A 1- TO 5-MW, RCS-BASED, SHORT-PULSE SPALLATION NEUTRON SOURCE

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Abstract

Two accelerator configurations, the linac/compressor ring scheme and the linac/RCS scheme, are commonly used to provide the proton beam power for a short-pulse spallation neutron source. In one configuration, a full-power linac provides the beam power and a compressor ring shortens the pulse length from 1-ms down to 1 µs. In the other, rapid cycling synchrotrons (RCSs) provide the beam power and also shorten the pulse length. A feasibility study of a staged approach to a 5-MW proton source utilizing RCS technology, allowing intermediate operation at 1 MW, was performed at ANL and is presented in this paper. This study is complementary to a study in progress at ORNL based on a linac and an accumulator ring. Our 1-MW facility consists of a 400-MeV injector linac that delivers 0.5-mA time-averaged current, a synchrotron that accelerates the beam to 2 GeV at a 30-Hz rate, and two neutron-generating target stations. In the second phase, the 2-GeV beam is accelerated to 10 GeV by a larger RCS, increasing the facility beam power to 5 MW.

1 INTRODUCTION

Three of the four pulsed sources now in existence use the RCS scheme; the other uses the linac/compressor scheme. Our concept uses RCS technology to attain, in two stages, a beam power of 5 MW. It complements the linac/compressor ring work mentioned below [1,2].

Two ongoing studies, the European Spallation Source (ESS) [3] being designed in Europe, and the National Spallation Neutron Source (NSNS) being designed at ORNL [4] by a collaboration including BNL, LBNL, and LANL, are using the linac/compressor ring scheme.

Distinct differences exist between the two methods. The linac/compressor ring tends to have a beam energy around 1 GeV, while the RCS energy is generally higher than 1 GeV. A high-energy linac is costly to build and to operate, making a linac with energy much higher than 1 GeV economically unattractive, and the beam current of an RCS is usually space-charge limited, thus the final beam power is obtained by increasing the energy. We chose a 2-GeV RCS for the 1-MW source and a 10-GeV RCS for the 5-MW source, leading to a beam current requirement of 0.5-mA for both machines.

1.1 Repetition Rate

The 30-Hz repetition rate was chosen after extensive consultation with IPNS users at ANL. The peak flux of a 30-Hz machine is twice that of a 60-Hz machine operating at the same average beam power, with a longer time separation between pulses. About half of the proposed NSNS instruments cannot operate at 60 Hz due to overlaps between consecutive pulses. The repetition rate has implications on the accelerator configuration since it is very difficult to operate a multi-MW linac/accumulator ring system at low repetition rates.

1.2 Upgrade Path or Phased Approach to 5 MW

The 2-GeV and 10-GeV cascading RCS system allows the 2-GeV RCS (RCS-I) to be used as a booster for the 10-GeV RCS (RCS-II). The booster/main ring arrangement enables us to reach 5-MW operation in two-stages. A 1-MW, 2-GeV facility is built in the first stage, and RCS-II with its associated building and support structures is added later to increase the facility power to 5 MW. First, the 2-GeV beam is extracted to the target stations via transfer lines; the 10-GeV target-station extraction line is completed along with RCS-II.

1.3 Beam Loss Considerations

A 5-MW facility based on a 1-GeV linac requires a 5-mA average current, while a 10-GeV RCS system requires 0.5 mA. A factor of 10 fewer protons must be handled by the RCS, giving it a strong advantage with respect to potential beam losses. Beam losses usually occur during injection and capture, not during acceleration or extraction. It is therefore preferable to have the minimum possible injection energy so that if there are losses, they occur at low energy and result in less activation. Beam transfer from RCS-I to RCS-II uses highly efficient bunch-to-bucket transfer.

2 FACILITIES DESCRIPTION

2.1 Facility Layout

Figure 1 shows the overall layout of a site-independent, self-contained 5-MW facility, consisting of: a 400-MeV H^- linac, 2- and 10-GeV RCSs, 10- and 30-Hz target stations, and beam transfer lines from both synchrotrons to both target stations. Also shown in Figure 1 are a central laboratory and office building to house the facility staff and two laboratory and office modules for users. The total building area is about 82,000 m^2. The installed electric power is ~ 80 MVA, with an expected average power usage of 45 MVA at 5 MW. Table 1 summarizes parameters of RCS-I and RCS-II.

