GRADUATE SUMMER SCHOOL
16-20 August 2021

Modelling of Plasma Ion source for Producing Highly Charged Ions

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Aix-Marseille Université (2020-21)

Motivation

- GANIL provides intense heavy ion beam to physicists: current ECR ion source beams are “star-shaped”(due to hexapole magnets); inhomogeneous; requires fitting for the LEBT{Low energy Beam Transport}
- Wastage of beams due to cutting off and shaping to get homogenous core.
- Limitations on scale up to high frequency ion source (currently ~50GHz) due to requirement of superconducting coils and hexapole.
- New source (PK-GANESA) developed by GANIL and Pantechnik[1] collaboration to address above issues
- Experimental study carried out[1] did not lead to expected results
- Internship aims to understand behavior of PK-GANESA by studying electrons transport prior to collisions.

Contents

ECR ion sources

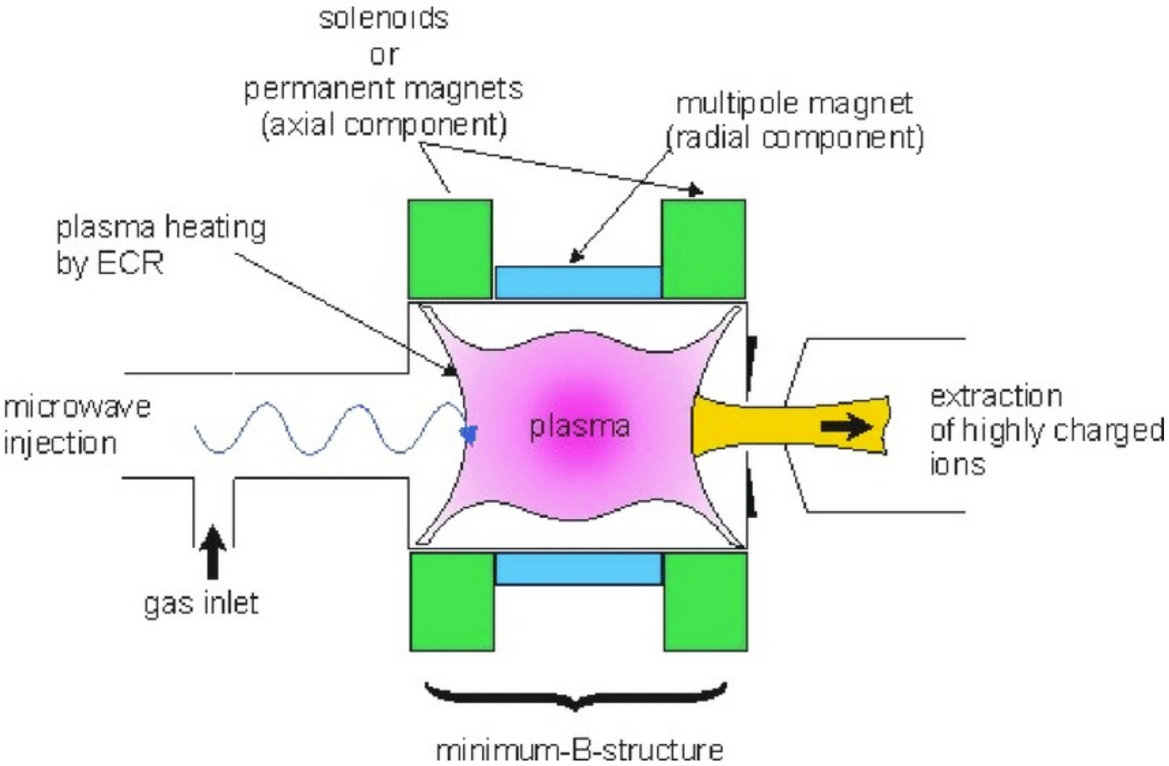
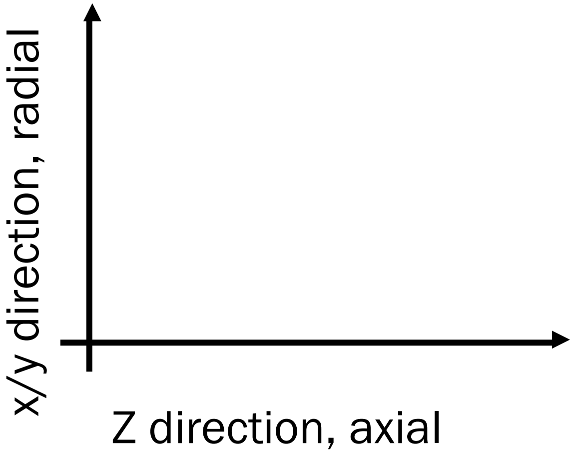


Fig 1: schematic of an ECR ion source

- Minimum B-magnetic structures
- Modification of open ended magnetic configuration by Geller[2]
- Ionization cross-sections depends on electron energies
- High charge states require energies ~ keV
- ECR heating heats electrons to keV



ECR Resonance Heating

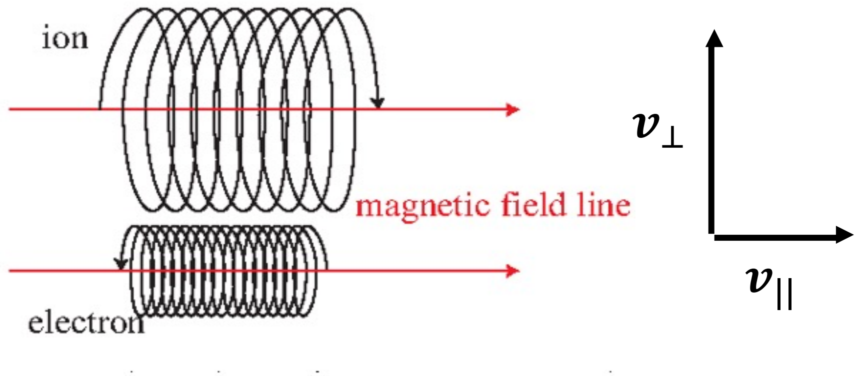


Fig 2: charged particle trajectory along a magnetic field

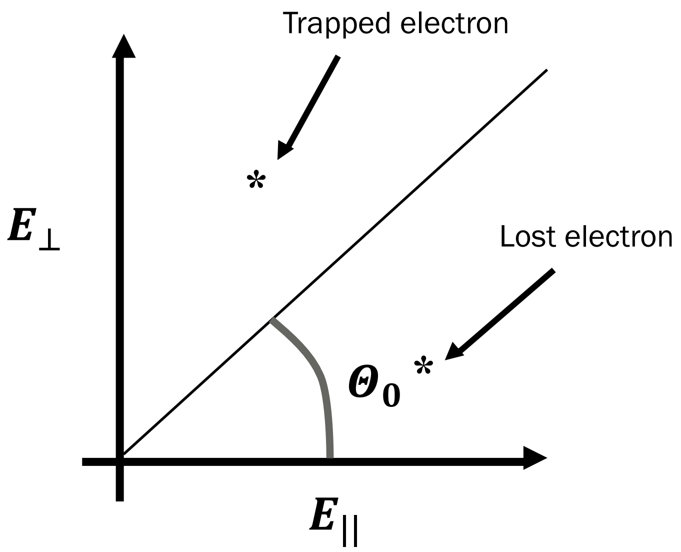
$$B_{ECR}[T] = \frac{f[GHz]}{28} \qquad (1)$$

$$\omega_{ce} = \frac{eB}{\gamma m_e} \qquad (2)$$

$$\omega_{ce} = \omega_{rf} = \frac{eB_{ECR}}{\gamma m_e} = 2\pi f_{rf} \qquad (3)$$

$$\Theta_0 = sin^{-1}\sqrt{\frac{B_{ECR}}{B_{max}}} \qquad (4)$$

- Electrons have helical trajectory along magnetic field lines.
- An electron with energy E ~ 1keV
- B_{ECR} = 0.35T (typical value of ion sources)
- Larmor radius, $\rho_{e^-} = 3.04\mu m$; ω_{ce} ~ 62.8 rad/s ~ 10GHz
- Larmor radius, $\rho_{Ar^{+1}}$ = 2.54mm for E ~ 1eV
- Typical ECR inner diameter ~ 6.6cm



Magnetic configuration for NANOGAN and PK-GANESA

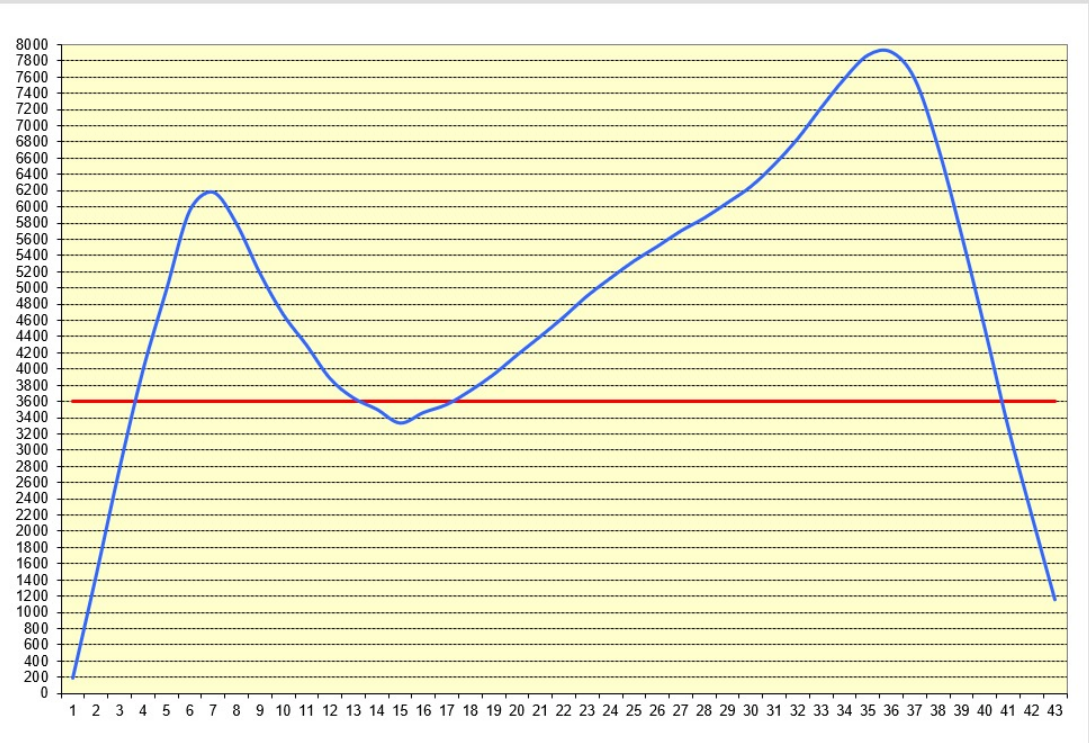


Fig 3: axial component of B along z for NANOGANIII

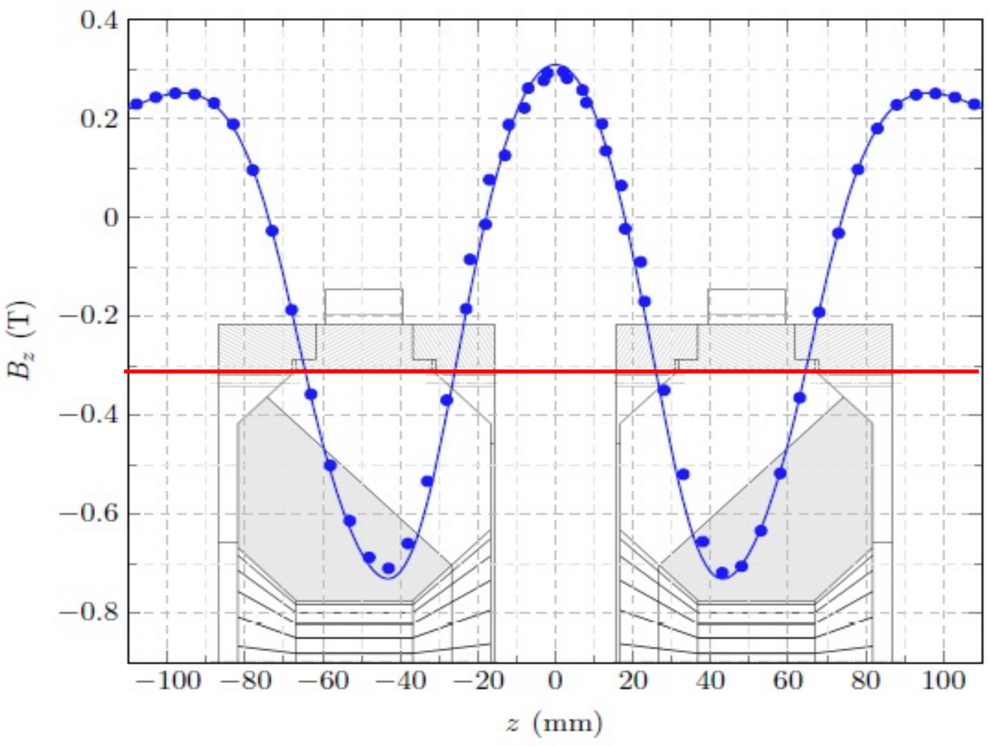
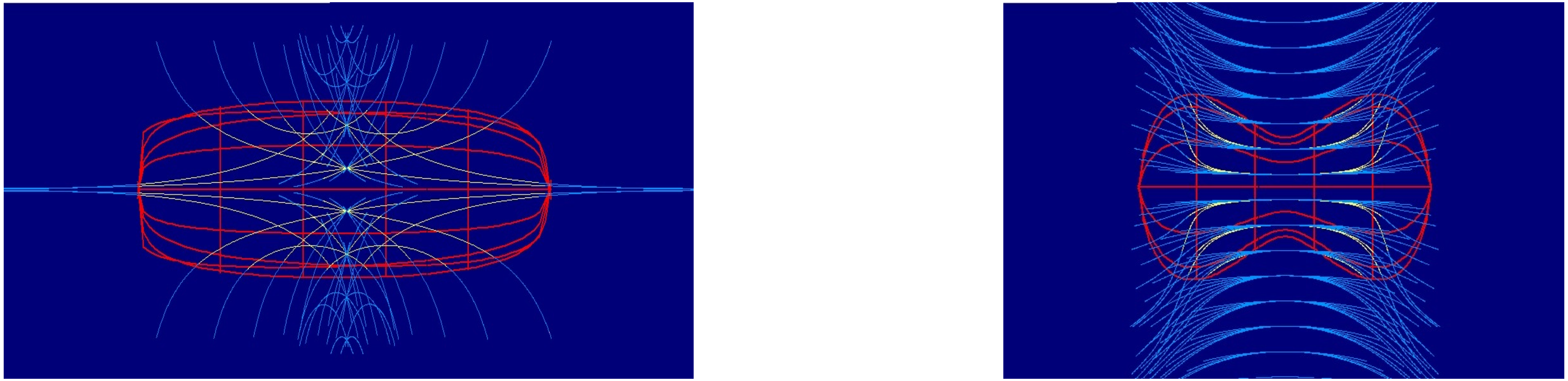


Fig 4: axial component of B along z for PK-GANESA

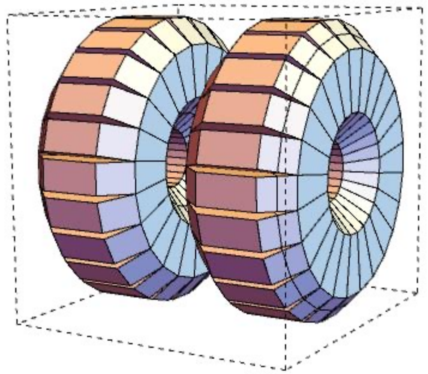
Resonant Surface for NANOGAN and PK-GANESA

