Combination of two ECRIS calculations: plasma electrons and extracted ions

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(GSI, Darmstadt, Germany)

European Union Seventh Framework Program FP7/2007-2014
Grant Agreement n° 262010 – ENSAR-ARES
(ARES = Advanced Research on Ecr ion Sources)

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1. MOTIVATION
2. THE ECRIS
3. THE TRAPCAD CODE
   - PLASMA ELECTRONS SIMULATIONS
4. THE KOBRA3-INP CODE
   - TRANSFER FROM TRAPCAD TO KOBRA
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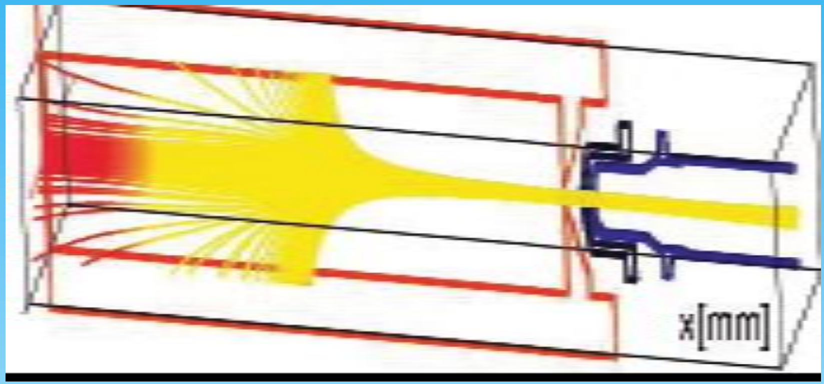

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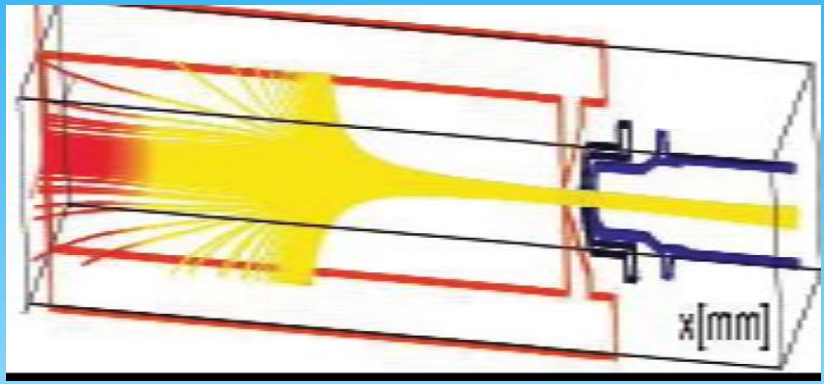

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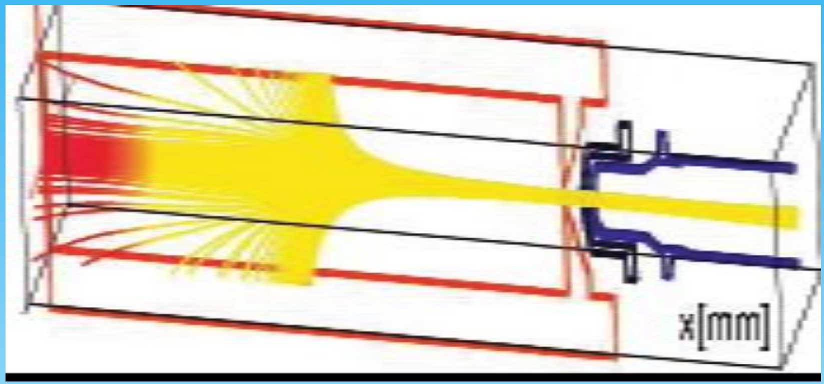

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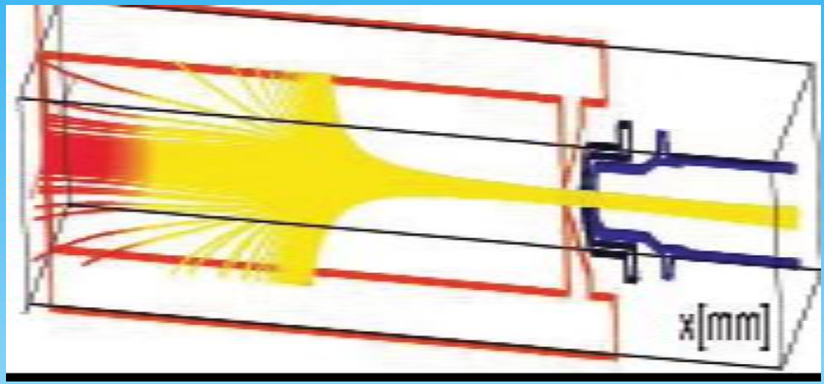

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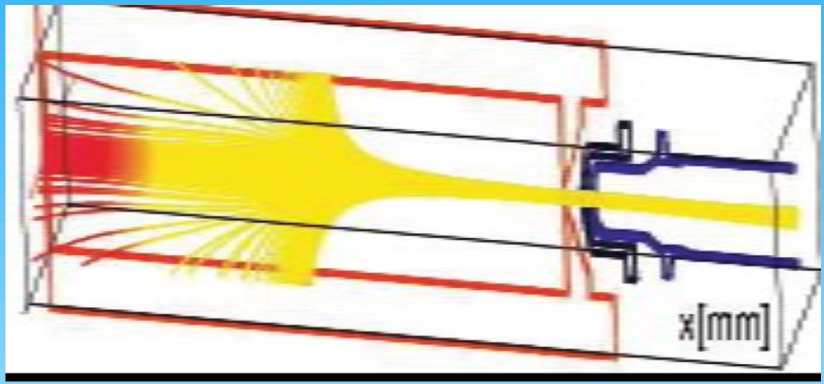

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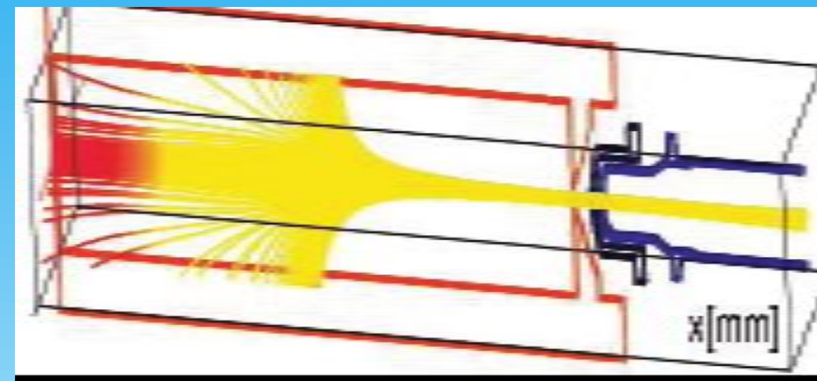

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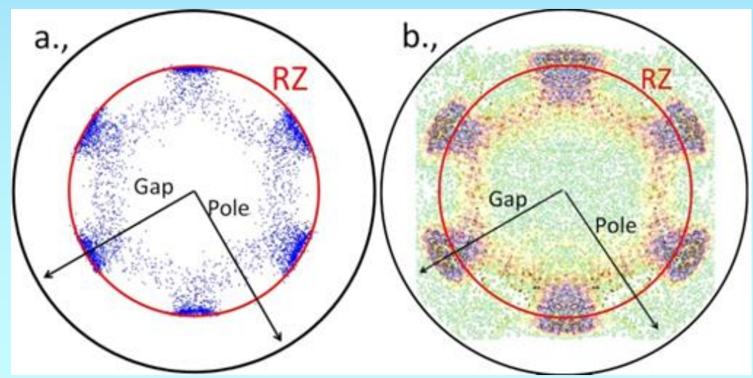

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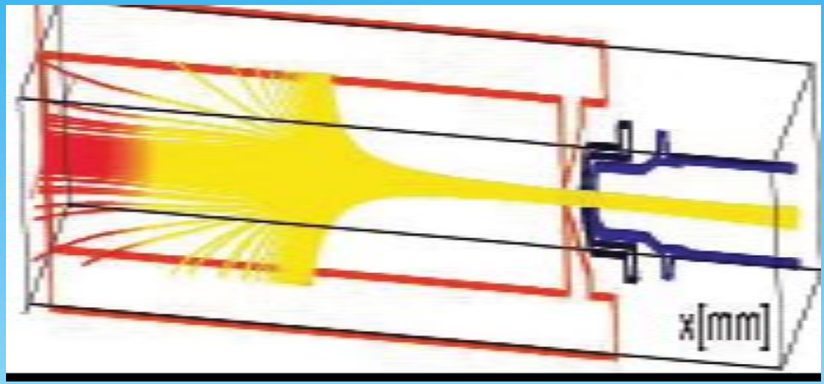

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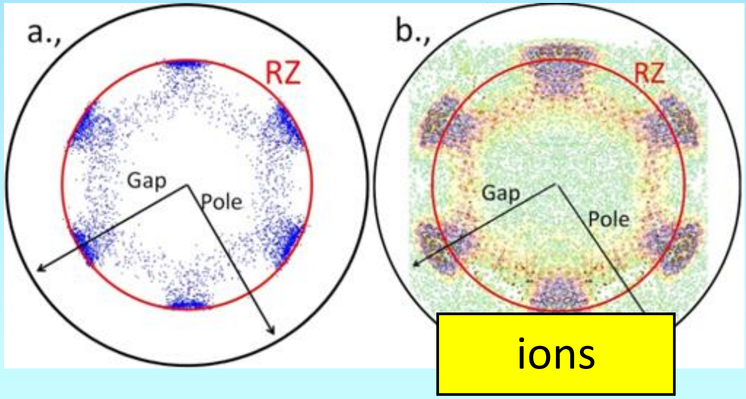

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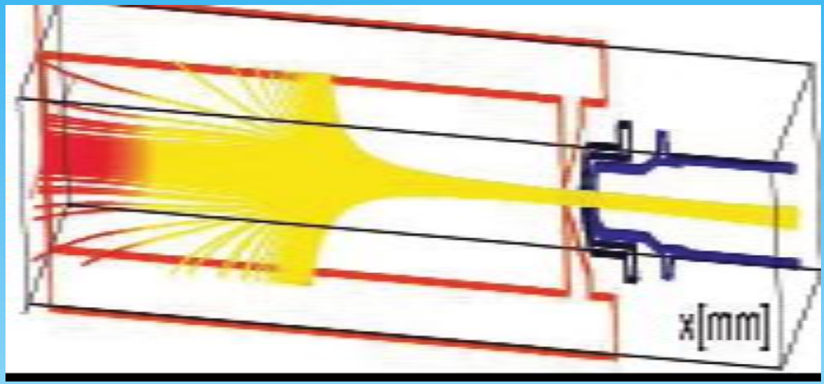

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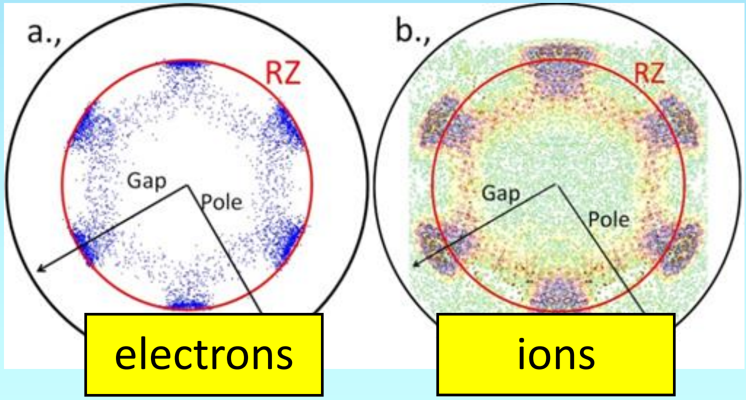

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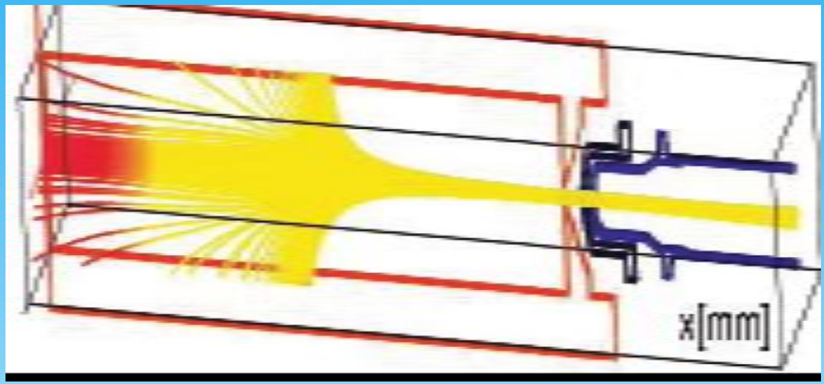

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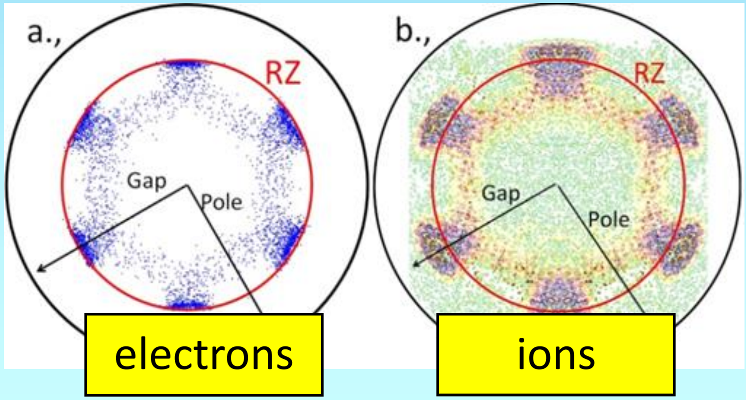

R. Rácz et al., Plasma Sources Sci. and Tech. 20 (2011) 025002(7)

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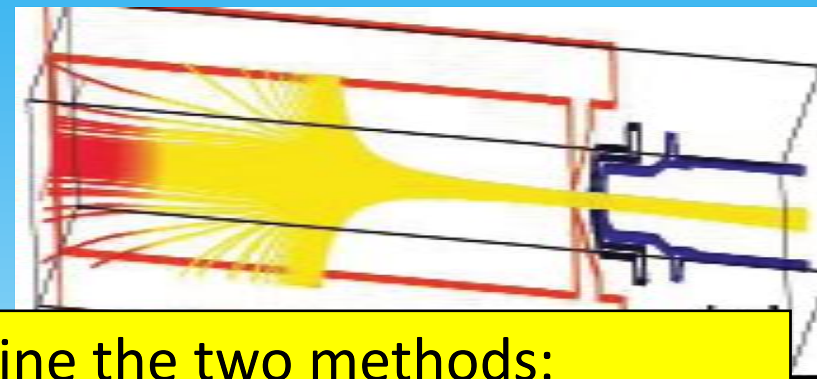

Therefore we decided to combine the two methods:
plasma **electron** cloud is simulated in a given ECRIS configuration
and
the coordinates of these electrons are used as
the starting positions of **ions** to be extracted.

2.
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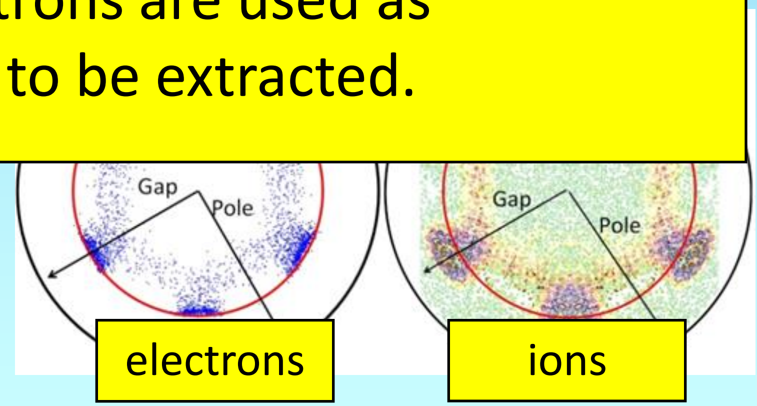

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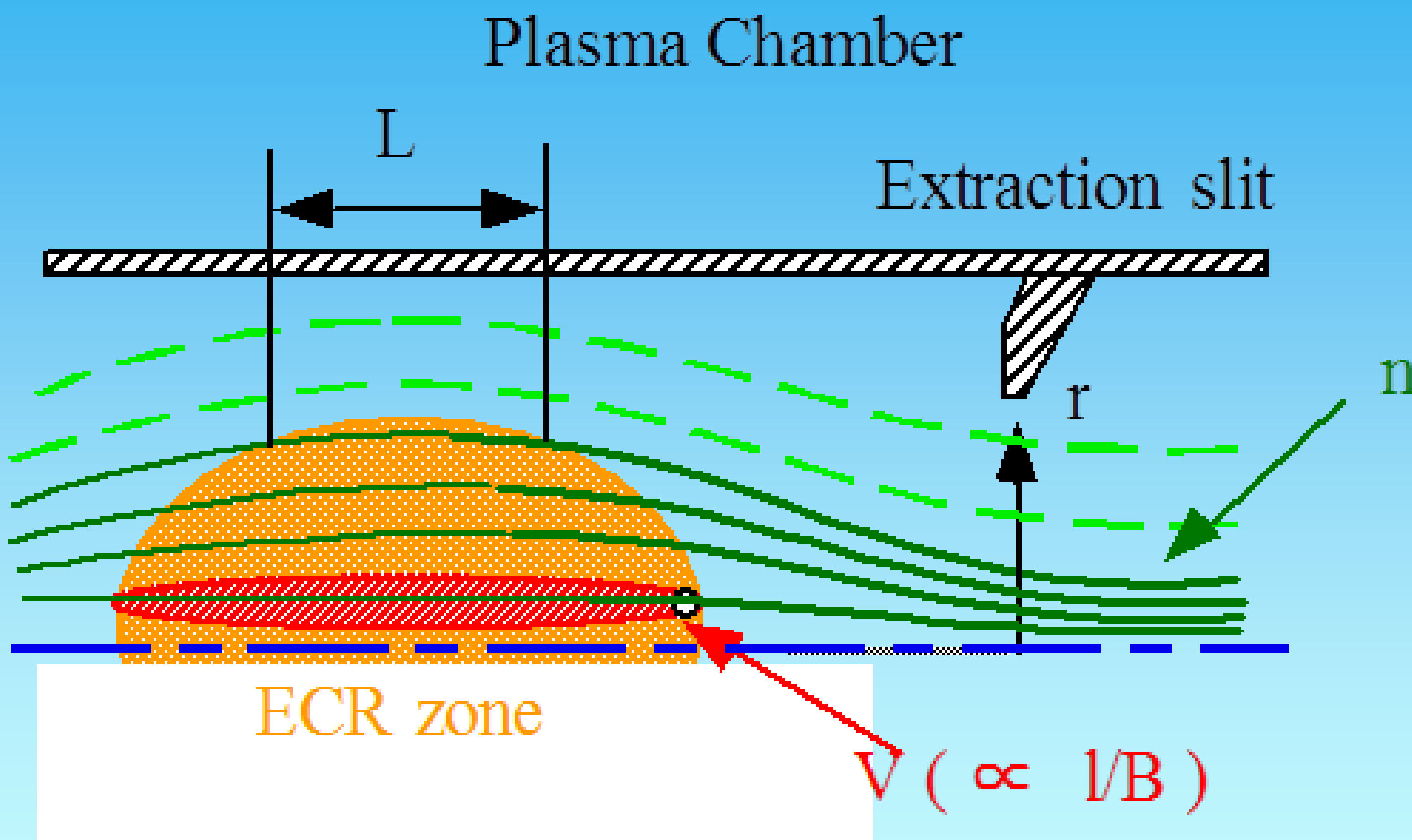
An early trial



It was assumed the highly charged ions are localized inside of the ECR zone and the ion trajectory from the ECR zone to the extraction aperture is tightly bound the magnetic flux line.

