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Confinement of Charged Fusion Products in Reversed Shear Tokamak Plasmas

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ABSTRACT.

Measurements of the decay of gamma (γ) rays (from interactions of alpha particles with beryllium) in JET Trace Tritium Experiments have demonstrated a significant sensitivity of γ -ray emission to the magnetic shear in the plasma core. In discharges with relatively high currents ($I > 2\text{MA}$) the γ -decay rate observed after a short tritium NBI blip corresponded with the classical slowing down rate of fusion alphas in the case of monotonic q -profile. However, in discharges with a current hole of the size of about $1/3$ of the plasma radius and in low current ($\geq 1\text{MA}$) discharges the measured decay time was much shorter than the classical slowing down time. Thus a strong reversed shear indicates a degradation of fast alpha confinement similar to that at low current ($I_p = 1\text{MA}$). Here we present first results of the numerical simulation of the relaxation of fast alpha distribution based on a kinetic model for NBI ions and fusion alphas in post blip plasmas. Modelling results are in a qualitative agreement with measurements in reversed shear and monotonic current plasmas.

1. INTRODUCTION

Recent tokamak studies [1-6] show the attractiveness of operational scenarios with Internal Transport Barriers (ITBs) that provide improved energy confinement with a reversed magnetic shear in the plasma core. Usually, such 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 distribution of fast alphas after NBI tritium blips into a deuterium plasma has been investigated recently in the Trace Tritium Experiments (TTE) on JET [8, 9]. In discharges with relatively high monotonic currents ($I > 2\text{MA}$) the observed decay rate of γ -rays (due to nuclear reaction ${}^9\text{Be}(a,n\gamma){}^{12}\text{C}$) was about 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, and also in low current ($\leq 1\text{MA}$) discharges the measured decay time was much shorter than the classical slowing down time; actually it was comparable to the decay time of DT-neutron production. Hence this indicates a rather strong RS effect on fast alphas similar to that seen at low current ($I_p = 1\text{MA}$). The purpose of the present paper is the modelling and elucidation of the reversed shear effect on the relaxation and confinement of fusion alphas in TTE on JET.

2. RESULTS OF γ -RAY MEASUREMENTS OF FUSION ALPHAS IN JET TRACE TRITIUM EXPERIMENTS

In TTE the information about relaxation of the fast-alpha distribution after 105keV tritium blips and during 80keV and 130keV deuterium injection 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



Taking steady-state deuterium and beryllium populations we conclude from the reaction dynamics of Eqs. (1, 2) that the resulting time behaviour of γ -ray emission is initiated by the evolution of the NBI triton population. The energy threshold in the reaction cross section of ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ selects fast alphas with energies exceeding 1.6MeV [9]. Therefore, at typical plasma currents in TTE ($I \leq 2.5 \div 3$ MA), the time τ_γ for 1/e-decrease of γ -ray emission [9] must be affected by $q(r)$ profiles, because $I \sim 2 \div 2.5$ MA is close to the critical current I_{cr} [10] required for good confinement of alphas with $E > 1.6\text{MeV}$ produced in a monotonic current (MC) plasma core. The reversed magnetic shear results in an increase of this critical current up to $3 \div 3.5$ MA and, consequently, in an enhanced effect of first orbit loss and radial transport of alphas on the decay rate of γ -emission. On-axis and off-axis co-injected beam tritons (Fig.1) were used in TTE.

Figure 1 displays also the γ -detector line-of-sight (LoS) in the poloidal and toroidal cross-sections of JET. The γ -ray decay times measured for different scenarios ($I_p/B_t = 1-2.5\text{MA}/2.25-3.2\text{T}$) are shown in Fig.2 as a function of the Spitzer slowing down time of MeV alphas, $\tau_{sa} \propto T_e^{3/2}/n_e$ [11], to account for various plasma densities and temperatures. As predominant electron heaters the fusion alphas are expected to slow down with a characteristic time $\tau_{sa}/2$. Figure 2 clearly demonstrates that, in monotonic $I > 2\text{MA}$ current discharges, γ -emission is characterised by a long decay-time in terms of the Spitzer-time τ_{sa} , which is about 3-4 times larger than the decay-time in RS and low current discharges. Moreover, according to Eq. (1), the measured γ -rate is dependent on the slowing down time of the parent tritons. One therefore would expect the characteristic γ -decays in excess of $\tau_{sa}/2$ also for low current plasmas and CH discharges. Indeed the opposite is seen in Fig.2. To evaluate the γ -ray decay in TTE we use first a 1D Fokker-Planck model that takes into account the time-dependence of NBI triton and fusion alpha distributions as well as the collisional ion transport, however neglecting pitch-angle scattering. Upon that a 3D modelling is additionally performed accounting for first orbit and radial transport effects of alphas.

