Modeling negative ion kinetics in a PIC-MCC algorithm

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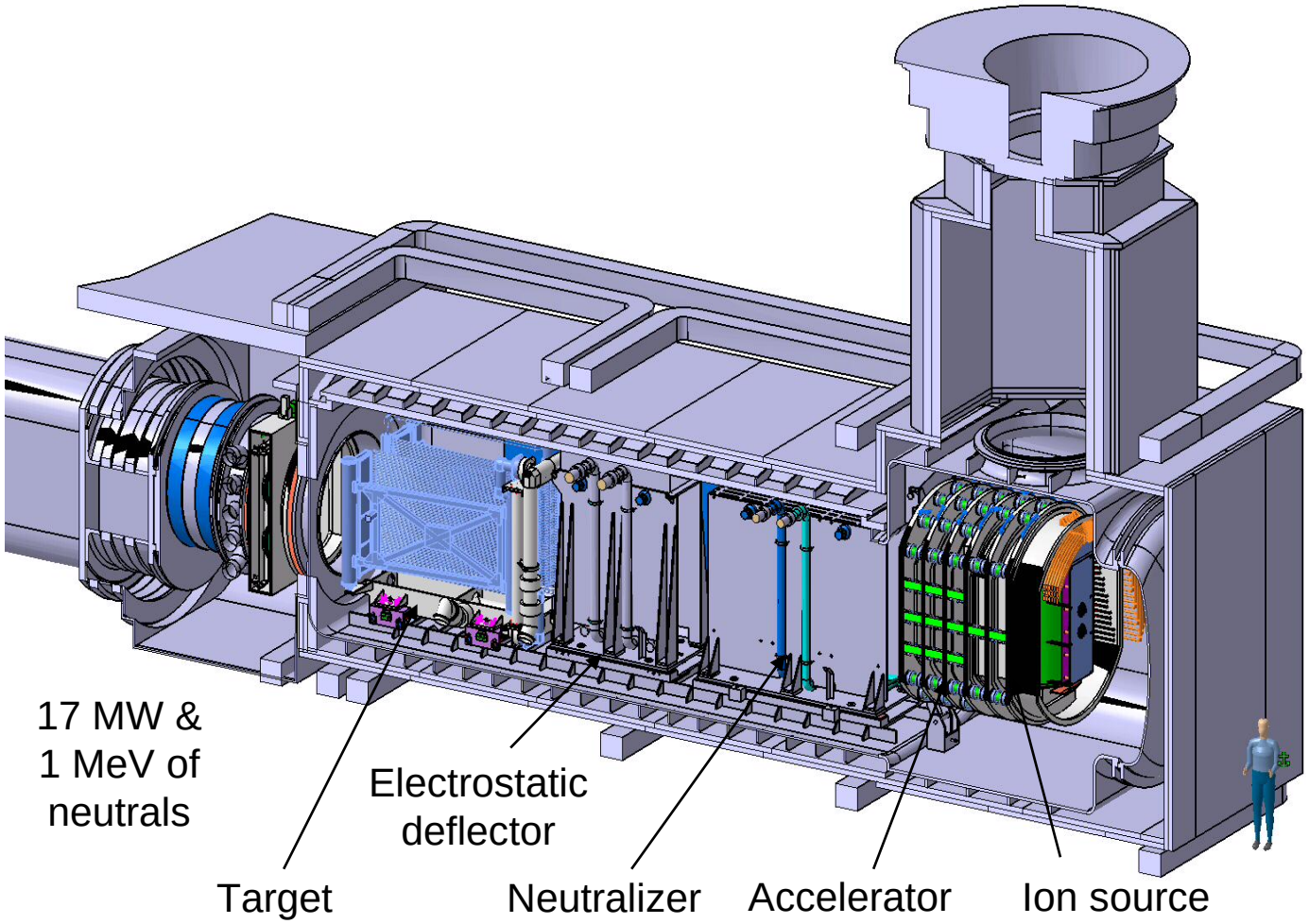
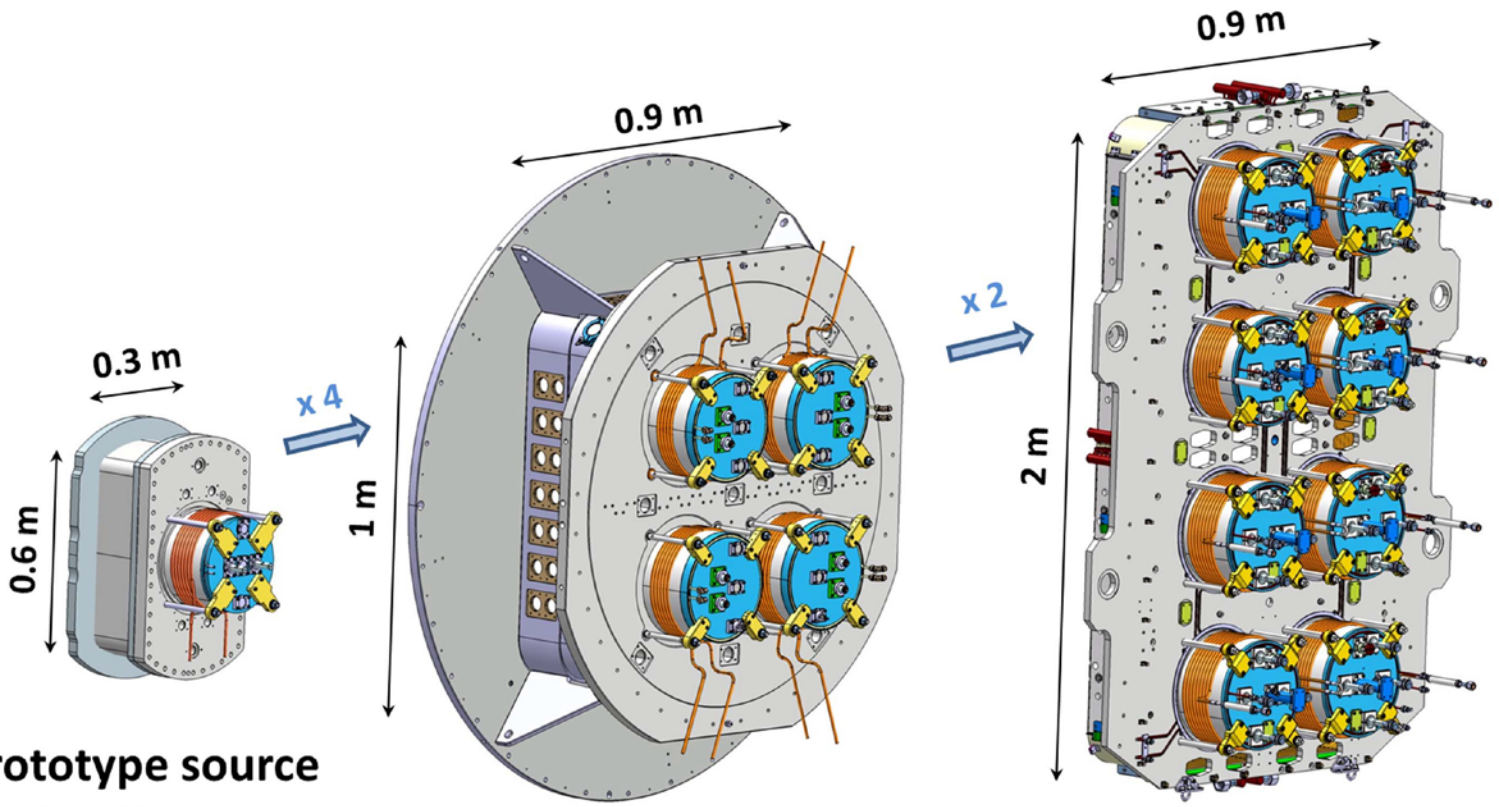
Scope: ITER Neutral beam injector (NBI)



