MINUS

Particle-based model of ITER-prototype negative ion source

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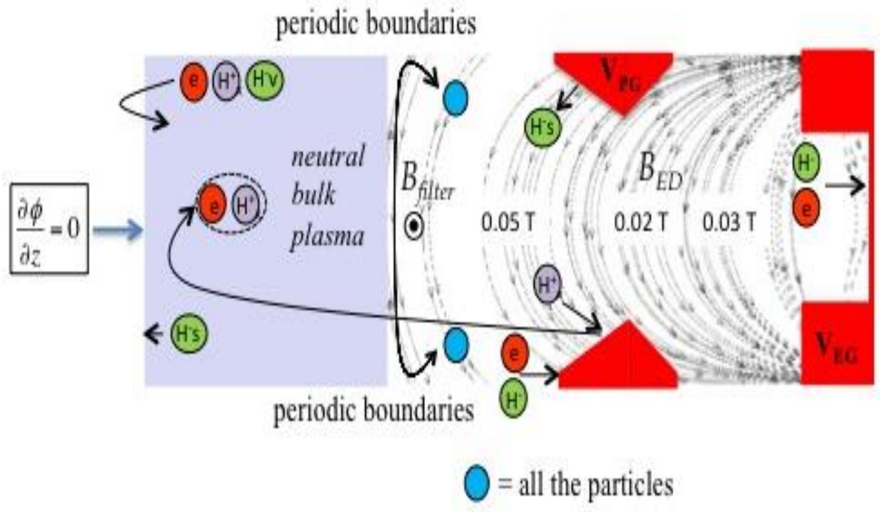
Outlines

- Our experience with extraction region models
- The full source model MINUS
- Plasma transport in expansion region
- Plasma condition at the entrance of extraction region
- The single aperture and the beam profile at EG

Lesson learned with extraction models



- One aperture (periodic conditions) against evidences of transversal dishomogeneity and oblique flow
- Strong influence of free parameters: - initial conditions (n, T, composition)
  - size and distance from PG of neutral bulk plasma
- Possible non-Maxwellian, non-neutral, non-ambipolar behaviors already in the neutral bulk plasma region
- Magnetic filter effects starts much farther from PG
- Which re-injection method of particle absorbed on PG if two kinds of H^- (from volume and from surface) are present ?

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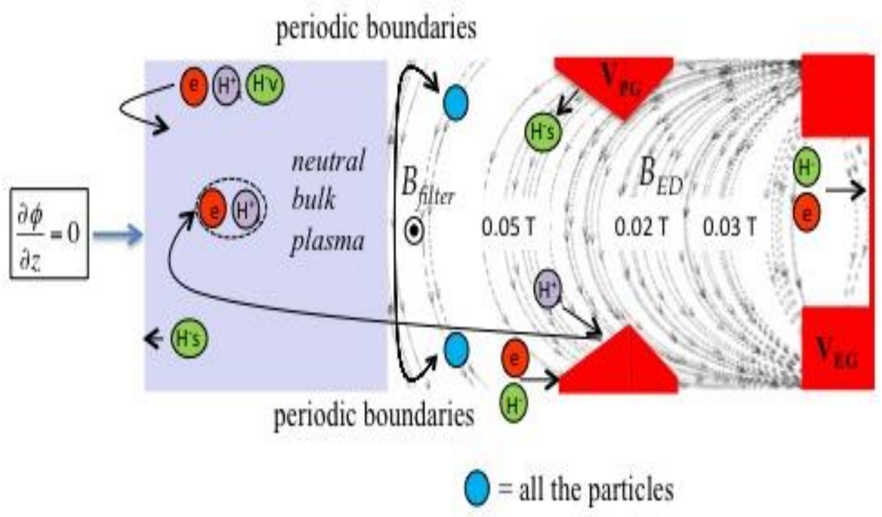
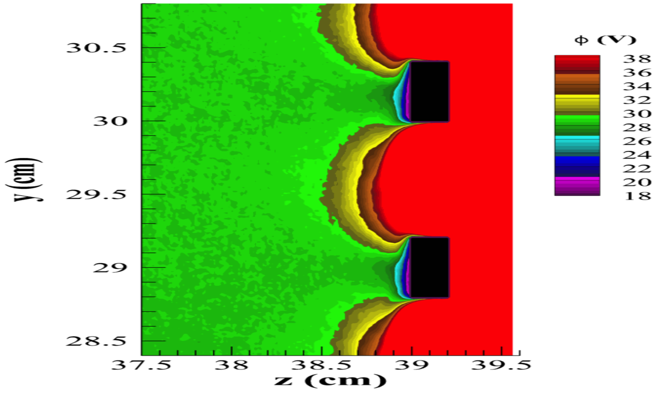


from MINUS



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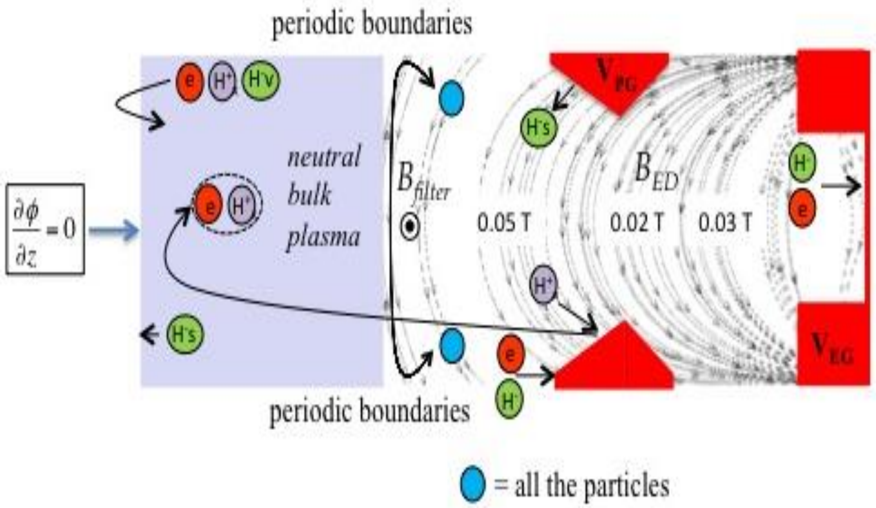

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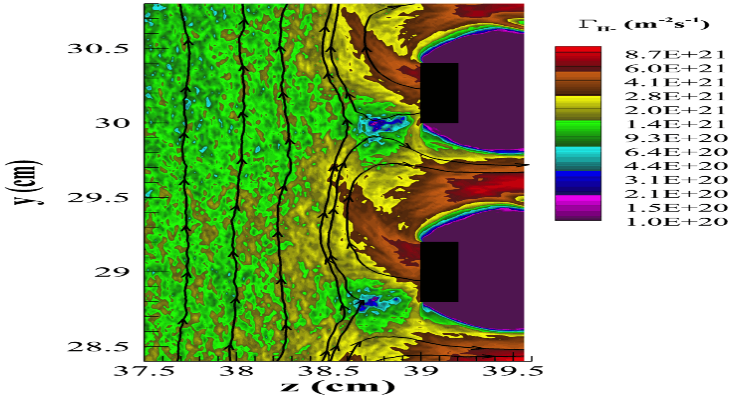

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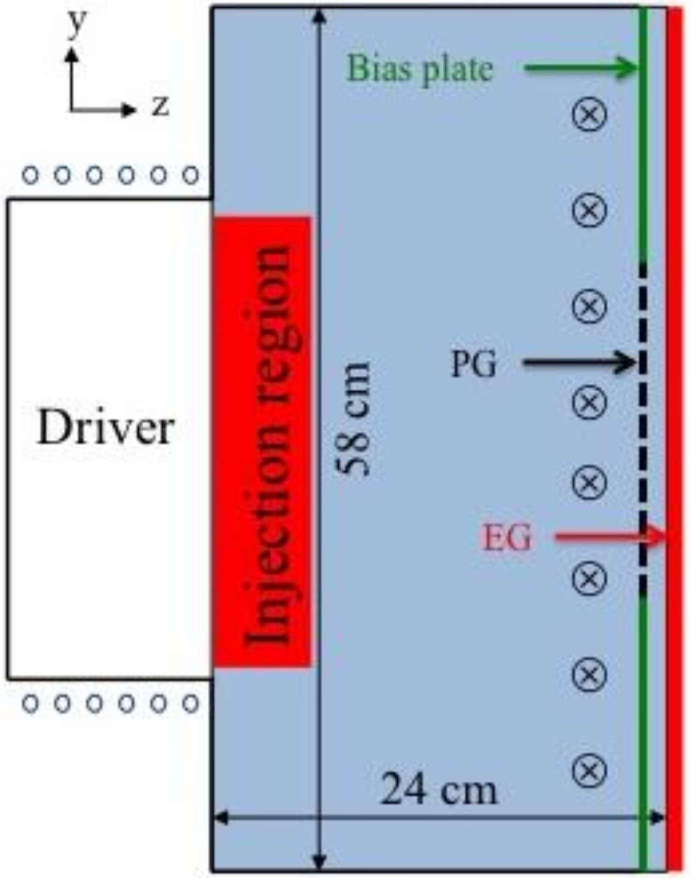
2.5D PIC-MCC full source Model: MINUS

Simulation domain

Expansion + Extraction + 1st acceleration step - multiaperture grid (10 apertures): BP, PG and EG included.



