Neutral Beam Injector (NBI) for Future Fusion Reactors

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Outline

01

NBI

- Towards Fusion reactors
- Fusion Reactor & Electricity
- Neutral Beam Injector
  - Advantages
  - Principle

02

Helicon plasma

- Experimental Setup
- Magnetic configuration
- Diagnostic tools
- Results

NBI

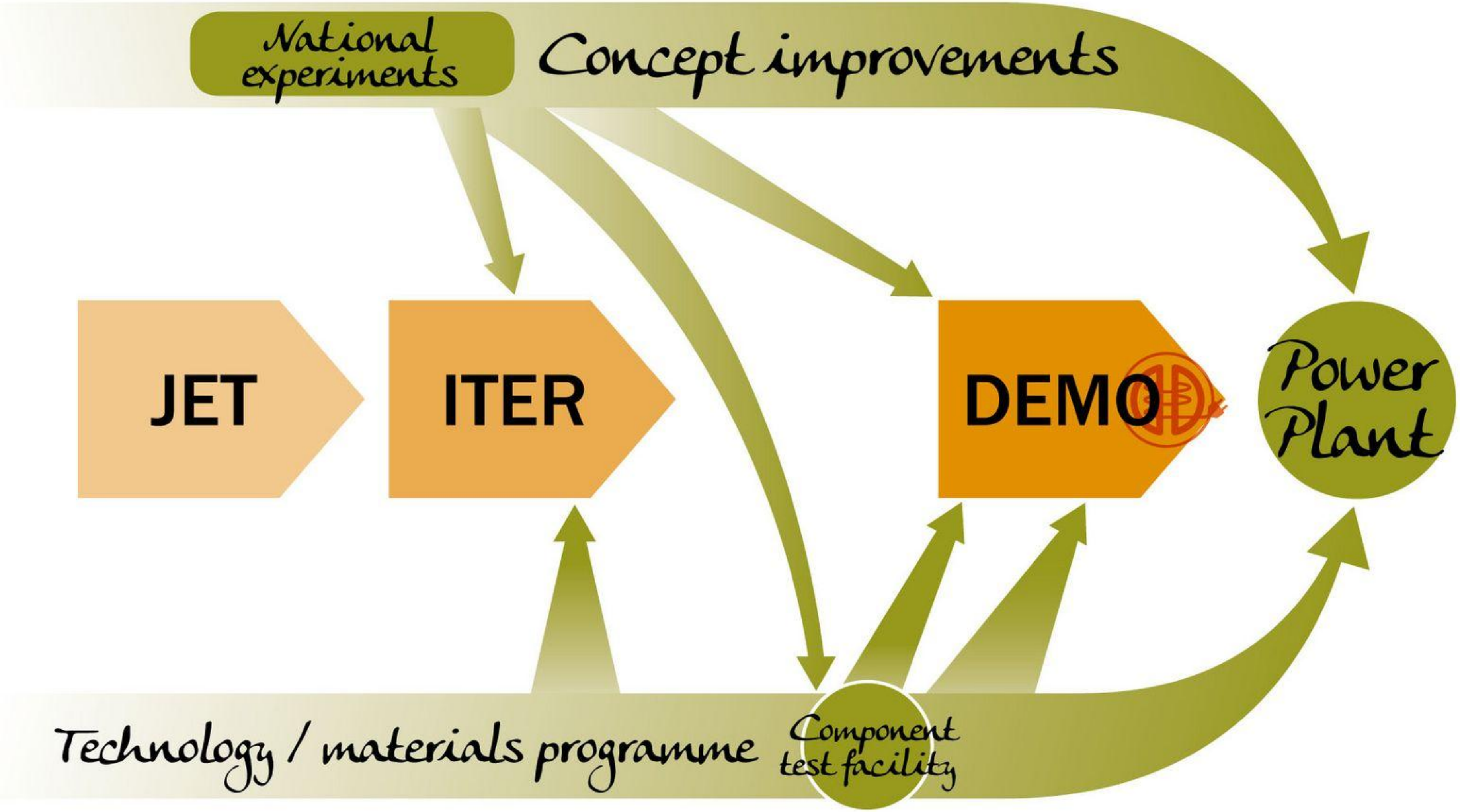
01 Fusion Reactors & electricity

02 Plasma heating in fusion reactors

03 Grounded Source accessibility and availability

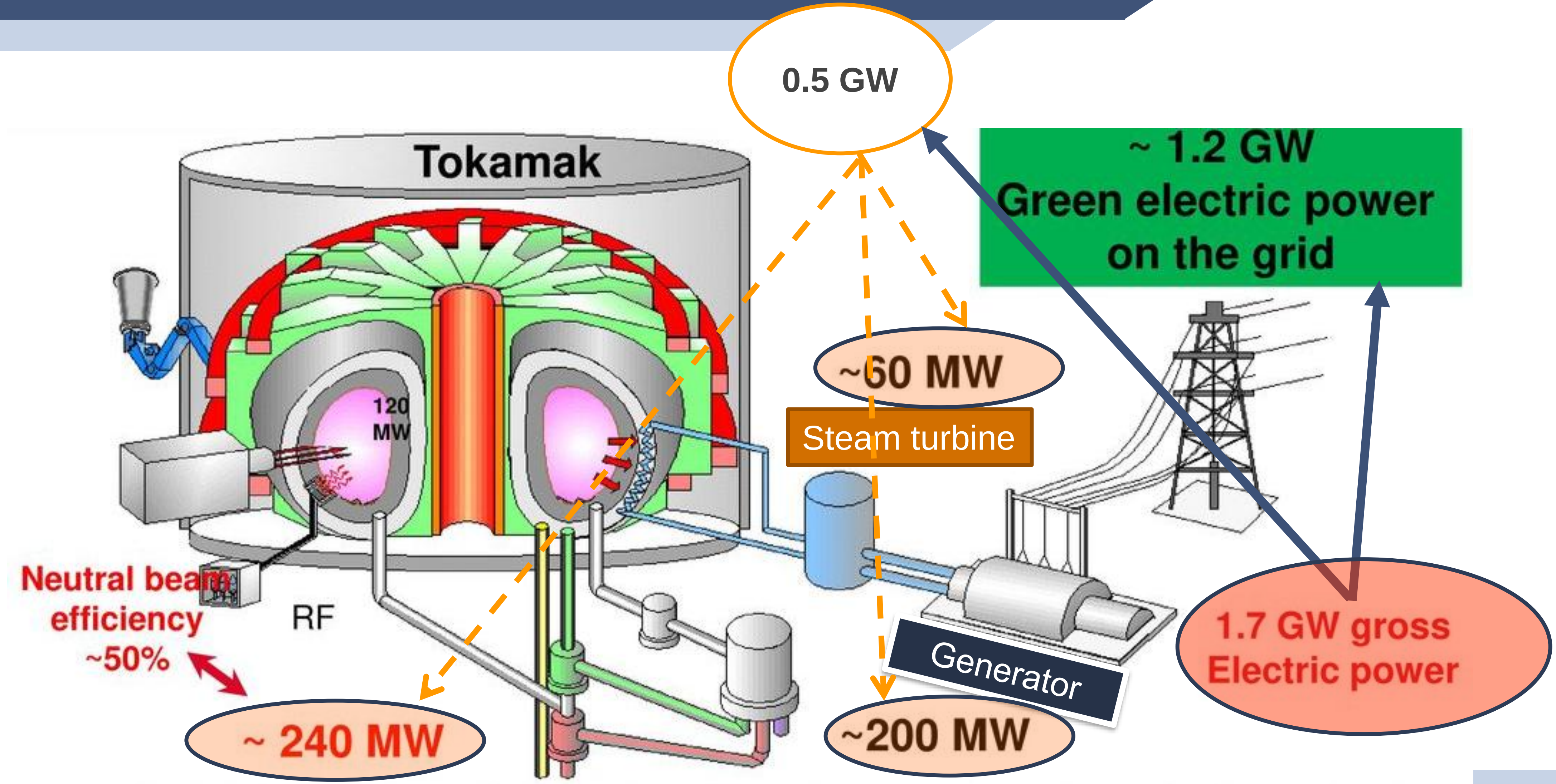
04 **Neutral Beam Injectors' principle**

Towards Fusion Reactors



Graphic: EUROfusion / CCFE

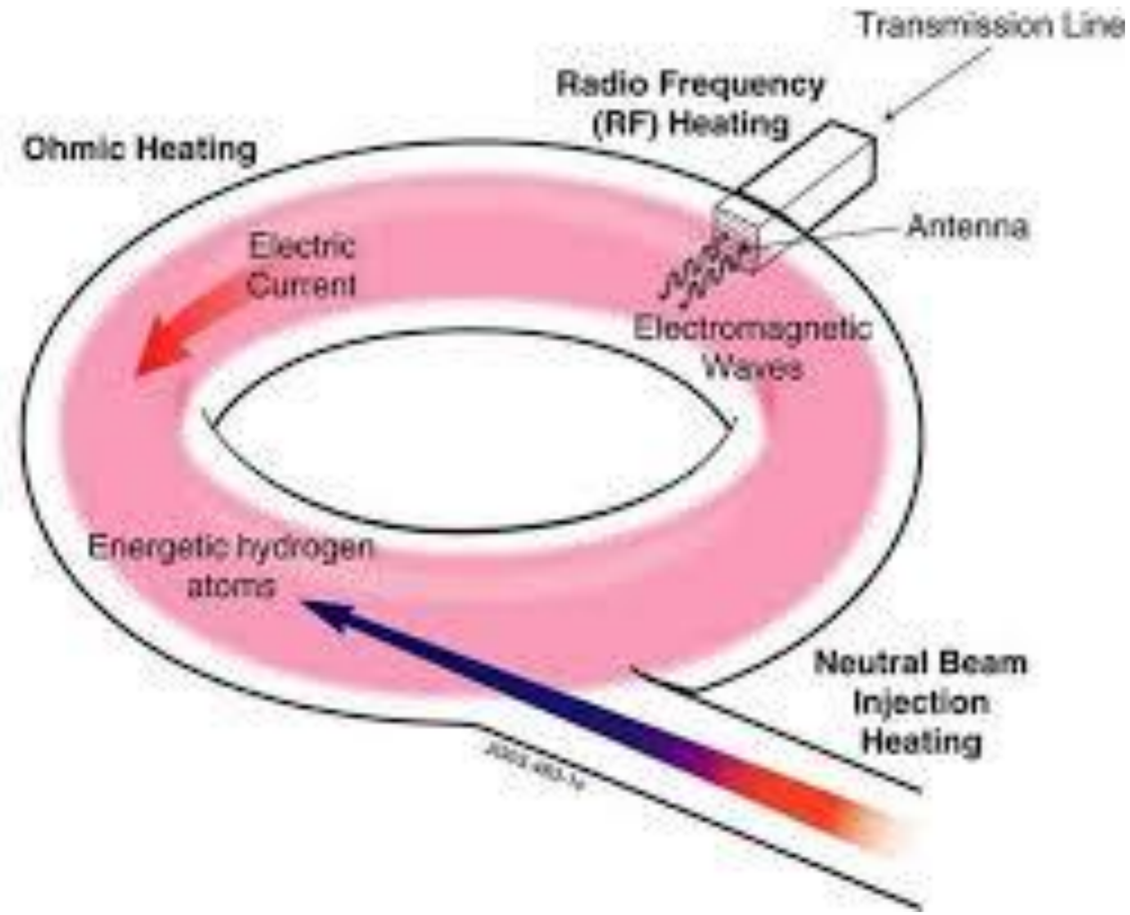
Fusion Reactors & Electricity

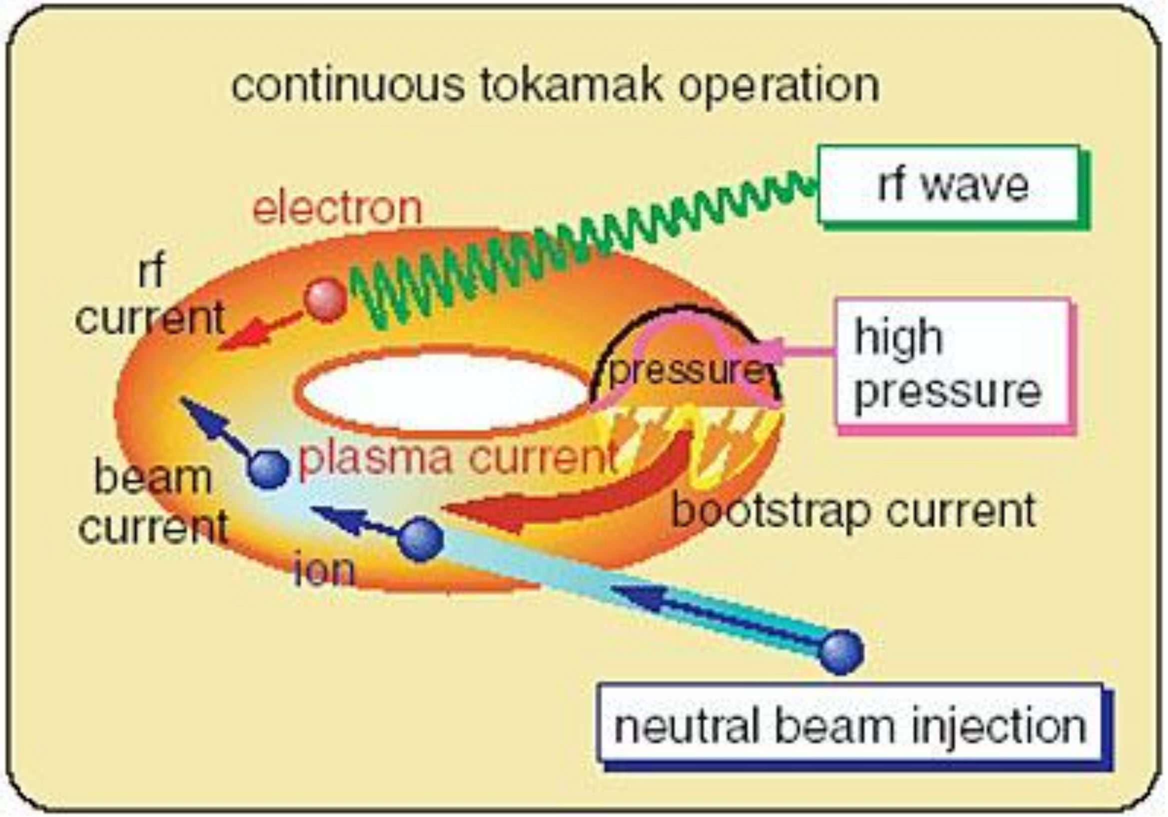


Neutral Beam system **efficiency** ⇔ Main penalty on the electricity production and cost

Challenge : Achievement of powerful neutral beams with efficiency > 50%

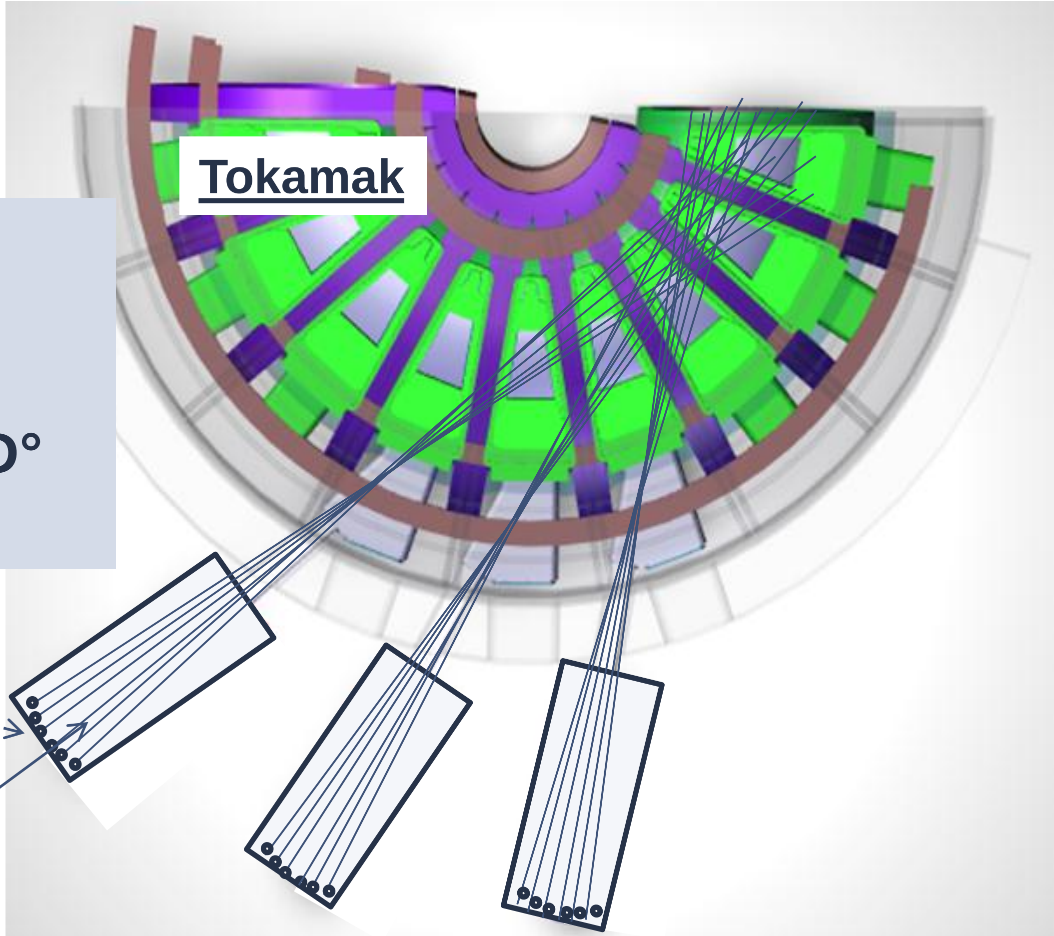
Plasma heating in fusion reactors





Modular concept

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

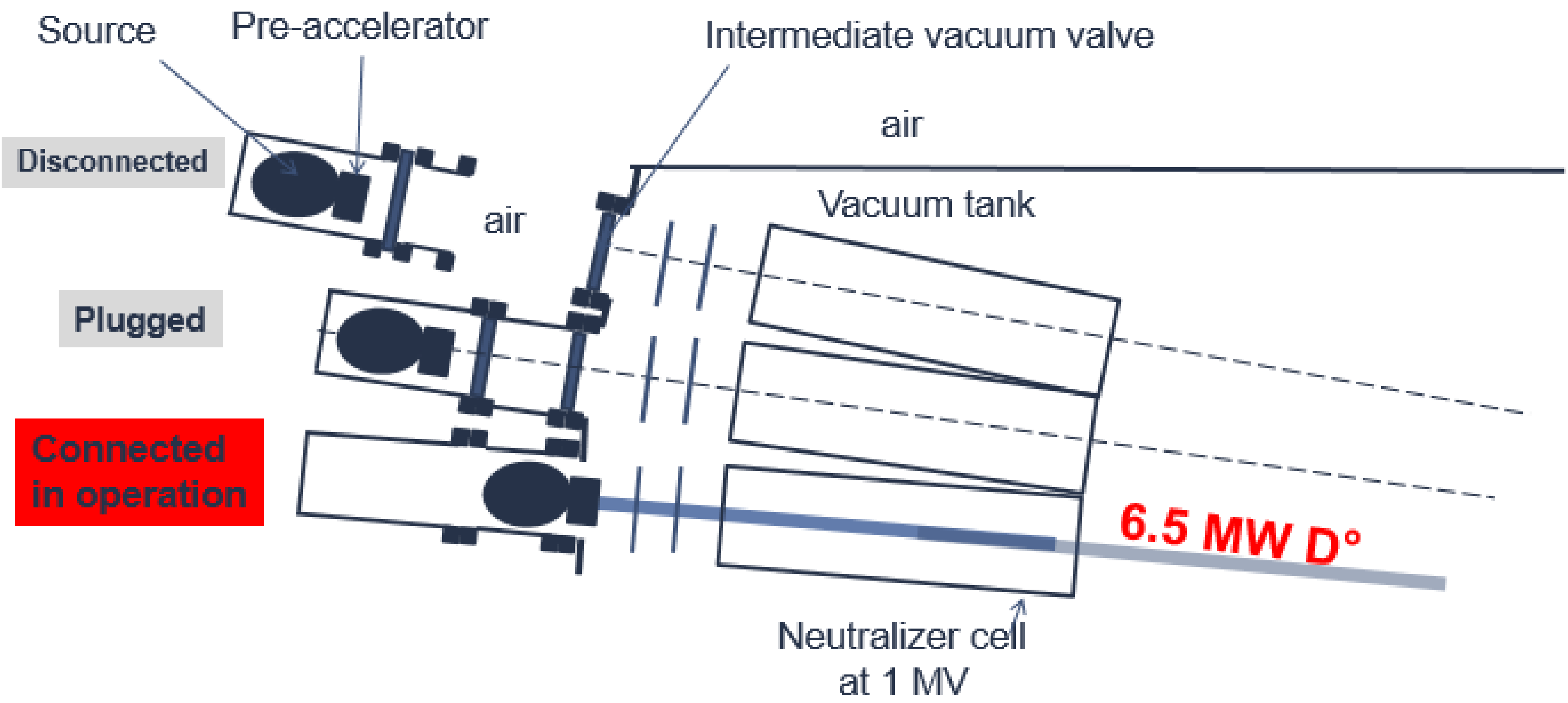


NB vacuum Tank

Six beam sheet in // per tank

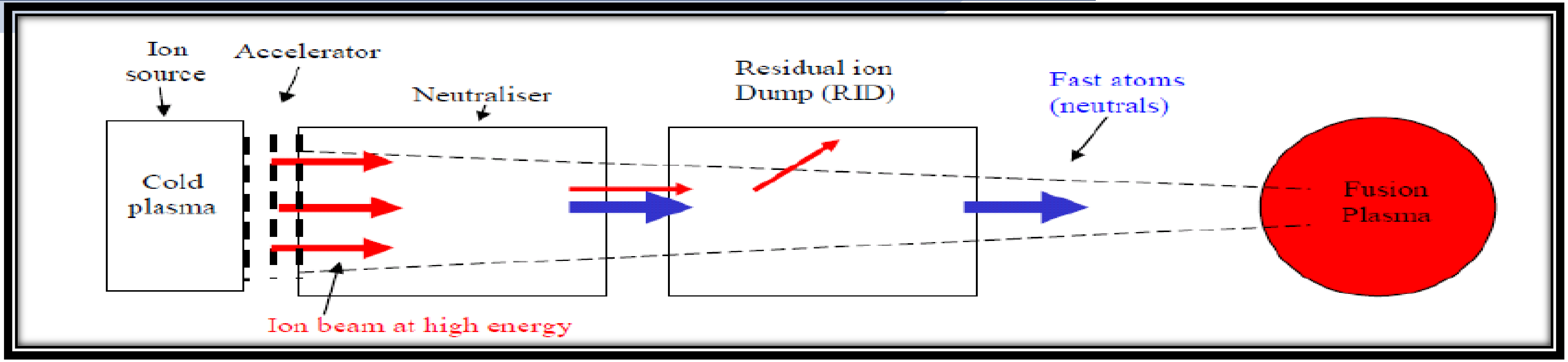
Photo-neutralization allows to achieve powerful neutral beam with high efficiency

