Confinement of Charged Fusion Products in Reversed Shear Tokamak Plasmas

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Abstract. Measurements of the decay of gamma (γ) rays (due to interactions of alpha particles with beryllium) in JET Trace Tritium Experiments have demonstrated significant sensitivity of γ-rays to the magnetic shear in the plasma core. In discharges with relatively high currents (I>2MA) observed γ-decay rate after a short tritium NBI blip was close to the classical slowing down rate of fusion alphas in the case of monotonic *q*-profile. In discharges with a current hole about 1/3 of the plasma radius and in low current (≤1MA) discharges the measured decay time was much shorter than the classical slowing down time, indicating rather strong reversed shear effect on the fast alphas similar to that seen at low current (I_p=1MA). In present paper the first results of the numerical simulation of the relaxation of fast alpha distribution based on the kinetic model for NBI tritons and fusion alphas in post blip plasmas are presented. Modelling results are in a qualitative agreement with measurements in reversed shear and low current plasmas. In the frame of this model the calculated decay rates are lower than measured in the monotonic *q* cases with high currents (I>2MA).

1. Introduction

Recent tokamak studies [1-6] show the attractiveness of operational scenarios with internal transport barriers (ITBs) that provide improved energy confinement with reversed magnetic shear in the plasma core. The corresponding scenarios are associated with hollow toroidal current profiles [2-6] and a weak poloidal field over a significant central region [4, 5]. Whereas the presence of ITBs is beneficial to the energy confinement of the bulk plasma, the reversed shear (RS) is expected to deteriorate the confinement of fast ions. In strong RS plasmas there is an almost currentless core. In such 'current hole' (CH) plasmas, the extent of the region of near-zero poloidal field can reach about 40-50% of the minor plasma radius. In comparison to a monotonic *q* tokamak, numerical simulations [7] show that a current hole induces a larger radial excursion of fusion alphas leading to enhanced first orbit and collisional losses, and, consequently, to an overall reduction of alpha heating.

Experimentally, the influence of a current hole on the relaxation of the density of fast alphas after NBI tritium blips into deuterium plasma has been investigated recently in Trace Tritium Experiments (TTE) on JET [8, 9]. In discharges with relatively high monotonic currents (I>2MA) the observed decay rate of γ-rays (due to nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$) was close to the classical slowing down rate of fusion alphas, while in 2.5MA discharges with a current hole as large as about 1/3 of the plasma radius as well as in low current (≤1MA) discharges the measured decay time was comparable to the decay time of *dt*-neutrons and was much shorter than the classical slowing down time, indicating rather strong RS effect on the fast alphas similar to that seen at low current (I_p=1MA). The purpose of present paper is the modelling of the reversed shear effect on the relaxation and confinement of fusion alphas in TTE experiments on JET.

2. Results of γ-ray measurements of fusion alphas in TTE

In Trace Tritium Experiments the information about relaxation of fast-alpha distribution after 105keV tritium blips can be inferred from the measurements of γ-ray emission arising from interactions of alpha particles with beryllium impurity ions. For adequate description of the γ-ray decay in the post blip period the following sequence of nuclear reactions should be considered

$$t + d \rightarrow n + \alpha, \tag{1}$$

$$\alpha + {}^{9}\mathrm{Be} \rightarrow n + {}^{12}\mathrm{C} + \gamma. \tag{2}$$

Taking into account the steady-state deuterium and beryllium populations one concludes from (1, 2) that the time behaviour of γ-ray emission is initiated by the evolution of NBI triton population. Energy threshold in the cross section of ${}^{9}\mathrm{Be}(\alpha,n\gamma){}^{12}\mathrm{C}$ reaction selects fast alphas with energies exceeding 1.6MeV only [9]. Therefore, at typical plasma currents in TTE (I ≤ 2.5÷3 MA) the γ-ray decay rate must be affected by $q(r)$ profiles because I ~ 2÷2.5 MA are close to critical currents, I_{cr}, required for good confinement of fast alphas with E > 1.6MeV produced in the plasma core at monotonic current (MC) [10]. A reversed magnetic shear results in an increase of the critical current up to 3÷3.5 MA and consequently in the enhanced contribution of the radial transport of alphas to the decay of the γ-rays. On-axis and off axis co-injected beam

