

3 JET Operations

3.1 INTRODUCTION AND SUMMARY

Since January 2000, CCFE has had the responsibility for the operation and safety of the JET facilities under the European Fusion Development Agreement (EFDA). The legal and financial provisions are defined by the JET Operation Contract (that confers the contractual management to the EFDA Associate Leader for JET). The JET research programme is carried out by Task Forces of visiting European scientists from fusion laboratories associated to EFDA, including CCFE, under the responsibility of the EFDA Associate Leader for JET.

Experimental campaign C26 ended on 7 April 2009 to allow the installation of the Enhanced Radial Field Amplifier (ERFA, see Section 3.5.1). All the work associated with this activity was ex-vessel and no machine vent was required. Plasma operations resumed on 14 July with one week of 'high level commissioning' (HLC) with plasma to bring the heating systems up in power. The C27 experimental campaign commenced on 27 July and ended on 23 October, with a two week period in August dedicated to converting neutral beam operation from deuterium to helium and to commission a modification to the ERFA to allow it to reach its full performance. The C27 campaign was the last opportunity to operate JET with all-graphite plasma-facing materials before installation of the ITER-like Wall (ILW) components consisting of all beryllium, tungsten and tungsten-coated graphite materials. In the latter part of campaign C27, operation at plasma currents up to 4.5MA was achieved for studies of the ELMy H-mode ITER baseline scenario at high power, and completion of physics preparation studies for the ILW documenting hydrogen retention, carbon source strength and carbon migration towards the divertor. A review of the scientific tasks highlighting the contributions of CCFE is given in Chapter 4. The machine shutdown to install the JET Enhanced Performance 2 (EP2) system upgrades commenced immediately after the cessation of experimental programme operations, on 24 October. The EP2 shutdown activity managed and conducted by CCFE as JET Operator is described in Section 3.6.

JET sub-systems have performed at a very high level of performance and availability throughout 2009, such as the power supplies, the plasma heating and current-drive systems and in total more than 80 diagnostic systems. The neutral beam heating system in particular continued to deliver excellent performance with high availability with record numbers of shots at the highest power levels >23MW.

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3.2 OPERATIONS OVERVIEW

JET commissioning and operation is conducted in a shift pattern, with two eight-hour experimental sessions per operational day. Between shutdowns for major upgrades, the general operating pattern of the JET device consists of periods of experimental campaigns interspersed with planned interventions for installation of new equipment, and periods of commissioning. During the campaign periods one day is allocated to routine maintenance in approximately every five weeks. Sometimes it is necessary to carry out unplanned interventions in response to equipment failure that result in a significant rearrangement of the experimental campaigns; however, in the period of this report no major unplanned additional interventions were required. Altogether, the operations during experimental campaigns in 2009 have been very successful from the point of view of the system availability and performance. A total of 1,055 technically successful pulses have been obtained, in 114 achieved programme sessions (Table 3.1).

Campaigns	Planned sessions	Achieved Programme sessions	Comm. + lost sessions	Successful plasma pulses	Programme Pulses (for physics)	Downtime in hours
C27 (HLC)	0	7	0	47	37	3
C27a (D2)	30	38	3	333	231	64
C27b(He)	18	24	0	196	125	32
C27b (H2)	18	13	0	135	114	7
C27b (D2)	10+30	32	3	344	279	55
C27 (total)	76+30	114	6	1055	786	162

Table 3.1: Summary of the C26 and C27 campaigns. Columns 2 to 4 show for each campaign the sessions originally planned for the experiments, the achieved sessions, the restart overspill sessions that had to be carried out during campaigns and the lost sessions. Columns 5 to 6 indicate the number of technically successful pulses and pulses that yielded results of value for scientific analysis

Because of the planned major shutdown at the end of October for the installation of the second Enhanced Performance series of JET upgrades (EP2, see Section 3.5 below), including the ITER-like Wall and Neutral Beam Enhancement, which required manned in-vessel access, the C27 campaign included experiments with reduced fusion neutron production in order to minimise short-term machine activation. This provided an opportunity to carry out experiments with hydrogen and helium plasmas, including use of helium neutral beams. These experiments are of great importance to understand how various key plasma scenarios (such as the ELMy H-mode) are affected by the change in plasma species, providing essential information for ITER which itself will have an extensive low-activation phase for commissioning and initial operation. The C27 campaign was divided into five phases of operation:

- a) C27 HLC: 'High Level Commissioning' with plasma (14-17 July);
- b) C27a: Deuterium I (20 July-14 August);
- c) C27b: Helium (7-22 September);
- d) C27b Hydrogen (23-30 September);
- e) C27b Deuterium II (1-23 October).

The first two weeks of C27a were mostly dedicated to the commissioning of the new vertical radial field amplifier (ERFA) in plasma operation (see Sections 3.4 and 3.5.1 below). Plasma restart/HLC started on 14 July with the vessel baked at elevated temperature (320°C) to improve conditioning. Seven sessions were

dedicated to re-establishing plasma with the new ERFA and to start the characterisation of the ERFA and control systems, and also to commission the additional heating systems and the pellet injector. A total number of 19 dedicated sessions were allocated to the ERFA commissioning in C27a, with additional time used parasitically for this purpose during scientific programme sessions.

The C27b campaign was preceded by a two week intervention in August for changing the neutral beams from deuterium to helium and for a modification to the ERFA that had been found to be necessary, during commissioning with plasma, to achieve its full performance. This was followed by a three day restart to bring the neutral beams up to high power in helium with plasma.

Neutral beam changeover from helium back to deuterium was done in parallel with the beginning of the hydrogen plasma campaign. Full deuterium operation resumed on 1 October. The experimental programme stopped on 23 October and the EP2 shutdown started promptly on 26 October.