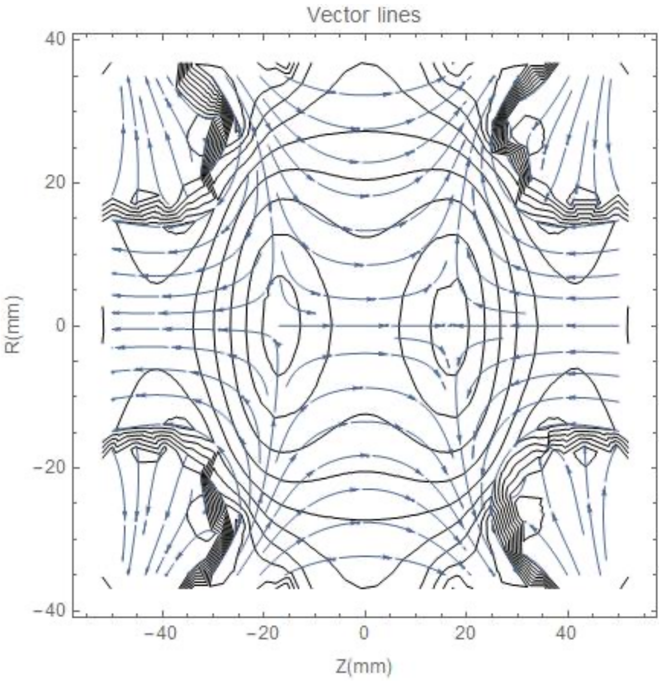


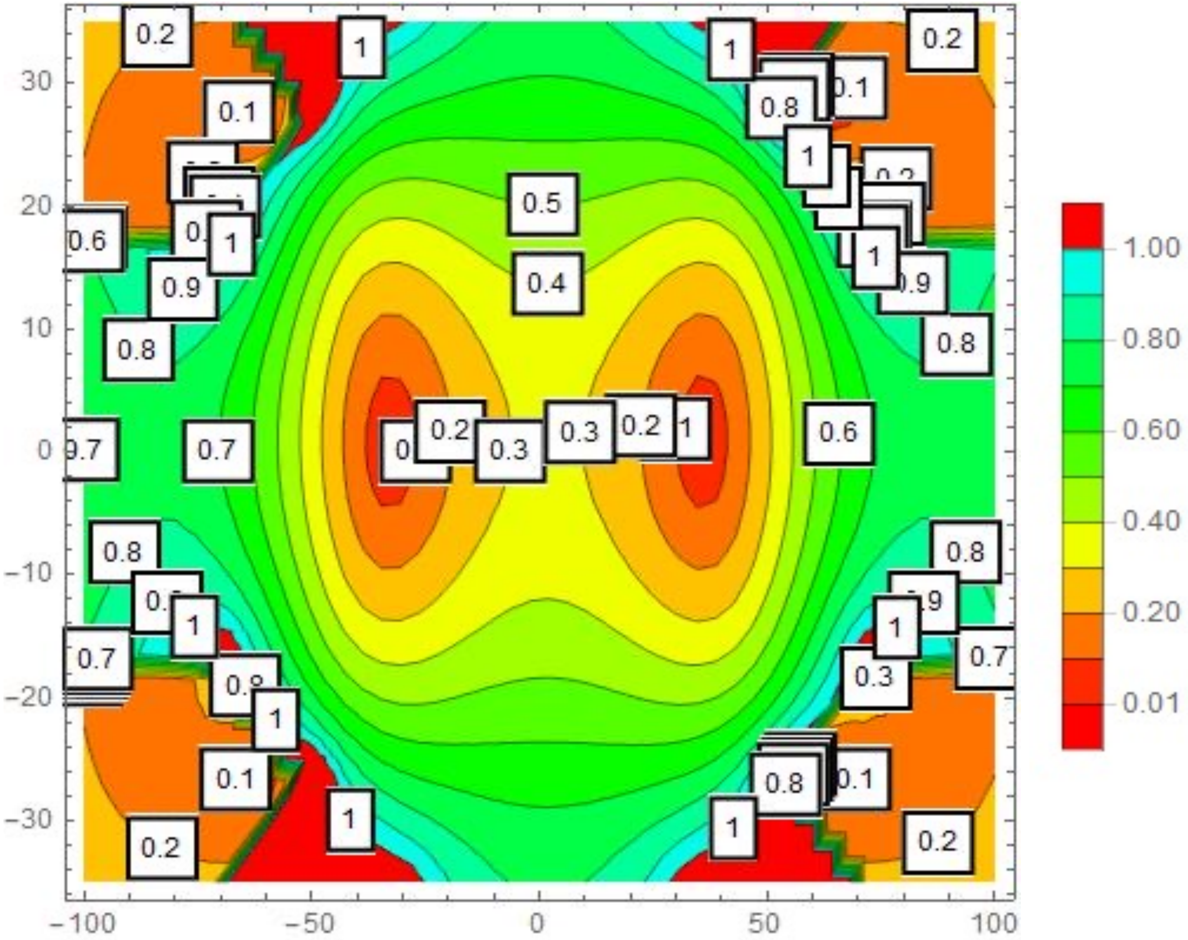
(a) *(b)*

Fig 5: Resonant surface and flux tube for (a)NANOGAN (b)PK-GANESA

Magnetic field configuration for PK-GANESA







TrapCAD

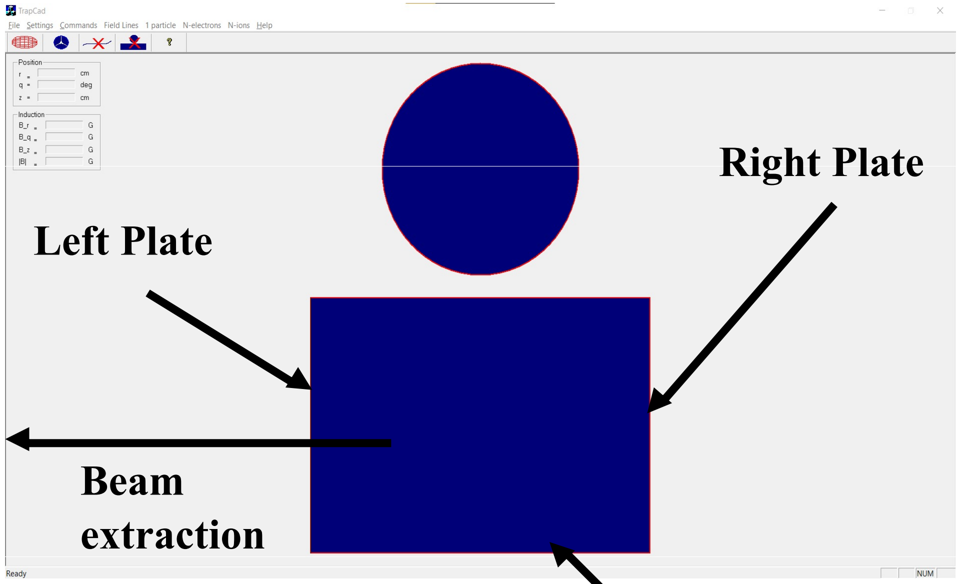


Fig 6: TrapCAD interface

Chamber walls

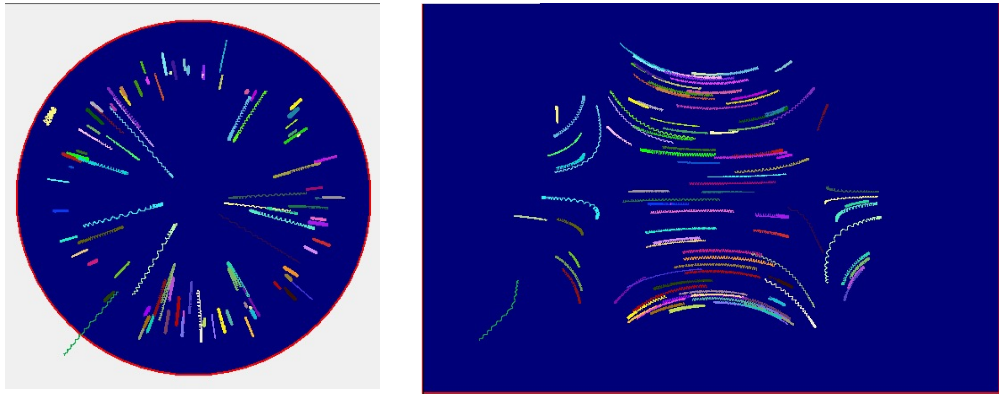
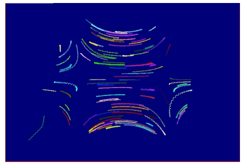


Fig 7: Visualization of particle trajectory

Inputs:
2 files {axial and radial Magnetic fields}

→ TrapCAD →

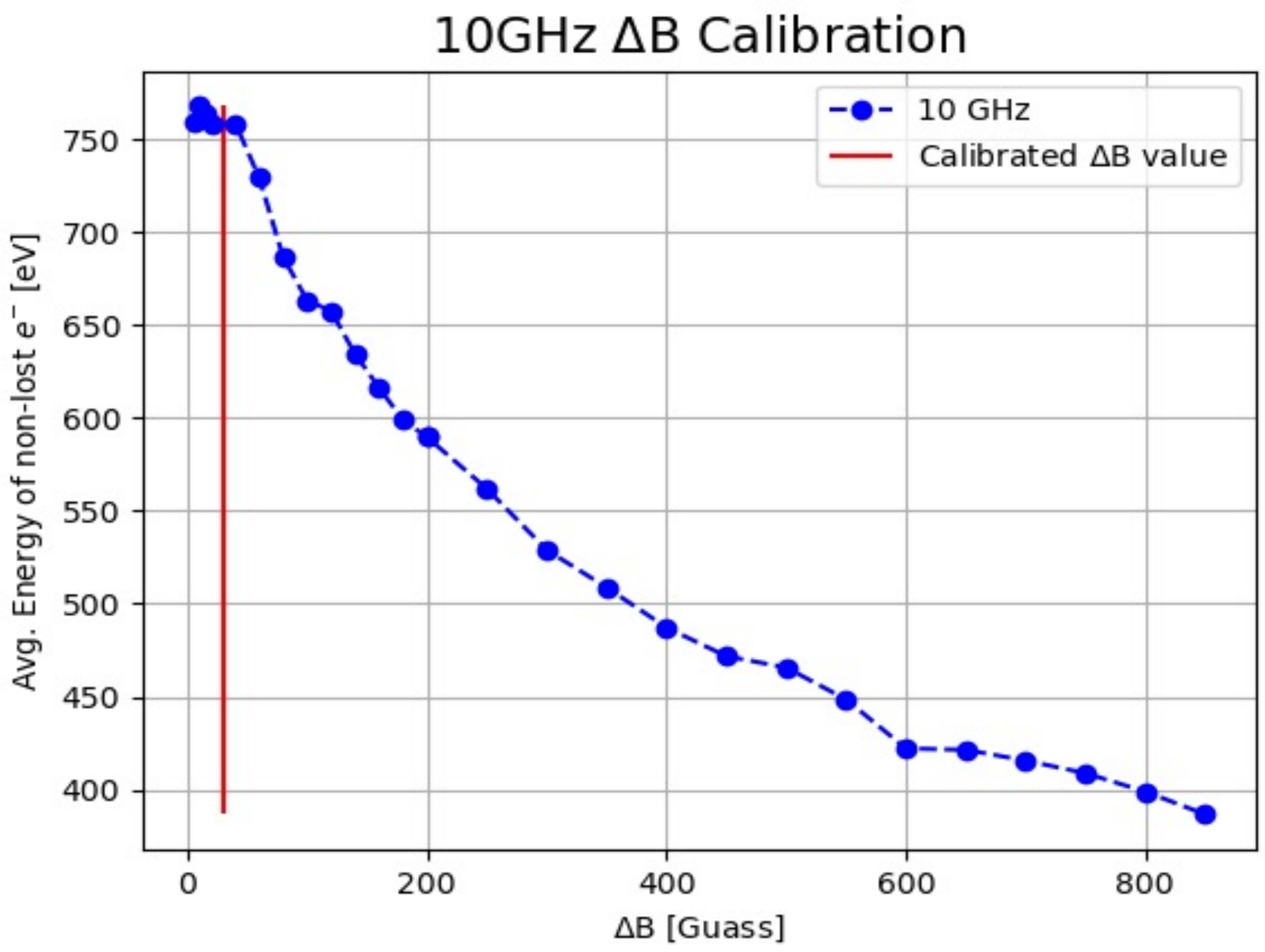
- Nonlost file
- LostLeftPlate
- LostRightPlate
- LostChamberWalls
- TimeParticleNr



- Developed at ATOMKI, Debrecen, Hungary
- Drawing of field line, flux tubes, resonance zones
- Calculation of several mirror ratios
- Simulates and visualizes particle trajectories
- ECR heating
- Multipole edge effects

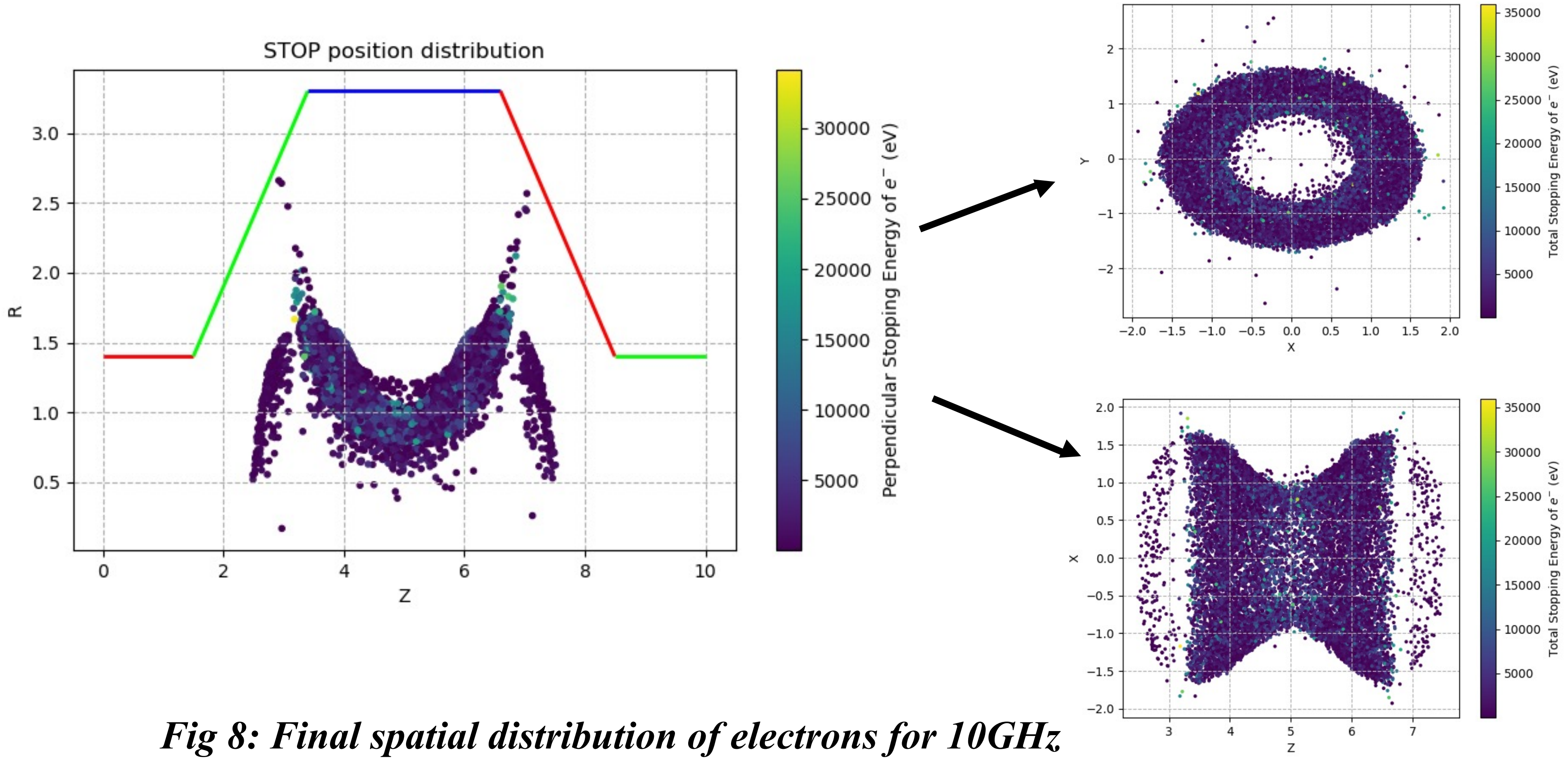
TrapCAD simulations

- **Goal:** ... **onizing to high ch...**
- Aim: Pe... ...lectric field accelera... Argon with electron...
- Investig...
- 3 Stages



- ΔB calib... ...iform initial electron
- ΔB = 30...
- ΔB = 80...

