# Recent results of NIO1 negative ion source and future improvements

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# NIO1 Characteristics and Scopes

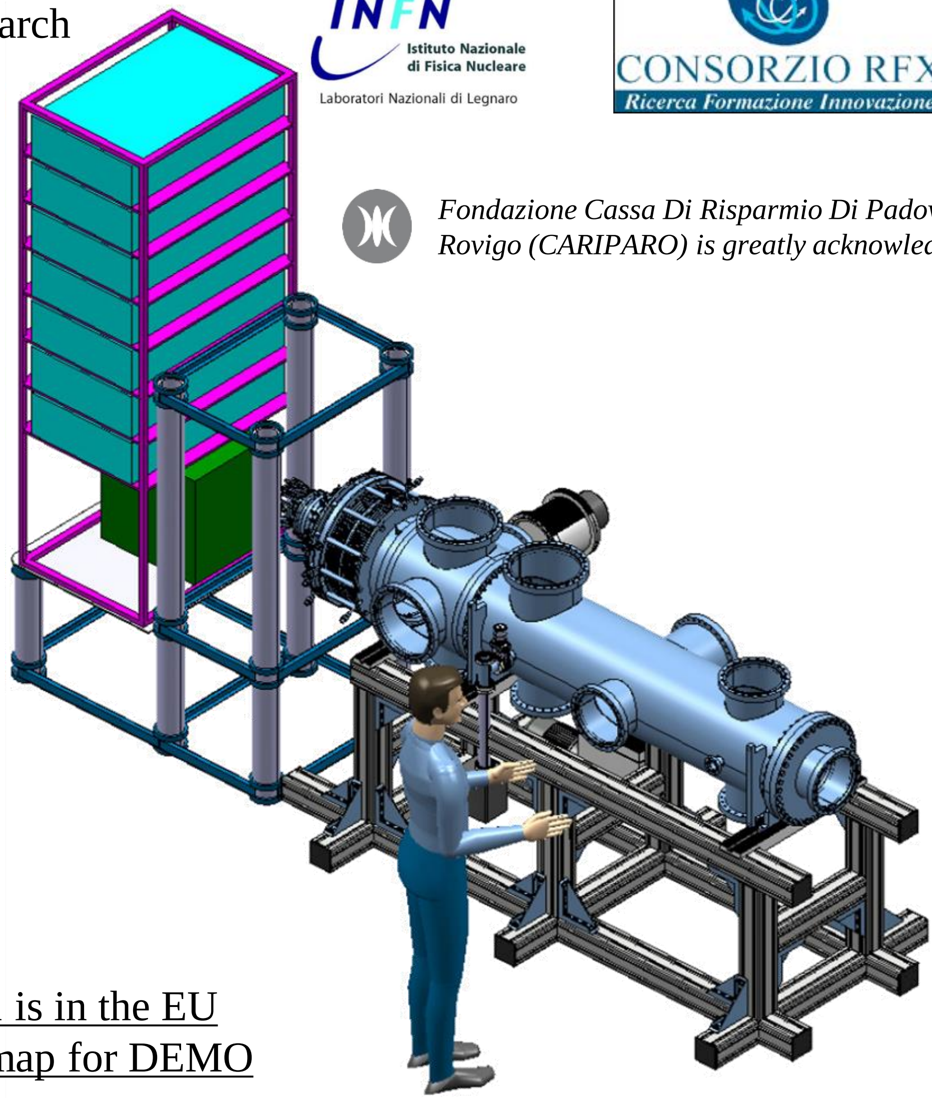
## NIO1: a Compact Negative Ion Source

- Developed in the context of nuclear fusion research
- Installed at Padova (CNR area)
- ICP Plasma
- 2.5 kW RF Power (f=2 MHz)
- Max beam energy: 60kV
- Max beam current:135mA
- Continuous operation
- Cs enhanced H- production

*Fondazione Cassa Di Risparmio Di Padova e Rovigo (CARIPARO) is greatly acknowledged*

## Scopes

- Physics of Negative ion formation and extraction
- Code Benchmark and validation
- Test Advanced concepts:
  - Alternative to Cesium
  - Energy Recovery system



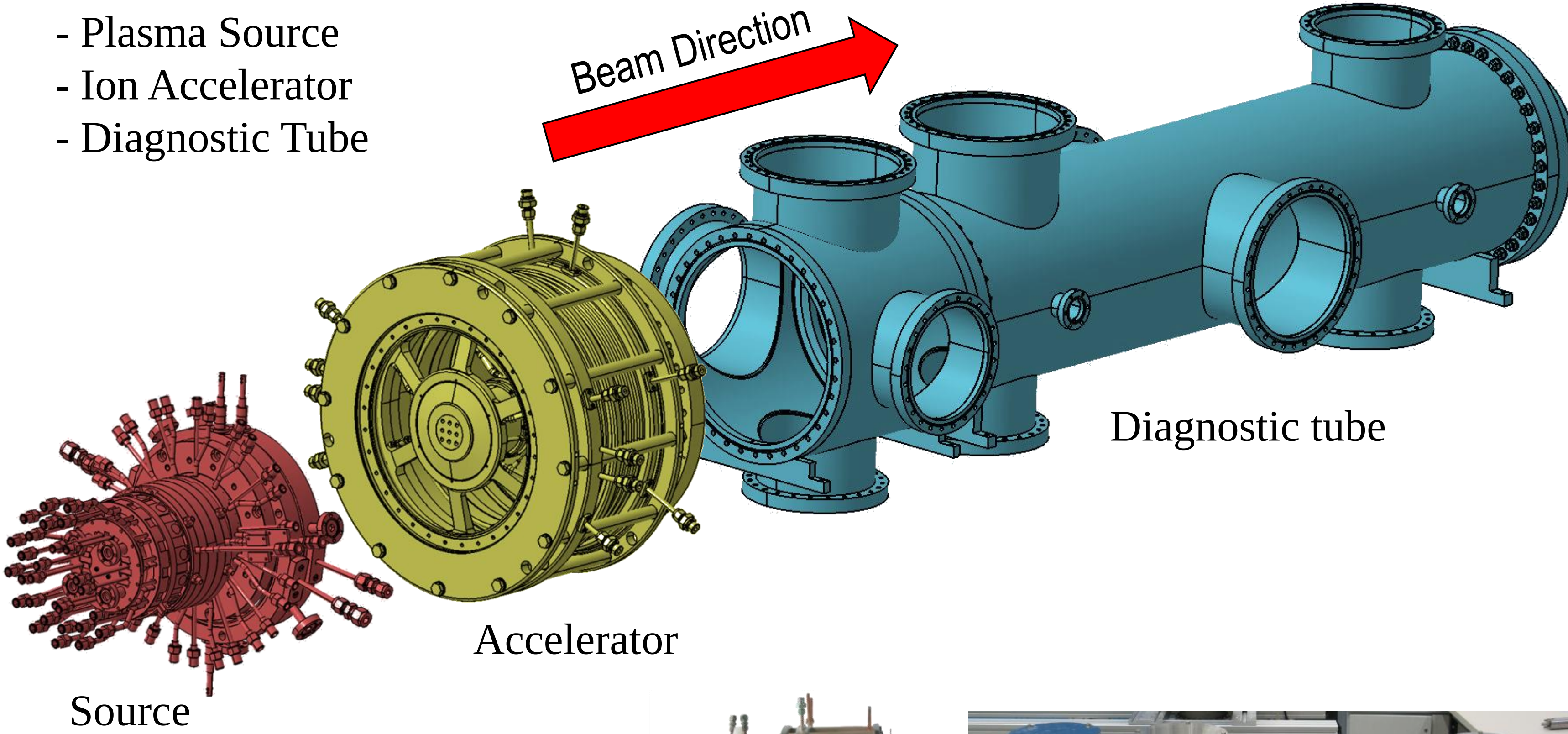
## Presentation Outline

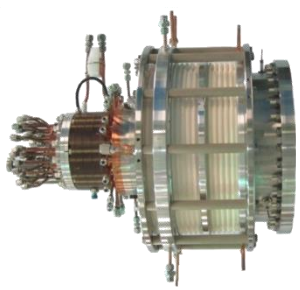
- Description of Experiment
- Status and experimental results
- Future improvements

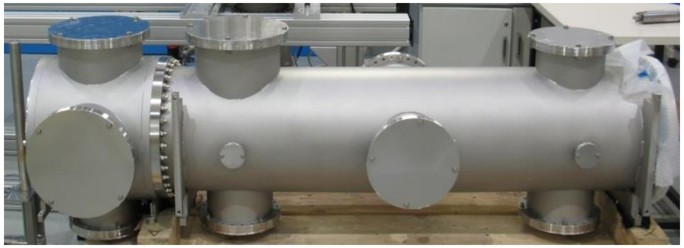
<u>NIO1 is in the EU roadmap for DEMO</u>

# Overview

- The core of experimental set-up can be divided in 3 functional parts:
  - Plasma Source
  - Ion Accelerator
  - Diagnostic Tube



