Plasma Physics and
Controlled Fusion



**TOPICAL REVIEW • OPEN ACCESS**

# 40 years of JET operations: a unique contribution to fusion science

To cite this article: F G Rimini *et al* 2025 *Plasma Phys. Control. Fusion* **67** 033001

OPEN ACCESS
IOP Publishing
Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **67** (2025) 033001 (17pp) https://doi.org/10.1088/1361-6587/adaee5

Topical Review

# 40 years of JET operations: a unique contribution to fusion science

**F G Rimini, JET Contributors[1] and the EUROfusion Tokamak Exploitation Team[2]**

UKAEA, Culham Campus, Abingdon OX13 3DB, United Kingdom

E-mail: Fernanda.Rimini@ukaea.uk

Received 23 October 2024, revised 17 December 2024
Accepted for publication 27 January 2025
Published 17 February 2025

**Abstract**

During its 40 years of operations, the Joint European Torus (JET) tokamak has consistently pushed the physics and engineering boundaries of fusion research, providing the scientific community with a unique testing ground for theories and innovative ideas. This paper covers a selection of remarkable contributions of JET to various fields of tokamak science, from transport and plasma heating studies to plasma-wall interaction and D-T experiments, and their impact on the fusion research progress.

Keywords: JET, operations, fusion, science, tokamak, D-T, plasma

## 1. Introduction

At the beginning of the 1970s, the world economy was shaken by an energy crisis driven by increasing oil prices. At the same time, the major progress made during the previous decade in magnetic confinement fusion research, and specifically in tokamak experiments, raised the appeal of nuclear fusion for energy production and stimulated a significant interest in building a generation of larger and more powerful experiments, making major steps towards reactor conditions.

The Joint European Torus (JET) Joint Undertaking design activities, starting in 1973, had the ambition of building a device capable of studying plasmas in conditions and dimensions approaching those of a reactor. This aim was articulated into four main areas of study: plasma-wall interaction (PWI), plasma heating, plasma behaviour as parameters approach the reactor range and the study of alpha particles, the latter requiring the experiment to operate with D-T mixture. To achieve these key aims, the JET Joint Undertaking had, from its beginning, several characteristics unique amongst the various fusion ventures initiated in this period. First of all, the project was set up as a European collaboration, rather than a national experiment, thus allowing it to gather scientific, engineering, industrial and financial resources from a wide pool, which would have been impossible for any single European nation. Secondly, the genius of the design team matched the ambitious brief of the committers in producing a versatile design, much larger and flexible than any other tokamak built or planned at the time, equipped with the most powerful confining magnetic field system conceived until then. In particular, the decision to adopt a D-shaped poloidal cross section, instead of a more conventional circular cross-section, not only enabled the use of high toroidal field but, also, allowed the study of plasma behaviour with increasing elongation and, as we will see later, the exploration of plasma confinement in both material and magnetic limiter conditions while maintaining a large plasma

[1] See Maggi *et al* 2024 (https://doi.org/10.1088/1741-4326/ad3e16) for JET Contributors.
[2] See Joffrin *et al* 2024 (https://doi.org/10.1088/1741-4326/ad2be4) for the EUROfusion Tokamak Exploitation Team.

volume. Lastly, the project was directly targeting reactor-relevant fusion research by aiming to operate with a D-T fuel mixture, then as now expected to be the fuel for the first generation of fusion power plants. Since D-T experiments were expected to leave the machine structure significantly activated and contaminated by tritium, the project included the ambition to exploit Remote Handling for in-vessel maintenance.

It is, clearly, impossible to do justice to the wealth of important results that JET has produced over the 40 years of its operation in a relatively short paper. We will, instead, focus on a selection of experimental studies addressing the four original aims, highlighting their unique contributions to progressing fusion research and we shall examine how successful the research in JET has been with respect to the original aim.

The paper is organized as follows: after a short section on the timeline of JET, we will present selected results in heat and particle confinement (section 3), PWI (section 4), Disruption physics (section 5), Radio Frequency Heating physics (section 6) and D-T fusion power experiments (section 7).

## 2. The timeline of JET

Following the exploratory activities of the JET Working Group, set-up in 1971, a design team for a new large size tokamak was formally established in 1973 and the main design for the device was completed by 1975 [1].

The goal for JET was to 'obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor', and the studies to be carried out at JET were expected to help defining the parameters, the size and the working conditions of a Tokamak reactor [2]. The overarching aim was articulated into four main areas of work:

(i) the scaling of plasma behaviour as parameters approach the reactor range
(ii) the PWI in these conditions
(iii) the study of plasma heating and
(iv) the study of alpha particle production, confinement and consequent plasma heating.

To realize this ambition, the device was planned to have a much larger size than any of the tokamaks operating at the time, be equipped with high power additional heating and suitably powerful magnetic fields, to ensure the generation of high plasma current and the confinement of highly energetic particles. The JET design differentiated itself from the tokamak panorama of the time not only with its size but, also, with the choice of a D-shaped poloidal cross-section (figure 1). The main engineering specifications in the original design and those actually achieved in the subsequent 40 years are given in table 1.

Around the same time two other large projects were in the early stages of design: TFTR in the USA [3] and JT-60 in Japan [4]. Together with JET, these experiments constituted the most important step forward in Magnetic Confinement Fusion since the demonstration of good confinement potential in tokamaks in the early 1960s [5].

In 1977 the Culham site, in the UK, was selected for the JET project and construction began. On 25 June 1983 the project achieved the First Plasma milestone with a hydrogen 50 ms pulse at plasma current of 19 kA. Longer pulses with plasma current 2–3 MA were routinely obtained later in 1983 and the design target of 4.8 MA current, in material limiter configuration, was reached in 1985 [2].

Figure 2 shows the timeline of the most significant events in JET history, and more details of the technical development over the 40 years are given in [6], while an overview of the early scientific output is given in [7, 8]. Two major engineering upgrades are worth mentioning here. The first is the installation in the 1992–94 shutdown of a pumped divertor in the lower part of the vessel [9], following the discovery at ASDEX of the H-mode high confinement regime in magnetic limiter configurations [10] and promising experiments in JET since 1986 [11]. Equipping JET with a versatile divertor, with several different designs tested over the subsequent years, gave scientists the unique opportunity to study heat load, impurity and density control and exhaust in conditions relevant to a Next Step fusion device. The second decisive upgrade came in the 2009–11 shutdown: the full replacement of the graphite plasma facing components (PFCs) with an ITER-like Be/W First Wall [12] allowed a full scale assessment of the capability of a metal wall to provide low hydrogenic retention while remaining compatible with high performance plasma regimes. The five D-T experimental campaigns on JET were, thus, carried out in a variety of First Wall conditions, from the preliminary tritium experiment (PTE) in carbon wall without divertor, to the first DT campaign (DTE1) and trace-tritium with divertor CFC and to the second (DTE2) and third (DTE3) campaigns with the metal wall (figure 2).

After 40 successful years 105 929 pulses carried out, JET tokamak operations ended in December 2023 and the project entered its decommissioning phase. The decommissioning at the end of the 1990s of the only other DT tokamak, TFTR in Princeton, did not exploit all the opportunities to gather precious engineering knowledge. The decommissioning of JET thus offers a major chance to provide insight on the impact of years of plasma operations, including several DT campaigns, on its components and, especially, its First Wall materials [13]. Presently, the JET Decommissioning and Repurposing Programme is in a transition period, from the end of JET science operations into the actual decommissioning activities, and the detailed decommissioning plan is being prepared. The high level aims of the programme are to ensure that lessons can be learnt efficiently from JET decommissioning, for example by proving new technologies and building the skills required for future Fusion Power Plants, while learning how to minimize waste and maximize tritium recovery. The post-operation JET activities are starting with *in-situ* de-tritiation tests, to be followed by removal of First Wall components to be subjected to in-depth material analysis.

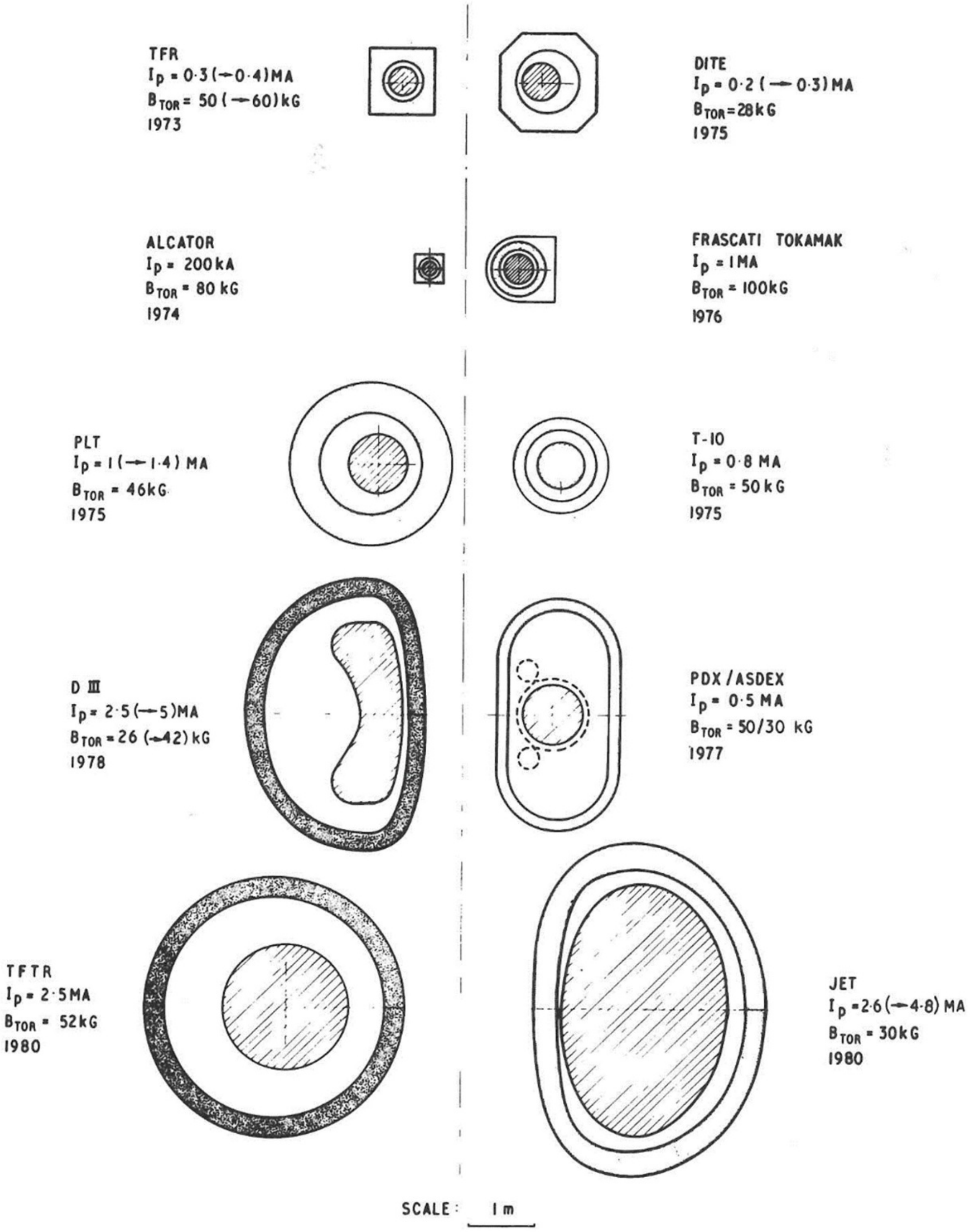


**Figure 1.** Size and magnetic fields of the JET tokamak compared with the devices operating at the time of JET design. Reproduced with permission from [1].

