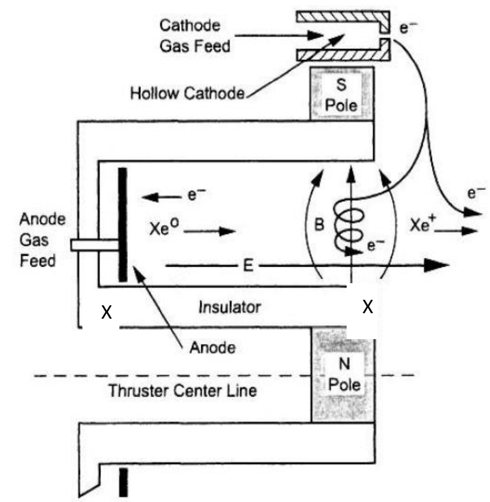
Plasma Characterization of a Hall Effect Thruster for a Negative Ion Source Concept



M. Fadone[1], V. Antoni[1,2], D. Aprile[1], G. Chitarin[1,4], A. Fassina[1], E. Martines[1], G. Serianni[1], E. Sartori[1,4], F.Taccogna[3], M.Zuin[1]

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[2]CNR Istituto Gas Ionizzati
[3]CNR Nanotec Bari, via Amendola 122/D, 70126 Bari, Italy
[4]Università degli Studi di Padova

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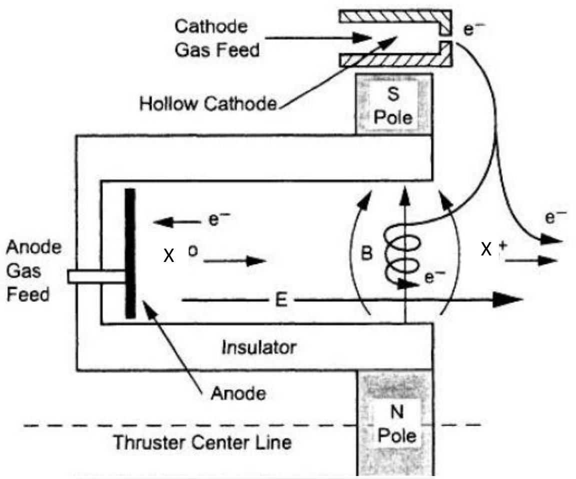
Introduction



D.M. Goebel, I. Katz, in Fundamentals and Electric Propulsion, (John Wiley & Sons, Inc., Hoboken, New Jersey),p.325-392

EuroFusion enabling research **EUF-ENR-17**

Experimental studies of Hall Effect Thruster technology modified to work in Hydrogen with energies compatible with the negative ion production

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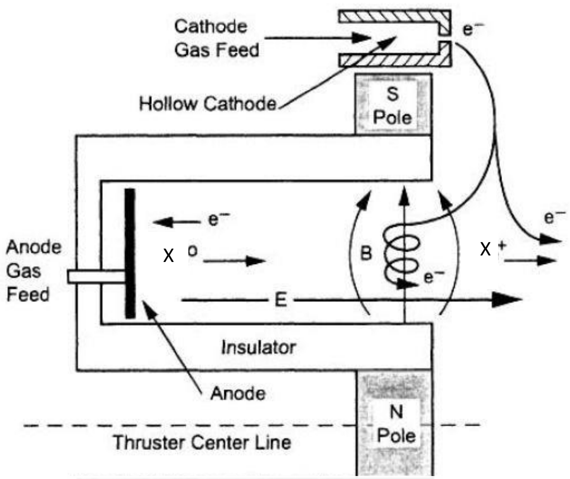

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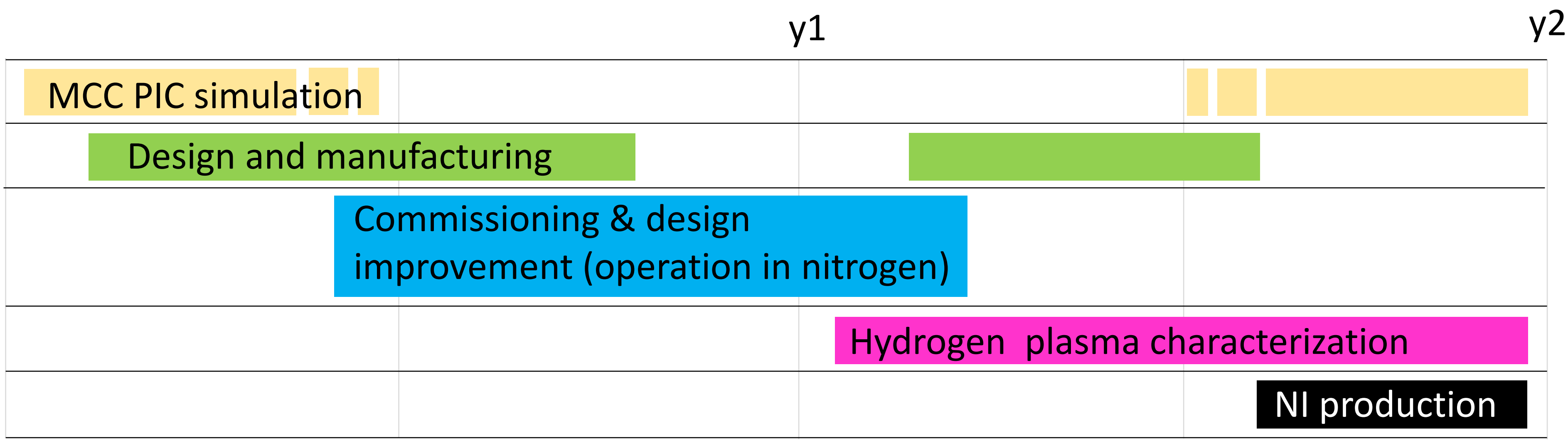
ATHENIS (Alternative Thruster Hall Effect Negative Ion Source Study)



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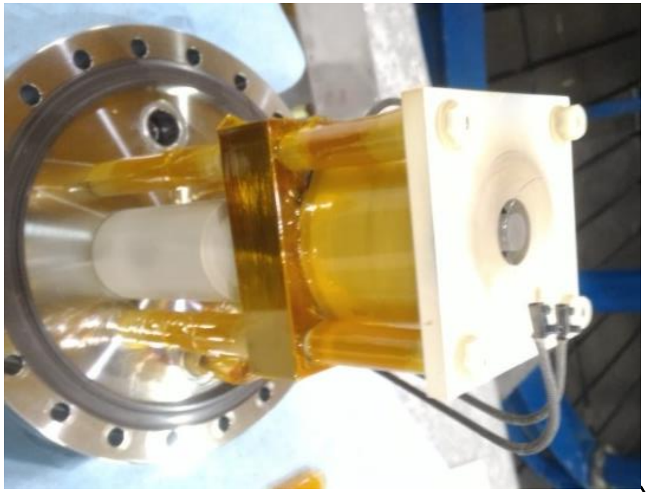

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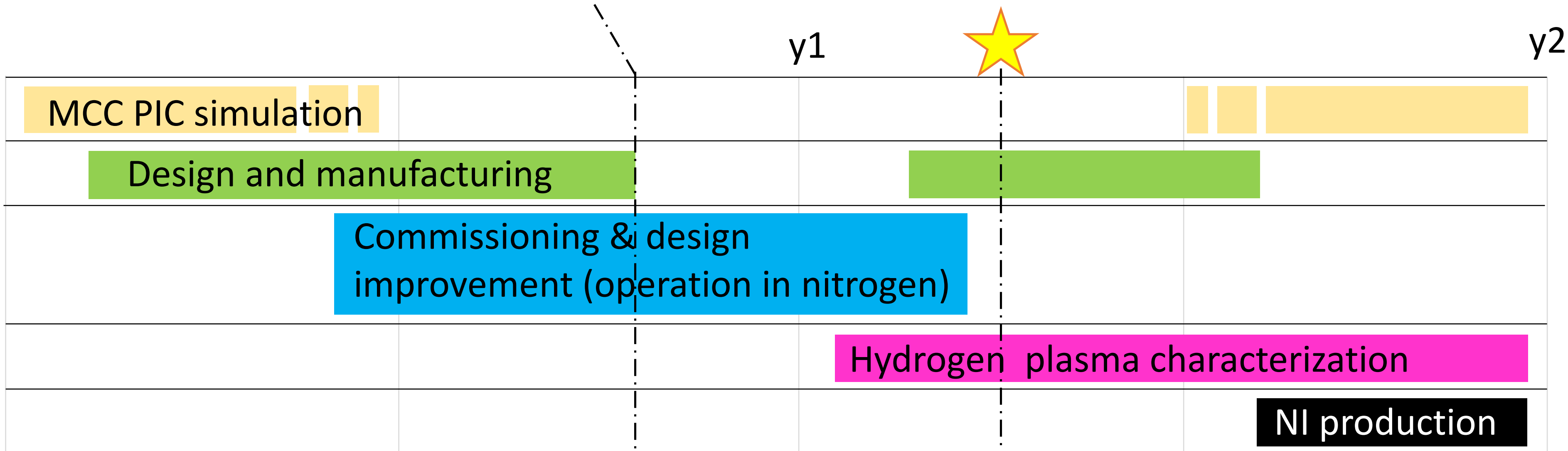
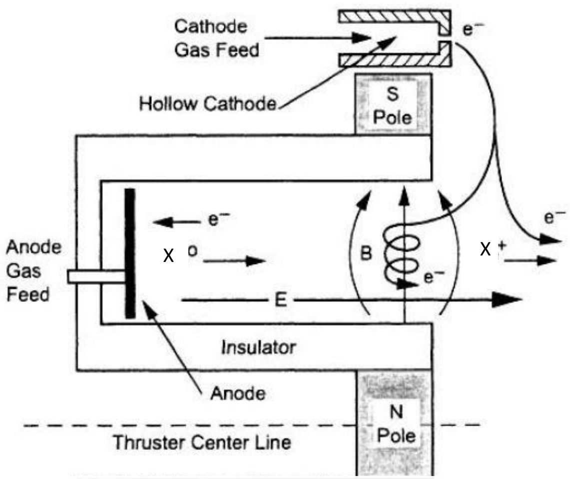


Motivations



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Features of Hall Thruster concept:

- Radial Magnetic Field with peak at the exit plane
- Axial Electric Field to accelerate ions
- Charge Neutralization through the cathode

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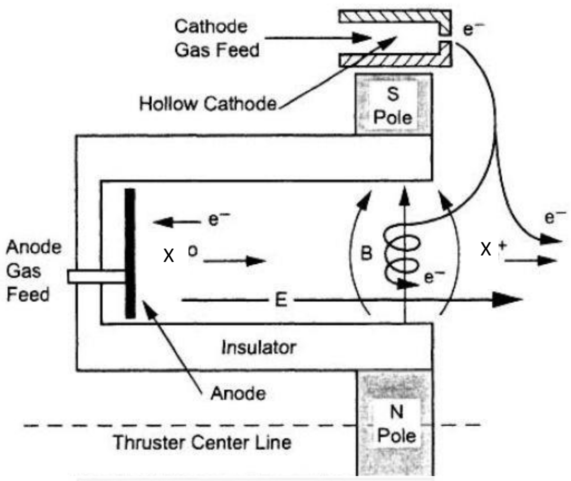

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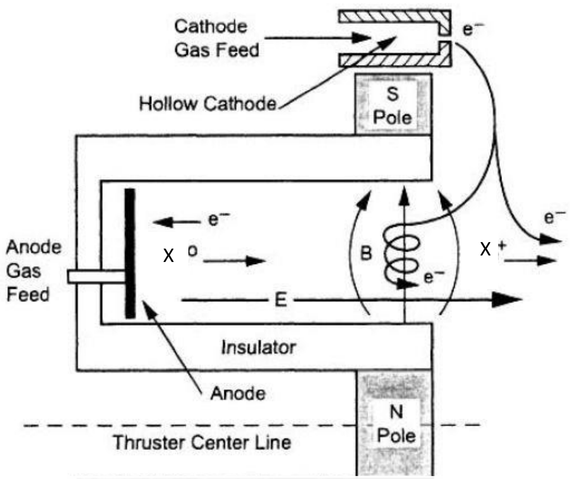
«Negative» features = Attractiveness for NI

