Status of NIO1 negative ions source and acceleration system

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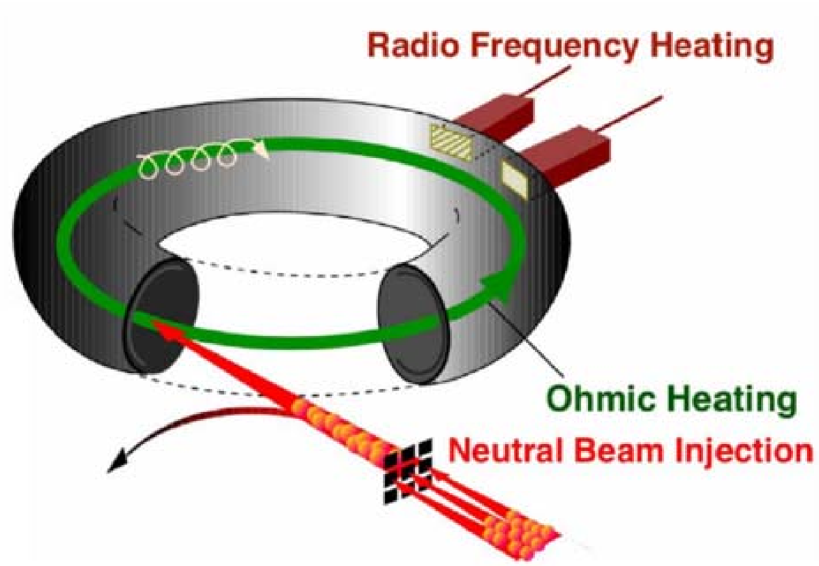
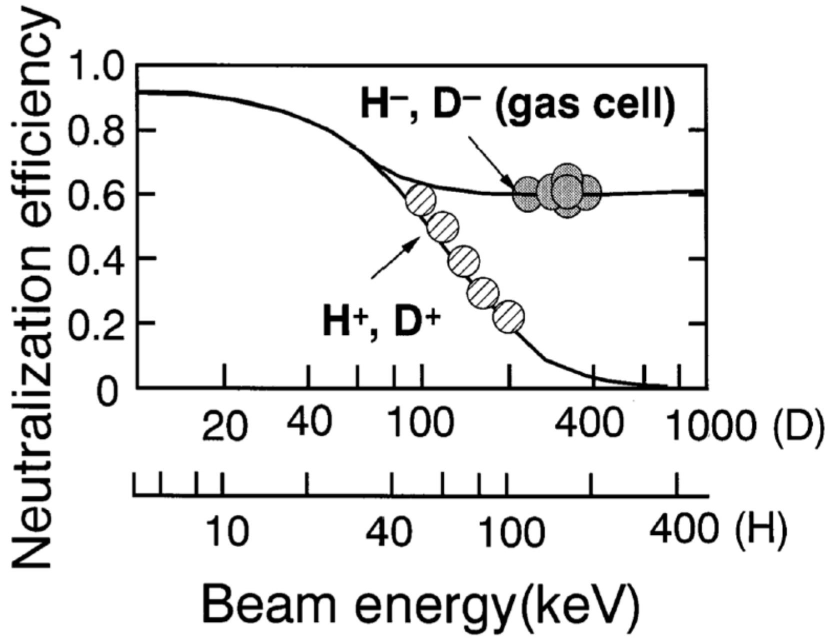
Negative ion beams for Fusion



In the case of ITER
A=2 Plasma
Plasma radius: 2 m
Average Plasma Density: 10^{20}

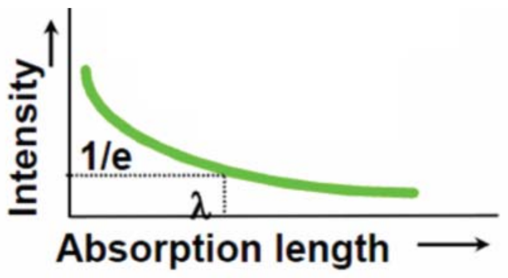
For $\lambda \approx R$
E ≈1000 keV



Experimental Measurement at JT-60U
[M. Kuriyama, Fus. Eng. Design, 39-40:115, 1998]

Adsorption length for ionization in plasma

$$\lambda = \frac{E}{18 \cdot n \cdot A} [m]$$



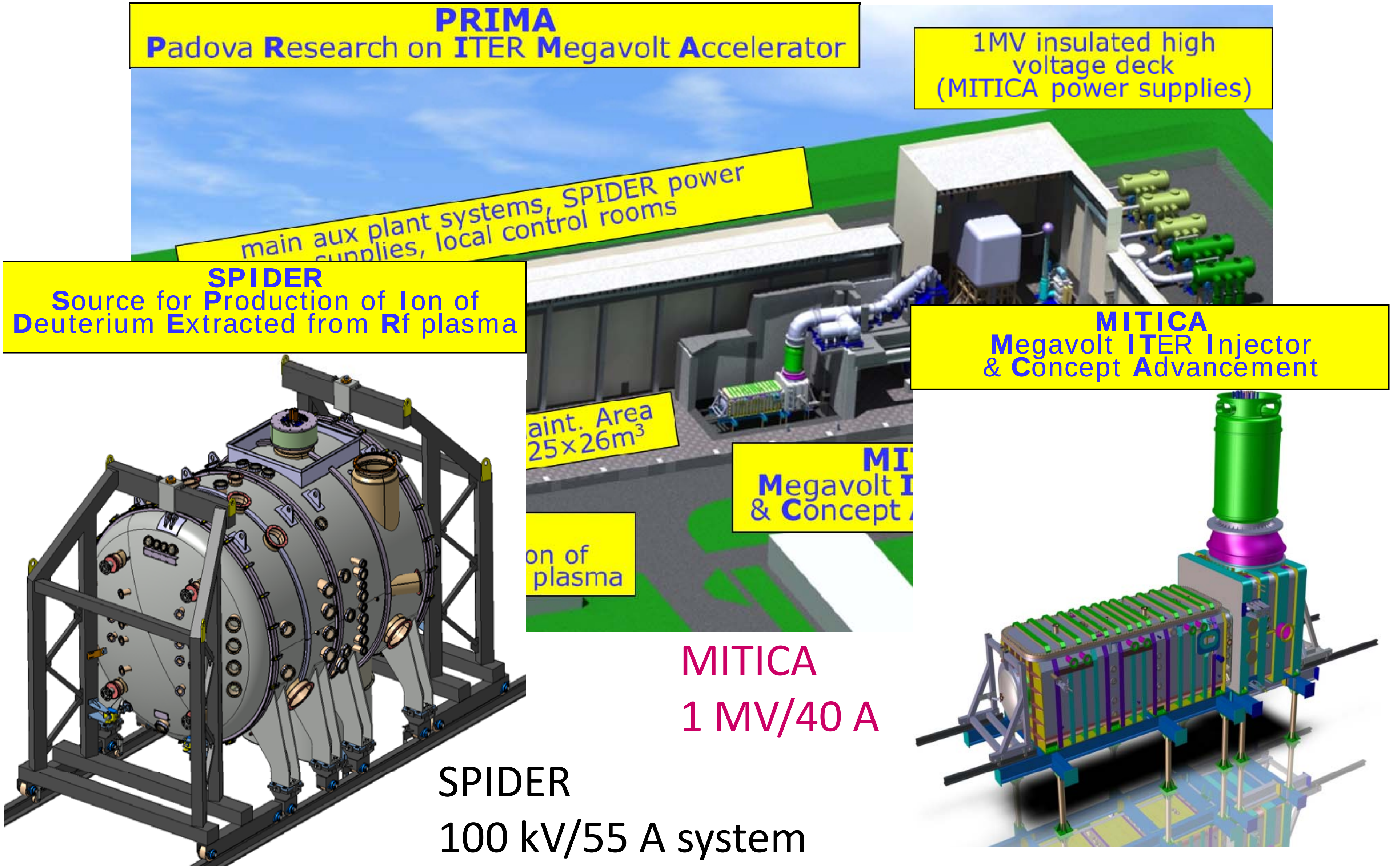
n in $10^{19} m^{-3}$, A in amu, E in keV

ITER neutral Beam test facility

The requirements of the NBI for ITER represent a huge extrapolation from existent NBI
A research program on NBI is being carried out in parallel with ITER construction

A dedicated test facility is under construction @Consorzio RFX, in Padova, Italy
In close collaboration with Japanese and Indian Iter domestic agencies

ITER neutral Beam test facility



MITICA
1 MV/40 A

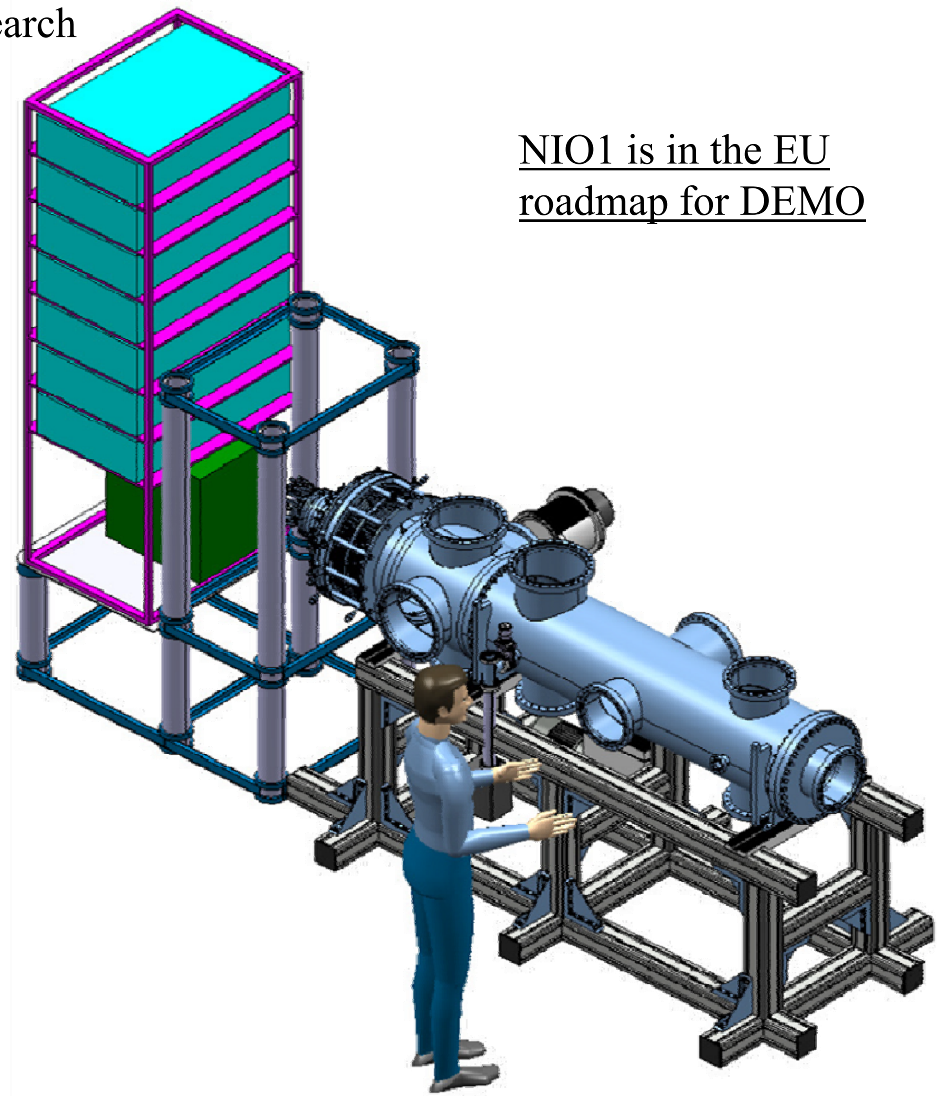
SPIDER
100 kV/55 A system

NIO1 Experiment: Overview

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

NIO1 is in the EU roadmap for DEMO



Scopes

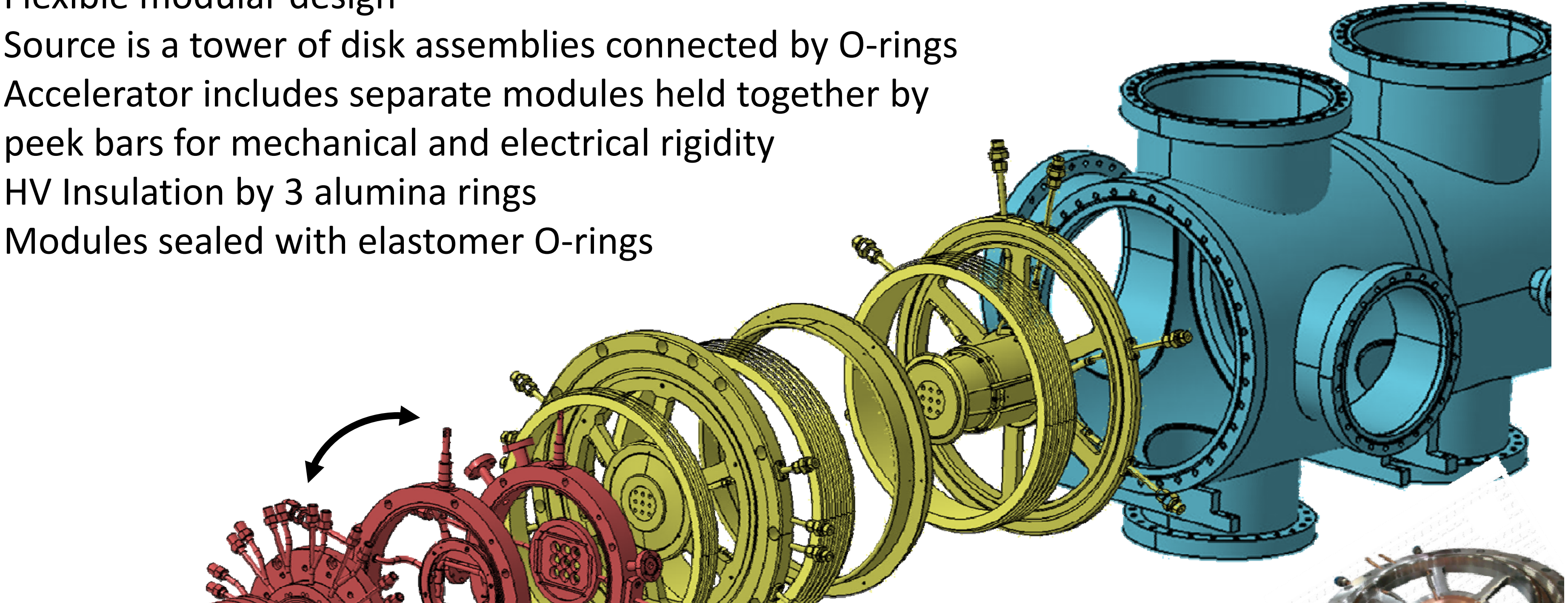
- Physics of Negative ion formation and extraction
- Code Benchmark and validation
- Test Advanced concepts:
  - Alternative to Cesium
  - Energy Recovery system

Presentation Outline

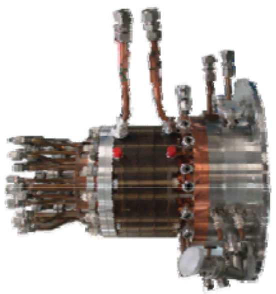
- Description of Experiment
- Status and experimental results
- Future improvements

