A STUDY TO ADAPT A WEAK FOCUSING SYNCHROTRON TO A STRONG FOCUSING PROTON STORAGE RING*

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Abstract

The high intensity of a storage ring makes it a powerful instrument for nuclear research by manipulating the beam duty factor from a machine such as the Los Alamos Physics Facility (LAMPF). Some of the proposed uses for an intense medium energy (800 MeV) proton storage ring are: (1) defense applications, (2) neutron pulse radiolysis, (3) duty stretcher for counting experiments, (4) pulsed source for an unstable particle storage ring, (5) study of beam dynamics, and (6) neutron time-of-flight spectrometer.

This study places the transition energy above the particle energy to avoid the negative mass instability. In order to attain maximum current storage, protons would be injected by H^- stripping inside the ring and thereby avoid the Liouville constraint. This low-duty mode has the design objective of 40 A circulating current. Another mode of operation, the high-duty mode, accepts 25 turns of proton injection by a combination of orbit and tune shifting; 120 times per second.

Extensive lattice calculations were performed to implement these concepts. These resulted in the choice of a racetrack configuration which could employ the California Institute of Technology synchrotron magnets that were originally the 1/4 scale Bevatron. These magnets would be fitted with new pole tips to form a strong focusing matrix with a π-2π matched insert in the long, straight sections.

Introduction and Applications

Figure 1 shows the rapid gains that have been made in a few short years in storage ring technology since the colliding beam proposal of Kerst et al.[1] and O'Neill[2] in 1956.

In the case of medium energy protons such as from LAMPF, storage rings are of interest because of their potential as charge accumulators and duty cycle manipulators. The powerful capabilities of such a system are evident in the case of using 800-MeV protons for evaporation/fission neutron production from heavy metal targets, in which case 20-40 neutrons/incident proton result.[3] A few of the applications of such a system which have been conceived to date are given in Table I.

To meet the objectives set forth in Table I, two distinct modes of operation of the storage ring have been planned in this study: a low-duty high-current mode characterized by charge exchange injection and a high-duty mode using multiturn proton injection. Each mode uses fast extraction. However, in the high-duty mode, the beam will be bunched into five packets and extracted individually. This poses severe requirements on the fast kicker parameters.

Table II summarizes the design objectives of this study. Reference 4 is a detailed preliminary study report on the Weapons Neutron Research (WNR) storage ring.

Lattice Considerations

Many lattice configurations and parameterizations were studied using the programs SYNCH[5] and 4-P.[6] Soon various guidelines became apparent. The lattice had to be compact to hold the beam rotational period to 250 nsec. A short period was desired to keep the bunching factor small and hence reduce rf requirements, and because the space charge limit is inversely proportional to the period.[4] Although a separated-function lattice was explored, we were led to a combined-function lattice for compactness. The complexities of the two modes of operation and the desire to minimize the P function and the momentum dependence (X_{eg}) led to the use of a matching straight section of a new type. The π-2π insert[7] has a unit transfer matrix for off-momentum, off-equilibrium orbit particles and provides a free drift region of 7 m in this design. The design goal of storing the highest possible charge suggests that the transition energy of the lattice should be higher than the beam energy to avoid the negative-mass instability. This also requires the lattice to be strong focusing. Before any firm decisions had been made on the lattice, the California Institute of Technology synchrotron (originally the 1/4 scale Bevatron model) became available as surplus property. Because the maximum rigidity of the electrons