2.5D PIC-MCC full source Model: MINUS

Assumptions-Limitations

- **Driver/Injection**

Driver is not included

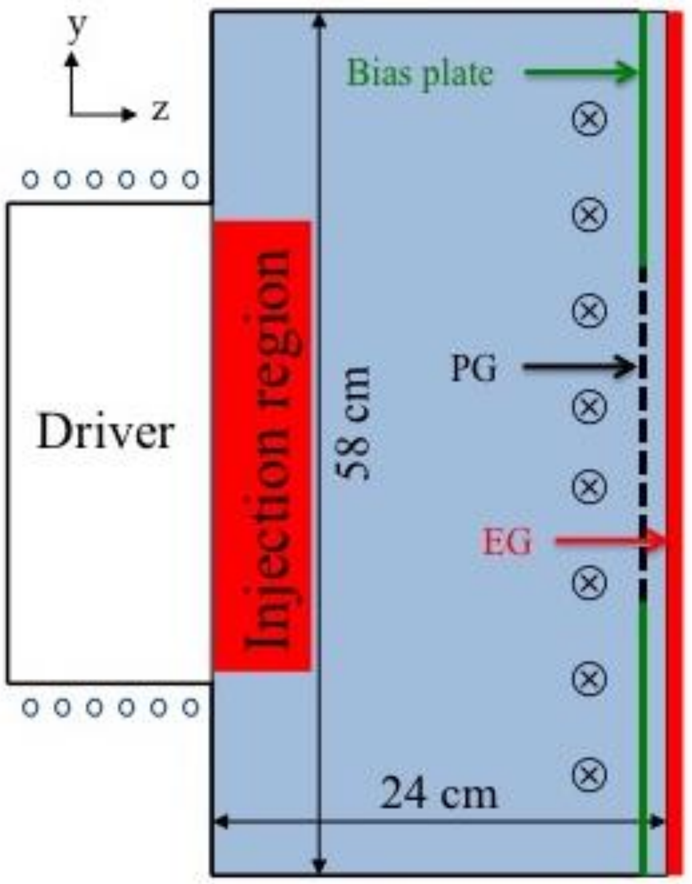
prescribed ambipolar neutral full-maxwellian flux of plasma particle injected in a thin area located at the driver exit plane

Plasma is produced [1] with a rate $w_{ion}=3x10^{23}$ $m^{-3}s^{-1}$

- 56% H_2^+ via direct ionization of H_2
- 44% H^+ ion production by 2 channels: dissociative ionization of H_2 and direct ionization of H

Full maxwellian distribution (temperature kept fixed)

- T_e=12 eV
- T_{H+}=1 eV
- T_{H2+}=1 eV



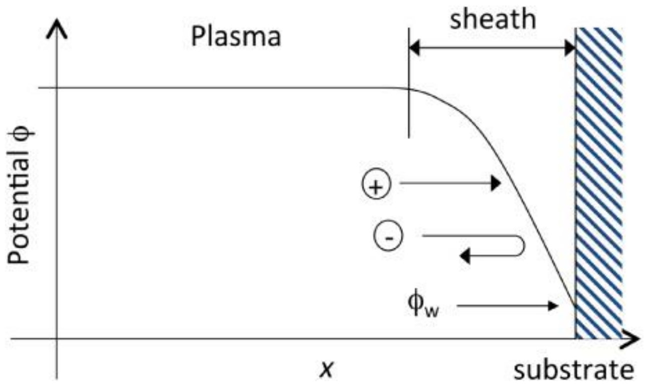
[1] J.P. Boeuf, G.J.M. Hagelaar, P. Sarrailh, G. Fubiani and N. Kohen , PSST. 20, 015002 (2011)

2.5D PIC-MCC full source Model: MINUS

Assumptions-Limitations

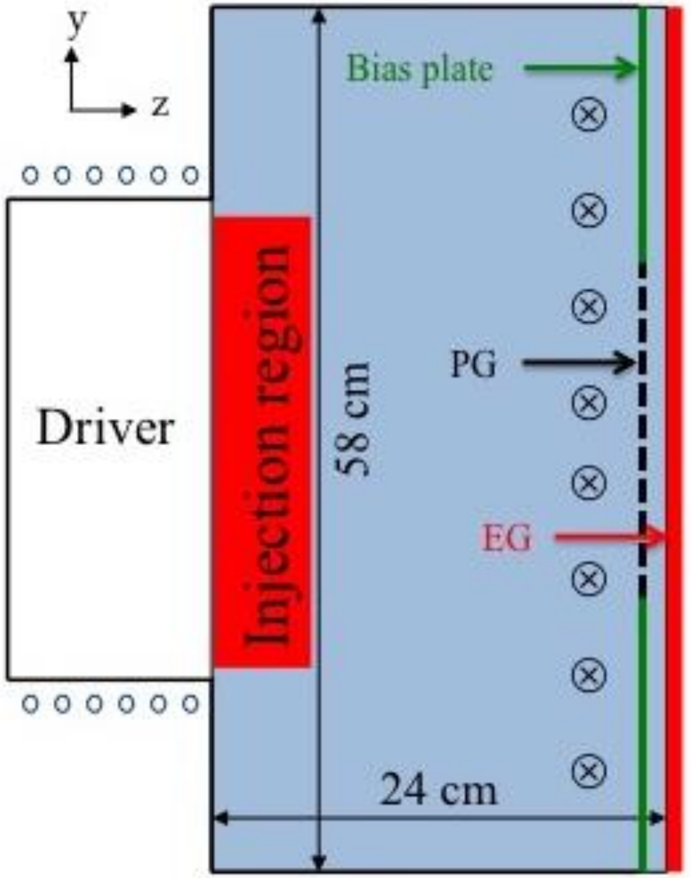
- Driver/Injection
- **Geometry**

2.5D cartesian geometry - 2D(y,z) electrostatic [1] – 1D(x) Monte Carlo
Particle tracked in x (magnetic filter field direction) but quantity considered uniform (E_x=0) -> no gradient effects in x
Particle-wall interaction are considered assuming thin-sheath approx.
A secondary electron emission coefficient Ύ=0.2 has been assumed



We are interested in ExB and diamagnetic drifts

$$\vec{v} = \vec{v}_E + \vec{v}_D = \frac{\vec{E}\times\vec{B}}{B^2} + \frac{k_B}{en}\frac{\nabla(nT)\times\vec{B}}{B^2}.$$



