Conceptual Design for One Megawatt Spallation Neutron Source at Argonne*

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Abstract

A feasibility study of a spallation neutron source based on a rapid-cycling synchrotron which delivers a proton beam of 2 GeV in energy and 0.5 mA time-averaged current at a 30 Hz repetition rate is presented. The lattice consists of 90-degree phase advance FODO cells with dispersion-free straight sections, and has a three-fold symmetry. The ring magnet system will be energized by 20 Hz and 60 Hz resonant circuits to decrease the dB/dt during the acceleration cycle. This lowers the peak acceleration voltage requirement to 130 kV. The single turn extraction system will be used to extract the beam alternatively to two target stations. The first station will operate at 10 Hz for research using long wavelength neutrons, and the second station will use the remaining pulses, collectively, providing 36 neutron beams. The 400 MeV negative-hydrogen-ion injector linac consists of an ion source, rf quadrupole, matching section, 100 MeV drift-tube linac, and a 300 MeV coupled-cavity linac.

I. INTRODUCTION

During the past two years there have been several studies on accelerator-based pulsed spallation sources in Europe, the United States, and elsewhere. Studies in Europe include a 5 MW source called the European Spallation Source (ESS) [1] and the Austron Project [2] for the eastern European countries. The ESS concept consists of an 800 MeV linac and three pulse compressor rings capable of accumulating and compressing pulse length to the order of 1 μs and delivering over 2 mA of time-averaged current in each ring for a total of 6.25 mA. Studies in the United States include Los Alamos National Laboratory's LANSCE-II and Argonne National Laboratory's IPNS (Intense Pulsed Neutron Source) Upgrade. These two U.S. studies center around sources with 1 MW of beam power.

For over a dozen years the IPNS facility has been providing research opportunities for the neutron scattering research community. The IPNS facility consists of a 50 MeV negative-hydrogen-ion linac and a 30 Hz rapid-cycling synchrotron (RCS) which accelerates 50 MeV injected beams to 500 MeV. The RCS accelerates 3 x 10^{12} protons per pulse at a repetition rate of 30 Hz, resulting in a time-averaged current of some 15 μA. The 1 MW study described here is for upgrading the IPNS system.

With respect to the choice of the accelerator's peak energy, several studies have shown that the neutron yield is proportional to beam power almost independent of beam energy up to several GeV beam energy [1]. This fact provides an opportunity to compare the lower-energy/higher-current case with a higher-energy/lower-current machine. That is to say, for a 1 MW facility, the choice of beam energy can be traded with choice of the beam current.

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A decision was made to initially study a higher-energy/lower-current configuration of the accelerator system with a majority of the acceleration taking place in a circular machine. The other study option was to perform all acceleration in a linac with a circular machine acting as a pulse compressor. Since the cost of a high energy linac is relatively expensive, the latter scheme usually tends to have lower energy and high current. The decision to accelerate in a circular machine was based on past experiences with a high intensity circular proton accelerator; that beam loss always occurs during injection and capture processes and not during acceleration or extraction processes. Furthermore, the lost particles create residual radiation around the accelerator components. This residual radiation can be minimized by injecting lower energy protons and handling fewer particles.

A. Choice of Repetition Rate

For a given time-averaged current, a higher repetition rate would provide an easier condition by lowering the number of particles to be accelerated per pulse. On the other hand, a higher repetition rate necessitates higher acceleration voltage. Repetition rates commonly used in this kind of setting range from 30 Hz at IPNS to 50 Hz at the ISIS facility in the U.K. Discussions with the user communities indicate that many experimental programs require lower repetition rates in order to avoid the so called "frame overlap" problem, therefore a repetition rate of 30 Hz was chosen. In order to facilitate those experiments requiring an even lower repetition rate, it is proposed to have two target stations: one receiving a 10-Hz beam and the other using the remainder of the pulses.

