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pT fusion by RF-heated protons in JET trace tritium discharges

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In magnetically confined fusion plasmas, other nuclear reactions can take place in addition to the main D-T, D-D and D-^{3}He fusion reactions. This is especially true, when plasmas contain ion populations with highly suprathermal energy distributions, created e.g. by RF-heating of the plasma ions. pT fusion is a neutron-producing reaction between tritons and energetic protons with a large cross-section above 1 MeV (Fig. 1). In prior work, it has been observed in JET through excess neutron production in purely RF-heated high-tritium fraction (>90 %) plasmas during the DTE1 campaign [1]. We have performed a systematic study of pT fusion in purely ICRF-heated plasmas with low tritium density (typically $n_t/n_e \sim 1\%$).

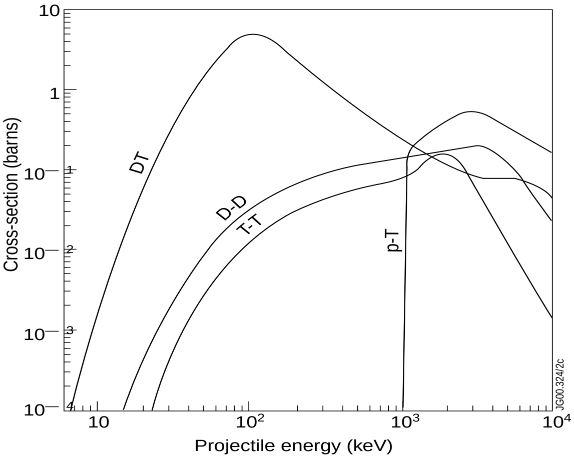

***Figure 1**. Microscopic cross-sections σ of common fusion reactions and the pT-fusion reaction*: T+ p + 764 keV → n + ^{3}He.

Reaction threshold for pT fusion is 764 keV in the center-of-mass (CM) frame and 1019 keV in the lab frame. In the CM frame, the neutron gets 75% of remaining energy but scattering is anisotropic, backward and forward scattering being preferred well above threshold. Due to kinematic effects a broad and anisotropic neutron spectrum is produced in the lab frame, slightly favouring high-energy forward-scattering with most incident proton energies [2].

The pT fusion reactivity in plasmas can be illustrated by a simple, zero-dimensional model. The pT fusion rate R_{pT} is estimated by assuming that fast protons (energy E) have (2D) Maxwellian distribution with temperature T: $f(E)=1/T\exp(-E/T)$, that fast protons have total energy W_{fast}, and that they move with velocity $v(E)$ in plasma with triton density n_t. The total number of fast protons is then W_{fast}/T, and the estimated pT fusion rate

$$R_{\mathrm{pT}} = n_t\, W_{\mathrm{fast}}\, [T^{-1} \int f(E)v(E)\, \sigma_{\mathrm{pT}}(E)\, dE\,] \;\equiv\; n_t\, W_{\mathrm{fast}}\, I_{\mathrm{pT}}(T).$$

Hence, the fusion rate depends on n_t, W_{fast}, and $I_{\mathrm{pT}}(T)$, the temperature-dependent ‘overlap integral’ of normalised proton flux and the reaction cross-section. The shape of $I_{\mathrm{pT}}(T)$ is shown in Figure 2. It is seen that pT rate is highly temperature sensitive below ~1000 keV but for very hot temperatures the yield depends only weakly on temperature. The most error-prone quantity is W_{fast} which needs to be evaluated carefully as common W_{fast} measurements have a large contribution from low energies where the assumed $f(E)$ is not valid.

