# PROGRESS IN TECHNOLOGY AT JET

A S Kaye[1], H Altmann[1], R Albanese[4], D Ciric[1], P Coad[1], D Brennan[1], F Durodie[5], T Edlington[1], D C Edwards[1], R Felton[1], T T C Jones[1], A Lioure[2], P Lomas[1], J Mailloux[1], I Monakhov[1], M Nightingale[1], J Pamela[2], R Pearce[1], V Riccardo[1], J Rapp[2], A Rolfe[3], E Surrey[1], S Rosanvallon[2], T Todd[1], A Walden[1]

1. Euratom Fusion Association UKAEA, Culham Science Centre, Abingdon, OX14 3DB, UK; ask@jet.uk
2. EFDA CSU, Culham Science Centre, Abingdon, OX14 3DB, UK
3. Oxford Technologies Ltd, Culham Science Centre, Abingdon, OX14 3DB, UK
4. Euratom Fusion Association ENEA-CREATE, Univ. Mediterranea RC, Loc. Feo di Vito, I-89060, RC, Italy
5. Euratom Fusion Association ERM, LPP/TEC, Royal Military Academy, B-1000, Brussels, Belgium

*JET supports ITER both in development of technology and in torus operations. The latter include the study of ITER-like scenarios, operation in tritium (a trace tritium campaign has recently been completed), mitigation of ELMs and disruptions, investigation of tritium retention, real time control of plasma parameters, and control of extreme plasma shapes. Operation of highly shaped ITER scenarios has been demonstrated. Heating systems are being upgraded, with the enhanced NB system in full operation, an ITER-like RF antenna under manufacture, coupling of LHCD over large distances achieved and external conjugate-T matching of an RF antenna demonstrated. New diagnostics including halo current probes and neutron and alpha particle detector are being installed.. In-vessel installation is being carried out remotely using up-graded remote handling tools. Analysis of tritiated samples from the 1997 tritium campaign, and the development detritiation methods for hard and soft waste continues. Substantial enhancement of JET to better exploit its capabilities in the preparations for ITER are presently being implemented.*

## I. INTRODUCTION

The JET Tokamak has played a leading role in the development of fusion science and technology for more than twenty years. For the past five years, UKAEA has operated JET for the European Commission as a user facility to be exploited by visiting scientists [1]. In the past year JET has achieved the most plasma pulses yet, the highest level of heating power, and successful re-commissioning of 4 Tesla operation. JET continues to contribute at the leading edge of a wide range of fusion related physics and technology issues, and has the potential to do so for many years yet.

Some key features make JET a strong contributor. These include the large dimensions which most closely approach ITER, the divertor, the availability of neutral beam, ICRH and lower hybrid heating/current drive systems, a wide range of diagnostics, including burning plasma diagnostics, the use of beryllium in the first wall, the capability to operate with and to recycle tritium, and the extensive remote handling capability which allows major enhancements to be implemented despite activation in tritium operations. In addition, there is cumulative experience in safe operation of a fusion nuclear facility and the management issues involved, and experience in the management of the operation and upgrade of a major collaborative fusion facility run by a host organisation for the benefit of visiting scientists and engineers.

Highlights of JET operations include the study of ITER relevant scenarios, disruptions, ELM mitigation and tritium retention, and the development of real time control of plasma parameters and improved plasma engineering to allow safe operation in extreme shape scenarios. External conjugate T matching of a pair of straps on an RF antenna, and effective coupling of the lower hybrid system with ITER-like gaps to the separatrix, have been demonstrated. A trace tritium campaign was completed last autumn and consolidated the capability for tritium operations on JET. The risk management of operation in ITER-like scenarios which have severe potential vertical forces in disruptions continues to evolve [2].

Enhancements completed since 2000 include new neutral beam power supplies and upgraded beam sources allowing higher power operation. During the present one year shutdown some twenty new or enhanced diagnostics are being installed, including new magnetics, halo sensors, lost alpha probes, and TAE antennas which are in-vessel, and being installed during ten months of remote handling operations. Despite the recent trace tritium operation, some manned access is also taking place all within the individual dose limits set for members of the public. A new ITER-like ICRF antenna is being procured, and will be installed towards the end of 2005.

