SSC-N-561

Report of the Workshop on SSC Linac Parameters

CDG, 10/10-11/88

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Meeting minutes

A meeting was held 10/10-11/88 to review the SSC linac design. The present design is the one described in the Conceptual Design Report. Things that happened since CDR:

- possibility of more luminosity (e.g. x10) (Tigner)
- new design of boosters LEB, MEB and HEB (Furman)
- advances made on linac designs in the last few years

CDG is about to launch the next iteration of SSC linac design. This meeting is to collect the wisdom of experts who were asked to help CDG identify the relevant issues, and to provide their advice.

Discussion sessions were

Tigner	Introduction
Thiessen	Suggestions for changes to the CDR
Schriber	Optimal frequencies and rf structures
Holmes	Emittance control
Chao	Beam diagnostics
Stiening	Provisions for later upgrades
Chao	Summary

Below are issues identified during the meeting, not arranged in any particular order, together with brief discussions.

1. Recent experience shows that the normalized rms transverse beam emittance coming out of a 50 MHz RFQ can be 0.18 π mm-mrad or lower, much smaller than 0.45 π mm-mrad assumed in CDR. Much has happened in the understanding of the operation of RFQ and DTL (Schriber, Wilson). Simulation shows that subsequent operation in 150 MHz DTL does not cause more than 10% increase in the emittance (Bhatia).

2. A smaller emittance means the possibility of achieving luminosity with less beam intensity. Space charge effect is identified to be the bottleneck as emittance is lowered. To take full advantage of the lower emittance means the linac energy needs to be increased from the present 600 MeV. Space charge tune shift will be smaller, presumably allowing speedier turn-on. This is to be considered even without the luminosity upgrade. An increase to e.g. 800 MeV would make the space charge effect no longer an issue. (Stiening). A study is needed to reoptimize the linac energy. In the optimization, it is the average, rather than the peak, luminosity that is to be optimized (Johnson). One has to also watch for the increase in beam-beam effect. (Staples)

3. The specification of a variable bunch spacing at multiples of 4.8 m has significant impact on the injector design. This spec is to be reviewed. (Johnson) A related question is what determines the tolerable population of the unwanted satellite bunches. This will affect the chopper design. (Steining)

4. Assuming 600 MeV linac, an energy upgrade to 1133 MeV is a magic value (Thiessen). At this energy, the beam velocity is 9/8 of the velocity at 600 MeV, and the 1-in-9 bucket injection scheme can be replaced by 1-in-8, without changing the high-frequency linac structure. Then only the RFQ, the chopper and the 150 MHz DTL need to be changed.

5. RF voltage in LEB is to be increased from 350 KV to 500 KV if the bucket area is to be maintained during acceleration with a constant rate (Thiessen, Colton). The beam can still be injected at 350 KV if desired.

6. Alignment and various error tolerances are to be set by the emittance growths due to longitudinal-transverse coupling effects (Staples). This is probably not serious for SSC parameters, but needs to be looked at.

7. An acceleration gradient of 12 MV/m is probably safe at 1.3 GHz. The present design is 9 MV/m. One needs to determine the design gradient and the number of klystrons by optimizing the (construction + operation) cost. (Schriber, Stiening)

8. Collective effects in the linac are not serious because (a) little are expected unless average current > 20 mA (space charge) and peak current > 0.5 A (wake fields) or so (Bhatia, Schriber), and SSC is mostly below that, (b) even above that, the emittance growth may be smaller than the safety margin provided, and (c) in case of unexpectedly strong collective effects, one can always try to increase the number of turns for multi-turn injection into the LEB (Holmes).

9. To increase the beam intensity in the collider does not necessarily mean the beam intensity in the linac has to be increased proportionally. Multi-turn injection into the LEB, followed by proper scraping to yield the needed emittance, could do the job provided space charge is tolerable (Holmes).

10. Simulation shows 50 MHz RFQ fails to meet the longitudinal emittance requirement as specified in CDR (Bhatia). Two alternatives: (a) relax the requirement which may not be critical (Thiessen), and (b) increase the RFQ frequency to 150 MHz, same as that assumed for the DTL1. The 150 MHz rf source should be an off-the-shelf item, although alternatives should be looked into. A choice of 450 MHz for DTL2 and 1.3 GHz for SCL seem reasonable (Schriber). The design and construction of 150 MHz rfq is not an issue (Owen).

11. Five possibilities exist for chopping (Bhatia): (a) a combination of 150 and 200 MHz rfq (originally suggested by Schempp, Swenson), (b) rf deflector after RFQ, (c) rf cavity followed by a spectrometer after RFQ (Thiessen), (d) a laser neutralizer (originally suggested by Worth), and (e) same as (c) but in the transfer line. A weak consensus is to choose (b), while paying attention to (d) for possible later use. Study is needed to see if the rf devices increase beam emittance. Tools exist to do this job. One advantage of (e) is that the spectrometer already exists. It also may cause less emittance growth compared with (c). The idea (Peterson) of replacing chopping by modulating the H- source was regarded impractical.

12. The preferred high-frequency rf structure would be either side-coupled or on-axis coupled, and not disc-and-washer. A comparison of the two choices would be available in several months time. Either should be easy to manufacture. (Schriber)

13. Transverse and longitudinal matching between linac sections have not been done. This is to be done taking into account of the various space requirements for the miscellaneous components envisioned. Tools exist for doing this.

14. Jittering of the LEB buckets, possibly leading to emittance dilution, could be an issue (Owen). This needs to be studied.

15. Control of beam energy and its spread is important. This translates into tolerances on the rf voltages and phases. It was suggested that (a) feedback systems be provided in the transfer line, and (b) these tolerances be set without taking into account the benefit of the feedback systems.

16. Adiabatic capture versus bunch-to-bucket injection schemes were compared. The bunch-to-bucket scheme imposes a tolerance on the bunch phase jitter (Owen), but the spec is straightforward to meet assuming a steady LEB (Thiessen). Its tolerance on energy jitter is about two times more stringent than the adiabatic capture scheme. The adiabatic capture scheme permits a lower average beam current in the linac (Holmes), provides a more uniform population among different bunches in the LEB (Stiening), but these are not regarded critical issues. The main issue is the adiabatic capture scheme does not allow a variable bunch spacing unless one provides more complicated rf schemes; while with a chopper, the bunch-to-bucket scheme does provide variable bunch spacing.

17. Two extreme possibilities were discussed but only briefly: (a) replacing the LEB by a 8-GeV linac (Holmes), and (b) replacing the SCL by a Very Low Energy Booster (Stiening). An examination of these possibilities needs to be included in future studies for a "decision memo".

18. An almost unanimous (one hesitating) suggestion was to equip the transfer line with a generous number of monitoring and correction devices. The basic structure of the CDR design is maintained, except that the 4-module 90 degree bend is changed to a 2-module 45 degree bend (Thiessen). Monitoring systems considered necessary were current monitors, centroid monitors, profile monitors, emittance boxes, strippers. Streak cameras or LINDA devices are also possibilities (Wilson). The exact number of each of the devices will have to be determined after a detailed study of the beam requirements as well as the expected errors.

19. The possibility of monitoring the beam in a beam dump line instead of the transfer line was suggested. (Chao) The advantage is the optics is more flexible and its errors do not have downstream consequences. The disadvantages are that it does not monitor pulse-to-pulse jitters and that it allows beam monitoring but not corrections. (Stiening) It was also suggested that the optics of the achromat bend does provide sufficient sensitivity for beam monitoring, although one needs to confirm it. (Thiessen)

20. Beta-function corrections in the transfer line can be done using the independently powered quadrupoles in the transfer line. It was not clear whether one needs or how to make dispersion corrections. This point needs to be studied.

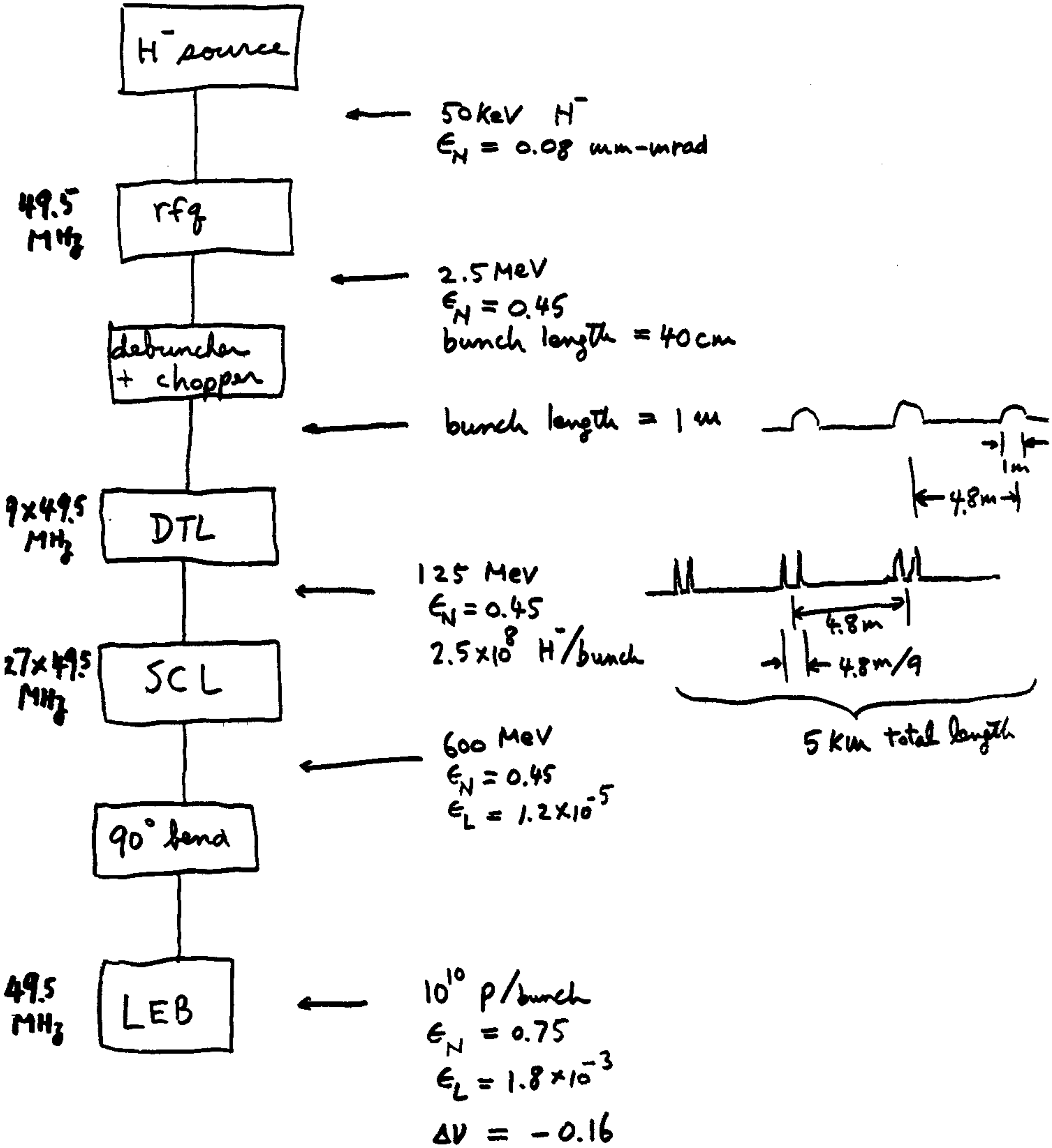
21. Beam energy centroid as well as its spread need monitoring and correction. These have to be done in the transfer line. Whether they need to be done at intermediate locations in the linac remains to be studied. Beam energy spread is much preferably controlled by an independent knob, although in principle some combination of rf voltages and phases can probably do it. A drift space of approximately 100 meters would be needed to provide the dedicated knob. Note that the system requirements are different for 600 MeV or 1.2 GeV operations.

22. Longitudinal and transverse matching from the transfer line before entering LEB need to be designed.

23. H- *stripping in quadrupoles* needs to be looked at for the linac energy upgrade. (Stiening)

24. In addition to the 100 meters of energy feedback system, and the additional SCL needed for increasing the beam energy, one can envision a large number of uses of drift spaces. It was suggested that drift spaces be made available provided proper matching can be achieved. Drift spaces alone are not expensive.

A. Chao



H⁻ source
50 KeV H⁻
ε_N = 0.08 mm-mrad
49.5 MHz
rfq
2.5 MeV
ε_N = 0.45
bunch length = 40 cm
debuncher + chopper
bunch length = 1 m
1m
4.8m
9×49.5 MHz
DTL
125 MeV
ε_N = 0.45
2.5×10^8 H⁻/bunch
4.8m
4.8m/9
5 km total length
27×49.5 MHz
SCL
600 MeV
ε_N = 0.45
ε_L = 1.2×10^-5
90° bend
49.5 MHz
LEB
10^10 p/bunch
ε_N = 0.75
ε_L = 1.8×10^-3
Δν = −0.16

Table 4.10-1
SSC Injector Parameters

	Linac	LEB	MEB	HEB
Injected particle	H^-	H^-	H^+	H^+
Injection momentum	0.0	1.21	8.0	100.0 GeV/c
Extraction momentum	1.22	8.0	100.0	1000.0 GeV/c
Circumference	125.0	249.6	1900.8	6000.0 meters
rf frequency (at extraction)	1336.0	62.0	62.5	62.5 MHz
Bunch spacing	4.8	4.8	4.8	4.8 meters
Average current (at extraction)	3.9	99.	92.	87. mA
Normalized transverse emittance (rms)	0.45	0.75	0.83	0.91 mm-mrad
Longitudinal emittance (rms area/π)	0.012*	1.8	1.8	35 meV-s
Cycle time	0.1	0.1	4.0	60.0 s

*At 1336 MHz.

the horizontal plane and, with the exception of LEB injection, are accomplished through single turn extraction and injection.

4.10.2 600 MeV H^- Linac

A chain of linear accelerators is utilized as the source of the particles that feed the Low Energy Booster (LEB). This chain consists of an H^- ion source, a radio-frequency quadrupole (RFQ) structure, a beam chopper, a drift tube linac (DTL), and a side-coupled linac (SCL), collectively called the "linac". This linac provides a beam of 600 MeV H^- particles through a transfer line to the LEB. The choice of linac energy is determined by the design of the LEB and is discussed in Section 4.10.3. H^- ions are used because, through the use of multiturn injection, they allow the creation of large circulating currents in the LEB without requiring a large peak current in the linac.

Beam

A scheme proposed by Colton and Thiessen [4.10-2] involves injection from the linac into pre-existing rf buckets in the LEB. This scheme sets the linac beam parameters.

The SSC main ring utilizes beams with 4.8 m bunch spacing and containing 10^{10} protons per bunch. The transfer energy between the linac and the LEB is 600 MeV (v/c = 0.792). The rf frequency at v/c = 1 is 62.457 MHz; therefore, the LEB frequency at injection is 0.792 × 62.457 = 49.46 MHz. The DTL frequency is chosen to be nine times this value or 445.2 MHz, and the SCL frequency is another three times, or 1336 MHz. The

LEB circumference is 249.6 m, corresponding to a revolution frequency of 0.951 MHz (1.051 μs/turn) at injection. The harmonic number is 52, which for a final bunch spacing of 4.8 m, requires filling all 52 buckets. For bunch spacings of 9.6 m, every other bucket would be filled.

