Negative ion kinetics inside a negative ion source (including ion extraction)

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THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

Outline/strategy of this work

- Model negative ion kinetics inside a fusion-type high brightness negative ion source
  - Assess the shape of the density and flux profiles
    - Are the negative ions magnetized?
  - Calculate mean-free-paths
- Simulate negative ion and co-electron extraction vs the plasma electrode (PG) bias
  - Evaluate the weight of each negative ion production processes
    - Dissociation of H_2 vs. positive ion and neutral atom impacts on the PG
- Calculate the negative ion current beamlet profiles on the extraction grid (EG)
  - Is it asymmetric?
    - What are the mechanisms leading to an asymmetry?

Numerical methodology

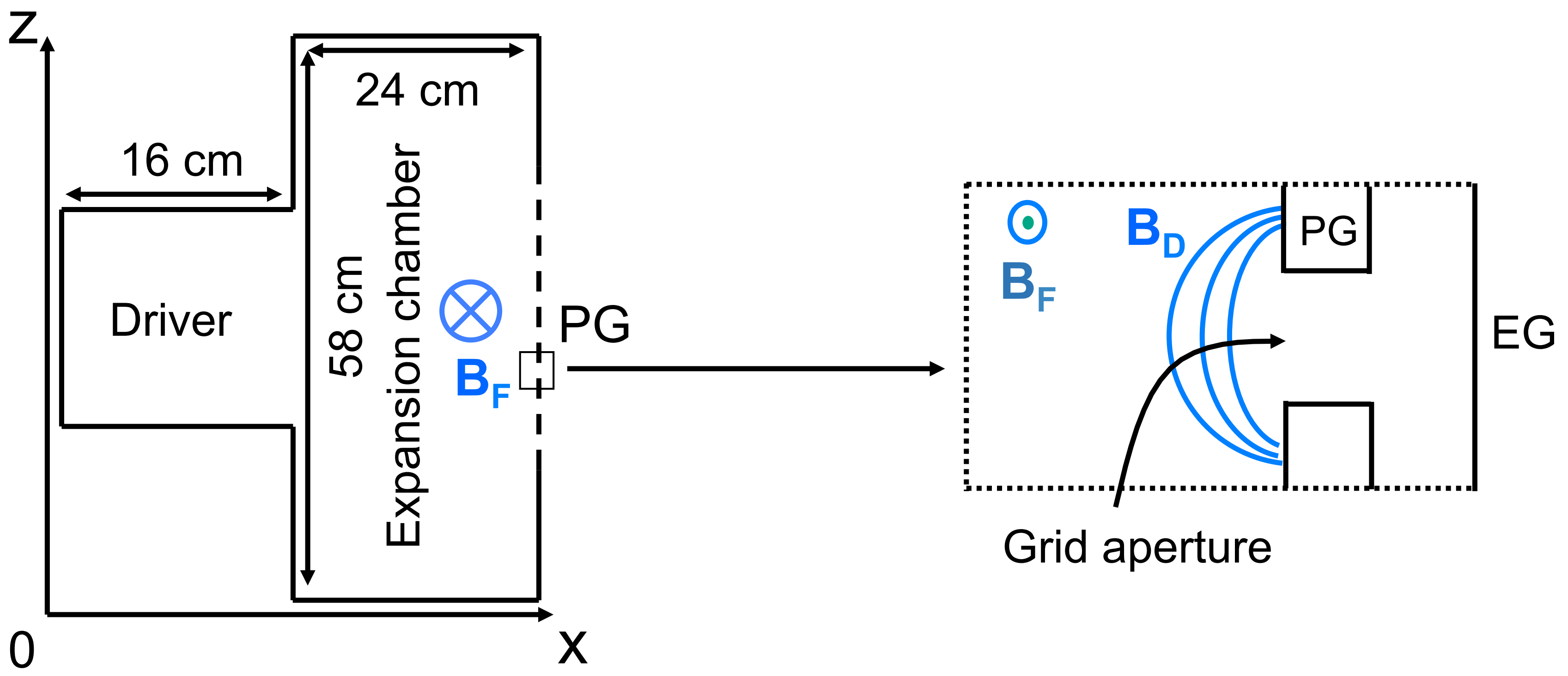
- 2.5D Particle-in-Cell (PIC) with Monte-Carlo Collision (MCC) model
  - We simulate the plane perpendicular to the magnetic field
    - This is where the plasma asymmetry takes place
  - “2.5D” because the particles kinetics along the magnetic field lines are simplified
    - Positive ion losses are evaluated via the Bohm velocity
    - Negatively charged particles drift in a constant potential profile
- The magnetic field is prescribed.
- Poisson’s equation is solved self-consistently
- We model lower plasma densities than in the real fusion-type ion sources
  - The density in the present work is either α=100 or 400 times smaller
- The neutral density profile is assumed constant
  - Values derived from experiments or from a DSMC model

