Alternative New Concept
Of An Efficient Negative Ion Source For Neutral Beams

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Introduction

The Neutral Beam Injector (NBI) system is one of the schemes of plasma heating for fusion application. For the reactor prototype DEMO, it requires the improvement of the efficiency of all processes entering in the production of the beam, among which the negative ion generation in the ion source.

Issues of present negative ion sources (RF and filament):

- Difficulty in keeping the negative ion current constant and reproducible
- Spatial inhomogeneous current density
- Elevated fraction of co-extracted electrons [1]
- High power required to sustain the plasma in the source [2]
- Fast electrons in the plasma source limit the generation of negative ions

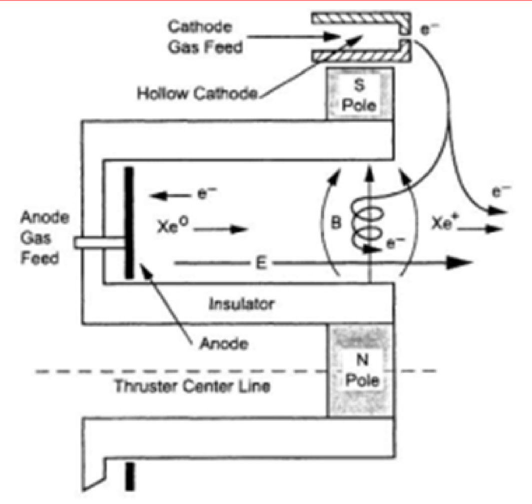
Purpose of this contribution is to present the research activity aimed to improve that efficiency by studying alternative sources

Objective: maximize the negative Hydrogen ion generation by surface conversion of neutral atoms on caesiated surfaces [3]-[4] . **Hall Thrusters** could be used as Hydrogen(H_2) dissociator.

Hall Thruster

Geometry:

- Gas injection system
- Dielectric annular chamber
- Magnetic circuit for a radial magnetic field at the channel exit
- Anode at the channel bottom
- External cathode



Hall thruster cross-section schematic [5]

Working principle:

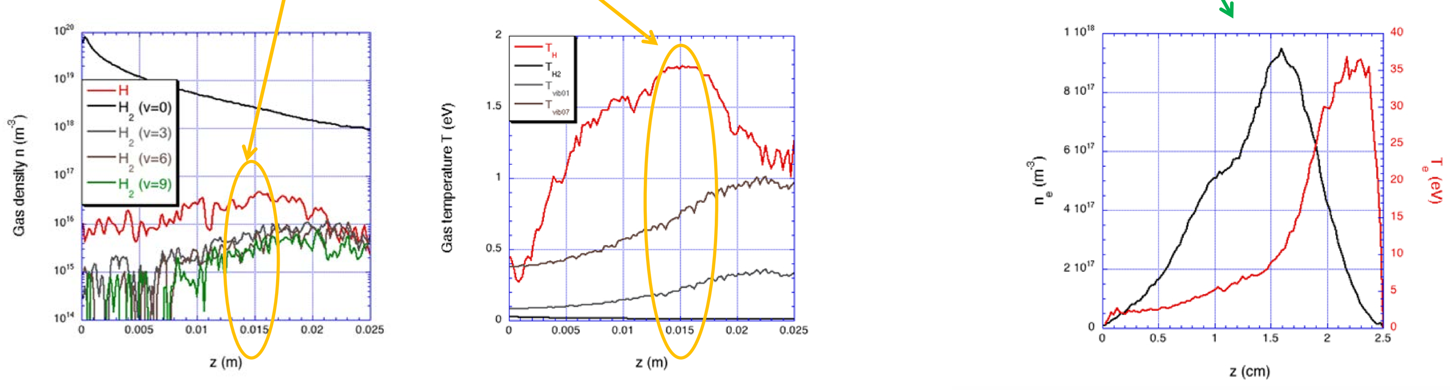
- External cathode emits electrons. Most of them go to the anode
- Radial magnetic field plus electrical discharge ⟹ electrons trapped in a cyclotron motion in the azimuthal direction
- Trapped electrons ⟹ volumetric zone of gas ionization ⟹ virtual cathode ⟹ ions accelerated and not influenced by the magnetic field(larger Larmor radius)
- Accelerated ions plus electrons ⟹ neutralized thrust

The atoms ejected by the device could be guided towards a caesiated sample to enhance the negative ion generation.