The LEB bucket-filling scenario utilizes a linac beam in which 2 of 9 DTL buckets are filled and laid in sequence into each of the 52 LEB buckets. The LEB is filled in 20 turns. Twenty turns require that beam be delivered for 21.0 μs. With 2.5×10^8 H^- per bucket the instantaneous peak current is 17.6 mA, and the average current over the pulse is 3.9 mA. The instantaneous current (17.6 mA) sets the linac design and determines the beam properties, such as emittance. Some of the relevant beam structure parameters are given in Table 4.10-2. Calculated properties are for a peak current of 17.6 mA. The LAMPF linac at Los Alamos routinely delivers a proton beam having this peak current at a duty factor 150 times that needed for the SSC.

The exact method of chopping the beam to provide the 2 in 9 filled 445.2 MHz rf buckets requires additional study. One possibility is to insert a beam deflecting system into the accelerator structures. Another is to operate the RFQ at 49.5 MHz. A study of the various possibilities led to the fortuitous result that the simplest system appears to work best. The use of a single 49.5 MHz RFQ is proposed and costed for the SSC.

Table 4.10-2
Linac Beam Structure

445.2 MHz buckets	
full	1 and 2
empty	3 thru 9
Number LEB turns to fill	20
Time to fill LEB	21.0 μs
Number H^- per 445.2 MHz bucket	2.5×10^8
Instantaneous current	17.6 mA
Current over macropulse	3.9 mA
LEB cycle rate	10 Hz
Beam duty factor	0.021%
Time averaged current	0.82 μA
H^- delivered per second	5.2×10^{12}
Normalized Transverse Emittance (rms)	0.45 mm-mrad
Longitudinal Emittance (rms area/π)	1.2×10^{-5} eV-s*
Energy Spread (rms)	0.25 MeV

*At 1336 MHz

Communications

The communications system is an important adjunct to the personnel safety interlock system. Audio and video loops provide multichannel communications networks through CATV modulators and demodulators that are placed at 192 meter intervals around the tunnel and at strategic locations in the refrigerator and other service buildings. Audio and video units can be plugged in as needed and portable receiver/transmitter units provide necessary communications with the main control room and between personnel engaged in service or repair.

5.15 Injector Complex

The SSC injector system design requirements have been described in Section 4.10. The details of the hardware are presented here with elements common to all the accelerators making up the injector grouped together. Descriptions of the linac, magnets, cryogenics, vacuum, power supplies, rf, beam transfers and aborts, diagnostics, controls, and test beams are included.

5.15.1 600 MeV H^- Linac

The designs of all components of the linac proposed for the SSC are based on those used in past or existing accelerator systems. While these components must be redesigned to be optimized for the SSC, their details and configurations are sufficiently close to permit their use for cost estimating purposes.

Ion Source

The H^- beam is created in an ion source, then formed into a laminar beam by an extractor, and matched to the input acceptance of the radio-frequency quadrupole (RFQ) with magnetic lenses. This assembly establishes the minimum beam emittance and determines the beam current.

A variety of ion sources are potential candidates for the SSC. The Dudnikov-type (Penning) ion source that is used on the Accelerator Test Stand (ATS) of the "White-Horse" program at Los Alamos [5.15-1] has the highest brightness of any known H^- source and has routinely performed at levels much higher than required by the SSC. It is the source chosen for the injector.

The SSC version of the Dudnikov source will deliver 13.8 mA of H^- particles at an energy of 50 keV and a normalized rms emittance of 0.08 mm-mrad. Permanent magnet quadrupoles match the beam to the input acceptance of the RFQ. Ion source operation at 50 kV dramatically simplifies the design, allowing the ion source and associated electronics to be enclosed in a small housing within a single equipment cabinet, as was done for the PIGMI program at Los Alamos. The equipment cabinet is a standard electronics rack ($0.6 \times 1 \times 2$ m high) that is mounted on casters and contains the high voltage power supplies, vacuum pumps, gas bottle, cooling system, and the electronic control modules. The ion source electronic equipment operates at 50 kV and is located on a high voltage deck situated within the cabinet. The necessary electrical operating power is supplied by a small 1 kVA isolation transformer. The hydrogen gas flow and water cooling are provided from ground potential through nonconducting tubes. Local control of the equipment on the high voltage deck is provided through nonconducting rods extending in from the cabinet face. Remote control and monitoring are provided through a fiber optics link to a microprocessor-based system located at ground potential. A vacuum valve permits an ion source to be changed without letting the accelerator structure up to air.

A second complete and identical ion source system is required for operational backup. A short diagnostic beam line is provided for source testing. Both systems occupy the same room, which may be manned during operation if a shield wall is installed at a convenient location along the low energy portion of the linac. A room of 4 × 5 meters provided with ready equipment access is required.

RFQ and Chopper

The RFQ structure, based on the concepts of Kapchinskii and Teplyakov [5.15-2], is a relatively new structure that is an ideal first accelerator for a linac chain because it can accept a high current, low velocity, dc beam, bunch it with high efficiency, and accelerate it to a velocity suitable for injection into a drift tube linac. RFQ accelerators have been built by the Los Alamos, Lawrence, and Brookhaven National Laboratories in the USA, by the Institute for Nuclear Studies and the National High Energy Physics Laboratory KEK in Japan, AECL in Canada, and by Saclay, GSI, and the University of Frankfurt in Europe.

An RFQ accelerator consists of four symmetrically located vanes (rods) supported by spiral mounts, as shown in Fig. 5.15-1. The vane tips approach each other rather closely and define a channel along the pipe centerline through which the beam travels. The vane tips are machined with a precise wavy shape which, when the pipe is excited properly with rf power, establish electric fields that confine, bunch, and accelerate the beam.

The major cost item is machining the vanes. The options available for vane mounting and cooling, rf feed, and field stabilization, all cost essentially the same. The estimate is based on cost experience with the ATS RFQ in the White Horse Program and the spiral mounted vane RFQ cold model developed in the Heavy Ion Fusion program at Los Alamos. Table 5.15-1 lists the RFQ specifications.

The full width of the output beam longitudinal bucket is 25 degrees at 49.5 MHz, which represents 225 degrees of one out of each nine cycles of the DTL frequency of 445.2 MHz.

To fill two adjacent DTL buckets and leave the next seven empty requires lengthening the pulse from the RFQ to 540 degrees (at 445.2 MHz). This is done by utilizing two 49.5 MHz cavities at the output of the RFQ. The first cavity creates a correlation between phase and energy that allows the beam to debunch rapidly in the following drift space. The second cavity lays the ellipse horizontally over 450 degrees of the $\delta\Phi$ axis. A beam chopper is intertwined amongst the cavities and focusing elements between the RFQ and DTL to remove every-other, two-out-of-three, etc., bunches to provide multiples of 4.8 m bunch spacing in the SSC main ring, if desired.

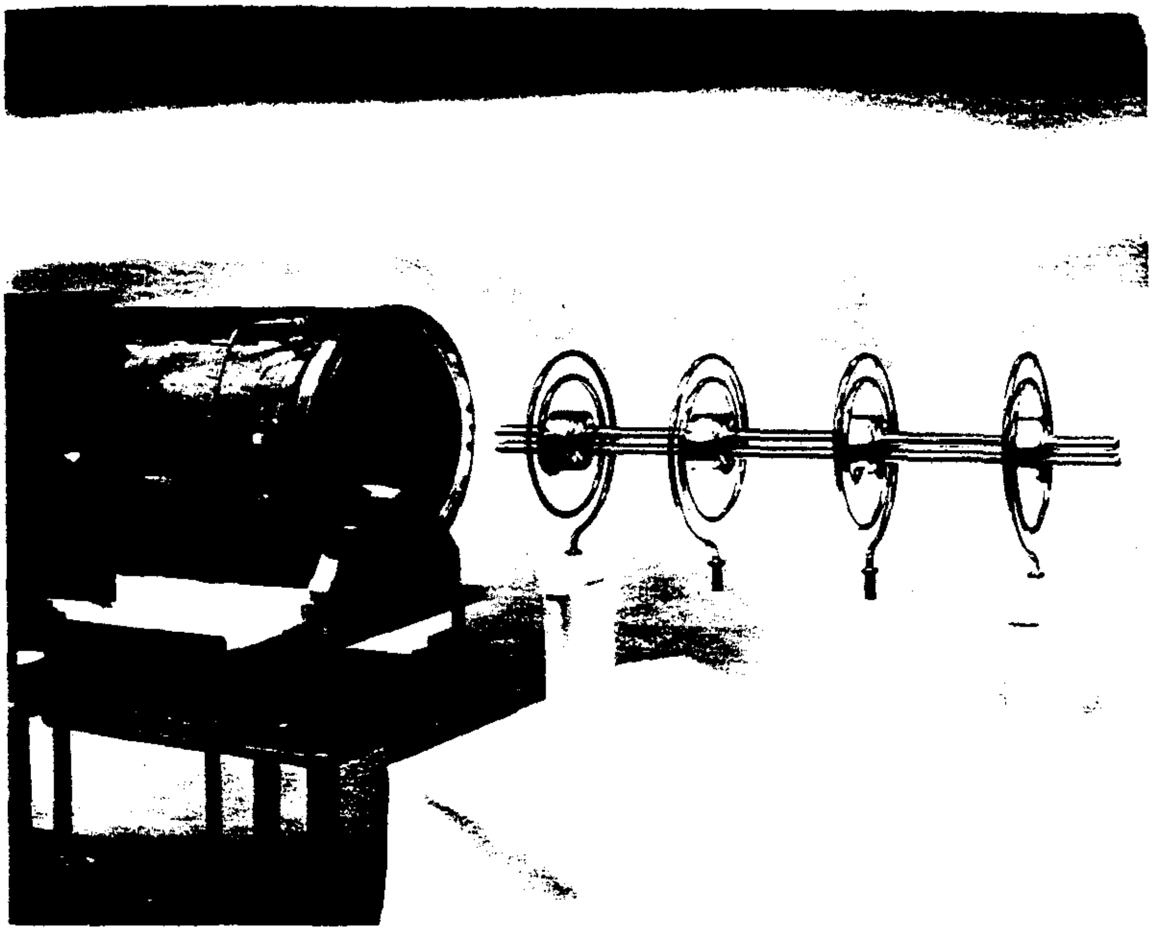


Figure 5.15-1. RFQ structure with spiral-mounted vanes (developed in the Los Alamos heavy ion fusion program).

Table 5.15-1
RFQ Specifications

Energy range (MeV)	0.05–2.5
rf frequency (MHz)	49.5
Power lost in copper (MW)	0.2
Maximum power to beam (MW)	0.04
ac to rf efficiency (%)	45
ac power for rf (kW)	0.39
Number of tanks	1
Total tank length (m)	3.0
Output beam current (mA)	13.0
Output beam emittance	
Normalized transverse (mm-mrad)	0.44
Longitudinal (rms) (MeV deg)	0.50

Drift Tube Linac

The drift tube linac is essentially identical in design to the one recently completed for the ATS at Los Alamos. Since the RFQ provides 2.5 MeV particles and permanent magnet quadrupoles are used in each drift tube, the drift tubes at the low energy end of the drift tube linac (DTL) do not present the spatial design problem traditionally experienced with this type of structure. The particles have sufficient velocity that it is relatively easy to incorporate the necessary focusing quadrupole magnet in the front end drift tubes, even at the 445.2 MHz frequency. The DTL will be contained in six tanks, each powered by a single klystron. Isolation valves, steering magnets, and beam diagnostic stations are placed between the tanks,

For reasons of alignment precision and ease of maintenance, girder-mounted drift tubes are selected over tank wall mounting. This method provides the option of installing the tanks with prealigned girders as subassemblies. If an alignment or drift tube problem arises, the entire girder is removed so that the drift tubes can be easily aligned relative to their nearest neighbors. The girder can be mounted either on the top or the bottom of the tank. Top mounting provides easier removal, permits prealigning the tanks, and ensures alignment of the drift tubes with the tank end walls. Aligning the drift tube girders with respect to each other is easier with bottom mounted girders, as they would be mounted on a common beam. The costs are the same in either case, so the actual method can be based upon experience gleaned from the stable of "White-Horse" Program DTLs which will use both methods.

The rf power requirements of the DTL are so low that rf heating cannot be used for controlling the temperature, and thus the dimensions, and thus the resonant frequency of the structure. The "cooling" system in this case actually helps the rf to elevate the temperature of the structure enough above ambient to provide a measure of control. The drift tube linac specifications are listed in Table 5.15-2.

Table 5.15-2
Drift Tube Linac Specifications

Energy range (MeV)	2.5–125
rf frequency (MHz)	445.2
Klystron turn-on time (μs)	8
Tank rf fill time (μs)	50
Total HV on time (μs)	79
Power lost in copper (MW)	10.4
Maximum power to beam (MW)	0.48
ac to rf efficiency (%)	45
ac power for rf (kW)	27
Number of tanks/Number of klystrons	6/6
Total length of tanks (m)	39.8
Accelerating gradient (MV/m)	4.52
Number of drift tubes	200
Beam capture (%)	30
Transmission of captured beam (%)	100
Output beam emittance	
Normalized transverse (mm-mrad)	0.45
Longitudinal (rms) (MeV deg)	2.0

Side Coupled Linac

The side coupled linac (SCL) is based upon the structure developed for LAMPF and copied for literally hundreds of other accelerators. This structure is used in essentially all commercially built x-ray machines over 100 keV that are used for radiography and medical therapy. A typical example is shown in Fig. 5.15-2. The dimensions are almost identical to those of the free electron laser accelerator at Los Alamos. The fabrication technique proposed is that used by Los Alamos for the electron microtron accelerators built for the National Bureau of Standards and the University of Illinois. This technique involves fabricating the structure in half-cells, i.e., a forged oxygen-free high-purity copper disk has one half of the accelerating cell machined into one side and one half of the coupling cell

