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ABSTRACT.

Aim of this paper is to perform calculations of fusion alpha loss in optimised shear scenarios in JET [1-2] associated with the hollow current profiles [2, 3]. Such scenarios trigger internal transport barriers at lower input power and render a high fusion performance in JET [1], and are considered to be an attractive avenue for the nearest JET research program. We examine here the effect of the toroidal current hole [2] in the central plasma region on both the first orbit (FO) loss as well as on the collisional loss of alphas [4,5]. The collisional loss of alphas is mainly due to scattering into the loss-cone in velocity space (i.e. pitch-angle scattering of marginally circulating counter-going alphas into unconfined (fat) bananas and due to neoclassical (NC) radial transport.

1. MODEL OF ALPHA PARTICLE TRANSPORT IN JET HOLLOW CURRENT PROFILES

Our investigation is based on a semi-analytical magnetic field model [6] with the hollow current profiles and flux surface shape parameters in JET obtained using the momentum reconstruction (MR) approach [7] combined with Motional Stark Effect (MSE) measurements [2]. In Fig.1 we display a reference MSE hollow current density profile (Pulse No: 51976) that is acceptably approximated by $j \sim x^{2l} (1-x^2)^m$ where $x = r/a$ denotes the normalized Flux Surface (FS) radius, a the plasma radius, and x_m determines the radial position of the maximum toroidal current density, m, l = 1, 2,.. . To reconstruct the equilibrium FS shape parameters and q-profiles for hollow JET currents we use the approach of finding moment solutions to the Grad-Shafranov equation with "fixed boundary conditions" proposed in [7]. The model hollow plasma current profile is chosen in the form $I(x)=I\{1-(1-x^2)^{m+1} [1+(m+1)x^2]\}$ with I designating the total plasma current. The plasma pressure is assumed as constant in the central plasma region and has been taken as $P(x)/P_0 = 1- ((x-x_m)/(1-x_m))^2\ \Theta\ (x-xm) \equiv p(x)$, where P_0 is the plasma pressure at the axis and Θ (x) is the Heaviside step function. The reconstructed profiles determining the hollow current JET magnetic configuration are shown in Figs.2 and 3. As can be seen, our reconstructed q-profiles (marked in Fig.2 as qMR) arein satisfactory trajectorial agreement with the MSE profile. The collisional loss of fusion alphas was calculated via a 3-dimensional (in the constants-of-motion (COM) space) Fokker-Planck code [4,5]. Two shapes of the alpha source term were used, $S_1 \sim (1-x^2)^8$ and $S_2 \sim n_d\, n_t <\sigma v>$, where n_d, n_t are the deuteron and triton densities. The plasma parameters taken were $T_e = 10\ p(x)$ keV, $T_d = T_t = 20\ p(x)$ keV, $n_e = 0.5 \times 10^{20}\ p(x)\ m^{-3}$, $n_d = n_t$, $Z_{eff} = 3$.

Inspecting the confinement domain in the plane spanned by the normalized magnetic moment $\lambda = \mu B0/E$ and the normalized radial coordinate r_{max}/a, where rmax is the maximum guiding centre radial coordinate along the bounce orbit, Fig.4 demonstrates a substantial reduction of the confinement domain of alphas at birth energy $E_0 = 3.5$MeV as the current hole region is enlarged (increasing x_m). In Fig.5 we show how an increase of the current hole region relocates the 3.5MeV alpha orbit with $\lambda = 1.05$ in 2MA JET hollow currents. We note that this effect is even stronger for orbits passing the central plasma region.