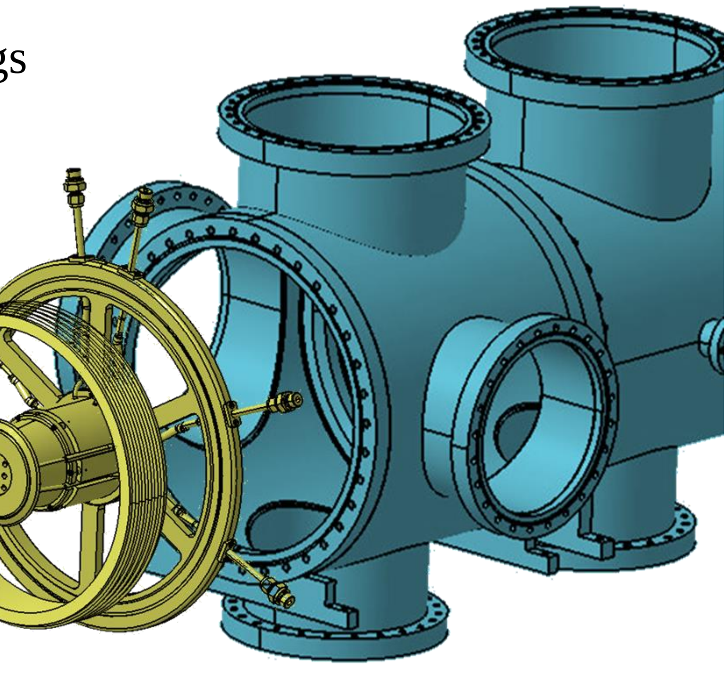



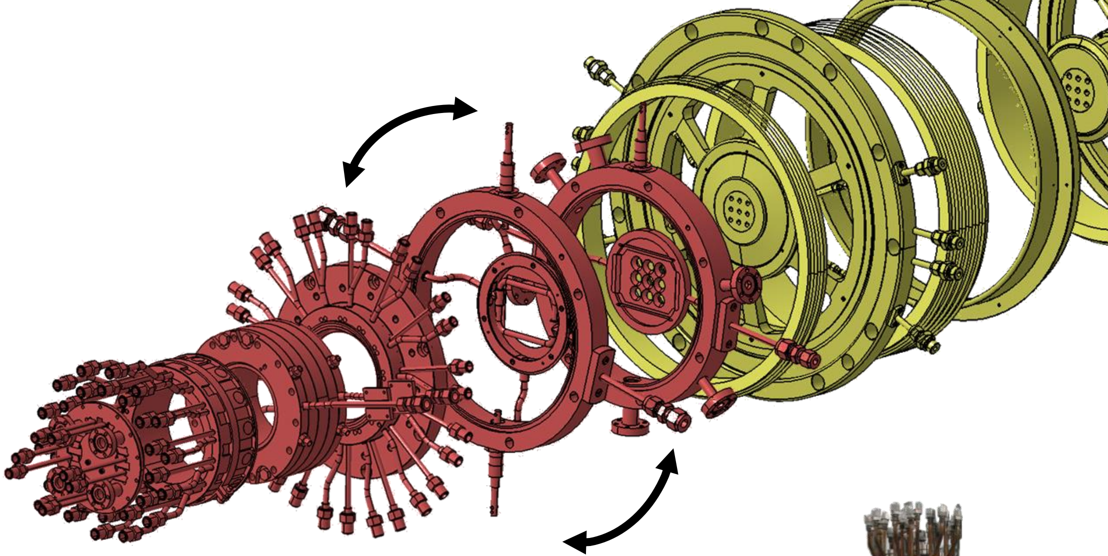



M. Cavenago et al. Rev. Sci. Instrum.81, 02A713 (2010)
M. Cavenago et al, AIP Conf. Proc. 1390, 640 (2011)
M. Cavenago et al., Rev. Sci. Instrum. 85, (2014)

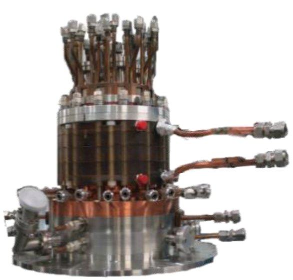
# Overview

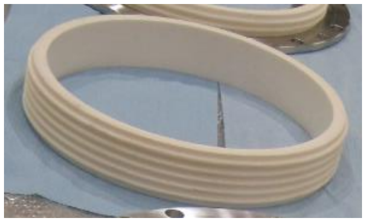
- Flexible modular design
- Source is a tower of disk assemblies connected by O-rings
- Accelerator includes separate modules held together by compression bars for mechanical and electrical rigidity (PEEK)
- HV Insulation by 3 alumina ring
- Modules sealed with elastomer O-rings

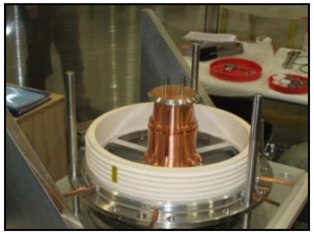


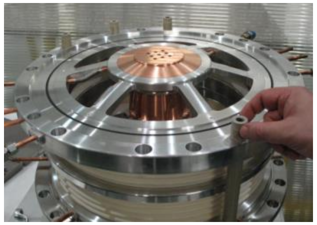


- Rotation of several parts by 90° is possible

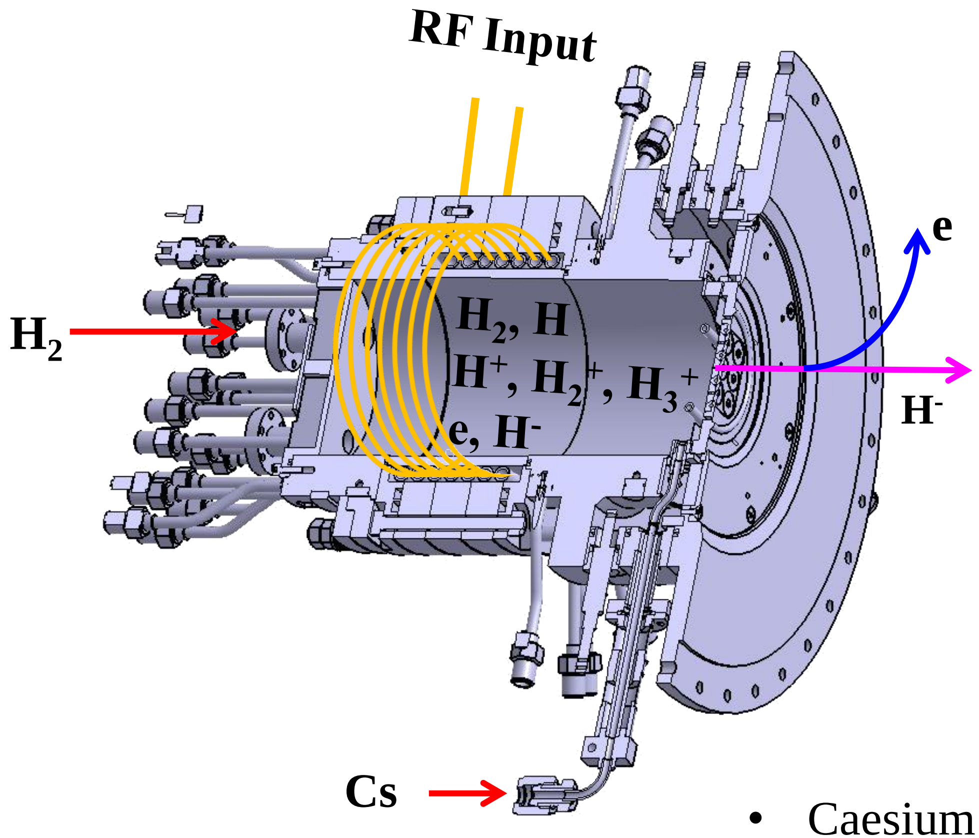








- Source itself is very modular:5 parts sealed by elastomer O-rings
- Copper gasket on CF16 Flanges (diagnostic ports and Cs oven)
- Plasma is generated in a  cylinder, R=5cm,L=20 cm
- Negative charges extracted by 3x3  apertures in the source front




- Source walls: copper alloy with molybdenum plating (sputtering!)

<u>The coil assembly</u>

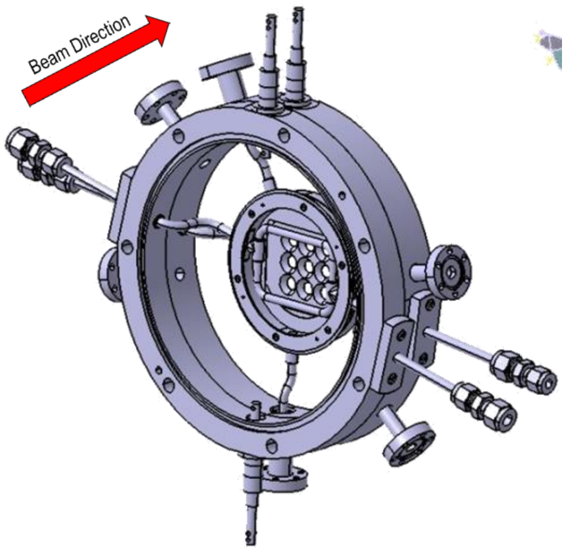
- 7 Turns copper wire, water cooled.
- Polysulfone shells to keep turns in place
- Alumina to insulate from the plasma

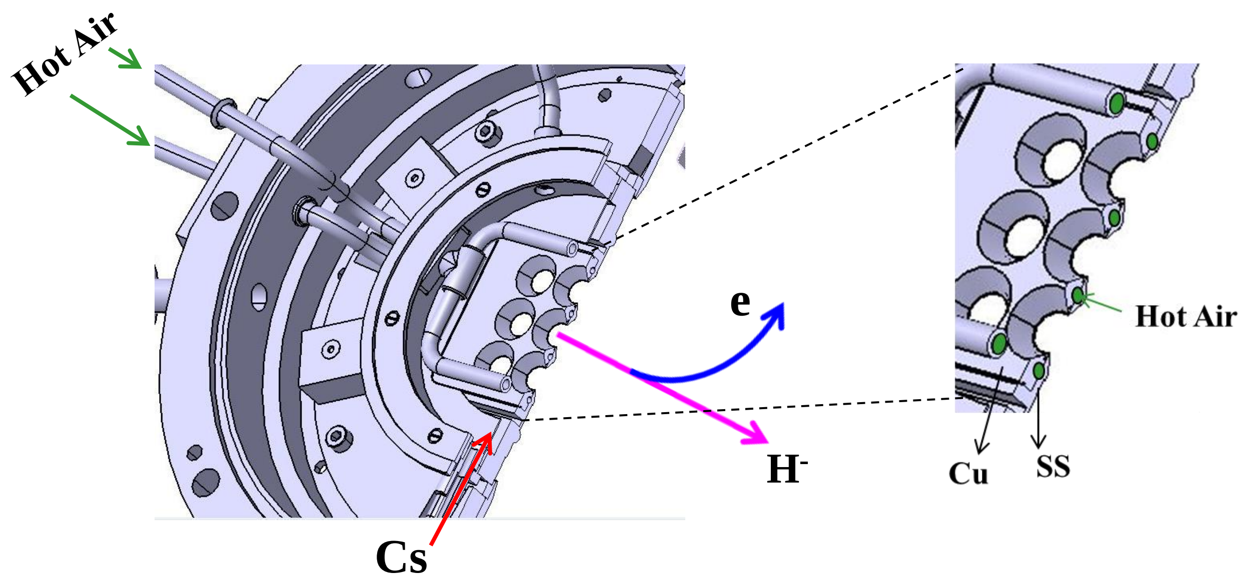
- Caesium injection controlled by oven temperaure.
- Thermally isolated copper pipe  (overheated >470 K )

