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ABSTRACT.

Since early 2000 the JET-EP program has been aiming at optimising JET for ITER-relevant plasma operations, from 2005 onwards.

The overall heating capability of JET will be increased to 40MW. The neutral beam system was up-graded but the major technical challenge is to build an ITER-like ICRH antenna, with particularly stringent specifications. The new divertor configuration will be able to absorb more than 300MJ per shot. The physics of the power handling will be monitored by sophisticated new diagnostics, e.g. a high-signal to noise bolometric tomography and an ambitious IR viewing system using a state of the art camera, looking at the antenna and the divertor. New halo sensors will be installed to better understand disruption phenomena. The new divertor's geometry allows high-triangularity ITER-like scenarios with a greater flexibility with respect to different plasma configurations. The control of extreme plasma shapes will be re-enforced and a new disruption mitigation system using a very fast gas valve will be provided. The diagnostic capability will be enhanced by several new systems designed to address a number of crucial physical phenomena for ITER. To study Tritium retention further, new technologically challenging erosion-redeposition diagnostics will be installed, particularly in the divertor region, both real time and integrating. New neutron detectors using the latest advances in scintillators and data recording techniques, detectors for fast _ particles with high pitch angle and energy resolution, high-resolution Thomson Scattering, with 20Hz repetition rate, will provide temperature and density profiles with a spatial accuracy close to two centimeters are the leading items of a much vaster programme.

This paper presents an overview of this program, emphasising the main objectives and pointing out the various technological challenges and innovations.

INTRODUCTION

The JET Enhanced Performance (JET-EP) programme has been under way since 2000. The first part of this programme is completed and about 15 new systems have already been installed in 2003 and are in operation at JET. A major shutdown has started in March 2004 to install about twenty new and up-graded systems on the machine, and to perform essential refurbishment. This shutdown will last until February 2005 and will be followed by a restart allowing the commissioning of the new systems. The JET-EP programme will then be completed with the new divertor and the enhanced diagnostic capability as early as July 2005, apart from the new ICRH antenna, which will be installed in two steps. The transmission lines, the poloidal limiter beams and their protection tiles as well as the main port bellows will be installed during this 2004 shutdown. The rest of the antenna namely the antenna straps and housing, and the inner vertical transmission lines, will be installed in a dedicated shutdown that will take place late 2005. JET will then be available with its full capability including the new ICRH heating power in June 2006.

This paper concentrates on the later part of the JET-EP programme, with some details about the main technological issues involved in this improvement of the JET capability as well as new systems recently added, and gives an overview of the installation phase currently under way.

1. INCREASING AND MASTERING THE HEATING POWER

The increase of the heating power is key to the improvement of the JET capability.

The up-grade of the Oct 8 neutral beam injector has been completed and fully commissioned during the C12 campaign in December 2003. A record JET NB power of 22.7MW has been achieved. To improve further this system, an up-grade of the neutraliser is currently under way with the objective of recovering the design value and bringing the maximum power to 1.7MW per PINI. This will be made possible by installing a septum in the neutralisation chamber to recover the neutralisation deficit. The expected maximum power will then be 25MW.

The crucial item regarding the heating systems is the new ICRH antenna. This new antenna is designed for a high power density (~8MW/m^2 in the range of 2-4Ω/m), which is one of the technological challenges, in particular for the straps. Besides, ELM resilience, achieved through a conjugate T system is key for its ITER relevance. The coupling efficiency is >90% in the frequency range 30-55MHz. The capacitor-actuator system, installed in-vessel, requires a high accuracy positioning under very high mechanical loads in case of disruptions. The design and manufacturing of such a system is extremely challenging. Once the antenna will be built, a thorough testing period will be necessary to test the matching algorithm of the 4 feed lines.

To handle the power, a new divertor will be installed. The components have been designed to withstand 40MW during 10s. (See [2])

In order to maximise the scientific exploitation of these upgrades in the additional heating systems and the power handling, a significant improvement of the diagnostic capability is also indispensable. In this respect, a new infrared camera and a modified bolometric tomography are expected to provide essential data for both operation of the facility and interpretation of the physics.

The new wide-angle infra red system was developed in order to image a large section of the tokamak in both poloidal and toroidal directions. The optics have a field of view of 70 degrees, viewing the divertor, the inner wall, the outer poloidal limiters, the ITER-like ICRH antenna and the top limiter. The field of view is shown **in** on Fig 1. The optical components are based mainly on reflective optics to sustain high neutron radiation. This diagnostic will be able to measure temperature with a large dynamic range, from operating temperature of 200°C up to a maximum temperature of 2000°C. The enhanced dynamic range is achieved by using a multi-exposure time: acquisition with three different exposure times is performed and the corresponding frames are combined in a single thermal image. In order to measure accurately the power and energy deposition during ELMs, a time resolution of the order of 100µs is achieved by reducing the image size to 128x8 pixels, and by using a 40MHz pixel clock. The system will provide a temperature map of the whole area. Unfortunately, the Tritium compatibility and the zooming capability of the system had to be given-up, due to their extreme complexity and high cost.