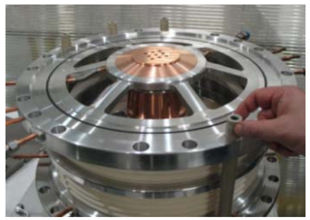
NIO1 experiment

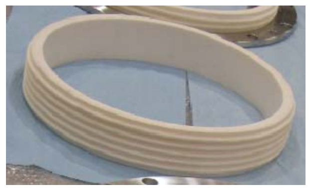
- Flexible modular design
- Source is a tower of disk assemblies connected by O-rings
- Accelerator includes separate modules held together by peek bars for mechanical and electrical rigidity
- HV Insulation by 3 alumina rings
- Modules sealed with elastomer O-rings

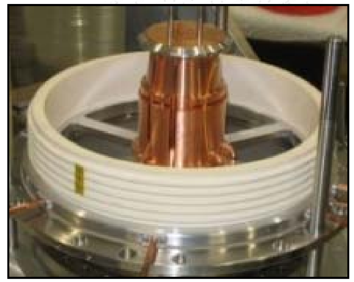


- Rotation of several parts by 90° is possible





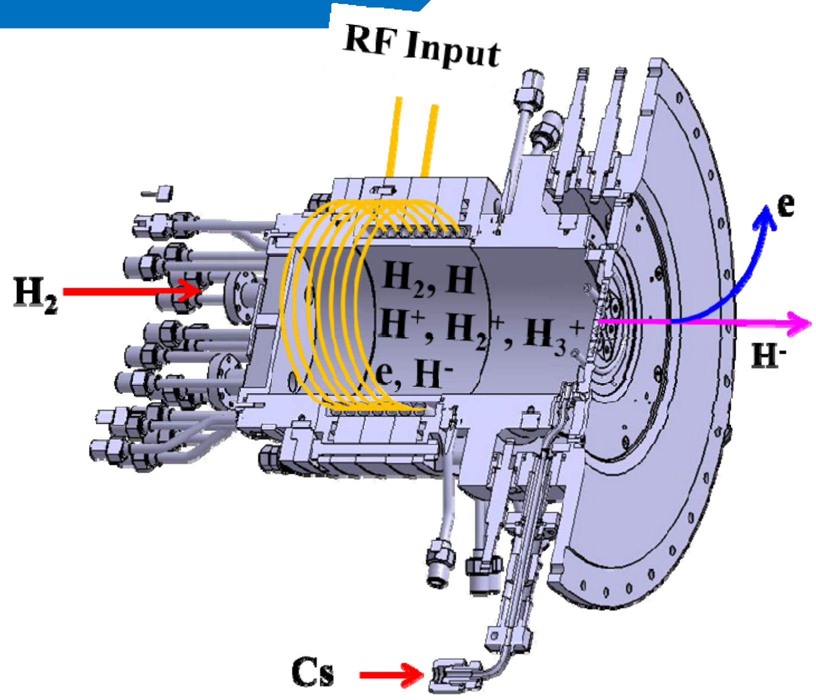


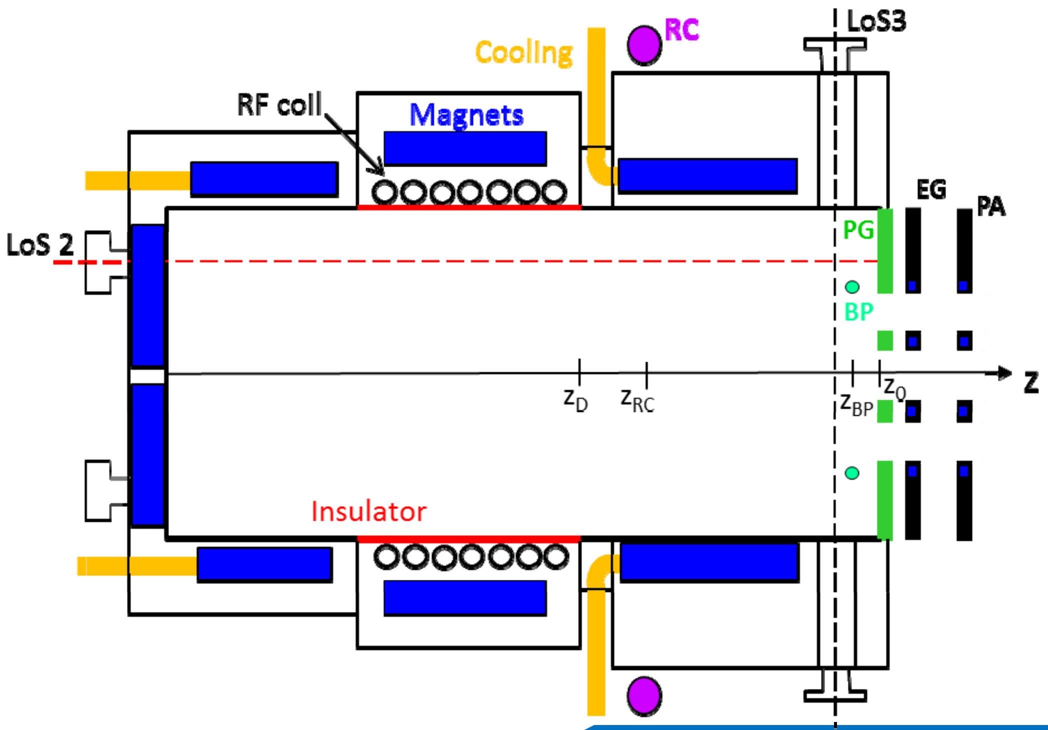


NIO1 experiment

Source of Negative ions

- ICP plasma (RF, 2 MHz)
- Multi stage Accelerator (PG, EG, PA, Repeller)
- Steady state (cw) operation
- Can be operated with different gases: (Air, H_2, O_2.)

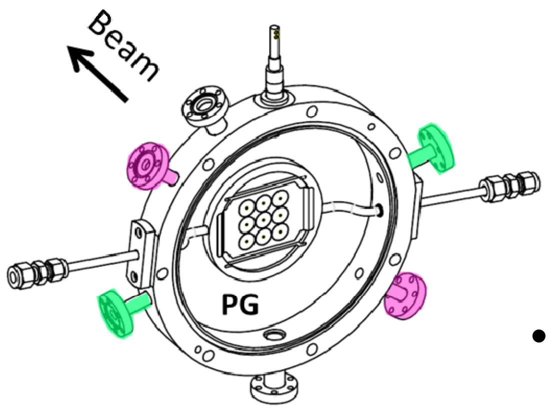


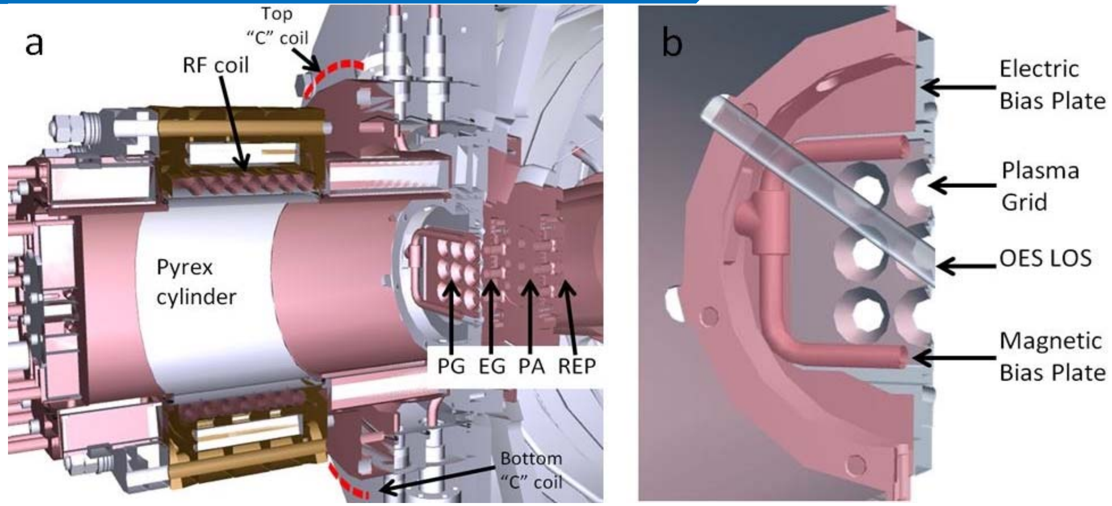


- Design values: 130 mA of H^- at 60 KeV
- Present performances (w/o Cs)
  - $I_{H-} \leq 7$ mA,
  - $I_{O-} \leq 3$ mA,
- Different B configurations are possible in NIO1
- E-H mode transition

NIO1 Plasma Chamber

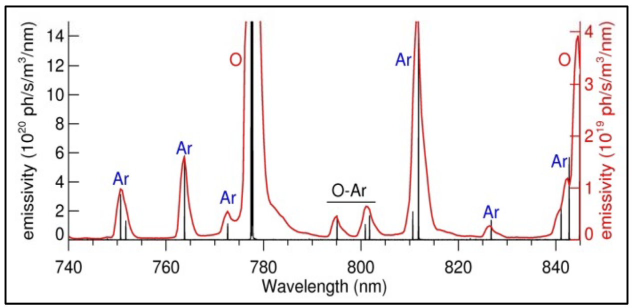
Plasma properties are monitored by spectroscopy. Many lines of sights (LOS) available.

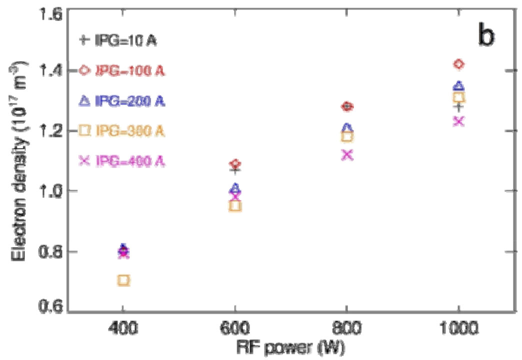




- Opposite lines of sight for cavity ring-down laser absorption spectroscopy (H^- density)

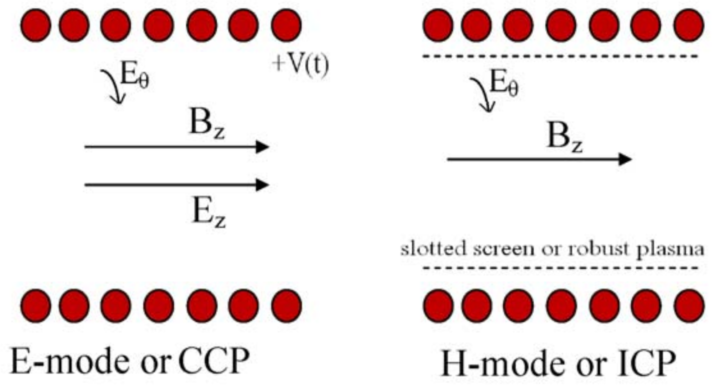
- Use of Argon fractions (≤ 10%) as a dopant of operational gases to get more reliable measurements (T_e, n_e, dissociation)



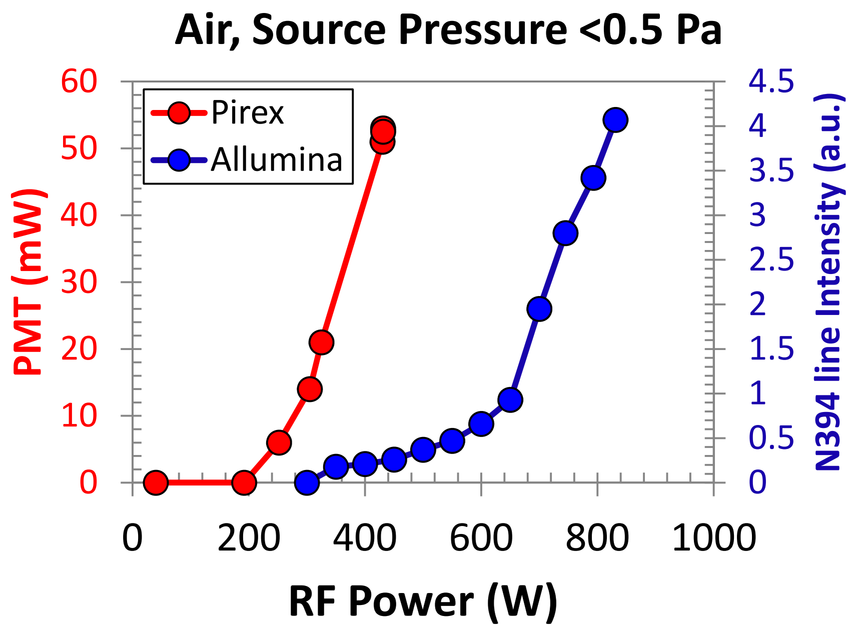


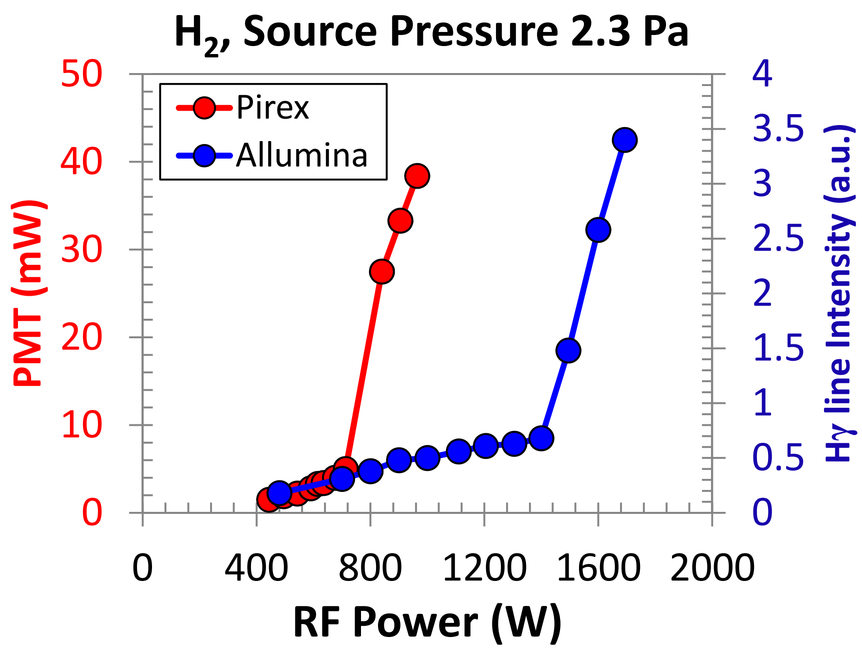
Capacitive-to-inductive transition

Simple explanation of coupling modes



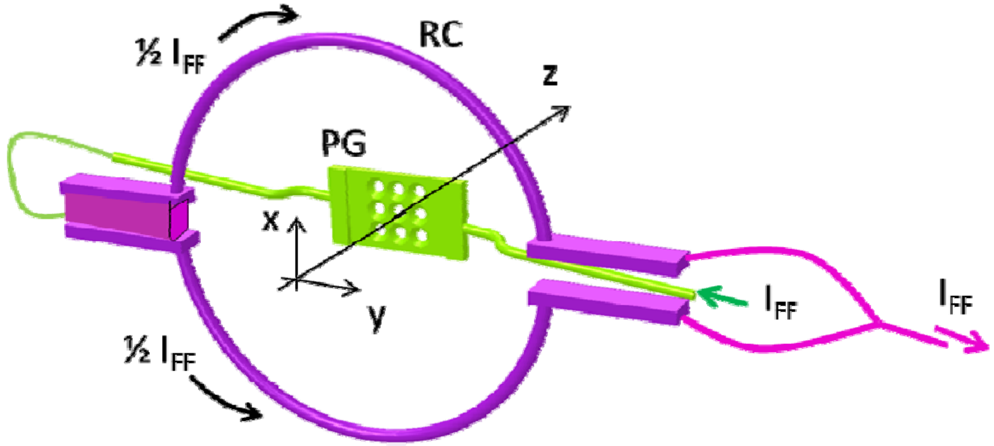
- Plasma light (PMT or filtered spectra) gives an immediate feedback on plasma response to RF power.
- A typical observation is the transition from a Electrostatic (E) mode to the electromagnetic (H) mode.
- The threshold power depends on the insulator material and status (alumina, borosilicate glasses)

