Microwave Discharge Ion Sources

Luigi Celona

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud
Via S. Sofia 64 - 95123 Catania
Italy
Applications based on intense proton beams

- **ADS for nuclear waste transmutation (and Energy production)**
  - Power range: 100 KW ÷ 10 MW
  - Energy range: 100 MeV ÷ 2 GeV
  - Average current: 100 μA ÷ 30 mA
  - Pulsed or CW

- **Radioactive ion beams**

- **Intense neutron spallation sources**

- **Radiation processing**

- **Neutrino factory**

<table>
<thead>
<tr>
<th>Proton driver</th>
<th>Energy (GeV)</th>
<th>Beam power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS: XADS Ind. burner</td>
<td>~ 0.6</td>
<td>~ 5</td>
</tr>
<tr>
<td></td>
<td>~ 1</td>
<td>~ 50</td>
</tr>
<tr>
<td>Spall. neutron source (ESS)</td>
<td>1.33</td>
<td>5</td>
</tr>
<tr>
<td>Irradiation facility</td>
<td>~ 1</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Neutrino factory (CERN)</td>
<td>2.2</td>
<td>4</td>
</tr>
<tr>
<td>RIB: “one stage” “two stages”</td>
<td>~ 0.2</td>
<td>~ 0.1</td>
</tr>
<tr>
<td></td>
<td>~ 1</td>
<td>~ 5-10</td>
</tr>
<tr>
<td>Facility</td>
<td>Beam</td>
<td>keV</td>
</tr>
<tr>
<td>--------------</td>
<td>------</td>
<td>-----</td>
</tr>
<tr>
<td>LEDA</td>
<td>p</td>
<td>75</td>
</tr>
<tr>
<td>IPHI</td>
<td>p</td>
<td>95</td>
</tr>
<tr>
<td>TRASCO</td>
<td>p</td>
<td>80</td>
</tr>
<tr>
<td>FAIR</td>
<td>p</td>
<td>95</td>
</tr>
<tr>
<td>ESS</td>
<td>p</td>
<td>75</td>
</tr>
<tr>
<td>IFMIF</td>
<td>D⁺</td>
<td>100</td>
</tr>
<tr>
<td>MYRRHA</td>
<td>p</td>
<td>100</td>
</tr>
<tr>
<td>DAEδALUS</td>
<td>H₂⁺</td>
<td></td>
</tr>
<tr>
<td>SPL</td>
<td>H⁻</td>
<td></td>
</tr>
<tr>
<td>SNS</td>
<td>H⁻</td>
<td>65</td>
</tr>
<tr>
<td>JKJ</td>
<td>H⁻</td>
<td></td>
</tr>
<tr>
<td>ADSS</td>
<td>H⁻</td>
<td>25</td>
</tr>
</tbody>
</table>

High reliability and high parameters’ reproducibility is requested (i.e. operator-independent)
Basic principles

HYPOTHESIS: ABSENCE OF MAGNETIC FIELD, PLANE AND MONOCROMATIC WAVE

\[ E = E_0 e^{i(kz - \omega t)} \]

For propagation into the plasma must be: \( k > 0 \)

\[ k^2 \approx \frac{\omega^2}{c^2} \left( 1 - \frac{\omega_{pe}^2}{\omega^2} \right) = \frac{\omega^2 - \omega_{pe}^2}{c^2} \]

\[ \omega^2 = \frac{n_e e^2}{\varepsilon_0 m_e} \]

\[ n_c = \frac{\varepsilon_0 m_e \omega_{pe}^2}{e^2} = 1.2283 \cdot 10^{-2} \cdot f^2 \text{[m}^{-3}] \]

Upper limit to density: \( n < n_c \)

The introduction of a magnetic field opens different coupling mechanism:

- **ELECTRON CYCLOTRON RESONANCE (ECR)** (see T. Thuiller lectures)

B-min magnetic configuration – ECR heating occurs at

\[ B_{ECR} = \frac{m_e \omega}{e} \]