[1] Poisson equation solver: http://www.mcs.anl.gov/petsc/petsc-as/

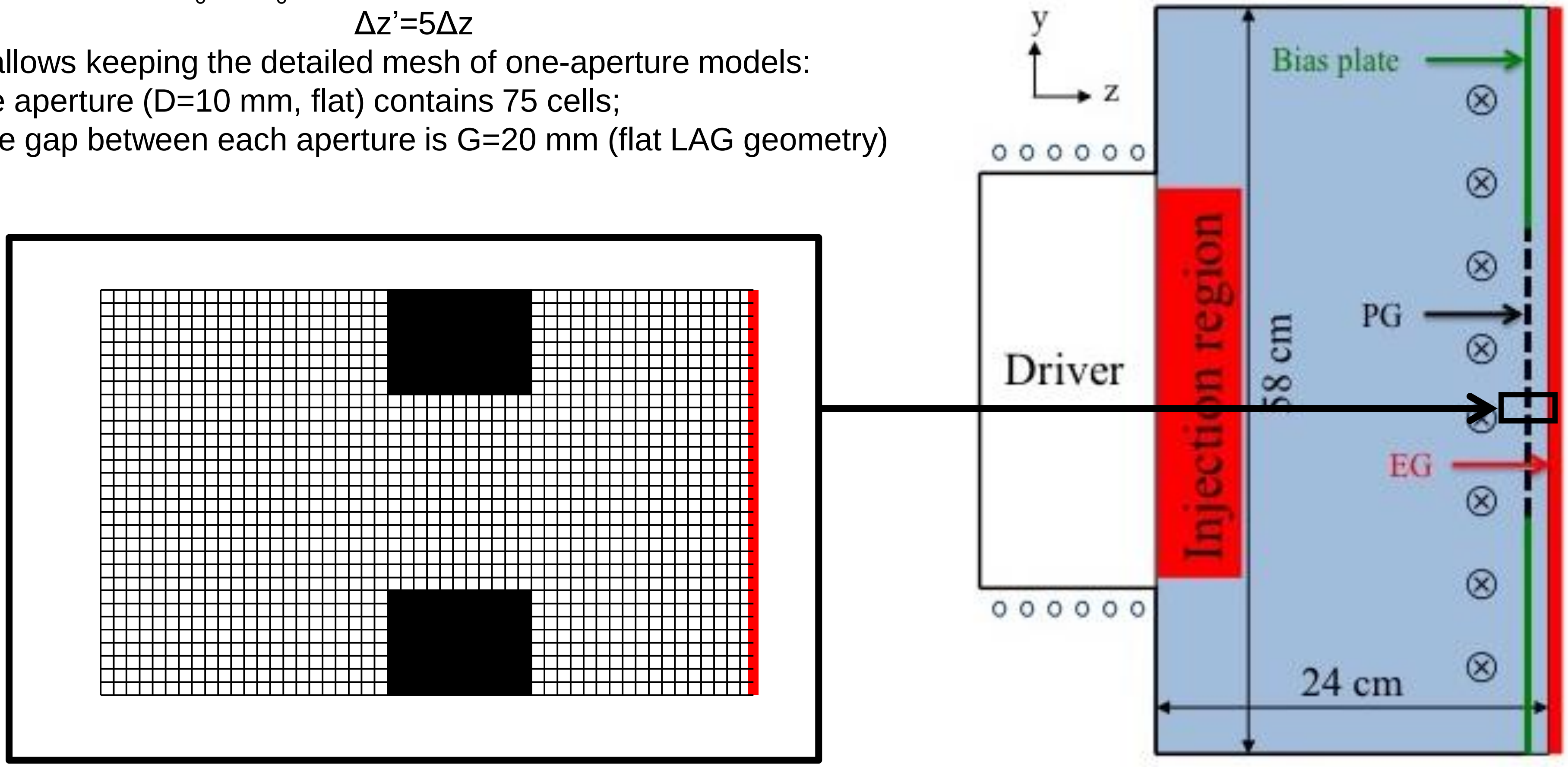
2.5D PIC-MCC full source Model: MINUS

Assumptions-Limitations

- Driver/Injection
- **Geometry**

Scaled model: $\varepsilon'_0 = 25\varepsilon_0$ ➔ $\Delta t' = 5\Delta t$;
$\Delta z' = 5\Delta z$

It allows keeping the detailed mesh of one-aperture models:
the aperture (D=10 mm, flat) contains 75 cells;
The gap between each aperture is G=20 mm (flat LAG geometry)



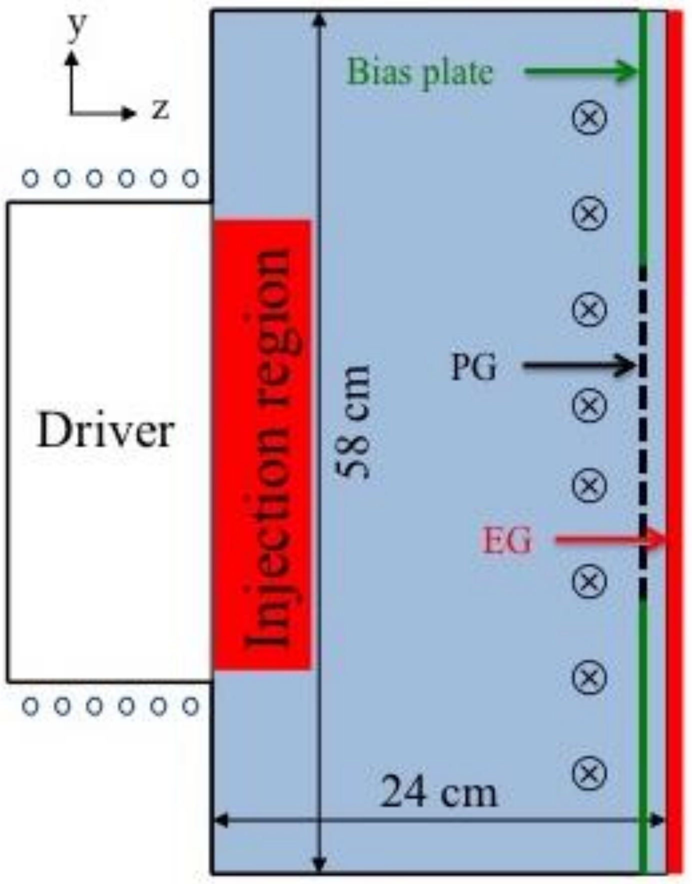
2.5D PIC-MCC full source Model: MINUS

Assumptions-Limitations

- Driver/Injection
- **Geometry**

Scaled model: $\varepsilon'_0=25\varepsilon_0$ ➔ scaling the extraction field ϕ_{EG}
The extraction voltage has been scaled assuming a generalized Child-Langmuir-like extraction law

$$j_e = \frac{4}{9}\varepsilon_0\left(\frac{2e}{M}\right)^{1/2}\frac{f_{EG}^{a}}{s^2}$$



Fitting the experimental values [1] for LAG system, it gives α=1.2 in place of the classical value 1.5.
ϕ_{EG}=9 kV corresponds to ϕ'_{EG}=1 kV in the scaled version.

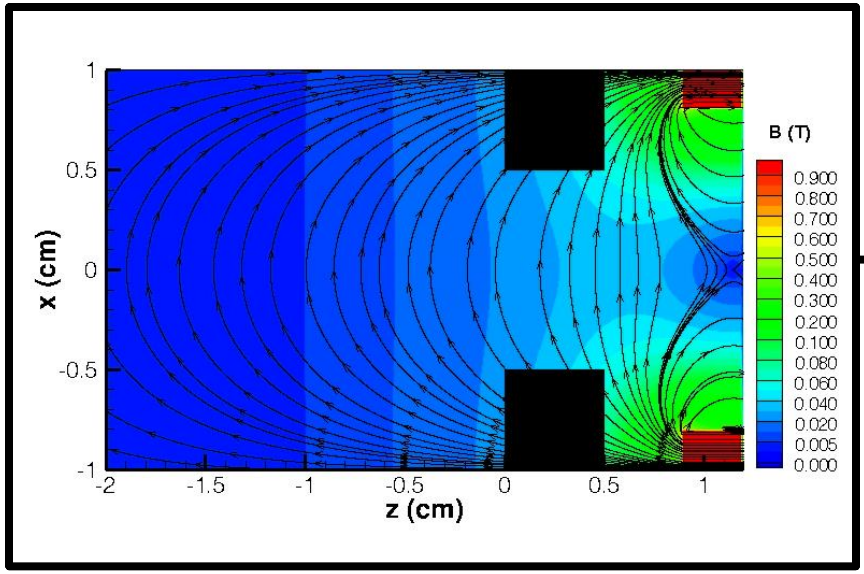
[1] Franzen P et al 2011 Nucl. Fusion 51 073035

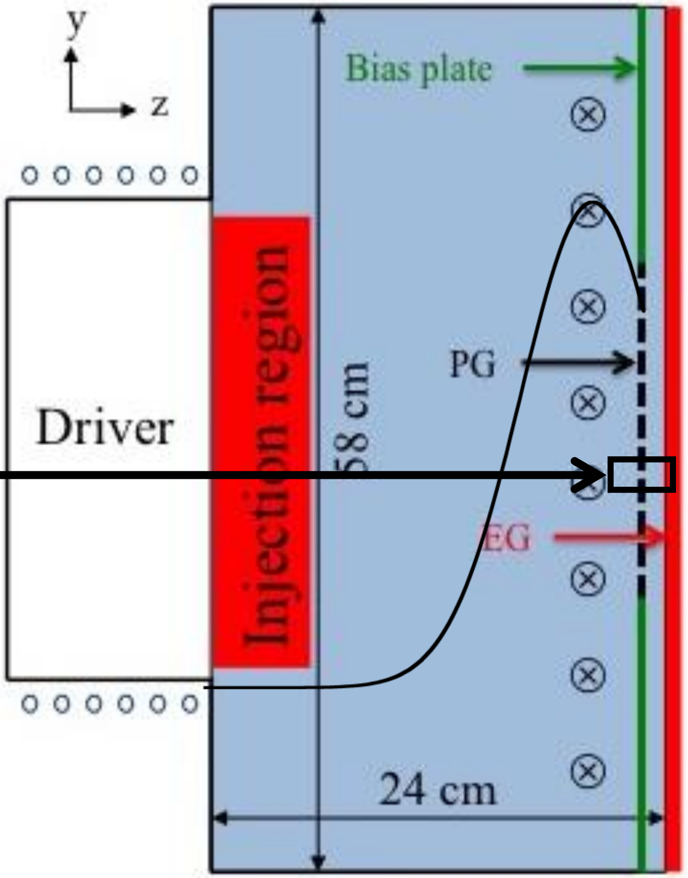
2.5D PIC-MCC full source Model: MINUS

Assumptions-Limitations

- Driver/Injection
- Geometry
- **Input data**

- Filter field: bell shaped z-profile with z_{max}=3 cm from PG and $B_{x,max}$=7 mT (standard configuration)
- Electron deflection field: prescribed 2D(y,z) map with alternating y-direction for adiacent apertures