Assumptions/ what the model can't do

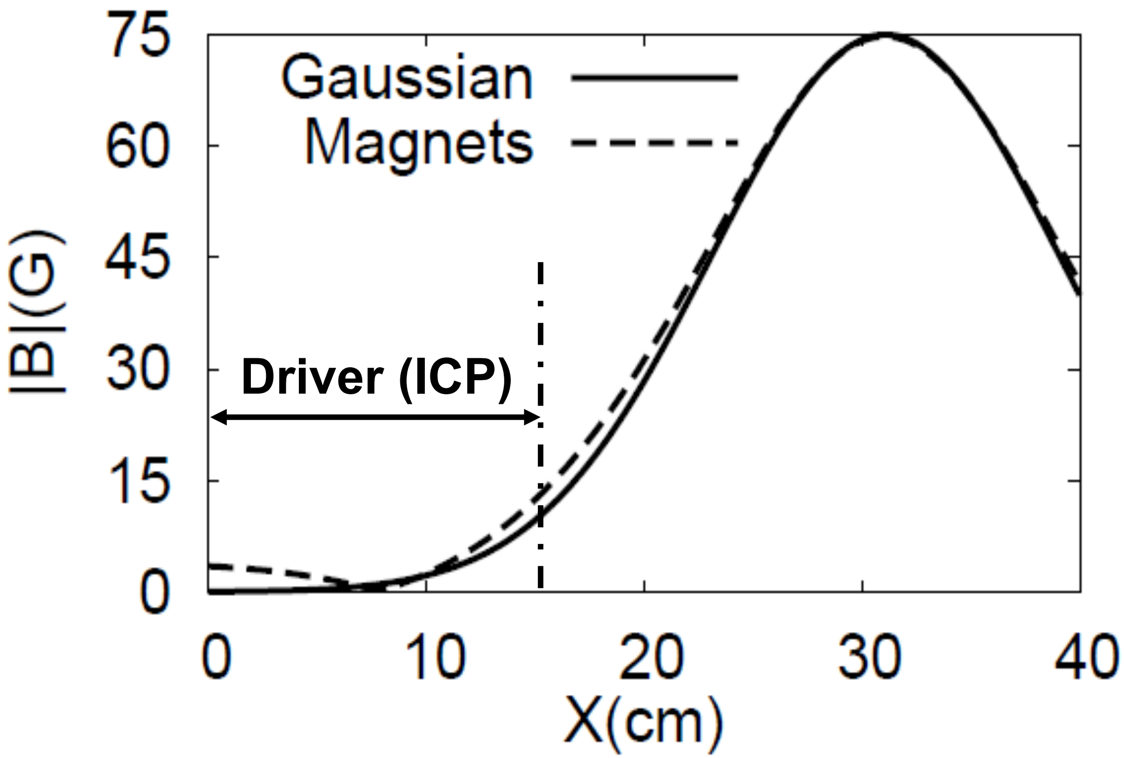
- We calculate plasma characteristics for densities of the order of 3×10^{15} m^{-3} (driver)
  - Corresponding to an absorbed power of ~150W (scaling factor $\alpha\sim400$)
- In the quasi-neutral plasma region the Boltzmann equation scales with the density
  - The plasma characteristics are hence similar to those of the real ion source
    - The plasma sheath is larger by $\alpha^{1/2}$
      - The sheath physics must be preserved (collision-less in our case)
- The properties of the extracted beamlets do not scale with the plasma density
  - Child-langmuir law $J=\mu V^{3/2}$
    - The extraction potential must be scaled accordingly
  - This model can't hence evaluate the absolute value of the extracted currents
  - Only variations with fixed parameters such as the PG bias for instance
- To model particle extraction the Debye length must be much smaller than the aperture
  - This condition imposes a lower bound for the scaling factor α

Simulation domain

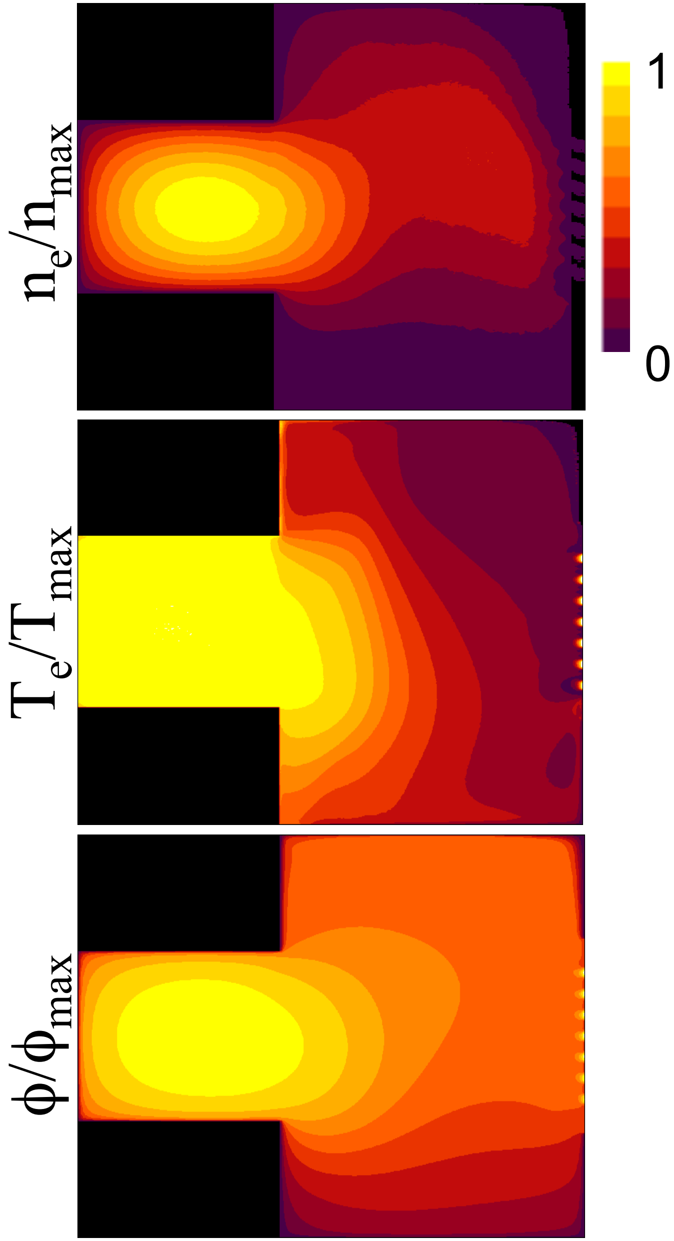
- We model the geometry of the ITER prototype at BATMAN
- Scaling factor α=400 (3×10^{15} m^{-3} in the driver, 150W absorbed RF power)
- Numerical resolution : 1024×1536 grid nodes, 40 particles per cell
- 7 extraction apertures (slits) in the PG, width of 15 mm.
- Extraction grid (EG) potential of 210V
- A H^- current density of 600 A/m^2 emitted on the PG with a temperature of 1 eV