- embedded magnetic field filter to confine energetic electrons before the plume
- Cylindrical symmetry
- possibility to control the axial energy of the particles to the plasma plume
- Very robust and reliable technology (long term space missions)

Motivations



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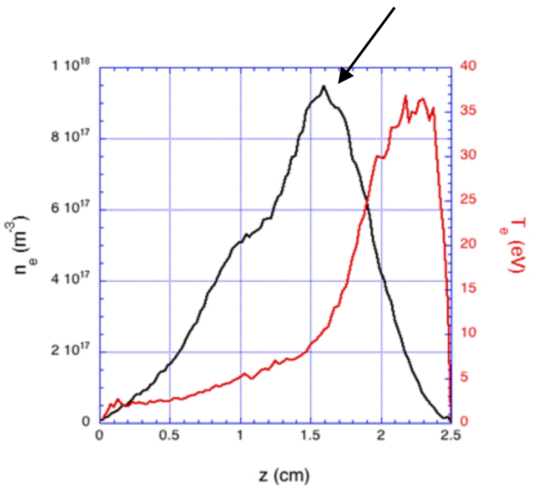

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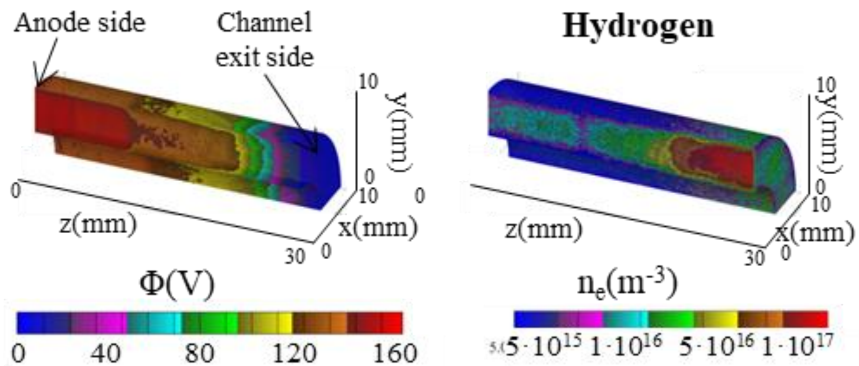

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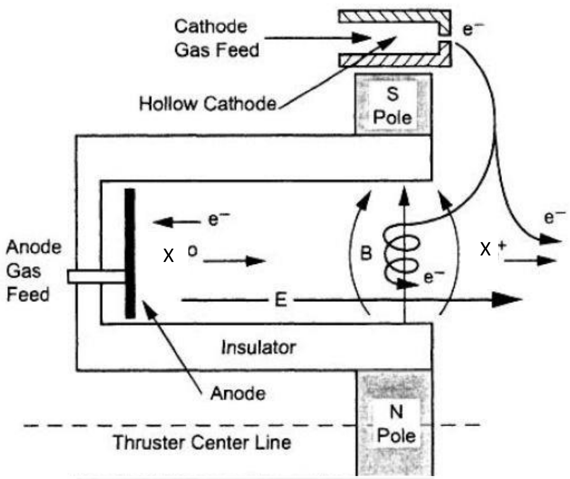

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in HT:
- heaviest noble gases are used to provide high specific impulse
- larger dimensions
- large gas flow

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- Radial Magnetic Field with peak at the exit plane
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«Negative» features = Attractiveness for NI

- possibility to control the axial energy of the particles to the plasma plume
- embedded magnetic field filter to confine energetic electrons before the plume
- Cylindrical symmetry
- Very robust and reliable technology

Not «Negative» features = possible showstoppers for H^-

- hardly ever been used with hydrogen
(low pressure discharges cannot be achieved,
or axial energy cannot be tuned down)
- high T_e in the plume
- gas flow is too high

Strategy

- Develop a Hall effect thruster design to maximise “NI-attractive” requirements
- Flexibility in the design to minimize the risks → modularity
  (no ignition of the plasma, not optimal geometry, too high discharge pressure, …)
- Characterization of Hydrogen plasma discharge in ~0.4Pa ()
- (next) Try to measure negative ions generated from a caesiated sample

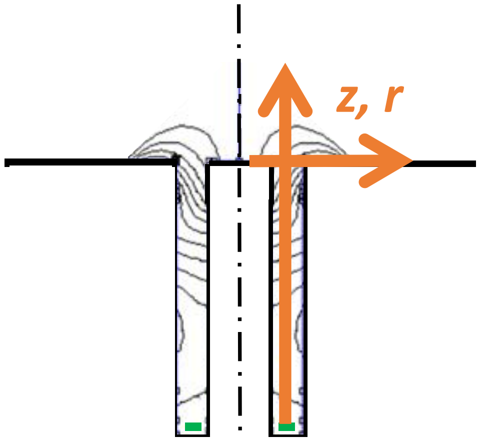
What we need:

- Spatial axial profile outside the HT of plasma density **n** and electronic temperature **T_e** (in the plume)
- Identify plasma species and their energy
- Plasma stability in different conditions, and behaviour of anomalous transport across the B field lines

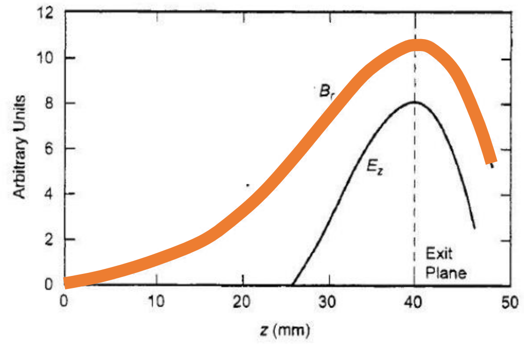
Outline

1. **Our recipe for a tasty Hall Effect Thruster (design)**
2. Manufacturing and commissioning of the thruster
3. Operation in N_2 (already different than noble gases)
4. Operation in H_2 – characterization of the plasma plume
5. Summary & next steps

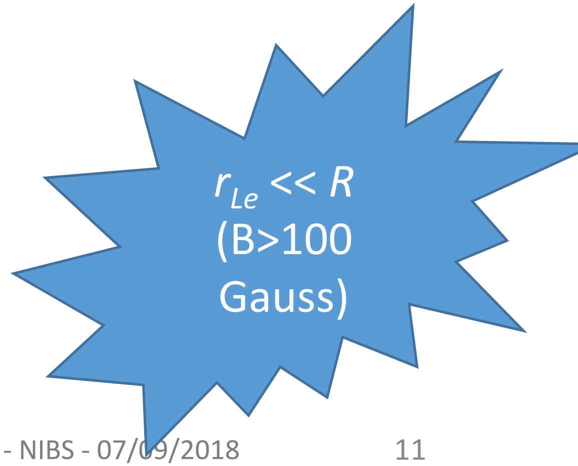
Hall Effect Recipe



Magnetic Field B



- Radial magnetic field inside the channel



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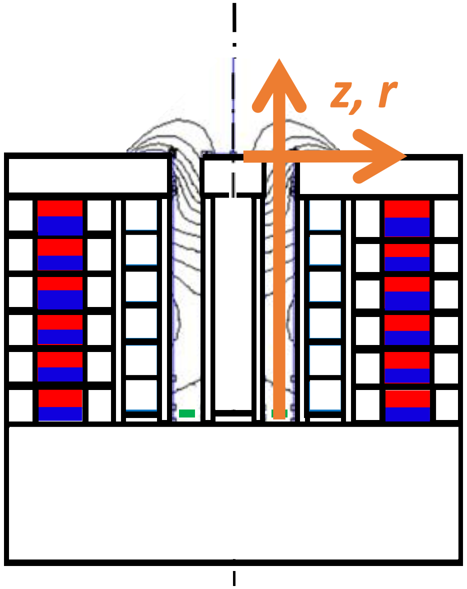

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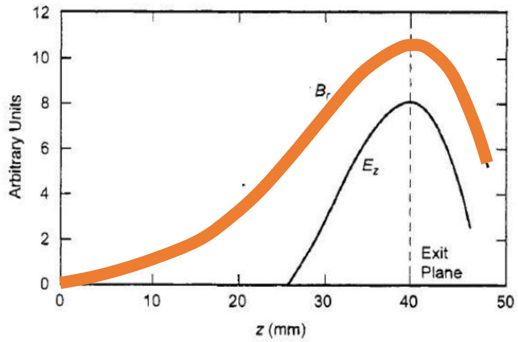

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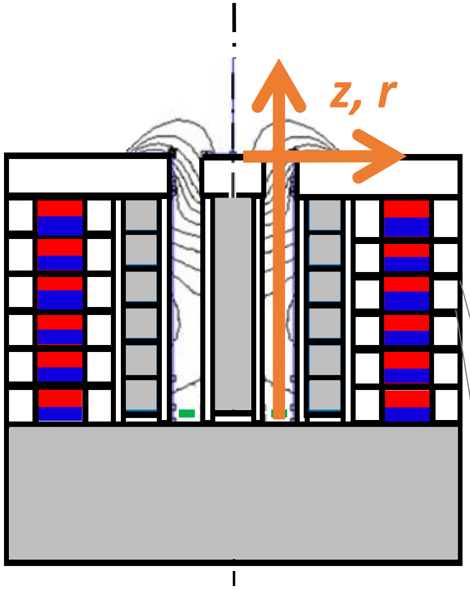

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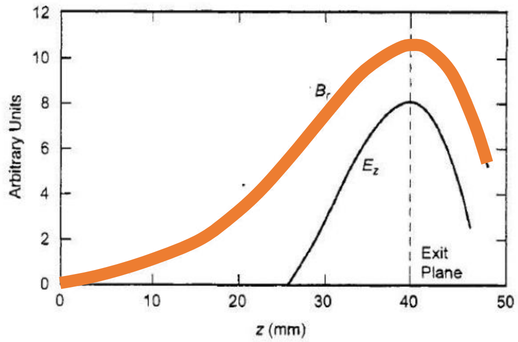
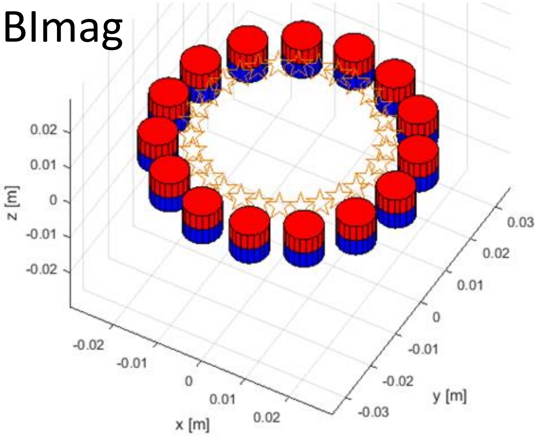


- Radial magnetic field inside the channel
- Modular approach for flexibility, NBImag simulations



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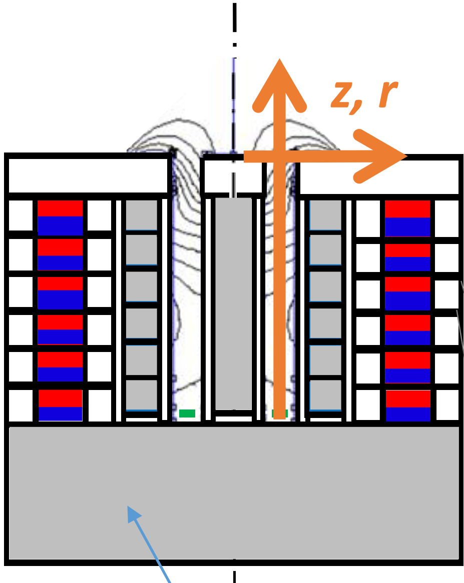
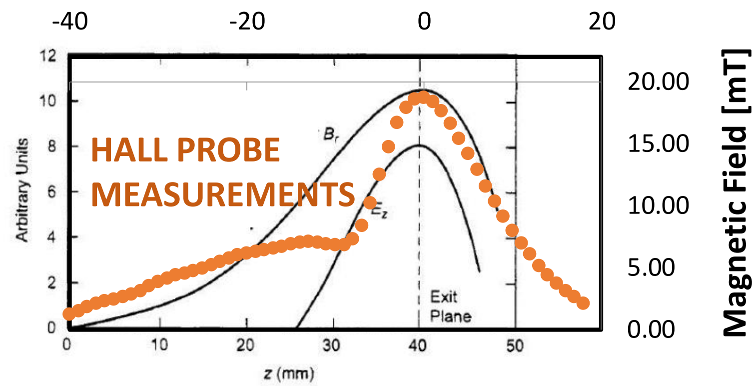


