EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)05/17

C. Damiani and contributors to the EFDA–JET workprogramme

JET Enhancements under EFDA

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[1] *EFDA CSU, Culham Science Centre, Abingdon, Oxfordshire OX14 3EA, UK*

[*] *See annex of J. Pamela et al, 'Overview of Recent JET Results and Future Perspectives', Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Proceedings of SOFT 2002 (Helsinki, Finland, 9–13 September 2002)

ABSTRACT.
A series of JET enhancements are currently conducted under EFDA. These enhancements can be divided in two categories.

Near term projects, implemented mainly in the 2000–2002 period, whose main objectives are:

- to increase the heating power of the JET Octant 8 Neutral Beam Injector (NBI);
- to improve the pellet fuelling capabilities;
- to improve the diagnostics capabilities, also in support of the detailed design of the ITER divertor and of the development of scenarios with internal transport barriers.

Longer term projects, in the 2000–2004 period, whose main objectives are:

- to consolidate the preparation of ITER plasma scenarios by increasing the present operating domain;
- to support design choices in key areas of subsystems of ITER.

An ITER-like ICRH antenna, new or improved Diagnostics, modifications to the existing divertor to operate at higher triangularity and higher power, which will be installed during the scheduled 2004 shutdown, constitute the technical scope of the long term enhancements.

The JET Enhancements benefit from significant contributions also from international collaborations with non-European laboratories.

The paper presents an overview of the scientific and technical objectives, the description of the systems under design, the organisation of the activities and the planning elements.

1. INTRODUCTION

The use of JET facilities under EFDA includes the implementation of enhancement projects.

The general objectives are to increase the JET fuelling and heating systems, to modify consequently the divertor, to improve the diagnostics capabilities, with the ultimate goal of enlarging the JET operating domain. This is mainly in view of providing ITER with additional output on plasma physics and in some cases also with the development of key technologies.

The way these enhancements projects are conducted, with the involvement of EFDA Associates and third parties (like US labs) in such a complex organisational environment, are a novelty for JET and can be considered an experiment per se.

The projects described in this document are the result of a selection of many proposals that have been scrutinised at JET (and in some cases by ad hoc groups) taking into account value and feasibility, and presented to, and approved by, the relevant EFDA committees.

2. SCIENTIFIC OBJECTIVES

These enhancements aim at enlarging the operational domain, i.e. at running plasmas with higher power, density and triangularity, with improved diagnostics and pellet fuelling.

The upgraded Octant 8 NBI and the new ITER-like antenna will increase the power delivered to the plasma from the currently available ~25 MW to a maximum of ~40 MW (for 10 s).

This, combined with the modifications to the present Mark II divertor, will permit to run higher power plasmas closer to the ITER design values (δ, κ, β_N, q_{95}, N^{GW}) in Edge Localised Mode (ELMy) H-modes at almost ITER matched triangularity (δ^U~0.44δ^L~0.56), like the following:

$$I = 3.5 \text{ MA/Bt} = 3.2\ T,\ N^{GW} = 1$$
$$I = 4.0 \text{ MA/Bt} = 3.2\ T,\ N^{GW} = 0.85$$

Furthermore, the diagnostics upgrades will permit measurements with increased time/space resolution of quantities like ion-electron temperature, density, magnetic shear, plasma current. This will improve the observation of edge-localised modes (ELMs) and Internal Transport Barriers (ITB) into the plasma. Moreover, upgraded real time capabilities will permit to control some of the key parameters of the plasma by feedback on heating and current drive systems.

Furthermore, the upgrade of the pellet injection system will permit to fuel the centre of the plasma more efficiently.

3. TECHNICAL SCOPE

The JET Enhancements programme, which consists of the design, procurement and installation of new systems, can be divided in two main groups, those ending mostly in 2002, and those ending after the installation during the 2004 shutdown.