# The Source: Extractor

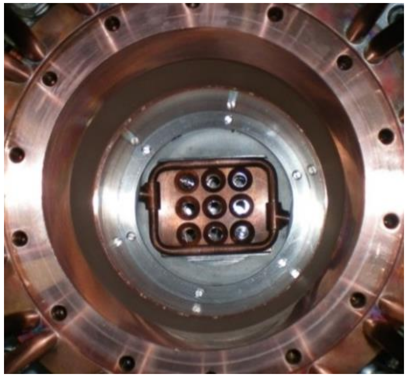


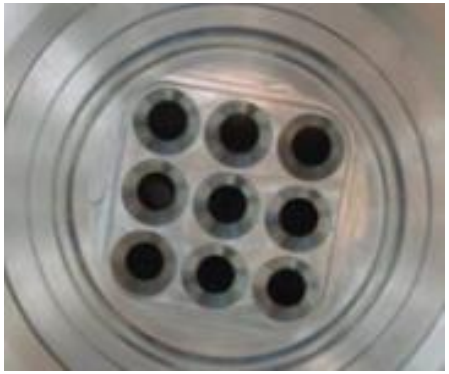
- H- are extracted from 9 apertures (Ø7.6 mm) arranged in a 3x3 pattern
- Plasma grid (PG) realized in electrodeposited copper + stainless steel (downstream)




- Cs injection in the proximity of PG
- PG and Bias circuit: dry air for heating to 400 K (Cs optimal coverage: 1/2 monolayer)

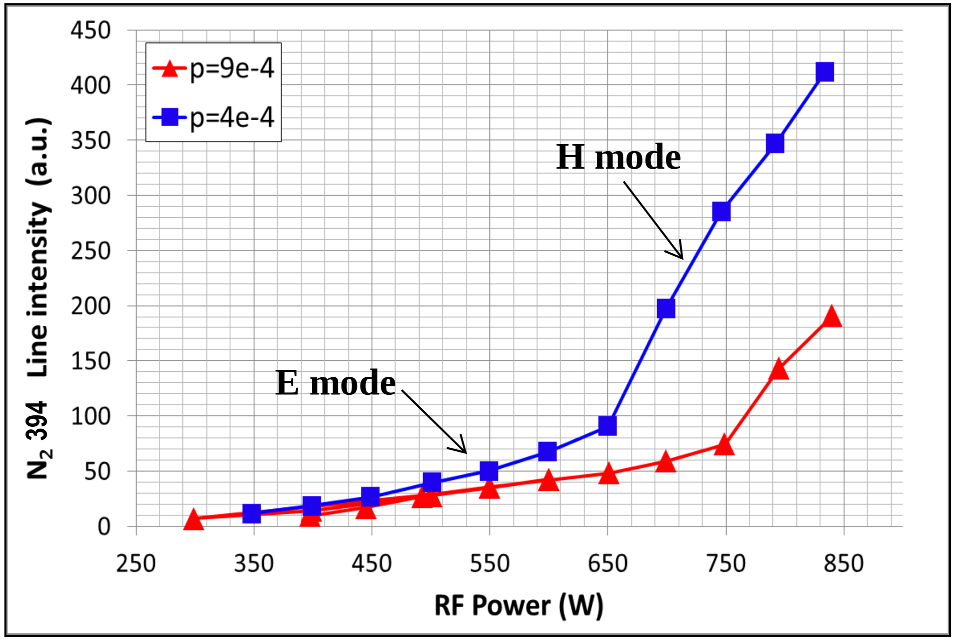




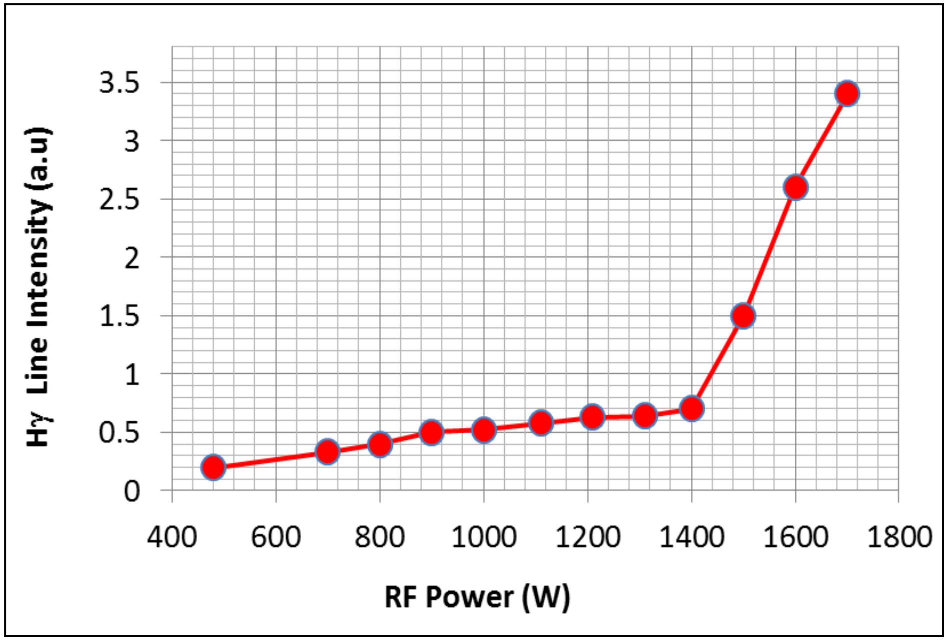
# Status of the Experiment: 2015 campaigns

First experiment in H2 and Air focused on plasma ignition and scaling with RF power and pressure

Gas: Air




Gas: $H_2$




- Air: transition from capacitive to inductive coupling at around 400 W
- Hydrogen transition occurs at higher power (P>1400 W)

# Towards 2016 campaigns

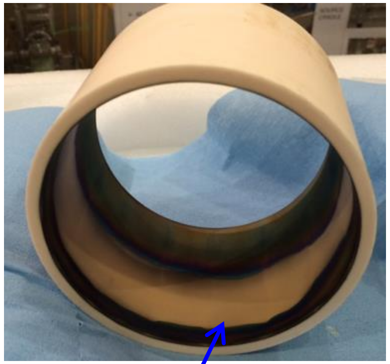
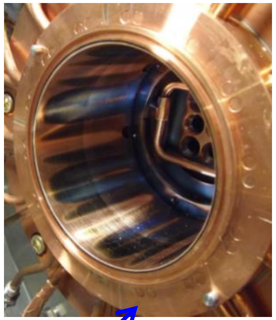
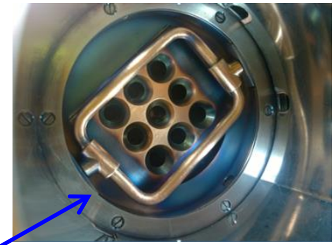


Experiment at high RF power (<1.7 kW) caused a damage on the allumina insulator (elastic bolt unbalanced loosening?) .

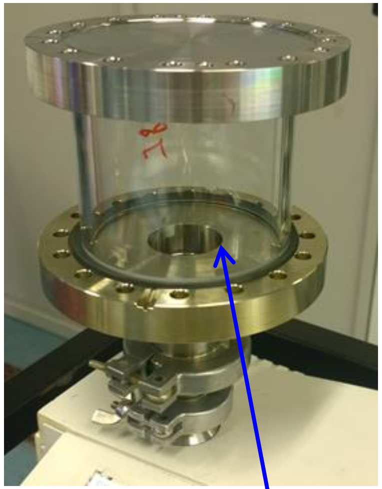
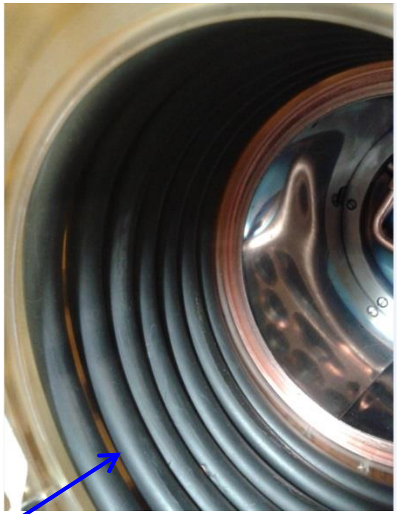
During the shutdown many improvements were made to the set up:

- Integration of PS completed (fast interlock, protection system,..)
- New insulator of Pyrex were procured and installed

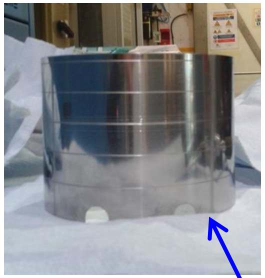
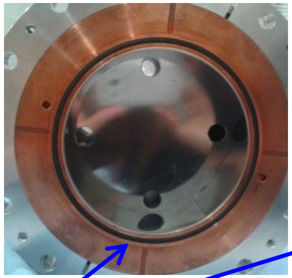
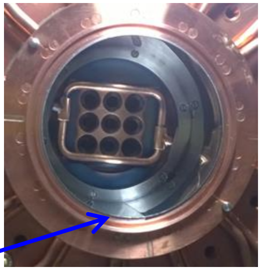
- Mo liners surronding the chambers