Ferromagnetic material

Magnetic Field B



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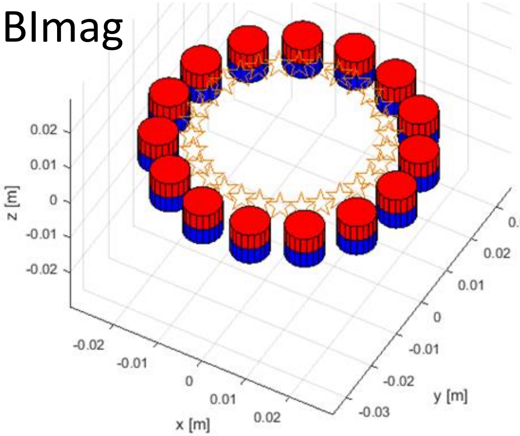
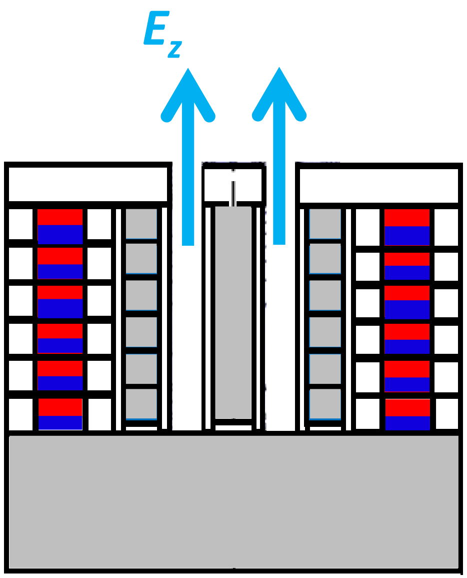
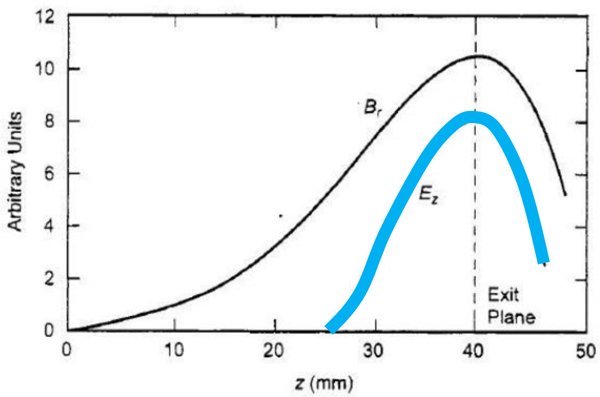


- Ferromagnetic material
- hall probe measurement of Br in the channel

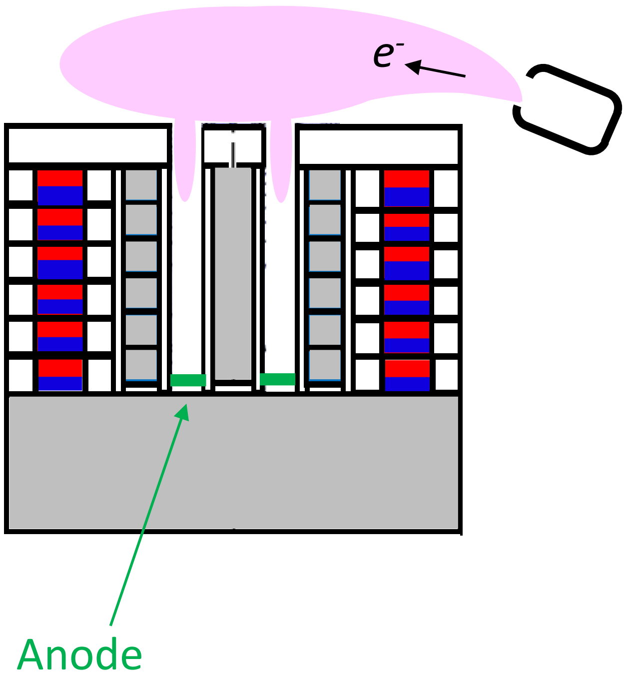
Hall Effect Recipe



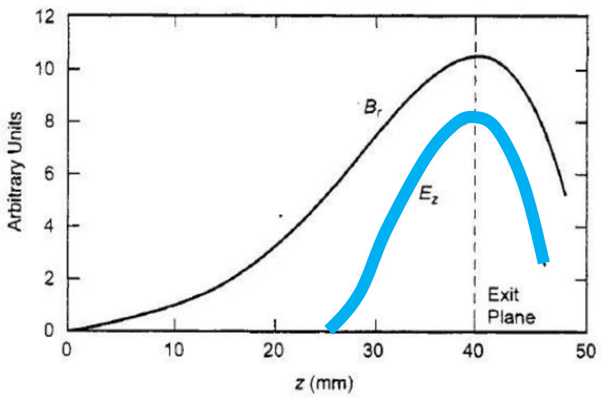
Electric Field



Hall Effect Recipe

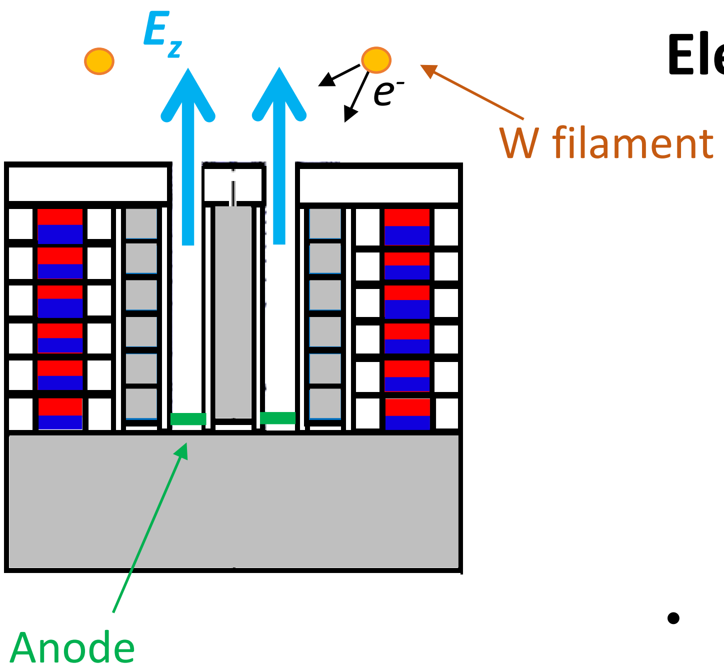


Electric Field

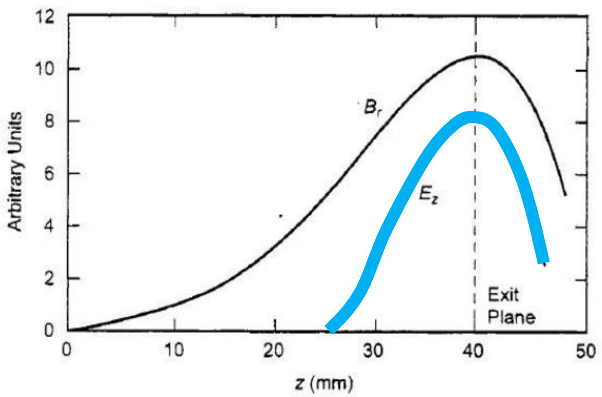


- Electric field between anode and hollow cathode
- First thrusters with tungsten filaments as emissive cathode
  (high power consumption and low life duration of the filament → Hollow cathode for space applications to increase the thruster life and low power consumption (benefit for space applications)

Hall Effect Recipe



Electric Field



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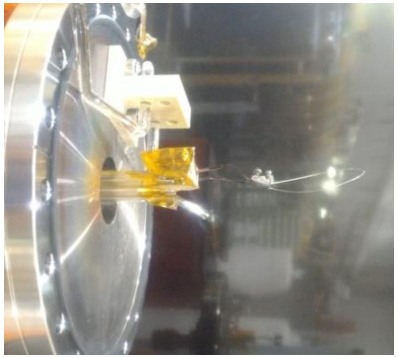
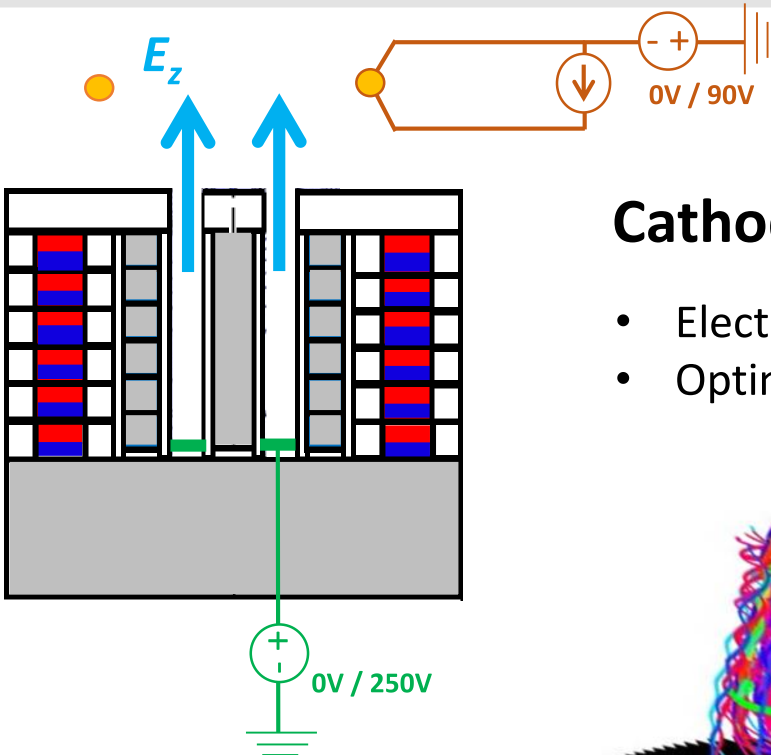


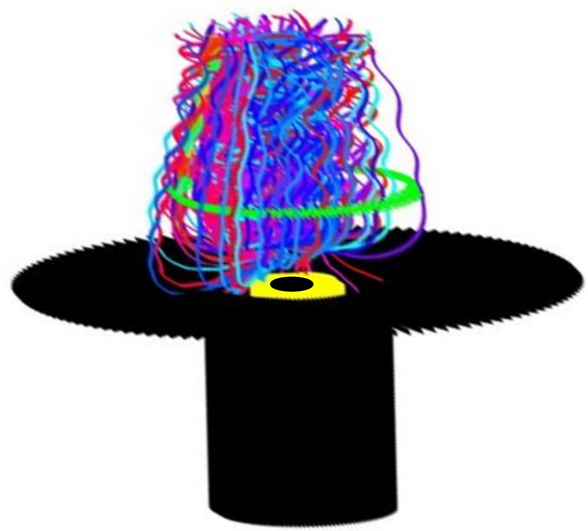
- We decided to use a Tungsten filament cathode as **fastest «time-to-plasma» option** despite their low reliability
- Hollow cathode is anyway necessary for reliable operation, stability, and to increase efficiency

