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An ECRH System for JET: A Feasibility Study

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ABSTRACT

For JET to fulfil its mission in preparing ITER operation, the installation of an Electron Cyclotron Resonance Heating system on JET would be desirable. The study described in this paper has investigated the feasibility of installing such a system on JET. The principal goals of such a system are: Current drive over a range of radii for NTM stabilization, sawtooth control and current profile tailoring and central electron heating to equilibrate electron and ion temperatures in high performance discharges. The study concluded that a 12 gyrotron, 10MW, system at the ITER frequency (170GHz) adapted for fields of 2.7-3.3T would be appropriate for the operation planned in JET. An antenna allowing toroidal and poloidal steering over a wide range is being designed, using the ITER upper launcher steering mechanism. The use of ITER diamond windows and transmission line technology is suggested while power supply solutions partially reusing existing JET power supplies are proposed. Detailed planning shows that such a system can be operational in about 5 years from the time that the decision to proceed is taken. The cost and required manpower associated with implementing such a system on JET has also been estimated.

1. INTRODUCTION

Among existing Tokamaks, JET is closest to ITER, both in terms of plasma parameters and in terms of technology. This fact, together with the recent increase in heating power, the installation of an all metal wall and JET's unique ability to operate with deuterium-tritium plasmas makes JET ideally suited to prepare ITER operational scenarios [1, 2, 3]. As ITER relies heavily on ECRH for current profile tailoring and Neoclassical Tearing Mode (NTM) control [4, 5], it would be highly desirable for JET to be equipped with an ECRH system as well. Therefore a study, investigating the feasibility of installing a substantial ECRH system on JET, has been undertaken. The present paper reports the findings of this study. An earlier JET ECRH system design was carried out in 2000-2002 [6]. Since this study, which never came to fruition due to financial constraints, both technology and the aims of an ECRH system have evolved and hence the proposed system differs significantly from the earlier design. Nevertheless, the previous design has formed an excellent basis for the present study. The study has undertaken technology assessment and physics calculations in parallel to converge on a design proposal, which can be implemented in a reasonable time without compromising performance while giving priority to the use of ITER technology.

2. PHYSICS INVESTIGATIONS

The main goals of a JET ECRH system is central electron heating to balance ion and electron temperatures in high power discharges, current profile tailoring and avoidance or suppression of Neoclassical Tearing Modes (NTMs) [7]. These goals can be translated into the requirement to drive current and/or heat at different normalised minor radii (ρ). NTM suppression requires localised current drive in the outer part of the plasma ($\rho = 0.6$-0.8), Current profile control requires current drive around mid radius while sawtooth control requires current drive near the $q = 1$ surface ($\rho = 0.1$-0.2). Finally electron heating for equilibration of electron and ion temperatures would require central power deposition. A system fulfilling all the requirements must therefore be able to drive localised current and/or heat over the complete range of plasma minor radii from the centre to $\rho = 0.8$. Before proceeding with detailed simulations the main JET scenarios to be used in the future were identified and two existing JET Pulse No's: 73344 and 77895, were selected to represent ELMy H-modes and advanced scenarios respectively. The experimental plasma parameters were then scaled to higher additional heating powers and to a variety of magnetic fields.

2.1. FREQUENCY CHOICE.

To limit the required gyrotron development, the study concentrated on frequencies where gyrotrons already exists (140GHZ, 170GHz) or where only minor design changes to existing gyrotrons would be required (113GHz, 150GHz). After ruling out 140GHz as being particularly badly suited for JET, the work focused on selecting either a dual frequency (113, 150GHz) gyrotron which would be a modified version of the ASDEX Upgrade dual frequency gyrotrons or a single frequency 170GHz gyrotron as developed for ITER. For each frequency (113, 150, 170GHz), plasma scenario and magnetic field, beam tracing calculations were performed over an extensive range of toroidal and poloidal injection angles [8,9]. For each combination of scenario, frequency and magnetic field, the maximum current which can be driven at a certain value of ρ was taken as a figure of merit representing the system performance for these specific conditions. Figure 1 summarises the ability of a 170GHz system to fulfil its various tasks in the H-mode scenario. It is seen that a 170GHz system will perform very well in the 2.7-3.2T range. Similar calculations, not shown in this paper, demonstrate that 150GHz performs well below 2.8 T while 113GHz is ideally suited for operation above 3.3T. Thus 113GHz/150GHz would be most performant at the maximum JET field. On the other hand such a choice would mean that the system performance around 3T, which will be used extensively in future JET operation, would be very limited. Given these considerations, in conjunction with the added complication associated with dual frequency gyrotrons, the choice was made to base the design on the use of ITER 170GHz gyrotrons. This choice allows the design of a system that almost exclusively uses ITER components with very significant added benefits both for ITER and for JET [10].

