Fermilab

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A TEVATRON IMPROVEMENT PROGRAM*

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I. Introduction

A modest Tevatron improvement program is suggested which would provide a storage ring for dedicated use as a $p\bar{p}$ collider at 2 TeV (c.m.) and as an ep collider at 0.2 Tev (c.m.). It could also serve as a useful test facility for some of the new developments necessary for an economical SSC. Because use could be made of utilities and facilities that are already installed as part of the tevatron, the cost of the $p\bar{p}$ option might be about 100 million dollars (not including the interaction halls or detectors). The additional cost of a 10x1000 GeV' ep option might be about 70 million dollars. The experimental facilities at B and D of the Tevatron might be extended for use with the new collider. As the technology of superconducting magnets develops, the cm energy of the $p\bar{p}$ and the ep colliders might be doubled.

The intention is either to double the capability of TeV I and TeV II, or to extend the capability by addition of an ep facility. Alternatively, by adding another proton ring, a high luminosity pp facility might also result.

II. The Tunnel

Perhaps the most prominent and most expensive features of this proposal, apart from the collision detectors, are the new tunnel and the magnet ring within it. The tunnel, of radius 0.95 Km, would be approximately concentric with the present 1 Km Main-Ring tunnel. As shown in Fig. 1a the new tunnel would be connected to the old tunnel by injection tunnels through which protons and antiprotons could be brought from the Tevatron for injection into the new storage ring.

Short access tunnels, each about 150 feet long, would pass under the ring-road to connect the present 24 Main-Ring service building to the new tunnel. Each access tunnel would connect to a vertical pipe containing a spiral stair case that would come to the surface near a service building. This would allow the liquid helium capability that presently exists around the Tevatron ring to be used for the new ring. Indeed, because the storage ring would not be ramped, because there would be fewer current leads, because the magnets would be narrower and longer than the Tevatron magnets, and because the magnets would be better thermally insulated, little helium capacity beyond that which will soon exist need be installed for the new ring.

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* This note represents the result of a few weeks work in the summer of 1983. Of course it is incomplete.

Fig 1a Plan
(not to scale)

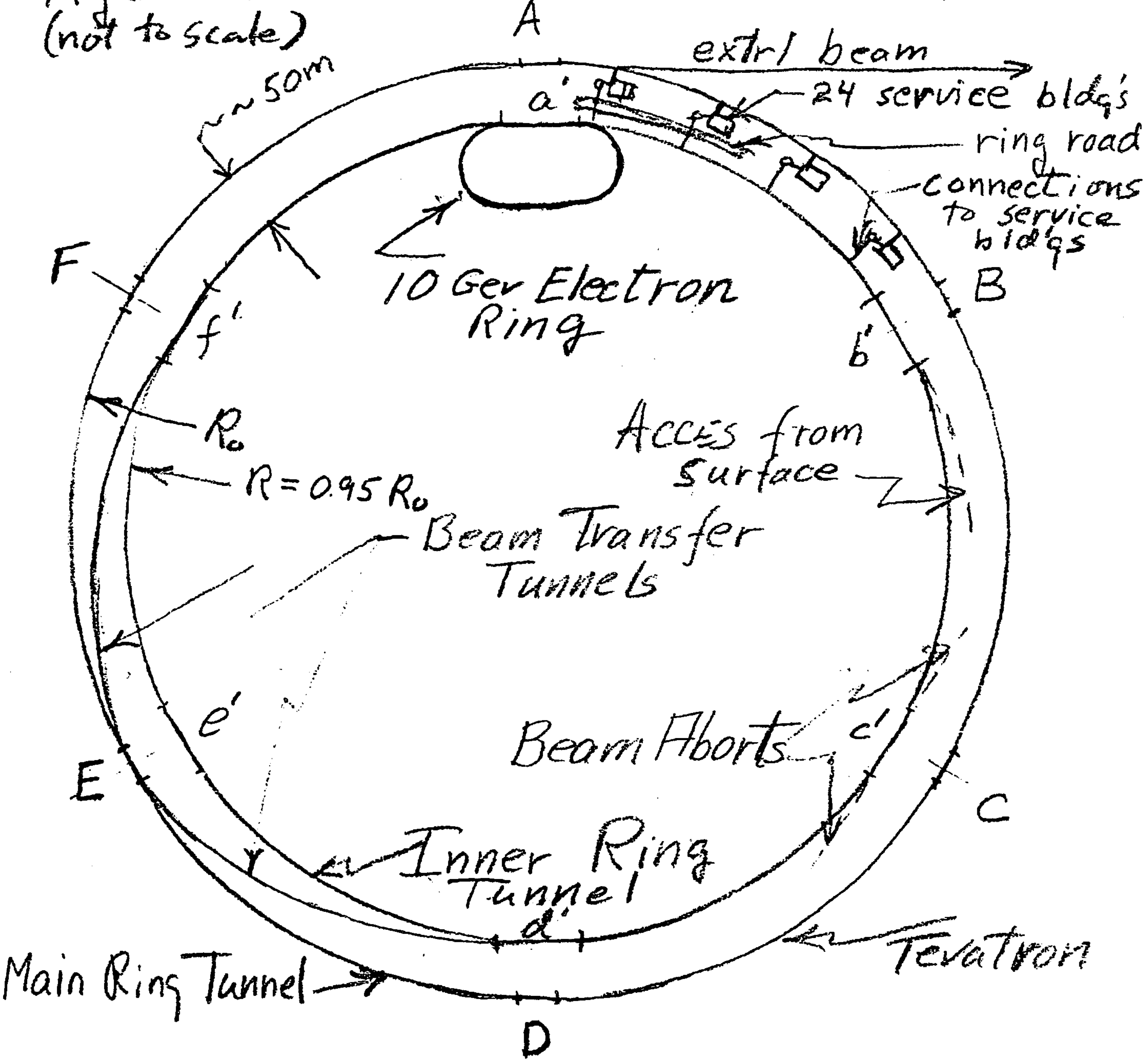
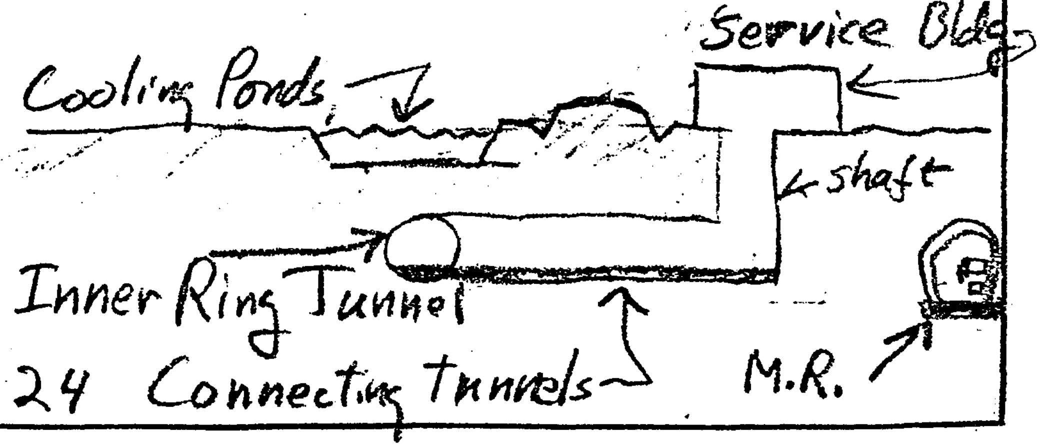


Fig 1b
cross section



The access tunnels would also make the Tevatron control circuits available for the control and monitoring of the storage ring: only small additions should be necessary. Current for magnet excitation, for correction coils, for vacuum pumps, etc., could be brought to the storage ring from the main-ring service buildings through the access tunnels.

The new tunnel would also have three "stubs" as shown in Fig. 1a; two for beam aborts, and one connected to an elevator for bringing magnets, etc., into the tunnel.

Finally, an elegant embellishment would be the electron storage ring tunnel shown in Fig. 1a at the interaction region A'. This would contain a 10 GeV electron ring which would serve for initial studies of 10x1000 GeV' ep collisions and which could eventually become an injector for a 30 (possibly even 40) GeV electron storage ring which might be located in the proton storage ring tunnel. A discussion of the ep option will come later in this report.

