Extracted and Electrode Currents in the Inductively Driven Surface-Plasma Negative Hydrogen Ion Source

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OUTLINE

1. Source description
2. Emission currents and its composition
3. First results on beam transport

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Scheme of BINP RF source

Surface-Plasma Source of Negative Ions with plasma production by inductive RF driver

RF Driver

H₂

Ignition

Faraday Screen

Antenna

Expansion Chamber

Cesium Seed

Filter Magnet

Plasma Grid

Extraction Grid

Acceleration Grid

Correction Magnet

\( U_{\text{PG}} \) 8 - 40 V

\( U_{\text{ex}} \) 7 - 12 kV

\( I_{\text{ex}} \)

\( U_{\text{ac}} \) 80 kV

\( I_{\text{ac}} \)

\( I_{\text{PG}} \)
New elements:

- Active temperature control of IOS grids (heating/cooling by hot fluid)
- Cesium seed to PG periphery
- Convex magnetic field in the IOS gaps
Test stand and measurements scheme

- H- beam was measured by Faraday Cup (at 1.6 m) and by calorimeter (at 3.5 m)
- IOS circuits currents $I_{ex}$, $I_{ac}$, $I_{AG}$ were used to control the outgoing H- beam and electron load
- Beam current $I_b = I_{ac} - I_{AG}$ consists of H- ions, outgoing the source.
- At optimal IOS voltages the difference $I_e = I_{ex} - I_b$ consists mainly of co-extracted electrons, and it was used as an upper limit of co-extracted electrons current.

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General Properties

IOS heating improves HV conditioning
Cold electrodes: 72 kV after 160 pulses,
15 min at 110 °C: 82 kV after 50 pulses,

IOS with convex magnetic field supports the enhanced HV holding under wide experimental change of source parameters.
General Properties

Driver with FS. Low power, long pulse
0.6 A, 81 keV, 25 s shot

RF power 17 kW. $P_{H_2} = 0.35 \text{ Pa}$, $U_{PG} = 17 \text{ V}$.
RF power was limited by voltage of RF power supply and by necessity to work at low $P_{H_2}$

Driver without FS. Higher power, shorter pulse
1.2 A, 85 keV, 1.6 s shot

Beam current 1.2 A, energy 85 keV, RF power 36 kW.
$P_{H_2} = 0.4 \text{ Pa}$, $U_{PG} = 9.7 \text{ V}$.

- H- beam current $I_b$ is about $\sim 60\text{-}70\%$ of acceleration circuit current $I_{ac}$
- Co-extracted electrons current $I_e$ is $\sim 30\text{-}50\%$ of extraction circuit current $I_{ex}$
- Power efficiency of H- ion production from RF discharge is $\sim 28 \text{ kW/A} = 28 \text{ keV/ion}$

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Beam and FC currents

Beam current, derived as $I_b = I_{ac} - I_{AG}$ corresponds to the real beam current, if

1. All leak currents of power supply $U_{ac}$ are prevented or excluded from $I_{ac}$
2. All “parasitic” collateral currents (co-extracted and secondary electrons, backstreaming positive ions) are included into the current of intercepted particles $I_{AG}$

Beam current $I_b$ and Faraday cup current $I_{FC}$ vs acceleration voltage.

- $I_b$ beam rise (+0.5A) is produced by improved beam transmission through IOS (+0.4A) and by decrease of H- stripping (+0.1A).
- FC current $j_{FC}$ increases due to beam focusing to FC.
- No saturation of $I_b$ and $j_{FC}$ currents was recorded with beam energy growth up to 85 keV.

Beam profile, scanned by FC

FC current $\int j_{FC} \cdot dS \approx 1$ A, $I_b=1.2$ A, energy 80 keV.
Beam divergence $\pm 60 \times \pm 50$ mRad
Extraction Circuit and co-extracted electrons currents

Extraction circuit current $I_{ex} \sim I_e + I_{H-}$ consists of co-extracted electrons and negative ions.