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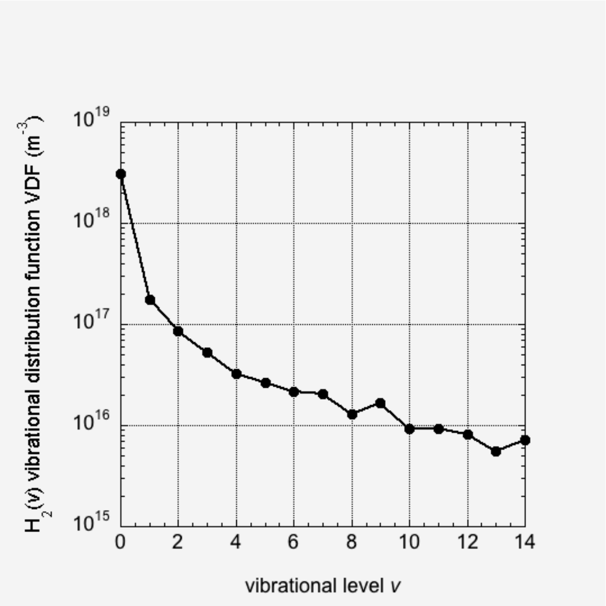
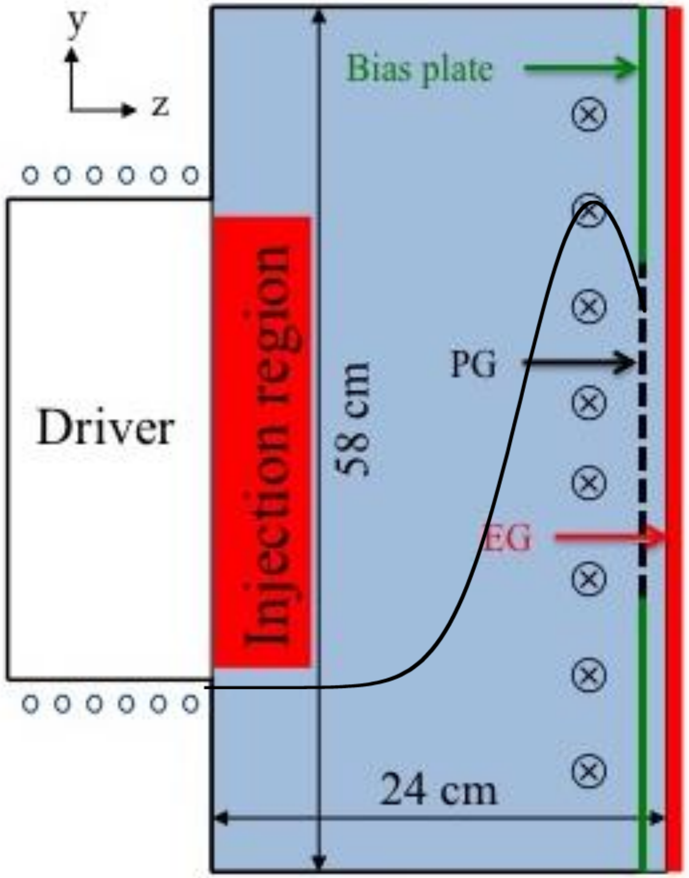
- Fixed H and H_2 density / temperature (0.8/3x10^{19} m^{-3} – 1/0.1 eV) with prescribed vibrational distribution corresponding to P=0.3 Pa and Power=40 kW





2.5D PIC-MCC full source Model: MINUS

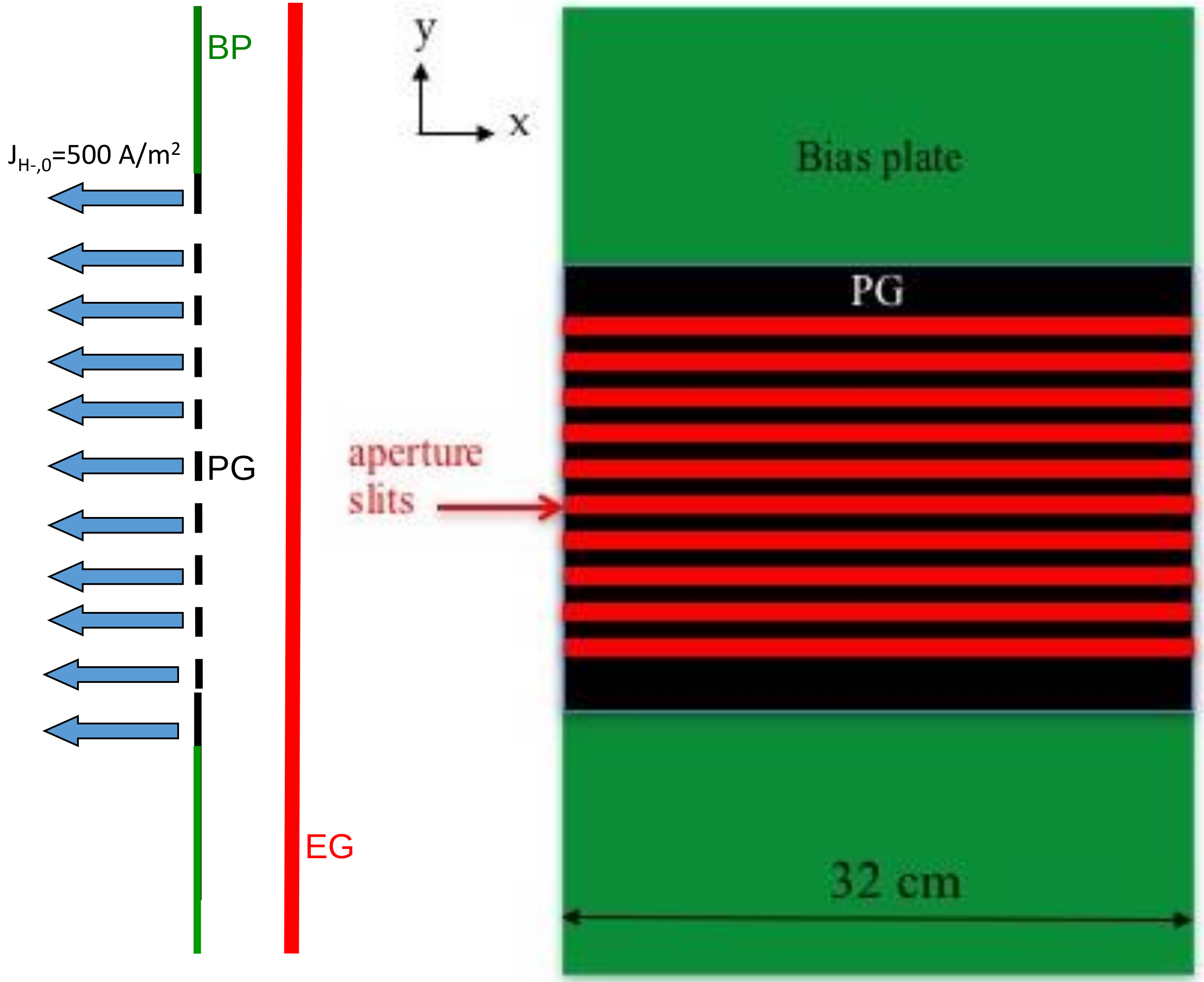
Assumptions-Limitations

- Driver/Injection
- Geometry
- **Input data**

- Most relevant volume collisions
- Self-consistent production of volume H^- and surface H^- by positive ion conversion [1]

$$Y(E) = \frac{R_N \eta_0}{E}\left(E - \frac{E_{th}}{R_E}\right)$$

- Fixed current density $J_{H-,0}$=500 A/m^2 of surface-produced H- by neutral conversion; uniformly launched along y at PG with half-Maxwellian distribution $T_{H-,0}$=0.8 eV
- The number of apertures have been decided in order to keep the production area equal to LAG. This guarantees a realistic negative ion current emitted from PG and then a correct continuity equation
- Unavoidably the extraction area is changed (larger by a factor 4); all results related to extraction are presented as density currents and not as currents



