THE NUMERICAL MODELLING OF ION BEAM-PLASMA INTERACTION IN ECRIS-BASED CHARGE BREEDERS

A. Galatà

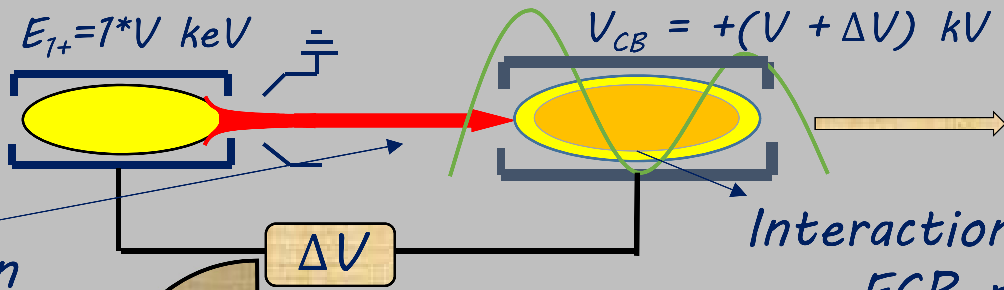
5th Geller Prize Ceremony

AKNOWLEDGEMENT

- The Committee
- INFN-LNL
- The Colleagues from LPSC: T. Lamy, T. Thuillier, J. Angot
- The Colleagues of the EMILIE Collaboration
- ECRIS Community: ARES Collaboration (guys from GSI, Sandor), ANL, all the others
- Last but not least: my friend from LNS (D. Mascali, L. Celona, S. Gammino, G. Ciavola, L. Neri, G. Castro, G. Torrisi, ...)

THANK YOU!

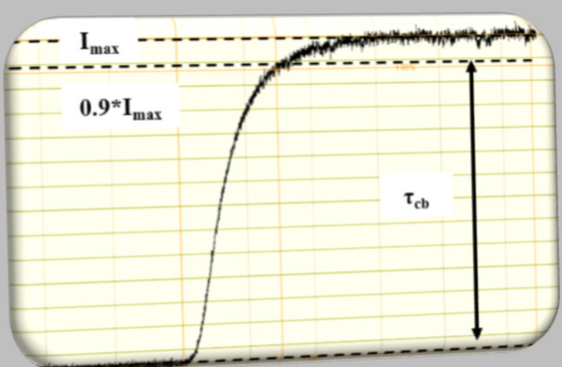
ECR CHARGE BREEDERS

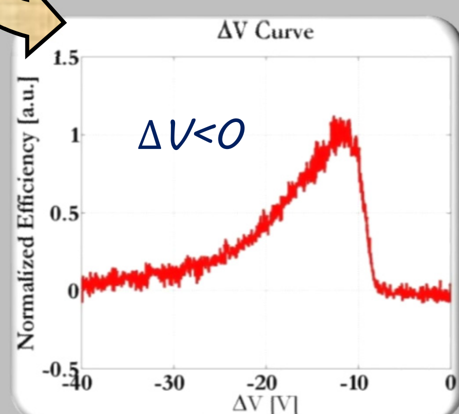


Focusing
Deceleration

Interaction with the ECR plasma

τ_{CB} (half life) <q+> (energy) Efficiency (Intensity)





$$\varepsilon_{q^+} = \frac{I_{q^+}}{q * I_{1^+}}$$

$$\varepsilon_{tot} = \sum_i \varepsilon_{q_i^+}$$

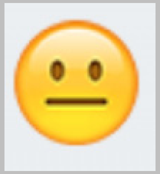
Fundamental parameter!

ME AND THE CHARGE BREEDING

It was 2010.........

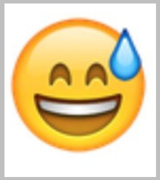
Hey Alessio! You are the new Responsible of the SPES-CB!!!

ME



What the **** is the SPES-CB?????

Don't worry… it is an application of ECR Sources! ;)



And then in 2012.........

Hey Alessio! For you PhD, why don't you write a code that reproduces the CB process???

Ooooookkkkkk!

I had never wrote a single line of a program in my life!

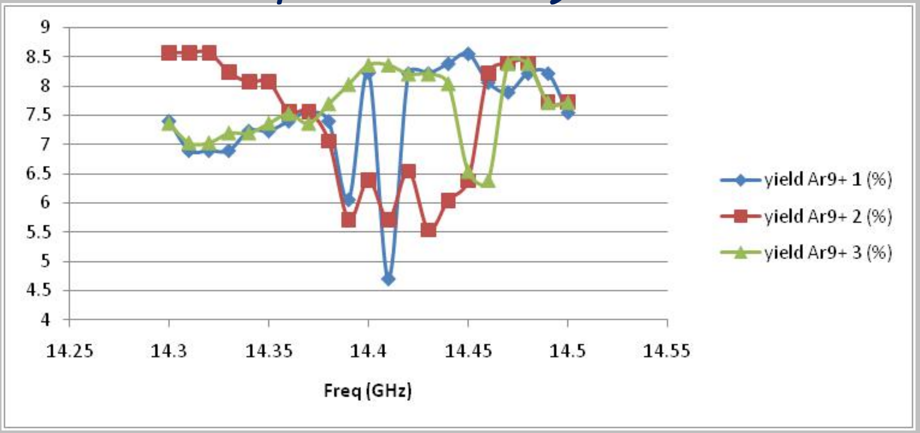
ME AND THE CHARGE BREEDING

ACTIVITY

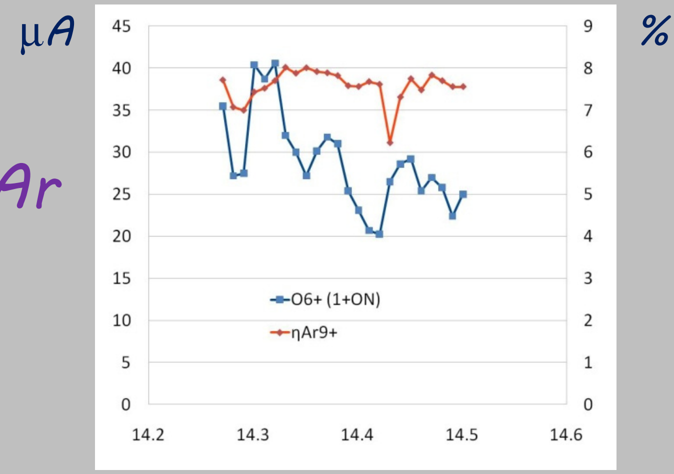
- CB Responsability within SPES since 2010
- Collaboration with LPSC since 2010

Frequency tuning experiments on Ar

Reproducibility



Ar Vs O



Results were not satisfactory at that time

* T. Lamy @ ECRIS 2010

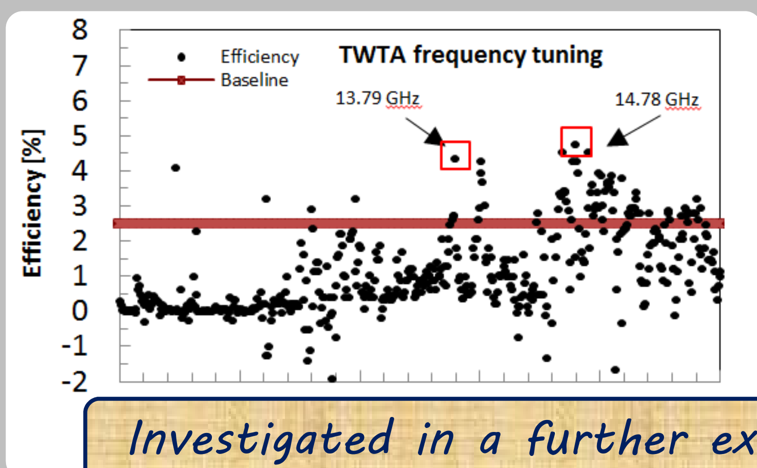
ME AND THE CHARGE BREEDING

ACTIVITY

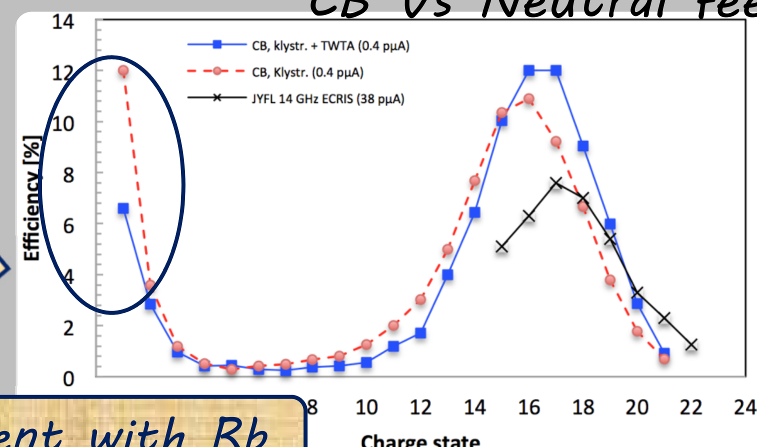
- 2012-2015: EMILIE Project (LNL+LNS)
  - ✓ Numerical simulations (see later!)
  - ✓ Fruitful experimental activity @ LPSC (led by JYFL)

FT and TFH on Ar and Kr efficiencies*

CB Vs Neutral feeding



?



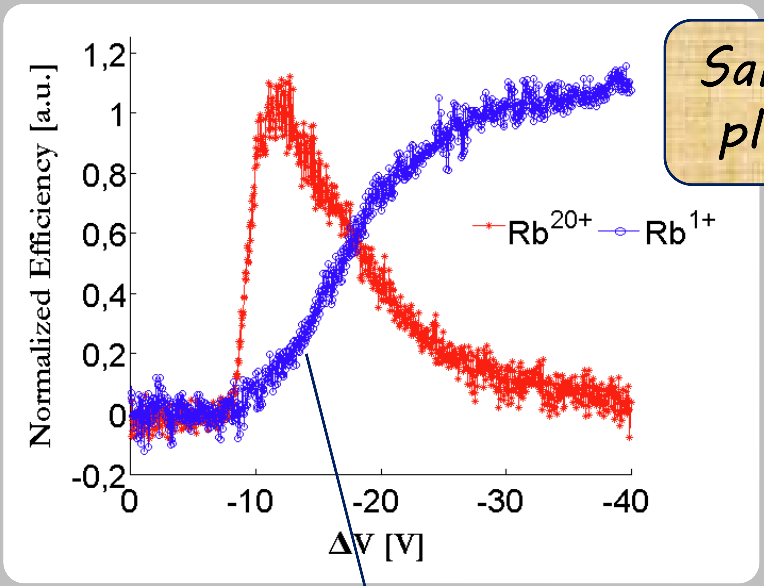
Investigated in a further experiment with Rb

* H. Koivisto et al, RSI 85, 02B917 (2014)

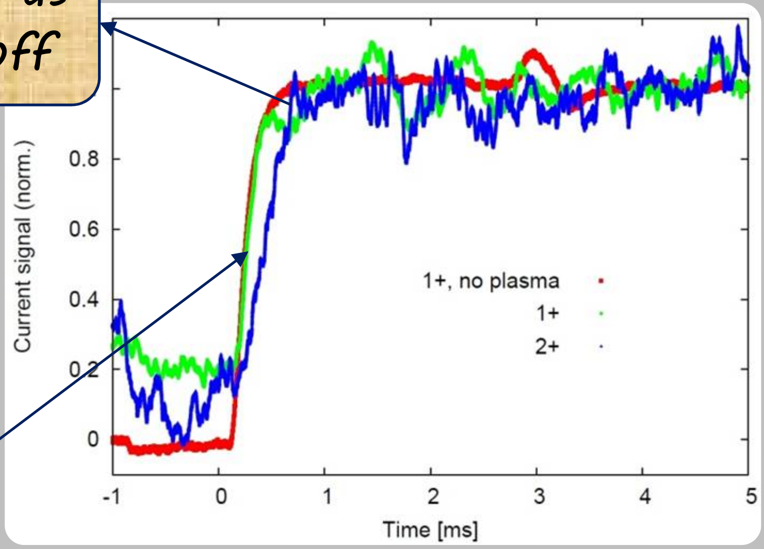
ME AND THE CHARGE BREEDING

EMILIE EXPERIMENT WITH Rb*

Investigation of anomalous 1+ efficiency



Same τ_{CB} as plasma off



1+ ions not captured?

*O. Tarvainen et al, PSST 24 035014 (2015)

ME AND THE CHARGE BREEDING

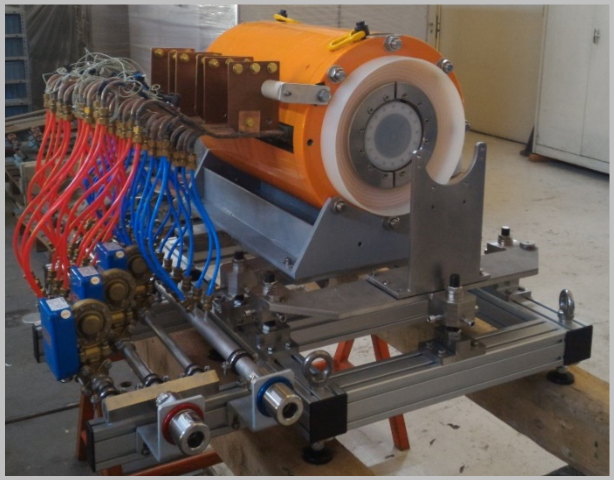
THE SPES-CHARGE BREEDER

- SPES under construction @ LNL
- June 2014: Research Collaboration Agreement INFN (LNL)-CNRS (LPSC)
  - ✓ Delivery within one year of a complete CB and ancillaries
- 2015: Acceptance tests and delivery @ LNL

UPGRADED VERSION OF PHOENIX FROM LPSC

			$\varepsilon_{rms,norm}$ [p*mm*mrad]	
Ion	M/q	η [%]	full	ion
Cs^{26+}	5.1	11·3	0·044	0·020
Xe^{20+}	6.6	11·2	0·030	0·010
Rb^{19+}	4.5	7·8	0·040	0·010
Ar^{8+}	5	15·2	0·04	0·030

Excellent beam quality!



BEAM-PLASMA INTERACTION IN ECRIS-BASED CHARGE BREEDERS

2012-2014
(PhD Thesis)

MOTIVATIONS

- ECR-CB: performances improved during the years but difficulties still exist (gaseous Vs condensable, light Vs heavy)
- No ECR-CB designed for this topic (just adapted): which parameters should be taken into account?
- To which extent an ECR-CB can be blindly tuned?

NUMERICAL SIMULATIONS CAN BE A POWERFUL TOOL TO TACKLE ALL THOSE ASPETCS

MOTIVATIONS

- Previous work from "Cavenago et al." and "Zhao et al."

NOVELTIES

- Fully 3D code
- Application of the Langevin formalism
- Influence of beam and plasma parameters (extensive analysis)
- Agreement with an entire experimental curve
- Density map
- Energy release map

STEPS

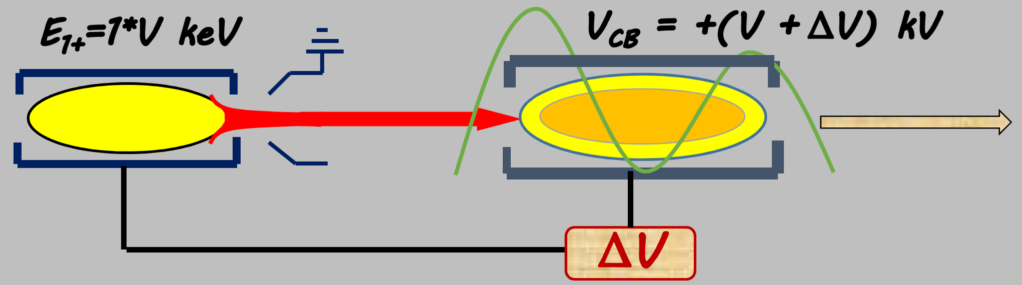
- Theory and numerical implementation of the process
- Benchmark on a simple beam-plasma interaction
- Implementation of a simplified ECR plasma model
- Realistic plasma model → Comparison with experiments
- Important information about the process
- Influence of different parameters (blind tuning?)
- ………………………………………………………………

A LOT OF WORK STILL TO BE DONE!

ECR-CB PECULIARITY

- ECR resonance
- Magnetic Trapping
- Charge creation and destruction

IN COMMON WITH ECR SOURCES



- Particles are injected as 1+ ions
  - Focusing
  - Deceleration (reflection)
- Coulomb collisions lead to thermalization and capture

PECULIARITY IMPLEMENTED IN THE CODE

THEORY

CHANDRASEKHAR*[1] (formalism)

⇓

BROWNIAN MOTION

⇓

- High number of collisions
- Friction coeff independent from v
- Random kicks independent from v

SPITZER*[2]

⇓

CHARGED PARTICLES

⇓

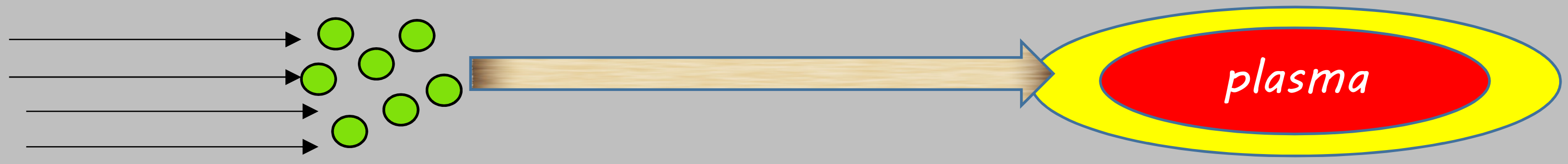
- High collision frequency (long range force)
- Friction coeff depends on v
- Random kicks depends on v

*[1] Rev Mod Phys, 15-1, 1943

*[2] Physics of fully ionized gases, Dover Books

THEORY

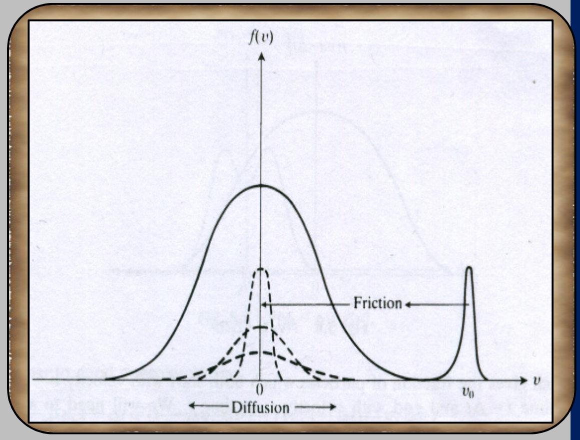
INTERACTION OF AN ION BEAM WITH A PLASMA



Plasma ions following a M-B distribution

Cumulative small angle collisions dominate

Motion deduced from a "test particle"



THERMAL EQUILIBRIUM REACHED FOR ANY INITIAL DISTRIBUTION

THEORY

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

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

Perp. Diffusion D

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

Par. diffusion $D_{//}$

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

Independent variable

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

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

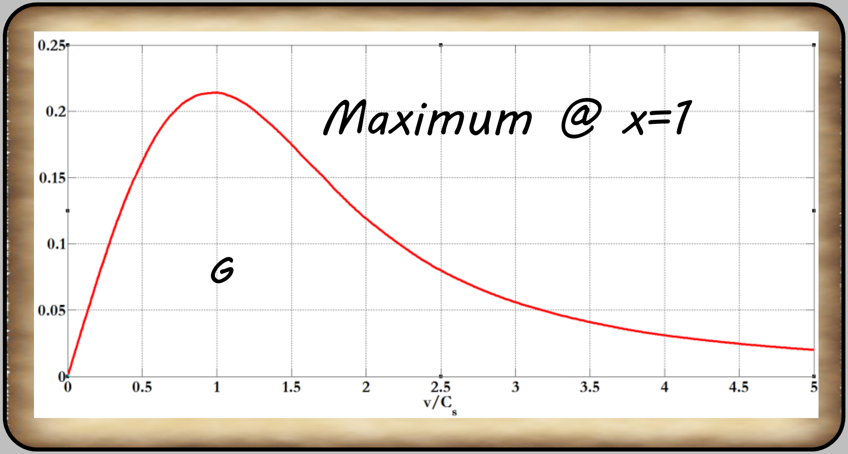
$$G(x) = -\frac{1}{2}\frac{d}{dx}\left(\frac{\Phi(x)}{x}\right) = \frac{\Phi(x) - x\Phi'(x)}{2x^2}$$

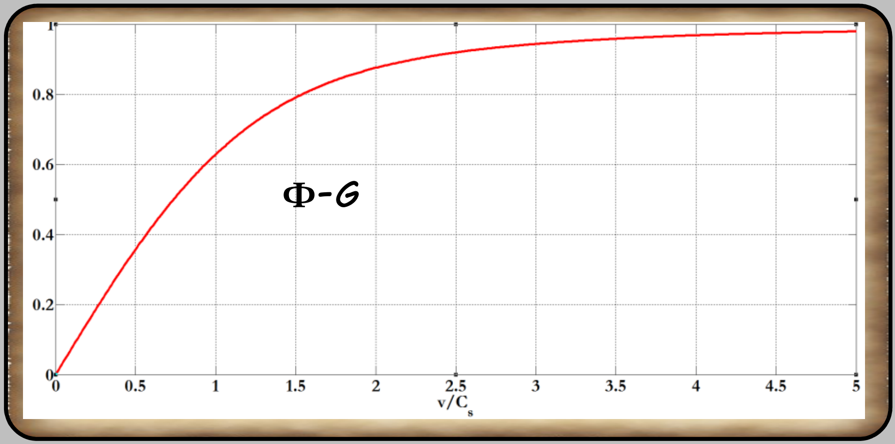
THEORY

TRENDS OF THE COEFFICIENTS

Similar to ΔV

Always increasing





$v \to 0$: no friction; isotropic diffusion

$v \to \infty$: transversal diffusion

Heavy particles dominated by friction

THEORY

CHARACTERISTIC TIMES

- Slowing down time τ_s

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

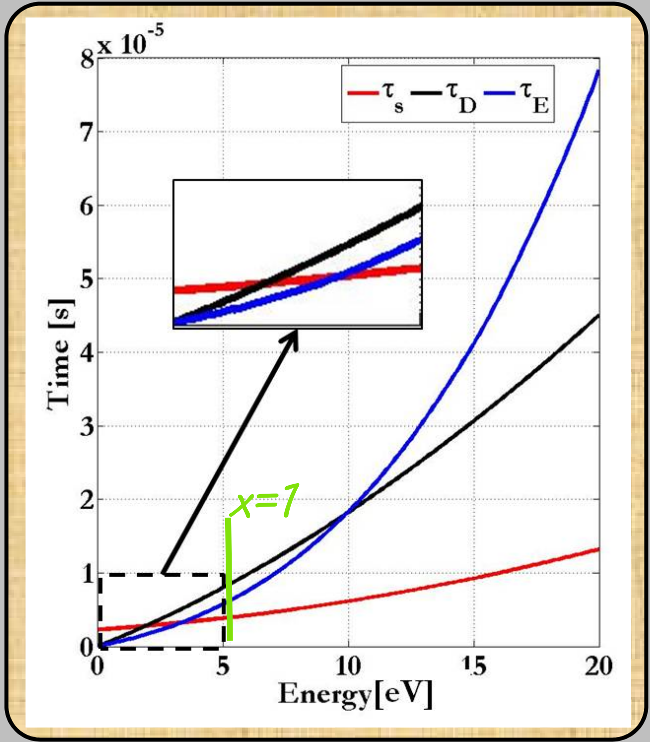
- 90° Diffusion time τ_D

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

- 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



$n_e=2\cdot6*10^{+18}\ m^{-3}$, $KT=1$ eV, $<z>=3$

THE NUMERICAL CODE

IMPLEMENTATION OF COULOMB COLLISIONS

- Forward Difference method

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

- MC approach fails → Langevin Equation* (Brownian motion)

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

SLOWING DOWN

DIFFUSION

*Journal of Comp. Phys. 138, 563-584 (1997)

THE NUMERICAL CODE

LANGEVIN EQUATION

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

1 2

1. Friction: $a = -\,\nu_s v$

2. Random vector v^{rand}

Distribution of random kicks

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

3 // v while 1,2 ⊥ v change at each iteration

Calculated for each particle from the F-P eq.