The KB5 bolometers are very similar to those of ASDEX Upgrade and Tore-Supra. They consist of an 8µ gold absorbing layer placed on a 20µ mica foil with a high-resistance (1.2kΩ) gold meander. The bolometer bridge supply voltage is 40V peak-to-peak at 50kHz. Due to an improved grounding concept along with better electrical shielding and use of lock-in technology at the 50kHz-carrier frequency in combination with a higher signal level due to the higher bridge voltage, a significantly enhanced S/N ratio will ensue. The detection limit (S/N=1) is typically ~ 2^{10-6} W/cm^2 for a 10msec time constant for this design, and this will permit higher time resolution than the present 20ms. All of the bolometer output signals could potentially be fed to the Real Time Control System if based signal carriers rather than optical fibres are implementated.

Additional to the heating systems and ancillaries, it is foreseen to have available in 2005 a pellet injection system with the following specifications in routine mode. Pellet size: 4mm3; LFS/TOP track: 5Hz, 250m/s; HFS track: 10Hz, 160m/s; LFS/HFS selection frequency: 10Hz.

2. EXTENDING THE OPERATIONAL DOMAIN OF JET FOR ITER RELEVANCE

To increase JET relevance for ITER preparation, the operational domain will be extended by allowing to run plasma configurations closer to the ITER ones and by adding a number of systems designed to better control and protect the machine.

The new divertor geometry is the corner stone of this topic. It 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~0.44 δ^L~0.56), like the following:

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

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

A pure software development, the so-called eXtreme Shape Controller (XSC), will allow running extreme plasma configurations. This is an extension of the already available software, but this new up-grade will make available at JET an integrated, session-leader-friendly, control algorithm that takes into account plant safety, both in terms of hardware and software. In addition to improve the control if the shape of in high elongation in high elongation and high triangularity discharges, the XSC was designed with a methodology of direct relevance to ITER.

The mitigation of disruption effects is a key factor for machine operation. A project was launched at the beginning of 2004 to install a new high-pressure valve with very stringent specifications: ~ 2ms to 60% opening and throughput of 10^6mb.l.s^{-1}. This valve will be able to operate under a 2T magnetic field, and thus could be further developed to operate in-vessel in the future, hence with much lower gas pulse transit times.

A new halo current detection will contribute to the understanding of the disruption phenomena. It consists of a delicate assembly of very thin (μ=0.65 mm), mineral insulated, high vacuum-sealed, cables wound onto a ceramic core. The manufacturing and assembly of these systems has proven to be quite difficult. The same kind of technology is applied to a new set of magnetic detectors, aiming at improving reconstruction calculations, studying MHD phenomena, and further improving the control of the shape.

3. ENHANCING THE DIAGNOSTIC CAPABILITY OF JET IN PREPARATION OF ITER

The diagnostic capability will be enhanced by several new systems designed to address a number of crucial physical phenomena for ITER.

Very important is the new set of items relevant to tritium retention study. New technologically challenging erosion-redeposition diagnostics will be installed, particularly in the divertor region, providing both time resolved and time integrated data (See[2]).

Besides, new neutron emission spectrometers will be installed. An up-grade of the present Magnetid Proton Recoil system will consist of a new hodoscope, with laminated scintillators of the so-called phoswich type, that will replace the present one of monolithic scintillators. Each detector consists of a laminated scintillator: a front layer stops proton up to 4 MeV in energy whereas a thick part stops them of up to about 20 MeV. This, added to an enhanced suppression of background radiation, aims at increasing the S/N ratio by more than a factor of 100.

A new TOFOR (Time Of Flight Optimised count Rate) system will be also added to the eutron emission spectroscopy capability. The TOFOR spectrometer shall consist of a CH-based plastic scattering scintillator S1 placed in a collimated neutron flux, and a ring-shaped array of scintillators S2 (placed on the sphere of constant time-of-flight), for detection of scattered neutrons. A very careful geometrical assembly is needed to meet the expected performance (see Fig 2). This is achieved by extensive simulations of the neutron response of the detectors and the light emission and transport. The count rate range will be of hundreds of kHz, improving by more than two orders of magnitude the present value for D plasmas.

The requirements of accuracy and stability, which are essential to the operation of the spectrometers, will be met through the development of a special control and monitoring (C&M) subsystem. The spectrometers will be monitored for stability over both short (transient) and long time periods, allowing remote examination.

