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THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING*

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ABSTRACT

The Spallaton Neutron Source Accumulator ring is described. Also described are the challenging accelerator physics problems associated with space charge issues, injection, extraction, and beam loss.

I. INTRODUCTION

The proton accumulator ring is one of the major systems in the design of the SNS. The primary function of the Accumulator Ring is to take a 1-msec-long 1.0-GeV H^- beam from the linac and compress it into a 0.5-μs-long beam by stacking them in the accumulator ring in over 1000 turns. We use H^- to P charge exchange injection to accumulate protons in many turns inside same phase space of the ring. The transverse beam emittance (full) and acceptance of the accumulator ring are 120π mm-mrad and 360π mm-mrad respectively in both planes. The final beam will have about 10^{14} protons per pulse, meeting the design specification of 1-MW design average beam power at 60-Hz repetition rate. Provisions have been reserved for a future upgrade to 2-MW beam power by a doubling of the stored current to 2×10^{14} proton per pulse without changes to either the magnet or the vacuum system. The lattice structure of the accumulator ring is a simple FODO lattice with fourfold symmetry. A missing magnet design is used to reduce the dispersion function to zero at the straight sections. The total circumference of the ring will be 220.688 m, and the transition energy of the ring is about 4.93, higher than the operating energy of 1.0 GeV to avoid the possible beam instability problems expected near transition energy. One of the major performance requirements will be to hold the average uncontrolled particle loss during the accumulation time to less than 2×10^{-4} per pulse. This stringent requirement is to hold down the residual radiation to a level that will permit hands-on maintenance except in a few localized areas, such as the injection, extraction, and collimation systems. To achieve this goal, special care has been exercised in the design of the H^- stripping, the rf stacking, and the collimator systems. Ongoing accelerator R&D and computer tracking studies of the space-charge effects and halo formation will ensure the achievement of this performance goal.

II. RING LATTICE

The storage ring lattice consists of four 90^0 arc and long straight sections, schematically shown in the fig. 1. Four FODO cells with a $\pi/2$ phase advance makes the arc section. Each half cell consists of a quadrupole, a .45m space, a 1.5m long dipole, a 1.55m space, and a quadrupole. The total length of the arc half cell is 4 meters. Four full cells of $\pi/2$ phase advance insures the zero dispersion in either side of the arc, however, introduction of fixed orbit bump in the injection straight disturbs the symmetric nature of the lattice and create small dispersion in all the straight sections. Two FODO cell without dipoles form long straight sections. The half cell length for straight sections are 5.293 meters.

Table I SNS Accumulator Ring Parameter

Kinetic Energy	1.0 GeV
Magnetic Rigidity	5.658 T-m
Circumference	220.688 m
Periodicity	4
Structure	24 FODO
β_{max} X/Y	19.2/19.2 m
Xp_{max}	4.1
$\nu_{X/Y}$	4.82/4.82
γ_T	4.933
$\xi_{natural}$ X/Y	-6.5/-7.3

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The phase advance in the straight sections are adjusted to make the tune of the ring to be 5.82 horizontal and 5.8 horizontal. The lattice functions for all four super periods are shown in fig.2. The relevant ring parameters are given below in table I. The ring is to accommodate the beam emittances of 120π mm-mr and acceptance or admittance(beam stay clear aperture) of 360π mm-mr which is more than twice the full beam emittances plus 1 Cm for the maximum possible orbit errors. The ring also has acceptance of maximum beam momentum spread of plus or minus 1% and the quadrupoles at the center of the arcs are 50% larger than others to accommodate this criteria. The quadrupoles in the center of straights have larger aperture for the extraction kicker and septum displacements. The primary assignment for the long straight sections are, injection, ejection, rf cavities, and last one for the beam scraping collimators. Any half cells not being used for the primary functions shall be used for other functions such as tune meter kicker, transverse damping system to name a few. The 1.55m space between a quadrupole and a dipole consists of beam position monitor(pickup electrode), correction dipole and skew quadrupole combination, higher order correctors, and a vacuum pumping port Injection straight section consists of one fixed horizontal orbit bump to accommodate H^- injection, and horizontal and vertical dynamic bumps to paint the injected protons in the transverse phase spac. It has been demonstrated that the tune of the lattice is quite flexible and can be changed order of half an unit without adverse change in the beta functions. The lattice has structure resonances at betatron tune values of 5 and 6, which is expected from 4-fold symmetry. However, there are no structure resonances at fractional tunes between 5 and 6, except for one at 5 1/3 which is some distance away from the working point.

