

DRAFT

B. Kyab

**DESIGN REPORT
TEVATRON 1
PROJECT**

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1. INTRODUCTION AND OVERVIEW

This report describes the design of the Tevatron I Project, which will enable Fermilab to produce proton-antiproton collisions in the Tevatron accelerator. Center-of-mass energies near 2 TeV, by far the highest available anywhere in the world for high-energy physics research until at least the decade of the 1990's, will provide enormous opportunities for exciting new physics.

After the energy, the most important parameter determining the utility of a colliding-beam facility is the luminosity, or interaction rate per unit cross section. The first goal of the Tevatron I project is to achieve a peak luminosity of $10^{30} \text{cm}^{-2} \text{sec}^{-1}$ for proton-antiproton collisions at the maximum energy in the Tevatron.

The luminosity depends on the intensity and phase space density of the interacting beams. The design luminosity of $10^{30} \text{cm}^{-2} \text{sec}^{-1}$ can be achieved with as few as 1.8×10^{11} protons and 1.8×10^{11} antiprotons of appropriate phase space density. The number and phase-space density of antiprotons produced by bombarding a dense target with one pulse of protons from the Main Ring are too small by orders of magnitude to achieve the design luminosity. Thus it is necessary to collect many pulses of antiprotons in an accumulator ring and to increase their phase-space density, i. e. to cool them, by roughly six orders of magnitude. To minimize user frustration and maximize the average luminosity, the accumulation time should be as short as possible, at least short compared to the luminosity lifetime, which is expected to be larger than thirty hours. The second goal of the project is to accumulate and cool the required number of antiprotons in five hours or less, starting with no antiprotons in the Accumulator.

The design presented here to meet these goals is based on the method of stochastic cooling developed by van der Meer, Thorndahl, and coworkers.¹ This method generates a non-uniform phase-space density distribution of the accumulated antiprotons, with only the high-density core useful for colliding beams. Thus the source has been designed to accumulate a total of 4.3×10^{11} antiprotons in 4 hours, of which typically 1.8×10^{11} antiprotons from the high-density core will be injected into the Tevatron. Subsequent accumulation cycles starting with the antiprotons left from the previous cycle will require considerably shorter times to achieve the necessary core density.

The amount of cooling to be done depends on the phase-space density at production. The higher the initial density, the easier it is to achieve the final density. The yield of antiprotons per incident proton is proportional to the product of the spatial solid angle and the momentum spread accepted by the beam-transport system, and the initial phase-space density can therefore be increased only by decreasing the spot size and time spread of the antiprotons. The initial protons that produce the antiprotons determine these parameters and it is therefore useful to reduce the proton spot size and time spread.

The proton rms spot size will be reduced to 0.38 mm by the use of standard quadrupole lenses. Further reduction would provide little gain because the apparent spot size is ultimately dominated by the large antiproton beam divergence and the finite length of the target.² The first collection lens must match the large angular divergence of the antiproton beam at the target into the small angular admittance that is characteristic of a beam-transport system or a storage ring. This is achieved by using a lithium lens of the type developed by the Institute of Nuclear Physics at Novosibirsk.³

The time spread can be minimized by rf manipulation of the proton beam in the Main Ring just prior to extraction. The narrow time spread and large energy spread of the resulting antiproton bunches can be transformed into bunches with a much lower energy spread by rf phase rotation in a separate ring called the Debuncher. The rf phase-rotation system⁴ makes it possible to start with a large momentum spread from the target, thereby increasing the antiproton flux. The reduced energy spread also greatly simplifies the design of the magnets and cooling systems of the Accumulator ring.

The design thus uses two fixed energy rings, the Debuncher and the Accumulator, located south of the Booster as shown in Fig. 1-1. The Accumulator has the same circumference as the Booster; the Debuncher is slightly larger. Both rings operate at a kinetic energy of 8 GeV, the Booster energy. The sequence of operations leading to colliding beams involves seven steps:

1. Proton Acceleration for Antiproton Production. Every two seconds, one Booster batch containing 2×10^{12} protons in 80 rf bunches is accelerated in the Main Ring to 120 GeV and held at that energy while the rf manipulation described in the next step is carried out.

2. Preparation of Protons for Targeting. The 53-MHz rf voltage is lowered to cause each proton bunch to spread in time to 9 nsec. The rf voltage is suddenly increased to 4 MV per turn and each proton bunch rotates by 90° in phase space in 1.3 msec to a short bunch of less than a nanosecond in width, but with an energy spread of about 0.4%. This train of short bunches is extracted from the Main Ring at F17 as soon as the bunch rotation is completed.

3. Antiproton Production and Transport. The short proton bunches strike a tungsten target, producing a train of 80 equally short antiproton bunches. The peak energy deposition in the target is the same as that used successfully at CERN. 1.1×10^8 8.9 GeV/c antiprotons are collected by the lithium lens and transported to the Debuncher. The momentum spread of the beam is 3% and the transverse beam emittances are 20π mm-mrad in each plane.

4. Bunch Rotation in the Debuncher. The antiprotons are injected into 53-MHz rf buckets in the Debuncher. The rf voltage is large enough

that the antiproton bunches rotate just as the proton bunches rotated in the previous step. After a quarter of a synchrotron oscillation, the narrow time structure and large momentum spread have been transformed into a small momentum spread and a broad time structure. The rf voltage is then rapidly lowered to match the bucket to the rotated bunch, and finally adiabatically lowered to reduce the momentum spread to 0.2%.

5. Transverse Cooling in the Debuncher. After the rf manipulations, the horizontal and vertical transverse emittances are stochastically cooled in the Debuncher from 20π mm-mrad to 7π mm-mrad during the almost two seconds before the next antiprotons are to be injected.

6. Antiproton Accumulation and Cooling. The antiprotons are extracted from the Debuncher and injected into the Accumulator. Successive batches are accumulated by rf stacking each batch at the edge of the stack. Between injection cycles, the stack is stochastically cooled using a combination of longitudinal and transverse cooling systems similar to the types developed by CERN for the AA ring.⁵ A new batch of antiprotons with a density of about 7 antiprotons per eV is deposited at the stack tail every 2 sec. The fresh batch is moved by the coherent force of the stochastic-cooling system away from the injection channel and toward the center of the stack. The strength of the coherent force diminishes exponentially as the particles move away from the edge of the tail, causing the particle density to increase. Diffusion forces resulting from the Schottky noise of the antiproton stack and the thermal noise of the amplifiers cause the antiprotons to migrate from the high-density region toward the low-density region. As long as the coherent force is greater than the diffusion forces, the stack builds up in intensity until it reaches the core region where the coherent force is zero. Some antiprotons are lost during transfer and rf stacking and some diffuse away from the stack into the chamber walls. Allowing for losses, 6×10^7 antiprotons are stacked in each pulse. In 4 hours, the core will grow to a density of 1.0×10^5 antiprotons per eV. The total number of antiprotons in the core will be 4.3×10^{11} . During this time the transverse cooling systems will have reduced the horizontal and vertical emittances to 2π mm-mrad.

7. Filling the Tevatron. After accumulation is complete, antiproton bunches of the desired intensity are individually extracted from the core, transferred to the Main Ring, accelerated to 150 GeV and injected into the Tevatron. The same number of proton bunches of similar intensity are prepared in the Main Ring and injected into the Tevatron. Whether it is better to inject the protons or antiprotons first will be determined empirically. Both beams are then simultaneously accelerated to the desired energy.

Sufficient antiprotons for a luminosity of $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ can be produced in 4 hours by this sequence, even with reasonable losses in production, cooling, and beam transfer. The project includes a Main Ring beam overpass

at B0 to allow antiproton accumulation to proceed in parallel with colliding beams in the Tevatron. The design luminosity can be achieved without exceeding a beam-beam tune shift of 0.0018 per crossing. As the Tevatron and the Antiproton Source become more reliable, longer collection times will become practical, resulting in higher luminosity.

Beam accumulation techniques are developing rapidly and it seems highly advisable to design an antiproton source that can accommodate future improvements. Accordingly, the third goal of this design is to incorporate flexibility for future improvements so that the Antiproton Source may ultimately achieve a luminosity of $10^{31}\text{cm}^{-2}\text{sec}^{-1}$. The potential for luminosity of the proposed source is exhibited in Table 1-I, which shows the relationship between the number of accumulated antiprotons and the luminosity.

The peak luminosity and accumulation rate are limited not by the antiproton production rate but by the cooling systems of the Accumulator Ring. Higher luminosities may be achieved through improvements in these cooling systems. The present design uses less than a half of the total number of particles collected in each accumulation cycle to reach its design luminosity of $10^{30}\text{cm}^{-2}\text{sec}^{-1}$. If future improvements can increase the final density by a factor of three, it will be possible to approach a luminosity of $10^{31}\text{cm}^{-2}\text{sec}^{-1}$. The design of the rings therefore includes provisions (aperture and straight-section space) for:

- (i) Momentum precooling in the Debuncher,
- (ii) Improved stochastic cooling in the Accumulator,
- (iii) Improved Main Ring extraction for antiproton production.
- (iv) Intermediate energy electron cooling in the Accumulator.

Other future improvements may include:

- (v) A superquadrupole to reduce beam size in the interaction region.

These features are not part of the initial design because it is difficult to foresee which improvements will be most feasible and cost-effective. The most beneficial choices will be clear only after some experience in operating the collider.

The design of each system and some possible future improvements are described in greater detail in the following sections.

Table 1-I. LUMINOSITY PROGRESSION

$N_{\bar{p}}$ (10^{11})	N_p (10^{11})	N_B	N_T (10^{11})	L ($10^{30} \text{cm}^{-2} \text{sec}^{-1}$)
0.8	0.8	1	0.8	0.65
0.6	0.6	3	1.8	1.0 (design goal)
0.8	0.8	3	2.4	2.0
1.0	1.0	3	3.0	3.0
1.0	1.0	6	6.0	6.0

$N_{\bar{p}}$ and N_p are the numbers of antiprotons and protons per bunch, N_B is the number of bunches, N_T is the total number of antiprotons, $\beta^* = 1 \text{ m.}$ is the value of β at the center of the interaction region, and L is the luminosity.

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2. PROTON ACCELERATION AND EXTRACTION FOR ANTIPROTON PRODUCTION

The production of antiprotons is done by bombarding a target with protons which have been accelerated to 120 GeV in the Main Ring. This chapter describes the acceleration of protons in the Main Ring and their subsequent extraction at F17.

2.1 Proton Acceleration

The accumulation cycle begins by accelerating a single Booster batch of protons in the Main Ring to 120 GeV with the existing rf system. This Booster batch consists of a string of 82 bunches spaced by 5.6 m; its total length is 457 m. A single batch fills less than one-thirteenth of the Main Ring circumference. The Booster intensity record for a single batch is 3.4×10^{12} . For the purpose of this report, it is assumed that an intensity of less than 2.0×10^{12} protons per Booster batch will be standard operating intensity for \bar{p} production. The minimum time needed to accelerate a single batch to 120 GeV in the Main Ring can be reduced to 1.87 seconds. A flat-top of less than 0.13 sec is added to provide time for the rf beam manipulation before extraction. The cycle time is 2 seconds. The major beam properties are given in Table 2-I.

A reasonable estimate for the normalized betatron emittance, based on measurements,¹ is 24π mm-mrad. This value includes 95% of the beam. If $\sigma_{H,V}$ denotes the rms beam size and $\beta_{H,V}$ the lattice amplitude function, the emittance can be expressed in terms of these quantities as

$$\epsilon_{H,V} = 6\pi \frac{\sigma_{H,V}^2}{\beta_{H,V}} .$$

The longitudinal phase-space area S of individual bunches in a booster batch has been measured to be 0.3 eV-sec or less.² If the particle distribution is biGaussian in these variables, this value includes 95% of the beam. There is reason to believe this number could be reduced to 0.2 eV-sec in the future when improvements are made to the Main Ring and the Booster rf systems.

For energies well above the transition energy, a bunch area S half as large as the bucket area, and a bunch shape matched to the rf bucket, the rms bunch length σ_e and rms momentum spread σ_p/p are

$$\sigma_e = (142\text{cm}) \frac{S}{\sqrt{VE}} \quad \sigma_p/p = (0.0112) \frac{S}{\sqrt{E^3/V}} .$$

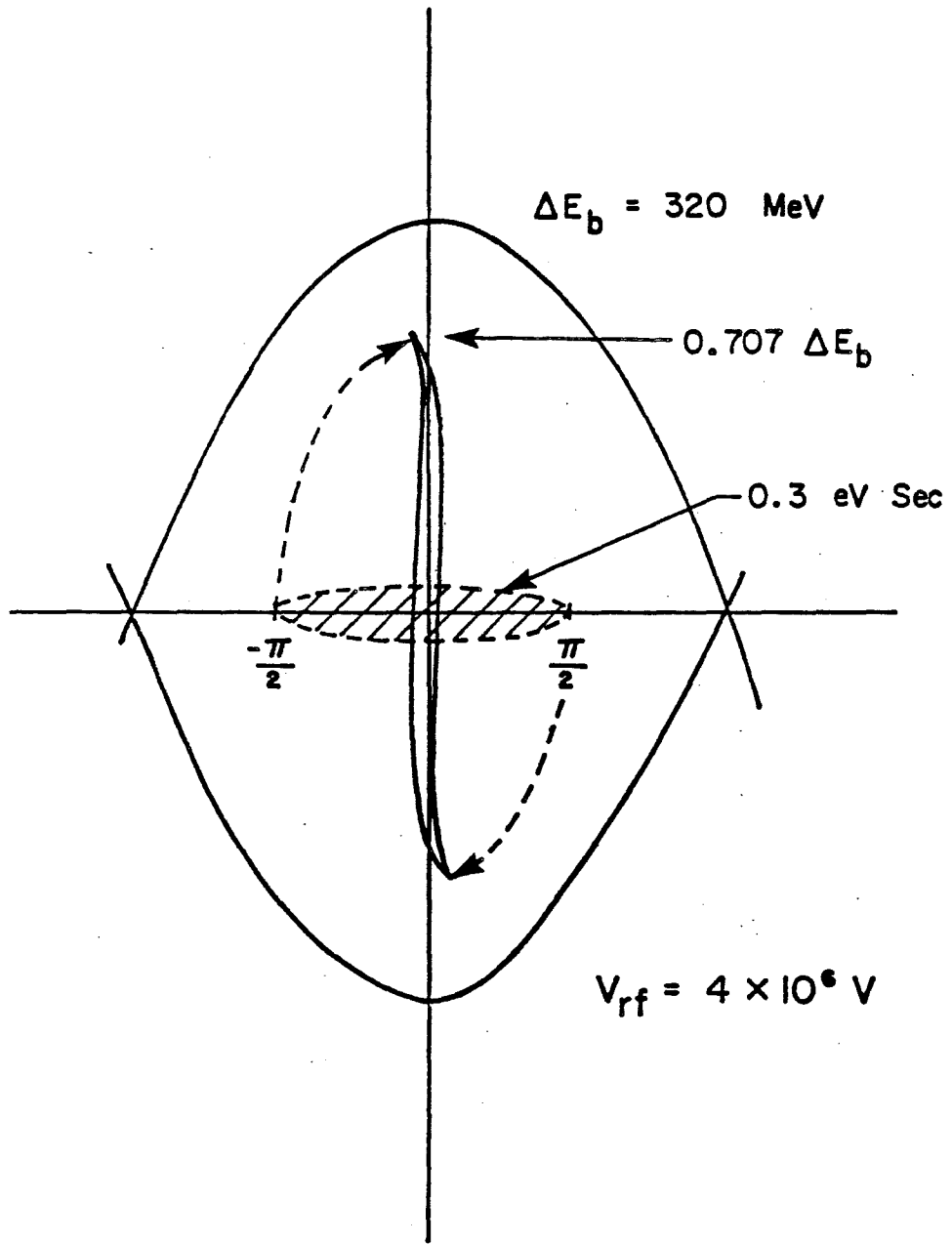


Fig. 2-1

The bunch area can be expressed in terms of these quantities as

$$S = 6\pi\beta E \frac{\sigma_e}{c} \frac{\sigma_p}{p} .$$

The bucket area of a stationary bucket B and the phase oscillation period T_s are respectively

$$B = (0.34 \text{ eV-sec}) \sqrt{VE} \quad T_s = (1\text{msec}) \sqrt{E/V} .$$

In all these equations E is in GeV, V in MV and S in eV-sec.

For a fixed antiproton momentum spread, the bunch area of the antiprotons is minimized by making the time spread of the extracted proton bunches as narrow as possible. At the end of acceleration when the rf voltage is 4 MV the relevant beam parameters are $T_s = 5.6$ msec, $\sigma_e = 16$ cm, $\sigma_p/p = 2.4 \times 10^{-4}$.

The rf voltage is slowly reduced from 4 MV to 30 kV so that the bunch motion remains matched to the rf bucket shape. At 30 kV, the beam parameters are $T_s = 65$ msec, $\sigma_e = 56$ cm, and $\sigma_p/p = 6.8 \times 10^{-5}$. The adiabatic reduction of the rf voltage is accomplished in 100 msec. At that moment the synchrotron phase of the bunch extends to $\pm 90^\circ$.

The rf voltage is then raised abruptly to 4 MV within two revolutions or 42 μ sec. The bunches are no longer matched to the buckets, so they start to rotate as in Fig 2-1. After a quarter of a phase oscillation or 1.4 msec, the time spread of the beam has been reduced by more than an order of magnitude. At that moment the beam parameters are $T_s = 5.6$ msec, $\sigma_e = 5.0$ cm, and $\sigma_p/p = 8.4 \times 10^{-4}$. After these operations are completed, a momentum spread of 0.4% contains 95% of the beam.

The results of recent bunch narrowing experiments in the Main Ring at 120 GeV (March 1982)², are shown in Figs. 2-2, 2-3, and 2-4. In these experiments the maximum rf voltage was limited to 3.6 MV. Shorter bunches can be obtained by using the full available 4 MV.

Measurements made in the Main Ring³ have shown that the available momentum aperture is $\pm 0.27\%$ for 90% beam transmission at 120 GeV with extraction equipment for the Tevatron in place. The loss of beam due to the 0.4% momentum spread is expected to be small, since very little of the beam will extend into the bad-field region of the aperture. As soon as the bunch rotation is complete, all 82 bunches are ejected at F17 into the 120-GeV transport line.

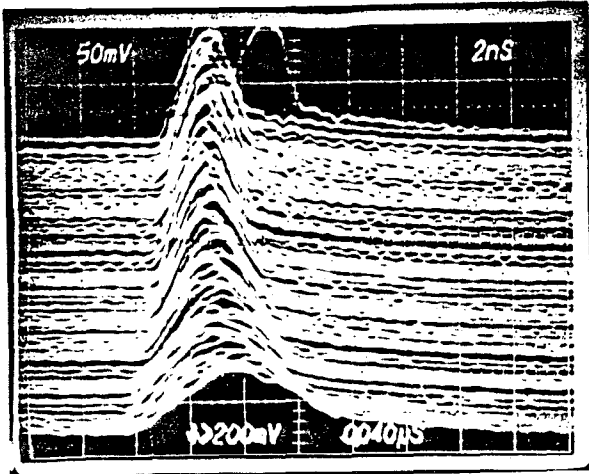


Figure 2-2

Bunch broadening resulting from slow reduction in rf voltage. Time progresses downward and total debunching time is 100 msec. Final bunch length is near 9 nsec.

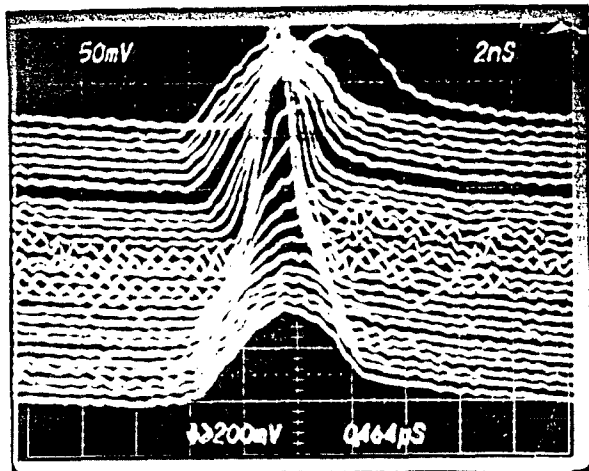


Figure 2-3

Rotation of mismatched bunch following sudden increase in rf voltage to 1 MV. Time progresses downward and traces are separated by about 100 msec. The displaced top trace is a mistrigger.

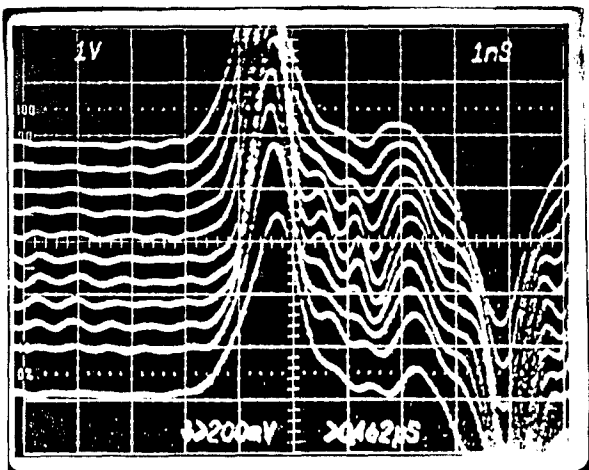


Figure 2-4

Bunch length pictures near the narrowest bunch time. Traces are separated by one machine turn, 20.9 μ sec. The narrowest bunch has length about 1 nsec. The beam pickup is a broadband transmission line pickup so inverted reflections from the downstream end of the pickup also appear. In this experiment the maximum rf voltage available was 3.6 MV. Narrower bunches can be obtained by using the full MV. A bunch with 95% full time width of 1 nsec corresponds to a physical length (one standard deviation) of 7.5 cm.

13.25
 1.50
 7050
 13250
 21200

13.25
 1.50
 7950
 66250
 132500

206600

Table 2-I. MAIN RING BEAM PARAMETERS

Proton Beam Kinetic Energy @ Extraction	120 GeV
Relativistic Factors: β	0.99997
γ	128.9318
B ρ , magnetic rigidity	4035.506 kG-m
Momentum, P	120.9347 GeV/c
Number of Booster batches accelerated	one
Number of Proton Bunches	82
Total number of protons per Batch	$<2.0 \times 10^{12}$
Main Ring Cycle Time	2.0 sec
Betatron Emittance, 95% of beam, (H and V)	$0.2\pi \mu\text{m}$
Longitudinal Emittance, 95% of beam at 120 GeV	0.3 eV-sec
RF harmonic number (h)	1113
RF Frequency @ 125 GeV	53.1035 Mhz
Revolution Period @ 125 GeV	20.96 μsec
Booster Batch Time Length	1.56 μsec
Transition Energy (γ_t)	18.75
Betatron tune number (H and V)	19.4
$\eta = \gamma^{-2} - \gamma_t^{-2}$	-0.0028
Maximum RF voltage	4.0 MV
Average Radius	1000 m

2.2 Extraction at F17

Extraction of 120-GeV protons from the Main Ring for the production of antiprotons takes place at location F17. Two Lambertson magnets deflect the extracted beam vertically by 32.2 mrad into the transport line, which is located just above the Main Ring magnets. The geometry and expected beam sizes at the Lambertsons are shown in Fig. 2-5 and 2-6. The horizontal beam size at 120 GeV includes the contribution of the $\pm 0.2\%$ momentum spread of the tightly bunched proton beam. The large horizontal size of the bunched beam uses most of the available Main Ring aperture to the inside of the Ring at the extraction point. As seen in Figs. 2-5 and 2-6, the septum of each Lambertson will be located well within the Main Ring aperture, preventing parasitic extraction at F17 during the 400-GeV slow-extraction HEP program. The Lambertsons will be withdrawn from the aperture during 400-GeV operation.

The relevant parameters of the Main Ring lattice are listed in Table 2-II.

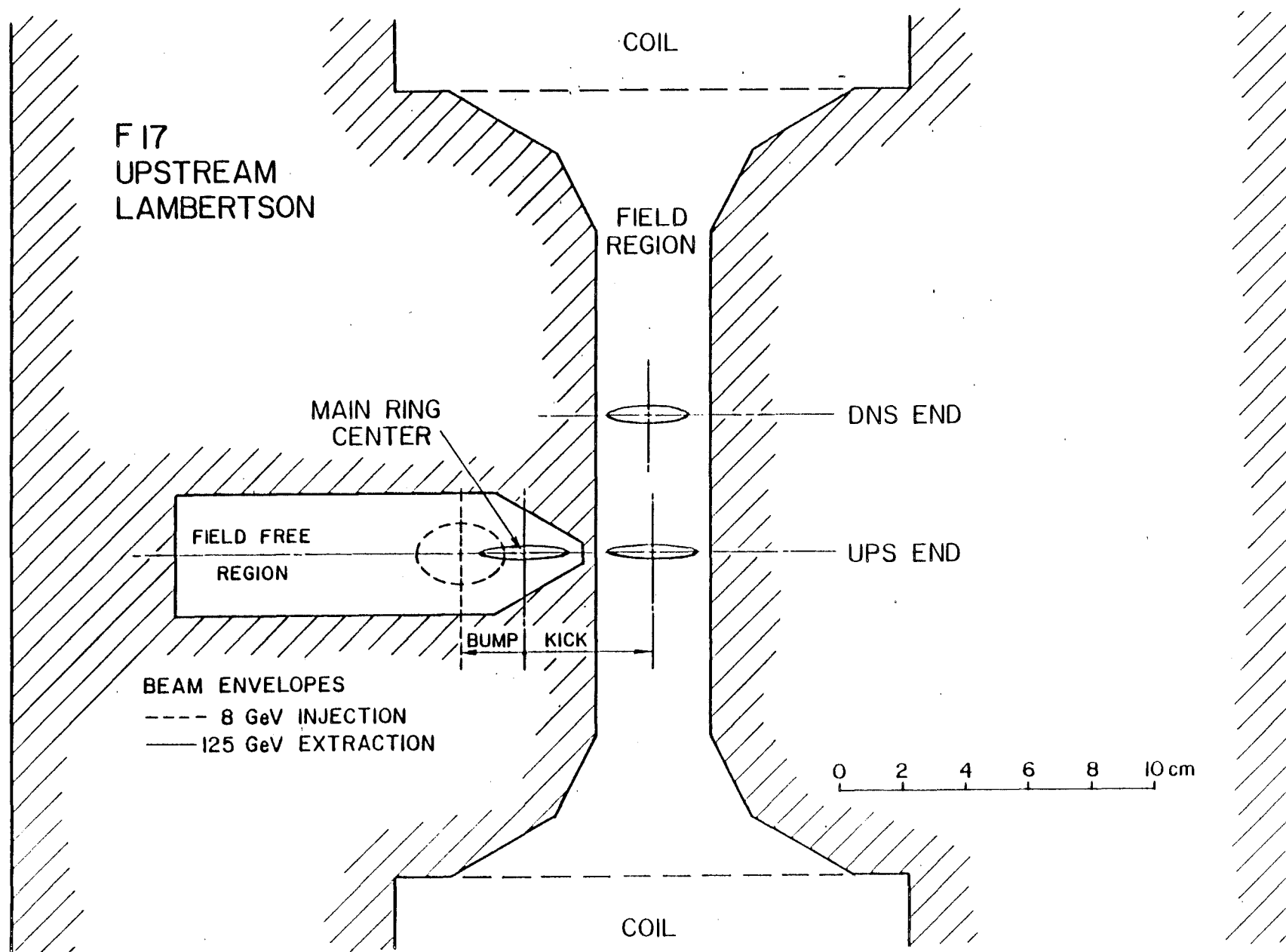


Fig. 2-5

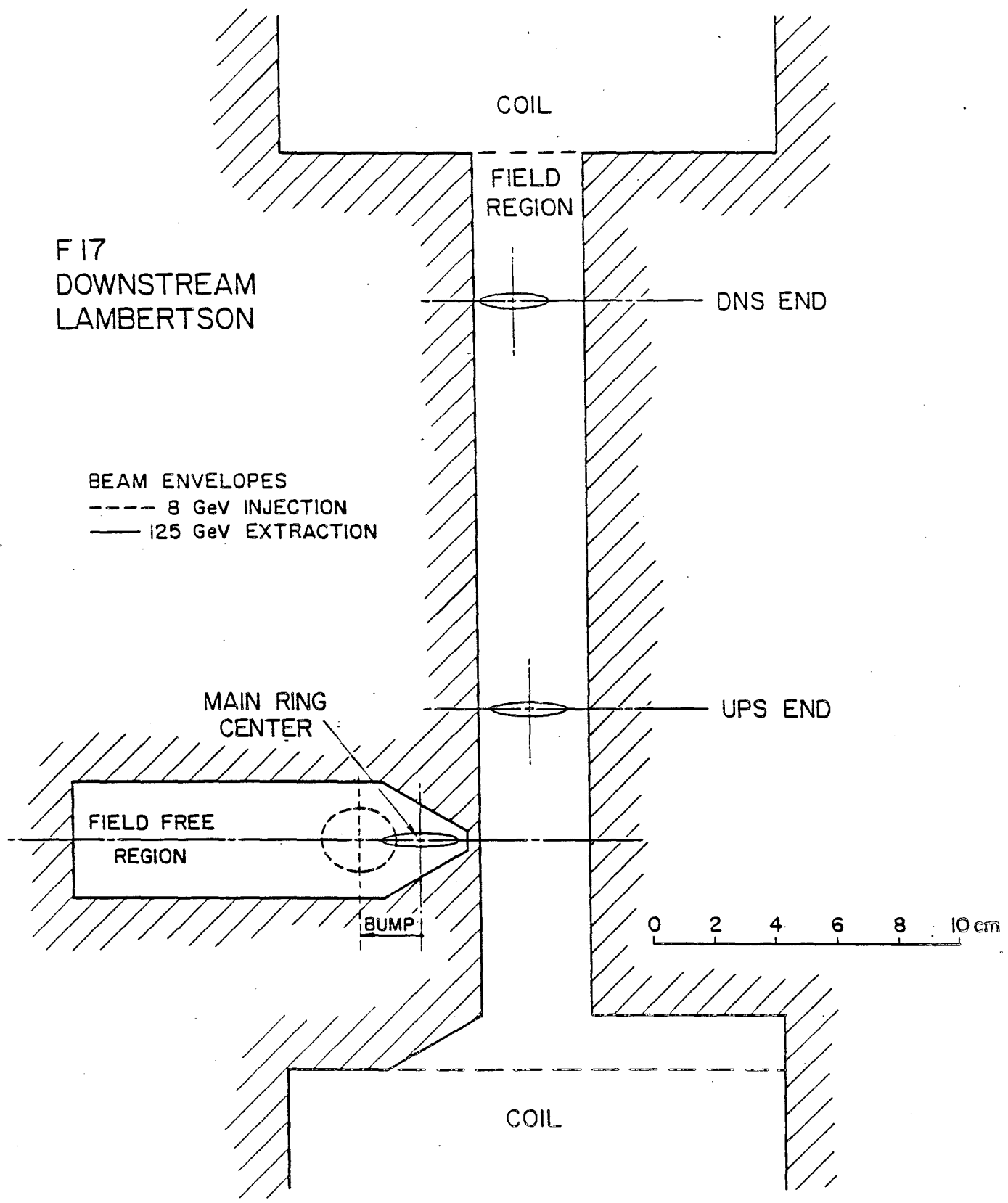


Fig. 2-6

Table 2-II. PROPERTIES OF SELECTED MAIN RING MINISTRIGHTS

Horizontal-Plane Lattice Functions

Location	β (m)	α	Phase Relative to F17 (Modulo 360°)	Space Available (in.)
C48 Kicker	102.4	0.467	-90.11°	(Existing)
F12	29.6	-0.573	-168.30°	0.0
F13	95.4	1.858	-135.74°	0.0
F14	28.4	-0.589	-99.29°	34.0
F15 (Bump 1)	97.3	1.839	-66.32°	42.5
F16	30.1	-0.624	-31.47°	42.0
F17 (Bump 2) (Extraction)	99.7	1.939	0.00°	32.0
F18 (Bump 3)	28.9	-0.558	35.20°	52.0
F19	94.3	1.816	68.42°	0.0
F21	28.9	-0.618	104.71°	28.0
F22 (Bump 4)	99.5	1.893	136.92°	27.5
F23	30.1	-0.598	171.32°	35.0
F24	97.4	1.906	203.21°	0.0
F25	28.4	-0.567	239.23°	35.0
F26	95.2	1.810	272.60°	43.5

The kicker at location C48 causes a -43 mm horizontal displacement at F17, which is sufficient to cross the Lambertson septum. The required angular deflection at C48 is obtained with a voltage of 60.0 kV, well within the present operating range of the device. Given the Main Ring lattice characteristics, the kick at C-48 results in an angular displacement of +0.847 mrad at F17 as well as the horizontal displacement. This residual angle can be cancelled with a 3° rotation of the first Lambertson extraction magnet.

A local four-magnet orbit bump at F17 is used to position the closed orbit during 8-GeV injection in the center of the restricted aperture at F17 and to move the orbit close to the Lambertson septa during 120-GeV extraction. Four standard 35-in. long bump magnets are placed at F15, F17, F18 and F22. The closed orbit at 120 GeV can be adjusted over a range of ±37 mm at location F17.

Vertical extraction was chosen since it allows the extracted proton beam to clear the Main Ring magnet, F17-1, just downstream of the Lambertsons with a minimum deflection. The return coil on the upstream end of F17-1 has been modified to permit the beam pipe containing the extracted

120-GeV to be as close to the magnet steel as possible. The length of the medium straight section at F17 limits the maximum energy that can be extracted to 120 GeV.

The Lambertson magnets are 204 in. long and are excited to less than 13 kG at 120 GeV. The second Lambertson accommodates a vertical beam translation of 5 in.

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3. ANTIPROTON PRODUCTION

3.1 Proton Transport from F17 to Target

The extraction energy for the protons to be used for antiproton production was 80 GeV in an earlier design. It was decided to raise this energy to 120 GeV in order to increase antiproton production. The earliest choice for a 120-GeV extracted beam was to upgrade the then-existing 80-GeV line, which extended 1000 feet from F17 to F25 within the Main Ring Tunnel. Although this design satisfied most of the project requirements, it possessed a number of undesirable features. Its estimated power consumption of 2MW would place a heavy burden on the operating cost of the Antiproton Source. The elements of the 80 GeV line were placed immediately above the Main Ring magnets, below which the Energy Saver magnets have now been installed. As a consequence, difficult operational problems would be encountered wherever work had to be performed on the Main Ring or the Energy Saver. It was necessary to dismantle the 80-GeV beam in many locations in order to install the Energy Saver. The location of the original \bar{p} hall, which is very close to F25, limited the ability to vary the proton targeting. The 80-GeV line had been put in the Main Ring tunnel because the 400-GeV operating schedule in 1977 and 1978 did not allow the several-month interruption that was believed to be needed to modify the Main Ring Tunnel at F18 in order to build a more flexible beam. This constraint is no longer relevant. For these reasons, a more efficient and flexible beam design was developed.

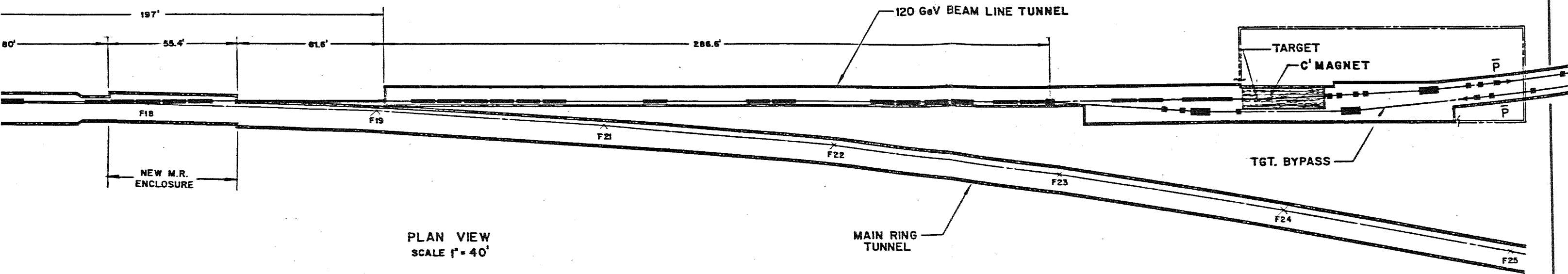
The design of the new 120-GeV proton transport line was based on the following requirements:

- (i) It must leave the Main Ring tunnel as close as possible to location F18.
- (ii) The target elevation is to be 7.0 feet above Main Ring beam height.
- (iii) It must transport a 120-GeV proton beam with a momentum spread of $\pm 0.2\%$.
- (iv) It must be possible to bypass the target and collection system in the reverse direction.
- (v) It must transport the 8.9-GeV/c cooled antiproton beam with an emittance of 2.0π mm-mrad.
- (vi) It must produce a round proton beam spot at the target which can be varied from 0.2 mm to 0.8 mm rms.
- (vii) It must have zero dispersion at the target.

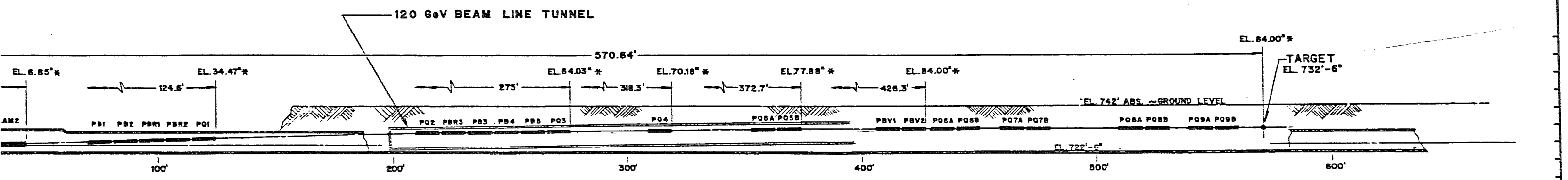
(viii) The power consumption must remain below 500 kW.

A layout of the beam is shown in Fig. 3-1 and its parameters are tabulated in Table 3-I. In Fig. 3-2 we show the behavior of the monoenergetic β_y , β_x , ζ_y , and ζ_x through the system from extraction to the target. The beam consists of 10 EPB dipoles excited to a field of 13 kG or less and 14-3Q120 quadrupoles excited to a field gradient of 4.75 kG/in. or less. Three of the dipoles, indicated by (R), are rotated by 45° to achieve the necessary vertical and horizontal bends with the minimum number of magnets. The Main Ring Tunnel must be widened over a distance of roughly 18 m in order to accommodate the four EPB dipoles and one 3Q120. The length of the beam is 174 m, of which 41 m is located in the Main Ring Tunnel. The remainder of the beam elements are located in a new 115-m long enclosure. The new enclosure and the Main Ring Tunnel are connected by an 18-m long pipe.

A 4.5° bending magnet, which bends the reverse antiproton beam to the left, is placed within the final focus section between PQ7B and PQ8A in order to allow the target and antiproton collection lens to be bypassed whenever cooled antiprotons are transported back to F17. The total power consumption of the beam is estimated to be less than 390 kw. In Table 3-II the gradients of the four final focusing quadrupoles, which obtain the required range of beam sizes, are listed.



PLAN VIEW
SCALE 1" = 40'



ELEVATION
SCALE 1" = 40'

* ABOVE MAIN RING BEAM

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
UNLESS OTHERWISE SPECIFIED		ORIGINATOR	
FRACTIONS DECIMALS		ANGLE	DRAWN <i>W. J. ...</i>
1	2	3	CHECKED
1. BREAK ALL SHARP EDGES 1/64 MAX.		APPROVED	
2. DO NOT SCALE DIMS.		USED ON	
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD.		MATERIAL	
✓ MAX. ALL MACHINED SURFACES			
 FERMI NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY			
120 GeV PROTON BEAM TRANSPORT LINE			
SCALE	PLANNED	DRAWING NUMBER	REV.
NOTED		Figure 3-1	A

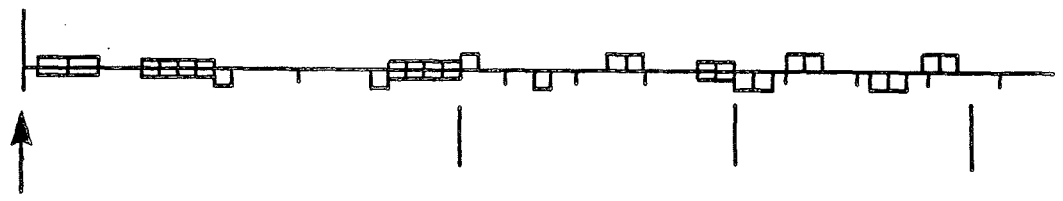
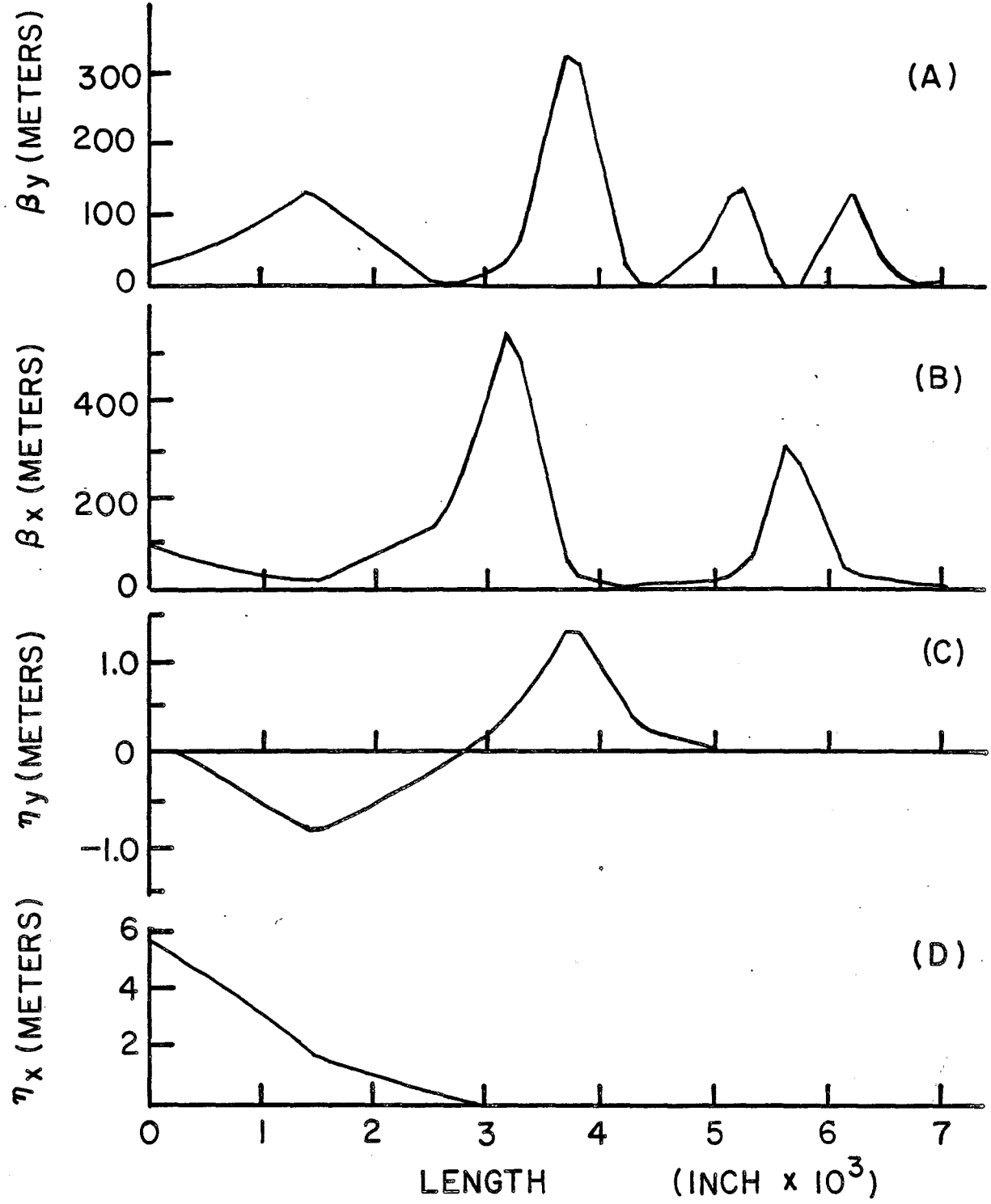


Fig. 3-2

Table 3-I. 120-GEV TRANSPORT ELEMENTS

NAME	DIST. TO F17(m)	TYPE	FIELD (T)	GRADIENT (T/m)	FUNCTION
P-LAM1	2.74	Lamberston	1.25		Bend up
P-LAM2	8.38	Lambertson	1.25		Bend up
PB1	21.7	EPB	1.271		Bend Left
PB2	25.0	EPB	1.271		Bend Left
PBR1	28.4	EPB (R)	1.271		Bend Left/Down
PBR2	31.7	EPB (R)	1.271		Bend Left/Down
PQ1	35.1	3PQ120		6.59	Vertical Focusing
PQ2	64.2	3PQ120		4.85	Vertical Focusing
PBR3	67.5	EPB (R)	1.271		Bend Right/Down
PB3	70.9	EPB	1.271		Bend Right
PB4	74.2	EPB	1.271		Bend Right
PB5	77.6	EPB	1.271		Bend Right
PQ3	80.9	3PQ120		12.09	Horiz. Focusing
PQ4	94.1	3PQ120		15.96	Vertical Focusing
PQ5A	107.3	3PQ120		18.30	Horiz. Focusing
PQ5B	110.7	3PQ120		18.30	Horiz. Focusing
PBV1	123.7	EPB	0.782		Bend Down
PBV2	127.0	EPB	0.782		Bend Down
PQ6A	130.7	3Q120		11.43	Vertical Focusing
PQ6B	134.1	3Q120		11.43	Vertical Focusing
PQ7A	139.6	3Q120		10.27	Horiz. Focusing
PQ7B	143.0	3Q120		10.27	Horiz. Focusing
PQ8A	154.9	3Q120		12.38	Vertical Focusing
PQ8B	158.3	3Q120		12.38	Vertical Focusing
PQ9A	163.9	3Q120		9.27	Horiz. Focusing
PQ9B	167.2	3Q120		9.27	Horiz. Focusing
TARGET	174.1				

Target Location in Site Coordinates

x = 585.94 feet
y = -2064.26 feet
z = 728.50 feet

Table 3-II. GRADIENT OF FINAL FOCUSING QUADRUPOLES
AS A FUNCTION OF BEAM SIZE AT THE TARGET, IN T/m.
(MAXIMUM GRADIENT 18T/m)
QUADRUPOLES

$\beta^*(m)$	$\sigma(mm)$	PQ6A/B	PQ7A/B	PQ8A/B	PQ9A/B
1.17	0.19	-13.2	+10.3	-12.1	+13.2
4.69	0.38	-11.4	+10.3	-12.4	+ 9.3
18.75	0.76	-10.3	+ 9.7	- 9.8	+ 2.0

3.2 Antiproton Yields and Targeting

The choice of the antiproton energy and that of the protons for their production depends on the production cross sections and practical considerations relative to the existing facilities at the Laboratory. This section describes the present targeting scenario for the production of antiprotons, based on the discussion of the three following topics:

1. details of the production cross sections obtained from existing experimental data;
2. the choice of primary proton energy, antiproton momentum, antiproton longitudinal acceptance and antiproton transverse acceptance; and
3. limitations introduced by targeting and the antiproton collection system.

3.2.1 Antiproton Production Cross Sections. The available experimental data on the cross sections for the production of antiprotons have been described by a phenomenological formula that includes the dependence on the incident proton energy, the antiproton momentum and the target nucleus.¹ For example, the yields of antiprotons from a tungsten target collected within a laboratory angle of 60 mrad for various proton energies are shown in Fig. 3-3. It can be seen that there is a plateau at 120 GeV for the production of antiprotons between 8 and 13 GeV/c.

3.2.2 Proton Energy. The yield of antiprotons per unit volume of phase space per unit time changes very slowly with proton energy above 150 GeV, when the Main Ring cycle time is taken into consideration. Although some gain in yield could be obtained by going to a higher energy, a proton energy of 120 GeV was chosen because it is the maximum energy that can be extracted from a medium straight section such as F17. F17 provides a convenient location for the Antiproton Source. The choice was also influenced by the rapid increase in operating cost as the energy of the

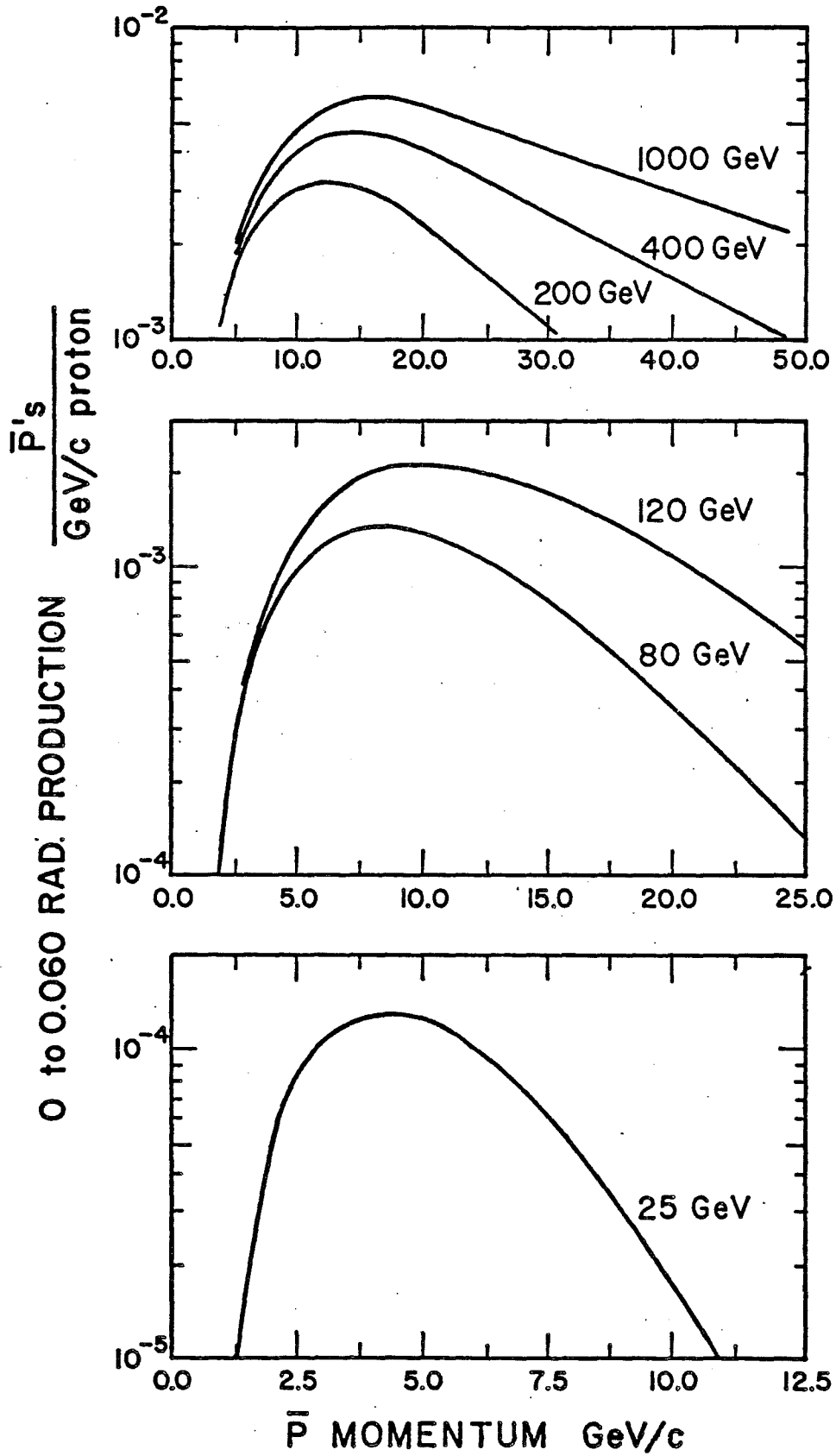


Fig. 3-3

Main Ring is increased. The energy of 120 GeV is also compatible with the Colliding Beams Detector overpass. The overpass, which is described in Chapter 7, will limit the maximum energy of the Main Ring to 200 GeV.

3.2.3 Antiproton Momentum. The optimum antiproton momentum is 10.0 GeV/c for an incident proton energy of 120 GeV. The yield is more than 90% of the optimum yield throughout the range from 7.5 GeV/c to 13.0 GeV/c. Since the normal injection momentum of the Main Ring, 8.89 GeV/c, is within this range of momenta, it is a reasonable choice. It has the advantage of permitting the transfer of antiprotons directly from the Accumulator to the Main Ring. In addition, it opens the possibility of utilizing protons directly from the Booster as an alternative source of particles during commissioning of the source.

3.2.4 Antiproton Longitudinal Acceptance. Stochastic cooling performance depends critically on the flux of \bar{p} 's injected into the Accumulator and on the particle density per unit of energy spread. This density, which is inversely proportional to the longitudinal emittance of the antiprotons, is determined in part by the time spread of the \bar{p} 's at production, as discussed in Chapter 2.

The Debuncher can debunch a total momentum spread of approximately 3% into a momentum spread that can be accommodated by the Accumulator. Although a larger momentum spread will result in a larger flux the Accumulator is not able to cool the larger flux. The \bar{p} collection and transport system is designed to accept 4% total momentum spread. The momentum spread of the \bar{p} 's transported to the Debuncher will be adjusted by collimation in the beam transport.

3.2.5 Antiproton Transverse Acceptance. The calculation of expected antiproton yields depend crucially on the collection system downstream of the target. A comparison of different collection systems has been performed², taking into account the large momentum spread of the antiproton beam. The advantages of a device such as the lithium lens that was developed at the INP in Novosibirsk³ are clear. It has a very short focal length and it focuses in both transverse planes. Based on the INP experience, the parameters of the lithium lens collector were chosen to be: Radius = 1 cm, Gradient = 1000 T/m, Length = 15 cm. Within the present technology developed at Novosibirsk, a repetition rate of 1 Hz is feasible. The lens has a focal distance of 14.5 cm. The short focal distance requires the use of a dense target.

Antiprotons yields have been calculated with a Monte Carlo program¹ that includes the phenomenological description of the production cross section, the development of hadronic showers in the target and \bar{p} production by secondaries, multiple scattering and absorption. The result of these calculations is shown in Fig. 3-4 for two different rms proton beam spot sizes, $\sigma_x = \sigma_y = 0.038$ cm and $\sigma_x = \sigma_y = 0.22$ cm. The number of antiprotons

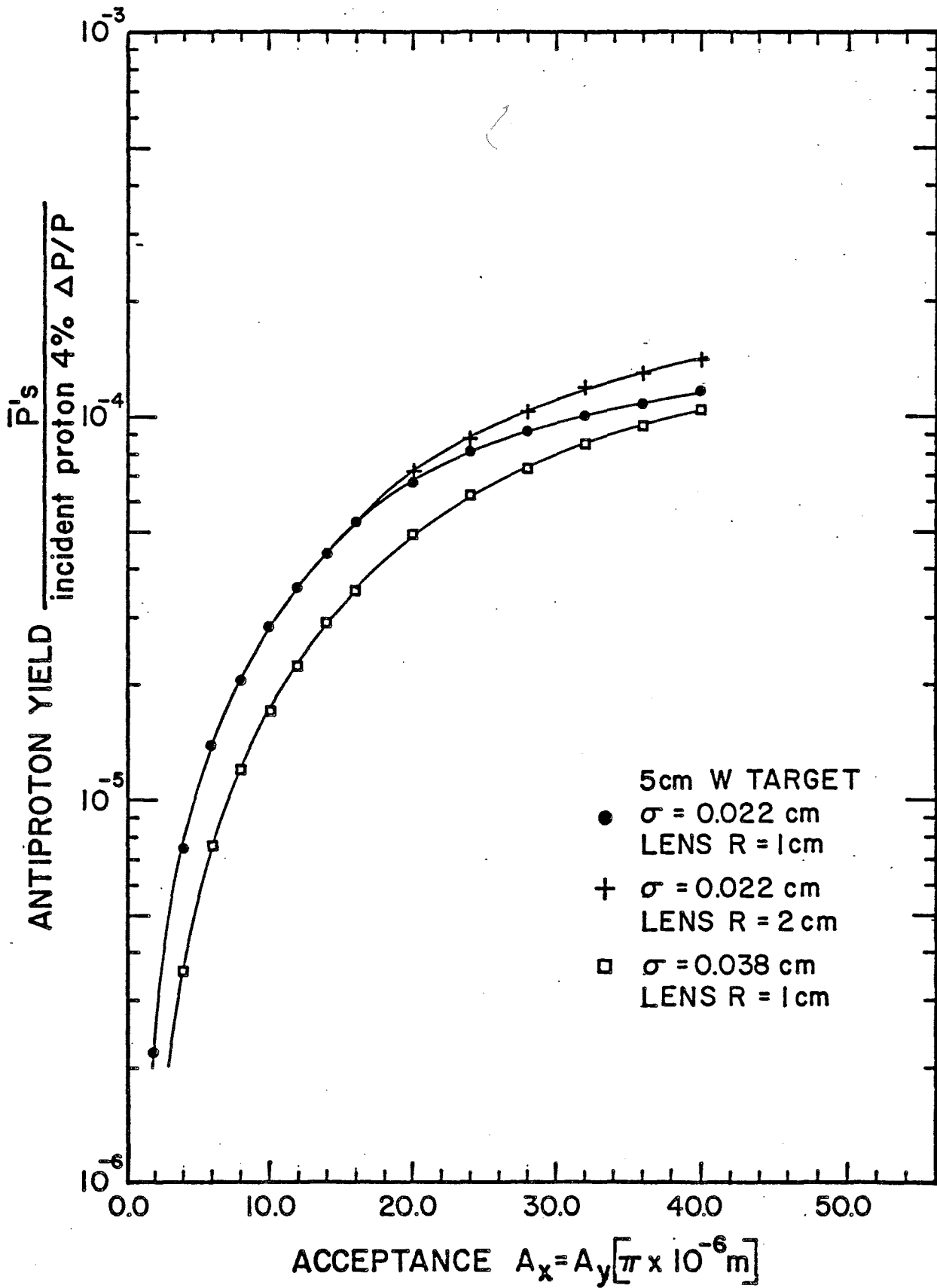


Fig. 3-4

increases approximately linearly with the transverse acceptance above 20π mm-mrad for $\sigma=0.038$ cm. For the smaller beam size, the departure from linearity above 20π mm-mrad is caused by the lithium lens radius and its gradient. The optimum target length is approximately 5 cm.

3.2.6 Targeting Limitations. Decreasing the proton beam size at the target increases the transverse phase-space density of the produced antiprotons, resulting in a larger yield within a given acceptance. The diameter of the proton beam cannot be reduced arbitrarily since the energy deposited by the beam per unit volume increases as the beam area decreases, causing the target to overheat.

The subject of high energy density deposition in targets was the subject of a Fermilab Workshop⁵. It was generally agreed that metal targets can sustain energy density deposition up to 200 Joules gm⁻¹ before the apparently onset of shock waves that could result in the destruction of the target. Calculations indicate that the CERN Antiproton Accumulator target sustains a maximum energy deposition of approximately 185 Joules/gm for tungsten. Both copper and rhenium (instead of tungsten) have been used at CERN for some time with no failures. The energy density deposited by a 120-GeV proton beam in tungsten has been calculated using the program MAXIM⁴. The maximum energy density deposited within a 5-cm long target is shown in Fig. 3-5 versus the rms size of the proton beam, σ . Within the errors of the calculation, it varies as σ^{-2} . Also shown is the maximum number of protons per pulse vs rms beam size, under the condition that the maximum allowable energy density is 200 Joules/gm.

Table 3-III shows the expected number of antiprotons per pulse as a function of beam size and maximum permissible proton intensity.

A feasibility study was carried out⁶ on sweeping the proton beam across the target to decrease the energy density deposited in the material. The antiproton acceptance must be simultaneously swept to track the proton beam spot. If the sweeping covers several proton-beam diameters, it is possible to target 3×10^{12} protons on beam spots corresponding to $\beta < 3$ m, which will give an increased number of antiprotons accepted per proton. The design of the target area makes it possible to incorporate a beam-sweeping system in the future.

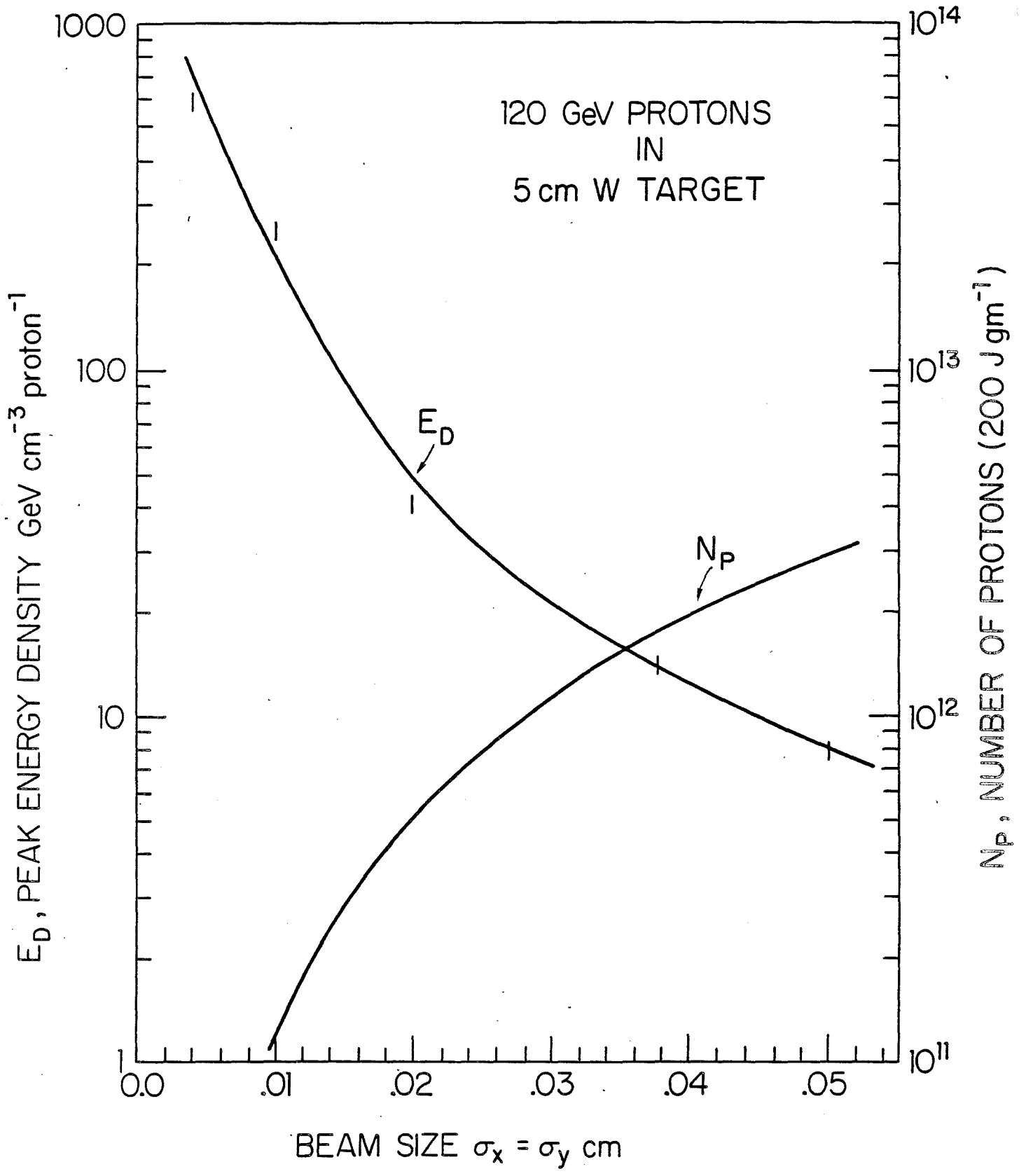


Fig. 3-5

Table 3-III. NUMBER OF ANTIPROTONS PER PULSE

$\beta^*(m)^+$	$\sigma_x = \sigma_y$ (cm)	N_p Max.	\bar{p}/p	\bar{p}/pulse
1.55	0.022	6.0×10^{11}	6.8×10^{-5}	4.1×10^7
3.07	0.031	1.2×10^{12}	4.9×10^{-5}	6.8×10^7
4.62	0.038	1.8×10^{12}	4.9×10^{-5}	8.8×10^7
8.00	0.050	3.0×10^{12}	3.3×10^{-5}	9.9×10^7

Notes: + β^* is for the proton beam at the center of the target
 $(\beta_x = \beta_y = \beta^*)$.
 † The yield in \bar{p}/proton is for 4% $\Delta p/p$ and 20π mm-mrad.

3.3 Antiproton Target System Components

The principal components of the target system are the target itself and the antiproton collection device. This section discusses the design and limitations of these two components.

3.3.1 Antiproton Production Target The computer code MAXIM⁴ has been used to calculate radial and longitudinal energy density distributions in a stationary tungsten target for an rms beam size of 0.038 cm. The results are plotted in Fig. 3-6. The temperature rise of tungsten corresponding to an energy deposition in Joules/gm may be estimated from the enthalpy reserve curve given in Fig. 3-7. As is shown in Fig. 3-6 it is anticipated that local peak energy densities will be approximately 200 Joules/gm for the present design parameters $\sigma = .038$ cm and 2×10^{12} protons per pulse. To decrease the number of thermal and stress cycles in the volume of material struck by the beam, the target will be rotated continuously, exposing a new volume of material to each beam pulse. Two possible configurations are shown in Figs. 3-8 and 3-9. During the target development stage the wedges shown in Fig. 3-8 will contain different materials to allow for comparative testing. Provision is also being made to test stationary targets of the CERN design.

The target must have a high density and high melting point. A compilation of mechanical properties for different materials was performed. A figure of merit to compare the mechanical properties is given by the yield stress divided by the coefficient of thermal expansion and the modulus of elasticity. On this basis rhenium, tungsten and tungsten-rhenium alloys are in increasing order for this figure of merit. The coefficient of heat conductivity could also be included in the figure of merit without significantly altering the choice of material.