3. GAMMA-RAY DECAY IN 1D KINETIC MODEL FOR NBI IONS AND FUSION ALPHAS

We start from the following system of kinetic equations for tritons, deuterons and fast alphas in the zero-loss limit of alphas:

$$\partial_t f_i = V^{-3} \partial_V V^3 n_{si} + V^4 v_{||i} \partial_V f_i - f_i / \tau_{ci} + S_i(V, t), \quad i = D, T, a. \quad (3)$$

Here v_{si} and v_{li} are the frequencies of slowing down and parallel diffusion of beam ions and alphas,

while τ_{ci} denotes the effective ion confinement time ($\tau_{c\alpha} = \infty$). The triton source term $S_T \sim P_{\text{TNBI}}/E_{T0}$ in Eq. (3) is nonzero only during the blip ($0 < t < t_b = \text{blip period}$), whereas the alpha particle source term

$$S_\alpha(E, t) \propto W(t, E) \int d\mathbf{V}_T d\mathbf{V}_D f_T(V_T, \tau) f_D(V_D, \tau) U \sigma_{DT}(U), \quad U = |V_T - V_D| \quad (4)$$

describes fusion alpha production during and after the blip (due to $f_T(t > t_b) \neq 0$). The factor W in Eq. (4) represents the broadening of the alpha source within the energy interval $|E - E_{0\alpha}| < \Delta E$ with $E_{0\alpha} = 3.5 \text{ MeV}$ and $\Delta E \cong 0.8[(3E_T E_{0\alpha})^{1/2} + (2E_D E_{0\alpha})^{1/2}]$. The choice of DE is due to conservation laws with the maxima of E_T and E_D taken here at their beam energy. In the case of a steady-state low temperature distribution of beryllium ions, the knowledge of $f_\alpha(t, E)$ allows to find the time evolution of the γ -ray emission rate as

$$S_\gamma(E, t) \propto dE E^{1/2} f_\alpha(E, t) \sigma_\gamma(U) E^{1/2}, \quad (5)$$

where σ_γ is the ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction cross-section. Important for the time dependence of S_γ are the following relations among collision rates of fast deuterons, tritons and alphas:

$$\begin{aligned} v_{||i} &\cong \frac{T_e}{2E_i} v_{si} v_{si} = v_{si}^e \left(1 + \frac{E_{ci}^{3/2}}{E_i^{3/2}}\right); \quad D, T, \alpha \\ v_{sT}^e &= \frac{1}{3} v_{sD}^e = \frac{1}{3} v_{s\alpha}^e \propto \frac{n}{T_e^{3/2}}; \quad E_{ci} = \kappa_i T_e, \quad \kappa_D \cong 19, \quad \kappa_T \cong 28, \quad \kappa_\alpha \cong 37. \end{aligned} \quad (6)$$

As seen from Eq. (6), the slowing down time of alpha particles on electrons, $\tau_{s\alpha}^e \sim 1/v_{s\alpha}^e$ is a fundamental scale for the time dependence of $S_\gamma(t)$. Additionally, in this model, the blip duration t_b and the confinement time τ_{cT} are basic time scales as well. It is important to note that the DT fusion rate is, aside from the major contribution of fusions of beam tritons with the thermal background deuterons, significantly increased also by beam deuteron reactions with tritons. As displayed in Fig.3, more intensive injection of beam deuterons enlarges the decay time of S_α after the blip, which is due to fusions of beam deuterons with thermalised tritons. A parameter significant for slowing down and velocity diffusion is the ratio T_e/E_i . For $T_e > E_{0i}/\kappa_i$ (the initial beam ion energies were $E_{0T} = 105 \text{ keV}$, $E_{0D} = 80$ and 130 keV) the ratio T_e/E_i affects essentially the beam ion slowing down. In the case of a quasi-monoenergetic triton distribution of half width $\Delta E_i/E_{0i} < (T_e/E_{0i})^{1/2}$ the small but finite parameter T_e/E_{0i} makes velocity diffusion even of greater import to the ion energy distribution than slowing down (due to $v_{||T} [d \ln f_T / d \ln E_T]^2 \gg v_{sT}$). Apparently, velocity diffusion produces tritons with $E_T > E_{0T} = 105 \text{ keV}$ and hence substantially impacts on the evolution of the alpha source term. The reason is the extremely strong increase of the DT fusion cross-section $\sigma_{DT}(E) \sim E^{5/2}$ for $50 \text{ keV} < E < 110 \text{ keV}$. Analogously, also the velocity diffusion of the 130 keV NBI deuterons contributes to the DT fusion rate. Note that, according to Fig. 3, a weak velocity diffusion

