Simulation of NBI ion losses using GPUs

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Outline

- Introduction - Motivation
- FOCUS code
- The model
- Results
- Conclusion

Introduction: NTMs and Ion Losses

- The (2,1) neoclassical tearing mode (NTM) has been proposed as a candidate to explain the larger than expected losses of high energy ions produced during neutral beam injection in ASDEX-U [1].

- Although the numerical simulations performed so far to study the effect of NTMs on energetic ions have reproduced several features observed in experiments, the agreement is not completely satisfactory.

- In this work we study the effect of NTMs on the confinement of energetic ions produced by NBI injection using FOCUS, a full orbit code that runs in Graphical Processing Units.

- GPU computing allows us to follow the evolution of a large number of particles with modest resources.

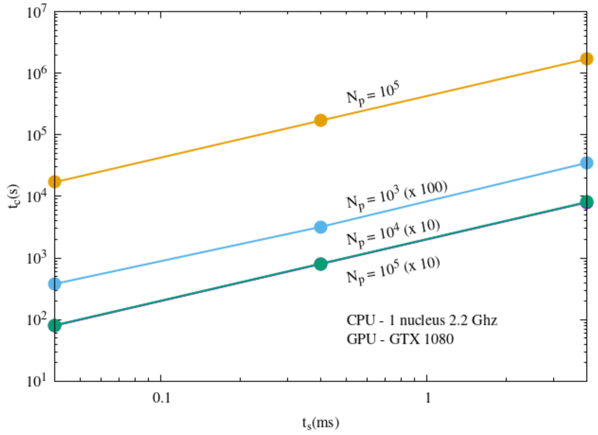
- A reconstruction technique that includes the experimental information available is employed to calculate the perturbed magnetic and electric fields.

[1] M. Garcia-Munoz et. al., *Nucl. Fus.* **47**, L10 (2007).

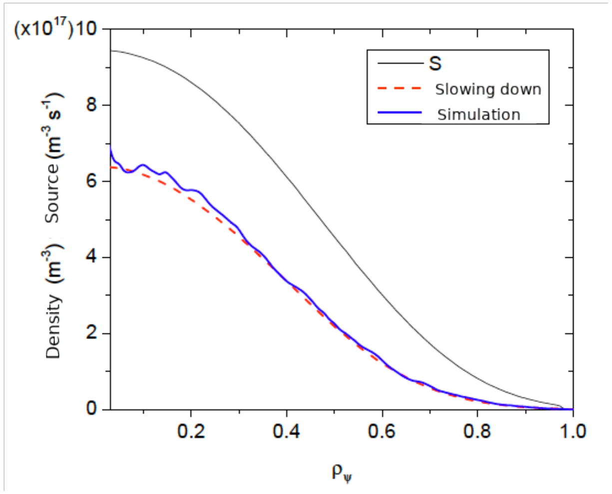
The Code FOCUS

- FOCUS: Full Orbit CUDA solver [2]
- The particles are considered tracers → perfectly parallelized code!
- Originally solves full orbit, a giro center solver was recently added.
- Elastic and Inelastic collisions true a Monte-Carlo operator are included.
- Can read EFIT, SOLPS, EIRENE data.

Speed Up
Analytical equilibrium circular section.
N_p: Number of particles N_i : Number of steps.
$N_p \times N_i = 10^5$ t_c: computational time t_s: simulated time

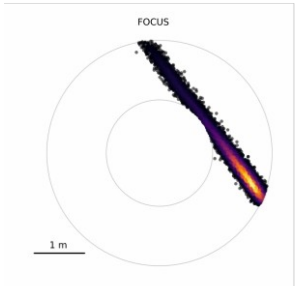


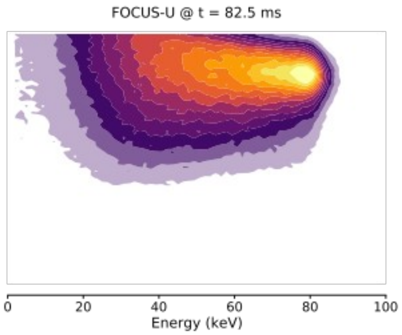
Slowing down distribution of alpha particles in ITER like.
Ions initially with 3.5 MeV fusion rate distribution.



We will like to simulate 2.5x 10^5 ions for 4 ms 2.5 x 10^6 time steps ~ years in our CPU.
Previous version of the code runs in cpu-cluster with MPI – much more cheaper on GPU.
9 hours in 1080 GTX Ti

NBI injection:



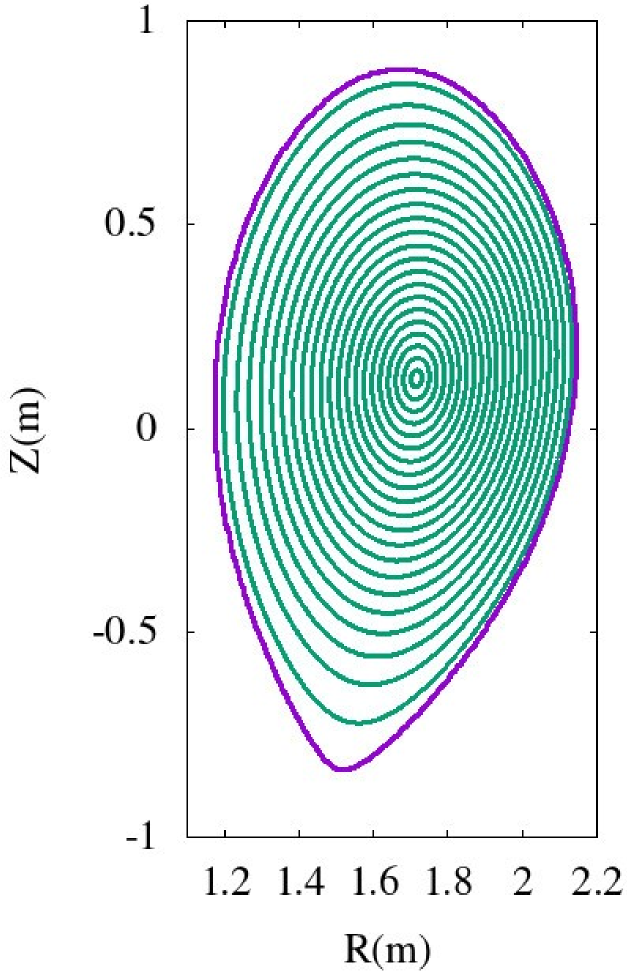


[2] C. F. Clauser et al. *Comput. Phys. Comm*. **234**, 126 (2019).