STEPS

- Theory and numerical implementation of the process
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- ....

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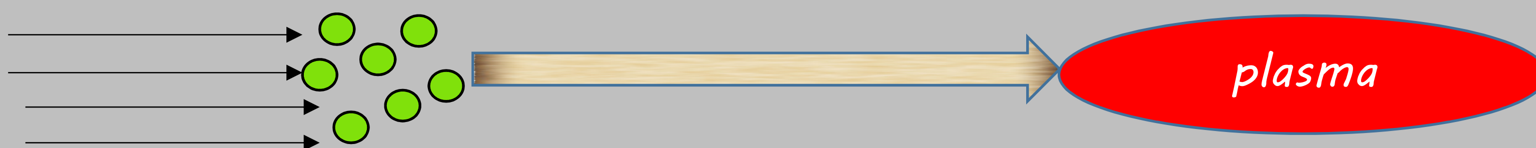
BENCHMARK

MONOCROMATIC BEAM Vs INFINITE PLASMA



- **Simulation**
  - ✓ N=10000
  - ✓ $T_{step} = 1*10^{-10}$ s
  - ✓ Int Time= $2.88*10^{-4}$ s
- **Injected Ions**
  - ✓ z_{inj}= 6
  - ✓ M_{inj}=132 (Sn)
  - ✓ $v_x=v_y=0$
  - ✓ $v_z=3.4*10^{+3}$ m/s
- **Plasma Ions**
  - ✓ $\langle z \rangle$= 3.5
  - ✓ M=16
  - ✓ $n_e \sim 2.5*10^{+16}$ ioni/m^3
  - ✓ KT= 1 eV

CHARACTERISTIC TIMES

$\tau_s = 1{\cdot}58*10^{-5}$ s

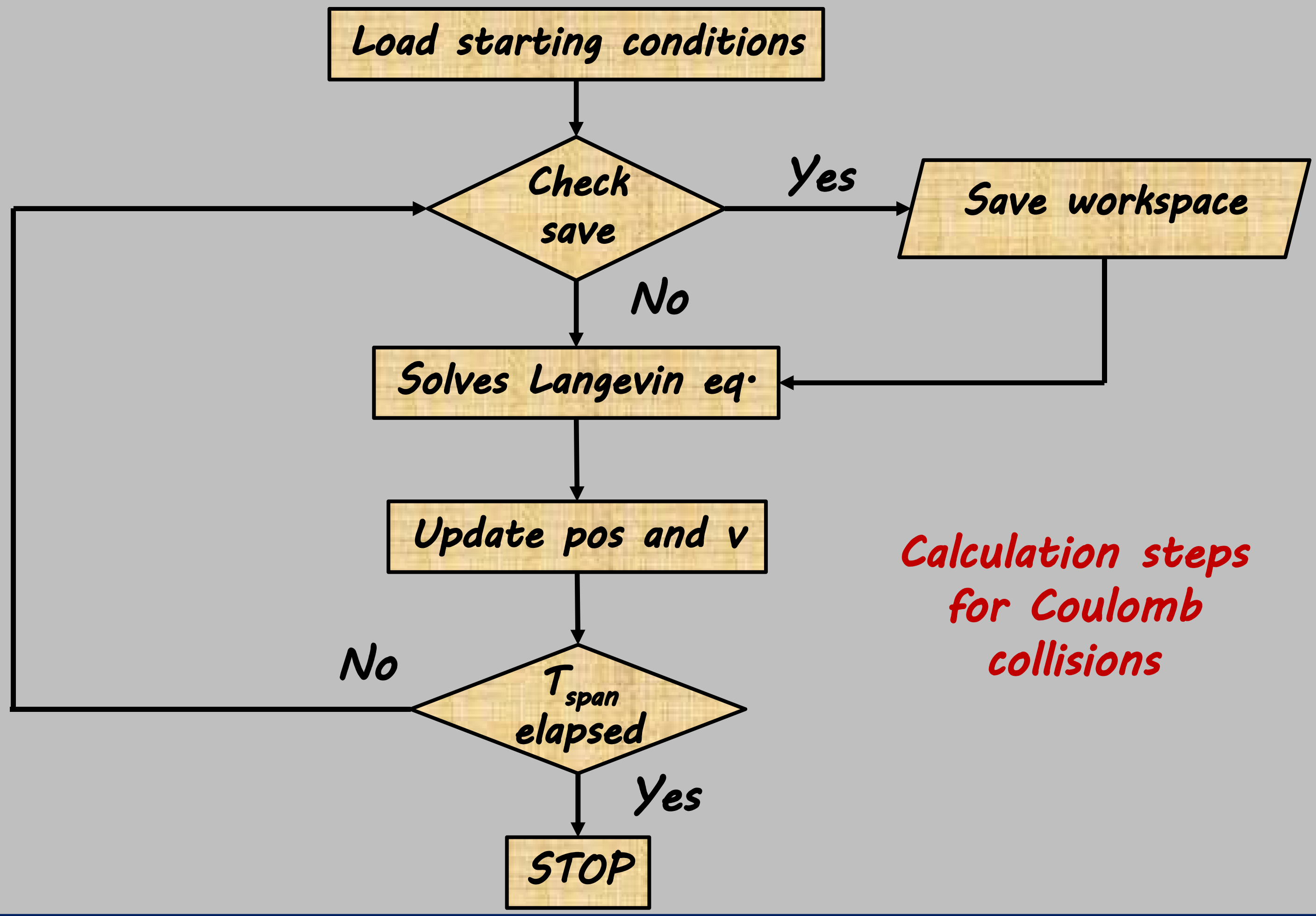
$\tau_D = 4{\cdot}88*10^{-5}$ s

$\tau_E = 3{\cdot}55*10^{-5}$ s

EXPECTED DEVIATION

σ_{exp}= 851·3 m/s

FLOW DIAGRAM

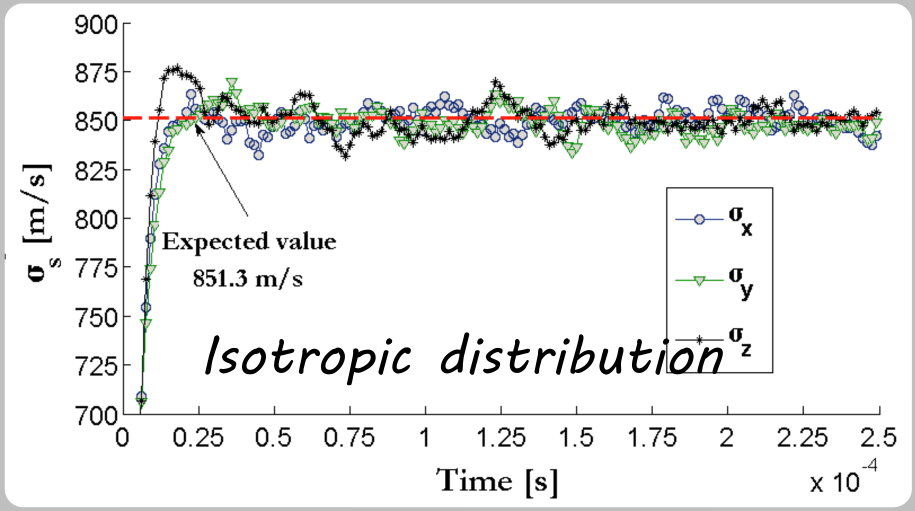


Calculation steps for Coulomb collisions

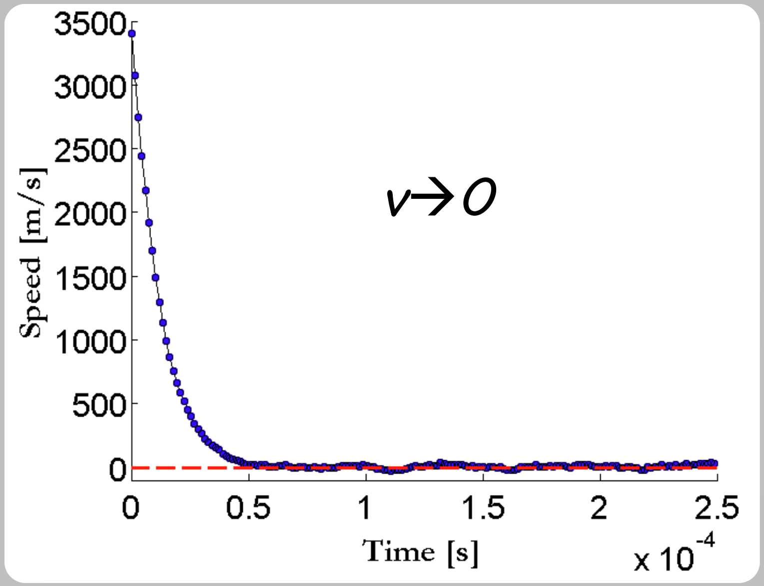
RESULTS

DISTRIBUTION OF THE INJECTED PARTICLES

Spread

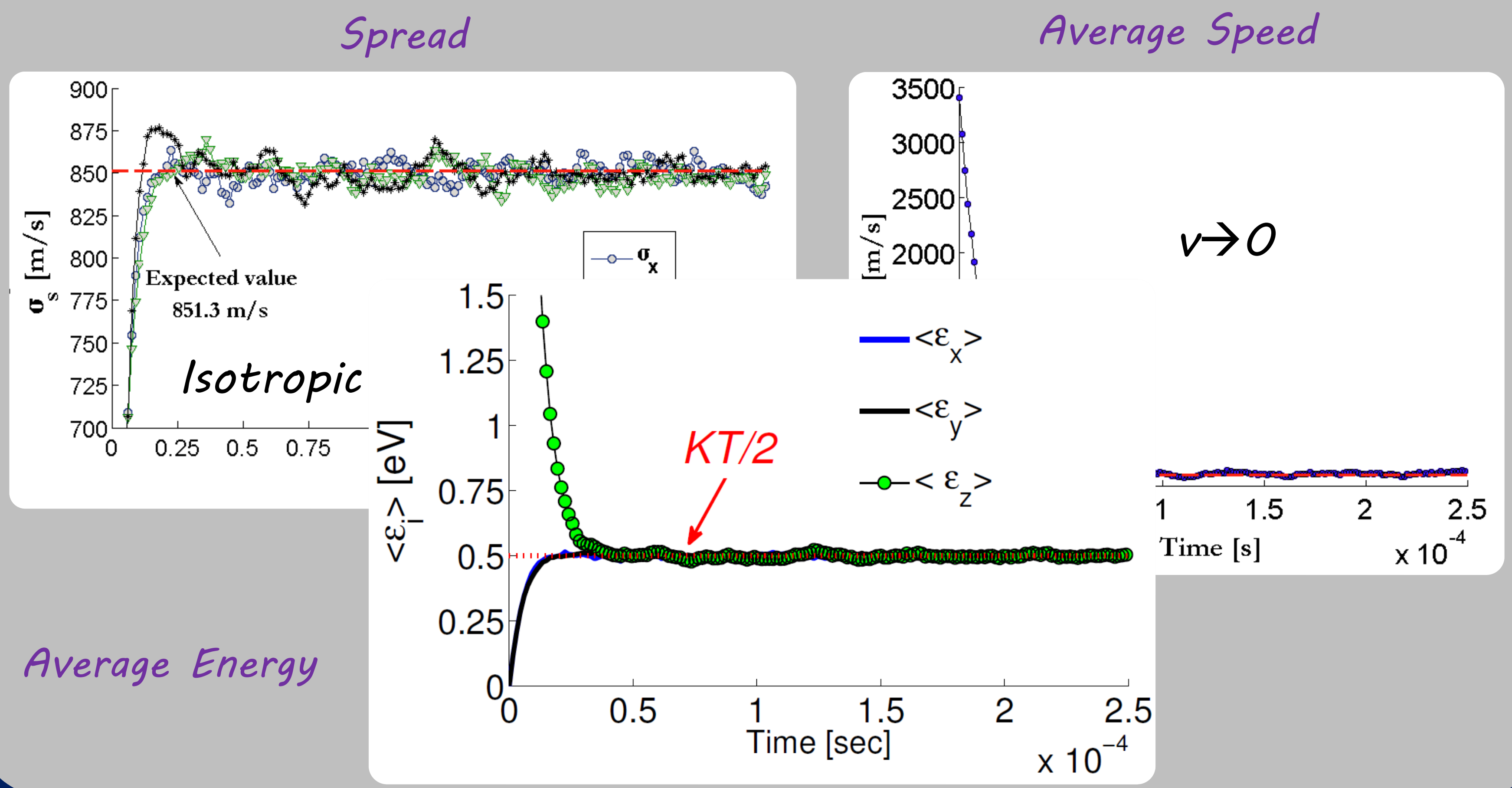


Average Speed



RESULTS

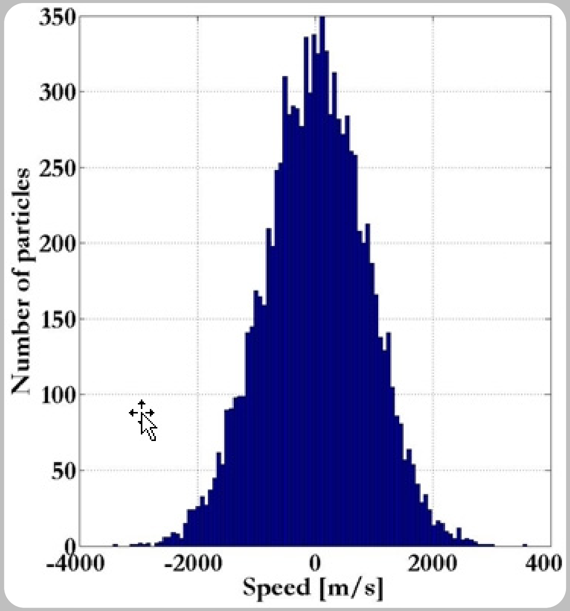
DISTRIBUTION OF THE INJECTED PARTICLES



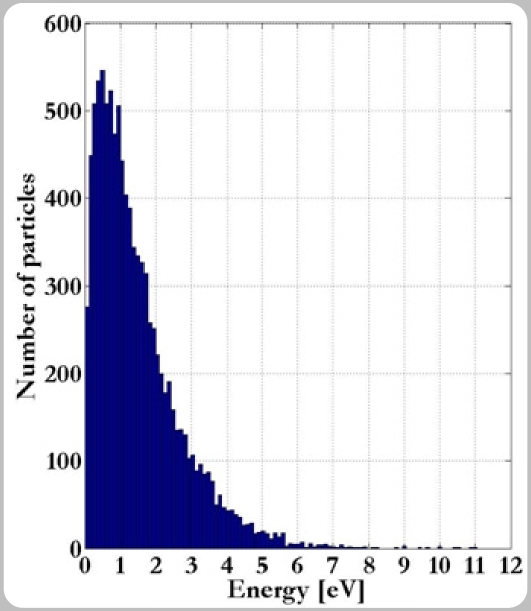
RESULTS

DISTRIBUTION OF THE INJECTED PARTICLES

1D velocity distribution



Energy distribution



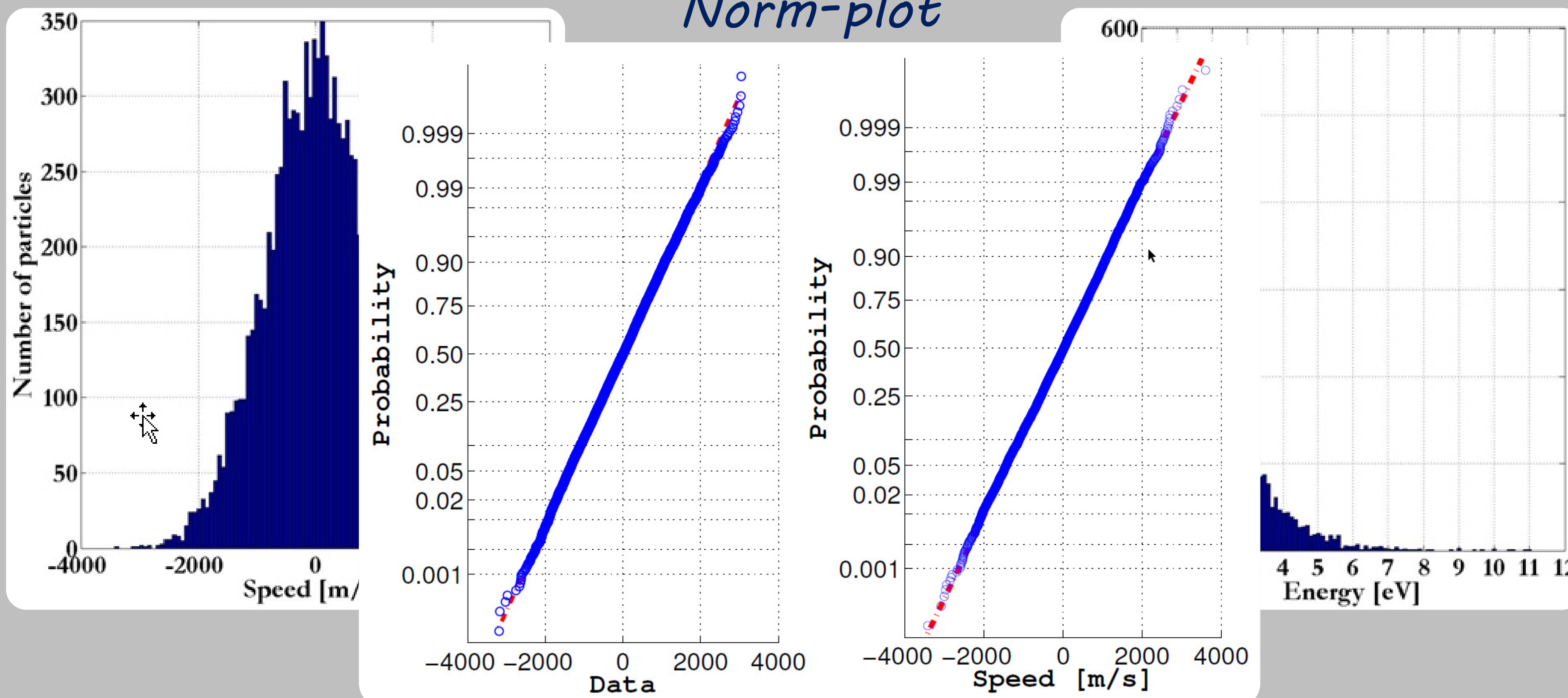
RESULTS

DISTRIBUTION OF THE INJECTED PARTICLES

1D velocity distribution

Norm-plot

Energy distribution



PARTICLES REACH A MB DISTRIBUTION @ KT

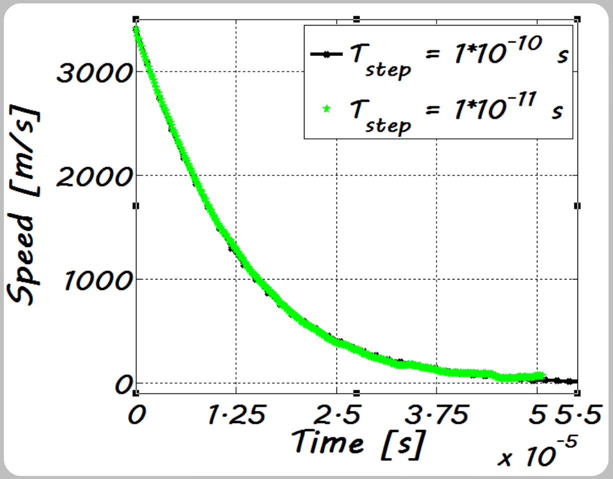
RESULTS

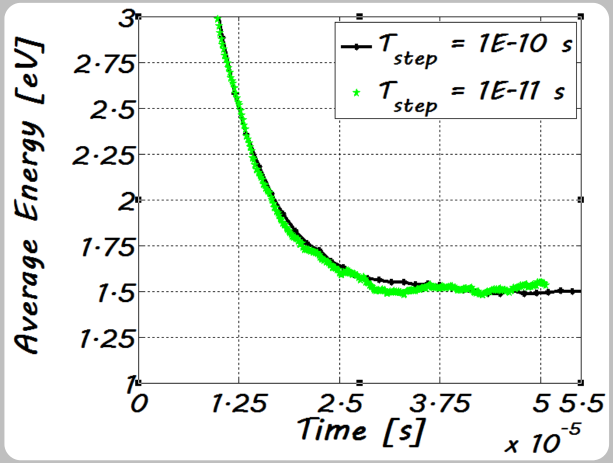
CHECKS

IS T_{step} ADEQUATE?