Allumina insulator source walls and PG after source opening

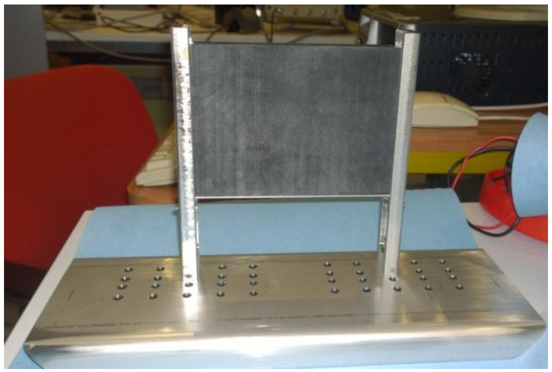
Pyrex Insulator

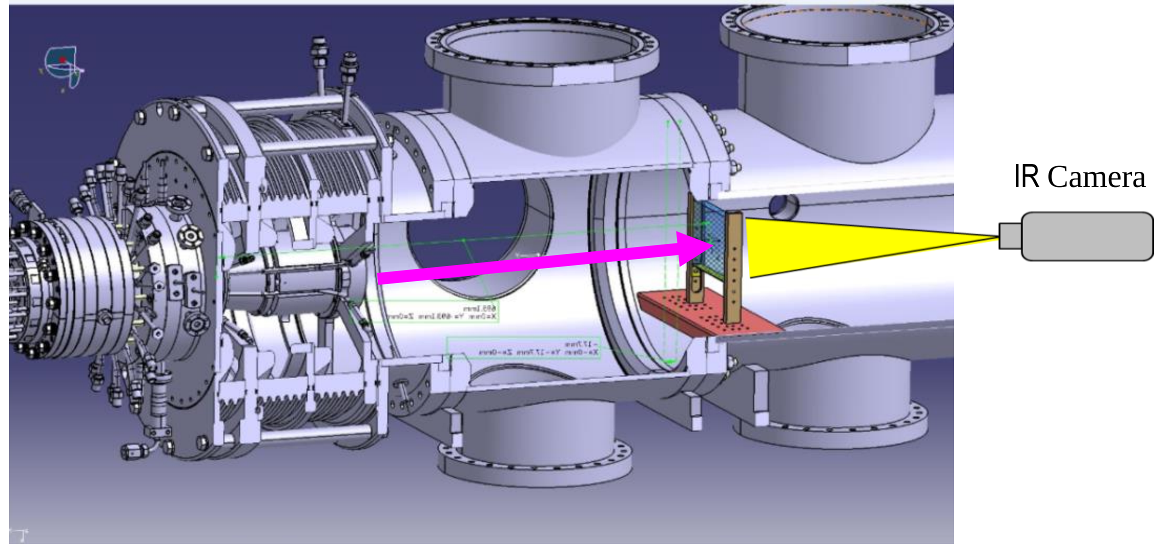




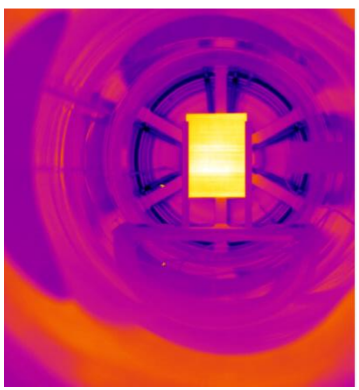
Mo cover

# Towards 2016 campaigns: New diagnostics

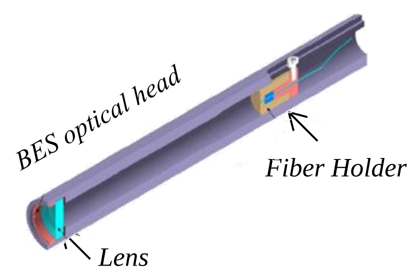
- Beam profile and calorimetry by CFC tile

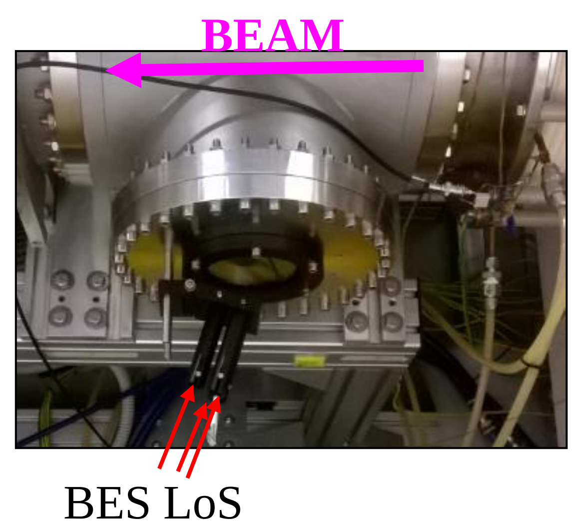




- Beam Emission Spettroscopy (BES): 3 lines of sight installed on a lateral port,
- New spectrometer procured

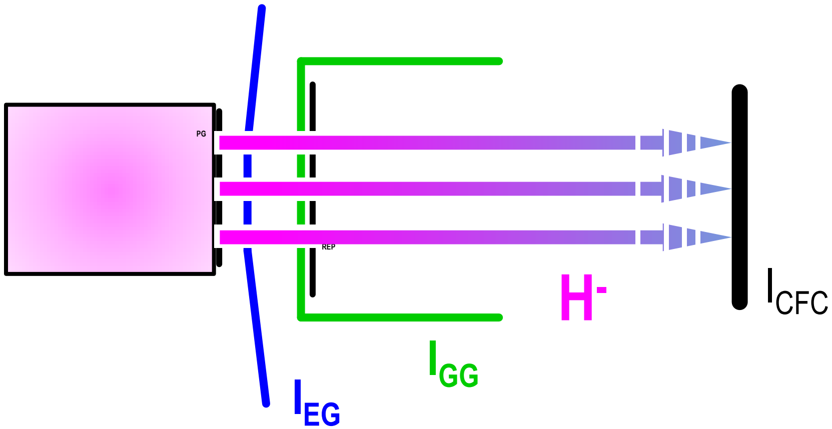


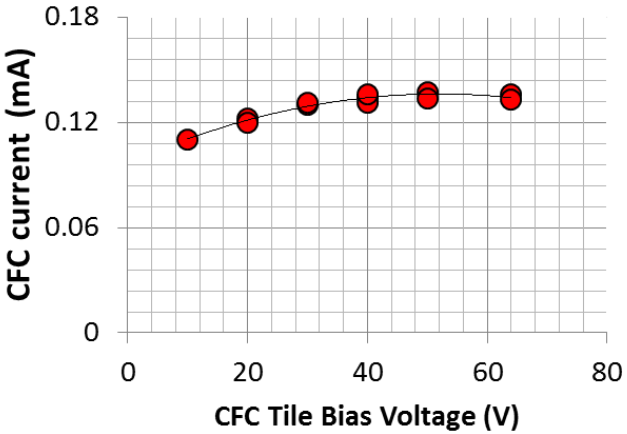




G. Serianni et al. AIP Conf. Proc. 1655, (2015)

# Towards 2016 campaigns: New diagnostics

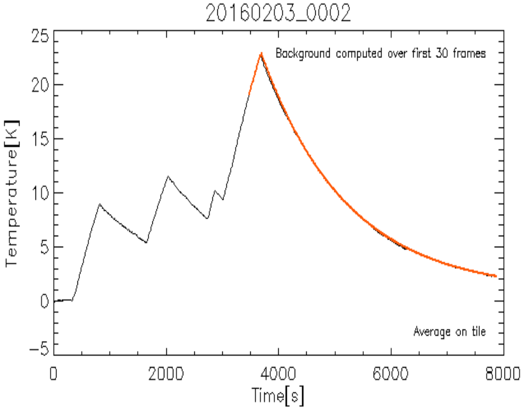
- CFC biasing and current measurment:
- Grounded Grid (also called PA)  current measurment

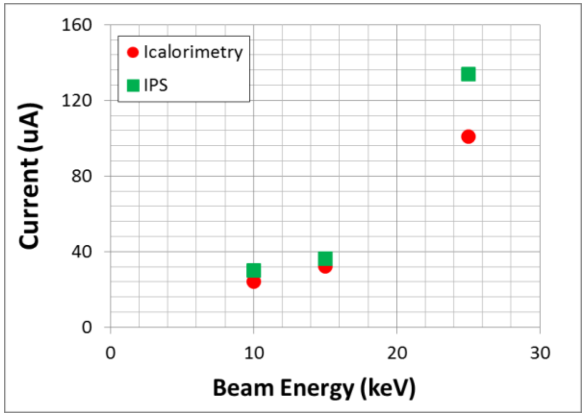



- Secondary electrons
  - on GG: automatically recollected
  - on CFC tile: a biasing is required

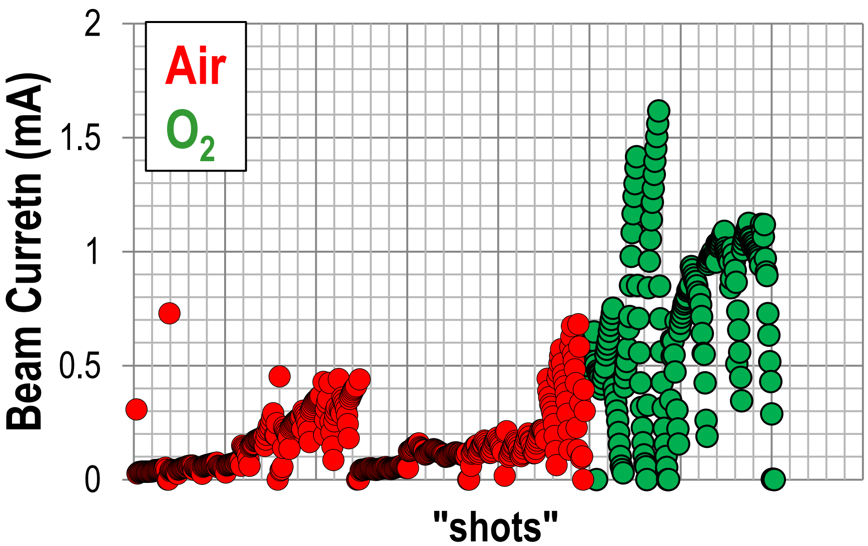
- Electric measure on CFC has a strong synergy with calorimetric estimation.