## 3. Heat and particle confinement

At the time of the JET design activities, although the tokamak had already demonstrated promising heat and particle transport characteristics, there were still major questions on the scaling of the behaviour to reactor conditions and on the nature and impact of 'anomalous' transport effects. Not only there were uncertainties on the transport mechanisms, but most of the data were collected in conditions dominated by ohmic heating. Since this would be negligible at the high temperature of a reactor, progress to reactor-relevant conditions would need exploitation, and characterization, of externally supplied additional heating.

As stated in the final design report [1], 'the fundamental aim of JET is to produce a large plasma which will represent a significant stage in research towards a reactor, with a view to testing the confinement principles of a Tokamak' and, more specifically, to 'answer the question of the losses which govern the plasma energy balance'.

Operating a device of such a large size was expected to bring advancements in several plasma properties, thought to be potentially very important to make significant progress towards reactor conditions. First of all, the large size accompanied by a powerful transformer primary and a relatively high toroidal field would allow the new device to achieve very high values of plasma current, of several MA, which did represent

**Table 1.** JET main technical specifications.

| | Design | Achieved |
|---|---|---|
| Minor/major radius | 1.25/2.96 m | |
| Toroidal field | 3.45 T | 4 T |
| Plasma current (limiter) | 3.8 (4.8) MA | 7 MA |
| Plasma current (X-point) | | 6 MA |
| Flat top duration | 10 s (20 s) | 60 s |
| Main fuel | H/D/T | H/D/T/He |
| NBI heating | 15 MW | 34 MW |
| ICRF heating (25–56 MHz) | 9–12 MW | 22 MW |
| LHCD (3.45 GHz) | | ~6 MW |
| Combined heating | | ~37 MW |
| Pellet injection | | Pacing and fuelling |
| Disruption mitigation | | Massive gas injection (MGI) shattered pellet injection (SPI) |
| Diagnostics systems | ~30 | ~ 90 |

up to a factor 10 with respect to any then existing tokamak. In turn, the combination of high current and size was expected to lead to an increase in heat and particle confinement.

We have anticipated in section 2 how the discovery of the H-mode improved confinement regime stimulated a significant change in the type of magnetic equilibria used for tokamak experiments. Since the presence of a poloidal field null (X-point), in the so-called 'magnetic limiter' configuration, was clearly identified as one of the main contributing factors to achieve H-mode, devices strived to operate in this magnetic configuration instead of with a 'material limiter' plasma. While JET began its operations and carried out confinement studies in material limiter configurations, with significant additional heating and up to 5 MA [2, 14], it soon started experiments with both single-null and double-null X-point equilibria, supported by an upgrade of the central solenoid. Eventually, with the design and installation of in-vessel coils and a lower divertor structure in 1992–94 [9], JET was fully equipped for H-mode confinement studies while maintaining a large volume and high current capability.

The development of engineering scaling laws, to extrapolate from present experiments to future machine, is one area where JET has made a unique contribution to H-mode confinement studies. The JET data has been essential to extend the plasma parameter range beyond what is possible in small/medium size tokamaks and, particularly, towards the expected conditions in ITER. As an example (figure 3), JET has been the device providing the data at highest thermal confinement time in type I ELMy H-mode for the formulation of the commonly used ITER98 scaling expression for the thermal confinement time [15]. The scaling laws for L-mode and H-mode, together with the accompanying global transport studies, have confirmed the assumptions that energy confinement scales strongly with plasma size and plasma current. For instance, the thermal energy confinement time in the ITER98(p,2) expression depends almost linearly on plasma current and almost quadratically on major radius, see equation (20) in [15]. Engineering scaling laws have, also, highlighted the importance of plasma vertical elongation in achieving higher thermal energy confinement times, thus validating the design choice of a non-circular cross section for JET. At the same time, it is important to note that JET data have also emphasized the limits of describing the plasma physics behaviour via the engineering scaling laws in certain reactor-relevant conditions. A recent, and significant, example is the weaker than in the ITER98 scaling degradation of the energy confinement with input power found in high beta Hybrid H-mode ITER-like Wall (ILW) scenarios, pointing to the influence of core pressure peaking at high power and the interplay between core and H-mode pedestal behaviour [16]. Theoretical analysis, based on linear and non-linear gyrokinetic modelling and linear magnetohydrodynamic (MHD), of confinement in these Hybrid H-mode conditions has revealed a clear impact of fast ion population on core microturbulence [17] and suggested how similar mechanisms could play a major role in next generation tokamak devices.

JET has, also, supplied data in a unique parameter range for studies of scaling laws based on *dimensionless* quantities. The use of dimensionless parameters is a convenient way to describe a complex system where a rigorous mathematical description does not exist and, in tokamak research, it is adopted to identify dominant transport mechanisms and extrapolate from present to future devices. JET has generally provided, simultaneously, the closest values of the dimensionless parameters commonly used to describe global confinement, namely normalized Larmor radius $\rho^*$ (figure 4), normalised beta $\beta_N$ and normalized collisionality $\nu^*$. In this area of confinement research JET data have been extensively used both in international databases and in dedicated *identity* experiments to validate theoretical assertions against experimental observations, and advance the predictive modelling capabilities which are essential in preparing for the next generation of fusion devices [18, 19]. One example is the comparative study of density peaking in JET and ASDEX Upgrade; this analysis clearly showed that collisionality is the most relevant parameter in determining the behaviour and suggested what this could mean for obtaining more peaked density profile in ITER [20].

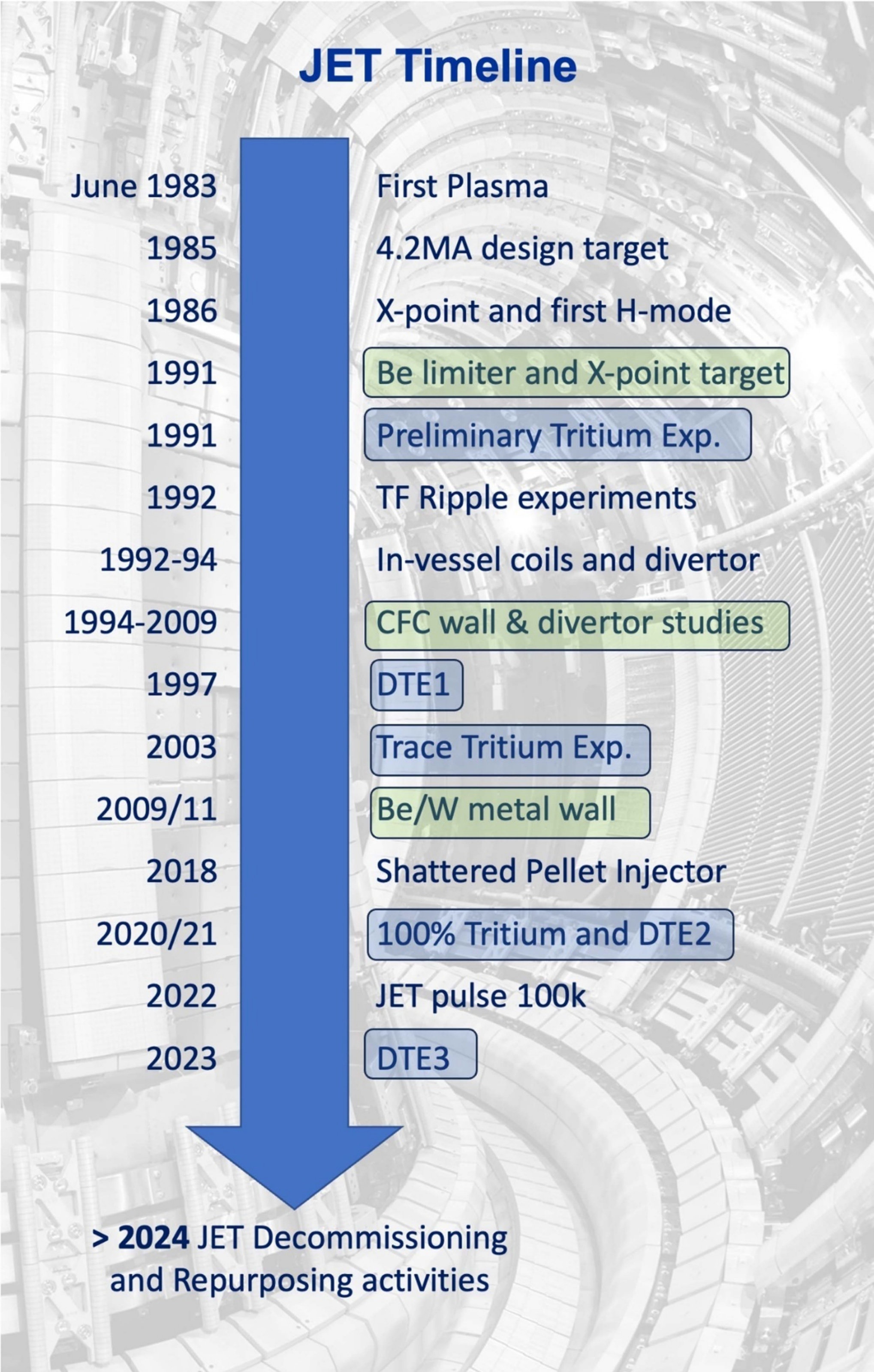


**Figure 2.** Timeline of the most significant events in the history of JET.

Another important area for extrapolation to future D-T devices, is the study of how the plasma behaviour changes with varying types of fuels. Thanks to its unique capability to operate at high additional heating power in a large variety of plasma fuels, including D-T, JET has been able to explore tokamak physics in several regimes, from L-mode to different flavours of H-mode, in various mixtures of hydrogen, deuterium, helium and tritium in both Carbon and metal wall