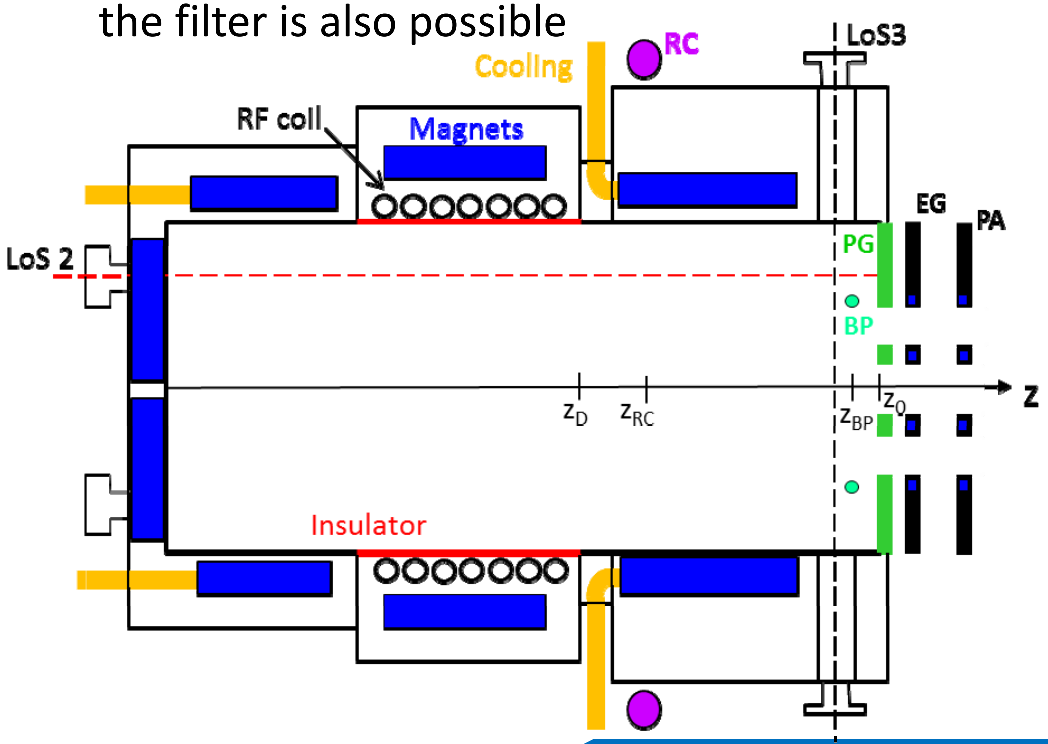


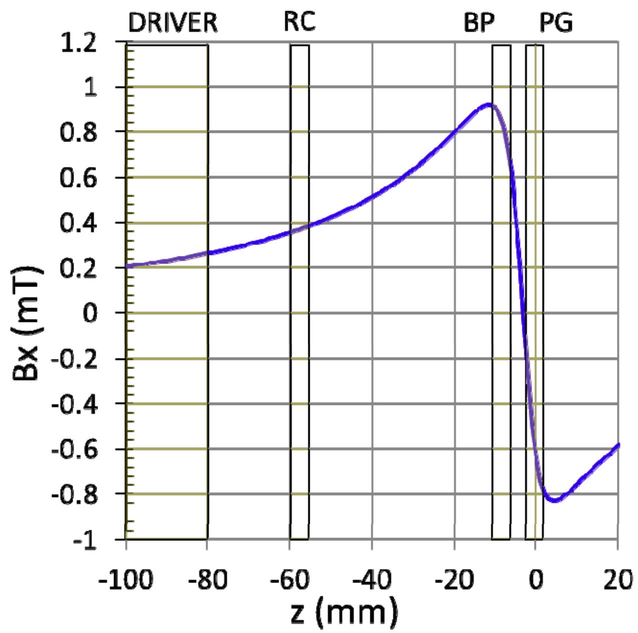


Electron Cooling: filter field

- A transverse B field is necessary to filter hot electrons: can destroy H^-.
- In NIO the B field can be regulated by flowing a variable current I_{FF} through the PG and return conductors
- $\int B \cdot dz$ up to 0.2 mT·m (at IFF =400A)
- Use of permanent magnets to enhance the filter is also possible