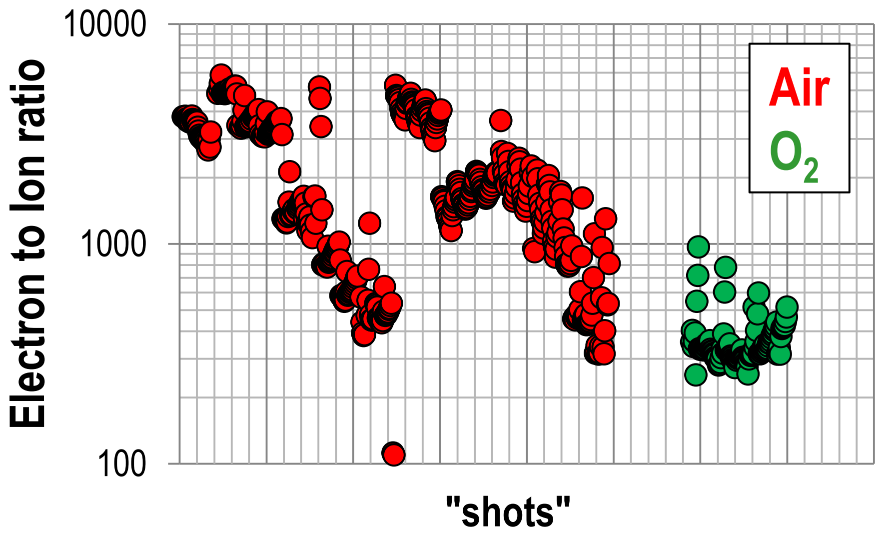


# 2016 campaigns: $O^-$ beams

- RF power was limited to < 800 W (Pyrex insulator)
- Beam extraction experiments in Air and $O_2$ (H2 plasma too weak)
- Use of O- has many advantages:
  - Relative abundance of O-
  - High beam density
  - Less deflected by EG magnets

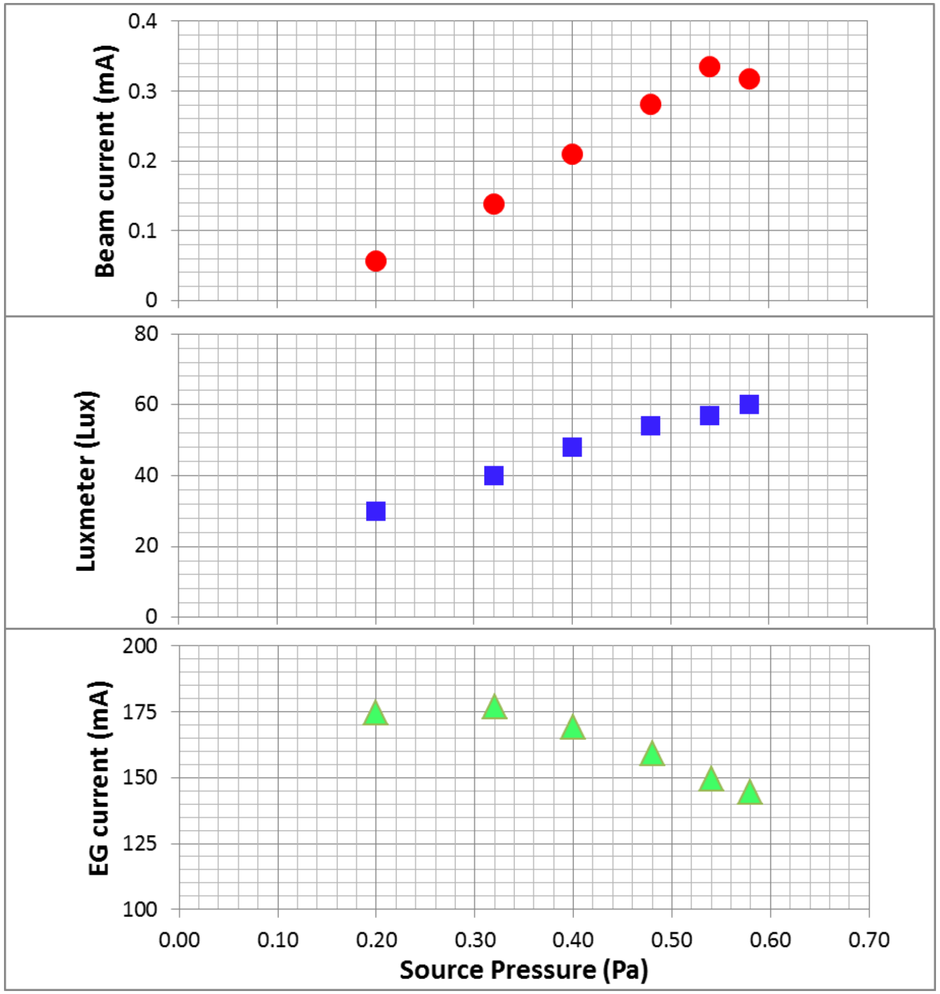



- Large electron currents are extracted
- EG magnets assure no electron leakage in the high voltage region:
- $I_{GG} + I_{CFC}$ assumed as the beam current.
- Beam current gradually increased up to >1 mA.

# Pressure scan in Air

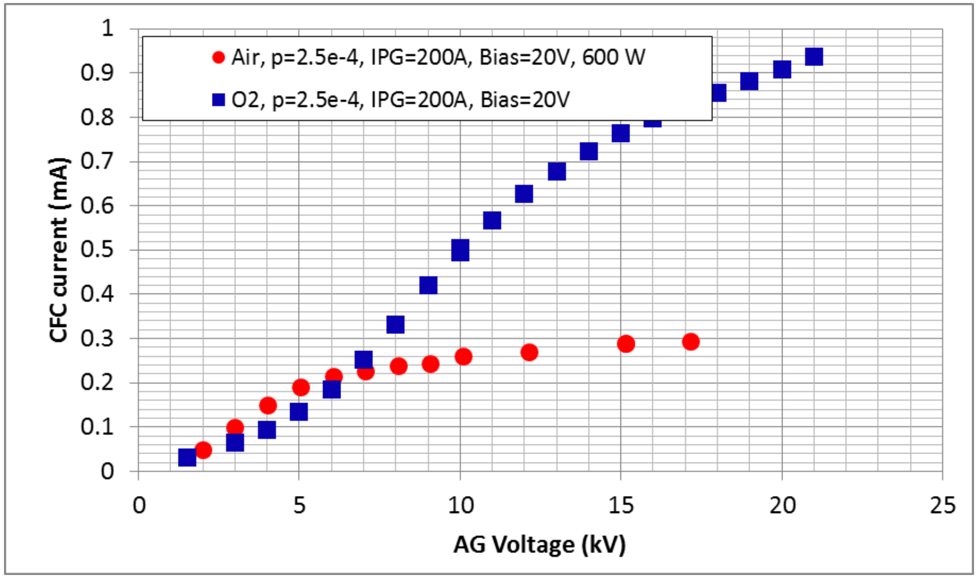
- From literature [Stoeffels, phys rev E, Tanaka ..]: In $O_2$ plasma we can expect a negative ions to electrons ratio ranging from 0.2 up to 10 , depending on pressure, RF power and e- temperature.

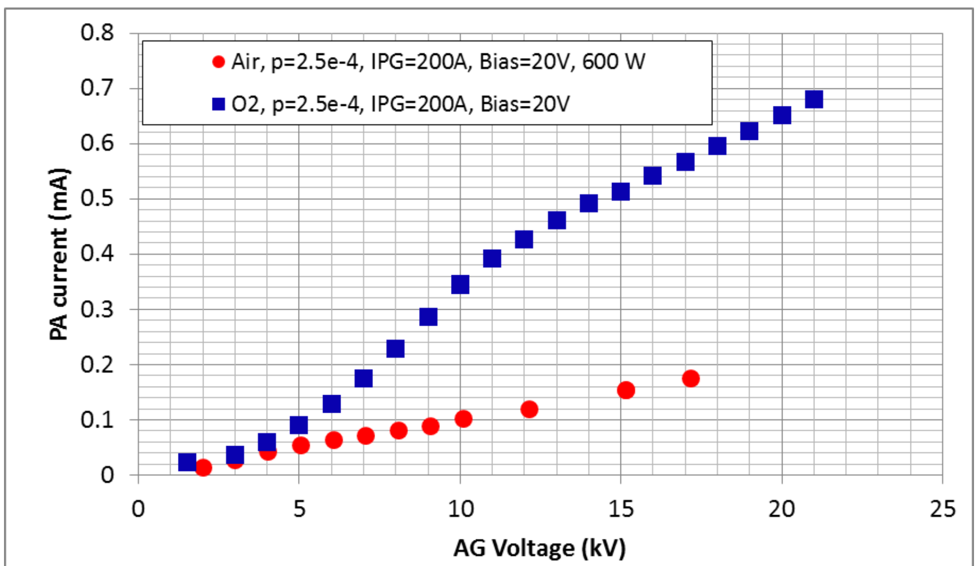



- Also in NIO1 Beam current strongly depend on gas pressure
- Electron current decreased with gas pressure
- Pressure is limited by accelerator breakdown; subject under investigation.

