Study of a Spallation Neutron Source based on Fast-Cycling Synchrotrons*

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Abstract

This paper is the summary of the conceptual design of a 5MW Pulsed Spallation Neutron Source (PSNS) conducted by an interdepartmental study group at Brookhaven National Laboratory. The design, with no reference to a specific site, is based on the use of a 600 MeV Linac followed by two fast-cycling 3.6 GeV Synchrotrons. The goals are an average proton power of 5 MW with beam pulses < 3 μs in duration, at the repetition rate of 10 - 60 beam pulses per second for the production of neutrons by spallation on targets.

1. INTRODUCTION

Since the beam power can be expressed as the product of beam kinetic energy and beam intensity, the design goal of 5 MW average power can in principle be obtained by trading proton beam intensity for energy. Depending on the relative balance between these two parameters, two basic approaches for the design of the PSNS facility may be considered. One choice is a relatively low proton energy (~ 1 GeV) accompanied by a higher beam intensity, which can be realized with a full-energy Linac followed by a number (one or more) of constant energy accumulator rings. The second choice is a higher proton energy (few GeV) accompanied by a commensurate lower beam current. Higher beam energy could be obtained with a linear accelerator, for example, with superconducting cavities; the cost, however, would be high and reliable operation difficult. At the present stage only fast-cycling Synchrotrons are appropriate for proton acceleration to high energy, with high average beam intensity.

The choice of design energy influences directly the proton to neutron yield and design of the target system. Higher proton energy is to be preferred because it eases many design considerations regarding beam performance. Taking the various factors into account, a design scenario was adopted making use of the higher proton beam energy option, i.e. an intermediate-energy injector Linac followed by two fast-cycling Synchrotrons. It was indeed determined that the proton energy of 3.6 GeV represents a good compromise between the design of the accelerator complex and the design of the target system with close to optimum proton-to-neutron yield.

2. ACCELERATOR DESIGN ISSUES

The Synchrotron scenario alleviates considerably the design considerations for the injector Linac, but requires careful examination of design issues which are peculiar to Synchrotrons. The most important one is the choice of the Linac energy. The present scenario would suggest as low a beam energy as possible, with most of the energy increase to take place in the Synchrotron in order to favor Linac reliability and minimum cost. Yet the low-energy injection into the Synchrotron creates a bottleneck to the beam performance because of the space charge effects. These can be reduced either by raising the final energy, so that the total amount of beam intensity is lowered, or by increasing the injection energy. The scenario we have investigated takes as a compromise one 600 Mev Linac followed by two 3.6 GeV Synchrotrons.

The number of synchrotrons (two) is driven by two additional considerations. One is again space charge: two synchrotrons, running in parallel, need half the total amount of beam current and therefore half of the amount of space charge effects. A second consideration is that the overall repetition rate of 60 beam pulses to the target per second is better achieved with two Synchrotrons each running 180° out of phase at the repetition rate of 30 Hz. Synchrotrons with cycles at 60 Hz have been built and successfully operated; nevertheless, considering the large beam intensity in the PSNS facility, safety and beam losses are better controlled at a lower repetition rate.

A list of the most important issues relevant to the design of high beam intensity fast-cycling Synchrotrons is as follows:

- Space charge effects at injection
- RF capture during injection
- RF acceleration
- Ramping of the guide field
- Vacuum

Space charge effects are particular important to Synchrotrons because of the low injection energy. The indicative parameter is the depression $\Delta\nu$ of the betatron tune given by

$$\Delta \nu = N r_p / 2B\beta^2\gamma^3 \varepsilon \qquad (1)$$

where N is the total number of protons circulating, $r_p = 1.535 \times 10^{-18}$ m is the classical proton radius, B the bunching factor which during the early part of the acceleration cycle is typically 0.3, β and γ are the usual relativistic factors, and ε is the beam emittance. Here the limit $\Delta\nu = 0.25$ is adopted, small enough to keep the beam tune spread away from major half-integral stopbands that may cause beam losses. Thus Eq. (1) relates closely injection energy, beam intensity and beam dimension, which also determines the gap of the magnets and therefore their feasibility and cost. The choice of two 3.6 GeV Synchrotrons together with the 600 MeV Linac requires a magnet gap close to 15 cm, which is technically anf financially acceptable.