RHCP wave strongly coupled

- **OFF RESONANCE HEATING**

K. Golovanivsky

ECRIS plasmas: stochastic heating or

Langmuir caviton collapses”

Proc. 11th ECRIS Workshop (1993), KVI, 996
Later on, Okada and others in Japan and elsewhere produced tens of mA of B\(^+\), As\(^+\), P\(^+\) and other monocharged ions, but Sakudo is recognized to be the pioneer.
First Ion Implanter
Discharge RF Power: 800W @ 2.45 GHz
Total beam current: 96 mA
Proton fraction: 86 %
Proton beam: 82.5 mA
Beam energy: 50 keV
Beam emittance (rms norm.): 0.13 $\pi$ mm mrad
Hydrogen mass flow: $\approx 2$ sccm
Chalk River
Taylor & Wills
Beginning of ’90s
Los Alamos source for LEDA
<table>
<thead>
<tr>
<th>Injector Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ gas flow (sccm)</td>
<td>4.1</td>
</tr>
<tr>
<td>Ion source pressure (mTorr)</td>
<td>2</td>
</tr>
<tr>
<td>Ion source gas efficiency (%)</td>
<td>24</td>
</tr>
<tr>
<td>Discharge power, 2.45 GHz (kW)</td>
<td>1.2</td>
</tr>
<tr>
<td>Beam energy (keV)</td>
<td>75</td>
</tr>
<tr>
<td>High voltage power supply current (mA)</td>
<td>165</td>
</tr>
<tr>
<td>DC1 current (mA)</td>
<td>154</td>
</tr>
<tr>
<td>DC2 current (mA)</td>
<td>120</td>
</tr>
<tr>
<td>Proton fraction (%)</td>
<td>90</td>
</tr>
<tr>
<td>Injector emittance ($\pi$mm-mrad) (1rms norm)</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Los Alamos source for LEDA

- Beam currents measured at DC1, DC2, and in the RFQ entrance collimator for 6.7 MeV RFQ.
- Beam focusing accomplished with LEBT solenoid magnets S1 and S2.
- Beam centroid controlled with steering magnets SM1 and SM2.
Since 1996, SILHI produces H+ beams with good characteristics:

- H+ Intensity > 100 mA at 95 keV
- H+ fraction > 80 %
- Beam noise < 2%
- 95 % < Reliability < 99.9 %
- Emittance < 0.2 \( \pi \) mm.mrad
- CW or pulsed mode
In CW mode, the source routinely produces **130 mA** total (> 80% H⁺) at 95keV.
Space charge compensation with $^{84}$Kr

Emittance plot (99%) without injecting gas in the beam line:

\[ p = 1.8 \times 10^{-5} \text{T} \Rightarrow \varepsilon_{\text{RMS}} = 0.335 \pi \text{ mm mrad} \]

Emittance plot (99%) injecting 84Kr in the beam line:

\[ p = 3.0 \times 10^{-5} \text{T} \Rightarrow \varepsilon_{\text{RMS}} = 0.116 \pi \text{ mm mrad} \]

Space charge compensation with Ar

Emittance plot (99%) without injecting gas in the beam line:
\[ p_1 = 1.8 \cdot 10^{-5} \, T, \quad p_2 = 1.2 \cdot 10^{-5} \, T \Rightarrow \epsilon_{\text{RMS}} = 0.291 \, \pi \, \text{mm mrad} \]

Emittance plot (99%) injecting Ar in the beam line:
\[ p_1 = 4.5 \cdot 10^{-5} \, T, \quad p_2 = 4.4 \cdot 10^{-5} \, T \Rightarrow \epsilon_{\text{RMS}} = 0.124 \, \pi \, \text{mm mrad} \]

Emittance plot (99%) without injecting gas in the beam line:
\[ p_1 = 1.6 \cdot 10^{-5} \text{ T}, \ p_2 = 1.2 \cdot 10^{-5} \text{ T} \Rightarrow \varepsilon_{\text{RMS}} = 0.386 \pi \text{ mm mrad} \]