3.3 OVERVIEW OF INTERVENTION ACTIVITIES AND MACHINE AVAILABILITY

This **ERFA intervention** (7 April to 14 July 2009) was dedicated to the installation and commissioning of the new radial field amplifier, and included a number of additional activities, including reinstating the former Poloidal Radial Field Amplifier (PRFA) to feed the Error Field Correction Coils (EFCC) at increased currents up to 3kA, warming up of the cryoplant to fix a sensor fault, and divertor baking to 200°C whilst raising the vessel baking temperature to 320°C for vessel conditioning in preparation for high-current, high-power H-mode operation. The activities of the ERFA intervention are shown below.

Plasma restart was initially planned for 17 June, but due to several technical difficulties (see below) the first restart plasma actually occurred on 14 July.

Date	Event
7/04/2009	ERFA Intervention start
01/05/2009	Machine instrumentation and protection modification for PRFA and ERFA work
29/05/2009	ERFA: Units all energized.
12/06/2009	ERFA: insulation failure on busbar during HV testing of P2 poloidal coil in preparation for connection of ERFA. PRFA: start of machine and personnel safety systems commissioning.
19/06/2009	Repair of P2 busbar fault requiring the removal of the high resolution Thomson scattering diagnostic and its realignment. ERFA: test with the amplifier driven by the plasma position controller on-going.
26/06/2009	P2 busbar repair completed ready for new high voltage tests. ERFA: ready for connection to coils when required in plasma restart programme. PRFA: dummy load test done. Ready for connection to EFCC.
03/07/2009	ERFA: commissioning on coil started
14/07/2009	First plasma

Table 3.2: Summary of the spring (ERFA) intervention work

The connection of PRFA to EFCC was carried out on 24 July, and became available for the physics programme on 7 September.

The **August intervention** (15 August to 26 August 2009) was planned for the neutral beam changeover from deuterium to helium, and for implementing the change to ERFA necessary to achieve its full performance. Helium neutral beam commissioning was completed successfully within the tight schedule as planned. During plasma operation with helium neutral beams it was necessary to regenerate both neutral beam injector cryopumps every night, due to the large inventories of argon built up as a result of using the argon frost cryosorption technique for pumping helium; the pumped divertor was also regenerated overnight and an optimisation of cryopump regeneration procedures was necessary to facilitate all three regenerations to be completed in a single night shift.

A summary of the lost experimental time, broken down by system and experimental campaign, is provided in Table 3.3. The JET operational time lost in the C27 campaigns due to faults during experimental sessions was about 18% of the available time, a number that is slightly higher than in 2008. This reflects the long duration of machine operation since the last major maintenance work on some critical systems (last performed in the 2007 shutdown), especially relating to cryogenics plant and power supplies.

System	C27 HLC	C27a	C27b He	C27b H ₂	C27b D ₂	C27 Total	%
Pulsed Power Supply	2	37	12	3	43	98	59
CODAS	1	6	2	0	4	13	8
Cryogenics	0	1	12	0	2	15	11
Heating/Fuelling	0	2	2	2	1	7	9
Cooling	0	3	1	0	0	4	3
Others	1	16	3	2	5	27	10
Total Down Time	3	65	32	7	55	163	
Sessions	7	41	24	13	35	120	
Total Time	52.5	307.5	180	97.5	262.5	900	
Down Time/Total (%)	6	21	18	7	21	18	

Table 3.3: Summary of lost experimental time in hours during C26 & C27 by system

3.3.1 PULSED POWER SUPPLIES (59% OF DOWNTIME)

One of the major causes of delay can be attributed to sticking of the PF flywheel generator during this period, although the total delays amounted to less than in 2008. The improvement is thought to reflect the cumulative effect of the several improvements and corrective actions undertaken over the course of several planned maintenance interventions, consistent with the interpretation that there is not just one single cause. A review of further major remedial actions on the generator was undertaken during late 2009 / early 2010, leading to a programme of improvements implemented during the early part of the EP2 shutdown. These improvements included refurbishment of the brake mechanism (and elimination of all asbestos-containing friction materials), replacement of the main thrust bearing pads, realignment of the guide bearings and honing of a bronze labyrinth oil seal on the main shaft.

A contributory factor for higher overall incidence of power supplies problems in C27 was the occurrence of side effects from operation of the newly implemented ERFA and the re-instatement of the PRFA, last used in 1992. These side effects included false tripping of the Direct Magnet Safety Systems (DMSS) of the

toroidal and poloidal coils, due to coupling of the hardwired DMSS voltage-difference circuits with the radial field and EFCC circuits that became sensitive to the higher voltages capable of being applied by the ERFA and PRFA than their former equivalents. As well as the actions needed to address the false tripping issues, the frequency of such trips led to additional wear and tear, e.g. on mechanical crowbar switches that were triggered as a result.

3.3.2 CRYOGENIC SYSTEM (11% OF DOWNTIME)

Most of the down time due to the cryogenic systems related to the TCF50 helium refrigerator supplying supercritical helium to the divertor cryopumps, resulting in unstable torus vacuum conditions due to small temperature fluctuations of the cryopumps. These problems, in particular, can be attributed to the extreme length of almost continuous operation service (more than two years) of the cryogenic plant since the last major overhaul. While four sessions had to be adjusted to take into account the absence of helium cooling on the divertor, the total loss of programme time for all these events was only about ten hours. In order to continue the programme during the repairs on the TCF50 refrigerator, a new mode of operation was developed in which the divertor pumps were supplied with supercritical helium from a stage of the neutral beam helium liquefier (TCF200), without loss of operation of the neutral beam systems. This mode of operation has now been fully established for routine use and will provide considerable extra operational flexibility in case of faults on the TCF50 in future.

3.3.3 CODAS (CONTROL AND DATA ACQUISITION SYSTEM, 8% OF DOWNTIME)

The time lost to CODAS events in 2009 corresponded mainly to a large number of short stoppages (30-45 minutes), none of which was serious.