*Kitagawa A. et al: Optimization of the radial magnetic field of an 18 GHz electron cyclotron resonance ion source at the Heavy Ion Medical Accelerator in Chiba. Review of Scientific Instruments 71 (**2000**)2:981-983*

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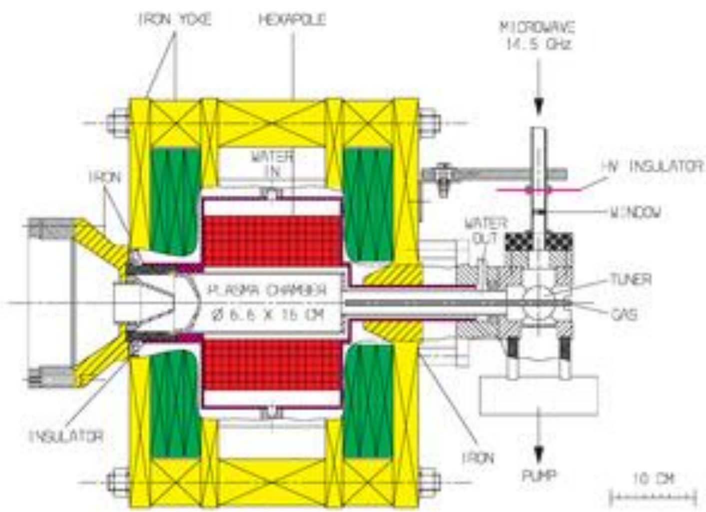
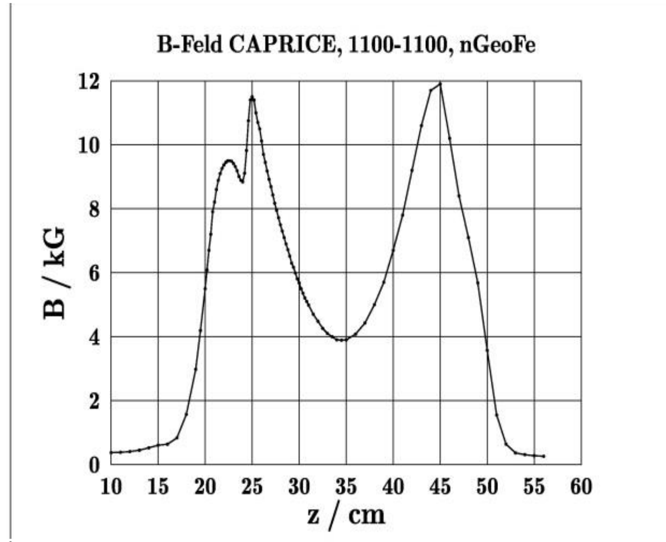
The ECRIS to be simulated

GSI-CAPRICE, 14.5 GHz, 1.2 Tesla

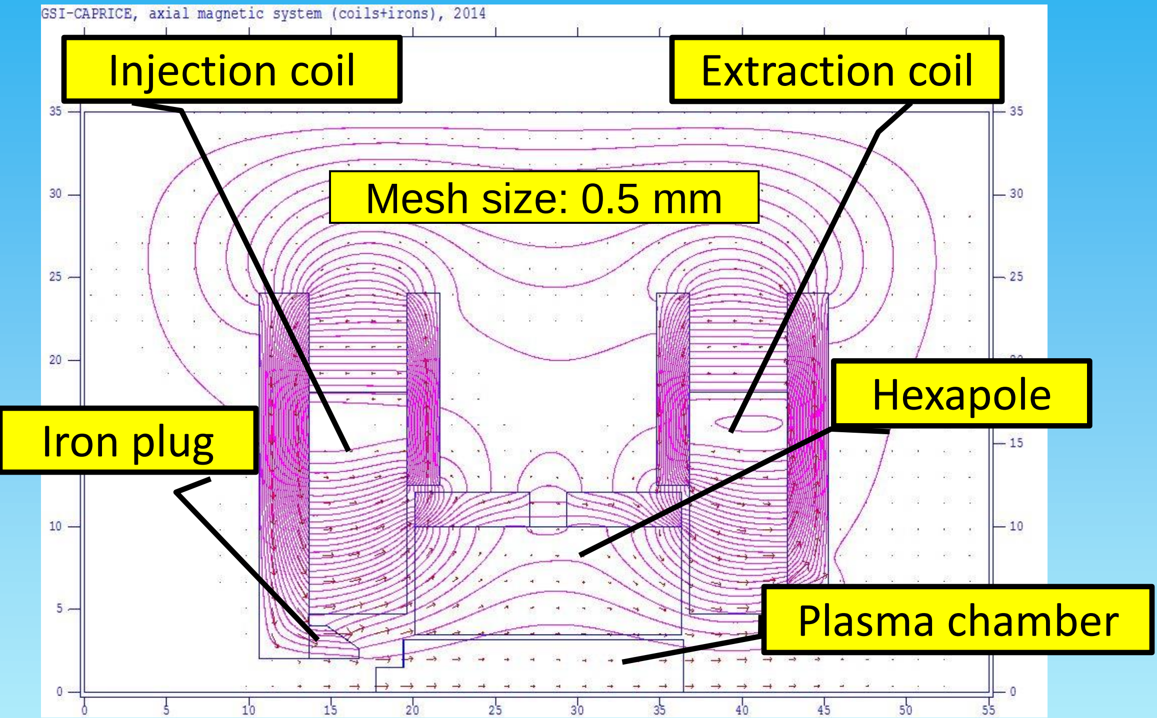
Plasma chamber length:	187 mm
Plasma chamber diameter:	63 mm
Injection coil current:	1100 A
Extraction coil current:	1100 A
Hexapole materials (VACODYM):	745HR/655HR





Russia

POISSON SUPERFISH calculation



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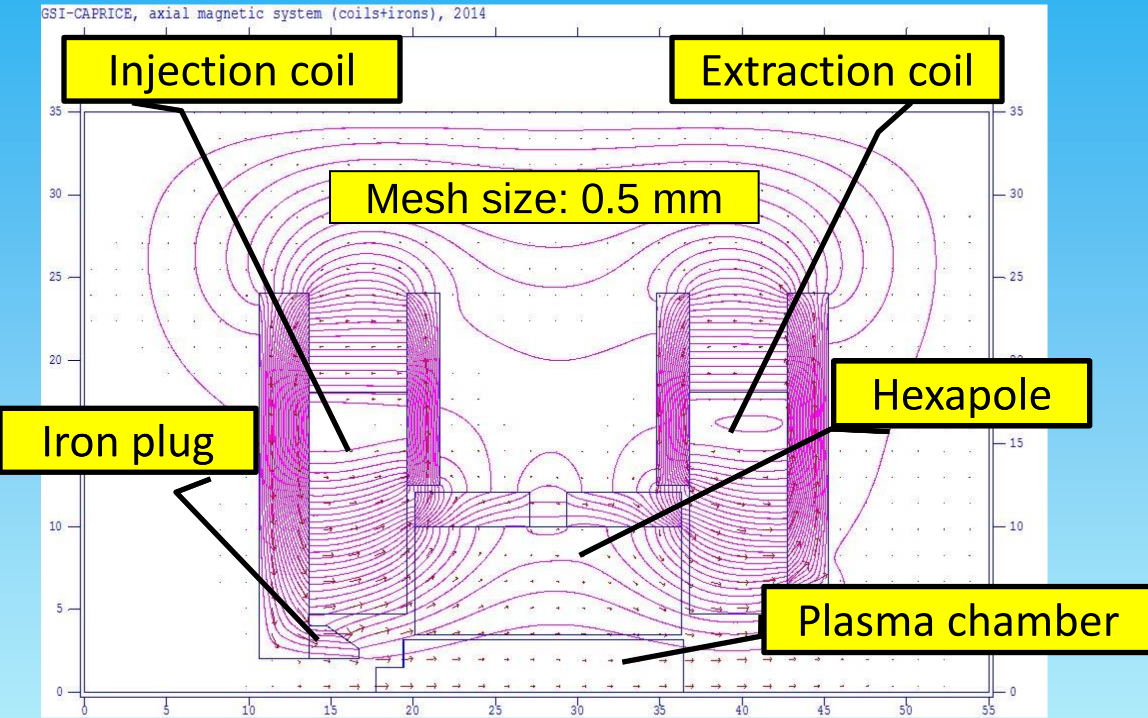

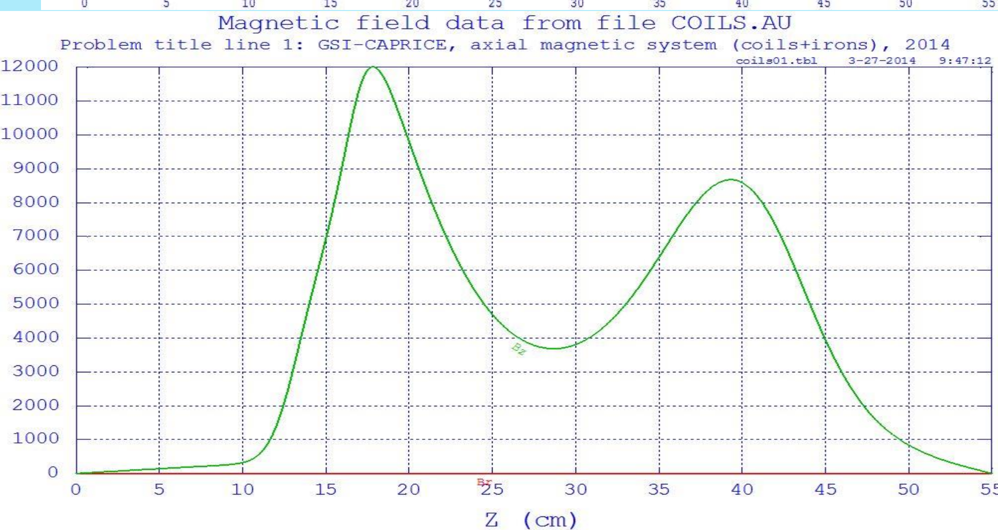

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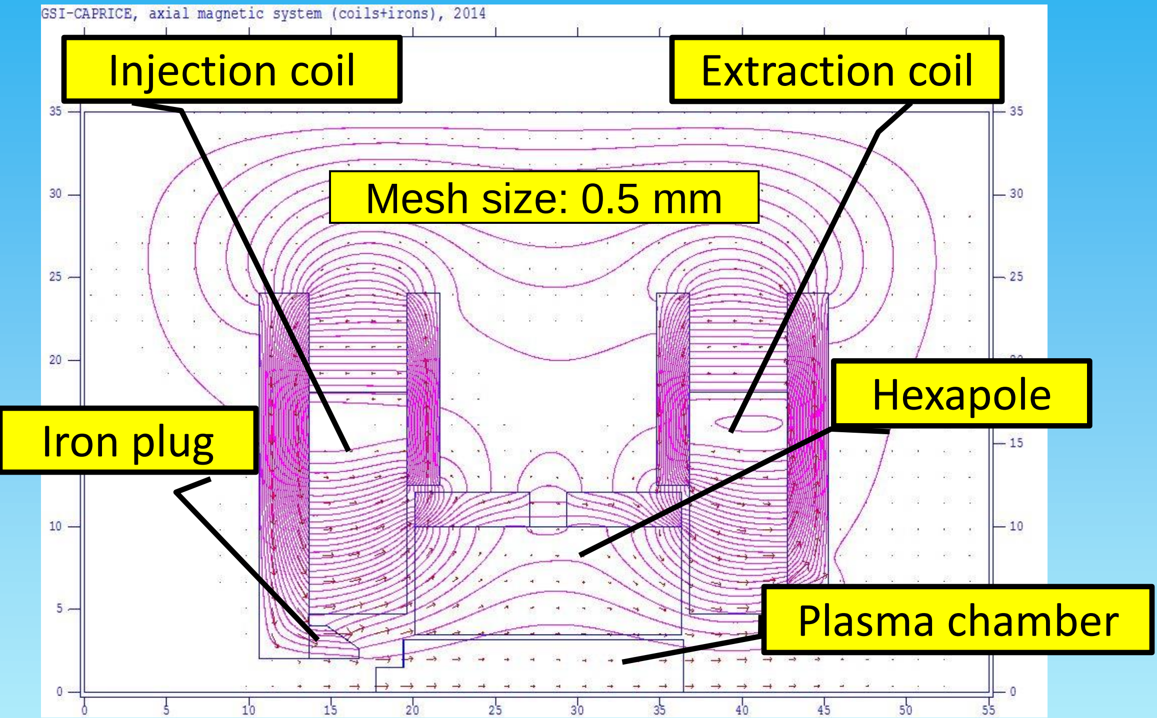

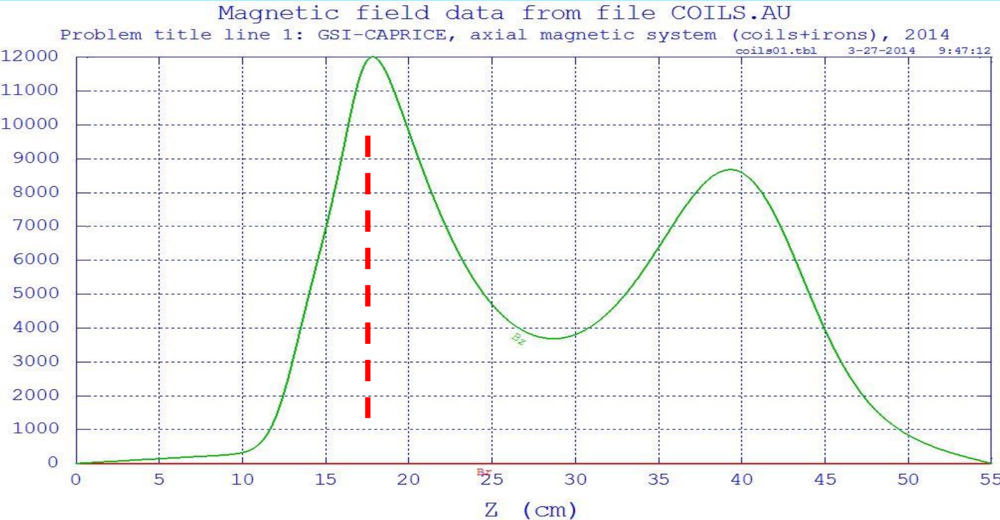

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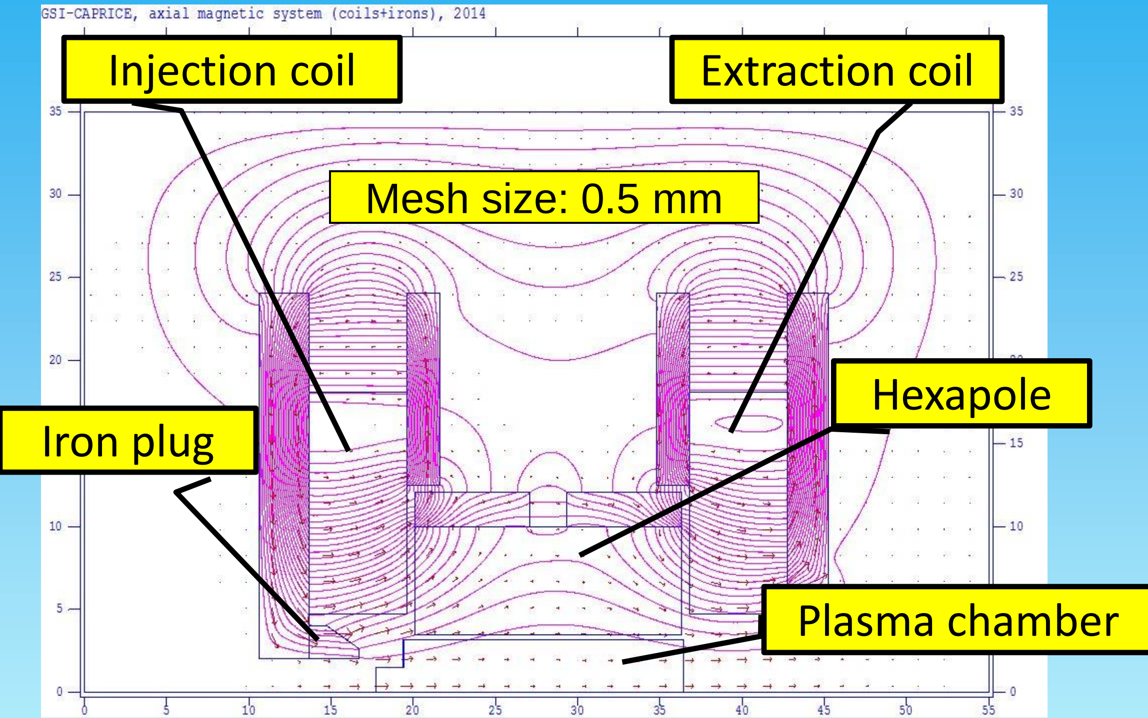

