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An Overview of an Accelerator-Based Neutron Spallation Source*

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Abstract. An overview of the feasibility study of a 1-MW pulsed spallation source is presented. The machine delivers 1 MW of proton beam power to spallation targets where slow neutrons are produced. The slow neutrons can be used for isotope production, materials irradiation, and neutron scattering research. The neutron source facility is based on a rapid cycling synchrotron (RCS) and consists of a 400-MeV linac, a 30-Hz RCS that accelerates the 400-MeV beam to 2 GeV, and two neutron-generating target stations. The RCS accelerates an average proton beam current of 0.5 mA, corresponding to 1.04×10^{14} protons per pulse. This intensity is about two times higher than that of existing machines. A key feature of this accelerator system design is that beam losses are minimized from injection to extraction, reducing activation to levels consistent with hands-on maintenance.

INTRODUCTION

Research based on slow neutron beams has been crucial to advances in fundamental sciences, technology, and medicine. Neutron studies have provided information critical to the understanding of new materials and have made key contributions to material sciences, such as the study of structure and excitations of high-T_c superconductors, interfacial structure of polymeric and magnetic layers, and spin dynamics in highly correlated metals.

Proton accelerators can be used to produce intense bursts of neutrons. Pulsed sources allow performance of real-time experiments and provide low background noise since the source is off for a good fraction of the time.

A proton synchrotron system capable of delivering 1 MW of beam power was designed for the Intense Pulsed Neutron Source (IPNS) Upgrade Feasibility Study at Argonne National Laboratory (ANL) (1,2). The RCS and associated research facilities are housed in the 50,000 m^2 of space in the former 12-GeV Zero Gradient Synchrotron (ZGS) area. The ZGS Ring Building houses a 190-m circumference, 2-GeV RCS. Two adjoining experiment halls house two neutron-generating target stations, each serving 18 neutron beamlines and instruments. Figure 1 shows the proposed facility layout. Enclosures for the linac and low energy transport line (LET) are the only new conventional facility construction and are also shown in Figure 1.

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DISCLAIMER

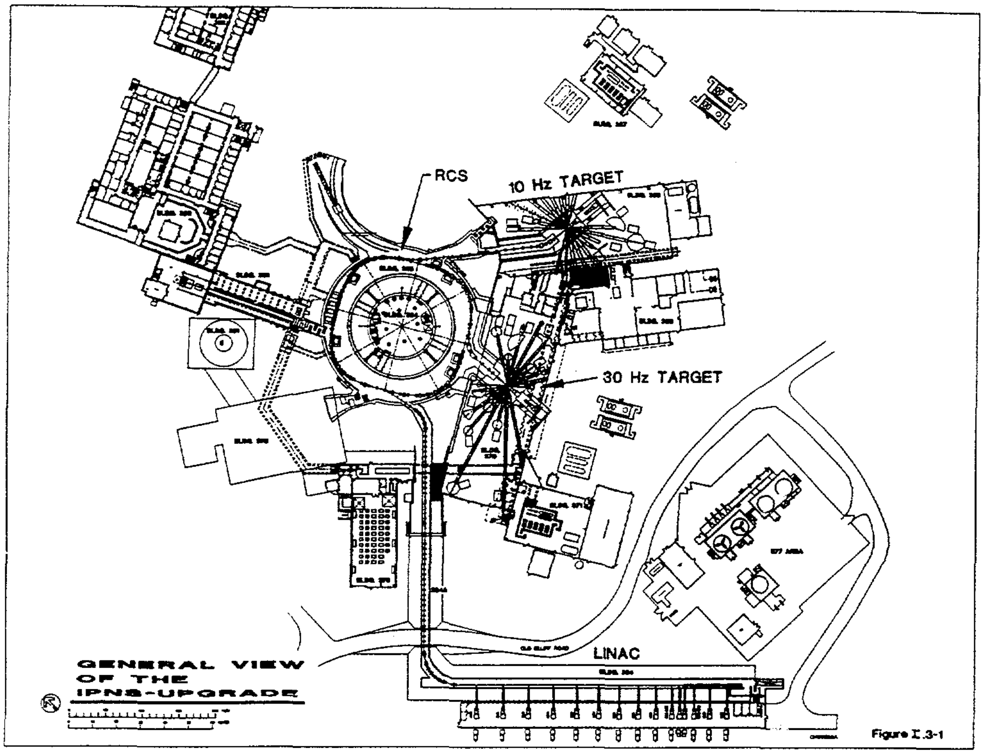

Figure 1. IPNS Upgrade Facility Layout.

ACCELERATOR SYSTEM

The important parameters that establish the requirements for the accelerator are the beam intensity, energy, pulse length, and repetition rate. The accelerator for the IPNS Upgrade pulsed spallation neutron source is required to produce a high-power (1 MW) proton beam with a short (<1 μs) pulse length and a reasonable pulse repetition rate (30 Hz). The proposed IPNS Upgrade accelerator system provides 1 MW of beam power by using a 400-MeV injector linac, followed by a 2-GeV RCS. Table 1 is a summary of the main RCS parameters.

