Fast Particle Orbits and Wall Load in a Compact Spherical Tokamak.

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Abstract. We investigate fast particle orbits and their impact on the wall loading in a compact Spherical Tokamak (ST). The generated α-particle losses may result in significant heating and erosion of the first wall and the dependence of the total and peak wall loads on the plasma current was studied. The full-orbit simulations of the α- particles indicate that a compact high field ST can be optimised for energy production by a reduction of the plasma current necessary for the α-particle containment.

1. Introduction

Due to the considerable improvement of the tokamak performance at tight aspect ratios /1,2/, fusion power plants /2/ and a steady state fusion neutron source /1/ were envisaged. In particular a compact neutron source is of interest for many branches of technology and basic research, and is considered as a step in the ST - path to Fusion Energy. Thus the neutron yield was calculated in /1/ for compact STs using the codes NFREYA and FIFPC to account for a full beam and flux surface geometry and and for the Fokker - Planck slowing down of the fast ions. In an ST Pilot plant /2/ α-particle losses may result in significant heating and erosion of the first wall. Therefore, starting with the thermonuclear source profile, α-particles are tracked until their orbit is closed or they hit the wall.

2. Deposition of and loading by the α - particles

The method to calculate a-particle orbits and their deposition on the wall is described in /2/. The rate of the α - particles generated in a ring ρ...ρ+Δ ρ, dg_α, is given by

$$dg_\alpha = 2\,\pi\,R_0\;2\,\pi\,\rho\,\Delta\,\rho\;n_t\,n_d <\sigma_f\,v>$$

where $\rho = \sqrt{V_F/(2\pi^2 R_0)}$ /1/ is the effective radius and V_F the flux surface volume. $<\sigma_f\,v>$ is the fusion rate coefficient.

We use simplified representation of the vessel wall. The vertical sides are divided in n_z and the horizontal sides in n_R sections ($n_z = 7$, $n_R = 3$ in the case of STs). To approximate a more elliptical boundary, the gridpoints adjacent to the corners can be connected thus reducing the number of gridponts to $2(n_z + n_R) - 4 = 16$.

3. Results

In Fig.1, α-particle orbits in ST FNS, R/a=0.5/0.3m, k=2.75, I_p/B_t=1.5MA/1.5T for different birth locations and pitch angles of the α-particles are shown. Depending on the starting pitch angle and the birth location, orbits with a large radial extension (left) or small radial extension (second left), or not confined orbits (right) may occur.

Fig. 2 shows alpha power deposition in a compact ST pilot plant. Comparison of full-orbit calculations and guiding centre approximation, left plot, shows visible, but not significant difference. The deposition profiles of the α-particles for I_p = 3, 4 and 6 MA are shown at the right plot and in the 3 MA case has a somewhat lower maximum because of expected deteriorating confinement of α-particles.

In Fig.3a, the heat wall loading from alphas for a pilot plant (R_o=60cm, a=40 cm, $\kappa = 3$, I_p=4 MA, P_{fus} = 27 MW) is given (in kW/m^2) for the gyro orbit model. Each beam stands for the loading on one of the 16 surface elements, the peak - loading is 1170 kW/m^2 for the 11th surface surface element at the poloidal angle ~ 120^o. The total loadings 2305 kW in the guiding center approximation and 1780 kW in the gyro orbit model differ according to the different containment fractions of 0.56 (guiding centre approximation) and 0.64 (gyro orbits). Fig.3b presents α-particle containment for the gyro (red) and for the guiding center models (blue). The containment at 4 MA decreases by 12% (gyro) if the plasma elongation κ increases from 4 to 3. Figs. 3c,d show the total and the peak wall loading for the full gyro (red) and the guiding center models (blue). It is clear that the guiding centre model overestimates the peak loading.

Fig.4 shows the stationary α - particle distribution f_α of ST FNS /1/ (left: contour plot of f_α, right: 3d-plot of f_α) at the plasma center and in the vicinity of the plasma boundary. The maxima are shifted to the critical velocity $v_c \propto \sqrt{T_e}$ because of the reduced interaction there. Due to the low critical velocity, the maximum is built in the vicinity of the origin.

The current dependence of the containment of the R/a=80cm/50cm pilot is similar to that of the R/a= 60cm/40cm pilot, the peak and total loading is roughly twice as large due to the larger plasma volume (Fig.5). No significant dependence of the containment on κ can be observed for the bigger device.

4. Conclusions.

For plasma currents below 4 MA, gyro-orbit simulations indicate an improvement of the alpha particle containment relatively to the guiding centre approximation, thus a reduction of the required plasma current, and so of the auxiliary power required for the current drive in a solenoid-less ST reactor. Whereas the guiding center and the full gyro model produce comparable results in the case of the deposition profiles, the results differ considerably in the case of peak loading calculations. Thus the full gyro calculation should be preferred.