2. MODELLING RESULTS

The calculated contributions (FO loss fractions, L_{FO}, neoclassical loss fraction L_{NC}) as well as the total loss incorporating both the former and, additionally, also loss cone scattering, L_{cone}, in the energy range $0.25<E/E_0<1$ are displayed in Fig.6 as a function of the radial position of the hollow current maximum. For both alpha source profiles, the shift of x_m from 0.32 to 0.6 results in 4-10 higher FO loss fractions. This loss enhancement is seen to be most significant if xm exceeds the critical value ~0.45, which is in qualitative agreement with [8]. As expected the transition from the peaked alpha source S_1 to the flat model, S_2, results in a drastic raise of FO losses. Further the poloidal distribution of FO losses appears to be quite sensitive to the shape of the alpha source. The ratio of maximum alpha loss flux to the flux of lost alphas averaged over the first wall, called the peaking factor p, are here p>5 for S_1 and p~4 for S_2. Consequently, for I≥2 MA where L_{FO}≤0.2, the maximum alpha heat load is W_α~$0.25pW_n L_{FO}$ ~$0.25W_n$. In Fig.7 we illustrate, for various radial positions of the current maximum, the contributions of L_{FO}, L_{NC} and total loss fraction L_{total} (=$L_{FO}+L_{NC}+L_{cone}$), as a function of the alpha energy. In the energy range $0.25<E/E_0<1$ the fraction of collisional loss L_{coll} (=$L_{NC}+L_{cone}$) varies from (1-2)% at $x_m = 0.32$ to (3-7)% at $x_m = 0.6$. At I≤2MA Lcoll exceeds (1/3-1/4)L_{FO}, whereas for conventional current profiles the axisymmetric collisional losses are typically ≤$0.1L_{FO}$ in the case of relatively low plasma current [4]. The reason of the collisional loss enhancement of alphas in the hollow current plasmas is a predominant increase of the collisional radial diffusion resulting in rather high ratio $L_{NC}/L_{cone}>1$, contrary to the monotonic j profiles, where usually $L_{NC}/L_{cone} \ll 1$.

SUMMARY AND CONCLUSIONS

Our predictive alpha loss calculation demonstrates that hollow current profiles in JET result in a moderate increase of FO losses of alphas if the current hole region is small, i.e. if the radial position of maximum current is $r_m/a<0.5$. For such cases with I>2.5MA the FO loss fraction is less than 15% and the alpha induced heat load is less than 20% of the neutron first wall load.

The presence of a current hole leads to enhanced axisymmetric collisional loss of alphas in the energy range $0.25<E/E_0<1$, amounting to about (3-7)% loss fraction at I<2.5MA. Radial diffusion contributes mainly to the axisymmetric collisional loss of alphas. We note however, that TF ripple collisional transport [9] has not yet been taken into account here, but may play a substantial role even in the present low-rippled JET operation with hollow current profiles [10,11].

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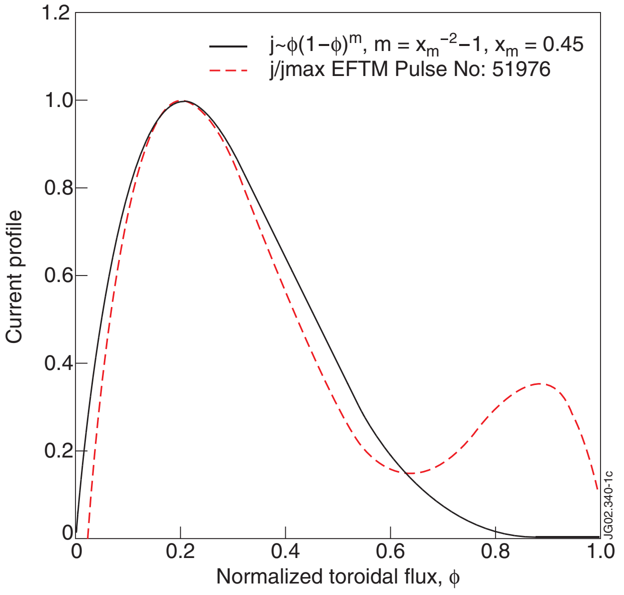

Figure 1: Reference MSE hollow current profile in JET (Pulse No: 51976)