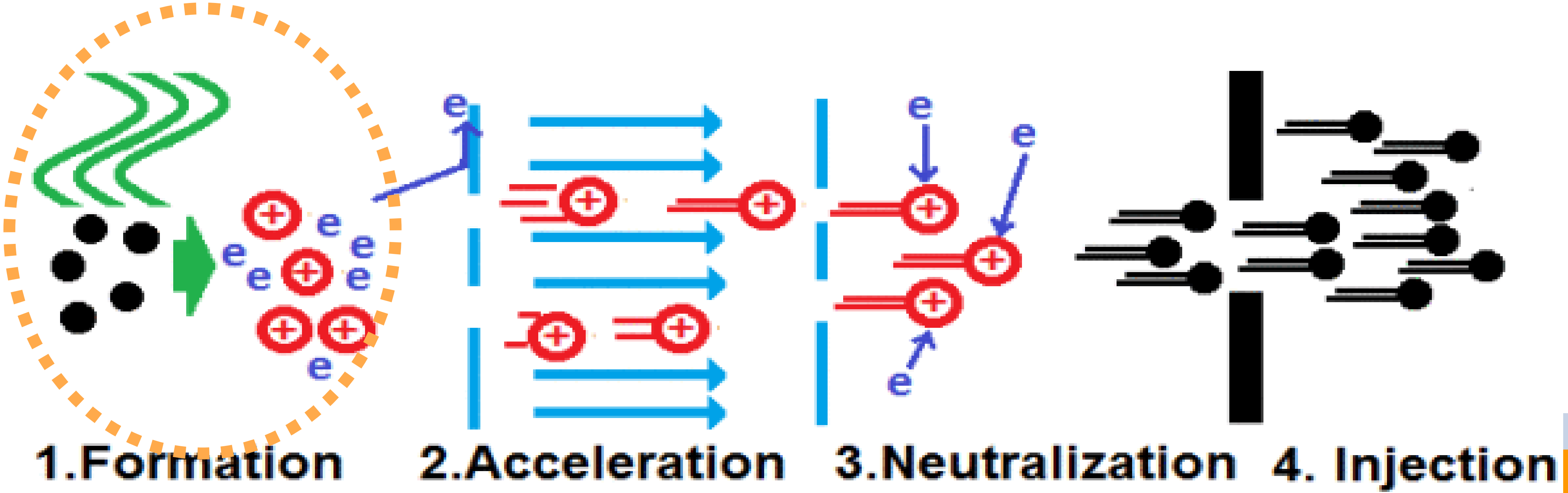
Grounded Source accessibility and availability



- Easy Maintainability by Remote Handling of the "source & pre-acc."
- High injector availability

Neutral Beam Injectors' principle





Plasma Source for –ve ion production

A Filament plasma source

B ICP source

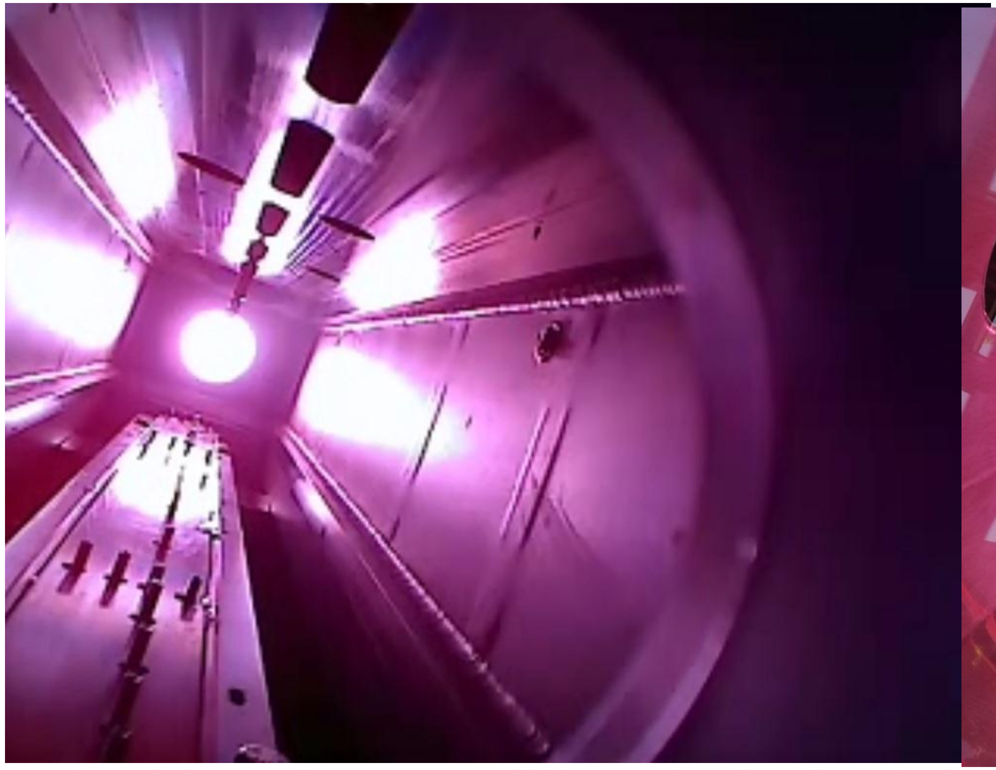
C Helicon Plasma source

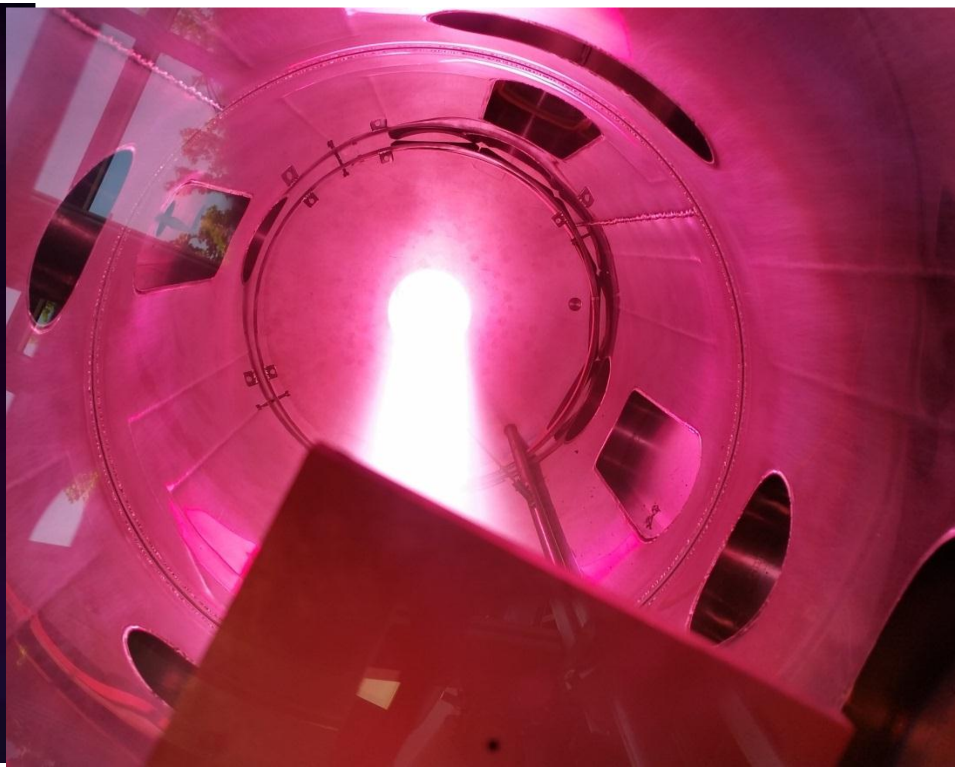
Helicon driver for Cybele

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

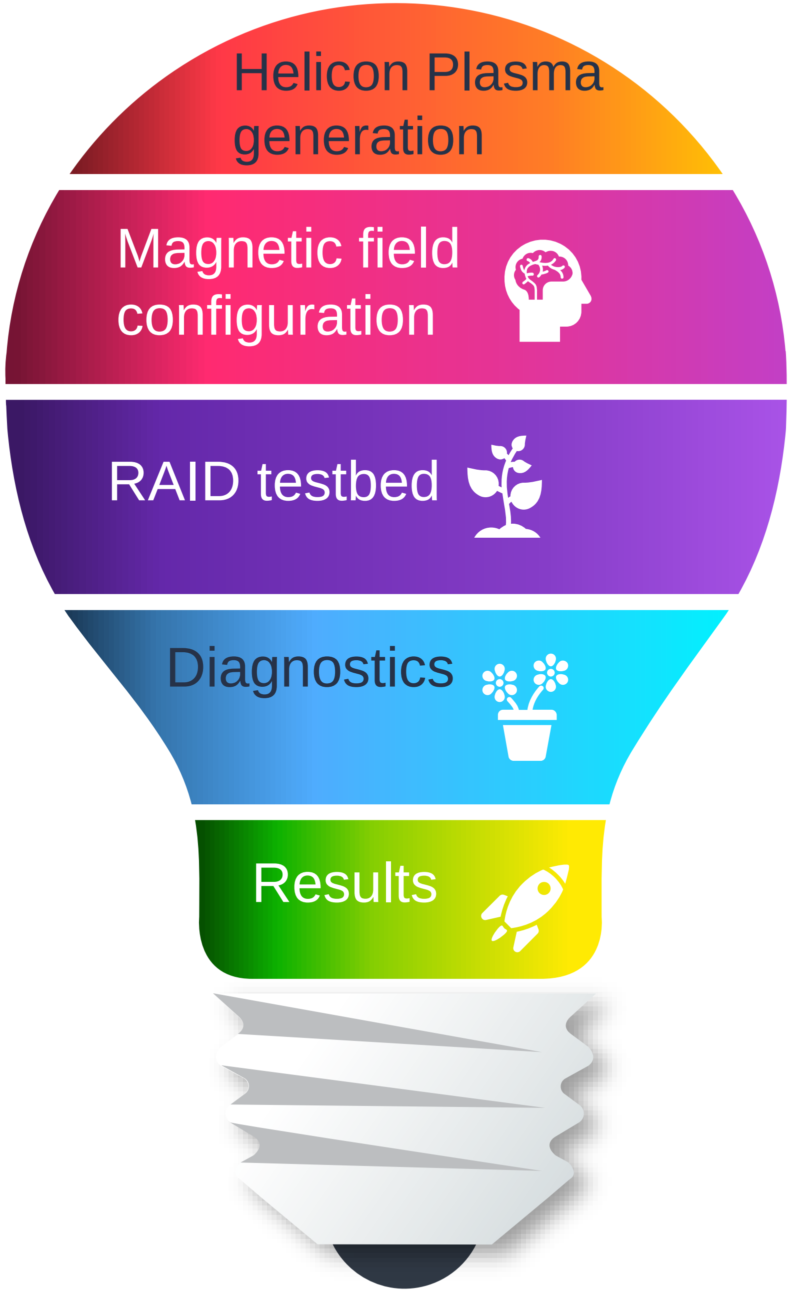




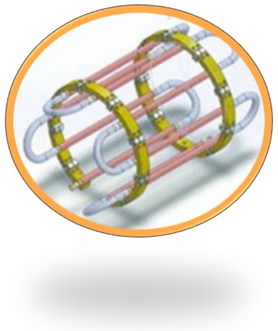
Plasma from ICP driver does not diffuse far in the Cybele source volume

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

Helicon Plasma

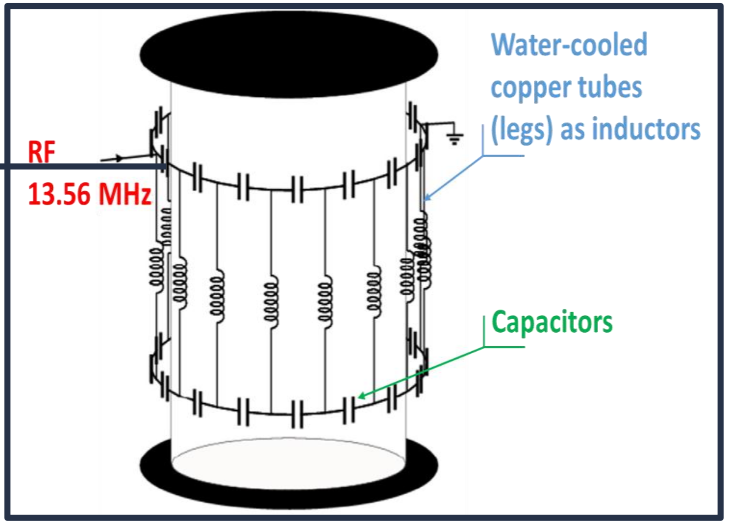


Helicon Plasma generation



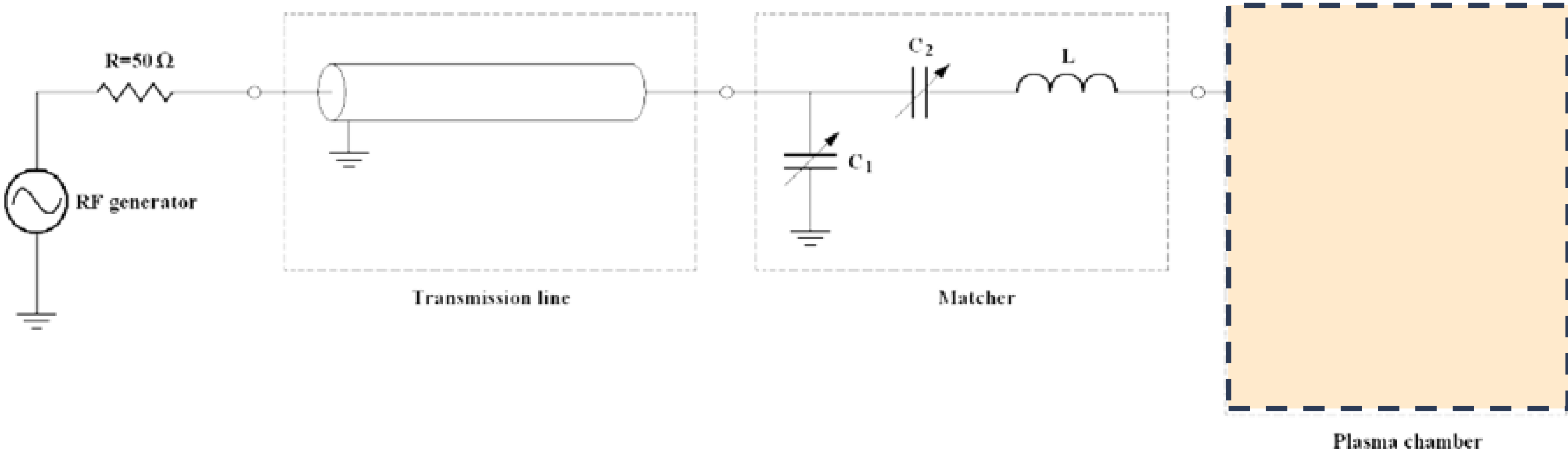
RF power supply 10 kW 13.56 MHz

Automatic matching box



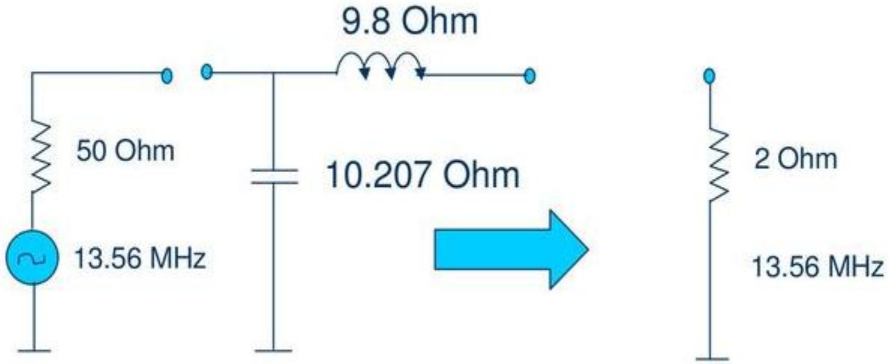
Antenna

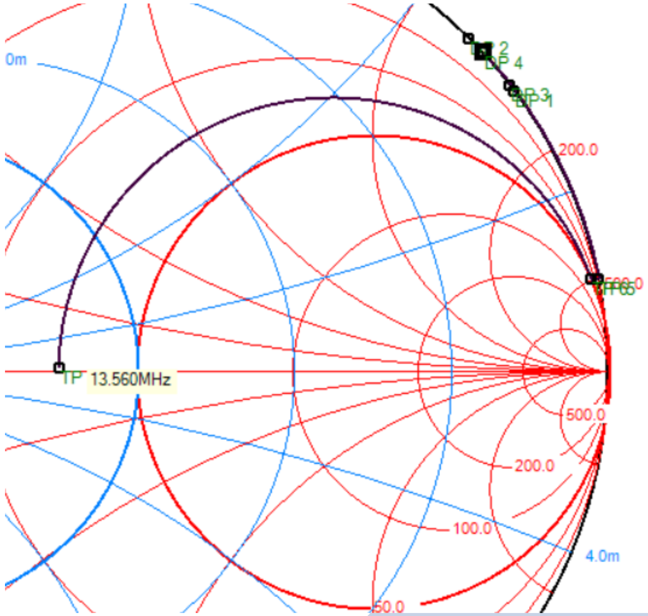
13.56 MHz matching circuit



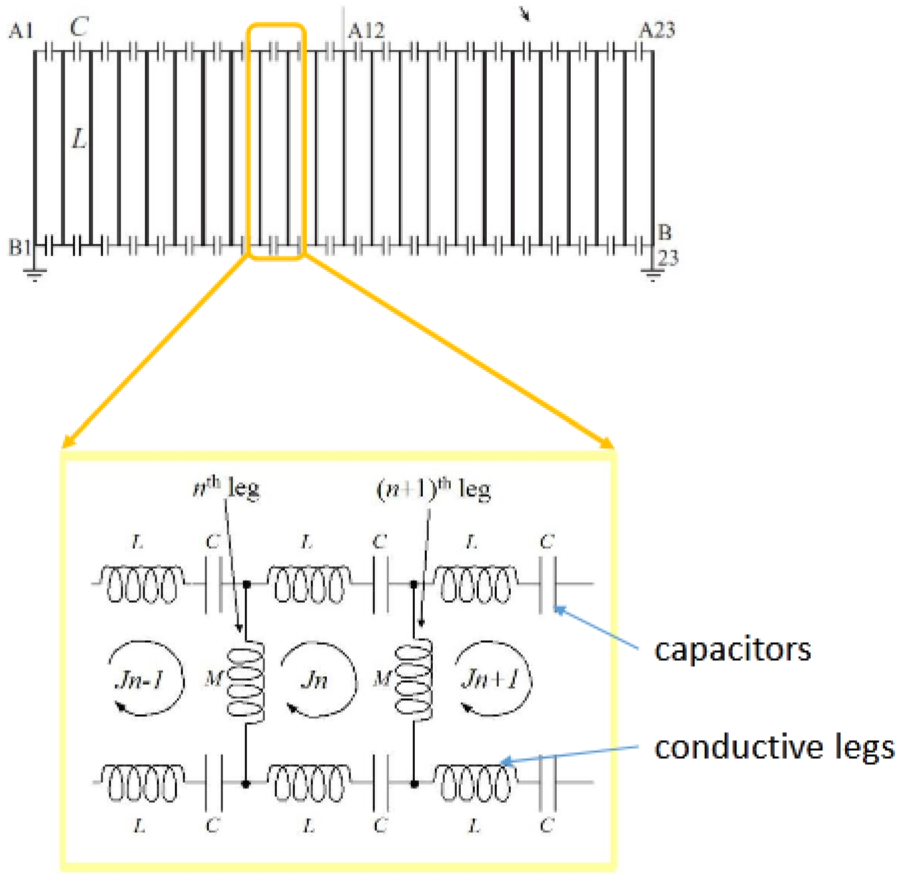
Impedance Matching

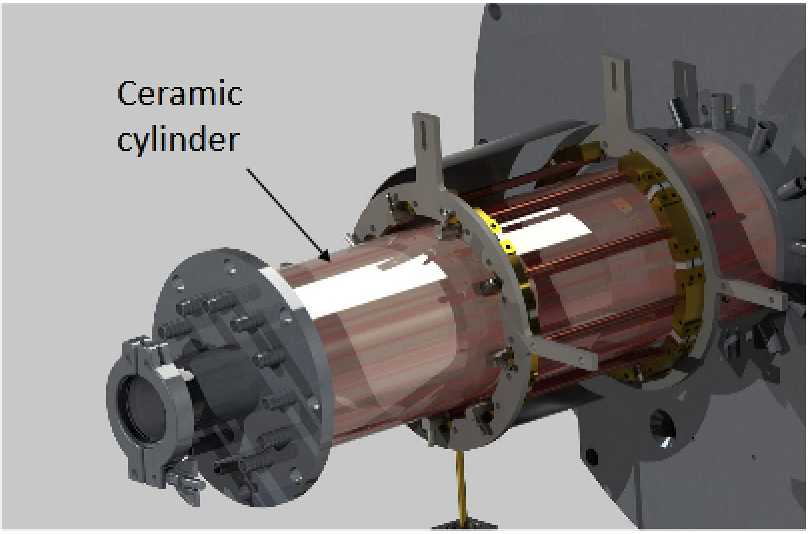
- From electrical science we know that inductors and capacitors have impedances with opposite signs. Inductors have positive sign and capacitors negative.





