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The Bypass-Storage Ring

Abstract

A bypass-storage ring system is explored in the context of its addition to the N.A.L. accelerator. It is shown that colliding beam center-of-mass energies of 140 to 280 GeV, as much as $4\frac{1}{2}$ times those of the CERN I.S.R., are feasible with this system. Superconducting magnets for the storage ring seem a natural development. Luminosities in the range of 10^{32} cm^{-2} sec^{-1}, or well above the CERN I.S.R. design values, would be anticipated. The geometry of a bypass-storage ring system is studied, and four self-consistent options are considered. Of these, two wherein the bypass is on the outside of the main ring are preferred. On comparing with a totally separate intersecting storage ring system, it is noted that the cost and size of the bypass-storage ring option are quite modest relative to its gain in energy, and that consequently the threshold of interest in a separate, intersecting storage ring system is forced up to energies of the order of a TeV.

I. General Concepts

The purpose of this note is to present the concept of a beam bypass-storage ring system in the context of the N.A.L. accelerator, to note the potential characteristics and performance of such a system, and to explore various specific methods of incorporating this facility into the main accelerator ring structure. Finally, the relationship of this system to a possible, larger set of intersecting storage rings is noted.

A bypass consists essentially of a section of accelerator structure arranged to bridge a fraction, typically 1/6 to 1/3, of the main accelerator ring, and into which the particle beam can be diverted and continue to circulate. The storage ring is used to accumulate batches of particles accelerated in the main machine on successive operation cycles, until a circulating beam of very high intensity is built up.

The use of a "bypass" or "beam siding" for an accelerator has been investigated in connection with the Brookhaven National Laboratory Design Study for a 300-1000 BeV Accelerator.[1] More recently, a proposal has been made to construct a bypass with a "low-β" insertion for the Cambridge Electron Accelerator in order to undertake colliding-beam experiments,[2,3] and a bypass facility for the CERN 300 GeV project has been discussed.[4] Similar systems for colliding-beam experimentation have also been considered in connection with the Berkeley design study.[5,6]

Such a bypass, in conjunction with a nearly tangent storage ring, is considered here as a major system or facility to augment the N.A.L. research capability. As a result of first stacking the beam in the storage ring and then re-injecting a portion of the stacked beam back into the accelerator, a much greater luminosity in the colliding beam region can be achieved than has previously been considered.[7] As a consequence, the potential luminosities significantly exceed the CERN I.S.R. design values and are comparable to those possible with an improved I.S.R.[8]

We have surveyed some of the more interesting options available for the later addition of a bypass and storage-ring (B-SR) to the N.A.L. 200 BeV accelerator. Such a facility would offer both interesting colliding-beam possibilities and an enhanced flexibility for the more conventional techniques of experimental physics.

The presence of the bypass enables many of the conflicting requirements of accelerator operation and experimentation to be decoupled. In particular, it permits colliding-beam luminosities at least as great as those of the CERN I.S.R. to be obtained with a single storage ring, by a process of storage and re-injection into the main ring.

For the normal techniques of physics experimentation the bypass offers the following possibilities:

i) The setting up of experiments close to a machine orbit while the accelerator is in operation with other experiments.

ii) Localization of beam loss and activation resulting from internal targeting and slow resonant extraction.

iii) Flexibility of modifying the local geometry of the accelerator to suit special experiments; for example, a very long field-free section.

iv) Manipulation of the circulating beam for stacking in betatron phase space over a fraction of the circumference in order to produce, for example, a short-duration, high intensity burst for neutrino experiments.

II. Physics.

The primary motivation for the B-SR is the attainment of very high center-of-mass energies. In Table I the appropriate energies are presented for the various options discussed here and for other large accelerators and storage ring systems. The physics which could be explored at these higher energies, the experimental techniques and feasibility, and the scientific justification have been presented and discussed at length, in particular by the CERN I.S.R. group.[9]

The utility of a colliding-beam device is limited by the interaction rates between the two beams. For the B-SR as described here, these interaction rates compare favorably with those typical of experiments at existing accelerators wherein a pion beam is incident on a liquid hydrogen target. They exceed the original design parameters of the CERN I.S.R.