Additional technology tasks are also being undertaken, including the management and disposal of intermediate and low level tritiated waste, and the study of highly tritiated carbon flakes from the 1997 tritium campaign. The remote handling capability has been further developed to include force feedback end-effectors to enable remote handling of heavy loads (up to 400 kg), and increasingly to use virtual reality techniques.

This paper reviews these many activities on JET and illustrates the contribution that JET has the potential to make in the continuing preparation for ITER operation.

## II. JET OPERATING RESULTS

### II.A ITER-Like Scenarios

High triangularity ELMy H-mode ITER reference scenarios have been widely studied at JET [3], achieving simultaneously an H factor of one, density above the Greenwald limit, and a normalised beta of 1.8, all exceeding the ITER reference design values, at a plasma current of 2.5 MA and triangularity of 0.47. The plasma current in these scenarios is limited by coil stresses, but operation in high performance ELMy H-mode up to 4 MA has been demonstrated at reduced triangularity.

Advanced scenarios with internal transport barriers have been developed with operation close to the Greenwald density, with full current drive at 1.8 MA for 20 seconds, with low rotation and nearly equal ion and electron temperature, and with large radius barriers.

### II.B Mitigation of ELMs and Disruption Studies

Thermal load to plasma facing components due to Edge Localised Modes (ELMs) are an issue for ITER and are being studied at JET. Impurity seeding to mitigate ELMs proved to be inefficient for large ELMs (type-I ELMs) and the heat flux of small ELMs was only partially dissipated [4]. Initial results with ELMy H-modes with benign type-II ELMs show good confinement with acceptable divertor heat load [5]. Whilst very promising, they are not easily accessible. In contrast, the robust type-III ELMy H-mode has been demonstrated at JET to potentially meet all the requirements for an integrated ITER scenario [6].

Tokamak disruptions produce electromechanical forces, heat loads and runaway electrons which strongly impact on the design and operating limits. In JET, the vertical force can lead to fatigue of the vacuum vessel. Highly shaped ITER relevant plasmas have been found to produce substantially larger vertical forces than traditional scenarios and have required the development of refined management controls over the usage of such scenarios at high plasma current [2]. JET has progressed in the understanding of disruptions following detailed analysis of both deliberate and accidental disruptions, has issued revised design criteria for JET components [7], and has contributed to the definition of the ITER disruption design criteria, in particular using data from the refurbished halo current diagnostics [8] and current quench duration data [9]. Two disruption focused enhancements are being implemented, the provision of improved spatial resolution halo current sensors [24], and of a massive flow fast gas injector (c.1 bar.l/ms) for disruption mitigation experiments. The new wide angle camera [23] will improve analysis of the disruption heat loads in the main chamber, previously studied using Langmuir probes [10] and important for the choice of the ITER first wall material. Systematic analysis of the residual plasma stored energy and thermal quench for high performance JET discharges [11] leads to improved life expectancy for the ITER divertor.

### II.C Real Time Control

The control of long pulse, steady state operation in highly shaped ITER relevant scenarios requires the development of a real time, feedback control capability on key parameters. Such a system has been developed at JET [12], and now allows simultaneous control of pressure, temperature and q profiles, of global radiation and of neutron rates utilising inputs from many discrete diagnostic systems including spectroscopy, LIDAR, bolometry, polarimetry, IR interferometry, magnetics and neutronics. Outputs are used to control the NB, RF and LH powers and gas introduction modules. The system can be configured for event driven experiments, e.g. to minimise neutron production by terminating underperforming pulses, and feedback control experiments, for example control of plasma beta using NB heating power. Further upgrades include improving multiple input/multiple output controls using MATLAB such as temperature and q-profile control with NB, RH and LH, and improving the signal/noise ratio in the diagnostics.

### II.D Extreme Shape Controller

The ITER reference scenarios utilise shapes that are difficult to produce in present generation devices including JET. The present JET shape control can only simultaneously control a small number of gaps to the vessel wall, which can lead to important errors in shape in ITER-like configurations, particularly in response to large variations in poloidal beta or internal inductance. A new extreme shape controller (XSC) has been implemented at JET [13]. This uses a linearised model of the plasma shape response to current variations in each of the eight coils to simultaneously control to good precision up to 36 gaps to the vessel wall. The new system has been installed in parallel with the existing controller, and has been extensively proven during 2003. Extreme scenarios, including internal transport barriers with large beta and inductance variations, have been run reliably; an example of shape control during plasma current ramp down is shown in fig.1.