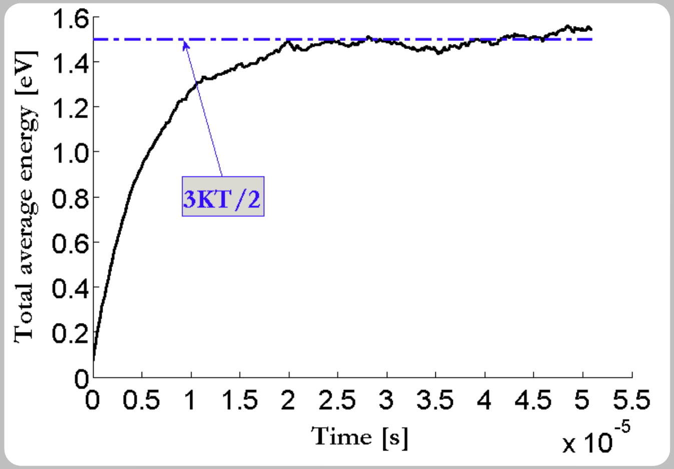
✓ N=2000

✓ Int Time = $5\cdot 1*10^{-5}$s





ION HEATING



STEPS

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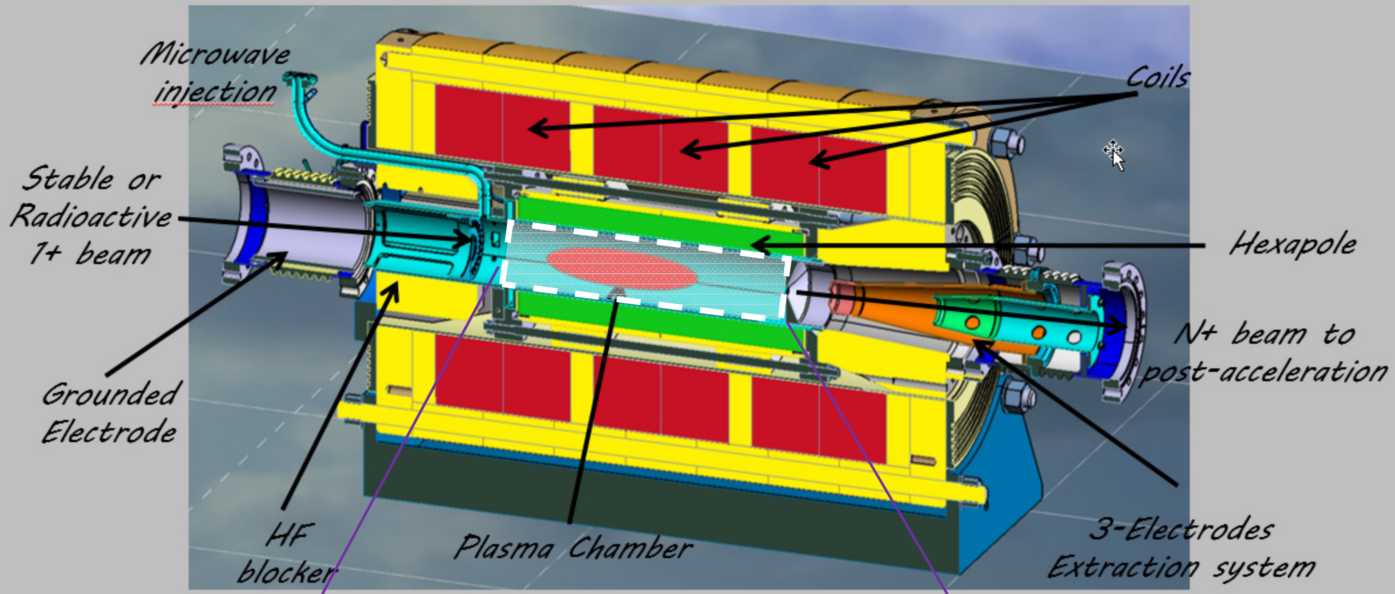
SIMULATION DOMAIN

PHOENIX BOOSTER



B_{max} at injextion

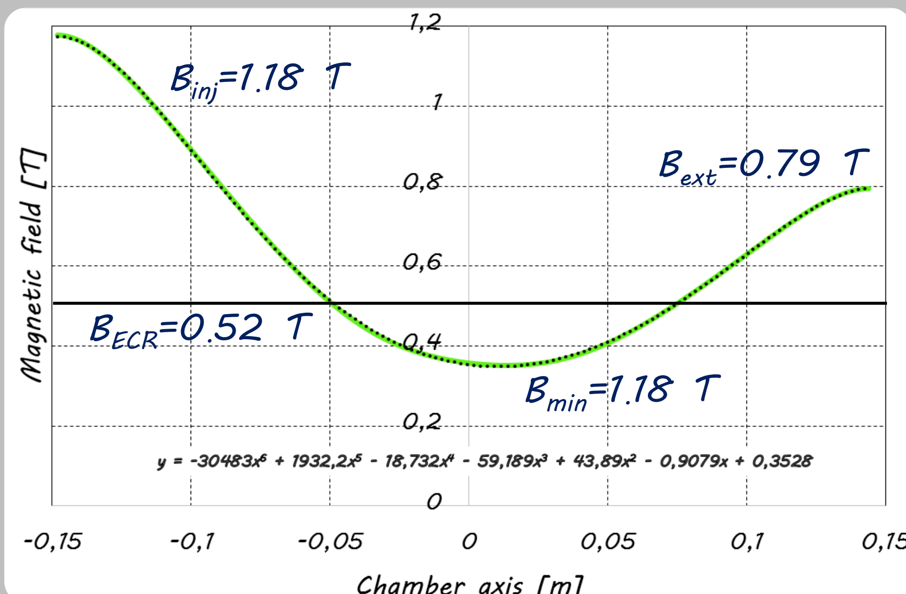
Cylinder:
- r = 36 mm
- l =288 mm

Extraction hole

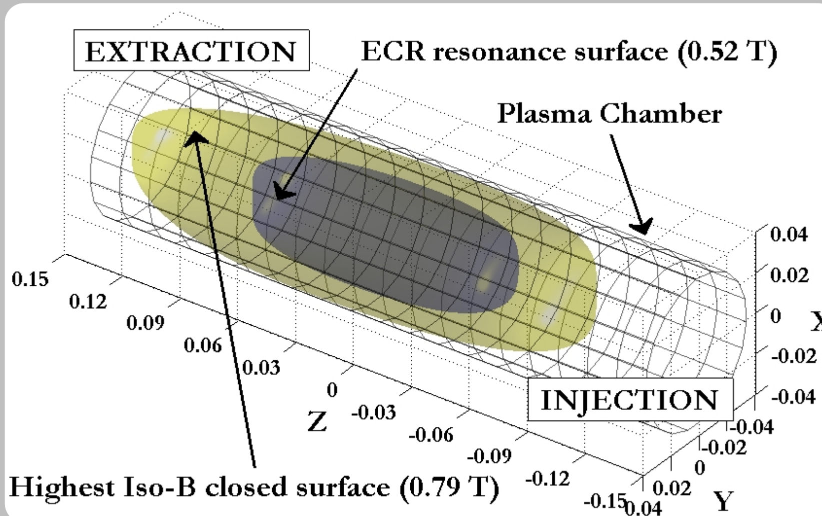
SIMULATION DOMAIN

MAGNETIC FIELD

IMPLEMENTED BY ANALYTICAL FORMULAS



$hex = 617\cdot 8\ T/m^2$



B_z: interpolation (6th order)

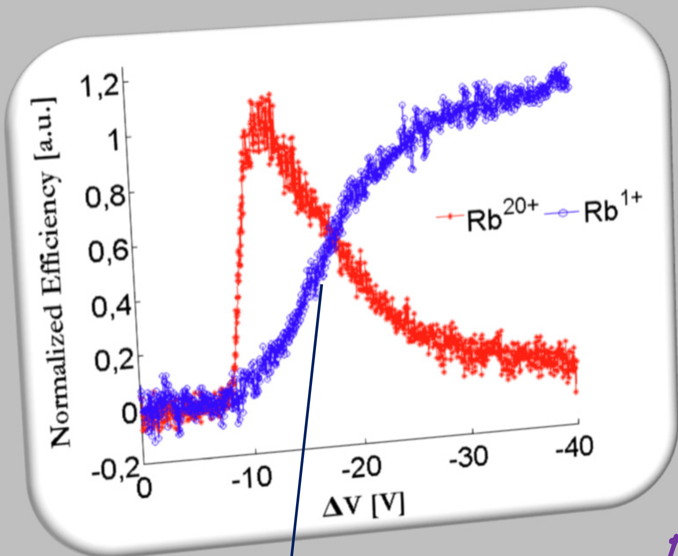
B_y: $-(y/2)*(dB_z/dz)+hex*(x^2-y^2)$

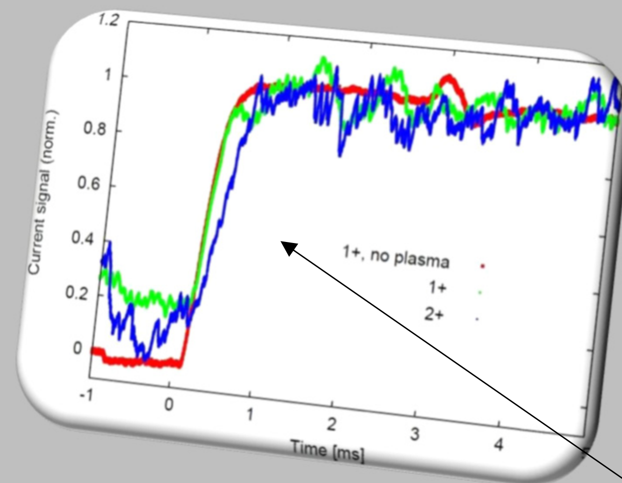
B_x: $-(x/2)*(dB_z/dz)+hex*xy$

VALIDATION

COMPARISON WITH EXPERIMENT

EMILIE experiment with Rb





PARAMETERS AND REQUIREMENTS

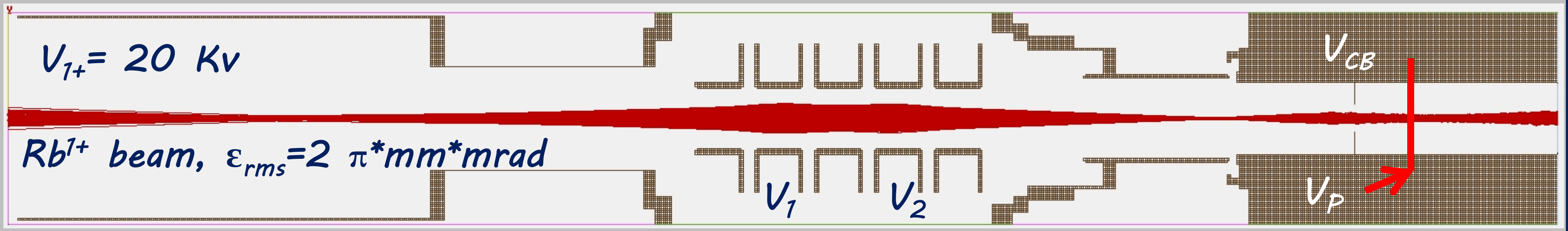
- $T_{span} = \tau_{1+} = 500\ \mu s$
- Global capture ≥ 40 % @ ΔV_{opt} ~ -12 V
- Rb^{1+} efficiency few % @ ΔV_{opt} ~ -12 V

REPRODUCTION OF THIS CURVE

BEAM INJECTION

REALISTIC STARTING CONDITIONS

Simulation of injection: SIMION*



Plasma potential

$$\Delta V_{exp} = -(V_{1+} - V_{CB}) = -(V_{1+} - V_P) + \Delta V_P$$

$$\Delta V_{exp} < \Delta V_{sim}$$

$$\Delta V_{sim} = -(V_{1+} - V_P) \rightarrow E_{inj} = (V_{1+} - V_P)/e$$

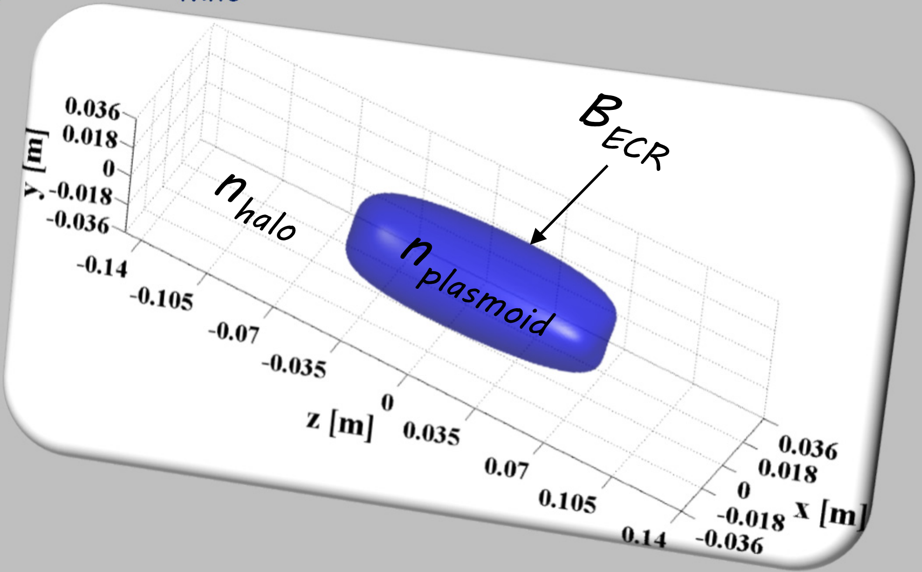
Shift towards smaller ΔV for simulated curves

Could this shift be a measure of the plasma potential?

* Thanks to J. Angot from LPSC

BASIC PLASMA MODEL

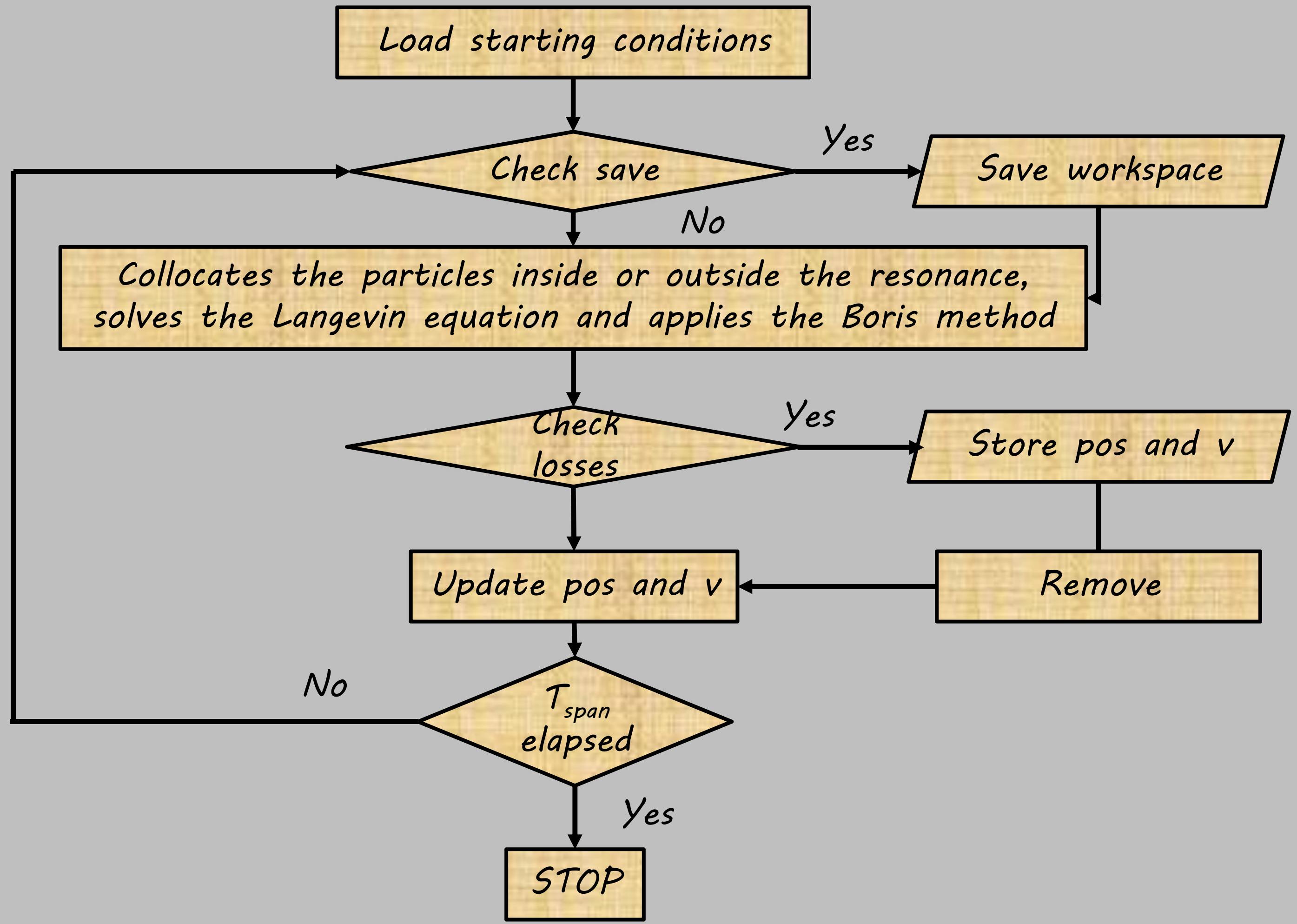
- plasmoid/halo scheme $n_{plasmoid}=100*n_{halo}$
- Boris method for B motion
- losses



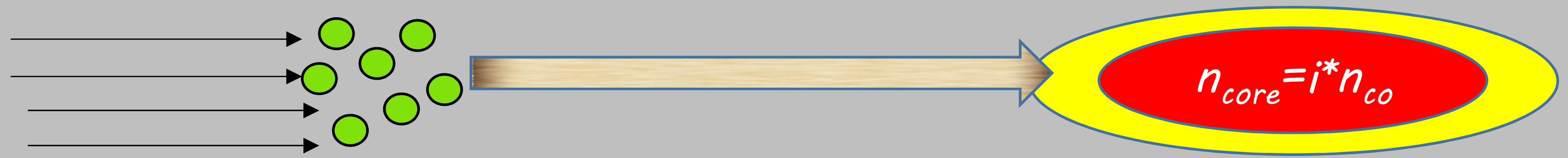
EVEN IF IONIZATIONS ARE NOT INCLUDED, THIS MODEL WILL GIVE USEFUL INFORMATION ABOUT THE «NON INTERACTING» 1+ IONS

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

BPM: FLOW DIAGRAM



BPM: KT_i=1 eV



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

$n_{co}=2\cdot6\cdot10^{18}$ m^{-3}
i=1, 0·6, 0·3, 0·1
<z>=2.5 (0)

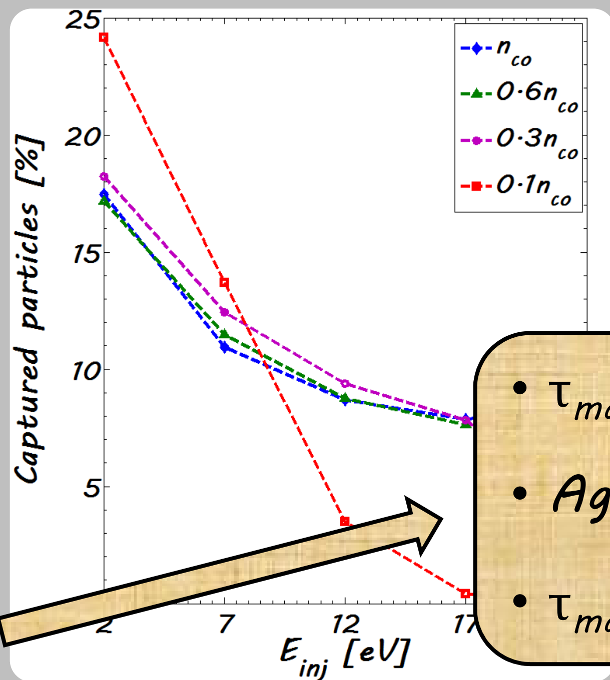
Plasma State?