This B-SR system differs from most other storage ring proposals in that the energies of the two beams are rather different. In the context of our current understanding of the nature of high energy nucleon-nucleon interactions,[10] the produced and scattered particles are characterized by a four-momentum-transfer, or by a transverse momentum, which depends very slowly on the total energy of the collision, so that the laboratory angles of interest in particular experiments are characteristic of each beam separately and are relatively independent of the energy of the other beam. Thus in the collision of a 50 GeV beam and a 200 GeV beam, the disposition of apparatus downstream along the 200 GeV beam would be relatively independent of whether the target were another 200 GeV beam, a 50 GeV beam, or a vessel of liquid hydrogen.

Besides the colliding proton-proton beam experiments, the B-SR system can open a number of other interesting possibilities:

1) The Storage Ring could be used with muons in the manner of Farley's experiments at CERN[11] to extend the determinations of the muon g-factor to higher precision.

2) Anti-protons could be stored in the ring at currents about 10^6 below the proton current of the main ring.[12] It is conceivable that $p\bar{p}$ colliding-beam experiments could be done.

3) The antiproton beams thus stored would be accumulated at the highest phase space density in their production spectrum, and, after a few milliseconds, they would be clear of virtually all other particles. This beam could then be extracted for experiments at the storage ring energy, decelerated in the storage ring for experiments at 0 - 10 GeV with higher $\bar{p}$ fluxes than are available in any other way, or re-injected into the main ring for acceleration to full energy (200-400 GeV). Such an antiproton beam, at an intensity of 10^6 - 10^8 per pulse, would be optimum for counter and spark chamber experiments at its full intensity.

III. Characteristics.

A. Radius, Energy, and Superconductivity.

We have assumed that the storage ring would be no larger than 100 meters radius and have carried two options, 50 m and 100 m radius, through our calculations. The basis here is that the scale of the B-SR should be such that it is an addition to the laboratory's facilities, just as a large bubble chamber or a new external beam would be, and not a significant change in the scale of the total laboratory operation. It is very probable that the use of superconducting magnets for storage rings will be practical by the time that the B-SR is constructed. Current work in this field on beam transport elements is almost directly applicable to storage ring magnets, and the cryogenics for the superconductors very nicely coincides with the optimal high-vacuum requirements for the storage ring. The principal reservations here are the questions of radiation damage to superconductors and the thermal heating of these materials from ionization. From the present state of the art, it appears that 50 kgauss is a very reasonable design field for storage ring magnets. If the storage ring is assumed to have a circumference factor of 1.5 (ratio of the ring radius to the radius of curvature in the magnets at peak field), the storage ring energies corresponding to a 50 and 100 meter radius and to a conventional and a superconducting magnet are listed in Table II.

The magnets in the beam bypass have been considered to be conventional and should be capable of operating D.C. at 18 kgauss. The radius of curvature assumed in these magnets is 500 meters, or half the overall radius of the main ring. This permits a circumference factor of 1.5, similar to the main ring. Thus, a 200 GeV beam in the main ring could be shunted through the bypass and held in circulation at constant energy. At this time, we do not find it essential to assume that the beam would be accelerated while passing through the bypass, although there may be reasons for preserving that option.

B. Mode of Operation.

For colliding-beam experiments, the B-SR would operate as follows: The main ring would accelerate protons from the booster to the storage ring energy, say 100 GeV, and then use one leg of the bypass as a one turn extraction channel to divert the protons into the storage ring. For a 100 m radius storage ring, the main ring beam would be stacked into 10 turns in the storage ring. The stacking would be most simply and desirably done in betatron phase space. This process would be repeated for successive pulses until a desired circulating beam was accumulated. This stacking process would take up to 15 minutes if the storage ring were filled to its space charge limit.

The maximum luminosity for colliding-beam experiments would be obtained by then extracting from the storage ring as much as half of the stacked beam and re-injecting it into the main ring backwards. This beam would then be accelerated to 200 BeV, or to the maximum energy at which the main ring magnets could be operated D.C., and then diverted through the bypass and held coasting at that energy while experiments are done. It should be noted that the luminosity attained in this way is significantly greater than would be attained by retaining the full beam in the storage ring and accelerating just that beam in the main ring which would be injected by the 10 GeV booster. Due to the rf problems in re-accelerating this stacked beam, the stacking in betatron phase space is particularly desirable.

