Scenario preparation for the observation of alpha-driven instabilities and transport of alpha particles in JET DT plasmas

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SCENARIO PREPARATION FOR THE OBSERVATION OF ALPHA-DRIVEN INSTABILITIES AND TRANSPORT OF ALPHA PARTICLES IN JET DT PLASMAS

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Abstract

In next-step fusion devices, toroidal Alfvén eigenmodes (TAEs) can be excited by the alpha particles resulting from DT fusion reactions, and may induce a significant redistribution of the energetic ions present in the discharge. During the last JET deuterium campaigns, a substantial experimental effort has been devoted to preparing scenarios maximizing the likelihood of observing alpha-driven TAEs in a future JET DT campaign. Discharges at low densities, large core temperatures associated with the presence of internal transport barriers and characterised by good energetic ion confinement have been performed. ICRH has been used in minority heating regimes to probe the TAE stability, and has resulted in the observation of core-localized modes. Significant progress has been achieved recently in order to make the scenario ready to be run in DT. This has included the test of ELM control methods, afterglow triggering using a dedicated real-time algorithm, and fuel introduction with T-compatible gas injectors. Extrapolated simulations of the best performing pulses to DT motivate the completion of this preparation effort in view of forthcoming JET DT campaigns.

1. INTRODUCTION

Good confinement of the fusion-born alpha particles is essential to ensure adequate burning plasma performance in next-step fusion devices. Among the processes determining this confinement, instabilities excited by energetic particles (EPs) may play a major role, and are currently being studied in various tokamaks using auxiliary power sources to sustain EP populations. Instabilities resulting from fusion-born alphas, on the other hand, can only be observed in deuterium-tritium (DT) plasmas. Since DTE1, the DT campaign conducted in the Joint European Torus (JET) in 1997, the device has undergone significant changes, among which the installation of a Be/W ITER-like wall (ILW) and the development of new diagnostics directly relevant to the physics of energetic ions, in particular alphas. The preparation of a new DT campaign (DTE2) in JET [Joffrin2019] thus includes various developments relevant to burning plasmas [Sharapov2008]. As JET is currently the only tokamak in which DT plasmas can be produced, these campaigns constitute the only opportunity to experimentally document the physics of alphas and related instabilities, and validate the numerical tools used to simulate their effects before ITER comes into operation.

Among the instabilities related to the presence of EPs, alpha-driven Toroidal Alfvén Eigenmodes (TAEs) have received some attention in the past. The rationale is that the features of the alpha population differ significantly from those of energetic ions created by external sources. As a result, the instability features may itself differ and its impact on the plasma performance remains to be evaluated. Because of the relatively low values of normalized alpha pressure (β_α) attained in the only two magnetic confinement fusion devices capable of DT operation to this day, TFTR [Nazikian1997] and JET [Sharapov1999], core-localized alpha-driven TAEs have been difficult to observe unambiguously. From these experiments and from results obtained during the present effort in JET [Dumont2018], it has been established that the optimum conditions for their observation include i) a sufficient alpha pressure, ii) an elevated safety factor (q), iii) an "afterglow phase" consisting of abruptly switching off all external EP and heat sources and relying on the longer slowing-down of alphas compared to other ions present in the pulse to isolate their impact on the destabilization of TAEs, as well as minimise ion Landau damping. The afterglow has been key to the success of the experiments performed in TFTR [Nazikian1997]. In terms of scenario, these conditions translate into low density to favour large electron and ion temperatures, large NBI power to maximise the fusion yield, no ICRH power before the afterglow phase to exclude any contribution from ICRH-driven ions to the TAE drive and an elevated q-profile. In preparation for

DTE2, advanced scenarios fulfilling these requirements have been under development in deuterium plasmas during the last experimental campaigns. In pulses at 3.4T/2.5MA, NBI waveforms have been fine-tuned to inject the power early in the pulse and thus obtain elevated q-profiles, while fulfilling the requirements of the ILW in terms of beam shine-through.