B. Choice of Machine Type

RCS technology is a mature technology. There are several operating proton machines of this type. Since the plan is to inject a lower energy beam and accelerate to a higher energy, using a proven technology provides the advantage of reliability. Furthermore, IPNS personnel have accumulated over 10 years of experience in operating a 30 Hz RCS. If the desired repetition rate was much higher than 30 Hz, another type of machine, such as the FFAG (Fixed Field Alternating Gradient), would be appropriate.

C. Use of Existing Infra-structure

The IPNS facility occupies a small fraction of the former ZGS (Zero Gradient Synchrotron) complex area, and nearly all of about 500k square ft. of space is available for the 1 MW upgrade of IPNS. The ZGS ring building, which is heavily shielded, can accommodate a synchrotron 200 m in circumference, and several of the former ZGS experimental area buildings can house the two target stations mentioned earlier.

II. SYNCHROTRON

A. Lattice Type

The FODO-type lattice was chosen for simplicity and flexibility. A 90° phase advance was chosen to facilitate a missing-magnet-scheme dispersion suppression for the straight section area, and to provide relatively high transition gamma. Lattice functions are shown in Figure 1, which shows the normal cells, dispersion suppressor cell, and long straight section cells which are missing-magnet normal cells. After having decided on the normal cells and the dispersion cells, the straight section cells can be added or

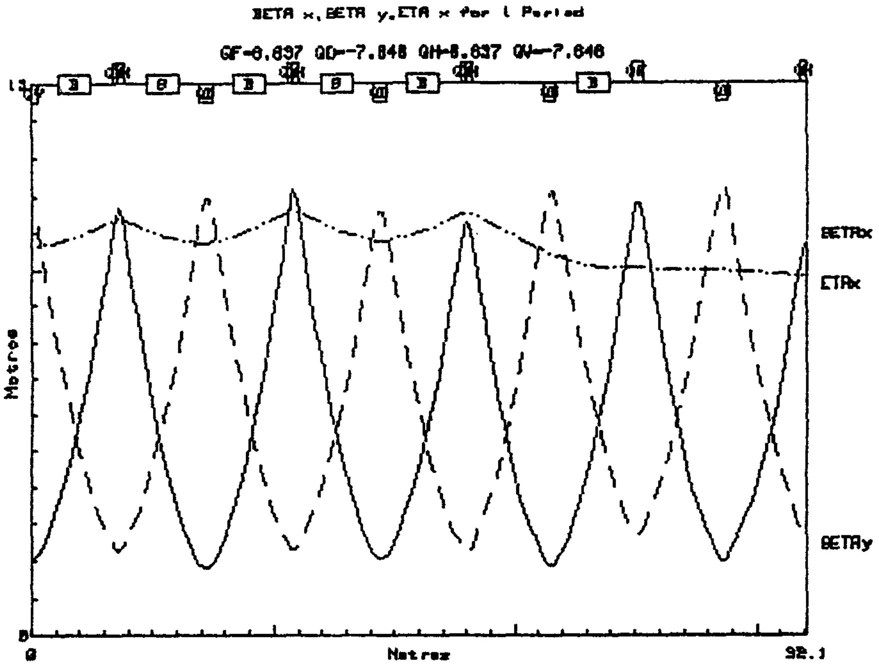

Figure 1. Lattice Functions (see text for details)

removed as the length of the straight section requires. (One half of the super-period is shown in the figure with the dispersion function displaced by 10 m for clarity.) For example, around the 1 MHz radio-frequency range, a typical cavity system provides about 10 kV rf voltage per meter of cavity. Thus if the required rf voltage is 120 kV, then there should be some 12 m of straight sections for the rf system.[3] A half-section diagram of the rf cavity is shown in Figure 2.

