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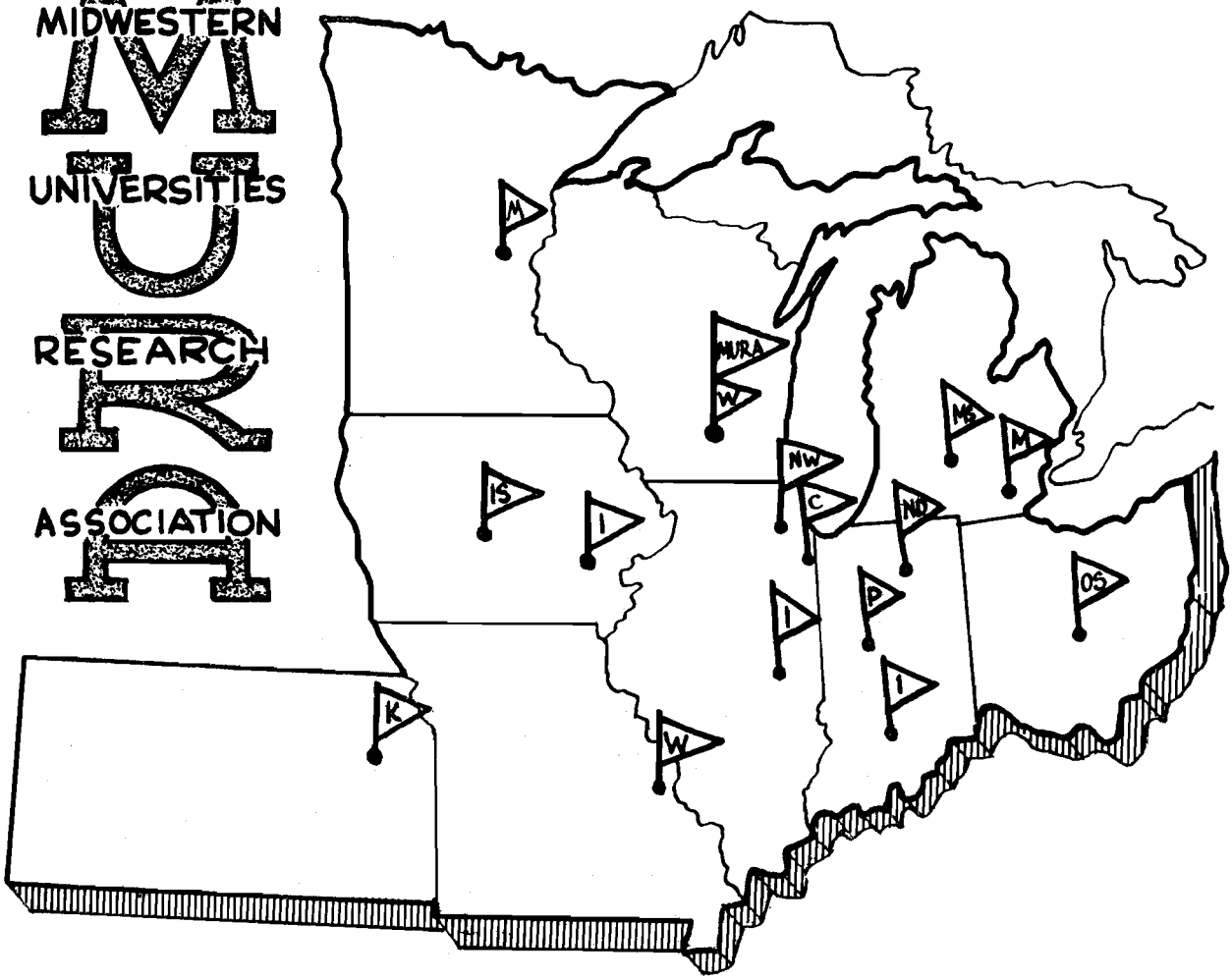

ESTIMATED PARAMETERS, PERFORMANCE AND COST OF COLLIDING BEAM DEVICES

K. R. Symon

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K. R. Symon

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INTRODUCTION

In this report we attempt to make a brief estimate of the probable performance characteristics and comparative costs of various methods which have been proposed to achieve colliding beams. For purposes of comparison, we will consider in each case a machine designed to produce two colliding beams of 15 Gev protons. The most thoroughly studied machine, and the only one about which we can be fairly definite as to cost and performance, is the two-way accelerator proposed by Ohkawa.[1] We will discuss this case first, and use it as a standard of comparison for the various storage ring possibilities and other methods.

TWO-WAY ACCELERATOR

A fairly detailed feasibility study for a 15 Gev two-way accelerator was made in 1957-58 by MURA,[2] and a cost estimate for this accelerator was made by William M. Brobeck & Associates.[3] A list of parameters is given in Table I.

A plan view of the complete accelerator is shown in Fig. 1. The accelerator ring would be approximately 1200 feet in diameter. Around this ring are situated 124 magnets whose total weight includes approximately 62,500 tons of iron and 3000 tons of copper. The power required is approximately 50,000 kilowatts. The accelerator proper is housed in a toroidal tunnel approximately 60 feet across inside and 45 feet high and is shielded

TABLE I

Parameters of the Accelerator

N = 66 (number of sectors per revolution)

N' = 2 (number of superperiods per revolution)

k = 212 $\left(= \frac{r}{B} \frac{\partial B}{\partial r}\right)$

E_{inj} = 50 Mev (injection energy)

E_o = 15 Gev (maximum output energy)

R_o = 180 meters (maximum radius of 15 Gev orbit)

ρ_o = 31 meters (minimum radius of curvature of 15 Gev orbit)

C = 5.8 (circumference factor)

ΔR = 4.9 meters (radial aperture)

A_{inj} = 35 cm. (vertical aperture inside vacuum tank at injection)

A_o = 6 cm. (vertical aperture inside vacuum tank at 180 m.)