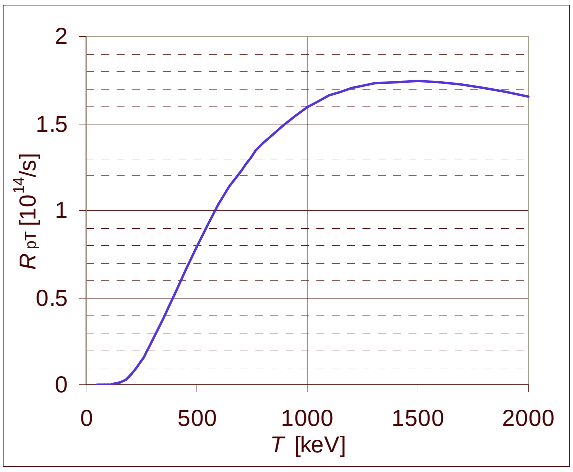

***Figure 2**. pT fusion rate calculated for W_{fast} = 1 MJ and $n_t = 10^{17}$ 1/m^3 as function of fast proton temperature using the simple model.*
For low T, very few protons exceed the threshold and the yield is very low. pT rate increases with T because more protons exceed threshold (on average by T, ie. also reaching for large σ_{pT}). The decrease at very high T is because decrease in the number of protons (for given W_{fast}) starts to overcome the increase in average cross-section.

pT fusion could, in principle, be detected through the produced neutrons or ^{3}He ions. As the production rate is low, only neutron detection is practically feasible. Neutron production from fusion reactions should also be low as the pT fusion neutrons must be detected against the background of DD and DT fusion neutrons, ie. low ion temperature is desirable. The detection was complicated by the fact that a soft, broad neutron spectrum is expected while the JET neutron diagnostics are optimised for detection of hard, nearly monoenergetic DD and DT neutrons. The pT fusion yield was determined indirectly as “neutron excess” $Y_{\text{pT}} = Y_{\text{tot}} - (Y_{\text{DD}} + Y_{\text{DT}})$, ie. the total neutron yield Y_{tot} subtracted by contributions from DD and DT fusion, $Y_{\text{DD}} + Y_{\text{DT}}$. Y_{tot} is taken from total yield monitor (KN1), while Y_{DD} and Y_{DT} from the neutron camera (KN3). The effects caused by soft neutron spectrum and emission anisotropy are left for further analysis.

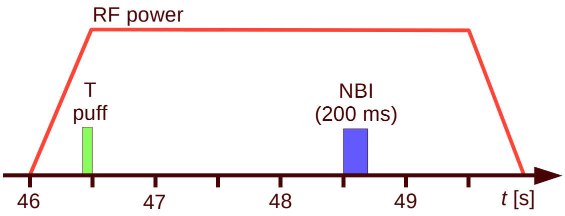

***Figure 3**. The nominal time profile of the experimental pulses. The RF power is first ramped up, and tritium is puffed just before reaching the maximum power. Then follows a 2 second steady state. A short diagnostic NBI blip is applied before the end of high power RF heating phase.*

The experiment was carried out with ICRF heated pulses with reference pulse selected to have highest achievable proton temperature and least possible MHD activity. The main parameters were toroidal field B_T=3.45 T, plasma current I_p=1.8 MA, electron density $n_e(0)=2\times10^{19}$ m^{-3}, and hydrogen fraction in plasma n_H/n_D=5-8 %. The applied ICRF power was 2.5-7.5 MW (typically, 6-7 MW). +90° phasing was selected to improve the fast ion confinement by creating an inward pinch [3], and power deposition was varied by using monochromatic and polychromatic heating in different pulses. The tritium puff was done just before reaching the maximum RF power. In the set-up pulses, no tritium was puffed, and in the main pulses 3 to 5 mg tritium was puffed. With pure RF heating, 7 pulses discussed in this paper were obtained. In addition, several discharges with added LHCD power were performed but the analysis of these will be presented later. The achieved pulse comparisons are: the same heating but with T puffing increasing from 0 to 5 mg (61256, 61257, 61258), monochromatic vs. polychromatic heating at same T puffing (61257 vs. 61259 and 61260), and same T puffing but different RF power level (61258 – 7.5 MW and 61261 – 2.7 MW).

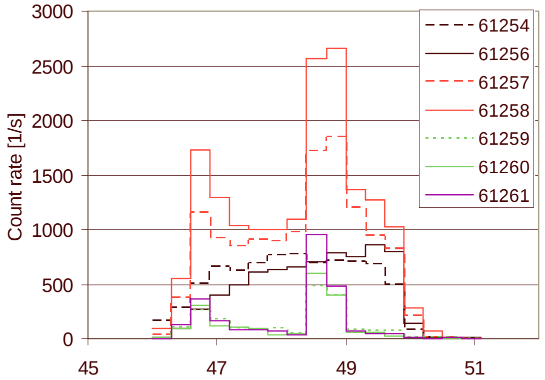

***Figure 4**.. 4.44-MeV γ-ray emission from the reaction $^{12}C(p,p'\gamma)^{12}C$ recorded by spectrometer during several discharges.*

