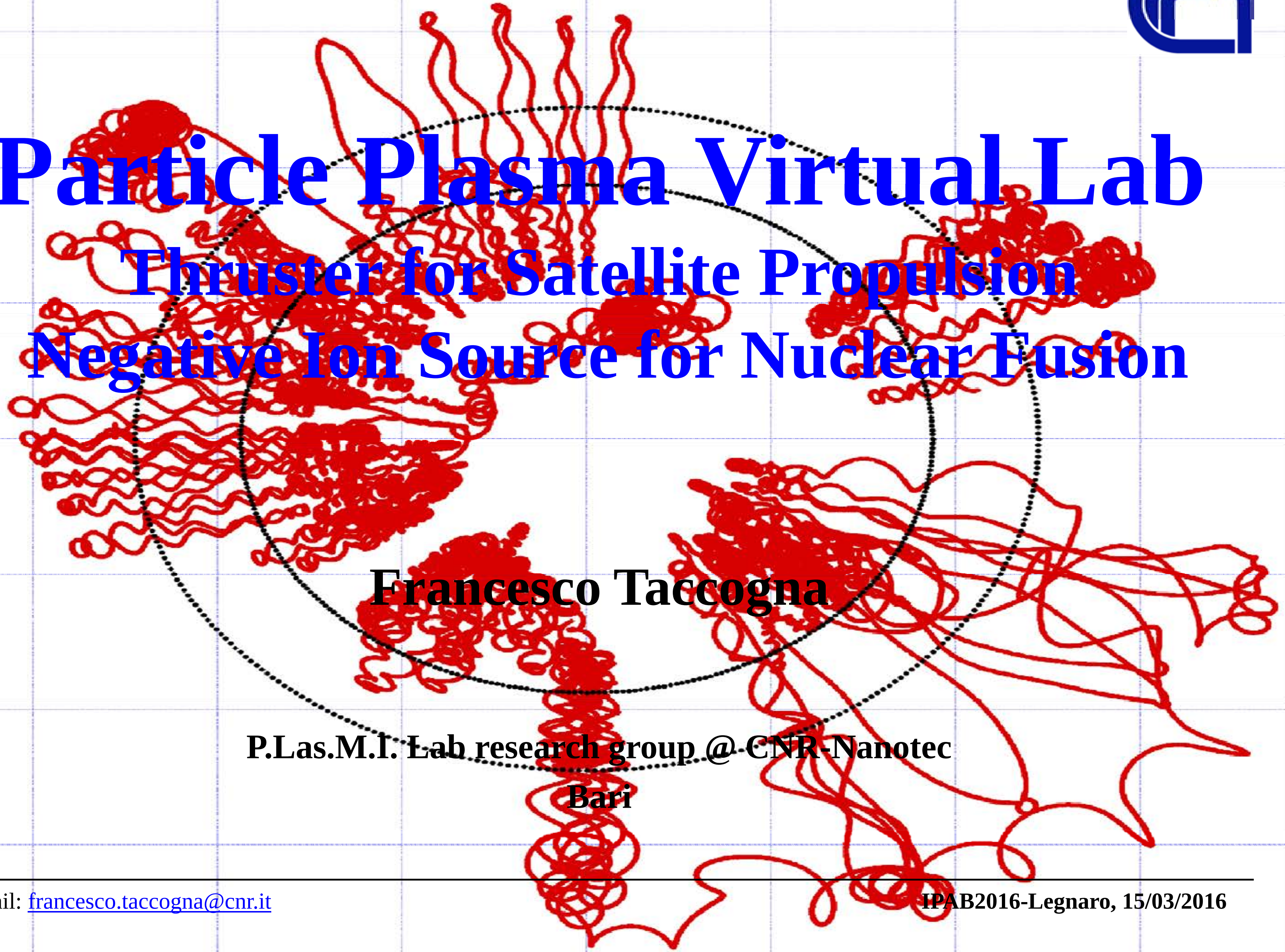

Particle Plasma Virtual Lab

Thruster for Satellite Propulsion
Negative Ion Source for Nuclear Fusion

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IPAB2016-Legnaro, 15/03/2016

Key-words

o **Particle-based kinetic representation of plasma-gas system: non-equilibrium ➔ distribution functions**

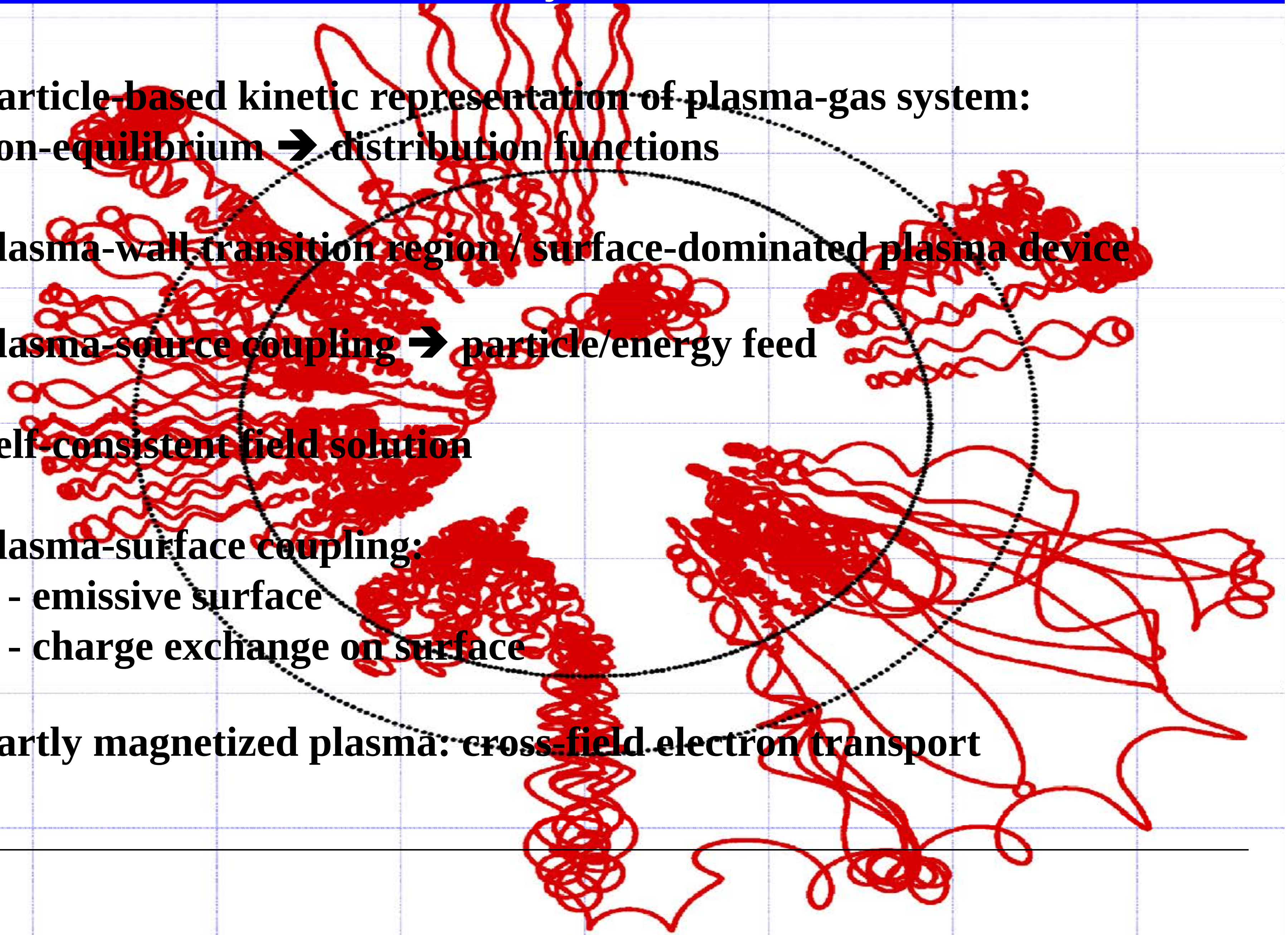
o **Plasma-wall transition region / surface-dominated plasma device**

o **Plasma-source coupling ➔ particle/energy feed**

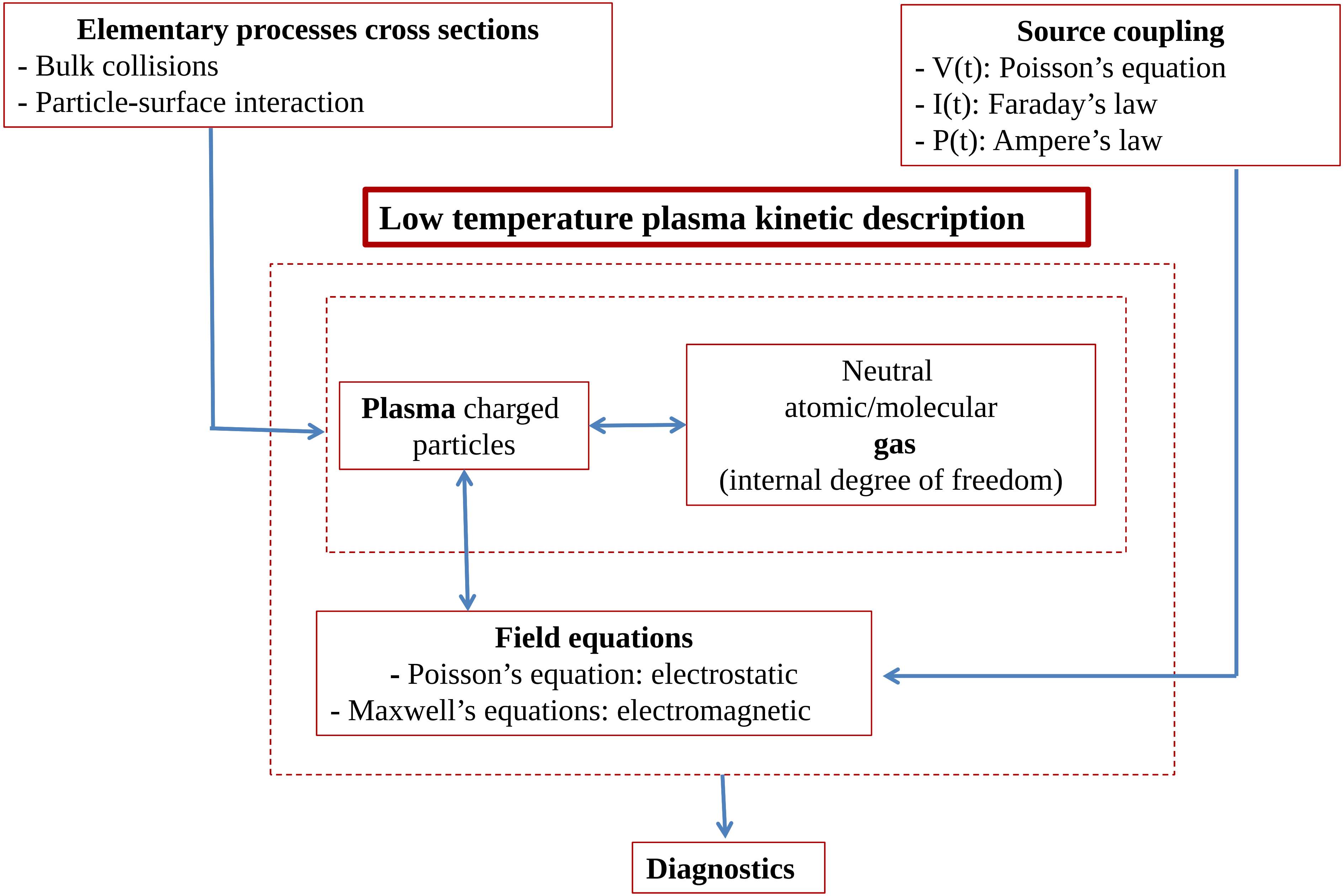
o **Self-consistent field solution**

o **Plasma-surface coupling:**
- **emissive surface**
- **charge exchange on surface**

o **Partly magnetized plasma: cross-field electron transport**



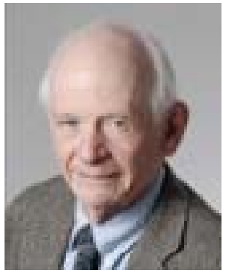
The IDEAL Plasma Model (less possible free parameters)

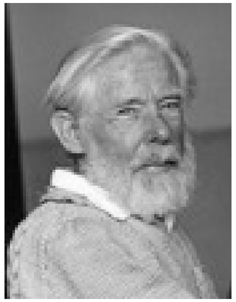


Particle-in-Cell Basics: Mathematical Formulation

- Solution of Boltzmann + Maxwell eqs.


