The contribution of INFN to the EMILIE Project

A. Galatà, on behalf of INFN team

Outline

- *Introduction*
- *Backgroung theory on charge breeding*
- *Charge breeding simulations*
- *Electromagnetic simulations*
- *Conclusions and perspectives*

INFN within EMILIE

LNL+LNS:

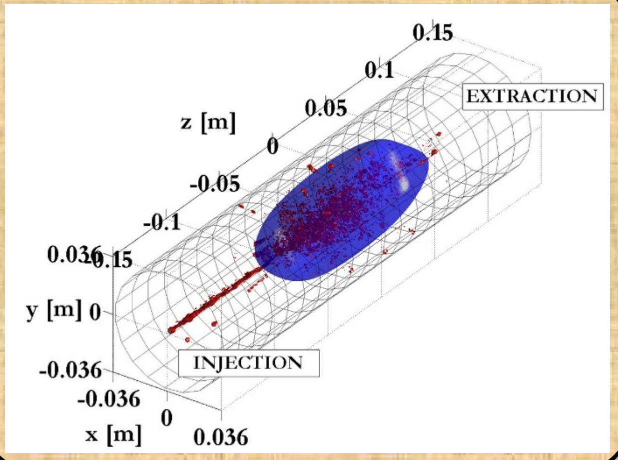
A. Galatà
G. Patti
L. Celona
D. Mascali
L. Neri
G. Torrisi

Roles:

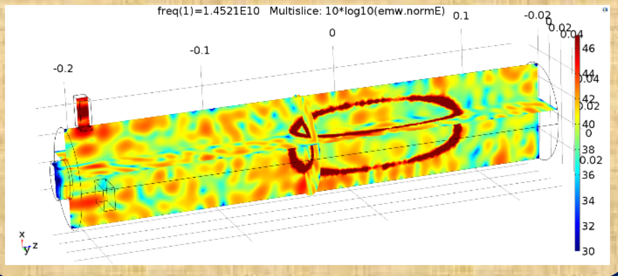
Deputy
WP3 Leader
Task 3.1 leader

GOAL
better understanding of the charge breeding process

Study of the capture process



Electromagnetic analysis



INFN activities: summary

Numerical tool for the CB process:

- ✔ *Developed in a Matlab environment.*
- ✔ *Implementation of the process validated by a simple model.*
- ✔ *Complete model benchmarked by experimental results.*

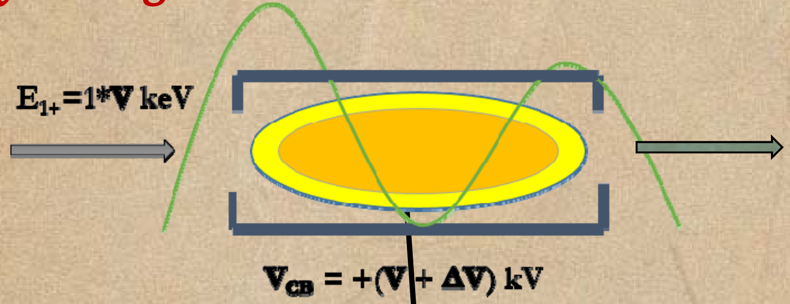
Electromagnetic study of the Phoenix plasma chamber:

- ✔ *Calculation performed with COMSOL.*
- ✔ *Interaction COMSOL-Matlab for the implementation of the plasma.*
- ✔ *Calculation of the resonant modes.*
- ✔ *Analysis in frequency domain.*
- ✔ *Confirmation of the frequency tuning effect, as observe during the SPES-CB acc. tests.*

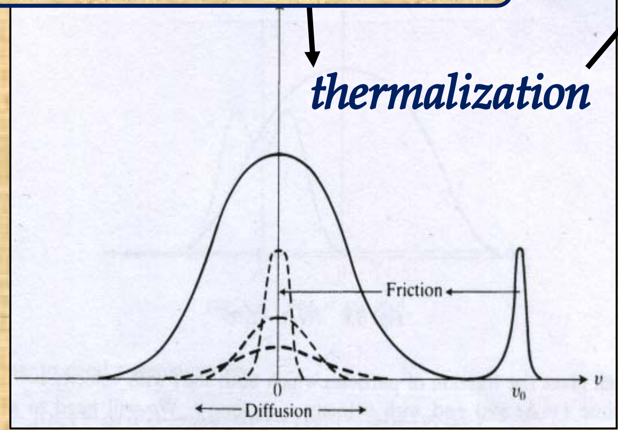
Study of the capture process

ECR-based CB process

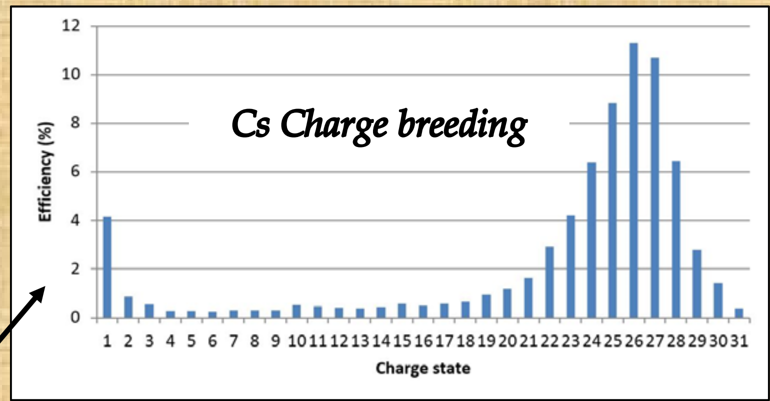
focusing, deceleration



Multiple Coulomb collisions



thermalization

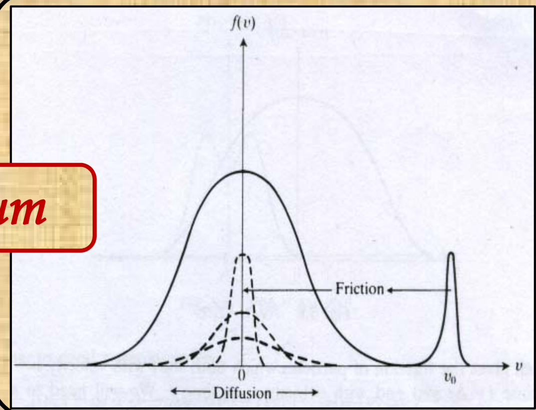


- ✓ *Step-by-step ionizations.*
- ✓ *Charge reduction (CE, EC…).*

In common with conventional ECR

Slowing down in a plasma

- ***Theory***: ***Chandrasekhar*** *(General)*, ***Spitzer*** *(Charger Particles)*



- *Ions moving in a MB plasma*

Thermal Equilibrium

- *Cumulative small angle collisions*

•*Coefficients of the Fokker-Plank equation*

$$\mathscr{D} f = \mathbb{C} = -\frac{\partial}{\partial \mathbf{v}} \cdot (\mathbf{A} f) + \frac{1}{2} \frac{\partial^2}{\partial \mathbf{v} \partial \mathbf{v}} : (\mathbf{B} f)$$

Dynamical Friction: $<\Delta v_{//}>$

Perp. diffusion: $<(\Delta v_{\perp})^2>=D_{\perp}$

Par. diffusion: $<(\Delta v_{//})^2>=D_{//}$

Coefficients

Equations

$$< \Delta \mathbf{v}_{\parallel} >= -\frac{A_D}{C_s^2}\left(1+\frac{m}{m_s}\right) G\left(\frac{v}{C_s}\right)$$

$$< (\Delta \mathbf{v}_{\perp})^2 >= \frac{A_D}{v}\left\{\Phi\left(\frac{v}{C_s}\right) - G\left(\frac{v}{C_s}\right)\right\}$$

$$< (\Delta \mathbf{v}_{\parallel})^2 >= \frac{A_D}{v} G\left(\frac{v}{C_s}\right)$$

$$C_s \equiv \left(\frac{2KT_s}{m_s}\right)^{1/2}$$

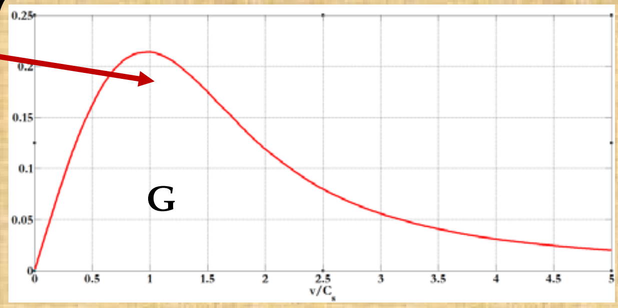
$$A_D \equiv 2\Gamma n_s = \frac{(ZZ')^2 e^4 n_s \ln\Lambda}{2\pi\epsilon_0^2 m^2}$$

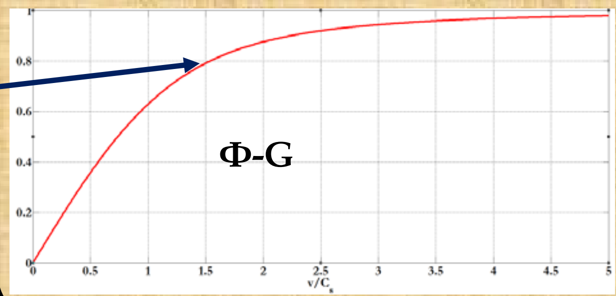
$$G(x) = -\frac{1}{2}\frac{d}{dx}\left(\frac{\Phi(x)}{x}\right) = \frac{\Phi(x) - x\Phi'(x)}{2x^2}$$

Similar to ΔV

Always increasing

Trends





v → 0: no friction; isotropic diffusion

v → ∞: transversal diffusion

Heavy particles dominated by friction

Characteristic times

- *Slowind down time τ_s*

$$\tau_s \equiv -\frac{v}{<\Delta v_\parallel>} = \frac{v C_s^2}{\left(1+\frac{m}{m_s}\right) A_D G\left(\frac{v}{C_s}\right)}$$

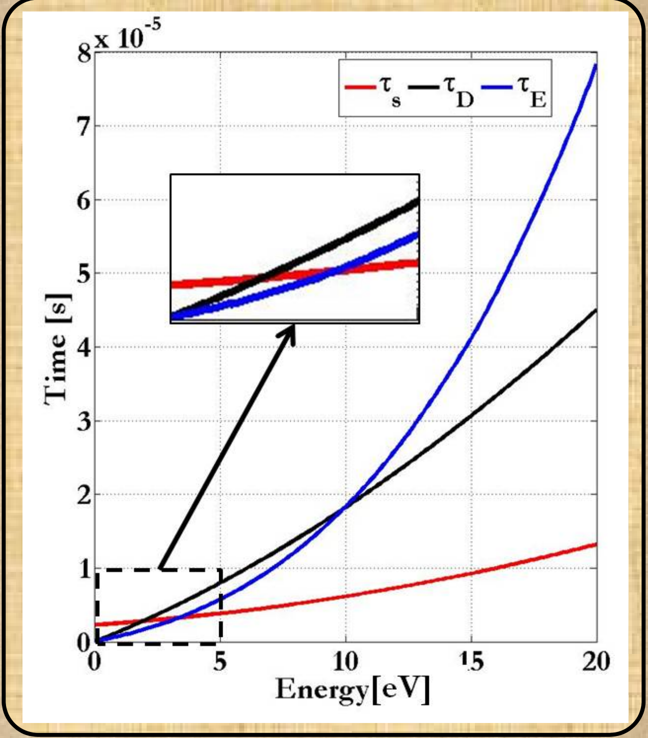
- *90° Diffusion time τ_D*

$$\tau_D \equiv \frac{v^2}{\langle(\Delta v_\perp)^2\rangle} = \frac{v^3}{A_D\left\{\Phi\left(\frac{v}{C_s}\right) - G\left(\frac{v}{C_s}\right)\right\}}$$

- *Energy equilibrium time τ_E*

$$\tau_E = \frac{E^2}{(\Delta E)^2} = \frac{v^3}{4A_D G\left(\frac{v}{C_s}\right)}$$