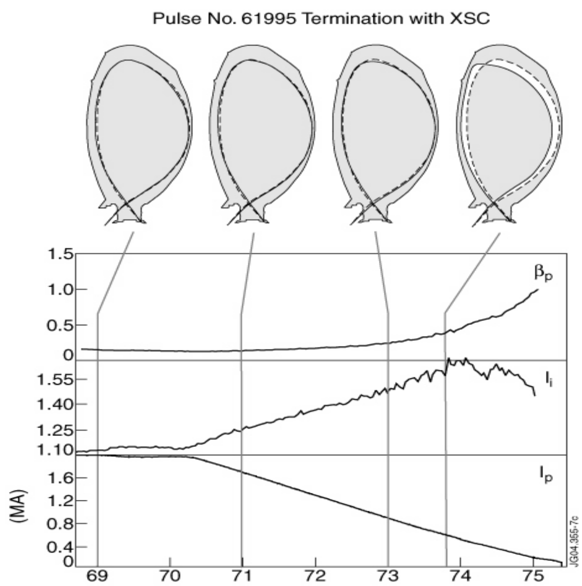


Fig 1. Plasma shape control during current rampdown using the extreme shape controller, showing measured (solid ) and programmed (dashed) shapes.

The XSC offers also new capabilities, such as strike point sweeping at constant shape, and strongly enhances the capability of JET in the study of ITER relevant high performance scenarios.

## III. TECHNICAL PROGRESS

### III.A Neutral Beam Heating Upgrades

The JET neutral beam (NB) upgrade involved modifying the accelerators of eight Positive Ion Neutral Injectors (PINIs) to increase the current from 30A to 60A at 130kV, installing an improved Box Scraper to handle the extra power, and major changes to the HV power supplies [14]. The first set of four upgraded PINIs was installed in 2001 and operated using the existing HV power supply modules (rated at 160kV/60A). The second set of four 130kV/60A PINIs was installed in 2002, and two new 130kV/130A switch mode power supplies [15,16] to power them were installed and commissioned in 2003. These power supplies utilise 120 series IGBT invertor modules feeding 120 isolation transformers whose rectified outputs are connected in series. Demanding requirements on output voltage stability and ripple (+/-1.3kV), during both load and line variations, necessitated careful optimisation of the control algorithms and compensation of effects due to asymmetry in the stray capacities [15]. Protection of the load in the event of breakdown is achieved by switching off the invertors on the LV side, rather than by a series tube as used on the existing supplies. The discharge of stored energy at the load during breakdowns arising from the inductance of the circuit on the HV side, around which a current path is always maintained via the rectifier diodes, has proven not to be an issue, cf fig 2. The slower decay is expected but the increased energy does not degrade the PINI's. The new HVPS modules have been commissioned on the PINI loads, and operation has been largely trouble free [16].

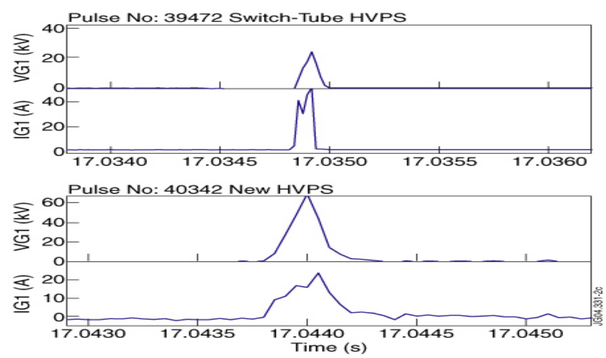


Fig.2. The PINI grid voltage and current in response to a trip of the new NB power supply and an existing unit.

A record 22.7MW of combined NB injection has been achieved since completion of this system, limited by the neutralisation efficiency [14]. The neutraliser is presently being upgraded by installation of a septum to improve the efficiency by reducing the gas heating [17] and achieve the 1.7 MW per PINI potential of the system.