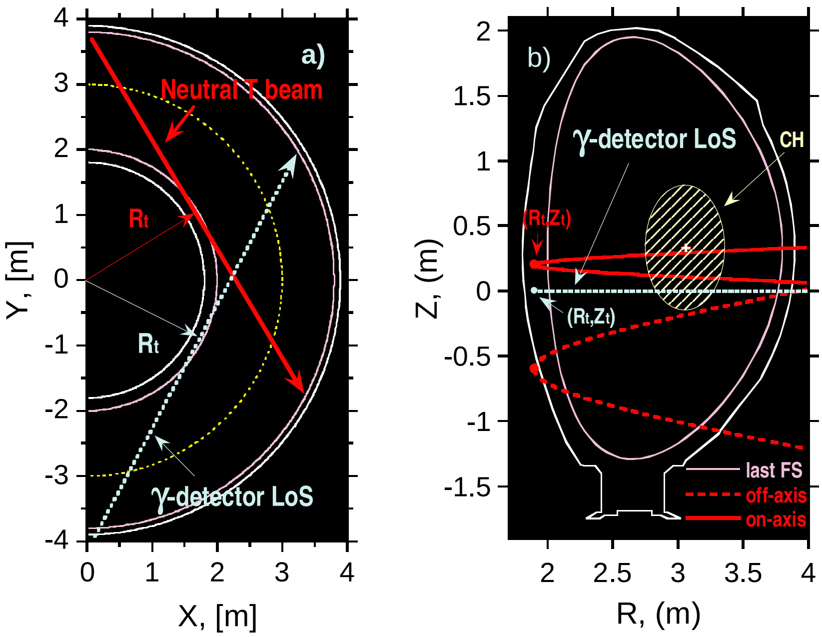

Fig. 1: Gamma detector line-of-sight (blue line) in poloidal and toroidal cross-sections in JET. Red lines show the trajectories of on-axis and off-axis tritium beams used in TTE.

tritons (see Fig. 1) were used in these experiments. Figure 1 displays also the γ-detector line-of-sight (LoS) in poloidal and toroidal cross-sections in JET. Measured γ-ray decay times for different scenarios (I_p/B_T=1-2.5MA/2.25-3.2T) are shown in Fig.2 as a function of Spitzer slowing down time of MeV alphas $\tau_{s\alpha} \propto T_e^{3/2}/n_e$ [11]. As electron heaters the alphas are expected to slow down with characteristic time $\tau_{s\alpha}/2$. This figure clearly demonstrates that in the monotonic I>2MA current discharges γ-emission is characterised by rather slow decay-rate

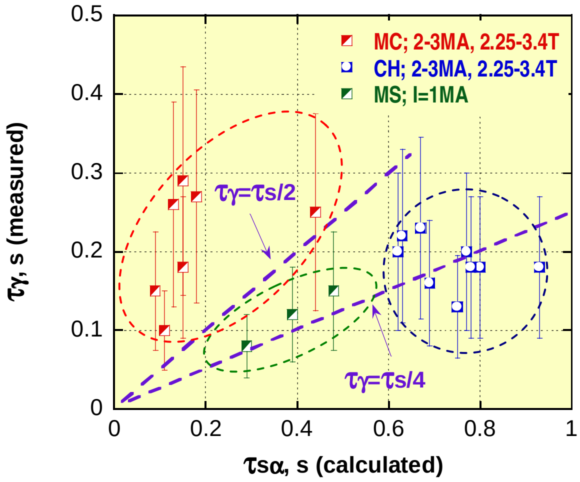

Fig 2: Measured decay rate of γ-rays from reaction $^9Be(\alpha,n\gamma)^{12}C$ after a short tritium NBI pulse compared to predicted decay from classical slowing down of alpha particles. Blue symbols – current hole plasma; red symbols – high monotonic current; green symbols – low monotonic currents.

which is about 20-40% of decay-rate in RS and low current discharges. The measured γ-rate decay is moreover dependent on the slowing down time of the parent triton distribution (reaction (1)). We therefore expect to see characteristic decays in excess of $\tau_{s\alpha}/2$. In fact the opposite is seen for the low current plasmas and CH discharges. To evaluate the γ-ray decay in TTE we use first a 1D Fokker-Planck model, which takes into account time-dependence of NBI tritons and fusion alpha distributions and collisional ion transport neglecting pitch-angle scattering. A 3D modelling accounting the radial transport of alphas will be performed then.