of beam ions is seen to result in both a reduced DT-fusion rate, S_α , as well as an enhanced decay of S_α after the T-blip when compared to the measured decay rate of 14MeV neutrons. Interestingly, in spite of the smallness of $T_e/E_{0i} = 0.06-0.08$, the fusion contribution of beam ions with energies higher than E_{0i} due to velocity diffusion, i.e. tritons with $E_T > 105\text{keV}$ and mainly deuterons with $E_D > 130\text{keV}$, is quite substantial. On the other hand, the longitudinal diffusion of alphas, n_{lla} , plays only an insignificant role in $f_\alpha(t,E)$ due to the relatively smooth energy dependence of the latter.

Figure 4 displays the time evolution of energy distributions of beam tritons, $f_T(t,E)$, and fusion alphas, $f_\alpha(t,E)$, in Pulse No: 61341 with $t_b = 0.3\text{s}$, $\tau_{\alpha e} = 0.75\text{s}$ and $T_e = 8.8\text{keV}$ during and after the T-blip. The time dependencies of the DT-fusion rate, S_α ($= 14\text{MeV}$ neutron yield), as well as of the γ rate, S_γ are shown in Figure 5 with the maximum of S_α reached at the end of the blip and the maximum S_γ occurring after the blip. We introduce now the model γ -decay time, $t_{\gamma\text{max}}$, as the time period corresponding to the decrease of S_γ from $S_{\gamma\text{max}}$ to $S_{\gamma\text{max}}/e$. Because the 1D kinetic model does not take into account the effects of first orbit loss and radial transport on alpha relaxation in the post blip plasma, the model time $t_{\gamma\text{max}}$ should be considered as the upper limit of the real t_γ . Indeed, for Pulse No: 61341 the model time $t_{\gamma\text{max}} = 0.32\text{s}$ is more than twice as large as the measured t_γ [9].

The importance of first orbit loss and enhanced radial transport of fast alphas for the physical interpretation of γ -ray measurements is manifested by the results of steady-state 3D Fokker-Planck calculations of the fusion alpha distribution along the γ -detector LoS for typical monotonic current and RS plasmas in JET TTE. This is illustrated in Fig.6, where $N(E)$ represents the fusion alpha distribution integrated along the LoS. A strong RS with an effective CH size [10] $r_*/a = 0.4$ at $I_p = 2\text{MA}$ is seen to decrease the alpha density about 50% near the mid-plane, which is equivalent to the effect of 45% reduction of I_p in the MC case. The fact that the density decrease is larger than that expected for confined alphas, indicates the consequence of spatial redistribution due to slowing-down induced radial convection. Neglecting this redistribution, then $N(E)$ should be proportional to $F=1-L$, with L denoting the fraction of first-orbit and collisional loss. According to Ref. [7] for a 2MA JET plasma the alpha loss fraction L is expected to be about 31% for monotonic q and should reach 40% in the case of a current hole with $r_*/a=0.4$. Hence the CH induced strong reversed shear results in 13% decrease of the total number of alphas confined in the 2MA JET plasma of Ref. [7], which is contrary to the 50% decrease of alphas along the γ -detector LoS modelled in Fig.6. This difference is assumed to occur due to the significance of RS on the redistribution of confined alphas. On the other hand, Fig. 6 suggests that there is almost no effect by RS and current magnitude on the energy dependence of $N(E)$.

Next we investigate the reversed shear effect on alpha relaxation in post blip JET plasmas by a time dependent Fokker-Planck modelling in the 3D constants-of-motion (COM) space.

