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PRELIMINARY DESIGN OF THE HIGH INTENSITY SYNCHROTRON (HIS) FOR THE PROPOSED INTENSE PULSED NEUTRON SOURCE FACILITY (IPNS) AT ARGONNE*

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Introduction

Argonne National Laboratory has proposed construction of an Intense Pulsed Neutron Source (IPNS) as a national facility for condensed matter research using neutron scattering and radiation damage methods.[1] Peak thermal neutron fluxes of 10^{16} n/cm^2-s at 60 Hz and epithermal fluxes in excess of 2×10^{16} n/cm^2-s-eV at 1 eV are provided. The heart of this facility is a high intensity, 800 MeV, 60 Hz repetition rate, proton synchrotron (HIS) whose extracted beam is used to produce spallation neutrons in a heavy target.

Fluxes such as those mentioned above require an average proton current of 480 μA (5×10^{13} protons/pulse at 60 Hz). This high intensity requirement necessitates special design considerations not only in the area of accelerator physics, but also for mechanical design and fabrication techniques to cope with the un-avoidable, high radiation levels to which equipment will be subjected.

Several essential differences between the design of this synchrotron and conventional ones are:

1. Use of H^- stripping injection.
2. Consideration of total phase space to accommodate space charge effects.
3. Use of radiation resistant construction techniques in magnets and other hardware.

Description of the HIS

The proposal assumes that the Zero Gradient Synchrotron (ZGS) at Argonne will be shut down, for which plans are now being developed. The IPNS facility will then utilize most of the present ZGS physical plant and as much existing equipment as appropriate. Fig. 1 is a plan layout of the HIS at the ZGS site.

As indicated in the figure, two extracted beam channels are provided; one to a neutron scattering facility and another to a radiation effects facility. The machine has been sized to conveniently fit inside the present ZGS tunnel, resting on the ZGS support structure.

The machine has a separated function, 16 period structure whose general parameters are shown in the table and in Fig. 2.

Injection

The emittance of the H^- beam used for injection at 100 MeV is expected to be small compared to the 80 x 40 (cm-mrad)^2 emittance desired for the 5×10^{13} protons initially injected into the accelerator. To produce these emittances requires that the orbits move horizontally and that the H^- injected beam move vertically during injection.

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Machine Parameters

Maximum kinetic energy	800 MeV
Intensity	5×10^{13} p/pulse
Repetition rate	60 Hz
Injection energy	100 MeV
Injection current	15 mA (H^-)
Number of turns injected	600
Magnet radius	7.000 m
Average radius	26.000 m
Number of straight section	16
Length of straight section	3.116 m
Number of periods	16
Structure	OMOFOMODO
Betatron frequency	
Horizontal	4.25
Vertical	5.25
Revolution frequency	0.79–1.55 MHz
Momentum compaction factor	0.077
β max vertical	17.5 m
β max horizontal	17.7 m
Beam emittance at 800 MeV	
Horizontal	π 24.3 cm-mrad
Vertical	π 12.1 cm-mrad
Momentum spread at 800 MeV	4×10^{-3}
Bending magnet field	
800 MeV	6.973 kG
Injection	2.119 kG
Number of bending magnets	32
Length of bending magnet	1.3744 m
Quadrupole magnet peak gradient	0.15 kG/cm
Length of quadrupole magnets	1.2 m
Number of quadrupole magnets	32.0
Peak energy gain per turn	112.0 keV
Harmonic number	1
RF frequency	0.79 – 1.55 MHz