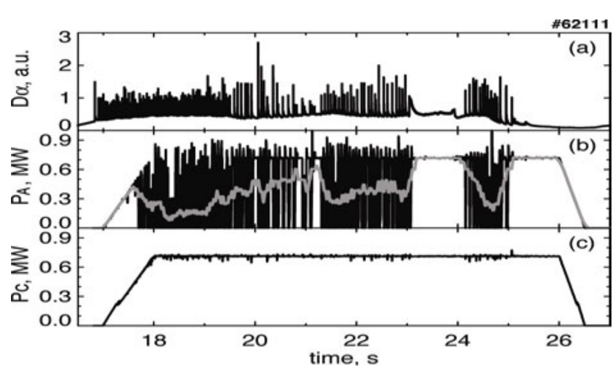


Fig 3. RF power coupled to an ELMy plasma using external conjugate T matching: (a) $D_\alpha$ radiation (b) RF power coupled on module A (grey curve is time average) (c) RF power coupled on module C (with conjugate T).

### III.B External Conjugate T Matching of an RF Antenna

A critical issue with ICRF heating is matching to ELMy plasmas. This is being intensively studied [18] and a key consideration in the design of new JET antenna (see section IV.C below). It has been demonstrated at JET [19] that an ELM-tolerant match can be reliably achieved using an external conjugate T on a pair of straps on an existing A2 antenna. The matching point is readily and reproducibly found, in part due to the relatively high losses in the long matched line, with good ELM resilience, cf fig 3 above. This result is important for the ITER application of ICRF.

### III.C Coupling of LHCD Launcher

Lower Hybrid offers a unique capability to efficiently drive current in the outermost 30% of the ITER plasma. A critical requirement for the application on ITER is the ability to couple power efficiently with distances c. 0.1m between the separatrix and the grill mouth. Gas puffing near the antenna has been previously shown to have the potential to achieve this. Tests at JET [20] have demonstrated that puffing of deuterium or deuterated methane in the vicinity of the grill generates a local electron density at the grill sufficient to allow effective coupling and efficient current drive over ITER relevant distances into ELMy plasmas, including configurations where the shape was ill-matched to the grill mouth.

## IV. NEW ENHANCEMENTS

Many diagnostic and divertor enhancements are being implemented during the present shutdown of JET, due to end in February 2005. A new ICRF antenna will be installed in late 2005.

### IV.A Divertor Modifications

The present divertor in JET comprises the gas box divertor installed in 1998 [21] without the septum, which was removed in 2001. A new septum is being installed which will allow the outboard strike point to be placed on the septum at full performance [22]. An additional row of tiles is also being installed inboard of the present divertor tiles as illustrated in fig 4, and allows the in-board strike point also to be moved further inwards. Together, these changes allow an increase in lower triangularity from 0.47 to 0.56, and will allow plasma configurations closely representative of the ITER reference scenarios. All tiles are carbon fibre composite with inertial cooling, and designed for a combined power deposition of 40MW for 10s. Divertor diagnostics are being restored and enhanced, with new magnetics and halo sensors, Langmuir probe arrays, and divertor bolometers.

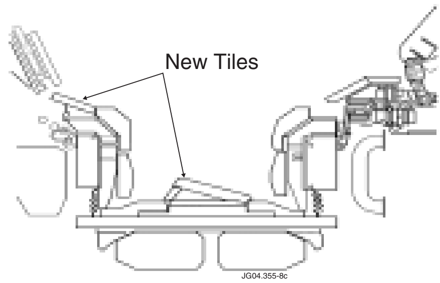


Fig 4. A cross section of the new EP divertor showing modified septum and inboard gap closing tiles.

### IV.B Diagnostics

Some 20 new diagnostic systems are being installed in the present shutdown as listed in table 1 [23]:

TABLE 1. New Enhancements

| Description | Characteristics |
|---|---|
| Infra-red viewing system | 70 degree view,<br>200-2000 C dynamic range<br>100 µsec response (ELM resolution) |
| Pellet extruder | 4 $mm^3$ volume<br>Low field side/Top: 5Hz,250m/s,<br>High field side: 10Hz,150m/s |
| Tritium retention | Quartz microbalances, Smart tiles,<br>Rotating detectors,<br>Deposition monitors |
| Magnetic Proton Recoil | Enhanced S/N (x100) neutron spectrometer |
| Time of Flight neutron detector | Enhanced detectors; high throughput spectrometer;<br>count rate x 2-300 |
| Edge Current | Improved periscopes and CCD detectors allows measurement of E(r) |
| Charge Exchange | Enhanced sensitivity and time resolution; more radial measurements |
| Reflectometry | New low transmission loss waveguide and launcher with off-axis capability for ECE |
| Bolometers | Enhanced S/N horizontal and vertical arrays; better spatial resolution in divertor;$2.10^{-6}$ $w/cm^2$ at 10 msec. |
| TAE antennas | Two diametrically opposed, four coil antennas to excite modes n=5-15 |
| Lost Alpha detectors | Faraday cup poloidal array:<br>$1nA/cm^2$-$100\mu A/cm^2$,1ms response<br>Scintillator probe:<br>$10pA/cm^2$-$1\mu A/cm^2$; 100 µs response |
| Magnetics | Two new poloidal arrays giving orthogonal field components, improved equilibrium reconstruction |
| Halo current sensors | Arrays of 8 coils each at four toroidal locations at top of vessel |