4. RESULTS OF 3D TIME-DEPENDENT FOKKER-PLANCK MODELLING

Our modelling is based on the time-dependent Fokker-Planck models for beam ions and fusion alphas. For beam ions the previous 1D kinetic equations are used again, whereas for fusion alphas the purely convective 3D COM Fokker-Planck description is applied, i.e. we neglect effects of

pitch-angle scattering and velocity diffusion and take into account only first orbit alpha loss. Calculations of the shear effect on γ -ray emission was performed for the $I_p/B_T = 2.5\text{MA}/3.2\text{T}$ plasmas both for the monotonic q and strong reversed shear induced by CH with a radial extension $r_*/a = 0.57$. Comparatively, we also model a monotonic low-current plasma with $I_p/B_T = 1\text{MA}/3.2\text{T}$. Figure 7 displays the calculated evolution of the γ -rate in sPulse No: 61340 for the 2.5MA monotonic current case, for CH equilibrium and for monotonic low-current plasmas. As seen, a strong reversed shear or a low MC lead to a drastic reduction of the γ -rate as well as of the γ -decay time. Figure 8 compares the model γ -rates (normalised to their maxima) after the end of blip with the γ -rate and DT-fusion rate obtained in the 1D model (without first orbit loss and effects of radial transport of alphas). The shown γ -rate time dependences clearly demonstrate the significance of first orbit loss and convective radial transport of alphas. In the MC case the 3D modelled t_γ turns out to be about $t_{\gamma_{\max}} = 0.29\text{s}$ in the 1D model. Nevertheless, a reversed shear or a reduction of plasma current will lower t_γ to values similar to the decay time of DT-fusions ($t_{\text{DT}}=0.12\text{s}$). Note that this latter effect agrees with the γ -ray measurements. Finally, using parameters of JET discharge #61340 also for a monotonic q -profile, Fig. 9 displays typical γ -emission profiles in the poloidal cross-section of JET at $t = 0.3\text{s}$ (end of blip) and $t = 0.6\text{s}$. Note that, in spite of an approximately 3 times reduction of the maximum γ -emission rate from the end of blip, $t = 0.3\text{s}$, to $t = 0.6\text{s}$, the γ -ray spatial profile along the detector LoS remains practically unchanged.

SUMMARY

The time-dependent Fokker-Planck modelling of the alpha particle relaxation after a short tritium NBI pulse into a deuterium plasma in JET has demonstrated the significant sensitivity of the MeV alpha-particle distribution to the magnetic shear in the plasma core. An essential effect of the loss and slowing-down induced radial transport of energetic alphas ($E > 1.6\text{MeV}$) on the dilution rate of their density is observed. In reversed shear and low-current plasmas, both this increased transport as well as the enhanced loss reduce the alpha-density decay-time (as compared to that in monotonic high-current plasmas). The reversed shear effect on alpha relaxation is found to be similar to the effect of current reduction at monotonic q . Results of the proposed modelling are in qualitative agreement with measurements of γ -ray emission from interactions of alpha particles with beryllium in JET Trace Tritium Experiments.