↓

$\upsilon_{coll} \leq \upsilon_{cycl}$ all n

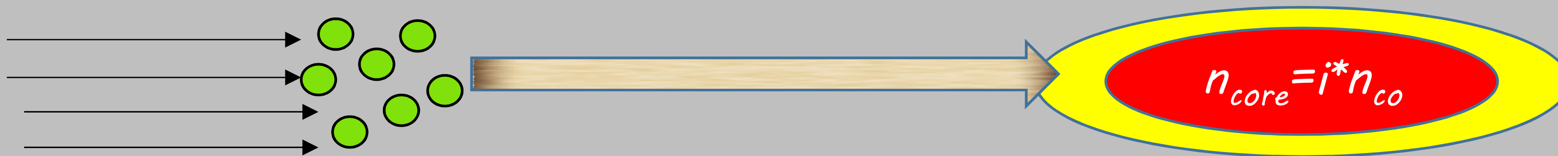
↓

MAGNETIZED IONS



- $\tau_{mag}=Rl/v_T$ ~ 400-600 μs
- Agreement with T_{span}
- τ_{mag} independent from n

BPM: $KT_i = 0{\cdot}376$ eV



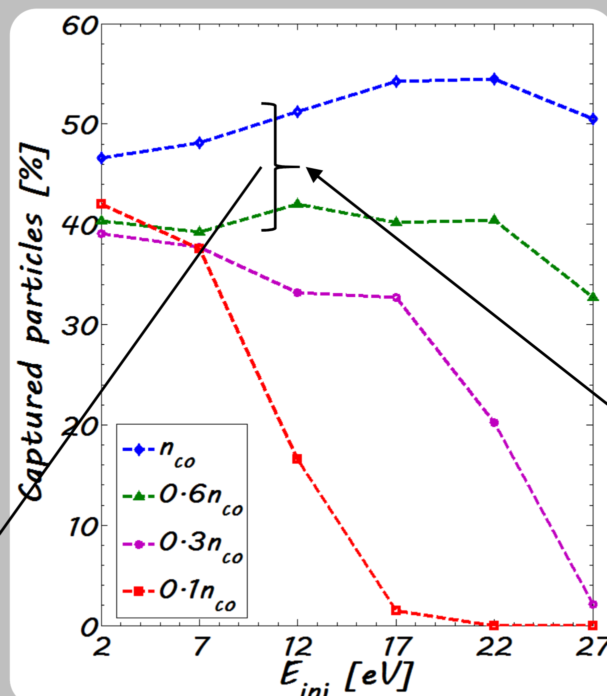
$1000\ Rb^{1+}$ ions

E_{inj} = 2:5:27 eV

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

SAME AS KT=1 eV

THE EFFECT ON BEAM CAPTURE IS EVIDENT



$n_{co} = 2{\cdot}6{\cdot}10^{18}\ m^{-3}$

$i = 1,\ 0{\cdot}6,\ 0{\cdot}3,\ 0{\cdot}1$

$\langle z \rangle = 2.5\ (0)$

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

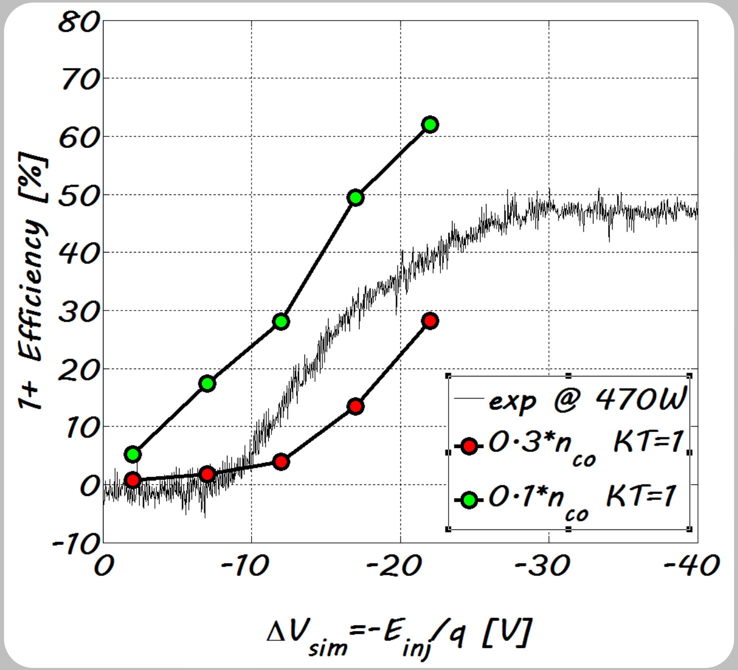
COLLISIONAL REGIME?

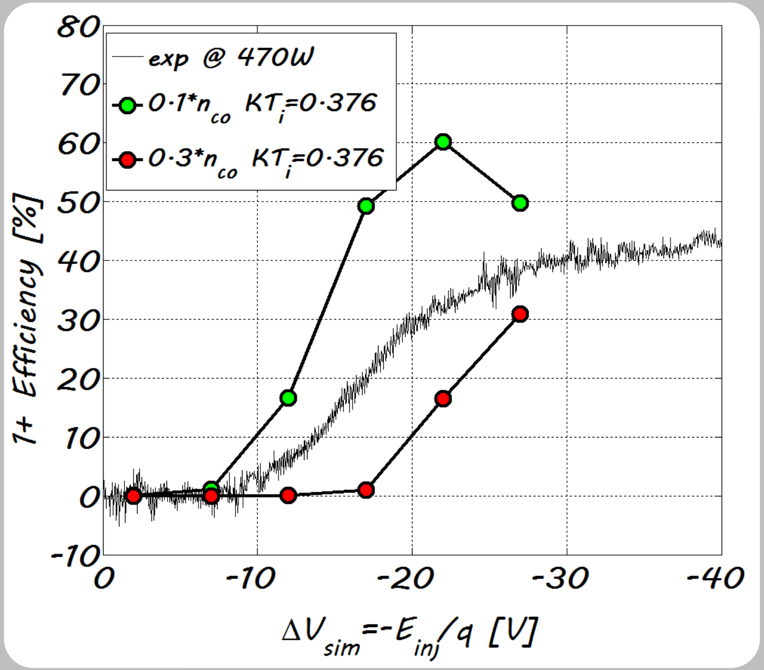
Whatever the regime.........

BPM: Rb^{1+} EFFICIENCY

RB^{1+} IONS LOST THROUGH THE EXTRACTION HOLE

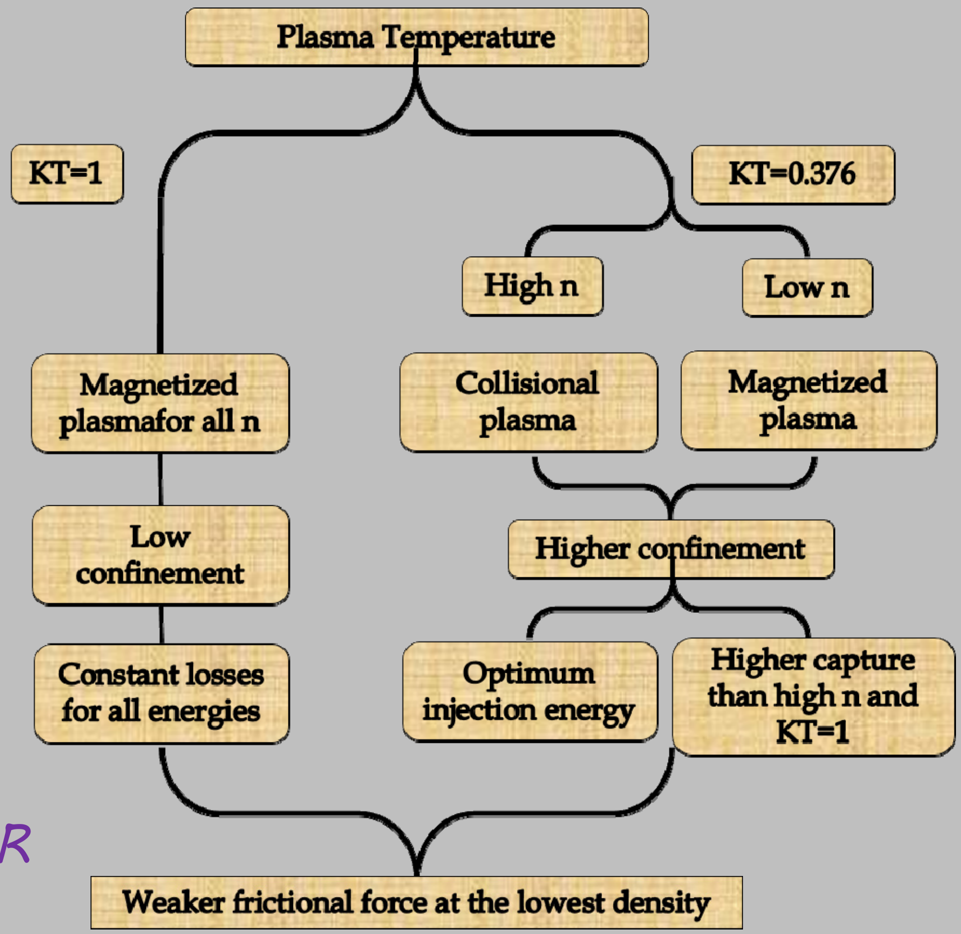
«Similar» trends but no agreement





FOR BOTH TEMPERATURES NO Rb^{1+} IONS EXTRACTED UNLESS $n \leq 0\cdot3*n_{co}$

BPM: SUMMARY



KT, KEY PARAMETER

STEPS

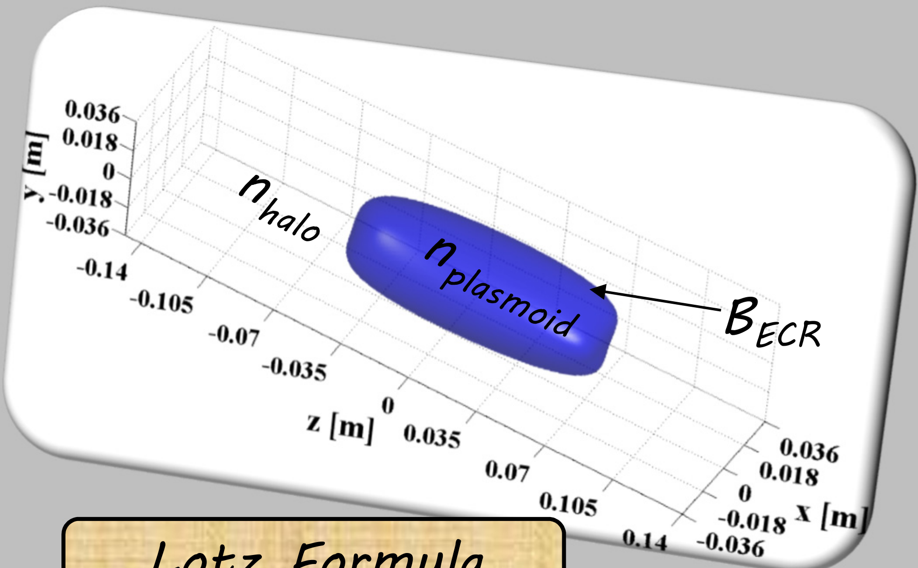
- Theory and numerical implementation of the process
- Benchmark on a simple beam-plasma interaction
- Implementation of a basic ECR plasma model
- Realistic plasma model → Comparison with experiments
- Important information about the process
- Influence of different parameters: blind tuning?
- ……………………………………………………………

A LOT OF WORK STILL TO BE DONE!

REALISTIC PLASMA MODEL

RPM=BPM+:

- POTENTIAL DIP
- Complete Lorentz force
- IONIZATIONS
  T_e(plasmoid)=1 keV
  T_e(halo)=0.1*T_e(plasmoid)



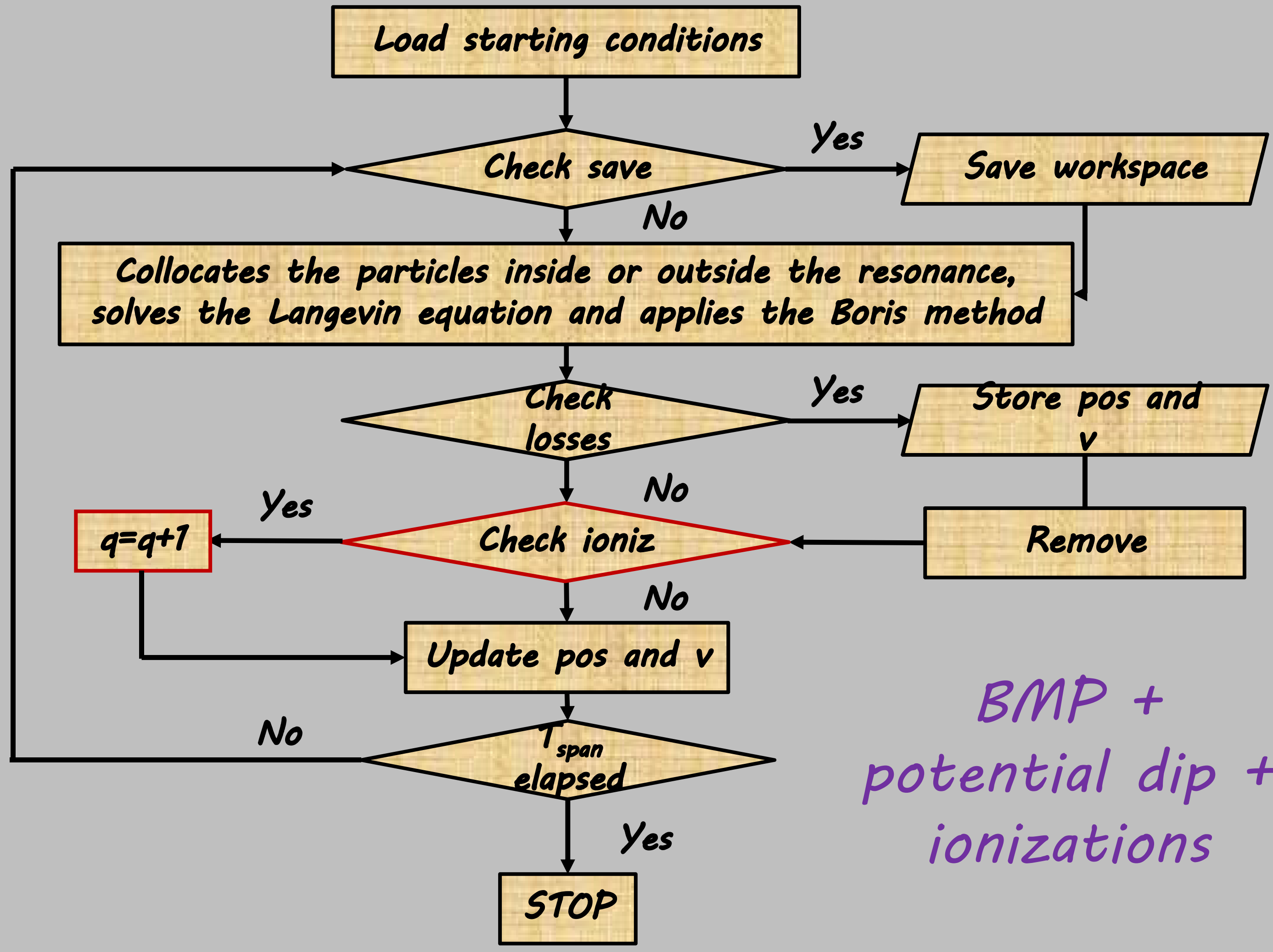
Lotz Formula

$$\left(\tau_{ion}^{(i\rightarrow i+1)} n_e\right)^{-1} = 6.7\cdot 10^{-7}\sum_{j=1}^{N}\frac{a_{ij}q_{ij}}{T_e^{3/2}}\left\{\frac{1}{P_{ij}/T_e}E_1(P_{ij}/T_e) - \frac{b_{ij}\exp c_{ij}}{P_{ij}/T_e + c_{ij}}E_1(P_{ij}/T_e + c_{ij})\right\}$$

MC Technique

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

RPM: FLOW DIAGRAM

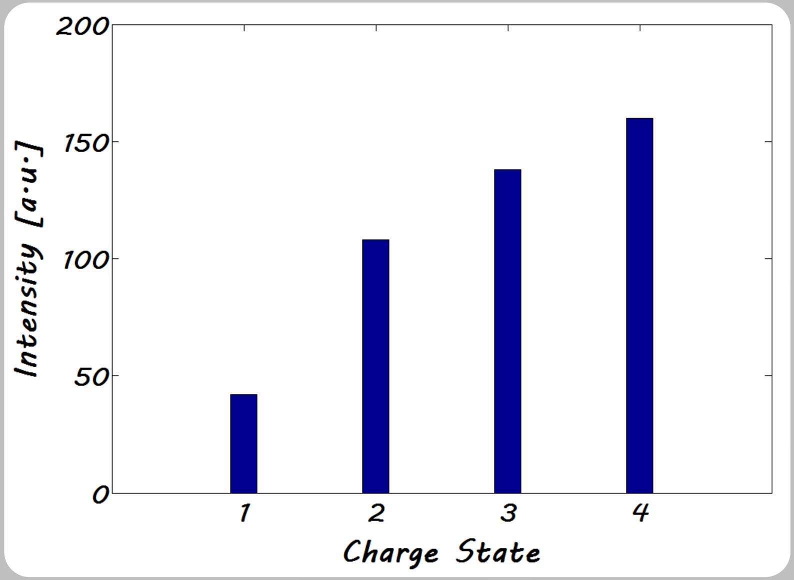


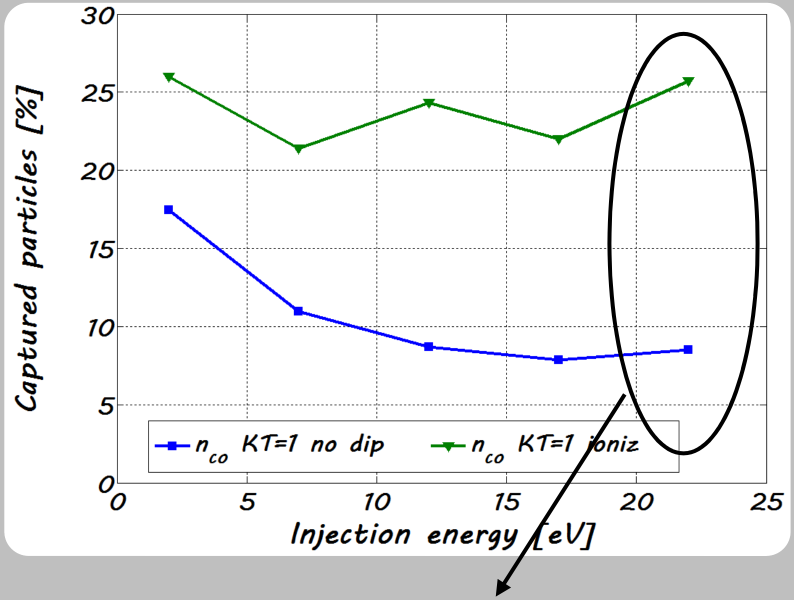
BMP + potential dip + ionizations

BPM Vs RPM

KT_i=1 eV $n=n_{co}$

IONIZATIONS TAKE PLACE





CAPTURE INCREASES UP TO A FACTOR > 3 BUT...

