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INTRODUCTION

Examining the evolution of alpha particle distributions produced during blips of tritium NBI into deuterium plasmas in JET is a new and promising approach in the study of fast ion behaviour in tokamak plasmas. Thus the decay of γ-rays emitted in nuclear interactions of fusion-born alphas with beryllium impurity ions was measured after a tritium NBI blip into a D-plasma [1,2]. In current hole and in low current JET discharges higher decay rates of γ-emission were detected, while some high current discharges without reversed magnetic shear demonstrated an anomalously long decay time τ_γ of γ-intensity. The wide range of γ-decay times (τ_γ ~ 50% to 150% of the slowing down time in the plasma centre) at high currents with peaked profiles (resulting in good confinement of α-s) indicates the sensitivity of alpha relaxation to the shape of the fusion source, to auxiliary heating and bulk plasma profiles, which were varied in these discharges. An important factor is the energy spectrum difference between fusion α-s produced in plasmas with small beam deuteron population and those born if the beam ion fraction is substantial. Here we extend the Fokker-Plank model used for simulation of α-induced γ-emission [3] to accommodate the effects of anisotropy and energy broadening in the α-source. Furthermore, the effect of the spatial inhomogeneity of alpha slowing down on the relaxation of alpha distributions is investigated as well as the dependence of the latter on the position in the plasma cross section. This is viewed to be important to the multichannel γ-ray diagnostics of fast ions envisaged in JET and in ITER.

1. QUALITATIVE ANALYSIS OF RELAXATION OF WELL CONFINED FUSION A-S PRODUCED IN SHORT TIME PERIODS

We start from the simplest kinetic equation for MeV alphas taking into account only energy and time dependences of their distribution and neglecting their loss and radial transport,

$$\partial_t f = 2E^{-1/2}\,\tau_s^{-1}\partial_E\left[(E^{3/2} + E_c^{3/2})f\right] + S(E,\,t)f \qquad (1)$$

Here $\tau_s \sim T_e^{3/2}/n$ is the Spitzer slowing down time, E_c the critical energy and S the alpha source term. Important for interpretation of γ-ray measurements is the time behaviour of the number of alphas, N_α, with energy exceeding the threshold energy E_{min}(≅1.6MeV) for the reaction ^{9}Be($\alpha,n\gamma$)^{12}C. This value can be readily obtained from Eq.(1) as

$$N_\alpha\,(t,\,E > E_{min}) = \int_0^\infty d\tau_E \int_0^{\tau_E} d\tau S\,(E,\,t-\tau),\ \tau_E = (\tau_s/3)\,ln\left[(E^{3/2} + E_c^{3/2})\,/\,(E_{min}^{3/2} + E_c^{3/2})\right] \qquad (2)$$