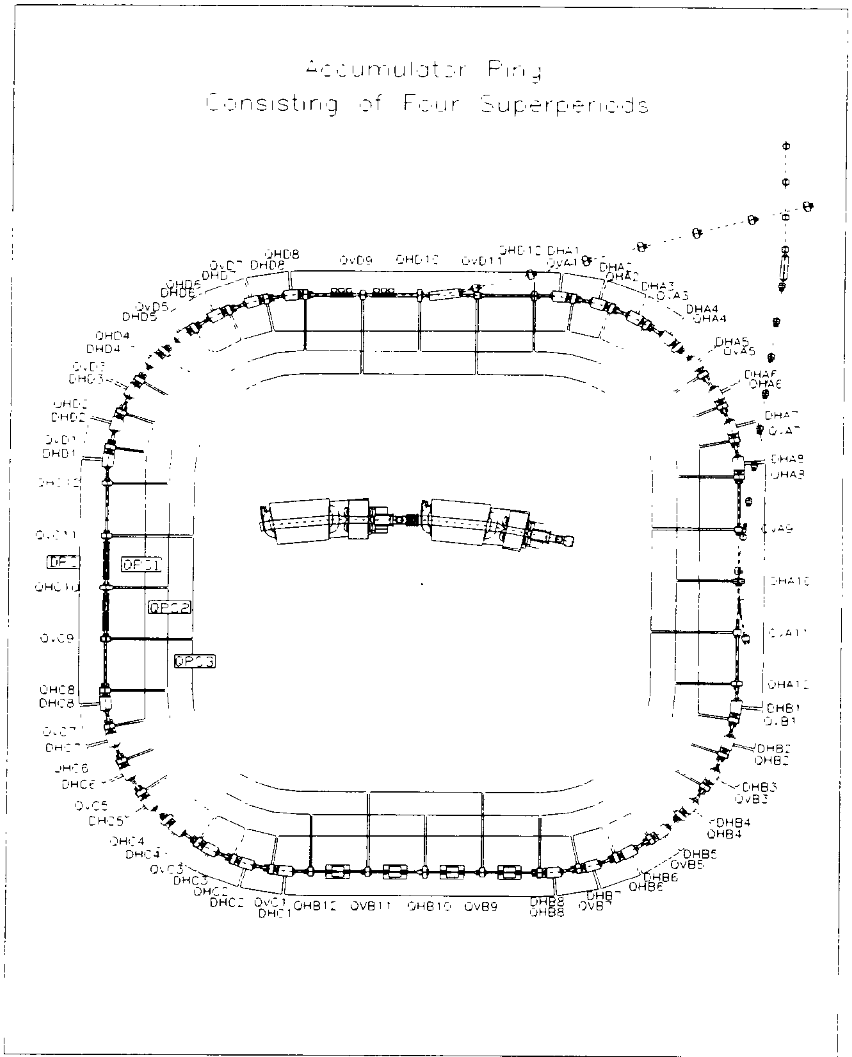

Fig. 1 Accumulator ring layout

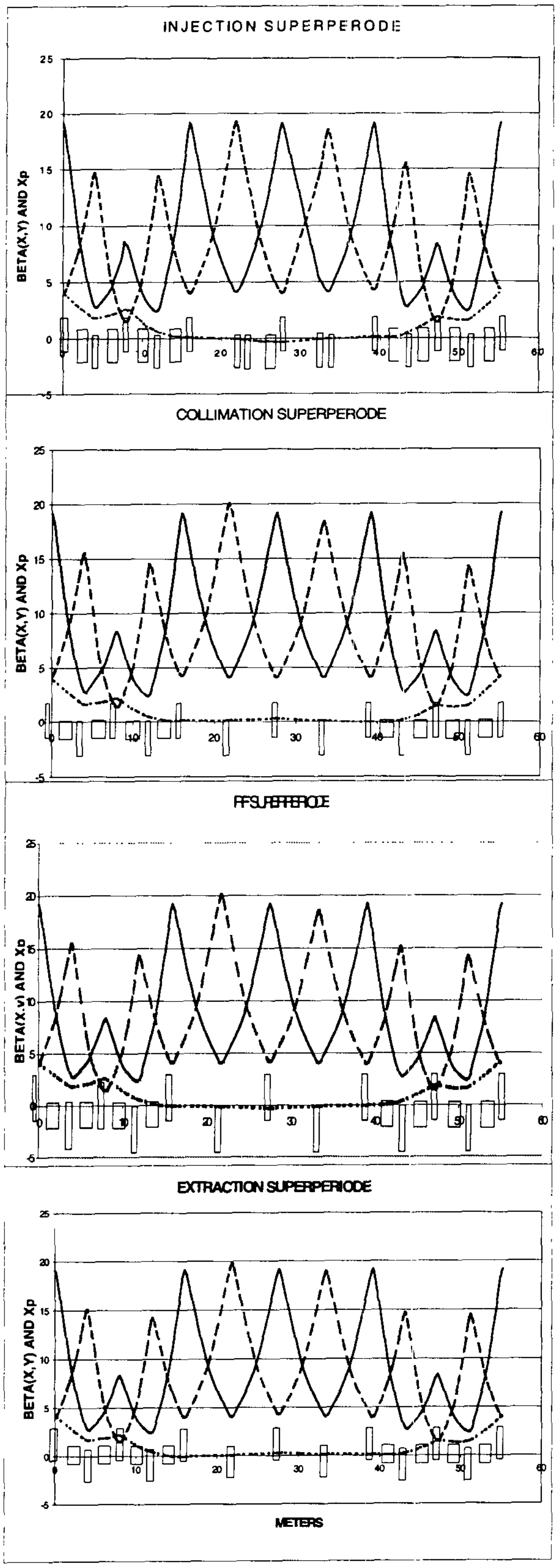

Fig 2 Lattice Functions

III INJECTION

Injection into the accumulator ring is an H^- charge exchange process that allows beam to accumulate in already occupied phase space. As described earlier, the beam from the Linac is chopped in the revolution frequency of the ring ensuring there will be a gap in the circulating proton beam. The following sections describe the process, the choice of the stripping foil, the different loss mechanisms, the disposal of non-captured ions, the dc and dynamic injection orbit bumps, and the hardware needed to implement the process.

Injection will take place in one of the near dispersion-free regions (straight section A) of the ring. The process is controlled by a large, especially designed, fixed orbit bump. The fixed orbit bump is a chicane consisting of three dipole magnets (IDH1-A9, IDH2-A9, and IDH3-A11) around the center of the straight section with the center magnet just upstream of the wide aperture quadrupole (QHA10) in the center of the straight section. To facilitate dumping the excited H^o ions from the stripping foil, injection takes place in the downstream fringe field of the center dipole (IDH2) of the chicane. This dipole, which is a C-type magnet, has a central magnetic field of 3 kG, and the stripping foil shall be located at the 2.5 kG field region of the magnet edge. The magnetic field value is important because the Lorenz electric field felt by the moving excited H^o's is such that the principal quantum numbers of n=4 or less, survive the field, whereas those at n=5 or higher, strip immediately. The spatial descending nature of the fringe field assures that the excited H^o not stripped immediately will probably not strip at all because the field is decreasing and hence the electric field felt by the H^o will be too low. The uncontrolled loss by the Stark stripping of the excited H^o is estimated to be on the order of 10^{-8} of the injected H^- beam. Even for the case where one completely miscalculates the space between the n=4 and n=5 states, the uncontrolled loss rate would be 10^{-6}.

