# Influence of neoclassical tearing modes on confined fast ions in ASDEX Upgrade

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## Introduction

Neoclassical tearing modes (NTMs) form large magnetic islands on magnetic surfaces with rational safety factors q=m/n where m and n are small integers. Islands cause flattening of plasma temperature and density profiles; therefore they significantly degrade the confinement. It was shown that the perturbed topology of the magnetic field leads to enhanced losses of fast ions from trapped orbits [1]. Moreover, a strong resonance was found between fast ions on banana orbits and rotating islands. In ASDEX Upgrade these losses were observed by the scintillation-based detector for fast ion losses, FILD [2, 3]. Evidence of fast ion losses due to NTMs was also found at other machines, such as DIII-D [4]. Although there are many experimental data on fast ion losses induced by neoclassical tearing modes, the influence of the latter on confined fast ions is not well studied. However, a stabilization of the fishbone instability was observed after the onset of NTM, which implies the reduction of trapped fast ions population inside q=1 rational surface [5]. In this contribution, a numerical study of the behaviour of confined fast ions is presented and qualitatively compared to the recent experimental findings with the FIDA diagnostic [6].

## Numerical study

Numerical studies were performed using a full-orbit tracing of fast deuterium in the self-developed parallel Monte-Carlo code. The solver uses a leap-frog numerical scheme and for the considered integration time (0.2 ms) results show no numerical heating. As we neglect collisions, the studied effect would be solely dependent on changes in topology of the magnetic field. Three million deuterium particles were seeded with a random pitch ($-V_{||}/V_{full}$, where parallel refers to the magnetic field) between -1 and 1, energies between 10 and 100 keV, and uniformly distributed in space. The 2/1 NTM was modelled according to equations 1-3 in [1] with the following parameters: $\rho = 0.05$, $\alpha = 0.04$, $\beta = 0.87$, $\gamma = 0.01$. The resulting island remained static and had a width of approximately 4 cm which is a realistic island width as indicated by electron temperature measurements by the electron-cyclotron emission diagnostic. Figure 1 shows changes in the fast ion population in the equatorial plain.

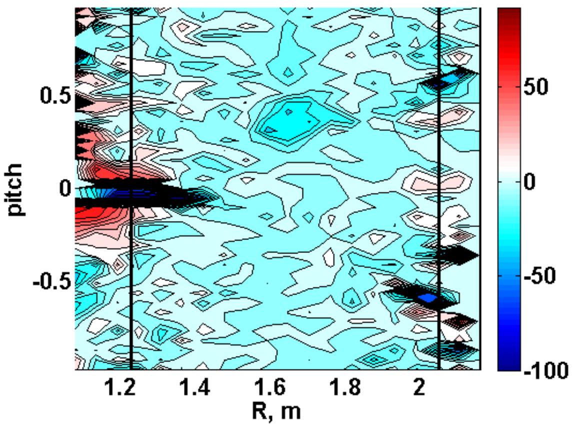

Figure 1 Changes in the fast ion content in the equatorial plain. Negative (blue) changes refer to the decreased amount of fast ions after introduction of the NTM. Black straight lines show radial position of the island.

One can clearly see that at the high field side there is a reduced number of particles with a small pitch.  Figure 2 shows changes in the fast ion density profiles for fast ions on passing and trapped orbits. At the position of the island on the high field side, where pitch is close to zero, particles are kicked from barely passing to trapped orbits and back depending on the relative phase between fast ion motion and the position of the island. This leads to the significant decrease of the particle density on the radial location of the island on the high field side and corresponding increase at the turning points of banana orbits. The process is reciprocal and at certain phase the trapped particles are also moved to the passing orbits, however it does not result in a significant increase of the density of passing particles because circulating on the banana orbit takes much longer than making a poloidal turn for passing particles, due to the long period which a particle spends on the turning tip of the banana trajectory. The difference for the passing particles in the plasma centre is due to orbit stochastization for passing particles. On figure 3 on can clearly see the transition of a passing particle into the trapped one. On the left of figure 3 the limits of particle’s motion is depicted as extreme values of the pitch on its orbit. The reference ion (black) is bouncing between two parallel horizontal lines, while the ion in the perturbed field (green) initially moves on the passing trajectory and then step-wise changes its value of pitch on HFS. Then the transition happens within 3 poloidal turns. At the end of the simulation (not shown on the figure), the fast ion in the NTM field returns to the passing trajectory. The changes are especially large on the high field side in the vicinity of the turning points of the banana, where velocity along the field lines is small. Increase in density due to NTM, as shown in Figure 2, is spread over a relatively large range of radii due to the various thickness of the banana orbit for different. Changes of the fast ion density in the vicinity of the magnetic axis are related to the stochastization of the orbit, as it is shown on figure 4.