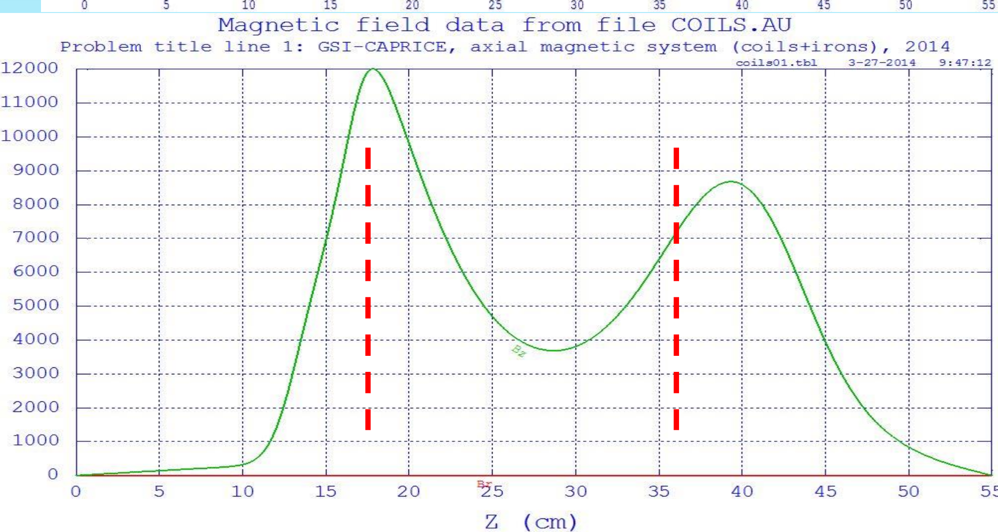

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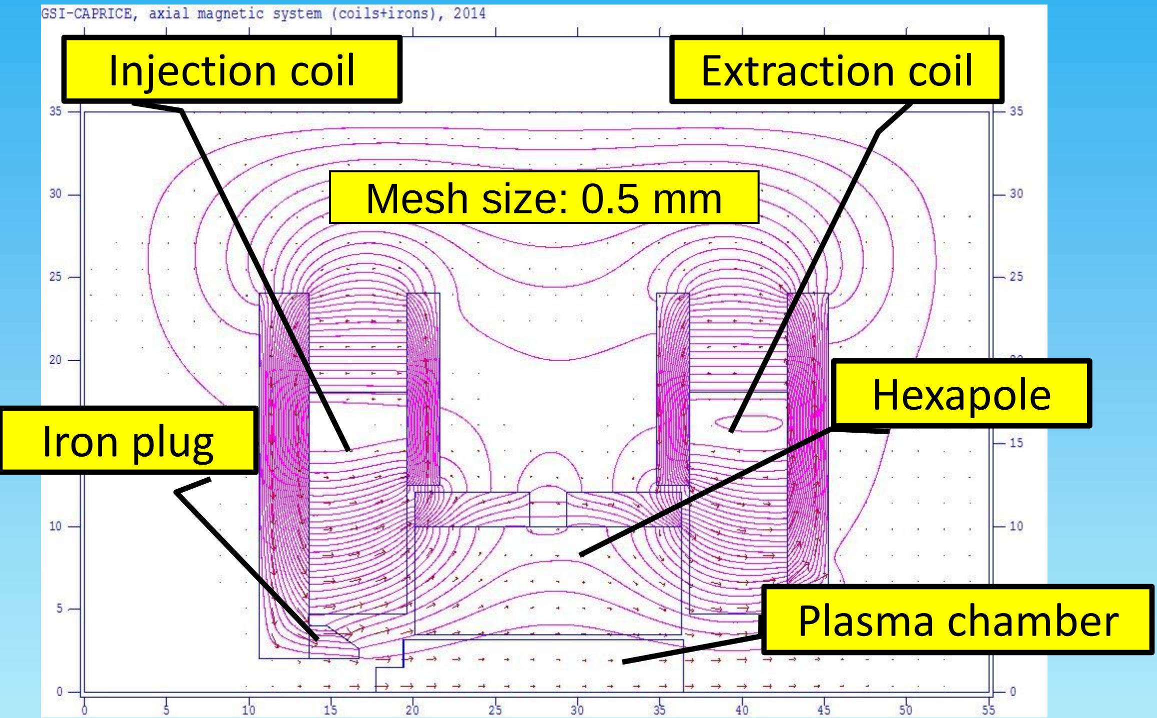

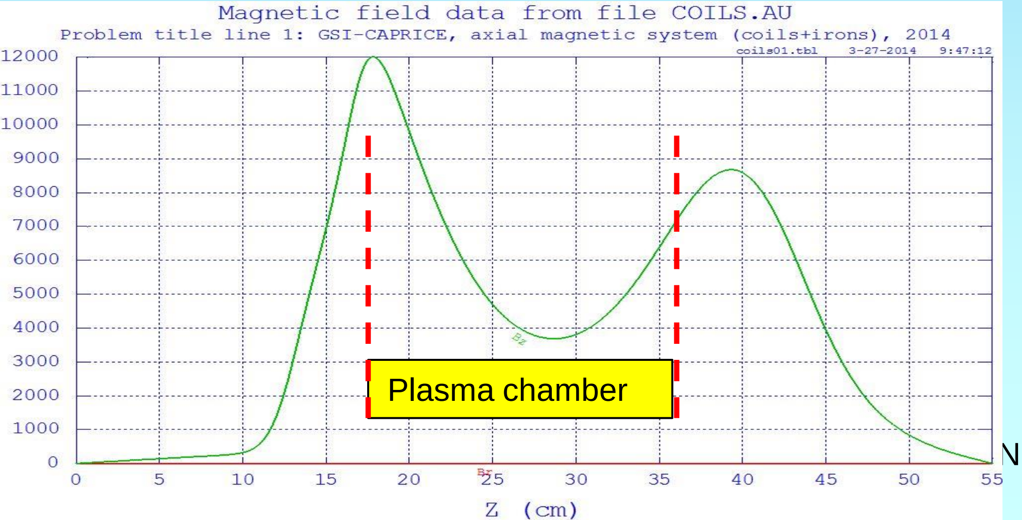

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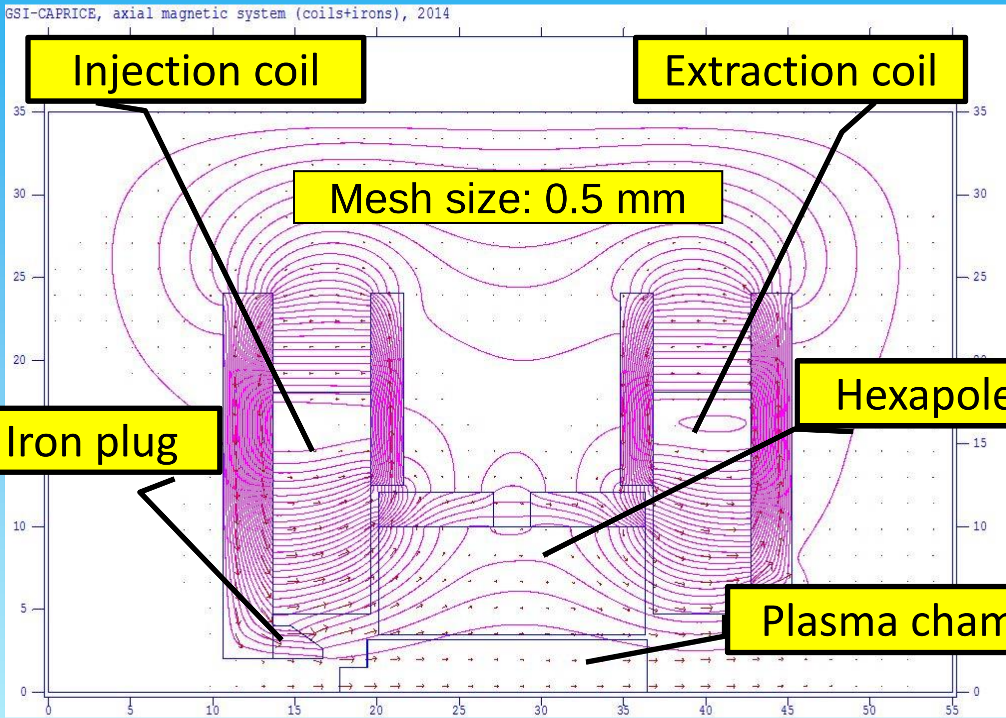

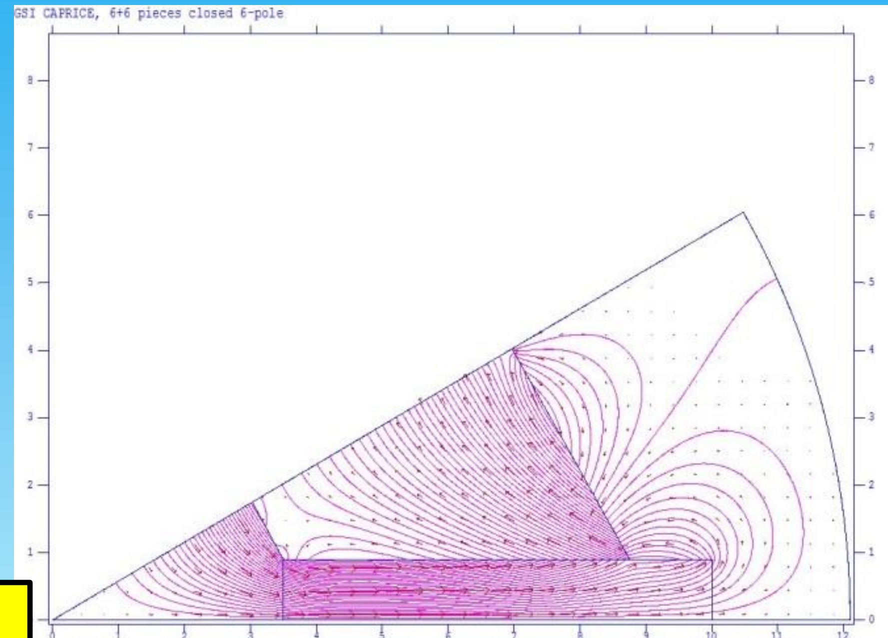

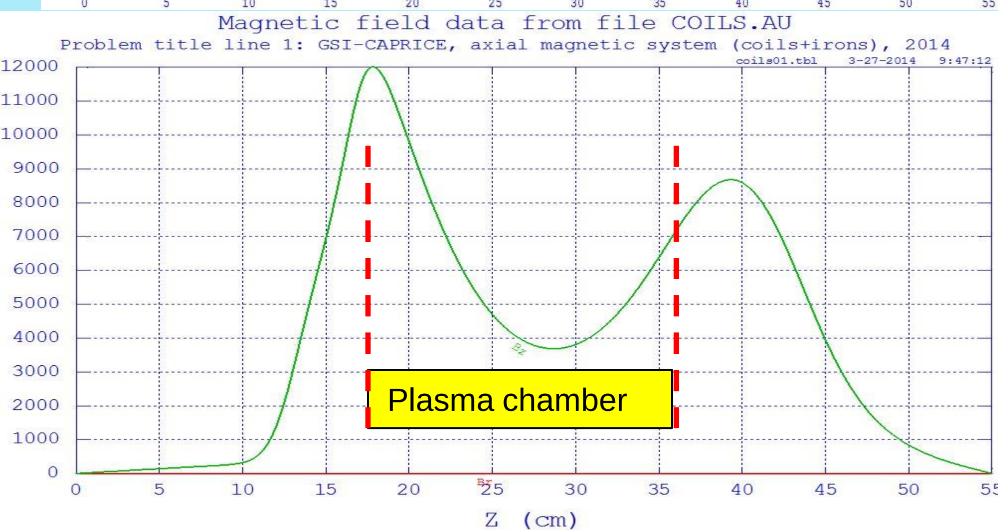

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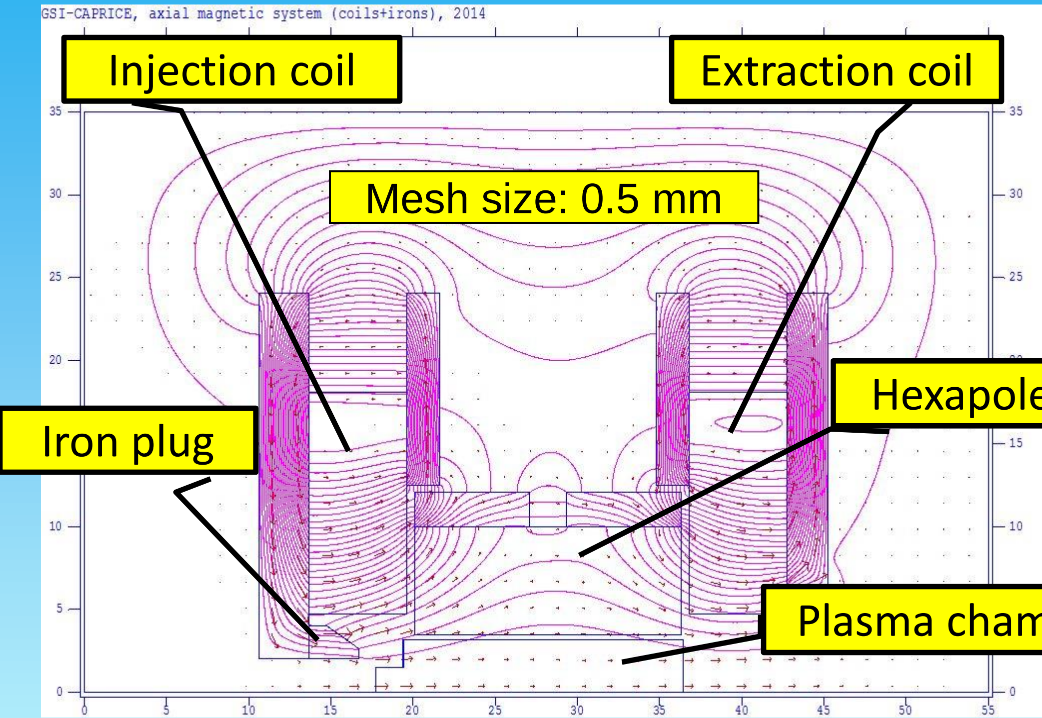

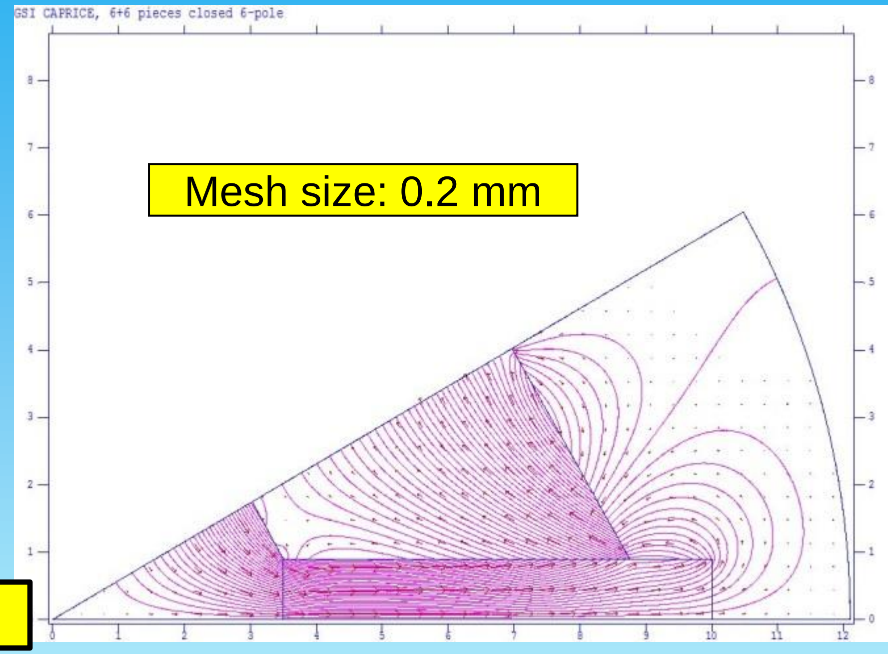

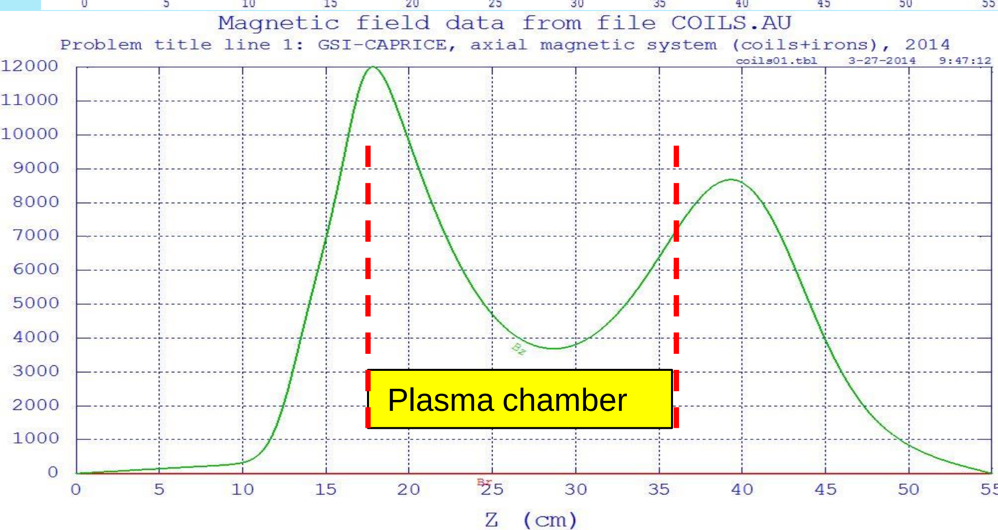

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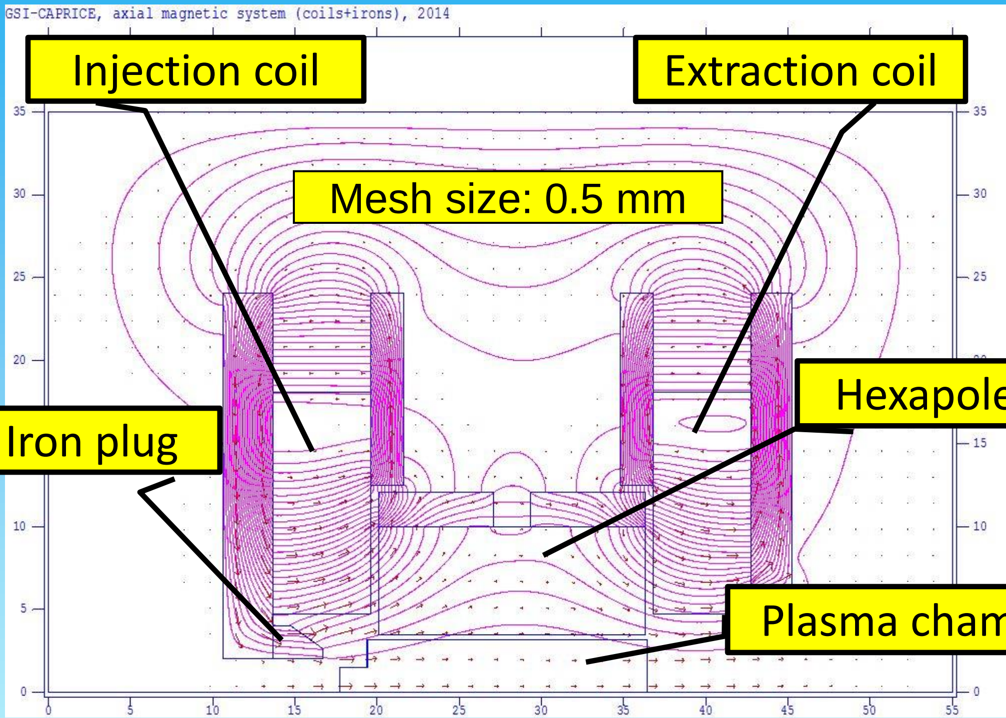

