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5 MW Pulsed Spallation Neutron Source

Preconceptual Design Study

June 1994

BNL Interdepartmental Study of a Pulsed Spallation Neutron Source

**Brookhaven National Laboratory
Upton, New York 11973**

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5 MW PULSED SPALLATION NEUTRON SOURCE
Preconceptual Design Study
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Table of Contents

PREFACE

1. INTRODUCTION

2. OVERVIEW OF THE FACILITY

- 2.1 Related Studies
- 2.2 Motivation for the Design Scenario
- 2.3 Neutron Yield
- 2.4 Accelerator Design Issues
- 2.5 Design Scenario of the Facility
- 2.6 Target/Moderator Systems

3. USER INSTRUMENTATION

4. ACCELERATOR SYSTEMS

- 4.1 Introduction
- 4.2 Linear Accelerator
- 4.3 Fast Cycling Synchrotrons

5. TARGET AND MODERATOR SYSTEM DESIGNS

6. BEAM LOSS, TARGET SHIELDING AND HANDLING

- 6.1 Beam Loss
- 6.2 Target Shielding and Handling

7. EXPERIMENTAL FACILITIES

8. SUPPORT FACILITIES, COMMON SERVICES

- 8.1 Computer Monitoring and Control Systems

9. CONVENTIONAL CONSTRUCTION

10. CONCLUSION, FUTURE STUDIES

PREFACE

There are two known methods for producing neutron sources sufficiently intense to meet the needs of the neutron scattering community. The first, fission in a reactor with a compact enriched uranium core surrounded by a heavy water reflector (the HFBR at Brookhaven, HFIR at Oak Ridge, and the high flux reactor at ILL in Grenoble) is based upon a reliable proven technology. The most powerful existing sources are of this type, and a conceptual design exists for an Advanced Neutron Source (ANS) with a steady state neutron flux (5×10^{15} n/cm²-sec) five times that of existing sources. With proper funding the ANS could be operating shortly after the turn of the century. It is not clear that fission reactor technology can be pushed much further, however, because of high thermal power densities in the core. The second approach is to use spallation neutrons produced by energetic protons ($E \approx 1$ GeV) incident on a heavy metal target. ISIS (Rutherford Appleton Lab, U.K.) is the most powerful existing source of this type (0.8 GeV, 200 μ amp; 160 kW proton power). Preliminary plans exist for a European Spallation Source (ESS) with an average proton beam power of 5 MW.

The relative merits of the two source types depend upon the experiment in question, and comparisons are made more difficult by differences in neutron spectrum and time structure (reactors are steady state, spallation sources are most often pulsed.) A properly designed 5 MW pulsed spallation source would produce about the same time averaged neutron flux as HFIR, and would be more powerful for the many experiments which can take advantage of the time structure. It has been suggested¹ that a 5 MW spallation source would be the natural complement to a 250 MW reactor, in that both would be equally effective for those experiments which can best utilize their respective characteristics.

In contemplating future U.S. neutron sources, the Kohn Committee² reaffirmed as top priority the funding and construction of the ANS. At the same time, the Committee called for the initiation of a serious design effort for a complementary spallation source. This Brookhaven National Laboratory study is a response to the Kohn Committee's recommendations.

This study has been pursued by an interdepartmental group of scientists/engineers (see below) of Brookhaven National Laboratory, on a part-time basis. Although the study is carried out by BNL staff only, it is intended as a "green field" study of a spallation neutron source facility without either the potential advantages or the design constraints of an existing facility or an existing site.

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Overall coordination of the PSNS study was the responsibility of a interdepartmental study panel (*above, **study coordinator) appointed by BNL's director, N.P. Samios.

This report has been edited by A. van Steenbergen, and compiled and prepared with the expert assistance of J. Thompson (NSLS).

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1. "Instrumentation and Techniques for the European Spallation Source", Report of an Expert Meeting, Coseners House, Abingdon, February 1992, A. Taylor, Editor, RAL-92-040.
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1. INTRODUCTION

This report describes a self-consistent base line design for a 5 MW Pulsed Spallation Neutron Source (PSNS). It is intended to establish feasibility of design and as a basis for further expanded and detailed studies. It may also serve as a basis for establishing project cost (30% accuracy) in order to intercompare competing designs for a PSNS not only on the basis of technical feasibility and technical merit but also on the basis of projected total cost.

The accelerator design considered here is based on the objective of a pulsed neutron source obtained by means of a pulsed proton beam with average beam power of 5 MW, in $\approx 1 \mu\text{sec}$ pulses, operating at a repetition rate of 60 Hz. Two target stations are incorporated in the basic facility: one for operation at 10 Hz for long-wavelength instruments, and one operating at 50 Hz for instruments utilizing thermal neutrons. The design approach for the proton accelerator is to use a low energy linear accelerator (at 0.6 GeV), operating at 60 Hz, in tandem with two fast cycling booster synchrotrons (at 3.6 GeV), operating at 30 Hz. It is assumed here that considerations of cost and overall system reliability may favor the present design approach over the alternative approach pursued elsewhere, whereby use is made of a high energy linear accelerator in conjunction with a dc accumulation ring. With the knowledge that this alternative design is under active development, it was deliberately decided to favor here the low energy linac-fast cycling booster approach. Clearly, the present design, as developed here, must be carried to the full conceptual design stage in order to facilitate a meaningful technology and cost comparison with alternative designs.

An overview of the PSNS design and substantiation of the basic system parameters is given in Section 2 of this report. This section is intended to provide the interested reader with a general overview only of the salient features of the present design approach. Expanded technical descriptions are presented in the remainder of the report.

With regard to the choice of instruments to accommodate a broad based scientific program, their execution and spatial disposition directly influence the 5 MW p-n target system design and also the parameters, such as the time structure, of the proton accelerator. Hence, an effort has been made to enumerate the various instruments and beam line options. This is presented in Section 3.

Detailed parameterization of the proton accelerator is given in Section 4, and further technical design aspects of the target and moderator system is presented in Section 5. Beam loss, shielding and handling considerations are addressed in Section 6 and a discussion of the experimental facilities is given in Section 7. Support facilities, common services and conventional facilities are discussed in Sections 8 and Section 9, respectively, and the need for further specific studies is indicated in Section 10.

Sequentially, this report will be complemented with an Addendum covering a "Work Breakdown Structure", "Construction Schedule", "Manpower Projection" and "Project Cost Estimate".

2. OVERVIEW OF THE FACILITY

2.1 Related Studies

The desired neutron flux specifications can be met with the following major accelerator requirements:

- average proton beam power, 5 MW
- beam pulse repetition rate, 10 and 60 Hz
- beam pulse length, less than 3 μ sec

This study benefitted from related studies elsewhere. Initially it examined the parameters and designs of existing spallation neutron sources, as enumerated¹ here in Table 2-1. Subsequently it took into account the conceptual designs of recent, ongoing, studies, directed towards higher neutron fluxes as specified, enumerated¹ here in Table 2-2. As a result of these initial studies an "intermediate energy Linac" - "Fast Cycling Synchrotron" (Linac-FCS) accelerator concept, aimed at $\approx 8 \times 10^{15}$ protons/sec was adopted.

Original specifications called for a staged construction approach with proton beam power of 1 MW - 5 MW. Upon examination of the accelerator parameter consequences of these specifications, it is evident that the SNS design would significantly exceed the present state of the art and performance of on-line accelerators. Hence, it would have to be anticipated that, during the early years of operation, the facility would run below specifications. Consequently, it was concluded that the design should be aimed at the full power requirement of 5 MW beam power. This would guarantee operation at the initial specification of 1 MW beam power at the conclusion of first-phase construction, and would realistically permit progression to the level of 5 MW beam power to be achieved over an extended period of time.

Table 2-1. Parameters of Existing SNS Facilities

<u>Ring</u>	<u>Location</u>	<u>E_{inj}</u> <u>(MeV)</u>	<u>E_{out}</u> <u>(GeV)</u>	<u>R_p</u> <u>(pps)</u>	<u>C</u> <u>(m)</u>	<u>Δt</u> <u>(μsec)</u>	<u>I</u> <u>(μA)</u>	<u>A/π</u> <u>(mm-mr)</u>
IPNS 500	ANL, Argonne	50	.5	30		0.1	13	
ISIS	RAL, U.K.	70	.8	50	163.4	.45	200	
KENS	KEK, Japan	40	.5	20		.05	5	
MPNS	Moscow, Russia	160					20	
PSR	LANSCE, Los Alamos	800	.8	20		.27	75	
*SINQ	PSI, Switz.	--	.59	continuous		--	1000	

*Under construction

Table 2-2. Parameters of Proposed Dedicated SNS Facilities

<u>Ring</u>	<u>Location</u>	<u>E_{inj}</u> <u>(MeV)</u>	<u>E_{out}</u> <u>(GeV)</u>	<u>R_p</u> <u>(pps)</u>	<u>C</u> <u>(m)</u>	<u>Δt</u> <u>(μsec)</u>	<u>I</u> <u>(mA)</u>	<u>A/π</u> <u>(mm-mr)</u>
ANS	Moscow, Russia	1000	10	50	573	2	.5	
AUSTRON	Austria	70-130	1.66	25-50	202	<1	.1	150
ESS	RAL/Wuppertal	800	3@0.8	50			6.3	
		1200	2@1.2	50				
		2400	1@2.4	50				
		800	3.0	50		3		525
IPNS-II	ANL, Argonne	400	2.2	30	196		.5	375
KEK/NEA	KEK, Japan	1500	1.5				2	
KENS-II	JHF, Japan	1000	1.0	50		≥ .2	.4	
LANSC-II	LANL, Los Alamos	800	0.8	120	145	.57	1.25	420
PSNS	BNL, Upton	600	2@3.6	30	363	1.2	1.4	320

2.2 Motivation for the Design Scenario

Since the beam power can be expressed as the product of beam kinetic energy and beam intensity, the design goal of 5 MWatt average beam power can in principle be obtained by trading proton beam intensity for proton 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. This approach has the advantage of a cheaper circular component (the accumulator ring) which may also be easier to design and to operate. The disadvantage is an expensive linac and higher beam intensity with consequences on cost, reliability and safety of the whole facility.

The second choice is a higher proton energy 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.

These two basic approaches: a full-energy Linac followed by accumulator rings, and a low energy linac followed by a fast cycling synchrotron have indeed been considered in various design proposals for similar PSNS facilities, as indicated in Table 2-2.

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 is adopted here 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. This will be further emphasized in Section 2.3

The synchrotron scenario alleviates considerably the design considerations for the injector linac, but requires careful examination of design issues which are peculiar to synchrotrons and not to accumulator rings. In section 2.4, a summary is presented of the basic design issues.

2.3 Neutron Yield

The parameter solution adopted here rests on the use of a relatively high proton beam energy to enhance the neutron production. The interest in higher proton energy stems from the experimental observations that the total neutron yield, Y_n , of low energy ($E \leq 15$ MeV) evaporation spectrum neutrons per incident proton increases approximately linearly with incident proton energy, E_0 . These data are shown in Fig. 2.-1 where the Dubna data of Vasilkov², et al. up to 8.1 GeV proton energy are shown together with the older ORNL-Chalk River data of Fraser et al.³ for $E_0 \leq 1.5$ GeV. At higher energies the neutron yield clearly drops below a linear extrapolation, but at lower energies it is reasonably represented by $Y_n \propto E_0$ neutrons/proton. With beam power given by $P = I E$ it is clear that the beam power is proportional to the total neutron yield, and is thus an appropriate parameter to characterize the merit of a neutron source.

From the user's point of view, however, the figure of merit is not necessarily the total yield since additional neutrons result from the hadron cascade and the neutron source region increases both transversely and longitudinally within the target volume with increasing E_0 . The experimenter benefits only from maximum flux at a given longitudinal position Z along the target where the neutron beamline emerges approximately perpendicular to the proton beam direction. Therefore the integrated $E \leq 20$ MeV neutron flux at the target surface was computed as a function of longitudinal position Z along a solid 20 cm diameter tungsten target for two limiting proton energies, 1 and 10 GeV, using the Monte Carlo code⁴ LAHET. Similarly, the neutron flux was computed as a function of radial position from the surface of the target, at $z = 10$ cm. The results are shown in Fig. 2.-2 and Fig. 2.-3, respectively, essentially confirming the approximate linear relation between neutron yield and proton energy noted above. Although the code has not been validated above $E \approx 3.9$ GeV and must be used with caution for detailed comparisons at higher energy, it is observed that the $E_0 = 10$ GeV neutron source has a greater longitudinal extent, as expected, but a lower yield than a 1 GeV source of ten times the proton intensity for small $Z \leq 14$ cm. With a segmented target and higher proton energy, more segments could be provided and thus more gaps made available for "flux trap" moderators, which appear to be the most desirable neutron sources in terms of least high energy neutron contamination. In the present target design a 3-segment, 7.5 cm per segment (for the first two segments) target with two "flux trap" gaps has been adopted.

It is evident from the above that a higher proton beam energy is favorable in increasing, for constant beam current, the usable neutron flux.

A lower bound on the choice of proton beam energy may be established by considering the tolerable energy deposition density in the target entry window or the target structure proper. Lower energy loss (MeV/g/cm²) is obtained for a typical window material, such as aluminum, or target material, such as lead, for proton beam energies $E_0 > 1.5$ GeV. In a comparison of peak power density deposited in a 10 cm diameter, 60 cm long Pb target, it was found⁵ that the value for a 5 MW proton beam with $E_0 = 3$ GeV is a factor of two less than for an $E_0 = 1$ GeV beam, i.e. 3.75 kW/cm³ instead of 7.7 kW/cm³. Similar conclusions were reached⁶ in comparing a 0.57 GeV source to a 3.5 GeV source. Hence, it is evident that, from the point of view of tolerable energy deposition density in the target or target window, E_0 should be > 1 GeV.

Taking the above-cited factors into account, the evident range for optimum proton beam energy is $1 \leq E_0 < 10$ GeV. With further consideration of competing technical parameters and cost factors, a parameter set was adopted encompassing 2 FCS's with maximum proton beam energy of 3.6 GeV and proton intensity per FCS pulse of 1.45×10^{14} p/p.

2.4 Accelerator Design Issues

There are distinct design aspects to be considered concerning acceleration of intense proton beams in fast cycling synchrotrons. The most important one is the choice of injector 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 experience 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 30 Hz synchrotrons running 180° out of phase. Synchrotrons with repetition rates of 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 listing 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 particularly important to synchrotrons because of the low injection energy. The indicative parameter is the depression $\Delta \nu$ of the betatron tune give by

$$\Delta \nu = \frac{Nr_p}{2\beta^2\gamma^3 B\epsilon}$$

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, the cited equation relates closely injection energy, beam intensity and beam dimension, which also determines the gap of the magnets and therefore their feasibility and cost. The interdependence of parameters is further indicated in Figure 2.-4 where the chamber aperture is given versus injection energy for one or two fast cycling synchrotrons. The choice of two 3.6 GeV synchrotrons together with the 600 MeV linac requires a magnet gap close to 15 cm, which is considered both feasible and affordable.

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 experience with the completed facility will permit determination of the actual $\Delta \nu$ limit in the present case. This would suggest a staging during construction when only 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. Also it is conceivable that by then the relative cost and performance of linac versus synchrotron will be better known and one will either proceed to the construction of the second synchrotron or to the extension of the linac to 900 MeV, which is large enough, according to Figure 2-4, to allow doubling of 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 in the second stage.

The 30 Hz synchrotron repetition rate can be obtained only with resonant sinusoidal excitation of the magnets. The variation in energy and therefore variation of the guide field is large, hence a limit on (dB/dt) was adopted, as $(dB/dt)(\max) < 50 \text{ T/sec}$. This has direct influence on the design of the magnets, its power supply and, in a particular way, the vacuum system. In turn, the maximum field value imposes a limit on the smallest total bending length and therefore on the overall synchrotron circumference which was then derived to be 362 m.

The large (dB/dt) value induces large eddy currents in a metallic vacuum chamber. The power dissipated would be too large to be disposed of by water cooling. Here a ceramic vacuum chamber with metallic strips to avoid electromagnetic interaction between the beam and the magnet lamination has been adopted.

The required ring acceleration system has no equivalent in an accumulator ring. The large beam intensity requires a balanced distribution of power between beam and rf cavities. The peak power delivered to the beam is 7 MW and the average power approximately 2 MW. The choice of harmonic number $h = 2$ eliminates rf induced instabilities and takes advantage of demonstrated frequency and voltage rf amplifier and ferrite devices.

Because of the acceleration and the absence of a constant field front-porch in the cycle, rf capture of beam required detailed numerical studies. To reduce beam losses during capture to less than 0.1% required that the number of turns to be injected is limited to 300 turns.

To achieve this low loss behavior at injection demands prebunching of the beam at the source to 50% of the rf wavelength at injection. This sets then the source peak current to 100 mA.

Clearly, the scenario of fast-cycling synchrotrons does present challenging issues requiring careful examination. The average beam current needed is one to two orders of magnitude above what has been achieved so far.

2.5 Design Scenario of the Facility

2.5.1 Summary

Schematically, the design scenario is shown in Figure 2.-5. A summary of the main parameters is given in Table 2-3. As a compromise between proton beam intensity requirements and accelerator size we have chosen a final kinetic energy of 3.6 GeV which is sufficient to ensure an energy conversion to neutrons close to 100% and does not demand long absorbing targets. We have chosen also 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 to generate a train of beam pulses at 60 Hz. The extracted beam pulses from the fast cycling rings are coalesced into a single external beam channel and then fast-switched onto two independent target stations T1

and T2 at a rate $R_1 + R_2 = 60$ Hz, for example $R_1 = 10$ Hz, $R_2 = 50$ Hz. If directed to a single, 60 Hz target, the average beam intensity on the target would be 1.4 mA (8.7×10^{15} p/sec).

The choice of the linac energy, 600 MeV, is a compromise between the cost of the linac and the cost, as related to ring vacuum chamber aperture, of the bending magnets in the synchrotrons. Indeed, the most severe limitation to the beam intensity is the depression of the betatron tune due to the space-charge forces. These forces can be controlled by using a larger beam size and therefore a larger magnet gap.

The operating scenario is as follows. Beam pulses of negative ions (H^-) 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 a time. Injection occurs by charge-exchange, that is by letting the negative ions be stripped of their electrons when traversing a foil placed at the location of injection. The beam is then accelerated to the final energy of 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 at the repetition rate of 30 Hz. 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. This procedure creates a beam pulse sequence of the desired intensity and duration 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 in the synchrotrons. The beam response to the space-charge effects and to the process of multi-turn injection cannot be assessed a-priori to a high degree of accuracy. Only experience with the actual accelerator complex will provide details of the beam performance.

Table 2-3. General Parameters of the Spallation Neutron Source

Beam Power	5	MW
Final Proton Kinetic Energy	3.6	GeV
Average Proton Beam Intensity	1.4	mA, on Target
Number of Synchrotrons	2	
Synchrotron Repetition Rate	30	Hz
Number of Protons/pulse	1.45×10^{14}	per Synchrotron
Synchrotron Circumference	363	m
Beam Pulse Length on the Target	< 1.24	μ s
Linac Energy	600	MeV
Linac Repetition Rate	60	Hz

A conceptual site arrangement of the principal SNS elements is given in Fig. 2.-6.

2.5.2 Linac Injector

The layout of the room temperature Linear Accelerator is shown schematically in Fig. 2.-7. Its principal parameters are given in Table 2-4.

The preinjector makes use of a negative-ion source, offset from ground by 50 kV. The beam is injected into 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 150 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.

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. The final peak current reaches values in excess of 400 mA.

The critical Linac parameters are its transverse emittance magnitude (0.4π mm mrad, normalized, rms) and its full momentum spread ($1.5 \cdot 10^{-3}$). These values allow the capture of the full intensity beam in the relatively large synchrotron betatron acceptance and momentum aperture.

Table 2-4. Summary of Linac Parameters

Repetition Rate	60	Hz
Pulse Duration	0.5	ms
Duty Cycle	2.8	%
Source Current	120	mA
Average Pulse Current	100	mA
Peak Current in Exit	> 400	mA
Peak Power to Beam	30	MW
Peak Power to rf Structure	30	MW
Total Peak Power	60	MW
Average Power	1.7	MW
Emittance (normalized)	0.4	π mm mrad
Momentum Spread	$1.5 \cdot 10^{-3}$	(full width)
RFQ: frequency	350	MHz
final energy	2.5	MeV
DTL: frequency	350	MHz
final energy	70	MeV
CCL: frequency	700	MHz
final energy	600	MeV
rf@injection in Synchrotrons	1.31	MHz

2.5.3 The 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 locating the accelerator RF cavities. We have chosen as a compromise a superperiodicity of two, with each superperiod made of an arc and an insertion as shown in Figure 2.-8. 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. For this purpose, we have 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.

Another important consideration, to take into account for determining the size of 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 50 T/s. This in turn assigns the maximum value of the bending field and of the circumference of the synchrotrons.

A summary of the synchrotron principal parameters is given in Table 2.5. A more detailed description and parameter enumeration is presented in Section 4.3.

Table 2.5. Summary of Synchrotron Parameters

Ring circumference (m)	363
Lattice structure	FODO
Number of cells	32
Number of dipoles/quads	48/64
Bending field (T)	0.19-0.69
Field variation (max) (T/s)	47
γ Injection/Ejection	1.64/4.84
Transition energy, γ_t	6.28
Betatron tunes, ν_x/ν_y	7.8/7.8
Chromaticity, ζ_x/ζ_y	-9.1/-9.3

The transition energy has a value large enough so that the whole acceleration cycle is performed well below the transition energy, and it never crosses this value. 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.

The distribution of the various functions is indicated in Figure 2.-8. Injection occurs in the central empty FODO cell of an insertion, and extraction is done in the diametrically opposite location. The RF cavities are distributed symmetrically around the ring in four locations where the dispersion is small. Locations with large dispersion are also available for beam collimators and scrapers.

A most severe limitation of the beam performance is space charge at injection. To cope with this, one allows the beam to grow to a sufficiently large size. Indeed, space-charge forces cause a tune-depression Δv which can be calculated. We require that the tune-depression Δv does not exceed the value 0.25; this in turn sets the beam emittance for the given beam intensity. A summary of the beam parameters at injection is given in Table 2-6.

Each turn injected has a period of 1.53 μ s and carries 4.77×10^{11} protons. To reach the design intensity $N = 1.45 \times 10^{14}$ one needs therefore the injection of 303 consecutive turns. To maintain the total beam within the space-charge limit, the final beam emittance area grows to 200 π mm mrad, considerably less than the available betatron acceptance of 320 π mm mrad.

There are two possible methods of injections: (i) each turn is injected exactly on the center of the rf buckets, which is obtained by adjusting the energy of the beam from the linac with the magnetic field ramp; and (ii) the energy of the beam from the Linac is kept constant during injection, in which case each turn is injected at a different distance from the rf bucket center, filling the buckets from the bottom up. With either method, the beam pulses are prechopped to about 50% the full length of the RF bucket.

Table 2.6 Beam Parameters at Injection

Injection Energy	600	MeV
Revolution Period	1.53	μ s
Number of Turns Injected	303	
No. of Protons per Turn	4.77×10^{11}	
Total Number of Protons	1.45×10^{14}	
Total Momentum Spread	0.8	$\pm\%$
Full Betatron Emittance	200	π mm mrad
Normalized Emittance	260	π mm mrad
Betatron Acceptance	320	π mm mrad

We have opted for an accelerating system harmonic number $h = 2$, i.e. 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. Principal rf parameters are listed in Table 2-7.

It is seen that a peak voltage per turn of 800 kVolt is required. This can be obtained with

eight cavities, each with two gaps operated independently from each other, and a peak voltage of 50 kVolt per gap. There is a considerable amount of power to be delivered to the beam. Each cavity absorbs a total of about 1 MW.

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

Table 2.7 Parameters of the RF System

Harmonic Number, h	2	
RF frequency at injection	1.31	MHz
at extraction	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	800	kVolt
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	
Length of a Cavity	3.6	m
Peak Voltage per Gap	50	kVolt
Number of Amplifiers/Cavity	2	
Amplifier Peak Power	500	kW

2.6 Target/Moderator Systems

2.6.1 Introduction

The major performance related objective for the BNL Pulsed Spallation Neutron Source (PSNS) target and moderator system is to provide the maximum flux possible for experiments. In addition, there should be an ability to tailor the flux spectra and time-structure characteristics to allow optimal utilization of the spallation neutrons. These objectives impact the target geometry and materials, the selection of moderator/reflector, and the arrangement of the beam lines and local moderators.

The design of the target and moderator system for the PSNS was based on a series of trade studies that were performed to evaluate the impact of a number of possible design options on engineering feasibility and expected performance. In addition to evaluating the neutron production and resultant fluxes, the design efforts addressed engineering details, including energy deposition

and heat removal from the target and related components, safety, handling, shielding, neutron utilization, etc. The parameters considered in the design studies were based on examination of current and proposed spallation targets, and extensive experience at BNL in the design of accelerator-driven targets and reactor systems obtained in connection with the Accelerator Production of Tritium (APT), Space Nuclear Thermal Propulsion (SNTTP), and other programs.

Some of the design options considered were:

Proton Energy	1 - 10 GeV
Target Material	Tungsten, Uranium, Lead
Structural Material	Stainless Steel or Aluminum
Coolant	Sodium, Lead, Helium, Heavy Water
Geometry	Rods, Particles

2.6.2 Description of Baseline Target/Moderator Configuration

The baseline BNL PSNS target is shown schematically in Figure 2.-9. It consists of three target regions, separated by two void zones known as "flux traps." Slab moderators are positioned opposite the flux traps, and above and below the "solid" target sections; these latter moderators are known as "wing moderators." Each moderator block has associated with it one or two beam tubes as shown in Figure 2.-10. The energy spectrum of the emitted source neutrons is modified by the slab moderators, and the neutrons then travel through the beam tubes to the various experimental end-users. Liquid hydrogen, deuterium and methane, and light water are candidates for the beam-tube slab moderators. The entire target, moderator blocks and beam tubes is embedded in a "moderator/reflector" region. In the present studies the surrounding moderator has been assumed to be liquid water, but in principal could be any moderator material (e.g., beryllium, plastic, etc.) that can survive the temperature and radiation environment. This region could also contain heavy materials such as nickel, and thereby serve as part of the reflector/shield structure. While water has been assumed for the present configuration because it eases target and beam tube handling, inspection, and repair, the choice is still open. In some situations it may be desirable to de-couple the flux in the beam tube from that in the surrounding regions, thereby changing the time structure of the neutron pulses available to experimenters. In these studies, decoupling was achieved with a thin cadmium layer on selected beam tubes and associated slab moderator blocks.

A distinguishing characteristic of the target regions in Fig. 2.-9 is that each represents a particle bed of tungsten spheres 1 - 2 mm in diameter. The spheres (particles) are retained between two porous walls (frits), and are cooled directly by heavy water which flows from an inlet plenum into the particle bed through the "cold frit." After passing through the bed, the coolant exits through the "hot frit" into an outlet plenum and then flows to a heat exchanger.

The particle bed approach was selected for the target because the performance objectives discussed above, along with the results of trade-studies performed at BNL and elsewhere suggest that the "optimum" target should be a balance between sufficient size to maximize the neutron

production per proton, and a configuration that maximizes the leakage of the neutrons out of the target to where they can be used productively. This implies a compact target(s), which in combination with a relatively high proton beam power results in high power densities. The excellent heat transfer characteristics of a particle bed configuration (resulting from a very high surface-to-volume ratio), make it particularly well suited for these conditions.

The parameters for the baseline target are given in the following table

Table 2.8 Parameters for Target/Moderator System

• Description:	
Split Particle Bed with 2-Flux Traps	
Tungsten Spheres ~1 - 2 mm OD	
Stainless Steel Frits	
External Neutron Multiplier (lead or beryllium)	
Heavy Water coolant	
• Thermal-hydraulic Operating Conditions	
Coolant Operating Pressure (Bar)	4 - 6
Coolant Outlet Temperature (°C)	80
Particle Surface Temperature (°C)	<116
Coolant Saturation Temperature (°C)	144
• Energy-Integrated Neutron Flux @ 5MW steady state	
Maximum Flux on Surface of Target	$\sim 7 \times 10^{14}$ n/cm ² -sec

The above results show that the expected operating temperatures and pressures are modest (as are the required coolant flow rates), with adequate margins to coolant boiling and tungsten melting ($T_{mp} = 3410$ °C).

The major safety issues associated with the target involve material behavior (oxidation, fatigue and mechanical shock), and heat removal in the event of an upset.

As noted in Section 2.5, the targets are expected to operate at a frequency of 10 -50 Hz; therefore the particles, and to a lesser extent the frits will be subjected to a varying temperature environment, which implies an undulating stress. In addition, the accelerator is able to produce its full beam power almost instantaneously, thus the thermal stress will be applied extremely rapidly. The concerns associated with these issues are fatigue failure of the target after a short operating time, and intolerable shock loads. These issues are both dependent on the temperature gradient generated across the components. Although the particles operate at a high power density, this effect is not expected to be serious since the particles are small, and tungsten is a good conductor; the resulting temperature rise is less than one degree across the particle. The resulting thermal stress is also extremely small (approximately 150 psi) and well within the limitations of tungsten. Furthermore, the rate and frequency at which the stress is applied should not cause any fatigue or shock load problems.

The other material issue associated with tungsten is the possibility of oxidation in the event of an over-temperature transient. Despite the high melting temperature of tungsten it is prone to attack by oxygen (tungsten oxide sublimates at 800 - 1000 K). This issue has not been quantified as yet; however, control of the free oxygen content of the coolant through a recombiner may be required.

The choice of tungsten and stainless steel as the target materials, and the low operating temperatures (approximately 400K max.) result in large thermal margins. Thus, these materials are very tolerant to under-cooling transients, such as pipe breaks or leaks, and should allow sufficient time for the back-up cooling system to operate. Several back-up systems are being considered. The most likely candidate is a system consisting of a large pressurized source of back-up cooling water. This system would be separated from the primary system by check valves, and automatically activated in the event of a drop in primary system pressure. Analyses to verify this design are still required. It should be noted that the efficient heat removal possible with a particle bed will also enhance the removal of post-accident heat from a target. Finally, light water can be used to provide additional back-up cooling since there are no criticality concerns.

References - Section 2

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Fig. 2.-1. Neutron Yield for a lead cylinder of 20 cm diam. x 60 cm , bombarded by protons

Fig. 2.-2 , Neutron Flux from Protons on Tungsten Target , Y vs Z
($E_n < 20$ MeV)

Fig. 2.-3 , Neutron Flux from Protons on Tungsten Target , Y vs R
($E_n < 20$ MeV; at $z = 10$ cm)

Fig. 2.-4 , Dipole Magnet Gap vs Linac Energy

Fig. 2.-5 , Design Concept of the Spallation Neutron Source

Fig.2.-6, Pulsed Spallation Neutron Source Conceptual Site Arrangement

Fig. 2.-7 , Layout of the 600 MeV Linac

Fig. 2.-8 , Magnet Lattice Structure, Fast Cycling Synchrotron
[Pulsed Spallation Neutron Source]

Fig. 2.- 9 , Spallation Target and Moderator Configuration

Fig. 2.-10 , Arrangement of Slab Moderators and Beam Tubes

3. USER INSTRUMENTATION

As noted, the major focus of neutron research today is on the atomic-scale properties of condensed matter with emphasis increasingly being placed on the characterization of materials of either technological importance or of particular interest to the life sciences community. Suggested sets of instruments for the two target stations are listed in Tables 3.1 and 3.2. The instruments were selected to be broadly representative of the current interests of the research community. Most of them employ time-of-flight for either monochromation, energy analysis or both processes. Those that do not were included because they play particularly important roles in either condensed matter or fundamental physics research and currently have no counterparts operating on time-of-flight principles.

As will be further indicated in Section 7, "Experimental Facilities", the beam layouts considered here would accommodate up to 16 beam lines in each experimental hall. In the enumeration of suggested instruments (Table 3.1 and Table 3.2) a number of beam lines have deliberately been left open to allow for future expansion of the experimental program. Depending upon the needs of the research community, these beamlines could be used for residual stress analysis, ultra-cold-neutron spectroscopy, Brillouin scattering studies, neutron tomography, neutron radiography, neutron depth profiling, neutron instrument development or some other application not yet foreseen. It is also noted that the proposed moderator configuration at the 10 Hz station would be compatible with installation of a fifth, horizontal, liquid-deuterium-filled flux-trap moderator supplying neutrons to a vertical beamline for a dedicated ultra-cold neutron facility.

Table 3.1
Suggested Instruments for the 50 Hz Target

Elastic Scattering Instruments	Number	Moderator	Q-Range (Å⁻¹)	Energy Transfer Range (meV)
High Intensity Powder Diffractometers	2	CH₄*	0.5-20	0
Single Crystal Diffractometers	1	CH₄*	0.2-40	0
Laue Diffractometer	1	CH₄*	0.2-40	0
Medium Resolution Small Angle Scattering Spectrometers	2	CH₄*	0.01-5	quasi-elastic
Liquids and Amorphous Solids Diffractometers	2	CH₄*	0.1-100	quasi-elastic
Inelastic Scattering Instruments				
eV Spectrometer	1	H₂O	0.2-200	0-2000
Large Energy Transfer Spectrometer	1	H₂O	0.2-20	50-2000
Direct Geometry Time-of-Flight Spectrometer	1	H₂O	0.2-50	20-1000
Time-Focussing Time-of-Flight Spectrometer	1	H₂O	0.2-50	2-1500
Backscattering Spectrometer	1	CH₄*	0.1-5	0-10
Spin Echo Spectrometer	1	CH₄*	0.1-5	0-1
Triple-Axis Spectrometers	2	H₂O	0.1-15	0-50

*or bilayer H₂O/H₂

Table 3.2
Suggested Instruments for the 10 Hz Target

Elastic Scattering Instruments	Number	Moderator	Q-Range (Å ⁻¹)	Energy Transfer Range (meV)
High Resolution Powder Diffractometer	1	CH ₄ *	0.2-10	0
Liquids and Amorphous Solids Diffractometer	1	CH ₄ *	0.1-50	quasi-elastic
High Resolution Small Angle Scattering Spectrometers	2	H ₂	0.001-1	quasi-elastic
Laue Diffractometers	2	H ₂	0.05-1	0
Reflectometers	2	H ₂	0.002-0.5	0
Interferometer	1	CH ₄ *		0
Inelastic Scattering Instruments				
Direct Geometry Time-of-Flight Spectrometer	1	CH ₄ *	0.2-20	1-30
High Resolution Backscattering Spectrometer	1	H ₂	0.03-2	0-10
Spin Echo Spectrometer	1	H ₂	0.03-2	0-0.5

* or bilayer H₂O/H₂

4. ACCELERATOR SYSTEMS

4.1 Introduction

As indicated in the foregoing, the conceptual design approach for the proton accelerator is based on the objective of 5 MW proton beam power, $\approx 1\text{-}2\ \mu\text{sec}$ pulse current duration and 60 Hz maximum repetition rate. Optimization of the commensurate accelerator system parameters led to favoring higher beam energy paired with lower maximum beam intensity. This is achieved with the choice of $E(\text{max}) = 3.6\ \text{GeV}$, with use of two fast cycling synchrotrons (FCS's) operating with excitation currents 180° out of phase, at a combined repetition rate of 60 Hz, with maximum beam current per Fast Cycling Synchrotron (FCS) of 1.45×10^{14} p/p. (Note that with use of a single FCS with $E(\text{max}) = 1\ \text{GeV}$ the required beam current would be 10^{15} p/p, essentially beyond present state-of-the-accelerator art.)

In general, the design approach for the proton accelerator has been towards usage of tested, state-of-the-art systems. Overall reliability and minimization of current loss anywhere in the sequence of accelerator components were major items of concern. It should be noted also that the use of two FCS's provides potentially for significant enhanced proton source "up-time", inherently only at a cost of temporary loss of a factor of two in proton beam intensity.

In the following, the principal accelerator systems are covered, as outlined below.

- 4.2 Linear Accelerator
 - 4.2.1 Parameters and Major Components
 - 4.2.2 H- Ion Source
 - 4.2.3 Chopping and Matching to the RFQ
 - 4.2.4 RFQ and Associated Transport
 - 4.2.5 Drift Tube Linac (DTL)
 - 4.2.6 Side Coupled Linac (SCL)
 - 4.2.7 RF Power Systems
 - 4.2.8 RF System Transient Response
 - 4.2.9 Proton Injection Line for the PSNS
 - 4.2.10 Linac Vacuum Systems
 - 4.2.11 Linac Diagnostic Instrumentation
- 4.3 Fast Cycling Synchrotrons (2 FCS)
 - 4.3.1 Overview and Basic Parameters
 - 4.3.2 Magnetic Lattice
 - 4.3.3 Transverse Losses from H- Multiturn Injection
 - 4.3.4 RF Capture Efficiency in the PSNS Synchrotrons
 - 4.3.5 RF System
 - 4.3.6 Low-Level RF Beam Control
 - 4.3.7 Ring Impedance, Beam Instabilities
 - 4.3.8 Beam Extraction
 - 4.3.9 Beam Scraping and Loss Localization
 - 4.3.10 Synchrotron Magnet Systems
 - 4.3.11 SNS Main Ring Magnet Power Supplies
 - 4.3.12 Vacuum System
 - 4.3.13 Ring Diagnostic Instrumentation
 - 4.3.14 Beam Transport FCSs - Targets

4.2 Linear Accelerator

4.2.1 Parameters and Major Components

The injector for the fast cycling synchrotrons must deliver a 600 MeV H^- beam with a peak current of 100 mA and a repetition rate of 60 Hz. The required beam pulse width is 450 μs , and the fast beam chopper has a 50% duty factor during the pulse for minimization of longitudinal beam losses at injection into the synchrotrons, so the average beam current is only 1.35 mA. These parameters are comfortably within present linac technology. This average current is similar to that at LAMPF, where beam loss is low enough to permit hands-on maintenance of the accelerator. Since this will be a new linac, which will be designed using improved codes, beam loss should not be a problem.