ℓ_o = 80 cm. (normal straight section length)

L_o = 9.3 meters (super straight section length)

L_M = 7.7 meters (length of normal magnet)

ν_x = 24.75 (number of waves of radial betatron oscillation per revolution)

ν_y = 4.30 (number of waves of vertical betatron oscillation per revolution)

$A_x \cong \pm 16$ cm. (radial betatron oscillation stability limit)

$A_y > 23$ cm. (vertical betatron oscillation stability limit)

by earth thrown around and over the tunnel. In addition to the laboratory building and buildings housing certain accelerator components, there are four experimental areas situated around the accelerator.

The accelerator is designed to serve two major experimental purposes. In the first place it will be possible to do colliding beam experiments at 30 Gev in the center-of-mass system. In the second place intense single beams of 15 Gev protons will be available for single beam experiments. Two of the four experimental areas are devoted to single beam experiments and two to colliding beam experiments.

Two experimental areas are devoted to colliding beam experiments, one of which is shown in Fig. 2. These are located at supersectors where two long straight sections approximately 9 meters in length separated by a magnet approximately 9 meters in length are available. Two beams of 15 Gev protons circulating in opposite directions around the accelerator will intersect in each of the straight sections.

The circumference of the accelerator is divided into 66 equal sectors. The normal sector which makes up the basic structure of the machine consists of one positive and one negative magnet. The positive and negative magnets are identical except for the direction of the magnetic field which is up in the positive magnet and down in the negative magnet. The symmetry of the accelerator between positive and negative magnet sectors guarantees the equivalence between clockwise and counterclockwise orbits which makes it possible to accelerate simultaneously beams circulating in opposite directions. The normal magnets are approximately 7 meters long, 6 meters wide

radially, and 2.5 meters high overall. Each magnet consists of three pieces separated by radial cuts. Each piece has a top and bottom half. Each half piece weighs approximately 80 tons. The magnets are separated by straight sections approximately one meter long.

In order to provide longer straight sections for the experimental areas, the normal sector structure is interrupted at four points around the circumference by a supersector. The supersector is formed from a group of five adjacent magnets by removing the second and fourth magnets and changing somewhat the width of the first, third and fifth magnets as shown in Fig. 3. Although analytical estimates indicated that such a structure would have stability limits not greatly different from those in a machine without superperiods, computational work has not yet confirmed this point.

The vacuum tank is in the shape of a donut 1200 feet in diameter with a trapezoidal cross section. The outer wall of the vacuum tank is fabricated of stainless steel and is designed to maintain a vacuum of approximately 10^{-6} mm. Hg. Convenient access can be provided through the walls of this tank for the insertion of probes, targets, etc. The basic vacuum of 10^{-6} mm. Hg. will be adequate for the initial adjustments and tests of the accelerator and for the acceleration of high intensity single beams. Since most colliding beam experiments will require a vacuum of 10^{-8} or 10^{-9} mm. Hg., it was proposed to provide for the insertion into the main vacuum tank of an inner vacuum tank or liner designed to maintain a vacuum of 10^{-9} mm. Hg.

Recent experimental work has shown that a much simpler vacuum system can be designed to reach a vacuum of 10^{-8} to 10^{-9} mm. Hg.

Protons will be injected at an energy of 50 Mev from a linear accelerator similar to those being designed for several high energy accelerators now under construction. The beam from the linear accelerator can be deflected into either of two inflection systems designed to inject in either the clockwise or the counterclockwise direction into the two-way accelerator. When high intensity single beams are accelerated, injection will occur at the rate of 10 pulses per second. When high intensity stacked beams are being accelerated for purposes of colliding beam experiments, approximately four pulses per second are injected for a period of about three minutes until the stacked beam has been built up. No further injection is then required during the lifetime of the stacked beam, which is about one hour at 10^{-8} mm. Hg.

Protons will be accelerated by two stages of radio-frequency acceleration. In the first stage, which is capable of a repetition rate up to 10 cycles per second, injected pulses are accelerated to 1.4 Gev and stacked at that point. In the second stage, which operates at repetition rates up to one per second, protons are accelerated from 1.4 Gev to the output energy in the case of single beam operation or to the high energy in case of a beam to be stacked for colliding beam experiments. The symmetry of the proposed accelerator is such that oppositely directed beams can be simultaneously accelerated by the same rf accelerating cavities.

In order to maintain the required misalignment tolerance of 0.008 inches r.m.s., it is planned to base the magnets on a reinforced concrete slab founded directly on horizontally stratified bedrock, preferably sandstone.

The accelerator tunnel will be partially below ground and will be shielded with 50 feet of earth on both sides and at least 20 feet on the top. The tunnel walls, which bear the load of shielding and support a 200 ton crane, will be founded independently of the magnet foundation, but also on rock.

A vertical cross section through a straight section is shown in Fig. 4. All but about 5 per cent (0.5 steradians) of the solid angle around the collision region is in principle accessible to detectors. It is possible to get within 0.02 radians of the forward direction of the beam.

In order to estimate the current densities which may be reached in an accelerator, we assume that it is possible to inject sufficient current to fill the accelerator to the space charge limit at injection. The space charge limited current is given to a good approximation by

$$I = I_o \, \nu \Delta\nu \left(\frac{a}{r}\right)^2 (\beta\gamma)^3 \, F \qquad (1)$$

where

$I_o = Mc^3/e = 3.129 \times 10^7$ amperes (for protons),

$\Delta\nu$ = allowable change in number of betatron waves per revolution,

a = cross-sectional radius of beam,

r = orbit radius,

$\beta = v/c$,

$\gamma = E/Mc^2$,

F = azimuthal bunching factor due to rf bunching of beam.

For the parameters in Table I, we get, with $\Delta\nu = 1/4$, F = 0.4

I = 0.26 amp.

With an injector which can supply 5 ma of injected protons, we require at least 52 turns injection to reach the space charge limit. It turns out to be possible to design an inflection scheme which should exceed 100 turns; the theoretical limit set by phase space considerations is 6000 turns. It therefore seems reasonable to take the current given by (1) as the circulating current at injection.