EVEN INCLUDING IONIZATION THE GLOBAL CAPTURE IS BELOW EXPERIMENTAL VALUES AT KT_i=1 eV

RPM

SAME SYSTEMATIC AS BPM

↓

After having repeated all the previous systematics it clearly came out that:

TO HAVE A REASONABLE GLOBAL CAPTURE AND Rb^{7+} IONS EXTRACTED

↙ ↘

LOW DENSITY (low n) | COLD IONS (low KT_i)

RPM KT_i=0.376 eV

LOW DENSITY, COLD IONS

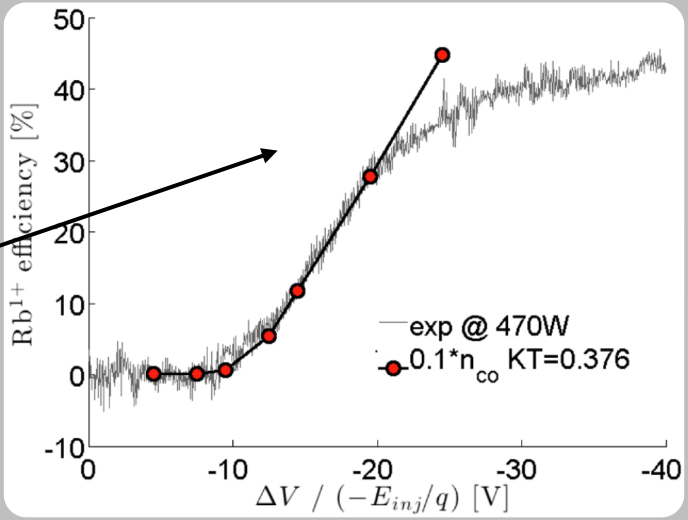
- $n=0.3*n_{co}$

E_{inj} [eV]	ε_{1+} [%]
2	0·00
7	0·00
12	0·10
17	0·72
22	11·04

⇒ NO Rb^{1+}

- $n=0.1*n_{co}$

E_{inj} [eV]	Captures [%]	ε_{1+} [%]
2	44·62	0·16
7	39·93	0·64
12	18·70	11·68
17	3·20	27·76
22	0·40	44·72

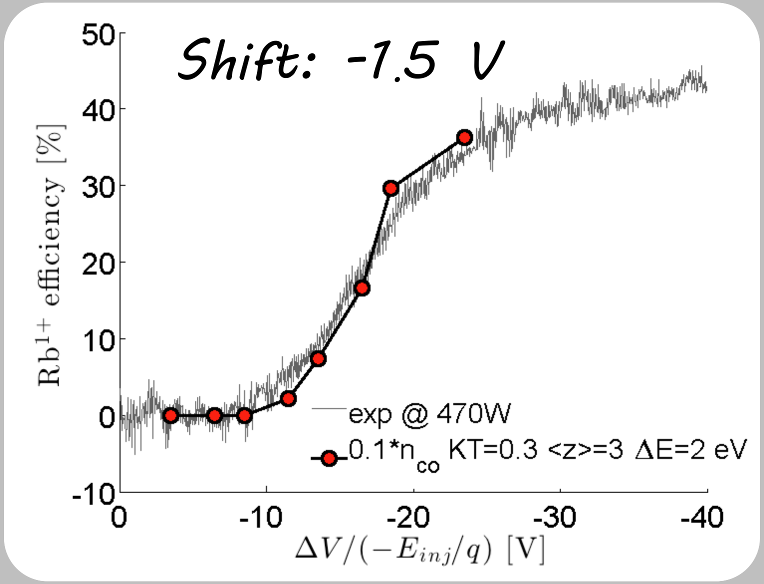


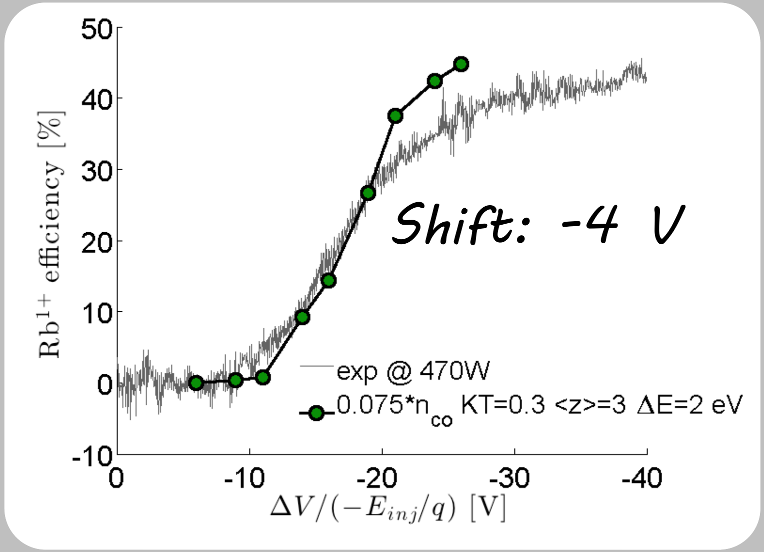
CAPTURE STILL TOO LOW

RPM: KT_i=0.3 eV

AGREEMENT WITH EXPERIMENTS!

$n=0.1*n_{co}$ <z>=3 ΔE=2 eV $n=0.075*n_{co}$





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

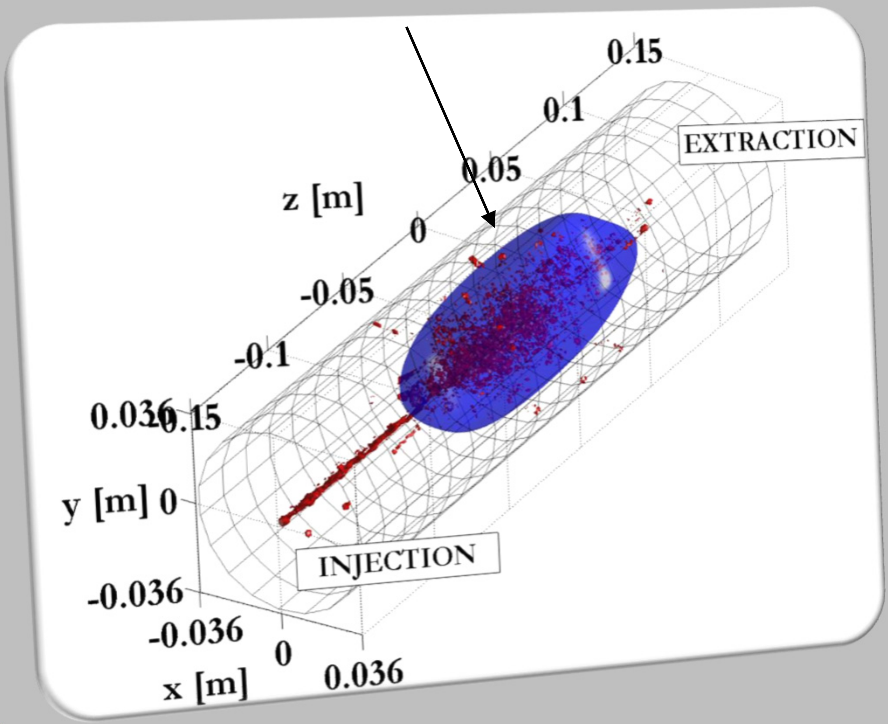
Einj [eV]	Captures [%]	ε1+ [%]	ΔVsim [V]
7	47.64	0.80	-11
10	39.51	9.28	-14

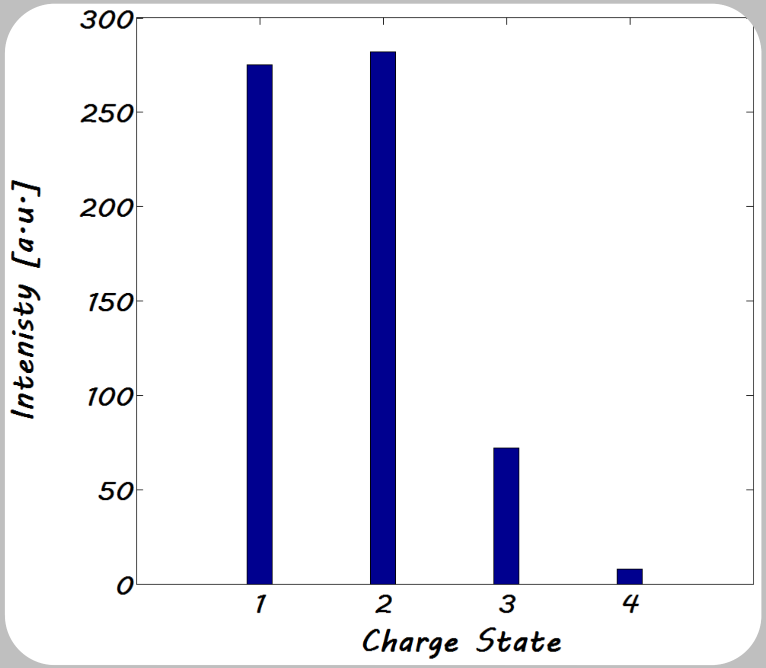
*A. Galatà et al., RSI 87, 02B507

SIMULATIONS DETAILS

$n=1\cdot 95*10^{+17}\ m^{-3}$; $KT_i=0.3\ eV$; $E_{inj}=7\ eV$; $Shift=-4\ V$

MOST OF THE PARTICLES TRAPPED IN THE PLASMOID

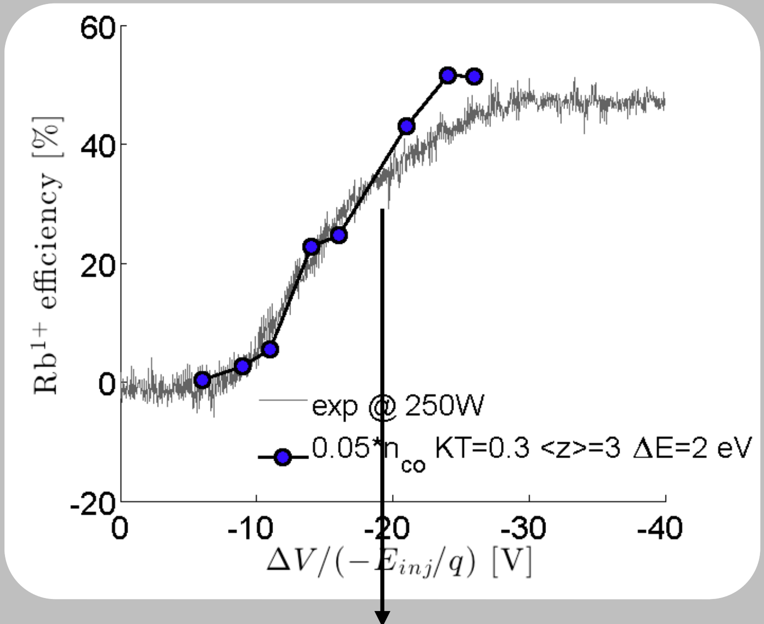




FIRST IONIZATIONS

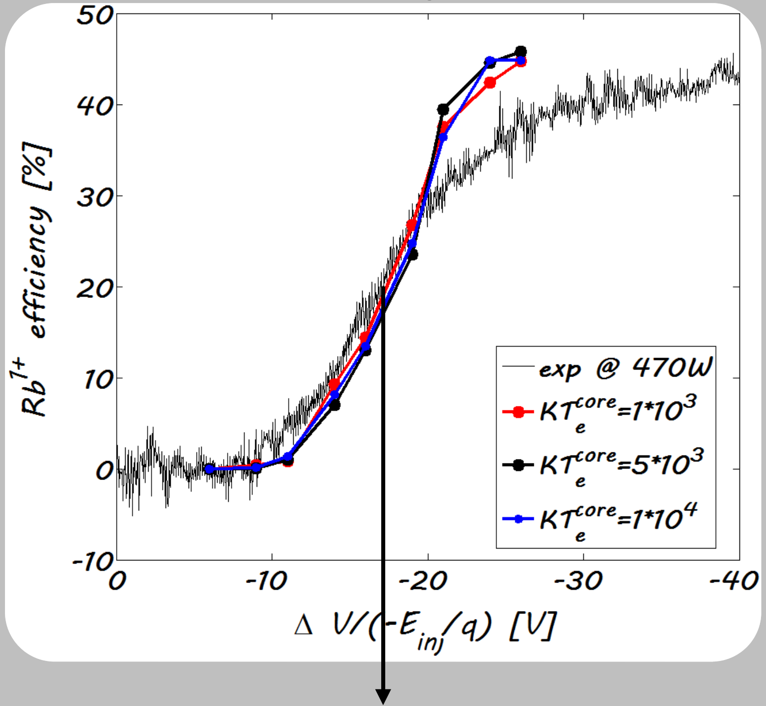
FURTHER RESULTS

$n=0.05*n_{co}$



EXPERIMENTAL CURVE AT LOWER POWER REPRODUCED BY LOWERING PLASMA DENSITY

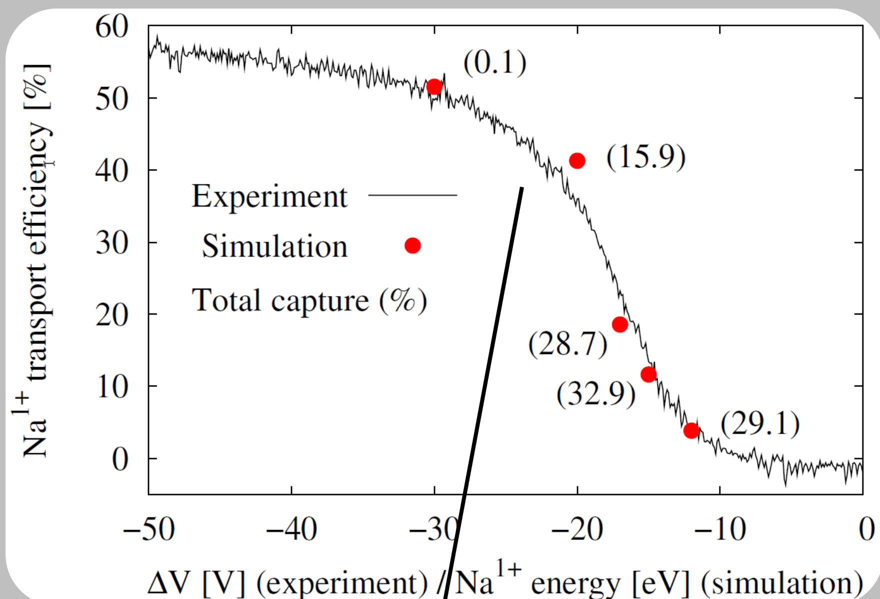
Eff. Vs KT_e(warm)



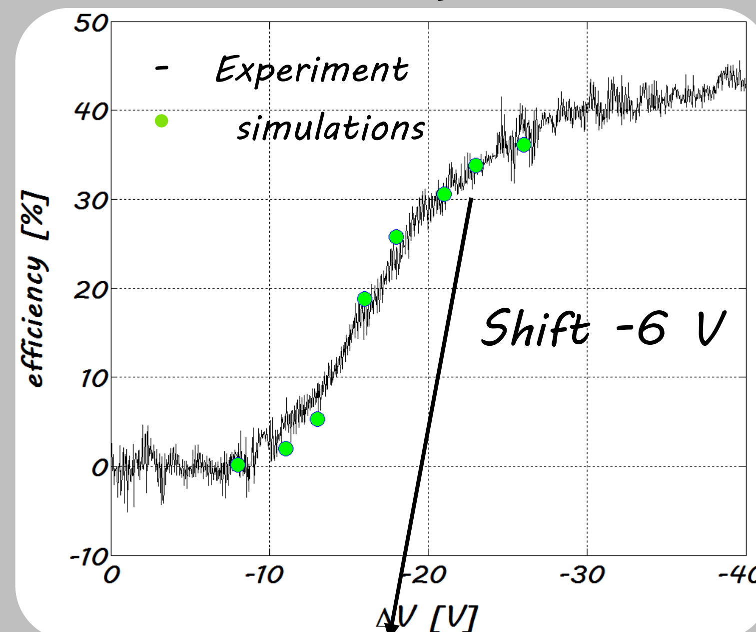
FIRST IONIZATIONS NOT SENSITIVE TO KT_e

FURTHER RESULTS

Na EXPERIMENTS*



Rb WITH logΛ=10



AGREEMENT ON CHARGE BREEDING OF LIGHT IONS

EVEN BETTER AGREEMENT

The value of logΛ should be calculated, not guessed

*O. Tarvainen et al, accepted by PRST-AB

STEPS

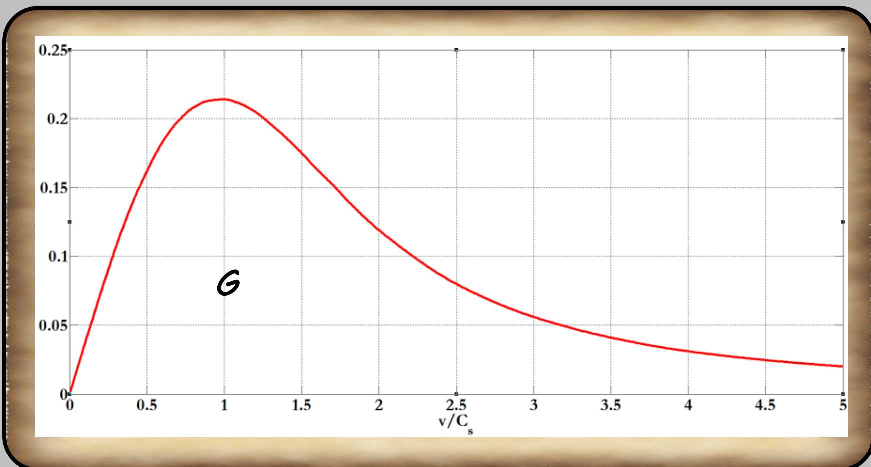
- Theory and numerical implementation of the process
- Benchmark on a simple beam-plasma interaction
- Implementation of a basic ECR plasma model
- Realistic plasma model → Comparison with experiments
- Important information about the process
- Influence of different parameters: blind tuning?
- ………………………………………………………………

A LOT OF WORK STILL TO BE DONE!

BALLISTIC OF THE PROCESS

DENSITY MAP

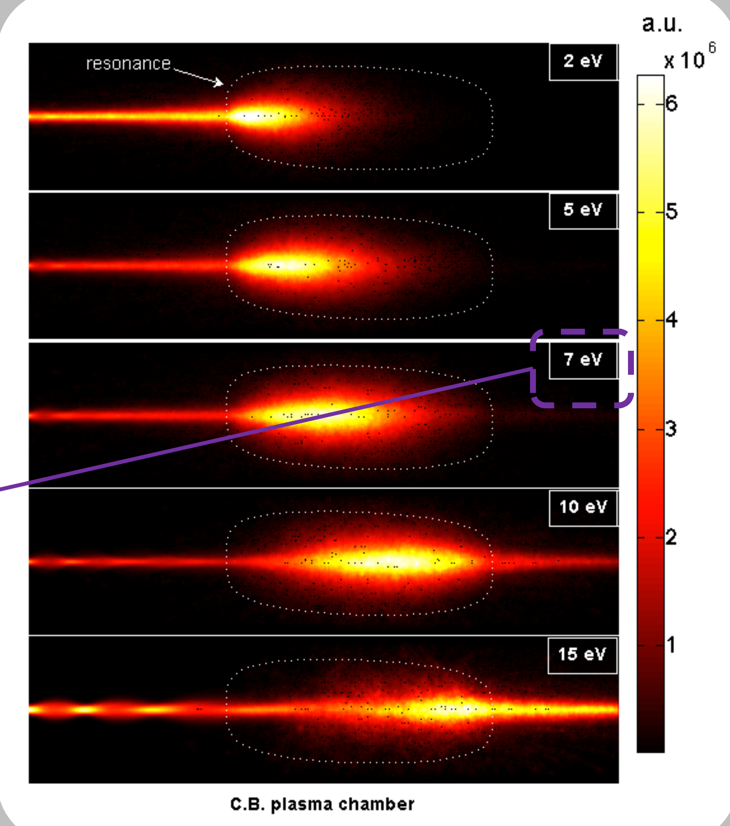
Optimum Injection Energy @ x=1?



E(x=1)= 1.6 eV for
Rb with KT_i=0·3 eV

AN EXTRA ENERGY IS NEEDED
FOR A PROPER CAPUTRE

Trapped particles Vs Energy



PLASMA PERTURBATION

EFFECT OF BEAM-PLASMA INTERACTION

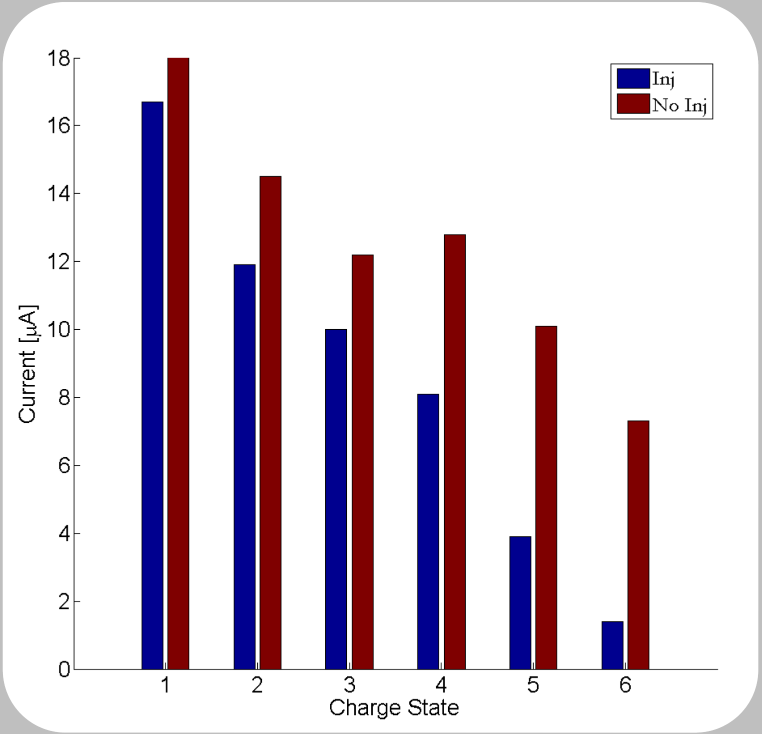
1 μA of Xe^{1+} injected ions

↓

Beam density much lower than plasma density, anyway...