Below, a "first pass" linac design is presented. Improvements are still to be made in the design of the various subsystems. Figure 4.2-1 shows schematically the proposed linac, and the main beam parameters of the various stages are given in Table 4.2-1. In the choice of frequencies there are many tradeoffs, but the frequency of 350 MHz, chosen for the RFQ and DTL, is about the lowest frequency at which klystrons are available. Emittance growth in the DTL would be larger at lower frequency, while at higher frequencies the structures (and apertures) become smaller, making this high beam current, relatively high duty factor linac more difficult with respect to beam losses and structure cooling. A frequency of 700 MHz was chosen for the SCL. This allows the SCL to have relatively large apertures, and klystrons around this frequency are readily available. Details on the various stages will be given in the following sections.

4.2.2 H^- ion Source

A Penning surface plasma H^- source, based on the LANL 4X source,¹ meets the requirements for the linac. This source has produced 150 mA of H^- at the 3% duty factor required, and with an excellent emittance ($\epsilon_{norm,rms} = 0.2 \pi$ mm-mrad). The source aperture diameter is 5.4 mm, and the arc parameters are 180 A, 100 V. This source uses cesium to enhance H^- production, and has an electron-to- H^- ratio less than 1. The 50 kV extraction voltage is higher than where it has been operated. There is extensive experience at BNL in the reliable operation of a surface plasma source at 100 mA and 35 kV for the AGS injector, although not at this duty factor. Therefore, some R&D will be required to design a reliable extractor at this duty factor. It has been estimated that the lifetime of the cathode will be approximately 4 weeks, which is acceptable since the time to change sources can be made short.

4.2.3 Chopping and matching to the RFQ

It is necessary to chop the beam before injection into the synchrotrons, since otherwise beam losses in the synchrotrons at injection would be unacceptable. With a revolution period at injection of 1.53 μs , and a harmonic number $h=2$, the chopping period will be 765 ns. Conservatively, it is

Table 4.2-1
LINAC BEAM PARAMETERS

H SOURCE

Type	Penning surface plasma source
Current	150 mA
Energy	50 keV
Emittance	0.2π mm mrad (normalized, rms)

RFO

Frequency	350 MHz
Energy	
Input	50 keV
Output	2.5 MeV
Current	
Input	125 mA
Output	105 mA
Emittance	
In, transverse	0.2π mm mrad (normalized, rms)
Out, transverse	0.23π mm mrad (normalized, rms)
Out, longit.	0.162π MeV-degrees (rms)

DTL

Frequency	350 MHz
Energy	
Input	2.5 MeV
Output	70 MeV
Current	
Input	100 mA
Output	100 mA
Emittance	
In, transverse	0.23π mm mrad (norm., rms)
Out, transverse	0.27π mm mrad
Out, longit.	0.418π MeV-degrees (rms)

SCL

Frequency	700 MHz
Energy	
Input	70 MeV
Output	600 MeV
Current	
Input	100 mA
Output	100 mA
Emittance	
In, transverse	0.27π mm mrad (norm., rms)
Out, transverse	$0.35 \times 0.42 \pi$ mm mrad (norm., rms)
Out, longit.	0.800π MeV-degrees (rms)
$\delta p/p$	$\approx 1.5 \times 10^{-3}$ (full width, full beam)
(before energy compressor)	

*The output emittance of the SCL will be improved in the next design iteration.

assumed that the chopping duty factor will be 50%, meaning that 383 ns wide beam "micropulses" will be delivered at a 1.3 MHz frequency. If one can demonstrate efficient injection into the synchrotron with wider micropulses, the peak linac current required can be reduced accordingly.

It is convenient to do this beam chopping at as low an energy as possible, since the voltages needed for chopping can be lower and one does not have to worry about the power of the dumped beam. However, there are issues that make the chopping less straightforward than one might expect. At BNL, we have demonstrated the problems with chopping a space charge neutralized beam electrostatically at low energy, when the beam current is high enough that space charge is important. The rejection of the chopped beam was poor, and the emittance of the unchopped beam was badly distorted due to space charge effects. Chopping after the RFQ, at 2.5 MeV, has the problem that the extra space required for chopping in this transport section can result in a significant emittance growth (factor of 2). We propose to match the high current beam from the source to the RFQ with a series of electrostatic quadrupoles, as is being tested at the University of Maryland.² An example of matching a round beam out of the source into the acceptance of an RFQ, taken from Reference 2, is shown in Figure 4.2-2. This type of transport keeps the beam unneutralized, while at the same time it is able to handle high beam currents. A modification to incorporate beam chopping directly into this structure can be made fairly easily. The voltages on quadrupoles will be separated to allow a deflecting voltage to be superimposed on the focusing voltages for beam chopping. Rise and fall times of 10 ns on the beam micropulses should be possible. We assume that 125 mA, out of the 150 mA ion source output, can be matched into the RFQ acceptance.

Two alternative methods for beam chopping will be considered as backups. First, one could match the beam between the source and RFQ with magnetic solenoids, as has been successfully used at BNL. The beam would then be space charge neutralized, and chopping would be done by modulating the energy of the beam so that it falls outside the energy acceptance of the RFQ. The second alternative would be to chop after the RFQ. Since the beam must be kept small to prevent emittance growth, a long drift space for chopping would be unacceptable. Therefore, one could build a series of short deflecting plates, alternating with quadrupole lenses, to chop the beam without long drift spaces.

The difficulties associated with cleanly accelerating a fast chopped beam will be addressed in section 4.2.8.

4.2.4 RFQ and Associated Transport

The RFQ will be a 350 MHz, 4-vane structure, accelerating the H⁻ beam from 50 keV to 2.5 MeV. The parameters of this RFQ are given in Table 4.2-2. The PARMTEQ output plot for the RFQ is shown in Figure 4.2-3. The transport line between the RFQ and DTL will be kept as short as possible to minimize emittance growth. A matching section with 2 bunchers and 4 quadrupole magnets, similar to the SSC linac design³, can be used, keeping the RFQ-to-DTL distance less than 1 m.

Table 4.2-2
RFQ PARAMETERS

Frequency	350 MHz
Input energy	50 keV
Output energy	2.5 MeV
Length	2.50 m
Peak rf field	18.7 MV/m (2.0 Kp)
Vane voltage	91 kV
Bore radius	3.5 - 2.2 mm

4.2.5 Drift Tube Linac (DTL)

The 350 MHz DTL can be modeled after the SSC 427 MHz design⁴, with appropriate changes to handle the higher current and duty factor. Based on currently available klystrons, a 350 MHz klystron operating at a peak power of 4 MW is very reasonable at our 3% rf duty factor and 500 μ s rf width. The 70 MeV DTL is therefore divided into 4 tanks, each requiring less than 4 MW of rf power, including 100 mA peak beam loading. The accelerating field is ramped in the first tank, and uniform in the other tanks. Table 4.2-3 gives parameters of the DTL. Figure 4.2-4 shows an output of a 1000 particle PARMILA run of this DTL, and Figure 4.2-5 shows a TRACE3D plot of the beam envelope through the DTL, using emittances equal to 5 times the rms values calculated at the RFQ output. The maximum 5rms beam size is $\approx$ 20% of the full aperture.

All quadrupoles in the DTL are identical, and they are close to those used in the SSC DTL, which are permanent magnet quadrupoles.⁴ These magnets are made of $\text{Sm}_2\text{Co}_{17}$, a material shown to have an excellent resistance to radiation induced loss up to a fluence of 2.6×10^{18} n/cm².⁵ Any beam loss in the DTL is most likely to occur at injection, where the beam energy is low, and neutron production by protons in copper or iron is very low. After initial matching into the DTL, any reasonable estimate for beam loss (even losses as high as 10^{-3} /m) results in the lifetime of these permanent magnets being much greater than the lifetime of the accelerator. The present design does not preclude the use of pulsed electromagnetic quadrupoles, should further experimental results on permanent magnet materials change the above conclusions.

Power from the klystron is split and fed into the DTL at the 1/4 and 3/4 point along the length of each of tanks 2 - 4. In tank 1, where the gradient is ramped, the feed points will be adjusted appropriately. A PFN and stepup transformer will be used for the klystron modulator.

Table 4.2-3
DTL PARAMETERS

Frequency	350 MHz
Input energy	2.5 MeV
Output energy	70 MeV
Synchronous phase	-30 deg.
No. of tanks	4
No. of cells	151
Bore radius	1 cm
Quadrupoles	
Type	Sm ₂ Co ₁₇
Focusing	FODO
Length	4.0 cm
Gradient	13.27 kG/cm

	<u>T1</u>	<u>T2</u>	<u>T3</u>	<u>T4</u>
E ₀ (MV/m)	2.4-3.5	3.5	3.5	3.5
E _{out} (MeV)	13.7	33.0	51	70.3
Length (m)	5.30	7.52	7.42	7.93
P _{Cu} (MW)	0.89	1.6	1.6	1.7
P _{tot} (MW)	2.0	3.5	3.43	3.59

4.2.6 Side Coupled Linac (SCL)

The SCL is the major cost item in the linac, so a partial cost optimization was done, particularly using information from the recently designed SSC and FNAL side coupled linacs. The input and output energies, and SCL frequency were fixed, and an optimization was done on the accelerating gradient of the structure. RF costs were calculated assuming a 5 MW, 700 MHz klystron could be made at our 3% duty factor. (The TH2104A operates at 5 MW, 3% df, 600 μ s pulses, at 1296 MHz). Operating costs over 10 years were also included in the optimization. Figure 4.2-6 shows the relative cost vs. gradient, showing a shallow minimum in E₀T at around 3.8 MV/m. At this gradient, the structure power is an acceptable 11 kW/m. In the present design, we have chosen a slightly more conservative effective gradient, with E₀T varying from 3.5 to 2.6 MV/m. This does not increase the cost significantly, and makes the structure somewhat longer, but reduces the number of klystrons required and reduces the copper power per meter. In addition, reducing the gradient, rather than the number of cells per module, to keep the power per module constant, gives a periodicity which is very desirable for the beam optics.

A side-coupled structure was chosen, as is used at LAMPF, FNAL, and at the SSC. The structure has the same modularity as the FNAL 800 MHz SCL⁶, with 16 cells per tank, and 4 tanks per module. For ease of manufacturing, all cells in a tank are the same length, designed for an average β through a tank. There is a spacing of $3\beta\lambda/2$ between tanks and also between modules.

Electromagnetic quadrupoles which are very similar to the FNAL design are used in every intertank/intermodule space. This periodicity gives the linac very good transverse and longitudinal optics. One klystron is used to power each module, with a total of 24 klystrons. Figure 4.2-7 shows a typical linac module. The SCL parameters are given in Table 4.2-4. The FNAL shunt impedance vs. β , derated due to the frequency difference of the two structures, was used in the power calculations. The SCL has a total of 1536 accelerating cavities and a total length of 248m.

Figure 4.2-8 and 4.2-9 show an output of a 1000 particle run of the SCL beam dynamics, and Figure 4.2-10 shows a TRACE3D plot of the beam envelope through the SCL, using emittances equal to 5 times the rms values calculated for the DTL output. The maximum 5rms beam size is $\approx$ 40% of the full aperture. This design is not yet optimum, and exhibits a fairly large transverse emittance growth in the first module. This will be improved in later designs, primarily by ramping the gradient in the first two modules.

Power from one klystron goes through three 3 dB splits and is fed into the center of each tank of a four tank module. As will be discussed in Section 4.2.7, a bridge coupler design could give rise to characteristics which would result in problems with the beam compensation required for beam loading and fast beam modulation. Splitting the power in this way has the extra advantage of reducing the power at each rf vacuum window. If the bridge coupler response is not found to be a problem, power can be split with a single 3 dB splitter and fed into bridge couplers situated between tanks 1 & 2 and tanks 3 & 4 of a module.

4.2.7 RF Power Systems

The radiofrequency power requirements for the linear accelerator are given in Table 4.2-3 for the drift tube linac and Table 4.2-4 for the side coupled linac. With beam chopping, the actual rf duty factor at the 4-5 MW level is less than 2%. Klystrons operating at power levels of 5 MW peak power, 120 kW average power are available commercially in both the 350 MHz and 700 MHz range, though the design would probably be customized to match the needs of the accelerator. In particular, it may be desirable, if not essential, to drive modulate each klystron at the chopper frequency in order to compensate for transient beam loading effects in both the drift-tube and side coupled cavities. This is due to the fact that the peak beam loading power is essentially equal to the excitation power in each module. It is therefore desirable to operate the klystron in a nonsaturated mode which probably requires a collector voltage of the order of 120 kV to 150 kV. Because of the high voltage requirement, in the interest of reliability, a line type modulator with a thyatron switch and a pulse transformer with the necessary core bias may be the system of choice rather than a hard tube modulator. The line-type modulator is simpler and more stable than a hard tube modulator, as well as more efficient, and does not have the expense of replacement of power-grid tubes. Yamazaki, et. al.⁷ have presented a design for such a modulator for the Japanese Hadron Facility. Their modulator, producing 15 MW for operation of a 6 MW klystron at 600 μ s pulse width and 3% duty factor, exactly fits our requirements. The modulator had a 20 kV PFN and a 7:1 transformer.

**Table 4.2-4
SCL DESIGN**

Frequency	700 MHz
Input energy	70 MeV
Output energy	600 MeV
Total length	248.1 m
P _{tot} (MW)	≈ 20
Modularity	
cells/tank	16
tanks/module	4
Intertank	3/2 beta*lambda
Synch. phase	-30 degrees
Bore radius	1.7 cm
Quadrupoles	
Type	Electromagnetic
Focusing	FODO
Length	7 cm
Gradient	2.0 kG/cm

<u>Module</u>	<u>beta</u>	<u>Energy</u> (MV)	<u>Length</u> (m)	<u>P(Cu)</u> (MW)	<u>P(beam)</u> (MW)	<u>P(tot)</u> (MW)	<u>E0*T</u> (MV/m)
1	0.401	86.0	6.26	2.32	1.60	3.93	3.52
2	0.434	103.5	6.81	2.30	1.75	4.05	3.52
3	0.465	121.9	7.34	2.21	1.84	4.05	3.44
4	0.494	141.2	7.83	2.14	1.93	4.06	3.36
5	0.521	161.2	8.28	2.07	2.00	4.07	3.28
6	0.546	181.7	8.70	2.01	2.05	4.06	3.28
7	0.569	202.7	9.07	1.95	2.10	4.05	3.2
8	0.590	224.0	9.45	1.89	2.13	4.02	3.12
9	0.610	245.6	9.78	1.83	2.16	3.99	3.04
10	0.628	267.8	10.09	1.86	2.23	4.09	3.04
11	0.645	290.2	10.38	1.80	2.24	4.04	2.96
12	0.661	312.6	10.65	1.74	2.24	3.98	2.88
13	0.676	335.6	10.90	1.77	2.29	4.06	2.88
14	0.690	358.4	11.13	1.71	2.29	3.99	2.8
15	0.703	381.7	11.35	1.73	2.33	4.06	2.8
16	0.715	404.9	11.56	1.66	2.31	3.98	2.72
17	0.727	428.4	11.75	1.68	2.35	4.04	2.72
18	0.738	451.7	11.93	1.62	2.33	3.95	2.64
19	0.748	475.3	12.10	1.64	2.36	4.00	2.64
20	0.758	499.2	12.26	1.65	2.39	4.05	2.64
21	0.766	522.8	12.41	1.58	2.36	3.94	2.64
22	0.775	546.6	12.56	1.60	2.39	3.98	2.64
23	0.783	570.7	12.69	1.61	2.41	4.02	2.64
24	0.791	594.4	12.82	1.54	2.37	3.91	2.56

A feed forward system for the drive to the klystron which will control both amplitude and phase during the normal build up of energy in the accelerator cavity, and during the extra power required for beam loading compensation, will be needed. This is particularly true as rf chopping is required to "match" the linac beam to the synchrotron.

The high power rf waveguide feed system will also require careful study because the modulation of the beam caused by the rf chopper will ensure that the beam/cavity interaction is always in a transient state. This is in effect a pulse modulation at a frequency of 1.31 MHz with a 50% duty factor. The response of the klystron amplifiers and the accelerating cavities to this type of drive modulation will require detailed study.

4.2.8 RF System Transient Response

The response of the accelerating cavities to both the beam and the rf compensation pulse that is required in order to maintain the desired field amplitude and phase stability for the required beam properties is of vital importance. When a pulse of energy and/or an intense beam is fed into an accelerating cavity the field distribution along the cavity is determined not only by the response of the accelerating mode, but also by the response of adjacent normal modes in the passband. For a drift-tube structure operating in zero, or π -mode, that is at the end of the passband, it can be shown that for a center coupled cavity, where the even numbered modes will be predominantly excited, the transient build-up curve for the resonant mode is^{8,9}

$$E = E_o e^{j\omega'_o t} \left[1 - e^{\frac{-\omega'_o t}{2Q_o}} \right] \quad (1)$$

while for the nonresonant modes ($n \neq 0$) it is

$$E = \sqrt{2} j E_o \frac{\omega_o'^2}{Q_o (\omega_n'^2 - \omega_o'^2)} \frac{U_n}{U_o} e^{j\omega_o' t} \quad (2)$$

$$* \left[1 - \frac{Q_o}{Q_{ext,o}} \left(1 - e^{\frac{-\omega_o' t}{2Q_o}} \right) - e^{\frac{-\omega_n' t}{2Q_n}} e^{j(\omega_n' - \omega_o') t} \right] \cos \frac{n\pi z}{L}$$

where ω_n' are the resonant frequencies of the n , nonresonant modes.

$$\omega_n' = \omega_n \left(1 - \frac{1}{2Q_{on}} \right) \quad (3)$$

$Q_{o,n} \dots$ are the unloaded quality factors, $Q_{ext,n}$ are the external quality factors

$$\frac{1}{Q_{ext,n}} = \frac{U_n^2}{\epsilon \omega_n Z_o} \quad (4)$$

where Z_o is the characteristic impedance of the waveguide in which only one propagating mode is assumed (note that for a bridge coupler arrangement this assumption may not be valid). At the surface, S' , where energy is coupled to the cavity, the cavity normal mode field, E_n , is related to the normalized tangential component of the waveguide mode $\bar{e}$ by:

$$E_n = U_n \bar{e} \quad (\text{where } U_n \text{ is a real coefficient}) \quad (5)$$

These derivations are all given in reference 8.

Equation (2) shows wiggles which arise from the beat between the free oscillation of the mode and the driving force; the angular frequency, Ω_{on} , being given by:

$$\Omega_{o,n} = \omega'_n - \omega'_o \quad (6)$$

The amplitude of the wiggle changes along the length of the cavity in the same manner as the axial component of the n th mode, and dies out in the steady state with a decay constant $\omega_n/2Q_n$.

There is also a delay of build up time between the center feed point and the ends of the cavity because of the summation of the zero mode field and the even- n mode fields, because of their z dependence, $\cos n\pi z/L$. It can be seen that all of these "higher order" terms take part in the field compensation at very small t and cancel out the lower order terms so there is no signal at the far end during the time $t < L/2c$. This is due to the argument that the wavefront velocity when a pulse or wave packet may travel a distance, is always equal to c ,¹⁰ no matter what the medium. Then, with zero amplitude and velocity equal to c a "forerunner" of the wave arrives. The forerunner grows slowly and falls as the main body of the signal arrives and increases with a build up curve similar to that at the driving point. Because of this behavior it is very difficult to estimate the delay for very short t (< 10 nsec).

In practice much of this transient response can be minimized by keeping the accelerating sections short, thus increasing the mode separation, and by feeding power into them at the $z = L/4$, and $3L/4$ points simultaneously. This effectively cancels the contribution of the $n = 1, 2$ and 3 modes for zero mode operation.

In a structure operating in $\pi/2$ mode, that is at the center of the passband, in the steady state, for the most part, the effects of the nonresonant modes are canceled out due to the symmetric frequency distribution of nearby modes around that mode. It can be shown that for the transient case, any phase shift produced is not in the first order, although amplitude changes corresponding to the field build-up occur in both even and odd numbered cells. The wiggles due to the beat

between the resonant and nearby modes can exist; however, the nearby modes are further separated from the resonant mode so that the amplitude of the wiggle is much smaller than that of the zero or π mode case. Reference 11 shows that the residual amplitude effects are an order of magnitude less in $\pi/2$ mode than for π -mode operation.

The beam loading effect in the accelerating cavities is also a transient one. To first order the beam induced wave excites only the synchronous accelerating mode. The decrease in field strength is given by

$$\Delta E_b \approx \frac{R_o I_o \omega_o^2 f_o \cos \phi_b}{2Q_{oo} t_o} \cdot t \quad (7)$$

where t is the time during the beam pulse, ϕ_b is the synchronous phase, I_o is the beam current averaged over the beam bunches, t_o is the transit time factor, R_o is the cavity shunt impedance per unit length and f_o is a form factor of the beam bunches.

For a short bunch with a constant phase spread of $\delta\phi$.

$$f_o = \frac{\sin \frac{\delta\phi}{2}}{\frac{\delta\phi}{2}} \quad (8)$$

Without application of a compensation pulse the field droop during a 375 nsec beam pulse for a typical accelerating cavity, loaded with a 100 mA beam, would be of the order of 0.05 to 0.1 MV/m, compared with an accelerating field of 2.5 to 5 MV/m.

Since the application of the rf compensation pulse to correct for beam loading causes a field and phase droop due to excitation of the normal modes as described above it is clearly necessary to design the accelerator to minimize those effects. SENICHEV et al.¹¹ have calculated the transient effect for the SSC Linac in which the rf power is fed from a single klystron through five bridge couplers to six accelerating tanks for a total of about 256 accelerating and coupling cells. It is clear that this arrangement is not desirable for our situation with a much higher beam current requirement and a beam modulated at 1.31 MHz. For the drift tube structure we must couple power into the structure at the $z = L/4$ and $z = 3L/4$ points and for the side coupled structure we should center couple to individual tanks with a single klystron and waveguide magic tees providing the feeds for four tanks in a module. This will reduce the transient effect by the ratio of the square of the module length to the individual tank length for the same beam current or by about one order of magnitude for our higher beam current.

It will also be desirable to utilize a feed forward system for each klystron to provide the correct amplitude and phase of the compensation pulse, modulated at 375 ns, for proper beam loading compensation. Ultimately, the effectiveness of this scheme will depend upon the bandwidth and slew rate of the klystron and rf drive system.

4.2.9 Proton Injection Line for the SNS

The layout of beam line between the linac and the SNS 3.6 GeV fast synchrotrons (injection line) is shown in Fig. 2.-5. The line is subdivided in two sub-lines, the first 170 meter long and the second 70 m long, separated by a 5 degree bending magnet. Half way in the first sub-line a 2.7 meter long RF debuncher is inserted.

The present design of the line is for 600 MeV H^- ions. The line is long enough to allow for an increased injection energy up to 900 MeV. The H^- are injected into the synchrotron(s) through an arrangement of four dipole magnets shown in Fig. 4.3-10. The H^- are stripped to H^+ in a foil placed between the 3rd and 4th dipole, and their trajectory radius of curvature changes its sign. The four magnets constitute a horizontal DC orbit bump. A fast bump is combined with the DC bump to bring the captured protons on an equilibrium orbit.

The purpose of the debuncher is to "stretch" the longitudinal phase length of the beam, reducing at the same time its momentum spread. The optics of the beam line between linac and debuncher, calculated with the code TRACE-3D is shown in Fig. 4.2-11. In the calculation a beam of 100 mA and emittance 0.75 mm-mrad was assumed.

This proton transport line has been designed with a regular FODO structure of 15 quadrupoles. The values of the Twiss parameters after the debuncher are:

$$\beta_x = 3.221, \alpha_x = 0.657, \beta_y = 16.136, \alpha_y = -2.605.$$

The energy spread of the 600 MeV H^- beam at the exit of the linac was calculated to be 366.76 keV. Because of the space charge, this spread becomes 2141.5 keV at the debuncher. It is reduced to 338.96 keV at the exit of the debuncher and to 36.37 keV at the stripping foil.

The optics of the line from the exit of the debuncher to the foil in the synchrotron(s) has been calculated with the code MAD. The line has been designed as a FODO arrangement of 9+9 quadrupoles between debuncher and line bend, and 6+6 quadrupoles between line bend and injection bump magnets. All quadrupoles are 0.50 meters long.

The strengths in the 18 quadrupoles of the first sub-line are $K = G/B\rho \text{ m}^{-2}$, with $G = GH = 2.39 \text{ T/m}$ and $G = GV = -2.50 \text{ T/m}$.

The bend in the line serves a two-fold purpose: it introduces a horizontal dispersion needed to match the dispersion at the stripping foil, and is useful to place a beam dump on the line and instrumentation to measure beam properties.

The horizontal Twiss parameter values required at the foil are:

$$\beta_x = 8.687, \alpha_x = 1.423, \eta_x = -0.4946.$$

These values have been matched with the following calculated gradients of the 12 quadrupoles in the second sub-line:

$$\begin{aligned} \text{GH10} &= 3.19 \text{ [T/m]} \\ \text{GV11} &= -2.40 \\ \text{GH11} &= 3.07 \\ \text{GV12} &= -1.49 \\ \text{GH12} &= 2.64 \\ \text{GV13} &= -2.33 \\ \text{GH13} &= 2.85 \\ \text{GV14} &= -2.09 \\ \text{GH14} &= 1.70 \\ \text{GV15} &= -1.55 \\ \text{GH15} &= 1.09 \end{aligned}$$

The result at the foil (μ is the phase advance in units of 2π) is:

β_x	α_x	μ_x	η_x	η'_x	β_y	α_y	μ_y
8.84	1.41	4.11	-0.49	0.36	10.26	-1.34	3.92

The resulting pattern of the β and η functions is shown in Fig. 4.2-12.

4.2.10 Linac Vacuum Systems

Turbomolecular pumps will be used on the ion source to handle the large hydrogen gas load, and the source chamber will be maintained at 10^{-5} - 10^{-6} Torr. Two cryopumps will be used on the RFQ, and first tank of the DTL will use three cryopumps. This will maintain both systems at 10^{-7} - 10^{-8} Torr. The remaining three DTL tanks will each be pumped by three large ion pumps. One ion pump will be connected to each SCL tank through a manifold which ties into the system at each lower coupling cell. Turbomolecular pumps will be used to rough out the RFQ, DTL, and SCL. Cold cathode vacuum gauges and ion pumps currents will be used to monitor and interlock the vacuum systems.

4.2.11 Linac Diagnostic Instrumentation

Because of the linac's high average current, beam instrumentation is of great importance. The diagnostics will allow proper matching between the various sections of the machine and to measure and help minimize beam loss. The types of instrumentation to be provided in each of the sections will be described. The full complement of instrumentation is shown in Table 4.2-5.

TABLE 4.2-5

DISTRIBUTION OF BEAM INSTRUMENTATION

	B C T	W S	E M U	B S M	W C M	B P M	B L M
Low Energy Beam Transport (LEBT)	1	1					
DTL Input Matching Section	1	1	1	1		3	
DTL Inter-Tank Spaces (Total)	3	3			3	3	4
CCL Input Matching Section	2	3	1	1		3	2
CCL Inter-Tank Spaces (Total)	24	24			6	24	96
Transport Line	6	12		2		10	17

BCT = Beam Current Transformer (Toroid)
 WS = Wire Scanner (Profile Monitor)
 EMU = Emittance Measurement Unit (Slit/Collector)
 BSM = Bunch Shape Monitor
 WCM = Wall Current Monitor (Lo-resolution Bunch Shape)
 BPM = Beam Position Monitor (Stripline)
 BLM = Beam Loss Monitor

Each of the various monitors will be described below.

4.2.11.1 Beam Current Transformers

Non-intercepting beam current monitoring is done with beam current transformers with the beam forming the primary (single turn) winding and the signal is developed across a secondary

winding. Typical bandwidth allows risetimes of under 100 nsec with droop of a few tenths of a percent per millisecond. For the proposed linac the risetime requirement can be relaxed, resulting in a corresponding improvement in the droop figure. The readout electronics will provide a sampled value for the typical current at a given sample time as well as the total charge in the beam pulse.

4.2.11.2 Wire Scanners

The transverse density distribution (beam profile) will be measured by stepping a pair of orthogonal wires across the beam pipe aperture. Since the direction of the drive is at 45-degrees to

the horizontal, the single motion provides a scan in both planes. Data is taken on successive linac pulses until the full scan is made. The wire scanner provides the best compromise between range and resolution at lowest cost. Only one electronics channel is required for each plane. The wire scanners are very compact longitudinally, which is important in the matching section and between tanks and modules. Since only a small percentage of the beam intercepts the wires, the technique is considered non-destructive.

4.2.11.3 Emittance Measurement Units

Since the generation of linacs which appeared in 1970 at BNL, FNAL and LANL, the conventional method of measuring emittance has been with the slit and multi-collector hardware. In this case a slit is moved across the beam to define the position of a sample which spreads according to its divergence. The resulting distribution, which is measured by the multi-collector array of electrodes (foil strips), represents the angular spread. The result is a direct measure of the transverse phase space in one plane. The measurement is destructive of the beam.

4.2.11.4 Bunch Shape Monitor

The Bunch Shape Monitor was invented by Witkover at BNL¹² in 1976 and further developed by Feschenko¹³ in 1986. It is capable of resolution of a fraction of a degree of phase at the linac RF frequency for the equivalent of tens of Giga-Hertz bandwidth, without degradation by the signal cable. The signal is generated by secondary electron emission from a wire intercepting the beam. Modulation of this signal by the linac RF produces an auto-correlation which down-converts the information to low frequency where it is easily detected. The observation point is moved along the bunch length by shifting the phase of the modulating RF.

4.2.11.5 Wall Current Monitor

The beam generates an image current on the surface of the beam pipe. A ceramic break is placed in the pipe and resistors distributed azimuthally around it connect the two pieces of beam pipe. The image current flows through the resistors developing a voltage across them which provides the bunch shape signal. The best example¹⁴ (at FNAL) has an upper frequency of 6 GHz before degradation by the signal cable. While this is not sufficient to see the details in the bunch shape (as the BSM can) it is a passive device which is also less expensive and will provide sufficient information for the Delta-T matching technique.

4.2.11.6 Beam Position Monitor

Beam Position Monitors will be of the stripline type which have been used at the BNL 200 MeV linac and the FNAL linac. In the BNL design the striplines are cut to the second harmonic to

minimize the length along the beam line. These have worked very well. Processing will be done at the highest frequency possible, after down conversion, to obtain the best frequency response.

4.2.11.7 Beam Loss Monitors

The beam loss monitor system is one of the most important diagnostic tools in a high average current accelerator. Since activation of the machine and tunnel will limit component lifetime and present a hazard to maintenance personnel, it is essential that beam loss be kept to a minimum. While beam current transformers read the transmitted current or charge, they are not sufficiently sensitive to see small deviations due to loss. This is particularly true here where it is desired to keep the loss to less than 0.1 %. On the other hand, the radiation signal is derived only from the lost beam and provide a better tool for reducing the losses. While liquid scintillator - photomultipliers have been used on some linacs in the past,¹⁵ problems with reproducibility, aging, and calibration make them less desirable than ion chambers for use as loss monitors. The long coaxial ion chambers used at BNL¹⁶ offer uniform coverage and linear fall-off with distance. These have been used in typical lengths of 15 to 25 meters to increase the volume exposed to the radiation but they may not be sensitive enough in the linac where the thick cavity walls provide shielding. However they do have sufficient sensitivity for use in the transfer lines. Proportional ion chambers with a typical gas gain of 1000 may be needed in the accelerating regions to observe losses 3 to 4 decades below the transmitted current. Such units have been tested in the AGS and AGS Booster for use in mapping heavy ion losses and appear to be suitable.

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Rep rate = 60 Hz

Beam width (300 turns) = 450 us

RF width = 500 us

RF duty factor = 3%

H- current = 100 mA (peak)

Chopper duty factor = 50%

Average current = 1.35 mA

Fig. 4.2-1

Electrostatic Quadrupole (Ref.3)

Fig. 4.2-2

FIG. 4.2-3. RFO PARTIED

Fig. 4.2-4. DTL PARMILA

Fig. 4.2-5. DTL TRACE3D

CCL COST OPTIMIZATION

Fig. 4.2-6

SNS SCL MODULE

Fig. 4.2-7

Fig. 4.2-8. Energy spread, phase and beam size vs. distance
(BNL SNS 70 MeV to 600 MeV, 700 MHz)

output phase-space projections at tank 97 ngood = 1000

Fig. 4.2-9. BNL SNS, SCL 6D phase space parameters.

Fig. 4.2-10. TRACE3D, SCL 70-600 MeV

Beam Envelope and Twiss Parameters from the Linac to the Debuncher.
The transverse and longitudinal phase spaces are shown.

Fig. 4.2-11

Beta functions and dispersion in the injection
line between debuncher and synchrotron

Fig. 4.2-12

4.3 Fast Cycling Synchrotrons (2 FCS)

4.3.1 Overview and Basic Parameters

A most severe limitation of the beam performance in the Fast Cycling Synchrotrons is the total beam intensity. An acceptable approach, which reduces the required beam intensity, has been adopted by using two FCS's, a relatively large top energy (3.6 GeV, without violating the main requirement of the users), and a sufficiently small circumference (363.2 m) which also allows a reasonable range of guiding field and associated ramp rate. Finally, the injection energy adopted (600 MeV) is sufficiently large to alleviate the most important of the limitations: space charge. The need to control the amount of space-charge has been clearly the most important criterion in the design of the synchrotrons. All the main parameters and the modalities for injection and rf capture are the consequence of this.

To cope with space charge, one allows the beam to grow to a sufficiently large size. Indeed space-charge forces causes a tune-depression $\Delta \nu$ which can be calculated¹ according to the equation

$$\Delta \nu = \frac{Nr_p}{2\beta^2\gamma^3 B \epsilon}$$

where N is the total number of protons circulating in the synchrotron, $r_p = 1.535 \times 10^{-18}$ m is the proton classical radius, B a bunching factor defined as the ratio of the average beam current to the peak current after rf capture and bunching, and β and γ are the usual relativistic factors. Finally, ϵ is the beam emittance, which measures the phase space area occupied by the beam. It is required that the tune-depression $\Delta \nu$ does not exceed the value 0.25; this in turn sets the beam emittance for the given beam intensity N . A summary of the main parameters is given in Table 4.3-1. The actual tune depression during the acceleration cycle is displayed in Figure 4.3-1.

Table 4.3-1. Main Parameters

Number of Synchrotrons	2	
Circumference	363.2	m
Repetition Rate	30	Hz
Field Excitation Waveform	sinusoidal	
Injection Energy	0.6	GeV
Extraction Energy	3.6	GeV
No. of Protons/Cycle/Ring	1.45×10^{14}	
Tune Shift, $\Delta \nu$	0.25	
Normalized Emittance (full)	260	π mm mrad
rf Harmonic Number	2	

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. The approach proposed here simplifies the design and the requirements of the Linac and of the accelerating rf system in the synchrotrons. It reduces, however, considerably the flexibility for longitudinal "painting" during the multi-turn injection, since essentially each turn injected from the Linac extends over the entire length of the rf buckets.

Another important parameter is the gap of the dipole magnets in the synchrotrons. The cost and the power consumption is essentially linear with it. A reasonable value for the magnet gap, which also allows for the thickness of the vacuum chamber, has been determined with choice of a strong focussing lattice which reduces the value of the vertical β - functions in the dipoles. Finally, we have taken, during the design, a ratio of 1.6 between the vertical betatron acceptance of the ring and the full beam emittance at injection.

Fig. 4.3-1. The Tune Depression during the Acceleration Cycle

4.3.2. Magnetic Lattice

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 locating the accelerating rf cavities. We have chosen as a compromise a superperiodicity of two, with each superperiod made of an arc and an insertion as shown in Figure 4.3-2. 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. For this purpose, we have 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.

The main parameters are listed in Tables 4.3-2 and 4.3-3., and a plot of the lattice functions is given in Figure 4.3-3.

TABLE 4.3-2. Synchrotron Parameters

Magnetic Rigidity : @ inj.	4.06	T-m
@ ext.	14.81	T-m
Circumference	363.20	m
Number of Superperiods	2	with mirror symmetry
Structure of half-Period	.CE .C .C .C .C .CE .C .C	
.CE empty FODO cell		
.C full FODO cell		
Number of FODO cells	32	
Cell Length	11.35	m
Drifts : Long	5.075	m
Short	1.1375	m
Dipole : type	rectangular magnet, bent,	H-shaped
total number	48	
length	2.8	m
bending radius	21.39	m
bending field	0.19 - 0.70	T
field variation	47.34T/s	
vertical gap	13.1 + 3.5 (beam & v.c.)	cm
Quadrupole : total number	64	
length	0.6	m
gradient	6.14	T/m
bore radius	12.0	cm

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 a tolerable amount. This in turn assigns the maximum value of the bending field and of the circumference of the synchrotrons.