Dawson


Birdsall


Buneman

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v}\cdot\frac{\partial f_\alpha}{\partial \mathbf{r}} + \frac{\mathbf{F}_\alpha}{m_\alpha}\cdot\frac{\partial f_\alpha}{\partial \mathbf{v}} = \left(\frac{\partial f_\alpha}{\partial t}\right)_c \Rightarrow \frac{\partial f_\alpha}{\partial t} - \mathrm{D}f_\alpha = \mathrm{J}f_\alpha$$

$$\mathbf{F}_\alpha = q_\alpha(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

$$\rho(t,\mathbf{r}) = \sum_\alpha q_\alpha \int f_\alpha(t,\mathbf{r},\mathbf{v})d\mathbf{v}$$

$$\mathbf{j}(t,\mathbf{r}) = \sum_\alpha q_\alpha \int f_\alpha(t,\mathbf{r},\mathbf{v})\mathbf{v}d\mathbf{v}$$

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon_0\mu_0}\nabla\times\mathbf{B} - \frac{\mathbf{j}}{\varepsilon_0} \qquad \nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \qquad \nabla\cdot\mathbf{B} = 0$$

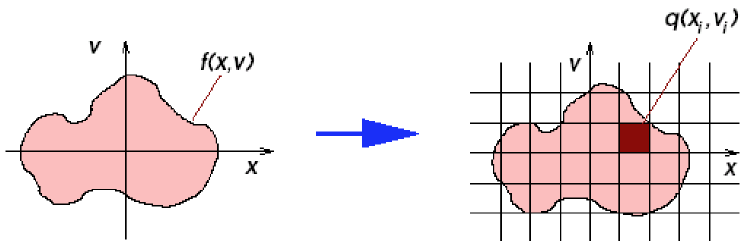
- Particle-based (Klimontovich-Dupree discrete) representation of distribution function f:

$$f(t,\mathbf{r},\mathbf{v}) = \sum_{i=1}^{N_p} w_i f_i(t,\mathbf{r},\mathbf{v}) \qquad f_i(t,\mathbf{r},\mathbf{v}) = S\left(\frac{\mathbf{r}-\mathbf{r}_i(t)}{\Delta_i}\right)\delta(\mathbf{v}-\mathbf{v}_i(t))$$

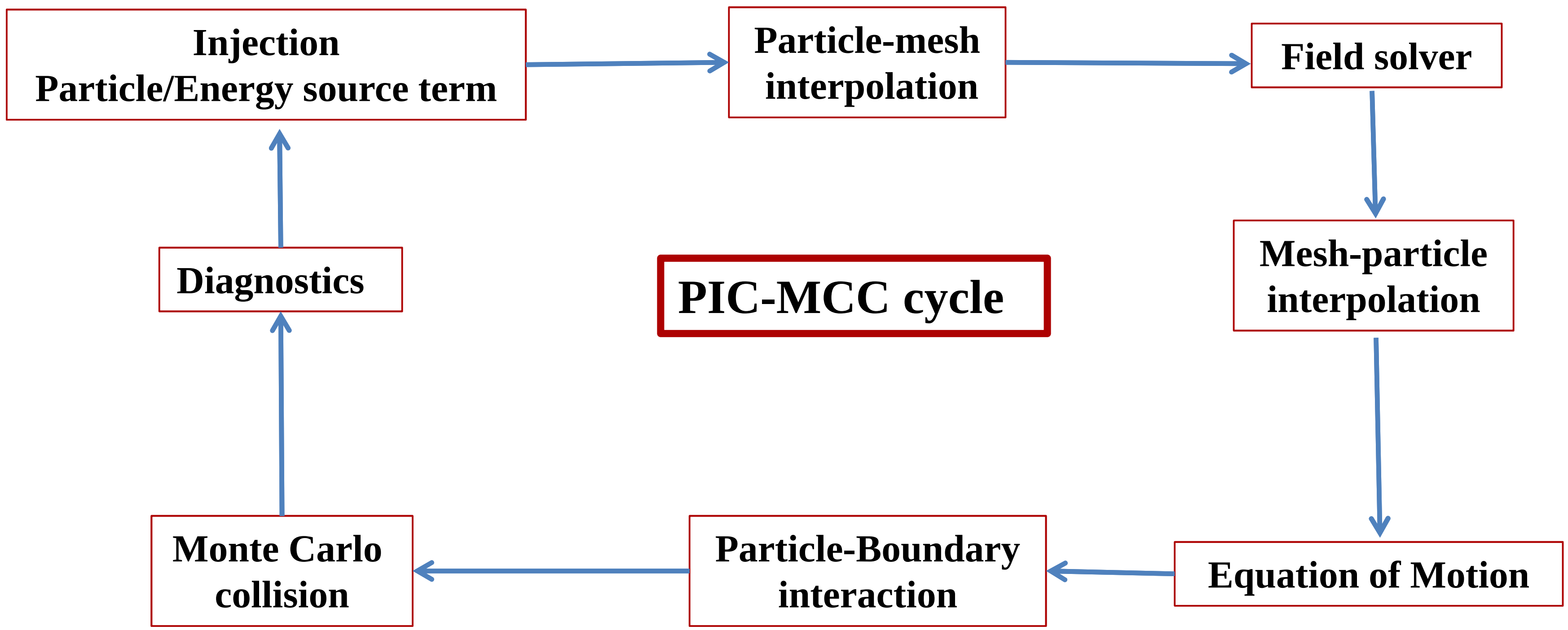
- Substituting gives eq. of motion (characteristics of Boltzmann eq.):

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i; \qquad \frac{d\mathbf{v}_i}{dt} = \frac{q}{m}\left(\mathbf{E}(x_i) + \mathbf{v}_i\times\mathbf{B}(x_i)\right)$$

- Solution of fields on a mesh + interpolation from mesh to particle (mixed eulerian-lagrangian description)
- The macro-particles can be regarded as Lagrangian markers embedded randomly in the Vlasov fluid moving with it through phase space



Particle-in-Cell Basics: the cycle

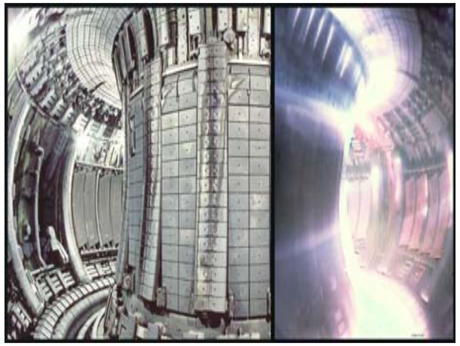


Gas Discharge Ion Source

- Hall-effect thruster
- RF-ICP negative ion source
- Atm-press. and microdischarge
- Microwave discharge

Plasma-wall transition

- Sheath
- Divertor region

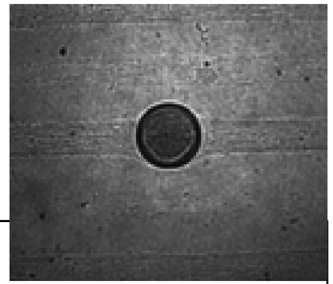


Particle-based Plasma Virtual Lab

Object in Plasma

- Langmuir probe
- dusty plasma
- nanoparticle synthesis in plasma
- supersonic object in plasma
- Solar wind-planet interaction

Laser-Induced Plasma



- plume expansion
- cavitation bubble dynamics
- laser-induced photodetachment

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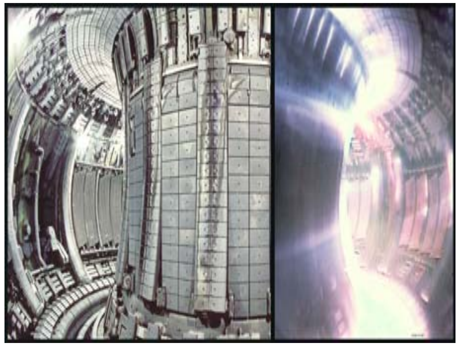

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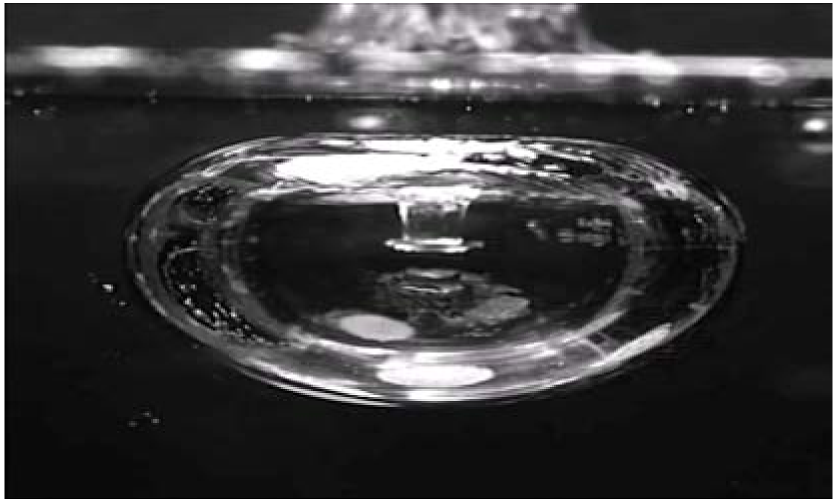

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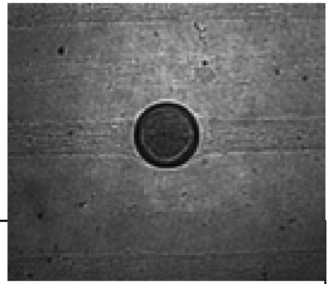

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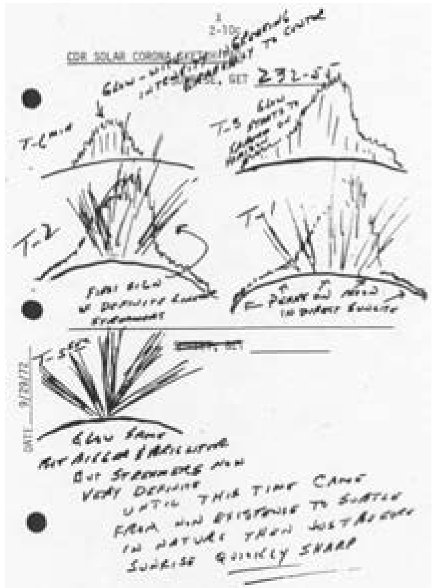

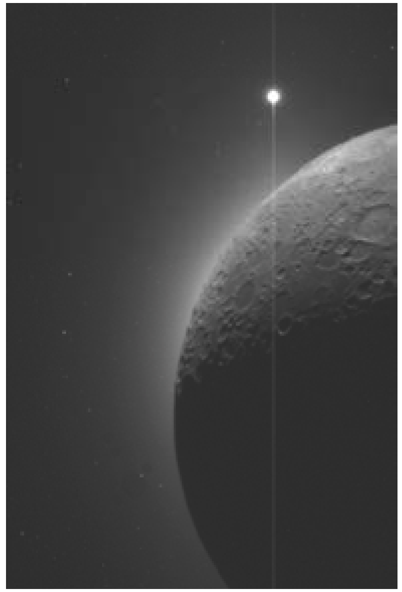

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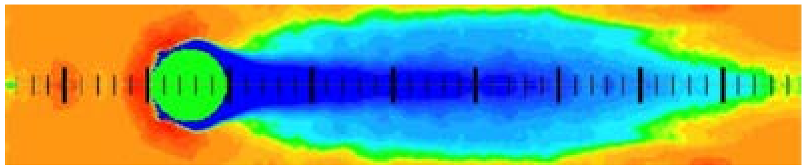