Magnetic filter field profile



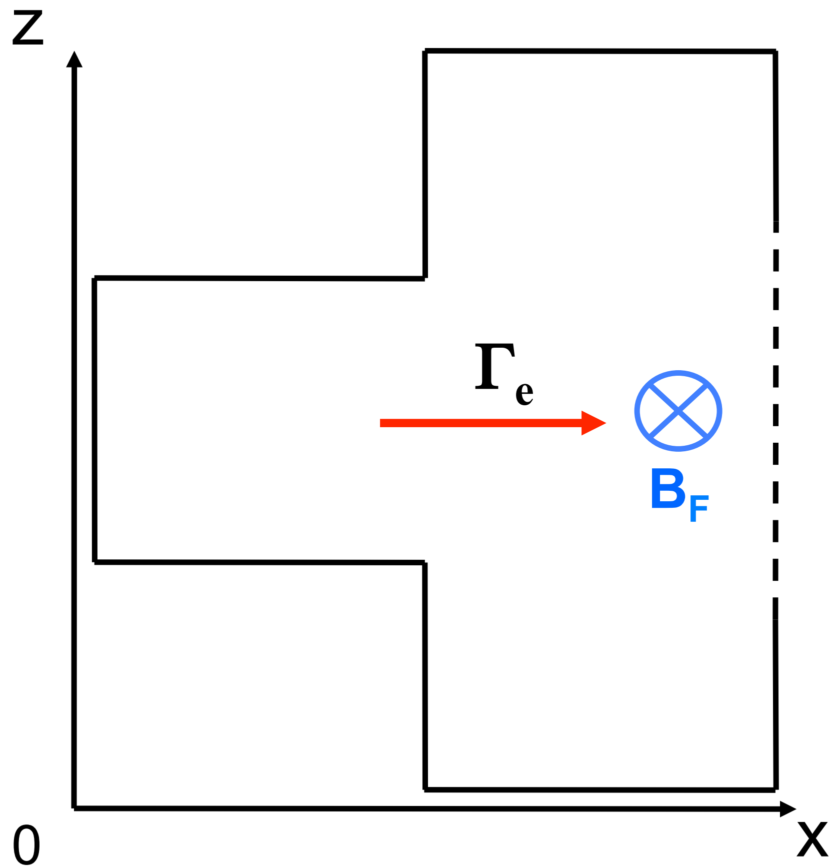
Plasma characteristics



- The PG bias voltage is set to 20V in the calculation
- The (scaled) plasma density is
  - 1.2×10^{18} m^{-3} in the driver
  - 3.5×10^{17} m^{-3} about 2 cm from the PG
- The electron temperature varies from :
  - 10 eV in the driver down to 1 eV near the PG
  - This is due to the magnetic field
- The plasma potential is about
  - 40V in the discharge and ~22V next to the PG

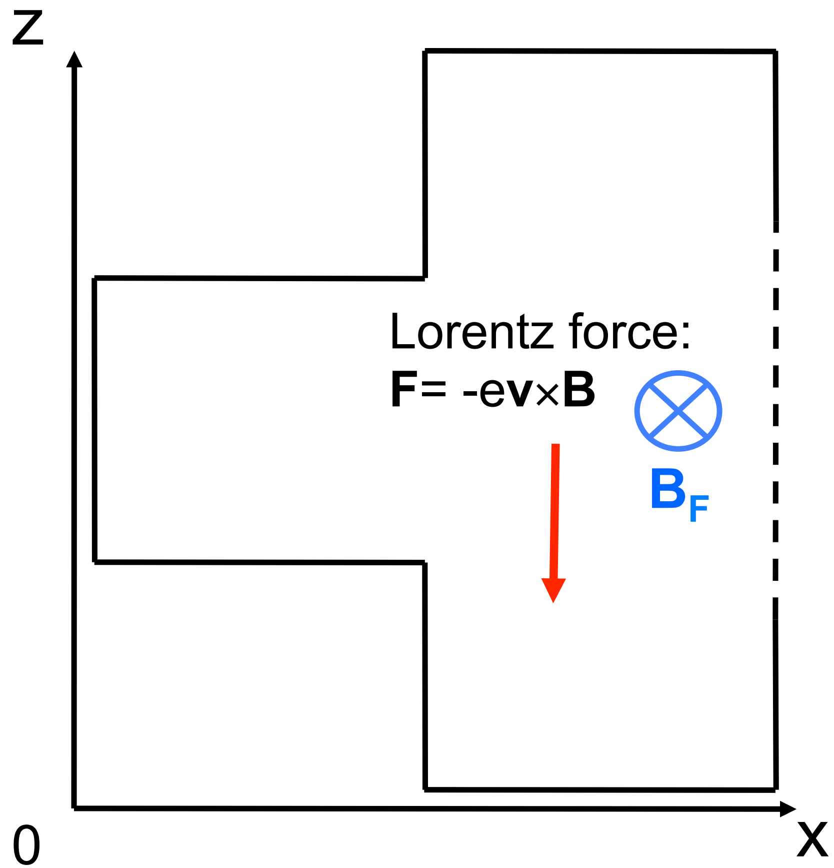
The plasma parameters are asymmetric!

Why is the plasma asymmetric?