Although we might be tempted to use the same kind of concrete-hoop tunnel that was installed for the Main Ring, it would be a more useful contribution to the SSC to explore more economical tunneling techniques. Thus we might bury culvert pipe. An 8 ft. diameter metal culvert would seem to be appropriate (the cost of spiral-wound culvert is about $85 per foot). This might be buried to the same depth as the Main Ring. If concentric, the new tunnel would lie just under the ponds. The water, normally at a depth of about 4 feeet, could be drained pond by pond as the culvert was installed. This would then require a 20 foot cut to be made for the installation. Because of the simple manner of connecting the sections of culvert (essentially with hose clamps), workers need never be in the trench except when under a moveable shield. This implies that the trench dug for installation could be made with nearly vertical walls, instead of the 2 (or 3) to 1 slope that is usually required, thus saving significantly in the amount of excavation. Were the cost of installing the tunnel to be $300 per foot, then the total for the tunnel would be about $8 million. Hence if a larger tunnel were deemed necessary, say 10 feet in diameter, then it too would be quite affordable.

III. The Lattice

The lattice need not be the same as in the Tevatron; indeed it should be optimized for the job to be done, colliding beams. For one thing the straight sections should be longer in order to have better collision areas. For another the relative positions of the straights might also be changed, for example, to ease the injection of the protons and antiprotons.

Designing a lattice is a highly technical procedure that would best be left to the experts. One lattice that has been considered has essentially been scaled down from that of the DC collider which had about twice the radius of the ring under discussion. The quadrupole focusing magnets can be considerably stronger than those used in the Tevatron, as will be discussed in the next section about magnets. This means that it should not be difficult to get a tighter lattice more appropriate for a collider. In any case, less peripheral space need be used for the quadrupoles, and more tricks can be played at the straights to obtain higher luminosity. It might be remarked that it would be desirable to keep the distance between quadrupoles to about 100 feet for reason of cost.

IV. Magnets

Because the protons would be injected at higher energy than in the Tevatron (it need not necessarily be 1 TeV) the aperture of the magnets can be smaller. Just how much smaller is a complicated matter that depends on practical as well as theoretical considerations. Thus making and using a narrower but longer magnet would contribute to the experience needed for designing the SSC.

The magnet shown in Fig. 2 represents one possibility that has some features that would make it economical to construct and to use. The magnet coil aperture is 1.5 inches, to be compared to the 3 inch coil aperture of the Tevatron dipoles. This implies that at the same magnetic field the stored energy in the new magnets would be about (depending on the coil shape) one quarter as much as in the Tevatron magnets. Hence we should be able to make the magnets four times longer than the Tevatron magnets and still be able benignly to dump the stored energy should the magnet go normal for some reason. Since about half the cost of the Tevatron magnets went into the ends rather than the body of the magnets, this suggests that we make the magnets about 80 feet long instead of 20.

A "layered" design of the coil is suggested instead of the "shell" arrangement that was used for the Tevatron magnets. This is partly because it avoids a 5 or 10 percent degradation in the current carrying capacity of the superconducting wire due to "keystoning" the cable, and partly because it will lend itself better to a method of production in which the magnets are "squeezed out like toothpaste" as opposed to being made in one long fixture. Not quite as dramatic as the above words imply, the idea is to fabricate the coils in 80 foot lengths, but not to great precision. Then, as shown in Fig. 2, a split interior form is placed around the stainless steel vacuum tube which will temporarily contain a short length of precision mandrel. The coil will then be adjusted to fit onto the inner form (it will be made of accurately stamped laminations) and the outer precision collars will then be assembled around the coil. This is to be done only a few inches at a time, after which a press will push a short length of the assembly together in a very precise manner, and keys will be inserted to lock the collars in place. Then the next few inches will be assembled and pressed into place, the interior mandrel being advanced so as to be under the section subject to high pressure. This is quite analogous to the way that the Tevatron quadrupole magnets have been made. Of course the magnet will be supported on an accurately-made fixture as it is fabricated.

Essentially all the magnetic field will come from the superconducting coils, for the magnet will be supported at the center of a vacuum pipe of large radius as shown in the illustration. The pipe will probably be made of steel of about one inch wall thickness, not to contribute to the field but to shield other devices and magnets, and to provide a strong and precise support for the inner magnet. The pipe might also be made of aluminum.

In the Tevatron magnets there is about two inches between the coil and the iron yoke and about one inch of vacuum space between the collar and the yoke.

This meant very large forces due to induced fields, and the necessity of short but thick thermal insulators to counter those forces. Large thermal losses were the inevitable result (mea culpa), and all this for a very small enhancement of the field, about 10 percent, or less, when the decreased current capacity of the conductor is considered.

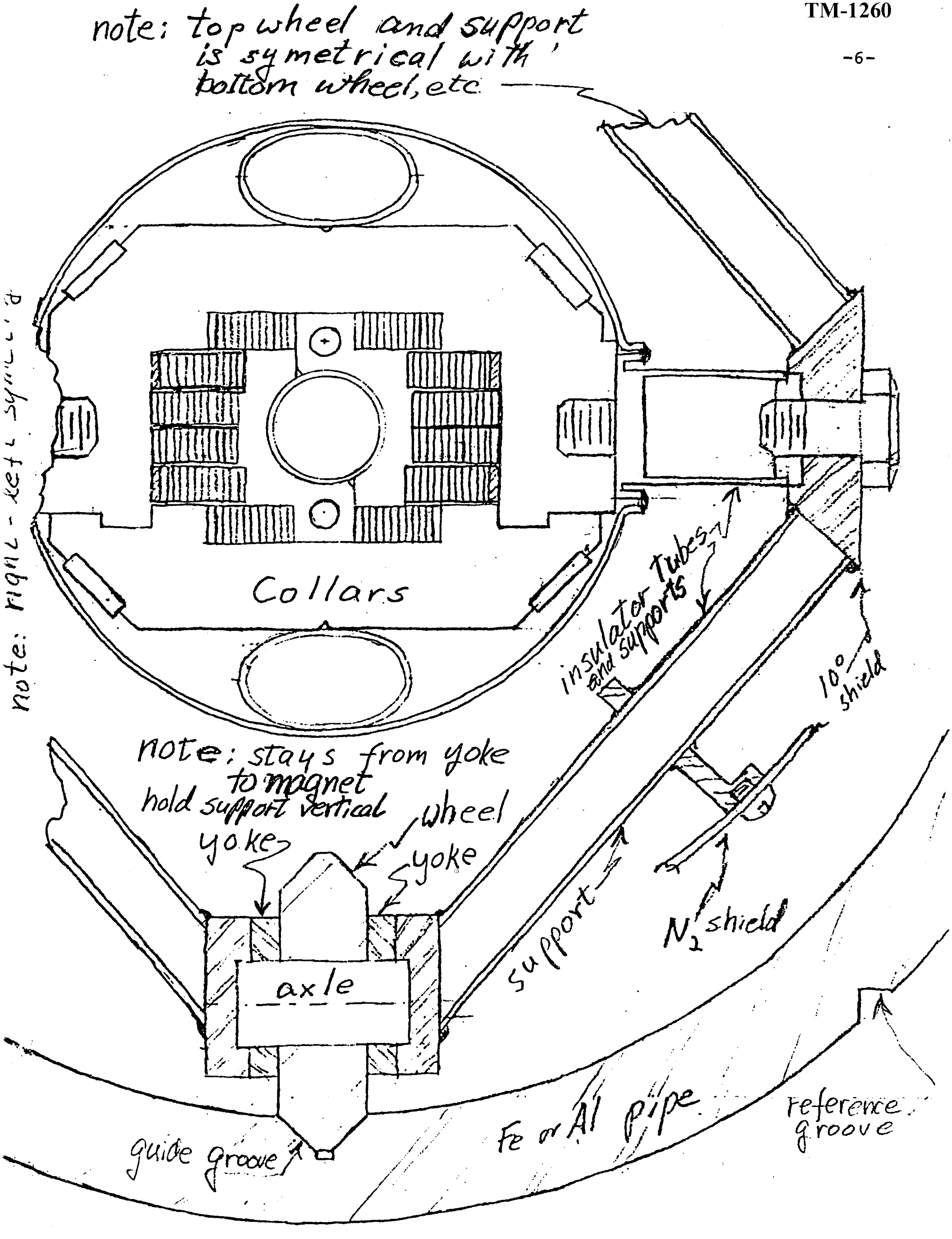
By abandoning the enhancement of field due to the iron by substantially increasing the distance between coil and iron, the induced forces are reduced by a factor of about ten, while room is provided for an adequately stiff insulator with low heat loss. The longer magnets will have a greater shrinkage in length on cooling down, about 3 instead of 3/4 inches, and it is proposed that this be taken up by the rather large wheels on the support structure as shown in Figure 2. The wheels will also facilitate the insertion of the inner magnet into the iron pipe.

