Trapped particle resonance effects on the NTM driven losses of energetic particles

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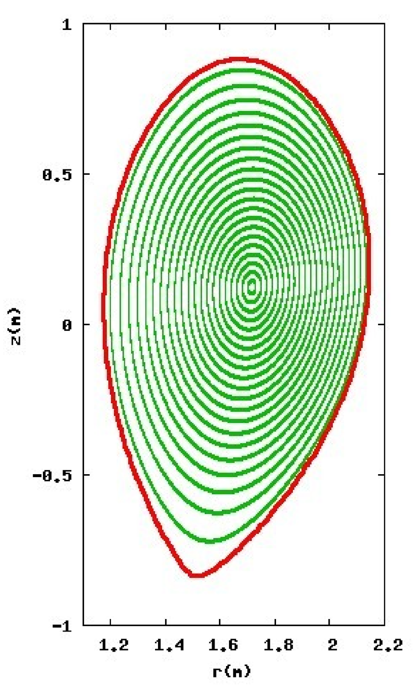
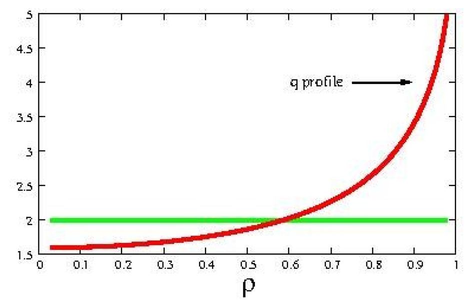
Introduction: NTMs and Ion Losses

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 [2], a full orbit code that runs in Graphical Processing Units. This allows us to follow the evolution of a large number of particles with modest resources. A reconstruction technique that includes the experimental information available [3,4] is employed to calculate the perturbed magnetic and electric fields.

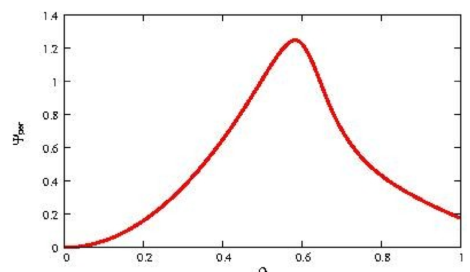
Magnetic Field

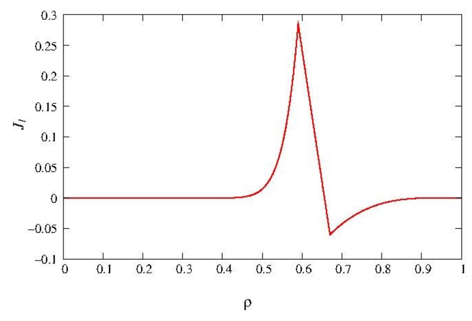
For simplicity, we use an analytical expression for the equilibrium magnetic flux derived by McCarthy [5] to fit a series of Asdex U discharges. The major and minor radii are R=1.71 m and a=0.51 m respectively and the vacuum toroidal field at r= R is B_0=2.5 T. The ion cyclotron frequency is used to normalize time and frequencies. The perturbed magnetic flux produced by the NTM, Ψ_{pert}, is calculated employing the reconstruction technique proposed by Igochine [5], 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 Ampere's law with the perturbed current density (J_{pert}). This calculation is performed in cylindrical coordinates so a mapping method is required. We use the method proposed by Jardin [6] and find that no spurious islands appear in the total magnetic flux provided that only one mode is included. In our case, the (2,1) dependence is taken to be exp (i 2 θ + i ϕ + ω t). We adjust the parameter h to match the island size.