Electrons are mostly produced inside the driver and flow toward the expansion chamber which is magnetized

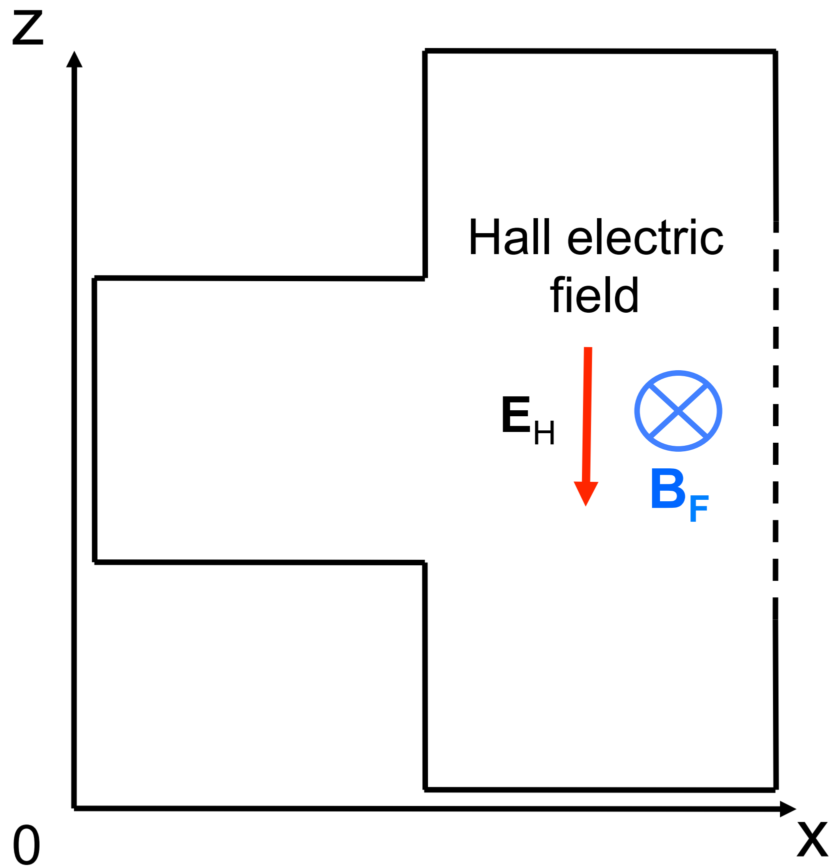
Why is the plasma asymmetric?



Electrons experience a Lorentz force inside the expansion chamber redirecting the flux toward the lateral walls of the ion source

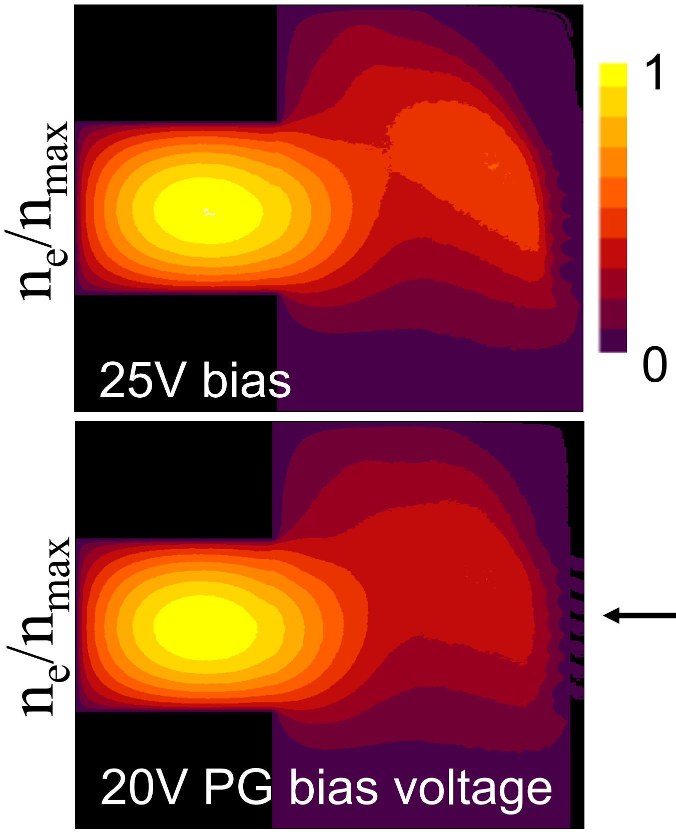
The Hall effect

Ions are not magnetized and a charge separation builds up in the plasma (polarization)



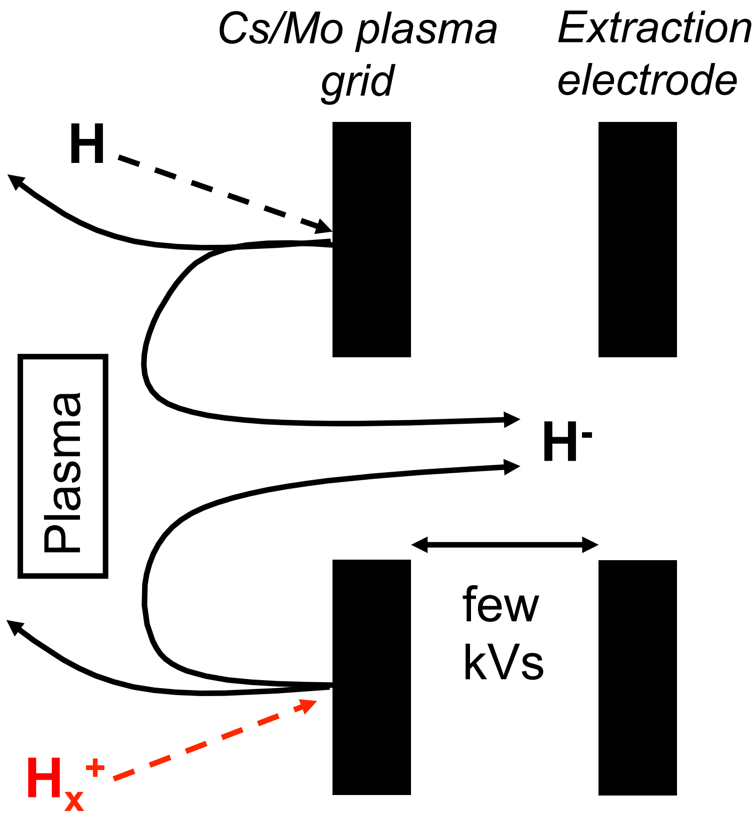
The Hall electric field (1) induce a transverse asymmetry in the plasma and (2) increases the transport of electrons across the magnetic filter field

