Plasma preparation for α-particle excitation of TAEs in JET DT plasmas

J. Mailloux[1], R. Dumont[2], V. Aslanyan[3], M. Baruzzo[4], C. D. Challis[1], I. Coffey[5], A. Czarnecka[6], E. Delabie[7], J. Eriksson[8], J. Ferreira[9], M. Fitzgerald[1], L. Giacomelli[10], C. Giroud[1], N. Hawkes[1], P. Jacquet[1], E. Joffrin[2], T. Johnson[11], D. Keeling[1], D. King[1], V. Kiptily[1], B. Lomanowski[12], E. Lerche[13], M. Mantsinen[14,15], S. Menmuir[1], K. McClements[1], S. Moradi[1], M. Nocente[16], A. Patel[1], H. Patten[17], P. Puglia[18], R. Scannell[1], S. Sharapov[1], E. Solano[19], M. Tsalas[20,21], P. Vallejos[11], H. Weisen[17] and JET contributors*

[1]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK, [2]CEA, IRFM, F-13108 Saint Paul Lez Durance, France, [3]MIT PSFC, 175 Albany Street, Cambridge, MA 02139, US, [4]Consorzio RFX, corso Stati Uniti 4, 35127 Padova, Italy, [5]Dept of Pure and Applied Physics, Queens Uni., Belfast, BT7 1NN, UK, [6]Institute of Plasma Physics AS CR, Za Slovankou 1782/3, 182 00 Praha 8, Czech Republic, [7]Oak Ridge National Laboratory, Oak Ridge, Tennessee, US, [8]Dept of Physics and Astronomy, Uppsala Uni., SE-75120 Uppsala, Sweden, [9]Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal [10]Uni. Milano-Bicocca, piazza della Scienza 3, 20126 Milano, Italy, [11]Fusion Plasma Physics, EES, KTH, SE-10044 Stockholm, Sweden, [12]Aalto Uni., P.O.Box 14100, FIN-00076 Aalto, Finland, [13]LPP-ERM/KMS, Ass. EUROFUSION-Belgian State, TEC partner, Brussels, Belgium, [14] Barcelona Supercomputing Center, Barcelona, Spain, [15]ICREA, Barcelona, Spain, [16]Uni. Milano-Bicocca, piazza della Scienza 3, 20126 Milano, Italy, [17]EPFL, CRPP, CH-1015 Lausanne, Switzerland,[18]Instituto de Física - Universidade de São Paulo Rua do Matão Travessa R Nr.187 CEP 05508-090 Cidade Universitária, São Paulo, Brasil, [19]Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain, [20]FOM Institute DIFFER NL-3430 BE Nieuwegein, The Netherlands, [22]now at ITER Organization, Route de Vinon sur Verdon, 13067 St Paul Lez Durance, France

JET DT experiments will provide a rare opportunity to investigate α-particle (α) physics, thereby improving confidence in predictions of their impact in ITER. Of particular interest are α driven Toroidal Alfvén Eigenmodes (TAEs), as they could cause significant fast particle redistribution, in turn causing reduced core heating or fast particle losses to the first wall[1],[2]. α driven TAEs were seen in TFTR DT plasmas with high core values of the safety factor q[3]. TAEs observed in the first full DT campaign in JET (DTE1) could not be attributed clearly to

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α−particles because ICRH fast ions dominated the fast particle beta gradient (β'_{fast})[4]. Recent JET experiments were devoted to preparing plasmas for observing α-driven TAEs in the next DT experiments (DTE2). These experiments are complementary to studies of TAEs driven by ICRH fast ions, because fusion α are isotropic, distributed throughout the plasma, and can thus excite TAEs modes on the high field side, in contrast to ICRH fast ions.