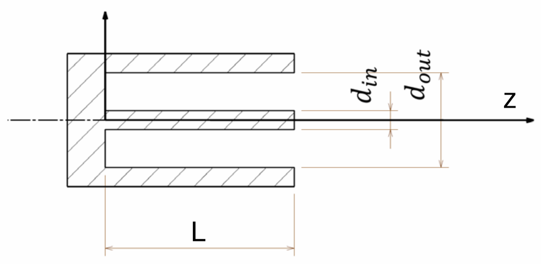
Numerical simulations

o Monte Carlo gas model [6] with 2D axial symmetric geometry

- Electron density and temperature profiles of a SPT100 as input (Xenon as fuel)
- Results with Hydrogen
- Peak of H density and T_H 1cm from the exit plane



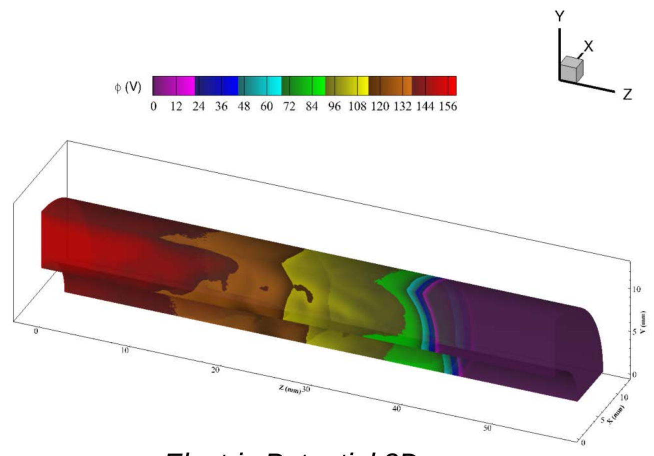
o self-consistent Particle-In-Cell/Monte Carlo Collision(PIC-MCC) [7]