If we assume an injected circulating current given by Eq. (1), with an energy spread $P\,T_1$, where T_1 is the injection kinetic energy, and P is the fractional energy spread from the injector, then Liouville's theorem sets an upper limit on the current density which can be achieved by beam stacking in an accelerator whose magnetic field scales according to the law

$$H \sim r^k . \tag{2}$$

If we assume a loss factor B due to mishandling of the beam during acceleration and stacking, the theoretical current density (amp. cm.$^{-2}$) is

$$J = \frac{2}{\pi} I_o \frac{a_2\, k\, \nu \Delta\nu F\, B\, \gamma_2^2}{P\, r_2^3} , \tag{3}$$

where the subscript '2' refers to the stacked beam. For the machine under discussion (a_2 = 2 cm., r_2 = 180 m., T_2 = 15 Gev), with B = 0.25, we find

$$J = 50 \text{ amp. cm.}^{-2} ,$$

and for the total current

$$I = 4\, a_2^2\, J = 800 \text{ amp.}$$

Formula (3) assumes that the space charge limit is most critical at injection. Since formula (1) gives 1700 amp. at 15 Gev, this assumption is justified for this case. Each beam therefore has an expected maximum density of 50 amp. cm.$^{-2}$ in a mean cross section of 16 cm.^{2}. (The actual beam dimensions are 4 x 8 cm.^{2} with a triangular density distribution in radius.) The beams intersect in the straight sections in the experimental areas at an angle of 0.18 radians. The energy spread of the stacked beams is about $\pm$ 0.15 Gev.

If we take as standard cross section for p-p collisions the geometrical cross section (5×10^{-26} cm.^{2}), the interaction density for interacting beams of density 50 amp. cm.$^{-2}$ is

$$R = \frac{2\, J^2 \sigma}{e^2 \beta c} = 3 \times 10^5 \text{ cm.}^{-3} \text{ sec.}^{-1} . \qquad (4)$$

The interaction volume in the present case is 4 x 4 x 20 cm.^{3}, so that the total interaction rate is 10^8 sec.$^{-1}$. This is a reasonable maximum rate if we wish to resolve individual events with present electronic techniques. Interesting events would have a cross section which would be some small fraction of the standard cross sections we have assumed. The background rate due to collisions with residual gas nuclei at 10^{-8} mm. Hg. in the interaction region is about 10^5 cm.$^{-3}$ sec.$^{-1}$, or roughly comparable with the p-p interaction rate. In resolving individual events, coincident p-p collisions (in time and space) are as troublesome as p-gas nuclei events, hence

this background rate is reasonable. There is also a general background due to events occurring throughout the accelerator resulting ultimately in a general fog of neutrons, gamma rays, and electrons. With the above figures, assuming that each proton lost ultimately results in 200 daughter particles distributed throughout a distance of one meter from the beam, the general background is about ten tracks per liter per microsecond, which is again quite tolerable. For these reasons the figure of 50 amp. cm.$^{-2}$ seems a conservatively large number for colliding beam experiments. Densities smaller than this by a factor of 10 would still probably be useable, and even lower densities could be used provided the vacuum can be proportionately improved.

A careful cost estimate of this accelerator has been made.[3] The estimate was intended as a maximum amount that the entire installation might cost. In cases where certain features were still undecided, the most expensive of the various alternatives was used as a basis for the cost estimate. For example the four large experimental areas are assumed to be within buildings covered with 20 feet of earth and provided with 75 ton traveling cranes. The resulting total estimate for the installation is $174,000,000 plus 15 per cent escalation and 14 per cent contingency. This figure includes $9,200,000 for research and operating equipment. A breakdown is given in MURA-460 (Table I). If we scale up the estimate for a 10 Gev spiral sector accelerator given in MURA-460 by the ratio of costs of the 10 Gev and 15 Gev radial sector machines given in the same report, we have for a high intensity spiral sector accelerator at 15 Gev the rough estimate $132,000,000 plus

escalation and contingency. Hence we may estimate the additional cost of providing for colliding beams in a two-way accelerator at 15 Gev each over a high intensity 15 Gev accelerator as $42,000,000 plus escalation and contingency.

STORAGE RINGS WITH FFAG ACCELERATOR

If an intense circulating beam can be built up in a single FFAG accelerator by beam stacking and extracted in a single turn, this beam can be transferred to a pair of storage rings in which oppositely circulating beams collide. A conceptual plan for such an arrangement is shown in Fig. 5. A pair of concentric storage rings similar to a design described by O'Neill would be used.[4]

The storage ring arrangement has a number of advantages. Since the radial aperture need be only enough to hold the stacked beam, (a few centimeters), there is experimental access to the colliding beam region on all sides. All but about 0.1 per cent (0.01 steradian) of the total solid angle around the interaction region would be accessible to experimental equipment, and detectors could be placed within nearly 0.01 radian of the forward direction. Since the storage ring vacuum chamber has a small aperture, and is separate from the accelerator, it should be relatively easy to maintain an ultra-high vacuum. The vacuum chamber may have an unbroken metal surface except for pumps and injection ports, and possible experimental access ports, so that a vacuum of 10^{-9} mm. Hg. or better should be quite feasible. The beam life at 10^{-8} mm. Hg. would be of the

order of an hour. The time required to accumulate two stacked beams in the accelerator and inject them into the storage ring is only a few seconds, so that the duty factor for storage ring experiments is nearly 100 per cent. Moreover, the accelerator, which can be designed to provide a high intensity beam at 15 Gev, can be used for this purpose at the same time the storage rings are used for colliding beam experiments.

In Table II we list the important parameters of the storage ring and a typical 15 Gev spiral sector accelerator. The parameters for the storage ring are scaled from a design worked out by O'Neill.[4] We have used a magnetic field of 19,000 gauss since these are relatively simple D.C. magnets, compared with either FFAG or AGS magnets. We have also used a radial aperture of 5 cm., since no room for acceleration is required in the storage ring. (The radial aperture of the vacuum chamber increases to 20 cm. in the interaction region where the two beams cross.)