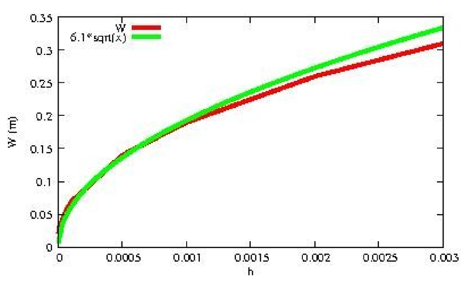

Equilibrium flux surfaces

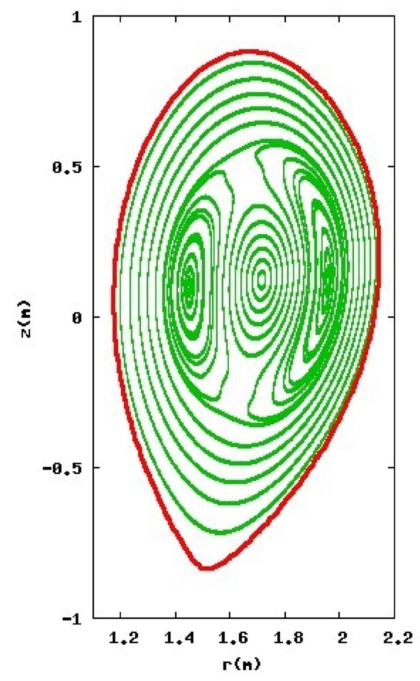


q profile


Calculated perturbed flux in a cylindrical geometry

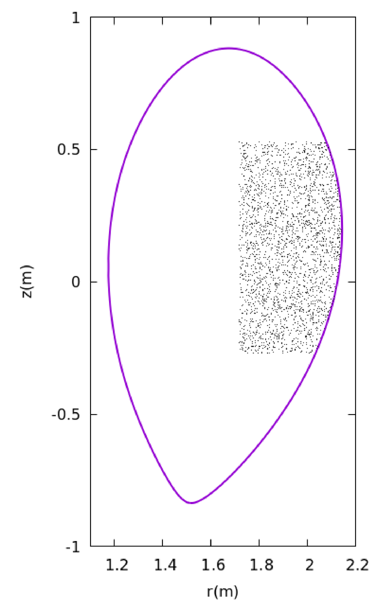

Perturbed current due to NTM.


Island size vs h

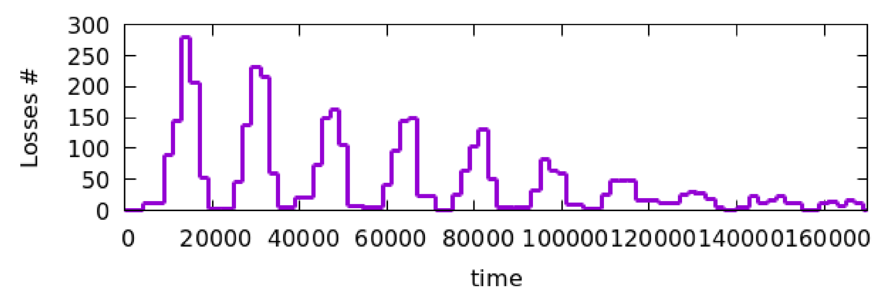

Perturbed flux when h = 0.001. No spurious islands appear.

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 distributed as shown in the figure with the same energy and pitch uniformly distributed between 0.2 and 0.9. In a typical run 250000 particles are evolved during 3.34 ms for each set of parameters using the code FOCUS that runs in GPUs [2]. When a particle reaches the last closed flux surface (LCFS) it is considered lost. When the energy is set to 70KeV and there is no perturbation 6.67% of the particles are early losses. 66% are passing particles and 26.6% are trapped particles. The passing and trapped particles are well confined.