The high-temperature behavior of tungsten-rhenium alloys shows considerable increase of yield stresses with respect to tungsten, but little change in the coefficient of thermal expansion or the modulus of elasticity. Tungsten-rhenium alloys are utilized in industry for

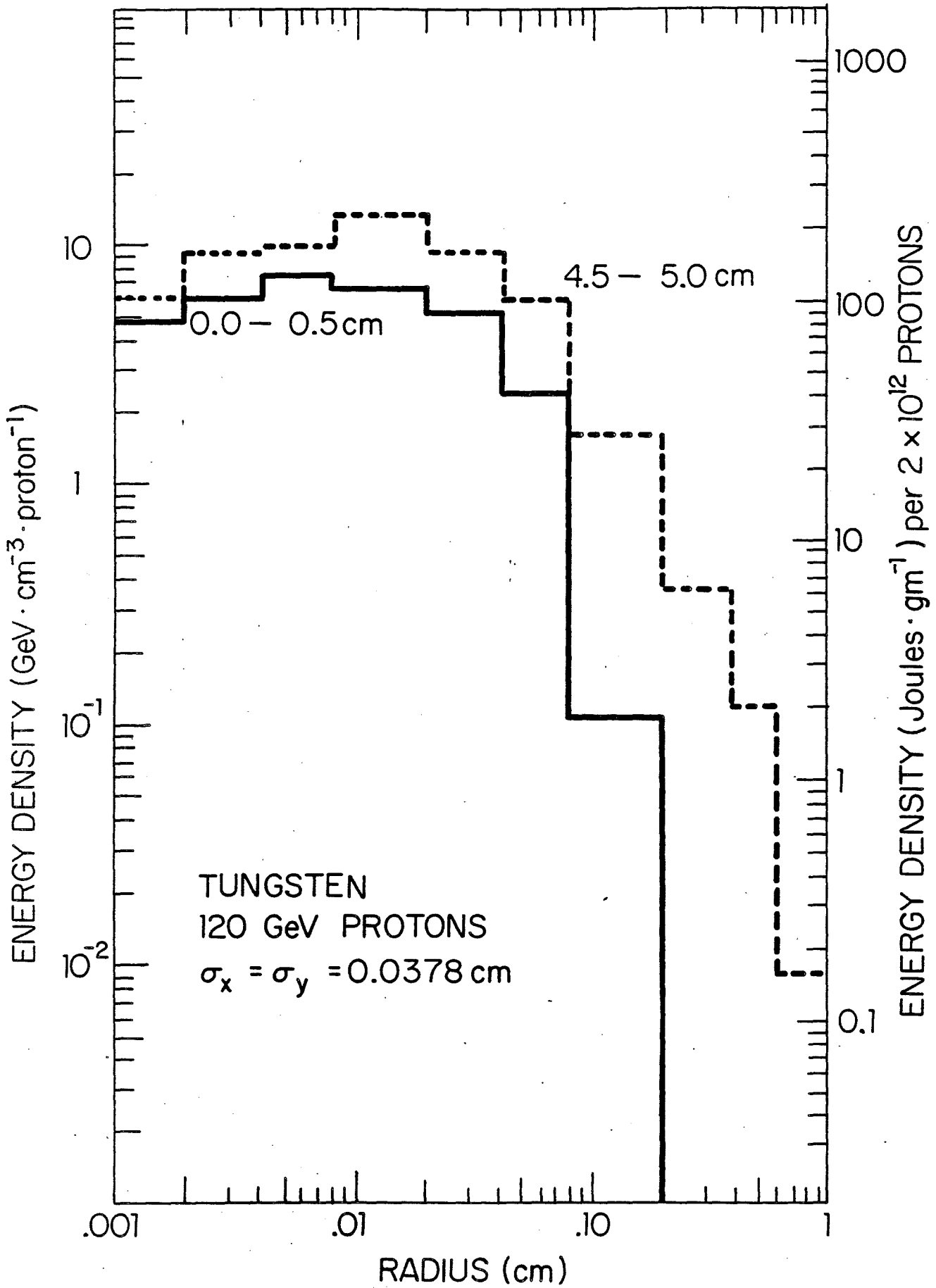


Fig. 3-6

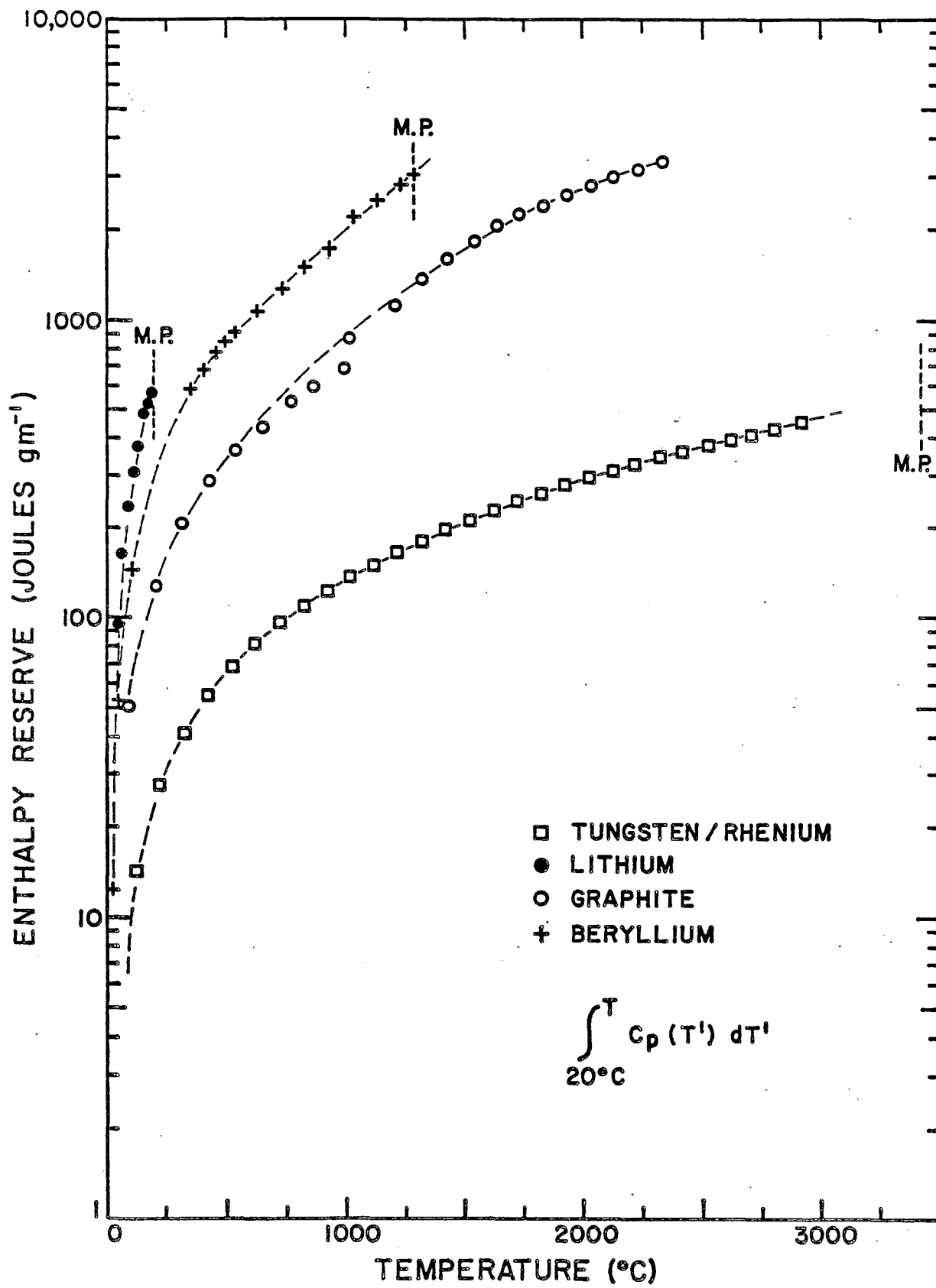
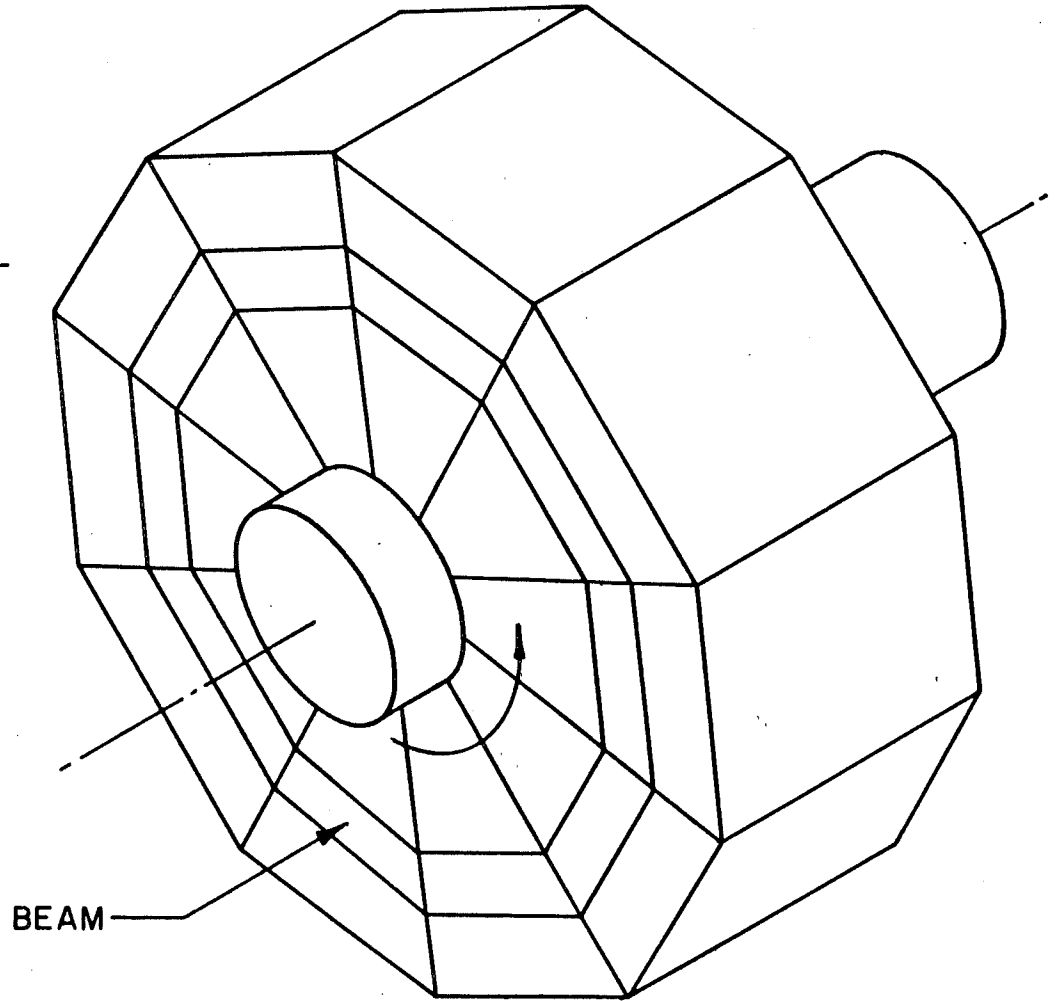
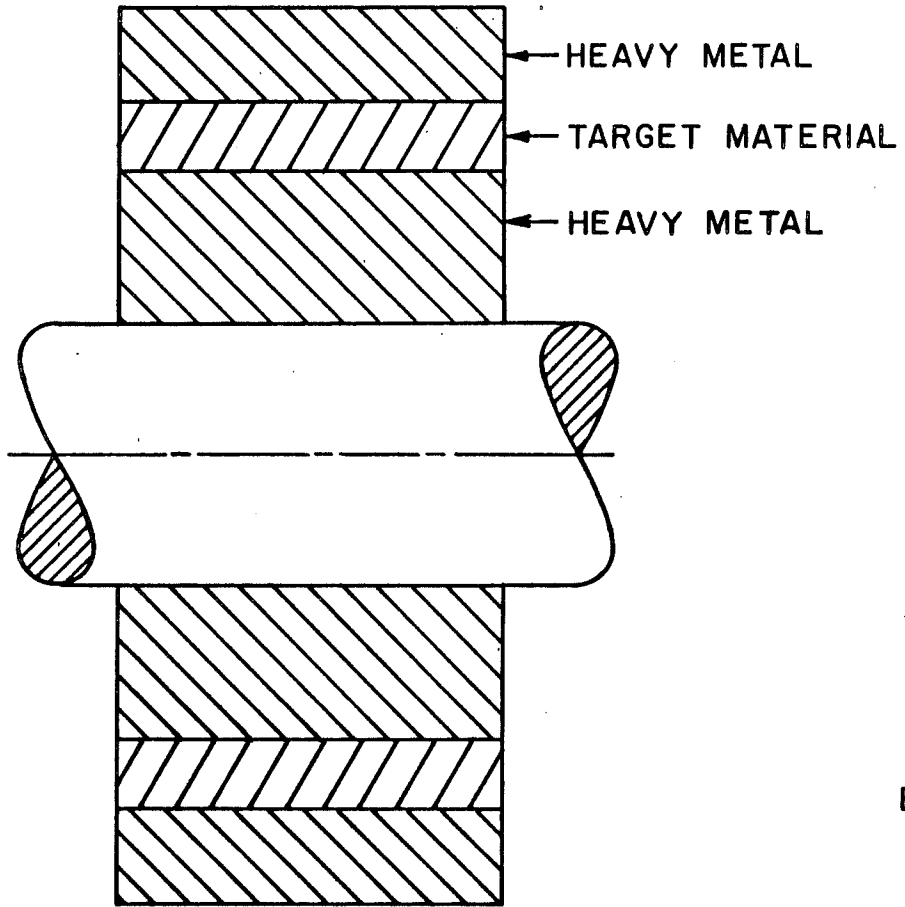


Fig. 3-7



0 1 2 3 4 5 cm

Fig. 3-8

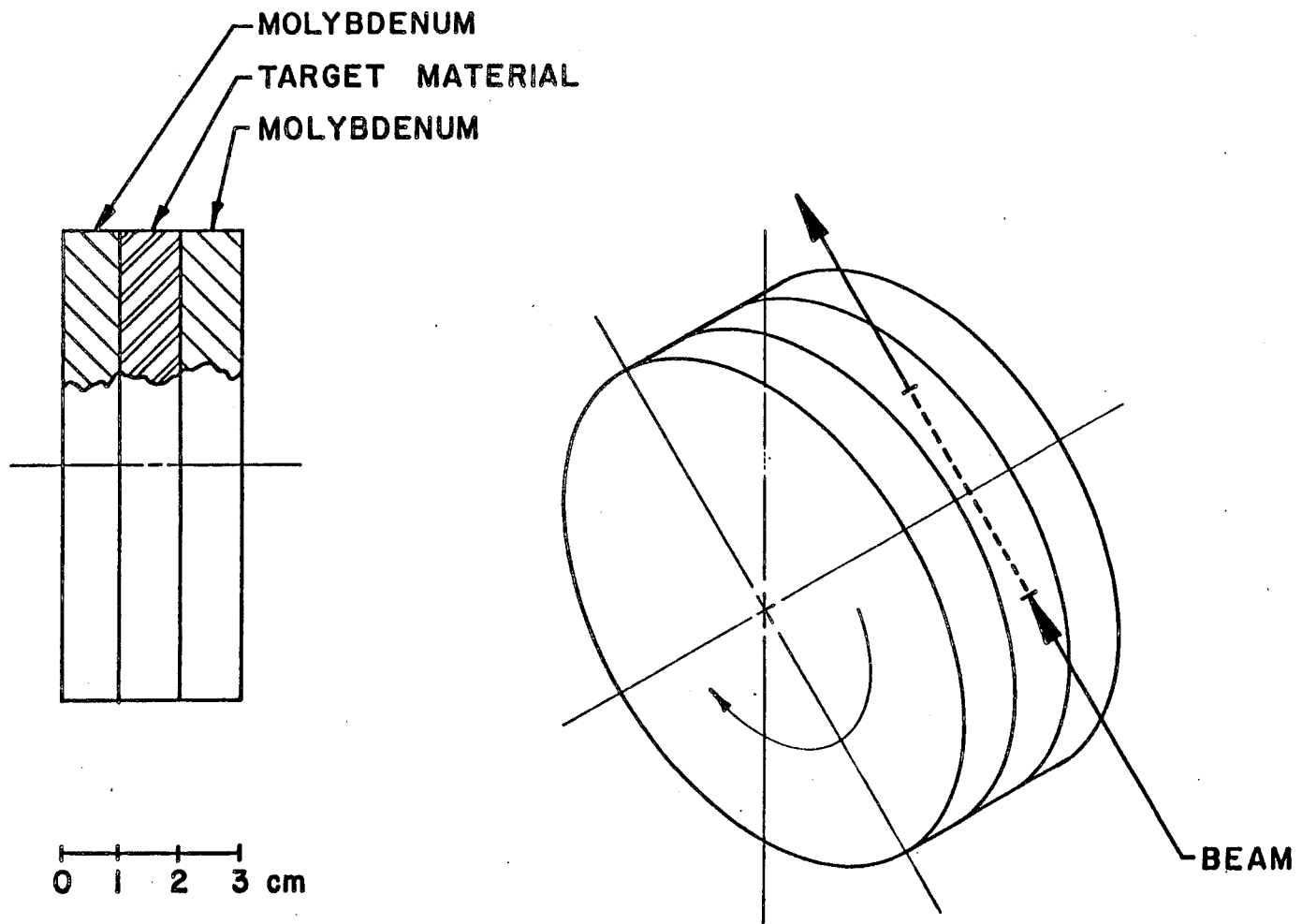


Fig. 3-9

high-temperature applications such as incandescent-lamp wire and targets for high-power x-ray tubes. A significant amount of experience with the technology for their fabrication exists. Tungsten has been used for all \bar{p} yield calculations, although a number of target configurations will be tested during the R & D phase of the target-station development. A summary of the target parameters is given in Table 3-IV.

Table 3-IV. TARGET PARAMETERS

Target Material	Tungsten/Tungsten Alloys
Length	5 cm
125 GeV protons/pulse	1.8×10^{12}
Total Beam Energy	3.46×10^4 Joules
Repetition Rate	0.5 Hz
Beam Pulse Duration	1.6×10^{-6} sec
Energy Deposited/proton	1.26 GeV (1.81×10^{-10} Joules)
Energy Deposited/pulse	346 Joules
Power Deposited	182 Watts
Average Temperature	100°C
Beam Size($\sigma_x = \sigma_y$)	0.038 cm
Peak Energy Density/proton	13.4 GeV/cm ³
Peak Energy Density/pulse	200.0 Joules/gm
Peak Temperature Rise	<1500.0°C
CERN	
Peak Energy Density ⁺	>185 Joules/gm
Peak Temperature Rise	1500°C
Average Temperature	800°C

⁺This rhenium target has been used for some time with no failures.

3.3.2 Antiproton Collection - the Lithium Lens A study has been made of the relative merits of \bar{p} collection schemes that utilize a lithium lens, a pulsed quadrupole multiplet, or a conventional quadrupole triplet.² Since it was found that the lithium lens is far more efficient for the collection of \bar{p} 's, this section concentrates on the lens. The other options which are discussed will be pursued if the lens development lags.

The basic physical principle of the lithium lens is that a uniformly distributed electric current in a cylindrical conductor produces an azimuthal magnetic field with a constant radial gradient. Charged beam particles traversing the length of such a conductor experience a force that focuses them toward the axis. Lithium is an appropriate material for such a focusing device because it is the least dense solid conductor, thereby minimizing \bar{p} absorption and multiple scattering.³ The lens under development uses a 15-cm long lithium cylinder of radius 1 cm and requires a current of 0.5 MA to produce the desired gradient of 1000 T/m. Joule heating caused by direct current in the lithium is prohibitively large, so

a 0.6 msec full-width unipolar sine-like pulse of amplitude 0.5 MA will be applied every two seconds. Each pulse will generate about 6000 Joules of heat and the problem of removing this heat dominates the mechanical design of the lens. It is desirable to keep the average temperature well below the 180°C melting point of lithium because the 1.5% volume expansion that occurs upon melting could shorten the lifetime of the lens. The magnetic induction H created by the pulsed current does not have a constant radial gradient, due to the skin effect. Fig. 3-10 shows the variation of H/H_{\max} during one pulse.⁷

Energy deposition in a lithium lens located 14.5 cm (one focal length) downstream of a 5-cm tungsten target was calculated using the program MAXIM. Contributions from secondaries emerging from the target as well as from non-interacting 120 GeV protons were included. The heating due to the beam was found to be small compared to Joule heating.⁹

In case the lithium-lens development lags, linear and non-linear horns of the types developed for the CERN AA ring could be utilized. To optimize the \bar{p} rate, they require significantly longer targets. Preliminary results indicate that horns would not provide as good a collection efficiency as the proposed lithium lens at our \bar{p} energy. The larger currents required for the 8.89 GeV/c \bar{p} 's, as compared with 3.5 GeV/c at CERN, may make the horn construction very difficult. Another option would be to install a 5Q36 triplet.² This would limit the \bar{p} production system to small momentum spreads and emittances, but could be useful in the early stages of running.

3.4 Target Hall

The antiproton production target, proton beam dump and the lithium lens for antiproton collection will be located in a vault downstream of the final quadrupole focusing system in the 120-GeV proton line. The dimensions of this vault are planned to be 7 ft by 33 ft with the floor located at 17 ft below grade, as shown in Fig. 3-11a and 3-11b.

The upstream end of the hall is separated from the proton-beam transport tunnel by 3 ft of steel shielding. Further shielding is placed around the external walls of the vault in the earth. Below the vault two separate impermeable membranes are used to collect irradiated ground water. Shielding configurations that limit the irradiations of the soil and the above-ground fluxes to permissible values have been designed to allow operation at an intensity of 10^{13} protons per second.

Downstream of the upstream end of the shield, within the target vault, a 3 ft high by 8 ft long and 2 ft wide volume of space is available for components. The space between this volume and the concrete walls and floors of the vault is filled with steel shielding. Access to the target station components is accomplished by raising one of a set of solid steel elevators into the Target Service Building. Each elevator segment extends 10 in. along the beam direction and 24 in. transverse to the beam. Each is 7 ft long in the vertical direction. The components are suspended from the bottom of the elevator. The 7 ft length makes it possible to place

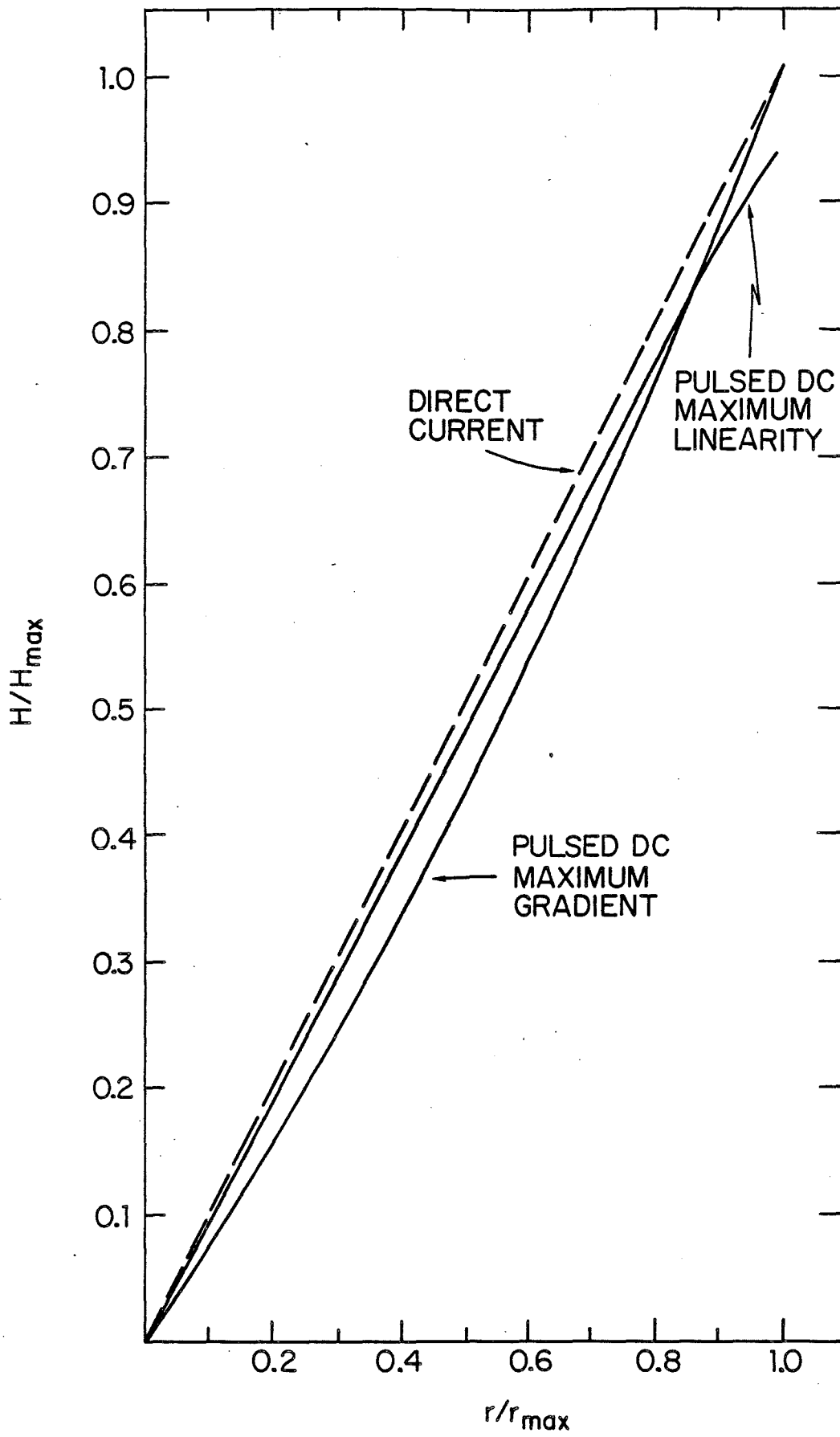
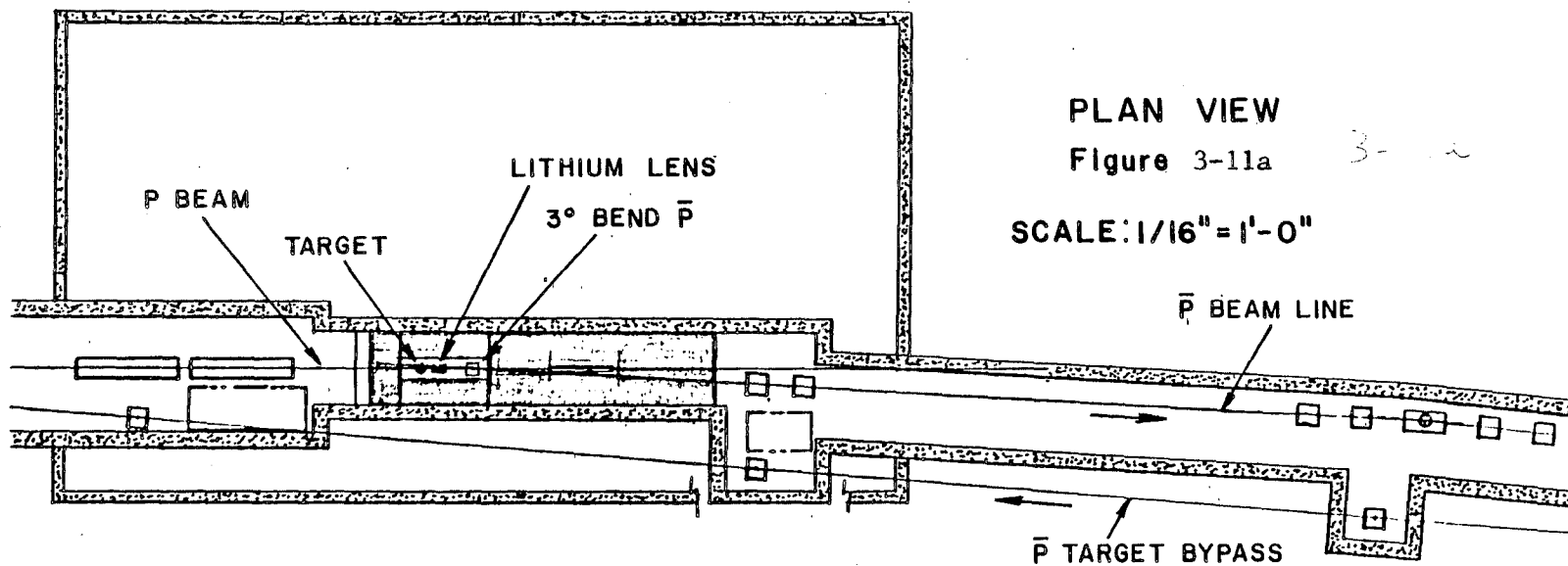


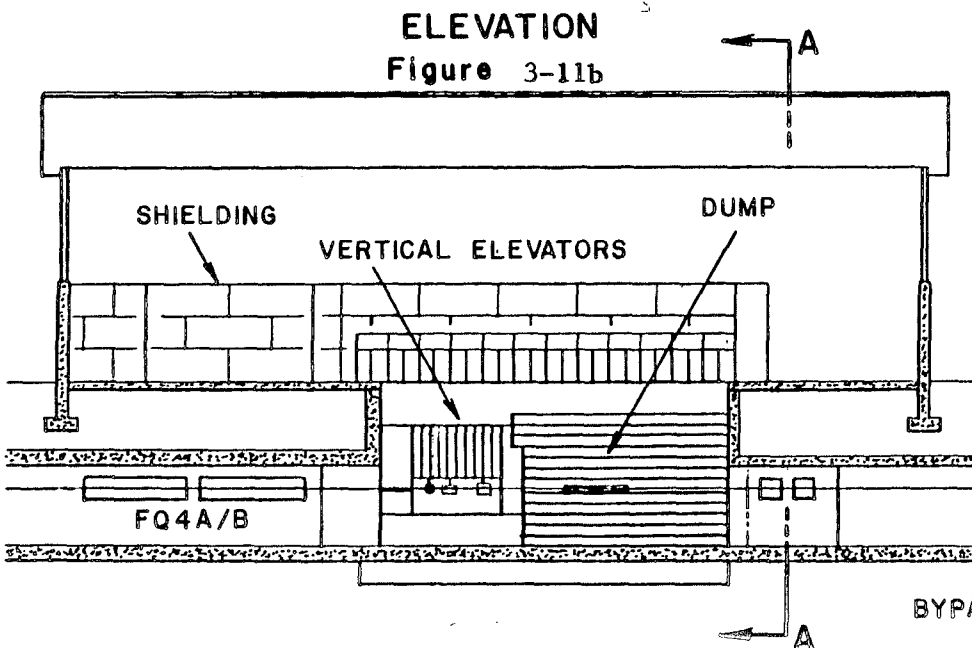
Fig. 3-10



PLAN VIEW

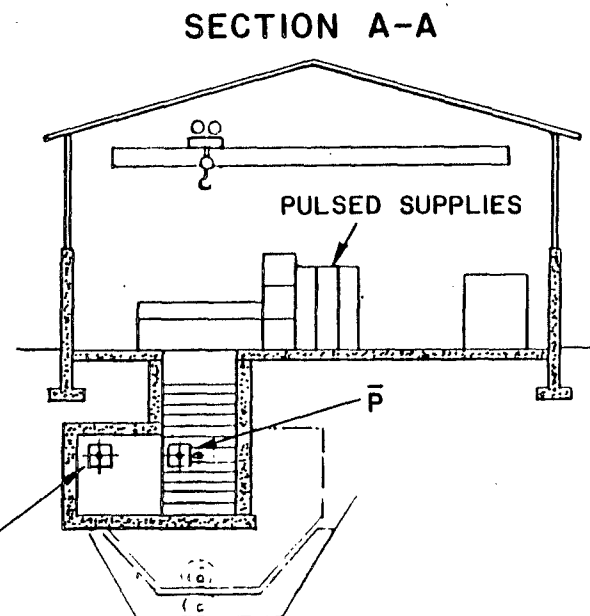
Figure 3-11a

SCALE: 1/16" = 1'-0"



ELEVATION

Figure 3-11b



SECTION A-A

electronics and control systems immediately above each elevator segment without danger of radiation damage. An additional 3 ft of concrete is required to keep the above-ground radiation levels within the Target Service Building below the maximum permissible level. Within the Target Service Building and surrounding the vault, a shielded area incorporating thick windows will be used to exchange elevator segments remotely. Work will be performed on components with remote manipulators. The manipulators will be used to exchange targets routinely. Access to the electronics at the top of the elevator segments will be possible when beam is not being delivered to the target station.

The last component in the beam before the dump is a pulsed magnet to bend the \bar{p} 's to the right by 3° , in order to separate them from the protons. The dump is a water-cooled graphite core 6 ft long surrounded by a steel jacket which fills the inside of the vault. The steel extends for 22 feet along the proton beam. The construction is similar to the dump developed for the Tevatron abort system.

3.5 Antiproton Transport to Debuncher

The antiproton transport line is shown symbolically in Fig. 3-12. This beam line can transport an 8-GeV beam with 20π mm-mm transverse emittance and $|\Delta p/p| < 4.0\%$. The match to the Debuncher is accomplished with an integrated efficiency of 80% over the 4.0% passband in $\Delta p/p$. Independent controls for emittance definition in both x and y planes and $\Delta p/p$ selection are possible using collimators. The detailed design can be found in Reference 9.

The "source" for the beam line is the center of the 5.0 cm \bar{p} production target. For the purpose of the transport calculations we have assumed a circular spot and a β^* of 2.25 cm. The lithium lens collector then performs point to parallel optics for negatives with a momentum of 8.9 GeV/c (8 GeV \bar{p}). The beam line consists of five basic sections: (i) cleanup, (ii) long transport, (iii) left bend, (iv) long transport, and (v) injector. Section (i) uses a pulsed C magnet to bend the 8 GeV \bar{p} 3° left, and two quadrupole doublets and another 3° bend left in order to complete the achromatic transformation. Charge, central momentum and vertical emittance ϵ_y are selected within this section using collimators. The long transport sections (ii) and (iv) consist of 90° FODO quadrupole cells and matching quadrupole lenses. The periodic structure has a cell length of 88.8147 feet with $\beta_{\max}/\beta_{\min} = 45.93\text{m}/7.98\text{m}$. The left bend (iii) which deflects the antiproton by 36.54° , consists using of six dipoles. Horizontal emittance (ϵ_x) selection is performed at the entrance and exit of this section where β_x is nearly 80 m. The fine $\Delta p/p$ selection is performed in the center of the left bend section where $\beta_x^* = 5.0$ m and a maximum in the dispersion $\zeta_x^* = 2.62$ m is obtained. The first-order momentum resolving power is $1.3\uparrow$ for $\epsilon_x = 20\pi$ mm-mr and $\Delta P/p = 1.0\%$ and 2.62 for $\epsilon_x = 5\pi$ mm-mr. The injector (v) is an achromatic vertical translation ending at the downstream end of the 2.0 m long Lambertson septum. The beam is deflected downward by 48 inches using 2.658° bends.

The components for the beam line are listed in Table 3-V and shown in Fig. 1-1. Fig. 3-12 shows the evolution of the monoenergetic β_y and β_x envelope functions and the beam dispersions ζ_y and ζ_x through the transport line from the target to the downstream end of the injection Lambertson. We have studied the match to the debuncher lattice as a function of $\Delta p/p$ by evaluating the transmission efficiency as a function of p with a Monte-Carlo calculation. We find the useful efficiency drops to near 50% at $\Delta p/p = \pm 2.0\%$. The integrated transport efficiency is greater than 80% over the full momentum spread of 4%. The loss is due to chromatic aberration effects in the transport line which cause an effective emittance growth.

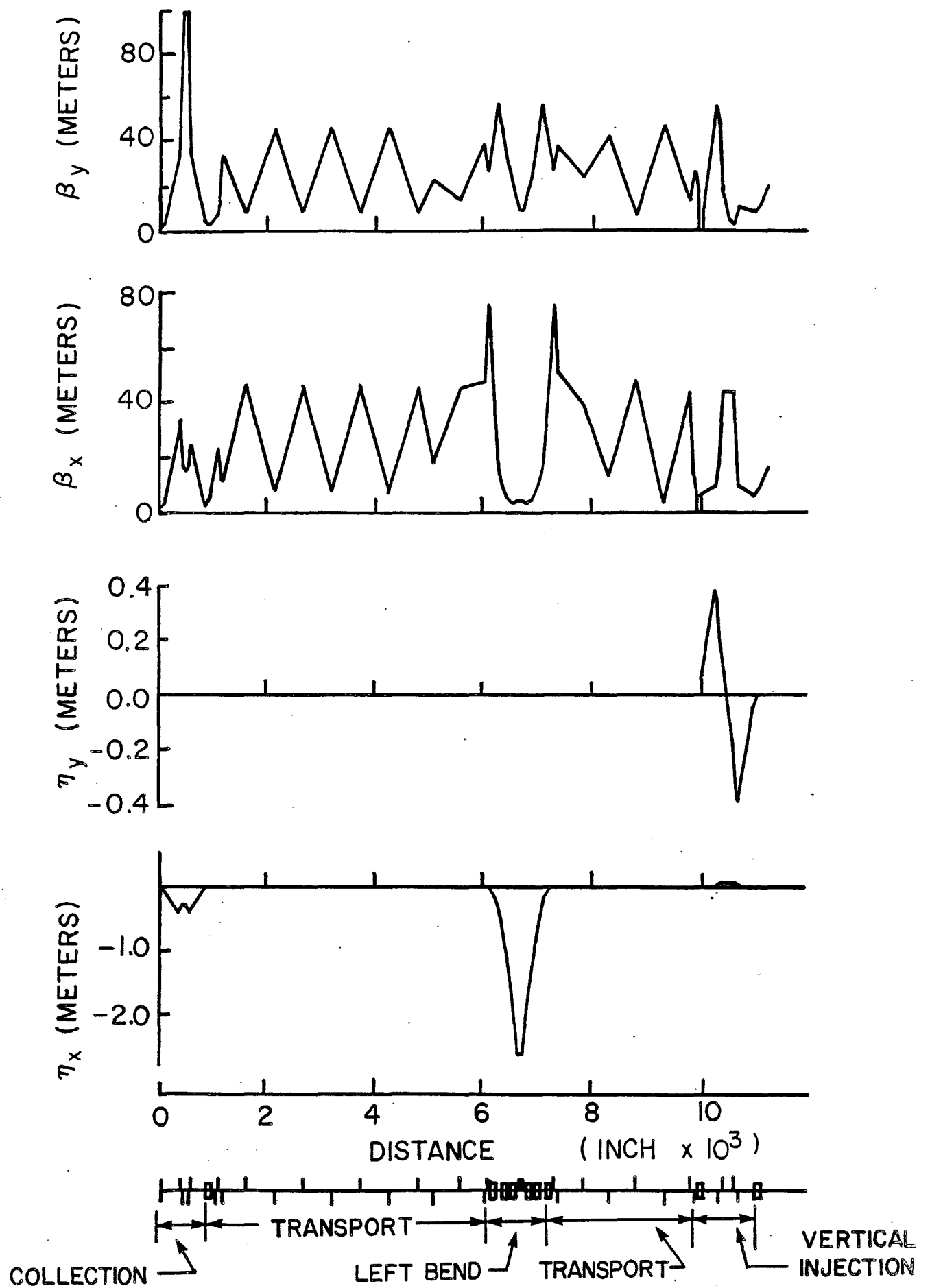


Fig. 3-12

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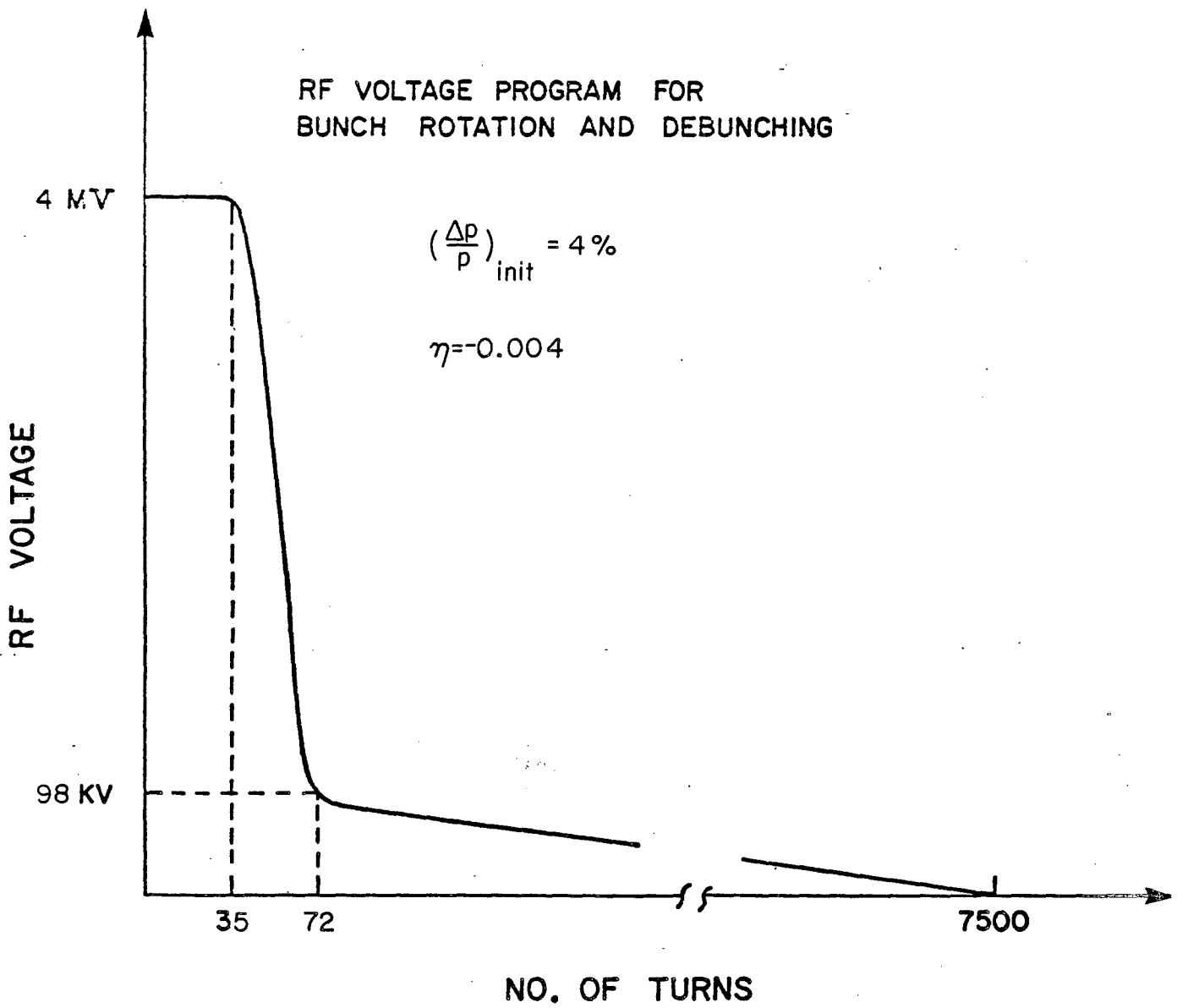


Fig. 4-1

- (i) The antiproton bunches, at the moment they have been generated at the target, have the same longitudinal distribution as the proton bunches, that is, an rms bunch length of 5 cm.
- (ii) The \bar{p} 's traverse a dispersionless drift of 100 to 400 m between the target and the first rf cavity. The rf voltage is generated by a single cavity.
- (iii) Two values of η were used. A value of -0.002 was used with an rf voltage of 2 MV and a value of -0.004 was used with an rf voltage of 4 MV. The results do not depend very much on the value of η although the case of $\eta = -0.002$ is somewhat worse.
- (iv) The bunches were allowed to rotate for 35 turns while the voltage was kept constant. The rotation was about 45° .
- (v) The voltage was then dropped to 98 kV in 35 turns (or 56 μ sec) to form a bucket matched in shape to the beam bunch, which had evolved into a grossly distorted S-shape that extended over $\pm 90^\circ$ in synchrotron phase.
- (vi) The voltage was slowly reduced to 5 kV or less.

A debunching time of 12 msec was chosen, since longer times did not significantly reduce the momentum spread while shorter times did increase the momentum spread. The final momentum spread is not sensitive to the other details of the time dependence of the rf voltage except during the early stage of rotation. The rf voltage program for the rotation and debunching operations is shown in Fig. 4-1 for the case of $\eta = -0.004$ and $\Delta p/p = 4\%$. Figures 4-2 through 4-5 show the beam shape at the end of some of the steps for $\Delta p/p = 3\%$. If the debunching could be done without dilution, 95% of the beam would be contained within a momentum spread of 0.11%. Computer simulations show that the debunched momentum spread is 0.2%. The factor of two dilution has several causes. It is caused in part by nonlinearities of phase oscillations of particles captured within rf bucket and in part by the variations of γ^{-2} of the particles and the momentum compaction factor γ_T^{-2} with energy. These variations and the presence of sextupole corrections in the ring lattice were taken into account in the simulations.

Calculations were done with smaller initial momentum spreads. The initial rf voltage of 4 MV and the final rf voltage of 5 kV were kept fixed for these calculations. These results, which are shown in Fig. 4-6, establish that the final momentum spread can be reduced significantly if the initial momentum spread is reduced by a relatively small amount. These calculations show that the debunched beam momentum spread is 0.2% if the bunched beam momentum spread is limited to 3%. The momentum spread of the \bar{p} beam will be limited to 3% by collimation prior to injection into the Debuncher. The Debuncher itself has a momentum aperture of over 4%. It may be possible to reduce the debunched beam momentum spread further if the rf voltage can be reduced adiabatically to a value much less than 5 kV.

Debunched Beam Spread
vs.
Initial Beam Spread
for $V=4\text{MV}$ and a Final $V=5\text{KV}$

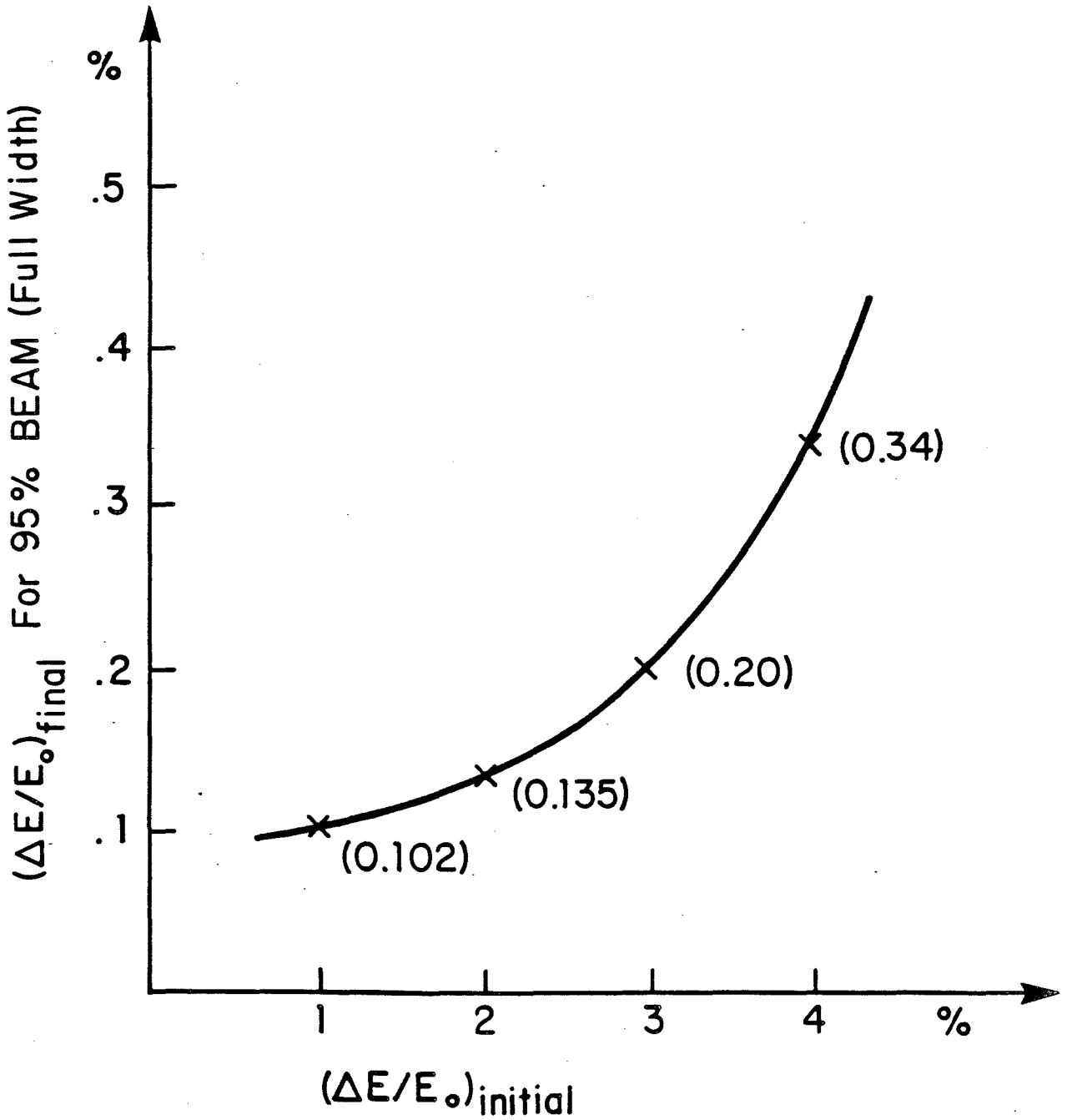
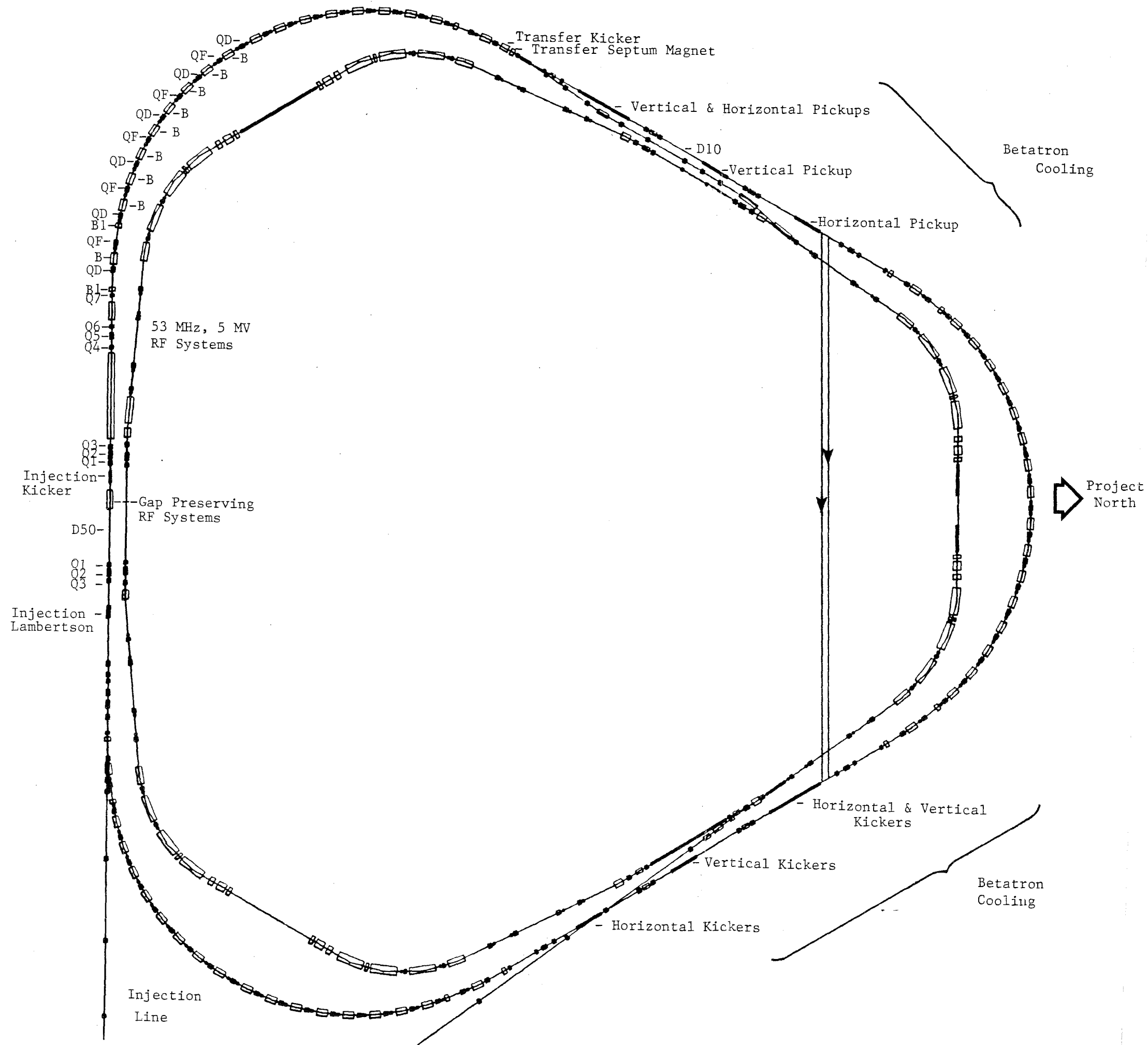


Fig. 4-6



DEBUNCHER LAYOUT
 Fig. 4-7

The final momentum spread was not changed when a higher-harmonic rf voltage was added¹. Harmonics of twice and three times the fundamental frequency were added in the simulations.

After the 53 MHz rf is turned off, a broad-band, low-frequency rf system is turned on to preserve the gap in the otherwise debunched beam. A 200-nsec gap is needed if the beam is to be transferred to the smaller Accumulator without loss. The rf system to make this gap is described in Section 4.5.2.

4.3 The Debuncher Ring Lattice

The rf voltage needed for bunch rotation is proportional to $|\eta|$. If $|\eta|$ is less than 0.002, the variation of $|\eta|$ with momentum will degrade the final momentum spread. On the other hand, a larger value of $|\eta|$ helps the betatron cooling and is needed if momentum precooling is to be done in the future. As a compromise η was chosen to be -0.0047. This choice makes γ_T close to 12. Choosing γ_T above the operating energy is desirable because it leads to strong focusing, which in turn leads to magnets with small apertures. The Debuncher Ring is made of 24 FODO regular cells, each of which is about 9 m long. Long straight sections with zero dispersion have been included to accommodate pickups and kickers for stochastic cooling. These sections also provide the space for rf cavities and injection-extraction magnets.

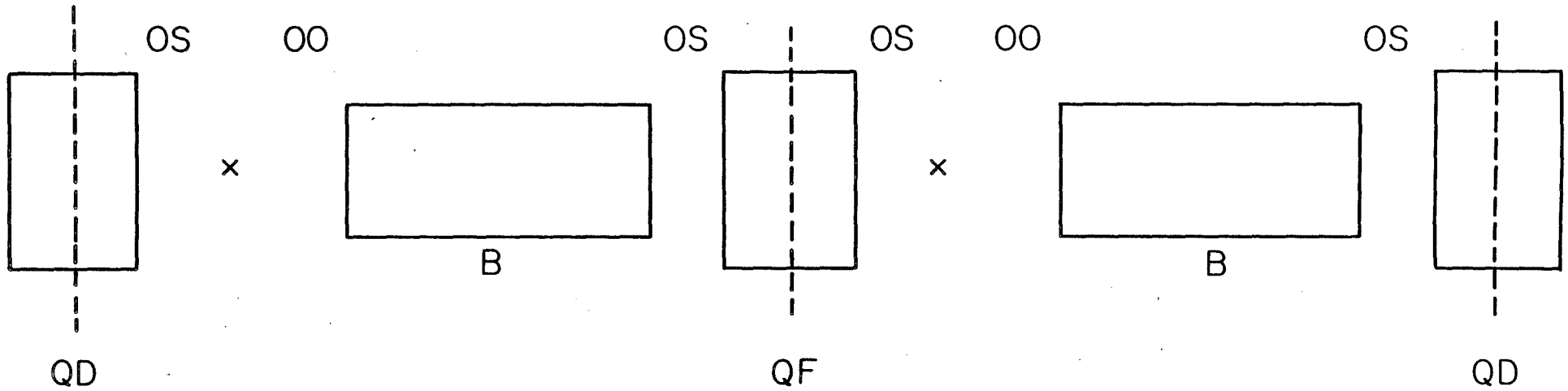
A threefold symmetry for the lattice was chosen because it closely matches the Accumulator Ring, which has threefold symmetry. This allows a reasonably convenient arrangement of straight sections with common equipment galleries. Figure 4-7 shows the overall Debuncher lattice. Figure 4-8 summarizes the parameters for a single cell. Locations around the ring are keyed with standardized code numbers. Figure 4-9 describes the dispersion-killer section. The packing factor, the ratio of bending length to circumference, is 21.3%.

The three long straight sections are symmetric about the center and are made of three low-beta insertions, each about 16 m long. The low-beta values are 6-7 m in both planes, created with triplets on both sides. One half of a long straight section is shown in Fig. 4-10. The purpose for the low-beta is to maintain the beam size in both horizontal and vertical direction within 20 mm for stochastic cooling. This is also the purpose of zero dispersion.

Each regular cell consists of a focusing quadrupole, a defocusing quadrupole, two dipoles and a correction package. The correction packages consist only of two families of sextupoles.

Steering dipoles will be located only in the long straight sections to steer the beams through the pickup and kicker systems for stochastic cooling. We do not expect much closed orbit distortion in the rest of the ring. We plan to compensate for any such distortion by moving quadrupoles. Steering dipole specifications are given in Table 4-II.

DEBUNCHER REGULAR CELL



$B = 16.75 \text{ kG}, 1.905\text{m}$

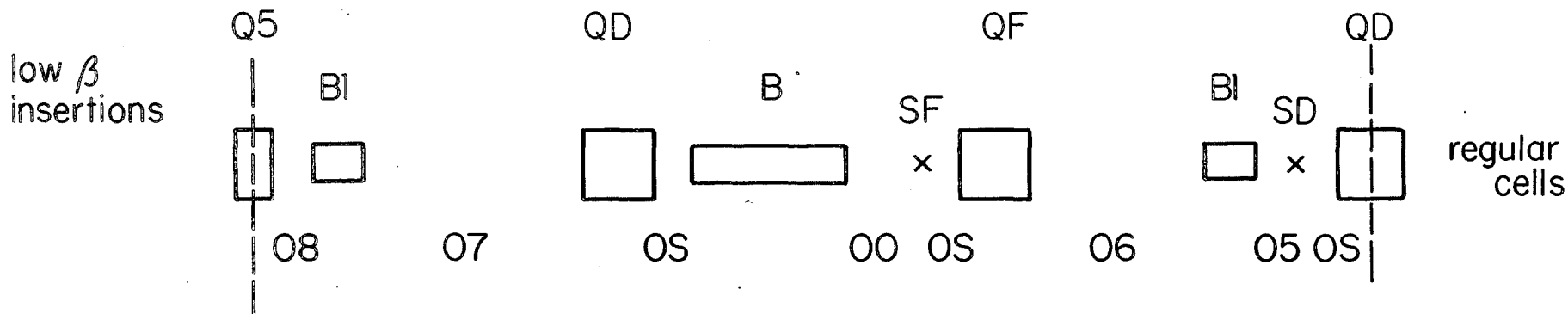
QF, $0.4064\text{m}, B \ 1/B_p = 0.4947\text{m}^{-2}$

QD, $0.4064\text{m}, B \ 1/B_p = -0.46842\text{m}^{-2}$

OO = 0.85623m

OS = 0.5m

Fig. 4-8



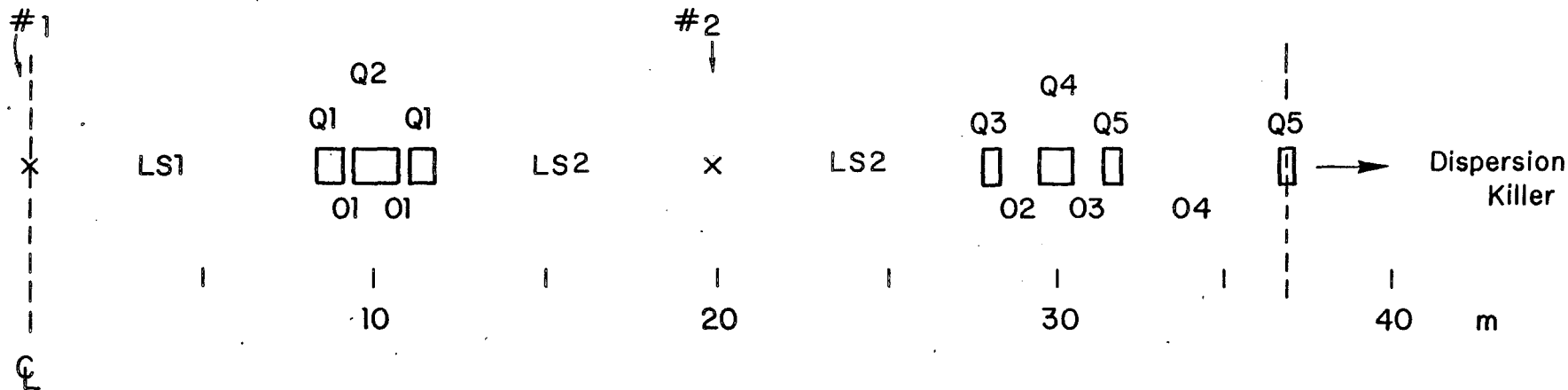
OS	0.5 m
00	0.85623
05	0.4315141
06	2.1363695
07	2.5758275
08	0.4822375

Length = 13.5385 m
 (1 and 1/2 regular cells)

BI: Length = 0.695323m
 Field = 16.75 kG

Dispersion-Killer Section

Fig. 4-9



01	0.354525 m	#1	}	β_H^*	=	6.64 m	α_H^*	=	0.0
02	1.1620			β_V^*	=	6.16 m	α_V^*	=	0.0
03	0.8183			α_p^*	=	0.00 m	α_p^*	=	0.0
04	4.8410								
LS1	8.2930 m	#2	}	β_H^*	=	6.35 m	α_H^*	=	0.018
LS2	8.0676			β_V^*	=	6.54 m	α_V^*	=	0.066
				α_p^*	=	0.00	α_p^*	=	0.000

Long Straight Section (One Half)

For the quadrupole specifications see table 4-IV

Fig. 4-10

Table 4-II. STEERING DIPOLES

	Horizontal	Vertical
Maximum closed orbit dist.	±5	±3 mm
Deflection	0.44	0.16 mrad
Effective Length	0.30	0.30 m
Maximum Field	440	160 G
Gap	40	80 mm
Ampere-turns	1400	1020 A-turns
Current Density	1.0	1.0 A/mm ²
Current	10	10 A
Turns	140	102 turns/mag
Resistivity	0.2	0.15 Ohm/mag
Voltage	2.0	1.5 V/mag
Thermal Loss	20	15 W/mag
Total Number	24	24

The basic function of the sextupoles is to flatten the chromaticity in both planes so that the variation in tune across the aperture is less than 0.03. Sextupoles 50 cm long are located next to each quadrupole in a region of significant dispersion. The sextupole specifications are given in Table 4-III. The variation of γ_T with momentum is displayed in Fig. 4-11. Figure 4-12 shows the variations of the betatron tunes and Fig. 4-13 the variations of the maximum values of β and α . Figure 4-14 gives the lattice functions across one-half period. Figure 4-15 shows the tune diagram with the range of tunes for a momentum spread of $\pm 2.2\%$. The heavy dot at the center is the tune of the beam after the rotation and beam debunching.