The geometry of the bypass and storage ring should be such that the ring crosses the bypass twice in a long straight section of the bypass, so that the storage ring would have a small bending magnet between the two straight sections which intersect the bypass. Both intersections would be at small angles--less than 0.1 radian. The beams may be made to intersect at both points or to be held apart vertically at either or both points.

C. Performance.

The available luminosities for colliding beam experiments depend on the space charge limits in the two rings and upon the various orbit parameters. For the storage ring we took the aperture and betatron wave length of the CERN P.S. The space charge limits are given in Table III for the various storage ring options and for the main ring at the storage ring energy (e.g., the energy at which the storage ring beam is re-injected into the main ring).

The luminosities corresponding to these figures are very large indeed. Assuming a crossing angle of 0.1 radian and a beam height at intersection of 1/3 cm (produced by a low-β magnet structure), we consider two modes of operation, one conservative and one closer to the limits. The main ring is being designed to contain up to 5×10^{13} protons from the 10 GeV booster, corresponding to about 0.38 ampere circulating. If 30 successive pulses from the main ring are injected into the storage ring, giving 1.5×10^{15} protons in the storage ring and if 5×10^{14} protons are re-injected into the main ring, leaving 10^{15} protons in the storage ring, the luminosity in the intersection region would be 2.5×10^{31} cm^{-2} sec^{-1}. For a higher energy storage ring and more elegant beam handling (to permit a larger $\Delta\nu$ shift, for example), one could stack 10^{16} protons in the storage ring and 2×10^{15} protons in the main ring to obtain a luminosity of 7×10^{32} cm^{-2} sec^{-1}. These values are tabulated in Table IV along with values for the CERN I.S.R. for comparison. It is clear that the capabilities of the B-SR compare very favorably with those of the CERN I.S.R. The latter, high-current option for the B-SR would correspond to a filling by 240 pulses from the main ring, corresponding to 15-20 minutes or less.

There should be no new problems encountered in achieving a vacuum of 10^{-9} or 10^{-10} torr in the storage ring, and it can be assumed that the interaction region would be bakable and cryopumped so that the residual gas there would not provide serious background problems for experiments. The main lifetime limitation would then be in the main ring, wherein a vacuum of the order of 10^{-8} torr is probably attainable. The 1/e lifetime due to nuclear interaction is 37 hours at this pressure. Multiple coulomb scattering will cause the beam to grow in this time,[13] where the characteristic growth time to an amplitude Y_o mm is proportional to $Y_o^2\ p^2/\beta_{average}\beta_{max.}P$, where p is the particle momentum and P is the pressure. Numerically, for a 200 GeV beam of ±6 mm amplitude and an aperture of at least ±10 mm, the interaction rate is not significantly affected by multiple scattering and the interaction rate falls in time primarily due to nuclear interactions. Thus in 5 hours the interaction rate would only decrease by 20%. Larger beams and/or larger apertures would further reduce the effect.

In order to limit induced activity in the main ring and also to improve the definition of the beam in the interaction regions, beam clippers would be installed in the bypass down stream from the interaction region. At the termination of an experimental run with the stacked beam, the beam in the main ring would probably be brought into a normal external beam channel for, e.g., a neutrino-type experiment.

It should be recalled that the induced radioactivity caused by an accidental dump of the stored beam would only be as bad as a continuous spill of a small fraction of the normal beam in continuous operation. For example, if beam from 5 minutes of normal injection and acceleration operation are stacked in the main ring for two hours and then all dumped accidentally, the induced activity is no worse than 4% of the beam being lost at the same locale over two hours of normal operation.

The onset beam-beam incoherent instabilities would be expected for 3 to 6×10^{16} protons in the storage ring, safely above the expected operating values.

