Construction Status and Issues of the Spallation Neutron Source Ring

Jie Wei

for the Spallation Neutron Source Collaboration

Talk at EPAC’04, Lucerne, Switzerland

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Outline

• Introduction

• Accumulator ring design summary
  – Favorable design decisions
  – Debatable design decisions

• Engineering status, **issues & solutions**
  – Magnet post-vendor iterations (shimming, sorting …)
  – Injection trail assembly (mechanical interferences,
  – Collimation and remote handling, target back-shine
  – Extraction, kicker impedance, RF
  – Vacuum, chamber coating, electron cloud mitigation
  – Diagnostics and instrumentation, infra-structure matching

• Summary
Spallation Neutron Source complex

- Under construction at Oak Ridge, Tennessee, U.S.
- Collaborated by 6 labs (LBNL, LANL, JLab, BNL, ORNL, ANL)
- Brookhaven National Laboratory is responsible for the design & construction of Ring & Transports
SNS commissioning at ORNL
Drift-tube-linac 1-3 results

- Reached design peak current 38 mA
- Routinely transported 100% beam
- Emittance at DTL-1 ~ 0.3 πμm

(Aleksandrov, Henderson, Holtkamp …)
Ring’s intensity goal
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Achromat RTBTRF Arc, extraction
Injection
Collimation
Linac dumpHEBT

Injection
Achromat
RF
HEBT
Linac dump
RTBT

Looking East Toward Dump
Low-loss design philosophy

• Localize beam loss to specific area for remote handling
  – 2-stage collimation: HEBT, Ring, (RTBT)
  – 3-step beam-gap chopping/cleaning: LEBT, MEBT, Ring

• A low-loss design
  – Space charge effects & resonance minimization
  – Magnet field compensation & correction
  – Proper lattice design with adequate aperture & acceptance
  – Injection painting; Injection & space-charge optimization
  – Impedance (extraction kicker) & instability control (e-p)

• Flexibility:
  – Adjustable in energy (+/- 5%), tunes (H 1 unit, V 3 units), injection painting, collimation; interchange RF cavities

• Accident prevention:
  – Design redundancy: immune to accidental linac & kicker errors
Beam-loss localization

- “Sacrifice” collimation region for the rest
- Two-stage system, efficiency above 90%
- Utilize large vacuum chamber aperture and long straight sections

(Catalan-Lasheras, Ludewig, Simos, Tuozzolo, McGahern, Tuozzolo, Cousineau, Davino…)

Ring primary scraper

injection septum & bumps

beam gap kicker

ext. septum

RF instrumentation

ext. kickers

moveable fixed scatterer collimators
Secondary collimator construction

- Length enough to stop primary protons (~1 m for 1 GeV beam)
- Layered structure (stainless steel particle bed in borated water, stainless steel blocks) to shield the secondary (neutron, γ)
- Fixed, enclosing elliptical-shaped wall for operational reliability
- Double-wall Inconel filled with He gas for leak detection

(Ludewig, Simos, et al)
Remote handling

- Overhead, around-the-ring crane
- Quick handling fixtures incorporated into shielding/absorber design
- Remote vacuum clamps; remote water fittings
- Passive dump window & change mechanism
- Rad. hardened magnets

(Murdoch, Pearson, Plum, et al)
Favorable design decisions

• Choose accumulator, not rapid-cycling synchrotron
  – Years of non-trivial battle to achieve good field with the Ring
  – Avoid potentially costly R&D needed for low-loss design

• Choose 4-fold lattice symmetry, not 3-fold
  – Collimator back-shine along vacuum pipe a serious concern
  – Avoid sharing injection with collimation for maintenance

• Choosing doublet straight/FODO arc lattice, not all FODO
  – Allow a robust, symmetric injection layout
  – Allow ideal collimator placement for high efficiency (>90%)

• Reserve upgrade potential for beam energy and power
  – Most magnet/power supply capable for 30% higher energy, matching future superconducting RF linac potential
Ring Lattice

**FODO arcs & doublet straights**

- Matched, hybrid lattice
  - FODO arc: easy-to-implement correction system, moderate magnet strength
  - Doublet straight: long, uninterrupted straight
    » Improved collimation efficiency
    » Robust injection

- Zero-dispersion injection
  - Independent painting in the transverse & longitudinal directions

\[ \nu_x = 6.23 \quad \nu_y = 6.20 \]

\[ \beta_x, \beta_y, \eta_z \]

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Debatable design decisions

• Solid-steel core for all ring dc magnets
  – Instead of laminated steel, solid steel was chosen to save cost, leading to large magnet-to-magnet field variations.
  – A big effort in measurement and shimming

• In-situ baking not allowed for vacuum chambers
  – Tight mechanical clearance between magnet pole & chamber
  – Chamber presently coated with TiN; material of lower SEY may be available although maintenance is non-trivial

• Field optimization of narrow-body quads
  – Large 20th pole remains although impact is negligible for a 1 ms accumulation

• Adequacy of spare components
  – Limited by budget availability
**Dipole field variation & shimming**

(Wanderer, Jain, ...