The main progress achieved with respect to previous results published previously [Dumont2018] is reported. The overall performance has been improved, mainly as a result of the larger Neutral Beam Injection (NBI) power available. Furthermore, several new features have been introduced in the scenario to make it fully ready for DT. These developments include ELM control by pacing pellet, gas fuelling with tritium-relevant injectors, and have allowed pulses relevant to DT to be obtained. In section 2 are discussed aspects related to the achievement of pulses with internal transport barriers in JET-ILW plasmas. The development and implementation of a bespoke algorithm aimed at triggering the afterglow phase at the time of maximum performance is presented in Section 3. Section 4 discusses aspects related to the observation of radiofrequency (RF)-driven instabilities, whereas the state of readiness of the scenario developed in view of its application in a forthcoming JET DT campaign is summarised in section 5.

2. INTERNAL TRANSPORT BARRIERS IN JET-ILW

Internal transport barriers (ITBs) have been key to reach good performance in past discharges performed in the framework of the effort to develop a scenario prone to the observation of alpha-driven TAEs in JET DT pulses [Dumont2018]. They are obtained in these deuterium plasmas by switching on the NBI power as early as possible in the discharge, in compliance with the requirements related to the minimal density needed to ensure that the NBI shine-through remains within acceptable limits. During the development process, NBI power in the range 20-25MW, i.e. at relatively moderate levels compared to the full capabilities of the NBI system installed in JET, has been employed in conjunction with RF power. This has the advantage of making the ITB triggering much clearer compared to pulses in which only NBI power is used. Time traces of one such typical NBI+RF pulse (94850) are shown in Fig. 1(a). The NBI power is switched on at t=44.5s and gradually increases to reach 20MW during the plateau phase. This auxiliary heating source is supplemented by 3.8MW of ICRH (Ion Cyclotron Resonance Heating) starting at t=45.5s. The ICRH frequency is set to 51MHz, and the power is predominately absorbed by the hydrogen minority ions (with typical concentrations in the range 2-5%) near the magnetic axis. Collisional relaxation using this scheme results in dominant core thermal electron heating [Lerche2016], thereby allowing the ITB development to be clearly observed on the ECE radiometer channels. In this pulse, the ITB starts to develop at t~45.9s, which coincides with the appearance of the q=2 surface in the plasma, as was confirmed by observation of the MHD markers corresponding to the appearance of well identified tearing modes in the plasma. This behaviour is typical of ITBs developing in pulses characterized by relatively low central shear [Joffrin2003]. In Fig. 1(b), the electron and ion temperature profiles, as well as the electron density profile, are shown before (t=45.7s) and after (t=46.3s) the ITB triggering. It is particularly clear on the ion temperature, which reaches ~13keV on axis for this pulse, but is also apparent on the electron temperature and density profiles. The rate of neutron rate increase becomes significantly larger once the ITB is triggered and reaches 2.6×10^{16}/s in this NBI+RF discharge. It must be stressed that although RF has proven quite useful to reveal the ITB and fine-tune various parameters and waveforms relevant to the scenario, a number of ITB discharges based on NBI power only have also been produced, confirming that ICRH is not a prerequisite to obtain ITBs and good performance in these pulses.