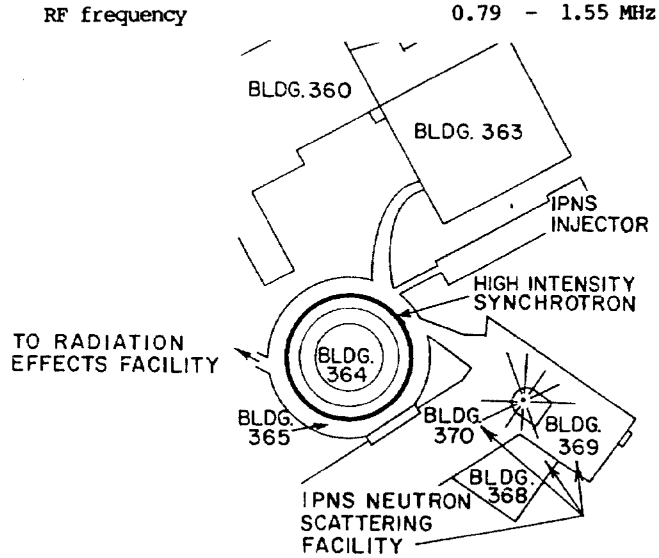

Fig. 1. IPNS layout

The H^- beam used for injection will enter the first magnet following a long straight section about 17.3 cm outside at an angle approximately -22.7° with respect to the straight section direction. After passing through the magnet the H^- ions will be at -10.3 cm and headed approximately in the direction of the central orbit. The fixed stripper will be located at this position.

The small horizontal oscillation amplitudes are produced by injecting at a time when the fields of the magnets are 4.5% larger than the central orbit field values. Since the magnet is oscillating at 60 Hz this condition is achieved naturally 740 μs before the minimum injection field is produced. Assuming 70% efficiency, 15 mA of H^- ions injected for 740 μs will produce 5×10^{13} circulating protons. Because of the non zero angle of this displaced orbit, it is necessary that protons coming from the stripper make an initial angle of −16.8 mrad with respect to the straight section if the small betatron amplitude is to be achieved.

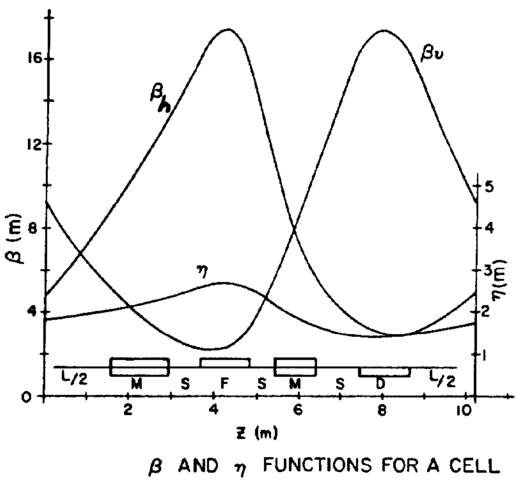

Fig. 2. Lattice function

As the field falls to the central orbit value, the protons created at the stripper have larger and larger betatron amplitudes until finally at the minimum field the amplitude can be made equal to $\sqrt{0.08 \times 1340} = 10.3$ cm. To achieve this amplitude it is necessary that the injection angle at the stripper be −15.8 mrad. This is only a change of 1 mrad compared to the initial angle but represents 5 cm of betatron oscillation amplitude. Moreover, because of the falling field during injection the H^- ions would naturally enter the stripper with a 9 mrad more positive angle. Therefore, in order to achieve the desired injection angles without moving the injection position it will be necessary to employ two oppositely directed pulsed steering magnets in the H^- beam.

The 40 cm-mrad vertical phase space can be produced by moving the H^- beam vertically from (y, y') = (−1.3 cm,−5.5 mrad) to (1.3 cm, 5.5 mrad) at the stripper. This combination of injection vertical positions and angles can be achieved using a single pulsed steering magnet of ±5.6 mrad located 1 m upstream from the injection point.

Extraction

Technically, single turn extraction from the synchrotron is straight forward. Operationally, the high repetition rate places stringent lifetime requirements on the high voltage thyratrons which fire the extraction kickers. This suggests applying the kicks in two successive long straight sections. For magnets 2 m long, useful apertures 0.15 m wide, and 90 ns rise time, the thyratron currents will be well below the 6000 A limit of deuterium thyratrons. Nevertheless, at 60 Hz continuous duty, the thyratrons will probably require monthly replacement. This appears to be a major operating cost item.

Fig. 3 indicates a possible extraction sequence.

It should be noted that kicker requirements can be further reduced by extracting from an off-momentum orbit, and will be considered more fully in the future.

