**FEASIBILITY STUDIES OF AN ACCELERATOR
FOR THE INTENSE PULSED NEUTRON SOURCE (IPNS)**

by

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SYNOPSIS

A proton linac plus synchrotron system was studied for the proposed Intense Pulsed Neutron Source (IPNS) at Argonne. An Alvarez H^- linac of 70 MeV and a high intensity fast cycling proton synchrotron to accelerate protons to 800 MeV will be the best choice to give a flux of 10^{16} thermal neutron/sec cm^2 at the surface of moderator with a spallation neutron target of W or U^{238} .

I. INTRODUCTION

The object of the Intense Pulsed Neutron Source (IPNS) is to study condensed materials (static and dynamic structures and also radiation effects) by means of very intense pulsed neutron beams at levels not attainable by steady-state reactors. Production of spallation neutrons by protons accelerated up to about 500 to 1000 MeV hitting a heavy metal target is the best way using current technology.

In the past the synchrotron has generally been considered as a low intensity machine. However, the use of H^- injection makes it possible to build a high intensity synchrotron, for example, of 10 times higher current than the Booster II injector of the ZGS. The high intensity synchrotron of medium energy (500-1000 MeV) has not been much explored in the past, mainly because of lack of demand for such a machine. The synchrotron requires as an injector a 50-100 MeV linac with H^- ion current of 10-20 mA.

II. GENERAL LAYOUT OF ZING AND IPNS FACILITY

The ZING facility which has already been discussed in detail¹ is essentially a time sharing machine using the protons accelerated to 500 MeV by the Booster II which will be built in the near future for the ZGS. The expected thermal neutron flux (peak value) is about 1.5×10^{15} $n_{Th}/sec\ cm^2$ using depleted U as the target for spallation evaporation neutron production.

The capability of ZING for research on condensed materials will be enormous utilizing its thermal and epithermal pulsed neutron fluxes. Especially, the expected epithermal flux will be one to three orders of magnitude larger than those obtainable by reactors. Some outlines were already discussed at the ZING Workshop on April 29-May 4, 1973, and summarized in a report.² The usefulness as well as future potential were also verified at many laboratories.³

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It is widely recognized that the present intensity of the neutron beams obtainable from steady state reactors is far below the level of demand. And it is technically very difficult as well as financially not feasible to build a steady state reactor which may deliver a thermal neutron flux of 10^{16} $n_{Th}/\text{sec cm}^2$. Therefore, the construction of an accelerator for this purpose should be considered.

The Canadian project "ING", which has unfortunately been stopped, could have been one of the facilities to accomplish this purpose, but was however designed to produce continuous neutron beams. The duty factor required for the pulsed neutron source of our present project is very low and the average power is roughly 0.001 of the power needed for the "ING" project.

In what follows we shall call the H^- linac-proton synchrotron combination to produce pulsed neutron beams, High Intensity Synchrotron (HIS), and the whole facility Intense Pulsed Neutron Source (IPNS).

For the efficient usage of the spectrometers and the experimental areas to be constructed for the IPNS, the accelerator complex should be installed close to the ZGS site.

III. REQUIRED SPECIFICATIONS FOR THE IPNS

(a) Neutron Flux

Upgrading to 10 times of ZING,

Peak thermal flux at the moderator surface,

1×10^{16} $n_{Th}/\text{sec cm}^2$, pulse width ≤ 30 μsec , up to 60 pulses per sec.

Peak epithermal flux,

2×10^{16} $n/\text{cm}^2 \text{ sec eV}$ at 1 eV, 2 - 30 μsec , up to 60 pulses per sec.

Total fast neutrons,

1×10^{15} n_f -pulse, pulse width ≤ 1 μsec , up to 60 pulses per sec.

Time average fast neutron flux,

$10^{14} - 10^{15}$ $n_f/\text{cm}^2 \text{ sec}$ at energies in excess of 0.1 MeV (close to the target).

Pulse width of accelerated protons must not be larger than 1 μsec .

(b) Other Requirements

Cryostat to cool the moderator down to liquid helium temperatures should be relatively easy to install. The fast neutron producing source should be compact. Otherwise the above mentioned level of slow neutron flux will not be attainable. The target assembly must be sturdy, and easily serviced. The level of contamination by electron and positron, X or gamma rays should be sufficiently low.

The neutron flux between the pulses should be very low at least less than 10^{-5} of those during the pulse.

IV. SOME CONSIDERATIONS ON POSSIBLE SYSTEMS OTHER THAN THAT PROPOSED IN THIS REPORT

(a) ZING-Fission Neutron Multiplication System

It is almost impossible to increase substantially the proton current and/or energy of the Booster II for the ZING.