3.3.4 PLASMA HEATING SYSTEMS (9% OF DOWNTIME)

Loss of programme time attributable to plasma heating systems is mainly related to neutral beam injection, as this was used on 81% of the plasmas, 46% of which additionally had Ion Cyclotron Resonance Heating (ICRH), and 11% with Lower Hybrid Current Drive (LHCD).

3.3.5 COOLING (3% OF DOWNTIME)

During campaign C27 cooling problems that had an impact on operation were limited to several small incidents. However, one more significant incident occurred at a weekend where a locking mechanism on a gate valve in the site water supply failed allowing the valve to slam shut. The resulting pressure surge caused rupture of a pipe serving new auxiliary equipment that had not yet been brought into service. Fortunately, despite the large loss of water from the circuit, no operational plant was affected and there was no loss of JET operation.

3.4 JET TECHNICAL DEVELOPMENTS AND PERFORMANCE HIGHLIGHTS

The main technical development during 2009 was completion of the Enhanced Radial Field amplifier (ERFA), and the Plasma Control Upgrade (PCU) necessary to take advantage of the ERFA's greater speed, voltage and current capability. Technical aspects of these enhancements are described in more detail in Section 3.5.1 below. The radial magnetic field circuit controls the vertical position of the plasma, which is inherently unstable for highly shaped plasmas like those essential for ITER operation. The ERFA/PCU enhancements have opened up the possibility to operate with such ITER-relevant plasma configurations at high

plasma current, particularly at high power where Edge Localised Modes (ELMs) produce large perturbations which the vertical position control system must accommodate. During C26 the baseline ITER ELMy H-mode scenario was extended to 4.5MA current with a toroidal magnetic field of 3.6T and 25MW combined neutral beam and ICRH power. This is the first time 4.5MA plasmas have been operated in JET since 1997. Operation at such high current and high power levels gives more confidence in the scaling of the confinement properties (and hence fusion performance) of the ITER baseline ELMy H-mode scenario to ITER size and conditions. This demonstrates JET’s unique capabilities in support of preparations for ITER operation.

The largest number of high power (>20 MW) and full power (>23MW) neutral beam pulses was delivered in any year in JET’s operating history. Comparative performance statistics for the JET neutral beam systems over past years is shown in Figures 3.1-3.4. A particular feature of these statistics is that the average neutral beam power and pulse length in 2009 have continued to improve significantly.

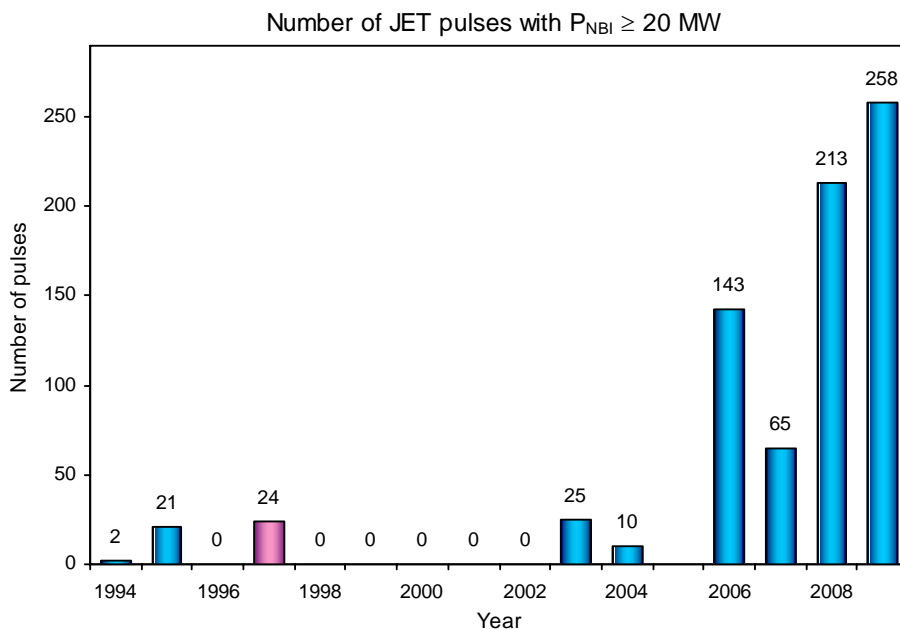


Figure 3.1: Number of JET pulses with high neutral beam power above 20MW by year

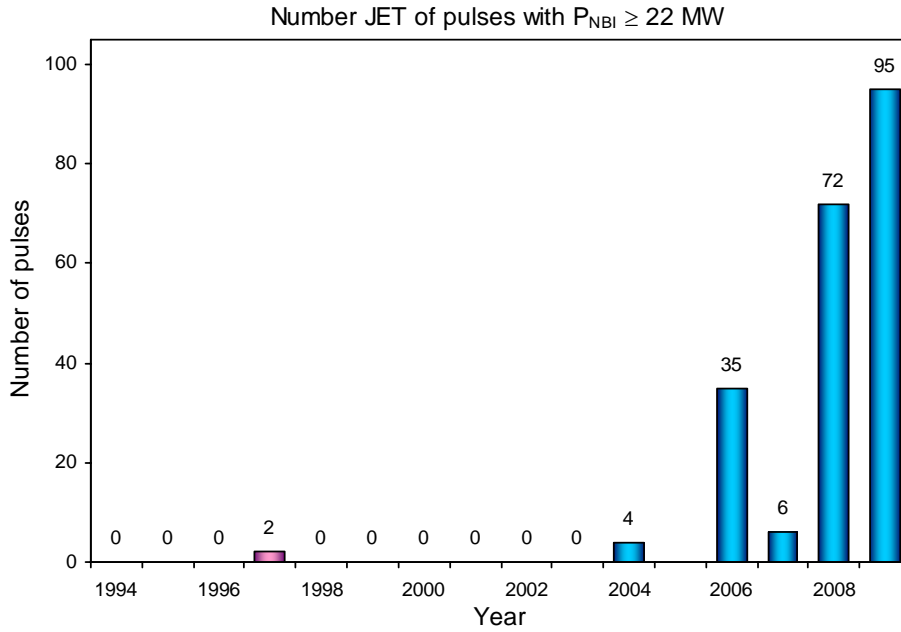


Figure 3.2: Number of JET pulses with very high neutral beam power above 22MW by year

