CRPP

Single particle orbits in anisotropic fully shaped plasmas

Martin Jucker, Jonathan P. Graves and W. Anthony Cooper

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, CH-1015 Lausanne, Switzerland

Overview

Anisotropic equilibria which are important in the context of e.g. ICRF heating are studied and its implications shown by the examples of the average toroidal magnetic drift frequency and the identification of tear drop orbits in the poloidal well of the magnetic field. Shown are the consequences of on- and off-axis heating, with either parallel or perpendicular pressure anisotropy, using newly derived exact canonical equations of motion. In general, due to the diamagnetic effect on the toroidal field, it is found that the perpendicular component of the pressure tensor, and its poloidal variation, determines the role of anisotropic pressure on single particle orbits.

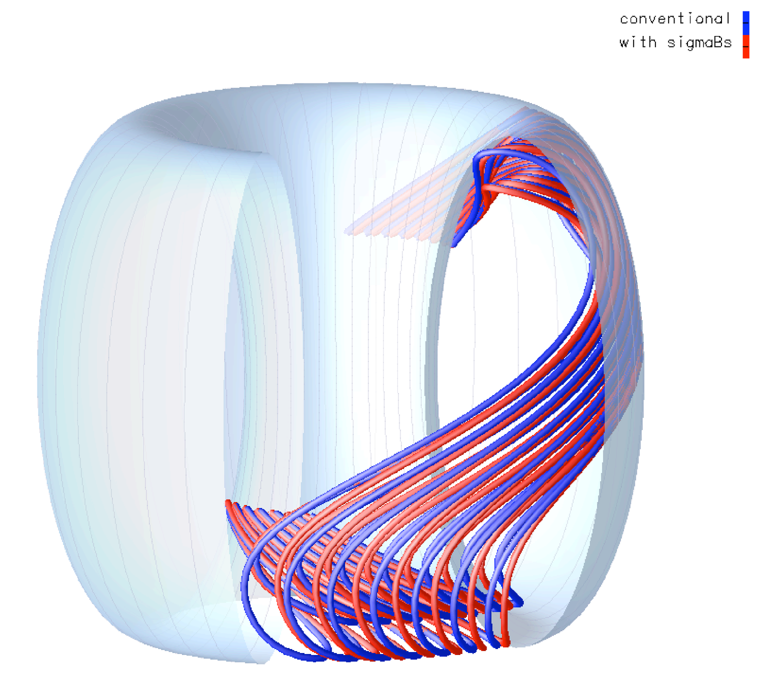
Exact canonical formulation

- Implemented new, exact canonical formulation in the single particle orbit code VENUS, including higher order radial magnetic field terms[1]
- The orbits can now exactly be identified with the drift velocity equation satisfying Liouville's theorem[2]

$$\mathbf{v_d} = \frac{e\rho\sigma[\mathbf{B}+\nabla\times(\rho_\parallel\sigma\mathbf{B})]}{\gamma m_0(1+\rho_\parallel\mu_0\mathbf{K}\cdot\mathbf{B}/B^2)}$$

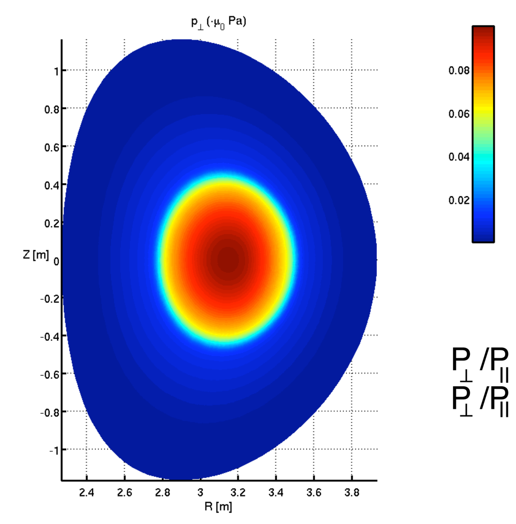
- These new terms give a contribution of the order of β.

The figure shows two orbits in a tight aspect ratio Tokamak (B0=5.6T,R0=1.1m, a=0.9m, κ=2.5) with β=2% and an energy of 500keV.



