EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–PR(01)53

J. Sanchez et al

Recent Experience and Future Plans for JET Diagnostics

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J. Sanchez[1]
and contributors to the EFDA-JET work programme

[1] Asociacion EURATOM/CIEMAT, 28040 Madrid Spain

Paper to be submitted for publication in Proceedings of Varenna 2001

1. INTRODUCTION

The operation of JET under the EFDA agreement has provided experience in two important areas concerning the future organisation of supra-national Fusion Facilities.

The scientific exploitation of the device during 2000 and 2001 has been done by scientists from the different European laboratories, with a significant role of the British UKAEA Association as Operator of the facility. The integration of the operation team with the visiting scientists has been quite successful, not only in the general areas of Tokamak Physics but also in the particular area of Diagnostics, which required a very close collaboration of both groups.

In addition to the operation of JET, a complex program to enhance the JET facilities (JET Enhanced Performance) is being prepared and could be implemented during the period 2001-2006.

The present paper will briefly discuss the aspects of the 2000-01 operation and enhancements (with emphasis on the diagnostics systems) and give an overall description of longer term enhancement project, focusing on the diagnostics. Given the broad spectrum of the activities described, involving the work of many persons, deep technical details will not be discussed but the author will try to provide a comprehensive list of references when available.

2. OPERATION OF JET DIAGNOSTICS DURING 2000-01

Under the EFDA agreement, JET operates as a “Users Facility”. The Operator team takes care of all the basic elements of the machine operation, including heating and diagnostics systems, whereas the European Associations (including the UKAEA) determine the scientific programme of JET and provide the staff for the experiments and analysis, organised into “Task Forces”.

The exploitation of the diagnostics system follows the same complementary organisation: Basic operation of existing diagnostics is carried by the Operator (up to the data acquisition, including calibration in many cases). The role of the visiting (or UKAEA) scientists, under Task Force Diagnostics (TFD) was:

- To collaborate with Operator personnel in the operation of diagnostics.
- To propose and perform diagnostic oriented experiments.
- To provide validation and scientific analysis of the data.
- To propose and construct new diagnostics or diagnostics enhancements (interface by OperatorTeam).

In parallel with the above explained philosophy, one of the main goals when preparing the campaigns was the formation of integrated teams, trying to avoid any mismatch between the members of the Operator Team (with an extensive JET experience) and the visitors (more than 60, in many cases visiting JET for the first time). The result was quite encouraging: thanks to the effort and enthusiasm from both sides the integration was excellent, leading to a successful operation of the diagnostics.

One of the advantages of the broad participation was that, for every system, we had the opportunity to get the visit of the best European (and US) experts. A number of systems like Li beam (edge density profile studies) [1], IR cameras (heat loads to divertor during ELMs) [2] and Doppler spectroscopy for poloidal rotation studies [3], among others, benefited from this fact. Even if the general recommendation for visitors interested on diagnostics exploitation was to stay for full experimental campaigns, short visits were welcomed as a possible seed for a future deeper involvement of the particular experts in the JET programme.

Diagnostics oriented experiments, requiring devoted machine time, were grouped in four areas: q profile measurements by MSE (leading among other results to the streaking observation of a core region whit zero plasma current on ITB discharges) [4], Electric field measurements by MSE (trying to use the comparison of full and half energy beam components) [5], High Z ablation experiments (identification of high Z impurity lines as erosion markers in a hypothetical high Z ITER) and He beam spectroscopy experiments (by the use of a He doping system in one of the Heating Neutral Beams) [6].

Validation activities are organised by the Data Validation Coordination Committee, which runs monthly meetings. Many of the problems analysed there triggered working groups or actions involving TFD members. In particular we can mention the effort on: ECE-Thomson comparison (both in the aspect of geometrical interpretation of Te profiles as in the possible effects of non-maxwellian electron distributions), comparison of edge profiles from different diagnostics [7], alignment of CXRS data, comparison of Zeff obtained from different diagnostics (Visible Bremsstrahlung and CXRS), magnetic reconstruction issues (iron core, zero current at plasma centre) and the work done on validation of interferometry data (fringe corrections).

