Fast ion transport in presence of magnetic perturbations using full-orbit and guiding-center simulations

Julio J. Martinell[1]*, Leopoldo Carbajal[2] and Rodrigo Saavedra[3]

[1]Instituto de Ciencias Nucleares, UNAM, Mexico; [2]Type One Energy; [3] CICESE

Abstract.

Fast ion dynamics is described following their full orbit (FO) and with guiding center (GC) approximation to study the transport across a magnetic island. FO gives larger transport in general and depends on the island width, ion energy and plasma density. Island rotation reduces the flux through the island for low velocity but substantially increases at a resonant frequency. The resonance is related to the trapped ion precession frequency. Inclusion of island electric field increases the radial flux because of the non-radial component of the E-field. Certain rotation conditions may act as transport barrier.

Magnetic island & fast ions.

Fast ion confinement is affected by presence of magnetic islands. Ion transport is simulated in a circular tokamak with magnetic islands with $B_\zeta(r,\theta) = B_0/(1+\epsilon cos\theta)$, $B_\theta(r) = \kappa\epsilon B_0/[q(r)(1+\epsilon\cos\theta)]$, $\epsilon = r/R$, $\kappa = \hat{\mathbf{J}}_p \cdot \hat{\mathbf{B}}_\zeta$. The safety factor is

$$q(r) = q_0\left(1+\frac{r^2}{\varepsilon^2}\right).$$

Magnetic island given by $\delta B = \nabla\times\delta A$ with $\delta A = \alpha(r)R\mathbf{B}\cos(n\varphi - \kappa m\theta + \omega_{mn}t)$. Island width is,

$$\delta r_{mn} \approx \sqrt{\frac{4q(r)b(r)R_0}{nq'(r)}},\quad q' = \frac{dq}{dr},\quad b = \frac{m\alpha}{\epsilon}$$

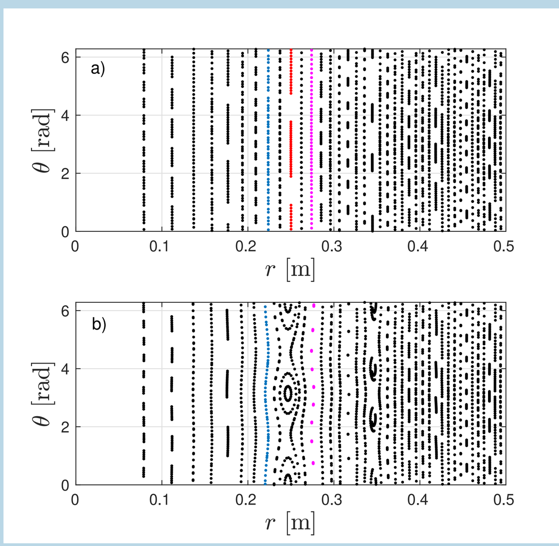


Figure 1: Poincaré section of $m/n = 2/1$ island.

Parameters: $B_0 = 2$ T, $R = 1.5m, a = 0.5m, q_0 = 1, q_a = 5$. Variation of: $\delta B/B_0 \sim 10^{-4}$ and 10^{-3}; $n = 10^{12}$ to $10^{14}cm^{-3}$;

- **FAST ions** (NBI ions) are followed with Full Orbit (FO) equations – KORC code – and with Guiding Center (GC) approximation – GCAF code. Energies $\mathcal{E} = 10\,keV, 50\,keV$

• Simulations start with ion population in a ring $r = 0.38a$. Island is at $r/a = 0.5$ ($q = 2$), $m/n = 2/1$. As they cross the island they are counted at $r = 0.54a$. Initially they are monoenergetic and mono-pitch.
The number of crossing ions is analyzed as function of time $N_{out}(t)$.

Code benchmarking

Codes were benchmarked to reproduce neoclassical transport, and the thermalization of fast ions towards Maxwellian distribution & isotropic pitch angle.