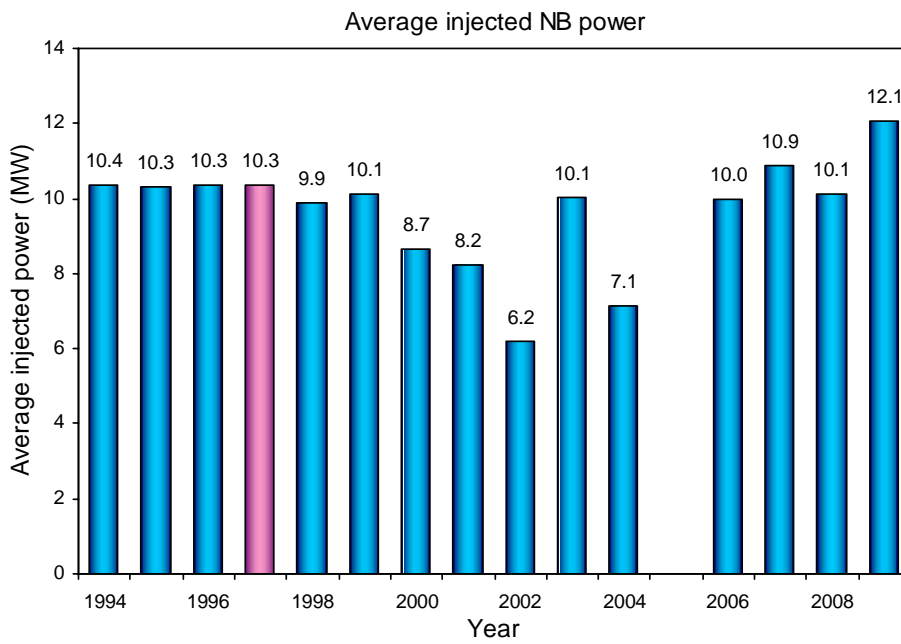


Figure 3.3: Average injected neutral beam power per pulse by year

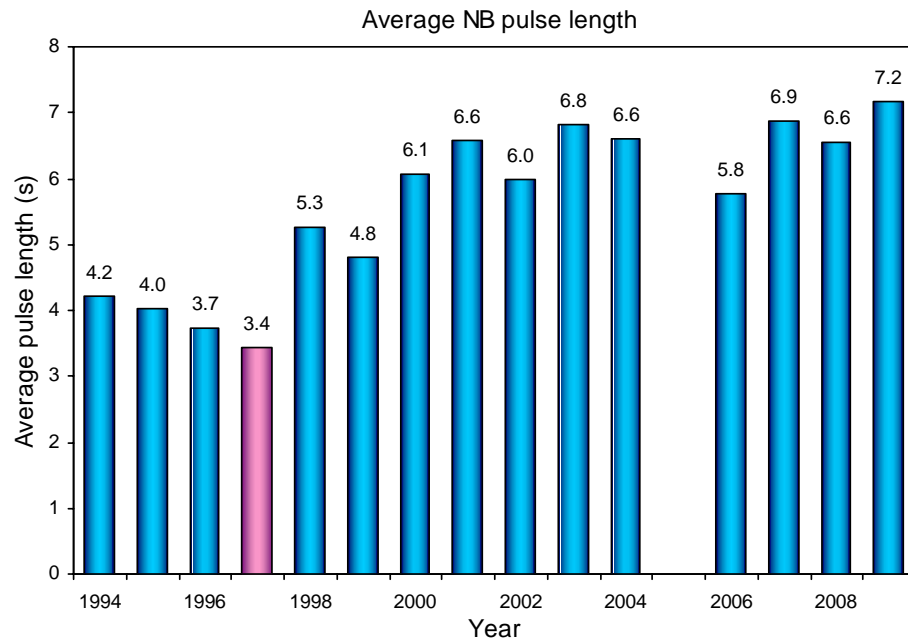


Figure 3.4: Average injected neutral beam pulse length by year

In the Neutral Beam Test Bed (NBTB) the programme to condition batches of upgraded neutral beam sources, as part of the Neutral Beam Enhancement (NBE) project, has continued (see Section 3.5.2). A further key activity on the NBTB, carried out by CCFE under the auspices of the JET Fusion Technology (FT) Programme, was the production and characterisation of the space-charge of a H^- beam generated using a JET-type ion source and a single-aperture accelerator (see Chapter 7). This was the first negative ion beam production on the JET facilities and the first at Culham since 1997.

One major JET system unfortunately did not operate in campaign C27. The ITER-like antenna (ILA) had been successfully commissioned in 2008 and early 2009. The ILA was aimed at proving key requirements for the ITER Ion Cyclotron Resonance Heating (ICRH) heating systems, and it successfully achieved most of its objectives as planned in 2008-9. In particular, it was shown that, for the reference ITER plasma scrape-off layer profiles, the ILA coupling results extrapolate to the required ITER antenna power within the design voltage range. Unfortunately, in March 2009, during campaign C26, a very small leak developed across the wall of a bellows section conveying cooling water to one of the variable high-voltage capacitors located within the torus vacuum envelope, and it was necessary to isolate and evacuate that section of the cooling circuit. Lifetime bench-tests of spare bellows resulted in similar failure at much less than the expected number of cycles and, as a precaution, it was decided not to subject any of the installed bellows to further routine actuation which precluded further ILA operation in C27, save for very low-power tests to confirm code modelling used to predict antenna characteristics. The other (A2-type) ICRH antenna systems were all extensively used during the C27 campaign, taking full advantage of the use of '3dB' coupler elements and External Conjugate-T (ECT) connection configurations of the transmission lines to these antennae that give excellent tolerance to load variations produced by plasma Edge Localised Modes (ELMs). These ELM-tolerant systems, first commissioned in 2008, have played a major part in extending the range of total power (in combination with neutral beams) and the power mix in plasma scenarios for ITER including the baseline H-mode with ELMs and an alternative scenario known as the hybrid mode.