3. Gamma-ray decay in 1D kinetic model for NBI tritons and fusion alphas

We start from the following system of kinetic equations for tritons and fast alphas in the no-loss limit (relevant to good confinement of fast alphas)

$$\partial_\tau f_i = -V^{-2}\partial_V\left(V^3\nu_{si} - V^4\nu_{\parallel i}\partial_V\right)f_i + S_i(V,\tau), \quad i = t,\alpha \tag{3}$$

Here ν_{si} and $\nu_{\parallel i}$ are correspondingly frequencies of slowing down and parallel diffusion of beam tritons and alphas. The triton source term S_t in Eq. (3) is nonzero only during the blip duration ($0<\tau<\tau_b$ = blip period) while the alpha particle source term

$$S_\alpha(V,\tau) \propto W(V,V_b)\int d\mathbf{V}_t\, f_t(V_t,\tau)V_t\sigma_{dt}(V_t) \tag{4}$$

describes alpha particle production after the blip (due to $f_t(\tau > \tau_b) \neq 0$) as well. Factor $W = \exp[-k\,(E^{1/2}-E_0^{1/2})^2/E_b]$ with $E_0 = 3.5MeV$ and $k \cong 1.3$ in Eq. (4) represents the broadening of alpha source term caused by the finiteness of E_b/E_0. Knowledge of $f_\alpha(\tau,V)$ allows to find the time evolution of the γ-ray emission rate S_γ in the case of steady-state low temperature beryllium ions as

$$S_\gamma(\tau) \propto \int dV V^2 f_\alpha(V,\tau)\sigma_\gamma(V)V\,, \qquad (5)$$

where σ_γ is the $^9Be(\alpha,n\gamma)^{12}C$ reaction cross-section. Important for S_γ time dependence are the following relationships between collisional rates of tritons and alphas

$$\nu_{\parallel i} \cong \frac{T_e}{2E_i}\nu_{si}\,, \quad \nu_{si} = \nu_{si}^e\left(1+\frac{E_{ci}^{3/2}}{E_i^{3/2}}\right), \qquad i = t,\alpha$$
$$\nu_{st}^e = \frac{1}{3}\nu_{s\alpha}^e \propto \frac{n}{T_e^{3/2}}, \quad E_{ct} \cong 28T_e, \quad E_{c\alpha} \cong 37T_e \quad . \qquad (6)$$

As seen from Eq. (6) the slowing down time of alpha particles on electrons, $\tau_{s\alpha}^e$ is a natural scale

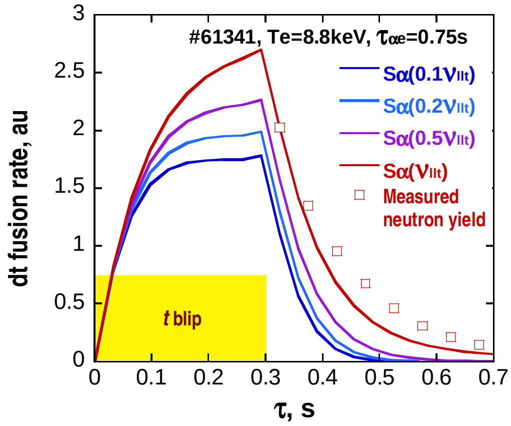

Fig 3: Variation of modelled alpha particle production $S_\alpha(t)$ with reduction of longitudinal diffusion rate of beam tritons, $\nu_{\parallel t}$, in shot #61341. Solid lines correspond to model time dependences; squared symbols represent measured 14MeV neutron emission after the blip end.