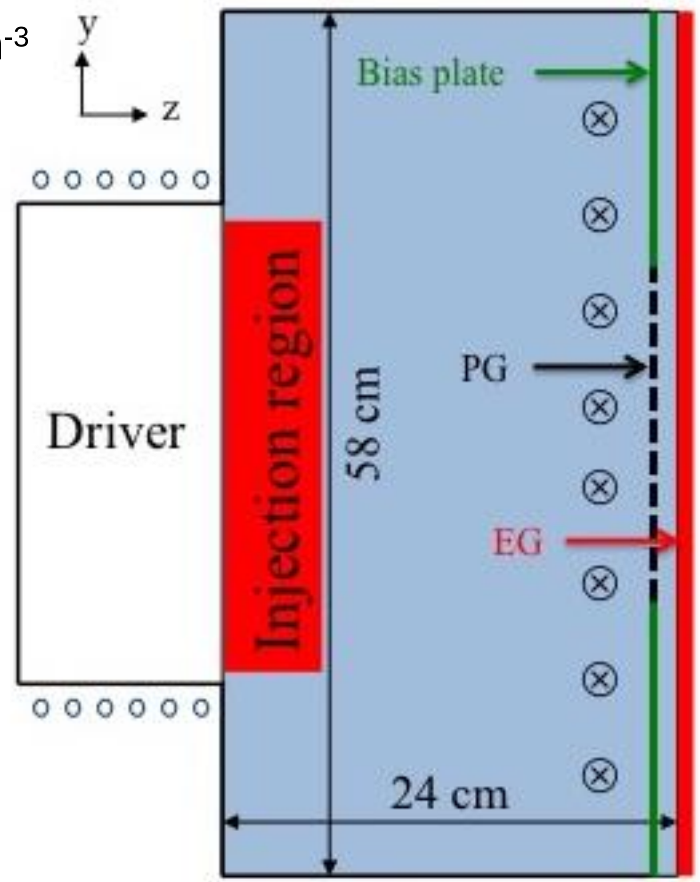
[1] M. Seidl, H.L. Cui, J.D. Isenberg, H.J. Know, B.S. Lee, S.T. Melnychuk, *J. Appl. Phys.* **79**, 2896 (1996)

2.5D PIC-MCC full source Model: MINUS

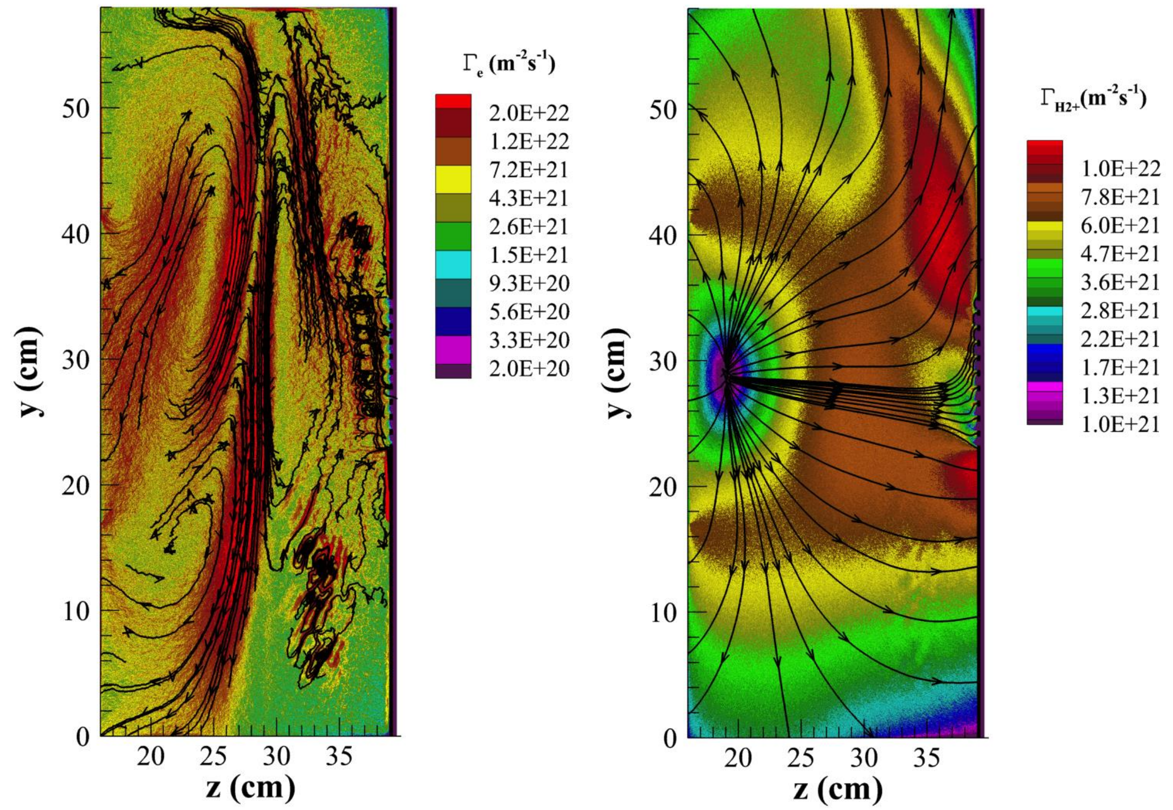
Simulation parameters-Performances

- $\Delta t = 2.5\text{x}10^{-11}$ s
- $\Delta z = 1.3\text{x}10^{-4}$ m ~ $2\lambda_{D,min}$
  minimum Debye lenght found in the domain $\lambda_{D,min}=6\text{x}10^{-5}$ m
  attached to PG due to negative ion production $n_{H-}=6\text{x}10^{17}$ m^{-3}
  $T_{H-}=3$ eV

  -> Ng=Ny x Nz=4350x1768
- $N_{part} = 2\text{x}10^{8}$ ($w=6.4\text{x}10^{7}$)
- OpenMP/MPI hybrid paradigm
- 4 μs /day @ MARCONI
  (4 nodes x 48 cores @ 2.1 GHz Intel Xeon 8160)
- $T_{tot}=80$ μs.