Simulation Results for PK-GANESA



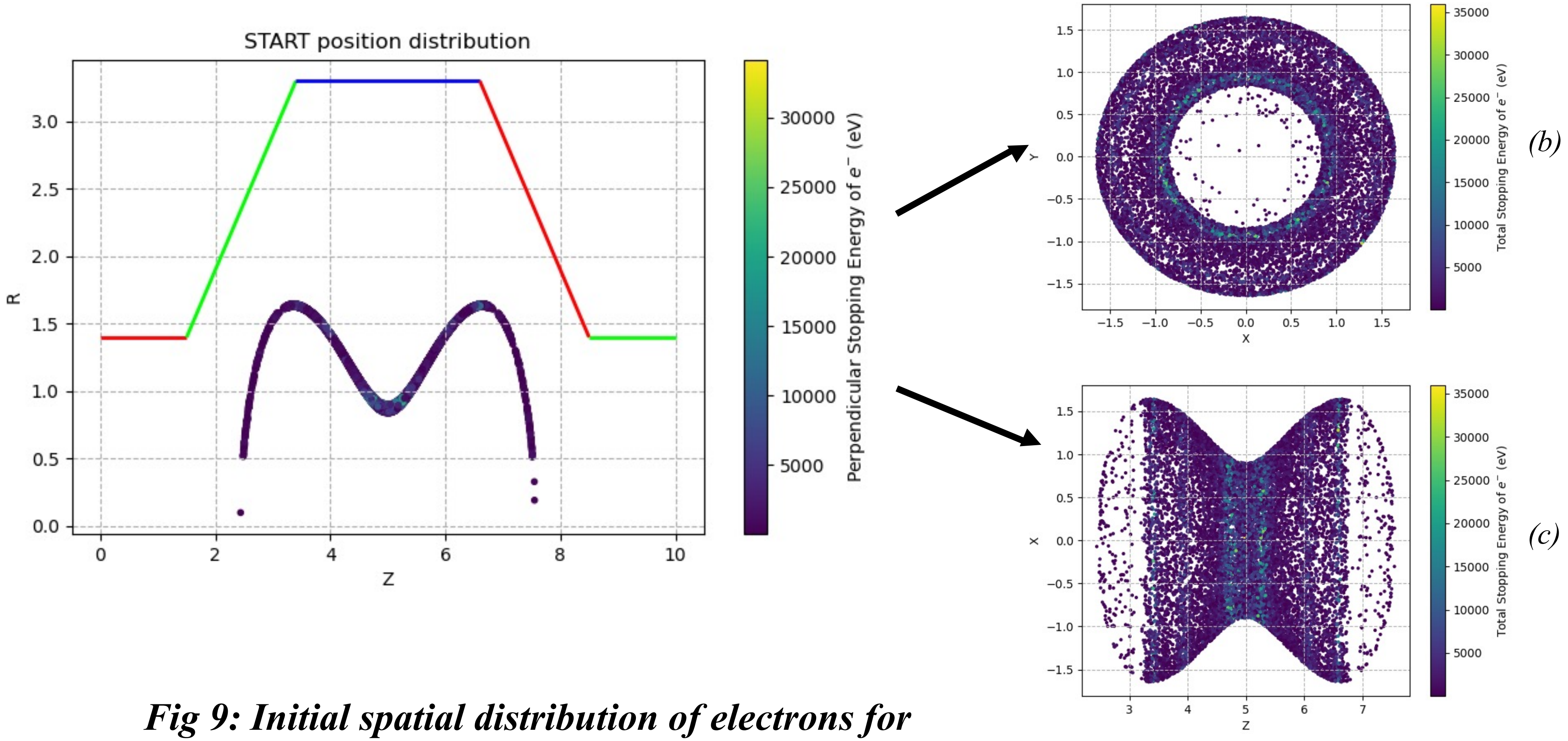
(b)

(c)

n_{e-} = 48000
f = 10GHz
P_{rf} = 800W
t = 20µs
B_{ECR} = 3571G

Fig 8: Final spatial distribution of electrons for 10GHz 800W RF heating (a) radial (b) axial projection

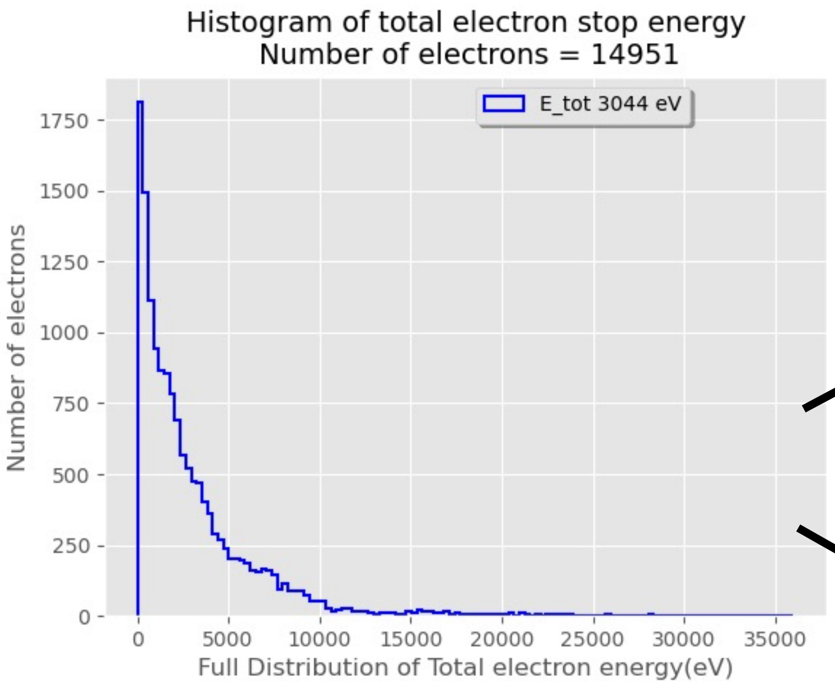
Simulation Results for PK-GANESA



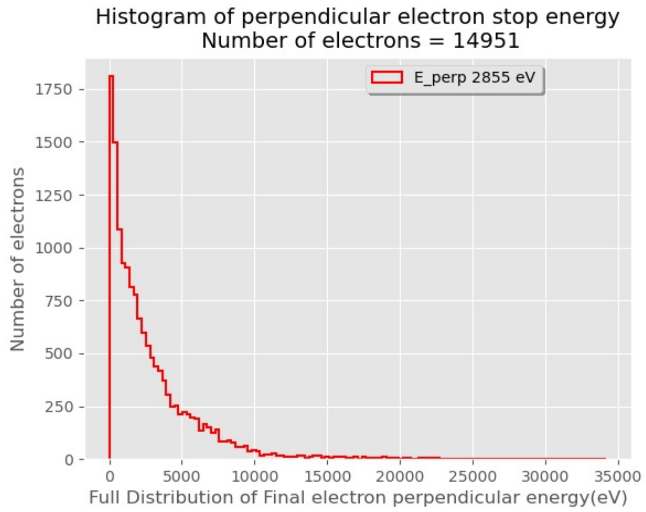
n_{e-} = 48000
f = 10GHz
P_{rf} = 800W
t = 20µs
B_{ECR} = 3571G

Fig 9: Initial spatial distribution of electrons for 10GHz 800W RF heating (a) radial (b) axial projection

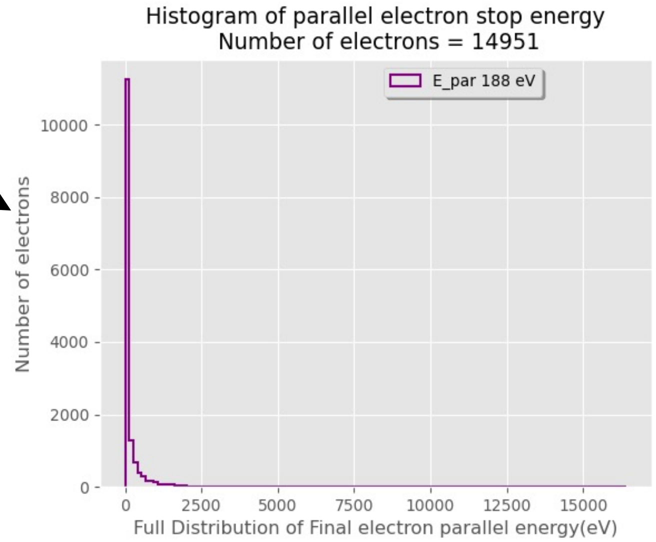
Simulation Results for PK-GANESA



(a)



(b)

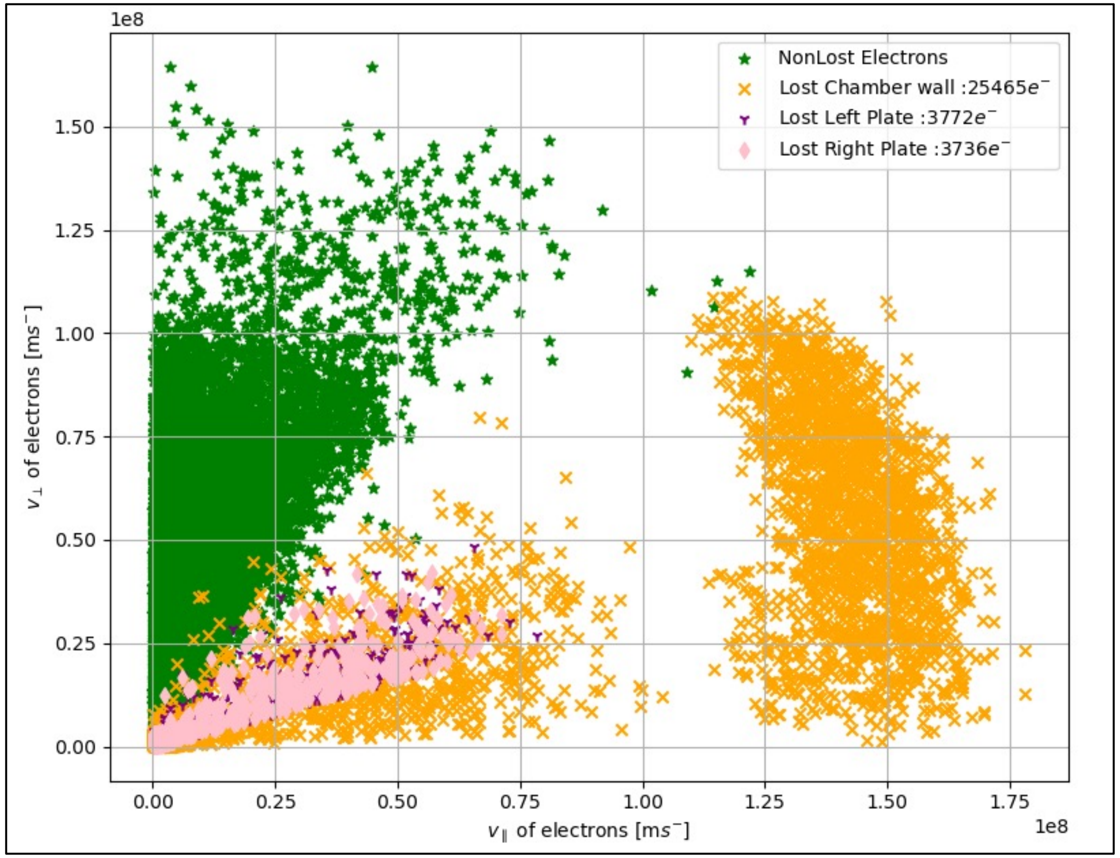


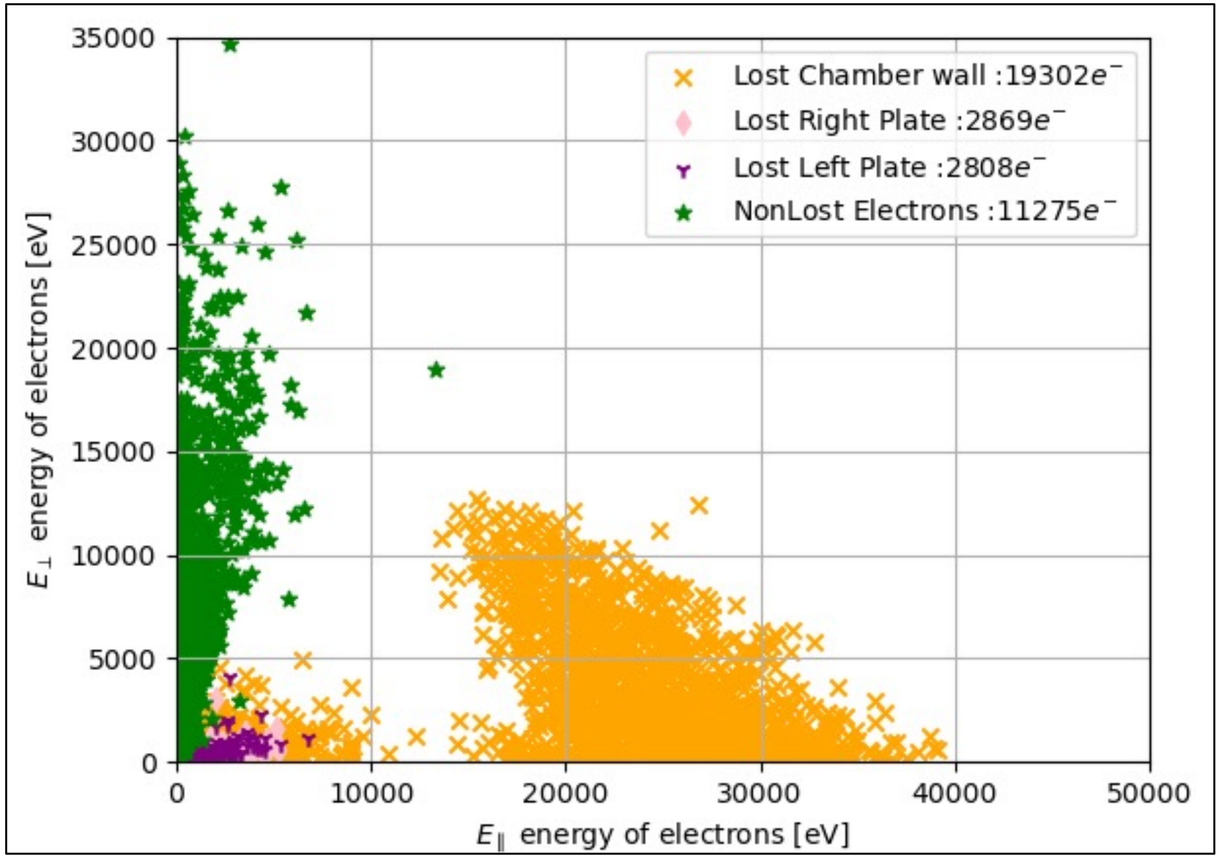
(c)