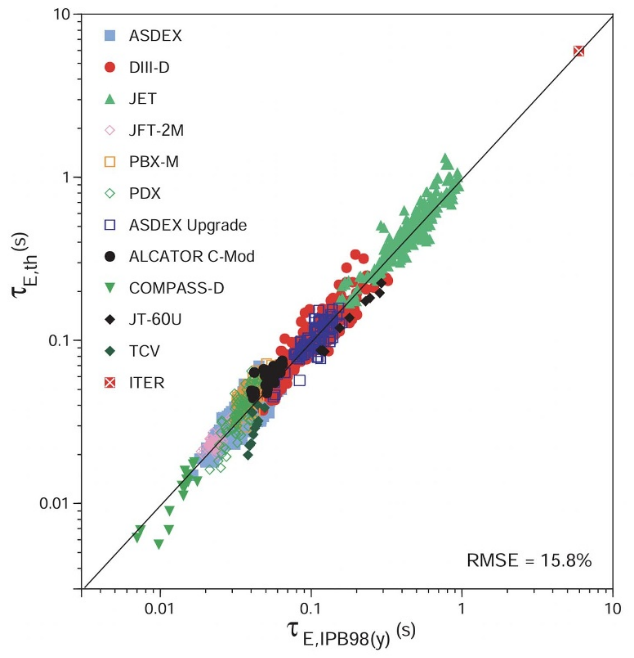


**Figure 3.** Comparison of H-mode thermal energy confinement time with the scaling expression in equation (18) of [15] for ELMy data in the ITER H-mode database version DB3. Reproduced courtesy of IAEA. Figure from [15]. Copyright (1999) IAEA.

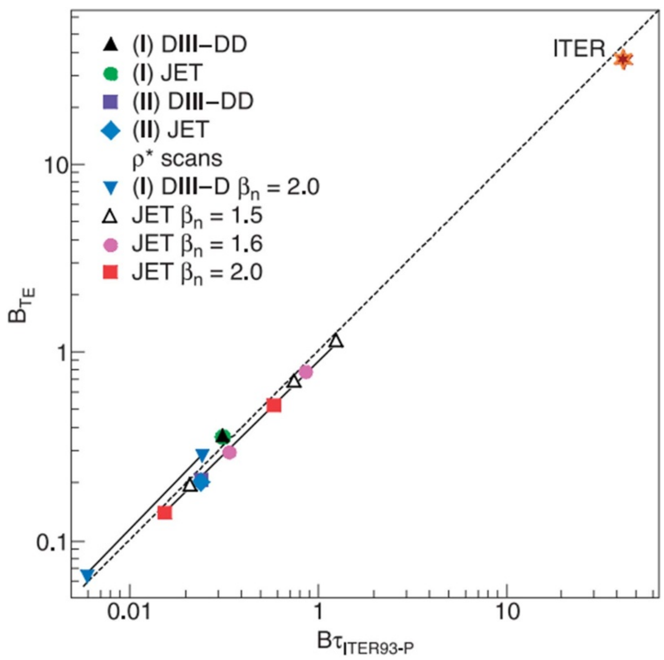


**Figure 4.** Comparison of BτE measured in $\rho^*$ scans on JET and DIII-D with the ITER93H-P scaling relation. Reproduced courtesy of IAEA. Figure from [15]. Copyright (1999) IAEA.

environment. JET has, thus, made exceptional contributions to studies of H-mode power threshold [21–23] as well as helping to disentangle heat and particle transport scaling with ion species [24, 25]. One example of unique results is the recent finding, in the DTE2 campaign, of clear coupling of core and edge ordering by isotope mass (figure 5), originating from the pedestal and proving once more that core and edge cannot be treated independently [26]. The wealth of experimental data has been accompanied by extensive theoretical and numerical studies, which have greatly helped steering the recent JET D-T experiments, understanding their results and looking ahead to what the implications could be for predicting the behaviour in ITER [27].

The JET results represent an extremely challenging, and directly reactor-relevant, database to validate transport modelling and contribute to the considerable progress in numerical predictive capabilities. In addition to the studies already quoted above, there have been many experiments dedicated to exploring the fundamental nature of transport in the unique JET conditions. For example, a specific line of investigation looked at the background and the threshold for the observed Ion Temperature *stiffness*, yielding valuable data for comparison with linear and non-linear gyrokinetic codes predictions [28, 29] and advancing the understanding of the role of rotational shear and current profile in achieving advanced confinement conditions in future tokamaks.

It is important to stress how the basis for achieving such a wide and unique range of parameters has been the extensive effort in scenario development at JET. From the early days of exploration of the H-mode, both as transient ELM-free and steady ELMy [14], to the development of high performance Hybrid [30] and Advanced scenarios, via injection of pellets [31] or exploitation of Lower Hybrid for current profile tailoring to study confinement with Internal Transport Barriers [32], and to the exploration of ELM-free H-mode in the metal wall environment, JET has covered all the scenarios that now form the foundation of the preparation of the next generation of fusion devices. Through the last 40 years, new theories or numerical modelling tools had to be validated to this dataset to be considered as providing a significant input in our plasma understanding and predictive capability. We expect modelling and theory validation activities to rely on the JET database well after the end of JET tokamak operations, to help answering critical questions and preparing for the next generation of fusion experiments.

## 4. PWI

The study of PWI when approaching reactor conditions was one of the original main objectives of JET. Over its 40 years of experiments JET has continuously evolved its vessel configuration and its PFCs, exploring the most relevant materials considered for next generation of fusion devices, on the way to reactor designs.

At the start of its plasma exploitation, JET was equipped with a simple Inconel First Wall; the data quickly showed how the high-Z metal wall was negatively impacting plasma performance and, between 1983 and 1988, the first wall was progressively covered by graphite (CFC) components on the innerwall, poloidal limiters and in the X-point target areas at the top and bottom of the vessel. The CFC First Wall, together

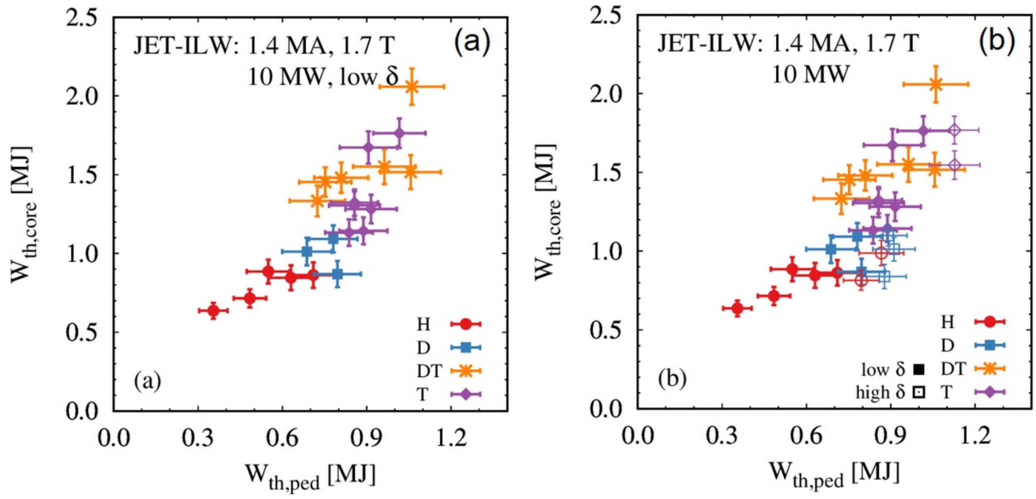


**Figure 5.** Core thermal stored energy as a function of the pedestal thermal stored energy for 10 MW plasmas of a gas puffing scan for different isotopes: (a) with low triangularity $\delta$ only and (b) also high $\delta$ plasmas. Reproduced from [26]. 

with use of Light Carbonization, was essential in obtaining good confinement plasma conditions, both in material and magnetic limiter configurations [33]. High energy transients and large ELMs were, however, found to cause large, performance degrading Carbon influxes, the so-called 'carbon-bloom' events. In the next evolution of the JET First Wall, toroidal belt limiters were installed and, following promising tests with beryllium evaporation, beryllium tiles replaced CFC in one of the toroidal belt limiter and one the X-point targets [34]. Importantly, the use of Remote Handling to carry out the installation of the beryllium components in 1990, for the first time in a magnetic confinement experiments, constituted a major milestone in fusion engineering and demonstrated the soundness of the original JET plans.

Even though operation with the beryllium PFCs showed a major reduction in the levels of low-Z impurities, oxygen and carbon, and an improvement in the density control in H-mode, the stable duration of the H-mode continued to remain severely limited by the poor power handling capabilities of the X-point targets [14]. In 1991 the decision was, thus, taken to install a pumped divertor in the lower part of the vessel, with in-vessel poloidal field coils, a divertor support structure and a toroidal cryopump [9]. In the following years, several divertor concepts were extensively studied, not only for their power handling and specific divertor physics characteristics but, also, for their compatibility with good core confinement [14, 35, 36]. While most of the PWI studies carried out in this period were not exclusive to JET, what was absolutely unique was the extension of these to D-T conditions. As an example, one of the main results of the DTE1 experiments was the confirmation of high hydrogenic fuel retention with carbon PFCs in all conditions, from L-mode to H-mode [37].

The need to firm up the basis for plasma components in the next generation of fusion devices, including ITER, prompted the decision to install a metal wall at JET [12]. The Components were chosen as a mixture of beryllium/Be-coated

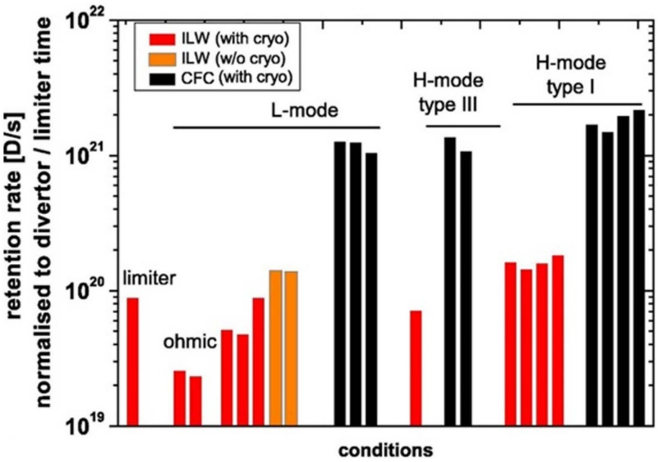


**Figure 6.** Long-term fuel retention rates in the JET-ILW, measured by global gas balance, and compared with equivalent conditions in carbon wall. Reproduced with permission from [39]. 