Finally, an ambitious programme of diagnostics enhancements has been prepared. Most of them lie within the JET EP project, described below, but also a number of shorter term enhancements have been developed during 2000-01 and will be available for the 2002 campaigns: the new microwave reflectometer for correlation studies of the density turbulence (US collaboration), the upgrade of the MSE system for operation with a new dedicated beam at 130 MeV (US collaboration), the development of new Langmuir probe heads for turbulence studies, the installation of a Quartz Microbalance [8] for deposition studies, the installation of high efficiency detectors for the edge LIDAR system and a number of refurbishments and maintenance actions undertaken by the Operator, i.e. the review and replacement of magnetic sensors.

3. THE JET EP PROJECT

The JET Enhanced Performance Project (JET EP) is a proposal for extending the JET operation beyond 2002, with a series of significant enhancements. The main physics objective is the support of ITER, trying to improve the subsystem design and the operation capabilities of the machine.

In order to accomplish the goals, the capabilities of the machine be upgraded with additional heating systems (7.5 MW NBI, to be commissioned in 2002, 5 MW ECRH at 113 GHz and a new ITER-Like ICRH antenna, able to operate in ELMy H mode), a new Divertor, able to handle the extra power, (as well as high triangularity configurations, which presently would have the strike points outside the divertor plates) and a comprehensive set of new or upgraded diagnostics, which will be discussed below.

The present schedule considers commissioning of JET EP enhancements during 2004, though the detailed strategy (schedule and project content) might change in accordance with the overall planning of the European Fusion Programme for the period 2003-06 (6^{th} Framework Programme).

3.1. DIAGNOSTICS FOR JET EP: GENERATION OF THE PROPOSAL

In order to prepare a proposal on the diagnostics enhancements for JET EP a working group (Diagnostics Working Group, DWG) was formed. This group involved both diagnosticians and general plasma physicists from the different Task Forces, from the Culham and Garching Close Support Units and members of the ITER Diagnostics Expert Group.

The reference elements for the DWG were the Physics programme of JET EP (with a strong ITER-driven component) and the ITER needs in terms of diagnostics physics and technology. Proof of principle diagnostics would be considered only if ITER relevant.

A summary list of the urgent Physics developments required for ITER is given below (extracted from the document on European Domestic Assessment of the ITER FEAT design)

- High density operation, (high confinement), safe Divertor operation, n_e peaking
- β-limit in ELMy H-mode: Neoclassical Tearing Modes.
- ELMs control (for aceptable lifetime of plasma facing components)
- Disruption mitigation, halo currents, runaway electrons
- T retention: codeposition and removal
- Advanced scenarios, sustainability, influence of energetic particles
- Heating technology/physics
- Diagnostics technology/physics

On the other side, the framework constraints included, in addition to the usual procurement budget and manpower ceilings, the specific condition of JET as a consolidated Tritium-compatible device. This required reinforced attention to the interface impact: port allocations, knock on relocations of systems, in vessel work (tritiated environment), availability of in vessel wiring, remote handling compatibility, waste disposal and impact on the shutdown duration.

Within the terms of reference, the DWG analyzed the possible enhancements taken into account some facts to be weighted against the resources demanded:

- Fraction of the programme which would benefit from the enhancement
- Commissioning date: when could the programme start using the enhancement ?
- Technical risks (to be kept to a minimum for a device like JET)
- Uniqueness of JET as diagnostic bed, for ITER driven developments
- Availability of interested experts within the European programme
- Existence of non EU interested parties able to contribute equipment and expertise.

3.2. PROPOSAL ON DIAGNOSTICS FOR JET EP

More than 80 possible enhancement actions were considered, those proposals were provided by external sources (individual scientists, Associations, CSU,s ITER...) or generated by the DWG itself in order to give response to identified needs. Within the given constraints, only a fraction of the proposed actions could be recommended for implementation, whereas many proposals of significant scientific value had to be left out. The proposed enhancements are commented below.

3.2.1. SYSTEMS FOR OVERALL SUPPORT OF THE JET PHYSICS PROGRAMME

3.2.1a. High Resolution Thomson Scattering.

Working with the traditional 90∫ geometry this system would complement the existing LIDAR (core and edge) systems, providing coverage for the edge and ITB regions (in practical terms the whole outer radius of the machine) with 10Hz repetition rate and 15mm spatial resolution. The physics aims of the system would be the studies of ITBs (which show sharp n_e and T_e gradients) and H-mode pedestal/ELMs (a primary concern for the operation of ITER), in addition to an overall benefit to every JET experiment.

The reference proposal has been produced after a deep analysis by a group of Thomson Scattering experts. The analysis work and the details of the final proposal are described elsewhere on this publication [9, 10] .

