Effects of finite orbits on neoclassical toroidal viscouse torque due to 3D perturbations in tokamaks

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Introduction

Nonaxisymmetric magnetic perturbations in tokamaks play an important role in determining plasma rotation by generating neoclassical toroidal viscous (NTV) torque [1, 2]. Such threedimensional magnetic perturbations arise from a variety of external and internal sources, including resonant magnetic perturbation (RMP) coils, intrinsic error fields, and magnetohydrodynamic (MHD) activity. Since sufficient plasma rotation is essential for plasma stability, precise modeling of NTV is necessary for present-day as well as future reactors.

In the low-collisional regime NTV is driven by orbital resonances, occurring when toroidal precession stops (superbanana resonance) or attains a rational ratio to the bounce frequency (drift-orbit resonance). Established models such as the Hamiltonian code NEO-RT [2] and GPEC/PENTRC [3] evaluate these resonances on flux surfaces, assuming the orbit width small compared with the radial scale of the perturbation. This thin-orbit limit however is not always fulfilled, especially for hot ions since orbit width scales the square root of mass and energy of the particle. Furthermore the radial structure of the perturbation usually gets very thin towards the edge which also leads to violation of the thin-orbit limit. Therefore an extended finite-orbit version (POTATO) of the Hamiltonian NTV code NEO-RT has been used to assess finite-orbit-width effects on NTV [4].

Orbit width and the breakdown of the thin-orbit limit

Figure 1 shows the radial structure of an n=2 perturbation applied to an ASDEX Upgrade discharge (30835) overlayed with orbit widths calculated by orbit tracing are shown for a variety of scaled ion masses (left). Furthermore the kinetic profiles of the used discharge are shown (right). It can be seen that for particles with physical deuterium mass trapped orbits are so

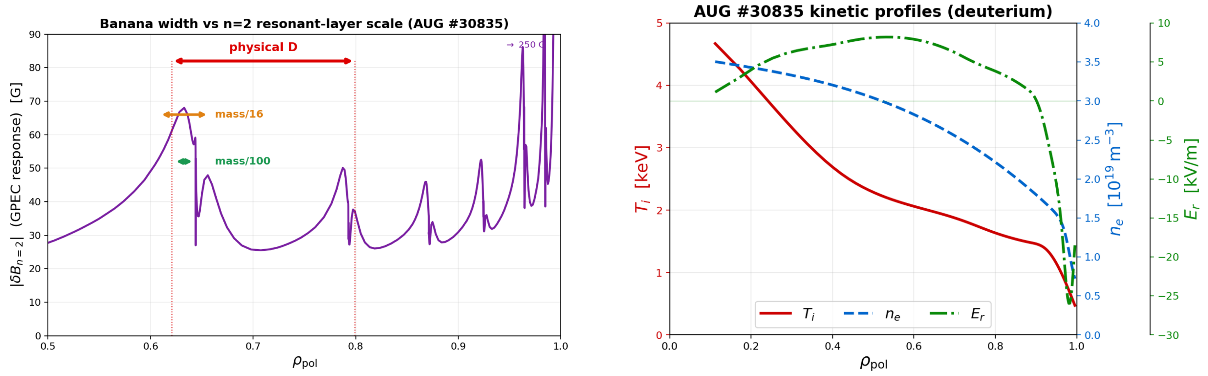

Figure 1: Left: Radial profile of magnetic perturbation calculated by GPEC overlayed with orbit width of trapped particles calculated by orbit tracing. Right: kinetic profiles of AUG discharge 30835

wide, that the particle reaches multiple different perturbation resonances, clearly violating the thin-orbit limit. When reducing the particles mass orbits approach the thin orbit limit.

Thin orbit benchmark of POTATO

To show that POTATO yields similar results to NEO-RT in the thin-orbit regime both codes where benchmarked on the perturbed AUG discharge 30835. To reach the thin-orbit regime both codes used deuterium ions with the mass scaled down by a factor of 1/1600. Otherwise the codes share the same kinetic profiles and perturbation spectrum which was calculated by GPEC. Figure 2 shows the calculated bounce (left) and toroidal precession (right) frequencies calculated by POTATO and NEO-RT. It can be seen that even though NEO-RT calculated the frequencies using only local quantities they agree very good with the full orbit traced frequencies calculated by POTATO.