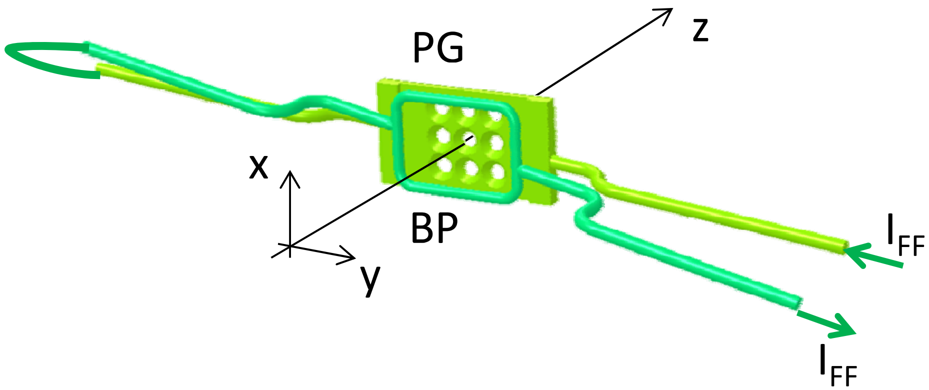




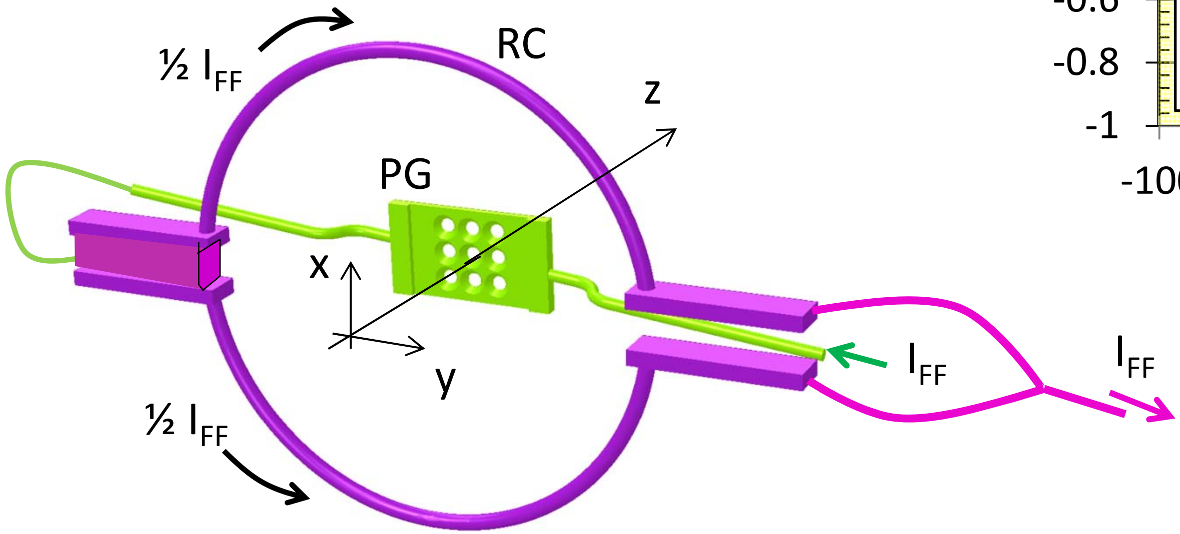


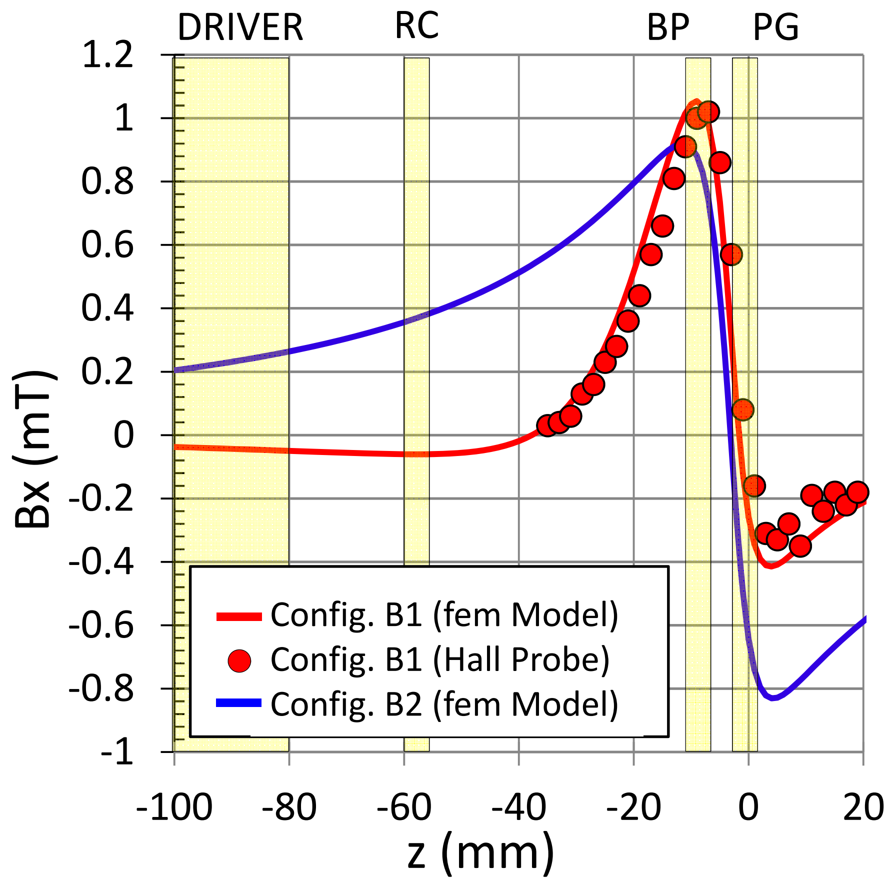
Electron Cooling: filter field

Configuration B1

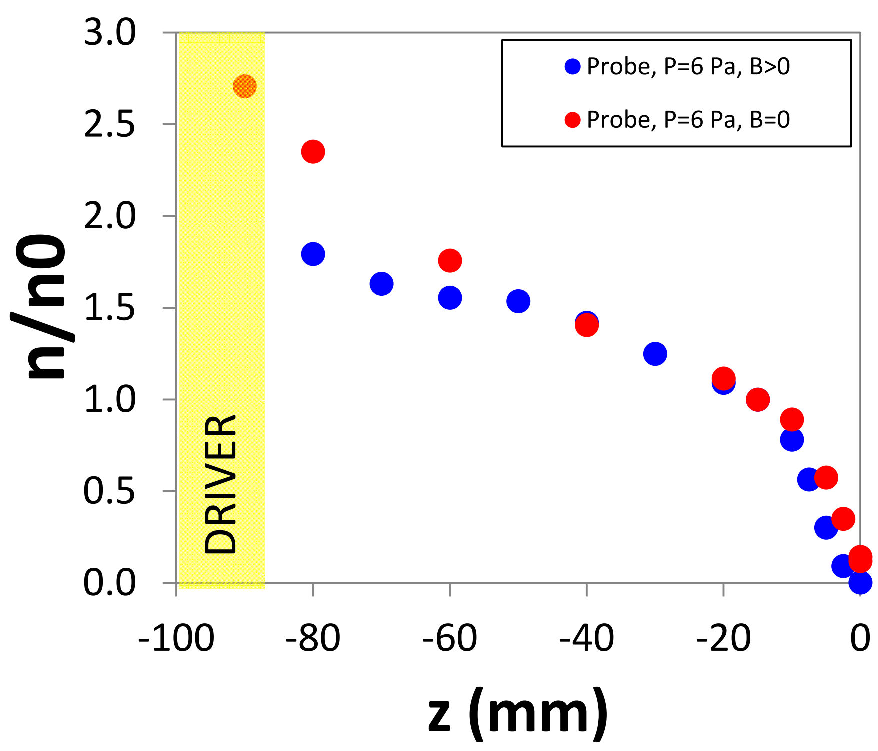


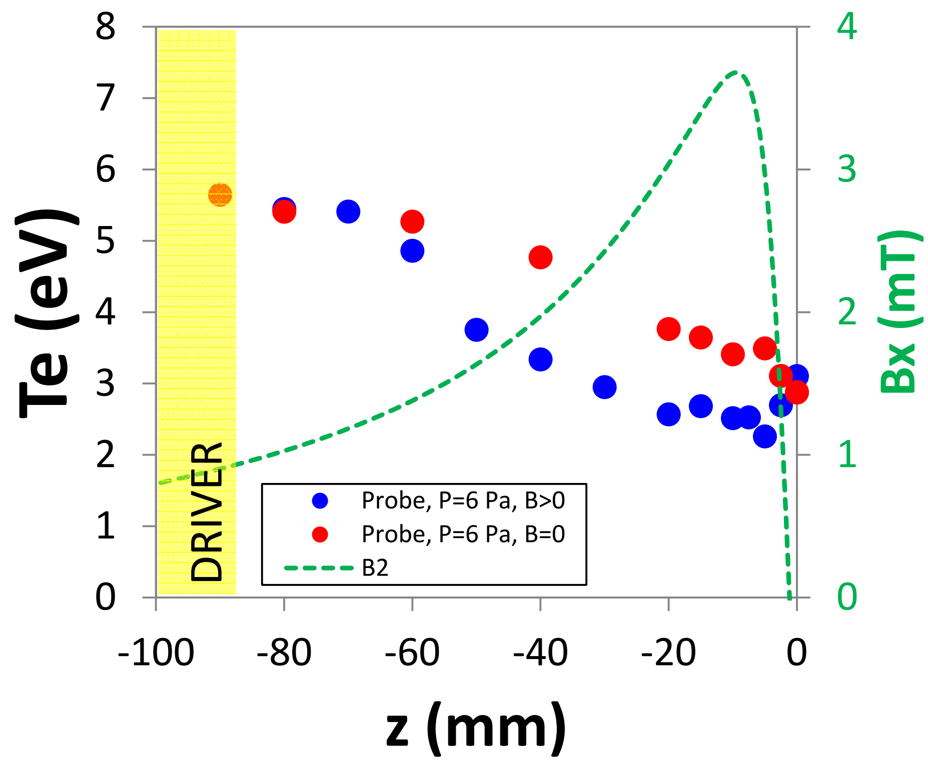
Configuration B2





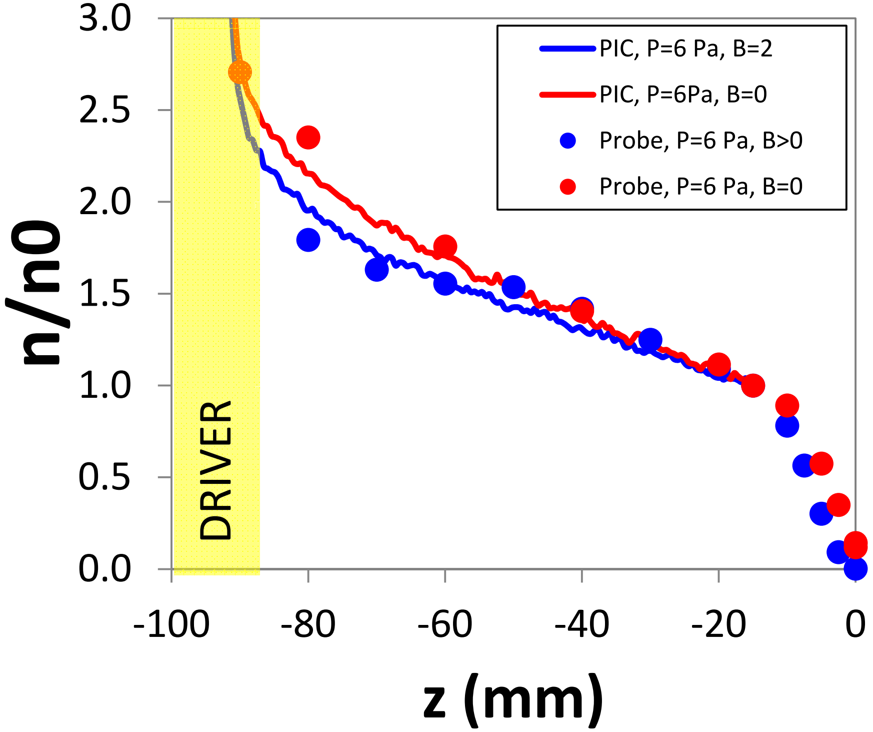
Electron Cooling: Probe measurments

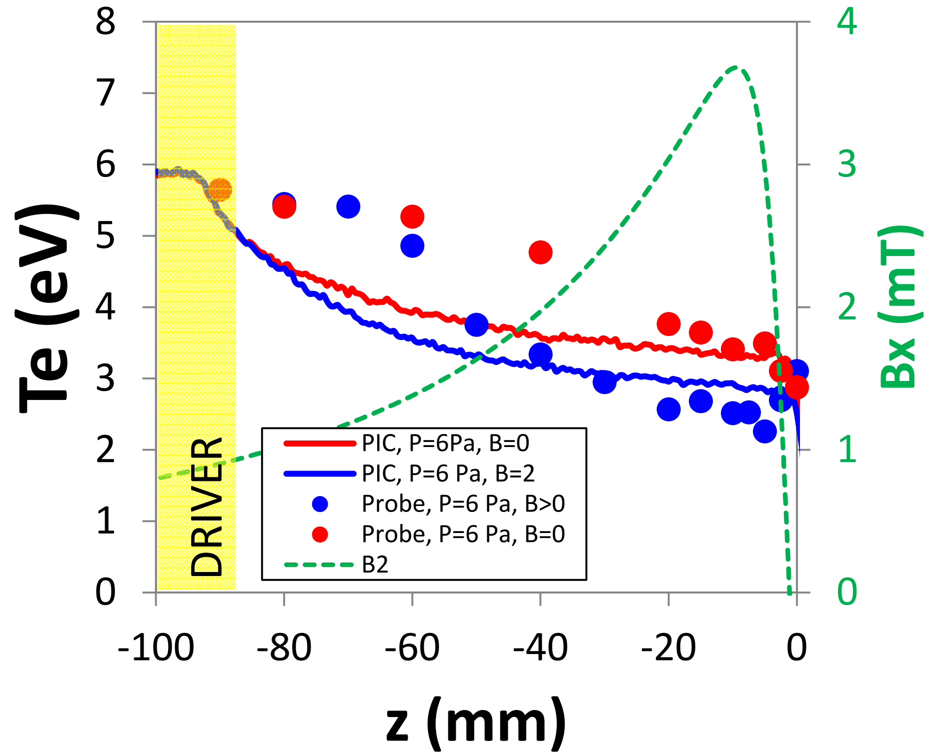




- The measured Te profiles show the electron cooling when the B field is turned on.
- The measurements were also compared with a 1D-3V PIC code of the plasma chamber
- The values of Te at the PG are in agreement with the measurements, but the behavior in the plasma volume differs from the probe measurements.

Probe vs. PIC: Effect of B on T_e along z



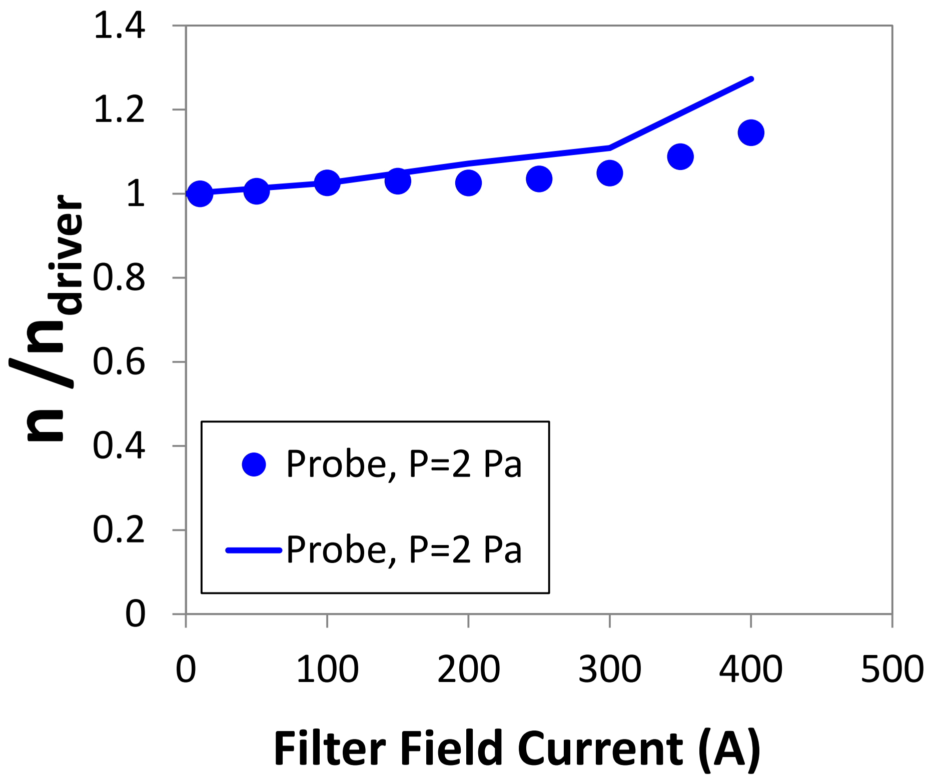


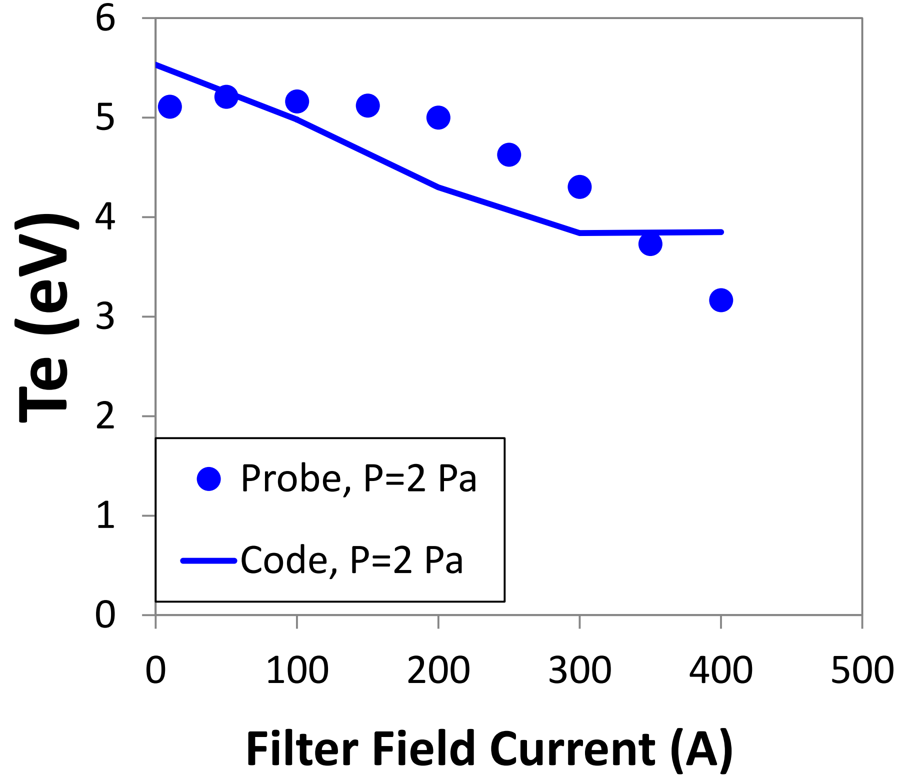
- The measured Te profiles show the electron cooling when the B field is used.
- At higher pressures the temperature is decreased even in absence of any B field.
- The values of Te at the PG are in agreement with the measurements, but the behavior in the plasma volume largely differs from the probe measurements.

Probe: Effect of B on T_e at z=-10

RF=1.1 kW
P= 2 Pa

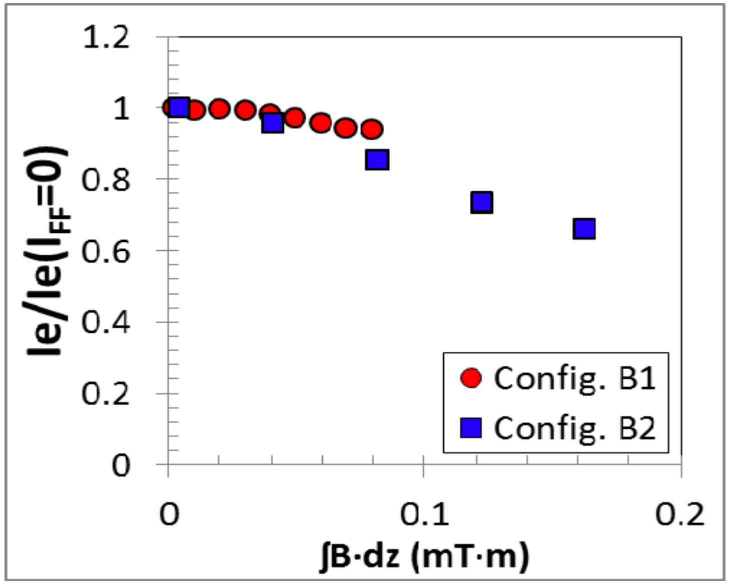
Probe at fixed position: 10 mm form the PG (z=-10)



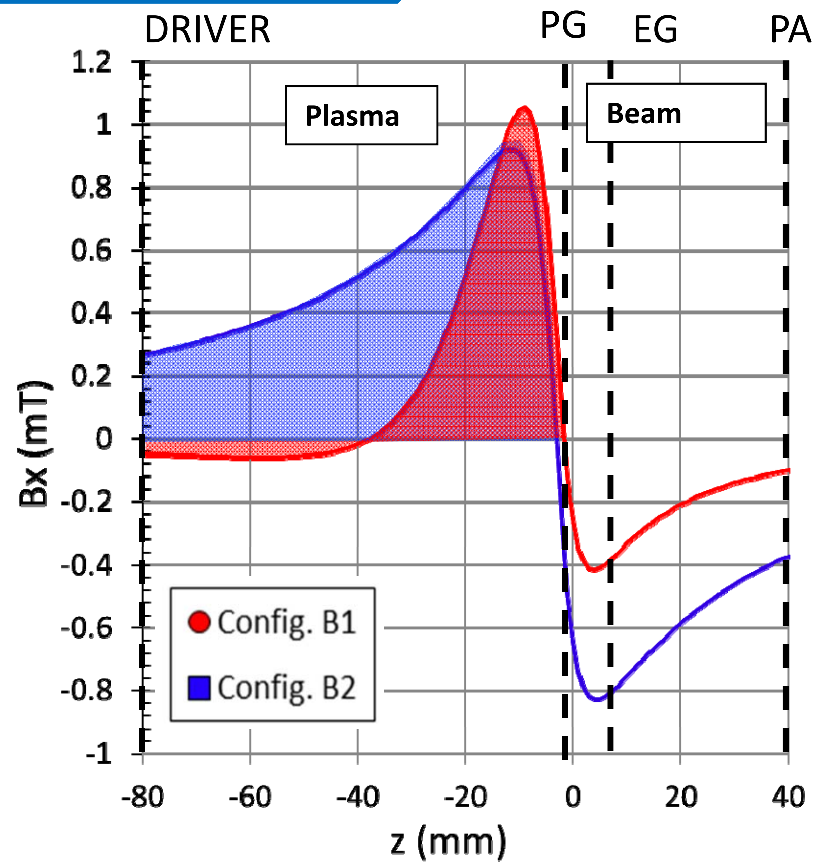


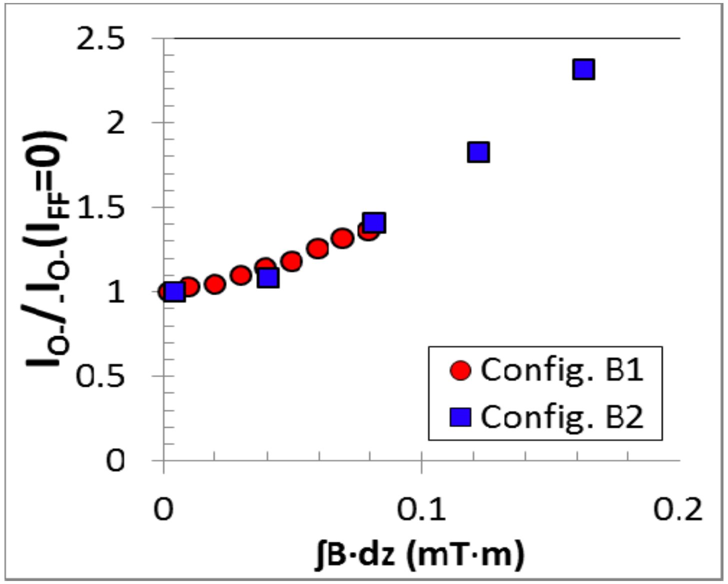
By increasing the filter field current (i.e.e the Bx intensity) the behavior of density and temperature calculated with the PIC code or deduced form the probe data are in qualitative agreement.

Electron Cooling: filter field



p=0.35 Pa
P_{RF}=800 W
V_{EG}=1.5 kV
V_{PA}=15 kV
$I_{O-} \approx 4$ mA
$I_e \approx 450$ mA

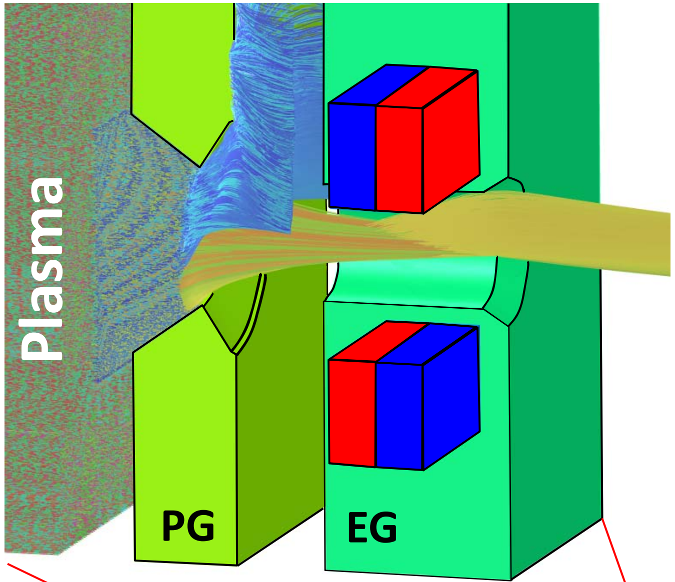




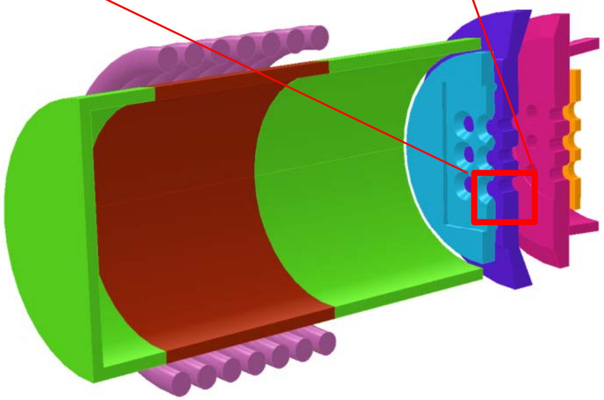
- I_e decreases rapidly with the new configuration (B2)
- I_{H-} increase is higher.
- In terms of $\int B \cdot dz$ the I_e trend is similar for both configurations
- No saturation of the effect: More B field is advisable!