The plasma asymmetry in enhanced by the PG bias voltage

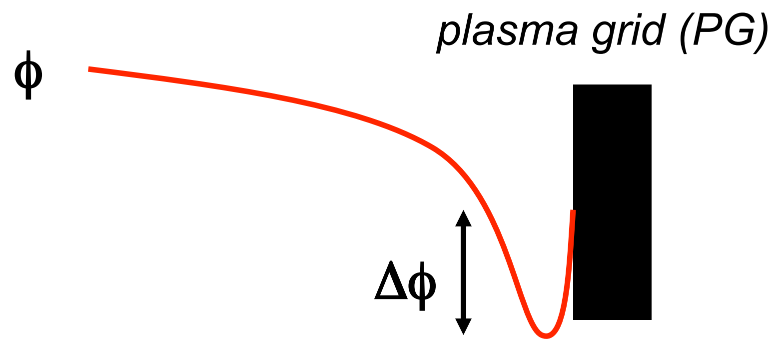


The PG is floating in the model

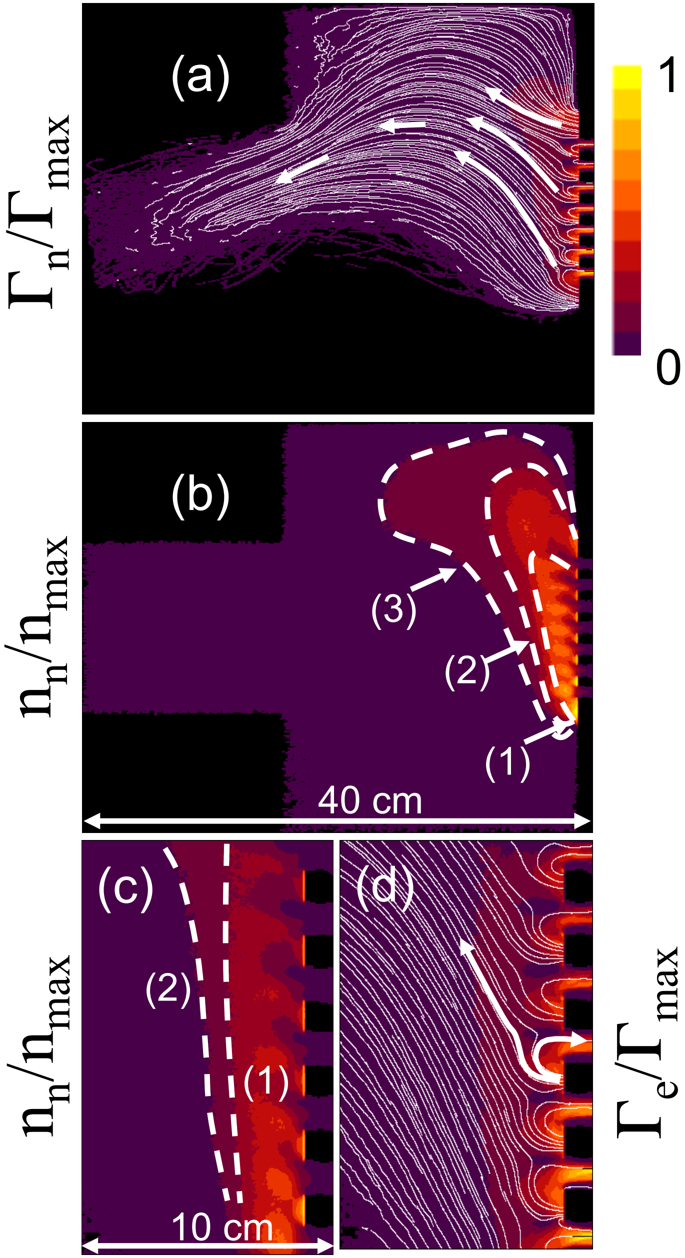
Principles for producing & extracting negative ions



- High brightness negative ion beams are produced on the plasma electrode surface
- Cesium is added to lower the metal work function (typically Cs/Mo converters)
- A high negative ion current emitted from the PG surface (typically >300 A/cm²) is space charge limited:
  - Formation of a virtual cathode
  - A large chunk of ions are hence reflected back onto the PG surface