Table 4-III. SEXTUPOLE MAGNETS

	<u>SF</u>	<u>SD</u>
Number	30	30
Strength for zero chromaticity $B''/B\rho$	1.2 m	-2.2 m ⁻²
Bore Radius	50.0	50.0 mm
Estimated Effective Length	0.50	0.50 m
Maximum Field, B''	71.3	131 T/m ²
Ampere-turns	1182	2170 AT/pole
Current	100	100 A
Turns	12	22 Turns/pole
Conductor Size		
Current Density		
Resistance	0.07	0.120 ohm/mag
Voltage Drop	7.0	12 V/mag
Thermal Loss	0.7	1.2 kW/mag
Power Supply		
Current	100	100 A
Voltage	130	360 V
Power	21	36 kW

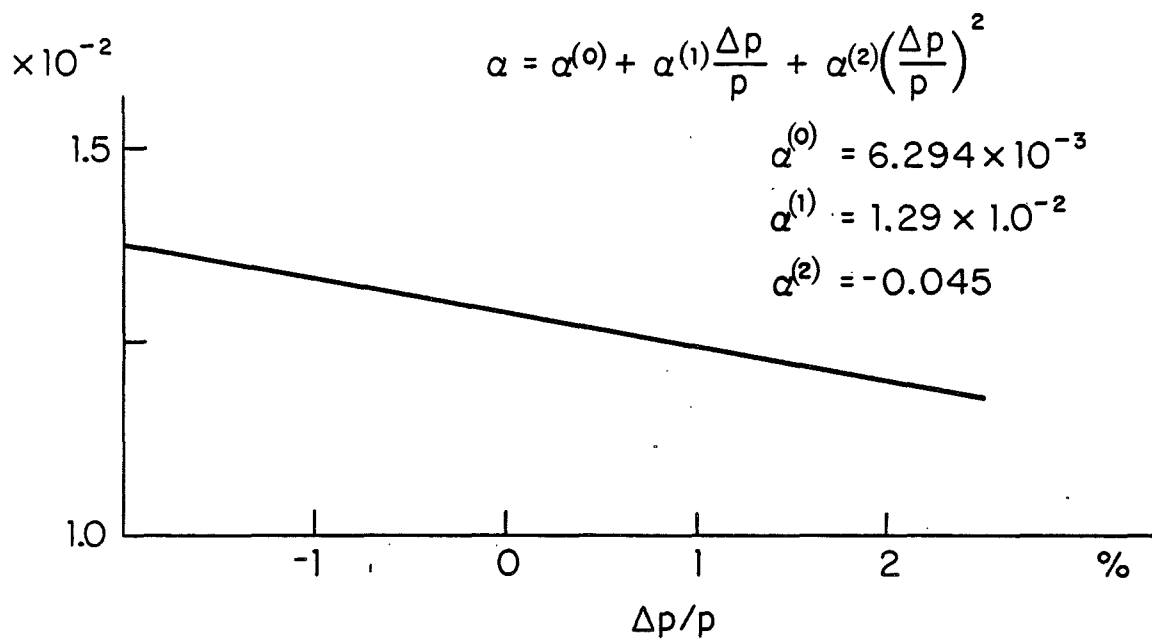


Fig. 4-11

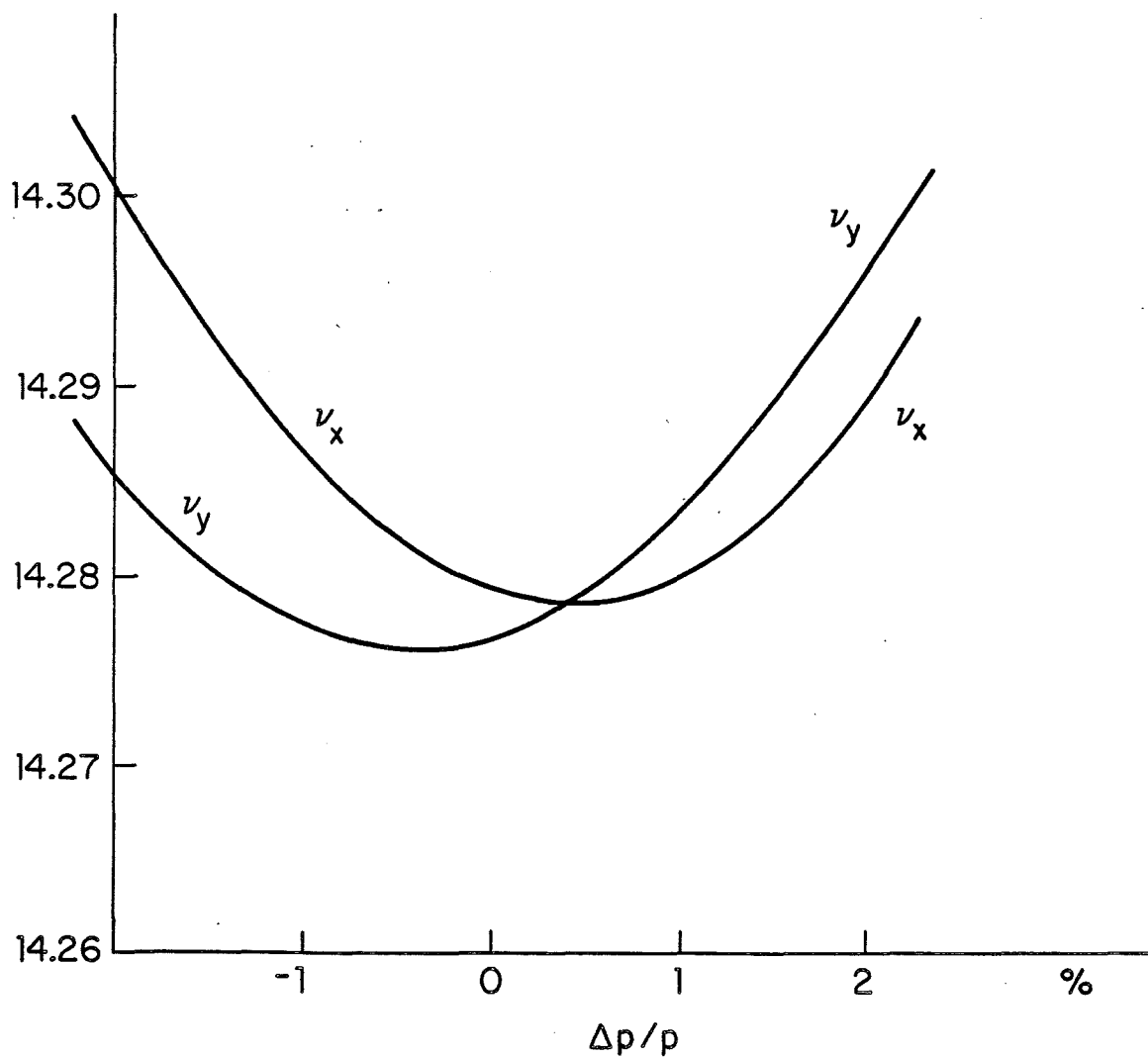


Fig. 4-12

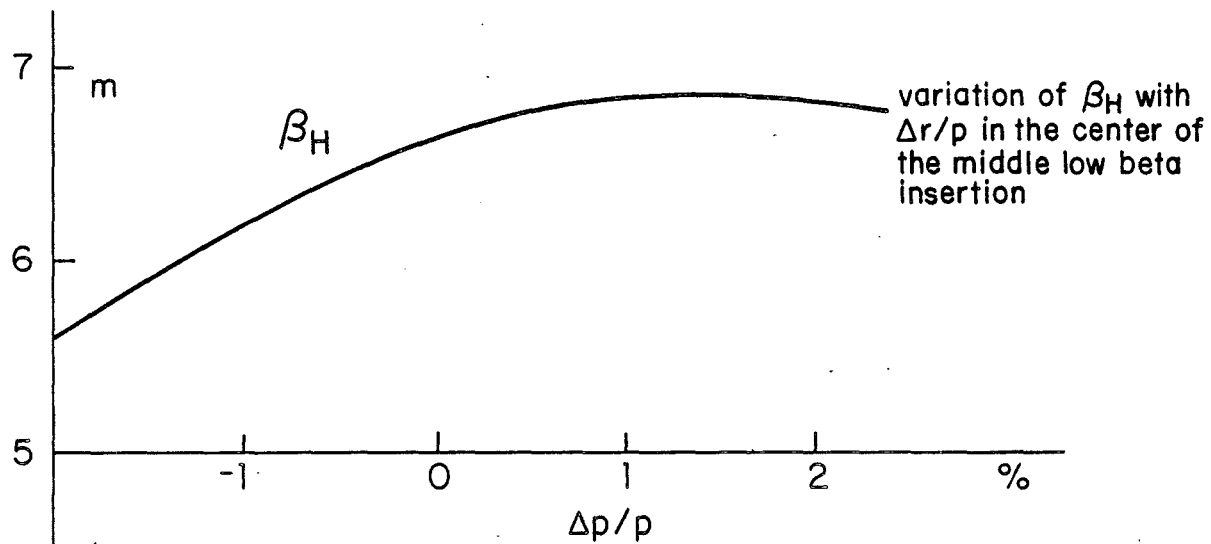


Fig. 4-13a

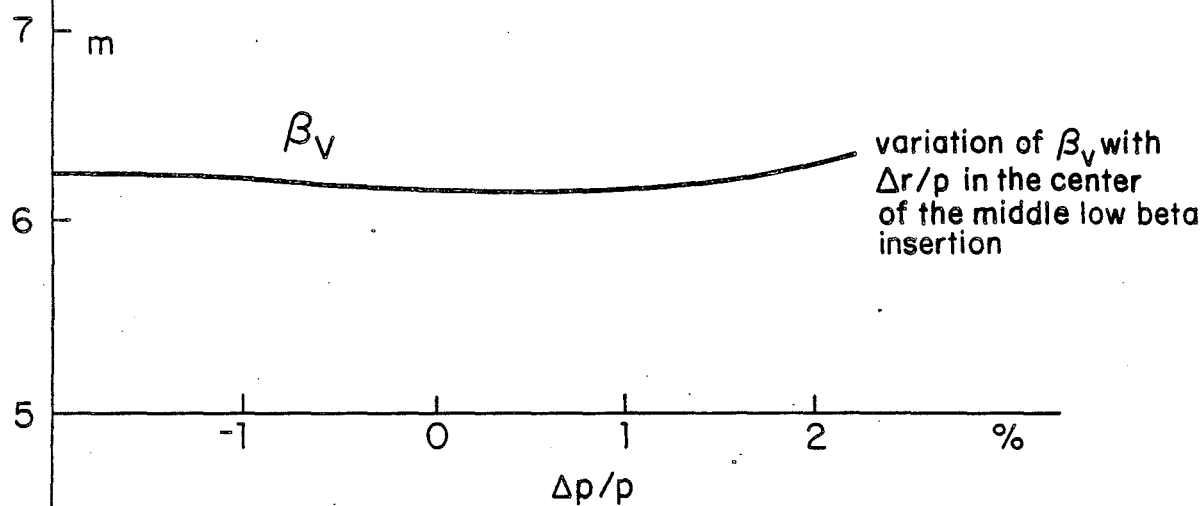


Fig. 4-13b

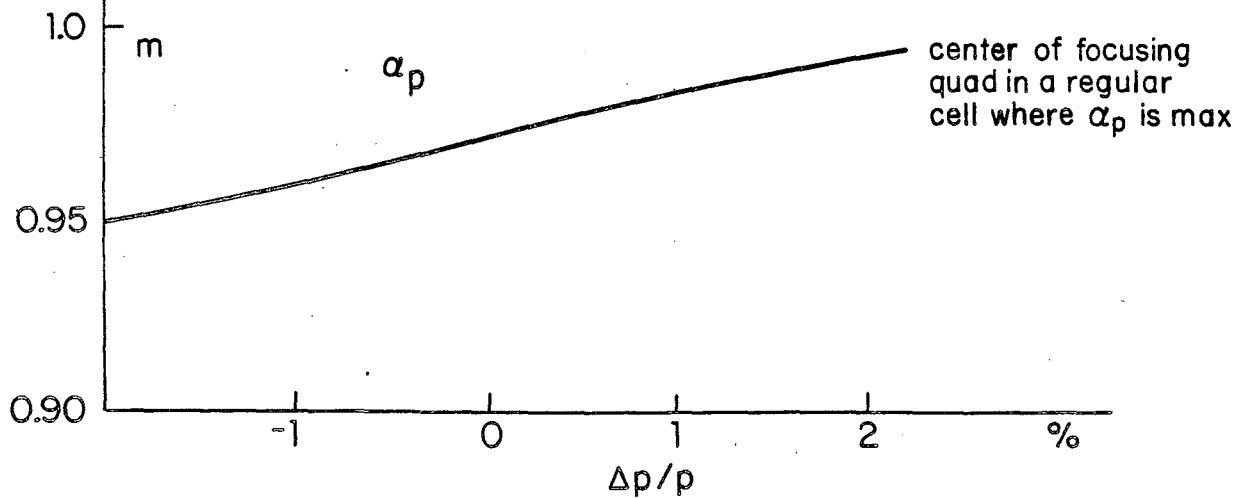


Fig. 4-13c

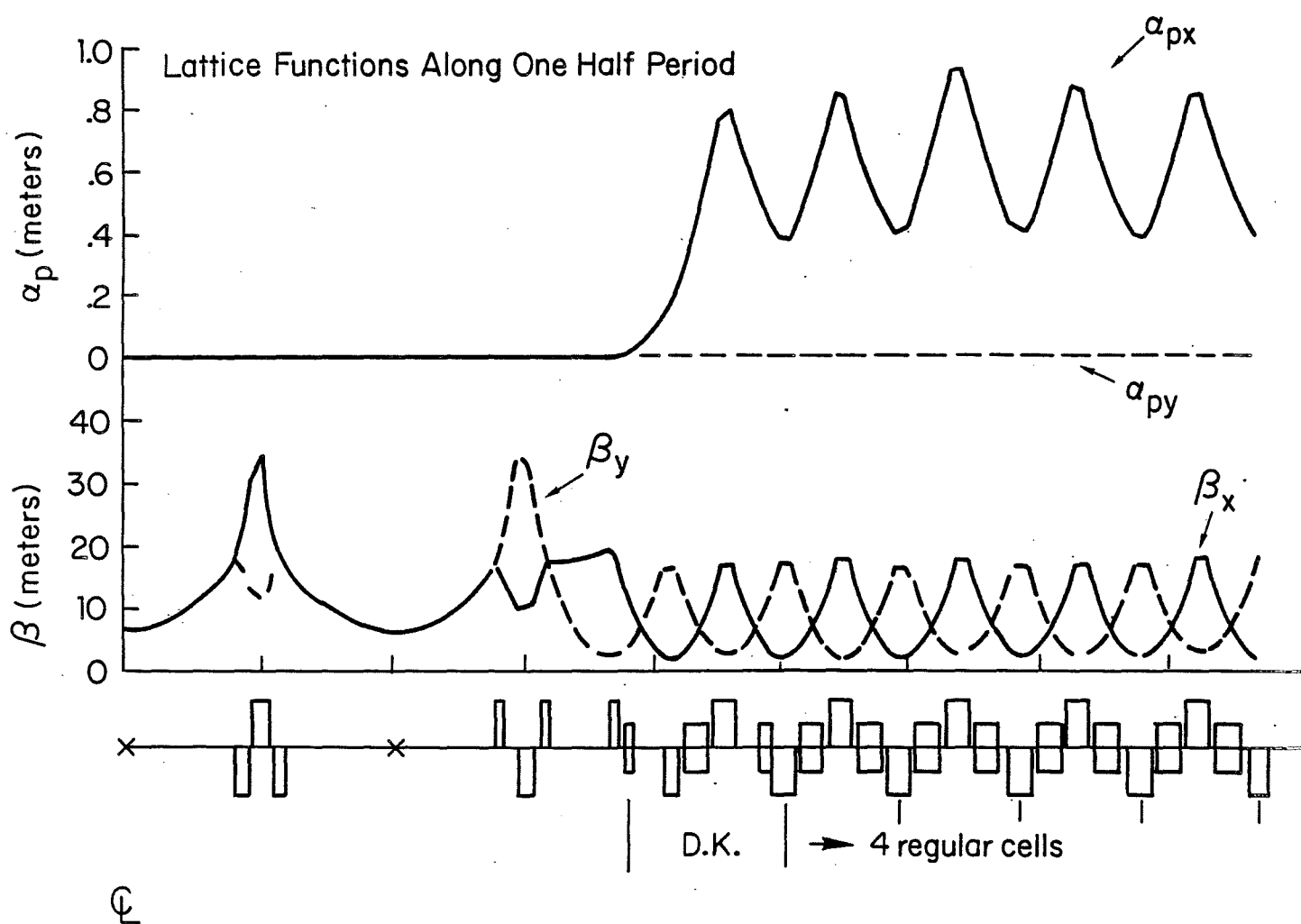


Fig. 4-14

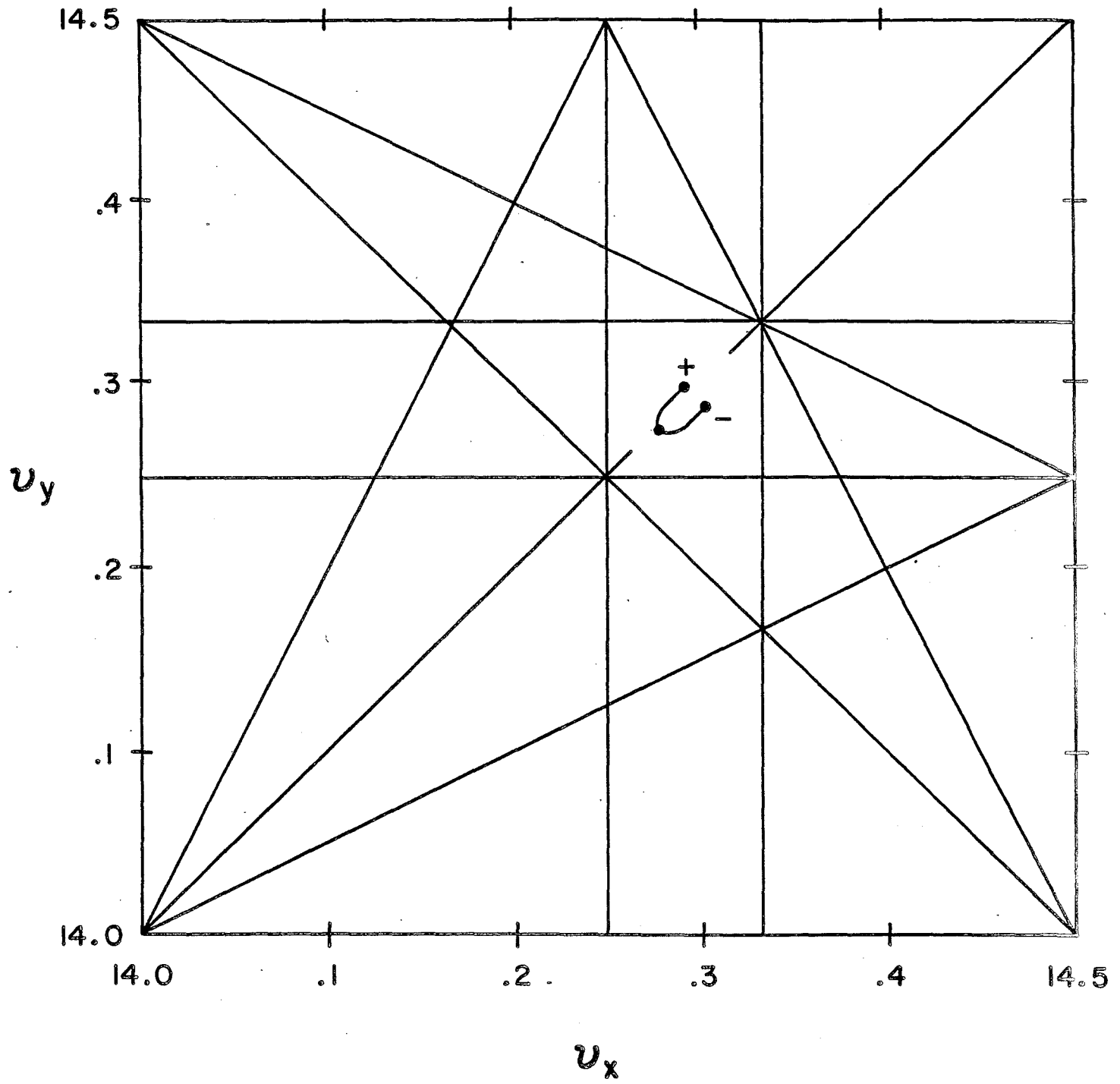


Fig. 4-15

Vacuum pumps will be distributed around the ring every few tens of meters. The lifetime for an 8.9-GeV/c beam is calculated to be few hours when the average vacuum pressure is 10^{-8} Torr. This vacuum can be achieved without baking the chamber, so no provisions for baking are included in the design. The vacuum pipe will be carefully treated and cleaned during construction and the vacuum is expected to be close to 10^{-8} Torr. Beam-position monitors are located next to each quadrupole.

4.4 Beam Injection and Extraction

4.4.1 Injection. The beam enters the Debuncher in the vertical plane at an angle of 50 mrad to the closed orbit. A Lambertson magnet located in a zero-dispersion region deflects the beam vertically onto an orbit parallel to the reference orbit and horizontally displaced by 40 mm at the downstream end of the magnet.. A kicker in a zero-dispersion location 60° in betatron phase away from the Lambertson kicks the beam onto the reference orbit. A schematic layout of these components is shown in Fig. 4-16. Figure 4-17 shows the envelope of the circulating and injected beam in the injection region. The injection channel has been designed to accommodate a beam with momentum spread of 4% and transverse emittances of 20π mm-mrad.

The Lambertson magnet specifications are:

Length	2.0 m
Bending Angle	50 mrad
Bending Radius	42.4 m
Magnetic Field	6.9 kG
Aperture	4 cm (h) x 17 cm (v)
Effective thickness	1 cm

The magnet is located in the upstream low-beta insertion.

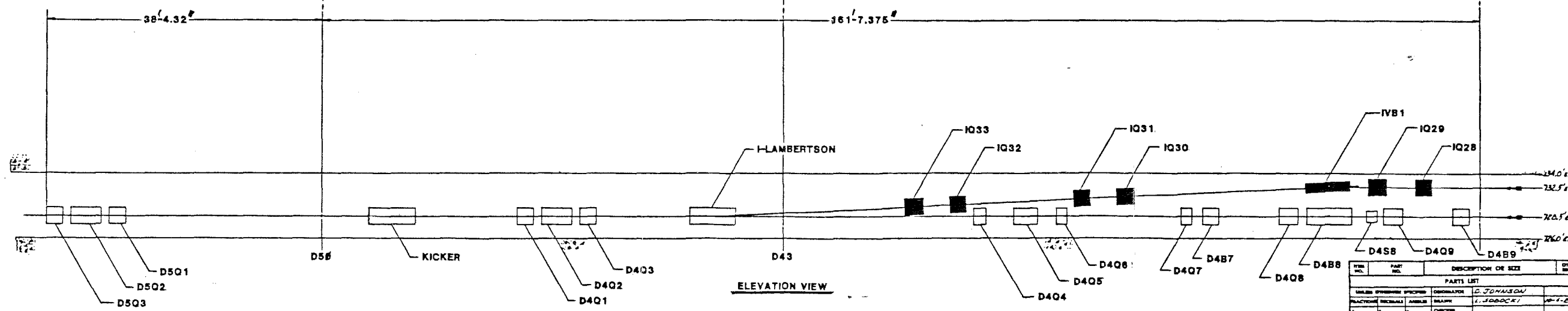
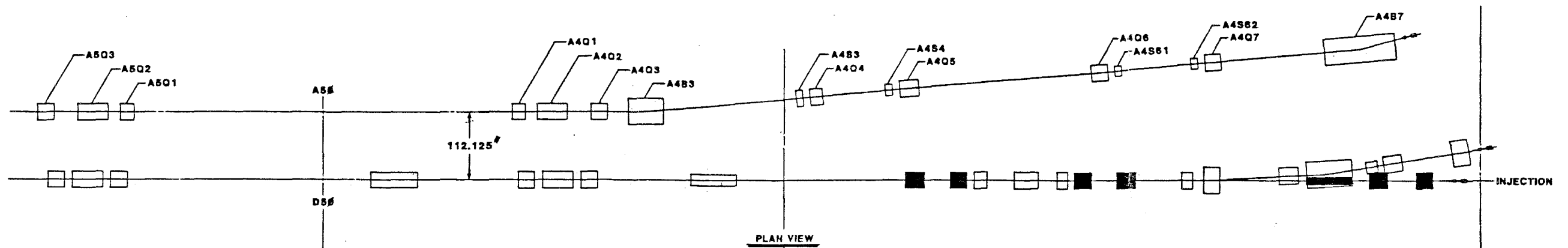
The kicker specifications are:

Length	3.4 m
Magnetic Field	525G
Fall-off Time	150-200 nsec ←
Aperture	5 cm (h) x 5 cm (v)

Reverse Injection

4.4.2 Debuncher to Accumulator Transfer

The beam transfer between the Debuncher and the Accumulator is a horizontal transfer taking place in the 10 straight section. Extraction from the Debuncher is accomplished with a 525 Gauss, 11 foot long kicker between quadrupoles D6Q7 and D6Q6, followed by a 15 kGauss, 7 foot long pulsed septum placed after D6Q4. The beam is then transported to the Accumulator through a string of two dipoles and six quadrupoles. At the Accumulator, the beam is injected onto a path displaced from the central momentum by $\Delta p/p = +0.775\%$ with an 11 kGauss, 12.5 foot long pulsed septum

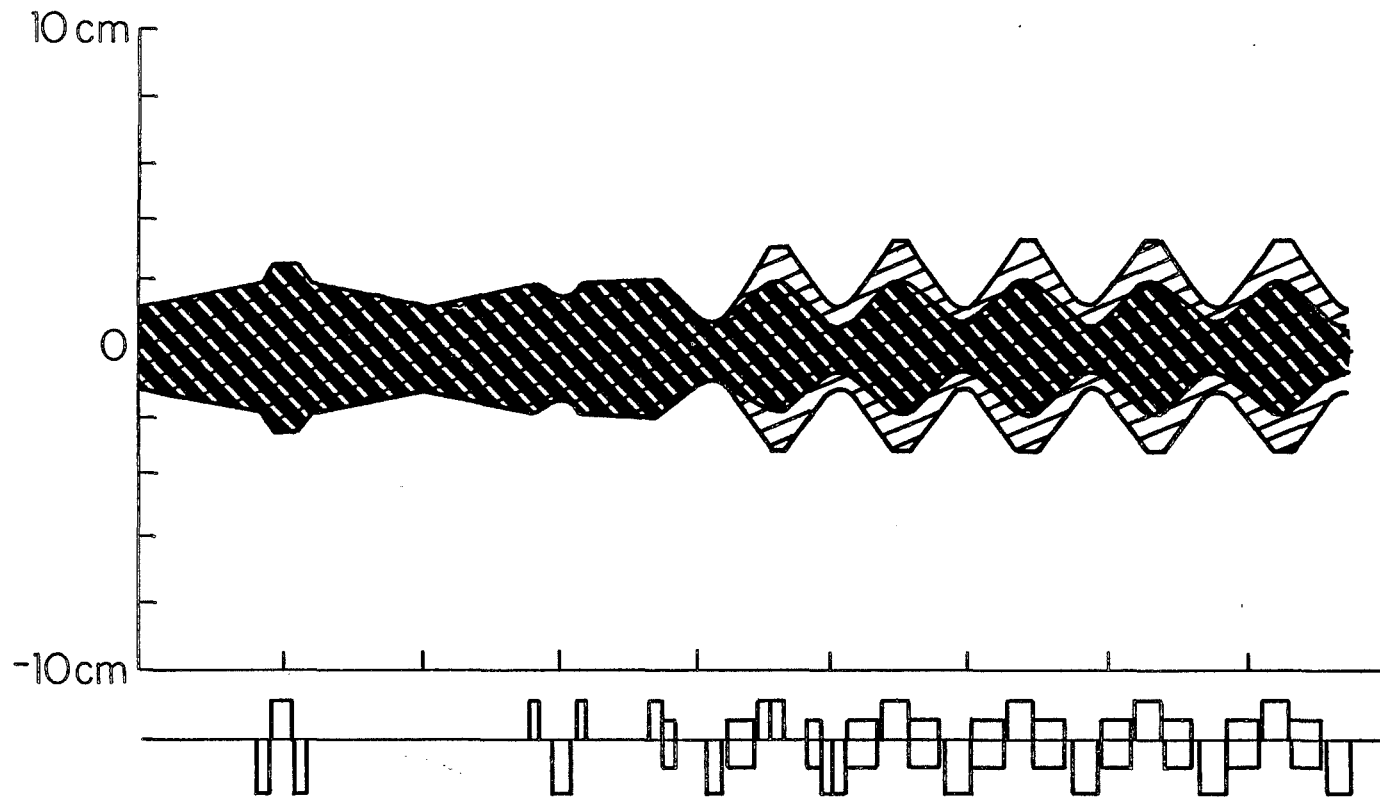


DEBUNCHER/INJECTION STRAIGHT SECTION(elevation)

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY.	REMARKS
PARTS LIST				
1		UNLESS OTHERWISE SPECIFIED		
2		MATERIALS		
3		FINISHES		
4		WARRANTY		
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
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46				
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49				
50				

Fig. 4-16

FERM NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY



Horizontal beam envelope before & after debunching

$$\epsilon_H = 20 \pi \text{ mm-mrad}$$

$$\Delta p/p = \pm 1.5\% / \pm 0.1\%$$

Fig. 4-17

placed between A1B3 and A1S3. Finally the beam is kicker onto the proper orbit in the Accumulator with a 500-Gauss, 7 foot long shuttered kicker placed in the A20 straight section. See Figs. 4-7 and 5-29. A plot of the lattice functions of the transfer line is shown in Figure 4-18 and the list of elements is given in Table 4-IV.

Table 4-IV
Beam Transfer Debuncher to Accumulator

<u>Element</u>	<u>Length</u>	<u>Field</u>
Debuncher kicker	3.3528m	524.81 Gauss
Septum TS1	2.1336	15.00 kGauss
Drift	3.0000	
Quad TQ1	0.4572	46.92 kG/m
Drift	1.4196	
Dipole TB1	2.1336	-12.34 kG
Drift	2.3087	
Quad TQ2	0.5283	58.44 kG/m
Drift	5.5377	
Quad TQ3	0.5715	-56.38 kG/m
Drift	4.6976	
Quad TQ4	1.2903	-48.93 kG/m
Drift	1.2265	
Quad TQ5	1.2903	-63.95 kG/m
Drift	1.6596	
Quad TQ6	0.5715	70.09 kG/m
Drift	7.8096	
Dipole TB2	3.8100	15.90 kG
Drift	4.1148	
Septum TS2	3.8100	-10.87 kG
Accumulator Kicker	2.1336	500.00 Gauss

4.5 Radio Frequency Systems

4.5.1 Antiproton Debuncher RF. The design criteria for the antiproton debuncher rf are:

- (i) Voltage gain per turn ≥ 4.7 MV.
- (ii) Maximum pulse length 100 μ sec (duty factor 5×10^{-5}).
- (iii) RF voltage pulse fall time from ≥ 4.7 MV to 100 kV 30 μ sec.
- (iv) Pulse repetition rate 0.5 Hz.
- (v) Minimum voltage gain per turn ≤ 5 kV.
- (vi) Adiabatic reduction of voltage from 100 kV to ≤ 5 kV in a time of 5 to 20 msec under program control.

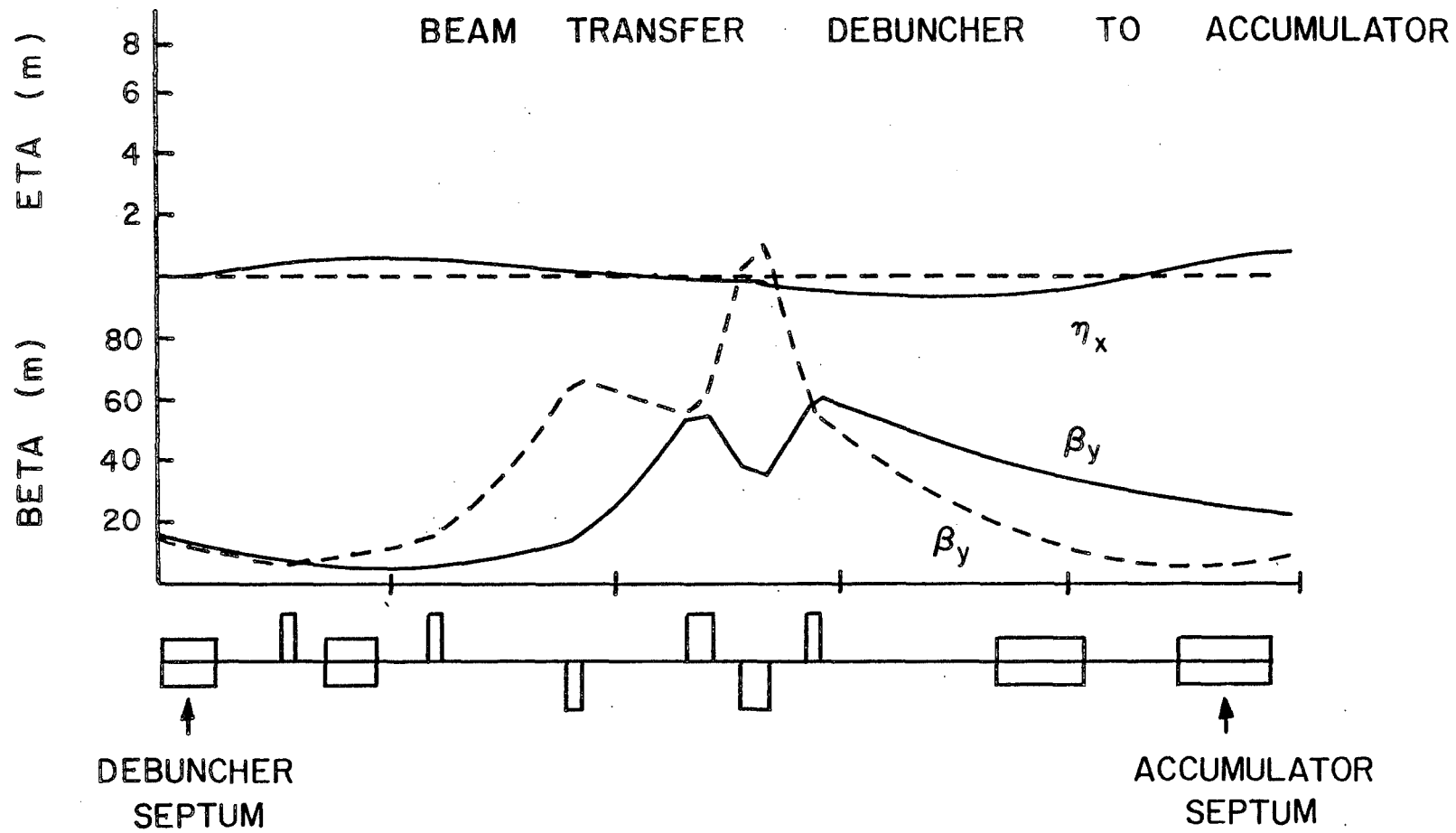


Fig. 4-18

A representative rf voltage waveform was shown in Fig. 4-1. The design is simplified by the fact that the beam intensity will not exceed 10^{10} particles when the rf voltage is on. Of the particles that emerge from the production target when it is struck by 2×10^{12} 120-GeV protons, approximately 2×10^{10} are within the acceptance of the beam transport and the Debuncher. Some 90% of these particles are mesons, of which 50% decay before reaching the injection straight section. After each successive turn, 63% of the remaining mesons decay. The remainder of the particles that reach the center of the injection straight section consist of muons, principally from pion decay, and electrons produced in showers in the target. The electrons lose 30 MeV per turn through synchrotron radiation and spiral out of the vacuum chamber within 20 turns.

The large rf voltage, low beam loading and small duty factor favor an accelerating cavity with a very high Q, hence a high shunt impedance, which requires very little rf drive power. But the short fall time of the rf voltage pulse is not obtained easily with a high-Q structure. Moreover, the physical size of high Q structures operating in the 53-MHz region would require much larger enclosures than are under consideration.

A compromise structure, which contains an intermediate cylinder that reduces both the Q and the physical size, is shown in Figure 4-19a. Figure 4-19b shows a SUPERFISH plot of the electric fields within one-quarter of the structure. The entire volume of each cavity will be evacuated, with rf power coupled through two small ceramic windows at the top. The plate through which rf power is introduced serves as a bedplate for the high-power driver amplifiers, which are mounted directly on top of the cavity and are completely enclosed. Thus high-power rf transmission lines are not needed and rf leakage is less likely. This may be important because rf noise could adversely affect stochastic cooling. Each cavity is driven by two relatively small 10-kW triodes operating in a cathode-driven grounded-grid configuration. In this configuration, the tubes are capable of delivering very large peak rf currents during the short pulse. Because the pulse is short and the duty factor is low, the average anode dissipation is only a few hundred watts.

The rf voltage is reduced quickly by reversing the phase of the power-amplifier excitation and raising the excitation amplitude to a very high level. The high peak-power capability of the tubes is used to "drive" the cavities off, even though the cavity time-constant is longer than the required turn-off time of 50 μ sec.

The peak rf voltage which each cavity can develop has been calculated to be larger than 650 kV. Eight of these 1.8-m long cavities provide the required 5 MV. Six cavities can be installed in the downstream low-beta 16-m long insertion after the injection kicker and two more cavities can be installed in the following 4.8 m long drift.

In order to reduce the rf voltage down to 5 kV or less during the adiabatic-debunching part of the rf program, six of the cavities are turned off and two of the cavities are held at 50 kV and their relative phases

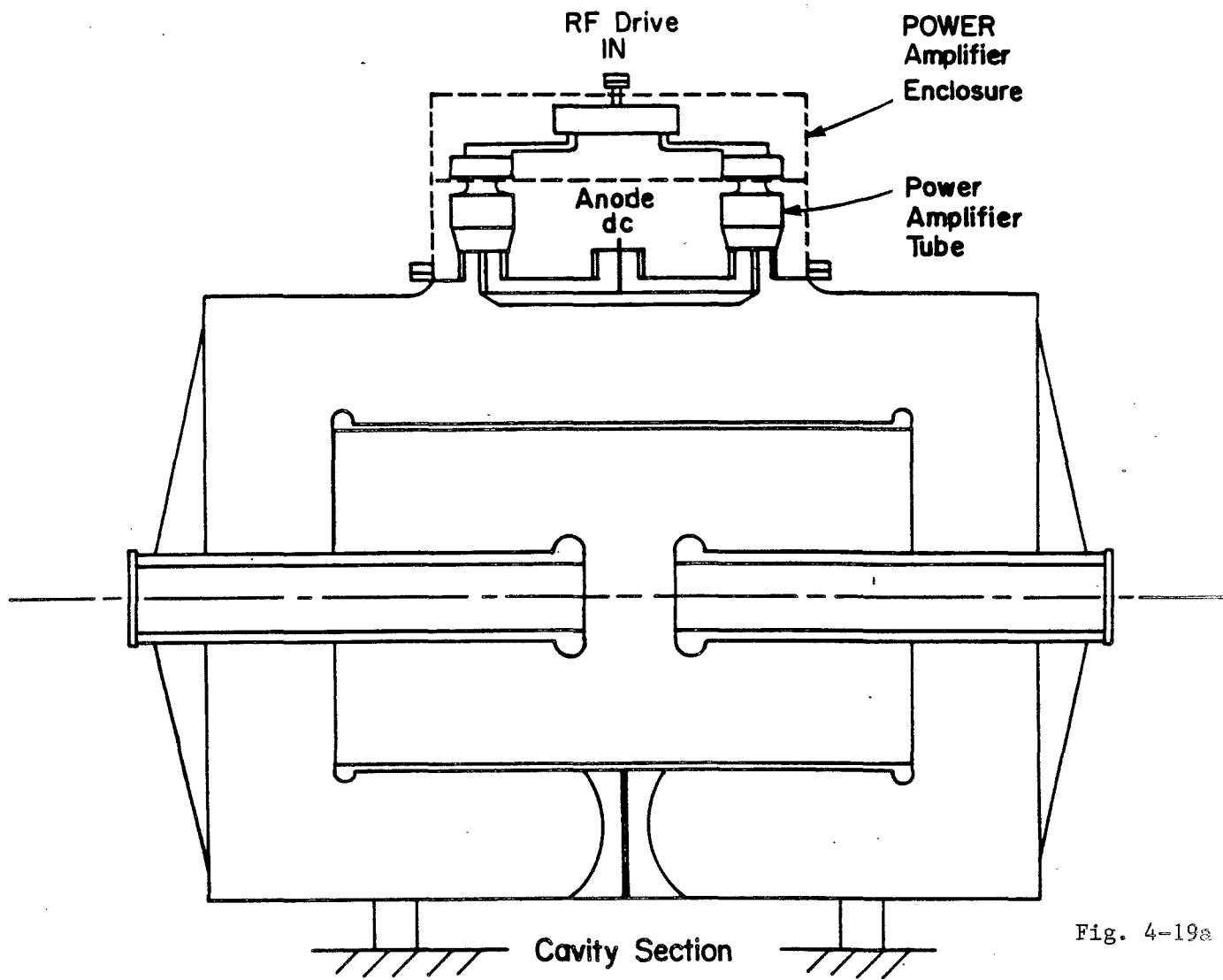
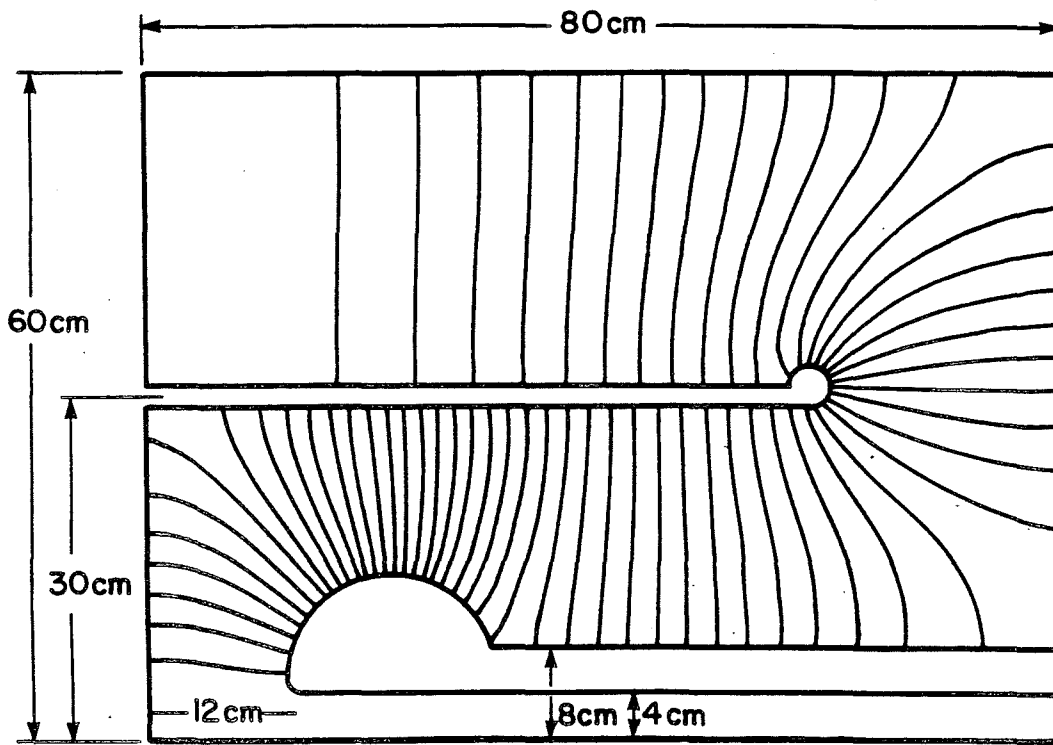


Fig. 4-19a



Superfish Computation of Fields

Fig. 4-19b

each changed by 90° in opposite directions. The resultant rf voltage gradually reaches a small value. This is done to avoid instabilities at low rf voltage that might arise from multipactoring.

In order to provide the structural rigidity necessary for complete evacuation and to reduce material costs, the cavities will be constructed from aluminum.

4.5.2 Gap-Preserving RF. Because the Debuncher circumference is larger than that of the Accumulator, antiprotons will be lost in the transfer to the Accumulator unless there is a gap in the Debuncher beam. Given the difference in circumference between the two rings and the need to allow for the fall time of the injection kicker, a gap greater than 200 nsec is needed.

An adequate gap can be created in the beam by a "barrier bucket" that excludes particles from its interior. It is created by a voltage that traces out a single complete sinusoidal oscillation for one-quarter of the rf period and then becomes zero for the remaining three-quarters of the period. A sketch of this waveform is shown in Fig. 4-20. The voltage waveform repeats itself every turn. The phase of the voltage is chosen so that it establishes an unstable fixed point between two back-to-back half-bucket separatrices. If the bucket height exceeds the beam energy spread, the beam will be forced away from the unstable fixed point by a distance determined by the ratio of the bucket height to the energy spread. The rf voltage is chosen so that the beam is excluded from a region between $\pm\pi/2$ radians in the "barrier bucket". This will create a gap of 221 nsec, as shown in Fig. 4-20. The peak amplitude required is 460 V. The Fourier series expansion of such a voltage waveform is given by

$$V(t) = 460 \frac{2h}{\pi} \sum_{n=1}^{\infty} \frac{\sin\pi n/h}{h^2 - n^2} \sin(n\omega_0 t)$$

where $\omega_0 = 2\pi f = 3.59 \times 10^6$ rad/sec and $h=4$. At frequencies above the 31st harmonic (17.7 MHz) the required amplitudes are reduced by more than three orders of magnitude. Amplifiers with a bandwidth between 0.1 and 30 MHz which are capable of delivering 300 W in a 50-ohm load are readily available. The required rf system can be broken into 150-V units, each consisting of a ceramic gap loaded with a 50-ohm resistor and surrounded by a shielding enclosure containing about ten large MnZn ferrite rings. The average power delivered to this system is very small. Since the physical size of each unit is dictated by the volume of ferrite required, each unit is 0.5 m in length.

An additional bonus associated with installation of the "barrier bucket" rf system is that it can be used in the "normal" $h=4$ mode to accelerate or decelerate 8 GeV protons across the ring aperture in tune-up testing of closed orbits and stochastic-cooling systems.

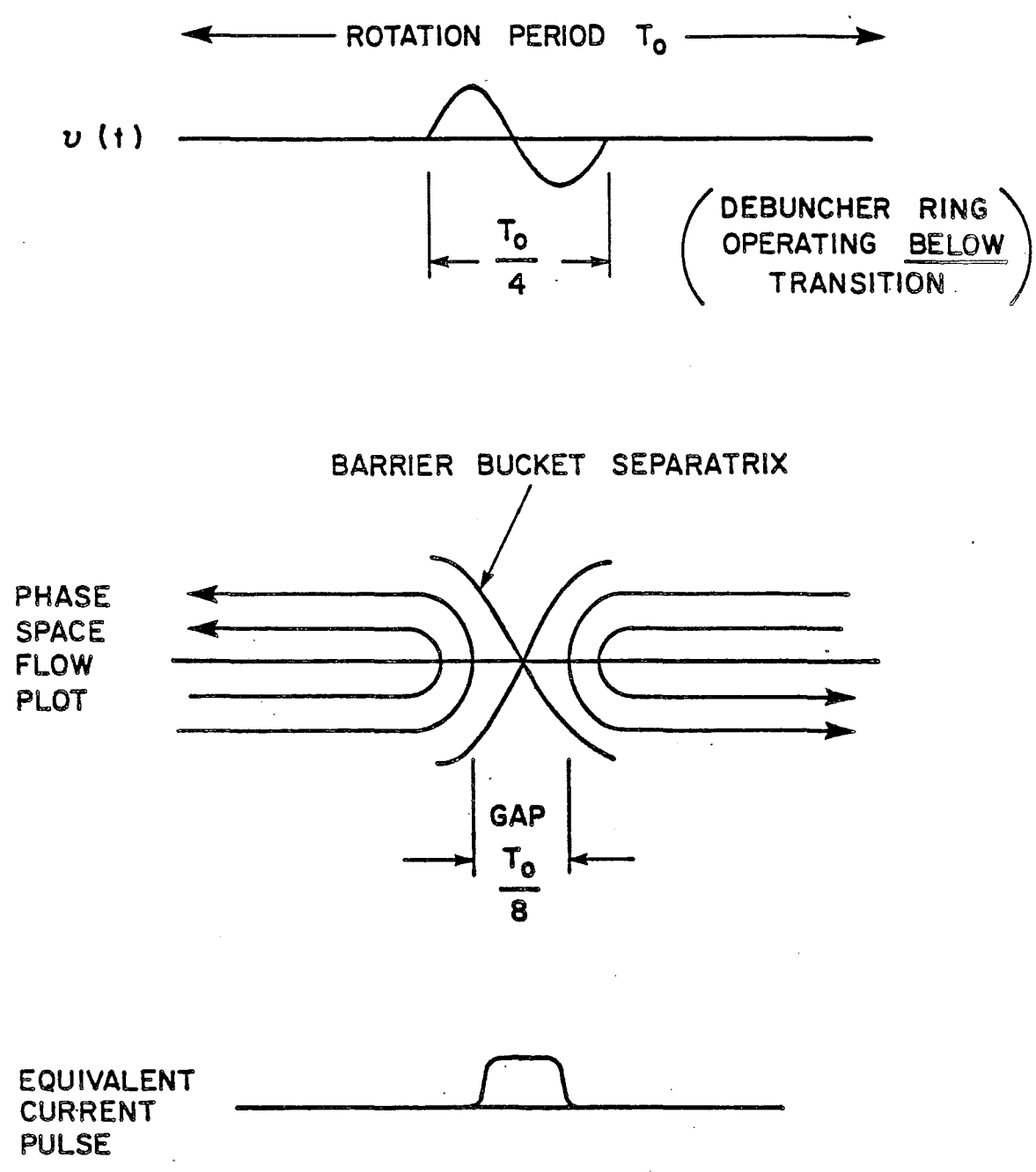


Fig. 4-20

4.6 Magnet and Power Supply Systems

The Debuncher magnet ring consists of 24 regular cells, 6 dispersion-killing units and 9 special low-beta insertions in the straight sections. There are two different-length dipoles that have the same profile. There are five different length quadrupoles, all having the same profile. All quadrupoles have the same profile as the small Accumulator quadrupole.

A beam with a 4% momentum spread and an emittance of 20π mm-mrad requires a good-field aperture of 75 mm (h) by 40 mm (v) in the dipoles and 80 mm by 50 mm in all quads. The good-field region of the dipole has been designed to be 100 mm x 60 mm. The sagitta of the beam is 22 mm and the long dipoles are therefore curved to match the orbit. The properties of these magnets are tabulated in Table 4-V.

The magnet ring is powered by five separate power supply buses, one for the dipole and one each for the regular focusing and defocusing quadrupoles. The two different kinds of triplets in the long straight sections are powered separately. The estimated power consumption of the ring is 2 MW.

Table 4-V. DEBUNCHER MAGNETS

Dipoles	Number	Arc length	Strength	Gap	Goodfield width
B	54	1.9050m	1.68T	60mm	100mm
B ₁	12	0.695323m	1.68T		

Quadrupoles

			Gradient	Poletip Radius
QF	30	.8128M	14T/m	44.5mm
QD	33	.8128	14 T/m	"
Q1	12	.7010	"	"
Q2	6	1.28778	"	"
Q3	6	0.5283	"	"
Q4(*)	6	1.0278	"	"
Q5	12	0.4572	"	"

(*) All the quadrupoles have a length and an aperture identical to the small quads for the Accumulator Ring. This magnet has a different length; identical magnets are used in beam-transport lines.

4.7 Betatron Cooling

4.7.1 Design Goal. The goal of the stochastic cooling in the Debuncher is to cool the beam emittance from 20π mm-mrad to 7π mm-mrad in both the horizontal and vertical planes. An emittance of 7π mm-mrad is the assumed beam size which can reliably be transferred into the 10π mm-mrad acceptance Accumulator ring with negligible beam loss. In addition to cooling the beam to fit into the Accumulator, it is desirable to make the beam injected into the Accumulator as small as possible. In the Accumulator the momentum stacking is done in part by a pickup that senses a particle's momentum by observing its position in a region of high dispersion. Betatron oscillations add undesired noise to this process².

4.7.2 Design Considerations. The betatron-cooling system is conceptually simple. It consists of a pickup that senses the positions and therefore the betatron amplitudes of the particles. The signal is amplified and applied to a kicker an odd multiple of 90° away in betatron phase. At the kicker, the position displacement that was sensed has been converted into an angular displacement. This angular displacement is decreased by a correcting kick, which thus decreases the betatron amplitude. As is well known, the cooling of a single particle is hampered by the presence of the other particles, which appear as a noise signal which heats the particle. For a properly designed system, the net effect over many turns is that cooling is achieved.

The process of betatron cooling is conventionally described by the equation³

$$\frac{dA}{dt} = -\frac{W}{2N} (2g - g^2(M+U))A,$$

(4.1)

where A is the betatron amplitude, W the amplifier bandwidth, N the number of particles, g the system gain, M the mixing factor and U the ratio of noise to signal power. The mixing factor M is given by

$$M = \frac{f^2 \psi(f) \Lambda}{2WN}$$

$$\frac{f_0 \psi(f)}{N n_e}$$

(4.2)

where $\psi(f)$ is the density of particles (number per Hz), f is the revolution frequency, f_0 is the revolution frequency (0.578 MHz) of the central momentum, and Λ is a constant of order unity ($\Lambda = \ln 2$ if the gain is independent of frequency).

Stochastic cooling during the 2-sec Debuncher cycle is difficult for several reasons. The first reason is that the mixing factor M is large compared to 1. M is inversely proportional to η , where

$$\frac{\Delta f}{f} = \eta \frac{\Delta p}{p}$$

(4.3)

The choice of the value of η was a compromise between the rf requirement for the bunch rotation (which favors a small η) and stochastic cooling (which favors a large η). The choice of $\eta = -0.0047$ leads to a mixing factor M of about 10 for the particles near the central momentum of the Debuncher, assuming a debuncher momentum distribution which is parabolic with a full width of $\Delta p/p = 0.3\%$.

A second problem is that the noise to signal ratio U tends to be large. The techniques to make U small are: 1) increase the Schottky signal as much as possible by using a large number of high-impedance pickups and 2) decreasing the noise temperature by cooling the pickup terminating resistors and the preamplifiers. The pickup system has been assumed to be loop couplers as described in 5.4.1. The parameters of the pickup and preamplifier system are given in Table 4-VI.

Table 4-VI. BETATRON COOLING SYSTEM PARAMETERS

Pickup Characteristic Impedance (Z_0)	75 Ω
Sensitivity (or coupling factor) (S)	1.6
Number of Pickups n_p	192
Maximum β at pickup β_p	10 m
Terminating resistor temperature θ_R	80K
Amplifier equivalent noise temperature θ_A	80K

A technical problem⁴ occurs when one tries to use a large number of pickups in a region of low β . The betatron phase advance becomes appreciable over the pickup array and there is a partial cancellation of

signal. For example, in a straight section 10 m long with a minimum beta at the center of 5 m, a pickup array centered in the straight section would give the best signal-to-noise ratio if the array length were limited to 8 m. At this length, the effectiveness of the array is 0.85 of what it would be if the betatron oscillation could be turned off. For this reason, both pickups and kickers have been divided into two sections 180° apart in betatron oscillation. With this division, the betatron oscillation dilutes the sensitivity by 0.05. This effect has already been taken into account in the sensitivity factor quoted in Table 4-VI.

The criterion for the thermal noise to be negligible is $U \ll M$. With the parameters of Table 4-VI,

$$U = \frac{2K_{\beta}(\theta_R + \theta_A) \times 10^{-23}}{s^2 Z_o e^2 f_o n_p N \beta_p \bar{\epsilon}} \quad \text{liked}$$

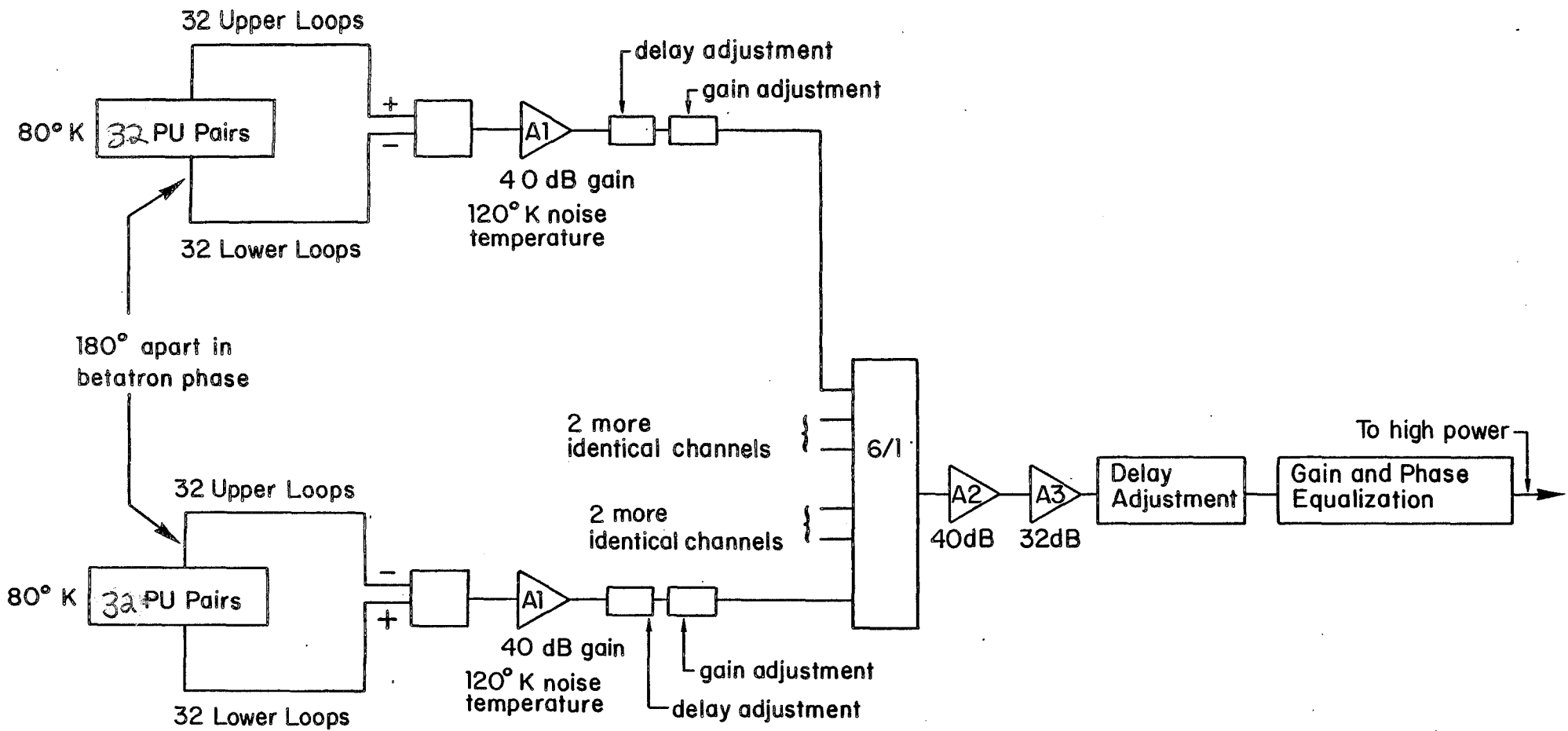
$$= 1.2 \text{ (initially) } \checkmark$$

(4)

where $K = 1.38 \times 10^{-23}$ joules/°K, $f_o = 1/T$ -revolution frequency, $\bar{\epsilon}$ =average beam size = 8π mm-mrad initially. However, as the beam is cooled to $\bar{\epsilon} = 0.8\pi$ mm-mrad, U will grow to 12, the same value as M , the mixing factor. Thus cooling will initially proceed not limited by thermal noise, but as the beam cools, the effect of the Schottky and thermal noise become comparable (note that the cooling equation (1) is written in a deceptive form because it does not explicitly show the dependence of U on $\bar{\epsilon}$).

A practical problem that occurs in fast stochastic cooling is that the power requirements are often very high. In the Debuncher, the best cooling rate is obtained for a power level of 1700W. However, as can be seen from Eq. (1), the gain can be decreased by a factor of 2 and the cooling rate will decrease by only $2g - g^2 = 3/4$. In the absence suppression, the power will decrease by a factor of 4. In the case that signal suppression is important, the decrease in power can be even greater because the system gain g increases more slowly than linearly with the amplifier gain. In a system with bad mixing like the Debuncher most of the thermal power is between Schottky bands and is largely unaffected by signal suppression. In this case, the thermal power is therefore more nearly proportional to amplifier gain squared than to system gain squared (g^2).

4.7.3 Hardware. A block diagram of the betatron cooling system is shown in Fig. 4-21(a-b). In brief, the pickup signal from 32 upper plate pickups is combined with 32 lower plate signals to provide a difference signal proportional to the position displacement of the beam. The signals from each set of 32 pickups amplified 40 dB are combined in an 6-fold combiner. Each combiner input has an adjustment for amplitude and delay. After combination the signal is further amplified by 72 dB to a level of about 25 dBm. An overall delay adjustment is followed by a gain and phase



Debuncher Betatron Cooling Systems

2-4 GHz Horizontal and Vertical Systems are Identical.

Fig. 4-21a

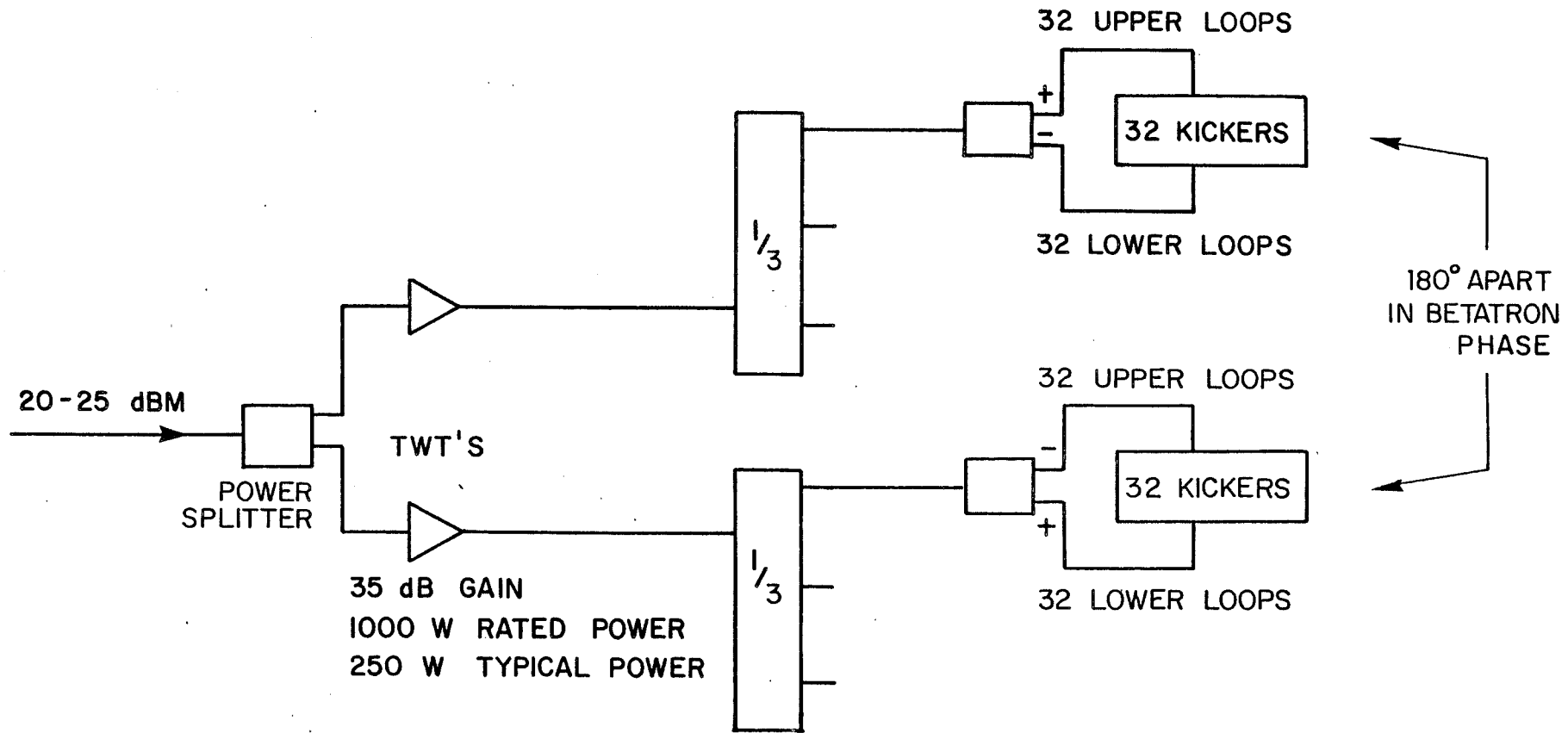


Fig. 4-21b

compensating circuit, to partially cancel the variations in the TWT (traveling wave tube) gain characteristics. The power is then split to drive two sets of TWT's, each of which drives an array of 96 kickers. The hardware components are described in more detail in Section 5.4.

4.7.4 Computer Simulation⁵. A simulation of the betatron cooling in the Debuncher was made to calculate the expected system performance. Included in the simulation were the pickup and kicker response functions, transit-time differences of the electrical signal and particles between pickup and kicker, and signal suppression. The amplifier was modeled as a physically unrealizable ideal amplifier having a gain g_A from 2 to 4 GHz and zero elsewhere. It was assumed that g_A was purely real. While the amplifier model was not realistic, measurements of the TWT tube amplifiers in the 1-2 GHz range show that, when externally phase compensated, these tubes can provide gain and phase characteristics that lead to cooling rates equal to or better than the 1-2 GHz "ideal" amplifier. The initial p distribution was taken from Fig. 3-4. It was assumed that the Debuncher had an emittance of 25π mm-mrad but that the transport line had already limited the beam size to 20π mm-mrad. The total output power was limited to 500W. The gain was continually adjusted to provide the best cooling within the 500W limit.

Figure 4-22 shows the initial and final beam distributions for particles at the central momentum. Ninety-nine per cent of the particles fall within an emittance of 7π mm-mrad. Also shown is the final curve for particles with a momentum offset of 0.075%, or halfway to the edge of the distribution. The cooling of these particles is somewhat better since they have a somewhat lower density, i.e., less Schottky noise. Since the noise figure assumed is somewhat speculative, Fig. 4-23 compares the final spectrum for design case $\theta_A = \theta_p = 100^\circ\text{K}$ and noise figures 2x and 3x worse. If the noise figures were worse because of the pickup sensitivity being less than supposed, the kickers would presumably be less sensitive in the same ratio. In this case, the total dissipated power would be larger than the design case of 500W. Figure 4-24 is a comparison of the final distribution for different power levels assuming the design case noise figure ($\theta_A = \theta_p = 80^\circ\text{K}$). As previously stated there is little advantage in running at power levels corresponding to the optimum gain.

The stochastic cooling system for the debuncher as designed will cool the beam emittance by about an order of magnitude. If the system fails to perform as designed, there is a substantial margin of safety in getting the beam to 7π mm-mrad for transfer into the accumulator.

