

LOW-LOSS RAPID-CYCLING-SYNCHROTRON DESIGN FOR THE SPALLATION NEUTRON SOURCE*

J. Wei[†], J. Beebe-Wang, M. Blaskiewicz, M. Brennan, P. Cameron, N. Catalan-Lasheras, G. Danby
C. Gardner, H.C. Hseuh, J. Jackson, Y.Y. Lee, A.U. Luccio, H. Ludewig, N. Malitsky, W. Meng
D. Raparia, A. Soukas, N. Tsoupas, J. Tuozzolo, R. Witkover, A. Zaltsman, S. Y. Zhang, BNL, USA
S. Danilov, J.D. Galambos, J.G. Wang, ORNL, USA
G.H. Rees, RAL, United Kingdom

Abstract

This paper summarizes a low-loss (10^{-3}) alternative design for the Spallation Neutron Source (SNS) based on Rapid-Cycling-Synchrotrons (RCS).

1 INTRODUCTION

The nominal SNS accelerator complex comprises a source and front end, a 1 GeV full-energy linac, and an accumulator ring and its transport lines. With a circumference of 248 meters, the accumulator ring compresses the proton beam to 0.6 μ s pulses of 2×10^{14} particles, and delivers them at a rate of 60 Hz to a liquid mercury target for spallation neutron production [1]. The alternative RCS design comprises a 400 MeV linac injecting into two vertically stacked synchrotrons, each accelerating beam pulses of 10^{14} protons at a repetition rate of 30 Hz from 400 MeV to 2 GeV, producing the same 2 MW total beam power (Fig. 1 and Table 1).

Each synchrotron has a four-fold symmetry comprising four FODO arcs and four dispersion-free straights. The four straights house injection, collimation, RF, and extraction systems. Beam injection is entirely contained in one straight, followed immediately by absorbers to protect against injection malfunction and beam halo. The beam cleaning and collimation section starts with a beam gap kicker located 90° in phase upstream of the primary scraper followed by absorbers covering a 2π betatron phase. RF cavities of both harmonic 2 and 4 occupy 50% of the available straights.

2 DESIGN PHILOSOPHY

Hands-on maintenance for the synchrotrons demands an average radio-activation below 1 – 2 mSv/hour 30 cm from the machine surface [2]. The corresponding uncontrolled fractional beam loss is 4×10^{-4} at 400 MeV. To achieve this unprecedented low beam loss, our design emphasizes five issues: space charge, aperture, injection, magnet compensation, and instabilities. A space-charge tune shift (<0.15) is realized with H^- painting; a transverse acceptance/emittance ratio of 3 allows beam tail and halo to be cleaned by the collimation system before hitting the rest of the ring; an initial stationary RF bucket confines the beam within its acceptance ($\Delta p/p = \pm 1.1\%$), while the vacuum chamber provides a full momentum aperture of $\pm 2\%$ for

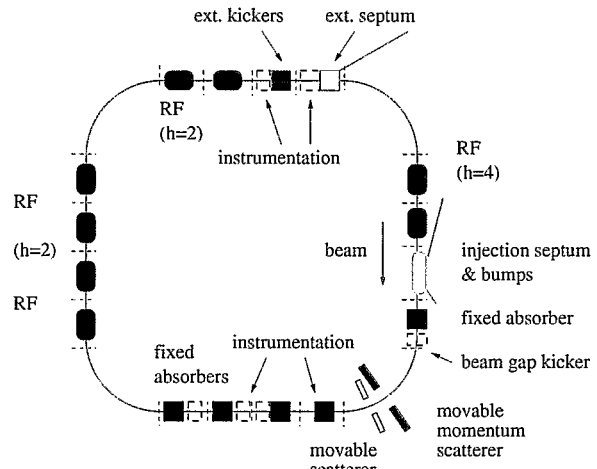


Figure 1: Rapid cycling synchrotron schematic layout.

momentum cleaning; the layout and magnetic field at injection are designed to prevent premature H^- and H^0 stripping and excessive foil hitting; the use of programmable power supplies moderates the required RF voltage and magnet ramp, resulting in a reasonable machine circumference and tolerable magnet eddy-current and saturation errors; finally, vacuum chambers are coated, chamber steps are tapered, bellows and ports are shielded, and injection beam momentum is broadened to avoid instabilities.

Beam loss is localized to shielded locations (collimation and injection regions) using multi-stage collimators. Momentum cleaning is achieved using a multi-turn beam gap kicker. With a design collimation efficiency of 95%, the total allowed fractional beam loss on the collimators is 1%.

Flexibility is another important design goal. Long uninterrupted straights make the injection independent of lattice tuning, allow for optimal phase-space collimation, provide balanced RF cavity arrangement, and reduce flanges and bellows connecting ceramic chambers. The working point can be easily adjusted over one unit in both the horizontal and vertical tune space. Fast-tuning trim quadrupoles are designed to vary the tunes during ramping. Extra clearance is reserved and programmable power supplies are used to accommodate both the correlated and anti-correlated injection painting so that various desired beam distributions and profiles can be realized. Adjustable, shielded cleaning scrapers are used in both the linac-to-ring transport (HEBT) and the ring. RF cavities of fundamental and second harmonics are physically interchangeable.