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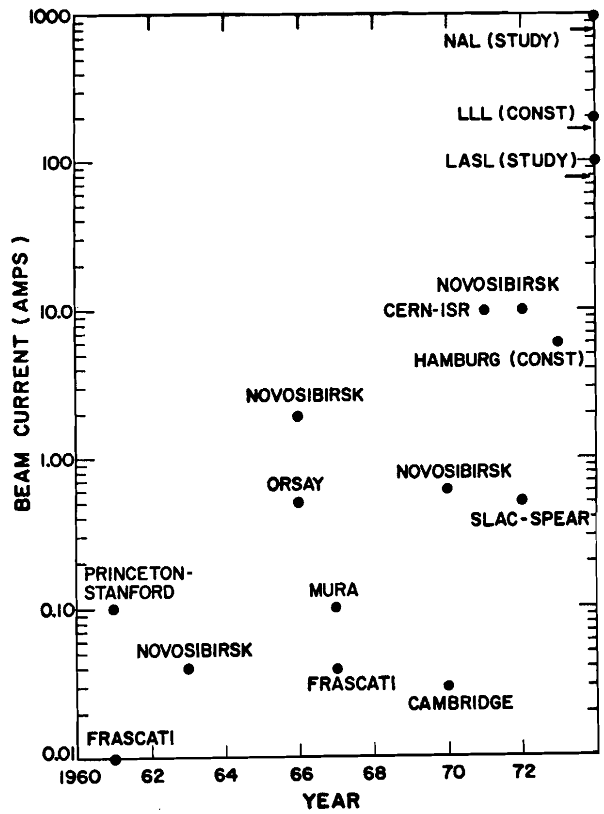

Fig. 1. Intensity evolution of various storage rings.

it had been accelerating ($\beta_p = 5.8\ T_m$) was close to that for 800-MeV protons ($\beta_p = 4.88\ T_m$), the design focused on this adaption. A new set of pole tips, vacuum system, and rf system would be required. The only compromise with a completely free design is that the magnetic efficiency is approximately 20% less. On the other hand, it was believed that the use of these magnets was economically sound and would lead to a larger aperture. This conclusion was because of the usual trade-off in magnet cost and aperture. An ecological appeal was the better utilization of natural resources. The parameters of the proposed lattice are given in Table III; Fig. 2 shows the proposed layout for the storage ring.

Pole Tip Design

The lengths of the pole tips were chosen, as shown in Fig. 2, to fit the iron yoke configuration of the CIT synchrotron. Given the gradient and aperture of the magnets, K. Halbach (LBL) designed the pole tips, using the synthesis program SMIRT and the magnetic vector potential analysis program POISSON.[8] Figure 3 shows the results of these calculations, and Fig. 4 shows the placement of the pole tips in the CIT magnets--note the staggering of the F and D tips, as well as the empty region on the left-hand side of the magnets.

TABLE I. Possible Uses of a Medium Energy Proton Storage Ring

Defense Applications: Neutron production of 10^{15}-10^{17} in a burst for material and neutronic studies.

Neutron Time-of-Flight Spectrometer Source: Average neutron production rate of 10^{15} neutrons/sec at 600 pulses/sec for neutron cross-section measurements.

Neutron Pulse Radiolysis: Direct study of radiation-produced transient chemical and biological species. Neutrons give much higher linear energy transfer than gamma radiation.

Polarized Proton Storage Ring: Polarization of the proton beam by multiple target traversals. Used for basic nuclear research.

Counting Experiments: By greatly increasing the duty, data rates for accidental-limited experiments could be increased by 200-40,000 times for LAMPF.

Pulsed Source for an Unstable Particle Storage Ring: Could be used for driving a muon storage ring for g-2 experiments or a colliding orbit unstable particle storage ring of the Precetron type.

Beam Dynamics: Used for the study of beam instabilities and techniques for higher intensities.

TABLE II. Design-Performance Specifications for WNR Ring

	Low-Duty Mode	High-Duty Mode
Peak Extracted Beam Current (A)	100	4
Pulse Duration for Above (nsec)	100	5
Maximum Number of Protons Stored	6×10^{13}	6×10^{11}
Maximum Repetition Rate	1/10 min	600/sec
Injected Particle Type	H^- ions	Protons
Injection Current (mA)	1.7	17
Injection Time	0.1 sec	6.5 μsec
Number of Turns Injected	2×10^4	25
Maximum Bunching Factor	10	10
Harmonic Bunching Number	1, 5	1, 5
Neutron Production (neutron/incident proton)	400	30
Instantaneous Neutron Production Rate (n/sec)	2×10^{23}	7×10^{20}
Neutrons/Pulse	2×10^{16}	1×10^{12}
Target Average Power (kW)	2	19
Beam Power (kW)	0.013	10