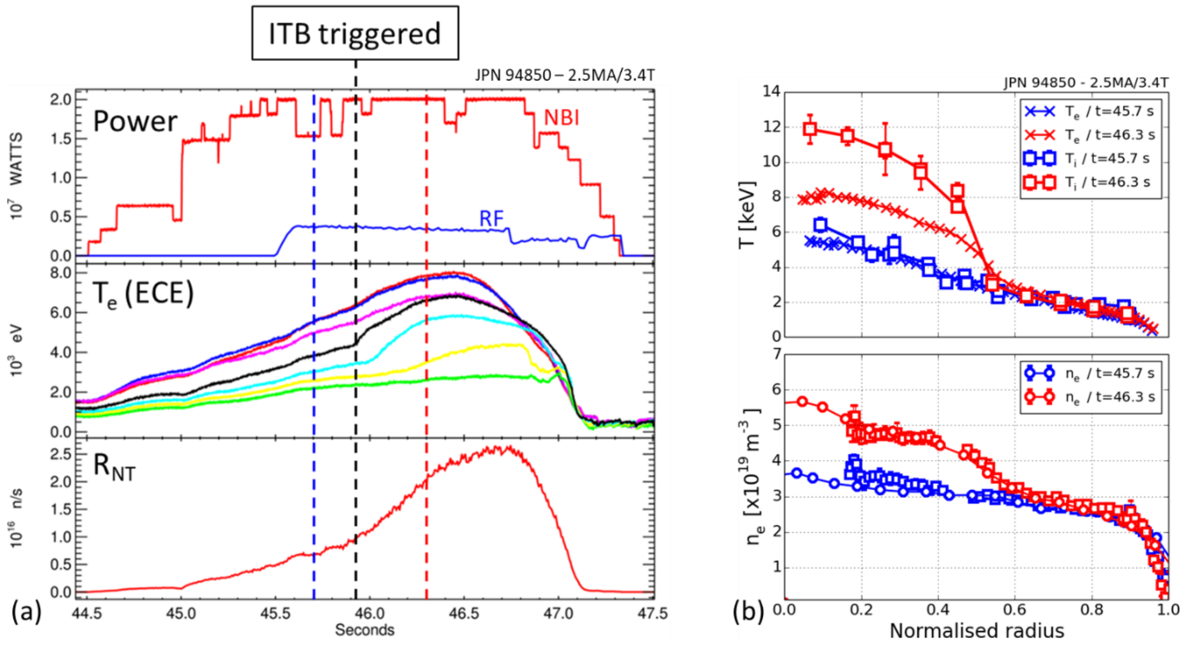

Figure 1: ITB triggered in JET pulse 94850. (a) From top to bottom: NBI and RF power; Electron temperature (ECE); neutron rate (b) Radial profiles (Top) Electron (x) and ion (squares) temperature profiles before (t=45.7s) and after (t=46.3s) the ITB triggering time (t=45.9s); (Bottom) Density profile.

In NBI-only pulses with P_{NBI} exceeding ~24MW, however, impurity accumulation has been an issue. The reason has been identified as the conjunction of neoclassical transport caused by the density profile peaking resulting from the ITBs, and periods characterized by ELM-free phases followed by large type-I ELMs causing impurity influxes. Outside of these periods, typical ELM frequencies in these pulses are found to be in the range 20Hz-80Hz with stationary radiated power levels. When ELM-free/type-I ELM periods occur, on the other hand, the radiated power is observed to increase sharply, generally exceeding the limits above which the real-time JET safety system terminates the discharge by ramping down the auxiliary power. Since ITBs are very beneficial to the performance in these discharges but necessarily induce density peaking, this issue has been tackled by testing several ELM control strategies to minimize the impurity source. In these pulses, neither vertical kicks nor changes in plasma current ramp-up rate were effective in preventing the alternating ELM-free/type-I ELM periods from happening. The injection of 1.4mm pellet at ~40Hz, on the other hand, has been identified as an effective method. Although it is not 100% efficient, i.e. not every pellet triggers an ELM, this triggering has been found be frequent enough to limit the duration of the deleterious ELM-free periods. This method has been tested with D pellets initially, and was confirmed to be effective with H pellets in another session as well. This scheme is therefore applicable during the JET T campaigns, during which the injection of D pellets is not possible. A drawback, in this case, is that the H minority concentration, n_H/n_e, was found to increase as a result. For instance, in pulse 97580, the minority concentration increases from n_H/n_e~4% at the time the first pellet is injected and reaches 10-12% during the peak performance phase. This could make it more difficult to use ICRH power in order to drive TAEs during T campaigns but does not affect the scenario applicability to DTE2, during which D pellets can be employed.