3.5 JET ENHANCEMENTS

A series of 24 upgrade projects form the second JET Enhancement Programme ('EP2'). These vary in scale, and include new or improved diagnostic systems as well as much larger projects such as the Enhanced Radial Field Amplifier (ERFA), Neutral Beam Enhancement (NBE) and the ITER-like Wall (ILW). Progress on these three larger projects is described in this section.

The major items required for the EP2 programme are manufactured by industry, mostly via contracts placed by the European Commission, with commercial management of the contract being carried out by the EFDA-JET Close Support Unit. Technical management of the contract is normally carried out within the project team for the particular EP2 enhancement. The project team and its leadership, from the initial design phase through procurement to commissioning, is in general provided by one or more European Fusion Associations following a call for interest. The project team works closely with CCFE as JET Operator throughout the project, and the Operator has responsibility for installation of equipment and preparation of necessary infrastructures, and assumes responsibility for eventual routine operation after handover following commissioning by the project team. Installation is subject to acceptance of equipment by the Operator to ensure compliance with all the applicable quality and safety requirements, and compatibility with technical interfaces.

The ERFA and NBE projects are both led by CCFE as Fusion Association. The ILW project, as an exception to the normal EFDA-JET Enhancement management arrangements, has been led by CCFE as Operator through all its project lifetime stages. This reflects the fact that the design of the very large number of in-vessel components and preparation for their installation are intimately related to the machine structure and the need to take into account requirements dictated by remote handling considerations, which are the Operator's responsibility.

3.5.1 ENHANCED RADIAL FIELD AMPLIFIER (ERFA)

The purpose of the ERFA is outlined in Section 3.4 above, and it is designed to deliver higher voltage, current and speed of response than the Fast Radial Field Amplifier (FRFA) that it has replaced. These improved performance characteristics are essential for reliable operation at high plasma current and high power in the presence of large ELMs, in order to maintain stable control of the plasma vertical position.

Three main activities were progressed in parallel over the course of this two-year project, culminating in the seven week duration 'ERFA Intervention' described in Section 3.3 above: improved detection, simulation and control algorithm for plasma vertical position as a separate Plasma Control Upgrade project (PCU, led by another Association); modifications to JET P2 and P3 Coils and busbars; procurement, installation and commissioning of the new 60 MVA (nominal) ERFA. The general objective of the ERFA and PCU project activities in 2009 was to demonstrate full operation of the entire plasma vertical position control system using the ERFA power supply prior to the start of the main EP2 Shutdown. This objective was fully achieved and, as described earlier, the upgraded system was routinely used during campaign C27 including high current, high power H-mode plasmas with ELMs which would not have been possible without the possibility of exploiting the improved performance characteristics of ERFA. Although a design requirement was that it must be able to return to FRFA operation within two weeks if necessary, routine operation of ERFA/PCU was very reliable and no roll-back to FRFA was needed.

The ERFA specification demanded a voltage/current capability of $\pm 12\text{kV} / \pm 5\text{kA}$ in four-quadrant control with a response time of better than $100 \mu\text{s}$. The ERFA design uses Insulated-Gate Bipolar Transistors (IGBT) as the main power switching device which has significant performance advantages over the progressively obsolete GTO based FRFA. Multiple four-quadrant inverter bridges are fed from a DC link and energy is exchanged between the DC link capacitors and the inductive radial field circuit during inverter switching in response to the demands of the plasma vertical position control algorithm. This design minimises the active and reactive power demands on the 36kV AC feeds to the ERFA. Four identical series connected modules are used, providing redundancy in case one module should trip. The IGBT switching sequence relies upon a novel and complex high speed control system for rotating the switched elements in order to distribute heating evenly between the main power devices and to minimise rate of change of output voltage thereby avoiding potentially damaging voltage transients on the JET coils.

The ERFA six-container equipment layout design allowed factory power testing to be completed with the minimal amount of disassembly prior to transportation and installation to the Culham site 2009 (see Figure 3.5). Dummy load testing started following four months of on-site installation work and was completed in late June. The requirement that return to FRFA operation must be possible within two weeks in the event of a serious ERFA problem dictated a dedicated ERFA connection box (Figure 3.6).



Figure 3.5: One of the six containerised power supply units being craned into final position



Figure 3.6: Connection box for selecting ERFA or FRFA operation of radial field circuit

In order to maximise the effectiveness of the ERFA it was necessary to allow for a reduced number of turns on the radial field circuit formed by parts of the P2 and P3 poloidal coil sets, thereby further increasing the volts/turn in order to increase speed of plasma response. It was also necessary to allow for different permutations of P2/P3 and to have the possibility of changing the polarity of the connections, or even leaving a complete winding (P2 or P3) out of circuit. For this new busbars, clamps and cooling manifolds were needed on the coils. The poloidal field coils making up the Shaping circuit also had to be rearranged in order to limit voltage induced by the faster changes of the radial field.

The first commissioning pulses showed an unacceptable drop in the ERFA output voltage on some of the more demanding pulses. A model study showed that this was due to eddy current losses in the JET structure being higher than expected. This was rectified by upgrading the current capability of the ERFA DC link capacitor charging circuit during the short break in plasma operations in August 2009 as discussed in Section 3.3.