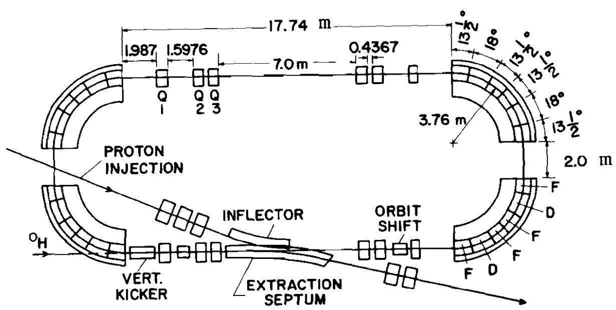

Fig. 2. Possible Layout of the Proposed WNR Ring Lattice.

Charge Exchange Injection

Charge exchange injection was adopted as the method for storing the largest currents. Table II shows that for H^- injection, 2×10^4 turns will be needed to obtain the design goal of 100 A, 100 nsec pulse. If the injection could be done directly with the H^+ beam, only 2×10^3 turns would be required, due to the ratio of H^+ to H^- currents available from LAMPF--but even this is much greater than present multiturn injection practice. Indeed, the 10^3 turns of protons using stripping of H^- is the highest we know of to date. H^- injection is not limited by Liouville's theorem, allowing Dimov to reach the space charge limit.[9]

Figure 2 shows H° atoms injected into the lattice and stripped where they merge with the circulating beam. Originally, H^- injection on a mirror-image orbit was considered, but this required a low-field magnet to avoid stripping the H^- ions ($B < 4$ kG) before they are on axis. The use of additional low-field magnets would introduce a superperiod of one into the ring unless the low-field magnets are added for compensation. We propose, instead, to magnetically strip H^- to H° in a 20-kG magnet external to the lattice, inject the neutral ions through the magnetic field, and strip to protons in a field-free region of the straight section. Magnetic stripping is preferred because the optimum thickness of a material stripper only results in 60% H°. The 40% of protons and H^- ions remaining would result in intolerable radioactivity in the ring. The statistical nature of the lifetime of an H^- ion in the magnetic field results in an emittance degradation of 2 ($2\pi/3$ cm mrad).

Calculations have shown the final stripping of H° to protons can best be done at this energy using a solid stripper foil. We have considered a carbon stripper, 131-μ thick, which would yield only 1% H° contamination. If the foil is cooled by radiation and thermionic emission, assuming a reduction in power density of approximately 13 may be achieved from betatron oscillations, the stripper will reach 1750°K after the first 500 μsec macropulse from LAMPF. The orbit may be shifted so that heating occurs only during injection. After the tenth macropulse and 40 A of circulating current, the stripper temperature would rise to 3100°K, which would correspond to an evaporation rate of 60%/sec.

TABLE III. Parameters of the Proposed WNR Ring Lattice

Overall Properties

Maximum Dimensions: 21.2 x 10.94 m
Period: 250 nsec
Equivalent Radius: 10.03 m
Ring Tune: $\nu_x = 4.39$, $\nu_z = 2.23$
Transition Energy: 3.2 GeV
Particle Energy: 800-MeV Protons
Admittance: $a_x = 200$ cm mrad; $a_y = 67.8$ cm mrad

Sector Magnets

Magnetic Gradient: $n_f = -12.03$; $n_d = 15.04$
Maximum β: $\beta_x = 5.59/\text{m}$; $\beta_y = 9.93/\text{m}$
Maximum x_{eq}: 1.072 m
Aperture: 10 x 20 cm
Magnet Weight: 155 tons of iron; 18 tons of copper
Magnet Power: 1 MW

Matching Inserts

Length of Insert: 17.74 m
Maximum Free Region: 7 m
Quadrupole Gradients: 0.442, -1.519, 1.514 kG
Quadrupole Length: 10, 35.6, 35.6 cm
Quadrupole Aperture: 15.24 cm

Multiturn Proton Injection

The injection of 25 turns of protons into betatron space 120 times per sec is performed by a combination of orbit shifting, using a pulsed dipole magnet, and tune shifting, using a pulsed quadrupole. This results in 60% phase packing density. Tune shifting is accomplished by a ferrite box magnet; the details are presented by Avery and Meads in the proceedings of this conference.