4.7.5 Effect of the gap on betatron cooling. The effect of the "barrier bucket" on stochastic cooling has been considered. Recall that the "barrier bucket" establishes a gap in an otherwise-continuous debunched beam. The process of creating this bucket adiabatically after betatron cooling, is time consuming, it is planned to turn the barrier bucket on as soon as the debunching is completed. This raises the question of the effect that such a gap has on the betatron cooling. Excitation of a beam

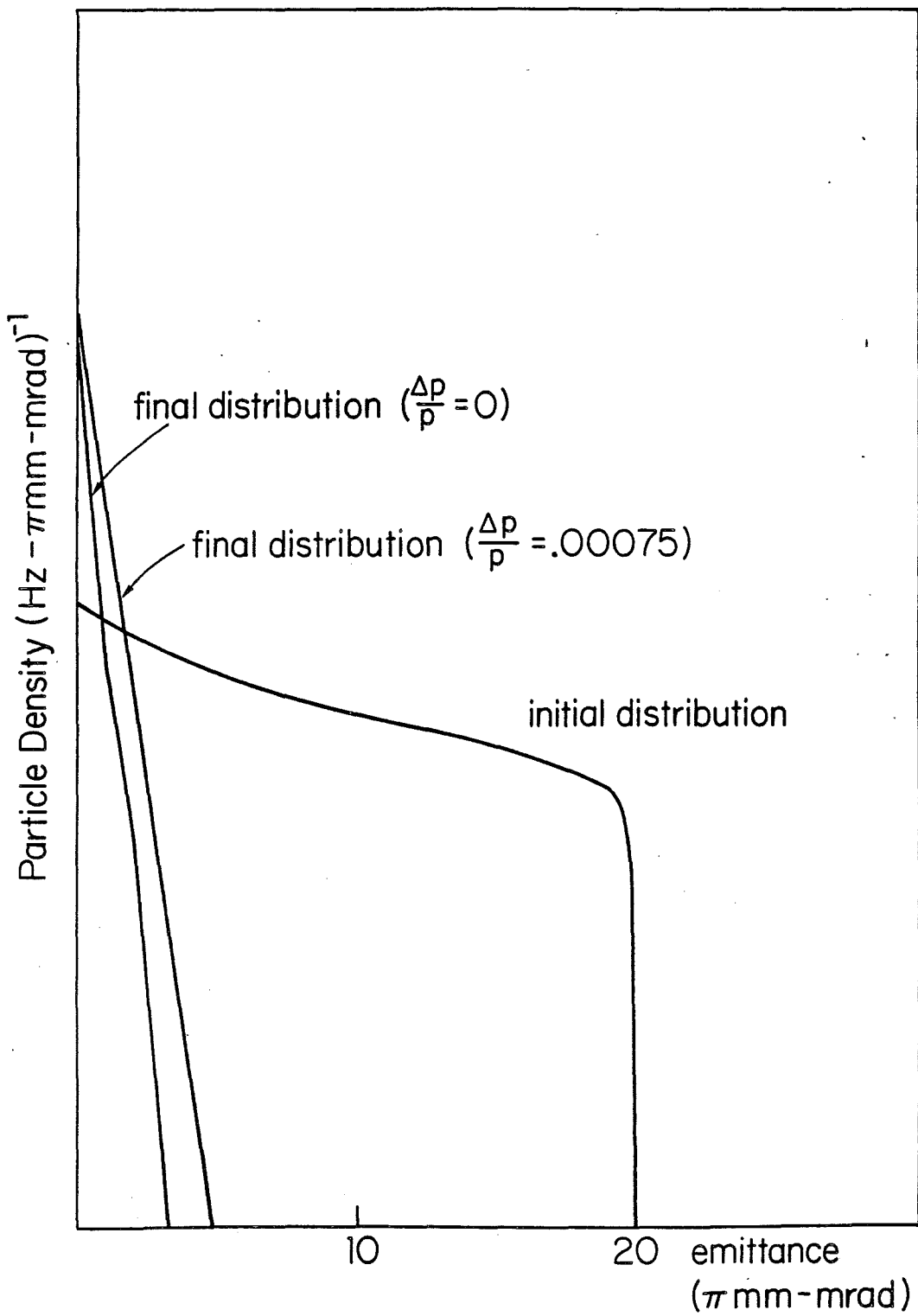


Fig. 4-22

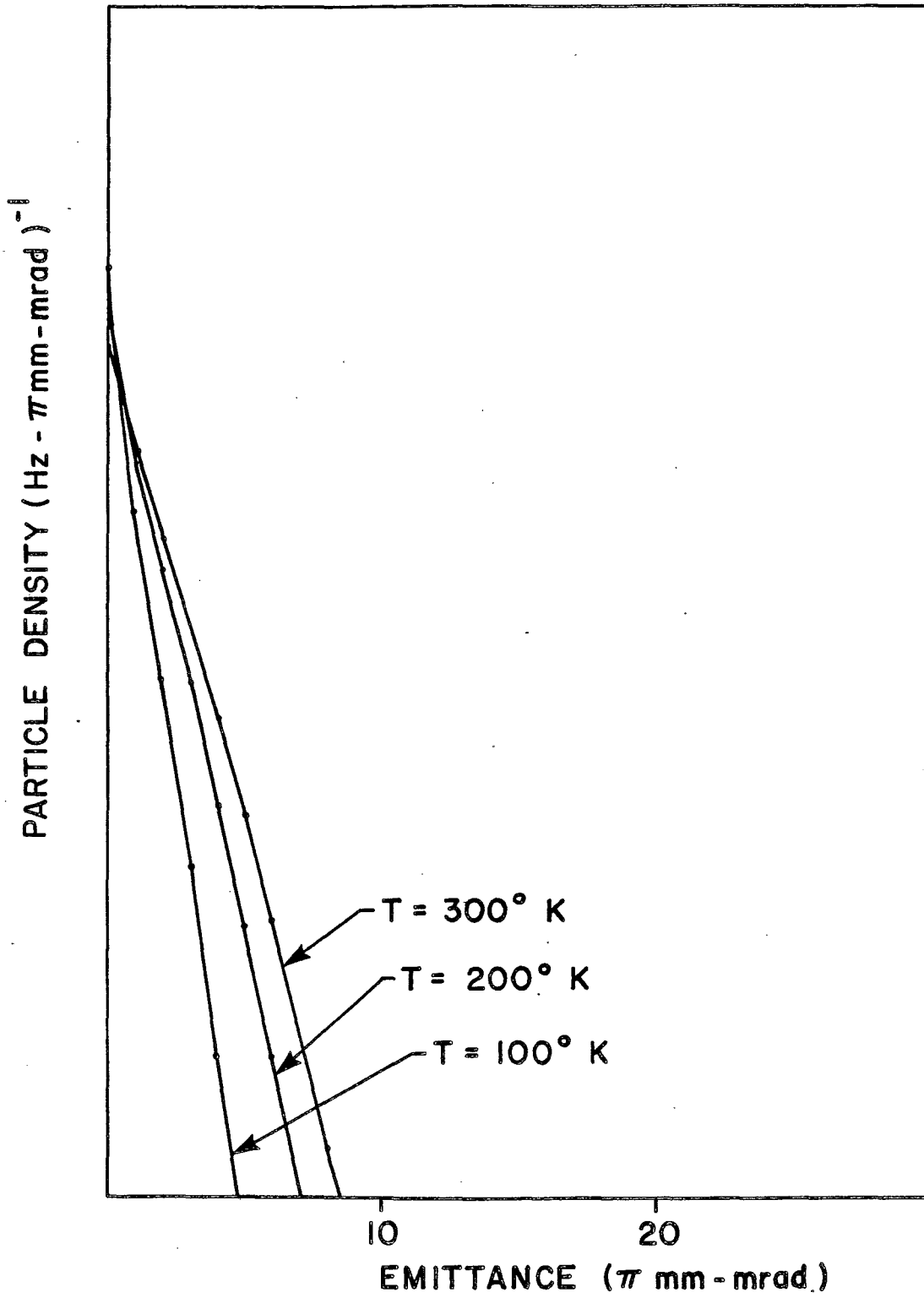


Fig. 4-23

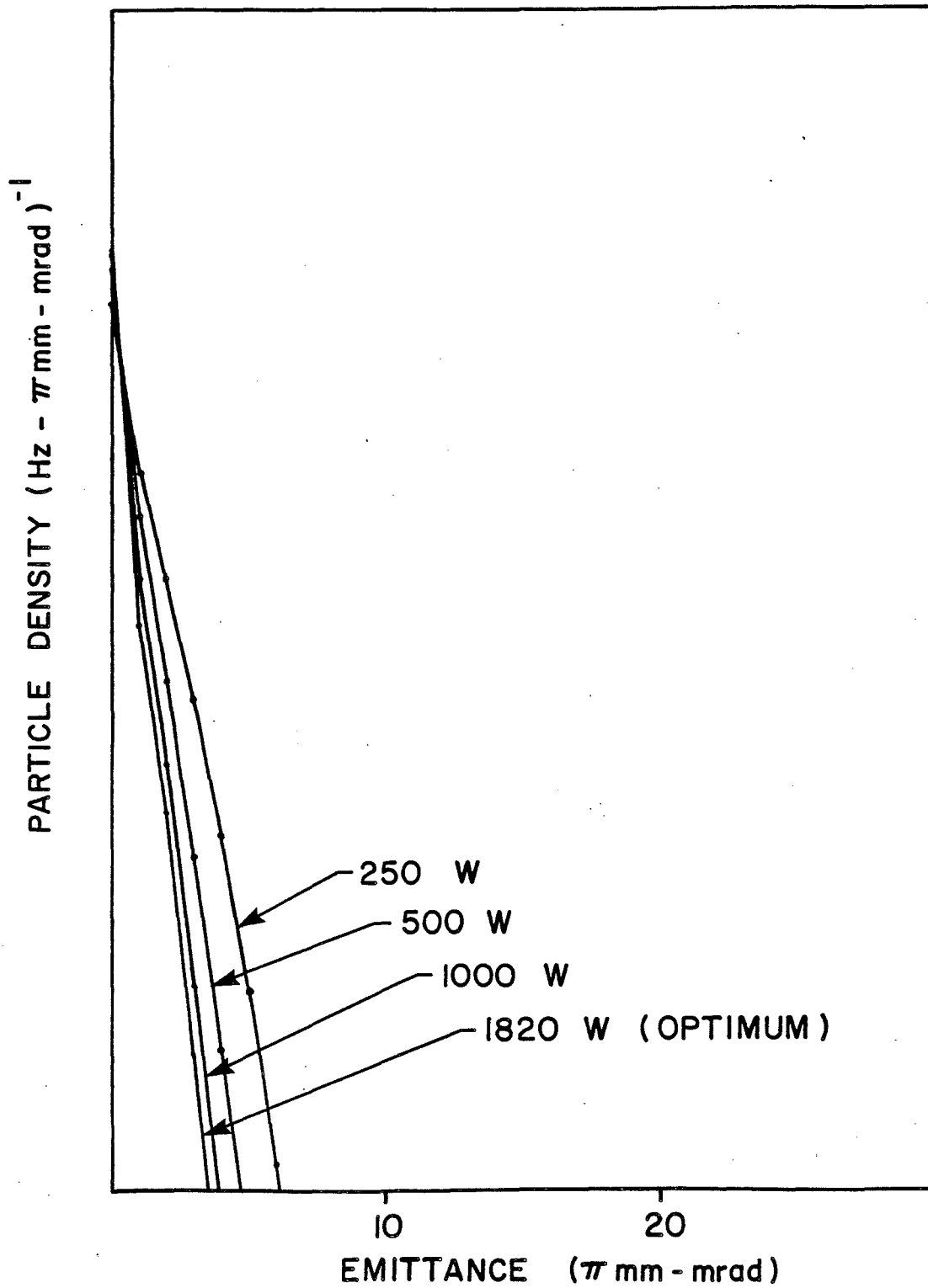


Fig. 4-24

pickup by the gap in the beam is equivalent to excitation by a single bunch in the ring with a current distribution equivalent to the missing current in the gap, as shown in Fig. 4-20. If the current is described by a \cos_2 dependence where it is changing and if the gap length is related to the total bucket length by a factor k , then the Fourier series representing the current distribution is

$$i(t) = i_{dc} \left\{ 1 + \frac{2h}{(k+1)\pi} \sum_{n=1}^{\infty} \frac{(\sin nk/\pi h + \sin n/\pi h)}{n(1-(1-k)_2(n/h)_2)} \cos n \omega_0 t \right\}.$$

For $h=4$, $k=0.5$, and $\omega_0=3.5 \cdot 10^6$, the maximum amplitude of signals in the region of 1 GHz ($\omega_0=1800^\circ$) is about $2 \cdot 10^{-8} i_{dc}$, which is much smaller than the thermal noise.

References

1. A. Ando and K. Takayama, FNAL TM-1073 or p Note 173 (1981).
2. J. Simpson, p Note 207 (1982).
3. D. Mohl, G. Petrucci, L. Thorndahl, and S. van der Meer, Physics Reports C, 58, 73-119 (1980).
4. J. Marriner, p Note 234 (1982), Fermilab.
5. J. Marriner, p Note 229 (1982), Fermilab.

Amp. Saturates?

5. ACCUMULATOR RING

5.1 Accumulator - Functional Summary

The first function of the Accumulator is to accept a pulse of \bar{p} 's every 2 seconds. In order to make room for this pulse, the \bar{p} 's must be compressed (cooled) into a smaller area of phase space. A technique to accomplish the continuous \bar{p} accumulation and compression has been developed at CERN and is the basis of this design. The technique consists of establishing a stack of \bar{p} 's with an energy density that rises approximately exponentially from the injection density (the low-density end is referred to as the "stack tail") and then culminates in a roughly Gaussian high-density region (the "core"). The density profile of the proposed system is shown in Fig. 5-1. Betatron amplitudes are also cooled during the stacking process. The design criteria for the accumulation process are given in Table 5-I.

Table 5-I. ANTIPROTON STACK PARAMETERS

Injected Pulse

Number of \bar{p} 's	7×10^7
$\Delta p/p$	0.2%
Horizontal and vertical emittance	10π mm-mrad
Time between injections	2 sec
Fraction of beam accepted	~85% of injected pulse
Flux	3×10^7 \bar{p} /sec

Final Stack

Number of \bar{p} 's	4.3×10^{11}
$\Delta p/p$	0.1%
Horizontal and vertical emittance	2π mm-mrad
Peak density	1×10^5 eV ⁻¹
Core width (Gaussian part)	1.7 MeV (rms)
Total stacking time	4 hours

5.2 Momentum Cooling

5.2.1 Introduction to Stochastic Stacking The stochastic stacking system consists of pickup electrodes, an amplifier system with electronic filters and phase-compensation networks, and kicker electrodes. Each particle produces an electronic signal that, when applied to the kicker, changes its momentum in the direction of the momentum of the core. The signal of each given particle thus produces a kick that tends to cool the beam into a small momentum width around the core. Other particles in the

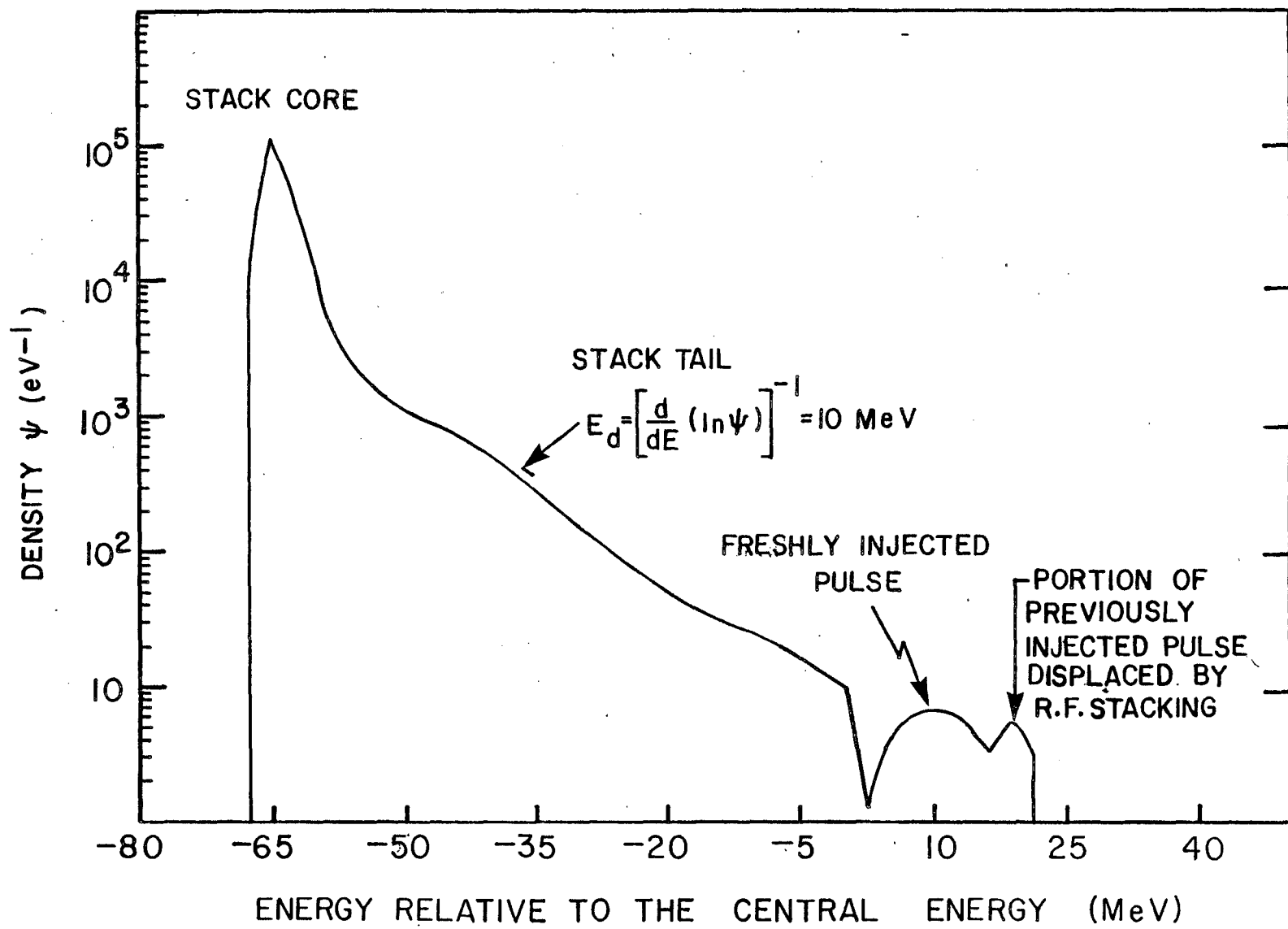


Fig. 5-1

beam with approximately the same revolution frequency produce random kicks on the given particles and cause diffusion or heating. The interesting systems, of course, are those in which cooling dominates over heating.

Momentum cooling is usually described in terms of the Fokker-Planck equation

$$\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial E} \left[-F\psi + (D_0 + D_1 + D_2\psi) \frac{\partial \psi}{\partial E} \right]$$

where $\psi = \partial N / \partial E$ is the particle density, F is the coefficient of the cooling term, D_0 is the coefficient of the heating term due to intrabeam scattering (described later), D_1 is the coefficient of the heating term due to thermal noise, and D_2 is the coefficient of the heating due to other particles. A derivation and discussion of this equation are given by Mohl et al.¹

A simplified version of the Fokker-Planck equation has been used by van der Meer² to describe the stacking process. It is assumed that the voltage on the kicker is exactly in phase with the particles that created it, that there is no amplifier thermal noise or intrabeam scattering, the feedback gain is independent of harmonic number, and that there are no beam-feedback effects. A more general approach, including thermal noise, is possible.³ While none of these assumptions is justified in the proposed system, the simplified discussion yields semi-quantitative results that can form the basis of a design.³ Following van der Meer, the flux can be written as

$$\dot{\Phi} = \underbrace{-\frac{V}{T}\Psi}_{\text{cooling term}} - \underbrace{AV^2\Psi \frac{\partial \psi}{\partial E}}_{\text{heating term}},$$

cooling coefficient F

where $N(E, t)$ is the number of particles with energy less than E and

$$\Phi = \frac{\partial N}{\partial t}$$

$$\psi = \frac{\partial N}{\partial E} ,$$

from which the Fokker-Planck equation

$$\frac{\partial \psi}{\partial t} = \frac{\partial \Phi}{\partial E}$$

follows. Here $V = V(E)$ is the average energy loss per turn and T is the revolution period. The constant A describes the strength of the heating term and is given by

$$A = \frac{\beta p \Lambda}{4T^3 W^2 |\eta|} ,$$

where $\beta = v/c$, p is the momentum, T is the revolution period, W is the bandwidth $= f_{\max} - f_{\min}$, $\Lambda = \ln(f_{\max}/f_{\min})$, and $\eta = \gamma_t^{-2} - \gamma^{-2}$. If the amplifier gain is not independent of frequency, Λ is modified. The ideal gain profile, in fact, rises linearly with frequency, but the exact value of Λ is not important for this discussion.

The Fokker-Planck equation is nonlinear in ψ and it is therefore usually solved numerically. Stationary solutions, $\Phi(E,t) = \Phi_0 = \text{constant}$, can often be found by elementary methods. These solutions are useful because in the stack tail between the core region and the injection region, the actual time-dependent solution is normally very close to the steady-state solution.

Consider $\Phi_0 = \text{constant}$ and $\psi(E,t) = \psi(E)$, and ask what the shape of the voltage profile $V(E)$ should be. The answer, as given by van der Meer, is to maximize $d\psi/dE$ everywhere and thus minimize the energy aperture which is required. This choice also minimizes the total Schottky power in the amplifier. The solution is

$$\Phi_0 = \frac{V}{T} = -AV^2 \psi \frac{d\psi}{dE}$$

$$\frac{d\psi}{dE} = -\frac{\Phi_0}{AV^2 \psi}$$

$$\text{For } V(E) = \frac{V_0}{E} \left(\frac{E}{E_0} \right)^{\alpha}$$

$$\Sigma_0 = 4\pi R^2 \frac{d\psi}{dE} = \frac{4\pi R^2 \Phi_0}{AV^2 \psi}$$

$$V(E) = -\frac{2\Phi_0 T}{\Psi(E)} = -\frac{2\Phi_0 T}{\Psi_1} e^{-(E_1 - E)/E_d}$$

where Ψ_1 is the initial stack-tail density at E_1 and E_d is the characteristic energy

$$E_d = -4A\Phi_0 T^2 = -\frac{\beta p \Lambda \Phi_0}{TW^2 |\eta|}$$

This equation exhibits the major design consideration. We know that $d\psi/dE$ is maximized by a gain profile $V(E)$ that is exponential in energy. The exponential slope $d\psi/dE$ is maximized by minimizing E_d . In the stack tail, we want a density increase of 1000, so we require a minimum momentum aperture of $\Delta p/p = \ln(1000) E_d/p = 6.91 E_d/p$. If we want to limit the aperture ($\Delta p/p$) required for the stack tail to 3/4%, then $E_d < 0.001 p \approx 10$ MeV for $p = 8.9$ GeV/c. Since we want to have Φ_0 as large as possible, we must make E_d small by choosing $TW^2 |\eta|$ to be as large as possible.

We have chosen to work with a maximum frequency of 4 GHz for the purposes of this report, but we intend to use frequencies up to 8 GHz for core cooling if our research program indicates that 8 GHz cooling systems are practical. The stack-tail system was chosen to have a maximum frequency of 2 GHz. As described below, the choice of frequency dictates the choice of η . By limiting the stack-tail system to 2 GHz, we are able to use a relatively high η ($\eta = 0.02$). The high value of η is useful for the core-cooling systems, where the core cooling times are inversely proportional to η .

The maximum value of η is limited once we choose f_{\max} . For a number of reasons, it is required that $\eta(\Delta p/p) f_{\max} T < \delta$, where δ is some number of order unity. The things that determine the value of δ are:

- (i) The Schottky bands must not overlap in a system that uses electronic filters for gain shaping. In such a system, the particle energy is sensed in the electronics by the connection between energy and the harmonics of the revolution frequency. If the relationship is not unique, it is difficult and probably impossible to design appropriate filters. In this case, $\delta = 1$ and $\Delta p/p = 1\%$ so $\eta < 0.03$ with $T = 1.6$ μ sec.
- (ii) The phase shift between PU and kicker must not vary across the momentum band more than about $\pm 45^\circ$. If PU and kicker are exactly opposite in the Accumulator Ring, then $\delta = 0.5$. If the stack-tail system is divided into subsystems with $\Delta p/p = 1/3\%$, then this constraint applies to each system individually, so $\eta < 0.05$.

- (iii) For reasons described below, the filters must have the peak of their response at the tail end and a notch in the core. Between Schottky bands, of course, the response must rise from the notch in the core back to the peak value. Since the rise back to the peak value cannot be done infinitely sharply, at least without undesirable phase characteristics, this requirement is more severe than 1) above. We have found that $\eta = 0.02$ is a suitable value for a maximum frequency of 2 GHz.

We have chosen a Booster-sized ring ($T = 1.6 \mu\text{sec}$) because it is large enough to accommodate the cooling-system hardware and can run at 8 GeV, a good energy for production of \bar{p} 's and their injection into the Main Ring.

5.2.2 Summary of Design Considerations. We have chosen $E_d = 0.001p = 10$ MeV to keep the required momentum aperture sufficiently small. The product $T f_{\text{max}} \eta$ is fixed by the requirement of a minimum spacing between Schottky bands. We have chosen $W = 1$ GHz with $f_{\text{max}} = 2$ GHz to yield a somewhat higher value of η (0.02) than would be the case if we chose a higher frequency. Higher frequencies also have the disadvantage that it is somewhat more difficult to build the quality of hardware that is required.

5.2.3 Building the Exponential Gain Profile. Once the parameters of the stack tail have been chosen, the next step is to build the required gain profile. We use a combination of two techniques. The first technique is to sense the particle momentum by sensing its position in a region of high momentum dispersion. The position sensitivity of the strip-line pickups we plan to use is given in Section 5.4.1. For large horizontal displacement x the sensitivity of these pickups becomes

$$S(x,0) \propto e^{-\pi x/h}$$

where h is the gap between plates. In our case, the momentum dispersion is $\alpha_p = 9$ m and we have chosen $h = 3$ cm. Thus for large ΔE ,

$$V(E) \propto e^{-|\Delta E|/E^*},$$

$$\text{where } E^* \sim \frac{\beta^2 E h}{\pi \alpha_p}$$

where $V(E)$ is the average (coherent) particle voltage gain per second ΔE is the difference between energy E and the energy where the pickup response is centered, and $E^* = 10$ MeV. In our system we use the pickups in the region where the falloff is not truly exponential, but the system can be characterized roughly by an E^* for the pickup response of approximately 15 MeV.

The second method of gain shaping is with filters. However, the main purpose of the filters is to reduce the thermal noise in the core. In order to maintain a flux of 3×10^7 into the stack tail, an amplifier system with very high gain (150dB) is required. Even with preamplifiers with low noise temperatures (80°K), the thermal noise produces an rms voltage of approximately 1500 V/turn. This noise voltage is (perhaps surprisingly) tolerable in the tail where the average (cooling) voltage gain is about 10 V/turn. In the core region, where the cooling voltage is a few mV/turn, this noise voltage must be reduced to a tolerable level. The filter does this by making a notch at all harmonics of the revolution frequency of the particles in the core. The filter also does some gain shaping in the tail region. The filters used are composed of a series of notch filters similar in concept to those used at CERN. A schematic diagram of the individual component filters is given in Fig. 5-2. The response of these filters is given by

$$\frac{V_{out}}{V_{in}} = (e^{-\gamma_1 \ell_1} - \xi e^{-\gamma_2 \ell_2})/2$$

where γ_1 , γ_2 and ℓ_1 , ℓ_2 are the propagation constants and lengths of the cables and ξ is a variable attenuation of order unity. To get a clearer picture of the operation of this filter the approximation $\xi = 1$, $\ell_1 = 0$, $\gamma_2 = \omega T_c / \ell_2$ where ω is the applied frequency and T_c the electrical length of the cable. In this case

$$\left| \frac{V_{out}}{V_{in}} \right|^2 = (1 - \cos \omega T_c) / 2$$

and the phase changes linearly with frequency except at the transmission zero where it takes a discontinuous jump of 180°.

It is probably worth mentioning that the absence of amplifier noise would not necessarily eliminate the need for filters. Non-linearities in the pickups, amplifiers and other components cause frequency mixing - as is well known to r.f. engineers. The input power at frequencies corresponding to the stack tail - where the power density is high - will mix in a non-linear device and produce output power at frequencies corresponding to the core where the power density must be low. The filters suppress the most dangerous part of the unwanted distortion because of the notch at the frequency of the core particles. (These particles are cooled by a separate system without filters, as will be described later.) It will be advantageous to place some of the filtering after the final amplifier to reduce the sensitivity to the non-linear distortions from that source.

Filters also suppress high power output from mixing at stack tail freq. that would produce high power core momentum freq. components.

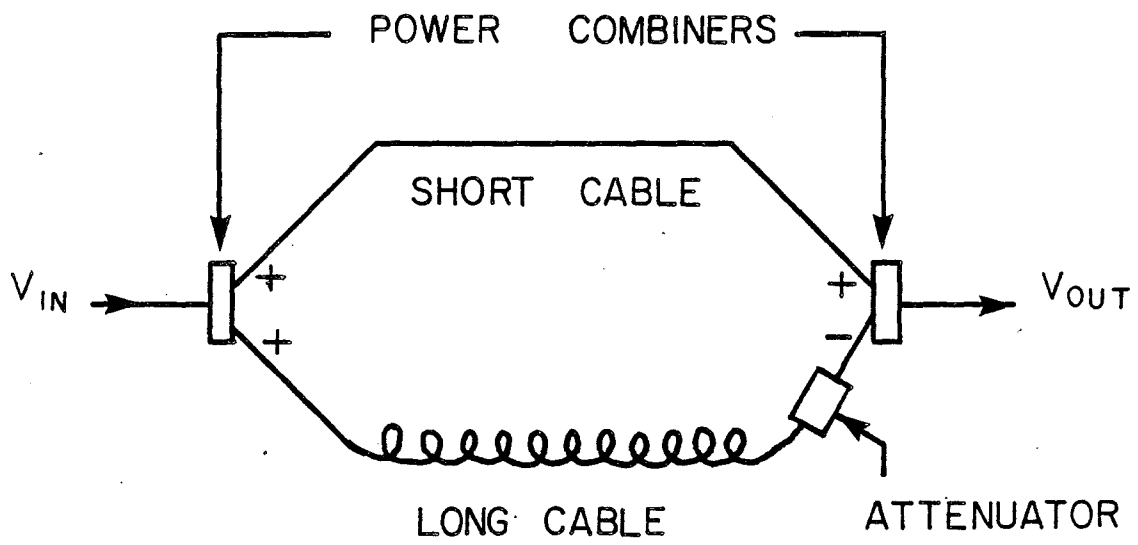


Fig. 5-2

The shape of the gain curve at the injection end is purposely different than the ideal exponential curve, becoming flat in the injection region because of several practical considerations:

- (i) It is desirable to keep the electronic gain between Schottky bands as low as possible. The gain between Schottky bands does not affect the cooling process, but the thermal power between Schottky bands is significant.
- (ii) To maximize the ratio of Schottky signal to thermal noise, it is desirable to place the pickups so they have maximum sensitivity to the freshly injected beam, i.e., so they operate in the non-exponential region.
- (iii) The exponential gain profile minimizes Schottky power only in the approximation that beam is injected in a steady state manner. In fact, each newly injected pulse substantially alters this picture since the density of particles will differ by factors of 2 or 3 from the steady state situation. By making the gain profile flatter in the injection region, we can reduce the required Schottky power immediately after a new pulse is injected.

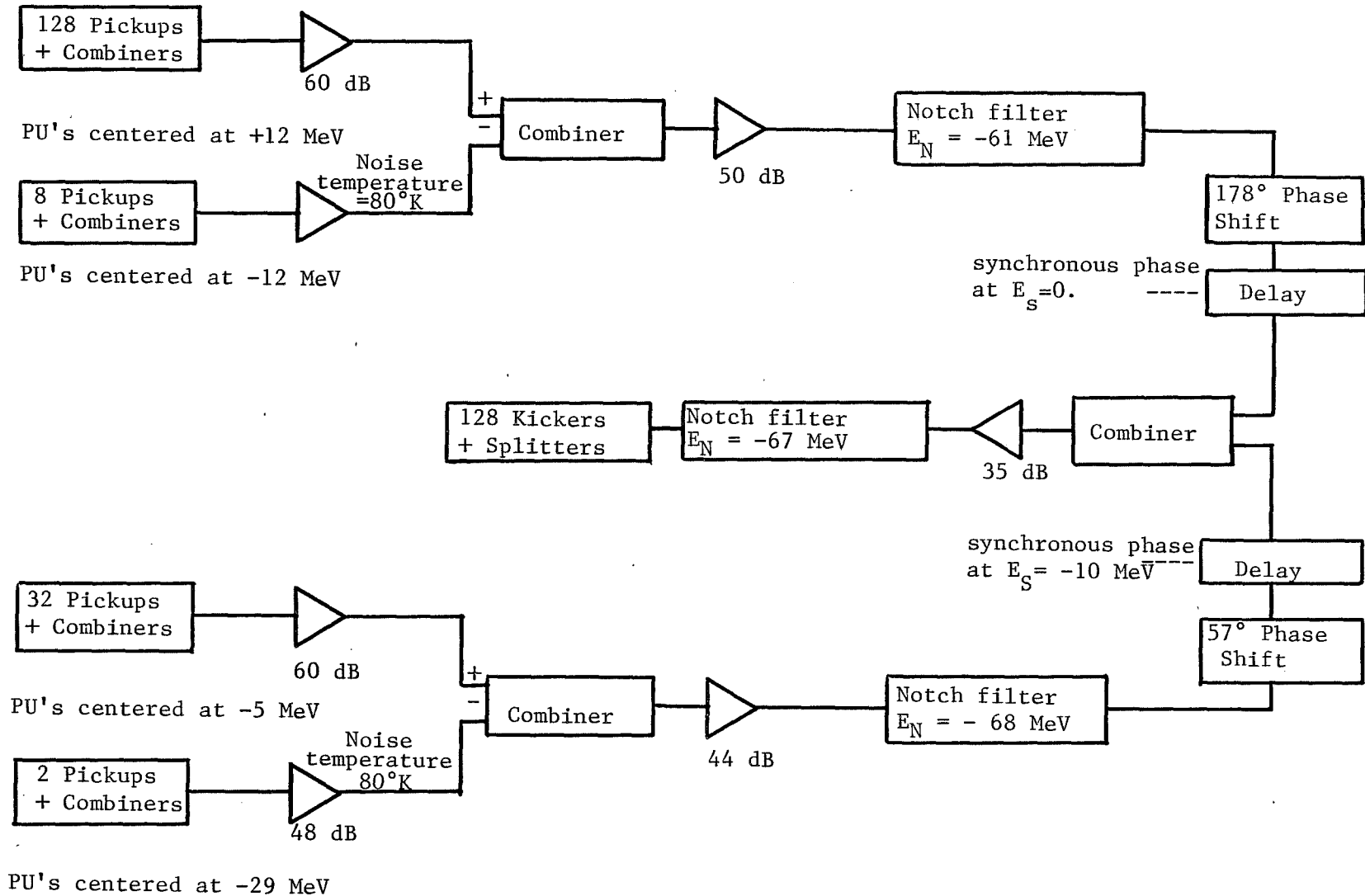
The stack-tail system we have designed consists of two sections of pickups and associated amplifiers and filters. The two sections make it possible to control undesirable phase shifts and thermal noise in the tail. A block diagram of the system is shown in Fig. 5-3. The number of pickups was chosen to be as large as possible to minimize the thermal-noise to Schottky-signal ratio and to minimize the total thermal power. In order to keep the betatron oscillations from substantially affecting the momentum cooling, the betatron amplitudes must be limited. To achieve the desired gain profile, the pickups have a plate separation of 3 cm. Calculations indicate that the beam size should be less than 2.4 cm to avoid trouble with betatron motion. For an emittance of 10π mm-mrad, the β function at the pickup must be 15 m or less. This requirement limits the pickup straight section to 15 m in length and a total of 200 pickups. The function of the subtracting pickups is discussed in the next section. The number of kickers was chosen to fill the straight section across from the pickups to minimize total power (inversely proportional to the number of kickers). The gain profile achieved with this system is shown in Fig. 5-4 abc for the Schottky bands at 1.1, 1.5 and 1.9 GHz.

Why & how
this mini
mize S/N
ratio?

Total power \propto #kickers

5.2.4 Signal Suppression and Stability. An important aspect of the cooling process, when using high-gain cooling systems, is signal feedback via the beam. A signal of frequency ω will modulate the beam at frequency ω , and this modulation will be sensed at the pickup. Thus the cooling system forms a closed-loop feedback system. This feedback system is analogous to amplifier systems with conventional electronic feedback. An expression for the beam feedback has been given by van der Meer⁵ and independently by Ruggiero.⁶ An approximate expression is

STACK TAIL MOMENTUM COOLING SYSTEM 1-2 GHz



ENERGIES ARE GIVEN RELATIVE TO THE CENTRAL ENERGY

Fig. 5-3

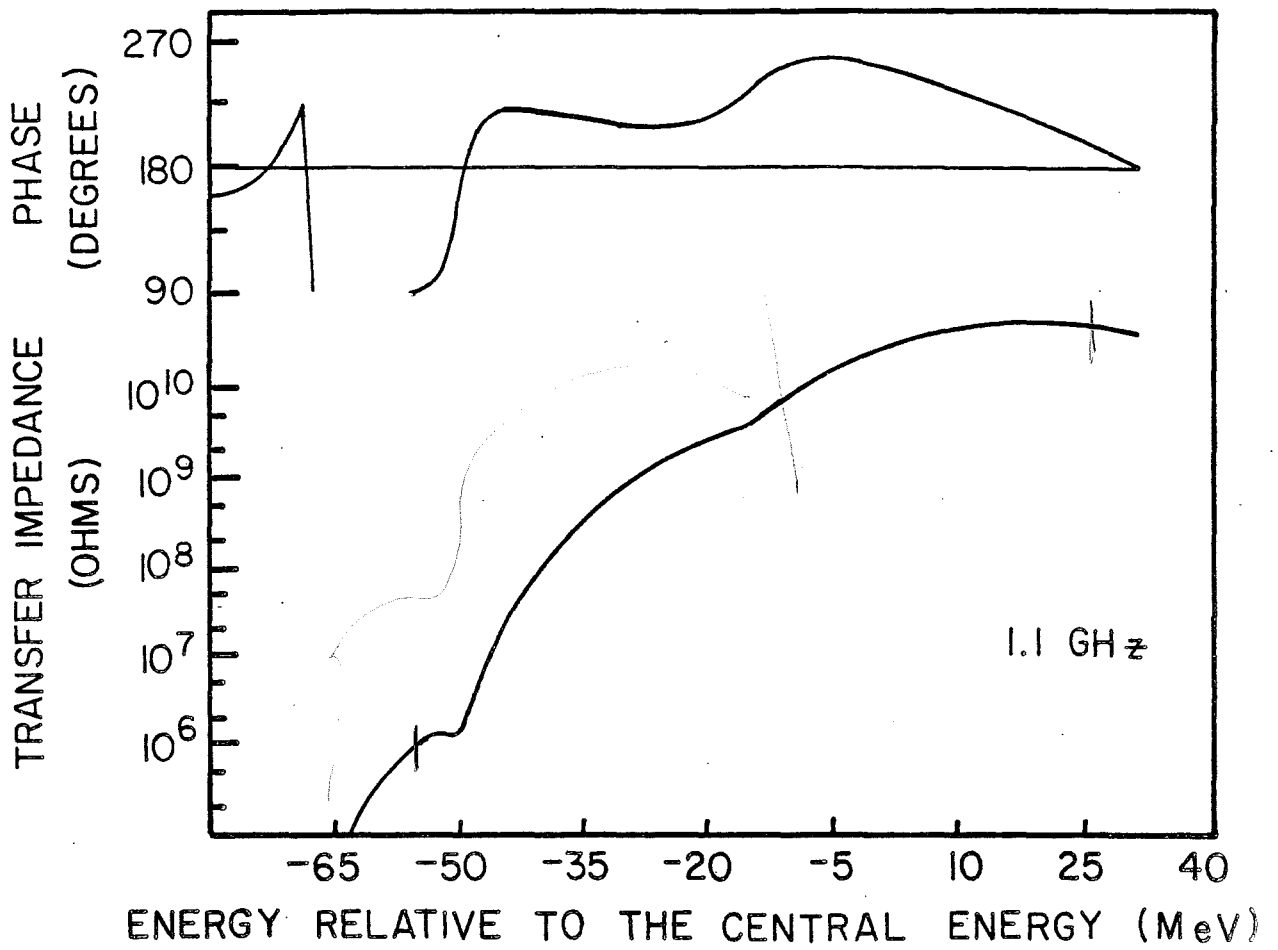


Fig. 5-4a

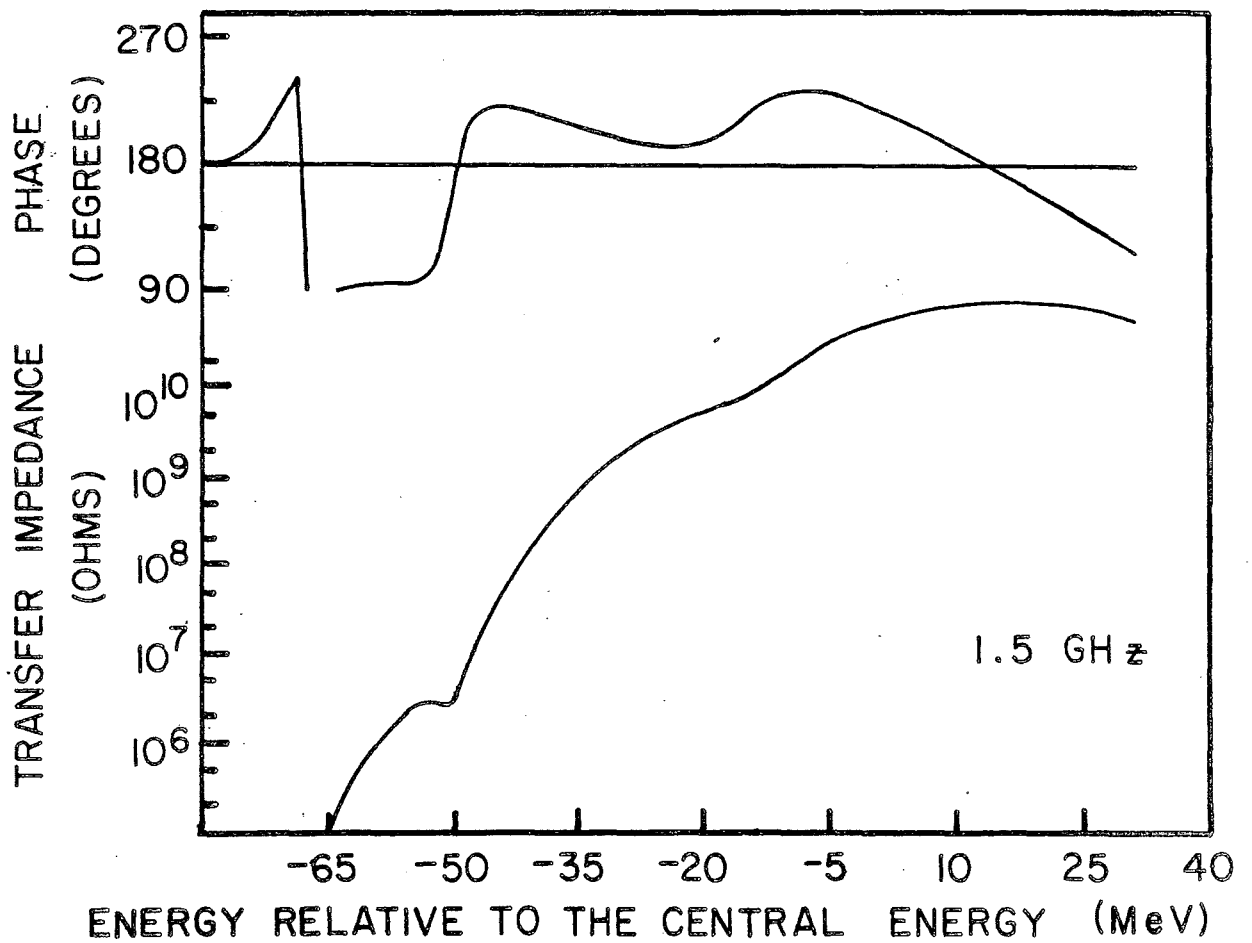


Fig. 5-4b

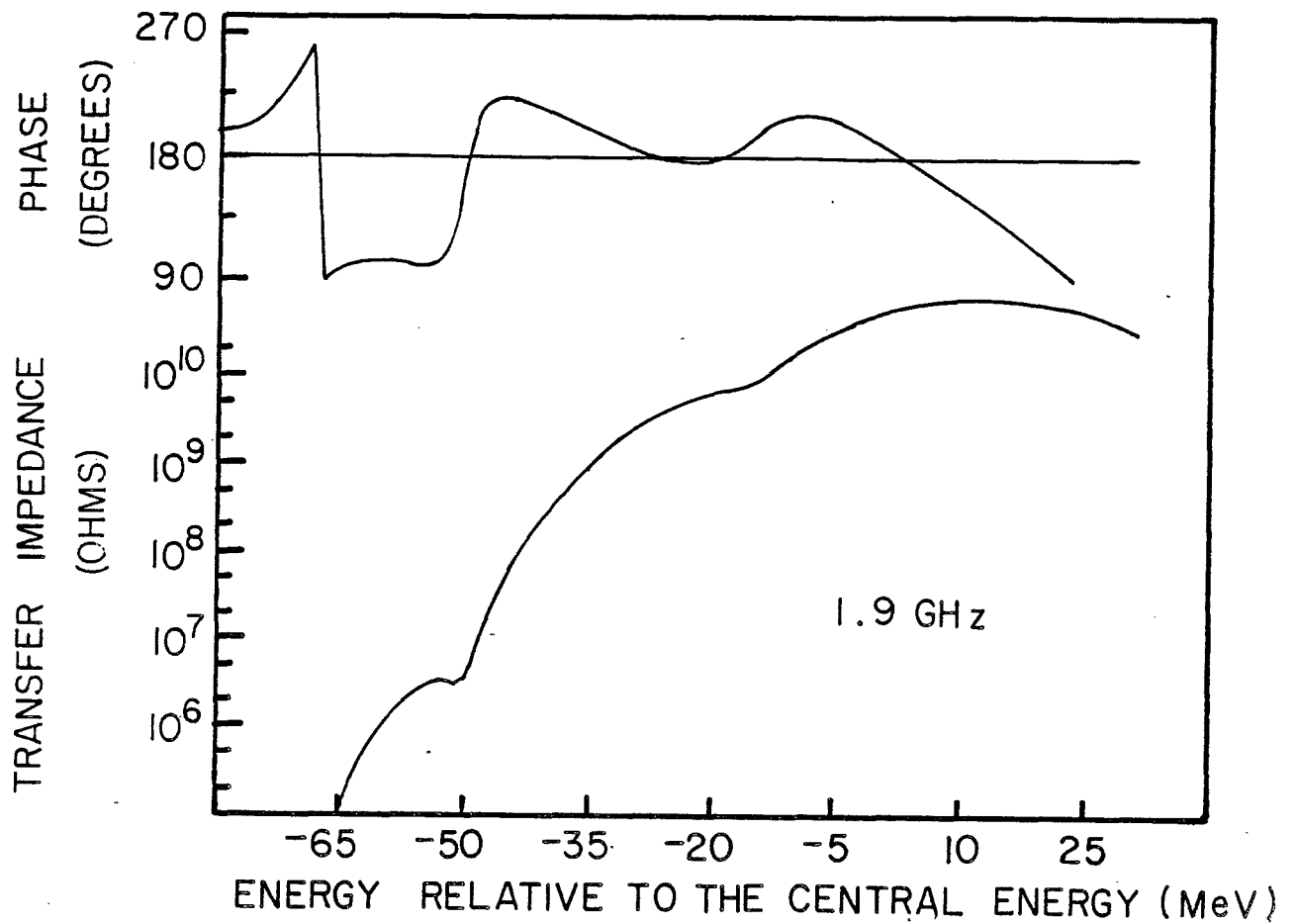


Fig. 5-4c

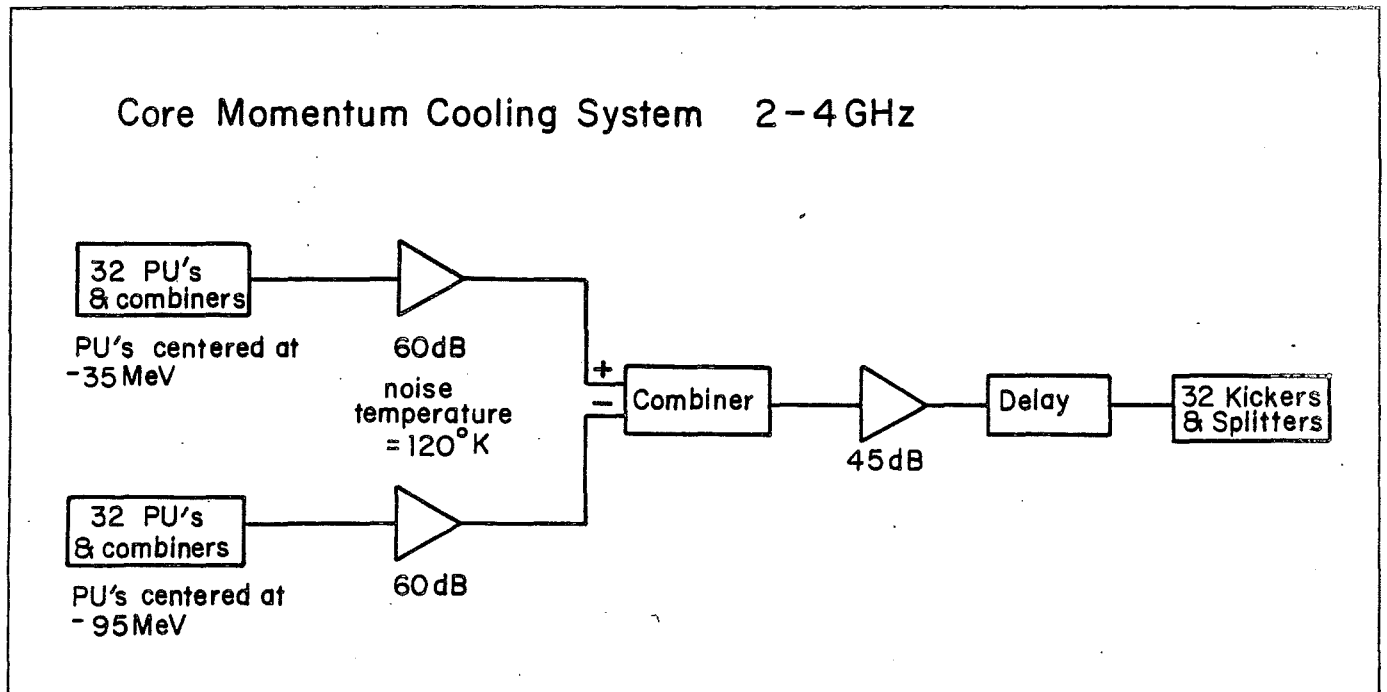


Fig. 5-5

$$F = \frac{I_p}{V} = j e f_0^2 P \int \frac{C P}{n k (E - E')} \frac{d\psi}{dE'} dE' - \frac{\pi e f_0^2}{n |k|} C P \frac{d\psi}{dE}$$

Beam feedback

where P denotes the principal value of the integral, I_p = induced current at the frequency $f = n f_0$ in the pickup due to modulation caused by voltage V on the kicker, f_0 is the revolution frequency corresponding to energy E ,

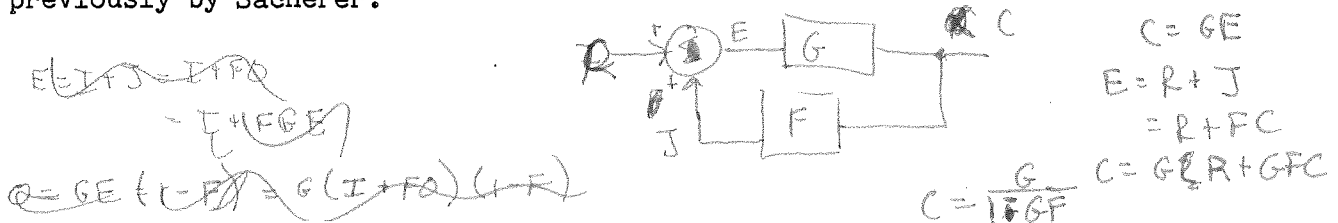
n is the harmonic number, e is the unit charge, $j = \sqrt{-1}$, $k = 2\pi df_0/dE$, C is the phase factor due to transit time differences between pickup and kicker, and $P = P(f, E')$ is the pickup sensitivity. P depends on E' because P depends on particle position, which depends on E' (usually exponentially). The dependence of P on f comes from electrical properties and is usually weak.

This approximation is valid when the Schottky bands are well separated but is a poor approximation for quantitative results for the system described here. Nonetheless, it is sufficient to expose the main features of the physical process.

The closed-loop gain of the system is given by $G' = G/(1-FG)$, where G is the open-loop gain ($G = V/I_p$) of the electronics going from pickup to kicker. If the real part of FG is less than zero, then $G' < G$ and the cooling signal is suppressed. If the real part is greater than zero the signal may be enhanced. If the real part of $FG > 1$, when the imaginary part is zero, the system is unstable. (This situation is completely analogous to the case of conventional electronic circuits with feedback).

In the approximate expression for F , one sees that there is a resistive (energy-absorbing) component of the beam response proportional to the gradient of the density at the driving frequency and a reactive component that depends on the asymmetry of the gradient about the driving frequency. It would be wrong to conclude, however, that the resistive term is the more important when looking at system stability. Both terms must be considered because the open-loop gain function G is a complex quantity; it unavoidably contains phase shifts from the filters and differences in time delays between pickup and kicker.

In fact, in the stack tail, the feedback can be dominated by the contribution from the particles in the core where $d\psi/dE$ is very large - 10^4 times larger than in the tail. Fortunately, $d\psi/dE$, which is increasing exponentially, is multiplied by the pickup response, which is decreasing exponentially. The rate of exponential increase of $d\psi/dE$ depends on the total gain profile, i.e., the product of pickup and filter response. The damping of $d\psi/dE$ in the feedback integral, however, depends only on the pickup response. Thus, it is important that the filter gain profile not be too sharp compared with the pickup in order to avoid severe problems with stability and signal suppression. The importance of the relative amounts of the gain profile derived from filters and pickups has been pointed out previously by Sacherer.⁷



An additional suppression of signal from particles in the core is provided by the subtracting pickups in each section. These pickups are placed closer to the core and normalized so that their sensitivity to the core region is equal and opposite to the sensitivity of the main pickups. In the stack tail, however, they subtract less than 10% of the signal. Several subtracting pickups followed by substantial attenuation are required to avoid having the subtracting pickups appreciably affect the amount of thermal noise in the pickups. Immediately after injection, the signal suppression is substantially larger because of the large values of $d\psi/dE$ created by the RF stacking process. The gradients quickly (after 200 msec) smooth out because of the diffusion terms in the Fokker-Planck equation. It appears that during the first 200 msec of the injection cycle, it may be necessary to reduce the amplifier gain in order to maintain beam stability. This gain reduction has been taken into account in computer simulations and, in any event, is only of minor importance.

5.2.5 Core Cooling. The same Fokker-Planck equation that describes the stack-tail system also describes the core system. In fact, the distinction between core and tail cooling systems is somewhat arbitrary. The asymptotic distribution is given by

$$\Phi = F\Psi + (D_0 + D_1 + D_2\Psi) \frac{\partial \Psi}{\partial E} = 0 = \frac{\partial N}{\partial t}$$

The cooling coefficient F has a zero at the peak of the core and a slope proportional to $g(E-E_c)$ where g is the electronic gain and E_c is the energy at the peak of the core. The other terms are heating terms. D_0 is the contribution of intrabeam scattering (via the Coulomb force) to the diffusion and has been calculated by Ruggiero⁸ to be $D_0 = 0.0015 N_p^2 (eV)^2/sec$, where N_p is the total number of antiprotons in the Accumulator. This value of D_0 corresponds to a momentum heating time of 2 hr. D_0 is independent of both g and E . D_1 is the contribution of thermal noise and is proportional to g^2 . D_2 is the Schottky heating term and is proportional to $g^2 (E-E_c)^2$. In our system D_1 is small compared with D_0 . Optimum performance occurs when g is adjusted so that intrabeam scattering dominates in the central part of the core and the Schottky heating term dominates at the edges of the core. Smaller values of g leave the cooling term F less than optimum ($g = 0$ means no cooling) and larger values of g mean that Schottky heating is larger than the cooling. Computer calculations show that densities in excess of $1 \times 10^5/eV$ can be reached.

The choice of 1 - 2 GHz bandwidth (and $\eta = 0.02$) for the tail system was made because of the desire to optimize core cooling. Since D_2 is proportional to $1/\eta$, a larger gain can be used to counteract intrabeam scattering in the core. Choosing a higher maximum frequency and the same momentum width for the stack tail system would have required a lower η for the lattice. This would have reduced the core cooling effectiveness.

Turn off cooling during RF stacking
Power limit
1KV

cooling term $\rightarrow g(E-E_c)$
intrabeam scattering $\rightarrow D_0$
thermal noise $\rightarrow D_1$
Schottky heating $\rightarrow D_2$

$D_1 \ll D_0$
 g adjusted so D_0 dominates at center of core & D_2 dominates at edge of core.

In 4 profile, peak density occurs at 65 MeV of reflector center energy. Thus, the gain profile for the core momentum was a notch at this energy.

A block diagram of the core cooling system is shown in Fig. 5-5. The zero in gain is obtained by subtracting the signals from two sets of pickups placed in a region of high momentum dispersion. One set of pickups is centered above the core energy and one is centered below. The signal is then applied to a kicker placed in a region of zero momentum dispersion. The gain profile for the core system Schottky bands at 2.2, 3.0, and 3.8 GHz is shown in Fig. 5-6 abc.

5.2.6 Numerical Calculations of Momentum Cooling. A computer simulation of the combined core and stack-tail momentum cooling systems has been made. These calculations use the full theory developed by van der Meer et al. and not the simplified models given here. It has been found that a core density of $1 \times 10^5/\text{eV}$ can be obtained after 4 hours of stacking with a flux of $3 \times 10^7 \text{ sec}^{-1}$. Figure 5-7 shows the stack profile as a function of time. Figure 5-8 shows the cooling term (F) including the effects of beam feedback after 3 hours. Figures 5-9 and 5-10 show the heating term coefficients $D_0 + D_1$ and D_2 . Figures 5-11 and 5-12 are stability plots: the real versus the imaginary part of the cooling system gain G times the beam feedback F. In this plot the system is stable if the curve does not enclose the point (1,0).

5.3 Betatron Cooling

5.3.1 Introduction. Betatron cooling is accomplished by using a pickup sensitive to the transverse displacement of the particles. In going from pickup to kicker the particle oscillates in betatron phase by an odd multiple of $\pi/2$, converting the position displacement to an angle displacement. Each given particle creates a signal in the pickup which, when applied to the kicker, decreases the angle displacement. Other particles with similar revolution frequencies contribute noise that tends to increase the betatron amplitude. This situation is similar to the momentum-cooling discussed earlier.

Betatron cooling is conventionally described in terms of the time decrease of the betatron emittance⁹

$$\frac{d\epsilon}{dt} = 2 \sum_{n=n_{\min}}^{n_{\max}} \sum_{\pm v} \frac{-2G_{n+v\epsilon} + \alpha G_{n+v\epsilon_0}^2}{|S|^2} \quad (1)$$

→ effect of Schottky signal
→ heating by thermal noise

The first term in the numerator describes the effects of the Schottky signal. (In the case of betatron cooling, the heating and cooling terms may be combined into a single term as has been done in Eq. (1) above.) The signal-suppression factor S is given approximately by

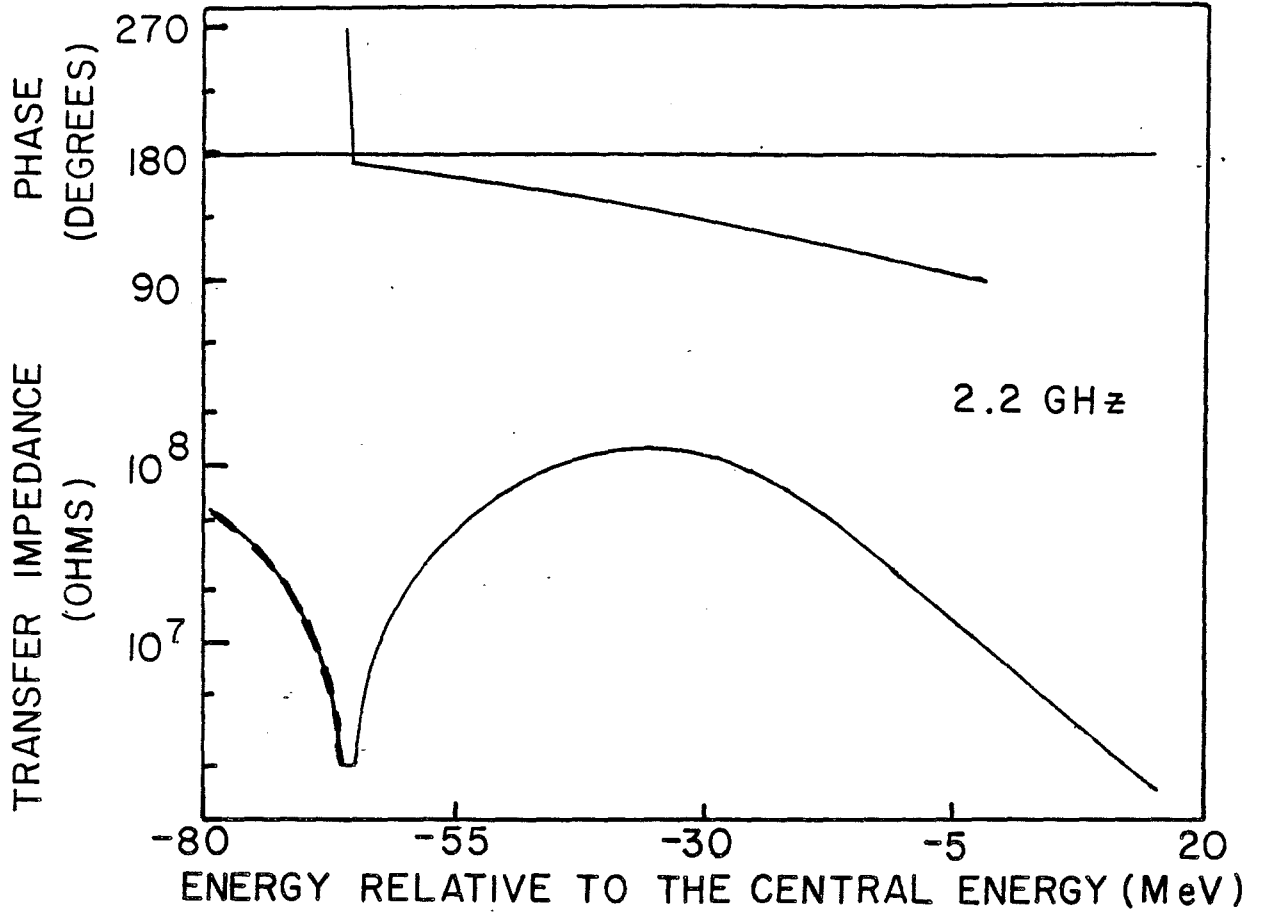


Fig. 5-6a

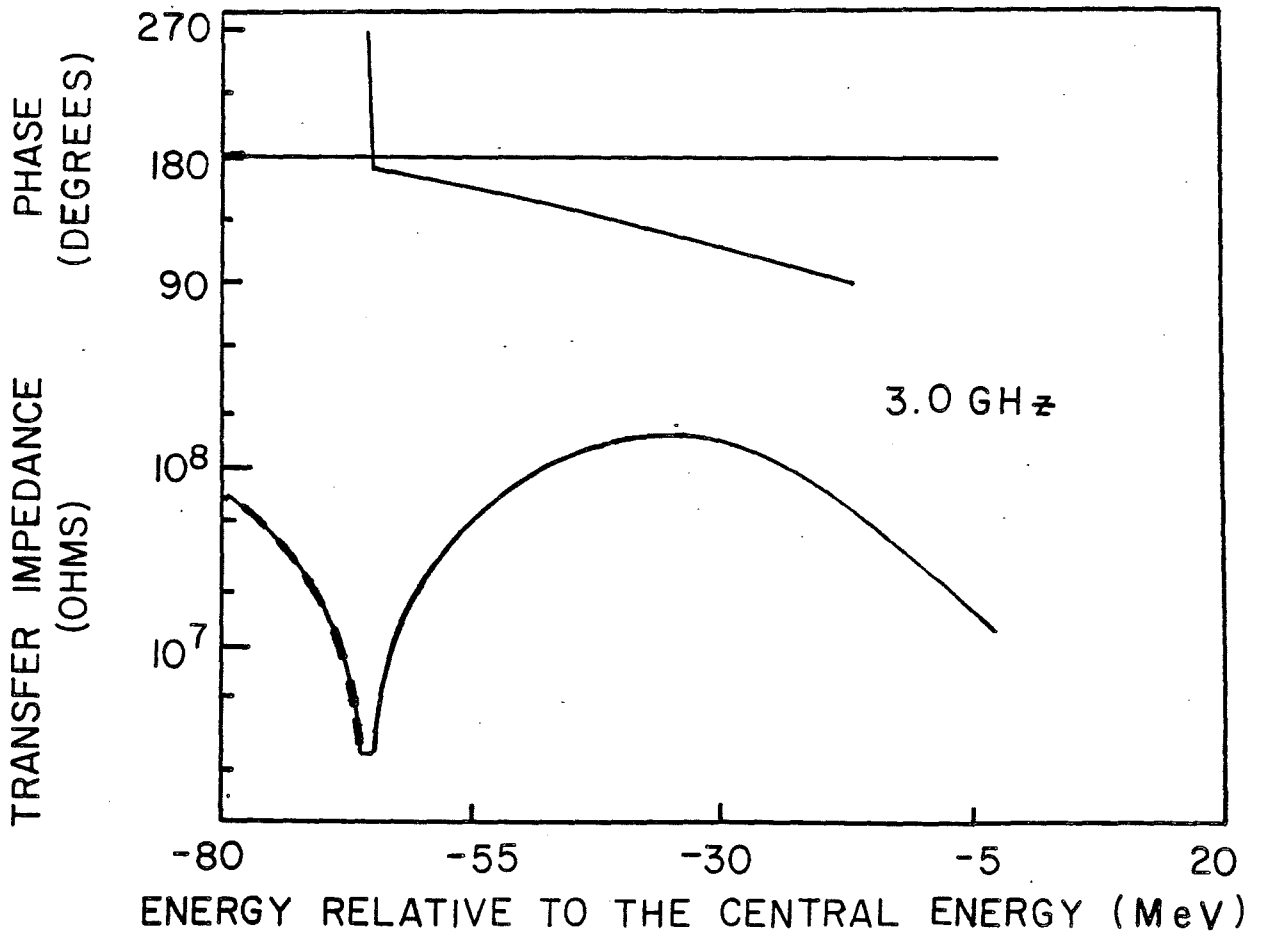


Fig. 5-6b

*Gain profile for core
momentum cooling*

*Gain profile for core
momentum cooling*

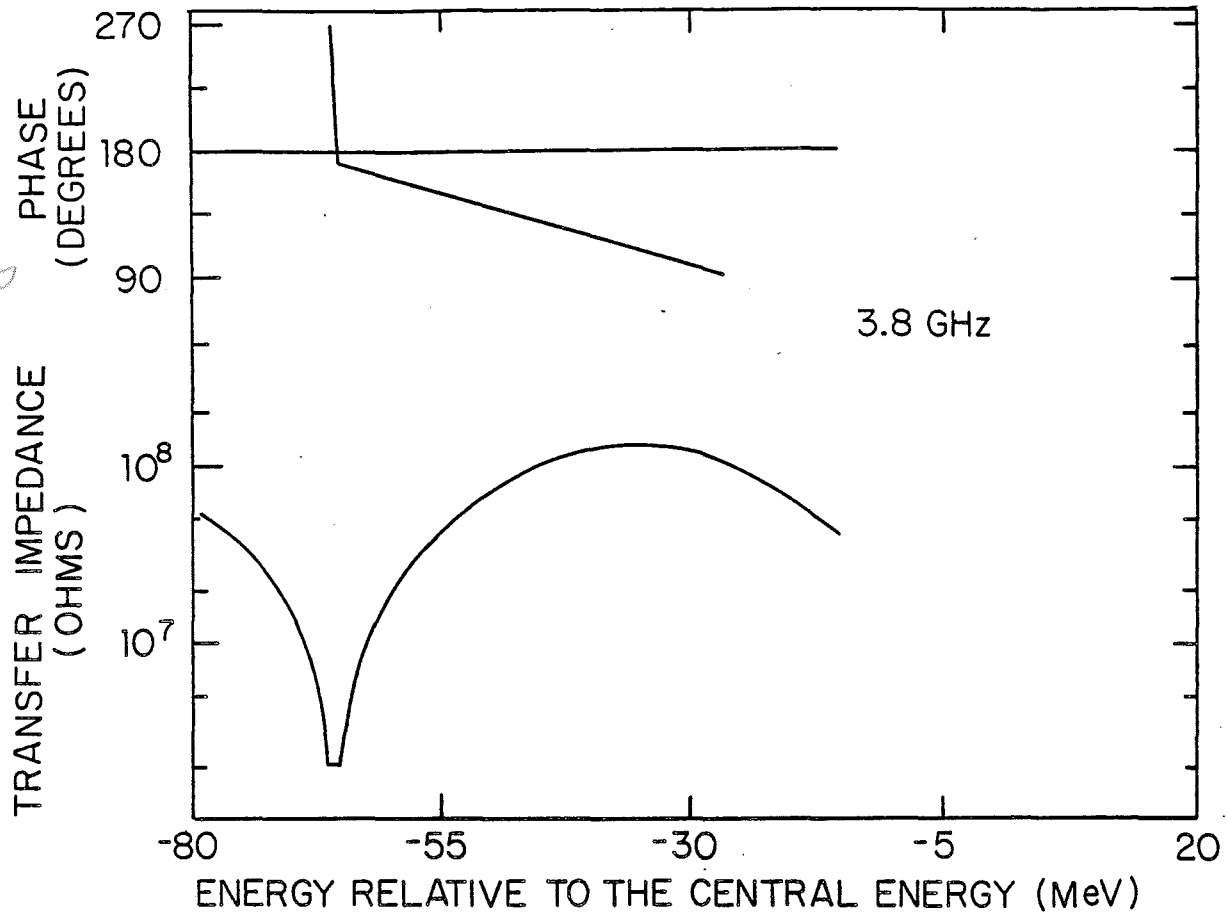


Fig. 5-6c

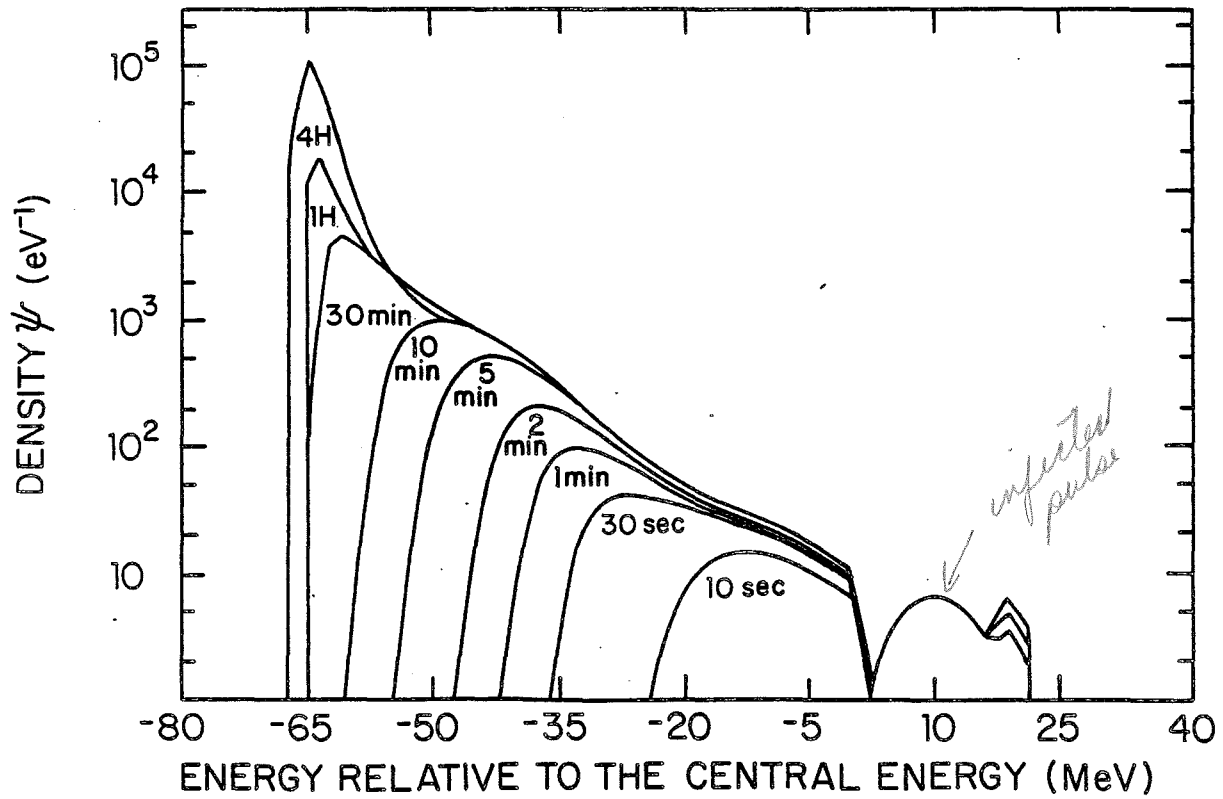


Fig. 5-7

cooling term varies by 40-50 dB over
energy range after 3 hours.