The latter group was initiated in the frame of the so called JET EP (Enhanced Performance) project, a major upgrade of the JET capabilities that was started in July 2000 after a positive recommendation of the CCE-FU Committee. Since then, however, the original JET EP scope has been reduced. The so called '3rd NBI' was cancelled at the beginning of 2001 due to lack of leading Association. The projects for an Electron cyclotron resonance heating and a new divertor were cancelled at the beginning of 2002, after the completion of most of the design activities, due to budget constraints of the European Fusion Programme.

The list of the two groups of enhancements is given below.

3.1 NEAR TERM PROJECTS

Heating and fuelling systems:

- **Octant 8 Neutral Beam Injection**
- <u>ICRH - 2nd Harmonic Protection</u> (to develop a protection of the generator against 2nd harmonic reflected waves)
- D2 Pellet Upgrade (*US*)
- <u>*ICRH - 3dB Coupler*</u> (feasibility study for the use of such device in JET)
- *Improved NBI Neutraliser* (measurements and studies on the NBI test bed facility in view of possible increase ~+25% of the neutralisation efficiency (and power) on NBI))

– *LHCD Coupling Improvement* (study of methods like gas injection and plasma ionisation in front of the launcher to increase the power coupling)

Diagnostics:

– Error Field Correction Coils (new set of external coils for NTM modes and q profile studies, and for disruption reduction)
– Quartz Micro-balance (measurements of carbon deposition in the shadowed region on a shot-to-shot basis, important ITER issue)
– Reciprocating Probe Head Upgrade (measurements of plasma edge quantities like T_i, T_e, impurities, mass transport).
– Reflectometer (to improve reflectometry for understanding the role of turbulence in the appearance of ITB)
– Pellet ablation spectrometer (US) (high time resolution instrument to measure the properties of the ablation cloud which surrounds injected pellets)
– Motional Stark Effect Upgrade *(US)* (measurement of the q-profile by upgrading one PINI at 130kV/60A on Octant 4 NBI and the optical system)
– Edge LIDAR Thomson Scattering (improved signal to noise measurement of T_e and n_e of edge plasma)
– Extreme Shape Controller (software for extremely shaped plasmas and vertical stabilisation even in the presence of large disturbances, like ELMs)
– ECE Radiometer (upgrade of heterodyne receiver, full radius, high resolution: 20–40 mm, 100 kHz)
– Real Time controller (real time monitoring of n_e, T_e, T_i, V_{rot} and q_r profiles, sustainability of ITBs)
– L_i Beam upgrade (improvement of the reliability of the L_i-beam diagnostic and investigation of a possible increase of beam current)
– ECE Michelson (absolute measurement of T_e, 5 ms time resolution and repetition rate, 10cm space resolution).

3.2 LONGER TERM PROJECTS (2004 SHUTDOWN)

Heating and fuelling systems:

– **ICRH - ITER-like antenna**

Divertor:

– **MarkII HD (Div. modifications)**

Diagnostics:

– Tritium retention studies (& 1stmirror test) (methods/devices to address the issues related to the expected T retention, in particular in the divertor area: important ITER issue)
– **High Resolution Thomson Scattering** *(US)* (T_e and n_e at edge and ITB, 1.5 cm resolution, 30 Hz max repetition rate, accuracy ~15%).