Figure 2 shows the proton injection from the inside of the ring. Although this allows the inflector to fit compactly near the extractor, it requires a beam line distinct from the H° injection beam line. Further study indicates that an electrostatic injector system may allow injection from outside the ring.

Extraction

The beam is extracted by a 1° vertical kick from a capacity-loaded transmission line kicker into a 7° iron horizontal extraction septum. The reason for the vertical kick is to take advantage of the flatness of the circulating beam. Engineering details of this system are yet to be resolved.

Vacuum

High vacuum is required in a storage ring to achieve long containment times. The relatively short containment time of the WNR ring ($\lesssim 1$ sec) implies a necessary vacuum of only 10^{-5} Torr. However, there is evidence that vacuum also affects beam stability. A vacuum of 10^{-8}-10^{-9} Torr is calculated using the analysis of the ion-produced throbbing beam instability of Hereward et al.[10]

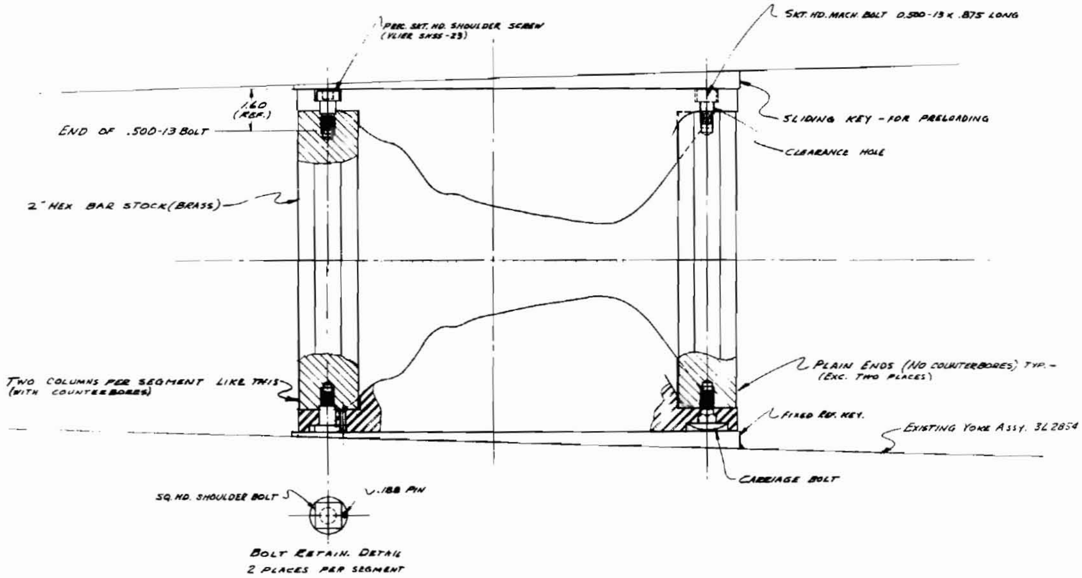

Fig. 3. Shape of pole tips, calculated to satisfy parameters of Table III.

