Laser System Design and Operation for SNS H- Beam Laser Stripping

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Outline

• Laser stripping principle and first stripping experiment
• Goal of the second laser stripping experiment and technical challenges on laser optics
• Laser system and operation for 10-μs macropulse H⁻ beam stripping
• Stripping experiment result
• Summary
Charge Exchange Injection Scheme in SNS Accumulator Ring

Front-End:
 Produce H⁻ beam pulse

LINAC:
 Accelerates H⁻ beam to 1GeV,

Accumulator Ring:
 Compress proton beam by a factor of 1060

Injection:
 Convert H⁻ to protons
Charge Exchange Injection Scheme in SNS Accumulator Ring

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SNS diamond foil

Ion Source

RFQ
DTL/CCL
SCL

88% c

p⁺
Charge Exchange Injection Scheme in SNS Accumulator Ring

**Front-End:**
Produce $H^-$ beam pulse

**Ion Source**

**RFQ**

**DTL/CCL**

**SCL**

**LINAC:**
Accelerates $H^-$ beam to 1GeV,

$88\% \text{ c}$

**Injection:**
Convert $H^-$ to protons

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$H^-$

$\text{RING}$

$p^+$
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SNS Laser Stripping Concept

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

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

**Step 3: Lorentz Stripping**  
\[ H^{0*} \rightarrow p + e^- \]

\[ \lambda_{laser} = \lambda_{1\rightarrow3} \times \frac{1}{\sqrt{1 - \left(\frac{v_{beam}}{c}\right)^2}} \cos(\alpha) \]  
\[ \gamma = \frac{1}{\sqrt{1 - \left(\frac{v_{beam}}{c}\right)^2}} \]

\[ \lambda_{1\rightarrow3} = 102.6 \text{ nm}, \quad v_{beam} = 0.87c, \quad \gamma = 2.05, \quad \alpha = 37.5^\circ, \quad \lambda_{laser} = 355.5 \text{ nm.} \]

Optical setup for first laser stripping experiment (September 2006)

Danilov et al., PRSTAB (2007)

H- beam current

Stripping magnets
Q-switch laser

Stripped electrons by laser

Stripping efficiency: 90%

Danilov et al., PRSTAB (2007)
Laser Stripping on 10-μs Macropulse

**Goal:** To demonstrate high-efficiency laser stripping on 10-μs macropulse which consists of 4,000 micro bunches of H⁻ beam.

**Technical challenges**

- Laser power
- Pulse structure and control
- Experiment in a highly radioactive environment
Laser Power Mitigation

- Apply dispersion tailoring to reduce transition frequency spread

\[ f_{\text{rest frame}} (1 \rightarrow 3) = \gamma_n (1 + \beta \cos(\alpha_n)) f_{\text{beam frame}} \]

- Squeeze particle beam longitudinally and vertically to maximize beam density within the photon-particle overlap area

Danilov et al., PRSTAB (2003)

Results in factor \(~10\) reduction in required peak laser power

- Matching time structure of laser pulses to ion beam

\[ 1 \, \mu s \quad 10 \, \mu s \]

402.5 MHz 402.5 MHz 402.5 MHz 402.5 MHz
Macropulse Laser – Master Oscillator Power Amplifier (MOPA)

**Seeder**: generate micro-pulses matching micro-bunch structure of ion beam

**Pulse Picker**: provide macro-pulses matching macro-bunch structure of ion beam

**Amplifier & Harmonic Converter**: boost power to the required level, e.g. 1MW @ 355 nm

- Micropulse: 30 – 50 ps @ 402.5 MHz
- Macropulse: 10 μs @ 10 Hz
- Peak power: 2 MW
- Average power: 4 W

Output wavelength: 355 nm

Macropulse Laser Setup

Spatial profiles

UV pulse width and peak power

Layout of 10 µs Stripping Experiment

- Experiment is in the transport line to the Accumulation Ring
- Laser is located remotely in Ring Service Building
- Laser transport line has to be installed

Concerns:
- Laser power loss
- Pointing stability
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Laser Beam Transport Line

