Ion source development for a Photoneutralization based NBI system of Fusion reactors

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High current H⁻/D⁻ negative ion sources required for fusion reactor (DEMO)

A DEMO NBI system requires a high (>50%) wall plug-efficiency

A blade-like shaped negative ion (NI) beam is considered for DEMO

Advantages by comparison with conventional negative ion based NB systems
  - Minimization of the gas injection (neutralizer cell)
  - Compatibility with advanced neutralization concept Photoneutralization (Siphore concept)
Remind Siphore concept

Plasma Drivers (Helicon)

0.1m

High reflectivity mirrors

Ion Beam width ~1cm

3m

~30m

0.3m

1MeV 10A*3 D- beam sheet

~ 3 MW / cm

Fabry-Perot cavity

=> 50% photodetachment 1MeV D-
Remind Siphore concept

Cavity duplication => 87% of Neutralization
=> Wall plug eff: ~60%

Ion source

Accelerations
(top view)

Electron deflection
$B_x = 10 \, \text{mT}$

Pre-accelerator grids

Single gap
post-acceleration

Photoneutralizer

Cavity duplication

Fabry-Perot cavity

$\sim 1 \, \text{cm}$

$1 \, \text{MeV} \ 10A \ast 3 \ D^{-}$

Ion Beam

width $\sim 1 \, \text{cm}$

High reflectivity mirrors

$0.1 \, \text{m}$

$3 \, \text{m}$

$0.3 \, \text{m}$

$\sim 30 \, \text{m}$

$1 \, \text{MeV} \ 10A \ast 3 \ D^{-}$

beam sheet

$0 \, \text{V}

100 \, \text{kV}$

$1 \, \text{MV}$

$\sim 3 \, \text{MW/cm}$

Photodetachment $1 \, \text{MeV} \ D^{-}$
Cybele source is adapted for the blade-like beam (1.2m x 0.15m)
Objective: to provide a uniform plasma column
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Cybele tested first (2012-14) with a transverse filter B-field
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Cybele tested first (2012-14) with a transverse filter B-field

Heated filament

Langmuir probes

Filter Field (300 Gauss.cm)

Vertical plasma distribution
Cybele source is adapted for the blade-like beam (1.2m x 0.15m)
Objective: to provide a uniform plasma column

Cybele tested first (2012-14) with a transverse filter B-field

⇒ The Filter field configuration is not adapted to produce a uniform plasma in Cybele
Cybele source is adapted for the blade-like beam (1.2m x 0.15m)
Objective: to provide a uniform plasma column

Cybele tested first (2012-14) with a transverse filter B-field

⇒ The Filter field configuration is **not adapted** to produce a uniform plasma in Cybele
⇒ Study of a new magnetic field topology
Vertical B-field topology

Cybele source \( x \rightarrow 0 \)

Iron core

Source

Plasma column

Lateral coils

1,2m

0,15m
Cybele source $x \leftarrow 0$

Iron core

Lateral coils

Plasma column

Source

Horizontal cross section of the source

Plasma grid

Langmuir probes

Lateral coil with iron core

Heated filaments

Movable Langmuir probes

Plasma width $\sim 15$ cm
Cybele with Tungsten filament cathodes

Radial plasma density distribution

\[ n_e = (1-5) \times 10^{17} \text{ (m}^{-3}) \]

Radial electron temperature distribution

\[ T_e = 2-9 \text{ eV} \]
Cybele with Tungsten filament cathodes (Arc power: 30 kW)

Radial plasma density distribution

\[ n_e = (1-5) \times 10^{17} \text{ m}^{-3} \]

Radial electron temperature distribution

\[ T_e = 2-9 \text{ eV} \]

Axial plasma density distribution
Cybele with Tungsten filament cathodes

Radial plasma density distribution

Radial electron temperature distribution

\( n_e = (1-5) \times 10^{17} \text{ m}^{-3} \)

\( T_e = 2-9 \text{ eV} \)

Axial plasma density distribution

Tungsten cathodes => Cs pollution => Not relevant for DEMO => RF plasma driver is needed
Plasma injection along the magnetic field lines

Iron rectangular frame

Lateral coils

Langmuir probe position (10, 30, 50 cm) for radial plasma distribution and plasma transport