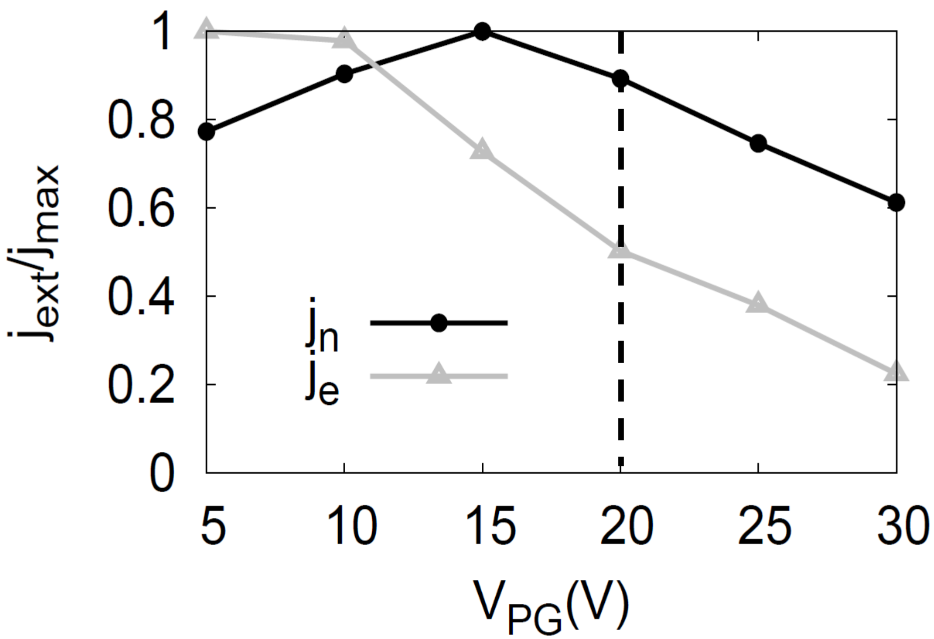


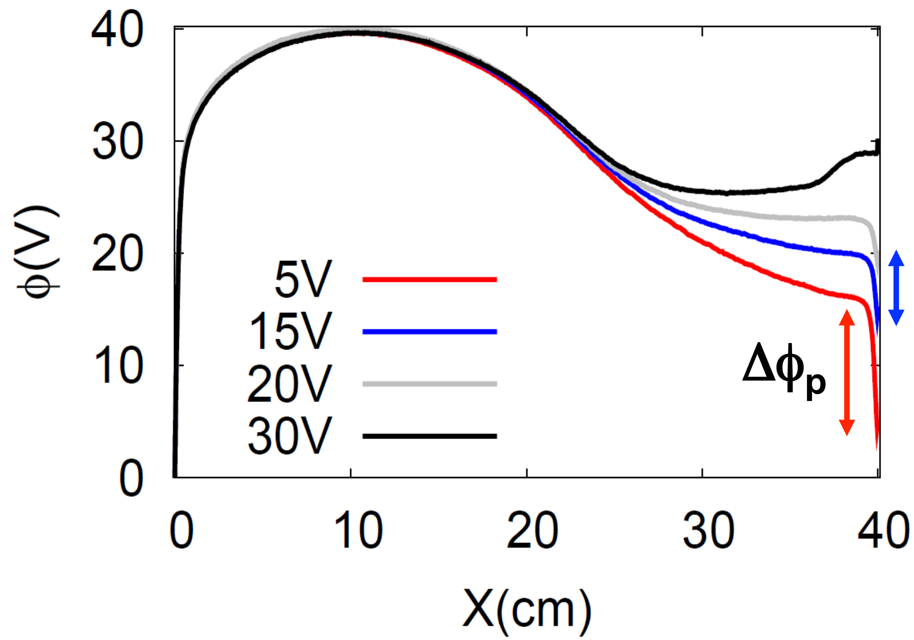
Negative ion kinetics inside the ion source volume



- A 20V PG bias was assumed in the model
- Negative ion mean-free-paths (2 cm from the PG):
  - Charge exchange with neutral atoms ~ 6 cm
    - Assuming a H density of 10^{19} m^{-3}
  - Destruction ~ 40 cm
  - ~20 cm for elastic collisions
- The negative ion Larmor radius is ~2.2 cm near the PG
- Ions are hence slightly magnetized (upward drift)
- The ion density profile is skewed (asymmetric)
  - Isocontours ($\times 10^{17}$ m^{-3}): 1 in (1), 0.5 (2) & 0.3 (3)
- Ions are only produced on the PG surface in the figure
  - Extracted ions were generated near the apertures
  - Probability of extraction ~50% in the model
- Virtual cathode depth: ~ -1V on average

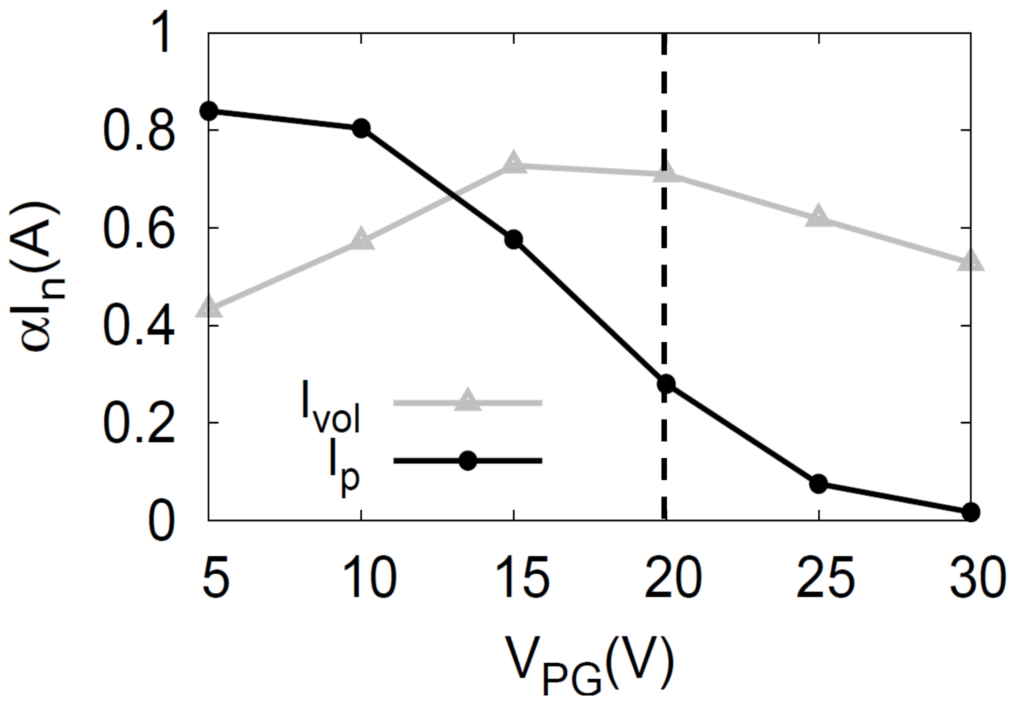
Negative ion and electron current extracted from the ion source vs. the PG bias