A short cell length and a phase advance close to 90° per cell have been chosen to reduce the vertical amplitude function and therefore the required vertical aperture. The choice of the phase advance per cell allows also easily for the insertion of drifts with vanishing or small dispersion by simply removing dipole magnets.

The transition energy has a value large enough so that the whole acceleration cycle is performed well below the transition energy, and it never crosses this value. This is considered ideal to avoid losses associated with transition energy crossing and with negative mass instability.

TABLE 4.3-3. Synchrotron Lattice Parameters

Phase Advance / Cell: horiz.	87.75	degrees
vert.	87.75	degrees
Betatron Tune : horizontal	7.8	
vertical	7.8	
Natural Chromaticity : horiz.	-9.11	
vert.	-9.30	
Transition Energy, γ_t	6.277	
β max : horizontal (QF)	18.85	m
vertical (QD)	19.16	m
dipole (Vert.)	13.46	m
η max (QF)	4.21	m
Betatron Acceptance	320	π mm mrad
Momentum Acceptance, full	2.0	%

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.

The small drifts of 114 cm on each side of the quadrupoles allow enough space for the insertion of beam position monitors, vacuum ports and steering magnets. The long drifts have a length adequate for accommodating rf cavities as well as injection and extraction magnets.

The fractional parts of the betatron tunes in the limit of zero beam-current have been chosen large enough so that, once the tune-shifts from space-charge have been subtracted, the tunes never cross half-integral values. The integral parts of the betatron tunes have been chosen to avoid being too close to potentially dangerous low-order resonances due to systematic magnetic imperfections, namely $2Q_h = \text{const.}$, $2Q_v = \text{const.}$, $Q_h - Q_v = \text{const.}$ and $Q_h + Q_v = \text{constant}$. These resonances are driven by factors that typically depend on some power of the amplitude lattice functions, which have, in the lattice here adopted, a very large periodicity.

The distribution of the various functions is indicated in Figure 4.3-2. Injection occurs in the central empty FODO cell of an insertion, and extraction is done in the diametrically opposite location. The rf cavities are distributed symmetrically around the ring in four locations where the dispersion is essentially zero. Locations with large dispersion are also available for the beam collimators and scrapers in the short drifts in the middle of the arcs where the dispersion is favorably large.

4.3.2.1 Expectation of Errors and Correction

To estimate the expectation value of the closed orbit distortion² in the synchrotrons, we have assumed the following misalignment and field errors³:

(1) Dipole field error (only in the horizontal plane). Random variation from magnet to magnet with gaussian distribution and rms error for the integrated bending field

$$\langle \Delta(Bl) / B\rho \rangle \approx 3 \times 10^{-4}$$

(2) Dipole axial rotation (only in the vertical plane). Random variation from magnet to magnet with gaussian distribution and rms error for the rotation angle

$$\langle \theta \rangle \approx 3 \times 10^{-4} \text{ rad}$$

(3) Random variation of quadrupole lateral displacement, horizontal and vertical, with gaussian distribution and rms error for the displacement

$$\langle d \rangle \approx 3 \times 10^{-4} \text{ m}$$

The analysis of the effect of the errors is greatly simplified by the large regularity of the lattice. The largest distortion of the closed orbit occurs in the middle of the focussing quadrupoles where the contributions to the expectation values from the errors given above are as follows: on the horizontal plane, 18 mm from the dipole field errors and 8 mm from the quadrupole lateral displacements; on the vertical plane, 2.5 mm from the dipole axial rotations and also 8 mm from the quadrupole lateral displacements. When these numbers are combined quadratically, we can expect as much 20 mm as the rms value of the distortion in the horizontal plane at QF, and less than 10 mm in the vertical plane at QD.

To correct the closed orbit, the Fermilab method⁴ has been examined. Pairs of position monitors and steering elements, located next to each other, are placed next to each quadrupole and divided in two families. Those pairs located next to QF act on the horizontal plane, and those next to QD on the vertical plane. The method applies a cascade of local three bump corrections. The required strength for the steering elements is

$$\int B \, dl = 600 \text{ Gauss-meter}$$

adequate for a maximum rigidity of 15 T-m, and to correct distortions of the closed orbit as large as 4 times the rms expectation values given above.

The nominal values of the betatron tunes in the synchrotrons are $\nu_H = \nu_V = 7.8$. There are four half-integer stopbands in proximity of these values corresponding to the resonances: $2\nu_H = 16$, $2\nu_V = 16$ and, a little further away, $2\nu_H = 15$, $2\nu_V = 15$. These resonances can be excited only by random errors². Assuming an rms value of 10^{-3} for the relative gradient error per quadrupole, the rms expectation value of the stopband width is 0.004, sufficiently small so that during most of the acceleration cycle they are expected to be of no consequences. The exception is during injection, when the tune spread within the beam (created by space charge and by the uncorrected chromaticity), is so large that part of the beam might have to cross one of the neighboring stopbands during the bunching process and the early stages of acceleration. It is not obvious at this stage where stopband correctors are required, also because the consequences of traversing a stopband at large speed may be negligible. If one decides for the inclusion of trim quadrupole correctors, they can be combined with the scheme for the control of the betatron tunes.

Fast Cycling Synchrotron - Spallation Neutron Source

Fig. 4.3-2

Optical Functions FCS-SNS, Injection/Ejection Straights

Optical Functions FCS-SNS, Lattice Superperiod

Fig. 4.3-3

4.3.3 Transverse Losses from H⁻ Multi Turn Injection

4.3.3.1 Introduction

With a total throughput of $8.7 \cdot 10^{15}$ p/s from the two 3.6-GeV rings, it is important that losses - particularly distributed loss around the rings - be minimized both for reasons of shielding requirements and activation of components. A reasonable limit for fractional distributed losses is $\leq 10^{-3}$. A major source of such losses would be scattering of the incident H⁻ beam and subsequent multiple traversals of the stripped protons out of the ring acceptance ellipses by multiple coulomb (MCS) and nuclear elastic scattering (NES). Indeed, Yamane, et al.⁵ have made an estimate of these losses for the Japanese Hadron Facility at 1-GeV incident H⁻ energy through a $250 \mu\text{g}/\text{cm}^2$ C¹² stripper foil and obtain scattering losses of $5.4 \cdot 10^{-4}$. Such losses could be higher for the 600-MeV H⁻ injection contemplated here. Therefore, a detailed Monte-Carlo simulation of multiturn injection through a carbon stripper foil was done to obtain quantitative loss estimates. It was found that under optimal conditions with a rapidly (exponentially) collapsing orbit bump of the ring horizontal (x) and vertical (z) acceptance ellipse through a $300 \mu\text{g}/\text{cm}^2$ "postage stamp" (10mm x 10mm) C¹² foil and with 300 turn injection of an H⁻ beam tracking the ellipse axis $y' = -(\alpha/\beta)y$, the scattering losses out of an $A_{xz} = 400\pi$ mm-mrad acceptance ellipse with 50% filling is only $(2.9 \pm 3) \cdot 10^{-5}$. Under worst case conditions with a large area (20mm x 160mm) foil, no tracking of the ellipse axis, and with 600 turn injection through a $600 \mu\text{g}/\text{cm}^2$ foil, the losses are $(3.3 \pm 1) \cdot 10^{-3}$. The computed losses are systematically about 10% too large due to an overestimate of the nuclear elastic losses resulting from an overestimate of the nuclear radius of C¹².

4.3.3.2 Formulation of Multiple Coulomb and Nuclear Scattering

The Moliere⁶ series expansion of the probability for MCS scattering into an angle between θ and $\theta + d\theta$ is given by

$$P(\delta) d\delta = \delta d\delta \left[2e^{-\delta^2} + \sum_{n=1}^{\infty} f_n(\delta) / B^n \right] \quad (2)$$

where the $f_n(\delta)$ are universal functions of the normalized angle $\delta = \theta/\theta_{\text{mcs}}$ with the rms multiple coulomb scattering angle $\theta_{\text{mcs}} = \langle \theta^2 \rangle^{1/2} = \theta_1 \sqrt{B}$. The θ_1 function as well as a function (θ_1/θ_s) required to obtain B are elucidated by Bethe and Ashkin.⁷ The evaluation of the $f_n(\delta)$ and Moliere B functions are given in detail elsewhere⁸; here we note that the present calculation evaluates all $f_n(\delta)$ functions over a larger angle interval, $0 \leq \delta \leq 1000$, in smaller angle increments $\Delta\delta$ ($= .01$ for $\delta \leq 20$) and with considerably better numerical accuracy than used in a previous calculation⁹. Also, all terms up to $n=10$ are evaluated here. Random angles are sampled from the integral of the probability function Eq.(1) using an improved random number generator¹⁰. The transcendental equation for Moliere's B does not allow solutions with $B \leq 1$ which, indeed, would result in a diverging series for Eq. (1); this limit corresponds to $\tau = 245 \mu\text{g}/\text{cm}^2$ for the C¹² foils of the present

calculation, and therefore foils thinner than $\tau=300 \mu\text{g}/\text{cm}^2$, for which $B=1.7994$ and $\theta_{\text{mcs}}=17.82 \mu\text{rad}$ are not considered.

For nuclear elastic scattering the optical model formulation of Fernbach, Serber and Taylor¹¹ (FST) is used which assumes a complex square well potential of radius R and obtains the differential cross-section in the center-of-mass (CM)

$$\frac{d\sigma}{d\Omega} = (kR)^2 R^2 [I_1^2(\delta) + I_2^2(\delta)] \quad (3)$$

in terms of dimensionless integrals I_1 and I_2 and the normalized angle $\delta = kR\sin\theta$ which are described elsewhere.⁸ The wavenumber $k = p/\hbar$ is obtained from the relativistic kinetic energy of the reduced mass $\mu = M_p M_c / (M_p + M_c)$ of the proton-C¹² system in the CM; $kR = 15.9778$ is obtained here with $R = r_0 A^{1/3}$ and $r_0 = 1.25 \text{ fm}$. Comparison of Eq. (2) with elastic cross section data of Jones¹² measured at $T_p = 597\text{-MeV}$ at LAMPF are shown in Fig. 4.3-4. We see that the first minimum of the theoretical curve occurs at an angle about 10% smaller than the data, and that a decrease in R of that amount would reproduce the correct position of the minimum which is determined by the first minimum of the Bessel function $J_0(kR\sin\theta)$ in the integrands of I_1 and I_2 . A reduction in R would also bring the magnitude of Eq. (2) into better agreement with the data at smaller angles, and into better agreement with the value for r_0 found for lower energy $p+C^{12}$ scattering.¹³

4.3.3.3 Computation Procedure

The coordinate and angle of an incident H^- is chosen at random from an assumed Gaussian beam with center fixed in the middle of a small area carbon "postage stamp" stripper foil similar to that used successfully at the LAMPF PSR.^{14,15} A random MCS angle is added and, if required, a random NES angle if a nuclear elastic event occurred as evaluated from the total elastic¹¹ cross section computed here as $\sigma_e = 145.3 \text{ mb}$. In addition, non-elastic events are calculated from the result $\sigma_{ne} = 233 \pm 5 \text{ mb}$ measured by Renberg, et al.¹⁶ at 552-MeV. The total nuclear cross section used here, $\sigma_T = \sigma_e + \sigma_{ne} = 378.3 \text{ mb}$ is in good agreement with the measured value of $370 \pm 9 \text{ mb}$ at 1000 MeV by Palevsky, et al.¹⁷

Next a random injection time t is selected for the particle between the start of injection t_i and the end of injection t_f and an initial turn number is computed based on the total number of injection turns desired. For 300 turn injection, $t_f - t_i = 458 \mu\text{sec}$ for the ring model used here.¹⁸ Use of a continuously variable injection time implies that points from all azimuthal positions in the ring are included and thus filamentation in phase space is avoided which would result from discrete injection intervals. The injected particle coordinates are then transformed to coordinates relative to the acceptance ellipse centers $X_c(t)$ and $Z_c(t)$. A rapidly collapsing function¹⁹ for the horizontal "bump", an exponential in the present case, is used. Also, a corresponding exponentially increasing function for the vertical is used.

$$\begin{aligned} X_c(t) &= A_H e^{-w_x t} \\ Z_c(t) &= A_v \left[1 - e^{-w_z(t+t_0)} \right] \end{aligned} \quad (4)$$

with $w_x = w_z$ and t_0 an initial time offset to give an initial displacement of the ellipse center and create a "hole" in the central phase space density.¹⁹ Preliminary results using a half-sinusoidal bump gave a large population peak at the ellipse center and thus an excessive space-charge tune spread. Reduced central particle density also leads to fewer subsequent foil traversals and thus lower scattering losses as well as less radiation damage and therefore longer foil lifetime.

Finally, a tune value ν is assigned to the particle so that a one-turn matrix can be constructed to transport the particle around the assumed linear machine for as many turns as is required to move the acceptance ellipse off the stripper foil. An amplitude-dependent tune as obtains for a non-uniform space charge density is used here (constant tune leads to phase space filamentation) although the form of the density function is not a priori known; a Gaussian density function is assumed.²⁰

$$n(r) = n_0 e^{-\alpha^2 r^2}$$

and, from a generalization of Laslett's²¹ derivation of uniform space-charge tune shift, as elucidated by Bruck²², the expression is obtained⁸

$$\begin{aligned} \nu &= \nu_0 - \Delta\nu = \frac{1}{2} \left[\nu_0 + \sqrt{\nu_0^2 - 4A(r)} \right] \\ \text{where } A(r) &= \frac{r_0 C N_0 (1 - e^{-\alpha^2 r^2})}{(2\pi)^2 \beta^2 \gamma^3 B (1 - e^{-\alpha^2 r_m^2}) r^2} \end{aligned} \quad (4)$$

where C is the ring circumference, B is the bunching factor, β and γ the usual relativistic factors, r_m the maximum radial extent of the machine acceptance, N_0 the total number of protons in the ring, $\alpha^2 = 1/2\sigma^2$ with σ the rms width of the Gaussian, and $r_0 = e^2/m_p c^2$ = classical radius of the proton. Eq. (4) is based on the assumption of a circular beam and uniform longitudinal particle density in the bunch; it reduces to the Laslett expression²² in the limit of uniform density ($\sigma \rightarrow \infty$) where the tune shift $\Delta\nu$ attains its minimum value and is independent of particle amplitude. In Fig. 4.3-5 the tune variation is shown for several values of the bunching factor B and corresponding beam width

are $\alpha_x = -1.361$, $\beta_x = 7.960$ m, $\alpha_z = 1.401$, $\beta_z = 8.449$ m and $\eta_x = 2.21$ m and result in tilted acceptance ellipses since $\alpha_{x,z}$ are non-zero. Therefore cases were considered where the bumped ellipse centers X_c and Z_c remain on the axes $x'=z'=0$ as well as cases where X_c and Z_c track the ellipse axes $y' = -(\alpha/\beta)y$ ($y=x$ or z). This axis is close to the symmetry axis of the tilted ellipse obtained²⁰ by diagonalizing the quadratic form of the rotated Courant-Snyder invariant, which gives the tilted ellipse major axis as⁸

$$y' = \frac{(1 + \alpha^2)}{\beta} \left[\frac{\alpha}{2} \pm \sqrt{1 + (\alpha/2)^2} \right] y \quad (5)$$

In either case the injection is terminated at $t=t_r$ with a clearance between the H^- beam center and acceptance ellipse edge of $5\sigma_{bx}$ where $\sigma_{bx} \approx 1.0$ mm is the rms width of the H^- beam of rms emittance $\epsilon_b = 1232\pi$ mm-mrad.¹⁸ A clearance of 3.6 mm is also taken between the acceptance ellipse and the inner edge of the stripper foil located at $X_{fo} = 60$ mm. The H^- beam center is at $X_{bo} = 65$ mm at the center of a 10 mm x 10 mm carbon foil; again $5\sigma_{bx}$ is allowed between the H^- beam center and foil edge to assure that losses from randomly selected H^- ions with an assumed Gaussian profile missing the stripper foil are $< 10^{-5}$. In the present calculation momentum dispersion effects are ignored which will increase the H^- beam size at the stripper foil from the H^- beam momentum spread¹⁸ of $\delta = \Delta p/p_0 = .005$ by $\sim \sqrt{2}$. Momentum spread will also result in a small spread in position X_c of the ring acceptance ellipse center.

4.3.3.4 Results and Conclusions on Distributed Injection Losses

A sample computer run (case 37, Table 4.3-4) showing the horizontal phase space distribution of $N=10^4$ incident particles is given in Fig. 4.3-6 to illustrate the geometry described above and the effect of the exponential "bump" of Eq. (3) and tune spread of Eq. (4) in producing a nearly uniform density distribution. Although a 2-mm radius "hole" was introduced at the ellipse center, there is still evidence of higher density in the central region. This is also apparent from the horizontal profiles produced by the program which are generally peaked above the $n(x) \sim [1 - (x/x_{max})^2]^{1/2}$ profile expected for a uniform phase space density. Lee and Ratner¹⁹ suggest that a parabolically collapsing bump will more closely approximate a uniform phase space population. In Table 4.3-4 the results are summarized from some of the computer runs in which foil thickness τ , injected turns, foil area and trajectory of incident H^- beam are varied (NBC = 0 means ellipse centers X_c and Z_c move along $x'=z'=0$; NBC=1 means X_c and Z_c movement along ellipse axis $y' = -(\alpha/\beta)y$. In runs 33-39 (except 37) the injected beam filled 50% of the acceptance with lost particles outside the $A_{x,z}$ area; in runs 28-31 losses are evaluated as all particles with final coordinates outside the filled phase area. Although the calculation uses specific model parameters for ellipse shape and ring tune, it is felt that the loss results are reasonably model-independent except for acceptance area and foil size.

TABLE 4.3-4. COMPUTED INJECTION LOSSES FROM PROGRAM HMINUSINJ

RUN	N (10 ⁶)	τ ($\mu\text{g}/\text{cm}^2$)	TURNS	Ax,z (mm-mr)	EBx,z (mm-mr)	foil size (mmxmm)	NBC	$\bar{N}_i$ (trav/p)	NLOST	NINT	NSCAT	loss function f_L (in 10 ⁻⁵)
36	4	300	300	400	200	10x10	1	4.91	117	144	47	2.92 $\pm$.27
38	4	300	600	400	200	10x10	1	7.35	148	211	69	3.70 $\pm$.30
33	2	600	600	400	200	10x10	1	7.33	135	174	59	6.75 $\pm$.58
35	3	300	600	320	160	10x10	1	8.35	168	183	68	5.60 $\pm$.43
39	2	300	300	400	200	10x10	0	12.16	129	172	61	6.45 $\pm$.57
37	3	300	600	400	400	10x10	1	4.03	116	89	38	3.87 $\pm$.36
34	.5	600	600	400	200	20x160	0	251	1644	1603	638	329 $\pm$ 8
29	3	300	300	200	200	10x10	1		130	94	31	4.33 $\pm$.38
28	3	300	600	200	200	10x10	1		216	139	45	7.20 $\pm$.49
31	1.5	300	600	200	200	10x10	0		490	256	99	32.7 $\pm$ 1.5
30	3	300	600	200	200	20x160	1		2903	1110	404	96.8 $\pm$ 1.8

4.3.3.4.1 Run 36 with $\tau=300 \mu\text{g}/\text{cm}^2$ and 300 turn injection gives the smallest fractional loss of all cases considered here, $(2.9 \pm .3) 10^{-5}$. Uncertainties quoted in the present report are rms statistical values. NLOST includes MCS and NES losses. The total number of nuclear interactions is $N_{\text{INT}} = N_{\text{non-elastic}} + \text{NSCAT}$; therefore the "local" non-elastic losses in this case is $N_{\text{ne}}=97$ which is comparable to the distributed losses NLOST. Essentially all of the elastic scattering events NSCAT are included in NLOST. The computer program also gives the average number of traversals per proton per initial turn number and number of particles lost as a function of initial turn number of the injected particle. These functions are shown in Fig. 4.3-7 for run 36 and illustrate that the number of traversals/proton is still largest for the initial turns. However, the overall average traversals/proton, $\bar{N}_i=4.91$, is $< 2\%$ of the number of turns. Comparison of run 38 to run 36 with the number of injected turns increased to 600 shows that the fractional losses have increased by a factor of only $1.27 \pm .16$, which is barely statistically different from unity and certainly small. Thus, there appears to be little penalty in transverse losses if we choose to double the length of the Linac pulse rather than double the Linac current from the specified¹⁸ 50 mA to 100 mA pulse to accommodate the $\sim 50\%$ chopping required for efficient longitudinal capture.

4.3.3.4.2 In Run 33 the foil thickness is doubled to $\tau=600 \mu\text{g}/\text{cm}^2$ and a loss increase is obtained of a factor of $1.82 \pm .22$ compared to run 38. Although the increase is not statistically different from 2, an increase less than a factor of 2 is expected; the NES losses are proportional to τ but the multiple coulomb scattering angle $\theta_{\text{mes}} \sim \sqrt{\tau}$. The argument in favor of a thicker stripping foil is that the $\text{H}^- \rightarrow \text{H}^+$ conversion fraction improves with increasing τ - indeed, the fractional conversion loss increases by a factor of $> 10^3$ by changing from 600 to 300 $\mu\text{g}/\text{cm}^2$. The fraction of beam converted from H^- to H^+ is given by Joy²⁴ as

$$f_{H^+} = 1 - \frac{\sigma_{-10} e^{-\sigma_{01} x} - (\sigma_{01} - \sigma_{-11}) e^{-(\sigma_{-10} + \sigma_{-11}) x}}{\sigma_{-10} + \sigma_{-11} - \sigma_{01}} \quad (6)$$

where σ_{-10} , σ_{01} and σ_{-11} are the cross sections for the reactions $H^- \rightarrow H^0 + e^-$, $H^0 \rightarrow H^+ + e^-$, and $H^- \rightarrow H^+ + 2e^-$ respectively, and $x = (N_A/A)\tau$ with N_A =Avogadro's number and A =target atomic weight. Webber and Hojvat²⁵ report that σ_{-11} is unmeasurably small (consistent with 0) for $T_H=200$ -MeV on C^{12} and present a graph of σ_{-10} and σ_{01} vs. T_H which gives the values $\sigma_{-10} \approx 1.2 \cdot 10^{-18} \text{ cm}^2$ and $\sigma_{01} \approx 0.5 \cdot 10^{-18} \text{ cm}^2$ at 600-MeV. The conversion fractions from Eq. (6) are then (with $\sigma_{-11}=0$) $f_{H^+}(300 \text{ } \mu\text{g/cm}^2) = .9991$ and $f_{H^+}(600 \text{ } \mu\text{g/cm}^2) = 1 - 6 \cdot 10^{-7}$. In Fig 4.3-8 f_{H^+} from Eq. (6) is shown as a function of foil thickness τ . Note that the conversion efficiency drops rapidly below $t=300 \text{ } \mu\text{g/cm}^2$ so, notwithstanding the computational difficulties noted in Section 4.3.3.2, foils much thinner than $300 \text{ } \mu\text{g/cm}^2$ would probably not be chosen anyway.

The argument against a thicker stripper foil is the increase in non-elastic losses. From run 38 with $t=300 \text{ } \mu\text{g/cm}^2$ these are $N_{ne}=73 \pm 12$ which leads to a fractional loss $f_{L(ne)} = (3.65 \pm .60) \cdot 10^{-5}$; in run 33 with $\tau=600 \text{ } \mu\text{g/cm}^2$ $N_{ne}=115 \pm 15$ is obtained for a fractional loss $f_{L(ne)} = (5.75 \pm .76) \cdot 10^{-5}$. The exact result should lead to a factor of 2 increase since $f_{L(ne)} \propto \tau$. This appears to be a small penalty in losses compared to the H^- conversion losses which would be avoided with a thicker foil.

4.3.3.4.3 A decrease in ring acceptance to $A_{x,z} = 320\pi$ mm-mrad resulted from a new lattice design²⁶. Again, filling this ring to 50% of the acceptance for a $300 \text{ } \mu\text{g/cm}^2$ foil and 600 turn injection in Run 35 a fractional loss larger than the corresponding $A_{x,z} = 400\pi$ mm-mrad case (Run 38) by a factor $1.46 \pm .21$ is obtained. MCS losses are expected to increase as the angle extent of the acceptance ellipse decreases, i.e. $\sim 1/\sqrt{A_{x,z}}$, and losses from the large angle NES events are expected to be unaffected. Thus a fractional loss increase greater than $\sqrt{400/320} = 1.12$ is expected. The penalty for the decreased acceptance of the new lattice is thus small.

4.3.3.4.4 Since the 4-bump orbit deformation proposed in Section 4.3.3.5 moves the acceptance ellipse centers along the lines $x'=z'=0$ and since it is proposed to fix the position of the incident H^- beam on the stripper foil, it is seen from Fig. 4.3-6 that the ellipse will move a smaller distance between the start and end of injection and thus the bump collapse will be slower, leading to larger losses, unless the angle of the H^- beam follows the ellipse axis. In Run 39 of Table 4.3-4 a case is shown where the H^- beam follows the $x'=z'=0$ axis for 300 turns and is compared to Run 36 where the H^- beam tracked the line $y'=-(\alpha/\beta)y$, $y=(x,z)$. The increase in fractional loss is a factor of $2.21 \pm .28$. However, this case was previously calculated as Run 31 of Table 4.3-4 where injected beam filled the 50% area $EB=200\pi$ mm-mrad but all particles scattered out of that 200π mm-mrad area were considered lost. This might be a more reasonable comparison because only 200π mm-mrad of the 400π mm-mrad acceptance is being filled with the expectation that particles between $EB_{x,z}$ and $A_{x,z}$ will subsequently be lost due to ring nonlinearities, instabilities, orbit deformation, etc. So, comparing Run 31 with Run 28 to determine the loss increase penalty for not tracking the ellipse axis, the fractional loss increase is a factor $4.54 \pm .37$. Thus, the consequence of fixing the incident H^- angle at $x'=z'=0$ could result in a significant loss increase, and hence it is proposed programming the angle of the H^- beam spot on the stripper foil with pulsed magnets as discussed in

Section 4.3.3.5, below. It should be noted that this additional complication from programming the H^- beam angle at the stripper foil could be avoided if an $\alpha=0$ location for the foil were provided with a lattice insertion. In the present FODO lattice these $\alpha=0$ points are at the center of the quadrupoles, which are ring apertures.

4.3.3.4.5 Finally, the effect of increasing the stripper foil area is studied in Run 34 to a somewhat generous width of 20 mm and a vertical size of 160 mm -- adequate to accommodate the vertical size plus vertical bump motion. Such a foil could be edge-supported on a conventional fork-shaped foil holder. Also in Run 34 the H^- beam was not tracking the ellipse axis. Compared to Run 33, the combined effect of larger area foil and not tracking gives an increased loss fraction factor of 48.7 ± 4.4 . A comparison of increased losses from only a foil area increase is given by Runs 30 and 28 as a factor of $13.44 \pm .95$. In Fig. 4.3-9 the average number of foil traversals/proton vs. injected turn number for the large area foil case 34 is shown. Note that the traversals/proton remains large throughout the injection period for this case.

4.3.3.5 Layout of the Injection System

The injection straight section shown in Fig. 4.3-10 is based on the initial lattice design¹⁸ of 4.4 m length and contains a 4-dipole D-C orbit deformation (magnets B1-B4) to translate the equilibrium orbit outward by $\Delta x = 14.87$ cm. This orbit displacement is intended to move the trajectory of the incident H^- beam outward so that it will clear the yoke of the upstream lattice quadrupole QD which has a horizontal half width of 45-cm, as well as facilitate the removal of the residual unstripped H^- beam (mainly H^0) downstream of the stripper foil. The stripper foil, located at the midpoint of the straight section between dipoles B2 and B3, is in the fringing field of these magnets to provide sweeping of knock-on electrons from the foil which, if trapped by the circulating H^+ beam, would contribute a defocusing quadrupole perturbation and thus additional tune shift as well as a driving term for half-integer resonances. The layout is similar to that proposed for the European Spallation Source^{27,28}, the TRIUMF facility²⁹, and the Los Alamos LANSCE-II design.³⁰

The magnetic field $B = 5.366$ kG is the field which will result in a magnetic stripping fractional loss for the H^- ions of $f_L = 10^{-4}$ in a distance of 1-m as computed from the proper lifetime τ_0 of the H^- ion in its rest frame in an external electric field $\mathcal{E}$. Scherk³¹ gives from the WKB approximation $\tau_0 = (A_1/\mathcal{E}) \exp(A_2/\mathcal{E})$ and, from the relativistic transformation of lab magnetic field B to H^- rest frame electric field $\mathcal{E} = \beta \gamma c B$, the lab system stripping length λ_s for the ion is obtained as

$$\lambda_s = \beta \gamma c \tau_0 = (A_1 / B) e^{A_2 / \beta \gamma c B} \quad (7)$$

The constants in Eq. (7) have been measured³² as $A_1 = 2.47 \cdot 10^{-6}$ volt-sec/m and $A_2 = 4.49 \cdot 10^9$ volt/m. The fraction of H^- beam lost in traversing a distance s in field B is $f_L(s) = 1 - e^{-s/\lambda_s}$. Therefore the loss fraction f_L in distance $s = 1$ m, the field B and the H^- ion kinetic energy E_K are related as

$$\left(\frac{A_1}{B} \right) e^{A_2/\beta\gamma cB} = - \frac{1}{\ln(1-f_L)} \quad (8)$$

with $\beta\gamma$ the usual relativistic factor

$$\beta\gamma = \left\{ \frac{E_K}{M} + \left(\frac{E_K}{M} \right)^2 \right\}^{1/2} \quad M = m_p c^2 \quad (9)$$

The transcendental Eq. (8) is solved numerically and given in Fig. 4.3-11 as B vs. E_K for several values of f_L . The value $B=3.75\text{kG}$ at $E_K=800\text{-MeV}$ in Fig. 8 for $f_L=10^{-5}$ is consistent with values used at Los Alamos³³.

Not shown in Fig. 4.3-10 are the fast bump magnets needed to give the exponential displacement of the horizontal and vertical acceptance ellipses as in Eqs. (3). The fast bumps consist of a pair of horizontal (H) and vertical (V) kickers in the straight section upstream of the injection straight and a similar pair of H and V kickers in the downstream straight - thereby comprising a 4-bump combination for each plane similar to the 4-bump D-C magnets. If the bump magnets have the same magnetic length $\ell_m=0.8\text{m}$ as the D-C magnets, then for the required angle deflection at the injection rigidity of $B\rho=4.066\text{ T-m}$ of 22.2 mrad , the required magnetic field is only $B_{\text{bump}}=1.129\text{ kG}$.

In Fig. 4.3-10 it should be noted that magnets B_1 , and B_4 are actually splitter magnets, or could indeed be two Septum magnets side by side which bend the H^+ and H^- beams in the same direction in B_1 and for B_4 , the circulating plus residual H^+ beams in opposite directions. A second stripper foil immediately upstream of B_4 to strip the H^0 's that emerge from the primary stripper foil S_1 is envisioned. Not shown in Fig. 4.3-10 are a pair of vertical and horizontal deflecting magnets in the primary H^- incident beam to provide the exponential time-dependent angle deflection of the H^- beam spot at S_1 so that the acceptance ellipse center X_c, Z_c will track the ellipse axes $(x', z') = -(\alpha/\beta)(x, z)$. The maximum deflection at S_1 as seen from the parameters in Figs. 4.3-6 and 4.3-10 is $x'_m=9.65\text{ mrad}$.

Elastic lab differential cross section, $p + C^{12}$, $E_p = 600\text{-MeV}$.

Fig. 4.3-4

Space charge tune shift vs. radius for Gaussian distribution.

Fig. 4.3-5

x-x' phase space distribution, 600 turn H⁻ injection through 300 µg/cm² C¹² stripper foil.

Fig. 4.3-6

Traversals/proton and proton losses vs. turn number in 300 turn H⁻ injection through 300 µg/cm² 10 mm x 10 mm C¹² foil at 600 MeV.

Fig. 4.3-7

H^- to H^+ conversion fraction, 600-MeV H^- on C^{12} .

Fig. 4.3-8

Traversals/proton and proton losses vs. turn number in 600 turn H^- injection through 600 $\mu\text{g}/\text{cm}^2$ 20 mm x 160 mm C^{12} foil at 600-MeV.

Fig. 4.3-9

FRACTIONAL MAGNETIC STRIPPING H^- LOSS = 10^{-4} /m
 $B = 5.366$ kG AT $E_k (H^-) = 600$ MeV
 ADMITTANCE $A = 400\pi$ mm-mrad

L straight = 444 cm
 NOT TO SCALE

$\beta_s = 7.96$ m
 $\alpha_s = -1.36$
 $\eta_{xs} = 2.21$ m

Injection straight section for spallation neutron source with
 600-MeV H^- . DC + fast bump.

Fig. 4.3-10

Magnetic stripping fractional loss for H^- ions.

Fig. 4.3-11

4.3.4 RF Capture Efficiency in the SNS Synchrotrons

The mechanism of RF capture in the 3.6 GeV proton synchrotrons of the SNS has been studied by numerical simulation in the longitudinal phase space with the code ESME³⁴ from Fermilab. This code solves the Courant-Snyder synchrotron equations for an ensemble of representative particles, given magnetic field and RF voltage as a function of time. Space charge and beam-to-wall impedance effects are also calculated as an additional acceleration voltage proportional to the total beam charge and dependent on the longitudinal shape of the beam bunch. For this, a table of impedance is used as input. For the SNS synchrotron, several injection and acceleration modes have been investigated, in order to minimize particle losses, namely: (i) injection at different times in the acceleration cycle, (ii) chopping the beam pulse from the linac at a number of phase windows, (iii) modulation of the injection energy or off-energy injection. Results are presented below.

The model and the parameters of the synchrotron for the simulations are as follows: the magnet cycle is sinusoidal, with corresponding proton kinetic energy ramping from 0.6 GeV at injection to 3.6 GeV in 16 msec. The total beam charge is $1.45 \cdot 10^{14}$ protons per pulse. Harmonic number is 2. The RF voltage reaches 0.7 MV at mid cycle and is tailored to keep the bucket area between 15 and 40 MeV-sec. The overall impedance of the machine has been assumed constant with a value of $Z/n = 10$ ohm (capacitive). The injection time duration is ~ 0.4 msec, corresponding to a train of 300 pulses from the linac. These parameters characterize the synchrotron as a fast cycling machine with a high beam intensity and, hence, large space charge induced effects.

30,000 representative particles have been used in the simulation, run on the Digital Corp. Alpha mainframe at BNL. To simulate multi-turn injection, the code ESME, that did not have this capability, was modified. This was an important step, because the injection cycle is taking a considerable share of the total accelerating time, and filling the bucket with all the charge at once would lead to an overestimate of the space charge effects.

Each injected pulse was represented in phase space by a distribution of representative points random uniform in phase and random gaussian in energy. The phase windows was taken between $\pm 60^\circ$ and $\pm 80^\circ$, corresponding to different degrees of chopping of the injected beam, and the σ of the energy gaussian was ± 0.2 MeV. The best results were obtained when the injection was done at the bottom of the sinusoidal magnetic field ramp. In this case, the first 150 pulses are injected while the field is decreasing and the following 150 turns are injected with the field increasing.

Figures 4.3-12 to 4.3-16 show results for a beam chopping of $\pm 70^\circ$.

Figure 4.3-12 shows the superposition of 5 buckets (one every 10 turns) and the injected population for 50 turns at the beginning of the injection cycle. In this case, the bucket height is 16.2 MeV and bucket area 14.6 MeV-sec. As the figure shows, the protons have started their synchrotron oscillation counter-clockwise in the bucket. Since the magnetic field ramp is decelerating, the cusp end of the bucket appears on the left end of the figure. Only a fraction of the many representative particles used in the simulation are shown, to make the figure more legible.

Figure 4.3-13 shows the superposition of 10 buckets and of the population for 100 turns, at the end of the injection cycle (turns 200 to 300). By this time the bucket is full, and the cusp appears on the right side, corresponding to an accelerating magnetic ramp.

Figure 4.3-14 shows 10 buckets and the population for 100 turns by the end of the accelerating cycle. Here, the bucket height is of the order of 60 MeV and the bucket area 40 MeV-sec. The final population occupies less than 2/3 of the available bucket space.

Figure 4.3-15 shows the losses together with some of the acceleration parameters, bucket area, proton kinetic energy and RF voltage as a function of time, during injection. Losses take place quite suddenly in the first half of the injection cycle, to reach their final value of 0.12%. Losses are mainly due to spilling of protons at the two ends of the bucket, right and left.

Figure 4.3-16 shows the same quantities as in Fig. 4.3-15 for the entire cycle. The figure shows that there are no further losses after the injection cycle is completed.

To further reduce capture losses, the first strategy was to chop the beam even more. Indeed, for a chopping of $\pm 65^\circ$, the simulation did not result in any loss of protons from the bucket, since the particles near the bucket ends were removed. However, a reduction in the phase window requires in turn a larger average current from the linac.

Figure 4.3-17 shows comparatively the losses for six cases, for chopping at $\pm 68^\circ$, $\pm 69^\circ$, $\pm 70^\circ$, $\pm 71^\circ$, $\pm 72^\circ$, and $\pm 74^\circ$. In all cases, after injection, no further losses appear. The figure shows that there is a very well defined loss threshold around 70° . The oscillations in the curves are in part artifacts of the calculations due to statistical errors when the number of particles in the simulation is not yet too large, but also indicate some loss and recapture by the moving bucket.