For engineering reliability, collimators are designed to

* Work performed under the auspices of the US Department of Energy

[†] wei1@bnl.gov

Table 1: Major parameters of SNS RCS design.

Quantity	Value
Linac:	
duty cycle	3.6 %
average current	1.1 mA
peak current	~50 mA
chopping rate	60 %
pulse length	0.60 msec
energy fluctuation	0.5 MeV
energy spread, ΔE_k (rms)	0.2 MeV
emittance (unnormalized, rms)	$0.5 \mu\text{m}$
transverse halo (5σ)	$<5 \times 10^{-4}$
beam gap residual	$<5 \times 10^{-4}$
RCS Ring:	
number of rings	2
vertical center separation	2 m
circumference	299.2 m
kinetic energy	0.4 – 2 GeV
beam power per ring	1 MW
repetition rate	30 Hz
number of proton	1.04×10^{14}
peak dipole field	0.91 T
peak ramp rate	29.4 T/s
up-ramp period	24 msec
RF harmonic	2, 4
peak RF voltage, $h = 2, 4$	300, 100 kV
RF syn. phase	$0^\circ - 20^\circ$
normalized emittance	$264 \mu\text{m}$
betatron acceptance	$520 \mu\text{m}$
additional clearance	5 mm
momentum acceptance (full beam)	$\pm 2 \%$
transverse tunes	7.82, 7.30
transition energy, γ_T	5.91
natural chromaticity	-9.93, -7.48
number of superperiod	4
lattice cell length	9.35 m

withstand an average 10^{-2} beam power, and to withstand two full beam pulses for commissioning and emergency handling. Various measures (a foil interchange mechanism, quick-disconnect flanges, crane, etc.) are adopted to make possible rapid removal and replacement of devices in high-radiation area.

To prevent beam loss under off-normal conditions, redundancy is built in critical areas. The extraction system is designed so that the beam is contained within the acceptance even when a kicker is mis-fired. The ring-to-target transport (RTBT) is designed with a proper phase advance so that kicker mis-fire will not cause a change in beam location on the target.

3 MACHINE DESIGN

3.1 Lattice

The lattice has a hybrid structure with FODO arcs and triplet straights. It combines the FODO's simplicity and ease of correction with the triplet's flexibility of long drifts.

Each arc consists of four 8-m long FODO cells. Five of the arc quadrupoles at sites of large dispersion are sandwiched by a chromatic sextupole and an orbit-correction dipole. The other quadrupoles are sandwiched by corrector packages containing both linear elements for orbit correction and decoupling, and nonlinear elements for resonance correction (Fig. 2).

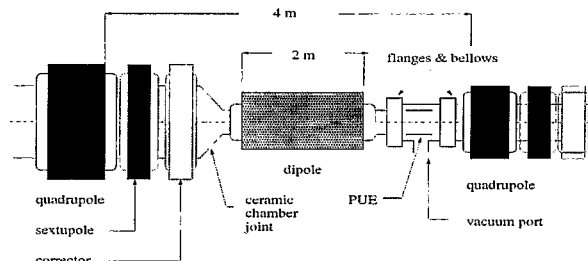


Figure 2: Arc half-cell layout.

The split-tune working point is chosen to avoid strong structure resonances, reduce coupling, and preserve painted beam distribution. The arcs and straights are optically matched to ensure maximum acceptance. A horizontal phase advance of 2π across each arc makes dispersion-free straights. Both the transverse tunes can be adjusted by one unit without significant optical mismatch.

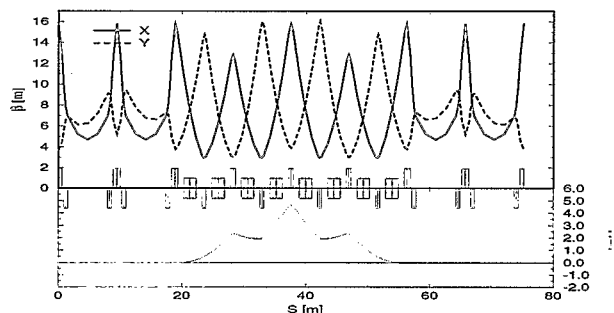


Figure 3: FODO-triplet lattice (one period).

3.2 Injection, Ramping, Extraction

Beam is injected dispersion free for independent transverse and longitudinal manipulation. Longitudinally, RF cavities in HEBT are used to correct the centroid and broaden the momentum for instability control. Transversely, painting is performed using either correlated or anti-correlated orbit bumps. The injection chicane and bump magnets (collapsed after injection) are contained in a drift section (Fig. 4) independent of lattice tuning. The maximum magnet field of 5.3 kG limits stripping loss below 10^{-7} per meter. Pole surface of the two dipoles near the stripping foil is specially shaped for electron collection.