The energies represented by the stored beams are remarkably high. A 100 GeV beam of 2×10^{16} protons corresponds to 300 megajoules of stored energy. It is well to bear in mind that the single pulse (5×10^{13}) beam at 400 GeV contains about 0.3 megajoules.

IV. Geometrical Options for the Bypass-Storage Ring.

We have considered four possible schemes for realizing the bypass-storage ring concept. In developing these designs, we have set several conditions. First, the bending radius in the bypass bending magnets must not be less than 500 meters, in order that magnets similar to those in the main ring may be employed. Second, the distance between the bypass straight section and the main ring must not be less than 50 meters. Third, the injection and extraction points of the bypass should be at long straight sections, and the maximum azimuth of the main ring to be bypassed must not exceed 120°, so that only 60° and 120° bypass options are considered. Finally, all designs assumed a 200 meter radius storage ring.

From a purely geometrical point of view, the bypass can be either on the inside or the outside of the ring for both the 60° and 120° cases. Layouts of the bypass-storage ring section of the main ring appear in Figure 1. The arrows indicate the direction of the beam during injection into the storage ring and re-injection in to the main ring.

The parameters of interest for the various options are given in Table V. Option III requires that the beam first be bent away from the main ring by 15° in order to realize the minimum distance condition and still have a straight section in the bypass of a useful length. Thus, while there is only a 60° change in direction of the beam in traversing the bypass, the total amount of beam bending required is 120°. The costs of the various options were obtained by applying standard cost estimating formulae.[14] These costs do not include the storage ring or extraction-injection equipment since these are assumed to be constants.

Of the four options, Options I and III have the additional advantage that an external proton beam might use a portion of the same extraction and transport equipment as does the bypass and, correspondingly, that an experimental hall built for a second external proton beam could replace a portion of the bypass tunnel. This is apparent in Figure 2, where two bypass-storage ring options are shown in relation to both the main ring and the site.

Each of the various options has its own advantages and disadvantages. Option I clearly involves the most extensive tunnel, vacuum chamber, and beam transport systems. However, it is on the outside of the main ring, where its installation would not disrupt the various services, roads, etc. that are currently planned for the inside of the main ring. Further, the relatively long straight section immediately after extraction of the beam from the main ring is particularly compatible with the external proton beam line mentioned above. Finally, the experimental hall at the interaction area is the most amenable to extension. With one exception the advantages just listed for Option I apply also to Option III. The exception arises from the extensive bending required to make the beam clear the main ring magnets. It is felt that the magnetic structures required in this instance will be less compatible with a second external beam experimental area. This situation could be alleviated by increasing the initial bend and installing additional straight section length in the extraction and injection sections of the bypass. However, this will considerably increase the total amount of bending required. Finally, it should be noted that Option III offers the shortest straight section and therefore the least clear space in the region of the interaction area. As seen in the figures, Option III is considered to not use the same long straight section as the second (future) external proton beam area uses.

Options II and IV suffer from the same disadvantages. First, their installation would disrupt the roads and services planned for the inside of the ring, and, second, they do not provide the possibility of shared facilities with an external proton beam.

The preferred options are therefore I and III, with every factor save economics favoring I. Depending on the details of the second external proton beam area, even the cost for Option I might be in its favor. It should be noted that the 120° bypass options require access to the main ring in the long straight section spanned by the bypass in order to re-inject the stored beam.

V. Recommendations.

In view of the considerations of Section IV, we recommend that provision be made for adding beam tunnels connecting nearly tangent to the two long straight sections on the southeast side of the main ring (clockwise beyond the planned internal target area). This would then provide for the later addition of either Option I or III of the B-SR system.

VI. Ultimate Storage Ring-Accelerator System.

On Figure 2 we have sketched a second 1000 meter radius ring within the site boundary. While it fits quite reasonably, with 1000 ft. minimum spacing to the site boundary, it is also near the maximum size ring which could be fit onto the present site.

It would be possible, as a major, future step in the evolution of N.A.L., to build a concentric, intersecting, superconducting double ring structure on this site to provide slow acceleration of stacked beams to about a TeV and colliding-beams experiments at energies equivalent to a 10^{15} eV proton on a stationary target.[15] Thus, for a circumference factor of 2.0 (as in the CERN I.S.R.), a 50 kgauss field would contain a 750 GeV beam and a 100 kgauss field, a 1500 GeV beam. In view of the continuing evolution of superconductors, it is reasonable that the latter figure would better represent the state of the art by the time such a program would be considered.