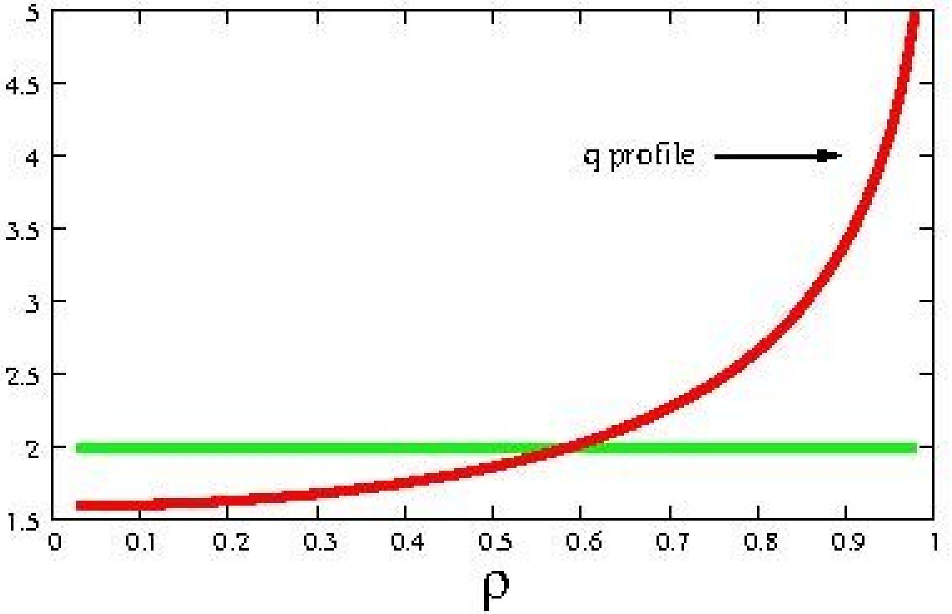
Magnetic Field

We use an analytical expression for the equilibrium magnetic flux derived by McCarthy [3] to fit a series of Asdex U discharges

Magnetic flux surfaces



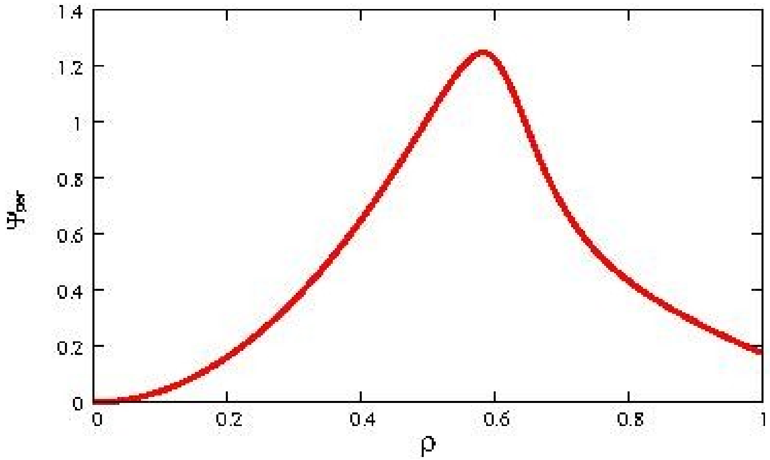
Safety factor q



[3] P. J. M. McCarthy, *Physics of Plasmas* **6** (9) 3554 (1999).

Perturbed Magnetic Field

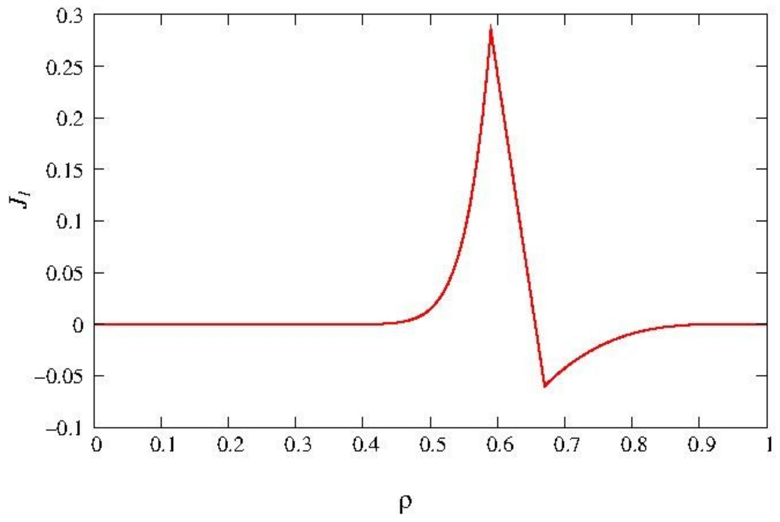
The perturbed magnetic flux produced by the NTM, Ψ_{pert}, is calculated employing the reconstruction technique proposed by Igochine [4], where a J_{pert} is reconstructed and can be written as $J_{pert} = h\, J_1(\rho)$, where h is a free parameter.



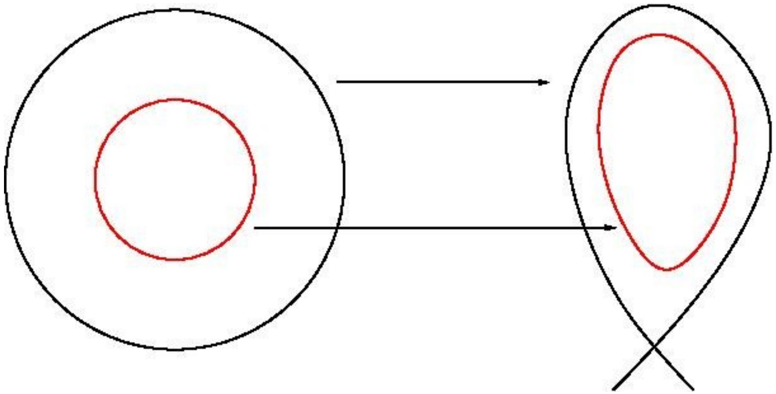
Ψ_pert is obtained by solving the Ampere's law in cylindrical coordinates with the perturbed current density (J_{pert}).

[4] V. Igochine et al, *Nucl. Fus.* **43** 1801 (2003).

Reconstructed Perturbed current



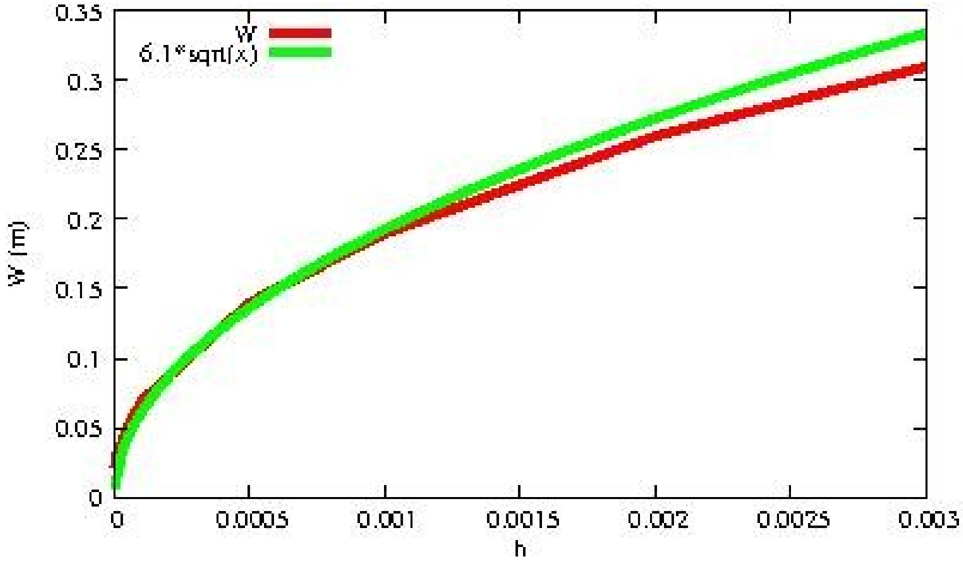
This calculation is performed in cylindrical coordinates so a mapping method is required.