The idea here is to weld support tabs onto the outside of the pipe every 20 feet or so and to support the pipe on a stiff mixture that would resemble the support structure in the tunnel. The 80 foot pipe will have a sagitta of about 4 inches due to the curvature of the orbit. This curvature would be approximately fabricated into the pipe. The supports and the fixture would have to be strong enough to force the exact curvature into the pipe. With the pipe in the fixture, reference grooves as indicated in Fig. 2 would be ground into the outside of the pipe. This could be done using a special grinding machine which would roll along a precisely surveyed and formed curved track on the fixture.

Next we would grind the deep grooves in the inside of the pipe at the top and bottom. These will be the tracks in which the wheels of the magnet supports will run. The interior grinding machine will run down the pipe on wheels that can guide the grinding wheel. An X-ray tube will run along with the grinder just below it, and a detector, such as in the airport search devices, will run along just above the grinder, both being outside the pipe. The X-rays will show the position of the outside grooves, and the inside grooves or tracks will be ground with reference to these grooves. When the inner magnet is inserted into the pipe, the support wheels should force it to be centered and vertical all along its length. A portable X-ray machine should allow us to check directly on the inner magnet should there be any doubt about is position or verticality.

The wheels are to be fastened to the magnet as indicated in Fig. 2. There would be a wheel on the bottom and a wheel above in the upper track. The two wheels would constitute a truck which would support both the magnet and the liquid nitrogen shield. The truck would fasten directly and firmly to the collar structure as shown in the illustration. The trucks would be spaced appropriately depending on the stiffness of the inner magnet, presumably every five feet or so. The Liq Na shields would be firmly attached to the trucks so as to incercept the heat leakage into the magnet, and would telescope, one section into the next. Also shown is a 10° intercept. The support structure shown in cross section would be kept vertical by stays.

Surveying and positioning the magnets would be a bit tricky. The magnets would come out of the factory as 80 foot-long units. They should be quite stiff and easy to manipulate. The ramped entryway or elevator should facilitate


note: top wheel and support is symetrical with bottom wheel, etc
note: right - left symmetric
Collars
insulator tubes and supports
10° shield
note: stays from yoke to magnet hold support vertical
yoke
wheel
yoke
axle
support
N₂ shield
guide groove
Fe or Al pipe
reference groove

putting them into the tunnel. The magnets could be rolled along the floor to the point of installation, just as were the Tevatron magnets, or they could be picked up on an overhead rail for transport to the place of installation. There the two ends of the magnet would be put in place as the traditional survey indicated and the middle point would then be locked in place. The remaining two support points would then be adjusted and locked. Perhaps three supports would be enough.

To further simplify the magnet construction and installation, the quadrupole and correction coil package might be contained along with the dipole in a single length of pipe, 90 to 100 feet long. These sections of pipe would be connected together at a junction-box at which current leads, correction leads, beam position detectors, pumps, etc., could be located. Presumably, the pipes would be welded to expansion bellows at these boxes. Within the pipe other bellow joints would be made to accommodate the several inches of contraction that would occur on cooling the magnets to liquid He temperature.

There should be a few words about quadrupoles. Because the coil aperture is one-half that of the Tevatron magnets, the gradient could obviously be twice as great. This can be used to have a tighter lattice, or to make the quads shorter and thereby the bending magnets longer.

V. The Glorious ep Option

Yes, Glorious! The physics has been demonstrated any number of times to be tremendous. By moving forthrightly, we could get to that physics in a few years.

As shown in Fig. 1a, the 10 GeV electron storage ring is essentially identical to that described in the "Fermilab Dedicated Collider, 1983." Indeed the following material is just copied, mutatis mutandis, from that proposal. The physics at 10 GeV on 1 TeV protons is given in the Columbia-Canadian-led Proposal #659, June 1981.

ELECTRON STORAGE RING
(copied from the DC Proposal)

The existence of the Tevatron Storage Ring will present a unique opportunity for the observation of extremely high energy electron-proton collisions with an electron storage ring of modest energy. Here we describe a 10-GeV electron ring tangent to the TSR at the utility straight section near the hi-rise. The electron ring has a 360-m long straight section that contains two interaction areas with longitudinally polarized electrons available in each. Luminosities of 5×10^{31} $cm^{-2}sec^{-1}$ might reasonably be expected. The electron-ring parameters are listed in Table V-1 and the layout of the ring is shown in Fig. V-1.

Table V-1. Electron-Ring Parameters

Energy	10.0	GeV
Injection Energy	5.0	GeV
Circumference	1659.7	m
Number of Bunches	98	
Bunch Separation	16.94	m
Bunch Frequency	17.7	MHz
Electrons/Bunch	8.5×10^{10}	
Emittance (Horizontal, rms)	.035	mm-mrad
Emittance (Vertical, rms)	.016	mm-mrad
Energy Spread	1.2×10^{-3}	
Tune (Horizontal/Vertical)	37.1/36.2	
Momentum Compaction	6.7×10^{-4}	
Polarization Time	14.8	min
Equilibrium Polarization	80.5	%
Energy Loss/Turn	13.2	MeV
Damping Time (Transverse)	8.4	msec
Bending Field	3.4	kG
Number of Interaction Regions	2	
Beam Size at Interaction Point (Horizontal, rms)	0.13	mm
Beam Size at Interaction Point (Vertical, rms)	0.09	mm

A. Luminosity

The bunch spacing shown in Table V-1 requires a rebunching by three in the Main Ring, producing one bunch every 56.6 nsec containing 6.9×10^{10} protons. This results in 371 proton bunches in the DC with a total of 2.5×10^{13} circulating protons. The proton beam is assumed to have an emittance $\varepsilon = 0.01\pi$ mm-mrad, the same value as in the Tevatron.

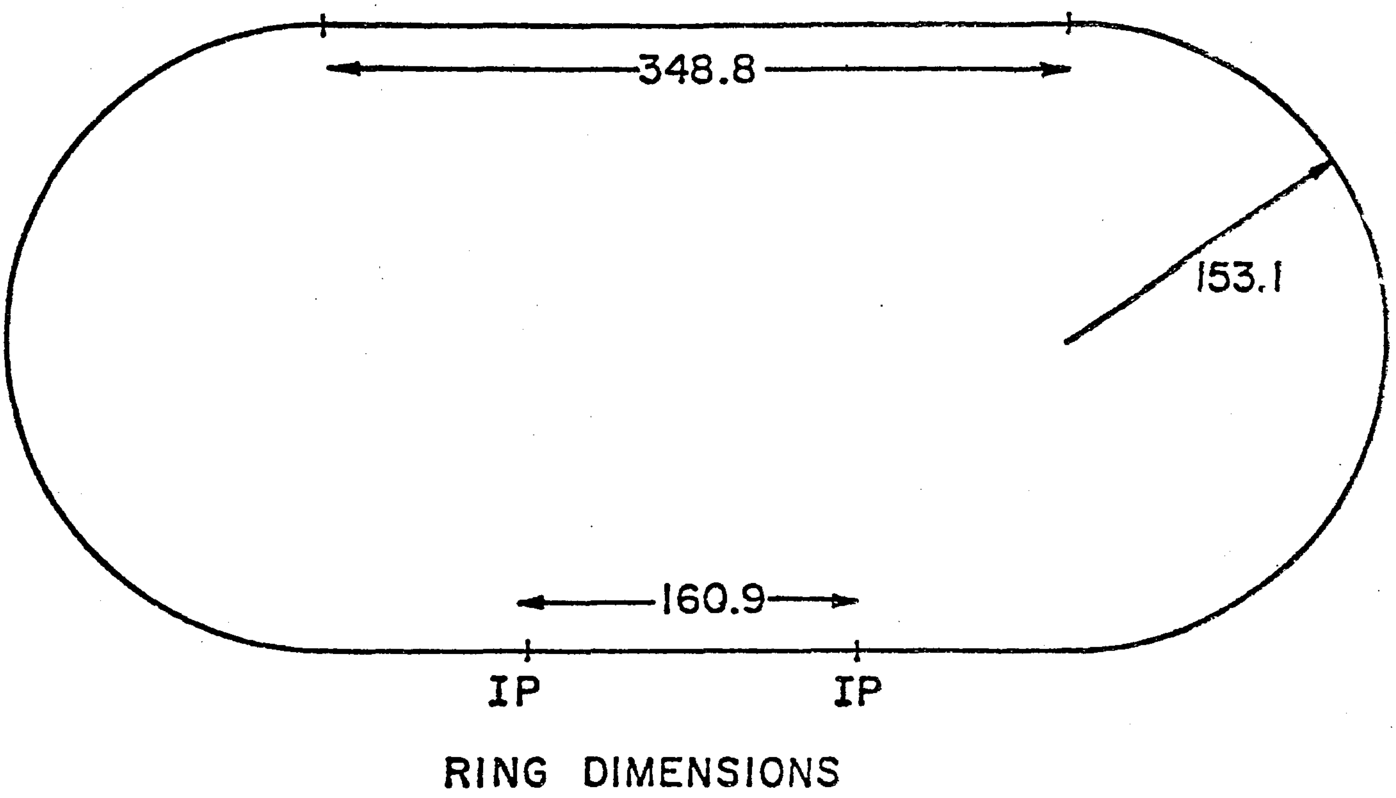


Fig. V-1. Physical Dimensions of the 10 GeV Electron Storage Ring (all dimensions are in meters).