for time dependence of $S_\gamma(\tau)$. In this model the $\tau_{s\alpha}^e$ together with blip duration τ_b are basic time scales. Note that a significant parameter of the model is T_e/E_i ratio. *At* $T > 4keV$ it results in the essential contribution to the beam triton slowing down. In the case of near mono-energetic triton distribution with half width $\Delta E_i/E_i < (T_e/E_i)^{1/2}$ the finiteness of T_e/E_i makes velocity diffusion even more significant than the slowing down (due to $\nu_{\parallel t}[\mathrm{dln}\, f_t/\mathrm{dln}E_t]^2 << \nu_{st}$). Velocity diffusion is important for the adequate description of the contribution of tritons with $E>E_b=105keV$ to evolution of alpha particle source term as shown in Figure 3. One can see that the weakening of the rate of velocity diffusion of beam tritons results both in reduction of the *dt*-fusion rate, S_α, as well as in the enhanced decay of S_α after the blip as compared to measured decay rate of 14MeV neutrons. From the other hand the longitudinal diffusion of alphas, $\nu_{\parallel\alpha}$, plays only insignificant role in their distribution at the high energies ($E_\alpha>1.5MeV$) considered here due to relatively smooth energy dependence of f_α.

Figure 4 displays the time evolution of energy distributions of beam tritons and fusion alphas in shot #61341 with τ_b = 0.3s, $\tau_{\alpha e}$ = 0.75s and T_e=8.8keV during and after the triton blip. Solid lines here are $f_\alpha(\tau,V)$ and $f_t(\tau,V)$ distributions obtained when neglecting the velocity diffusion of alphas. It is seen that in spite of the smallness of T_e/E_b = 0.083 the contribution of tritons with E > 105keV to alpha production is very important. The reason is the extremely strong increase of the DT fusion cross-section $\sigma_{DT}(E)$ with the triton energy($\sigma_{dt} \sim E^{5/2}$ at 50keV

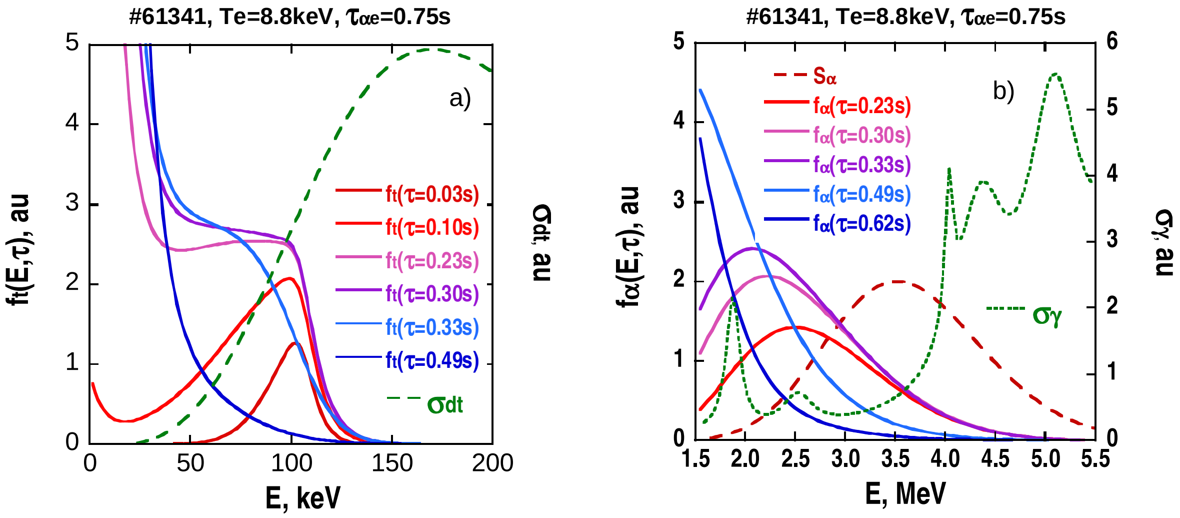

Fig. 4: Time evolution of energy distributions of beam tritons (plot a) and fusion alphas (plot b) in shot #61341 with τ_b = 0.3s, $\tau_{\alpha e}$ = 0.75s and T=8.8keV during and after the triton blip.