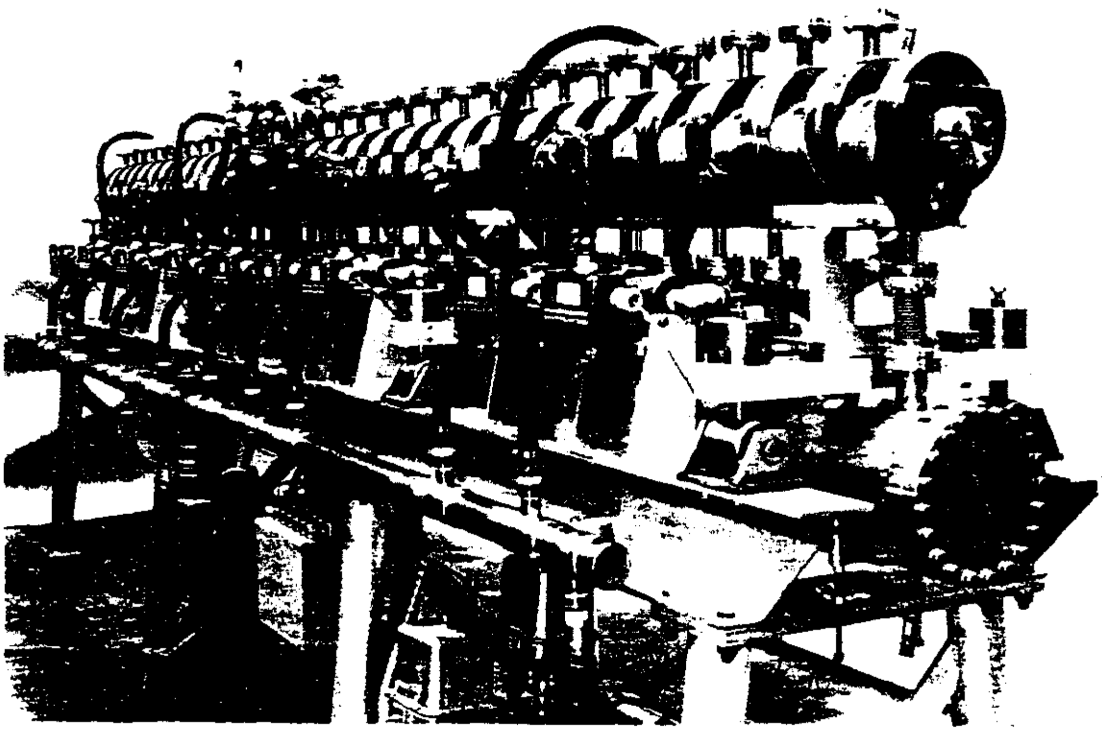


Figure 5.15-2. Typical side-coupled linac.

machined into the other. The two cells are deep enough into the billet faces that they intersect, forming the slot through which rf power flows. Cooling passages, keying, and vacuum ports are also machined in the faces. Most of the forming is done on a numerically controlled milling machine and, with the proper jigging and tooling, is accomplished in only minutes per billet. This technique reduces the total number of pieces that must be made and the number of brazes that must be done; it also reduces the amount of inspection, cleaning, furnace stacking, and leak checking required. The structure might weigh more since the excess copper is usually not all machined away as it has been when utilizing the LAMPF SCL assembly technique.

Eleven accelerating cells, with their ten intermediate coupling cells, are brazed together into a cluster. A permanent magnet quadrupole is inserted into the ends of the cluster and other clusters are bolted on, thereby building up a module, which is powered by one klystron. The vacuum pumpout tube extending from every other coupling cell is welded to a vacuum manifold that runs the length of each module. The vacuum pumps hang from this manifold pipe. The space between modules is occupied by a vacuum valve, a pair of steering magnets, and a diagnostics station.

The SCL "cooling" system functions in the same frequency controlling fashion as that for the DTL. Important parameters for the side coupled linac are called out in Table 5.15-3.

Radio-Frequency Power Systems

The RFQ and beam shaping cavities require one 49.5 MHz rf system. The DTL requires six 445.2 MHz rf systems. Seven of the 445.2 MHz systems will be installed, with the seventh serving as a test stand and spare. A minimum of eight 445.2 MHz klystrons will be procured.

The SCL requires six L-5081, 1336 MHz klystrons. Seven 1336 MHz systems will be installed and a minimum of eight klystrons procured. The seventh system will serve as a test stand. Both test stands are provided with water cooled dummy loads to permit full power tube testing and conditioning.

The klystrons are sized to provide approximately 17% more power than required when accelerating the beam. This extra capacity is required to provide overdrive to excite rapidly the structures to their proper level and to provide a margin of power for control purposes.

Pulse forming networks are utilized to hold the high voltage pulse to the klystrons up for the approximately 100 μs required of the rf systems. A modular arrangement, which includes the klystron, waveguide, modulator tank,, pulse forming network, high voltage filter, ac to dc HV power supply and control chassis, is used for each rf system. These modules have a footprint of 3×7 m for the 445.21 MHz systems and 1.5×12 m for the 1336 MHz system. The floor space must be doubled over these equipment footprint sizes to provide code mandated clearances for maintenance and to allow for equipment changes. The traditional arrangement is to provide a basic weatherproof building located above the accelerator structure and site the klystrons directly over the tanks and modules they serve. The waveguides pass from the klystrons downward through pipes embedded in the tunnel backfill to the accelerator. The 445.2 MHz klystrons require a 5 m ceiling height, while the 1336 MHz klystrons require 3.7 m.

Table 5.15-3
Side Coupled Linac Specifications

Energy range (MeV)	125–600
rf frequency (MHz)	1336
Klystron turn on time (μs)	6
Module fill time (μs)	30
Total HV on time (μs)	57
Power lost in copper (MW)	104
Maximum power to beam (MW)	1.8
ac to rf efficiency (%)	31.5
ac power for rf (kW)	295
Number of modules/Number of klystrons	6/6
Total length of modules (m)	75.0
Accelerating gradient (MV/m)	9
Number of cells	913
Focusing quadrupoles	
Placement	1 every 11 cells
Length (cm)	5.08
Gradient (T/m)	60
Beam transmission (%)	100
Output beam emittance	
Normalized transverse (mm-mrad)	0.45
Longitudinal (rms) (MeV deg)	5.9

Transfer Line

Figure 5.15-3 shows the transfer line between the linac and the Low Energy Booster (LEB). The transfer line forms a spectrometer, which, when used with strippers removes any beam halo and off-momentum tails. The quadrupole magnets have a 15 cm bore and the dipole bore is 7.5 cm high by 15 cm wide. A 22.5 degree bend module that is 20 m long, consisting of five quadrupole focusing magnets and two dipole benders, is utilized. The dipoles are two meters long and have 0.46 T fields. Space is provided to add two more of these dipoles between the existing ones so that, by reducing their fields to 0.32 T, this line will transport a 1 GeV beam through the existing components. Four of the 22.5 degree bend modules are used to provide a 90 degree bend for injection tangentially into the LEB.

The transfer line is heavily instrumented to provide complete tailoring and characterization of the beam. Instruments include six current monitors, 14 centroid monitors, 11 profile monitors, and two streak cameras. Five 4-jaw strippers are used to shape the beam, and they require three beam dumps to dispose of the discarded particles. The third beam dump also is used to absorb the total beam when the linac is being tuned up. A beam plug reduces the chances of unwanted beam going beyond the linac during tune up. A debuncher cavity is placed centrally in the transfer line for beam shape control.

Instrumentation, Control, and Safety Systems

The linac instrumentation, control, and safety systems are an integral part of the whole SSC control system. Distributed control modules monitor the outputs of the various components and compare these with the desired set points that reside in computer memory. Most components are capable of being driven by the computer to new positions.

A fast protect system prevents beam from being started down the accelerator, or shuts it off, if conditions are not right for the beam to be properly handled. That is, the rf systems must have the proper fields established in the tanks and all magnets must be at the proper settings. Beam spill monitors trip the fast protect system if their setpoints are exceeded.

A personnel protection system provides barriers, visual indicators, access restriction keying, and manually operated "scram" switches to reduce the probability of accidentally operating the machine with personnel in dangerous locations. Electrical gear will incorporate the normal protective devices mandated by code, as well as power interrupting interlocks used with experimental equipment having dangerous levels of electrical energy.

5.15.2 Magnets

The three circular accelerators in the injector string have in common the need for dipole magnetic fields for bending the protons, quadrupole magnetic fields for focusing, and sextupole magnets for correcting chromaticity. The LEB and Medium Energy Booster (MEB) magnets utilize copper coils and iron yokes, while the High Energy Booster (HEB) requires superconducting magnets. Special magnets, such as kickers, septa, and correction elements are also needed. These magnets are not described here as they are virtually identical to the magnets of this type presently in use at Fermilab. The beam transfer lines between the LEB and MEB, and between the MEB and HEB, use LEB style and MEB style magnets respectively. Magnets used in the HEB to SSC line are described in Section 5.9.

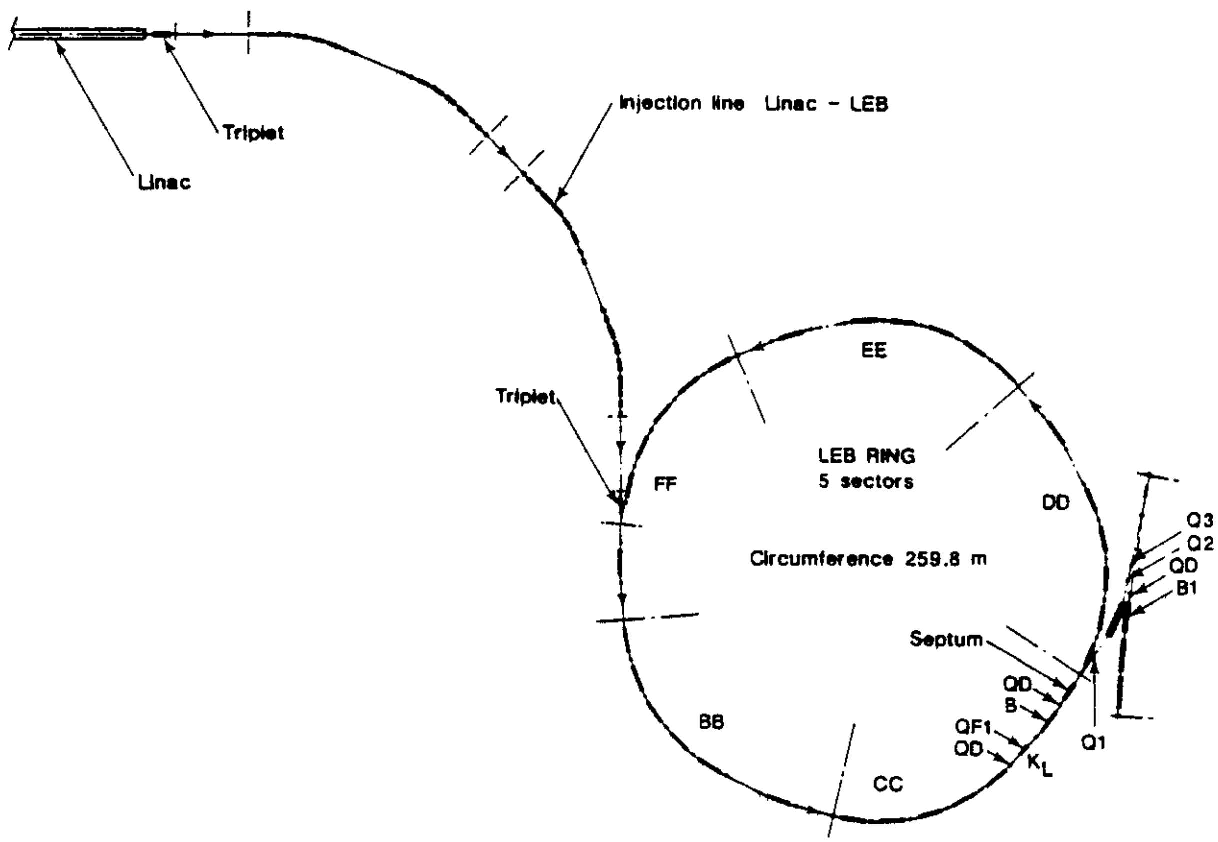


Figure 5.15-3. H^- transport line between the Linac and the Low Energy Booster, the LEB layout, and also the LEB to MEB transfer line..

New proposed LEB parameters

Table 1. LEB Parameters

	CDR	New Lattice
Injection momentum	1.22	1.22 GeV/c
Extraction momentum	8.0	8.45 GeV/c
Circumference	249.6	342.7 m
Harmonic number	52	72
Number of bunches	52	72
Protons per bunch	1.0×10^{10}	1.0×10^{10}
Circulating current (extr.)	99	100 mA
Norm. tr. emittance (*rms*)	0.75	0.75 mm–mrad
Longitudinal emittance (*rms*)	1.8	1.8 meV–sec
Horizontal tune	4.39	11.84
Vertical tune	4.41	11.78
Transition gamma	10.5	10.3
Natural chromaticities (H, V)	–5.2 , –4.9	–15.3 , –15.6
Lattice type	FODO	FODO
Superperiodicity	5	2
Maximum beta (arcs)	21.5	11.9 m
Maximum dispersion	10.1	0.84 m
Number of dipoles	30	16 / 64
Dipole length	4.5	0.9 / 1.8 m
Dipole field (max)	1.24	1.37 T
Full good field aperture (Hor)	80	80 mm
Number of quadrupoles	40	94
Quadrupole length	0.3	0.6 m
Max. quadrupole strength (B')	18.4	20.6 T/m
Full good field aperture	80	80 mm
Number of sextupoles	10	64
Number of sextupole families	2	2
Max. sextupole strength (lB'')	5.6	48.5 T/m
RF frequency (injection)	49.5	49.9 MHz
RF frequency (extraction)	62.0	63.0 MHz
RF voltage	350	350 kV
Synchronous phase angle	30°	30°
Cycle time	0.1	0.1 sec

What's New In SSC Injection Since CDR

a presentation for
SSC Injector Workshop
by
Arch Thiessen
10 October, 1988

LEB Transverse Injection

- H- Injection...,
  Colton & Thiessen,
  LA-UR-88-2532

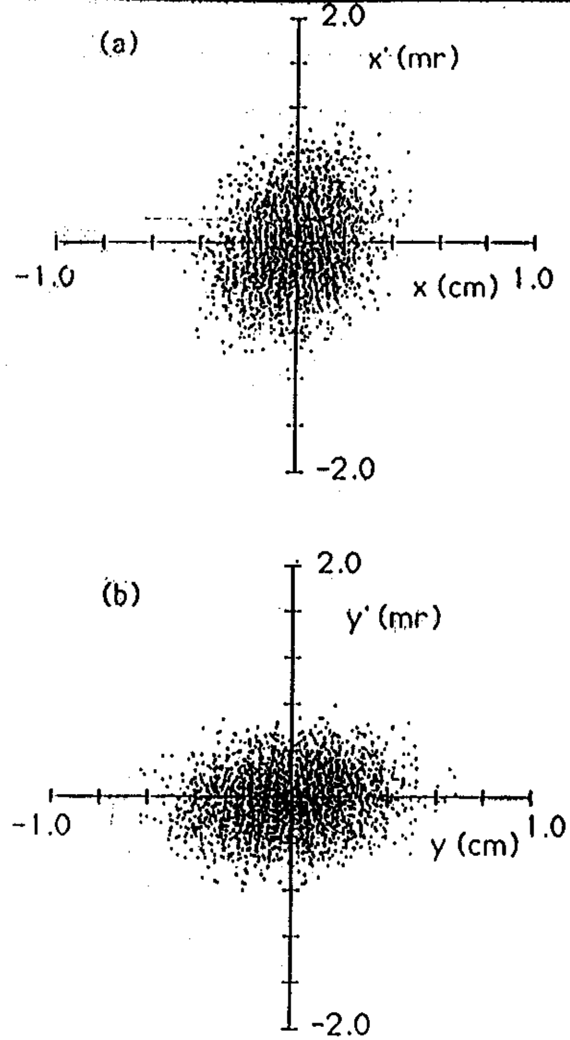
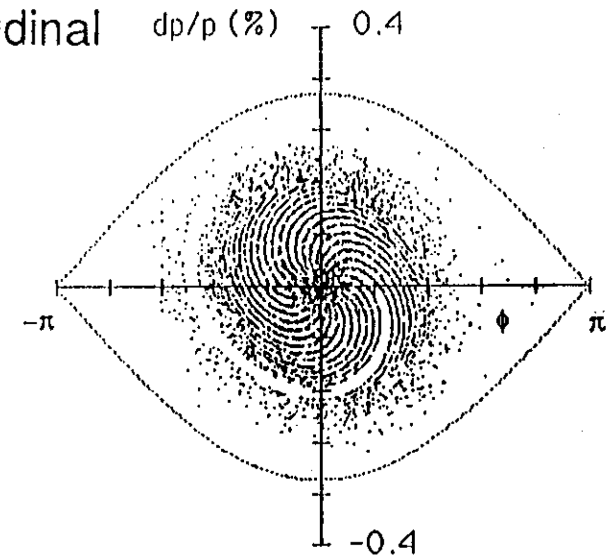


Figure 8: Injection phase-spaces at the foil location after 20 turns of injection: (a) x-x' distribution; (b) y-y' distribution – y is measured relative to a 2.33 cm bump.

