A 10-GeV, 5-MW PULSED PROTON SOURCE FOR A SPALLATION SOURCE AND A MUON COLLIDER *

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ABSTRACT

A design study of a 5-MW pulsed proton source based on a 10-GeV rapidly cycling synchrotron (RCS) has been completed. The RCS operates at a 30-Hz repetition rate. A 2-GeV, 1-MW RCS (RCS-I) described elsewhere [1,2], becomes a booster synchrotron after a minor modification. Two booster bunches are transferred into waiting buckets in the 10-GeV RCS (RCS-II). Proton source performance requirements for a 5-MW spallation source are identical to requirements for a 2-TeV on 2-TeV muon collider with a luminosity of 10^{35} cm^{-2} sec^{-1} except for the bunch length at extraction [3]. The muon collider requires a 3-ns rms bunch length, while the neutron source has no bunch length requirement. The short bunch length just prior to extraction can be obtained by means of a special rf system. Beam losses are minimized from injection to extraction, reducing activation to levels consistent with hands-on maintenance. Details of the study are presented.

1 INTRODUCTION

This study of a 10-GeV, 5-MW proton source is an extension of a feasibility study of a 1-MW, 2-GeV, 30-Hz pulsed neutron source to upgrade the ANL Intense Pulsed Neutron Source (IPNS) [1,2]. The harmonic number in the 2-GeV machine was increased from one to two in this 5-MW study. Beam transfer from RCS-I to RCS-II is performed using highly efficient bunch-to-bucket transfer. A detailed study of this transfer showed that no-loss injection can be achieved. RCS-II accepts the 2-GeV (0.5-mA) beam from RCS-I and accelerates it to 10 GeV.

The facility layouts are such that construction of the 5-MW system does not interfere with the 1-MW source operation except during the final link-up between the two. The geometric separation allows for staged construction of the 5-MW facility and utilizes all previous investments.

2 LATTICE

Required features of the 10-GeV lattice are: 1) the transition energy, γ_t, must be larger than the extraction energy so that the lattice has a relatively large slip factor, $\eta = \left|\gamma^{-2} - \gamma_t^{-2}\right|$, 2) there must be enough straight-section length for a 200-m-long rf cavity system, and 3) the straight sections should be dispersion-free so that the rf cavities can be placed in dispersion-free regions. The circumference of RCS-II must be a multiple of that of RCS-I to have a harmonic relationship between the two rf systems during bunch transfer. The circumference ratio is four, thus RCS-II has a circumference of 761.6 m.

Requirement 1) is satisfied if the lattice has a large horizontal tune since γ_t is proportional to the horizontal tune. A FODO cell lattice with 90° phase advance in both transverse planes was chosen for the normal cell to obtain a higher tune. Figure 1 shows 1/2 of a super-period with reflective symmetry at both ends, and Table 1 lists the overall RCS-II lattice parameters.

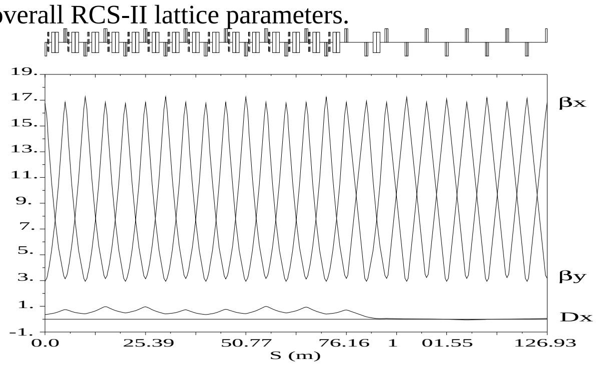

Figure 1: Lattice functions for 1/2 super-period, with normal, dispersion-suppressor, and straight-section cells.

Dispersion suppression is achieved by removing a dipole from a normal cell. The missing-dipole scheme suppresses the dispersion function when the vertical phase advance is slightly less than 90° while maintaining a horizontal phase advance of 90°.

Table 1: 10-GeV RCS-II Lattice Parameters.

Parameters (Bρ = 36.352 T-m)	**Value**	**Units**
Circumference	761.6	m
Superperiodicity	3	
Total Nr. of Cells	75	
Nr. of Normal Cells	45	
Nr. Dispersion-suppressor cells	6	
Nr. of Straight-section cells	24	
Nominal Cell Length	10.155	m
Straight Section Length	4.277	m
Bending Radius	26.392	m
Transition Energy γ_t	14.83	
Horizontal Tune, ν_x	19.20	
Vertical Tune, ν_y	18.19	
Nat. Chrom., $\xi_x=(\Delta\nu)_x/(\Delta p/p)$	–23.90	
Nat. Chrom., $\xi_y=(\Delta\nu)_y/(\Delta p/p)$	–23.06	
Maximum β_x	16.84	m
Maximum β_y	17.26	m
Maximum Dispersion Function	1.0	m

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3 APERTURES

The 2-GeV beam from RCS-I has a transverse emittance of 128 π mm mr. The beam-stay-clear (BSC) acceptance of RCS-II is defined by twice the emittance and ± 1% of the momentum spread of the incoming beam.