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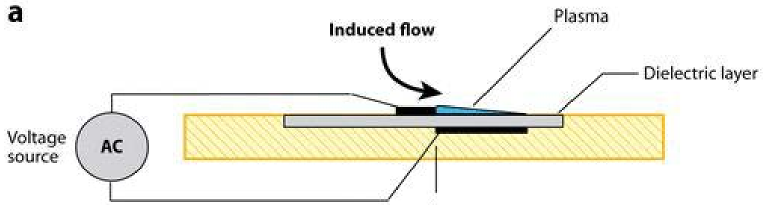

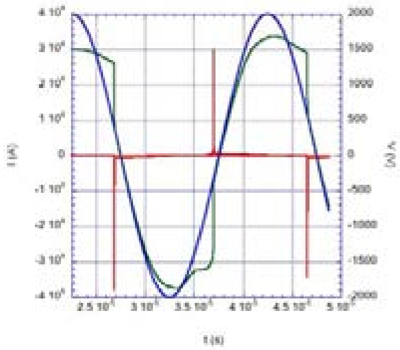

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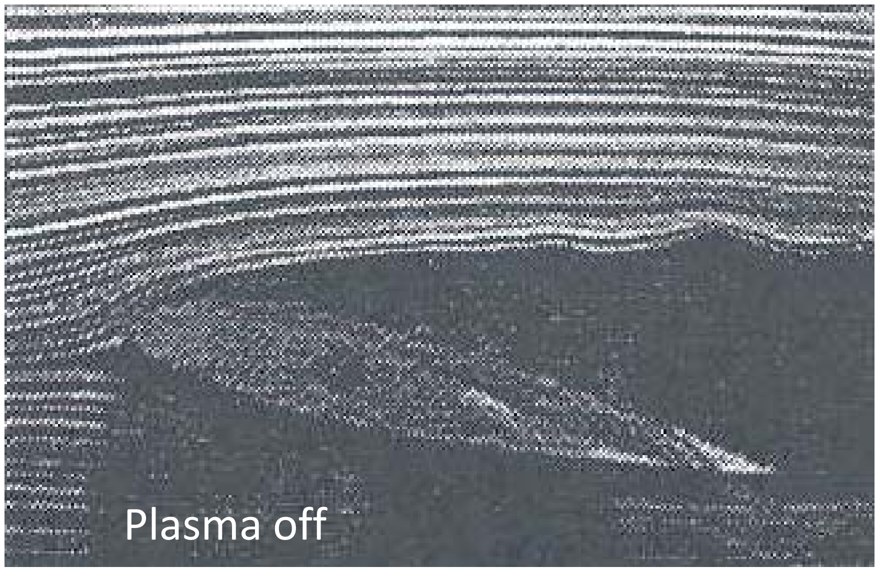
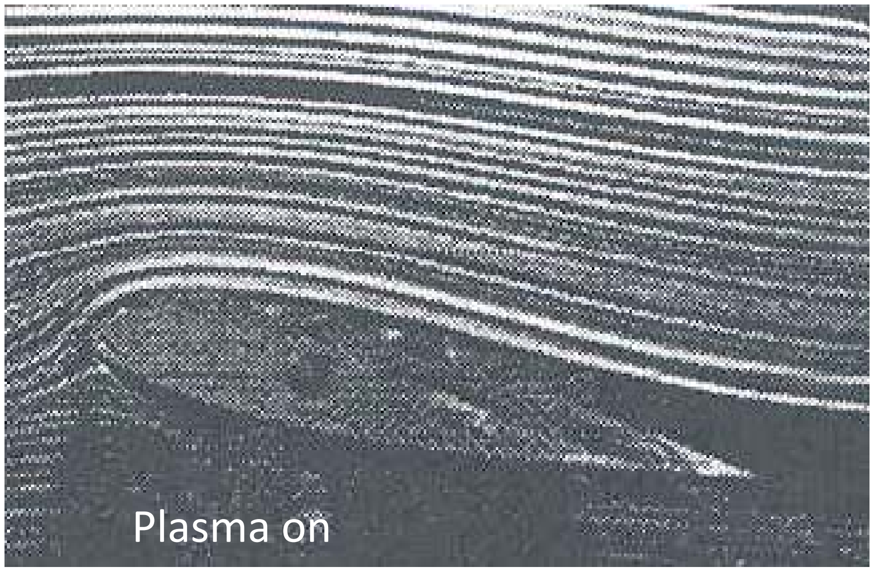




Gas Discharge Ion Source

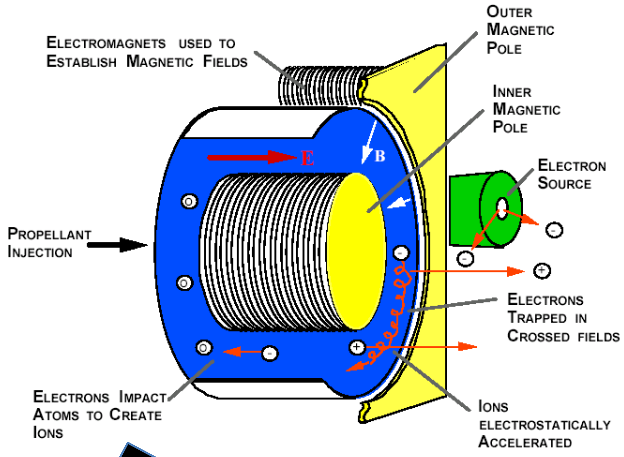
- **Hall-effect thruster**
- **RF-ICP negative ion source**
- Atm-press. and microdischarge
- Microwave discharge

Particle-based Plasma Virtual Lab

SPACE: Hall-Effect thruster

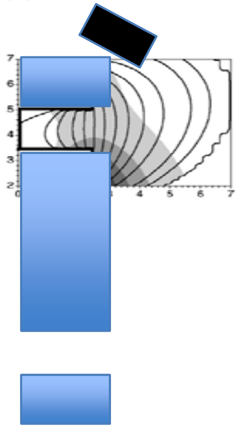
Hall-Effect Thruster

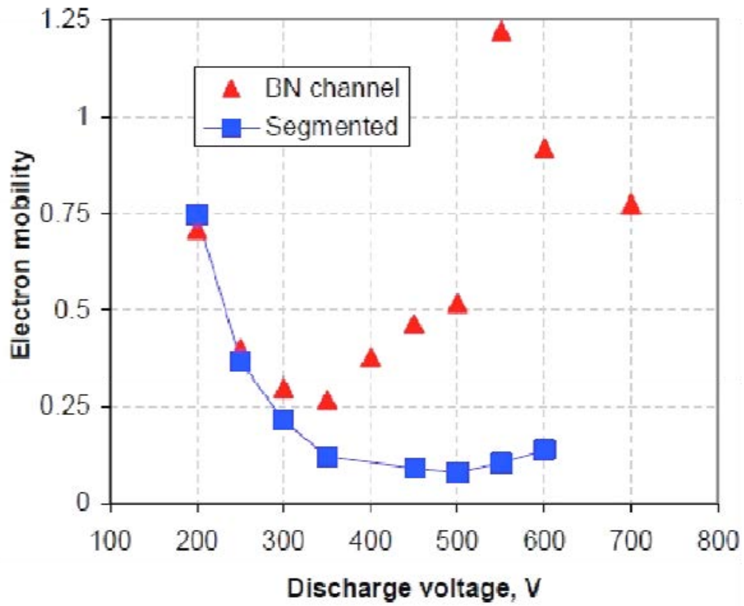
Column length x Inner radius x Outer radius	L=2.5 x R_{in}=3.5 x R_{out}=5 cm
Propellant mass flow rate	$\dot{m}$ = 3 mg/s
Input power	P = 1350 W
Discharge voltage	V_d = 300 V
Discharge current	I_d = 3.2 A
Max radial magnetic field	$B_{r,max}$ = 150 G



RELATED TOPICS

- ❑ Electron xB Transport
- ❑ Secondary Electron Emission
- ❑ Sheath Instability
- ❑ Ion wall erosion
- ❑ Plume divergence
- ❑ Plasma-em signal interference





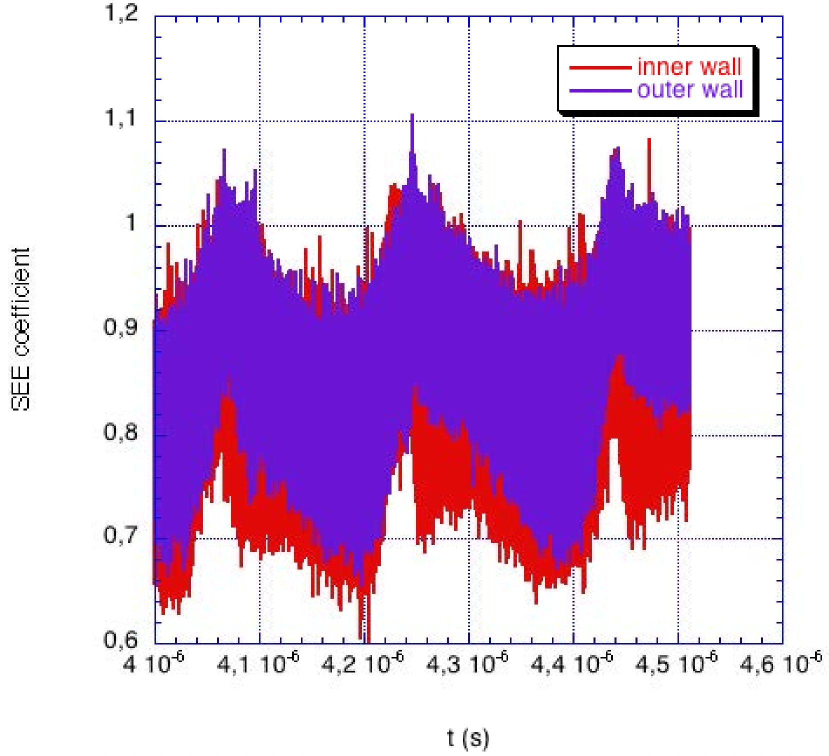
CODES

- ❑ CHANNEL -> 3D PIC (acceleration discharge)
- ❑ NEAR-FIELD PLUME -> 3D PIC (first 10 cm from exhaust)
- ❑ CHANNEL+NEAR-FIELD PLUME -> 3D PIC
- ❑ FAR_PLUME -> 3D Hybrid PIC (plume of single/cluster)

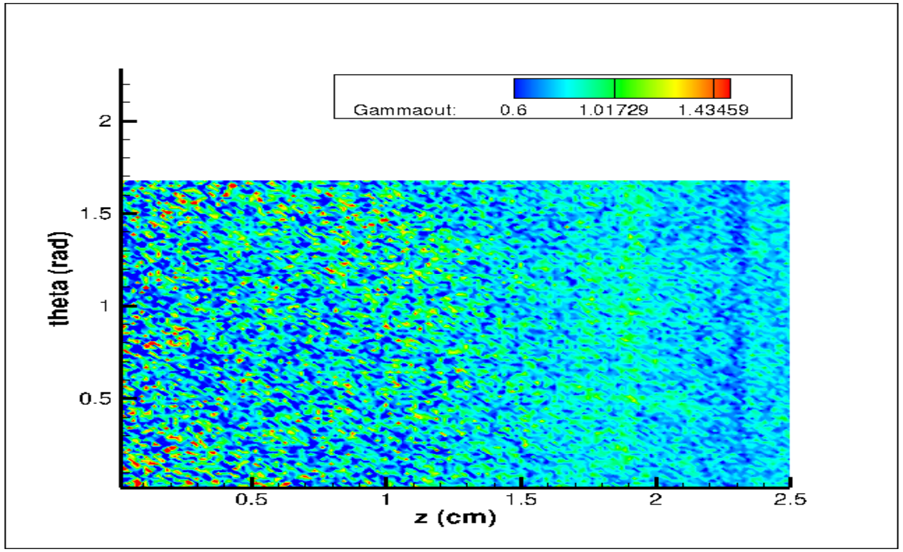
Sheath instability induces azimuthal fluctuations (I)