The presence of highly energetic proton tail was established by nuclear γ -ray measurements and by high-energy neutral particle flux measurements. The neutral particle analysis (with energy in the range 270 to 1100 keV) indicates a proton temperature of 440-500 keV for the steady state for all other pulses except 61261 (290 keV). Fig. 4 shows the emission of 4.44-MeV γ-rays from the reaction $^{12}\mathrm{C}(p,p'\gamma)^{12}\mathrm{C}$ having a 5-MeV threshold. Background from $^{12}\mathrm{C}(n,n'\gamma)^{12}\mathrm{C}$ reaction is also present, especially after the T puff and the NBI blip. Assessment with GAMMOD code [4] shows that for the discharge 61256 the tail-temperature $<T_p>$ is in the range 0.8–1.0 MeV. In the polychromatic and low-power discharges 61259-61 the $<T_p>$ was below 0.5 MeV and the recorded signals are mainly background correlated with neutron measurements. The small temperature differences observed in the NPA measurements are not sufficient to explain the large differences in the γ measurements between monochromatic and polychromatic heating. It should be pointed out that there is a large energy gap between the NPA and proton γ measurements, from 1 to 5 MeV. Also, NPA measures only along a single line, and is sensitive only to specific part of particle phase space while the γ measurement is more general. Measurement of the pT fusion yield could provide new data in the energy gap between the NPA and γ measurements.

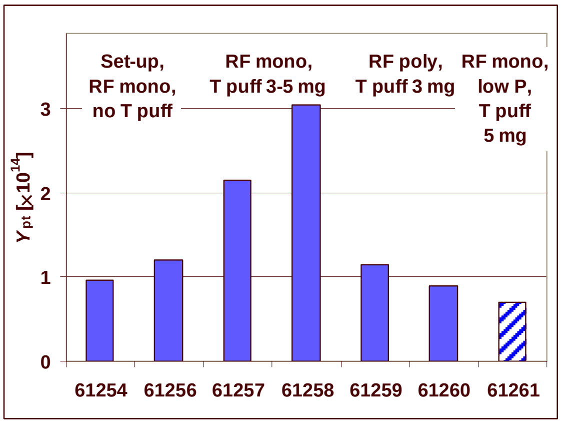

***Figure 5**. Neutron excess in the pT fusion pulses, integrated over time preceding diagnostic NBI blip (until 48.5 s).*

The time-integrated pT yield results are shown graphically in Figure 5 and numerically in Table 1. The results are mainly in line with expectations, apart from the relatively large signal in the set-up pulses with no T puffing. This could arise from tritium being released from the machine walls, however, the neutron yield from DT fusion was very low in these pulses. The yield is seen to increase with tritium puffing in otherwise identical pulses (61256-61258) which is strong evidence that the increase is being produced by pT fusion. The polychromatic case shows smaller neutron excess, which is consistent with the weak hot proton component seen in the γ-ray signals. Finally, the low-power pulse shows a small excess signal, in line also with NPA measurements with low tail temperature. The diagnostic uncertainties are greatest in the low power and polychromatic cases because DT neutrons dominate the total neutron yield. This decreases the accuracy of determining the DD yield and neutron excess.

To verify the observations, the excess neutron fraction was evaluated for a number of other pulses in the TTE campaign. These results are shown in Figure 6. Large pT neutron excess is observed only in the RF heated pulses (no NBI) of the pT fusion experiment (blue points). Other pulses show negligible pT yield. This is consistent with the facts that a hot proton tail is required to induce pT fusion and a low neutron background is needed to observe it.

