Characterization of the helicon plasma generated inside the Cybele negative ion source with different magnetic field configurations

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No electricity production
Plasma heating: NBI: 2*17MW D° at 1MeV
NBI Expected efficiency :<28%  [1]
The ITER NBI is under construction RFX testbed (MITICA) commissioning in 2023

500MW of electrical power on the net
DEMO1: pulsed reactor
NBI: ~ 50MW D° at 1 MeV
Overall efficiency > 40 % [2]

DEMO2: Steady state
NBI: ~110MW D°, 1-2 MeV (current drive)
Overall efficiency > 60 %

Blade like beam concept for future fusion reactors

**NBI: with plasma neutralizer**

Blade-like Beam D- (10A, 1MeV)  Plasma neutralizer  65% neutralization rate

**with photoneutraliser** [3]

Ion source & Pre-accelerator

Plasma driver  10 cm

3 m

Blade like beam D- (10A)

93% photo-detachment

CW 1 kW Laser

Potential advantages of blade-like beams:
Reduce the gas load along the beam line
Increase the overall injector efficiency
Essential for plasma neutralizer and photoneutralizer

Ion Source concept based on magnetized plasma column for blade-like beams

Ion Source with 30 kV acceleration

Co-extracted electrons
More than 1 e⁻ per D⁻ requirement for ITER source

Cesium monolayer on PG

Extraction region
Cold plasma for the D⁻ production
$T_e < 1$ eV

Hot and dense plasma core
$T_e \sim 10$ eV, $n_e \sim 10^{18}$ m⁻³

RF Plasma driver

3 m

D⁻ beam

magnetized Plasma column

Side view

Acceleration grid (AG)

30 kV

10 kV

0V

EG

D⁻ trajectory in the plasma

Horizontal cross section
Investigation of plasma drivers for magnetized plasma columns at CEA

1) 2014 Filamented cathode [3]
   - plasma vertically uniform along the vertical axis,
   - peak $N_e \sim 4 \times 10^{17} \text{m}^{-3}$ and $T_e \sim 9\text{eV}$
But, not relevant for Cs operation, due to the pollution by W

2) 2016 ICP plasma driver: (results presented NIBS 2016)
Plasma density drops rapidly along the vertical direction at the driver exit => Plasma non-uniform

3) Since 2017 test of the Helicon driver developed by EPFL (see previous talk WO8 R.Agnello)

Operating conditions relevant for NI source:
- Low B-field (~10 mT)
- Quite Uniform plasma column (along 1.5m)
- High density in the center (>10^{18} \text{m}^{-3})
- Low $T_e$ on the edge for NI production (~1-2eV)
But, RAID geometry does not allow extraction of a long blade-like negative ion beam

Uniform axial B-field (15-20mT), Negligible transverse B-field \( (R_{pl} << R_{coil})\)

Very good conditions for the Helicon discharge
Extraction of Negative Ions

Ion source concept

Need to test the performance of Helicon antenna in another magnetic field topology than with external coils
Two magnetic field topologies compatible with implementation of an accelerator

Lateral coils

Internal Helmholtz coils

Plasma driver

Magnetized plasma column

Top view

Front view

Front view

Plasma driver

Magnetized plasma column
**Lateral coils**

$B \sim 100 \, G$

**Internal Helmholtz coils**

$B_{axis} \sim 100-160 \, G$

- **Helicon antenna**
- **Solenoid around antenna**
- **Magnetized plasma column**
Experimental setup Lateral coils

**Source side view**

Experimental conditions:
- Magnetic field – 100 G
- RF power – 3kW
- Gas pressure - ~ 0.3 Pa (H)
- Bias plates: 0V : -90V

**Horizontal measurements**
Movable Langmuir probe can move horizontally from the wall to the PG

**Vertical measurements**
Five fixed Langmuir probes for Vertical measurements
Studies of the magnetic column with Lateral coils

3D simulations of e-trajectories (without plasma) with lateral coils

Helicon driver

Ballooning of the plasma

Plasma interception with PG => Decrease of Ne
Vertical plasma density distribution

Vertical profiles close to PG (extraction region):

RF power – 3kW  
Gas pressure - ~ 0.3 Pa (H)

Average plasma density is 1-1.5*10^{16} m^{-3}

<table>
<thead>
<tr>
<th>Source bottom</th>
<th>Helicon EPFL RAID</th>
<th>Helicon IRFM</th>
<th>Filament IRFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>30kW</td>
<td>3kW</td>
<td>3kW</td>
</tr>
<tr>
<td>Ne (plasma edge)</td>
<td>2*10^{17}</td>
<td>~1.2*10^{16}</td>
<td>~2*10^{17}</td>
</tr>
</tbody>
</table>
**Vertical plasma temperature distribution**