- ✓ The secondary electron emission coefficient fluctuates in time taking value larger than the critical SCS regime value for very short period.
- ✓ The inner and outer wall value are correlated showing a radial connection between the walls.
- ✓ The period of SEE oscillation is correlated to the radial electron transit time $\Delta t=2\times10^{-7}$ s: electrons emitted from one wall behave like a beam impacting the opposite wall

SEY evolution



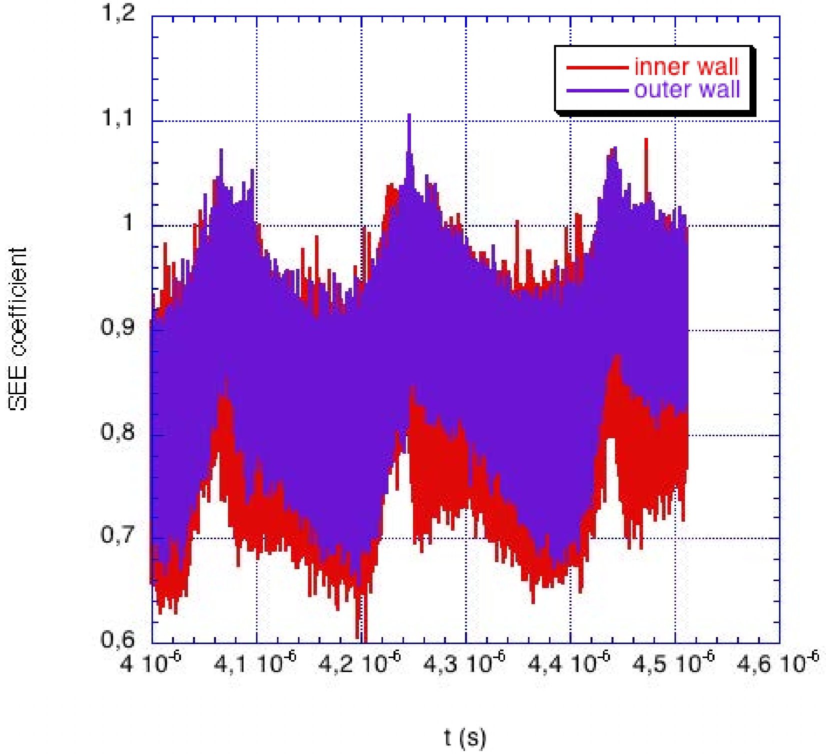
evolution of SEY map @ outer wall



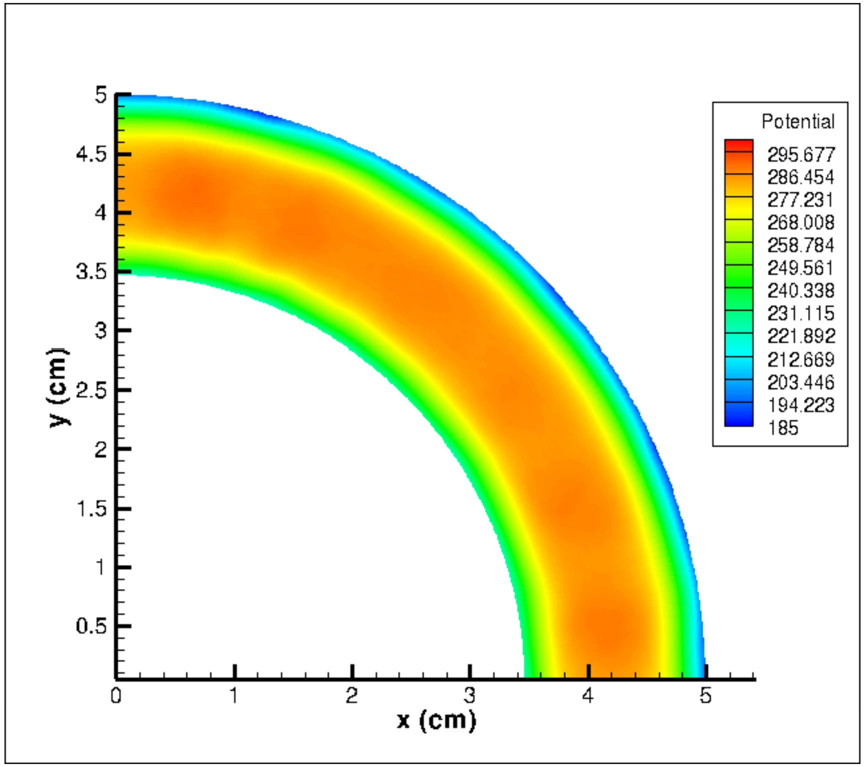
Sheath instability induces azimuthal fluctuations (II)

- ✓ The secondary electron emission coefficient fluctuates in time taking value larger than the critical SCS regime value for very short period.
- ✓ The inner and outer wall value are correlated showing a radial connection between the walls.
- ✓ The period of SEE oscillation is correlated to the radial electron transit time $\Delta t=2\times10^{-7}$ s: electrons emitted from one wall behave like a beam impacting the opposite wall

SEY evolution



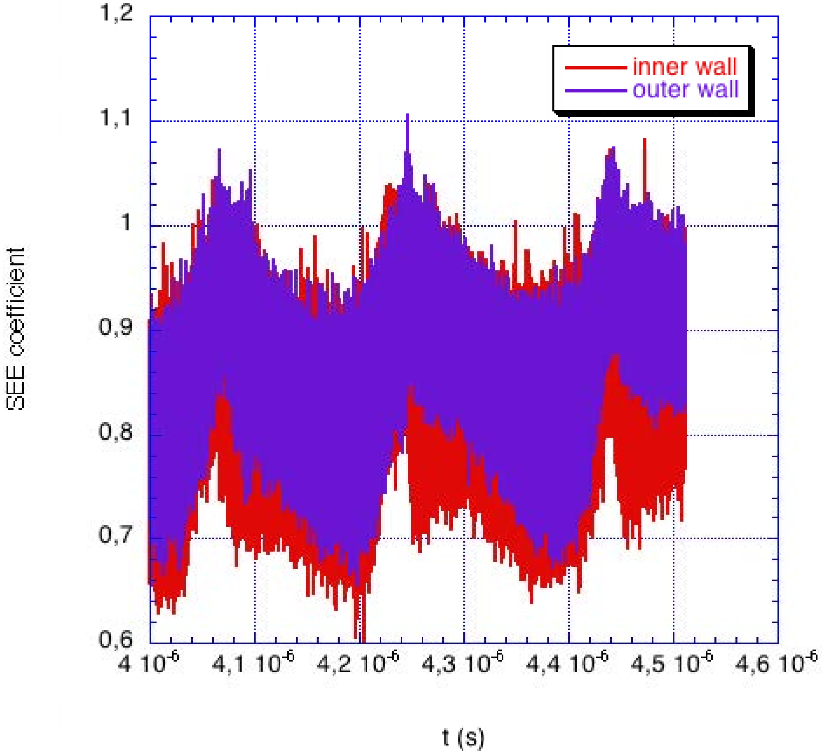
evolution of electric potential in xy map



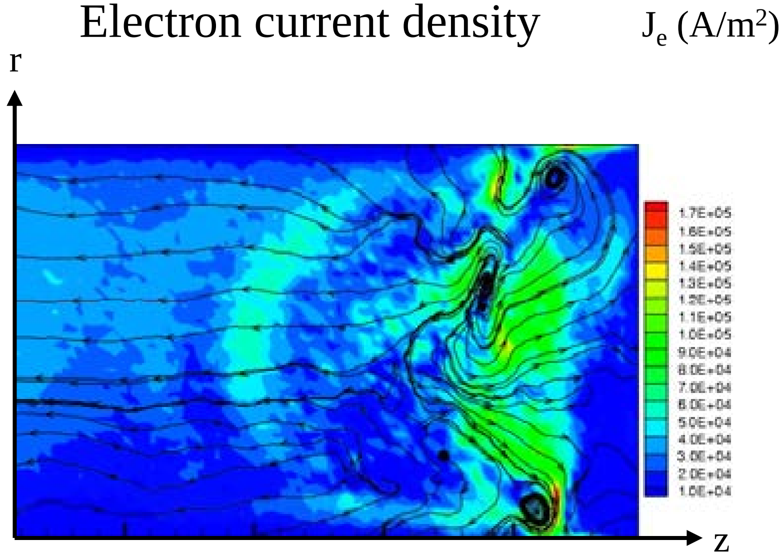
Sheath instability induces azimuthal fluctuations (III)

- ✓ The secondary electron emission coefficient fluctuates in time taking value larger than the critical SCS regime value for very short period.
- ✓ The inner and outer wall value are correlated showing a radial connection between the walls.
- ✓ The period of SEE oscillation is correlated to the radial electron transit time $\Delta t = 2\text{x}10^{-7}$ s: electrons emitted from one wall behave like a beam impacting the opposite wall