Results: Non ambipolar transport in expansion region



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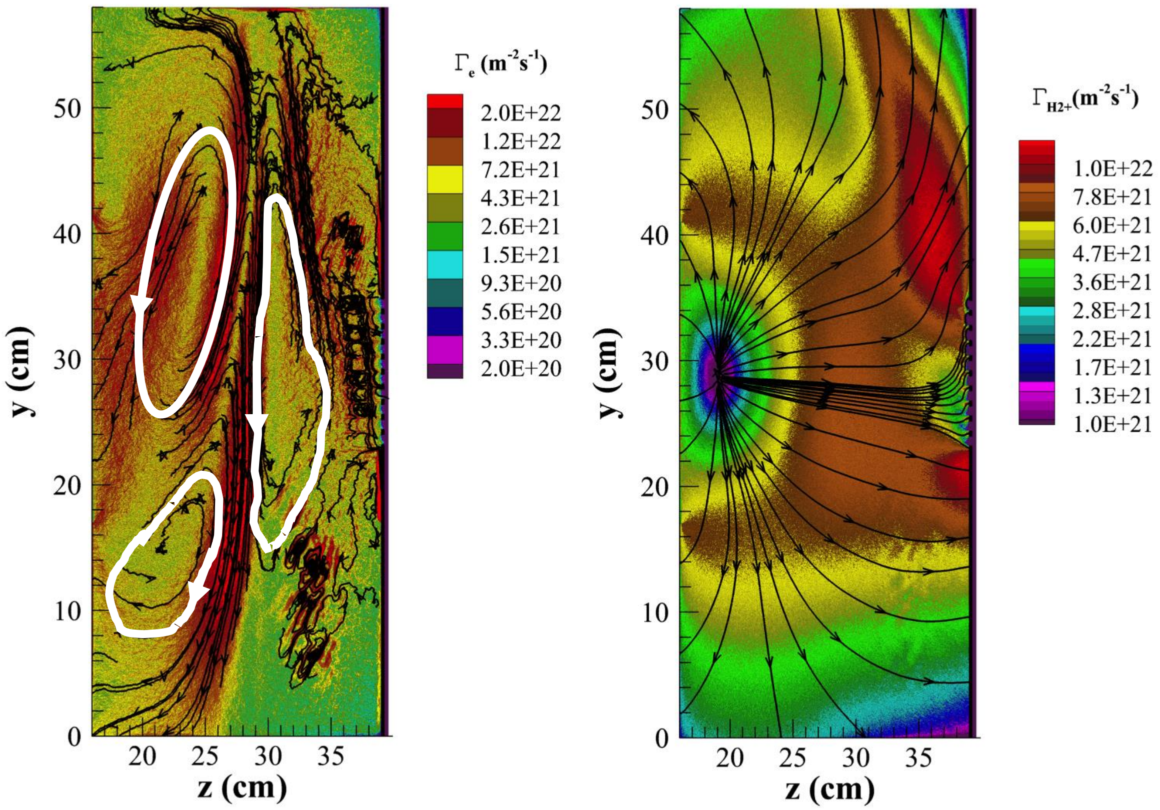
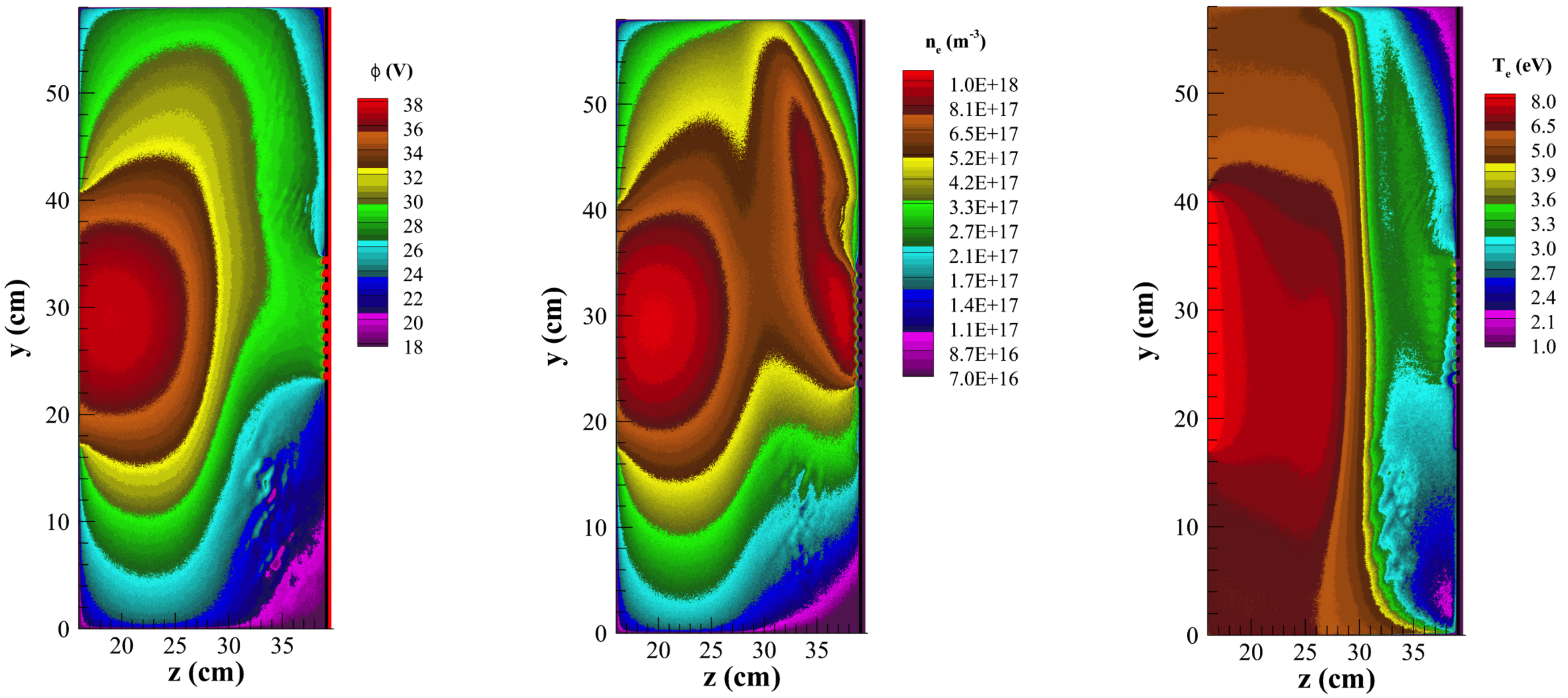


The electron flow exhibits a complex distribution.
It is first evident a strong electron flow directed towards the bottom surface at the entrance of the magnetic filter region.
It is the effect of electron density and temperature gradients that induces a diamagnetic drift.
This electron flow interferes with the electron flow coming from the driver bending it in anticlockwise direction in the upper part and in clockwise direction in the lower part. As a result of this interaction, an electron backflow towards the driver sidewall and a short-circuit close to the bottom surface are established.
Only some electrons (the low-energy one after many collisions) are able to escape and cross the filter region towards the PG.
Streamlines show a transition from classical to anomalous regime. From here to the plasma grid a more chaotic transport characterized by the presence of small-scale eddies and magnetic mirroring along the electron deflection magnetic field lines is established.

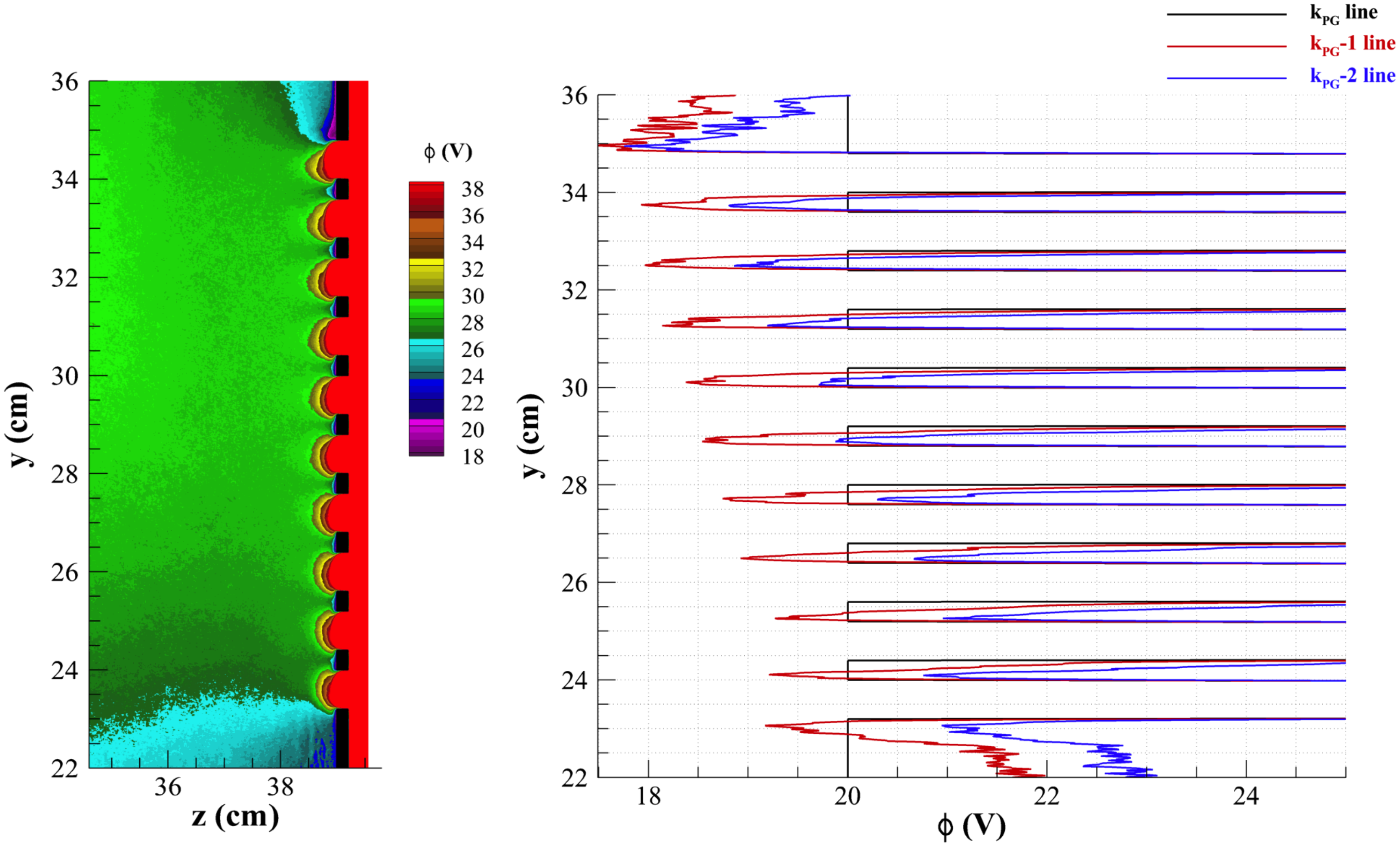
Results: Vertical Asymmetry



This clearly shows the working principle of magnetic filter field: making the electron transit time larger and the flux almost entirely parallel to the magnetic field lines in the filter region, electrons reduce their energy by collisional events and move faster along transversal direction. These effects reduce both the electron temperature and density downstream of the magnetic filter region.