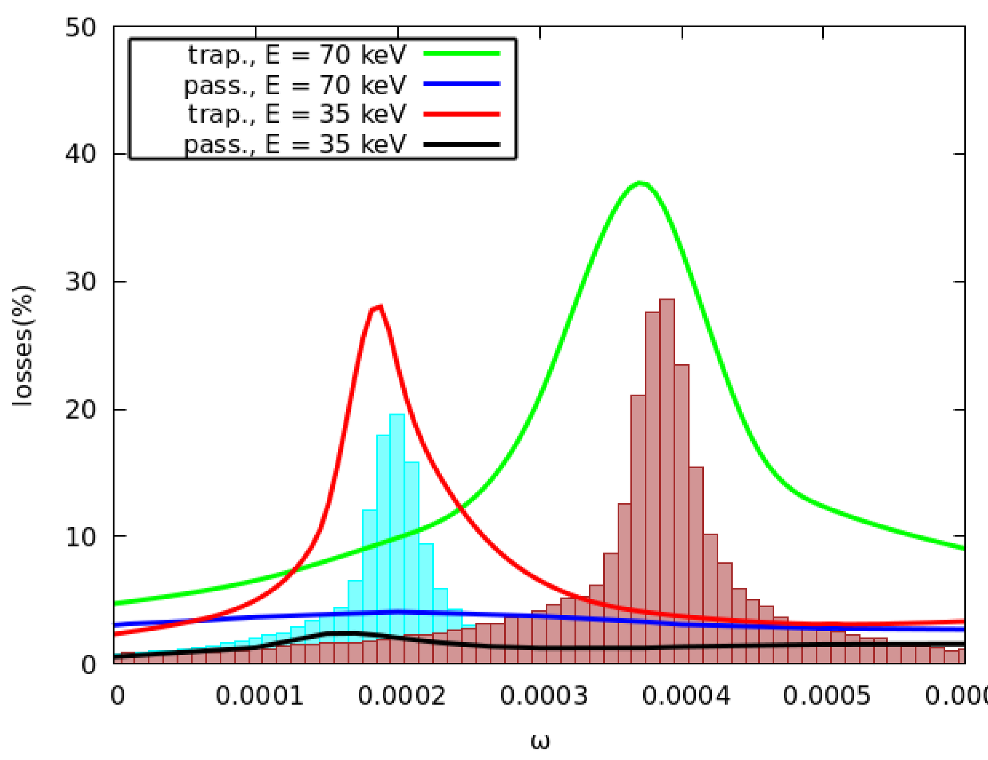


Ion losses at a fixed toroidal section.



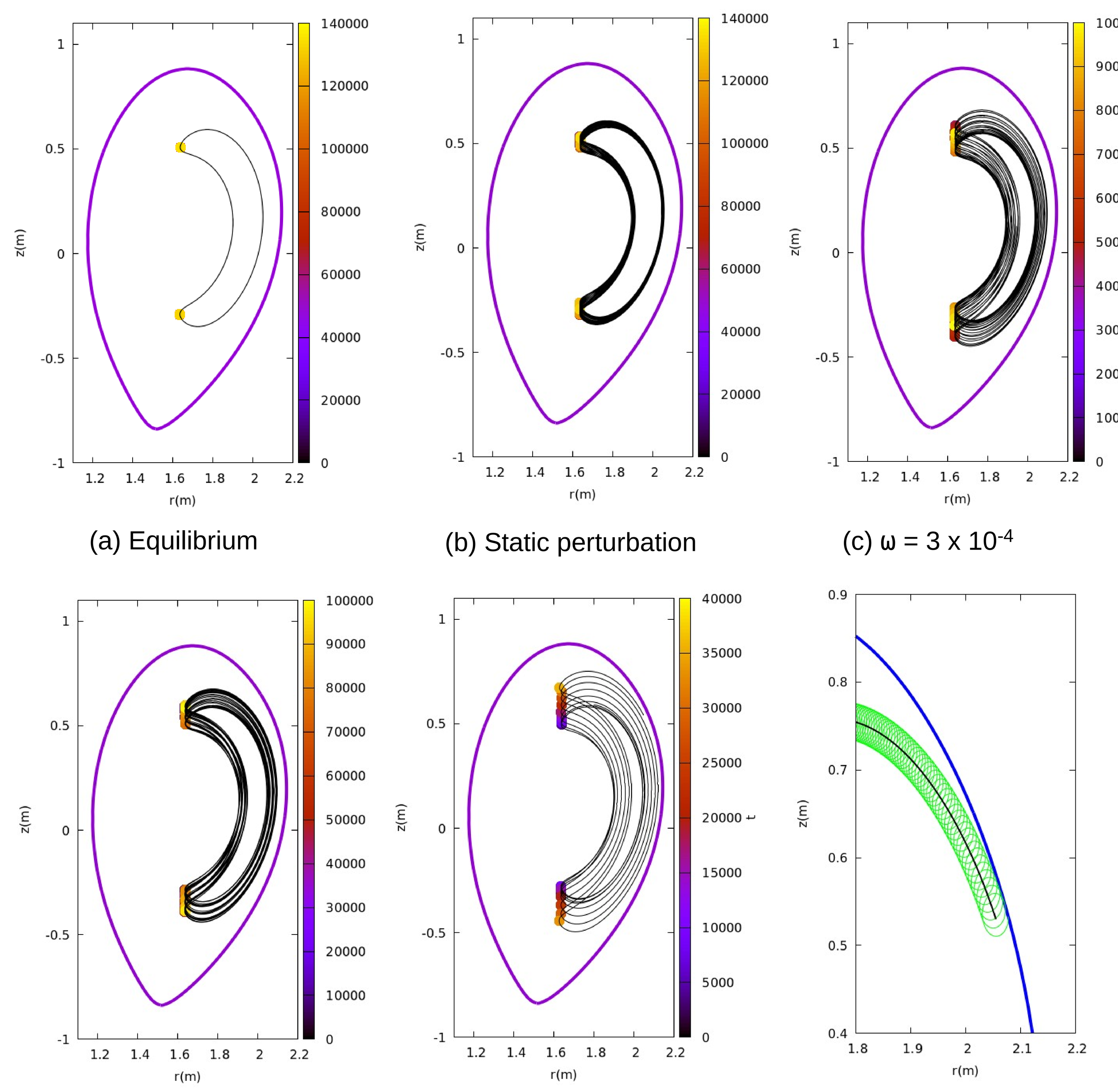
To produce this figure, we followed 330000 trapped particles. The frequency of the mode was set to the value that produces the maximum ion losses. We collect the particles that are lost with toroidal coordinate [0, π/16].