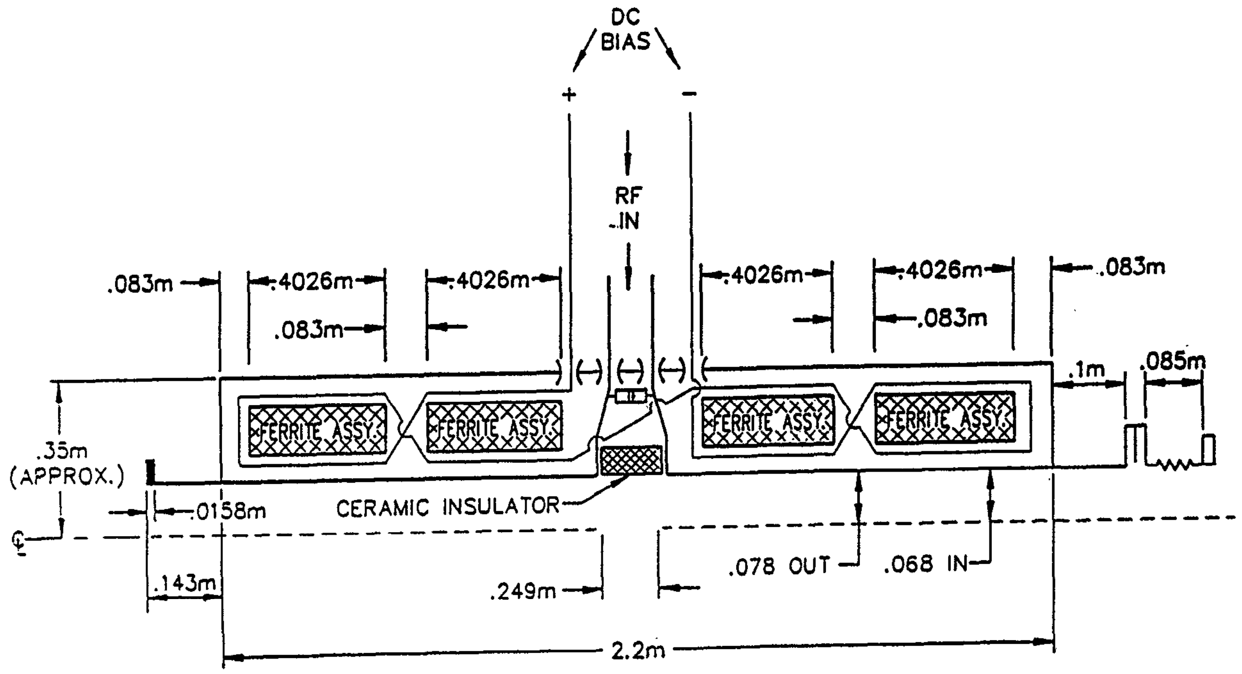

Figure 2. rf Cavity Half-section

B. Choice of B(t) and dB/dt

The lattice shown in Figure 1 can accelerate protons up to 2.2 GeV if the maximum magnetic field is about 1.5 T, which is commonly used value for this type of machine. It was decided to design a 2.2 GeV machine and to operate at 2 GeV for reliability reasons. The space charge limit discussed below implies the injection energy of the machine would be 400 MeV; this corresponds to the injection field of 0.417 T. A 30-Hz sinusoidal excitation of the ring magnets would require 180 kV of peak rf voltage. However, utilizing two (one 20-Hz and another 60-Hz) resonant power supplies for energizing the ring magnet with 20-Hz excitation and 60 Hz de-excitation enables the peak voltages to be lowered to some 120 kV.[4] The ring magnet excitation current and voltage waveforms are shown in Figure 3.