A motivation for holding this possibility open is the increasing evidence from Cosmic Ray experiments that, above about 2×10^{14} eV, average transverse momenta increase and the qualitative nature of the interactions seems to change.[16] On the other hand, a separate I.S.R. system for protons of only 200 to 400 GeV appears to represent too little gain in energy or luminosity over the B-SR, especially considering the much greater size and cost. It therefore seems that the most propitious course for NAL would be to build a B-SR system as a facility at an early date and to leave provision for the eventual construction of a 1 km superconducting ring system for TeV physics.

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Table I

Laboratory and Center-of-Mass Energies of the Bypass-Storage Ring as well as Various Accelerators and Colliding Beam Devices
(All units are GeV with the rest mass of the proton approximated as 1 GeV/c^2.)

Device	Kinetic Energy Beam 1	Kinetic Energy Beam 2	Center-of-Mass Energy	Equivalent* Lab Energy
B.-S.R.	200	25	141	10^4 (=10 TeV)
	200	50	200	2×10^4 (=20 TeV)
	200	100	283	4×10^4 (=40 TeV)
N.A.L.	200	0	20	200
	400	0	28.3	400
CERN I.S.R.	30	30	60	1800
LARGE I.S.R. WITH N.A.L.	1000	1000	2000	2×10^6 (=2000 TeV)

* The energy of a proton on a stationary target proton giving the same center-of-mass energy.

Table II

Storage Ring Energies for Different
Fields and Radii
(assuming a circumference factor of 1.5)

Radius (meters)	Magnetic Field (kilogauss)		Proton Energy (GeV)
50	20	conventional magnet	20
100	20	conventional magnet	40
50	50	superconducting magnet	50
100	50	superconducting magnet	100

Table III

Space Charge Limits*

Energy GeV	Main Ring Protons	Main Ring Current (amperes)	Storage Ring Protons	Storage Ring Current (amperes)	Radius (meters)
25	3.1×10^{14}	2.4	4.8×10^{15}	720	50
50	6.3×10^{14}	4.8	9.6×10^{15}	1450	50
				720	100
100	1.2×10^{15}	9.6	1.9×10^{16}	1450	100

*The transverse, unneutralized, incoherent and coherent limit including image effects to produce $\Delta\nu$ of $\frac{1}{4}$.

Table IV

Luminosities Attainable with the B-SR
and with the CERN I.S.R.

	$N_{main\ ring}$	$N_{storage\ ring}$ (R=50m)	Luminosity, L $cm^{-2}\ sec^{-1}$
B-SR	5×10^{14}	10^{15}	2.5×10^{31}
	2×10^{15}	10^{16}	7×10^{32}
I.S.R. Design Values			4×10^{30}*
Possible Improvement			$\sim 10^{33}$

*Reference 8.

Table V

Bypass-Storage Ring Options*

Option	Free Straight Section (containing beam-beam intersections) (meters)	Perpendicular Distance to Main Ring (meters)	Minimum Distance between Storage Ring and Main Ring (meters)	Total Straight Section Length in Bypass (meters)	Total Bend	(meters)	Estimated Cost of Bypass (millions of dollars)
I External 120°	295	250	50	1450	120°	1040	18.0
II Internal 120°	866	250	50	866	120°	1040	14.6
III External 60°	≥100	≤90	≤90	≥100	120°	1040	10.2
IV Internal 60°	560	65	65	560	60°	520	8.0

*Assuming 1) 500 m radius of curvature in non-straight portions of bypass,
2) 50 m minimum distance between the two rings,
3) 200 m diameter storage ring.

Figure Captions

Figure 1. The four options for a bypass-storage ring. The storage ring is sketched in each case with a radius of 100 meters. Also indicated is a possible reverse stub for re-injecting a portion of the stacked beam into the main ring counter-clockwise.