The natural tune of the 90° FODO lattice is 18.75 in both transverse planes. The working point was chosen taking a large space-charge tune spread into account, since the lattice must provide adequate dynamic aperture to contain the beam. Space-charge effects are greatest during the low energy injection, when the maximum tune shift in each plane is about 0.18. There is an additional tune spread due to the momentum spread. The chromatic tune shift due to a 1% momentum spread is larger than the space-charge tune spread. Chromaticity correction is necessary, especially during injection.

Extensive tracking studies showed the optimal tune range to be $19 < \nu_x < 19.25$ and $18 < \nu_y < 18.25$ to provide enough dynamic aperture to contain the beam at injection. We chose the lattice tunes to be $\nu_x = 19.20$ and $\nu_y = 18.19$. The working point, including the space-charge tune spread, is clear of structure resonances as shown in the tune diagram in Figure 2.

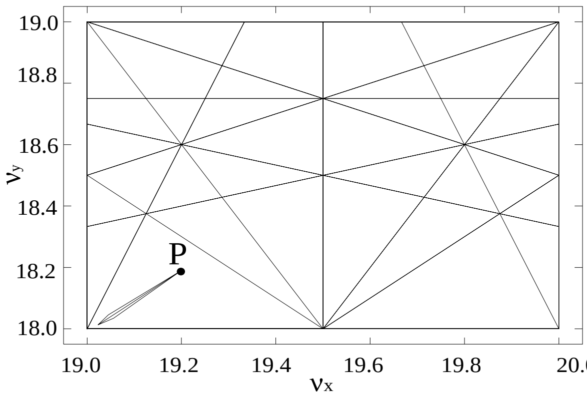

Figure 2: Resonance diagram for 1st through 4th orders, including the working point, P, and the tune spread.

The lattice dynamic apertures at the design and depressed tunes are shown in Figure 3, along with beam size at injection and the BSC. Figure 3(a) shows the dynamic apertures at chromaticities $\xi_{x,y} = 0$ and -5. We expect the operating chromaticity to be near $\xi_{x,y} = -5$, with a dynamic aperture larger than the BSC. Figure 3(b) shows the dynamic aperture when the lattice is adjusted to the space-charge depressed tune. Particles at the edge of the beam oscillate with large amplitude at this tune, so dynamic aperture is critical. This consideration was included in the choice of working point resulting in the large aperture at the depressed tune, shown in Figure 3(b).

4 INJECTION AND ACCELERATION

Each pulse of the RCS-I extracted beam contains two bunches separated by 332 ns. Each bunch contains 5×10^{13} protons, and the two bunches from each RCS-I pulse are transferred into waiting RCS-II buckets.

The RCS-I rf frequency at extraction is 3 MHz, with a harmonic number of 2. Two RCS-I bunches are injected into two buckets of the 6-MHz RCS-II rf system. Due to the change in rf frequency and the ratio of circumferences of the machines, RCS-II has 16 buckets (harmonic number = 16) of which only two are occupied by the beam, separated by an empty bucket.

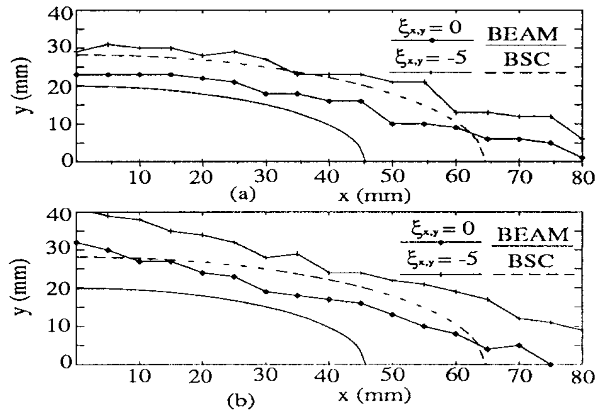

Figure 3: Dynamic aperture of the lattice at different chromaticities. (a) Lattice at the design tune $\nu_x = 19.20$ and $\nu_y = 18.19$. (b) Lattice at the space-charge depressed tune $\nu_x = 19.08$ and $\nu_y = 18.07$, where a uniform charge distribution is assumed.

The rf programming for the 1- and 5-MW machines is critical to no-loss operation. A program that captures and accelerates 1×10^{14} particles per pulse with no losses was obtained using Monte Carlo methods to track particles from injection to extraction [4,5].

The 2-GeV beam from RCS-I has a single bunch area of 3.7 eV sec; this bunch is injected into a slightly larger waiting bucket in RCS-II as shown in Figure 4. The dashed line in Figure 4 represents the Hamiltonian contour whose height, ΔE, and whose enclosed area are equal to those of the injected beam. The 3.7 eV sec bunch is matched to a contour of a 3.7 eV sec phase space area within a 5.8 eV sec bucket.