A schematic of the injection straight section and the orbit bump is shown in Fig. 3. At the upstream end of the chicane, in the HEBT injection line, there are a 1.9 degree dipole (HDH14) and a 2.5 meter long septum magnet with a 3 kG field to bring the beam from the HEBT line to the foil, while avoiding the upstream quadrupole (QVA9) and the circulating beam. At the downstream of the center quadrupole (QHA10), there is a 2-meter long septum magnet (DDH1) with a field of 5 kG to take the unstripped H^- and H^o ions to the external injection dump. In addition, a water-cooled copper block is located immediate downstream and 1.25 cm outside of the stripping foil to intercept the stripped electrons from the H^- injected beam.

Two sets of kickers (pulsed dipoles), a set of four (4) for each plane (IKDH1 through IKDH4 and IKDV1 through IKDV4), are used to create dynamic orbit bumps in order to paint the optimum phase space of the injected proton population. The kickers are located in the space between QHA8 and QVA9 as well as between QVA11 and QHA12. The optimum distribution will be determined by computer simulation and by experimentation. However, the present plan is to charge the bump magnets to an initial direct current and, at the proper time in the injection process, to discharge them through an external resistor creating an exponentially decaying magnetic field. The initial amplitude and the decay time constant impart the spatial distribution to the circulating protons. This scheme has the advantages of simplicity and reliability of operation. Fig. 5.4.1-2 shows the basic scheme of painting in phase space.

