CNRNANOTEC
INSTITUTE OF NANOTECHNOLOGY

Hall Thruster Virtual Lab

Francesco Taccogna Pierpaolo Minelli
Francesco Michetti, Antonio Taurisano, Elio De Marinis

P.Las.M.I. Lab @ CNR-Nanotec
EnginSoft SPA
Bari
(Italy)

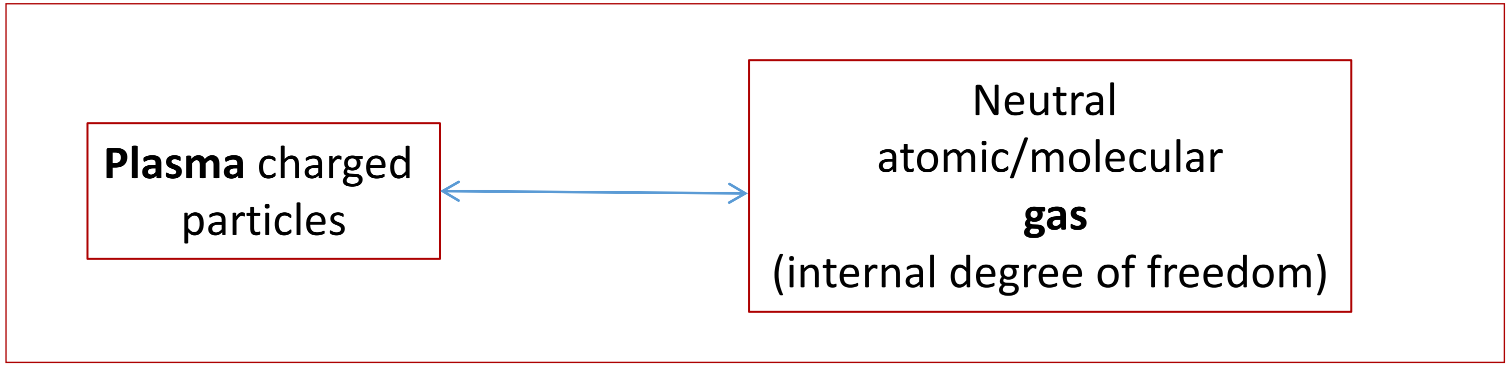
e-mail: francesco.taccogna@cnr.it

Low temperature plasma kinetic description

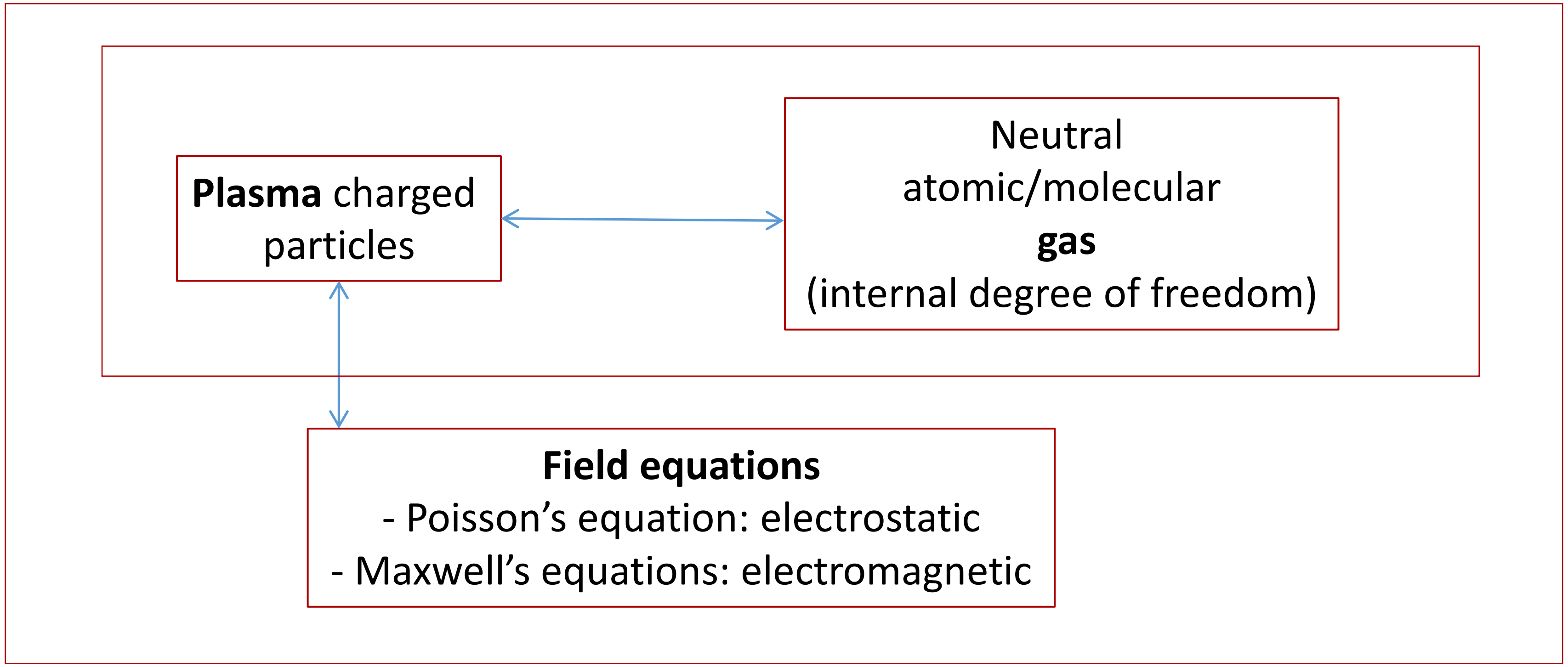
Low temperature plasma kinetic description

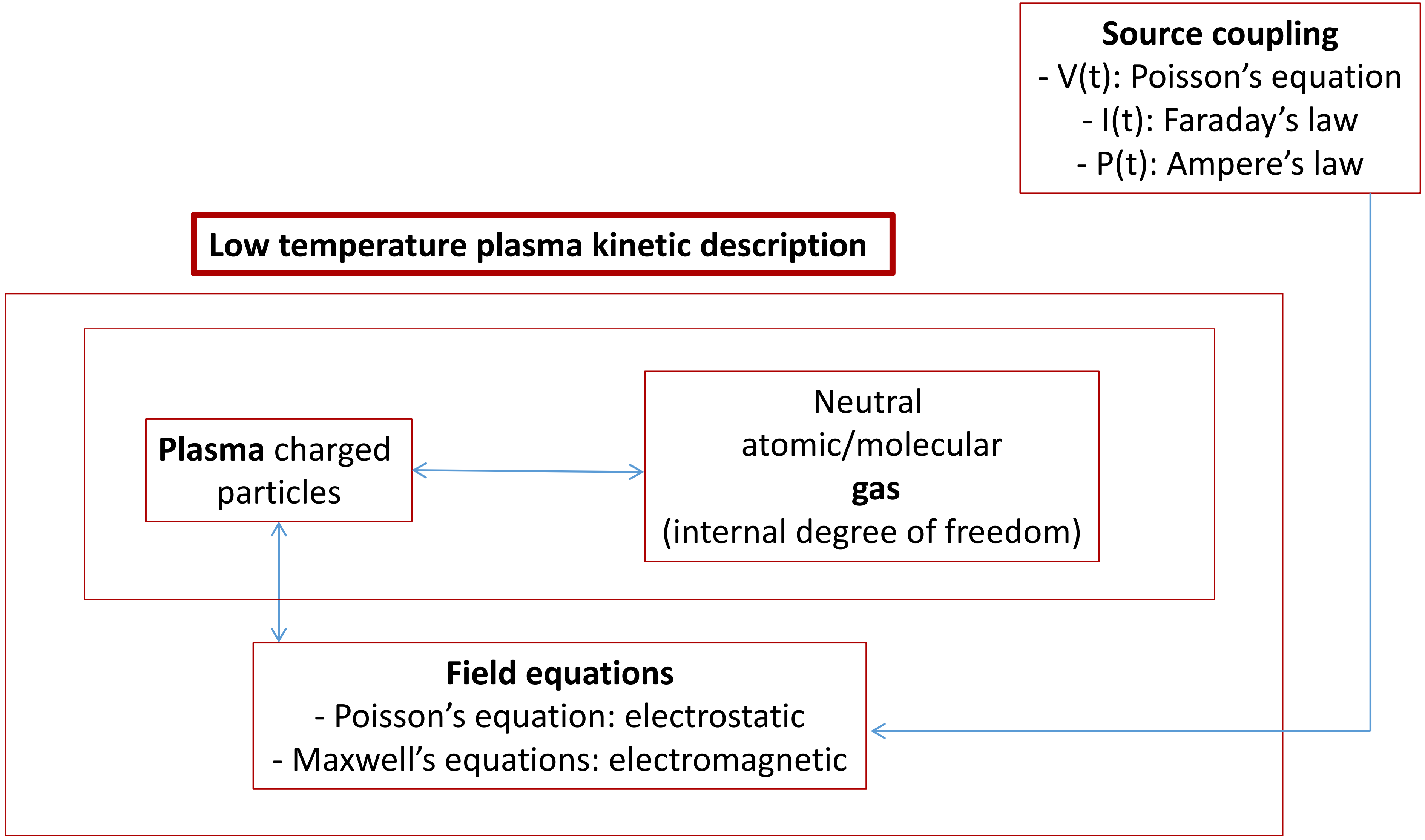
Plasma charged particles

Low temperature plasma kinetic description

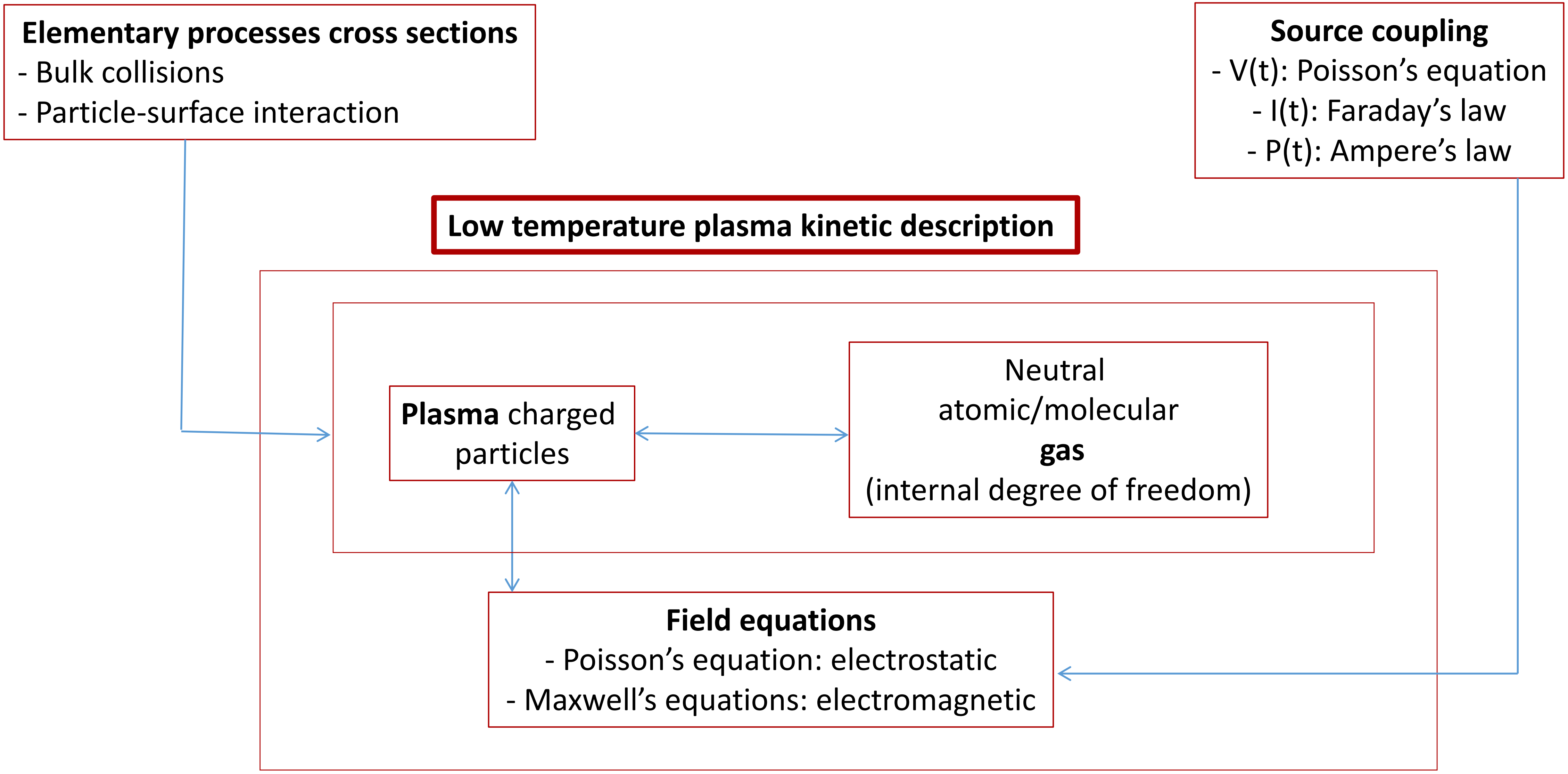


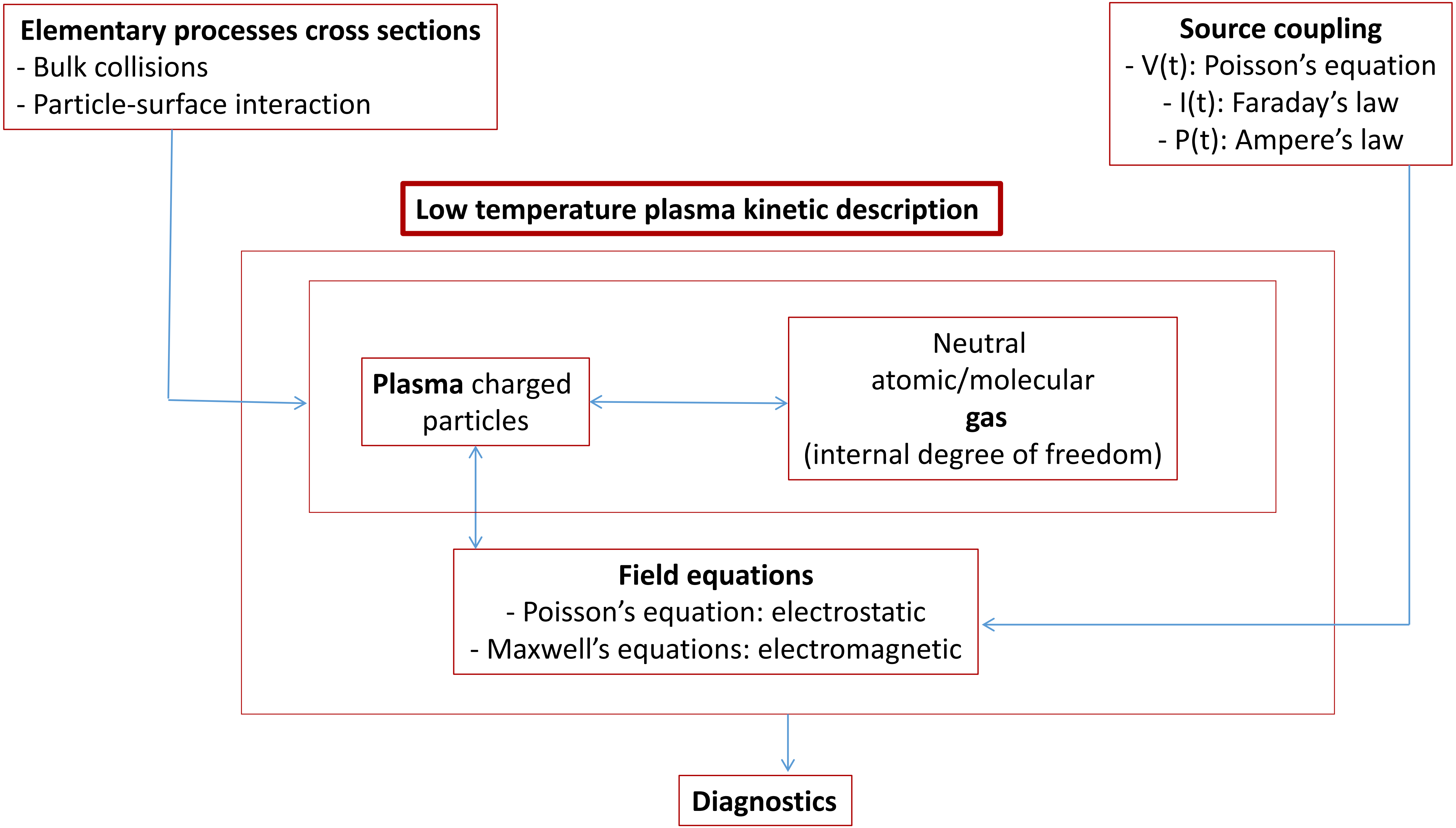
Low temperature plasma kinetic description





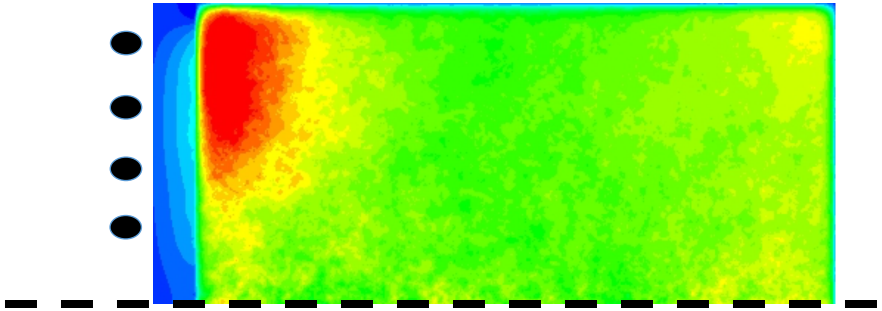
Source coupling
- V(t): Poisson's equation
- I(t): Faraday's law
- P(t): Ampere's law
Low temperature plasma kinetic description
Plasma charged particles
Neutral atomic/molecular **gas** (internal degree of freedom)
Field equations
- Poisson's equation: electrostatic
- Maxwell's equations: electromagnetic


Elementary processes cross sections
- Bulk collisions
- Particle-surface interaction
Source coupling
- V(t): Poisson’s equation
- I(t): Faraday’s law
- P(t): Ampere’s law
Low temperature plasma kinetic description
Plasma charged particles
Neutral atomic/molecular gas (internal degree of freedom)
Field equations
- Poisson’s equation: electrostatic
- Maxwell’s equations: electromagnetic


