NEGATIVE ION AND HELICON WAVE PHYSICS ON THE RESONANT ANTENNA ION DEVICE (RAID)

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### WHICH NEGATIVE ION SOURCE FOR DEMO?

**Table: DEMO¹**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>D⁻</td>
</tr>
<tr>
<td>Beam Energy [keV]</td>
<td>800</td>
</tr>
<tr>
<td>Current [A]</td>
<td>34</td>
</tr>
<tr>
<td>Filling pressure [Pa]</td>
<td>0.2</td>
</tr>
<tr>
<td>Beam on time [s]</td>
<td>7200</td>
</tr>
<tr>
<td>Extracted e-/D- fraction</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Neutralization efficiency</td>
<td>&gt;0.65</td>
</tr>
</tbody>
</table>

**Challenges for plasma physics and technology**

[1] P. Sonato et al., *Conceptual design of the beam source for the DEMO NBI: main developments and R&D achievements*, Nucl. Fusion **57** 056026

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**Diagram:**

**NEGATIVE ION SOURCE**

- **3 m**
- **10 cm**
- **Blade-like D⁻ beam**
- **CW 1 kW Laser**
- **93% photo-detachment**

**The Cybele concept for DEMO NBI**

(Iaroslav Morgal’s presentation at 14:30)
OUTLINE

1) The Resonant Antenna Ion Device (RAID)

2) Experimental study of the helicon plasma source in H$_2$ and D$_2$ plasmas
   
   2.1) 3D plasma profiles and helicon wave measurements
   
   2.2) Negative ion population measurements
       • Optical Emission Spectroscopy (OES)
       • Cavity Ring-Down Spectroscopy (CRDS)
       • Langmuir Probe Photodetachment

3) Summary and Outlook
THE RESONANT ANTENNA ION DEVICE (RAID)

Birdcage resonant antenna

“Blue core” → signature of helicon wave

2-axis probe mounting for 3D plasma measurements

Water cooled end-plate

PLASMA SOURCE: BIRDCAGE ANTENNA

Resonance frequencies:

\[ \omega_m = \frac{1}{\sqrt{C \left( M + 2L\sin^2\left(\frac{m\pi}{2N}\right) \right)}} \]

\( m = 1, 2, \ldots, N-1 \)

Operating frequency: 13.56 MHz

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A HELICON WAVE PROPAGATES ALONG THE PLASMA COLUMN

3D helicon wave propagating, $H_2, 3000$ W

Schematic of the magnetic probe

3 axes B-dot coils

Probe head
3D MEASUREMENTS SHOW PEAKED DENSITY AND TEMPERATURE PROFILES

$I_{\text{sat}}$

Hydrogen plasma, 3kW, 200 G

Radial position (mm)  Axial position (mm)

$T_e$ (eV)

Radial position (mm)  Axial position (mm)
RF POWER AFFECTS ELECTRON DENSITY PROFILES

Electron density profiles are calibrated with a 100 GHz microwave interferometer

COLUMN AXIS
PEAKED $T_e$ PROFILE IS FAVORABLE FOR VOLUME PRODUCTION OF NEGATIVE IONS

$H_2 + e^- \rightarrow H_2^* + e^-$  
Ro-vibrational excitation of $H_2$

$H_2^* + e^- \rightarrow H^- + H$  
PLASMA EDGE

Temperature profile favorable for volume production of $H^-$ (dissociative attachment)
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OPTICAL EMISSION SPECTROSCOPY REVEALED NEGATIVE ION DENSITY PEAKED OFF AXIS

Line emission profiles are interpreted by YACORA [1]

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CAVITY RING DOWN SPECTROSCOPY TO MEASURE LINE-INTTEGRATED NEGATIVE ION DENSITY

Photodetachment process: $\text{H}^- + h\nu \rightarrow \text{H} + e^-$

Mirror mountings to hold high reflectivity mirrors ($R>99.99\%$)

The extinction time of light in the optical cavity depends on medium absorbance

Nd:YAG laser →
- 5 ns pulse
- 10 Hz repetition rate
RING-DOWN SIGNAL SHOWS AN EXPONENTIAL DECAY

A photo of CRDS experimental setup

\[ \bar{n}_{D^-} = \frac{L}{c\sigma d} \left(\frac{1}{\tau} - \frac{1}{\tau_0}\right) \]