< E < 110*keV*) at $E \sim E_b$. The time dependencies of *dt*-fusion rate, S_α (= 14MeV neutron yield), as well as the γ-rate, S_γ, are shown in Figure 5. It is seen that both rates are essentially non-steady state with maximum S_α reached at the end of blip and maximum S_γ reached after the end of blip. We introduce the model γ-decay time, $\tau_{\gamma 0}$, as the time interval corresponding to the

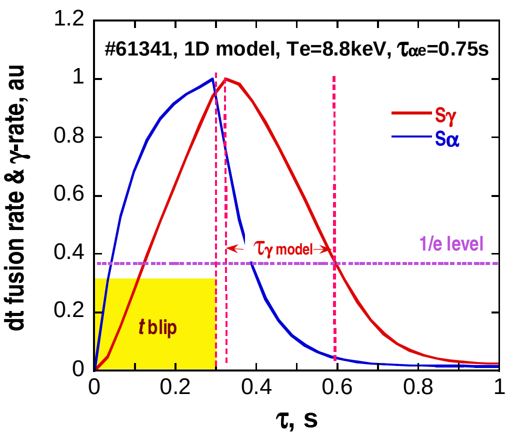

Fig 5: Modelled alpha particle and γ-rates as a function of time for shot #61341 with τ_b = 0.3s, $\tau_{\alpha e}$ = 0.75s and T = 8.8keV. $\tau_{\gamma 0}$ = 0.26s is the time corresponding to decay of γ-emissivity from maximum at t=0.33 to the 1/e level of the maximum at t=0.59s.

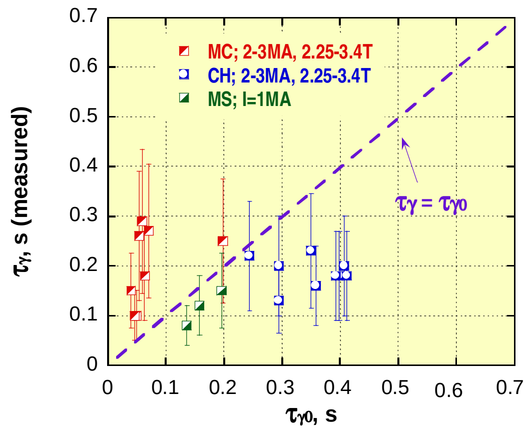

Fig 6: Measured decay rate of γ-rays vs decay time obtained from 1D kinetic model for NBI tritons and fusion alphas.

decrease of S_γ from $S_{\gamma max}$ to $S_{\gamma max}/e$. For shot #61341 the model time of γ-ray decay $\tau_{\gamma 0}$ = 0.26s, that is twice as large as measured τ_γ. Model γ-decay time $\tau_{\gamma 0}$ following from 1D kinetic model do not take into account the effect of radial transport on the alpha particle relaxation in post blip plasma. Therefore we use the plot τ_γ versus model $\tau_{\gamma 0}$ to clarify the radial transport effect of alphas on the γ-relaxation. This plot is shown in Figure 6 and clearly demonstrates the effect of magnetic shear on fast alpha confinement in plasmas with moderate plasma currents. One of the possible explanations of this effect is the convective radial transport of fast alphas induced by

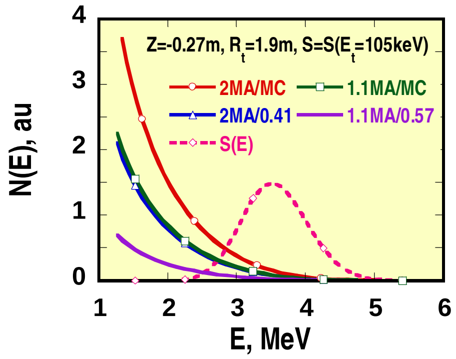

Fig. 7: Calculated distributions of DT alphas with E>1.5MeV along the LoS of the JET γ-ray spectrometer for MS and strong RS plasmas (current hole plasmas with the size of "zero" poloidal field region r_*/a=0.41 and 0.57).