n_{e-} = 48000
f = 10GHz
P_{rf} = 800W
t = 20μs
B_{ECR} = 3571G

Fig 10: EEDF for 10GHz 800W RF heating (a)total (b)perpendicular (c)parallel

Loss cone visualization PK-GANESA

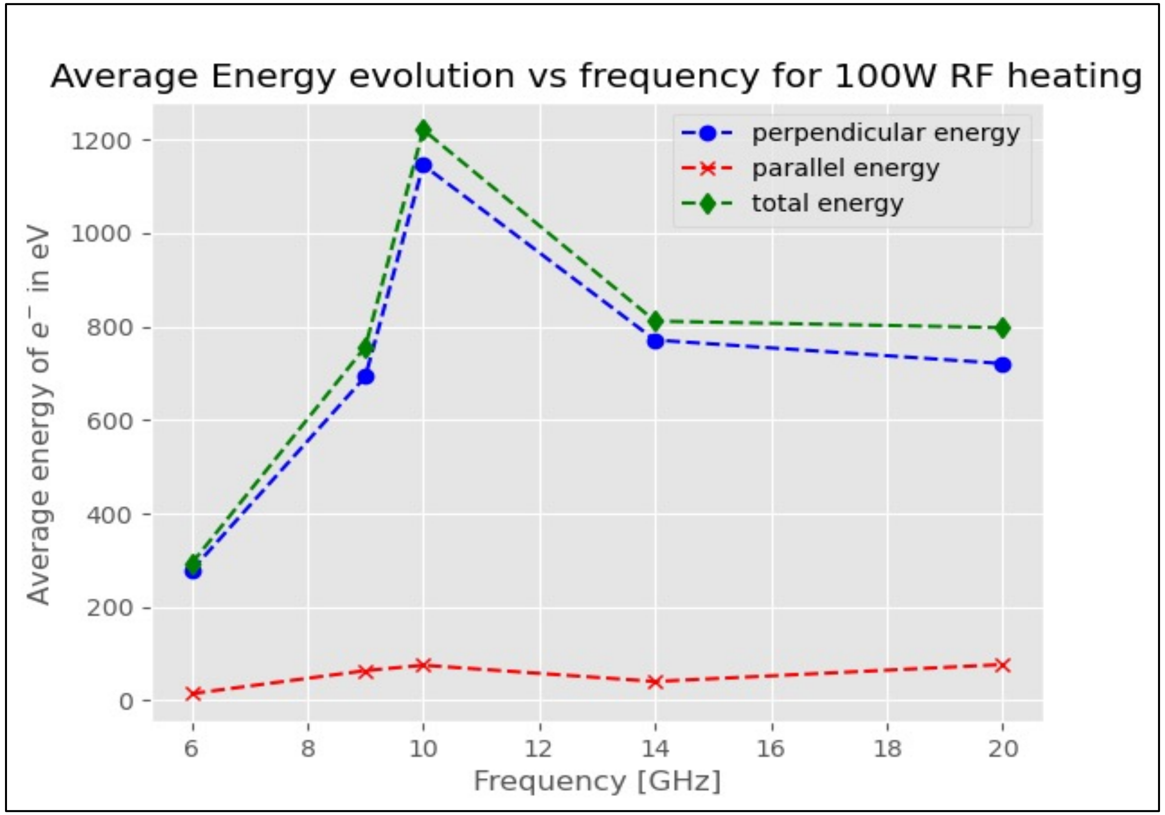




- Electrons with higher perpendicular energy are trapped
- Electrons with higher parallel energy are lost

Fig 11: Loss cone visualization in velocity and energy space

Simulation Results for PK-GANESA

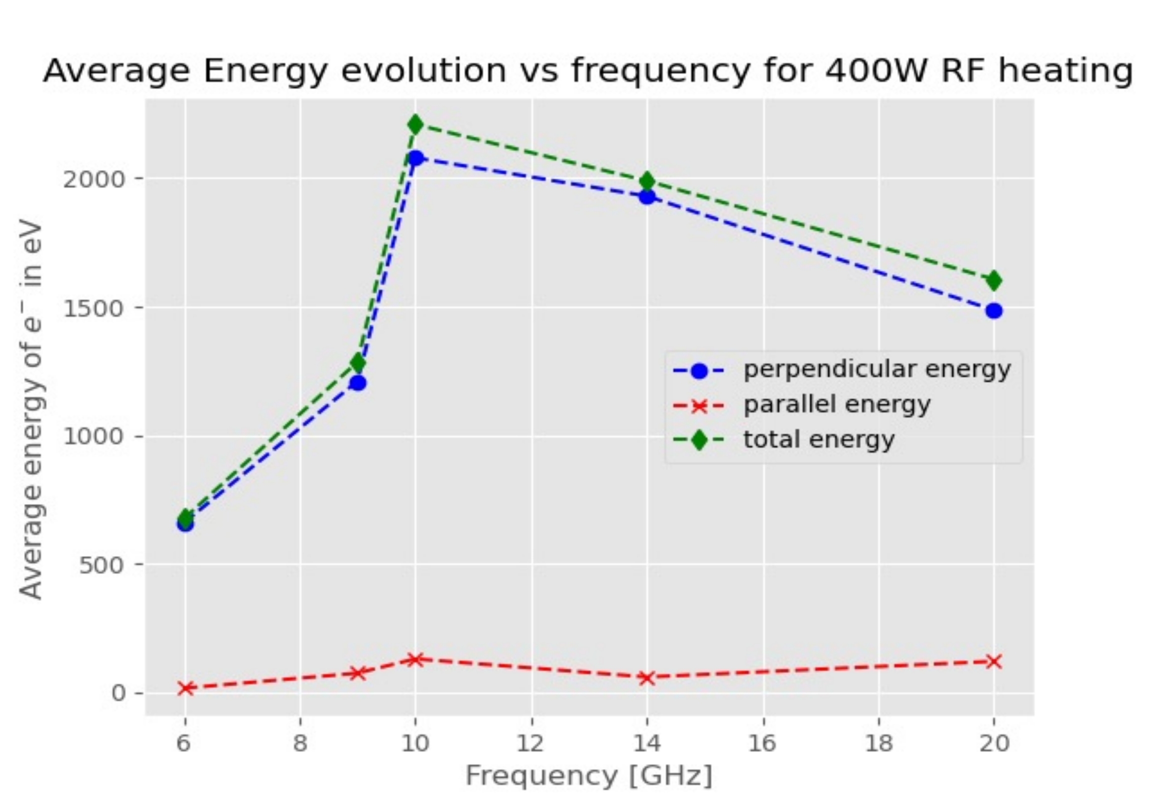


(a)

- At lower heating powers, 10GHz is the obvious choice in terms of average energy gained

Fig 12: Average energy evolution vs frequency for (a) 100W (b)400W (c)800W 10GHz RF heating

Simulation Results for PK-GANESA

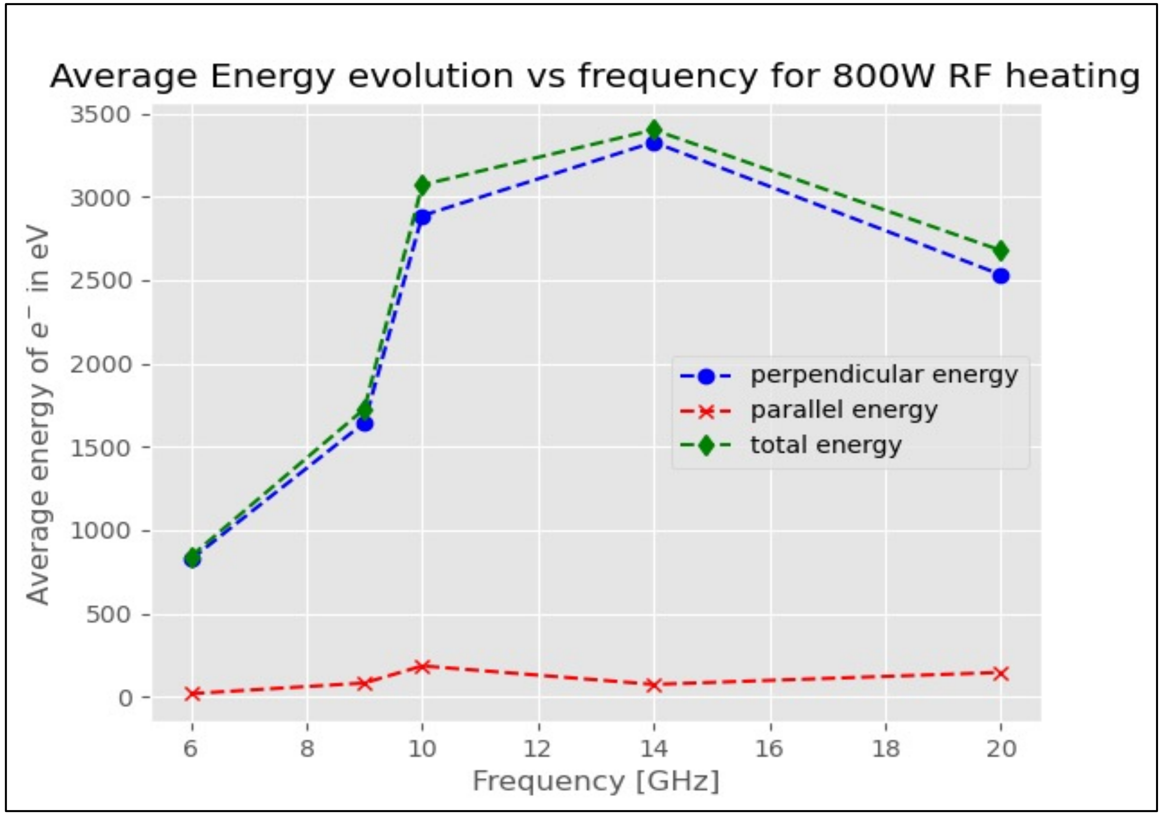


(b)

Fig 12: Average energy evolution vs frequency for (a) 100W (b)400W (c)800W 10GHz RF heating

- At lower heating powers, 10GHz is the obvious choice in terms of average energy gained
- With increasing power 14GHz starts improving

Simulation Results for PK-GANESA



(c)

- At lower heating powers, 10GHz is the obvious choice in terms of average energy gained
- With increasing power 14GHz starts improving
- But at the highest RF heating power that has been simulated yet, it is indeed a better choice.
- But electron energy is one of the parameters of source performance

Fig 12: Average energy evolution vs frequency for (a) 100W (b)400W (c)800W 10GHz RF heating

