Optically-Pumped Polarized H\(^-\) and 3He\(^{++}\) Ion sources development at RHIC

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- Polarized H\(^-\) ion injections for high brightness (luminosity) colliders.
- Optical pumping polarization technique
- High-intensity polarized H\(^-\) ion source at RHIC
- Polarized 3He\(^{++}\) source development at RHIC
- High-intensity un-polarized magnetron H\(^-\) ion sources at RHIC

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The Story of Spin
Shin’ichiro Tomonaga

It is a **mysterious beast**, and yet its practical effect prevail the whole of science. The existence of spin, and statistics associated with it, is the most subtle and **ingenious design of Nature** - without it the whole universe would collapse. (from the preface)

“Reality is not what it seems”
Spin is a window in the quantum world

exploring spin is of fundamental importance
RHIC High-Luminosity Relativistic Heavy Ion (Polarized protons) Collider

Achieved peak luminosities (100 GeV, nucl.-pair):
- Au–Au 120\times10^{30} \text{ cm}^{-2} \text{ s}^{-1}
- p\uparrow–p\uparrow 50\times10^{30} \text{ cm}^{-2} \text{ s}^{-1}

Other large hadron colliders (scaled to 100 GeV):
- Tevatron (p – p\bar{p}) 35\times10^{30} \text{ cm}^{-2} \text{ s}^{-1}
- LHC (p – p, design) 140\times10^{30} \text{ cm}^{-2} \text{ s}^{-1}

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

Planned or possible future modes:
- Au – Au 2.5 GeV/n (~ SPS cm energy)
- p\uparrow – Au* 100 GeV/n (*asymmetric rigidity)
eRHIC Design Concept

- Design goal: \( L = 10^{34}\text{cm}^{-2}\text{s}^{-1} \)

- eRHIC takes full advantage of existing RHIC complex, entirely re-using injection chain and one of RHIC rings.

- Electron storage ring and the electron injector (400 MeV linac and RCS) are added inside the existing RHIC tunnel.

- Wide coverage in Center-of-Mass energy: 29-140 GeV
  \[ E_p: 41-275\text{ GeV}, \quad E_e: 5-18\text{ GeV} \]

- Polarized beams (e, p, \(^3\text{He}, \text{d}\)) with variable spin patterns

- Luminosity limitation factors on based of experience from previous colliders

- Hadron cooling is required to reach \( L = 10^{34}\text{cm}^{-2}\text{s}^{-1} \);
  Without cooling the peak luminosity reaches 4.4 \( 10^{33}\text{cm}^{-2}\text{s}^{-1} \)
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.
Workshop on high-energy spin physics, Protvino, 1983

G. Budker, G. Dimov, … polarized H+ ion beam strip injection to circular accelerators, 1977, Pol. H+ ion beam intensity was ~5 µA.

Yaroslav Derbenev

“Siberian snake” proposal, 1974

Anatoli Zelenski

A new polarized source technique. Equal intensity for polarized and un-polarized proton beams.
Proton polarization techniques

Dissociator → Separating 6-pole magnet → RF transition → ECR ionizer → H⁺

Optically-Pumped cell → Optically-Pumped cell → Cs cell → H⁻

Optically-Pumped cell → Cs beam → H⁻

Optically-Pumped cell → Plasma ionizer → H⁻

Optically-Pumped cell → Na cell, 8% → H⁻

Optically-Pumped cell → He cell, 70% → H⁺

Polarization by electron spin

Proton source → H⁰ source → OPTIS

Optical pumping

Polarization Transfer to protons
Spin-transfer polarization in proton-Rb collisions

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

Laser beam is a primary source of angular momentum:

$10 \text{ W (795 nm)} \rightarrow 4 \times 10^{19} \text{ h} \nu/\text{sec} \rightarrow 2 \text{ A, } H^0 \text{ equivalent intensity}$
ECR based RHIC OPPIS, 2000-2012

Y. Mori, KEK-1986-90 first operational OPPIS

29.2 GHz ECR proton source

SCS solenoid

Probe laser

Rb-cell

Cryopumps

Pumping laser

Na-jet Ionizer cell

Sona-transition
RHIC OPPIS produces reliably 0.5-1.0mA polarized H⁻ ion current. Polarization at 200 MeV: P = 80%. Beam intensity (ion/pulse) routine operation:

<table>
<thead>
<tr>
<th>Source</th>
<th>Linac</th>
<th>AGS</th>
<th>RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 10^{12} H⁻/pulse</td>
<td>- 5 \cdot 10^{11}</td>
<td>- 1.5-2.0 \cdot 10^{11}</td>
<td>- 1.5 \cdot 10^{11} /bunch</td>
</tr>
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</table>

A 29.2 GHz ECR-type source is used for primary proton beam generation. The source was originally developed for dc operation.