2.2. REQUIRED POWER.

For each of the principal aims of the system the required power has been evaluated. For NTM stabilisation the assessment has been made by solving the generalised Rutherford equation [11]. Assuming a beam width of 5cm, the power needed to stabilise the 2,1 NTM has been found to increase from 3 MW to 7MW when the toroidal field is increased from 2.5T to 3.2T, with lower power required for the 3,2 mode. If the beam width is increased to 10cm the required power exceeds 10MW the 2,1 mode at high toroidal fields. It is therefore essential to design the antenna for minimal beam width. If the power can be modulated at 10-20kHz in phase with the NTM, the required power can be significantly reduced especially when the beam width is large in comparison with the NTM island size. It would therefore be desirable to use power supplies allowing such modulation. For

Sawtooth control the power required has been assessed using simulations based on the Porcelli model [7]. In order to reduce the sawtooth period by a factor of two in the presence of fast ions, power in the range of 2.5MW has been found to be sufficient. Full simulations using the CRONOS code [12] have found that with 10MW of ECRH power the electron and ion temperatures can be equilibrated, even in the presence of 35MW of NBI heating power. By reducing the total NBI power and by using JET's ICRH system, together with 10MW of ECRH, dominant electron heating can be achieved with powers of 20-30MW. Further CRONOS calculations have shown that 10 MW of ECRH is sufficient to reverse the q-profile locally around mid radius, with a very flat q-profile inside the ECRH deposition radius. From these calculations it is concluded that a 10MW ECRH system will fulfil all the principal goals set out at the start of the feasibility study. As especially current profile control and central heating experiments would benefit from more power, the feasibility of upgrading to higher powers at a later stage is being considered.

3. SYSTEM DESIGN

Based on, and in parallel with, the physics studies, work is progressing towards a conceptual system design. Firstly the difficult problem of how to physically integrate such a substantial system into the already very busy JET environment has been addressed. Given the power level it was found that an entire main horizontal port would be required to house the ECRH antenna. Having considered each of the 8 JET main ports the decision was taken to propose to replace the ITER like ICRH antenna with the ECRH antenna. This choice was considered as the one having the least impact on JET operation given that the ICRH antenna in question is not operational at present. Given the size of a 10 MW plant it was concluded after thorough investigations that a new plant building would be required. Figure 2 shows the proposed building location together with transmission line routing and antenna location.

3.1. PLANT.

The plant design is based on using the ITER gyrotrons being developed by GYCOM and the Institute of Applied Physics in Nizhniy Novgorod, Russia [13,14]. These gyrotrons have produced 1MW of power for hundreds of seconds which, given the JET 20 second pulse length requirement, is more than adequate. To reliably inject 10MW of ECRH power into the JET plasma 12 1MW gyrotrons will be required. The gyrotron magnetic field of the order of 7T is produced by superconducting cryo-magnets. As the existing JET cryo plant is unable to produce sufficient liquid helium for 12 magnets it has been decided that purchasing 'cryogen free' magnets, which have recently become commercially available, is the most convenient and economic solution. To avoid interference between the fields from adjacent magnets, which can lead to gyrotron collector damage, a minimum inter gyrotron distance of 4.5m has to be observed. In addition to the gyrotrons, the plant building has to house the part of the high voltage power supply equipment which must be installed near the gyrotrons and the rather bulky gyrotron cooling plant [15].

