Negative Ion Source Technology for Accelerators

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Applications

Tandem accelerators

Cyclotron extraction

Multi-turn injection into rings

Neutral Beams

Other negative ions are used for material modification and characterization
Early attempts at producing negative ion beams:

- Charge exchange of positive beams
  - gas cells - very inefficient <2%
- Low work function oxide coated filament - very low current
- Extraction from existing ion sources...

A 1937 tandem with a charge exchange gas cell
Off Axis Duoplasmatron Extraction
Off Axis Duoplasmatron Extraction

Displacement

1960’s George Lawrence
Los Alamos
Off Axis Duoplasmatron Extraction

![Graph showing electron and H⁻ currents vs. displacement](image)
Off Axis Duoplasmatron Extraction

Direct Extraction
Negative Ion
Duoplasmatron

30 µA DC
H⁻ current

discharged
intermediate
electrode
duoplasmatron
Early 1970s Budker Institute of Nuclear Physics
Novosibirsk
Production of H⁻ ions by surface ionisation with the addition of cesium

Surface Plasma Sources (SPS)

Gennady Dimov  Yuri Belchenko  Vadim Dudnikov
Cesium! – The magic elixir

More reactive

An amazing donor of electrons = great for making negative ions

1 electron in the outer orbital
Elemental Cesium Ampoule

Cesium Chromate
Cesium Coverage

Pure molybdenum

Work Function (eV)

Pure Cesium

Cs Thickness (monolayers)
Control cesium oven temperature to vary cesium vapor pressure to control cesium coverage

or vary cesium chromate cartridge temperature
Fundamental Geometry

Magnetron

Penning
Magnetron Surface Plasma Source

- Anode
- Cathode
- Hydrogen
- Cesium Vapour
- Extraction Electrode
- $H^-$ Beam
- Electrons
- $\approx 10$ mm
- Magnetic Pole Pieces
The Magnetron is a popular source

80 mA of H⁻ but only at low duty cycles < 0.5%
BNL 2 A Beam H⁻ Magnetron for NBI
Budker Semiplanotron

Planotron = magnetron

FIG. 1. A principal view of the Honeycomb surface-plasma source with a semiplanotron geometry of discharge electrodes. Magnetic field direction is shown by arrows: 1—magnet pole, 2—anode, 3—cathode, 4—plasma layer, 5—cavities for H_2 and Cs feed, 6—insulator, 7—electron collector, 8—multirod extractor, 9—multirod accelerating electrode.

11 A Semiplanotron for NBI
Penning SPS Ion Sources

• Invented by Dudnikov at BINP in the 1970’s
• Low noise
• Scaled versions developed by LANL in the 80’s and 90’s
• DC hollow cathode sources developed by Belchenko et al. at BINP
• Still used for operations by Moscow INR and ISIS
Negative Ion Beam

Piezo Hydrogen Valve

Cesium Oven

Cesium Vapour Heated Transport Line

50 A Discharge

Source Runs at 50 Hz Rep Rate

Hollow Anode

+17 kV Extraction Voltage

Piezo Hydrogen Valve

H₂
Cathode
Hydrogen Feed
Heated
Cesium
Transport Line
Air Cooling
Source Body
Hollow Anode
Discharge
Power Feed
Thermocouples
2X source:
60 mA 2 ms 50 Hz or
150 mA 0.8 ms 50 Hz
H⁻ currents
Filament Cathode Multicusp Surface Converter Source

- Heated Filament Cathode
- Anode
- Multicusp Magnets
- Outlet Aperture
- Hydrogen Feed
- Cesium Vapour
- Multicusp Magnets
- Anode
- ≈ 100 mm
- H⁻ Beam

Surface Converter Electrode -300 V

Heated Filament Cathode

Anode

Multicusp Magnets

Cesium Vapour

Multicusp Magnets

H⁻ Beam
Solid Emission Surface
Filament Cathode Multicusp Surface Converter Source

16-18 mA 1 ms 120 Hz
LANL with multiple filaments: 1 A of H⁻
SNICS (Source of Negative Ions by Cesium Sputtering)
Middelton et al

Currents in μA

<table>
<thead>
<tr>
<th>Element</th>
<th>Current (μA)</th>
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<tbody>
<tr>
<td>H−130</td>
<td>Si−430</td>
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<tr>
<td>D−150</td>
<td>P−125</td>
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<tr>
<td>Li−4</td>
<td>S−100</td>
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<tr>
<td>BeO−10</td>
<td>Cl−100</td>
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<tr>
<td>B−60</td>
<td>CaH3−0.8</td>
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<tr>
<td>B2−73</td>
<td>TiH−10</td>
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<tr>
<td>C−260</td>
<td>VH−25</td>
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<tr>
<td>C2−40</td>
<td>Cr−5</td>
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<tr>
<td>CN−12</td>
<td>MnO−4</td>
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<tr>
<td>CN−(15N) 20</td>
<td>Fe−20</td>
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<td>O−300</td>
<td>Co−120</td>
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<tr>
<td>F−100</td>
<td>Ni−80</td>
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<tr>
<td>Na−4.0</td>
<td>Cu−160</td>
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<tr>
<td>MgH2−1.5</td>
<td>ZnO−12</td>
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<tr>
<td>Al−7</td>
<td>GaO−7</td>
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<tr>
<td>Al2−50</td>
<td>Ge−60</td>
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<td></td>
<td>I−220</td>
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<td></td>
<td>Bi−3.5</td>
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Produces a large range of different negative ions
1970s Cesium Revolution!