KEK-BNL-TRIUMF-INR, Moscow Collaboration
KEK-BNL-TRIUMF-INR, Moscow Collaboration
OPPIS with atomic H⁰ injector

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!
Pulsed OPPIS with the atomic hydrogen injector at INR, Moscow, 1982-1990. First generation

Atomic $H^0$ injector

Helium ionizer cell

Lamb-shift polarimeter

$H^-$ current - 0.4 mA
$H^+$ current - 4.0 mA, P=65%, 1986
Atomic H⁰ ionization efficiency in the He cell

H⁰ + He → H⁺ + He + e

![Graph showing H⁺ fraction vs. energy (keV)]

- Energy (keV) range: 0.1 to 10 keV
- H⁺ Fraction range: 0 to 1

80% ionization efficiency at 10 keV.
Pulsed OPPIS at TRIUMF, 1997-99. Second generation. Motivated by proposals for polarized beam for FNAL and HERA

A pulsed $H^-$ ion current of a 10 mA was obtained in 1999. Polarization 40% limited by solenoid field.
Superconducting Solenoid delivered to BNL in 2012

Magnet designed and built by Cryomagnetics to BNL specification
Solenoid is fully re-condensing ~0.7 W extra cooling power

152 mm in diam. warm aperture, total length-115 cm
OPPIS with atomic $H^0$ injector and He-ionizer cell at RHIC, 2012-19
The RHIC OPPIS with atomic hydrogen injector, Run-2013

BNL, BINP, Novosibisk, INR, Moscow- collaboration
"Fast Atomic Beam Source", FABS, BINP, Novosibirsk, 2011

Plasmatron

FABS produces 100-150 mA equivalent H0 beam intensity Within the Na-jet ionizer acceptance.

4-grid proton extraction system

H2 Neutralization cell

~ 2.5 A equivalent H0 beam
FABS 4-grid (spherical) Ion Optical System with “geometrical focusing

1820 holes, 1.0 mm in diameter

R1, grid1-180 cm
R2, grid2-150 cm
R3, grid3-120 cm
R4, grid4-120 cm

2.5-5.0 A of proton beam At 6-10 keV energy
Atomic H beam profile measurements vs. distance from the source

- High-brightness Proton source
- H2-neutralizer cell
- Deflecting magnet
- Bending magnet
- Movable CEM beam Profile monitor
- Atomic H beam profile measurements vs. distance from the source
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

~300 mA/cm²
OPPIS with atomic $H^0$ injector and He-ionizer cell at RHIC, 2012-19

Diagram showing the OPPIS setup with the following components:
- Atomic H injector
- He-ionizer cell
- Rb-cell
- Sona transition
- Na-jet cell
- Neutralizer $H_2$-cell
- CP1
- TMP1

Reactants and products:
- $H^+$
- $H_2$
- $H^0$
- He
- $H^+$
- Rb
- $H^0$
- Na
- $H^-$
Residual un-polarized $H^0$ beam component suppression by energy separation

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

He-ionizer cell

Deceleration

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

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

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

$H^0(30\%)$

$H^+(70\%)$

-4.1 kV

-4.0 kV

-4.1 kV

-2-3 kV

+0.1 kV

Rb -cell

-4.1 kV

-0.1 kV
He-ionizer cell and 3-grid energy separation system

He-pulsed valve

3-grid beam deceleration system
IxB-pulsed valve operation principle

Lorentz (Laplace) force moves the flexible conducting plate in the high (~3–5 T) magnetic field.
For I=10 A, L=5 cm, F=2.5 N. Current pulse duration ~100–500 us
OPPIS with atomic $H^0$ injector layout, 2013

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

NL $\sim 2 \cdot 10^{15}$ at/cm$^2$
L $\sim 2-3$ cm

Nozzle 500 deg.C
Collector $\sim 150$ deg.C
Return line
Boiler $\sim 500$ deg.C

Brookhaven Science Associates
Na-jet cell is isolated and biased to -32 keV. The H⁻ beam is accelerated in a two-stage acceleration system to achieve 35 keV at the exit of the Na-jet ionizer cell.
Variable collimator In DB2 to improve Energy resolution.

23.7 deg bender

Lamb Shift Polarimeter

FC4 35.0 keV

FC-Tk1, 750keV
H⁻ ion beam current accelerated to 200 MeV, June-2017

Rb-cell
Temp.-105 deg.

1.05 mA

300 us
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.

| Rb-cell thickness-NL X 10^{13} atoms/cm^2 | 4.5 | 5.5 | 7.5 | 10.4 |
| Linac Current, μA | 440 | 520 | 740 | 1050 |
| Booster Input × 10^{11} H/pulse | 10.0 | 12.0 | 14.0 | 17.1 |
| Pol. %, at 200 MeV | 86 | 86 | 84.5 | 83 |
RHIC Polarized beam in Run 2013-17

OPPIS → LINAC → Booster → AGS → RHIC

1.0 mA x 300us → $18 \cdot 10^{11}$ polarized $H^{-}$/pulse

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

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

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

~$1.8 \cdot 10^{11}$ p/bunch, P~65-75% at 100 GeV

P ~ 60-65% at 255 GeV
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Production of polarized $^3$He$^{++}$ beam in EBIS.