$^{85}Rb^{1+}$ in oxygen plasma



*n_e=2.6*10^{+18} m^{-3}, KT=1 eV, <z>=3*

Collisions in the code

- *Forward Difference method:*

$$v(t+1)=v(t) + a^{*}T_{step} \rightarrow x(t+1)=x(t)+ v^{*}T_{step}$$

- *MC approach fails* → *Langevin Formalism*

$$\boxed{\Delta v_{Lang} = v(t+1)-v(t) = -\nu_s v(t)^{*}T_{step}+v^{rand}}$$

Slowing down → $\boxed{\text{Friction: } a=-\nu_s v}$

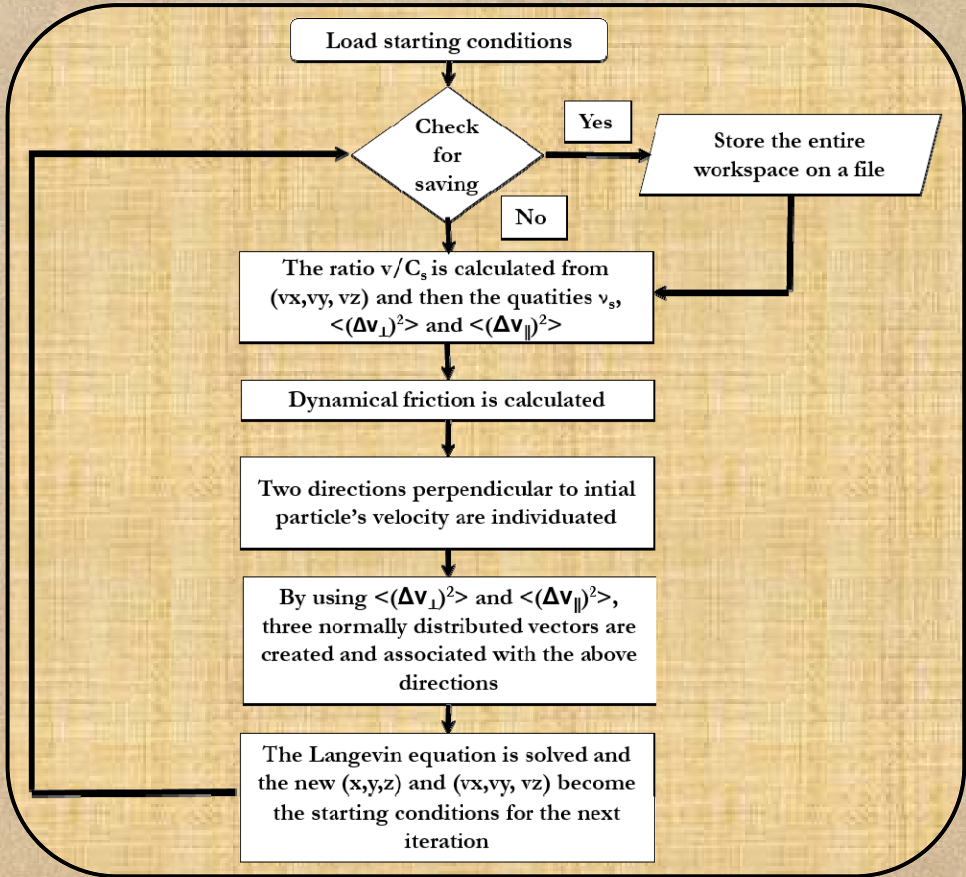
Diffusion → $\boxed{\text{Random vector } v_{rand}}$

$$\phi(\mathbf{v}^{rand}) = \frac{1}{(2\pi T_{step})^{3/2} D_\perp D_\parallel^{1/2}} \exp\left(-\frac{v_3^2}{2D_\parallel T_{step}} - \frac{v_1^2+v_2^2}{D_\perp T_{step}}\right)$$

Where Axes 3 // v; Axes 1,2 ⊥ v

Flow diagram

Calculation steps for Coulomb collisions



Benchmark

- <u>***Injected Ions***</u>

✓ $z_{inj} = 6$
✓ $M_{inj} = 132$ (Sn)
✓ $v_x = v_y = 0$
✓ $v_z = 3.4*10^{+3}$ m/s

- <u>***Plasma Ions***</u>

✓ $<z> = 3.5$
✓ $M=16$
✓ $n_e \sim 2.5*10^{+16}$ ioni/m^3
✓ KT= 1 eV

plasma

Characteristic times

$\tau_s = 1.58*10^{-5}$ s
$\tau_D = 4.88*10^{-5}$ s
$\tau_E = 3.55*10^{-5}$ s

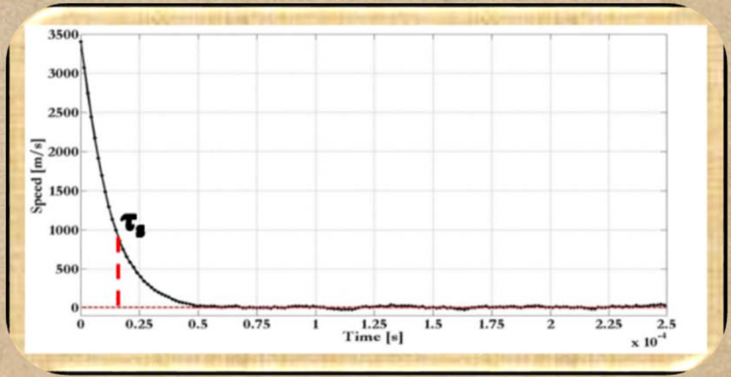
- <u>***Characteristics of the Simulation***</u>

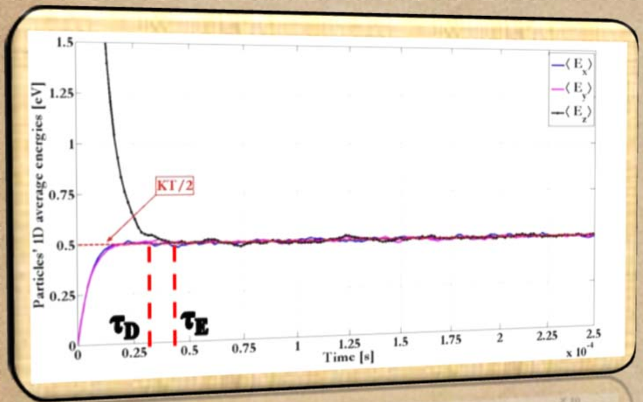
✓ N=10000
✓ $T_{step} = 1*10^{-10}$ s
✓ Int Time= $2.88*10^{-4}$ s

σ_{exp}= 851.3 m/s

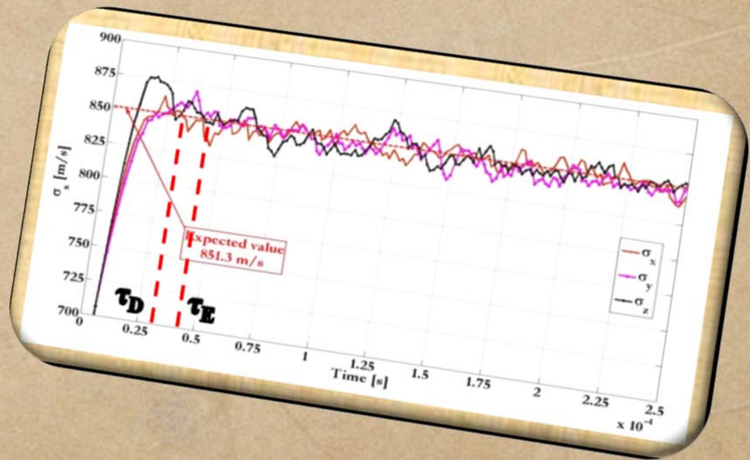
First results

Average Speed



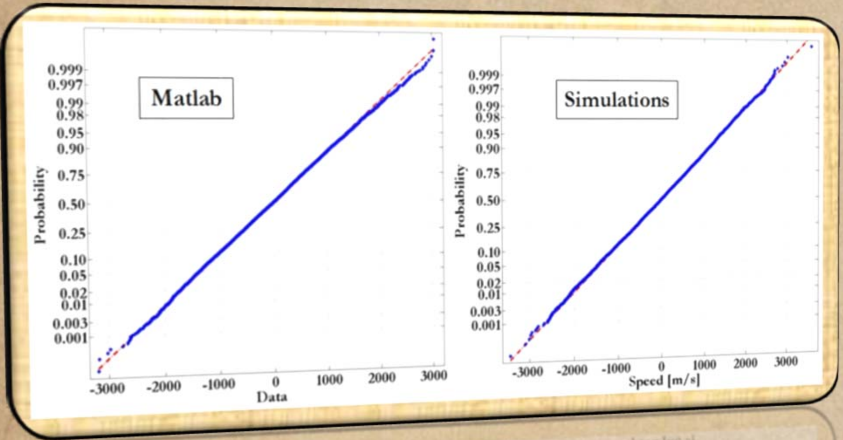


Average Energy

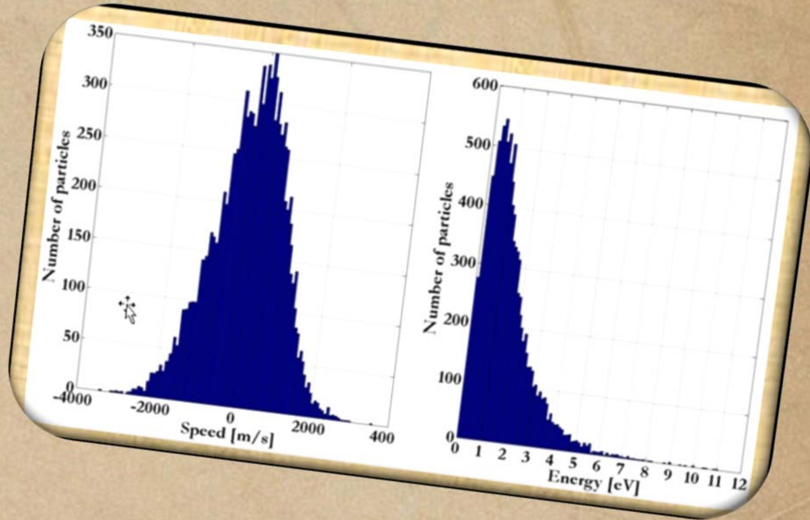


Spread

Thermalization



Verification: "normplot"