Simulation Results for PK-GANESA

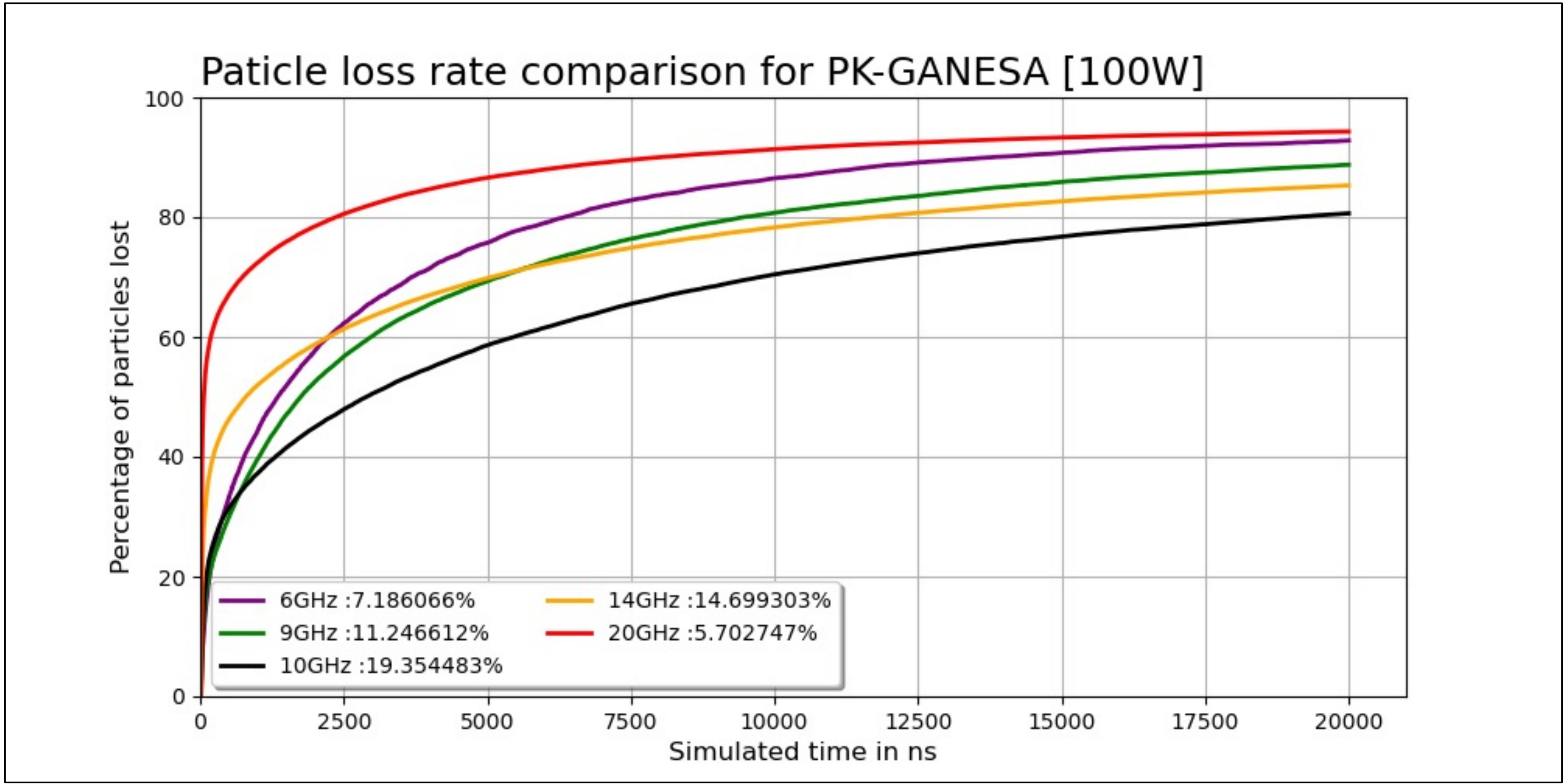


Fig 13: Particle loss rate comparison for 100W RF heating for PK-GANESA

Simulation Results for PK-GANESA

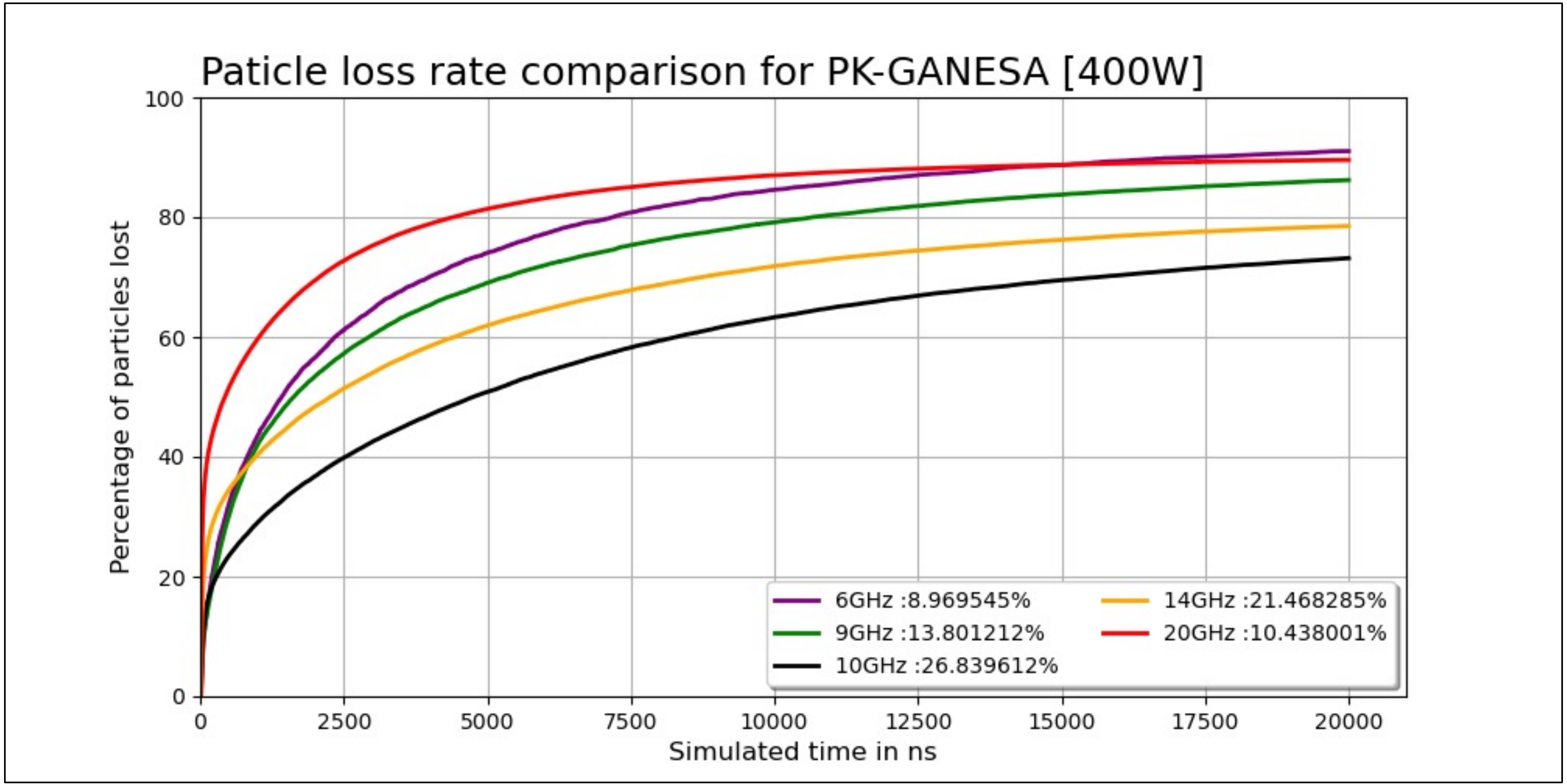


Fig 14: Particle loss rate comparison for 400W RF heating for PK-GANESA

Simulation Results for PK-GANESA

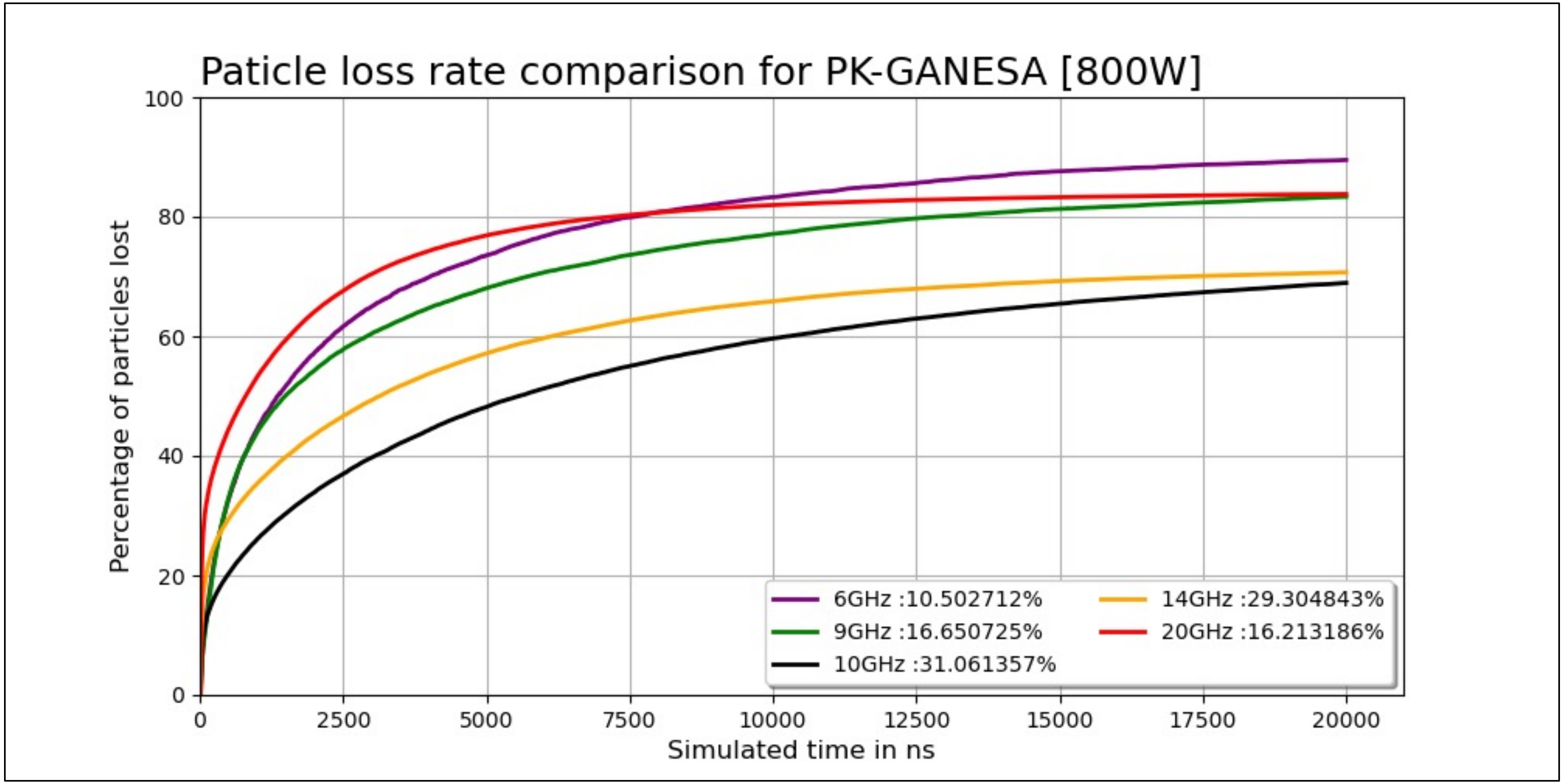
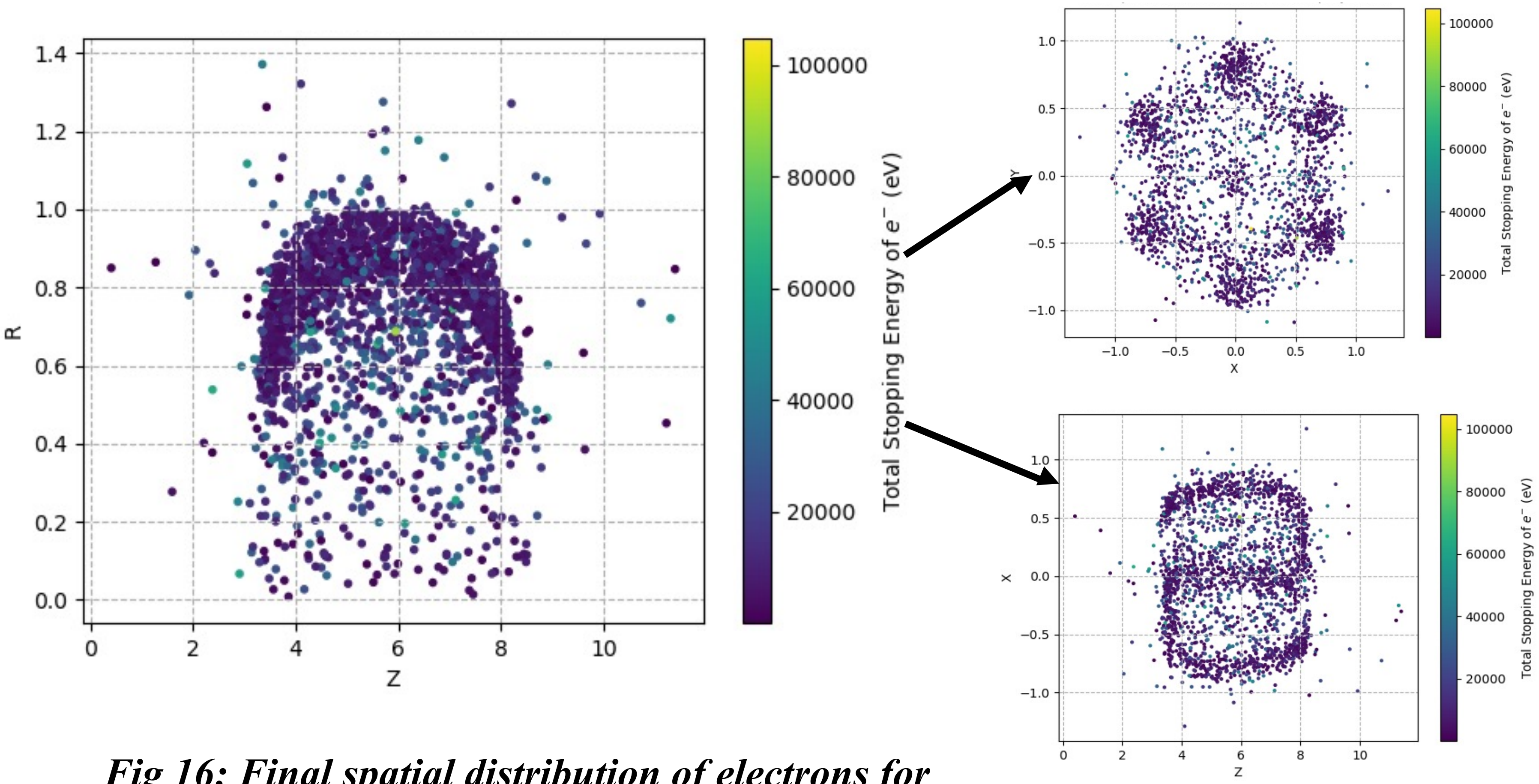


Fig 15: Particle loss rate comparison for 800W RF heating for PK-GANESA

Simulation Results for NANOGANIII



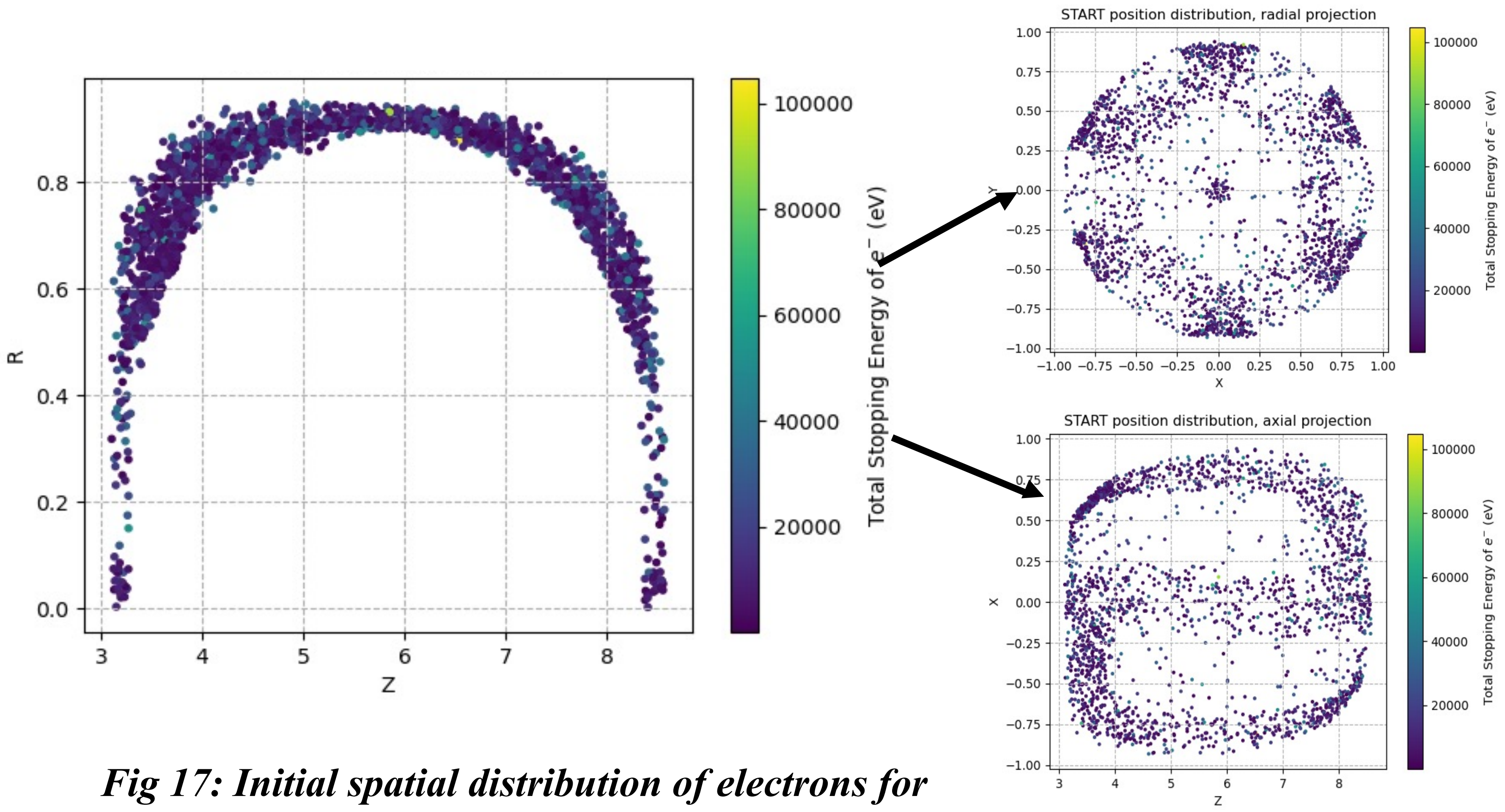
(a)

(b)

n_{e-} = 60000
f = 10GHz
P_{rf} = 800W
t = 20μs
B_{ECR} = 3571G

Fig 16: Final spatial distribution of electrons for 10GHz 800W RF heating (a) radial (b) axial projection

Simulation Results for NANOGANIII



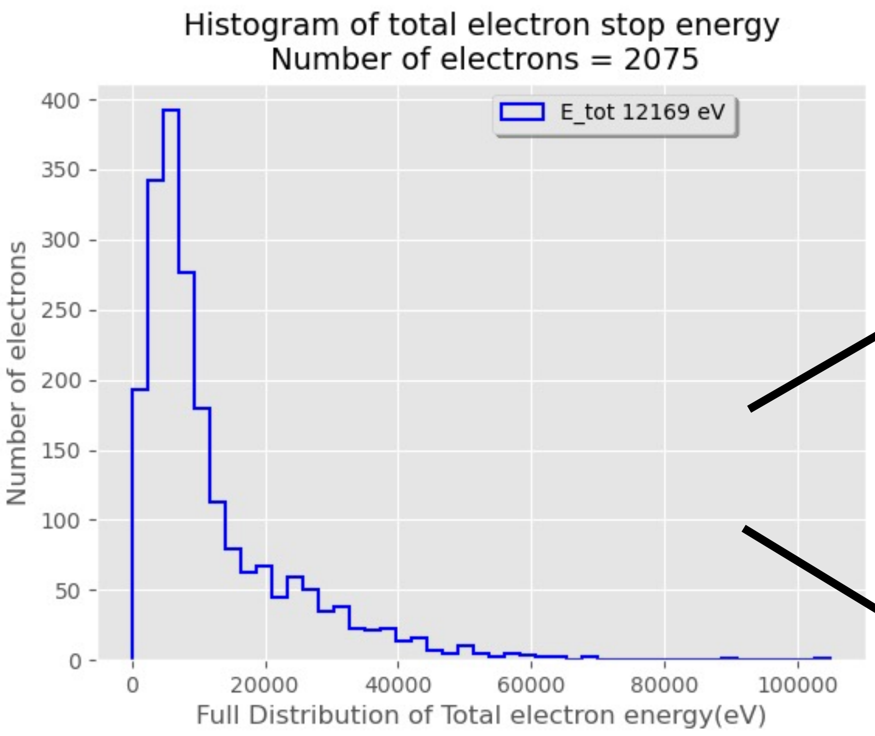
(a)