With a β^* in the TSR of 8.5 m, the electron beam can be matched to the proton beam with an emittance of ε/π = 0.025 mm-mrad and a β^* of 0.55 m in both transverse planes. We have chosen round colliding beams and zero-angle crossing between electrons and protons for several reasons. A round beam is the more natural configuration for the proton beam, and the presence of vertical bending magnets within the electron ring (used for polarization rotation) produces a nearly round electron beam without the use of vertical/horizontal coupling. Zero-angle crossing allows for the use of meter-long proton bunches and so does not place any stringent requirements on the proton RF system.

The luminosity is estimated at $6.2\times10^{31}\text{cm}^{-2}\text{sec}^{-1}$ as shown in Table V-2. The required electron current is 240 mA and the assumed tune-shift limits are $\Delta\nu_e = 0.030$ and $\Delta\nu_p = 0.0040$ (per interaction region). The assumed electron and proton tune shifts are consistent with the present experience in existing colliding-beam facilities. However, on the other hand, the electron ring described here has fairly good damping and there is also a preliminary indication that the use of a round beam might allow one to survive higher tune shifts than in the e^+e^- machines currently operational. Since Table V-2 reflects a total number of protons that is perhaps 33% below the capabilities of the DC, the prospects for raising luminosities toward $9\times10^{31}\text{cm}^{-2}\text{sec}^{-1}$ through an increase in the number of circulating protons seem promising.

Table V-2. Luminosity

	Protons	Electrons
Energy	1000.	10. GeV
N/Bunch	6.9×10^{10}	8.5×10^{10}
Bunch Frequency	17.7 MHz	
Current	0.20	0.24 mA
Emittance (Horizontal)	.01	.035 mm-mrad
Emittance (Veritical)	.01	.016 mm-mrad
β^*_H/β^*_V	8.5/8.5	.48/.53 m
Beam Size (Horizontal, rms)	0.12	0.13 mm
Beam Size (Vertical, rms)	0.12	0.09 mm
Crossing Angle	0. mrad	
Lumonsity	6.2×10^{31} cm^{-2}sec^{-1}	
Tune Shift (Horizontal)	.0029	.027
Tune Shift (Vertical)	.0040	.030

B. Polarization

Longitudinally polarized electrons are provided in each interaction region. The rotation from transverse (the equilibrium spin direction in the arcs) to longitudinal is produced by the six-magnet rotator shown in Fig. V-2. In the figure the angles refer to helicity precession through each dipole arising from the g-2 of the electron. The area between the two interaction regions is filled with the eight-magnet rotator shown in Fig. V-3. This series of magnets flips the helicity of the electron and guarantees that the spin has the proper orientation as it reenters the arc. This also results in the opposite helicity at the two interaction points. Reversing of the helicity from its naturally arising orientation can be carried out using resonant spin-flipping techniques pioneered at Novosibirsk.

Great care has been taken in integrating the rotators into the ring in a way that the natural polarization is maintained by minimizing the effects of stochastic depolarization. The means by which polarization levels of greater than 80% can be maintained have been discussed in the Columbia e^-p proposal (Fermilab Proposal 659) and will not be iterated here. It is sufficient to point out that the prescription described there has been followed and the result is a polarization level as calculated by the program "SLIM" of 80% and a polarization time of 15 min. The polarization level is almost completely limited by the reverse bending introduced in the rotator magnets themselves. The spin level has been enhanced through the use of eight "kink" magnets within the ring. These magnets are located in the special spin-betatron decoupling cells described below. The kink magnets are responsible for 14% of the total radiated power within the ring. Without these magnets the polarization level would be $\sim$ 70% and the polarization time $\sim$ 32 min.

C. Lattice

The overall dimensions of the ring have been shown in Fig. V-1. the ring is a racetrack design consisting of two arcs of mean radius 153 m, a straight section of length 349 m containing two interaction regions separated by 160.9 m, and a 349 m off-side straight section which accommodates the RF and injection systems.

The guide field in the arcs is based on the standard FODO cell shown in Fig. V-4. The cell shown provides 90° phase advance/cell. The required quadrupole gradient is 177 kG/m for the 60 cm long quadrupoles shown, and the magnetic bending field is 3.4 kG. In addition, each arc contains two of the special cells shown in Fig. V-5. These structures are used to decouple the spin and betatron motion (which are strongly coupled within the FODO cell shown in Fig. V-4) by providing 360° of betatron phase advance and only 180° of spin phase advance each. The quadrupole magnets shown in Fig. V-5 are identical to those in the standard FODO cell. Two of the dipole magnets are also identical to those in the standard FODO cell. However, the other two are high-field (20 kG) "kink" magnets. The kink magnets have the same integrated kick

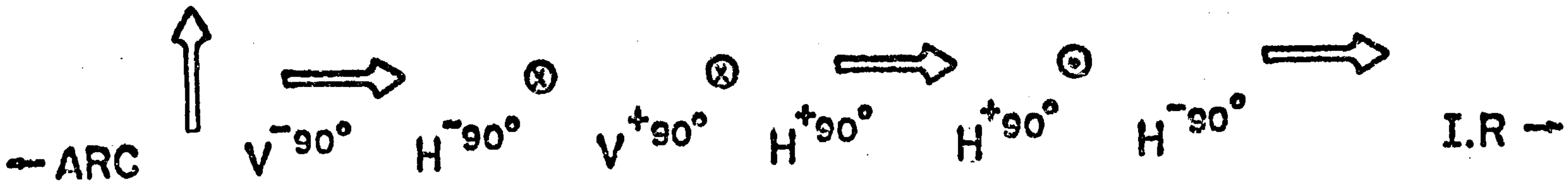


Fig. V-2. Action of the Spin Rotator.

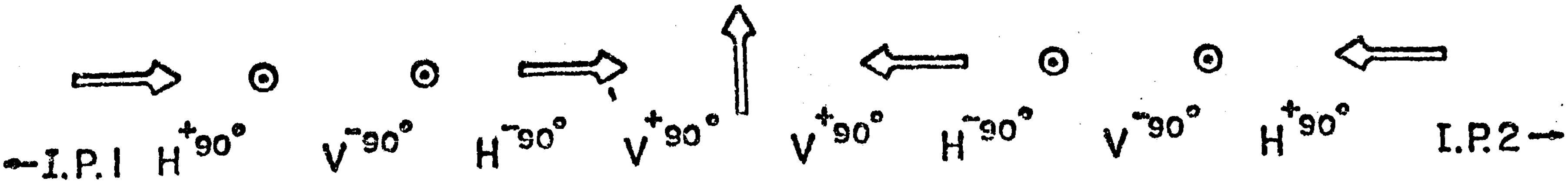


Fig. V-3. Transformation of the Spin Helicity between the two Interaction Points.

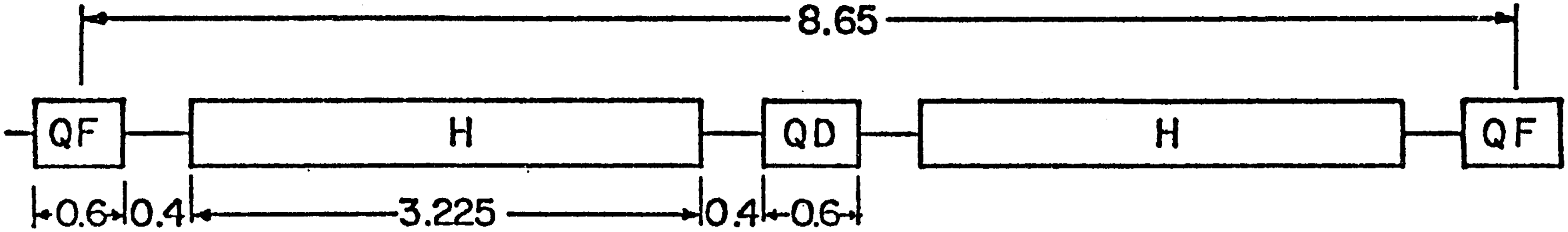


Fig. V-4. Standard 90° FODO Cell.

as the standard dipole but because of their high fields enhance the polarization level and reduce the polarization time. In addition, because of their location in a region of low H the "kink" magnets actually result in a reduction in both the horizontal and vertical beam emittance. The complete lattice functions through the arcs are shown in Fig. V-6. The last ten quadrupoles at each end of each arc have their strengths adjusted to provide matching into the straight sections, dispersion suppression, and spin matching. Each arc is completely symmetric around its midpoint.