P=600 W
Vext=0.8 kV
Vacc=8 kV

# $O_2$ Plasma



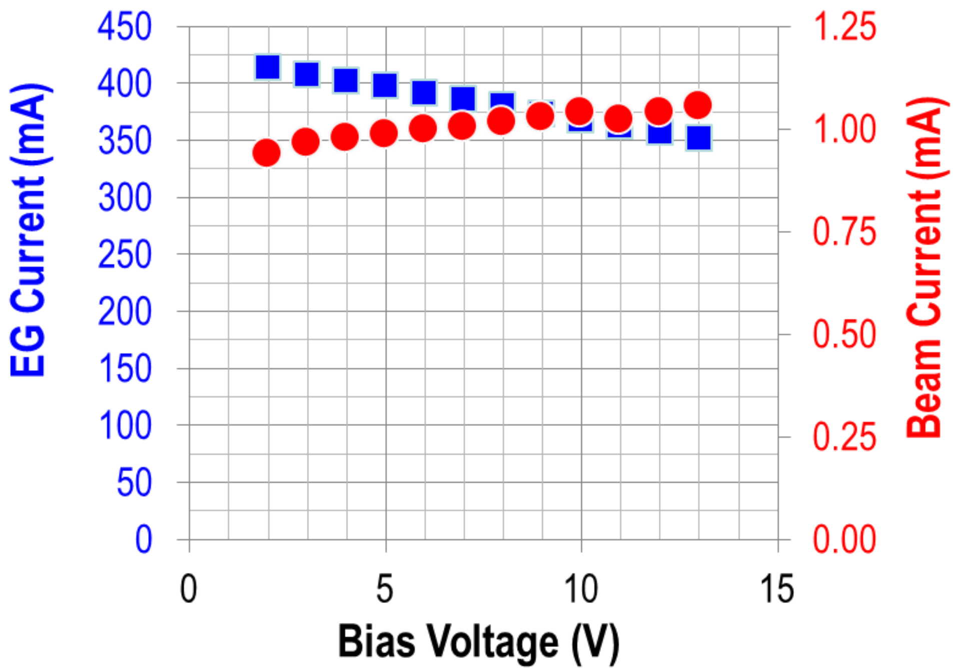

$O_2$ Plasma characterization in progress

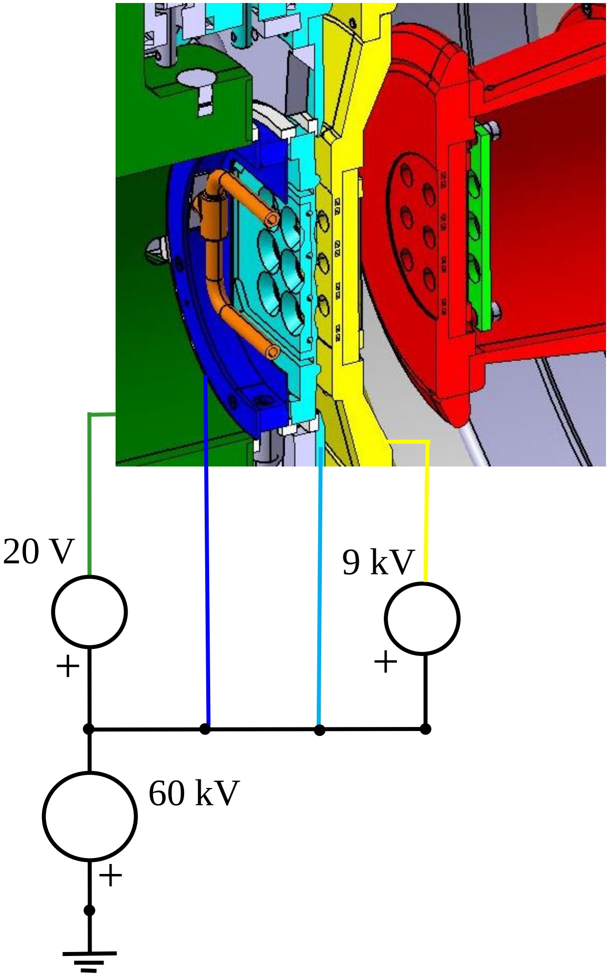
Using pure oxygen gives a factor of 3 in beam current under the same conditions

Less than the naïve expectation of 5 (stoichiometric ratio)

# Bias Voltage Scan

Many part can be biased independently thanks to macor insulators.
In the actual set-up the PG assembly was biased with respect to the source walls.



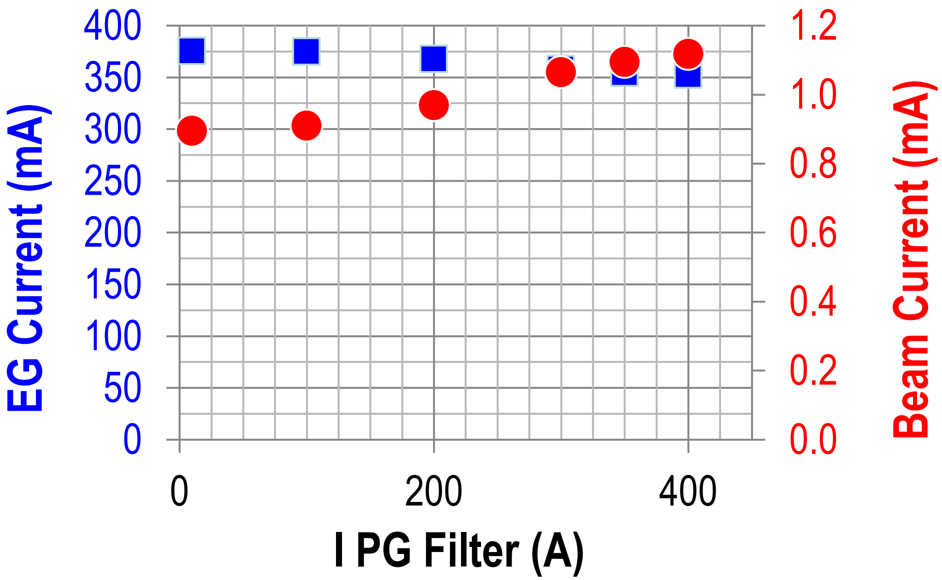



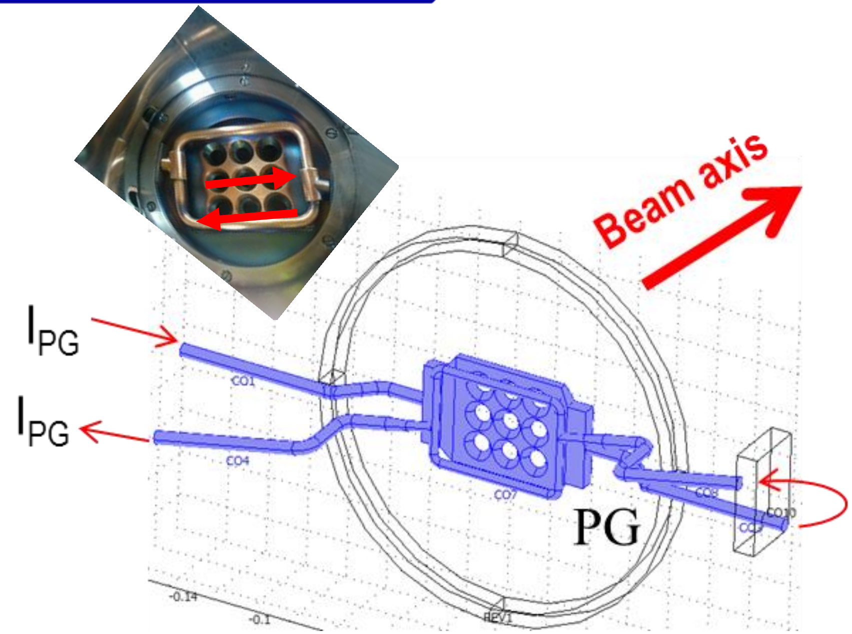

- Strong reduction of coextracted electrons
- Increase of beam current

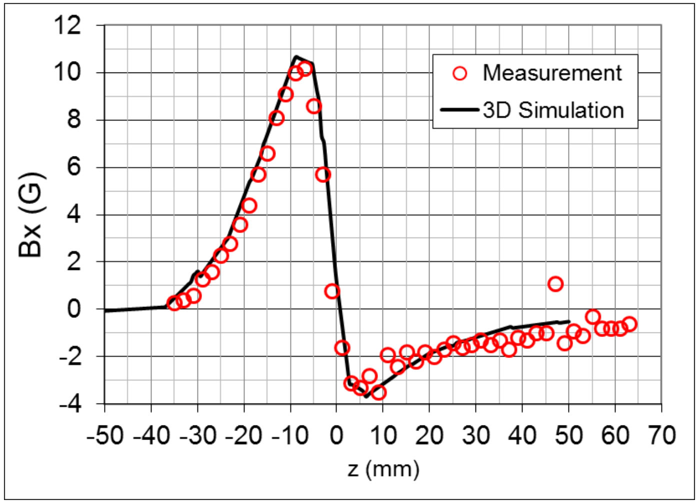
# Filter Field Scan

A tranversal Magnetic field is used to filter out the high energy electrons form the extraction region.

Filter field generated by 0.4 kA current flowing into the PG and its return pipes



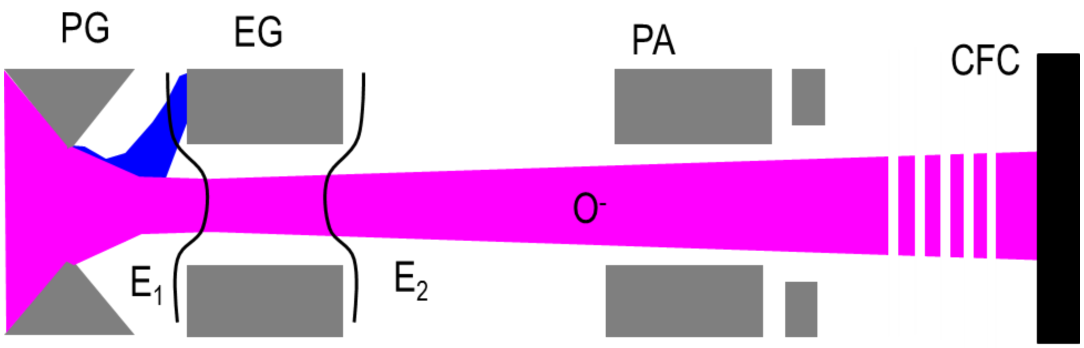

Electron current is decreased and beam current increases: destruction of $O^-$ is reduced in the proximity of PG