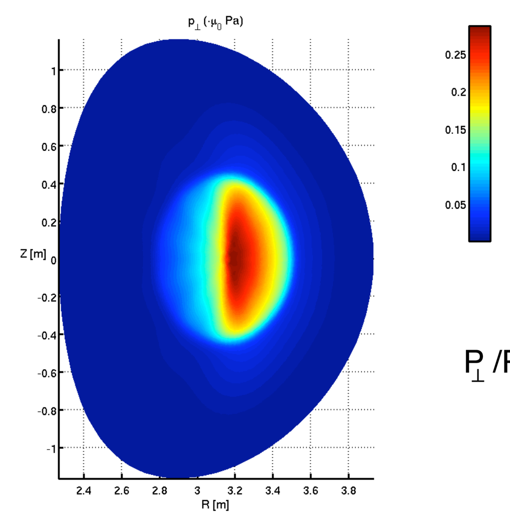
The newly introduced terms in the Hamiltonian formulation contribute to the orbit in the order of β. Blue: the orbit neglecting the additional terms, red: using exactly canonical equations of motion.

$p_\perp/p_\parallel \gg 1 \Rightarrow p = p(r,\theta)$



$P_\perp/P_\parallel = 1$
$P_\perp/P_\parallel = 1/10$

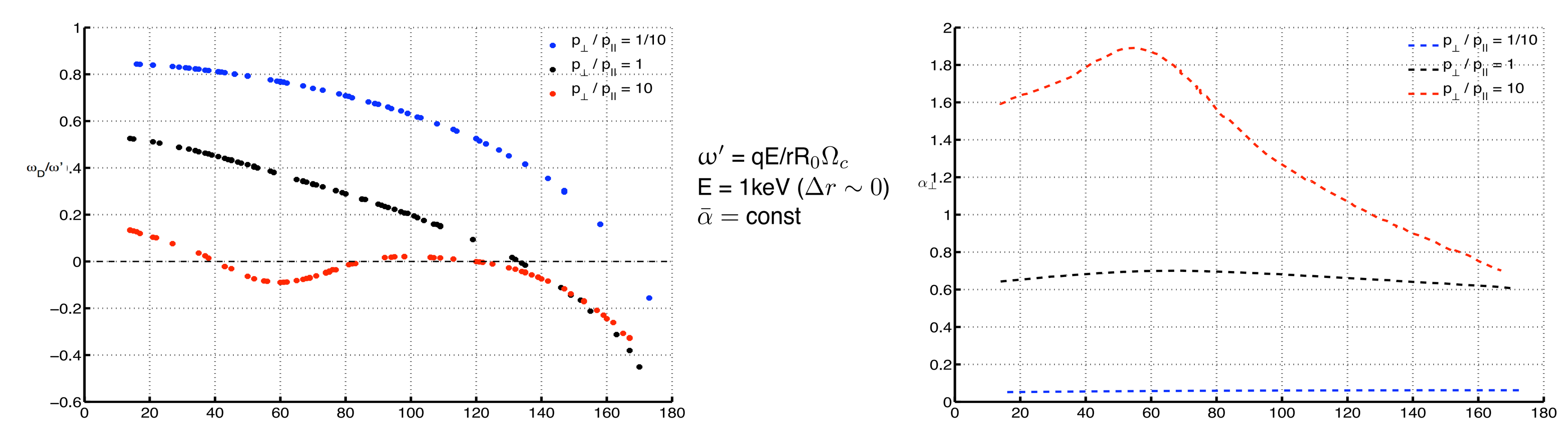
B0 = 3.1T
R = 3.2m
a = 1m
κ = 1.4
δ = 0.4
<β> = 0.7%
max β = 8%



$P_\perp/P_\parallel = 10$

- Large pressure gradient at r/a = 0.4, for enhanced diamagnetic effect on the toroidal field[3,4]
- $\bar{\alpha} \equiv \langle -R_0q^2/2B_0^2(p')\rangle_\theta \approx 1.03$
- Introduced Bi-Maxwellian distribution function into the equilibrium code VMEC[5,6]
  ⇒ parallel and perpendicular hot pressures can have different values everywhere
  ⇒ pressure is no longer a flux surface quantity but has poloidal dependence