Elementary processes cross sections
- Bulk collisions
- Particle-surface interaction
Source coupling
- V(t): Poisson's equation
- I(t): Faraday's law
- P(t): Ampere's law
Low temperature plasma kinetic description
Plasma charged particles
Neutral atomic/molecular gas (internal degree of freedom)
Field equations
- Poisson's equation: electrostatic
- Maxwell's equations: electromagnetic
Diagnostics

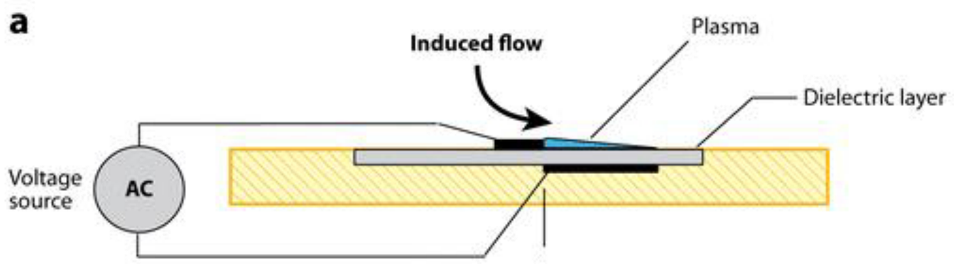
Particle-based Plasma Virtual Lab

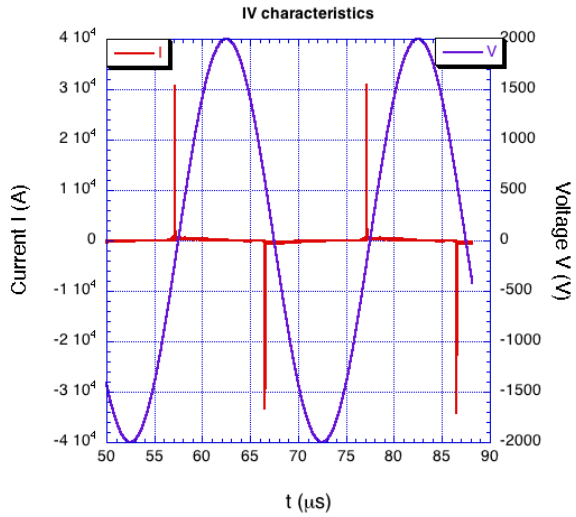
- **Gas-discharges:**
  - DC
  - RF-CCP
  - **RF-ICP**
  - DBD
  - APMD



Particle-based Plasma Virtual Lab

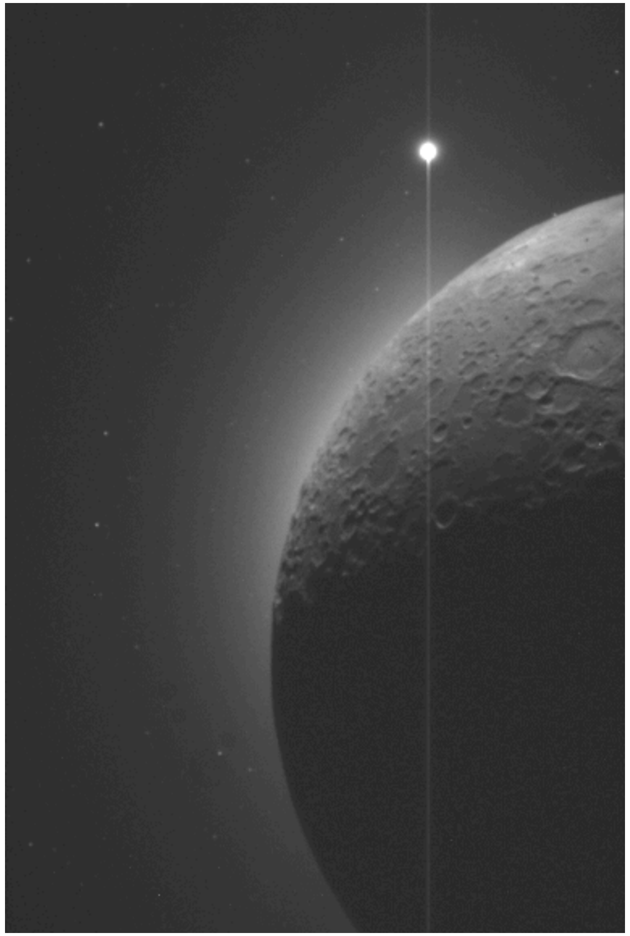
- **Gas-discharges:**
  - DC
  - RF-CCP
  - RF-ICP
  - **DBD**
  - APMD





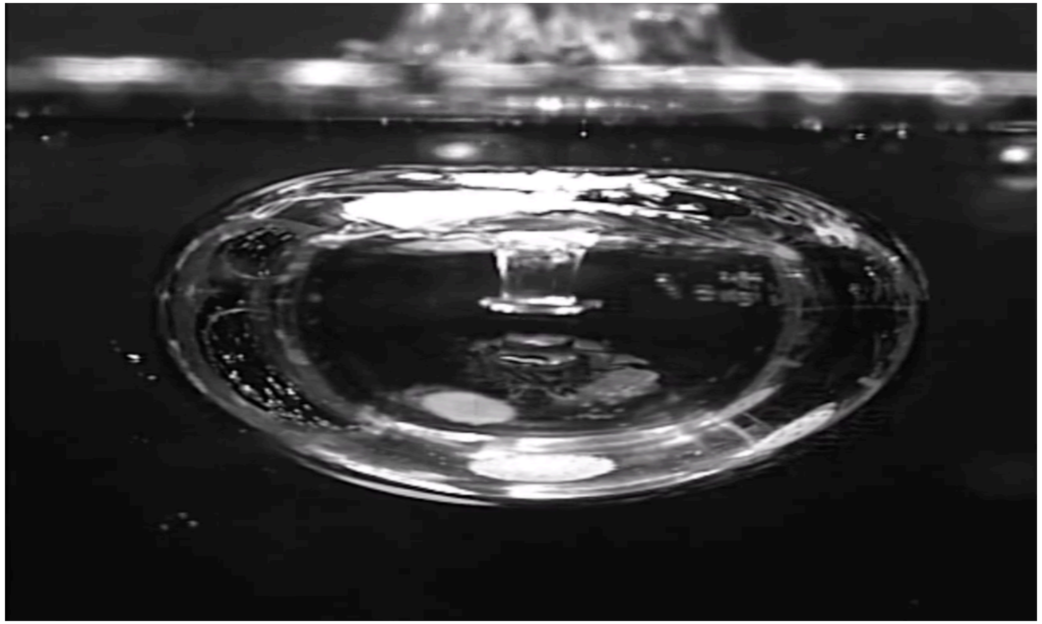
Particle-based Plasma Virtual Lab

- Gas-discharges:
- **Plasma-wall transition region:** - Plasma Sheath
  - Divertor Region
  - Dusty plasmas

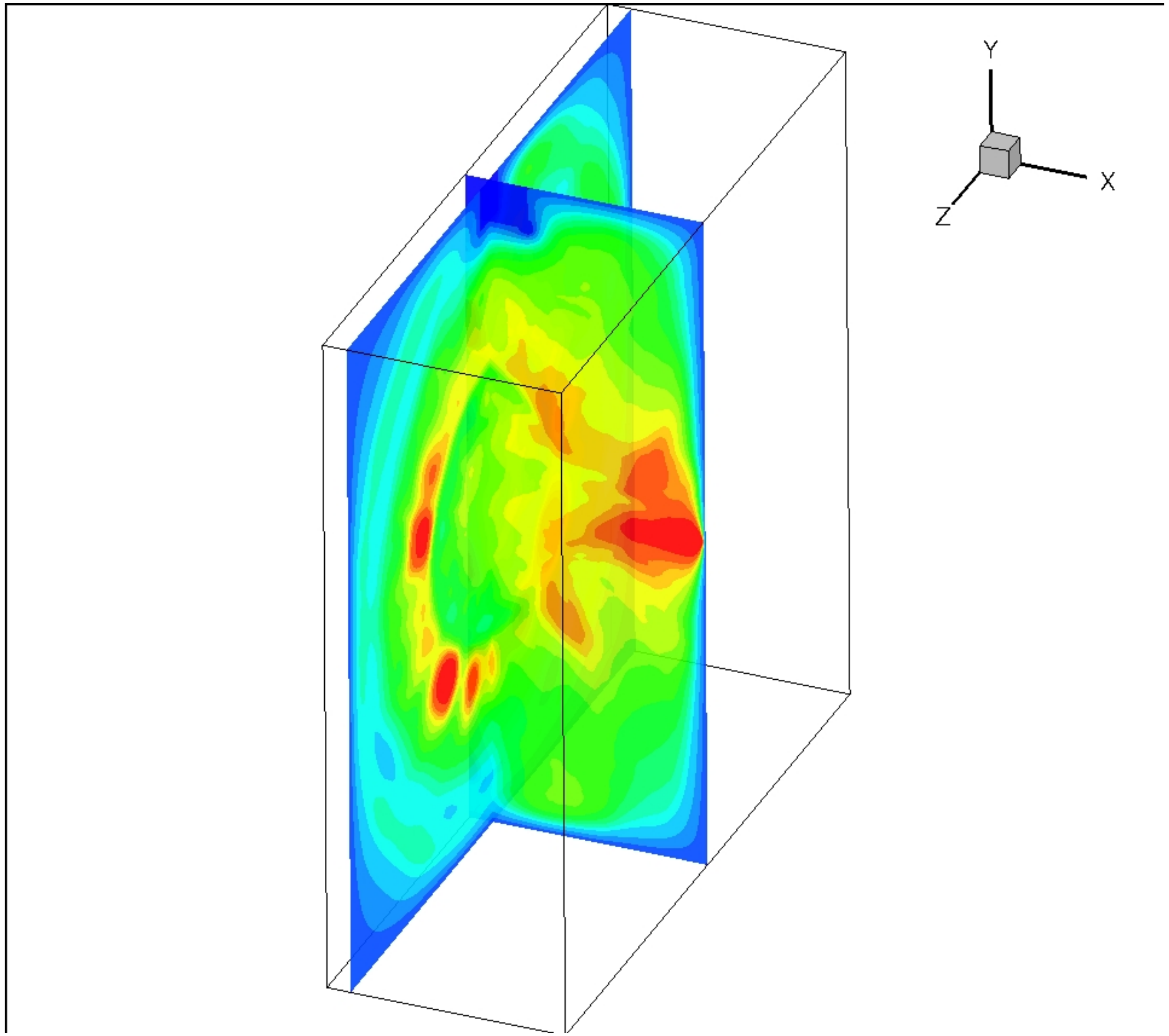


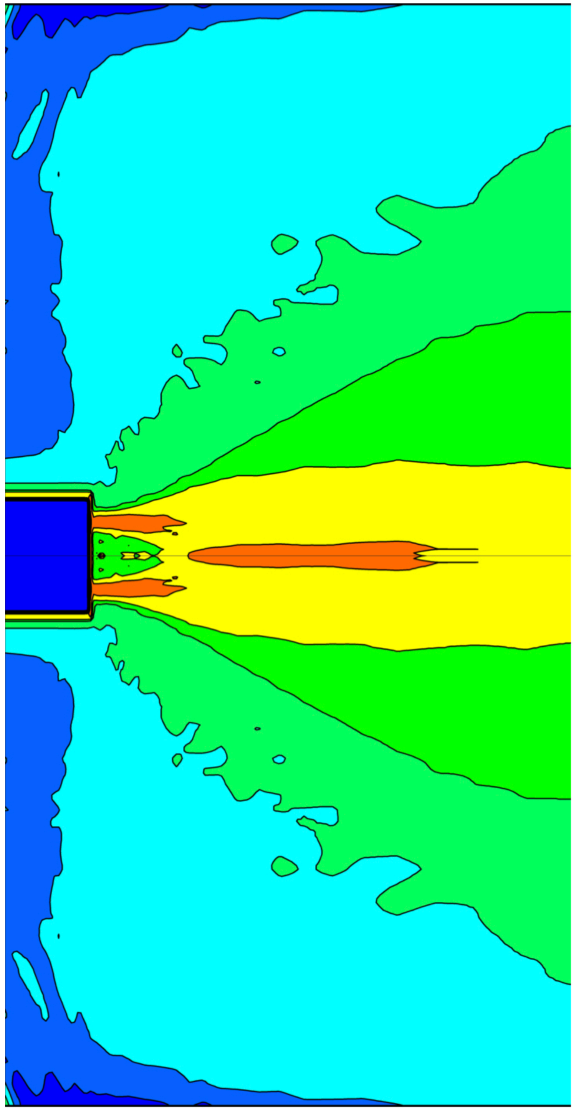
Particle-based Plasma Virtual Lab

- Gas-discharges:
- Plasma-wall transition region
- **Laser-induced plasmas in liquid**



HT VIRTUAL LAB





Hall Thruster PIC Models @ CNR-Nanotec_PLasMI lab

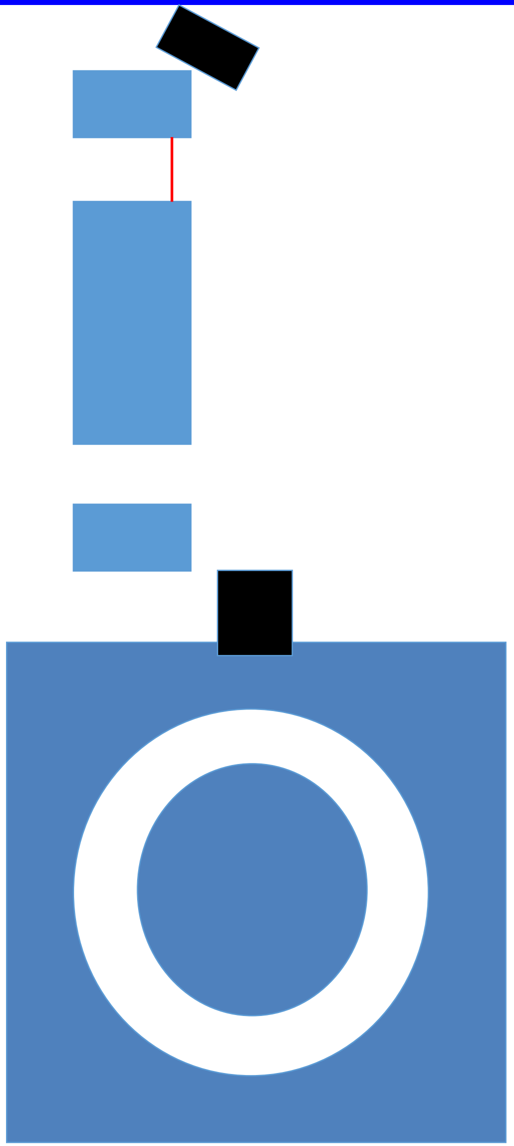
Model	Year	Assumptions	Findings
1D(r) channel	2006	injection; E_z; $\nu_{anomalous}$	SEE-instability
2D(r,z) channel	2003	$\nu_{anomalous}$	acceleration mechanism
2D(r,θ) channel	2007	injection; E_z	r-θ correlation
3D(r,θ,z) channel	2011	- geometrical scaling - no scaling	r-θ-z correlation
3D(x,y,z) NFplume	2014	geometrical scaling	- Anomalous transport in NFP - Electron cooling
3D(x,y,z) Channel+NFplume	2016	geometrical scaling	channel-plume coupling
3D(x,y,z) Hybrid Plume	2000	Fluid-Boltzmann electrons PIC ions	- CX and IEDF - Multichannel configuration

1D(r) Model

o **1D(r) / acceleration region**

- Domain: from inner to outer wall
- Initial condition: neutral uniform Maxwellian plasma
- Injection condition: particle leaving axial domain are replaced by new particles

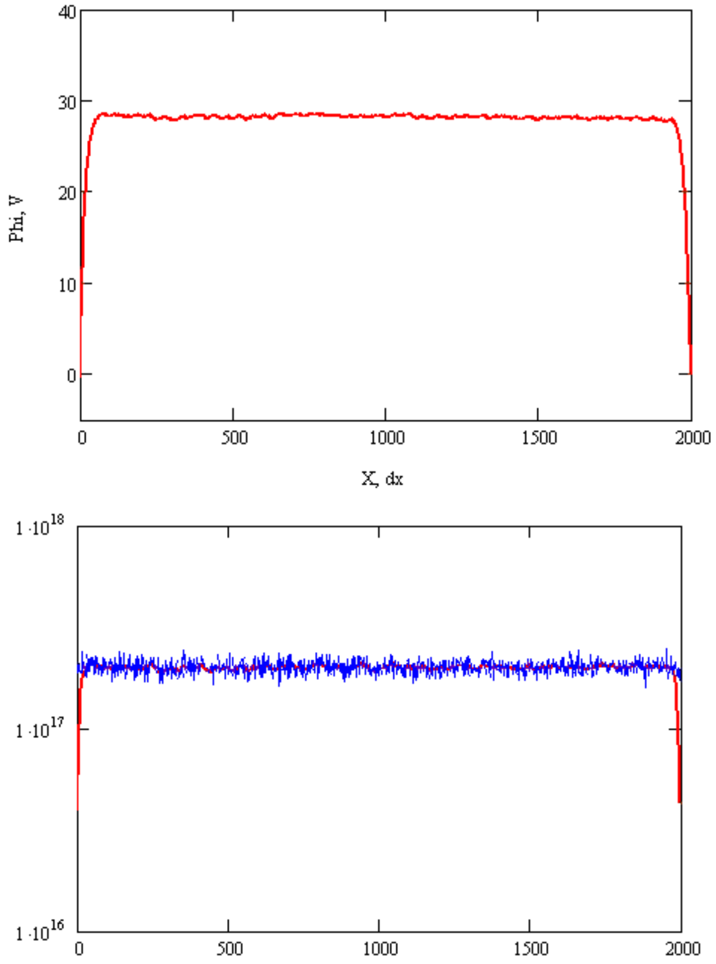
- Field solve: Dielectric surface conductivity neglected $\frac{\partial \phi}{\partial r} = \frac{\sigma}{\varepsilon_0}$
- electron-atom MCC module
- electron-wall SEE module
- Realistic size, ion mass, vacuum permittivity
- Assumption: - fixed axial electric field E_z
  - anomalous collisions (azimuthal fluctuation contribution)
- Numerical parameter: - N_r=2000 (grid points)
  - N_p/N_r=200 (particles per cell)