To minimize eddy current and maintain a good field quality, programmable power supplies are used to moderate ramp rate below 30 T/s. The linear up-ramp takes 24 ms, and the down ramp 8 ms. RF synchronous phase is below 20° , and the bucket area is monotonically increased to minimize beam loss (Fig. 5). Once accelerated, the two beam bunches, each 150 ns long and 550 ns apart, are kicked

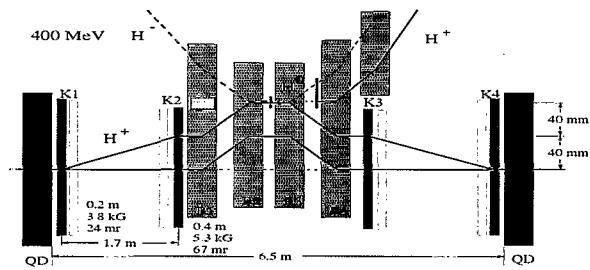


Figure 4: Injection system layout.

vertically in a single turn by 8 fast ferrite kickers and then extracted horizontally by a Lambertson septum.

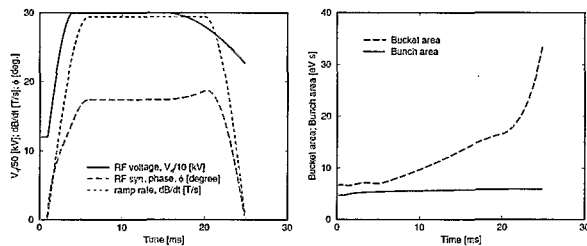


Figure 5: Ramping of RF voltage, phase, magnetic field, RF bucket and bunch area.

3.3 Aperture, Collimation, Loss Collection

Linac H^- beam halo is cleaned by foil scrapers in the HEBT. Halo generated by ring injection, capture, and beam-gap residual are cleaned by a two-stage collimation system assisted by a beam-in-gap (BIG) kicker.

The vacuum chamber provides an acceptance of more than 3 times the full beam emittance, and twice the full momentum spread. The transverse clearance allows efficient two-stage collimation, and the longitudinal clearance allows collection of momentum halo using the BIG kicker.

3.4 Magnet, Field Error, Correction

Laminated dipole, quadrupole, sextupole, and multipole magnets are designed with their peak field below saturation (~ 1 T). Poles of dipoles and quadrupoles are shaped to minimize integrated errors (sextupole and do-decapole, respectively) to 10^{-4} level. Errors from the fringe field, whose fractional contribution is proportional to the ratio between beam emittance and magnet length [3] (about 10^{-3}), can be compensated by correctors.

Separate trim quadrupoles are designed to compensate the tracking error between the main dipole and quadrupole field. Arc sextupoles powered in four families are used for chromaticity adjustment and off-momentum matching. Correctors up to octupole are used for orbit correction, decoupling, and resonance compensation.

3.5 RF Shielding, Coating, Instability Control

Ceramic vacuum chambers about 1 cm thick with internal silver strips 0.15 mm thick, terminated at one end with resistor-capacitor networks, give high impedance to the eddy current but low impedance to the image current. Steps are tapered, and ports and bellows are shielded to reduce

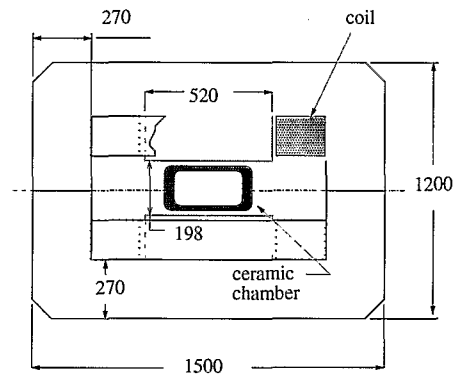


Figure 6: Dipole magnet cross section (unit: mm).

impedance. The inner surface of the chamber is coated with TiN to reduce secondary emission and potential electron cloud. Space for fast damper system is reserved as a future remedy.

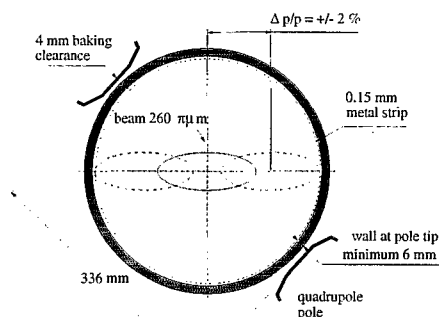


Figure 7: Quadrupole magnet chamber and clearance.

4 CHALLENGES & COMPARISON

Although RCS choice is in general better for energy and power upgrade, it is shown for the 2 MW SNS facility to be technically challenging and less cost-effective comparing with the accumulator ring choice [4]. To meet the stringent beam loss requirement, the RCS design challenge includes cleaning of beam loss from ramping and RF capture, development of programmable magnet power supply, construction of large-bore magnets with laminated coils, construction of large-aperture vacuum chambers with RF shielding, control of magnetic field errors due to ramping eddy current and saturation, need for separate quadrupole magnets for eddy current mismatch compensation, instability (head-tail, e-p like (PSR), etc.) control, and preservation of desired beam distribution for the target.

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