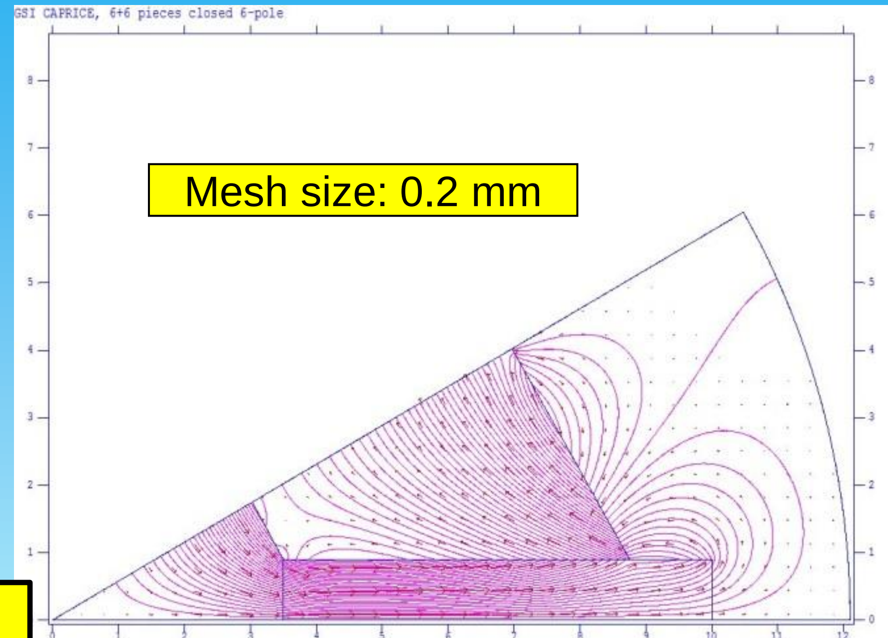

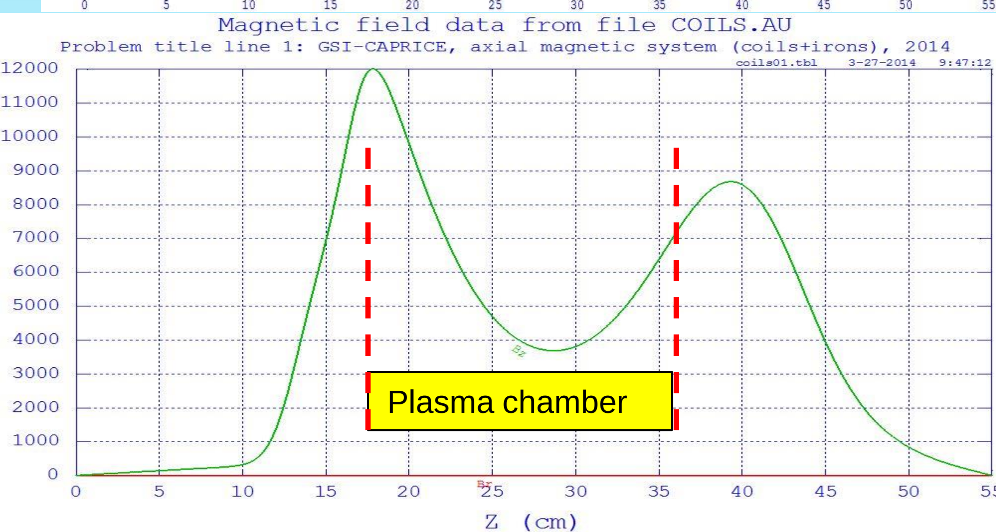

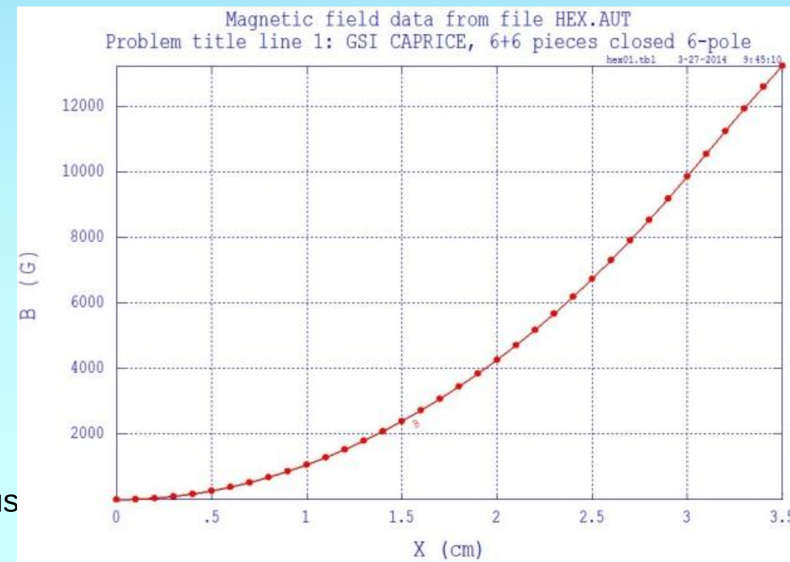

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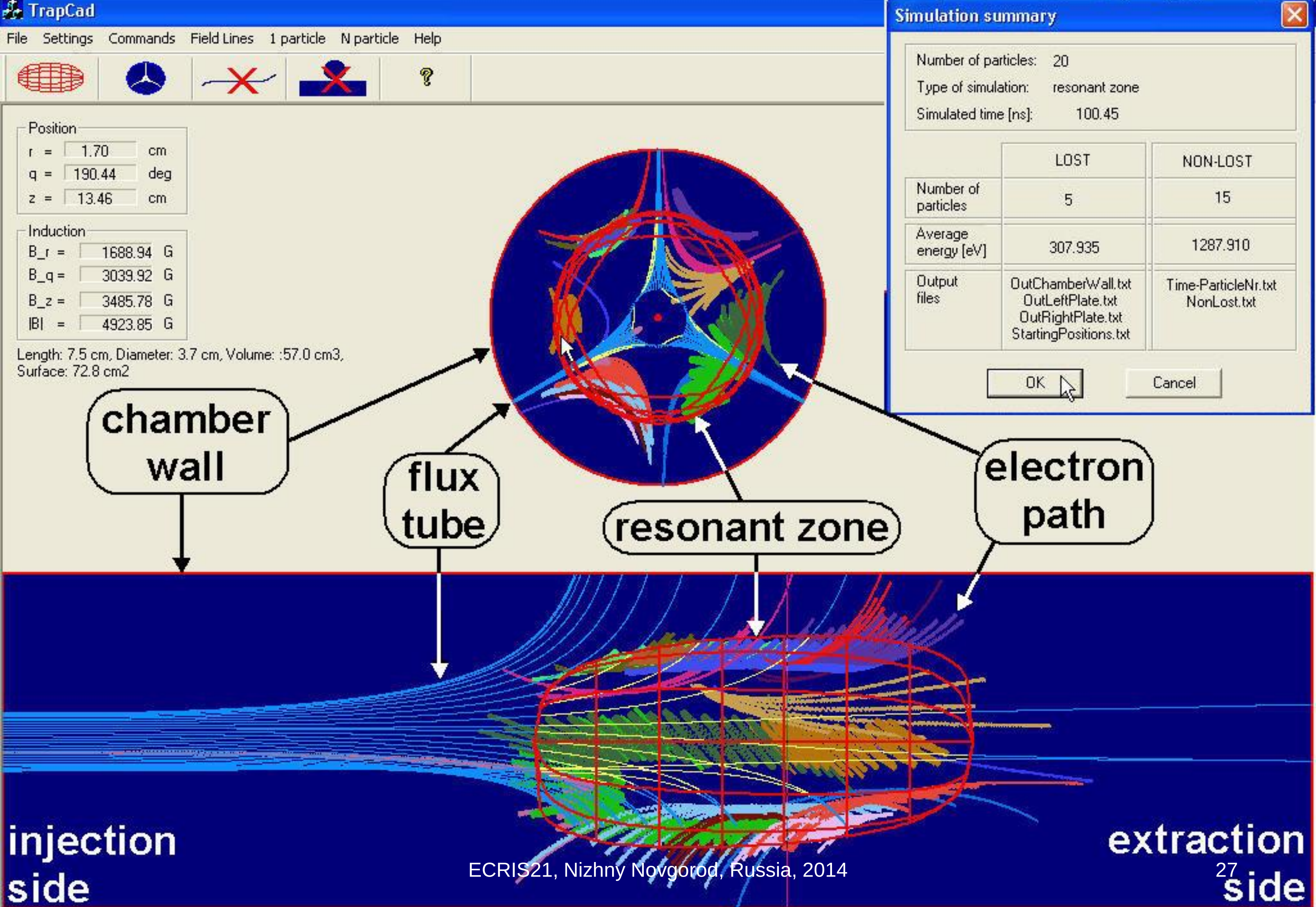
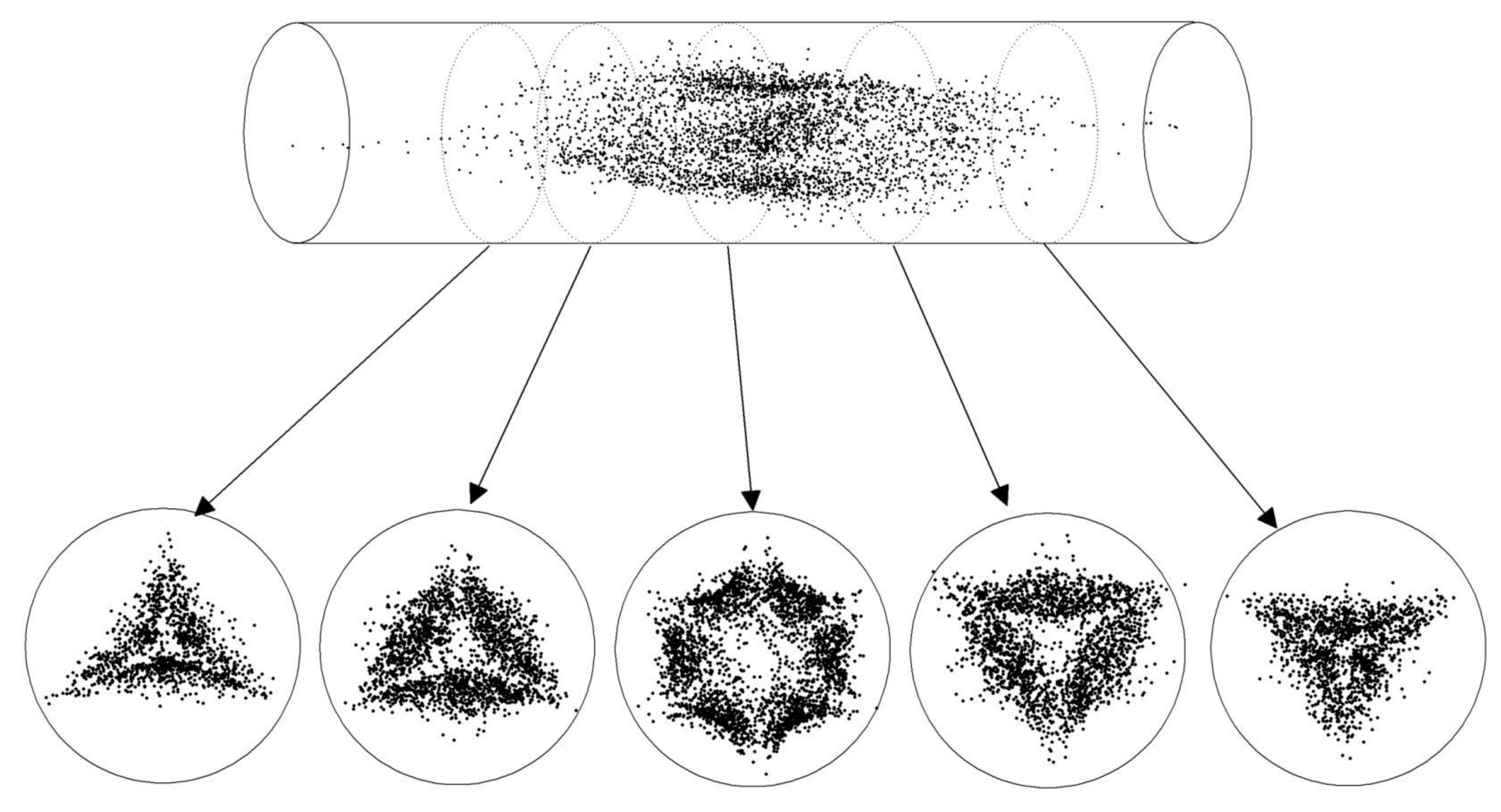
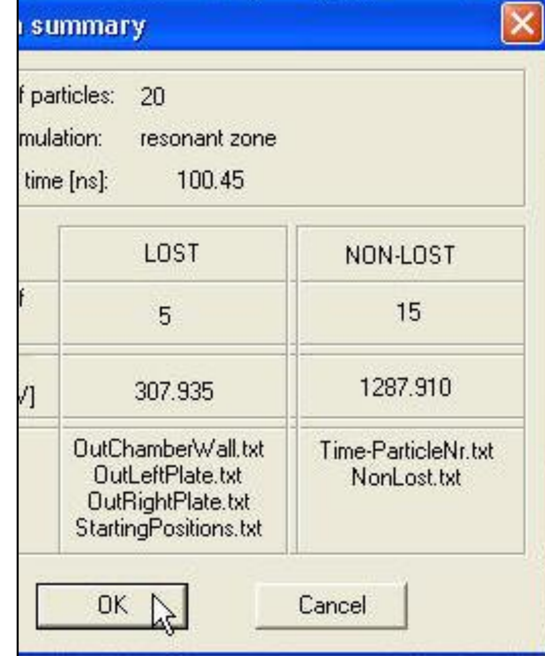
ECRIS plasma electrons simulation

- TrapCAD code: since 1994…
- More than 20 users
- „Multiple-one-particle” code
- Realistic magnetic field (2D-3D)
- Stochastic ECR heating
- Magnetic field: PoissonSuperfish
- Only electrons
- Plasma potential not included
- Collisions not included


TrapCad
File
Settings
Commands
Field Lines
1 particle
N particle
Help
Position
r = 1.70 cm
q = 190.44 deg
z = 13.46 cm
Induction
B_r = 1688.94 G
B_q = 3039.92 G
B_z = 3485.78 G
|B| = 4923.85 G
Length: 7.5 cm, Diameter: 3.7 cm, Volume: :57.0 cm3,
Surface: 72.8 cm2
Simulation summary
Number of particles: 20
Type of simulation: resonant zone
Simulated time [ns]: 100.45
LOST
NON-LOST
Number of particles
5
15
Average energy [eV]
307.935
1287.910
Output files
OutChamberWall.txt
OutLeftPlate.txt
OutRightPlate.txt
StartingPositions.txt
Time-ParticleNr.txt
NonLost.txt
OK
Cancel
chamber wall
flux tube
resonant zone
electron path
injection side
extraction side





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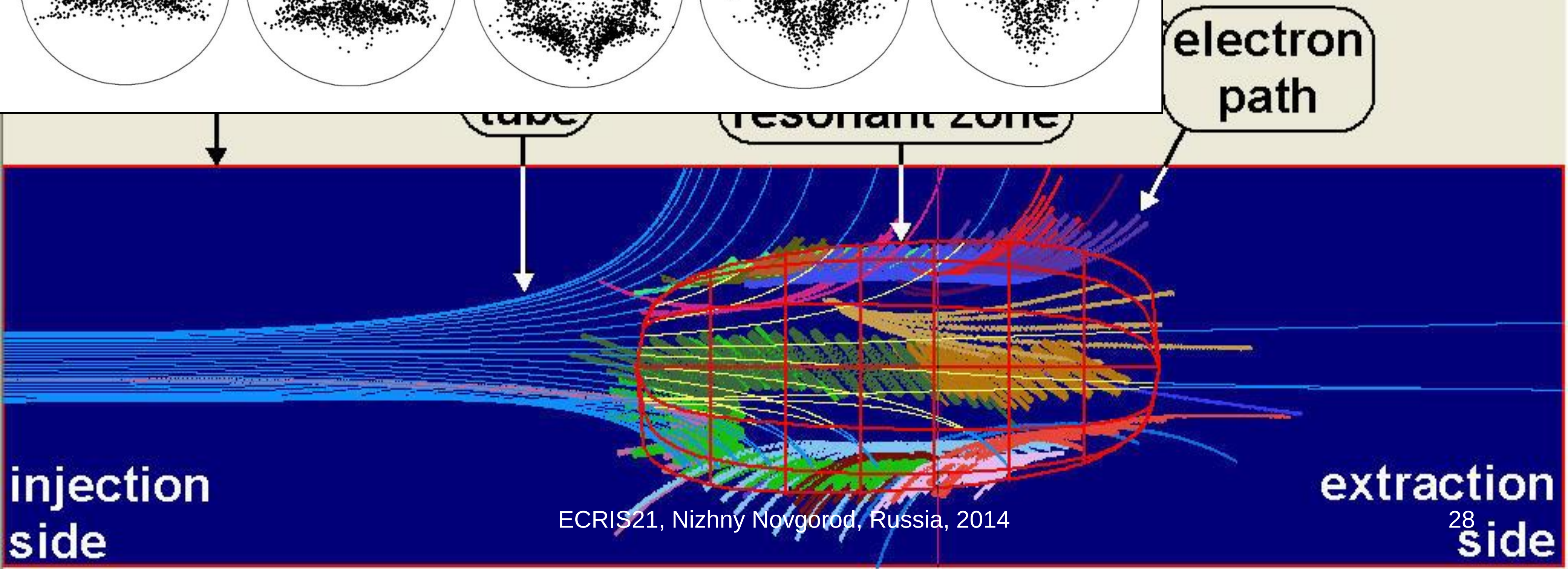