One half of the interaction region straight section is shown in Figs. V-7a and V-7b. As stated above, the interaction region is designed to provide rotation of the electron polarization out of the transverse plane and onto the longitudinal axis. Shown in the figure are the location of both the electron and proton beamline elements. The separation between the two beams is 24 cm at the entrance to the first proton quadrupole 18.5 m from the interaction point, and is 60 cm at the electron dipole labelled V3. The electron beamline elements upstream of V2 are seen by the proton beam and are discussed in the following section.

The free space available to the experimenter is ±5.0 m surrounding the interaction point. The beta function at the interaction point has a value of about 0.55 m in both dimensions. The horizontal dispersion and its derivative are both zero at the interaction point. The vertical dispersion is also zero although its derivative is 0.15. The maximum value of beta through the interaction region is only 230 m. The insertion satisifeis all the lattice requirements for cancelling any contributions to stochastic depolarization. As a result of the vertical crossing shown in Fig. V-7, the plane of the electron ring is located 1.3 m above the plane of the DC. The two interaction regions are separated by 160.9 m (9.5 times the bunch separation) and have electrons of opposite helicity.

The off-side straight section is shown in Fig. V-8. It contains two 15 m and one 21 m long magnet-free regions of modest beta that can be used for RF and injection.

The tune of the electron ring is close to 37 both horizontally and vertically. The high tune is a consequency of the need for a low emittance to match the electron beam to the proton beam. The tune can be controlled through adjustment of the quadrupole magnets in the off-side straight section and in the dispersion supressors. The natural chromaticity of the ring is -78 horizontally and -69 vertically. The chromaticity will be controlled by sextupole magnets placed immediately following each quadrupole in the arcs. The energy spread in the machine is 1.2×10^{-3}.

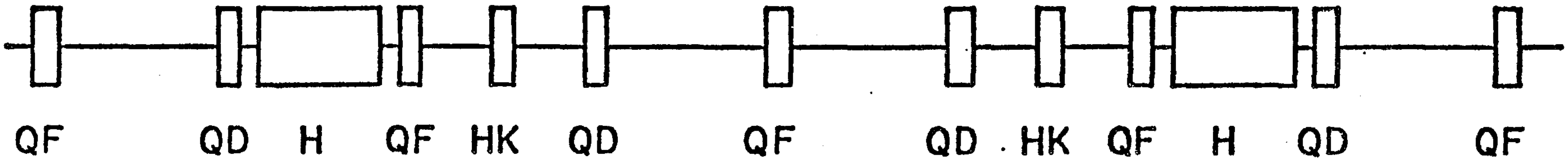


Fig. V-5. Spin-Betatron Decoupling Structure (HK are kink magnets run at 20 kG for enhanced polarization).

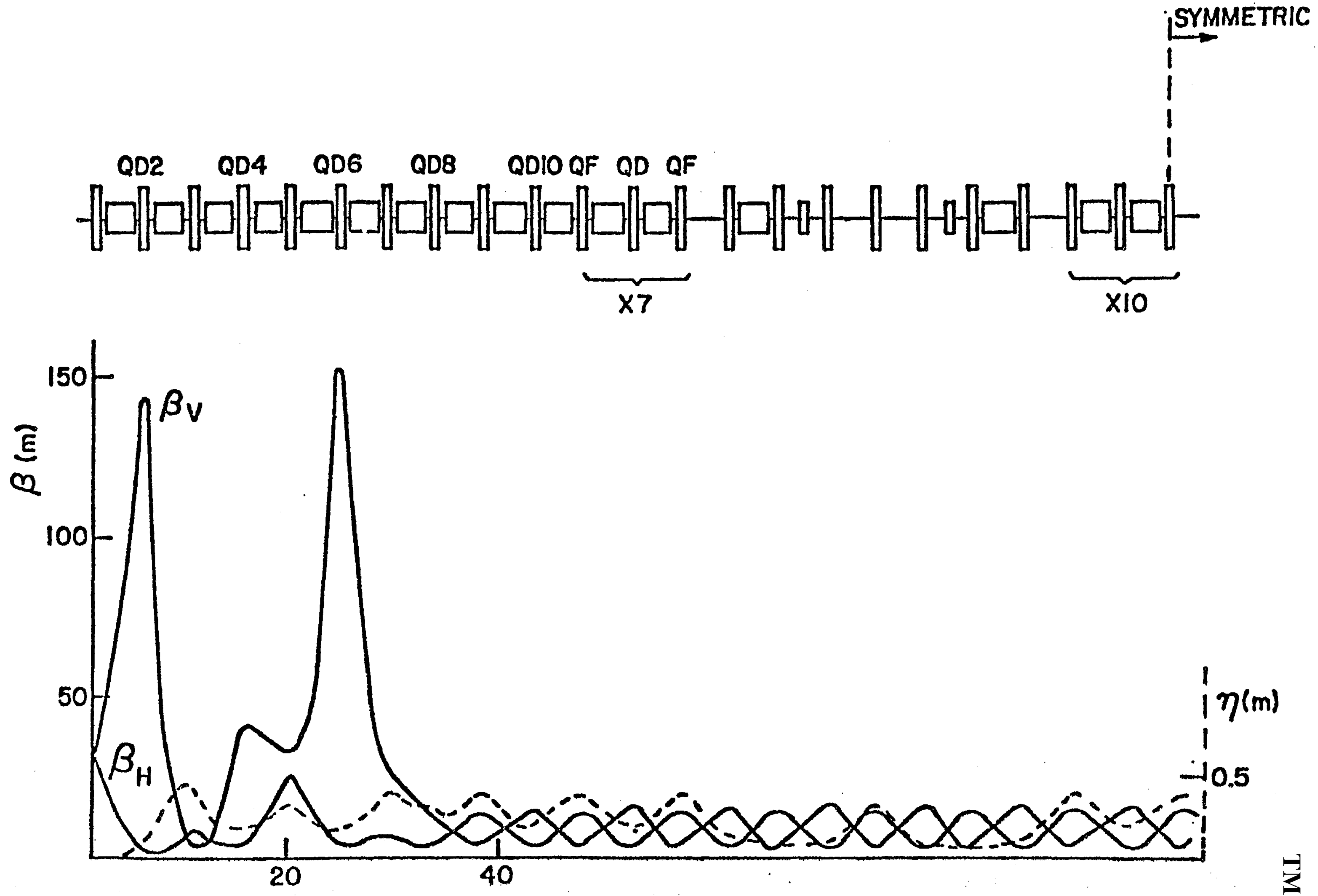


Fig. V-6. The Lattice through One-Half of an Arc.