3. AFTERGLOW PHASE DEVELOPMENT

In addition to good performance, this scenario also requires the introduction of an afterglow phase in the pulse, during which all auxiliary power is abruptly switched off in order to ensure that the only energetic ions present in the DT discharge are alphas once the NBI ions have thermalized [Dumont2018]. Ideally, the NBI power should be switched off at the time of maximum performance, t_{peak}. However, t_{peak} is determined by various factors, and can vary depending on small differences in the precise waveforms of density, or in the relative concentrations of the species present in the plasma, including impurities. These quantities are known to depend on parameters such as wall condition, which cannot be entirely controlled. Clearly, t_{peak} will also be different in plasmas with DT or T fuel compared to D pulses as a result of the different resistivities and thus current diffusion dynamics. More generally, it has been identified that 100% reproducibility was not achievable, a fact which is taken into account in the experiment strategy for DTE2. Therefore, a real-time control algorithm has been developed to maximize the physics outcome during the afterglow phase despite these uncertainties inherent to the operation of any fusion device. The algorithm is designed to trigger the afterglow when the two following conditions are fulfilled: 1) the neutron rate exceeds a certain threshold, $R_{NT}>(R_{NT})_{min}$; 2) the rate of change of R_{NT} becomes smaller than a preset value $dR_{NT}/dt<(dR_{NT}/dt)_{lim}$. This typically occurs around the maximum R_{NT} value, and therefore triggers the afterglow at the optimal time provided sufficient performance has been obtained. Figure 2 shows the time traces of JET pulse 95973, during which this algorithm has been employed.