SEY evolution

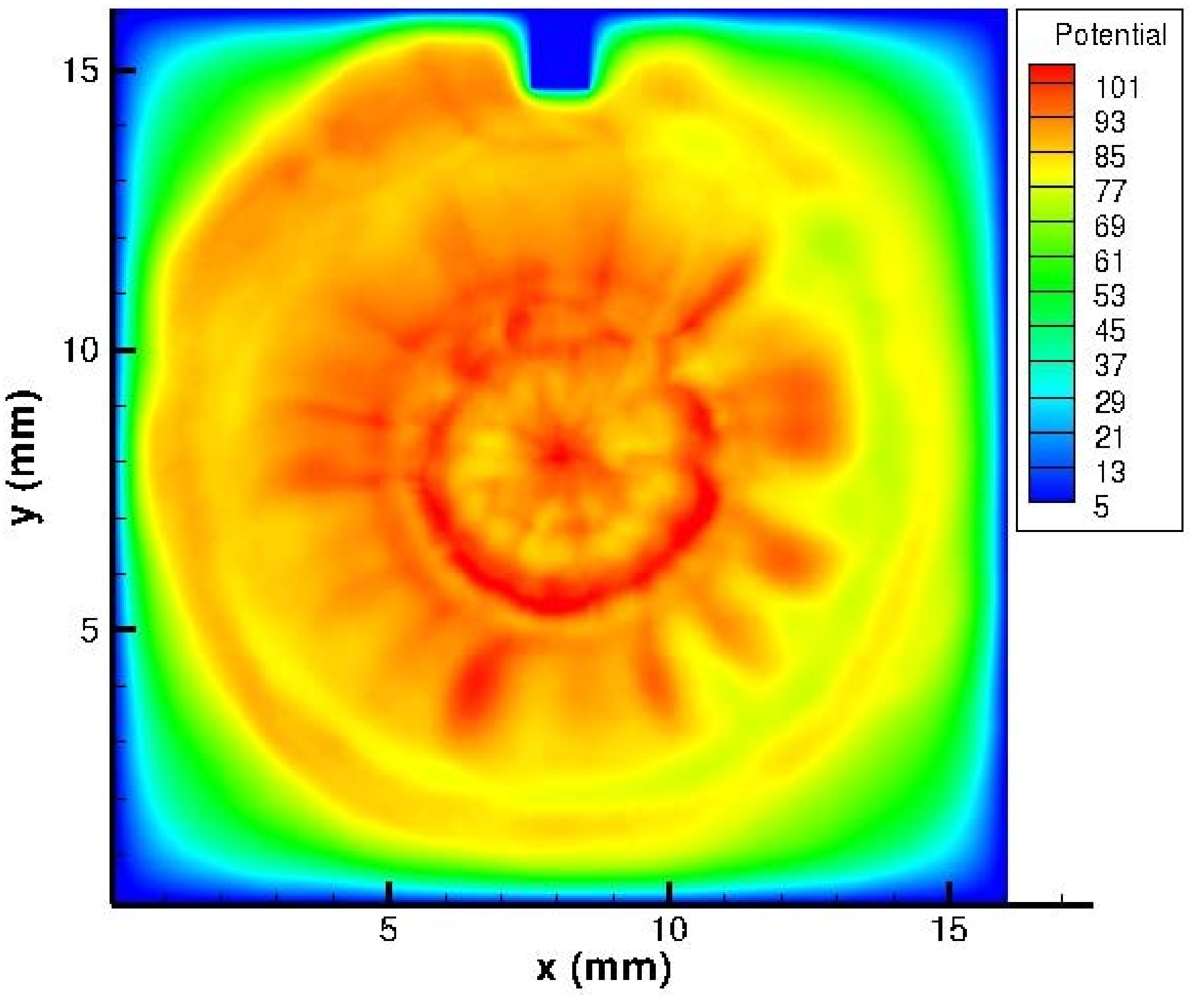


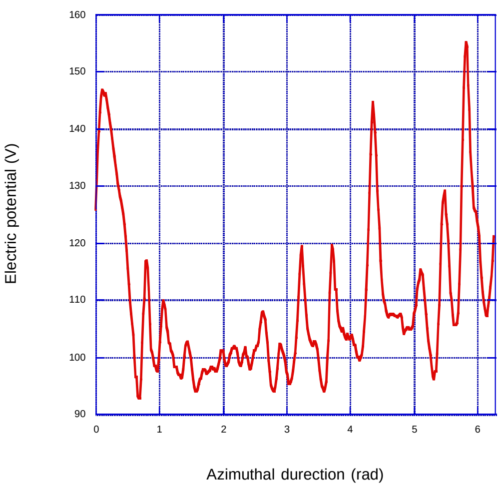
Electron current density

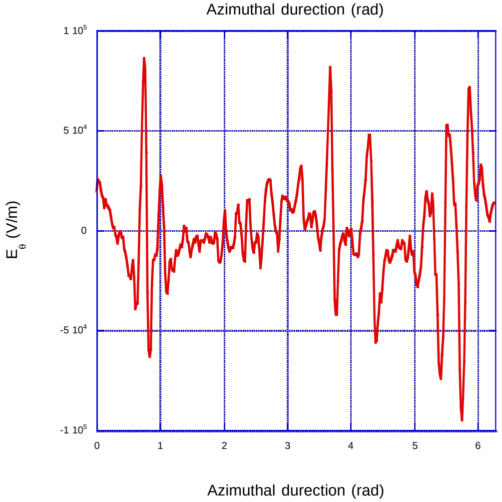


Azimuthal fluctuation in NFP Region

- ✓ Azimuthal fluctuation detected in the first cm's downstream the near-field plume region (m=20)
- ✓ Possible ion acoustic wave driven by the cathode / lower hybrid wave
- ✓ Important role of the magnetic mirror effect and ionization
- ✓ The electron-wall interaction on the exit plane plays a crucial role to drive the electrons inside the channel and to cool down the electron temperature.





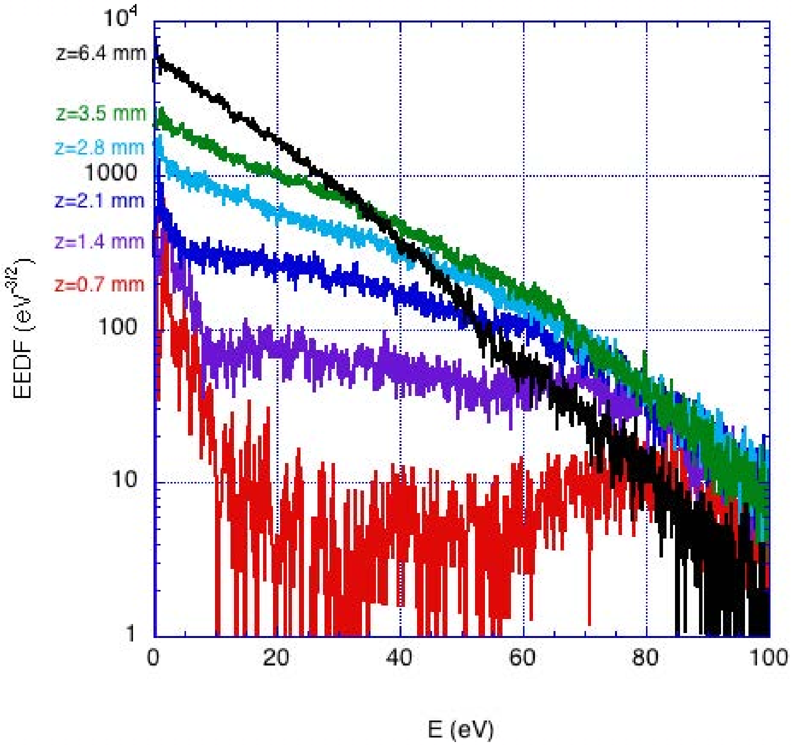


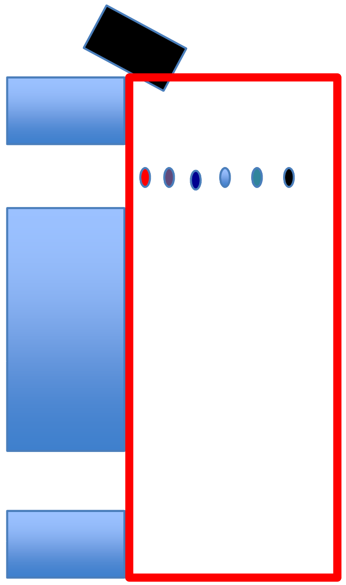
EEDF in NFP Region

✓ Moving upstream towards the exit plane 3 different population appear:

- Low energy Maxwellian population
- Middle energy trapped (magnetic mirror) electrons
- ExB bump on tail electrons

The expansion in the near field plume region needs a kinetic description





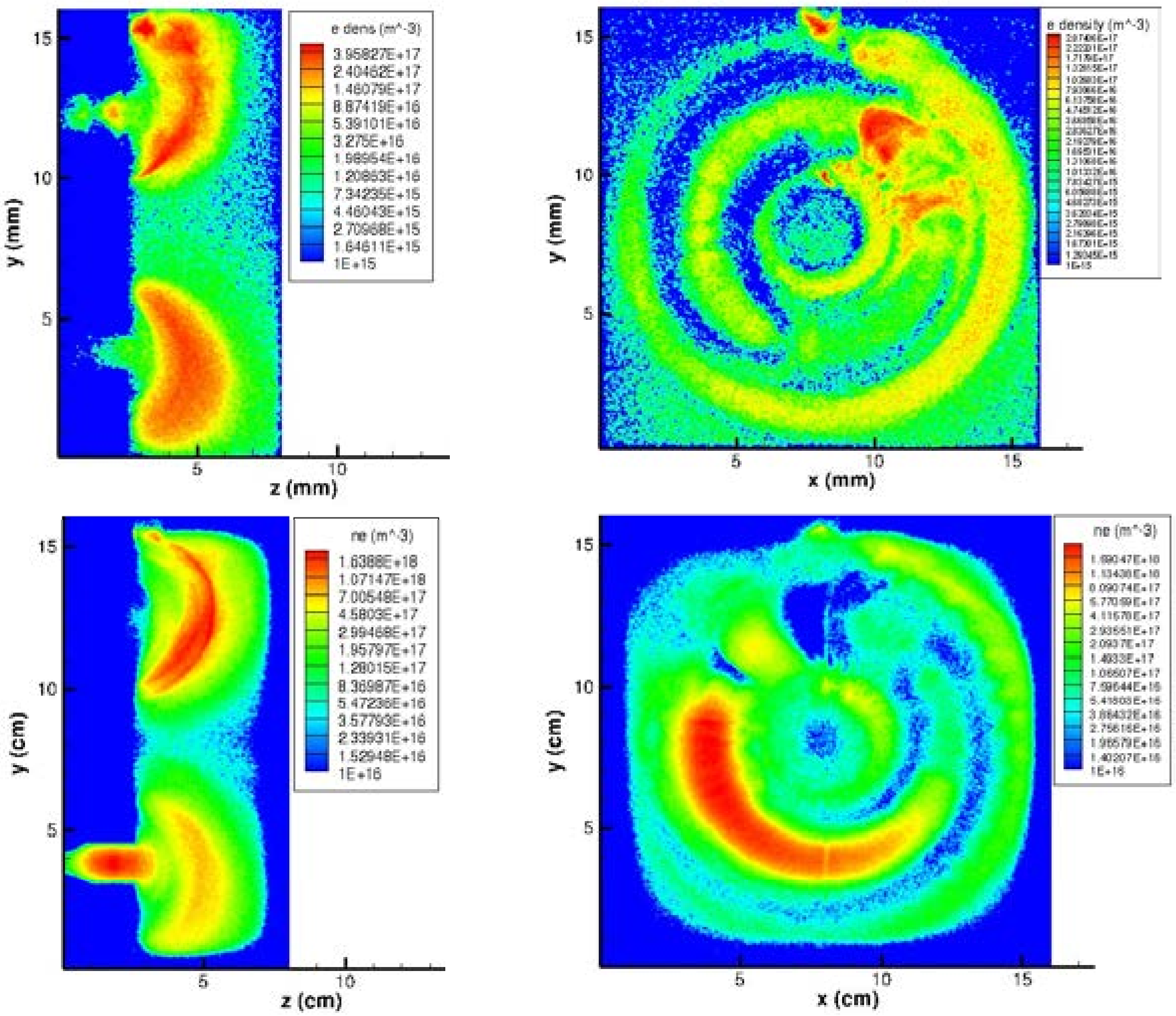
The full domain (channel+plume) model

- ✓ Recently we are working on a 3D channel+plume model
- ✓ HPC intensively used: Hybrid parallelization (MPI+OpenMP)
  320x320x160 cells with 2x10^9 particles
- ✓ GUI for user friendly