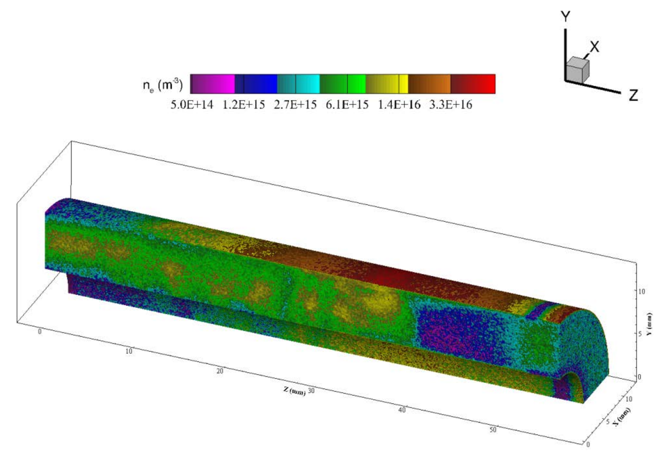


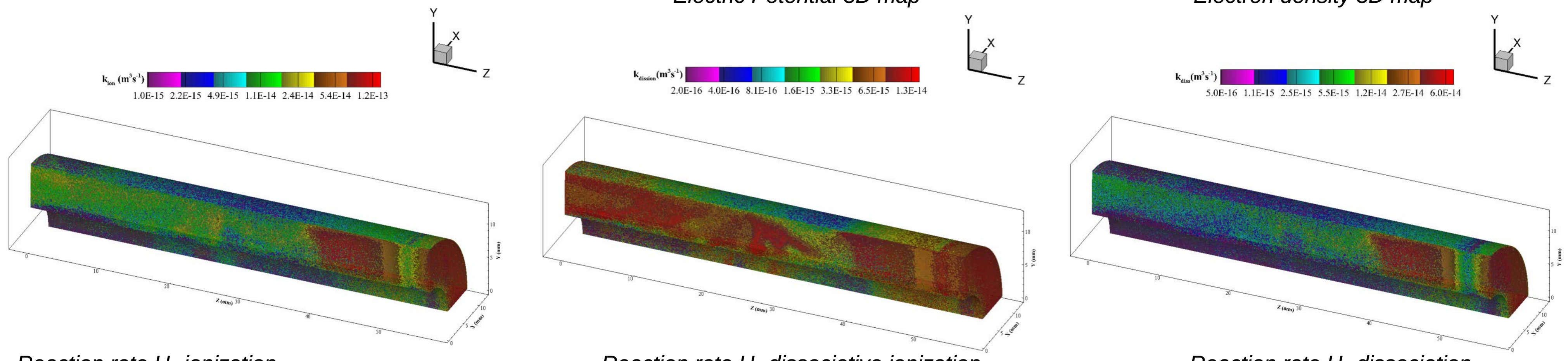
- 3D in cylindrical coordinates in angular sector of the channel
- exit plane where the cathode condition (ϕ=0) is forced to occur
- Initialization of all the quantities remaining fixed during the PIC cycles
- Injection, scatter, field solve, push, plasma-boundary interaction and Monte Carlo collision modules iteratively solved
- Time-resolved and steady state diagnostics computed in a dedicated module.

Case study: ATHENIS

- d_{out}= 25 mm
- d_{in}=12 mm
- L=56 mm
- Voltage anode-cathode V_d=160 V
- nominal discharge current I_d=0.75 A
- discharge power of P_d=120 W
- Hydrogen mass flow rate $\dot{m}$ =0.15 mg/
- maximum magnetic field $B_{r,max}$=100 G