References

/1/ A Nicolai, M Gryaznevich, Plasma Phys. Control. Fusion **54** (2012) 085006

/2/ M Gryaznevich, A Nicolai and P Buxton. Fast particles in a steady-state compact FNS and compact ST reactor. Nuclear Fusion **54** (2014), accepted for publication

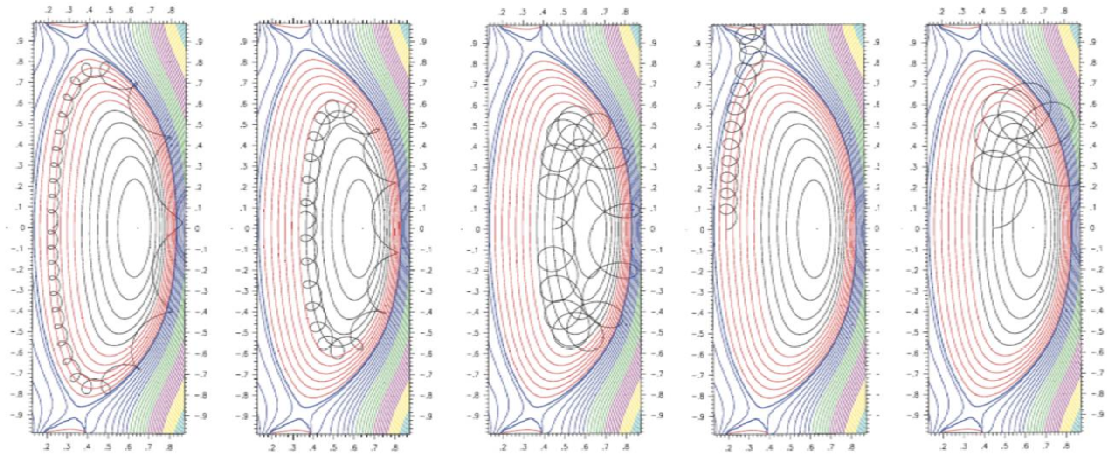
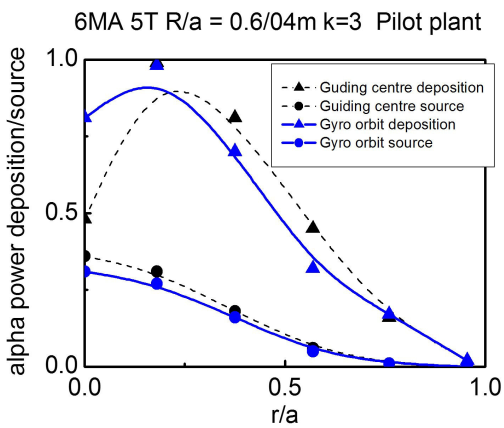


Fig.1. Alpha particle orbits in ST FNS, R/a=0.5/0.3m, k=2.75, I_p/B_t=1.5MA/1.5T for different birth locations and pitch angles of the α-particles.



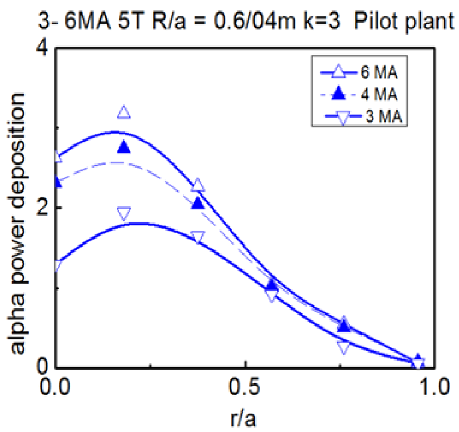
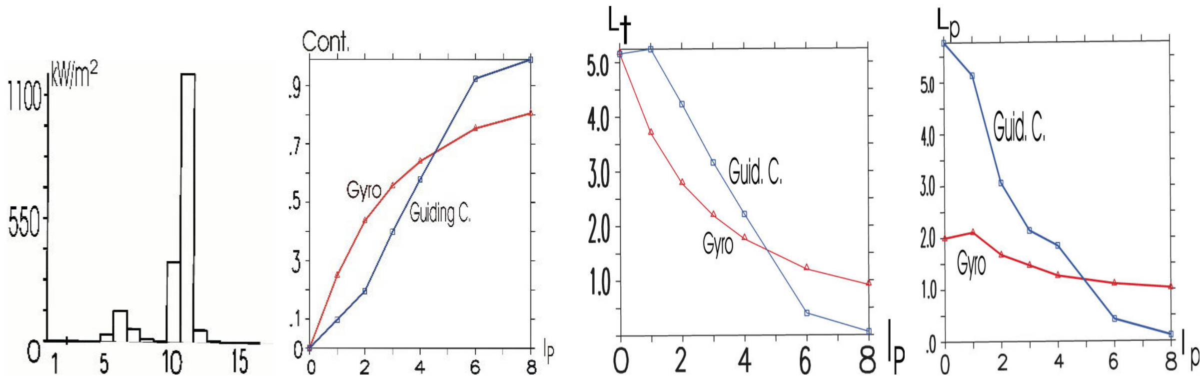