The results presented were obtained after a careful optimization work. We tried also to decrease the losses without closing too much the chopping acceptance window, by modulating the energy of the injected protons to match the motion of the bucket, in phase space, and to inject at a slightly higher energy than the bucket center of mass. Also, the injection timing was varied, and the RF voltage shape as well. In the case of injection entirely on the rising part of the magnetic ramp, one could in principle try to chop the beam asymmetrically, since the bucket itself stays non symmetric, a strategy that has worked well in other cases.³⁵ The results of all these attempts were rather marginal.

In conclusion, the simulation indicates that the RF capture losses in the longitudinal phase space can be contained within the limits of 10^{-3} to 10^{-4} . However, transversal space charge and impedance effects on the blow-up of the beam were not investigated. Simulation on similar machine structures has indicated in the past that in general one should expect transversal and longitudinal effects to be of the same order of magnitude.

SNS. 1994/01/10.16:11:12 run 201 p.7

Buckets and population for the first 50 turns of injection (at 0.6 GeV). Injection time centered on the bottom of the sinusoidal magnetic ramp. Chopper window $\pm 70^\circ$.

Fig. 4.3-12

SNS. 1994/01/10.17:35:39 run 203 p.4

Buckets and population for the last 100 turns of injection. Chopper as in Fig. 1.

Fig. 4.3-13

Buckets and population for 100 turns near the end of the acceleration cycle (at 3.2 GeV).
Chopper as in Fig. 4.3-12.

Fig. 4.3-14

SNS. 1994/01/10.16:48:55 run 201 p.0

-70 +70 deg
 $Q=1.4e14$
 30,300 parts in sim
 multi-turn injection
 symm inj around t=0
 no energy modulation

Bucket area, proton kinetic energy, RF voltage and losses during the injection process. Losses suddenly appear in the first half of the injection. Chopper as in Fig. 4.3-12.

Fig. 4.3-15

SNS. 1994/01/13.10:11:43 run 203 p.1

Bucket area, proton kinetic energy, RF voltage and losses during the entire acceleration, from 0.6 to 3.6 GeV. Chopper as in Fig. 4.3-12.

Fig. 4.3-16

SNS. 1994/01/13.13:07:10 run 203 p.2

Comparison of losses during injection for six different chopper windows. Losses start to appear at $\pm 67^\circ$, to exceed 1% at $\pm 75^\circ$. After injection, with the parameters chosen, there are no further losses.

Fig. 4.3-17

4.3.5 RF System

4.3.5.1 Introduction

The rf system for the synchrotrons of the spallation neutron source is designed to accelerate 1.4×10^{14} protons/pulse to an energy of 3.6 GeV. Injection energy is 600 MeV. The synchrotron repetition frequency is 30 Hz. The choice of RF operating frequency, i.e. 1.3 to 1.6 MHz, is the second harmonic of the revolution frequency. The advantages of such a low frequency system are: 1) there will be two bunches in the machines and the time between bunches will be sufficiently long to allow for the rise time of the extraction kicker. No "missing bunch" operation will be necessary, which simplifies injection, and transient beam loading problems are avoided. 2) With only two bunches there are no unstable coupled-bunch modes of longitudinal instability. 3) In multi-gap low frequency cavities the transient time factor is essentially unity because the rf wavelength is much longer than the cavity dimensions. 4) Cavities in this low frequency range are basically lumped-element type structures, where the sources of the inductance and capacitance are clearly identified. This allows effective control of higher order mode impedances. 5) Ferrite-loaded low-frequency cavities are necessarily low impedance structures; ferrites are lossy. This low impedance makes it possible to achieve system stability without large amounts of feedback in a heavily beam loaded system. 6) Extensive experience exist at BNL in building rf systems in this range of frequency, voltage, and power level.

The major rf system parameters are listed in Table 4.3-5. The system configuration showing the cavity cross-section and the RF excitation is given in Figure 4.3-18. Four ferrite water-cooled stacks are arranged to form two gaps. The gaps are connected in parallel, with external bus bars. The bus bars are also used in the bias circuit, feeding the ferrite tuning current. This is shown in Figure 4.3-19. A figure-eight winding couples two stacks within a gap to balance the gap voltage, equalizing the RF voltage across each stack.

4.3.5.2 Cavity Design

The cavity uses Philips (Ferroxcube) 4M2 ferrite. Small sample loss measurements of this ferrite are available in the range of 2.5 MHz to 4.2 MHz. Figure 4.3-20 gives this data. This ferrite is used in the AGS Booster Band III cavity. This data has been projected to a frequency of 1.3 MHz. The RF injection frequency (1.3 MHz) determines the maximum RF flux density, hence the required volume of ferrite.

The design value for peak flux density is limited by the maximum heat loss that can be accommodated with water cooling. Experience limits water-cooled ferrite to an average dissipation of 200-250 mW/cc; or 400-500 mW/cc for a 50% duty factor. The projected ferrite loss at 1.3 MHz would allow a flux density of 400 Gauss. For a conservative design the flux density is limited to 300 Gauss. Ferrite ring sizes are consistent with rings that have been previously utilized, i.e. the AGS Booster uses $23 \times 50 \times 2.7 \text{ cm}^3$ rings and the AGS uses $20 \times 50 \times 2.8 \text{ cm}^3$ rings.

Table 4.3-5
RF System Specifications

Intensity	1.4×10^{14} protons/ring/pulse
Harmonic Number	2
RF Frequency at Injection	1.31 MHz
RF Frequency at Extraction	1.62 MHz
Repetition Rate at Extraction	30 Hz
Duty Factor	50%
Peak Voltage	800 kV
Beam Current (dc component)	18.1 Amperes
(rf component)	28.3 Amperes
Peak Power to Beam	7 MW
Peak Power Dissipated in Ferrite	1 MW
Total Peak Power	8 MW
Number of Cavities	8
Gaps per Cavity	2
Length of Cavity	360 cm
Peak Voltage	100 kV/Cavity, 50 kV/gap
Number of Amplifiers per Cavity	1
Amplifier Peak Power	1 MW
Robinson Resistance	45.7 k Ohms/ring
	5.7 k Ohms/cavity

The design parameters and heat loss calculations are given in Table 4.3-6. The costs estimate is based on a cost of \$1500 per Booster ring.

The electrical parameters of the cavity are given in Table 4.3-7. The tuning capacitance is to a large extent determined by the volume of ferrite and cannot be arbitrarily selected. The adequacy of a gap capacitance of $650 \mu\mu\text{F}$ is determined by evaluating the transient beam loading. The injection of an impulse of current with a moment that is equivalent to the charge per bunch ($11.2 \mu \text{ Coul}$), retards the RF voltage by 19° . By comparison, injection from the Booster into the AGS produces a phase retardation in the RF voltage of 25° to 30° . The equivalent steady-state beam loading, measured by the stress on the tuning loop, is evaluated in terms of the fractional detuning of the resonant circuit. The fractional detuning of .043 is 20% of the cavity tuning current needed to follow the rf sweep. The detuning of the cavity is less than one half of the loaded cavity bandwidth.

Lacking measured data on Ferrite loss in the frequency range of 1.3 - 1.6 MHz a conservative design is employed. If, based on future loss measurements in this frequency range, a larger value of flux density can be employed, than the volume of ferrite can be reduced. This will increase the value of gap capacitance and also reduce the cost of ferrite.

Table 4.3-6
Cavity Design Parameters and Heat Loss Calculations

Ferrite Rings

Material:		Philips 4M2
OD	=	50 cm
ID	=	20 cm
Ferrite Thickness	=	2.8 cm
Cooling Plate Thickness (edge cooling)	=	0.3 cm
Number of Plates per Stack		25
Length of Stack	=	77.8 cm
2 Stacks per Gap		
4 Stacks per Cavity		
Total Length of Stacks	=	311.2 cm
Volume of Ferrite	=	450,000 cm ³
Weight of Ferrite	=	2245 kg
Estimated Cost of Ferrite		\$168,000

Performance

Maximum Voltage	50 kV/Gap 100 kV/Cavity
Flux Density Maximum	300 Gauss
Peak Dissipation	0.2 W/cm ³
Average Dissipation	0.1 W/cm ³
Peak Dissipation in Cavity	90 kW
Tuning Range of Cavity	1.3 to 1.6 MHz
Unbiased Value of μ	140
Initial Value of μ	92
Final Value of μ	60

4.3.5.3 RF Design

Each cavity is excited by a one-tube Class AB₁ power output stage. The tube is link coupled to the cavity through a one-turn transformer formed between the beam pipe and the plate lead. The RF link runs through the annulus formed between the beam pipe and the ferrite rings as is shown in Figure 4.3-18. The RF flux magnetically couples the link with the beam pipe. Other than a RF bypass capacitor, no additional RF components are required.

The insulation of the plate lead is stressed only by the DC plate supply voltage, 27.5 kV. Silicon insulated leads rated at 60kV DC are available with an CD of 1 cm.

The power tube is a tetrode EIMAC 8973. With water cooling of the anode, the tube is rated to dissipate 1 MW. The tube operating voltages and calculated electrode currents and dissipation are given in Table 4.3-8. These values are compared with their rating. The plate circuit is designed on an average basis, while the grid and screen are designed on a peak basis. The plate thermal time constant, 200 milliseconds, is much greater than the cycle on time, 16.7 milliseconds. The grid and screen thermal time constants are comparable with the cycle on time. The grid drive power is estimated on a configured bandpass filter coupling the driver to the output stage. The design is conservative; the tube is operated well within rating.

The rf load line is constructed on the constant current characteristics of the tube, Figure 4.3-21. The rf phase is indicated as a running parameter on the load line. The dynamic plate resistance r_p is calculated as a function of RF phase from the tube characteristics. Each value of r_p contributes to the tube's output resistance R_{eq} as a function of the value of voltage swing or RF phase. This calculation is summarized in Table 4.3-9.

Table 4.3-7
Electrical Parameters of Cavity

Inductance	22.9 μ H/gap ($v = 50$ kV) 45.8 μ H/cavity ($v = 100$ kV)
Tuning Capacitance	650 pF/gap ($v = 50$ kV) 325 pF/cavity ($v = 100$ kV)
Ferrite Loss Resistance	27.8 k Ohms/gap 55.6 k Ohms/cavity
Unloaded Q of Cavity	(Ferrite losses) 183
Loaded Q of cavity (Ferrite losses, amplifier with 10 db of feedback)	10.4
Transient Beam Loading	$\Delta Q = (\text{Charge per Bunch}) = 11.2 \mu\text{Coul}$ $C = 325$ pF $V = 100$ kV $\frac{\Delta Q}{CV} = .344$
Induced Phase Shift	19° - impulse 12.1° - half wave sinusoid
Steady State Beam Loading	
Beam Current	28.3 A (peak rf)
ΔC	28 pF/Cavity
Fractional Detuning	$\frac{\Delta F}{F} = .043$

The calculated value of R_{eq} is combined with the ferrite dissipation to give the output resistance R_{out} and is compared with the Robinson resistance. These results are given in Table 4.3-9. Since the output resistance R_{out} is greater than the Robinson resistance, negative voltage feedback must be employed to keep the resistance below the threshold for beam-loading instabilities. As a minimum 4.8 dB of feedback (gain reduction) is required. Practically 10 dB of global feedback should be employed.

Table 4.3-8
Tube Parameters EIMAC 8973, Class AB₁ Operation

		<u>Tube Rating</u>
Plate Voltage	27.5 kV	30 kV
Screen Voltage	1.5 kV	2.5 kV
Grid Voltage	-400 Volts	
Peak Grid Drive Voltage	370 Volts	
Grid Drive Power	500 Watts	
Zero Signal Plate Current	10 A	
Peak Plate Current	180 A	
# Average Plate Current (Peak)	62 A	
* (Aver.)	36 A	110 A
Peak Load Power	1000 kW	
# Plate Dissipation (Peak)	705 kW	
* (Aver.)	490 kW	1000 kW
P _{BB} - Plate Power Supply	1705 kW	
# Peak Screen Current	10 A	
# Average Screen Current	1 A	
# Screen Dissipation	1.5 kW	7.5 kW

* Averaged Basis, Tube on time 16.7 millisec.

Plate thermal time constant 200 milliseconds

Peak Basis

Averaged during tube on time

Table 4.3-9
Beam Damping for EIMAC 8973

BEAM DAMPING

Ring

Beam Power	7 MW
Accelerating Voltage	800 kV
Number of Cavities (stations)	8
Robinson Resistance	45.7 k Ohms
	5.71 k Ohms/station

EIMAC 8973

From Load Line

$$\frac{1}{R_{eq}} = \frac{1}{3} \left[\frac{.067}{r_p(15^\circ)} + \frac{0.5}{r_p(15^\circ)} + \frac{0.933}{r_p(75^\circ)} \right]$$

Req = 759Ω at 25 kV level

referred to 100 kV level 12.14 kΩ

$R_{ferrite}$ 55.6 kΩ
 $R_{out} =$ 9.96 kΩ

requires negative voltage feedback

Minimum Gain Reduction 1.75 dB
 (4.8 dB)

Design for 10 dB of Feedback

4.3.5.4 Alternate RF Design

An alternate RF design employing a classical push-pull amplifier is given in Figure 4.3-22. This arrangement employs two water cooled tubes operated Class AB₂ and rated for a plate dissipation of 300kW/tube. To match the voltage ratings of the tube and gap, each ferrite stack is tapped at ½ the stack length. The tube operating voltages and calculated electrode currents and dissipation are given in Table 4.3-10. The output resistance of the amplifier is calculated and

compared with the Robinson resistance, Table 4.3-11. To provide adequate damping 16 dB of global feedback should be provided for the alternate configuration.

A second configuration, matching the voltage rating of the tube and gap, utilizes four gaps. The ferrite rings are divided into 8 stacks, two stacks per gap. The value of tuning capacitance is doubled ($1300 \mu\text{F}/\text{gap}$). This arrangement is shown in Figure 4.3-23. The cavity design shown in Figures 4.3-22 and 4.3-23 are driven by the same power stage. The designs shown here are balanced and do not require a figure-of-eight RF winding.

To a large extent the output resistance of the cavity is dependent on the squares of the voltage ratio between cavity and tube. The plate resistance of tubes in this power range have relatively similar values of r_p at the same current level, i.e., the tubes are designed with the same value of perveance. For the level of beam loading encountered in this application, the Robinson criterion cannot be satisfied with an open-loop amplifier. Negative voltage feedback must be employed. To minimize the quantity of feedback required, tubes with the largest rated value of plate voltage should be employed.

The large value of gap voltage employed might require that the cavity be immersed in a dry inert gas under a few atmospheres of pressure. This will increase the sparking threshold potential within the cavity structure by a factor that is approximately proportional to the pressure. Based on experience with the AGS Booster cavity (45 kV per cavity) an increase in the sparking potential by a factor of 2.25 is known to be sufficient.

The low value of output resistance required for this application can be achieved with a cathode follower. Two characteristics of the cathode follower render this configuration unsuited for the intended application. With the bandwidth requirement of 300 kHz and an input capacitance to the tube of $1000 \mu\text{F}$, the RF drive power is comparable with that of the final stage. The drive power is estimated as 400 kW. In addition the cathode follower driving a resonant load can be unstable. At frequencies where the load appears capacitive, the configuration is that of a Colpits oscillator.

4.3.5.5 Cavity Bias and RF Balance

A scheme for tuning the cavity is also shown in Figure 4.3-19. The bias or tuning current is directed through the cavity by employing the bus bars, beam pipe, and cavity body with two DC breaks as a continuous loop. The net flux encircled by the loop within the cavity structure of four ferrite stacks is zero. The loop encircles the flux contained within the bus bar structure. A balanced low pass filter isolates the residual magnetic flux from the tuning loop. Otherwise this flux would induce voltages within the loop and bias supply.

A figure-eight winding balances the gap voltage, equalizing the dissipation in each half of the ferrite stacks. The beam does not respond to an unbalance of the gap voltage. The beam is accelerated by the net gap voltage. Balance of the gap voltage minimizes dissipation within the

ferrite and voltage stress within the cavity. This winding is optional and its inclusion must be evaluated in terms of the final design numbers.

Table 4.3-10
Tube Operation (alternate design) EIMAC 4CM300,000
Class AB₂ Operation

		<u>Tube Rating</u>
Plate Voltage	15 kV	20 kV
Screen Voltage	2 kV	2 kV
Grid Voltage	-500 Volts	
Peak Grid Voltage	560 Volts	
Zero Signal Plate Current	5 A	
Peak Plate Current	180 A	
Peak Plate Dissipation	430 kW	
Average Plate Dissipation (50% Duty Factor)	252 kW	300 kW
Average Plate Current		
CW Basis	62 A	
50% Duty Cycle	36 A	50 A
P _{BB} - Plate Supply	930 kW/tube	2 required
Average Screen Current	2.2 A	
Screen Dissipation		
CW Basis	4.4 kW	6 kW
50% Duty Cycle	2.2 kW	
Average Grid Current	1 A	
Grid Driver Power for Two Tubes	1500 Watts	
Grid Dissipation	60 Watts	2 kW

Can use Thomson TH 573

Table 4.3-11
Beam Damping for Alternate Design

Using 4CM 300.000

2 Tubes
 $r_p = 400\Omega/\text{tube}$ from Booster studies
 Class B = 800Ω at 12.5 kV level
 Referred to 100kV level 51.2 k Ohms/Tube
 2 Tubes 25.6 k Ω
 R_{ferrite} 55.6 k Ω
 R_{out} 17.5 k Ω

Requires negative voltage feedback
 Minimum Gain Reduction 3.06 (9.7 dB)
 Design for 16 dB of feedback

4.3.5.6 Conclusion:

The design of an rf system for the synchrotrons of the Spallation Neutron Source is described. The system works at a low frequency using the second harmonic of the revolution frequency. A system based on a 1 MegaWatt tetrode, link coupled to a two-gap cavity, is shown to be superior and more conservative to other schemes using two 300 kW tetrodes coupled to two or four-gap cavities. The designs are based on straightforward extensions of techniques recently employed in the AGS Booster and AGS rf system upgrade.

2 of 3

SYSTEM CONFIGURATION
CAVITY CROSS-SECTION AND RF EXCITATION

Fig. 4.3-18

Fig. 4.3-19

FERRITE BIAS SCHEME USING BUS BARS AND CAVITY STRUCTURE
ARROWS INDICATE BIAS CURRENT

C = TUNING
CAPACITOR

Ferrite Loss Measurements (2.5-4.5 Mhz)
and Projection to 1.3 Mhz

Fig. 4.3-20

Load Line Construction
1 MW Class AB₁ Power Amplifier

Fig. 4.3-21

ALTERNATE DESIGN

Fig. 4.3-22

4.3-43

Fig. 4.3-23

4.3.6 Low-Level RF Beam Control

The rf systems of the synchrotron will be equipped with the standard complement of feedback control loops. The required loops are: 1. a fast phase loop to damp coherent dipole synchrotron oscillations, 2. a radial control loop that regulates the beam position throughout the acceleration cycle, 3. automatic level control on the voltage of each acceleration cavity, and 4. a tuning servo for each cavity that keeps the cavity on resonance as the rf frequency changes. The presence of rf feedback loops at the cavity power amplifiers relaxes significantly the demands of these low-level control loops. Since the machines operate with only two bunches, no bunch-by-bunch longitudinal damping will be called for. The rings will have a fast longitudinal beam pick-up, such as a wall-current monitor, to feed the phase feedback loop, and a pair of radial pick-ups, situated approximately one-half betatron wavelength apart, to supply the radial feedback loop.

One special requirement of the low-level beam control equipment arises from the fact that the rf harmonic number is two, whereas the number of accelerating cavities is eight. The implication of this is that cavities cannot be placed on the ring such that the rf phase of all the cavities is the same. If the physical angle between the cavities on the ring is 45 degrees the electrical phase between them must be 90 degrees. The 90 degrees of electrical phase must be maintained as the rf frequency changes. However, because the cavities are individually powered with separate power amplifiers, the phase shift can be implemented in the low-level circuits. Modern rf technology with digital frequency synthesizers and high speed linear components provide the means for very accurate and frequency-independent phase shifters.

The low-level beam control system will use an on-line measurement of the effective magnetic field in the ring to pre-program the rf frequency and control the precise timing of beam injection and extraction. Typically this measurement is made in a reference magnet located outside the ring but electrically in series with the ring magnets. This allows the measurement to be made inside the vacuum chamber so that eddy current effects that influence the magnetic field acting on the beam can be taken into account.

4.3.7 Ring Impedance. Beam Instabilities

4.3.7.1 Estimate of the Ring Impedance

The particles circulating in the synchrotrons induce currents and fields in the vacuum chamber, bellows, pick-up electrodes, rf cavities, and other beam components such as kickers, dampers, and septum magnets. These induced currents and fields react back on the beam and can give rise to unstable beam motion. To calculate these effects, a coupling impedance Z is defined³⁶. For the longitudinal case, Z is the longitudinal voltage produced per unit of current.

The impedance of the beam components were estimated using the program ZOVERN³⁷. The dominating impedance is that of the vacuum chamber. Since γ never exceeds 5 and because of the low cut-off frequency, the beam is well-shielded from free space by the vacuum chamber.

The largest contribution to the longitudinal coupling impedance is given by the space charge,³⁸ it is

$$Z / n = i Z_0 g / 2 \beta \gamma^2 \quad (1)$$

with $Z_0 = 377$ ohm and $g = 1 + 2 \log (b/a)$, $n = f/f_0$, where f_0 is the revolution frequency. At injection $g \approx 1$ and $Z/n = 100 i$ ohm, and at extraction $g \approx 4$ and $Z/n = 30 i$ ohm. The space-charge impedance has a cut-off in the proximity of:

$$n_c \approx \gamma R / b \quad (2)$$

For an average $b = 8$ cm, the cut-off harmonics range between 1200 and 3500.

The other large contribution is expected from the electromagnetic environment within the dipole and quadrupole magnets and depends on the method of manufacturing the vacuum chamber. At the present, to avoid excessive eddy currents due to the large field variation, a thick ceramic vacuum chamber is being contemplated. The ceramic alone exposes the beam directly to the presence of the magnet lamination. The lamination impedance is essentially resistive over a large bandwidth, essentially up to the cut-off set by the inner dimension of the vacuum tank. Extrapolation from the estimates³⁹ and the measurements of the Fermilab Booster magnet⁴⁰ gives an impedance of about 50 ohm / m. This value, coupled to the large bunch intensity and the short length of the bunches, is too large to be tolerated because it causes an energy loss³⁹ which is comparable to the actual rate of energy gain required for the acceleration cycle. It is thus mandatory to cover the interior side of the ceramic vacuum chamber with metallic strips running along the length of the magnet. The strips are to be separated sufficiently to impede the flow of eddy currents, and are to be wide enough to provide at the same time effective screening of the beam from the lamination impedance, at least in the frequency range extending to cut-off. The thickness of the strips is also important. As a general criterion, we require that the thickness is at least two times the skin depth at the lowest frequency of concern which is a mode of betatron oscillation corresponding to the

frequency $f_0 = (n - \nu) f_0$, where n is the closest integer to the betatron tune ν . With our parameters $f_0 \approx 100$ kHz. Using Silver as the conductor, a thickness of at least 0.15 mm is required.

The next item to investigate is the resistivity of the walls. With the precaution taken of a ceramic vacuum chamber covered with properly chosen metallic strips, we can assume that to first approximation the entire vacuum chamber is metallic. In the regions of bending and quadrupole magnets the material is silver, and in the straight sections stainless steel. We take the model of a smooth vacuum chamber of cylindrical geometry with a radius $b = 6$ cm in the dipoles, and $b = 10$ cm in the quadrupoles and straight sections. The thickness of the wall is a few skin depths at the lowest frequency f_0 given above. The skin depth is

$$\begin{aligned} \delta &= 0.47 \text{ mm} / n^{1/2} && \text{for stainless steel} \\ &= 0.073 \text{ mm} / n^{1/2} && \text{for silver} \end{aligned} \quad (3)$$

The total contribution of the resistive vacuum chamber to the longitudinal coupling impedance is,⁴¹

$$Z / n = 0.9 (1 - i) \Omega / n^{1/2} \quad (4)$$

All the quantities above are independent of the beam energy. There is a cut-off harmonic number n_c for this contribution also, which is 3500.

There are 64 beam position monitors, each made of two parallel strip lines 15 cm long with their termination impedance matched to the characteristic impedance of 50 ohm. There are also 8 similar devices used as clearing electrodes distributed in the region of injection. The combined contribution of the beam position monitors and clearing electrodes is estimated to be⁴²

$$Z / n = -0.8 i \Omega \quad (5)$$

There are also 128 bellows made of Inconel. We take as a model the configuration adopted in the AGS Booster. Each bellow has 15 ribs or convolutions. The convolutions are 12 mm high and the distance from the peak of one convolution to the next is 20 mm. Each convolution acts as a small resonating cavity^{39,43} with several dominating modes. There is only one resonant frequency within the pipe cut-off which is at $f_r = 6.2$ GHz. The figure of merit of the resonance is $Q \approx 7000$ and the shunt impedance is $Z_s \approx 100$ kOhm. If all the convolutions were identical in shape, their total contribution to the longitudinal coupling impedance would be, at resonance,

$$|Z / n| = 13 \text{ k}\Omega \quad (6)$$

However, the convolutions will not be identical (and if they would naturally be too much alike they can be intentionally altered so as to be dissimilar). Since they are not all the same, there will not be a single sharp resonance line but instead a distribution of resonating frequencies. If it is assumed that the resonating frequencies are randomly distributed over a range equal to $\pm 10\%$ of the central frequency, then, at resonance,

$$|Z/n| = 14 \text{ ohm} \quad (7)$$

Below the resonating frequency, the coupling impedance is inductive and small⁴⁴,

$$Z/n = -2.3 i \Omega. \quad (8)$$

There are 128 locations where the vacuum chamber changes shape; these are the transitions between the dipole and the quadrupole magnets. ZOVERN treats steps as going from one circular geometry to another. In the synchrotrons, the portion of the beam tube in the dipoles is somewhat rectangular in cross section. But if the chamber is treated as a circular pipe of 6 cm radius going to one with a 10 cm radius, for the total coupling impedance contribution⁴⁵,

$$Z/n = (1 - i\pi) 0.1 \Omega \quad (9)$$

The beam sees eight rf cavities, each with two gaps. For all the cavities, which act simultaneously, $h = 2$. In order to determine Z/n , it is necessary to know the shunt impedance of each gap and the Q of each cavity for the beam loading of interest. This information is not yet available.

In order to calculate the longitudinal coupling impedance of the other beam components - kicker magnets, magnets for the damping system, septum magnets, electrostatic septum, etc. - it is necessary to know the length of each component, the resistivity of the ferrite, the relative permeability of the ferrite, and the mean distance of the ferrite from the beam. For the transverse coupling it is necessary to know the distance from one side of coil to the other for each coil. This information is not yet all available.

There are four major contributions to the transverse coupling impedance⁴⁶ in the synchrotrons.

1. The Space Charge. The expression for the contribution is

$$Z_{\perp} = \frac{iRZ_0}{\beta^2 \gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2} \right) \quad (10)$$

where as usual $Z_0 = 377 \text{ ohm}$, a is the average beam radius and b is the vacuum chamber radius. There is a weak variation of the values of $Z_{\perp}$ during the acceleration cycle:

$$\begin{aligned} Z_{\perp} &\approx 1.6 i \text{ M}\Omega / \text{m} \text{ at injection} \\ &\approx 0.9 i \text{ M}\Omega / \text{m} \text{ at extraction} \end{aligned}$$

2. The Wall Resistivity. The expression for this contribution is

$$Z_{\perp} = \frac{(1-j)R}{b^3} \left(\frac{2RZ_0\rho}{\beta(n-\nu)} \right)^{1/2} \quad (11)$$

where R is the average radius of the closed orbit, ρ the wall resistivity, and ν the betatron tune number. The contribution is small compared to the space-charge effect.

For $(n - \nu) = (8 - 7.8)$,

$$\begin{aligned} Z_{\perp} &\approx 7.5 \text{ i k}\Omega / \text{m at injection} \\ &\approx 6.8 \text{ i k}\Omega / \text{m at extraction} \end{aligned}$$

3. In the circular approximation, by virtue of the deflection theorem, the longitudinal coupling impedance estimate can be translated into an equivalent transverse coupling impedance

$$Z_{\perp} = \frac{2R}{\beta b^2} \frac{Z}{n-\nu} \quad (12)$$

If we take $|Z / (n - \nu)| \approx 1 \text{ ohm}$ as previously estimated, then

$$|Z_{\perp}| \approx 22.8 - 18.5 \text{ k}\Omega / \text{m}$$

4. Finally there are transverse modes proper due to several resonating structures, like rf cavities, but they are difficult to estimate and can usually be observed with the beam itself or with measurements with wires on a bunch.

4.3.7.2 Beam Instabilities

As usual, these can be classified as longitudinal and transverse instabilities, and bunch-to-bunch and individual-bunch instabilities. The presence of only two beam bunches greatly simplifies the analysis, since it essentially removes from any concern the coupled-bunch type of instability^{47,48}. Nevertheless the bunches are relatively long and internal modes peculiar of the individual-bunch type of instability^{46,47} are expected to develop. Fortunately the bunch area and the resulting beam momentum spread are large enough to introduce a considerable amount of Landau damping⁴⁹.

We shall treat next the longitudinal and transverse individual-bunch instability separately. We expose first some features which are common to both. In absence of a complete theory of instability for bunched beams, the coasting beam theory is usually applied ad hoc^{50,51}, where average currents and momentum spreads are replaced with the peak values. Instabilities are described by a wavelength λ and a mode number n related to each other as $n = 2\pi R / \lambda$. The wavelength is at most the bunch length L and correspondingly the mode number has to be sufficiently larger⁵¹ to be of any concern, that is $n > 2\pi R / L$.

The strategy is to determine first the growth rate of the instability for the worst case in the absence of Landau damping. The growth rate is then compared to the frequency of the synchrotron oscillations⁵¹. The beam may be unstable only if the growth rate is larger than the synchrotron frequency, except in the transverse direction where the head-tail type of instability may take place. If the beam is determined to be unstable, then the amount of Landau damping required for stability is estimated. The beam bunch may be unstable also when two modes of oscillations next of each other are affected by a frequency shift which would bring them to overlap⁵². In the last case, the instability is said to be turbulent⁵³.

Finally we point out that the acceleration cycle is entirely below the transition energy. This is judged to be the most favourable situation from the beam stability point of view. This fact is to be kept present for the understanding of the following comments. We have used the recently developed program⁵⁴ PACSTO to estimate the beam stability.

1. Longitudinal. We have seen that the beam-wall coupling impedance is dominated by the space-charge contribution. At the same time, the resistive contribution should be kept to a low value which we have assumed to be 3 ohm. Because of this more or less fortunate situation, it is not obvious that an electromagnetic screening of the beam from the magnet lamination is required. The only effect of concern due to the magnet lamination³⁹, as we have seen, is the energy dissipated to the resistive impedance.

It is easily seen that the beam is stable against longitudinal microwave instability. Eventually only the presence of the resistive wall impedance could make the beam unstable. We have taken a contribution of 3 ohm to the resistive part of Z/n , and we have added an inductive wall contribution of $-10 i$ ohm due to the space charge. The U' and V' parameters^{41,55} which are given by

$$U' - iV' = -i \frac{2eI_p \beta^2 Z/n}{\pi \alpha \parallel \eta \parallel E (\Delta E/E)_{FWHM}^2} \quad (13)$$

are plotted in Figure 4.3-24 during the acceleration cycle. These parameters are evaluated to determine the beam stability⁵⁵. In good approximation the beam is stable if the following condition is satisfied

$$|U' - iV'| < 0.7 \quad (14)$$

In Eq. (13) I_p is the bunch peak current plotted in Figure 4.3-25, E is the particle total energy, ΔE is the energy spread and $\eta = 1/\gamma_t^2 - 1/\gamma^2$. Even in the case that Eq. (14) is not fulfilled, in order for a bunch to be unstable either one of two conditions are to be satisfied. The first condition⁵¹ requires that the growth rate of the instability is larger than the synchrotron frequency. The ratio of these two quantities, referred to as the Hereward parameter is plotted in Figure 4.3-26. The beam can be unstable also when the difference of the frequency shifts of two neighboring modes is larger than the revolution frequency⁵². The ratio of the difference to the revolution frequency,

referred to as the coupled-mode factor, is also plotted in Figure 4.3-26. It is seen that neither of the two conditions are satisfied and, therefore, that the beam is stable.

2. Transverse. The lowest mode number that can support an instability across the bunch is given approximately by the bunching factor, defined as the ratio of the beam peak current displayed in Figure 4.3-25 to the average current which varies between 15 and 18 A during the acceleration cycle. The lowest mode number thus ranges between 4 at injection and 9 at extraction. The most dangerous mode is $n = 8$ because of its proximity to the betatron tune $\nu = 7.8$.

In the worst case of no Landau damping, the growth rate of an instability within an individual bunch in the transverse plane is given by⁴⁶

$$\tau^{-1} = \frac{i_p R_0}{e v \gamma Z_0} \operatorname{Re}(Z_{\perp}) \quad (15)$$

where $r_0 = 1.535 \times 10^{-18}$ m, the classical proton radius. This formula is valid in the case that the growth rate is larger than a synchrotron oscillation period (fast head-tail instability). Only the real part of the transverse coupling impedance $Z_{\perp}$ gives a contribution to the instability growth rate. We could identify only the resistivity of the wall as the major contributor to the real part of $Z_{\perp}$, especially in the low frequency range. Inserting the corresponding value, we obtain $\tau^{-1} \approx 1$ kHz throughout the acceleration cycle. This is to be compared to the synchrotron oscillation frequency that varies between 5.2 kHz at injection and 0.65 kHz at extraction. Thus no resistive-wall instability should be expected.

Another large contribution to $Z_{\perp}$ is expected in proximity of the vacuum chamber cut-off where the bellows have a resonance and the longitudinal coupling impedance is expected to be, as we have seen, as large as 14 Ω . By means of the deflection theorem, $Z_{\perp} \approx 200$ k Ω / m, which yields a growth rate, in absence of Landau damping, $\tau^{-1} \approx 30$ kHz, considerably larger than the synchrotron oscillation frequency and, therefore, represents a possible instability. The associated mode number though is very large, $n \approx 10,000$.

The imaginary part of the transverse impedance $Z_{\perp}$ enters in the stability criterion that can be written as^{56,57}

$$Z_{\perp} = \frac{E_0 \pi \nu \beta \gamma}{e I_p R} \parallel (n - \nu) \eta + \xi \parallel \frac{\Delta p}{p} \quad (16)$$

where E_0 is the proton rest energy, $\Delta p/p$ is the bunch momentum spread, ξ the chromaticity and $\eta = \gamma_t^{-2} - \gamma^{-2}$. Because of the large contribution of space charge to the transverse coupling impedance, the stability criterion cannot be easily satisfied with the uncorrected chromaticity alone. On the other hand, the stability criterion is satisfied for sufficiently large mode numbers, $n > 50$ at injection and

$n > 500$ at extraction. In conclusion, fast transverse instability, typical of coasting beams, are not expected to appear in the synchrotrons.

The only other concern left is the possibility of slow head-tail instabilities^{46,58}, for which the stability criterion above does not apply. The parameter of relevance is the accumulated betatron phase shift

$$\chi = \xi Q \omega_0 \tau_L / \eta \quad (17)$$

where τ_L is the bunch length in time units. For the case of uncorrected chromaticity this quantity is positive and large (we are constantly below transition energy and $\xi < 0$), ranging between 150 at injection and 900 at extraction. The head-tail mode numbers m which are stable, also in the absence of Landau damping, can be estimated from the condition $m < \chi / 2 \pi$, which gives $m \approx 25$ at injection and ≈ 150 at extraction. Thus also the head-tail instability is unlikely to appear in the synchrotrons.

The U' and V' parameters during the Acceleration Cycle
 Fig. 4.3-24

Bunch Peak Current during the Acceleration Cycle
 Fig. 4.3-25

The Hereward and the Coupled-Mode Factors

Fig. 4.3-26

4.3.8 Beam Extraction

Extraction from the SNS fast cycling ring is performed in one turn. The basic extraction equipment consists of an orbit bump, a ferrite-core fast kicker, and an extraction septum. Just prior to reaching the proper proton beam extraction energy, the orbit bump is energized to bring the edge of the circulating beam close to the extraction septum. Then, at the proper energy, the fast kicker is triggered and deflects the beam across the septum into the external beam transport channel. The kicker rise time is sufficiently fast so that the beam crosses the septum in the space between two adjacent rf bunches or approximately 300 nanoseconds. The extraction septum is a Lambertson type and deflects the beam vertically.

The location of the extraction system will be in the long straight section which is opposite to the injection area. The straight section consists of four drift spaces of 5.075 meters each in a FODOFODOF arrangement, where the F's and D's refer to focusing and defocusing quadrupoles, respectively. The Lambertson septum is placed in the last drift space between the D and F quadrupoles. This placement avoids the necessity of a specially-constructed, wide quadrupole, which would be the case if the septum were placed downstream of an F quadrupole. The deflection of the septum is 200 milliradians which is required to clear the downstream quadrupole. This can be accomplished with a septum field of 0.8 Tesla over a length of 3.7 meters. The 0.8 Tesla field is the highest practical field for this type of septum. A full list of parameters for the septum is shown in Table 4.3-12.