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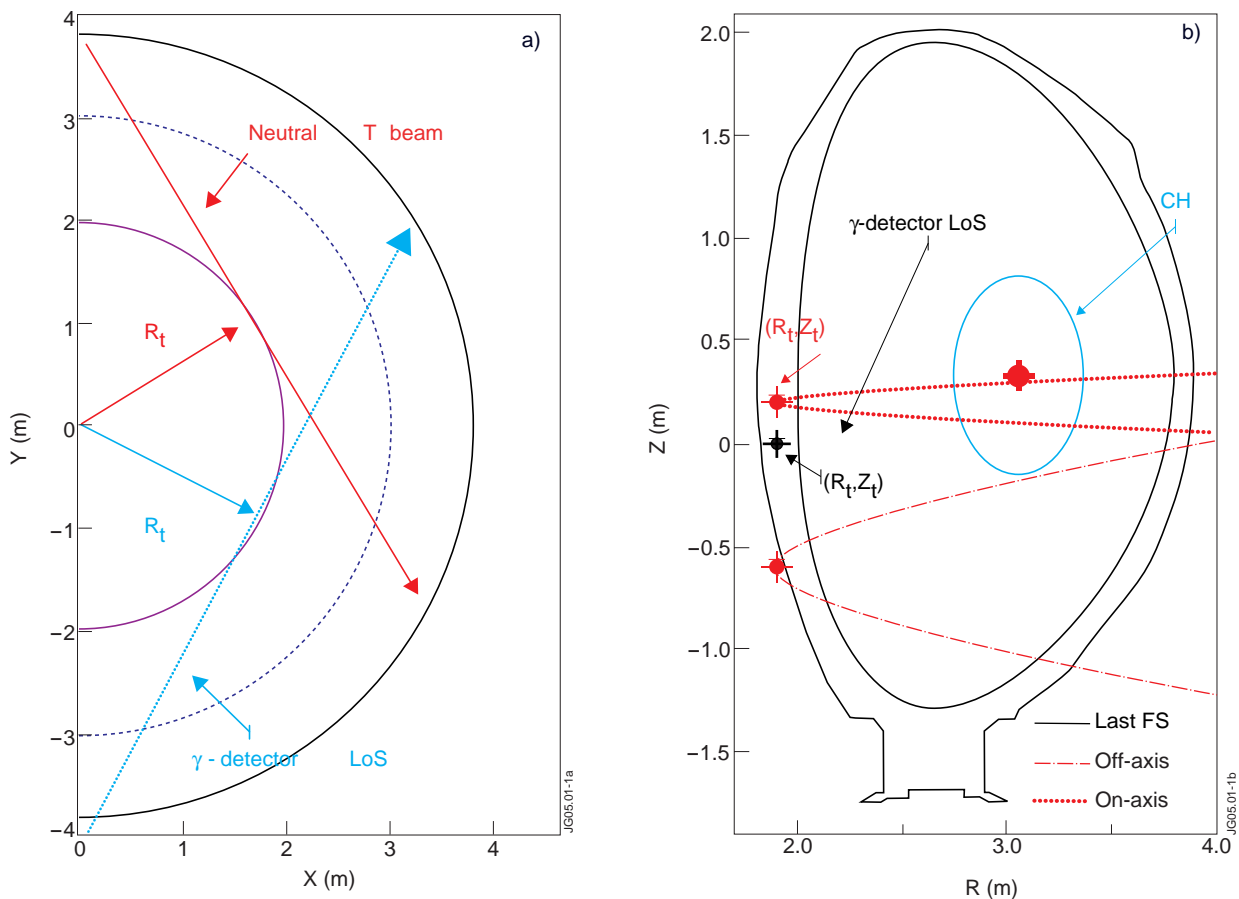


Figure 1: Gamma detector line-of-sight (blue line) in poloidal and toroidal cross-sections in JET. Red lines show the trajectories of on-axis and off-axis tritium beams used in TTE.

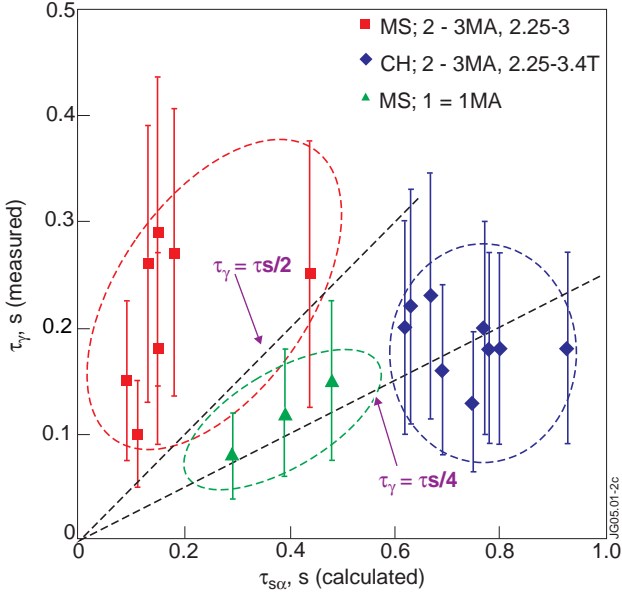


Figure 2: Measured decay rates of γ -ray emission from the reaction ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ after a short tritium NBI pulse compared to the classical slowing down of alpha particles. Red symbols – high monotonic current plasma; green symbols – low monotonic current case; blue symbols – current hole plasma.