3.2. POWER SUPPLIES.

The GYCOM Gyrotrons considered are diode type depressed collector gyrotrons, which by slowing the electron beam down in a retarding field after the interaction cavity recovers a significant part of the beam energy increasing the gyrotron efficiency to well in excess of 50%. To run these gyrotrons a main power supply rated at −65kV, 50A and a body supply rated at 30kV, 50mA are required. Following the upgrade of the JET NBI system, 4 old power supplies have become redundant and could be used for the ECRH system [16]. Dividing each old NBI supply into 2 independent (80kV, 60 A) units and changing the polarity, allows these supplies to feed 8 gyrotrons. The voltage from the old NBI power supplies is regulated by a tetrode regulator enabling fast modulation up to 15-20kHz. If the old NBI supplies are used it will be necessary to purchase 4 new solid state power supplies to feed the last 4 gyrotrons. The modulation capability of the new power supplies is likely to be limited to a few kHz. If the existing power supplies are not re-used, 12 new power supplies need to be bought. Though this is a simpler solution, it is significantly more expensive and it strongly limits the modulation capability. The proposed power supply choice is therefore to feed 8 gyrotrons from the modified NBI power supplies and to purchase 4 new power supplies to feed the remaining gyrotrons.

3.3. TRANSMISSION.

As quasi-optical transmission lines are incompatible with the JET environment it is proposed, as for ITER, to use evacuated waveguides for transmitting the power to the antenna [17]. Given the frequency choice this means that ITER components can be used for the entire transmission line. As transmission line cost and power loss is dominated by the number of mitre bends, substantial efforts were made to minimise the number of such bends and a solution using only six mitre bends per line has been found as illustrated in figure 2. A thorough assessment has concluded that installing a single window in each waveguide near the torus is sufficient for tritium containment. The window should be as proposed in the ITER ECRH torus diamond window design [18]. To reduce the risk of contaminating the line with tritium in the case where this window is damaged, a valve, permitting the window to be removed without breaking the JET vacuum, is required. Another valve situated near the torus hall wall will isolate the torus hall from the rest of the world when the line in the torus hall is disconnected as will be required for certain JET shutdown activities.

3.4. ANTENNA.

In designing the antenna, high priority was given to the use of the ITER upper launcher steering mechanism thereby significantly reducing the required design work while providing a valuable operational test for ITER [19]. As a maximum of two such steering mechanisms can be mounted inside a single JET port an antenna consisting of two modules, each launching the power from 6 gyrotrons into the plasma, has been designed. The beam tracing calculations described earlier showed that, to fulfil the system aims, the toroidal injection angle range should cover −25° to + 25° while the poloidal range should be sufficient to move the absorption region from the plasma centre to

$\rho = 0.8$ for all toroidal injection angles. Though priority should be given to co-current drive, the ability to drive counter current is desirable for current profile tailoring and to experimentally decouple the effects of current drive and heating. To control NTMs and sawteeth the poloidal angle must be controllable in real time while the toroidal injection angle only needs to be changed between shots. The ITER steering mechanism should therefore be used for real time poloidal injection angle control while a simpler mechanism can be used to vary the toroidal injection angle between shots.

Figure 3 shows the proposed antenna design with the ITER steering mechanism located at the back of the port where more space is available [20]. Only the upper half of the antenna is shown, the lower half being the mirror image of the upper half. The antenna relies on the propagation of Gaussian beams emitted by waveguides terminated at the port back plate. From the waveguides the beams diverge until they encounter fixed focusing mirrors which direct the beams, in groups of 6, onto a plane poloidal steering mirror mounted on the ITER steering mechanism. Rotating this mirror around a horizontal axis allows control of the poloidal injection angle. After the poloidal steering mirror, the beams encounter the toroidal steering mirror; a large vertical mirror that can be rotated around a vertical axis for toroidal injection angle control. For co-current drive the beams are injected directly from the toroidal steering mirror. By rotating the toroidal steering mirror beyond the point corresponding to the maximum positive toroidal injection angle the beams will be reflected by the final vertical mirror allowing counter-current injection. With this arrangement the full required range of injection angles can be reached. Having the steering mirrors at the back of the port has the added advantage of reducing the electromagnetic forces on these mirrors during plasma disruption. The waveguides will be terminated in tapers to improve the purity of the emitted Gaussian beams. Tapers and focusing mirrors are designed to minimise the beam size in the plasma. The design of a mechanical port plug structure to support the antenna mirrors, a preliminary version of which is shown in figure 4, has started and computations assessing the structural integrity of this design are proceeding.