Vertical profiles $T_e$ measured **close to PG**:
- RF power – 3kW
- Gas pressure - ~ 0.3 Pa (H)

Temperature drops from 9 eV on the top to 4eV in the bottom

<table>
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<th>Lateral IRFM</th>
<th>EPFL RAID</th>
</tr>
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<tr>
<td>Power</td>
<td>30kW</td>
<td>3kW</td>
<td>3kW</td>
</tr>
<tr>
<td>$T_e$</td>
<td>~4-5eV</td>
<td>~4-9eV</td>
<td>~1-2eV</td>
</tr>
</tbody>
</table>

(50cm from driver exit)

**High $T_e$** with Helicon at IRFM with lateral coils

WO8 Agnello, EPFL
Plasma characterization with Langmuir probes

Horizontal plasma distribution

1) Low peak density $3 \times 10^{16} \text{ m}^{-3}$ (compared to $\sim 10^{18} \text{ m}^{-3}$ at RAID EPFL)

2) Broad horizontal profile due to curved magnetic field lines

3) $N_e$ and $T_e$ don’t have Gaussian distribution

4) Hot electrons on the front side of the source close to PG

Questions: Hot e- results from plasma drift or local heating processes by interaction with the waves ???
=> Need further investigations
Plasma characterization with Internal Helmholtz coils

Top view

1000A ~ B=10mT

Coil edge       main axis       Coil edge

L-probe

B_r

B_z

R_{pl} \sim 5\text{cm} \sim R_{coil} = 5.5\text{cm}
-i) Plasma density is peaked (nearly Gaussian profile)
-ii) Two e- populations:
   ~60% of total amount of e- are “cold” with uniform distribution (~6eV)
   ~40% “Hot” e- are localized at the edge of plasma column (~10-20eV)

The two humps of hot e- suggest Inductive plasma generation in the antenna !!

-iii) For the same operating conditions low $N_e \sim 1.5 \times 10^{16}$ m$^{-3}$ (compared to $~10^{18}$ m$^{-3}$ RAID EPFL)

Question: Does the antenna generates an ICP or Helicon wave in the column?

=> Need to implement magnetic probes in the plasma => Collaboration with EPFL
Wave characterization in the plasma column

The B-dot probe (provided by EPFL)

Three components of the Helicon wave measured

Preliminary measurements indicate the presence of helicon wave in the plasma

Damping of the helicon waves
Along the column (Top to bottom)
Open questions (Hypothesis): Identification of this “Abnormal” e- heating process
  -i) Resonant heating with Helicon waves, plasma turbulence, ???
  -ii) Interaction of the wave with the horizontal component of B ???
  -) Low Hybrid resonance?  $f_{\text{LH}} \sim 10 – 50$ MHz (helicon antenna at 13,56MHz)
  -) Alfven waves ? Alfven wave velocity same order than electron velocity
    => Electron heating by Landau damping

 ➤ Further investigations are required
Thank You for attention!
Effect of the big conduction plate at the distance 6 cm from the plasma column has to be checked
3D simulations of e-trajectories (without plasma)
Transition from ICP to Helicon??
Low B filed (80-90 G, 3kW)
Helicon??? Still questionable 
150G, 3kW), less plasma on the wall side compare to PG
Helicon?? Still questionable 150G, 4kW), more plasma on the wall side
Helicon??? Still questionable
150G, 5kW), again more plasma on the wall side
Development of a 10 kW Helicon antenna (Bird-cage type) at RAID testbed (EPFL) to provide a dense magnetized plasma column

Helicon antenna is essential for creation of the homogeneous plasma column

- Low B-field (~10 mT)
- ITER relevant operating pressure (~0.2 Pa)

But no NI extraction possible in such topology

The **GOAL** at CEA IRFM is to get similar results as in EPFL [4]

With another magnetic topology

Radial cooling (Te < 2eV)
Cybele with Helicon driver

Lateral coils (configuration 2017)

Helicon antenna

Magnetized plasma column

Probe position

Plasma Grid (PG)

Lateral coils B~100 G

1.2 m
Lateral coils
(OLD configuration)
B ~100 G

Set of 11 vertical coils
(NEW configuration)
Baxis ~100-160 G

Helicon antenna
Solenoid around antenna
Magnetized plasma column
Helmholtz coils

Experiments started in March 2018
Co-extracted electrons
More than 1 $e^-$ per $D^-$
requirement for ITER source

Cesium monolayer
on PG

Extraction region
Cold plasma for
the $D^-$ production
$T_e < 1$ eV

Hot and dense plasma core
$T_e \approx 10$ eV, $n_e \approx 10^{18}$ m$^{-3}$

[3] H. Hotop and W. C. Lineberger,
1) Two specific magnetic field configurations (Lateral coil and set of Helmholtz coils) were tested.