LEB Longitudinal Injection

- H- Injection...,
Colton & Thiessen,
LA-UR-88-2532

"1 of 9"
Longitudinal



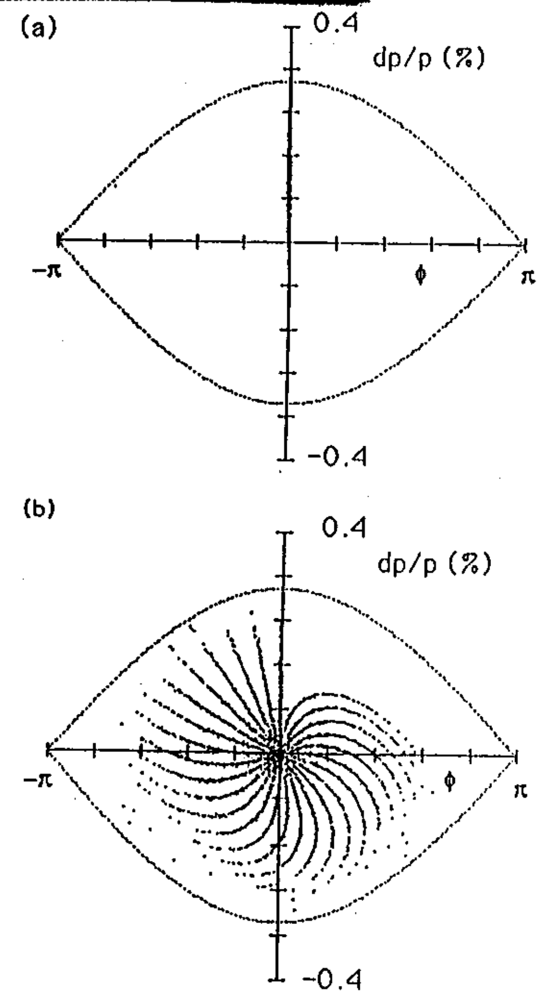


Figure 4: (a) Injected microbunch within an existing 49.9 MHz rf bucket. (b) Longitudinal phase space after 26 turns of injection. Rms single bunch area $A_s = 1.82\pi \times 10^{-3}$ eVs.

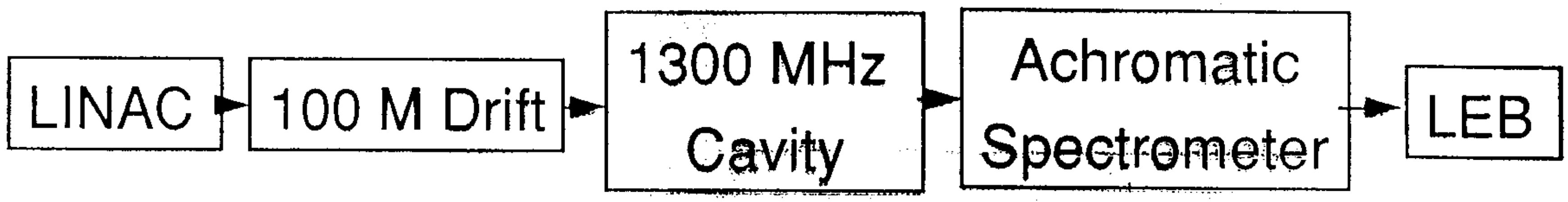
Important: Linac Output dp/p must be controlled

- dp/p rms 0.05% required
- dp/p offset 0.12%

- little or no dp/p width control available in linac
- requires long drift followed by cavity
  - 100 M drift, ~2 MV 1300 MHz
  - ballpark of cavity required

- only way to measure dp/p - **switchyard spectrometer**

Recommendation



Other Items

- Chopper Design
  - LAMPF has 40 MHz Chopper & Slow Chopper
  - Difficult to Control Transverse & Longitudinal
  - EHF has a design
- RFQ Choice
  - 50 MHz vs 200 MHz
  - note that 200 MHz requires additional chopper

Future Upgrades

- All Large Synchrotrons Have Upgraded Injection Energy !
- A Magic Energy Exists
  - 1132.5 MeV - 1 of 8 Injection
  - velocity = 9/8 x Velocity(600 MeV)
- To Upgrade
  - Replace RFQ & Chopper
  - Add 532.5 MeV SCL Linac
- Recommendation
  - leave extra 75 meter space!
  - design spectrometer with missing magnets
  - leave space in LEB for 1132 MeV injection

T. Bhatia
Oct. 10, 1988

SSC LINAC

LEB LATTICE

Painting Scheme

⇒

Defines SSC Linac Parameters

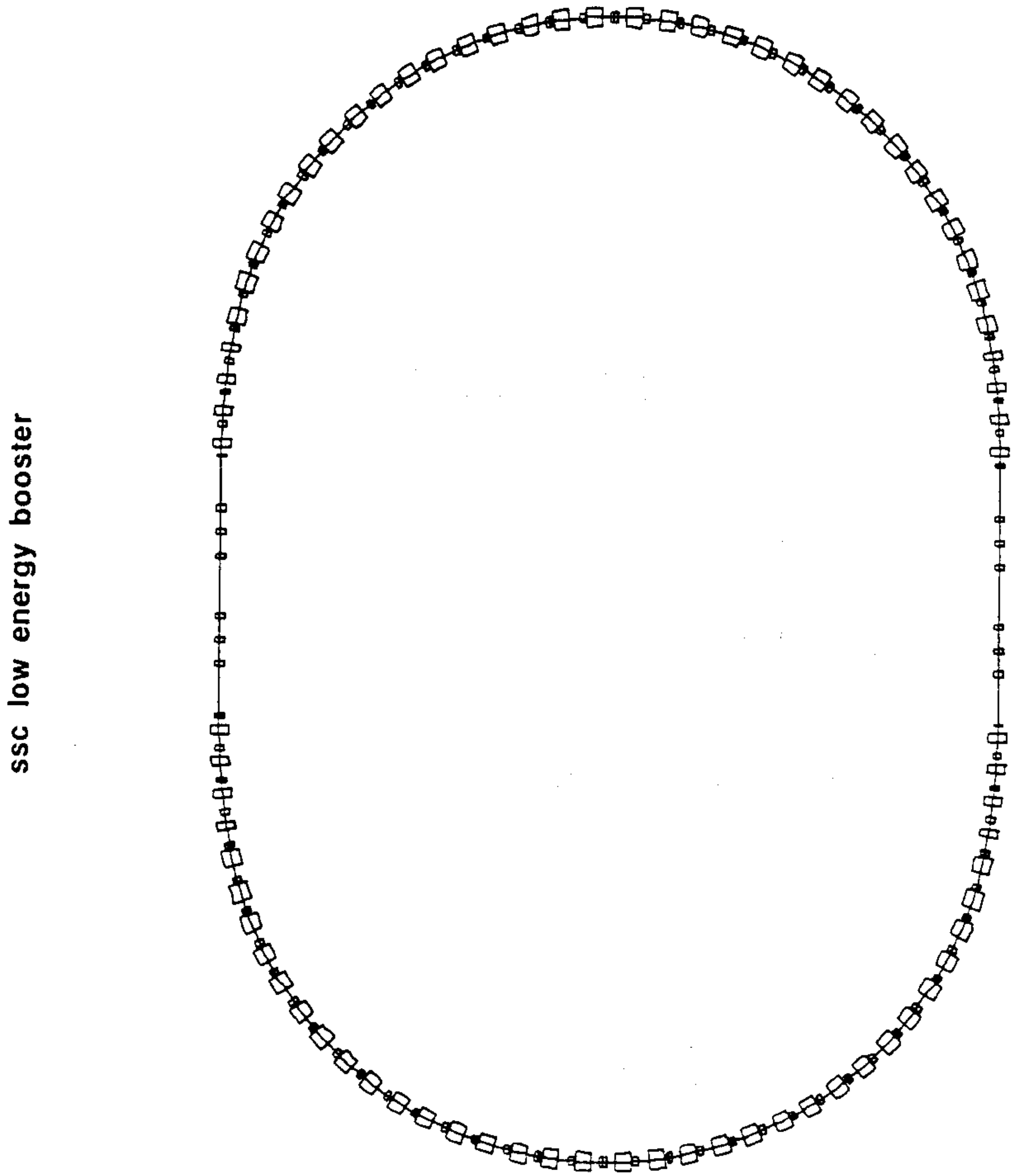


Figure 1: Plan view of the Low Energy Booster. Circumference is 342.71 m.

SSC LEB

1.22 GeV/c → 8.45 GeV/c

or 0.600 Gev → 7.56 GeV

50 MHz micro bunch structure

3.8×10^8 H^- per micro bunch

ε^t (n, rms) = 0.45 π mm·mrad

ε^ℓ (n, rms) = 1.7×10^{-5} eV·s
= 5.4 π mm·mrad

circumference = 342.71 m

26 turn injection

SSC LINAC PARAMETERS

600 MeV

50 MHz beam bunch structure

ε^t (n, rms) $< 0.45\,\pi$ mm·mrad

ε^ℓ (n, rms) $< 5.4\,\pi$ mm·mrad

$(1.7 \times 10^{-5}\ \pi\ \text{eV·s})$

3.8×10^{8} part./bunch

$$\underline{3.8 \times 10^{8}} \times \underline{50 \times 10^{6}} \times \underline{1.6 \times 10^{-19}} \times \underline{10^{-3}}$$