4. COST AND PLANNING

Detailed planning shows that the proposed system can be built in approximately 5 years, using 114 man-years. To be able to install the antenna prior to the start of JET tritium operation, planned for 2015, efforts aiming at having the detailed antenna design completed by the end of 2011 are continuing. The cost of the system has been estimated to be in the range of 55 Million Euro. This estimate is believed to be fairly accurate as it is largely based on estimates obtained from potential manufacturers. The total price is also in good agreement with the actual cost of similar systems and the cost estimate from the previous JET ECRH design.

CONCLUSIONS

A study to asses the feasibility of installing an ECRH system on JET has concluded that a 10 MW, 170GHz system would significantly improve JET's ability to fulfil its role in preparing ITER operational scenarios. Technical work proceeding in parallel with the physics investigations has resulted in a proposed system design which can be installed in 5 years and which can fulfil all physics requirements.

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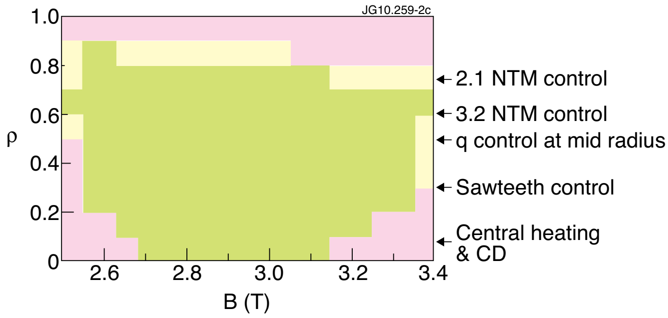

Figure 1: Operation diagram at 170GHz for the H-mode scenario. Green means that the envisaged functions (listed on the right) are possible, red not possible, yellow marginally possible.