Hall Effect Recipe

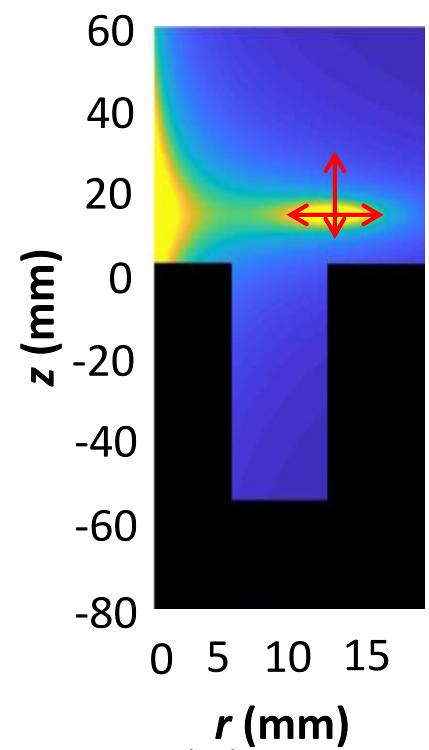


Cathode position

- Electron tracing in vacuum to obtain ionization rate
- Optimization of (*z*, *r*)



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



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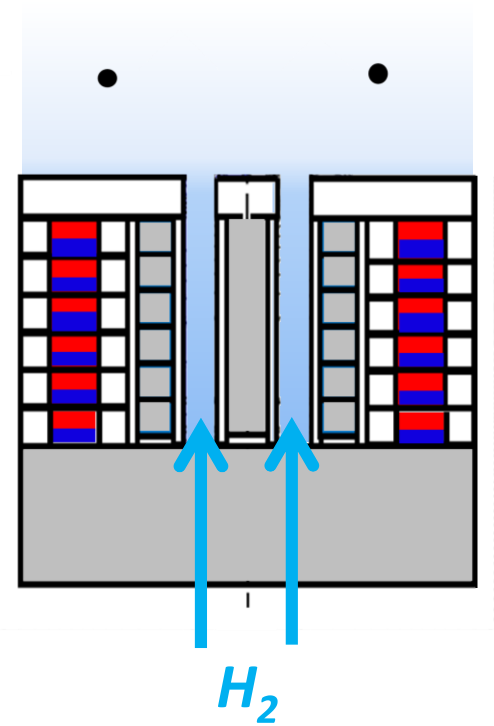
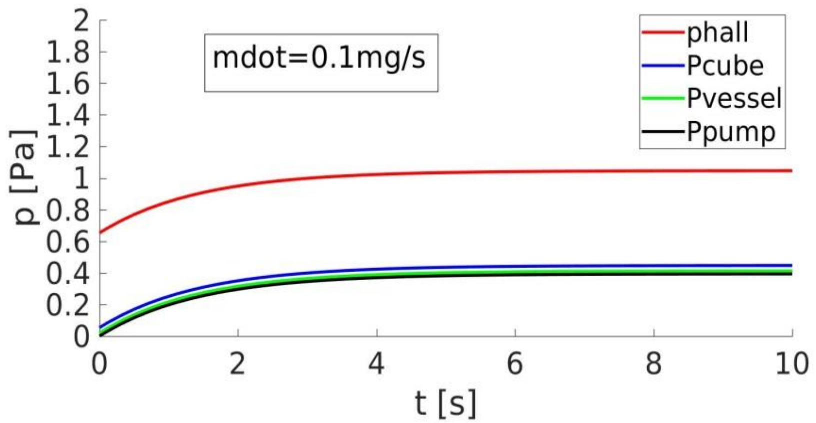


Gas flow

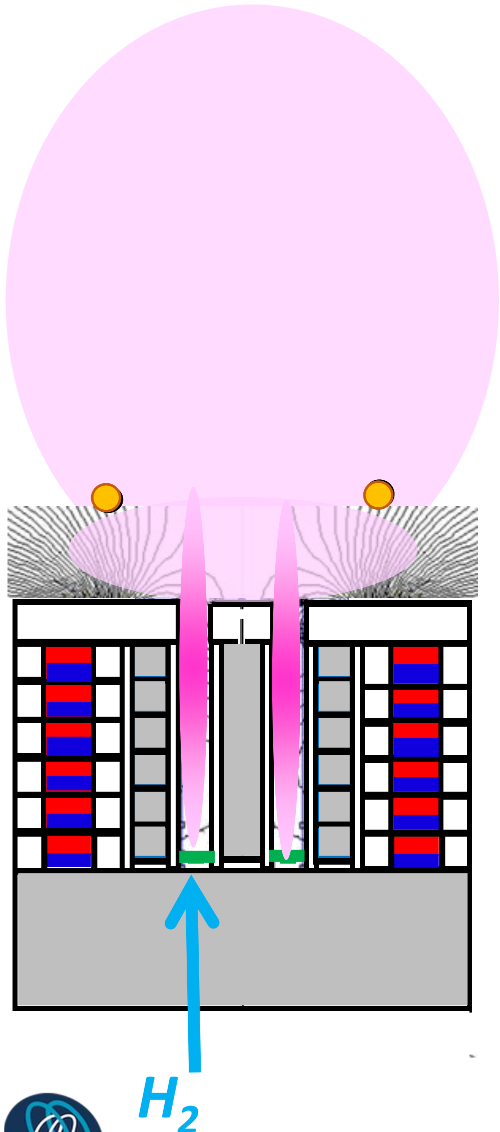
- Minimize pressure out of the channel



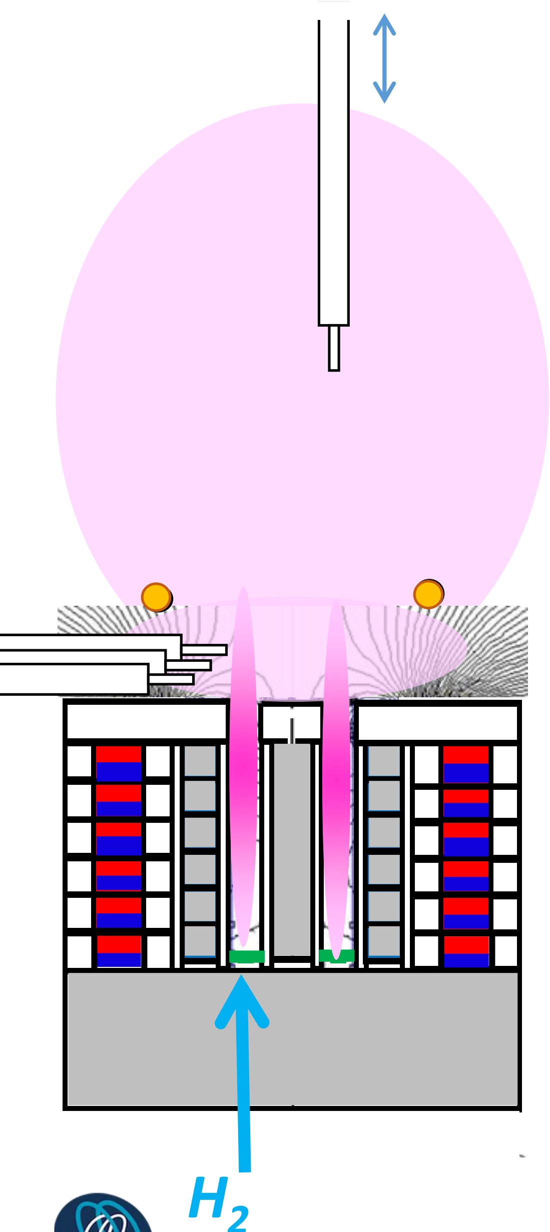
- Plasma ingition condition at low hydrogen pressure from PIC simulation

Hall Effect Recipe

Plasma discharge (hopefully)



Hall Effect Recipe



Plasma discharge (hopefully)

- Electrostatic probes at discharge channel exit
- Movable probe in the plume

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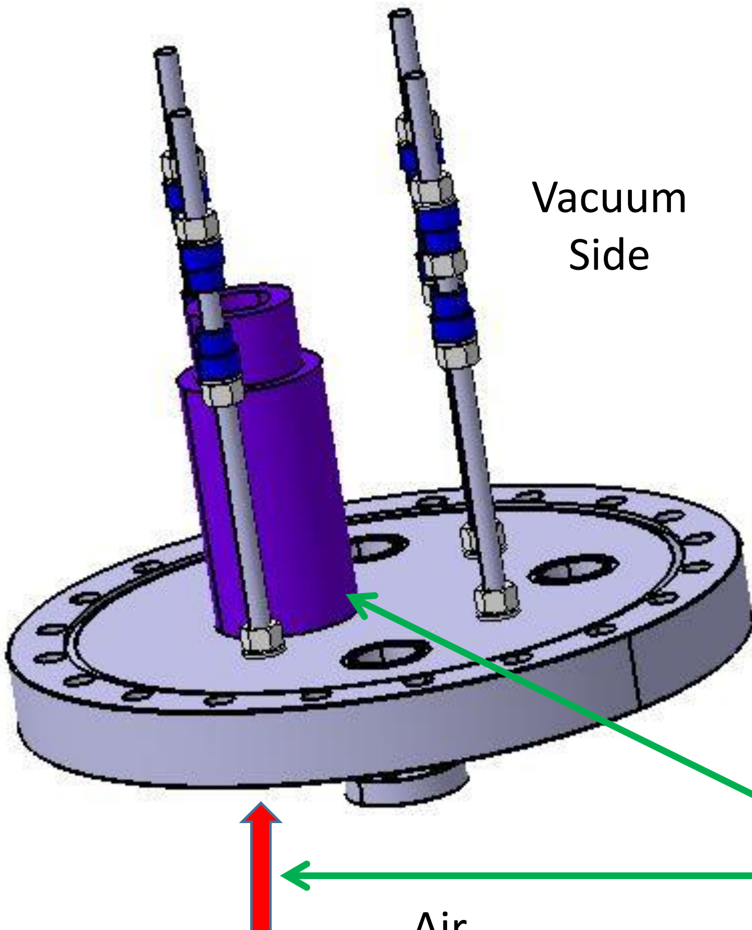
Setup