Fig.2. Alpha power deposition in compact ST reactor. Left: comparison of full-orbit calculations and guiding centre approximation. Lower curves (dots) show source profiles. Blue: gyro orbit model, black: guiding center approximation. Right: comparison of alpha power deposition calculated using full orbits for different plasma currents.



(a) (b) (c) (d)

Fig.3. a – Wall loading profile of α - particles in the pilot plant (I_p = 4 MA) using the full gyro description, b - α-particle containment for the gyro (red) and for the guiding center model (blue) model.

c - total loading for the full gyro (red) and the guiding center model (blue). d - peak loading for the full gyro (red) and for the guiding center model (blue).

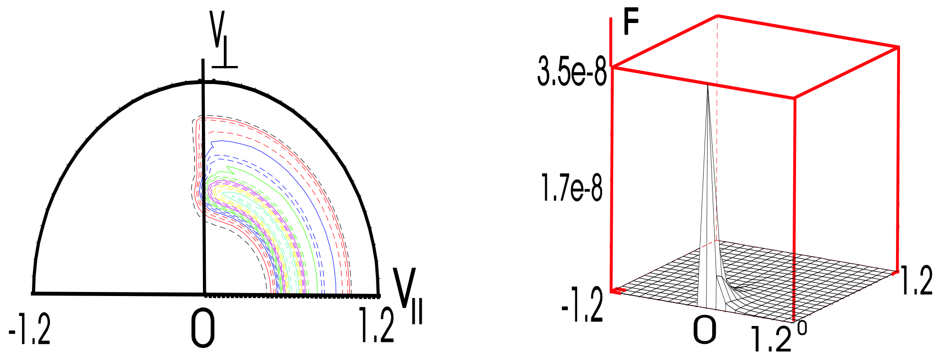


Fig. 4. Contour plot of the distribution function $f_\alpha(x, \theta, t)$ in the stationary state (left) (unit /1/ $msec^3/cm^6$) of ST FNS. The maximum (10^{-7} $msec^3/cm^6$) is build up at the critical velocity v_c given by T_e at the plasma center $T_e(\rho=0)$=5.4 keV. Right: 3d-plot of $f_\alpha(x, \theta, t)$ in the stationary state at the plasma boundary ($T_e(\rho\approx50$ cm$)\approx0.1$ keV).

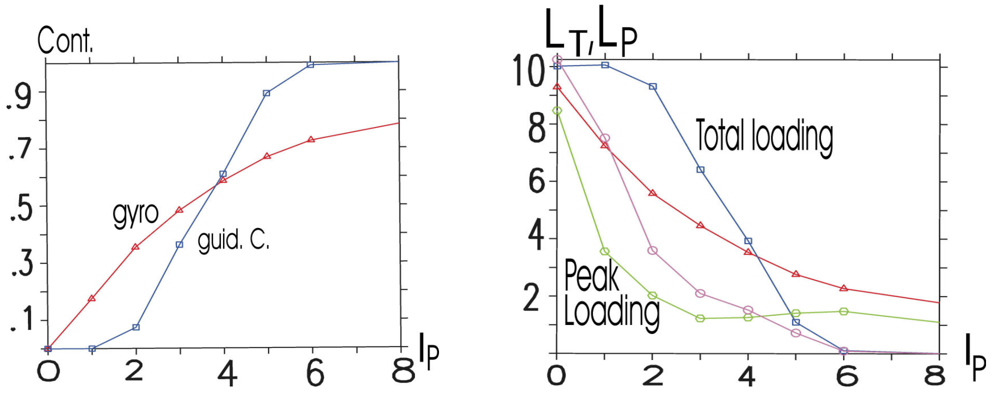


Fig 5. Containment of the R/a =80cm/50cm k=3 ST pilot plant (left): red gyro, blue guiding centre model Right: total loading (MW) and peak loading (MW/m^2), blue (total) and green (peak) for guiding centre model, red (total) and pink (peak) for gyro orbit model.