Here τ_E is the alpha slowing down time from energy E to E_{min} (limit of detection). For alphas produced by a mono-energetic source during a very short time ($t \ll \tau_E$), i.e. $S \sim \delta(E-E_0)\delta(t)$, the number of alphas with $E > E_{min}$ is $N_{\alpha 0}(t)=const$ during the time interval $0 < t < \tau_E(E_0)$ and is zero for $t > \tau_E(E_0)$ (see Fig.1 with $\tau_0 \equiv \tau_E(E_0=3.5MeV)$). An evident characteristic of γ-emission is its correspondence to the evolution of alphas in time. Hence the γ-measurements will reflect the time delay τ and aberration from the fusion source shape. Note from Fig.1(a), that a wide-spread alpha source energy spectrum may essentially modify $N_\alpha(t)$ due to the energy dependence of τ_E. In the simplest case of alphas produced uniformly with energies $E_1<E<E_2$, the shape of $N_\alpha(t)$ is given by $N_{\alpha 0}(t)$ integrated over τ_E in the range $\tau_E(E_1)<\tau_E<\tau_E(E_2)$. Note that, for $\Delta E\neq 0$, $N_\alpha(t)=const$ for $0<t<\tau_E(E_1)$ and decreases from maximum to zero for $\tau_1[\equiv\tau_E(E_1)]<t<\tau_2[\equiv\tau_E(E_2)]$. Fig.1(a) displays $N_\alpha(t)$ in the case of a rather wide energy spectrum of S with $E_2=2E_1=5$MeV (expected when NBI tritons and NBI deuterons contribute substantially to fusion alpha production). It is seen here that the relaxation time of N_α, which we denote by τ_α, is about $\tau_E(3.5\text{MeV})\cong(0.3\text{-}0.4)\tau_s$. Cutting the source energy spectrum results in a decrease of τ_α. Note that such an τ_α-decrease one may expect due to first orbit (FO) loss of alphas that cuts the high energy range. Further, a dispersion of τ_E can be caused by the radial dependence of $\tau_s=\tau_s(r)$ due to temperature and density profiles. Taking into account that typically $\tau_s(0)>>\tau_s(a)$, the shape of $N_\alpha(t,\tau_s=\tau_s(r))$ can be qualitatively represented by the dashed red line in Fig.1(b), where the solid line demonstrates the effect of the large radial extension of alpha orbits, $\Delta r=r_{max}-r_{min}\neq 0$. The orbit averaged τ_E is determined by $\tau_s(<r>)<\tau_s(0)$ and is a maximum, τ_{max}, for alphas crossing the central area, whereas τ_{min} occurs for orbits located at the plasma edge ($<r>\sim a$). Thus radial excursions of alphas should result in an reduction of the relaxation time τ_α shown by the solid line in Fig.1(b). Finally, Fig.(1c) displays the combined effect of finite energy spectrum and radial inhomogeneity of τ_s on the relaxation of fast alphas produced by a short time fusion source. It is seen that, due to $\Delta E\neq 0$ and $\tau_s=\tau_s(r)$, the relaxation time τ_α can cover a rather wide interval from $\tau_\alpha>\tau_0(3.5\text{MeV})$ to $\tau_\alpha<<\tau_0(3.5\text{MeV})$. A quantitative examination will be carried next.

2. MODELLING RESULTS OF THE RELAXATION OF FUSION α-S IN D-PLASMAS WITH TRITIUM AND DEUTERIUM NBI

The main difference among fusion alphas born in thermal-thermal, beam-thermal and beam-beam DT reactions is the significant energy broadening as well as the anisotropy induced by non-thermal reactants. Actually, according to the laws of momentum and energy conservation, fusions of tritons having energy E_T with deuterons of energy E_D result in a broadening of the alpha source over the energy interval $|E-E_{0\alpha}|<\Delta E$ with $E_{0\alpha}=3.5MeV$ and $\Delta E\cong 0.8[(3E_T E_{0\alpha})^{1/2}+(2E_D E_{0\alpha})^{1/2}]$. For $105keV$ beam tritons and $130keV$ beam deuterons used in TTE the interval width is $\Delta E=1.6MeV$ and fusion alpha birth energies can appear in the range $2MeV<E<5MeV$. Moreover, the evident anisotropy of the beam ions in velocity space induces anisotropic birth velocity distributions of α-s. Figures 2(a), (b) display typical modelled contours of the fusion alpha source in the case of 130keV deuterons and 105keV tritons co-injected into a deuterium plasma. Figure 2(c) demonstrates the modelled pitch-angle averaged energy spectra of alphas born in thermal-thermal, beam-thermal and beam-beam DT reactions. In comparison with a-s produced in thermal-thermal fusions, here both significant energy broadening and anisotropy of beam-beam and beam-target alphas are clearly seen.

2.1. EFFECT OF THE BROADENING OF THE ENERGY SPECTRA OF FUSION SOURCE

The influence of the broad fusion source energy spectrum on the alpha relaxation can be evaluated in the simple1D kinetic model, Eq.(1), neglecting spatial dependencies of the alpha distribution.