**Integral Transfer Function at 1.0 GeV in SD17 Dipoles**

- As built, Std.Dev.= 0.165%
- Shimmmed as needed, Std.Dev.= 0.010%

**Summary of Field Quality in SD17 Dipoles**

Harmonics in "Units" at a reference radius of 80 mm

(10 Magnets; Center Position)

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>1.0 GeV</th>
<th>1.3 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.T.F. (T.m/kA)</td>
<td>(0.25241)</td>
<td>(0.24597)</td>
</tr>
<tr>
<td>Fld Angle (mr)</td>
<td>(-0.81)</td>
<td>(-0.84)</td>
</tr>
<tr>
<td>(b_0)</td>
<td>(10000.0)</td>
<td>(10000.0)</td>
</tr>
<tr>
<td>(b_1)</td>
<td>(-105.16)</td>
<td>(-103.79)</td>
</tr>
<tr>
<td>(b_2)</td>
<td>(0.30)</td>
<td>(-6.13)</td>
</tr>
<tr>
<td>(b_3)</td>
<td>(2.11)</td>
<td>(2.54)</td>
</tr>
<tr>
<td>(b_4)</td>
<td>(1.15)</td>
<td>(-0.45)</td>
</tr>
<tr>
<td>(b_5)</td>
<td>(0.06)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>(b_6)</td>
<td>(-0.32)</td>
<td>(-0.51)</td>
</tr>
<tr>
<td>(b_7)</td>
<td>(0.15)</td>
<td>(0.14)</td>
</tr>
<tr>
<td>(b_8)</td>
<td>(-0.06)</td>
<td>(-0.05)</td>
</tr>
<tr>
<td>(b_9)</td>
<td>(-0.05)</td>
<td>(-0.05)</td>
</tr>
<tr>
<td>(b_{10})</td>
<td>(-0.19)</td>
<td>(-0.19)</td>
</tr>
<tr>
<td>(b_{11})</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>(b_{12})</td>
<td>(0.12)</td>
<td>(0.12)</td>
</tr>
<tr>
<td>(b_{13})</td>
<td>(0.01)</td>
<td>(0.01)</td>
</tr>
<tr>
<td>(b_{14})</td>
<td>(-0.09)</td>
<td>(-0.09)</td>
</tr>
</tbody>
</table>

**Normal Harmonics**

- As built, Std.Dev.= 0.165%
- Shimmmed as needed, Std.Dev.= 0.010%

**Integral Transfer Function at 1.0 GeV in SD17 Dipoles**

- Magnet Number
- Integral Transfer Function (T.m/kA)

**coil angle calibr. drifts**

**Sector dipole**
Magnetic field iterations

- Field quality goal at full 480πμm acceptance (rms)
  - 10^{-4} main magnets
  - 10^{-3} sextupole, chicane
  - 10^{-2} correctors

- Design iterations
  - chamfer & cross-section

- Post-vendor re-iterations
  - pole alignment, iron shimming, coil shimming, coil flipping

- Sorting
  - ITF and sextupoles

- Resonance correction under space charge
  - Multipoles up to octupole components

**tune (6.36,6.22), N=10^{14}**
- measured error, 3Qx=19 & 2Qx+2Qy=25 resonances
- correction with sextupole (0.09 T/m) & octupole (0.7 T/m^2)

(Fedotov, Parzen, Raparia, et al.)

(Jackson, Jain, Lee, Meng, Papaphilippou, Raparia, Tepikian, Tsoupas, Tuozzolo, Wanderer...)
Arc quad

21-cm ID quads: iron shimmed, sorted
- Initial field variation rms ~3x10^{-4}; final 0.8 ~ 1.4 x 10^{-4} (rms)
- Sorted in 3 power-supply families
- Trim quad coil available for back-up

26-cm ID quads iron shimmed, re-aligned
- ~1mm re-alignment to reduce sext. $b_3$

(Jackson, Jain, Lee, Meng, Raparia, Tepikian, Tsoupas, Tuozzolo, Wanderer…)

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Narrow-body quad

• Design
  - Narrow body to clear injection and extraction
  - Pole tip shape iterated for 12-pole
  - Large ($2 \times 10^{-3}$) 20-pole from narrow geometry; no noticeable effect during 1 ms accumulation
  - Correctable with pole shape scalloping if needed

• Post-vendor
  - ~10 unit skew sext $a_3$ measured
  - Coil shimming applied
### Field comparison