Emittance plot injecting N2 in the beam line:
\[ p_1 = 4.5 \cdot 10^{-5} \text{ T}, \ p_2 = 4.5 \cdot 10^{-5} \text{ T} \Rightarrow \varepsilon_{\text{RMS}} = 0.13 \pi \text{ mm mrad} \]

Space charge compensation with H2

Emittance plot (99%) without injecting gas in the beam line:
\[ p_1 = 1.6 \cdot 10^{-5} \text{T}, \quad p_2 = 1.2 \cdot 10^{-5} \text{T} \quad \Rightarrow \quad \varepsilon_{\text{RMS}} = 0.292 \pi \text{mm mrad} \]

Emittance plot (99%) injecting H2 in the beam line:
\[ p_1 = 5 \cdot 10^{-5} \text{T}, \quad p_2 = 4.9 \cdot 10^{-5} \text{T} \quad \Rightarrow \quad \varepsilon_{\text{RMS}} = 0.198 \pi \text{mm mrad} \]

Space charge compensation with $H_2, N_2, Ar, Kr$

- In all the cases considered, a decrease of beam emittance has been observed with the increase of beam line pressure.
- Using $^{84}$Kr gas addition a decrease of a factor three in beam emittance has been achieved losing less than 5% of the beam current with a small increase of pressure (from 1.8E-5 Torr to 2.4E-5 Torr).

TRIPS performance vs. forward power

CERN Accelerator School and Slovak University of Technology, Senec, June 2012
L. Celona, Microwave Discharge Ion Sources

The TRASCO linac (1 GeV, 30 mA)

Proton Source → RFQ → Medium energy ISCL linac → 3 sections high energy SC linac

80 keV  5 MeV  100 MeV  ~200 MeV  ~500 MeV  >1000 MeV

Proton beam current: 35 mA dc
Beam Energy: 80 keV
Beam emittance: $\varepsilon_{RMS} \leq 0.2 \pi \text{ mm mrad}$
Reliability: close to 100%

TRIPS (TRasco Intense Proton Sources) requirements
Proton beam current: 35 mA dc

Beam Energy: 80 keV

Beam emittance: $\varepsilon_{\text{RMS}} \leq 0.2 \, \pi \, \text{mm mrad}$

Reliability: close to 100%

Based on CRNL-LANL-CEA design

MANY INNOVATIONS
### TRIPS operating parameters

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>80 keV</td>
</tr>
<tr>
<td>Proton current</td>
<td>35 mA</td>
</tr>
<tr>
<td>Proton fraction</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>RF power, Frequency</td>
<td>2 kW (max) @ 2.45 GHz</td>
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<tr>
<td>Axial magnetic field</td>
<td>875-1000 G</td>
</tr>
<tr>
<td>Duty factor</td>
<td>100% (dc)</td>
</tr>
<tr>
<td>Extraction aperture</td>
<td>8 mm</td>
</tr>
<tr>
<td>Reliability</td>
<td>≈100%</td>
</tr>
<tr>
<td>Beam emittance at RFQ entrance</td>
<td>≤0.2 π mmmrad</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>80 keV</td>
</tr>
<tr>
<td>Proton current</td>
<td>55 mA</td>
</tr>
<tr>
<td>Proton fraction</td>
<td>≈90% (estimated)</td>
</tr>
<tr>
<td>RF power, Frequency</td>
<td>Up to 1 kW @ 2.45 GHz</td>
</tr>
<tr>
<td>Axial magnetic field</td>
<td>875-1000 G</td>
</tr>
<tr>
<td>Duty factor</td>
<td>100% (dc)</td>
</tr>
<tr>
<td>Extraction aperture</td>
<td>6 mm</td>
</tr>
<tr>
<td>Reliability</td>
<td>99.8% @ 35 mA (over 142 h)</td>
</tr>
<tr>
<td>Beam emittance at RFQ entrance</td>
<td>0.07π mmmrad @ 32 mA</td>
</tr>
</tbody>
</table>
TRIPS (TRasco Intense Proton Source)
Extraction electrodes
TRIPS mounting procedure: from the grounded flange to the 100 kV flange.
A layout of the whole set-up at INFN-LNS:
1- Demineralizer; 2- 120 kV insulating transformer; 3- 19” Rack for the power supplies and for the remote control system; 4- Magnetron and circulator; 5- Directional coupler; 6 – Automatic Tuning Unit; 7- Gas Box; 8- DCCT 1; 9- Solenoid; 10- Turbomolecular pump; 11- DCCT 2; 12- Quartz tube; 13- Beam stop.
Microwave injection and beam extraction optimisation