Inconel in the main chamber, solid tungsten and W-coated CFC in the divertor and high heat flux areas of the main chamber [38]. This was the combination chosen in the ITER design at the time, to be tested on JET as a risk mitigation approach. The so-called ILW, installed almost entirely via Remote Handling in a very demanding 18 months shutdown, was ready for exploitation in the summer of 2011. Over the next few years, the experimental results proved a significant reduction of long term hydrogenic fuel retention in all operating scenarios, figure 6 [39]. The experience of starting operations on a large metal device like JET, combined with the good news of lower retention and the data acquired in medium size devices [40], was crucial to inform the decision of ITER to install directly a metal wall, rather than using CFC components for their first non-active campaigns.

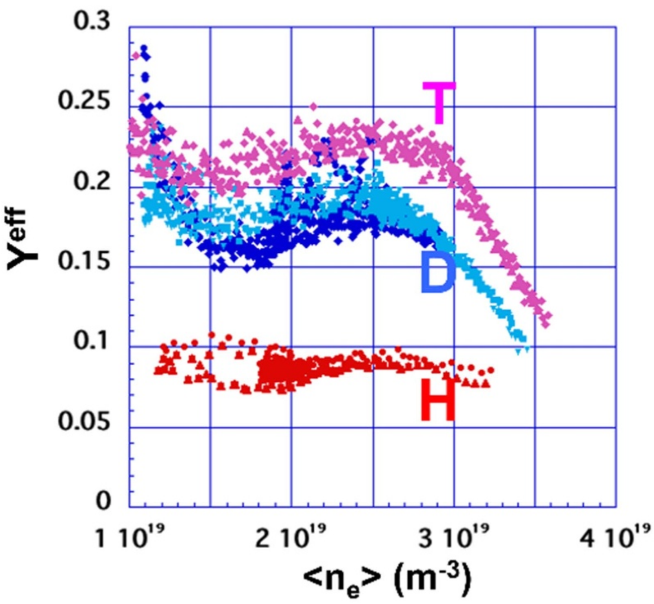


**Figure 7.** Effective Be sputtering yields measured at JET's inner Be limiters by visible spectroscopy. The deuterium data, marked in cyan and blue, have been obtained in different experimental campaign, as described in [41]. Reproduced from [42]. 

The combination of ILW and the unique capability to operate with tritium offered the opportunity to assess experimentally the influence of plasma isotope on the PWI in metal wall environment. As an example, the dependence of Be and W sputtering yields from isotope mass on sputtering and erosion has been measured in helium and hydrogenic plasmas (figure 7), from hydrogen to tritium [41, 42]. Ohmic L-mode experiments in material limiter configuration have clearly shown how the beryllium erosion yield increases with isotope mass. In another set of experiments, the W erosion in the divertor region was investigated in ELMy H-mode conditions [39]. The gross W erosion, which is due to impinging hydrogenic and light-Z impurities ions and is caused by both inter-ELM and intra-ELM sputtering, has also been shown to increase with isotope mass [43]. In the extreme case of 100% tritium H-modes the combination of low ELM frequency, stronger beryllium erosion and higher sputtering due to the high mass tritium results in much higher W sputtering than in deuterium. The consequence is a major difficulty in controlling the high-Z impurity in the plasma, unless a very large flow of gas is applied which, in turn, reduces the H-mode quality and the plasma performance.

Overall, the PWI in the ILW environment had a major impact on the confined plasma behaviour. Much of the JET campaign time from 2011 was dedicated to understanding and controlling the effect of high-Z impurities on core and edge plasma, developing integrated high performance scenarios and, eventually, carrying out further D-T experiments [44–46]. As an example, the scenario development focussed on the use of neutral gas and pellet ELM pacing to control the ELM activity, as well as the exploitation of core Ion Cyclotron Resonance Heating to control the high-Z impurity transport [47]. In addition, the development of a high pedestal temperature in the Hybrid H-mode allowed for the first time the demonstration of impurity screening via neoclassical effects in the H-mode pedestal [48], which is expected to be dominant in controlling the impurities in ELM-mitigated ITER scenarios.

Over the years, campaigns exploring plasma behaviour with different isotopes also offered the opportunity to investigate methods for removal of hydrogenic species, tritium in particular, from the PFCs and provide key information to ITER on fuel removal. Several techniques, from baking of the vessel to 320 C, to glow discharge cleaning and exploitation of the ICRF system for ion cyclotron wall conditioning, were explored, initially in hydrogen and deuterium conditions. They were, then, applied after the DTE2 and DTE3 campaigns, together with high power plasma pulses on specific, high fuel retention regions of the divertor to successfully reduce the plasma tritium content to very low levels in a relatively short period, thus allowing recovery of the retained tritium, and resumption of deuterium experiments without excessive production of 14 MeV neutrons and activation in the Torus Hall [49]. In the last year of JET operations, a new system was also installed to carry out laser-induced desorption coupled with quadrupole mass spectrometry (LID-QMS) to investigate hydrogenic species, and in particular tritium, desorption in real tokamak conditions. The LID-QMS system has been exploited for the first demonstration of *in situ*, space-resolved measurements of fuel retention, including tritium during and after DTE3 [50].

## 5. Disruption physics and runaway electron (RE) generation studies

Disruptions, a rapid and catastrophic loss of magnetic and thermal confinement, are an inherent property of tokamak plasmas [51]. The consequences of disruption transients can be diverse: electromagnetic loads on the vessel systems, localized heat loads on the PFCs and the likelihood to generate confined beams of energetic electrons for which the electric field acceleration prevails over collisions, the so-called REs. Disruptions constitute a major risk for a future tokamak-based fusion power plant and are one of the highest priority research areas in present devices. As the tokamak reaching the highest values of both magnetic and stored thermal energy, disruptions physics studies have always been at the core of the JET research plan. Unlike in small and medium size tokamak devices, where disruptions are not always considered as a problem, optimising the scenarios to minimize the likelihood of un-intentional disruptions, and their impact if unavoidable, together with effective real-time Event Detection and Exception Handling have always been a major concern in planning and executing JET experiments, foreshadowing closely how the next generation of tokamaks will have to operate.

The high risks for the integrity of the device, not always adequately predicted by the limited theories at the time, were

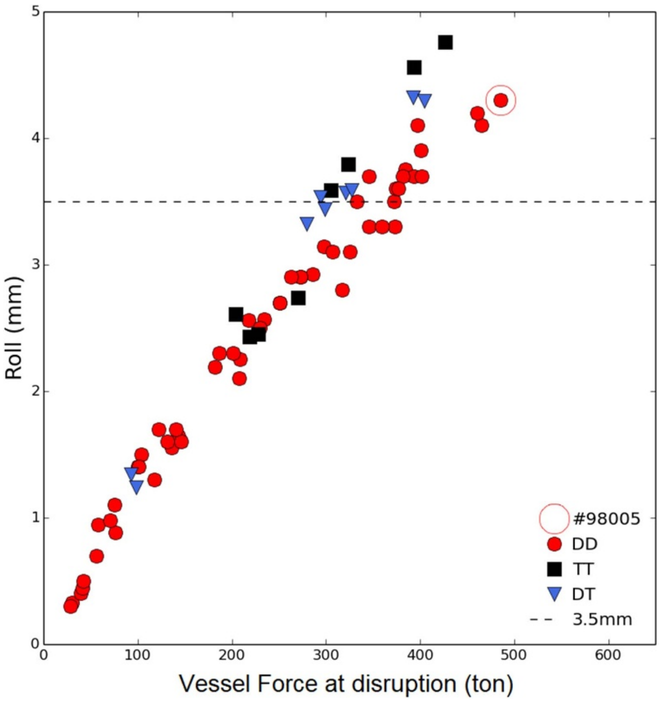


**Figure 8.** Sideways vessel displacement as function of disruption forces for high current experiments in JET. The highest values in the plot correspond to MGI mitigated disruptions in 3.5 and 4 MA pulses. The dashed line at 3.5 mm indicates the engineering limit for normal, low current operation.

observed experimentally from the very start of the exploitation of JET. As early as 1983/84, the insufficient vertical stabilization in elongated equilibria gave rise to a particularly dangerous class of disruptions, the vertical displacement event, in which vertical position control is lost at full plasma current and thermal energy. The electro-magnetic (EM) forces in these cases are larger than in other kinds of disruptions: one of such events, at relatively modest plasma current, generated forces of ∼250 tonnes [52]. The engineering analysis of such event predicted that an equivalent disruption at plasma current of 4.8 MA would have generated forces above 800 tonnes and could have caused irreparable damage to the vessel components. A subsequent upgrade of the real-time vertical control system, together with the installation of robust mechanical supports, allowed the full exploitation of the device to continue safely up to currents of 7 MA and, later, to cope with the increased demands of elongated single and double-null X-point configurations up to 6 MA. The combination of careful machine engineering and rigorous machine protection, encapsulated in a series of clear Operating Instruction defining the permitted operational parameter space, allowed the machine to be operated safely for high priority experiments even in conditions where disruptions of EM forces up to 500 tonnes could cause vessel rolling movement up to 5 mm (figure 8).

The installation of the ILW brought new challenges in the area of disruptions. From the start of ILW plasma operations, in 2011, the frequency of non-intentional disruption rose from around 3% up to 10%–15%. While part of this increase could be attributed to the need to re-learn to operate in what was, essentially, almost a new machine, some of the causes of disruptions were inherent in the high-Z metal wall environment and became a persistent feature of the last years of JET [53]. Not only disruptions became more frequent, but their impact on machine integrity was more problematic. With ILW, in the absence of an intrinsic low-Z impurity like carbon, the natural radiation level in un-mitigated disruption is reduced. A first consequence is that the localised thermal heat loads on the wall are higher and so is the risk of melting the fragile beryllium main chamber PFCs. Additionally, the lower radiation causes a substantially slower current quench: while this is beneficial to reduce the induced eddy currents in the vessel and the transient electric fields, the latter decreasing the likelihood of RE generations, it does increase significantly the duration of halo currents and the resulting EM forces [54].

Safe operation with the ILW, therefore, required the implementation of increasingly sophisticated real-time algorithms to detect incoming disruptions [55], coupled with the use of active, real-time triggered mitigation via massive gas injection (MGI). The JET disruption database, also, became the most challenging test ground for the development of real-time algorithms for disruption prediction and avoidance, in particular exploiting the opportunities offered by novel Machine Learning approaches [56]. Once more, with its machine protection and disruption management features, JET anticipated and provided a realistic testbed for some of the crucial aspects of operation in the next generation of large fusion experiments.