The rf voltage program for the accelerating cycle is depicted in Figure 5. Rf voltage increases from 0.7 MV to a peak of 1.9 MV during the first eight ms of acceleration to maintain a 5.8 eV sec bucket area. It is then decreased gradually from 1.9 MV to 1.7 MV until the end of acceleration. It is kept high to ensure a fast enough synchrotron frequency to allow the particles in the bunch to follow the rapid change of the synchronous phase near extraction. The bucket area grows from 5.8 eV sec to 106.3 eV sec, and the bunch area is 3.7 eV sec throughout the cycle. The bunch height at extraction is ±102.5 MeV and the bunch length is ±11.3 ns.

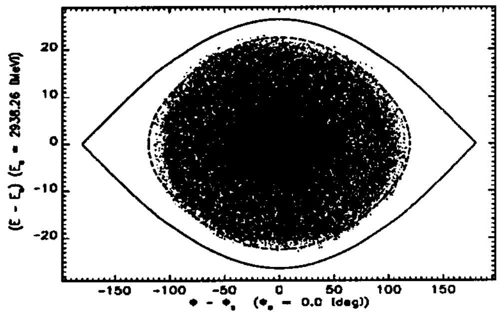

Figure 4: Rf bucket and phase space distribution at injection in the RCS-II. The dotted line indicates the contour enclosing an area of 3.7 eV sec.

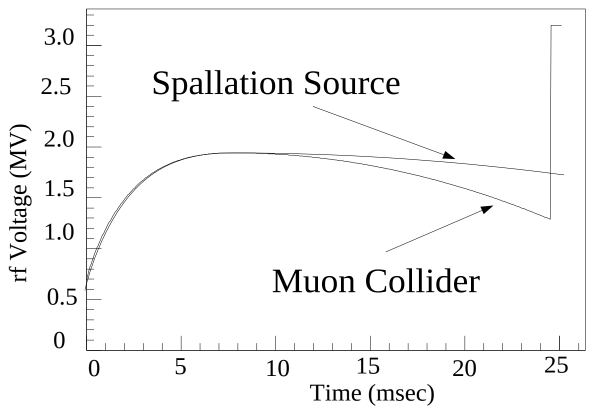

Figure 5: Rf voltage program for the spallation source and the muon collider acceleration cycles.

The RCS-II bunch length at extraction can be tailored for specific applications by rf manipulation. The typical full bunch length at extraction without manipulation is between 22 and 25 ns. The bunches can be shortened from 25 ns to 15 ns by bunch rotation prior to extraction and can also be lengthened using a combination of bunch rotation and debunching. The phase space distribution of the bunch at the end of rotation is shown in Figure 6, for shortened (a) and lengthened (b) bunches.

Longitudinal and transverse instability thresholds were obtained after the coupling impedances were estimated, as discussed in detail in reference [5]. The analysis lead to an rf voltage profile and to beam parameters that minimized instabilities and beam losses.

5 SUMMARY

A design study for a pulsed spallation source based on a 5-MW, 10-GeV RCS is complete. The injector is the accelerator system from a 1-MW source that consists of a 400-MeV linac and a 30-Hz, 0.5 mA, 2-GeV RCS. The 10-GeV RCS accepts beam from the injector and accelerates to 10 GeV. Beam transfer from the 2-GeV synchrotron to the 10-GeV machine utilizes highly efficient bunch-to-bucket injection, so that the transfer can be made without beam loss. The synchrotron lattice uses FODO cells of 90° phase advance. Dispersion-free straight sections are obtained using a missing magnet scheme. Beam losses are minimized from injection to extraction, reducing activation to levels consistent with hands-on maintenance. The low losses are achieved by providing large dynamic aperture in the transverse plane and sufficient bucket area in the longitudinal plane.

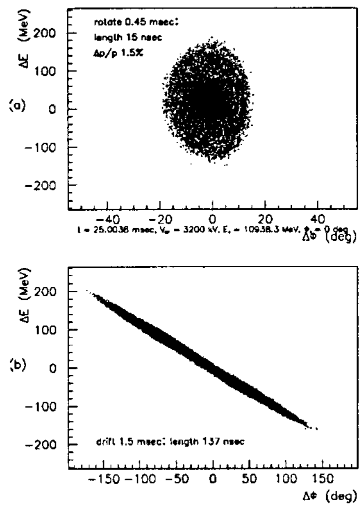

Figure 6: Bunch rotation with an rf voltage of 3.2 MV (a) and debunching with zero rf voltage (b).

REFERENCES

[1] "IPNS Upgrade - A Feasibility Study," ANL Report ANL-95/13 (April, 1995).

[2] Y. Cho, et al., "A 2-GeV, 1-MW Pulsed Proton Source for a Spallation Source," these proceedings.

[3] R. B. Palmer, et. al., "Beam Dynamics Problems in a Muon Collider," BNL Report 61580 (March 16, 1995) and references therein.

[4] Y. Cho, E. Lessner, and K. Symon, "Injection and Capture Simulations for a High Intensity Proton Synchrotron," Proc. of the European Particle Accelerator Conference, pp. 1228 (1994).

[5] Y. Cho, et al., "A 10-GeV, 5-MW Proton Source for a Pulsed Spallation Source," Proc. of the 13th Int'l. Collaboration on Advanced Neutron Sources, October 11-14, 1995, Paul Scherrer Institut, Villigen, Switzerland, pp. 758-773 (1996).