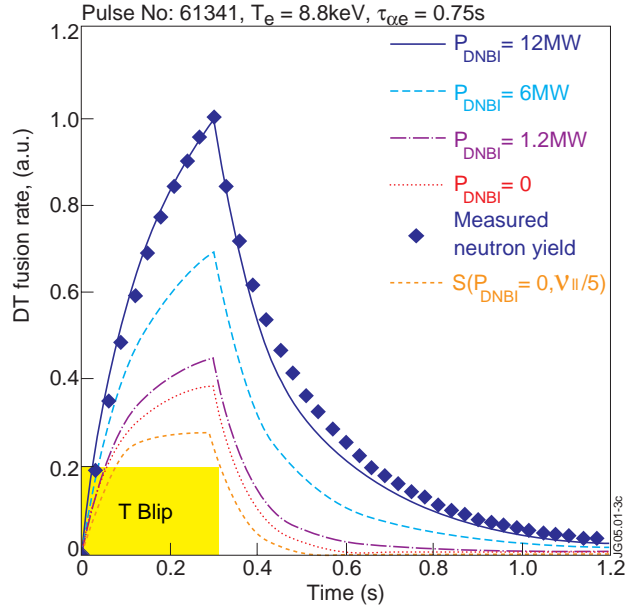


Figure 3: Variation of modelled alpha particle production $S_\alpha(t)$ with reduction of deuterium injection power P_{DNBI} and longitudinal diffusion rate of beam ions, $v_{||}$, in Pulse No: 61341 at $P_{TNBI} = 1.2\text{MW}$. The squares represent the measured 14MeV neutron rate, while all lines correspond to modelled time dependences with the dashed line displaying a case of beam ion velocity diffusion reduced to $v_{||}/5$.

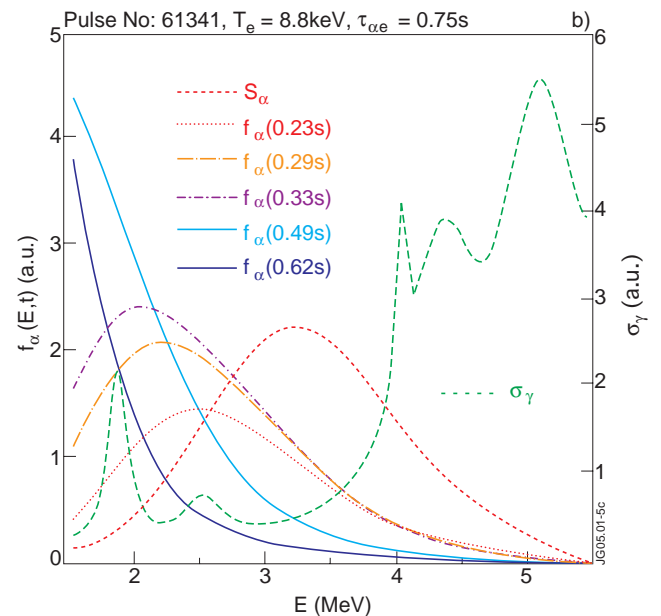
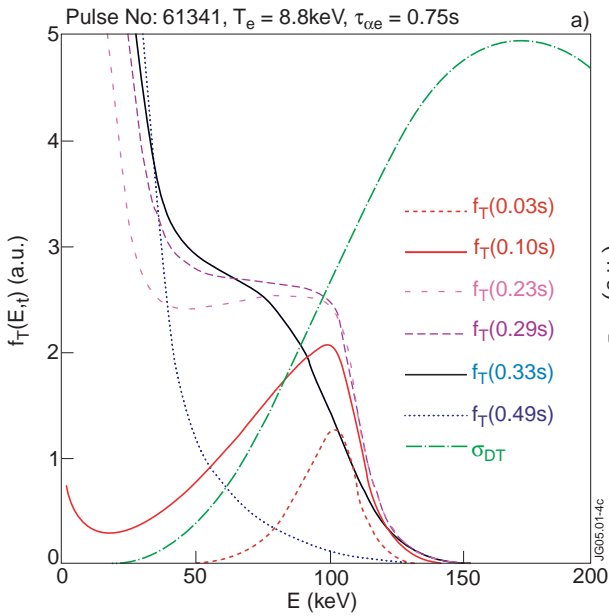


Figure 4: Time evolution of energy distributions of beam tritons (plot a) and fusion alphas (plot b) during and after the triton blip in Pulse No: 61341 with $t_b = 0.3\text{s}$, $\tau_{\alpha e} = 0.75\text{s}$ and $T = 8.8\text{keV}$.