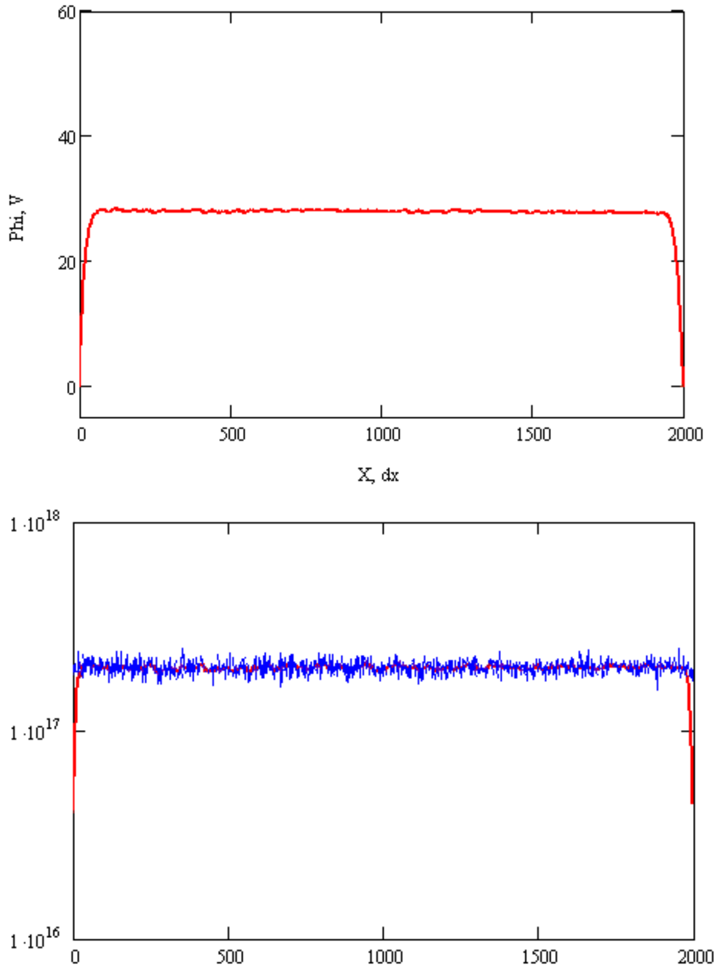
1D(r) Results

2 different regimes have been simulated

Ez=100 V/cm

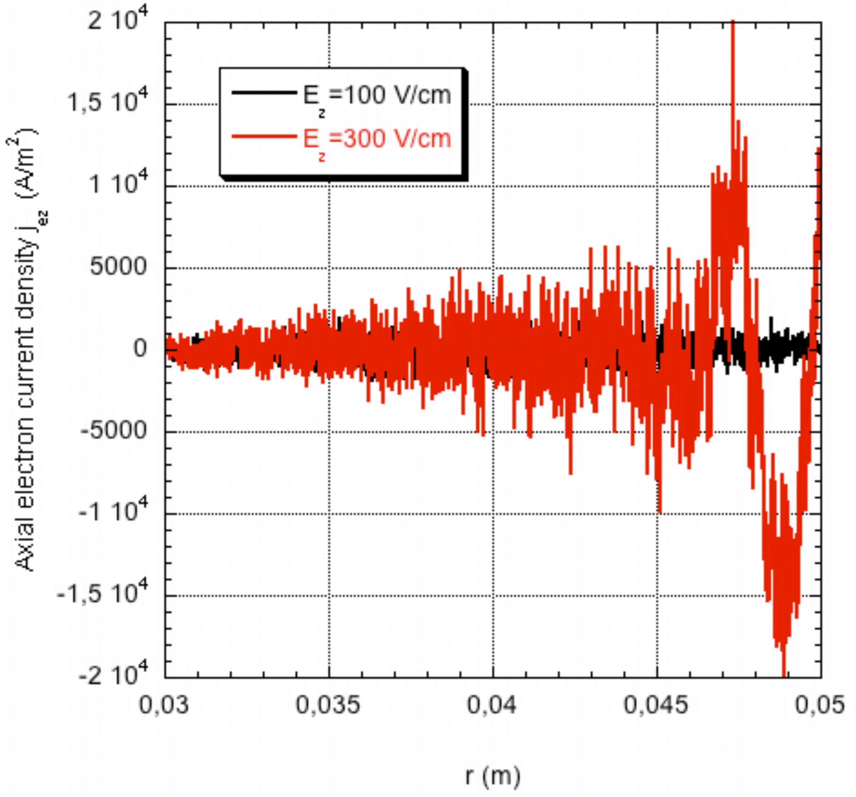


Ez=300 V/cm



1D(r) Results

Near-wall conductivity



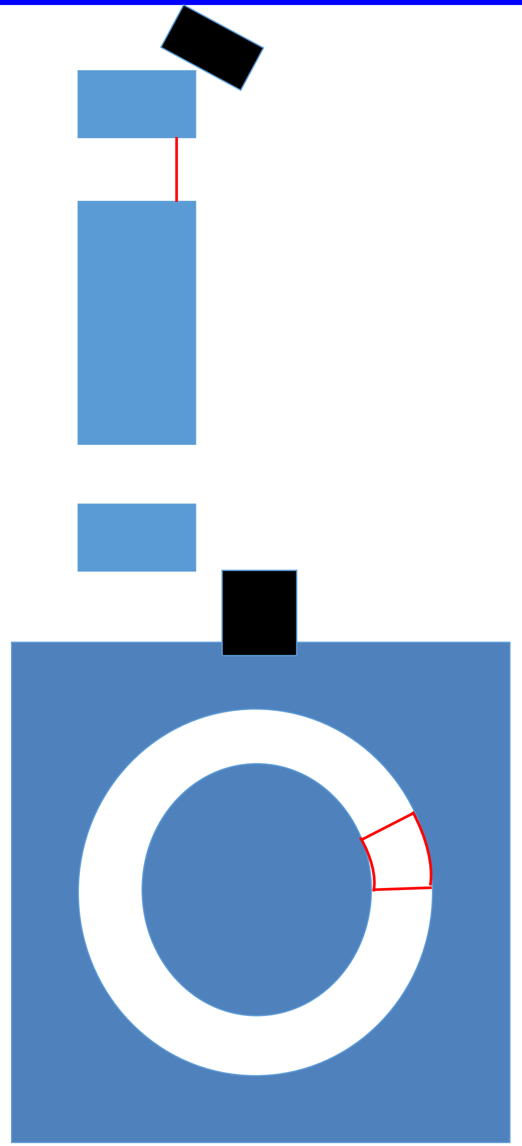
2D(r,θ) Model

o 1D(r) / acceleration region

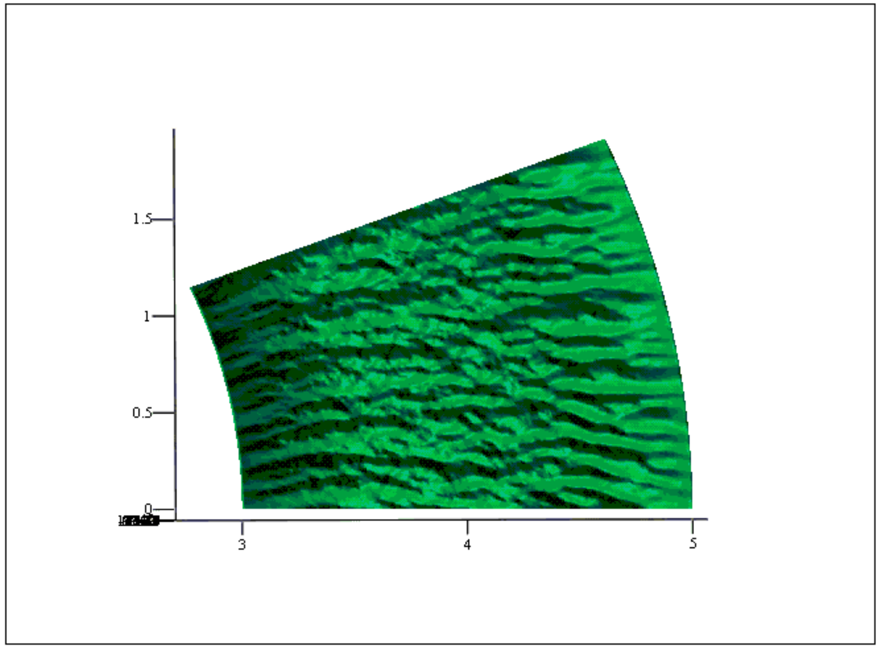
o 2D(r,θ) / acceleration region

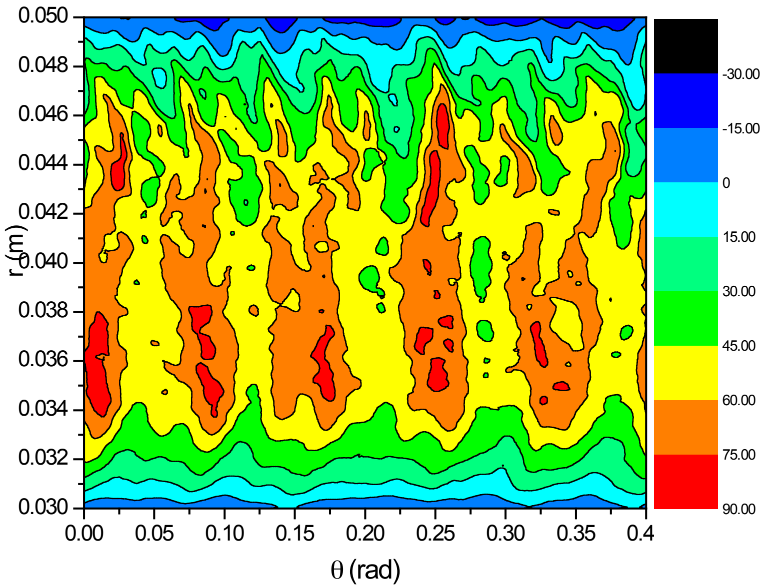
- Domain: - radial from inner to outer wall;
  - azimuthal: $\pi/16$
- Initial condition: neutral uniform Maxwellian plasma
- Injection condition: particle leaving axial domain are replaced by new particles

- Field solve: Dielectric surface conductivity neglected $\frac{\partial \phi}{\partial r} = \frac{\sigma}{\varepsilon_0}$
- electron-atom MCC module
- electron-wall SEE module
- Realistic size, ion mass, vacuum permittivity
- Assumption: - fixed axial electric field Ez
- Numerical parameter: - $N_g = N_r x N_\theta = 800x512$ (grid points)
  - $N_p/N_g = 50$ (particles per cell)

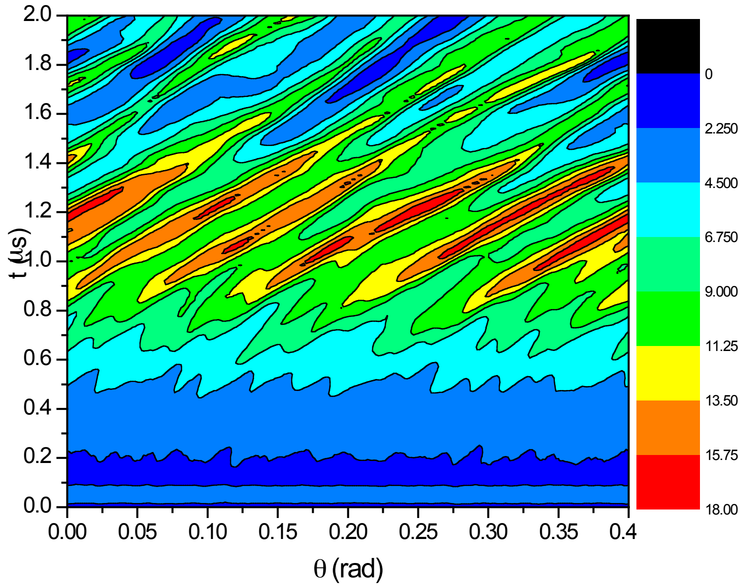


2D(r,θ) Results



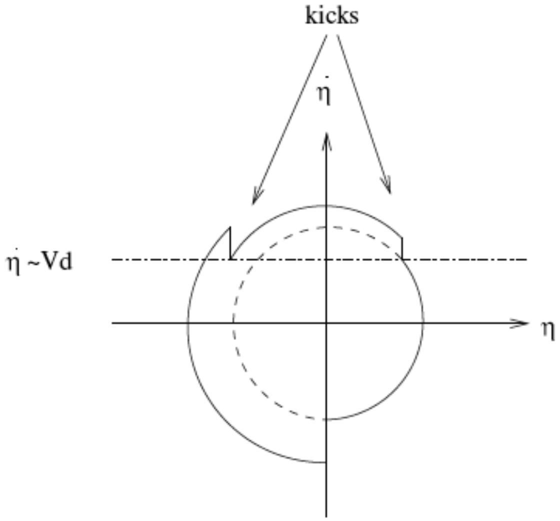


- Azimuthal fluctuations characterized by a wavelenght λ_{θ}=3 mm. The azimuthal modulation is not confined in the bulk region but it reaches the lateral walls modulating even the sheaths that are no longer mono-dimensional.
- Space charged saturation regimes are periodically detected for very short time.
- The azimuthal fluctuation has a frequency of about 3 MHz.



Tracer particle orbit approach: stochastic web map

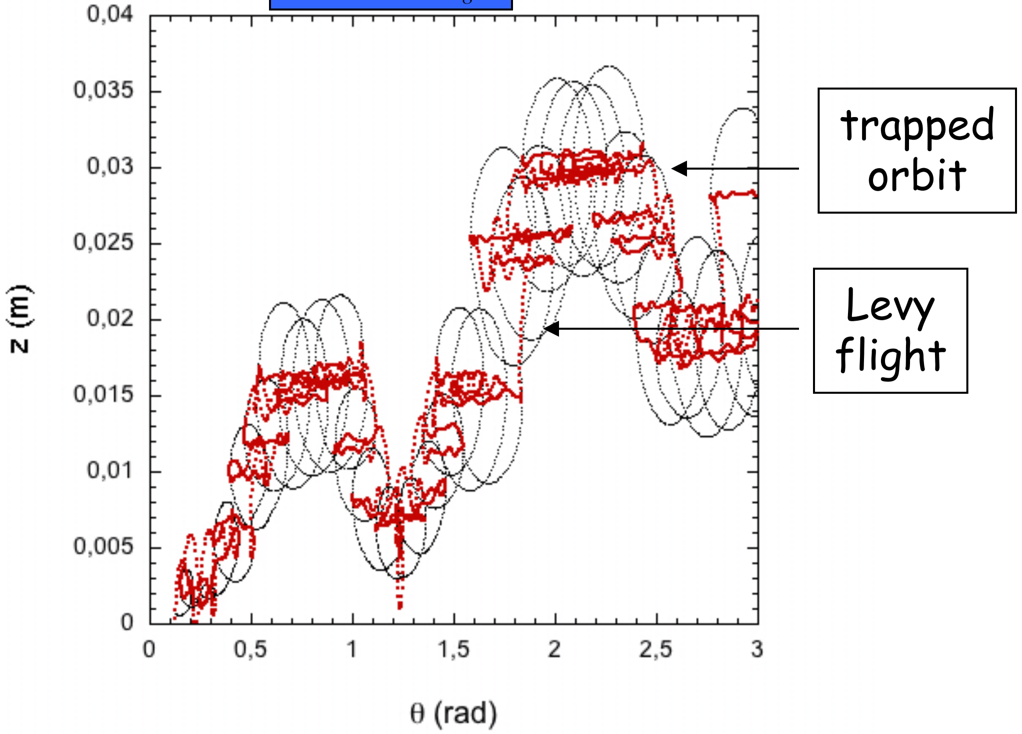
$N_p=10^7$
$E_\theta=\alpha E_z \Sigma_n \cos(k_\theta \theta - \omega_n t)$
- $n=4$
- $\alpha=5$
- $\omega_0=2\pi\nu_0$ (ν_0=3 GHz)
- k_θ=28 rad^{-1}



kicked rotor:

$$\ddot{\eta} + \Omega^2 \eta = \sum_k \chi_k \cos\left[k(\eta + \theta_{gc}) - (\omega_k - k v_d)t\right]$$

$$\dot{z} = \Omega(\eta + \theta_{gc})$$



Combination of particle trapping in eddies for long times and jumps over several sets of eddies in a single flight leading to anomalous diffusion coming from space and time correlations (interaction between electron dynamics and coherent structures).