Parameter	Unit	Fast Kicker	Septum
Type		Full Aper, Fe	Lambertson
Number/Sections		1/5	1/1
Deflection	mrاد	9.5	200
Core Length	m	4.0	3.7
Aperture (HxV)	cm	28 x 18	16.6 x 20
Peak Field	kG	0.5	8.0
Current	kA-kAT	5.1	105
Voltage	kV/Section	80	--
Rise Time	usec	0.15	DC
Repetition Rate	Hz	30	DC
P.S. Type		PFN	Multiphase SCR

Table 4.3-12, Beam Extraction Components

The beam deflection of 9.5 milliradians, required to jump the 1 centimeter thick septum, is provided by a full-aperture, ferrite beam kicker system. The proton beam emittance is 88 (mm-mr) with a 2 percent momentum spread. The beam emittance of 320 mm-mr at injection is damped adiabatically to 88 mm-mr at the extraction energy. The kicker strength has to be 0.14 Tesla-meter and can be accomplished within a 5.0 meter straight section length (say 4.0 meter). Its rise time has to be shorter than the bunch-to-bunch spacing of the beam at extraction, or 300 nanoseconds. The kicker magnet will be rectangular in cross-section and will be divided into several sections to limit the peak voltage per section to values easily handled by existing switch tubes. The design parameters for the extraction fast kicker and its pulser are also shown in Table 4.3-12. The orbit deformation will be accomplished by separate dipole magnets pulsed by standard capacitor discharge power supplies. These will produce half-sine wave current pulses into the inductive magnets.

4.3.9 Beam Scraping and Loss Localization

Numerical simulations were performed⁵⁹ to estimate the efficacy of a simple beam scraping block in confining energy loss from rf capture inefficiency to a local region of the lattice. As discussed in Ref. 59 the very nature of the rapid cycling machine leads to the expectation that this loss will dominate the total beam loss.

The scraping block must be placed at (or very near to) the point of highest dispersion in the lattice to intercept uncaptured orbits which behave as increasingly off-momentum particles as the magnetic field rises. In the simulations a scraper composed of steel and 35 cm in length was shown to have an efficiency of greater than 75% for such orbits, where efficiency is defined as the number of protons which interact in the scraper divided by the number of protons incident. Furthermore, most outscattered protons emerge with large transverse divergence and interact in the lattice "close to" the scraper location. The basic conclusion of Ref. 59 is that 98% of injection capture loss could be confined to an approximately 8 m long section of the lattice.

The scraping simulations were performed at a time when the lattice design was not fully mature. Specifically, the lattice assumed in Ref. 59 had some long (~ 4.5 m) drift spaces which were coincident with regions of high dispersion. The scraper block could therefore be positioned a few meters away from the nearest magnet in order to minimize radiation damage effects in the magnet coil. In the lattice adopted, however, the highest dispersion (~ 4.1 m) occurs in a region where the drift space available is only 1.14 m in length. The primary concern therefore becomes the possibility of radiation damage in the conductor. The energy deposition in the "hot spot" of the magnet coil (a quadrupole) closest to the scraper was calculated (see also Sect. 4.4.2) to be 3.15×10^9 rad per 10 year of operation assuming a 1% rf capture loss. This exceeds the normal magnet coil insulation radiation limit of $\sim 10^9$ rad but gives a reasonable lifetime for a high rad coil (polyamide) whose limit is $\sim 2 \times 10^{10}$. At higher loss levels a special quadrupole with ceramic insulation might be considered.

4.3.10 Synchrotron Magnet Systems

4.3.10.1 Introduction.

The two 3.6 GeV fast cycling synchrotrons proposed operate at 30 Hz each with a biased sinusoidal excitation of the magnets. The very intense 5-MW pulsed neutron source requires 1.4×10^{14} protons per pulse in each of the rings, operating phased so that 60 Hz can be delivered to targets. The proposed solution to the 30 Hz vacuum chamber problem is to use ceramic chambers with a metallic grid or surface adjacent to the beams. This results in chamber walls which are estimated to be 1 cm thick.

The high intensity required results in magnets of large cross section to give the necessary acceptance, further increased to accommodate the thick walled vacuum chambers. These features, plus the necessity for 30 Hz excitation, requires special attention to magnet design features. Minimal losses of the very intense proton beams is mandatory and requires very high quality beam optical properties.

4.3.10.2 Dipole Magnets

The cross-section of a dipole magnet is shown in Fig. 4.3-27. Each unit is 2.8 m long and is curved through 7.5° .

The vacuum chamber inside dimensions are 16.5 cm vertically x 22 cm horizontally. This requires an 18.5 cm magnet gap. The pole width has been selected to be the minimum consistent with good uniformity over the necessary injection aperture. The 12 turns per pole racetrack coils are actually formed from a complex conductor. A cable-like conductor of 3 mm transposed and insulated strands surrounds a 1.2 cm diameter cooling water tube. A 50% overall packing factor of Cu conductor is assumed in each of the 12 turns of 2.54 cm x 7.5 cm cross-section.

The iron laminations can be punched from ≤ 0.5 mm silicon steel. The top and bottom magnet halves each require an assembly of 126 cm wide x 42.5 cm high laminations. These can be shuffled left to right to eliminate left-right punch and die asymmetry in the laminated assemblies. Insulation is required at the horizontal midplane matching surfaces. Alternatively, the midplane stampings are stepped so the top and bottom laminations only touch at the outside extremities. Curvature can be fabricated into the cores by assembly of sub-blocks from coated B-staged laminations which use partial width laminations on block ends. The entire 2.8 m long glued assemblies of half magnets can then have peripheral straps welded on them (not shown).

The FCS dipole magnet parameters are given in Table 4.3-13 and Table 4.3-14. Note the high Q (DC) assumes no losses other than the dc resistance of the copper coil. In practice losses will occur in the resonant power supply, in the magnet iron, as well as ac losses in the magnet coil. The core losses estimated are for a 2.8 m slice from magnets of infinite length. The magnet ends, even with

careful shaping, will have additional iron losses due to longitudinal end fields. For the 2.8 m long dipole these should add only a modest increase in core losses.

Coil ac losses are hardest to estimate. If cable is produced where the strands are fully insulated and yet adequately cooled, the ac losses should be quite small compared to dc resistive losses. However, several high frequency synchrotrons have used Cu or Al strands which are solder filled, resulting in ac losses which are a significant fraction of the dc resistive losses. This not only reduces Q significantly, with resulting major power supply cost impact, but will result in appreciable magnetic field aberration. This is not acceptable for a high performance, high intensity proton machine. If in the future it becomes necessary to pursue such a coil design, the magnet will have to be larger with resulting increase in stored energy so the coil is well removed from the aperture region so the exact location of current is not critical to field shape.

4.3.10.3 Quadrupole Magnets

The cross-section of the quadrupole is shown in Fig. 4.3-28. A 4-fold assembly is used, permitting race track coils to be assembled on the pole of each quadrant. The quadrupoles are very short (0.6 m) compared to the large 25 cm diameter bore. The glued quadrants can be assembled between end plates to give accurate 4-fold symmetry to control aberrations. Additional welded straps (not shown) can be applied to the periphery. Since the beam-stay-clear horizontal (BSCx) is greater than the BSC vertical, see Fig. 4.3-29, the ceramic chamber is not circular. In addition, in special sections for injection and ejection, the openness of the magnet on both midplanes permits special vacuum chambers to be used for beams entering or leaving the ring. Furthermore, the yoke return steel laminations can be cut away at midplane to produce a "figure of eight" design if required where a beam approaches the location of a yoke return. The missing steel can be added to the remaining two returns.

The parameters of the quadrupoles are also listed in Tables 4.3-13 and 4.3-14.

The 16-turns per pole coils are similar in construction to the dipole coils. A 0.72 cm diameter water cooling tube is at the center of an approximately 2.2 cm x 2.8 cm bundle of 3 mm insulated and transposed Cu strands.

Very careful shaping of quadrupole ends will be required to reduce aberrations because of the small length to diameter ratio. End effects may contribute significant ac field effects and will reduce the magnet Q value due to longitudinal eddy currents in the laminations. The same conditions on producing transposed, insulated and well cooled strands apply as in the dipole coil case.

Two FCS rings are required. These can be vertically stacked, preferably with the two quadrupoles slightly spaced apart. The dipoles will be spaced further apart with the upper magnet resting on supports well above the lower one. A tentative conceptual arrangement is shown in Fig. 4.3-30 and Fig. 4.4-6.

TABLE 4.3-13. SNS MAGNET PARAMETERS.

	<u>Dipoles</u>	<u>Quads</u>
Number	48 (curved)	72
B injection (600 MeV)	1.9 kG	2.4 kG
B extraction (3.6 GeV)	6.9 kG	8.7 kG
Length	280 cm	60 cm
Gap/radius	18.5 cm	12.5 cm
Core w x h	126 cm x 85 cm	100 cm x 100 cm
Core material (0.5 mm)	SiFe	SiFe
Number of laminations	11,200	4,800
Core Weight (gross); stamped	(23.5 tonnes); 16.3	(4.6 tonnes); 2.76
Number turns/pole	12	16
Conductor w x h	2.5 x 7.5 cm	2.2 cm x 2.8 cm
Conductor strands	3 mm Cu	3 mm Cu
Cooling hole diameter	0.5 inch	0.3 inch
Coil Weight (strands)	3,400 lb.	834 lb.
Current injection	1170 amps	740 amps
Current extraction	4270 amps	270 amps
Current (ave); dc	2720 amps	1720 amps

TABLE 4.3-14. SNS MAGNET PARAMETERS.

	<u>Dipoles</u>	<u>Quads</u>
Inductance/magnet	7.63 mhy	4.30 mhy
Resistance (dc)/magnet	3.27 m Ω	7.12 m Ω
$\tau = L/R$ (dc)	2.33 sec	0.60 sec
wL	1.44 Ω	0.81 Ω
$Q_{(DC)} = wL/R$	400	114
Dipole (3000 amps dc)		
Power	30 KW	28 KW
Quad (2000 amps dc)		
Core losses*	2 KW hysteresis 4 KW eddy	~ 1/3 of dipole
Coil ac losses	Small to large	(see text)
End effect losses	modest (normalized to 2.8 m)	large (normalized to 0.6m)

* Assumes 1 kW/tonne at 30 Hz and 15 kG sinusoidal.

It can be observed that the approximately 1 m center to center beam line separation can be reduced if the quadrupole steel flux return was partially a "figure of eight" design with greater width and reduced height. However, given the 30 Hz operation at very high proton intensities and the shortness of the quadrupoles, this introduces the risk of loss of 4-fold field symmetry with resulting octupole.

4.3.10.4 Comments on Magnet Requirements.

* The AGS Booster is in part a high intensity proton accelerator of intermediately fast rise rate pulse capabilities up to 10T/sec. Great care was taken, successfully, to make the magnets of high quality to avoid stop bands within its acceptance. Even so, at the highest intensity levels it was found that the introduction of skew sextupoles of very small amplitude had a large effect on peak intensities. For the present design every effort should be made to make the dipoles field integral uniform and also the gradient integrals uniform. Beam losses due to resonances can have a serious impact on the vacuum chambers and other components and contaminate the synchrotrons.

* Correction magnets, both normal and skew, need to be added to the lattice, up through octupoles, with provisions for space for other unforeseen corrections.

* As indicated above, the magnet designs assume transposed stranded coils. Early design fast cycling synchrotron accelerators used solder filled stranded conductors which were quite lossy. For electron machines, assuming the orbit is corrected, larger field aberrations can be tolerated than seems appropriate in the present case. Such losses inevitably generate field aberrations, unless magnet designs are used which greatly screen the coil location from the aperture. An early goal of a more advanced study should be the demonstration of satisfactory fully insulated coils.

* In sequential SNS studies, the vacuum chamber material may be reconsidered. While the ceramic appears to be the correct choice, a backup of thin walled metal chambers, plus self correction of aberrations as was used in the AGS Booster, may be further explored. This is more difficult, but results in smaller magnets and does reduce the stored energy of the resonant power supplies. This in turn reduces the relative impact of magnet end effects.

Fig. 4.3-27 , FCS Dipole Cross-Section

Fig. 4.3-28 , FCS Quadrupole Cross-Section

Fig. 4.3-29

FCS-SNS, Beam Stay Clear Envelope

BSC Definition: $E_x/P_i = E_y/P_i = 320.E-6$; $DP/P = \pm 0.01$

Vertical "Stacking" of two FCS's, concept

Fig. 4.3-30

4.3.11. SNS Main Ring Magnet Power Supplies

4.3.11.1. Introduction

The magnetic fields in the SNS Main Ring (MR) magnets will have the basic shape of biased sine waves. The operating frequency for each ring is set to be 30 Hertz. Since the magnets may be assumed to be constant inductances, the usual method of powering is to resonate them with electric energy which is stored in external capacitors. This scheme was first proposed by M. G. White⁶⁰ and was used in the Princeton-Penn Accelerator. Many variations of the scheme have been utilized over the years in the construction of rapid cycling accelerators at various Laboratories.⁶¹⁻⁷⁰ The scheme has the advantage of producing uniform, smooth, repetitive cycles with only the makeup of energy that is lost in the oscillation process. Injection is accomplished on the low portion of the wave and extraction is performed near the top. The disadvantages are that the waveform is fixed by the primary circuit parameters and thus it cannot be altered easily. It is also relatively expensive to execute since electrical energy storage in capacitors is costly.

4.3.11.2. General

The SNS will utilize resonant excitation schemes to power the main ring dipole and quadrupole magnets independently. The general form of the excitation will be given by:

$$B(t) = B_0 - B_1 \cos \omega t; \quad I(t) = I_0 - I_1 \cos \omega t, \text{ where}$$

$\omega = 2\pi \nu$, is the angular oscillation frequency; B_0 , I_0 are the dc bias values and B_1 , I_1 are the peak values of the biased cosine wave.

Three separate supplies will be constructed. The main parameters of the MR magnets are shown in Table 4.3-15. The dipoles, as can be seen, are a more dominant system due to their large gaps and the larger amounts of stored energy.

In designing the SNS MR magnets, the most important parameter is the choice of the number of turns. This selection determines not only the currents and voltages, both ac and dc, but also since these magnets have high energy storage, it becomes a very important consideration with respect to size, reliability, choice of materials, and hence cost.

The MR magnets shall operate within their linear region (i.e. no saturation) to enable the PS system to stay close to the series resonant frequency condition. The other important requirement is that the current in all MR magnets of the same type shall be equal. Coupled chokes will be employed to aid in equalizing the currents since large numbers of cells are used.

The major components for the resonant excitation system will be located in the ring for close coupling to the magnets. They will be placed below the beam height to reduce radiation damage. As an alternative, the possibility of remotely locating the components in an adjoining equipment gallery

above or next to the ring should be investigated. These latter locations may provide some advantages. The problem is to not increase the losses in the cabling systems and buswork. The cables will be stranded conductors and arranged in a quadruplex arrangement to minimize their inductances. The interconnecting systems will be in a foldback arrangement to avoid complete loops of high currents.

4.3.11.3. Dipole Power Supply

In order to reduce the voltage-to-ground and across the magnets and capacitors, the powering system is constructed in cells, in which the total number of magnets are broken up into groups and each group is resonated with its own capacitor. The voltage-to-ground is a very critical rating for the magnets and ultimately leads to their most likely failure mechanism, with turn-to-turn failures being a close second. In our case, because the SNS is designed to be a very high intensity machine, the magnet reliability will be greatly affected by the voltages impressed which stress the ground and turn insulations, especially with the likelihood of radiation damage. The magnets will have sufficient ground and turn insulation and will be tested to voltages greater than 25 kilovolts. In our design the cell sizes are chosen to maintain an adequate safety margin in the voltages applied to magnets and the rest of the power supply components. Modularity also assures that the design stays within today's "state-of-the-art" semiconductor and capacitor ratings.

Taking these factors into consideration, the choice of parameters for the MR magnets are as shown in Table 4.3-15. We have chosen a relatively low number of magnet turns, $N=24$, even though this makes the current higher. The schematic of the powering system is shown in Figure 4.3-31. The most important parts of the external PS system are the capacitors, dc by-pass chokes, the dc power supply and the ac makeup power supply. These elements are briefly described in the following sections. A unit cell of the MR dipole is shown in Figure 4.3-32. The dipole system will consist of 24 cells. In this a capacitor of 2780 microfarad is resonated with two dipoles and a by-pass choke. By using a number of cells, there is no voltage build-up circling the ring. The maximum voltage across a magnet is 1570 volts rms, and to ground it is approximately 2250 volts peak. The complete electrical parameters for the dipole system is shown in Table 4.3-16.

4.3.11.3.1 Capacitors

The capacitors will be ac storage types which can withstand voltages of both polarities and have long life on the number of energy charge/discharge cycles. They will be made up of larger numbers of small units in series/parallel arrangements to store the energy and to handle the ac currents without overheating. They shall have low dielectric loss and low equivalent series resistance to keep the energy loss at a minimum. Their temperature coefficient of resistance shall be low enough so that the frequency does not drift with their ambient temperatures. Smaller units will be connected in parallel in order to be able to tune each cell at the exact resonant frequency (see Table 4.3-16). Capacitors will be individually fused for protection.

4.3.11.3.2 Choke/Transformers

The chokes have two basic requirements. First, they are used to by-pass the dc component of the magnet current around the capacitors, and second, they are used to equalize any differences between the individual resonant cells through tight mutual coupling, and thus act as transformers. In our case, the chokes will be constructed as individual components rather than as a single device, which would be too large. From an energy storage point of view, a near optimum value of the individual choke inductance is two times the value of the magnets it is resonated with.^{68,69} Their Q factor shall be high (say 30-35) to assure low losses. A third potential use of this element is that the make-up energy can be coupled into the system on the primary side of the choke/transformers as opposed to a series connection with the magnets. These units shall have isolated primaries for this purpose. Their hook-up is shown in Figure 4.3-31 and the ratings are shown in Table 4.3-16.

In constructing the chokes, much care has to be taken to assure constant inductances over the required operating ranges, and also a reduction of the amount of stray flux.^{64,70} In this case, a shell-type core construction is preferable.

4.3.4.3.3 DC Power Supply

The dc PS establishes the bias on the oscillatory wave of current through the SNS MR magnets. In our case, it will be built into at least two equal units which will be connected in series with the magnets and choke secondaries at locations which have low voltages to ground. These units will be 12-pulse multiphase, adjustable, units which are readily available commercially. They will have passive filters to reduce harmonic ripple in the dc output and hence cut down the excitation of parasitic modes in the Accelerator. The ratings are given in Table 4.3-16.

4.3.11.3.4 AC Power Supply

The size and number of the ac, or energy make-up, PS's is determined by how well the system losses are controlled in the design of the SNS MR magnets and supporting systems. The other variable is how this lost energy is injected back into the oscillatory circuit. It can be coupled directly by programmable PS's in series with the resonant circuit main loop, by similar units which are ac coupled, or by pulsed energy coupled into the system at the appropriate time in the machine cycle. The most straight-forward scheme is the latter. This will be used in our case. Banks of capacitors will be charged on a long-time basis (typically 20 milliseconds) and discharged into the system during the recovery part of the cycle when no beam is in the machine. This may take typically 5 milliseconds. The units will be constructed in modular fashion and tied into the systems at the appropriate points in the primaries of the choke circuits (see Figure 4.3-31.)

4.3.11.4 Quadrupole Power Supplies

Depending on the energy of each quadrupole system several choices are available in powering these MR magnets. Resonant type systems similar to the dipole would be a straight-forward scheme with the major requirement of synchronization between all systems. All systems shall track by resonating at exactly the same frequency (30 Hz). The quadrupole ps design is identical to the dipole system described above with changes to the number of cells and the ratings of the dc and ac power supplies. Alternatives are the use of switchmode converters or cycloconverters to directly power the magnets. These have the advantages of programmability, higher degrees of feedback regulation, and being commercially available. However, their main disadvantage is that the power has no intermediate storage stage and comes directly from the line. This can cause disturbances which are unacceptable at high power. They cause ac voltage and phase flicker effects. Therefore, the capacitor resonant scheme will be used, one for each set of main ring quadrupoles.

The design parameters for the horizontal and vertical quadrupole magnet systems are identical and are given in Table 4.3-16.

Table 4.3-15. SNS Magnet System Parameters

PARAMETER	UNIT	DIPOLE	QUAD.
Number Required		48	64
Bending Radius	m	21.39	--
Field Strength (Inj.)	kG;kG/m	1.897	19.2
Field Strength (Extr.)	kG;kG/m	6.922	62.0
Pole Tip Field	kG	--	8.3
"Good Field" (b/B<1.e-4)	cm x cm	10 x 10 --	
"Good Field" (g/G<1.e-4)	cm(rad.)	--	11.0
Length	m	2.8	0.6
Gap Height - Radius	cm	18.5	12.5
Pole Width	cm	55.0	--
Core w x h	cm x cm	126x85 100x100	
Core Material		Si Stl	Si Stl
Lamination Thickness	mm	0.5	0.5
Core Weight	klbs.	45	8
No. Turns/Pole	No.	12	16
Conductor w x h	cm x cm	2.5x7.5 2.5x2.5	
Conductor Material		Cu	Cu
Cooling Hole Dia.	in	0.5	0.3
Coil Weight	klbs.	3.4	1.0
Cooling Water Ckts.	No.	2	4
Cooling Water/Ckt.	gpm	10	5
Cooling Presure Drop	psi	50	50
Water Temp. Rise	C	15	15
Amp-Turns (Inj.)	kAT	28.1	12.0
Amp-Turns (Extr.)	kAT	102.5	38.8
Inductance/Magnet	mHy	7.6	4.3
Resistance/Magnet	mOhm	3.3	7.1

Table 4.3-16. SNS Magnet Electrical System Parameters

Parameter (per string)	UNIT	DIPOLE	(H+V)QUAD.		
Frequency	Hz	30			30
Frequency	rps	188.4			188.4
Number of Magnets	No.	48			32
Ampere Turns (Inj.)	kAT	28.1			12.0
Ampere Turns (Extr.)	kAT	102.5			38.8
Current - dc	Amp	2721			1586
Current - ac peak	Amp	1550			836
Current - ac rms	Amp	1096			591
Current - max. (Inj.)	Amp	4271			2422
Current - min. (Extr.)	Amp	1171			750
Current Density	A/sq in	1500			1700
Inductance/Magnet	mHy	7.6			4.3
Inductance/Choke	mHy	30.4			34.4
Capacitance/Cell	uFd	2780			2460
Resistance/Magnet	mOhm	3.3			7.1
Resistance/Choke	mOhm	10			15
No. Cells	No.	24			8
PER CELL					
Voltage - dc total	Volt	45			69
Mag Voltage - ac peak	Volt	4440			2511
Mag Voltage - ac rms	Volt	3139			1776
Voltage to Ground	Volt	2229			1278
Energy - peak	kJ	138.5			50
Power - dc total	kW	125			110
Mag Power - dc	kW	25			18
Mag Power - ac (coil)	kW	8			5
Mag Power - ac (core)	kW	6			2
Mag Power - ac (total)	kW	14			7
Mag Res. - ac eff.	mOhm	12			20
Mag Current - rms total	Amp	2933			1693
Choke Current - dc	Amp	2721			1586
Choke Current - ac peak	Amp	775			418
Choke Current - ac rms	Amp	548			296
Choke Energy - peak	kJ	186			69
Choke Q	No.	35			35
Choke Res. - ac eff.	mOhm		164		185
Choke Power - dc	kW	74			38
Choke Power - ac	kW	10			12
Cap Current - ac rms	Amp	1644			888
Cap Eq. Ser. Res.	mOhm	3.9			4.4
Cap Power - ac	kW	10.5			3.5
PER RING					
Inductance - Magnets	mHy	364.8			137.6
Inductance - Chokes	mHy	729.6			275.2
Resistance - Total	mOhm	440			382
Capacitance - Total	uFd		67000		15000
Voltage - dc	Volt	1200			606
Power Loss - dc	MW	3.3			1.0
Power Loss - ac	MW	1.3			0.25
Number dc PS modules	No.	2			2
Number ac PS modules	No.	1			1
Total ac Line Power	MVA	4.5			1.5

Fig. 4.3--31
Schematic of SNS M.R. Powering System

Typical M.R. Cell Layout
Fig. 4.3--32

4.3.12. Vacuum System

The goal of the FCS vacuum system is to provide a friendly environment for the transport of the beam during the acceleration cycles. The operating pressure of the FCS vacuum system will be in 10^{-8} Torr range and is needed to minimize the beam-residual gas ionization. The various beam-residual gas interactions relevant to FCS are described in first section. The dipole and quadrupole chambers will be fabricated out of high strength alumina to reduce the eddy current effect of the fast cycling magnets. The vacuum chambers, vacuum pumps and other hardwares will be detailed in the successive sections.

4.3.12.1. Vacuum Consideration

The following beam-residual gas interactions are considered in assessing the required vacuum levels in FCS; the nuclear scattering, the multicoulomb scattering and the residual gas ionization. The nuclear scattering cross sections σ_n are proportional to the geometrical cross section of the target nucleus and are usually less than $3 \times 10^{-25} \text{ cm}^2$ for most common residual gases in a clean vacuum system. The beam loss due to nuclear scattering is given by

$$\frac{\Delta I}{I} = \int \beta_c \sigma_n N dt$$

with N being the residual gas density in the vacuum system. To have $\Delta I/I \leq 1 \times 10^{-5}$ over 16 msec, N has to be less than $8 \times 10^{10} \text{ molecules/cm}^3$ or pressure less than $2.5 \times 10^{-6} \text{ Torr}$.

The multicoulomb scattering causes the growth of the rms beam size. The fraction of the increase can be calculated by⁷¹

$$\frac{\Delta \sigma_y}{\sigma_y} = \int k \frac{\beta_y}{p^2 \epsilon} N dt$$

with σ_y the transverse beam dimension, $k = 1.085 \times 10^{-23} (\text{GeV/c})^2 \text{ m}^3 \text{ sec}^{-1}$, β_y the betatron amplitude, p the momentum and ϵ the transverse emittance. The fraction of beam growth over 16 msec will be $< 2 \times 10^{-4}$ at a vacuum of $2.5 \times 10^{-6} \text{ Torr}$.

The residual gas ionization sets the most stringent requirement on the vacuum levels. The newly created ions repelled by the beam potential will bombard the chamber wall and desorb molecules. The ionized electrons could be trapped in the potential well of the beam causing partial neutralization of the beam, or they could bombard the beam envelopes and liberate more secondary electrons.

4.3.12.1.1 Pressure Increase due to Ion Desorption

The ions will receive an energy corresponding to the potential at where they are created. For a pencil like unbunched beam in a circular chamber, the potential is given by

$$V = \frac{\lambda}{2\pi\epsilon_0} \ln \frac{r_0}{r} \quad r \geq a$$

$$V = \frac{\lambda}{2\pi\epsilon_0} \times \left(\frac{r^2}{2a^2} - \frac{1}{2} + \ln \frac{r_0}{a} \right) \quad r < a$$

with r_0 the radius of the vacuum chamber and a , the radius of the beam, and $\lambda = I/c$, the linear charge density. For FCS with $I \sim 20$ A, and $r_0/a = 5$, an ion created at the edge of the beam will receive an energy of over 1 keV. The beam wall potentials for a bunched non-circular beam in a non-circular beam envelope have been derived previously^{72,73}. The resulted energy of the ions hitting the wall ranges from sub keV to tens keV.

The ion desorption coefficient η , the number of molecules desorbed per incident ion, will depend on the material and surface treatment of the chamber wall, and to a lesser degree on the energy of the ions. It ranges from less than 1 for a baked and glow discharge cleaned surface to over 10 for an unbaked surface. If the rate of desorption is higher than the rate of removal, the pressure will rise exponentially and leads to pressure instability. This could happen if η is large, the conductance of the chamber is small or the pumps are spaced too far apart.

The pump down time constant of the FCS chambers is in the order of seconds which is much longer than the 33 msec acceleration cycles. Therefore the behavior of the vacuum system in the presence of the beam would be similar to that of a storage ring. The equivalent beam current used in the calculation equals to half of the actual accelerated beam current.

The flow of the residual gas from x to $x+dx$ along the chamber can be represented by

$$A \frac{dN(x)}{dt} = q + \sigma_i N(x) \eta + C \frac{d^2 N(x)}{dx^2}$$

with A the cross sectional area of the chamber, $N(x)$ the gas density at location x ($x = 0$ midway between pumps), q the thermal outgassing rate per unit length of the chamber, σ_i the ionization cross section of the residual gas ($< 2 \cdot 10^{-18} \text{ cm}^2$), and C the linear conductance of the chamber. Then the equilibrium gas density (at $t \rightarrow \infty$) without and with beam can be expressed by⁷⁴

$$N(x) = q \left(\frac{L}{S} + \frac{L^2 - x^2}{2C} \right)$$

$$N(x) = \frac{q}{CW^2} \left[\frac{\cos Wx}{\cos WL - \frac{WC}{S} \sin WL} - 1 \right]$$

with $2L$ the distance between pumps, $2S$ the size of the pumps and $W^2 = I\sigma_i\eta/C$. The gas density (and pressure) will become infinite if the denominator in the last equation approaches zero. We have, hence, the pressure stability condition of ' $\cos WL - (WC/S) \sin WL > 0$ ' or ' $WL \tan(WL) < SL/C$ '. For each set of S , L and C , there exists a critical value of $I^*\eta$ when the pressure will increase exponentially and becomes unstable. The critical value of $I^*\eta$ versus pump spacing for FCS is plotted in Fig 4.3.-33. If we position a lumped ion pump of 200 ℓ/s every 5.7m (length of a halfcell), then $(I^*\eta)_{crit}$ will be approximately 50 A.

The allowable $I^*\eta$ will be less than $(I^*\eta)_{crit}$ and will be decided by the tolerable pressure rise with beam. The ratios of pressures with and without beam are plotted versus $I^*\eta$ in Fig. 4.3-34. If a ten-fold increase in pressure is tolerable, then $I^*\eta$ has to be less than 40 A and η less than 2.5. To achieve such a low η value, the vacuum chambers have to be thoroughly cleaned and insitu baked. The thermal outgassing rate of a mildly baked chamber will be in the 10^{-11} Torr. $\ell/sec.cm^2$ range. Static pressure of low 10^{-9} Torr can be achieved and the operating pressure with beam will be in low 10^{-8} Torr range.

4.3.12.1.2 The Effect of the Ionized Electron

The initial energy of most electrons will be < 10 eV, which is too low to escape the potential well of the beam if the beam is unbunched. For the bunched beam of FCS, the bunch spacing is approximately 0.5 μsec which is long enough for the electrons to be pushed toward the beam envelopes by the bending field of the magnets. No accumulation of electrons is expected here. In the long straight sections, some electrons might be trapped and oscillating in the beam potential. Clearing electrodes, if necessary, will be positioned at a few strategic locations. Operating at ± 10 kV, these clearing electrodes will generate a field of over 100 kV/m and should be sufficient to remove any trapped electrons.

Secondary electrons will be ejected from the chamber surface when bombarded by the ionized electrons. These electrons can be attracted by the next beam bunches and hit the wall again liberating more electrons. With the exception of alumina, the secondary electron yields of standard vacuum chamber materials are < 1 if the energy of the electrons is less than 100 eV. By coating the side wall of the alumina ceramic chambers with silver (mainly for conducting the image current of the beam), the secondary electron yield can be reduced.

4.3.12.2. Vacuum Chambers

The layout of the standard halfcell chambers is given in Fig. 4.3-35. It consists of chambers for dipole, quadrupole and straight sections. The chambers must provide a smooth and low impedance path for the image current of the beam, which usually has harmonic components up to gigahertz. Special attention will be given to the smooth transition of the chambers. The transitions should not have any steps. RF finger contacts should be used inside the bellows. The pumpout ports will be screened.

4.3.12.2.1 Dipole and Quadrupole Chambers

The dipole and quadrupole chambers will be made of ceramic material. This will reduce the eddy current effect (both thermal and magnetic) from the fast changing magnetic field. Eddy currents of hundreds amperes and thermal loads of several kilowatts per meter are expected for a thin wall chamber made of Inconel.

High strength and high purity alumina ceramic will be used to fabricate the chamber. Several approaches have been developed to fabricate long ceramic chambers. At Rutherford Laboratory, the ISIS chambers were fabricated by jointing short straight sections of ceramic pipes together using glass glazing⁷⁵. Wire cages following the beam aperture were fitted inside the chambers to form the rf shield and to conduct the high frequency image current. A different approach was used by Triumf in collaboration with Science Application International Corporation (SAIC) in fabrication of the prototype chambers for Triumf's Kaon Factory⁷⁶.

In the SAIC approach, the aluminum oxide powder is isostatically pressed in a mold to form a pipe of appropriate cross section. The curvature (bending radius) of the chamber is obtained by firing the pipe horizontally (with its sides on the top and the bottom) and allowing the whole chamber to slump with gravity. Prototype chambers up to 3 m in length have been fabricated by SAIC for Triumf. The chambers are coated with metallic strips to conduct the image currents. These strips will be terminated at the end of chamber with capacitors which present high impedance to the low frequency eddy current and low impedance to the high frequency image current. The strips are formed by coating the inner wall with silver based paste. The chambers are then fired to remove the organic in the paste and to provide adequate bonding of the strips to the alumina. Silver film thickness up to 0.5 mm can be achieved reliably.

The SAIC approach will be adopted for FCS's ceramic chambers since it requires smaller magnet gaps, has better thermal contact of strips to the chamber and has fewer glass joints which are potential sources of leaks. The cross sections of the FCS dipole and quadrupole chambers are shown in Fig. 4.3-36. The walls of the dipole chambers have to be thick enough to prevent their slumping during firing. If necessary, the top and bottom walls may be machined down. The cost of machining is appreciable and has to be weighted against the added cost of a larger magnet gap. A space of 4-5 mm between chamber and magnet pole is allocated for heating jackets needed for insitu bake. The heating jackets will also damp any vibration which is detrimental to ceramic chambers.

Round ceramic flange with vitreous glass coating will be glazed to one end of the ceramic chamber by a fused glass seal. Metal seal of Helicoflex type and demountable V-type clamp will be used to join this flange to the flange of the adjacent stainless steel chamber. The stainless steel chamber will have bellows to allow the ease of sealing and to avoid stressing the glazed joint. To insert the chambers through the magnet gaps, the other end of the chamber can't have a round flange. It will be coated with vitreous glass coating as the sealing surface. A stainless flange and a soft metal seal will be fitted to this surface.

Silver strips of 0.15 mm in thickness, corresponding to ~ 3 times of the skin depth, will be bonded to the inner wall of the chambers. One end of the strips will be connected to the stainless steel chamber using spring contact held between the adjacent flanges. The other end of the strips will go around the end face of the ceramic chamber and terminated with capacitors.

Development work is required to design and evaluate the reliability of the sealing mechanism, the rf contacts and the capacitor terminations. To ensure the stability of the beam, the ion desorption coefficients and the secondary electron yields of alumina and the silver strips also have to be studied and minimized.

4.3.12.2.2. Straight Section Chambers

The short straight sections as detailed in Fig. 4.3-35 contain the bellows, the beam position monitor and the pumpout port. To minimize the radiation induced stress corrosion, the thin wall bellows will be made of inconel. Internal sliding contacts will be provided to shield the bellows and the pump port. The remaining components will be fabricated of stainless steel. All the side port flanges will be of Conflat type, compatible with flanges of the commercial available pumps, valve and feedthroughs.

The long straight sections will house the r.f. cavities, injection and extraction equipment. A few clearing electrodes will be installed here to remove the trapped electrons. The potential well in the long straight sections will be analyzed carefully to decide the locations and the size of the clearing electrodes.

4.3.12.3. Vacuum Pumps and Other Vacuum Hardware

The FCS ring will be divided into 12 vacuum sectors isolatable with all metal gate valves. The gate valves are interlocked by the vacuum sensors upstream and downstream of the valve. Each vacuum sector is to be bakeable insitu to 120°C. All the chambers will be wrapped with heating jackets and thermocouples. The bakeout will be carried out with mobile bakeout cart fashioned after AGS Booster bakeout cart. Industrial programmable logic controllers and PC based software will control and monitor the bakeout process.

Mobile roughing carts will be used to rough down the vacuum sectors and to maintain the vacuum during in situ bake. Each roughing cart consists of a dry mechanical pump and a turbomolecular pump. The roughing cart will be valved out and removed from the tunnel when roughing and bakeout are complete.

Due to the difficulty in incorporating distributed pumping inside the ceramic vacuum chambers, lumped ion pumps will be used for the FCS. As detailed in section 4.3.12.1.1, one ion pump of 200 l/sec every 5.7 m (length of a halfcell) will be sufficient to meet the beam stability requirement of $I \cdot \eta < 40$ A. With the installation of additional pumping at the second short straight section, the limit on $I \cdot \eta$ can be increased to 100 A. The additional pumping also provide safety margin against the failure of individual pumps. At operation pressure of 10^{-8} Torr, the lifetime of the ion pumps will exceed 10 years.

4.3.12.4. Vacuum Instrument and Control

To avoid excessive heating by beam spill on the silver strips, the glazed joints and the seals, the temperatures of the ceramic pipes have to be monitored closely using the thermacouples installed for insitu bake. One set of pirani and cold cathode gauges will be installed at each vacuum sector as primary vacuum gauges. The ion pump current will give a more detailed pressure profile around the ring. A residual gas analyzer will also be installed at each vacuum sector and will provide a quick analysis of the partial pressures.