↓

INJECTED IONS AFFECT PLASMA IONS CONFINEMENT

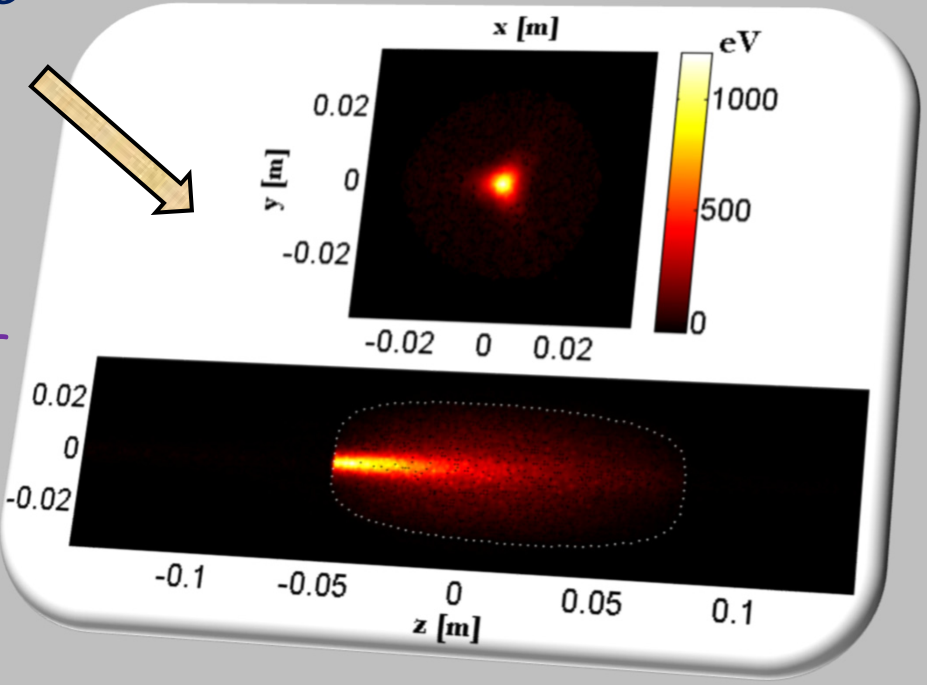


→ DIRECT ION HEATING?

PLASMA PERTURBATION

ENERGY RELEASE MAP

- Ions loose energy just inside the plasmoid
- The energy is released in a thin plume around the axis



CAN INJECTED IONS HEAT LOCALLY PLASMA IONS?

LOCAL ENERGY RELEASE
VS
PLASMA EQUIPARTITION

PLASMA PERTURBATION

LOCAL ENERGY RELEASE Vs PLASMA EQUIPARTITION

ION HEATING

N particles loose almost all their energy in a time τ_e

⇓

Scaling @ 1 μA the calculated energy density

⇓

$<H_{ing}>$~2E-8 eV mm^{-3} s^{-1}
(locally up to 2 order of magnitude higher)

PLASMA E EXCHANGE

Plasma ions exchange an energy density $3/2 n_i K T_i$ in a self-collision time τ_c

⇓

H_{plasma}~3E-13 eV mm^{-3} s^{-1}

<

DIRECT ION HEATING SEEMS TO BE NOT POSSIBLE

PLASMA PERTURBATION

POSSIBLE EXPLAINATION

PLASMA INSTABILITY?

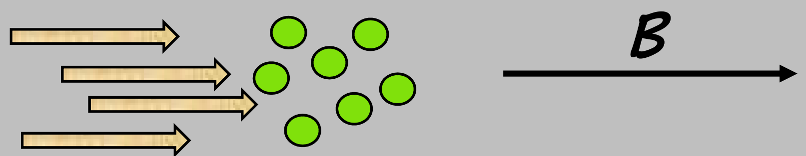
PHYSICAL REVIEW VOLUME 129, NUMBER 4 15 FEBRUARY 1963

Instabilities in a Plasma-Beam System Immersed in a Magnetic Field

JACOB NEUFELD AND HARVEL WRIGHT
Health Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee*
(Received 15 March 1962; revised manuscript received 11 January 1963)

- *Ion beam interacting with a plasma immersed in a magnetic field*

IF IONS MOVE ALONG B



EM WAVES CAN BE EXCITED AT ANY VELOCITY

PLASMA PERTURBATION

EXCITED WAVES

DISPERSION RELATION

$$Y^2 - \frac{1}{\beta^2}\left[Y + \sqrt{1-\beta^2}\right] - \frac{A^2 Y^2 (1+\alpha)}{(Y+1)(\alpha Y - 1)} = 0$$

$Y = \tilde{\omega}_\mathrm{i}/\Omega_\mathrm{i}$

Excited frequency

$A = \omega_\mathrm{i}/\Omega_\mathrm{i}$

Prop. to plasma density

$\alpha = m_\mathrm{e}/M_\mathrm{p}$

Excited waves are RHCP and propagate along B

IF $\beta \ll 1$ (this case)

$\tilde{\omega}_i \sim \Omega_e$

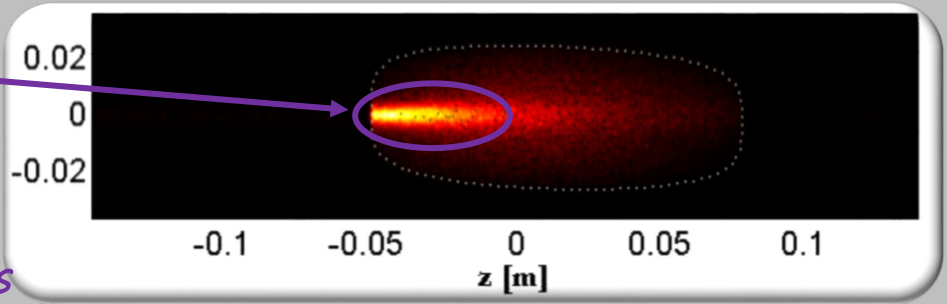
PLASMA PERTURBATION

FROM THIS PHYSICS CASE

Almost all the energy released
in a small valume where
12·97 GHz < Ω_e < 14·52 GHz

⇓

Range of the excited frequencies



ECR condition can be extended as in gentle-gradient case
(see Canobbio E, Nucl. Fusion 9 27, 1969)

Similar influence of B_{min} (see Tarvainen O et al, RSI 87 02A703)

HYPOTHESIS*: BEAM-PLASMA INTERACTION BROADS ECR CONDITION LEADING TO CYCLOTRON INSTABILITY

* A. Galatà et al, PSST 25, 045007 (2016)

PLASMA PERTURBATION

GROWTH RATE

- σ_i prop to beam dens/plasma dens
- σ_i varies with ion speed as $e^{-\frac{Z+0.05}{v\cdot\tau_s}}$ during slowing down

$$N_1 = \left| \frac{-A^2(1-\beta^2)(\alpha Y-1)^2(Y+1)^2}{Y^2[2(\alpha Y-1)^2(Y+1)^2]+A^2(Y+2)} \right|^{1/2}$$

$$N = \sigma_i^{1/2} N_1$$

INSTABILITIES EXCITED AT THE OF THE PATH ARE STRONGER

IN THE PRESENT HYPOTHESIS THE BEAM IS A ‘SPARK’ THAT IGNITES THE ‘FIRE’ OF THE INSTABILITY; IT THEN BURNS THANKS TO THE PLASMA THAT MAKES THE FUEL.

PLASMA PERTURBATION

GROWTH RATE

- σ_i prop to beam dens/plasma dens
- σ_i varies with ion speed as $e^{-\frac{Z+0.05}{v \cdot \tau_S}}$ during slowing down

$$N_1 = \left| \frac{-A^2(1-\beta^2)(\alpha Y-1)^2(Y+1)^2}{Y^2[2(\alpha Y-1)^2(Y+1)^2]+A^2(Y+2)} \right|^{1/2}$$

$$N = \sigma_i^{1/2} N_1$$

INSTABILITIES EXCITED AT THE OF THE PATH ARE STRONGER

A DEDICATED EXPERIMENT TO VERIFY THIS HYPOTHESIS IS UNDER PLANNING

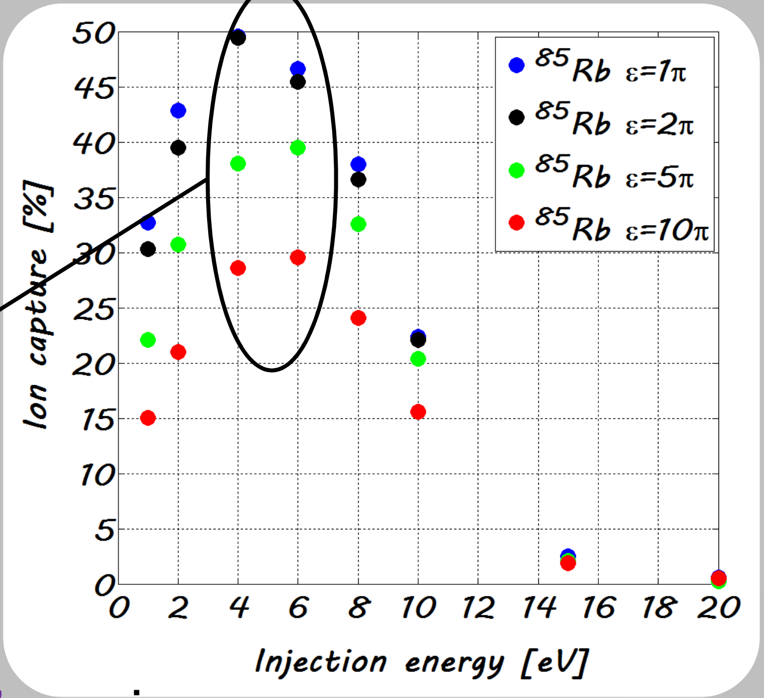
BEAM PROPERTIES

INFLUENCE OF EMITTACE

$1\pi \rightarrow 2\pi \rightarrow 5\pi \rightarrow 10\pi$*

Reference

- ✓ No remarkable difference between 1 and 2 π
- ✓ Curves have the same trend
- ✓ Emittance shift the maximum to higher energy



THIS COULD BE A PROBLEM IN CASE OF BLIND TUNING!

* Thanks to J. Angot from LPSC

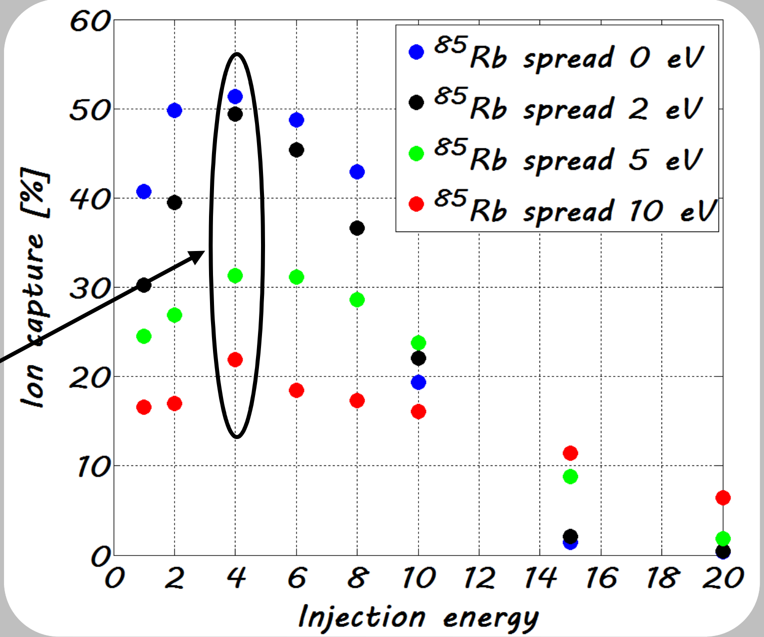
BEAM PROPERTIES

INFLUENCE OF ENRGY SPREAD

0 eV → 2 eV → 5 eV → 10 eV*

Reference

- ✓ Huge variations between 2 eV and 5 eV
- ✓ Curves broaden and flatten
- ✓ Peaks always at the same position



OK FOR BLIND TUNING!

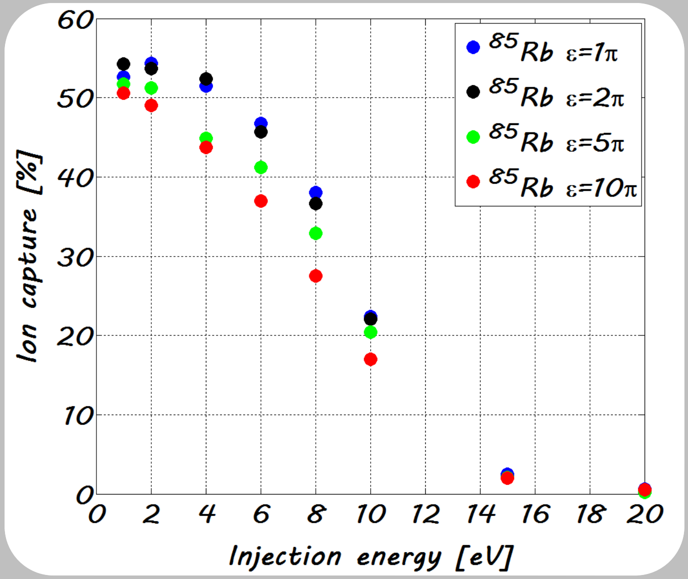
* Thanks to J. Angot from LPSC

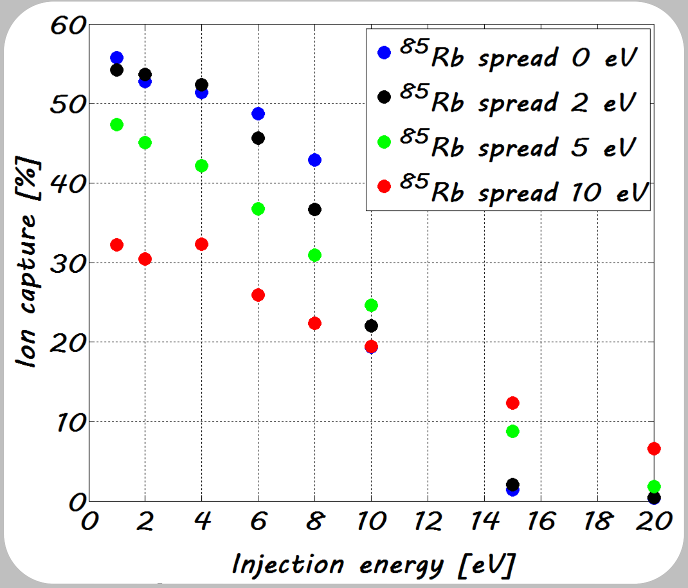
BEAM PROPERTIES

EMITTANCE Vs ENRGY SPREAD

CAPTURE OF TRANSMITTED PARTICLES

- ✓ Differences are less evident
- ✓ Curves still similar to ΔV





- ✓ Differences still evident
- ✓ Broader curves, shapes modified (tend to be linear with energy)

BLIND TUNING

ISOL FACILITIES

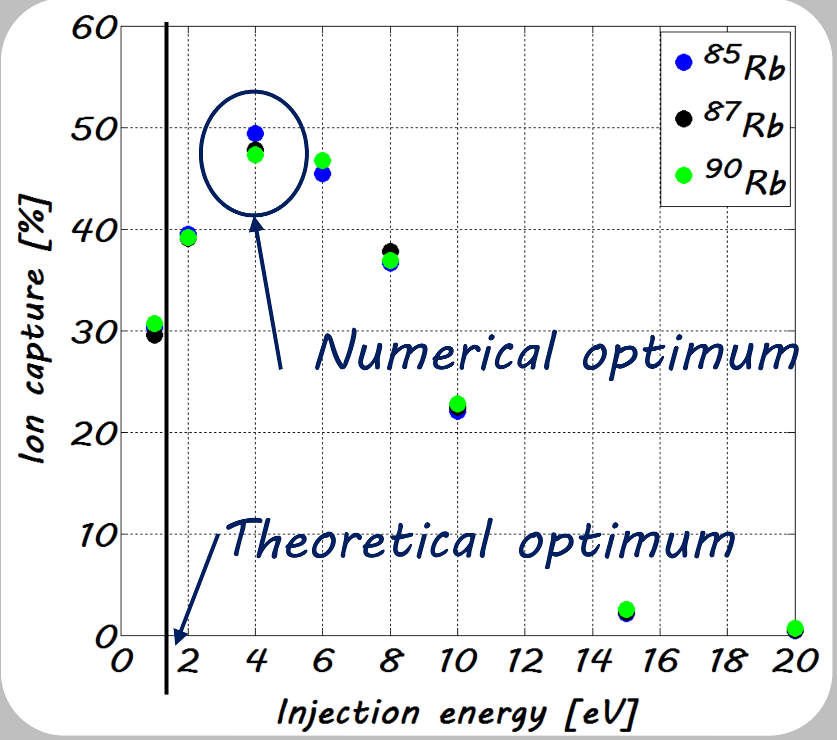
$^{85}Rb \rightarrow ^{87}Rb \rightarrow ^{90}Rb$

Stable Reference ← → Radioactive Ion

INFLUENCE OF MASS

$\Delta M/M = 3{\cdot}5$ %

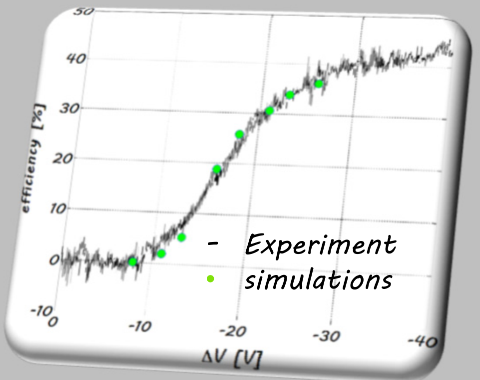
BLIND TUNING IS POSSIBLE!