Scope: Negative ion sources for fusion applications

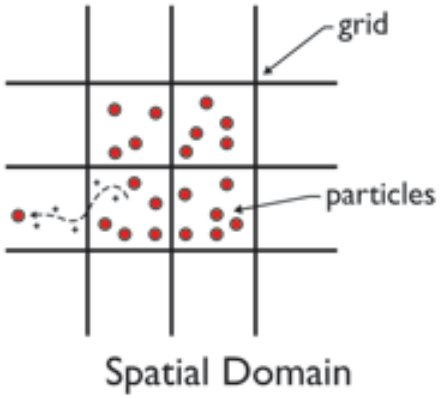


Prototype source
BATMAN (5 s)
MANITU (cw plasma, pulsed beam)

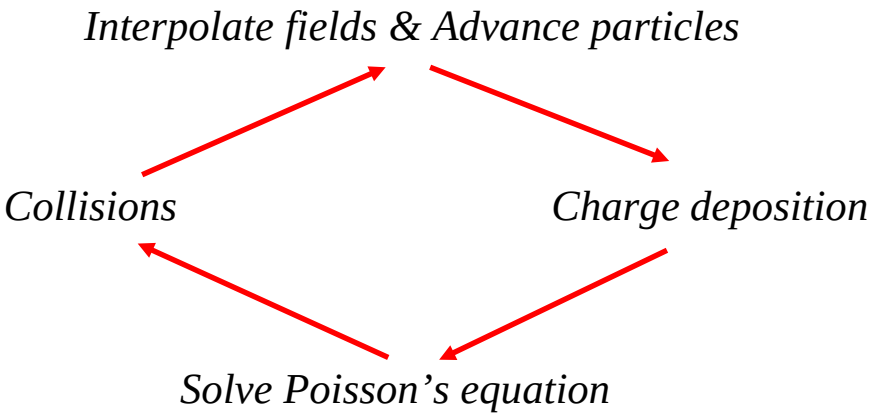
ELISE (with beam)
RADI (without beam)

SPIDER
MITICA
HNB, DNB

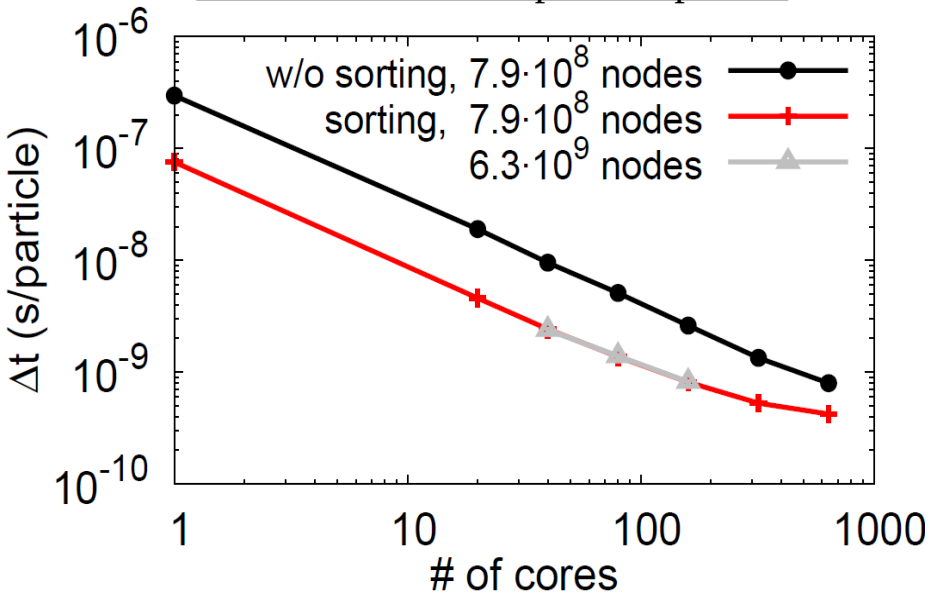
Numerical model: Particle in Cell (PIC) with Monte-Carlo-Collisions (MCC)



- The model is fully “homemade”
- Parallelized (hybrid MPI and OpenMP)
- Poisson solver is a multi-grid (geometric)
- Magnetic field is prescribed