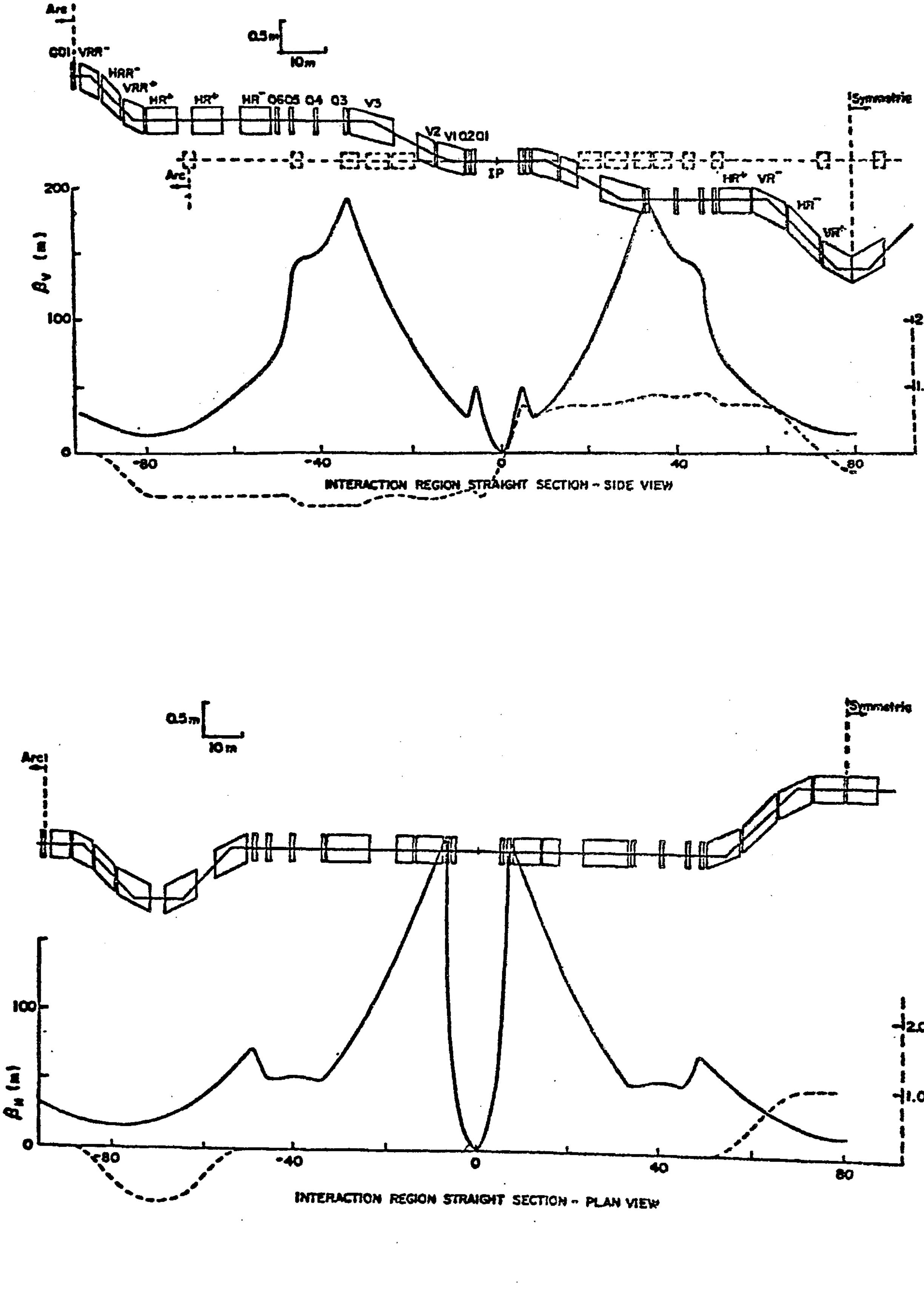


Fig. V-7. Electron Ring through one Interaction Region (a) Side View, (b) Plan View.

D. Interaction Regions

The interaction region shown in Fig. V-7 is designed to: 1) Maximize the luminosity while leaving sufficient free space for the detector; 2) keep the operation of the proton and electron rings as independent as possible; 3) minimize the amount of synchrotron radiation reaching both the detector and the superconducting elements of the DC.

The electrons and protons will come into collision in the utility straight section near the village. The proton ring-quadrupoles that produce the desired β^* of 8.5 m with a free space of ± 18.5 m are shown in Fig. V-9. These quadrupoles are all run with field gradients less than or equal to those in the arcs of the DC. The total horizontal betatron phase advance through the straight section is 1.04 wavelengths, eliminating the need for any changeover between ep and pp running.

The arrangement of dipole magnets in the electron ring is similar to that described in previous e^-p proposals at Fermilab. The magnets V0, V1, and V2 fill most of the distance from the interaction point to the first proton quadrupole. The magnet V0 is a ± 5.0 m long, 67-G air-core dipole which provides sufficient bending to insure that all radiation from the dipoles V1 and V2 can be shielded from the DC. V0, V1 and V2 bend the electron beam, 1 mrad, 22.5 mrad, and 15 mrad respectively. The magnetic and radiation characteristics of these magnets are given in Table V-3.

Table V-3. Interaction Region Magnets

Name Bunch	#	B(kGauss)		Radiated L(m)	Critical Power(W)	Photons Energy(keV)
V0	4	.067	5.0	6.8	0.4	1.7×10^{10}
V1	4	1.25	6.0	2.9×10^{3}	8.3	2.9×10^{11}
V2	4	1.25	4.0	1.9×10^{3}	8.3	2.6×10^{11}
V3	4	1.28	10.0	5.0×10^{3}	8.5	6.7×10^{11}
HR	10	3.30	7.0	2.3×10^{4}	21.9	1.2×10^{12}
HRR	2	4.98	4.6	3.5×10^{4}	33.1	1.2×10^{12}
VR	4	3.30	7.0	2.3×10^{4}	21.9	1.2×10^{12}
VRR	4	4.98	4.6	3.5×10^{4}	33.1	1.2×10^{12}

It is unavoidable that some of the radiation from V0 enter the DC beampipe. To reduce this radiation as much as possible, a mask is placed just upstream of the first DC quadrupole. The proton beam size

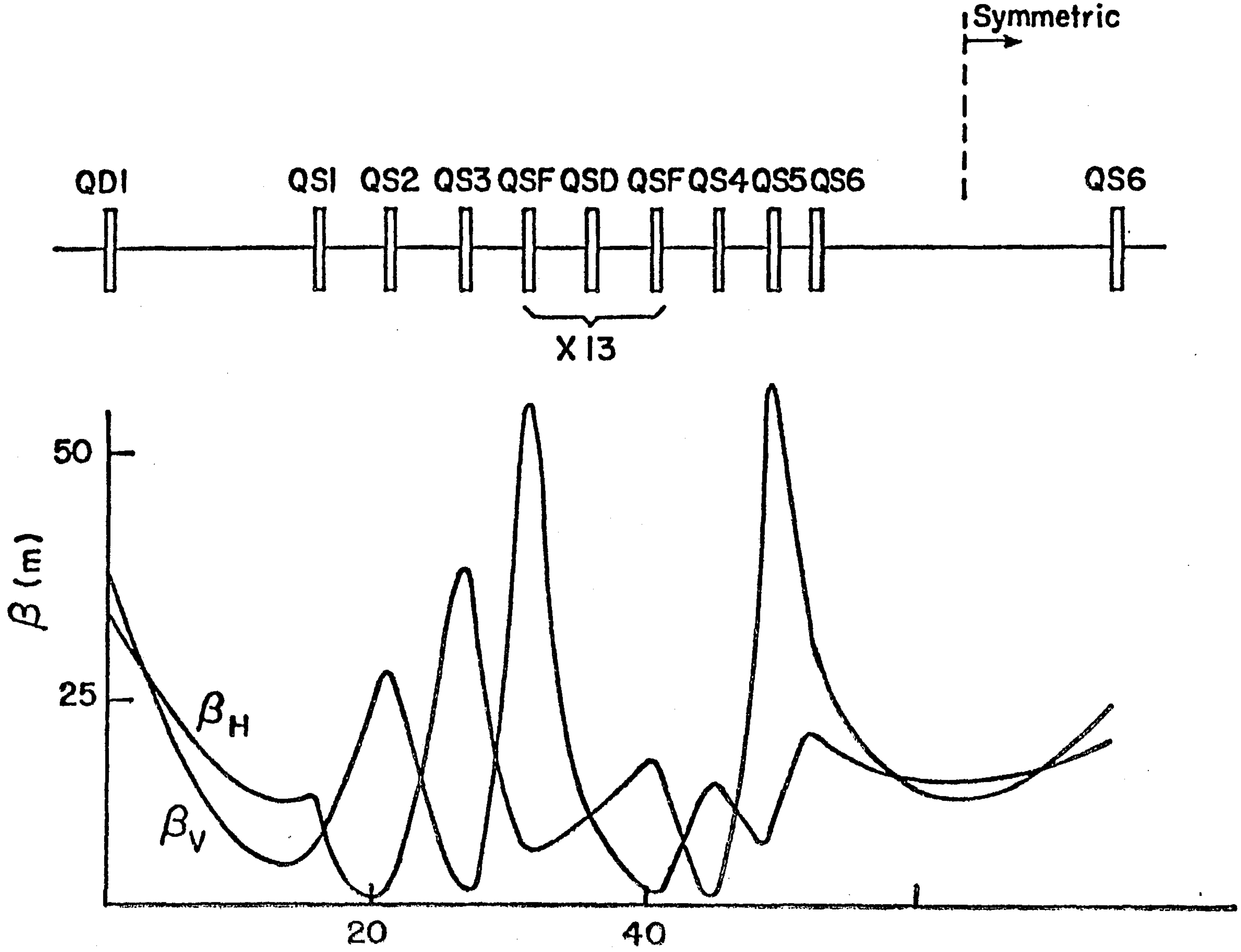
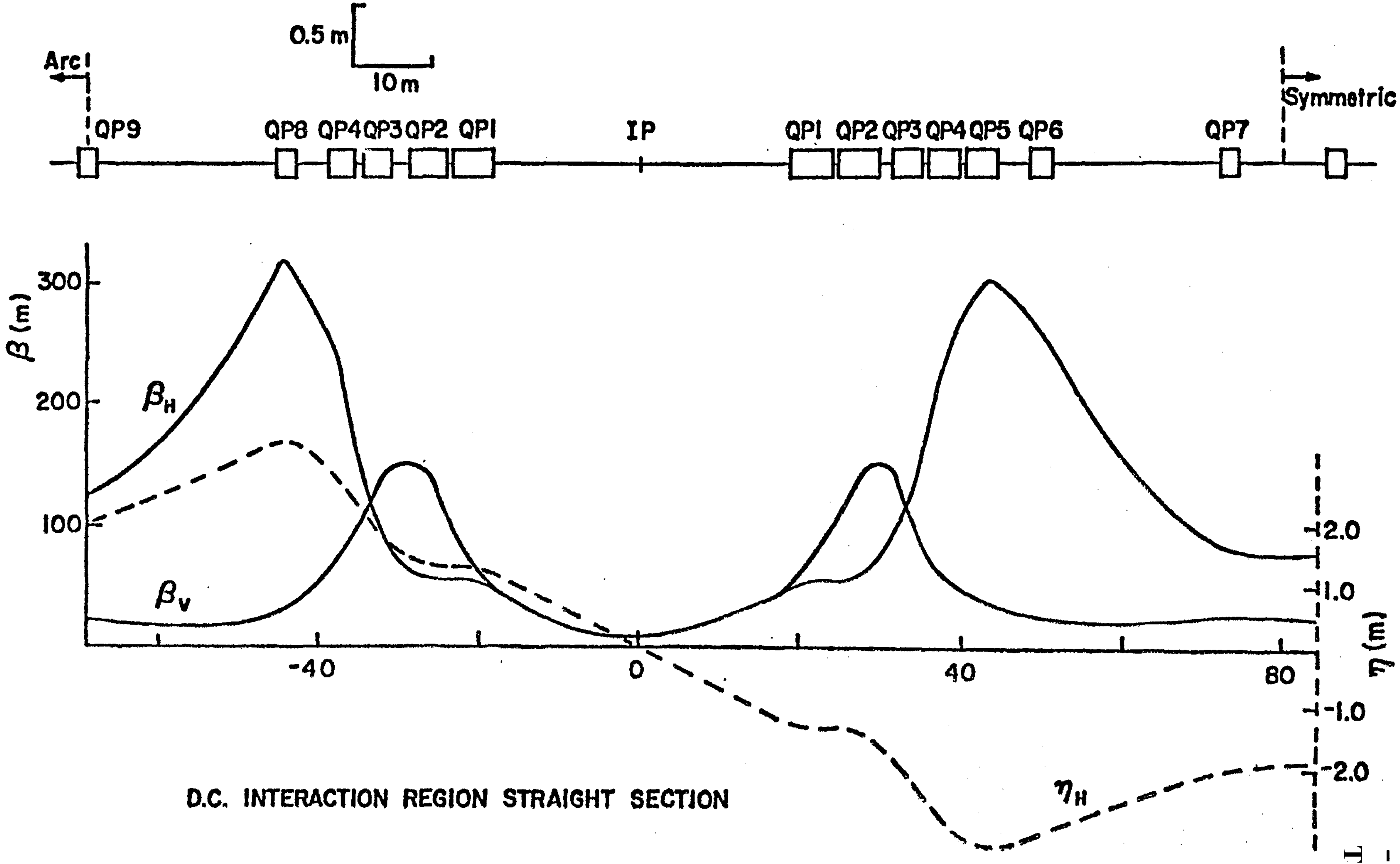


