The RHIC Optically Pumped Polarized H⁻ Ion Source

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- Optical pumping polarization technique
- Charge-exchange spin-transfer collisions
- High-brightness atomic beam source
- High-intensity polarized H⁻ ion source at RHIC
- Polarized 3He++ source development at RHIC
- Summary
RHIC High-Luminosity Relativistic Heavy Ion (Polarized protons) Collider

**Achieved peak luminosities (100 GeV, nucl.-pair):**
- Au–Au  \(120 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}\)
- \(p \uparrow - p \uparrow\)  \(50 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}\)

**Other large hadron colliders (scaled to 100 GeV):**
- Tevatron \((p-p\text{bar})\)  \(35 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}\)
- LHC \((p-p\text{, design})\)  \(140 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}\)

**Operated modes (beam energies):**
- Au–Au  \(4 \text{ 2010-100, 31, 19.5, 3.9, 5.5 GeV}\)
- d–Au*  \(100 \text{ GeV/n}\)
- Cu–Cu  \(11, 31, 100 \text{ GeV/n}\)
- \(p \uparrow - p \uparrow\)  \(11, 31, 100, 250 \text{ GeV}\)

**Planned or possible future modes:**
- Au–Au  \(2.5 \text{ GeV/n (\sim SPS cm energy)}\)
- \(p \uparrow - \text{Au*} 100 \text{ GeV/n}\) (*asymmetric rigidity)
Electron Beam Ion Source (EBIS) at RHIC

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm² Current Density
- Any species, switch between species in 1 sec
The RHIC OPPIS upgrade with atomic hydrogen injector, Run-2013-17

BNL - BINP, Novosibisk, INR, Moscow - collaboration
High intensity polarized \( H^- \) ion source and “Siberian Snakes” made possible the high luminosity RHIC operation with colliding polarized protons beams to study:

- proton spin structure,
- fundamental tests of QCD and electro-weak interaction.
SPIN-TRANSFER POLARIZATION IN PROTON-Rb COLLISIONS

Laser-795 nm
Optical pumping
\( Rb: NL(Rb) \sim 10^{14} \text{ cm}^{-2} \)

Proton source
\( \rightarrow \)
\( Rb^+ \)
\( \rightarrow \)
\( H^+ \)
\( \rightarrow \)
\( H^+ \)
\( \rightarrow \)
\( Rb^+ \)

Sona transition

Ionizer cell
\( \rightarrow \)
\( H^- \)

Na-jet ionizer cell:
\( NL(Na) \sim 3 \times 10^{15} \text{ cm}^{-2} \)

ECR-29 GHz
\( H^+ \) source
\( \sim 50 \text{ mA, 2.8 keV} \)

Supercconducting solenoid 25 kGc

Charge-exchange collisions: \( \sigma \sim 10^{-14} \text{ cm}^2 \)

1.5 kG field

Electron to proton polarization transfer

Laser beam is a primary source of angular momentum:

10 W (795 nm) \( \longrightarrow \) \( 4 \times 10^{19} \text{ h} \nu/\text{sec} \) \( \longrightarrow \) 2 A, \( H^0 \) equivalent intensity.
High-brightness proton beam inside strong 2.5 T solenoid field produced by atomic H beam ionization in the He-gas ionizer cell

The primary proton beam and Equivalent atomic H intensity current is 2.5 A at 6.5 keV beam energy!
Hydrogen atomic beam ionization efficiency in the He-cell

\[ H^0 + He \rightarrow H^+ + He + e \]
OPPIS with atomic H$^0$ injector layout, 2013-17

- Neutralizer H$_2$-cell
- Atomic H injector
- He-ionizer cell
- Rb-cell
- Sona transition
- Na-jet cell

Flow Diagram:

- $H^+$ to $H_2$
- $H_2$ to $H^0$
- $H^0$ to He
- He to $H^+$
- $H^+$ to Rb
- Rb to $H^0$
- $H^0$ to Na
- Na to $H^+$
FABS produces 100-150 mA equivalent H0 beam intensity within the Na-jet ionizer acceptance.
4-grid spherical Ion Optical System

F $\sim$ 200 cm, $\delta \alpha$ -10 mrad

1820 holes, 1.0 mm in diameter

2.5-5.0 A of proton beam at 6-10 keV
Beam energy

R1, grid1-180 cm
R2, grid2-150 cm
R3, grid3-120 cm
R4, grid4-120 cm
Atomic beam profile measurements

High-brightness Proton source

Deflecting magnet

200 cm

Bending magnet

H₂-neutralizer cell

Movable 45-200 cm Secondary Emission Monitor, SEM
Atomic beam intensity profile vs. distance from the source.