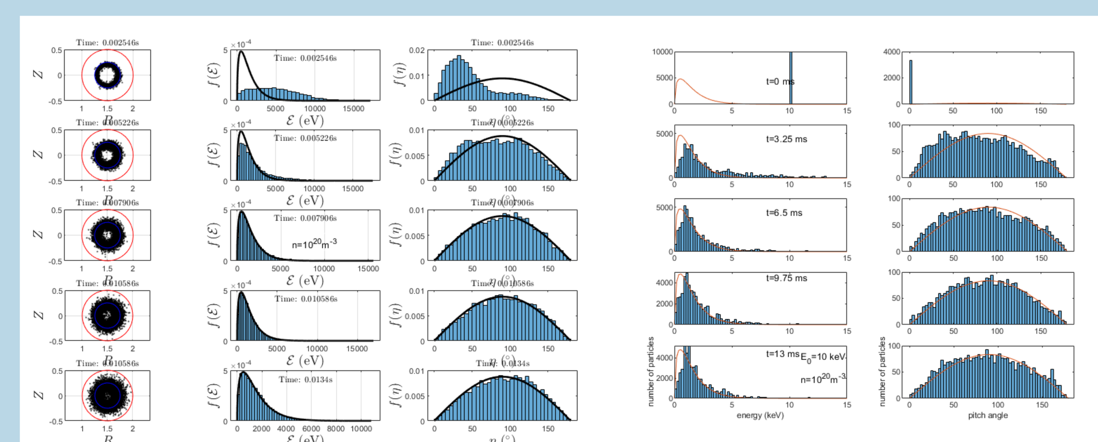
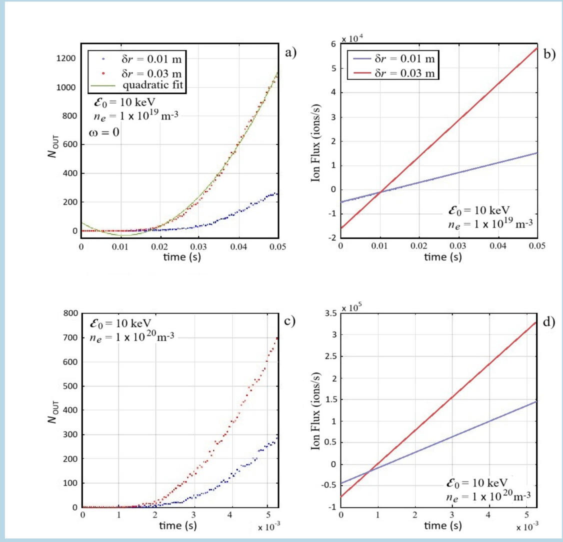


Figure 2: Thermalization of fast ions with FO and GC due to Coulomb collisions. Left: space diffusion in time. Velocity and η evolution

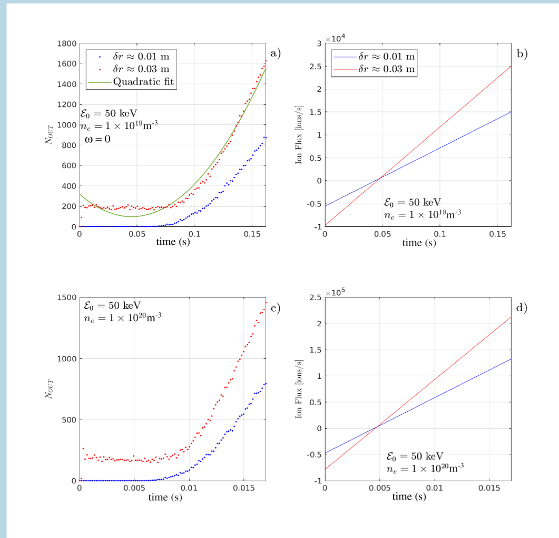
Collisions included with stochastic operator consistent with Fokker-Planck form.

FO/GC transport results comparison.