3.2.1b. Upgrade Of The Heterodyne and new Michelson ECE Spectrometers.

The existing ECE heterodyne system will be upgraded with 48 new channels, this will improve the coverage of the whole plasma radius under a great variety of configurations. (20-40mm, 10μs resolution)

The new Michelson system (100mm, 5 ms resolution) will provide the coverage of the full ECE spectrum, allowing comparison of the different harmonics. This system might substitute the aged existing Michelson and would be useful as calibration standard. The system will also play an important role on high density DT discharges (1st harmonic under cutoff), where detailed time evolution of the central T_e is required to assess the alpha heating.

3.2.1c. Real Time Profile Analysis.

The sustainability of ITBs needs the control on real time of the plasma profiles (being of capital importance the current profile control).

An ambitious programme has been already started for the integration of profile diagnostics in a real time analysis system (which will be used as the “sensor” part of a feedback loop, to be completed by “actuators” as gas injection or heating systems) [11, 12]. During 2001 and 2002 data from a number of systems (ECE, polarimetry, FIR interferometry, CXRS, MSE and magnetics) will be included in the real time VME server. The project will require some moderate effort on hardware procurements and interfacing but will need a substantial effort to generate the fast algorithms (diagnostic specific) necessary for the real time analysis.

3.2.1d. Li Beam for Edge Density Measurements.

The aim of this project will be the improvement of reliability and performance for the 50 kV Li beam, which already operated during the 2000-01 campaigns. The work to be done will include the development of a new source for the beam and the improvement of the analysis software. This diagnostic will play an important complementary role on the characterization of the edge density profile (relevant for ELM and pedestal physics).

3.2.1e. He Doped Beam for Edge n_e and T_e Measurements.

This (modest cost) activity would be the continuation of the experiments performed during 2000-01 on the use of he doped heating beams as edge diagnostic. Preliminary results [6, 13] show good prospects for n_e measurement, whereas the sensitivity of the method for T_e is smaller. The proposed upgrade involves the installation of He doping systems in both NBI boxes and the development of remote operation tools to make the diagnostic routinely available. Analysis will progress on the actual feasibility of this diagnostic, mainly in the weaker (presently) T_e side, which unfortunately can be hardly obtained from other diagnostics.

3.2.1f. Fast Data Acquisition System.

The main fast Data acquisition system in JET is “CATS”, a very sophisticated transputer-based system, able to operate with intelligent triggers, which has been of great help during the last ten years. Nevertheless, this system is difficult to upgrade and its performance has been surpassed by the simpler “crude force” modern systems, equipped with large memory and fast ADCs.

The aim of the new fast DAQ would be to provide full discharge coverage for the systems requiring high sampling rate (up to 2 Ms/s, 12-14 bit). Presently these systems are limited on the number of channels and must operate with “time windows” leading to loss of the relevant data if the events are not properly synchronised.

The project will use a Lynux based system, controlled by PCs with digitising boards able both to store the data locally (64 Ms) or to channel it into the PC memory for continuous sampling. Isolated inputs will be used for higher quality signal recording..

3.2.1g.Vertical Bolometer Camera.

It will substitute the, presently unreliable, vertical bolometer. It will have a high density of channels viewing the Divertor region. This camera, together with the existing horizontal ones (to be relocated) and those located in the Divertor (to be refurbished) will complete a basic bolometry system to ensure the global radiation measurements, radial profiles and main plasma/divertor radiation ratio.

3.2.1h. Current Profile and E Field Diagnostics.

The successful results of the existing MSE system will be complemented in two areas, the first one (already consolidated as a project) would be the upgrade of the poloidal rotation CXRS system for the measurement of radial electric fields, the second one (still under assessment) would be the development of a Li beam-based spectrometer for edge current studies. This system would use either traditional polarimetry of the Zeeman split lines or a new technique [14] based on line intensity ratio measurements. The measurement is considered of capital interest for edge stability studies, linked to ELM control.

3.2.1i. Core CXRS Upgrade.

The final decision on upgrade of this key diagnostic is presently being refined. The main targets will be: improvement of s/n and time resolution, installation of a He dedicated spectrometer (determination of He^3 concentrations on minority heating experiments) and, possibly, improved resiliency to NBI unavailability (by having redundant systems looking to beams from both injectors).

3.2.1j. Magnetics Upgrade.