To meet the increasing demand of upgrading neutron flux to at least ten times of the ZING value, neutron multiplication by a fast subcritical assembly which will surround the target, would be necessary. However, the fission density and rate required to supply such a high flux of neutrons becomes considerably high, and the heat production rate will be of the order of 0.35 MW/liter in the core, and the total power around 4 MW.⁴ It is a well established fact that the heat removal capacity of the core structure can exceed this level in the fast breeder reactor. However, in the present case, even though the total heat production rate is approximately 4 MW, there are two other factors which must be considered. First, very high flux density is required which is not necessarily required in FBR core. The core must also have a high atomic density of fuel material and be as compact as possible. Secondly, the thermal and inertial shock expected to be produced by the extremely sharp rise and fall of the fission reaction has not yet been fully analyzed, notwithstanding the considerable research and development work done.⁵⁻⁹

There exist some more drawbacks beside the just mentioned technical uncertainty. First, though the background flux is very low, the integrated background neutrons produced between pulses due to the delayed neutron emission will reach a considerably high level ($\sim 9\%$) as compared to the useful neutrons in the pulse and this for many measurements would be the ratio of background to signal. This might give some trouble in very precise measurements. Secondly, the CTR radiation effect research requires a very high intensity fast neutron flux (preferably 14 MeV) for fusion reactor studies. Fast neutrons of these energy ranges can be produced efficiently by the spallation reaction, but not by the fission reaction. Further, an important class of radiation effects measurements requires the lowest possible ratio of gamma ray flux to neutron flux. Spallation neutron production is much more attractive this way than fission production. Therefore, the addition of a fission neutron multiplying system will not contribute

very much for the upgrading of the radiation effects research capability. Thirdly, the potential hazard to environment due to the fission products must be considered, even though the quantities expected in such a small core are far below those of the usual power reactors. The multiplying system is a subcritical assembly of the nuclear fuel. The maintenance procedure will be more elaborate and the maintenance cost will be substantially higher than those for particle accelerators.

(b) Some Other Accelerators, etc.

Because the final technical limitation is always encountered with the problems of heat removal capability, photoneutron production by any powerful electron accelerator will be ruled out.*

The D-T fusion reaction has a large reaction cross-section to produce 14 MeV neutrons, but the neutron flux obtained from these devices (rotating target, etc.) are several orders of magnitude smaller than needed here. A synchrocyclotron in the 800 MeV range would have a lower peak current. A proton linear accelerator is a very powerful machine to produce intense neutrons. The LAMPF of LASL holds presently the capability to be the most intense neutron generator, provided it can produce the design average current of 1 mA and that all the protons will be solely used for the neutron production. However, the pulse length of the accelerated protons is 500 μ sec, far wider than can be tolerated for our requirement. This can only be shortened to the order of 1 μ sec if the proton beam is injected in a storage ring. A storage ring is a machine of much similarity with the synchrotron; the main difference being the constant magnetic field and the relatively low power of the constant frequency k.f. system. The construction and operation cost of a 800 MeV linac-storage ring combination is certainly higher than that of a 800 MeV fast cycling synchrotron and the 50-100 MeV linac injector.

The linac on itself may be able to produce a narrow proton burst ($\leq 1 \mu$ sec), but in this case to meet the intensity requirements the linac must accelerate an 8.0 A proton beam which is at least two orders of magnitude higher than presently achieved.

Another possibility is to accelerate deuterons instead of protons since the deuteron is the best particle for neutron production at low energy. However, in the spallation energy range there is little difference with protons of the same kinetic energy. If the energy per nucleon of the deuterons is the same as the energy of the protons, the deuteron may produce twice as much neutrons in spallation reaction in heavy metal targets. The number of spallation-evaporation neutrons produced per nucleon is roughly expressed by the following formula

$$n \approx (K - 120)(A + 20) \times 10^{-4} \quad (1)$$

* Heat production per neutron is roughly in the ratio of 100:10:1 for photoneutron process, fission process and for nuclear spallation process.

where n = number of neutrons produced per incident nucleon

K = kinetic energy of nucleon in MeV

A = target mass number, with target dimension assumed to be, diameter 10.2 cm, length 61 cm target material (Be-Pb).

For a U^{238} target the relation is given by

$$n \approx 2(K - 120)(A + 20) \times 10^{-4} \quad (1')$$

Thus deuteron acceleration is not advantageous if the total kinetic energy is the same as that of the proton.

Suppose we build a new linac, the parameters of which will be optimized for deuteron acceleration investing the same amount of construction cost as for protons. The total length of the resonator tank will be the same. The injection energy of the deuteron will be twice that of the proton but the final energy is the same. The deuteron synchrotron needs magnets producing larger fields or having larger radius because of the approximately $\sqrt{2}$ times larger momentum of the deuteron of the same kinetic energy as the proton. At the same energy per nucleon, the deuteron momentum would be twice that of the proton.

Thus the acceleration of deuterons is not very attractive even if we take into consideration the higher neutron production density along the particle path in the target (cf., Sec. V.a).

The future fusion reactor, if it is feasible, will be a very intense neutron source. However, only the pulsed fusion reactor may satisfy the specification outlined in Sec. III. Furthermore, the realization of these fusion reactors appears to be very remote.