If we use formula (3) above, with the parameters given in Table II, and with F, B, P, $\Delta\nu$ as in the previous section, we obtain for the current that can be stacked in a 15 Gev spiral sector accelerator,

$$J = 85 \text{ amp./cm.}^2 .$$

Note that in spite of a smaller beam diameter and a more conservative value of k and of B_{max}, we still achieve the same beam density as the two-way machine because of the factor r_2^3 in the denominator. The total current is

$$I = 340 \text{ amp.}$$

Since the betatron wavelength in the storage ring is about half that in the accelerator, by inserting appropriate magnetic lenses between the two machines,

TABLE II

Possible Parameters for a 15 Gev Spiral Sector Accelerator

Energy	15 Gev
Mean Orbit Radius	75 m
Maximum Magnetic Field	15,000 gauss
Vertical Aperture (Injection)	10.5 cm.
Output Beam Radius	1 cm.
N (Sectors)	30
k (Mean Field Index)	50
Circumference Factor	2
ν_x	5.6
ν_z	4.8

Possible Parameters for a 15 Gev AG Storage Ring

Energy	15 Gev
Mean Orbit Radius	40 m
Maximum Magnetic Field	19,000 gauss
n approximately	35
k + 1 (momentum compaction)approx.	40
Circumference Factor	1.35
Vertical Aperture	5 cm.
Radial Aperture	5 - 20 cm.
ν_x	6.6
ν_z	7.3
Beam Radius	0.7 cm.
N (Sectors)	8
Straight Section	2.6 m
Crossing Angle	0.15 radians
Weight Fe.	1200 tons
Weight Cu.	300 tons
Power	6.4 MW

we can reduce the beam radius to 0.7 cm. in the storage ring. The theoretical beam density in the storage ring is

$$J_{SR} = J_{AC}\left(\frac{a_{AC}}{a_{SR}}\right)^2 \frac{k_{SR}}{k_{AC}} = 85 \text{ amp./cm.}^2 \times 2 \times \frac{40}{50} = 140 \text{ amp. cm.}^{-2} .$$

If we lose no more than a factor of three in density in the transfer process, the current density in the storage ring will be

$$J = 50 \text{ amp. cm.}^{-2} ,$$

and the total current will be

$$I = 100 \text{ amp.}$$

O'Neill[5] has studied the problem of beam extraction from a synchrotron and injection into a storage ring. Terwilliger (MURA-427) has studied the problem of extracting the beam from an FFAG synchrotron in a single turn. Both conclude that the problems can be solved. Since the spiral sector accelerator has almost twice the circumference of the storage ring, about 50 per cent of the beam can be thrown away in turning on and off the extraction magnet in the accelerator and in switching on the injector in the storage without loss of density in the storage ring. Any beam lost from the ring in switching off the injector represents a loss of beam to the ring however. The injection problem here is particularly simple, in that only one turn is to be injected.

Terwilliger (MURA-487) has proposed a method of superposing equilibrium orbits by means of a properly designed static perturbation in the field gradient. By this means the current densities given above for either the two-way accelerator or the storage ring can be increased by a factor of the order of 5, or

TABLE III

Cost Estimate for 15 Gev Storage Rings. (thousands of dollars)

Utilities, D.C. Supplies, Buildings & Tunnels	
Engineering design and supervision	$ 200
Utilities	800
Tunnel	1,500
Experimental building and shielding	3,500
Buildings	500
Magnet power	1,100
	7,600
Storage Ring Construction	
Engineering design and supervision	800
Magnet core	600
Magnet coils	300
Magnet accessories and miscellaneous	500
Magnet cooling	200
Vacuum system	1,000
Beam handling and injection system	300
Instruments and controls	300
	4,000
Development	1,000
Administration, management, services	500
Research equipment	3,000
Total (less accelerator)	$16,100

alternatively, the beam radius and hence the total current may be decreased without decreasing the density.

In Table III, we present a very rough cost estimate for the storage ring. Engineering and management costs are estimated at one-tenth the Brobeck estimate for the 15 Gev two-way machine, that is, slightly more than proportional to the total cost. Magnet iron and copper are estimated at the same cost per pound as the two-way machine, although this is probably an overestimate. It is assumed that there will be two colliding beam buildings of roughly the dimensions of those for the two-way machine. Magnet power is estimated at the same cost per kilowatt as for the two-way machine. Other costs are uneducated guesses. The result is $16,100,000 for the complete storage ring installation plus escalation and contingency.

STORAGE RINGS WITH PULSED FIELD SYNCHROTRON

In order to utilize a pair of storage rings with a pulsed field synchrotron, it is necessary to stack many pulses from the synchrotron in the storage ring. To do this, an rf system is required in the storage ring to accelerate or decelerate particles away from the injector.

In principle the same ultimate phase space limits hold in this case as in the storage ring with an FFAG accelerator, provided the same parameters are used for the ring, and for the injector into the accelerator, and provided the space charged limited current density [formula (1)] is the same at injection in both accelerators. In practice, it appears somewhat more difficult to reach the theoretical limits, because of the necessity of transferring and

stacking many pulses in the storage ring. For example, if the energy spread from the injector is .001 x 50 Mev = 50 Kev as in the above example, a single pulse will adiabatically undamp to about 150 Kev at 15 Gev. If this pulse is to be transferred and stacked in the storage ring without loss of phase density, then the extraction energy from the accelerator, and the synchronous rf pickup energy in the storage ring must match within less than 150 Kev in 15 Gev, or one part in 10^5. It is possible that this might be done by some kind of beam control of the radio frequency in the storage ring. Note that in the FFAG machine, this precise control is needed at the injector. The oscillator must be turned on within 50 Kev of 50 Mev or one part in 10^3. At the high energy, many pulses are stacked, so that the oscillator need only be turned off with a precision corresponding to the energy width of the stack, say 150 Mev.