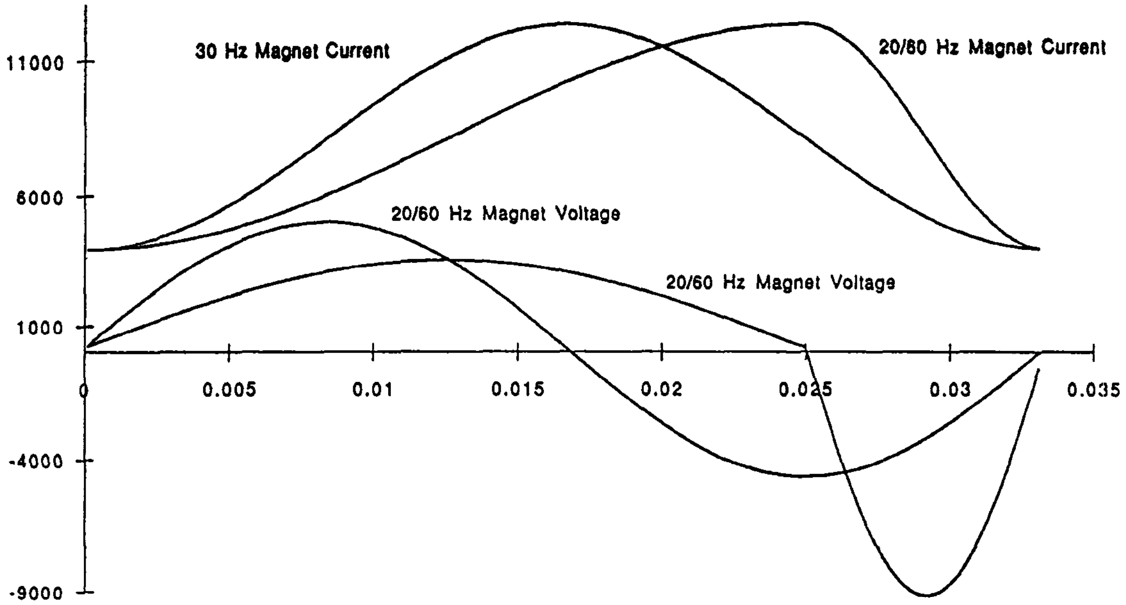

Figure 3. Ring Magnet Current and Voltage Waveforms

C. Space Charge Limit and Injection Energy

Typical transverse phase space acceptance of this type of accelerator varies from 200 π-mm-mr to 500 π-mm-mr. An iterative study using the beta-function shown in Figure 1 and reasonable apertures of quadrupole magnets showed that a choice of 375 π-mm-mr in both transverse planes is about optimum for the quadrupole magnet designs. The number of protons per pulse required to make a 0.5 mA time-averaged current is 1.04 $\times 10^{14}$. If the injection energy is 400 MeV, the acceptance of 375 π-mm-mr in both planes together with an assumption that the allowed space charge tune shift is 0.2, gives about 1.4×10^{14} protons per pulse. Therefore, 400 MeV was chosen as the injection energy. A cross-section of the ceramic vacuum chamber inside the quadrupole and sextupole magnet apertures is shown in Figure 4. The figure includes the beam envelopes in the quadrupoles and also shows the 5 mm allowance between the vacuum chamber and magnet pole tips.

D. Injection

In order to facilitate a multi-turn acceptance-filling injection into the synchrotron, a phase-space-painting