| | |
|---|---|
| Disruption mitigation | High pressure fast acting gas valve; 2 ms, $10^6$ mb.l/s |
| Thomson scattering | Enhanced resolution 20 Hz x 63 channels with 15mm resolution |

Some of these replace existing systems but with improved performance, others give a new capability. Of particular technology interest are the halo probes [24], the lost alpha detectors (both Faraday cups and scintillator probe) [23], and tritium retention diagnostics [25].

### IV.C RF Antenna

A new ICRF antenna is under manufacture. This antenna is representative of the ITER reference design [26] and is intended to demonstrate ITER relevant coupled power density (7 MW coupled to JET) into ELMy plasmas at ITER clearances to the separatrix.

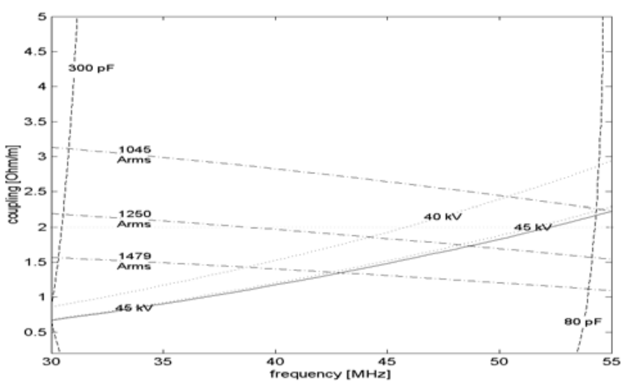


Fig.5. The operating frequency of the JET ITER-like RF antenna is limited by the capacitance range, and the minimum coupling resistance at full power by the voltage or current limits of the capacitor.

The antenna utilises eight electrically short straps, connected poloidally in pairs with conjugate T matching using internal capacitors. This configuration potentially offers strongly enhanced power density due to the short straps combined with ELM tolerant matching of the antenna. The operating domain of the antenna is shown in fig.5. The matching of conjugate T antennas is the subject of intensive study in the RF community [18] and is critical to the success of this antenna.

Two modules of the existing A2 antennas are being linked via 3dB couplers to isolate their generators from mismatched loads during ELMs, as demonstrated elsewhere with good results [18]. This frees two generator modules (8 MW) for use on the ITER-like antenna.

## V. TECHNOLOGY DEVELOPMENTS

### V.A Remote Handling

JET has a well established remote handling capability which has been used in major in-vessel operations, notably the exchange of the divertor tiles following the deuterium/tritium experiment (DTE) in 1997 [27]. The present year long shutdown includes some 10 months of fully remote in-vessel operations, interspersed with four manned interventions totaling 1 month. This RH capability allows major in-vessel enhancements to be implemented despite full tritium operation in 1997 and a trace tritium campaign completed only 3 months before the shutdown. Whilst activation levels at the start of the present shutdown were 300 μSv/hr, decreasing to around 130 μSv/hr by the end, the shutdown is being implemented with a dose ceiling of c. 40 man.mSv.

The RH tasks are more ambitious than in previous shutdowns. A new force control system on Boom end-effectors allows remote in-vessel transfer of loads up to 400 kg. Virtual reality methods are increasingly used for preparing and implementing the work. Structural welds have been carried out remotely for the first time using MIG. Extensive remote in-vessel photogrammetry [28] is being used to prepare final machining drawings of components for installation, with a tolerance on installed position compared to machine datums of c. 0.5mm.