A pulse of 10^{12} particles in an AGS of 60 meter radius represents a circulating current of 0.1 amp. The beam radius will be, say 0.3 cm. Let us assume control of the extraction energy and pick up energy in the transfer process within the required one part in 10^5 or 150 Kev. We can hardly hope to fill up more than one turn of betatron phase space in the storage ring since the pulse from the synchrotron is only 50 per cent longer than the circumference of the storage ring, and it seems unlikely that it would be practical to inject successive pulses into different regions of betatron phase space (but at the same energy!). The radial width due to a 150 Kev energy spread in the storage ring of Table II is given by

$$\frac{r}{E}\frac{dE}{dr} \doteq \frac{r}{p}\frac{dp}{dr} = 1 + k , \qquad (5)$$

so that

$$\Delta r = \frac{\Delta E}{E} \frac{r}{1 + k} , \tag{6}$$

or

$$\Delta r = 10^{-3} \text{ cm.}$$

If we assume as above a factor of 3 loss in transfer plus a factor 4 loss in stacking, we can stack about 60 pulses in 0.6 cm. The circulating beam will then be 6 amperes, and the current density

$$J = \frac{6 \text{ amp.}}{4 \times (0.3 \text{ cm})^2} = 2 \text{ amp./cm.}^2 .$$

O'Neill[4] arrives at the same current density for a storage ring pair he has designed at 3 Gev.

As in the two preceding cases, this figure can be improved by superposing equilibrium orbits. In this case, the theoretical limiting density obtained by superposing equilibrium orbits is perhaps a factor 3 higher than in the two preceding cases because the beam radius we start with is 0.3 cm. rather than 1 cm. Thus the density might be increased by a factor of 15 in this way.

If a weak-focusing synchrotron is used, the situation seems more unfavorable because of the mismatch in betatron oscillation frequencies. In principle, by using matching lenses, the beam area can be reduced in the storage rings from its area in the synchrotron by the ratio of the betatron wavelengths, but this would result in a very small beam in the storage ring, if it could be done. It is difficult to see how this could be utilized,

unless some heroic method of stacking in betatron as well as synchrotron phase space could be devised.

A storage ring pair for a pulsed synchrotron could have essentially the same parameters as in Table II, except that a radial aperture of perhaps 15 cm. instead of 5 cm. would be required to accommodate the rf acceleration required for stacking. This would increase the magnet weight to perhaps 2500 tons, and would double the cost of iron in Table III. There would in addition be the cost of the rf system, say $300,000. The total cost of the storage rings in this case would therefore be about $17,000,000 plus escalation and contingency.

OTHER POSSIBILITIES

Christofilos[5] has designed an air core AGS, two of which he suggests might be used in tandem for colliding beams. Only one pulse would be accelerated in each synchrotron, and there could be no stacking. By injecting H_2^+ ions and stripping in the synchrotron to avoid the phase space limitation at injection, the machine would be filled to the space charge limit. He calculates that a current density of 0.5 amps. cm.$^{-2}$ might be reached, within a beam cross section of 0.1 cm.^{2}, with a total circulating current of 0.05 amp. The cost of the extra synchrotron he estimates at $30,000,000.

It is perhaps also worth mentioning that if it is possible to extract a stacked beam from an FFAG machine in one turn, it is conceivable that an ultra-high field pulsed bending magnet could be used to turn the beam back on itself so that the leading half of the pulse could interact with the trailing

half. The beams would interpenetrate only once for of the order of 0.3 microsecond for each extracted pulse, i.e., once every few seconds. The number of interactions would be small, say one to ten per pulse, but if a picture is to be taken of the interactions, we want only about one interaction per picture. During the 0.3 microsecond burst, the interaction rate, and the ratio to background are the same as for continuous colliding beams. Indeed the background could be much less because the beams would be traveling through a narrow tube away from the accelerator and magnets, and in which a very good vacuum could be maintained. The geometry is moreover very favorable. The cost is difficult to estimate, but would probably be much less than storage rings, and might depend strongly on what power and facilities are already available at the site.

REFERENCES

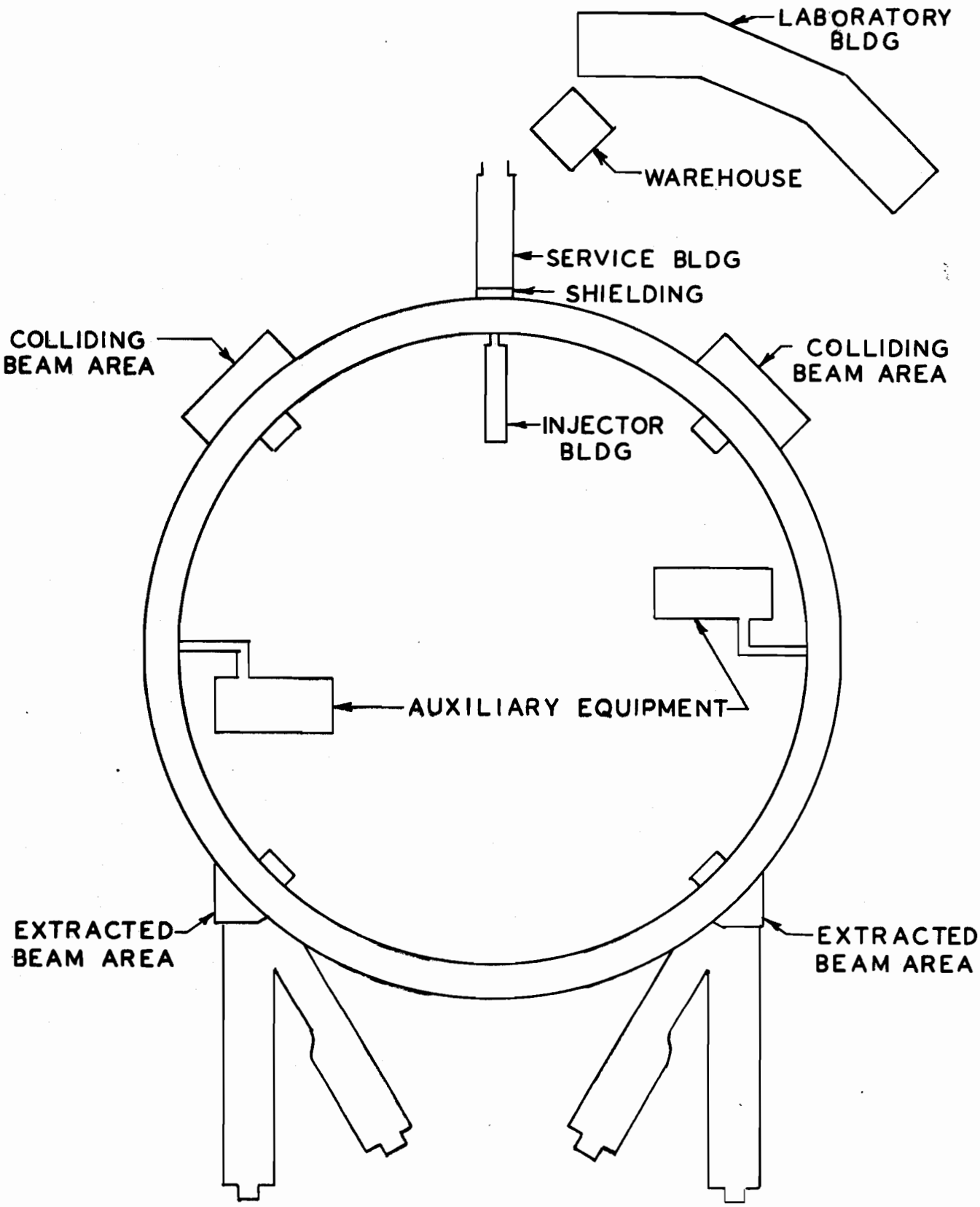
1. T. Ohkawa, Rev. Sci. Instr. 29, 108 (February, 1958).