Ion losses vs NTM frequency when E_1 = 0



Ion losses vs NTM frequency. The histogram bars show the toroidal precession frequency of the trapped particles of 35 keV (cyan) and 70 keV (light red). When the frequency of the NTM matches the toroidal precession frequency of the trapped particles the losses increases significantly. The losses of passing particles show a mild dependence on the NTM frequency.

Orbit of a particle when B_1 is on for different NTM frequencies.

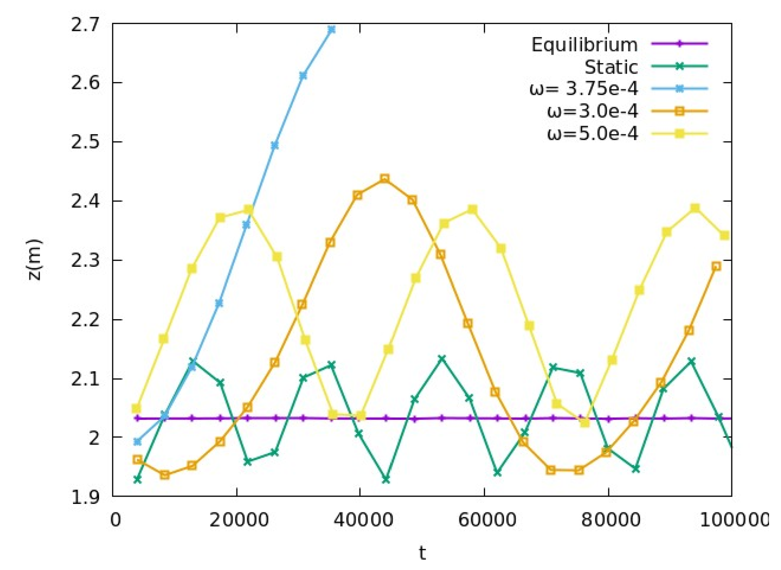


(a) Equilibrium (b) Static perturbation (c) ω = 3 x 10^{-4}

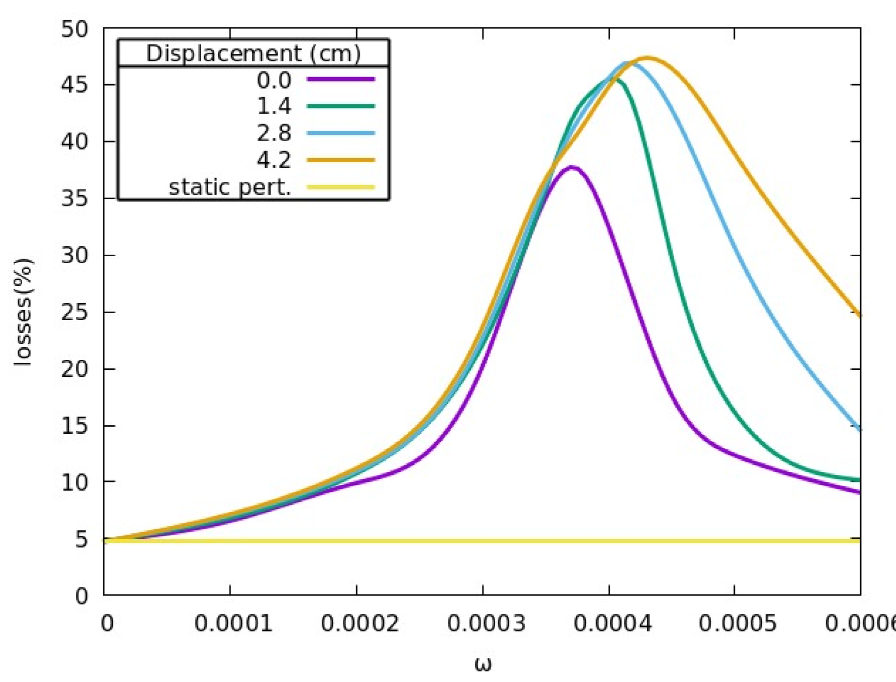
(d) ω = 5 x 10^{-4} (e) ω = 3.75 x 10^{-4} (f) ω = 3.75 x 10^{-4}

When ω = 3.75 x 10^{-4} frame (e) the particle is lost. The colored point indicates the bouncing position and the color scale is time. LFCS is in blue. In (f), the full orbit (green line) touches the LFCS but the GC orbit (black line) doesn't.