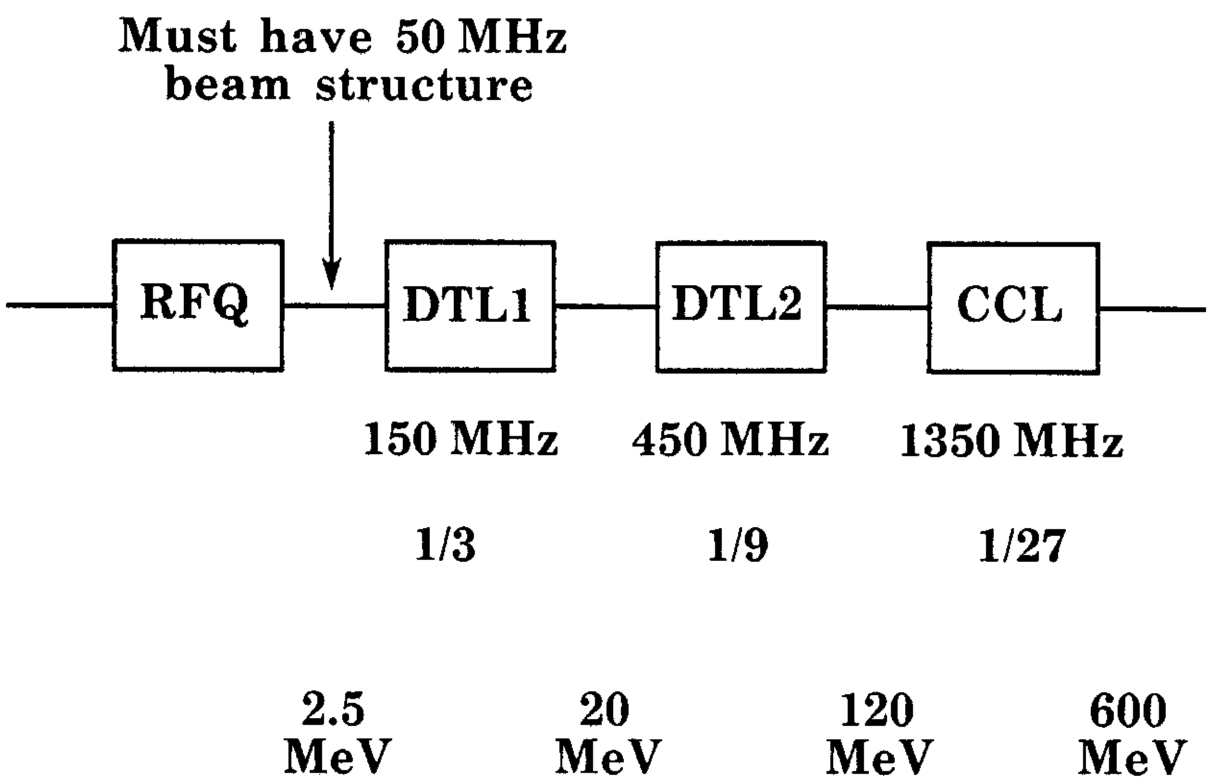
or 3.04 mA average beam

Pulse length $72 \times 26 \times 20$ ns $= 37.44\ \mu$s

Rep. rate 10 Hz

Duty factor 0.037%

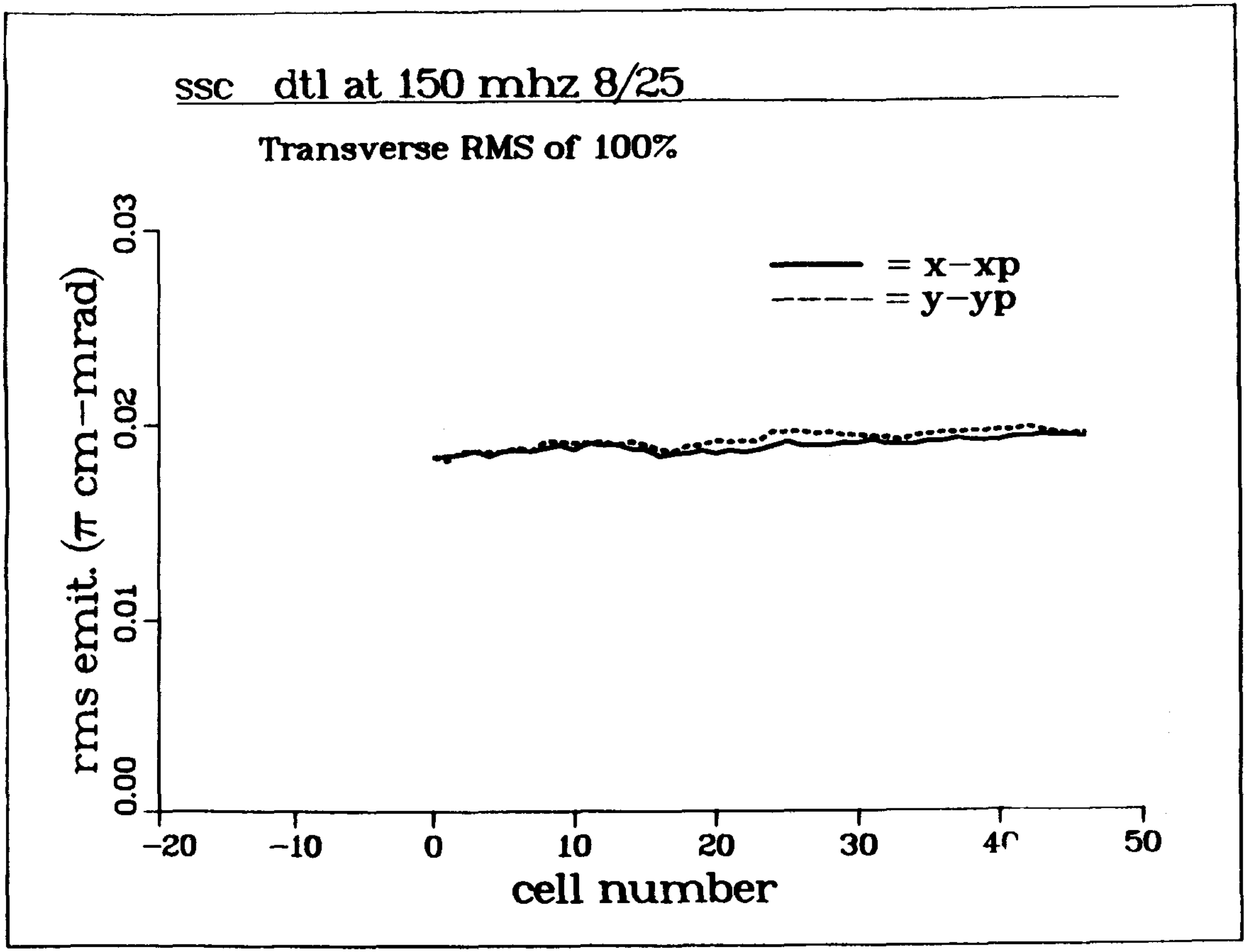
SUGGESTED SSC LINAC



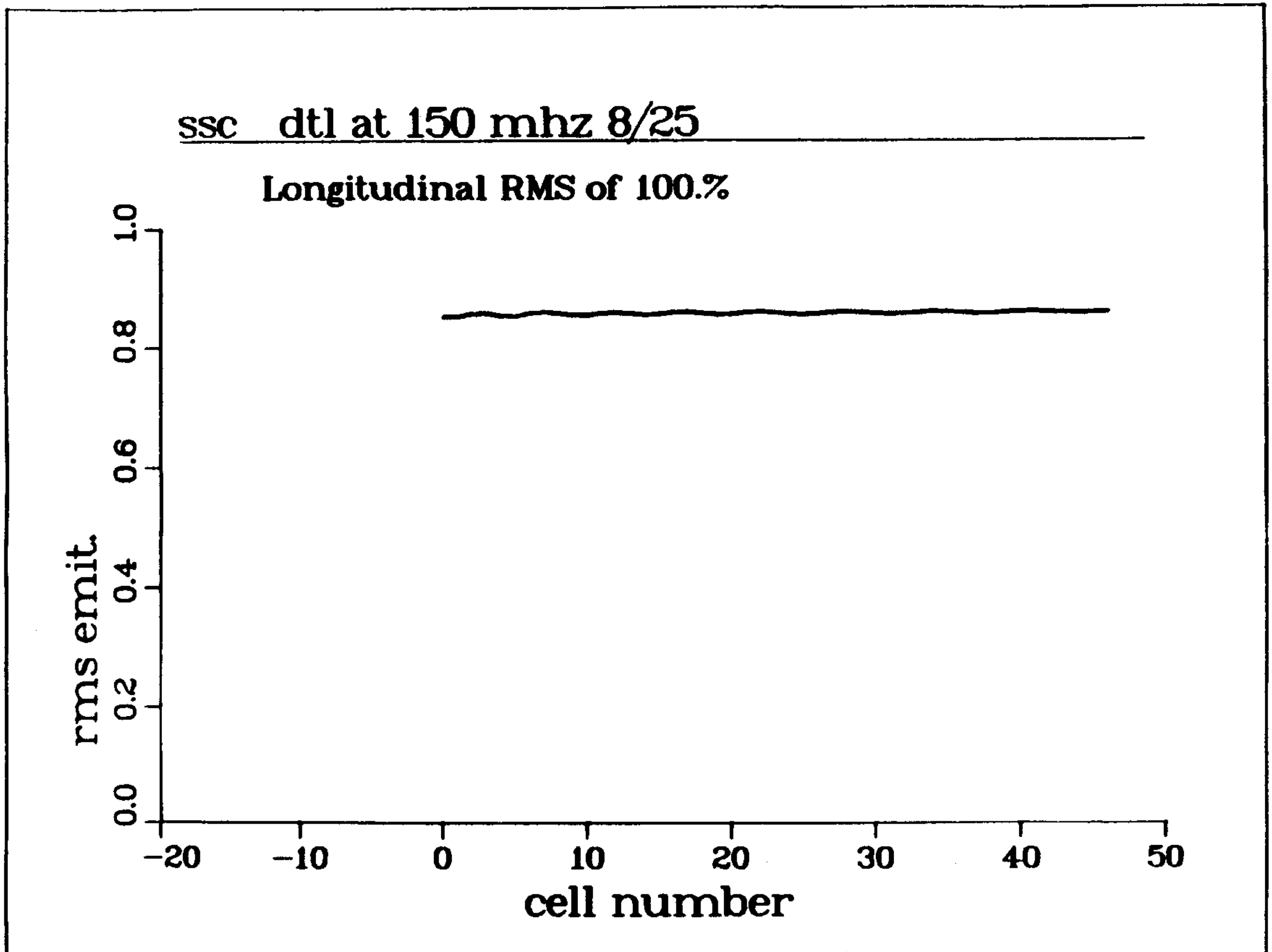
At 600 MeV $\varepsilon^t < 0.45\,\pi$ mm·mrad

$\varepsilon^\ell < 5.4\,\pi$ mm·mrad

TRANSVERSE EMITTANCE - DTL1



LONGITUDINAL EMITTANCE – DTL1



Assuming ~10% growth (transverse and longitudinal) in each structure following the RFQ

At RFQ end must have

$$\varepsilon^{t} < \mathbf{0.35}\ \pi\ \mathbf{mm \cdot mrad}$$

$$\varepsilon^{\ell} < \mathbf{4.2}\ \pi\ \mathbf{mm \cdot mrad}$$

SSC LINAC

2.5 MeV H^- RFQ

f	C_{out}	ε_o^t	ε_o^ℓ	
MHz	mA	π mm·mrad	$\pi\ 10^{-5}$ eV·s	π mm·mrad
50	3	0.18	2.60	8.26
100	6	0.15	1.00	3.18
150	9	0.14	0.45	1.43
200	12	0.12	0.30	0.95

<u>Either</u>

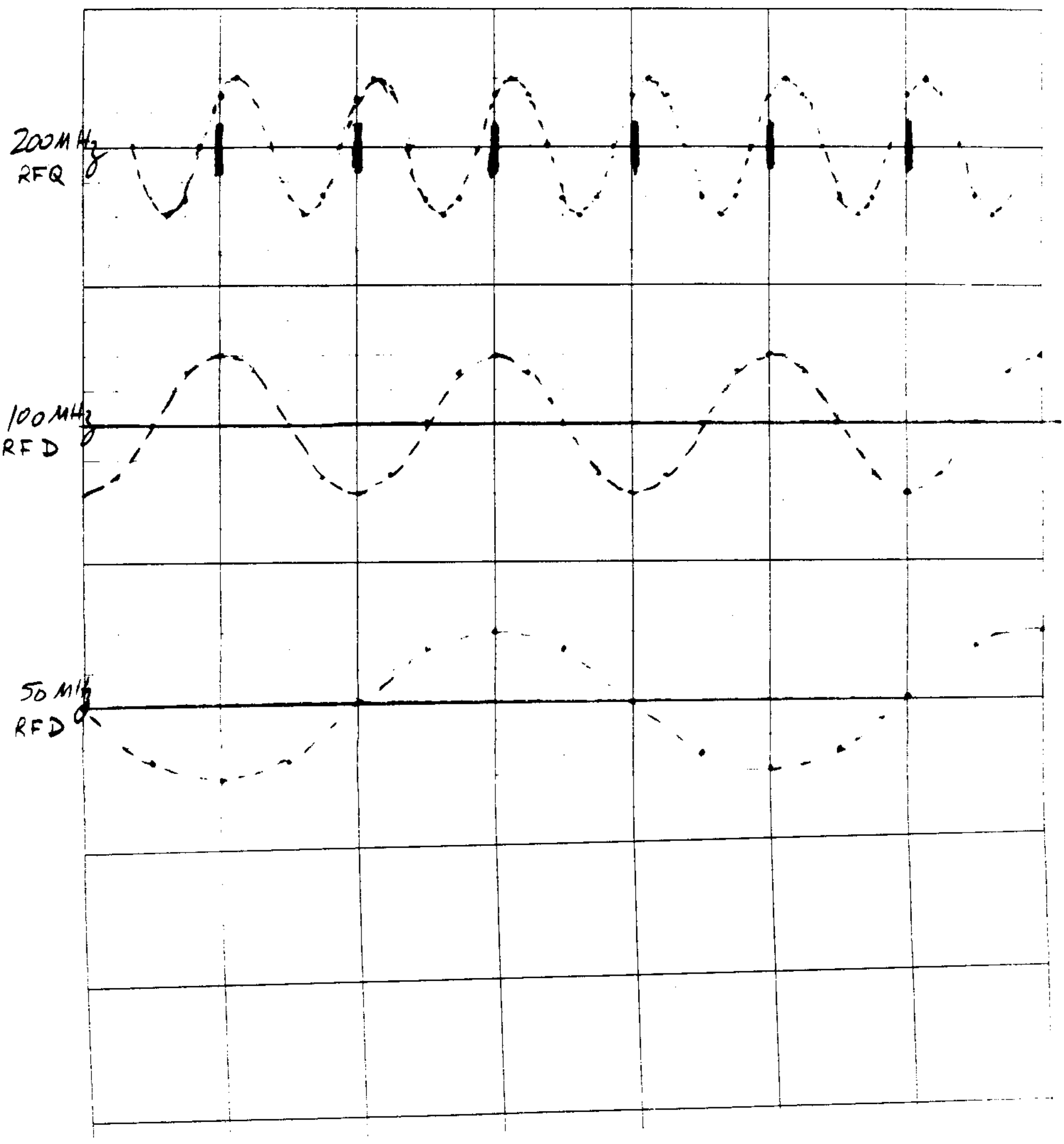
1. **Relax the ε^{ℓ} requirement by $\times 2$**

   $\Rightarrow$ Start with 50 MHz RFQ

<u>Or</u>

2. **Start with higher frequency RFQ and convert the beam bunch structure to 50 MHz**

RF DEFLECTOR SCHEME



1. 50 MHz

2. a. 150 – 200 MHz

b. RF Def. ______

c. Laser Neut. ______

– d. long Def 2.5 MeV
600 MeV

S. Holmes

(Transverse) Emittance Control in the SSC Linac

1. SSC Specification
2. SSC Linac Specification
3. Performance of Fermilab Linac
4. Emittance Dilution Effects
5. Questions

SSC Specification

$N = 7.3 \times 10^9$ /bunch

ϵ (normalized, rms) = 1 mm-mrad

Bunch separation = 4.8 m (I_{beam} = 73 mA)
(9.6, 19.2 m also available)

SSC Linac Specification

The real spec is:
Fill the LEB in a finite # of turns via H^- injection, such that

$$\epsilon \leq .73 \text{ mm-mr}$$

$$N \geq 7.3 \times 10^9$$

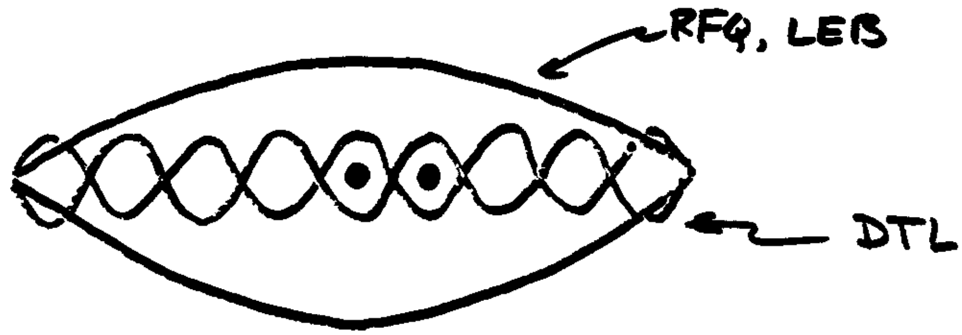
out of LEB.

In SSC CDR ϵ is determined by space charge in the LEB:

$$\Delta\nu_{sc} = .16 \quad \text{(Conservative)}$$

These requirements are satisfied by CDR Linac

	E_{out}	Current	ϵ	f
Ion Source	50 kV	13.8 mA	.08 mm-mr	—
RFQ	2.5 MeV	13.0	.44	49.5 MHz
Cavities, Chopper	"	"	"	"
DTL	125	3.9 (macro) 17.6 (micro)	.45	445.2
SCL	600	3.9	.45	1336



2.5×10^8 H^-/bunch → $J_{peak} = 17.6$
× 2 bunches/LEB bucket $I_{av} = 3.9$
× 20 turns

1×10^{10}

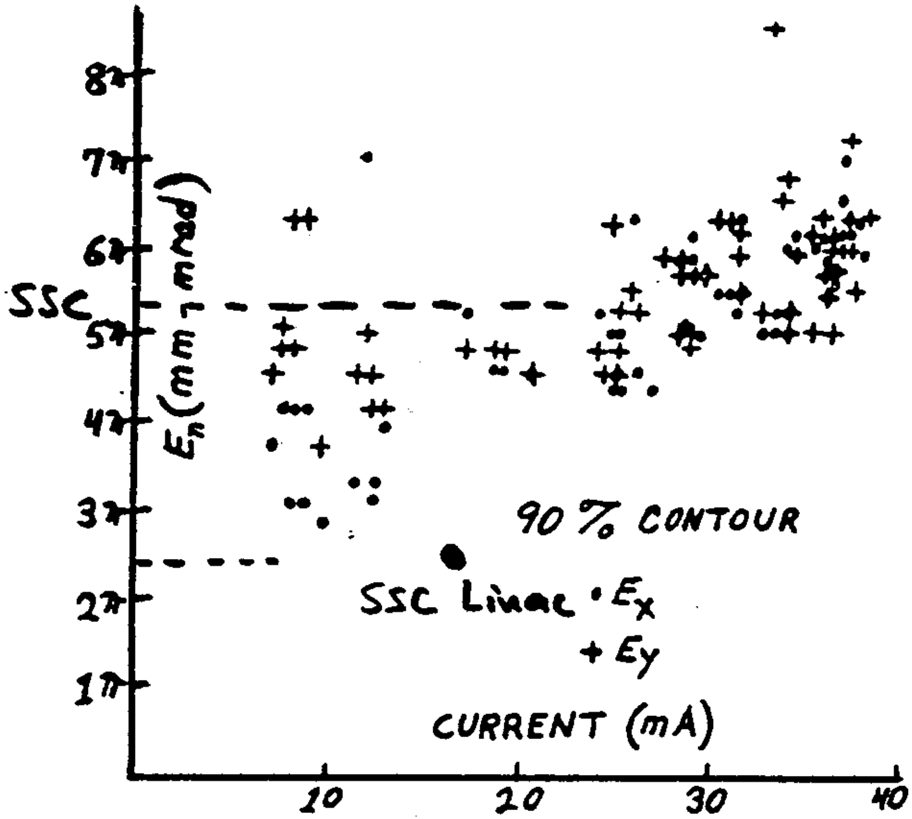
Note: All emittance growth is assumed to be below 2.50 MeV.