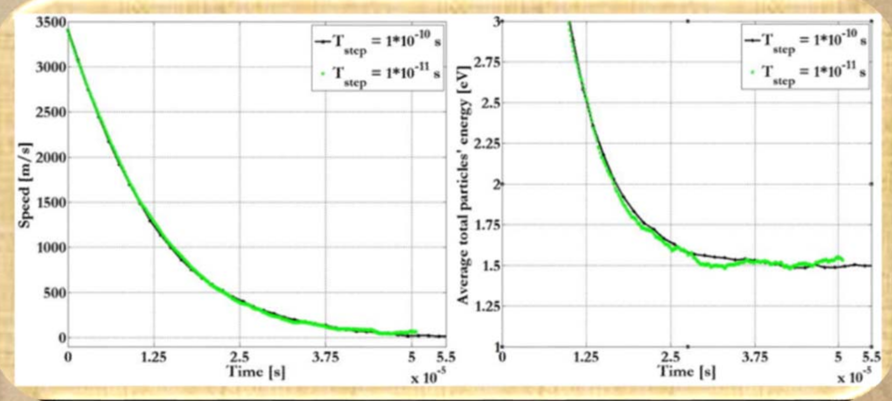


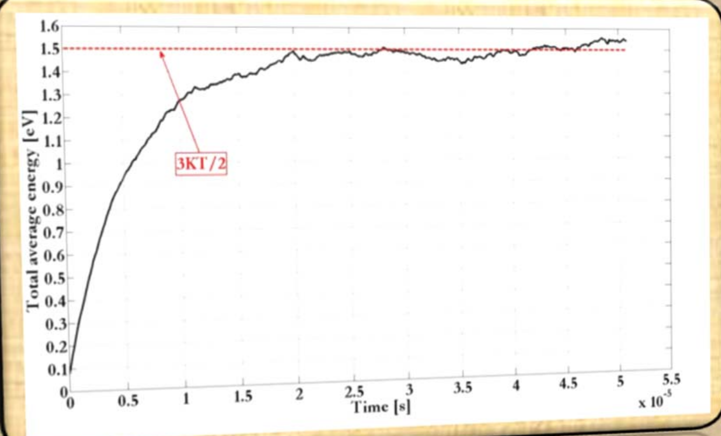
Maxwell-Boltzmann Distribution

Thermal Equilibrium effectively reached

Checks

Smaller T_{step}: 10^{-11}s





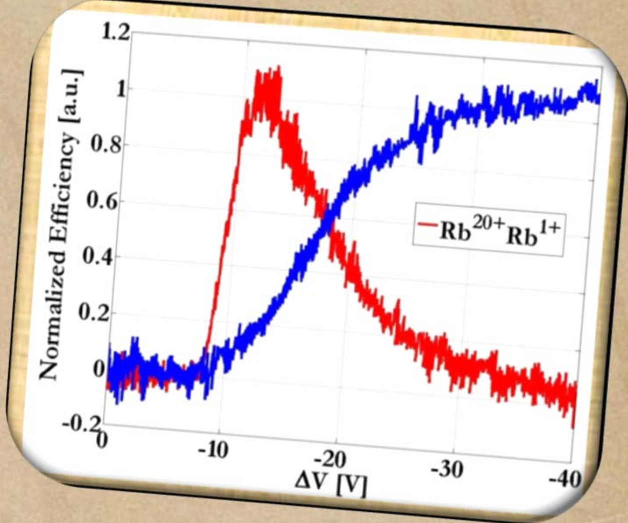
Slower particles: v_i = 340 m/s

Cooling and Heating

1+ beam capture by the Phoenix booster

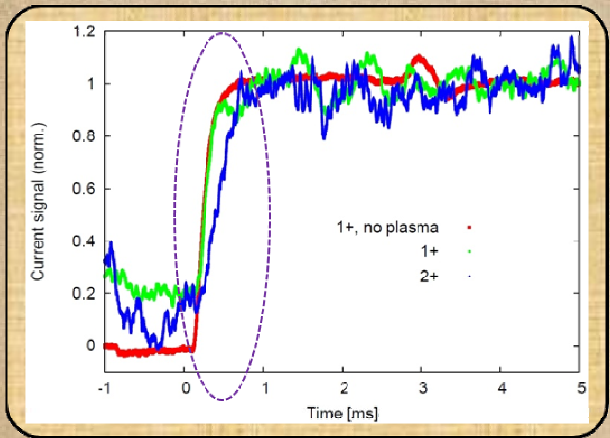
Rb experiment

*O. Tarvainen et al, PSST 2015



Anomalous ΔV curves for 1+ ions
- ✓ *Optimum ΔV ~ -12 V*
- ✓ *Total capture < 50%*

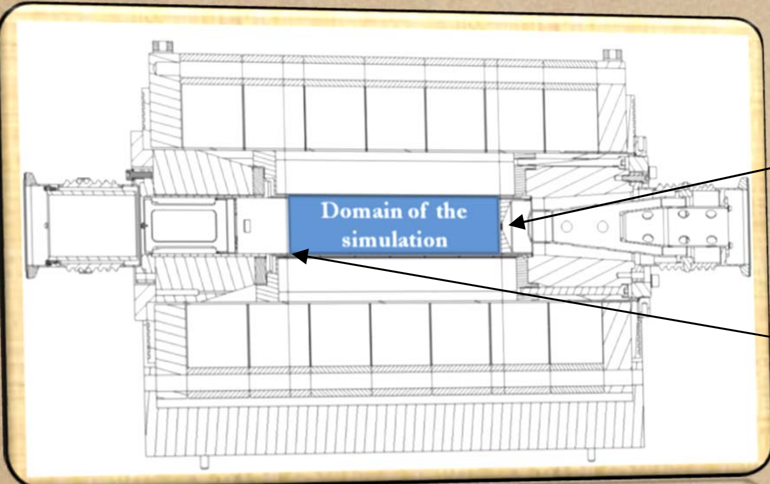
Ions weakly interacting with the plasma



Same CB time as plasma off (500 µs)

NUMERCAL SIMULATIONS GOALS
- *Reproduction of Rb^{1+} ΔV curve*
- *T_{span} = 500 µs*
- *Global capture ≥ 40 % @ ΔV_{opt} ~ -12 V*
- *Rb^{1+} efficiency few % @ ΔV_{opt} ~ -12 V*

Simulation domain



Extraction hole

B_{max} at injextion

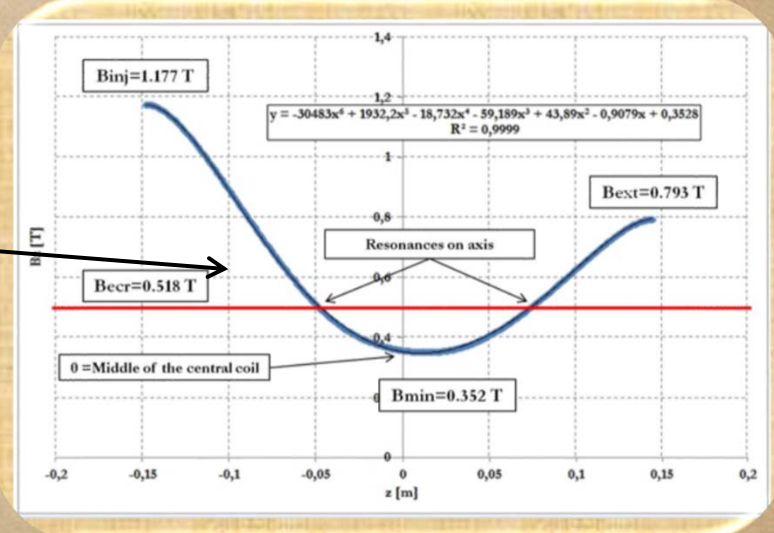
Analytical formulas for the magnetic field

B_z: interpolation

B_y: $-(y/2)*(dB_z/dz)+hex*(x^2-y^2)$

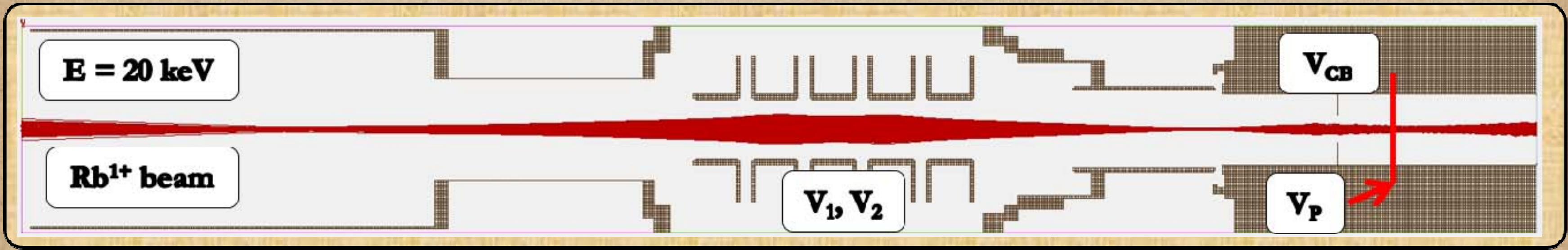
B_x: $-(x/2)*(dB_z/dz)+hex*xy$

$hex=617.8\ T/m^2$



Starting conditions

Simulation of injection: SIMION



*Thanks to J. Angot and T. Lamy

Injection Energy: $q^*(20\ kV - V_P) = -q^*\Delta V_{sim}$

- *Experimental Vs Simulated Curves*

✓ $\Delta V_{exp} = V_{CB} - 20\ kV$

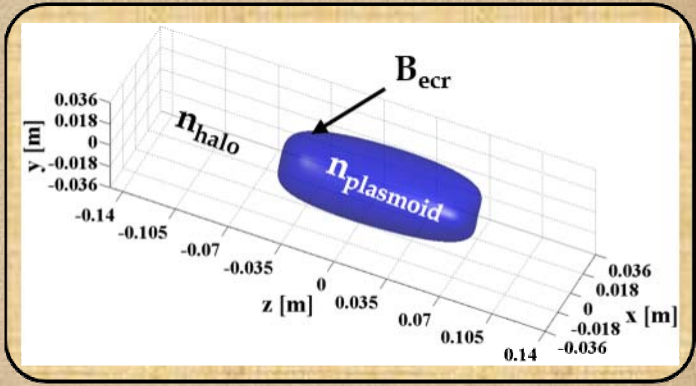
✓ $\Delta V_{sim} = V_P - 20\ kV$

Shift towards smaller ΔV for simulated curves

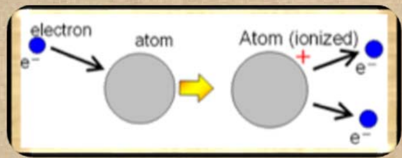
Stepwise plasma modeling

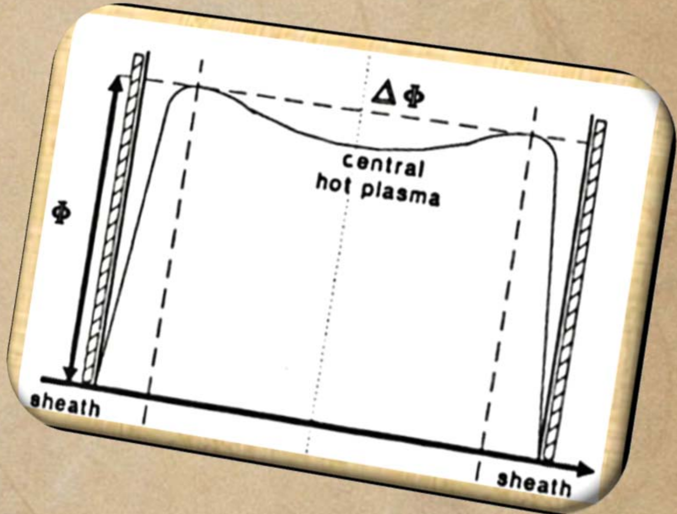
Basic plasma model (BPM)
- ✓ plasmoid/halo
- ✓ Boris method for B motion
- ✓ losses

$$v(t+1)=v(t) - \nu_s{*}v(t){*}T_{step}+v^{rand} + q[v(t)xB]$$



Refinement
- ✓ potential dip
- ✓ plasmoid/halo
- ✓ Complete Lorentz force ExB
- ✓ losses