2. Proposal for a High Energy Research Facility, March 14, 1958.

3. William M. Brobeck & Associates, Review of the MURA Proposal for a High Energy Research Facility, August, 1958.

4. G. K. O'Neill and E. J. Woods, "Intersecting Beams with Storage Rings." Princeton-Penn Accelerator Project Internal Report GKO'N-12 EJW-2. (To be published).

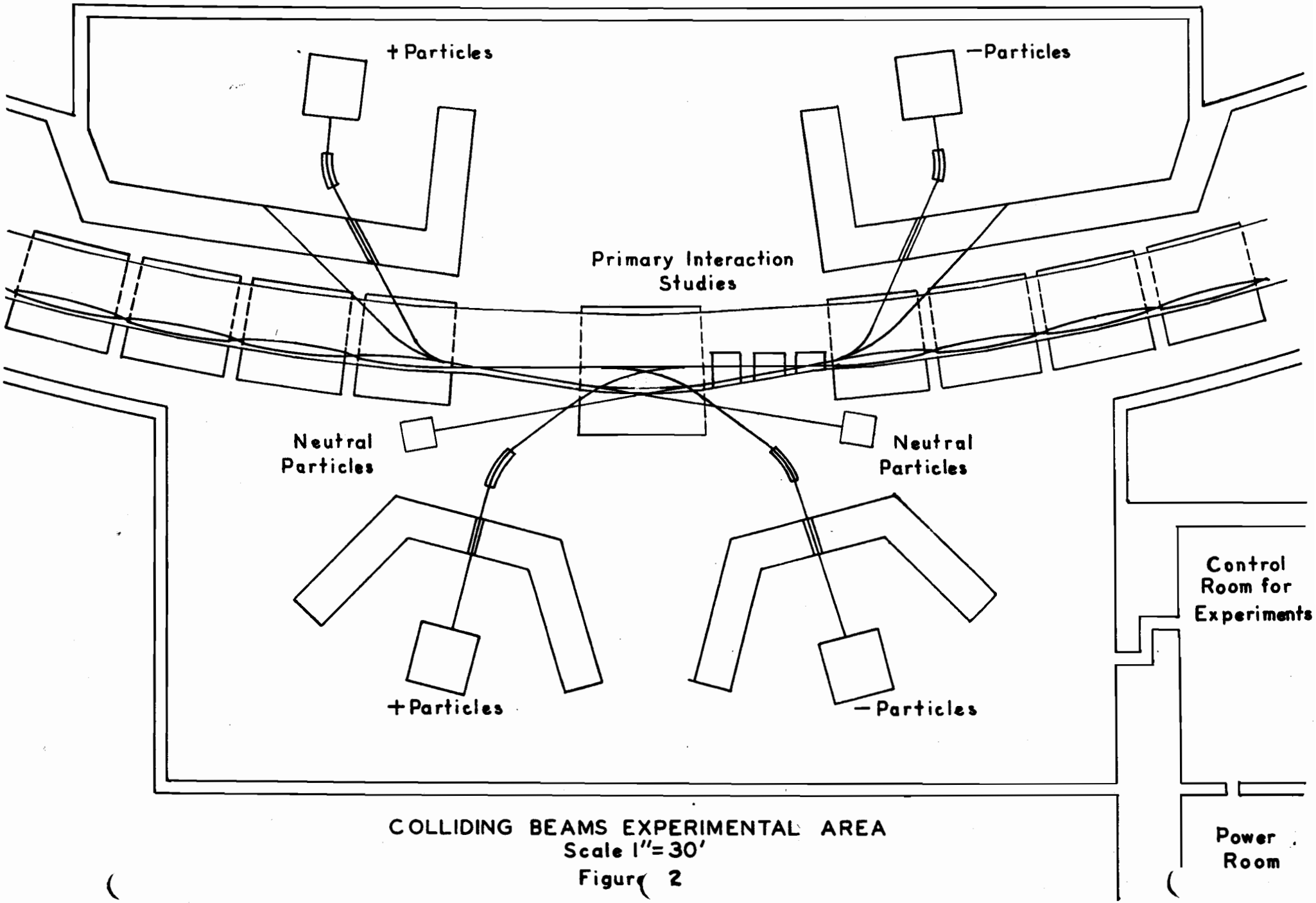
5. N. Christofilos, "Proposed Air Core Strong-Focusing Synchrotron." UCRL-4310-08 CVL-1. Oct. 12, 1957. We are indebted to Dr. Christofilos also for a private communication regarding more recent developments regarding the air core synchrotron.