Plasma development. The plasma parameters were selected to maximise TAE drive and minimise damping. α-driven TAE growth rate $\gamma/\omega \propto q^2\beta_\alpha'$[2] ($\beta_\alpha = \alpha$ beta, $\omega = V_A/2qR$, and the Alfvén velocity $V_A = B/(\mu_0\rho_i)^{1/2}$ with $\rho_i = \Sigma m_i n_i$), hence can be enhanced at elevated q_{min} and at high fusion power. To minimise electron collisional and Landau damping, low electron density (n_e) and high ion temperature (T_i) respectively were sought, while high B_T was selected to reduce radiative damping, and damping on beams fast ions at resonance $V_{//,beam} = V_A/3$. Plasmas with n_e 30% lower than that of JET-ILW shots at similar plasma current ($I_P \leq 3.0$MA) and power ($\leq$ 26MW) were achieved by reducing n_e at the start of heating. The combination of low n_e, and high B_T and I_P led to plasma edge with type III ELMs. After the L-H transition, $n_{e,edge}$ shows no (or small) increase, while a high T pedestal is established (T_i=T_e up to 1.2keV), consistently with other type-III ELMs plasmas in JET[5]. High q_{min} was obtained by applying the heating power early in the discharge, when I_P is still ramping up. The value of q_{min} was selected by changing the heating start time. Fig. 1 shows the range of q-profile investigated: with q_{min} between 2 and 3.5, and low magnetic shear (-r/q×dq/dr) in the core. I_P and q_{min} were selected to ensure simultaneously high fusion rate and low fast particle loss. High DD fusion rate was obtained in shots where an internal transport barrier (ITB) was formed. Based on q and MHD observed in some shots, the ITB is thought to be linked to the q=2 surface, as seen previously in JET with C-wall[6]. Core T_i up to 2 times greater than T_e is obtained in some shots. ITBs are also seen in T_e and n_e (Fig. 2). The frequent small ELMs in this regime help keep the plasma impurity content low, but could not be maintained at the highest power used, due to transitions to ELM-free and type-I ELMs, causing impurity influx. Fast core impurity accumulation due to the n_e and T gradients limited the useful plasma duration (Fig. 3). Core radiation peaking occurred faster in plasmas with NBI-only compared to NBI+ICRH. The high power phase needs to last just long enough to build up the α population, after which the NBI power can be switched off to reduce TAE damping, and α-driven TAEs can be excited as the α slow down more slowly than NBI fast ions (‘afterglow’ scenario, e.g. Fig.4). Radiation peaking may lead to plasma disruptions, hence robust real-time monitoring and controlled plasma termination schemes are needed for DTE2.

TAE stability. Ions accelerated to MeV energies by ICRH (H minority heating) were used to diagnose the TAE stability in the afterglow scenario. TAEs are observed in most shots, with a threshold in ICRH that depends on the NBI power, presumably because of damping by NBI fast ions. Fig. 4 shows an example where TAEs are observed (frequency range 140-180kHz) while NBI=10MW, but disappear at higher NBI power. TAEs are seen again when NBI is turned off, after a time consistent with NBI fast ions thermalisation. Using an upgraded TAE antenna[7], TAE damping in X-point plasmas was measured, enabling comparison with TAE damping predictions, as reported in[8]. The finite n MHD stability code MISHKA[9] was used to identify which TAE modes can exist in shot 92416 at the time of NBI turn-off. Core modes with n=4,5 and 6 are found. The next step is to calculate the excitation and damping for these TAE modes if excited by ICRH fast ions in 92416, and by α in a predicted DT plasma.

Predicted alpha power and beta. NBI-only discharges are foreseen for this experiment in DT, to ensure clear observations of α-driven TAEs. TRANSP [10] modelling of the NBI-only discharge shown in Figs.1 and 2 was performed using the experimental profiles (T_i, T_e, n_e and toroidal rotation) and z_{eff} (assuming a flat profile) to check the sensitivity to T_i and impurity content. The energy content, total neutrons and radiated power are severely underestimated if Be is used as the only impurity, as this leads to high dilution when z_{eff} increases from 6.0s. A much better match is found when W is assumed to be the dominant impurity. This is consistent with spectroscopy analysis indicating that Ni and W concentration (mid-radius and core) increases from 5.7s, while Be, Ne and C concentrations remain low (~0.1-0.2%). The impact of T_i was checked: the mid (lower) range of error bars lead to a slight overestimation (underestimation) of neutrons. Predictions using these experimental profiles, assuming 50% D, 50% T plasma content and beams, were performed. Core β_α 0.08% to 0.12% is predicted (Fig. 5), slightly higher than in TFTR plasmas with α-driven TAEs (0.02%-0.07%)[3].

Summary and future work. New operational space in JET-ILW was developed: low n_e plasmas with high q_{min}, and DD fusion power enhanced by ITBs. NBI-only plasma developed for DTE2 should provide sufficiently high β_α and β_α' for α-driven TAEs to be excited. Suitable core TAEs can exist although full stability calculations remain to be done. More operational development work is needed to ensure the plasmas can be run reliably in DT.

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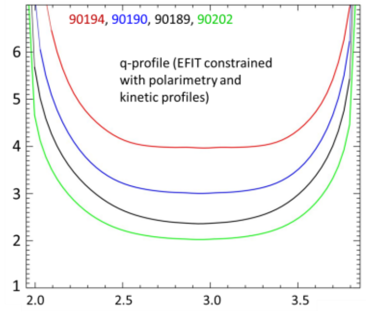