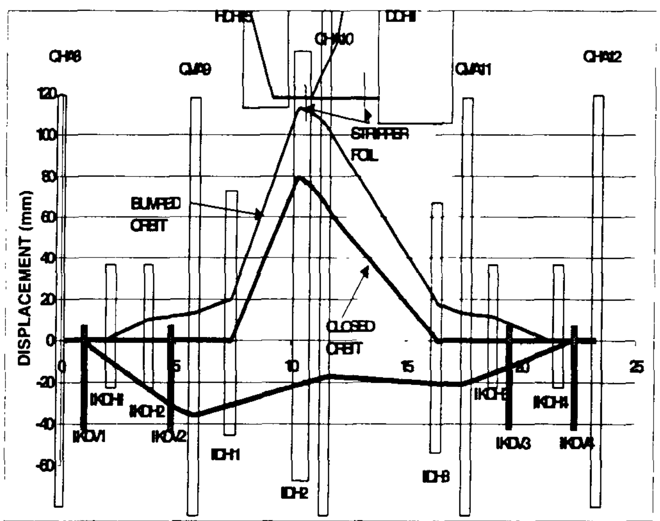

Fig. 3 Schematic of injection bumps

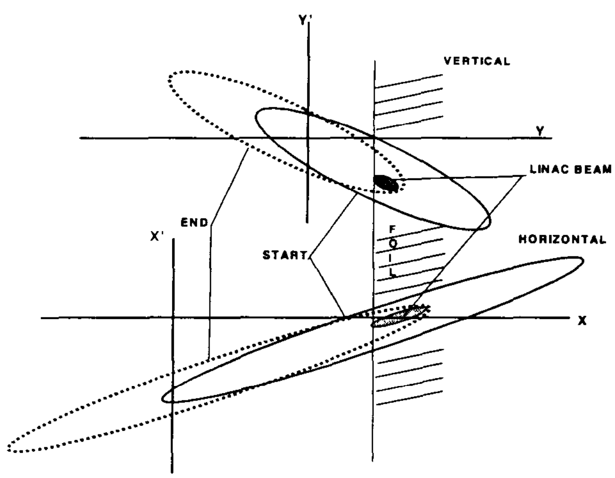

Fig. 4 Phase space diagram of painting scheme

IV INJECTION LOSS AND DISPOSAL OF UNUSED PROTON

Because of the proton power in the SNS, the injection loss and subsequent beam loss due to all injection mechanisms has to be kept manageable. There are several injection loss mechanisms. These are: 1) the Linac beam missing the stripping foil, 2) H^o's emerging from the foil which is a function of the thickness of the foil, 3) H^-'s emerging from the foil which is calculated to be negligible, and 4) circulating beam loss due to Coulomb and nuclear scattering on the foil. Loss mechanism 1) is related to the stripping foil size and this loss should be kept to less than a few percent. This beam loss along with loss due to mechanism 3) is well known and a controlled dumping of the waste beam is planned. Loss mechanism 4) is directly related to the thickness of the foil and the amount of circulating beam hitting it, which is proportional to the foil size. The foil size is chosen such that it provides a compromise between mechanisms 1) and 4). The thickness of the foil is determined by mechanisms 2), 4) and the foil heating problem described later. Present plans call for a carbon foil of size of 8 mm x 4 mm and a thickness of 200 to 400 $\mu g/cm^2$.

The H^- ions that miss the stripping foil and the H^o's emerging from the foil should be disposed of in a proper beam dump. The size of the stripping foil is chosen such that the foil covers 5σ of the linac beam distribution, and a distribution tail of about 2% of the incoming Linac beam misses the foil. This is a compromise between this loss and the loss due to Coulomb and nuclear scattering of the stored protons. Recently very precise measurements of the cross-sections for H^- in carbon have been obtained by Gulley, et al[2]., as follows:

$$\sigma_{1,0} = (6.76 \pm 0.09)\ 10^{-19} cm^2$$
$$\sigma_{0,0} = (2.64 \pm 0.05)\ 10^{-19} cm^2$$
$$\sigma_{1,1} = (0.12 \pm 0.06)\ 10^{-19} cm^2$$

For a 400 $\mu g/cm^2$ thick foil, about 0.82 % and for a 200 $\mu g/cm^2$ about 9% of the incoming H^- ions will emerge as H^o. The population of their quantum state is measured to be $n^{-2.8}$ where n is the principal quantum number.

The H^o's that emerge from the foil are converted to protons by a thick foil placed in their path. The downstream quadrupole bends the H^-'s into the 5- kG septum magnet, but because of the high magnetic field a small fraction will be stripped to neutral particles. If a thick foil is placed in their paths inside the septum, they will be converted to protons. Placement of the foil will be determined after careful measurement of the magnetic field, so that the median of the protons emerging from the septum will be parallel with the protons from the H^o's. The plan is to place the foil inside the magnet where the field integral is equal to the field integral traveled by the H^-. A set of two quadrupoles and two trim dipoles placed downstream in the injection dump line will focus and steer the protons on the water-cooled dump.

The stripped electrons from the incoming H^- beam have a momentum of 0.923 MeV/c and a magnetic rigidity of 0.003 T-m. Inside the 2.5 kG magnetic field, the electrons will curve with a 1.2 cm radius, and they will be intercepted by a copper block that is placed imediate downstream and 2.4 cm radially outward of the foil. The collection block is water cooled as the electron power is expected to be about 1/900 of the proton power (i.e. about 1 kW for a 1MW SNS). The generation of free electrons inside the ring has to be minimized in order to reduce the possibility of them causing an instability to the stored protons. The possibility of secondary electrons emerging from the collection block is eliminated by the fact that it is located inside a 2.5 kG field.