V. PROPOSED H^- LINAC-PROTON SYNCHROTRON SYSTEM

(a) Neutron Producing Target and Choice of Acceleration

To attain the required peak flux $\hat{\phi}$ of slow neutrons at the surface of the moderator of 1×10^{16} $n_{Th}/\text{sec cm}^2$, the number of fast neutrons reaching the core-facing surface of the moderator must be about 1×10^{12} n_f/cm^2 pulse, in the configuration as shown in Fig. 1.¹

The spallation-evaporation neutron production density ρ in the target, the neutron spectrum and the angular distributions were Monte-Carlo calculated at LASL for a proton beam of 800 MeV, U^{238} , Pb and Ta targets of (10-20) cm diameter and (10-30) cm long.¹¹ For 800 MeV protons on U^{238} , exponential decrease of ρ is seen and the $1/e$ length along the proton path is 12.3 cm which is the high energy nucleon mean free path in U, whereas the proton range of 800 MeV in U^{238} is 24 cm. Figure 2 shows one of the results obtained at LASL. Beyond 24 cm, neutron production decreases below the exponential decay.

$M = (CH_2)_n$ moderator ($\sim 10 \times \sim 10 \text{ cm} \times \sim 5 \text{ cm}$)

Be = Be metal reflector surrounding the moderator

Fig. 1. Conceptual target and moderator assembly.

Fig. 2. Radial and axial distribution of the production of evaporation neutrons in a 7.5 cm radius, 30 cm long U^{238} target with 800 MeV protons incident on axis (LASL Report LA-4789).

As the size of the moderator is not required to be very much larger than 10 cm × 10 cm × 5 cm, a region of the highest neutron production density of 15 cm will be sufficient.

Table I. The range of proton and deuteron of several energies in some metals.

Energy of Proton or Deuteron	Range	W ($\rho = 19.3$)	Pb (11.5)	U (18.7)
500 MeV	R_p (cm)	11.7	19.5	12.2
	R_d	7.6	12.7	7.8
800 MeV	R_p	23.2	39.0	24.0
	R_d	16.7	28.0	17.2
1000 MeV	R_p	31.7	53.5	32.8
	R_d	23.5	39.3	24.2

Table I summarizes the ranges of protons and deuterons for several particle energies and target materials. As seen in this Table the shorter range of a deuteron beam results in a more localized neutron production as compared to protons of the same energy.

Figure 3 shows the number of neutrons produced in W-target per proton together with the range of proton and linear neutron production density. Comparing this with the ZING project estimate^{1,9} for 500 MeV proton incident on a U^{238} target we obtain

$$\frac{n(800 \text{ MeV} + W)}{n(500 \text{ MeV} + U^{238})} \approx 0.8$$

Acceleration to more than 800 MeV is not recommendable.

The thermal neutron flux obtainable at the moderator surface depends critically on the configuration of target-reflector-moderator assembly. A cooling system for target as well as moderator is required and the moderator efficiency is not always the same as in the case of low intensity model measurements. Using W target instead of U^{238} and a proton energy of 800 MeV, 4.0×10^{13} protons per pulse at the target will be required to obtain 1×10^{16} $n_{Th}/\text{sec cm}^2$ during the pulse from the surface of moderator. Assuming 80% for the acceleration efficiency, 5.0×10^{13} protons/pulse at injection will be needed. Effects of the proton beam emittance and energy spread will be discussed later. More accurate Monte Carlo calculations of slow neutron fluxes are now being pursued by S. G. Das, J. M. Carpenter, and R. E. Prael.

R = Range of proton in W metal

n = Number of neutrons produced in
W target (10 cm ϕ $\times$ 60 cm)
per proton

ρ = Linear neutron production density

Fig. 3. Range of proton, number of neutrons produced per proton, and the linear production density of neutron in W target.

In actuality, high energy protons of 500-800 MeV will evoke fission process in the target material heavier than Th, whereas, spallation evaporation is the main process in the target like W or Pb. The total cross-section for both processes is of the same order of magnitude, reaching $1.5 \sim 2$ barns.

The long living induced radioactivity expected in these targets will amount to the order of $10 \sim 30$ mCi per gram of the target material, after long irradiation period and after waiting for one day for cooling off in both of fission and spallation process. The proposed target assembly of about 20 kg of W or U^{238} will be activated to the order of 1 KCi after one day cooling following one week irradiation. Long living fission products such as Sr^{90} or Cs^{137} will be produced in lesser amount than in the case of low energy proton bombardment, whereas long life radio isotopes produced by spallation are not necessarily in small quantity.

The neutron yield in U^{238} is almost twice larger than in W, and the heat generation per neutron in the former is about 1.7 times higher than in the latter.

The average kinetic energy of spallation neutrons is much higher than that of fission neutrons, and thus the W target is more useful for the radiation effect study.

The merit or demerit of W vs. U^{238} is very close. It may be more safe to assume a W target at the present stage of design study.