slowing down. An importance of the radial transport of fast alphas for interpretation of γ-ray measurements is confirmed by the results steady-state 3D Fokker-Planck calculations of the distribution of fusion alphas along the LoS of γ-detector for typical monotonic q and RS plasmas in JET TTE shown in Fig. 7. One can see that strong RS with effective CH size r_*/a = 0.4 at I_p = 2MA results in about 50% decrease of the alpha density near the mid-plane, equivalent to the effect of 45% decrease of I_p in the MS case. Note that this density decrease essentially exceeds that of expected for the fraction of confined alphas, F=1-L, with L the fraction of first-orbit and collisional loss. According to Ref. [7] for 2MA JET plasma the alpha loss fraction L is expected to be at the level about 31% in the case of monotonic q and should reach 40% in the case of current hole with r_*/a = 0.4. Hence CH induced strong RS results only in 13% decrease of the total number of alphas confined in 2MA JET plasma contrary to 50% decrease of the number of alphas along the γ-detector LoS. This difference is due to the significant RS effect on the redistribution of confined alphas in poloidal cross-section due to slowing down radial convection. On the other hand, the energy distributions appear unaffected by RS and current magnitude.

To investigate reversed shear effect on alpha relaxation in post blip JET plasmas we carry out the time dependent Fokker-Planck modelling in 3D constants of motion space.

4. Results of 3D time-dependent Fokker-Planck modelling

Our modelling is based on the time-dependent Fokker-Planck models of the beam tritons and fusion alphas. To simplify numerical calculations when describing tritons we neglect their radial transport induced by collisions as well as the pitch-angle scattering effect. For fusion alphas we apply purely convective 3D COM Fokker-Planck model, i.e. we neglect effects of pitch-angle scattering and velocity diffusion. Investigation of the shear effect on γ-ray emission was performed for the I_p/B_T=2.5MA/3.2T plasmas both for the monotonic q and strong reversed shear induced by CH with radial extension r_*/a = 0.57. We carry out also modelling for the low-current monotonic q plasma with I_p/B_T=1MA/3.2T. Figure 8 displays the calculated evolution of the γ-rate in shot #61340 for monotonic current, CH equilibrium and for monotonic low current

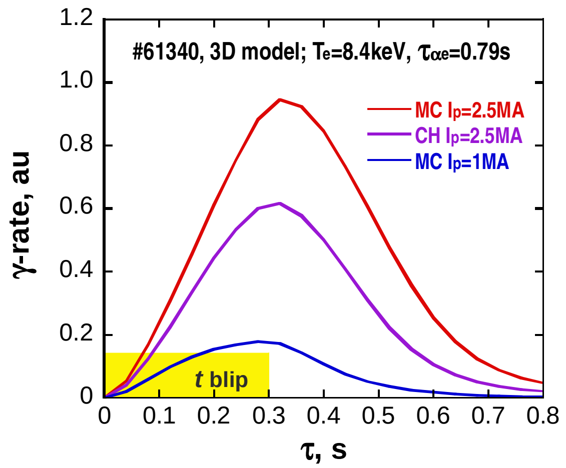

Fig 8: Effect of strong reversed shear and plasma current reduction on modelled γ-rates for shot #61340 with τ_b = 0.3s, $\tau_{\alpha e}(0)$= 0.79s and $T_e(0)$ = 8.4keV, $n_e(0)$ = $3.8{\cdot}10^{19}m^{-3}$. Red curve corresponds to monotonic 2.5MA current, violet curve - strong reversed shear (CH, r_*/a = 0.57) and blue curve – 1MA monotonic current.