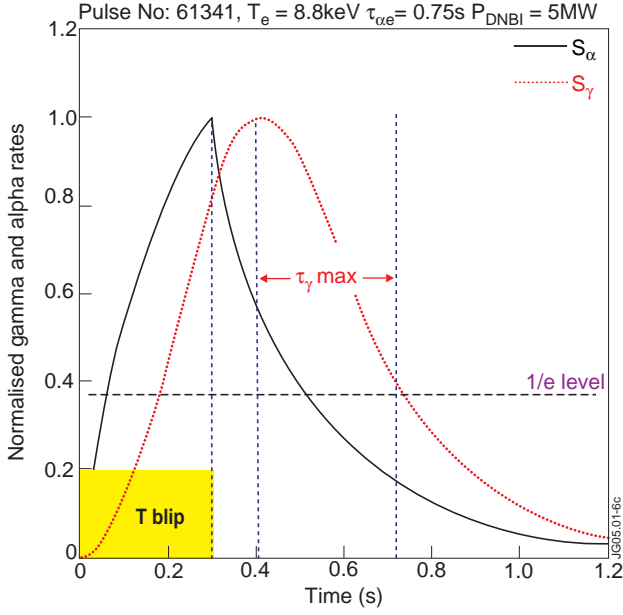


Figure 5: Modelled alpha production and γ -rates as a function of time for Pulse No: 61341 with $t_b = 0.3s$, $\tau_{\alpha e} = 0.75s$ and $T = 8.8keV$. The model time $\tau_{\gamma max} = 0.32s$ corresponds to the decay of γ -emissivity from its maximum at $t=0.40s$ to its $1/e$ level at $t=0.72s$.

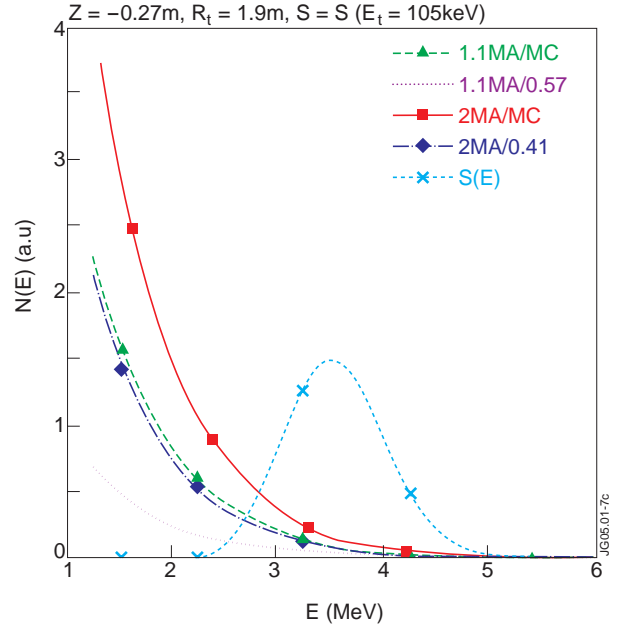


Figure 6: Calculated energy distributions of DT alphas with $E > 1.5MeV$ along the LoS of the JET γ -ray spectrometer for MC and strong RS plasmas (current hole plasmas with an effective size of “zero” poloidal field region $r^*/a=0.41$ and 0.57).

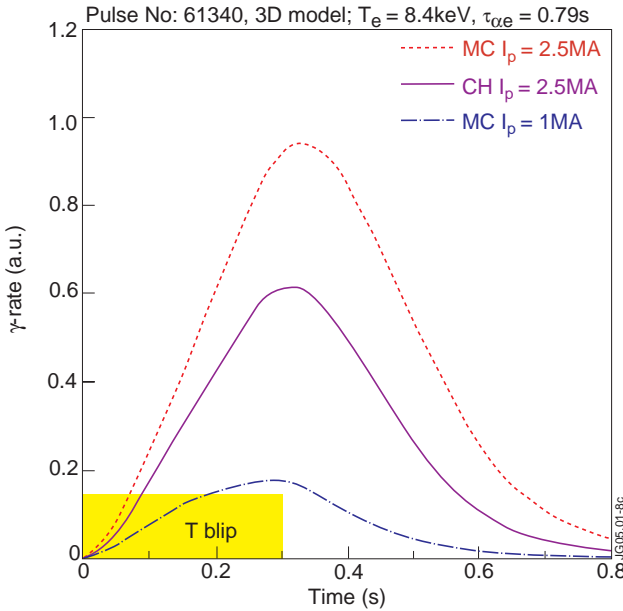


Figure 7: Effect of strong reversed shear and plasma current reduction on modelled g-rates for Pulse No: 61340 with $t_b = 0.3s$ and the central values $\tau_{\alpha e}(0)=0.79s$, $T(0)=8.4keV$, $n_e(0) = 3.8 \cdot 10^{19} m^{-3}$. The red curve corresponds to a monotonic 2.5MA current, the violet curve to a strong reversed shear (CH with $r^*/a = 0.57$) and the blue curve to a monotonic 1MA current.