Extraction system upgrade

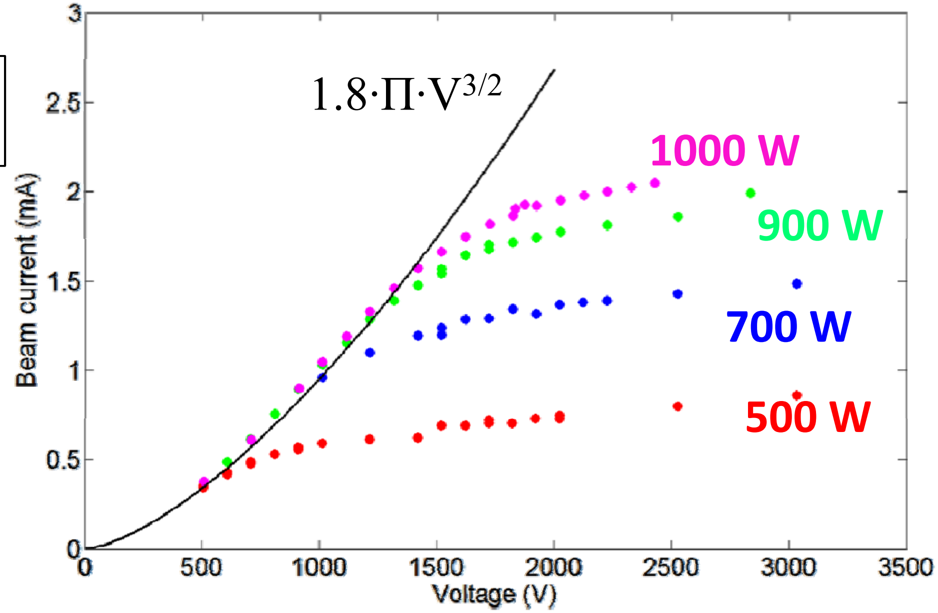
The accelerator is composed by 4 electrodes. The extraction Grid (EG) is polarized positive to attract negative charges from the plasma



3D beam extraction simulation



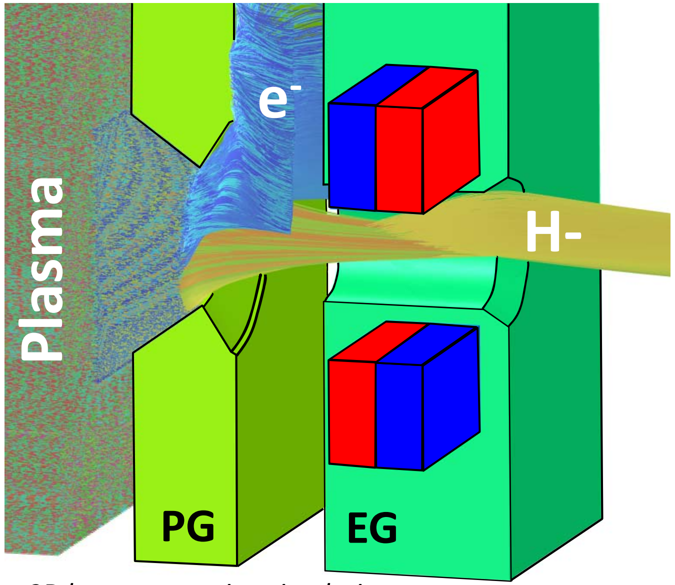
O^- beam
p=0.35 Pa



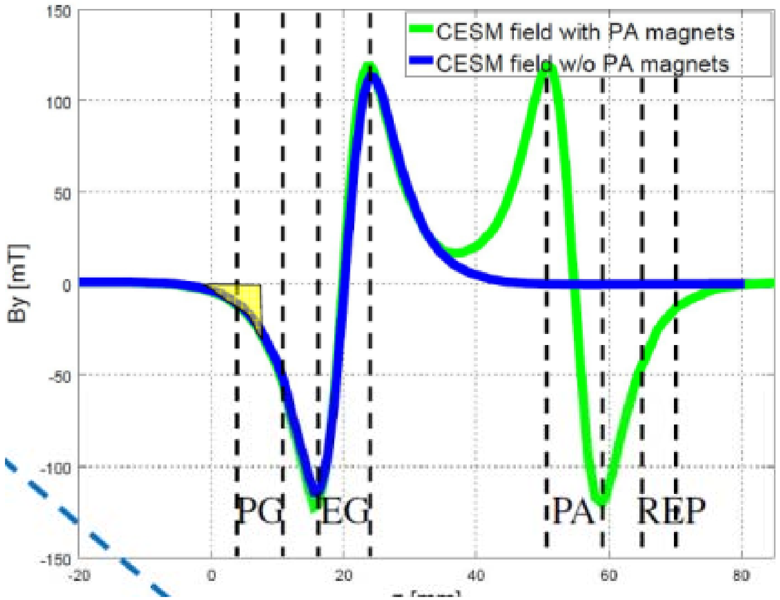
- The optics of the ion beam is strongly depend on the E field in the PG-EG gap, where the beam space charge is important.
- in NI sources one can easy run out of ions--> saturation of current
- In the CL limited region current do not depend from Prf

Extraction system upgrade

The accelerator is composed by 4 electrodes. The extraction Grid (EG) is polarized positive to attract negative charges from the plasma



3D beam extraction simulation

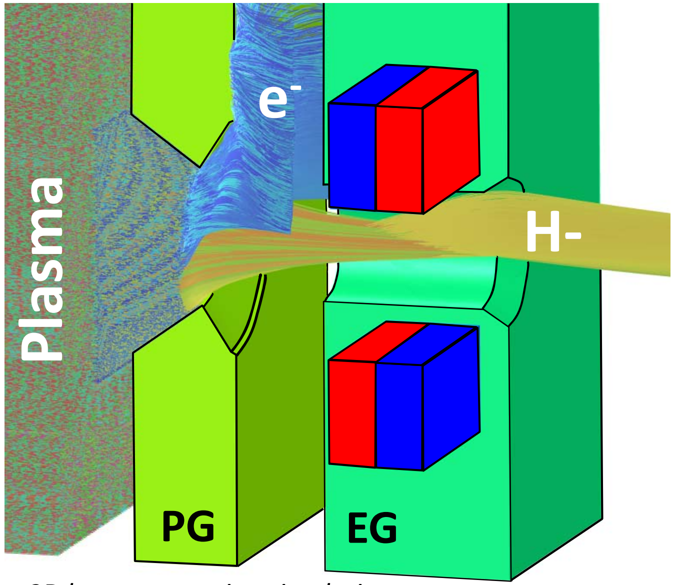


Co-extraction of e- is a major issue of negative ion sources. Magnets are embedded in the EG to deflect them before the high voltage stage.

Magnets too weack: electron leak in the HV region
Magnets too strong: electrons clouds in the gap→ voltage holding issues!

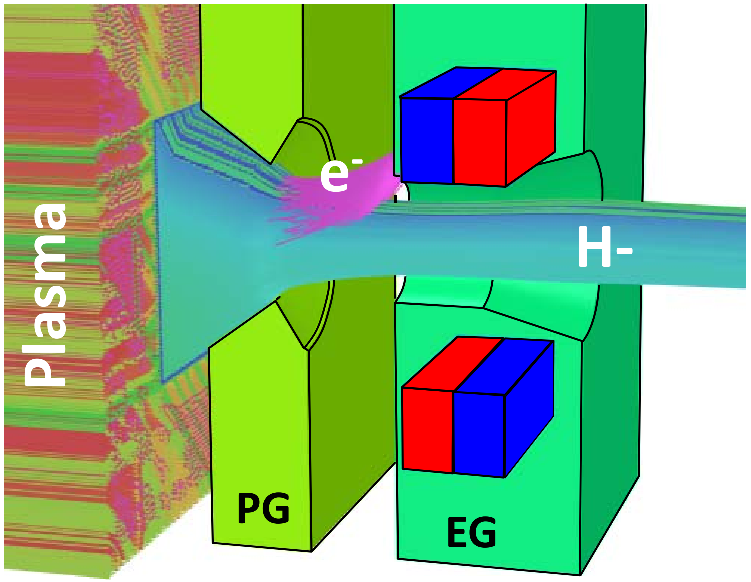
Extraction system upgrade

NIO1 original extractor



3D beam extraction simulation

NIO1 new extractor

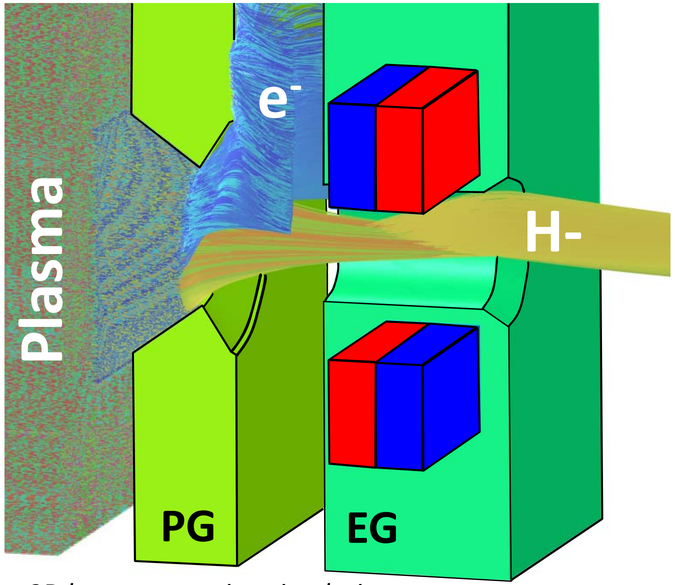


The extraction system was redesigned. The EG apertures are now enlarged →converging electrostatic lens penetrates more.
Optimization in terms of:

- Divergence of the beam
- Deflection of electrons
- Deflection of ions

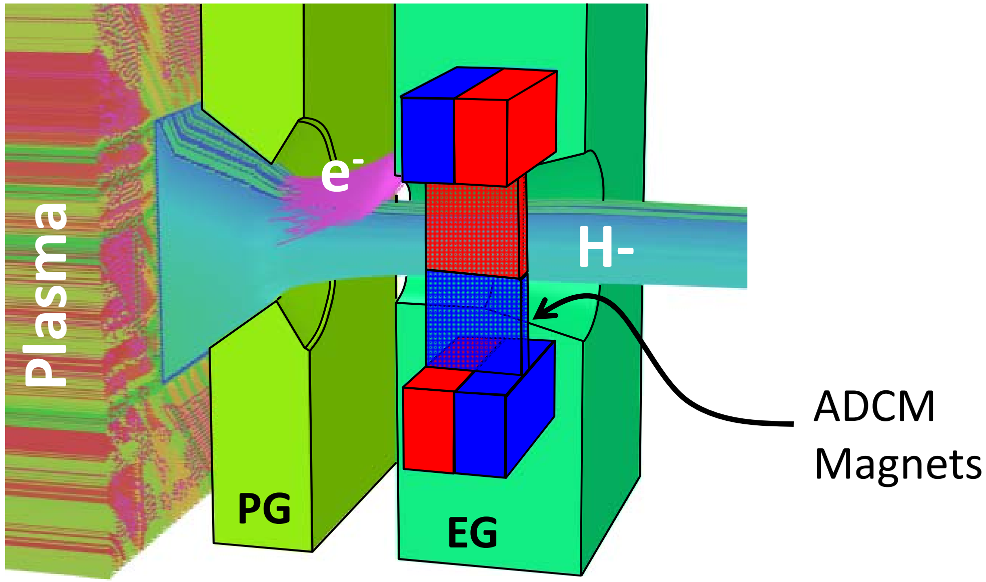
Extraction system upgrade

NIO1 original extractor

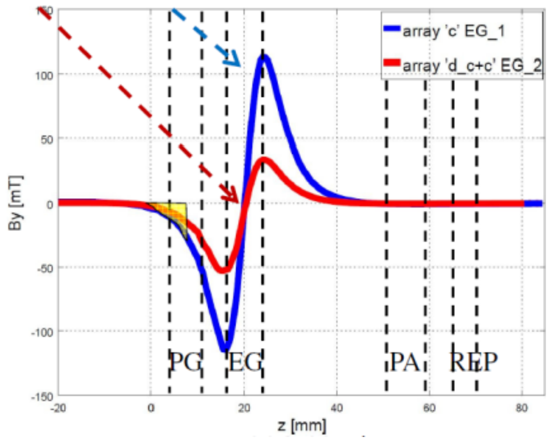


3D beam extraction simulation

NIO1 new extractor



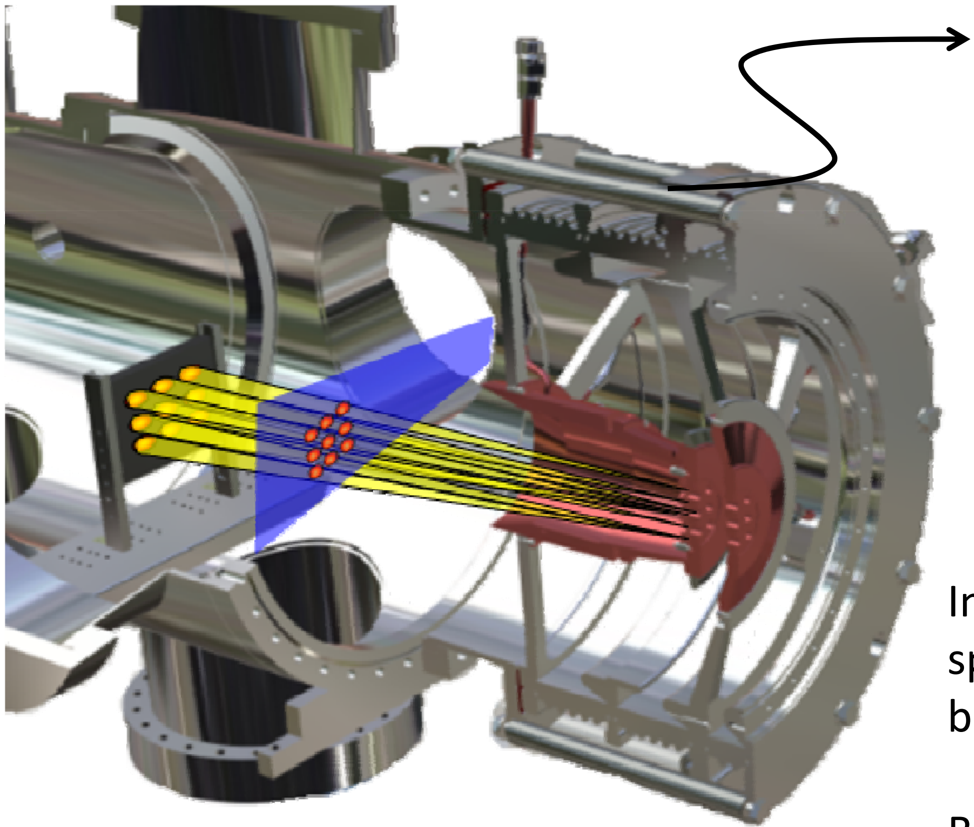
Ion beam also suffer a small deflection→ not negligible after 27 m!! (x2 beam size increase)

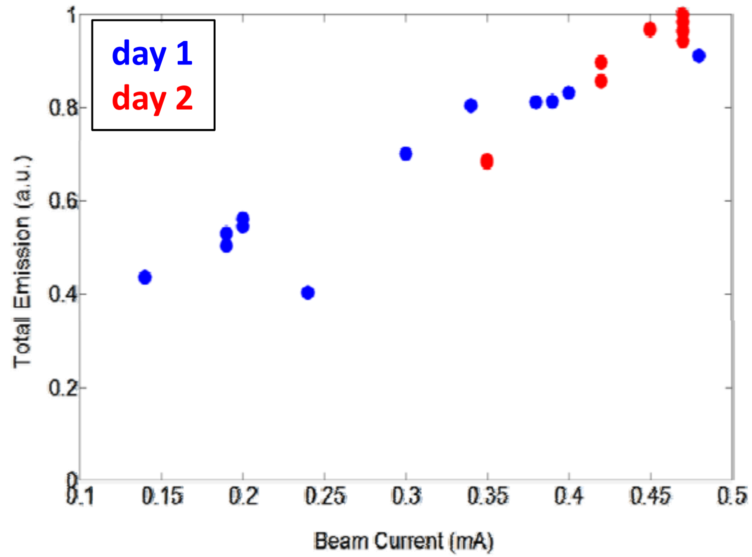


- A novel method (RFX patented) that cancel the ion deflection was implemented in the ITER NBI design
- Preliminary tests in Japan ->OK
- Test in NIO1 in next months

Beam Tomography: linear CCD

PRELIMINARY!