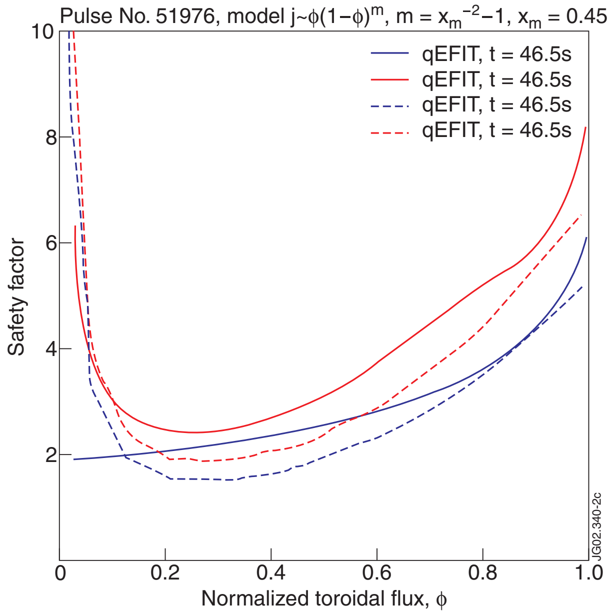

Figure 2: Safety factor profiles corresponding to hollow j profiles of Fig.1

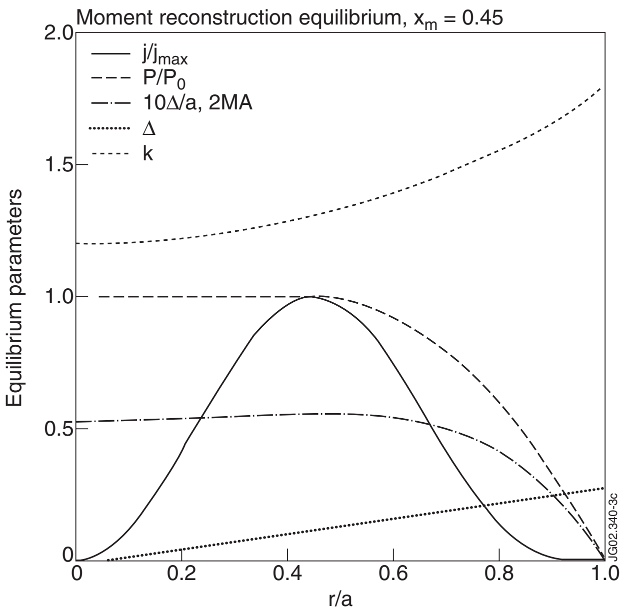

Figure 3: Profiles of P/P_0, j/j_{max} and reconstructed FS parameters

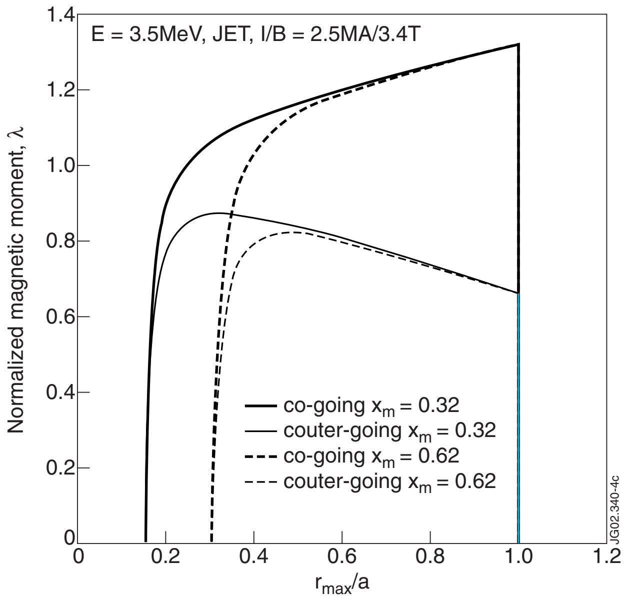

Figure 4: Confinement domains of 3.5MeV alphas in the λ - r_{max} plane

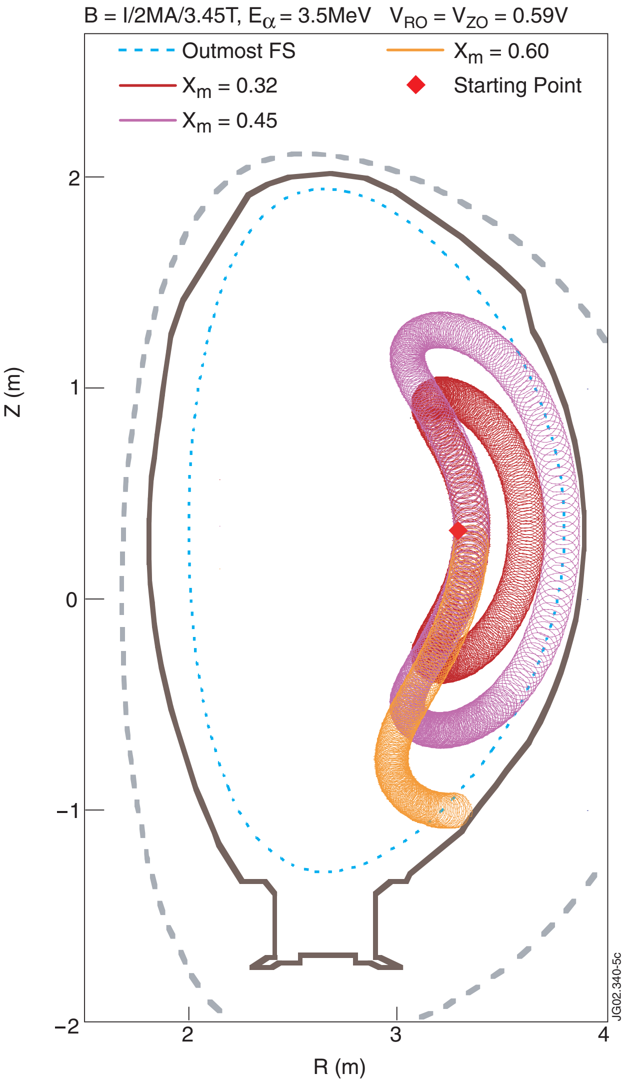