4.3.13 Ring Diagnostic Instrumentation

Beam instrumentation systems in the Fast Cycling Synchrotrons (FCSs) have two functions: reduce beam loss during set-up and, maintain low loss during operation. The Beam Loss Monitor (BLM) system and the Beam Current Transformer (BCT) are the primary tools for assuring that there is low loss during normal operations. Set-up and studies primarily depend on other diagnostic systems for measurement of the beam properties which lead to the low loss during operation. The beam diagnostic instrumentation which will be used for these purposes will be described below.

Fig. 4.3-33

Ratio $P(I = I) / P(I = 0)$ versus $I \cdot \eta$ [A]

Fig. 4.3-34

LAYOUT OF HALF CELL VACUUM CHAMBERS

STRAIGHT SECTION CHAMBER

Fig. 4.3-35

QUADRUPOLE CHAMBER CROSS SECTION

DIPOLE CHAMBER CROSS SECTION

Fig. 4.3-36

4.3.13.1 Beam Loss Monitors

While it is conceptually possible to measure losses by comparing successive readings of a BCT, in practice the small differences would be hard to resolve. It is far more practical to measure the radiation produced by particle loss directly. A figure of 1 part in 10^4 would result in 1.45×10^{10} protons being lost, which is several decades higher than losses observed in the AGS Booster at energies between 600 MeV and 1.3 GeV. An ion chamber with fast response (argon gas with suitable electric field) is the best detector choice on the basis of cost, reproducibility, stability and low maintenance. Long coaxial chambers, which have been used at the AGS in the Linac⁷⁷, Booster⁷⁸, and AGS ring⁷⁹, have the advantage of complete end-to-end coverage and $1/r$ response, but require a supporting gas system. Sealed glass units have been used at FNAL⁸⁰ and will be used at RHIC. While these are "point"-detectors and have a $1/r^2$ fall off with distance from the loss, they can provide effective coverage by proper placement.

Detectors will be located at each of the 72 quadrupoles in the FCSs, where the beam is at a beta-max and most likely to hit. Other detectors will be located in the injection and extraction regions and at scrapers. A number of relocatable units will be provided which will be placed as operational requirements dictate. Provision for 96 channels will be made for each ring. Threshold detectors will monitor the signals and provide a trip signal within 10 μ s when a programmable level is exceeded, allowing the beam to be dumped if desired. A time history for each channel will be provided for the entire cycle with the data taken at typically 100 μ s intervals. The electronics will be based on those developed for RHIC which is being designed with these features.

Some fast monitors will also be provided for relative loss measurements on the bunches. These will be scintillator-photomultipliers and will be digitized on a bunch-by-bunch basis, primarily for studies purposes.

4.3.13.2 Beam Current Transformers

The circulating current in the rings will be monitored using beam current transformers. A magnetic feedback type transformer will be used in order to provide the low frequency response needed for a 10 - 60 Hz repetition rate with a 0.1% droop. In this design the beam forms the primary winding which magnetizes the core. This signal is picked up by the secondary winding which is then amplified and coupled back into the transformer in the same sense as the beam signal, which compensates the droop. Using this technique, which was developed by Hereward⁸¹, droop time constants of 1000 seconds may be achieved. This is well in excess of what is required for the FCSs. Gain switching will be provided to allow measurement of a single bunch injected for studies.

4.3.13.3 Wall Current Monitor

The bunch longitudinal density distribution must be monitored to provide information for the RF system and data from which the momentum distribution may be inferred. A design similar to that in the Linac (see section 4.2.9) will be used.

4.3.13.4 Closed Orbit Measurements

The closed orbit system is one of the primary studies and set-up tools. There will be one single plane detector at each of the 64 quadrupoles, the measurement plane corresponding to the focussing plane of that quad. Because stripline BPMs have a limited linear range which could be a problem for large or off center beams, capacitive pick-up electrodes (PUEs) will be used. Additional PUEs will be provided for use by the RF System and the Damper. The design of the electronics will be straight forward since the frequency and bunch length will not vary significantly throughout the cycle. The analog front-end circuitry, which will be designed to amplify and integrate a single bunch, will be incorporated into the RHIC BPM electronics board. This VME/VXI format board, which also houses a digital signal processor (DSP) and dual ported memory, will process the amplified bunch signals to provide both average orbit and bunch-by-bunch history over the entire cycle. This will be very useful in case of a beam dump and will provide data for calculating injection position and angle. At least 3-decades of gain will be provided to allow for studies ranging from a single injected bunch to 500 injected turns.

4.3.13.5 Fractional Tune Measurement

Small angle beam kickers will be installed for both planes to ping the beam for measurement of the fractional tune. Readout of the full-cycle memory from the PUEs one-quarter wavelength downstream of the kickers will provide the data for an FFT analysis to yield the tune.

4.3.13.6 Beam Profile Monitor

Knowledge of the profile and the beta-function at that location allows the emittance to be calculated. Injection errors due to poor painting or mismatch, and instabilities which will cause emittance growth through the cycle can also be observed. Interactive techniques using scrapers or flying wires may cause too much loss and may not have a long lifetime in the beam. A residual gas ionization profile monitor will give some measure of the beam shape but with the high space charge expected, distortion of the applied electric field may be too severe to allow simple correction and extraction of the profile. This will require further study.

4.3.14 Beam Transport, Fast Cycling Synchrotrons to Targets

The 3.6 GeV protons will be extracted from each FCS with an extraction system incorporating a slow orbit bump, fast extraction kicker and Lambertson septum magnet. The extracted beams will be deflected vertically, with the "lower" beam to be directed initially downward, and the upper beam directed upward to permit the transport of the beams above and below the two magnet rings. External to the rings proper, the two beamlines would be merged into one combined line by means of additional vertical deflectors and a fast bipolar vertical deflector operating at a 60Hz deflection frequency; indicated as Do in Fig. 4.3-37.

The transfer line between Do and the spallation neutron target stations is divided arbitrarily

into three sections, as also shown in Fig. 4.3-37. The first section, approximately 50m in length transports the two (coalesced) beams to a fast horizontal switch, shown as D1 in Fig. 4.3-37, which will serve to select, in a cycling frequency range of 0-60Hz, the frequency of operation of each target (i.e., eg. 10Hz-50Hz). The second section, nominally 100m in length directs the combined beams to a beam dump. A third and fourth beamline section ($\leq 300\text{m}$ each) provide for transport to the two targets.

Optical transport computations have been done in a preliminary manner only. Section 1 is simply a FoDo structure (~ 12 quadrupoles) maintaining beam sizes below 2 cm and providing for matching of the Twiss parameters to the sequential sections. The dump line will make use (not shown) of ~ 12 quadrupoles. It will permit diagnostic monitoring of the beams and provide for safe beam disposal in case of anomalous FCS extracted beam behavior. The third and fourth beamline section, i.e., the "expander" lines, will branch out at 5 degree ($\pm$) from the D1 to dump line. The purpose of these lines is to transport the beams to the targets and transversely expand the beams to approximately $20 \times 20 \text{ cm}^2$ at the targets.

The beam density in the target area should be kept as uniform as possible. To achieve this result, in the design of the expander lines, the following features have been included:

- 1) The lines contain, at 1/3 of their length, a further 5 deg. horizontal DC bend, dipoles D2 and D3 in Fig. 4.3-37, to compensate for the dispersion induced by the switching magnet D1. The first section of each expander line, between D1 and D2 (D3) is then designed as an achromat. This condition is important to keep the beam stable at D2 (D3) so the optics in the subsequent 2/3 of the line can correctly work. This section between D1 and D2 (D3), 100m long, contains an array of ~ 20 quadrupoles in a FODO arrangement.
- 2) The beam expansion function is performed by an arrangement of 16 quadrupoles and 2 pairs of octupoles. The octupoles transform the transverse gaussian-like beam density distribution into a quasi rectangular distribution. This is due to the third order optical aberrations in the beam focussing induced by the octupolar field, superimposed on the linear terms of the quadrupoles, that would preserve the gaussian distribution. The effect of octupoles on the distribution and its optimization has been experimentally demonstrated, e.g., for the 200 MeV H^+ beam of the Radiation Effect Facility at Brookhaven.⁸² It is also worth noting that by varying the relative strength of the octupole families, one can achieve on the target an illumination of rectangular, other than square shape.

An even better uniformity, if needed, could be achieved by adding dodecapole magnets (inducing order 5 terms in the focussing).

Beam Transport Fast Cycling Synchrotrons to Targets

Fig. 4.3-37

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5. TARGET AND MODERATOR SYSTEM DESIGN

5.1 Introduction

A feasibility study of a compact high power density target for a spallation neutron source was undertaken. The target arrangement consists primarily of heavy metal, with appropriate cooling passages. A high intensity proton beam of intermediate energy is directed at the target, where it interacts with the heavy metal nuclei. The subsequent spallation reactions produce several neutrons per proton resulting in an intense neutron source. The proton beam is assumed to have an energy of 5 MW, and to be cyclic with a repetition rate of 10Hz - 60Hz.

The study was divided into two broad sections. First, an analysis of preliminary target designs was undertaken to ensure the overall feasibility of the concepts involved in the design and eventual construction of such a high power density target. Second, two proposed target designs, based on the first set of analyses, are investigated in more detail. Special care is taken to ensure that the neutron fluxes in the moderator are at the desired level, no material compatibility problems exist, and the target is able to operate in a reliable and safe manner.

Several target materials, coolant types, and target arrangements are investigated in the first section. The second section concentrates on a single target material and geometric arrangement. However, several structural material choices are investigated with the aim of minimizing the effects of structural heating, and associated thermally induced stresses. In the final section the conclusions of this preliminary study are summarized.

5.2 Design and Analysis of Preliminary Targets

Several combinations of target geometry, materials and coolant types were initially investigated in order to gain experience regarding the feasibility of designing a target which would operate with a maximum beam power of 5MW. These investigations took the form of physics calculations of full density cylindrical heavy metal targets. The metals chosen were tungsten and uranium-238 embedded in a light water reflector. Proton beam energies of 1 GeV and 10 GeV were used in these studies, implying beam currents of 5.0×10^{-3} amps. and 5.0×10^{-4} amps respectively. The fluid dynamics and heat transfer investigations considered the following options, as given in Table 5.1.

Table 5.1 - Preliminary Geometry and Coolant Combinations.

Geometry	Coolant		
	Helium	Sodium	Lead
Rods (Axial)*		Sodium	Lead
Particle Bed (Radial)#		Sodium	Lead

* Arranged along direction of proton beam.

Arranged at right angles to direction of proton beam.

In carrying out the fluid dynamics and heat transfer analyses it was assumed that the power was deposited uniformly in the target, that the length was equivalent to 30 cm of solid target material, and that all of the beam power (5MW) was deposited in the target.

5.2.1 Nuclear Analyses

The nuclear analyses for proposed targets were based on the use of sophisticated computer codes to model the expected behaviour of the target/moderator system. The calculational models must simulate the interaction of the incident proton beam with the target constituents, predict the particles and product nuclei that are produced, and then follow the particles through subsequent transport and interactions until they are absorbed or leak from the system. In addition, these predictions must eventually take into account the build-up, burn-out, and decay of nuclei with time, and the impact of these processes on the time-dependent behaviour of the system as a whole. To date, calculational methods that satisfy the above stated requirements in an integrated fashion do not exist. Therefore, these initial analyses represent only a detailed simulation of the system at essentially $t=0.0$ (time-dependent characteristics will be considered in the next design phase).

The major outputs required from the nuclear analyses of the target are:

- Flux levels and space and energy-dependent spectra available for experimenters.
- Nuclear heating, both prompt (and eventually decay), for setting cooling requirements, determining material performance, and evaluating accident scenarios/consequences.
- Eventually, isotopic inventories as a function of time to estimate source terms, identify potential materials compatibility problems, and estimate system performance and define operations.

The nuclear design methodology that was selected to perform these tasks will be described below. In addition, some of the validation of the design methodology will be discussed.

5.2.1.1 Nuclear Design Methodology

The methodology employed for the nuclear evaluation of all proposed spallation source target/moderator configurations is summarized in Fig. 5.-1. The basic tool is the Los Alamos National Laboratory (LANL) developed LAHET Code System (LCS) which consists of two major modules: 1) LAHET, a modified version of the HETC intranuclear cascade code for evaluations above 20 MeV, and 2) HMCNP, a modified version of the well known MCNP transport code for calculations from 20 MeV down to thermal energies. A number of additional codes are also provided with the LCS to perform linking between modules and post-process the results.

The fact that both LAHET and HMCNP are Monte Carlo codes is of particular significance to the design of the proposed spallation target/moderator configurations. Both codes employ a combinatorial surface/cell specification of the problem geometry which permits modelling of the target configurations with minimal approximations. In addition HMCNP employs nuclear data from the ENDF/B files in essentially unapproximated point-wise form which avoids the complications associated with collapsing the data to a group structure and *a priori* knowledge of the space-energy dependent spectra in the system. In addition, HMCNP utilizes the $S(\alpha, \beta)$ formalism for scattering off the bound moderators, and water molecules in the coolant/reflector. The major limitation of Monte Carlo is the statistical nature of the results; this is inherent to the method, and creates difficulties when localized information is desired. In principle, however, the accuracy of the predictions is limited only by the accuracy of the nuclear data, the detail to which the actual geometry is modelled (which as noted above does not have to conform to the regular meshes required by most deterministic methods), and the number of particle histories considered. This last point is not trivial, however, and typical design calculations place considerable demands on computer resources in terms of running time and storage.

The above discussion is reflected in Fig. 5.-1 which shows that the only inputs required for the LCS analyses are the target geometry and materials, the minimally processed ENDF/B nuclear data, and the starting distribution of protons which is assumed to be a pencil beam, uniform over the beam footprint, and constant in energy. Throughout the following sections it should be noted that features of the various targets that are expected to have an impact on the nuclear design calculations are preserved. Coupling between the LAHET and HMCNP calculations is via a file that is written by LAHET which contains the space-energy-angle coordinates of neutrons which have slowed down below 20 MeV. These neutrons are subsequently transported by HMCNP until they are captured or leak from the system.

Note that the above analysis is essentially static in nature, i.e., the impact of spallation and activation product build-up/decay is not accounted for in either the LAHET or HMCNP analyses. Adjunct calculations should be performed later to account for time-dependent effects. These calculations would employ either the LANL developed CINDER-90 or BNL modified ORIGEN2 codes.

5.2.1.2 Validation of Methodology

Confidence in the ability of the above methodology to simulate the nuclear performance of proposed target/moderator systems accurately is based on comparisons of results of calculations with these methods with experimental results.

Extensive validation of the LAHET code for the prediction of neutron yields, differential data, isotopic production, and heating has been performed by both LANL and BNL for a range of incident proton energies, and a variety of materials. Some of the results of these comparisons to experimental data are given in References 1-4.

The MCNP code has been used extensively for radiation transport and criticality calculations in nuclear reactor and other applications. It is also used by the Cross-Section Evaluation Working Group (CSEWG) to evaluate the accuracy of nuclear data in the ENDF/B because of its ability to do highly accurate simulations of nuclear experimental configurations. Some of the results of benchmark calculations for MCNP are given in References 5-7.

As noted above, LAHET, and MCNP are state-of-the-art codes which are well suited for, and have demonstrated applicability and accuracy for the nuclear design of the spallation source and moderator targets as evidenced by cross code comparisons, and comparisons to experimental results. Differences do exist, however, in part due to uncertainties and inconsistencies in experimental results. Therefore, a series of experiments in the areas which exhibit the greatest experimental-to-calculational differences, and which are most significant for defining expected target performance and safety are also being performed as part of the current APT activities. The objective of these additional experiments is to reduce the uncertainties in the experimental data so as to improve the current estimates of uncertainties/biases in the calculational methodologies, and better focus efforts to improve the confidence in the model predictions.

The analyses performed in the initial phase of the study considered a solid metal target of either tungsten or uranium-238, 10 cm. in radius, and surrounded by a 100 cm. thick light water reflector. Fig. 5.-2 shows a schematic arrangement of this geometry. The beam spot was assumed to have an area of 1 cm.², and impinge on one of the flat surfaces of the cylinder. The results of these calculations take the form of neutron/proton (n/p) ratios and the spatial distributions of the neutron flux in the moderator volume. The n/p ratios for the two target materials and two neutron energies are summarized in Table 5.-2 and Table 5.-3:

Table 5.-2 - n/p ratios for a Tungsten target.

	<u>1 GeV</u>	<u>10 GeV</u>
Evaporation & Cascade	24.8	247.0
<u>n,xn</u>	<u>1.8</u>	<u>22.5</u>
Total	26.6	269.5

Table 5.-3 - n/p ratios for a Uranium-238 target.

	<u>1 GeV</u>	<u>10 GeV</u>
Evaporation & Cascade	32.8	319.3
<u>n,xn</u>	1.7	20.6
<u>Fission</u>	<u>11.6</u>	<u>125.2</u>
Total	46.1	465.1

The above results indicate that the number of neutrons produced per proton scales approximately linearly with proton energy. Thus, for the same total beam power it is expected that the same total number of neutrons would be produced, regardless of proton energy. The difference between these two cases would manifest itself in the spatial distribution of the neutron flux. The higher energy proton beam would penetrate deeper into the target and thus the neutron flux profile would be expected to be flatter, compared to the profile resulting from a lower energy proton beam.

Detailed spatial neutron flux distributions are shown on Figures 5.-3 and 5.-4. The axial flux distribution along the surface of the target is shown in Fig. 5.-3. The relative high peak flux and subsequent rapid drop off is seen for the neutrons produced by the lower energy protons, while a flatter distribution results for neutrons produced by the high energy proton beam. The radial distributions (Fig. 5.-4) all have a similar shape, since this distribution is primarily determined by the moderating properties of the moderator. Neutrons leaking into the moderator have essentially the same distribution in energy in all cases, since the bulk of the neutrons are created by evaporation (tungsten) or evaporation and fission (uranium-238), and are therefore characterized by similar emission spectra.

The radial distributions of neutrons for different energy groups are shown in Fig. 5.-5. In these figures the neutron fluxes are grouped into four energy groups, three epi-thermal (lower energy boundaries of 0.821MeV, 5.53KeV and 0.625eV, respectively) and one thermal. It is seen that the neutron flux profiles in the epi-thermal groups are monotonically decreasing, while those for thermal neutrons show a distinct peak in the spatial distribution. These shapes are a function of the moderator properties; in a heavy water moderator, for example, the peak would occur at a point further removed from the target surface than that accompanying the light water moderator assumed here.

The uranium-238 target produces a peak neutron flux of approximately 2.0×10^{15} n/cm.²-s., while the tungsten target yields a peak neutron flux of approximately 1.0×10^{15} n/cm.²-s. The increase, by approximately a factor of two, for the uranium target is due to the extra neutrons produced by fission. Both targets would parasitically absorb all of the neutrons which leak back into the target following slowing down in the moderator, since both have significant neutron absorption cross sections.

5.2.2 Fluid Dynamics and Heat Transfer Analysis

Fluid dynamics and heat transfer analyses were carried out for the selected combinations described in Table 5.-1. Based on the physics results it was decided to concentrate on a target using tungsten as the heavy metal. This decision was based on the elimination of fission products, which was felt to be more important than the higher flux possible with uranium-238. Furthermore, tungsten has the advantage of an extremely high melting point, which will enhance the safety in case of an over heating malfunction, in addition to having demonstrated performance as a spallation target in LANSCE. In order to develop a specific design the physics results developed above for 1GeV protons with a total beam energy of 5MW was assumed. From the spatial distributions calculated above it can be seen that the bulk of the neutrons are produced in the first 30 cms. of the target. Thus, a target length equivalent to 30 cms of tungsten was chosen. In order to cool the target it must be arranged with sufficient cooling passages. Two arrangements were considered at this preliminary stage.

First, a configuration consisting of rods arranged in a hexagonal pattern. The rod pitch/diameter ratio was chosen in such a manner as to yield an overall tungsten density of

approximately 80%. (Note, pitch denotes the distance between rod centers.) To compensate for the lower density the target length was increased to 37.5 cm. Assuming that the rods are 5.0 mm in diameter, the desired pitch is 5.3 mm. A total of 127 rods are used in the target, resulting in an outside diameter of 6.89 cm.

The second configuration consists of a particle bed of tungsten spheres randomly packed in a co-axial volume formed by two porous tubes (frits). Since randomly packed spheres have an average void fraction of approximately 35%, the length of the cylinder is required to be 47.0 cms. The outside cylinder is assumed to be 7.0 cm in diameter, and the inside cylinder diameter is set by fluid dynamic considerations. The tungsten spheres will be assumed to be 2.0 mm. in diameter.

The two target configurations described above are shown in Figures 5.-6 and 5.-7, and will be contained in a co-axial pressure vessel. In the rod target, inlet coolant flows axially along the annular channel formed by the outside of the heavy metal target and the pressure vessel. Before entering the target the coolant cools the window. It enters the target at the same end at which the proton beam enters the target, flows axially along the rods, and out the far end. The coolant leaves the target volume through a co-axial feed pipe. In all the target configurations three coolants were considered i.e. gaseous helium, liquid sodium, and liquid lead. In the case of the particle bed target, the coolant enters in a plenum in front of the window and then flows axially through an annular volume cooling the pressure vessel. Finally, it turns and enters another annular plenum surrounding a frit, which feeds the packed bed of tungsten particles. The coolant flows radially through the bed, and then axially out of the target. Only lead and sodium will be considered as coolants in this case, since the outlet duct will be a streaming path in the case of helium.

5.2.2.1 Rod Target

The parameters of primary interest at this conceptual stage of the design are the operating pressure, inlet and outlet temperature of the coolant, and the maximum target temperature. The temperature rise and operating pressure of the coolant must be consistent with the heat generated in the target. The inlet temperature and flow rate are thus chosen to be consistent with the pressure vessel and window strength requirements, while the outlet temperature must still be acceptable. In order to estimate the rod centerline temperature, the temperature rise above the coolant temperature due to the coolant boundary layer and conduction through the rod must be estimated. The temperature rise due to the coolant boundary layer is controlled by the heat transfer coefficient and the heat transfer area. For gases the heat transfer coefficient is determined using the Dittus-Boelter correlation, while for liquid metals the Lyons-Martinelli correlation is used. The heat transfer area is determined from geometric considerations. The target pressure drop is estimated for flow along smooth rods. A summary of the above parameters and other parameters of interest are given below, Table 5.-4.

Table 5.-4 - Preliminary Rod Target Results.

<u>Parameter</u>	<u>Coolant Type</u>		
	Helium	Lead	Sodium
Inlet Pressure (psi)	1500.0	900.0	150.0
Inlet Temperature (K)	300.0	675.0	400.0
Outlet Temperature (K)	800.0	875.0	800.0
Pressure Drop (psi)	170.0	760.0	34.0
Max. Rod Temp. (K)	900.0	1000.0	850.0
Coolant Exit Vel. (m/s)	600.0	28.0	20.0
Pressure Vessel Wall *, Δt (mm)	2.0	2.0	1.5
Coolant Specific Heat (J/kg-K)	5200.0	150.0	1300.0

*Assume the vessel and window are manufactured of Incalloy-X
(73%Ni,15%Cr,6.5%Fe,2.3%Ti, and traces of Mn,Si,Nb,Al, and C)

The preliminary results presented above indicate that in every case a compromise must be made, and it is clear that further analysis is required. In the case of the helium cooled target it is clear that operating pressure, exit temperature, and the exit velocity have not been optimized. It might be necessary to increase the pressure in order to reduce the exit velocity. However, this would increase the pressure vessel wall thickness, increasing the neutron parasitic absorption. The shortcomings of the lead cooled target are directly attributable to the relatively low value of specific heat and relatively high melt temperature. Since the outlet temperature is being limited to values between 800K and 900K a relatively high liquid lead mass flow rate is required to cool the target, implying a high pressure drop. Thus, although liquid metal cooled systems generally operate at low pressures this is not the case with lead in this particular application. Finally, in the case of a sodium cooled target a reasonable compromise seems possible. However, the use of sodium in close proximity to hydrogenous moderators will pose facility safety problems. This fact might eliminate sodium as a possible coolant for the proposed design.

5.2.2.2 Particle Bed Target

Several of the shortcomings implied by the preliminary analysis of a rod target can be overcome by considering a radial-flow, particle-bed target. In this case (see Fig. 5.-7) an outlet duct is lined up co-axially with the proton beam. This duct is filled with coolant under operating conditions. However, if the coolant is not sufficiently dense, then it could become a streaming path for both protons and neutrons, and would thus create a shielding problem for the rest of the facility. A measure of the coolant worth as a suitable proton shield is the product NZ (N = number of nuclei/unit vol. and Z = charge). The values of NZ for the two metals of interest are given below:

<u>Material</u>	<u>NZ</u>
Sodium	0.242
Lead	2.458

As can be seen from this comparison, lead is expected to be far better than sodium at preventing proton leakage out the outlet duct, and helium would be unacceptable by this standard. The particle bed has an outside diameter of 7.0 cms. , the bed and frits are 2.5 cms. thick, and the outlet duct has a diameter of 2.0 cms. Using the above assumptions and the relevant information from the rod target analysis, the following parameters for the particle bed target can be estimated, Table 5.-5.

Table 5.-5 - Preliminary Particle Bed Target Results.

<u>Parameter</u>	<u>Coolant Type</u>	
	<u>Sodium</u>	<u>Lead</u>
Outlet Pressure (psi)	100.0	150.0
Inlet Temperature (K)	400.0	675.0
Outlet Temperature (K)	800.0	875.0
Pressure Drop (psi)	5.0	40.0
Max. Particle Temperature (K)	825.0	900.0
Coolant Exit Velocity (m/s)	51.0	36.5

It appears that many of the difficulties associated with a liquid lead cooled rod target array can be eliminated by adopting the radial flow particle bed type design. Finally, it should be pointed out that if lead is chosen as the coolant it will also become part of the neutron producing medium. Thus the 47 cm. long column of lead forming the outlet duct will not only act as an efficient proton shield, but also as a viable neutron source

5.3 Preliminary Design and Analysis of the Proposed Targets

The exploratory analyses carried out above were used to configure target designs for the BNL spallation source. Based on the above analyses it is clear that the high power densities expected in this target and its cyclic operational mode require that the target include the following features:

- 1) A large heat transfer area per unit volume, to ensure acceptable metal surface temperatures,
- 2) A short conduction path length to ensure low cyclic stresses as the proton beam intensity rises and falls,
- 3) A coolant which can operate at reasonably low pressures and temperatures to ensure that the pressure vessel wall thickness is not excessive. Additionally the coolant should be compatible with an emergency cooling system, and
- 4) All metal components should have a melt temperature which is as high as possible, to ensure a large temperature margin in the event of an upset condition.

The above requirements can be satisfied most easily by selecting a particle bed type target, and arranging the cooling paths in such a manner that the maximum bed thickness is no more than approximately 5 cm - 10 cm. In addition pressurized heavy water (D₂O) will be used as the coolant.

Heavy water would be compatible with light water, which would be used as the emergency coolant, while any of the liquid metals proposed above would not be compatible with light water. Pressurized helium would be compatible with light water, but the required operating pressures in this case would be excessively high. Two target configurations, based on the above conceptual requirements will be outlined below. In the first configuration the particle beds are arranged at right angles to the proton beam, while the second configuration will consist of beds arranged parallel to the beam.

5.3.1 Description of first Target Configuration.

The initial target configuration, which satisfies all the above requirements is shown in Figure 5.8. The overall dimensions are approximately 15x15x60 cms., with the long dimension in the direction of the proton beam. As can be seen from the figure, the target consists of a series of particle beds contained between porous plates (frits) arranged at right angles to the direction of the proton beam. The tungsten particles, which are the primary target, are assumed to have an outside diameter of 500 microns. In the present investigation tungsten, stainless steel, beryllium, and aluminum will be considered as possible frit materials. Furthermore, it is seen that the coolant passages are arranged in such a manner that a single inlet plenum feeds alternate frit pairs, while the other frit pairs feed the single outlet duct. In this manner any of the frit-particle bed-frit combinations (also known as elements) can be varied in thickness in the direction of the beam to optimize neutron production, leakage, energy deposition, cooling requirements, and mechanical considerations. The target is expected to operate in a pulsed mode (10Hz.-60Hz.) with a proton beam energy of 3.6 GeV and a total beam power of 5 MW.

It is expected that substantial amounts of energy will be deposited in the frits. This will be particularly true in those designs using tungsten frits, since the porosity of the frits will be lower than that of the randomly packed particle bed. It will thus be important that the heat transfer area per unit volume in the frits be comparable to that in the particle beds. This requirement will put stringent conditions on the frit hole size and pitch. In order to carry out the initial physics calculations it will be assumed that the frits will have a porosity of 20%, while that for the particle beds is 35%. The target will consist of four different frit-particle bed-frit combinations, with each combination repeated four times, as tabulated in Table 5.-6 and shown in Figure 5.-8.

Table 5.-6 - Dimensions for the Frit-Bed-Frit Combination.
(All dimensions in cms.)

<u>Zone</u>	<u>Frit Thickness</u>	<u>Bed thickness</u>	<u>Coolant Passage</u>
1	0.2	1.0	0.3
2	0.2	2.0	0.3
3	0.3	3.5	0.3
4	0.3	5.0	0.3

The particle bed is relatively thin at the point where the proton beam enters the target, and becomes progressively thicker up to the imposed maximum of 5 cms. Two frit thicknesses are assumed, the thicker frits corresponding to the thicker beds. This arrangement was chosen to allow for any increased mechanical loads resulting from the thicker beds. Finally, all coolant passages were kept at the same thickness, the primary pressure drop will be adjusted by the frit pressure drop and any orificing in the inlet plenum feed to the coolant passages.

The variation of the tungsten solid fraction as a function of distance from the front face of the target is shown below (Table 5.-7). Two cases are considered, one assuming tungsten frits, and the second assuming one of the other frit materials. It is assumed that the heat deposition will be primarily in the tungsten, and thus a solid fraction with low values close to the front face and increasing with depth into the target is desired.

These results indicate that in both cases the desired tungsten density variation can be achieved. However, in the case using tungsten frits the target has a higher density compared to the case using other frit types. Aluminum, beryllium, and stainless steel will also be heated by the proton beam, but the heat deposition should be lower, since it varies approximately as NZ . Based on this simplistic algorithm it is expected that steel frits would have half the heat deposition of tungsten frits; for aluminum and beryllium frits the heat deposition would be lower by approximately an order of magnitude.

The coolant will be introduced into the target at a pressure of 5.0 bars and a temperature of 40°C. The frit, particle-bed combination is expected to have a pressure drop of ≈ 1.0 bar. Thus, from fluid property tables it can be determined that at the outlet to the target the saturation temperature is 143.6°C. Therefore, if boiling is to be avoided the coolant temperature must be below 143.6°C at all locations.

The above preliminary description of the first proposed target will be used in the subsequent nuclear analyses. Following these analyses the target configuration will be modified to account for any undue cooling or material challenges.

Table 5.-7 - Tungsten Solid Fraction as a Function of Zone.

<u>Zone</u>	<u>Solid Fraction</u>	
	Tungsten Frits	Other Frits
1	0.5647	0.3765
2	0.5926	0.4741
3	0.6471	0.5333
4	0.6456	0.5614

5.3.1.1 Nuclear Analyses

Nuclear analyses of the design were carried out using the LAHET code system described above. The primary quantities of interest at this stage of the analysis are the neutron flux possible in the surrounding moderator, and the heating rate in the target components.

The total fluxes on the surface of the above target, and the energy deposited in the various target regions are given in Figures 5.-9 and 5.-10, respectively. The flux plots show the enhancement of the neutron flux achievable when the target is surrounded by a neutron multiplying material such as lead or beryllium which has a significant n, xn production cross section. Note that the energy deposition is only from the LAHET portion of the calculation (i.e., $E > \sim 20$ Mev) which represents the dominant contribution to the heating.

The heat deposition calculation was carried out for each volume within the target. Thus, the heat deposition was determined for all sixteen frit-bed-frit-coolant combinations, and selected vessel walls. These values are used in the thermal analysis to compute the coolant and solid component temperatures. These results are given in Table 5.-8 for the cases using tungsten, stainless steel, and beryllium frits. The heat deposition rates as given were used to determine the coolant, and metal temperatures for the three possible frit choices. Close to the front of the target, where the heating is most intense, the steel frit heating is approximately 60% of the heating in the tungsten frits. Furthermore, the beryllium frits experience approximately half the volumetric heating of the stainless steel frits. Since these determinations are by Monte Carlo calculations, the lack of a sufficiently large number of particle tracks causes scatter in the results far from the target surface. However, the most intense heating occurs in the first few elements, where the statistics are sufficiently good. Furthermore, it can be seen that the heat deposition in the tungsten particle beds is essentially the same for the three cases. Finally, there is a significant amount of heat deposited in the coolant.

5.3.1.2 Heat Transfer and Fluid Dynamics Analysis

In this section the temperature of the coolant, and metal components; and the cyclic thermally induced stress levels will be estimated as a function of the frit material. These estimates will be carried out for the first frit-bed-frit combination using tungsten frits. The largest amount of heat is deposited in this arrangement, and thus requires the highest coolant flow rates. Furthermore, it will be assumed that the beam spot at the entrance to the target is 4cms.x 4cms., and subsequently expands as it moves into the target. Thus, the entire heat deposited at this position appears in this relatively small volume, resulting in the highest power density. Finally, the solid volume involved must be further reduced to reflect the component porosity.

Table 5.-8 - Component Heat Deposition (Energy in Watts)

Component	Tungsten Frits	Stainless Steel Frits	Beryllium Frits
frit	2.1144(4)	1.2397(4)	5.5111(3)
bed	9.3358(4)	9.3392(4)	9.2999(4)
frit	2.4400(4)	1.3686(4)	3.5711(3)
coolant	4.5995(3)	4.4486(3)	4.2303(3)
frit	2.6535(4)	1.3322(4)	6.3834(3)
bed	1.0777(5)	1.0692(5)	1.0291(5)
frit	2.4693(4)	1.5642(4)	4.1186(3)
coolant	4.8214(3)	4.6313(3)	4.3211(3)
frit	2.6558(4)	1.5424(4)	3.0542(3)
bed	9.3154(4)	9.4919(4)	9.0132(4)
frit	2.6973(4)	1.7729(4)	6.6900(3)
coolant	3.8907(3)	5.6401(3)	5.2121(3)
frit	2.3553(4)	1.1265(4)	3.3850(3)
bed	9.2514(4)	9.6110(4)	9.3827(4)
frit	2.2197(4)	1.1005(4)	4.8918(3)
coolant	2.9916(3)	3.1838(3)	5.4857(3)
frit	1.7730(4)	1.0614(4)	3.4274(3)
bed	1.6489(5)	1.8338(5)	1.7794(5)
frit	2.0339(4)	1.2266(4)	2.4701(3)
coolant	5.1514(3)	4.2577(3)	4.1228(3)
frit	2.0598(4)	1.1141(4)	3.5898(3)
bed	1.5238(5)	1.5769(5)	1.5779(5)
frit	1.7785(4)	1.0731(4)	3.8249(3)
coolant	3.4908(3)	3.7144(3)	3.5034(3)
frit	1.6913(4)	9.8291(3)	2.3414(3)
bed	1.5321(5)	1.5733(5)	1.5290(5)
frit	1.7232(4)	1.1040(4)	4.0578(3)
coolant	3.7843(3)	4.1788(3)	2.9050(3)
frit	1.5294(4)	1.0923(4)	4.3207(3)
bed	1.3002(5)	1.4600(5)	1.4946(5)
frit	1.3624(4)	9.2707(3)	5.3482(3)
coolant	2.2307(3)	2.9791(3)	2.8315(3)
frit	1.9516(4)	1.1728(4)	4.3053(3)
bed	1.9901(5)	2.0564(5)	2.1006(5)
frit	1.8844(4)	1.4374(4)	3.2386(3)
coolant	2.0772(3)	1.6820(3)	1.6265(3)
frit	1.7724(4)	1.0540(4)	3.6859(3)
bed	1.7100(5)	1.8156(5)	2.0579(5)
frit	1.4765(4)	9.2430(3)	3.5167(3)
coolant	2.3706(3)	4.4488(3)	4.2465(3)
frit	1.7704(4)	1.3178(4)	5.4900(3)
bed	1.1984(5)	1.4622(5)	1.5543(5)
frit	1.1899(4)	7.2503(3)	2.9633(3)
coolant	1.5912(3)	1.8774(3)	1.2474(3)
frit	1.1136(4)	8.7732(3)	1.7808(3)
bed	8.8486(4)	1.0667(5)	1.2592(5)
frit	9.7196(3)	5.7291(3)	1.5014(3)
coolant	8.9933(2)	1.4429(3)	1.2082(3)
frit	8.7257(3)	6.7132(3)	1.7019(3)
bed	1.0987(5)	1.3042(5)	1.5396(5)
frit	1.1933(4)	8.4982(3)	2.0582(3)
coolant	6.7259(2)	6.3516(2)	1.6416(3)
frit	5.0212(3)	4.3740(3)	1.4171(3)
bed	8.0363(4)	9.7805(4)	1.1806(5)
frit	4.6578(3)	2.6382(3)	1.6739(3)
coolant	4.2903(2)	5.1474(2)	6.4488(2)
frit	5.6921(3)	2.8277(3)	1.0327(3)
bed	6.1372(4)	7.6562(4)	9.7734(4)
frit	3.4710(3)	2.4633(3)	9.2138(2)
coolant	4.6387(2)	6.2026(2)	6.3388(2)
frit	3.8934(3)	2.3028(3)	9.5202(2)
bed	3.5724(4)	4.9163(4)	5.7137(4)
frit	2.2587(3)	2.2985(3)	4.6157(2)
coolant	3.5688(2)	4.3157(2)	2.9518(2)

Based on the above assumptions regarding the beam and energy deposition, and assuming that the coolant inlet conditions are 40°C and 5 bars, it is possible to determine the temperatures throughout the first element. The coolant outlet temperature from each component can be estimated from the flow rate, the enthalpy rise, and the equation of state (thermo-physical property tables). This flow rate and the flow area results in a velocity from which a Reynolds number and subsequently a Nusselt number can be estimated. The Nusselt number and the frit or bed design result in a heat transfer coefficient and an area per unit volume respectively. The Nusselt numbers are determined by using appropriate correlations. In the case of the frits a correlation due to Dittus-Boelter is used, and in the case of the particle bed a correlation due to Achenbach as modified by G. Maise⁸ is used. The frits are flat plates made of either tungsten or stainless steel, 2mm. - 3mm. thick, and with holes on a hexagonal pattern. The hole diameter is chosen to be 172 micron, on a 365 microns pitch. These dimensions are chosen to result in the desired area per unit volume of frit to yield a reasonable temperature rise between the coolant and the frit surface.