Existed $^3$He$^{++}$ sources intensity- 50nA

- Injections of $^3$He gas polarized in the external cell into EBIS.
- $^3$He polarization inside the EBIS in high (5.0T) magnetic field. No polarization losses during beam transport through gradient magnetic field.
- EBIS is used for efficient ionization and accumulation of polarized $^3$He$^{++}$ ions to the full capacity $10^{12}$ total charge ($5\cdot10^{11}$, $^3$He$^{++}$ ions).
“Extended” EBIS upgrade with new “injector” solenoid for polarized $3\text{He}^{++}$ ion production

Polarization and ionization in high magnetic field will produce $3\text{He}^{++}$ ion beam with $P \geq 80\%$
Extended EBIS superconducting solenoids, April 2018

5.0 T field, about 1.0 T field at minimal solenoid separation-30 cm
Jan, 2016, Sealed cell, OD-30 mm-Pol.- 88%, Field-2.0 T

Probe laser absorption polarimeter
Polarization measurements

Isolation Valve (IV) open: 34.9%
Isolation Valve (IV) closed: 65.1%
Polarization equilibrium: 80.3%
3He-gas purification and filling system

Modified Cryo-pump for 3He purification and storage
3He -optically-pumped cell in the high magnetic field

Long, small diameter drift tube works like a 3He storage cell, which reduces gas load to the EBIS vacuum system and increases polarization due to ionization localization in the high magnetic field region.
The development of the 3He polarizing apparatuses, the spin-rotator, and the nuclear polarimeter at the 3He++ ion beam energy 6.0 MeV (in the high-energy beam transport line after the EBIS drift-tube Linac) is funded by the DOE Research and Development Funds for the Next Generation Nuclear Physics Accelerators Facilities.
Summary

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

• The polarized $^3$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.
High-intensity un-polarized H- sources
And injector development at BNL
35 keV LEBT upgrade with three sources for Run-2020

Prototype of H\(^+\) injector for high-energy accelerators, with high cost downtime

- To RFQ
- Magnetron - S1
- OPPIS
- Laser beam
- Pulsed bending magnet, 45 deg.
- Magnetron - S2
- 23.7 deg. dc bending magnet
BNL magnetron H⁻ ion source

TABLE 1. Typical running parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁻ current</td>
<td>90-100 mA</td>
</tr>
<tr>
<td>( J ) (H⁻)</td>
<td>1.5 A/cm²</td>
</tr>
<tr>
<td>Extraction voltage</td>
<td>35 kV</td>
</tr>
<tr>
<td>Electron/H⁻</td>
<td>0.5- 1.0</td>
</tr>
<tr>
<td>Arc voltage</td>
<td>140 – 160 V</td>
</tr>
<tr>
<td>Arc current</td>
<td>8 – 18 A (see note)</td>
</tr>
<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 0.6 ) sccm</td>
</tr>
</tbody>
</table>

Power efficiency : \( \sim 100 \) mA H⁻/1.5 kW arc-discharge power

FIGURE 2. Source with the anode cover removed. Permanent magnets are visible on the sides of the source.
Jan. 2018, two magnetron sources in operation
~120 mA H⁻ current

Arc current-14A
Arc voltage-150 V

Upgrades:
Pulsed valve
Temperature control
Arc-PS
Extraction system ets...
H⁻ magnetron source current in Run-2019

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
Dec. 5, 2017, Arc-18A, Source current L1-130 mA, current after RFQ L5-80 mA

L1-130 mA

L5-current after RFQ 750 keV energy Current -80 mA

L4-current At injection To RFQ-110 mA

800 us pulse duration
Dec 5, 2017, L1-100 mA, L4-75 mA, Arc-10A, 750 us - pulse duration
Polarization facilities at RHIC

\[ L_{\text{max}} = 1.6 \times 10^{32} \text{s}^{-1}\text{cm}^{-2} \quad 50 < v_s < 510 \text{GeV} \]

- Absolute H^{-} jet polarimeter
- RHIC pC "CNI" polarimeters
- RHIC pC "CNI" polarimeters
- 200 MeV polarimeter
- AGS pC "CNI" polarimeter
- AGS, 24GeV
- STAR
- PHENIX
- Spin Rotators
- EBIS
- LINAC
- Booster, 2.5 GeV
- Pol. H^{-} ion source
- Siberian Snakes
No new operational $^3$He ion sources were built. A number of new ideas were proposed and tested (not successfully).

Spin-exchange and “metastability-exchange” techniques for $^3$He atoms polarization were greatly improved due to laser development and demanding applications.