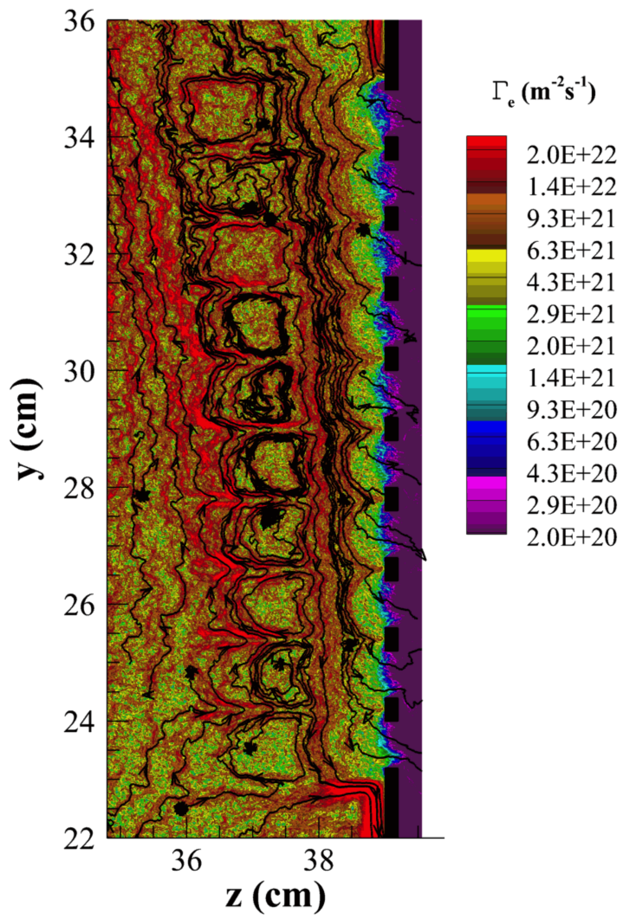
All the quantities show a marked top-bottom asymmetry due to the aforementioned magnetic drifts.

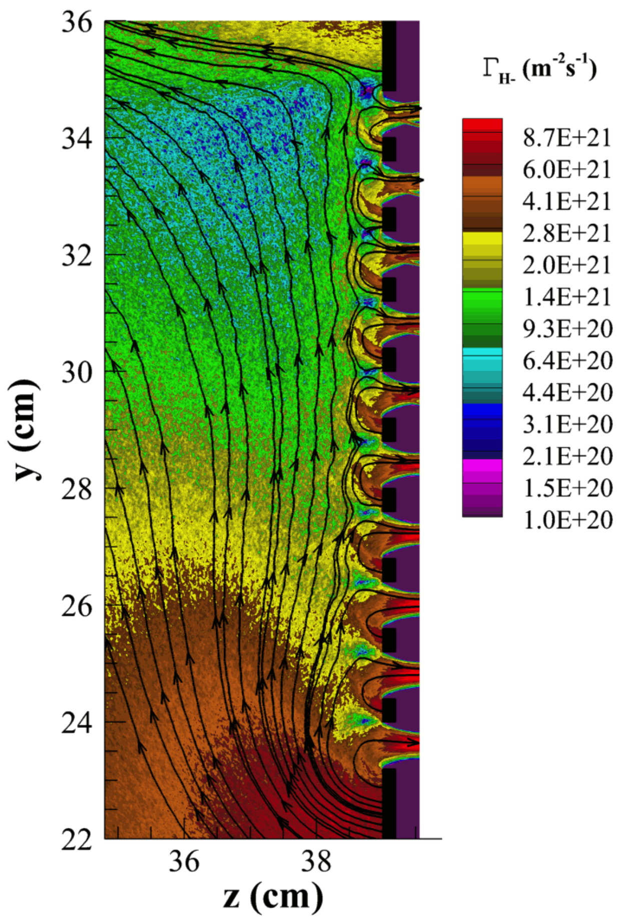
Results: Extraction Region

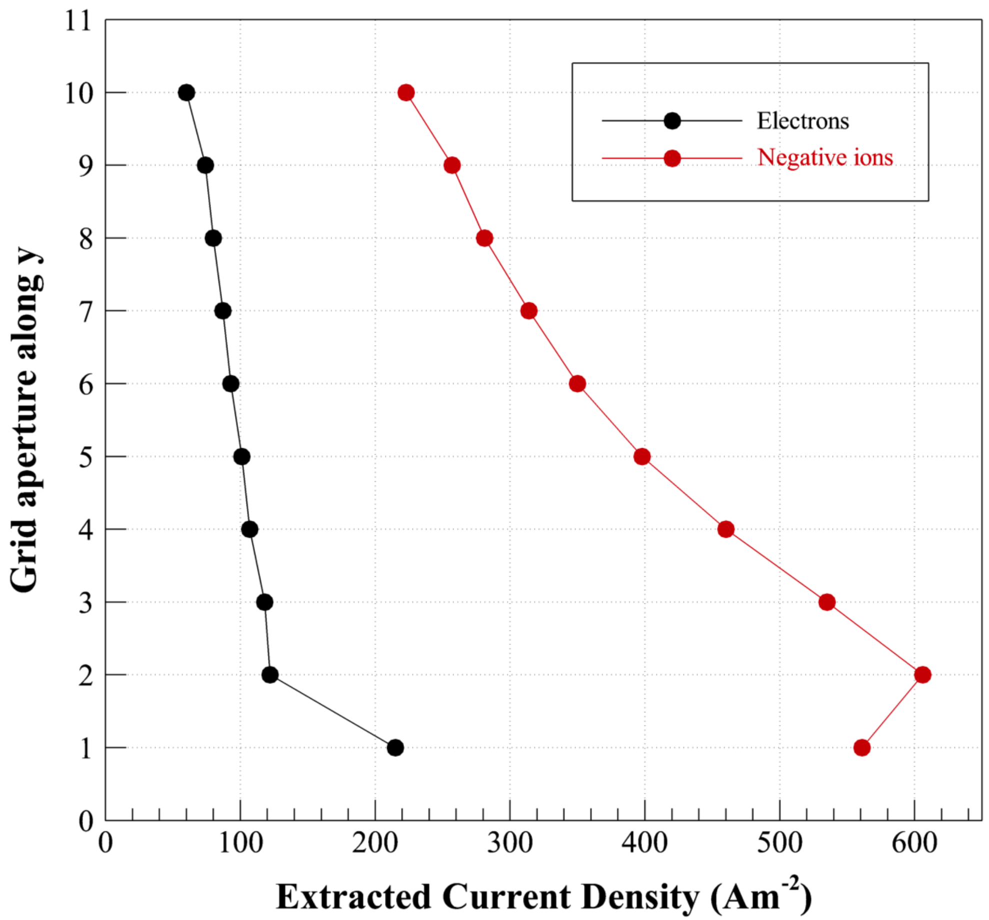


All the quantities show a marked top-bottom asymmetry due to the aforementioned magnetic drifts. Meniscus shape and potential well are not uniform along the different apertures.

