ASAC 2009 Presentation

Accelerator R&D Activities
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Talk outline

- Instabilities + Space Charge
- Laser stripping
- Sequence of developments as SNS ring intensity increases
- Nonlinear accelerator lattices with regular motion and large tune spread to kill instabilities and mitigate space charge effects
Instability-related Features of Ring Design

Common high intensity design features:

High energy spread design and broadband feedback provision +

For eP instability mitigation:

a) Electron collection near stripper foil;

b) Experiments of 1999 showed significant reduction of electrons in a coated spool piece of PSR vacuum chamber. This led to a decision to coat all pieces of VC with TiN;

c) Solenoids near the regions with high loss;

d) Clearing electrode near the stripper foil;

e) Electron detectors for electron accumulation study.
Instability-related Ring Design Features (cont...)

Extraction kicker:
• First estimations show thresholds around 1E10^14 protons.
• BNL team redesigned and re-measured kickers, lowered transverse impedance by factor 2.

Injection kicker and resistive wall:
• Impedances are dangerous below the integer tune, may cause closed orbit instability.
• Chamber coated with Cu (~0.7 um), and TiN (~0.1 um), to mitigate resistive wall and e-p instability.
• Advanced estimation of transverse impedance was done.
Choice of correlated painting for SNS

a) correlated
b) Anti correlated

Upper plots – correlated,
Lower for plots – anti correlated.
Conclusion – anti correlated is much worse because of distributions with tails

Painted beam (correlated painting)

Not an ideal profile – we need constant density elliptical beam for target.

Correlated painting creates not self-consistent beams

Anti correlated painting – not self-consistent during all moments of injection. Is there any injection that creates space charge self consistent distributions at all moments of injection?

Yes (see next slide)
3D self-consistent distribution painting

3 types of 3D self-consistent distributions found (see Danilov et al, PRSTAB 6, 094202 (2003), one of them below

\[ f = \frac{C}{\sqrt{H_b - H}} \delta(X'_0 - Y_0...) \delta(Y'_0 + X_0...), \quad H < H_b \text{(0 otherwise)} \] {3,2} case,

\[ H = a(\delta^2 + \Omega_s^2 s / \Pi^2) + bR^2, \quad \text{circular transverse motion, linear longitudinal well;} \]

\[ H = a\delta^2 + bR^2, \quad \text{circular transverse motion, barrier cavity.} \]

Transformation \( x \rightarrow x + D\delta \)

should preserve constant density

Linear longitudinal focusing
3D ellipsoid with constant density

Transformation \( x \rightarrow x + D\delta \)

should preserve constant density

Excellent coincidence!!!

From spreader cavity

A — normalized cavity voltage

Details in Holmes, et al, “Barrier Cavity option for SNS”, ICFA2006, Tsukuba
Bunch shape scanning (courtesy Z. Liu)

Longitudinal shape of the bunch drastically affects the ep instability. We were able to cleanly extract $1.13 \times 10^{14}$ ppb after making the trailing edge steep by changing the phase of 2nd harmonic RF.

Maximal charge extracted was $1.3 \times 10^{14}$, but with large loss.
**Bunch length scanning 18μC**

12.5 kV main 2 RF stations (left), and 5.5 kV (right) for flat beam the e-p instability disappears.
E-p Instability with and w/o Chromaticity

Zero chromaticity (left), and the natural one (right).
One can see a dramatic change of the instability spectrum

1) RF 1.1/1.3 = 12.6 MV, chromaticity = 0, RF 2.1 = -25
Stripping Foil Limitations

- The SNS will use 300-400 $\mu g/cm^2$ Carbon or Diamond foils
- Two important limitations:
  1. **Foil Lifetime**: tests show rapid degradation of carbon foil lifetime above 2500 K, yet we require lifetime > 100 hours
  2. **Uncontrolled beam loss**: Each proton captured in the ring passes through foil 6-10 times: leads to uncontrolled loss of protons