The reflectometry project, consisting essentially of high S/N corrugated waveguides (objective >30dB) will improve considerably JET's capability on this type of diagnostics. A new system has been added recently: on the same launcher, an oblique ECE system with new smooth waveguides will operate in the range 100-400 GHz, and allow a much better interpretation of the temperature measurements. This system will be installed for the first time on JET.

Detection of ICH tail ions and the mechanisms of fast ion losses during MHD activity will be done by two new detector assemblies: Faraday cups and a scintillator probe. The Faraday cups will detect the current of lost fast ions at multiple poloidal locations, with a dynamic range from ~1 nA/cm^2 to ~100 µA/cm^2, a ~1ms time resolution The energy resolution of the foil detector will be ~15-25% for 3.5MeV µ particles. The dynamic range of the scintillator will be from fast ion loss densities at the wall of ~10 pA/cm2 to ~1 µA/ cm^2, with a time resolution of ~100 µs, the pitch angle resolution of ~5 degrees and the energy resolution of ~30%. Those detectors will be installed the closest ever to the plasma in JET.
On the route to ITER, a major problem resides in understanding the physics and the scaling of the barriers (both of ITBs and edge pedestal). To attack this issue, JET-EP will be equipped with a High Resolution Thomson Scattering, which will complement the present LIDAR systems. With a spatial resolution of about 1.5cm and a repetition rate of 20 Hz, this diagnostic should provide very significant information on both the gradients in the edge and in the core (see fig. 3).

Apart from those projects, a number of other systems, equally crucial for the future JET capability are part of the JET-EP: TAE antennas (High n (5-15)
mode excitation for damping measurements), Edge Current profile, Charge exchange spectroscopy.

A number of these systems, in particular the bolometry and all the temperature and density measurements, will be accessible in real-time, allowing the control of plasma shape, current and pressure profile in view of ITER scenarios.

4. IMPLEMENTING JET-EP ON THE MACHINE

The first part of the programme, consisting of the so-called "short-term" projects, has been completed and the instruments have been already used during 2003 campaigns. The whole list of the systems installed can be found in [3]

From the original plan of the short-term projects, only the pellet injection system has not been to date implemented.

The manufacturing phase has now started for all the projects, and is even completed for a few items. This phase has proven to be quite a complex one, because of the time schedule but above all because of the extremely complex interface between the new systems and the machine itself. Due to very strong constraints from safety, of both the hardware and the people, a great number of verifications and procedures had to be put in place, which were difficult to evaluate at the outset of JET-EP. This is an extra challenge, which imposes technological constraints on top of the original ones, and would require a very quick and efficient exchange of information. This experience will be further examined and lessons will be drawn, in particular in the perspective of ITER.

Implementing on the machine all the systems described in this paper (see also [3]) and bringing JET to the best condition possible to achieve its new performance, implies a huge number of activities to be performed during the 2004-2005 shutdown. This shutdown is managed through a very detailed and tight plan of activities, of which the installation of the EP-systems is only part. Making sure that all the delivery dates are compatible with the plan and the required on-site work in preparation of technologically complex installation is also a real challenge for the whole community working on this programme. (See also [4]).

All efforts are made to meet the pump-down date at the end of February 2005.

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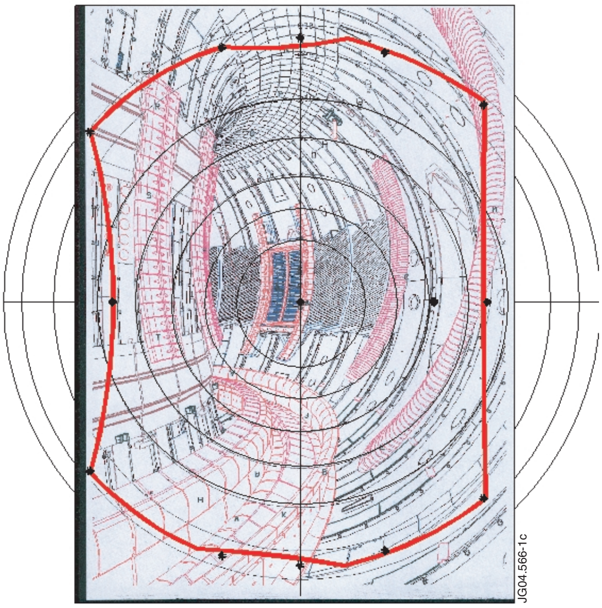