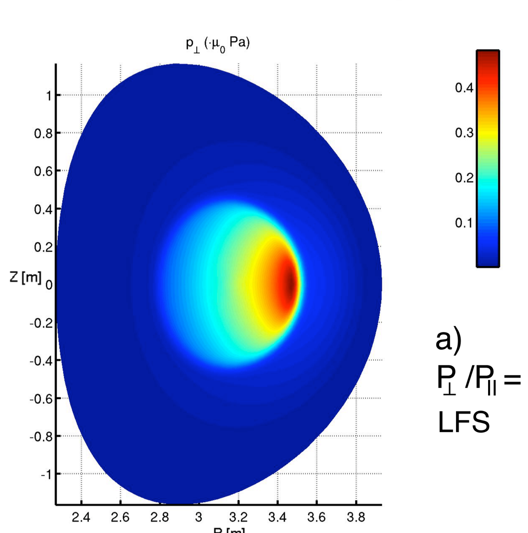
$p = p(r,\theta) \Rightarrow \omega_D = \omega_D(\alpha_\perp(\theta))$



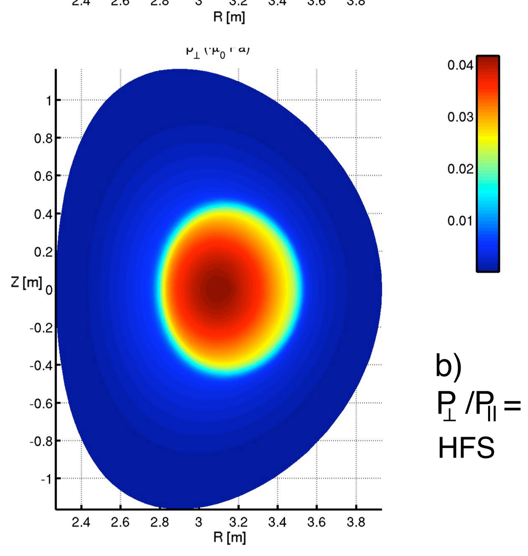
a) Normalised drift frequency as a function of bounce angle $\omega_D/\omega'(\theta_b)$ b) $\alpha_\perp(\theta_b)$

- $p_\perp \neq p_\parallel \Rightarrow \alpha = -R_0q^2/B_0^2(p'_\perp + p'_\parallel)/2 \neq \alpha_\perp = -R_0q^2/B_0^2(p'_\perp)$
- Toroidal precession drift frequency depends on $\alpha_\perp$, not α, i.e on $p'_\perp$
- ω_D depends strongly on bounce angle due to poloidal dependence of $\alpha_\perp$
- Keeping $\bar{\alpha} = \langle\alpha\rangle_\theta$ constant, ω_D is higher/lower for $p_\perp/p_\parallel < 1/ > 1$