SNS Ring Service Building

SNS Accumulator Ring

~21 m
Laser Beam Transport Line

SNS Ring Service Building

M1
M2
M3
M4

Pico-motor actuators
Camera

100.56°

SNS Accumulator Ring

M5
M6
M7
M8

100.56°

33.75°
11.25°
Optics around the Stripping Chamber

Diagram showing the setup with labels for BCM, QV29, QH28, Stripping magnets, Wirescanner axis, Beam splitter, Power meter, Camera, Vacuum chamber, and H+ beam. Laser transport pipe, Optical table, Moveable mirror, and Moveable lens are also shown.
Laser Beam Pointing Stability

Laser beam after LTL

Position variation: ± 0.37 mm (H) × ± 0.33 mm (V)

Laser beam at IP

Position variation: ± 0.10 mm (H) × ± 0.11 mm (V)
<table>
<thead>
<tr>
<th>Laser output specifications</th>
<th>Required</th>
<th>Delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro-pulse length</td>
<td>10 us</td>
<td>10 us</td>
</tr>
<tr>
<td>Micro-pulse width</td>
<td>&gt; 30 ps</td>
<td>30 – 50 ps (adjustable)</td>
</tr>
<tr>
<td>Peak power</td>
<td>1.5 MW</td>
<td>2.5 MW (at pulse width 35 ps)</td>
</tr>
<tr>
<td>Laser Transport Line (LTL) performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission efficiency</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>Maximum power delivered on optical table in tunnel</td>
<td>&gt; 1 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td>Maximum power delivered to stripping chamber</td>
<td>1 MW</td>
<td>1.2 MW (limited to 1 MW at experiment)</td>
</tr>
<tr>
<td>Pointing stability at the exit of LTL</td>
<td></td>
<td>± 0.37 mm (H) × ± 0.33 mm (V)</td>
</tr>
<tr>
<td>Laser beam parameters at the photon-H⁻ interaction point (IP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal beam divergence (4σ)</td>
<td>2 mrad</td>
<td>2.6 mrad</td>
</tr>
<tr>
<td>Vertical beam size (4σ)</td>
<td>0.8 mm</td>
<td>1.1 mm</td>
</tr>
<tr>
<td>Maximum power delivered</td>
<td>1 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td>Pointing stability at the IP</td>
<td></td>
<td>± 0.10 mm (H) × ± 0.11 mm (V)</td>
</tr>
<tr>
<td>Laser beam size and intensity on vacuum windows*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam size (4σ) on entrance vacuum window at the default position</td>
<td>3.4 mm (H) × 3.1 mm (V)</td>
<td></td>
</tr>
<tr>
<td>Beam size (4σ) on exit vacuum window at the default position</td>
<td>2.7 mm (H) × 2.9 mm (V)</td>
<td></td>
</tr>
</tbody>
</table>

Y. Liu et al., NIMA 847, 171-178 (2017)
Laser-Ion Beam Alignment

- Vertical position alignment of laser beam based on photo-detachment measurement
- Phase matching between laser and ion beams
- Final steps:
  - Insert stripping magnets, confirm $H^0$ conversion.
  - Vary laser incoming angle to fine tune resonant frequency.
  - Only indication of correct angle is stripped beam (sensitivity $\sim 0.1^\circ$).
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![Beam Loss Monitor](image-url)
Laser-Ion Beam Alignment

• Vertical position alignment of laser beam based on photo-detachment measurement
• Phase matching between laser and ion beams
• Final steps:
  – Insert stripping magnets, confirm H$^0$ conversion.
Final Stripping Results

March 28, 2016

Stripping efficiency > 90%


BCM has ~6% noise.
Future Work – Scalability to 1-ms/60-Hz Laser Stripping

• Macropulse laser amplifier
  – Current flash-lamp pumped Nd:YAG amplifier can produce UV pulses over 30 – 50 ps with max peak power 3.5 MW at 10 μs.
  – Macropulse duration is limited to 30 μs.
  – Fiber amplifier has excellent beam qualities but no macropulse amplification available.
  – Solid-state amplifiers with 1 ms burst duration are needed.

• Laser stripping in optical recycling cavity
  – It is highly desirable to enhance and recycle the laser power with an optical cavity.
  – We developed a novel technique to solve this problem.

Summary

• Laser assisted hydrogen beam stripping method has been developed at SNS for high intensity proton beam production

• We have successfully demonstrated laser stripping on 10-μs H⁻ macropulses
  – Manipulation of ion beam parameters
  – Development of macropulse laser system
  – Installation of laser transport line

• Research on laser stripping in a power recycling optical cavity is on going.