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ABSTRACT.

Hollow current operation scenarios realised in JET [1,2] are accompanied by an increased drift of charged particles outwards from the current hole area. The corresponding enhancement of radial transport results in an essential degradation of alpha confinement in tokamak reactors as compared to traditional operation with monotonictoroidal currents [3]. In the present study we investigate the effect of a toroidal current hole on the distribution function of fusion alpha particles as well as on the electron and ion power deposition profiles and on the alpha induced current in JET. Numerical results of predictive 3D Fokker-Planck modelling are presented for D-T fusion alphas confined in hollow current JET discharges.

1. MODELLING RESULTS

Our kinetic calculations of the distribution of confined alphas are based on a 3D (in Constants-Of-Motion (COM) space) steady-state Fokker-Planck code [4]. The modelling accounts for the fast ion transport resulting from slowing-down of alphas as well as from their pitch-angle scattering on bulk plasma particles in an axisymmetric magnetic field with the Flux Surfaces (FS) and safety factor profiles corresponding to a specific JET hollow current equilibrium (Pulse No: 51976, I/B = 2.5MA/ 3.45T). The hollow current profiles are characterised by the normalised flux surface radius, $x_m = r_m/a$, where r_m indicates the position of the maximum value of the current density. The plasma parameters used accord with JET Pulse No: 51976. Following Ref. [3] we assume two shapes of the alpha source term: S1(r) exhibiting pronounced peaking and matching with the fusion source profile of Pulse No: 51976, and S_2(r) representing a relatively flat thermonuclear source profile expected in steady-state operation of a hollow current tokamak.

For total toroidal currents $I \leq$ 3MA considered here, substantial current hole sizes will effect strong radial collisional transport even for 3.5MeV alphas. For toroidally trapped particles the radial diffusion rate, $D_{rr}/(a-r_m)2$, is thus of the order of the pitch-angle scattering rate, while the slowing-down induced radial convection rate, $d_r/(a-r_m)$ is comparable to the slowing-down frequency.

Note in this context the importance of the qualitatively different effect of pitch-angle scattering and of deceleration of alphas. Pitch-angle scattering induced transport resulting in enhanced collisional loss of alphas (~ 0.3-0.5 of first orbit loss) cannot vary the alpha distribution function in the MeV-range as strong as the 40÷100 times more influential slowing-down induced radial convection. The typical effect of the current hole induced radial transport on the COM alpha distribution function f_α becomes evident from Fig.1 that exhibits pronounced non-monotonic dependences on the maximum radial coordinate rmax of the guiding center along the bounce orbit as well as on the normalised magnetic moment $\lambda = \mu B_0/E$. Since several quantitative characteristics are masked in this 3-dimensional plot, we choose to turn to more informative contour representations of f_α in the following figures. Figure 2 shows the contours of the distribution function of 3.5MeV alphas in the (λ, r_{max})-plane for monotonic (x_m=0) and for two hollow current cases (x_m=0.45 and x_m=0.6). It is seen that the current hole affects the radial distribution of confined 3.5MeV alphas mainly near the inboard bound of the confinement domains. The radial dependence of f_α becomes flatter there in the current hole case with $x_m = 0.45$ (Figs.2(b), 2(e), and appears even non-monotonic for the case $x_m = 0.6$ (Figs.2(c), 2(f) with the maximum of f_α at r_{max}/a ~ 0.7, which differs consequentially from the monotonic current case (Figs.2(a), 2(d). Further, in comparison to smaller x_m (Figs. 3(a),(b) as well as to counter-going alphas (Figs. 3(d), (e), (f), the distribution of 1MeV co-going alphas in the presence of a large current hole ($x_m = 0.6$, Fig. 3c) features a relatively strong non-monotonic dependence also on the normalised magnetic moment with the maximum of f_α at λ ~ 1. A possible explanation of the non-monotonic profile f_α (r_{max}, l) is the enhanced role of slowing-down induced radial convection of fast alphas near the current hole. As seen from Fig.4, for $x_m = 0.6$ the slowing-down of 3.5MeV alphas crossing the plasma core leads to their accumulation in the rather narrow radial range $0.5 < r_{max}/\mathrm{a} < 0.7$. Note that in the case of monotonic current the slowing-down of paraxial 3.5MeV alphas results in the distribution of partially thermalised alphas in a rather wide range of r_{max}/a ~ 0-0. 6 for moderate plasma currents I~2-3MA.