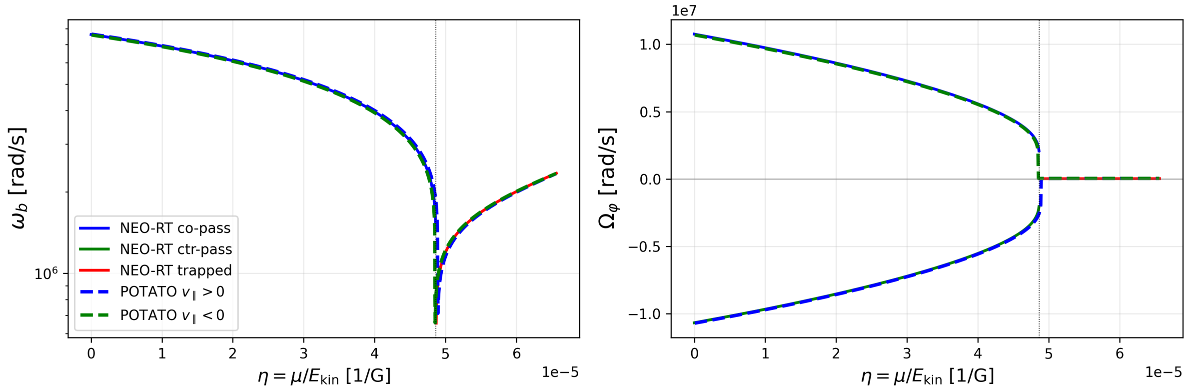

Figure 2: Orbital frequencies calculated by NEO-RT (solid) and POTATO (dashed) for ions with mass scaled down by 1/1600. Left: bounce frequency, right: toroidal precession frequency

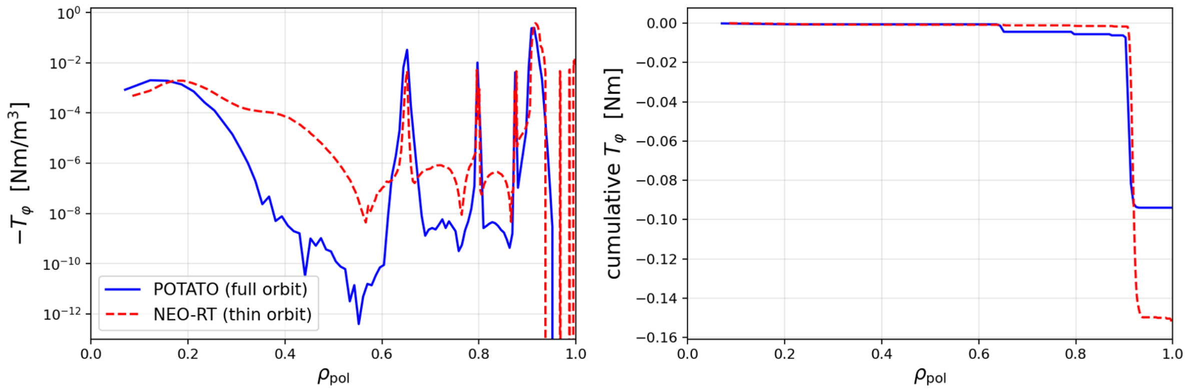

Figure 3: NTV torque density (left) and integral torque (right) calculated by NEO-RT (dashed) and POTATO (solid) for scaled down ion mass from above

Figure 3 shows the calculated NTV torque density (left) and integral torque (right) using POTATO and NEO-RT. It can be seen that up to around ρ_{pol} 0.9 both codes show good agreement. It should be noted that POTATO only calculates NTV up to a cutoff of 0.9 as the code cannot handle orbits leaving the separatrix yet. Therefore disagreement in the edge region is expected.

Full orbit results

For the same discharge NTV torque was also calculated using deuterium ions with the real physical mass. As stated before at this mass trapped orbit width becomes comparable to the radial structure of the perturbation and thin-orbit limit breaks down. Figure 4 shows the bounce (left) and toroidal precession frequencies (right) from POATAO and NEO-RT. It can be seen that when considering finite-orbit width effects bounce and precession frequecies are shifted compared to their thin-orbit limit values. As a consequence also the resonance positions of the orbital resonances important for NTV calculations are shifted. Figure 5 shows the corresponding NTV torque density (left) and integral torque (right). It can be seen that both radial distribution and total torque differ significantly from the thin-orbit value. Besides the resonance shift, the produced torque also gets redistributed along the full orbit width in POTATO which leads to a broadening of the resonant peak. It should also be noted that with increasing orbit width also particles from further inside the plasma cross the separatrix which as said before is not yes treated properly in POTATO. Also including these particles may have siginificant impact on the calculated torque.