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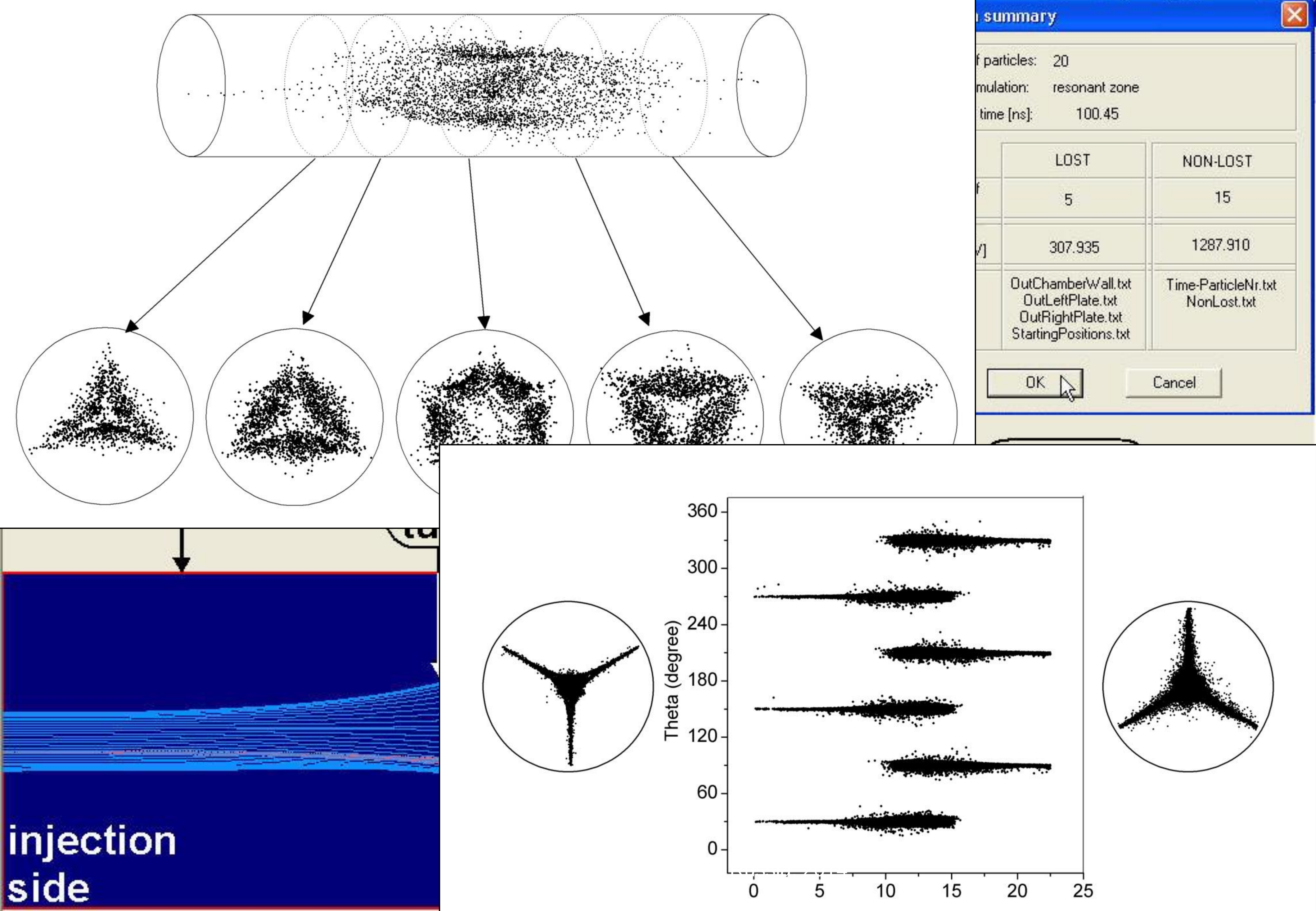
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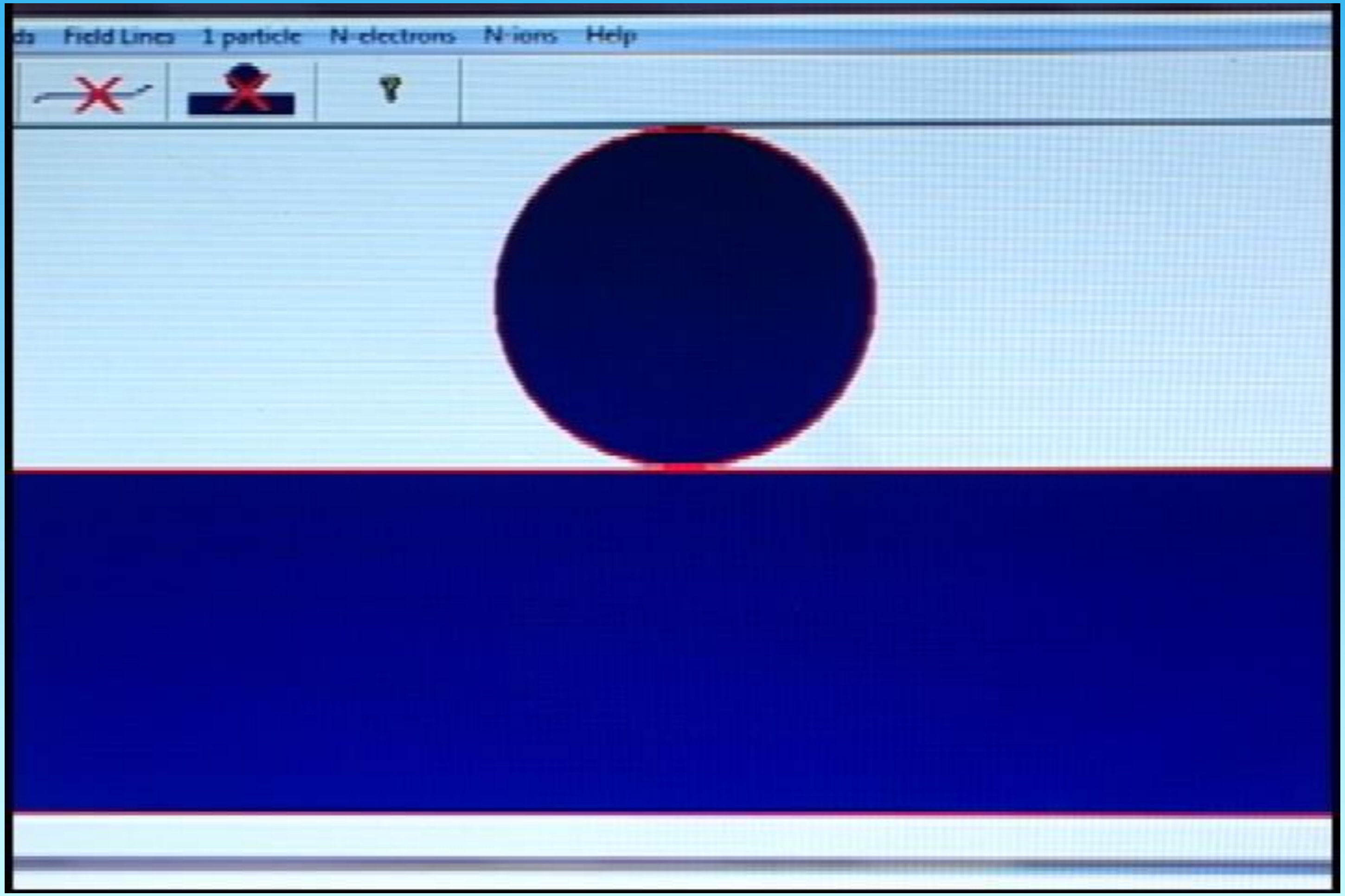
OK
Cancel
injection
side
Theta (degree)
360
300
240
180
120
60
0
0
5
10
15
20
25

TrapCAD demonstration: 50000 electrons, 10 sec



GSI-CAPRICE plasma electrons simulations

Number of electrons:	4 million
Start position (resonant surface)	5200 +/- 200 gauss
Perp. energy components:	1 - 100 eV, random
Parallel energy components:	1 - 100 eV, random
RF frequency:	14.5 GHz
RF power:	1000 W
Simulated time:	200 ns
Number of lost particles:	2396026 (59.9 %)
Number of non-lost particles:	1603974 (40.1 %)
Average energy of lost particles:	118 eV
Av. energy of non-lost particles:	2753 eV

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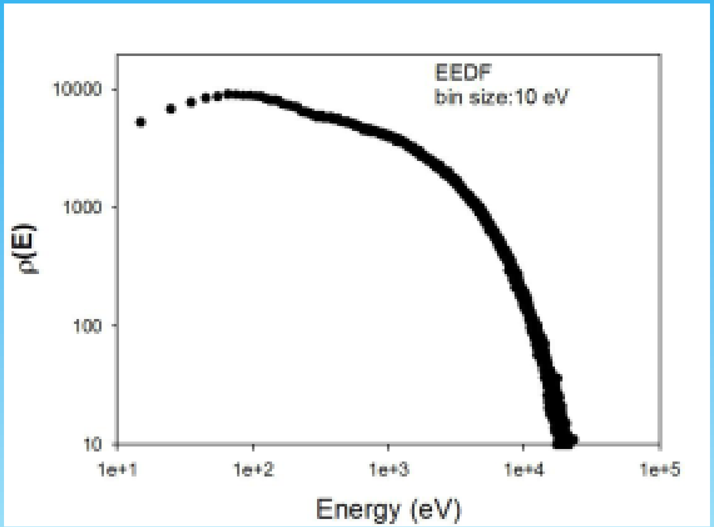

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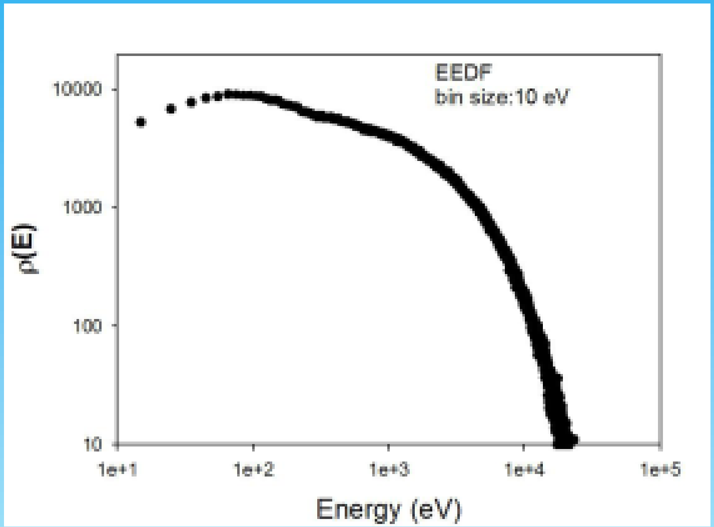

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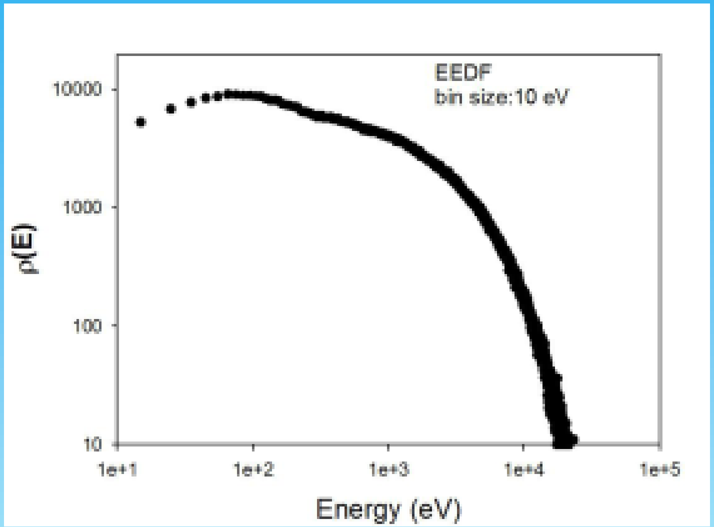

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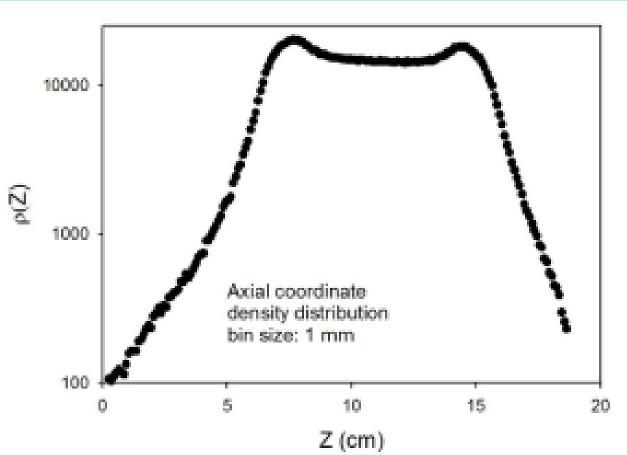
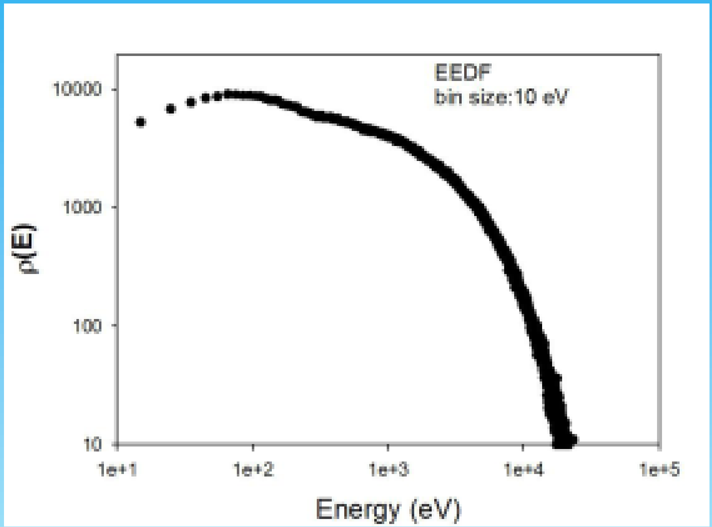


GSI-CAPRICE plasma electrons simulations

Number of electrons:	4 million
Start position (resonant surface)	5200 +/- 200 gauss
Perp. energy components:	1 - 100 eV, random
Parallel energy components:	1 - 100 eV, random
RF frequency:	14.5 GHz
RF power:	1000 W
Simulated time:	200 ns
Number of lost particles:	2396026 (59.9 %)
Number of non-lost particles:	1603974 (40.1 %)
Average energy of lost particles:	118 eV
Av. energy of non-lost particles:	2753 eV



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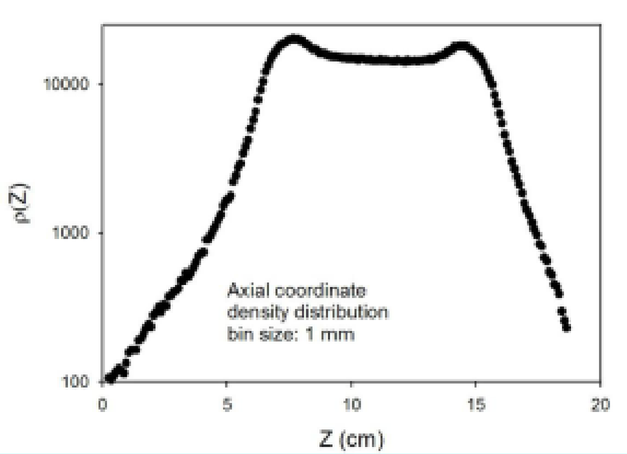
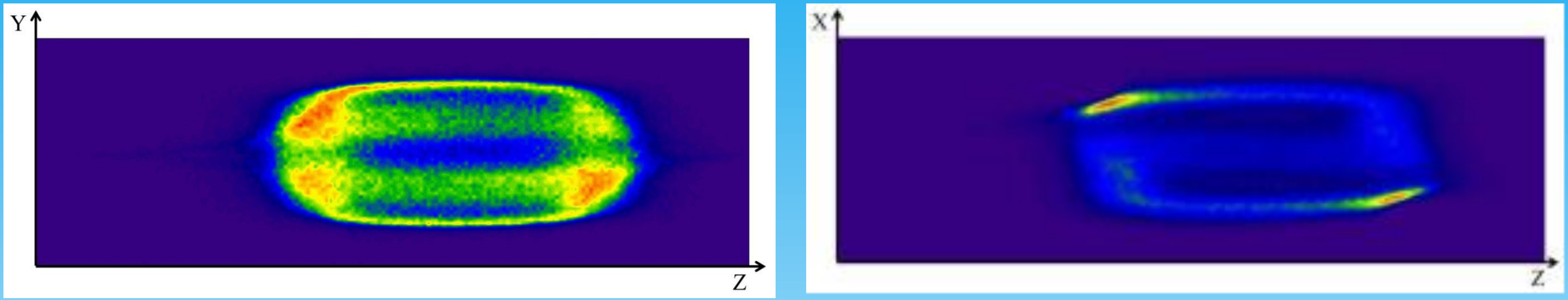


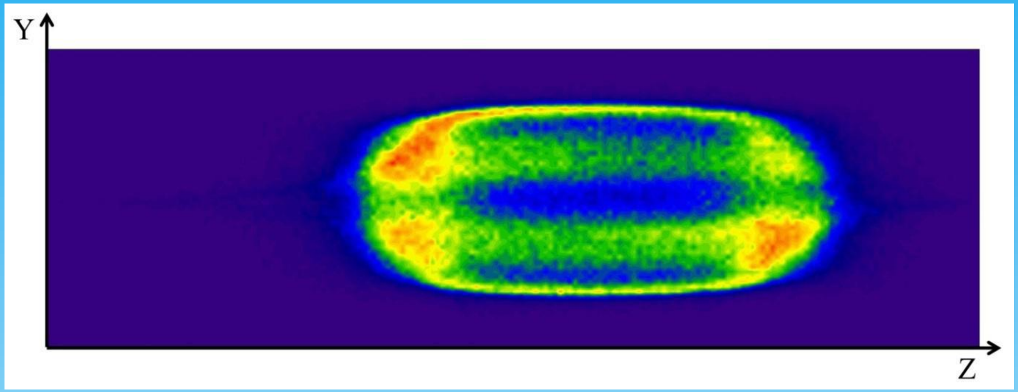
The axial distribution of the non-lost electrons. Left: injection side.

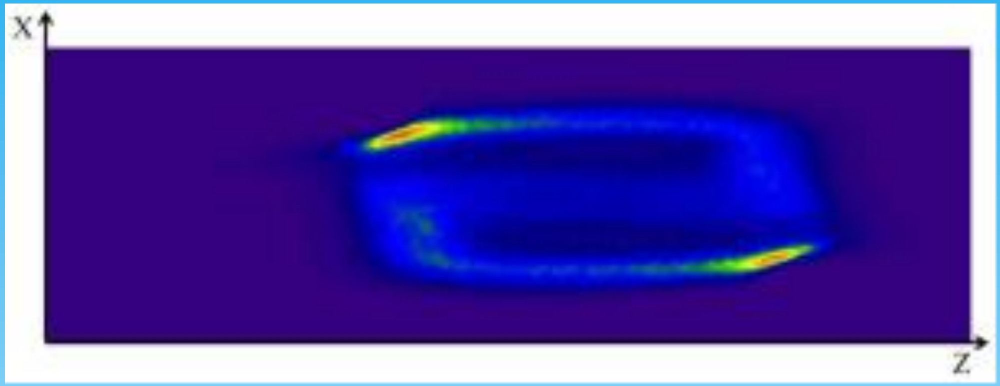
GSI-CAPRICE plasma electrons simulations



Radial (side-view) projection of the electron cloud from the direction of a magnetic gap (left) and from a magnetic pole (right).