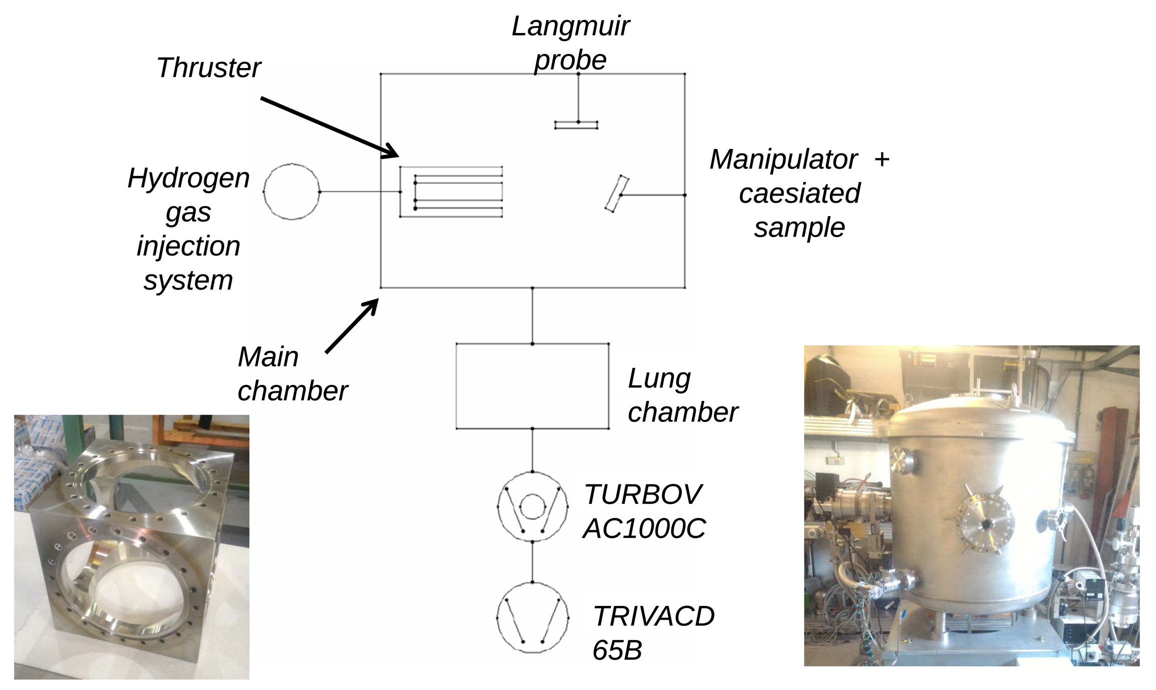

Electric Potential 3D map


Electron density 3D map

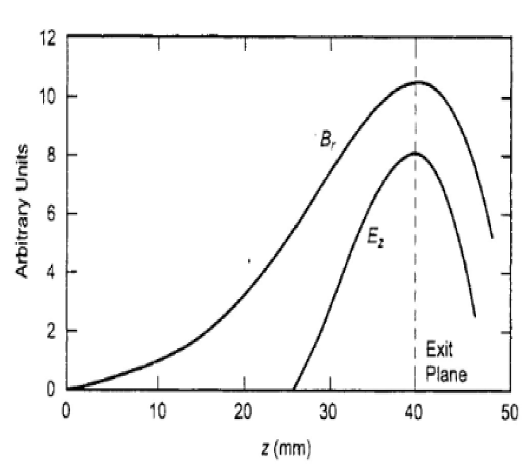

Reaction rate H_2 ionization *Reaction rate H_2 dissociative ionization* *Reaction rate H_2 dissociation*

- Length of the channel do not follow the Melikov-Morozov[8] rule for scaling
- Poor thrust efficiency
- Plasma ignition with such low hydrogen mass flow still possible
- Reaction rates of the dissociative channels one order of magnitude lower than ionization
- 2 zones of electron confinement as expected