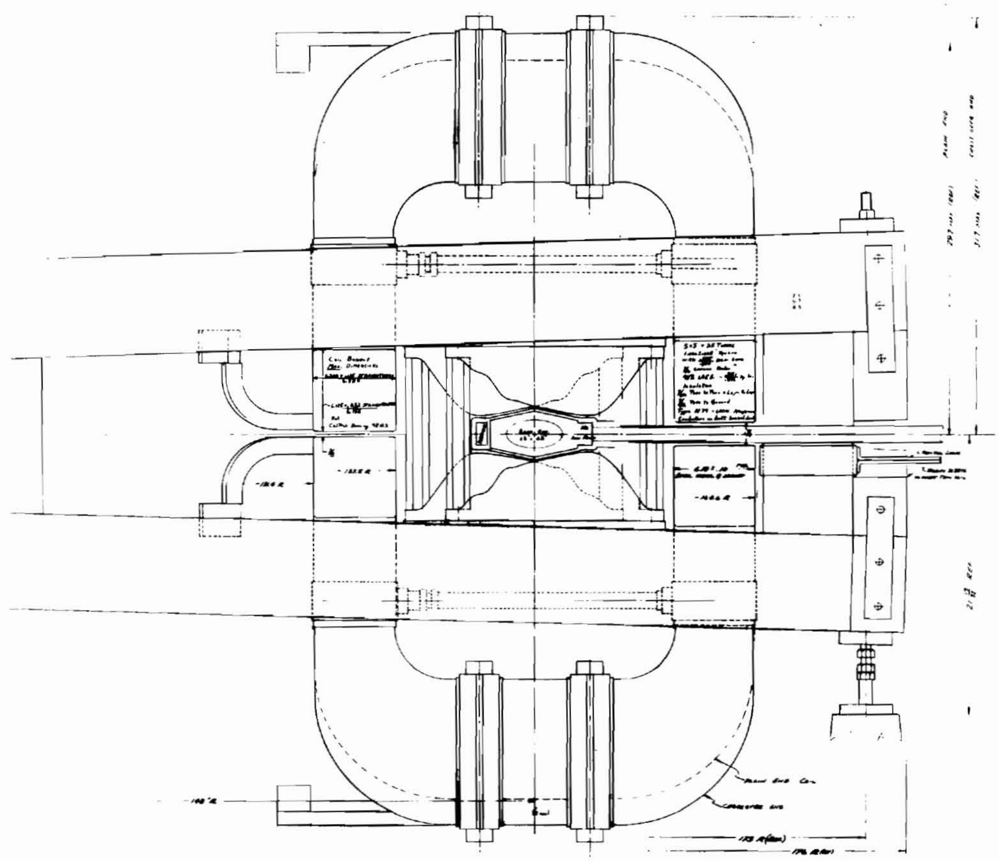

Fig. 4. Placement of pole tips in CIT magnets.

To suppress the resistive wall instability, aluminum is specified for the vacuum chamber material. This is readily extruded into shapes of complex cross sections, such as used in the SLAC-SPEAR storage ring. Following the SLAC design, we also plan to use distributed ion pumps, for reasons of economy and pumping speed, but also to avoid gas bumps which could lead to integral beam instability excitation. Total vacuum pumping speed required is 20,000 l/sec, based on a vacuum load of 60 m^2 of surface using conservative outgassing rates. The vacuum system is shown in Fig. 5.

Magnet Alignment

The small size of the ring permits alignment by means of Invar radius vectors from five survey monuments. We believe that better accuracy can be achieved--less expensively--in this manner than by using the overlapping cord method employed in tunnel architecture.

The basic procedure is to emplace the lower return yoke and to locate on fiducial marks machined into the lower pole tip at the time of manufacture. The upper pole tip will be located by machined nonmagnetic supports and, hence, located to an accuracy of about 0.001 in. The remainder of the yoke is then installed and any air gaps removed by shimming.

Instabilities

Beam instability analysis has been performed on the proposed ring matrix. The calculated incoherent space charge limit with a bunching factor of 0.4 is 371 A, with no charge neutralization. If the nonsinusoidal character of the betatron oscillations is considered, this drops to 88 A, suggesting that neutralization may be necessary to attain the design goal. By designing the transition energy of the ring to be above the beam energy it is not possible to have negative mass instability.[11]

Beam cavity interactions[12] and the longitudinal resistive wall effect[13] have been investigated and do not appear troublesome. The transverse resistive wall effect[14] leads to millisecond growth rates and will probably need feed-back stabilization.[15] The head-tail instability may require sextupole adjustment of the chromaticity.[16]

