Relaxation of Fusion Alpha Distributions in Tritium NBI Experiments

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1. 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 \( \tau_\gamma \) of γ-intensity. The wide range of γ-decay times \( \tau_\gamma \sim 50\% \) 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.

2. Qualitative analysis of relaxation of well confined fusion α-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,

\[
\frac{\partial f}{\partial \tau} = 2E^{-1/2}\tau^{-3}\partial E \left[ \left( E^{3/2} + E_c^{3/2} \right) f \right] + S(E,\tau).
\]

Here \( \tau \sim T_{sp}^{3/2}/n \) 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, \( N_\alpha \), with energy exceeding the threshold energy \( E_{min} \approx 1.6\text{MeV} \) for the reaction \( ^{9}\text{Be}(\alpha n)^{12}\text{C} \). This value can be readily obtained from Eq. (1) as

\[
N_\alpha(t, E > E_{min}) = \int_0^\infty d\tau E^{-1/2}\tau^{-3}\left[ \left( E^{3/2} + E_c^{3/2} \right) f \right] S(E,\tau).
\]

Here \( \tau_\alpha \) 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 \( t<<\tau_0 \), i.e. \( S \sim \delta(E-E_0)\delta(t) \), the number of alphas with \( E>E_{\text{min}} \) is \( N_\alpha(t)=\text{const} \) during the time interval \( 0<t<\tau_0(E_0) \) and is zero for \( t>\tau_0(E_0) \) (see Fig.1 with \( \tau_0 \tau_0 \). An evident characteristic of \( \gamma \)-emission is its correspondence to the evolution of alphas in time. Hence the \( \gamma \)-measurements will reflect the time delay \( \tau \) and aberration from the fusion source shape. Note from Fig. 1a, that a wide-spread alpha source energy spectrum may essentially modify \( N_\alpha(t) \) due to the energy dependence of \( \tau_0 \).

In the simplest case of alphas produced uniformly with energies \( E_1<E<E_2 \), the shape of \( N_\alpha(t) \) is given by \( N_\alpha(t) \) integrated over \( \tau_0 \) in the range \( \tau_0(E_1)<\tau_0<\tau_0(E_2) \). Note that, for \( \Delta E\neq 0 \), \( N_\alpha(t)=\text{const} \) for \( 0<t<\tau_0(E_1) \) and decreases from maximum to zero for \( \tau_0[\tau_0(E_1)]<\tau_0[\tau_0(E_2)] \). Fig.1a displays \( N_\alpha(t) \) in the case of a rather wide energy spectrum of \( S \) with \( E_2=2E_1=5\text{MeV} \) (expected when NBI tritons and NBI deuterons contribute substantially to fusion alpha production). It is seen here that the relaxation time of \( N_\alpha \), which we denote by \( \tau_\alpha \), is about \( \tau_\alpha(3.5\text{MeV})\equiv(0.3-0.4)\tau_0 \). Cutting the source energy spectrum results in a decrease of \( \tau_\alpha \). Note that such an \( \tau_\alpha \)-decrease one may expect due to first orbit (FO) loss of alphas that cuts the high energy range. Further, a dispersion of \( \tau_\alpha \) can be caused by the radial dependence of \( \tau_\alpha=\tau_\alpha(r) \) due to temperature and density profiles. Taking into account that typically \( \tau_\alpha(0)>>\tau_\alpha(a) \), the shape of \( N_\alpha(t,\tau_\alpha=\tau_\alpha(r)) \) can be qualitatively represented by the dashed red line in Fig.1b, where the solid line demonstrates the effect of the large radial extension of alpha orbits, \( \Delta r=r_{\text{max}}-r_{\text{min}}\neq 0 \). The orbit averaged \( \tau_\alpha \) is determined by \( \tau_\alpha(<r>)<\tau_\alpha(0) \) and is a maximum, \( \tau_{\text{max}} \), for alphas crossing the central area, whereas \( \tau_{\text{min}} \) occurs for orbits located at the plasma edge \( (<r>-a) \). Thus radial

\[
\frac{\Delta E}{E_0} = 0.1
\]