Re-1.40 cm at the distance: L=100 cm from the source

Re-1.98 cm at the distance: L=200 cm from the source

FWHM-2.3 cm

FWHM-3.25 cm
Atomic beam intensity profile vs. distance from the source measured with the movable secondary emission monitor.

Total equivalent H beam intensity 2.5 A

Re - half-width of beam intensity profile at -1/e level.
Beam profile FWHM = 1.67 Re

Distance from the source: L-cm

F ~200 cm, δα -10 mrad

New IOS#2

IOS#1

Re
H⁻ ion beam production in the H2 neutralizer cell

High-brightness Proton source

Deflecting magnet

200 cm

H2-cell

Bending magnet

H2-neutralizer cell

FC

H⁻

H⁺
75 mA $H^-$ ion beam current at 10 keV in FC at the distance 200 cm from the source. IOS #3

Total proton beam current - 4.7 A. With 2.0% $H^-$ ion beam yield total $H^-$ beam current is 94 mA. Time scale 100 us/div
**H⁻ ion beam production in the H2 neutralizer cell**

- High-brightness Proton source
- H₂-neutralizer cell
- Deflecting magnet
- H₂-cell
- Bending magnet

Diagram showing the path of H⁻ ions from the proton source through the H₂-neutralizer cell, reflecting, and then being neutralized. The path is marked with 200 cm distance.
$H^-$ ion beam production in the H2 neutralizer cell

High-brightness Proton source

Deflecting magnet

H2-cell

Bending magnet

H2-neutralizer cell

200 cm
$H^-$ ion beam production in the H2 neutralizer cell

High-brightness Proton source

Deflecting magnet

H2-cell

Bending magnet

H2-neutralizer cell

$H^-$ ion beam is transported 2.5 times better than H0 beam due to additional focusing by space-charge of H+ beam!!!

A.Kolmogorov poster, We09
An energy dependence of the H⁻ ion beam yield drops to 1.8% at 20 keV (and 1.4% at 30 keV). The primary proton beam current strongly increases with the beam energy (from 3.2 A at 8.0 keV to 4.7 A at 10 keV). And H⁻ ion beam current increases from 50 to 75 mA.

Therefore, it is expected at 20-30 keV beam energy it is possible to produce a 100-200 mA of the H⁻ ion beam intensity (in Cesium-free source), which might be useful for some accelerator applications.

The H⁻ beam emittance is similar or smaller than neutral hydrogen beam emittance, which is estimated ≤ 0.5 π mm mrad.
New OPPIS with atomic $H^0$ injector layout, 2013-17

Neutralizer $H_2$-cell

Atomic H injector

He-ionizer cell

Rb-cell

Sona transition

Na-jet cell
Residual un-polarized $H^0$ beam component suppression by the energy separation

$H^0 + He \rightarrow H^+ + He + e$

$H^0(6.5 \text{ keV})$

He-ionizer cell

$H^0(70\%)$

$H^0(30\%)$

Deceleration

$H^0(2.5 \text{ keV})$

$H^0(6.5 \text{ keV})$

-4.1 kV

-4.0 kV

-4.1 kV

-2-3 kV

+0.1 kV
He-ionizer cell and 3-grid energy separation system.
“Electro-dynamic” valve operation principle.

Lorentz force to the flexible conducting plate in the high (~ 3-5 T) magnetic field.
For I=100 A, L=5 cm, F=15 N. Current pulse duration ~100 us.

\[d\mathbf{F}_A = I [d\mathbf{l} \times \mathbf{B}]\]
Optically-pumped Rb-vapor cell

Rb-cell preparation for the Run-2017, higher 6.0 kV deflecting plate voltage.
New OPPIS with atomic $H^0$ injector layout, 2013-17

CP1  TMP1

Neutralizer $H_2$-cell

Atomic H injector

He-ionizer cell

Rb-cell

Sona transition

Na-jet cell

$H^+$  $\rightarrow$  $H_2$  $\rightarrow$  $H^0$  $\rightarrow$  He  $\rightarrow$  $H^+$  $\rightarrow$  Rb  $\rightarrow$  $H^0$  $\rightarrow$  Na  $\rightarrow$  $H^+$
Sodium-jet ionizer cell

Transversal vapor flow in the N-jet cell. Reduces sodium vapor losses for 3-4 orders of magnitude, which allow the cell aperture increase up to 3.0 cm.