A carbon foil is used to strip the electrons of the H^- beam because of the resiliency and high sublimation temperature of the material. The sublimation temperature of carbon is above 3500 degrees C°. The foil is heated by the energy deposited by the proton and the two accompanying electrons. Since they all have the same velocity, they should have the same energy loss in a given material. There is no data available for what fraction of the energy lost by the beam contributes toward heating of the material. At higher energies, the efficiency is estimated to be as low as 30%. However, for our calculations we assume that all the energy loss contributes to the heating of the material. For a 1 MW SNS injection, the Linac has the following parameters. The effective average current at the injection point is 18.2 milliamperes within the unnormalized rms emittances of 0.14 pi mm-mr in both planes. The peak current density at the foil, where the beta-functions are 16 m and 5 m, is about 3700 A/m^2. The temperature at the spot will rise very quickly toward equilibrium where the heat input and the black body radiation become equal. Since the heat input is proportional to the thickness of the foil, while the black body radiation is proportional to the surface area, a thicker foil results in a higher resultant temperature. For the Linac current assumed for the SNS injection, up to 400 $\mu g/cm^2$ thickness carbon foil can survive the injection, whereas thicker foils may reach their sublimation temperature. However, the mechanism of foil breakage is more complicated than just simple foil evaporation.

With the foil located in the falling magnetic field of the chicane magnet, the uncontrolled loss due to excited H^o decay is minimized. Other words, one can contemplate a use of much thinner stripping foil as thin as 200 $\mu g/cm^2$. More detailed calculations and experiments will be carried out to determine the optimum thickness of the stripping foil. Presently, a foil thickness of 200 to 400 $\mu g/cm^2$ is being contemplated.

V RADIO FREQUENCY

After the beam is accumulated, inside the ring, it will be extracted in one turn using a kicker magnet. A 250ns gap is required to allow for the 200ns kicker rise time and the SNS design calls for a radio frequency (RF) system to maintain the gap. Previous work[3] has established that a dual harmonic RF system with h=1 and h=2 has significant advantages over a single frequency system. A barrier bucket RF system is even better but there are unresolved issues, such as beam loading, which require more R&D. Therefore, the design for the SNS RF system is a dual harmonic system running with h=1 and h=2. The possibility of upgrading to a barrier cavity system is considered. Table II summarizes the requirements for the RF system. The design has a RF amplitude of 40kV at h=1 and 20 kV at h =2 with the voltages phased so that the small amplitude synchrotron frequency vanishes.

Table II Ring RF Parameters

Circumference	220.668m
γ_{Tr}	4.933
h=1 Voltage	40. KV
h=2 Voltage	20 KV
Space Charge Z/n	i150Ω
Broadband Wall Resistance	50Ω
Proton Kinetic Energy	1 GeV
Injected Bunch Length	546 n-sec
RMS Injected Energy Spread	2.2 MeV
RMS Energy Spread at Extraction	4.2 MeV
# Proton at Extraction	2.08 x 10^{14}
h=1 Beam Impedance without Feedback	4500Ω
h=1 Beam Impedance with Feedback	1200Ω
Bucket Area(Zero Current)	17 eV-sec
Bunch Area(Zero Current)	10 eV-sec
Peak beam Current	96 Amps
Beam Gap at Extraction	265 n-sec