Figure 5 displays the FS averaged radial profiles of the alpha particle density n, of the normalised longitudinal velocity $\langle V_{||}\rangle/V_0$ ($V_0 = 1.3\times10^7$ ms^{-1}, speed at birth), as well as of the normalised electron and ion power deposition profiles, P_e/n and P_i/n, for different current hole sizes. As shown in Fig. 5a, the presence of a current hole and the transition from a peaked source profile to a flat one cause both reduction and flattening of $n(r)$ in the plasma core. Further the strong radial convection of fusion alphas associated with larger x_m shifts the maximum of $n(r)$ to a radial position in the order of x_m. From Fig.5b we see for r<0.5 a that the averaged longitudinal velocity of alphas $\langle V_{||}\rangle/V_0$ is analogously varied from –0.02 (flat S_2(r) and $x_m = 0$) to 0.12 (peaked S1(r) and $x_m = 0.6$). At the plasma edge $\langle V_{||}\rangle$ reaches ~ $0.2V_0$ indicating the significant pitch-angle anisotropy of confined alphas. Note that $\langle V_{||}\rangle/V_0 = j_\alpha/(2enV_0)$, where j_α is the alpha induced current. Finally Fig.5c displays the profiles P_e/n and P_i/n which appear practically unchanged by variation of the shapes of plasma current and fusion source, i.e. they are effected the same way as $n(r)$.

SUMMARY

The current hole induced radial transport in JET hollow current equilibria is demonstrated to influence mainly the spatial distribution of confined alphas in the plasma core while leaving their distribution at the plasma periphery practically unchanged. A non-monotonic radial and pitch-angle distribution of partially thermalised alphas as well as a crucial reduction of their density is observed in the central ($r/a < 0.7$) area of the plasma. This peculiarity of the charged fusion product distribution function may be important for alpha driven instabilities in hollow current tokamaks. Non-monotonic current profiles result in a significant reduction and flattening of electron and ion power deposition profiles in the plasma core. The current hole effect on the alpha bootstrap current appears to be important, even most essential in the case of a flat fusion source term. The contribution of fusion alphas to plasma flows is seen to be substantial.

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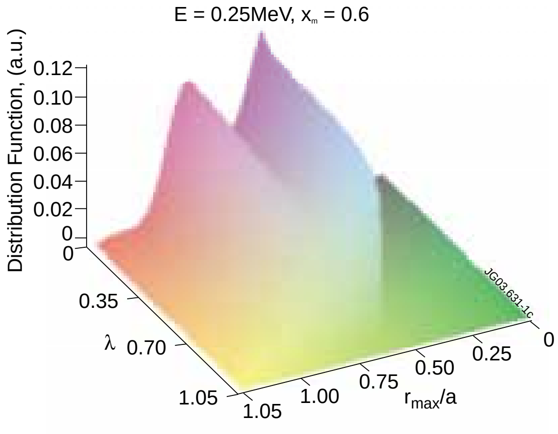

Figure 1: Distribution function of co-going 0.25MeV alphas in JET-like hollow current equilibria with x_m = 0.6