Reservoir - operational temperature. Tres. ~500 °C.
Nozzle - Tn ~500 °C.
Collector - Na-vapor condensation: Tcoll.~120 °C
Trap- return line. T ~ 120 - 180 °C.

NL ~2·10^{15} \text{ atoms/cm}^2
L ~ 2-3 \text{ cm}
H⁻ beam acceleration to 35 keV at the exit of Na-jet ionizer cell

Na-jet cell is isolated and biased to –32 keV. The H⁻ beam is accelerated in a two-stage acceleration system.
H⁻ beam acceleration to 35 keV at the exit of Na-jet.

Na-jet cell is isolated and biased to –32 keV. The H⁻ beam is accelerated in a two-stage acceleration system: 35 keV to 28 keV to 15 keV.
Low Energy Beam Transport line.

Variable collimator in DB2 to improve Energy resolution.

23.7 deg bender

Lamb Shift Polarimeter

FC4 35.0 keV

FC-Tk1, 750 keV
H\textsuperscript{-} current at 200 MeV-1.050 mA, June12, 2017

Rb-cell
Temp.-105 deg.
### Beam intensity and polarization at 200 MeV

- Reliable long-term operation of the source was demonstrated.
- Very high suppression of un-polarized beam component was demonstrated.
- Small beam emittance (after collimation for energy separation) and high transmission to 200 MeV.

<table>
<thead>
<tr>
<th>Rb-cell thickness-NL</th>
<th>4.5</th>
<th>5.5</th>
<th>7.5</th>
<th>10.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Current, μA</td>
<td>440</td>
<td>520</td>
<td>740</td>
<td>950</td>
</tr>
<tr>
<td>Booster Input $\times 10^{11}$</td>
<td>10.0</td>
<td>12.0</td>
<td>14.0</td>
<td>17.1</td>
</tr>
<tr>
<td>Pol. %, at 200 MeV</td>
<td>86</td>
<td>86</td>
<td>84.5</td>
<td>83</td>
</tr>
</tbody>
</table>

Rb-cell thickness, NL $\times 10^{13}$ atoms/cm$^2$
Polarization in AGS, 23 GeV, Run-2017

Run 76471  V3  $l=1.60$  Stat=38.5 (41.0)  $P = 78.3 \pm 2.3\%$

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Stat.</th>
<th>Polar.</th>
<th>(no corr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>19.3</td>
<td>78.3±2.3</td>
<td>(73.6±2.3)</td>
</tr>
<tr>
<td>90deg</td>
<td>6.6</td>
<td>77.9±3.2</td>
<td>(73.2±3.3)</td>
</tr>
<tr>
<td>90degUp</td>
<td>6.6</td>
<td>77.9±3.2</td>
<td>(73.2±3.3)</td>
</tr>
<tr>
<td>90degDn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45deg</td>
<td>12.7</td>
<td>78.9±3.3</td>
<td>(74.3±3.3)</td>
</tr>
<tr>
<td>45degUp</td>
<td>6.3</td>
<td>84.5±4.7</td>
<td>(79.6±4.8)</td>
</tr>
<tr>
<td>45degDn</td>
<td>6.4</td>
<td>73.5±4.5</td>
<td>(69.2±4.7)</td>
</tr>
</tbody>
</table>

Det. Mask=0xFF  R.C. = 1.00
Polarization at 23 GeV in AGS

\[ \chi^2 = 26.1 / 23 \]

\[ P(1.74) = 73.1 \pm 0.44 \]

\[ dP/dl = -5.2 \pm 0.55 \]

\[ P(0) = 82.1 \pm 1.0 \]

\[ P(1.8) = 72.8 \pm 0.4 \]
255 GeV beams Polarization measured with the H-jet polarimeter in Run-2017

\[ \langle P \rangle = 0.5491(17) \quad \chi^2 = 485.0 / 187 \]

\[ \langle P \rangle = 0.5629(17) \quad \chi^2 = 554.1 / 187 \]
RHIC Polarized beam in Run 2013-17

OPPIS

LINAC

Booster

AGS

~1.8 \cdot 10^{11} \text{ p/bunch}, P \sim 65-75\% \text{ at 100 GeV} 
\quad P \sim 60-65\% \text{ at 255 GeV}