Figure 3(a) demonstrates the modelled evolution of fast *a*-s with E>1.7MeV, for the fusion rate $S(t)$ measured in JET Pulse No: 61044 at 16MW NBI of deuterium, that resulted in a substantial population of beam deuterons; hence the energy spectra are predominated by beam- beam and beam-target fusions. Fig.3(a) displays the evolution of *a*-density for different values of Spitzer times τ_s, where the dashed curves correspond to narrow (thermal) source spectra and the solid lines demonstrate the effect of energy spreading in $S(E,t)$. The time behaviour of $N_a(t)$ is characterized by the slowing-down induced delay τ_d~0.2(0.3)t_s for narrow (wide) spectrum. The shape of $N_a(t)$ differs noticeably from the time dependence of the fusion source only during the NBI blip and a short post blip period ~$\tau_E \cong \tau_s/3$, after that $N_a(t) \sim S(t-\tau)$, i.e. it is shifted by the time delay only. The analogous behaviour is seen for the relaxation of gamma emission, as illustrated in Fig.3(b).

2.2. EFFECT OF RADIAL ALPHA PARTICLE TRANSPORT AND OF FO LOSS

The impact of the radial transport and FO loss of alphas on their relaxation was investigated via a time dependent Fokker-Planck modelling in 3D-COM space [3], taking into account the effects of finite energy spectrum. The model allows evaluate a minimum loss effect of alphas as it takes into account only slowing down induced transport and neglects the pitch-angle scattering induced loss. Calculations were carried out for JET Pulse No: 61340 in a 2.5MA/3.2T plasma with moderate size ($r < 0.3a$) Current Hole (CH) and FO loss ~17-19% and with $\tau_s(0)$= 0.8s. To investigate effect of enhanced FO loss (~50%) the plasma current was reduced to 1.25MA. Fig.4(a) compares the evolution of gamma emission depending on the τ_s radial profile and FO loss level at wide $S(E)$. It is seen that both the inhomogeneity of τ_s and I decrease reduce the delay of gamma emission by about (0.05-0.1)s. However, in the case of homogeneous τ_s the 50% FO loss drops the delay of γ-emission only at spread $S(E)$, as evident from Fig.4(b). This FO loss induced decrease of τ is about (0.05-0.07)s and is not seen in the case of narrow spectrum. Finally, Fig.5 compares the modelled and measured decay times τ_γ of averaged γ-emission (over detection time of 250ms) for Pulse No: 61340 as affected by reduction of I and by spectrum broadening. At enhanced loss we see a reduction of τ_γ, which becomes more pronounced in the case of homogeneous τ_s. Nevertheless, the modelled τ_γ overestimates the measured value by >0.1s, indicating that losses other than FO loss might cause this discrepancy.

2.3. DEPENDENCE ON THE POSITION OF THE LINE OF SIGHT

Important for envisaged multichannel γ-ray diagnostics of fast ions in JET and ITER is the study of *a*-relaxation depending on the position in the plasma cross section. Modelling of γ-emission observed along the lines Z=const in the poloidal cross section (Z=0 corresponds to the mid-plane) was carried out. Interestingly, for –0.5m<Z<0.5m the line integrated gamma emission is only weakly dependent on Z, while it becomes significant at Z>1m corresponding to *a*-orbits passing the plasma edge (maximum and minimum major radius in the mid-plane). This strong dependence is due to the vertical slowing-down induced drift of alpha orbits. This drift results in the enlargement of the vertical orbit size of co-going *a*-s and in decrease of this size for trapped and counter-going ones.

Therefore γ-emission at large Z is induced mainly by partly thermalized co-going a-s. Though there the intensity of γ-emission is relatively small, it is characterized by a strong delay relative to the fusion source and is sensitive to the shape of $S(E,\xi,t)$.

CONCLUSION

The modelling of distribution functions of alphas produced in JET by NBI blips of tritium into deuterium plasmas demonstrated the importance of source energy spectrum broadening and its anisotropy for alpha relaxation. First orbit losses and radial transport affect the alpha relaxation and are shown to reduce the delay time of alpha induced gamma emission. However, additional loss mechanisms should be accounted for to match the modelling with the measurements. An unambiguous study of gamma emission evolution requires multichord measurements with reasonable time resolution (small as compared to alpha slowing down time).