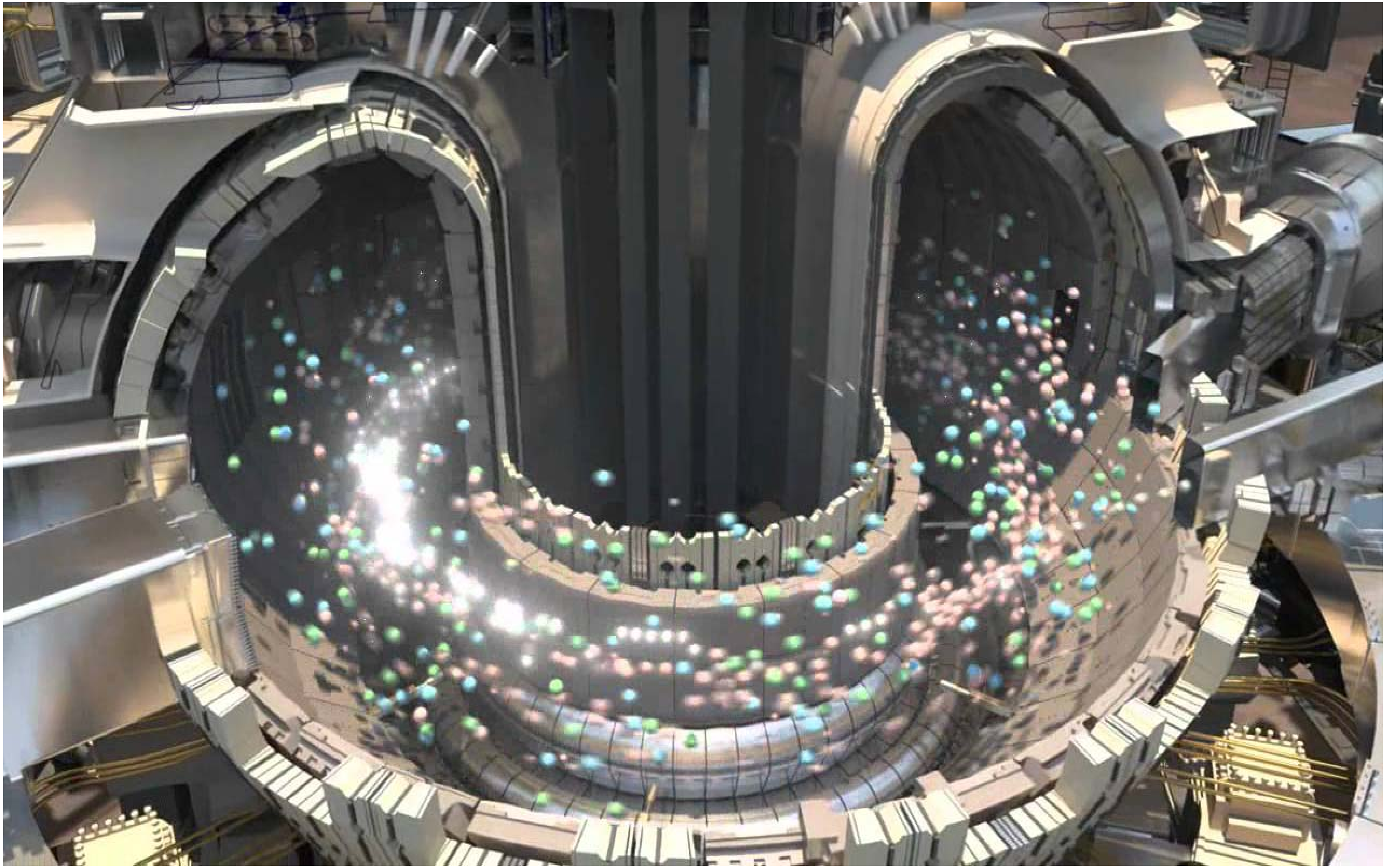
Rotating spoke instability

t=3.5 μs

t=4 μs



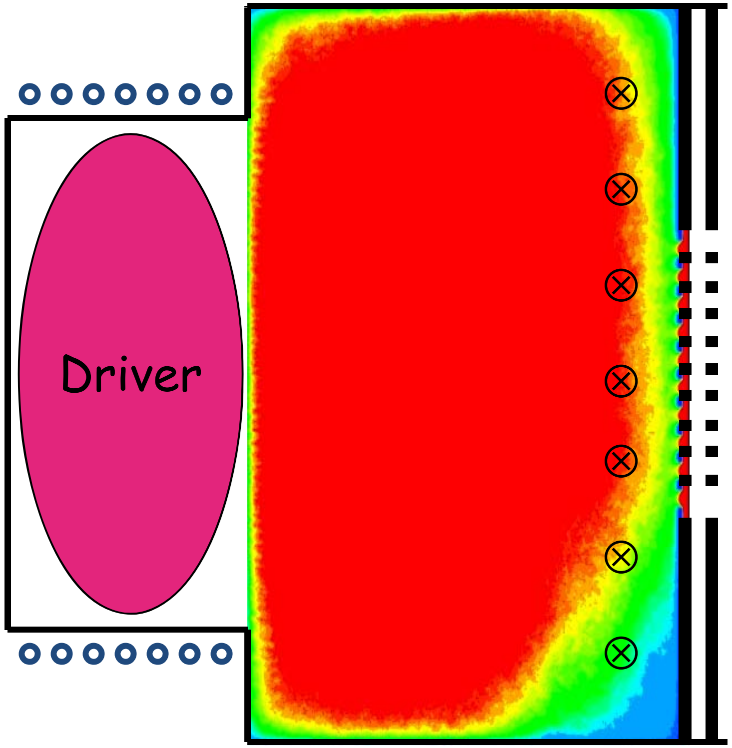
ENERGY – Negative ion source



ITER-relevant Negative Ion Source

RF-ICP Hybrid Negative Ion Source

Expansion Chamber Size	23x32x58 cm
Size Driver Radius	16xD=24.5 cm
Input Power	170 kW
Frequency	1 MHz
Pressure	0.6 Pa
Filter / Electron Suppression Magnetic Field	5 mT / 1 T
Extraction grid (CEA)	126 holes x D=8 mm
Extraction grid potential PG/EG/GG	-25 kV / -15 kV / 0



RELATED TOPICS

- ❑ RF inductive coupling
- ❑ Vibrational kinetics
- ❑ Gas and Cs dynamics
- ❑ Electron xB Transport
- ❑ Electronegative Sheath
- ❑ H- Bulk/Surface Production
- ❑ H- transport/extraction

CODES

- ❑ DRIVE -> 2D(r,z)-cyl PIC (driver region)
- ❑ EXP -> 1.5D DSMC (expansion region)
- ❑ EXTRA -> 3D PIC (extraction monoaperture)
- ❑ MINUS -> 2.5D PIC (expansion+extraction multiaperture)

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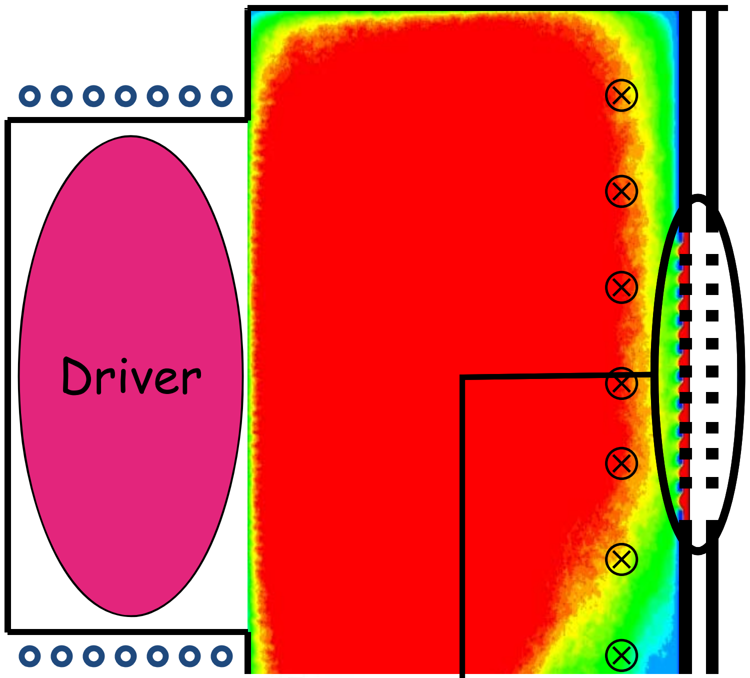

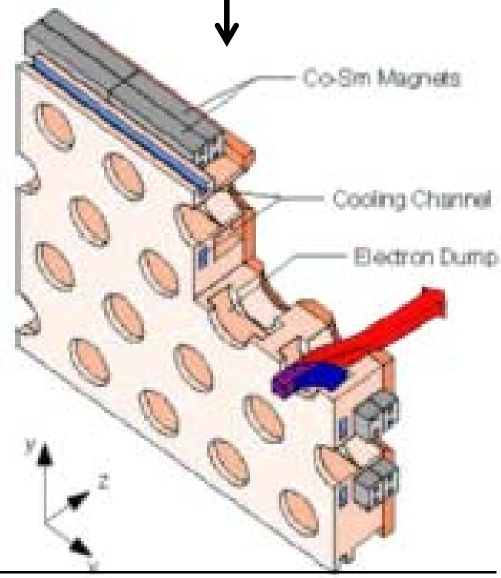

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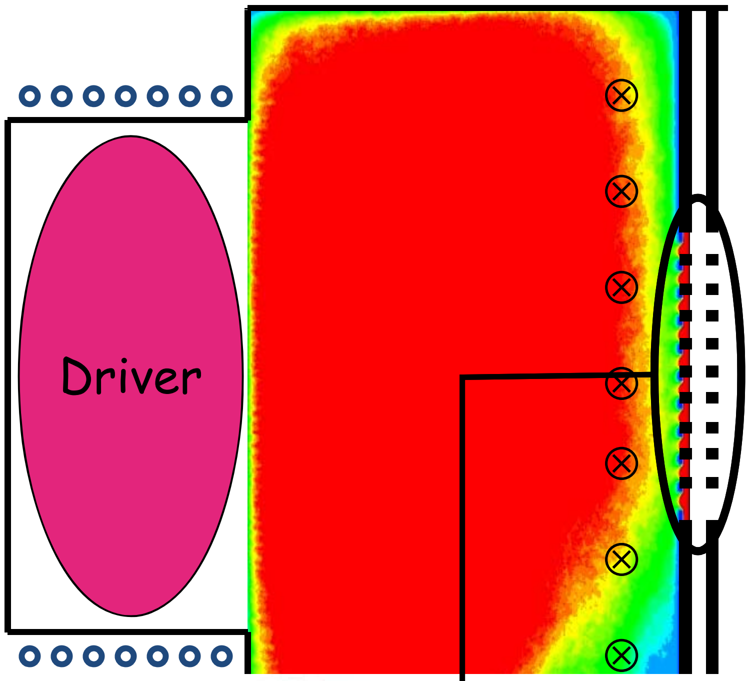

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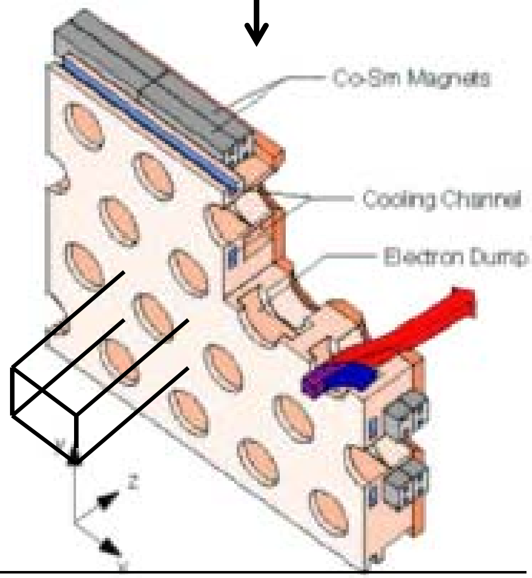

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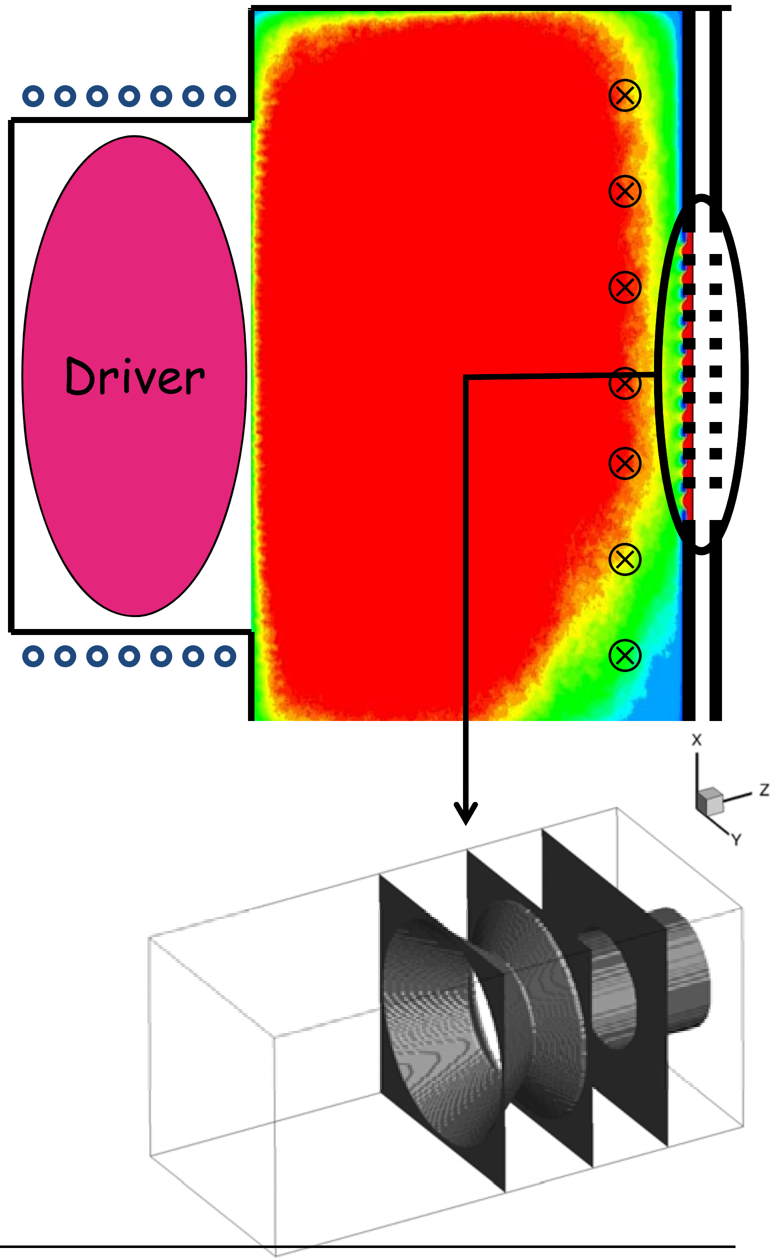