2D(r,z) Model

o 1D(r) / acceleration region

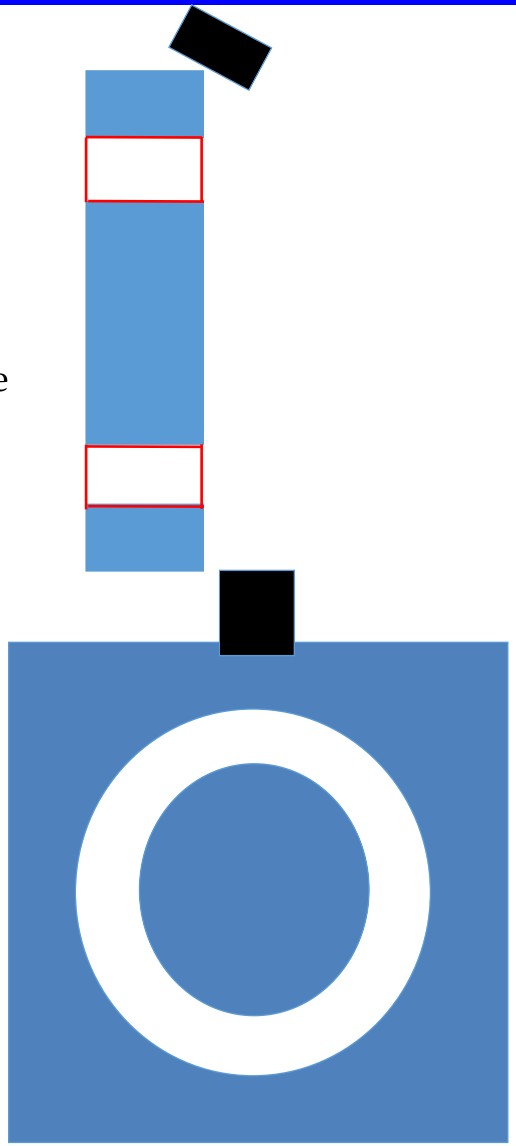
o 2D(r,θ) / acceleration region

o **2D(r,z) / discharge channel**

- Domain: - radial from inner to outer wall;
  - axial from anode to exit plane
- Initial condition: start from scratch
- Injection condition: steady-state electron current control method from exit plane

$$\Delta n_{e,inj} = \Delta n_e^{anode} - \Delta n_i^{anode} - (\Delta n_i^{exitplane} - \Delta n_e^{exitplane})$$

- Field solve: Dielectric surface conductivity neglected $\frac{\partial \phi}{\partial r} = \frac{\sigma}{\varepsilon_0}$
- electron-atom MCC module
- electron-wall SEE module
- Realistic size, ion mass, vacuum permittivity
- Assumption: - fixed potential (cathode) at the exit plane
  - anomalous collisions (azimuthal fluctuation contribution)
- Numerical parameter: - $N_g=N_r x N_z=1000x1600$ (grid points)
  - $N_p/N_g=50$ (particles per cell)

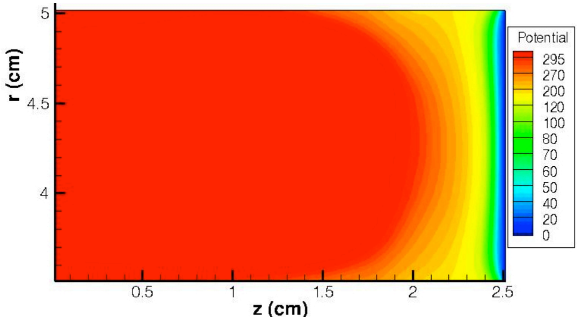


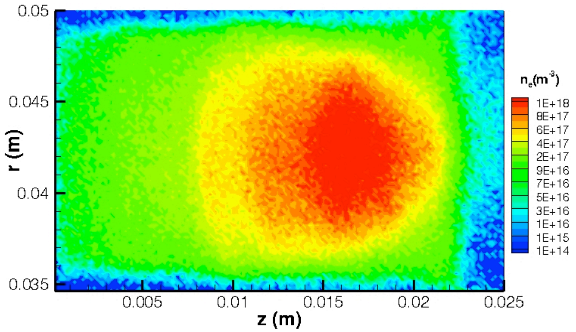
2D(r,z) Results

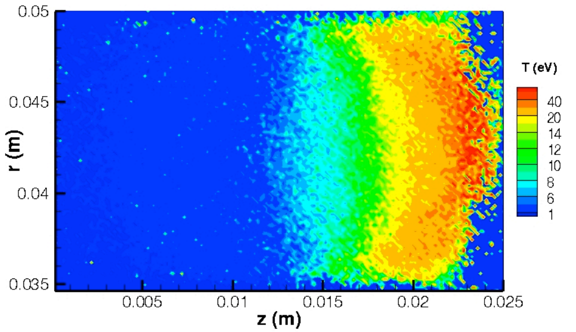
All the most important features of the Hall discharge have been reproduced with a good agreement with measurements.

The axial distribution shows the acceleration occurring in the last fifth part of the channel length where the electron temperature reaches its maximum value of Te=40 eV at z=2.2 cm.

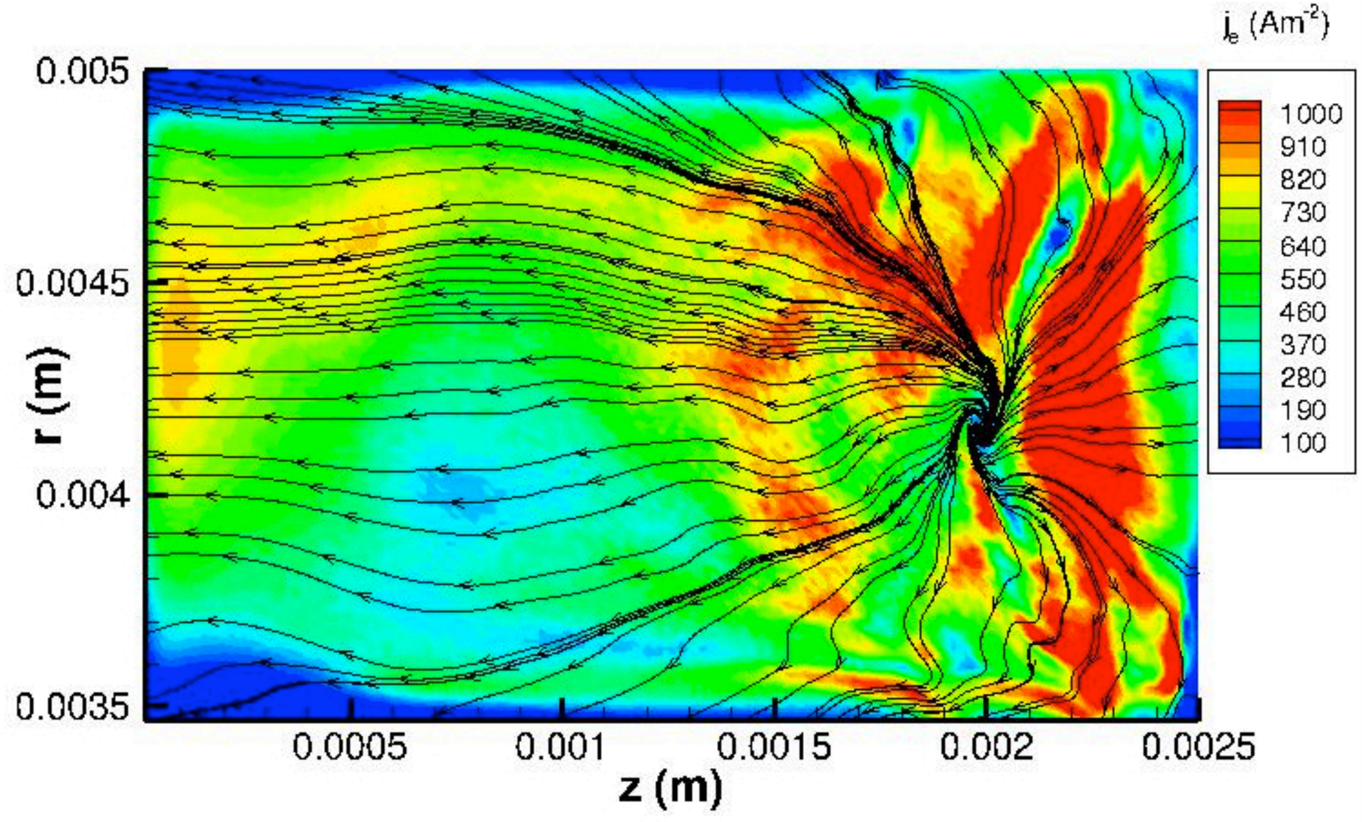
The radial behaviour shows a very slight asymmetry between inner and outer wall. Inverted sheaths are detected in the acceleration region where a strong secondary electron emission due to the high ExB drift occurs.







2D(r,z) Results



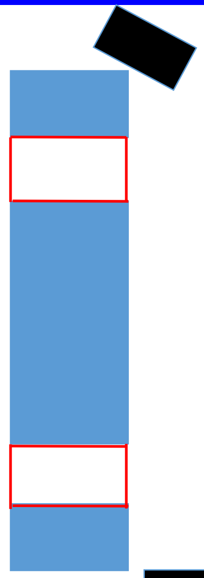
3D(r,θ,z) Model

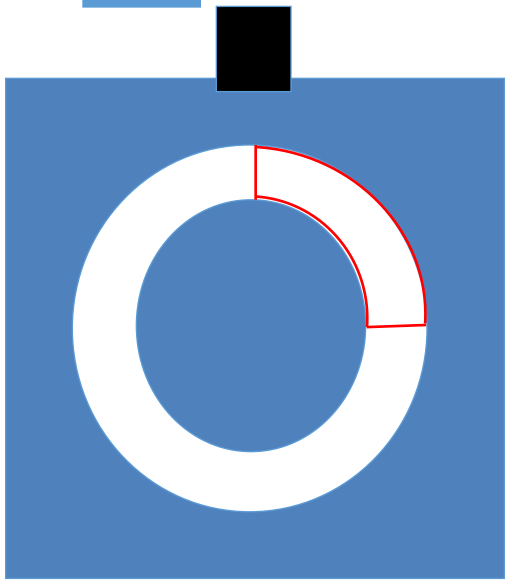
o 1D(r) / acceleration region
o 2D(r,θ) / acceleration region
o 2D(r,z) / discharge channel
o 3D(r,θ,z) / discharge channel

- Domain: - radial from inner to outer wall;
  - azimuthal: $\pi/2$
  - axial from anode to exit plane
- Initial condition: start from scratch
- Injection condition: steady-state electron current control method from exit plane

$$\Delta n_{e,inj} = \Delta n_e^{anode} - \Delta n_i^{anode} - (\Delta n_i^{exitplane} - \Delta n_e^{exitplane})$$

- Field solve: Dielectric surface conductivity neglected $\frac{\partial \phi}{\partial r} = \frac{\sigma}{\varepsilon_0}$
- electron-atom MCC module
- electron-wall SEE module
- Realistic ion mass, vacuum permittivity
- Assumption: - fixed potential (cathode) at the exit plane
  - geometrical scaling
- Numerical parameter: - $N_g = N_r x N_\theta x N_z = 100x128x160$ (grid points)
  - $N_p/N_g = 50$ (particles per cell)





3D(r,θ,z) Geometrical Scaling

Reduction of size *L* keeping constant most relevant non-dimensional parameters:

Ionization $\frac{\lambda_{eN}}{L} \approx \frac{1}{n_N \sigma L} = k$

Confinement $\frac{\rho_{L,e}}{L} \approx \frac{v_e}{BL} = k$

∋ the discharge still keeps its plasma characteristics:

$\omega_p >> \nu_{eN}$ (low collisionality)

$L >> \lambda_D$ (global quasi-neutrlity)

$\rho_{L,e} >> \lambda_D$ (unmagnetized sheath)

$\rho_{L,i} >> L$ (unmagnetized ion)

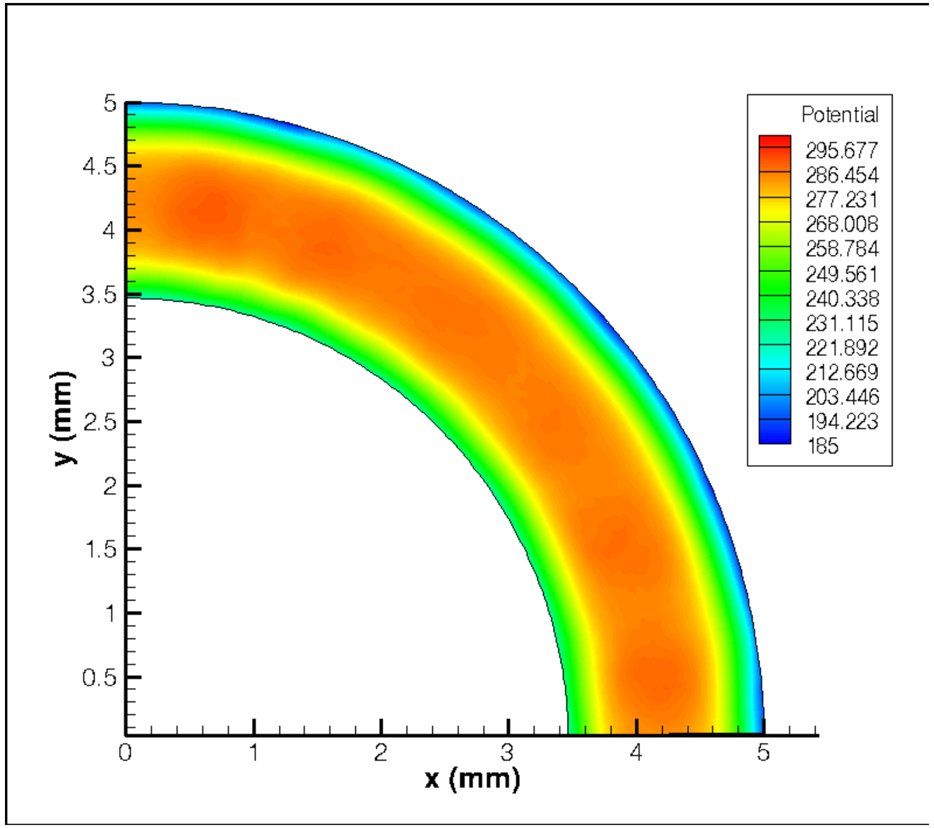
$L >> L_{grad}$ (gradient driven instability)

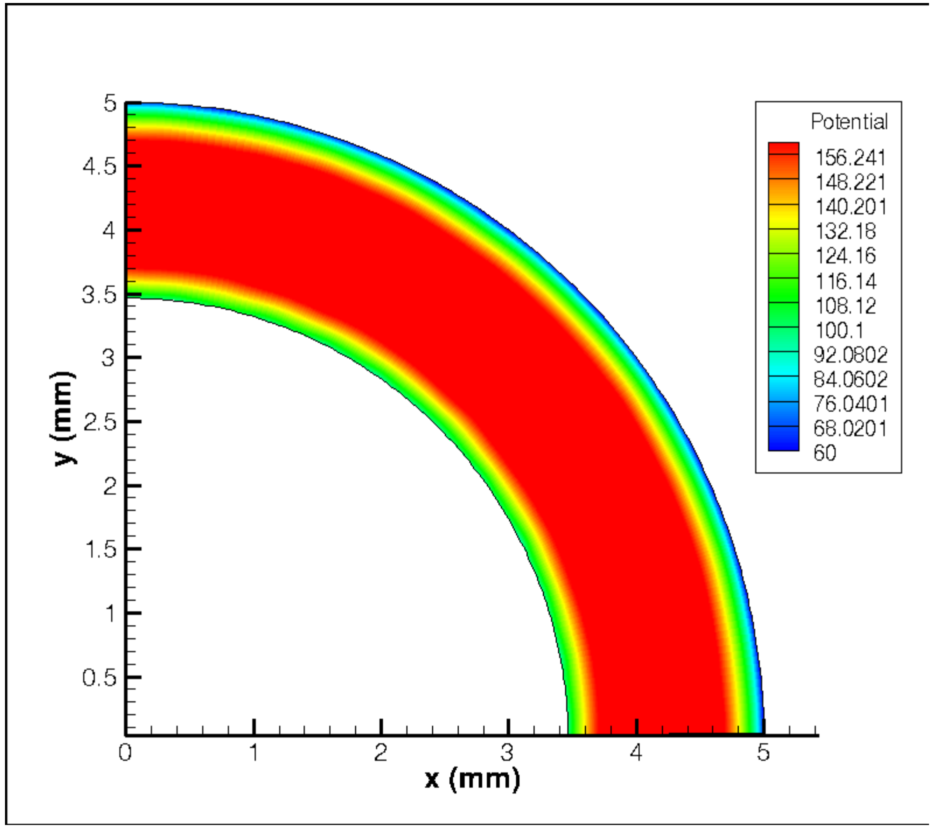
$\gamma^{-1} >> \tau_i$ (instability growth > ion convection)

Length	$L = fL^*$
Magnetic field	$B = f^{-1} B^*$
Neutral density	$n_G = f^{-1} n_G^*$
Current	$I_D = f^{-2} I_D^*$

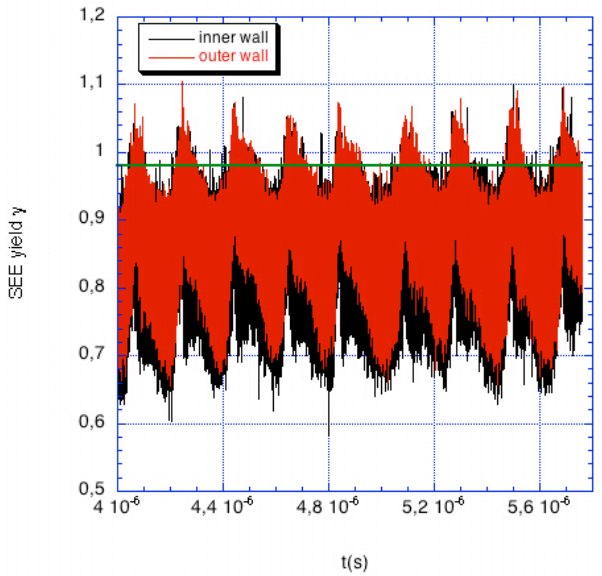
Unavoidably S/V changes !
keep under control SEE