Gas Injection



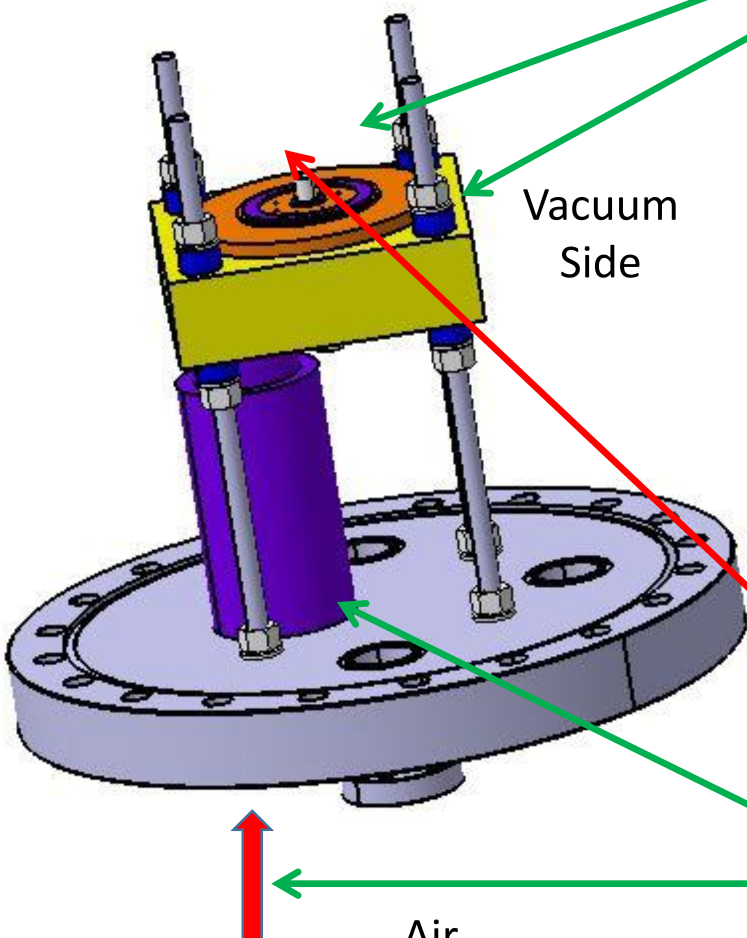
Vacuum Side

Air Side

- PEEK gas channel
- Gas Injection

Mass flow Controller

Setup



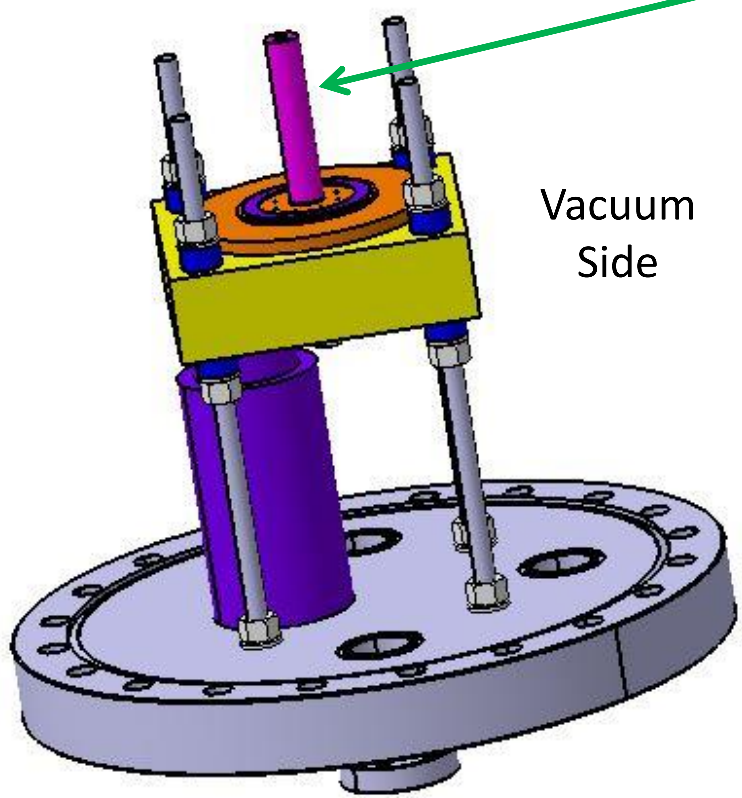
- Injection Plate
- Squared plate base

- PEEK insulation rings
- Central cylinder potential screw

- PEEK gas channel
- Gas Injection

Setup

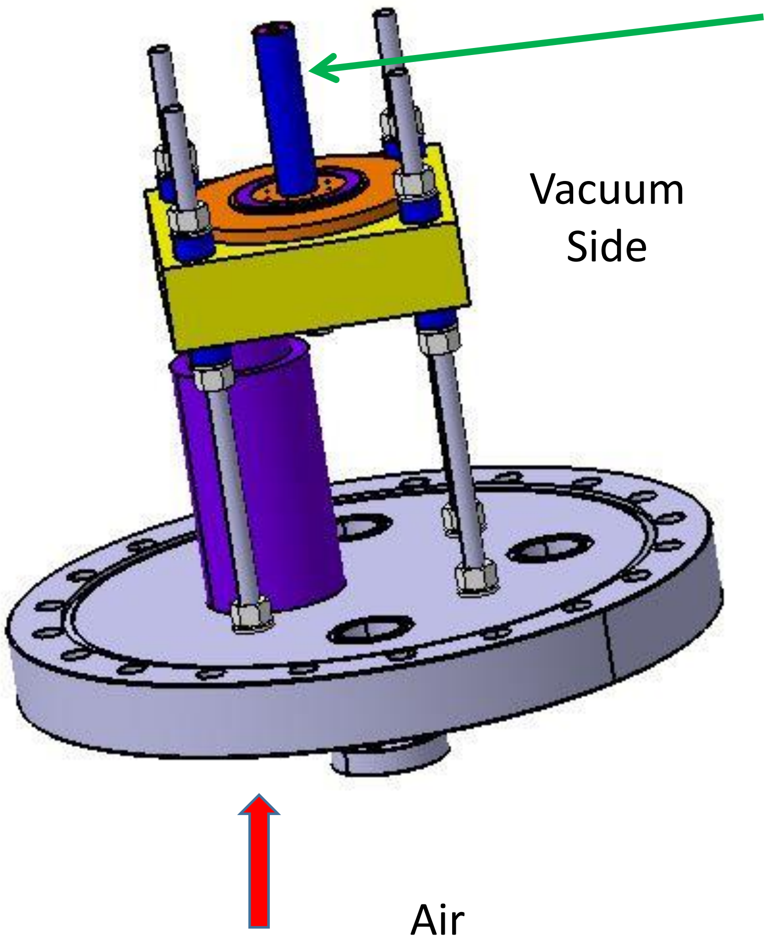
- Central cylinder



Vacuum
Side

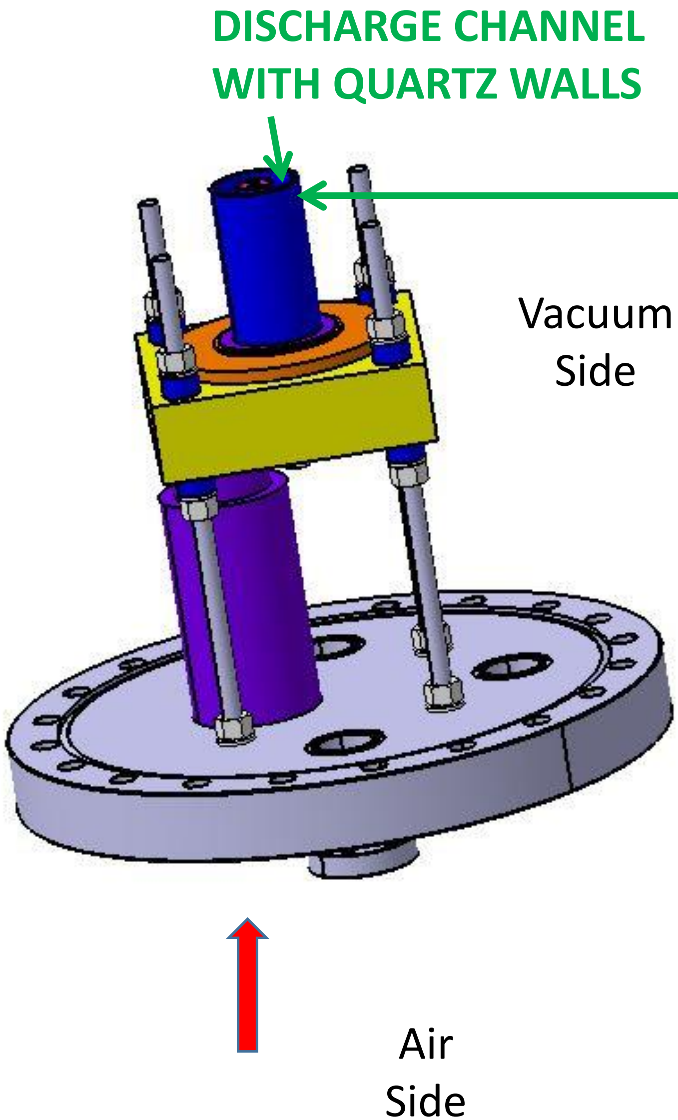
Air
Side

Setup



- Central cylinder
- Internal Quartz tube

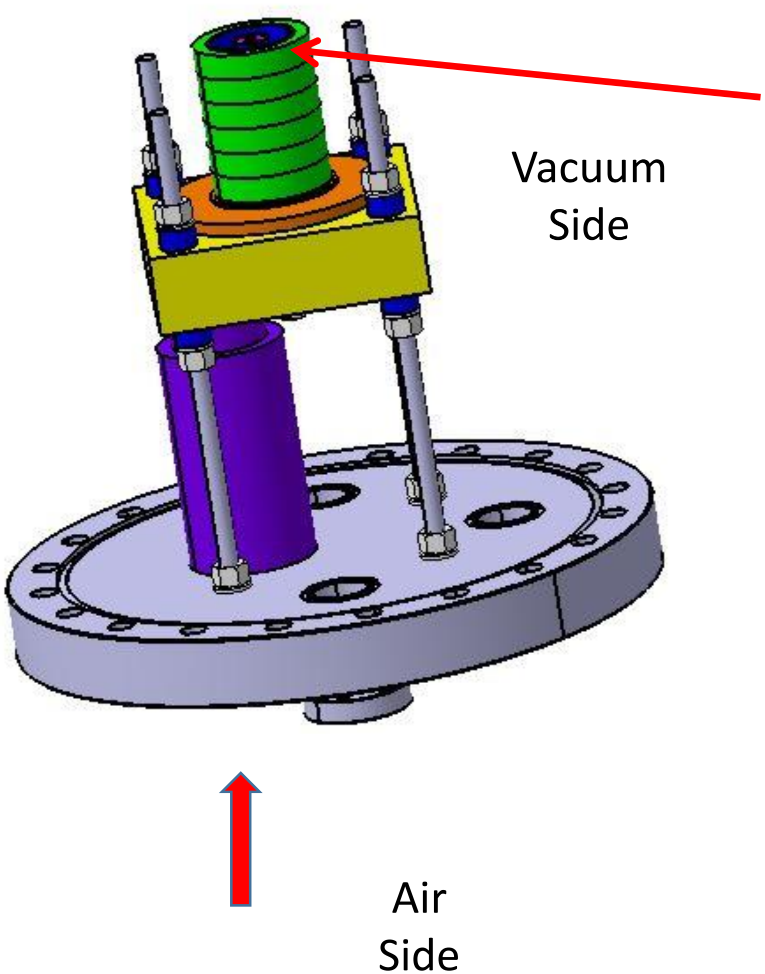
Setup



- Central cylinder
- Internal Quartz tube
- External Quartz tube

Setup

- Central cylinder
- Internal Quartz tube
- External Quartz tube
- Ferromagnetic rings



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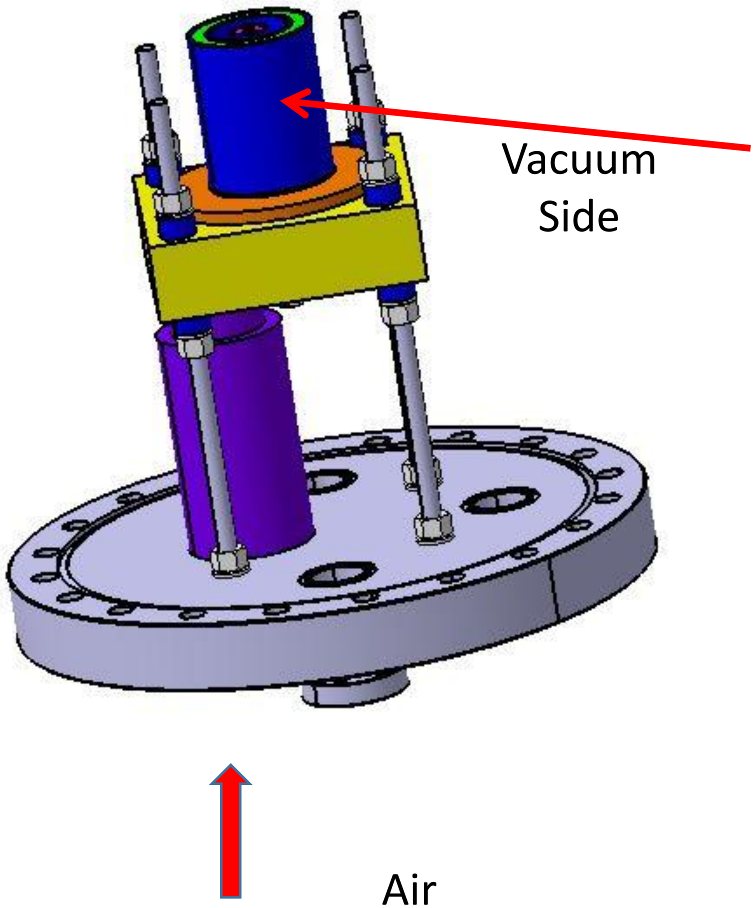
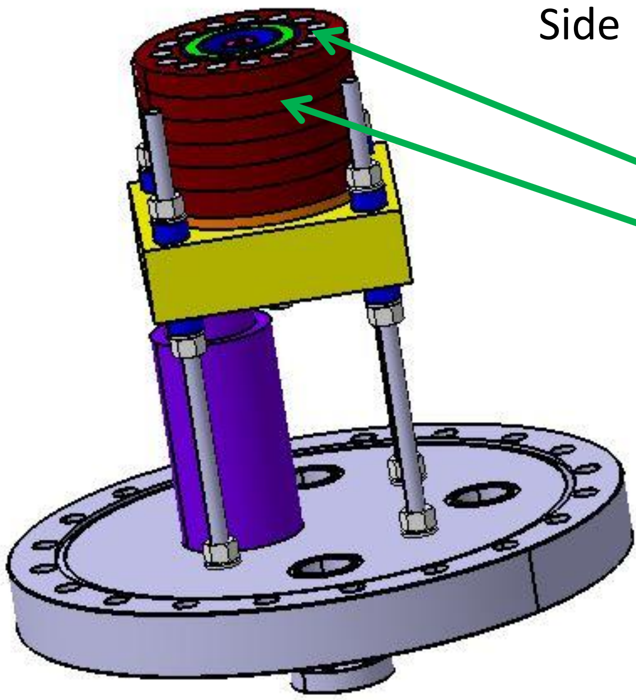