Bird-cage antenna for helicon-wave production





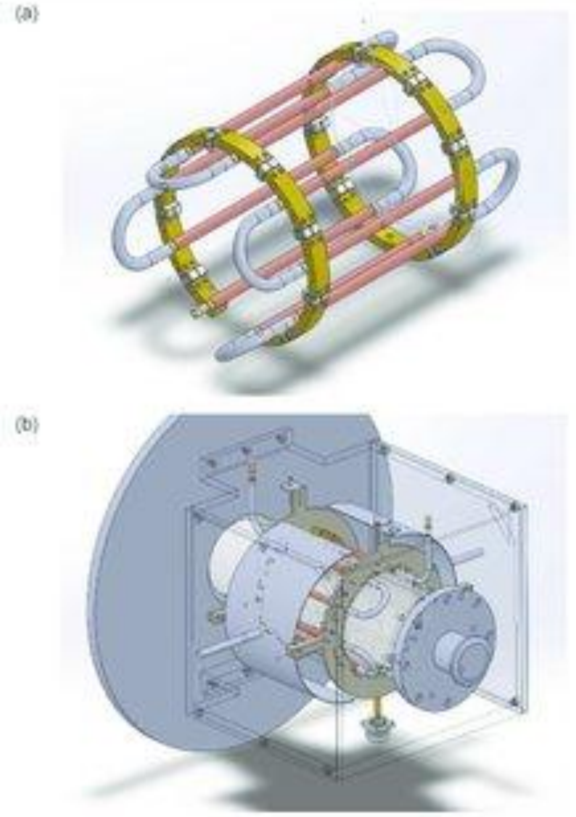
Resonance frequencies:

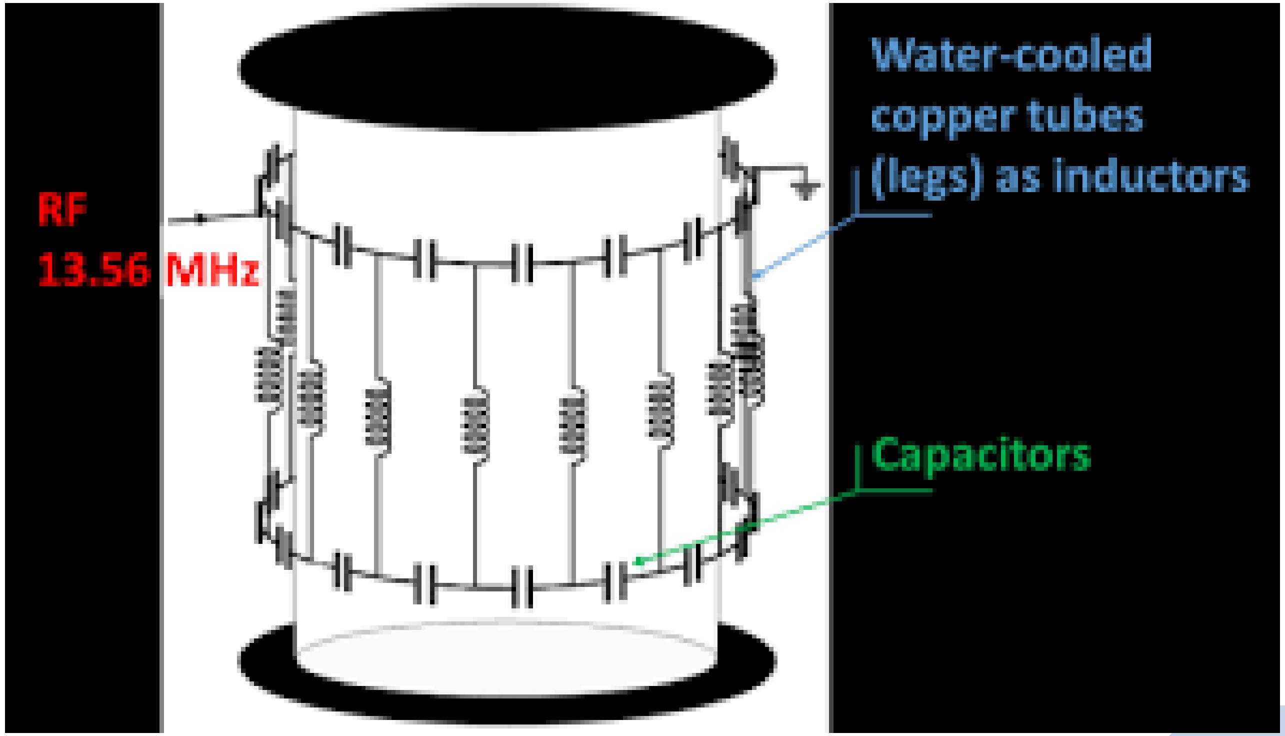
$$\omega_m = \frac{1}{\sqrt{C\left(M + 2L\sin^2\left\{\frac{m\pi}{2N}\right\}\right)}}$$

m=1,2,...N-1

Frequency: **13.56 MHz**

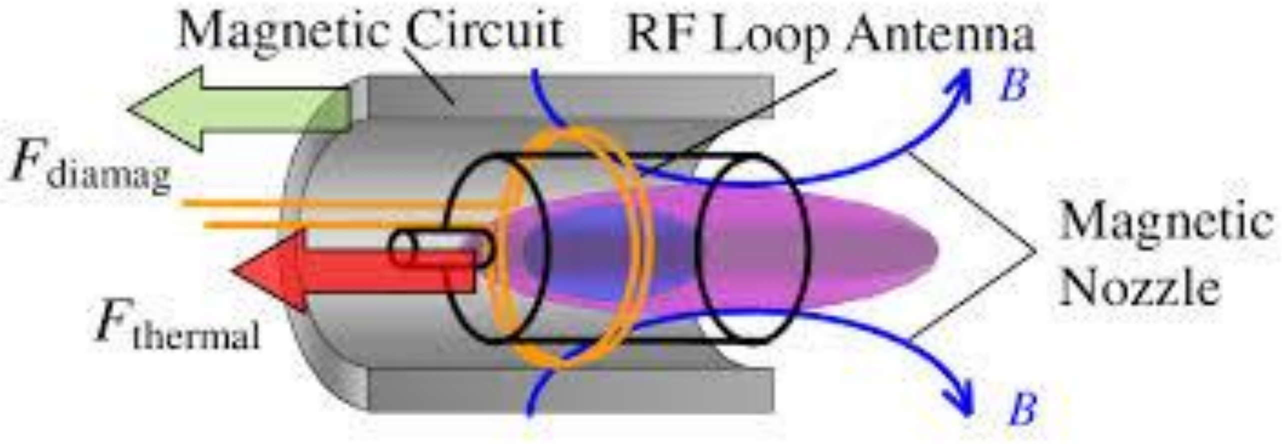
Bird-cage antenna for helicon-wave production

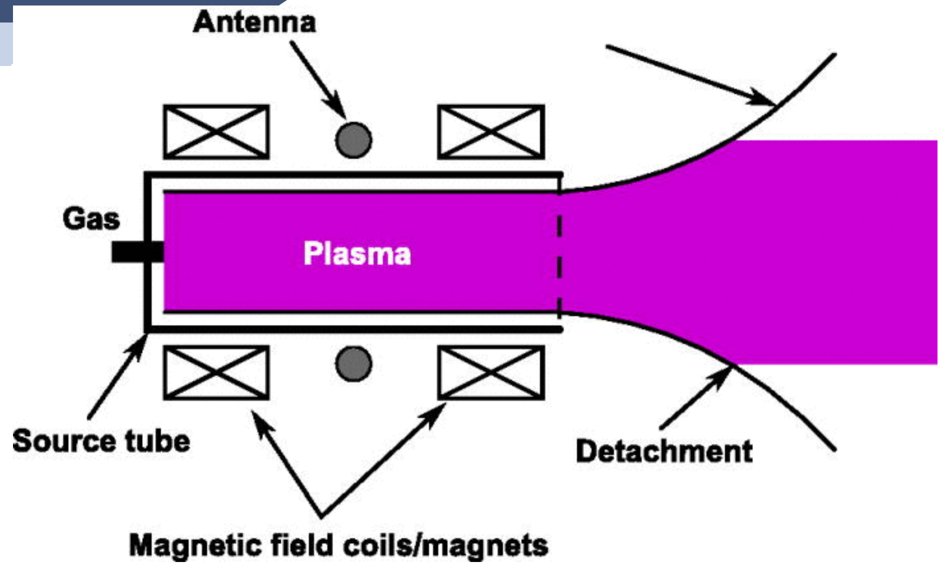


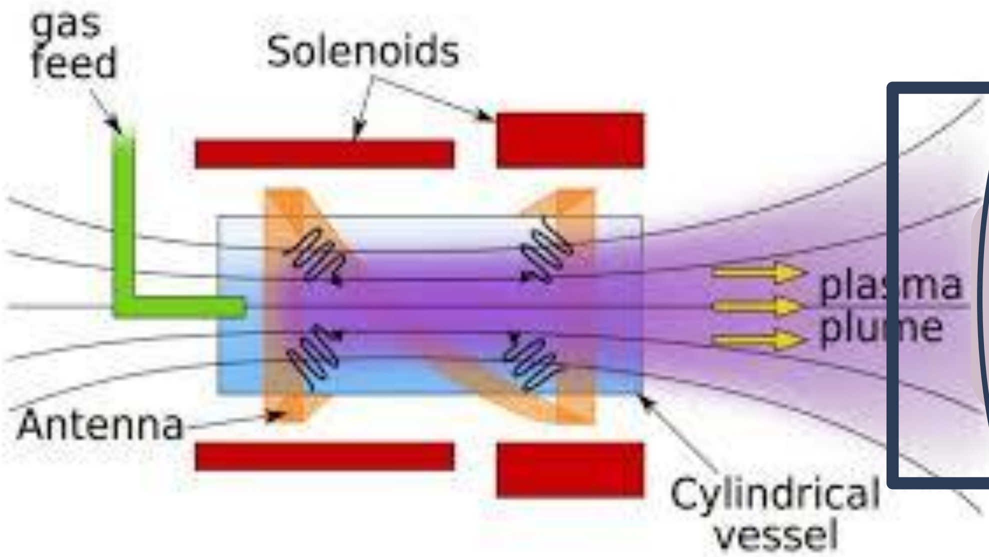


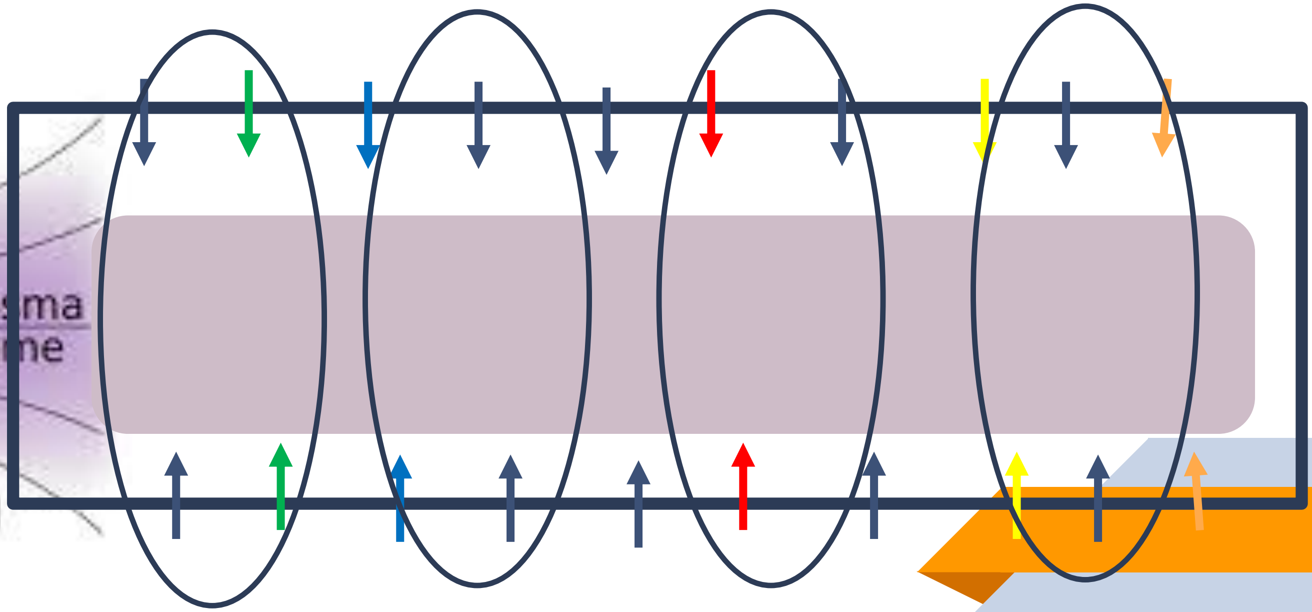
Plasma produced inside the helicon antenna (RAID)

Helicon Plasma

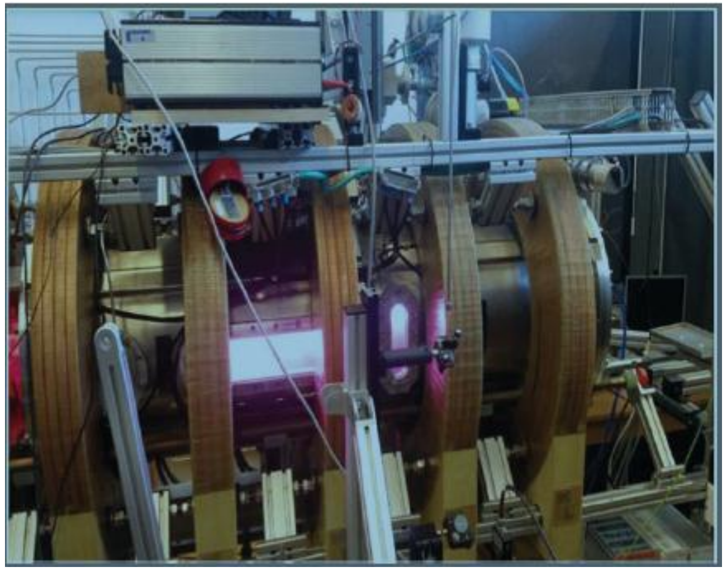








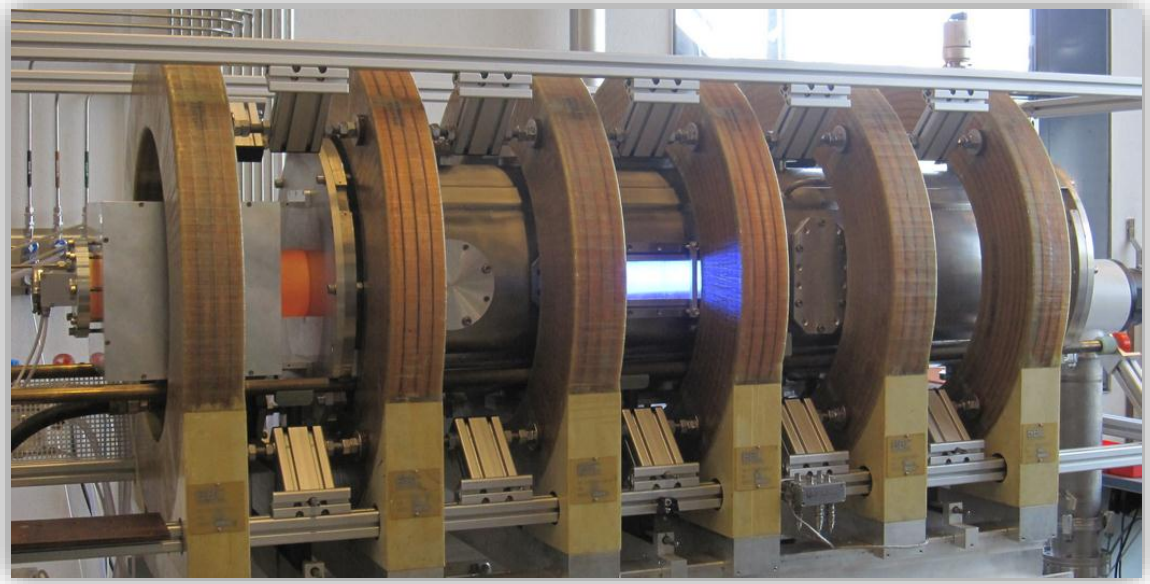
RAID testbed



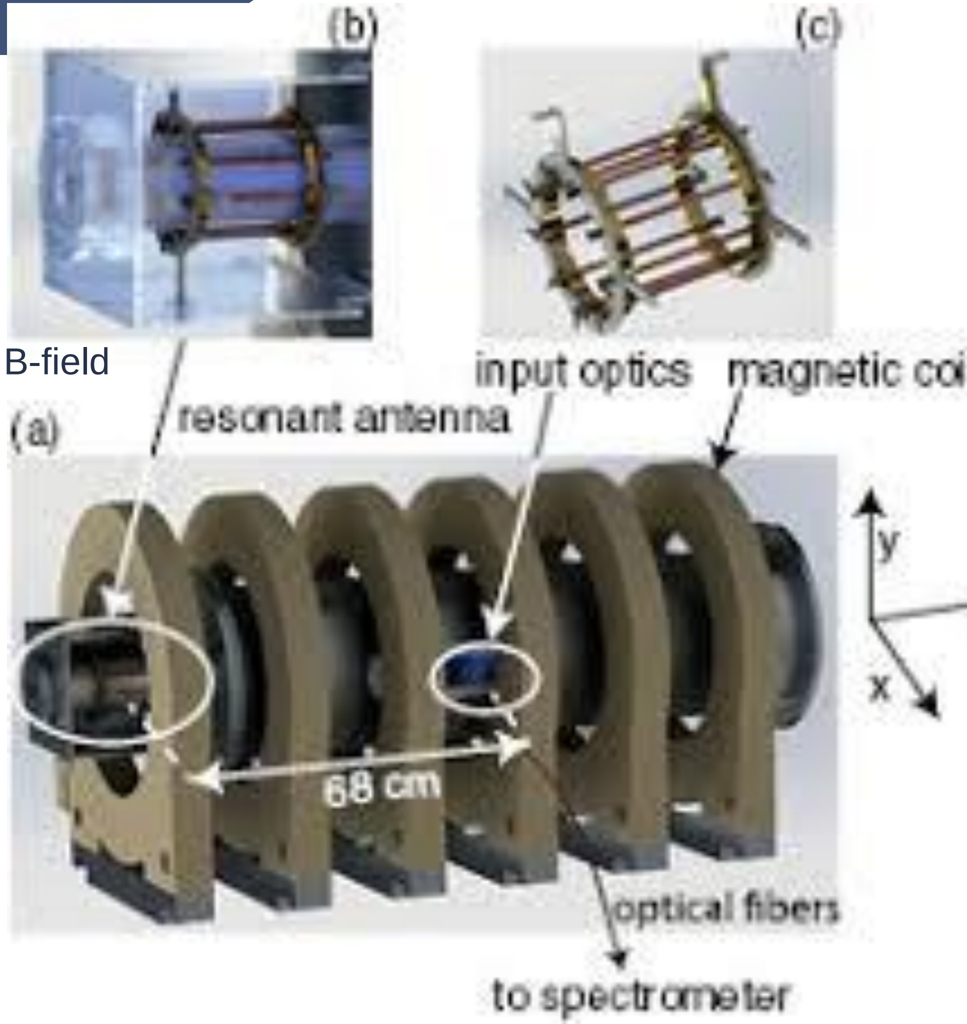
EPFL, Switzerland

RAID testbed (EPFL , Switzerland)

External magnets



Uniform axial B-field
Negligible transverse B-field



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} 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

Need to test the performance of Helicon antenna in another magnetic field topology

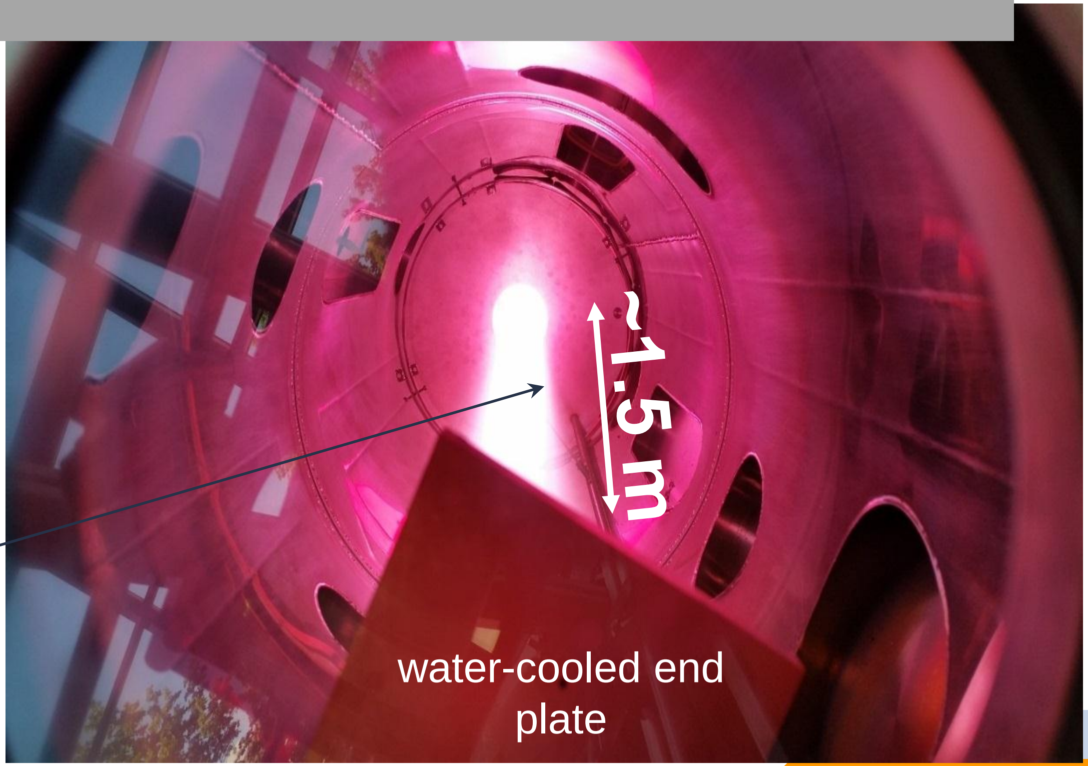
RAID testbed

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

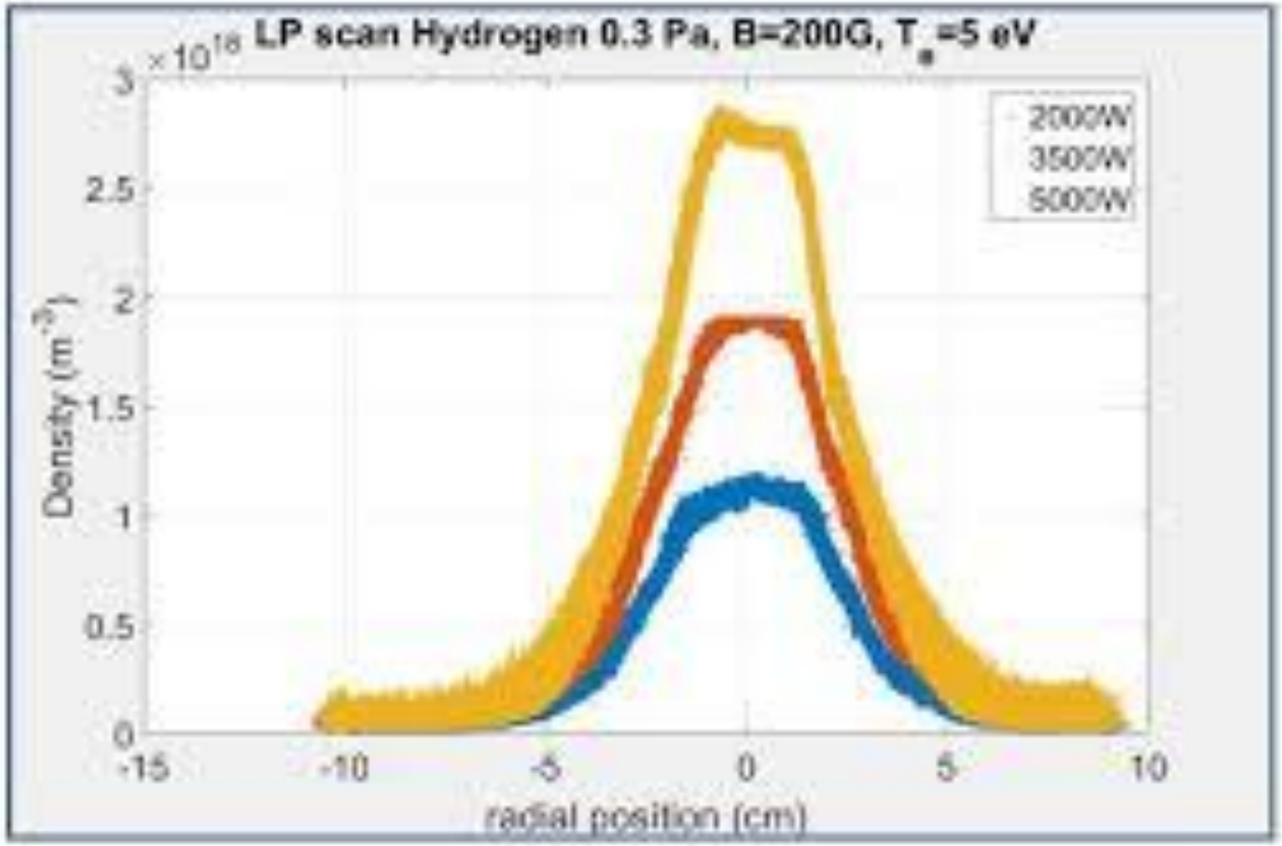
Helicon Bird-cage antenna meets the specifications:

- Low B-field (~10 mT)
- Low operating pressure (~0.2 Pa)
- Stable plasma discharges in H_2 and D_2 up to 10 kW plasma (achieved)
- Nearly constant section
  ⇔ Uniform plasma distribution along $B_{//}$

A 3 kW, 0.3 Pa, B= 12 mT, H_2 plasma jet



RAID results



Profile power scan in Hydrogen plasma

Langmuir Probe

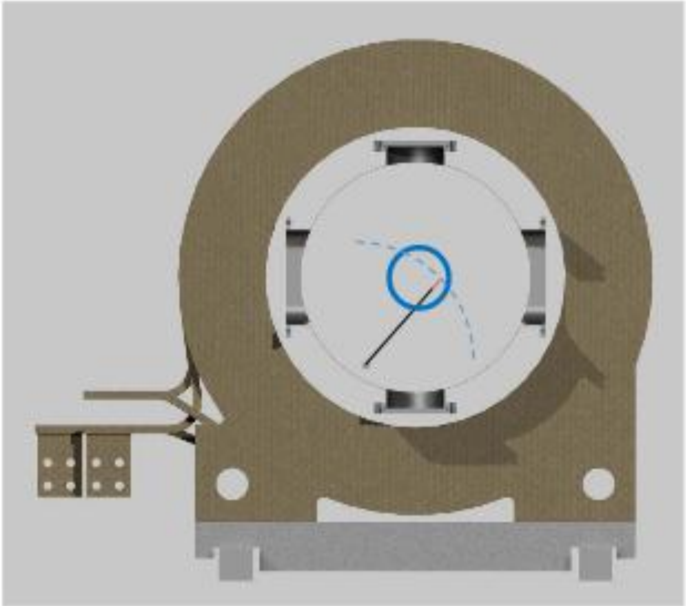
Plasma density and temperature measurements

Langmuir probe

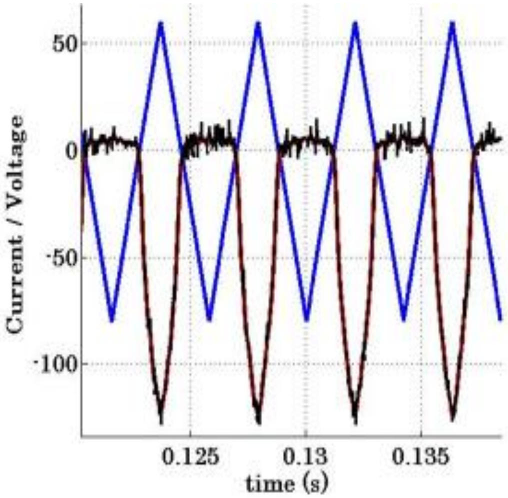
Langmuir Probe (LP) profiles

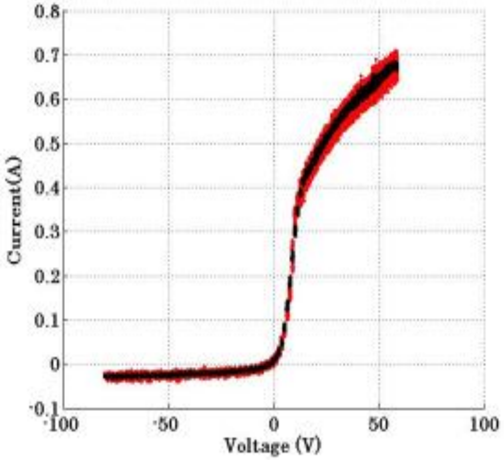
The LP can be either used in:

- ion saturation current→ **ion density**
- voltage sweep mode → **electron temperat**



The 2-axis Langmuir probe inside RAID



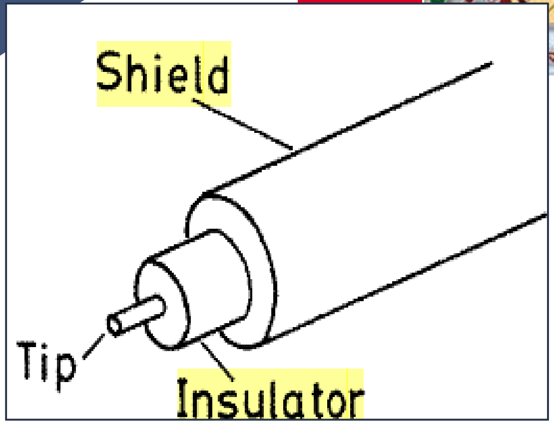


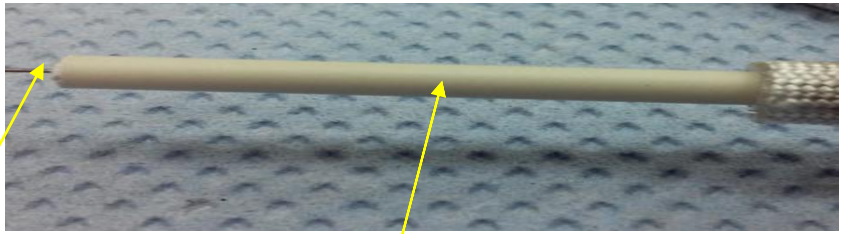
We have measured peak densities:

$n_e = 1.7 \times 10^{19}\ m^{-3}$ in Argon plasma (4kW, 800 Gauss)

$n_e = 2.3 \times 10^{18}\ m^{-3}$ in Hydrogen plasma (5kW, 200 Gauss)

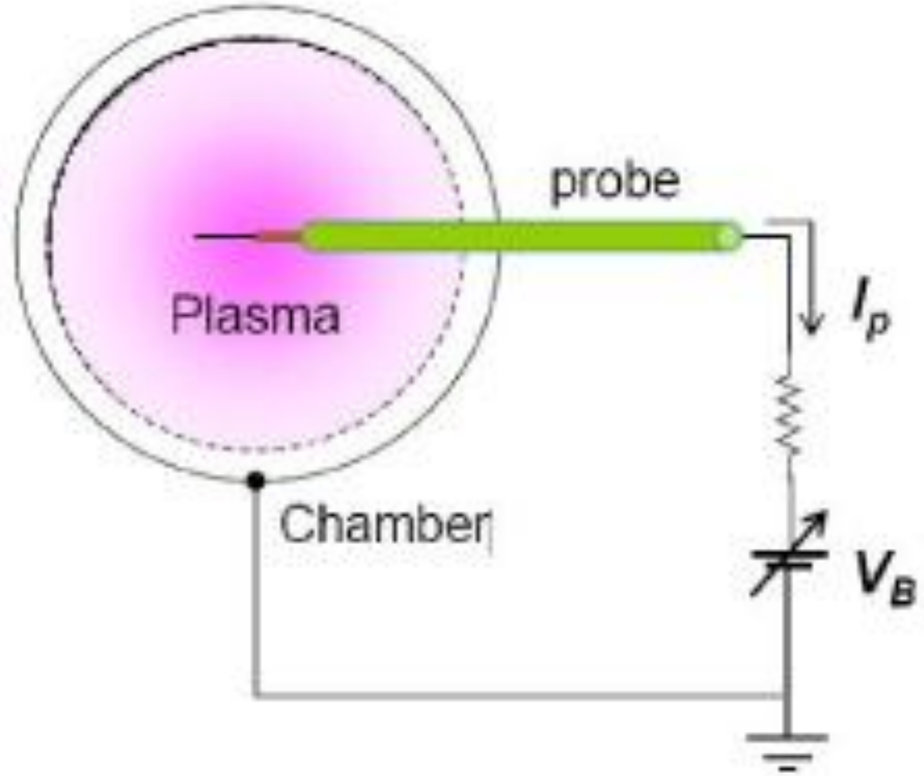
Langmuir probe





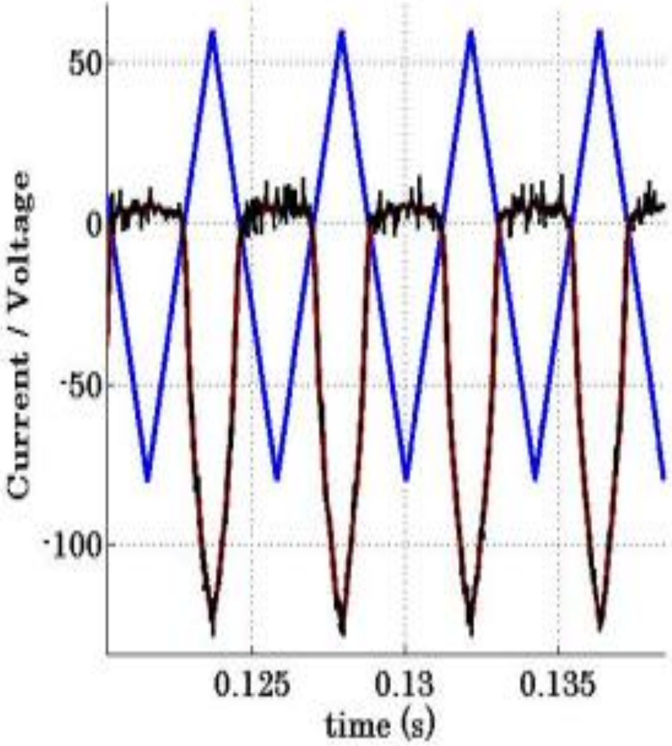
Tungsten

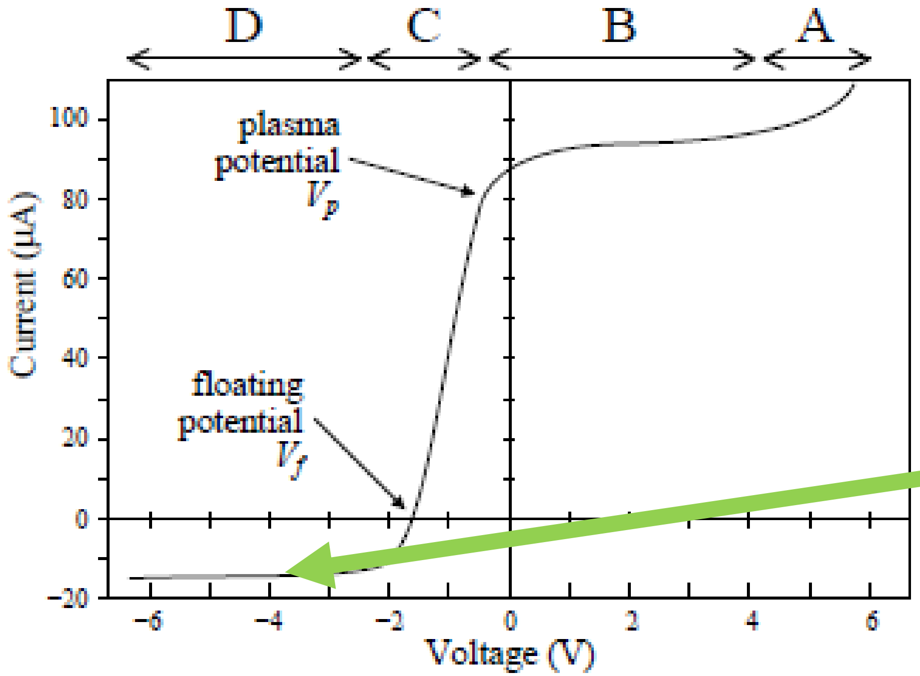
Ceramic



Plasma Density & Temperature Measurements

$$I_{pr} = I_{sat}[1 - \exp(V_{pr} - V_f)/T_e]$$





Te ☑

Isat

$$n_e = \frac{I_{sat}}{qA_s \exp(-1/2)} \sqrt{\frac{M}{k_b T_e}}$$

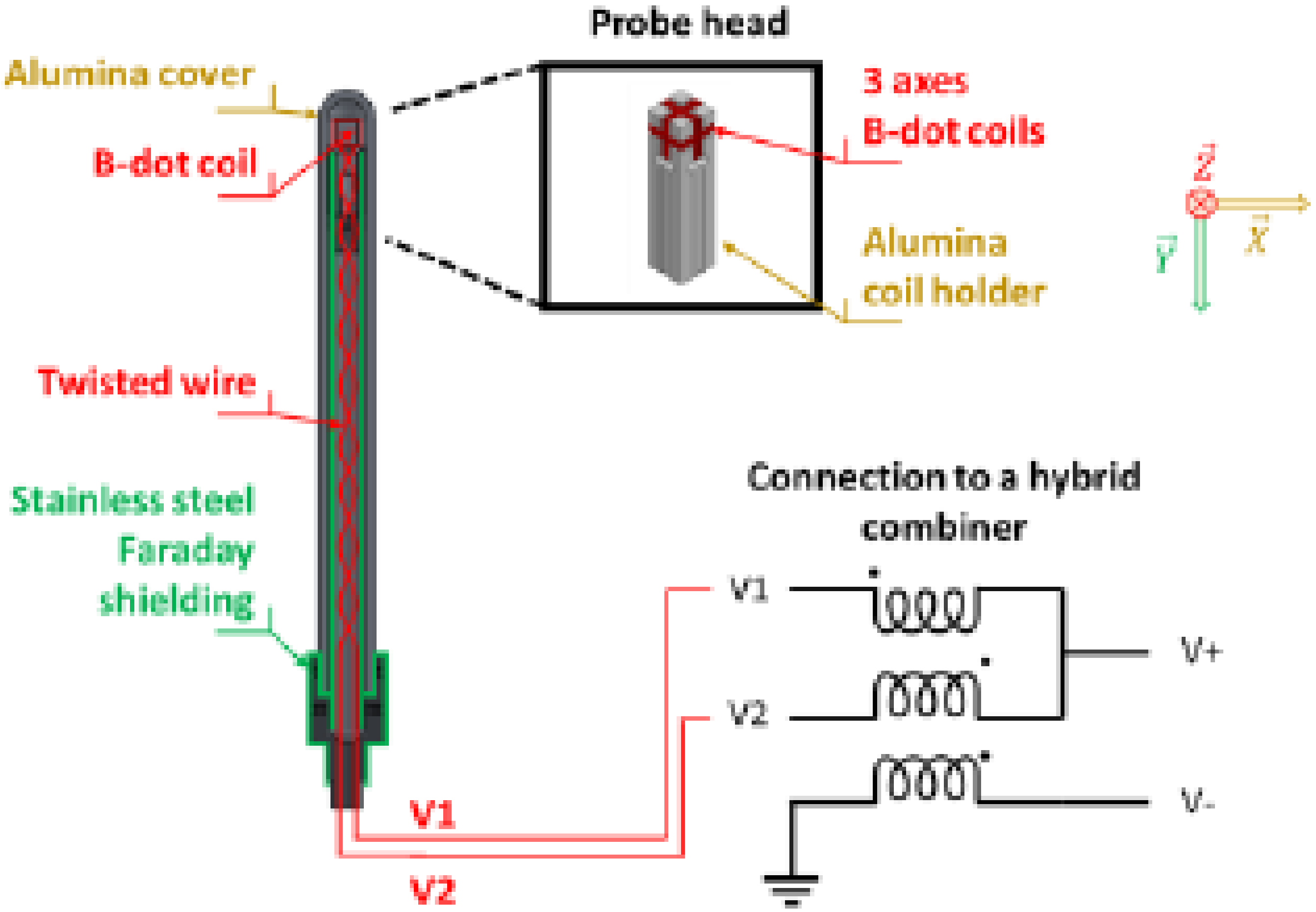
where the new terms are M for the ion mass and A_s which represents the area of the probe sheath.

http://plasma.hanyang.ac.kr/pa/technology.html
https://www.davidpace.com/example-of-langmuir-probe-analysis/