In 2018/19 the installation of a shattered pellet injector (SPI), in collaboration with the ITER Organization and the Oak Ridge National Laboratory and in direct support of ITER design activities, was another crucial moment proving the unique role of JET as the closest test ground for trials of disruption mitigation methods to prepare the next generation of fusion devices [57]. The new SPI system, although not used for real-time machine protection, has provided unprecedented data to advance the understanding of SPI plasma shutdown [58].

The physics of high current REs generation and control is one area where the JET SPI experiments have explored new, exciting, and promising routes for avoidance and mitigation of RE beams. It is important to note, before we go into more details on the results, that RE are not usually generated in the JET disruption: special scenarios, thus, had to be developed to ensure reliable and reproducible RE production. The risks of the damage brought by RE impact upon the ILW wall, both on the W and Be components, were also managed very carefully to balance the high scientific interest of the SPI experiments with the rest of the programme, including the unique D-T campaigns. On the other hand, the significant melting damage observed on impact of high current Runaway Beams on First Wall [59], in conditions which can only be achieved at JET, emphasizes the importance of developing effective RE mitigation methods in view of ensuring successful machine and investment protection in ITER and the next generation of high current tokamak experiments.

The dedicated JET experiments have demonstrated how effective SPI can be in avoiding RE generation while still mitigating the impact of heat loads and forces, for example if SPI

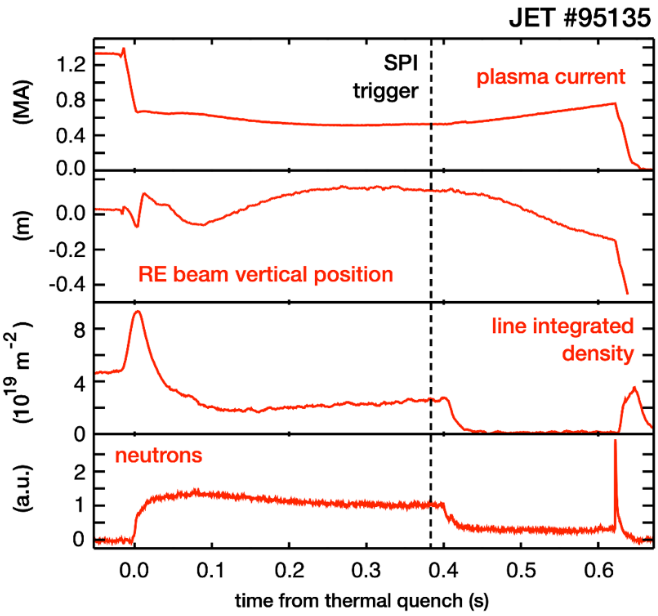


**Figure 9.** 'Benign' termination, thanks to injection of deuterium shattered pellet, of a runaway electron beam.

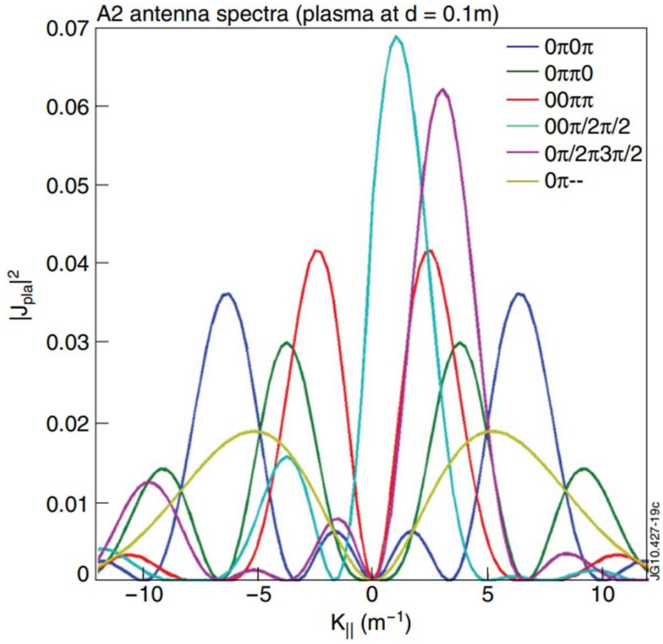


**Figure 10.** Heating and current drive power spectra for JET A2 ICRF antenna system at 42 MHz $|Jplal|^2$ represents the power density for given plasma-antenna distance and SOL conditions. The spectra are normalised to produce the same total power for all cases, while k|| is the wave number parallel to the magnetic field. Reproduced from [62]. 

is injected early enough in the disruption phase and/or if it contains enough deuterium [60]. In addition, and similarly to MGI observations, it was confirmed that using high-Z materials in SPI is not effective in suppressing a fully-formed RE beam without causing localised heat loads on the PFCs. One of the more surprising, and promising, discovery was the achievement of *benign* termination of RE beams in cases of injection of pure deuterium SPI (figure 9) [60]. This effect is thought to be caused by a large MHD instability together with the absence of RE re-generation in the clean companion plasma. Although the study of this very promising *benign* termination scenario is still in its early stages, and the extrapolation to the next generation of fusion devices is an open question, the discovery of this effect demonstrates once more the importance of experimental investigations in JET, the tokamak that has so far the closest conditions to those future devices.

## 6. Physics of radio frequency heating and current drive

As we have seen, two of the main objectives of JET were the study of fast particles, and in particular of the fusion alpha population, and of plasma heating. The evolution of the heating systems is described in more details in [6, 61] and references therein, from the modest power at the start of JET to the diverse, multi-megawatt systems in the ILW phase. It is important to stress that not all systems reached their maximum power capability in the same time window, which is why the sum of the individual power in table 1 is higher than the actual combined heating power. In addition, for the Radio Frequency and Microwave systems the coupled power can be significantly less than the generator output, especially in H-mode conditions.

In this section we will focus on studies of ICRF Heating and Current drive, which have provided over the years a wealth of new and unique results, advancing our understanding not only on plasma heating but also on heat transport and fast particle physics.

The JET ICRF system was designed not only to be powerful, as befitting such a large machine, but also extremely versatile. Several antenna designs were tested, culminating in the so-called A2 system, powered by up to 32 MW of generator power and operated at frequencies from 25 MHz to 56 MHz. The wide frequency range allowed ICRF heating, at fundamental and harmonics of the Ion Cyclotron frequency, at all values of Toroidal Field used for JET experiments and on a variety of resonant species, including tritium for D-T conditions. The spatial localisation of the ICRF power deposition can be tailored by changing the wave frequency and also to some extent by the phasing of the antennas. Phasing between the antenna straps can, also, be changed to obtain different wave spectra and explore both heating and current drive physics (figure 10).

Over the years, ICRF heating has been one of the pillars of the JET research activities. The applications, as summarized for example in [61], varied from contributions to core and reactor-relevant H-mode confinement studies, to investigation of the impact of energetic particles on core plasma confinement [63] and to exploration of impact of RF fields on Scrape-Off Layer and impurity production. Lately, in the ILW environment, the core power deposition provided by the ICRF system has been essential in regulating the transport

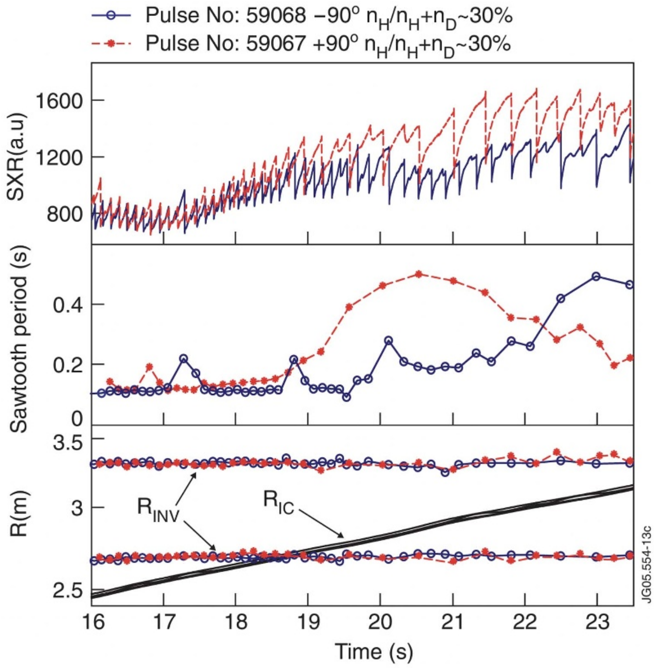


**Figure 11.** Soft x-ray signals, showing the core sawtooth activity, for two discharges with $n_H/(n_H + n_D) \approx 30\%$ and positions of the inversion radius (Rinv) and ion cyclotron resonance (RIC). Solid line and rings, #59068 with −90◦ ICCD; dashed lines and stars #59067 with +90◦ ICCD. Reproduced courtesy of IAEA. Figure from [66]. Copyright (2006) IAEA.

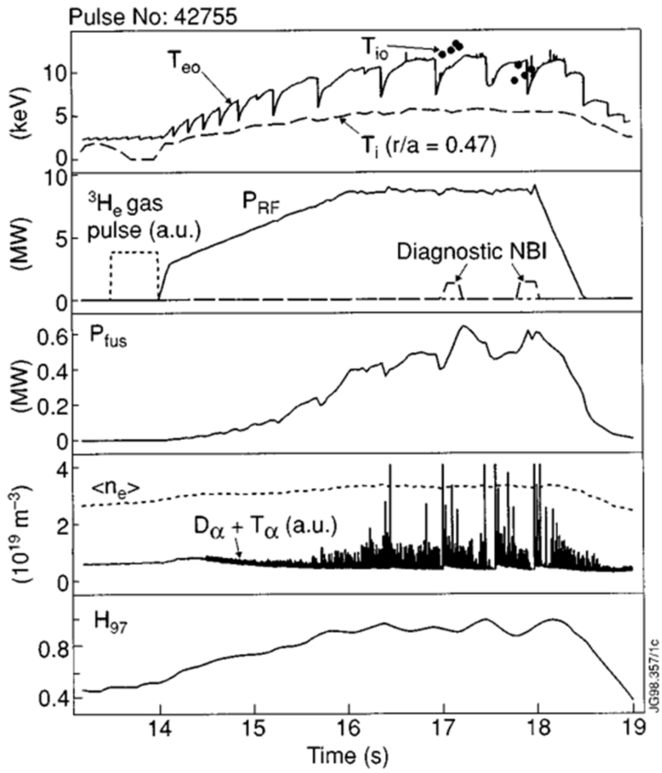


**Figure 12.** Main parameters of the $^3$He minority ICRH discharge which generated central ion temperatures up to 13 keV. This plasma had 10% $^3$He concentration, Ip = 3.3 MA and BT = 3.7 T. Reproduced courtesy of IAEA. Figure from [67]. Copyright (1999) IAEA.

of high-Z impurities and allow the achievement of high performance [47].