Fig. V-8. The Lattice through the Off-Side Straight Section.



0.5 m
10 m
Arc
Symmetric
QP9
QP8
QP4
QP3
QP2
QP1
IP
QP1
QP2
QP3
QP4
QP5
QP6
QP7
β (m)
300
200
100
β_H
β_V
-40
0
40
80
2.0
1.0
-1.0
-2.0
η (m)
η_H
D.C. INTERACTION REGION STRAIGHT SECTION

Fig. V-9.

at this point is 0.3 mm (rms). A 2-cm diameter hole provides clearance for the proton beam and subtends an angle of ±0.54 mrad at the interaction point. Thus, 55% of the radiation produced in V0, i.e., 7.5 W, enters the DC beampipe and must be removed by the refrigeration system.

The proton beam is allowed to pass through the magnets V0 and V1. At the entrance to V2 the two beams are separated by 8.8 cm. This is sufficient space to make V2 a septum magnet. The perturbation to the proton beam caused by V0 and V1 can then be easily corrected by a pair of proton magnets located on the proton beam side of V2. The proton beam is also allowed to pass through the electron quadrupoles Q1 and Q2. Their effect is very small and easily compensated.

Because the bunch spacing in both the electron and proton beams is 16.94 m, subsequent to the interaction of an electron and proton bunch at the interaction point there will be a passing of bunches 8.47 m away. Since the (vertical) beam separation at this point is 8.4 mm, and the electron and proton beam sizes (rms) are 0.97 mm and 0.20 mm respectively there will be no interaction at this point.

E. Vacuum System

The vacuum system is required to maintain an average pressure of 10^{-8} Torr in order to insure a beam lifetime dur to beam-gas bremsstrahlung of greater than 20 hours. The beam lifetime due to this mechanism can be calculated in terms of the probability of an electron emitting a photon of energy greater than the energy aperture of the machine as a result of an encounter with a gas molecule:

$$\tau = \frac{1.58\mathrm{x}10^{-7}\ X_o/(PM)}{-\ln f - 0.625 + f + 0.375 f^2} = \frac{1.58\mathrm{x}10^{-7}/PM}{\text{hours}}$$

where X_o is the radiation length (g/cm), M is the molecular weight (g), P is the pressure (Torr), and f is the ratio of the energy acceptance to the beam energy. If we assume that the energy acceptance is determined by the RF system (see following section), and the residual gas is 75% H + 25% CO, we find

$$\tau = \frac{22\mathrm{x}10^{-8}}{P(\text{Torr})}\ \text{hours}$$

The main gas load arises from gas desorption from the vacuum chamber wall due to synchroton radiation. The linear power density in the arcs is 3.4 kW/m and the gas load is estimated to be $1.2\text{x}10^{13}$ molecules/sec/m assuming a desorption coefficient of $6\text{x}10^{-6}$. This translates into a gas load of $3.5\text{x}10^{-7}$ Tℓ/sec-m. A total pumping capacity of 35 ℓ/m-sec is then required for a vacuum of 10^{-8} T. This capability is easily attained using distributed ion pumps of the CESR or PEP design. Commercially available ion pumps can also be installed throughout the ring to serve as holding pumps when the magnetic fields in the dipoles are either low (as at injection) or turned off.

The vacuum chamber itself is somewhat smaller than the CESR or PEP chamber, although the design can be similar. The maximum required aperture outside the interaction region is 45 mm ($\pm 15\sigma$). As such, a vacuum chamber 50 mm in diameter suffices. Bakeout procedures for reducing the desorption to the desired level have been developed at SLAC and PEP.

Pressures of about 10^{-10} Torr are needed in the interaction region to reduce backgrounds in the detector to tolerable levels.

F. RF

The design of the rf system is influenced by a wide variety of considerations. These include a desire to provide a sufficient quantum lifetime, minimize the synchroton-oscillation tune, optimize the bunch length, maximize the shunt impedence, and minimize the effect on beam instabilities. In addition, the state of the available technology, cost, and ease of construction must be taken into account. It appears that the constraints imposed by the storage ring design and by construction and cost considerations can be met with a design based on the existing CESR system.

Table V-4 summarizes the characteristics of the rf system both for operation at 10 GeV and at the injection energy of 5 GeV. The energy loss per turn due to synchrotron radiation at 10 GeV is 13.2 MeV (this does not include higher-order mode losses). The rf voltage is chosen so that a quantum lifetime of 100 hours is obtained. It is also assumed that the voltage is programmed during the injection and acceleration process such that the synchrotron tune remains constant. Note that the injection bunch length given assumes no bunch lengthening. As is discussed later, bunch lengthening by a factor of two may be expected at injection.