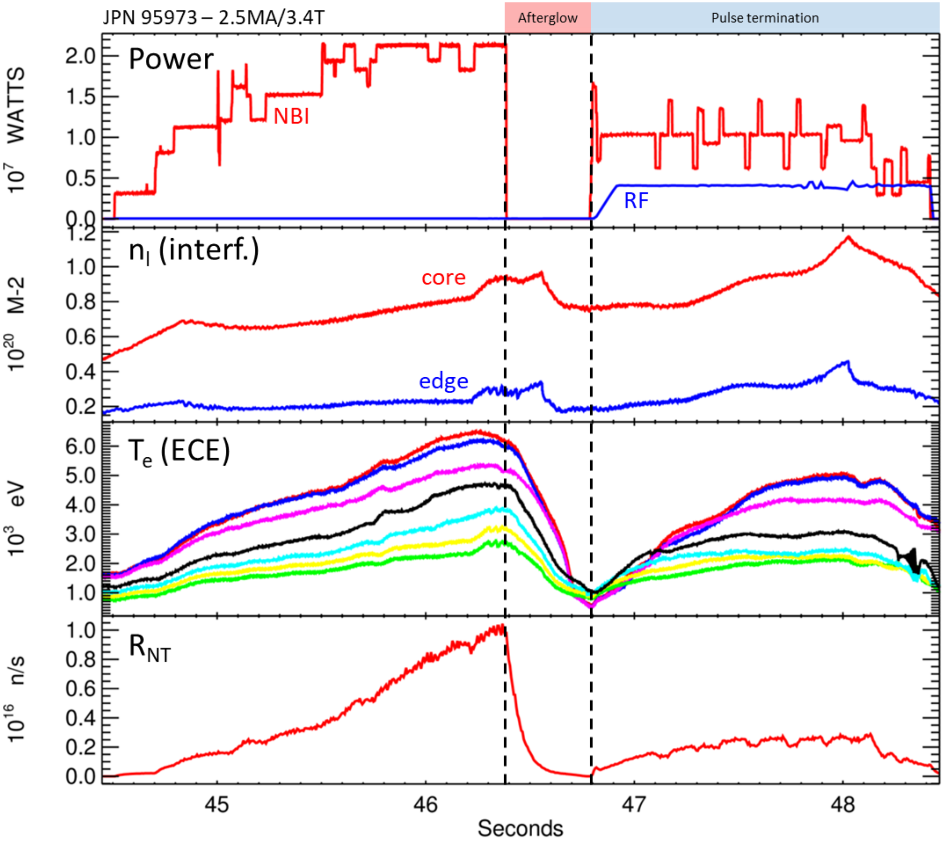

Figure 2 : Real-time triggering of afterglow phase in JET pulse 95973. From top to bottom: auxiliary power (NBI and RF); core (channel 3) and edge (channel 4) line-integrated density (interferometry), electron temperature (ECE), DD neutron rate.

In this pulse, a total of 22MW of NBI power was injected in the plasma, with no RF before the period of interest. The algorithm was set with $(R_{NT})_{min}=8\times10^{15}$/s and $(dR_{NT}/dt)_{lim}=1\times10^{13}/s^2$. The neutron rate increases and the algorithm triggers the afterglow at t=46.38s based on the fulfilling of the two previous conditions. The afterglow phase lasts for 400ms (a preset duration), during which no external power is injected in the plasma. A combination of RF and NBI power is then reapplied in order to ensure that the pulse is safely terminated, a necessary condition for candidate pulses for the DT campaign. The same real-time algorithm has also been used for the detection of “duds”, i.e. underperforming discharges which should be terminated in order to minimize the tritium consumption and spare the total DT neutron budget. The criteria for this early termination are based on excessive radiated power fraction, excessive radiation peaking and/or insufficient neutron rate when the neutron rollover occurs.

4. RF-DRIVEN INSTABILITIES

In order to observe TAEs in JET D plasmas, it is necessary to destabilize them using ICRH power. Pulses with combined RF and NBI power and displaying instabilities have proven the most useful for stability studies [Nabais2018]. In line with what has been reported in [Dumont2018], discharges with RF power during the NBI phase and/or during the afterglow for have been performed with the objective to destabilise various modes. Figure 3 shows an example of such a discharge. Pulse 95979, with 23MW maximum NBI power, exhibits a clear ITB starting around t=45.6s. The neutron rate reaches 2.8×10^{16}/s. 3.8MW of RF power at 51MHz has been coupled to the plasma starting at t=45s. The magnetic spectrogram reveals the presence of modes excited shortly after the application of ICRH. A study of the toroidal numbers reveals that they are n=3-7 TAEs, i.e. similar to the core TAEs observed in past discharges. Furthermore, these TAEs disappear when the NBI power increases to its maximum value. This tends to confirm that the modes are damped by NBI ions, although the presence of the ITB also induces an increase in ion temperature, which also contributes to TAE damping. A detailed analysis of the weight of the various mechanisms involved is currently underway. Interestingly, after the TAEs have disappeared, it is possible to observe relatively broad modes in the range of 60-120 kHz. These instabilities have been observed in several pulses with ITBs, and are being currently being studied. The results will be reported elsewhere [Fil2021].