FO time evolution of N_{OUT} for ions with $E_0 = 10$ keV and $E_0 = 50$ keV, respectively, with parallel injection, for two densities (different collisionality) *Transport faster at high n.*



(a) Wider islands produce faster transport.



(b) Ion flux $= dN_{out}/dt$ obtained from parabolic fit to N_{out}.

Figure 3: Populations followed up to thermalization of fast ions. When ion energy increases the flux is reduced. Can be interpreted in terms of the collisionality since high-energy ions are less collisional and, thus, have reduced radial transport.

GC results for ions crossing the island and fluxes. Run up to thermalization time.

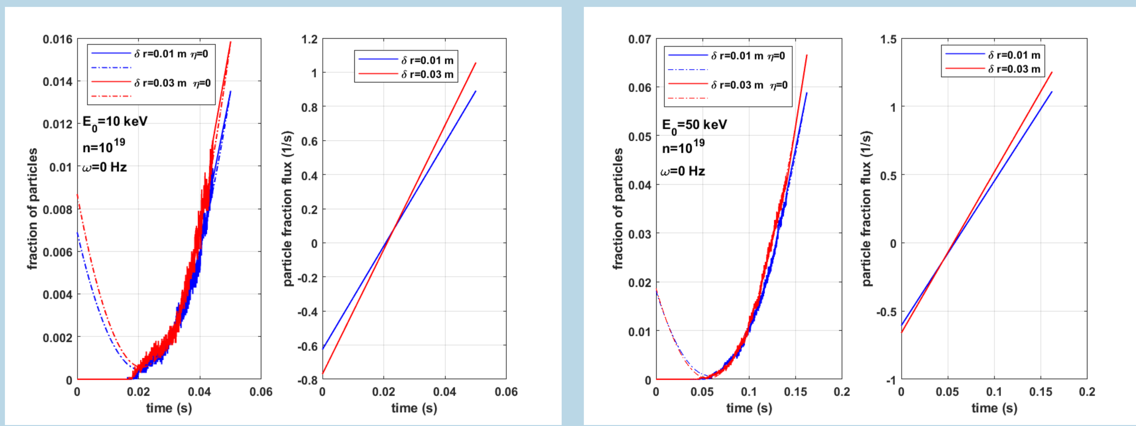


Figure 4: Left: 10 keV ions for low density plasma show small variation with island width with high flux for wide island. Right: Same behavior for 50 keV ions, but sightly larger fluxes are obtained.

Island rotation

Rotation can be either in the direction of the ion rotation (co-rotation) in counter-rotation. Important difference between FO and GC: in GC, there is very small difference between co- and counter-rotation ($\omega > 0; < 0$), in FO difference is large.

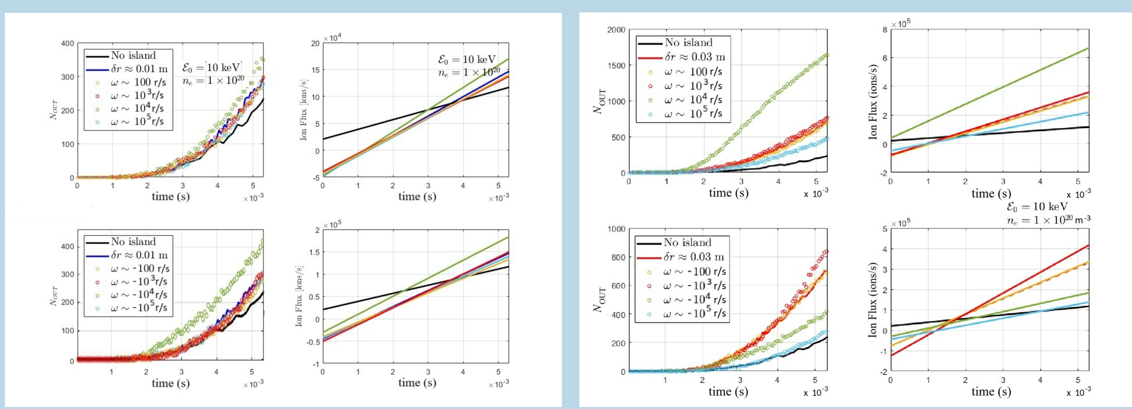


Figure 5: FO ions. Upper panel, co-rotation, lower counter-rotation. Black line is with no perturbation while the color line is for static island.