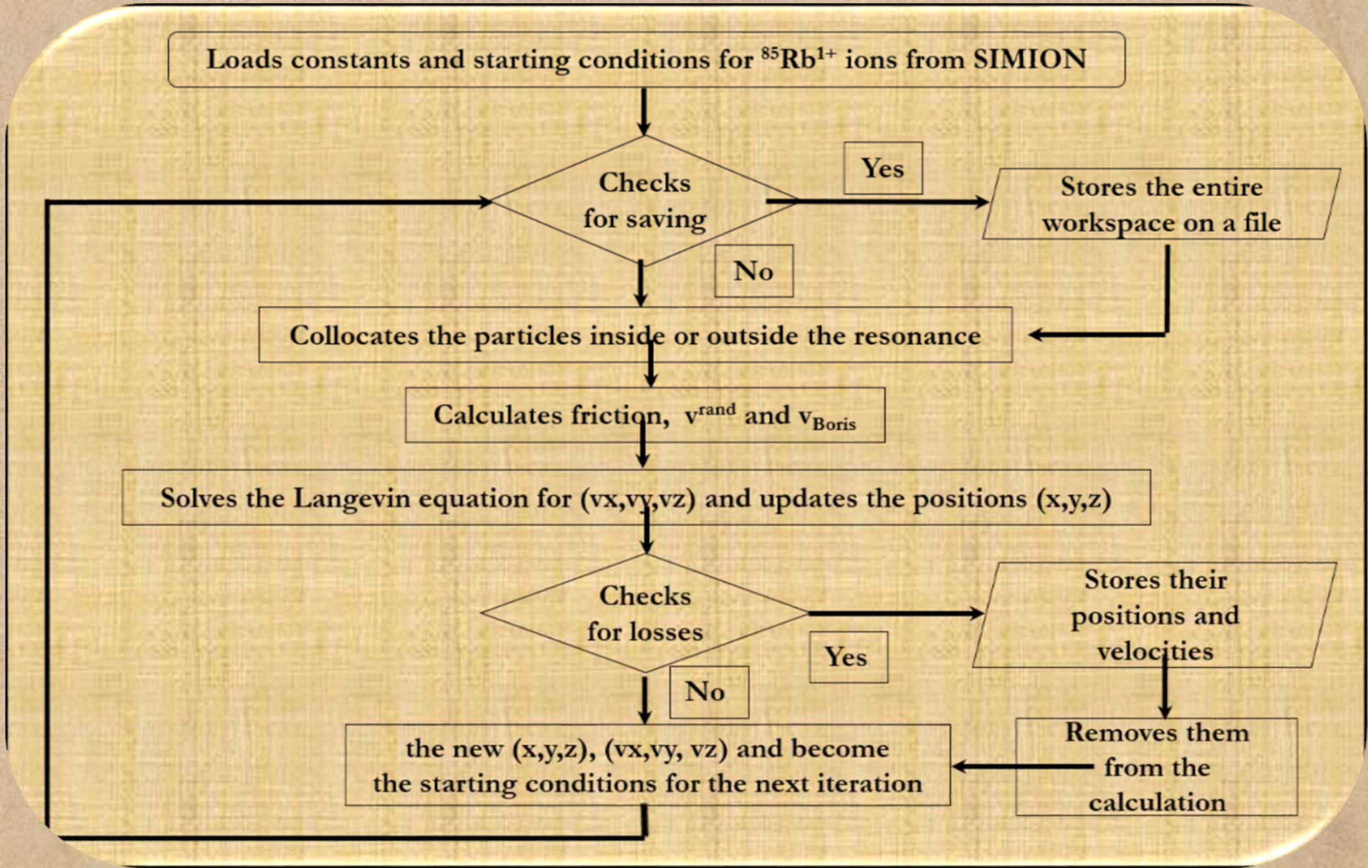




Complete plasma model (CPM)
- ✓ Potential dip
- ✓ ionizations
- ✓ plasmoid/halo
- ✓ Complete Lorentz force ExB
- ✓ Stepwise ionizations
- ✓ losses

$$v(t+1)=v(t) - \nu_s{*}v(t){*}T_{step}+v^{rand} + q[E+ v(t)xB]$$

BPM: flow diagram

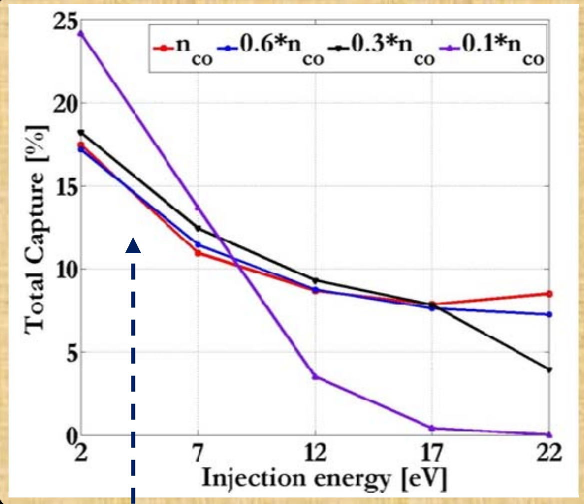


BPM: KT_i=1 eV

$n_{core}=i^*n_{co}$

1000 Rb^{1+} ions
E_{inj} = 2:5:22 eV

$n_{co}=2.6\cdot10^{18}\ m^{-3}$
i=1, 0.6, 0.3, 0.1
<z>=2.5



?

Plasma State

$\nu_{coll} \leq \nu_{cycl}$ *all n*

Magnetic Regime

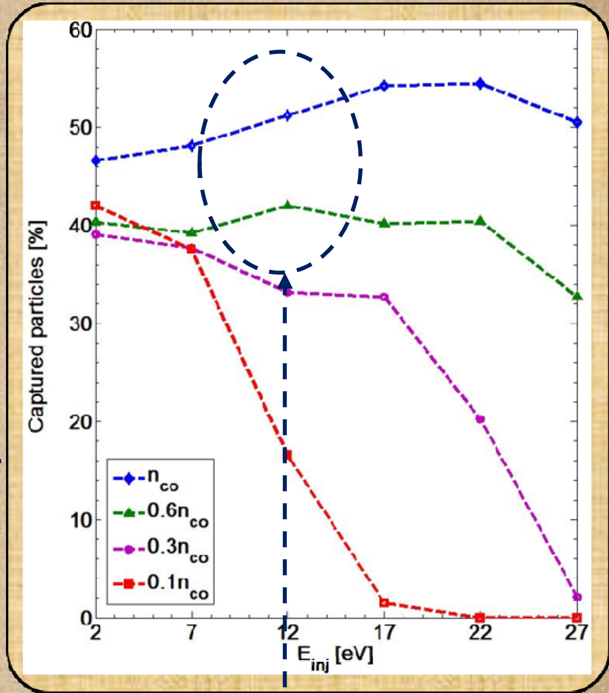
- $\tau_{mag}=Rl/v_T \sim 400\text{-}600\ \mu s$
- *Agreement with T_{span}*
- *τ_{mag} independent from n*

BPM: KT_i=0.376 eV

$n_{core}=i^*n_{co}$

1000 Rb^{1+} ions
E_{inj} = 2:5:27 eV

$n_{co}=2.6\cdot10^{18}\ m^{-3}$
i=1, 0.6, 0.3, 0.1
$\langle z\rangle=2.5$



?

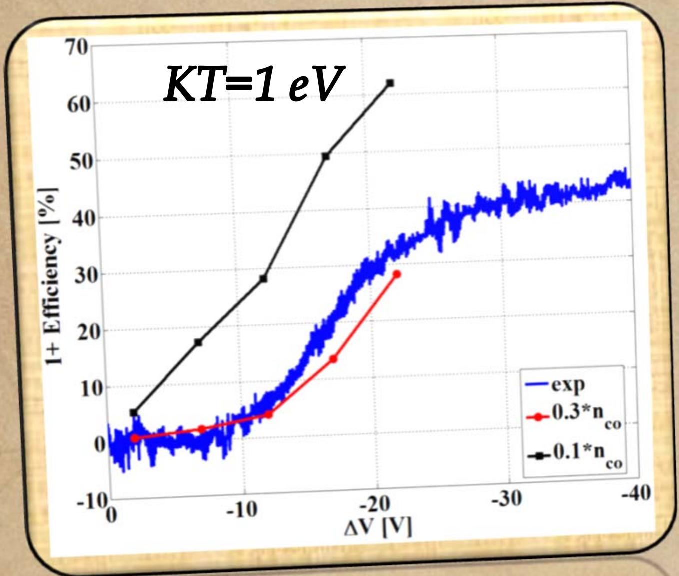
Plasma State

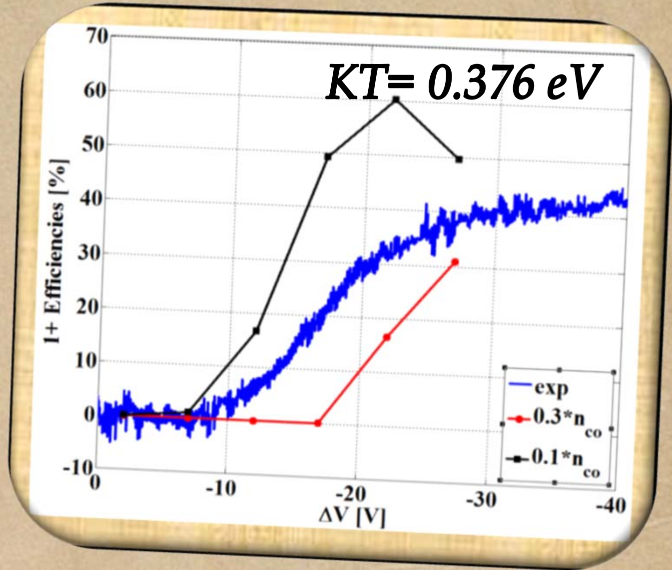
$\upsilon_{coll} > \upsilon_{cycl}$ high n