DTL capture is 30%.

Fermilab Linac

	PreAcc	Linac (in)	Tank 1 (out)	Linac (out)
E (MeV)	.75	.75	10	200
I (mA)	50	50	35	35
ϵ_H (mm-mr)	0.19	.44	.95	.95
ϵ_V (mm-mr)	0.29	.49	1.0	1.0

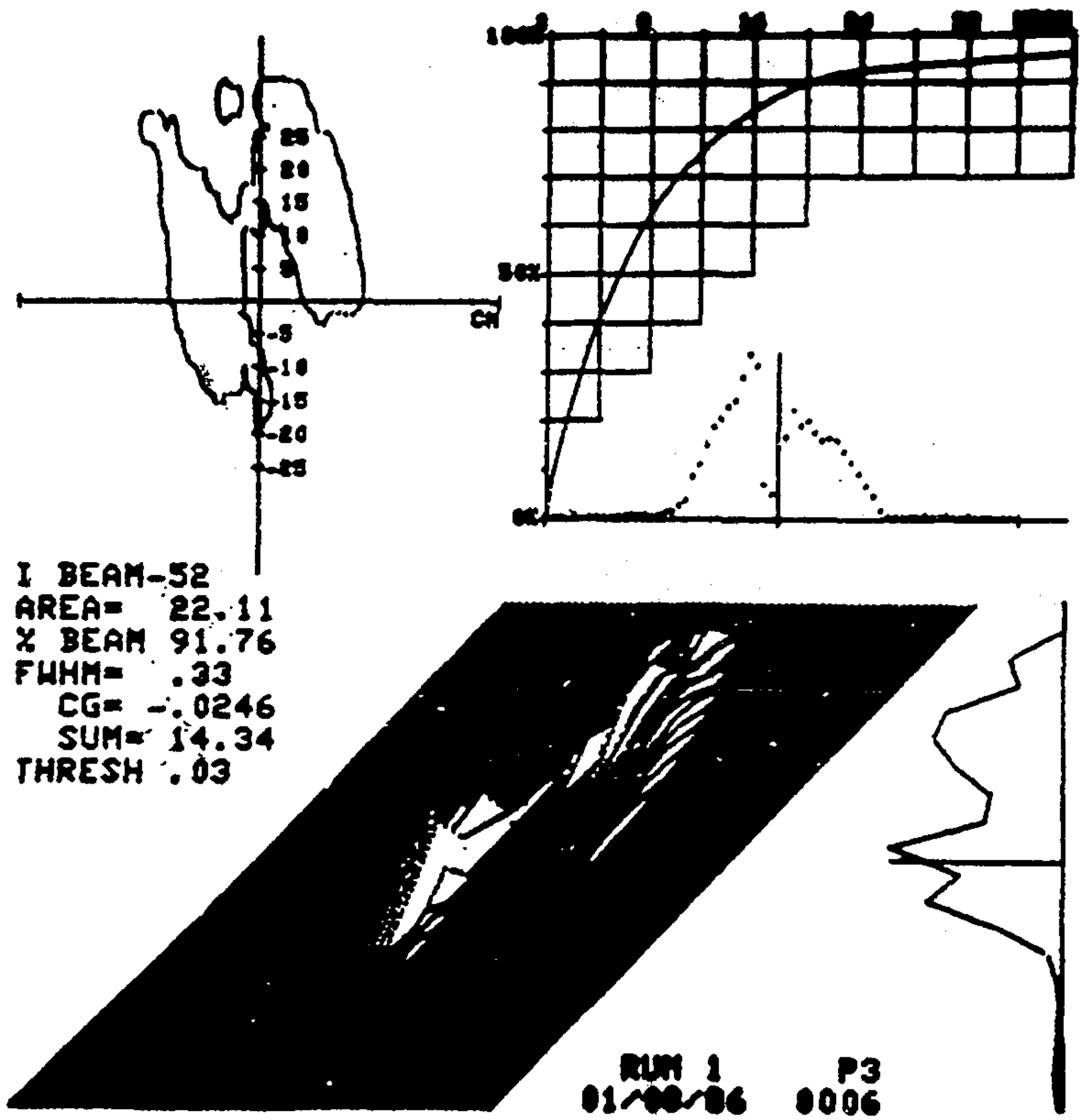
Note: All beam loss + growth below 10 MeV.



200 MeV LINAC OUTPUT EMITTANCE VS.
BEAM CURRENT FOR VARIOUS CONDITIONS

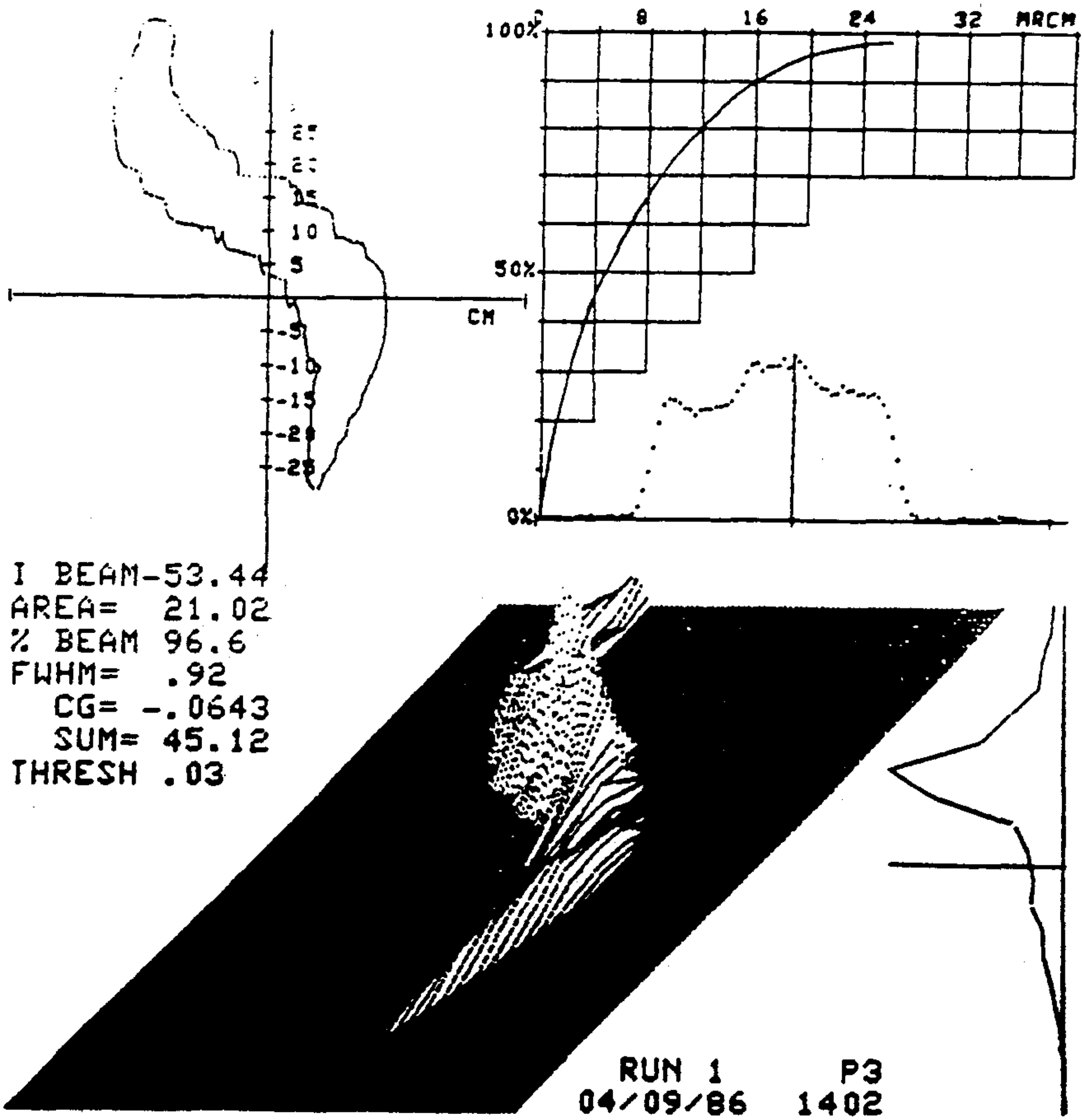
LINAC INPUT EMITTANCE (horz)

750 keV LINE at LOW PRESSURE (2 X 10 -6 Torr)



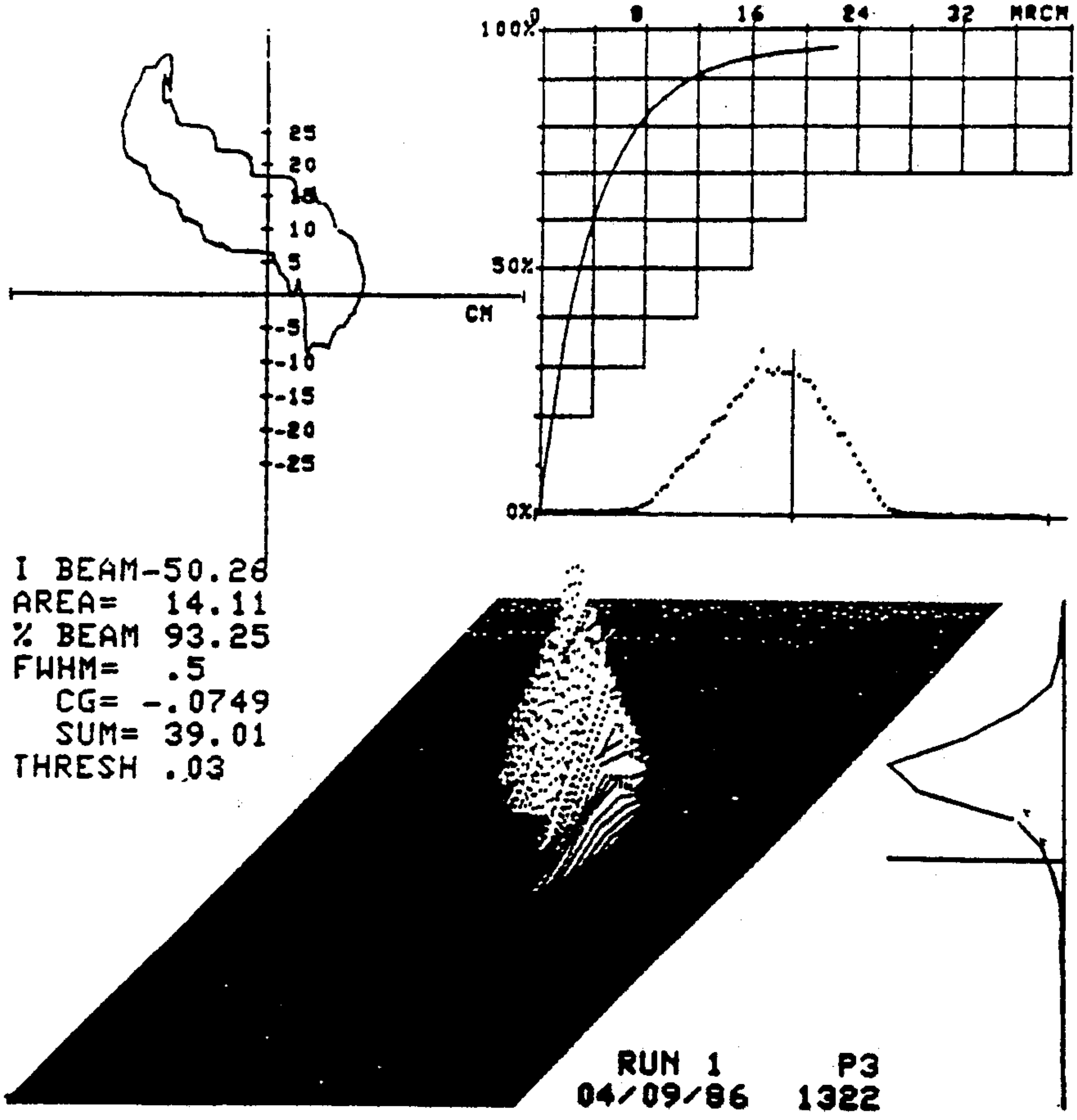
LINAC INPUT EMITTANCE (horz)

750 keV LINE at LOW PRESSURE (2 X 10 -6 Torr)