Effect of varying rotation is more noticeable for wide island, reducing transport. For narrow islands with counter-rotation, the flow can be **lower** than that with no islands: transport barrier?
Resonances observed at $\omega \sim 10^4$ rad/s: FO & GC
• **Parametric dependencies for final fluxes.**

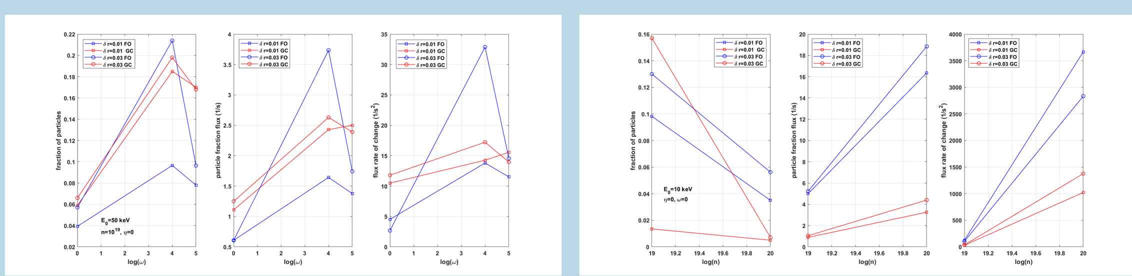


Figure 6: Left: Resonant frequency seen in FO and GC but small difference with width for GC. Right: In FO and GC, the ion crossing decreases with plasma density, while the flux and the flux rate always increase.

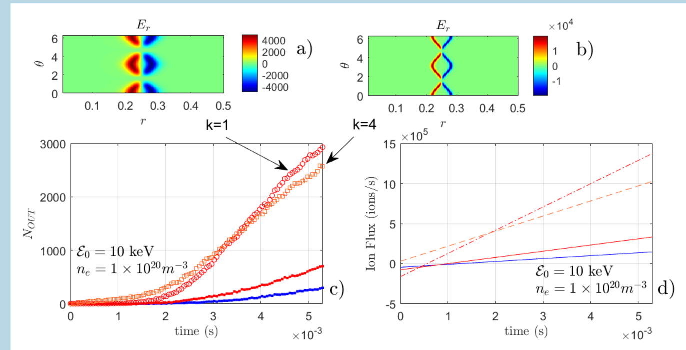
Due to ions thermalization at high n in a short time and not many of them can cross the island, even though the transport is larger than for low density.

Island electric field & discussion.

Including island-produced E-field by transport processes:

$$\phi(r,\theta,\zeta) = \phi_0\left(1 - \frac{1}{1+\exp\{-k(r-ro-d(1-\cos^2\varphi_{mn}))\}} - \frac{1}{1+\exp\{k(r-ro+d(1-\cos^2\varphi_{mn}))\}}\right)$$