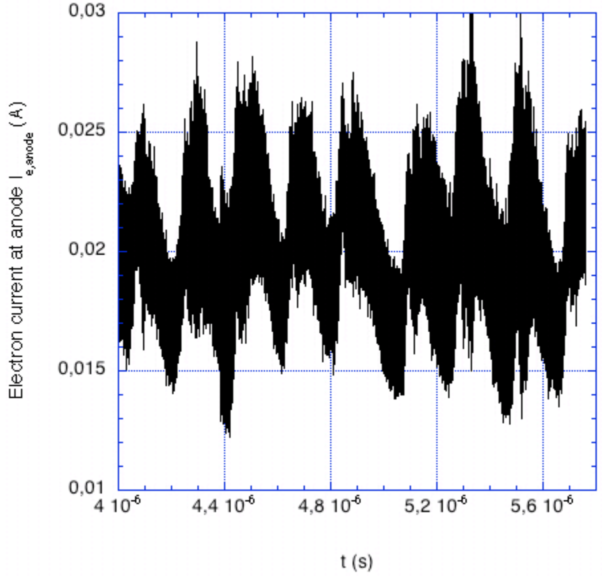
3D(r,θ,z) Results

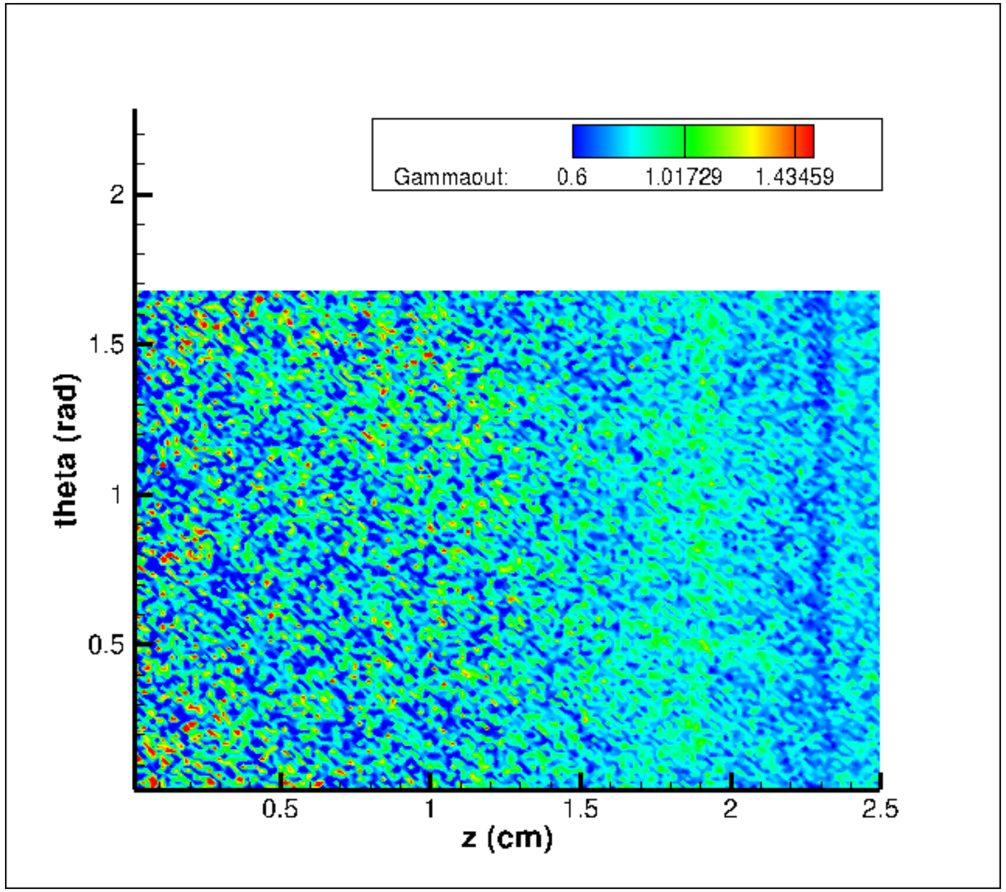




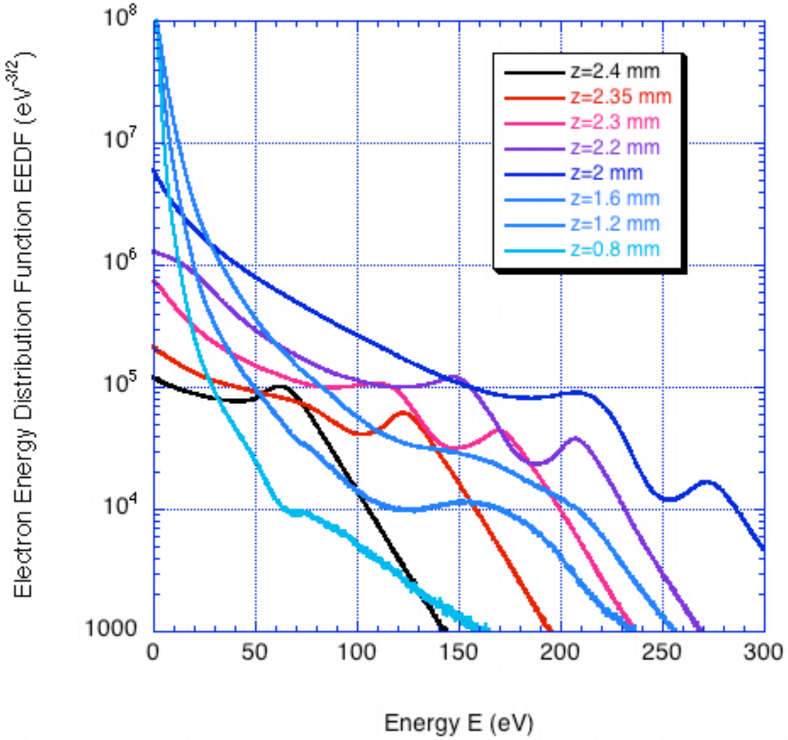
3D(r,θ,z) Results

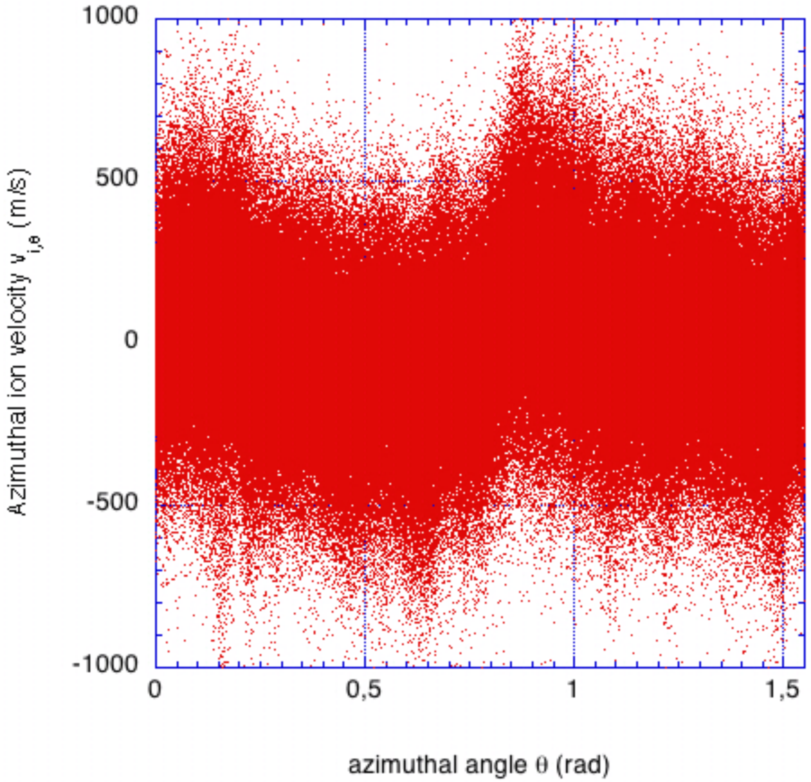




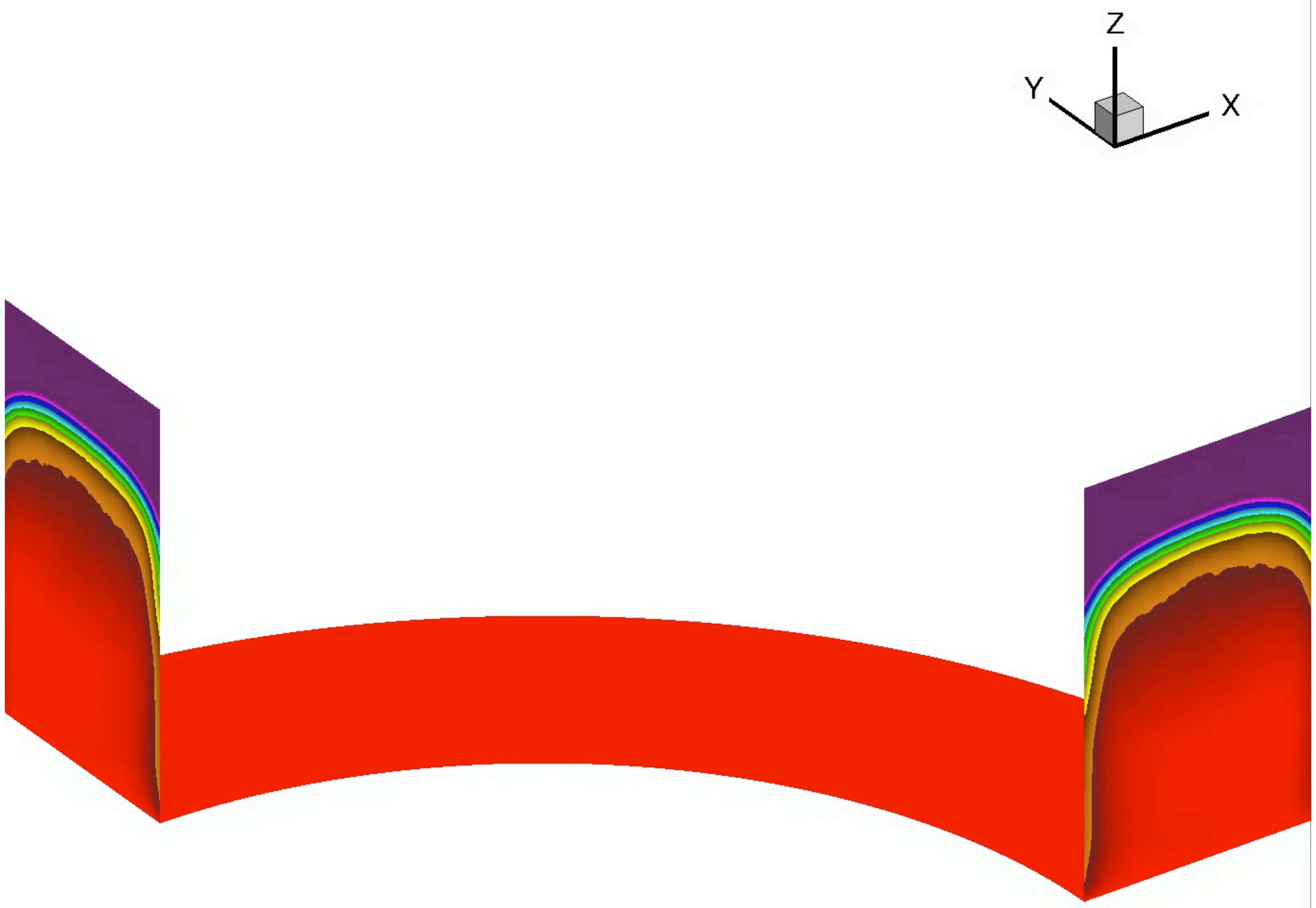


3D(r,θ,z) Results

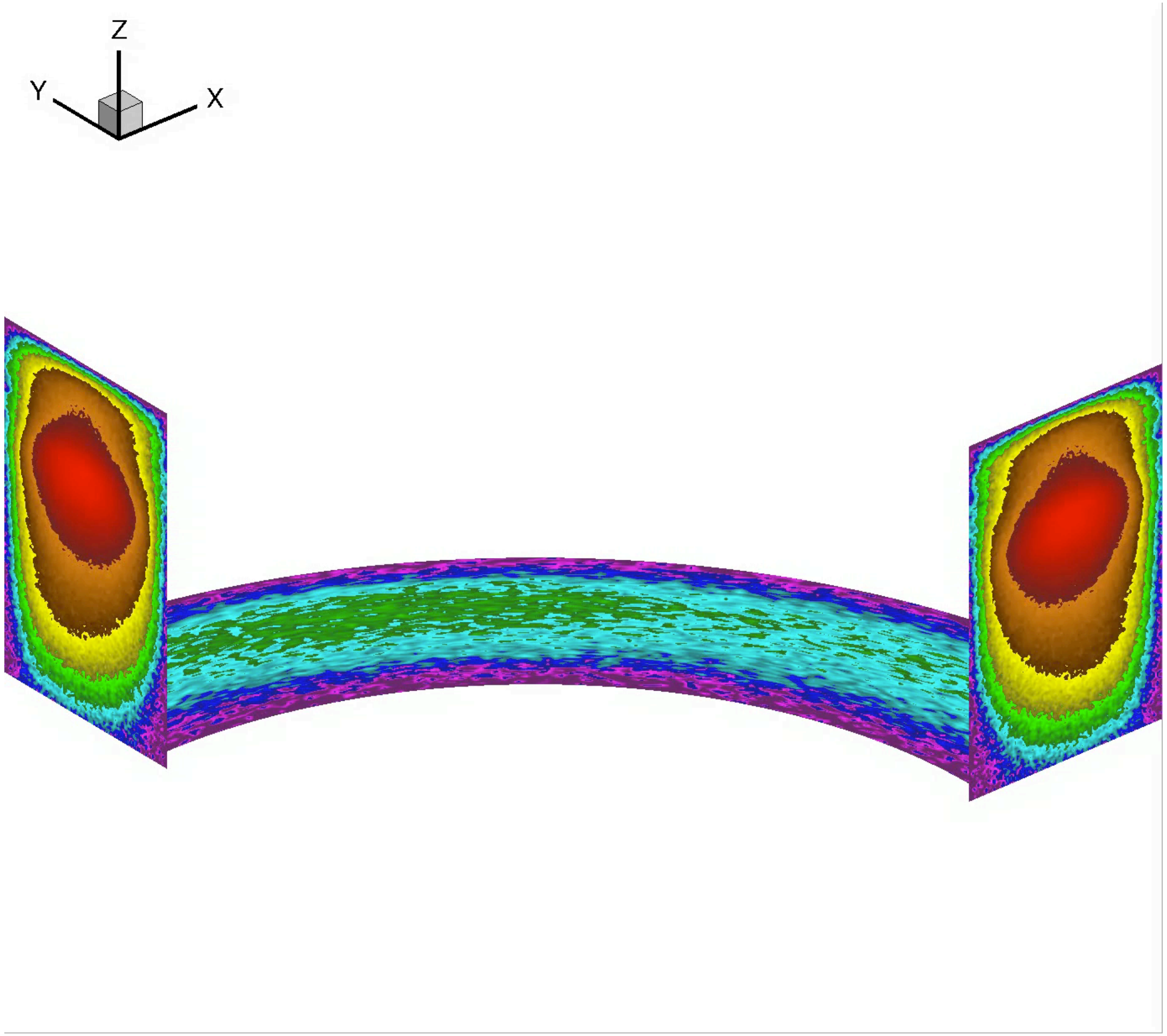




3D(r,θ,z) Results



3D(r,θ,z) Results



3D(x,y,z) Model

o 1D(r) / acceleration region
o 2D(r,θ) / acceleration region
o 2D(r,z) / discharge channel
o 3D(r,θ,z) / discharge channel
o 3D(x,y,z) / discharge channel + near-field plume

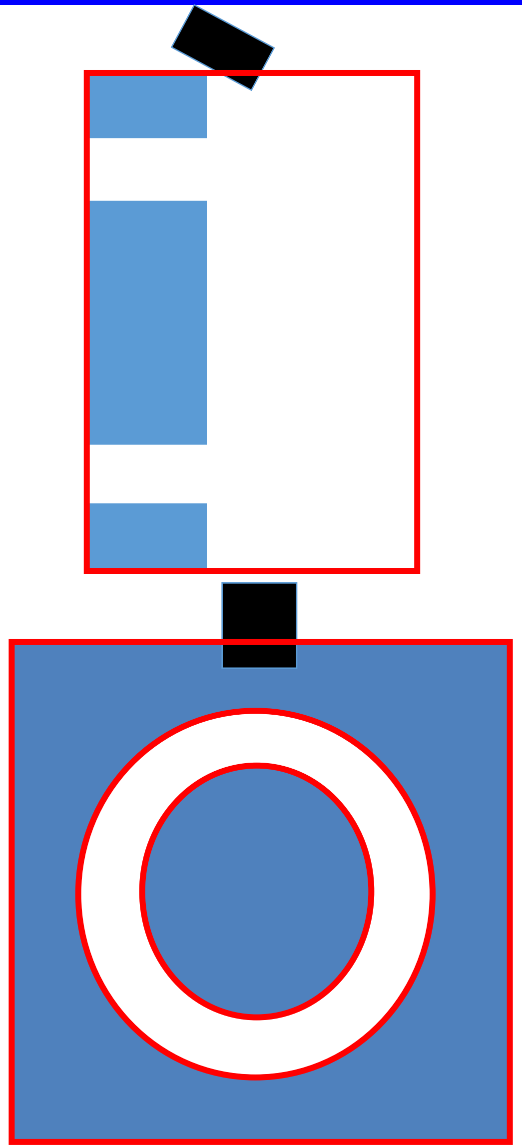
- Domain: - transverse x,y: 16 cm
  - axial from anode to 6 cm from exit plane
- Initial condition: start from scratch
- Injection condition: steady-state electron current control method from cathode

$$\Delta n_{e,inj} = \Delta n_e^{anode} - \Delta n_i^{anode}$$

- Field solve: complete (even in the dielectric)

$$\nabla \cdot \left[\varepsilon \nabla \phi \right] = -\frac{\rho}{\varepsilon_0}$$

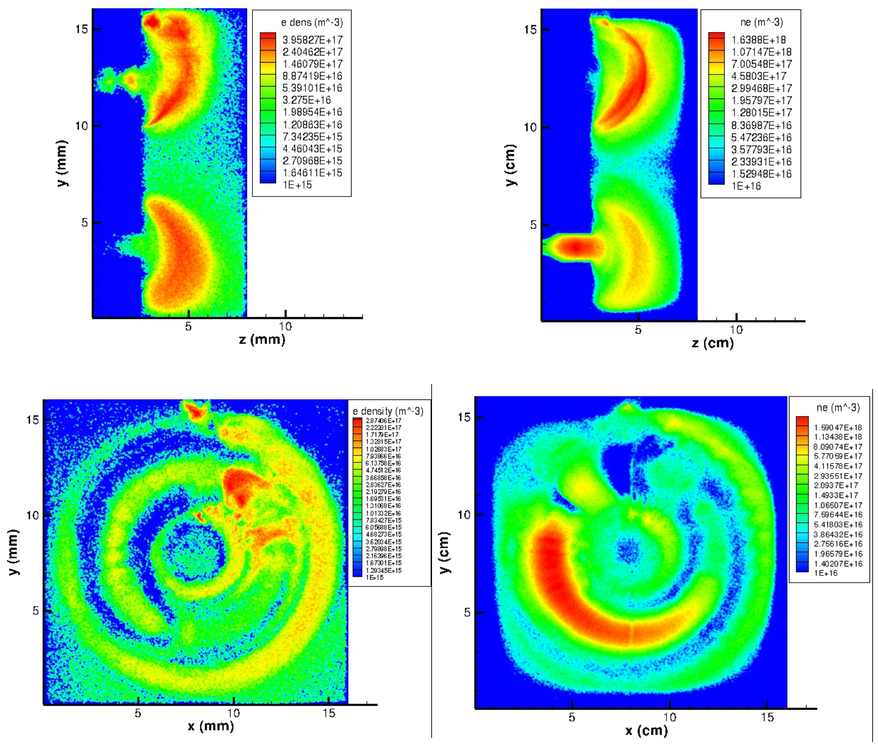
- electron-atom MCC module
- ion-atom TPMC module
- electron-wall SEE module
- Realistic ion mass, vacuum permittivity
- Assumption: - fixed potential at outflow boundaries
  - geometrical scaling
- Numerical parameter: - $N_g = N_r x N_\theta x N_z = 320x320x160$ (grid points)
  - $N_p/N_g = 40$ (particles per cell)