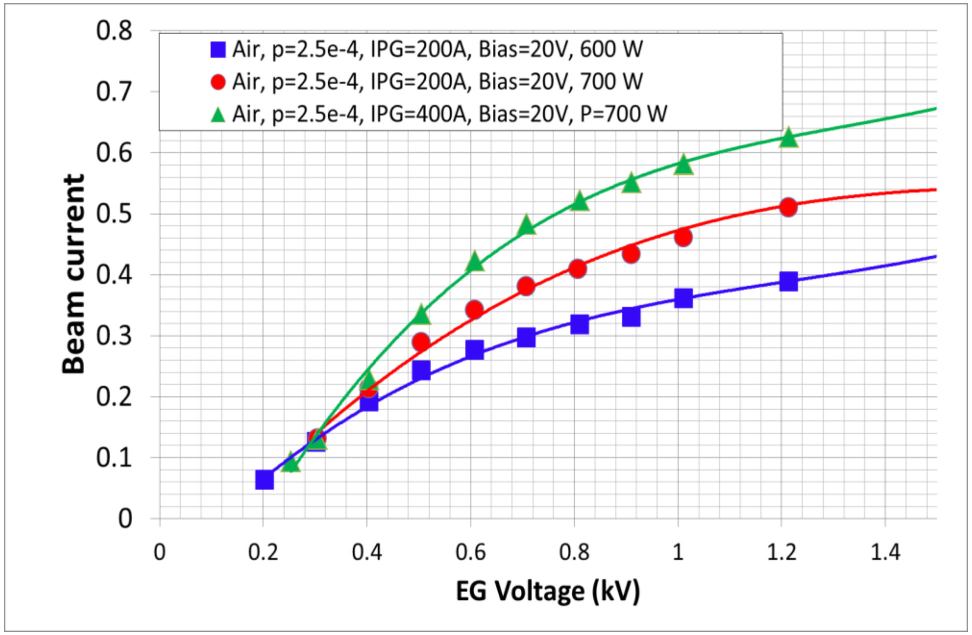
# Beam Optics

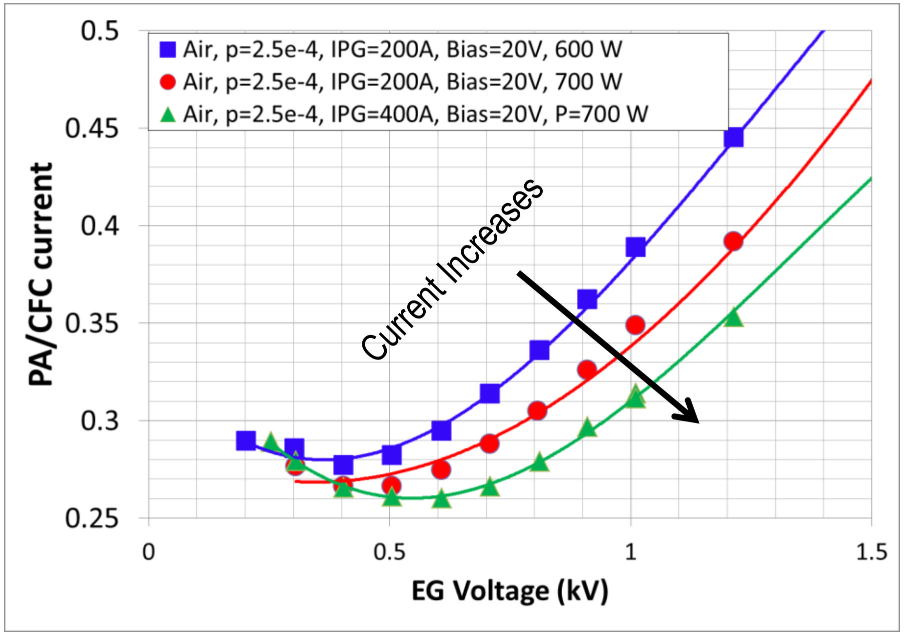
Constant ratio VGG/VEG=10

At firt order focal length is hence kept constant: thin lens approximation

$$f=(E_2-E_1)/4V$$



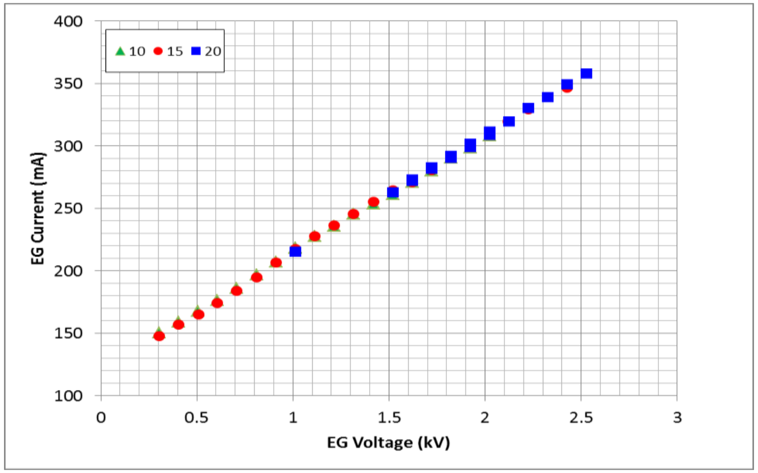



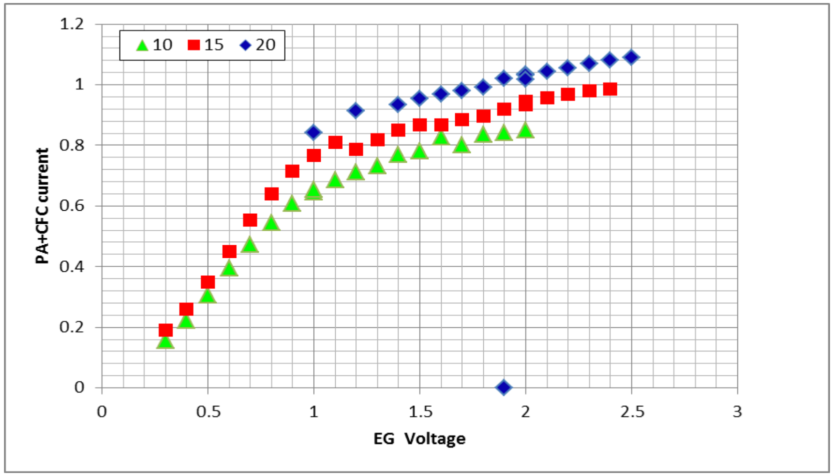

Beam divergence proportional to the ratio of PA/CFC current

When beam current is increased the optimal voltage is increased accordingly

# Comparison with beam simulation

Current scaling with EG voltage was taken from real measurement




Assuming all EGcurrent is carried by electrons and all CFC+PA current is carried by O-:

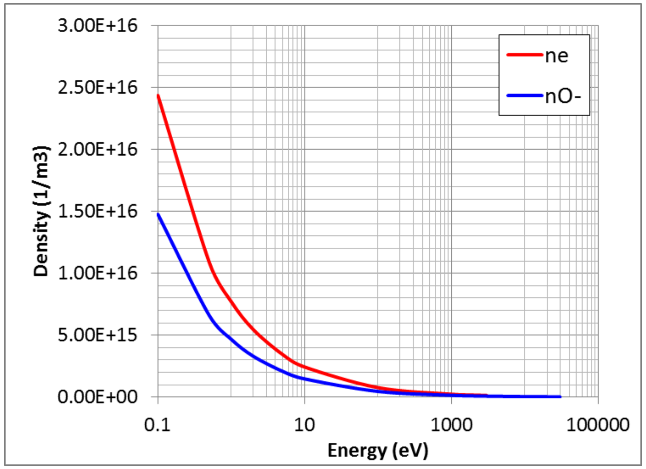
$I_e$ =300 mA
$I_{O-}$ =1 mA

Hence

$J_e \approx 750\ A/m^2$
$J_{O-} \approx 2.5\ A/m_2$

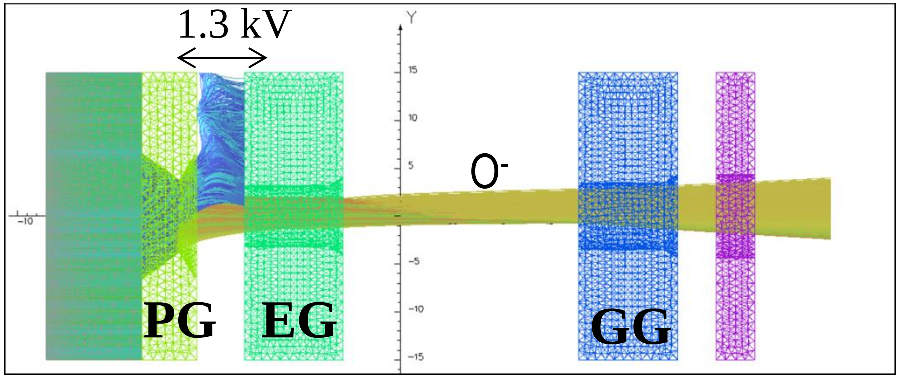
Since
mO-/me ≈33000
vO-/ve ≈182

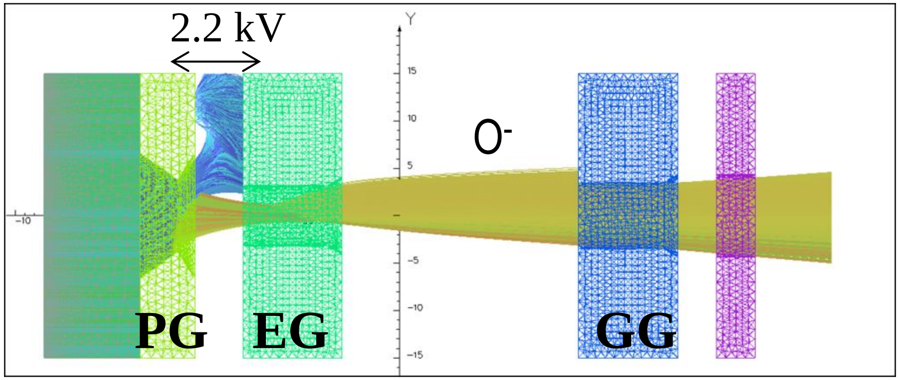
Both specie contributes to space charge in the PG-EG gap