(b) Intensity Limitation in the Synchrotron

Space Charge Limit

The space charge forces between a particle and the beam modify the effective focusing force and make the betatron frequencies intensity dependent. The beam intensity must be less than a value that would shift the betatron frequency to the nearest harmful resonance. In the IPNS synchrotron, as in most other accelerators, the vertical dimension of the beam is smaller than the horizontal dimension and the space charge limit is determined by the allowable vertical betatron frequency shift. For a beam of elliptical cross-section with horizontal axis W and vertical axis H, the space charge limit is given by

$$N = \frac{\pi H(H + W) \nu_v \Delta \nu_v \beta^2 \gamma^3 B F}{4 r_p R},$$

where ν_v is the vertical betatron frequency, $\Delta \nu_v$ is the allowable shift in ν_v , r_p is the classical proton radius ($r_p \approx 1.54 \times 10^{-18}$ m), R is the mean radius of the synchrotron, B is the bunching factor given by $B = (\text{bucket area}/2\pi \text{ bucket height})$ and F is a factor determined by the image charge and current.

$$F = \frac{1}{1 + \frac{H(W+H)}{H_g^2} [\epsilon_1 (1 + B\gamma^2\beta^2) + \epsilon_2 B\gamma^2\beta^2 (\frac{H_g}{G})^2]}$$

where H_g = vertical vacuum chamber gap, G = magnet gap. For a beam between two parallel plates at a distance H_g satisfying the condition $H_g \gg \sqrt{W^2 - H^2}$ the image coefficients are given by¹³

$$\epsilon_1 = \frac{\pi^2}{48} \quad \text{and} \quad \epsilon_2 = \frac{\pi^2}{24} .$$

In general the coefficients ϵ_1 and ϵ_2 are smaller than the values given above. The beam envelope varies in dimension along the circumference of the synchrotron

$$H = 2\sqrt{\beta_v Q_v} \quad \text{and} \quad W = 2\sqrt{\beta_h Q_h}$$

where β_v and β_h are respectively the vertical and horizontal betafunctions (Sec. V.c). πQ_v and πQ_h are the vertical and horizontal phase space areas occupied by the beam. In the IPNS synchrotron we find

$$\frac{v\beta_v}{R} \approx \frac{v\beta_h}{R} \approx 1.25 .$$

On the other hand, for $(W+H)H \approx H_g^2 = G^2$ and $B = 0.45$ we find for the image factor $F \approx 1/1.25$. The expression for the space charge limit reduces to

$$N = \pi \frac{Q_v + \sqrt{Q_v Q_h}}{r_p} \Delta_v \beta^2 \gamma^3 B .$$

The phase space areas occupied by the beam must be smaller than the acceptance of the synchrotron

$$\text{Vertical acceptance} \quad A_v > \pi Q_v$$

$$\text{Horizontal acceptance} \quad A_h > \pi Q_h .$$

For $N = 5 \times 10^{13}$, $Q_v = 1/2 Q_h$, $\Delta v_v = 0.25$, $\beta^2 \gamma^3 = 0.166$ (70 MeV injection) and $B = 0.45$ we have

$$Q_v = 5.5 \times 10^{-4} \text{ rad-m}, \quad Q_h = 11 \times 10^{-4} \text{ rad-m}$$

Collective Instabilities

The beam in the IPNS synchrotron is continuous during the injection. The synchrotron operates below the transition energy, therefore, no negative mass effect will occur. The growth rate of the spontaneous bunching due to resistive walls and/or inductive walls is of the order of milliseconds or longer, while the total injection time is only 850 μ sec. Therefore, it is not likely that spontaneous bunching will occur during the injection.

For the same reason we may expect that the transverse instabilities will not be serious during the injection.

The bunched beam longitudinal instability must also be considered. The simplest coherent mode is the dipole rigid bunch motion (i.e., harmonic oscillation of the bunch center with respect to R.F. phase). For a smooth circular vacuum chamber the growth rate for a single bunch is given by¹⁴

$$\frac{1}{\tau} = 0.0134 \Omega_s \frac{|Z_{||}|}{V \cos \phi_s} I G(\nu_s) ,$$

where

$$\Omega_s = \frac{\omega_o}{\beta} \sqrt{\frac{|\eta| \text{ eV } \cos \phi_s}{h 2\pi E_s}}$$

is the synchrotron frequency, $Z_{||}$ is the coupling impedance, V is the peak accelerating voltage, ϕ_s is the synchronous phase, h is the harmonic number, E_s is the total energy of the synchronous particle and $\eta = 1/\gamma_t^2 - 1/\gamma^2$. (γ_t = transition energy in units of $m_0 c^2$, γ particle energy in units of $m_0 c^2$.) The function $G(\nu_s)$ is given by

$$G(\nu_s) = \sum_{k=1}^{\infty} \frac{\sin 2\pi k \nu_s}{k^{5/2}} , \quad \nu_s = \frac{\Omega_s}{\omega_o}$$

ω_o = particle angular velocity.