- **KB5 bolometry** (new main chamber bolometry for medium-resolution measurements of the bulk plasma emissivity and high-resolution in the divertor area)
- Halo sensors (measurements of disruption halo currents, current density, toroidal and poloidal distribution. Important ITER issue)
- Magnetics (equilibrium and high frequency coils to improve reconstruction, vertical stability, study of MHD phenomena)
- TAE antennas *(US)* (High *n* (5–15) Toroidal Alven Eigen mode excitation for damping measurements – 8 antennas into the vessel)
- Microwave access (new system for reflectometry diagnostics, consisting of antennas, waveguides, quasi-optical interface units. Waveguide technology full ITER relevant).
- Infra Red view (new camera for wide angle thermography in the main chamber and divertor, for real time machine protection and analysis of the power deposition during disruptions and ELMs. Optics technology full ITER relevant)
- Edge Current profile (upgrade of poloidal Charge eXchange Recombination Spectroscopy CXRS system with new periscopes, viewpoints, fibers, spectrometers and CCD detectors. Feasibility study for a Lithium Beam based diagnostics (US))
- CXRS *(US)* (upgrade of core CXRS system with the aim of enhanced sensitivity and time resolution, more radial measurements, increased impurities simultaneously measured, with new periscope, fibres, spectrometers and CCD detectors.)
- Fast digitisers *(US)* (new fast data acquisition system boards and software for various diagnostics, capable of recording data at high bandwidth (MHz range) and over long periods (up to 10s))
- Time Of Flight Optimised Rate neutron spectrometer (new, high accuracy, TOF spectrometer for DD plasmas with scintillators, photo-multipliers, software etc.: measurement of ion temperature and *D* population components when perturbed by auxiliary heating).
- Magnetic Proton Recoil (upgrade of the existing MPR with new scintillators, photo-multipliers, software etc. for neutron emission at 14 MeV, also useful for 2.5 MeV Alpha knock-on + D/T concentration measurements)
- Lost alphas (US) (new Faraday cups and scintillator detectors to measure the loss distribution of DD charged fusion products (1 MeV ^3H, 3 MeV ^1H, and 800 keV ^3He ions), 3.5 MeV DT alpha particles, and ICH tail ions to the walls)

Note: project <u>underlined</u> are completed, in *italic* are only study and test, in **bold** have a bigger scale (≥1¤m), US contribution is not major when in italic.

Among the lists of enhancements, it is worth to mention in particular the following.

Octant 8 NBI upgrade

This upgrade aims at approximately doubling the injected power capability of Octant 8 (expected gain ~ 7.6 MW D_0) by doubling the current capability (from 30 to 60A) of the 8 Plug-In Neutral Injectors (PINIs). The beam energy will be in the range 120–130 keV.

This requires four main actions:

- Purchasing new High Voltage power supplies (PS),
- Purchasing new set of extraction grids and re-gaping the 8 PINIs,
- Purchasing new ion source bodies,
- Upgrading a Box Scraper to accommodate the higher power loading.

Upgraded pellet injector (see Figure 1)
With a new extruder (able to produce pellets in a range of size variability from one half up to twice the size of the present full-sized pellet), and with a quasi-vertical track through a 3rd flight tube, pellets will be launched from the top inboard corner at speeds up to 500 m/s into the plasma, with a significant increase in penetration and fuelling efficiency.

ITER-like antenna ICRH (see Figure 2)
It is an increase of the heating systems capabilities (+ 7.2 MW) and overall the demonstration that the design and technology adopted can be applied to ITER.

The main features are the following.

- New ICRF antenna with high power density (~8 MW/m^2) at ITER relevant coupling (in the range of 2–4 Ω/m) and plasma-antenna distance.
- New transmission lines (and modifications to the existing A2 antenna lines to improve coupling).
- High coupling efficiency (>90%) in the frequency range 30–55 MHz.
- ELMs resilience.

Mark II HD Divertor (see Figure 3)
This is a modification of the existing divertor: a new Septum Replacement Plate (SRP), a high field gap closure plate (HGCP) and upgrade/refurbishment of divertor diagnostics.

The main features are the following.

- Capability to run high triangularity ITER like scenarios (δ^U~0.44 and δ^L~0.56)
- Key equilibria: Type-I ELMy H-mode, 3.5 MA/ 3.2 T, $<\delta>$~0.5, N^{GW}= 1; Type-I ELMy H-mode, 4.0 MA/ 3.2 T, $<\delta>$~0.5, N^{GW}= 0.85
- Flexibility with respect to different plasma scenarios (Optimised shear & Advanced Tokamaks): triangularity down to ~0.2; low/high β, low/high X-point
- Adequate pumping capability.