One of the more original, and unique, applications of the JET ICRF system was the demonstration of local current drive effects on sawtooth activity. Phasing the ICRF antenna array to produce a toroidally asymmetric k// spectrum can generate non-inductive currents, by interaction with either bulk electrons or a resonant ion population [64]. As theoretically predicted, for example in [65], if the resonance is located close to the location of the $q = 1$ surface, the minority Ion Cyclotron Current Drive would change the shear at this surface, hence potentially modifying the sawtooth activity. Dedicated experiments [66] showed very clear effects on the sawtooth activity when different wave spectra were used, driving either co- or counter-current locally around the $q = 1$ surface (figure 11). These results confirmed the significant progress and increasing maturity of our understanding of ICRF physics and fast particle effects, the latter particularly important for looking ahead to reactor conditions with heating dominated by fast alpha particles.

It is, however, in the area of heating of D-T plasmas that the flexibility of the ICRF system has provided the most groundbreaking results. As we have seen, the system was designed to make possible the assessment of heating scenarios relevant for next generation of D-T devices, in particular with resonances at harmonics of tritium or fundamental minority of He3. From the early DTE1 campaign in 1997, significant experimental time was dedicated to these unique RF studies, for example demonstrating the potential for bulk ion heating by ICRF alone, using a (He3)DT scheme (figure 12) and giving a first experimental proof of the feasibility of deuterium minority heating [67] in ICRH only conditions. This latter heating scenario was further optimized, via accurate predictive modelling, and successfully exploited in high performance DTE2 and DTE3 experiments to accelerate the injected deuterium beam ions and significantly increase the non-thermal fusion power, resulting in record D-T fusion power and energy [68]. Second harmonic heating of tritium, which is ITER reference ICRF heating scheme in D-T plasmas at full field, was successfully integrated in JET high-performance plasma in DTE2 [69]. Another novel application of ICRF to D-T plasmas, targeting bulk ion heating in reactor grade plasma conditions, is the so-called 3-ion heating scheme, exploiting the presence of intrinsic or seeded low-Z impurities in a mixed-ion plasma. After demonstrating the feasibility of this heating scenario in non-active conditions [70], the scenario was successfully ported to D-T plasmas [71].

The powerful and versatile ICRF system has, over the years and across the major changes in the environment of the JET device, provided major contributions to the original project objectives and demonstrated its versatility for reactor relevant applications, for example proving its applicability as an effective tool for wall conditioning and de-tritiation in [49], which is very promising for ITER and similar devices.

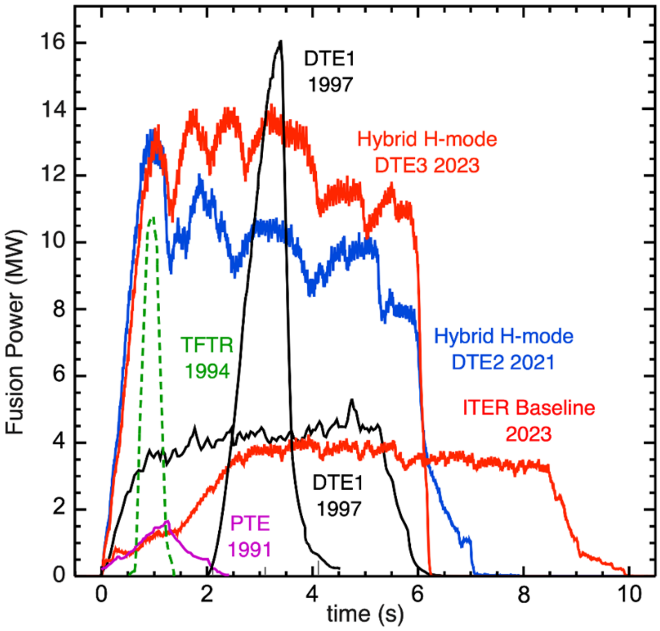


**Figure 13.** D-T fusion energy records obtained in TFTR and in JET, PTE, DTE1, DTE2 and DTE3, in different transient and steady H-mode scenarios. With 'ITER Baseline' it is designed the seeded H-mode scenario at high current and high triangularity.

## 7. D-T fusion power studies

Fusion research in JET was firmly aimed, from the very beginning, at exploring conditions approaching those expected in a thermonuclear reactor, including actual experiments with D-T fuel mixture.

After less than 10 years of plasma operations, the first D-T experiments were carried out. The 1991 PTE, although limited in scope and in fusion power, was a major landmark in fusion research, the first time that fusion power had been generated by controlled thermonuclear reactions for peaceful purposes. In two short high power pulses (figure 13), with tritium concentration $\sim$10%, fusion power in excess of 1.5 MW was produced transiently [72]. The data from these pulses was essential in starting to build a more realistic physics picture of D-T plasmas and prepare for the subsequent, more extensive D-T campaigns. As importantly, the experience gained by safely operating with tritium was essential in giving confidence in the processes, the staff training and the technology adopted for safe tritium handling at JET.

The next set of D-T experiments, the DTE1 campaign in 1997, had a much wider and ambitious physics programme, covering fusion power production in both transient and steady-state H-mode scenarios, as well as investigating isotope effects on transport and PWI and, as we discussed in section 6, an extensive exploration of the physics of ICRF heating in D-T. Just before this set of experiments took place, a D-T campaign was carried out on the TFTR tokamak [73]: the combination of *friendly competition* and strong collaboration between the JET and TFTR teams was a distinctive feature of this period in tokamak research, contributing to the exceptional success of both experiments. The DTE1 experiments, achieving record fusion power (figure 13) both transiently [74] and in steady ELMy H-mode [75] and highlighting the importance of isotope effects in all the regimes explored, were a major step forward in fusion research and increased significantly the confidence in the plans for the next generation of tokamak devices, and in particular ITER.

A further, short trace tritium campaign took place in 2003 with experiments focussed on investigating tritium particle transport via perturbative measurements. The main output was a confirmation that tritium diffusion is well above neoclassical levels in all regimes and the observation that plasma core behaviour as function of local physics parameters is best described by gyro-Bohm scaling with an additional inverse beta dependence [76].

As discussed in section 4, one of the main outcomes of the D-T experiments carried out in Carbon wall environment, both in TFTR and in JET, was the significant retention of tritium in the PFCs [37, 77]. These observations lead to the decision to abandon carbon as First Wall material for the active phase of ITER and gave additional impetus to the search for alternative PFC materials, resulting in the installation of the ILW at JET. In parallel to the ILW installation, plans for a further D-T campaign were initiated, with a much greater scope than DTE1, a major upgrade of the Neutral Beam Heating system and a much expanded set of diagnostics. A complementary full power campaign of 100% tritium experiments was, also, planned to further extend the range of isotope studies.

In addition to studies of tritium retention in metal wall conditions, the 2021 DTE2 campaign had ambitious objectives for fusion power and energy production, aiming at improving on the DTE1 output in steady H-mode conditions, as well as continuing the exploration of isotope physics, alpha heating and ICRF heating schemes, exploiting the new, upgraded set of core and pedestal diagnostics. We will only highlight, in the following, a few results from DTE2 and a more complete overview can be found in [42] and references therein.

The characterization of the confinement properties of the alpha particles born in the D-T fusion reactions is critical to confirm the efficiency of heating by alpha particles, the dominant heating source in a reactor. High energy alpha particles, for example, are expected to be resonant with Alfvén waves, which could lead to increased transport and redistribution, or even significant losses, of the fast alpha population. In previous D-T experiments, in TFTR [78] and JET [79], some evidence for alpha particle effects had been detected, and the alpha physics studies were revamped in the last D-T campaigns, taking advantage of significant improvements in diagnostics [80]. A high fusion power scenario, the so-called *afterglow* originally developed at TFTR, was exploited to minimize, by choice of the heating power mix and careful timing of the additional power pulse, the competing effects due to other fast ion populations. Modes were clearly observed, in D-T pulses and not in the reference pulses in deuterium, on several diagnostics systems after the NBI was switched off

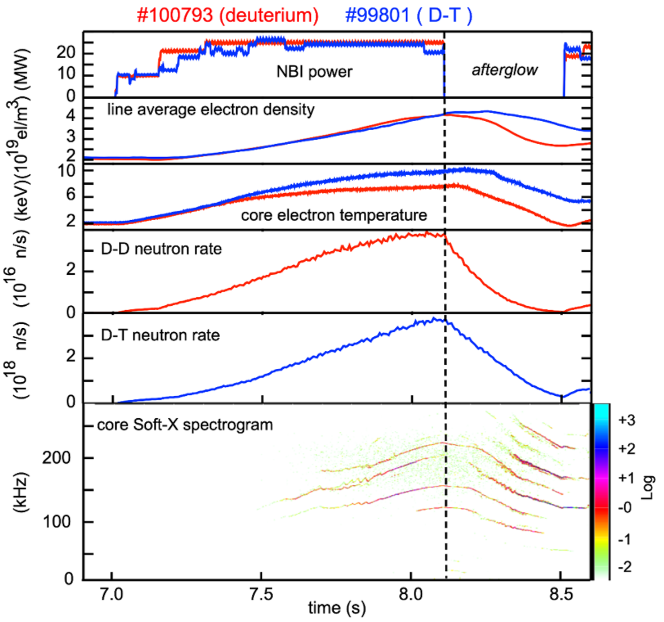


**Figure 14.** Time evolution of the main parameters of the afterglow scenario in D-T, #99801 in blue, compared with its reference in deuterium, #100793 in red, together with the fusion power trace and Fourier spectrogram of soft-x-ray measurements of TAE activity for the D-T pulse.

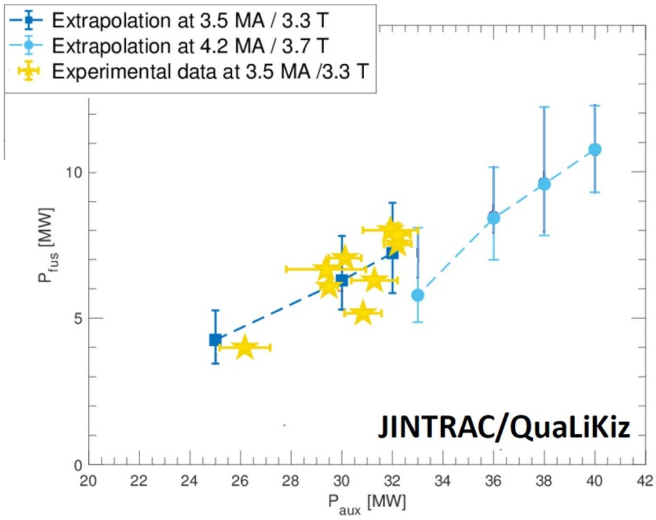


**Figure 15.** Comparison of D-T fusion power achieved in DTE2 in the baseline scenario at 3.5 MA (gold stars) with predictive modelling based on extrapolations from D plasmas at $\beta_N \sim 1.8$ (blue squares) using JETTO-Qualikiz within the JINTRAC workflow. Reproduced from [42]. 