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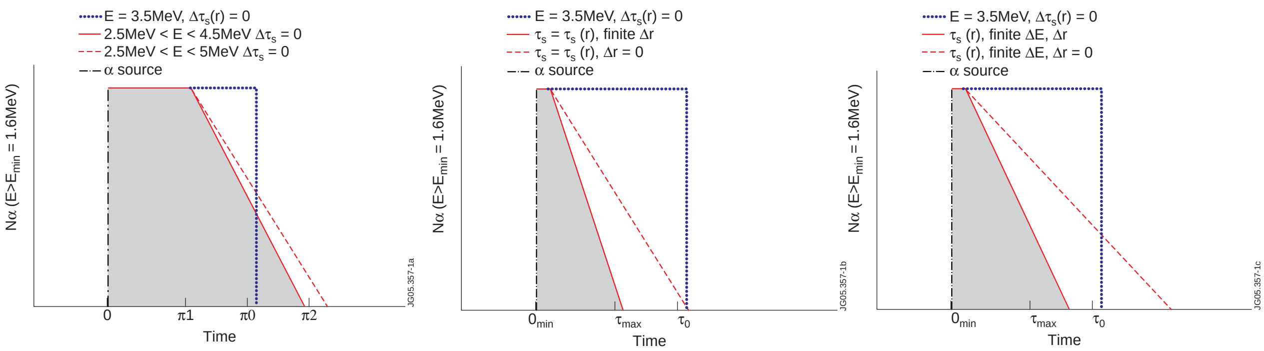
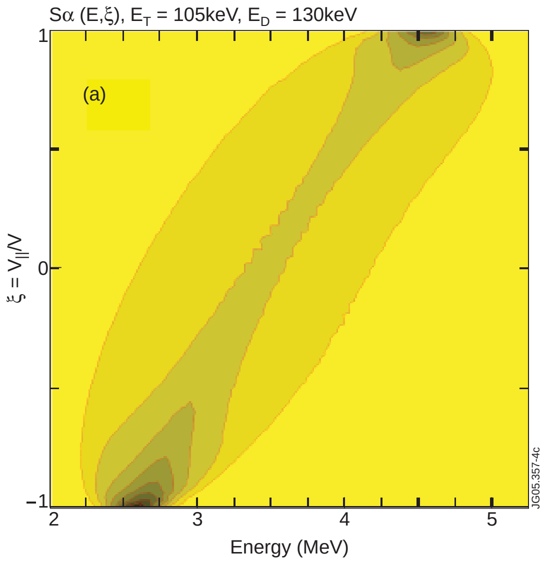
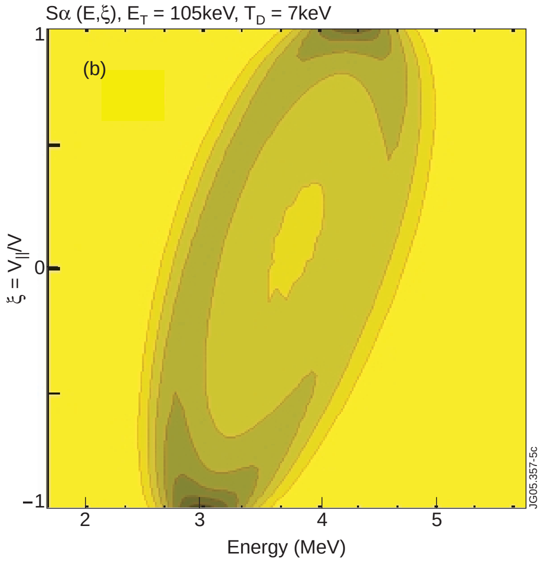


Figure 1: Qualitative depiction of the relaxation of fast alphas produced by a short time fusion source in the case of wide-spread source energies and homogeneous t_s (Fig.1(a)), monoenergetic source and inhomogeneous t_s (Fig.1(b)), and broad source energy spectrum and inhomogeneous t_s (Fig.1(c)).