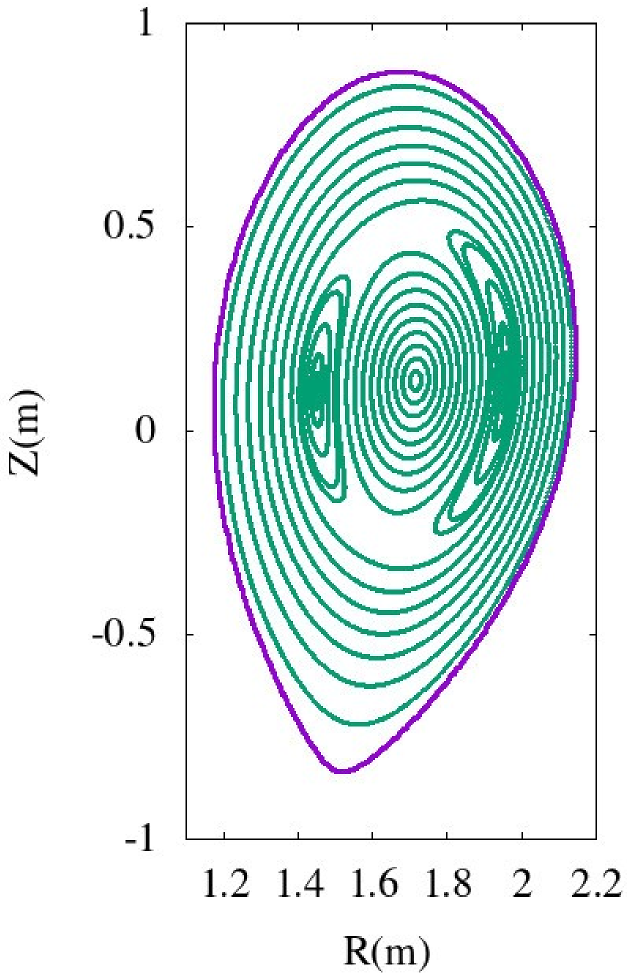
Cylindrical to flux coordinates

Perturbed Magnetic Field

We use the method proposed by Jardin [5] to construct flux coordinates. We find that no spurious islands appear in the total magnetic flux provided that only one mode is included. In our case, the (2,1) dependency is taken to be exp $\{i (2 \theta + \phi + \omega t)\}$. We adjust the parameter *h* to match the island size.



We adjust the parameter h to match the island size.



Perturbed flux when h = 0.0003
W : 11cm

[5] S. Jardin. *Computational Methods in Plasma Physics*, CRC press. (2010).

Initial particle distribution

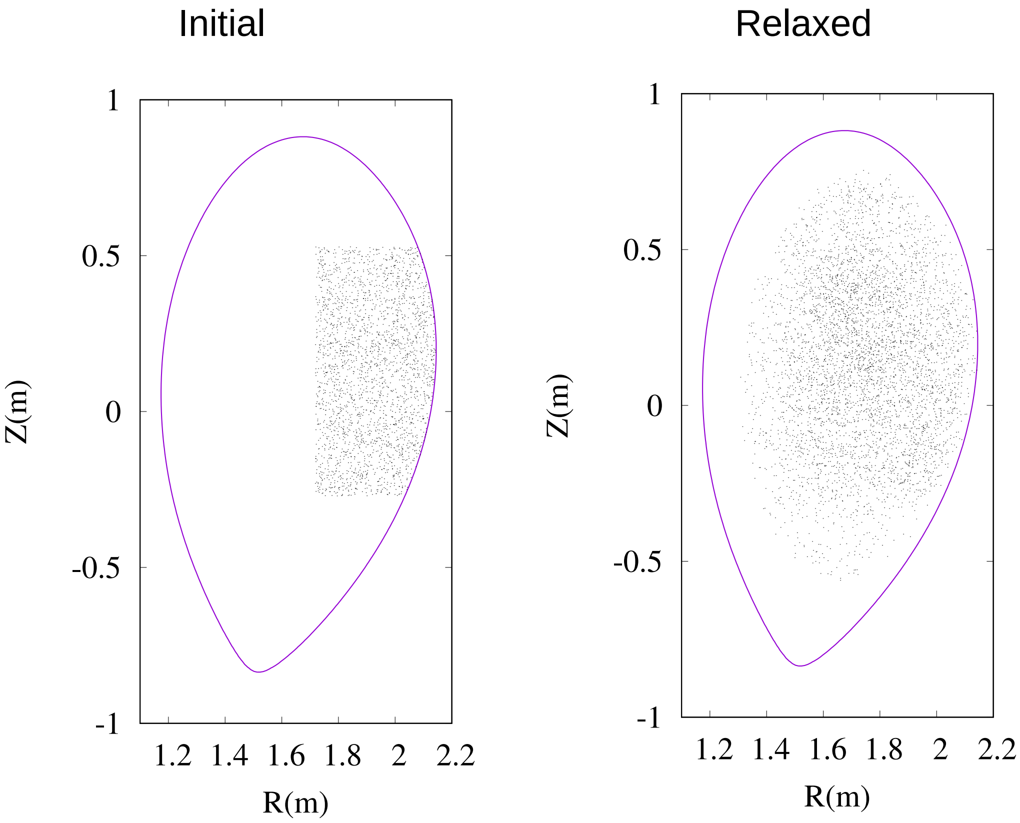
In the experiment described in [1] the energetic ions are generated by NBI.

We emulate the NBI distribution by a collection of particles:

Fixed energy, Pitch uniformly distributed between 0.2 and 0.9.

In a typical run/simulation 250000 particles are evolved during 4.17 ms for each set of parameters, using the code FOCUS that runs in GPUs.

When a particle reaches the last closed flux surface (LCFS) it is considered lost.



In short simulations performed employing only the equilibrium magnetic field

E(keV)	Trap(%)	Pass(%)	Early loss(%)
93	19.7	64.8	15.5
46.5	26.3	66.7	7

Ion dynamics in NTM

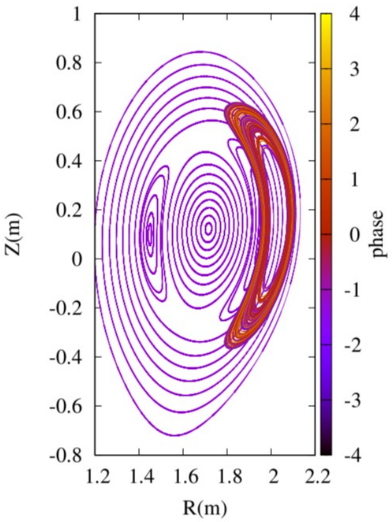
The NTM affects the dynamics of the ions. For an ion of E=93 keV, the width of the banana orbit can be comparable to the width of the island.

The information about the location of the orbit in the poloidal plane is partially contained in the toroidal component of the canonical angular momentum, P_ϕ

Toroidal precession frequency (ω_p) $7.9 \times 10^{-4} < \omega_p < 8.1 \times 10^{-4}$. Bouncing frequency 6 times ω_p

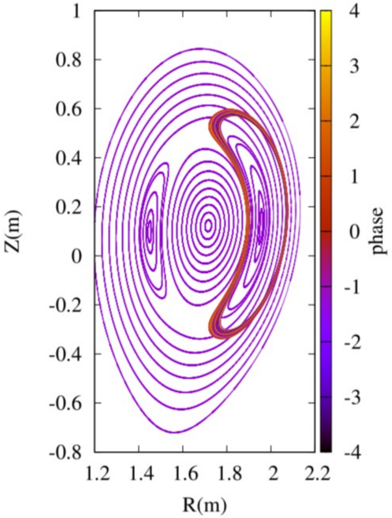
Initial phase of the particle $\delta_0 = 2\,\theta_0 - \phi_0$

Orbit outside the island.