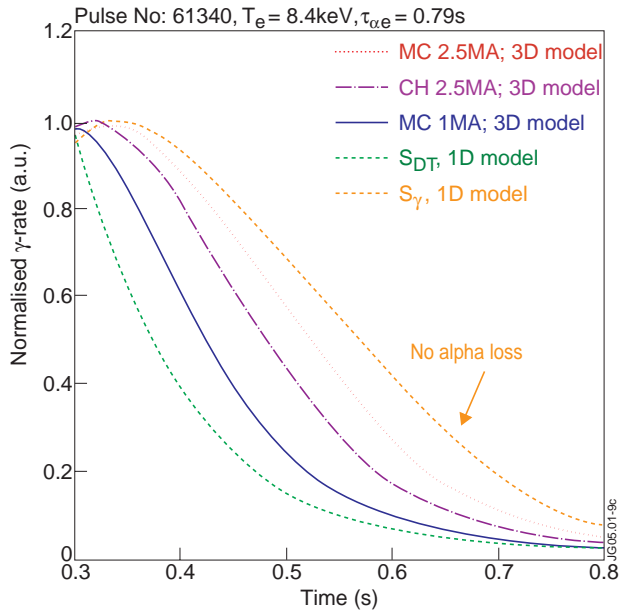


Figure 8: Relaxation of normalised γ -rates after the tritium-blip in Pulse No: 61340 according to the 3D model. The red curve corresponds to a monotonic 2.5MA current, the violet curve to strong reversed shear (CH with $r^*/a = 0.57$) and the blue curve to a monotonic 1MA current. The dotted lines represent the decays of DT-alpha production and γ -emission in the 1D model.

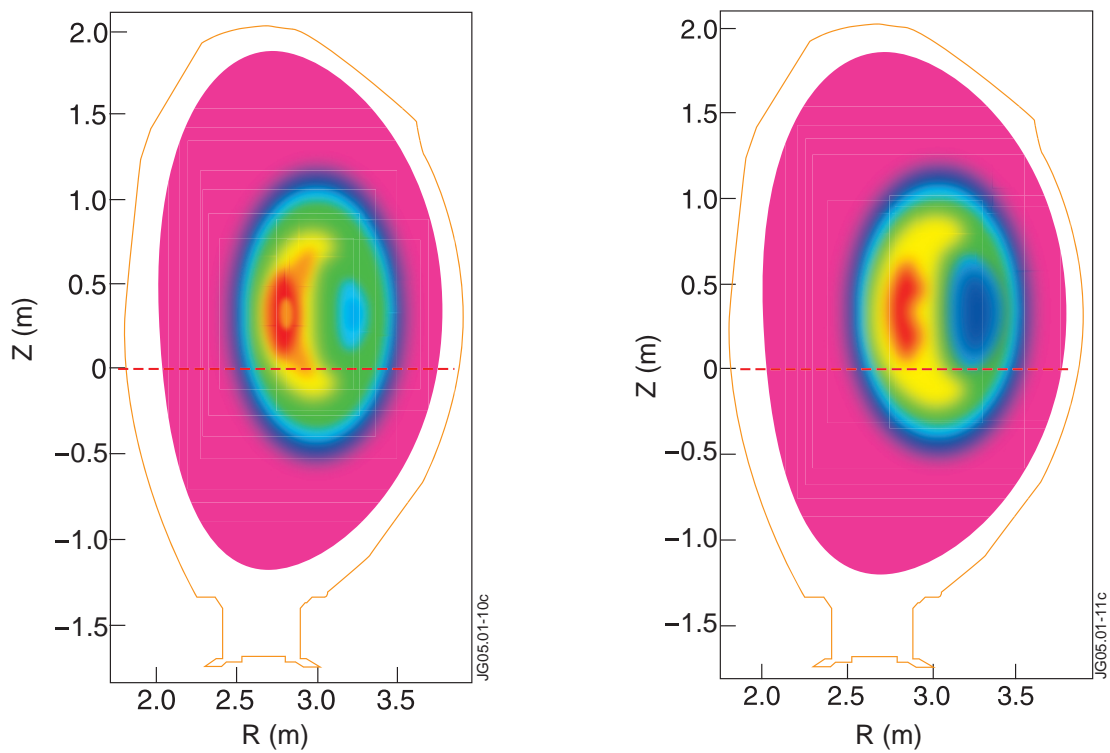


Figure 9: Modelled γ -ray emission profiles in the poloidal cross-section of JET in post-blip plasma of Pulse No: 61340 [($t = 0.3s$ (left) and $t = 0.6s$ (right)]. Dashed lines show the γ -detector LoS.