(b)

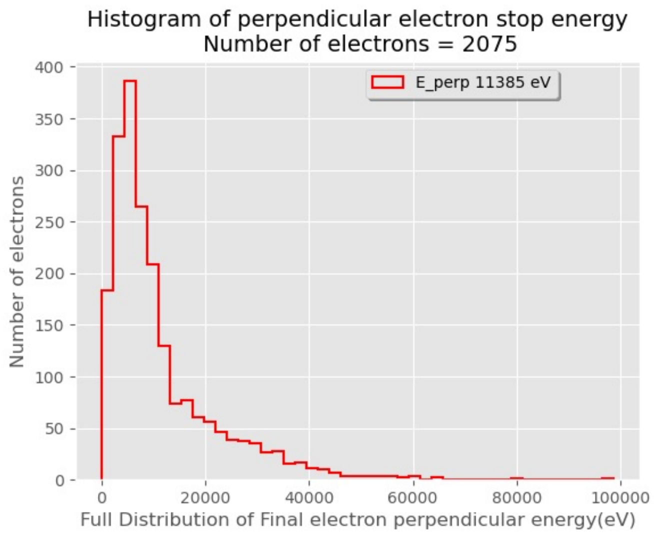
n_{e-} = 48000
f = 10GHz
P_{rf} = 800W
t = 20μs
B_{ECR} = 3571G

Fig 17: Initial spatial distribution of electrons for 10GHz 800W RF heating (a) radial (b) axial projection

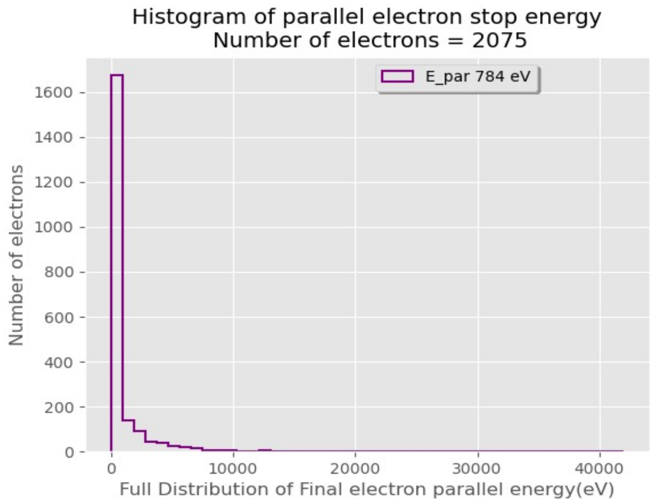
Simulation Results for NANOGANIII



(a)



(b)

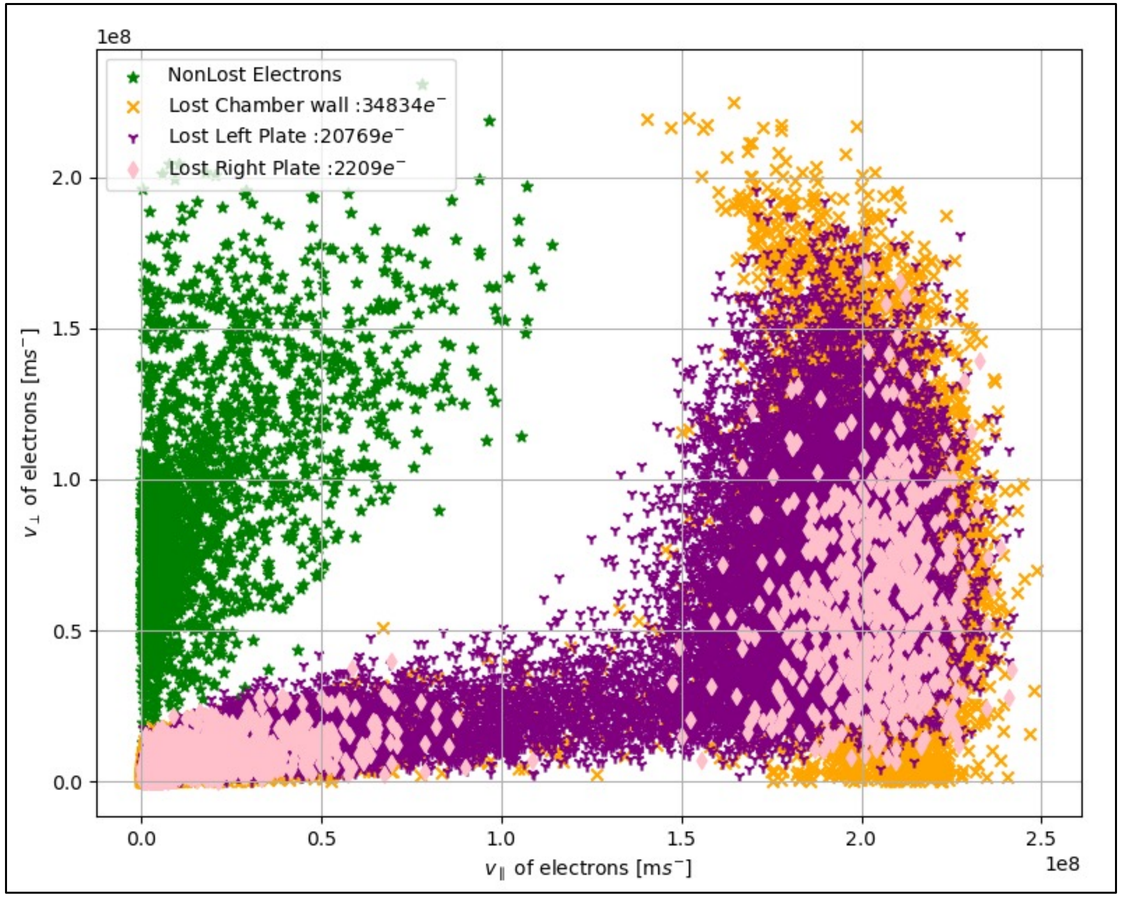


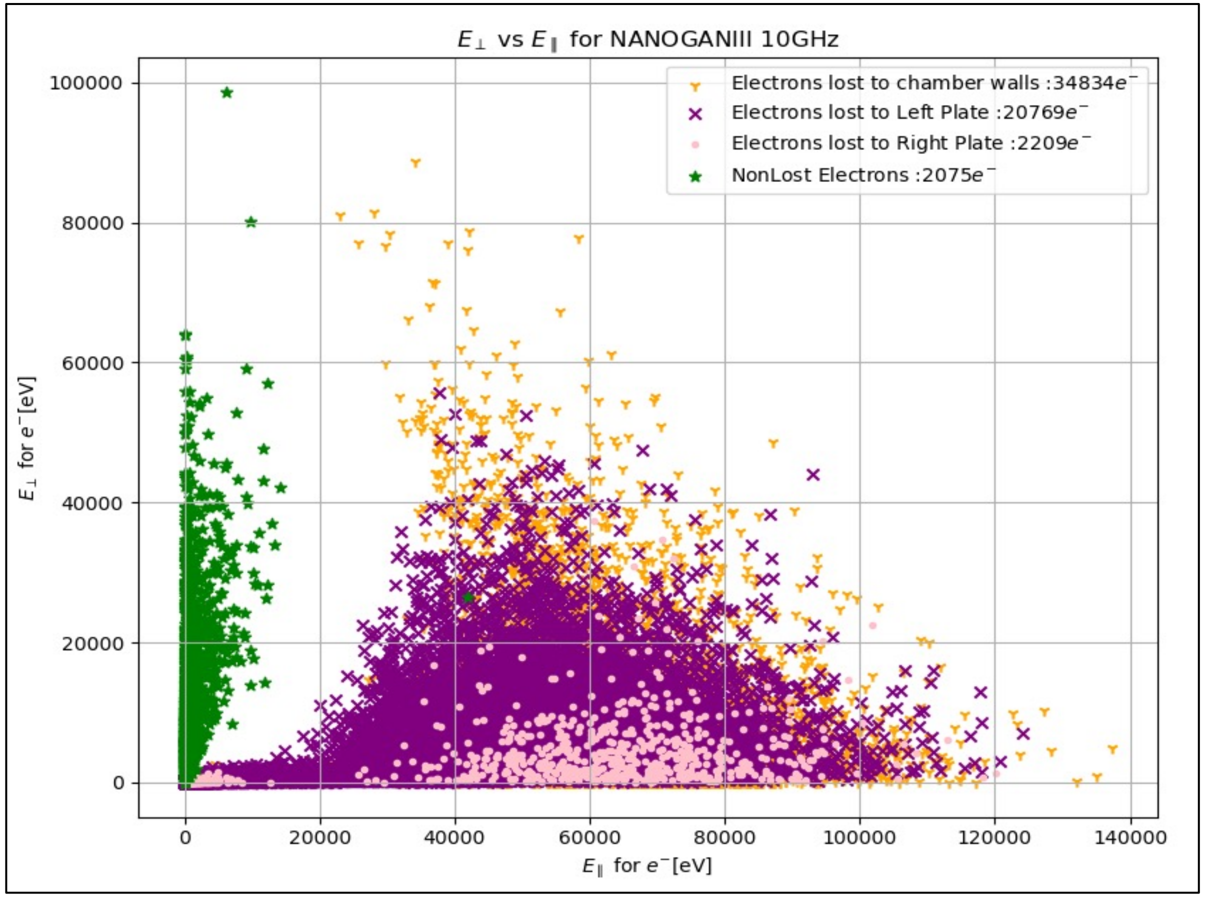
(c)

$n_{e-} = 48000$
$f = 10GHz$
$P_{rf} = 800W$
$t = 20\mu s$
$B_{ECR} = 3571G$

Fig 18: EEDF for 10GHz 800W RF heating (a)total (b)perpendicular (c)parallel

Loss cone visualization NANOGANIII





- Losses on the left side of the source higher than right side, consistent with the axial magnetic configuration

Fig 19: Loss cone visualization for NANOGANIII

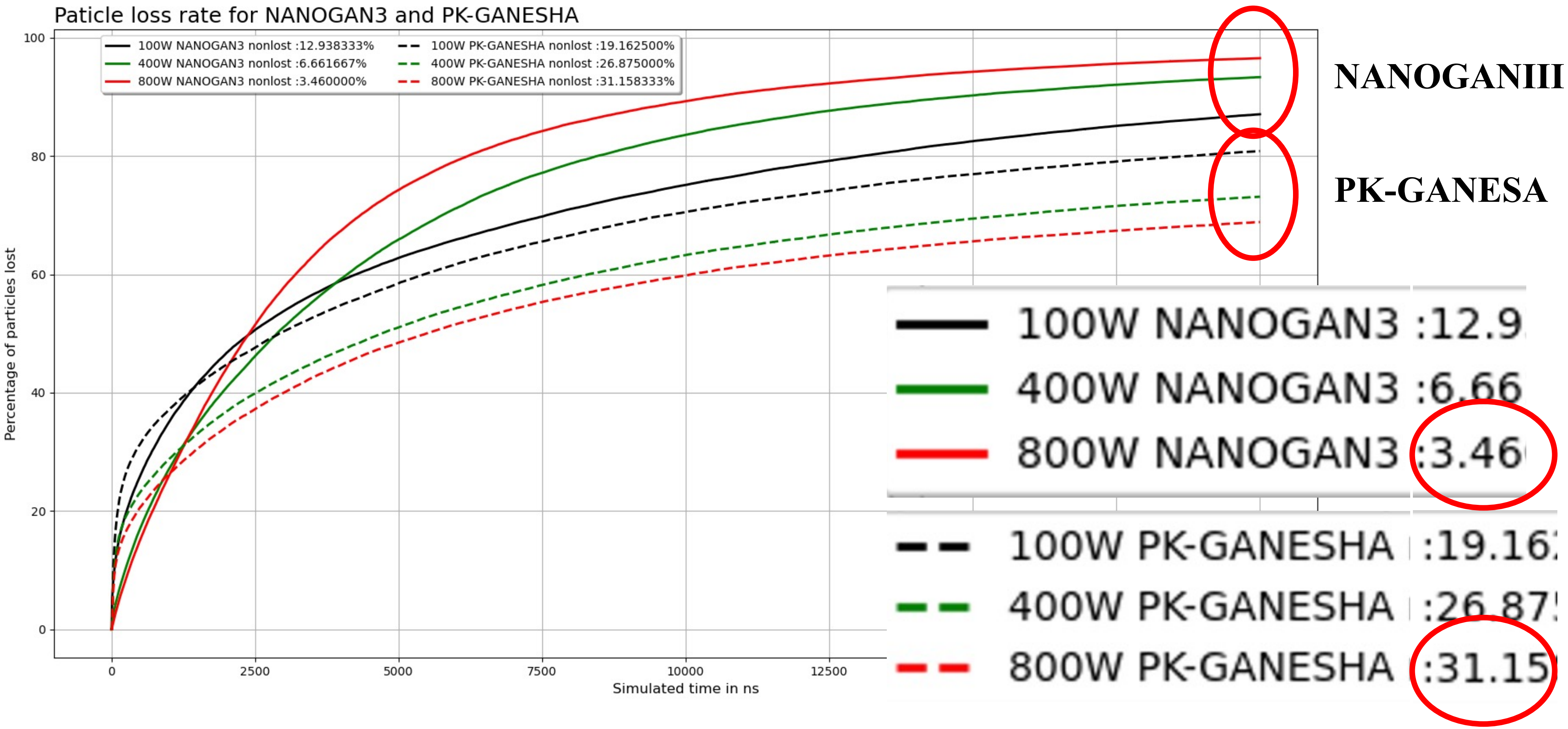
Performance comparison for NANOGAN and PK-GANESA

The performance for the two sources is compared based on:

a. Electron Trapping quality
b. Energy gained by electrons
c. Charge state distribution of ions produced

