Fast ion redistribution in helical tokamak equilibrium states and RMP from PIC full-f calculations

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Plasma in modern fusion devices is maintained and controlled by various heating systems operating at energetic regimes. Large populations of non-thermal ions are produced, either via ICRH, NBI and/or α-emission. Tokamak instabilities perturb the electromagnetic structure and the motion of particles becomes complex, sometimes chaotic. Some instabilities will saturate at large amplitude and form stationary configurations. For instance, the $n = m = 1$ infernal mode consists of a helical displacement of the inner core region and is related to many tokamak phenomena including snakes, long-lived modes in spherical or more conventional devices. Such internal helical states occur in hybrid-like regimes when there is a radially extended region where the safety factor is close to unity. Recent calculations predict the possibility of helical equilibria in ITER hybrid scenarios [1]. Experiments show that they strongly affect fast particles. This conclusion is evidenced by the neutron emissivity, related to ionization processes between fast ions and background deuterium/tritium. In MAST discharges, it is found that when a Long-live mode (LLM) [2] develops, as q_{min} approaches unity, the neutron signal drops in the central region of the plasma. When q_{min} crosses unity and the LLM fades away (equivalently the helical displacement shrinks), fast ion confinement is restored and the neutron signal returns to its initial intensity. It appears that the helical geometry is fully responsible for the expulsion of the hot particles out of the core region. Such interpretation demands for theoretical and numerical confirmation.

Self-consistent fast ion distributions are usually obtained using a code that solves the guiding-centre equations, with an appropriate fast ion source (e.g. NBI pinis) and sink (e.g. collision operators). Straight field-line coordinate systems, such as Boozer coordinates, are ordinarily convenient due to the simple separation of longitudinal and cross-field motion, and the simple expression of magnetic differential operators. However, these coordinates are found to be near-singular at the boundary of the internal helical region associated with an $n = m = 1$ infernal mode. The ANIMEC code [3] produces an equilibrium helical state despite choosing for example an axisymmetric fixed boundary. This equilibrium solver assumes the existence of nested flux surfaces based on the premise that instabilities eventually saturate into stationary solutions to the force balance equation. The boundary, the pressure profile and the initial guess for the magnetic axis are based on experimental data. ANIMEC then uses an MHD-energy minimization principle to work out the 3D geometry of the flux surfaces and the components of the magnetic field.

A qualitative and quantitative estimate of the redistribution of NBI fast ions during a helical internal state is obtained by numerically solving the guiding-center orbits in this particular magnetic configuration. VENUS-LEVIS is used as a particle-in-cell (PIC) code following an ensemble of $\sim 400'000$ weighted markers representing the slowing-down distribution of fast ions. An NBI module has been devised to provide the source of markers and a collection of Monte-Carlo operators, mimicking Coulomb collisions with background plasma, act as sinks [4]. The fields are not affected by the hot distribution and mutual interaction between fast particles is not taken into account. The outcome of the code is a self-consistent estimation of the saturated fast ion distribution from NBI and the associated flux-averaged moments (fast ion density, pressure, current, etc.). For the purposes of fast ion transport, it is arguably sufficient to consider the lowest order expansion in the guiding-centre approximation - the higher orders only being relevant for gyro-kinetics and the study of turbulence. In contrast, full Lorenz force orbit simulations can be justified for energetic ions in compact tokamaks. The non-canonical phase-space lagrangian technique used by [5] is especially suited for a general and coordinate independent formulation. Following that approach, the implemented guiding-centre drift equations are

$$\dot{\rho}_{||} = \frac{\boldsymbol{E}^* \cdot \boldsymbol{B}^*}{\boldsymbol{H} \cdot \boldsymbol{B}^*} \qquad \dot{\boldsymbol{X}} = v_{||}\frac{\boldsymbol{B}^*}{B^*_{||}} + \frac{\boldsymbol{E}^* \times \boldsymbol{B}}{B^*_{||}B} \tag{1}$$

where $\mathbf{X}$ is the position of guiding-centre, $\rho_{||}$ is the parallel gyroradius ($v_{||} = \rho_{||}qB/m$), $\mathbf{B} = \nabla \wedge \mathbf{A}$ magnetic field, $\mathbf{B}^* = \mathbf{B} + \rho_{||}\nabla \wedge \mathbf{B}$, $\boldsymbol{E}^* = -\left(\frac{\mu}{q} + v_{||}\rho_{||}\right)\nabla B$. These equations share the same conservation properties as those derived in the Hamiltonian canonical formalism, The underlying symplectic structure entails conservation of energy in time-independent cases, conservation of toroidal momentum in axisymmetric geometry, Liouville equation for phase-space volume, etc. These are essential for stable and consistent numerical implementation of guiding-centre motion.

Numerical challenges are encountered near the magnetic axis and the region bounding the helical core. The magnetic axis is a singular point in toroidal flux coordinate systems. A spline-Fourier[1] representation of the fields on a non-linear radial grid combined with a pseudo-cartesian patch overcomes this issue [6]. The spline-Fourier representation of the equilibrium is poten-

[1] Cubic spline in the radial direction, Fourier recomposition in the poloidal and toroidal variables