Tipical decay signals in two conditions: in vacuum (no plasma) and in a D\(_2\) plasma
A JUMP OF $\tau$ IS OBSERVED WHEN $D_2$ PLASMA IS TURNED OFF: DISAPPEARANCE OF NEGATIVE IONS

The $\tau$ jump is used to estimate negative ion density.
NO JUMP OF $\tau$ IS OBSERVED WHEN Ar PLASMA IS TURNED OFF

NGON plasma, 700 W

Ar plasma

Plasma is turned off here
LINE-INTEGRATED NEGATIVE ION DENSITY INCREASES WITH POWER

Average negative ions densities increase with power

R. Agnello et al. Cavity Ring-Down Spectroscopy to measure negative ion density in a helicon plasma source for fusion neutral beams (submitted to Review of Scientific Instruments)
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LASER PHOTODETACHMENT TO MEASURE NEGATIVE ION DENSITY PROFILES

Negative ion density $n_-$ can be calculated from:

$$\frac{n_-}{n_e} = \frac{i_{pd}}{i_{dc}}$$

- $i_{pd}$ → photodetachment current
- $i_{dc}$ → direct electron current
LASER PULSES PHOTODETACH ELECTRONS FROM NEGATIVE IONS $\text{H}^-/\text{D}^-$

\[
\frac{\Delta n_-}{n_-} = 1 - \exp\left(-\frac{\sigma E}{\hbar \nu S}\right)
\]
TYPICAL PHOTODETACHMENT SIGNALS IN H₂ AND D₂ PLASMAS
PHOTODETACHMENT AMPLITUDES INCREASE ON PLASMA EDGE

\[ \frac{n_-}{n_e} = \frac{i_{pd}}{i_{dc}} \]
$n_{H^-}$ AND $n_{D^-}$ INCREASE WITH POWER
# Comparison between Negative Ion Densities Obtained with Different Diagnostics

## Negative Ion Densities at 3.5kW RF Power

<table>
<thead>
<tr>
<th></th>
<th>$n_{H^-}$</th>
<th>$n_{D^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical Emission Spectroscopy</strong></td>
<td>$(2.3 \pm 1) \times 10^{16}$ m$^{-3}$</td>
<td>$(4.5 \pm 2) \times 10^{16}$ m$^{-3}$</td>
</tr>
<tr>
<td><strong>Cavity Ring-Down Spectroscopy</strong></td>
<td>$3.3 \times 10^{16}$ m$^{-3}$</td>
<td>$2.5 \times 10^{16}$ m$^{-3}$</td>
</tr>
<tr>
<td><strong>LP Photodetachment</strong></td>
<td>$1.3 \times 10^{16}$ m$^{-3}$</td>
<td>$0.5 \times 10^{16}$ m$^{-3}$</td>
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SUMMARY

• Demonstrated the production of a dense and homogeneous plasma column in H\(_2\) and D\(_2\) up to 5kW of injected power and the propagation of a helicon wave

• Negative ion diagnostics (OES, CRDS and LP photodetachment) show a negative ion population and density increasing with RF power in H\(_2\) and D\(_2\) plasmas.
A plasma distribution is considered in the shaded volume

\[ \nabla \times \nabla \times \vec{E} = k_0^2 \vec{\chi} \vec{E} \]

Radial electric field vector along the z-axis

In the next future
- Time dependent model
- Include transport and diffusion
Thank you for your attention
Backup: Ratios $n_{H^-}/n_e$ and $n_{D^-}/n_e$ increase on edge and are independent on electron density.

In agreement with spectroscopy

No agreement with spectroscopy
Backup: \( n_e \) profiles are calibrated by interferometric measurements

\[
\Delta \varphi = \frac{e^2}{2\omega \epsilon_0 m_e} n_{e,\text{peak}} \int n_{e,\text{norm}} dl
\]
IV sweeps are used to extract plasma parameters: $I_{dc}$, the electron current collected at $V = V_{bias}$.

**H$_2$** / 0.3 Pa / 200G / radial position=40 mm

**D$_2$** / 0.3 Pa / 200G / radial position=40 mm

**H$_2$** / 0.3 Pa / 200G / radial position=65 mm

**D$_2$** / 0.3 Pa / 200G / radial position=65 mm
Backup: Ar and H light during plasma ignition