Performance of the particle pusher



Physical chemistry of hydrogen including negative ions

- Vibrational excitation of H_2 needs a high T_e (~10 eV)
- Dissociative attachment of H_2 (#17, table I) occurs for T_e ~1 eV

~60 reactions implemented in the PIC-MCC model

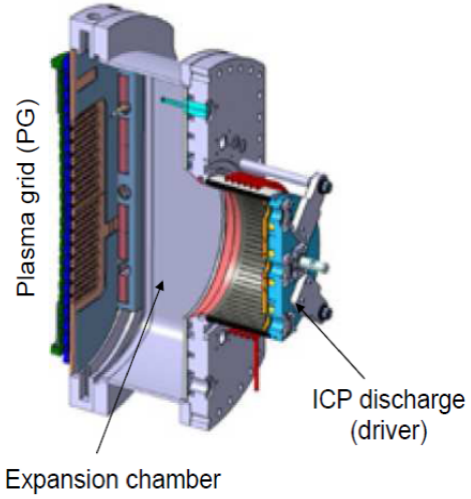
Table 1. Electron collisions.

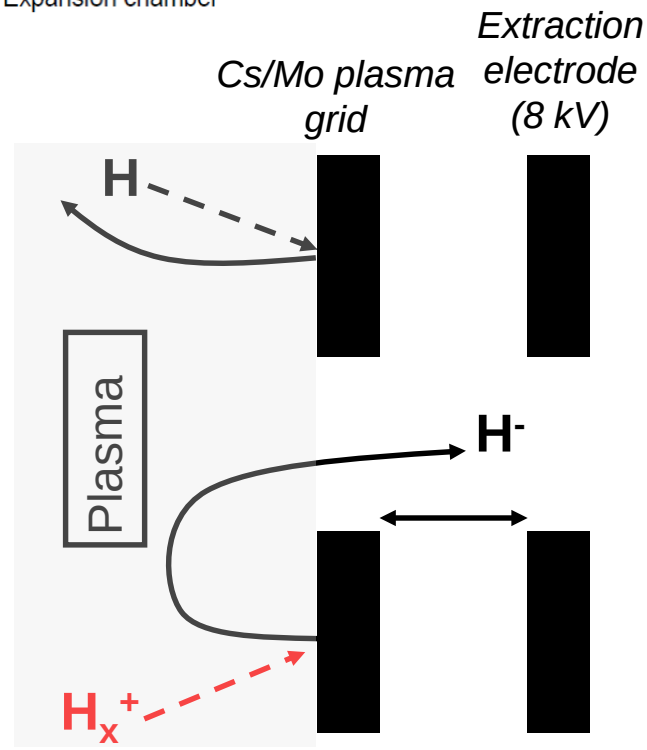
#	Reaction	Cross section reference
1	$e + H \rightarrow e + H$ (elastic)	[71–75]
2	$e + H \rightarrow e + H$ (inelastic, 4 proc.)	[32]
3	$e + H \rightarrow 2e + H^+$	[32]
4	$e + H_2 \rightarrow e + H_2$ (elastic)	[76]
5	$e + H_2 \rightarrow 2e + H_2^+$	[32]
6	$e + H_2 \rightarrow 2e + H^+ + H$ (2 proc.)	[32]
7	$e + H_2 \rightarrow e + H_2$ (inelastic, 16 proc.)	[32–38]
8	$e + H_2 \rightarrow e + 2H$ (3 proc.)	[32, 77]
9	$e + H_3^+ \rightarrow 3H$	[32]
10	$e + H_3^+ \rightarrow H + H_2$	[32]
11	$e + H_3^+ \rightarrow e + H^+ + 2H$	[32]
12	$e + H_3^+ \rightarrow e + H^+ + H_2$	[32]
13	$e + H_2^+ \rightarrow 2H$	[32]
14	$e + H_2^+ \rightarrow e + H^+ + H$ (2 proc.)	[32, 77]
15	$e + H_2^+ \rightarrow 2e + 2H^+$	[77]
16	$e + H^- \rightarrow 2e + H$	[32]
17	$e + H_2^* \rightarrow H^- + H$ (1% of H_2)	[77]
18	$e + H_2^+ \rightarrow e + H_2^+$	(Coulomb) [22]
19	$e + H^+ \rightarrow e + H^+$	(Coulomb) [22]
20	$e + H_3^+ \rightarrow e + H_3^+$	(Coulomb) [22]

Table 2. Heavy particle processes.