Fig. 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 \( \tau_\alpha \) (Fig.1a), monoenergetic source and inhomogeneous \( \tau_\alpha \) (Fig.1b), and broad source energy spectrum and inhomogeneous \( \tau_\alpha \) (Fig.1c) excursions of alphas should result in an reduction of the relaxation time \( \tau_\alpha \) shown by the solid line in Fig.1b. Finally, Fig. 1c displays the combined effect of finite energy spectrum and radial inhomogeneity of \( \tau_\alpha \) on the relaxation of fast alphas produced by a short time fusion source. It is seen that, due to \( \Delta E\neq 0 \) and \( \tau_\alpha=\tau_\alpha(r) \), the relaxation time \( \tau_\alpha \) can cover a rather wide interval from \( \tau_\alpha>\tau_\alpha(3.5\text{MeV}) \) to \( \tau_\alpha<<\tau_\alpha(3.5\text{MeV}) \). A quantitative examination will be carried next.

3. Modelling results of the relaxation of fusion alphas 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 \( |E-E_0|<\Delta E \) with \( E_0=3.5\text{MeV} \) and \( \Delta E \equiv 0.8[(3E_T E_D)^{1/2}+(2E_T E_D)^{1/2}] \). For 105keV beam tritons and 130keV beam deuterons used in TTE the interval width is \( \Delta E=1.6\text{MeV} \) and fusion alpha birth energies can appear in the range \( 2\text{MeV}<E<5\text{MeV} \). Moreover, the evident anisotropy of the beam ions in velocity space induces
target beam-beam fusions and (b) beam-target fusions. Fig. 2c shows pitch-angle averaged energy spectra of alphas from scattering induced loss. Calculations were carried out for JET shot #61340 in a 2.5MA/3.2T plasma, neglecting the pitch-angle effects of finite energy spectrum. The model allows evaluating a minimum loss effect of alphas as a time dependent Fokker-Planck modelling in 3D-COM space [3], taking into account the impact of the radial transport and FO loss of alphas on their relaxation.

3.1. 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 simple 1D kinetic model, Eq. (1), neglecting spatial dependencies of the alpha reactions. In comparison with α-s produced in thermal-thermal fusions, here both significant energy broadening and anisotropy of beam-beam and beam-target alphas are clearly seen.

3.2. 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 evaluating 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 shot #61340 in a 2.5MA/3.2T plasma with moderate size \((r < 0.3a)\) current hole (CH) and FO loss ~17-19% and with \(\tau(0)\)
To investigate effect of enhanced FO loss (∼50%) the plasma current was reduced to 1.25 MA. Fig. 4a compares the evolution of gamma emission depending on the $\tau_s$ radial profile and FO loss level at wide $S(E)$. It is seen that both the inhomogeneity of $\tau_s$ and $I$ decrease reduce the delay of gamma emission by about (0.05-0.1)s. However, in the case of homogeneous $\tau_s$ the 50% FO loss drops the delay of $\gamma$-emission only at spread $S(E)$, as evident from Fig. 4b. This FO loss induced decrease of $\tau_s$ 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 $\tau_{\gamma}$ of averaged $\gamma$-emission (over detection time of 250ms) for shot #61340 as affected by reduction of $I$ and by spectrum broadening. At enhanced loss we see a reduction of $\tau_s$ which becomes more pronounced in the case of homogeneous $\tau_s$. Nevertheless, the modelled $\tau_{\gamma}$ overestimates the measured value by >0.1s, indicating that losses other than FO loss might cause this discrepancy.

### 3.3. Dependence on the position of the line of sight

Important for envisaged multichannel $\gamma$-ray diagnostics of fast ions in JET and ITER is the study of $\alpha$-relaxation depending on the position in the plasma cross section. Modelling of $\gamma$-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 $Z>1$m corresponding to $\alpha$-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 $\alpha$-s and in decrease of this size for trapped and counter-going ones. Therefore $\gamma$-emission at large $Z$ is induced mainly by partly thermalized co-going $\alpha$-s. Though there the intensity of $\gamma$-emission is relatively small, it is characterized by a strong delay relative to the fusion source and is sensitive to the shape of $S(E,\xi,t)$.

### 4. Summary

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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### References

3. V. A. YAVORSKIJ, et al., ibid, paper TH/P4-4