#### Regular quad (ring arc)

<table>
<thead>
<tr>
<th>n</th>
<th>(b_n)</th>
<th>(a_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>1</td>
<td>10000</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>−0.27</td>
<td>1.21</td>
</tr>
<tr>
<td>3</td>
<td>0.30</td>
<td>1.32</td>
</tr>
<tr>
<td>4</td>
<td>0.07</td>
<td>0.47</td>
</tr>
<tr>
<td>5</td>
<td>1.07</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>−0.01</td>
<td>0.10</td>
</tr>
<tr>
<td>9</td>
<td>−0.52</td>
<td>0.41</td>
</tr>
</tbody>
</table>

#### Narrow-body quad (ring straight)

<table>
<thead>
<tr>
<th>n</th>
<th>(b_n)</th>
<th>(a_n)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>1</td>
<td>10000</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>2.97</td>
<td>2.86</td>
</tr>
<tr>
<td>3</td>
<td>0.04</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>0.38</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>2.58</td>
<td>0.38</td>
</tr>
<tr>
<td>7</td>
<td>−0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>9</td>
<td>−21.7</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Injection region mechanical clearance

- Mechanical interference found
- Quad edge trimmed & re-welded to minimize ITF variation for all beam energy
Stripped electron collection

- Tapered magnet to guide stripped electrons (~ 2 kW), compensated for the circulating beam
- Carbon-carbon collector on water-cooled copper plate
- Clearing electrode (~ 10 kV) to reduce scattered electrons
- Video monitors on foil & collector

(Meng, Brodowski, Lee, Abell, Macek et al)
**Injection chicane measurements**

- Integral measurement confirmed field compensation \((10^{-3})\)

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Chicane #2 (2154.8 A)</th>
<th>Chicane #3 (1732.0 A)</th>
<th>Chicane #2 (2154.7 A) + Chicane #3 (1733.2 A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\int Bdz (Tm))</td>
<td>0.306</td>
<td>0.2016</td>
<td>0.5012</td>
</tr>
<tr>
<td>(b_1)</td>
<td>-1.8</td>
<td>-4.1</td>
<td>-1.9</td>
</tr>
<tr>
<td>(b_2)</td>
<td>-8.2</td>
<td>-9.4</td>
<td>-9.2</td>
</tr>
<tr>
<td>(b_3)</td>
<td>1.2</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>(b_4)</td>
<td>0.0</td>
<td>-0.4</td>
<td>-0.1</td>
</tr>
<tr>
<td>(b_5)</td>
<td>0.5</td>
<td>-0.7</td>
<td>0.0</td>
</tr>
<tr>
<td>(b_6)</td>
<td>-0.9</td>
<td>0.0</td>
<td>-0.6</td>
</tr>
<tr>
<td>(a_1)</td>
<td>116.0</td>
<td>-158.2</td>
<td>6.2</td>
</tr>
<tr>
<td>(a_2)</td>
<td>-8.0</td>
<td>9.6</td>
<td>-0.9</td>
</tr>
<tr>
<td>(a_3)</td>
<td>8.0</td>
<td>-11.3</td>
<td>0.3</td>
</tr>
<tr>
<td>(a_4)</td>
<td>-0.5</td>
<td>0.4</td>
<td>-0.1</td>
</tr>
<tr>
<td>(a_5)</td>
<td>1.5</td>
<td>-1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>(a_6)</td>
<td>0.1</td>
<td>-0.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

- Point-coil measurement confirmed field angle for electron collection
Extraction kicker

- Ferrite kicker inside vacuum pipe
- Optimize saturable inductor to effectively “shorten” rise time (200ns)
- Improved flat-top flatness (~0.5%)
- PFN termination: lower impedance
- Increase magnet height to halve coupling impedance (same drive)
- Shield the terminating resistance, reducing cable reflection
Vacuum chamber coating

Injection kicker ceramic chamber double coating
- Cu (~ 0.7 µm) for image current passage
- TiN (~ 0.1 µm) for electron cloud suppression
- Thickness uniformity < ± 30%

Extraction kicker ferrite patterned TiN coating
- ~ 0.1 µm TiN on ≥ 90% ferrite inner surface
- Masked for eddy-current heating control
- Masked near HV conductor to prevent circuit shorts
Electron-cloud mitigation

- Inner surface coated with TiN SEY ~ 1.6, no baking/activation
- Solenoids applied in collimation region
- Clearing electrode (10 kV) near injection foil
- Beam-position-monitors act as clearing electrodes (+/- 1 kV)
- Beam-in-gap kicker to clear residuals
- Extra ports for beam scrubbing

(Wang, Blaskiewicz, Furman, Macek, Pivi, Zhang, Hseuh, He, et al)
### Instrumentation

(Russo, Dawson, Sandberg, Shea ...)