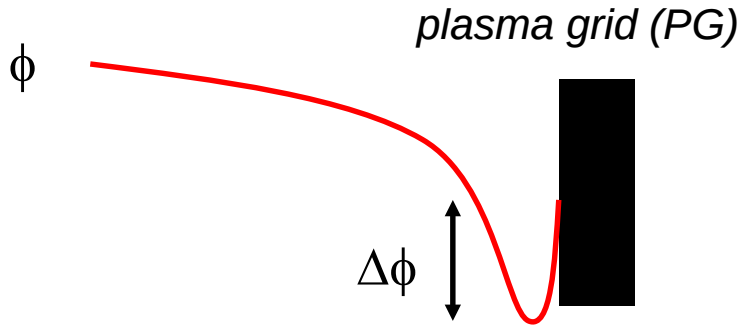
#	Reaction	Cross section reference
1	$H_3^+ + H_2 \rightarrow H_3^+ + H_2$ (elastic)	[78]
2	$H_3^+ + H \rightarrow H_3^+ + H$ (elastic)	
3	$H_2^+ + H_2 \rightarrow H_3^+ + H$	[43, 78]
4	$H_2^+ + H_2 \rightarrow H_2 + H_2^+$	[78]
5	$H_2^+ + H \rightarrow H_2^+ + H$ (elastic)	[79]
6	$H^+ + H \rightarrow H + H^+$	[80]
7	$H^+ + H \rightarrow H^+ + H$ (elastic)	[80]
8	$H^+ + H_2 \rightarrow H^+ + H_2$ (elastic)	[78]
9	$H^+ + H_2 \rightarrow H^+ + H_2$ (inelastic, 4 proc.)	[41–43, 78]
10	$H^- + H \rightarrow e + 2H$	[32]
11	$H^- + H \rightarrow e + H_2$	[32]
12	$H^- + H_2 \rightarrow H^- + H_2$ (elastic)	[43]
13	$H^- + H \rightarrow H^- + H$ (elastic)	[43]
14	$H^+ + H^- \rightarrow 2H$ (2 proc.)	[32]
15	$H^+ + H^- \rightarrow H_2^+ + e$	[32]
16	$H^- + H_2 \rightarrow H_2 + H + e$	[32]
17	$H^- + H \rightarrow H + H^-$	[81]
18	$H + H \rightarrow H + H$	[80]
19	$H + H_2 \rightarrow H + H_2$	[80]
20	$H_2 + H_2 \rightarrow H_2 + H_2$	[82]