The coupling impedance is approximately given by

$$Z_{||} = \frac{2\pi R}{G} (1 + i) R_s .$$

$R_s = (\omega_o \mu \mu_o / 2\sigma)$ is the surface resistivity, where we have assumed that the pole tips are the vacuum chamber walls; μ and σ are respectively the permeability and conductivity of the wall material. In the IPNS synchrotron just after capture we find $|Z_{||}| \approx 13$ ohm, $V \cos \phi_s \approx 3$ kV, $|\eta| = 0.8$, $h = 2$

and $v_g \approx 1.2 \times 10^{-3}$. It is not difficult to show that $G(v_g) \ll 1$ so $1/\tau \ll 2.6$ or $\tau \gg 380$ msec. In reality the wall is not circular and smooth but the growth rate is so large compared to the acceleration time that we may expect that the bunched beam resistive wall instability can be ignored. The rotation frequency, moreover, changes by a factor 2.3 during the 8.3 msec acceleration time that we may expect that the bunched beam resistive wall instability can be ignored. The rotation frequency, moreover, changes by a factor 2.3 during the 8.3 msec acceleration time. For the same reason we can neglect the inductive wall effect.

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 of $k < \nu < k + 1/2$ insures for a single bunch stability against the resistive wall effect. However, dipole coherent instability can occur due to ions in the residual gas. The proton beam will ionize the molecules of the residual gas. In general the electrons have enough energy to escape to the vacuum chamber walls in a time interval short compared to the rotation period of the beam. Since the beam is bunched, capture of the electrons in the potential well of the proton is not possible.

The effect of the ion cloud can be suppressed by the introduction of an octopole field which provides Landau damping for the coherent oscillations. A servo system will also be used. These methods have been applied successfully in several accelerators.

The Head Tail Instability

The betatron frequency ν and the angular velocity ω_0 depend on the momentum of the particle. Therefore, the betatron phase difference between a nonsynchronous and the synchronous particle changes as the nonsynchronous particle moves from the head to the tail of the bunch or vice versa. The amount of this phase shift is given by

$$\chi = \frac{1}{2} \Delta(\nu \omega_0 t_s)$$

where t_s is the synchrotron oscillation period. The angular velocity ω_0 averaged over the period t_s is the same for all particles of the bunch. Thus

$$\Delta(\omega_0 t_s) = \langle \omega_0 \rangle t_s + \omega_0 \langle \Delta t \rangle = 0 \quad .$$

Substitution of this in the expression for χ gives

$$\chi = \frac{1}{2} \Delta(\nu \omega_0 t_s) = \frac{1}{2} \left(\frac{d\nu}{dp} \Delta p \right) \omega_0 t_s \quad .$$

Using the relations:

$$\xi = \frac{dv}{dp} \frac{p}{v} \quad (\text{the chromaticity})$$

and

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2} = - \frac{d\omega_o}{dp} \frac{p}{\omega_o},$$

we obtain

$$\chi = - \frac{1}{2} \frac{\xi}{\eta} v (\Delta\omega_o) t_s = \frac{\xi}{\eta} t_\ell, = \frac{1}{2} \frac{\xi}{\eta} v \omega_o \Delta t_s = \frac{\xi}{\eta} v \omega_o t_\ell$$

where $t_\ell = (1/2) \Delta t_s$ is the bunch length in seconds. For small values of χ it can be shown¹⁵ that the growth rate can be written in the form

$$\frac{1}{\tau} = K \chi.$$

where the quantity K is the positive or negative depending on the mode number. However, for zero chromaticity $\chi = 0$, $\xi = 0$ and regardless of the mode number

$$\frac{1}{\tau} = 0 \quad \text{or} \quad \tau = \infty.$$

Therefore, sextupole magnets to correct the chromaticity must be included in the design.

(c) The Choice of the Lattice Structure

The cell structure periodicity N and the betatron frequency v should be chosen to avoid operation close to serious resonances. The maximum betatron function $\beta_{\max}$ which determines the magnet aperture should be as small as possible. This requirement implies the choice of large N and v , but a large value of N reduces the length of each straight section. As a compromise the following cell structure has been chosen. The number of cell periods $N = 16$; the betatron frequencies are $v_h = 4.25$ and $v_v = 5.25$. The 16 straight sections are each 2.5 m long to allow sufficient space for R.F. cavities, kicker and septum magnets, coherent oscillations damping system, etc. To accommodate the high intensity beam the synchrotron acceptance and therefore the apertures of the dipole and quadrupole magnets must be large. To keep the power loss within a reasonable value a maximum bending field of 6 kG, and a maximum gradient of 0.5 kG/cm are chosen. The increase of the synchrotron circumference due to the low field choice is negligible compared to the straight section length required for the R.F. cavities, etc. Figure 4 shows the cell structure and the computed beta-functions and momentum compaction function for the following parameters

β_h = Horizontal beta function

β_v = Vertical beta function

χ_p = Momentum compaction function

Fig. 4. Cell structure (1/16 of circumference), β -function and momentum compaction function.

$$\begin{aligned}
 L &= 2.5 \text{ m} \\
 M_1 &= M_2 \approx 1.6 \text{ m} \\
 S_1 &= 0.3 \text{ m} \\
 S &= 0.5 \text{ m} \\
 Q_F &= Q_D = 0.6 \text{ m}
 \end{aligned}$$

For better versatility a separated function magnet system is chosen.