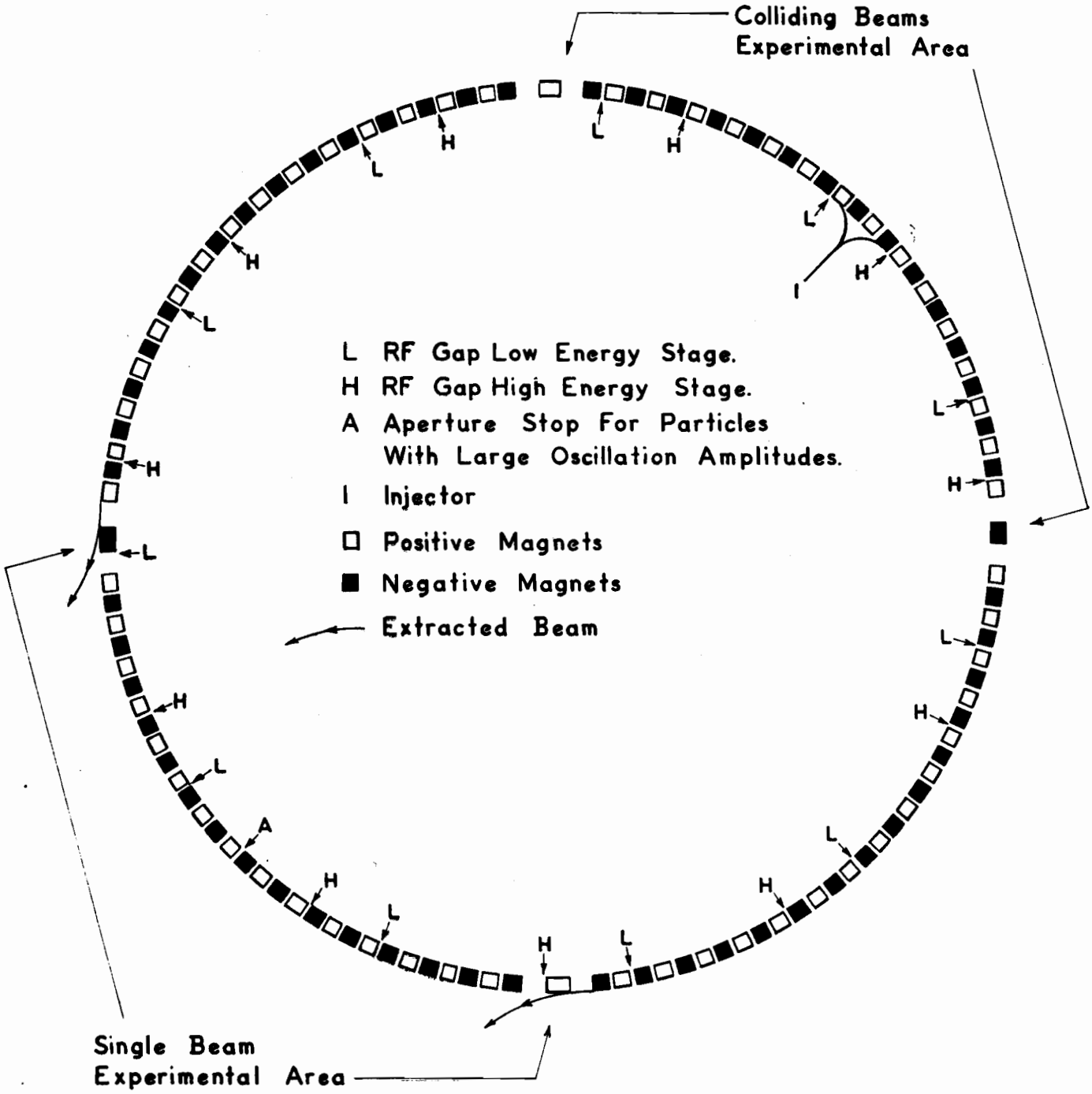
ACCELERATOR LAYOUT

SCALE 1/4"=60'

FIGURE 1



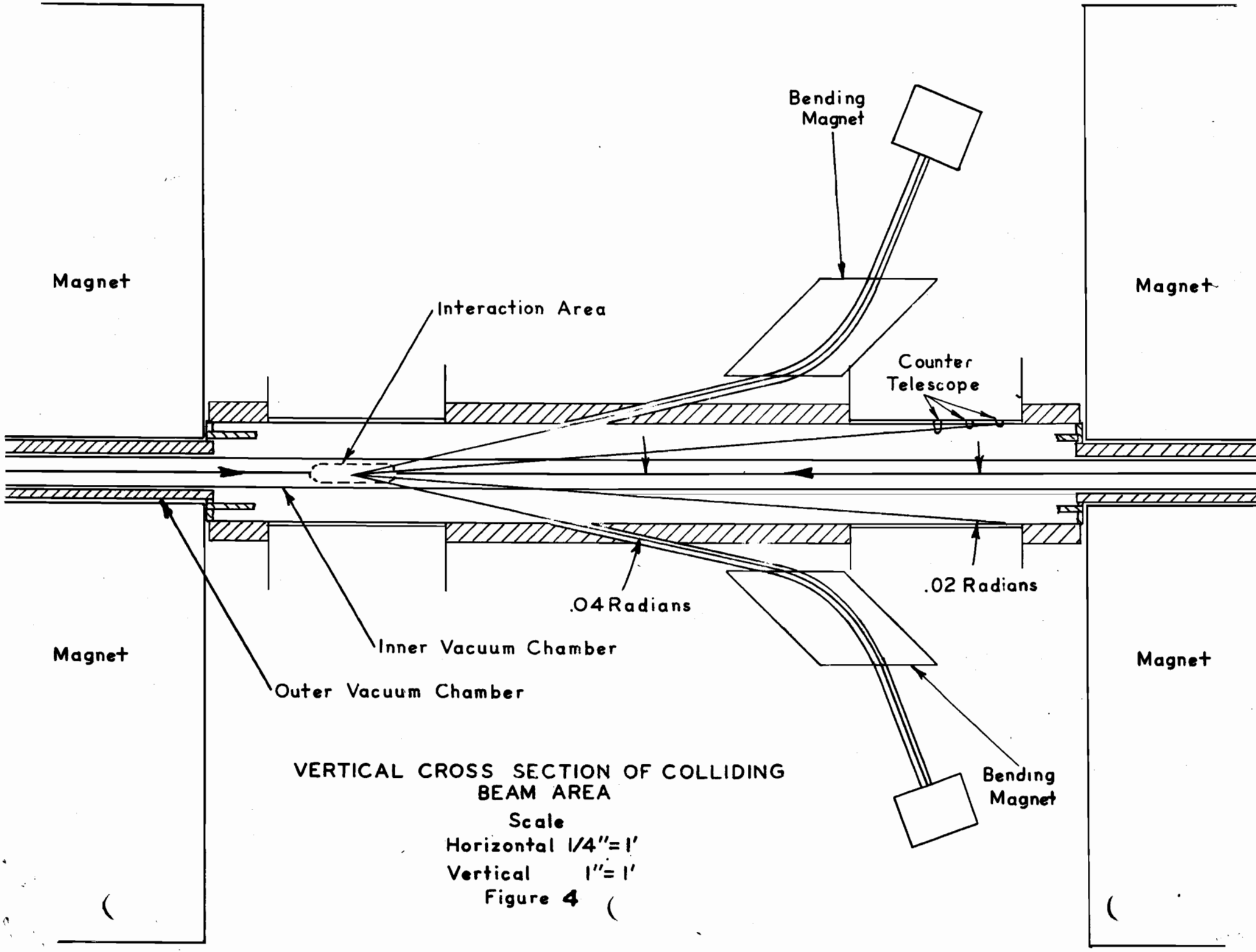
COLLIDING BEAMS EXPERIMENTAL AREA
Scale 1″=30′
Figure 2