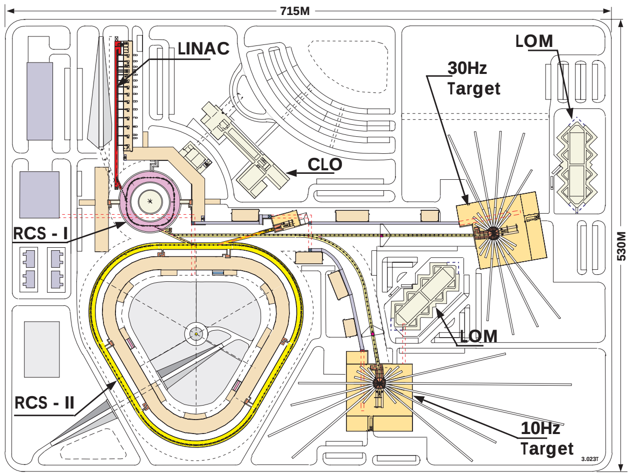

Figure 1: Site-independent 5-MW facility layout.

Table 1: Parameters of RCS-I and RCS-II

Parameters	RCS-I	RCS-II	
Circumference	190.4	761.6	m
Super-periodicity	4	3	-
Total number of cells	28	75	-
Nominal straight-section length	2.90	4.28	m
Bending radius	6.62	26.39	m
Horizontal tune, ν_x	6.82	19.19	-
Vertical tune, ν_y	5.73	19.13	-
Transition Energy, γ_t	5.40	14.47	-
Nat. chromaticity, $\xi_x=(\Delta\nu)_x/(\Delta p/p)$	-7.23	-24.78	-
Nat. chromaticity, $\xi_y=(\Delta\nu)_y/(\Delta p/p)$	-6.88	-26.24	-
Maximum β	12.0	20.3	m
Maximum η function	2.2	1.1	m

2.2 Target Stations for 1-MW and 5-MW Operation

Our plan is to reuse the 1-MW target stations, with some modifications, for the 5-MW source. The biological shield is the most costly item in a target station. The shield, which can cost some tens of million dollars, is usually made of iron and steel. The shielding of a 5-MW target is $\approx\sqrt{2}$ thicker than that of a 1-MW target. The actual neutron-generating target and moderator assembly cost around a million dollars but have a volume of only about one cubic meter. The target station's mechanical structure should therefore be designed to accommodate the shielding thickness of a 5-MW target-moderator assembly, including potential geometry changes.

3 THE 2-GEV ACCELERATOR SYSTEM

A detailed description of the 1-MW accelerator system appears elsewhere [1,2], thus only a brief summary is presented here. The previous work mainly addressed a site-specific design utilizing existing buildings and infrastructure of the former Zero Gradient Synchrotron (ZGS) facility. The ZGS enclosure accommodates a 200-m-circumference ring, and a 2-GeV energy permits use of that enclosure. The ring energy could easily be increased if a site-independent optimization were made. The choice of a 2-GeV beam energy fixed the average beam current at 0.5 mA, which in turn set the required number of protons/pulse at 1.04 $\times10^{14}$ for a 30-Hz repetition rate.

3.1 Lattice, Aperture, and Stacked Beam Emittance

The lattice is described in detail in [1]. Desired features include: 1) a transition energy » 2 GeV so there is a large slip factor, $\eta = |\gamma^2 - \gamma_t^{-2}|$, to facilitate radio-frequency (rf) beam manipulation, 2) dispersion-free straight sections equipped with rf systems and the H^- injection stripper foil, and 3) at least 20 m total length of straight-section space for rf cavities. The large rf space requirement is because, in the 1- to 2-MHz frequency range, typical cavity energy gains are 10 kV/m, and the required peak rf voltage is estimated at 200 kV. To achieve the desired features, a 90^o phase advance FODO cell was chosen as the normal cell. A dispersion-suppressor cell is constructed by removing one dipole from a normal cell. Empty cells are obtained by removing both dipoles from a normal cell. The straight-section length is obtained by adding as many empty cells as required. A periodicity of four was chosen to best use the existing ZGS enclosure.

An assessment of the ring magnet apertures was made, taking into consideration the lattice functions and the machine apertures. A ring acceptance of 750 π mm mr makes the physical dimension of the aperture close to that of ISIS. Injected beam will be stacked within an emittance of 375 π mm mr to provide some space for beam scraping and catching of the scraped beam. This leaves a space equivalent to 40% of the beam size between the chamber wall and the beam.

3.2 Injection, Rf Capture, and Acceleration

Using the required 10^{14} protons/pulse, a planned allowable incoherent space charge tune shift of 0.15, and a stacked beam emittance of 375 π mm mr, we can calculate the $\beta^2\gamma^3$ term of the Laslett equation. The relativistic parameters, β and γ, come from the injection energy, so an injection energy of 400 MeV satisfies the 10^{14} protons/pulse requirement. As noted above, a lower injection energy is a desirable feature. The linac operates at a 30-Hz repetition rate with a pulse length of 0.5 ms, giving a duty factor of 1.5%. The peak current of the macropulse is 44 mA, with 75% of the beam chopped to facilitate no-loss injection. The chopper is located between the ion source and the radio-frequency quadrupole. Either Penning- or volume-type negative hydrogen sources could be used as they are capable of delivering ~50mA peak current with a 1.5% duty factor. The injection of H^- ions enables us to paint both transverse phase-space planes in a preset manner. The linac energy spread is adjusted for longitudinal phase-space painting to fill the total bucket area of 9 eV s.