The energy of the RCS is determined by several factors, including neutron yield, heat removal from the target, ease of machine construction and serviceability, and available space in the ZGS Ring Building. The neutron yield is roughly proportional to proton beam energy from several hundred MeV to about 10 GeV. The neutron production rate is proportional to the beam power. Neutron-generating target designers can accommodate beam energies of 1 to 3 GeV. The ZGS Ring Building can accommodate a circular machine with a circumference of about 200 meters. The 30-Hz, separated-function RCS has a peak dipole field of 1.5 T, corresponding to a beam energy of 2.2 GeV. All accelerator hardware is designed to be able to operate up to 2.2 GeV, although the nominal operating energy is 2 GeV. The time-averaged beam current must be 0.5 mA for a 2-GeV beam.

Table 1. Main Parameters of the RCS.

Parameters	Values	Units
Circumference	190.4	m
Super-periodicity	4	-
Number of normal cells	12	-
Number of dispersion-suppressor cells	8	-
Number of straight-section cells	8	-
Injection energy	400	MeV
Nominal extraction energy	2.0	GeV
Maximum design energy	2.2	GeV
Dipole field at 2.2 GeV	1.5088	T
Number of dipoles	32	-
Number of quadrupoles	56	-
Number of sextupoles	32	-
Horizontal tune, ν_x	6.821	-
Vertical tune, ν_y	5.731	-
Normalized transition energy, γ_t	5.40	-
Natural chromaticity, $\xi_x = (\Delta\nu)_x/(\Delta p/p)$	-7.23	-
Natural chromaticity, $\xi_y = (\Delta\nu)_y/(\Delta p/p)$	-6.88	-
Maximum β function	12	m
Minimum β function	2.2	m
Maximum η function	2.2	m
Minimum η function	-0.06	m
Maximum energy gain/turn	81.4	keV

The choice of synchrotron repetition rate dictates several machine parameters, such as the number of protons per pulse to be accelerated to achieve the time-averaged current, as well as the peak radio-frequency (rf) voltage. The repetition rate also influences the data-taking process of the scientific research program. The choice of 30 Hz as the source repetition frequency was based upon a survey of scientific users. The accelerator delivers one out of three pulses to a 10-Hz station, and a high-frequency station receives two pulses of the 30-Hz pulse train.

The decision to design the RCS for the highest possible extraction energy and the lowest possible injection energy was driven by beam loss considerations. Beam losses must be minimized during the injection, acceleration and extraction processes. It is preferable to have beam losses occurring at the lowest possible energy and least amount of beam current. Lower particle energy implies lower production of residual radioactivity, and lower beam current implies lower losses for the same fractional losses. In RCS the beam is injected at 400 MeV and is accelerated to 2 GeV. The injection energy is determined by the space charge tune shift, RCS repetition rate, and time-averaged current. A machine operating at 30 Hz with a 0.5-mA average current requires an acceleration of 1.04×10^{14} protons per pulse. The repulsive forces between the particles is large and can cause the tune to be shifted from the design value to values that may induce beam instabilities and losses. The tune shift is proportional to the number of protons in a pulse and inversely proportional to the beam energy and phase-space area of the stacked beam. For horizontal and vertical phase space-areas of 375 $\pi \times 10^{-6}$ m rad, the allowed tune shift of 0.15 gives the time-averaged beam current as a function of injection energy. The allowed tune shift of 0.15 is quite comfortable for reliable operation. Figure 2 shows the average current versus the injection energy.

RCS LATTICE

The requirements and desirable features for a high intensity proton machine lattice are: 1) a large transition energy, 2) enough straight section length for radio-frequency cavities and injection and extraction hardware, and 3) dispersion-free straight sections for injection in order to implement charge-exchange injection (3). To implement all these features, a FODO cell of ~ 90° phase advance in each transverse phase space was chosen for the normal cells that make up the arc of the ring. The dispersion suppression cell is achieved by removing one of the dipoles from a normal cell. The dispersion-free straight sections are formed by adding normal cells with both dipoles removed. A superperiod is constructed by arranging normal cells, dispersion-suppressor cells, and empty cells followed by their mirror images. The superperiodicity is 4 to take optimal advantage of space in the ZGS tunnel. Figure 3 shows 1/2 of a superperiod with reflective symmetry at both ends. Studies have shown that the lattice has a large dynamic aperture and is stable against alignment and construction imperfections (4).