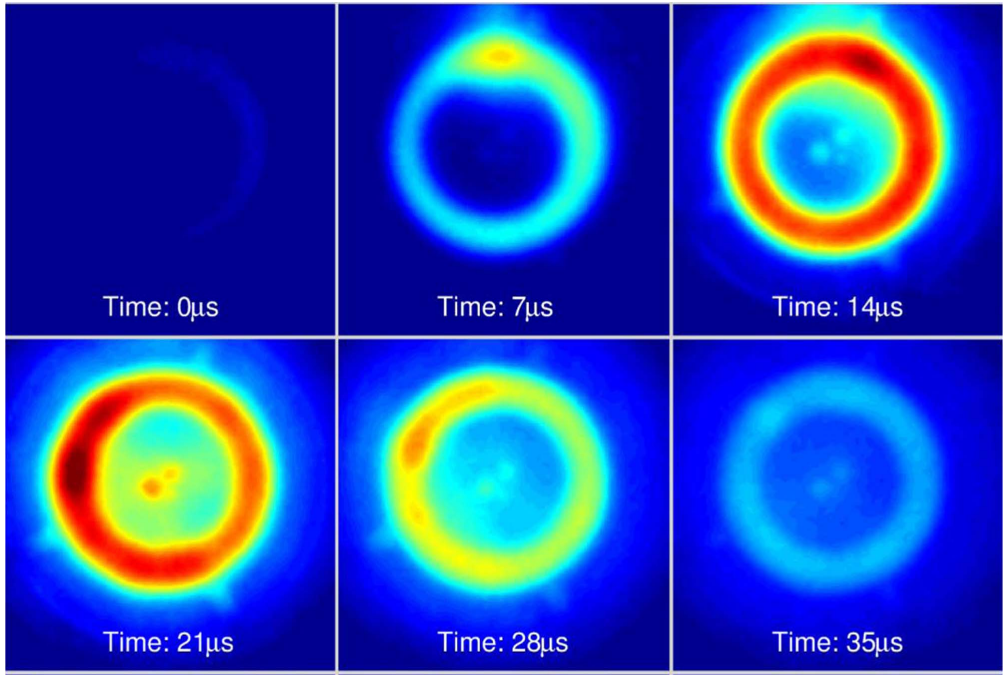
3D(x,y,z) Results

t=3.5 μs

t=4 μs

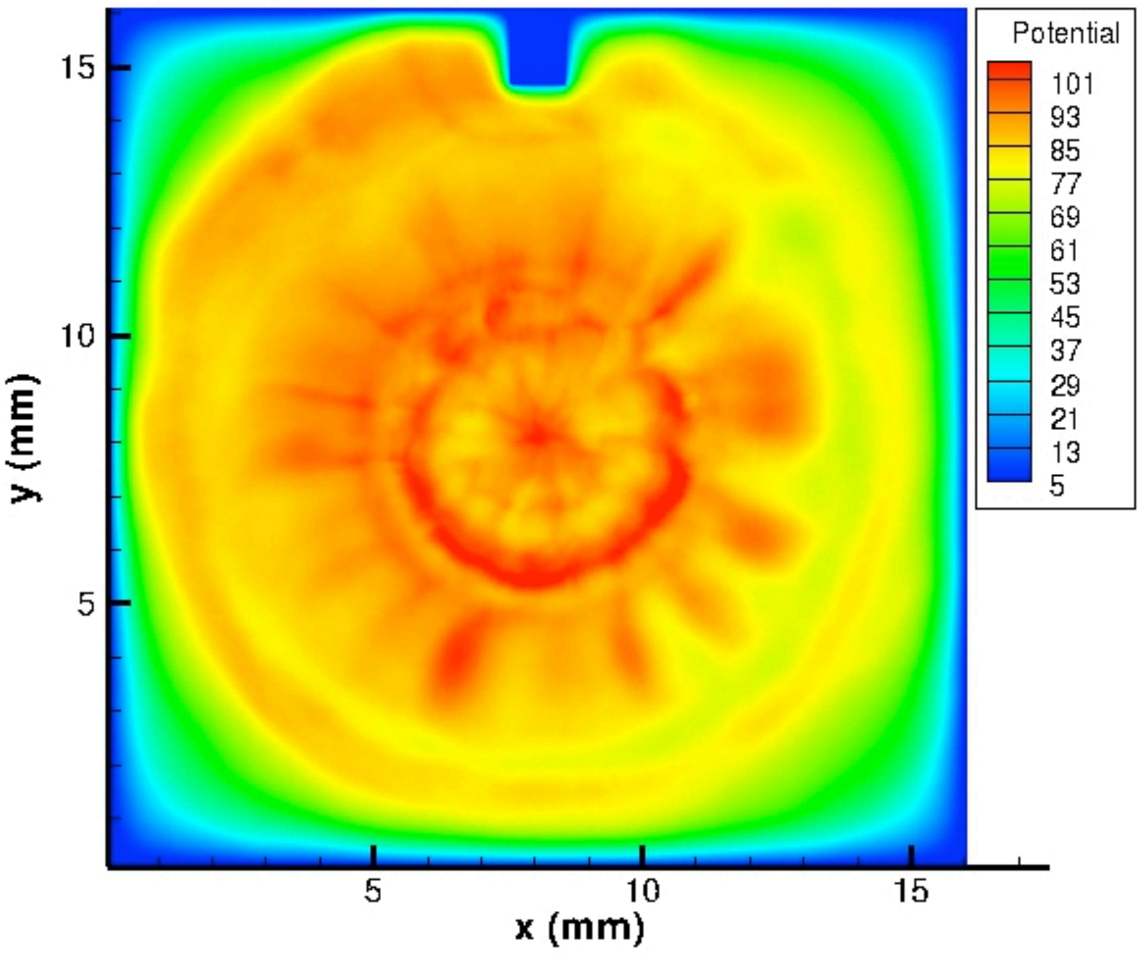


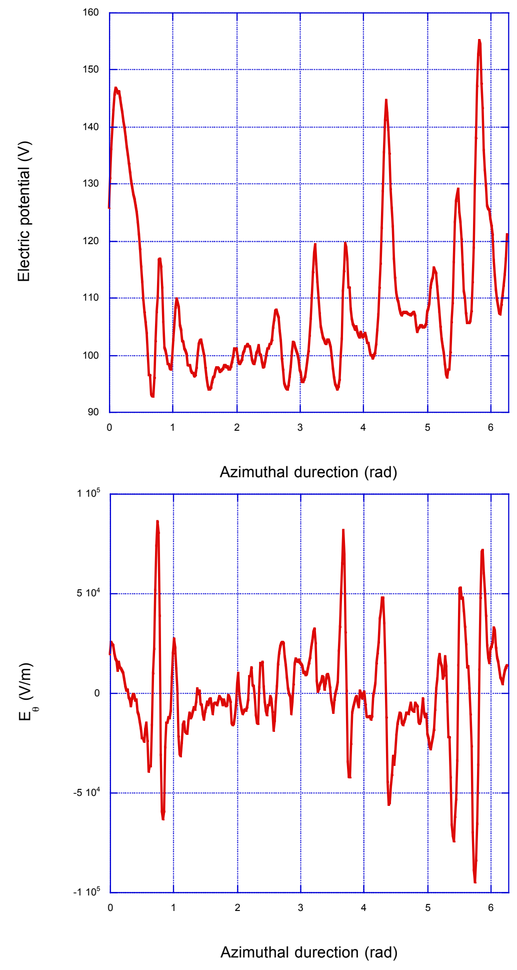
Thruster start-up reveals a bright ionization period.
The cathode introduces azimuthal asymmetry, which persists for about 30 μs into the ignition



C. L. Ellison, Y. Raitses, and N. J. Fisch, IEEE TPS 2011

3D(x,y,z) Results





3D(x,y,z) Hybrid Model

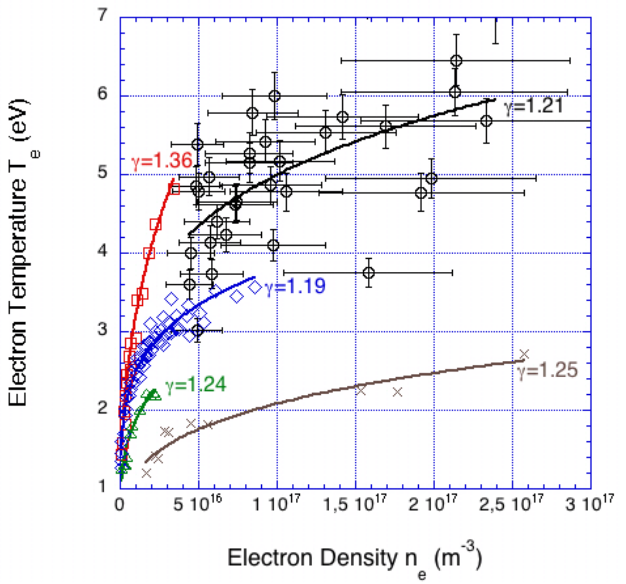
- o 1D(r) / acceleration region
- o 2D(r,θ) / acceleration region
- o 2D(r,z) / discharge channel
- o 3D(r,θ,z) / discharge channel
- o 3D(x,y,z) / discharge channel + near-field plume
- **o 3D(x,y,z) / far-field plume**

- Domain: - transverse x,y: 0.5 m
  - 1m from exit plane
- Initial condition: start from scratch
- Injection condition: prescribed ion current from exit plane (current distribution from discharge channel output)
- Field solve: quasi-neutrality $n_e=n_i$ (inversion of Boltzmann relation)

$$\phi(x,y,z)=\phi_0-\frac{kT_{e,0}}{q(\gamma-1)}\left[1-\left(\frac{n_e(x,y,z)}{n_{e,0}}\right)^{\gamma-1}\right]$$

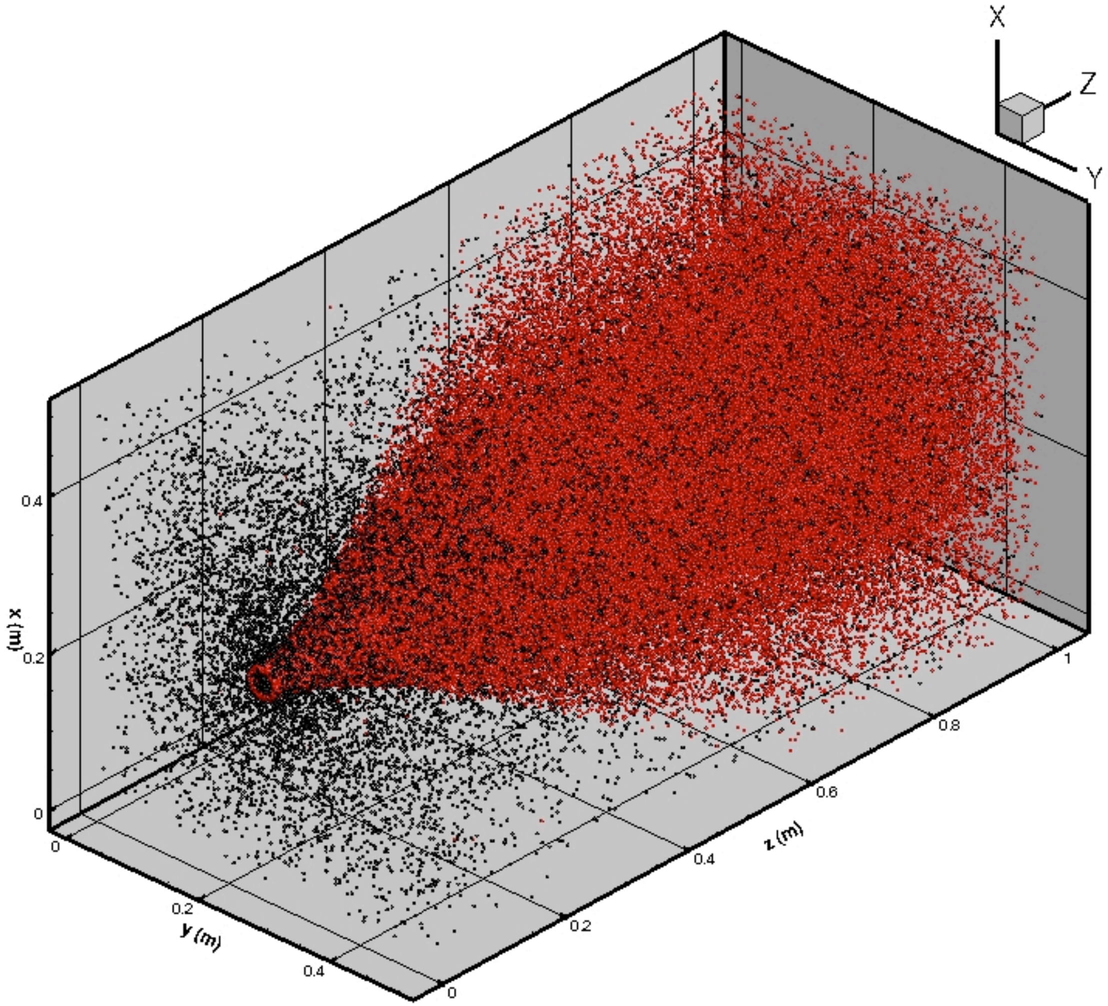
- ion-atom TPMC module
- Electron: fluid-like (adiabatic relation γ=1.3)

$$T_e(x,y,z)=T_{e,0}\left(\frac{n_e(x,y,z)}{n_{e,0}}\right)^{\gamma-1}$$

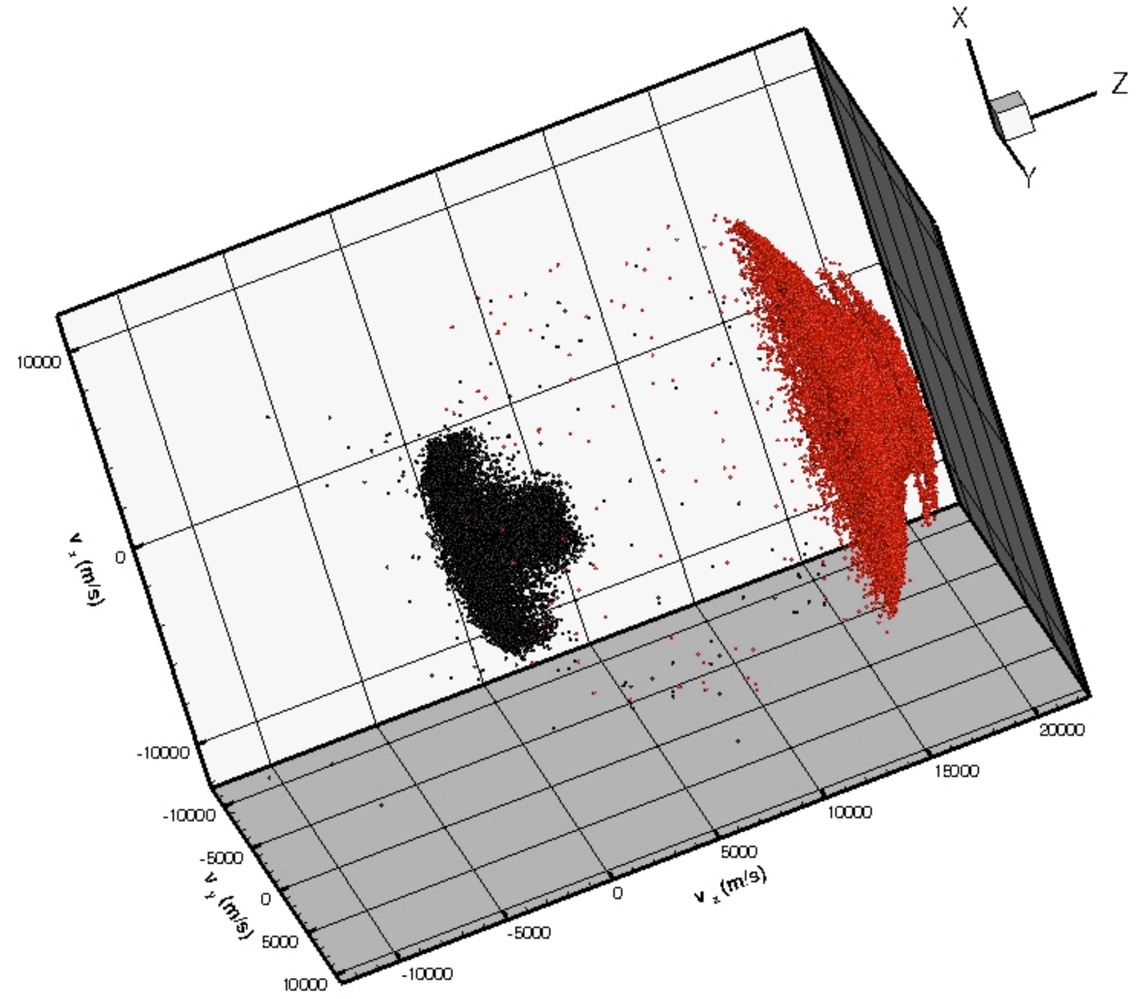


- Numerical parameter: - $N_g=N_r x N_\theta x N_z$=100x100x200 (grid points)
  - N_p/N_g=20 (macroions per cell)