Figure 1. field of view of the new wide angle IR viewing system

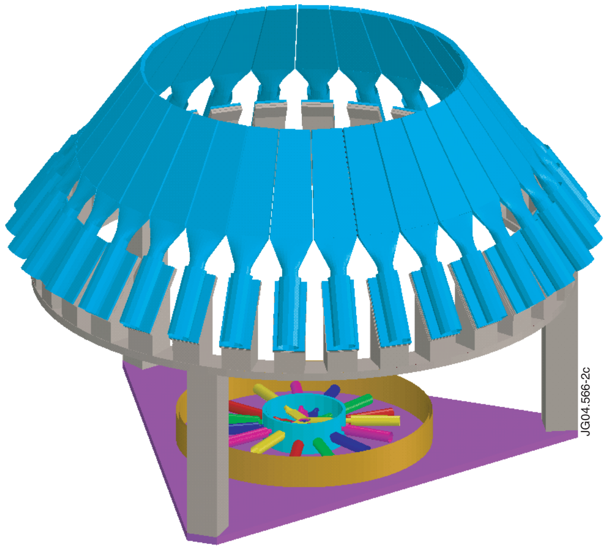

Figure 2. overview of TOFOR

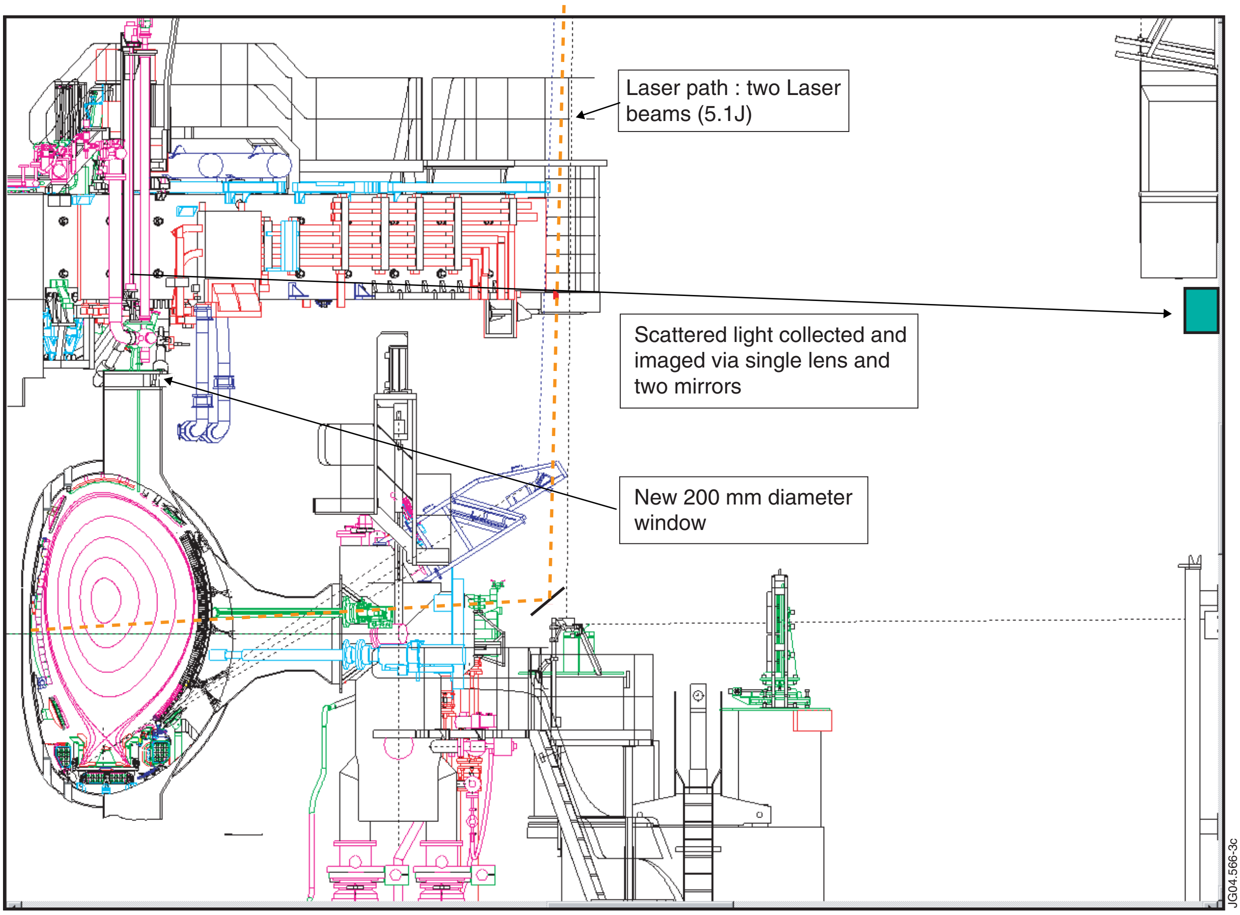

Figure 3. overview of the new high-resolution Thomson scattering system.