Z coordinate of the upper bouncing position as a function of time.



Ion losses when E_1 is on at different displacements amplitudes.



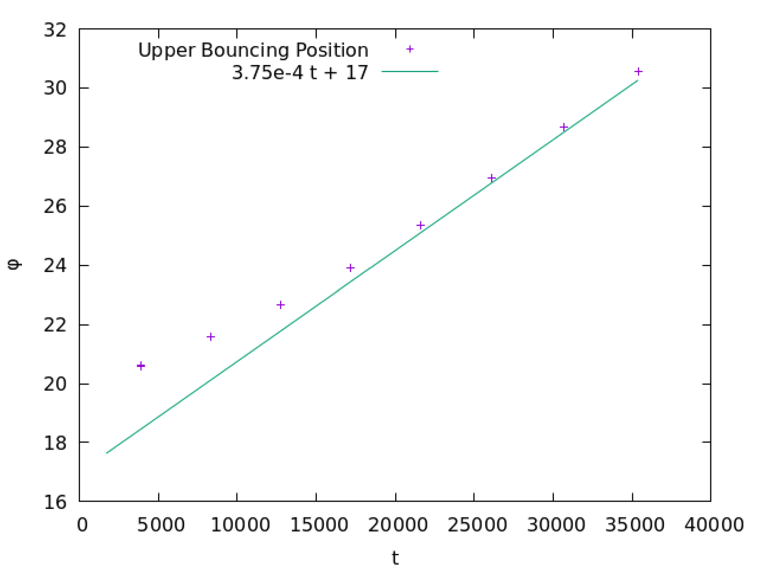
Ions Losses vs NTM frequency when B_1 and E_1 are on. The electric field of the NTM transfers energy to the particles increasing their average precession frequency.

Conclusions:

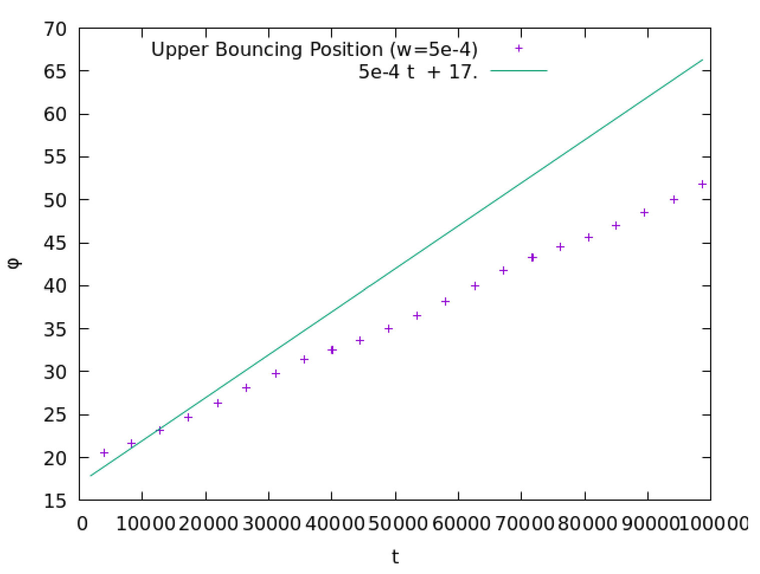
The main result of this study is that when the frequency of the NTM matches the toroidal precession frequency of the trapped particles, the losses increase significantly. According to our simulations, the main losses correspond to trapped particles (with average pitch at the loss point of 0.42). This is in agreement with experiments performed in ASDEX U [1], where the lost ions had a well defined energy and pitch.

The perturbed electric field changes the resonance frequency of trapped particles losses, and increase the maximun losses at resonance. This is due to an increase in the average energy of the particles and a contribution of the E_1 x B drift.

Toroidal coordinate of the upper bouncing position as function of time.



ω = 3.75 x 10^{-4}



ω = 5 x 10^{-4}

The straight line is the phase velocity of the NTM.

References

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