- The gap $\Delta\phi_p$ between the plasma potential and the PG bias decreases with the bias
  - Electrons can hence be increasingly more collected by the PG
    - Less are extracted
- The lower gap and flattening of the potential raise the residence time of the H^- ions
  - This is why the H^- current increases up to a floating PG
- The virtual cathode depth also increases with the bias (lower positive ion flux)
  - It is the dominant effect for PG voltages > 20V (hence the decreasing ion current)

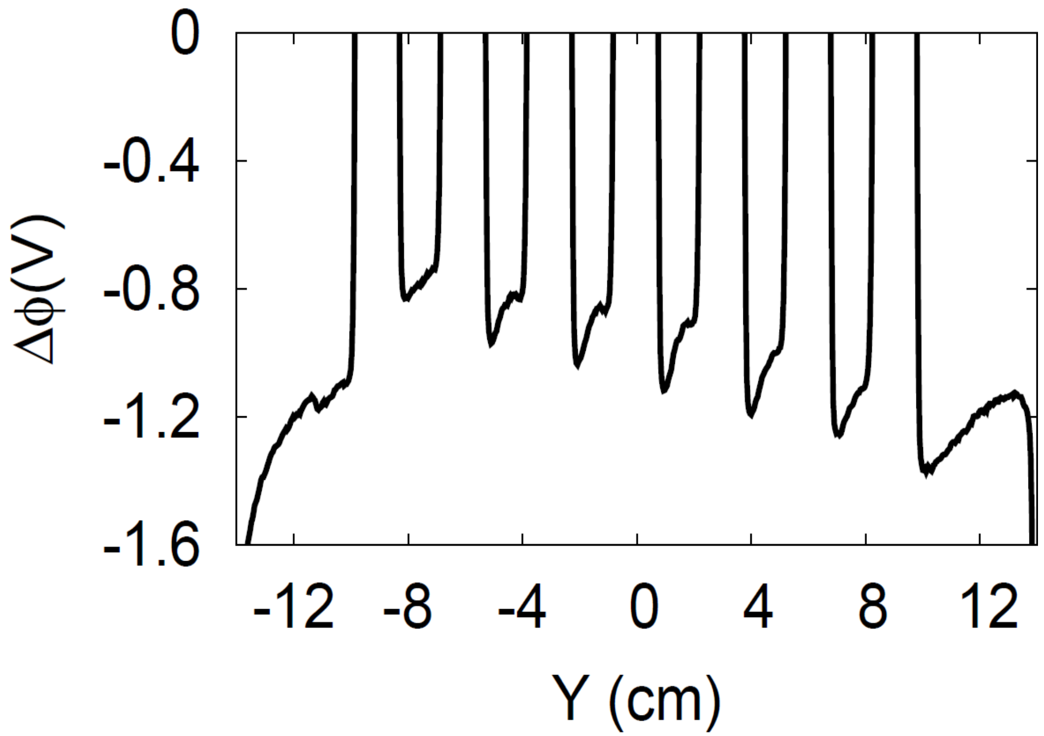
Extraction of negative ions produced in volume or via positive ion impacts on the PG vs. the PG bias

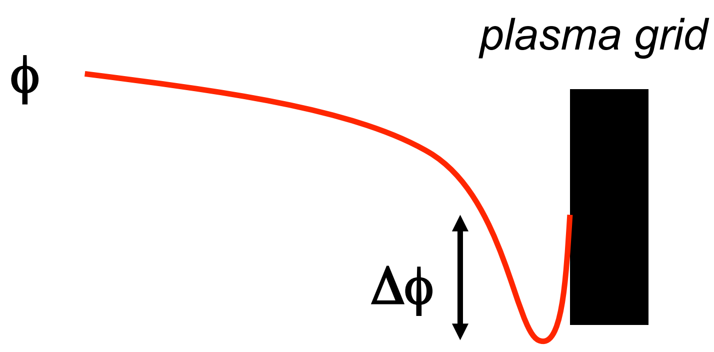


For a 20V PG bias voltage and an absorbed RF power of 150W (α=400):

- 5% of the extracted negative ions originate from positive ion impacts on the PG
- 14% from volume processes (dissociation of H_2)
- 81% directly extracted from the PG surface