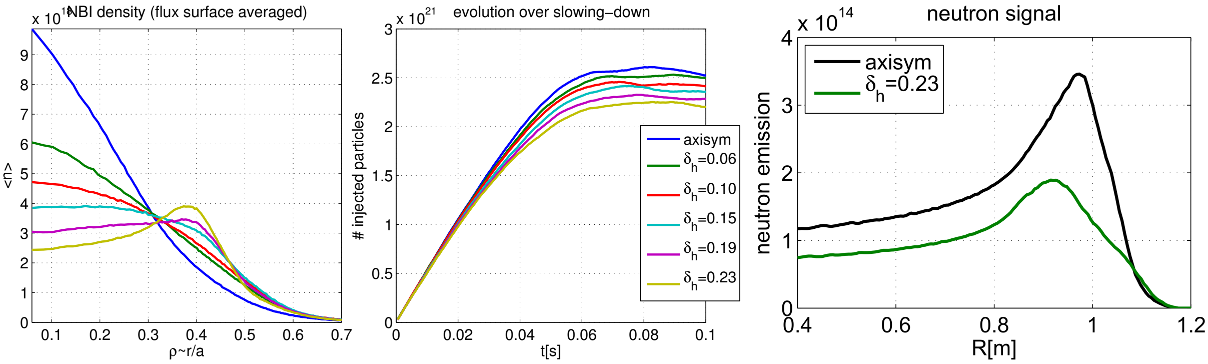

Figure 1: Fast ion density reducing in the core region with increasing helical displacement. Time evolution of the slowing-down distribution of 60 KeV NBI particles. Neutron emission due to fast deuterium.

tially useful for investigating fast ion transport in the presence of resonant magnetic perturbations (RMPs). For helical core equilibria, the singular axis becomes important to resolve since it winds over large portions of the plasma and the particles tend to have large radial excursions, encompassing the axis many times over a simulation. The transition region around q_{min} (where the $1/1$ structure depletes rapidly) is problematic because of the extreme compression of flux surfaces. In ANIMEC coordinates, the jacobian is close to becoming zero. In Boozer coordinates, constant poloidal angle curves are bent to the point where they are essentially parallel to flux surfaces. This difficulty is partially overcome by adapting the time-step proportionally to the phase-space jacobian.

It is observed that, on top of their usual radial drift, fast ions undergo large radial excursions from the inner helical core to beyond the transition region. This implies that hot particles visit larger regions of the plasma and have a flattened density profile. The latter drops proportionally to the helical displacement in the region around the magnetic axis (see Fig.1) and, in the most extreme helical displacement, is peaked off-axis, meaning that NBI deposition is no longer on-axis. The combined effect of the magnetic axis twisting around the torus and the orbits lying on larger portions of the equilibrium partially explains this phenomenon. As seen on a poloidal cut of the density (see Fig.2), as the helical core's size grows and as the compression of the flux surfaces increases, co-passing particles tend to accumulate in the uncompressed region of the magnetic equilibrium. This hot density tube helically winds around the torus on the opposite side of the magnetic axis. This also explains why the NBI are deposited off-axis. These observations compare well with the experimental data through the implementation of a virtual diagnostic of the neutron camera.

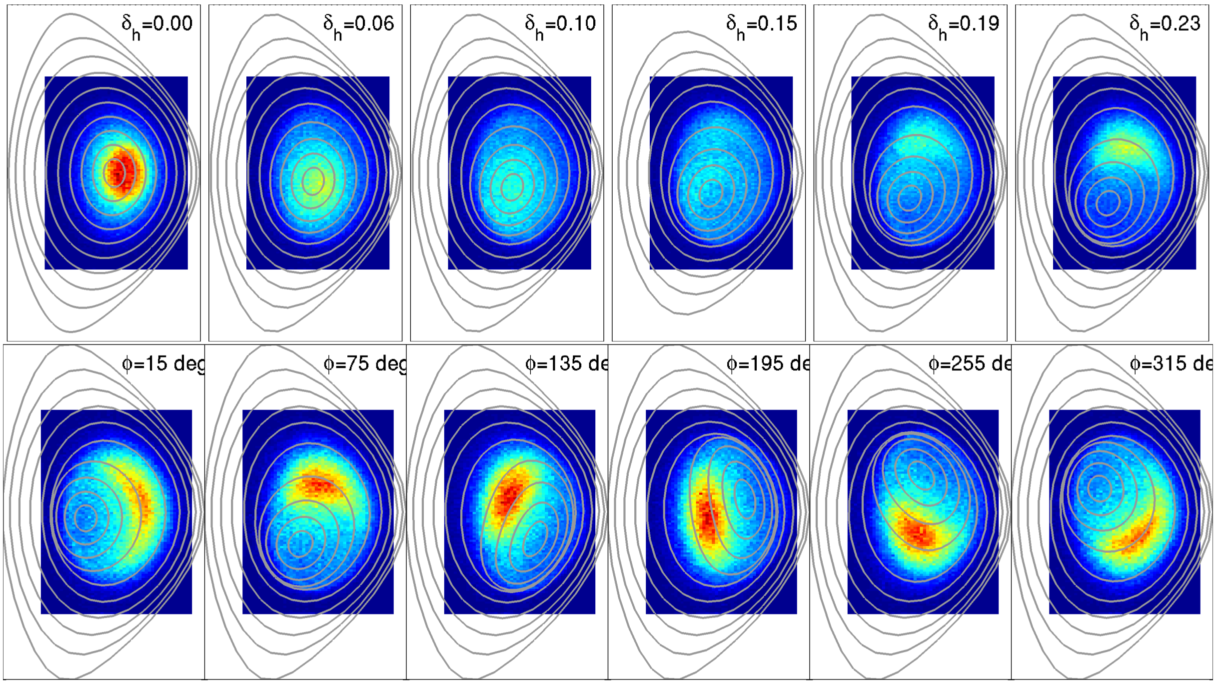

Figure 2: Poloidal cut of the fast ion density, gently shifting towards the uncompressed region with the increase of the helical displacement. Density curling around the magnetic axis in the uncompressed region for the most distorted kink.

Acknowledgments

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