- Central cylinder
- Internal Quartz tube
- External Quartz tube
- Ferromagnetic rings
- External PEEK insulation

Setup

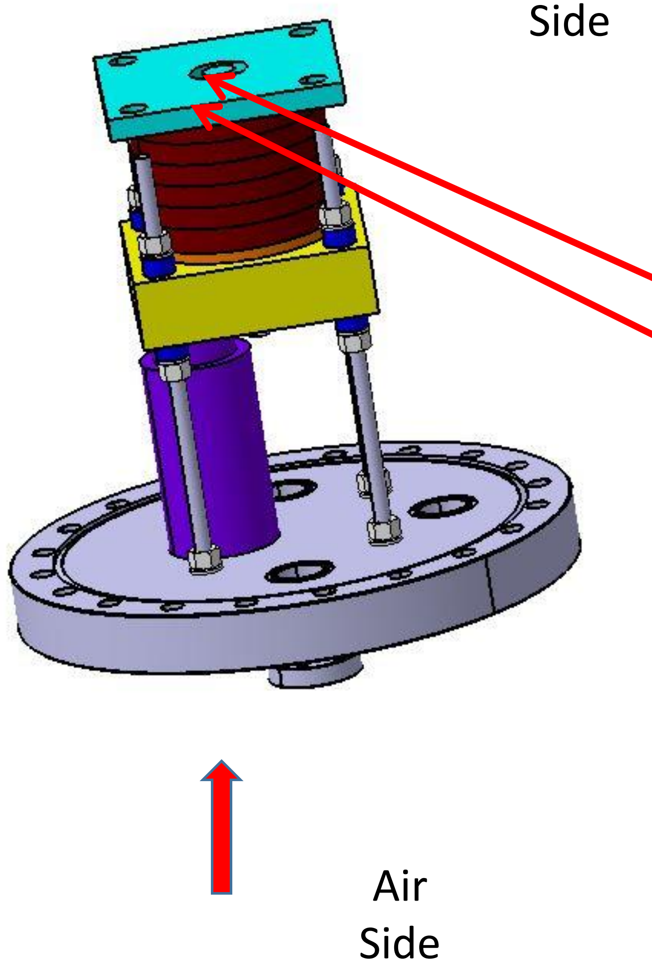
Vacuum Side



Air Side

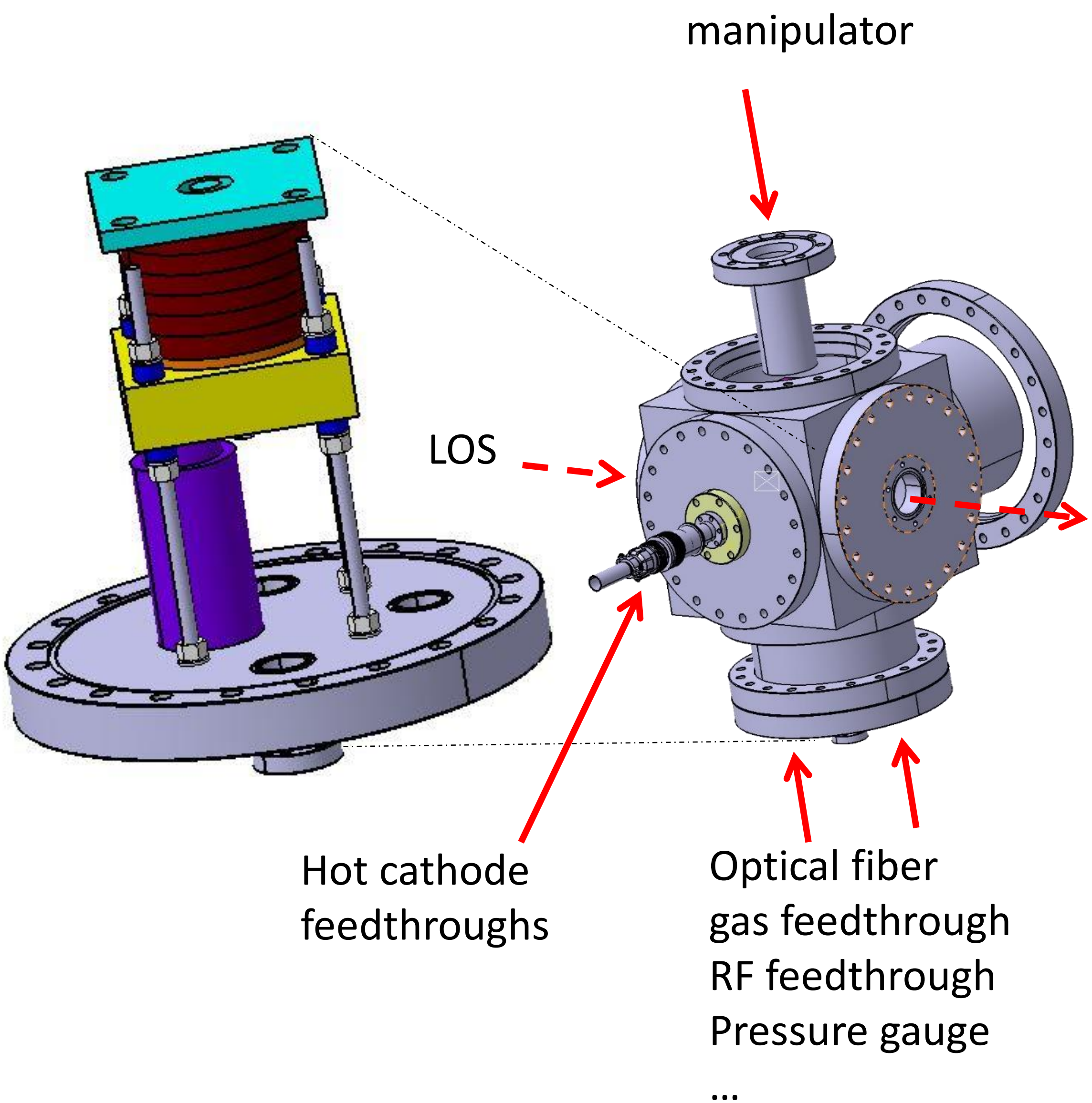
- Central cylinder
- Internal Quartz tube
- External Quartz tube
- Ferromagnetic rings
- External PEEK insulation
- Permanent magnets
- Aluminum rings hosting the magnets

Setup

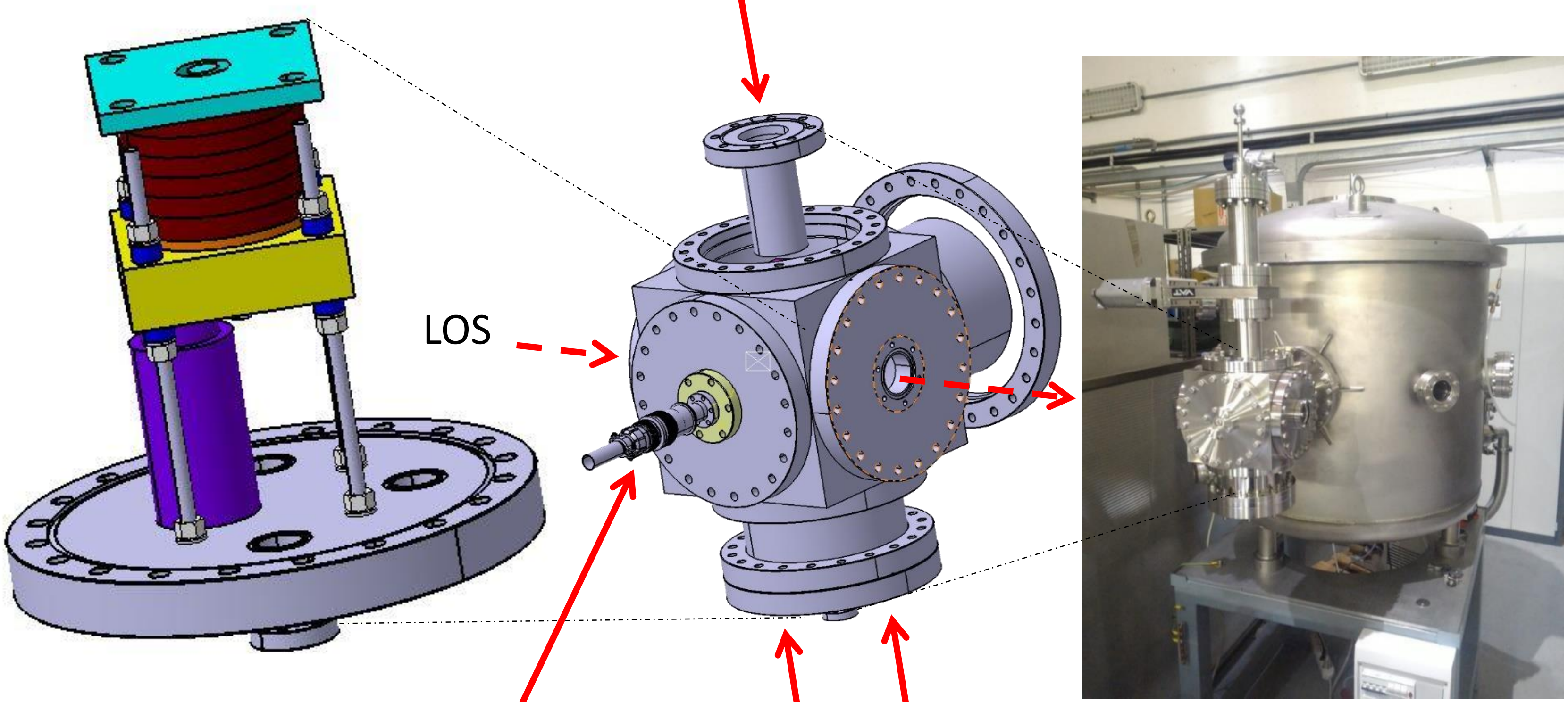


- Central cylinder
- Internal Quartz tube
- External Quartz tube
- Ferromagnetic rings
- External PEEK insulation
- Permanent magnets
- Aluminum rings hosting the magnets
- Boron Nitride cap
- Boron Nitride plate

Setup


manipulator
LOS
Hot cathode
feedthroughs
Optical fiber
gas feedthrough
RF feedthrough
Pressure gauge
...