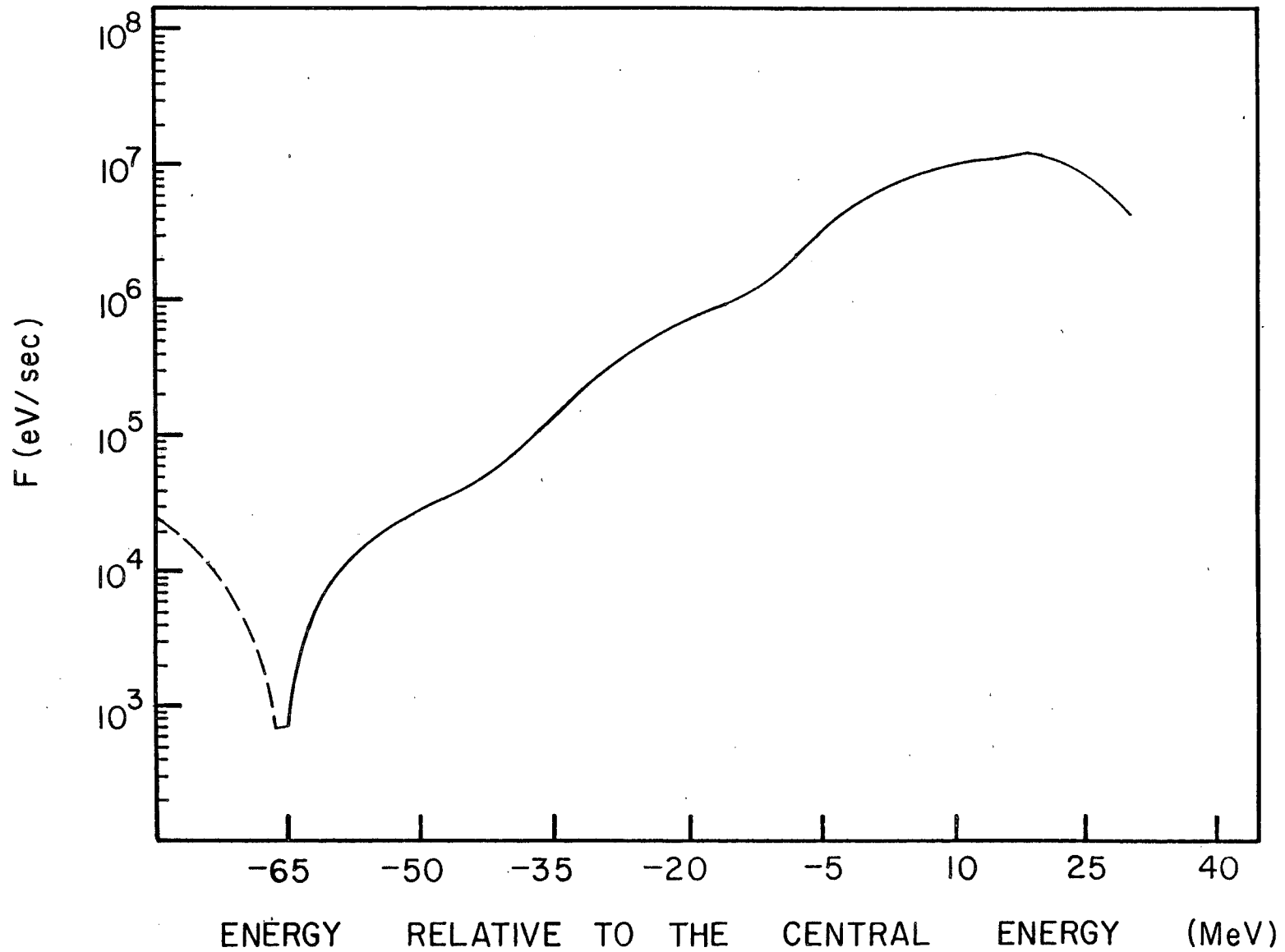


Fig. 5-8

Heating terms:

$D_0 + D_1$ (eV²/sec)

→ thermal
intra-beam
scattering

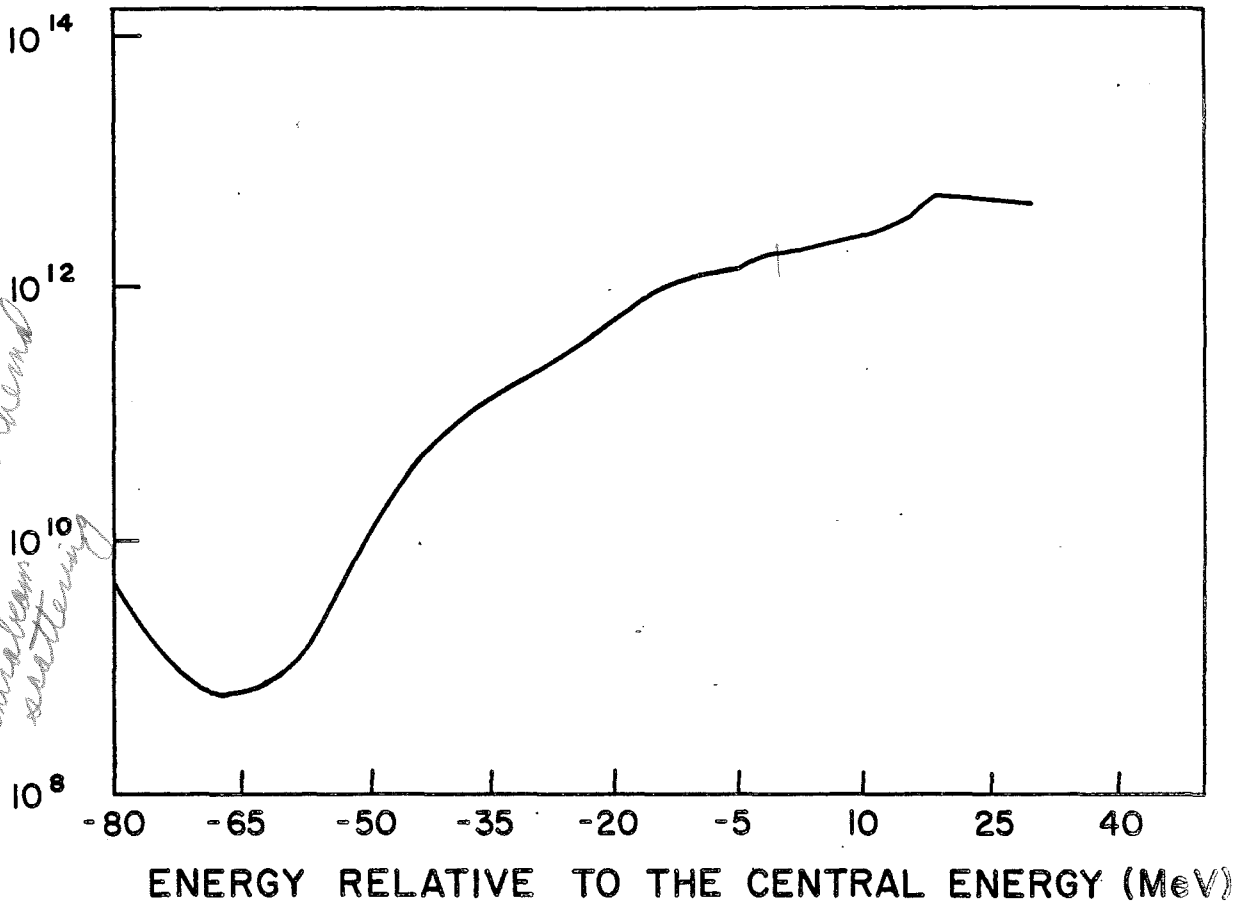


Fig. 5-9

→ Schottky heating

D_2 (eV³/sec)

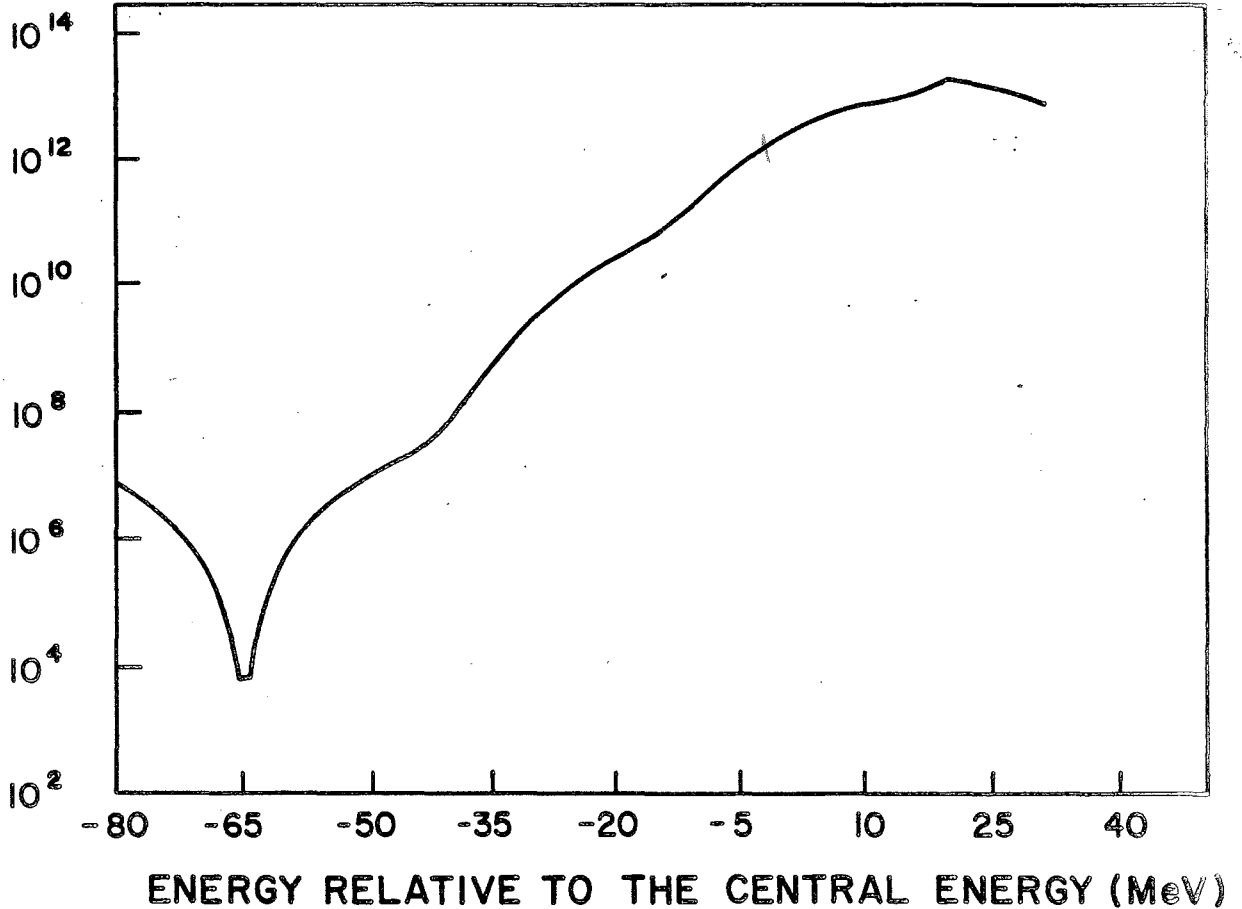


Fig. 5-10

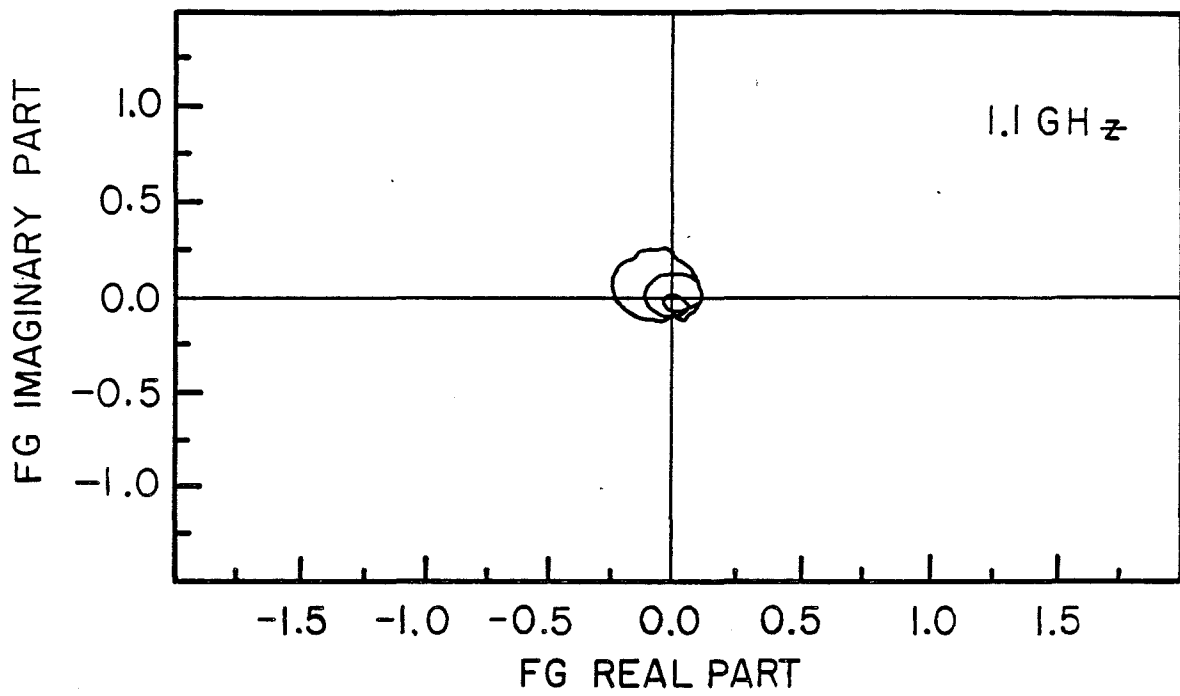


Fig. 5-11a

$$G' = \frac{G}{1 + FG}$$

Stable if $FG \neq (1, 0)$.

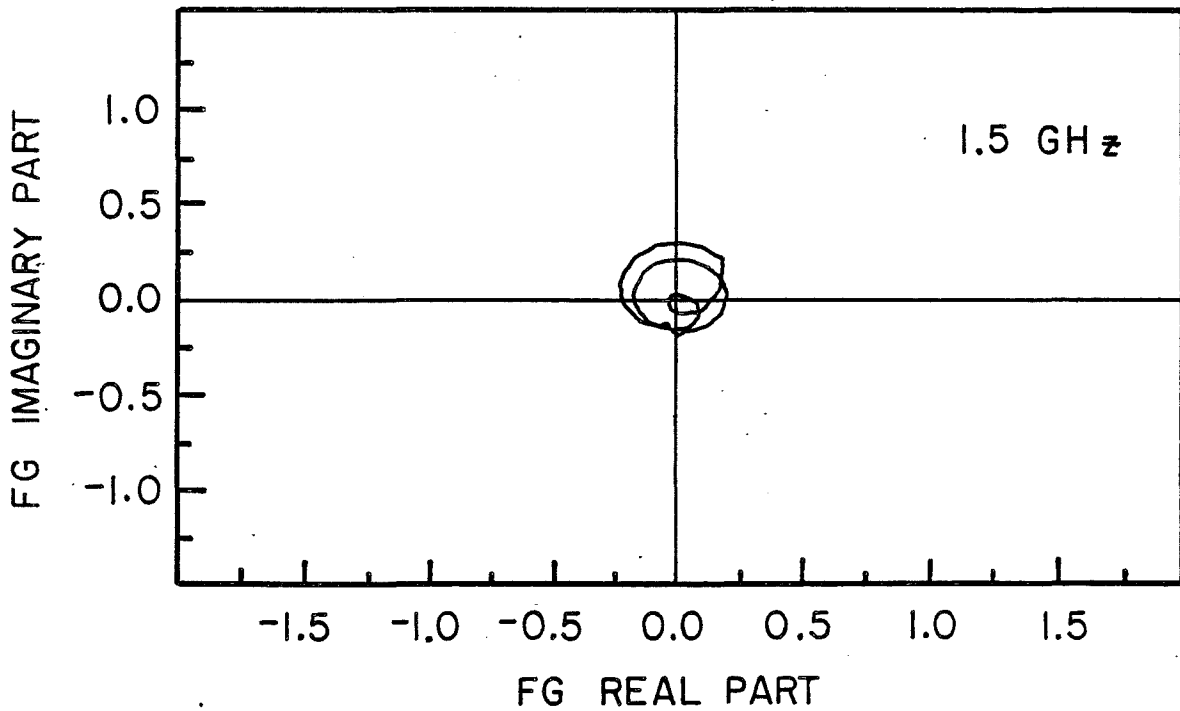


Fig. 5-11b

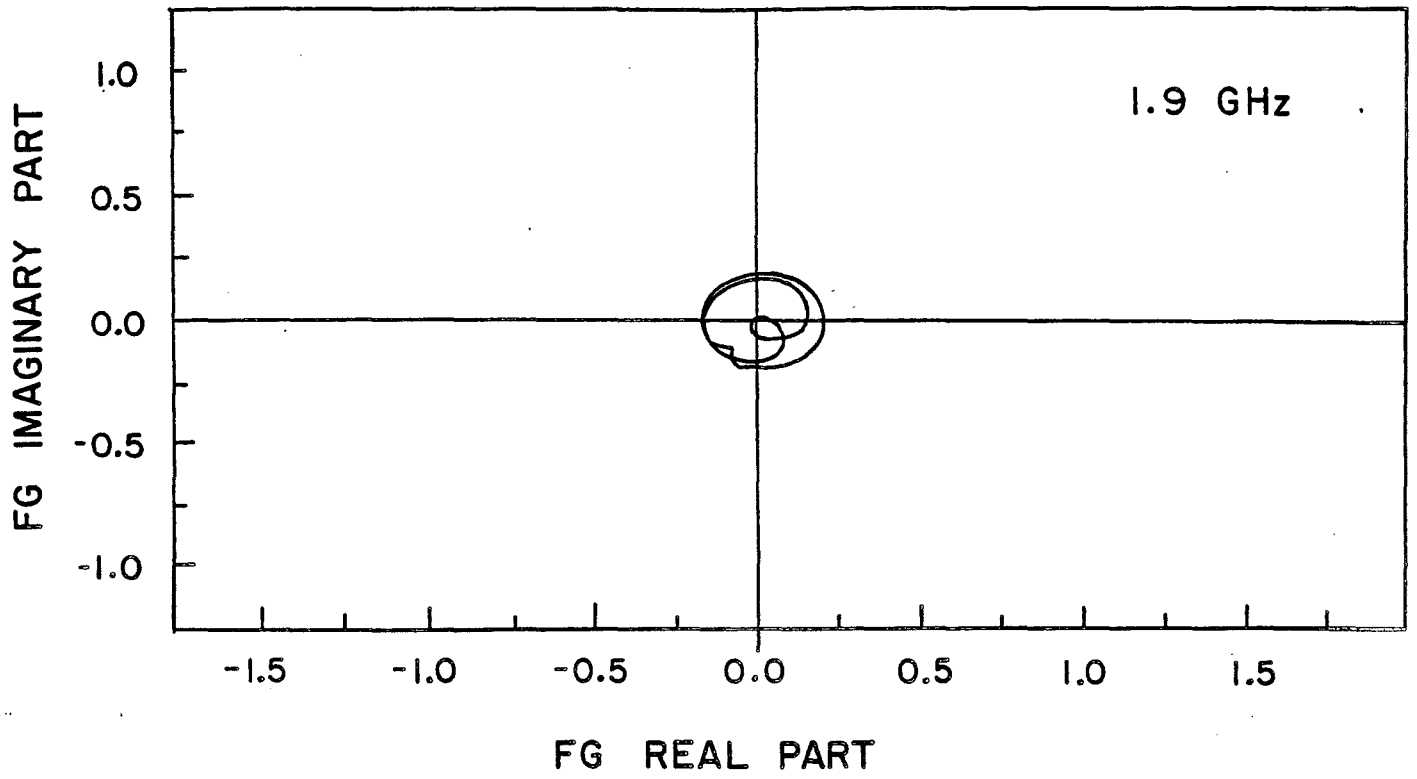


Fig. 5-11c .

*|FG| increases with increases
in frequency (why?)*

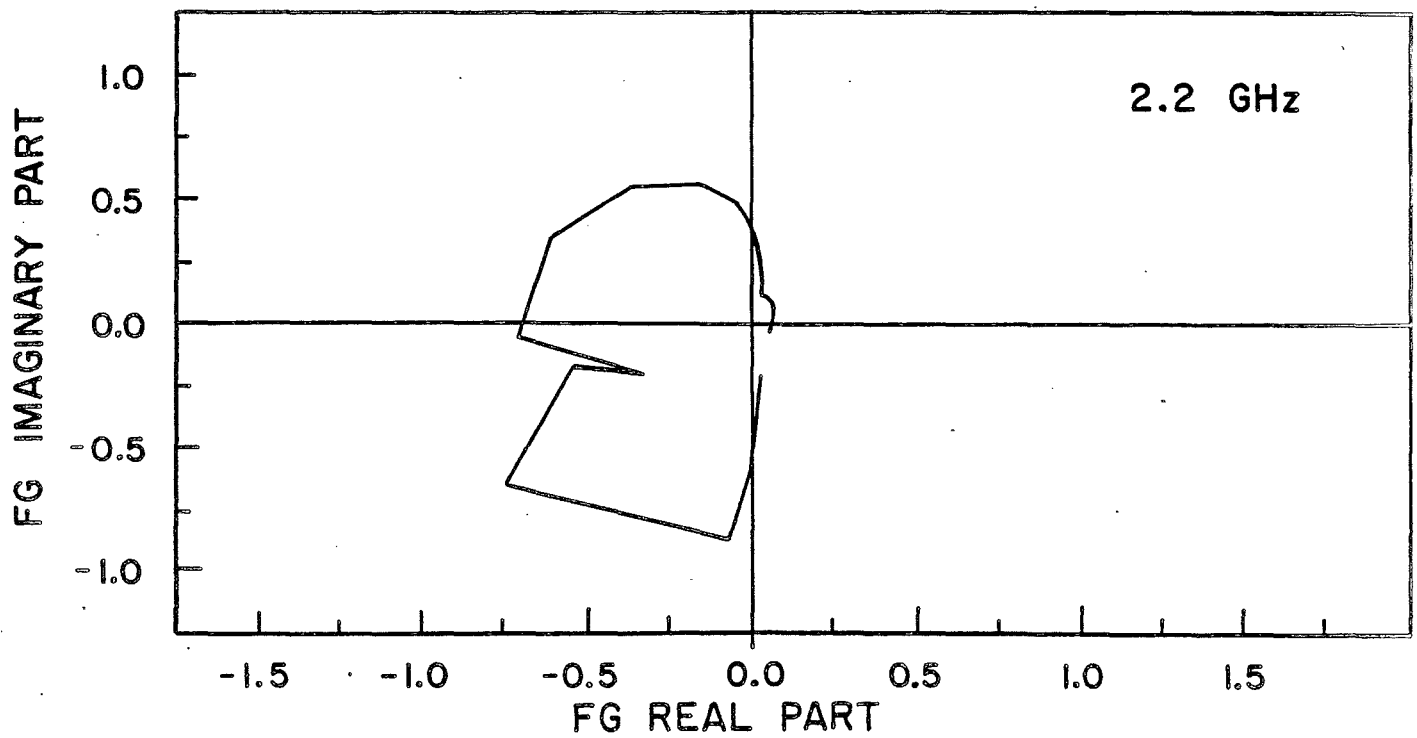


Fig. 5-12a

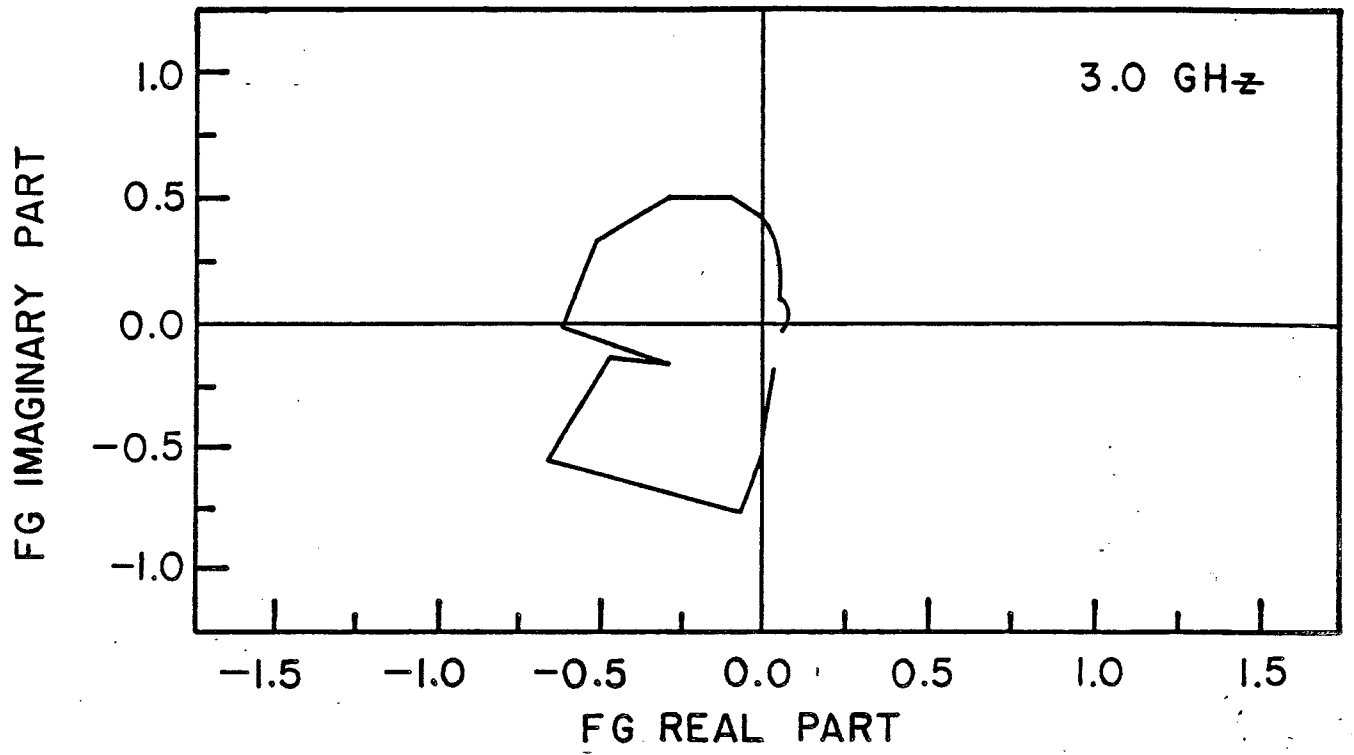


Fig. 5-12b

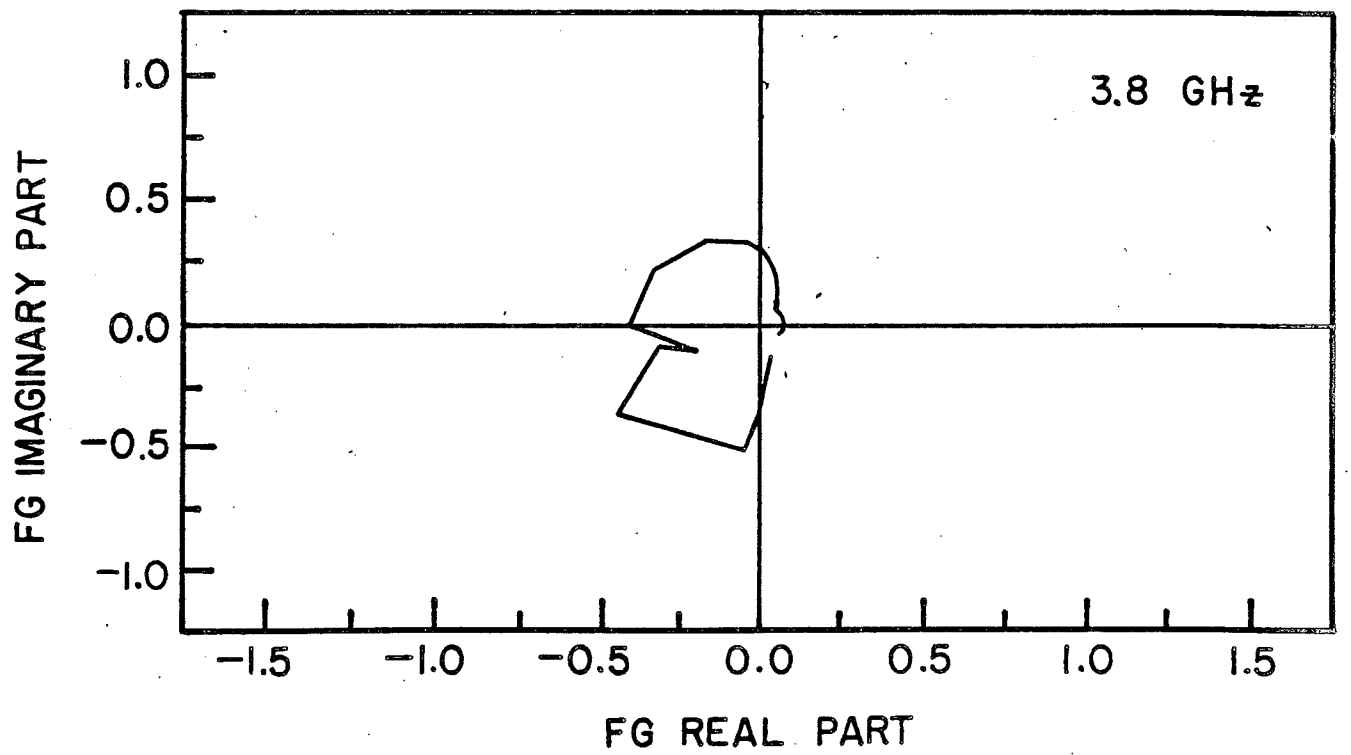


Fig. 5-12c

$$S = 1 + \frac{G_{n\pm v}}{n\pm v} \psi(E) \frac{\beta^2 E}{\eta} T \quad (2)$$

The exact expression for S contains, in addition to the "pole term" given above, a principal-value integral over the distribution $\psi(E)$. At the center of a symmetric distribution, the principal-value integral vanishes. Away from the center, $|S|$ tends to be smaller than S at the center of the distribution. Thus, we can get approximate, but slightly pessimistic, results for betatron cooling in the core by considering only particles at the peak of the distribution. In the case of betatron cooling in the tail, the gain $G_{n\pm v}$ is sufficiently small that S can be set to 1.

The second term in the numerator of Eq. (1) describes the heating by thermal noise. Here

$$\alpha = 2TU_0, \quad (3)$$

where T is the revolution period, U_0 is the ratio of thermal noise power to Schottky signal power per particle at time $t = 0$, and ϵ_0 is the emittance at $t=0$. The total thermal power is given by

$$P_{th} = k(\Theta_R + \Theta_A) g_A^2 W, \quad (4)$$

where k is Boltzmann's constant, Θ_R is the pickup termination temperature, Θ_A is the amplifier equivalent noise temperature, g_A is the amplifier voltage gain and W is the bandwidth.

The Schottky power per pickup per particle is

$$P_{sch} = \frac{1}{2} \cancel{A} e^2 f_0 Z_{pu} \frac{s^2}{h^2} \beta_p \epsilon_0 g_A^2 W \quad (5)$$

= 1/2 of Btron oscillation

where Z_{pu} is the pickup impedance, s is the pickup sensitivity, h is the pickup gap, β_p is the β function at the pickup. The ratio of thermal to Schottky power is

$$U_0 = \frac{2 k(\Theta_R + \Theta_A)}{\cancel{A} e^2 f_0 Z_{pu} (s/h)^2 \beta_p \epsilon_0}$$

pickup temp. → amp. noise temp.

The solution of Eq. (1) may be written as

$$\epsilon = (\epsilon_0 - \epsilon_\infty) e^{-t/\tau} + \epsilon_\infty \quad (7)$$

with

$$\epsilon_\infty = U_{0GT} \epsilon_0 \quad (8)$$

and

$$\frac{1}{\tau} = 2 \frac{TW}{\xi} R(\xi G) \quad (9)$$

$$\xi = \frac{\psi(E)\beta^2 E}{\eta W} \quad (10)$$

$$R(x) = \int_1^2 \frac{4xdt}{(1+x/t)^2} \quad (11)$$

Equations (8) through (11) have assumed that the gain G_{n+v} is constant and equal to G . Equation (11) is an approximation to the sum from equation (1); the limits of integration assume an octave bandwidth. The gain G is related to pickups, kickers, and amplifier gain by

$$G = \frac{2\sqrt{\beta_k \beta_p}}{3\pi} \frac{s_p s_k}{h_p h_k} \frac{e^2 f_0^2 Z_{pu} \sqrt{N_p N_k}}{Wp} \epsilon_A, \quad \delta x \text{ too high} \quad (12)$$

where $\beta_p(\beta_k)$ is the betatron function at the pickup (kicker), $s_p(s_k)$ is the pickup (kicker) sensitivity, $h_p(h_k)$ is the gap height in the pickup (kicker), $N_p(N_k)$ is the number of pickups (kickers), e is the electric charge, $f_0 = 1/T$ is the particle revolution frequency, Z_{pu} is the pickup and kicker impedance, and p is the momentum.

We will build two betatron cooling systems: a stack-tail system and a core-cooling system. The stack-tail system has both pickups and kickers

placed in dispersive regions and has a low sensitivity to particles in the core. The core-cooling system has both pickups and kickers placed in regions of zero dispersion and is therefore equally sensitive to particles in the core and tail. The gain of the core system is so low, however, that it has little effect on the tail. The core cooling system is somewhat simpler and will be discussed first.

5.3.2 Betatron Cooling in the Core. In the case of the core cooling, the gain of the system is determined by the energy density of particles in the core.

The function R has its maximum of 1.5 at about $x = 1.5$. The gain G is therefore

$$G = \frac{1.5\eta W}{\beta^2 E \psi(E_c)}$$

$$= 7 \times 10^{-8}, \text{ sec}^{-1},$$

where $\psi(E_c) = 10^5/\text{eV}$ is the peak core density, $W = 2 \text{ Ghz}$ (from 2 to 4 GHz) $\eta = .02$, $\beta^2 E = 8.8 \times 10^9 \text{ eV}$. Then ϵ_∞ is $0.06 \pi \text{ mm-mrad}$ and negligible compared to a final emittance of $2 \pi \text{ mm-mrad}$. Thus, as might have been expected, thermal noise can be neglected.

The cooling time τ is found from Eq. (9) to be sec^{-1} hours. Particles that have an emittance much larger than the average emittance of the core will be cooled considerably faster, however, since the cooling correction is proportional to betatron amplitude. The intrabeam scattering diffusion times have been calculated to be 9 hr horizontally and large and negative (corresponding to slight damping) vertically. The amplifier power gain (90° dB) and power level (5 W) are modest. A block diagram of the system is shown in Fig. 5-13.

5.3.3 Stack-Tail Betatron Cooling. The stack tail betatron cooling system uses the same pickups as the second section of the tail momentum-cooling system. The pickup plates are centered at -5 MeV relative to the central energy. For horizontal signals the pickup is most sensitive at its edges at +15 MeV and -25 MeV. Most of the cooling takes place at the -25 MeV edge because the momentum cooling system is pushing particles much more slowly past the -25 MeV edge than the +15 MeV edge. The pickup is most sensitive at its center (-5 MeV) for signals in the vertical direction. The kickers are also placed at -5 MeV in a region with high dispersion. A block diagram of the system is shown in Fig. 5-14.

Approximate calculations of the system performance have been made with Eq. (1) except that the time variable has been replaced with the energy variable, using the relationship

CORE BETATRON COOLING SYSTEM 2-4 GHz

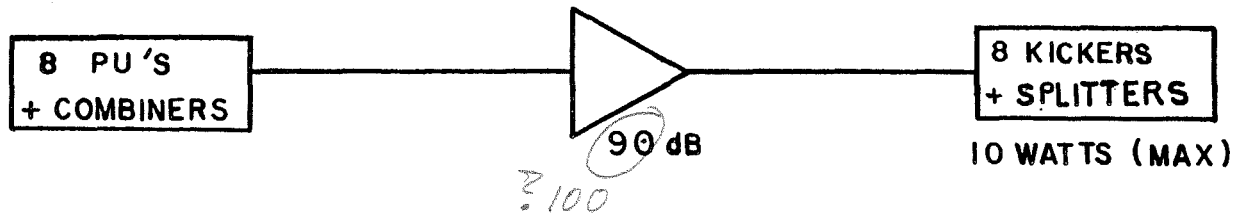


Fig. 5-13

STACK TAIL BETATRON COOLING 1-2 GHz

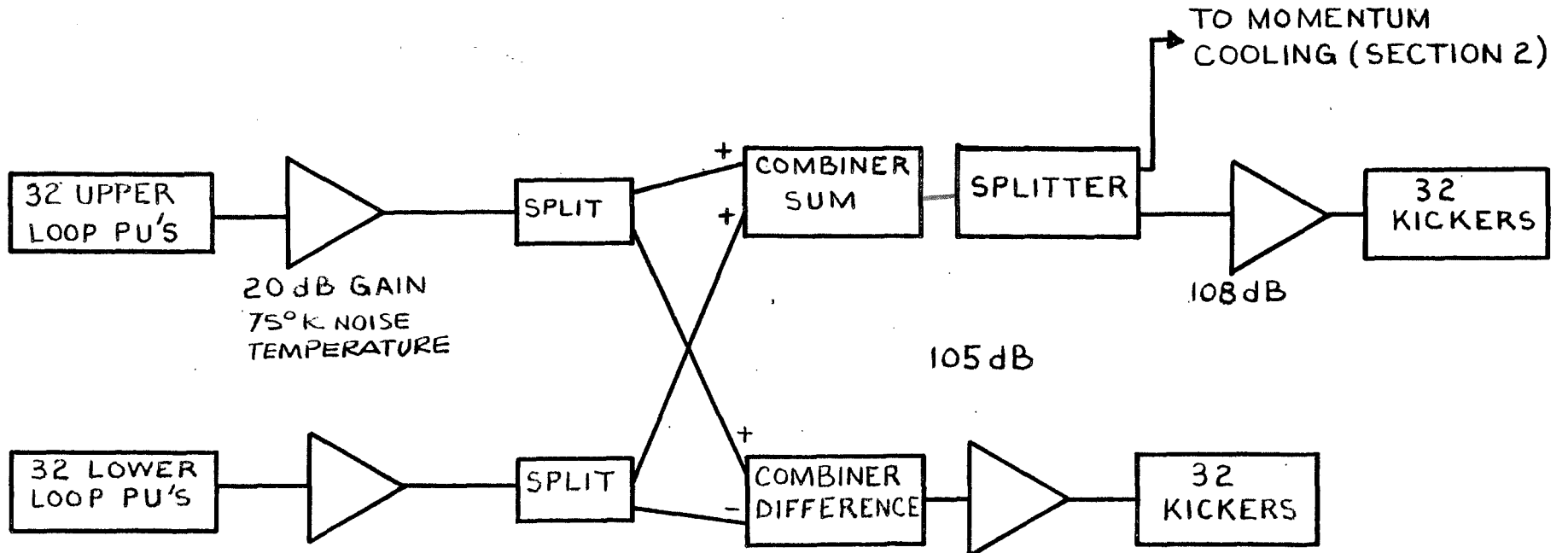


Fig. 5-14

$$\frac{dE}{dt} = \frac{\bar{\phi}}{\psi(E)},$$

where $\bar{\phi}$ is the flux of particles and $\psi(E)$ is the density of particles. This approximation ignores fluctuations in energy gain in the stacking process. With this approximation, Eq. (1) is easily integrated numerically. Figure 5-15 shows the emittance reduction as a function of energy. The power in each system is less than 20 W.

5.3.4 Operation of Betatron Cooling Systems. In the Accumulator we have available two betatron cooling systems, either of which is capable, or nearly capable, of cooling the beam emittance from 10π to 2π mm-mrad. The core system is clearly required so that a core of \bar{p} 's may be held for several hours without diffusion. The tail system serves two functions: 1) to cool the betatron amplitudes in a system with a low particle density (it is not necessary to wait one half to one hour for the core cooling system to do its work) and 2) to counteract possible betatron heating by the momentum cooling system. The size of the latter effect is difficult to estimate; it depends on how well we are able to build the momentum kickers for the stack-tail system. If the effect is larger than expected, the gain of the stack-tail system can be raised to achieve better cooling, but, of course, the power requirements will be greater. Tentatively, however, we would plan to use the stack tail system to reduce the beam emittance from 10π to 3π or 4π mm-mrad and use the core system to reduce it below 2π mm-mrad.

5.4 Stochastic Cooling Hardware

The purpose of this section is to outline the hardware and techniques we expect to use in order to meet the design requirements presented above. Although the design is not complete, it has been carried out in sufficient detail to make reliable cost estimates. In several instances alternative designs are possible. We present here the design which is most sound technically. Research and development are presently in progress to investigate alternatives which could lead to better system performance, reliability, or cost reduction.

Each stochastic cooling system is composed of 5 basic parts: beam pickup electrodes, low level electronics (including preamplifiers), medium level electronics (including gain and phase correction circuits, filters etc.), high level electronics (including travelling wave tubes), and kicker electrodes. As several of the cooling systems share common elements in their design, and the performance of these elements is necessary for the proper functioning of the cooling system, they are discussed below.

5.4.1 Pickup Electrodes The design of the 1 to 2 GHz and the 2 to 4 GHz

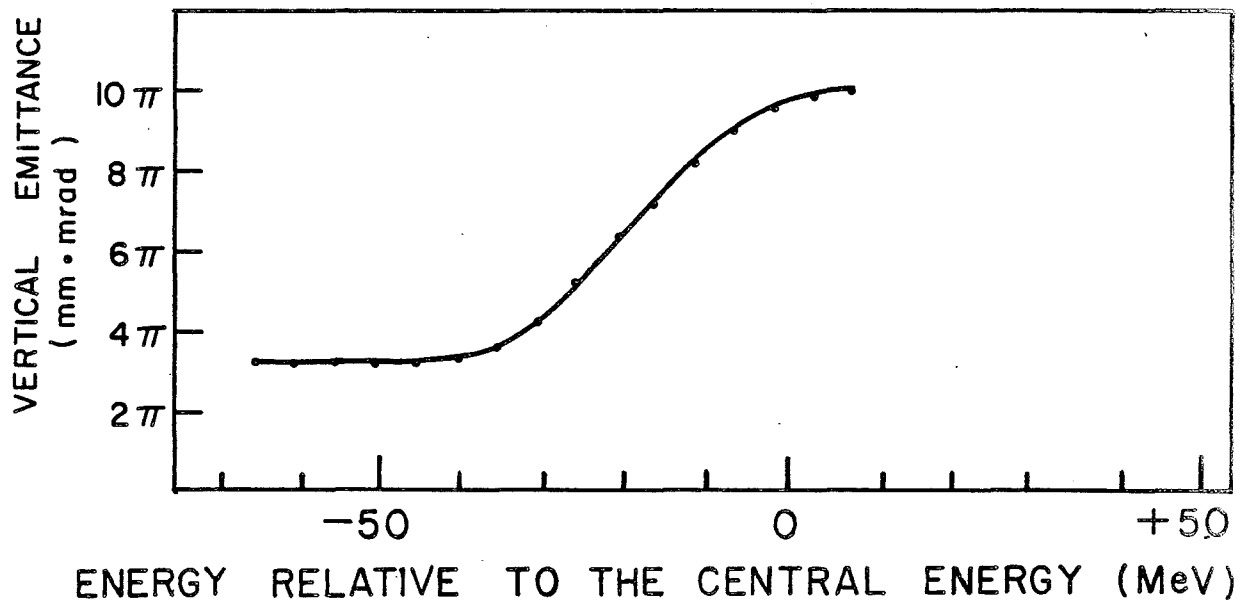
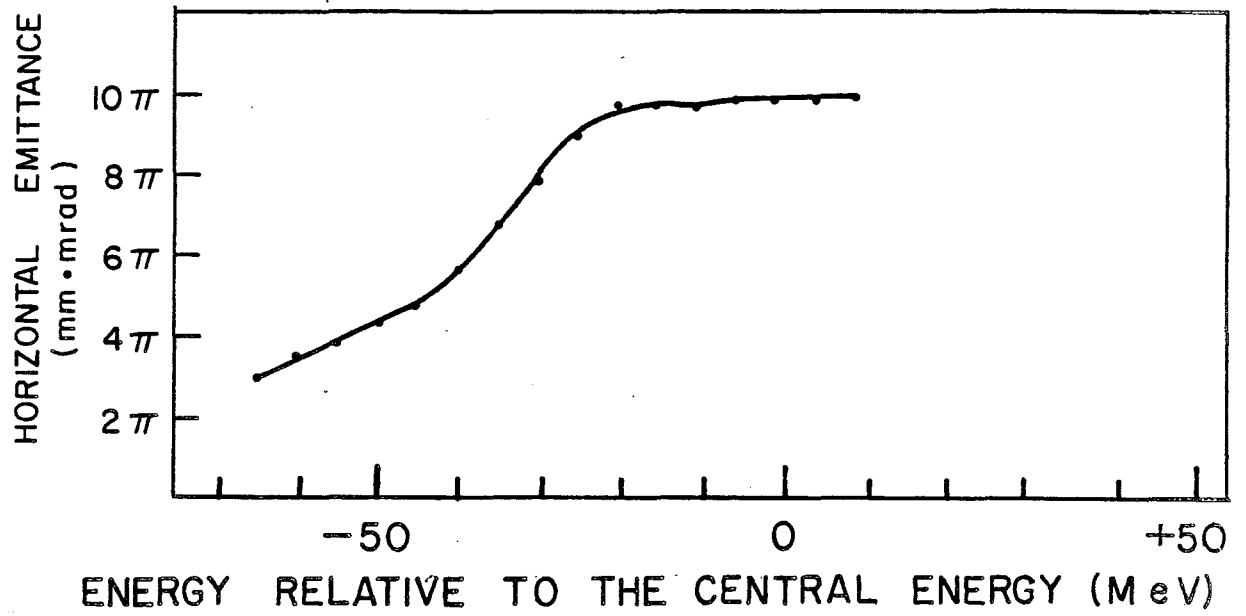


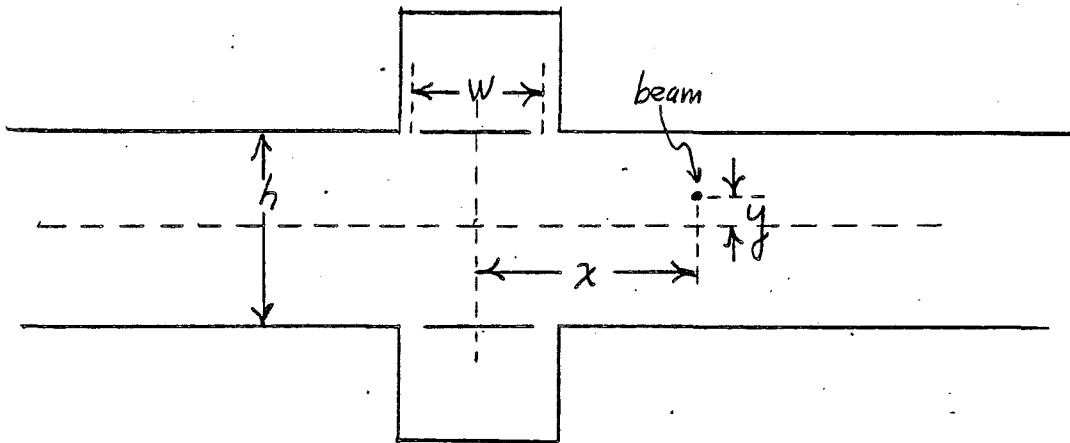
Fig. 5-15

stochastic cooling systems is based on the known¹¹ and measured¹² performance of quarter-wave loop (directional coupler) pickups. The loop pickup is a segment of transmission line of well defined characteristic impedance on which beam wall (image) currents can be induced. The magnitude of the voltage induced on it depends on its characteristic impedance Z_{pu} , its effective length l , its geometrical coupling $e(x,y)$ (which depends on the transverse beam location as well as the height of the vacuum chamber, and the amplitude of the beam current $i_b(\omega)$):

geometric coupling of a pickup plate

$$V_{pu}(\omega) = e(x,y) Z_{pu} \sin\left(\frac{l\omega}{c}\right) e^{i\pi/2} i_b(\omega)$$

where the 90° phase shift at the reference plane (the center of the loop) is due to the inductive nature of the coupling. The geometry of a typical pickup pair is shown below:



Here, h is the full height of the gap between the electrodes and w is their effective width. If the signals are added in a microwave power combiner circuit and the output signal is referenced to a transmission line of impedance Z_0 , the output voltage is

$$V_{out}(\omega) = s(x,y) \sqrt{\frac{Z_{pu}Z_0}{2}} \sin\left(\frac{l\omega}{c}\right) e^{i\pi/2} i_b(\omega)$$

where $s(x,y) = e(x,y) + e(x,-y)$

$$Y_0 = \frac{h}{d} \sqrt{\frac{2Z_0}{Z_p}} \frac{1}{\sin \frac{l\omega}{c}}$$

~2

$$= \frac{1}{\pi} \left\{ \tan^{-1} \left(\frac{\sinh \frac{\pi}{h}(x + w/2)}{\cosh(\pi y/h)} \right) - \tan^{-1} \left(\frac{\sinh \frac{\pi}{h}(x - w/2)}{\cosh(\pi y/h)} \right) \right\}$$

For $x = y = 0$:

$$s(0,0) = \frac{2}{\pi} \tan^{-1} \{ \sinh(\pi w/2h) \}$$

Transfer impedances of pickup pairs in sum mode are defined with a centered beam at center frequency ($\omega = \pi c/2\ell$) and in a $Z_0 = 50$ ohm transmission line

$$Z_s = s(0,0) \sqrt{25 Z_{pu}}$$

$$\text{At large } x, \quad s(x,0) \rightarrow \frac{4}{\pi} e^{-\pi x/h} \sinh(\pi w/2h)$$

If the differences of the signals in the pickup electrode pair are combined into a transmission line of impedance Z_0 , the output voltage is

$$V_{out}(\omega) = d(x,y) \frac{y}{h} \sqrt{\frac{Z_{pu} Z_0}{2}} \sin\left(\frac{\ell \omega}{c}\right) e^{i\pi/2} i_b(\omega)$$

$$\text{where } d(x,y) = \{e(x,y) - e(x,-y)\} \frac{h}{y},$$

and the difference mode transfer impedance at $x = 0$ is

$$Z_d(0,y) = d(0,y) \frac{y}{h} \sqrt{25 Z_{pu}}$$

$$\text{where } d(0,y) \cong 2 \tanh(\pi w/2h)$$

As microwave power combiners add power of coherent signals, the coupling

impedance of η_p loop coupler pairs is $\sqrt{\eta_p}$ times the impedance for a single pair, in both sum and difference modes. Figures 5-16 and 5-17 show a typical electrode assembly.

Based on calculations, as well as measurements with both wires and electron beams, the loop coupler characteristics shown in Table 5-II are the values we use in the Design Report.

Table 5-II Loop Coupler Characteristics

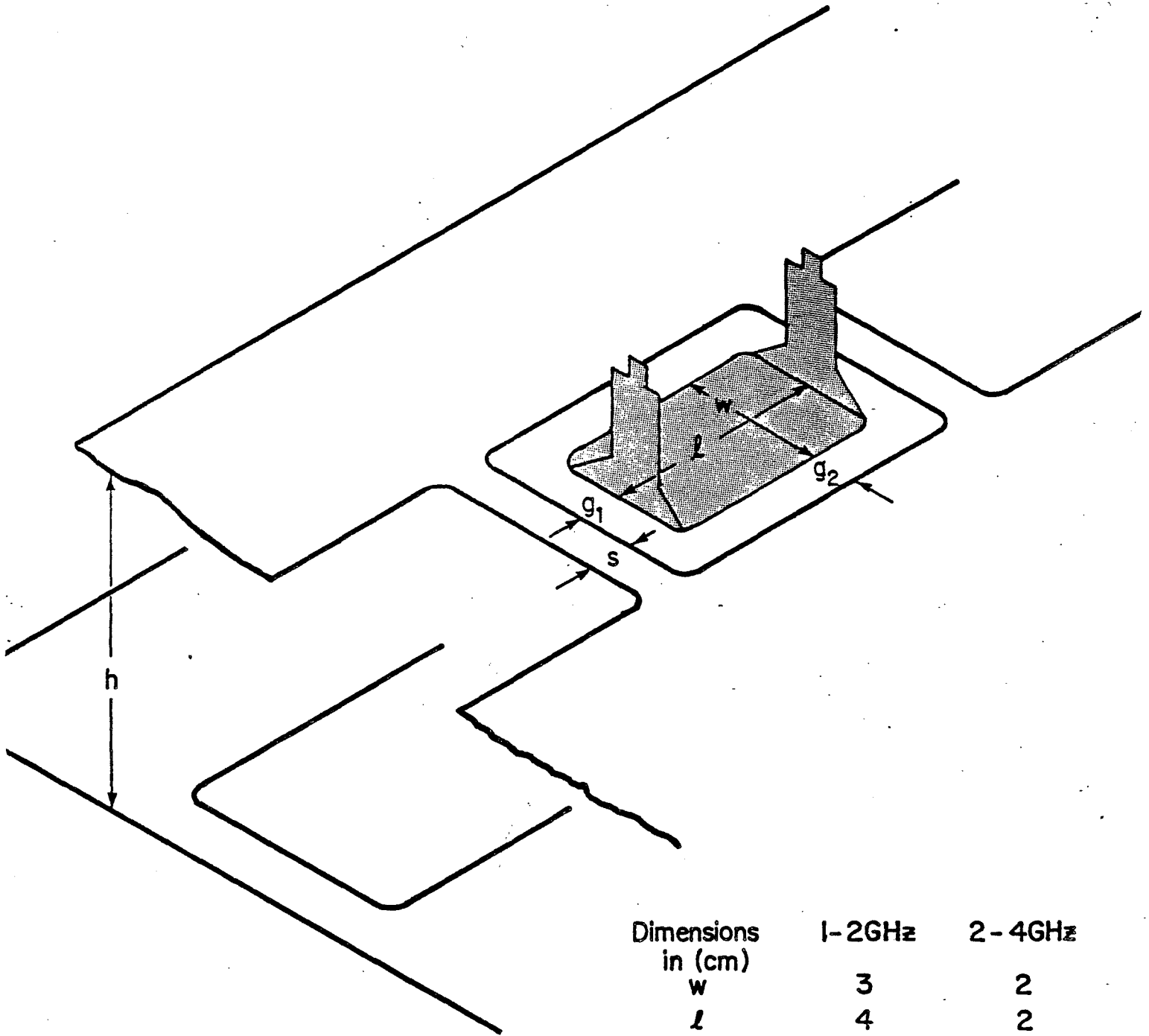
Characteristic		1-2 GHz band	2-4 GHz band
characteristic impedance	Z	100	75 ohms
height (gap) typical	h^{pu}	3.0	3.0 cm
effective width	w	4.0	2.5 cm
pairs per meter		15	25 per m
<u>Sum Mode</u>			
$s(o,o)$.843	.664
transfer impedance	Z_s	42.2	28.8 ohms
<u>Difference Mode</u>			
$d(o,y)$		1.94	1.73
transfer impedance	Z_d	3230	2500 ohms/m

5-16, 5-17 5-18

The electrode assemblies shown in Figures ~~band, 6;~~ ~~band, 7;~~ and ~~band, 8~~ are approximately 2.5 meters long (for the 1-2 GHz band) and contain 32 pickup pairs. The signals are combined separately for top and bottom electrodes using a double-sided teflon printed circuit board. The air-spaced ground plane yields a group velocity of about 0.98c. The electrodes are back-terminated in their characteristic impedance, and the whole assembly is cooled to liquid nitrogen to reduce the thermal noise power from the back termination, the skin effect losses in the circuit board, and teflon outgassing. In the 2-4 GHz band, it is quite possible that slot couplers will have a higher coupling impedance per unit length than loop couplers. A research and development program is underway in this area.

5.4.2 Preamplifiers Commercial gallium arsenide field effect transistor (GaAsFet) amplifiers are available in the microwave frequency bands required for stochastic cooling. Although their thermal noise characteristics are relatively low (a 2.0 db noise figure amplifier, available in the 1-2 GHz band, has an equivalent noise temperature of 170 K) it would still contribute nearly 70% of the total thermal noise power. The design therefore includes preamplifiers cooled to liquid nitrogen temperatures. We expect equivalent noise temperatures of 75 K (NF = 1.0 db) and 120 K (NF = 1.5 db) for 1-2 GHz and 2-4 GHz amplifiers respectively. Minimization of thermal noise is not only important in relation to beam heating, but also in relation to the cost of extra travelling wave tube installed power required to amplify it.