Results: Extraction Region

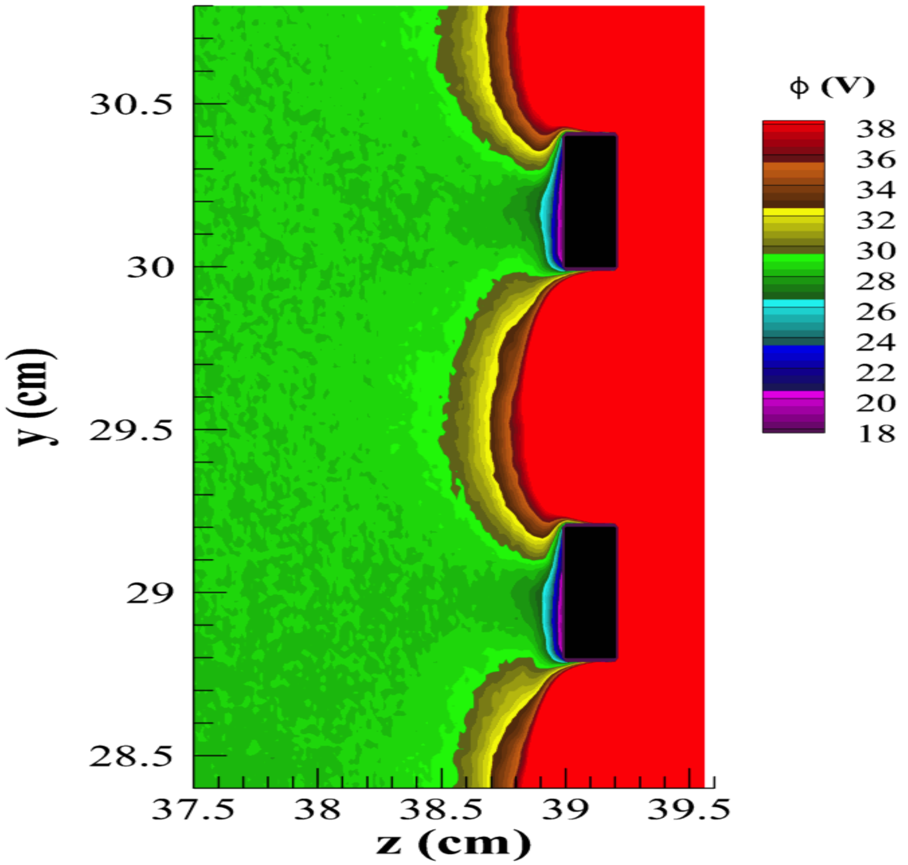


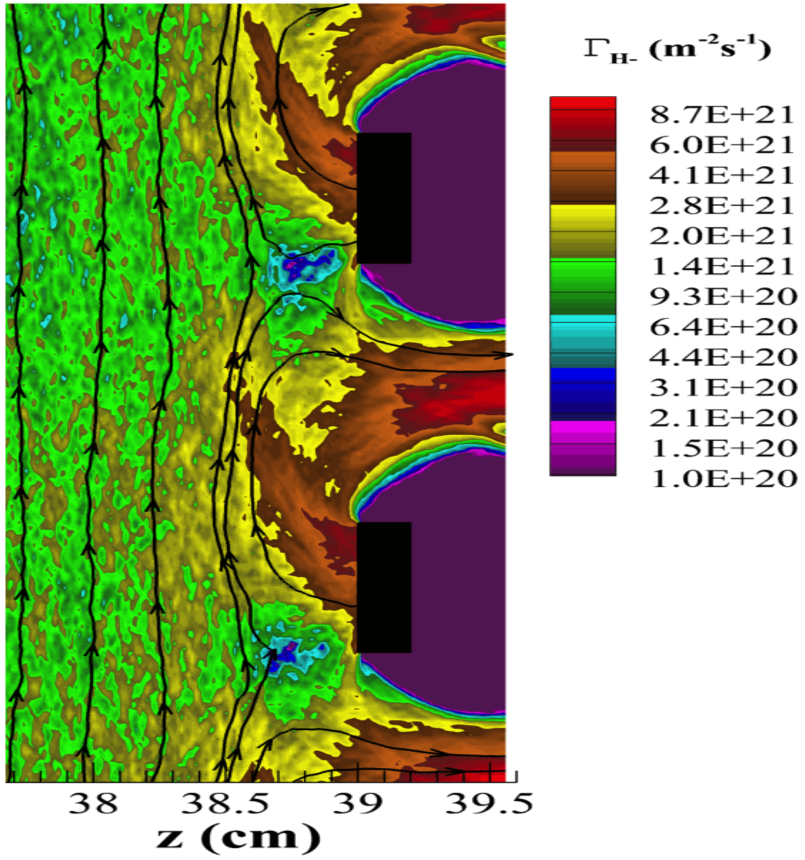




Due to the inhomogeneous plasma condition induced by the magnetic filter field, the extracted currents show a non uniform distribution along the different apertures.
Both electron and negative ion currents peak at the bottom aperture.

Results: Meniscus Shape



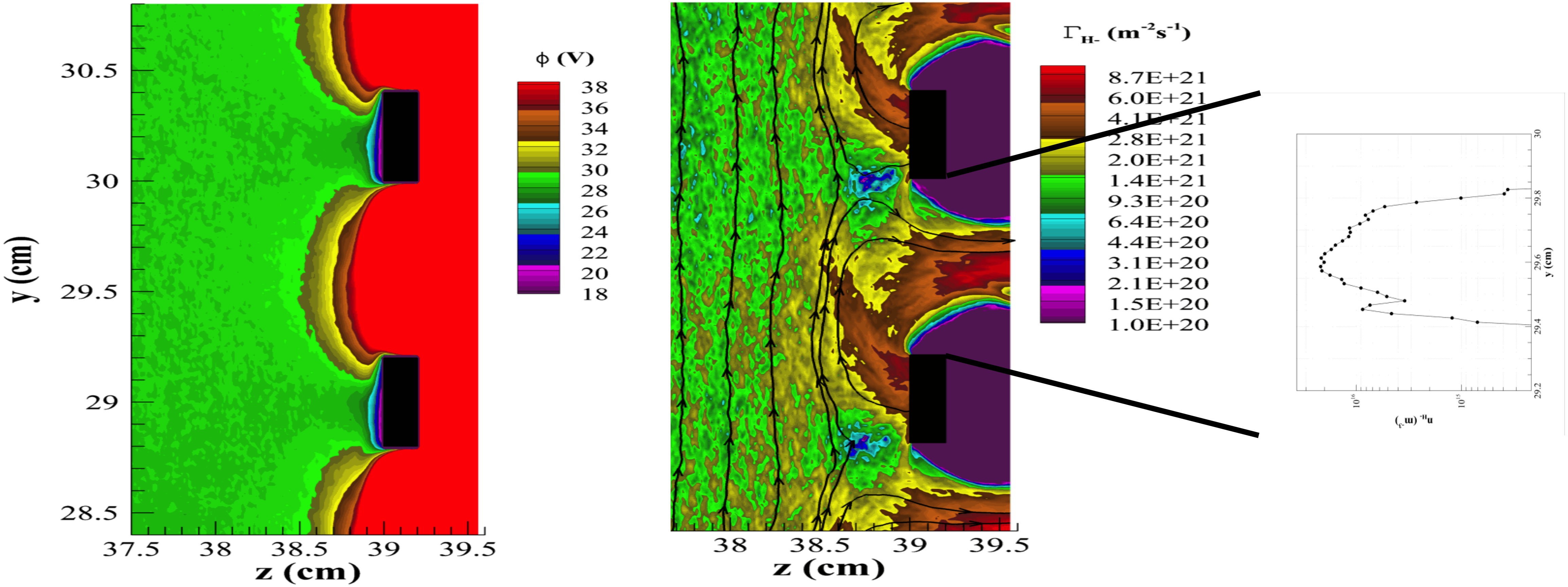


The meniscus shape is presented as asymmetrical lobes with a penetration length inside the source increasing from the bottom to the top aperture. Even the potential well attached to the PG surface is not uniform between two adjacent apertures, but it reaches a maximum depth of 2 eV from one side, the upper one, of the aperture and it is absent on the other side, the lower one.

The location of absence of the potential well corresponds to the place where a larger positive ion flow arrives. Therefore, surface-produced negative ions have preferential trajectories always directed towards the bottom part of the source and the extraction occurs where the negative ion streamlines intercept the meniscus.

The asymmetry detected around every single aperture has an impact on the quality of the single beamlet extracted.

Results: Single beam profile



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Conclusions

- Extraction region numerical models:
  Very good tools for basic understanding of plasma-wall transition region….not for optimizing a real complex device
- MINUS is able to solve at the same time plasma transport in the expansion region and extraction-acceleration physics up to the level of the single aperture
- First results confirm the difficulty of the single aperture model: disomogeneity-non periodicity (asymmetry)-non maxwellian-non ambipolar conditions at the entrance of extraction region
- The electron transport across magnetic filter is determined by a short-circuit self-developping due to the interaction between horizontal flow coming from the driver and vertical magnetic drift
  Non ambipolar transport seems to be present in the x-direction too (extra short-circuit)
- Negative ion extraction is electrostatic and determined by the interception between the oblique negative ion flow from PG and the meniscus -> this seems the reason why a chamfered grid increases the extraction probability
- PG bias voltage / magnetic filter configurtion effect under study
- Deuterium effects are future studies;
  in the meanwhile we are trying to reduce the value of the scaling factor