Setup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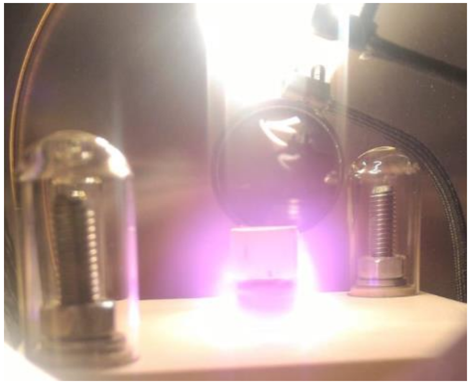
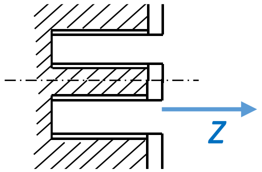
Operation in N_2

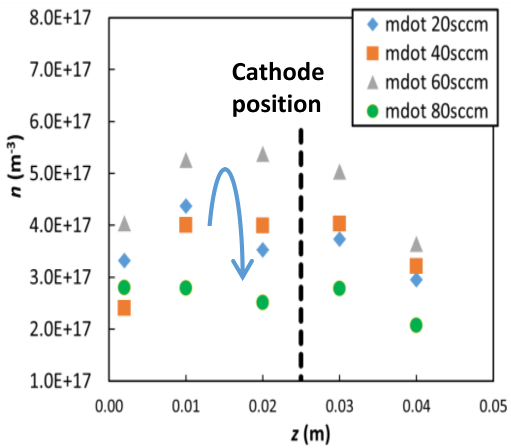


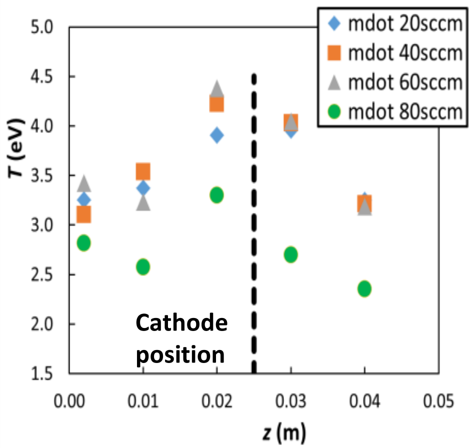
- N_2 safer than H_2
- Molecular gas, Similar ionization energy
- Through N_2 experience, upgrades of the experiment (substitution of melted parts, improvements of electric insulation)
- Definition of the best cathode position
- Determination of the main parameters which affect the plasma discharge ($\mathbf{V_{discharge}}$, $\mathbf{I_{filament}}$, $\mathbf{p_{chamber}}$)

Operation in N_2



Axial study of electronic density and temperature





[1] D. Desideri and G. Serianni, "Four parameter data fit for Langmuir probes with nonsaturation of ion current", Review of Scientific Instruments, Vol.69, n.6 (1998).

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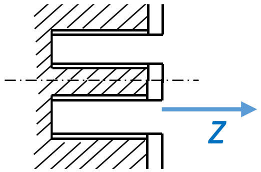
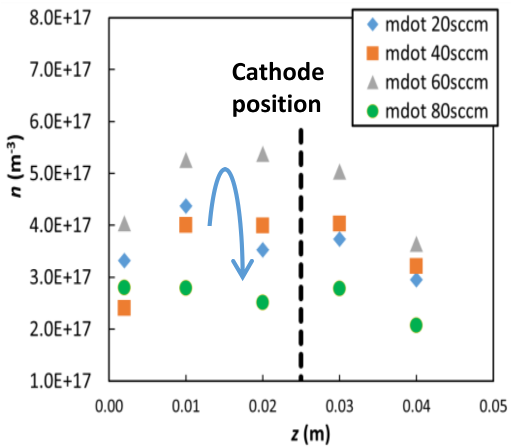
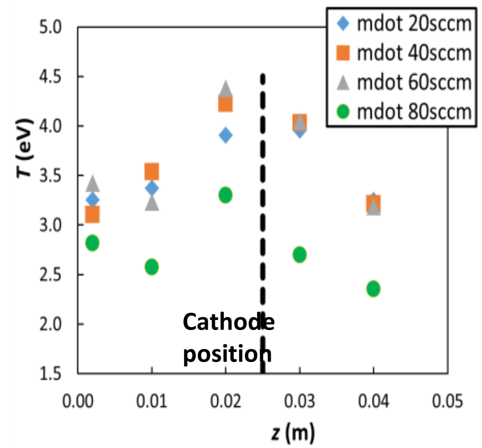
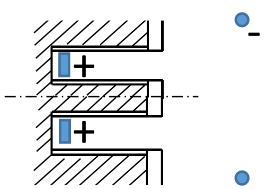


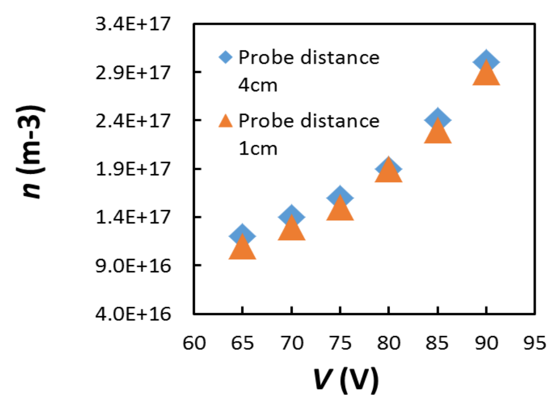
Axial study of electronic density and temperature

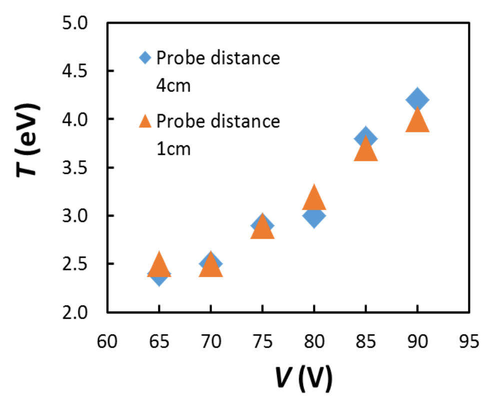






Temperature and density vs discharge voltage





- **n** and **T_e** raises with **$V_{discharg}$**
- **$V_{discharge}$** controlled through **$I_{filament}$**
- Constant axial profile of **n** and **T_e**
- Optimum mdot at 60sccm

[1] D. Desideri and G. Serianni, "Four parameter data fit for Langmuir probes with nonsaturation of ion current", Review of Scientific Instruments, Vol.69, n.6 (1998).

Outline

1. Our recipe for a tasty Hall Effect Thruster (design) ✓
2. Manufacturing and commissioning of the thruster ✓
3. Operation in N_2 (already different than noble gases) ✓
4. **Operation in H_2 – characterization of the plasma plume**
5. Summary & next steps

Operation in hydrogen

Objectives

- Plasma characterization far from the exit of discharge channel
- Find the minimum operational pressure to maximize the mean free path (for H^0, H^-)

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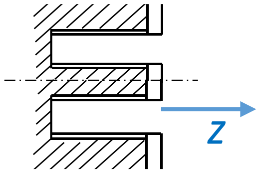

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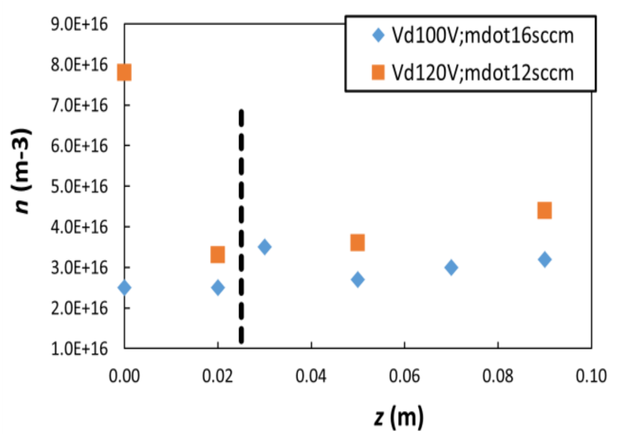
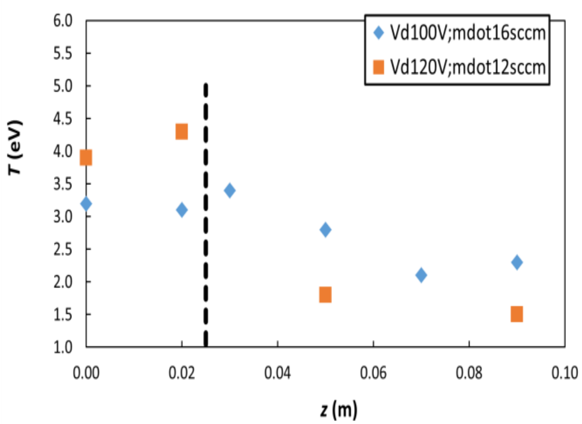
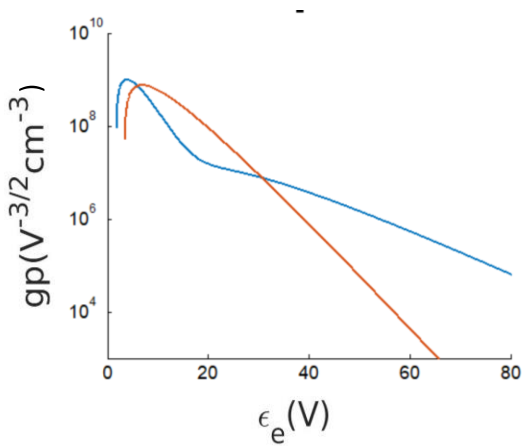




Comments

- Almost constant ion density profile in the plume
- T_e profile decays beyond the cathode
- ~10^{16} m^{-3} density (~10^{17} m^{-3} for N_2)

Double electron population



Electron energy probability function g_p versus ε_e [1] measured at the exit of the discharge channel for two cases at different anode voltages:

- Double electronic population identified in few cases near the exit plane or far away
- Phenomenum still under investigation (Magnetic field influence near the exit plane, acceleration of thermal electrons to compensate H+ energetic ions far from the device [2])
- → study for plasma instabilities

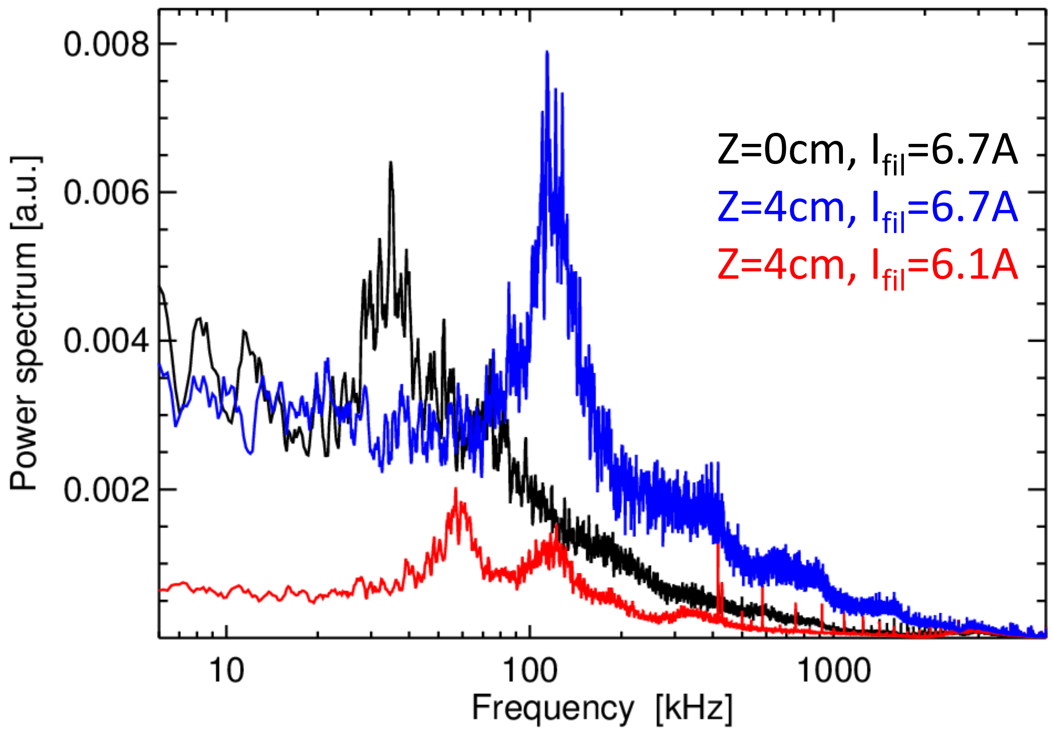
[1]M. A. Lieberman, A. J. Lichtenberg, «Principles of Plasma Discharges and Materials Processing», Wiley-Interscience, 2° edition, cap. 6 and 11]
[2] S. Gallian, J. Trieschmann, T. Mussenbrock, R. P. Brinkmann, and W. N. G. Hitchon, "Analytic model of the energy distribution function for highly energetic electrons in magnetron plasmas", Journal of Applied Physics 117, 023305 (2015)