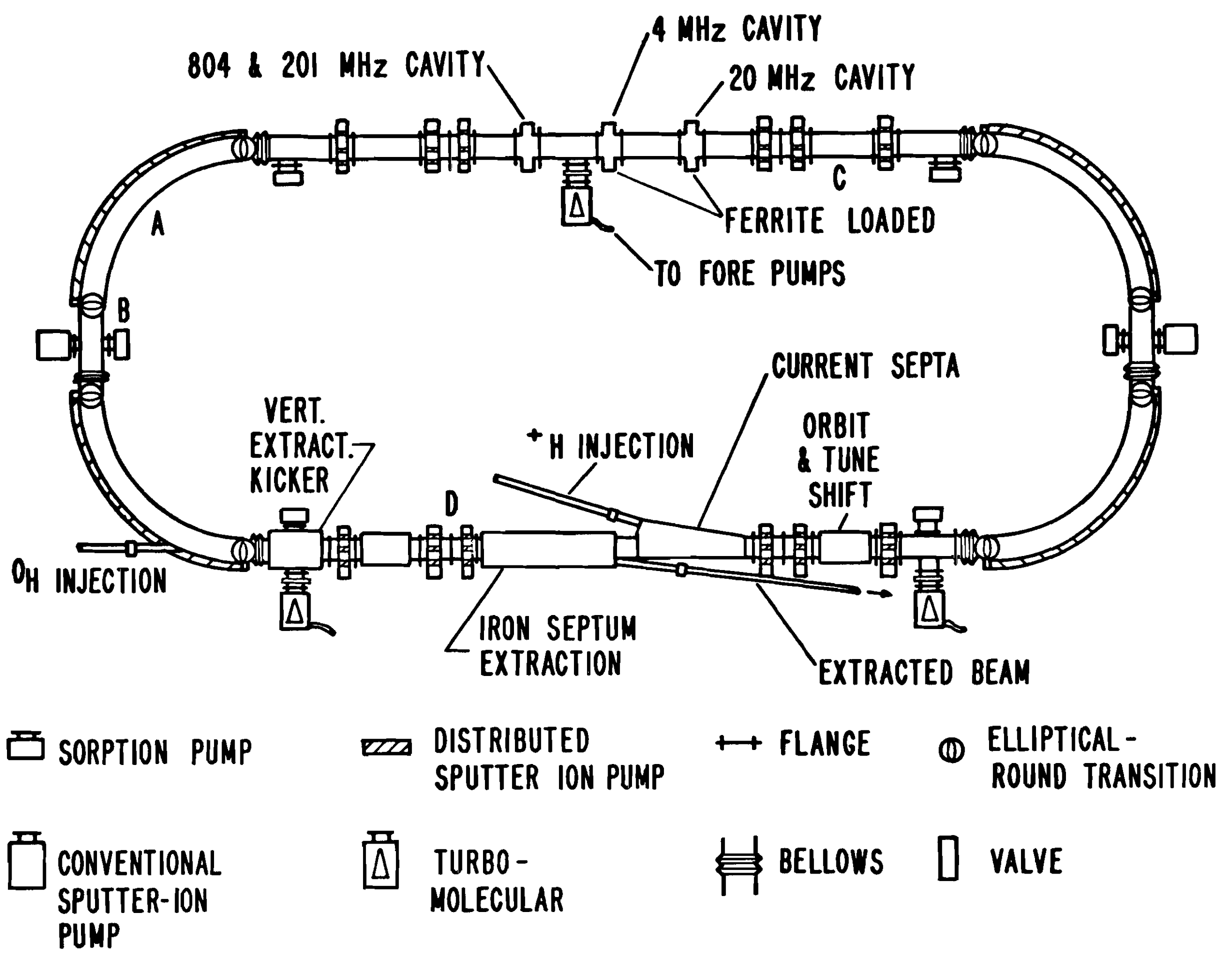

Fig. 5. Proposed vacuum system for the WNR ring.

Present Storage Ring Status

Since completion of this design study, emphasis has shifted from both proton and negative hydrogen injection to negative hydrogen injection for both modes of operation. Negative ion injection for both modes is attractive, for it would result in increased brightness in the high-duty mode (a most important feature), significant simplification and reduction in ring hardware, and operation between the two limits in the design study, thereby greatly increasing machine capability. Furthermore, since it has been demonstrated at LASL that one can pre-bunch in the negative ion source itself, negative injection for both modes would eliminate the need for large, low-frequency buncher cavities for use in the high-duty mode.[17] This should not only result in considerable cost savings, but also simplification of the buncher complex in the storage ring itself will reduce the problems of stored beam cavity interactions--thereby reducing another constraint on the ultimate stored-beam capability in the low-duty mode.