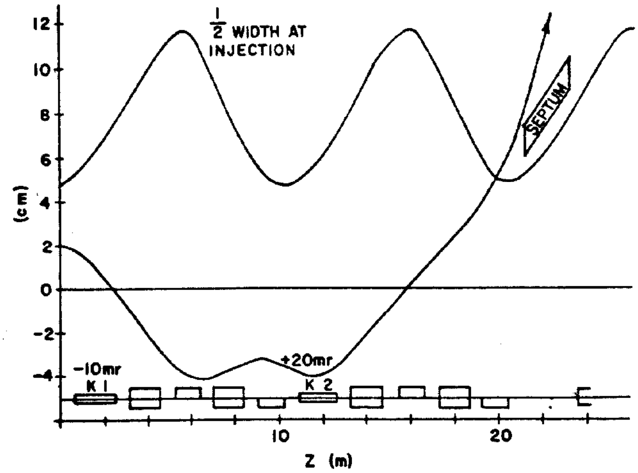

Fig. 3. Possible extraction sequence

Intensity Related Effects

a. Space charge effects

In a strong focussing synchrotron the momentum compaction factor is small compared to unity. Hence, the transverse beam dimensions are mainly determined by the betatron amplitudes. On the other hand, the longitudinal particle distribution depends upon the phase motion. In the expression for the space charge limit, the bunching factor B_f is the ratio between average and maximum linear charge density. The maximum linear charge density is at synchronous phase. The mean linear charge density is proportional to the beam bucket height averaged over the circumference. Thus,

$$B_f = \frac{\text{beam bucket area}}{2\pi \text{ full bucket height}} = \frac{2\sqrt{2}\,\alpha(\Gamma)}{\pi\,\gamma(\Gamma)}$$

where $\Gamma = \sin\varphi_s$. The quantity $\alpha(\Gamma)/Y(\Gamma)$ is equal to $\sqrt{2}/2$ for $\Gamma = 0$ and decreases to zero for $\Gamma = 1$. Since the machine lattice, the magnet cycling time, and the injection and extraction energy are fixed , a large bunching factor implies a large longitudinal beam emittance. For a peak accelerating voltage of 175 kV per turn, the longitudinal acceptance is 3.22 eV-s for a harmonic number h = 1. In order to prevent beam spill during the acceleration a longitudinal beam emittance of 2.8 eV-s is used in the bunching factor calculation. The maximum incoherent Laslett tune shift occurs about 1 ms after RF capture where $\gamma^3\beta^2 = 0.295$ and B_f is approximately 0.4. For a image force factor F = 1.25, $\nu_x = 4.25$, $\nu_y = 5.25$, $\epsilon_x = 80$ cm-mrad, $\epsilon_y = 40$ cm-mrad, $N = 5 \times 10^{13}$ and beta functions as given in Fig. 2 the incoherent tune shifts are $\nu_x = 0.17$ and $\nu_y = 0.22$. These tune shifts are calculated for a uniform particle distribution neglecting the longitudinal space charge effect. The longitudinal space charge forces reduce the bunching factor and consequently increase the tune shifts by a small amount (less than 10%). Fig. 3 shows the tune shifts spread for a quadratic particle distribution in the bunch. The line OP gives the tune spread in the case of a uniform transverse distribution.

b. Unbunched beam instabilities

Since the HIS operates below the transition energy, no negative mass effect will occur. The growth of the spontaneous bunching due to resistive walls, cavities, etc. is of the order of milliseconds or longer. The energy spread of the coasting beam is approximately 1%. The total injection time is less than 800 μs. For all these reasons we may expect that the longitudinal and transverse instabilities can be neglected during the injection.

c. Bunched beam longitudinal instabilities

The choice of harmonic number h = 1 implies that coupled bunched motion will be absent. Dipole motion of the bunches may be present. However, the large longitudinal emittance of the beam and the fast acceleration may prevent this instability from developing. It will be necessary to keep the bunch length as large as possible during the acceleration cycle.