Production of negative ions on surfaces



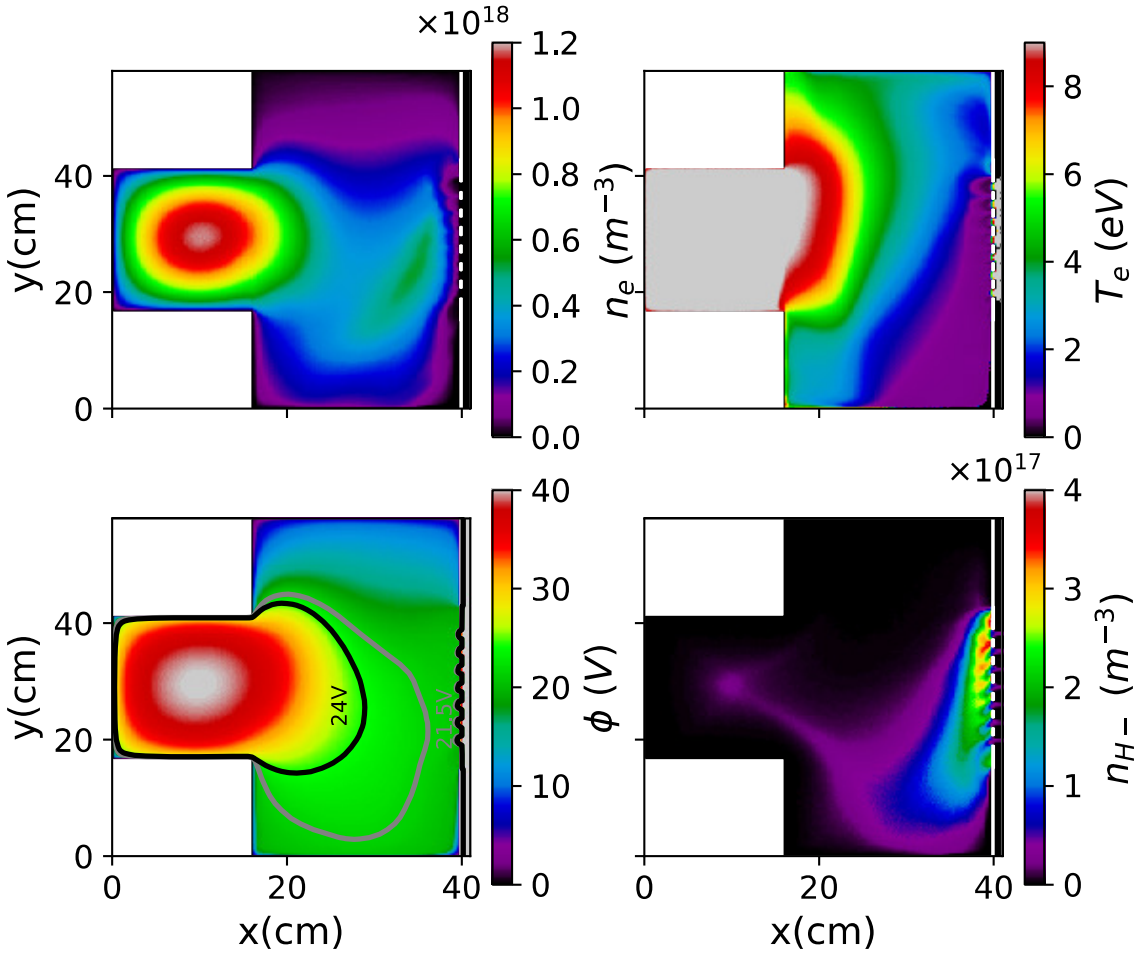


- High brightness negative ion beams are produced on the plasma grid (PG) surface
- Cesium is added to lower the metal work function (typically Cs/Mo converters)
- A high negative ion current emitted from the PG surface may be space charge limited:
  - Formation of a virtual cathode
  - A large chunk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