In order to deliver negative ions with variable duty factor to the WNR storage ring, the LAMPF switchyard has been redesigned, as shown in Fig. 6. The design employs 3.85 kG transport magnets and kicker magnets so the beam will not be stripped and can be shared without significant loss with other LAMPF users. After emerging from the switchyard, the beam is bent down to a transport tunnel to the WNR laboratory some 300 ft away. Beam optics are such that no magnets are necessary inside this tunnel for the 300-ft span. This, together with the fact that the vacuum line may be pumped from both ends, greatly simplifies construction and reduces cost.

A cutaway view of the WNR laboratory facility as presently envisioned is shown in Fig. 7. The design employs a 90° bending magnet to bend the proton beam into the ground. This allows a neutron target to be placed on the vertical axis and time-of-flight tubes to be arrayed as spokes in a wheel parallel to the ground. The design also includes a low background, low current target room placed on the other side of the main transport system. The storage ring is planned to be placed upstream from the laboratory. The transport system is designed to allow either target area to be occupied while the other is in operation, to minimize setup time loss and to be able to be generalized to incorporate other scattering areas at a later date. Completion of the laboratory is planned for August 1974.

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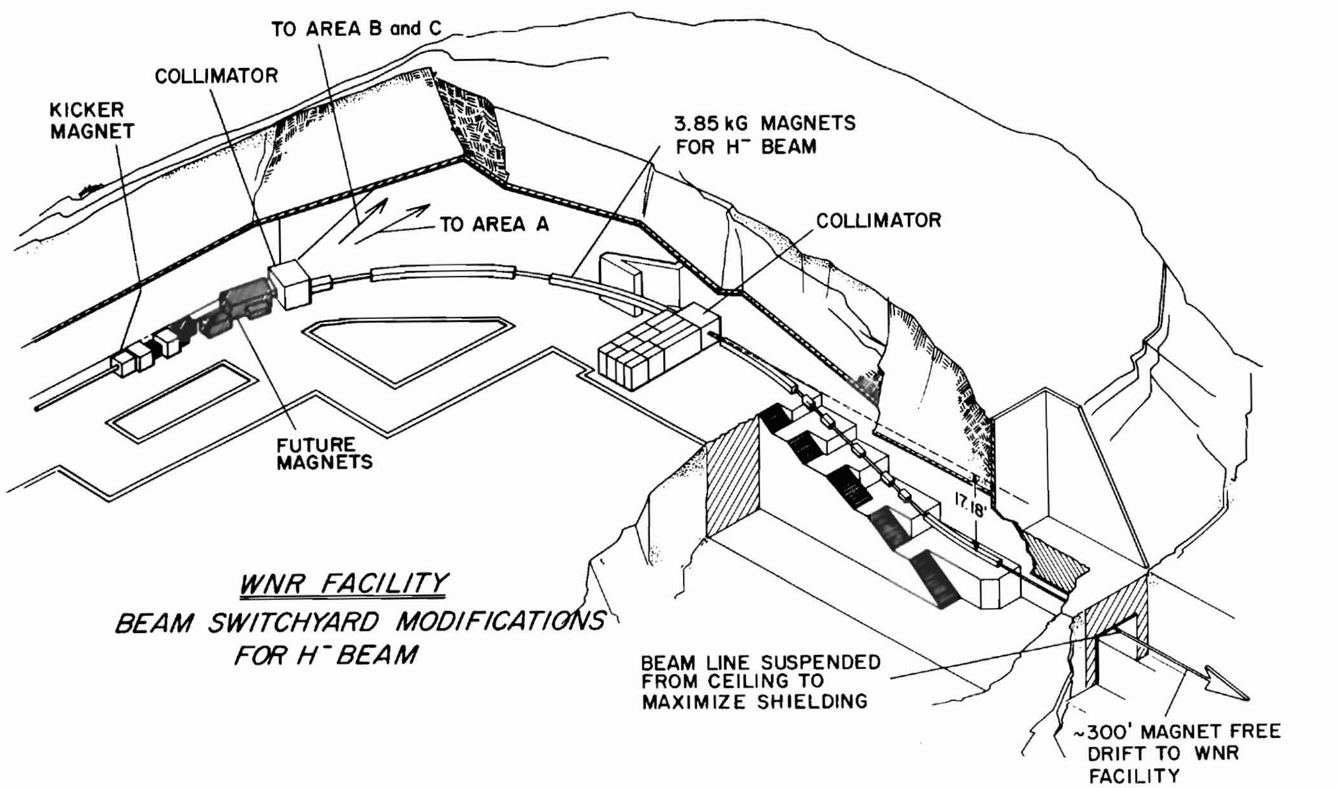