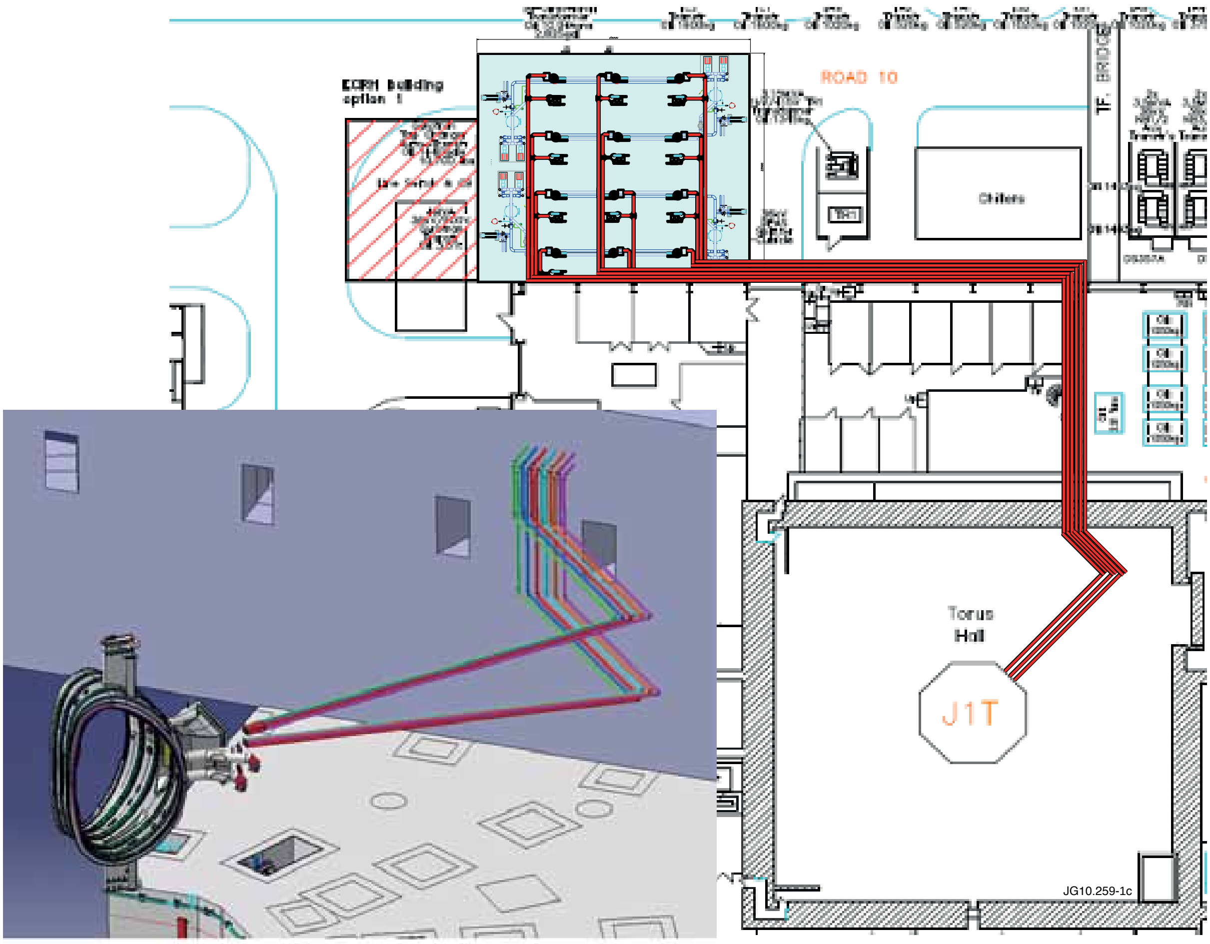

Figure 2: Building, Transmission Line, Port.

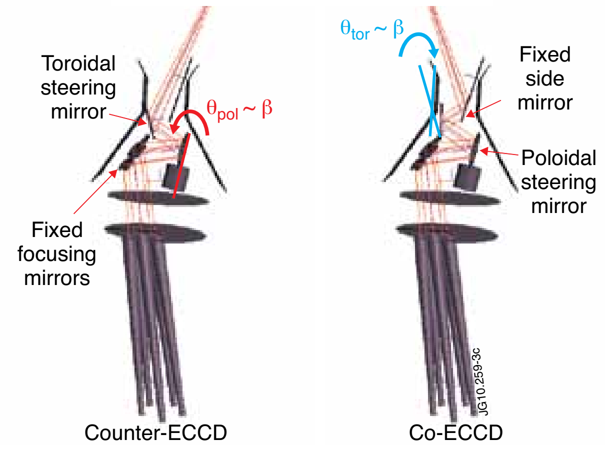

Figure 3: Schematic of the antenna – top view.

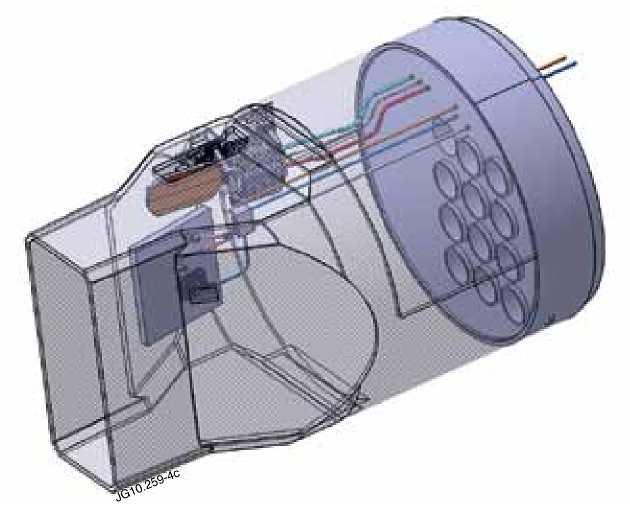

Figure 4: Antenna – mechanical structure.