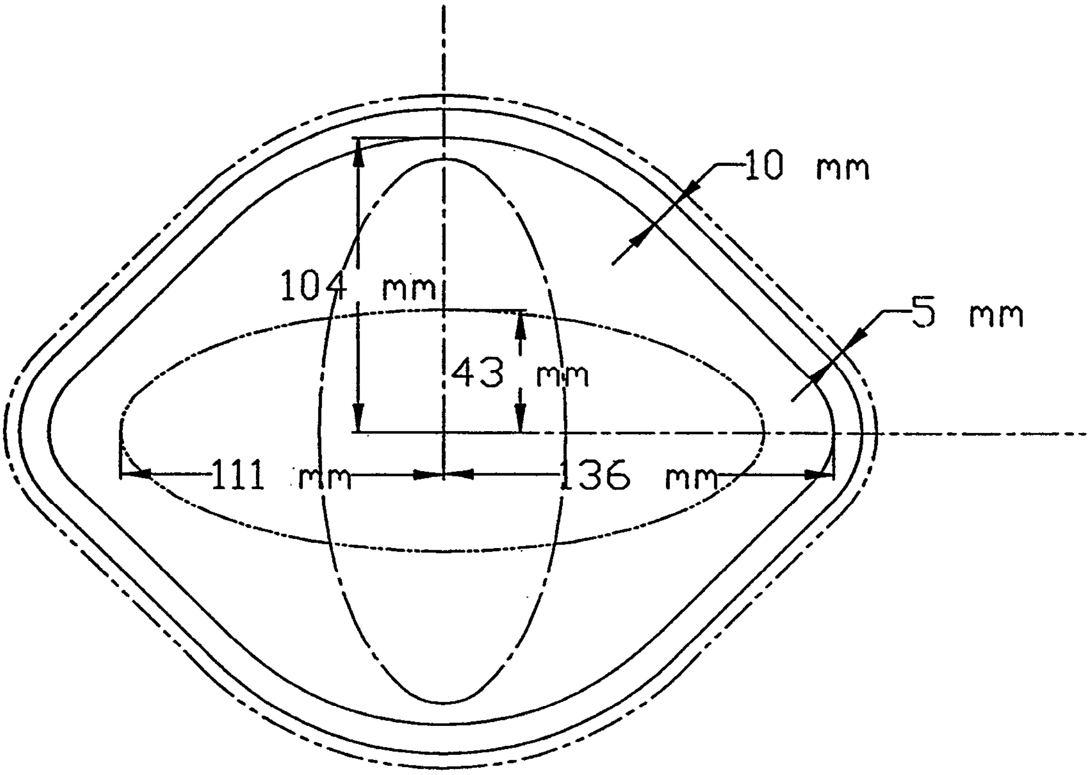

Figure 4. Vacuum Chamber Cross-section

scheme is used which incorporates a negative-hydrogen-ion beam and a "stripper foil" system. The stripper foil system "strips" the electrons and changes the negative-hydrogen ions to positive-hydrogen ions (charge exchange injection).

III. INJECTOR

A. Injector Requirements

The negative-hydrogen-ion source must deliver 1.04 x 10^{19} per pulse at a 30 Hz rate to provide 0.5 mA of the time-averaged current. This corresponds to a pulse current of 33 mA for a pulse width of 0.5 msec. If the available pulse current is 50 mA, then the pulse width could be 0.33 msec. Another implication here is that for a revolution period of 1 μs, 300 to 500 turns need to be injected. The space charge limit requires that the final energy of the injector should be approximately 400 MeV.

B. Injector Configuration

The injector system consists of the negative-hydrogen-ion source, a 2 MeV rf quadrupole, a beam chopper to facilitate loss-free capture, a 100 MeV drift-tube linac, and a 300 MeV coupled-cavity linac. It is contemplated that the frequency for both the rf quadrupole and the drift-tube linac will be 400 MHz and 1200 MHz for the coupled-cavity linac. This choice was made to take advantage of recent progress in linac technology from the SSC Laboratory and Fermilab.

IV. SUMMARY

Table 1 shows the parameters of the accelerator system, and the facility layout is shown in Figure 5. Figure 5 also shows the existing IPNS facility as well as the proposed two target stations. Further R&D continues on various hardware design studies, together with simulation studies of injection and capture. [3] The conclusion of the study team is that the RCS technology is appropriate and practical for a 1-MW pulsed spallation source.

Table 1 Major Parameters

Circumference	192.6	(m)	Horizontal Tune	7.28	
Injection Energy	400	(MeV)	Vertical Tune	6.21	
Maximum Energy	2.2	(GeV)	Transition Gamma	6.04	
Nominal Energy	2.0	(GeV)	Peak Rf Voltage	120	(kV)
No. of Protons/pulse	1×10^{14}		Harmonic Number	1	
Average Current	0.5	(mA)	rf Frequency @Injection	1.103	(MHz)
Injection Field	0.417	(T)	rf Frequency @Extraction	1.456	(MHz)
Extraction Field	1.341	(T)	Number of Cavities	6	
Bending Magnet Length	1.3	(m)	Maximum Beam Current @Extraction	61	(A)
Quadrupole Max. Gradient	8.6	(T/m)	Average Power Delivered to Beam	900	(kW)
Quadrupole Length	0.5	(m)	Number of Extraction Ports	2	
			Number of Target Stations	2	