Almost 1000 JET pulses with the upgraded ERFA and the modified radial field coil circuit were obtained in campaign C27, including operation at high power and high current.

3.5.2 NEUTRAL BEAM ENHANCEMENT (NBE)

NBE is a major EP2 Neutral Beam Enhancement project to increase the neutral beam heating power on JET by 50% (to >34MW) and to double the pulse length (to 20 seconds). The project continued to make good progress throughout 2009/10. The main activities within this CCFE-led project are: modifying all the Positive Ion Neutral Injector (PINI) ion sources to produce a higher proportion of deuterium positive molecular ions that are easier to neutralise, and re-optimising the accelerators for 125kV / 65A deuterium beam operation; modifying some

beamline components to cope with a four-fold increase in that part of the residual ion power arising from molecular ions and to cater for the pulse length increase; replacing the 'duct scrapers' that protect the torus entry ports with a new actively-cooled design replacing the previous assembly that relied on thermal inertia; replacing the high voltage power supplies serving 8 PINIs with four new 130kV/130A HV power supply modules; and upgrading the 36kV AC distribution and protection system to cater for the increased power demands.

The installation and dummy load commissioning of the new HV power supplies was completed during 2008/09. The activities over 2009/10 concentrated upon completing the procurement of all the beamline components, preparation for the EP2 installation shutdown, and the initial phases of the shutdown itself (the EP2 Shutdown activity is presented separately in Section 3.6).

The largest and most technically complex beamline component to be procured was the pair of actively cooled duct scraper panels. During the final stage of manufacture of these items (under an EFDA Article 7 contract placed by the European Commission) some problems due to CuCrZr bronze alloy material defects were experienced. Although this material has been very extensively used in the past in the JET beamlines for actively cooled components without any problems, the problem was traced to a slightly different material production process necessitated by the requirement for material billets in larger size than formerly. Fortunately, only a minority of the elements of the actively cooled duct scraper used the larger material billet (the remaining elements used the standard production size). It was possible to change the larger element manufacturing process to use a fabrication method utilising pieces made from the standard size billets. The material problems were therefore overcome, and all components required for installation were delivered by the end of December 2009, which left some contingency with respect to the dates by which they were required for the installation programme. A schematic of the new duct scraper assembly is shown together with a photograph of one of the new actively cooled panels in Figures 3.7 and 3.8.

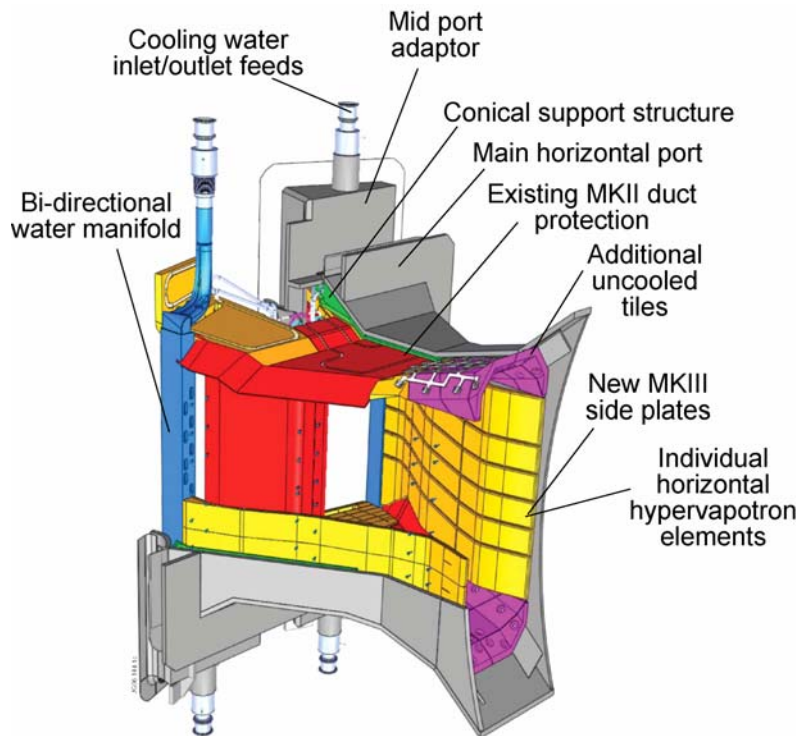


Figure 3.7: Schematic of actively cooled neutral beam duct scraper assembly. A photograph of the side panel (coloured yellow) is shown in Figure 3.8



Figure 3.8: Photograph of new actively cooled neutral beam duct scraper panel

The installation of the modified residual ion dump components required removal of the 'central column' assemblies from both neutral injector boxes. This is a major operation, and is the first time that both central columns have been removed at the same time during JET operation under EFDA. The central

columns are highly complex and large assemblies comprising beam deflection magnets, actively cooled ion dumps and beam calorimeters. No vacuum leak testing or welding can be carried out until the complex cooling circuits have been dried out thoroughly. As a potential shutdown critical path activity, the drying process was studied in depth prior to the start of the shutdown and new process equipment (based on water vapour pumping by cold trap) was procured and commissioned prior to the shutdown. This has proved very successful and the central column modification work has progressed well to date and is no longer on the critical path.

The actively cooled duct scraper installation has also progressed well and has remained on schedule, despite some additional unplanned work to take account of detailed errors in the as-built drawings of the support structures which are to be re-used (removed for the first time since their installation in 1992/93).