CONCLUSIONS

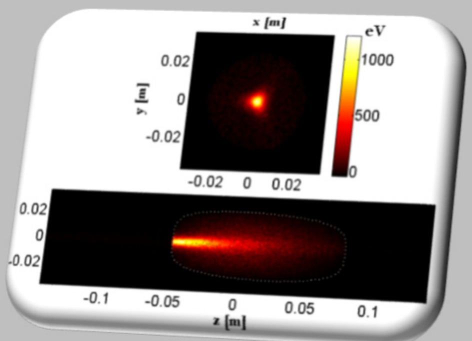
ION BEAM-PLASMA INTERACTION CORRECTLY SIMULATED:

- ✓ Single particle approach
- ✓ Plasmoid/halo scheme of increasing complexity
- ✓ Agreement with theorectical expectations
- ✓ Agreement with experiments



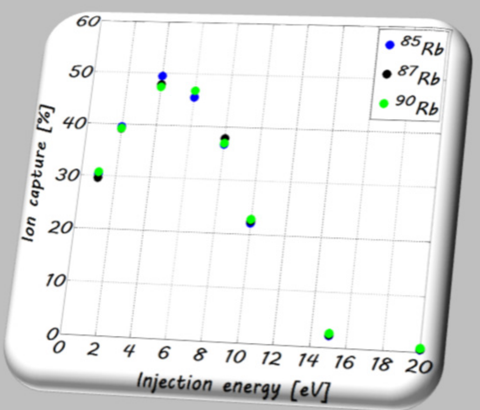
IMPORTANT OUTPUTS:

- ✓ Key role of ion temperature
- ✓ Plasma instabilities
- ✓ Ballistic (extra energy)



PREDICTIVE TOOL:

- ✓ Influence of beam emittance
- ✓ Influence of beam energy spread
- ✓ Injection of different masses

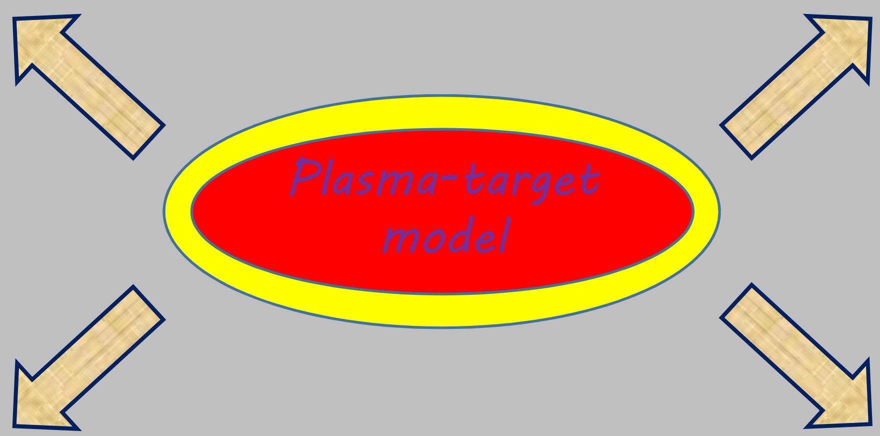


PERSPECTIVES

IMPROVE THE PLASMA-TARGET MODEL

ECR HEATING AND
COULOMB COLLISIONS

ELECTROMAGNETIC
CALCULATIONS

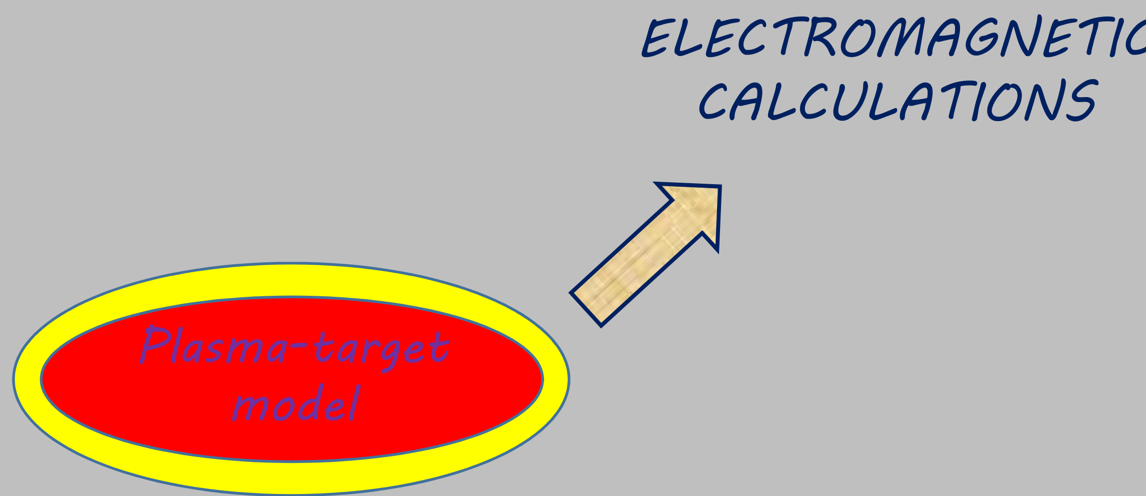


PRECISE TOTAL
ELECTRON DENSITY MAP

WARM ELECTRONS DENSITY
ESTIMATE AND DISTRIBUTION

PERSPECTIVES

IMPROVE THE PLASMA-TARGET MODEL



WORK ALREADY STARTED WITHIN EMILIE
WITH A LNL-LNS COLLABORATION

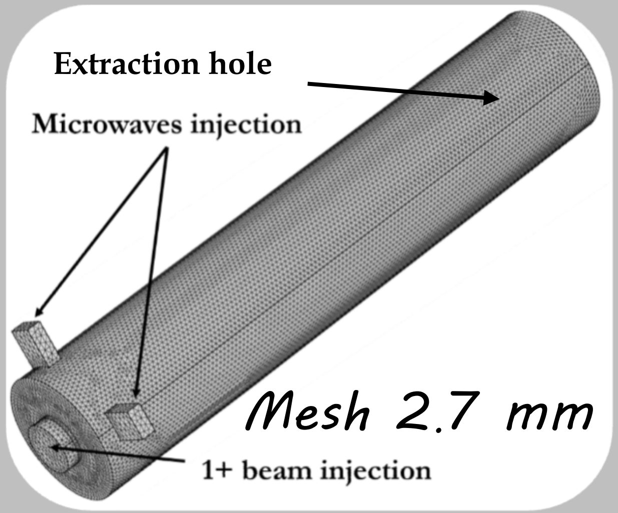
PERSPECTIVES

ELECTROMAGNETIC SIMULATIONS

GEOMETRY

- HF blocker-ext hole: L~353 mm
- Extraction hole is a wave cut off region
- Artificial numerical "Absorbing boundary condition" at injection

ALL IMPORTANT GEOMETRICAL DETAILS TAKEN INTO ACCOUNT

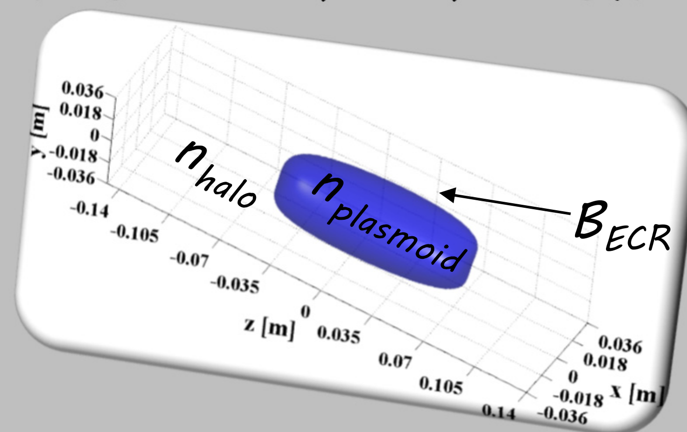


PHOENIX PLASMA CHAMBER

ELECTROMAGNTIC SIMULATIONS

FROM VACUUM TO ANISOTROPIC PLASMA

- Calculations in vacuum
- Calculations with a plasma: plasmoid-holo scheme



ISOTROPIC PLASMA

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

Single-value Dielectric Constant*

ANISOTROPIC MAGNETIZED PLASMA FULL 3D DIELECTRIC TENSOR

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

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

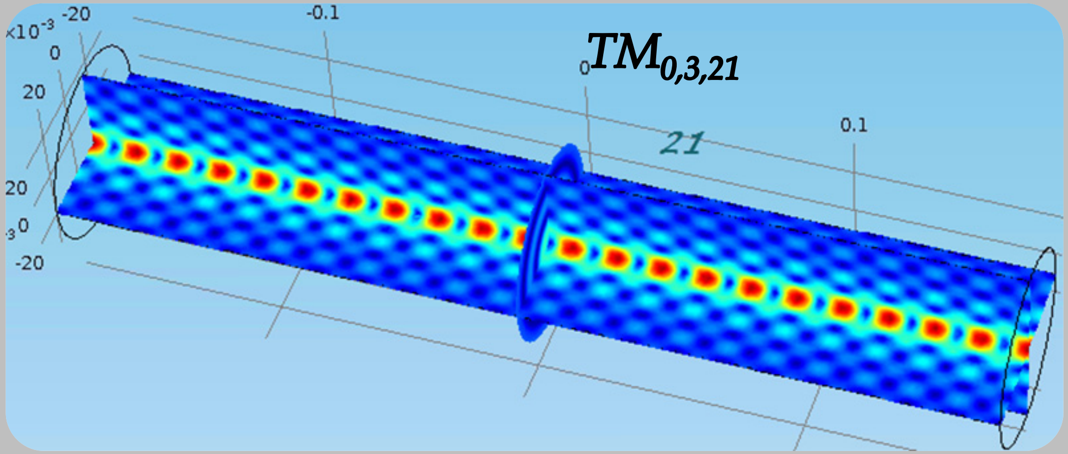
ELECTROMAGNTIC SIMULATIONS

RESONANT MODES

EMPTY CAVITY

- ✓ 200 resonant frequencies around and below 14.521 GHz.
- ✓ ~20 modes in 14.3-14.6 GHz (some degenerate).
- ✓ Closest mode to the operating frequency: $TM_{0,3,21}$ (14.525 GHz)

SIMPLIFIED GEOMETRY
(no holes, waveguides)



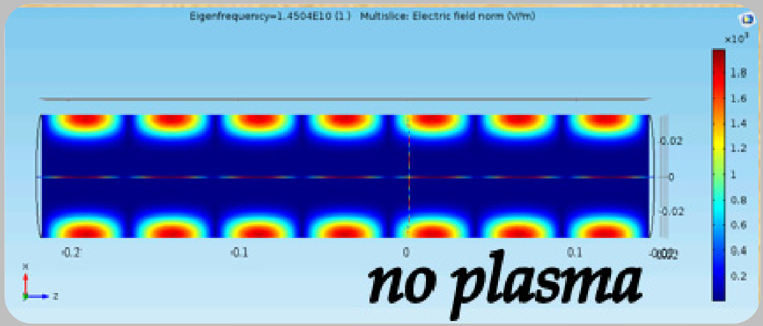
ELECTROMAGNTIC SIMULATIONS

RESONANT MODES

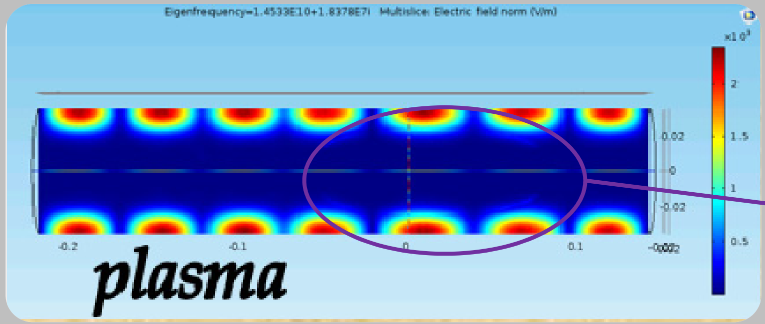
ISOTROPIC PLASMA:

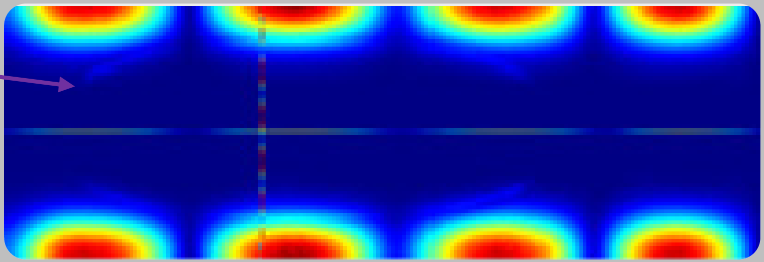
✓ Identified two frequency shifts

- $TE_{8,1,16}$: 14.477 GHz → 14.504 GHz
- $TE_{9,1,7}$: 14.504 GHz → 14.533 GHz



$TE_{9,1,7}$





ELECTROMAGNTIC SIMULATIONS

FREQUENCY DOMAIN

TWO SPECIFIC FREQUENCIES:
- ✓ 14.521 GHz (operating)
- ✓ 14.324 GHz (SPES-CB acc. tests).

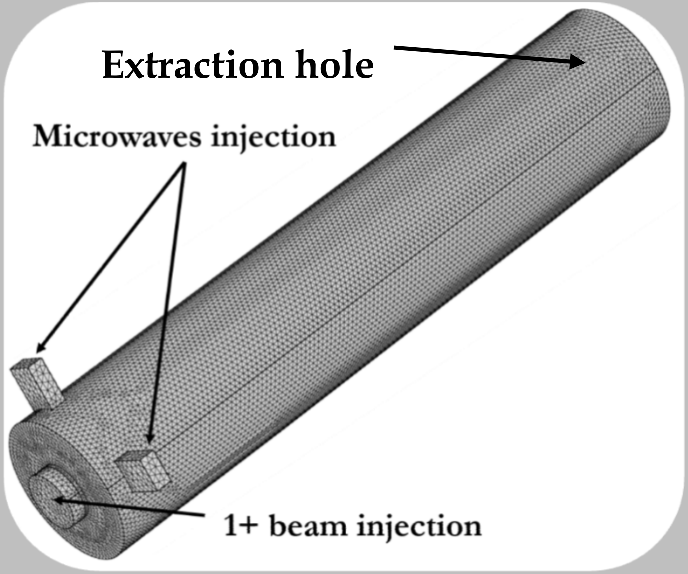
Real geometry (waveguides, holes)

Boundaries: PML, IBC, port & port-off

Magnetic field

Plasma: $n=2.5*10^{+17}\ m^{-3}$

Interaction COMSOL-MATLAB



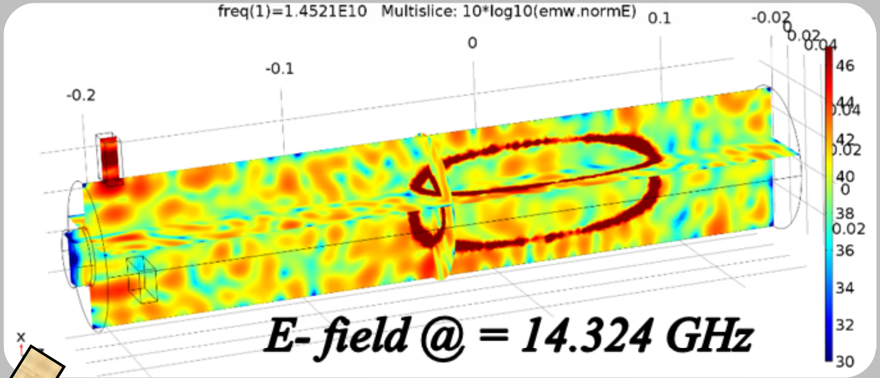
ELECTROMAGNTIC SIMULATIONS

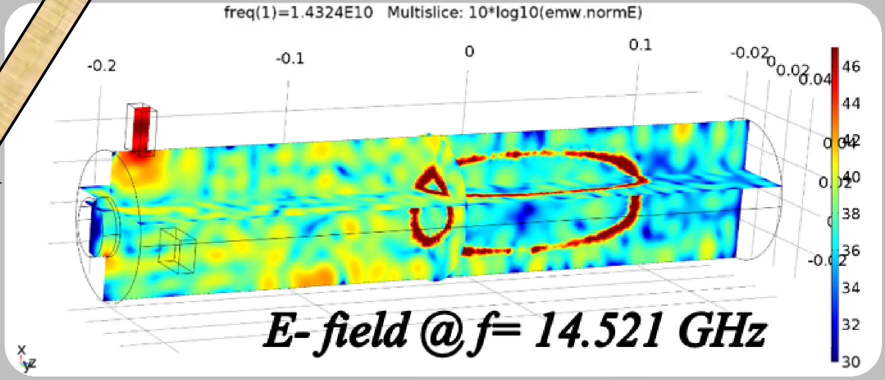
FREQUENCY DOMAIN

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 !

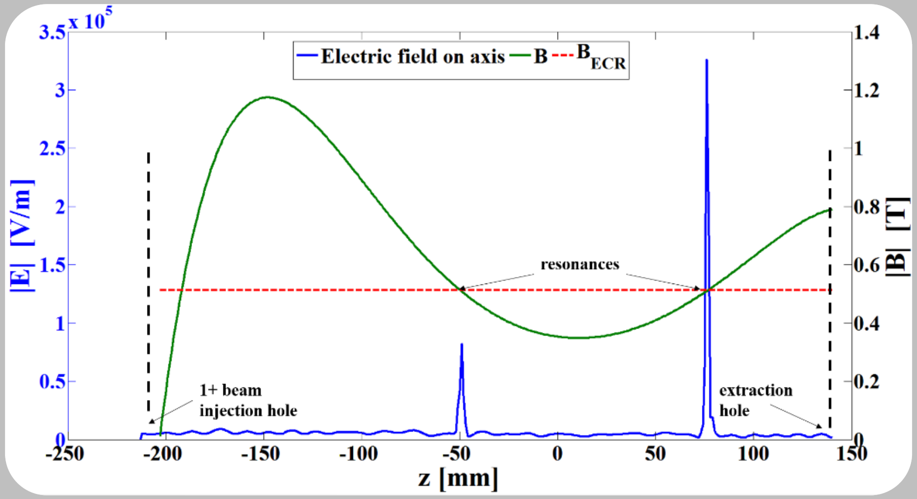
*A. Galatà et al, RSI 87, 02B505 (2016)

ELECTROMAGNTIC SIMULATIONS

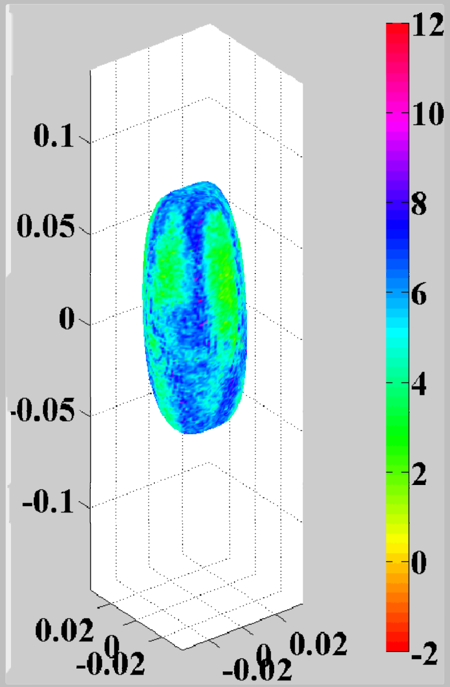
FREQUENCY DOMAIN

14.324 GHz

ELECTRIC FIELD INTENSIFICATION AT THE RESONANCE



Logarithmic plot



ELECTRIC FIELD ON THE RESONANCE SURFACE

*A. Galatà et al, RSI 87, 02B505 (2016)

ELECTROMAGNTIC SIMULATIONS

SUMMARY

Resonant modes computation including a simple plasma model

Plasma modeling in two steps (plasmoid/halo):

- ✓ ISOTROPIC PLASMA: observed frequency shift
- ✓ ANISOTROPIC PLASMA: evidence of the frequency tuning effect as 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.

FINAL SUMMARY

ION DYNAMICS
WITH COLLISIONS
AND IONIZATIONS

ECR HEATING
WITH COULOMB
COLLISIONS

TOWARDS A
SELF-CONSISTENT ECR
PLASMA DESCRIPTION

ELECTROMAGNETIC
CALCULATIONS

INFN LNL

INFN LNS

THANK YOU SO MUCH AGAIN

and.........

Wonderful Conference!

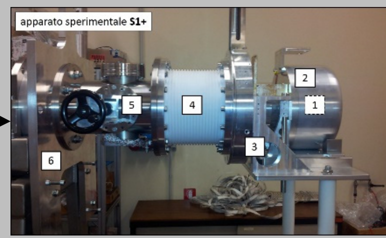
THE SPES-CB

thanks to J. Angot, T. Lamy, T. Thuillier

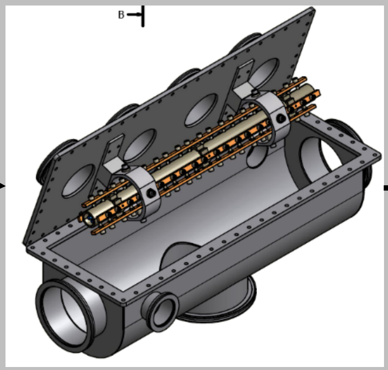
SPES

Cyclotron
p 70 MeV 700 µA

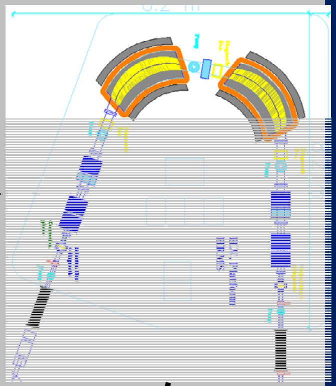
Target-Ion Source system



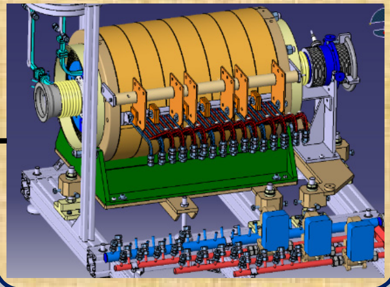
Beam cooler



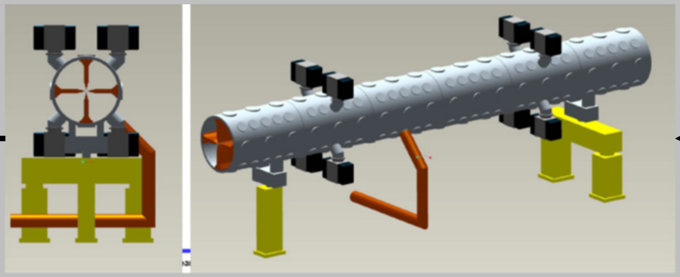
HRMS



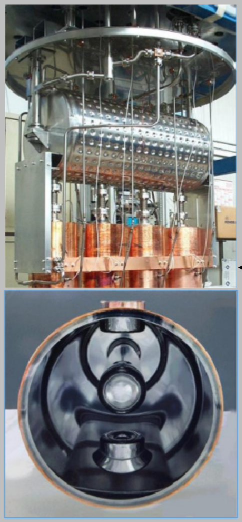
CB



New RT RFQ



ALPI



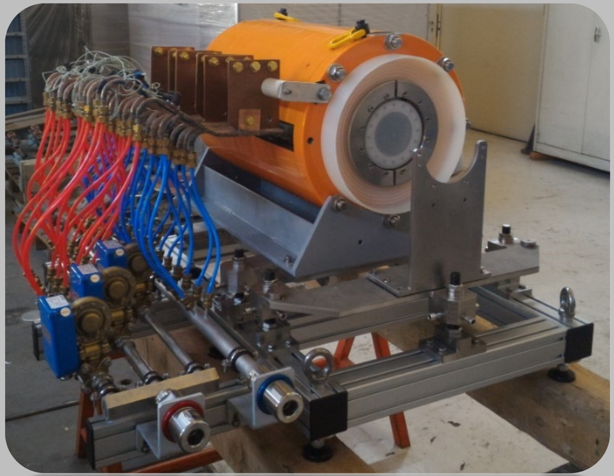
POST-ACCELERATION

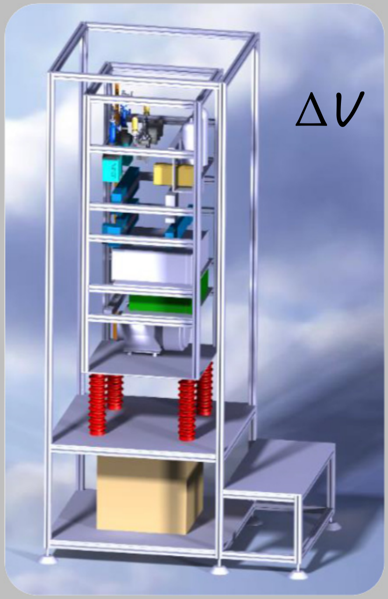
SPES
exotic beams for science

THE SPES-CB

- 2^{nd} generation ECRIS (2000)
- 3 coils
- Permanent magnet hexapole
- 2 microwave ports