(d) The Choice of the Injection Method (H^- versus H^+) and the Injection Energy

The H^- injection in a synchrotron increases the beam intensity because we can take advantage of the better betatron amplitude distribution and longer injection time. The maximum number of turns for H^+ injection in a strong focusing synchrotron cannot exceed 30 turns, whereas injection of H^- can last for 700 turns or longer.

The longer rotation period for a smaller injection energy reduces the current requirement of the H^- source to a level which gives reliable operation. On the other hand a low injection energy results in a larger beam size if the space charge limit is fixed. The final choice of the injection energy should be a compromise, taking into account cost, extraction problems, source development, etc. The required H^- current I , the maximum vertical beam height $H_{\max}$ and the horizontal beam quality Q_h at 800 MeV are summarized in Table II as a function of the injection energy E_i for a space charge limit $N = 5 \times 10^{13}$, 700 turns injection with 70% efficiency and the beam quality ratio $Q_h = 2 Q_v$.

TABLE II

E_i	30	50	70	90	100	MeV
I	9.6	12.3	14.3	15.9	16.6	mA
$H_{\max}$	25.3	19.3	16.2	13.9	13	cm
Q_h	43.8	33.1	27.4	23.6	22	mrاد-cm

Table II shows that the beam size and therefore the required magnet aperture decreases with increasing injection energy. On the other hand the H^- current increases with the injection energy. For this feasibility study we choose tentatively an injection energy of 70 MeV. The required H^- current $I = 14.3$ mA is about 5 times the current injected in Booster I. This extrapolation seems within the reach of the present state of the technology of the H^- source. If in the future it turns out that higher H^- beam could be produced, an increase of the injection energy to 90 or 100 MeV may be advantageous.

(e) The Injection and Extraction Methods

The bending magnetic field varies with time as

$$B = B_1 + \frac{1}{2}(B_e - B_1)(1 - \cos\Omega t)$$

where

$$B_1 = 1.573 \text{ kG}$$

$$B = 6 \text{ kG}$$

$$\Omega = 120 \pi / \text{sec}.$$

The injection of H^- will be started at $t = -850 \mu\text{sec}$, lasting to $t = 0$ when the magnetic field reaches the minimum value B_1 . At the start of the injection the equilibrium orbit is located 8.5 cm inside of the center of the vacuum chamber, i.e., $\Delta R = -8.5 \text{ cm}$. The H^- injection stops when the equilibrium orbit reaches the center of the vacuum chamber ($\Delta R = 0$). The stripper foil will be installed on the periphery of a rotating disk, the axis of which will be horizontal and at the inner side of the synchrotron donut. A steering magnet with a sawtooth shaped field will sweep the injected H^- beam vertically over a distance of $\pm 4 \text{ cm}$ to follow temporarily the motion of the stripper foil. Initially, due to its betatron motion, the proton will traverse the foil once in every 4 turns. When the equilibrium orbit expansion is larger than the size of the foil, the proton will miss the foil entirely. For example, if the foil width is 2 cm, the protons make on the average approximately 50 traversals during the injection pulse. The vertical steering of the beam will distribute the beam over the available vertical acceptance of the synchrotron. The change in the magnetic field during the injection spreads the beam over the horizontal phase space. A more detailed orbit calculation may be needed to obtain the total number of traversals for each injection process.

If we assume 50 traversals for all the injected protons, the total number of traversals will be 2.5×10^{15} per pulse or 1.5×10^{17} per second. If we assume $10^{20} - 10^{21}$ traversal/cm² before the foil is destroyed, the life will be 0.5 - 5 hours for a foil of approximately 3 cm² effective area. The number of foils on the disk determines the servicing interval of the stripper system. Some research and development may be necessary to find a better stripper material and method.

Extraction of the 800 MeV protons will be in a single turn using a kicker magnet and a septum magnet. The septum magnet should be located one sector downstream of the kicker magnet, which is located downstream of M_2 . As the phase advance of the betatron oscillation per sector is given by $\sigma_x = v_x 2\pi/N \approx \pi/2$, the beam displacement and divergence at one sector downstream is given by

$$\Delta x \approx \beta_x \sin\sigma_x \theta, \Delta x' = (\cos\sigma_x - \alpha_x \sin\sigma_x) \cdot \theta$$

where β_x is the horizontal betafunction value at the location of the kicker (septum) magnet, $\alpha_x = -1/2 \beta'_x$, and θ is the amount of the deflection due to the kicker magnet.^x The injected beam is approximately 16 cm wide at the location of the septum magnet. Assume the septum is located at 8.25 cm from the center of the beam. Since the beam is approximately 8 cm wide at 800 MeV Δx must be $8.25 + 8/2 + \text{septum thickness}$. For a 1 cm thick system we have $\Delta x = 13.25$ cm. At the septum magnet $\beta_x \approx 4$ m and we find

$$\theta = \frac{\Delta x}{\beta_x} \approx 0.033 \text{ radian}$$

which requires the kicker magnet strength

$$B_k \ell_k = 4.881 \times 0.033 \approx 0.16 \text{ Tesla-m} = 1.6 \text{ kG-m} .$$