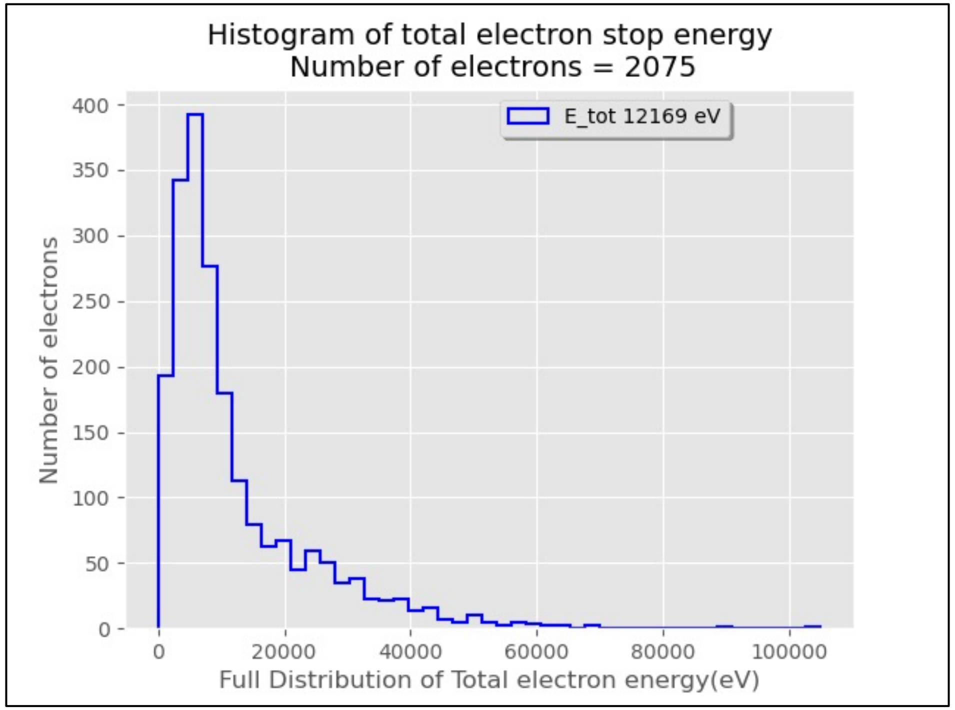
Performance comparison for NANOGAN and PK-GANESA

Electron Trapping quality

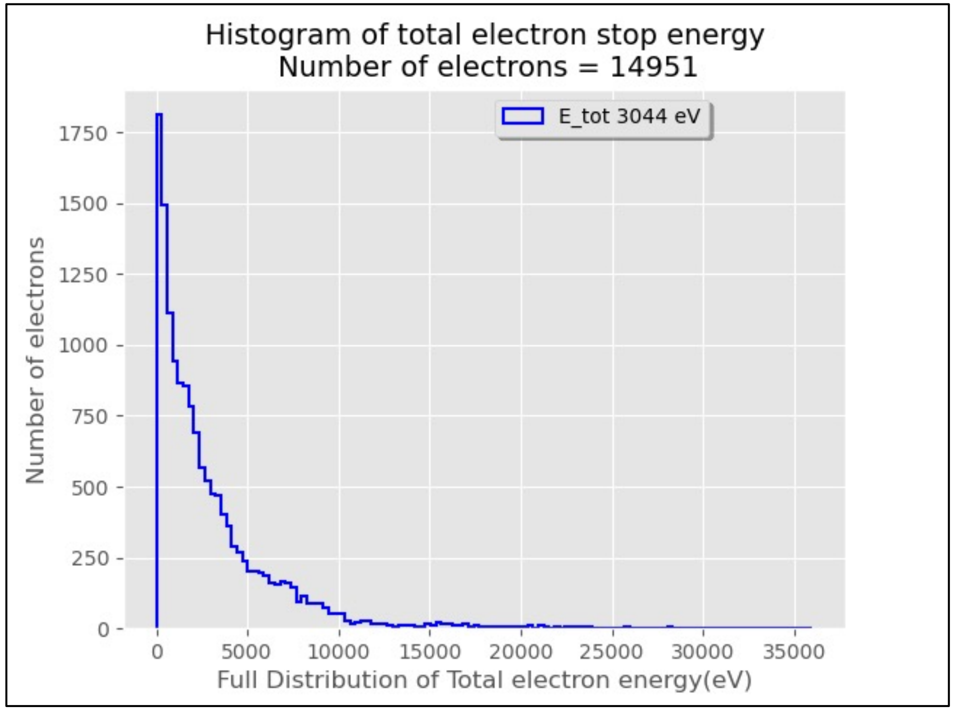


Performance comparison for NANOGAN and PK-GANESA

Energy gained by electrons



(a)

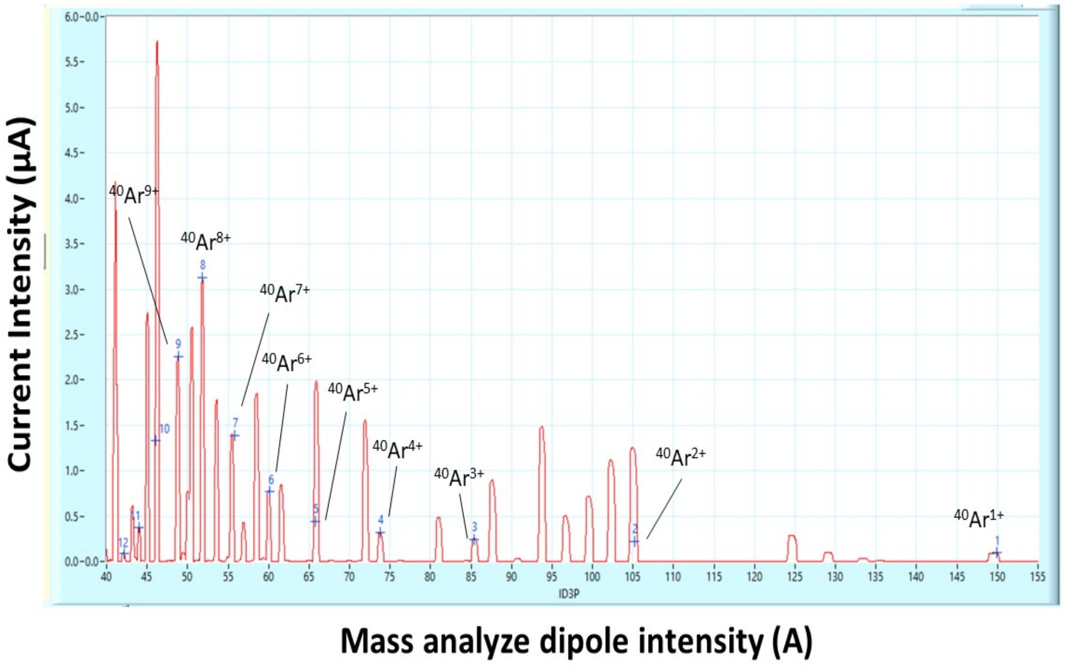


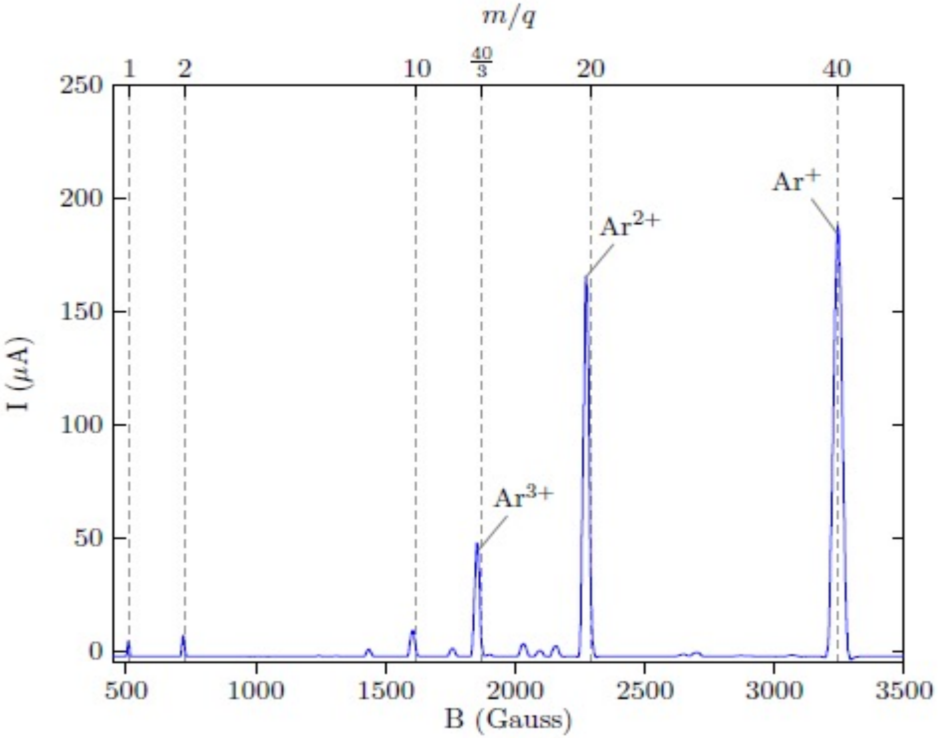
(b)

Fig 20: EEDF for (a)NANOGANIII (b) PK-GANESA

Performance comparison for NANOGAN and PK-GANESA

Charge state distribution of ions produced





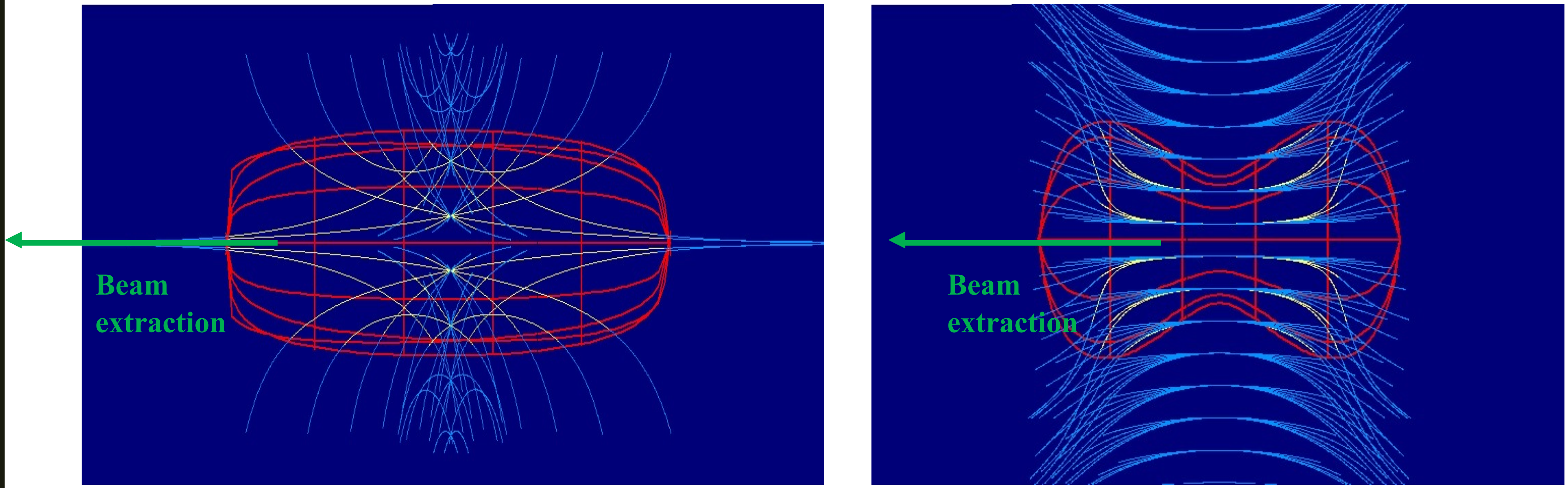
(a) *(b)*

Fig 21: Charge state distribution for (a)NANOGANIII (b) PK-GANESA

Conclusion

- Electron trapping is much better for PK-GANESA than NANOGANIII (~10x more)
- Energy gained by electrons for PK-GANESA is less than NANOGANIII (~3x less)
- Although hypothetically we should have multicharged ions, it seems we are not able to extract them.

Conclusion

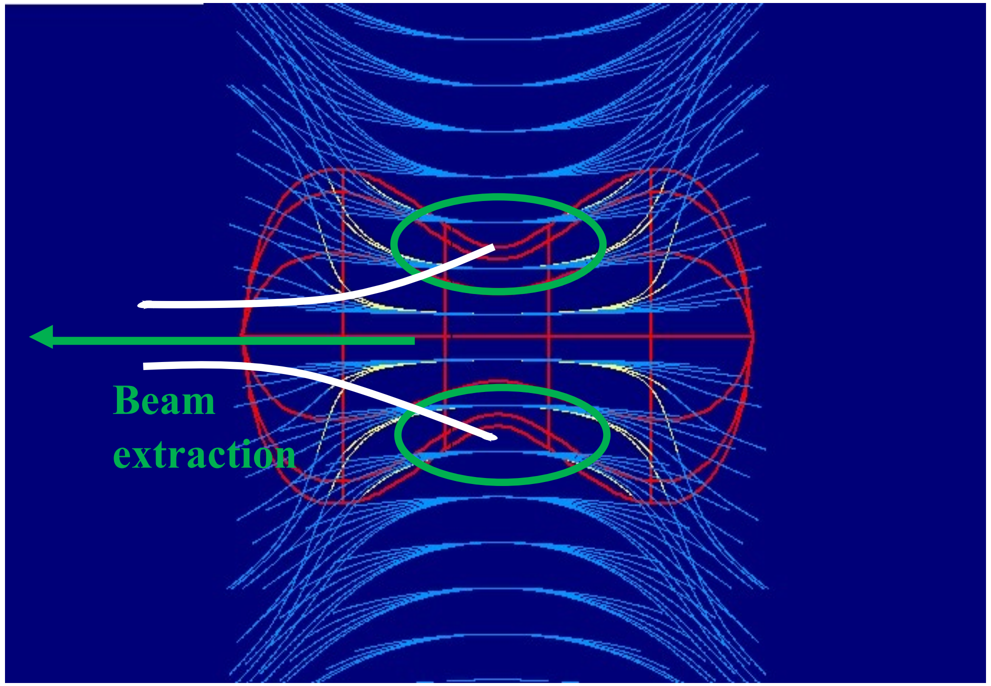


(a) (b)

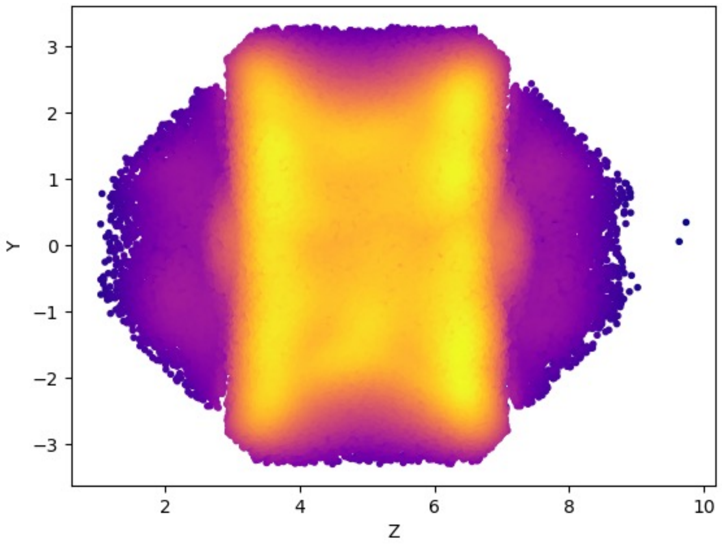
Fig 22: Flux tube for (a)NANOGANIII (b) PK-GANESA