The control of some of the proposed plasma shapes, as well as the improved configuration control which will be required for detailed analysis of edge stability (among other elements), recommend to refurbish and upgrade the aged system of magnetic sensors. A detailed study, with cost/performance optimisation of the possible upgrade, is underway.

3.2.1k. Divertor Diagnostics.

The implementation of the new (Mark III High Power) Divertor will require the reinstallation of several diagnostics and will provide an opportunity for the refurbishment of several systems, in some cases with minor upgrades.

The main systems considered are:

Langmuir probes (90+30), Thermocouples (42), Bolometers (7 Cameras+ upper view KB5), Pressure Gauges (2), Quartz microbalances (2), Long term samples (mech. indexes, marker films, sticking boxes..), Thermal He beam, μw antennas for interferometry/reflectometry, Equilibrium and Halo Coils.

3.2.2. SPECIALISED SYSTEMS

3.2.2a.TAE Antennas.

TAEs are actively excited and the damping rate measured with magnetic sensors (also reflectometry, ECE) to the determine their stability properties. The proposal includes the installation of 8 antennas, able to excite the ITER relevant high n (10-15) modes. The system can indirectly determine q values and isotope ratio n_D/n_T (linked to the Alfven frequency).

3.2.2b. Time of Flight Neutron Spectrometer.

To be used for 2.5 MeV DD neutrons, this system will be designed for high count rate [13], useful on high performance and ICRH discharges. Line integrated fuel Ti and flow rotation (if tangential view) will be provided.

3.2.2c. Vertical VUV spectrometer.

It will substitute the existing vertical VUV spectrometer equipped with an unreliable vibrating mirror. Resolution on space, wavelength and time will be gained by using a CCD detector.

3.2.3 ITER RELEVANT SYSTEMS (URGENT MEASUREMENT OR TECHNOLOGY DEVELOPMENT)

3.2.3a. Halo current sensors.

Very important to determine the possible effect of disruptions on ITER (forces). Detailed design of coils and locations is underway.

3.2.3b. Microwave Access.

For Reflectometry and ECE, using corrugated waveguides (38mm diam) for broadband operation (the reference solution for these diagnostics on ITER). They will be complemented with quasioptical launchers able to focuse the beams.

3.2.3c. Infrared Viewing system.

The main goal will be the detection of thermal loads to the first wall, as possible side applications: alpha particle losses (geometrical distribution) and synchrotron radiation from runaways (disruptions) are also considered. The system will include zoom capabilities and a fast camera will be used for 100µs resolution.

3.2.3d. Tritium retention diagnostics.

Very urgent ITER need. In addition to the already programmed long term samples and quartz microbalances, shuttered samples, spectroscopy systems and other novel techniques will be discussed for further implementation.

3.2.3e. Mirror Tests for ITER.

Technology task to assess the effects of the plasma erosion and redeposition on plasma facing mirrors for ITER. Samples will be placed on the JET Divertor, with different orientations and, possibly, shutters to select type of plasma.

3.2.4. DT DIAGNOSTICS

JET has already a comprehensive set of DT diagnostics, tested during the DTE1 campaign. For a possible DT campaign on JET EP, a few complementary systems are considered.

3.2.4a. Lost Alpha Detectors.

Either with Faraday cup or scintillator box technology, should be able to determine the energy of the escaping alphas. Also an important test for ITER.

3.2.4b. Magnetic Proton Recoil Spectrometer Upgrade.

This would improve background noise and extend to 2.5 MeV the successful existing 14 MeV MPR system [16]. With this upgraded capabilities the system will aim to the analysis of the alpha knock on spectrum (linked to the pressure of fast alpha particles)[17] and the comparison of DD to DT peak intensity (for isotope ratio measurement).

3.2.4c. Neutral Particle Analyzer Upgrade.

The upgraded high energy NPA system could be useful for alpha particle distribution measurements (also a new detector able to discriminate alphas from fast deuterons is included in the design) with a rough spatial resolution (achieved by the implementation of three channels along the plasma radius). One of the goals of the system would be the analysis of alpha particle redistribution by MHD phenomena.

ACKNOWLEDGEMENTS

The author is deeply indebted to many collaborators: TFD and Operator team members, components of the JET EP Diagnostic Working Group and proponents of the more than 80 proposals received, many of them with a substantial background work behind.

This work has been conducted under the European Fusion Development Agreement

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