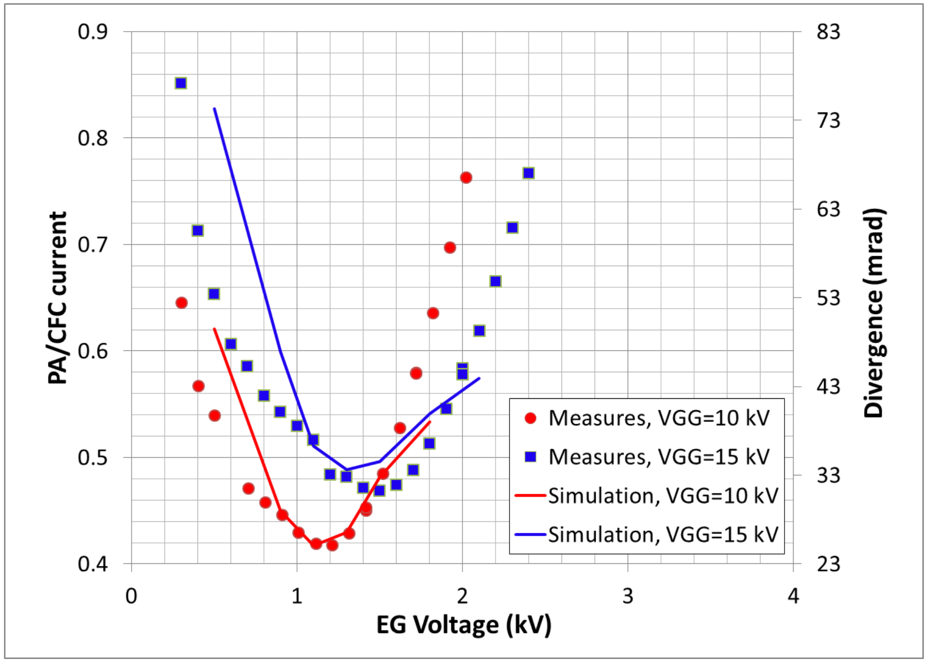


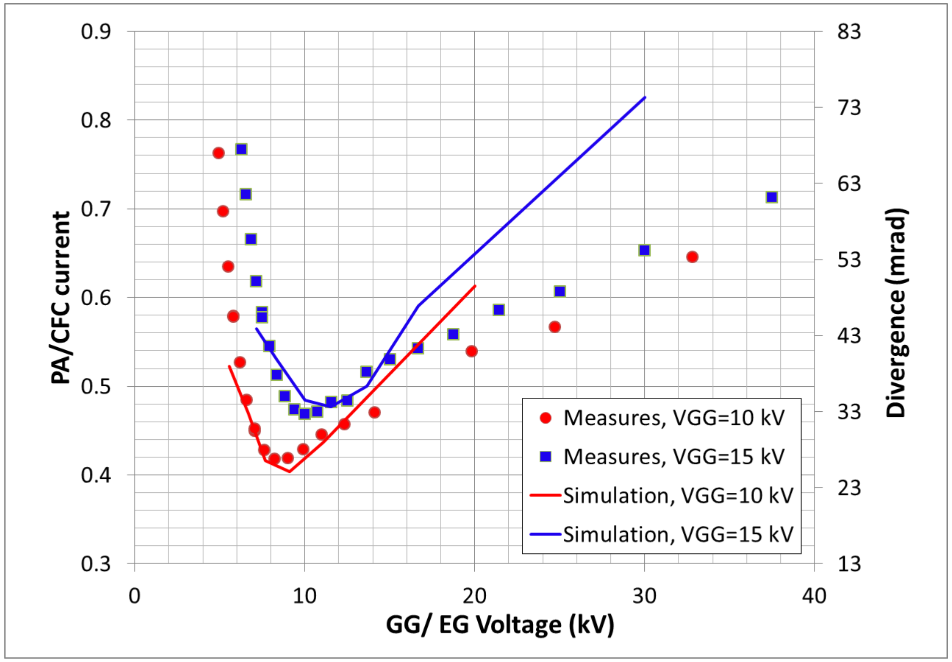
# Comparison with beam simulation: Fixed Vacc

No electron leackage in the high energy region. Limited beam interception on PA



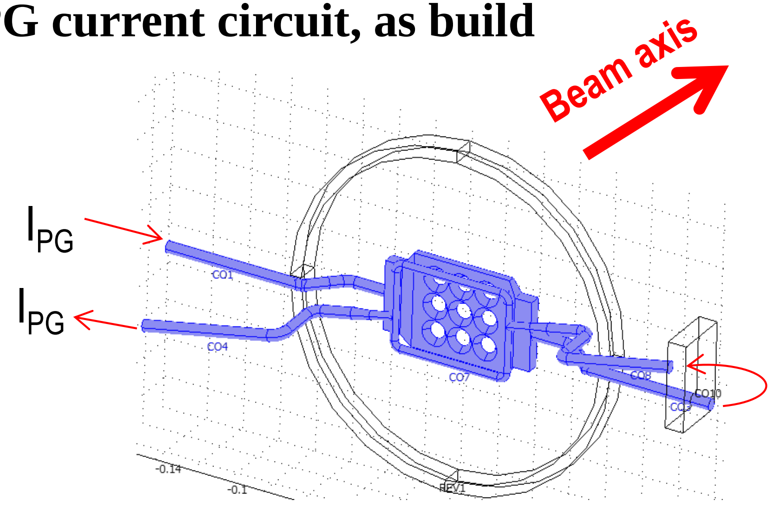



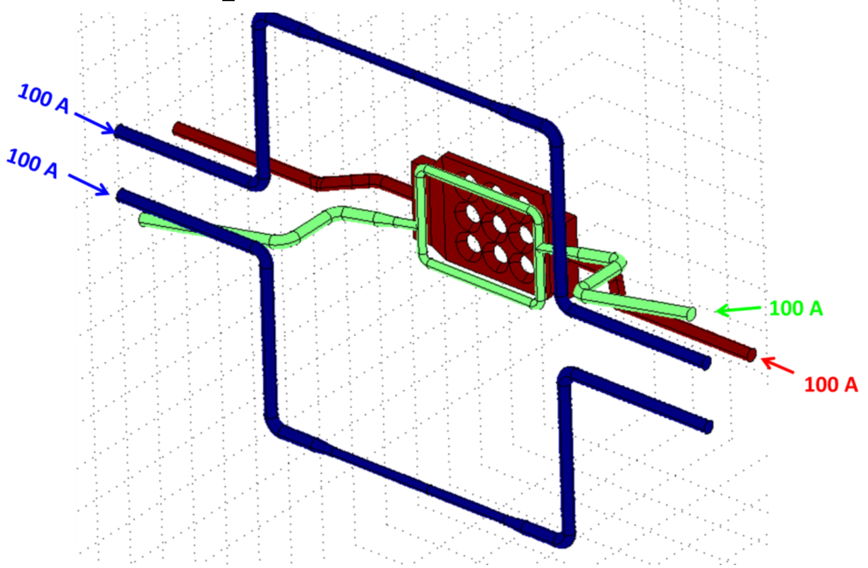



# Status of the Experiment: Future improvements

**PG current circuit, as build**

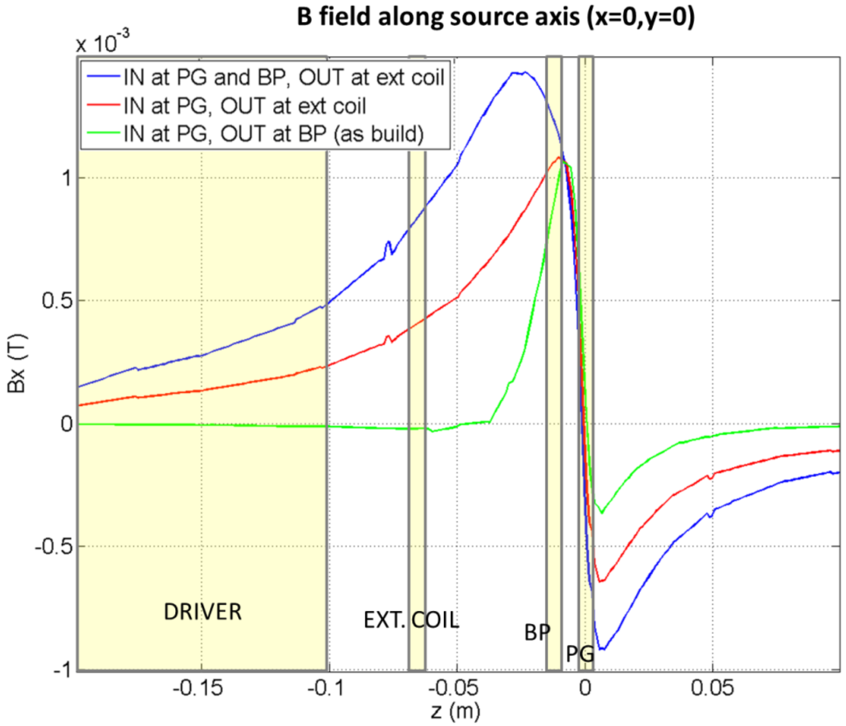



**New concept: under realization**




$$\boxed{\nabla T_e \propto \int B \cdot dl}$$

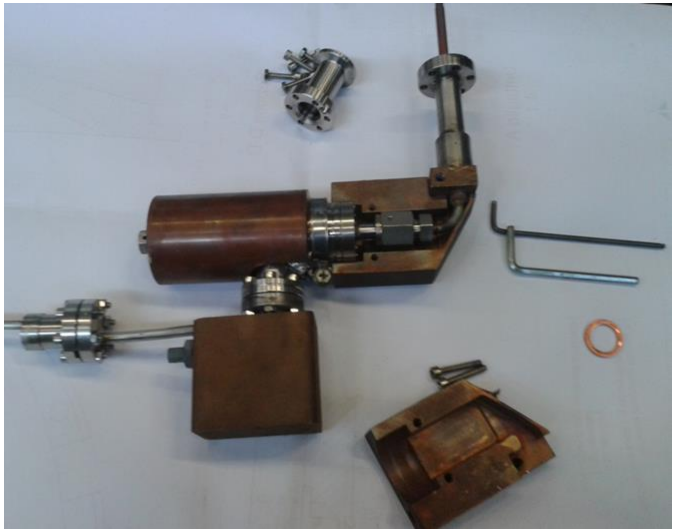
- With the new concept more then a tenfold increase in B·dl is possible
- Careful check of B penetration in the driver region

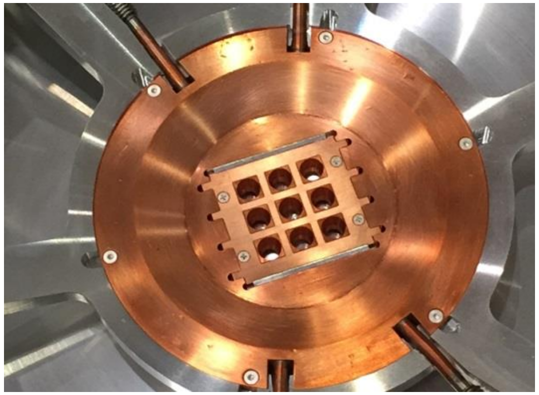


# Status of the Experiment: Future improvements

- New EG: Ready to be installed
- Cs oven: deposition test

- Commissioning and/or installation of new components and diagnostics
  - FES
  - Electrostatic Probes
  - Tomography
  - Cavity ring Down





# Thank you!