Figure 2. A possible schematic master plan for the N.A.L. site showing both the bypass-storage ring and a possible future 1000 meter radius superconducting accelerator-intersecting storage ring booster system. Two options are indicated for the bypass-storage ring; Option I with solid lines and Option III with dotted lines.

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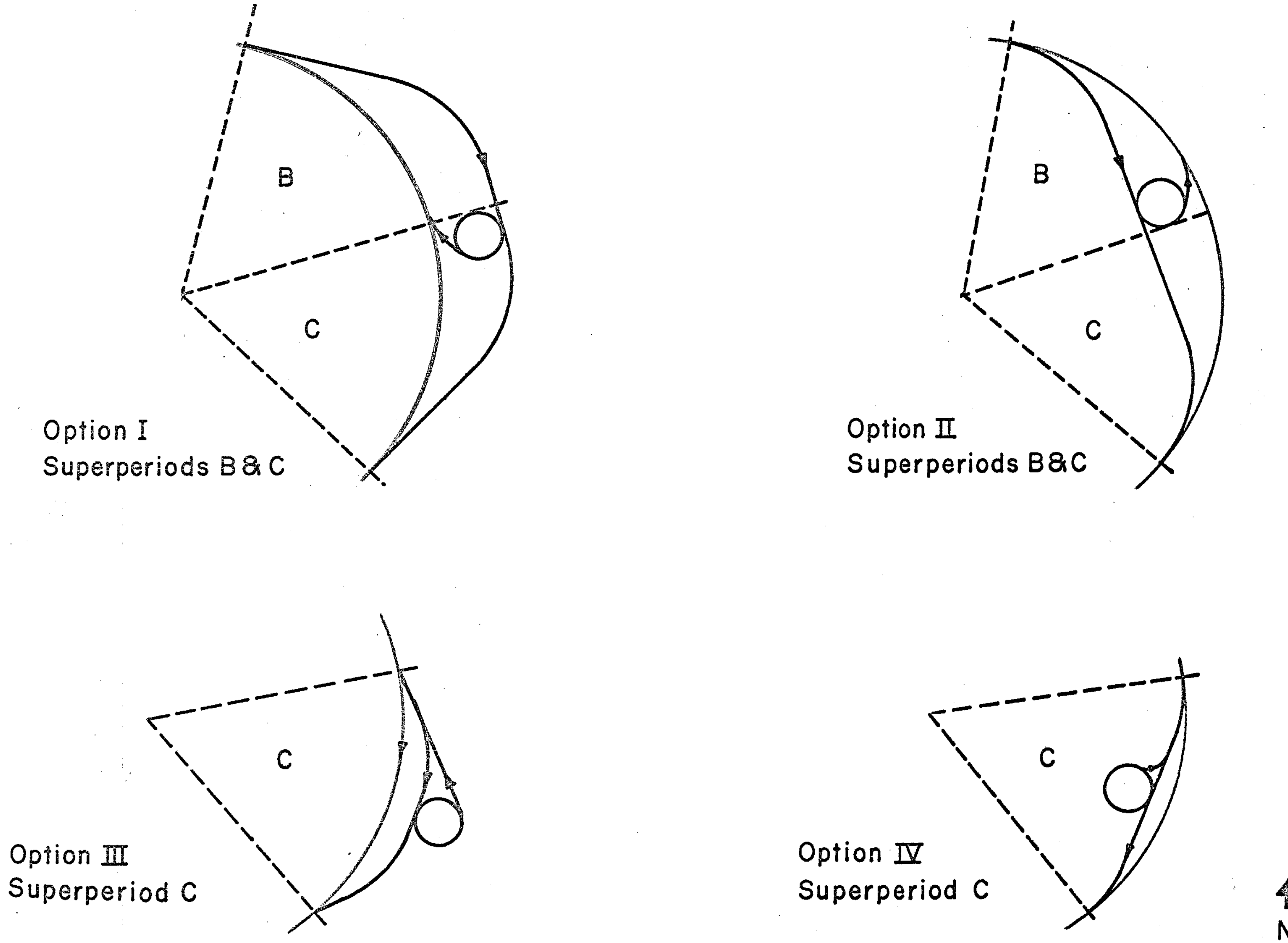