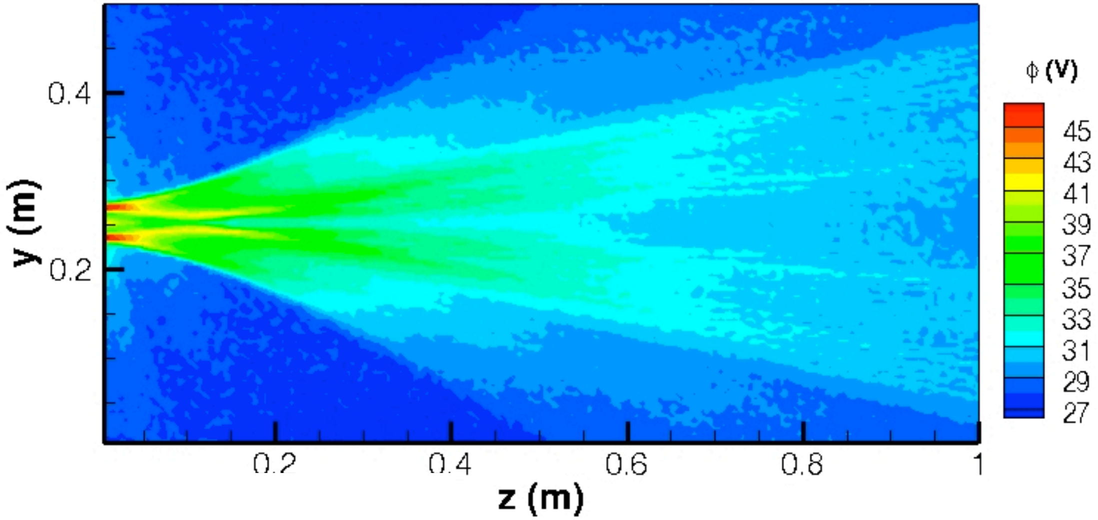
3D(x,y,z) Hybrid Results

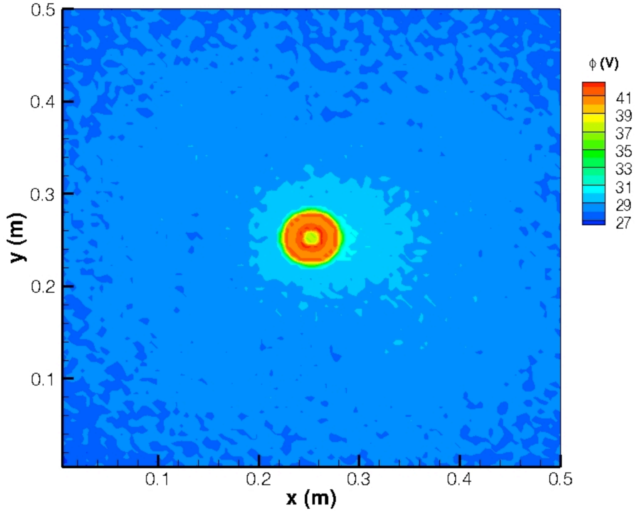


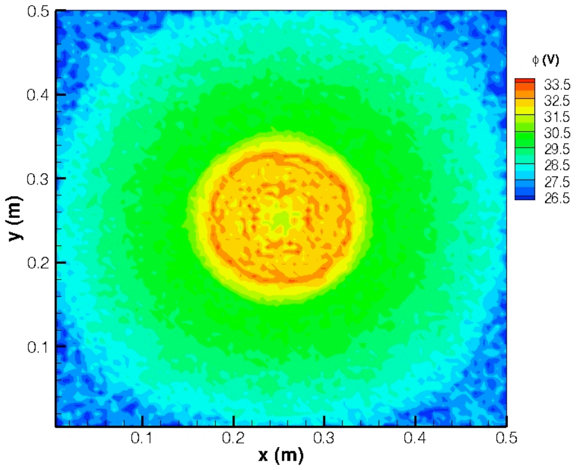
3D(x,y,z) Hybrid Results



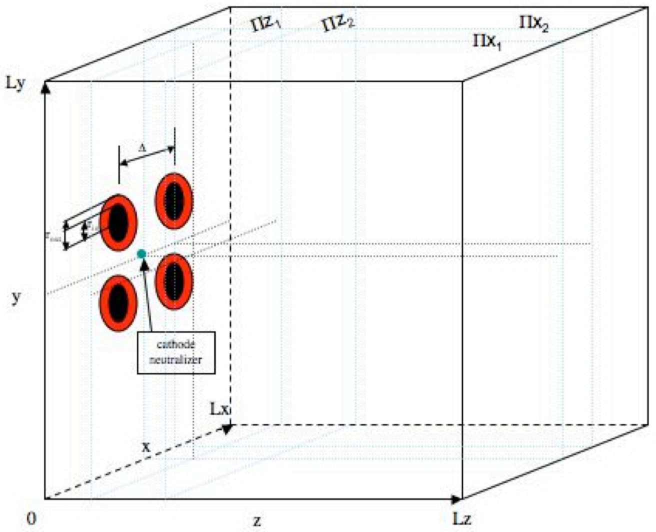
3D(x,y,z) Hybrid Results

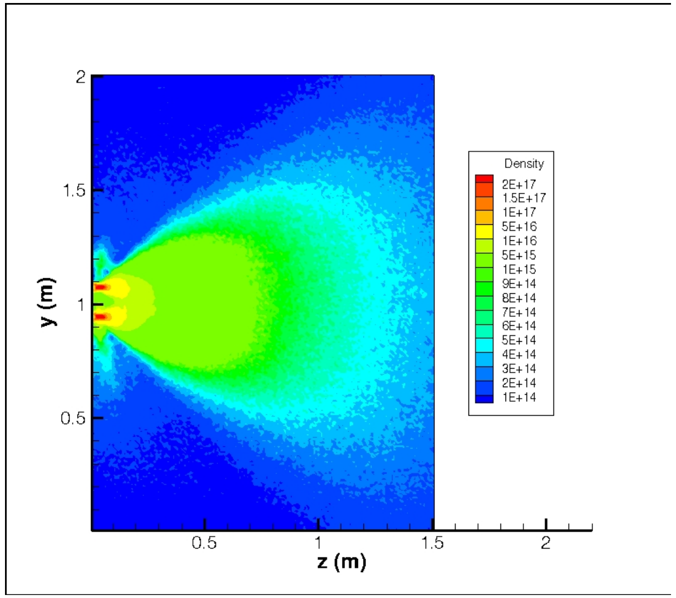


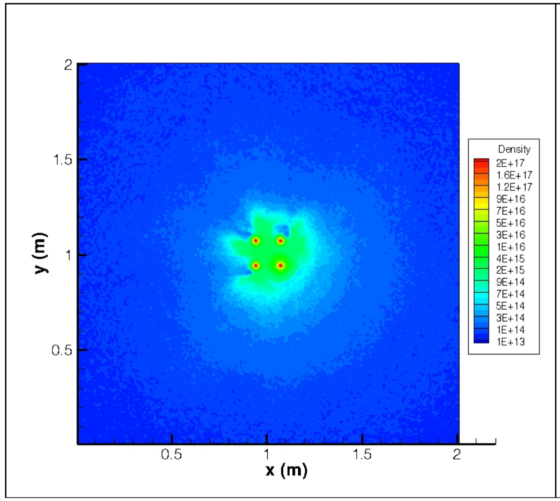


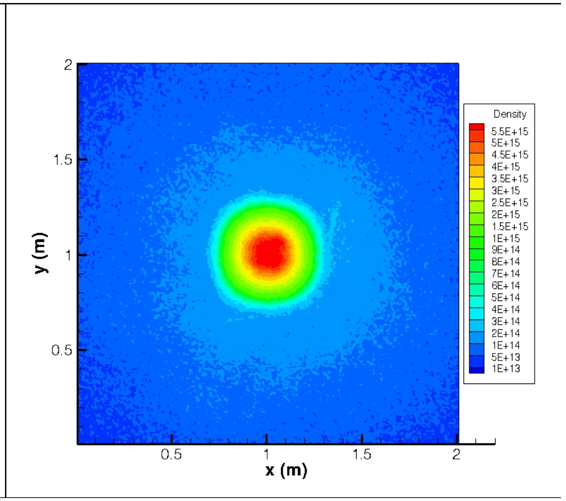


3D(x,y,z) Cluster Hybrid Results

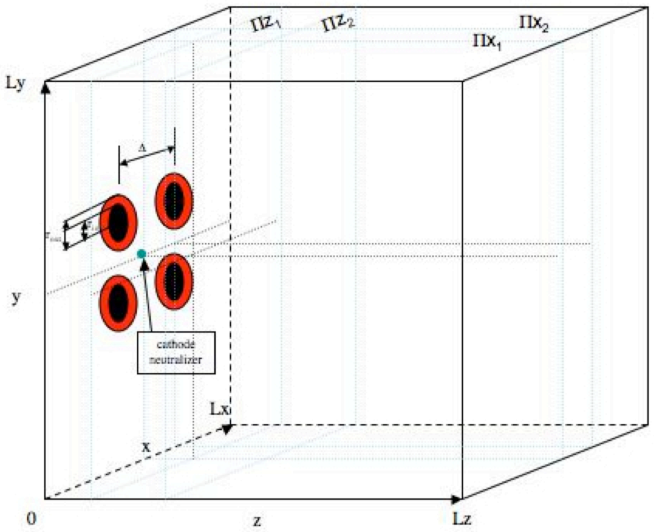


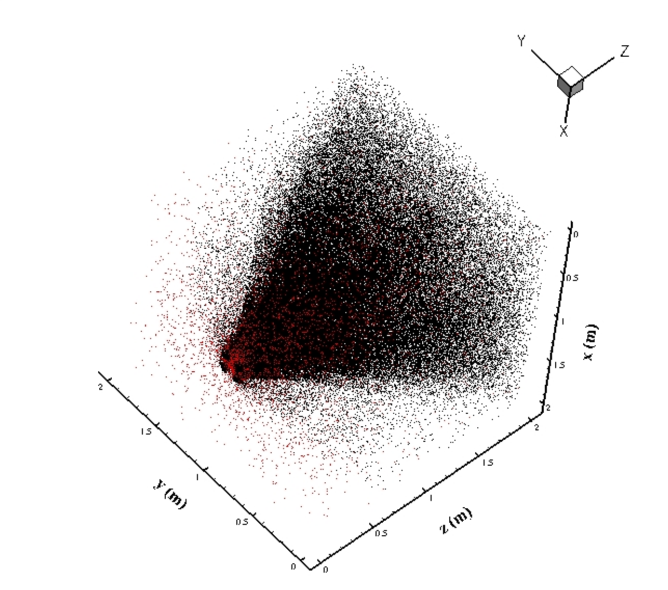


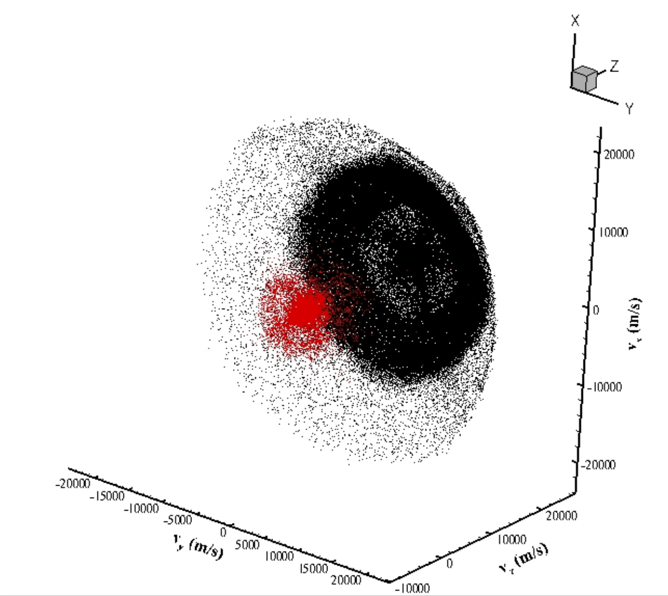




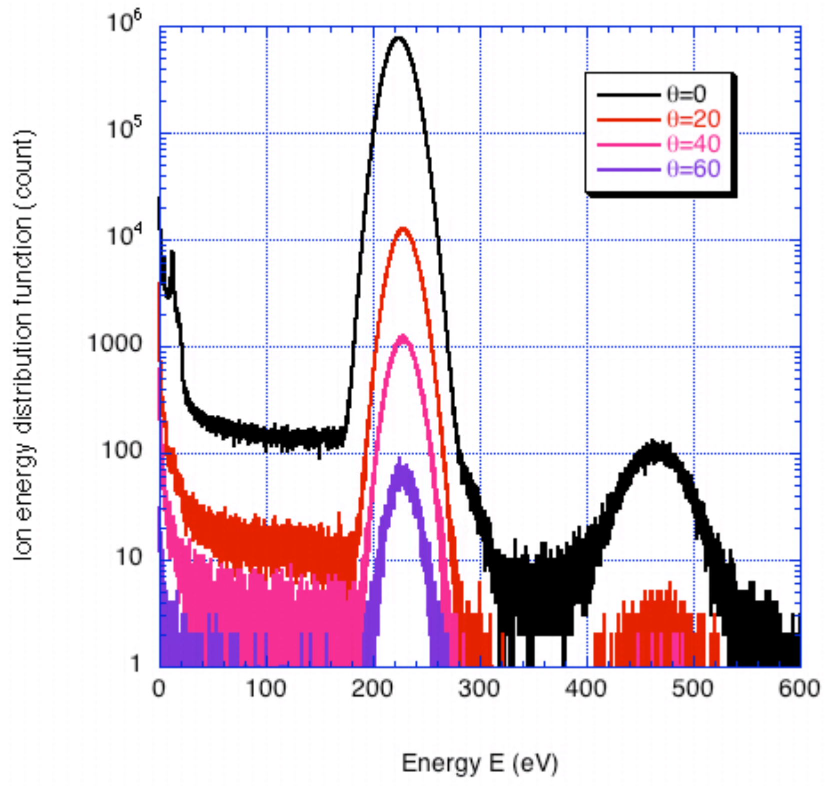
3D(x,y,z) Cluster Hybrid Results

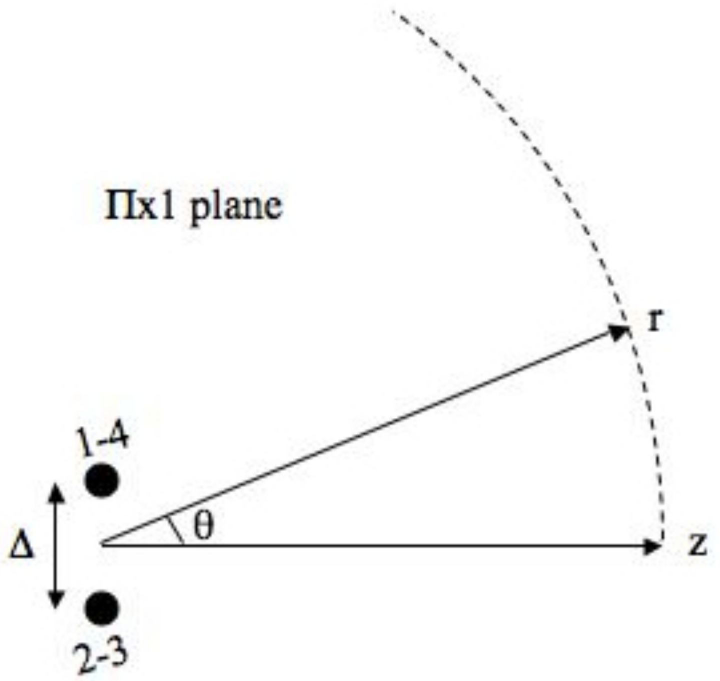






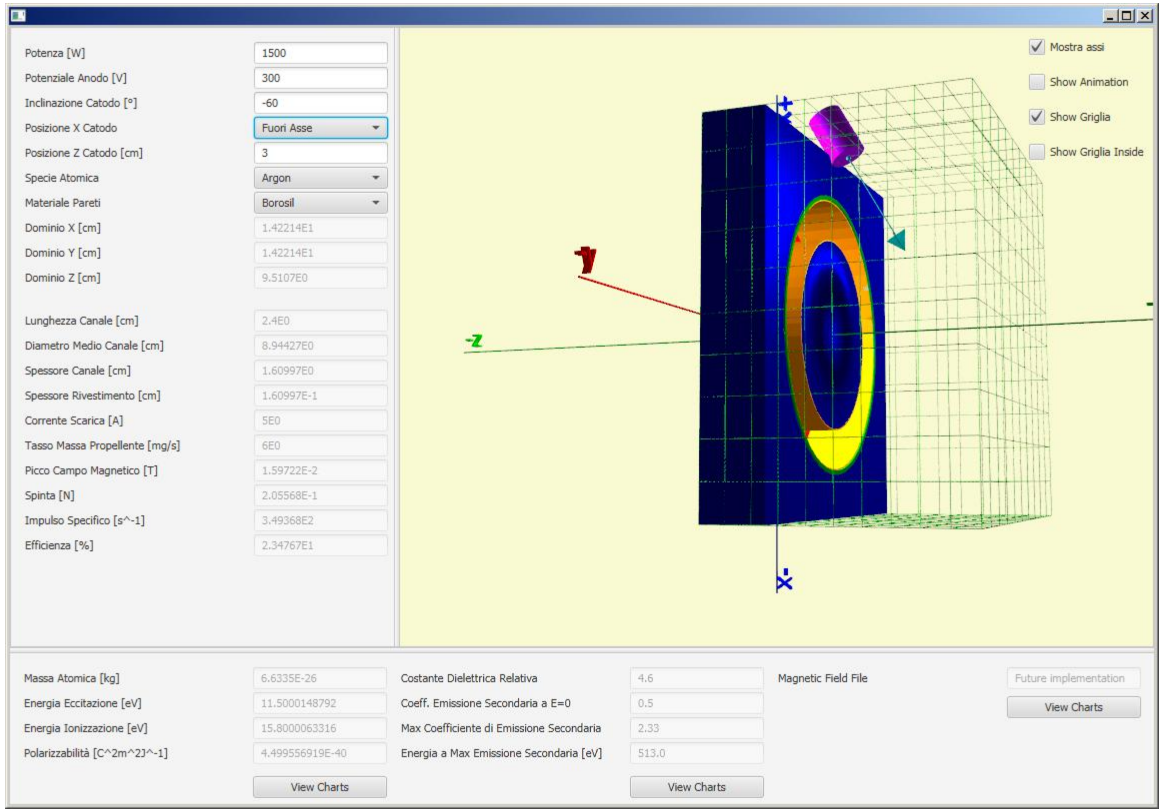
3D(x,y,z) Hybrid Results





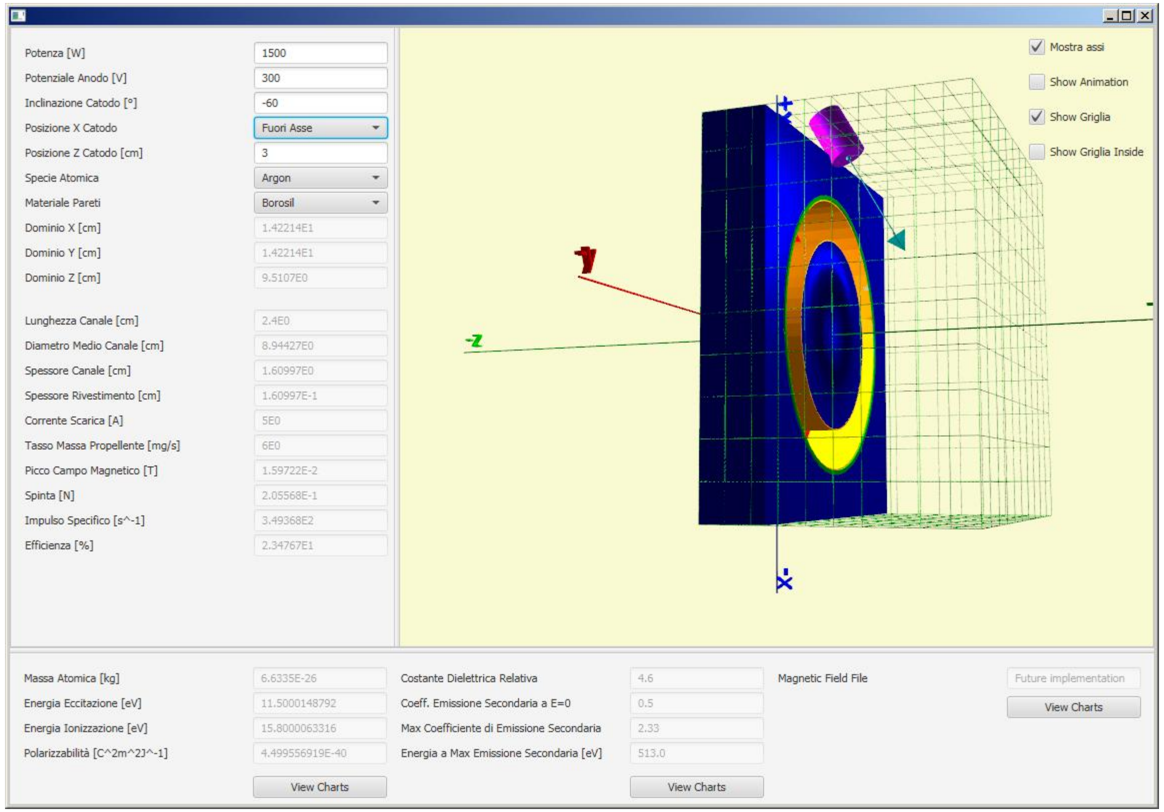
GUI for channel+NF plume Model

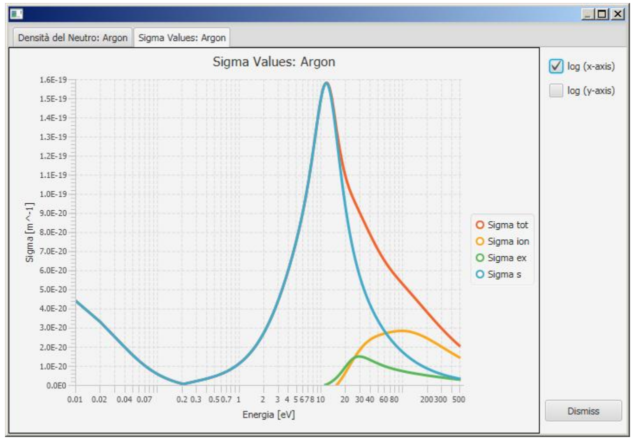
- ✓ GUI for user friendly (by EnginSoft) (see demonstration at poster session)