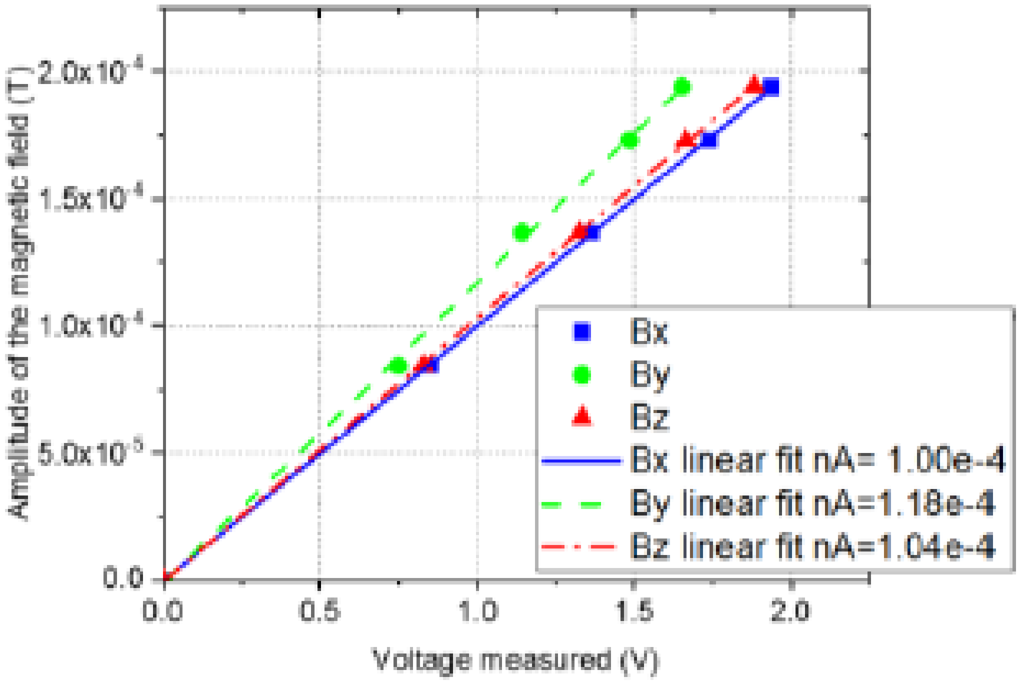
B-dot Probe

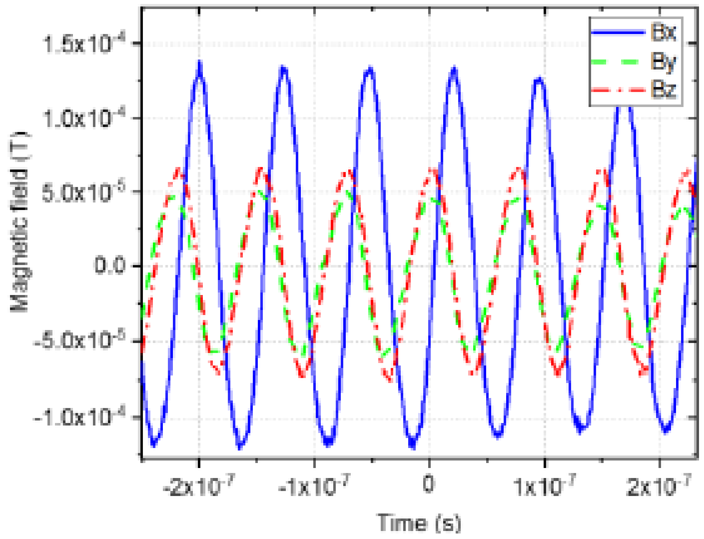
Magnetic field measurements

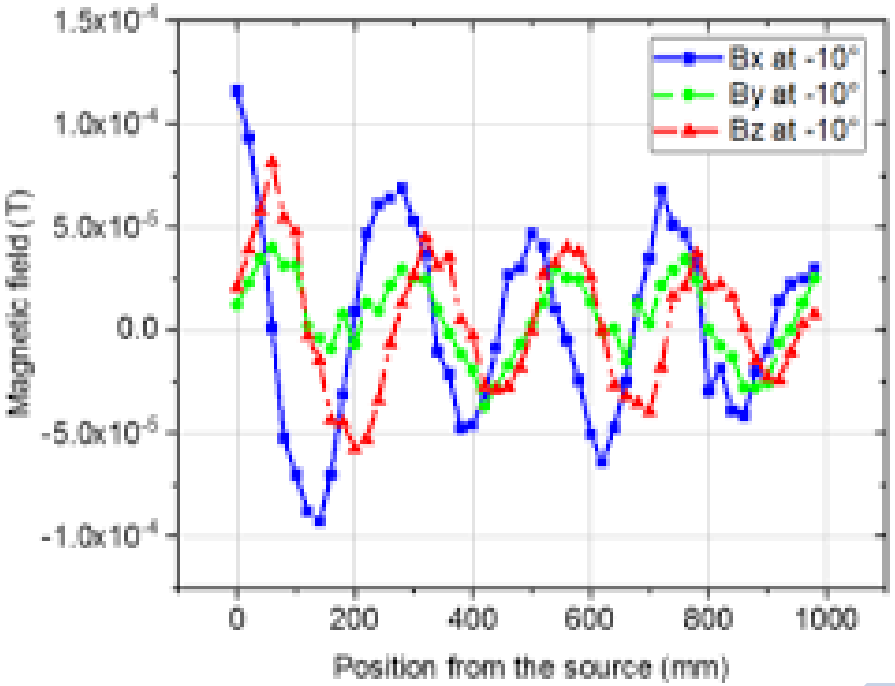
B-dot probe arrangements



B-dot probe results



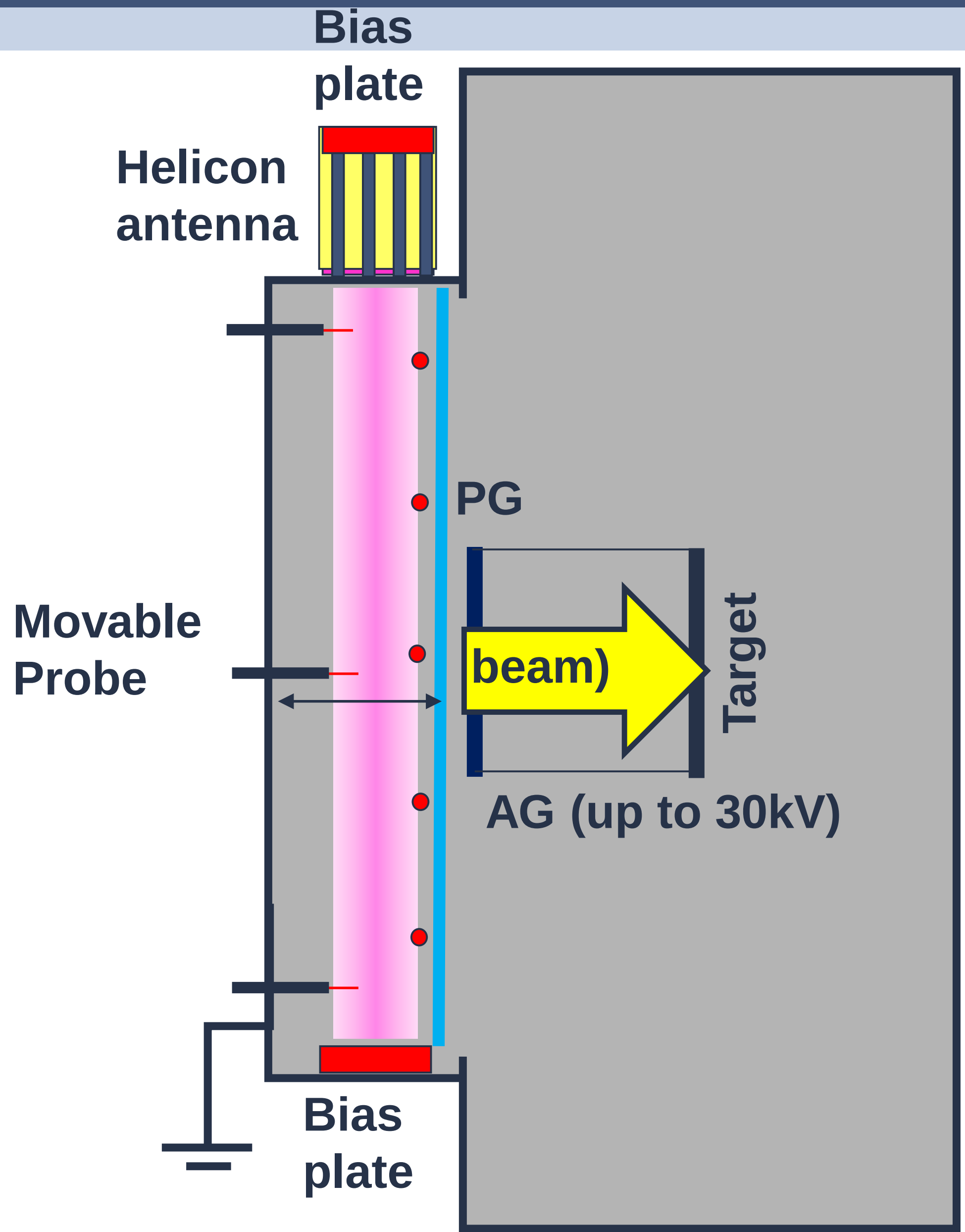




Two magnetic configurations

Lateral and Helmholtz coils

Experimental setup Lateral coils



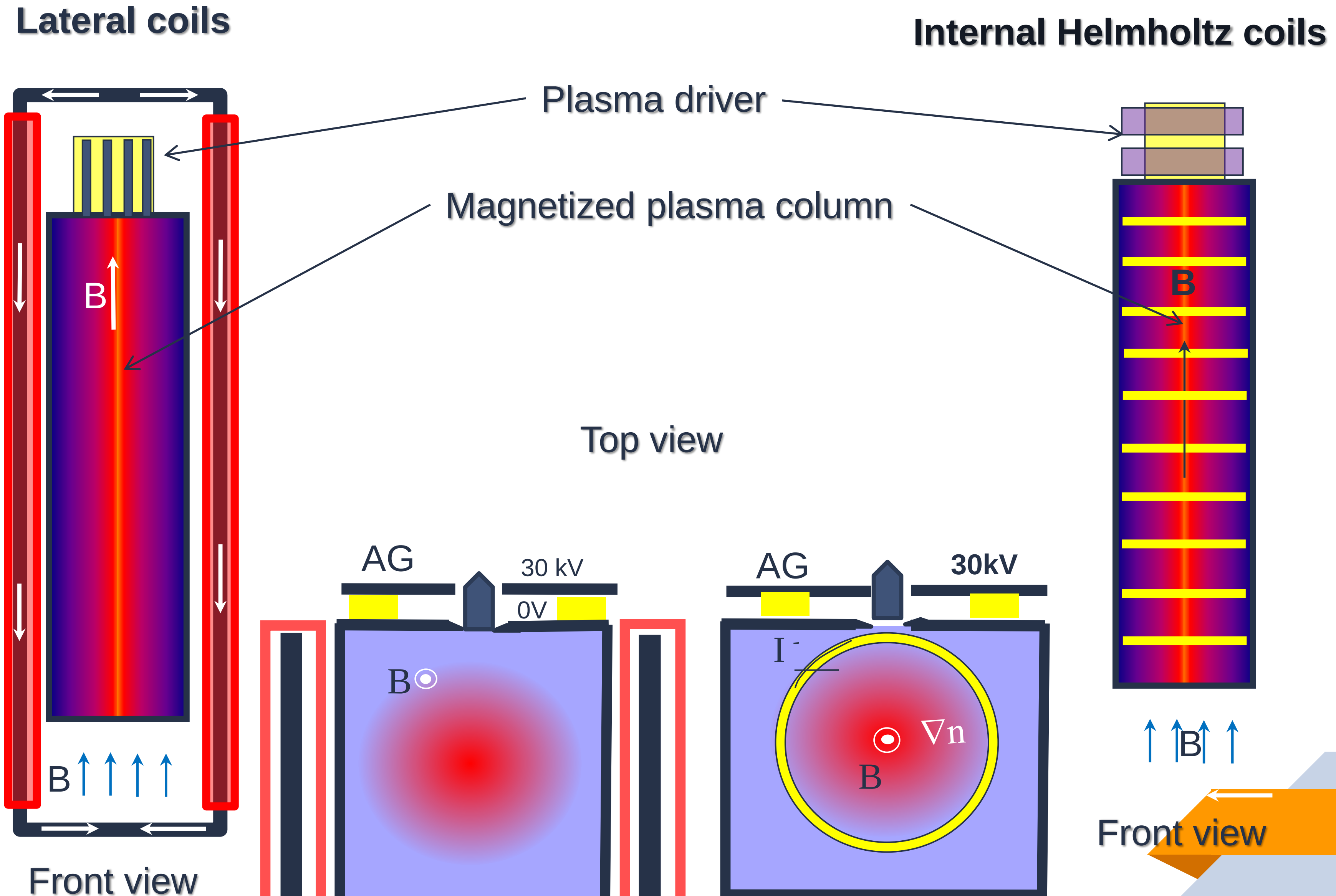
Source side view

Experimental conditions:
Magnetic field – 100 G
RF power – 3kW
Gas pressure - ~ 0.3 Pa (H)
Bias plates : 0V : -90V
Plasma Grid : grounded, floating , +5V

Movable probe can move from the wall to the PG
Vertical measurements

Five fixed probes for vertical measurements

Two magnetic field topologies compatible with implementation of an accelerator



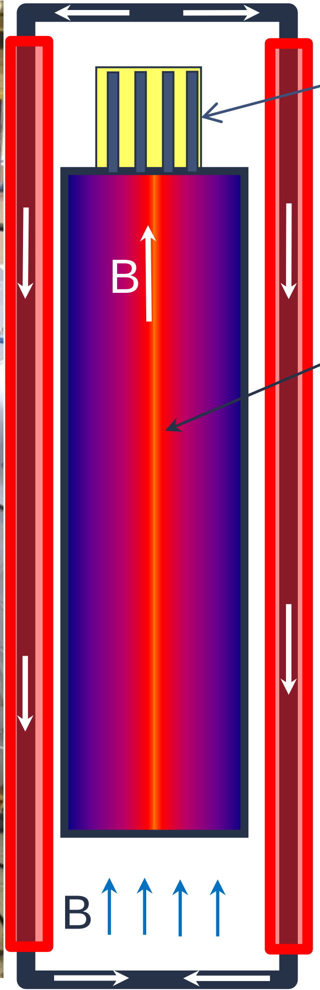
Experimental setup 2018

Lateral coils

B~100 G

Internal Helmholtz coils

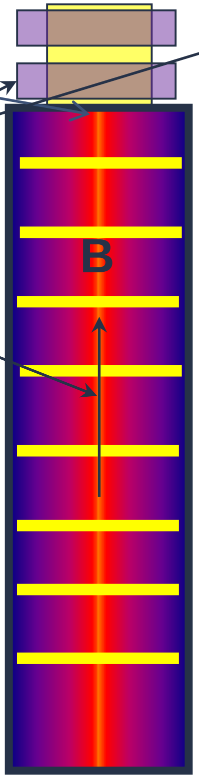
B_{axis} ~100-160 G



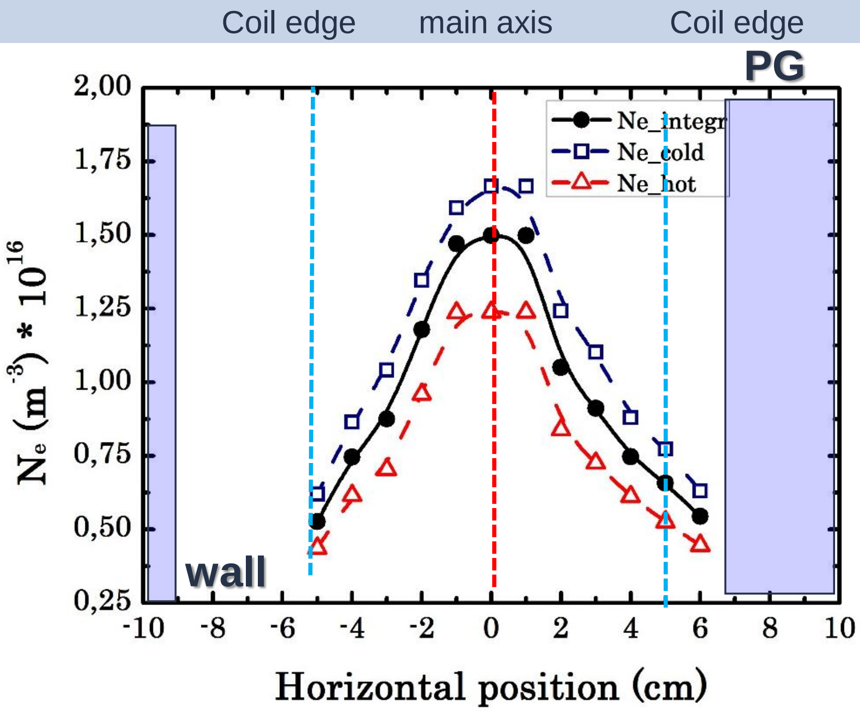
Helicon antenna

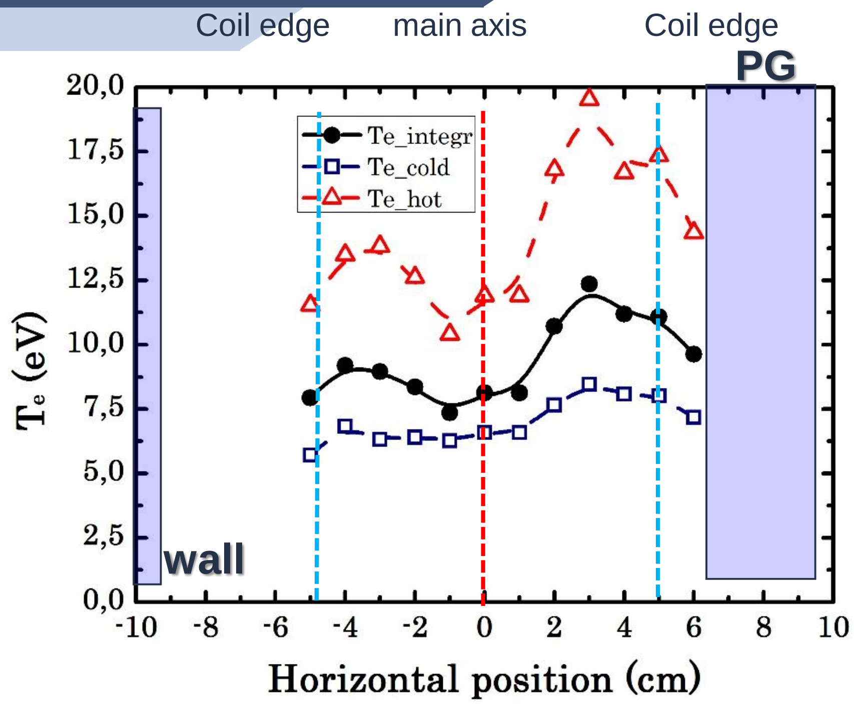
Solenoid around antenna

Magnetized plasma column



Plasma characterization with Langmuir probes (Horizontal plasma distribution)

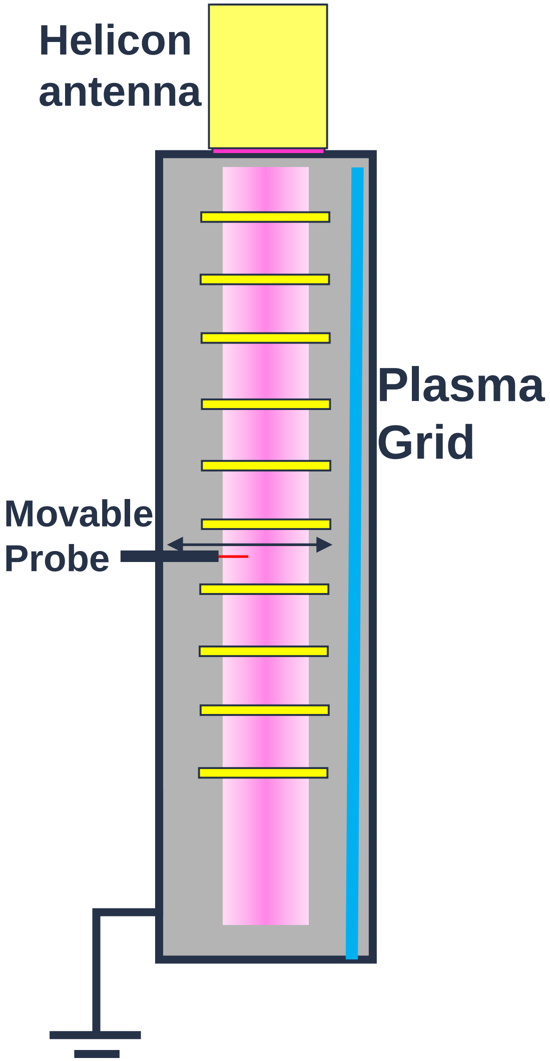


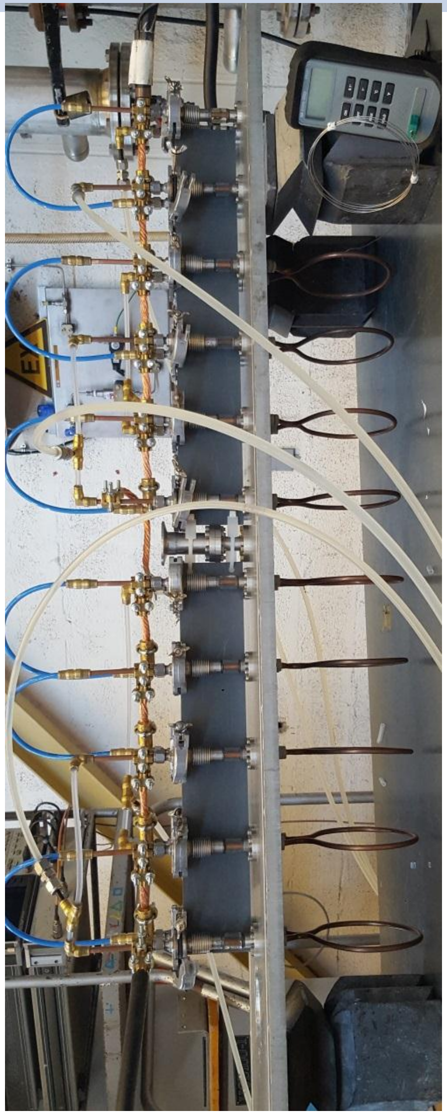


-i) Plasma density is peaked (nearly Gaussian profile)

-ii) For the same operating conditions low n_e~**1.5*10^{16} m^{-3}** (compared to ~10^{18} m^{-3} RAID EPLF)

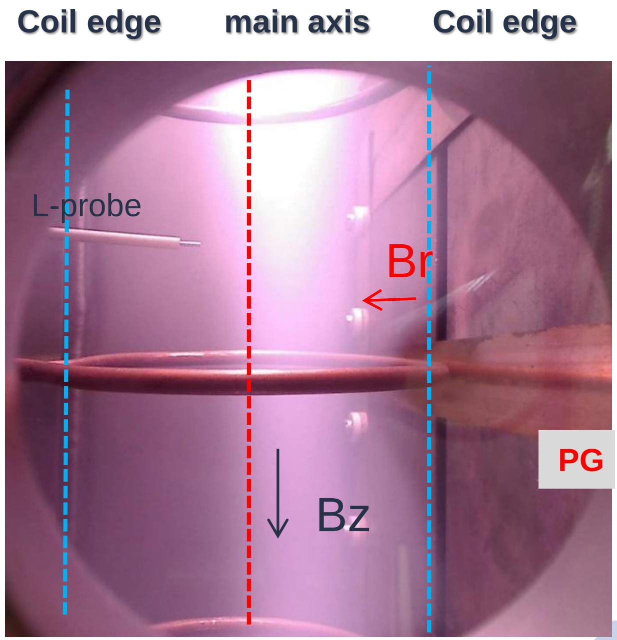
Plasma characterization with Internal Helmholtz coils