2) The Langmuir probes measurements have highlighted a plasma asymmetry between the back and front side (PG) of the source, a dense plasma core is shifted to the back wall of vacuum chamber, while on PG, the plasma is hotter (6-7eV) due to the primary electron drift – not favorable for production of NI.

3) A new magnetic configuration composed of Helmholtz coils implanted within the source vacuum chamber, tested and characterized in 2018.

4) The Langmuir probes measurements revealed also a plasma asymmetry between the back and front side (PG) of the source, a dense plasma core is shifted to PG, while on PG, the plasma is hotter – not favorable for production of NI.

5) New set of experiments will be performed in August for detection of the Helicon wave propagation inside the source volume.

6) Need to compare the results with EPFL with implementation of the metal plate close to the plasma border.
1) The lateral coil configuration requires the perfect transverse (or lateral) alignment of the Helicon antenna with vertical magnetic field (sensibility is few mm range).

2) With the perfect alignment we have slab plasma shape. It is can be the advantage for the NI extraction in the future.

3) The small misalignment induce a strong drift of e- and inhomogeneous plasma in the transverse direction.

4) Cylindrical plasma column (EPFL type) can be obtained in with the implementation of solenoidal coil --> the program for the 2018 (Characterization of the plasma in this magnetic field topology)
Simulations of th 3D e-trajectories in the set of Helmholtz coils

Plasma column produced by the Helicon driver surrounded by *Set of 9 coils inside vacuum chamber*  
$B_{\text{vert}} = 110$ Gauss

A new magnetic field configuration is under development for Cybele.

Start of the experiment in February 2018
Magnetized bulk plasma

Low temperature ($T_e \sim 10$ev), and weekly magnetized ($B=100-500$ G) plasma

e\- magnetized (move mainly along MF lines)
i\+ unmagnetized (can move across MF lines). Ambipolar $E_r$ builds to confine $i^+$

Axial MF creates:
1) Sharp $\nabla n(r) \nabla T(r)$
2) Hot and dense plasma core, lower density and colder plasma edge
3) Ambipolar $E_r$ due to ion diffusion ($D_i$) across MF
4) Different types of instabilities (rotational, ExB drift, diamagnetic drift, )

$$n(r) = n_0 J_0 \left( \frac{ar}{R_{pl}} \right), \alpha = f(\mu_i, \mu_e, \Theta_{ei}, D_i, D_e)$$
Simulations of th 3D e-trajectories in the small lateral coils
Implemented inside the source volume under vacuum

We discovered that close to The grounded wall we can have sharp $\Delta$Ne and $\Delta$Te. Which is favorable for production of the NI. We can shift the Helicon driver close to the grounded PG.

But for this, we need to install the lateral coils inside the vacuum chamber very close to plasma column.
How to get uniform blade-like beam

The vertical inhomogeneity of the beam required < 10%

Plasma Drivers

3m

~1cm

Magnetized plasma column along $B_0$

Plasma is homogeneous along the vertical axis $ExB$ drift can cause only azimuthal plasma rotation

Heated Filament (~70V)

Filter Field

Vertical plasma distribution

strong plasma inhomogeneity along vertical axis

The main problem of conventional ion sources (ITER like in IPP Garching) is plasma vertical drift which they can not overcome

Plasma particles injected along $B$ field
Experimental results

Effect of the bias on the top and bottom plates

Variation of the top and bottom bias potential ~4 cm from the back wall

With increasing of the negative bias
1) Both Vpl and Vfl drops by ~ 15V
2) Ne increases until -60V of bias, after that constant
3) Te linearly decreasing from ~4.5 to ~ 3.5eV

(60 cm from the Helicon driver, PG is grounded, Prf 3kW, p=0.3 Pa, B=100G, H).
Experimental results (Lateral coil)

Plasma distribution from top to bottom

Transverse distribution of plasma parameters

---- Top 10cm, center 60cm, ..........bottom 110 cm from the exit of Helicon driver

1) $V_{pl}$ is nearly the same in the all source volume
2) $V_{fl}$ drops towards the bottom
3) $N_e$ is almost twice higher on the center (close to PG) with respect to extremities
4) $T_e$ has two maximums at -4cm and close to PG at the top.