Fig. 6. Beam switchyard modifications for H^- beam.

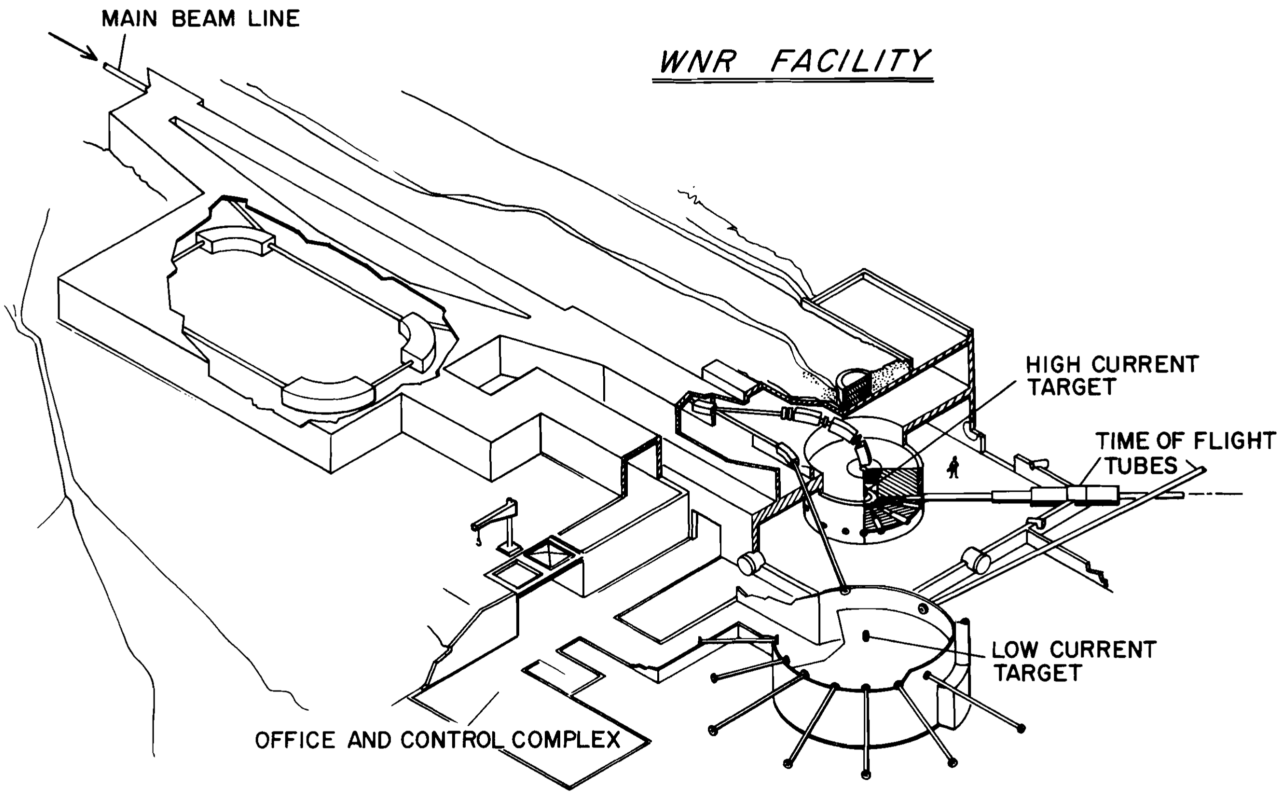

Fig. 7. Layout of WNR facility with proposed storage ring.

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