Coupling between magnetic filter and extraction in ITER-relevant negative ion source

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Outline

- Critical aspects of existing models

- Full-size Source Model with detailed extraction: MINUS

- Results

- Conclusions
NIS Models

Kinetic self-consistent methodology: 2 kinds of approaches are present

EXTRACTION ZOOMED MODEL

FULL-SIZE SOURCE MODEL
NIS Models

EXTRACTION ZOOMED MODEL

+ Fine resolution (aperture contains tens of cells) -> study of different PG shape
+ Good statistical level (number of part. per cell)
+ No scaling (real vacuum permittivity)
+ 2D/3D model
+ Detailed electron deflection field
+ Surface-produced negative ions
+ Optimization of aperture size/shape
+ Meniscus shape and beam optics

- One aperture (periodic conditions)
- Strong influence of free parameters (initial conditions, re-injection system)
- Anisotropic fluxes and possible non-Maxwellian behavior
- Magnetic filter effects starts much farther from PG
NIS Models

FULL-SIZE SOURCE MODEL

+ Model of the plasma expansion and electron transport across the magnetic filter field
+ Dis-homogeneity along PG
+ Self-consistent plasma condition at the entrance of the extraction region
+ Positive ion flux at PG (ion conversion)
+ BP and PG bias effect
+ Plasma-gas coupling
+ 3D model

- Scaled model (fake vacuum permittivity) -> density scaling
- Not appropriate in case of non-linear transport mechanisms
- Cell size larger than the single aperture
- EG field penetration (meniscus) not solved
- Driver not self-consistently included
Simulation domain
Expansion + Extraction + 1st acceleration step multiaperture grid (10 apertures):
BP, PG and EG included.
Assumptions-Limitations

• Driver/Injection

The driver is not yet simulated: prescribed ambipolar neutral full-maxwellian flux of plasma particle injected in a thin area located at the driver exit plane.

Following [1], plasma is produced with a rate $w_{\text{ion}} = 3 \times 10^{23} \text{m}^{-3} \text{s}^{-1}$

- 56% H$_2$\textsuperscript{+} via direct ionization of H$_2$
- 44% H\textsuperscript{+} ion production by 2 channels: dissociative ionization of H$_2$ and direct ionization of H.

Full maxwellian distribution:

$T_e = 12 \text{ eV}$ $T_{\text{H}^+} = 1 \text{ eV}$ $T_{\text{H}_2^+} = 1 \text{ eV}$

Assumptions-Limitations

• **Driver/Injection**

• **Geometry**

2.5D cartesian geometry - 2D(y,z) electrostatic \(^1\)

Particle tracked in x (magnetic filter field direction) but quantity considered uniform \((E_x=0)\)

Particle-wall interaction are considered assuming thin-sheath approximation;

A secondary electron emission coefficient \(\gamma=0.2\) has been assumed

We are interested in \(E_x B\) and diamagnetic drifts

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

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\(^1\) Poisson equation solver: http://www.mcs.anl.gov/petsc/petsc-as/
Assumptions-Limitations

• Driver/Injection

• Geometry

Scaled model: \( \varepsilon_0' = 25 \varepsilon_0 \Rightarrow \Delta t' = 5 \Delta t; \)
\( \Delta z' = 5 \Delta z \)

It allows keeping the detailed mesh of one-aperture model
The aperture (D=10 mm, flat) contains 25 cells;
The gap between each aperture is G=20 mm.
Assumptions-Limitations

- **Driver/Injection**
- **Geometry**
- **Input data**
  - Filter field: bell shaped $z$-profile with $z_{\text{max}}=3$ cm from PG and $B_{x,\text{max}}=7$ mT (standard configuration)
  - Electron deflection field: prescribed 2D($y,z$) map with alternating $y$-direction for adjacent apertures
  - Fixed $H$ and $H_2$ density with vibrational Boltzmann distribution
Assumptions-Limitations

• Driver/Injection
• Geometry
• **Input data**
  - Most relevant collisions included
  - Self-consistent production of volume H- and surface by ion conversion [1]

\[ Y(E) = \frac{R \eta_0}{E} \left( E - \frac{E_{th}}{R_E} \right) \]

- Fixed current density \( J=660 \text{ A/m}^2 \) of surface-produced H- by neutral conversion; uniformly launched along y at PG with half-Maxwellian distribution \( T=0.8 \text{ eV} \)

\[ J_{H-,0}=660 \text{ A/m}^2 \]

Simulation parameters-Performances

- $\Delta t = 2.5 \times 10^{-11}$ s
- $\Delta x = 4 \times 10^{-4}$ m $\sim 3\lambda_{D,\text{min}}$ (minimum Debye length found in the domain $\lambda_{D,\text{min}} = 1.3 \times 10^{-4}$ m) $\Rightarrow$ $N_g = N_y \times N_z = 1450 \times 589$
- $N_{\text{part}} = 2 \times 10^8 \Rightarrow N_{\text{part}} \times \text{cell} = 200$ ($w = 2 \times 10^8$)
- OpenMP/MPI hybrid paradigm
- 5 $\mu$s/day @ 8 Intel Xeon E5-2650Lv2 10-core CPU
- $T_{\text{tot}} = 100$ $\mu$s.
Results: The electron flux

Co-extracted electron current evolution has an intermittent behavior due to a turbulent transport across the filter typical of low pressure discharges (Magnetron, Hall-effect thruster, etc.);

The electron flow exhibits a quite complex distribution. First, they are drained towards the bottom wall due to diamagnetic drift ($v_y = \nabla P \times B$). Here, a grazing electron flow is established: the unbalanced negative charge generates an ambipolar electric field along y-direction (short-circuit effect) which in turn induce a transport across the filter field lines through the ExB drift.

Although the total diffusion must be ambipolar, the one-dimensional part of the losses need not be ambipolar: ions diffuse almost uniformly inside the source, while electrons diffuse primary along x and y. Furthermore, a strong asymmetrical flux is collected on PG.
Results: Electric Potential / Electron Density / Electron Temp
Extraction: aperture by aperture - $J_e$

impossible to reproduce this dynamical information in one-aperture model

<table>
<thead>
<tr>
<th>$J_e$ (A/m$^2$)</th>
<th>$J_{H^-}$ (A/m$^2$)</th>
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<tr>
<td>1.6</td>
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<tr>
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<td>808</td>
<td>146</td>
</tr>
<tr>
<td>9200</td>
<td>231</td>
</tr>
</tbody>
</table>

5 cm from PG
Extraction: aperture by aperture: $J_{H^-}$

good uniformity -> suitable conditions for monoaperture models
-> indirect proof of the fundamental role of atomic conversion on PG
Alternative solution to solve the problem of inconsistency of extraction models:
First attempt to develop a 2.5D PIC-MCC model of the full-size source with detailed extraction region

Results show:
- non-ambipolar character of the diffusion across B-filter
- leading role of magnetic drifts (diamagnetic and ExB)
- asymmetry with dynamical and non-omogeneous plasma conditions at every apertures
- the most important formation mechanism is by neutral conversion and the negative ion extraction is uniform
- 23% of the surfaced-produced negative ions is extracted

Future works are:
- speed-up the execution of the code by programming optimization….we still have margins of improvements (allow increasing the number of cells by a factor 3x3 … the number of particles x cell is already fine)
- load D$_2$ cross-sections database
- magnetic filter field optimization