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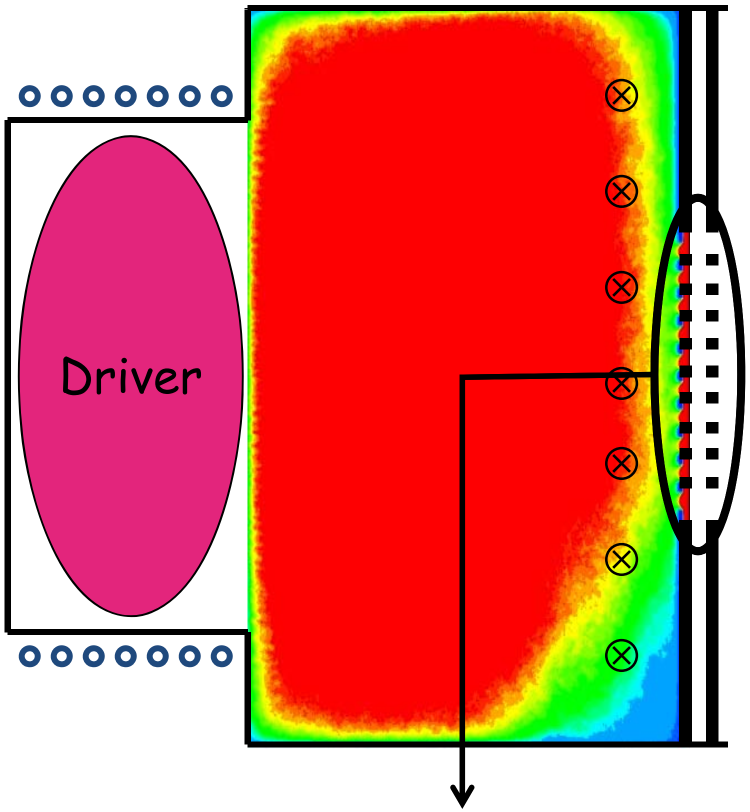

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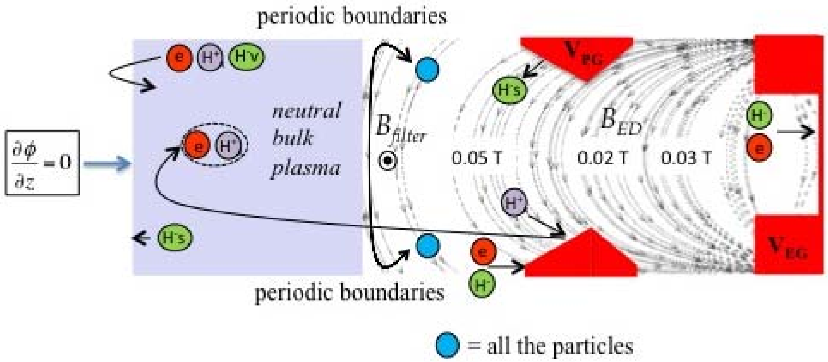

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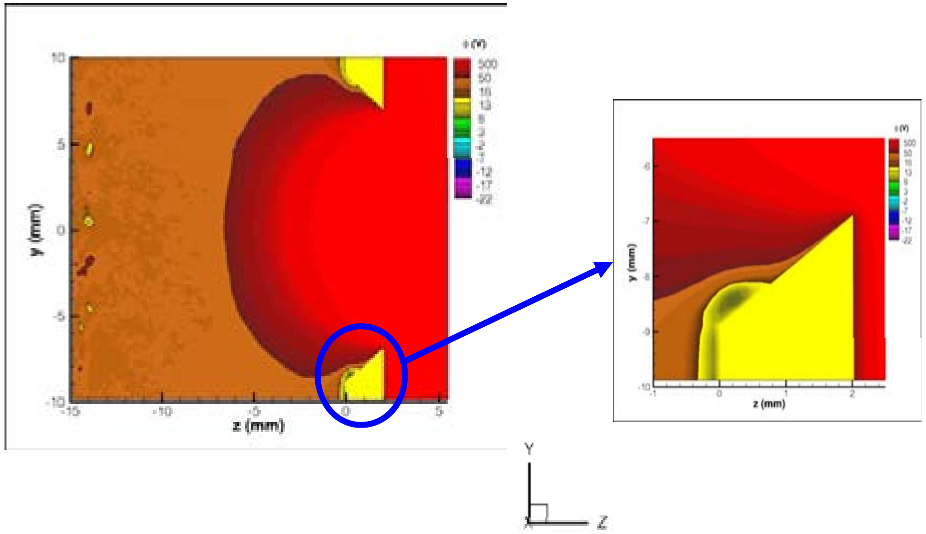
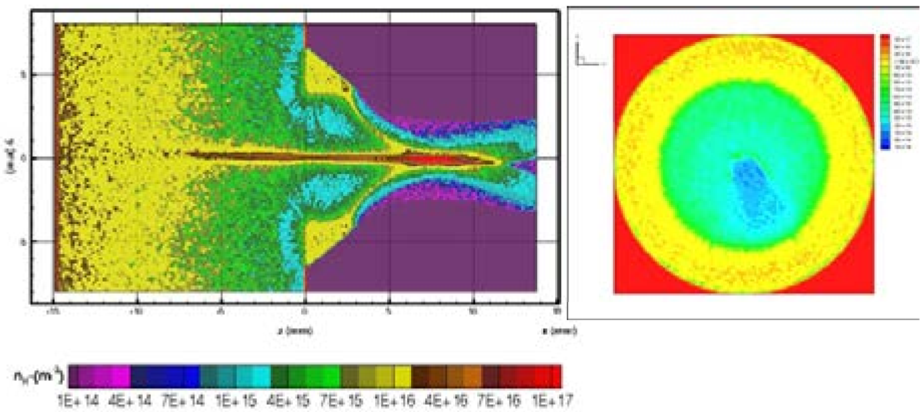
- ❑ **EXTRA -> 3D PIC (extraction monoaperture)**
- ❑ **MINUS -> 2.5D PIC (expansion+extraction multiaperture)**

EXTRA – negative ion transport towards mono-aperture





- Virtual cathode attached to PG reflects back the non-neutralized negative ion flux: just 25% of surface-produced negative ions are able to escape;

- Close to PG exit, the EG field penetration helps removing extra H-;

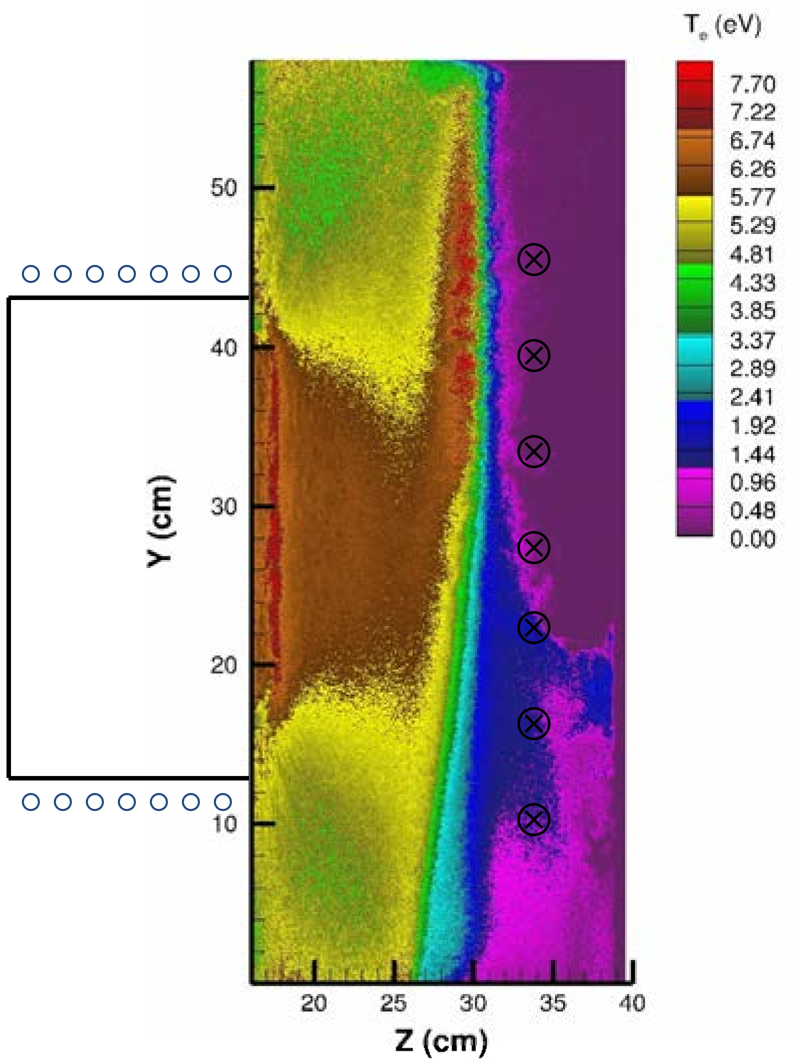
- The meniscus penetrates 0.5 cm in the source region;

- This creates trials visible in the negative ion density which influences the beam optics in the acceleration part.

- The volume and surface-contributions are distinguishable;

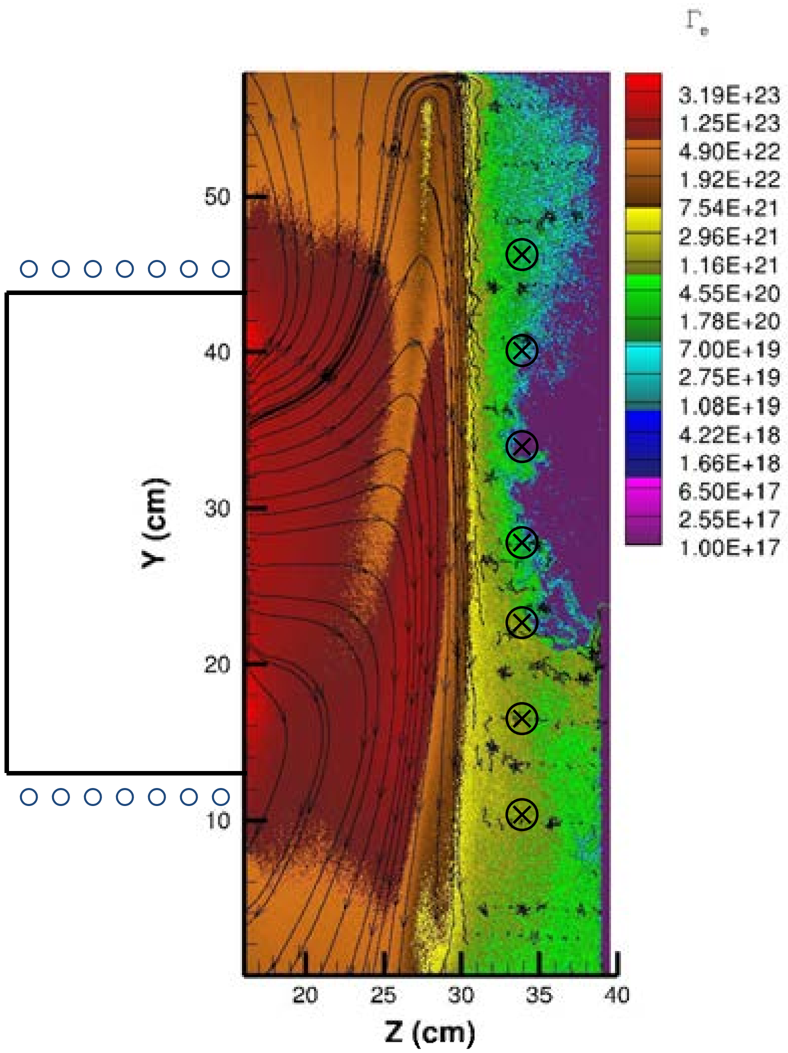
- The y-asimmetry in the resulting beam is a signature of electron deflection magnetic field.