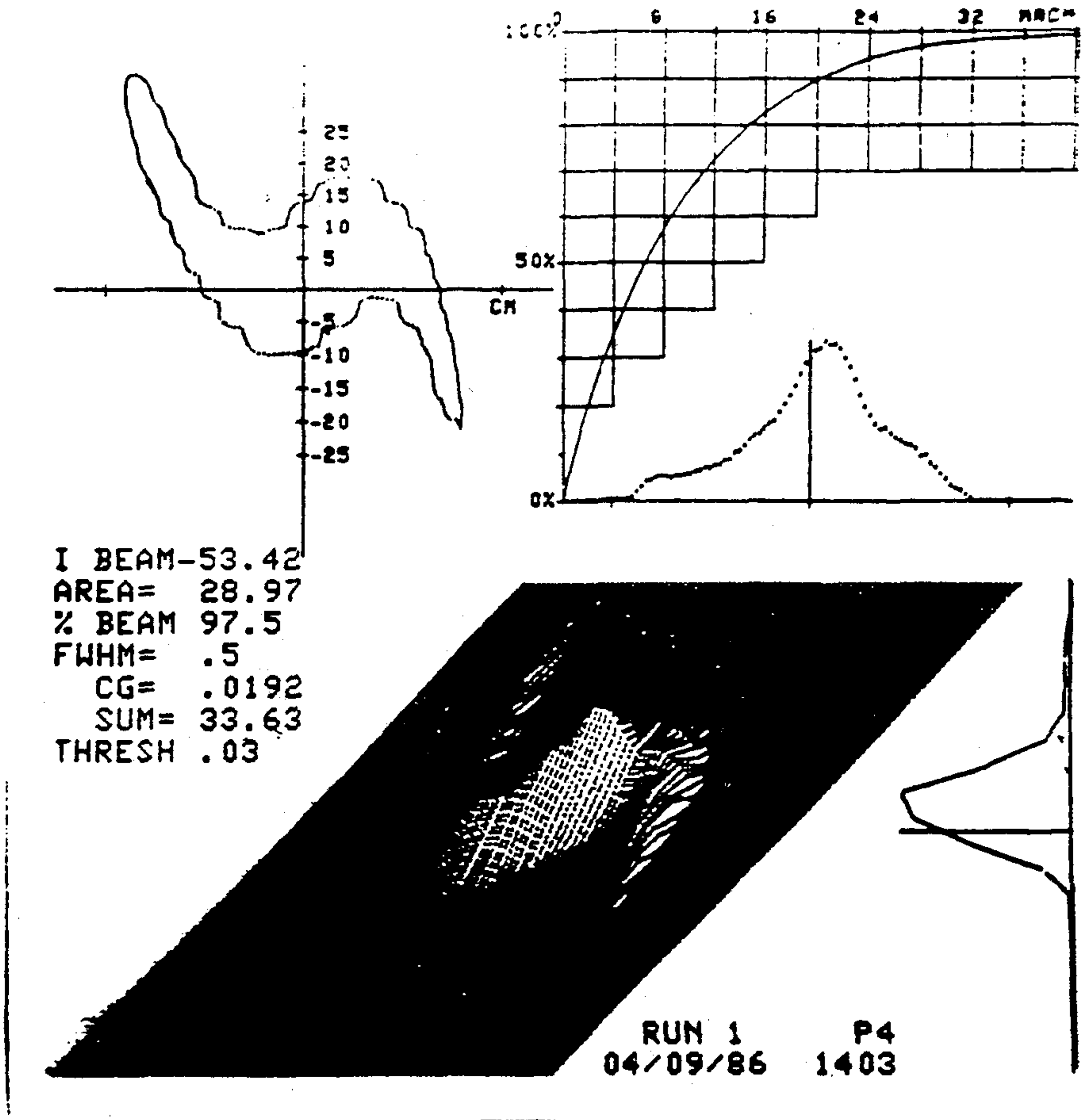
LINAC INPUT EMITTANCE (horz)

750 keV LINE at HIGH PRESSURE (1.5 X 10 -5 Torr)



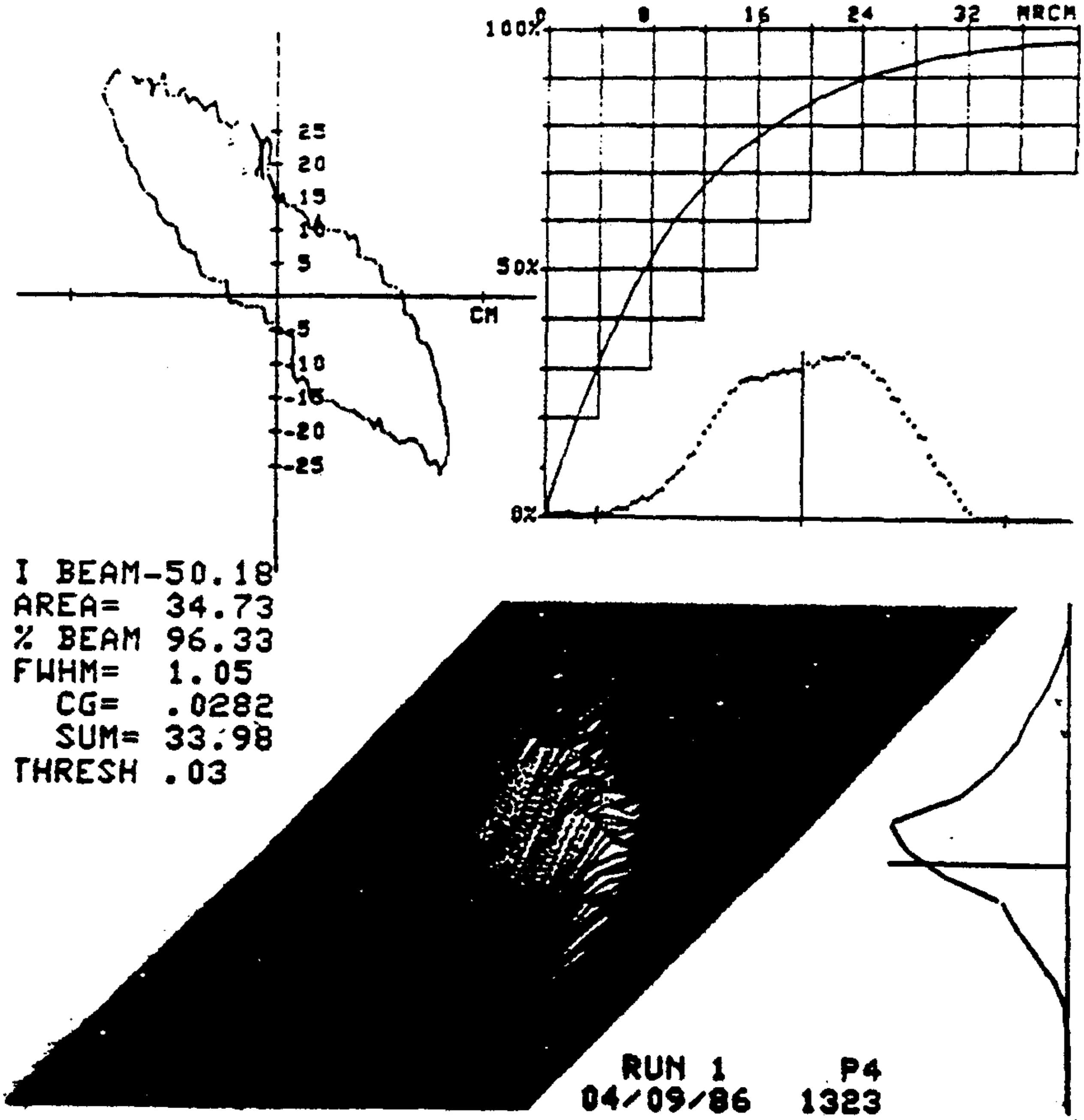
LINAC INPUT EMITTANCE (vert)

750 keV LINE at LOW PRESSURE (2×10^{-6} Torr)

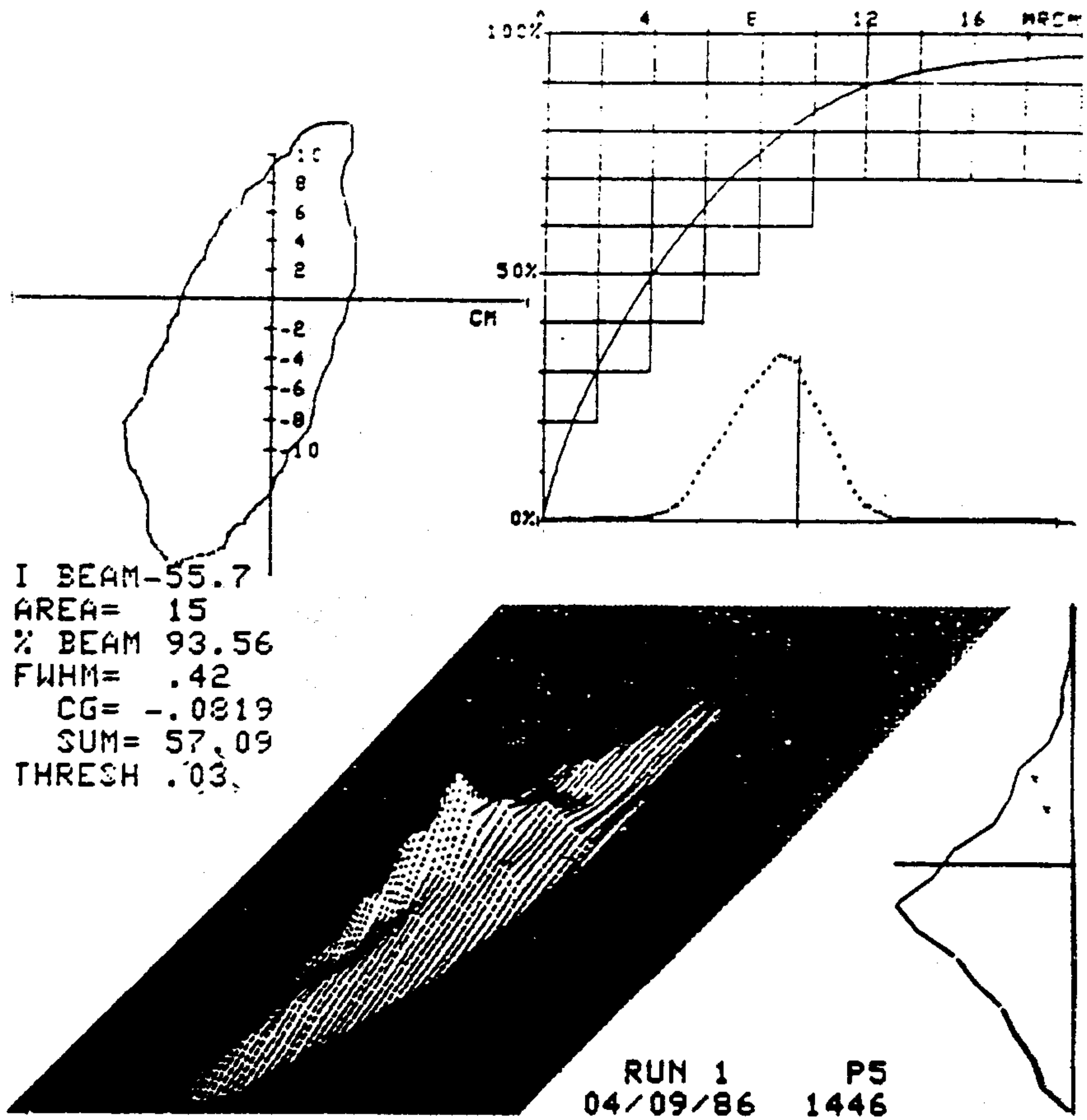


LINAC INPUT EMITTANCE (vert)

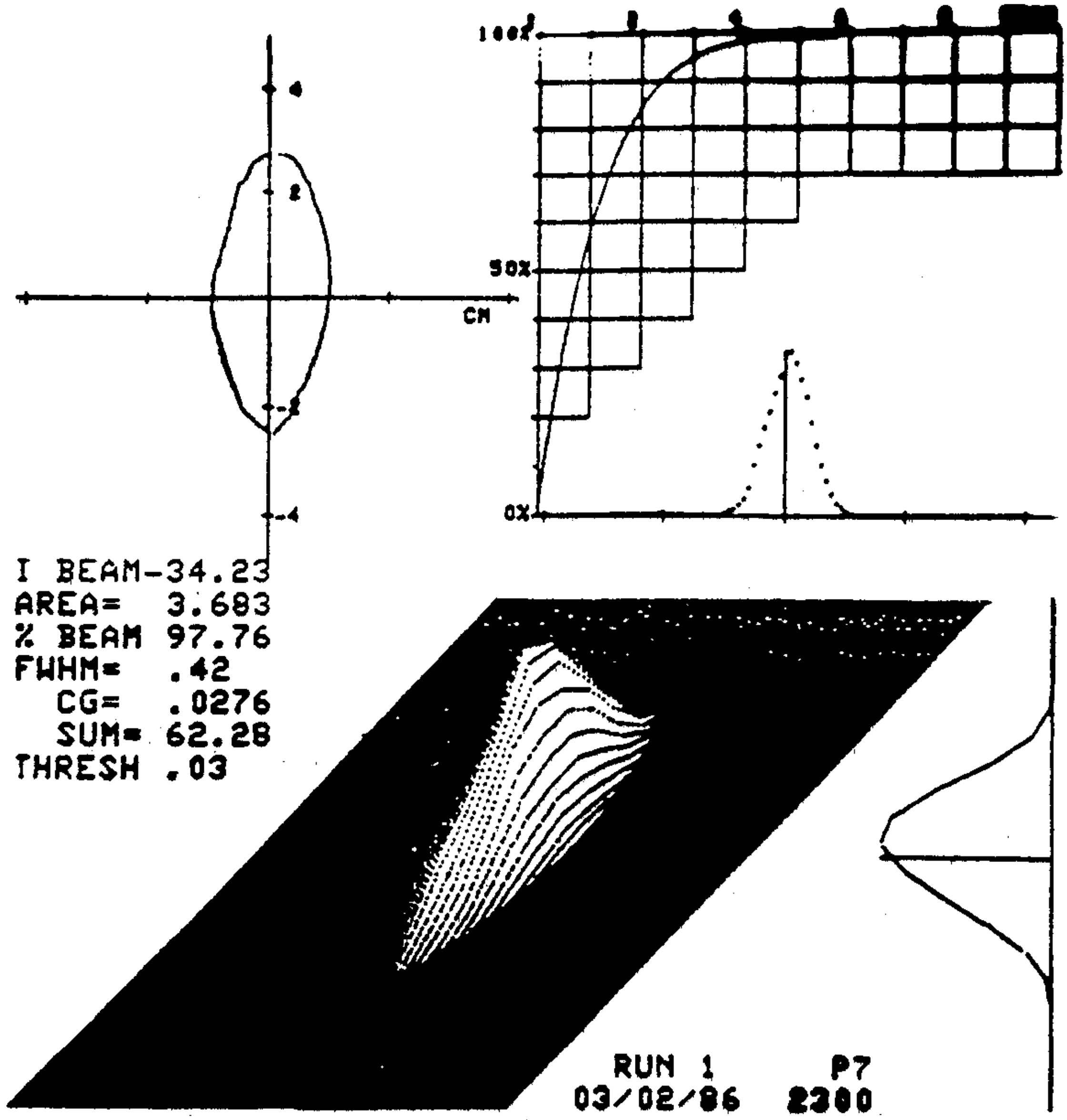
750 keV LINE at HIGH PRESSURE (1.5 X 10 -5 Torr)