GSI-CAPRICE plasma electrons simulations





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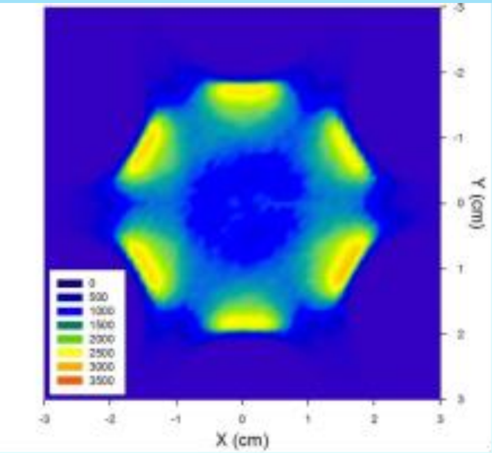

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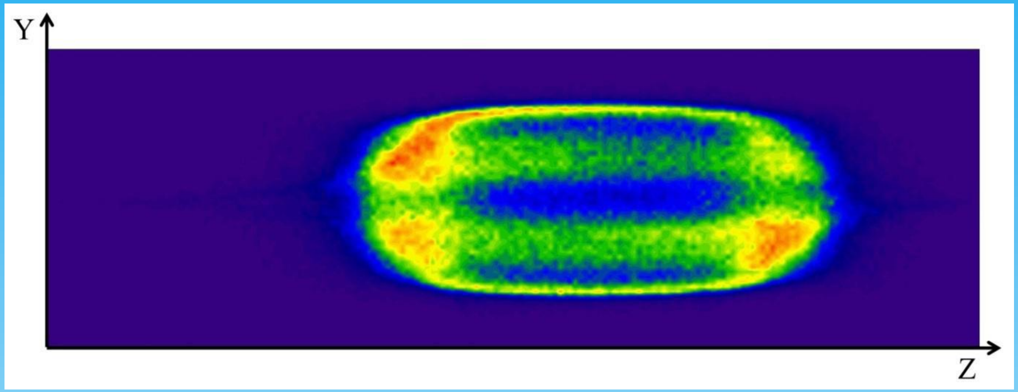

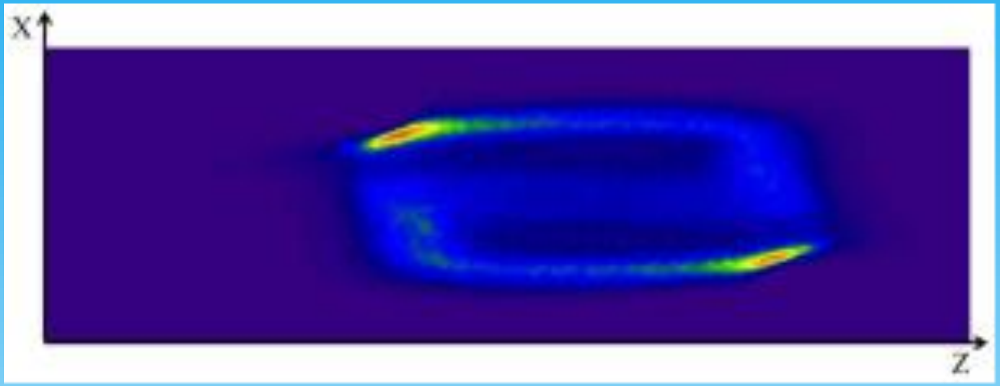

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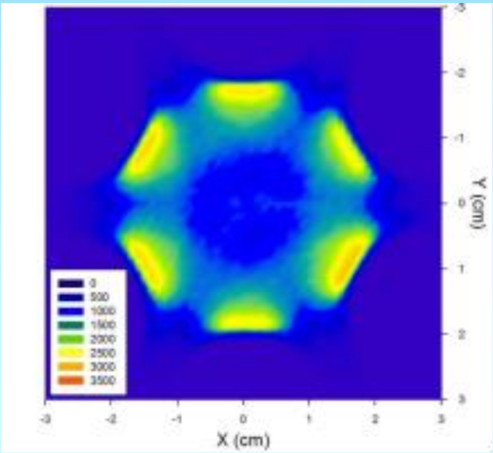

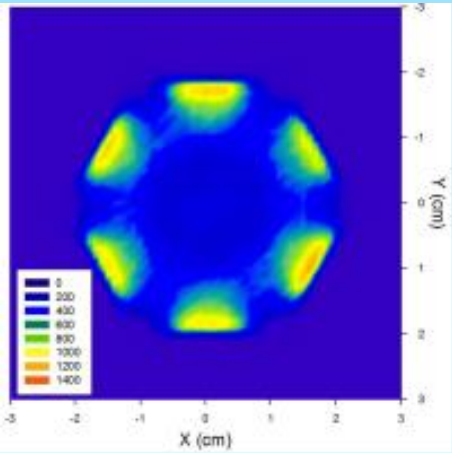

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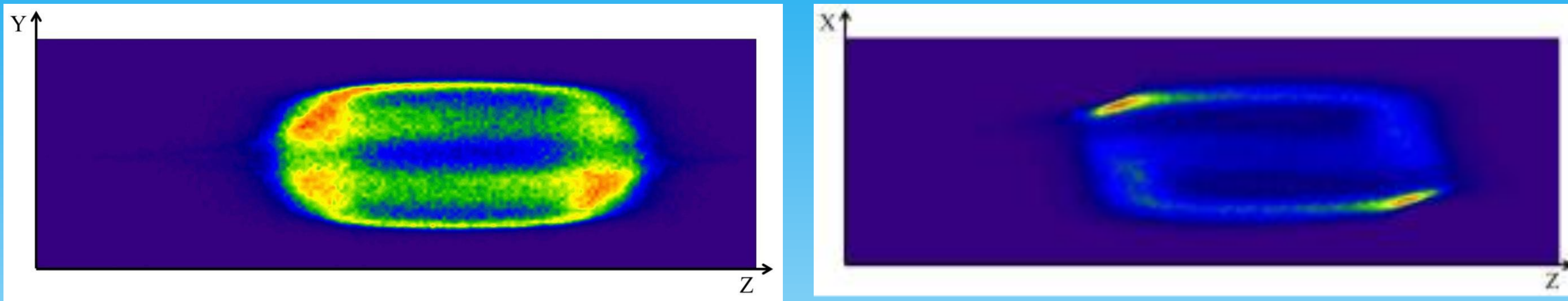

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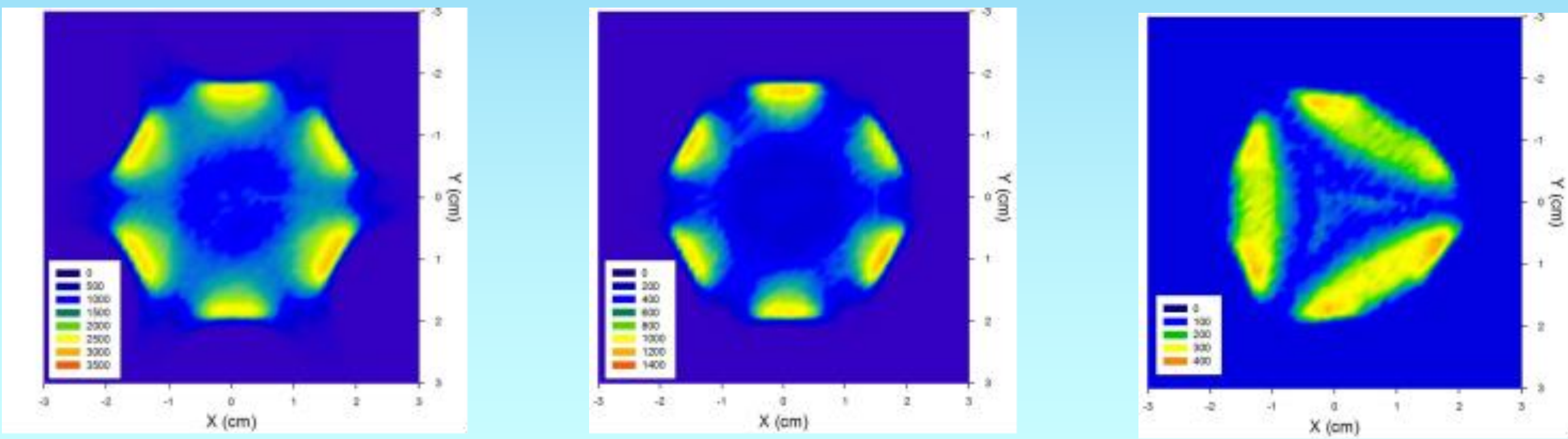

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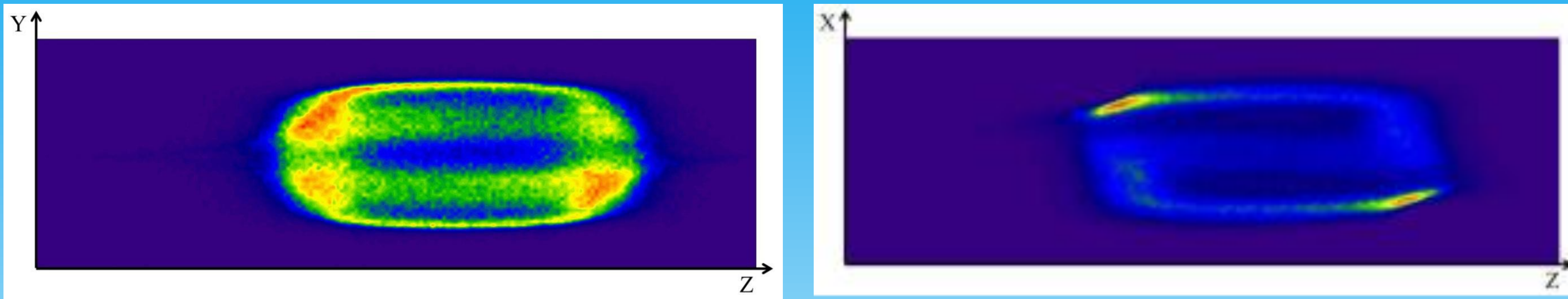

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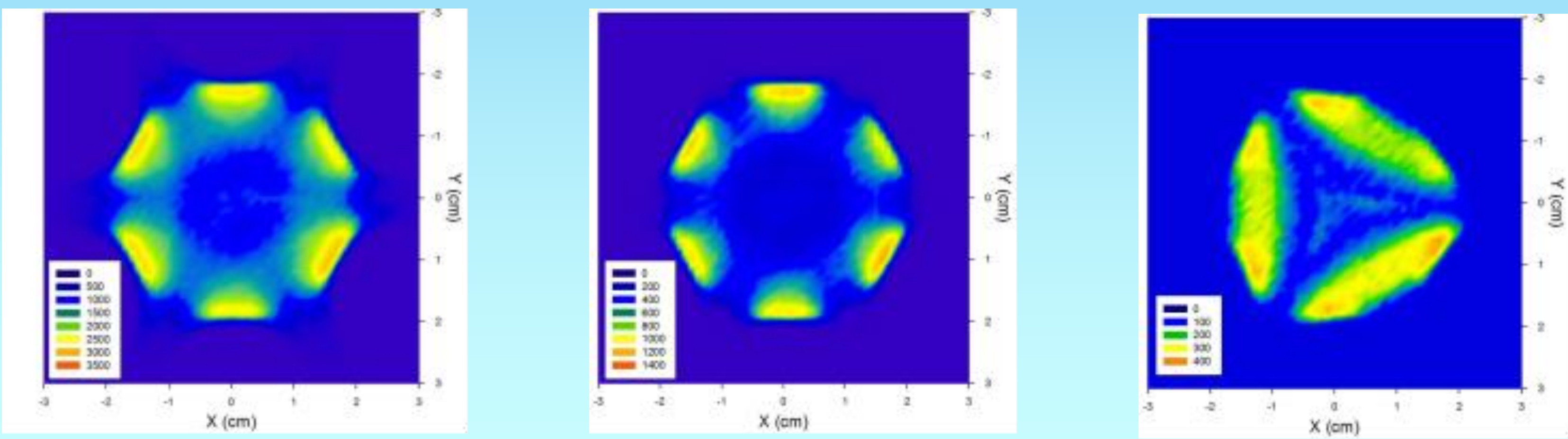
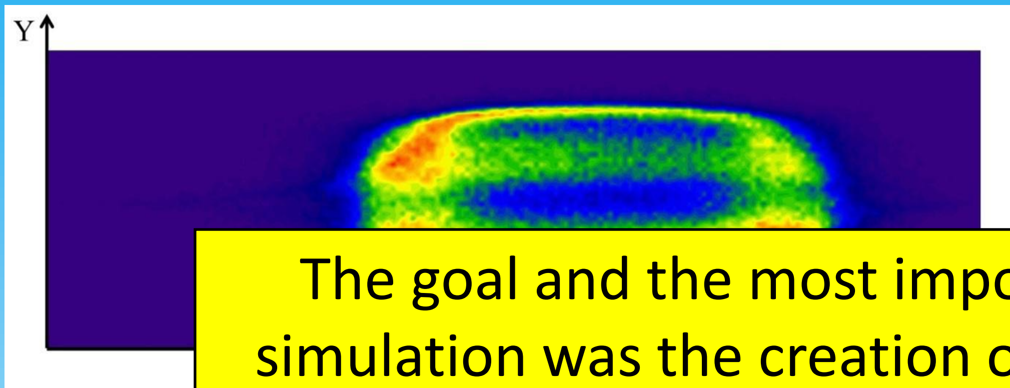


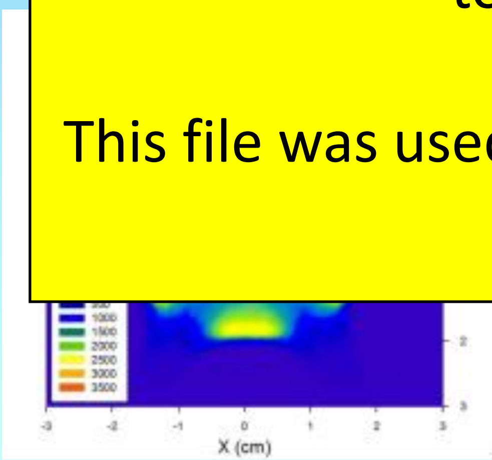
Axial (end-view) projection of the non-lost electrons. Left: all electrons, middle: warm electrons (3 keV <E< 10 keV), right: warm electrons close to the extraction side (Z>13cm).

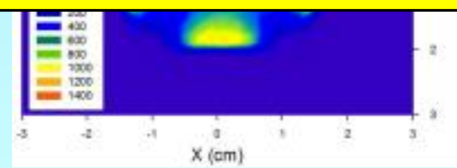
GSI-CAPRICE plasma electrons simulations

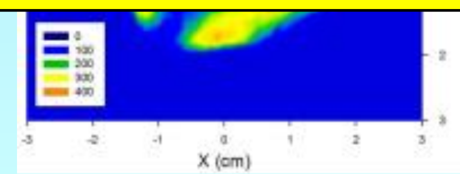


The goal and the most important result of the TrapCAD simulation was the creation of the huge **non_lost.txt** ASCII file containing the starting and ending coordinates (x, y, z) and the starting and ending energy (parallel, perpendicular, total) of all **non-lost electrons**.

This file was used as basic database for the simulation of the **ions extraction.**







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OUTLINE

1. MOTIVATION
2. THE ECRIS
3. THE TRAPCAD CODE
   - PLASMA ELECTRONS SIMULATIONS
4. **THE KOBRA3-INP CODE**
   - **TRANSFER FROM TRAPCAD TO KOBRA**
5. ION EXTRACTION FROM INSIDE THE PLASMA CHAMBER

The KOBRA3-INP Code

KOBRA-3 generate emittance plots.

Projection of the 6-dimensional phase space into the 2D drawing plane.

Example: vertical emittance
$\mathcal{E}_y = \iiiint f(y,y') \, dx \, dz \, dx' \, dz'$

Other projections are also important for accelerators.

Coupling from the y-plane to the perpendicular one.

$\mathcal{P}_y = \iiiint f(y,z') \, dx \, dz \, dx' \, dy'$

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The final coordinates of the non-lost electrons (calculated by TrapCAD) were used to start at all of these places an ion (by KOBRA). Each ion was started with a very low starting energy.