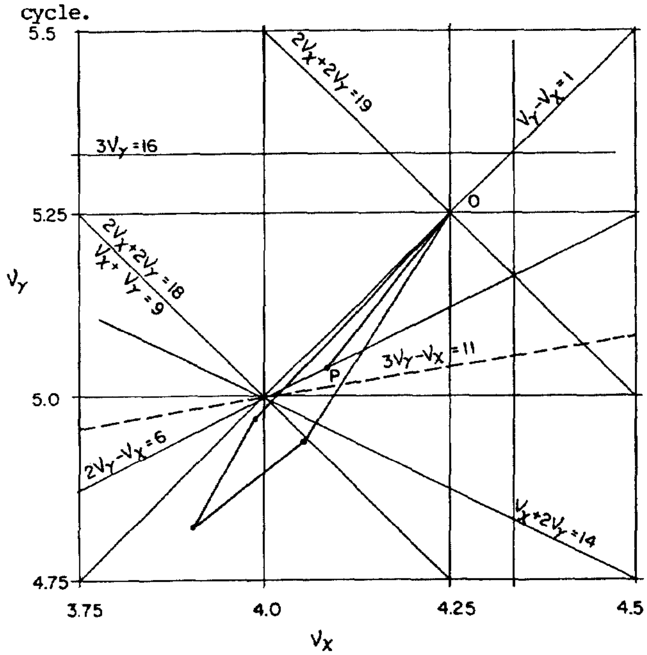

Fig. 4. Tune map of the HIS

d. Bunched beam transverse instabilities

In the bunched beam there are two classes of transverse instabilities; namely, the rigid bunch instability and the head tail instability. The choice $k < \nu < k + \frac{1}{2}$ insures single bunch stability against the resistive wall effect. Dipole instability could develop due to ions of the residual gas. The growth rate of this instability can be made small by decreasing the pressure in the vacuum chamber.

In the head tail instability, the leading particles in the bunch induce oscillations of particles in the tail of the bunch. After half a synchrotron period the situation is reversed and the tail particles are now at the head of the bunch. A generative effect can be introduced resulting in instability. It can be shown that for small values of the chromaticity $\xi = \frac{d\nu}{dp}\frac{p}{\nu}$ the growth rate is proportional to ξ.[2] Sextupole magnets will be needed to correct the chromaticity. In addition, octupole magnets will be used to provide Landau damping if necessary.

Ring Magnets, Vacuum Chamber, and Power Supply

Due to the high intensities of this machine, the design of the magnets in the ring must allow for exposures to high fluxes of ionizing radiation. The flux densities may not be uniform around the entire ring, but at this time the approach is to design all of the magnets to sustain the highest fluxes that are expected in the ring. This will be somewhat more conservative than required but will avoid the disadvantages of having to design and build magnets of two or three different types.

The primary concern at this time is for the electrical insulation of the magnet coils. A conventional epoxy and glass system is not considered as a viable choice at this time. Other coil insulation systems being considered are anodized aluminum, flame sprayed aluminum, mineral insulated copper conductor, glass bonded mica, aluminum egg crating and hydraulic cement. Each of these has certain disadvantages, and when the operating requirements of the magnets are more fully defined, a choice will be made from these or possibly from some that have not been listed.

Several alternatives for the vacuum chamber are being considered. The choice is essentially whether to provide a real vacuum chamber, (e.g. plated ceramic or a very thin metallic with an outer vacuum system) or to use a liner to shield the laminations from electromagnetic beam fields as in done in the ZGS 500 MeV booster.

The ring magnets are resonated to 60 Hz and excited from a pulsed power supply. Chokes with auxiliary windings are paralled with the seriesed resonating capacitors to provide dc bypass for the bias current. A current pulse whose energy is equal that of the cyclic ac power loss of the network is supplied during the descending portion of the magnet current waveform.

Accelerating System

The peak current represented by the beam is several tens of amperes, most of it consisting of higher harmonics of the fundmental RF frequency. For reasonable cavities it can be shown that the stored energy in the cavity is much less than the energy fed to the beam each turn. Two amplifier configurations are being considered to accommodate the beam load, push-pull cascade or single ended cathode follower, the latter being favored at this time.

Eight stations consisting of two gaps each will supply the 175 kV peak voltage required in the accelerating cycle. With 1 m of ferrite per gap, care must be exercised to avoid thermal problems in the ferrite. Preliminary analysis suggests that a practical way to avoid thermal problems is to keep the ferrite at a moderate, constant bias and to mechanically tune the gap capacitance during the acceleration cycle. Amperex type 8918 triodes, rated at 300 kW average dissipation are being considered for the final amplifiers. Other aspects of the accelerating system are conventional.

Summary

Feasibility of a synchrotron meeting the requirements is supported by design considerations thus far. The ideas presented above may, of course, change significantly as the design is refined.

References

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2. F. J. Sacherer, Proc. IX International Conference in High Energy Accelerator. Stanford, p. 347, 1974.