The mechanical design, coolant parameters, and the temperature within the first element are summarized in the Tables 5.-9, 5.-10. and 5.-11 below.

Table 5.-9 - Mechanical Parameters for Frits and Bed

Frit Porosity	0.2
Particle Bed Porosity	0.35
Frit Thickness (cm.)	0.2
Bed Thickness (cm.)	1.0
Frit Hole Diameter (micron)	172
Frit Hole Pitch (micron)	365
Beam Cross Section (cm. ²)	16.0

The above table shows that the frits have a lower porosity than the particle beds. Thus, it is expected that the heating in frits per unit volume will be more intense than in the particle beds, if the same material is used in both. This leads to a frit design containing many tiny, closely spaced holes in the frits to ensure an adequate heat transfer area.

Table 5.-10 - Coolant Parameters

Coolant Inlet Temperature (°C)	40.0
Coolant Inlet Pressure (Bar)	5.0
Coolant Flow Rate (kg/s)	1.664
Coolant Outlet Pressure (Bar)*	4.0
Coolant Saturation Temperature (°C)	143.6

* Estimated

The above flow rate is modest, and results in a flow velocity of 3.2 m/s through the frit hole structure.

Table 5.-11 - Temperature Profile in Frit-Bed-Frit Structure

	<u>W.</u>	Frit Type <u>St. Steel</u>	<u>Be. *</u>
#1 Frit Power Density (w/m ³)	5.51(9)	3.23(9)	1.0(9)
Outlet Temperature (°C)	43.0	42.0	41.0
Surface Temperature (°C)	109.0	78.0	52.0
Bed Power Density (W/m ³)	8.98(9)	8.98(9)	8.98(9)
Outlet Temperature (°C)	56.5	55.2	55.0
Surface Temperature (°C)	105.0	103.7	104.0
#2 Frit Power Density (W/m ³)	6.35(9)	3.56(9)	1.0(9)
Outlet Temperature (°C)	69.3	57.2	55.0
Surface Temperature (°C)	129.2	96.0	67.0

* From estimated heat deposition

The above results indicate that the tungsten frits are heated at a much higher rate than the stainless steel frits. The heat deposition in the tungsten frits is seen to be very similar to that deposited in the tungsten particle bed, while there is a much larger difference in the case using stainless steel frits. An even larger difference is expected in the case using beryllium frits. As a result of this relatively high heating rate in the all tungsten case the highest surface temperature is only 13° C below the saturation temperature. The corresponding temperature for the case using stainless steel frits is approximately 50° C below the saturation temperature, while the surface temperature in the case using beryllium frits is expected to be approximately 70° C below the saturation temperature. Based on this result it would be desirable to use stainless steel or beryllium frits. The alternative is to increase the target operating pressure, thus increasing the saturation temperature. An increase in pressure would imply thicker vessel walls, which is not desirable.

An estimate was made to determine the thermal transient, and the implied thermally induced stress in the target components as the accelerator beam pulses on and off (approximately 10Hz-60Hz). This analysis was carried out by assuming that the accelerator beam reached full power instantaneously, and the subsequent temperature transient within the frits or particles was estimated by using published solutions to the heat conduction equation. Details of this analysis are given in the Appendix 3-I. The following conclusions can be reached from this analysis:

- 1) In the particle bed the high thermal conductivity of tungsten (163 W/m-K), and the short conduction path (250 microns) ensure that the temperature rise from the particle surface to the center is no greater than approximately 44.8° K. This rise occurs very rapidly and implies a thermal stress of 7.0(3) psi., which is acceptably low. No stress related problem is expected in the particle bed.
- 2) Four frit materials were considered in this analysis i.e. tungsten, stainless steel, beryllium, and aluminum. The heat deposition was estimated for the beryllium and

aluminum cases. In all these cases the thermal transient lasted longer than in the particle bed, because the conduction path is longer.

- 3) The equilibrium temperatures, and implied thermal stresses are given in Table 5.-12 below.

In order to evaluate these temperature and stress results it should be pointed out that they are applied cyclically. Thus, the stresses must be evaluated as inducing fatigue failures. With this criterion in mind, it is clear that stainless steel is not acceptable as a frit material, since cyclic stress levels of this magnitude are too high to ensure failure free operation. All the other cases result in acceptable stress levels. The high values for stainless steel are due to its poor conductivity, relatively high expansion coefficient and relatively high heat deposition. Thus, based on the transient analysis it is suggested that one of the three remaining candidate materials be used as the frit material. Aluminum is not an acceptable frit material, despite its acceptable performance during normal operation. Its relatively low melt temperature could lead to premature frit melting, and potentially trigger a metal water reaction. In conclusion, the above analysis suggest for this target design that the frits be made of beryllium and the particles of tungsten. This would ensure the production of an acceptable neutron flux in the moderator while also ensuring an acceptable mechanical design with a large thermal margin to ameliorate upset conditions.

Table 5.-12 - Temperatures and Stresses in Frits

<u>Material</u>	<u>Equilibrium Temp.(K)</u>	<u>Stress (psi)</u>
Stainless Steel	29.0	1.03(4)
Tungsten	58.0	9.06(3)
Beryllium	13.0	5.35(3)
Aluminum	18.0	2.63(3)

5.3.2 Description of Second Target Configuration

The second target configuration which satisfies all the requirements outlined in section 3.2 is derived from the two bed target configuration shown in Fig. 5.-11. It consists of three target sections, separated by two flux trap sections. The target sections each consist of a particle bed configured in the direction of the proton beam with frits along two walls to admit the coolant. The pressure vessel forms the other two walls. Coolant enters the bed through one frit, flows through the bed at right angles to the beam, and exits through the other frit. Inlet and outlet plena for the coolant water are arranged above and below the frits. Cooling for the window and assorted structures to contain the particle beds is admitted through plena situated between the outer wall and that containing the particle beds. A beryllium flux multiplier surrounds the target volume. The current design of this component consists of a particle bed of beryllium spheres, cooled by heavy water. The coolant inlet pressure in the main target will be six atmosphere, while in the case of the multiplier volume only approximately half that pressure will be required. The tungsten particles of the target volumes are 1 mm in diameter. This size represents a compromise between bed pressure

drop, and maximum particle surface temperature. In the case of the beryllium particles in the multiplier a much larger range of particle sizes can be considered, since the conditions are less stringent. As in the first case, the target is expected to operate in a pulsed mode (10Hz.-60Hz.) with a proton beam energy of 3.6 GeV and a total beam power of 5 MW.

In this target arrangement the bulk of the proton energy is deposited in the tungsten particle bed. The structural walls in the direct path of the beam will all be subject to heating and will require cooling. These components consist primarily of the front window, and assorted walls to contain the particle bed. The most desirable materials for these components should have low values for NZ, ensuring low heating rates, and reasonably high operating temperature capability. The final selection will be made following the determination of heat rates.

All tungsten target volumes are 22cm wide and have varying thickness in the direction of the beam. The first section has a thickness of 7.5 cm, the second is 7.5 cm thick, and finally the last section is 39.5 cm thick. The flux multiplier surrounds the target volumes, and is 5 cm thick. All coolant passages are 2.5 mm thick, except the main coolant inlet and outlet plena, which are tapered, being 5 mm thick at the inlet end, and 2 mm thick at the other end. The tapered arrangement is necessary to compensate for the decrease in dynamic head of the coolant as it slows down, essentially coming to rest at the narrow end.

"Wing" type moderators will be placed adjacent to the target volumes, while "flux trap/back-scatter" type moderators will be placed adjacent to the flux trap volumes. These moderators can act as either "back-scatter" or "flux trap" moderators depending on which side of the moderator the flux is extracted. This will depend on the arrangement of the beam tubes. A maximum of sixteen beam tubes are possible with the currently configured target. As noted in Sect. 7, these consist of two for each "wing" moderator (four/target implying a total of twelve), and two corresponding to each flux trap volume (one acting as a "back scatter" beam tube, the other acting as a "flux trap" beam tube for a total of four). It is assumed that all of the beam tubes will be arranged horizontally. Conceptually the moderator volumes are assumed to be rectangular with approximate dimensions of 10cmx10cmx5 cm. thick. The exact dimensions are dictated by the adjacent target or flux trap size. All the beam tubes are assumed to be 7.5 cm in diameter.

In this target configuration it is also assumed that the proton beam is rectangular with a maximum foot print of 5 cmx20 cm. This beam spot size reduces to a minimum the possible heating and gas generation (due to proton interactions with the window material) in the window and should increase the reliability of the target.

The above description of the second proposed target will be used in the subsequent physics and heat transfer analyses. Following these analyses the target configuration will be modified to reflect any cooling or materials problems which might be uncovered in the initial analysis.

5.3.2.1 Nuclear Analysis

The nuclear analyses of the proposed target design described above was carried out using the LAHET code system. The detailed geometry modelled in the LAHET/HMCNP simulations are shown in Figures 5.-12 and 5.-13 which represent slices through the target in the two planes perpendicular to the direction of the beam. Note that the particle beds, target structure, wing and flux-trap moderators and associated beam tubes are explicitly represented. The primary quantities of interest at this stage of the analysis are the neutron flux available to the users, and the heating rate in the target and moderator components.

In addition to generating preliminary estimates of the heating in the target for input to the thermal-hydraulic analyses, the nuclear analyses determined the fluxes and energy-dependent spectra in simulated beam tubes associated with various wing and flux-trap moderators: light water, liquid hydrogen, liquid deuterium, and liquid methane. Systems where the beam tubes and moderator were coupled, or decoupled by 1mm. cadmium liners were considered. Typical results are presented in Figures 5.-14 and 5.-15. Note that, even though the Cd liner reduces the thermal flux level it is expected that the time structure will have advantages for some experimental applications. This requires further evaluation.

The heat deposition calculation was carried out for each volume within the target. Thus, the heat deposition was determined for the window, three target volumes, structural components, flux multiplier, and cryogenic moderators. These results are given in Table 5.-13 for a case in which the first and second target volumes are nodalized as shown in Fig. 5.-13.

The heat deposition rates were used to determine the metal and coolant temperatures. It is seen that the target volumetric heating is highest in the first target volume, and drops off with distance into the target. The average heating in the three target volumes is approximately 95 kW/cm, 66 kW/cm, and 20 kW/cm respectively. Interestingly the heat deposition within each target volume is comparatively constant with distance along the proton beam. This characteristic is partially due to the proton energy chosen for the target (3.6 GeV), it makes the coolant distribution system less complicated and more reliable. In addition it is seen that if the window were made of aluminum its heating would be approximately half what it would be if it were made of stainless steel (6.73 kW vs. 15.16 kW). The structural stainless steel walls, which separate the target particle beds from the flux trap volumes, experience varying degrees of volumetric heating. The front wall of the first target experiences a heat deposition of 13.21 kW, while the back wall of the third target experiences a heat deposition of 3.39 kW. However, it should be pointed out that except for the last wall, all other walls experience a volumetric heating rate of greater than 8 kW. Furthermore, the volumetric heat deposited in the beryllium flux multiplier is 18.41 kW, which implies a modest heat deposition, since it has a substantial volume. Finally, the heat deposited in the cryogenic moderators is seen to be comparatively low for the front target volumes, reaching a peak at the second target volume, and dropping off slightly at the third target volume. The average heat deposition in the three sets of "wing" moderators is seen to be 290 W, 742 W, and 705 W respectively. This trend together with the target heating trend indicates that the moderator heating is mostly due to proton beam spillage, and secondarily due to neutron energy deposition. The total cryogenic refrigeration requirement for this target arrangement is seen to be 5.177 kW.

Table 5.-13 - Component Heat Deposition
(Energy in Watts)

<u>Component Description</u>	<u>Energy</u>	<u>Component Total</u>
Window (Aluminum)	6.7277(3)	6.7277(3)
Window (Stainless Steel)	1.5158(4)	1.5158(4)
Stainless Steel wall (front)	1.3204(4)	1.3204(4)
Target (1,1)	9.3287(4)*	
Target (1,2)	9.6545(4)	
Target (1,3)	1.0186(5)	
Target (1,4)	8.8543(4)	6.9499(5)
Target (1,5)	9.3196(4)	
Target (1,6)	9.6164(4)	
Target (1,7)	1.2539(5)#	
Stainless Steel wall (back)	1.0412(4)	1.0412(4)
Stainless Steel wall (front)	1.0409(4)	1.0409(4)
Target (2,1)	6.8102(4)*	
Target (2,2)	6.7270(4)	
Target (2,3)	6.6179(4)	
Target (2,4)	6.6543(4)	4.7579(5)
Target (2,5)	6.5672(4)	
Target (2,6)	6.0809(4)	
Target (2,7)	8.1211(4)#	
Stainless Steel wall (back)	9.0581(3)	9.0581(3)
Stainless Steel wall (front)	8.3460(3)	8.3460(3)
Target (3)	7.5878(5)**	7.5878(5)
Stainless Steel wall (back)	3.3908(3)	3.3908(3)
Beryllium multiplier	1.8413(4)	1.8413(4)
Flux Trap Mod. (1,1)	2.3913(2)	
Flux Trap Mod. (1,2)	3.4821(2)	
Flux Trap Mod. (2,1)	5.7821(2)	
Flux Trap Mod. (2,2)	5.3510(2)	
Wing Mod. (1,1)	2.0349(2)	5.1770(3)##
Wing Mod. (1,2)	3.7765(2)	
Wing Mod. (2,1)	9.7430(2)	
Wing Mod. (2,2)	5.0968(2)	
Wing Mod. (3,1)	6.6026(2)	
Wing Mod. (3,2)	7.5103(2)	

* Target slices 1 cm thick.

Target slice 1.5 cm thick.

** Total heating in third target volume.

Total cryogenic refrigeration load.

5.3.2.2 Heat Transfer and Fluid Dynamics Analysis

In this section the temperature of the coolant, and metal components will be estimated. In addition the thermally induced stresses due to cyclic operation of the target will be estimated. In carrying out these estimates the beam spot sizes will be assumed to be 5 cm x 20 cm. The most intense heating per unit volume will occur in the front target, since the beam tends to expand as it enters the target, affecting a larger volume and thus reducing the volumetric heating per unit volume.

Based on the above assumptions regarding the beam size, energy deposition, and assuming that the coolant enters the target at 6 bars and 40°C, it is possible to determine the temperatures throughout the target. The coolant flow rate can be determined from the inlet conditions, the enthalpy rise, and the equation of state of water. This information can be used to determine the Reynolds number, and subsequently the Nusselt number. The Nusselt number is used to determine the heat transfer coefficient. In addition, the particle bed pressure drop can be estimated using the Reynolds number.

The mechanical design of the frits in this target is not as challenging as in the first particle bed target arrangement since they are not in the direct path of the proton beam. Their porosity is dictated primarily by the need to control the axial coolant distribution. Since the heat generation within each target is comparative constant in the axial direction (see above) the coolant flow distribution problem is comparatively simple. The particle bed consists of tungsten particles with an appropriate coating to minimize oxidation of the tungsten. The mechanical parameters are given in Table 5.-14.

Table 5.-14 - Mechanical parameters for particle bed

Particle diameter range (micron)	1000 - 2000
Particle bed porosity	0.35
Bed thickness at inlet (cm)	6.0
Axial length of first two beds (cm)	7.5

The inlet coolant parameters are given below, Table 5.-15.

Table 5.-15 - Coolant Parameters

Coolant inlet temperature (°C)	40
Coolant inlet pressure (Bar)	6.0
Coolant flow rate (first target) (kg/s)	4.2
Coolant outlet pressure (Bar)	4.0
Minimum coolant saturation temperature (°C)	143.6

The above mass flow rate implies an axial inlet plenum flow rate, which depends on the plenum thickness, as given in Table 5.-16.

Table 5.-16 - Coolant velocity for varying plenum size
(Velocity at plenum mouth)

<u>Plenum size (mm)</u>	<u>Coolant velocity (m/s)</u>
5.0	3.85
3.0	6.41
2.0	9.62

The above coolant velocities are acceptably low, and should not pose any dynamic head problems for the target components. The temperature profile within the target is given below, Table 5.-17.

Table 5.-17 - Temperature profile within target bed

Power density (W/m ³)	1.4479(8)
Coolant outlet temperature (°C)	80
Particle surface temperature (1000 micron) (°C)	93.5
Particle surface temperature (2000 micron) (°C)	115.7
Bed pressure drop (1000 micron) (N/m ²)	1.1121(5) [16.2 psi]
Bed pressure drop (2000 micron) (N/m ²)	5.1307(4) [7.45 psi]

The heating rate in the particles is modest compared to that of the first target design, since the beam spot is larger in this case. This lower heating rate leads to comparatively modest particle surface temperatures. In the case of both possible particle sizes the temperatures are significantly below the coolant saturation temperature. In the case of the smaller particle sizes (1000 micron) the bed pressure drop is marginally acceptable, and thus the larger particle size (2000 micron) will be adopted for the preliminary design.

An estimate was also made of the surface temperature of two possible window materials. Both aluminum and stainless steel were considered as possible candidates. In this analysis it was assumed that heat could only be removed from one face of the window, the other face being treated as an insulator. It was found that a coolant mass flow rate of 0.1 kg/s is required to remove the heat deposited in the window assuming an outlet temperature of 60°C. The following coolant conditions were assumed for this analysis, Table 5.-18.

Table 5.-18 - Window cooling conditions

Coolant inlet pressure (Bars)	6.0
Coolant inlet temperature (°C)	40
Coolant outlet temperature (°C)	60
Mass flow rate (kg/s)	0.1
Coolant velocity (m/s)	0.2

The above conditions do not allow for a sufficiently low film drop in the case of aluminum, and thus the coolant velocity must be increased to ensure an acceptable window surface temperature. An increase in the coolant velocity to 10 m/s, through the same 2mm thick coolant passage behind the window will have the desired effect. In this case the mass flow rate will be 4.4 kg/s, the coolant outlet temperature will drop to essentially 40.5°C, and the aluminum surface temperature will be 62.2°C. These temperatures are very modest, and should be acceptable for operation with 6061 series aluminum. In the case of stainless steel the heating rate is approximately twice as high, implying proportionately higher temperatures. However, stainless steel can operate safely at higher temperatures, with the coolant saturation temperature being the limiting value. If it is found that 10 m/s is too high a velocity, since it requires a high pressure drop, it can be reduced to approximately half that value with aluminum without compromising the operation.

The cyclic stresses induced in the aluminum window were estimated to be 3820 psi, which is within the acceptable limit for aluminum. A more detailed analysis will have to be undertaken if aluminum is chosen for the final design.

5.4 Safety Implications

The safety issues to be discussed here involve material behavior (oxidation, fatigue and mechanical shock), and heat removal in the event of an upset.

5.4.1 Material Behavior

The source is expected to operate in a cyclic fashion, thus the particles and the frits will be subject to an undulating temperature and stress environment. This varying stress field could cause fatigue failures in the target, and subsequently be a safety hazard. However, as pointed out in the above discussion, with the use of a particle bed target concept the thermally induced fatigue failures should be of no concern, even at these high power levels. In the case of the first target design special care will have to be taken in the choice of frit materials to ensure acceptable thermal behavior.

The other material issue associated with tungsten is the possibility of oxidation in the event of an over-temperature transient. Despite the high melting temperature of tungsten it is prone to attack by oxygen (tungsten oxide sublimates at (800K-1000K)). This issue has not been quantified yet, however it might be necessary to control the free oxygen content of the coolant. In addition the particles could be coated with a suitable oxygen resistant layer to impede this attack. The oxygen could be created continuously by the dissociation of the coolant in the radiation environment. An online catalytic recombiner might be necessary to prevent the buildup of large quantities of gas.

5.4.2 Back-up Heat Removal

The choice of tungsten, stainless steel and beryllium as possible target materials and the low operating temperature results in a thermal margin of several thousand degrees. Thus, these materials are very tolerant to under-cooling transient such as pipe breaks or leaks, and should allow sufficient time for a back-up cooling system to operate. Several back-up systems are possible and would be considered in more detailed designs. However, a system consisting of a large pressurized source, separated from the primary system by check valves (which can be automatically activated in the event of a drop in primary system pressure) is the most likely candidate. It should be noted that the efficient heat removal possible with a particle bed will also enhance the removal of post-accident heat from the target. Finally, it is permissible for this back-up heat removal system to use light water, since there are no criticality concerns in this system.

5.5 Conclusions

The following conclusions can be drawn from this study:

- 1) It is possible to generate a total neutron flux of 10^{15} n/cm²-s using the proposed target designs.
- 2) Two particle-bed-based target arrangements were discussed and analyzed:
 - Particle beds arranged at right angles to the direction of the proton beam to ensure minimum bed thickness, but with frits in the beam. The selection of tungsten particles 500 microns in diameter, and frits made of beryllium 2mm - 3mm. thick ensures that no fatigue failures are likely to occur, that the coolant is always well below the saturation temperature at the 5 bar operating pressure, and that the melt temperatures of the components are well above the operating temperature.
 - Particle beds arranged along the direction of the proton beam. In this case the frits are out of the direct beam, but the beds tend to be thicker, requiring larger particle diameters to reduce the bed pressure drop. The selection of tungsten particles 2000 microns in diameter and frits made of stainless steel situated outside of the proton beam has the advantage that the particle bed absorbs most of the volumetric heating. The other advantages from the above target also apply.
- 3) The question of tungsten oxidation by free oxygen generated by radiation-induced coolant dissociation needs to be addressed.
- 4) A back-up cooling system for the target to guard against under-cooling will rely on the large thermal margin and the efficient heat transfer possible from a particle bed.

References - Section 5

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TARGET DESIGN: NUCLEAR ANALYSIS METHODOLOGY

Fig. 5.-2
**Schematic Representation of Heavy Metal Target
Surrounded by a Reflector**

Fig. 5.-3

**BNL PULSED SPALLATION SOURCE
TUNGSTEN TARGET / LWTR MODERATOR
AXIAL FLUX DISTRIBUTIONS @ SURFACE**

BEAM SPOT 1 cm² IN CENTER OF W ROD
ROD(OD/L) = 20 cm./100 cm.

Fig. 5.-4

BNL PULSED SPALLATION SOURCE
TUNGSTEN TARGET / LWTR MODERATOR
RADIAL FLUX DISTRIBUTIONS @ PEAK AXIAL

BEAM SPOT 1 cm² IN CENTER OF W ROD
ROD(OD/L) = 20 cm./100 cm.

Fig. 5.-5

**BNL PULSED SPALLATION SOURCE
RADIAL GROUP FLUX DISTRIBUTIONS @ PEAK
AXIAL OF OD = 20 cm.; L = 100 cm. TARGET**

x GROUP-1: W • 1 GeV ♦ GROUP-2: W • 1 GeV
 ▲ GROUP-3: W • 1 GeV ■ GROUP-4: W • 1 GeV

— GROUP-1: W • 10 GeV + GROUP-2: W • 10 GeV
 * GROUP-3: W • 10 GeV □ GROUP-4: W • 10 GeV

BEAM SPOT 1 cm² IN CENTER OF ROD
 E(min): gp-1 0.821MeV; gp-2 6.631KeV
 group-3 0.625 eV

Rod O.D. - 5mm
Pitch - 5.3 mm

Tungsten Rod Target

Fig. 5.-6

Particle Diameter 2 mm

Tungsten Particle Target

Fig. 5.-7

Fig. 5.-8
Schematic Illustration of Spallation Target
Based on Particle Bed Technology

Fig. 5.-9
TOTAL FLUXES ON SURFACE OF TARGET

Fig. 5.-10
ENERGY DEPOSITION FROM LAHET ($E > 20\text{MeV}$)

Fig. 5.-11
Two Bed Target

04/06/94 09:23:41
 PDSNEX4: 3-SECTION W
 TARGET: 3.6GEV; SS-FRITS; MWTR
 MOD: Be MULT
 prohibid = 04/06/94 09:18:38
 basis:
 (.000000, 1.000000, .000000)
 (.000000, .000000, 1.000000)
 origin:
 (.00, .00, .00)
 extent = (70.00, 70.00)

Flux Trap Moderators and Beam Tubes opposite "Void Gaps"

Fig. 5-12

04/06/94 09:23:00
 PDSNEX4: 3-SECTION W
 TARGET: 3.6GEV; SS-FRITS; MWTR
 MOD: Be MULT
 prohibid = 04/06/94 09:18:38
 basis:
 (1.000000, .000000, .000000)
 (.000000, .000000, 1.000000)
 origin:
 (.00, .00, .00)
 extent = (70.00, 70.00)

Fig. 5.-13

Wing Moderators above and below the three Particle Beds

Fig. 5.-14 **BEAM FLUXES FOR LIGHT WATER
FLUX TRAP & WING MODERATORS**

Fig. 5.-15 **EFFECT OF CADMIUM LINER ON
BEAM TUBE FLUX SPECTRA**

Appendix 5-I. Transient Heating in Target Components

In this appendix details of the transient heating in the target particles and the frits will be estimated. In all cases it will be assumed that the beam power appears instantaneously in the component of interest. The subsequent temperature transient in the component is estimated by using published closed form solutions to the heat conduction equation. All solutions assume that the component temperature is a combination of two components. First, a steady state solution equivalent to the removal of 5 MW of heat from the target, second a transient component given by 1/60 of the amount, resulting from the pulse. The steady state profile is assumed to shift instantaneously due to the pulse. The total temperature difference is assumed to be the time varying temperature pulse. Since, the temperature pulse will relax on the outside surface first, thus the total gradient will be based on the temperature difference from the surface to the maximum centerline temperature. This temperature difference will be used to estimate the thermal stresses in the components. Heat deposition is assumed to be spatially constant in all components. In the first section the tungsten particles will be considered and in the second section four frit candidates (tungsten, stainless steel, beryllium, and aluminum) will be considered.

Transient Heating of Target Particles

The assumptions in this analysis are given below:

- Spherical Geometry radius = a
- Constant heat generation starting at t=0, Q (w//m3)
- Material , Tungsten.
- Temperature T(r,t)=0 at t=0 and all values of r.

Solution for steady state heating in spheres is given by:

$$DT(steady) = \frac{Q}{2} \left[\frac{a^2}{K} + \frac{a}{h} \right]$$

Where:

K = Material Conductivity
h = Heat Transfer Coefficient

Solution for adiabatic heating during pulse is given by:

$$DT(trans.) = \frac{Q}{\rho C f}$$

Where:

C = Specific Heat
 ρ = Density
f = Frequency of pulses

The following constants and thermal properties were assumed for tungsten;

C = 134.4 W-s/Kg-K
 $r = 1.935(4)$ Kg/m³
h = 2.79(4) W/m²-K
a = 6.271(-5) m²/s Thermal Diffusivity.
K = 1.63(2) w/m-K Conductivity
a = 5.0(-4) m Radius
Q = 1(10) w/m³ Energy Deposition.

The two components of temperature referred to above can now be calculated, and are given by:

$$\begin{aligned}DT(\text{steady}) &= 33.5 \text{ K} \\DT(\text{trans.}) &= 11.3 \text{ K}\end{aligned}$$

The total implied temperature increase per pulse is thus the sum of these values, and is 44.8 K.

The thermal stress implied by this temperature difference between the surface and the particle center is given by:

$$s = \frac{a_{\text{exp}} D T F}{2(1-\eta)}$$

The following thermal and mechanical properties were assumed for tungsten;

$a_{\text{exp}} = 4.5(-6)/\text{K}$ Coefficient of Expansion
E=5.0(7) psi Modulus of Elasticity
n= 0.28 Poisson's Ratio

It is seen that the thermal stress is approximately 7000 psi., which is within fatigue limits for tungsten. No stress related problem is expected in the particle bed.

Transient heating of frits.

Transient heating of frits only applies to the first particle bed target concept. In the second concept the frits are well outside of the primary proton beam, and radiation induced heating is expected to be relatively low.

Relationships similar to those described above can be used to estimate the cyclic thermal stress in the frits in the first target design. The following thermal properties are assumed for the four frit material candidates:

		S. Steel	W.	Be.	Al.
C	Specific Heat	4.6(2)	1.34(2)	1.73(3)	9.0(2)
r	Density	7.82(3)	1.94(4)	1.85(3)	2.70(3)
h	Heat Trans. Coef.	2.60(4)	2.60(4)	2.60(4)	2.60(4)
a(m ² /s)	Thermal Diffusivity	4.44(-5)	6.27(-5)	4.29(-5)	8.42(-5)
K(w/m-K)	Conductivity	1.63(1)	1.63(2)	1.45(2)	2.04(2)
l(m)	Slab half thickness	1.0(-3)	1.0(-3)	1.0(-3)	1.0(-3)
Q(w/m ²)	Energy Deposition	4.0(9)	1.0(10)	1.0(9)*	1.5(9)*

* Estimate.

Based on the above values the following temperature increases are calculated for the various candidate frit materials

Material	Temperature increase (K)
Tungsten	58.0
Stainless Steel	29.0
Beryllium	13.0
Aluminum	18.0

The following thermal and mechanical properties were used to compute the maximum implied thermal stress for each of the four cases.

	S. Steel	W.	Be.	Al.
a _{exp} (/K) Coefficient of Expansion	1.78(-5)	4.5(-6)	1.8(-5)	2.0(-5)
E(psi) Modulus of Elasticity	2.76(7)	5.0(7)	4.4(7)	1.0(7)
n Poisson's Ratio	3.05(-1)	2.8(-1)	3.0(-2)	3.3(-2)

The implied cyclic thermal stresses for these four cases are:

	Stress (psi)
Stainless Steel	1.03(4)
Tungsten	9.06(3)
Beryllium	5.35(3)
Aluminum	2.63(3)

Except for the case of stainless steel the cyclic stress levels are acceptable and should not cause any thermally induced fatigue failures. In the case of stainless steel, the cyclic stress level are too high to ensure failure free operation. This high stress level is due primarily to the poor conductivity of stainless steel, and the relatively high heating rate. It is thus suggested that one of the other three candidate materials be used as the frit material.

6. BEAM LOSS, TARGET SHIELDING AND HANDLING

6.1 Beam Loss and its Effects

6.1.1 Expectation on Beam Losses

The average proton current on target of the Spallation Neutron Facility is 1.4 mA. That is a factor one hundred larger than the corresponding design value of the AGS Booster, which at the moment is running at about half this value. Beam losses in the AGS-Booster complex of a few percent are presently experienced. At these levels, the radiation exposures are manageable, but there is clearly a desire to do somewhat better and to improve the system efficiency. By scaling, even allowing an increase of the minimum radiation exposure level, the Spallation Neutron Facility cannot tolerate beam losses at rates exceeding 0.1%. Since most of these losses are expected in the synchrotrons, where also the energies are larger, the design of the synchrotrons and of the whole cycle from injection to extraction focussed on the major concern of controlling the loss rate to an acceptable level. Below are listed the locations and amounts of beam losses that can reasonably be expected. Shielding and radiation protection should be based on these figures.

Injection: This occurs at the lowest energy of 600 MeV. It takes about 0.5 ms to inject 300 turns of negative ions that are stripped by traversing a foil. The total number of protons injected is 1.45×10^{14} per cycle and per ring. Most of the losses are caused by the scattering in the foil; thus, the design is optimized for limiting the loss rate to well below 0.1%. Nevertheless, losses as high as 3% may be expected during start-up and commissioning of the rings in the high-intensity mode. As one gets more experience with hands on the machine, the loss rate will lower correspondingly. The injection losses are expected to occur in the injection straight section and in the region downstream.

rf Capture: The beam that has survived injection, must be captured by the rf system in buckets and, at the same time, accelerated. A problem, typical of fast cycling synchrotrons, arises due to the fact that the rf capture occurs for a significant period of time during the cycle, at a rate which makes the field variation significant. As a consequence, the rf capture is not adiabatic. The process takes about a few milliseconds and involves the energy range between 600 and 800 MeV. Computer simulations show that it is reasonable to expect loss rates not exceeding 0.1%. Nevertheless, for the same reasons cited above, the radiation shielding should be designed for losses as large as 3%. The losses are concentrated around the regions where the dispersion is large, that is in the middle of the arcs. It is there that collimators and beam scraper can be located to intercept the beam halo.

Acceleration: Once the beam has been injected and captured, very low losses are expected during the acceleration cycle. Transition energy remains well above the entire cycle: a feature intentionally included in the design. Losses may be caused by failures or by uncontrollable beam behavior, like unexpected instabilities. Still one should assume a level of loss at 1%, uniformly distributed over the energy range between 0.6 and 3.6 GeV. Again the losses are expected to occur in the middle of the arcs where the dispersion is large.

Extraction: Beam is extracted in a single turn. The operation, including a period of time antecedent to extraction proper, when the beam is prepared and bumped, will take only a small fraction of a millisecond. Loss rates as high as 1% should be considered; but they are also at the full beam energy (3.6 GeV). The location of the losses is the extraction straight section and the region downstream.

Both synchrotrons are located in the same tunnel. Thus the figures of beam loss quoted above, though they have been expressed as beam fractions, cause obviously twice the level of the radiation activation. Moreover, all the events of losses occur at the rate of 30 Hz in a synchrotron. Since the two rings are 180° out-of-phase, the overall loss events in the tunnel occur actually at the rate of 60 Hz.

6.1.2 Beam Abort System

For the Linear Accelerator a fast beam interrupt system will monitor the RF amplitude and phase of all the Linac sections, it will also monitor distributed radiation loss, and all the transport quadrupole and dipole current values. If any of these parameters move outside preset range values the linac beam will automatically be turned off by means of the fast chopper unit within a time interval of less than 5 microsec.

Following beam injection into the FCS's, similar radiation monitors and beam component parameter monitors will establish normal beam behaviour or establish anomalous behaviour. In case of the latter, beam injection will be inhibited on the next cycle. Normal operation will be reestablished following corrective action regarding system components and, sequentially, a limited duration lower intensity restart mode. In addition, in case of aberrant behavior following FCS injection, the beam will preferentially be dumped at ring scraper collimators, where adequate shielding will be provided. A set of "fast" closed orbit bumps will be incorporated in the ring magnet system for this objective.

6.1.3. Radiation Effects in the SNS

Serious quantitative considerations have been given to spallation-neutron-source materials performance criteria and their implications for the selection and qualification of radiation-resistant materials for more than fifteen years. Therefore, at this point in time a substantial body of literature exists that relates to these subjects. The unique aspect that a spallation neutron source brings to the discussion is the high energy of its proton beam and subsequent spallation neutrons. An additional problem arises from the anticipated high fluxes of these particles. At

its planned ejection energy of 3.6 GeV, the proton beam of the SNS poses questions for materials selection that go beyond present knowledge. Most relevant experimental data bearing upon this subject have been obtained at energies that lie between 600 and 800 MeV. Extrapolation of existing data from these lower energies will be necessary, thereby introducing uncertainties into facility design considerations.

6.1.3.1. Required Information

Estimates of radiation damage to SNS components will require certain knowledge that will have to be derived from a combination of existing data, new calculations and key experiments. If materials selection is based upon criteria other than performance in the SNS radiation environment, then qualification of the selected materials will be necessary. On the other hand, if radiation resistance is used as the initial criterion, then time, effort and expense can be reduced through reliance on available data. Therefore, the first phase of a radiation-damage assessment program for the SNS should consist of the following actions:

1. Determination of proton and neutron fluxes and energy spectra at various positions in the SNS, especially the target. This will require calculations plus extrapolation of available results from lower-energy proton irradiation experiments.
2. Preliminary selection of materials for the major components of the facility: LINAC, Fast Cycling Synchrotron (FCS), and Target.

The second phase of a radiation-effects program would address the performance of the selected materials in the anticipated SNS environment. This assessment would have to consider materials property degradation arising from the unique SNS characteristics:

- high point-defect generation rate
- high transmutation product generation rate
- high-energy recoil spectra
- high thermal-neutron flux
- high ionizing radiation flux
- high production rates of H and He

Special concerns of the materials evaluation would deal with mechanical properties and radiation-induced corrosion and its consequences.