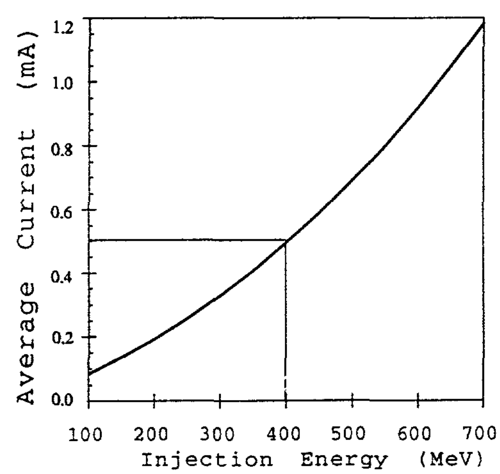

Figure 2. Average Current as a Function of Energy from Space Charge Limit.

RF VOLTAGE PROGRAM

A key goal of the design study was to devise an rf program that prevents beam loss from injection through acceleration to extraction. The rf program was obtained using a Monte Carlo program that tracked the particles from injection to extraction.

Figure 4 shows the rf voltage program and the corresponding bucket and bunch areas. When the first turn arrives at the start of injection, 40 kV is required to contain the linac beam that is 75% chopped (25% removed) and has a 2.5-MeV energy spread. During injection the voltage is raised to 69 kV to compensate for space-charge effects and to give a somewhat larger bucket of 9 eV s. After 7.5 ms of acceleration, the bucket area is increased to make the momentum spread of the circulating beam large enough to stay below instability thresholds (5,6) and to provide a synchrotron frequency large enough so that the particles in the bunch can follow the rapidly changing synchronous phase angle near the time of extraction.

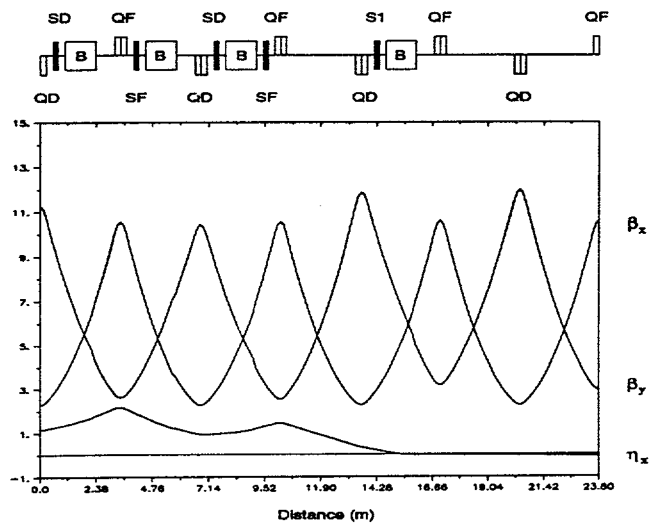

Figure 3. Lattice Functions for 1/2 of a Superperiod.

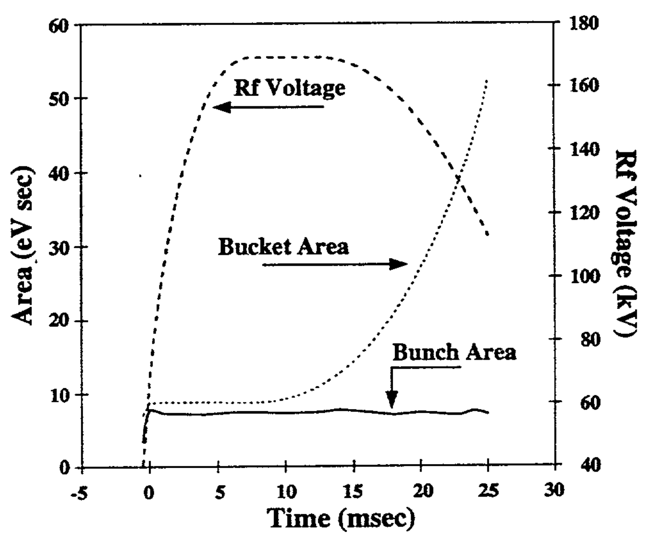

Figure 4. The Rf Voltage Program, Showing Bunch and Bucket Areas Over the Complete Cycle.

The RCS rf system has 10 single-ended, ferrite-loaded cavities to generate the required 180 kV. There are ten straight sections dedicated to the cavities.

IMPEDANCE AND INSTABILITIES

The coupling impedance of the RCS is dominated by space charge which is capacitive for both the longitudinal and transverse components. The RCS operates below the transition energy and is not expected to have longitudinal microwave instability. A detailed study of longitudinal impedance and instability was performed, and results are presented in reference (5). Similarly, the transverse impedance and instabilities were analyzed, and details are presented in reference (6). These studies showed that the machine can be operated stably.

SUMMARY

The IPNS Upgrade Feasibility Study resulted in the design of an accelerator system capable of producing 1 MW of proton beam power while maintaining low losses. The full power can either be delivered to one of the two neutron-generating targets or can be split between them. Low losses are critical to assure hands-on maintenance of the machine; these are achieved by providing large dynamic aperture in the transverse plane and sufficient bucket area in the longitudinal plane.

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