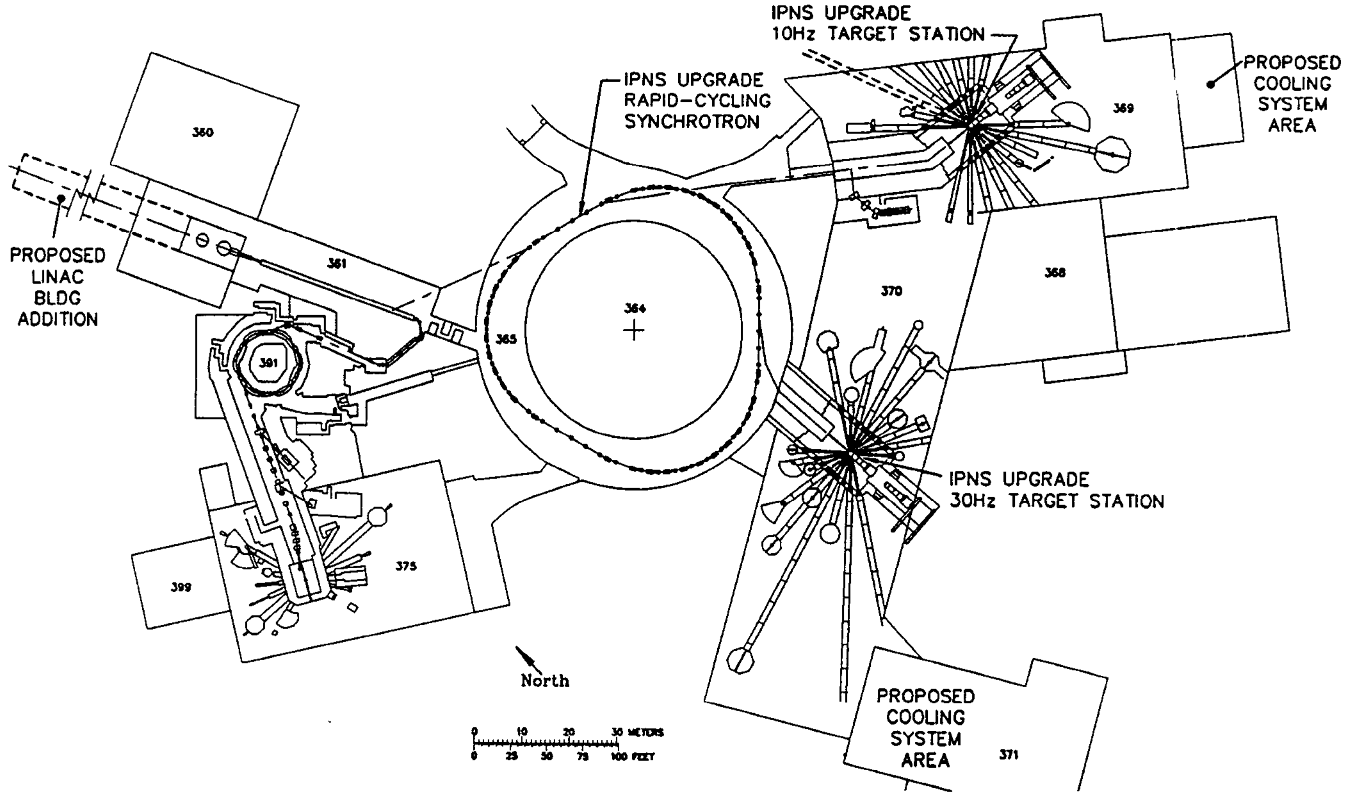

Figure 5. IPNS Upgrade Facility Layout

V. REFERENCES

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