**Microwave Injection**

Use of a step binomial matching transformer with a field enhancement factor \(E_{s4}/E_0 \approx 1.95\) \((a_2=0.0126\,\text{m})\)

**Beam extraction**

The extraction process has been deeply studied with the aim to increase the source reliability and to keep emittance low. The used codes were AXCEL-INP and IGUN.

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Optimum magnetic field profile
LEBT with Saclay EMU

beam sampler

permanent magnets

wire

electron catcher

HV electrodes permanent magnets

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The measured value is slightly above the theoretical value and in good agreement with the AXCEL calculation.
Emittance measurements

RMS Norm. Emittance ($\pi \text{ mm mrad}$)

Beam current (mA)

with Argon
without Argon

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TRIPS reliability test: 35 mA @ 80 kV

Availability over 142h 25’= 99.8 %

Parameter
- Extraction voltage: 80 kV
- Puller voltage: 42 kV
- Repeller voltage: -2.6 kV
- Discharge power: 435 W
- Beam current: 35 mA
- Mass flow: ≈0.5 sccm

START 22/05/2003 19:32
STOP 28/05/2003 17:57
TRIPS performance vs. forward power

- Operating voltage = 80 kV
- Optimized magnetic field profile
- Electron donor = BN disks
- Mass flow = 0.6 sccm
- Extraction aperture = 6 mm
- Current density up to 210 mA/cm² (close to $J_{\text{child}}$)
TRIPS performance vs. mass flow @ 450 W

Beam currents (mA)

I\text{EXTR}

I\text{DCCT1}

I\text{BS}

Mass flow (sccm)
Typical densities and temperatures of MDIS plasmas

Density of ions along the chamber axis

Langmuir Probe measurements

Electron temperature of the bulk plasma
• New extraction system and accelerator column simplified to reduce the dimensions.
• New ionisation chamber.
• Insulation of coils, microwave and gas system to eliminate the HV-platform (implies a further simplification of the electronics involved in the control of the source because all the instrumentation will be placed at ground potential).
NEW MAGNETIC SYSTEM

- Based on three rings of NdFeB permanent magnets
- The ARMCO iron components lower the off axis magnetic stray field values, detrimental for the reliability, by keeping high the field inside the plasma chamber
- Very good matching between the measurements and the numerical simulation carried out with the OPERA code
**VIS DESCRIPTION**

**EXPECTED PERFORMANCES**
- It will produce large proton beams (above 35 mA) and H\(^2\) beams (above 20 mA).
- Emittance values below 0.2 \(\pi\) mm mrad are expected.
- High reliability.
- Long time operations will be ensured.