### V.B Tritium Technology

*V.B.1 Operational Studies*

Tritium technology has been a major area of development at JET since first tritium operation in 1991, and more particularly since the 50% tritium DTE campaign of 1997. During DTE, a substantial fraction of the injected tritium was found to be retained in the torus. Much effort has since been applied to understanding this phenomenon with a view to ameliorating the effect in ITER. This has included detailed analysis, which is on-going, of the flakes and divertor samples removed from JET after DTE - these flakes have contained up to 40% atomic content of tritium in carbon. Many diagnostics have been installed in JET to study the migration of material around the first wall [24], and in particular in the divertor, notably including a quartz microbalance with local electronics which was installed in the JET divertor in 2001. Various coated tiles have been installed during shutdowns for subsequent removal and analysis. Operations have included silane and $^{13}C$ puffing to study deposition processes. Results of these studies [29] show erosion from the first wall and outer divertor, and a strong inboard drift of impurities (carbon and beryllium) in the scrape-off layer (SOL) towards the inner divertor, cf fig 6.

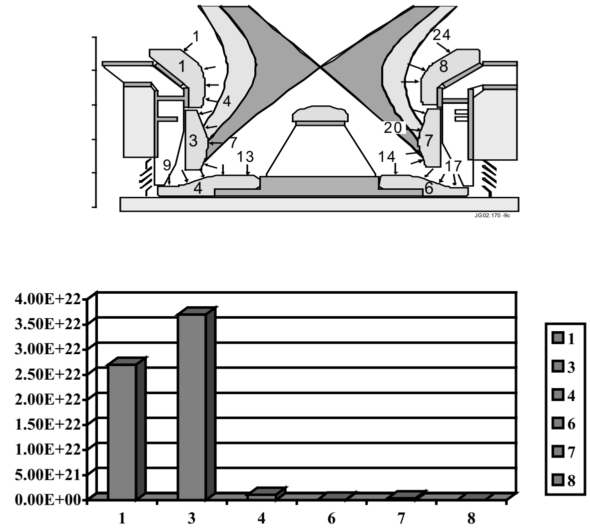


Fig 6. Location of $^{13}C$ on the JET divertor tiles, following injection at the top of the vessel. The abscissa refers to the tile number in the cross-section above.

Erosion attributed to chemical sputtering leads to inwards migration of carbon towards shadowed areas at the inner divertor under some conditions. The sub- divertor co-deposited carbon flakes account for the bulk of retained tritium in JET. These are being studied at various laboratories. The specific activity is 1 TBq/g, some of the tritium being strongly bound to the carbon. The specific surface area is around 5 $m^2$/g.

*V.B.2 Tritium Technology Development*

ITER will use supercritical helium cooled cryosorption pumps to provide both high pumping speed and rapid regeneration. These are coated with activated charcoal to pump helium. The characteristics of this activated charcoal when exposed to tritium is being assessed in a large scale test in the JET tritium facility. This panel was first used at the end of the Trace Tritium Experiment (TTE) to pump gas from the torus and showed the expected very high pumping efficiency [30]. Tests with higher tritium levels are on-going.

*V.B.3 De-tritiation*

De-tritiation is critical for reducing in-vessel inventories, recovering tritium and reducing waste management costs. The use of flash lamps to detritiate CFC tiles in-situ by ablation has recently demonstrated remotely in the JET vessel [31]. Treated and untreated tiles will be characterised in order to determine the process efficiency. Focused laser beams have achieved an ablation rate of 0.02-0.2micron/J/$cm^2$ for graphite and co-deposited layers respectively. A high repetition rate Nd-YAG system is being developed for use in JET using optical fibres to transmit the beam into the vessel [30]. Many of the tiles removed from JET are classified as intermediate level waste. Technologies for reducing the tritium content to low level are being evaluated, including heating in an oxygen methane flame [32].

The design of a water detritiation facility suitable for use at JET is progressing at FZK [33], with input from JET. In particular, a Liquid Phase Catalytic Exchange column, and electrolyser with solid or liquid electrolyte are being evaluated, and the most promising are being subject to endurance tests by FZK, SCK-CEN and ICSI.