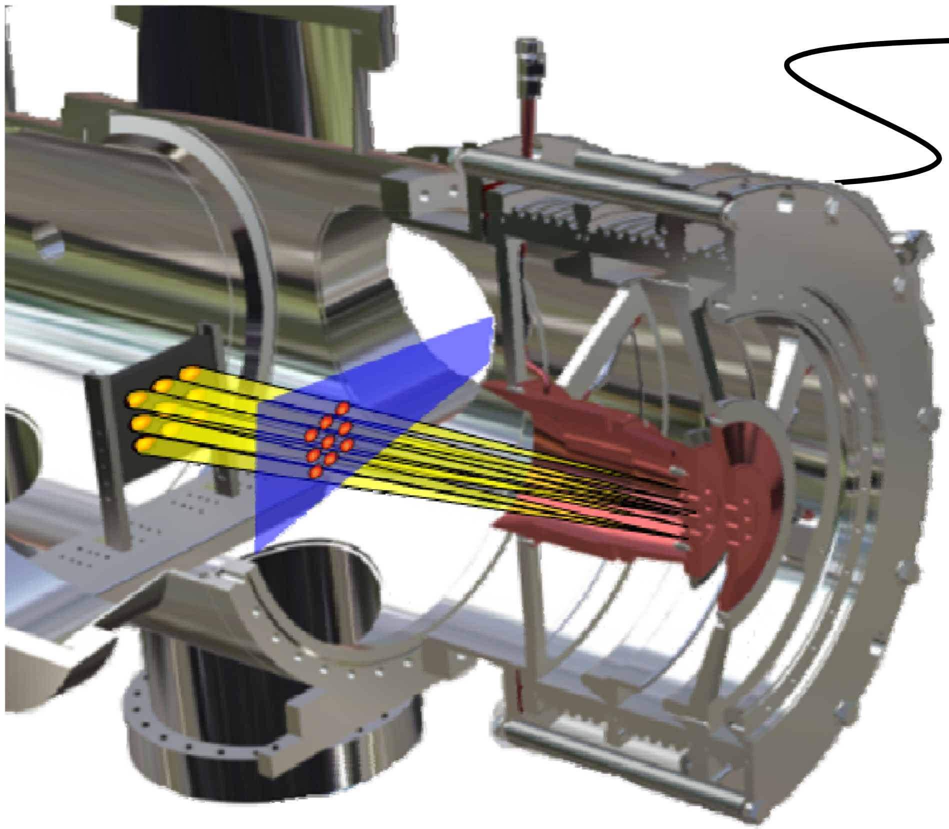


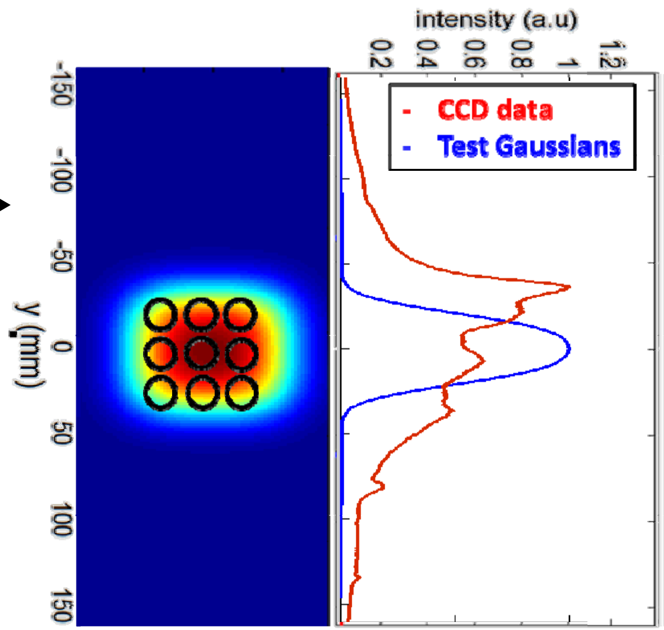
In the beam line the beam emission spectroscopy (BES) Allow to measure the beam (broadening of the Doppler peaks)

Beam tomography → for beam uniformity
A linear CCD array was installed recently

Beam Tomography: linear CCD

PRELIMINARY!



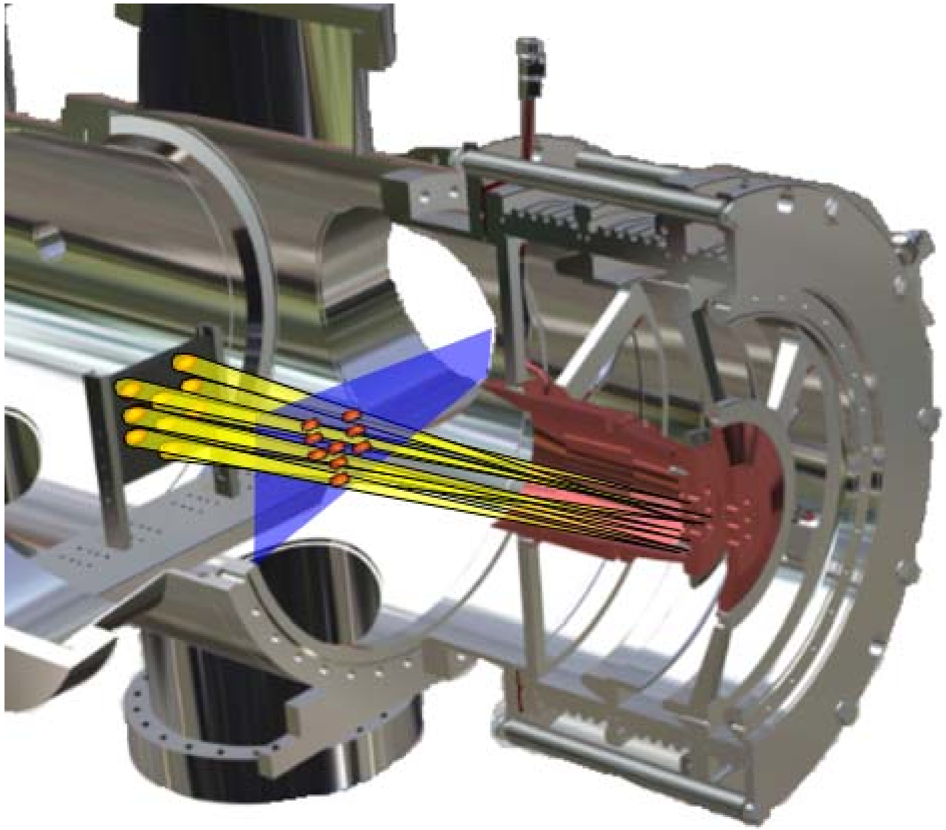


Test Gaussian parameters:
Beam divergence: 35 mrad
Magnetic deflection: 0 mrad
Tomographic plane: 0.25 m from GG

The first data show a largely asymmetric beam, whereas in principle one may expect a Gaussian profile.

Beam Tomography: linear CCD

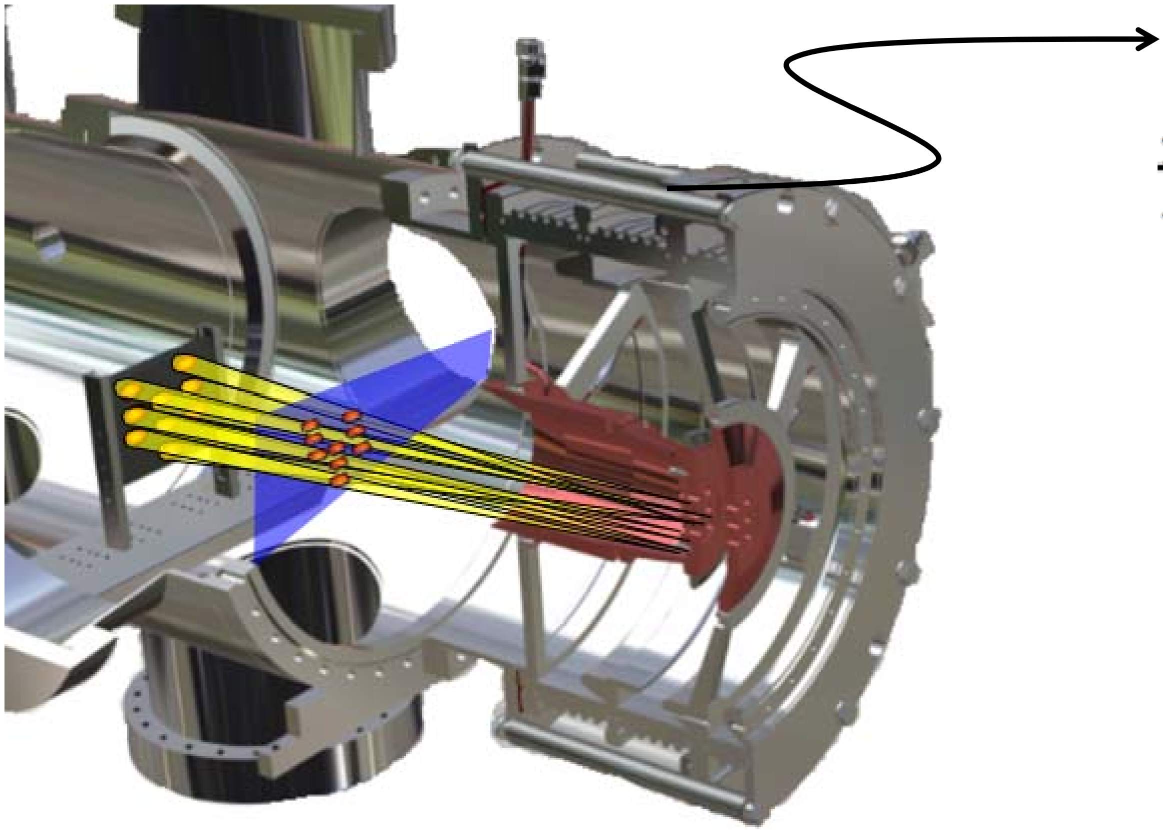
PRELIMINARY!

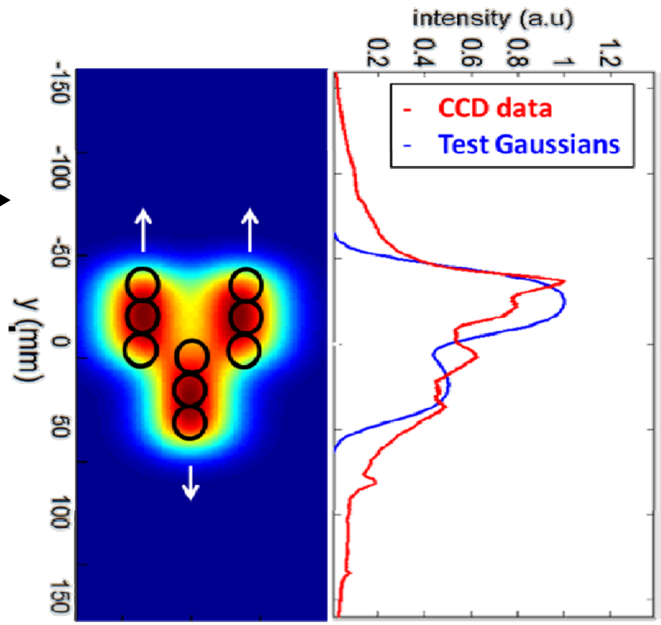


The first data show a largely asymmetric beam, whereas in principle one may expect a Gaussian profile. The asymmetry is probably induced by the Magnets in the EG: deflected beamlets (column by columns)

Beam Tomography: linear CCD

PRELIMINARY!