Off-axis heating



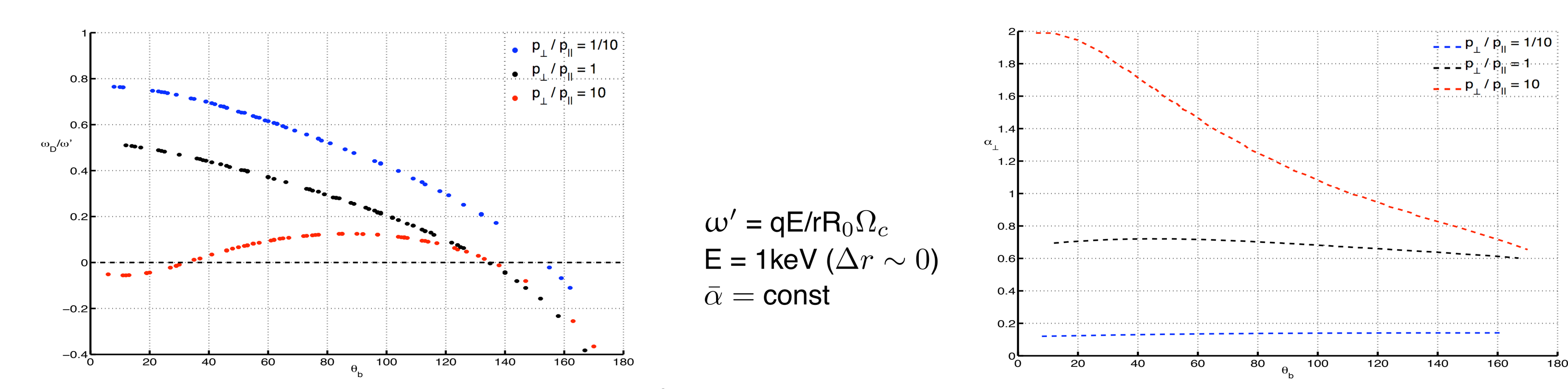
a)
$P_\perp/P_\parallel = 10$
LFS



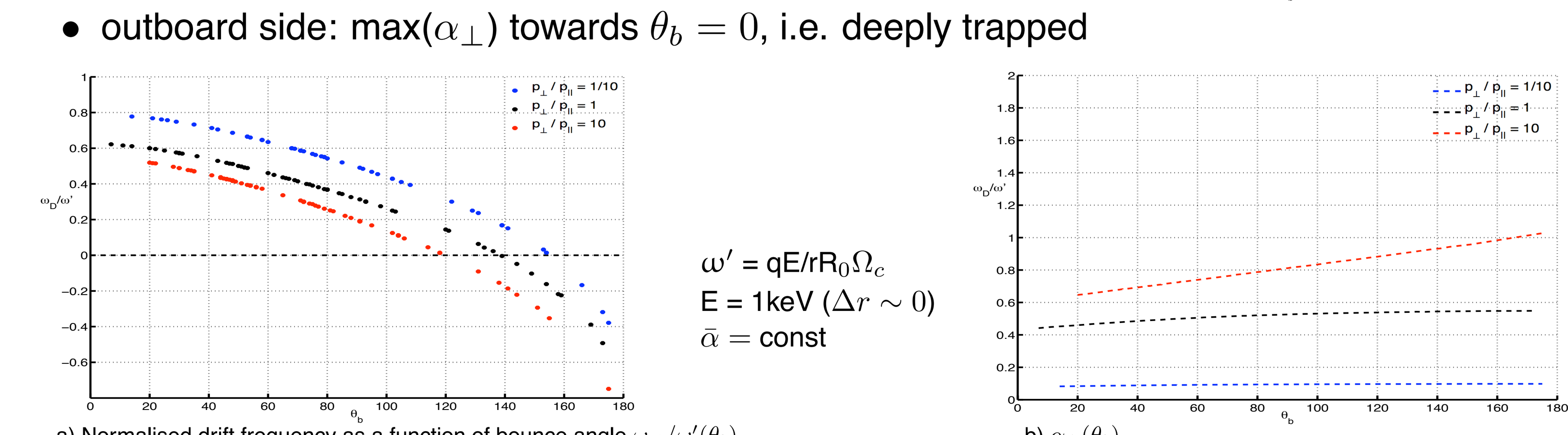
b)
$P_\perp/P_\parallel = 10$
HFS

- define hot particle deposition layer at $B = B_c$, where $p_\perp/p_\parallel$ equals the chosen value
- choosing B_c gives the spatial location of heating ($B \sim 1/R$):
  - $B_c < B_0$: LFS heating (a))
  - $B_c = B_0$: central heating (above)
  - $B_c > B_0$: HFS heating (b))
- here, the pressure gradient (max($\alpha_\perp$)) is located at $r/a = 0.4$, whereas $B_c \approx B(r/a = \pm 0.7)$
- LFS (a)): more deeply trapped particles
  ⇒ more localised, peaked pressure profile
- HFS (b)): more barely trapped particles
  ⇒ more similar to isotropic case
- for all these cases, $\bar{\alpha} \approx 1.03$