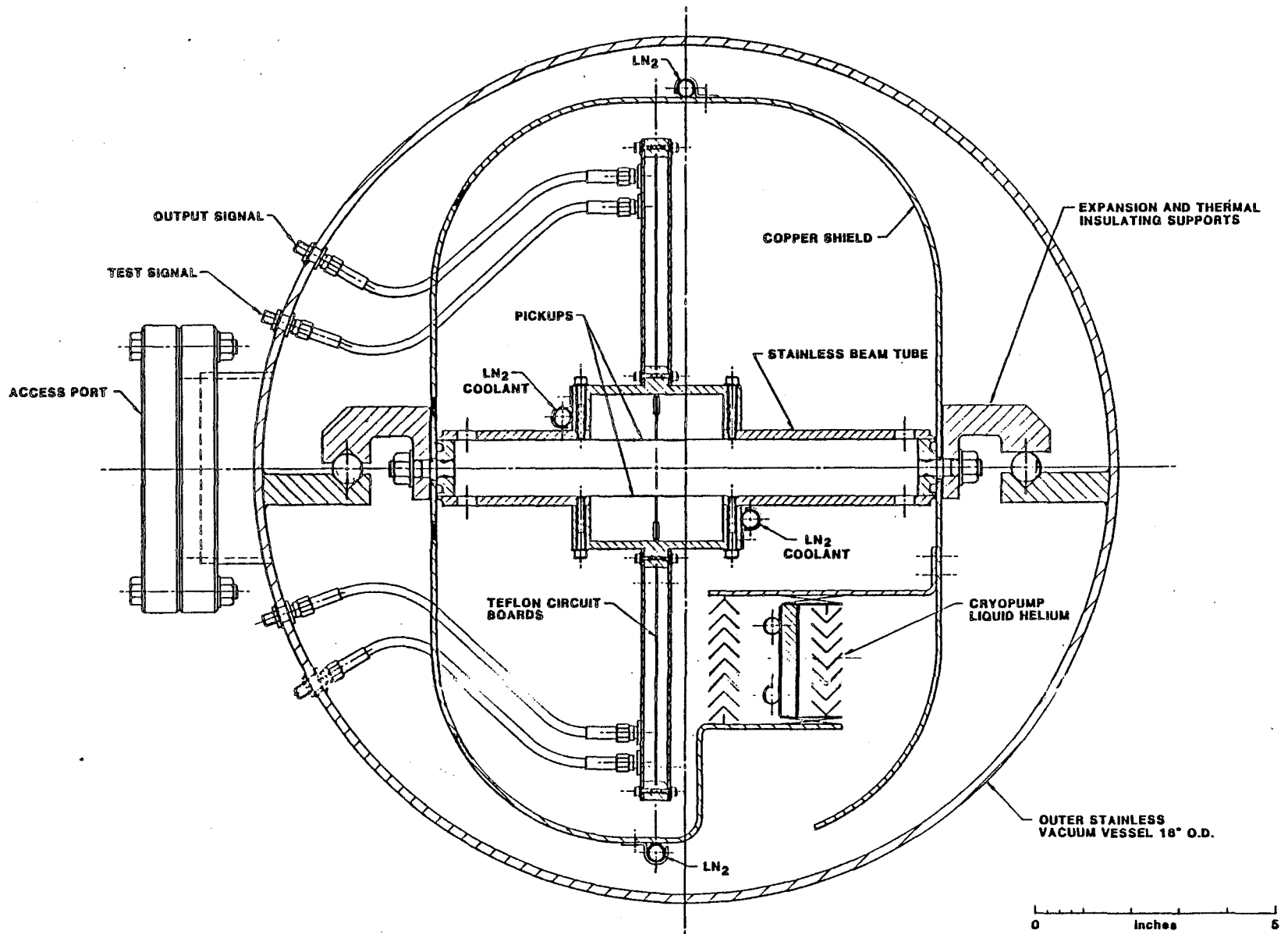
see at. 3a-71
4
2 + 3a-71



Dimensions in (cm)	1-2GHz	2-4GHz
w	3	2
l	4	2
g ₁	1	0.5
g ₂	1	0.5
g ₃	1	0.5
h	3	3
s	1	1

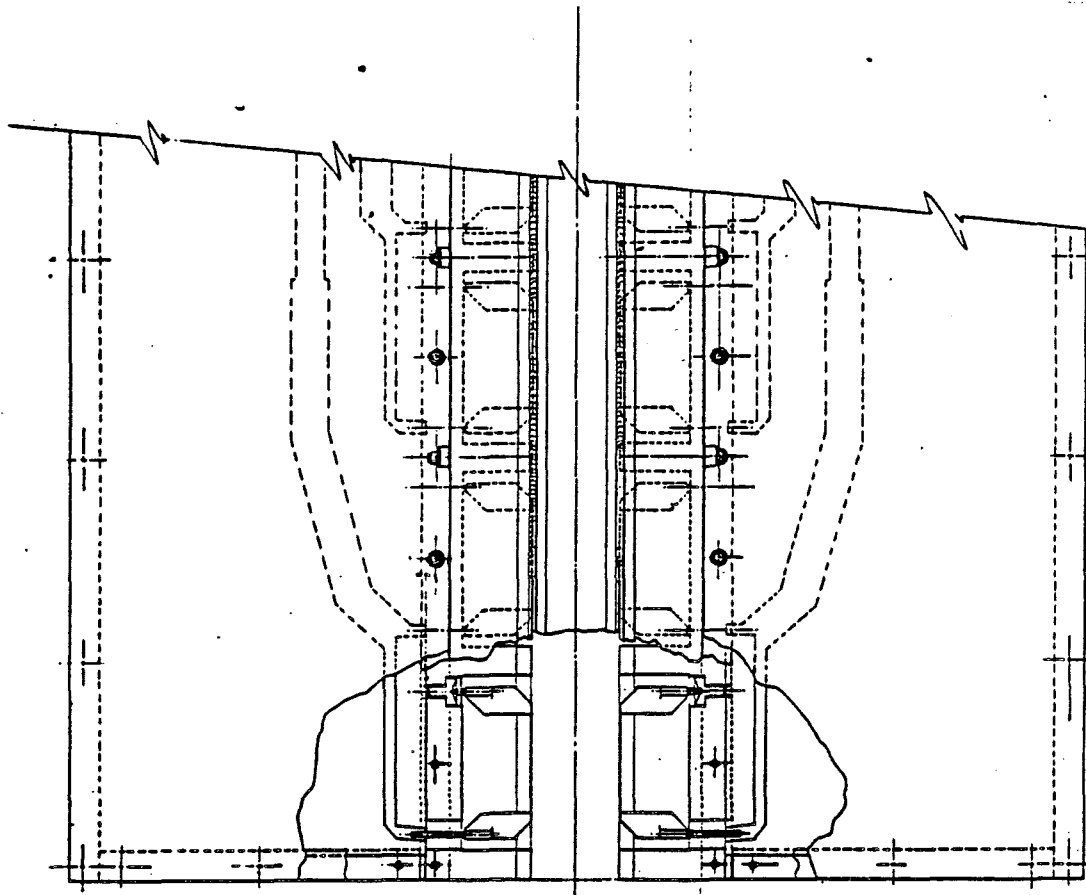
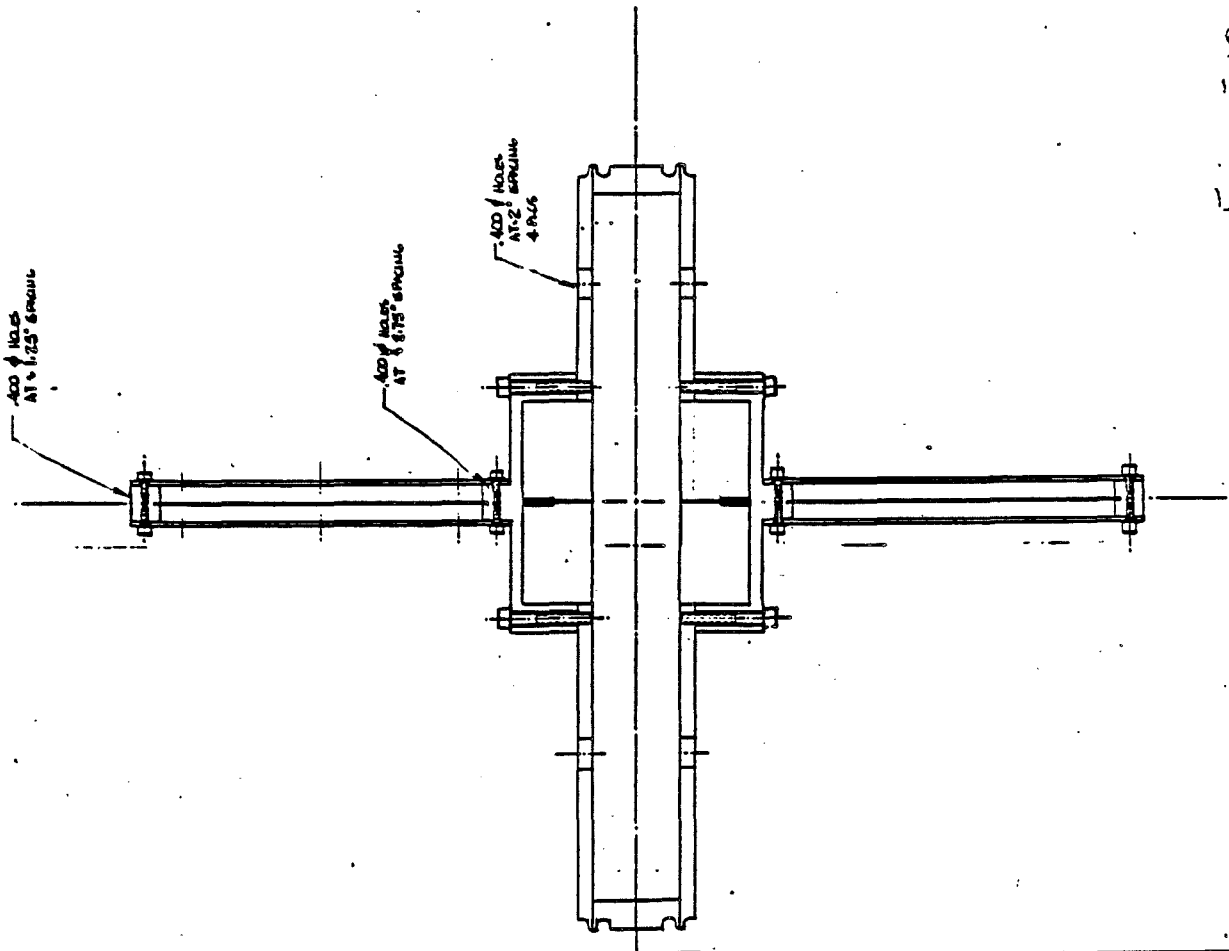
Fig. 5-16

g₃ is the distance to the ground plane (not shown) above the pickup electrode



1-2 GHz PICKUP ELECTRODE ASSEMBLY CROSS SECTION

Fig. 5-17



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DATE	3/10/50
DESIGNED BY	G.H. PICKUP
CHECKED BY	(BEEBELEY-1)
APPROVED BY	
UNIT OR	
MATERIAL	
PREPARED BY	
DATE	
BY	
NO.	3000
REV.	2910

FERM NATIONAL ACCELERATOR LABORATORY
U.S. Department of Energy

ANTIPROTON SOURCE
1-2 G.H. PICKUP
(BEEBELEY-1)

Figure 5-18

Commercially available GaAsFet amplifiers designed to operate in the Mil spec temperature range (-55 C to 70 C) have been successfully operated as low as 77 K₁₄. In this case a 1-2 GHz amplifier achieved an equivalent noise temperature of 120 K (NF = 1.5db). GaAsFet amplifiers have been specially designed for operation at liquid helium temperatures, and equivalent noise temperatures of 20 K (NF = .2 db) have been achieved in narrow band operation₁₅ (0.5 GHz bandwidth at 1.5 GHz). We are undertaking parallel R&D efforts to test commercially available amplifiers at liquid nitrogen temperatures, and to develop our own design. The amplifiers will be housed in separate vacuum systems closely coupled to the electrode assemblies shown in Figure 5-17.

5.4.3 Notch Filters Notch filters are needed in our design of the stochastic cooling system for several reasons. In one system, the stack tail momentum cooling system, notch filters are used both for reducing the microwave power at frequencies corresponding to particles in the core, and to assist in shaping the gain vs momentum (frequency) in the stack tail. In systems with poor signal to thermal noise ratio, notch filters are useful in reducing the extra travelling wave tube installed power required to amplify it. If momentum cooling is implemented in the debuncher, a notch filter would be used to produce a phase inversion of the pickup sum signal at the harmonics of the central revolution frequency. The tolerance on the frequency deviation of the notch centers at each harmonic of the revolution frequency ω_0 in the frequency bandwidth is of the order of (for the accumulator)

$$\left| \frac{\omega_n - n\omega_0}{n\omega_0} \right| < \eta \frac{\delta p}{p} \sim .5 \times 10^{-5}$$

Where $\eta = 0.02$, p is 8.9 GeV/c and δp is about 2 MeV/c.

Filter designs include both shorted stubs, which use reflections from the shorted end of a long transmission line (nominally half the circumference of the accumulator ring), and correlator types, which use the constructive and destructive interference of the same signal transmitted over two transmission lines (whose lengths differ by about the circumference of the accumulator ring).

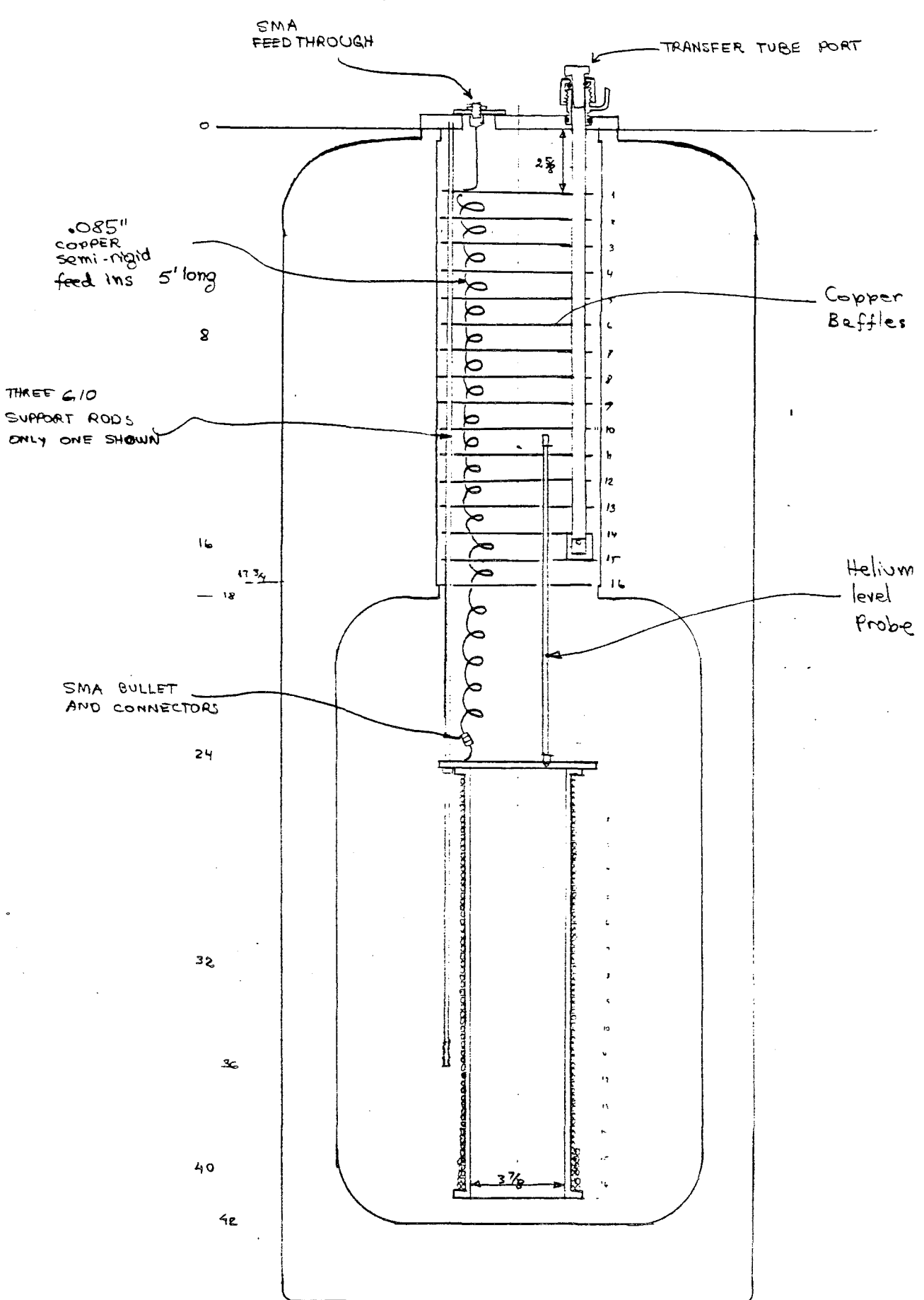
In our application here, the large circumference of the accumulator ring, in combination with the very high frequencies used in the electronics, impose severe restrictions on the selection of transmission lines. In room temperature transmission lines, the skin effect conductor resistance causes dispersion as well as attenuation. This is reduced by using larger diameter transmission lines. However, the maximum size of the transmission line is limited as higher order modes become evanescent, and affect the dispersion. In particular, in a 7.5 cm diameter 50 ohm transmission line the TE₁₁ mode propagates at frequencies above 2.0 GHz. These effects are only marginally better at 76.6 ohms, the impedance at which skin effect losses are minimized.

Our design is based on superconducting transmission line correlator type notch filters. We have achieved notch dispersion of less than 1×10^{-5} in the 1-2 GHz band using a 1.6 mm diameter 50 ohm superconducting transmission line about 86 m long. Early measurements using the line in the shorted stub mode showed that small discontinuities in the line created voltage standing waves (VSWR's) which added to the dispersion. In the correlator circuit, the reflected power is absorbed by the matched source impedances (or the isolated port of a hybrid splitter) and is only re-reflected forward by additional discontinuities. Hence a correlator design is less sensitive to discontinuities than is the shorted stub design. A schematic of the 86 m superconducting line is shown in its liquid helium cryostat in Figure 5-19. The superconducting line is wound into a coil 40 cm long and 10 cm diameter. In the present design, the helium cryostat must be refilled every two days. Figure 5-20 shows the notch dispersion obtained with this line in the 1-2 GHz band and the 2-4 GHz band. It has been found for example that the notch dispersion can be improved by use of carefully matched hybrid splitters and combiners. Research and development in superconducting transmission lines is in progress.

5.4.4 Travelling Wave Tubes (TWT's). The power amplifier stages in all our cooling systems are travelling wave tube amplifiers. Several commercial units are available in the 1-2 and 2-4 GHz bands with saturated output power ratings up to 200 watts. Travelling wave tubes are also available with power ratings above 1 kW.

Numerical studies show that in the stack tail momentum cooling system, the depth of the notches between the Schottky bands must be at least 40 db deep in order not to excessively heat the core. Even though notches of this depth can be obtained with the filters discussed above, the intermodulation distortion which occurs at higher power levels in TWT's can rapidly fill these in. Second order intermodulation distortion can occur at the edges of the operating band of octave bandwidth TWT's. Operation of the TWT's in a push-pull mode however can reduce the second order IM products effectively. However, third order IM distortion can occur at midband frequencies and is not reduced by operating the TWT's in push-pull mode. Measurements using a single TWT and a notched white noise source show that the remaining notch depth at the TWT is only 13 db at full power (200 watts), but improves to about 30 db at 10 watts per TWT. This is shown in Figure 5-21. The highly peaked Schottky spectrum produces a third order intermodulation distortion which is naturally peaked in rather than between the Schottky bands, providing another 12 db of notch depth at core frequencies. Hence we would need to use of the order of 160 TWT tubes to provide an estimated 1.6 kW to 160 kicker electrode pairs.

The potential cost saving of being able to run the TWT's at 100 watts rather than 10 has stimulated interest in using superconducting correlator filters on the output of the TWT's. In principle, the filter need only provide a notch depth of the order of 20 db, the remainder being provided by the TWT IM distortion reduction of 13 db, and the IM form factor of the Schottky bands of the order of 12 db. As a correlator filter using a



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Fig. 5-19

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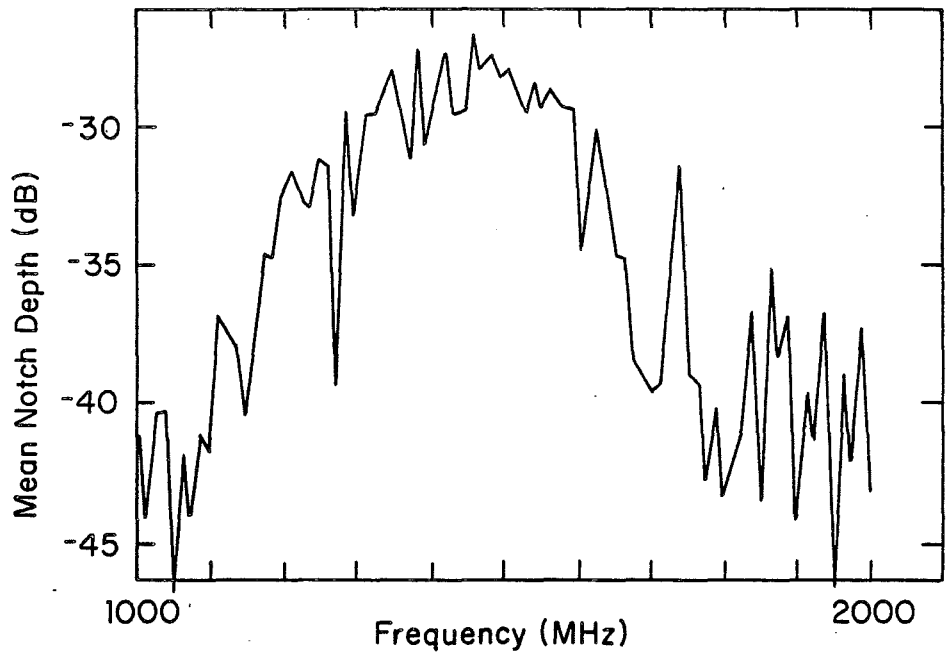
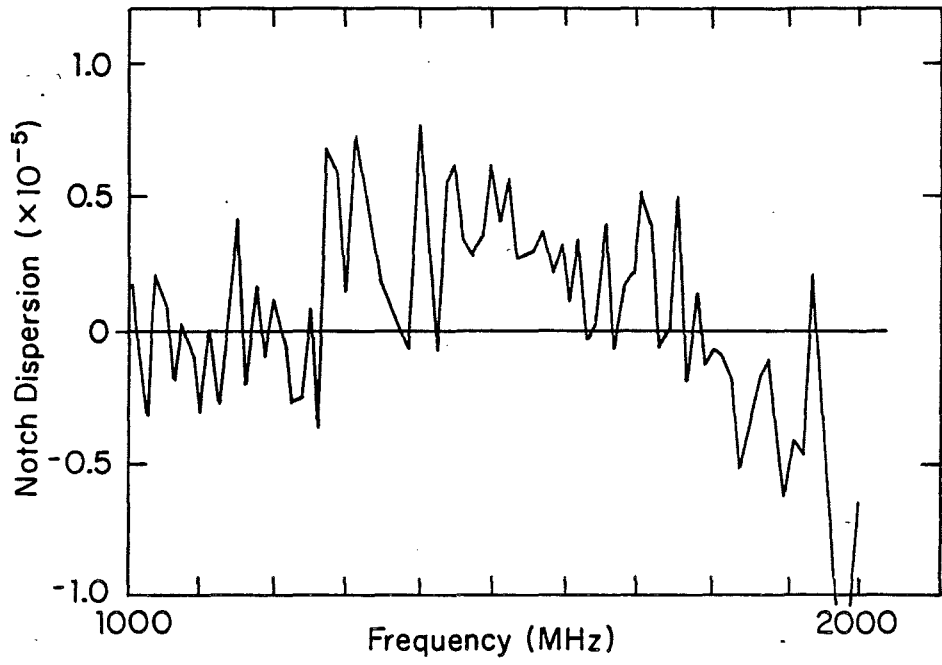


Fig. 5-20a

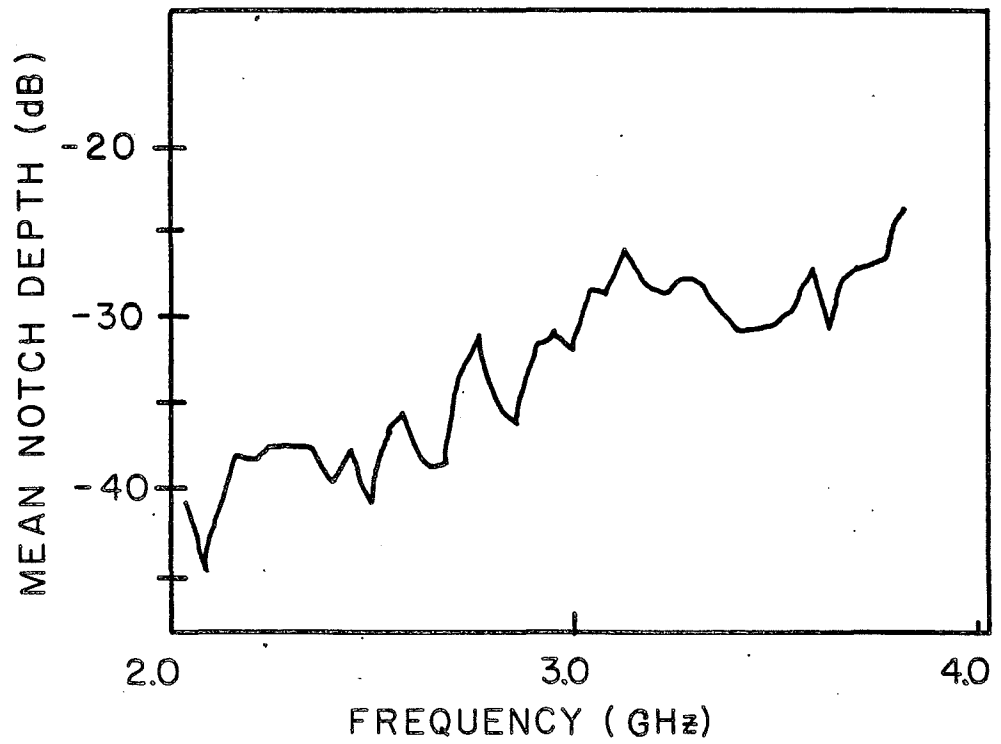
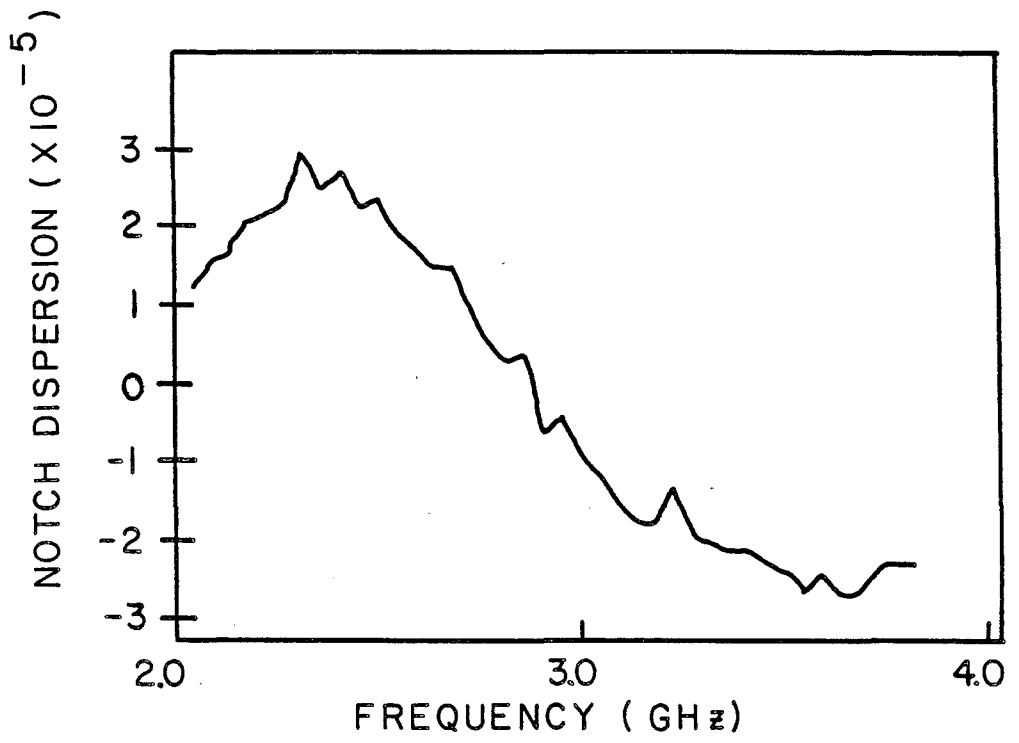


Fig. 5-20b

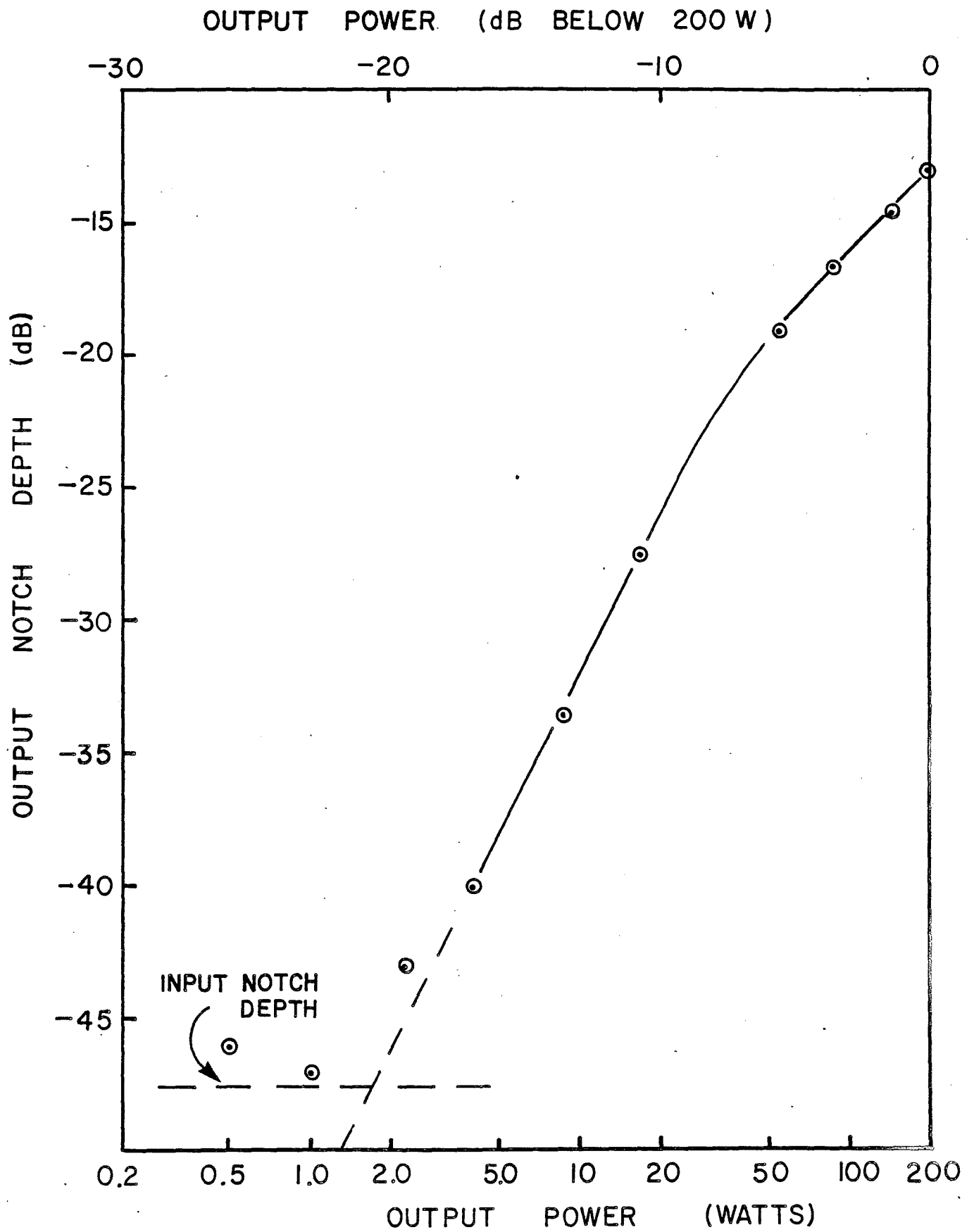


Fig. 5-21

superconducting transmission line is nearly lossless, we are investigating the possibility that such a filter could be used on the TWT outputs. Calculations show that the superconducting line could dissipate about 0.7 watts/meter without quenching. Measurements presently show that attenuation in a 80 m line is less than 0.5 db at low power levels (corresponding to 0.3 watts per meter at 200 watts forward power). Calculations of the anomalous skin effect and dielectric losses yield similar values. Hence a research and development program is going on in this area. The present design is based on using the post TWT filters with each tube in a push-pull pair operating at about 40 watts. The circuit arrangement is shown in Figure 5-22.

5.4.5 Kicker Electrode Assemblies The kicker electrode assemblies are conceptually similar to the pickup electrodes except that the printed circuit combiner board is now a power divider, and the terminating resistors must dissipate 5 to 7 watts each (into a heat sink). Cryogenic pumping does not appear to be needed if the teflon circuit board is prebaked at 150 C, hence allowing the terminating resistors to be water cooled rather than liquid nitrogen cooled.

5.4.6 Other Considerations Most of the components in the stochastic cooling electronics have a limited bandwidth of about an octave, and this normally causes the frequency derivative of the phase delay to be frequency dependent. This leads to two parameters which need to be known for each element. The group delay (the slope of a straight line fit to the phase delay vs frequency data in the operating band) and the phase intercept (the zero frequency intercept of the above straight line) need to be measured for each component and accounted for the final system. Deviations from the average group delay at particular frequencies, as well as gain nonuniformity may have to be corrected. Special circuits to cause gain shaping and constant phase offset will need to be designed and built. In brief, the group delay is adjusted using cables so that the information signal arrives at the kicker at the correct time. The phase intercept correction assures that it arrives with the correct phase angle. The gain correction assures that the signal power is properly apportioned to each Schottky band.

The dispersion in the transmission lines carrying the signals across the ring also needs to be considered. In the 1-2 GHz stack tail systems, the largest diameter coaxial line which we can use is 1 5/8" diameter rigid line (air dielectric) as the TE₁₁ mode becomes evanescent above 3.5 GHz. Calculations show that the expected dispersion is about 3 over the 1-2 GHz band for 150 m of line, based on the known skin effect losses. Preliminary measurements indicate that it may actually be somewhat larger, possibly due to excitation of non-evanescent modes at 2 GHz. In the 2-4 GHz range, the transmission line diameter would have to be limited to about 7/8", and the calculated dispersion would be about 8. This line will probably be of the foam dielectric type, as the time delay requirements are not overly restrictive.

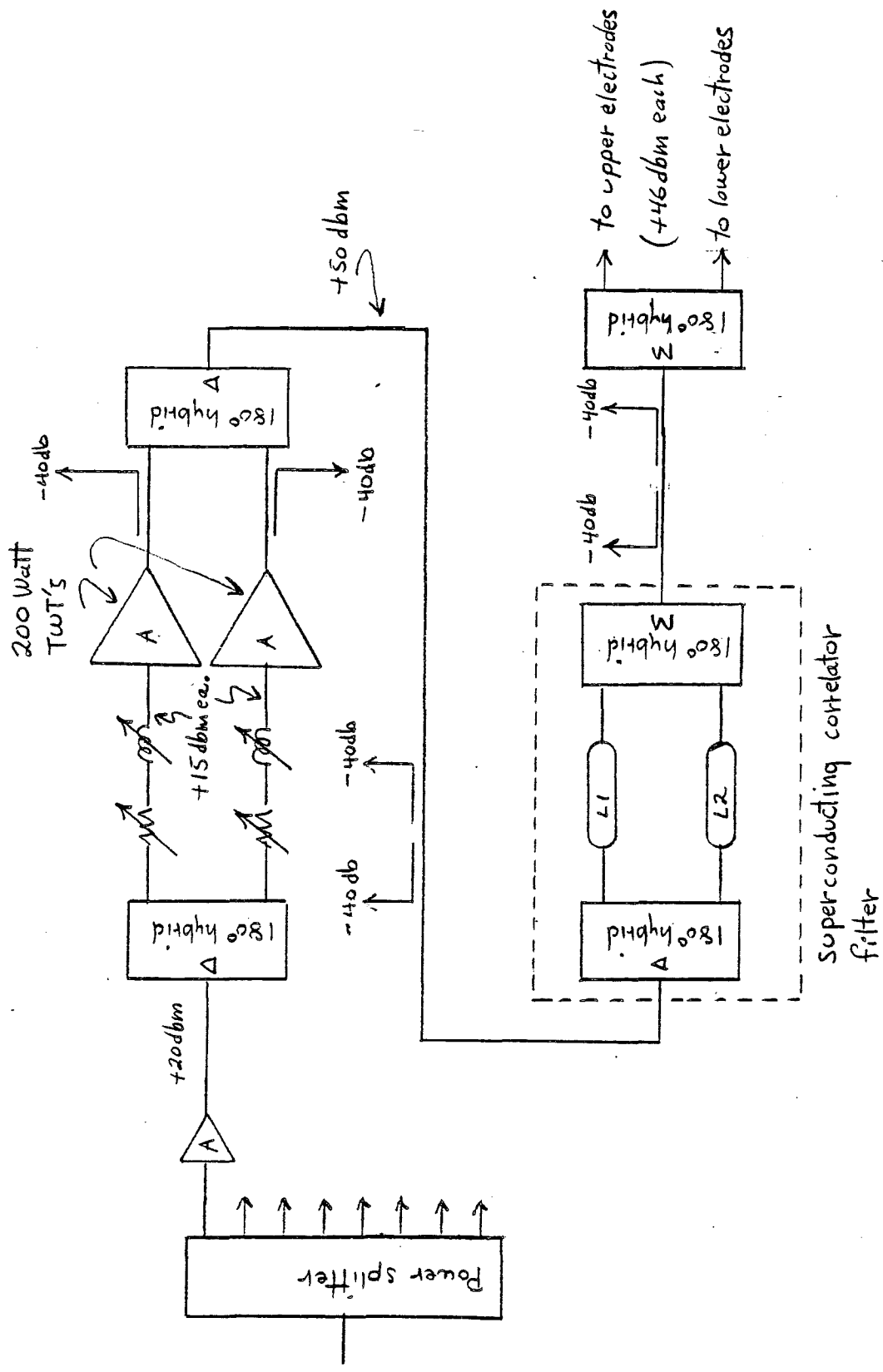
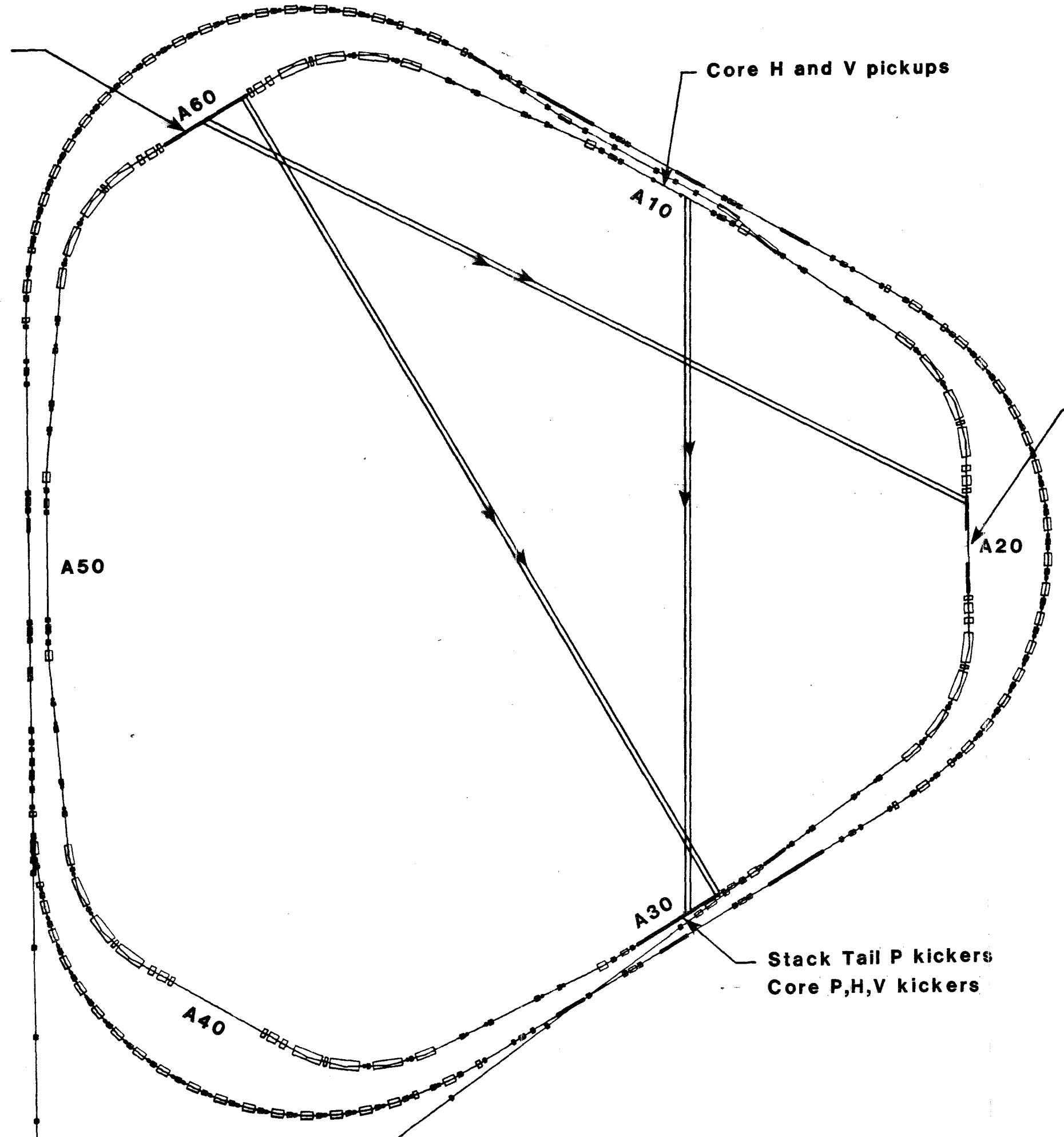


Figure 5-22: TWT push-pull circuit with superconducting correlator filter.

Stack Tail P,H,V pickups
Core P pickups

Core H and V pickups



Stack Tail V and H kickers



Stack Tail P kickers
Core P,H,V kickers

ACCUMULATOR STOCHASTIC COOLING SYSTEM LAYOUT

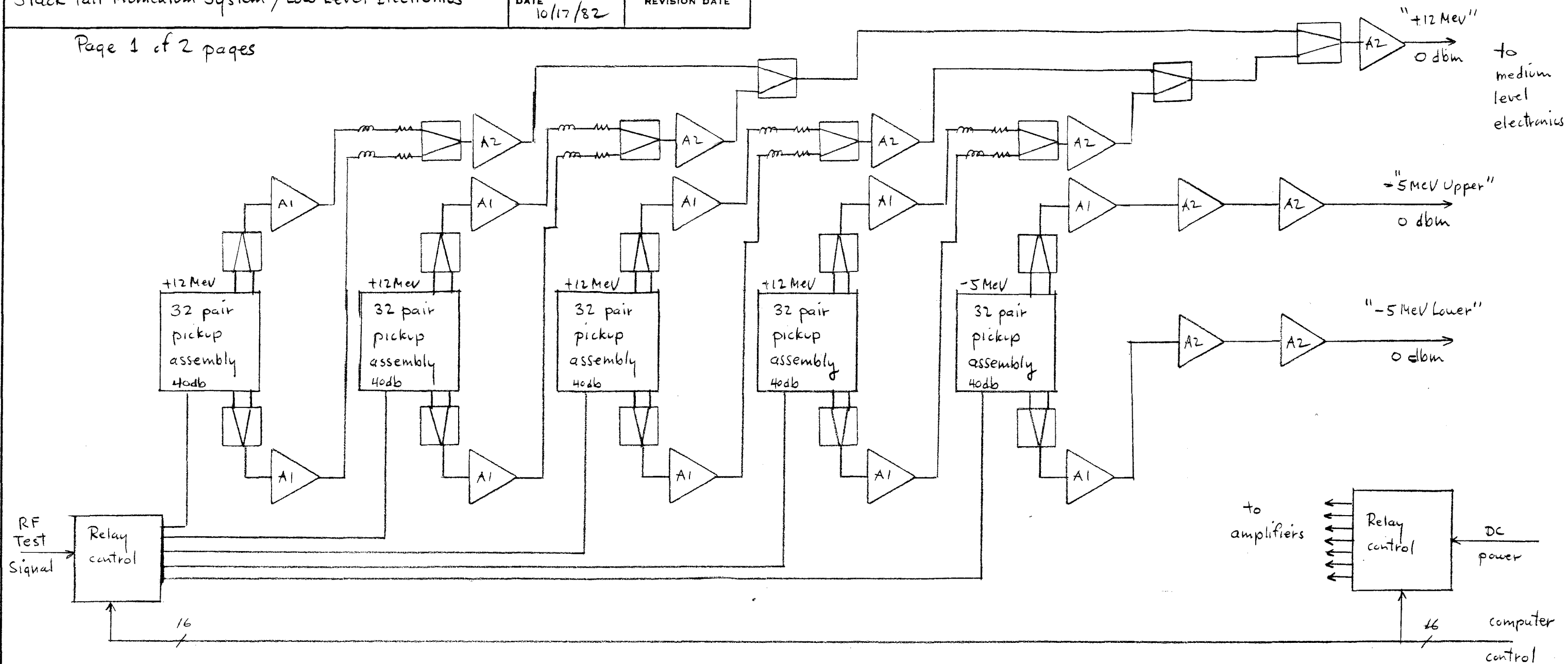
Fig. 5-23



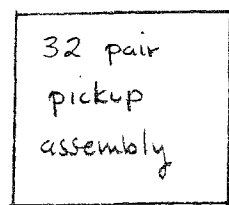
SUBJECT Stack Tail Momentum System / Low Level Electronics

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DATE 10/17/82 REVISION DATE

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Notes



= 2.4 m long module containing 32 pair of 1-2 GHz loop couplers cooled to 77°K. Upper and lower electrode signals are separately brought to cooled GaAs fet amplifiers through vacuum chamber walls. A 40 db coupler built into assembly allows insertion of test signal.



= 2:1 power combiner



low noise GaAs fet amplifier cooled to 77°K. Gain about 30 db. Equivalent noise temperature about 75°K



Commercial bipolar 1-2 GHz amplifier, Avantek # UTC-20-104 or equiv [gain = 23 db; equiv noise temp = 500°K]

-m- manually adjusted linear delay pad

-u- manually adjusted attenuator pad.

Figure 5-24a - Stack Tail Momentum Low Level Electronics



SUBJECT
Stack Tail Momentum System / Low Level Electronics

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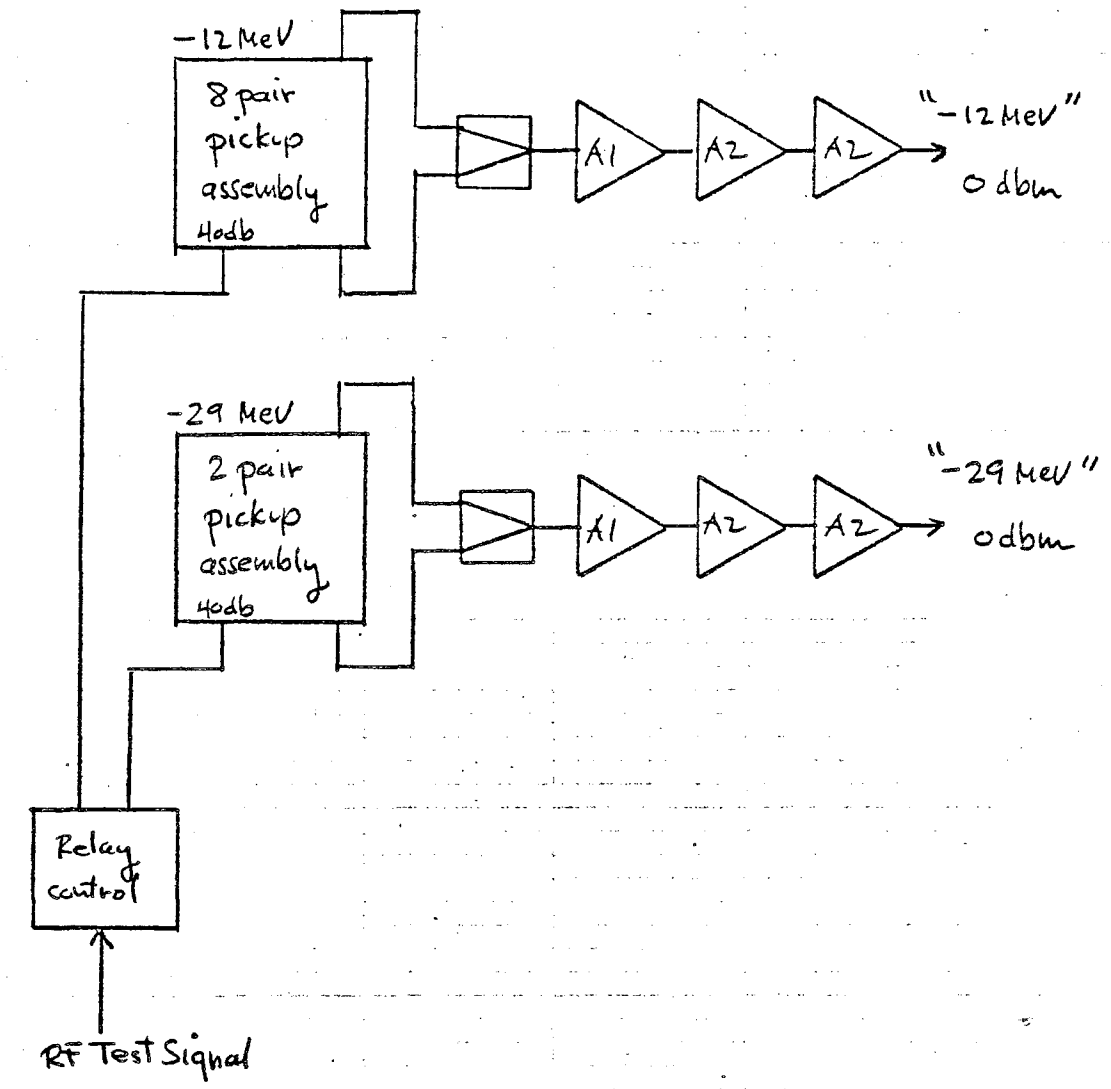


Figure 5-24 b Stack Tail Momentum Low Level Electronics

5.4.7 Accumulator Stochastic Cooling System Layout There are 6 specific cooling systems in the Accumulator. Their location is shown in Figure 5-23. Their basic operating parameters are outlined in Table 5-III. All 3 stack tail systems operate in the 1-2 GHz band, while the 3 core systems operate in the 2-4 GHz band. All kicker assemblies have been located remotely from the pickup electrodes to minimize coupling and feedback.

The largest system is the stack tail momentum cooling system, requiring about 1600 watts of microwave power. The pickup electrodes are located in the 10 m dispersion short straight section A60, and the kickers in the zero dispersion long straight section A30. A block diagram of the low level electronics is shown in Figure 5-24a and b. Groups of 32 pickup electrodes are summed on an internal edge-supported teflon printed circuit board into low noise preamps. Signals are separately amplified for the upper and lower electrodes to allow for gain and phase correction, as well as for forming both sum and difference signals. Signal processing is done in the medium level of electronics as shown in Figure 5-25. This includes 3 notch filters (superconducting correlators) with notch minima set at +4, -2, and -3 MeV relative to the core. After gain and phase corrections, the signals are amplified to about +20 dbm and transmitted across the ring to the high level electronics (TWT's). At present we estimate that 40 TWT's are needed if we can operate them at 40 watts each and maintain a 30 db notch depth at the core frequency (this number includes the Schottky form factor of about 12 db). Post TWT filters (superconducting correlators) would have to provide about 10 db additional.

The stack tail betatron cooling systems derive their pickup signals from the stack tail momentum system as shown in Figure 5-26. The kickers, however, are in straight Section A20, where the dispersion is about 10 m. These systems each require only about 20 watts, and can be powered by a pair of TWT's without filtered outputs.

The core momentum system pickups are located in the high dispersion straight Section A60 along with the stack tail pickups. As indicated in section 5.2.5 and Figure 5-5, the core momentum pickups are double rows of pairs, each pair in sum mode. The difference signal of the two rows is then formed. These signals are processed as shown in Figure 5-27 and sent to kickers in the zero dispersion straight section shared with the stack tail momentum kickers. This system requires about 10 watts.

The core betatron system pickups are located in the zero dispersion straight section A10. The signals are processed as per Figure 5-28 and also sent to kickers in zero dispersion straight section A30. Each system requires about 10 watts.



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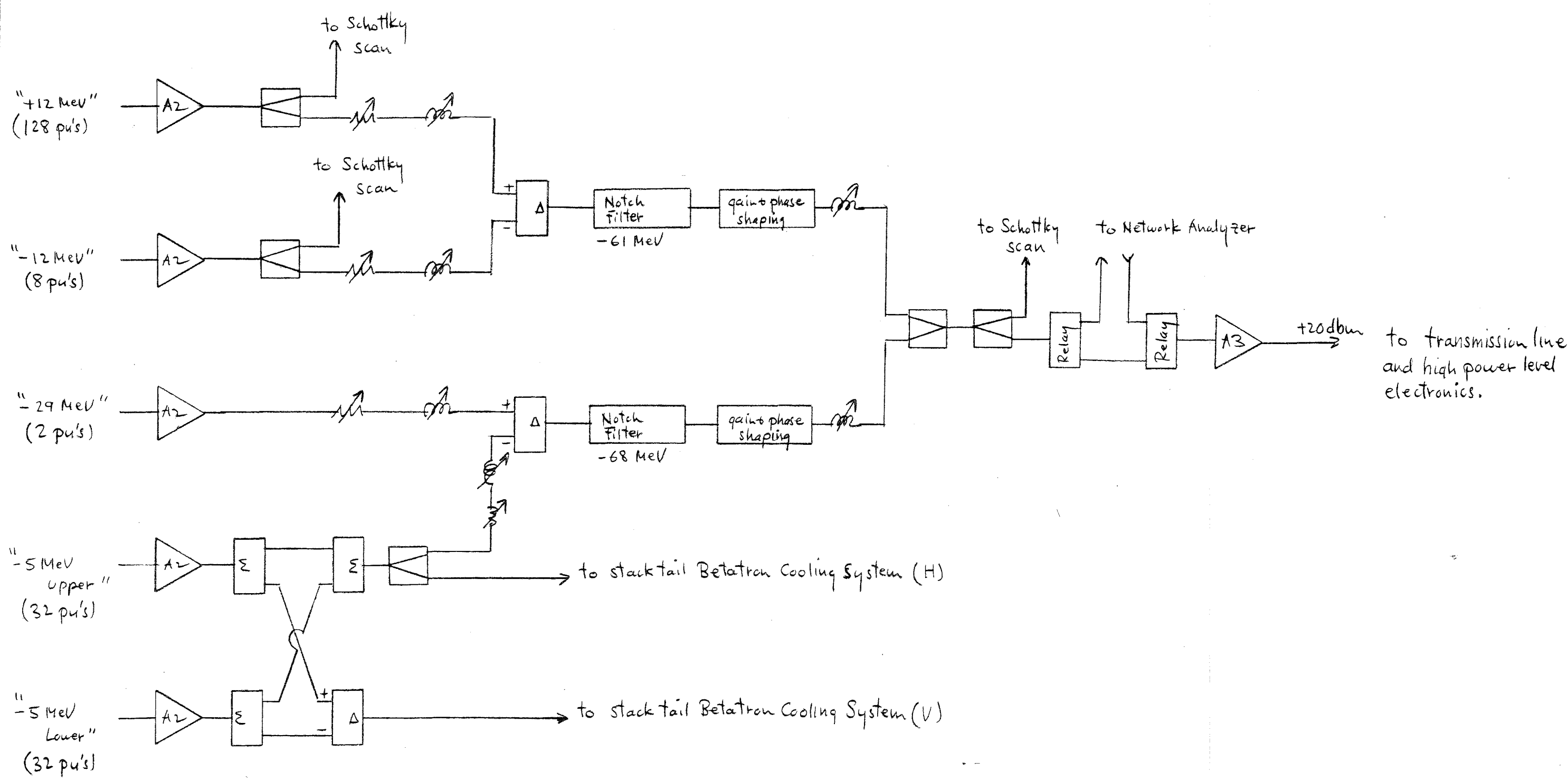


Figure 5-25: Stack Tail Momentum Cooling / Medium Level Electronics

Fig. 5-25

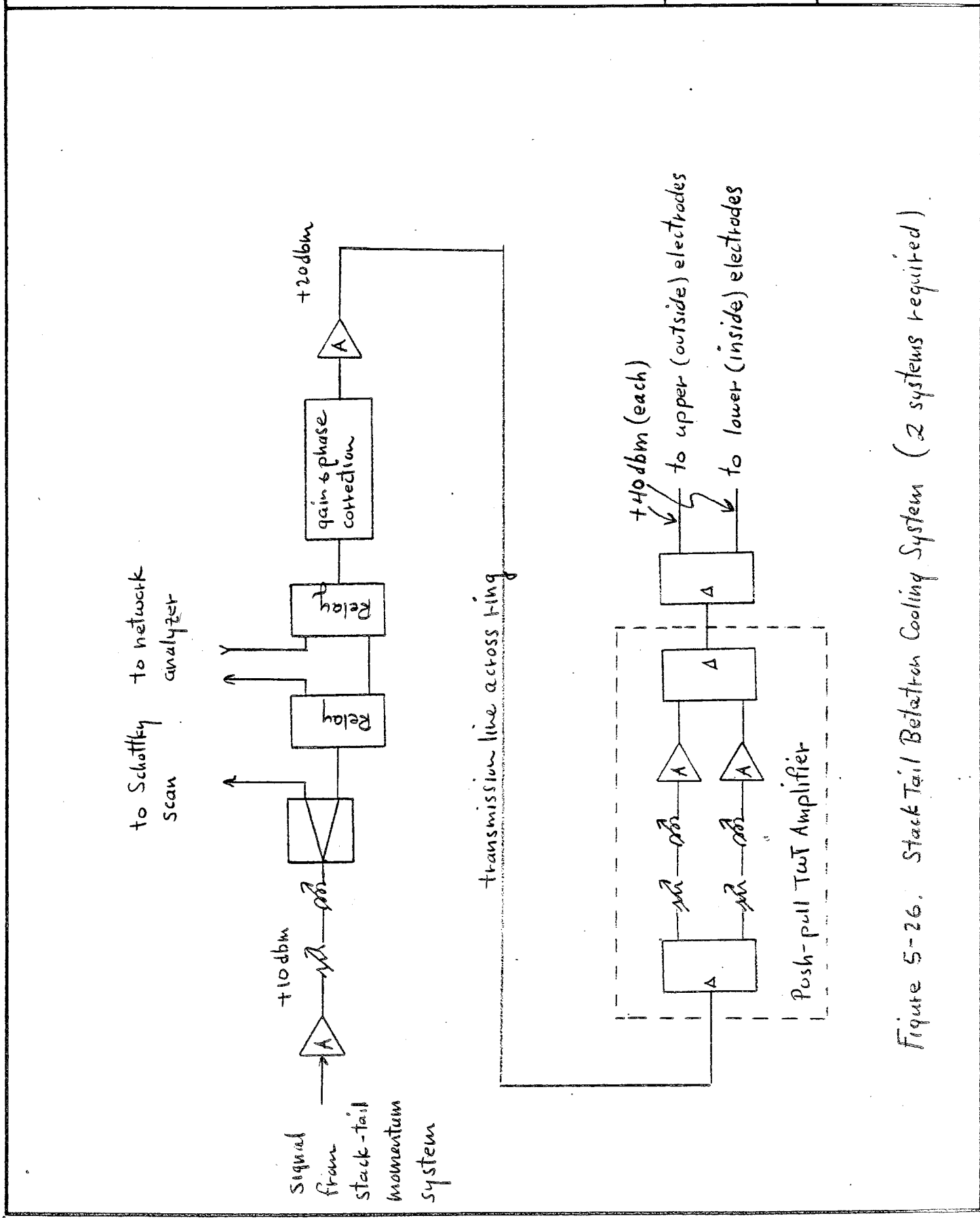


Figure 5-26. Stack Tail Betatron Cooling System (2 systems required)

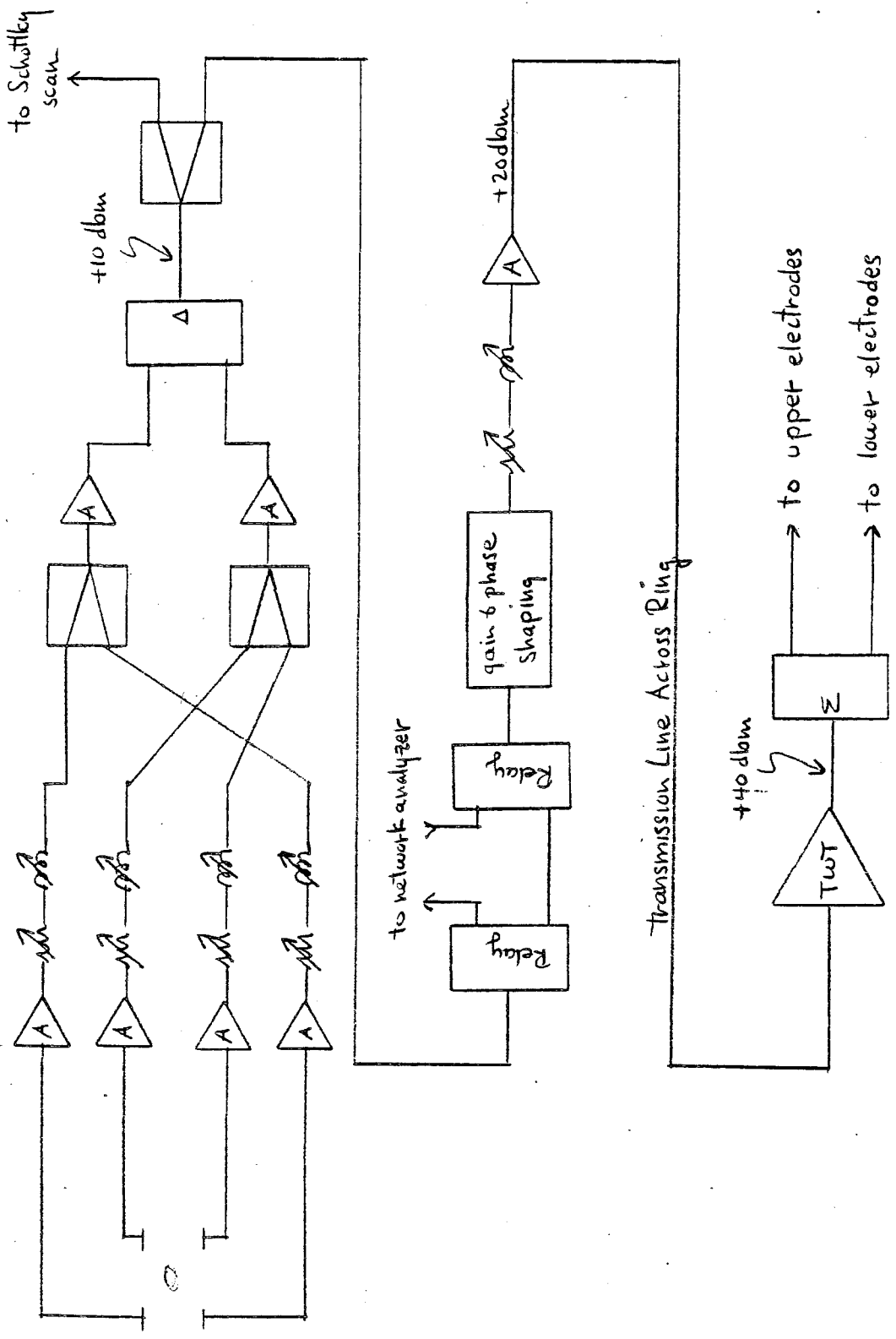


Figure 5-27. 2-4 GHz Core Momentum Cooling System

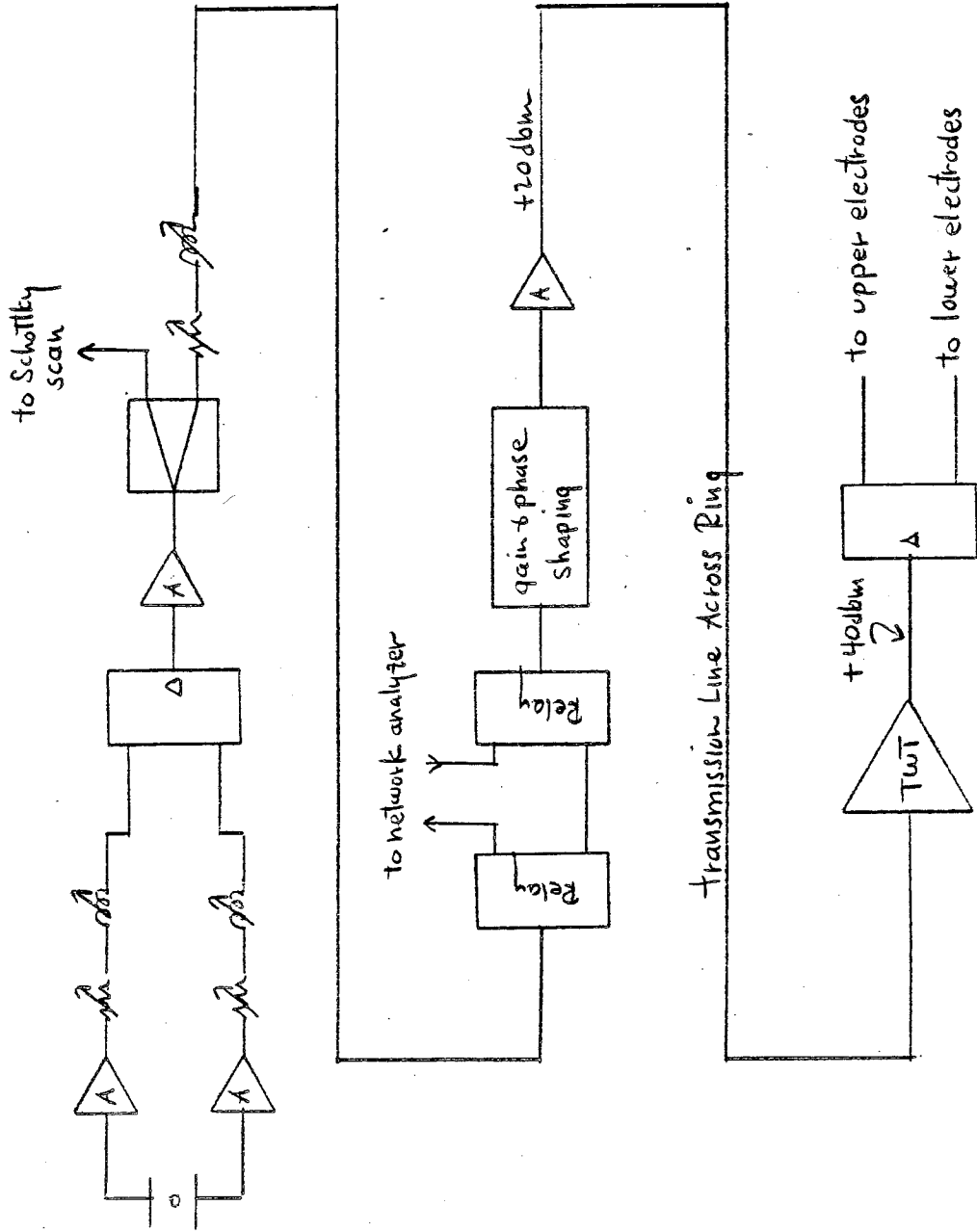


Figure 5-28. 2-4 GHz Core Betatron Cooling System (2 systems required)

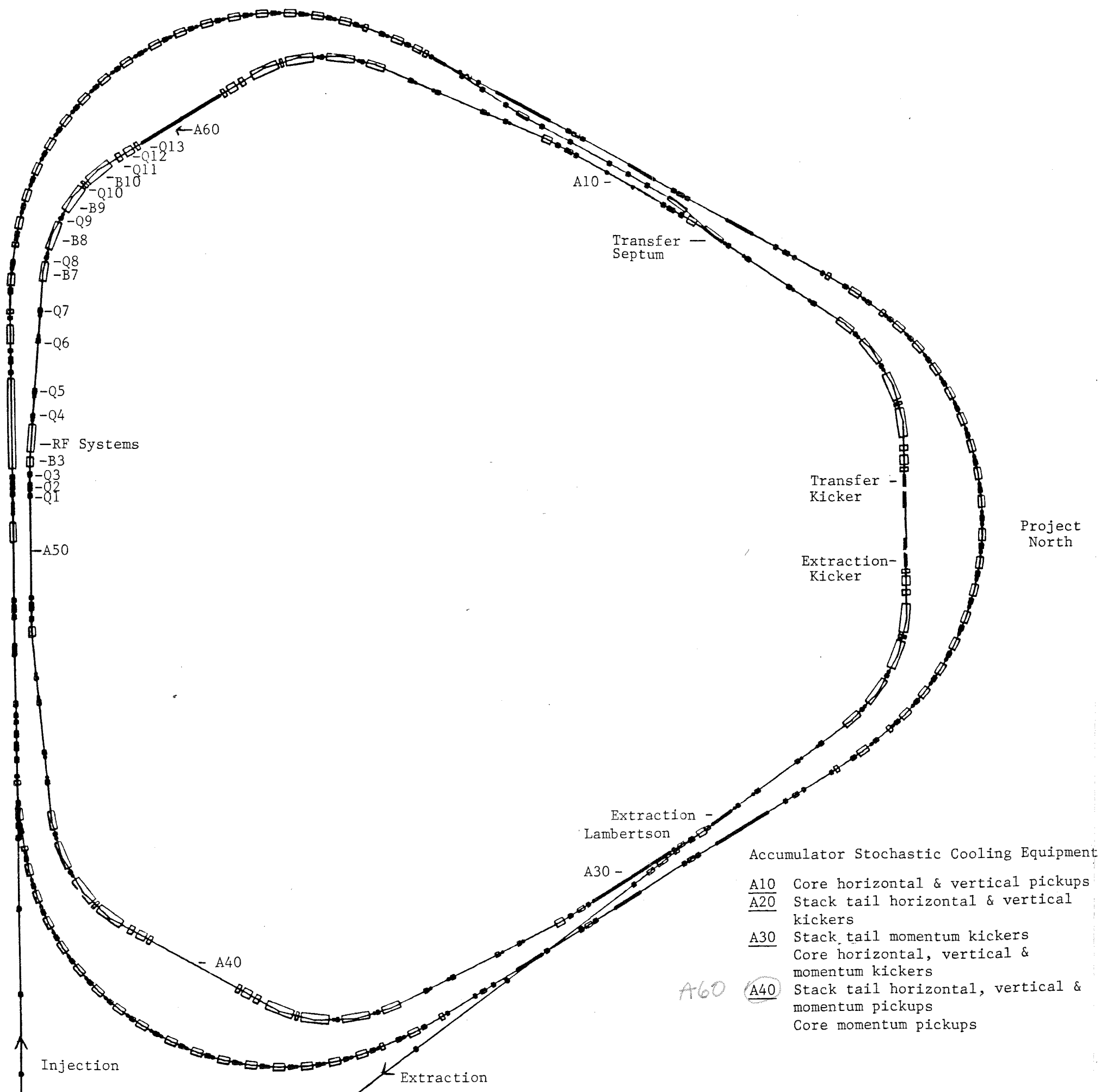
Table 5-III Accumulator Stochastic Cooling Systems

	<u>Stack tail Momentum</u>	<u>Stack tail Betatron</u>	<u>Core Momentum</u>	<u>Core Betatron</u>
Frequency band	1-2GHz	1-2GHz	2-4GHz	2-4GHz
Number of pickup pairs (loops)	128+32+8+2	(32)	32 + 32	8(x2)
Pickup characteristic impedance	100 ohms	100 ohms	75 ohms	75 ohms
Pickup sensitivity s(0,c or d(o,y)	.84(s)	1.94(d)	.66(s)	1.73(d)
Back termination thermal noise temperature	80°K	80°K	80°K	80°K
Amplifier equivalent thermal noise temperature	75°K	75°K	120°K	120°K
Amplifier gain (net)	145db	125db	95db	90db
Number of filters (superconducting corrulators)	22(3)*	0	0	0
Output power				
-Schottky	1400W	10W(x2)	10W	10W(x2)
-thermal	200W	10W(x2)	0	0
-total	1600W	20W(x2)	10W	10W(x2)
Number of TWT's (200 watt saturated power)	40(160)*	2(x2)	1	1(x2)
Number of kicker pairs (loops)	160	32(x2)	32	8(x2)
Kicker characteristic impedance	100 ohms	100 ohms	75 ohms	75 ohms
Kicker sensitivity s(0,c or d(o,y)	.84(s)	1.94(d)	.66(s)	1.73(d)
Spare time delay with air dielectric line ($\beta=.998$)	5 nsec	23 nsec	230 nsec	110 nsec
Spare time delay with heliax ($\beta=.991$)	165 nsec	-15 nsec	185 nsec	78 nsec

*If possible TWT filters are not used.