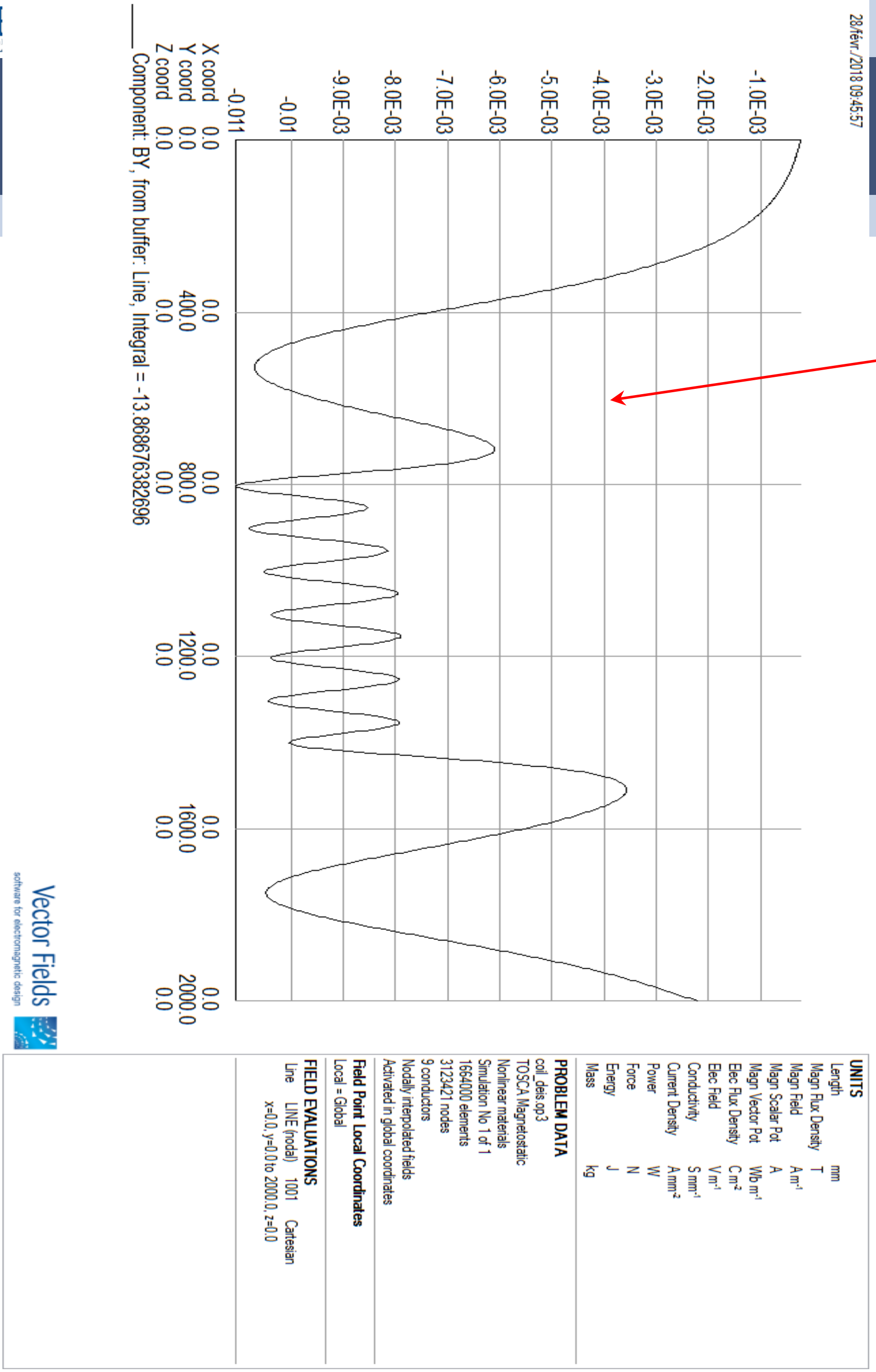


Top view

1000A ~ B=100G



Significant modulation of B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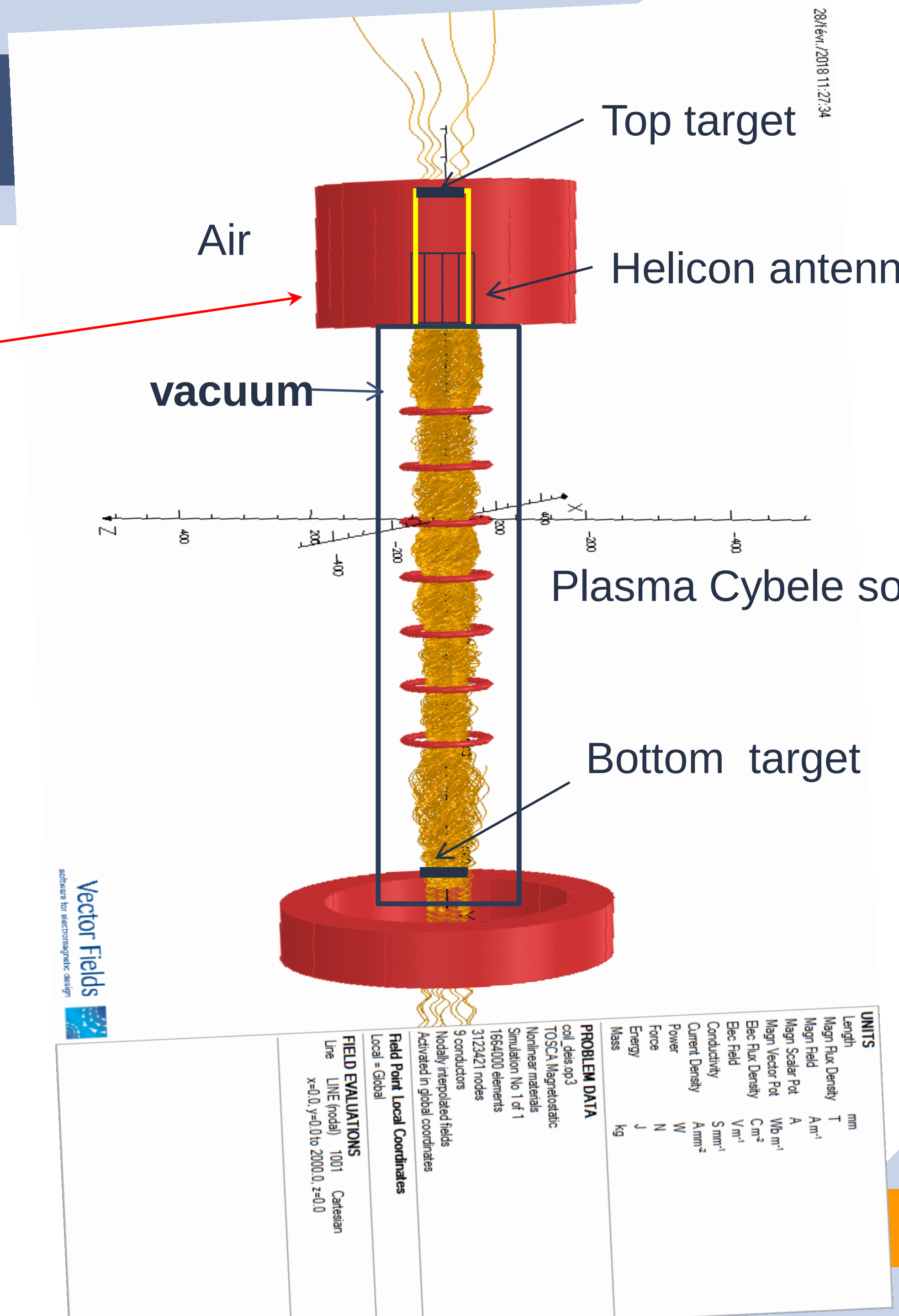
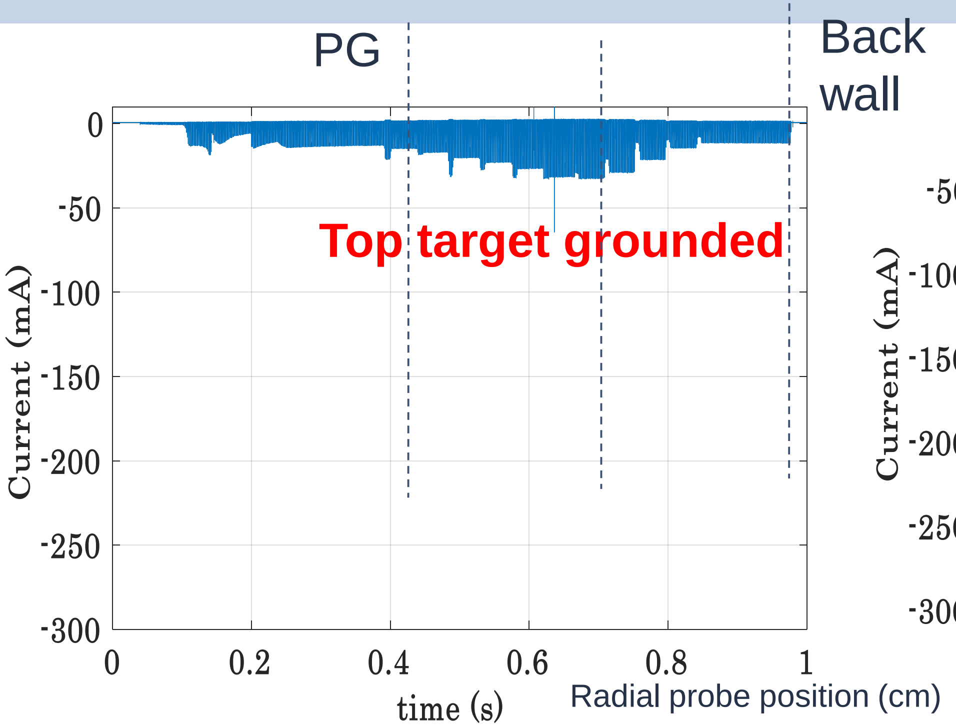
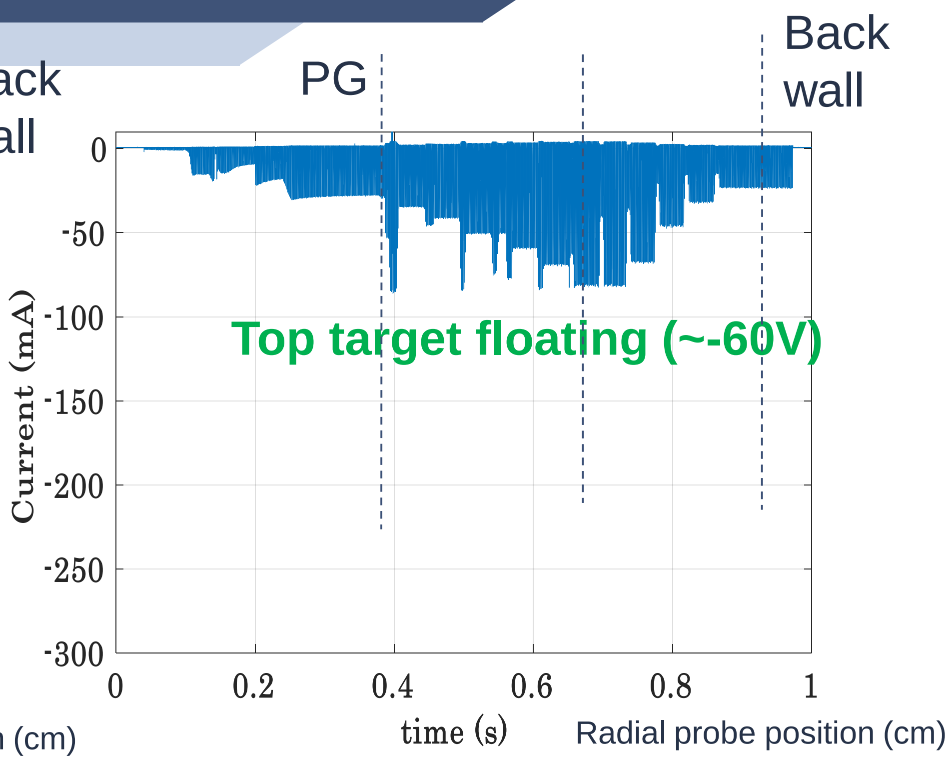
Component: BY, from buffer: Line, Integral = -13.868676382696
Vector Fields
software for electromagnetic design


28/févr./2018 11:27:34
Top target
Air
Helicon antenna
vacuum
Plasma Cybele source
Bottom target
Vector Fields
software for electromagnetic design

Effect of the Top target polarization on the plasma density (ne) in the source volume?





With grounded target (high conductance for plasma electrons), plasma attenuated (factor 3) in the source volume

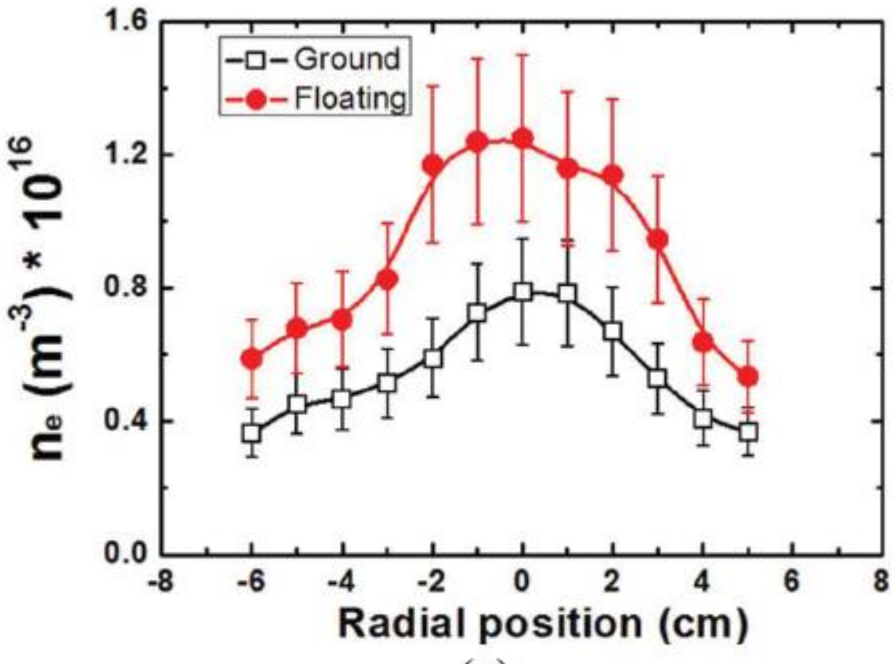
With grounded target, the plasma is probably very dense => RF power absorption

=> Low RF power in the source volume

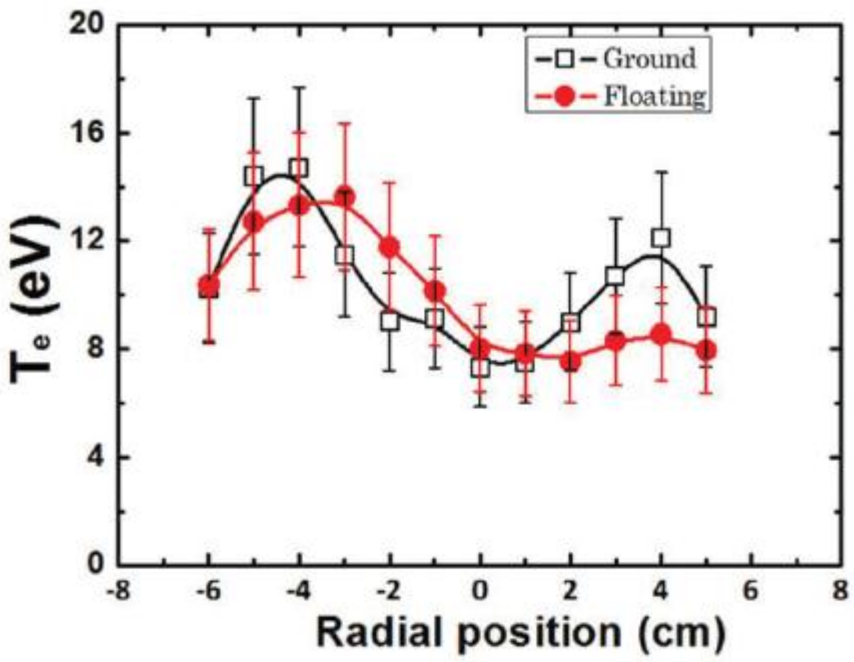
Note: Observation of metal coating on the ceramic (sputtering of Mo from the target)

=> High and hot plasma above the antenna

Comparison

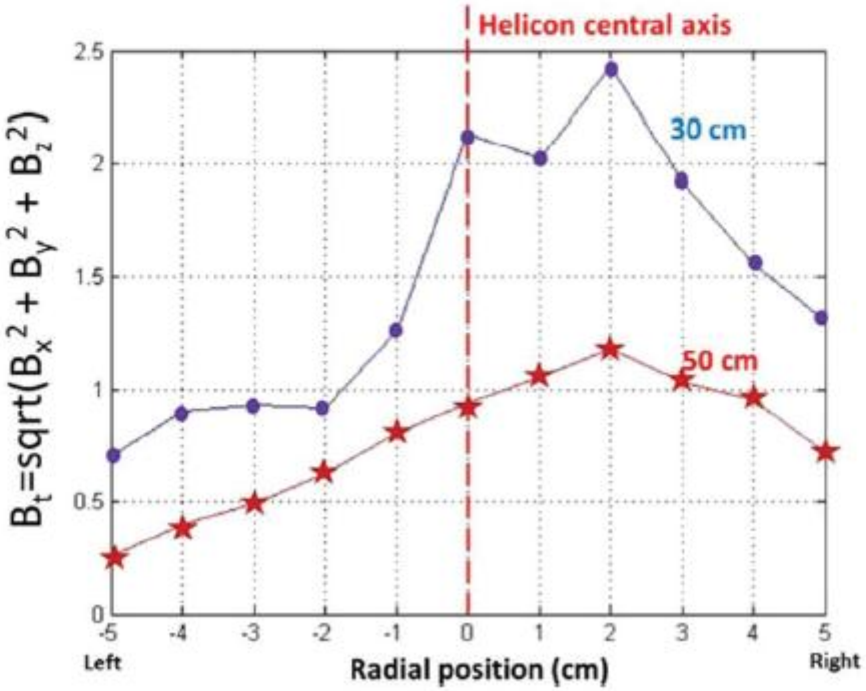


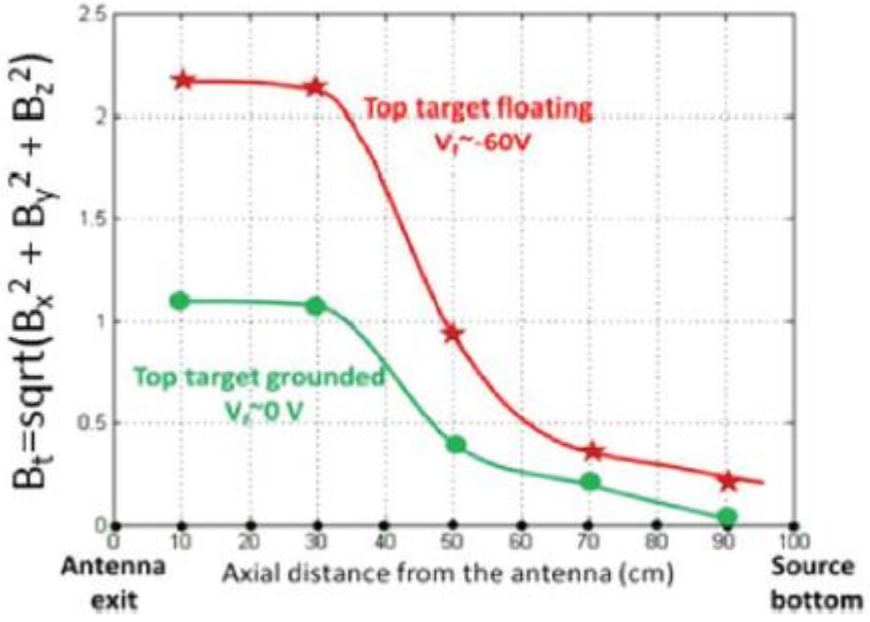
(a)



(b)

Magnetic field





Bdot measurements

Bdot probe at the <u>Helicon exit</u>

Grounded

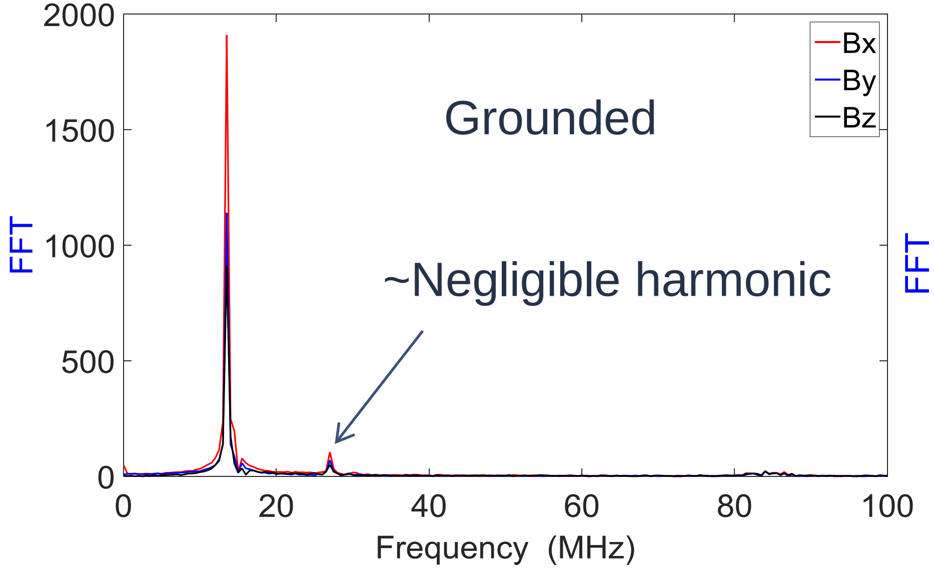
Vcoil = 8.4V
Bx= 1,9 V
By= 1,2 V
Bz= 0,89 V

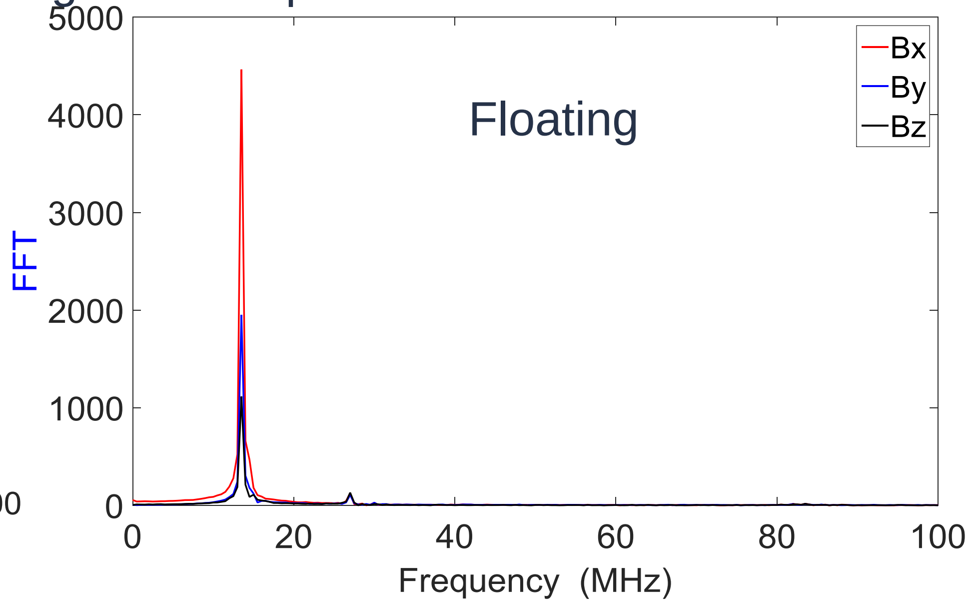
Floating

Vcoil= 8,7V
Bx= 3,66 V
By= 2,12 V
Bz= 1,96 V

Bdot probe at mid-height

FFT of the wave signal in the plasma center





A helicon wave probably propagates above the antenna (enhanced with target grounded) and absorb the RF power

$\Rightarrow$ Need to block the formation of the helicon wave and plasma on the top

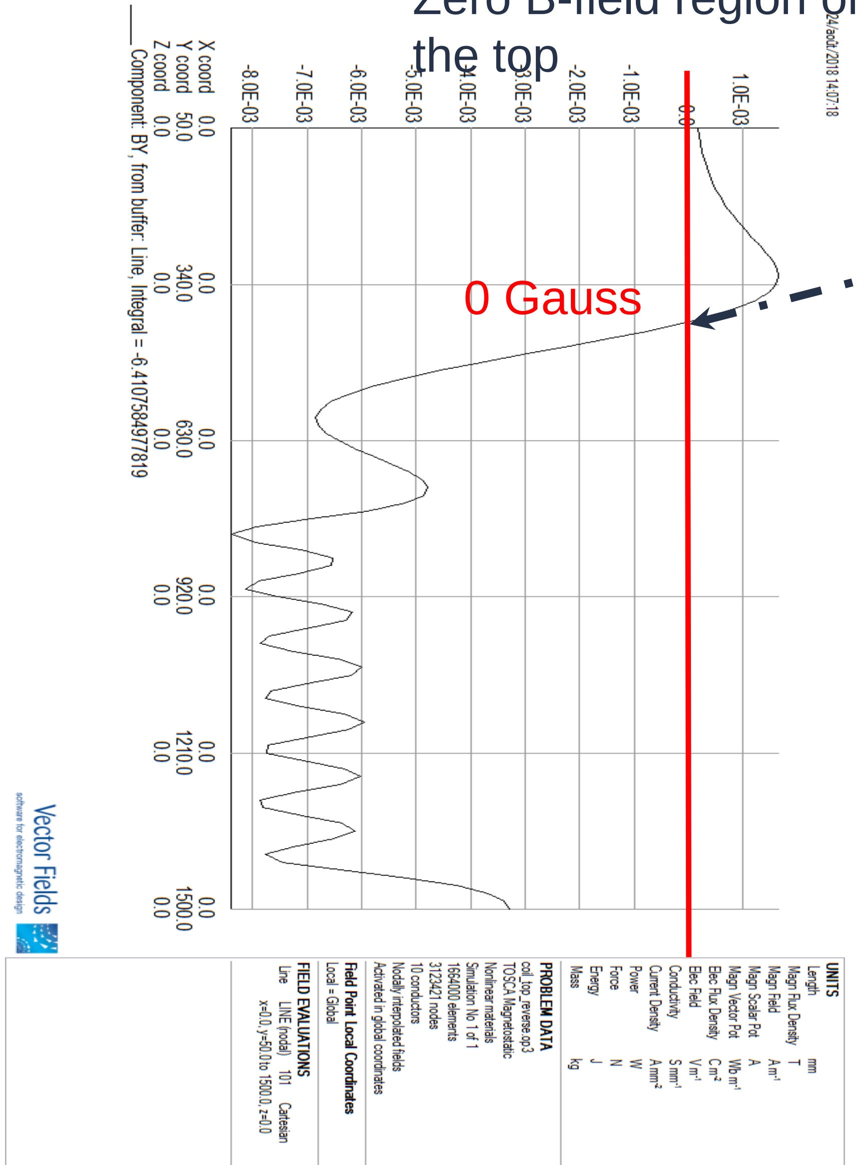
$\Rightarrow$ Zero B-field region on the top => **Need modification of the top coil**