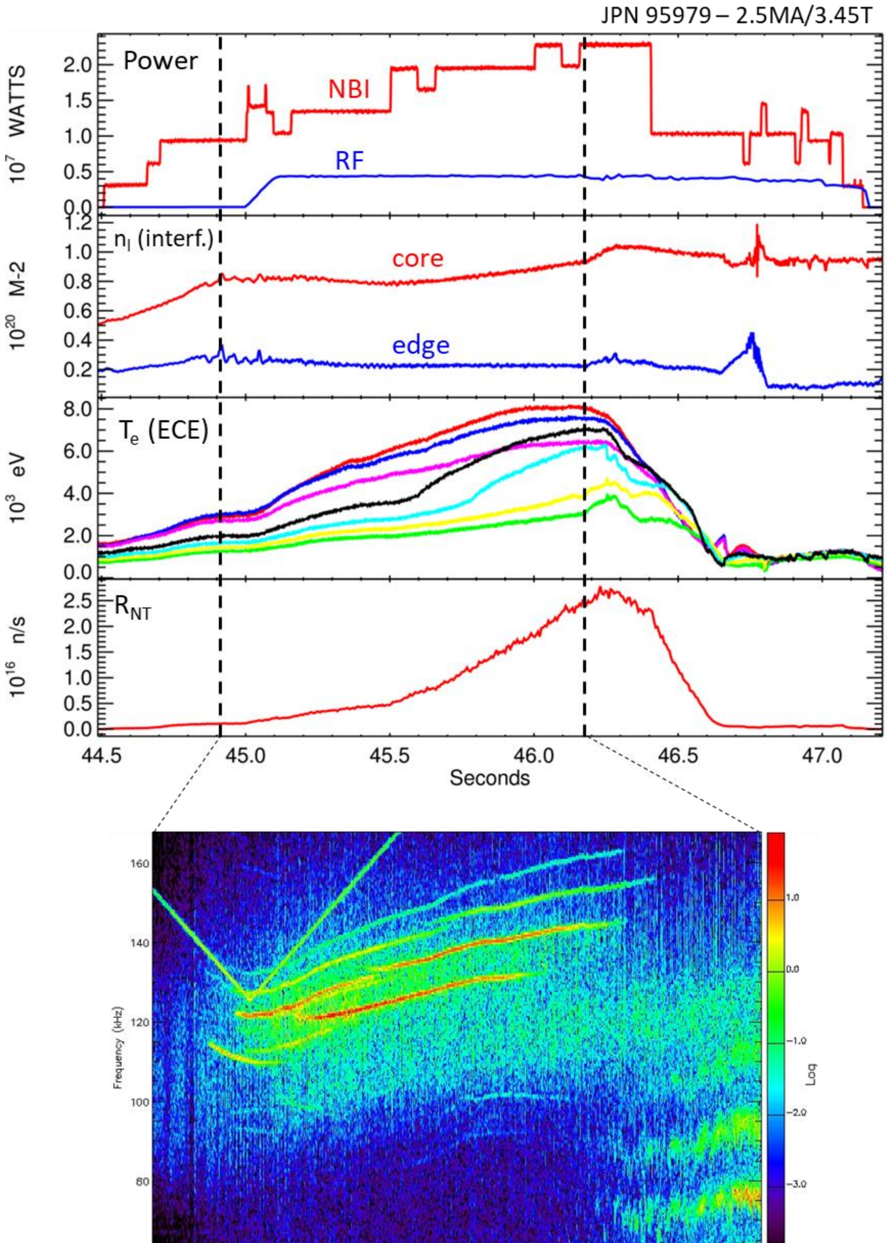

Figure 3 : JET pulse 95979. (Top) Time traces: NBI and RF power, core (channel 3) and edge (channel 4) line-integrated density (interferometry), electron temperature (ECE), DD neutron rate. (Bottom) Magnetic spectrogram. Core-localized TAEs excited by ICRH-driven ions with toroidal numbers 3-7 are observed in the presence of RF power, and disappear when the NBI power reaches its maximum.

As an alternative to hydrogen minority RF heating, helium 3 (^{3}He) minority heating at 33MHz has also been tested by injecting ^{3}He ions in small concentrations (1-3%) in deuterium plasmas. Exciting TAEs with a different species is helpful to further benchmark numerical simulations. Furthermore, ^{3}He ions are particularly well diagnosed by the energetic particle and neutron diagnostics installed in JET [Nocente2020]. However, during the session devoted to this particular study, only up to 4MW of RF power could be coupled to the plasma, and no TAEs have been observed. However, it was found that the performance obtained in plasmas with ^{3}He minority was comparable to plasmas with H minority, and ITBs were observed, accompanied by the same broadband modes in the range 60-120 kHz as described previously.