6.1.3.2. Existing Knowledge Base

Owing to the long history of radiation-effects research, a large database has been established from materials testing in mixed-spectrum reactors, in fission-neutron spectra, and in 14 MeV neutron fluxes. Experimental programs have been accompanied by extensive

calculations using specialized neutron transport codes and radiation damage codes. At the International Conference on Accelerator-Based Transmutation held at PSI in 1992, the Organization of Economic Cooperation and Development (OECD) organized a special task force to evaluate several codes, such as NMTC, HETC, LAHET, NCNP, and the Pre-equilibrium model code for calculating the relevant radiation-induced quantities for comparison with experimental data. Benchmark problems are being set up to validate these codes for the several applications. Brookhaven National Laboratory is participating in this activity.

In addition to the research and testing associated with fission and fusion power, a growing body of data has been accumulated by European scientists with heavy reliance upon the capabilities that have been developed at Los Alamos. The SNQ project at the KFA-Julich was one of the first to give serious consideration to an experimental program utilizing high energy protons at LAMPF. It was followed by the ISIS project in England, and the current SINQ project at the Paul Schering Institute in Switzerland.

In the United States, research on the APT and the ATF at Brookhaven and Los Alamos has been producing new insights into spallation-source designs that take into account the anticipated radiation effects. There is an active materials qualification effort carried out by BNL, SNL, and LANL in the APT program. Also, the transmutation products produced need to be predicted because of 1) source form, 2) materials degradation, and 3) waste stream concerns. Codes such as ORIGEM and CIMDEK-90 can be used to deduce the production cross sections for these elements. Experimental work will be required to benchmark these codes for the higher-energy protons.

All of these data are available in reports or publications. The principal investigators are colleagues who are well known to BNL staff members, and who have been frequent visitors to the Laboratory. They can be regarded as a potential resource for BNL if it should plan to move ahead with the conceptual design of a spallation neutron source.

6.1.3.3. Information to be Acquired

The principal goal of a radiation effects program for a spallation neutron source based upon the present BNL design must be to compare the consequences of utilizing a 3.6 GeV proton beam with those of an 800 MeV proton beam. Even though the lower energy database is modest, it represents the only cost effective resource for the initial phase of the proposed program.

For a future project, plans would have to be implemented to extend the experimental work and the associated radiation damage models to higher energies. Because fluence as well as flux is an important variable for certain kinds of materials properties, these plans will require long lead times. In the higher-proton-energy regime proposed for the SNS, the resultant neutron spectra will be shifted to higher energies. Since the n, α and n, H cross sections increase dramatically with increasing proton energies, this predicts H and He production and He/dpa and H/dpa rates much in excess to that within our experience and data base. Effects of H and He

and synergisms with dpa will be a major research concern. Given the high source currents that are proposed, it is unlikely that an accelerated testing program could be initiated at any existing facility. Therefore, the time required to accumulate relevant radiation exposures would be lengthy.

6.1.4. Radiation Dose in Magnet Coils of the 3.6 GeV FCS

6.1.4.1. Introduction

In the foregoing (Sect. 4.3.9), a numerical simulation of the effects of beam loss due to rf capture inefficiency was reported. The primary purpose of that study was to estimate the degree to which such beam loss, wherein the primary loss is from the momentum aperture of the accelerator, could be localized in the lattice. Subsequent to that simulation, changes in the lattice design have occurred with the result that the regions of highest dispersion are now coincident with the regions of highest magnet density. Although the conclusions of the cited study on loss localization are not changed, the beam scraper must now be placed extremely close to a magnet to intercept orbits outside the rf buckets instead of in a 4.5m straight section as assumed earlier. The primary concern in such a geometry is the potential of radiation damage to the coils of the magnet.

6.1.4.2. Geometry

The scraper is assumed to be placed in one of the short (1.14m long) drift regions immediately in front of a horizontally focussing quadrupole, where the dispersion is high, 4.1m. The scraper is assumed to be steel and 35 cm. in length. The elements in the beam direction are the following:

<u>Element</u>	<u>Length (cm)</u>
Drift (with scraper)	35
Drift	38
Quad	60
Drift	114
Dipole	280

The approximations for the geometric cross section of the magnets are shown in Figs. 6.-1 and Fig. 6.-2. For ease in coding, the beam pipe and apertures have been simplified considerably, but the position of the coil regions relative to the beam axis is correct. The ideal magnet field values at injection (600 MeV) energy are assumed within the apertures and ignored elsewhere. The apertures are a radius of ≤ 10.7 cm for the quadrupole and a vertical half-aperture of 8.5cm, extending horizontally to 27cm in the dipole. The ceramic beam pipe is approximated by aluminum with $\rho = 1.8$ g/cc, the coils by copper with $\rho = 8.9$ g/cc, and the poles by pure iron with $\rho = 7.8$ g/cc.

6.1.4.3. Simulation Results

The Monte Carlo program CASIM^{*} was used to calculate energy deposition in a restricted region of the coils as shown in Figs 6.-1 and 6.-2. The source is 600 MeV protons which are forced to interact at a depth of up to 1mm in the face of the scraper. From Ref. 4.3-59, the expectation is that 75% of off-momentum (uncaptured) protons will interact in such a scraper, whereas the remainder will out-scatter from the face of the scraper with transverse directions large enough to interact in a relatively restricted region (within 10m) of the lattice downstream from the scraper.

Not surprisingly, the maximum energy deposition is found to be in the tip of the quadrupole coil and the dipole section closest to the beam center line indicated in Fig. 6.-2. The energy deposition density in these "hot-spots" vs. distance along the beam direction extending as far as 2m into the dipole is shown in Fig. 6.-3. The error bars shown on the dipole points are estimates only from three independent CASIM runs with different random number seeds. The statistics on the quadrupole energy density was high enough for the error to be less than 5%.

6.1.4.4. Discussion

Although the energy density in the dipole coil is lower than in the quadrupole coil by some 2 orders of magnitude, this neglects the outscattered orbits, some of which will interact in the region of the dipole. No attempt has been made to perform a simulation so sophisticated as to include this effect. It would appear reasonably prudent to assume that the maximum energy density in the dipole is reduced by 1 order of magnitude from that in the quadrupole.

The maximum energy density of 5.5×10^{-4} GeV/cc-p in copper is 10^{-11} rad/p. The dose per second, assuming a capture loss of 10^{-3} then becomes:

$$1.4 \times 10^{14} \text{ p/pulse} \times 30 \text{ pulses/sec} \times .75 \times 10^{-3} \times 10^{-11} \text{ rad/p} = 31.5 \text{ rad/sec.}$$

In a 10^7 sec year, the dose is 3.15×10^6 rad which should be compared with the normal magnet coil insulation radiation limit of 10^9 rad and high rad (polyimide) coil limit of 2×10^{10} rad. A reasonable lifetime is obtained if high radiation resistant insulation is used, even at the 1% loss level. At higher loss levels, a special quadrupole with ceramic insulation, which halves the current density, might be required locally.

* A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975).

6.2 Target Shielding and Handling

As is clear from the above discussions, the proposed spallation neutron source target with its associated moderators, beam tubes and reflector represents a complicated system. While initial nuclear and thermal design scoping analyses have been performed for the target and its immediate environment (moderator blocks and reflector) to provide estimates of operating characteristics and performance, a great deal of work remains to be done before the target system can be characterized as a base line design. This additional effort would be focussed primarily on defining the engineering details of how the coolant would be supplied to the target and moderators. Related to this issue is the shielding required around the target to permit experimenters and their equipment access to the beam neutrons without subjecting them to excessive radiation doses due either to neutrons and/or gammas from the source, produced as a result of interactions with intervening structures or to activation. The amount, composition, and geometry of the required shielding will have a major impact on the engineering details of the piping configurations, the resultant performance of the target relative to RAMI (Reliability, Availability, Maintainability, and Inspectability) considerations, and handling operations for the target and associated components (moderators, beam tubes, reflector and shield components). The fact that the cooling media (and the components they come in contact with) will likely activate during operation means that shielding and radioactive contamination/potential release considerations must also be factored into the design and layout of piping runs and heat exchangers and will necessitate the use of intermediate cooling loops.

6.2.1. Shielding

In this section we will discuss some issues related to the characteristics and the design of the shield for the target/moderator-beam tube/reflector system. (In principle, shielding for auxiliary piping and components is required only due to the coolant activation, and does not differ fundamentally from that needed at similar reactor based facilities).

Shielding of the target system is more complicated than that associated with a reactor based facility due to the very high energy neutrons generated as a result of the spallation process. The bulk of the neutrons produced by the spallation process are due to evaporation with a characteristic mean energy of a few MeV and have an isotropic angular distribution (i.e., very similar to a fission reactor). A non-negligible fraction of the neutrons, however, are produced with energies approaching those of the incident protons. The angular distribution of these very energetic neutrons is highly anisotropic, with the probability density of very high energy neutrons decreasing as the angle with respect to the direction of the proton beam increases.

No explicit calculations with respect to shielding requirements have been performed to date. It is expected, however, that the selection of 3.6 GeV for the proton beam energy will require a significant effort to arrive at a shield configuration in terms of materials and geometry that satisfies dose requirements with reasonable cost, performance and handling characteristics.

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The traditional shielding materials for spallation neutron source targets have been combinations of iron and concrete; these affect, primarily the neutrons above and below $\sim 20\text{MeV}$, respectively. It is probably undesirable to rely exclusively on these materials for the present design (with its potential maximum energy neutrons of 3.6 GeV), because the resultant over-all size of the shielded target might adversely affect performance by pushing experimental facilities too far from the source, thereby unacceptably reducing beam intensity. Possibly neutron guides can be used to offset this potential penalty. Consequently, a "high performance," shield that represents an optimization between cost and performance will be employed. This shield would be a composite structure including a metal with improved performance relative to iron for attenuating high-energy neutrons, and with a hydrogenous component, possibly incorporating neutron absorbing poisons to attenuate and absorb low-energy and thermal neutrons. In configuring the shield and selecting materials consideration must also be given to shielding against the secondary neutron and gamma production in the shield structure.

6.2.2 Handling

This section will concentrate on handling of the target, moderators, and associated piping required for cooling. The placement of the target and moderators is discussed in Section 2.6.2. Briefly, the target and moderators need to be surrounded by a thick (approximately 7m) biological shield. All access to the target and moderators has to be through the shield. In addition, individual components need to be accessible for inspection and removable for service/repair. A possible arrangement is shown in Figure 9.-4, Fig. 9.-5 and Fig. 9.-6 of Section 9. Target cooling will be by pressurized heavy water, while the moderators will be cooled by various cryogenic systems (depending on the moderator design).

In the case of the three target volumes, the inlet heavy water is at a pressure of 0.6 MPa and a temperature of 313 K . In the case of the moderators, cryogenic lines supplying liquid hydrogen, and ambient temperature lines supplying light water will be required. The cryogenic lines will require vacuum insulation to minimize heating by conduction to the line and volumetric heating due to the radiation field in which they are required to operate. The latter requirement will put limits on the possible materials of construction of the piping system.

The target and moderator volumes need to be arranged in such a manner that they can be removed for maintenance and repair (and, in general, to take into account RAMI considerations). This requires that the total assembly be removed following irradiation and moved to an appropriate repair facility. The removal of irradiated parts from such a facility will require that the assembly be enclosed in a shielded cask to minimize worker exposure. In addition, while the target is in the cask, it will require cooling to remove decay heat. The latter requirement may be met by merely leaving the target in a flooded condition while in transit. However, detailed analyses will be required to determine the heating rate and transit time.

The most convenient manner to satisfy the above conditions is to locate the target and moderator in a single "plug", as shown in Figure 9.-6 of Section 9. In this manner, the removal of

the assembly is facilitated by lifting the plug out of the biological shield and placing it in a shielded cask located in the target handling room. Sufficient clearance must therefore be provided in the target handling room to accommodate the required vertical range of motion. From this point, the cask containing the assembly can be moved to a repair facility either adjacent to the target handling room or in some central location.

- All piping connections for target and moderator cooling, and cryogenic liquids must be made outside the "plug", and above it to minimize the possibility of losing coolants in the event of pipe breaks. Thus, these connections will have to be broken in the target handling room prior to removal of the assembly, and auxiliary cooling connected if necessary. The auxiliary cooling lines can be flexible hoses. The cask will have to be designed in such a manner as to receive the entire plug containing the targets, moderators and associated piping.

After repair or servicing the assembly is returned and placed in position in the biological shield and the appropriate cooling lines connected. At this stage, it is ready for a final check and the resumption of operation. It is felt that such a single modular-unit construction will be the most convenient for handling, servicing and transporting the assembly. Details of the plug design, with its complex piping layout, would need to be addressed in a next phase of the PSNS design. Finally, such a design, using two assemblies could result in a relatively short down time. While one "target module" is being repaired or serviced the other could be in operation thus only the time for removal and connection is lost.

One Quadrant of a Quadrupole
Fig. 6.-1

One Quadrant of a Dipole
Fig. 6.-2

Maximum Energy Density in the
Magnet Coils vs. Z (beam direction)

Fig. 6.-3

7. EXPERIMENTAL FACILITIES

7.1 Introduction

Although reactor-based and spallation neutron sources have different advantages and disadvantages, the consensus view is that almost all of the research done at steady-state, reactor-based sources can also be done - not always in the same way, but with essentially the same end result - at pulsed spallation sources. There are, however, certain spectroscopic techniques that work best with steady-state neutron sources and others that are better suited to pulsed beam sources. As would be expected, time-of-flight methods for neutron monochromation and energy analysis, i.e. techniques which specifically exploit the time structure of the beams, are particularly well-matched to pulsed spallation sources. Naturally, they will be emphasized in the beamline and instrument plan developed for this facility. But since there are active and important areas of neutron research that do not adapt easily to time-of-flight methods, we have also chosen to include instruments that derive little if any benefit from the time structure of the beams.

In time-of-flight spectroscopy, the optimum choice of pulse repetition rate depends on the energy spectrum of the incident neutrons and on the amount of energy transferred during the scattering process. Instruments utilizing lower energy neutrons are generally more efficiently served by lower repetition rate sources. To best accommodate the differing repetition rate requirements of instruments employing substantially different neutron energies, an arrangement of two physically identical spallation targets is proposed: one a 50 Hz target, taking five of every six proton pulses, and the other a 10 Hz target, to which every sixth proton pulse would be directed. Instruments employing epithermal and thermal neutrons would be served by the 50 Hz target; the 10 Hz target would supply neutrons to instruments operating primarily with neutrons of subthermal energies. This approach makes the most efficient use of the neutrons produced by the proton beam and at the same time maximizes the number of experimental facilities that can be served by the accelerator system.

7.1.1 Moderator and Beamline Arrangement

Condensed matter research - the primary function of today's reactor-based and spallation neutron sources - requires neutrons with energies in the epithermal, thermal and subthermal range, energies well below those generated in the primary spallation process. Excess energy is removed by successive collisions of the neutrons with atoms (or molecules) in moderators placed as close to the target as the heat loading will permit. Both the dimensions of the moderators, their locations and the choice of moderating materials are dictated by the need to obtain in each beam tube the greatest possible flux of neutrons within a given spectral range while at the same time maintaining good heat transfer and an optimal time structure in the beam. Spallation source moderators are typically of the order of 10 cm in lateral dimension and 4-5 cm thick and contain liquids composed predominantly of light atoms.

Each of the two proposed three-section, heavy-metal spallation targets will feed neutrons to six 10x10x5 cm wing moderators and four 7.5x10x5 cm flux-trap moderators as shown in Fig. 7.-1 and described in Section 2.6. (Here, and in what follows, the dimensions given should be regarded as approximate since they have not yet been optimized by detailed neutronics calculations.) Altogether the six wing moderators are intended to support twelve beams and the four flux-trap moderators, four beams. All sixteen beams will be of dimensions 7.5x7.5 cm. Tentatively, four of the ten moderators at the 50 Hz target station would operate with liquid methane, the other six with ambient temperature water. At the 10 Hz station, two moderators would contain liquid methane and the other eight, liquid hydrogen. The final decisions as to which moderators will serve which beam lines at each target station should be considered at a later stage of the design process.

All of the moderators are envisioned as being in closed loop systems with forced, pump-driven circulation of the moderating liquid through external heat exchangers. In the case of the liquid methane moderators, it is recognized that although they perform well from the neutronic point of view they have unresolved problems relating to radiation-induced polymerization of long-chain hydrocarbons and to radiation-induced molecular dissociation. It may be that a fractional distillation process for continuous removal of long-chain hydrocarbons and hydrogen gas from the circulating liquid can be developed. If not, bilayer moderators of ambient temperature water and liquid hydrogen would perform almost as well.

7.1.2 Configuration of Experimental Beamlines

Identical beamline layouts, shown in Fig. 7.-2 are proposed for the 50 and 10 Hz stations. The 15° angle between beams provides sufficient room for monochromating choppers and rotating shutters at the biological shield face and for adequate shielding around the beams and spectrometers. In a horizontal target facility of the type proposed here, the moderators will be at three different heights above the experimental floor. Thus the four beams served by the flux-trap moderators and the six served by the top row of wing moderators will be, respectively, 10 and 20 cm higher than the six beams served by the wing moderators of the bottom row.

The lengths of the individual beamlines will depend on the requirements of the particular instruments they serve. Instruments whose performance is solely determined by the time-averaged flux need to be located as close to the biological shield face as possible while those utilizing the pulsed character of the beam for monochromation and energy analysis could be anywhere from 10 to as much as 150 meters away, depending on what distance gives the best compromise between resolution and intensity. As with the moderators, final decisions as to which beamlines will serve which instruments and where the instruments will be located on the experimental floor should be made at a subsequent stage of the design process.

It is considered that each of the target stations be located in an experimental hall 100 meters in diameter and that the halls be situated as shown in Fig. 7.-3. With this arrangement the two stations would have common target handling, laboratory, shop and office space and at least half the beams at each station could be extended beyond the boundaries of the experimental halls to a distance of

100 meters or more without intersecting either the accelerator shielding or a beam from the other station. Experimental halls of this size would accommodate almost all of the instruments contemplated; the few needing unusually long flight paths would be located outside the halls in separate small buildings.

Because spallation sources produce neutrons of considerably greater energy than reactors, the biological shielding around the targets will have to be on the order of six meters thick; roughly 2.5 times thicker than the equivalent reactor shielding. Although the greater thickness of spallation-source shielding is partly compensated by the greater size of reactor pressure vessels, instruments at a spallation source shield face are still anywhere from 30-50 percent farther from the region of peak thermal flux than at an equivalent reactor-based installation. These greater distances translate into roughly a two-to-threefold decrease in time-averaged flux, making spallation sources a somewhat less attractive alternative for applications such as triple-axis or spin-echo spectroscopy which do not derive any important benefit from the pulsed nature of the beam.

It would be useful to explore the possibility of using either supermirror or nickel-coated neutron guides in individual beamlines to increase the useful flux at the instrument locations. Plans are currently being formulated to install supermirror-coated guides at the HFBR. If experience shows them to be radiation resistant enough to be located inside as well as outside the biological shield, then it is possible that more competitive performance of thermal spectrum instruments operating on the time-averaged rather than the peak flux could be achieved in this way.

A three-section target arrangement of the type proposed can only supply neutrons to a radial array of sixteen individual beams if each of the wing moderators serves as a source of two beams. Furthermore, to maximize beam intensity, minimize fast neutron contamination and, at the same time, maintain good pulse structure, it is important that the beamlines be normal to the moderator emitting surfaces and that they view only the moderators, i.e. no sightlines should intersect the targets. Satisfying all of these conditions simultaneously requires that the moderators be angled with respect to the target centerlines and that the emerging neutron beams cross inside the biological shield. A possible near-target arrangement at each of the three beamline planes is shown in Fig. 7-4.

Spallation Target and Moderator Configuration

Fig. 7.-1

Schematic representation of the three-section spallation target. High energy neutrons generated in the target sections will be scattered into six angled wing moderators and four flux-trap moderators supplying lower energy neutrons to sixteen beam lines.

Beam Line Layout in the Experimental Halls

Fig. 7.-2

Possible arrangement of the sixteen beam lines in each experimental hall. Twelve of the beam lines will be supplied with neutrons by the wing moderators and four by the flux-trap moderators.

Tentative arrangement of the two Experimental Halls

Fig. 7.-3

The proton beam will be switched between two experimental halls; one containing a 50 Hz target for beam lines employing thermal neutrons, the other a 10 Hz target for beam lines utilizing subthermal neutrons.

8. SUPPORT FACILITIES, COMMON SERVICES

8.1. Computer Monitoring and Control Systems

The computer monitoring and control system will support operation of the accelerators and provide operator access for setup of accelerator conditions. It will also provide for archiving and restoration of accelerator states and record keeping for administrative purposes.

8.1.1. Architecture

The architecture of a modern accelerator control system has achieved a mature form. It consists of a Local Area Network (LAN) which provides communications between peer nodes. These nodes are of three types:

1. Operator Stations which provide the interface between operators and accelerator systems.
2. Front End Computers (FECs) which are dedicated to the support of accelerator systems and closely coupled to accelerator hardware.
3. Server nodes which provide computing and data storage facilities to the other nodes.

8.1.2. Local Area Network

Rapid development in this arena continues to occur but compatibility and interoperability are achieved allowing gracious upgrades to networks. Presently the optimum choice for the network backbone is the Fiber Digital Data Interchange (FDDI) standard, a fiber optic network providing 100Mhz performance. This is conveniently subdivided into 10Mhz Ethernet segments to support all but the most demanding nodes. These facilities are widely supported in the computer communications industry and are therefore an economically sound choice.

Future developments may be expected to make greater use of fiber connections for superior reliability and noise immunity. The FDDI backbone may be supplemented or replaced by the Asynchronous Transmission method (ATM).

8.1.3. Operator Nodes

The operator interface to the accelerators will be provided by powerful graphic workstations which are now the workhorses of both operations and development in the field. The use of these workstations cannot be separated from the software systems under which they operate, notably the UNIX operating system in its Open Systems Foundation (OSF) form and the X-windows windowing system which allows the flexible presentation of multiple views of the system on each workstation. The use of these components allows manufacturer independence in that they are supported on the products of many different manufacturers and the most appropriate hardware for economy and performance can be selected for a given application.

3.1.4. Front End Computers

A conventional and widely adopted solution for this component has also reached maturity. This is based on the VME bus industry standard. Multiple processors from many manufacturers may be installed in this bus and a wide variety of commercial input/output modules to interface to accelerator equipment are available. Software for the FECs is not yet at the stage of standardization achieved in general purpose workstations, but a number of UNIX-like real-time operating systems are available and have been adopted for use in accelerator projects. The use of a Field Bus to provide modest distributed control from a given FEC is convenient. A number of such buses are available but none has achieved dominance. In this connection, the use of Programmable Logic Controllers (PLCs) has become commonplace as an industrial solution to the simpler and slower of the control problems. The field buses used by these systems are candidates for more general use.

An important development in the implementation of FECs is the assignment of system responsibility to the accelerator experts of the relevant sub-systems. This has advantages in eliminating a demanding interface level between accelerator experts and programmers.

8.1.5. Data Base and Software

A key component of the management and operation of a modern accelerator is a general purpose data base. A commercial data base will be selected for this purpose. The data base will contain models of the accelerator systems, records of accelerator operations, details of relations between accelerator components and archival data for the definition of states of the accelerators. Real time extensions of the commercial data base facilities will be developed to improve the performance in areas in which the commercial systems have been found wanting.

An Object Oriented approach to control software has been shown to offer advantages. The discipline and modularity imposed by this approach promote accuracy and ease of modification. An object oriented strategy will be used in both the operator station applications and the front end computers. Object orientation is being extended to data base concepts and usable systems may be available on the time scale of this project.

8.1.6. Timing Systems

An area of accelerator operations which is not commercially supported is that of timing. The synchronization requirements of an accelerator complex do not appear to have industrial analogs. This area has therefore received considerable attention from accelerator designers and comprehensive designs are available from the BNL AGS Booster, RHIC and Fermilab. The SNS complex will be supported by distribution of real-time, gauss-time (magnetic field dependent), radio-frequency and time-of-day clocks. The use of a synchronous data link broadcasting universal parameters of accelerator conditions will need to be evaluated.

9. CONVENTIONAL CONSTRUCTION

9.1. Introduction

The BNL Pulsed Spallation Source (PSNS) will occupy a triangular-shaped site approximately 750 meters long by 400 meters wide as shown in Fig. 9.1. The four primary structures that determine the configuration of the facility are the linac, with its accompanying klystron gallery, two fast-cycling 3.6-GeV synchrotrons which are housed in a tunnel below grade, and two experimental halls that contain the targets and experimental beamlines. Beam transport tunnels connect the linac and synchrotrons, and the synchrotrons to the experimental halls. At this preliminary stage of design, no attempt has been made to find the most cost-effective configuration. The schematic site plan in Fig. 9.-1 is intended to identify the building elements and their approximate areas for feasibility and cost estimating purposes.

While the present design of the PSNS is considered to be site-independent for the purposes of this report, it is nevertheless valid to state that Brookhaven National Laboratory is an ideal physical site for this facility. The Brookhaven site is generally flat and located on glacial outwash sand with outstanding stability and soil bearing properties. The water table is approximately 27 feet below average grade, allowing for dry tunnels and foundations. Electric power, water, steam, storm and sewerage systems are available at or near several candidate sites at the Laboratory.

The four primary structures and connecting tunnels have an aggregate area of 33,400 sq meters or 359,300 sq feet. A summary of areas is noted in the table below:

Building Element	Area (sq. meters)
Linac tunnel	1015
Klystron Gallery	7730
Tunnel (Linac to Synchrotron)	1650
Synchrotron Tunnel & Support Bldgs.	4040
Tunnels (Synchrotrons to Experimental Halls)	2450
(2) Experimental Halls	15708
TOTAL	33400 (359,300 sq ft)

9.2. Linac-Klystron Gallery

The 290m long linac is housed in a tunnel that may be constructed of either a cast-in-place reinforced concrete box or a near-circular multi-metal plate structure with a concrete slab base. The tunnel, as its name implies, is below grade and the earth is bermed to provide economical shielding. Preliminary calculations show that the equivalent of two meters of ordinary concrete shielding is required between the linac tunnel and occupied areas.

The klystron gallery runs parallel to the linac tunnel and is separated from the linac tunnel by earth shielding. A sectional view is shown in Fig. 9.-2. The klystron gallery is on the second floor of a two-story structure. The lower floor, which contains air-conditioning and cooling water equipment, power supplies, and electrical distribution, is below grade. The second floor is on grade and is serviced by an overhead crane. The building has concrete retaining wall foundations and an upper section of structural steel and insulated metal panels. The klystron gallery is contiguous with a high bay, one story service area of approximately 2800 sq. meters. The klystron gallery adds 2465 sq. meters on each of two levels bringing the total area of the klystron gallery, first floor equipment bay, and service area to 7730 sq. meters.

The linac is shown in Fig. 9.-2 in a multiplate tunnel about 4 meters dia. and 290 meters long. The method of materials handling has not been fully studied. If fork lifts and monorails are the methods of choice, the multiplate tunnel cross-section now shown will be used. If, however, full overhead crane coverage is necessary, the concrete box structure will be used. It is anticipated that the linac tunnel and equipment bay will be ventilated and the humidity controlled, but not be air-conditioned for comfort. Portions of the klystron gallery and service area that are occupied or which contain sensitive electronics will be air-conditioned.

9.3. Linac to Synchrotron Tunnel

As can be noted in Fig. 9.-1, the 600 MeV proton beam from the linac is transported through a 250 meter long tunnel to the synchrotron building. In this space, there is 170m reserved for optional future expansion, 10m for diagnostics, and 70m to magnetically separate and transport the two proton beams for injection into the two fast-cycling synchrotrons. The transport tunnel will be a continuation of the linac tunnel shown in Fig. 9.-2 and be at a similar depth below grade.

9.4. Synchrotron Tunnel and Support Buildings

The two fast cycling synchrotrons share the same tunnel at different elevations as seen in Fig. 9.-3. Each ring has a circumference of 363.2 meters. A schematic of the ring, shown in Fig. 2.-8, locates the 600 MeV injection straight, the 3.6 GeV ejection straight and the four RF cavity stations.

The synchrotron building complex is comprised of the below-grade tunnel, and six on grade structures located above the RF cavities and injection and extraction points of the synchrotrons. These are seen in Fig. 9.1.

The tunnel is of multiplate construction, about 6 meters wide x 4 meters high. As with linac components, material handling has not been fully studied, although radioactive components may require some remote handling. For this concept, we will rely upon magnet transport carts to install, remove, and transport magnet assemblies, and local monorails and fork lifts to move RF cavities and other equipment.

There are four buildings on-grade above the RF cavities. Each will have an area of approximately 560 sq meters for the RF drive systems and electronics associated with the cavities below. The building will also contain magnet power supplies to serve each sextant of the synchrotron rings. There are two additional buildings located above and adjacent to the injection and extraction areas. These will be two-story structures, the lower portion of which is at the same elevation of the tunnel to provide access to the tunnel for personnel and equipment. The upper portion of one building will contain the control room and work areas. Both buildings will contain HVAC and process water equipment to service their respective half of the ring building, as well as electrical power and distribution centers. Each building is sized at about 300 sq meters below grade and an upper portion with an area of approximately 600 sq meters.

The buildings are of reinforced concrete construction below grade and a conventional steel joist, girder, and column system above grade. Components from the synchrotron tunnel will be lifted to grade level by overhead cranes which will also service work areas on the upper level.

The synchrotron tunnel will be air-conditioned as will occupied spaces and areas containing sensitive equipment in the six buildings described above. Truck access will be made available to all six buildings.

9.5. Synchrotron to Experiment Hall Tunnels

Proton beams from each 3.6 GeV synchrotron are extracted and sequentially split, with the 10 Hz beam directed towards the target in one Experimental Hall, and the 50 Hz beam deflected towards the target in the second Experimental Hall. Each proton beam travels through a tunnel similar in cross-section to the linac tunnel. There are several bends in each beam transport line which will reduce neutron back-scattering. There is a horizontal dog leg and vertical bends near the Experimental Halls to raise the elevation of the proton beams to that of the targets which are about two meters above grade.

The earth cover above the tunnels is equivalent to 3.7 meters of ordinary density concrete. As the tunnels rise to meet the Experimental Halls, they will change from the multiplate circular cross-section to a cast concrete box structure of appropriate thickness to protect personnel outside the tunnel from harmful radiation.

9.6. Experimental Halls

There are two buildings, each of which contain a target assembly and target handling facilities, associated shielding, an experimental floor, and laboratory, office, and work areas. The shape, elevations, and size of the buildings are strongly influenced by the functional requirements. Fig. 9-4 is a plan view of the incoming proton beam and a schematic arrangement of a target assembly and associated neutron channels. This is described in greater detail in Section 7. There are 16 beamlines displaced at three elevations to maximize their number and enhance source quality.

The required biological shield is of dense concrete of about six meters in thickness. A plan view of the targets, beamlines, and shield is given in Fig. 9.-5. As the beamlines move further out from the targets, they are spaced approximately equally apart in two sets of eight beamlines. Beamlines must clear the proton beam tunnel and the radiation cone downstream of the targets.

A vertical section through the target and shield is given in Fig. 9.-6. There is a target handling area above, where new targets are readied for installation and used targets are removed, stored, examined, or inserted into a cask for removal from the building. The target handling area is sealed to prevent the spread of radioactive contaminants. Most operations will be performed using remote equipment.

As previously noted, the proton beam will slope upward from the transport tunnel, which is several meters below grade. The experimental floor is planned to be at or slightly above grade for better stability and convenience. The mid-plane of the targets will be about 1.5 meters above the experimental floor.

There is access directly under the targets for cryogenic and other coolants, and instrumentation cables. Refrigerators, cryogen storage, and process equipment are also located at a lower level adjacent to the target cave. The lower level also contains truck access for cask removal and delivery of supplies. There is a separation between the experimental floor and all of the activities required to handle, cool, examine, and discharge the targets, moderators, and associated components.

The size of the building and the stay-clear area immediately outside the building are strongly influenced by the beamlines. Beamlines within the building are designed for a maximum length of 40 meters from the source (target). At this time, we are suggesting a circular building comprised of an 84 meter diameter high bay. This includes a two meter wide perimeter aisle. Contiguous to this high bay area would be an eight meter wide annulus for user offices, labs, set-up, and support areas. Thus, we show a total of 100 meters diameter for each Experimental Hall.

Figure 9.-1 shows the possible direction of a small number of long beamlines from each Experimental Hall. It is possible for them to extend as long as 100 meters beyond the buildings. For now, we envisage that a typical long beamline will be in an outdoor tubular housing that will terminate at a small outbuilding.

Fig.9.-1, Pulsed Spallation Neutron Source Preliminary Site Plan

Figure 9.-2

SECTION THROUGH LINAC TUNNEL, KLYSTRON GALLERY & MECHANICAL EQUIPMENT AREA

Figure 9.-3
SECTION THROUGH SYNCHROTRON TUNNEL

Figure 9.-4

TARGET & BEAM LINE GEOMETRY

Figure 9.-5

PLAN VIEW THROUGH TARGET MID-PLANE

Figure 9.-6

VERTICAL SECTION THROUGH TARGET & SHIELD

10. CONCLUSION, FUTURE STUDIES

In considering the various design options for a 5 MW Pulsed Spallation Neutron Source (PSNS), it is evident from the present preconceptual design study, covered in the foregoing, that the scenario of a PSNS making use of Fast Cycling Synchrotrons (FCS's) is indeed feasible. In addition, it has significant merit because of the lower beam intensity required as a result of trade-off to higher beam energy. Notwithstanding this trade-off the required beam performance still exceeds the present state of the art. Hence, a number of critical issues have been identified during this study that require further research and development. The resolution of these issues would constitute the primary thrust of a more formal PSNS conceptual design study. Some of the major issues to be addressed are indicated below.

Several critical design issues concern the design of the 600 MeV linear accelerator injector to the FCS's. The feasibility of a pulsed negative-ion source with beam current in excess of 100 mA, with a duty factor of several percent, needs to be demonstrated. This beam is to be chopped to the 50% level to accommodate lossless capture in the sequential FCS's. A critical design issue is where this should occur, upstream or downstream of the RFQ, since this affects beam loss and the dynamics of the beam itself at the low energy stage of acceleration where space charge effects are important. The RFQ proper requires further detailed study to parameterize and optimize beam bunching, beam acceleration and beam focussing. Similar detailed studies need to be done to optimize the Drift Tube Linac section and the Coupled Cavity Linac section of the 600 MeV linac. Computer codes like SUPERFISH and MAFIA must be used to further optimize these structures for "figure of quality" Q , shunt impedance and acceleration gradient. Beam loss must be contained throughout the entire length of the linac structure. The detailed dynamics of fast beam chopping and possible associated beam halo formation, with consequent beam loss, also requires further study. The FCS injection requires specifically optimized beam parameters from the linear accelerator. Associated with this, the linac debuncher dynamics needs to be further addressed especially in view of multiturn injection during the early part of the field ramp of the FCS's.

Critical design issues associated with the FCS's may be categorized as those related to optimized beam dynamics such as multiturn charge-exchange injection, rf capture and beam acceleration, space charge effects and coherent instabilities; and those related to accelerator hardware components such as synchrotron magnets and associated resonant power supplies, rf acceleration components and ring vacuum systems.

Extensive simulation studies of multiturn injection, beam accumulation and beam acceleration of the intense proton beams into the FCS need to be carried out. This should encompass the use of a comprehensive simulation program for beam transport, charge exchange injection and multiple orbit tracking. The program to be used should treat the beam stripper foil coulomb and nuclear interaction, including chromatic loss and straggling, and should treat the stacking of the six-dimensional synchrotron acceptance in a self-consistent manner, including transverse and longitudinal space-charge tune shift from intense beam distributions of arbitrary shape.

The total number of protons per pulse accelerated in the FCS is one order of magnitude larger than presently accelerated in any similar accelerator. Hence, intensity dependent instabilities, like those resulting either from space-charge incoherent effects or from coherent oscillations induced by the interaction with the vacuum chamber equipment require further study, with enhanced regards also to potential beam instability cures. Also, the early model development of a large aperture, low impedance, internally strip metallized, ceramic vacuum chamber is relevant in this respect.

Because of the relatively high repetition rate of the fast cycling synchrotrons, some of the accelerator components, such as the synchrotron magnets, rf system power amplifiers and ring vacuum chambers require further detailed design studies to demonstrate technical feasibility with available technology.

Regarding the PSNS target system design, a three-stage target/moderator-moderator/beam tube configuration has been defined and evaluated. Flux spectra at the local moderators have been enumerated for the target structure surrounded by a water moderator/reflector. Further studies should validate this design approach, refine the configuration and optimize the performance characteristics. This should include:

- a) Evaluation of the beam tube neutron fluxes (spectra, time profile and intensities, especially in the thermal energy range) at the actual experimental locations. This requires explicit consideration of the actual shielding geometries and the engineering design of the target/moderator/reflector complex.
- b) Consideration of the beam time structure and enhanced analyses of distributed energy deposition, thermal/stress aspects and thermal/hydraulic engineering designs.
- c) Further validation of the target particle bed technology including the design approach to target handling and consideration of possible fragmentation of the target pellets, erosion of the pellet coating, etc. Also, possible tungsten oxidation as a result of the presence of free oxygen in the coolant needs to be considered.

Taking into account the high beam intensity of the 3.6 GeV proton accelerator under consideration here, it is essential to study the potential for radiation damage of accelerator and target components and develop a radiation assessment program which will encompass material selection, flux and energy spectra, and performance testing of selected materials in simulated PSNS environments.

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