$I_{H-}$ included the outgoing beam $I_b$ and H-ions, intercepted or stripped during transport through the IOS.

Table 1. Extraction circuit current composition at optimal IOS voltages

<table>
<thead>
<tr>
<th>Extraction circuit current</th>
<th>Outgoing Beam, $I_b$</th>
<th>H- ions to EG and AG</th>
<th>H- ions, stripped in the IOS</th>
<th>Co- extracted electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9 A</td>
<td>1.2 A H-</td>
<td>-</td>
<td>0.1 A (electrons, detached from H- ions)</td>
<td>0.6 A $\approx 30%$ of $I_{ex}$</td>
</tr>
</tbody>
</table>
Extraction Grid current

EG current $I_{EG} = I_{ex} - I_{ac}$ consists of:
- co-extracted electrons,
- intercepted H- ions,
- backstreaming positive ions,
- and outgoing secondary electrons.

EG current drop (0.5 A), recorded with $U_{ac}$ rise is mainly produced by secondary electrons, outgoing from EG.
Acceleration Grid current

AG current $I_{AG}$ vs acceleration voltage $U_{ac}$

Blue dashed line – PBGUNs modeling of H- ion interception

At $U_{ac}=0$, $I_{AG}$ current consists of incident H- ions (~0.3A) and of electrons, detached from H- ions in the AG+GG support.

$U_{ac}$ rise increases the electrons transport to AG across the magnetic field. $I_{AG}$ current is maximal at $U_{ac}=20$ kV.

At $U_{ac}=75$ kV, $I_{AG}$ current consists of secondary electrons. Part of electrons are accelerated to full $U_{ac}$ voltage.
Acceleration Grid current is decreased with $U_{PG}$ growth

Co-extracted electrons current $I_e$ and acceleration grid current $I_{AG}$ vs PG bias voltage

Driver without FS. Beam energy 93 keV, RF power 35 kW. $P_{H_2} = 0.4$ Pa,

AG current $I_{AG}$ decreases and saturates at level $\sim 0.3$ A with the $U_{PG}$ growth.

The part of $I_{AG}$ current is produced by co-extracted electrons and it decreases proportionally to $I_e$.

Other $I_{AG}$ components (electrons, detached from H-, intercepted H- ions and the secondary electrons, emitted by BS+ ions) are varied, but its sum remains at level $\sim 0.3$ A in spite of $U_{PG}$ growth.
Beam and IOS electrode currents composition

Emission currents dependencies permits to evaluate the IOS electrode currents composition.

Table 2. Example of emission and electrodes current composition for standard source parameters and optimal IOS voltages

<table>
<thead>
<tr>
<th>Beam Component</th>
<th>Outgoing Beam current $I_b$</th>
<th>Extraction Grid current</th>
<th>Acceleration Grid current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Component</td>
<td>$H^-$</td>
<td>e</td>
<td>SEE + BS⁺</td>
</tr>
<tr>
<td>Co-extracted</td>
<td>1.2</td>
<td>0.6</td>
<td>- 0.3</td>
</tr>
<tr>
<td></td>
<td>e detatched from H⁻ ions</td>
<td></td>
<td>e</td>
</tr>
<tr>
<td>Current, A</td>
<td>0.1</td>
<td>~0.3</td>
<td></td>
</tr>
</tbody>
</table>

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• Beam transport length 3.5 m, Y-shift 44 cm, maximal slope of trajectory 14°.
• Magnet 1: $\int B_y \, dz = 1 \, \text{T} \cdot \text{cm}$, Magnet 2: $\int B_y \, dz = 1.8 \, \text{T} \cdot \text{cm}$.
• 2 cryopumps 100 m\(^3\)/c each; rated H- ions stripping by gas (120 keV) ~ 10%
Bending Magnets and Sectioned Calorimeter

View into the LEBT tank
at front - magnet #1, behind it – magnet #2
at center – FC (inlet aperture Ø 17 cm), at back -
calorimeter window 25x25 cm.