- Soviets spread the word and develop sources
- BNL Krsto Prelec et al. develop the magnetron for NBI
- LANL Paul Allison et al. develop the Penning
- Berkley Ehlers+Leung develop Surface Converter sources
- Fermilab Chuck Schmidt et al. develop the BNL magnetron for accelerators
**Volume Production**

\[ \text{H}_2^* + e (\leq 1 \text{ eV}) \rightarrow \text{H}^- + \text{H}^0 \]

Dissociative attachment of low energy electrons to rovibrationally excited \( \text{H}_2 \) molecules

Developed by Ehlers + Leung at LBNL

Torvis- Brookhaven National Laboratories by Prelec and Alessi

... and many others
15 mA DC H⁻
Multicusp Volume Source
LAB$_6$ Filament Volume Source

- High electron temperature plasma region
- Low electron temperature plasma region
- Extraction electrode
- H$^-$ beam
- Anode
- Electron dump
- Filter magnets
- Plasma chamber
- LAB$_6$ cathode filament
- Multicusp magnets
- Section on B-B
- Section on A-A

≈ 100 mm
LAB$_6$ Filament Volume Source

36 mA @500 $\mu$s 25 Hz
Internal RF Solenoid Antenna Volume Source

- High electron temperature plasma region
- Low electron temperature plasma region
- Extraction electrode
- H⁻ beam
- Anode
- Electron dump
- Filter magnets
- Plasma chamber
- RF Power Supply: 50 kW

Section on B-B

Section on A-A

Multicusp magnets
External RF Solenoid Antenna
Volume Source

- External antenna solenoid
- Volume Source
- ≈ 100 mm
- Plasma chamber
- Electron dump
- Extraction electrode
- H⁻ beam
- Low electron temperature plasma region
- High electron temperature plasma region
- Anode
- Electron dump
- Filter magnets
- Plasma chamber
- RF Power Supply 50 kW
- Multicusp magnets
- Section on A-A
- Section on B-B
DESY Source

Jens Peters
Late 1990’s

40 mA H\(^-\)
150 \(\mu\)s, 3 Hz
ISIS RF H⁻ Ion Source (under construction)

30 mA H⁻
250 μs, 50 Hz
External RF Solenoid Antenna
Volume Source

High electron temperature plasma region

Low electron temperature plasma region

Extraction electrode

H⁻ beam

Electron dump

Filter magnets

Plasma chamber

Anode

Multicusp magnets

External solenoid plasma region

RF Power Supply
50 kW

≈ 100 mm

Section on B-B

Section on A-A
External RF Pancake Antenna Volume Source

External antenna solenoid

RF Power Supply
50 kW

Plasma chamber

Filter magnets

≈ 100 mm

High electron temperature plasma region

Low electron temperature plasma region

Extraction electrode

H⁻ beam

Anode

Electron dump

Section on A-A

Section on B-B

External RF Pancake Antenna Volume Source

Multicusp magnets

Plasma chamber
External RF Pancake Antenna Volume Source

7.5 mA H⁻ DC
Holmes et. al. Culham UK

Add Cesium

40 mA = apparent limit of the volume process

Destruction process dominate
Best of both worlds?

Volume + Surface
Internal RF Solenoid Antenna Volume Source with Surface Converter

- High electron temperature plasma region
- Cesiated surface converter
- Extraction electrode
- H⁻ beam
- Anode
- Electron dump
- Filter magnets
- Plasma chamber
- ≈ 100 mm

RF Power Supply
50 kW

Section on B-B

Multicusp magnets

Section on A-A
SNS Internal RF Solenoid Antenna Volume Source with Surface Converter

Cesium Chromate Cartridges

Martin Stockli

60 mA H⁻¹ ms, 60 Hz
Cesiated Internal RF Solenoid Antenna Volume Source with Surface Converter

Elemental Cs

110 mA H⁻ 0.6 ms 25 Hz
Internal RF Solenoid Antenna
Volume Source with Surface Converter

- High electron temperature plasma region
- Cesiated surface converter
- Extraction electrode
- H⁻ beam
- Anode
- Electron dump
- Filter magnets
- Plasma chamber
- RF Power Supply (50 kW)
- Multicusp magnets
- Section on A-A
- Section on B-B
External RF Solenoid Antenna
Volume Source with Surface Converter

- High electron temperature plasma region
- Filter magnets
- Plasma chamber
- Extraction electrode
- H⁻ beam
- Ceramic plasma chamber
- Electron dump
- Anode
- External Antenna solenoid
- Multicusp magnets
- RF Power Supply 50 kW
- Section on B-B
- Section on A-A
Cesiated External RF Solenoid Antenna Volume Source

Rob Welton

40 mA H⁻
1 ms, 60 Hz

Cesium Chromate Cartridges
Cesium-133 External RF Solenoid Antenna Volume Source

Jacques Lettry

Elemental Cs

50 mA H
0.5 ms, 3 Hz
Thank you for listening

Enjoy spotting the developments being presented at NIBS2020:
Higher currents
Novel materials
New technologies