As the beam accumulates in the SNS the compensation current from the generator needs to increase. This situation will be dealt with using a feedforward system that will adjust the input into the low-level drive. Another option would employ a wall current monitor signal to measure the harmonic amplitude of the beam current and send this signal to the drive. Along with compensating the beam current it is also necessary to assure that the system is stable to perturbations in beam energy and phase. The beamloading parameter is given by $Y= I_b R_t / V_g$ where I_b is the harmonic amplitude of the beam current, R_t is the effective resistance of the power amplifier and cavity in parallel, V_g and is the gap voltage. As a rule of thumb stability requires Y<2 while the SNS design without feedback has Y=6. We will reduce the effective R_t using one-turn delay feedback which operates only on the low level drive signal and does not require any additional equipment in the tunnel. Using this technique and assuming a quality factor of Q=10 the effective resistance can be reduced by a factor of 4 over a full bandwidth of 200 kHz and restores stability for high beam current. Even with beam loading compensation working effectively it is still essential that the synchronization signal for the LINAC chopper be derived from the vector sum of the actual gap voltage of the cavities[3]. This assures that even though there will be phase shifts between the low-level drive signal and the actual gap voltages the freshly injected beam will always be deposited in the center of the bucket. The consequences of this slowly varying phase during the macro pulse on beam loading in the LINAC should be considered.

It is likely that the hardware used for the conventional RF system can be upgraded to a barrier cavity system without significantly changing the high power components. With 8 gaps and 10kV per gap the beam dynamics appears feasible. Barrier cavity operation will use the h=2 gap capacitance. For a gap voltage of 10 kV and R/Q = 150Ω per gap the peak power amplifier current is 130A. Roughly, the tube current will be a square wave with a base value of zero amps for half the revolution period, and 130A for the rest of the revolution period. In actual operation, the current pulse will be smooth and losses in the cavity will need to be compensated. The problem of beam loading in a barrier cavity system is currently under investigation.

VI BEAM EXTRACTION

The beam will be extracted from the accumulator ring in a single turn, taking place in less than one beam revolution period of approximately 800 n-sec. The selected scheme is to use a two-step process consisting of a fast kicker and a Lambertson septum magnet. Extraction will take place immediately after the injection stacking process is completed. The accumulated beam will have a gap of 250 ns to enable the magnetic field in the fast kicker to rise to its extraction level within this gap. Extraction from the accumulator has to exhibit a high level of reliability and reproducibility, since it is not desirable to dump beam within the ring. A high degree of modularity is also built into the systems for this purpose. Timing for extraction is very crucial. While extraction must occur as soon as possible after injection is complete, nevertheless enough time must be allocated to provide synchronization to the target beam choppers and to the ring RF system.

Extraction will take place in one of the accumulator ring's long straight sections (section D). The fast kicker provides a vertical kick which clears the magnetic septum and the septum provides the large angle horizontal deflection to extract the beam into the Ring-to-Beam-Target (RTBT) transport line. A short dipole in the RTBT line is used to straighten out the vertically kicked beam. The kicker is centered around the vertical focussing quadrupole (DVQ9), while the Lambertson magnetic septun is located just downstream of horizontal quadrupole (DHQ10).

The fast kicker system consists of a large number of sections of rectangular-frame, ferrite core magnets, powered by closely-coupled pulse forming networks which are discharged when they receive a synchronized timing trigger. The number of magnet sections and PFN's is eight (8), which has several advantages. The first is that the inductance and hence the voltage per module is reduced to the level where components can operate more reliably. In addition, the extraction design is such that the full beam can be extracted within the acceptance of the RTBT line and transported to the target even one of the kicker fail to fire, thus the reliability. The fast ejection system has to be capable of operating at the maximum rate of 60 pulses per second. At this rate the number of pulses accumulated by the switching thyratrons will be quite high and have to be closely monitored. The usual indication is a slow increase in the tube turn-on jitter time.

VII BEAM ABORT

For abnormal conditions, since no beam can be dumped continuously in the ring, stored proton inside the ring and in liac system should be extracted to a beam dump. No other beam pulses shall be admitted into the main ring after one of these conditions are sensed. The neutron target is chosen to be the abort dump, since the target system is equipped to handle the proton pulses of this magnitude. The condition can arise from a lot of areas such as high beam loss monitor signals caused by transverse or longitudinal instabilities in the ring, main ring and RTBT power supplies out-of-tolerance, and any other system faults. Therefore, readiness of the extraction and beam transport system should be one of the pre-condition to start the process of acceleration.