There are two plasma electron populations:
First closer to wall at -5-4cm with high density
Second is low density e-population which drifts close to PG

(PG grounded, V bias -47V, Prf 3kW, p=0.3 Pa, B=100G, H).
Effect of the bias on the top and bottom plates

Transverse distribution of plasma parameters

Probe location: centre position (behind the PG)

Increasing of Negative bias
1) Vpl drops
2) Vfl drops
3) Ne increases
4) No effect on Te

Behavior of profiles from wall to PG
1) Vpl is almost constant
2) Vfl drops toward PG by 7-10V
3) Ne has maximum at -5cm
4) Te increases from 4 to 6 eV

(60 cm from the Helicon driver, PG is grounded, Prf 3kW, p=0.3 Pa, B=100G, H).
Effect of The Plasma Grid polarization

Transverse distribution of plasma parameters
Probe location: centre position behind the PG

1) $V_{pl}$ drops close to PG by 2-3V
2) $V_{fl}$ drops towards PG by 8-10V, no effect from PG polarization
3) $N_e$ has maximum at -5
4) No effect on $T_e$, increases towards PG at 3eV

No real effect from the PG polarization. Other experiments decided to perform with grounded PG

(60 cm from the Helicon driver, V bias -47V, Prf 3kW, p=0.3 Pa, B=100G, H).
Different RF power
Different gas (H2 or Ar)

Above 16kV the breakdowns occur more frequently
IV characteristics
IV characteristics
Prf = 3kW
Gas H, p=0.3Pa
B_field ~ 100G (280V set on the born)
PG grounded
V bias top and bottom plates = -55V
(350V set on the born)
probe ramp -80V : +60V
serial resistor 15 Ohm

Plasma_potential = 8.8835 V
Float_potential = -1.9139 V
Ion_saturation_current = -0.0155 A
dens_int = 2.9865 \times 10^{17} \text{ m}^{-3}
Te_int = 3.9158 \text{ eV}
dens_EEDF = 1.8521 \times 10^{17} \text{ m}^{-3}
Te_EEDF = 4.0506 \text{ eV}
Experimental results

Current measured separately on the Plasma Grid, top and bottom bias plates

Variation of the bias potential. Plasma Grid grounded

equal
Experimental results

Effect of the pressure

Optimal pressure = 2.1mTorr (0.3Pa)
Highest plasma density
Experimental results

Effect of magnetic field

Saturation of the frame coil
(can not increase the Magnetic field higher that 100G)

Magnetic field is not high enough
to support the propagation of the helicon wave
Comparison between ICP and Helicon

**ICP RF plasma on Cybele**

\[ P_{RF} = 25 \text{ kW, no magnetic field} \]

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

\[ P_{RF} = 3 \text{ to } 5 \text{ kW} \]

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

Helicon plasma driver is essential for the magnetized plasma column of Cybele
Helicon driver for Cybele

Development of a 10 kW Helicon antenna (Bird-cage type) at RAID testbed (EPFL) to provide a dense magnetized plasma column

Helicon Bird-cage antenna meets the specifications:

- Low B-field (~10 mT)
- Low operating pressure (~0.2 Pa)
- Stable plasma discharges in H₂ and D₂ up to 10 kW plasma (achieved)
- Nearly constant section
  \(\Rightarrow\) Uniform plasma distribution along \(B_{\parallel}\)

A 3 kW, 0.3 Pa, B= 12 mT, H₂ plasma jet

1.5 m

water-cooled end plate
Experimental results

Plasma instability??
Conditioning??
Experimental setup

- Cybele with negatively biased Top and bottom plates and Plasma grid (grounded, floating or positively polarized +5V)
- Magnetic field – 100 G
- RF power – 3kW
- Gas pressure - ~ 0.3 Pa
- Bias plates : -25V : -90V
- Plasma Grid : grounded, floating, +5V
- Probe sweep – [-80V : 60V]
- Sweep frequency – 10 Hz
Mirror; diameter ~ 10 cm

3 MW cavity

1 MeV 10A D⁻ beam sheet: 1 cm wide, and 3 m high

Laser CW, $P_0 \sim 1$ kW

9 MW D⁻ at 1 MeV

30 to 50 cm

15 to 20 m
Electrical setup installation of the 30 kV pre-accelerator

With High Voltage breakdown – risk of damaging PG, arcing etc.
⇒ Interruption of the current in the µs range (fast switch multi-breakdown system)
⇒ Removing the stored energy in the HV wires by a snubber (to avoid grid damages)
⇒ The reset of the Static interrupter in the 10 ms range
⇒ HV holding and beam conditioning involves several tenses of HV breakdowns per second