$\upsilon_{coll} <\sim \upsilon_{cycl}$ low n

Collisional Regime

BPM: Rb^{1+} efficiency

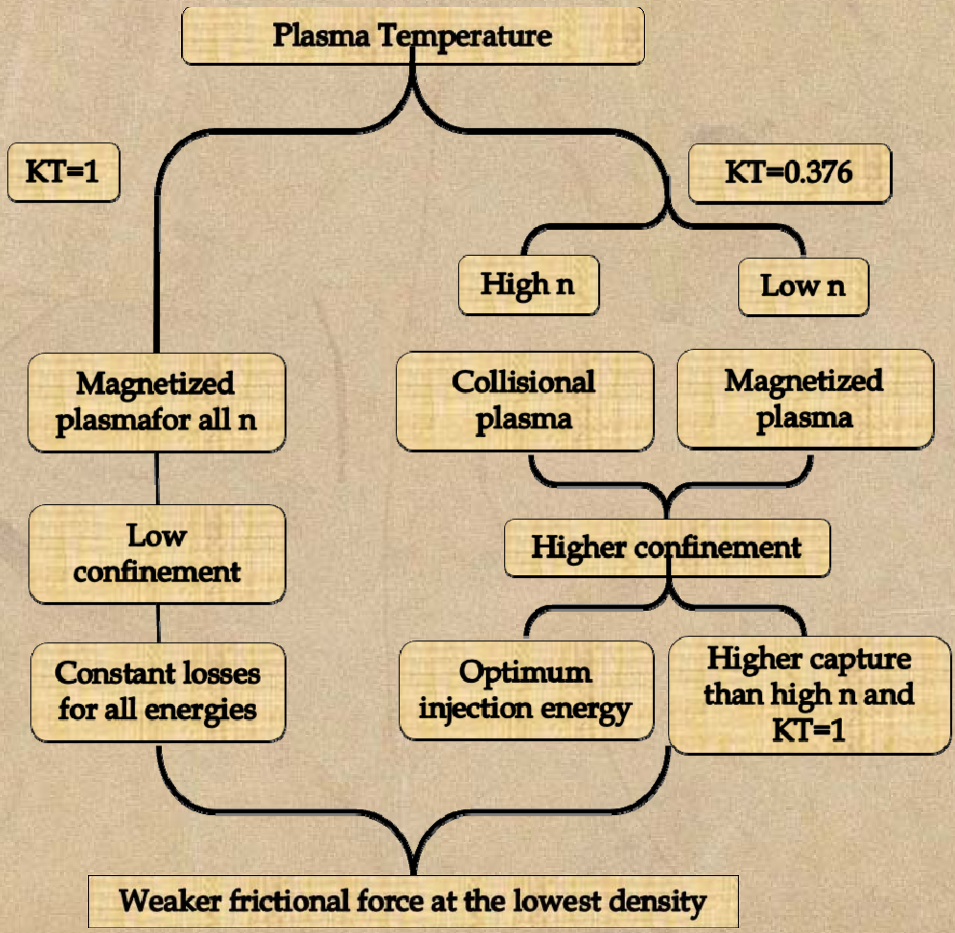




Similar trends but no agreement

For both temperatures no Rb^{1+} ions extracted unless $n<0.3*n_{co}$

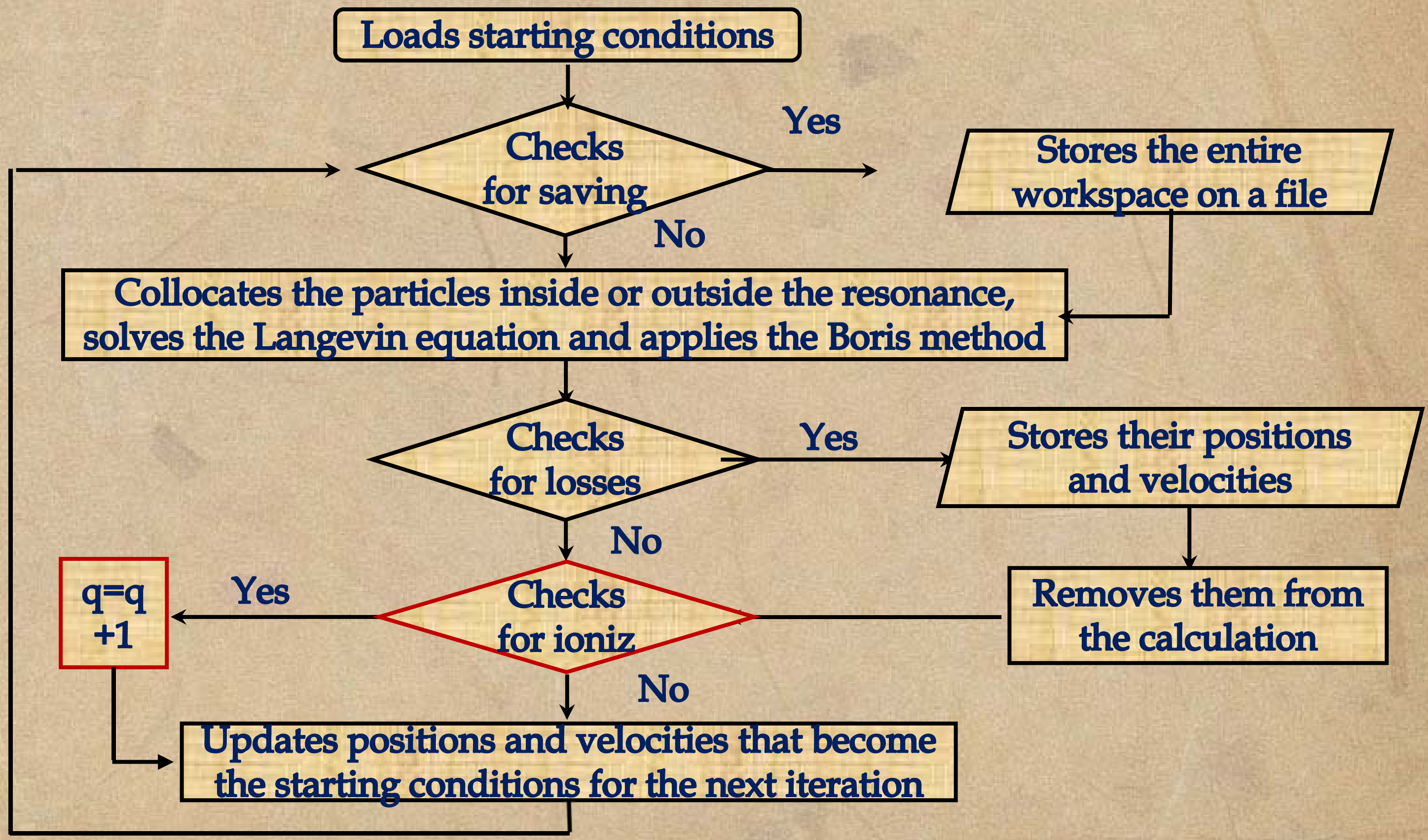
BPM: summary



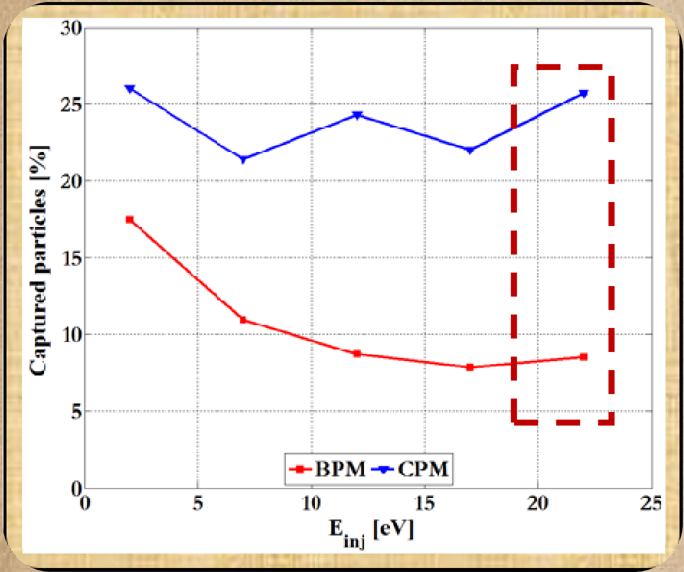
KT_i
Key parameter

CPM flow diagram

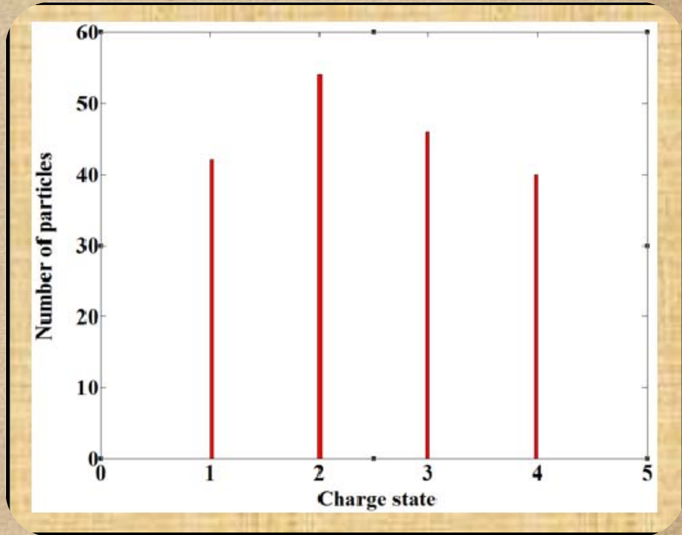
BMP + potential dip + ionizations



BPM Vs CPM



KT_i=1 eV n=n_{co}



Capture increases up to a factor > 3

Ionizations take place

Even including ionization the global capture is below experimental values at KT_i=1 eV

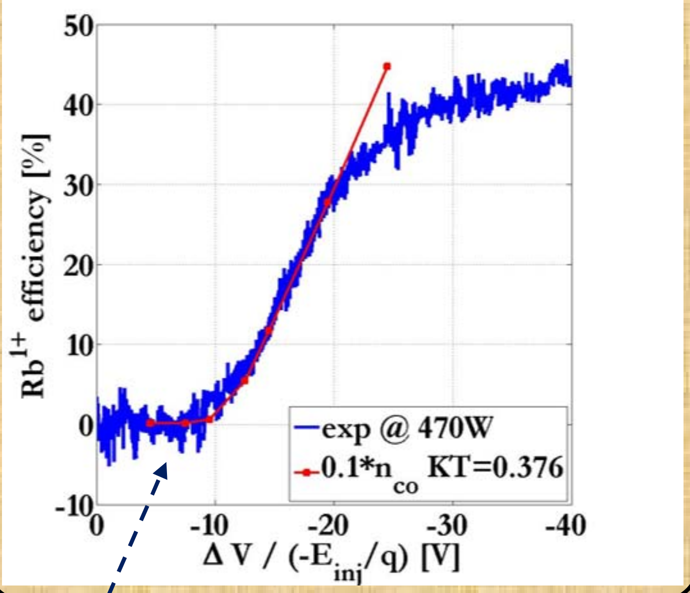
After many comparison we observed that to have a reasonable global capture and Rb^{1+} ions extracted both n and KT_i had to be low

CPM:KT=0.376 eV

*KT_i=1 eV n=0.1*n_{co}*

E_{inj} [eV]	Losses [%]	Captures [%]	ε_{1+} [%]
2	59.70	44.62	0.16
7	60.80	39.93	0.64
12	58.00	18.70	11.68
17	59.80	3.20	27.76
22	59.60	0.40	44.72

The capture is still too low



Rb^{1+} efficiency agrees with experiments

Requirements not completely fulfilled yet

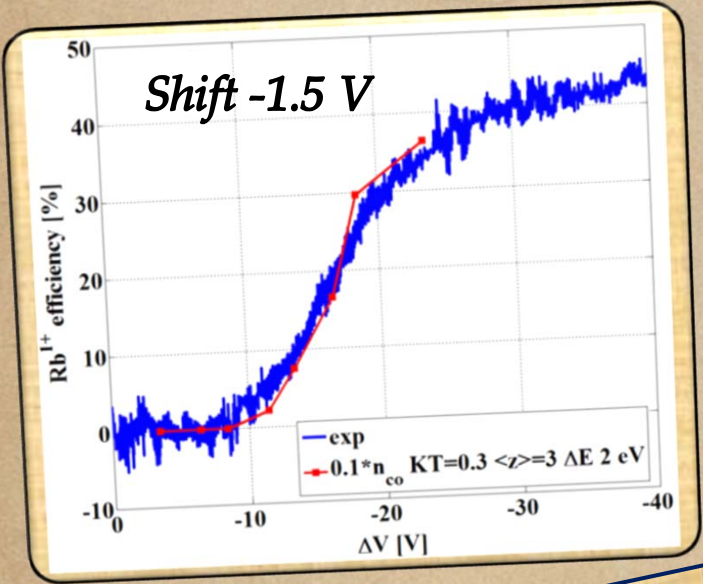
CPM: KT_i=0.3 eV

$n=0.1*n_{co}$

E_{inj} [eV]	Captures [%]	ε_{1+} [%]	ΔV_{sim} [V]
10	44.71	2.16	-11.5

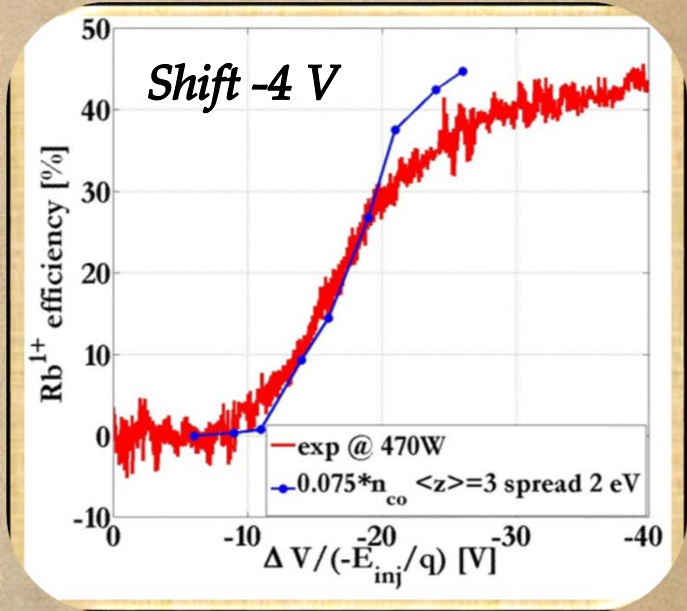
$n=0.075*n_{co}$

E_{inj} [eV]	Captures [%]	ε_{1+} [%]	ΔV_{sim} [V]
7	47.64	0.80	-11
10	39.51	9.28	-14