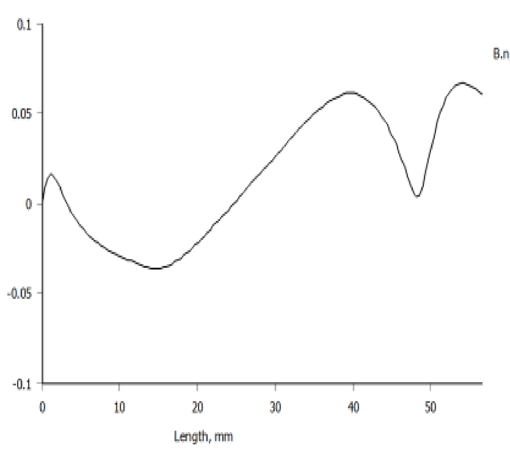
ATHENIS layout



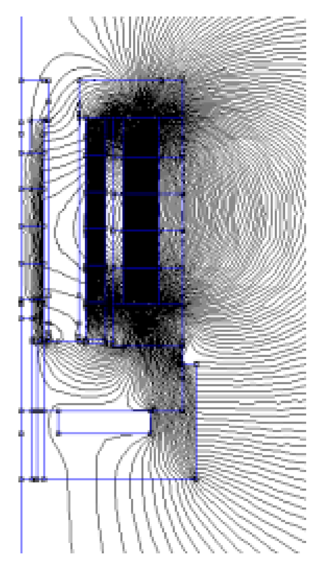
Magnetic Confinement



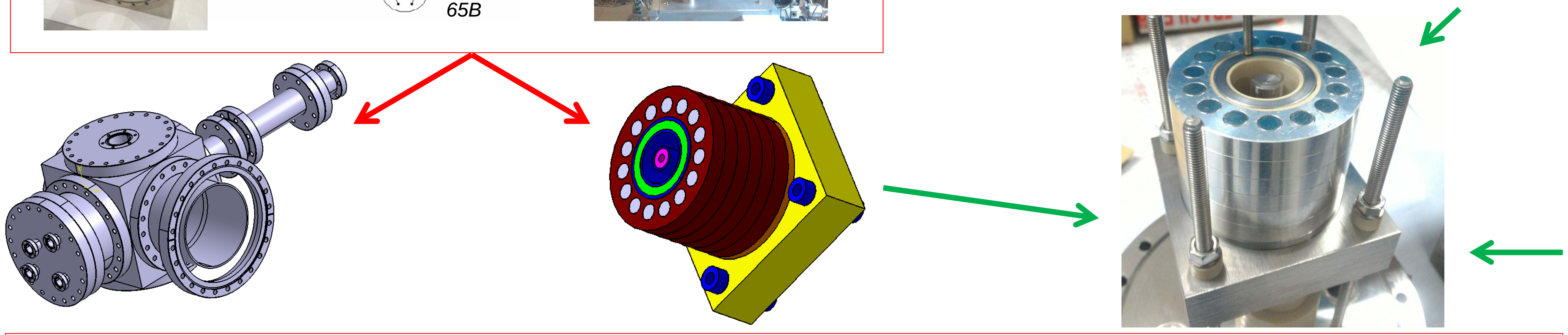
Ideal radial magnetic field and axial electric field along the channel[5]



Real radial magnetic profile for ATHENIS


Magnetic field contour plot for ATHENIS

- Double peek of the magnetic profile instead of a single one
- Thrust efficiency decreases but the real aim is the electron confinement
- Rings of permanent magnets allows immediate flexibility in terms of geometry adaptation



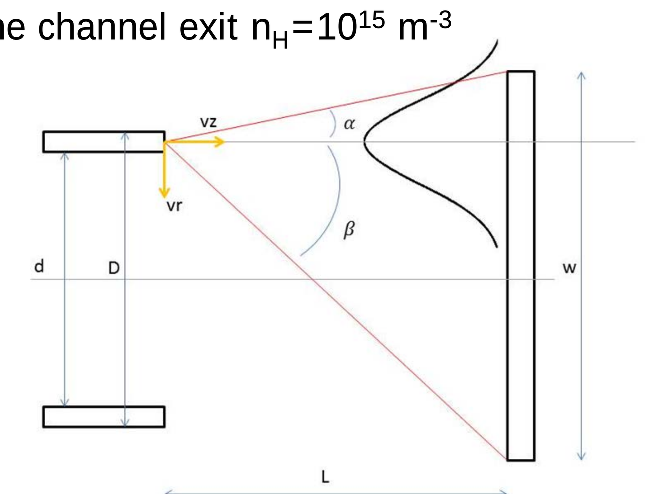
H^- enhancement

- D=25mm;
- d=12mm;
- L=56mm;
- $p_{Hall} \approx 1.1Pa$
- $p_{chamber} \approx 0.15Pa$

$$\lambda = \frac{KT}{\sqrt{2}\sigma^2 p_{ch}} \qquad \sigma^2 = \pi d_{H_2}^2 [9] \qquad \lambda_{lim} = 1.54m$$

- Maxwellian velocity distribution ⟹ Radial velocity with Gaussian profile
- Total Impact Probability $P = P_\alpha - P_\beta$ $\quad P_\alpha = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{v_{r\alpha}}{v\sqrt{2}}\right)\right]$

  with radial velocity as $v_{r\alpha} = v\frac{\frac{D-d}{2} - \frac{w}{2}}{L}$
- Hydrogen flux $\varphi = \frac{1}{4} n \sqrt{\frac{8\,k_B T}{\pi\, m_H}} A$
- Hypothesized hydrogen density at the channel exit $n_H = 10^{15}\ m^{-3}$
- Conversion $H \rightarrow H^-$ through impact on caesiated surface → 12%
- Expected current measured in the order of μA



Conclusions

Experimental campaigns will begin in mid-November. The first phase consists of the plasma ignition: plasma characteristics will be measured through a Langmuir probe. In the second phase, the caesiated sample will be installed on the manipulator and first current measurements will be taken. In the third phase, we will optimize the system.

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