5.5 Accumulator Lattice

The lattice of the Accumulator has been designed to accept the injection of antiprotons every few seconds at an energy of 8 GeV, momentum stack and stochastically cool the antiprotons, accumulate over a period of several hours a very dense core of antiprotons, and, finally, extract a high-intensity beam to re-inject into the Main Ring and Tevatron. The requirements on the lattice are twofold. The Accumulator must be a high-class storage ring capable of reliable operation, and it must accommodate all the conditions imposed by the stochastic cooling systems. The second set of requirements has led to the general design of this ring and its somewhat unusual appearance, while those of the first set have also been incorporated. These general conditions are listed below:



- Accumulator Stochastic Cooling Equipment
- A10 Core horizontal & vertical pickups
 - A20 Stack tail horizontal & vertical kickers
 - A30 Stack tail momentum kickers
 - Core horizontal, vertical & momentum kickers
 - A40 Stack tail horizontal, vertical & momentum pickups
 - Core momentum pickups

ACCUMULATOR LAYOUT

Fig. 5-29

- (i) The momentum mixing factor must be correct.

$$|1/\gamma_T^2 - 1/\gamma^2| = 0.02$$

where γ_T is the transition gamma of the ring and γ is the relativistic gamma factor of the particle. Thus for 8-GeV kinetic energy the ring must have

$$\gamma_T = 5.4 \text{ or } 10.6$$

- (ii) There must be several long straight sections, some 16 meters long, with very small transverse beam sizes. Some of these must have zero dispersion, and the rest dispersion, s of ≈ 10 m. This requirement leads to the lower choice of transition gamma.
- it \rightarrow 0 dispersion*
- (iii) Betatron cooling straight sections must be an odd-multiple of $\pi/2$ apart in betatron phase. Pickup and kicker straight sections must be far enough apart physically so that a chord will be at least 75 nsec shorter than the arc for signal-transfer purposes.
- (iv) The β values of the lattice should be about the same for the horizontal and vertical planes in the straight sections.
- (v) The ring should match the Booster circumference.
- (vi) There should be easy injection and extraction schemes.
- (vii) The beam everywhere should be as small as possible, consistent with the large-dispersion straight sections.
- (viii) The ring must have very good chromaticity corrections, be situated far from any resonances, have tuning flexibility, and generally be a good storage ring.

The result of the above criteria is given below. The ring is a six-sided figure in which the bending has been concentrated to produce high values of dispersion in some straight sections and zero dispersion in others. This gives a machine of superperiodicity three with six 16-meter long straight sections, alternating between zero and ten meter dispersion. The machine is mirror symmetric about each straight section. The straight sections have small beta-functions in each plane, consistent with the aperture requirements needed for the stochastic cooling equipment and have the necessary phase relations. A plan view of the ring is shown in Figure 5-29, the lattice functions for one sixth of the ring are plotted in Figure 5-30 and the structure and lattice parameters are listed in Table 5-IV.

*High dispersion in A60 due to bending.
Low dispersion in A10 straight sections*

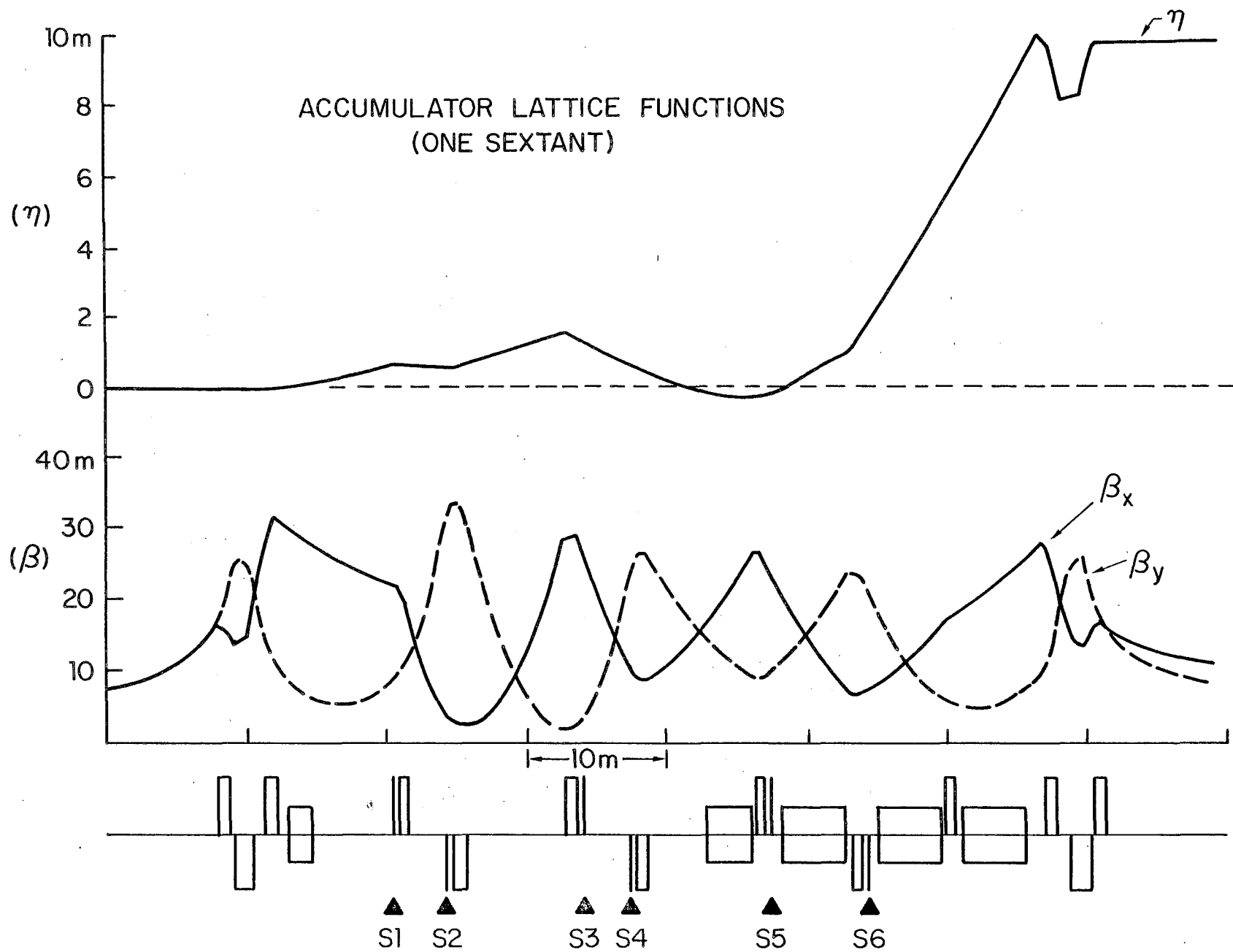


Fig. 5-30

Injection into and extraction from this machine are done in a similar manner. The injection orbit is displaced radially outward by approximately 0.8% in $\Delta p/p$. The shuttered kicker in the high-dispersion straight section is closed just before the \bar{p} 's are injected. The momentum displacement is enough to allow the injected beam to clear the shutter. Beam is transferred from the Debuncher ring via the 4-m long, 8-kG current septum magnet located at the upstream end of a zero-dispersion straight section. It arrives at the kicker and is kicked onto the injection orbit. The kicker is 2 m long and has a field of 500 G. The shutter is then opened and the beam is rf stacked. A drawing of the injected, stacked and accumulated beams at the position of the shuttered kicker is shown in Figure 5-31. The injection and extraction positions are shown on Figure 5-29.

Extraction from the Accumulator is essentially identical to the injection except the beam is extracted vertically with a Lambertson magnet, raising the beam four feet above the ring level to be transported back to the Main Ring. A layout of the extraction straight section is shown in Fig. 5-32.

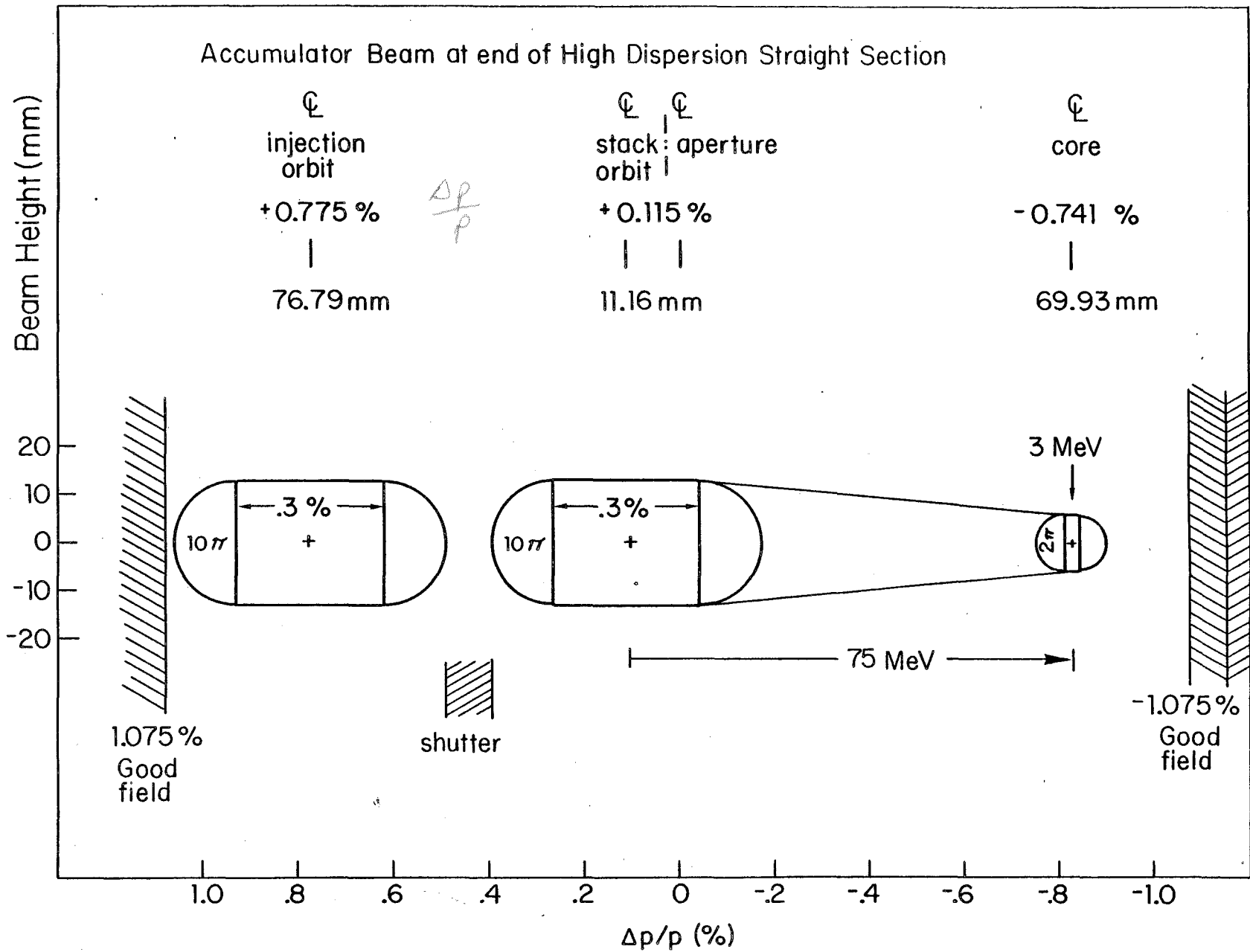
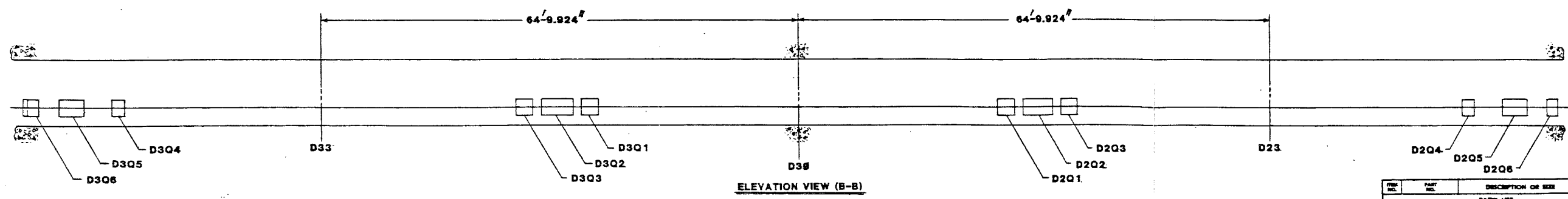
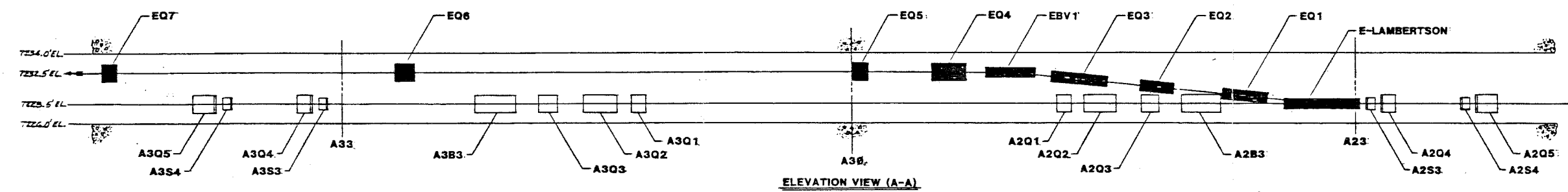
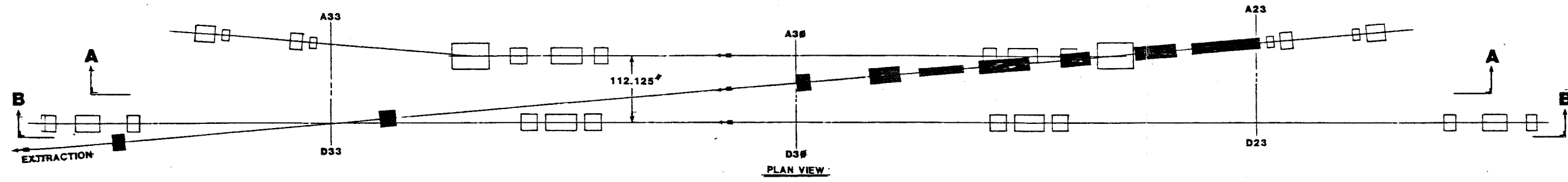


Fig. 5-31



EXTRACTION STRAIGHT SECTION

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY.
PARTS LIST			
DESIGNED BY	OPERATOR	E.L. JOHNSON	
DRAWN BY	ENGINEER	L. JOHNSON	
CHECKED BY	APPROVER		
1. DRAW ALL SHARP EDGES 2. DO NOT SCALE DIMS. 3. DIMENSIONS IN ACCORD WITH THIS DRAWING 4. HIDE ALL HIDDEN SURFACES			
DATE		MATERIAL	
PERM NATIONAL ACCELERATOR LABORATORY UNITED STATES DEPARTMENT OF ENERGY			
Figure 5-32			
SCALE	PLANS	DRAWING NUMBER	BY
1:50			

Table 5-IV. ACCUMULATOR PARAMETERS

1. General

Energy	7.9 GeV
Bend field	16.85 kG
Magnetic bend radius (ρ)	17.46 m
Radius	75.45 m
Revolution time	1.59 μ sec
Superperiodicity	3
Focusing structure	Separated function FODO normal cell
Nominal working point	

ν	6.61
ν_x	8.61
ν_y	

Nominal chromaticity

ξ_x	-9.12
ξ_y	-12.71

Chromaticity Corrected Parameters

	Injection Orbit	Stacking Orbit	Core Orbit
Energy (GeV)	8.00	7.94	7.87
$\Delta p/p$ (%)	+0.775	+0.115	-0.741
ν_x	6.61	6.61	6.61
ν_y	8.61	8.61	8.61
ξ_x	-0.14	-0.21	-0.14
ξ_y	-2.79	-0.36	3.59
γ_T	5.09	5.33	5.65
$1/\gamma_T^2 - 1/\gamma^2$	0.028	0.024	0.20

2. Magnets

Number of dipoles	30
Number of quadrupoles	78
Number of sextupoles	36

A. Small aperture dipoles

	<u>Length</u>	<u>Field</u>	<u>Number</u>
(B3)	5.0 ft.	16.89 kG	6
(B7)	10.0 ft.	16.89 kG	6
(B8)	15.0 ft	16.89 kG	6

B. Large aperture dipoles

(B9)	15.0 ft.	16.89 kG	6
(B10)	15.0 ft.	16.89 kG	6

C. Small aperture quadrupoles

(Q1)	22.5 in	99.23 kG/m	6
(Q2)	50.7 in	-99.23 kG/m	6
(Q3)	27.6 in	99.23 kG/m	6
(Q4)	20.8 in	99.23 kG/m	6
(Q5)	32.0 in	-99.23 kG/m	6
(Q6)	27.6 in	99.23 kG/m	6
(Q7)	27.6 in	-99.23 kG/m	6
(Q8)	18.0 in	99.23 kG/m	6
(Q9)	18.0 in	99.23 kG/m	6

D. Large aperture quadrupole

(Q10)	18.0 in	30.95 kG/m*	6
(Q11)	33.3 in	88.63	6
(Q12)	58.5	-88.63	6
(Q13)	24.4 in.	88.63	6

*Q10 will be built with missing turns to run in series with the other large aperture quadrupoles.

E. Sextupoles

(S3)	12.0 in.	728.56 kG/m ²
(S4)	12.0 in.	-869.76
(S61)	12.0 in.	437.11
(S62)	12.0 in.	-869.76
(S8)	12.0 in.	-728.53
(S9)	12.0 in.	-217.44

3. Structure

A. Drift Lengths

LS	314.9 in.
01	19.8
02	39.8
03	35.6

04	227.5
05	103.6
06	289.9
07	116.5
08	174.7
010	55.5
011	29.2
012	19.6
LS*	313.1
0S	12.0
0	20.0
00	24.0

B. Sextant Structure (s)

LS (Q1)	01 (Q2)	02 (Q3)	03 (B3)	04 (S3)
0S (Q4)	05 (S4)	0S (Q5)	06 (Q6)	0S (S61)
07 (S62)	0S (Q7)	08 (B7)	0 (Q8)	0S (S8)
00 (B8)	0 (Q9)	0S (S9)	00 (B9)	0 (Q10)
0 (B10)	010 (Q11)	011 (Q12)	012 (Q13)	LS*

C. Ring Structure

S(S)S(S)S(S)
 Length of central orbit 474.0702 m
 1555.348 ft

4. Aperture and Acceptance

Maximum Lattice functions (central orbit)

	β_x	β_y	α_p
LS (center)	7.78 m	7.60 m	0.00 m
LS* (center)	11.00	8.22	9.67
Small aperture dipole	29.78	21.32	0.83
Large aperture dipole	25.17	7.46	8.74
Small aperture quad	30.23	34.13	1.56
Large aperture quad	27.33	27.43	9.92
Sextupole	26.02	27.55	1.39

Required beam

Emittance $\epsilon_x = \epsilon_y = 10\pi$ mm-mrad
 Momentum aperture $\Delta p/p = 2.30\%$

<u>Beam Size</u>	A_x	A_y
Small aperture dipole	52.4 m	29.2 mm
Large aperture dipole	219.6	17.3
Small aperture quadrupole	68.3	36.9

Large aperture quadrupole	246.3	33.1
Sextupole	62.1	33.2

5.6 RF Stacking System

With the injection shutter closed, antiprotons are injected from the Debuncher ring with a total momentum spread of about 0.2%. The energy spread (18 MeV) and the Accumulator ring revolution period (1.59 μ sec) result in an injected longitudinal emittance of about 29 eV-sec. This beam is bunched adiabatically and decelerated by 0.7% to the end of the tail of the previously stacked antiprotons where it is released by adiabatic debunching. Adiabatic capture can begin immediately following injection and can proceed during the time required for removal of the shutter, about 0.1 seconds.

With a phase-oscillation period of 10 msec and a deceleration time of 30 msec, the entire operation of establishing a moving bucket, deceleration, and adiabatic debunching can be accomplished within 0.1 seconds after the beam is injected.

At frequencies well below the GHz cooling band, the cooled core may be subject to longitudinal instabilities induced by the shunt impedance of the stacking rf cavity or other similar device. The stability criterion resulting from various dispersion analyses can be written in a limiting form

$$\left| \frac{Z}{n} \right| \leq F \frac{(\Delta E/E)^2 E_s \eta}{I},$$

where the form factor F is about unity for a conservative estimate of the stability of a roughly Gaussian distribution and ΔE is the full width at half maximum.

The cooled core has the parameters

Δp FWHM	4.1 MeV/c
N (antiprotons)	$4.3 \times 10^{11} \bar{p} * 1.6 \cdot 10^{-19} C/\bar{p} * 1.59 \mu\text{sec}$
I	4.32×10^{-2} Amperes
η	0.02

With these parameters the critical value of Z/n is about 1000 ohms. The rf voltage required to establish a given phase-space increases linearly with the harmonic number and, because the power required is $V^2/2R_{sh}$, the

required rf power increases linearly, given the stability limit on the shunt impedance. Consequently, to minimize the cost, size, and complexity, it would appear that rf stacking should be done at the lowest possible harmonic number. On the other hand, very low harmonic numbers and very low voltages result in excessively long synchrotron periods that are not consistent with the rapid production cycling rate. An adequate compromise appears to be $h = 10$, 6.289 MHz. An rf system at this frequency with an effective shunt impedance of $10 \text{ k}\Omega$ meet the requirement that $Z/h \approx 1 \text{ k}\Omega$. The parameters associated with rf stacking at $h = 10$ are listed in Table 5-VI. The shunt impedance of the bunching cavity is in agreement with this stability requirement for harmonics of interest.

Table 5-V. RF STACKING PARAMETERS

Injected Longitudinal Emittance	29 eV sec
Stacking rf Total Bucket Area	30 eV sec
Stationary Bucket RF Voltage	7.8 keV
Stationary Bucket Phase Oscillation Period	9.4 msec
$\Delta p/p$ Required for Stacking	0.7%
Δ (cp) $E = \sqrt{E_0^2 + (pc)^2} = pc$ for $\beta=1$	62.2 MeV
Deceleration Synchronous Phase Angle	10 degrees
$\Gamma = \sin \phi_s = \sin(10^\circ)?$	0.1736
Moving Bucket Factor $\alpha(\Gamma)$	0.6964
RF Voltage During Acceleration	16.1 kV
Time Required for Deceleration	30.2 msec
Number of Cavities	1
Cavity Structure	40 NiZn Ferrite Cores
Cavity Small Signal Shunt Impedance	10 $\text{k}\Omega$
Peak RF Power Requirement	10 kW
Average RF Power Requirement (Cooling, etc)	1 kW
Harmonic Number	10
RF Starting Frequency	6.28695 MHz
$\eta = \gamma_t^{-2} - \gamma^{-2}$	0.019-0.023
β	0.99447
Injection Orbit Circumference	474.202 m
Stacking Efficiency*	98%

*Based on computer simulation

5.7 Accumulator Magnets

The main magnet system consists of 30 dipoles and 78 quadrupoles. In Table 5-IV is shown a list of magnets, lengths, strengths and required apertures. The required apertures were calculated assuming construction tolerances of 2.5×10^{-4} (relative standard deviation) for dipole strengths, dipole level angles (radians), and quadrupole random position

errors (meters). Sufficient space is allowed for at least 4σ , where σ is the standard deviation of the expected orbit position error, or the beam emittance plus momentum spread plus 10 mm whichever is larger. In addition, space is left for 4 mm (thickness plus deflection) vacuum chamber thickness and 5 mm insulation thickness. Several mm must be included also for copper heat transporters to bake the chamber (dipoles) with heaters on the edges.

There are three lengths of dipoles, all with field strengths of 1.689 T. There are 2 different apertures: 3 different lengths in the smaller aperture; one, in the larger. Their properties are described in Table 5-VII, Because of the large sagitta, these magnets will be curved. The coils will be made of four pancakes plus single-layer saddle coils.

There are 13 different quadrupoles, of two different profiles. Q1-Q9 have pole tip radii of 43.3 mm and 6 different lengths. Q10-Q13 have pole tip radii of 84.1 mm and four different lengths. The properties of these quadrupoles are shown in Table 5-IX. Each quadrupole will have a shunt with capability of about 10% of the quadrupole strength. The coils are fabricated in individual layers and assembled on the quad half cores, which are then assembled as a complete magnet. All quadrupoles have the same gradient, 9.7845 T/m.

There are 30 sextupole magnets of one kind. The maximum strength is 120 T/m, which permits the poles to be parallel-sided. A coil can be made of one flat pancake. These magnets are divided in 4 families which are operated on 4 individual current busses. Their (maximum) specifications are shown in Table 5-VIII.

Table 5-VII. DIPOLES

Lengths	4.572	3.048	1.524	m
Outside dimensions				
gap	60	60	60	m
Good field aperture	100	100	100	mm
Conductor				
Pancake coils	1"x1.25", 0.375" hole dia., 1/16" corner, 1.1362 in. area			
Saddle coils	1.343"x0.787", 0.578" hole dia., 1/16" corner, 0.7911 in.			
Turns				
Pancake coils	56			
Saddle coils	16			
Conductor lengths				
Pancake coils	567.5	400	229.5	m
Saddle coils	182.5	134	85.3	m
Total conductor length	750	534	315	m
Cu Wt	10,769	7,666	4,520	lb
Current	1.181	1.181	1.181	kA
Resistance(43°C)	19.2	13.67	8.06	mΩ

*Pancake vs.
saddle coil.*

Power	26.8	19.6	11.24	kW
Total dipole power	669			kW
Total Cu Wt	267			klb
Full cross section Fe area	0.615			m ²
FeWt	48	42	20.6	x10 ³ lb
Total Fe wt	1.624			x10 ⁶ lb

Table 5-VIII. ACCUMULATOR QUADS (LARGE BORE)

Lengths	0.178 to 1.274	0.457 to 1.274	m
	total 16.3	total 37.6	m
Poletip radius	84.1	43.27	mm
Conductor	0.82 square	0.4096 square	in.
Total conductor length (all magnets)	24,228	47,083	ft
Cu Wt	35,565	27,344	lb
Current	810A	202.5A	A
Resistance (all magnets)	0.442	3.354	Ω
Power (all large quads)	290	137.7	kW
Full cross section (Fe area)	0.476	0.183	m ²
FeWt	134.5	119.4	10 ³ lb

Table 5-IX ACCUMULATOR SEXTUPOLES

Max. B"	120	T/m ²
ℓ eff	0.3	m
poletip radius	50	mm
NI	2000	AT/Pole
Max. I.	200	A
N	10	Turns
Conductor	(3.294") ²	with 0.181½ϕhole
Current density	4.0	A/mm
R	19	mΩ
Max. voltage drop	3.8	volt
Max. ohmic loss	760	watt
Weight, cu	50	lb
Fe	450	lb
No. of magnets	36	
Power supply	1 200A x 50V (12-magnets)	
	2 200A x 50V (12-magnets)	

3 120A x 15V (6-11)

4 50A x 6V (6-11)

5.8 Accumulator Vacuum System

Diff between single + multiple Coulomb scattering?

5.8.1 Vacuum Requirements. The base pressure is determined by the effects of the residual gas on the accumulated antiproton beam. These effects include particle loss by single Coulomb scattering and nuclear interactions, beam heating by multiple Coulomb scattering, energy loss by ionization, and effects of neutralization by positive ions attracted to the negative beam.

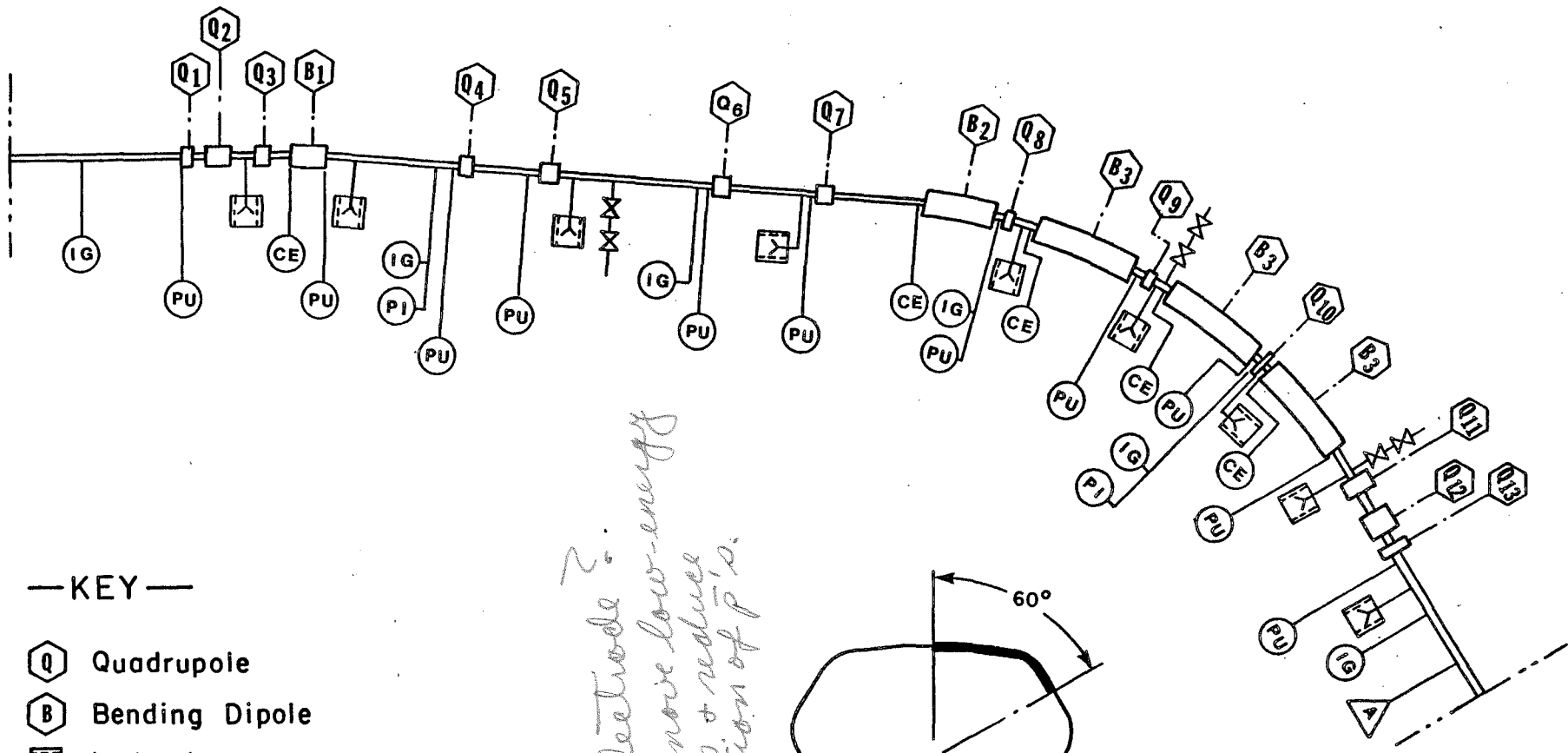
A detailed analysis has been made¹⁰ of these effects. As a result, the system is designed for a nominal pressure of 3×10^{-10} Torr (nitrogen equivalent). At this pressure, the single-scattering lifetime will be 240 hr and the nuclear-interaction lifetime will be 2000 hr. Thus these effects are negligible. The heating rate for the final stack from multiple scattering will be 2×10^{-5} /sec, 10 times less than the cooling rate. (Here a gas composition of 50% H₂, 50% N₂ or CO is assumed). The energy loss per antiproton will be 20 keV/hr. Both the heating and energy loss can be easily compensated by the stochastic-cooling systems. We will keep the nominal design value of the neutralization factor $H < 0.03$. With this value, the scattering by positive ions trapped in the beam will be increased less than 2%. The vertical space-charge tune shift will be reduced by 10^{-3} . Thus these neutralization effects are negligible.

5.8.2 Vacuum system layout and characteristics. The pressure requirement can be met with sputter ion-pumps. Furthermore vacuum-annealed austenitic high-tensile stainless steel will be used for the chambers so that specific degassing rates of better than 1×10^{-12} Torr- ℓ /cm⁻²-sec can be attained. The maximum design bakeout temperature is 300 C.

Figure 5-33 shows the vacuum-system layout over one-sixth of the Accumulator ring. The sputter ion pumps should have a speed of 200 ℓ /sec. The stochasting cooling P.U. and kickers will be isolated with all metal valves, during the bakeout, to prevent any vacuum contamination. These valves will divide the ring into about 5 irregular vacuum sectors.

The baking equipment (heaters, controls, thermal insulation) will be installed in a permanent fashion to allow bakeout to proceed without major preparations. Exceptions are areas that cannot tolerate the high temperature; e.g., pump magnets, cable feedthroughs and special devices.

Pump-down during bakeout will be carried out using mobile turbopump sets with liquid-nitrogen cold traps. This will allow the use of a large number of pumps in any given section being baked. These carts will be connected to metal valves distributed for that purpose throughout the system. Tests indicate that the pressure during bakeout has little effect on the success of the bake.



— KEY —

- Q Quadrupole
- B Bending Dipole
- ☒ Ionisation Pump 200 l/s
- ▲ Gas Analyser
- PU Beam Position Pick-Up Electrode
- CE Clearing Electrode
- IG Ionisation Gauge
- PI Pirani Gauge
- ☒☒ Port for Mobile Pump Station

*clearing electrode?
used to remove low-energy
positive ions & reduce
neutralization of p's.
CE is inserted
before each
dipole.*

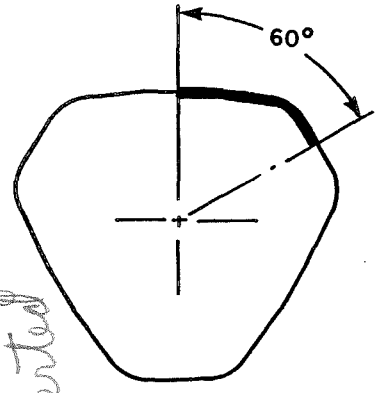


Figure 5-33

Vacuum gauges include 6 Pirani gauges to monitor pumpdown, 36 Bayard-Alpert ionization gauges, and 6 mass-analyzer heads, located near areas of complex equipment to monitor leaks and contamination.

The arrangement has not been completely specified for the straight sections where the stochastic cooling equipment is located. The equipment will be capable of being baked at a maximum temperature of 150 C and materials compatible with the high vacuum requirements will be used. Cryogenic pumping techniques may be used to provide a pumping speed of up to 2000ℓ/sec/m.

Clearing electrodes will be installed to remove low-energy positive ions and thus keep the neutralization factor $H < 0.03$. There will be a pair of electrodes at the downstream end of each magnet. Ions move longitudinally to the electrodes by $\vec{E} \times \vec{B}$ drifting caused by the beam electric field and the ring guide field. This kind of system has been used successfully in the ISR.

The straight sections between magnets will also need clearing electrodes to avoid trapping ions in the cool-beam potential of 5 V. We plan to apply a dc potential of more than 5 V to the clearing electrodes and to the beam-position detector electrodes whenever these are in a suitable location.

All devices and ring sections will undergo a preliminary bake and low-pressure test before being installed. Their design will conform with strict rules of choice of material and will be subject approval by the vacuum coordinator.

The vacuum control system will be constructed along the design evolved for the Tevatron. It is highly modular and economical. Most of the required modules and device controls have already been developed, including ion pump supplies and ion gauge controllers. A card cage containing all control modules interfaces to the host computer through a CAMAC module. Much of the necessary software can be used or adapted.

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6. EXTRACTION OF ANTIPROTONS FROM THE ACCUMULATOR
AND TRANSFER TO THE MAIN RING

6.1 Accumulator Beam Manipulation and Extraction.

Prior to extraction of the first \bar{p} bunch, a nearly Gaussian distribution of \bar{p} 's will exist in the core. The density can be characterized by two numbers, the total number of \bar{p} 's in the core, N_0 , and the rms energy spread, σ . If ϵ represents the energy difference between the particle energy and the most probable energy of the particles in the core, then the density function $\psi(\epsilon)$ can be written as

$$\psi(\epsilon) = \frac{N_0}{(2\pi)^{1/2} \sigma} \exp\left(-\frac{\epsilon^2}{2\sigma^2}\right)$$

The example presented here uses the following values for these parameters; $\sigma = 2.0$ MeV, $N_0 = 4.5 \times 10^{11}$ and $\psi(0) = 10^5 \text{eV}^{-1}$. Because we want to extract an ensemble with the smallest longitudinal emittance, we begin the adiabatic capture with a bucket centered at the peak of the distribution. We plan to extract a single bunch containing 8×10^{10} \bar{p} 's. These \bar{p} 's exist within a range of ± 452.5 keV. The revolution period of the ring is 1.59 μsec , so the longitudinal emittance of the core region selected is 1.44 eV-sec. The Accumulator parameters which are used in this calculation are $\bar{R} = 75.4716$ m, $\eta = 0.02$, $E_s = 8.938$ GeV, and $\Delta p/p \approx 1.6\%$ ($\Delta p = 142$ MeV/c) from core to extraction orbit. Because η (i.e. $\gamma_t^{-2} - \gamma^{-2}$) varies over the aperture, the rf parameters determining bucket areas must be varied accordingly.

The rf voltage required to develop a single bucket of area 1.44 eV-sec at harmonic h is $V = 2.44 h^3$. At $h = 1$, only 2.44 V is required and it may be difficult to establish such a low voltage with sufficient precision to control accurately the number of \bar{p} 's extracted. We propose to extract using a single $h = 2$ bucket with the remaining bucket suppressed. The required rf voltage is 19.5 V. Following adiabatic capture, a moving bucket will be established for deceleration to the extraction orbit.

The time required for this unstacking process depends upon the choice of rf voltage and synchronous phase angle. In order to minimize both the disturbance of the stacked \bar{p} 's and the particle loss from the moving bucket, the bucket will be moved very slowly with a small phase angle. After the first \bar{p} bunch has been extracted and placed in the Tevatron at 150 GeV, the duration that this bunch is required to reside in the Tevatron at low field depends upon the time required to extract the remaining bunches from the core. If the lifetime at 150 GeV is not long enough, it may be necessary to accelerate the process. Optimization of this time can only be accomplished after the Energy Saver and the Antiproton Source are

$$\frac{1000}{1.59} (1000) = 1000 \quad 1.59 \sqrt{1000} = 10^6 \quad 1.59 \sqrt{100.000} = .63$$

$f_0 = .63 \text{ MHz}$ in 2
accumulator

operational. The rf voltage required to maintain the specified bucket area, the deceleration rate, and the time required for deceleration to the extraction orbit are shown in Table 6-I for several synchronous phase angles.

Table 6-I. RF PARAMETERS FOR DECELERATION TO THE EXTRACTION ORBIT
(CONSTANT BUCKET AREA 1.44 EV-SEC.)

ϕ_s (deg)	$\Gamma = \sin \phi_s$	$\alpha(\Gamma)$	V_{rf} (volts)	Decel. Rate (MeV/sec)	Decel. Time (sec)
10	0.1736	0.696	36.2	3.33	43
20	0.3420	0.4918	72	12.93	11
30	0.500	0.3334	157	41.1	3.5

Frequency and phase control of the rf system during unstacking may be improved by a phase-lock system that partially locks the system to the coherent component of beam current. Since this component of current is of order 10 mA, detection and phase locking should not be technically difficult. The bunch length during the unstacking process will be about 500 nsec.

When the bunch reaches the extraction orbit, the rf voltage is raised to 100 V, resulting in a total bunch length of 200 nsec or about 60 meters. Since the momentum spread $\Delta p/p$ of this bunch is 5.2×10^{-4} , it can easily be injected into the Main Ring. The h=2 suppressed bucket unstacking system is capable of producing a gap voltage of only 100 V, so the remaining 900 V is to be generated by a fixed frequency h=2 system at 1.26 MHz. This system will, of course, create two buckets but only one will be populated with antiprotons because of the prebunching of the suppressed-bucket system. The total 1000-V bucket height will be about 12 MeV or $\pm 0.13\%$, so these buckets will not adversely affect antiprotons remaining in the cooled core.

After the 200 nsec bunch is established at the extraction orbit, the extraction kicker shutter is closed, isolating the bunch from the remaining accumulated beam, and the single bunch is extracted and injected into the Main Ring.

Movement of the extraction bucket through part of the stack is a form of displacement acceleration resulting in partial replacement of some of the \bar{p} density in the core. Moreover, the cooling system will very quickly fill the depleted region left by the extracted bunch. During subsequent acceleration of the extracted bunch to 150 GeV and prior to the next extraction, core cooling systems will re-establish a \bar{p} density in the core that is adequate for extraction.

The single-bucket rf wave consists of one complete sinusoidal wave with a period of one-half the rotation period. Because the fundamental frequency is 0.632 MHz, such a wave can easily be generated with Fourier components below 100 MHz. The accelerating structure may consist of an insulating gap in the beam pipe in parallel with a 50- Ω resistance of sufficient power-dissipating capability. This structure will be contained within a shielded enclosure with sufficiently high shunt inductance (introduced by high-permeability ferrite) so that the load presented to a broad-band amplifier will be essentially real over the operating range. The power requirements will be less than 100 W. The 50- Ω real impedance presented to the beam by this structure is well within the longitudinal-stability impedance limit.

The additional 900 V at $h=2$ is required only at a single frequency at the extraction momentum. It will be developed by a single ferrite-loaded resonant accelerating cavity with a shunt impedance of 2 k Ω . This shunt impedance meets the beam-stability requirement and the required voltage can be developed with an excitation power of 200 W.

Extraction from the Accumulator occurs using a 2.1336 m long shuttered kicker and a 2.921 m long Lambertson extraction septum. The extraction orbit is rf displaced radially outward to 0.775% in $\Delta p/p$. At point A20 in the high dispersion straight section (see Fig. 5-29) the extraction closed orbit is displaced to 76.7888 mm outward. The orbit parameters are $\beta_x=11.27$ m, $\beta_y=8.91$ m, and $\alpha_x=\alpha_y=0$. The shuttered kicker is centered 6.32 m downstream of point A20; an inward kick of 2.0 mr moves the extraction closed orbit to $x=38.571$ mm and $x'=-2.771$ mrad at the entrance to the Lambertson extraction septum. Figure 6-1 shows the extraction orbit from the kicker center to the Lambertson entrance. At this point the orbit parameters are found to be $\beta_x=20.5$ m, $\beta_y=6.056$ m, $\alpha_x=2.152$, and $\alpha_y=0.692$ relative to the closed orbit. The Lambertson extraction septum then bends the beam up by 100 mrad.

An achromatic translation system restores the extracted beam to target height ($\Delta z=+48$ inches). Then the beam is taken through four modules consisting of: (i) long transport, (ii) left bend, (iii) long transport, and (iv) target bypass. Following this, the beam rejoins the 120 GeV proton line just downstream of quadrupole PQ7B and is reverse-injected into the Main Ring at F17. The orbit parameters are identical for 120-GeV protons and 8-GeV antiprotons at the notch point, the downstream end of PBV2: they are $\beta_x=22.78125$ m, $\beta_y=117.9955$ m, $\alpha_x=1.2588$, and $\alpha_y=6.68625$.

The long transports use quadrupoles in a 90° FODO channel and matching lenses. The periodic structure uses a cell length of 166.73 feet with $\beta_{\max}/\beta_{\min}=86.5716$ m/14.9158 m. The left bend uses three dipoles for a 18.462° bend. The long transport (iii) parallels the long transport carrying the hot p to the Debuncher. The target bypass is an achromatic transport using three dipoles and three quadrupoles. Figure 6-2 shows the behavior of the monoenergetic β_y , β_x , η_y , and η_x functions through the extraction system, starting at the Lambertson and ending at the downstream end of PBV2. The sections are explicitly indicated below in Fig. 6-2.

KICKED EXTRACTION ORBIT IN ACCUMULATOR

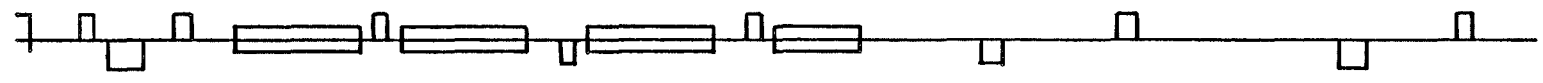
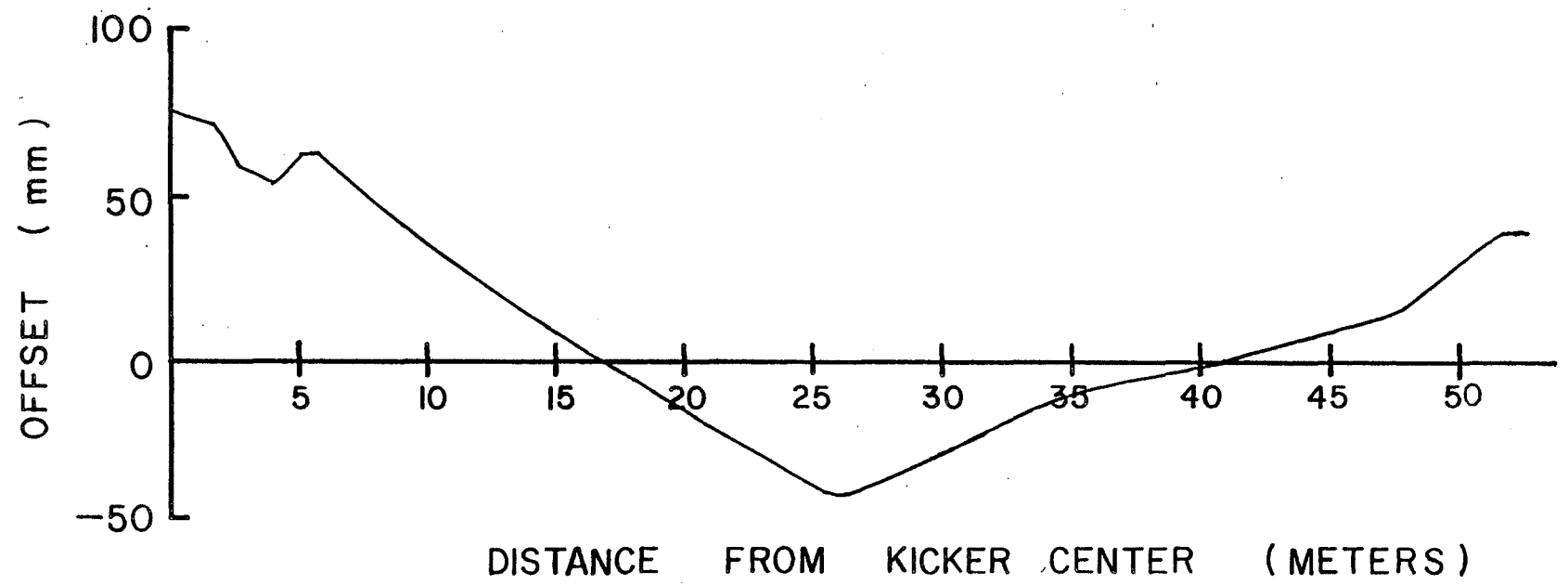


Fig. 6-1

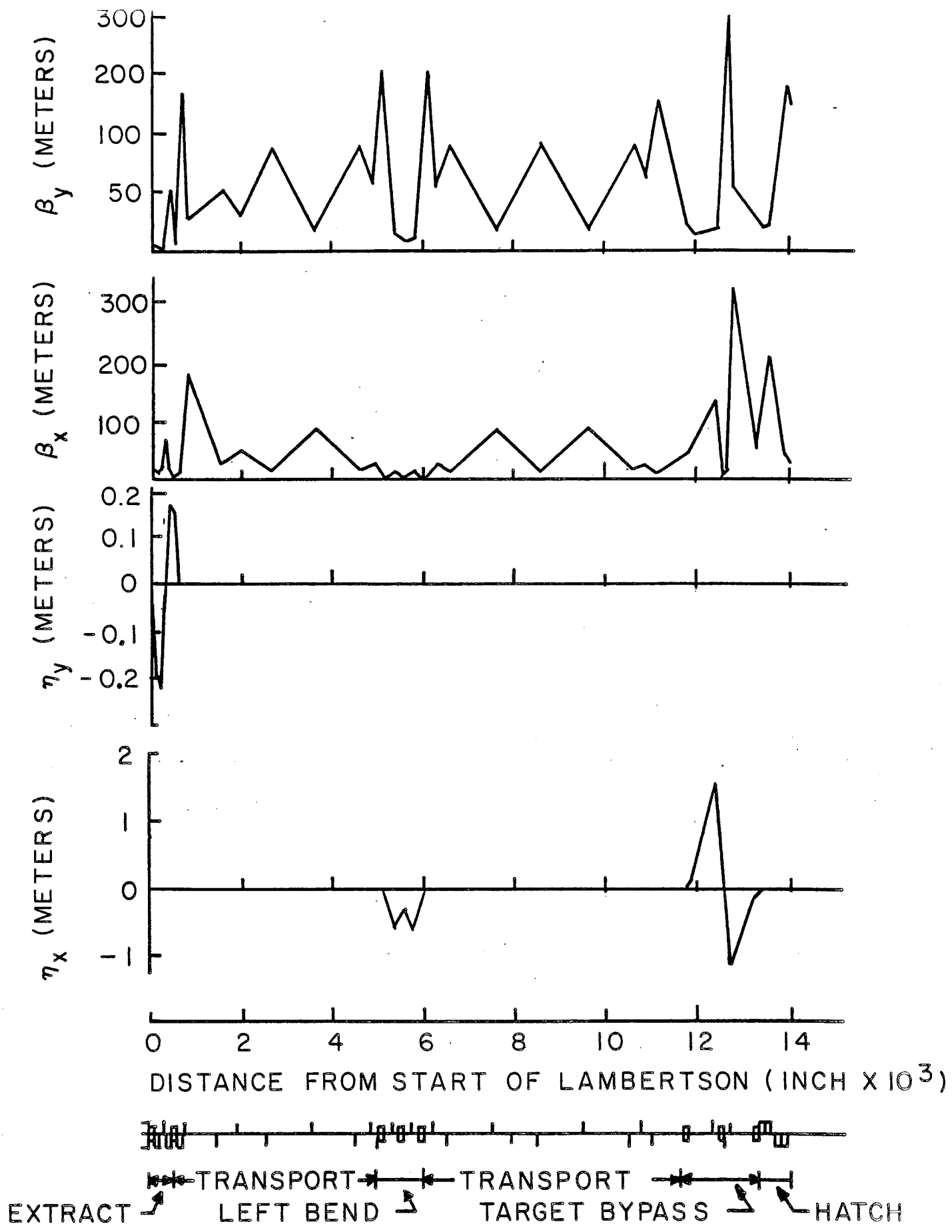


Fig. 6-2

Table 6-II list the antiproton transport line elements from the Accumulator to the match point in the proton extraction line (EB6).

Table 6-II

Beam Transport Accumulator to Target Bypass AP-3

X,Y,Z Site Coordinates

Coordinates given at end of element (toward target)

Main Ring Station A0 at X=0.0, Y=0.0

NAME	LENGTH (IN)	FIELD (KG KG/M)	X (FT)	Y (FT)	Z (FT)
ACCUMULATOR RING					728.500
E-LAMBERTSON	115.00	10.15	-117.122	-1350.941	728.979
EQ1	70.00	-127.48	-112.527	-1357.542	729.786
EQ2	50.00	127.48	-106.606	-1366.049	730.826
EQ3	85.90	-127.48	-100.057	-1375.455	731.976
EBV1	75.00	15.56	-95.285	-1382.312	732.500
EQ4	50.70	-131.44	-91.314	-1388.015	732.500
EQ5	22.50	131.44	-85.482	-1396.394	
EQ6	27.60	-51.90	-52.235	-1444.157	
EQ7	20.80	36.31	-30.981	-1474.690	
EQ8	18.00	-36.31	-0.404	-1518.617	
EQ9	18.00	36.31	47.223	-1587.038	
EQ10	18.00	-36.31	94.850	-1655.459	
EQ11	18.00	118.68	110.006	-1677.231	
EQ12	18.00	-121.20	118.763	-1689.812	
EB1	98.42	12.85	124.946	-1697.918	
EQ13	27.60	121.20	134.665	-1709.080	
EB2	98.42	12.85	148.585	-1724.389	
EQ14	27.60	121.20	159.453	-1734.434	
EB3	98.42	12.85	174.946	-1748.148	
EQ15	18.00	-121.20	177.758	-1750.231	
EQ16	18.00	118.68	190.075	-1759.355	
EQ17	18.00	-36.31	211.388	-1775.146	
EQ18	18.00	36.31	278.371	-1824.774	
EQ19	18.00	-36.31	345.353	-1874.403	
EQ20	18.00	36.31	412.335	-1924.032	
EQ21	18.00	-36.31	479.317	-1973.660	
EQ22	22.50	58.46	497.168	-1986.886	
EQ23	18.00	-61.65	511.765	-1997.698	
EB4	98.42	12.42	561.916	-2035.391	
EQ24	22.50	142.71	596.212	-2066.856	
EB5	75.00	12.22	608.552	-2078.510	
EQ25	27.60	-142.61	611.629	-2081.812	
EQ26	32.00	142.26	617.027	-2087.606	
EB6	75.00	12.22	652.141	-2124.948	732.500
EQ27	120.00	11.02	661.097	-2133.163	

$$\frac{1113}{53} = 83 \frac{21}{100}$$

$$\begin{array}{r} 2.5148 \\ \underline{21} \\ 2.5148 \\ \underline{50.2960} \\ 5444 \end{array} = 52.8108$$

EQ27 IS THE SAME MAGNET AS PQ7B IN THE 120 GEV PROTON TRANSPORT LINE
 (*) FIELD VALUES ARE FOR POSITIVE BEAMS.

6.2 Main Ring RF Capture and Acceleration

6.2.1 Introduction. We describe here the management of a single 1.5 eV-sec \bar{p} bunch in the Main Ring. The Main Ring is not capable of accelerating such a large emittance in a single bunch without excessive particle loss. For this reason, the bunch is broken up into several (5 or 7) adjacent bunches, accelerated to 150 GeV, and reconstituted into a single bunch at 150 GeV.

$$h = 53 \text{ is } \frac{1}{2} \text{ the freq. at } h = 1113$$

$$\frac{2.5148}{52.8108}$$

6.2.2 Injection and Rebunching. The \bar{p} bunch, about 200 nsec in length, is injected into a matched bucket in the Main Ring at $h=53$. The frequency is 2.5148 MHz and the bucket length, or period, is 397.6 nsec. By locking the phase of the Main Ring rf to that of the Accumulator the \bar{p} bunch can be injected accurately into the Main Ring bucket. The required bucket height is 6.5 MeV, requiring 3300 volts at 2.5148 MHz.

After injection, the $h = 53$ rf voltage is raised adiabatically to 15.5 kV so that the bunch length shrinks to 132.5 nsec, which spans exactly 7 'normal' $h = 1113$ rf periods in the Main Ring. With the bunch held at this length by the $h = 53$ rf voltage, the $h = 1113$, 52.813 MHz voltage is raised adiabatically so that the bunch is rebunched into seven bunches. The bunch with the largest area, located at the center of the ensemble of bunches, has a longitudinal emittance of about 0.3 eV-sec. This can be accelerated easily in the Main Ring. This rebunching process is shown in Figs. 6-3 through 6-5 for a uniform initial distribution in the $h = 53$ bucket. After capture in $h = 1113$ buckets, the ensemble of seven adjacent bunches is accelerated to 150 GeV.

The longitudinal phase space area is expected to increase by a factor 1.5 during acceleration. Recent studies in the Main Ring and careful simulation of transition crossing indicate that bunches with initial longitudinal emittance in the range of 0.2 to 0.3 eV-sec are diluted by a factor of about 1.25 between injection and $\gamma=21$, above transition. This dilution is accompanied by a slight bunch-to-bucket mismatch so that further dilution resulting from coherent bunch motion within the bucket results in total dilution during acceleration of about a factor of 1.5.

6.2.3 Bunch Recombination at 150 GeV. At 150 GeV, the Main Ring field is held on flat top while the seven adjacent bunches are coalesced into a single bunch. The $h=1113$ rf voltage is reduced slowly over a period of 0.1 seconds to about 12 kV by counterphasing equal numbers of rf cavities. With this voltage the bucket containing the center bunch is nearly full. Adjacent buckets are not quite full and the total longitudinal emittance of all the bunches is about 2.2 eV-sec. At this time the $h=53$ rf system is turned on at a voltage level (700 V) such that the $h=53$ bucket is matched

H=53 BUNCH OF 1.5 EV_S AT 8 GEV IN M R TURN # 0
 HBCKT 1.48E+01 [MV], SBCKT 7.46E+00 [EV-S], ES 8.9383E+03 [MV], NUS 3.62E-04
 OPDT 0. CMEV/S], THS 0. [RAD], THFP 5.927533E-02 [RAD]
 EV1 1.679E-02 [MV], EV2 1.000E-02 [MV], H1 53., H2 1113., ETA -8.17492E-03

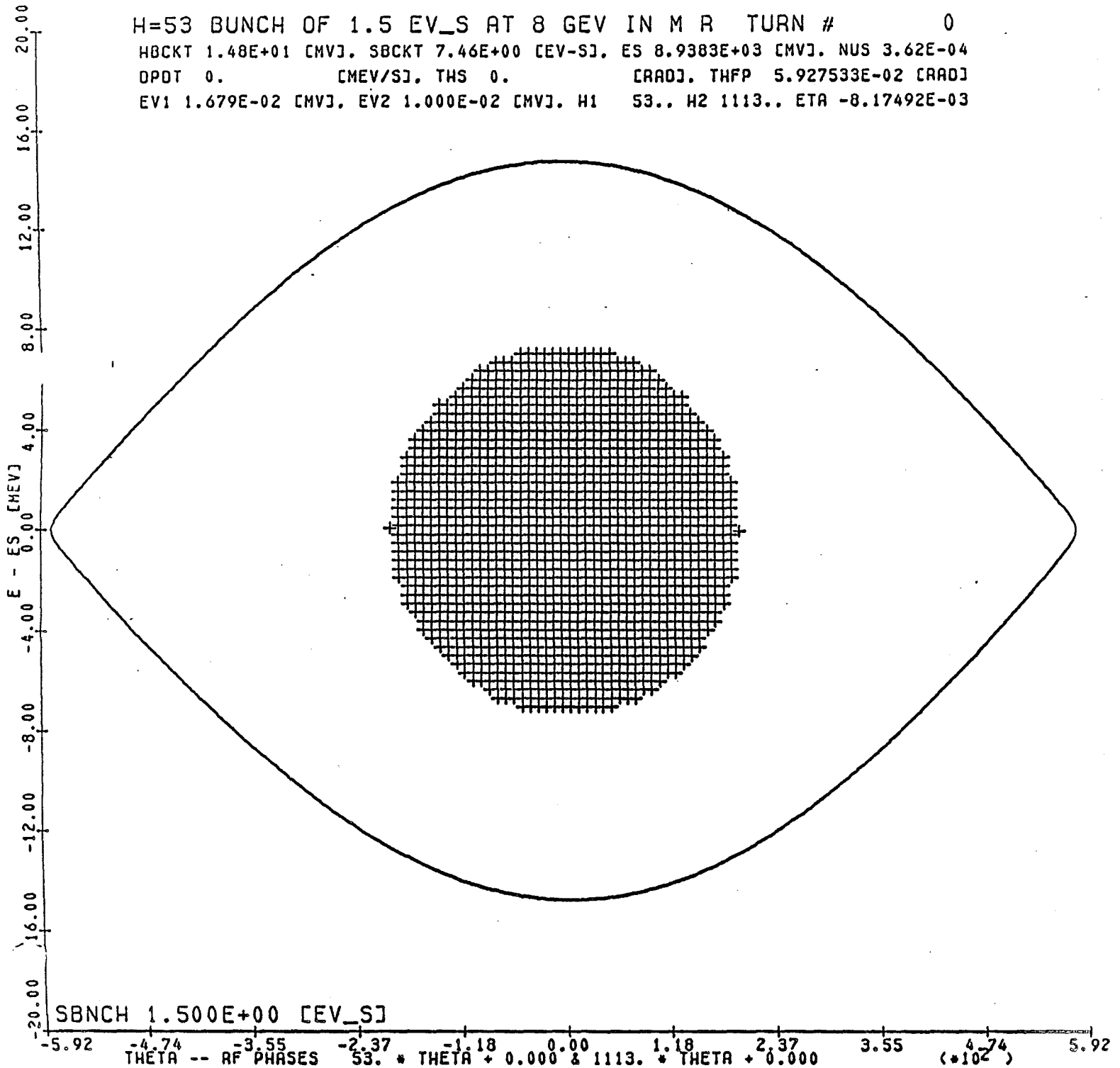


Figure 6-3 Uniform distribution of antiprotons with longitudinal emittance 1.5 eV-sec matched to h=53 bucket in Main Ring. The bunch covers a time span of about 133 nsec, or seven h=1113 stationary bucket lengths.