MINUS - Filter Field: Electron Temperature



- Te drops down from 10 eV to 1 eV
- The drop starts in grad(B) region
- Cooling mechanism:
electron residence time increases ->
electrons loose energy via collisional processes

MINUS - Filter Field: Electron xB Transport



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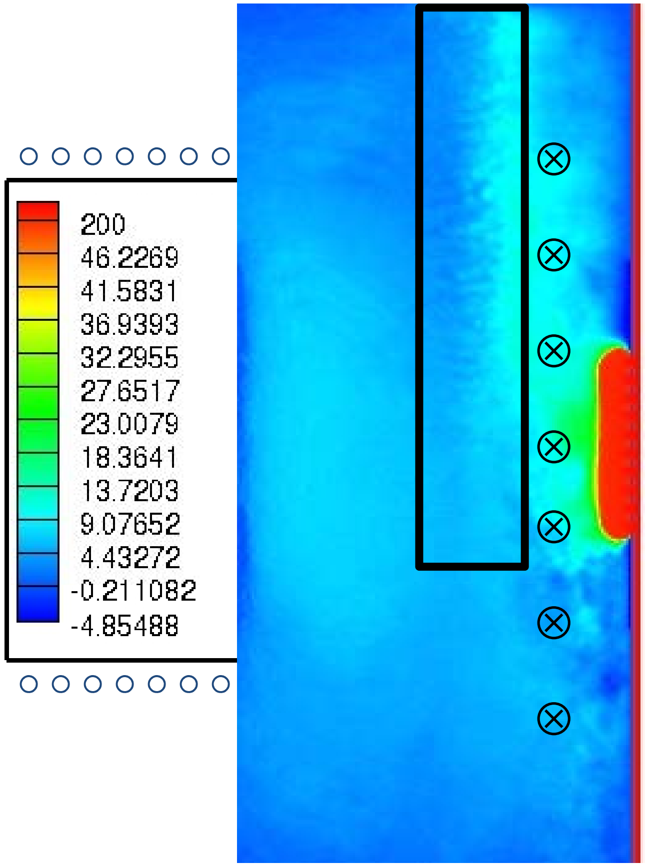
- j_{ez}xB drift is directed to the bottom
- The presence of the wall induces an ambipolar E_y
- E_yxB drift increase the axial current

MINUS - Filter Field: Electron xB Transport



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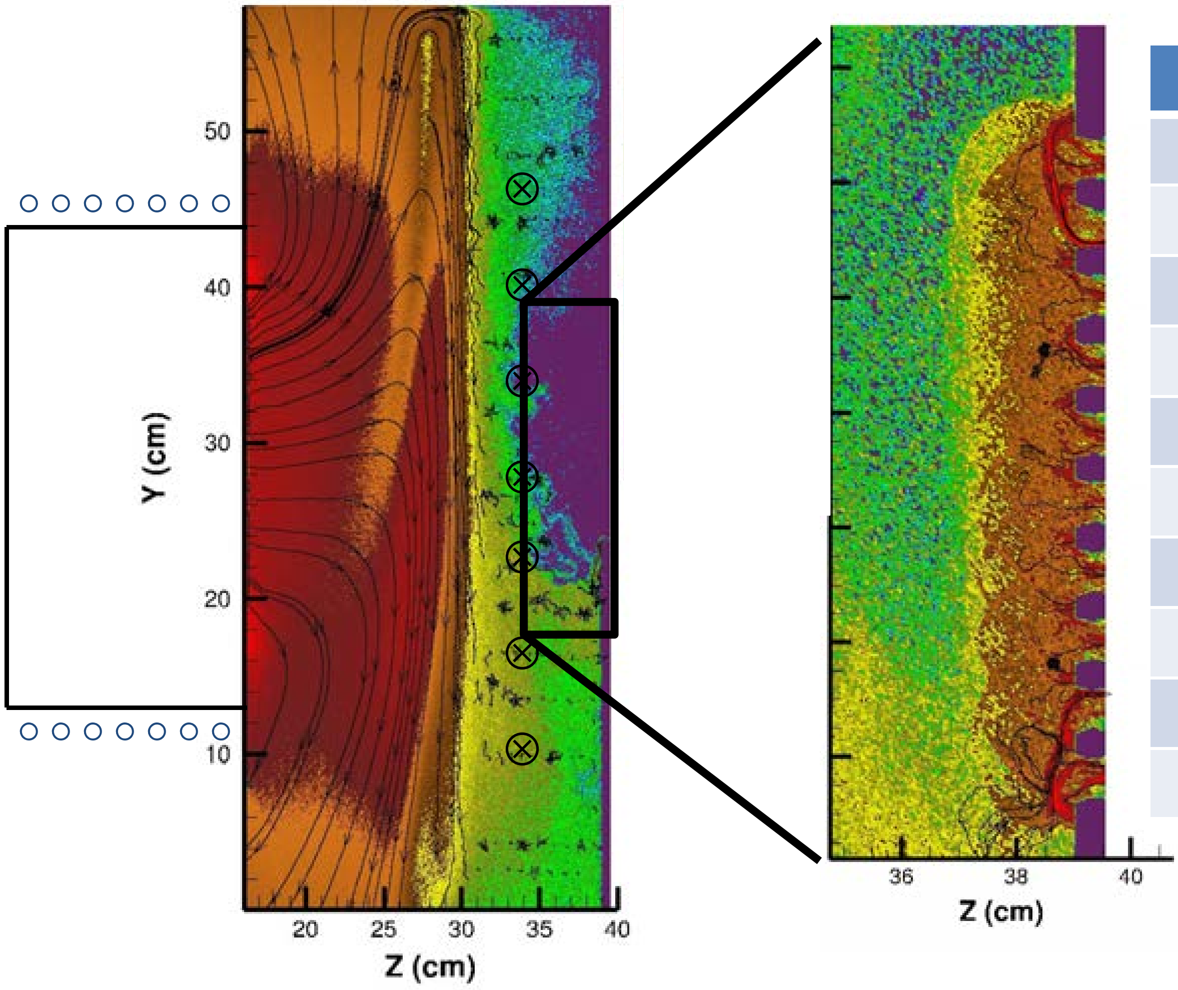
- j_{ez}xB drift is directed to the bottom
- The presence of the wall induces an ambipolar E_y
- E_yxB drift increase the axial current
- An additional anomalous mechanism driven by instability has been detected: y-modulation

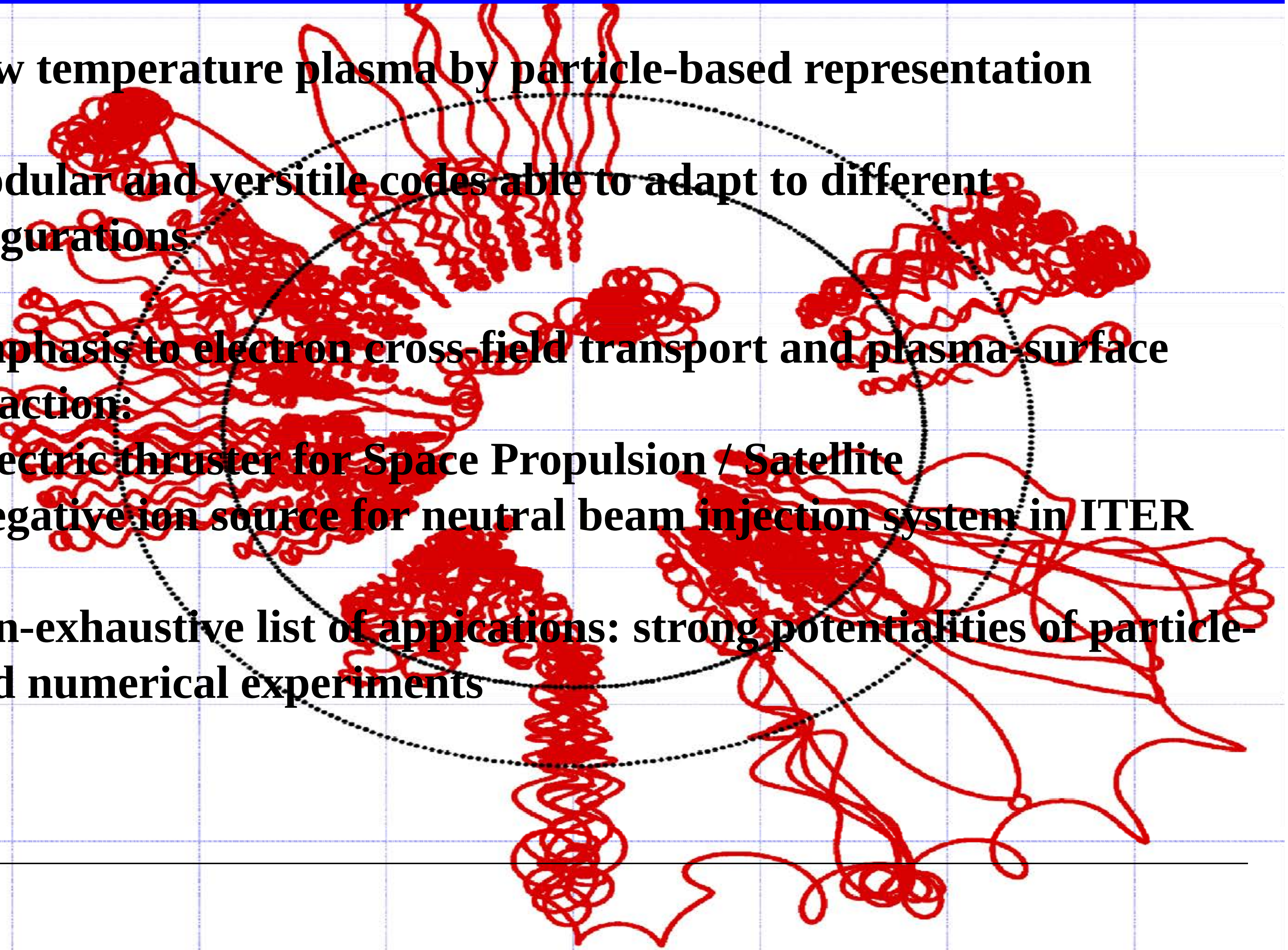
MINUS - Extracted current aperture by aperture

No correlation between plasma asymmetry and negative ion beam homogeneity:
confirmation of the leading role of atoms in the surface-production of negative ions



J_e (A/m^2)	J_{H-} (A/m^2)
0.6	167
0.7	304
0.6	166
0.6	171
0.6	188
0.7	181
0.7	185
0.7	195
1.3	285
107	206

Conclusions



o **Low temperature plasma by particle-based representation**

o **Modular and versitile codes able to adapt to different configurations**

o **Emphasis to electron cross-field transport and plasma-surface interaction:**

- **Electric thruster for Space Propulsion / Satellite**
- **Negative ion source for neutral beam injection system in ITER**

o **Non-exhaustive list of appications: strong potentialities of particle-based numerical experiments**