The rise time Δt of the kicker field must be shorter than half the R.F. period at 800 MeV. Assuming a harmonic number $h = 2$ we find $\Delta t = 0.125 \mu\text{sec}$. The kicker voltage is given by

$$V_k = \left| \frac{d\psi}{dt} \right| \approx \frac{B_k \ell_k D}{\Delta t} ,$$

where D is the width of the kicker magnet gap. At 800 MeV the beam cross section at the location of the kicker magnet is $\sim(\pi/4) 8.5 \times 6 \text{ cm}^2$. Taking $D = 14.5$ cm we obtain

$$V_k = \frac{0.16 \times 0.145}{0.125 \times 10^{-6}} = 186 \text{ kV}$$

This voltage is rather high; it may be necessary to reduce the harmonic number or increase the injection energy. An 8 kG-m septum magnet with 1 cm entrance septum could guide the beam out of the synchrotron.

(f) Magnet and Vacuum System

The width of the bending magnets and the bore of the quadrupole magnets are determined by the required space for extraction. Some parameters of the magnets are given below

Bending magnets		M ₁	M ₂
Dimension (cm) (width × height × length)		90 × 40 × 160	75 × 46 × 160
Gap dimension (cm)		40 × 10	30 × 16
Weight (tons)	Fe	4.25	3.6
	Cu	0.3	0.45
Maximum field		0.6 Tesla	0.6 Tesla
Power input		16.2 kW	39.4 kW
Quadrupole magnets		(Q _F and Q _D)	
Maximum gradient		0.05 Tesla/cm	
Bore radius (cm)		12.5	
Weight (tons)	Fe	2.3	
	Cu	0.3	
Power input (kW)		26	

Vacuum System

Because of the high repetition rate the eddy current in the walls of a metal vacuum chamber would give an unacceptable field distortion. As in the Booster II, the pole tips will be a part of the vacuum chamber. The design pressure should be 5×10^{-7} mm Hg or better. Experience with Booster II may show that a better vacuum is necessary. A ceramic vacuum chamber is then required.

(g) Accelerating System

The most important feature of the R.F. system for the proposed synchrotron is the high power required to accelerate the intense proton beam. The design allows at least 8 straight sections, each 2.5 m long to accommodate the R.F. cavities. The choice of the harmonic number will be determined by the kicker voltage limitation and R.F. power requirement. In the meantime, a harmonic number of $h = 2$ is tentatively chosen. The cavities must be excited in the appropriate phase relations, that is

$$V_i = V_{mi} \sin h(\omega t - \phi_i)$$

where V_{mi} = peak voltage of cavity i

ω = angular velocity of proton

ϕ_i = phase of cavity i .

The required phase relationships between the cavities are easily maintained. The required energy gain per turn is given by

$$\begin{aligned}
 eV_a &= e \sum_i V_{mi} \sin \phi_{si} = 2\pi R \rho e \dot{B} \\
 &= \pi R \rho \Omega e (B_e - B_i) \sin \Omega t \\
 &\approx 88 \sin \Omega t \text{ KeV} .
 \end{aligned}$$

The maximum value of 88 KeV will be reached when $t = 4.17$ msec. ϕ_{si} is the synchronous phase angle of cavity i and all ϕ_{si} should be about 30° . Figure 5 shows the required energy gain per turn and some related quantities during the acceleration period. The revolution frequency increases from $f_i = 0.86$ MHz at injection to $f_c = 1.97$ MHz at 800 MeV. The revolution frequency at $B_{\max}$ is $f_B = 1.71$ MHz and the beam current at this instant is

$$I = N e f_B = 5 \times 10^{13} \times 1.6 \times 10^{-19} \times 1.71 \times 10^6 = 14 \text{ A} .$$

The peak power delivered to the beam is $P_b = IV_{a \max} = 1.23$ MW. Assume there are 8 R.F. cavities each with a shunt resistance $R_c \approx 5$ K ohm and a peak voltage $V_{mi} = 25$ kV. The total R.F. peak power is then

$$P_{\text{peak}} = 8 \frac{V_{mi}^2}{R_c} + P_b = 2.23 \text{ MW}$$

The R.F. power will vary as shown in Fig. 5, which is roughly proportional to B^2 . In Table III for comparison some quantities of the R.F. system of Booster II and the IPNS synchrotron are shown.