Table V-4. RF System

	Peak	Injection	
Energy	10.0	5.0	GeV
Energy Loss/Turn	13.2	0.8	MeV
RF Voltage	16.5	4.9	MV
Frequency	496.	496.	MHz
Harmonic Number	2744	2744	
Synchrotron Tune	0.017	.017	
Bunch length	1.09	0.54	cm
Energy Acceptance	0.007	.016	
Quantum Lifetime	100		hours
Power into Beam	3.2	0.2	MW
Cavity Shunt Impedence	340	340	M
Total Length	12.6	12.6	meters
Total RF Power	4.0	0.9	MW

Three CESR modules containing 14 cells each are used to provide the required 16.5 MV. The total length is then 12.6 m. These cavities reside in the center of the off-side straight section. This region is designed to have a fairly low ($\sim$ 12 m) β in an attempt to minimize the adverse effect of the rf cavities on beam stability. The total power requirement is 4.0 MW. This power can be supplied by eight 500 kW, 500 MHz klystrons.

G. Magnets

The total number of magnetic elements in the ring is 702. This includes 228 dipoles, 300 quadrupoles, and 174 sextupoles. All magnets are completely conventional in design. Their operating characteristics are given in Table V-5.

Table V-5. Magnet Characteristics

Magnet	Length	Strength	#	Aperture(HxV)	Comments
Dipoles					
V0	5.00 m	.067 kG	4	6	Air core
V1	6.00	1.25	4	6x12	Interaction Region
V2	4.00	1.25	4	6x12	Interaction (Septum)
V3	10.00	1.28	4	6x12	Interaction
HR	7.00	3.30	10	12x6	Rotator
HRR	4.63	4.98	2	12x6	Rotator
VR	7.00	3.30	4	6x12	Rotator

VRR	4.63	4.98	4	12x6	Rotator
H	3.23	3.38	184	12x6	Standard Dipole
HK	0.55	20.00	8	12x6	Kink Dipole
Quadrupoles					
QF	0.60	178. kG/m	86	6. cm	Standard quad.
QD	0.60	-178.	84	6.	Standard Quad.
Q	0.60	222.(Max)	40	6.	Dispersion Supr.
Q	0.60	196.(Max)	66	6.	Off-side Straight
Q1	0.80	-177	4	9.	Ineraction Region
Q2	0.80	-177.	4	9.	Interaction Region
Q3	0.80	151.	4	7.5	Interaction Region
Q4	0.80	-18.	4	7.5	Interaction Region
Q5	0.80	-33.	4	7.5	Interaction Region
Q6	0.80	36.	4	7.5	Interaction Region
Sextupoles					
SF	0.25	0.31 kG/cm^2	86	6.	
SD	0.25	0.40	88	6.	

The arcs of the ring contain 184 standard and 8 "kink" dipoles. These magnets have lengths of 3.225 m and 0.545 m respectively. The field strengths are 3.38 kG and 20.00 kG. Since the maximum beam size through the arcs (±15σ) is 32.5 mm horizontally and 45 mm vertically, a magnet aperture of 120 mm by 60 mm is adequate for containing the beam within the beampipe.

We plan that these will be C-magnets in order to provide ease of access to the vacuum chamber. The design of these magnets is completely conventional. The remaining dipoles consist of 20 rotator magnets and 16 interaction-region dipoles. The only exceptional magnets in this group are the 67-G air-core dipole at the interaction point and the septum magnet V2.

The 276 quadrupole magnets in the arcs and off-side straight section are each 60 cm long with a bore diameter of 60 mm. The field gradients in the standard quadrupoles are 178 kG/m and in the disperson-supression region range up to 222 kG/m. This results in a maximum pole tip field of 6.7 kG for the given aperture. The remaining 24 quadrupoles occupy the two interaction regions. These quadrupoles are all 80 cm in length. The only difficult ones are the quadrupoles Q1 and Q2 closest to the interaction region. These magnets require an aperture of 90 mm and a field of 177 kG/m (in Q1). The corresponding field at the pole tip is 8.0 kG.

Sextupoles are distributed throughout the ring to correct the natural chromaticity of the machine. If two families are used, the strengths are modest--0.31 kG/cm^2 and 0.40 kG/cm^2 for a length of 25 cm.

There are 154 such sextupoles in the ring and they, like the quadrupoles, require an aperture of 60 mm. The fields at the pole tips are then 1.4 kG and 1.8 kG respectively.

H. Injection

The choice of injection energy into the 10-GeV storage ring is made on the basis of the beam-stability characteristics of the ring when operating at the injection energy. We believe that it is single-beam instabilities that provide the ultimate limit on the amount of charge that can be injected into the storage ring at a given energy. We have examined three sorts of instabilities: 1) The beam lifetime due to Touschek scattering; 2) the current threshold for the onset of head-tail turbulence; and 3) the expected degree of bunch lengthening. Estimates are based on previous experience at SPEAR, PEP, and DORIS. We conclude that an injection energy of 5 GeV is the minimum for which we can reliably expect to be able to fill the 10-GeV ring with the required number of electrons. At this energy, the Touschek lifetime is calculated to be 1.1 hours and the current limit due to the head-tail effect to be 3.5 mA/bunch in the absence of bunch lengthening. However, it is expected that bunch lengthening will occur at injection resulting in bunch lengths of 1 cm rather than 0.5 cm given by the RF system.

The injection system consists of an 120-MeV linac (followed by an additional, 80 MeV for positron injection) followed by a rapid-cycling (15 Hz) 5-GeV booster synchrotron. Some fraction of the Mark III linac from HEPL may be available for use as a source of electrons and positrons for the booster ring. The Mark III linac was originally built as a prototype for SLAC and as such has an identical accelerating structure. The linac has been out of commission for several years, but is being revived now for use in a free electron laser project. This project requires only half the thirty 10-ft sections of the linac. The acquisition of five of these sections would provide an ideal injector into the booster. When driven by a modern SLAC klystron, each 10-ft section is capable of supplying 40 MeV of acceleration. The total available energy of 200 MeV is adequate for both electron and positron injection.

The booster ring has a circumference of 338.7 m (20 bunches). The electrons (or positrons) are injected directly into the booster at 80 MeV every 67 msec. They are then accelerated up to 5 GeV. Since the (transverse) damping time in the booster ring is 25 msec, the beam in nearly completely damped when it is extracted from the booster and injected into the 10-GeV ring.

Electron and positron accumulation takes place in the storage ring. Bunches from the booster are stacked in transverse phase space and moved onto the central orbit by radiation damping. The electron filling time for a system based on such a linac-booster injection system is calculated to be 4 sec for an electron-gun current of 2 A and the linac operating without either a prebuncher or buncher. The positron accumulation time has been calculated using the shower-generation program "EGS", assuming a booster admittance of $50\pi \times 10^{-6}$ m for $\Delta p/p = \pm 4\%$ an electron-gun current of 5 A, and the use of both a prebuncher and buncher. The resultant calculated filling time is 35 sec.

I. Future Upgrading

Future extension of the e^-p center of mass energy into the range $\sqrt{s} > 500$ GeV is possible with an electron ring residing within the tunnel, using the storage ring described here as an injector. The optimum energy for an electron ring within the DC tunnel lies in the range 30-35 GeV. At 40 GeV, the radiated energy is 375 MeV/turn and the radiated power is 100 MW for a circulating current of 150 mA. The luminosity attainable is about 1×10^{32} cm^{-2} sec^{-1} under assumptions similar to those given earlier. A possible parameter list for such a ring is given in Table V-7. An injection energy of 15 GeV is needed to ensure beam stability at injection.

Table V-7. 40 GeV e-Ring Parameters

Energy	40	GeV
Injection Energy	15	GeV
Circumference	13210	m
Bunches	390	
Electrons/Bunch	5.3×10^{10}	(150 mA)
Tune	78	
Dipole Field	1.1 kG	
Number of Dipoles	624	
Dipole Length	12.1	m
Cell Length (90)	30.2	m
Energy Loss/Turn	188	MeV
Luminosity	1×10^{32}	cm^{-2} sec^{-1}

The 10 GeV storage ring described here can be operated as a 15 GeV synchrotron for injection into a higher energy machine by raising the field in the bending magnets to 5.0 kG, removing the rotator magnets, and installing additional rf. At 15 GeV the radiated energy is 45 MeV/turn so a voltage of $\sim$ 50 MV is required. However very little power is required because of the small circulating current. The beam emittance will increase (compared to 10 GeV operation) due to the increased energy and lowered tune if the quadrupole fields remain fixed. But removal of the rotator magnets nearly compensates for these effects

and results in a horizontal emittance which is only 40% higher than at 10 GeV, and a vertical emittance which is of course much less. As a consequence all apertures are completely adequate for operation at 15 GeV.

Injection would proceed as described previously with accumulation taking place within the storage ring and the injection system cycling at 15 Hz. Since the ratio of the circumference of the 40 GeV ring to the 15 GeV booster is approximately 4:1, filling times of four (or less if a smaller circulating current is required) times those given for the 10 GeV ring would be expected.