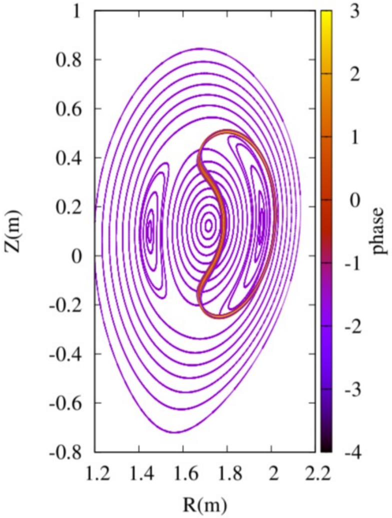
$2.14 < P_\phi < 2.26$

Orbit inside the island.



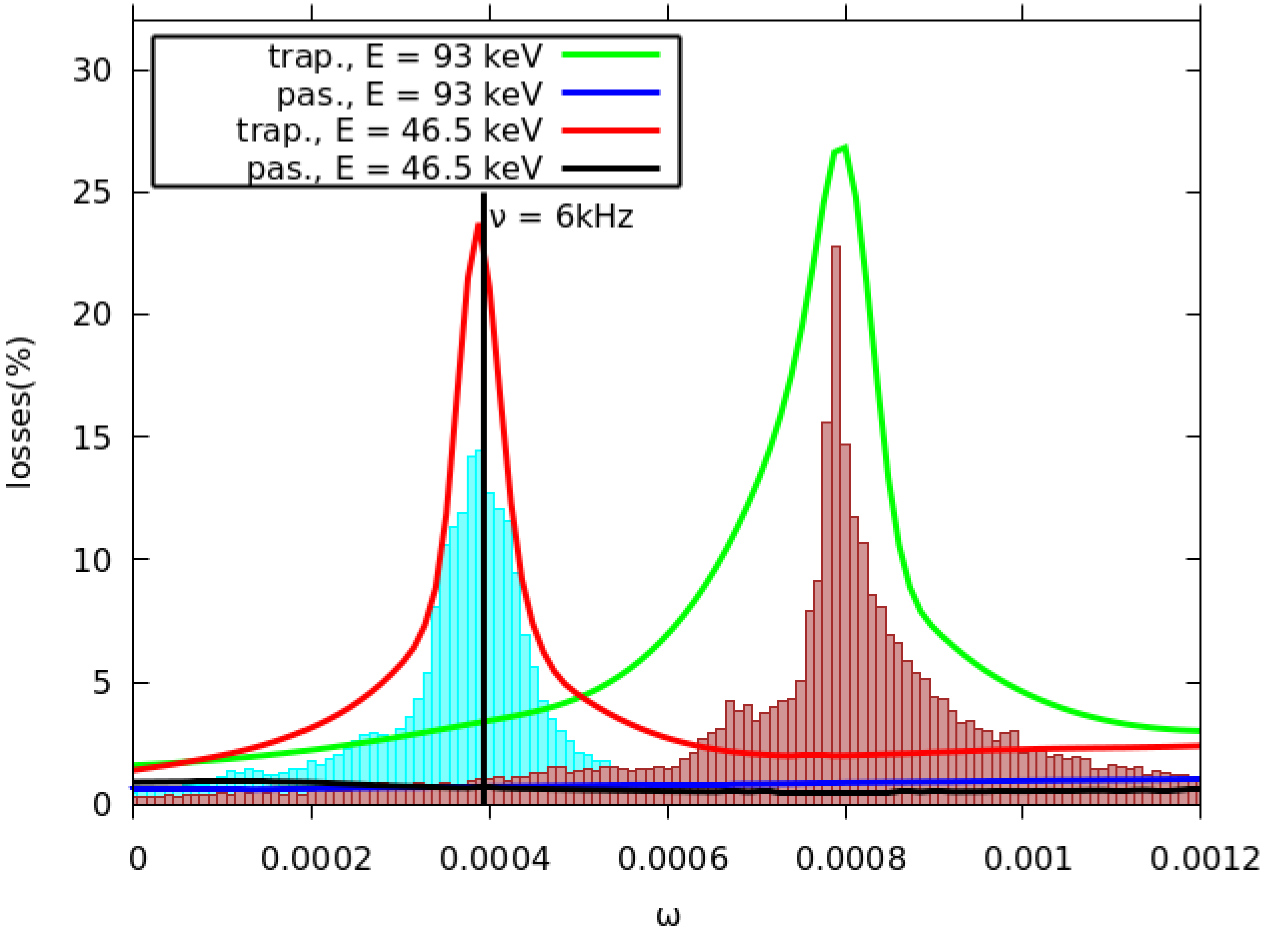
$3 < P_\phi < 3.05$

Orbit part inside part outside the island.



$3.94 < P_\phi < 4.1$

Ion losses vs NTM frequency

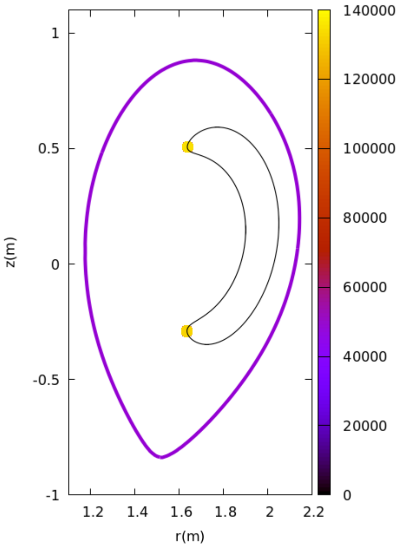


Trapped and passing ion losses as a function of the normalized NTM frequency. The histograms show the trapped precession frequencies for E = 93 keV in pink and for E = 46.5 keV in cyan. W = 11 cm

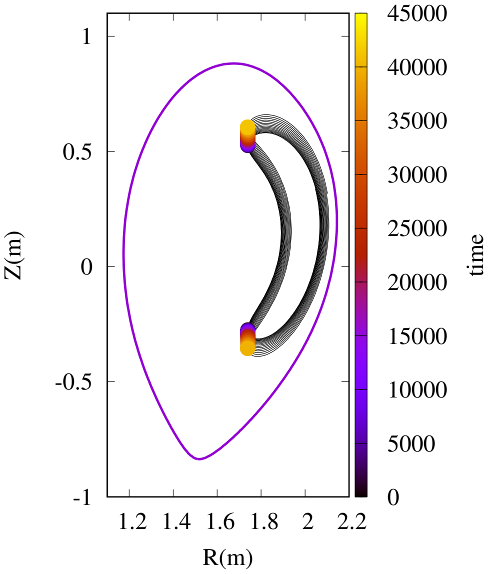
When the frequency of the NTM matches the precession frequency of the trapped particles the losses increases significantly. Passing particles losses show no dependency on the NTM frequency. The frequency is normalized with the ion cyclotron frequency. The vertical black line is the value reported in the experiment.