4. PROJECTS ORGANISATION

The JET Enhancement programme is co-ordinated by EFDA CSU Culham, with the management of the overall planning and of the contracts related to the implementation of the activities. The individual projects are lead by Project Leaders (PL) proposed by EFDA Associates and nominated by the EFDA Associate Leader for JET. Project teams are set up with the involvement of one or more Associations. In some cases collaborations with US laboratories are organised that could range from 'minor' participation to leadership.

The JET Operator is in charge of the integration and installation of the enhancements into the JET facilities, and nominates an Operator Representative for each project.

Industrial suppliers are involved for the procurement of the components. The complex and multifaceted organisation of the enhancement projects is summarised in Figure 4.

5. PLANNING AND BUDGET ELEMENTS

The planning of the various projects is build in order to fit with the JET operation and shutdown periods, which in turn are driven also by the site installation and commissioning of the new systems. This holds in particular for Oct. 8 NBI upgrade and for the longer-term enhancements. The 2004 JET shutdown is specifically tailored for the ITER-like antenna, divertor and diagnostics.

Here only some elements are now given.

The Oct. 8 NBI project schedule is delayed respect to the original one, due to the longer technical realisation of the HV transformers for the new PS. Site installation and commissioning of these, by far the most important components of this upgrade, are scheduled to start in January 2003 and the upgrade will be operational in August 2003.

According to the current schedule, after the start of the JET shutdown in March 2004, the ITER like antenna components will be available from June 2004 for assembly and tests. In vessel installation is foreseen in December 2004, aiming at a JET pump down in January 2005. The delivery and installation of the other enhancements are organised in compliance with the above key dates.

With regard to the budget, the projects are implemented through several tens of contracts with the Associations, the industry, the JET operator, and bilateral agreement with US DOE, each category of contract having a different share of funding between the Commission and the EFDA Associates.

While a detailed presentation on the budget is largely out of the scope of this paper, an idea of the size of the enhancement programme is given by the total of the Art. 7 procurements, in the order of €25m, and of the JET Operator external costs, approaching the €10m scale.

CONCLUSIONS

The enhancement programme is a significant upgrade of the JET capabilities and will permit to reinforce the focus on an ITER-relevant programme.

The involvement and co-operation of the EFDA partners in these activities, despite the complex environment and organisation, is showing clearly a value in terms of competencies and ideas contributing to the scientific and technical output of JET.

The success of this programme requires a continuous support from the Associations, from the JET Operator and from third parties to ensure that the objectives are achieved on schedule.

ACKNOWLEDGEMENTS
The list of contributors to the enhancements would have probably taken most part of document.

Therefore, I can only acknowledge in general all those professionals and technicians working on the JET enhancement programme, they all are actually co-authors of this paper.

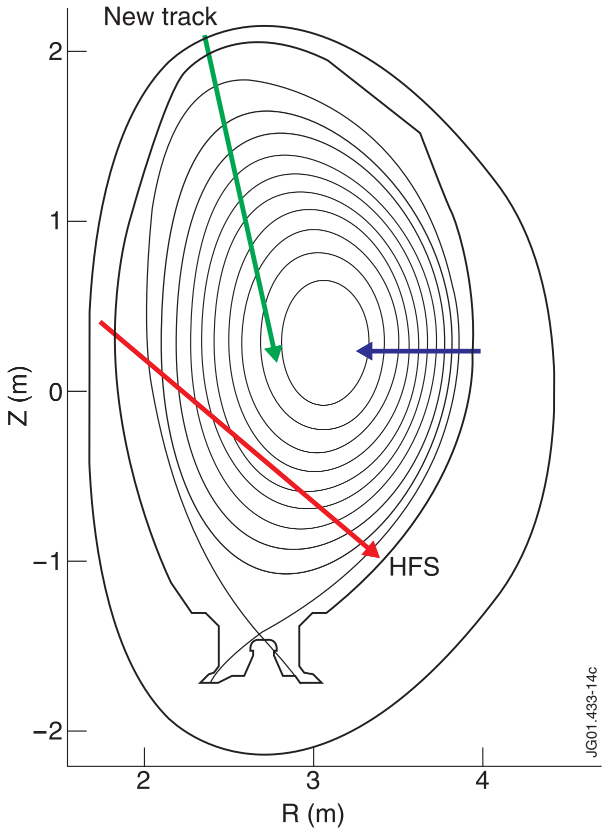

Figure 1: Upgraded pellet injector.