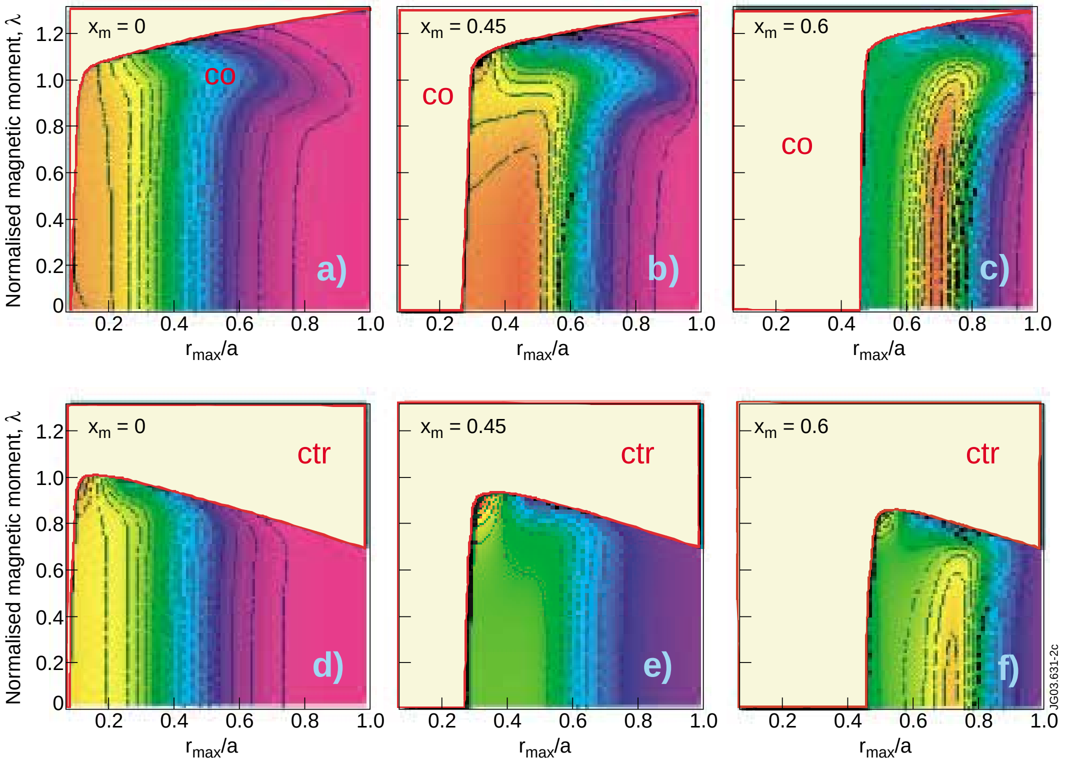

Figure 2: Contours of the distribution function of 3.5 MeV alphas in the (λ,r_{max})-plane for x_m = 0, 0.45 and 0.6.