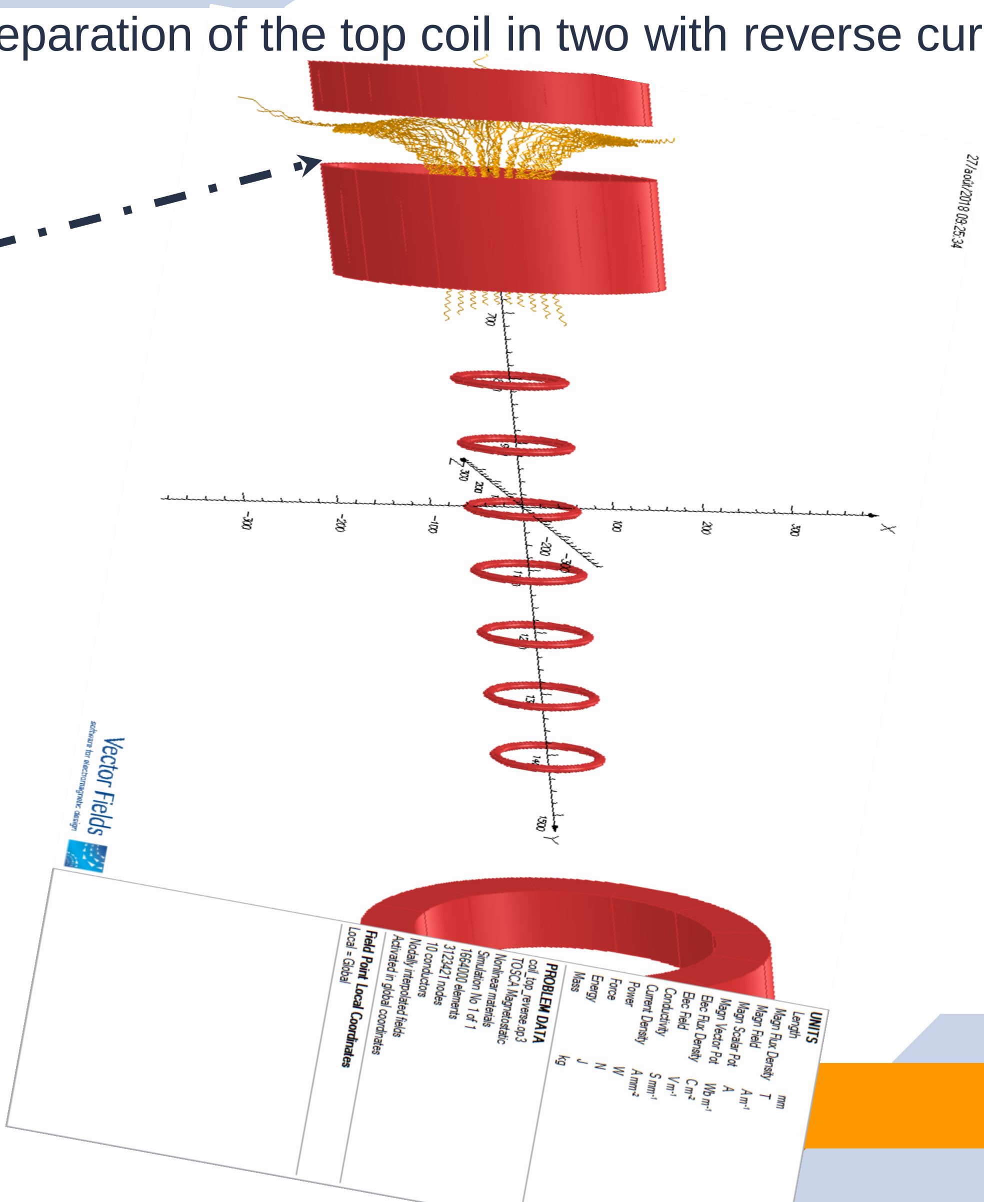
Reversed Magnetic field

around antenna

Modification of the top coil

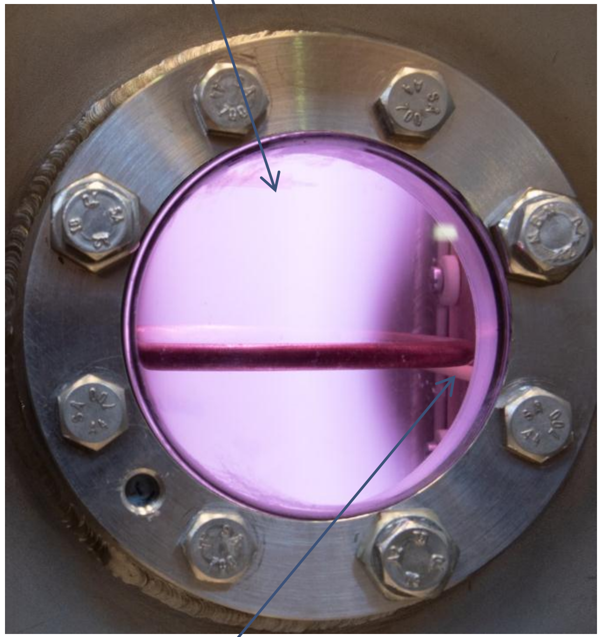
Zero B-field region on the top => separation of the top coil in two with reverse current on the top



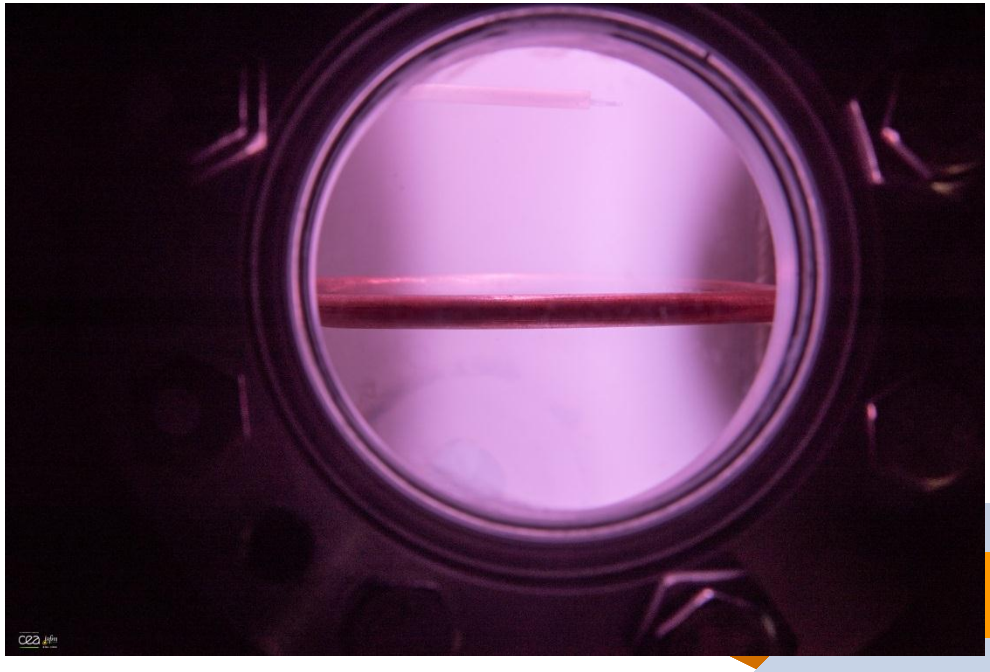


Evidence of brighter plasma

Movable langmuir probe
Plasma perturbation ?



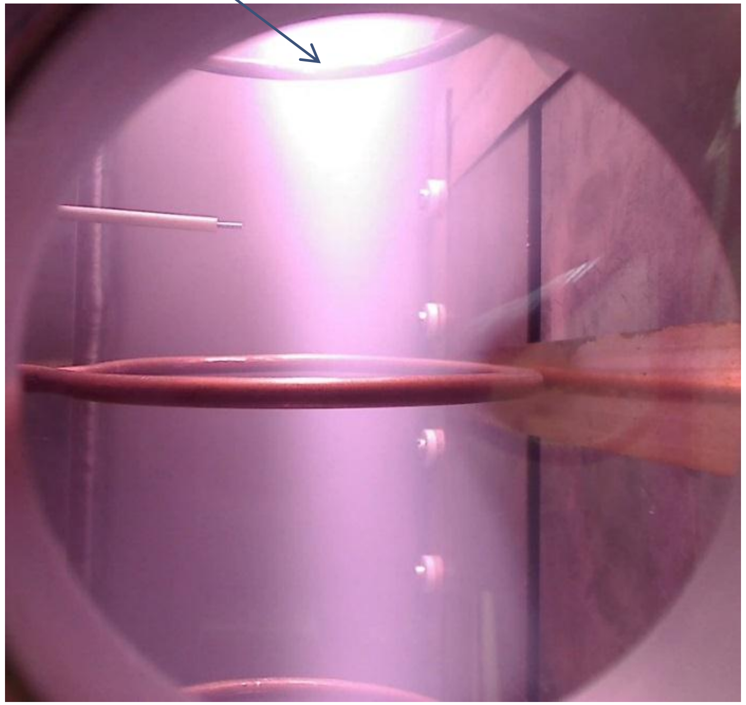
Transvserse probe
(1 cm from PG)



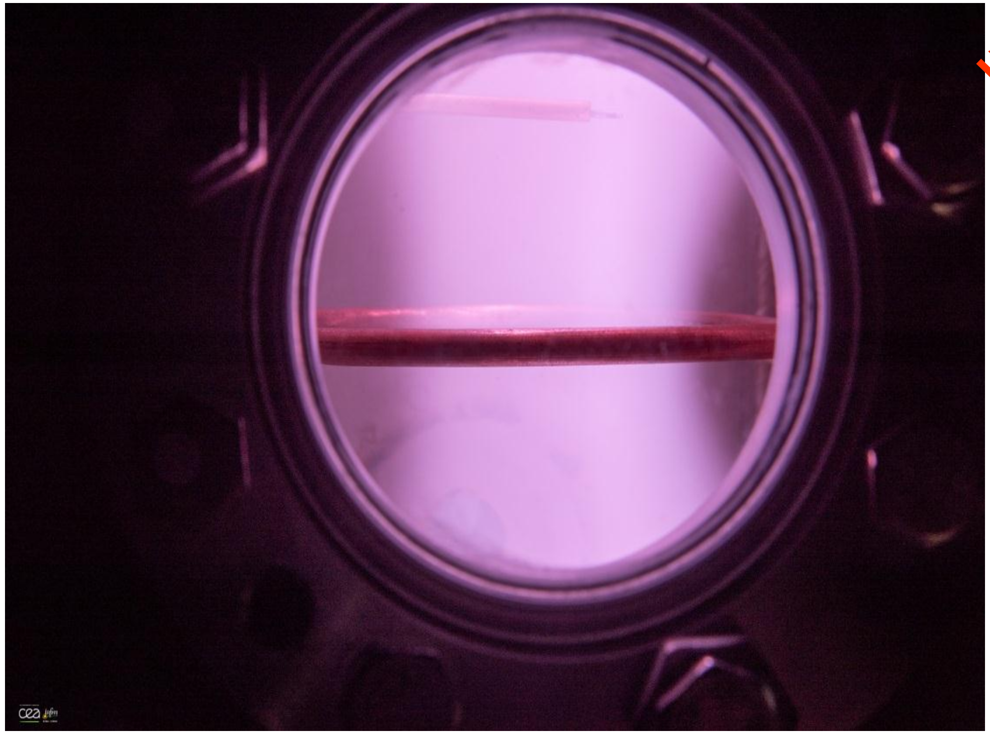
Effect of the reversed field around the helicon antenna

Before

Light from the plasma on the Top



No light from the plasma on the Top !



After

$V_{floating}$ on the top target: **~-60 V**

Target floating: $V_{floating}$: **~-13**

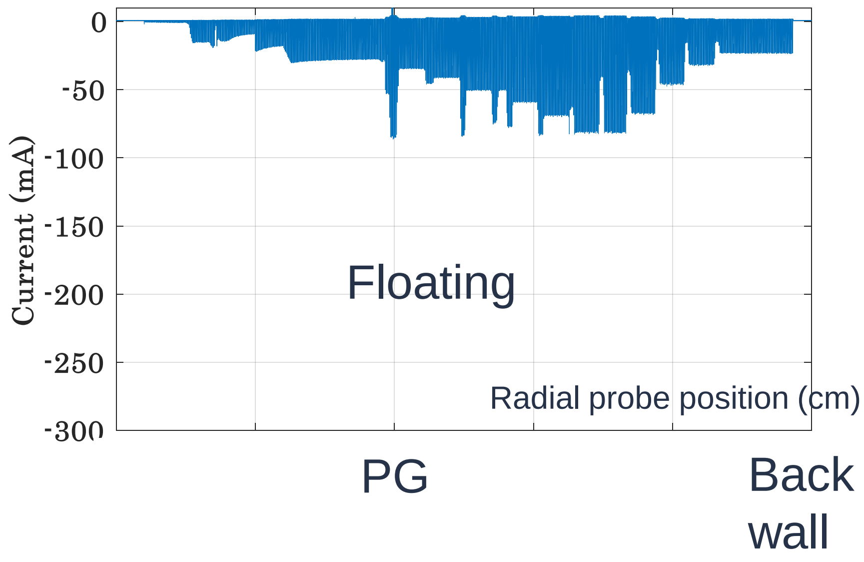
=> It remains a plasma between the antenna and target !!

Target grounded: no effect on the plasma parameters

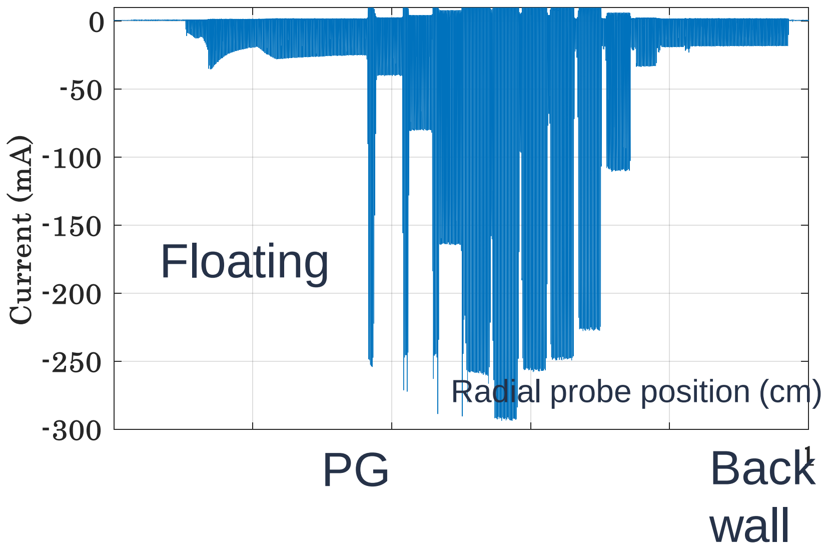
=> quite the same ne, Te, VP in the source volume

Measurement of the plasma parameters with the movable LP

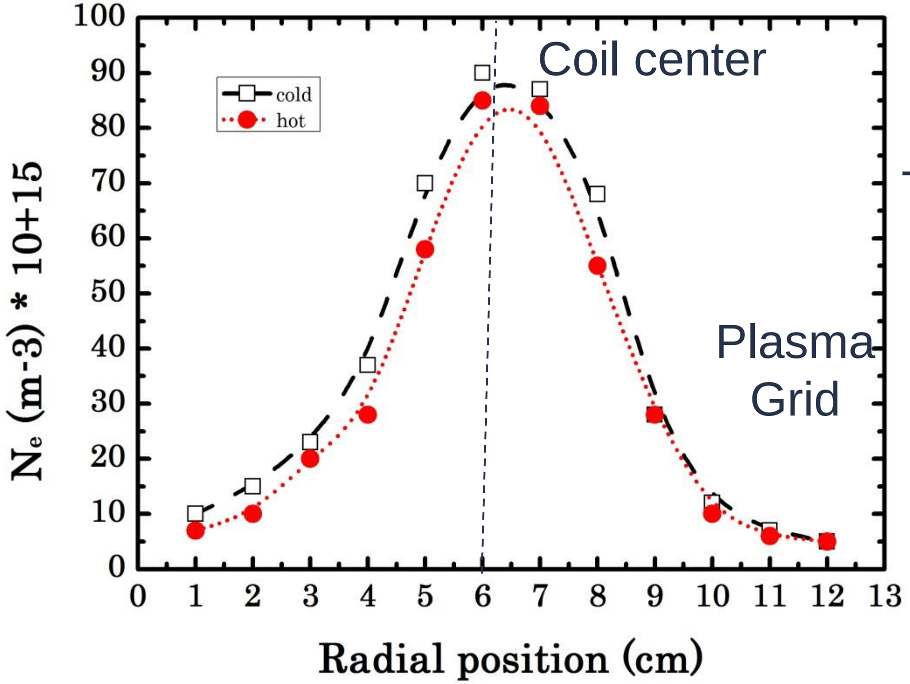
Before

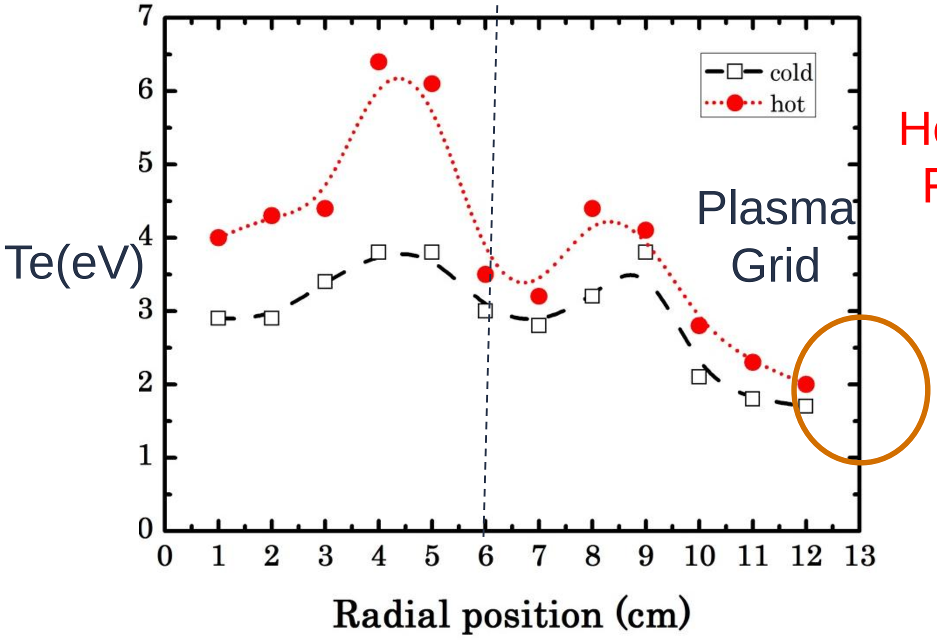


After



Electron density & temperature



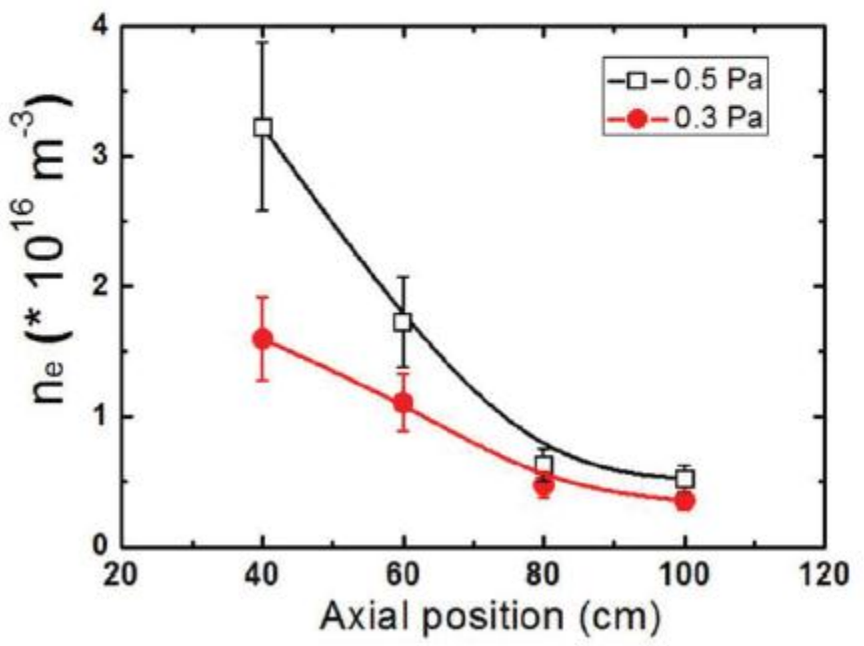


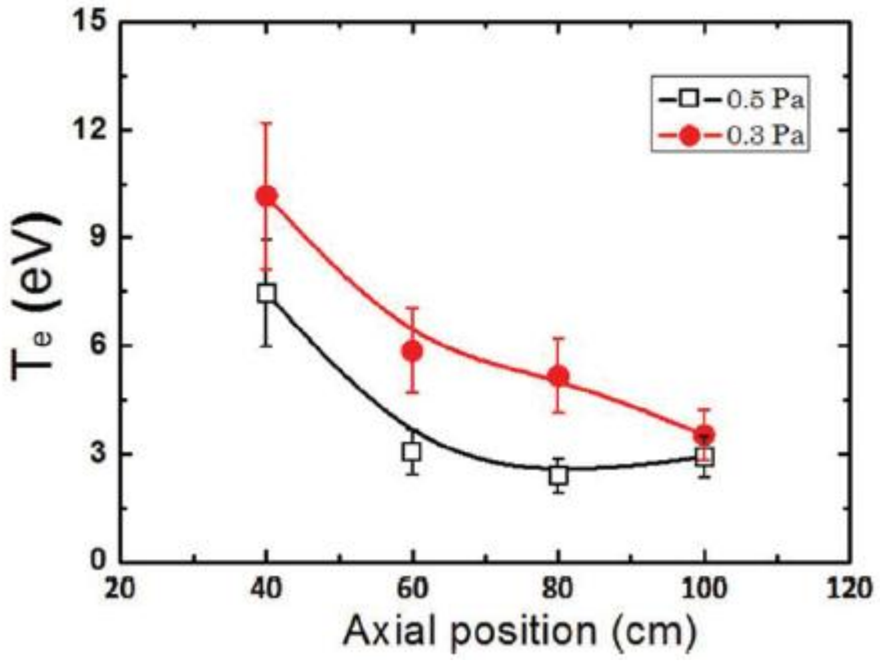
Radial Plasma parameters (after):
P_{RF}= 3 kW;
Top coil: 50 Gauss,
Helmholtz coils: 117 Gauss
Ps~2,5 µbar, Shot≠ 1943