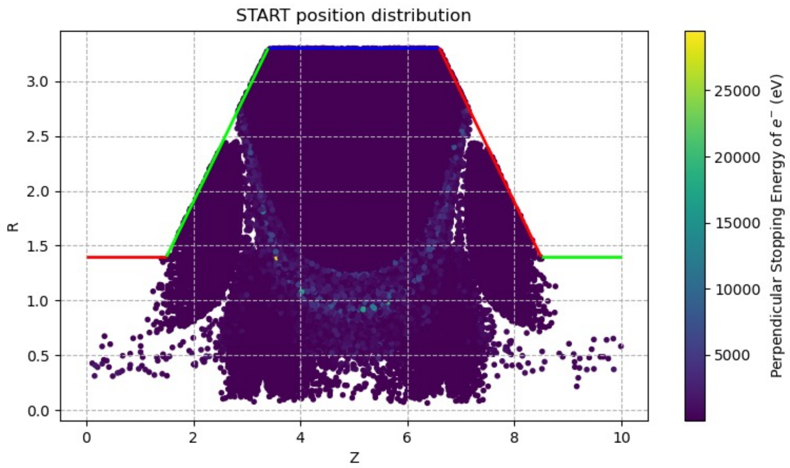
Discussions

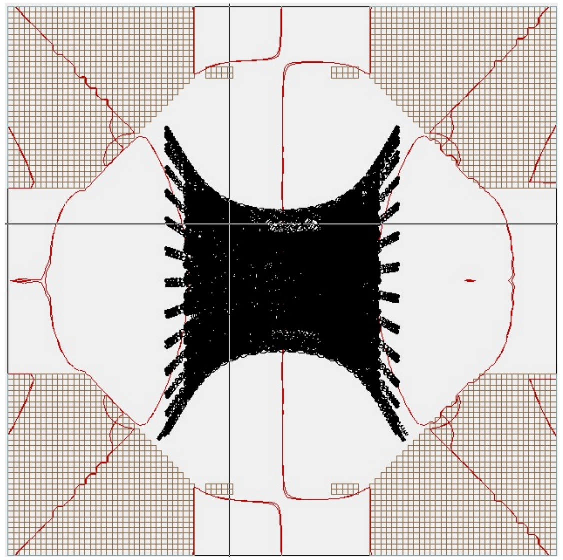
- Study of ion trajectory using SIMION to visualize ion trajectories
- How to create a channel for guiding ions towards extraction

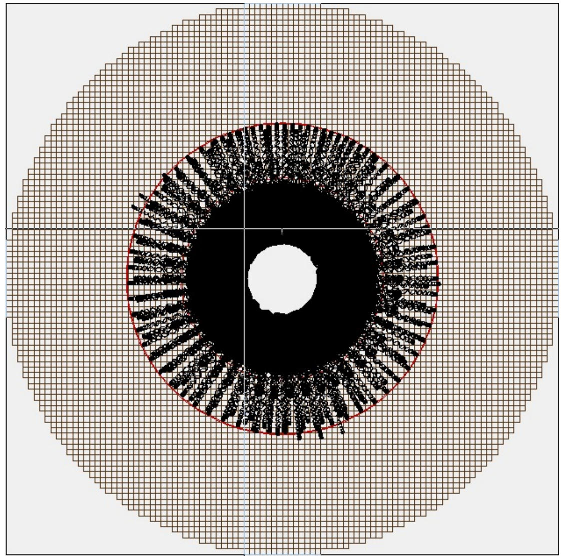


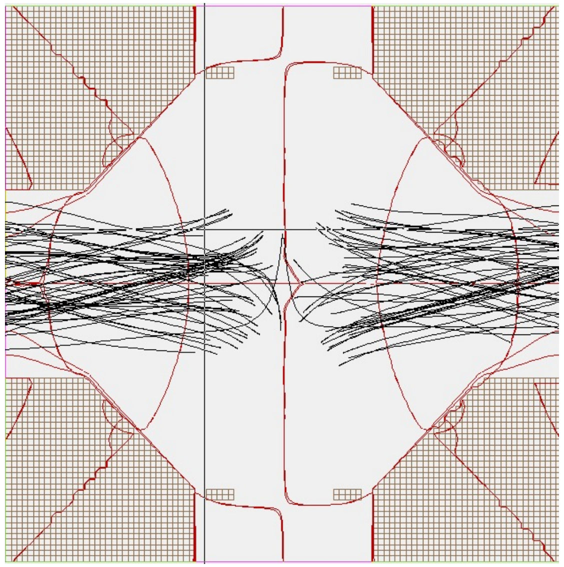
Current Progress…



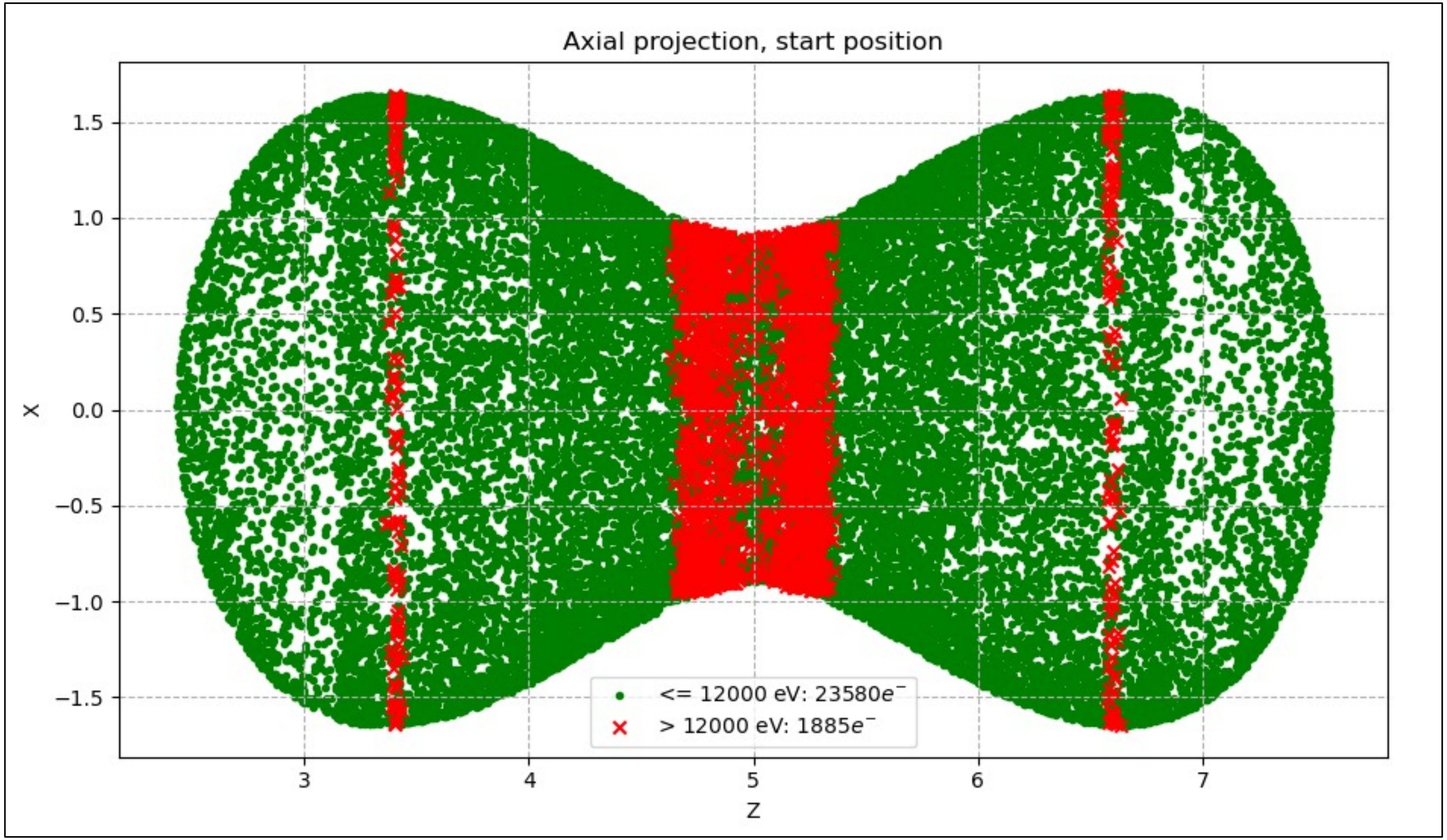




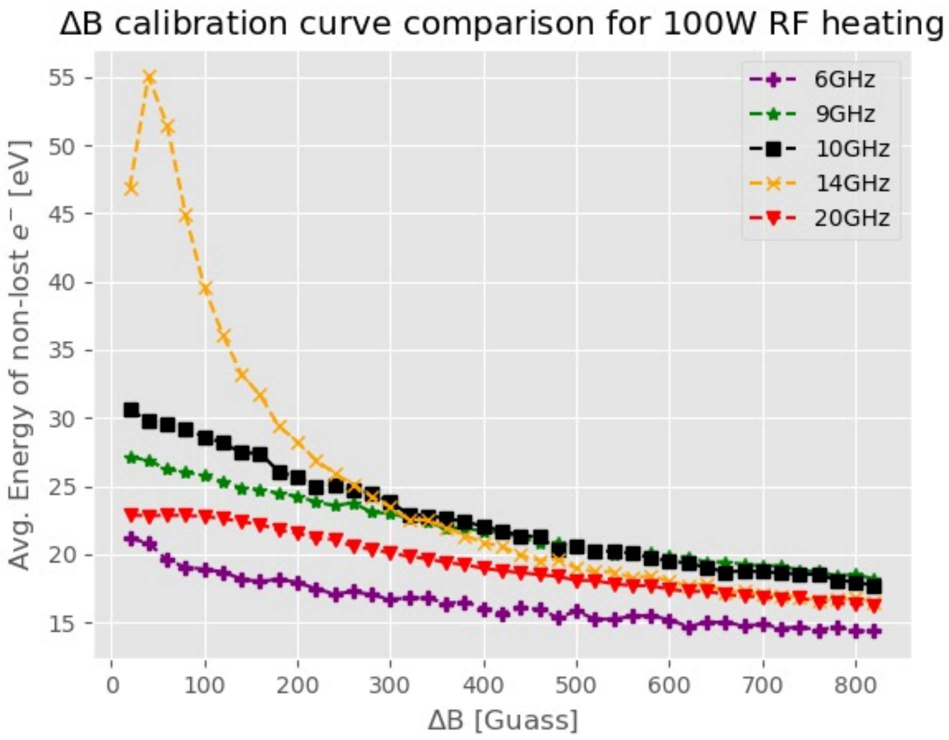


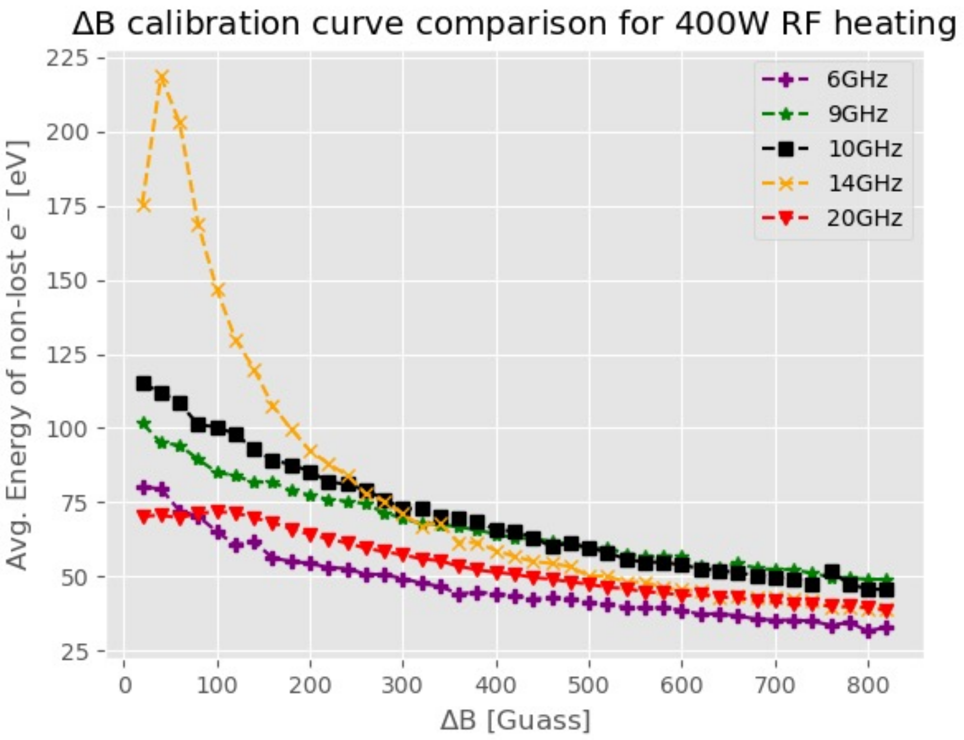


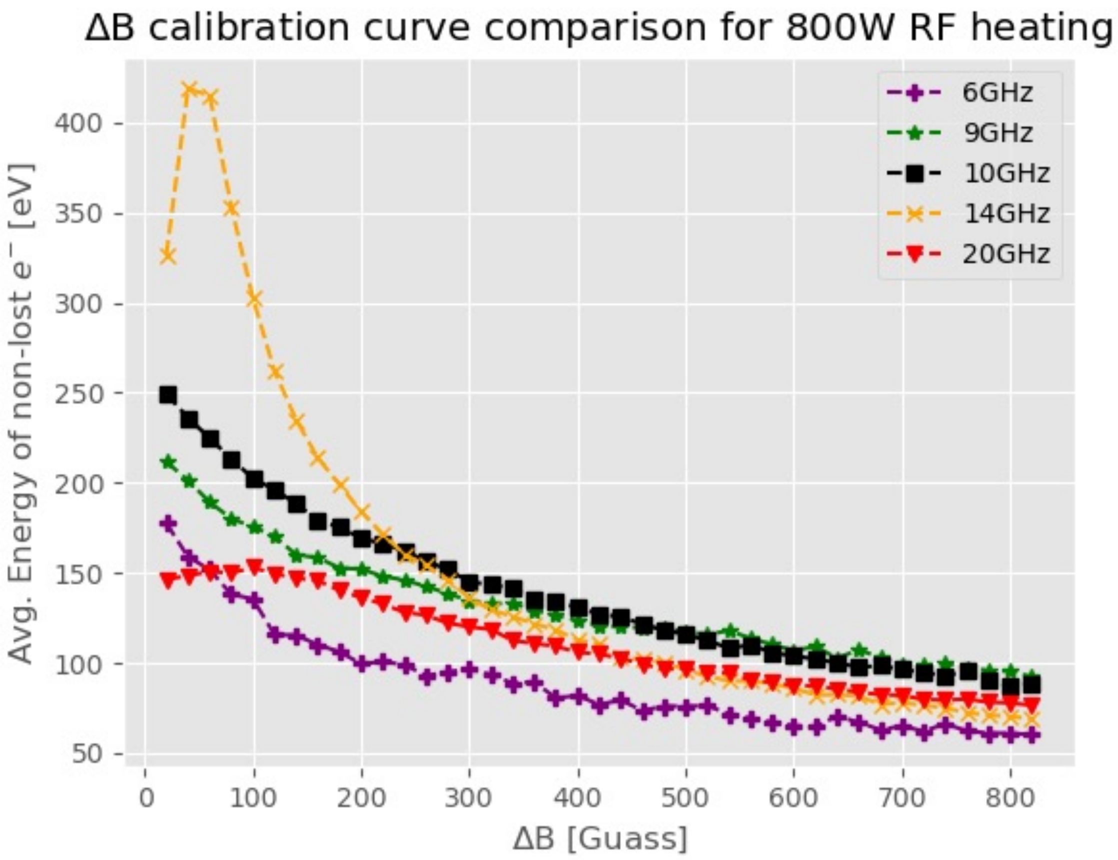
THANK YOU



Axial projection, start position
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
X
3
4
5
6
7
Z
<= 12000 eV: 23580e^-
> 12000 eV: 1885e^-


ΔB calibration curve comparison for 100W RF heating
Avg. Energy of non-lost e⁻ [eV]
55
50
45
40
35
30
25
20
15
0
100
200
300
400
500
600
700
800
ΔB [Guass]
6GHz
9GHz
10GHz
14GHz
20GHz


ΔB calibration curve comparison for 400W RF heating
Avg. Energy of non-lost e⁻ [eV]
225
200
175
150
125
100
75
50
25
0
100
200
300
400
500
600
700
800
ΔB [Guass]
6GHz
9GHz
10GHz
14GHz
20GHz


ΔB calibration curve comparison for 800W RF heating
6GHz
9GHz
10GHz
14GHz
20GHz
Avg. Energy of non-lost e⁻ [eV]
ΔB [Guass]
400
350
300
250
200
150
100
50
0
100
200
300
400
500
600
700
800