Summary and Outlook

It has been found that NEO-RT and POTATO agree only at scaled down ion mass to also reach thin-orbit limit in POTATO. At the physical mass, finite-orbit width effects shift the resonances

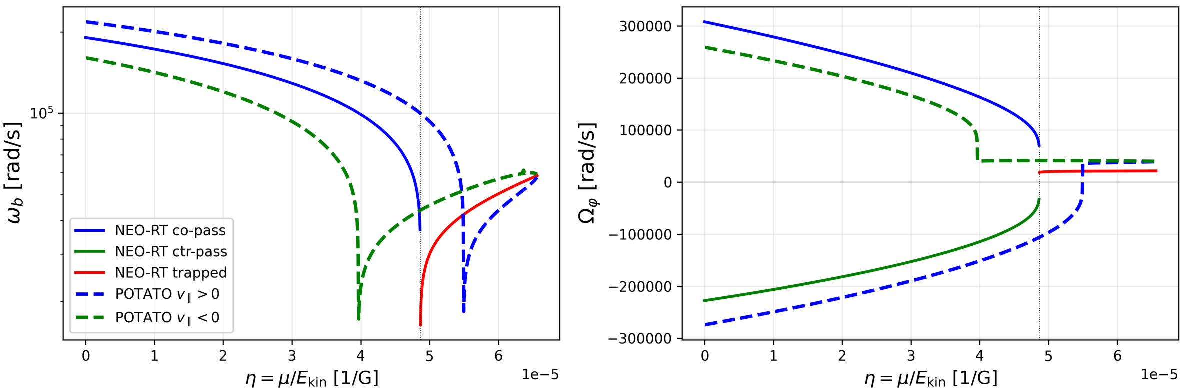

Figure 4: Orbital frequencies calculated by NEO-RT (solid) and POTATO (dashed) for physical deuterium ion mass. Left: bounce frequency, right: toroidal precession frequency

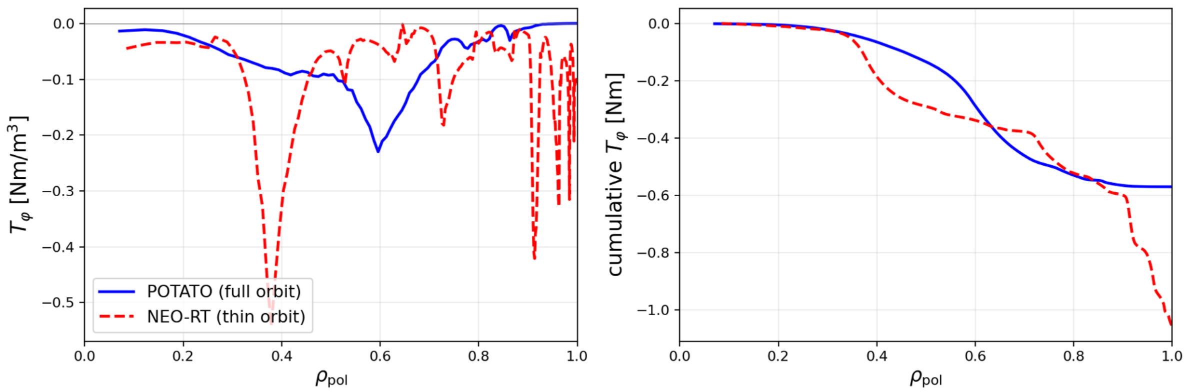

Figure 5: NTV torque density (left) and integral torque (right) calculated by NEO-RT (dashed) and POTATO (solid) for physical ion mass from above

and redistribute the NTV torque radialy. These effects are already visible for ASDEX Upgrade and are expected to be stronger for ITER. Future work will extend POTATO across the separatrix to treat orbits leaving the confined plasma, removing the present edge truncation.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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