CHARACTERISTICS	
f [GHz]	14.5
Max Power [kW]	2
Binj [T]	1.2
Bmin [T]	0.4
Bext [T]	0.8
Brad [T]	0.8
Chamber length [m]	0.288
Chamber radius [m]	0.036



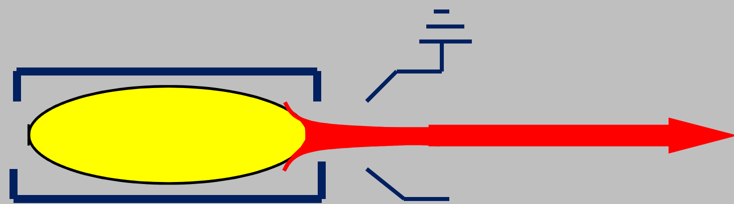


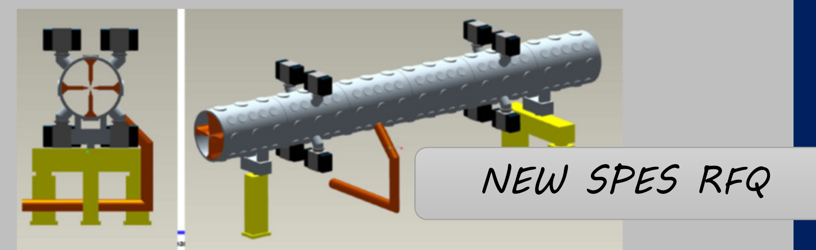
UPGRADED VERSION OF PHOENIX FROM LPSC

RECENT UPGRADES
+
SPES REQUESTS

SPES-CB IMPROVEMENTS

THE EXTRACTION SYSTEM

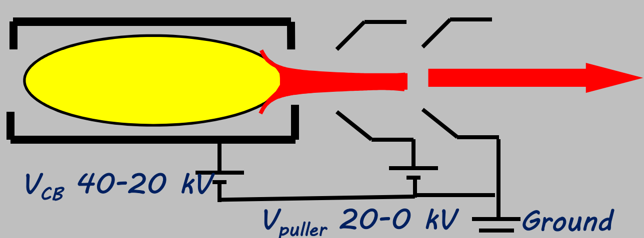




CB: variable A/q

RFQ: fixed v

VARIABLE CB EXTRACTION VOLTAGE (V=20-40 kV)

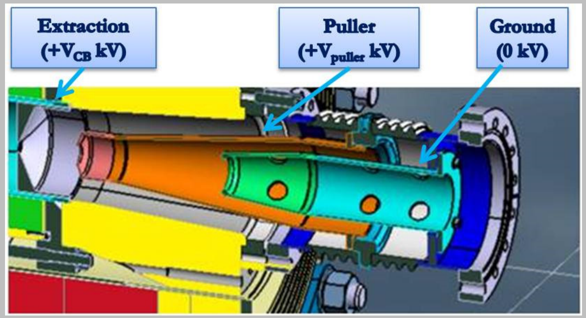


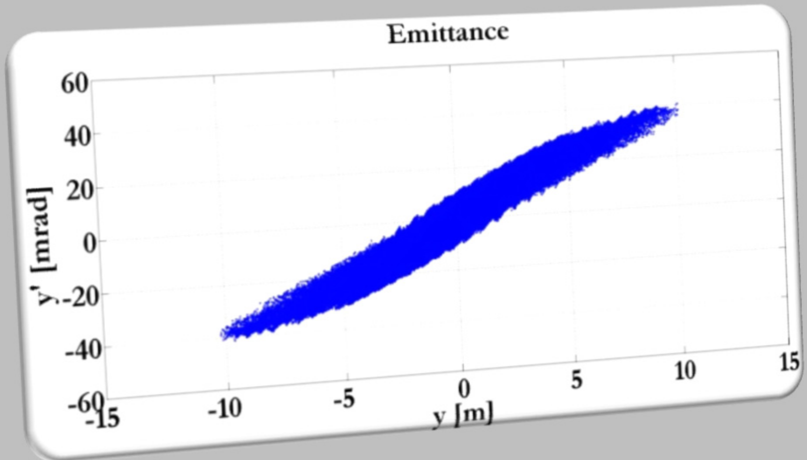
CHOICE OF A THREE ELECTRODES EXTRACTION SYSTEM TO HAVE FLEXIBILITY

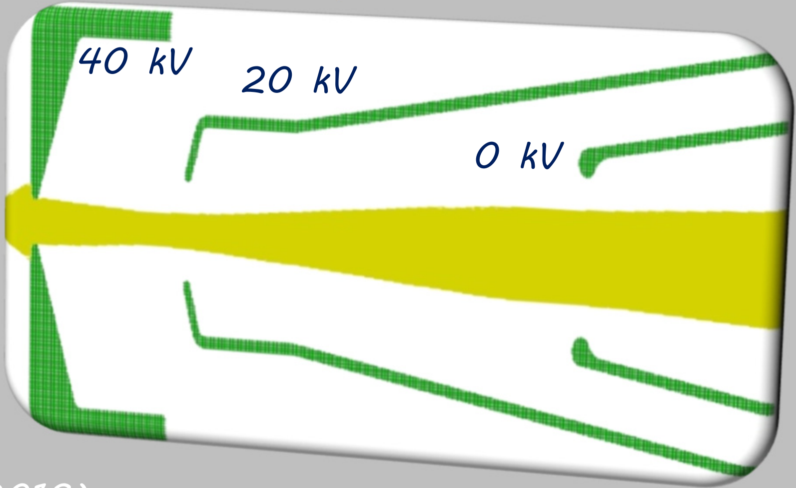
SPES-CB IMPROVEMENTS

3 ELECTRODES EXTRACTION SYSTEM FROM LPSC DESIGN

- 3D Geometry with potentials
- Boundary conditions
- 3D magnetic map
- V_P (20V)
- KT_e (10 eV)
- Ions initial pos and v (KT_i 0.5 eV; Bohm criterion)







*A. Galatà et al, NIM B 376, 329-333 (2016)

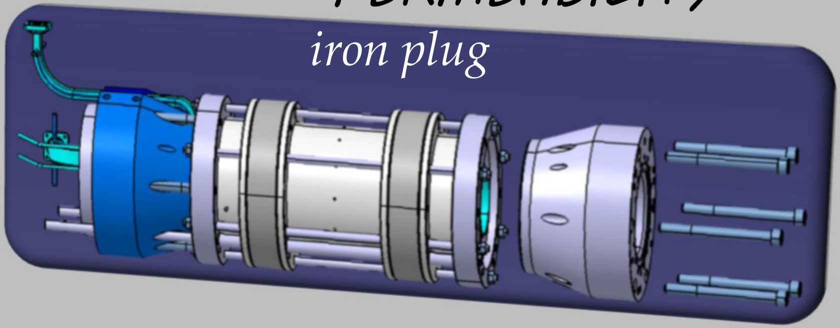
SPES-CB IMPROVEMENTS

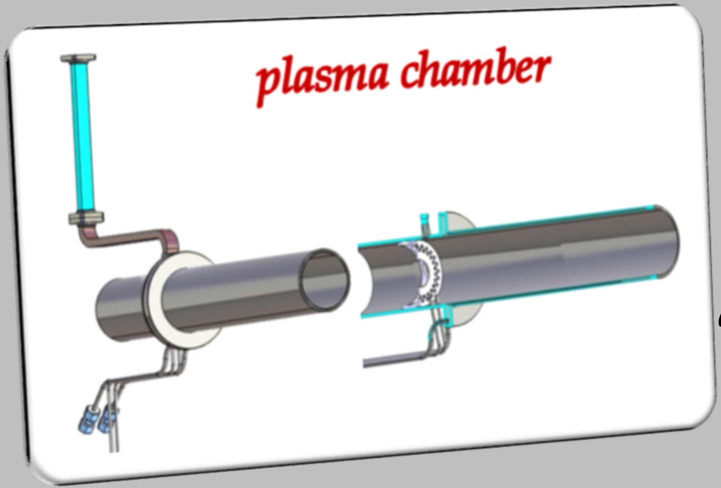
CLEANLINESS*

REDUCTION OF STABLE BACKGROUND

- Treatments on extraction iron plug
- Treatments on plasma chamber
- Almost all metal sealings

NORMALIZING
FINAL ANNEALING
BETTER MAGNETIC
PERMEABILITY





AISI 316 LN: 2 HEAT TREATMENTS
DURING MACHINING TO
LIMIT OUTGASSING

*A. Galatà et al, RSI 87, 02B503 (2016)

SPES-CB IMPROVEMENTS

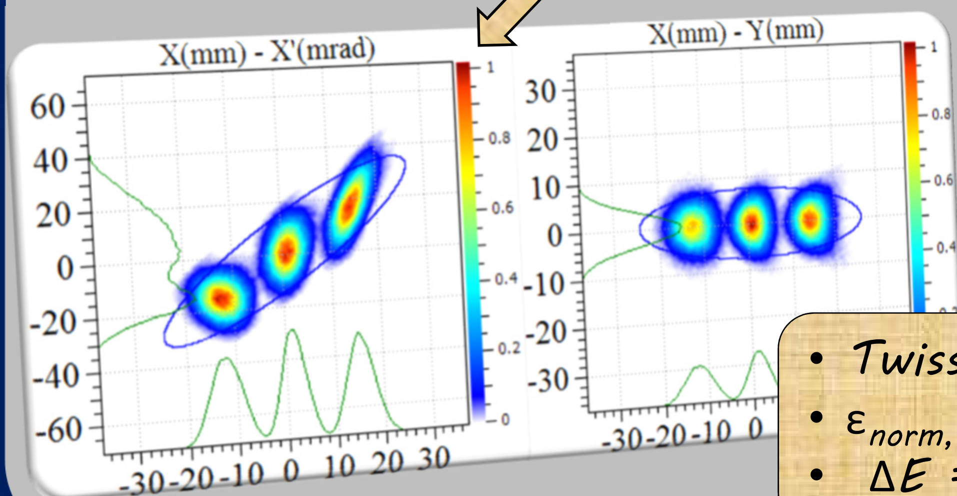
CLEANLINESS

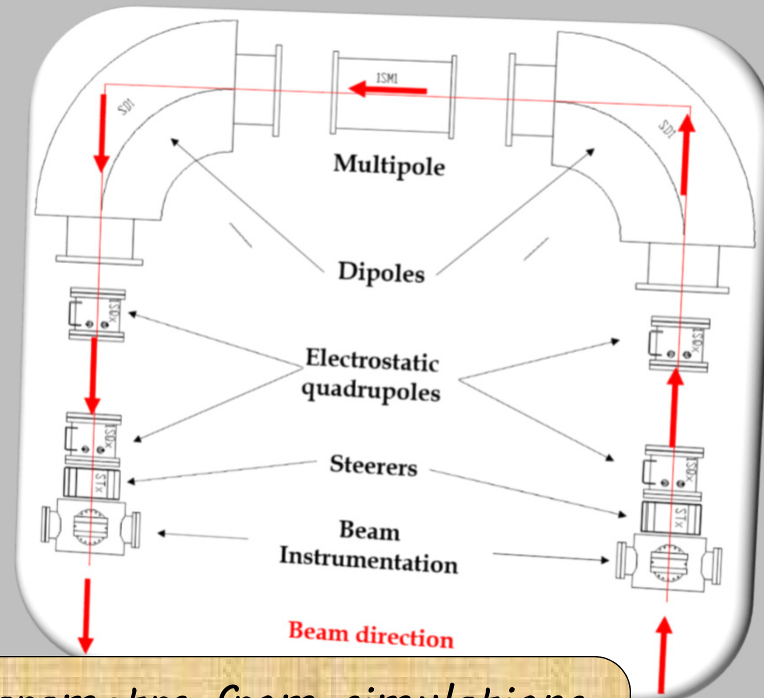
MEDIUM RESOLUTION MASS SPECTROMETER

DIPOLES:

- R=750 mm
- $\Phi=90^0$
- Edge=33.35 °
- B=0.2 T
- Gap=± 35 mm

EXPECTED RESOLUTION: 1/1000





- Twiss parametrs from simulations
- $\varepsilon_{norm,\ rms}$ = 0.1 π*mm*mrad
- ΔE = 15 eV

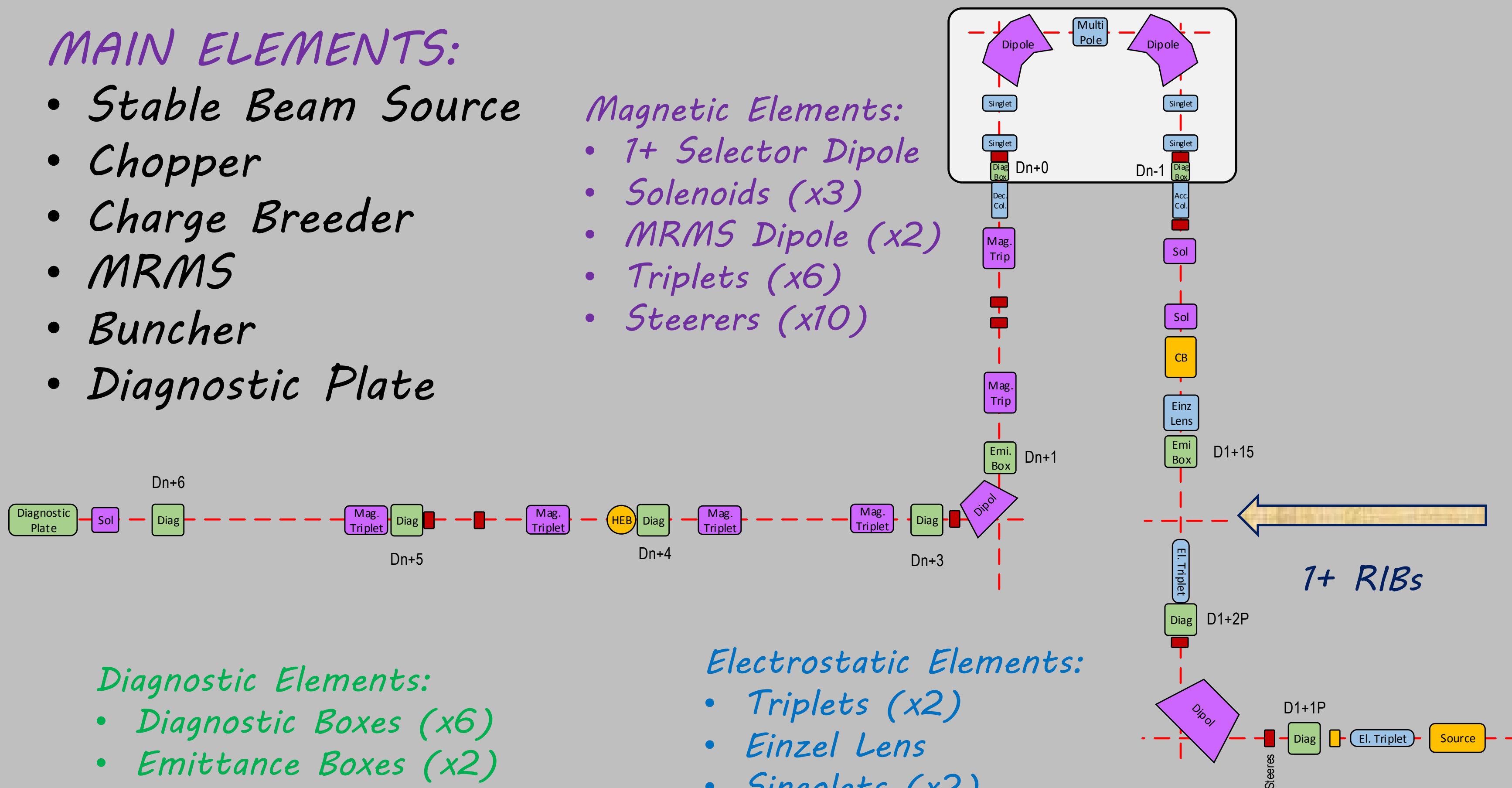
SPES-CB BEAMLINE

MAIN ELEMENTS:

- Stable Beam Source
- Chopper
- Charge Breeder
- MRMS
- Buncher
- Diagnostic Plate

Magnetic Elements:

- 1+ Selector Dipole
- Solenoids (x3)
- MRMS Dipole (x2)
- Triplets (x6)
- Steerers (x10)



Diagnostic Elements:

- Diagnostic Boxes (x6)
- Emittance Boxes (x2)
- Slits Boxes

Electrostatic Elements:

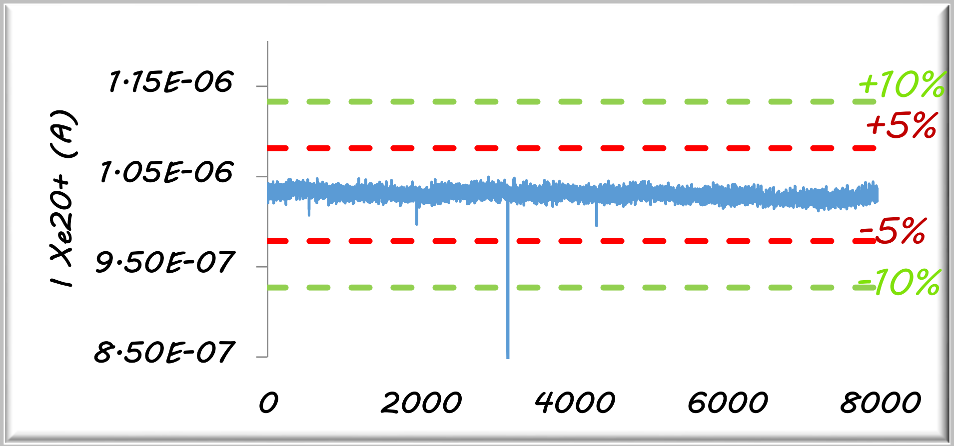
- Triplets (x2)
- Einzel Lens
- Singolets (x2)
- Multipoles

SPES-CB ACCEPTANCE TESTS

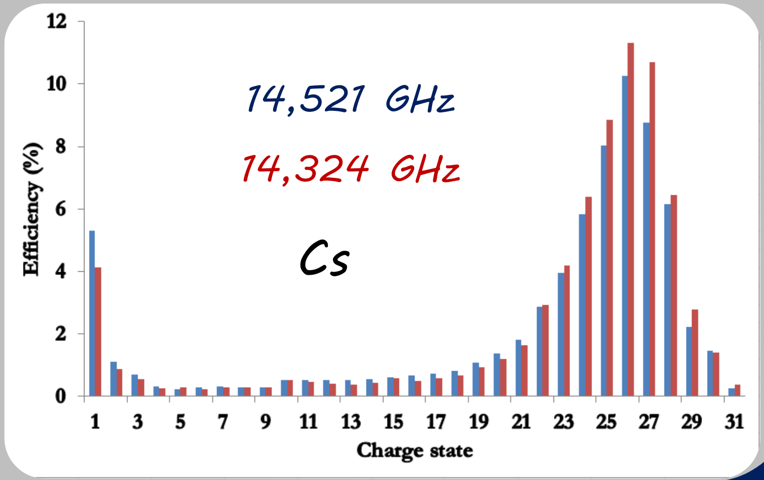
- Requirements FULFILLED
- Very LOW EMITTANCE of the n+ beam

			$\varepsilon_{rms,norm}$ [p*mm*mrad]	
Ion	M/q	η [%]	full	ion
Cs^{26+}	5.1	11.3	0.044	0.020
Xe^{20+}	6.6	11.2	0.030	0.010
Rb^{19+}	4.5	7.8	0.040	0.010
Ar^{8+}	5	15.2	0.04	0.030

EXCELLENT BEAM STABILITY



FREQUENCY TUNING IS EFFECTIVE



*A. Galatà et al, RSI 87, 02B503 (2016)

THANK YOU SO MUCH AGAIN
and.........

Wonderful Conference!