TABLE III

	Booster II	IPNS Synchrotron
Proton beam and repetition rate	5×10^{12} ppp, 30 Hz	5×10^{13} ppp, 60 Hz
Max energy gain per turn	10.5 KeV	88 KeV
Beam current at $B_{\max}$	2 A	14 A
Peak beam power	21 KW	1.23 MW
Peak cavity loss	~ 120 KW	1.0 MW
Total R.F. peak power	~ 141 KW	2.23 MW

Fig. 5. R.F. cavity characteristics.

VI. SHIELDING AND TRANSPORT SYSTEM

An ideal accelerator will need no shielding because there is no loss of the accelerated particles. In practice, however, it is not possible to eliminate all the shielding, especially at the transfer of the particles from pre-accelerator to linac and from linac to synchrotron.

The IPNS accelerator complex should be located at the area north of the 12 foot bubble chamber. The conventional earth cover and concrete shielding should decrease the radiation hazard to an acceptable value. To reduce the effect of roof and skyshine, the location of the accelerator complex and the neutron experimental building should be at least 100 m apart. Skyshine interference of neutrons from accelerator to neutron experimental equipments must be carefully avoided since it is not expedient to cover the experimental area with heavy shielding. For the neutron scattering measurements it is important not to spill protons during the beam transport from the synchrotron to the neutron target system. The counting rate in almost all of the important inelastic scattering measurements is sometimes as low as several counts per minute. Even if we install heavy shielding around the spectrometer, we always must leave some holes for vacuum manifolds, cables, etc., which make it difficult to prevent the neutrons to get into the spectrometer.

Stray fast neutrons are also very troublesome. Shielding walls around the spectrometer sometimes increases instead of reducing the background because of the slowing down of these neutrons. A 0.1% proton beam loss at some point 20 m from the spectrometer will give a fast neutron flux of $\sim 10^4$ $n_f/\text{sec cm}^2$ on the shielding wall of the measuring device, which will be enough to be a source of increasing background. Since the output proton beam of the synchrotron may have a momentum spread of the order of 0.3%, an achromatic transport system (ATS) will be necessary.

One of the authors (M.K.) suggested the horizontal proton beam inlet for the ZING Facility because of its easiness of handling the target assemblies (neutron target and radiation effect target) and also of the reduction in construction expenses. It may also work for the IPNS. The experimental area will come out something like shown in Fig. 6, in which the horizontally bent proton beam by ATS will reach the target through a rather long path. The beam pipe approaching the shielding facility should be covered by concrete shielding, and preferably made of thin Al pipe. The upstreaming neutrons through the proton beam hole will be well collimated. The Q magnets which will be installed in or outside of the shielding facility should have the bore radius larger than the neutron beam. In this way, we may be able to secure a low neutron background in the experimental area.

Fig. 6. Conceptual layout of the experimental area for IPNS Facility.

Accelerator Parameters

a. Pre-accelerator-Cockcroft-Walton

Energy	750 KeV
H ⁻ current	≥ 25 mA (H ⁻)

b. Linear Accelerator

Energy	70 MeV
R.F. frequency	200 MHz
Number of cavities	3
Beam pulse length	~ 900 μ sec
Pulse rate	60 Hz
Duty factor	5.5%
Total linac length	~ 45 m
Beam current	~ 15 mA (H ⁻)
Peak cavity excitation power	~ 6 MW
Total peak power	~ 7 MW
Emittance	$\pi 2$ mrad-cm
Momentum spread $\Delta p/p$	$\sim \pm 3 \times 10^{-3}$

c. Proton Synchrotron

Maximum kinetic energy	800 MeV
Intensity	5×10^{13} protons/pulse
Repetition rate	60 Hz
Injection energy	70 MeV
Injection current	14.5 mA (H ⁻)
Number of turns injected	700
Magnet radius	8.135 m
Average radius	20.37 m
Number of straight sections	16
Length of straight section	2.5 m
Number of periods	16
Structure of period	OMOFODOMO
Betatron frequency	
Horizontal	~ 4.25
Vertical	~ 5.25
Revolution frequency	0.86 - 1.97 MHz
Momentum compaction factor	0.06
$\beta_{\max}$ vertical	11.9 m
horizontal	11.5 m
Beam emittance at 800 MeV	
Horizontal	$\pi 27.5$ mrad-cm
Vertical	$\pi 13.8$ mrad-cm
Momentum spread at 800 MeV:	
$\Delta p/p$	1.9×10^{-3}
Bending magnet peak field	6 kG
Injection field	1.513 kG
Number of bending magnet	32
Length of bending magnet	1.6 m

Quadrupole magnet peak gradient	~ 0.5 kG/cm
Length of quadrupole magnets	0.6 m
Number of quadrupole magnets	32
Total iron weight of magnets	204 Tons
Total copper weight of magnet coils	21.6 Tons
Total power input	1.7 MW
Peak energy gain per turn	88 KeV
Harmonic number h	2
R.F. frequency:	
Minimum	1.72 MHz
Maximum	3.94 MHz
Number of R.F. station	8
Maximum cavity voltage	25 KV
Total R.F. peak power	~ 2.23 MW

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