ICP-driver

Plasma injection along the magnetic field lines
Radial distribution of plasma ($P_{RF}= 30$ kW, $p_{gas} = 0.3$ Pa)

Probe position – 10cm from driver exit

**Density** variation between centre and edge is only 2 times.

**Temperature** is between $1.5 – 3$ eV does not depend on B-field (0-2.5 mT)

<table>
<thead>
<tr>
<th>P= 30 kW</th>
<th>$n \times 10^{17}$ (m$^{-3}$)</th>
<th>$T_e$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filaments</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>ICP</td>
<td>1.7</td>
<td>2.5</td>
</tr>
</tbody>
</table>
Plasma transport along the vertical axis ($P_{RF} = 30$ kW, $p_{gas} = 0.3$ Pa)

Plasma is not uniform along source axis.

Strong plasma density drop over 30 cm
After 2.5mT no RF coupling to the plasma
The magnetic field doesn’t improve the plasma transport in the source volume
Effect of axial magnetic field

After 2.5mT no RF coupling to the plasma
The magnetic field doesn’t improve the plasma transport in the source volume

Vertical B-field increases the transverse plasma resistivity reduce of the RF-induced current
Cybele with ICP driver

Plasma parameters vs Pressure & RF power

- **Active power (kW)** vs **Density (m$^{-3}$) * 10$^{17}$**
- **Gas pressure (Pa)** vs **Density (m$^{-3}$) * 10$^{17}$**

- **Temperature (eV)** vs **Density (m$^{-3}$) * 10$^{17}$**
- **Temperature (eV)** vs **Gas pressure (Pa)**
Conclusion with ICP:
The plasma density doesn’t peak in the center (flat radial distribution)
Non-uniform plasma distribution along vertical axis (along the B-field)
Cut-off with magnetic field higher than 2.5 mT
**Conclusion with ICP:**
Flat radial distribution \((T_e, n_e)\) and lower in comparison with filamentosed source
Non-uniform plasma distribution along vertical axis
Cut-off with magnetic field higher than 2.5 mT (B-field 10 mT is needed)
\(\Rightarrow\) **ICP is not adapted for Cybele**
\(\Rightarrow\) A new type of plasma driver required
\(\Rightarrow\) 2012-2016: Collaboration with EPFL for the development of a helicon antenna for Cybele: specifications: (B~ 10 mT, pressure: 0.3 Pa)
Comparison between ICP and Helicon

**ICP RF plasma on Cybele**

- $P_{RF} = 25$ kW, no magnetic field

**Helicon plasma on the RAID testbed (EPFL)**

- $P_{RF} = 3$ to 5 kW

**Plasma from ICP driver does not diffuse far in the Cybele source volume**

Helicon plasma source is essential for the magnetized plasma column of Cybele (I. Furno, talk on Friday)
Conclusions

1) Cybele ion source is suitable studying of negative ion production for the blade-shaped ion beam.
2) Two magnetic field configuration were tested. The Tranverse magnetic field induce the strong plasma inhomogeneity.
3) The vertical magnetic field topology the plasma is homogeneous along the vertical axis
   => dense & hot plasma in the center
   => cold plasma on the edges
4) Different types of plasma generator were tested (Filamented source, ICP). Did not give desirable parameters.
   = Tungsten filaments not relevant for DEMO
   = ICP not uniform plasma distribution
5) Helicon is most promising candidate for Cybele. It will be implemented on Cybele in November 2016 and will be tested on negative ion production.
The electrons in ICP driver are accelerated by the RF azimuthal E-field ($E_\phi$) experience a radial Lorentz force ($F_r = v_\phi \times B_z$) => reducing of the radial diffusion and conductivity decreases => increasing of the skin-depth => reduce of the RF-induced current.

Vertical B-field increases vertical diffusion => radial diffusion and conductivity decreases => increasing of the skin-depth => reduce of the plasma. => For B-fields larger than 2.5 mT, it becomes impossible to couple the RF active power to the plasma.
RF electrical set up

Ground Decoupling between the RF generator and the antenna circuit
Matching impedance

Gas – Hydrogen
Pressure – 0.3 Pa (ITER condition)
Set point of the generator power : 30 kW

Measured Frequency : ~0.94 MHz

Active power coupled to the plasma 23-26 kW at the matching (~ 0.75-0.85 of total power)