Figure 1
Four Options for Beam Bypass and 100 meter Radius Storage Ring

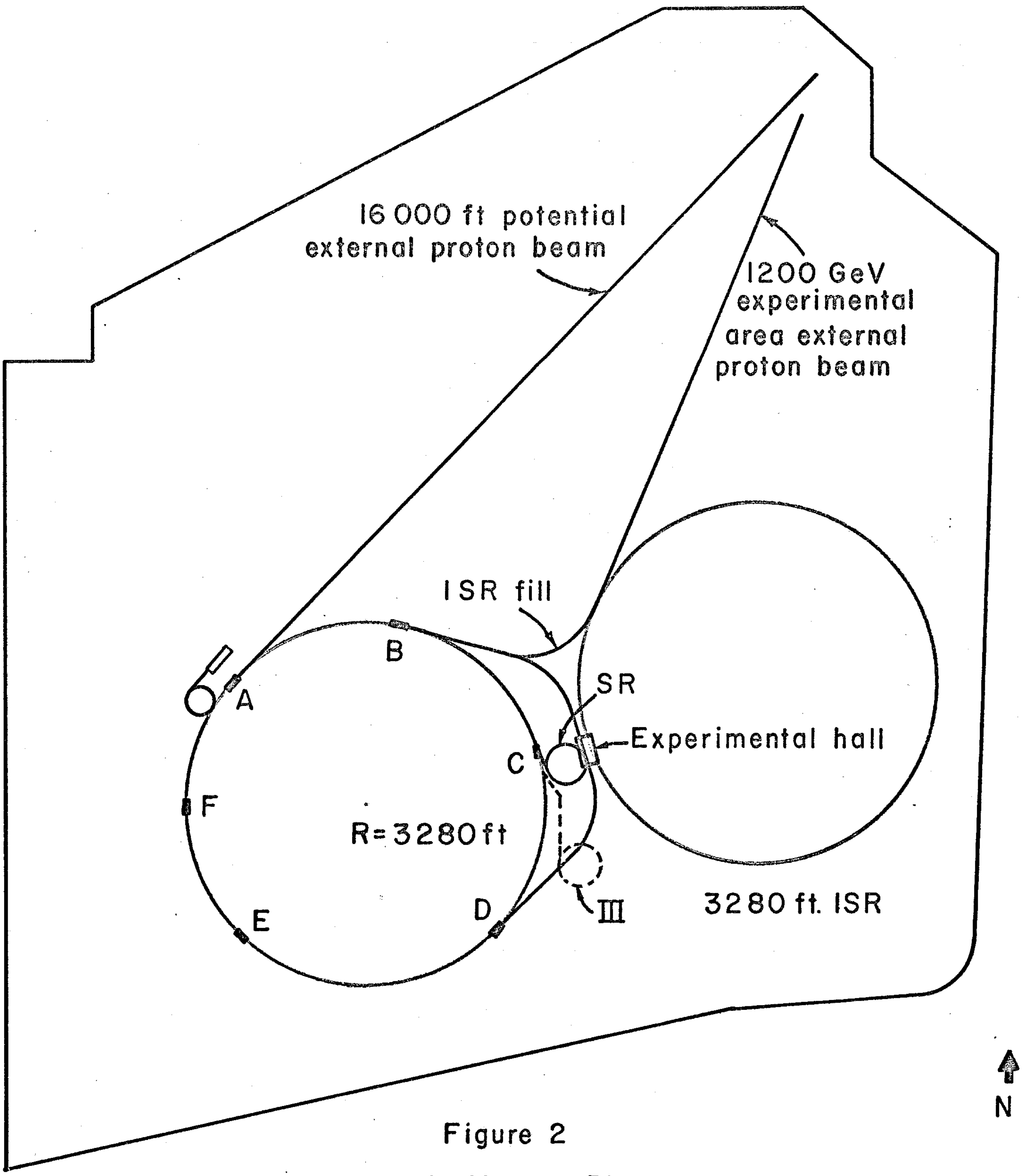

Figure 2

Schematic Master Plan