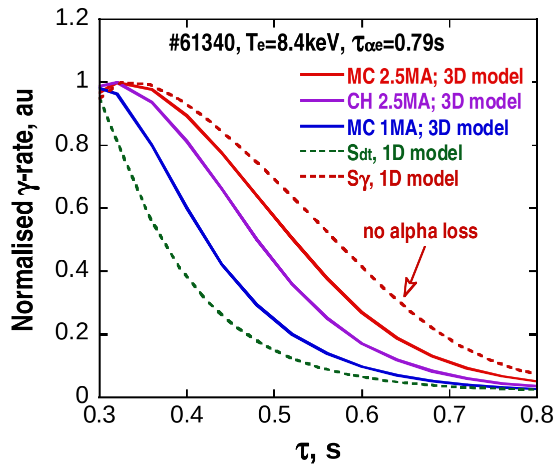

Fig 9: Relaxation of γ-rates after the tritium-blip in shot #61340 according to 3D model. Red curve corresponds to monotonic 2.5MA current, violet curve - strong reversed shear (CH, r_*/a = 0.57) and blue curve – 1MA monotonic current. Dotted lines represent decays of dt-fusion rate and γ-rate in 1D model.

plasmas. It is seen that strong reversed shear and low current result in drastic reduction of γ-rate as well as in the deterioration of the γ-decay time. Fig. 9 demonstrates the normalised model γ-rates after the end of blip in comparison with γ-rate and *dt*-fusion rate resulting from 1D model (i.e. neglecting radial transport of alphas). Shown γ-rate time dependences clearly demonstrate significant effect of convective radial transport on the γ-emission decay time. It is seen that in the MS case the modelled τ_γ is close to the $\tau_{\gamma 0}$=0.29s obtained when neglecting alpha particle radial transport. Nevertheless, reversed shear as well as reduction of plasma current reduces τ_γ to the values close to the decay time of *dt*-fusion rate (τ_n=0.12s). Note that this effect is in agreement with γ-ray measurements, however modelled τ_γ in the case of monotonic q are less than $\tau_{\gamma 0}$, contrary to measurements shown in Fig. 6. Finally Fig. 10 displays the typical γ-ray emission profiles in the JET poloidal cross-section which are calculated with parameters of the discharge #61340 with monotonic q-profile at τ = 0.3s (end of blip) and τ = 0.6s. Note that in spite of about 3 time reduction of the maximum γ-emission at τ = 0.6s (as compared to those at the end of blip) the γ-ray profile did not change relative to the detector LoS.

5. Summary

The time-dependent Fokker-Planck modelling of the alpha particle relaxation after a short tritium NBI pulse into deuterium plasma in JET has demonstrated significant sensitivity of the

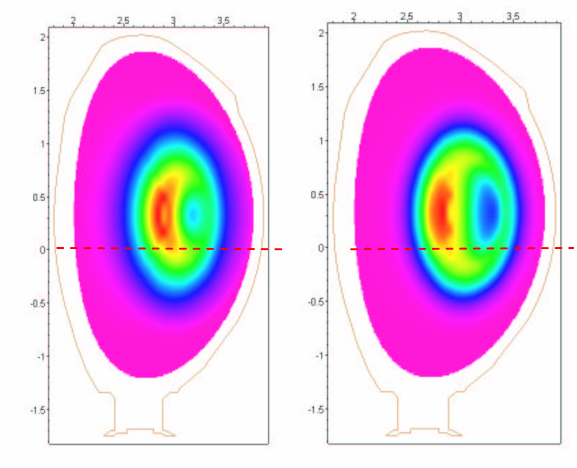

Fig. 10 Modelled γ-ray emission profiles in the poloidal cross-section of JET in post-blip plasma of shot #61340 [(τ = 0.3s (left) and τ = 0.6s (right)]. Dashed lines show the γ-detector LoS.

MeV alpha-particle distribution to the magnetic shear in the plasma core. Essential effect of the slowing-down induced radial transport of energetic (E>1.6MeV) alphas on the decay rate of their density is observed. In the reversed shear and low-current plasmas this transport reduces the alpha-density decay-time (as compared to those in monotonic shear high-current plasma). Reversed shear effect on alpha relaxation is found to be similar to the effect of current reduction at monotonic q. Results of present modelling are in qualitative agreement with measurements of γ-ray emission due to interactions of alpha particles with beryllium in JET Trace Tritium Experiments. At the same time there is an essential discrepancy between measured and calculated decay rates in monotonic q high-current cases. It should be noted, however, that two effects important for these discharges have not been accounted yet: significant beam-beam contribution to *dt*-fusion rate as well as the 3rd harmonic resonance for beam tritons.

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