There are uncertainties on the exact validity of the space charge limit as calculated. Present operating experience for various facilities show a range of limiting values for $\Delta\nu$. Only

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experience with the completed facility will permit determination of the actual limit in the present case. This suggests staging of construction whereby one synchrotron is built first, yielding at least 2.5 MW, subsequent to which the actual space charge limit is determined. It may be possible that the figure $\Delta\nu = 0.25$ adopted presently will be shown to be conservative, in that case one will proceed to increase correspondingly the current toward the design goal without having to resort to the construction of the second Synchrotron. Alternatively, one may construct the second Synchrotron or extent the Linac to 900 MeV, which will double the beam intensity, and thus attainment of the full 5 MW beam power requirement, with the same original magnet gap. The only drawback of this approach is the requirement for the first Synchrotron to be capable to operate also at 60 Hz.

3. BASIC SCENARIO OF THE FACILITY

An outline of the scenario is shown in Figure 1 and a summary of parameters is given in Table 1. We have chosen two identical Synchrotrons housed in the same tunnel, operating simultaneously at the repetition rate of 30 Hz, with their power supplies 180° out of phase from each other. The average beam intensity is 1.45×10^{14} protons/pulse for each Synchrotron; and the proton beam intensity impinging on the target is 8.7×10^{15} protons/sec, or 1.4 mA average beam current.

TABLE 1. General Parameters of the PSNS

Total Power of Facility	5	MW
Final Proton Kinetic Energy	3.6	GeV
Average Proton Beam Intensity	1.4	mA
Number of Synchrotrons	2	
Synchrotron Repetition Rate	30	Hz
Number of Protons /Synchrotron	1.45×10^{14}	
Synchrotron Circumference	363.2	m
Beam Pulse Length on Target	1.24	μs
Linac Energy	600	MeV
Linac Repetition Rate	60	Hz

The scenario works as follows. Beam pulses of negative ions are accelerated to 600 MeV in the Linac at the repetition rate of 60 Hz. The pulse duration is long enough to allow injection of many turns in one Synchrotron at the time. Injection occurs by letting the negative ions be stripped of their electrons when crossing a foil placed at the location of injection. The beam is then accelerated to 3.6 GeV and immediately extracted and transported to one of two experimental targets. The Synchrotron is ramped with a guide field having a pure sinusoidal waveform. As the beam is being extracted from the first Synchrotron, the second Synchrotron is being filled with a Linac beam pulse of the same duration and intensity which it accelerates to the same final energy and at the same repetition rate. The procedure then repeats periodically alternating filling and acceleration from one Synchrotron to the other, thus creating a beam pulse sequence at the repetition rate of 60 Hz.

An important consideration of the study is the control of the beam losses to a level of less than 0.1% throughout the entire acceleration cycle. This has some consequences on the size of the betatron acceptance of the magnetic rings and on the size of the rf buckets during beam capture and acceleration in the Synchrotrons (see Tables 3 and 4).

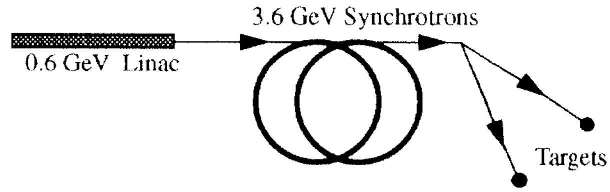

Figure 1 Layout of the PSNS Facility

4. THE INJECTOR LINAC

The layout of the Linac, which is made of room-temperature components, is shown in Figure 2. The most important parameters are given in Table 2. The preinjector makes use of a negative-ion source offset from ground by 50 kV. The beam is injected in the RFQ, operating at 350 MHz, where it is captured, accelerated to 2.5 MeV and longitudinally compressed. The source delivers a beam pulse of 0.5 ms duration at the repetition rate of 60 Hz. The pulse duration is adjusted to correspond to about three-hundred turns being injected in any one of the two Synchrotrons. The source current is 120 mA to allow for possible losses during capture by the RFQ. The pulse peak output current from the Linac is taken to be 100 mA. To control the losses, prebunching or chopping to 50% of the rf wavelength at injection is required between the ion source and the RFQ and after the RFQ.

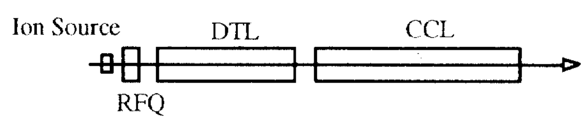

Figure 2 The 600 MeV Injector Linac

The Drift Tube Linac (DTL) operates at the same frequency of 350 MHz, which is 267 times the frequency of the accelerating rf system at injection in the Synchrotrons. The beam is accelerated in the DTL to 70 MeV and it is longitudinally compressed by another factor of two to prepare for the beam capture in the subsequent and last Linac component: the Cavity Coupled Linac (CCL) operating at 700 MHz, twice the frequency of the RFQ and the DTL. The beam is then accelerated in the CCL to the final energy of 600 MeV and compressed even further.