Figure 1. q-profiles at start of heating for different heating start time

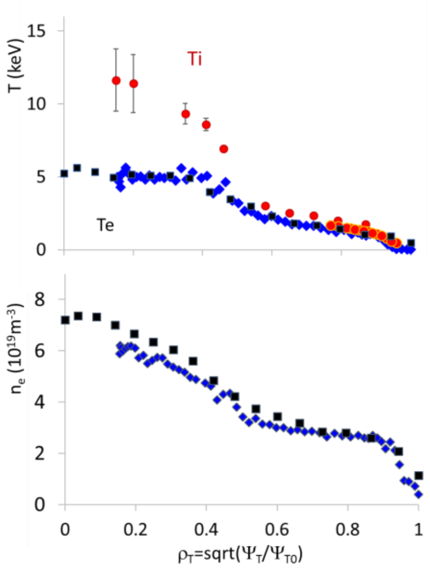

Figure 2 – Profiles for 92054 at 6.4s (averaged 25ms) for a) Ti (CX), T_e, b) n_e. n_e and T_e from high resolution Thomson scattering (blue) and LIDAR (black)

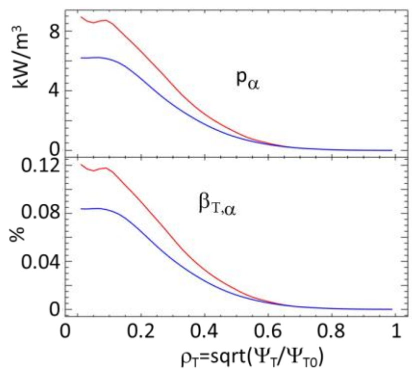

Figure 5 – predicted α power density and toroidal beta for 92054 with 50%D, 50%T plasma and beam with exp. Ti (red), with lower range T_i (blue)

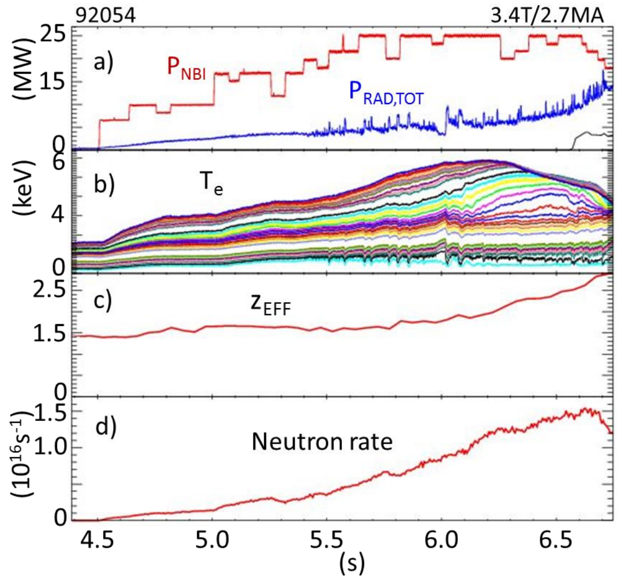

Figure 3- Shot 92054: a) NBI and total radiated power, b) T_e at several radii, with evidence of ITB from ~6.07s and core T_e reduction from 6.2s,c) z_{EFF}, d) neutron rate.

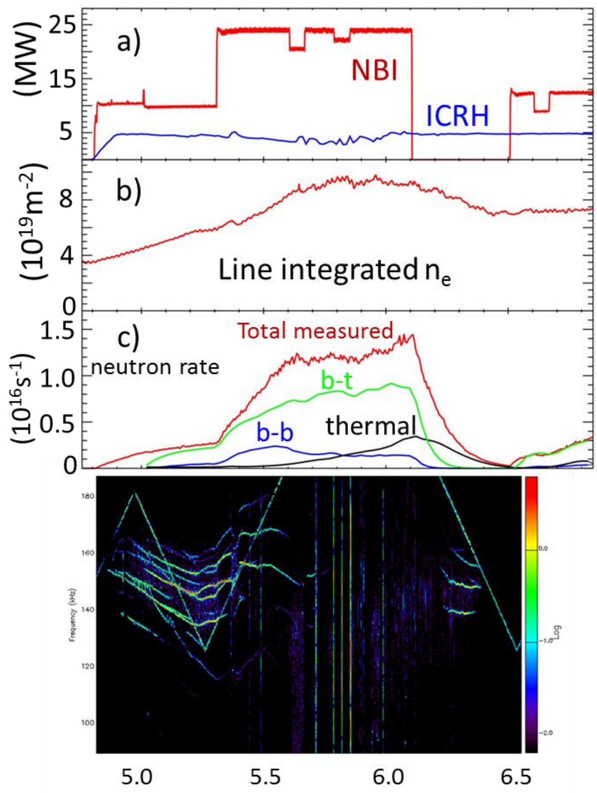

Figure 4 – shot 92416 (3.4T/2.7MA) top: a) NBI and ICRH power, b) line integrated n_e, c) DD neutron rates measured (red) and from TRANSP [10] calculations for thermal plasma (black), beam-beam (blue) and beam-target (green) DD reactions, bottom: magnetic spectrogram