Heating location ⇒ location of maximum $\alpha_\perp$



- outboard side: max($\alpha_\perp$) towards $\theta_b = 0$, i.e. deeply trapped

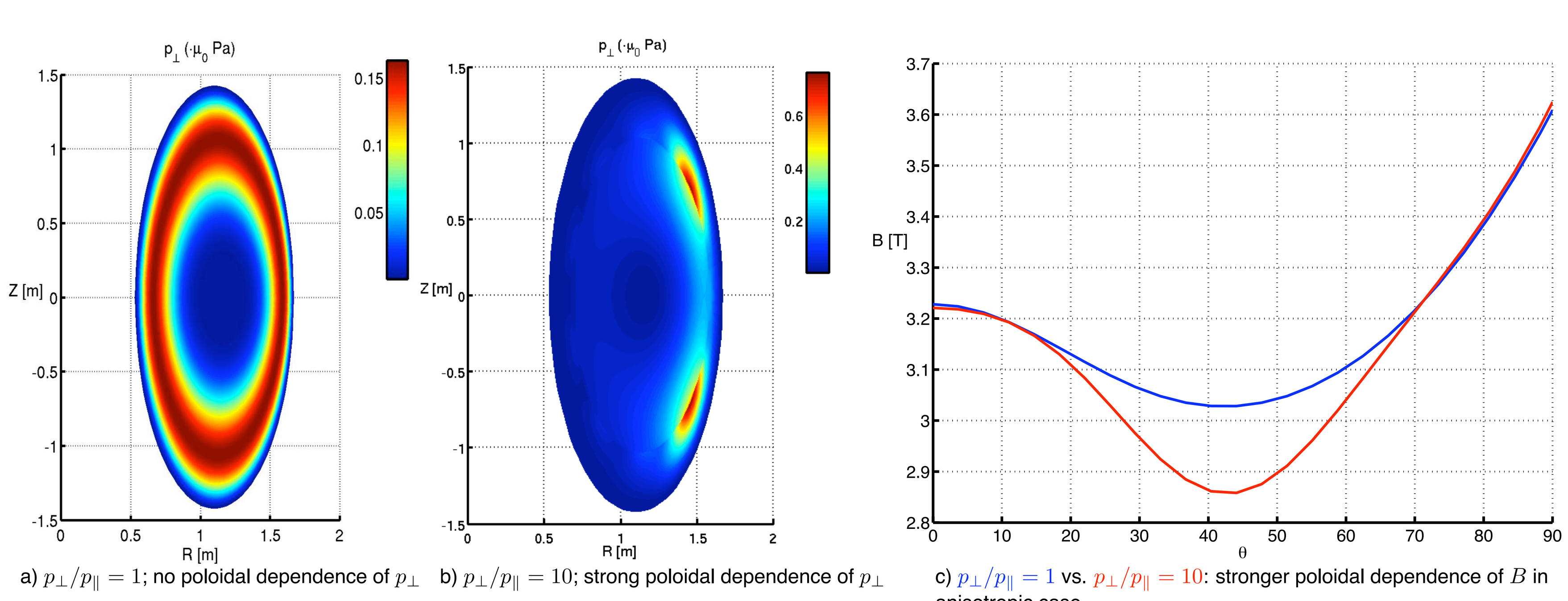


a) Normalised drift frequency as a function of bounce angle $\omega_D/\omega'(\theta_b)$ b) $\alpha_\perp(\theta_b)$

- inboard side: max($\alpha_\perp$) towards $\theta_b = \pi$, i.e. barely trapped

$p = p(r,\theta) \Rightarrow B = B(r,\theta)$

- poloidal pressure dependence opens the way for new equilibria.
  ⇒ magnetic wells in poloidal direction can be generated or at least deepended

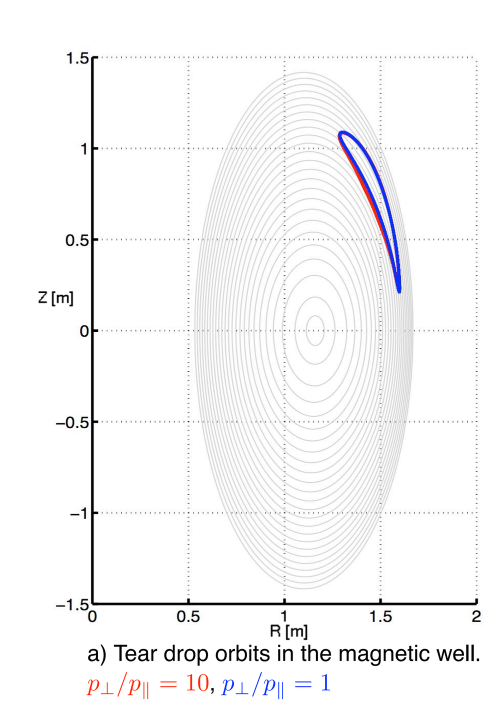


a) $p_\perp/p_\parallel = 1$; no poloidal dependence of $p_\perp$ b) $p_\perp/p_\parallel = 10$; strong poloidal dependence of $p_\perp$ c) $p_\perp/p_\parallel = 1$ vs. $p_\perp/p_\parallel = 10$: stronger poloidal dependence of B in anisotropic case