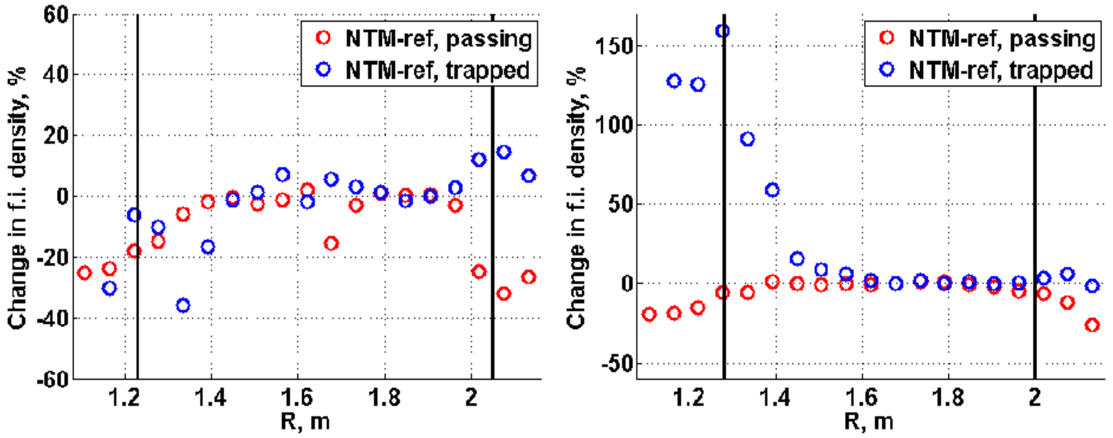

Figure 2 Changes in density for trapped (blue) and passing (red) fast ions at the equatorial plane (left) and 12 cm above it (right)

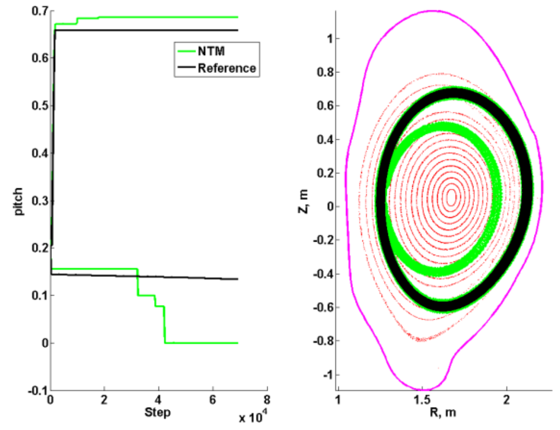

Figure 3 Poloidal projections of fast ion trajectories with the energy of 80 keV started on the q=2 surface (LFS, equatorial plain) of a reference ion (black) and ion in the NTM field (green). Boundaries of particle motion shown as extreme values of pitch (left).

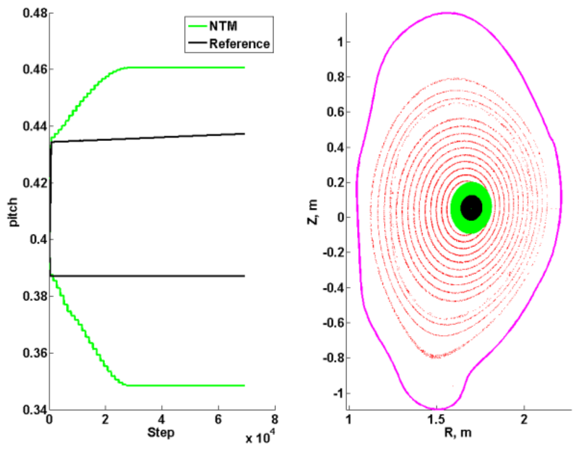

Figure 4 Poloidal projections of fast ion trajectories with the energy of 80 keV started in the plasma centre of a reference ion (black) and ion in the NTM field (green). Boundaries of particle motion shown as extreme values of pitch (left).

## Comparison with experimental data

A discharge # 30383 with NTMs was conducted. There a 2/1 NTM and 1/1 kink mode during neutral beam injection were triggered. Fast ion D-alpha spectroscopy (FIDA) was available for measuring co-passing, counter-passing, and trapped particles. Due to the complicated shape of FIDA weight function [7] and its convolution to the fast ion velocity distribution function, it is not always obvious to say which part of the fast ion population contributed to the measured changes. However, the first analysis indicates, that in the plasma centre the population of counter-Ip passing fast ions increase and of the co-Ip passing decreases. This is similar to the observations in simulations and not connected to the physical transport of particles in and out of the plasma, but rather due to the changes in the orbit topology which results in the fact that fast particles are spending more or less time in the neighbouring locations.

The most interesting results which also lead to the transport changes are related to the transition from passing to trapped particles, which has two implications: possible losses of the resonant trapped particles and increased fast ion density in more central regions. The effect should be especially strong on the high field side in the vicinity of the turning points of the banana particles. Unfortunately, it is difficult to test with the FIDA diagnostic since there are no HFS measurement volumes. The next experiments will combine FIDA LFS profile measurements with the CTS diagnostic measuring locally on the high field side and will use the velocity-space tomography method to clarify the velocity-space location of the changes due to the NTMs [8, 9].

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