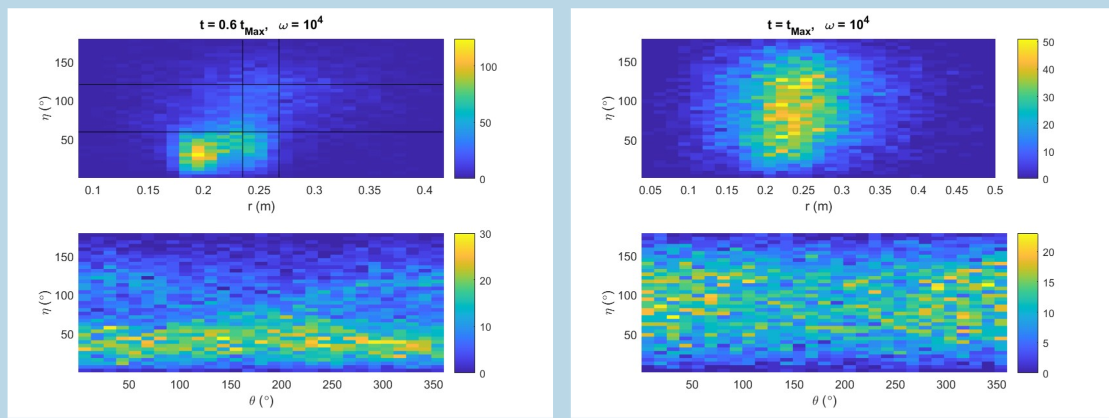
k, d determine the breadth, $2\varphi_{mn} = m\kappa\theta - n\zeta$; no rotation. Has a 3D strcuture, not radial:



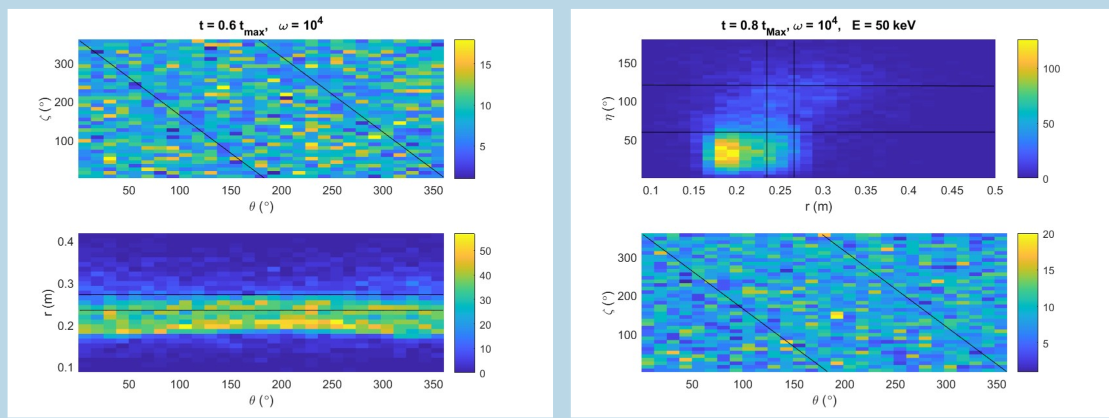
E-field increases flux, for two potential breadths. 3D nature of E-field causes flux to increase.

• **Understanding the reason for rotation resonance.**

It's of the order of precession frequency of trapped ions, so look for correlations with island position.



Ion population, FO 10 keV for two times. There is correlation of island position with trapped ions (bands), only at $t = 0.6\,t_{max}$



Left: FO Ion population in (θ,ζ) plane for 10 keV; shows bunching on field line. Right: 50 keV ions pitch angle distribution: trapped particles resonate with island position (marked with bands).

Conclusions.

• Finite Larmor radius effects, present in FO simulations, are quite important in determining the transport of fast ions in presence of magnetic islands.
• Wider islands produce larger radial flux in both FO and GC simulations.
• Island rotation frequency, first deceases ion flux and then increases with frequency reaching a maximum at a frequency of the order of the precession frequency of trapped ions. Then it decreases again: resonant process (like in [1, 2]).
• Island E-field increases the rate of ion radial crossing. This is a mere 3D effect.
• For narrow islands the reduction for counter-rotation can yield flows even below those without island, thus acting as a sort of transport barrier.

References.

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[2] L. Bardoczi, M. Podesta, W. W. Heidbrink, and M. A. Van Zeeland, "Quantitative modeling of neoclassical tearing mode driven fast ion transport in integrated transp simulations," Plasma Phys. Control. Fusion 61, 055012 (2019).

*martinel@nucleares.unam.mx

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