  Presently, injection area is the most activated at SNS

SNS Foil
Glowing
160 kW

Foil lifetime degrades
Three-Step Stripping Scheme

- Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser [V. Danilov et. al., Physical Review Special topics – Accelerators and Beams 6, 053501]

\[ f(1- > 3) = f_{laser} \frac{E}{E_0} \left(1 + \frac{v_{beam}}{c} \cos(\alpha)\right) \]

Step 1: Lorentz Stripping
\[ H^- \rightarrow H^0 + e^- \]

Step 2: Laser Excitation
\[ H^0 (n=1) + \gamma \rightarrow H^{0*} (n=3) \]

Step 3: Lorentz Stripping
\[ H^{0*} \rightarrow p + e^- \]
Approach that Overcomes the Doppler Broadening

- By intersecting the $H^0$ beam with a *diverging* laser beam, a frequency sweep is introduced:

![Diagram of intersecting beams]

- The quantum-mechanical two-state problem with linearly ramped excitation frequency shows that the excited state is populated with high efficiency.

- Estimations for existing SNS laser (10 MW 7 ns) gave 90% efficiency.
Laser Stripping Assembly

Magnets (BINP production)

Optics table (1st experiment)
1st experiment – failed
2nd 50% efficiency achieved (v. chamber failure afterwards)
3rd – 85% achieved
4th – 90% achieved

Straightforward use is costly – laser power needed is $10 \text{ MW} * 0.06 = 0.6 \text{ MW}$
Laser power reduction – intermediate experiment

- Matching laser pulse time pattern to ion beam one by using mode-locked laser instead of Q-switched
  \(~ \times 25\) gain

- Using dispersion derivative to eliminate the Doppler broadening due to the energy spread
  \(~ \times 10\) gain

- Recycling laser pulse
  \(~ \times 10\) gain

- Vertical size and horizontal angular spread reduction
  \(~ \times 2-5\) gain

By combining all factors the required average laser power can be reduced to \(50 – 120\)W, which is within reach for modern commercial lasers.
## Mode locked laser parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Offered</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>355nm</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>30 μJ</td>
<td></td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>10 μs</td>
<td>&gt;10μs possible with programmable waveforms</td>
</tr>
<tr>
<td>SLM Oscillator</td>
<td>mode locked</td>
<td></td>
</tr>
<tr>
<td>Temporal Profile</td>
<td>flat envelope</td>
<td></td>
</tr>
<tr>
<td>Beam Diameter</td>
<td>~5mm</td>
<td></td>
</tr>
<tr>
<td>Spatial Profile</td>
<td>Like Powerlite</td>
<td>Harmonics at laser</td>
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<tr>
<td>Beam Divergence</td>
<td>Like Powerlite</td>
<td></td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 Hz/402.5 MHz</td>
<td>Macropulse rate / micropulse rate</td>
</tr>
<tr>
<td>Shot to Shot Stability</td>
<td>3% RMS</td>
<td>For pulse envelope</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vert</td>
<td></td>
</tr>
<tr>
<td>Jitter</td>
<td>&lt;50ns</td>
<td>Macropulse envelope</td>
</tr>
<tr>
<td>Interface</td>
<td>GUI</td>
<td></td>
</tr>
<tr>
<td>Laser Head size</td>
<td>3’ x 6’ x 13”</td>
<td>Larger table available for upgrades</td>
</tr>
<tr>
<td>Cabinets</td>
<td>CAB35</td>
<td></td>
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<tr>
<td>Electrical Requirements</td>
<td>30A 1 phase</td>
<td></td>
</tr>
<tr>
<td></td>
<td>220V</td>
<td></td>
</tr>
<tr>
<td>Water Requirements</td>
<td>2 x Powerlite</td>
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</table>

- **Fiber Seed Injection**
- **Modulator**
- **DUAL 5mm Heads**
- **DUAL 6mm Heads**
- **ASE Suppressor**
- **LBO Harmonic Generators**
- **3’ x 6’ Breadboard**

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Managed by UT-Battelle
for the Department of Energy
**Fabri-Perot and Inside Crystal Conversion Schemes**