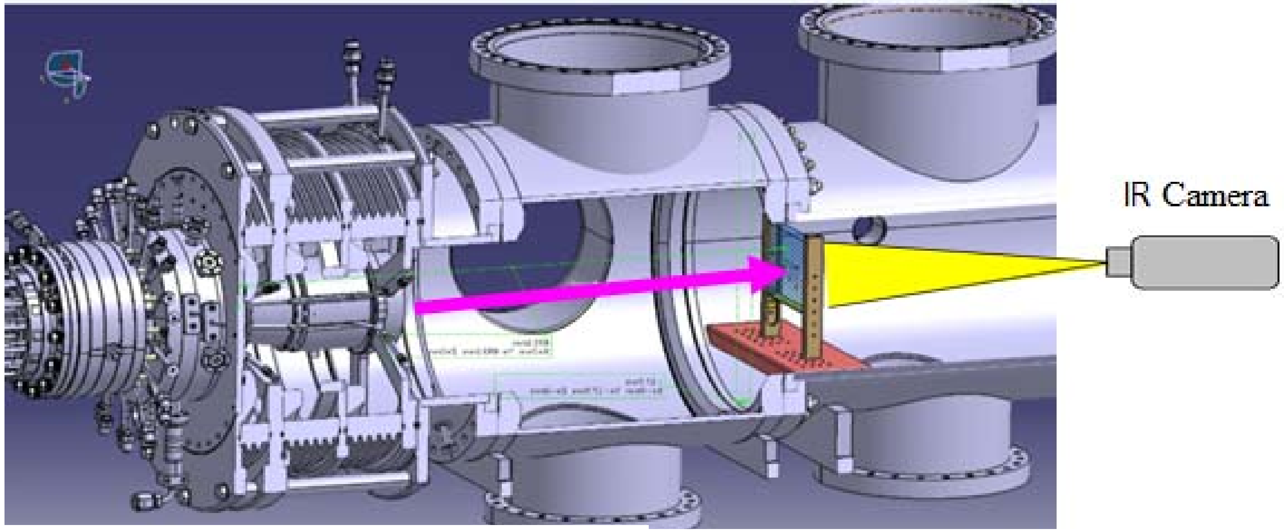


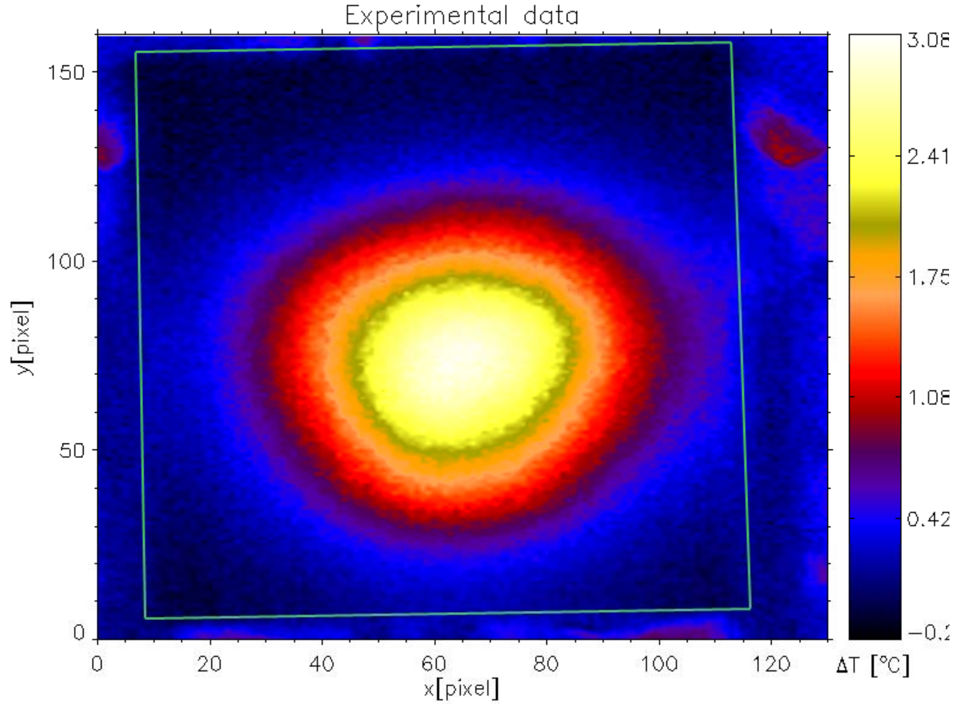


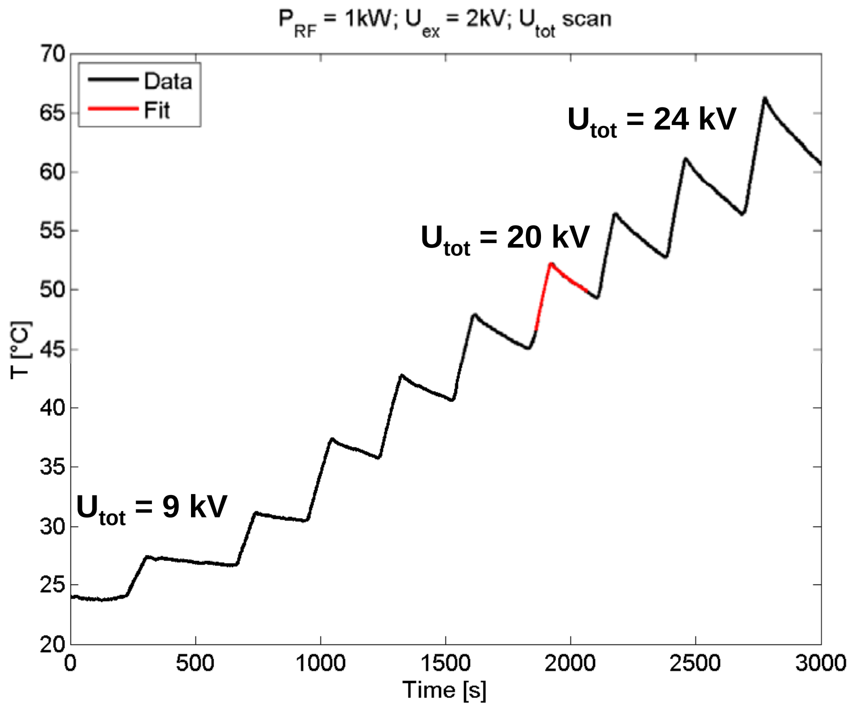
Test Gaussian parameters:
Beam divergence: 35 mrad
Magnetic deflection: 70 mrad
Tomographic plane: 0.25 m from GG

The first data show a largely asymmetric beam, whereas in principle one may expect a Gaussian profile. The asymmetry is probably induced by the Magnets in the EG: deflected beamlets (column by columns)

Beam characterisation by mini-STRIKE

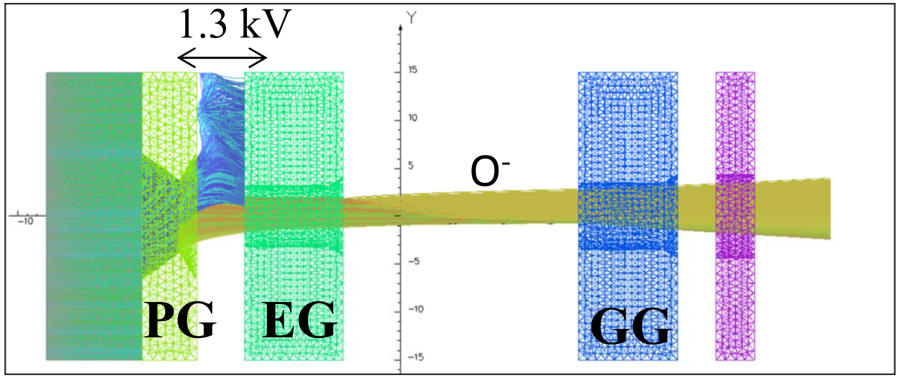


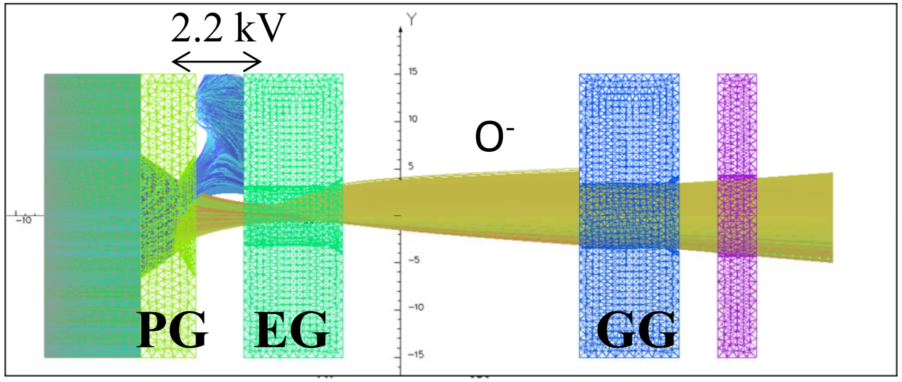


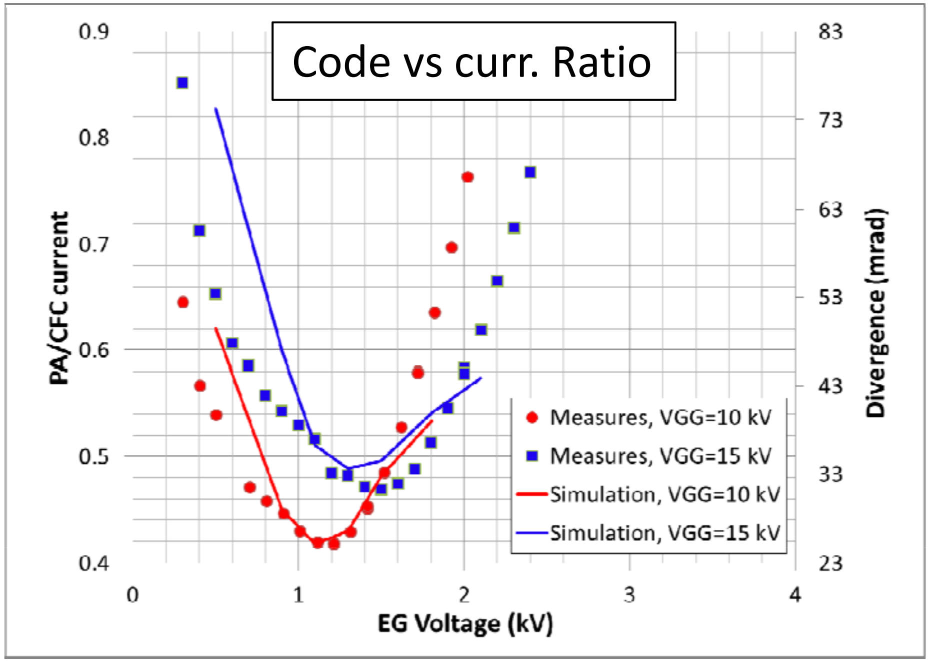


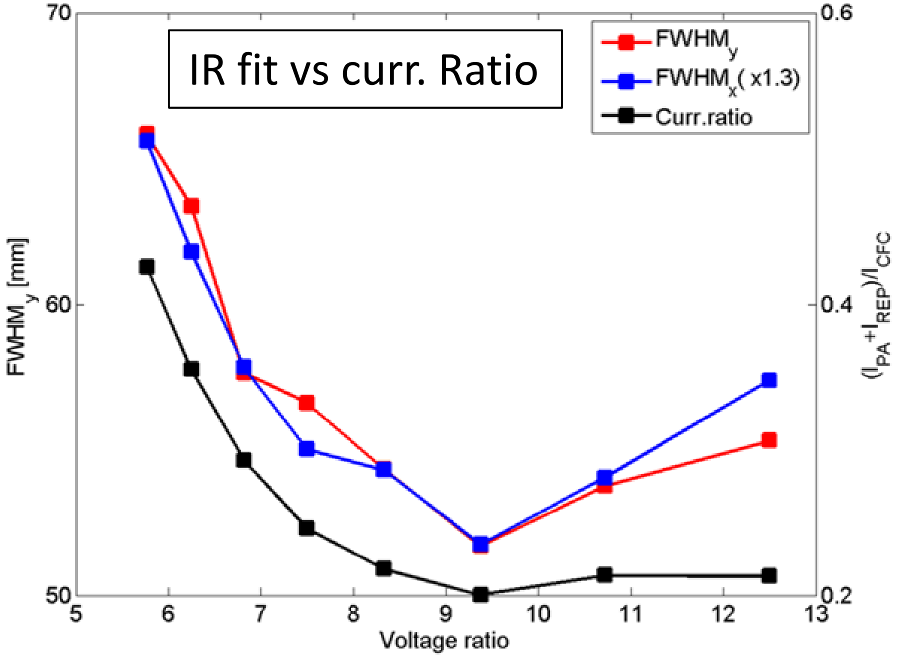
Data vs. beam simulation: Fixed Vacc

A reasonable agreement was found in codes-experiment benchmarks, both in terms of electric measurements, and IR data.

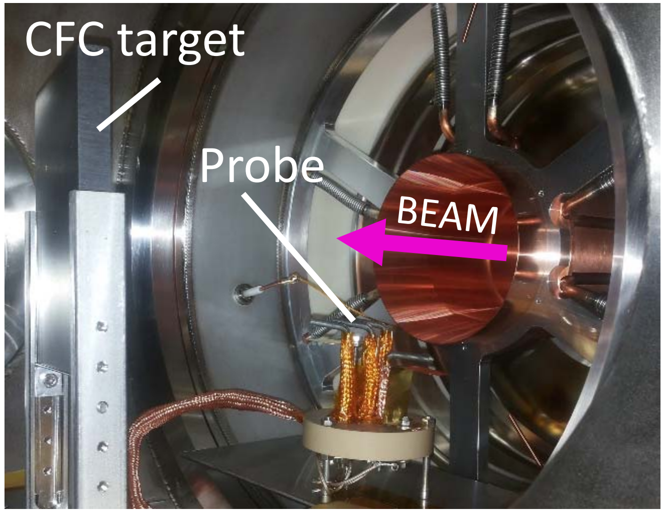


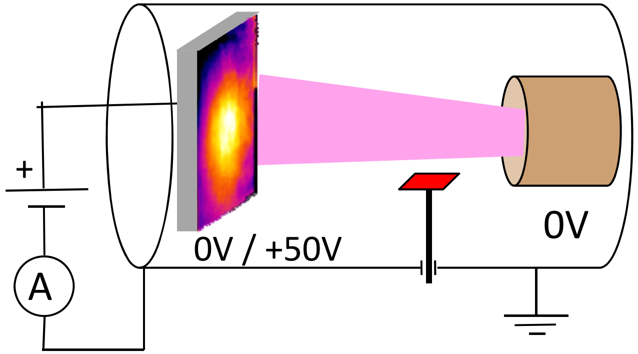






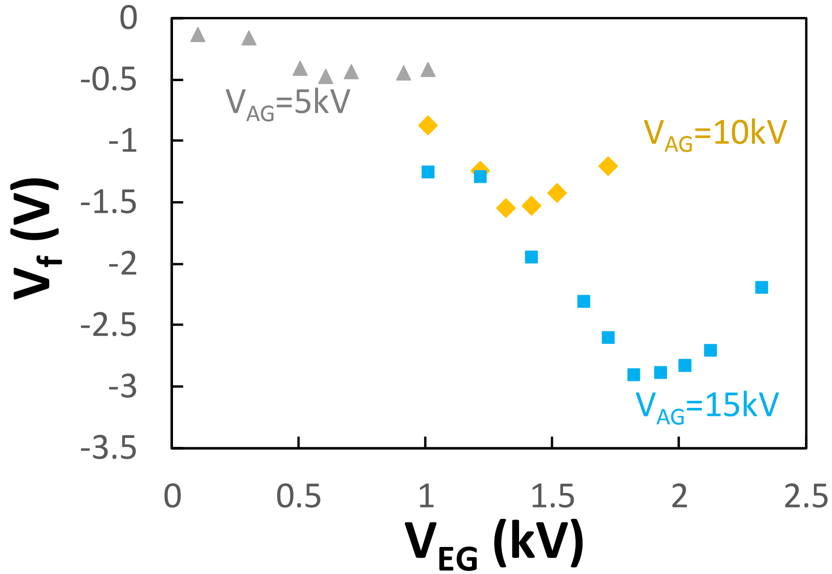
Beam Langmuir probe: I-V characteristic

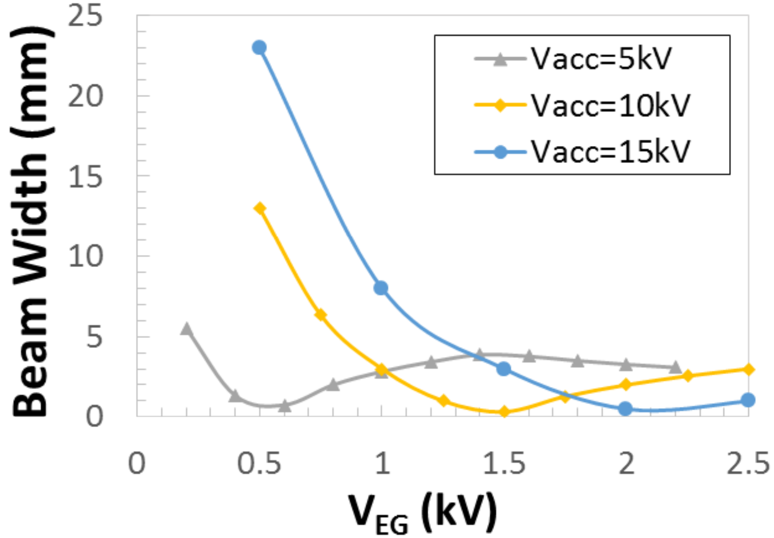




Typical Values:

Te ~ 6 eV,
n ~ 1x10^{12} m^{-3} ,
Vp ~31 V

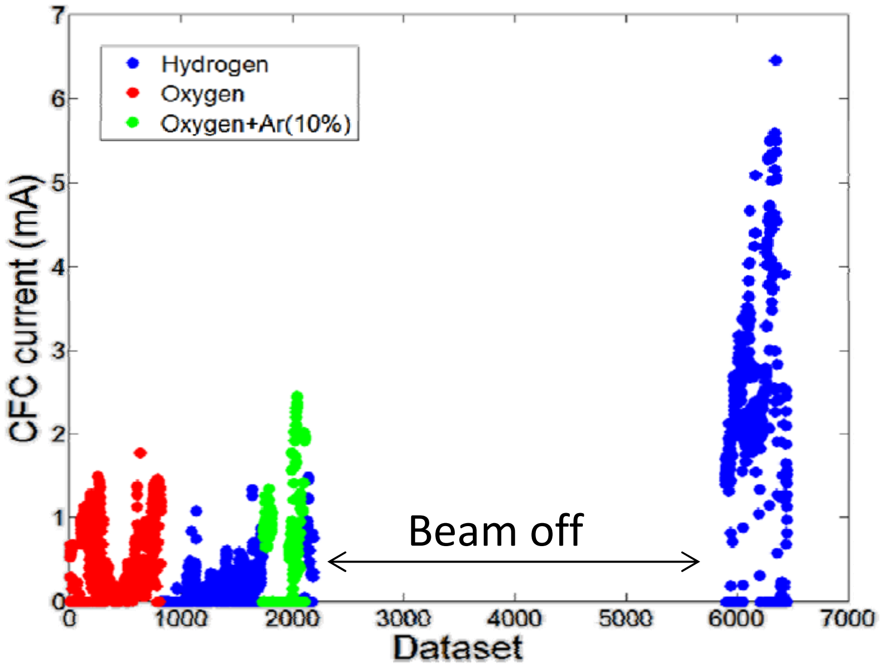


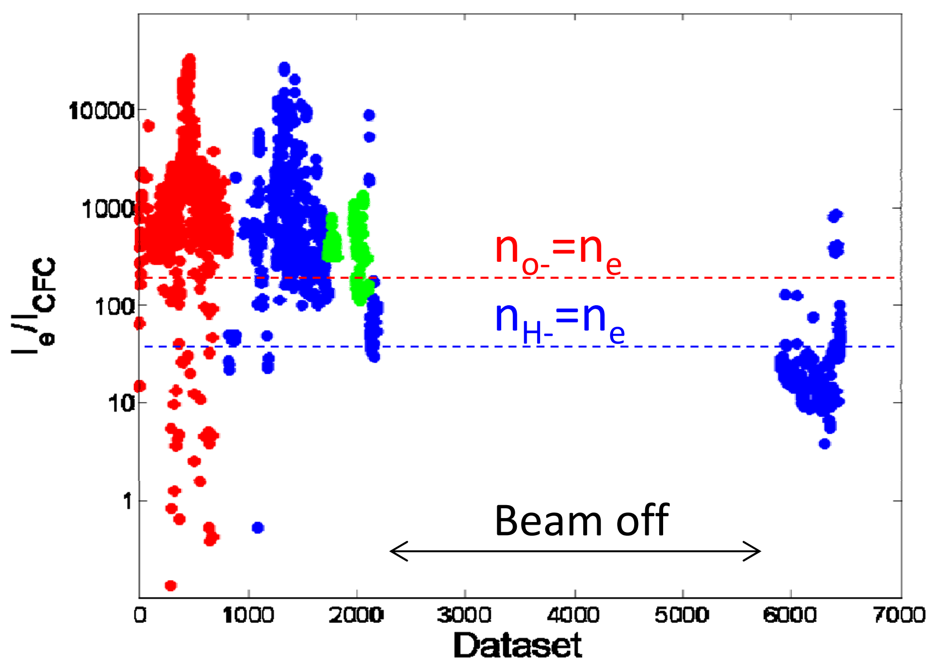


- the maximum absolute value of the floating potential is found in the correspondence of the best optics: when the ratio V_{acc}/V_{EG}~6.2

Beam Performances so far

Operation of source and beam are at steady state.
A database of records representing instantaneous quantity is also compiled in parallel.
Operation with several gases is possibile at NIO1. In 2016 we focused on O_2, O_2+Ar and H_2

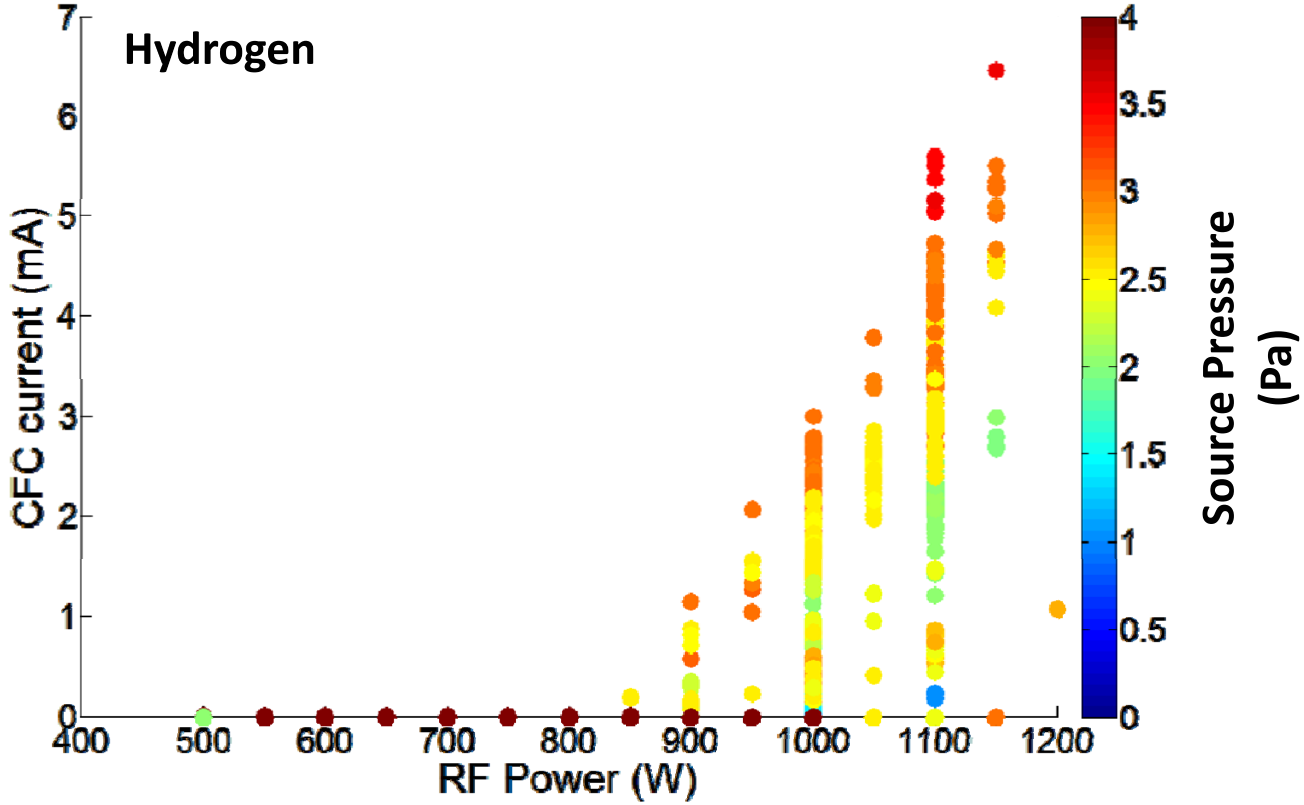




- Extracted negative ion current $j_{H-} \sim 30$ A/m^2
- Negative ions H- becomes dominant in terms of space charge in the extraction region

Beam Performances so far: H_2

- As a general trend, beam current increases with Power and source pressure (Ps)
- Air/Oxygen are operated at low pressure (<1 Pa)



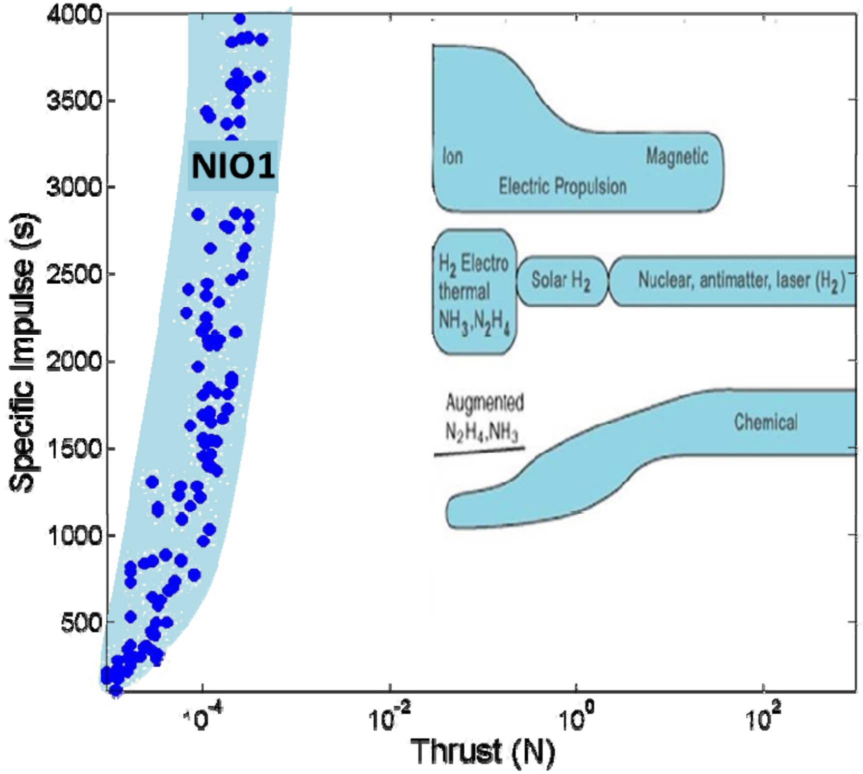
Nonetheless many other improvement were necessary

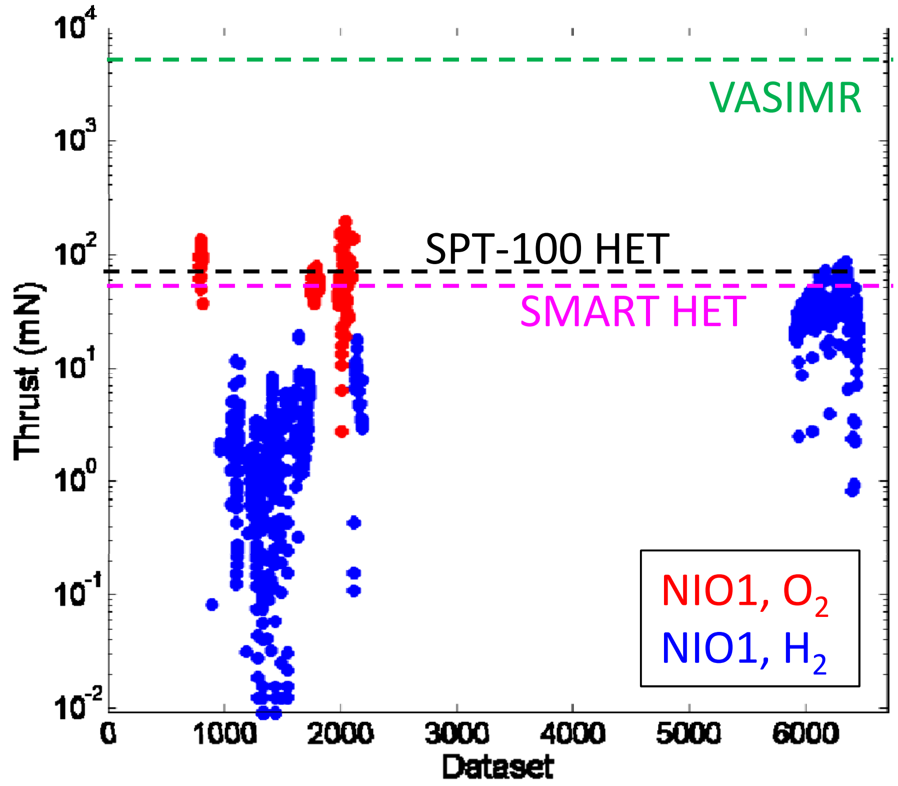
- Voltage holding
- Filter field
- Source Bias Plates
- -……

NIO1 Thrust ☺

Let's put this performances in the space propulsion perspective

Range of Thrust and Isp for different propulsion system
(from: http://dawn.jpl.nasa.gov/)





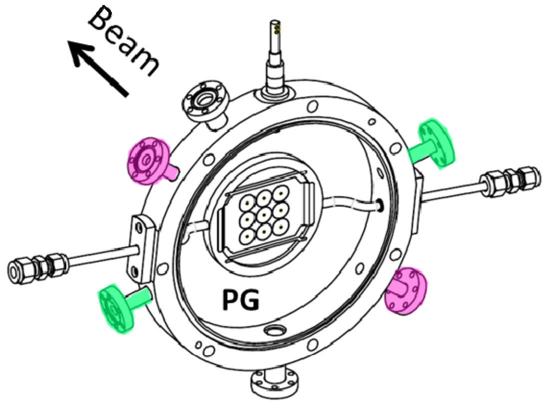
Still a lot of job to do to decrease the weight from >1 ton!

Acknowledgments: NIO1 was set up in collaboration and financial support of INFN group 5 (Technological Researches), INFN-E (Energy Researches), F4E (Fusion for Energy) and EUROFusion.

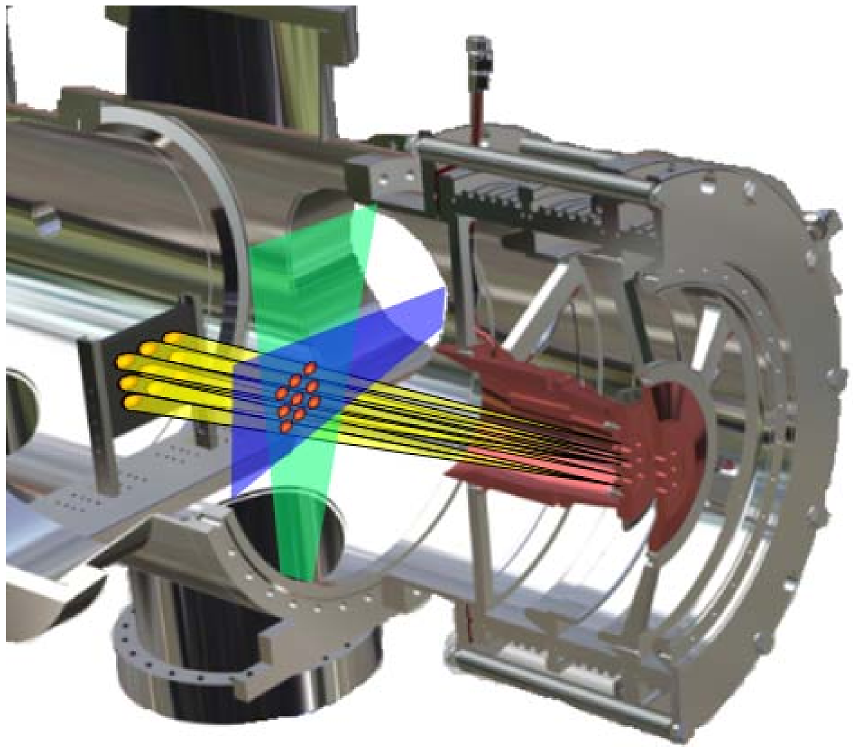
NIO1 experiment: Diagnostics

Available
In progress
Planned

Source
- Spectroscopy (many Lines of sight)
- cavity ring down
- Laser Absorption (Cs monitor)
- Langmuir probes



Beam
Electric Measurements (H- /e- current)
- Graphite fibre calorimeter+ IR camera
  (Or Copper Calorimeter +Pepperpot for high power)
- Beam emission Spectroscopy
- Emittance Scanner
- Tomography



Beam Plasma
- Langmuir probe
- Retarding field energy analyzer
- Movable probe