Table 1 Main parameters of the experimental pulses. Neutron yields integrated up to NBI blip at 48.5 s

Pulse	RF power [MW]	Heating scheme	Tritium puff [mg]	W_{fast} (magnetic) [MJ]	Total neutron Yield	DT neutron yield	DD neutron yield	Excess neutron yield
61254	6.6-7.2	monochr.	0.0	0.54	3.2×10^{14}	7.8×10^{12}	2.2×10^{14}	1.0×10^{14}
61256	6.3-7.2	monochr.	0.0	0.59	3.4×10^{14}	7.7×10^{12}	2.2×10^{14}	1.2×10^{14}
61257	7.1-7.4	monochr.	3.0	0.60	7.7×10^{14}	2.7×10^{14}	2.9×10^{14}	2.1×10^{14}
61258	7.4-7.6	monochr.	5.1	0.63	1.1×10^{15}	4.7×10^{14}	3.3×10^{14}	3.0×10^{14}
61259	4.6-5.6	polychr.	3.2	0.48	5.1×10^{14}	2.7×10^{14}	1.2×10^{14}	1.2×10^{14}
61260	4.3-6.3	polychr.	3.0	0.48	4.9×10^{14}	2.7×10^{14}	1.3×10^{14}	0.9×10^{14}
61261	2.7-4.5	monochr.	5.1	0.11	3.8×10^{14}	2.8×10^{14}	0.3×10^{14}	0.7×10^{14}

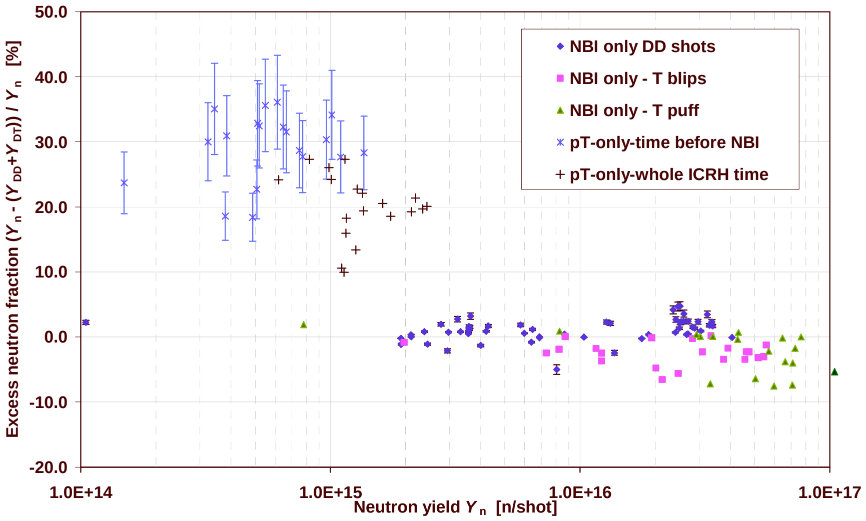

Figure 6*.* *Neutron excess as fraction of all neutrons in a number of pulses in the TTE.*

The anomalous excess neutron yield in the setup pulses could possibly be explained by DD fusion induced by fast-deuterons but not accounted for as DD yield. Emission of 3.09-MeV γ:s from the reaction ^{12}C($d,p\gamma$)^{13}C was observed, and analysis shows, e.g. in 61256 a deuterium tail with temperature 0.15–0.25 MeV. Such deuterons would produce a wide neutron spectrum, not entirely detected as DD neutrons. Another explanation could be neutron-producing nuclear reactions between the fast ions and impurity ions present in plasma, e.g. ^{9}Be(p,n)^{9}B and ^{9}Be(d,n)^{10}B. Further work is needed to fully resolve the issue.

Using the simple theory for pT yield to estimate the triton density in plasma, one can check the consistency of the measurements. As example, pulse 61258 had $W_{\text{dia}} \approx$ 630 kJ (uncorrected) and T close to 500 keV (NPA). The neutron excess was 3.0×10^{14} in about 2 s, of which $\approx 2\times10^{14}$ can be attributed to pT fusion, ie. pT rate was about 1×10^{14} 1/s. Using Fig. 2, this pT rate would be reached with an average triton density of 2×10^{17} 1/m^3, corresponding to about 1 % of electron density. With T=800 keV, one would get $n_t \approx 1\times10^{17}$ 1/m^3.

To summarise, an experiment to study pT fusion reactions has been performed at JET. Neutrons from pT fusion have been observed, and the neutron yield depends on plasma parameters as expected apart from some discrepancies at very low tritium concentration. The results show that it is important to consider the contribution from pT fusion reactions while analysing neutron measurements in purely RF heated experiments in tritiated plasmas.

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[3] Eriksson, *et al.*, PRL **81**, 1231 (1998).
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