<z>=3

ΔE=2 eV

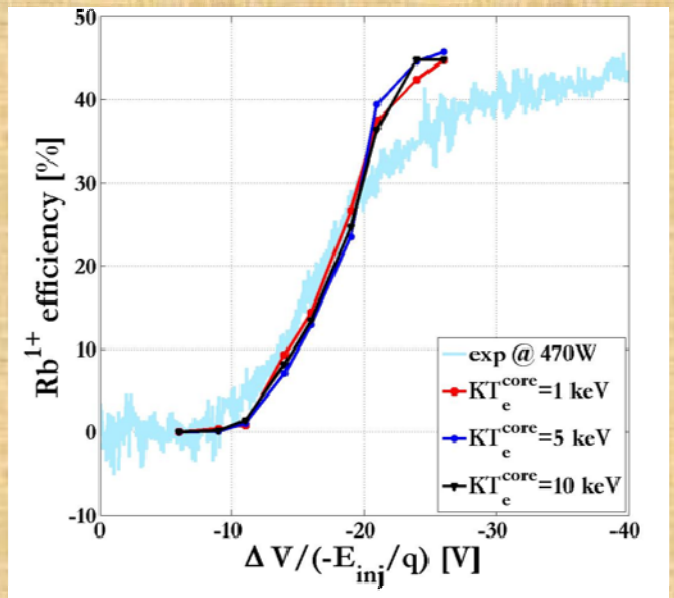


Agreement with experiments

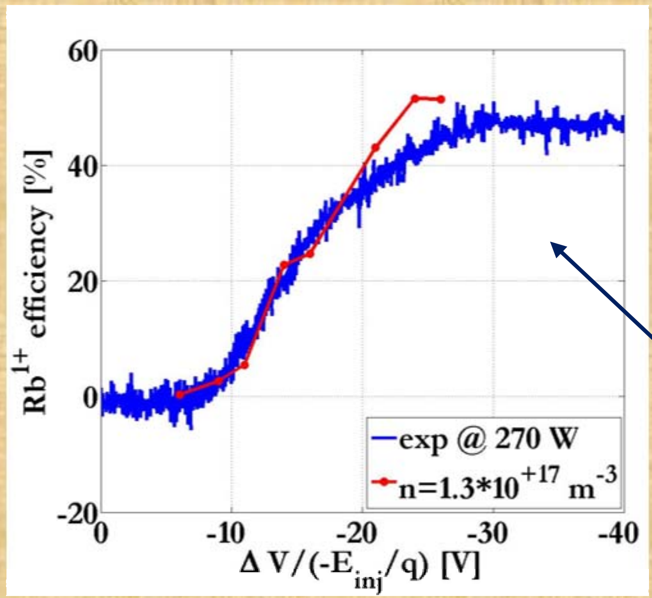
***A. Galatà et al., ICIS 2015 NY**

CPM: further calculations

Warm electrons temperature



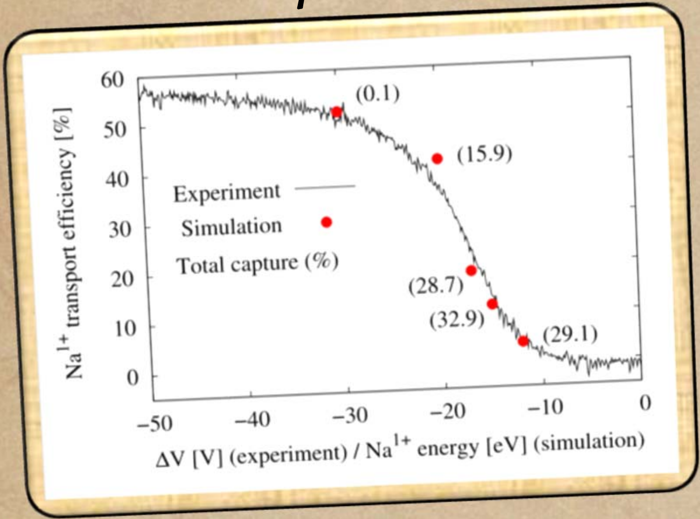
First ionizations not sensitive to KT$_e$



Experimental curve at lower power reproduced by lowering plasma density

CPM: further calculations

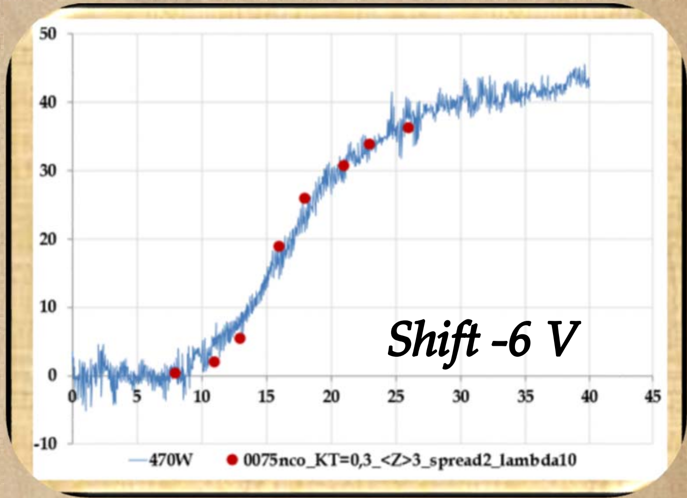
Na experiments



*O. Tarvainen et al, submitted to PRST-AB

Agreement for charge breeding of light ions

Previous simulations with logΛ=10

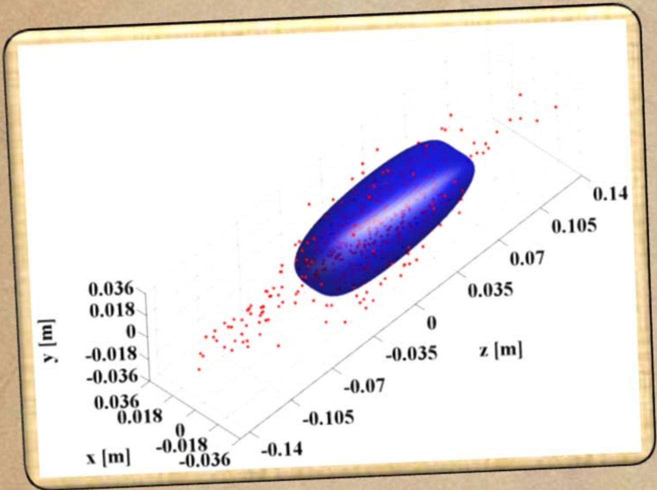


logΛ has to be estimated precisely

Final simulation: results

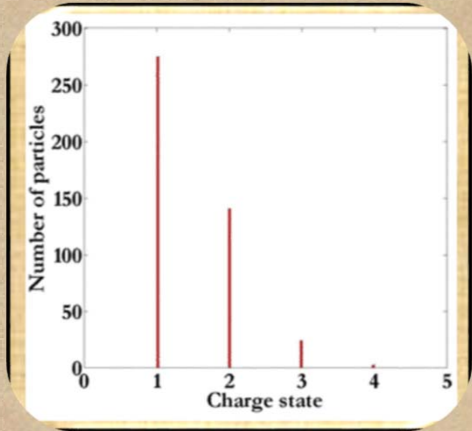
$n=1.95\cdot10^{17}\ m^{-3};\ \Delta V_{sim}= -11V$

Particles distribution



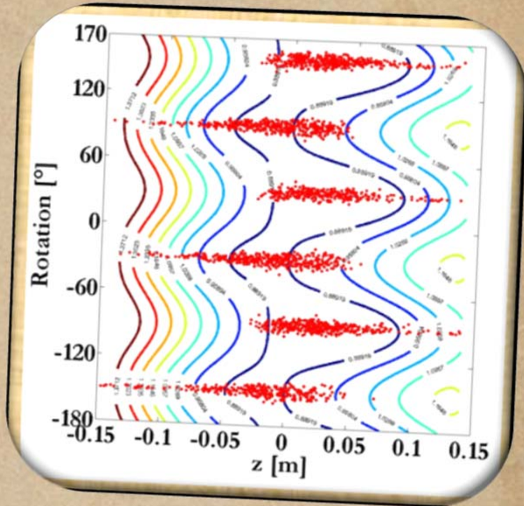
Most of the particles are within the plasmoid

Ionizations



First ionizations take place in agreement with the estimated ionization times

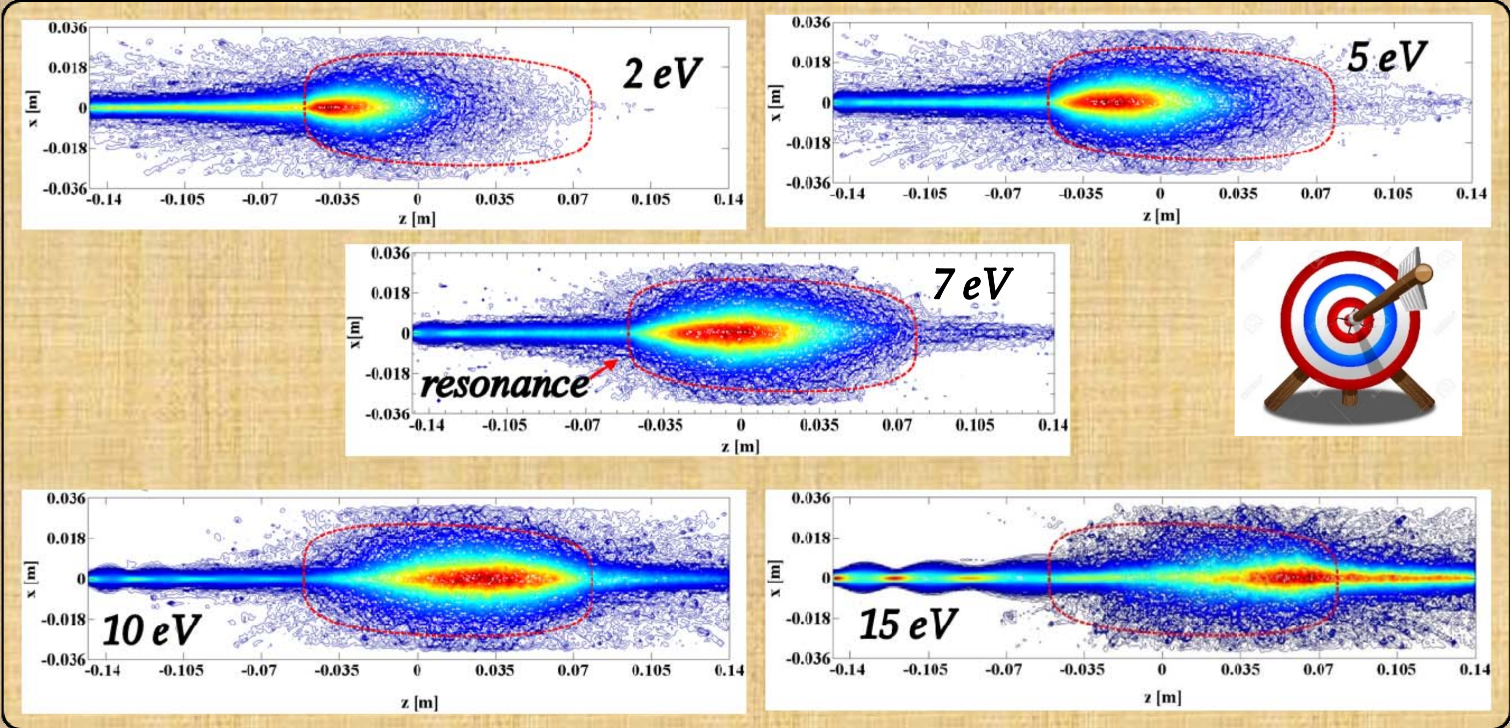
Losses



Losses are mostly radial

Final simulation: ballistics

Density map **A. Galatà et al, submitted to PSST*



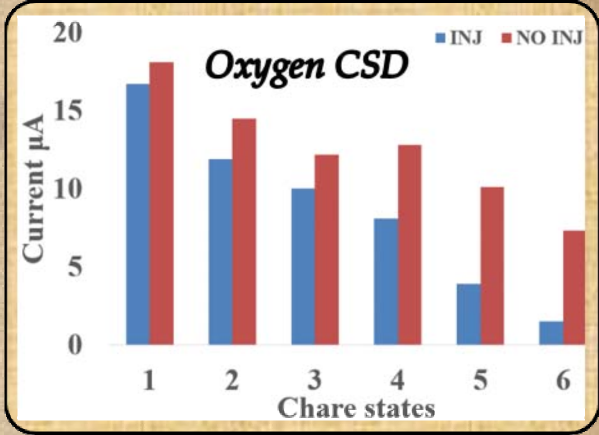
The optimum injection energy is evident

Injected ions need an extra energy to be stopped deep inside the plasma

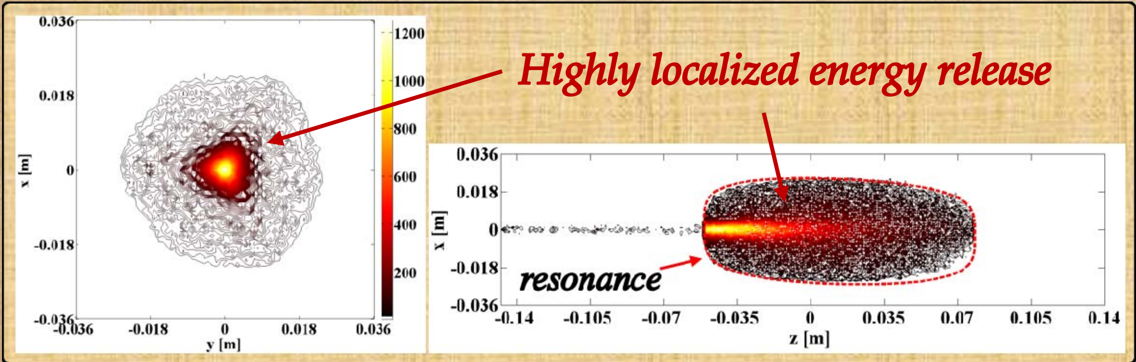
Final simulation: energy release

Injected ions have a clear influence on the plasma

Xe injection



Energy release map



Possible explanation:
direct ion heating
or…….stay tuned!