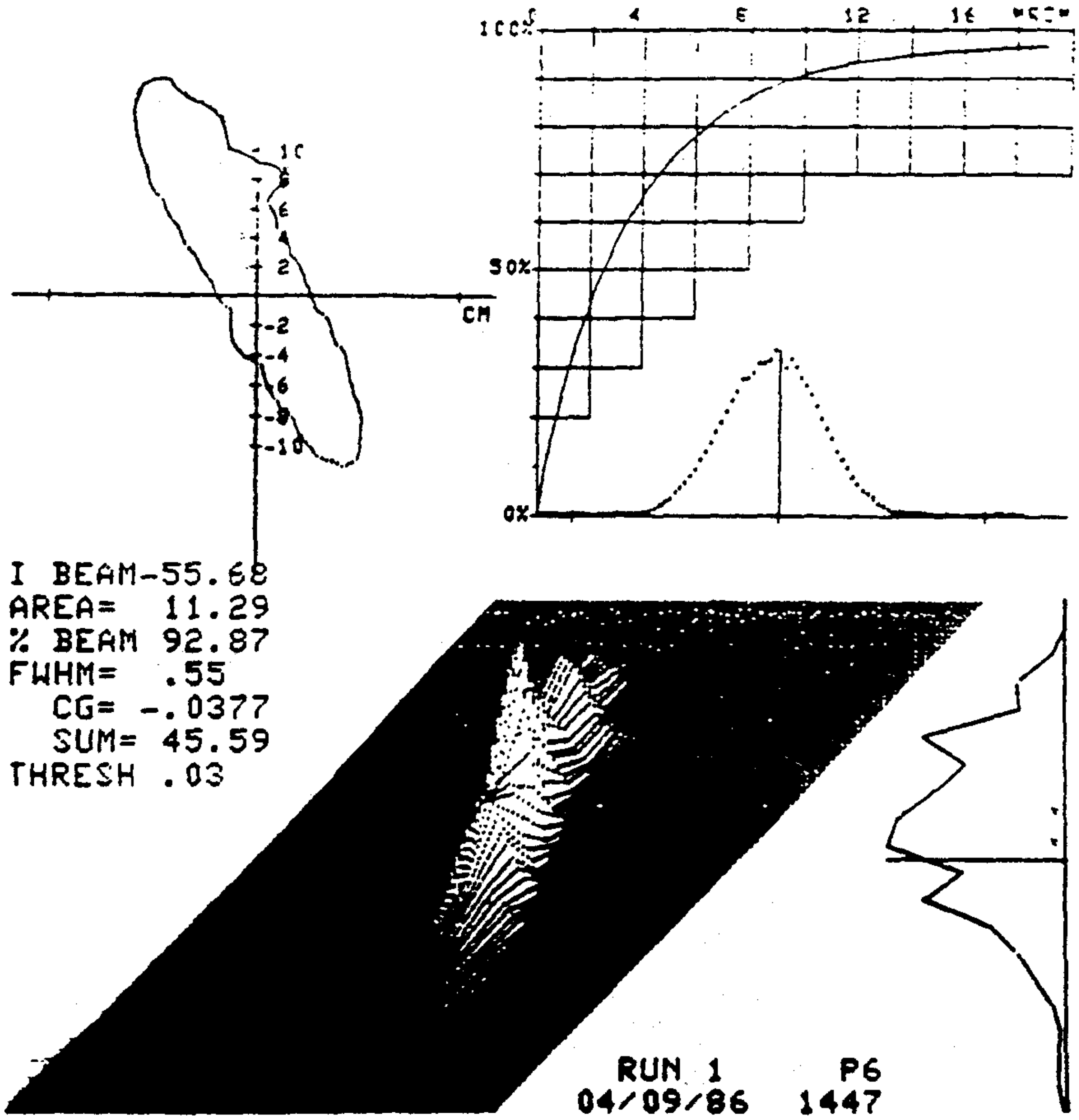
LINAC TANK 1 EMITTANCE (horz)
10 MeV



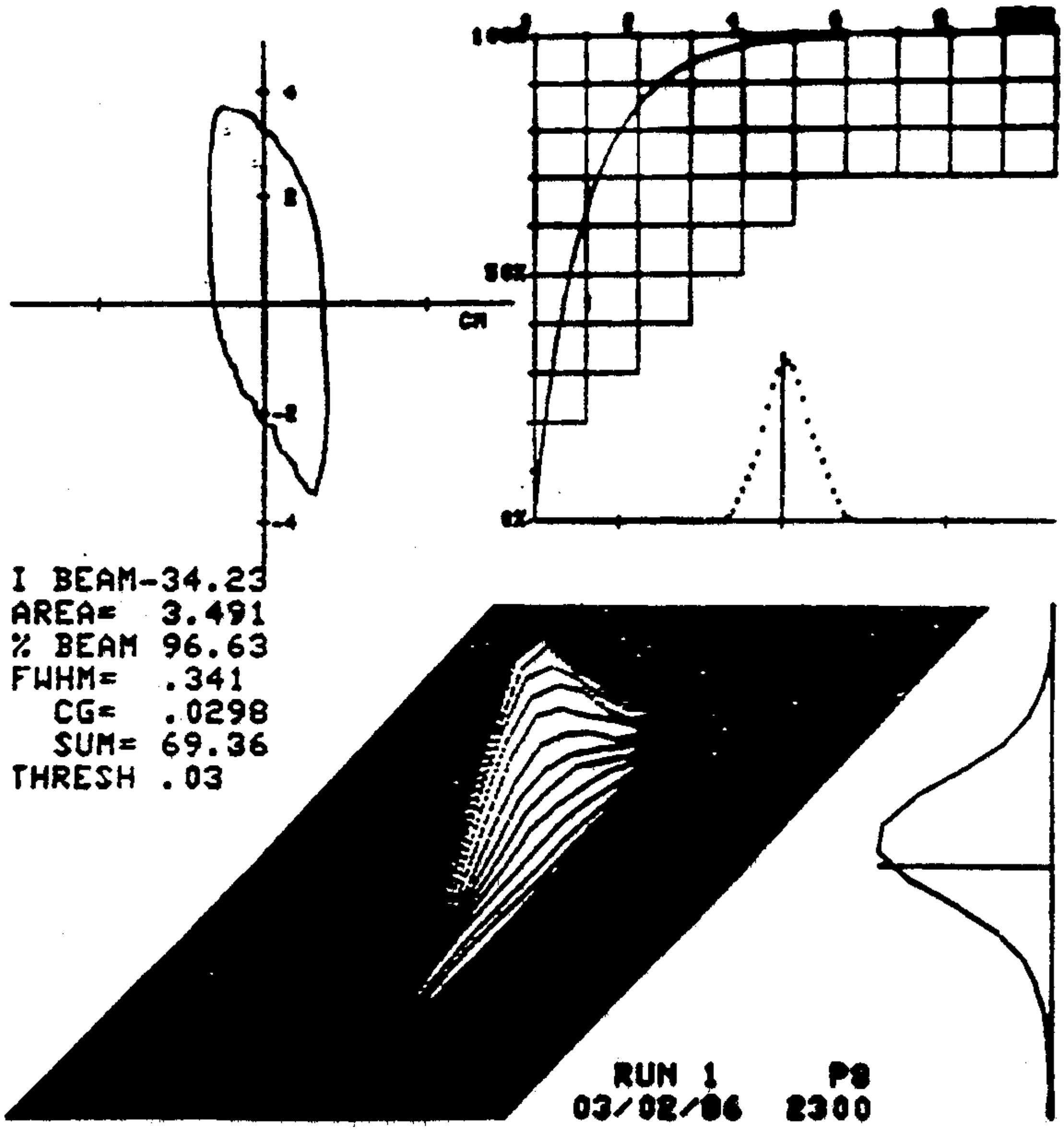
LINAC OUTPUT EMITTANCE (horz) 200 MeV



LINAC TANK 1 EMITTANCE (vert)
10 MeV



LINAC OUTPUT EMITTANCE (vert)
200 MeV



Emittance Dilution

① Mismatch to Linac

② Space Charge

$$X'' = -k^2(z)X - \frac{e E_{sc}(x)}{m\gamma^3 v^2}$$

↑ Focussing elements ↑ Space Charge

$$E_{sc} \propto \frac{N}{\epsilon}$$

⇒ Get beam going quickly - RFQ

or,

Keep N small - multiturn into LEB

③ Alignment

④ Longitudinal/Transverse Coupling.

⑤ Transition from DTL → SCL.

→ Studied for FNAL Linac Upgrade

200 MHz DTL → 800 MHz SCL

$\Delta\epsilon \lesssim 2\%$ with appropriate transition section.

Questions

① Does any of this matter?

- Since N/ε is ultimately limited by LEB, why not just turn up turns and turn down N to meet spec.

  or, perhaps collimate at LEB exit.

- Why not run with Ipeak = Iav and do adiabatic capture in LEB?

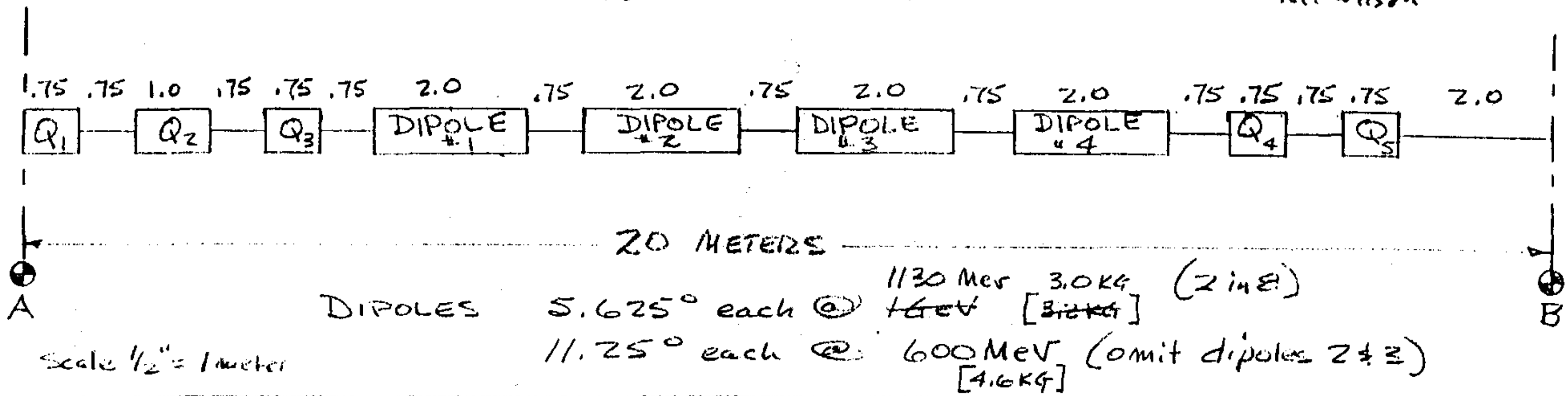
  or, Higher frequency RFQ? Better DTL capture efficiency.

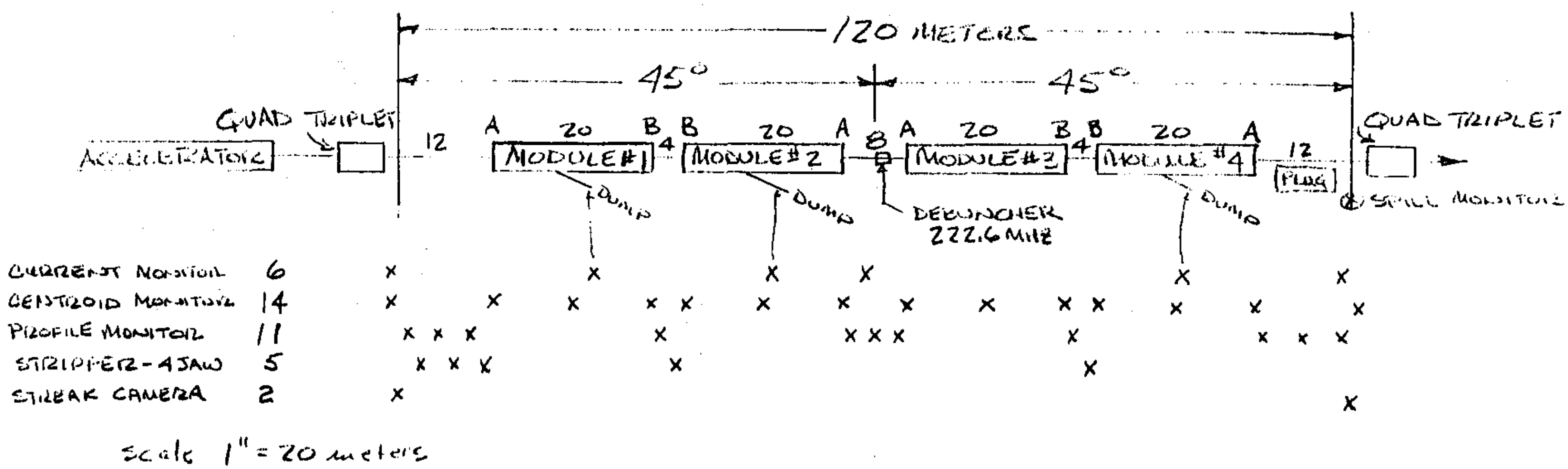
② How about replacing LEB with an 8 GeV Linac?

- This probably makes spec. on linac more stringent.

1.29.8
Mak…
Arch
M. Wilson

22½° BEND MODULE





10-11-88
R. Steining

LINAC UPGRADES

1. LUMINOSITY

$$\mathcal{L} \propto \frac{M^2}{\epsilon} \qquad \sigma \propto \frac{1}{E^2}$$

EVENT RATE $\propto \mathcal{L}\sigma$

$\Rightarrow$ NEED HIGHEST ENERGY AND HIGHEST LUMINOSITY AT THE SAME TIME.

SYNCHROTRON RADITION

$$P \propto \frac{E^4}{\rho}$$

PROTON LOSES 124 KeV/REV AT 20 TeV

AT DESIGN SPEC

$$P_{TOTAL} = 18.3 \text{ kW}$$

PROBABLY LOST AT 4.3°K $\Rightarrow$ 18 MW OF REFRIGERATOR POWER

MAGNETS ARE MOST SENSITIVE TO HEAT LOAD AT 20TeV

⇒ METHODS OF INCREASING $\mathcal{L}$ AT 20 TeV ARE EXPENSIVE IF $\mathcal{N}$ INCREASE IS THE ROUTE.

⇒ NEED TO PRESERVE OPTION OF $\mathcal{L}$ INCREASE VIA ϵ DECREASE.

<u>LEB INJECTION IS WEAK POINT FOR ϵ REDUCTION.</u> SHOULD PRESERVE OPTION FOR HIGHER ENERGY INJECTION

a. H^- STRIPPING AT HIGHER ENERGY IN BENDS (DO QUADS STRIP ALSO ?)

b. QUANTIZED OR CONTINUOUS ENERGY INCREMENT OPTIONS ?

c. DEBUNCHERS + DRIFTS MUST WORK AT HIGHER ENERGY

$$\Delta V \propto \frac{1}{\gamma^2}(\beta\gamma)^{\frac{1}{2}} \frac{1}{\beta\gamma} = \gamma^{-\frac{5}{2}}/\sqrt{\beta}$$

E-B   BEAM SIZE   RESPONSE

600 → 800 MeV

$\Delta V \rightarrow 0.48\,\Delta V$

2. POLARIZATION

SPACE FOR PRODUCTION
DIAGNOSTICS

3. MISSING BUCKET OPTIONS

SPACE TO DO LATER IF NOT AT $t=0$.

4. OTHER USES FOR LINACS

TEST BEAMS
MEDICAL RESEARCH

5. SPACE FOR THINGS NOT YET INVENTED!