The number of injected turns will be about 500. The desired proton distribution is achieved by injecting H^-

ions through a 250-μg/cm^2-thick carbon stripper foil using programmable injection positions and angles in the transverse phase planes. The horizontal closed orbit is moved away from the foil as injection progresses, using four bumper magnets. The vertical injection angle is programmed. Programming of the horizontal injection position and the vertical injection angle results in the expected K-V particle distribution.

The rf acceleration voltage is related to the dB/dt of the ring dipole, thus it is desirable that dB/dt be fairly low. This is achieved at a 30-Hz repetition rate by energizing the ring at a 20-Hz rate and de-energizing it at a 60-Hz rate. The required peak rf voltage is lowered by 1/3.

Since beam loss prevention is one of the most important concerns in multi-MW proton sources, an extensive simulation study to eliminate beam losses was performed [1]. Variable parameters in the Monte Carlo tracking calculation included the rf voltage programming during injection and capture, the ring magnet dB/dt, incoming beam energy spread, gap length after chopping the linac macro-pulse, and desired Δp/p of the beam throughout the acceleration cycle in order to satisfy the Keil-Schnell longitudinal stability criteria. We tracked 5×10^4 macro-particles representing 10^{14} particles with 75% chopped (25% discarded) beam and an incoming-beam energy spread of ± 0.4%. We can inject and accelerate to 2 GeV with no losses. In addition, the study resulted in a determination of the optimum rf voltage programming for no-loss acceleration, and the algorithm to control Δp/p of the beam to satisfy the Keil-Schnell criteria. Details are presented in [1].

The coupling impedance between the circulating beam and its surroundings in the RCS is dominated by space-charge effects that vary with the beam energy. Both longitudinal and transverse stability have been studied extensively and are described in references [5,6].

4 THE 10-GEV ACCELERATOR SYSTEM

Figure 1 shows the 5-MW facility layout, obtained by adding an RCS of energy ≥ 10 GeV adjacent to the 1-MW facility. RCS-I is a booster for the 10-GeV machine. The 1-MW target stations are upgraded as described earlier. A preliminary description of RCS-II is given in [7].

4.1 Lattice, Beam Transfer, and Injection

The RCS-II lattice has the same requirements as the RCS-I lattice. We use the 90° phase advance FODO structure as the normal cell, a missing dipole FODO cell for the dispersion suppresser cell, and FODO cells without dipoles as the straight section cells. A total straight section length of 200 m is required to accommodate the rf cavities that produce ≈ 2000 kV of rf voltage. RCS-II's circumference must be an integer multiple of that of RCS-I so the rf systems are harmonically related. The harmonic relationship between the two rings is essential in making the bunch-to-bucket transfer from the smaller ring to the larger ring. This feature of transferring bunches from RCS-I to waiting buckets of RCS-II permits no-loss injection into the large ring. The lattice and its performance on single particle dynamics are described in [7].

The RCS-I rf system has a harmonic number 2 and a frequency range from 2.2 to 2.9 MHz. To improve the efficiency of RCS-II's rf system, a harmonic jump occurs in the 10-GeV ring. This is achieved by giving RCS-II a frequency range of 4.4 to 5.8 MHz. Bunch-to-bucket matching between the two rings is achieved by adjusting the rf voltage of RCS-I at extraction and the rf voltage of RCS-II at injection. Figure 2 shows the phase-space distribution at injection into RCS-II.

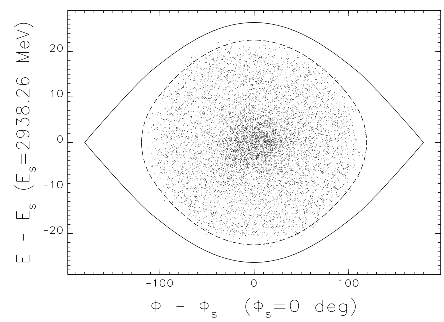

Figure 2: Rf bucket and bunch phase-space distribution from RCS-I at injection into RCS-II. The dotted line indicates the contour enclosing an area of 3.7 eV s.

4.3 Impedance and Collective Instability

RCS-II operates below transition energy. The coupling impedance is dominated by space charge effects, and an analysis similar to that for RCS-I was also performed.

5 ACKNOWLEDGMENTS

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