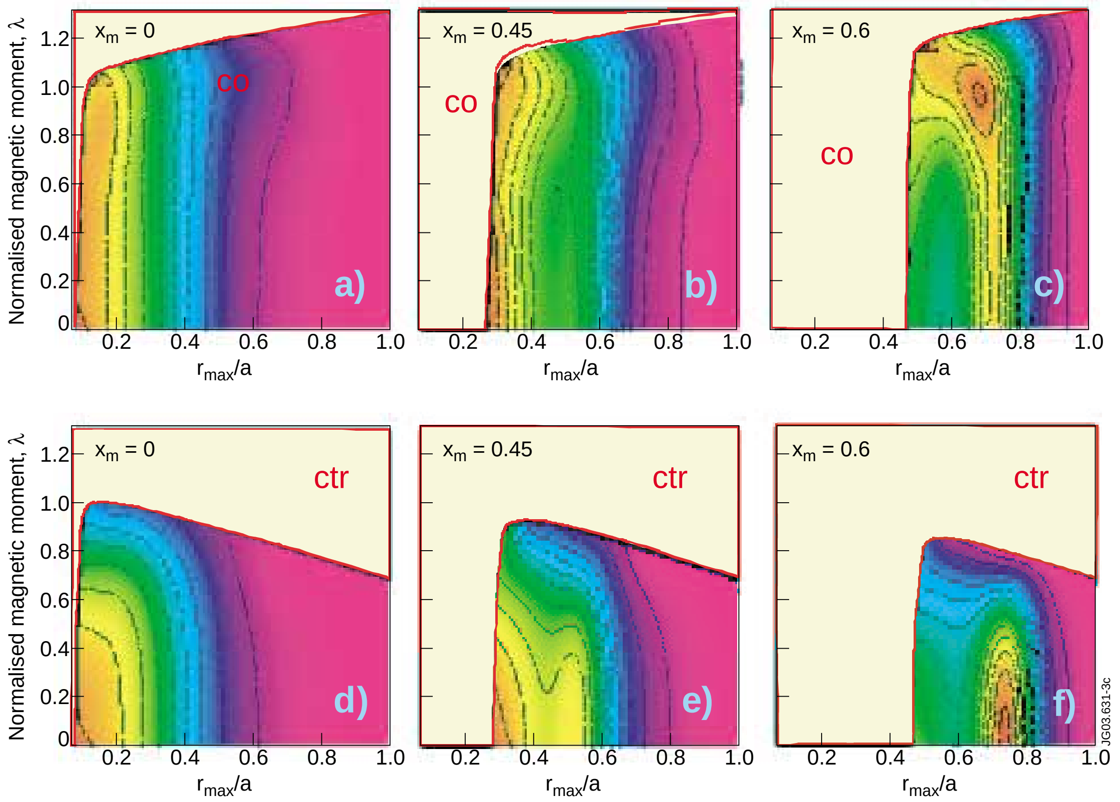

Figure 3: Contours of the distribution function of 1 MeV alphas in the (λ,r_{max})-plane for x_m = 0, 0.45 and 0.6.

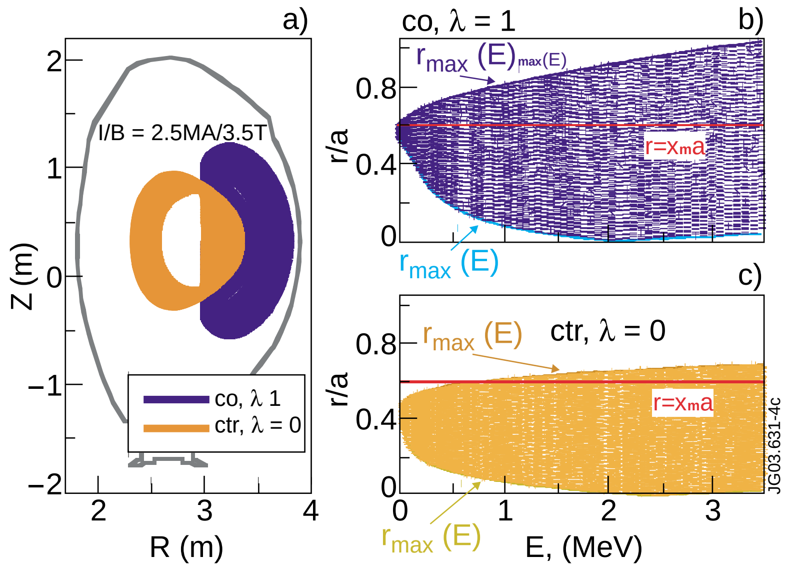

Figure 4: Slowing-down repositioning of 3.5MeV alpha orbits in HC JET equilibrium

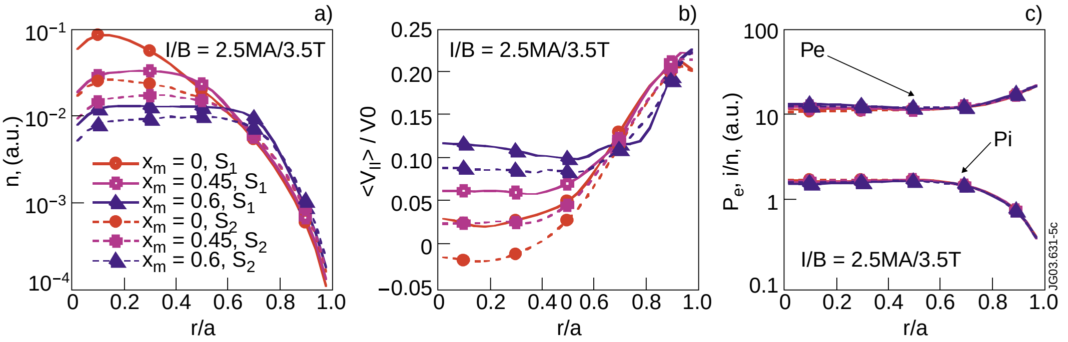

Figure 5: Alpha particle density, normaliszed longitudinal velocity and normalised power depoistion to electrons and ions versus FS radius for various current hole sizes and different source terms.