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ABSTRACT.

An ECRH (Electron Cyclotron Resonance Heating) system has been designed for JET in the framework of the JET Enhanced-Performance project (JET-EP) under the European Fusion Development Agreement (EFDA). Due to financial constraints it has recently been decided not to implement this project. Nevertheless, the design work conducted from April 2000 to January 2002 shows a number of features that can be relevant in preparation of future ECRH systems, e.g., for ITER.

1. INTRODUCTION

The ECRH system was designed to comprise 6 gyrotrons, 1 MW each, in order to deliver 5 MW into the plasma [1]. The main aim was to enable the control of neo-classical tearing modes (NTM). One of the major items was the plug-in launcher, steerable in both toroidal and poloidal angle, and able to handle 8 separate mm-wave beams. Water cooling of all the mirrors was a particularly ITER relevant feature. Another important issue was the power-supply and modulation system, including series IGBT switches, to enable independent control of each gyrotron and all-solid-state body power supplies to enable fast modulations up to 10 kHz.

2. PHYSICS BACKGROUND

The frequency of 113.3 GHz is chosen for reasons of compatibility with the envisaged 170 GHz at ITER. ECRH and ECCD are possible both in the $X2$ (cold resonance at $2T$) and O1 (cold resonance at $4T$) mode. Since JET-EP will probably not operate at $B_t > 3.5T$ for a significant number of pulses, the situation is similar to that envisaged in ITER, where the 170 GHz cold resonance is at $6T$, but the central field is $5.3T$ at maximum. The whole exercise of discussing ECRH physics in JET-EP and the implications for the system design (such as launcher geometry, installed power, modulation frequencies, etc.) can therefore be thought of as prototypical for ITER itself. In order to assess the possibilities for physics studies, a series of reference equilibria is constructed based on existing JET discharges that are scaled by simple physics rules to JET-EP parameters [2]. Then, ray or beam tracing techniques coupled with an absorption model are used to infer the deposited-power and driven-current profile [3].

The modelling uses the exact geometry of the launcher, including the different launching positions of different beams and the Gaussian optics of the focused beams. In addition to central H&CD, the following ECRH specific tasks are discussed:

- NTM stabilisation, where, based on the modelling of successful experiments in ASDEX Upgrade, power and modulation requirements are assessed;
- $j(r)$ control in advanced scenarios, where either central counter-CD or off-axis co-CD are envisaged as a tool to control reversed-shear profiles;
- transport studies using modulated ECRH to infer the electron heat transport without directly heating ions or inputting particles or momentum; and

- exploration of scenario with $T_e \geq T_i$, which will be dominant in ITER under α-heating, but are not accessed in present day low-density, ion-heated discharges.

These applications and their implications on the system design are studied in detail [2]. It is shown that with the envisaged 5 MW in the plasma, many of the above-mentioned goals are achievable and significant contributions to the understanding of reactor-grade plasmas can be expected.

3. THE TRANSMISSION-LINE SYSTEM

The system includes 6 over-moded evacuated, corrugated waveguide lines of 63.5 mm diameter for transmitting the 6 MW (10 s) at 113.3 GHz from the gyrotrons to the launching antenna in the fundamental HE_{11} mode [4]. The lines will be on average 72 m in length and have each 9 miter bends for an estimated transmission efficiency of 91%. The last leg of the waveguide leading to the torus will be designed to accommodate for the torus movement during disruptions and thermal cycles, see Figure 1.

All lines will also be designed to be compatible for 170 GHz operation. Tritium safety aspects have played an important role in the design of the transmission-line system. At JET the safety rules require 2 windows for tritium containment, with vacuum inner space monitoring for leak detection. Furthermore, fast valves will be installed to enhance the safety of the system.

4. THE LAUNCHER

The launcher is designed to inject a maximum of 8 beams, each 1 MW into the JET plasma [5]. It is designed as a plug-in module, in order to minimize the installation time, see Figure 2.

The last mirrors of the system are steerable in order to have the maximum flexibility in the orientation of each beam. Double wall hoses will supply the cooling water. The hoses consist of two coaxial ‘bellows’, each one is reinforced with stainless-steel weaving, see Figure 3.

For the JET-EP-ECRH system, a mm-wave beam from a wave-guide output is launched into the plasma after reflecting on several curved mirrors and a movable flat mirror. The flat mirror reflects two incoming beams into the plasma. The mirror can be moved using two steering rods, whose combined strokes determine the orientation of the mirror surface. The input of the launcher is a waveguide of 63.5 mm in diameter. This corresponds to a beam waist (w_0) of 20.4 mm at the waveguide output.

The main criterion used for assessing the performance of the launcher is the energy density at the resonance plane. See for the beam radius in the optimised set-up Figure 4.

5. THE DOUBLE DISK WINDOW UNIT

In the novel design for the double-disk window unit, direct contact between the coolant and the CVD-diamond disk is avoided [6]. The cooling of the CVD disk is provided indirectly by heat conduction through a copper tube which is brazed directly to the CVD disk, as shown schematically in Figure 5.