**V.C Operation with Tritium**

A further tritium campaign, the Trace Tritium Experiment (TTE), was carried out during the autumn of 2003 [34]. The campaign was severely constrained by the limits to activation of the machine - the dose rate was required to be less than 320 μSv/hr at the start of in-vessel manned operation, giving a limit of $10^{19}$ DT neutrons. The total tritium input to the torus was limited to 0.5g from the gas inlet system. A further 5 g was used in the octant 8 NB injector, two PINI's of which were used to inject tritium beams [35].

The physics aim of TTE was to study tritium transport and fast ion dynamics in the main plasma [36]. A second objective was to refresh the capability to safely operate with tritium in JET [37]. This covered many issues, notably the training and experience of around 100 key staff, the fitness for purpose of critical plant, and the safety management system for operation in tritium. TTE required the mobilisation of gramme quantities of tritium in the torus hall, and preparation for TTE covered almost all of the work that would have been necessary for a full tritium campaign. During preparations over a period of 18 months all of the Key Safety Related Systems (KSRE) for TTE, both for the torus and the tritium plan, were assessed for fitness for purpose and a number of remedial actions taken, notably to improve the personnel access and control system. The Safety Case for the campaign was presented to the appropriate review bodies. Improved accounting procedures were adopted based on high precision instrumentation [38]. The performance of the tritium gas injection module was enhanced to allow precise injection of very short (80 ms) pulses of tritium to enable adequate resolution of spatially and temporally resolved measurements of the 14MeV neutron emission. The campaign was implemented during a five week period in Autumn 2003 and achieved the physics objectives [34,36] within the prescribed constraints. The activation of the machine since first tritium use in 1991, including TTE, is shown in fig 7 – the contribution from TTE to the long term cobalt 60 content is negligible.

The tritium was recovered to the tritium plant. A total of 17 gas chromatography runs were carried out to separate the tritium and deuterium, and some 6.7 bar.l of 99.6% pure tritium recovered [38]. On completion of the campaign, the tritium was recovered to the uranium beds, with tritium newly retained in the torus being within the

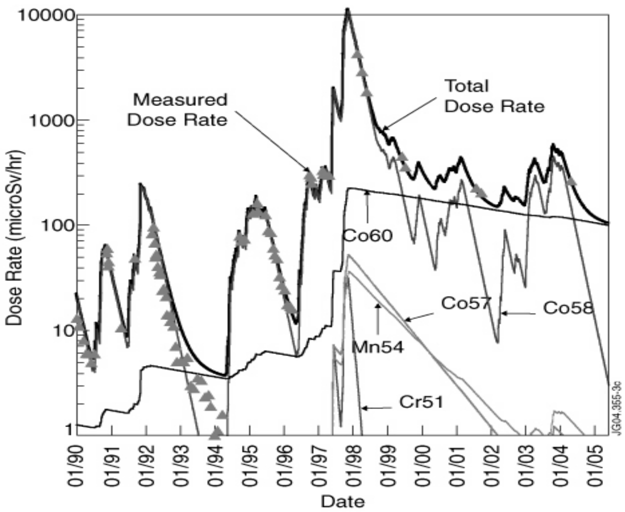


Fig 7. Dose rate predicted and measured on the centreline of the torus since the preliminary tritium experiment (PTE) in 1991.

tolerance of the accounting. The two reservoir model used to simulate tritium retention in the vessel was improved to include the dominant effect of deuterium fuelling in this campaign and fitted the observed tritium recovery from the vessel well [34].

Whilst a technical review of TTE has identified a number of improvements to the plant which are now being implemented, the campaign demonstrated an on-going capacity for tritium operations on JET.

## VI. CONCLUSION

JET has unique capabilities to operate with tritium and beryllium in a large volume, diverted plasma. These features allow operation of JET to provide strong support for ITER with results ranging from studies of high performance, highly shaped ITER scenarios, through ELM and disruption mitigation studies to development of real time control and extreme shape control systems. Many enhancements have been implemented over the past 5 years, notably the NB heating upgrade and a wide range of diagnostics, including burning plasma diagnostics. The coupling of LHCD over large distances to the separatrix, and matching of an RF antenna to ELMy plasmas with external conjugate T coupling are both important advances for ITER. A further trace tritium campaign has been completed, and intensive study of tritium retention continues, as does the study of detritiation of solid waste. The JET remote handling capability has being further enhanced, enabling major in-vessel improvements to the machine to be implemented notwithstanding the on-going use of tritium

## VII. ACKNOWLEDGMENTS

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