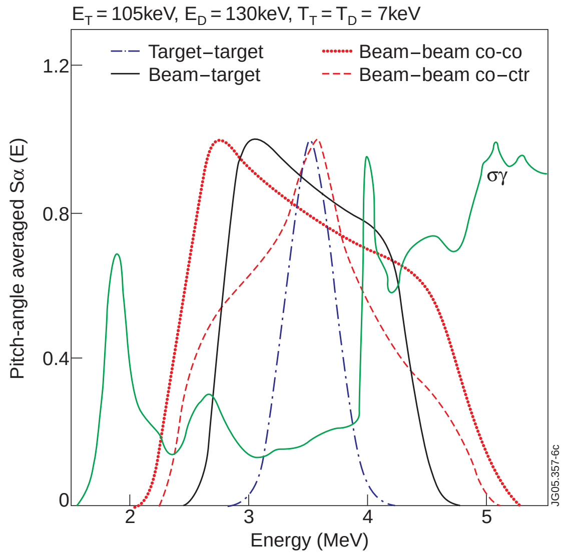


Figure 2: Contours of alpha source spectra in the (E,$V_{//}$/V)-plane from (a) beam-beam fusions and (b) beam-target fusions; Fig.2(c) shows pitch-angle averaged energy spectra of alphas produced by beam-beam, beam-target and target-target reactants.

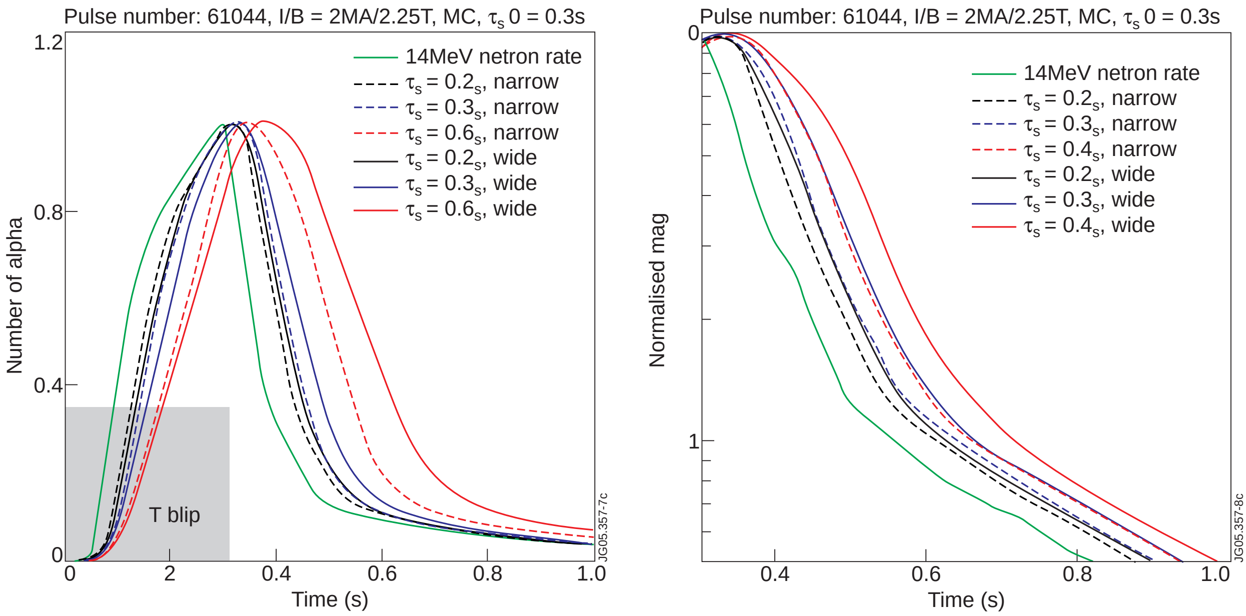


Figure 3: Modelled evolution of fast alphas with E>1.7MeV (left) and of alpha induced gamma emission (right) for wide and narrow fusion sources