-) Radial distribution of the plasma potential constant : No plasma fluctuation measured with the probe and high speed camera

~ 2 eV at the edge

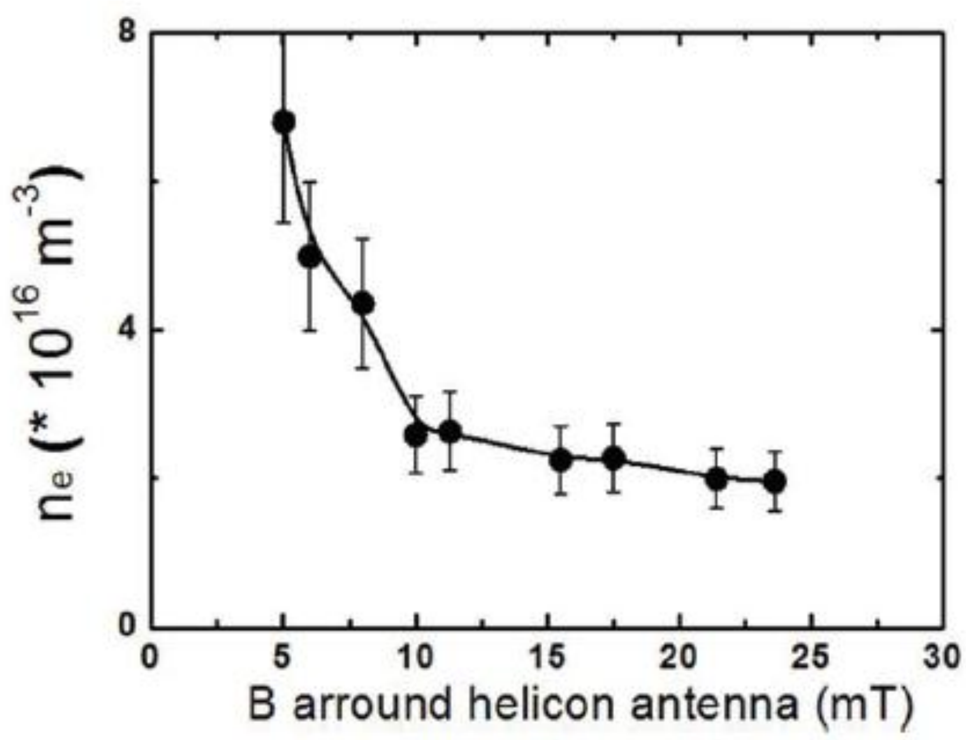
Effect of gas pressure on the plasma parameters

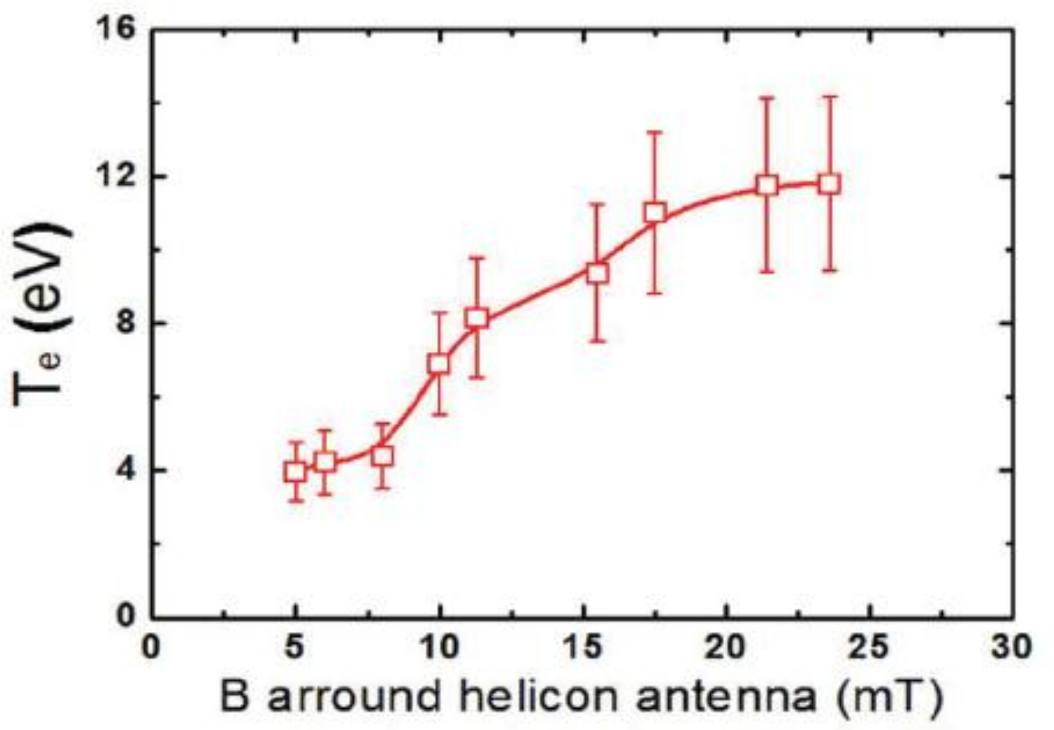




Effect of the B-field on the plasma parameters: P_{RF}= 1.5 kW
Scan of the B-field intensity around the antenna (Top solenoid)

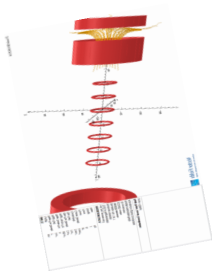
Langmuir probe in the plasma center

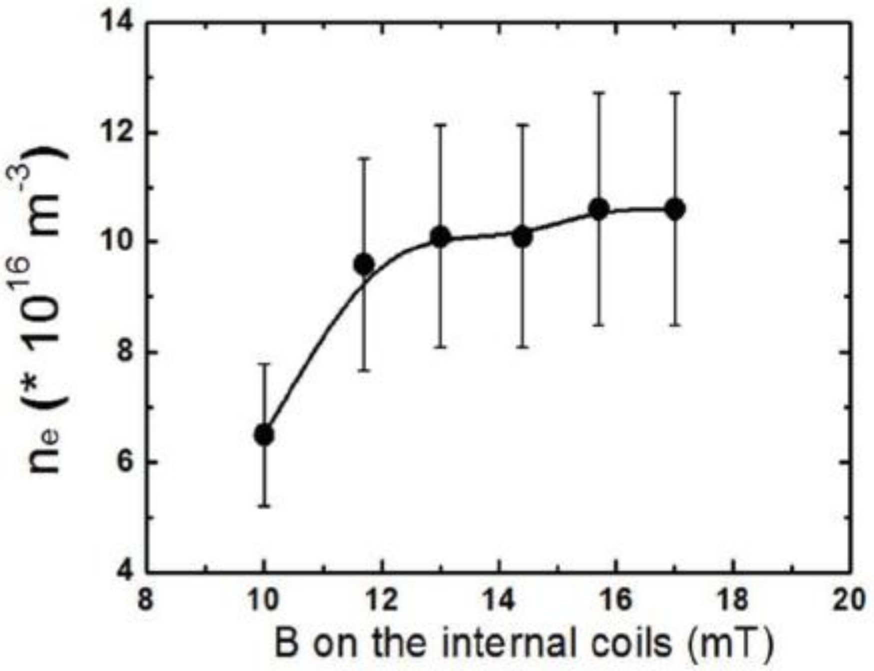


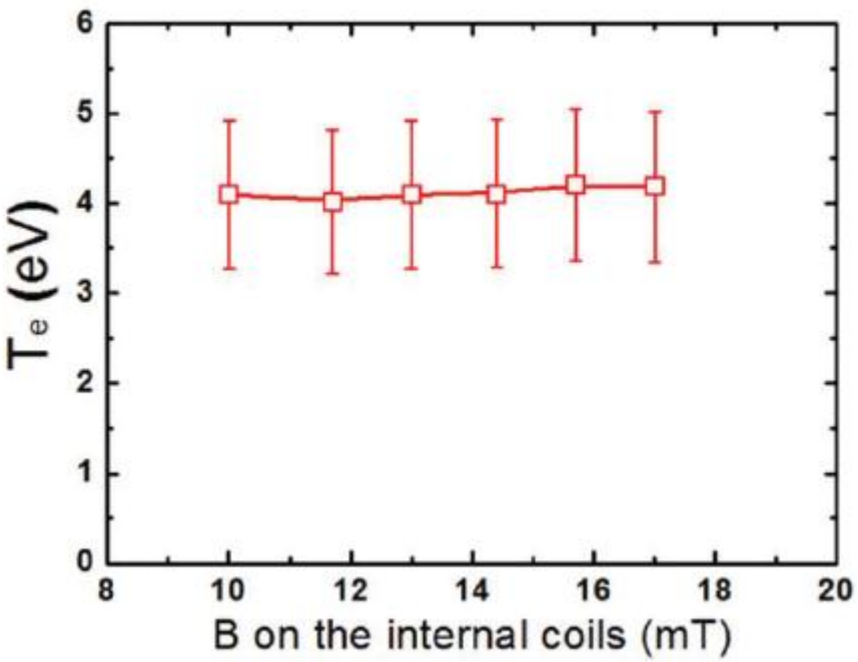


Effect of the B-field on the palsma parameters: P_{RF}= 1.5 kW
Scan of the internal Helmholtz coils with 50 Gauss on the Top

Langmuir probe in the plasma center

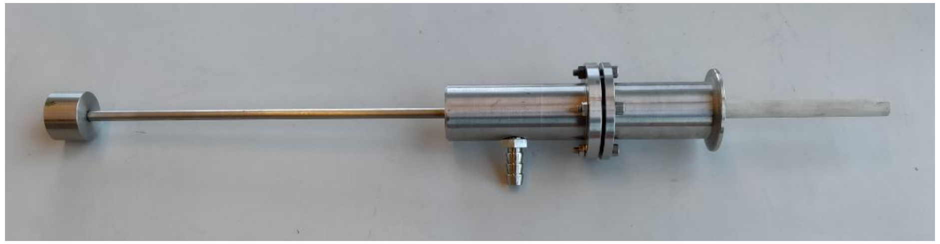




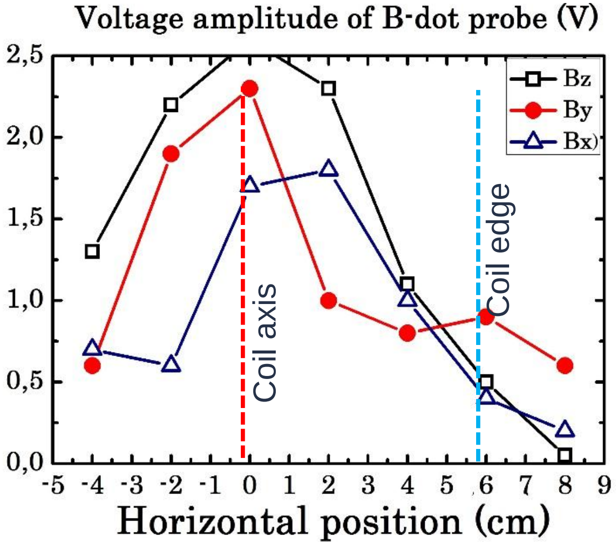


Helicon wave propagation (Helmholtz coils)
Wave characterization in the plasma column

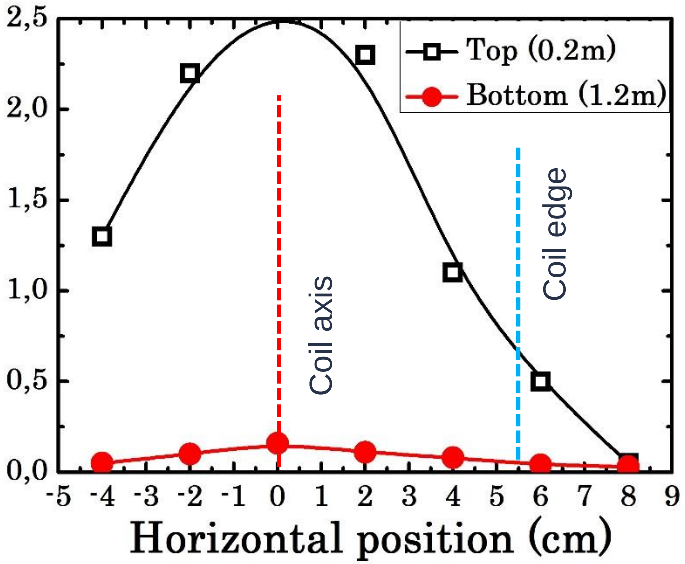
The B-dot probe (provided by EPFL)



Three components of the Helicon wave measured



Radial Amplitude of Bz (V)



Damping of the helicon waves

Along the column (Top to bottom)

Comparison between different configurations

Table 1. Comparison of the plasma parameters for different source configurations.

Configurations	n_e, centre (m^{-3})	T_e, centre (eV)	n_e, edge (m^{-3})	T_e, edge (eV)
Grounded	7.9×10^{15}	7.3	3.7×10^{15}	10.27
Floating	1.25×10^{16}	8	5.9×10^{15}	10.4
Reversed B	1.13×10^{17}	3.25	6.5×10^{15}	2.3

Gas temperature measurements

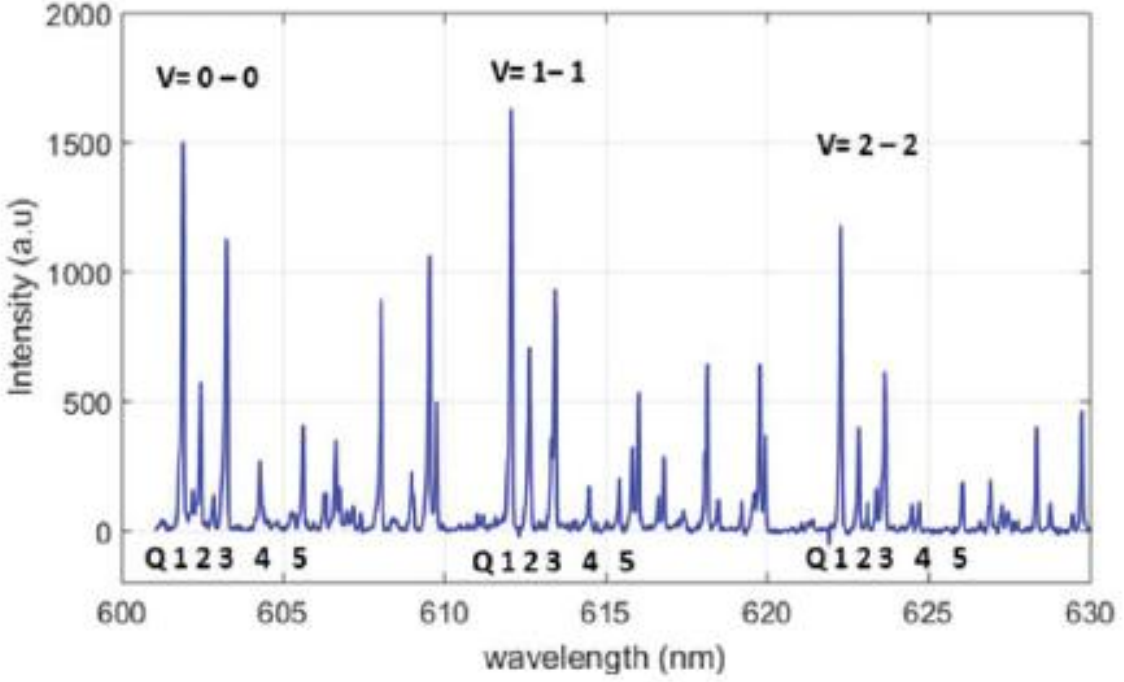
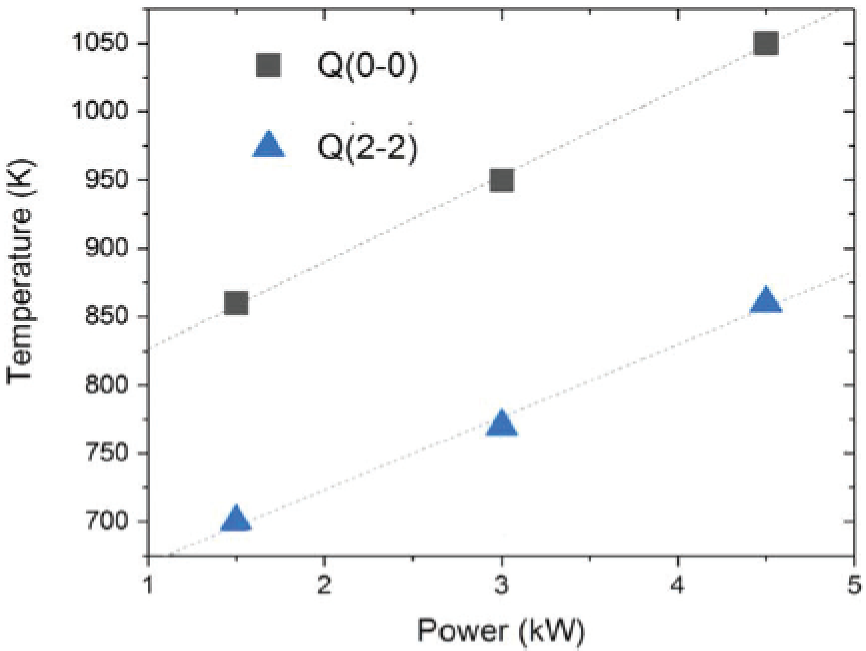


Figure 22. Spectrum of the Fulcher-α $\Delta v = 0$, 1 and 3 branches with labelled lines used for calculation of rotational temperature. The experimental conditions are 3 kW of RF power, 0.3 Pa H pressure and 10 mT magnetic field in the floating configuration.



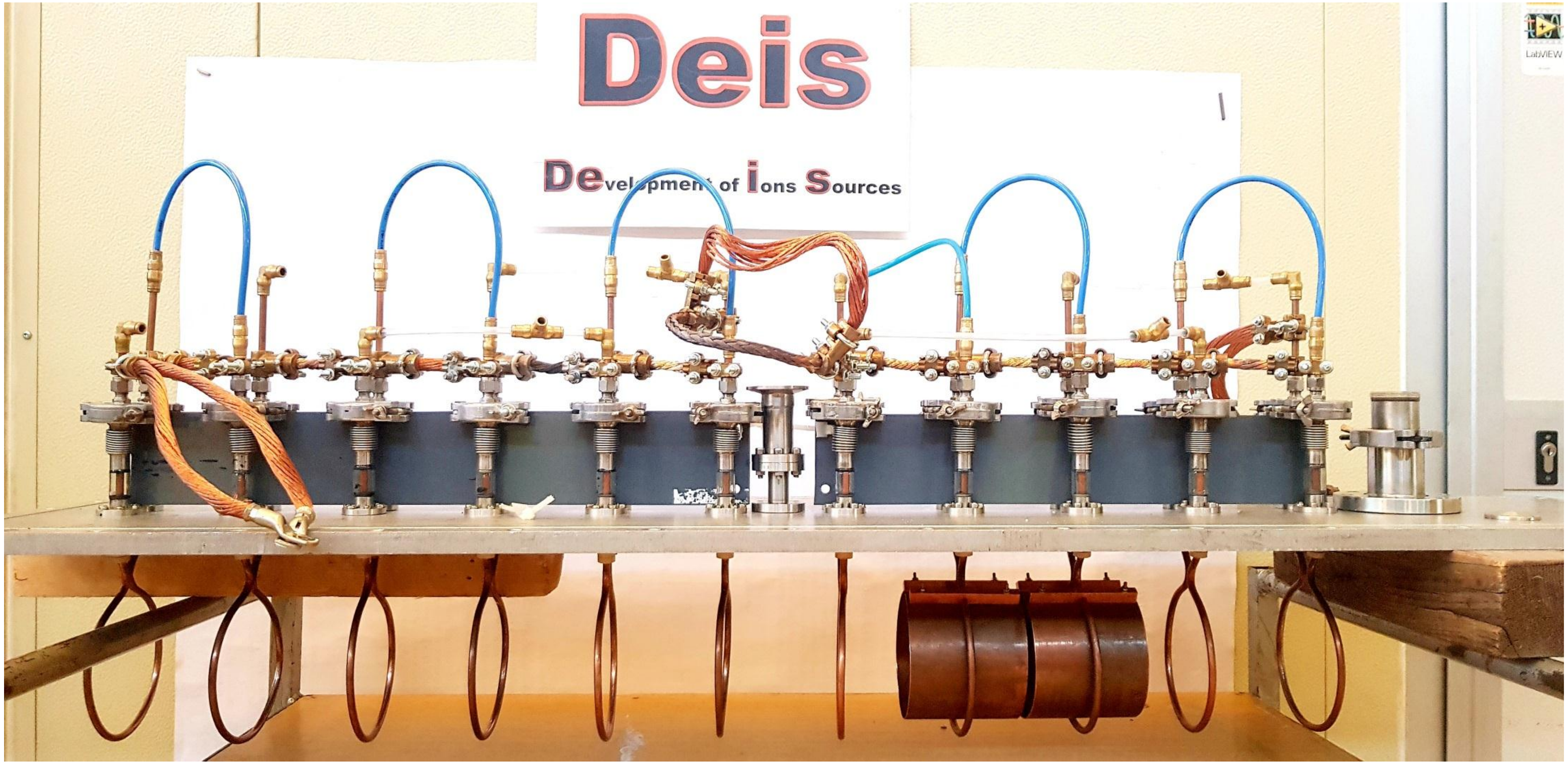
✓ we also have measured slightly higher T_g value when the end-plate was floating than for the grounded condition.

Conclusions

- Two specific magnetic field configurations (Lateral coil and set of Helmholtz coils) were tested.

- 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 –ve ions.
-
- A new magnetic configuration composed of Helmholtz coils implanted within the source vacuum chamber , tested and characterized.

- 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.
- A reversed magnetic field around the helicon antenna has been tested and characterized
- It gives a dense plasma column and less electron temperature at the edge which can be used for production of –ve ions.


Deis
Development of ions Sources
LabVIEW

THANKS!

Any questions?

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