GUI for channel+NF plume Model

✓ GUI for user friendly (by EnginSoft)

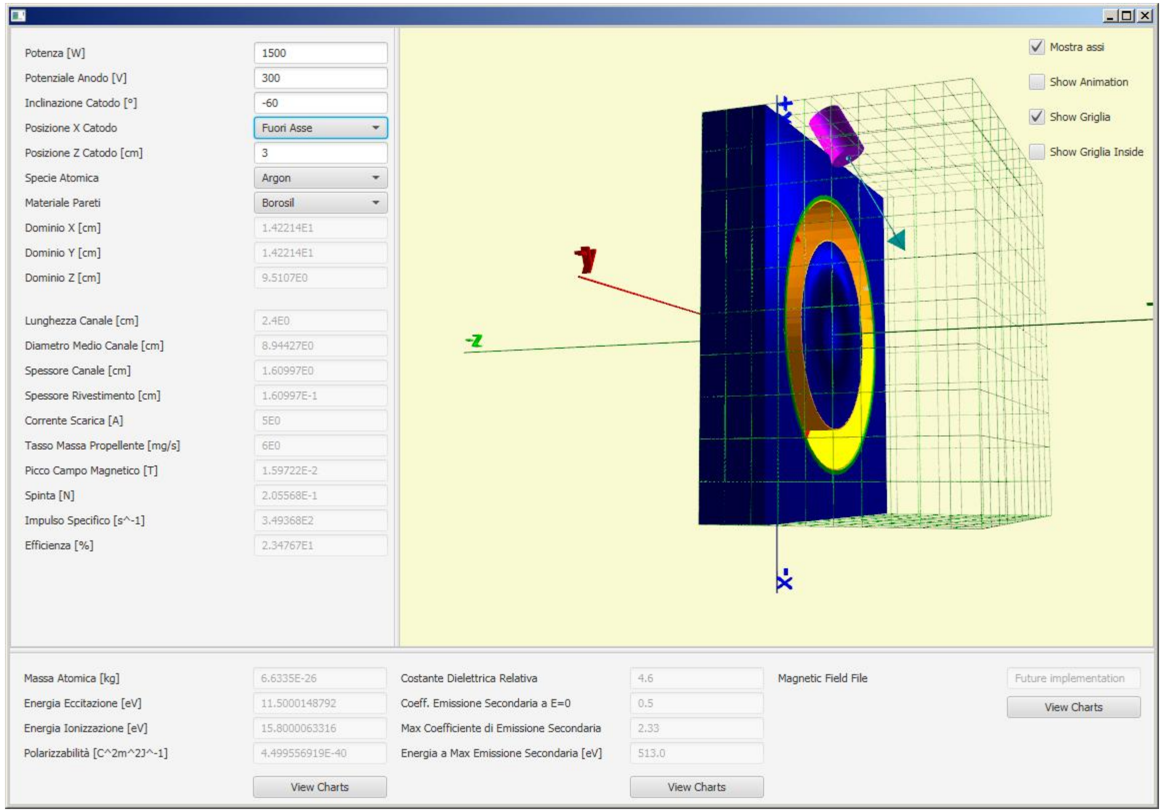


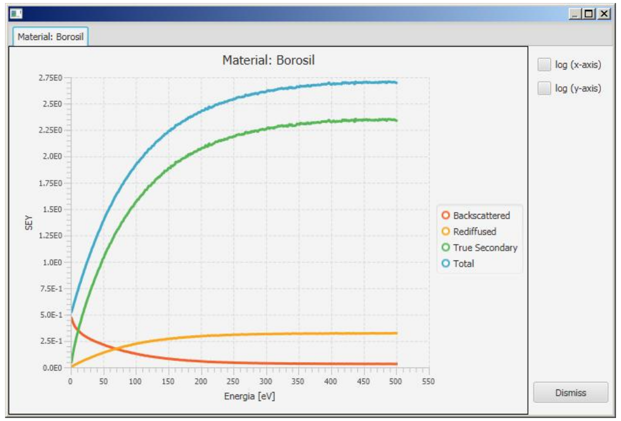


Gas propellant collision data

GUI for channel+NF plume Model

- ✓ GUI for user friendly (by EnginSoft)

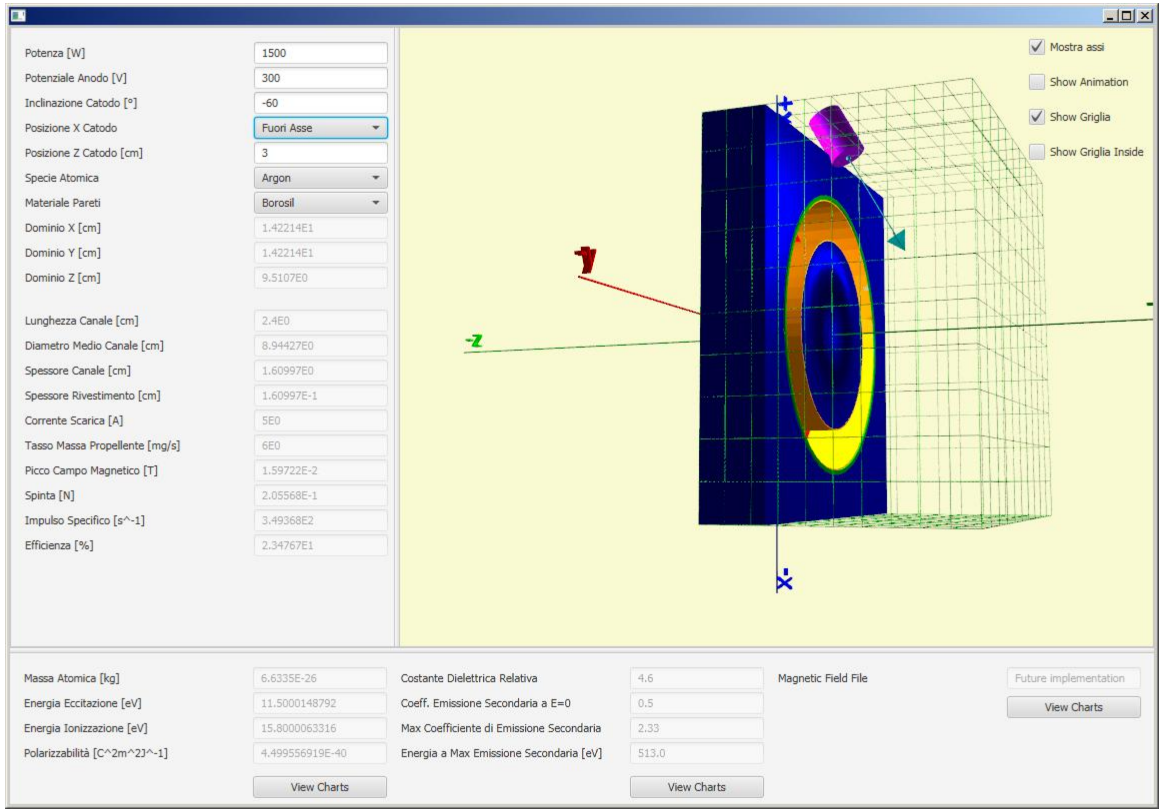




Electron-wall SEE data

GUI for channel+NF plume Model

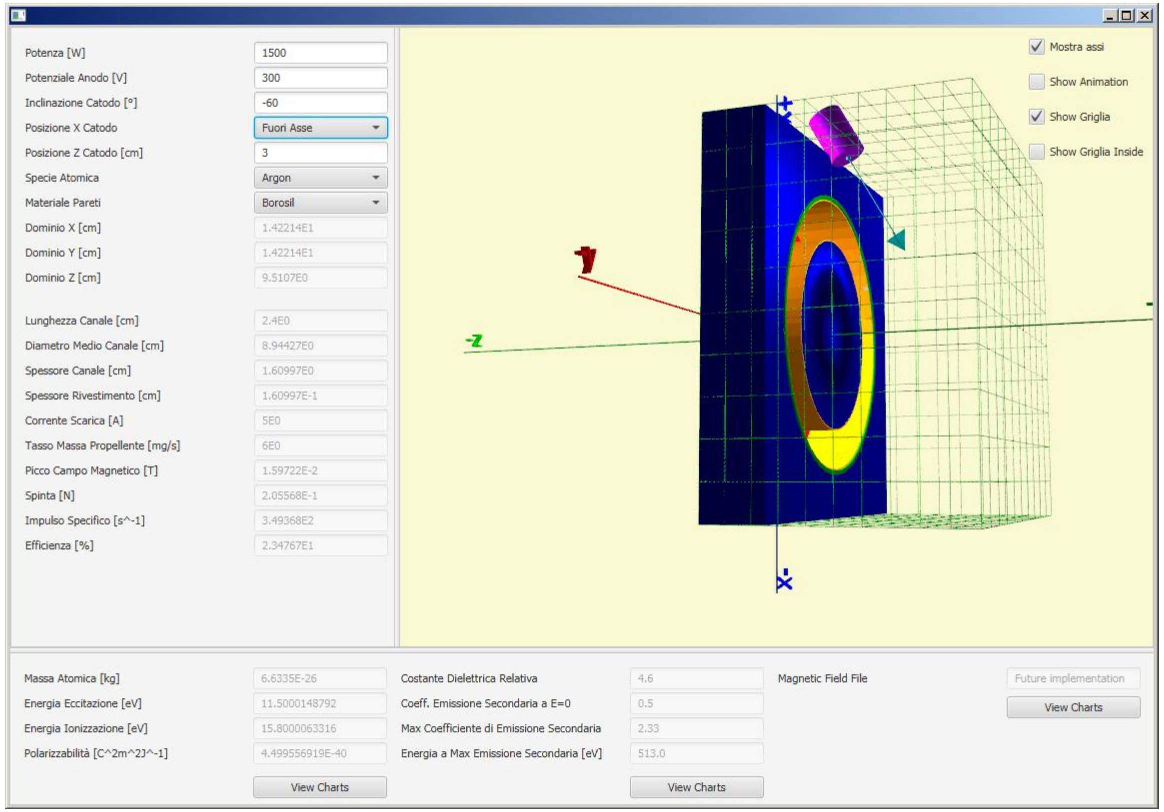
- ✓ GUI for user friendly (by EnginSoft)

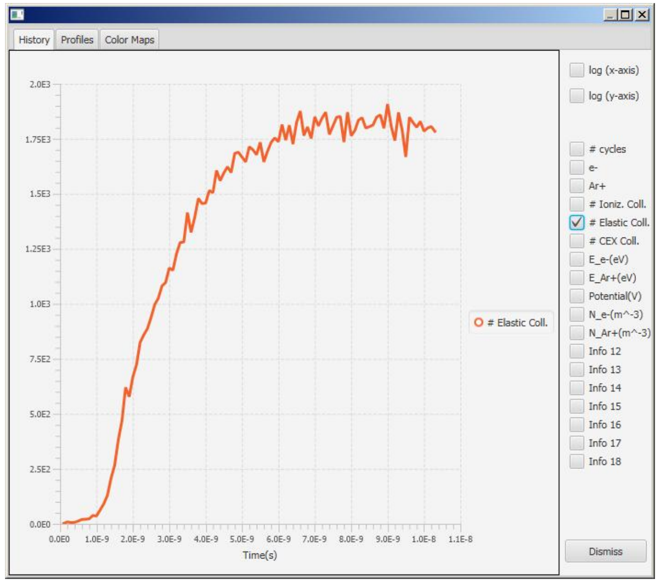


Import Magnetic field map

GUI for channel+NF plume Model

- ✓ GUI for user friendly (by EnginSoft)

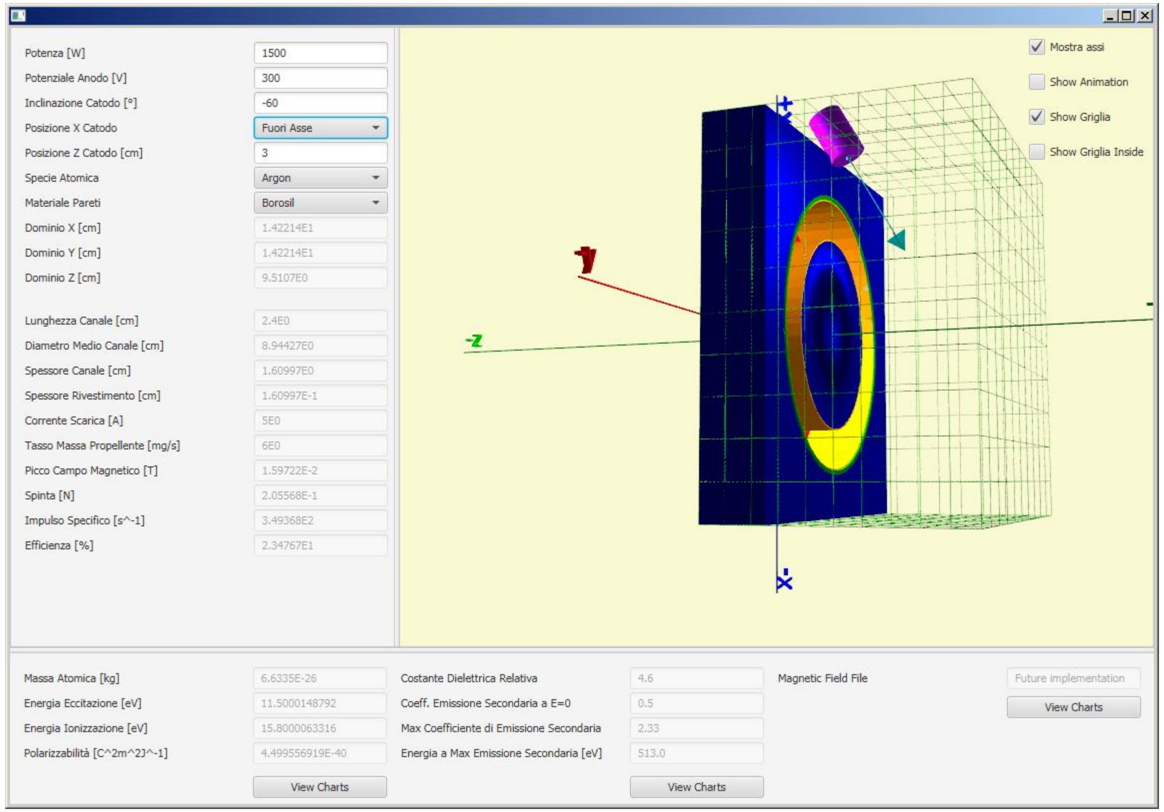


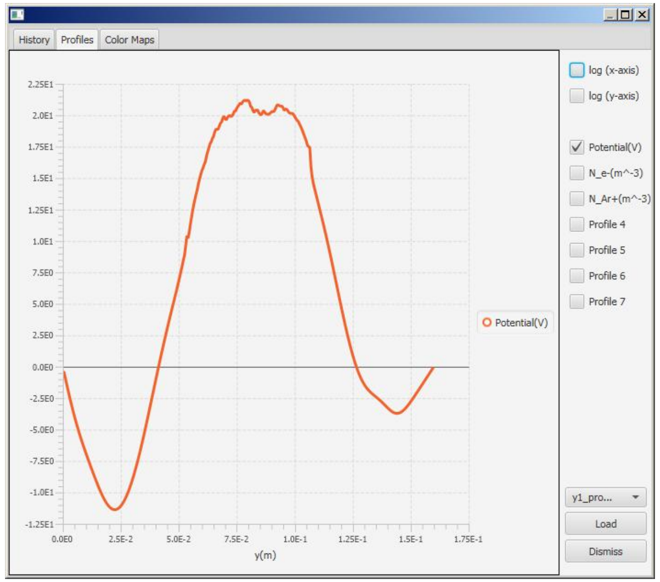


Output data

GUI for channel+NF plume Model

✓ GUI for user friendly (by EnginSoft)





Output data

Conclusions

- **Importance of having a detailed representation up to a kinetic level: deviation from Maxwellian has important macroscopic effects (instability, wall losses and sheath, ionization rate, etc.)**

- **PIC-MCC easy to implement / modular / versitile / allows to reproduce in detail plasma-boundary interaction / good scalability by HPC**

- **Low-dimensionality models help to understand limitations of using fixed external parameters (that otherwise play a relevant role due to strong correlation among the different dimensions)**

- **PIC-MCC is helping us to understand fundamental low T plasma phenomena but our intuition is important for the interpretation of results**