Ion dynamics in NTM

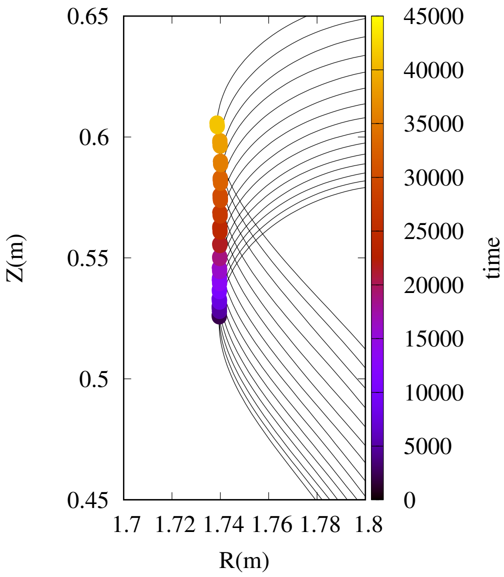
B_0



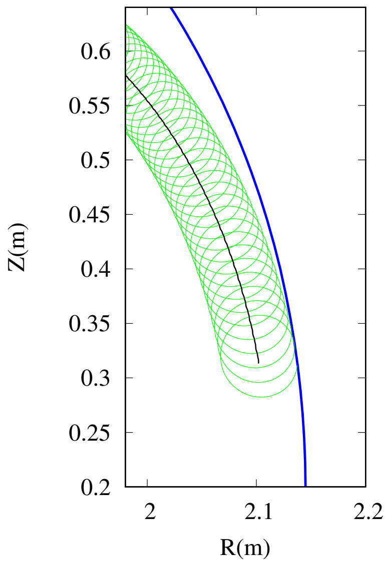
$B_0 + B_1$



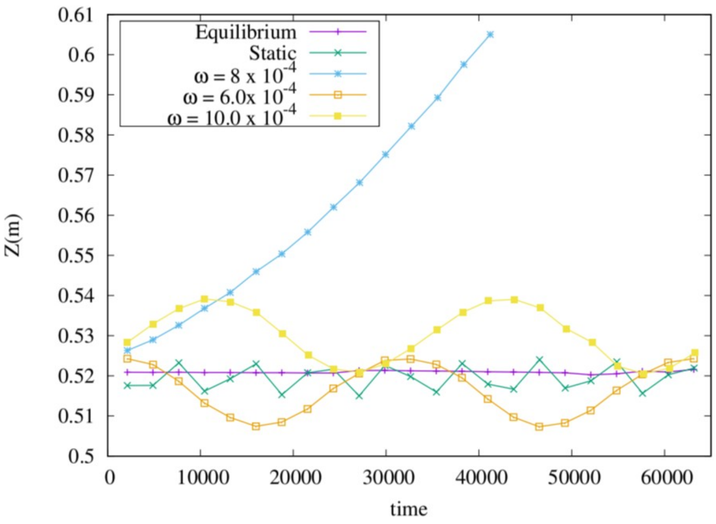
Zoom of the bouncing point



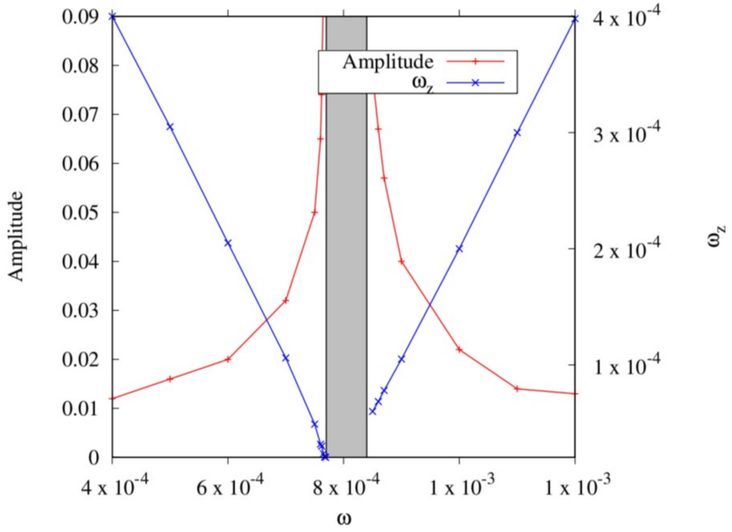
Lost point. The ion touches the LCFS



Bouncing point vs time for different mode frequencies

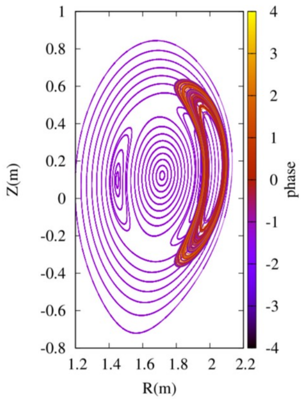


Amplitude of the bouncing vs ω

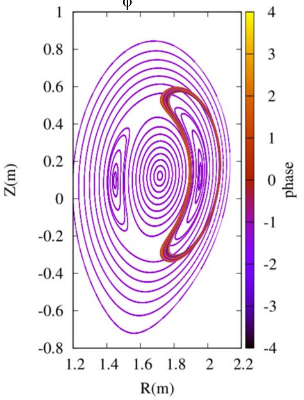


Ion dynamics in NTM

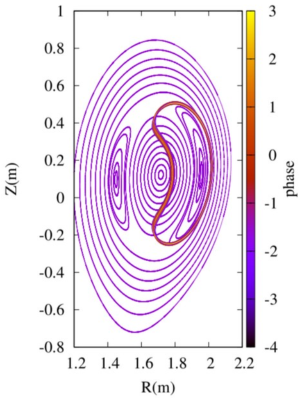
$2.14 < P_\phi < 2.26$



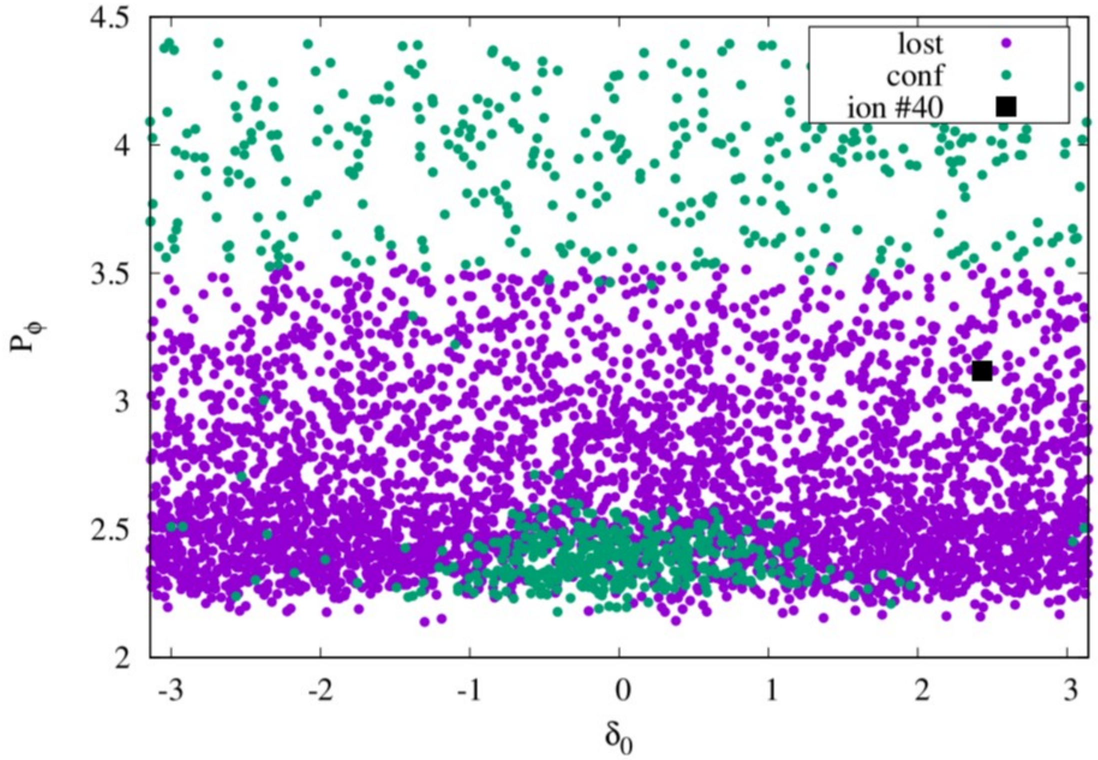
$3 < P_\phi < 3.05$



$3.94 < P_\phi < 4.1$



$P\phi$ and initial phase of confined ions (green) and lost ions (blue). Mode frequency $\omega = 8 \times 10^{-4}$



$7.9 \times 10^{-4} < \omega_p < 8.1 \times 10^{-4}$

Conclusions