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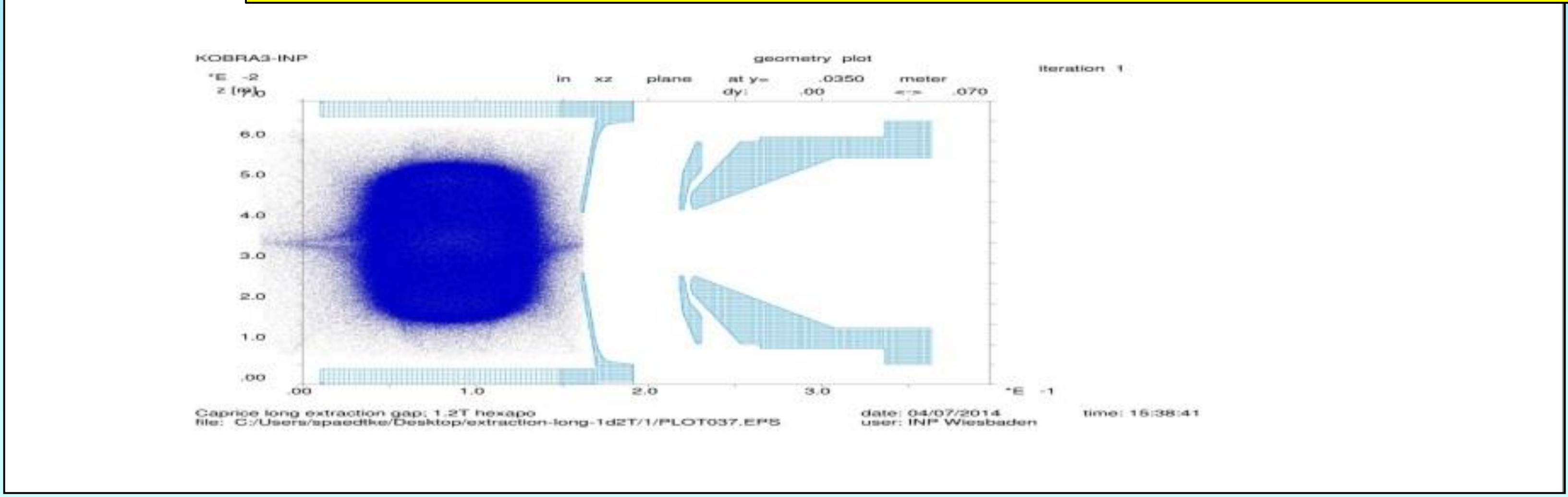

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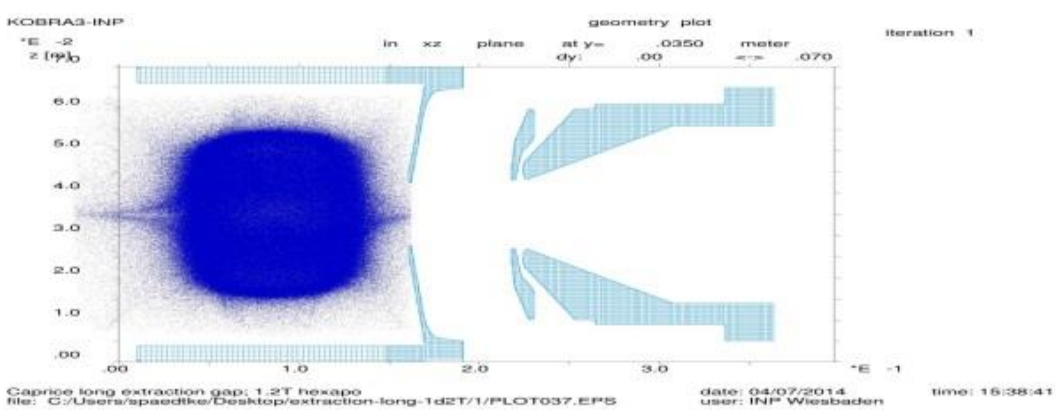
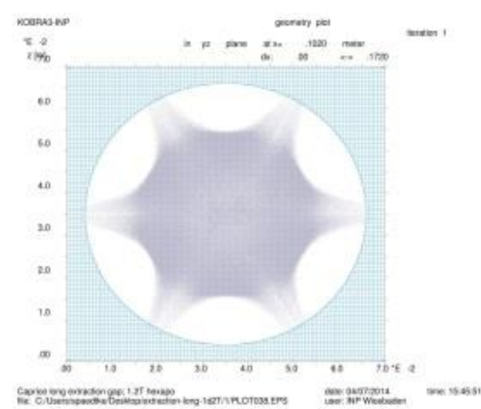
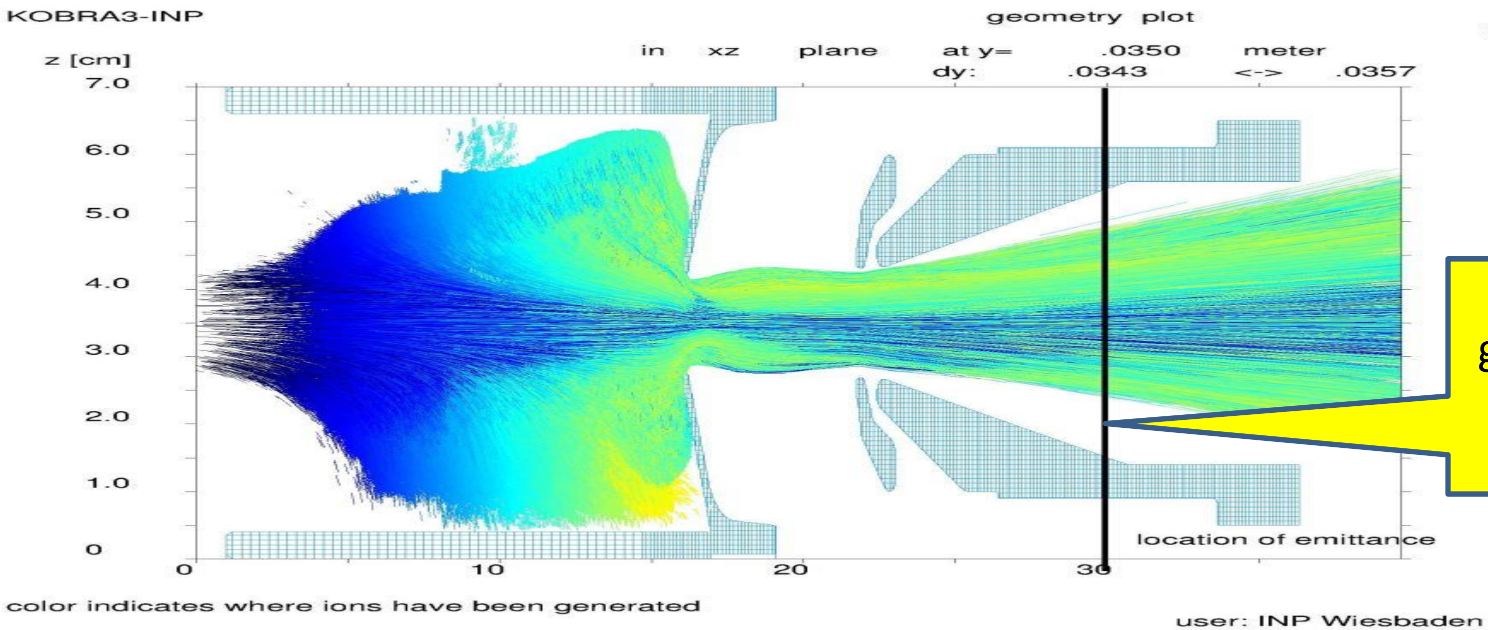




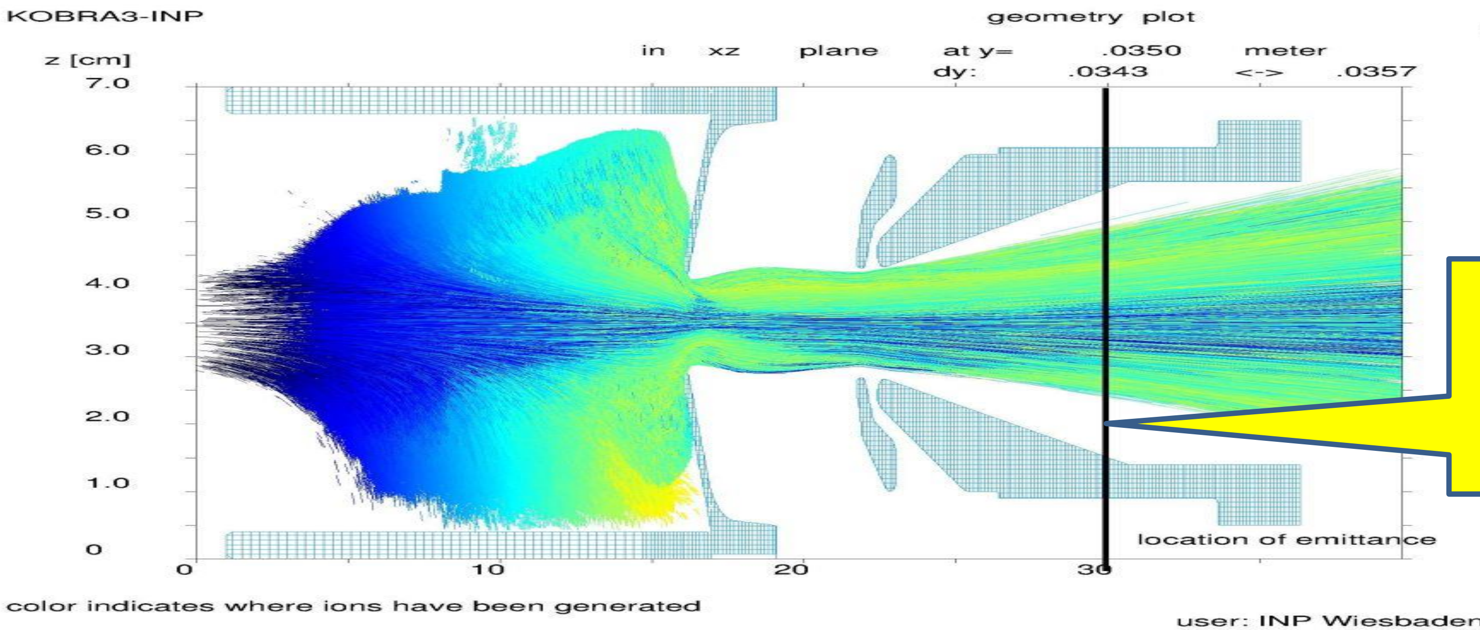
Ray-tracing by KOBRA



All emittances are given x=30 cm, y=3.5 cm, z=3.5 cm (beam direction: x)

GSI-CAPRICE, typical trajectory plot. The ions are coming from deep inside the plasma. Black are particles coming from the injection side, blue from the middle, green and yellow from the extraction side. The emittance calculations are performed at 30cm.

Ray-tracing by KOBRA



All emittances are given x=30 cm, y=3.5 cm, z=3.5 cm (beam direction: x)

Ion	Extracted (%)	Disc space (GB)
Ar+	14	26
Ar3+	12	34
Ar5+	10	28
proton	7	35

GSI-CAPRICE, typical trajectory plot. The ions are coming from deep inside the plasma. Black are particles coming from the injection side, blue from the middle, green and yellow from the extraction side. The emittance calculations are performed at 30cm.

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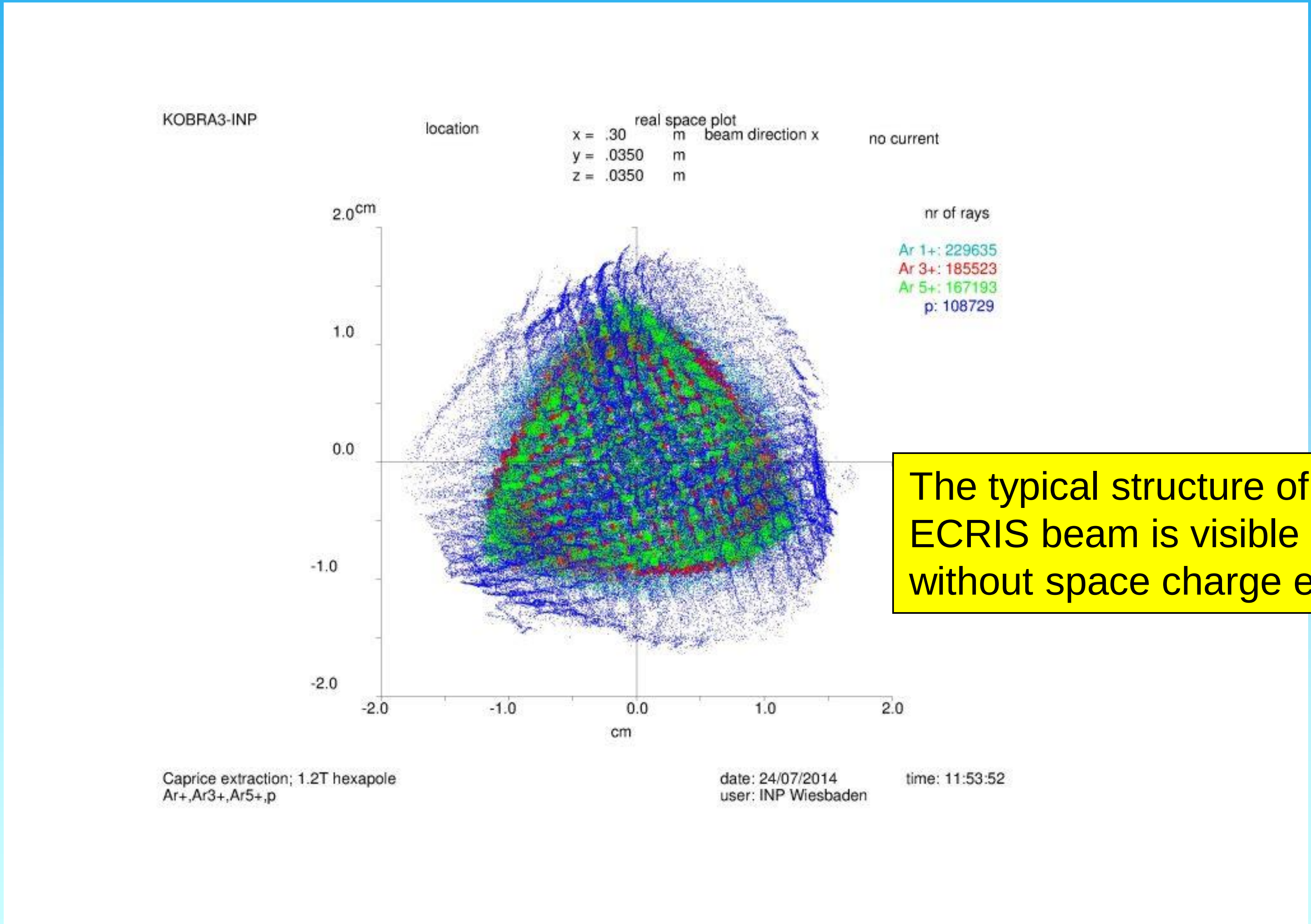
Result-1: real space emittance plots



The typical structure of an ECRIS beam is visible already without space charge effects.

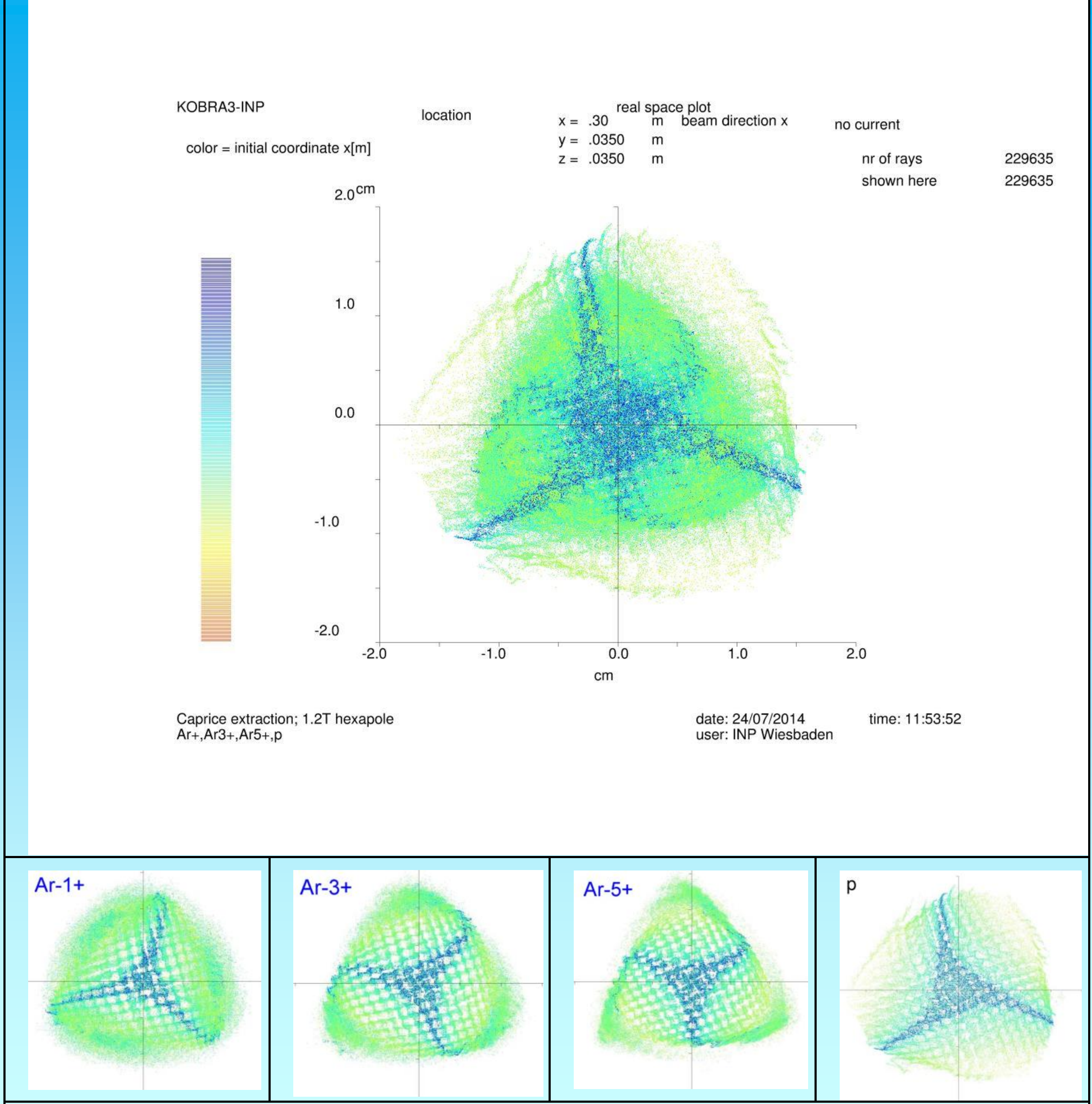
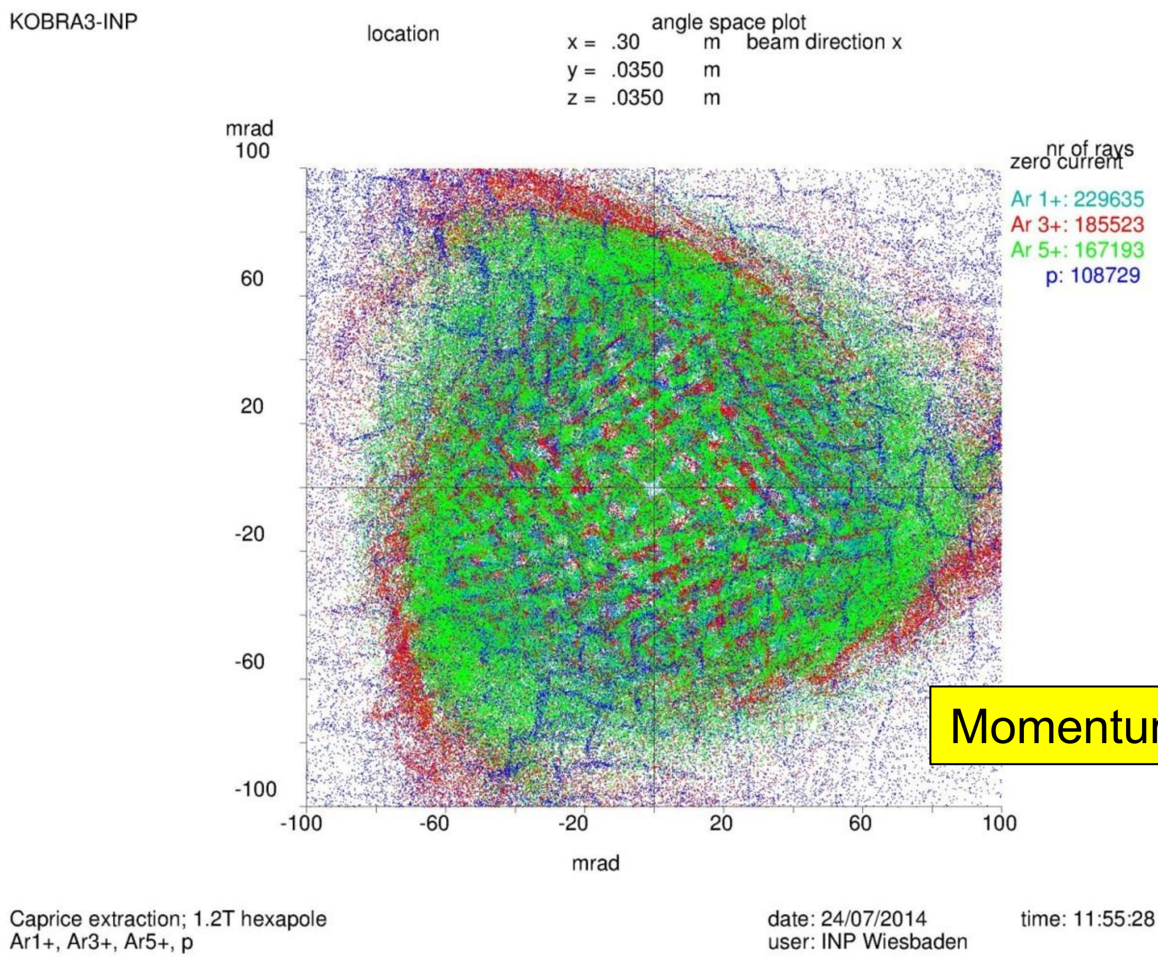