Plasma instability analysis

Motivation: Plasma instability, mainly ExB electron drift induced[1], believed to determine cross-field electron transport and reduce Hall thrusters perfomances

Preliminary analysis of electron density fluctuations highlights the presence of various plasma instabilities

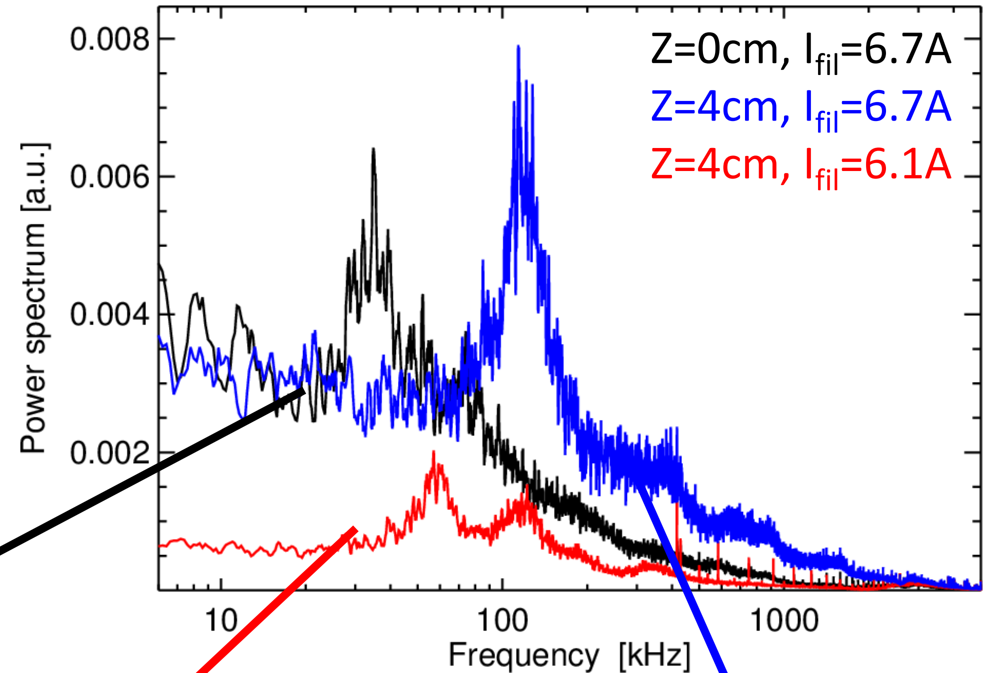
Spectral properties depend on plasma condition (power operating level) and positions

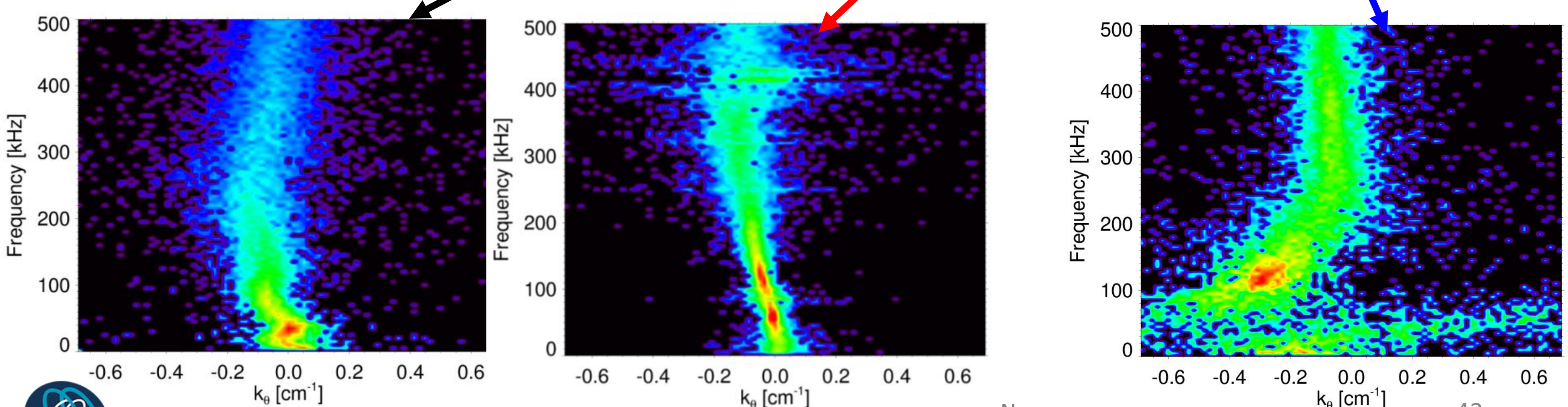


[1] Lafleur et al., Phys. Plasmas 25 (2018)

Plasma instability analysis

Two-point technique used to determine exp. dispersion relation (phase and group velocity) for instability identification.

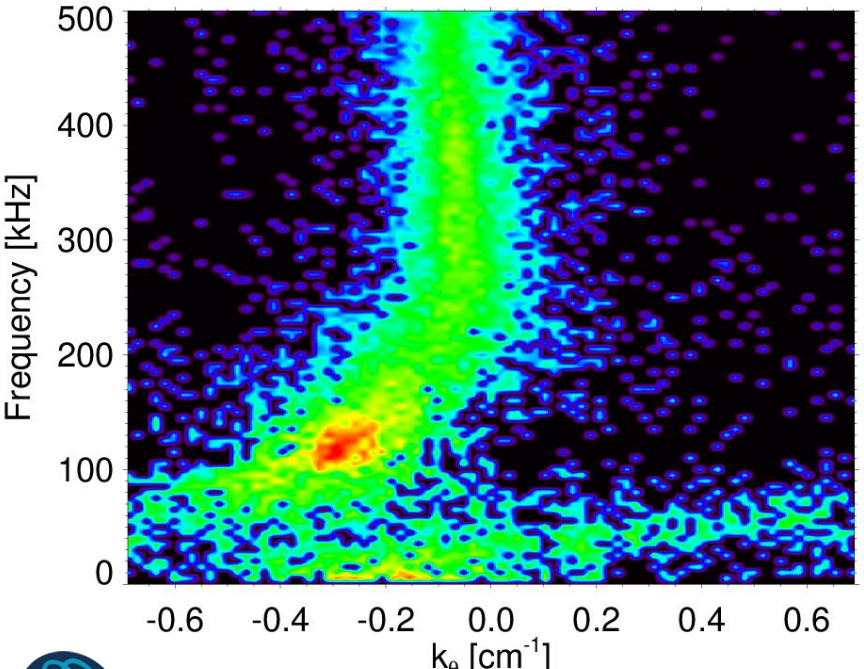


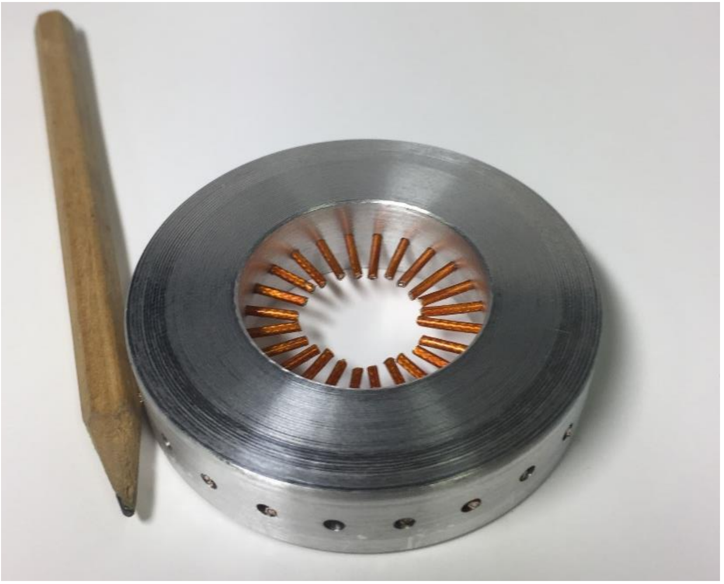


Plasma instability analysis

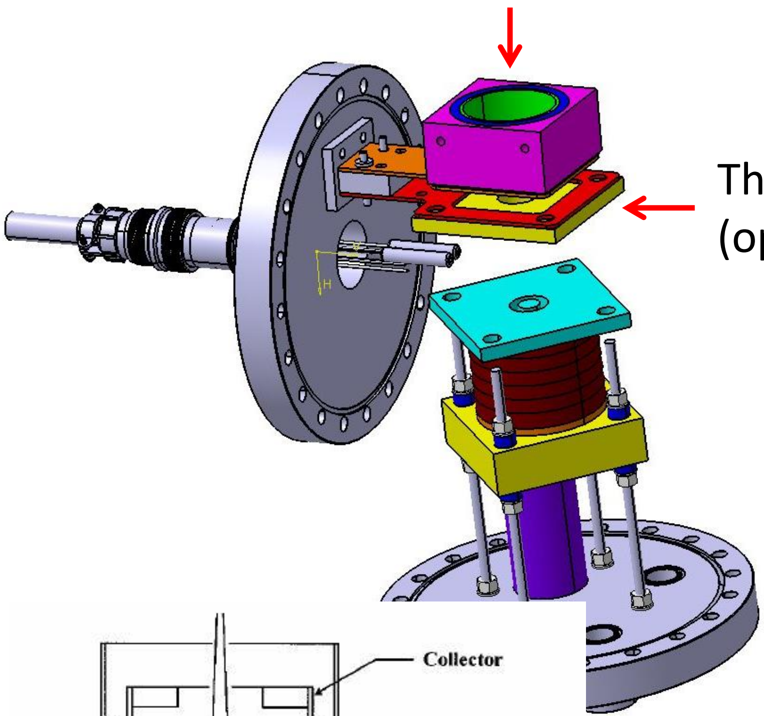
Aliasing affects wavelength determination (small scale instability).

New diagnostic system based on complete azimuthal array of Langmuir probes, for high mode number analysis realized and planned to be used in the next future.





Conclusions and next steps



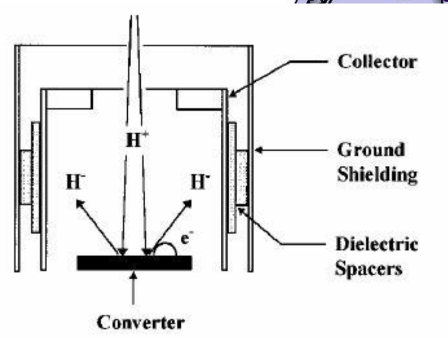


FIG. 1. Schematic of ion backscattering experiment.

- The specifically designed a Hall effect plasma generator was successfully operated in hydrogen
- In the plume, thin plasma with *n* $3 \cdot 10^{16}$ m^{-3} is found, with T_e 2-2.5 eV

Next:

- Installation of optic fiber for spectroscopic measurements
- Pre-caesiated sample (Alternatively, in situ by use of SAES dispensers)
- Hollow cathode to replace tungsten filament

[M. Seidl et al, "Negative surface ionization of hydrogen atoms and molecules",
Journal of Applied Physics 79, 2896 (1996)]

Summary

- H_2 simulations shown that HT can generate excited H_0
- HT in house to study the possibility to generate H^-
- Experience through N2 injection helped to understand the response of the thruster and the upgrades to avoid the failures encountered during this process
- Characterization of plasma discharge in H2
- Constant axial density profile (~10^{16} m^{-3} for H2,~10^{17} $m^{-3}$for N_2)
- Slow T decay along z-axis until 2eV
- $\mathbf{V_{anode}}$, $\mathbf{I_{filament}}$ **and** $\mathbf{p_{chamber}}$ main parameters which affect the plama
- Next phase collecting H^- and improving plasma analysis diagnostic