5. THE FAST-CYCLING SYNCHROTRONS

The magnet lattice of the Synchrotrons is chosen to accommodate several beam functions and operations. Space is provided for beam injection and extraction, and for the rf cavities. We have chosen a superperiodicity of two, with each superperiod made of an arc and an insertion. Considering the large tune-depression caused by space-charge forces, it is important to implement the highest periodicity as possible to eliminate the effects of low-order resonances due to systematic magnet imperfections. We have thus opted for a cyclic sequence of simple FODO cells which preserves the periodicity of the amplitude lattice functions to a high degree and that of the dispersion function to a lesser degree, by removing bending magnets where straight insertions are required.

TABLE 2. 600 MeV - Linac Parameters

Linac Pulse Duration	0.5	ms
Duty Cycle	2.8	%
Source Current	120	mA
Average Pulse Current	100	mA
Peak Power to Beam	30	MW
Peak Power to rf Structure	60	MW
Total Peak Power	90	MW
Average Power	2.7	MW
Emittance (normalized, rms)	0.4	π mm mrad
Momentum Spread (full)	1.5×10^{-3}	
RFQ : frequency / final energy	350 MHz/ 2.5 MeV	
DTL : frequency / final energy	350 MHz/ 70 MeV	
CCL : frequency / final energy	700 MHz/ 600 MeV	

Another important consideration, to take into account for determining the size of the accelerators, is the fast variation of the bending field due to the large repetition rate. We have constrained the field variation not to be in excess of 47 T/s. This in turn assigns the maximum value of the bending field and of the circumference of the Synchrotrons.

TABLE 3. Synchrotron Parameters

Circumference	363.204	m
Lattice Structure	32 FODO Cells	
Number of dipoles/quads	48/64	
Bending Field	0.19 - 0.69	T
Transition Energy, γ_t	6.28	
Betatron Tunes, $\nu_{h,v}$	7.8 / 7.8	
Natural Chromaticity, $\xi_{h,v}$	-9.1 / -9.3	
Revolution Period @ inj.	1.53	μs
Number of Turns injected	303	
Number of Bunches	2	
Momentum Spread, max	0.8	± %
Betatron Emittance @ inj.	200	π mm mrad
Normal. Emittance (full)	260	π mm mrad
Betatron Acceptance	320	π mm mrad

The transition energy has a value large enough so that the whole acceleration cycle is performed well below the transition energy. This is optimum to avoid losses associated with transition energy crossing and with negative mass instability.

Because of the lattice regularity, the uncorrected chromaticity equals about the betatron tune. Since the beam momentum full spread does not exceed the value of one percent, the resulting tune spread resulting from the uncorrected chromaticity is only a fraction of the one induced by the space-charge tune-depression; thus correction of the natural chromaticity with sextupole magnets may not be required.

6. THE VACUUM SYSTEM

The large rate of field change induces large eddy currents in a metallic vacuum chamber. The power dissipated would be too high to be disposed with water cooling. Thus a ceramic vacuum chamber with metallic strips, to avoid electromagnetic interaction between the beam and the magnet lamination, has been adopted. This solution also provides optimal vacuum environment, < 10^{-8} torr, particularly to avoid production and trapping of electrons.

7. THE RF CAVITY SYSTEM

We have opted for an accelerating harmonic number h = 2, with two rf buckets per revolution. This requires a frequency swing from 1.31 to 1.62 MHz to compensate for the variation of the beam velocity. Major rf parameters are listed in Table 4. A peak voltage per turn of 800 kVolt is required. This is obtained with eight cavities, each with two gaps operated independently from each other, and a peak voltage of 50 kVolt/gap. Each cavity absorbs a total of about 1 MW.

TABLE 4. Parameters of the rf System

Harmonic Number, h	2	
rf frequency inject. / extr.	1.31/1.62	MHz
Total Bunch Area	8	eV - s
Bucket Area	16 to 32	eV - s
Synchrotron Tune ν_s, max	0.008	
Peak Voltage per turn	800	kV
Peak Power to the Beam	7	MW
Peak Power Dissipated	1	MW
Total Peak Power	8	MW
Number of Cavities	8	
Number of Gaps per Cavity	2	
Peak Voltage per Gap	50	kV
Number of Amplifiers / Cavity	2	
Amplifier Peak Power	500	kW

The cavities are located in four locations placed symmetrically around the ring where the dispersion is small.The number of synchrotron oscillations per turn ν_s is relatively small, and does not cause concern with the possibility of betatron-synchrotron coupling.

Computer simulations have determined that in order to maintain the beam loss level during the rf capture to below 0.1%, each beam bunch from the Linac has to be chopped to about 50% the rf vavelength. The number of turns that can be safely injected is also limited to about 300.