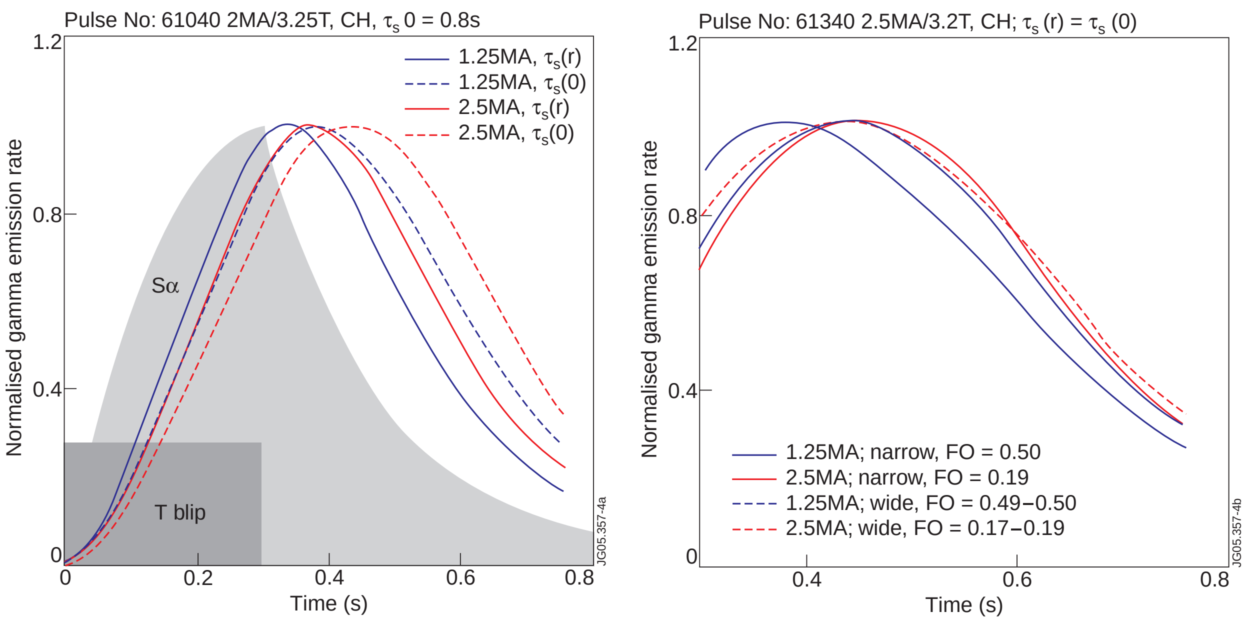


Figure 4: Modelled evolution of γ-emission rates for homogeneous and inhomogeneous τ_s from a wide energy spectrum source (left), and in the case of wide and narrow S(E) for homogeneous τ_s (right).

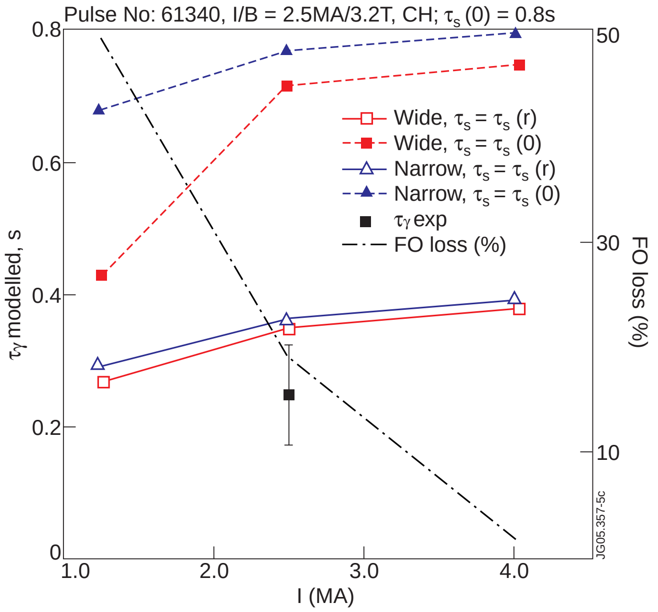


Figure 5: Modelled decay times of γ-emission vs I for homogeneous and inhomogeneous Spitzer time τ_s and for wide and narrow S(E).