Figure 5: Gyro-orbits of 3.5 MeV alphas for different hollow currents but equal initial conditions and same outmost flux surface.

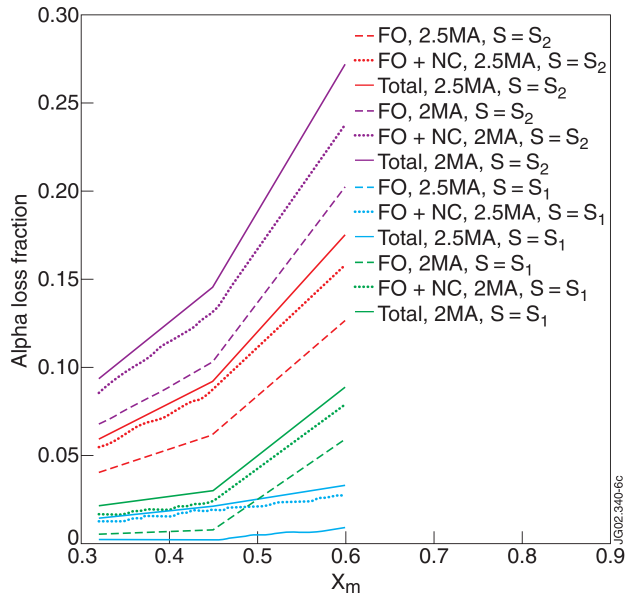

Figure 6: First orbit loss versus maximum current position.

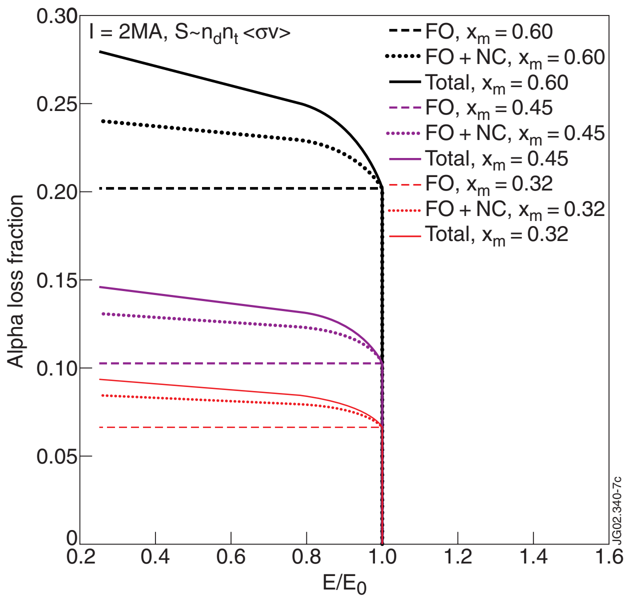

Figure 7: Alpha loss contributions versus energy for various hollow current profiles.