ACCELERATOR ARRANGEMENT

Scale 1" = 200'

Figure 3



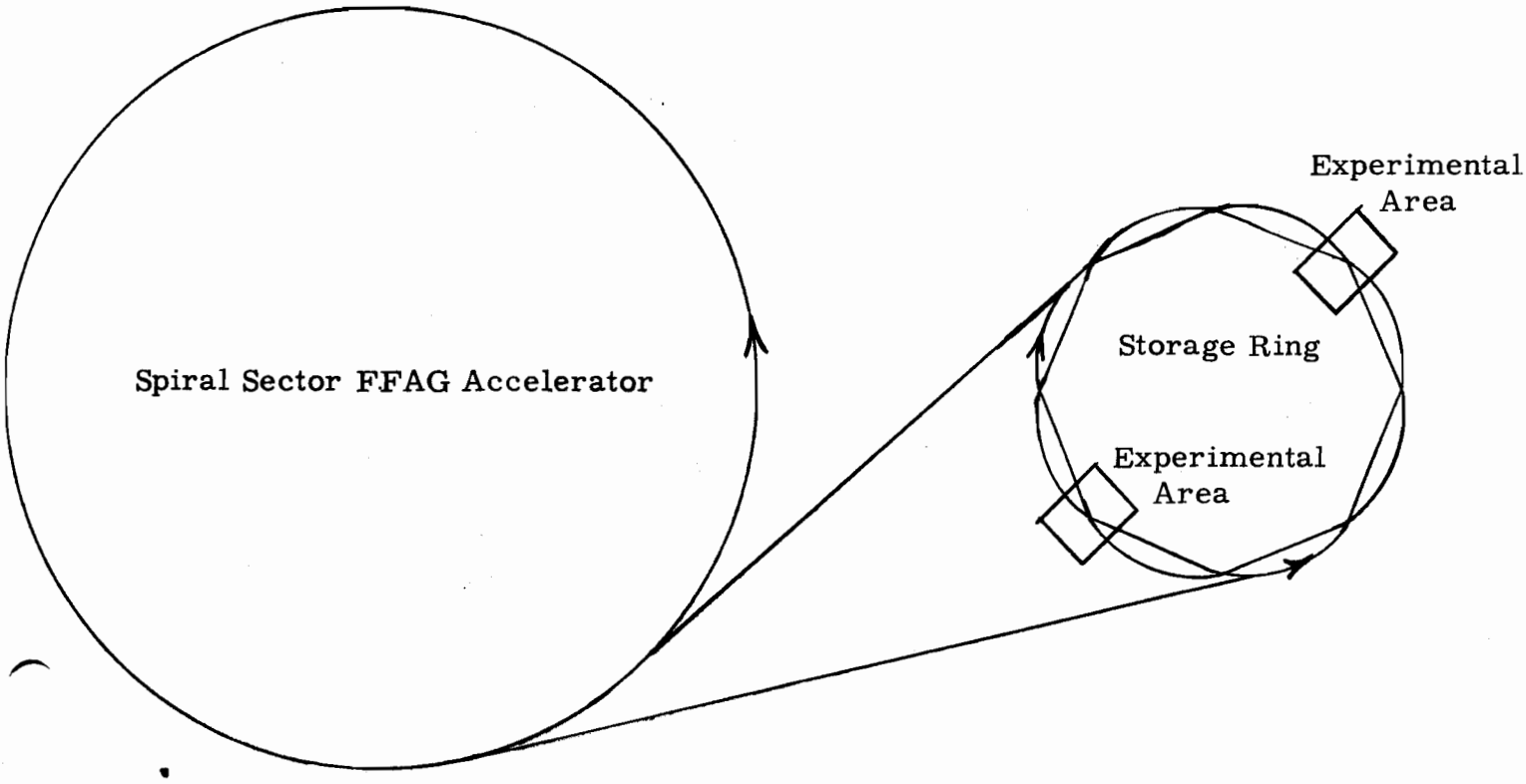
VERTICAL CROSS SECTION OF COLLIDING BEAM AREA

Scale

Horizontal 1/4"= 1'

Vertical 1"= 1'

Figure 4



15 Gev Spiral Sector FFAG Accelerator with Concentric AG Storage Rings

Fig. 5