Due to the increase in residual (i.e. un-neutralised) power arising from molecular ions in the NBE PINI configuration, it was originally decided not to install the fully-configured NBE PINIs prior to installation of the upgraded beamline components. Although the PINI accelerators have been progressively exchanged for the NBE-type over the past three years, the PINIs had been re-installed with the standard ion-source configured for maximum atomic ion production. However, during the ERFA intervention a pair of PINI beam sources were modified to the full EP2 configuration including the ion sources. This allowed measurements to be made during campaign C27 which confirm the achievable performance and critical power loads on beamline components in advance of the full NBE upgrade. The EP2 configured PINIs delivered up to 2.08MW per beam at 112kV acceleration voltage. This implies that the minimum target total power delivery of 34MW will readily be achievable from all 16 beams.

3.5.3 ITER-LIKE WALL (ILW)

The ILW is the single largest upgrade project on JET since installation of the pumped divertor in 1992-4. The ILW project was approved by the EFDA Steering Committee in April 2005. The project is led by CCFE as JET Operator under the JET Operation Contract (JOC) with core engineering and installation related activities based at JET including secondees from other EURATOM Fusion Associations. Certain specialist technical tasks have been based outside JET but under the overall management of the JOC ILW team.

The objective of the ITER-like Wall (ILW) Project is to install in JET, a beryllium (Be) wall and an all tungsten (W) divertor which is now the planned material configuration for the DT phase of ITER. In combination with other EP2 enhancements to JET, ILW will provide a test bed for integrated scenarios with ITER relevant edge conditions and compatibility with the wall, thus speeding up the early phases of ITER.

The ILW project consists of two main strands. Engineering Design and Manufacture which designs and procures all the new components required inside JET, and Installation Preparation which is responsible for all the preparatory work and procurements required to install the new wall. Because most of the installation will be by remote handling the effort involved in tool design and manufacture, procedure preparation, training etc. is a very substantial part of the overall job.

By April 2009, eight out of 19 European Commission Article 7 procurement contracts were completed and with all but two expected to complete by the end of June 2010. An example of some major components undergoing assembly and inspection at the manufacturer is shown in Figure 3.9. The parts database

(BATS) showed that by early April, the project had received inspected and accepted 74,000 of the 86,000 parts required for the new wall. As manufacturing is drawing to a close, the focus in 2010 has increasingly been on assembly of components into tile assemblies ready for installation.



Figure 3.9: Assembly and inspection of the first 'Inner Wall Guard Limiter' on its jig at the beryllium manufacturer

One of the greatest technical challenges for the project has been development of a coating process which applies tungsten to carbon fibre composite (CFC) tiles used in the JET divertor. These coatings have to withstand very high temperatures and proved difficult due to the anisotropic nature of CFC material. The project worked with the Romanian Fusion Association in development of a new process which has proved very successful with most of the required tiles coated and delivered by April 2010 and zero rejects after 10% were heat flux tested in an ion beam facility (GLADIS) run by the Max-Planck Institute for Plasma Physics in Garching (Germany). In April 2010 the first tiles (like those shown in Figure 3.10) were being installed on assemblies removed from JET.



Figure 3.10: Assembly of metal parts into the back of tungsten coated carbon fibre composite tiles

In previous shutdowns, all in-vessel remote handling operations have been carried out with a single long boom and Mascot manipulator. Due to the time required to move the boom to collect individual components this system would be too slow. For this reason a second long remote handling boom was procured to allow a complete set of tiles and tools to be delivered to the area of work. Up until start of the shutdown in October 2009, 'mock-up' trials which simulate the real working environment were carried out using the two booms in the in-vessel training facility (IVTF), Figure 3.11.

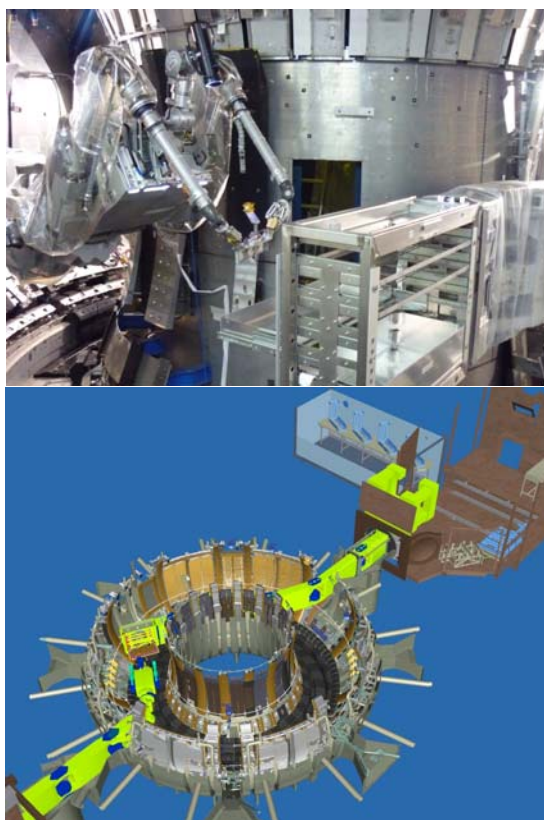


Figure 3.11: 'Mock-up' activity involving two remote-handling booms in the in-vessel training facility to practise operations prior to installation of equipment on the JET torus

The Installation Preparation strand which provides all the remote handling (and manual) tools, installation procedures, mock-up components and trials has advanced considerably during the year and due to its excellent progress over the year is off the critical path for the project. Almost all its tasks are complete apart from production of the installation procedures.

3.6 EP2 SHUTDOWN PROJECT

The on-going EP2 Shutdown is the most significant since the installation in JET of the Divertor Assembly in 1992-94. It consists of three Remote Handling (RH) and two manual in-vessel phases. Although activities for the in-vessel installation of the ILW form a major part of the shutdown, there is also a significant range of ex-vessel tasks including the installation of the remaining EP2 diagnostic enhancements and the work associated with the Neutral Beam Enhancement (NBE).