1.0 \text{ mA x 300\micro\second} \rightarrow 18 \cdot 10^{11} \text{ polarized H}^-/\text{pulse.}

9.0 \cdot 10^{11} \text{ polarized H}^-/\text{pulse at 200 MeV routinely in Run-17, Polarization-85\%}

(2.5-3.0) \cdot 10^{11} \text{ protons /pulse at 2.3 GeV}

(2.0-2.5) \cdot 10^{11} \text{ p/bunch, P-70\%}

Exquisite Control of Systematics
• ³He polarization by optical pumping and metastability-exchange technique inside the EBIS in high (5.0T) magnetic field. No polarization losses in ³He⁺ state.

• EBIS is used for **efficient ionization** and **accumulation** of polarized ³He⁺⁺ ions to the full capacity $10^{12}$ total charge ($5\times10^{11}$, ³He⁺⁺ ions).
3He-gas purification and filling system

Non-magnetic brass pneumatic remotely controlled Isolation Valve
Jan 18, 2016, Sealed cell, OD-30 mm-Pol.- 88%, Field-2.0 T

Probe laser absorption polarimeter
EBIS upgrade with new “injector” solenoid for polarized $^3\text{He}^{++}$ ion production, 2017-2019.

BNL-MIT collaboration

Optical pumping in High magnetic field

Polarization and ionization in high magnetic field will produce $^3\text{He}^{++}$ ion beam with $P \geq 80%$

Up to $5 \times 10^{11}$ $^3\text{He}^{++}$ ions/pulse
Injector upgrade with the second magnetron H\textsuperscript{-} ion source in 2017, as a part of high intensity Linac upgrade. The source and Linac pulse duration increase to 1000 us. Current-55-60 mA.

Prototype of the advanced injector for high-energy accelerators.
BNL magnetron $H^-$ ion source

**TABLE 1. Typical running parameters**

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<th>Value</th>
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<td>H- current</td>
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<td>J ($H^-$)</td>
<td>1.5 A/cm$^2$</td>
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<td>Extraction voltage</td>
<td>35 kV</td>
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<td>Electron/H-</td>
<td>0.5-1.0</td>
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<tr>
<td>Arc voltage</td>
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<tr>
<td>Arc current</td>
<td>8 – 18 A (see note)</td>
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<tr>
<td>Rep rate</td>
<td>7.5 Hz</td>
</tr>
<tr>
<td>Pulse width</td>
<td>700 µs</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.5 %</td>
</tr>
<tr>
<td>rms emittance</td>
<td>$\sim 0.4 \pi$ mm mrad</td>
</tr>
<tr>
<td>Cs consumption</td>
<td>$&lt; 0.5$ mg / hr</td>
</tr>
<tr>
<td>Gas flow</td>
<td>$\sim 2$ sccm</td>
</tr>
</tbody>
</table>

**Power efficiency**: $\sim 100$ mA $H^-/1.5$ kW arc-discharge power. Average-10W

**Very reliable operation. Typically for 6 months run.**

**FIGURE 2.** Source with the anode cover removed. Permanent magnets are visible on the sides of the source.
BNL magnetron H⁻ ion source

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Similar source is in operation at Fermilab and was used for the long time at HERA injector.

Power efficiency: ~ 70 mA / kW arc-discharge power

Very reliable operation. Typically for 6 months run.

FIGURE 2. Source with the anode cover removed. Permanent magnets are visible on the sides of the source.

FIGURE 1. Schematic of the BNL magnetron H⁻ ion source.
$H^-$ magnetron source current at BNL

Source current 110 mA
Injection to RFQ-80 mA
750 keV after RFQ-65 mA
200 MeV out of Linac-55 mA

Extractor voltage-35 kV
FIGURE 10. $\text{H}^+$ beam-current – extraction-voltage characteristic measured at 2 and 6 Hz repetition rates, the reference values measured on the original Magnetron at 7.5 Hz are extracted from ref. 6.
Summary

• The RHIC high intensity polarized H- source provides required beam intensity for present RHIC and future high-luminosity eRHIC collider operation.

• The polarized $^3\text{He}^{++}$ ion source on the basis of new EBIS injector is under development at BNL for future eRHIC collider.

• High intensity un-polarized H$^-$ ion source development is in progress as a part of Linac intensity upgrade.