ADIABATIC CAPTURE AT H=1113 FROM H=53 BUTURN # 1509
 HBCKT 5.15E+00 [MV], SBCKT 1.24E-01 [EV-S], ES 8.9383E+03 [MV], NUS 2.65E-03
 DPDT 0. CMEV/S], THS 0. [RAD], THFP 2.822635E-03 [RAD]
 EV1 1.679E-02 [MV], EV2 4.296E-02 [MV], H1 53., H2 1113., ETA -8.17492E-03

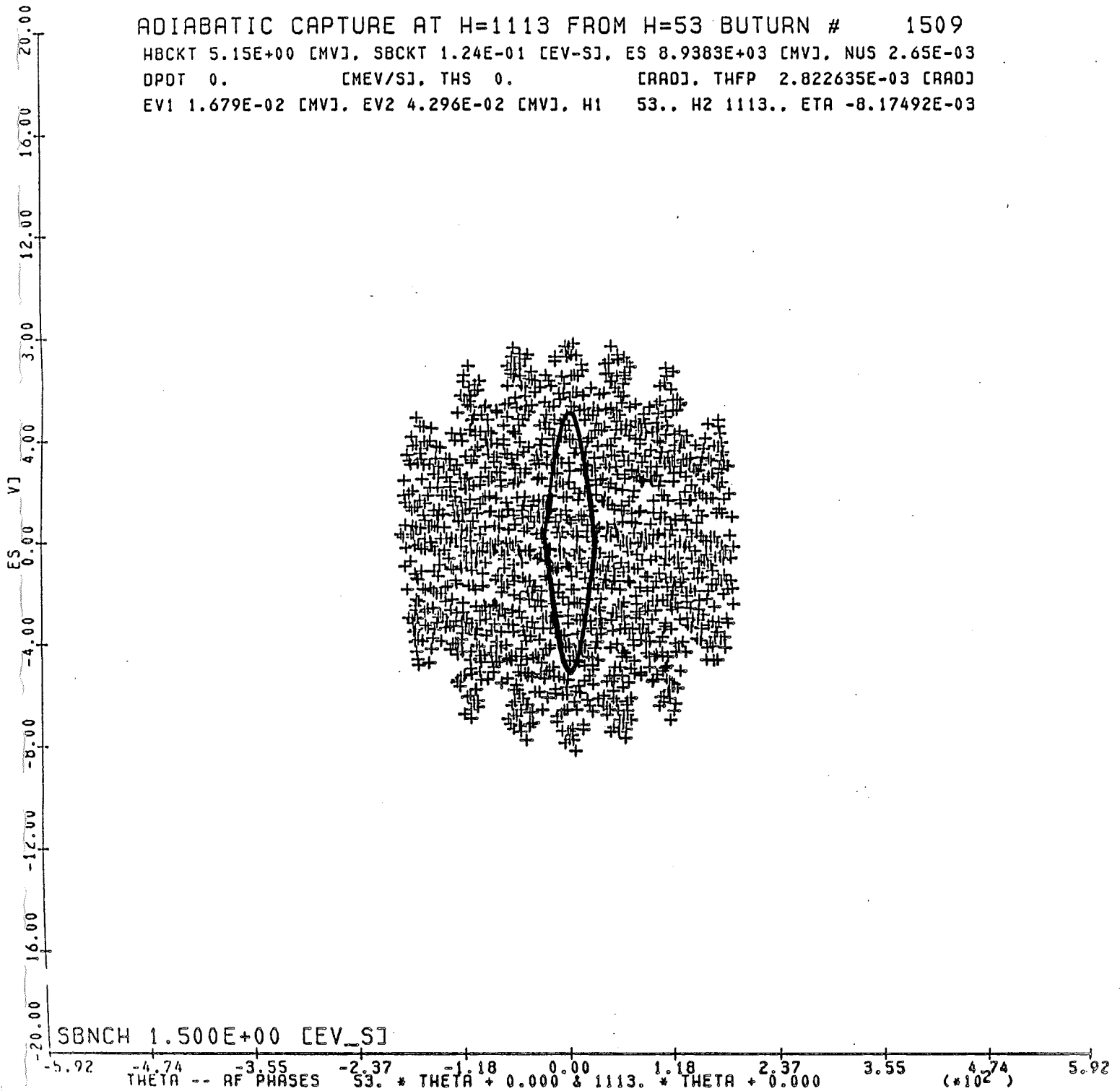


Figure 6-4 Antiproton distribution within an h=53 bucket partially bunched at h=1113 after 1509 turns. The h=1113 bucket size is shown for the center bucket.

FINAL H=1113 BUNCHES

TURN # 2499

HBCKT 1.75E+01 [MV]. SBCKT 4.22E-01 [EV-S]. ES 8.9383E+03 [MV]. NUS 9.03E-03
 OPDT 0. [MEV/S]. THS 0. [RAD]. THFP 2.822635E-03 [RAD]

EV1 1.679E-02 [MV]. AV2 4.976E-01 [MV] H1 53. H2 1113. ETA -8.17A92E-03

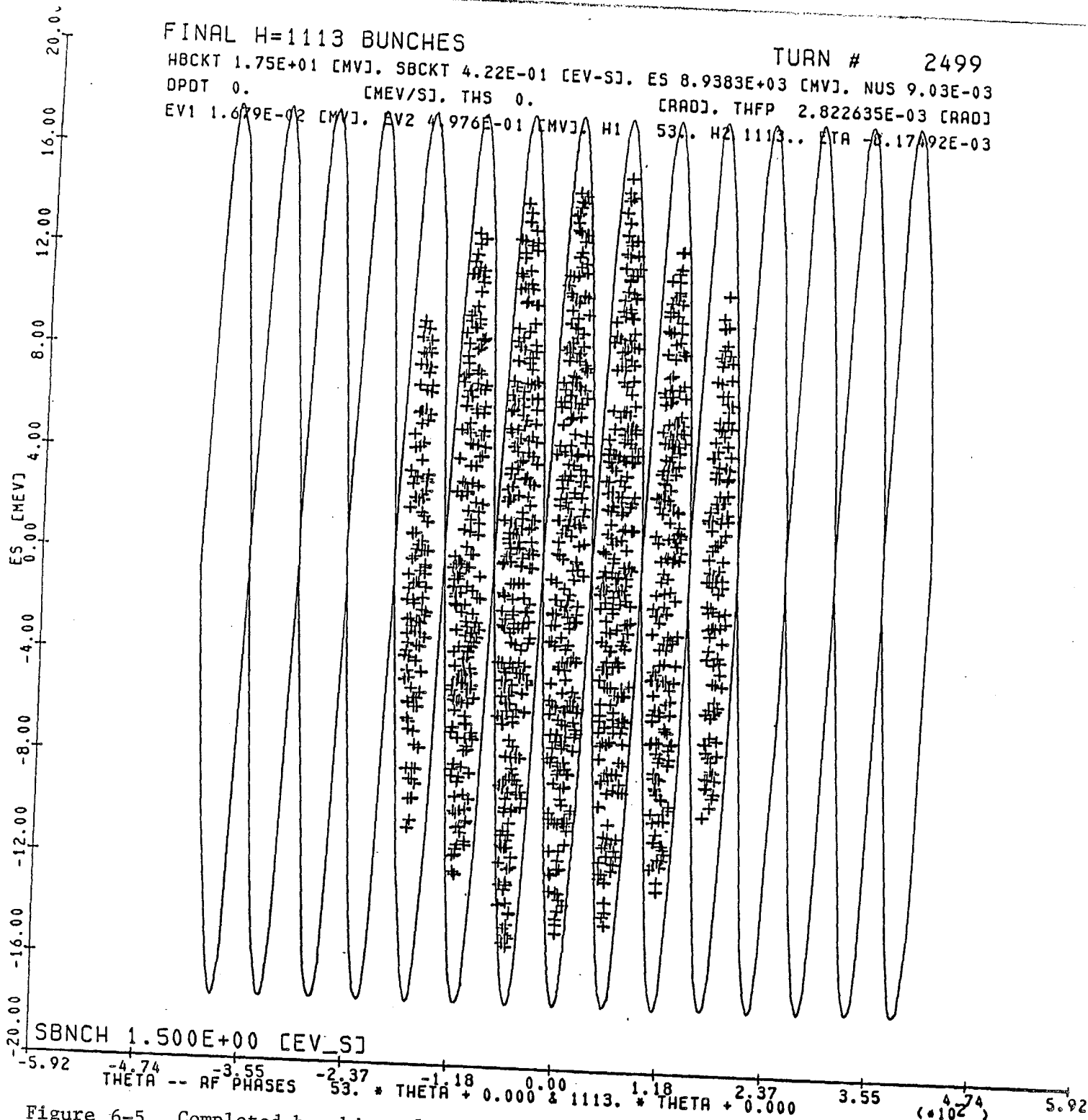


Figure 6-5 Completed bunching of antiprotons within seven adjacent h=1113 buckets. The center bunch has longitudinal emittance of 0.32 eV-sec and the sum of all emittances is 1.6 eV-sec.

to a 2.2 eV-sec distribution extending over the filled $h=1113$ buckets, 132 nsec. At the same time the counterphased Main Ring rf voltage is turned off and replaced by a single small $h=1113$ rf cavity at 12 kV. The voltage of this cavity is then lowered slowly to (nominally) zero so that the seven adjacent bunches are adiabatically debunched into matched orbits in the $h=53$ bucket. A simulation of this process, starting with bunch distributions derived from previously simulated acceleration is shown in Figs. 6-6 through 6-8. The result is a uniform bunch of about 2.4 eV-sec matched to the $h=53$ bucket and spanning a range $\pm\pi/3$.

At this point, the $h = 53$ rf system is suddenly raised to a level of about 65 kV while the $h = 1113$ voltage is removed. The low-momentum p bunch, which extends over $7/21$ (or $\pm\pi/3$) of the $h = 53$ bucket, now begins a coherent synchrotron motion into a vertical strip. Since the charge does not extend far into the bucket, this motion is quite linear. After slightly more than one-quarter of a synchrotron-oscillation (about 0.11 sec or 5200 turns), the $h = 53$ voltage is removed and the vertical distribution is recaptured in an $h = 1113$ bucket of a size chosen to match accurately the rotated distribution. The re-applied voltage will create a bucket height of about 125 MeV and the p's (or p's) are expected to fill this bucket, so the final p bunch longitudinal emittance is as large as 3 eV-sec. The $h = 1113$ rf voltage required for this is 500 kV.

In Fig. 6-9, we show the results of a preliminary experiment in bunch coalescing. The experiment is done at $h = 159$ using four adjacent proton bunches. The successive oscilloscope traces starting at the bottom of the pictures show two or four proton bunches merging into a single bunch of larger intensity and emittance, as expected. Since the bucket covered only seven $h = 1113$ bucket lengths, the four bunches extended farther into the bucket than is proposed. This results in a more nonlinear process than will occur in the proposed scheme.

The same sequence could also be done with ensembles containing more bunches or fewer bunches. If nine adjacent bunches were accelerated each bunch would have smaller longitudinal emittance and less dilution would occur during acceleration. Unfortunately the ensemble would extend further into the $h=53$ bucket and the rotation process would be subject to greater nonlinearity. For five bunches the converse would be true. The optimum number of bunches to be accelerated will be determined experimentally when the commissioning begins.

Following recapture, the rf voltage is raised to 1 MV. As a result, the bunch length shrinks to 12 nsec full width, and the bunch height grows to ± 166 MeV, corresponding to a momentum spread $\Delta p/p$ of $\pm 1.1 \times 10^{-3}$. The bunch parameters are ideal for injection into pre-established matching buckets in the Tevatron.

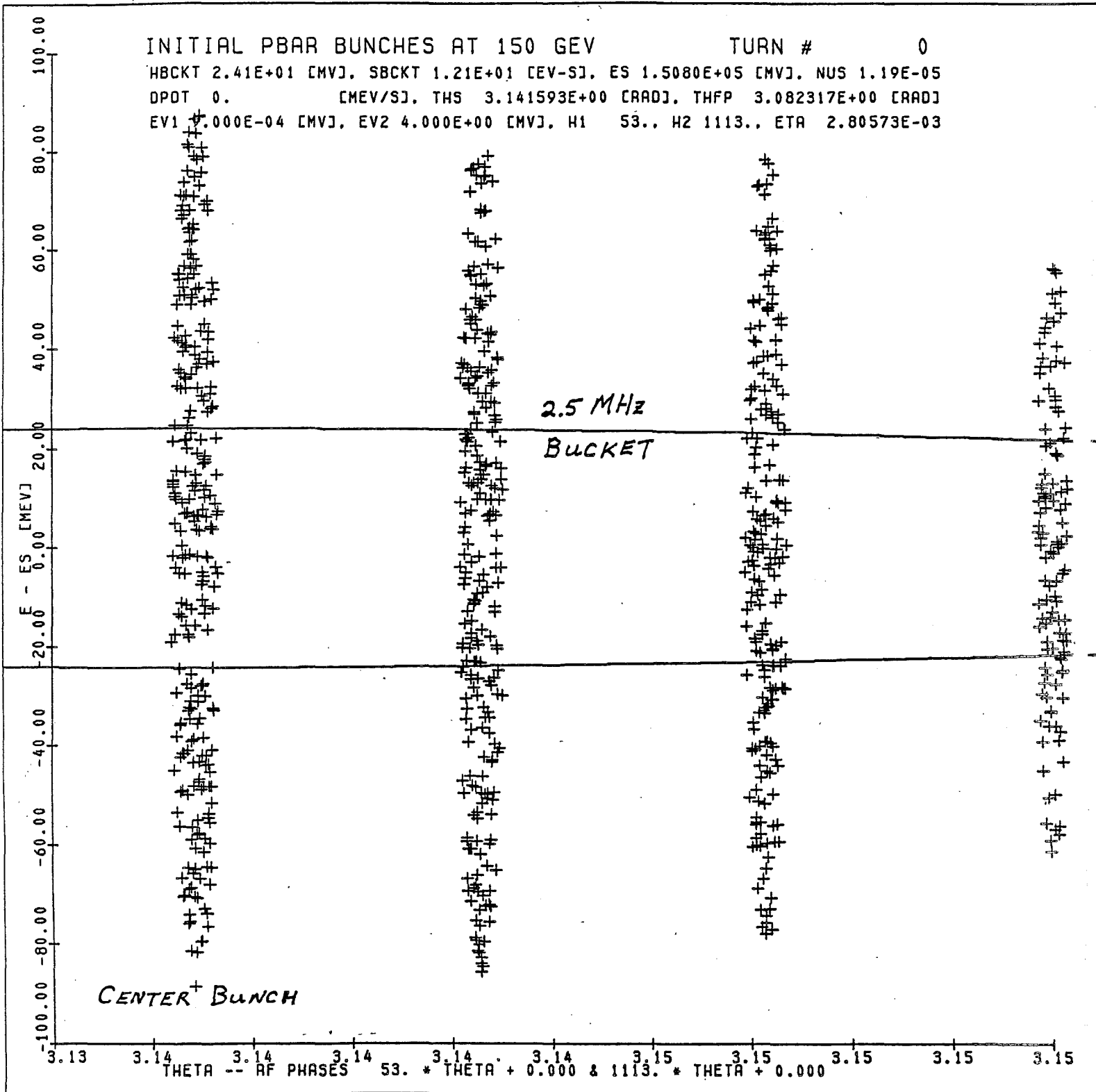


Fig. 6-6 Adjacent antiproton bunches in matched h=53 bucket prior to final h=1113 debunching.

H=53 BUNCH OF PBARS AT 150 GEV/C TURN # 23858
 HBCKT 2.41E+01 [MV], SBCKT 1.21E+01 [EV-S], ES 1.5080E+05 [MV], NUS 1.19E-05
 DPOT 0. CMEV/S], THS 3.141593E+00 [RAD], THFP 3.082317E+00 [RAD]
 EV1 9.000E-04 [MV], EV2 1.000E-06 [MV], H1 53., H2 1113., ETA 2.80573E-03

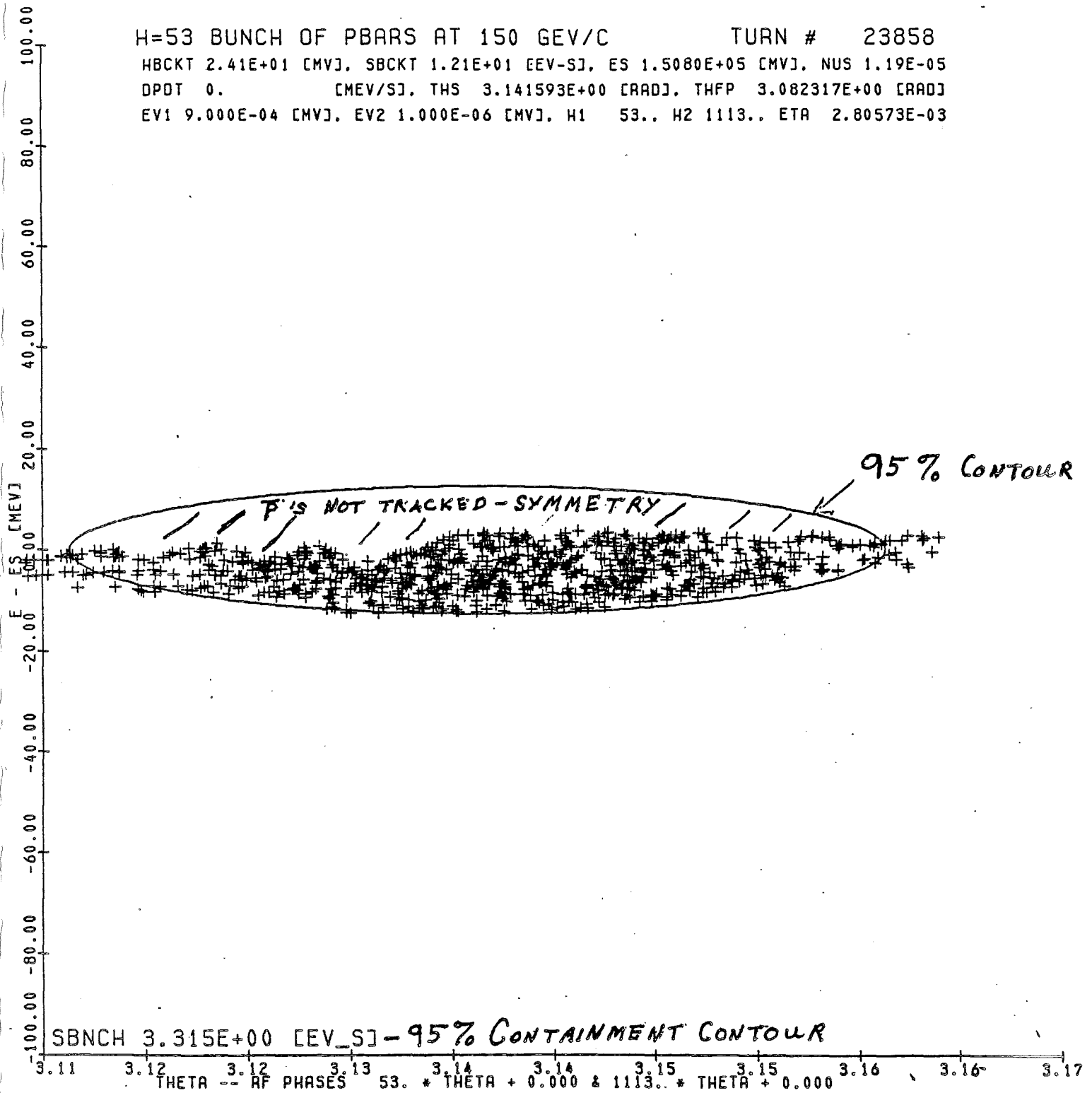


Fig. 6-7 Antiproton distribution within h=53 bucket following adiabatic removal of h=1113 rf voltage. The bunch extends over a range $\pm\pi/6$ radius within the bucket and the longitudinal emittance (95%) is 3.3 eV sec.

ROTATED PBAR BUNCH AT 150GEV/C

TURN # 26559

HBCKT 2.00E+02 [MV]. SBCKT 1.00E+02 [EV-S]. ES 1.5080E+05 [MV]. NUS 9.86E-05
DPDT 0. [MEV/S]. THS 3.141593E+00 [RAD]. THFP 3.082317E+00 [RAD]
EV1 6.200E-02 [MV]. EV2 1.000E-06 [MV]. H1 53.. H2 1113.. ETA 2.80573E-03

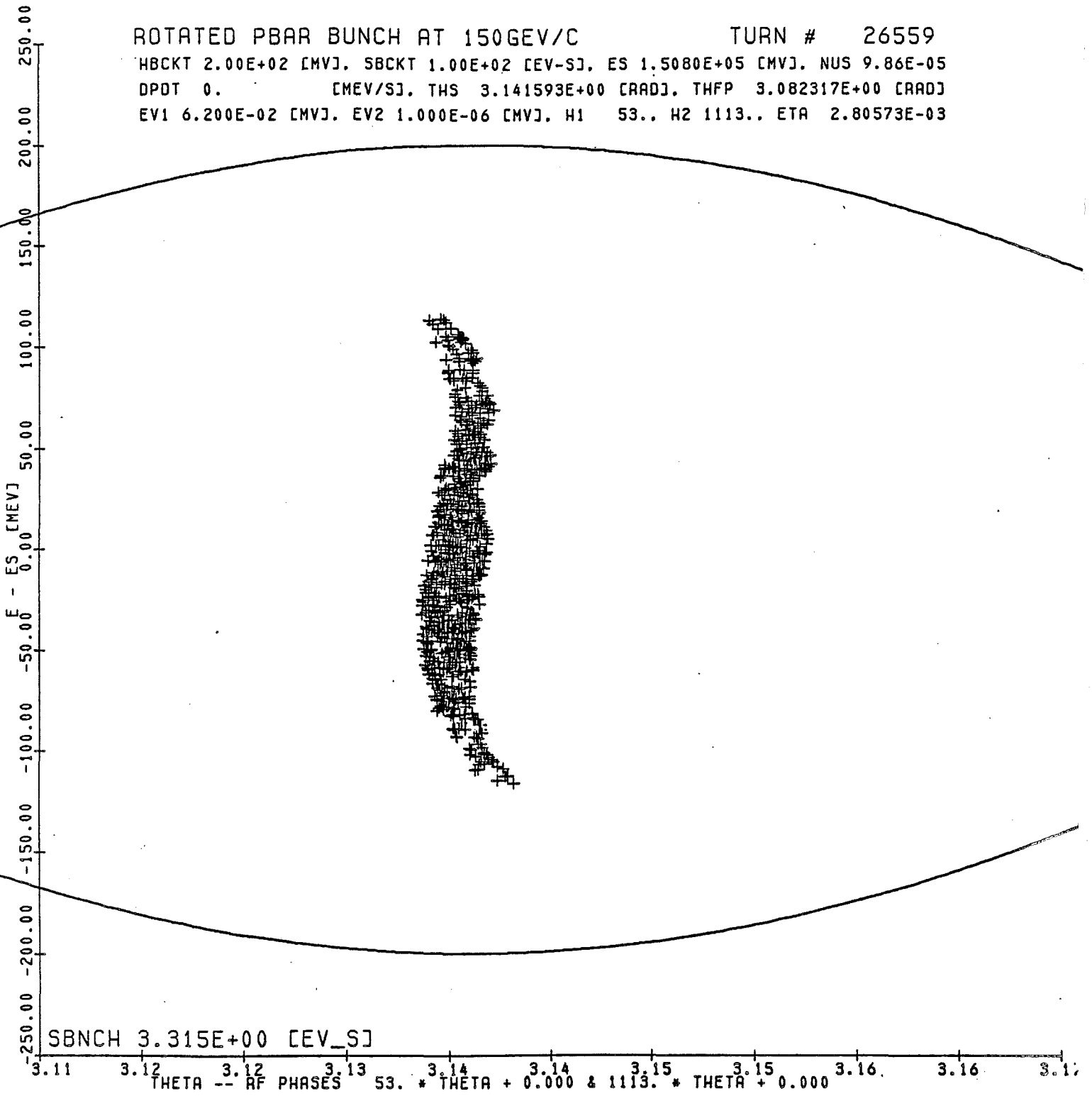


Fig. 6-8 Antiproton distribution following bunch rotation in h=53 bucket.

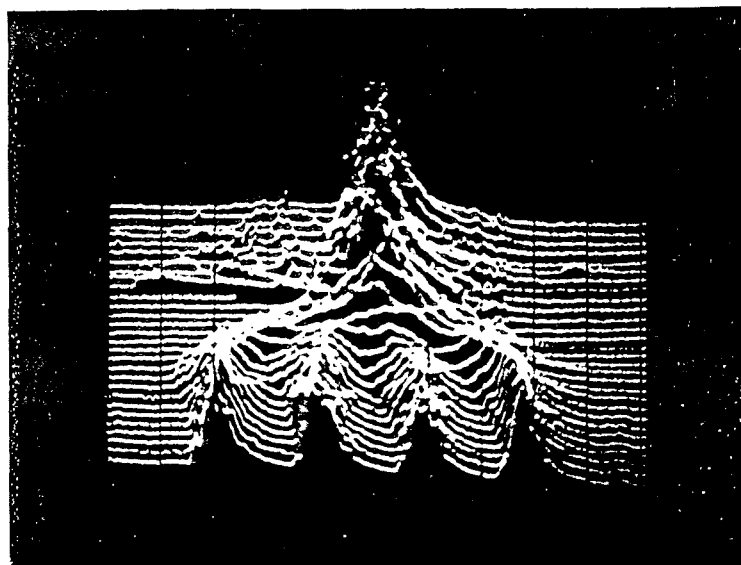
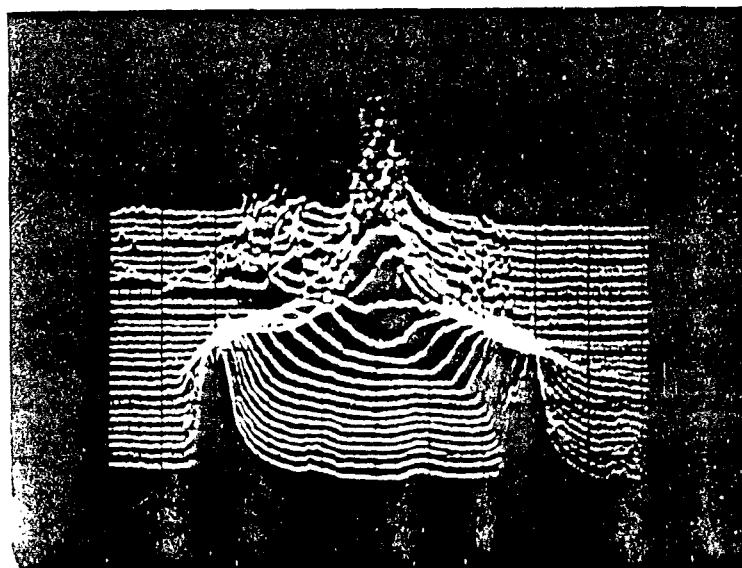


Fig. 6-9 Results of an early experiment in combining adjacent 53 MHz bunches in a lower harmonic bucket. The experiment was done at $h=159$ (7.5 MHz) where the lower harmonic bucket spans seven buckets. In the top picture two bunches, separated by two empty buckets are coalesced. In the bottom picture, four adjacent bunches are coalesced into a single bunch. Time progresses upward in each picture.

7. THE MAIN RING IN TEVATRON I

7.1 Functions of the Main Ring in Tevatron I

The Main Ring is required to perform five separate functions in the Tevatron I mode.

1. Acceleration of protons for antiproton production. During antiproton production and accumulation, the Main Ring will be required to accelerate single batches of protons (approx. 83 bunches) of intensity greater than 2×10^{12} protons per batch to 120 GeV. This will be done routinely on a 2-sec. cycle. Each of these acceleration cycles must include the bunch narrowing technique and extraction at F17 described in Chapter 2.

During this mode of operation, a special low-level rf system must be used. This system will contain provision for transient beam-loading compensation and rf-cavity counterphasing. In addition, the technique for phase-locking the Main Ring to the Booster will be slightly different than that used during fixed-target operation.

2. Injection of \bar{p} 's from the Accumulator into the Main Ring. Bunches of antiprotons containing 10^{11} \bar{p} 's must be transported to the Main Ring and injected.

3. Acceleration of antiprotons to 150 GeV. After a sufficient number and density of antiprotons have been established in the Accumulator, the Main Ring must be used to accelerate small ensembles of antiproton bunches to 150 GeV. This acceleration cycle must include the bunch manipulations at 8 GeV and at 150 GeV described in Sections 6.1 and 6.2. Special additions to the rf systems will be required to accomplish these manipulations. Following these acceleration cycles, the single antiproton bunches must be extracted at E0 for injection into the Tevatron.

4. Acceleration of protons to 150 GeV. The Main Ring will be required to accelerate small ensembles of protons to 150 GeV, where they will be combined to form single proton bunches containing 10^{11} protons. This operation will be similar in many respects to the antiproton acceleration described above and the same special additions to the rf systems will be utilized.

5. Transfer of particles from the Main Ring into the Doubler. Transfers of 150 GeV protons and antiprotons are both described in Chapter 8.

7.2 Antiproton Injection

The antiproton bunches from the Accumulator are matched into the proton extraction line at EB5. They are then transported back down the 120-GeV extraction line and injected into the Main Ring at the F17 Lambertson. Special low current power supplies are used to power the 120-GeV extraction line to ease regulation problems caused by running large power supplies at 5% levels.

The C48 kicker is also too strong for the reverse injection of the antiprotons at 8 GeV, thus an additional small kicker located at F14 needs to be added. The kicker is a 25 inch long ferrite (tape-wound steel) 380 gauss magnet with a rise and fall time of 20 μ sec. The gap is 5x3 inches (HXV) and the required current is 2280 amps. When fed by 400 feet of 5 parallel RG213's as a simple L-C discharge circuit, the required capacitance is 23 μ F and the required discharge voltage is 1165 volts.

7.3 Main Ring Acceleration and Rebunching Hardware

The processes of accelerating small groups of protons and cooled antiprotons to 150 GeV has been described previously in Chapter 6. In those descriptions reference was made to an rf system in the Main Ring operating at $h=53$ (2.515-2.529 MHz) and providing about 65 kV. This requirement will be met by installing two heavily ferrite-loaded rf cavities, each operating at the 20 kW level. These cavities will be refurbished and slightly modified cavities from the Princeton Pennsylvania Accelerator (PPA). Operation of these cavities in the Main Ring will require installation of an anode power supply of about 8 kV, 15 A (120 kW). Small additions to the low-level rf system will also be required to provide appropriate rf driving signals phase-locked to the integrally related $h=1113$ 53 MHz rf.

Small additions to the control system will also be required for remote operation of these systems.

7.4 Main Ring Overpass

The performance of both the Antiproton Source and the Collider Detector can be significantly improved by bypassing the Main Ring beam around the Collider Detector. This bypassing - called here the "Overpass" - has at least two advantages:

- (i) It allows elimination of the asymmetric hole for the Main Ring through the Collider Detector;
- (ii) It allows accumulation of antiprotons to proceed simultaneously with colliding-beam operation. This will increase the average luminosity of the entire system by eliminating the pause of several hours while the antiproton beam is being refreshed.

The design of an overpass for the Main Ring has been worked out in detail by T.L. Collins and is presented here. There are a number of constraints that such a design must satisfy:

- (a) Space must be generated for additional bending elements;
- (b) The new path must close smoothly on to the old path to high precision in both horizontal and vertical dimensions and at all energies with a minimum of programmed external control.
- (c) The path lengths must be the same in old and new paths, or differ by an integral number of rf wavelenths;
- (d) the betatron functions must match, as in any insertion;and
- (e) Any residual dispersion introduced outside the bypass must be negligibly small.

The bypass design limits Main Ring operation to 200 GeV or less. Some magnets are operated at twice the normal field. Consider a set of four bending magnets. The outer two magnets will be unchanged to provide the normal horizontal bend. The inner magnets will be rolled about the beam axis to produce a vertical bend of 32.471 mrad. Such four-magnet sets placed symmetrically around the long straight section (for example, at A41 and B12) will produce a 19-ft vertical separation, enough to miss the entire detector. The new orbit connects smoothly on both ends. A total of four sets (16 magnets) is in the additional circuit. The additional excitation of this circuit will be provided by a separate power supply.

The bypass has approximately 8 in. of extra orbit length. This undesired length is cancelled by combining the vertical bends with a slight inward bend to "cut across" the arc. The inward bend can be accomplished easily by a small inward roll of the vertical-bend magnets.

The betatron functions are easily matched across the insertion. The vertical dispersion introduced in the remainder of the ring must be balanced with some care. It has been reduced by this balancing to approximately 0.5 m, which is noticeable, but tolerable. Coordinates of the bypass insertion magnets are given in Table 7-I and the effect on the dispersion is shown in Table 7-II.

Table 7-I
Table 7-I. OVERPASS COORDINATES

Numbers in parentheses are for the original main ring ($Z=\theta_v=0$).

Station	x(Feet)	y(Feet)	θ_h (rad)	Z(inches)	θ_v (rad)
A39	962.531 (962.531)	2,285.083 (2,285.083)	.8175454 (.8175454)	0.000	0.00000
A42	1,034.911 (1,034.808)	2,350.493 (2,350.639)	.8535781 (.850017)	19.286	.0322656
A43	1,109.464 (1,109.175)	2,413.368 (2,413.813)	.8860663 (.882488)	57.063	.0322656
A44	1,186.021 (1,185.554)	2,473.789 (2,474.539)	.9185544 (.914959)	94.840	.0322656
A45	1,264.500 (1,263.864)	2,531.691 (2,532.754)	.9510426 (.947430)	132.617	.0322656
A46	1,344.818 (1,344.023)	2,587.013 (2,588.396)	.9835307 (.979902)	170.393	.0322656
A47	1,426.890 (1,425.946)	2,639.697 (2,641.406)	1.0160189 (1.012373)	208.180	.0322656
A48	1,533.772 (1,509.547)	2,703.332 (2,691.728)	1.00448499 (1.044844)	226.656	.0000000
B0	1,686.376 (1,685.357)	2,787.887 (2,789.756)	1.0692033 (1.069198)	226.656	.0000000
B11	1,772.743 (1,771.723)	2,835.248 (2,837.117)	1.0692033 (1.069198)	226.656	.0000000
B12	1,870.616 (1,869.596)	2,887.172 (2,889.042)	1.1016746 (1.101669)	226.656	.0000000
B13	1,958.274 (1,957.352)	2,929.994 (2,931.709)	1.1304914 (1.134140)	207.364	-.0322641
B14	2,047.177 (2,046.446)	2,970.092 (2,971.504)	1.1629795 (1.166611)	169.589	-.0322641
B15	2,137.335 (2,136.786)	3,007.281 (3,008.386)	1.1954677 (1.199083)	131.815	-.0322641
B16	2,228.654 (2,228.275)	3,041.523 (3,042.315)	1.2279558 (1.231554)	94.040	-.0322641

B17	2,321.037 (2,320.818)	3,072.779 (3,073.256)	1.2604440 (1.264025)	56.625	-.0322641
B18	2,414.047 (2,413.981)	3,102.116 (3,102.275)	1.2766880 (1.280261)	18.491	-.0322641
B19	2,507.920 (2,507.920)	3,128.673 (3,128.673)	1.3127319 (1.312732)	.000	.0000000

Table 7-II. MOMENTUM DISPERSION IN THE BEND PLANE WITH AND WITHOUT BYPASS

	with bypass	without bypass		with bypass	without bypass
A39 =	2.86m	2.84m	A42 =	5.77m	5.67m
A43 =	3.45	3.32	A44 =	5.63	5.36
A45 =	2.63	2.50	A46 =	3.36	3.26
A47 =	1.36	1.40	A48 =	1.74	2.00
B12 =	1.07	1.26	B13 =	2.02	2.13
B14 =	1.71	1.68	B15 =	4.04	3.84
B16 =	3.00	2.84	B17 =	5.91	5.65
B18 =	3.02	2.94	B19 =	4.17	4.13

9. INTERACTION REGIONS AND EXPERIMENTAL FACILITIES

9.1 EXPERIMENTAL AREAS

9.1.1 B0 Experimental Area. A general purpose detector is being designed and constructed by the Colliding Detector Facility Department, CDF. The desire to measure antiproton-proton collisions and available technology demand a large, massive and complicated apparatus. The B0 Colliding Beam Experimental Area has been designed to handle the assembly, installation, operation and maintenance of such a detector.

The project includes the following:

B0 Collision Hall- an underground structure that will replace approximately 100 feet of the Main Accelerator enclosure, and will contain the experimental physics detectors and both the accelerator and Energy Saver beam components. On the outside wall (away from the accelerator center) will be a large door and movable shield wall that will provide access to the Assembly Hall.

B0 Transition and Equipment By-pass Enclosure- an underground structure that connects the Collision Hall to the existing Main Accelerator enclosures, and provides a passage for personnel, utilities and a magnet-moving vehicle around the B0 Collision Hall.

B0 Assembly Hall- a large pit at the elevation of the Collision Hall and adjoining to the shield-door passage, with a service floor at grade level, all covered by a high-bay building with an overhead crane. The various experimental physics detectors will be assembled, tested and serviced in this hall prior to placement in the B0 Collision Hall.

B0 Site Development- hardstands, access roads, drainage facilities, relocation of utilities, extension of services and temporary earth retaining structures for construction sequencing and adjacent road and building protection.

B0 Primary Power- 13.8 kV feeders, substations and switchgear for extending primary power to the B0 Experimental Area and into the B0 Assembly Hall.

The B0 Collision Hall connects with and becomes a part of the Main Accelerator and Energy Saver enclosures. All systems, services and utilities are designed for compatibility with these systems. Access to the B0 Assembly Hall will be from the adjacent Road D near the Industrial Buildings.

At the time of writing, construction of the B0 area has been in progress for more than three months.

9.1.2 D0 Experimental Area. This experimental area is still in the process of definition and conceptual design. It is expected that a collision hall of approximately 2000 sq. ft. will be built at D0.

9.2 LOW-BETA DESIGN

9.2.1 Lattice Design. As discussed in Chapter 6, the \bar{p} and p bunches are placed at equal spacings around the circumference of the Tevatron, arranged so that one of their crossings occurs in the B0 long straight section, the location of the Collider Detector Facility. There will also be crossings in the D0 long straight section, where space is reserved for a second colliding-beam experimental area, at present in a primordial state of design.

The luminosity can be enhanced for given beam currents by focusing the beams down to narrow waists at the collision point, using extra quadrupoles on either side of the collision point. These quadrupoles give a decrease in the amplitude function β and the low β gives the narrow waist.

It is desirable for our purposes to achieve a minimum β value of 1 meter. Given the Tevatron lattice and dimensions, it is possible to achieve this minimum with a design that utilizes quadrupoles having gradients of 25 kG/in. and requires replacement of a single normal-cell quadrupole on either side of B0, at A48 and B12, by longer quadrupoles. The design uses four separately powered quadrupole buses and either can be adiabatically varied from the normal $\beta^* = 72$ m configuration to $\beta^* = 1$ m, while causing very little betatron mismatch or manipulation outside the interaction region except for correction-quadrupole changes to preserve the overall tunes and sextupole changes to maintain the desired chromaticity.

A layout of the 25 kG/in. low-beta insertion is shown in Fig. 9-1. It requires the replacement of the 32-in. quadrupoles at A48 and B12 with separately powered 66-in. quadrupoles and the addition of two 180-in. quadrupoles and 6 144-in. quadrupoles within the long straight section. These ten quadrupoles are powered anti-symmetrically on four separate circuits and must reach a maximum gradient of 25.5 kG/in. at 1 TeV. In order to keep maximum luminosity point close to the Tevatron B0 location, the quadrupoles at A48 and B12 must be pushed as far upstream as possible. To do this, the normal dipole interface-to-quadrupole magnetic length has been reduced from 18.137 in. to 7.137 in. by changing the upstream bellows and moving the beam detector to the downstream end of the quadrupoles. This motion puts the maximum luminosity point 0.9 in. downstream of the Tevatron B0 for the final low beta of 1 m.

9.2.2 Transition to Low Beta. For normal fixed-target operation, Q1 must run at approximately 10 kG/in. and Q2, Q3, and Q4 must all be off. By contrast, in the low-beta configuration, all the quadrupoles must be on and running quite hard. The problem is to find a method of connecting these two solutions in a stepwise continuous manner while maintaining the overall tune of the Tevatron. This is by no means a simple straightforward

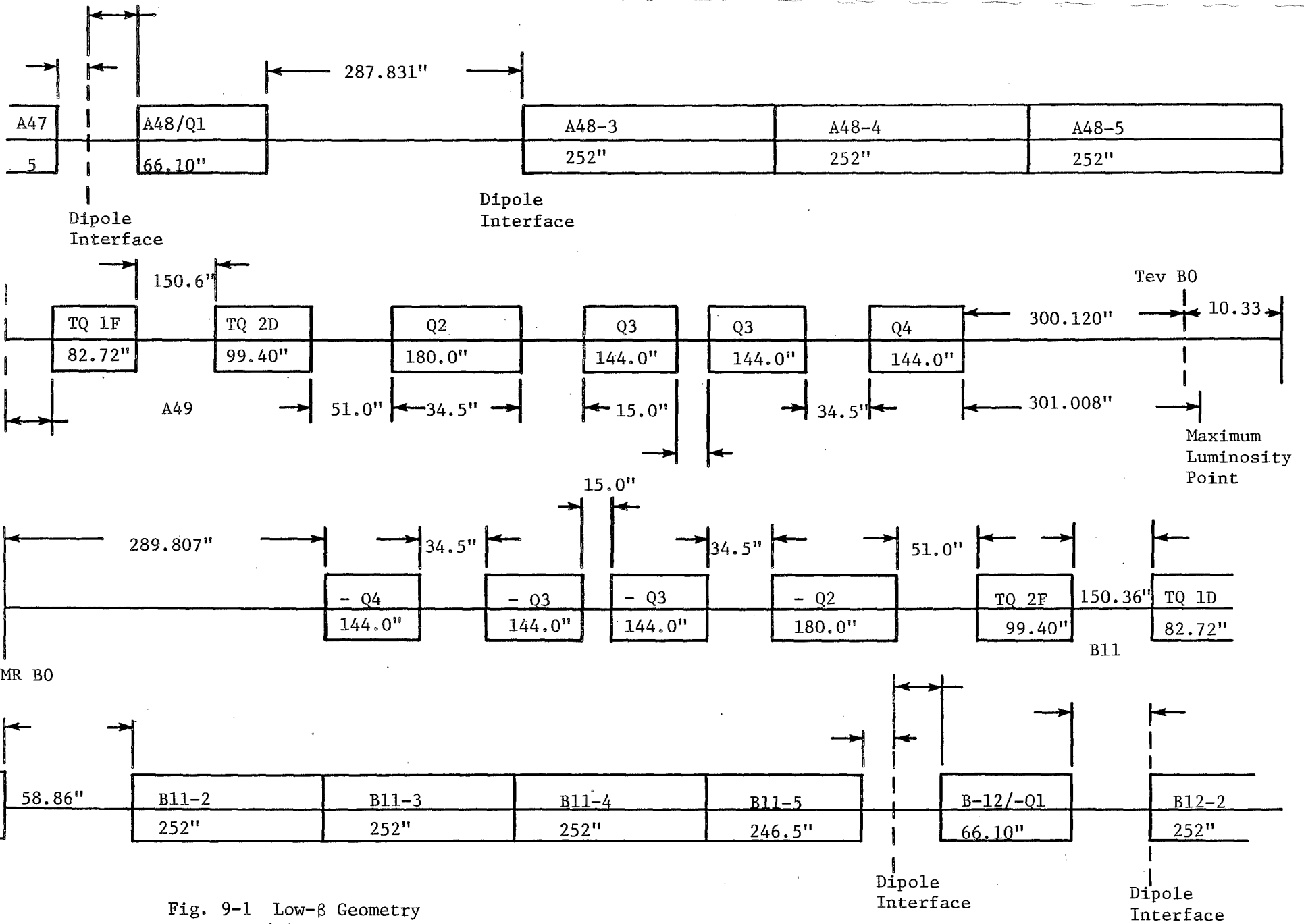


Fig. 9-1 Low- β Geometry
(all dimensions in inches)

process. The two solutions are in fact quite different and probably cannot be connected without disturbing the normal lattice functions outside the insertion region. A method has been found, however, that does not greatly disturb the rest of the ring. This sequence takes the lattice from a returned fixed mode to a low beta of 1 m.

In all of this sequence, the Tevatron has been returned to 19.585 in each plane. For particle-antiparticle collisions it is desirable to be above the half integer and the value of 0.585 centers the tune in a region free of all resonances of order lower than 11th. The correction quadrupoles consist of two families, QFC and QDC, located next to the corresponding quadrupoles, QF or QD, at all stations 13 through 47. These corrections have a range of approximately ± 2 kG/in. at 50 amps. QFC has ranges from +0.4 kG/in. to -0.9 kG/in. QDC is given by

$$QDC = 0.0457 - QFC \text{ (kG/in.)}$$

In this turn-on sequence, there is some disturbance to the lattice functions outside the insertion region, for three distinct reasons:

1. The "off" solution and the "low-beta" solution are, in fact, quite different. It is doubtful that they can be connected without allowing some mismatch.
2. The initial sequence, in steps of less than 1/3 kG/in., was not a very smooth curve. Some amount of mismatch was allowed in order to produce smoother curves.
3. It was found that a higher luminosity can be achieved in the "1 meter low-beta" by introducing some mismatch. This is because the long straight sections are not exactly antisymmetric; one side has more dipole edge focusing than the other, while the low beta quads of necessity are symmetric.

The amount of disturbance to the normal lattice, however, is quite small and should cause no problem since this turn-on will not start until high energy where the beam is very small.

9.3 Hardware Modifications

9.3.1 Magnets. Special quadrupoles have been designed and are being built for the B0 interaction region. These magnets use special cable with 20 micron filaments and a copper-to-superconductor ratio of 1.3 (as opposed to 8 microns and a ratio of 1.8). This cable has a short sample limit of 5250A at 6.5T. The new quadrupole has added turns to reach higher fields.

There are many new features of the new design. The strength of the coil collars has been carefully considered, as has quench protection. A smaller cross section is being considered to give less interference with the Collider Detector. Because the special quads are powered separately

from the regular Superconducting Ring magnets, the regular excitation currents are bypassed through the quads in a notch at the outside of the coil collar.

The beam monitor and correction magnet at B12 have been redesigned in a special package and relocated downstream of the special quad. Dipole fields will arise from quad misalignment. Even though shimming will be done, misalignments in the high- β regions adjacent to the low- β interaction region can give large orbit distortions and trim dipoles are being designed for correction.

9.3.2 Power Supplies and Bus. Four separate power supplies and associated circuits will be needed for the 1-m β^* design. The supplies will be modified Tevatron holding supplies capable of providing up to 6000 A. The supplies will be located in an annex to the B0 service building and the power will be transported to the magnets via water-cooled copper bus (total length of 4 circuits is 2700 ft). For a current of 6000 A, the power consumed by the bus is 770 kW. Power will enter the magnets through lead boxes constructed especially to fit the 15-in. space provided for them.

9.3.3 Refrigeration. Liquid He refrigeration needs are as follows: quadrupoles (50 W), four pairs of 5 kA leads at 10 W each (40 W + 56 l/hr), two turnaround boxes at 10 W each (20 W), two feed boxes (45 W) and U tubes (5 W), for a total of 160 W plus 60 liters per hour. This refrigeration need can be met initially by the A4(C4) and B1(D1) satellite refrigeration systems. Later, it may be desirable to provide stand-alone refrigeration, and it would certainly be needed if operation at 1.8 K is desired. The 60 liters per hour of liquid He would come from the Central Helium Liquifier through the A4 and B1 refrigerator and magnet systems. The estimated LN₂ requirement is 250 W. Refrigeration estimates for the interaction-region detector magnets are not included here, because it is expected that those needs will be satisfied with but separate refrigeration.

9.3.4 Vacuum. Pressure in the interaction region straight section should not exceed 10^{-9} Torr. This means the warm vacuum pipe through the detector plus a transition piece on either side will require special preparation (possible bakeout). The transition pieces will contain isolation valves and ion pumps, as well as the connections to turbomolecular and roughing pumps.

10. PERFORMANCE AND LUMINOSITY

In this section we describe the colliding-beam performance at 1000 GeV in the Energy Saver. For this purpose, we assume that beams of protons and antiprotons have been accelerated and are circulating in opposite directions so they collide in the center of the low-beta insertion in B0, as well as at other azimuths.

10.1 Beam Geometry

As an example, it is possible to create three bunches of antiprotons each with 8×10^{10} particles and each with a longitudinal phase area of 3 eV-sec, which we define as the area including 95% of the population with a biGaussian distribution. To prepare the necessary number of antiprotons in the Accumulator takes a little more than two hours.

Similarly we can assume that three proton bunches, each with 10^{11} particles and a longitudinal area of 3 eV-sec coexist with the antiproton beam. Both beams have equally spaced bunches since the harmonic number 1113 can be divided by 3. In principle there are, therefore, six collision regions equally spaced. We assume here that the two beams are not kept separated by special electrostatic deflectors, the design of which appears to be difficult because of lack of space in the Energy Saver and because of the large rigidity of the particles. An important parameter to determine the bunch dimensions is the peak rf voltage V at 53.1 MHz. We assume here that two sets of four cavities exist and that orthogonal control of the two beams is possible. In this mode of operation, there will be a total of 1.4 MV/turn for each beam.

Using the equations of Chapter 2, which apply to the Tevatron as well as to the Main Ring, we obtain for the rms bunch length $\sigma_e = 40$ cm and for the rms momentum spread $\sigma_p/p = 1.2 \times 10^{-4}$. The area of the stationary bucket is 12.7 eV-sec, four times larger than the bunch area. Finally the phase-oscillation period is $T_s = 27$ msec.

10.2 Beam Cross Section at the Collision Point

As a result of the transverse stochastic cooling in the Debuncher and Accumulator Rings, and because the two beams have roughly the same number of particles, the two beams have the same emittance, which is also the same in both horizontal and vertical planes. The normalized emittance is assumed to be 24π mm-mrad. That is, $\epsilon_V = \epsilon_H = 0.023 \pi$ mm-mrad at 1000 GeV. This includes 95% of the beam with biGaussian distributions.

A low-beta figure of 1 m is expected in both planes and therefore

$$\sigma = 0.062 \text{ mm}$$

or

$$\sigma^2 = 4 \times 10^{-5} \text{ cm}^2$$

Since the low-beta insertion has very small dispersion, there will be negligible contribution to the beam size from momentum spread.

10.3 Luminosity

Because the low-beta value of 1 m is larger than the rms bunch length (0.4 m), a formula for luminosity valid for constant beam sizes is a good approximation. Thus

$$L = \frac{N_p N_{\bar{p}} B f_0}{4\pi\sigma^2},$$

where $N_p = 10^{11}$ is the number of protons per bunch, $N_{\bar{p}} = 8 \times 10^{10}$, the number of antiprotons per bunch, $B = 3$, the number of bunches per beam, and $f_0 = 4.77 \times 10^4$ Hz, and the revolution frequency. This gives

$$L = 2.2 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}.$$

This luminosity figure is definitely within reach with the methods and the techniques described in this report. Several alternative luminosity scenarios can be invented. For instance, it is possible to replenish the collider every hour with one single bunch of protons and antiprotons with 10^{11} particles each, for a luminosity of $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$.

Higher luminosity figures can also be expected, as high as $6 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, by improving either the stochastic cooling (a factor of two), or the beam intensity in the Main Ring and Tevatron (also possibly by a factor of two) or with 6 bunches per beam instead of 3 as assumed here.

10.4 Beam-Beam Tune Shift

Collisions are head on, the emittances of both beams in both planes are all equal, and the lattice functions are approximately the same in both planes. Therefore, the beam-beam tune shift is the same for both beams (except for possible variation of charge from bunch to bunch), is independent of the beam energy, and does not depend on the lattice functions. The linear beam-beam tune shift is given by

$$\xi = \frac{3 N r_0}{2 \epsilon_N},$$

where $N = 10^{11}$ is the number of particles per bunch, $\epsilon_N = 24\pi$ mm-mrad is the normalized emittance and $r_0 = 1.535 \times 10^{-18}$ m is the classical proton radius. We have

$$\xi = 0.003/\text{crossing}$$

Even with a low-beta insertion, the beam cross-section in the other five collision regions with normal β values is round and the contribution to the beam size from the momentum spread is negligible. Therefore the tune shift per crossing, in case the two beams are not separated, is the same at each crossing as long as the collision is head-on or at least at an angle $\theta \ll \sigma/\sigma_e$. If there are a total of 6 crossings, the total tune-shift per turn

$$\xi_{\text{tot}} = 6 \xi = 6 \times 0.003 = 0.018.$$

10.5 Single-Beam and Luminosity Lifetime

We have investigated four possible sources of lifetime deterioration in the Tevatron: residual gas, intrabeam scattering, beam-beam effects and beam-beam cross sections¹³. At the same time an analysis of periodic or random crossings of nonlinear resonances has been initiated. This will help to determine not only possible limits on the amount of nonlinearities in the Energy Saver superconducting magnets, but also on the amount of coherent and incoherent noise amplitude allowable.

10.5.1 Effects of Residual Gas¹. The following effects have been investigated:

- (i) Multiple Coulomb Scattering
- (ii) Single Coulomb Scattering
- (iii) Nuclear Scattering

The first effect causes a constant beam-emittance growth, which leads to both a luminosity decay as well as a single-beam lifetime if an aperture limitation is taken into account. Nevertheless the single-beam decay due to multiple Coulomb scattering is quite negligible. The second and third effects cause an intensity decay, but the last effect is more important than the second one.

The average vacuum pressure expected in the Tevatron is 10^{-8} Torr in the warm regions and 5×10^{-11} Torr in the cold regions with the following gas composition:

warm region: 60% H_2 and 40% CO
 cold region: 75% H_2 and 25% He

The intensity decay per beam due to single Coulomb and nuclear scattering is

$$\frac{1}{I} \frac{dI}{dt} = -1.07 \times 10^{-6}/\text{sec} .$$

The emittance growth due to multiple Coulomb scattering is

$$\frac{1}{\epsilon} \frac{d\epsilon}{dt} = 1.3 \times 10^{-6}/\text{sec} .$$

These effects combined lead to a luminosity decay of

$$\frac{1}{L} \frac{dL}{dt} = -3.44 \times 10^{-6}/\text{sec} ,$$

a loss of 13% of the luminosity in 10 hours.

10.5.2 Intrabeam Scattering². To estimate intrabeam scattering diffusion rates for the colliding-beams mode, we have used the same computer code we used to estimate intrabeam scattering for the Accumulator. For our estimate, we have used the actual Tevatron lattice with the low-beta insertion. From the computer code we have empirically found the following formulas for diffusion rates, which apply to a bunched beam at 1000 GeV. For the momentum spread

$$\frac{1}{\tau_p} = \frac{1}{\sigma_p/p} \frac{d\sigma_p/p}{dt} = \frac{A_p I_p}{(\sigma_p/p)^{m_p} \epsilon^r p} \quad (10-1)$$

and for the horizontal betatron emittance

$$\frac{1}{\tau_x} = \frac{1}{2\epsilon_x} \frac{d\epsilon_x}{dt} = \frac{A_x I_p}{(\sigma_p/p)^m \epsilon_x^r} \quad (10-2)$$

There is actually damping for the vertical betatron emittance.

In these equations σ_p/p is the rms momentum spread, $\epsilon = 2\sigma^2/\beta$ the rms betatron emittance, which we assume to be the same in both planes, and I_p is a measure of the bunch peak current

$$I_p = \frac{N_B e\beta c}{2/\pi \sigma_e},$$

where N_B is the number of particles per bunch, βc the particle velocity, and σ_e is the rms bunch length. Also

$$A_p = 5.7 \times 10^{-23} \text{ Amp}^{-1} \times m^r \times \text{hour}^{-1}$$

$$A_x = 12.6 \times 10^{-23} \text{ Amp}^{-1} \times m^r \times \text{hour}^{-1} .$$

If $\sigma_p/p = 1.2 \times 10^{-4}$, $\sigma_e = 40 \text{ cm}$, $N_B = 10^{11}$, then $I_p = 3.4 \text{ A}$, and if $\epsilon = 0.0077 \text{ mm-mrad}$, then

$$m_p = 2.2 \quad r_p = 1.4$$

$$m_x = 0.7 \quad r_x = 2.0$$

We obtain as initial diffusion rates

$$\frac{1}{\tau_p} = 5.2 \times 10^{-6} / \text{sec}$$

$$\frac{1}{\tau_x} = 1.1 \times 10^{-6} / \text{sec} .$$

The actual variation of σ_p/p and ϵ_x is obtained by simultaneous integration of Eqs. (10-1) and (10-2). The result is shown in Fig. 10-1.

There is a loss of luminosity caused by intrabeam scattering diffusion in the horizontal betatron oscillation. Assuming vertical and horizontal

**Beam Momentum Spread and Emittance Variation
with Time Due to Intrabeam Scattering**

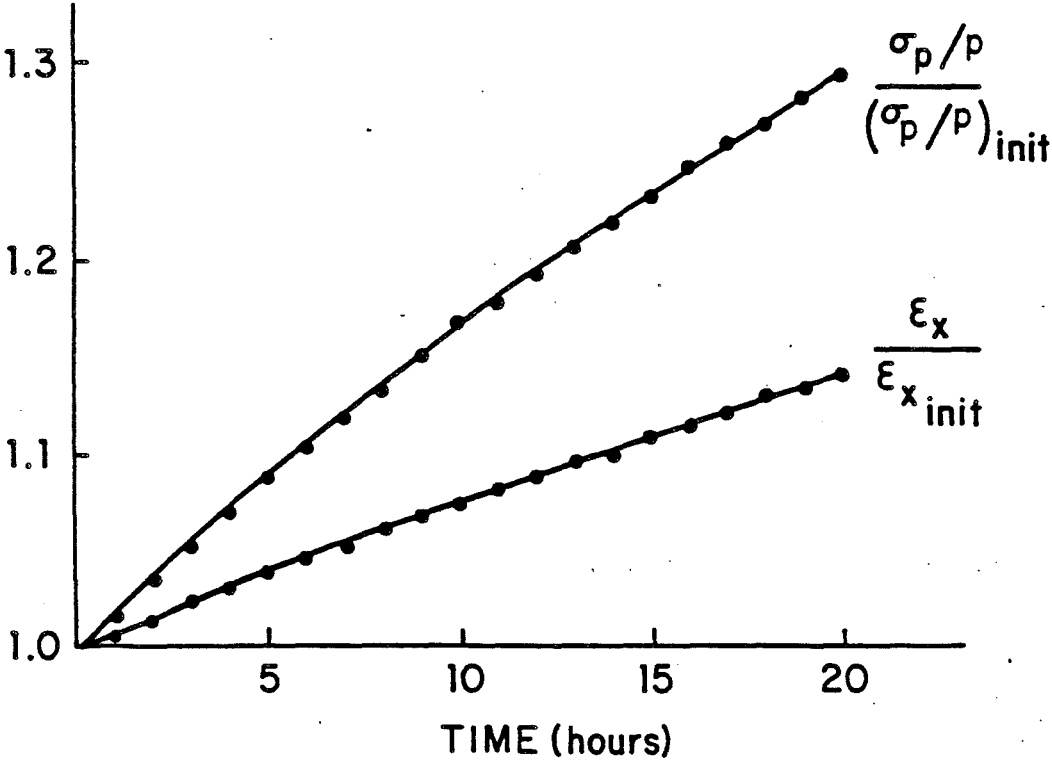


Fig. 10-1

coupling, the loss of luminosity after 10 hours is about 7%. After the same period of time (10 hours), the bunch area has increased by 32%.

10.5.3 Beam - Beam Effects. Beam-beam effects have been extensively simulated on the computer. Several issues have been discussed, studied, and, we hope, resolved.

A systematic search for Arnold's diffusion for the Tevatron parameters has given negative results.^{3,4} We have been able to simulate in some cases up to 20 minutes real time of collisions. From our data, we can extrapolate beam-beam lifetimes of several days. We believe the stability of the system arises from the "roundness" of the beam geometry and of the lattice functions.⁵

We found that the addition of the nonlinear beam-beam interaction to a system already affected by external random noise (such as gas scattering) causes an enhancement of the diffusion rates.⁶ The largest enhancement encountered was a factor 6 for a beam-beam tune shift of 0.06 in proximity to the fourth-order resonance.

We have investigated beam-beam interactions with the beam centers offset or oscillating around each other.⁷ This could be caused by either a dipole oscillation or a finite dispersion in the collision region coupled to the momentum oscillation. We have not noticed any effect of significance.

Of more serious concern are the effects created by betatron tune oscillations. If proper care is not taken, it is possible to cause an emittance growth of a factor two in a few minutes.⁸ Fortunately, we have found a threshold and the growth can be tuned out by either adjusting the betatron tunes or by improving the power-supply regulation to better than 10^{-4} and flattening the lattice chromaticity.

At present, we are investigating multiple crossings per revolution, 2 or 6 instead of 1.

10.6 Beam-Stability Considerations in the Tevatron. As we have seen, each beam is made of three bunches, each with 10^{11} particles and a longitudinal area of 3 eV-sec. The beam intensities, both average and peak, are very modest and dilute. A considerable effort has been made in the recent past to estimate the longitudinal stability of each beam for both individual bunch and bunch-to-bunch modes.^{9,10,11} The beam wall impedance expected in the Tevatron was estimated to be $|Z_n|/n < 1$ ohm. Because of the low longitudinal beam density, we believe the beams are quite stable. Moreover, a longitudinal damper operating on each individual bunch is planned.

Fewer calculations have been done for the case of transverse instabilities. But again, we do not foresee major problems. In addition,

a transverse active damper has been proposed¹² that will be fast enough to operate on individual bunches in both radial and vertical modes of oscillation.

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11. COMMISSIONING AND OPERATION; DIAGNOSTICS AND CONTROLS

11.1 Commissioning

Because of the tight construction schedule and the desire to have $p\bar{p}$ collisions as soon as possible, we must minimize the commissioning time for the \bar{p} source. In particular, we propose a rather complete set of diagnostic devices as well as emphasis on the ability to inject protons parasitically into the two \bar{p} rings from the Booster either via the Main Ring or a direct transfer line from the Booster to the Debuncher.

By reversing the magnetic-field polarities in the Debuncher, Accumulator and appropriate transfer lines, all the functional devices can be debugged and optimized with protons from the Booster. (It is necessary to have the test protons circulate in the same direction as the \bar{p} 's in order to allow the testing of the stochastic-cooling systems). The tune diagrams of the two rings can be explored and the acceptances optimized before \bar{p} 's must be produced by the Main Ring. In addition, the high proton density from the Booster will allow the simulation of dense \bar{p} stacks in the Accumulator so that instabilities and their cures can be investigated. This work is particularly important because the ultimate luminosity of the Tevatron $p\bar{p}$ collider may well be determined by the maximum core density in the Accumulator.

For first operation, however, the emphasis will surely be on rapid \bar{p} production rather than maximum core density. This means that measurement of ring acceptances and transfer efficiencies will have high priority during initial running-in. The stochastic-cooling systems will also require some development to achieve their anticipated flux acceptance. The two rf systems in each ring can also be debugged with protons from the Booster. The \bar{p} production process can be studied and optimized independent of much of the activity in the Debuncher and Accumulator. Activities in the Main Ring tunnel and possible interferences with the fixed-target high-energy physics program may make studying the \bar{p} production more difficult, although parasitic operation should be possible.

For transfer of antiprotons into the Main Ring and Tevatron, occasional dedicated study periods will be useful and necessary before collider operation.

11.2 Diagnostics

11.2.1 Accumulator and Debuncher Diagnostics.

1. Schottky signals. From the Schottky signals one can measure the betatron tunes and momentum distributions of the beams. For low-intensity \bar{p} beams of 10^7 particles, as in the Debuncher, one may have to develop resonant Schottky pickups to enhance the sensitivity. One also uses the Schottky signals to determine the effectiveness of the stochastic cooling.

2. Position electrodes. Information from the horizontal or vertical position pickups placed near the quadrupoles in each ring is necessary to correct closed-orbit errors, measure position vs momentum dependence and correct injection errors. These electrodes will also be used for ion clearing if that is found to be necessary. The newly developed pickups and electronics used for the Tevatron seem to have the desired sensitivities.
3. Beam transformers. A sensitivity of $1\mu\text{A}$ or approximately $10^7\bar{p}$ will be necessary. Some development work may be necessary to achieve this level.
4. Profile monitors. To see the effectiveness of the betatron stochastic cooling and to see resonance blow-ups, beam profiles must be measured. For the high-intensity core, a flying-wire scanner as used at the CERN SPS would be ideal. A $50\text{-}\mu\text{m}$ wire travelling at 10 m/sec would only cause about 0.03% beam loss and $0.03\pi\text{ mm-mr}$ emittance growth per scan. The ionization monitor as developed for the Fermilab cooling ring would also be ideal, especially for the low-intensity beams of the Debuncher. Horizontal and vertical scrapers at regions of high and low α_p are also planned.
5. Aperture scans. To scan the apertures and measure lattice parameters, the normal rf systems will be used to deposit beams at different momenta. Computer-controlled magnetic correction elements then can be varied to compare calculated vs. measured betatron tune variations. To study effects of large betatron amplitudes, the beam can be blown up with single-turn kickers or the $1\text{ to }50\text{ MHz}$ damping system can be fed with reversed feed-back sign or noise.

11.2.2 Targeting and Beam Transfer Diagnostics.

1. The target area will be equipped with secondary emission monitors (SEM) and transformers in appropriate places. Because of the sensitivity of the lithium lens to an incident proton beam off-axis, the steering of the incident beam will have to be closely monitored. Segmented Wire Ion Chambers (SWICs) will be used for automatic monitoring of the proton beam incident on the target.
2. All beam transfer lines will be equipped with SWICs or similar profile monitors, including at least 3 in each ring to allow matching of phase-space parameters. Some development may be needed to make a profile monitor suitable for injection matching and compatible with the accelerator vacuum.
3. Low intensity \bar{p} beam lines, i.e., from the target to the Debuncher and between Debuncher and Accumulator, will have some

high-sensitivity (low-mass) profile monitors such as proportional chambers.

11.3 Controls

The operation of the \bar{p} source will eventually be controlled from the main control room (MCR) of the accelerator complex by the normal operation crew. Thus, the accelerator control network (ACNET) now being implemented for the Tevatron, which will eventually be used for the Booster, Linac, Main Ring and Switchyard, will be used for the \bar{p} source.

Details of methods of interfacing devices in the \bar{p} source to ACNET, e.g., via serial CAMAC, can and should be determined based on experience with the new Tevatron system. In any case, the control system for the \bar{p} source will be compatible with and as similar as possible to the other accelerator systems controlled from the MCR. We expect that many of the procedures and programs developed during \bar{p} running-in will become the backbone of the operational system.

For the commissioning period, at least one ACNET console will be needed in the gallery over the Debuncher and Accumulator.