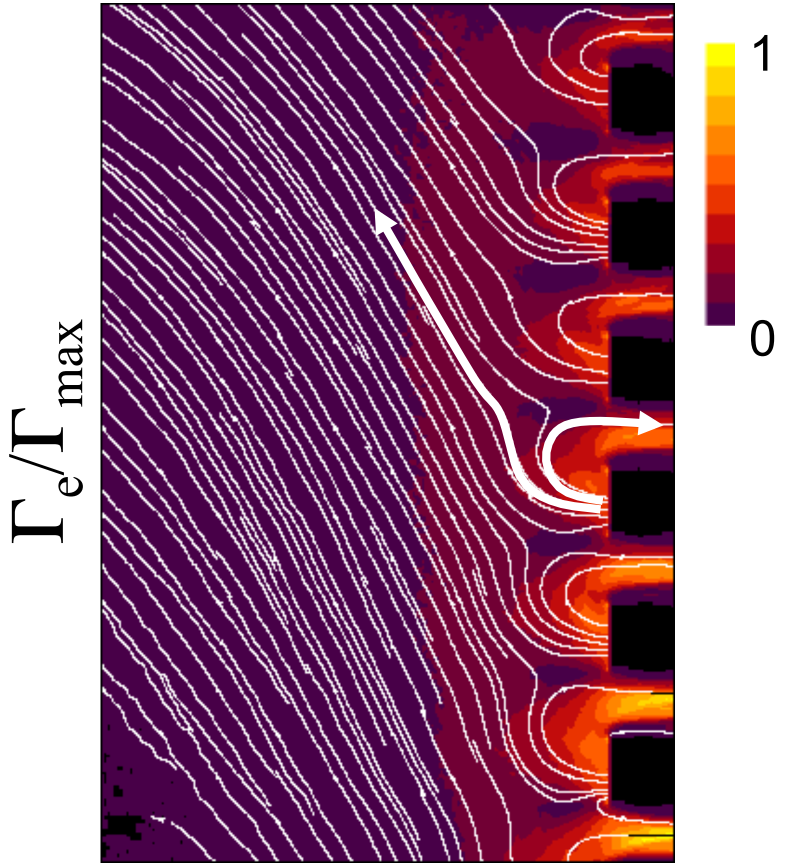
Virtual cathode profile along the plasma grid surface

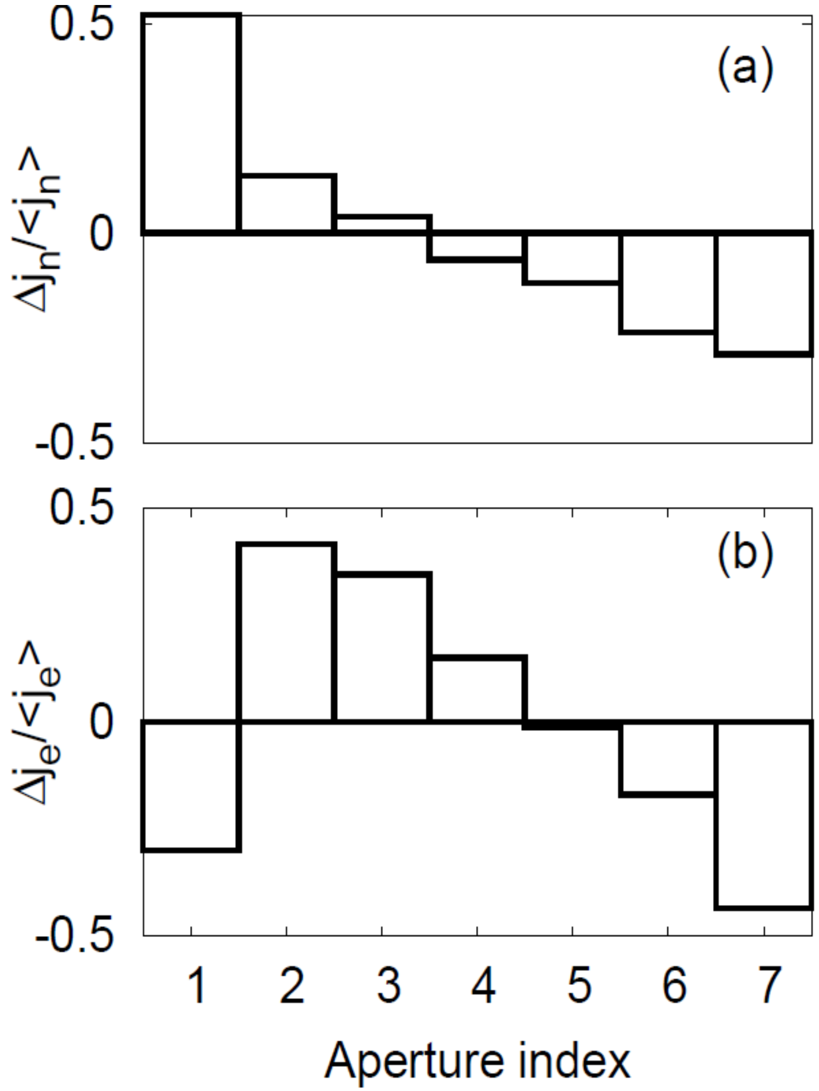




- Drawing an electron current across the magnetic filter generates a plasma asymmetry
  - Hall effect
- This asymmetry is also found:
  - On the virtual cathode profile in the model
    - As a consequence, on the extracted negative ion beamlet profile as well

Negative ion and co-extracted electron beam profiles on the extraction grid





The negative ion beam current spread is beyond the +/- 10% requirement for the ITER-NBI in the model

Conclusion

- We have simulated the negative ion kinetics inside an ITER prototype ion source
- We used a PIC-MCC algorithm and modeled smaller densities than in the real source
    - Due to the constraints on the PIC technique even in 2D (Debye length on mesh)
- We showed that the Hall effect induce an asymmetry in the plasma parameters
- This is because the electron magnetic drift is intercepted by the walls of the ion source
- The asymmetry is enhanced by the PG bias voltage
- The negative ions are slightly magnetized and the profiles are asymmetric as well
    - Including the negative ion beamlet current density on the EG
- The beam asymmetry is likely dependant on the shape of the magnetic filter field
    - This question should be addressed in future work
- Optimal extraction for H^- ions is found for a bias voltage near a floating PG
    - This is confirmed by experiments on BATMAN
- The co-extracted electron current density is also asymmetric
    - This may be an issue for the EG on ITER
- Although we modeled lower plasma densities, this work does raise questions about the possible consequences on the ITER NBI of the asymmetry in the ion source