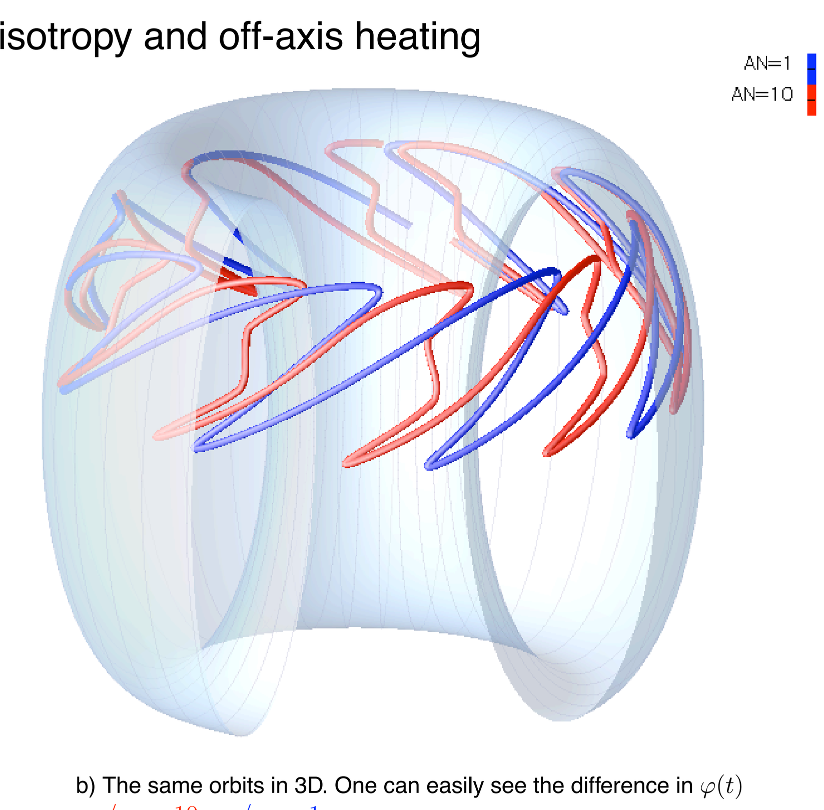
B0 = 4.6T, R = 1.2m, a = 0.9m, κ = 2.5, δ = 0, <β> = 0.9%

Non-standard orbits

- important toroidal orbit corrections due to anisotropy and off-axis heating
- here, $B \searrow \Rightarrow v_\parallel = \sqrt{1-\lambda B} \nearrow \Rightarrow \phi(t) \nearrow$



a) Tear drop orbits in the magnetic well. $p_\perp/p_\parallel = 10$, $p_\perp/p_\parallel = 1$



b) The same orbits in 3D. One can easily see the difference in $\varphi(t)$ $p_\perp/p_\parallel = 10$, $p_\perp/p_\parallel = 1$

References

[1] G.A. Cooper *et al.*, "Exact canonical drift Hamiltonian formalism with pressure anisotropy and finite perturbed fields", *to be published in Phys. Plasmas*
[2] R.B. White, A.H. Boozer and R. Hay, *Phys. Fluids* **25**, 575 (1982)
[3] J.W. Connor, R.J. Hastie and T.J. Martin, *Nucl. Fusion* **23**, 1702 (1982)
[4] M.N. Rosenbluth and M.L. Sloan, *Phys. Fluids* **14**, 1725 (1971)
[5] W. Cooper, S. Hirshman, S. Merazzi and R. Gruber, *Comp. Phys. Comm.* **72**, 1 (1986)
[6] W.A. Cooper *et al.*, *Nucl. Fusion* **46**, 683-698 (2006)

Acknowledgments

This work was supported by part by the Swiss National Science Foundation.