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**SOURCE BODY**

**HIGH VOLTAGE PLATFORM**
Generates an off-resonance magnetic field (<0.1 T), along the plasma chamber axis.

**PERMANENT MAGNET**

**MICROWAVE SOURCE**
2.45 GHz Microwave operative frequency (Magnetron or TWT).

**FOCUSING SOLENOID**

**EXTRACTOR**
80 kV Extraction voltage.
Water-cooled Bend

Microwave pressure window
Placed behind the bend in order to avoid any damage due to the back-streaming electrons

DC- Break
• Low microwave losses
  - Good voltage insulation up to 100 kV

It is used to measure the forward and the reflected power

Dual-arm Directional Coupler

Automatic Tuning Unit

Waveguide /Coax Adapter
Excites the TE_{10} dominant mode in WR340 waveguide

Matching Transformer
It realizes a progressive match between the waveguide impedance and the plasma chamber impedance, thus concentrating the electric field at the center of the plasma chamber

BN Disk

Water-cooled copper plasma chamber

Automatic Tuning Unit
Adjusts the modulus/phase of the incoming wave to match the plasma impedance
MW LINE 2/3: MATCHING TRANSFORMER

Matching transformer coupled to the plasma chamber

S\textscript{21} Vs FREQUENCY FOR THE TWO STRUCTURES

VIS TRANSFORMER INSERTION
LOSS 0.0085 dB @ 2.45 GHz

10 % ENHANCEMENT WITH VIS TRANSFORMER

Four step double ridges

TRIPS ELECTROMAGNETIC FIELD @ 2.45 GHz, 500 W

VIS ELECTROMAGNETIC FIELD @ 2.45 GHz, 500 W
DESCRIPTION
It consists of 31 aluminum sections of a WR340 waveguide insulated one each other by means of 30 fiberglass disks 0.5 mm thick in the metal separation gap.

PERFORMANCES
• Electrical Insulation up to 100 kV
• Transmission coefficient -1.4 dB @ 2.45 GHz
• Low radiated electromagnetic field
The extraction geometry will employ only four electrodes. A plasma electrode at 80 kV voltage, two water-cooled grounded electrodes screening electrode and a 3.5 kV negatively biased electrode inserted between the two grounded electrodes in order to avoid secondary electrons due to residual gas ionisation going up to the extraction area.

**TRIPS Five-electrodes topology**
- on-line optimisation of the extracted beam
- wide range of operations (10-60 mA)

**VIS Four-electrodes topology**
optimized for a 40 mA beam (90% proton, 10% H$_2^+$)

The rms normalized emittance calculated with Axcel code, 11 cm far from the extraction electrode is 0.04 $\pi$ mm mrad.
The PM source of Saclay produced 85 mA total beam at 80 kV, for 4 days with no beam off.
Passive method to increase and to improve the intensity of the ion beam

BN disk and wall coating effects

**BN disk**
- Inner diameter: 79 mm.
- Outer diameter: 89.5 mm.
- Length: 95 mm.

**AL₂O₃**
- Inner diameter: 79 mm.
- Outer diameter: 89.5 mm.
- Length: 95 mm.

**BN**
- Inner diameter: 7.8 mm.
- Outer diameter: 89.5 mm.

thick BN plates are located at two extremities of the plasma chamber.
Al₂O₃ tube is nested within the plasma chamber, it covers the entire walls from one side to other
Figures show the trends of the extracted current and the proton fraction as a function of microwave powers at $2 \cdot 10^{-5}$ mbar (on the left) and at $2.5 \cdot 10^{-5}$ mbar (on the right). The improvement of the performance with the use of the alumina tube and of the disk of BN disk can be explained by means of two different theories. For the first one the BN and the alumina are electron donors that influence the plasma essentially by emitting cold electrons. The second one explains this phenomenon by introducing the Simon currents within the plasma.
Well established items

• Larger current, larger brightness, better reliability seem to be realistically achievable in few years’ term
• There are ‘billion $’ projects leading the run (ESS and IFMIF for p,d as it is SNS for H⁻)
• Study of pulsed operation (2 ms-20 Hz) needs more insights
• Looking for short pulse rise time (100 ns)
• Beam dynamics vs. plasma simulations
• LEBT optimization
• Plasma chamber dimensions are not a free parameter
• Electron donors may help
• Microwave coupling may give some positive surprise
• Magnetic field probably not...
• Space charge will be always a nightmare!