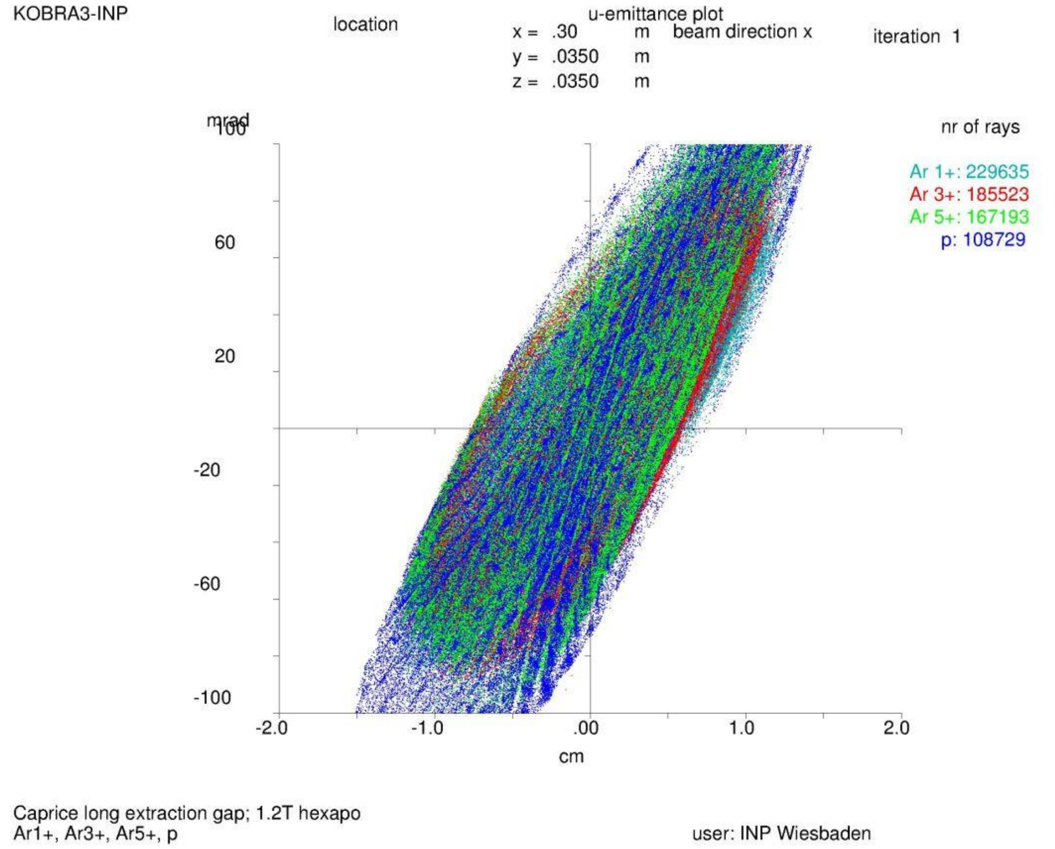
Figure 9. Real space (y-z) emittance plots. Up: all charge states. Down: individual charge states.

Result-2: angular momentum space emittance plots



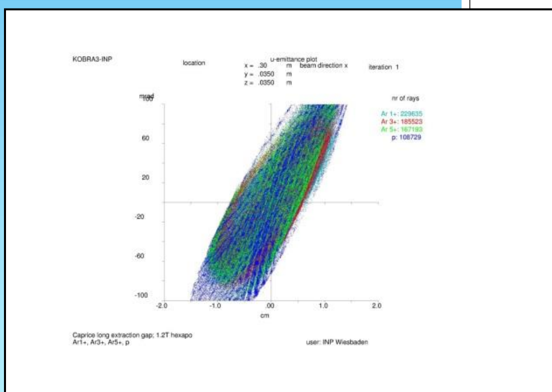
Momentum space (y'-z') plot.

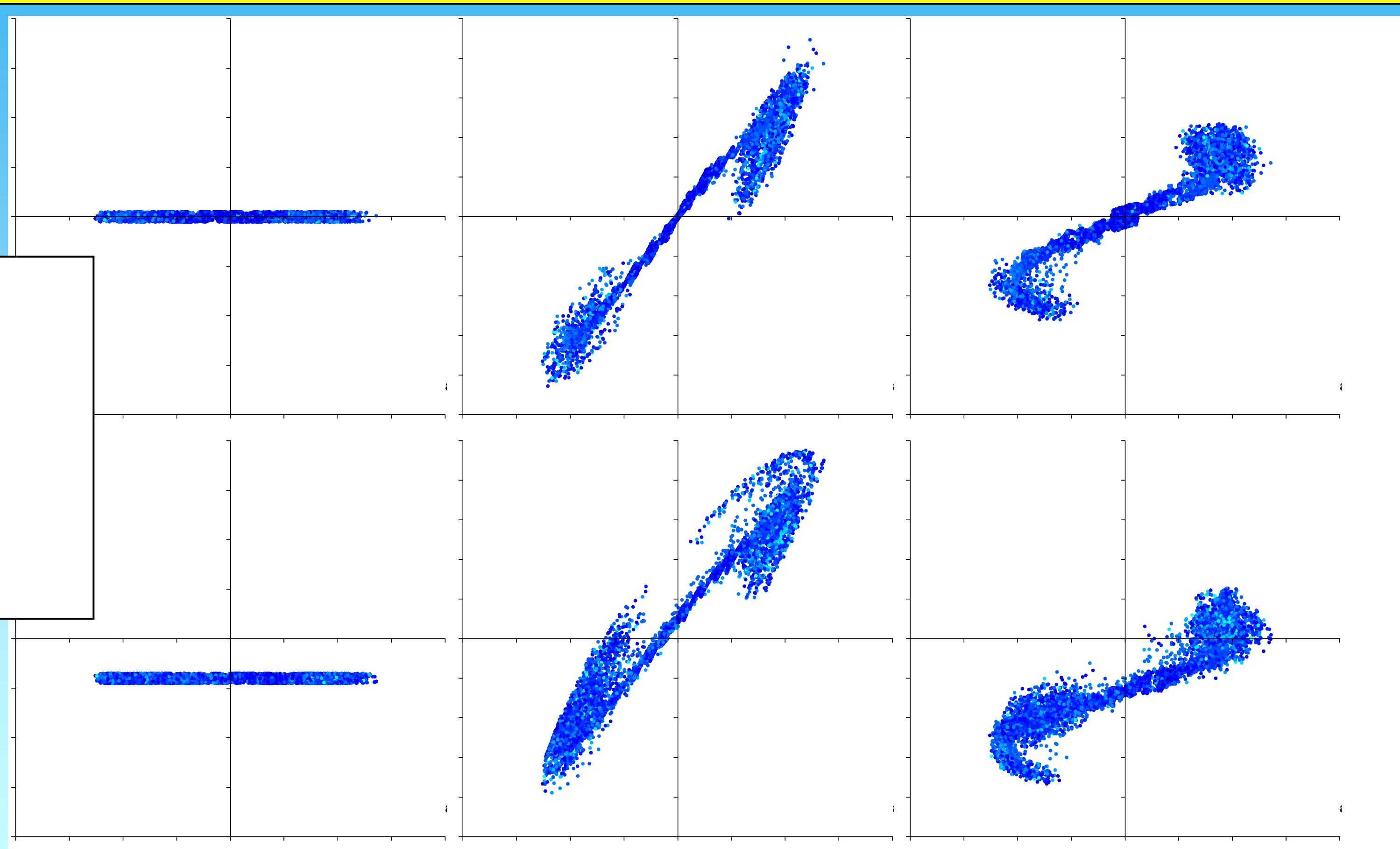
Result-3: classical emittance plots



One of the transverse emittances, y-y'.

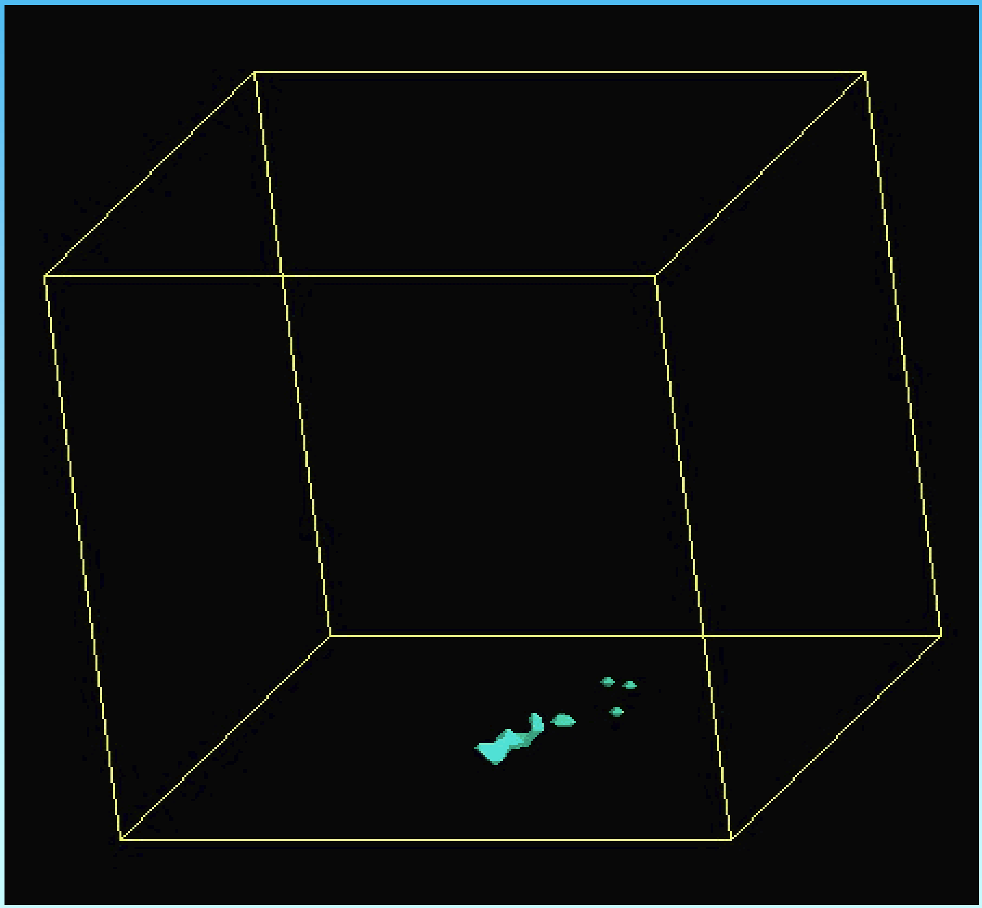
The emittance with the above given definition for each charge state is much larger than the emittance given by the pepper pot definition. If the emittance diagnosis is limited to slices between n*dy and (n+1)*dy it can be seen, that it consists of a serious of emittance figures with much smaller size.

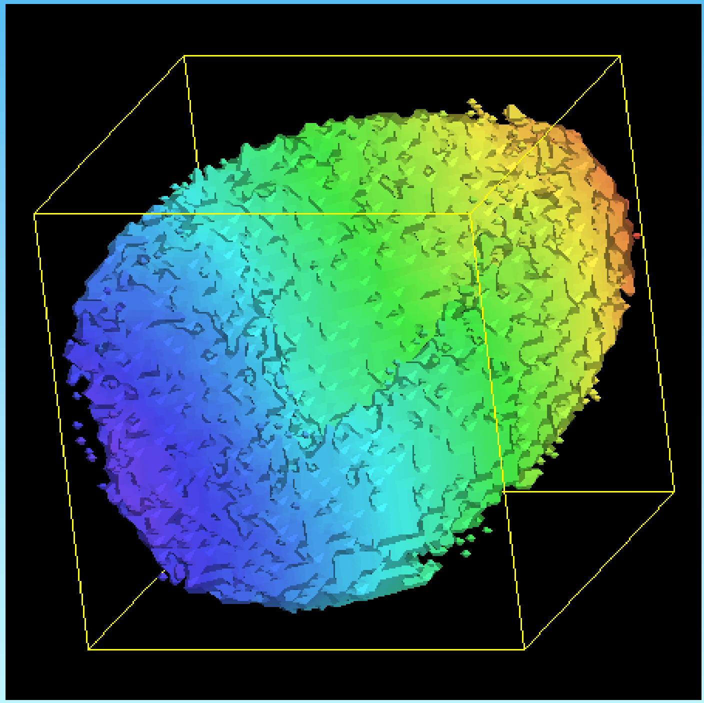




Left real profile (y-z), middle horizontal emittance (y-y'), right: horizontal mixed phase space (y-z'). First row: a slit selects ions only close to the vertical center, second row a slit selects ions from a negative vertical location.

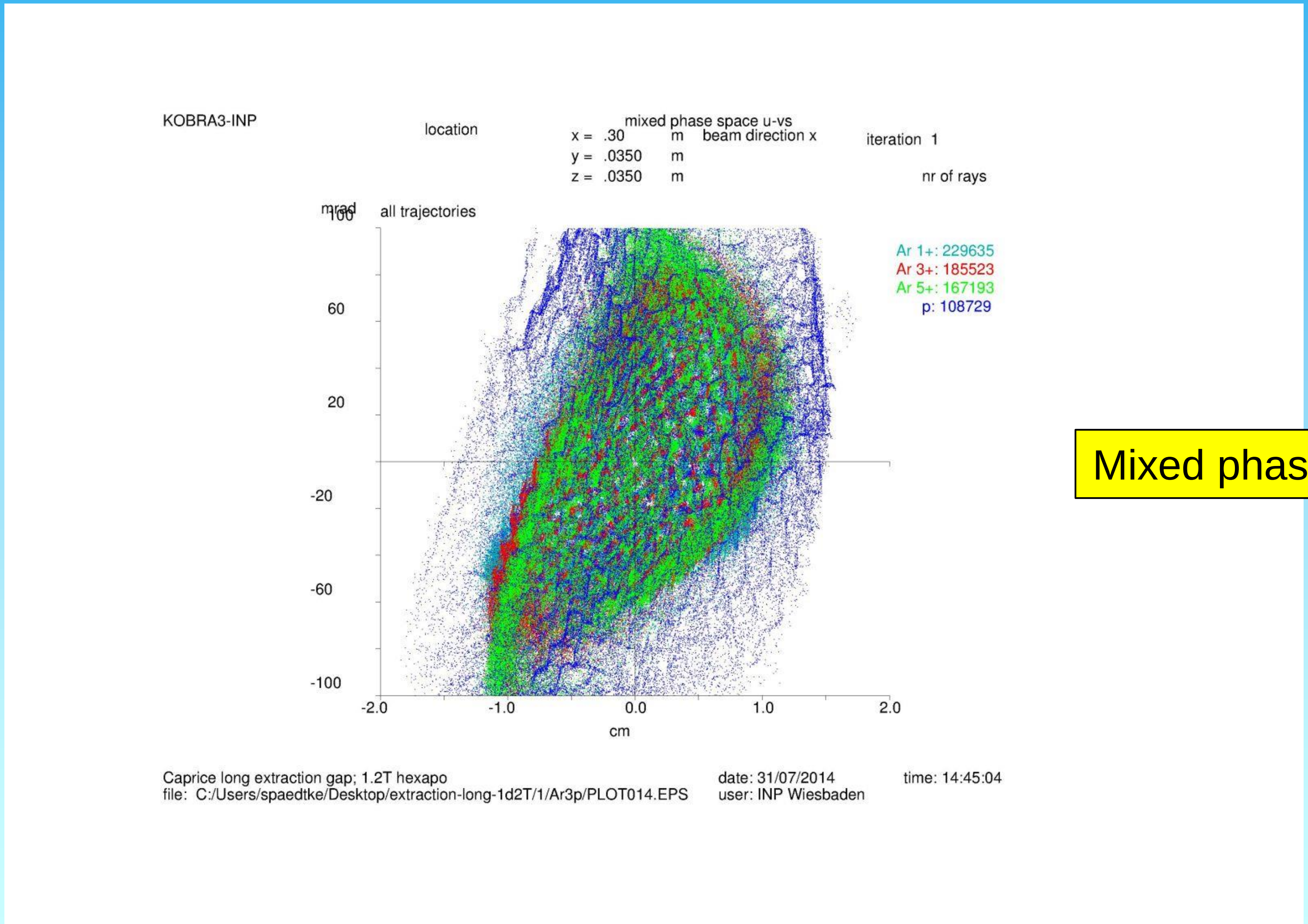
Horizontal emittance (y-y') depending on the slit position





Superposition of 50 slit emittance figures

Result-4: mixed phase space emittance plots



Mixed phase space y-z'.

CONCLUSION

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- Our work showed that to do a realistic ion extraction simulation it is necessary and possible to start the ions from inside the plasma chamber.

- The starting positions of the ions are developed by positions of the plasma electrons.

- The first ray-tracing and emittance diagrams are very promising because the known structure of an ECRIS beam could be reproduced.

- In the next steps the following tasks are planned to be carried out:
  - introducing space charge,
  - energy filtering of the electrons,
  - concentration to specific charge states,
  - improvement of diagnostic properties in the simulation (pepper pot diagnostic)
  - further comparison with experiments.