**A. Galatà et al, submitted to PSST*

Conclusions to CB simulations

Slowing down and capture correctly implemented in a single particle approach:

- ✓ *Coorrect implementation of equations*
- ✓ *Model of increasing complexity.*
- ✓ *Agreement with theorectical expectations.*
- ✓ *Agreement with experiments for a narrow set of plasma parameters.*

Important outputs:

- ✓ *Key role of ion temperature.*
- ✓ *Density estimation in agreement with experimental results within EMILIE.*
- ✓ *Energy deposition map.*

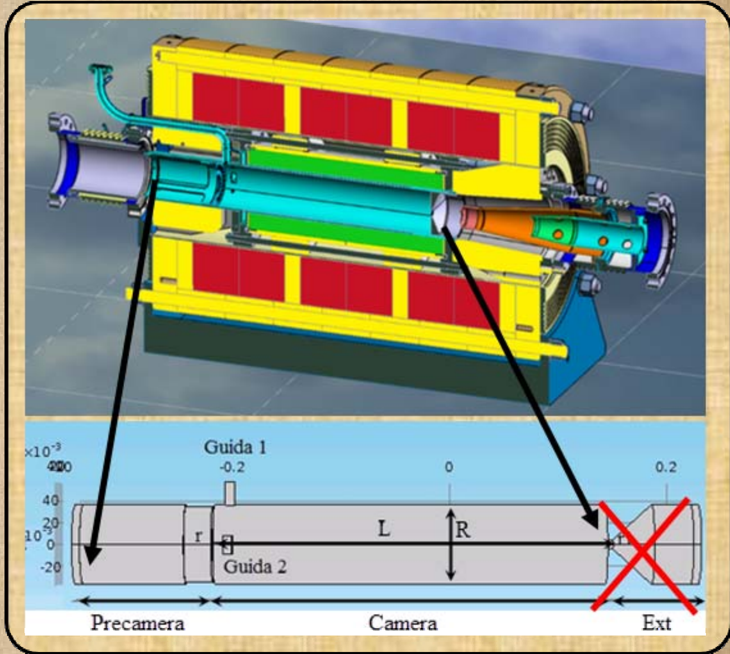
Predictive tool for the capture process:

- ✓ *Influence of beam emittance.* ← *Important for the blind tuning!*
- ✓ *Influence of ion mass.*
- ✓ *Injection of different masses*

Electromagnetic simulations of the Phoenix plasma chamber

Geometry

- *Artificial numerical "Absorbing boundary condition" at injection*
- *Extraction hole is a wave cut off region*
- *Chamber: from HF-blocker to ext. "plate" L~353 mm, R=36 mm, r=14 mm.*
- *Pre-Chamber: no influence for PML boundary conditions*



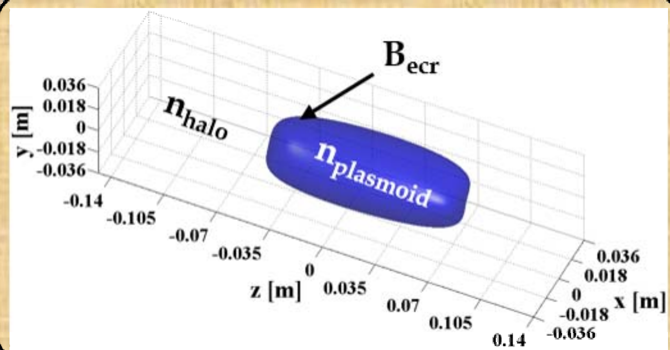
Simulation Domain: only the geometrical details that impact on electromagnetic propagation, as apertures and ports, are taken into consideration

Plasma modeling

from vacuum cavity to anisotropic plasma-filled cavity

Vacuum cavity (mesh 2.7mm)

Plasma-filled cavity (mesh 2.7mm):



✓ *Density profile as plasmoid/halo scheme ($n_{halo}=n_{plasmoid}/100$)*

✓ *Isotropic plasma*

$$\frac{\varepsilon}{\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega(\omega - \Omega_e) - i\kappa\omega},$$

→ *Dielectric constant of an R-wave everywhere**

**Evstatiev et al. RSI 85, 02A503 (2014)*

✓ *Anisotropic magnetized plasma Full 3D dielectric tensor*

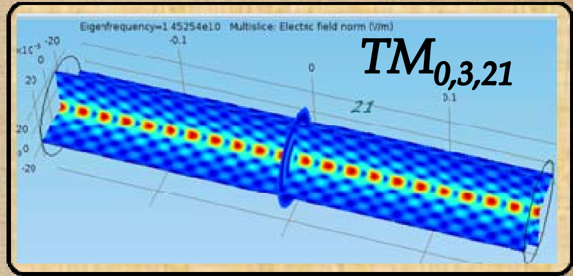
Depends on magnetic field and plasma parameters (n_e, T_e, ω_{coll})

$$\frac{\bar{\bar{\varepsilon}}}{\varepsilon_0} = \begin{bmatrix} 1 + j\frac{\omega_p^2}{\omega}\frac{A_x}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_z + D_{xy}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_y + D_{xz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{-C_z + D_{xy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_y}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{C_x + D_{yz}}{\Delta} \\ j\frac{\omega_p^2}{\omega}\frac{C_y + D_{xz}}{\Delta} & j\frac{\omega_p^2}{\omega}\frac{-C_x + D_{zy}}{\Delta} & 1 + j\frac{\omega_p^2}{\omega}\frac{A_z}{\Delta} \end{bmatrix}$$

Resonant modes

Empty cavity:

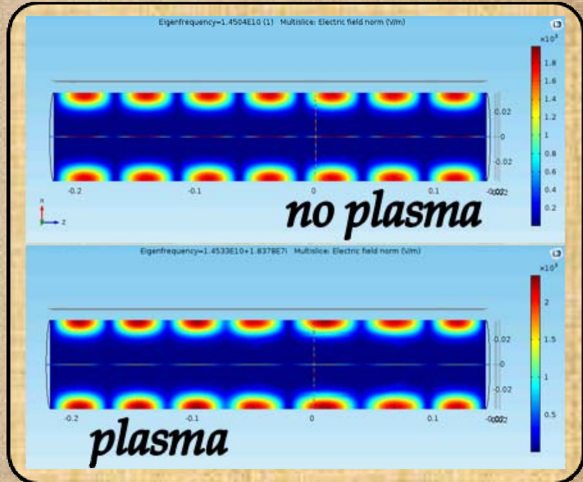
- ✓ *200 resonant frequencies around and below 14.521 GHz.*
- ✓ *~20 modes in 14.3-14.6 GHz (some degenerate).*
- ✓ *The closest mode to the operating frequency is $TM_{0,3,21}$ (14,525 GHz)*



Isotropic plasma:

- ✓ *Only a limited number of frequencies calculated (limits from computational resources).*
- ✓ *Identified two frequency shifts*
  - ➢ *$TE_{8,1,16}$: 14.477 GHz → 14.504 GHz*
  - ➢ *$TE_{9,1,7}$: 14.504 GHz → 14.533 GHz*

$TE_{9,1,7}$



Frequency domain

Two selected frequencies:

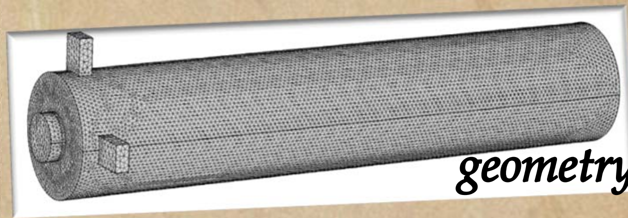
- ✓ *14.521 GHz*
- ✓ *14.324 GHz (SPES-CB acc. tests).*

Real geometry (waveguides, holes, pre-chamber doesn't matter)

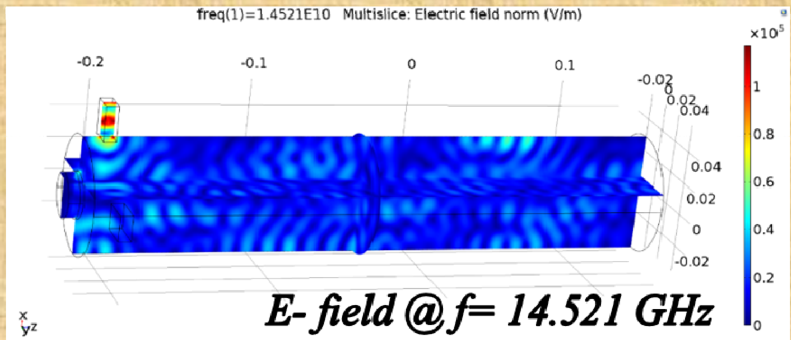
Boundaries: PML, IBC, port & port-off

Empty Cavity

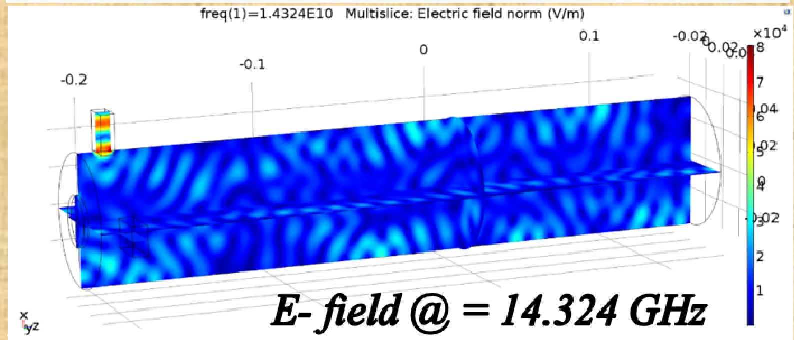
- ✓ *High reflection at waveguide input*
- ✓ *Most of the rest goes through the HF-blocker*
- ✓ *14.324 slightly better matched to the cavity (P_r= 38.2% instead of 43.8%)*



geometry



E- field @ f= 14.521 GHz



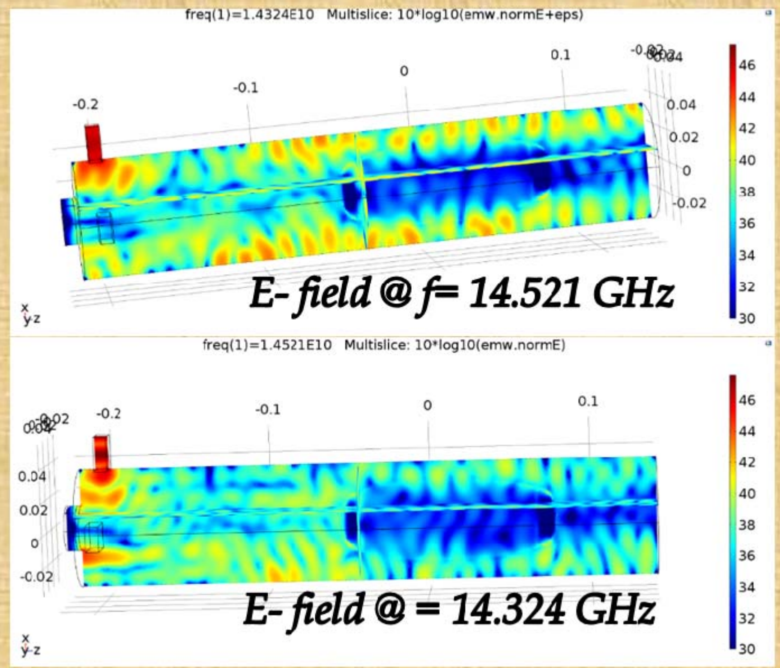
E- field @ = 14.324 GHz

Frequency domain

Isotropic plasma

- ✓ *Magnetic field*
- ✓ *$n=2.5*10^{+17}\ m^{-3}$, $KT_e^{warm} = 1\ keV$*
- ✓ *Interaction COMSOL-MATLAB*