5. SCENARIO READINESS FOR DTE2

The highest neutron rate in a NBI-only advanced discharge has been achieved in JET pulse 96852. 31MW of NBI power has been injected in this plasma, resulting in the triggering of an ITB around t=46.3s and the neutron rate reaching $2.55x10^{16}$/s. The afterglow in this pulse has been triggered on neutron rollover by the bespoke algorithm described in section 2. Pacing pellets were also present, and no particular issues related to ELMs were encountered in this discharge. The time traces are shown in Fig. 4(a).

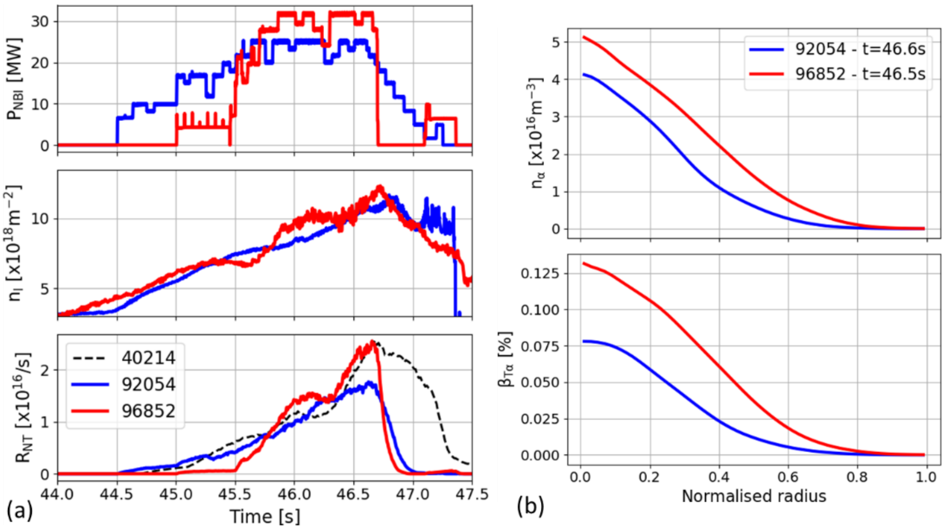

Figure 4: Comparison of JET pulses 92054 and 96852. (a) Time traces: NBI power, core line-integrated density (interferometry), DD neutron rate; also shown is the neutron rate for reference JET carbon wall pulse 40214, shifted by -0.31s. (b) TRANSP extrapolation to DT of pulses 92054 and 96852: (top) alpha density; (bottom) normalised alpha pressure.

In this figure, pulse 96852 is compared to the best performing NBI-only discharge 92054 reported previously [Dumont2018], and also to pulse 40214 performed in JET with its former carbon wall, which was considered the best candidate for alpha-driven TAE studies in DT at the time. It can be seen that pulse 96852 constitutes a significant progress compared to pulse 92054, and achieves a neutron rate similar to pulse 40214.

TRANSP simulations have been performed to interpret the measurements of pulses 92054 and 96852. These simulations have then been extrapolated to DT using the same profiles, but replacing the deuterium by DT fuel. As shown in Fig. 4(b), in these extrapolated simulations, it is found that the normalized fusion alpha pressure, $\beta_\alpha(0)$, reaches a value around 0.13%, i.e. significantly larger that the values typical of the successful alpha-driven TAE experiments performed in TFTR [Nazikian1997]. It should also be remarked that this TRANSP extrapolation of pulse 96852 is quite similar to a previous simulation of pulse 92054 in DT for a total NBI power of 31MW performed with the CRONOS code [Garcia2019], and confirms the reliability of these simulations. Although these result encourage the completion of this effort in view of the DTE2 campaign, non-linear stability calculations are now underway to check whether the drive associated to fusion alphas will be sufficient to overcome the damping mechanisms remaining during the afterglow (radiative damping, thermal damping…) Ultimately, since these pulses are now ready to be reproduced in T and in DT plasmas, only their experimental realization will confirm that unstable alpha-driven TAEs can indeed be observed in JET-ILW.

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