The main result of this study is that when the frequency of the NTM matches the precession frequency of the trapped particles, the losses increase significantly.

In the experiments reported in [2], the 93 keV ions have a precession frequency that is approximately twice the experimental mode frequency.

The 46.5 keV ions have a precession frequency that matches the mode frequency. This indicates that a large fraction of the trapped 46.5 keV ions could be lost. Unfortunately, there are no experimental measurements of the losses at energies below 60 keV to check our conclusions.

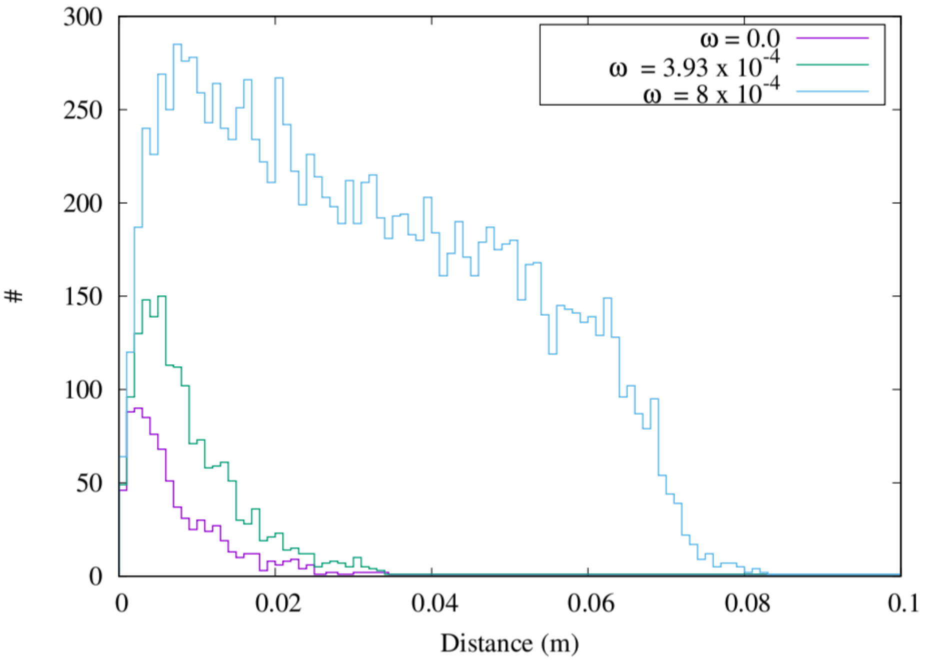
For our conditions, passing ion losses are small and have a very weak frequency dependence.

THANK YOU!

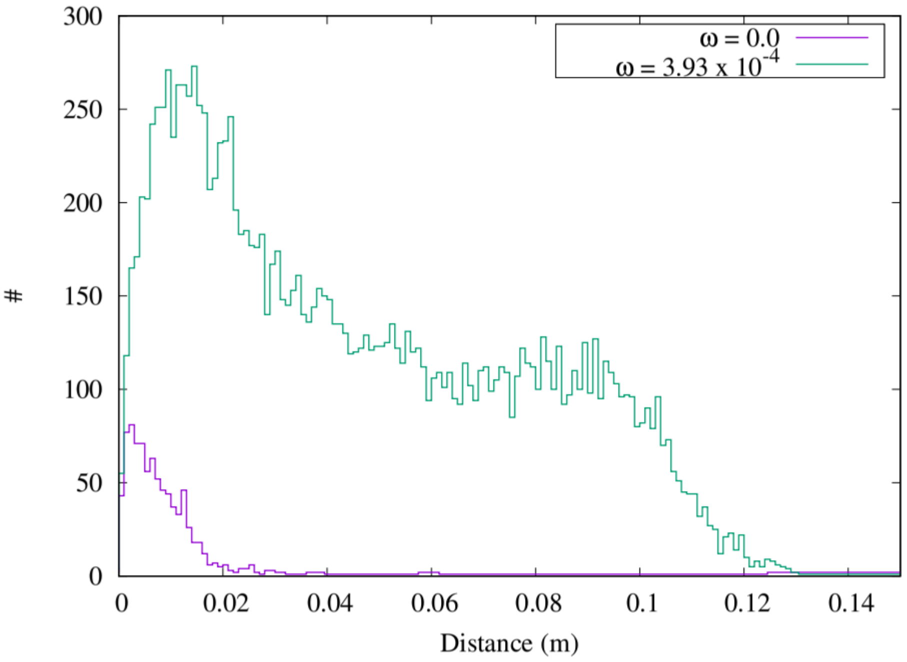
Extra slides

Distance of the outermost point of the unpertubed orbit. The ions is lost when the mode is on