	14.324 GHz	14.521 GHz
P_{input} [W]	100	100
P_f [W]	100	82.6
P_{hole} [W]	7	8.2
P_{w2} [W]	0.5	3.3
P_{plasma} [W/%]	89.1/89.1	68.7/83.2



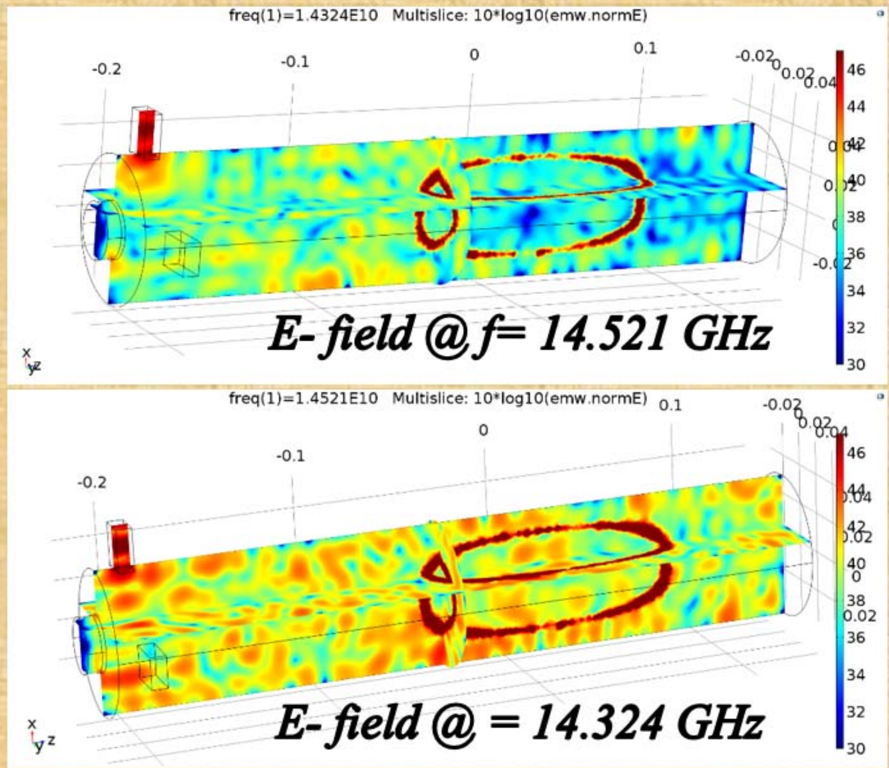
*A. Galatà et al, ICIS 2015 NY

Frequency domain

Anisotropic plasma

Full 3D dielectric tensor

	14.324 GHz	14.521 GHz
P_{input} [W]	100	100
P_f [W]	92.6	68.4
P_{hole} [W]	14.5	41.3
P_{w2} [W]	0.8	3.0
P_{plasma} [W/%]	74.5/80.4	16.6/24.4

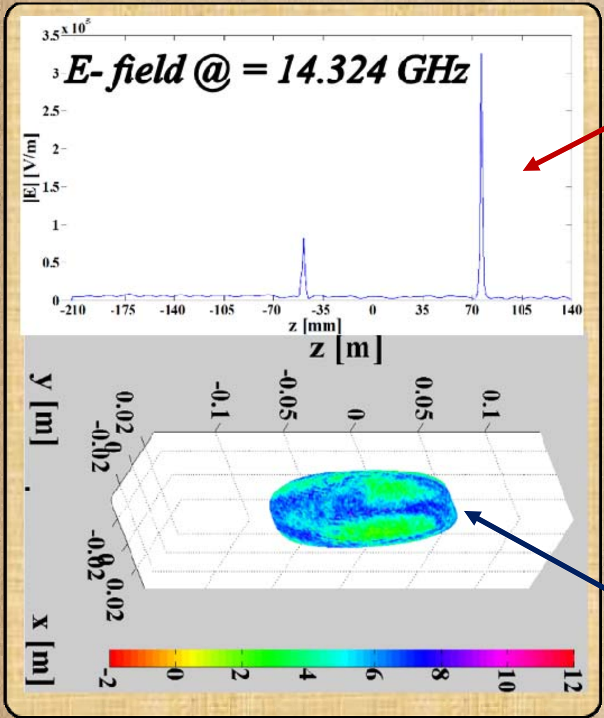


Numerical evidence of the frequency tuning effect !

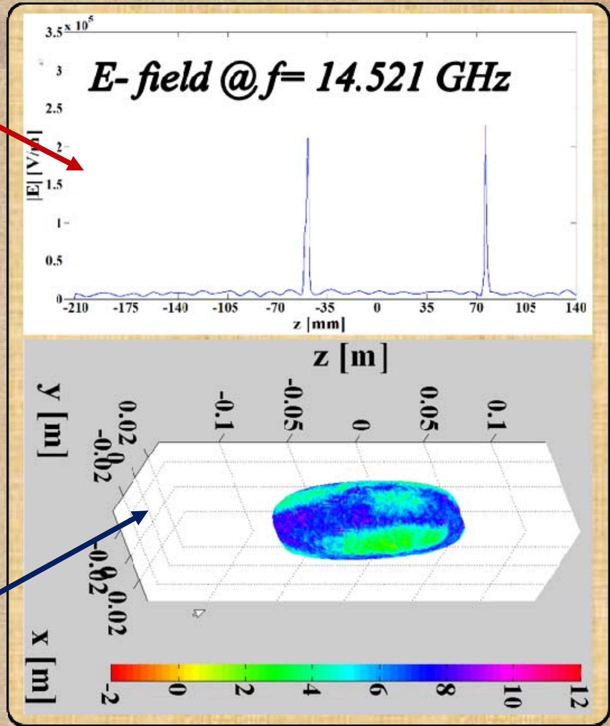
**A. Galatà et al, ICIS 2015 NY*

Frequency domani

Electric field intensification @ ECR layers



Resonant absorption of microwaves



Electric field distribution on the ECR surface
(log-scale)

Conclusions

Resonant modes computation including a simple plasma model

Plasma modeling in two steps (plasmoid/halo):

- ✓ *"isotropic plasma" allowed us to estimate the frequency shift of certain resonant mode*
- ✓ *"anisotropic plasma" complete 3D dielectric tensor evaluate the power absorptions by the plasma: comparison between 14.521 GHz and 14.324 GHz supports the frequency tuning effect experimentally observed*

⇩

The presented model can be considered already predictive if one aims at comparing two or more different frequencies, for a given geometry and plasma structure.

.....and perspectives

A complete predictability will be reached after implementing a more realistic plasma-target model in a self consistent picture of the plasma thanks to

- ✓ *Electrons dynamics in the EM field.*
- ✓ *Density map as a function of temperature.*

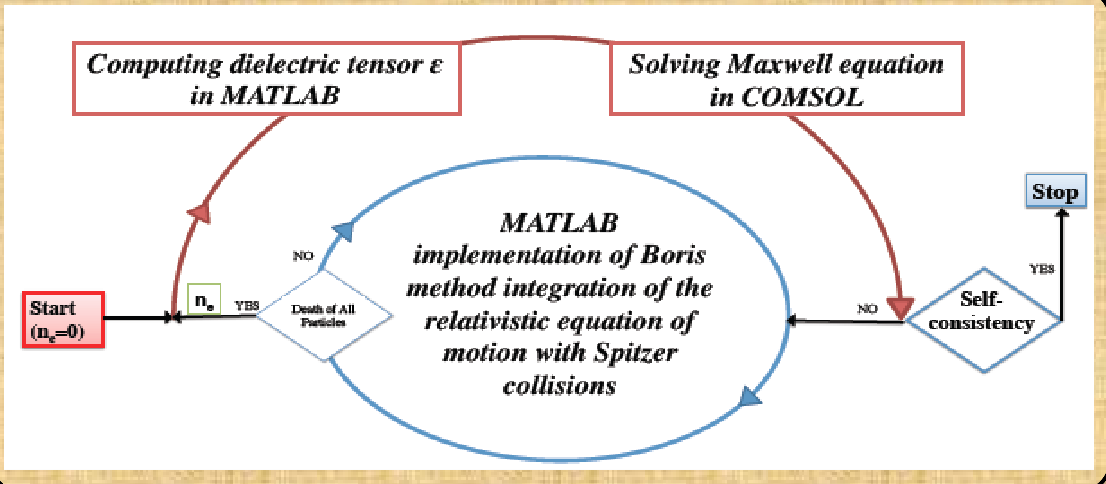
Preliminary results on 3D-full wave and kinetics numerical modelling plasma

$$\frac{d}{dt}\gamma\vec{v} = \frac{q}{m}\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

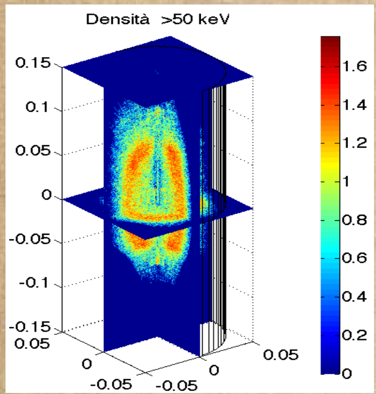
$$\frac{d}{dt}\vec{x} = \vec{v}$$

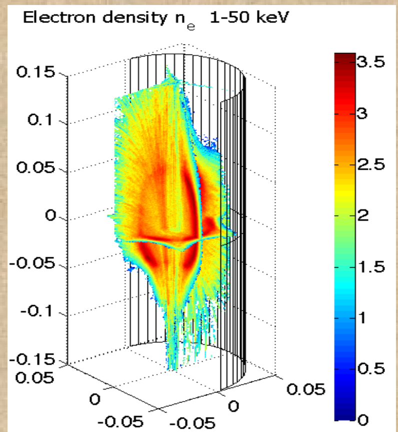
$$\vec{\nabla} \times \vec{E} = j\omega\mu\vec{H}$$

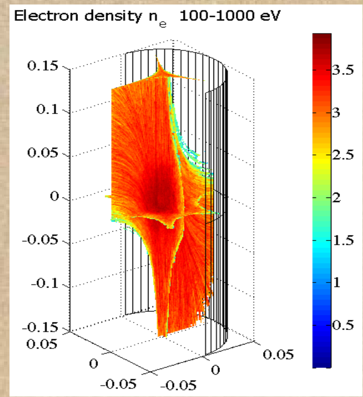
$$\vec{\nabla} \times \vec{H} = -j\omega\overline{\overline{\varepsilon}} \cdot \vec{E}$$



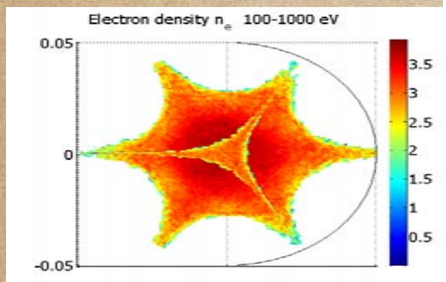
Towards self consistency

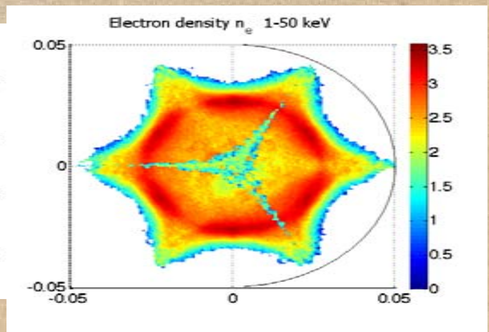






Simulated electron density distribution at different Enegy ranges considering the RF field excited into the plasma filled cavity





*the plasma concentrate mostly **in near resonance region**:*
*a **dense plasmoid** is surrounded by a **rarefied halo***

electrons at different energies distribute differently in the space:
cold electrons in the core, hot ones in near ECR regions

D. Mascali, et al. European Physical Journal – D

Thanks again for this wonderful experience!