The tests revealed a proper working of the multi-breakdown system.
The interruption occurs before the release of stored energy.
The energy detected after a breakdown is less than 5mJ.
Tank with mirrors

~ 20 m

Bioshield

Technical gallery

Tokamak hall
Nuclear island

D-T Plasma

Ion source

Radiation shielding

Ultra-stable table

0.2 m

Photon beam

1 MeV D°
Modular concept
⇒ Six beamlines in // per tank
⇒ 50 MW D° per tank
⇒ Three tanks in //: ~ 150 MW D°
⇒ Overall efficiency: ~70%

Photo-neutralization allows to achieve powerful neutral beam with high efficiency
Remind Siphore concept

Acceleration (top view)

Electron deflection $B_x = 10$ mT

Pre-accelerator grids

Single gap post-acceleration

Photoneutralizer

Cavity duplication => 87% of Neutralization

=> Wall plug eff : ~60%
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 \(\sigma_r\) => decreasing \(I_{\text{plasma}}\). => For B-fields larger than 2.5 mT, it becomes impossible to couple the RF active power to the plasma.

Vertical B-field increases vertical diffusion => radial diffusion and conductivity decreases => increasing of the skin-depth => reduce of the RF-induced current
RF electrical set up

Ground Decoupling between the RF generator and the antenna circuit
The tests revealed a proper working of the multi-breakdown system. The interruption occurs before the release of stored energy. The energy detected after a breakdown is less than 5mJ.
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)
Photo-neutralization seems ideal
- No gas injection => Strong reduction of D^− losses
- Clean: No pollutant
- Potential High neutralization rate (η > 90%)

But
- Low photo-detachment cross-section

$$\sigma \sim 3.6 \text{ to } 4.5 \times 10^{-21} \text{ m}^2 \text{ for } \lambda = 1064 \text{ nm}$$

Photo-neutralization requires high photon power!!
- 1MeV D⁻ blade-like beam
- D⁻ beam width: d ~ 1cm
- 50 % photo-detachment rate

D⁻ Ion velocity, 
|v|~ 10⁷ m/s at 1MeV

\[ P_{\text{photon}} = h c \cdot \frac{|v| d}{\sigma \lambda} \]

\[ P_{\text{photon}} \sim 3 \text{ MW} \]
High reflectivity mirrors

L = L_0 n

Resonance ⇔ 2L = q\lambda  ⇔ Constructive interferences

Cavity amplification

S

R = 99.99 %

\[ \delta \nu = \frac{2(1 - R)}{\sqrt{R}} \]

P_{in} = P_0 \times S

Photon power stored within the cavity:

High cavity sensitivity to variations of the optical length:
vibrations, etc.
Photo-neutralization experiment in cavity

- Vacuum tank
- Optical cavity
- Laser: 10 W
- 10 kW intra-cavity photon beam
- ~1 m

- H⁻ beam: 1 keV and 1 mm diameter
Photo-neutralization experiment in cavity
Preliminary results

Observation of $H^-$ and $H^0$ on micro-channel detectors

$\Leftrightarrow 50\%$ photo-detachment achieved in CW regime

Neutral beam tank (Top view)

6 independent ion sources, spatially oriented

Recovery electrodes

Calorimeter

6 x 8 MW of D° at 1 MeV

~48 MW of D° in the plasma core

Photoneutralizer (93%)

Cryo-pump panel

6 independent ion sources spatially oriented

~1.4 m

1 MV Bushing

Beam scraper
Neutron shielding

Control of the plasma profile

Bioshield

Bioshield

Control of the plasma profile
One SIPHORE beam-sheet principle

(Top view)

Photon beam ⇔ 93% photodetachment

Post-acceleration 1MeV, 10 A D⁻

Energy recovery 1 A D⁻ at 50 keV

Neutral beam 9 MW D° at 1MeV

Potential distribution

The ion source and pre-acc. are referenced to the ground potential

CEA | 23 March 2017 / Eurofusion KOM meeting
One SIPHORE beam-sheet principle
(Top view)

Photon beam ⇔ 93% photodetachement

Post-acceleration 1MeV, 10 A D⁻

Energy recovery 1 A D⁻ at 50 keV

Ion source grounded ⇒ Huge simplification of the electrical set-up

- Fast switch in the pre-accelerator allows to switch on/off the 10 A D⁻ beam in the µs range
- It is conventional technology of present NBI systems (JET, etc.)
  - Temporal modulation of the D° beam