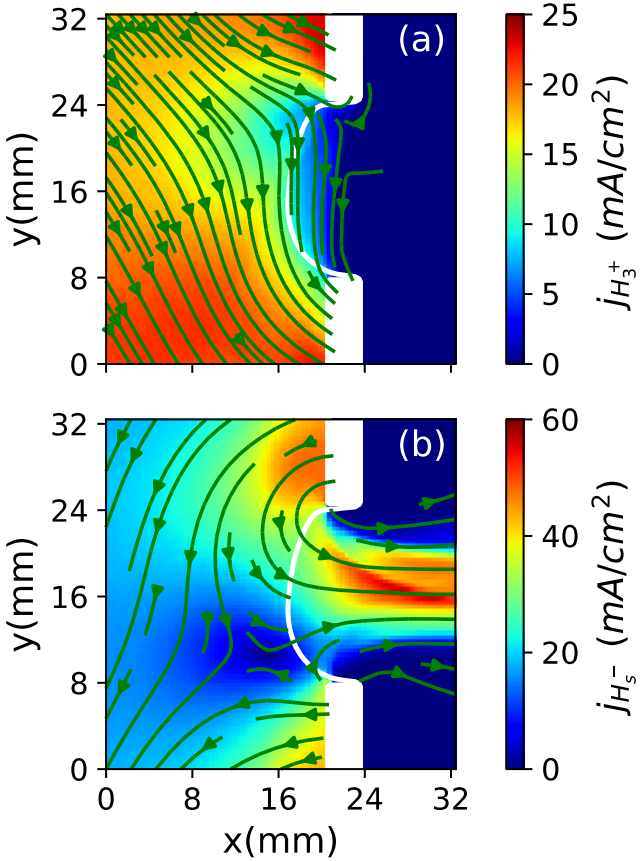


G. Fubiani *et al.*, Phys. of Plasmas **25** (2018)
G. Fubiani *et al.*, New Journal of Physics **19** (2017)

Examples: plasma properties of a fusion-type negative ion source

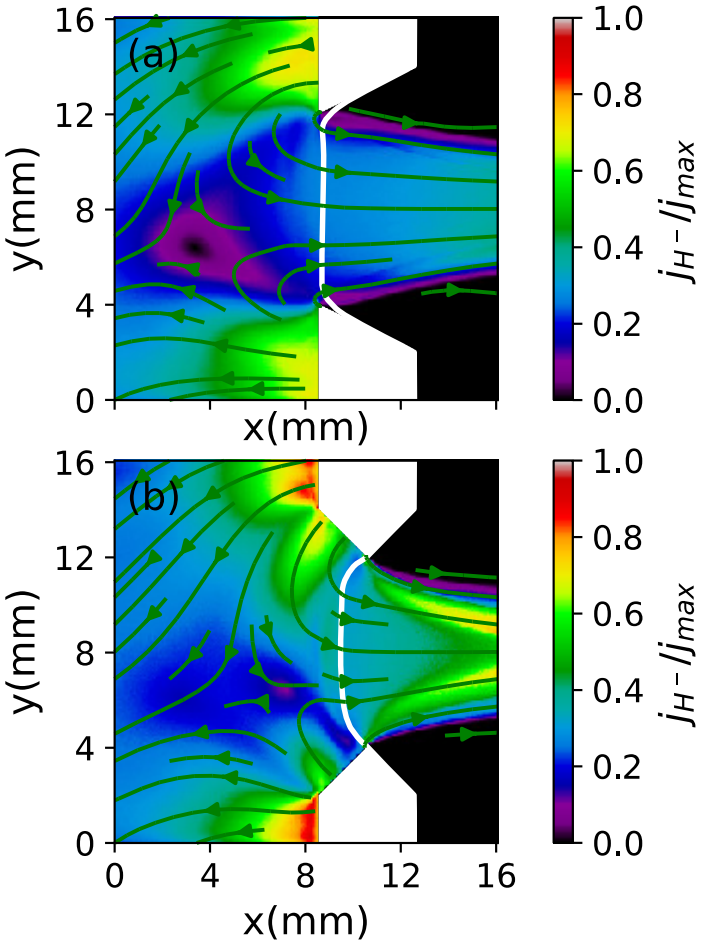


Zoom near one aperture



Negative ions produced in volume account for 10 to 20% of the total amount extracted

Examples: Modeling negative ion extraction; chamfered vs. bevel *slit* apertures geometries