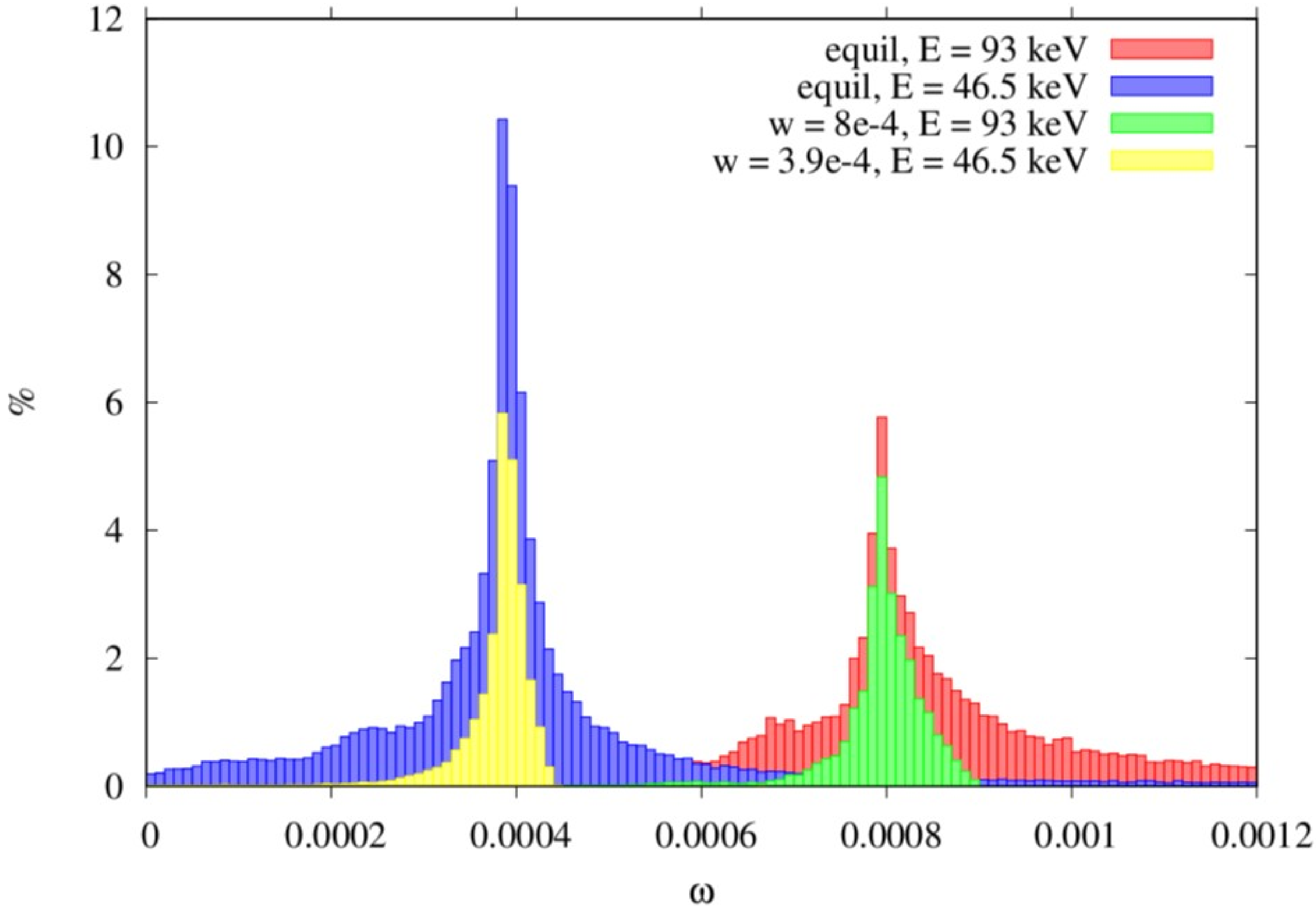
E = 93 keV



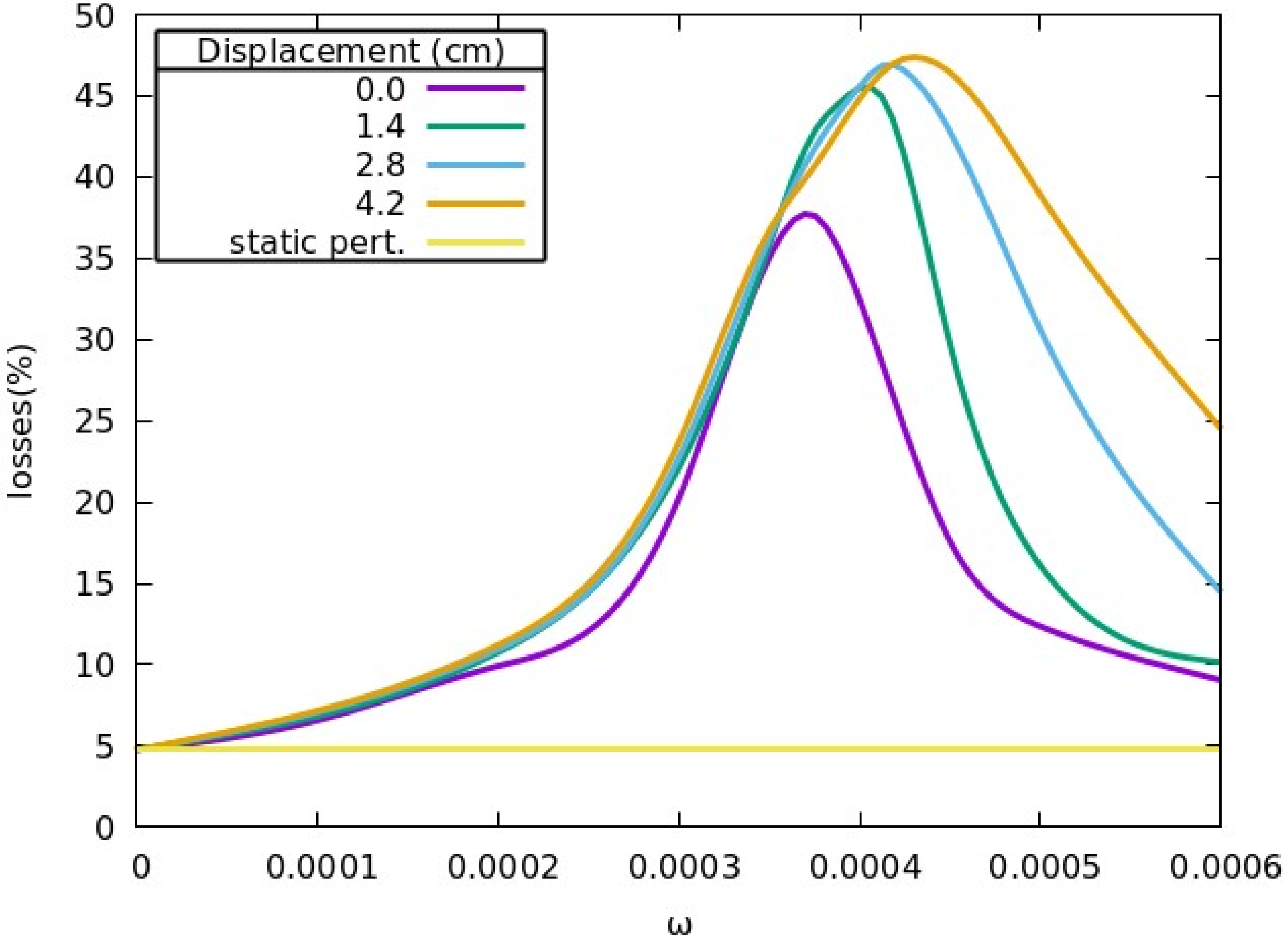
E = 46.5 keV



Distribution of precession frequencies

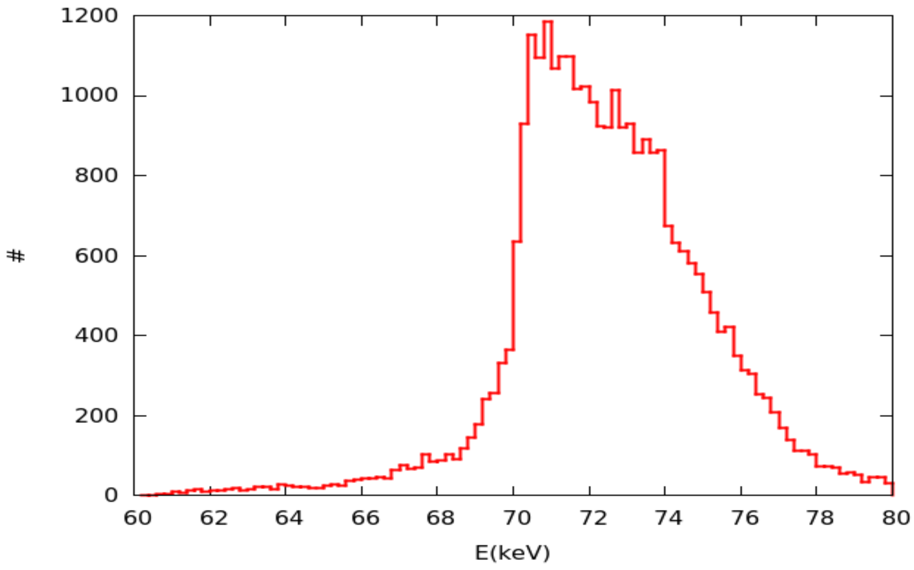


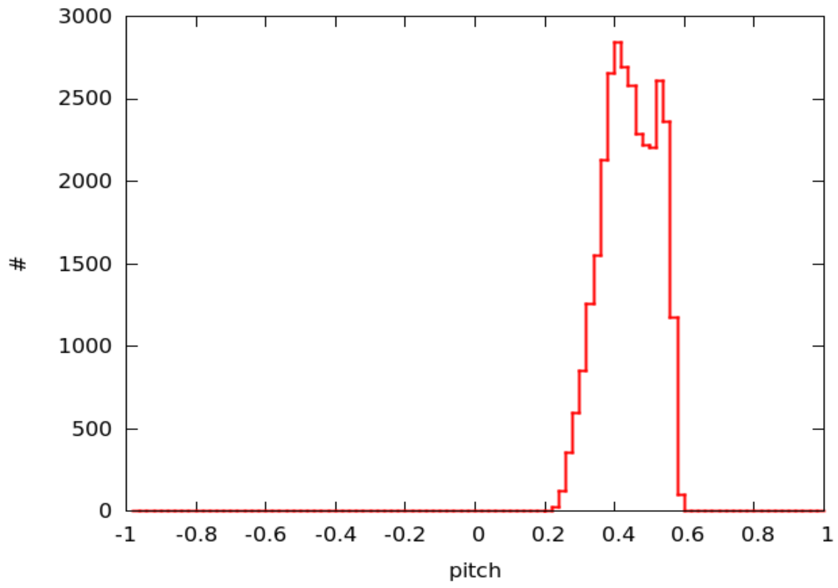
Ion losses when E_1 is on at different displacements amplitudes.



Ions Losses vs NTM frequency when E_1 is on. The electric field of the NTM transfers energy to the particles increasing their average precession frequency.

Distribution of Ion losses when E_1 is on.



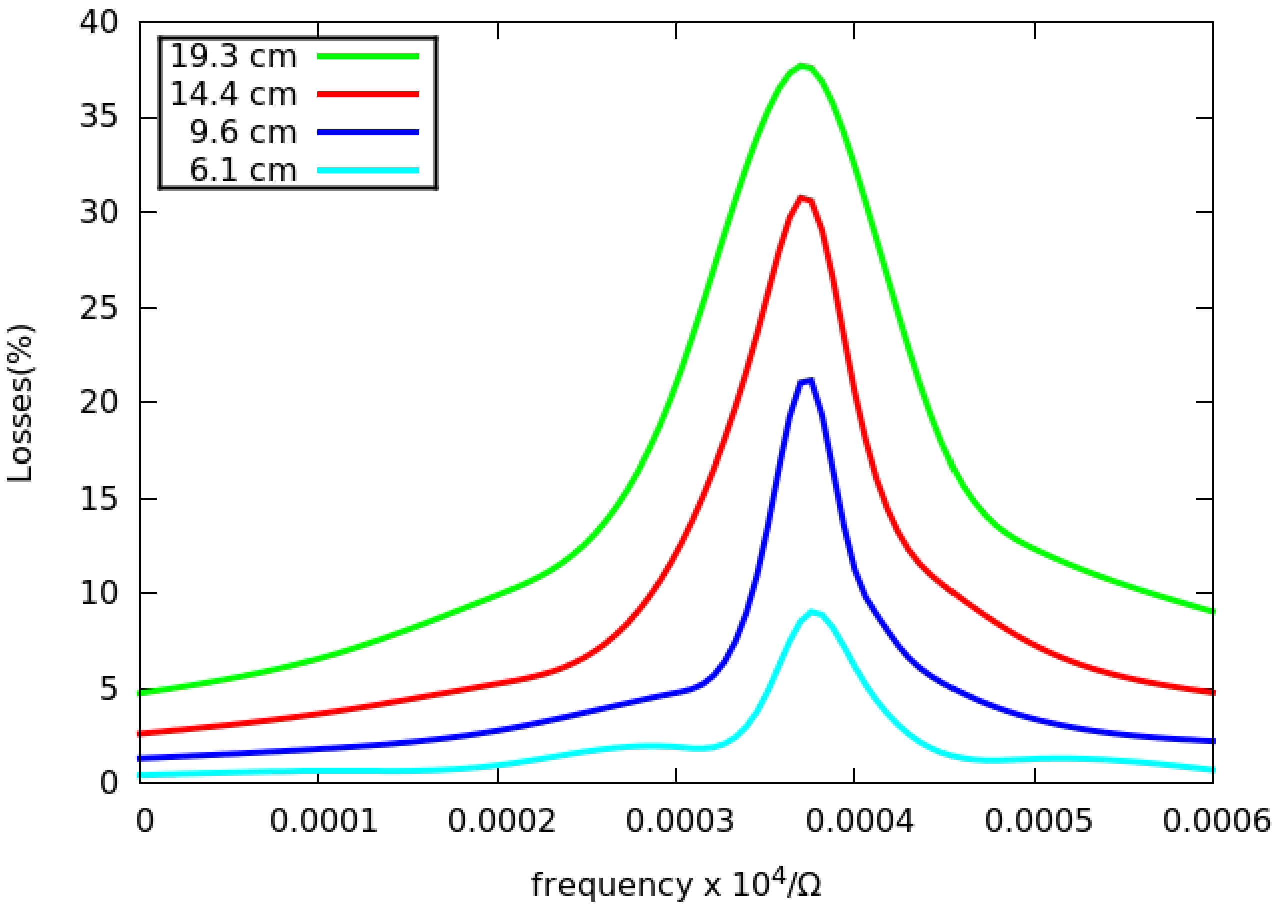


Histogram of ions losses vs energy .

Histogram of ions losses vs pitch.

E_1 is on with a displacement amplitude of 1.4 cm. The electric field of the NTM transfers energy to the ions. When E = 0, the energy is constant and equal to 70keV.

Ion losses vs NTM frequency different island sizes



Ions Losses vs NTM frequency. For different different island sizes (or B1 pertubation).

Parameters.

- Code is dimensionless
- Minor radius a = 0.50 m
- Major Radius R = 1.71 m
- B = 2.5 T

- Island size W = 19cm, h = 0.001, |dB/B| ~ 0.005
  dB ~ 0.0125 T~ 125 Gauss.

- 4.12 ms ~ 2.5 millon time steps.
- We run this in a GTX 1080 Titan ~ 10 hours.