(figure 14); modelling strongly supports the interpretation that these are Toroidal Alfvén (TAE) modes destabilized by the alpha particle population [81]. In the *afterglow* phase, correlating with the TAE activity, losses of core 3.5 MeV alpha particles were also clearly observed with the new fast ion loss detector (FILD) and Faraday cups diagnostics. FILD, in particular, has provided an impressive wealth of radially and energy resolved alpha particle measurements related to MHD activity like fishbones and ELMs [82]. The elusive bulk electron heating by slowing down alpha particles was also detected both in the *afterglow* experiments and by analysing the electron temperature response to dedicated fusion power modulation [83].

The experiments to push the production of high fusion power to more steady conditions, with duration limited by the JET copper Toroidal Field coils capabilities, were carried out in several scenarios, including Baseline, Hybrid and Impurity Seeded H-modes (figure 13). The preparation for the DTE2 high fusion power studies was based on the extensive exploration and optimization in ILW of various high confinement scenarios in deuterium, crucially accompanied by an unprecedented predictive modelling effort with advanced transport models [84]. Over several years prior to DTE2, the continuous interplay between experiments and modelling was essential in developing high confinement and performance plasma conditions, while promoting a deeper understanding of the plasma physics underlying the results. The success of the latest JET D-T campaigns lies as much in the demonstrated capabilities of the core confinement predictions as in the achievement of record fusion energy (figure 15).

One last D-T campaign followed in 2023. DTE3 focussed on studies of impurity seeded H-mode, highly radiative scenarios and small or no-ELMs regimes, as well as exploring real-time control schemes relevant for D-T operations [85]. It is interesting to note that, although the DTE3 campaign was shorter than DTE2, it delivered a higher number of plasma pulses for the scientific programme: this was due to an extensive activity of optimizing the operational processes and the experimental conditions on the basis of the recent DTE2 experience. The later D-T campaigns do constitute a significant progress in producing, and understanding, high performance conditions in steady conditions, over 15–20 thermal confinement times, and in a more reactor-relevant metal wall environment (figure 13).

Together with plasma physics experiments, and the PWI aspects discussed in section 4, the JET D-T campaigns were also a unique opportunity for neutronics studies in preparation for the next generation of fusion devices and, eventually, the fusion power plants [86]. The fusion power measurements were underpinned by an accurate in-vessel calibration of the 14 MeV neutron diagnostics, carried out before DTE2 [87]. Later, during the D-T campaigns, the neutron induced activation and damage in ITER functional materials was studied by exposing relevant samples to significant neutron fluxes. In addition, two novel neutronics experiments were carried out in DTE3: the first explored the activation of water in the Neutral Beam cooling loop, providing a realistic testbed for the assumptions and modelling tools used for ITER predictions.

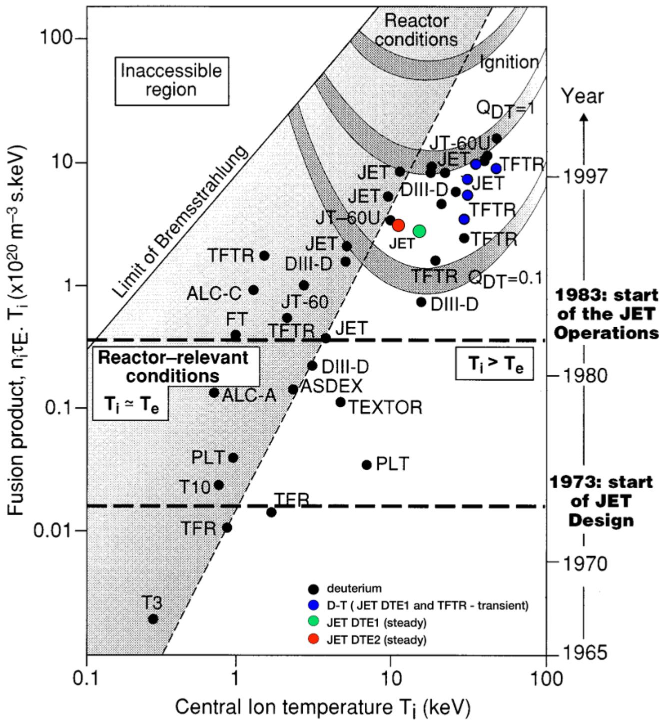


**Figure 16.** Progress in the Lawson parameter $n\tau_E T_i$ over the last 40 years of tokamak research. The values are extrapolated from deuterium pulses, apart from where indicated for JET and TFTR results. Adapted from figure 26 of. Reprinted from [8], Copyright (1999), with permission from Elsevier.

A second experiment, in collaboration with CERN, looked at realistic neutron irradiation effects on electronic components to contribute to qualification of electronics in future fusion power plants.

Progress towards conditions for more efficient fusion energy production is measured, in controlled thermonuclear fusion, by the so-called Lawson parameter $n\tau_E T_i$ [88]. The results of JET, together with the two other large tokamaks TFTR and JT-60/JT-60U [89], have been fundamental in realizing significant progress in the Lawson parameter (figure 16). Importantly, the contribution of JET [90, 91] and TFTR [73] has been in D-T conditions, and not only in extrapolation from deuterium plasmas. Additionally, the crucial significance of latest JET D-T campaigns lies in the achievement of fusion energy records in steady conditions, over several thermal energy confinement times and in a metal wall environment. Building on the experience of the early JET and TFTR experiments, the DTE2 and DTE3 campaigns have brought the experiments as close as possible to reactor conditions, demonstrating the massive growth in the maturity of physics and technology underpinning fusion energy research.

Now, at the end of JET experiments, we can ask ourselves how the results, particularly in D-T conditions, compare to the stated aims of the project. In the original Design Report [1], the target for plasma performance was deliberately non-quantitative, as the authors acknowledged that ‘The main reason for the JET experiment is to discover how plasma parameters scale, as the current and physical dimensions increase from present day experiments. It follows that it is not possible to give reliable estimates for the parameters that will be obtained’. Based on the theories and scaling laws available at the time, the expected plasma parameters in JET covered a region between 3 keV and 10 keV in ion temperature and extending for more than orders of magnitude in the Lawson parameter. While the most optimistic extrapolations did, indeed, suggest that JET could achieve breakeven with heating power in the range 15–40 MW, the authors of the report were consistently cautious in committing to the quantitative breakeven target. Eventually, the Lawson criterion values achieved at JET are in the middle range of those predicted, with ion temperatures close to the top of the extrapolations when input power is in the 30 MW range. And, more importantly, the data accumulated by JET, and TFTR, in the highest performance D-T conditions have constituted a priceless, unique basis to progress in understanding the physics of thermonuclear plasma and supporting the design of the next generation of fusion facilities.

## 8. Conclusions

At the time of its design, JET represented a huge step in plasma parameters from existing devices, with a very ambitious set of objectives: over the last 40 years JET has demonstrated major scientific success in all the specific areas targeted in the original design.

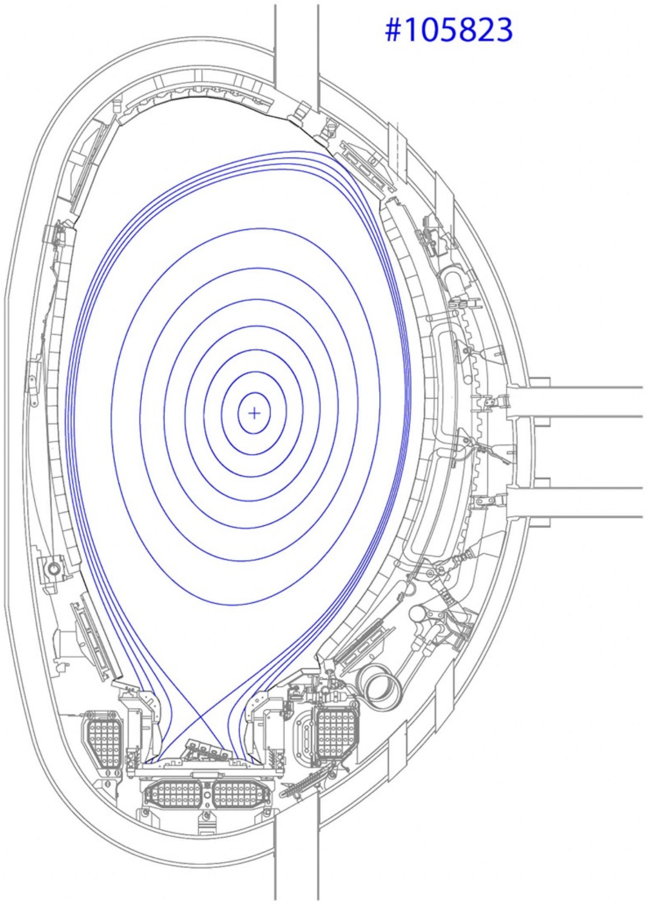


**Figure 17.** Equilibrium for JET #105823, $t \sim 14$ s, at 1.5 MA/2.3 T, for studies of H-mode with negative triangularity.

The basis for this success lies, first of all, in the vision, ambition and exceptional talent of design team, strongly supported by the European political powers of the time. The design team already had one of the defining, and most valuable, characteristics of the later JET Team, that is a very strong integration of physics and engineering, encouraging a continuous dialogue between these two sides. Openness to new physics ideas and engineering innovation, constantly adapting to new technologies and looking into new areas of research were at the core of the evolution of JET, all the while keeping firmly in mind the need to ensure personnel safety and investment protection. This approach has allowed JET to remain at the forefront of fusion physics and engineering research throughout its 40 years of operation, carrying out cutting-edge experiments, like exploration of DEMO-relevant small or no-ELM scenarios or negative triangularity impact on H-mode (figure 17), up to the very last day of plasma operations.

In the author's opinion, however, the main legacy of JET is having provided the example for a collaborative structure and a training centre for European fusion research scientists. The success of JET has principally been due to its main asset, its team, the result of collaboration between people with very different expertise and background, working towards a common purpose (figure 18).

## Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

## Acknowledgment

This manuscript has been drafted on the basis of documentation published by the JET Team over the last 40 years. The main author would like to specifically acknowledge the help, and support, of Drs C.D. Challis, L.-G. Eriksson, J. Jacquinot, E. Joffrin, Y. Kamada, A. Kappatou, Y. Kazakov, E. Lerche, D. Mc Donald, C.F. Maggi, J. Mailloux, M. Mantsinen, V. Parail and C. Reux.

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200—EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.


**Figure 18.** JET Team staff watching (a) the first plasma, on 25 June 1983, and (b) the last plasma, on 18 December 2023. © United Kingdom atomic energy authority.

## ORCID iD

F G Rimini https://orcid.org/0009-0001-2917-0455

## References

[1] European Commission The JET project: design proposal of the joint European torus EUR 5516e (EUR-JET-R5) Commission of the European Communities
[2] Rebut P H and Keen B 1987 *Fusion Technol.* **11** 13
[3] Princeton Plasma Physics Lab TFTR conceptual design report 1976 Westinghouse Electric Corp. PPPL-1275, PH-R-OOI
[4] Tamura S 1986 *Plasma Phys. Control. Fusion* **28** 1377
[5] Artsimovich L A *et al* 1965 *J. Nucl. Energy* C **7** 305
[6] Rimini F G (JET Contributors) 2024 JET: 40 successful years of fusion research *IEEE Trans. Plasma Sci.* **52** 3561–73
[7] Wesson J The science of JET, JET–R(99)13 2000
[8] Keilhacker M JET Team 1999 *Fusion Eng. Des.* **46** 273–90
[9] Huguet M *et al* 1991 Design of the JET pumped divertor *Proc. 14th IEEE/NPSS Symp. Fusion Engineering* vol 1 pp 440–3
[10] Wagner F *et al* 1982 *Phys. Rev. Lett.* **49** 1408
[11] Tanga A *et al* 1987 *Nucl. Fusion* **27** 1877
[12] Paméla J, Matthews G F, Philipps V and Kamendje R 2007 An ITER-like wall for JET *J. Nucl. Mater.* **363** 1–11
[13] Stokes T, Damjanovic M, Berriman J and Reynolds S 2023 Detritiation of JET Beryllium and Tungsten *Fusion Sci. Technol.* **80** 479–85
[14] Keilhacker M, Gibson A, Gormezano C and Rebut P H 2001 *Nucl. Fusion* **41** 1925
[15] ITER Physics Expert Group on Confinement and Transport *et al* 1999 *Nucl. Fusion* **39** 2175
[16] Challis C D *et al* 2015 *Nucl. Fusion* **55** 053031
[17] Garcia J, Challis C, Citrin J, Doerk H, Giruzzi G, Görler T, Jenko F and Maget P 2015 *Nucl. Fusion* **55** 053007
[18] Luce T, Petty C C and Cordey J G 2008 *Plasma Phys. Control. Fusion* **50** 043001

[19] McDonald D C, Andrew Y, Huysmans G T A, Loarte A, Ongena J, Rapp J and Saarelma S 2008 Chapter 3: eLMy H-Mode Operation in JET *Fusion Sci. Technol.* **53** 891–957
[20] Angioni C *et al* 2007 *Nucl. Fusion* **47** 1326
[21] Righi E *et al* 1999 *Nucl. Fusion* **39** 309
[22] Solano E *et al* 2023 *Nucl. Fusion* **63** 112011
[23] Birkenmeier G *et al* 2023 *Plasma Phys. Control. Fusion* **65** 054001
[24] Bhatnagar V P *et al* 1999 *Nucl. Fusion* **39** 353
[25] Horvath L *et al* 2021 *Nucl. Fusion* **61** 046015
[26] Schneider P A *et al* 2023 *Nucl. Fusion* **63** 112010
[27] Garcia J *et al* 2022 *Plasma Phys. Control. Fusion* **64** 054001
[28] Mantica P *et al* 2009 *Phys. Rev. Lett.* **102** 175002
[29] Mantica P *et al* 2011 *Phys. Rev. Lett.* **107** 135004
[30] Joffrin E *et al* 2005 *Nucl. Fusion* **45** 626
[31] Tubbing B J D *et al* 1991 *Nucl. Fusion* **31** 839
[32] Ekedahl A *et al* 1998 *Nucl. Fusion* **38** 1397
[33] Rebut P H, Dietz K J and Lallia P P 1989 *J. Nucl. Mater.* **162** 172–83
[34] Keilhacker M 1990 Overview of results from the JET tokamak using a beryllium first wall *Phys. Fluids* **2** 1291–9
[35] Campbell D J *et al* 1997 *J. Nucl. Mater.* **241** 379–84
[36] Fundamenski W 2008 Chapter 6: scrape-off layer transport on JET *Fusion Sci. Technol.* **53** 1023–63
[37] Andrew P *et al* 1999 *Fusion Eng. Des.* **47** 233
[38] Matthews G F *et al* 2011 *Phys. Scr.* **2011** 014001
[39] Brezinsek S 2015 Plasma-surface interaction in the Be/W environment: conclusions drawn from the JET-ILW for ITER *J. Nucl. Mater.* **463** 11–21
[40] Rohde V, Kallenbach A, Mertens V and Neu R 2009 *Plasma Phys. Control. Fusion* **51** 124033
[41] De La Cal E *et al* 2022 *Nucl. Fusion* **62** 126001
[42] Maggi C F *et al* 2024 *Nucl. Fusion* **64** 112012
[43] Douai D *et al* 2023 Overview of plasma-wall interactions studies in JET-ILW H, D, T and DT campaigns. *Preprint: IAEA Fusion Energy Conf.* (EX/8-5) https://doi.org/10.1103/PhysRevLett.131.075101
[44] Nunes I on behalf of the JET Contributors 2016 *Plasma Phys. Control. Fusion* **58** 014034
[45] Mailloux J *et al* 2022 *Nucl. Fusion* **62** 042026
[46] Angioni C *et al* 2014 *Nucl. Fusion* **54** 083028
[47] Lerche E *et al* 2016 *Nucl. Fusion* **56** 036022
[48] Field A R *et al* 2023 *Nucl. Fusion* **63** 016028
[49] Matveev D *et al* 2023 *Nucl. Fusion* **63** 112014
[50] Zlobinski M *et al* 2024 *Nucl. Fusion* **64** 086031
[51] Wesson J 1997 *Tokamaks* 2nd edn (Oxford Science Publications) pp 349–67
[52] Bertolini E, Mondino P L and Noll P 1987 The JET magnet power supplies and plasma control systems *Fusion Technol.* **11** 71–119
[53] De Vries P *et al* 2014 *Phys. Plasmas* **21** 056101
[54] Rimini F G *et al* 2015 *Fusion Eng. Des.* **96** 165–70
[55] Stuart C I *et al* 2021 *Fusion Eng. Des.* **168** 112412
[56] Pau A, Fanni A, Carcangiu S, Cannas B, Sias G, Murari A and Rimini F 2019 *Nucl. Fusion* **59** 106017
[57] Baylor L R *et al* 2021 *Nucl. Fusion* **61** 106001
[58] Gerasimov S N *et al* 2024 *Phys. Scr.* **99** 075615
[59] Reux C *et al* 2015 *Nucl. Fusion* **55** 093013
[60] Reux C *et al* 2022 *Plasma Phys. Control. Fusion* **64** 034002
[61] Noterdaeme J-M, Eriksson L-G, Mantsinen M, Mayoral M-L, Eester D V, Mailloux J, Gormezano C and Jones T T C 2008 Chapter 9: physics studies with the additional heating systems in JET *Fusion Sci. Technol.* **53** 1103–51
[62] Czarnecka A *et al* 2012 *Plasma Phys. Control. Fusion* **54** 074013
[63] Garcia J *et al* 2024 Stable deuterium-tritium plasmas with improved confinement in the presence of energetic-ion instabilities *Nat. Commun.* **15** 7846
[64] Bhatnagar V P, Start D F H, Jacquinot J, Chaland F, Cherubini A and Porcelli F 1994 *Nucl. Fusion* **34** 1579
[65] Porcelli F *et al* 1996 *Plasma Phys. Control. Fusion* **38** 2163
[66] Eriksson L-G *et al* 2006 *Nucl. Fusion* **46** 951
[67] Start D F H *et al* 1999 *Nucl. Fusion* **39** 321
[68] Lerche E *et al* 2023 *AIP Conf. Proc.* **2984** 030005
[69] Mantsinen M J *et al* 2023 *Nucl. Fusion* **63** 112015
[70] Kazakov Y *et al* 2021 *Phys. Plasmas* **28** 020501
[71] Kazakov Y *et al* 2023 *AIP Conf. Proc.* **2984** 020001
[72] Rebut P-H 1992 *Plasma Phys. Control. Fusion* **34** 1749
[73] Hawryluk R J 1999 Results from D—T experiments on TFTR and implications for achieving an ignited plasma *Phil. Trans. R. Soc.* A **357** 443–69
[74] Keilhacker M *et al* 1999 *Nucl. Fusion* **39** 209
[75] Jacquinot J *et al* 1999 *Nucl. Fusion* **39** 235
[76] Zastrow K-D *et al* 2004 *Plasma Phys. Control. Fusion* **46** B255
[77] Skinner C H *et al* 1997 Plasma wall interaction and tritium retention in TFTR *J. Nucl. Mater.* **241** 214–26
[78] Hawryluk R J *et al* 1994 *Phys. Rev. Lett.* **72** 3530
[79] Thomas P R *et al* 1998 *Phys. Rev. Lett.* **80** 5548
[80] Fitzgerald M *et al* 2023 *Nucl. Fusion* **63** 112006
[81] Kiptily V G *et al* 2023 *Phys. Rev. Lett.* **131** 075101
[82] Bonofiglo P J *et al* 2024 *Nucl. Fusion* **64** 096038
[83] Mantica P *et al* 2024 *Nucl. Fusion* **64** 086001
[84] Garcia J *et al* 2023 *Nucl. Fusion* **63** 112003
[85] Kappatou A *et al* submitted
[86] Litaudon X *et al* 2024 *Nucl. Fusion* **64** 112006
[87] Batistoni P *et al* 2018 *Nucl. Fusion* **58** 106016
[88] Lawson J D 1957 *Proc. Phys. Soc.* B **70** 6
[89] Kamada Y *et al* 2002 Fusion plasma performance and confinement studies on JT-60 and JT-60U' *Fusion Sci. Technol.* **42** 185–254 (Special Issue on JT-60)
[90] Kim H-T, Sips A C C, Challis C D, Keeling D, King D, Joffrin E, Szepesi G, Buchanan J, Horton L D and Yuan X 2020 *Nucl. Fusion* **60** 066003
[91] Hobirk J *et al* 2023 *Nucl. Fusion* **63** 112001