3.6.1 STRATEGY

There is a continued requirement to complete the EP2 Shutdown as soon as possible in order to obtain important results from JET operation with the ILW. A strategy was agreed between EFDA and CCFE to achieve this.

- The starting date of the in-vessel operations should be as early as RH preparations allow.
- The full planned scope of shutdown and enhancement work to be maintained and necessary diagnostic calibration tasks included.
- The intensity of the RH activities should be as high as practicable and with a firm target of achieving pump-down of the vacuum vessel by the end of 2010.

3.6.2 PLANNING AND ORGANISATION

The above strategy led to the overall plan consisting of an initial phase of ex-vessel activities allowing the early removal of the NIB central support columns before the installation of the in-vessel access facilities.

A revised shutdown organisation and communication structure was introduced in order to clarify the responsibilities for activities undertaken and ensure visibility of this within the planning. In addition formalised scope change requests and exception reporting was introduced.

The detailed plans continued to be developed and refined with over 8,000 tasks programmed during the shutdown period.

The recruitment of Shutdown related personnel continued into the early phase of the shutdown reaching the maximum planned team in December 2009.

3.6.3 PREPARATION WORK

Preparation work continued through 2009 and into the early part of the shutdown itself as infrastructure and systems were finalised and commissioned. This phase of the Shutdown is vital to ensure smooth progress when the machine operations end and operational areas become available for maintenance and upgrades.

In particular the following were completed:

- Final setup and commissioning of the Beryllium inspection facility including slit boxes for work on new Be ILW components;
- Finalisation and commissioning of the enhanced Assembly Hall controlled ventilation system including connection to the new Beryllium inspection facility;

- Final build of three new ISO transport containers (with 'Chesim' doors for connection to the facilities) for the storage of the removed carbon first wall components;
- Upgrade of both manual and remote access ISO storage containers for compatibility with the new extended TCTF boom and task module component and RH tool storage system;
- Construction of storage and handling facilities within the Beryllium handling facilities for the refurbishment of the divertor tile carriers, including ventilated tents, slit boxes, and test jigs;
- Establishment of a laser scanning facility for the dimensional measurement of carbon tiles removed from JET;
- Continued work to complete the Beryllium machining workshop;
- Construction of a second containment facility for a neutral beam central support column;
- Installation of a new storage stillage for NIB shielding panels.

3.6.4 SHUTDOWN ACTIVITIES

A Access phase

The C27 operational campaign finished on the late shift on 23 October and Shutdown activities started the following morning. After gaining access to the Torus Hall the vacuum vessel docking shims were installed and the procedures for vessel cool down commenced.

Preparatory works were started including building access scaffolds and de-cabling diagnostics. Where possible lifting was undertaken using the machine mounted cranes and progress made on NIB preparations. Following the Thomson scattering Raman scattering calibrations the Torus hall shield beams were raised and activities with the 150te overhead crane commenced. Vessel venting was completed.

Diagnostics were removed from octants 1, 4, 5, and 8 to allow key NBE work and clear space for the installation of the in-vessel access facilities. Whilst access was possible vessel turbo pumps and Beryllium evaporators were removed from octants 1 and 5. Welded vacuum windows in the Octant 5 door were successfully replaced.

The CSCs from octants 4 and 8 were removed and installed in the prepared tents in the Assembly Hall. Both had their internal pipework dried quickly using new specially designed vacuum drying systems.

Outside of the Torus Hall work progress of the Tile Carrier Transfer Facility (TCTF) modifications continued and LHCD hydraulics maintenance was started. Work on the Flywheel Generator Converters and other power supply installations commenced.

B In-vessel access facilities installation

The start of the installation of the facilities required for both remote and manual access to the JET vacuum vessel commenced on 26 November as planned. This included the installation of both boom systems (octant 1 and 5) and their additional sub systems. This was a significant milestone and the culmination of a long programme of enhancement and testing work. Once installed in the torus

hall an intense programme of final commissioning commenced in order to ready the systems for the first phase of in vessel work.

In parallel with these activities work continued to ready octants 4 and 8 for the removal of the Neutral Beam duct scrapers from the main horizontal ports. This is part of the NBE project and necessitated the removal of the Rotary High Vacuum Valves which sit between the port and the Neutral injection boxes.

C Remote handling phase 1

In-vessel work commenced in earnest on 12 January 2010 with opening of the pumping chamber doors and the installation of in-vessel infrastructure, cameras and lighting. The high resolution in-vessel photography survey was completed along with the selective vacuuming of the tiles for tritiated flake analysis. Tile removals commenced, transferring them into an ISO container attached to the TCTF at Octant 1. The extended seven day per week shift work was established.

The first ISO container change was undertaken delivering tiles and tile carriers to the Beryllium Handling Facility either to be stored or to be modified for the ITER-like Wall. This was a significant test of the downstream logistics and showed that it could be achieved with minimal impact on the in-vessel activities and the Shutdown critical path.

This phase was completed on 21 March 2010 and had removed some 1,150 tile assemblies from the vacuum vessel. This included all elements of the Divertor which had been transferred to the Beryllium Handling facility for refurbishment for the ILW. In addition the first in-vessel remote welding of the shutdown had been completed using services running through the upgraded Octant 1 boom. Teams, which consisted of 75-80% new personnel, had responded positively to the challenges of the intense shutdown programme and made great efforts to climb the learning curve to ensure safe and efficient work.

Ex-vessel the octant 4 and 8 duct scrapers were successfully removed and transferred to the assembly hall for refurbishment.

D Manual phase 1

The first package of manual work in-vessel was successfully completed in on 29 March. This involved the rostering of personnel from many areas of the Shutdown Project in order to ensure that all teams had previous in-vessel experience. The work included the removal of redundant diagnostic mirrors at octant 4 and the clearing of the route for the new ILW embedded diagnostic conduits. Although planned to take eight days the work progressed well and was achieved in seven.