- 372.4 mm
- 50 mm
- $R_{187.3}$ mm

3 PZTs for alignment, length adjust

**Design and production:** Light Machinery

**Finesse:** ~ 37

**Designed power amplification factor:** ~ 10

**R > 92% at 355 nm**

**Inside Crystal Conversion**

Flat mirror is transparent to fundamental harmonics and reflects 355 nm light
Optical Setup of Ring Cavity (Z. Zhao, Y. Liu)

Power amplification factor 13 (low rep rate) ≈ 100 in typical setup obtained in red light with the test 80 MHz laser

Light source: mode-locked laser (80.5 MHz)
Cavity frequency: 402.5 MHz
**Approach to the solution of the problem**

**Laboratory frame**

\[ \vec{B}_L \quad \vec{E}_L \]

**Particle rest frame**

\[ \vec{E}_S \quad \vec{E}_L \]

**Lorentz Transformation of EM fields**

**Wave function has the following form**

\[ \Psi(\vec{r}, t) = \sum_{j=1}^{14} c_j(t) \psi_j(\vec{r}) \quad \Psi(\vec{r}, 0) = \psi_1(\vec{r}) \]

**Probability to find electron in atom**

\[ c_j^2(t) \quad \text{population of } j \text{ level} \]

\[ p_{\text{in}}(t) = \sum_{i=1}^{14} c_i^2(t) \quad 1^2 + 2^2 + 3^2 = 14 \]

\[ p_{\text{autoionization}}(t) = 1 - p_{\text{in}}(t) \]
“Froissart-Stora” in presence of field \( E \neq 0 \)

Parabolic coordinates. Quantum numbers: \((n_1, n_2, m)\)

\[
\begin{align*}
(0,0,0) & \\
(0,0,-1) & \\
(0,1,0) & \\
(1,0,0) & \\
(0,0,1) & \\
(0,0,-2) & \\
(0,1,-1) & \\
(1,0,-1) & \\
(0,2,0) & \\
(1,1,0) & \\
(2,0,0) & \\
(0,1,1) & \\
(1,0,1) & \\
(0,0,2) & \\
\text{Sum} & \\
\end{align*}
\]
2008 Progress in Laser Stripping

- Laser room is under preparation for experiments – the new laser and other equipment is about to be installed there;
- Test Fabri-Perot cavity produced amplification about 30 for red light;
- Crystal scheme was developed, crystals ordered for experiments;
- A code (ORBIT module) was developed to calculate and optimize the stripping efficiency in arbitrary magnetic and electric field (an important step for final injection design)
Large Picture of Ring Developments

Physics
- Minimization of impedances
- Feedback system
- Self-consistent space charge injection

Technology
- TiN coating
  - $1 \times 10^{14}$ ppp
- Laser stripping Diamond foils
  - $2 \times 10^{14}$ ppp
- Barrier cavity
  - $3 \times 10^{14}$ ppp

SNS ring is here now
- Ongoing development

Introducing very large tune spread without resonances – “Integrable” Accelerator Lattices
How solutions look like?

Special lens profiles (on the left)
Special betatron phase advances (1/4) between the lengths

The kicks – octupole $x^3$,
This lens – $x/(1+x^2)$ (and many other Integrable forms)

Phase space integrable (left), and octupole (right), the scale 5 times less for octupoles
Examples of 2D integrable systems with strongly coupled motion

Resonance free 2D integrable accelerator phase space –
The motion is on Liouville tori in 4D phase space.

Family of solutions is very rich – one can create finite number of resonances.
Phase space near resonance below.
Benefits from “Integrable” optics use

- Extreme tune spread – 30-50% of betatron tune
- No resonances, no particle loss
- Suppression of instabilities and space charge effects
- Order of magnitude jump in beam brightness
- Reduction of vacuum chamber and magnet size – order of magnitude money savings for future projects for future projects
Conclusion

- SNS developed a successful approach for the ring to get above $10^{14}$ ppp (or 1 MW)
- New physics and technology is under development to go to 3 MW
- Nonlinear “integrable” accelerator optics is advanced to possible practical implementation to introduce large spread without resonances