- Part of machine protection; fast response
- Wide dynamic range
  - Intensity three order-of-magnitude; amplitude 30 times
- Turn-by-turn capability
- Presence of electron cloud

#### Detectors

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Number</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Position M</td>
<td>44</td>
<td>dual plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(includes 2 RF radial loop)</td>
</tr>
<tr>
<td>Beam Loss M</td>
<td>75</td>
<td>ion chamber</td>
</tr>
<tr>
<td>Fast BLM</td>
<td>12</td>
<td>photomultip.</td>
</tr>
<tr>
<td>Beam-In-Gap</td>
<td>1</td>
<td>kicker+PMT</td>
</tr>
<tr>
<td>Ion. Profile M</td>
<td>2</td>
<td>H+V</td>
</tr>
<tr>
<td>Wire scanner</td>
<td>2</td>
<td>H+V</td>
</tr>
<tr>
<td>Coherent Tune</td>
<td>1</td>
<td>kick/PU</td>
</tr>
<tr>
<td>Incoherent Tune</td>
<td>2</td>
<td>PLL &amp; QMM</td>
</tr>
<tr>
<td>Beam Current M</td>
<td>1</td>
<td>FCT</td>
</tr>
<tr>
<td>Wall Current M</td>
<td>2</td>
<td>including RF</td>
</tr>
<tr>
<td>E-detector</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Wide-band damper</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>High moment</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

- Luminescence profile study

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Tune diagnostics, halo scraper, dampers
(Cameron, Fedotov, Raparia, Russo, Henderson, Danilov ...)

Added new beamline components for full-power & beyond operations

- Dipole / quadrupole mode incoherent tune measurement pick-ups and kickers (4 units)
- Diagnostics halo scraper
  » In addition to collimation scraper
- Wide-band dampers
  » Possible e-p instability damping
  » Possible resistive instability damping
Infrastructure matching & installation

• Ring crane capacity iteration
  - Increased assembly weight with increased ring capacity to 1.3 GeV and added chromatic sextupoles
  - Minimum crane capacity restored to 20 tons; design modified to match reduced crane height

• Magnet/cable resistance, water capacity, power supply ratings
  - Power supply ratings to match actual magnet/cable resistance, operating temperature, and water volume & pressure

• Global coordinates & database
Ring hardware

Ring RF cavities

Diagnostics resonance pick-up

Extraction kicker chamber

Winding of radiation resistant coil on RTBT doublet magnet

(Zaltsman, Smith, Pai, Pearson, Seaberg, et al)
Handling & shipping

Ring injection kickers in ORNL tunnel

Ring injection septum at BNL during trial assembly

Ring injection kicker shipped to ORNL
Summary

• SNS has been a test bed of multi-laboratory collaboration

• Brookhaven is on its way to deliver promised fine products on time and on budget

• We are looking forward to ring commissioning in 2005
Acknowledgements

• Thank you, Our friends & collaborators!

• The entire SNS teams (ORN, LANL, …)

• Review committees’ constructive advice (ASAC, DOE, DAC, …)

• And …

Thanks to the devoting team

Thank you for your attention!

EPAC’04, Jie Wei
# SNS Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy, $E_k$ [MeV]</td>
<td>1000</td>
</tr>
<tr>
<td>Uncertainty, $\Delta E_k$ (95% probability) [MeV]</td>
<td>+/- 15</td>
</tr>
<tr>
<td>SRF cryo-module number</td>
<td>11+12</td>
</tr>
<tr>
<td>SRF cavity number</td>
<td>33+48</td>
</tr>
<tr>
<td>Peak gradient, $E_p$ (β=0.61 cavity) [MV/m]</td>
<td>27.5 (+/- 2.5)</td>
</tr>
<tr>
<td>Peak gradient, $E_p$ (β=0.81 cavity) [MV/m]</td>
<td>35 (+2.5/-7.5)</td>
</tr>
<tr>
<td>Beam power on target, $P_{max}$ [MW]</td>
<td>1.4</td>
</tr>
<tr>
<td>Pulse length on target [ns]</td>
<td>695</td>
</tr>
<tr>
<td>Chopper beam-on duty factor [%]</td>
<td>68</td>
</tr>
<tr>
<td>Linac beam macro pulse duty factor [%]</td>
<td>6.0</td>
</tr>
<tr>
<td>Average macropulse H- current, [mA]</td>
<td>26</td>
</tr>
<tr>
<td>Linac average beam current [mA]</td>
<td>1.6</td>
</tr>
<tr>
<td>Ring rf frequency [MHz]</td>
<td>1.058</td>
</tr>
<tr>
<td>Ring injection time [ms] / turns</td>
<td>1.0 / 1060</td>
</tr>
<tr>
<td>Ring bunch intensity $[10^{14}]$</td>
<td>1.6</td>
</tr>
<tr>
<td>Ring space-charge tune spread, $\Delta Q_{sc}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

assuming 4% injection loss to dump; 4% target window loss; linac max. ~20° phase