The structure of H-beam and its neutral satellites
was scanned by LEBT magnetic field change

Sectioned calorimeter
with 15 water-cooled rods. Front area 44 x 27 cm

Beam distribution was measured by
thermocouples, attached to rods. Total Beam
Power to calorimeter was measured by cooling
water temperature increase
Main Group consists of transported H- beam + neutrals, produced by H- ions stripping in section C.

Group 1 is produced by H- ions stripping in section A, before bending by magnets.

Group 3 is produced by H- ions stripping in central section B, after ions bending by magnet 1.

Group 1 is not shifted by magnets field.
Main Group and Group 3 are shifted by magnets field change.
Beam Scan by LEBT magnetic field change

Temperature rise of thermocouples in calorimeter central vertical row vs LEBT magnet #1 field

Top axis $X$ – beam horizontal shift along calorimeter window, calibrated by $X$- row of thermocouples. Left axis $Y$ – ordinate of thermocouples. Temperature scale in °C
Measurement points are shown by crosses

Beam Main Group and Neutral Group 3 are separated
Beam Scan by LEBT magnetic field change

Power to calorimeter $W_c$ and temperature rise of central thermocouple $\Delta T$ vs LEBT magnet #1 field top axis $X$ – beam horizontal shift along calorimeter window. H- Beam 46 kW, 80 keV

Power $W_c \approx 24$ kW (main group) - at $X=0$
Power $W_c \approx 4$ kW (group 3) - at $X=240$ mm

Total power to calorimeter $24 + 4 + 4 = 32$ kW is lower, than the injected power 46 kW:

a) Beam is broader, than calorimeter window
b) Cooling water temperature rise is low, part of beam power does not measured

$\sim 20$ kW H- beam of 46 kW injected beam is measured by SC
Beam size at Calorimeter Plane
measured by central vertical row of thermocouples

Beam Y-size at calorimeter plane.
ΔT - temperature rise of thermocouples, Y – ordinate of thermocouples (X=0)
Circles – 86 keV,  I_b = 1.1 A, I_c = 0.46 A,
Triangles – 85 keV, I_b = 0.75 A, I_c = 0.55 A;
Squares – 80 keV, I_b = 0.55 A, I_c = 0.3 A

Beam size increases with beam current growth
Beam is broader, than calorimeter window height 24 cm
First results on Beam Transport

Table 3. Parameters of Beam transport through the LEBT

<table>
<thead>
<tr>
<th>Discharge power, kW</th>
<th>Beam current, A</th>
<th>Beam Energy, kV</th>
<th>Vacuum, $10^{-3}$ Pa</th>
<th>Rated stripping by gas</th>
<th>Must be at SC after stripping</th>
<th>H- Beam at calorimeter, A</th>
<th>Beam size (FWHM), cm</th>
<th>Full Beam at calorimeter, plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.55</td>
<td>80</td>
<td>7.3</td>
<td>28%</td>
<td>0.4 A</td>
<td>0.25</td>
<td>16</td>
<td>~0.3 A</td>
</tr>
<tr>
<td>36</td>
<td>1.2</td>
<td>85</td>
<td>3.5</td>
<td>13%</td>
<td>1 A</td>
<td>0.54</td>
<td>26</td>
<td>~0.8 A</td>
</tr>
</tbody>
</table>

Measurements error is produced by low rise of calorimeter’ cooling water temperature
**SUMMARY**

- **H-** ion beams with current >1A and energy ≥90 keV are regularly produced.
- Power efficiency of H- ion production from RF discharge is 28 kW/A, or 28 keV/ion.
- The composition of IOS electrodes currents was clarified.
- Acceleration grid current 0.3-0.5 A could be decreased by increase of positive PG bias.
- **H-** ion beam with current ~1 A was transported to distance 1.6 m.
- **H-** ion beam with current > 0.5 A and energy 85 keV was transported through the LEBT to distance 3.5 m.
Thank you for attention