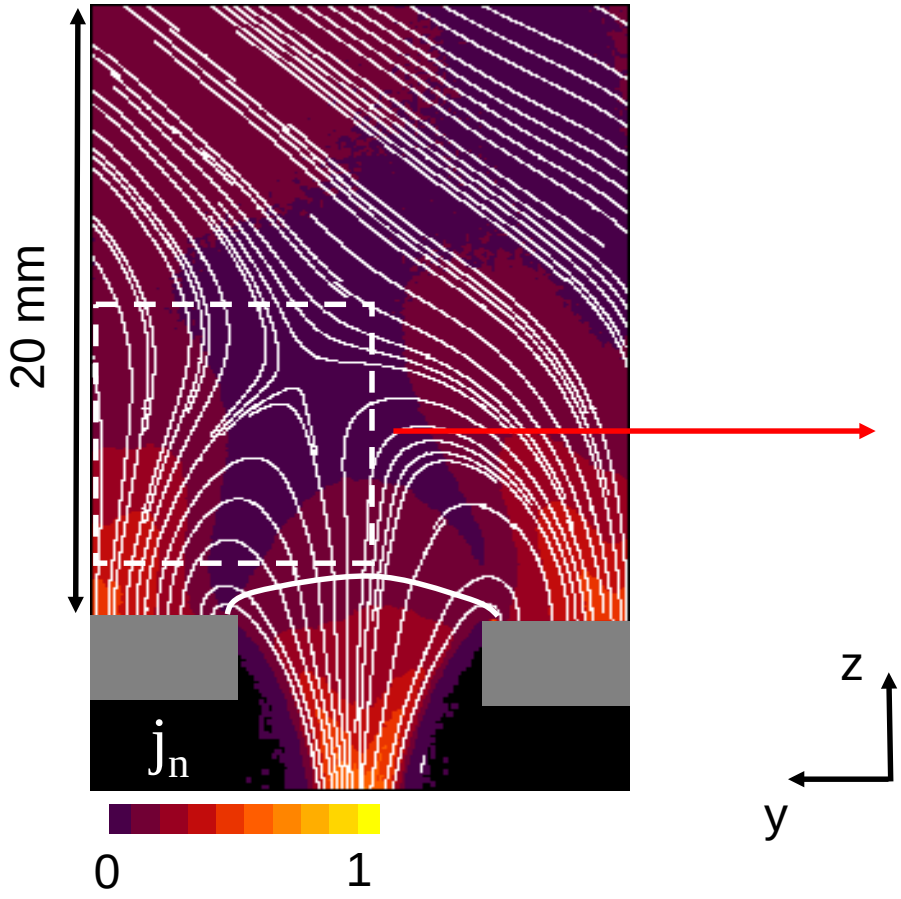


- Extracted negative ion current is *somewhat proportional* to the grid surface area facing the plasma
- In agreement with the experiments*
- Aberrations are generated on the chamfered surface
- Need a 4096×2048 mesh nodes to properly resolve the virtual cathode ($<n_p>= 3.10^{17}$ m^{-3})

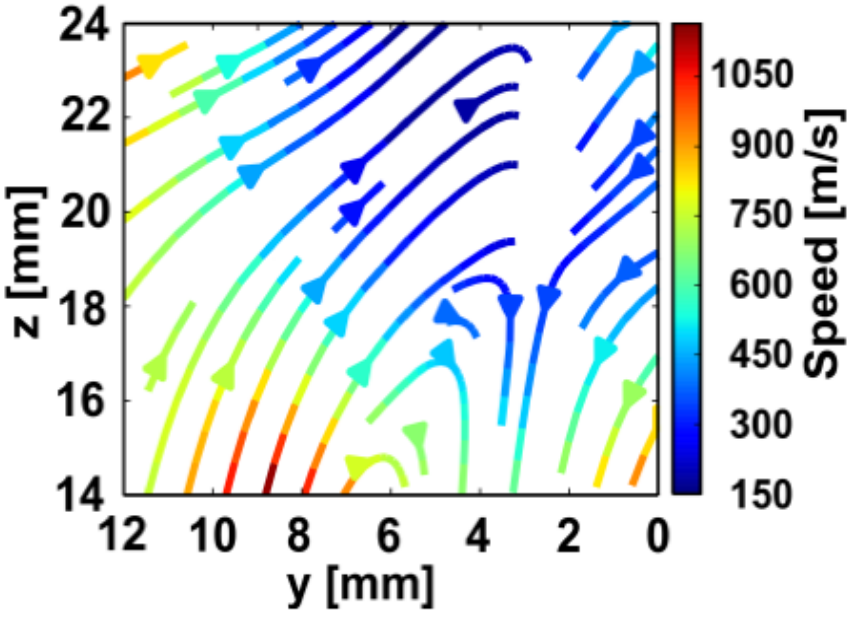
*M. Kashiwagi et al., Rev. Sci. Instrum. **85**, 02B320 (2014)

Examples: Model prediction vs. experiments

Negative ion flux calculated by the model



Negative ion flux measured experimentally



Courtesy of Tsumori et al., NIFS, Japan

Slight magnetization of the negative ions affect the beamlet current density profile