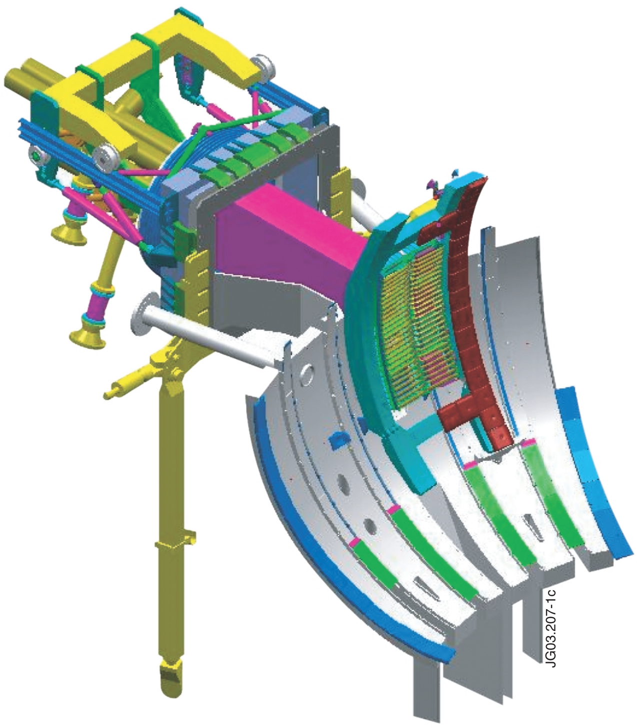

Figure 2: ITER like antenna 3-D view.

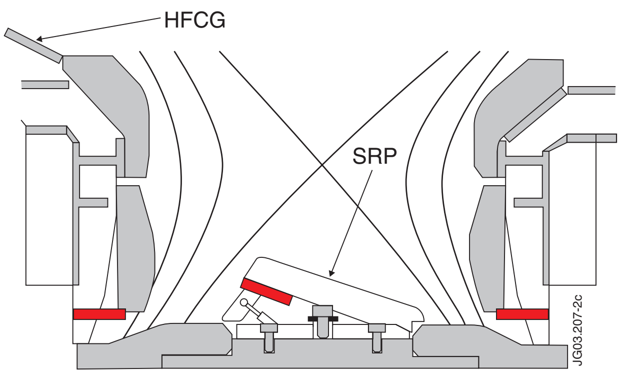

Figure 3: Mark II HD divertor.

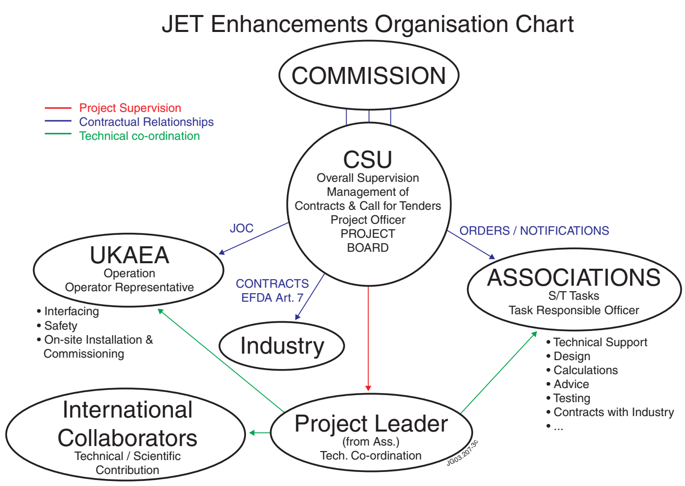

Figure 4: JET Enhancements organisation chart.