Such a design becomes possible with a new brazing technique developed at Thales Electron Devices (TED), France. For reasons of thermo-mechanical stresses during brazing, the thickness of the copper tube must be 1 mm over a length of about 10 mm before it can be increased to a larger value for the enclosure of a cooling channel. A schematic design of such a double disk window unit is shown in Figure 6. The dimensions are in agreement with the requirements of a WG63 transmission line. The thickness d_{disk} of the CVD disks and the distance d_{gap} between the disks determine the microwave transmission characteristic. As is evident from Figure 6, the mechanical design of the double disk window becomes very simple if only one cooling channel on one side of the CVD disk is needed.

An advantage of this design is that there is no direct contact between the CVD disk and the coolant, there is no risk of water (coolant) leakage in case of cracks inside a CVD disk. This practically eliminates the risk of tritium contamination of the coolant. Consequently, it is not necessary anymore to cover the rim of the CVD disk with a copper sheath as was foreseen in the ITER window design with direct cooling of the CVD disk. Further on there is no risk of trapped mm-waves inside the disk. In addition, there are no problems with corrosion. By using a brazing of the copper tube on one side only, the distance between the disks can be made as small as desired. This improves the transmission characteristic and reduces the sensitivity to mechanical tolerances.

6. THE GYROTRON POWER SUPPLIES

The configuration of the gyrotron power supply is described by [7]. The gyrotron is very sensitive to internal arcs. Energy deposition must be limited to as low as 10 J. To limit the energy, fast IGBT switches are connected in series with the gyrotrons. These switches can disconnect the gyrotron from the power supply within a few ms. Such switches based on IGBT technology are already designed and commercial available for moderate repetition rates. The mm-wave output power of the gyrotron can be modulated either by the body voltage or the collector voltage. A disadvantage of modulation by the body power-supply only, is the higher heat load on the collector. For large power modulation, simultaneous modulation of the collector voltage is to be considered. This can be achieved by switching on and off the collector voltage completely by means of the series IGBT switch at the required switching frequency of 10 kHz. A test of such an IGBT switch from the Japanese IDX Company was very successfully executed at the Japan Atomic Energy Research Institute [8]. See test set-up in Figure 7. This switch has been developed under the direction of JAERI and build by IDX. The switch consists of an array of 100 water-cooled IGBTs and is rated for 100 kV DC, 100A continuous. At a voltage level of 70 kV, a 10 kHz square-wave modulation was achieved during a pulse train of 1 ms. The test results are given in Figure 8.

CONCLUSIONS

A conceptual design of an ECRH system for JET was undertaken. A technically feasible design was developed, which could meet the physics objectives. Amongst others, the value of the system for extrapolation to ITER of NTM stabilisation techniques was demonstrated. Unfortunately, due to budgetary constraints, it was decided not to implement the project.

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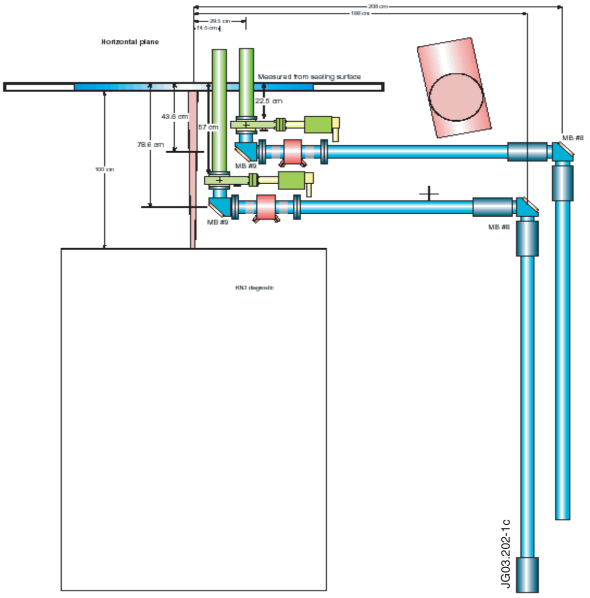

Figure 1: The connection between the evacuated waveguides and the launcher. The double-disk windows and the fast valves can be seen.

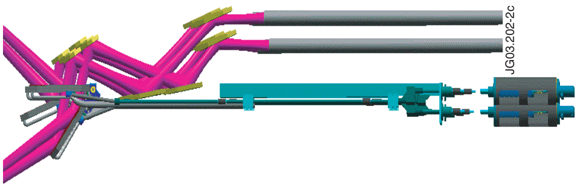

Figure 2: Launcher assembly.

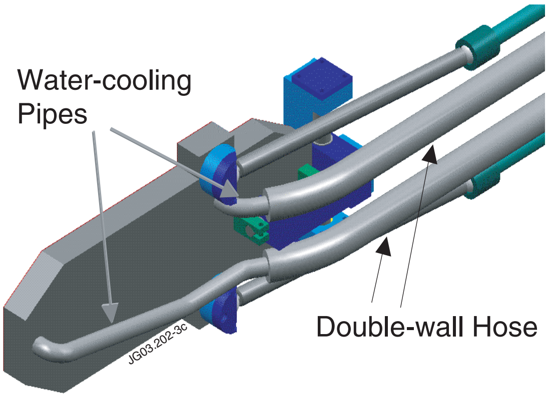

Figure 3: Steerable mirror with water cooling.

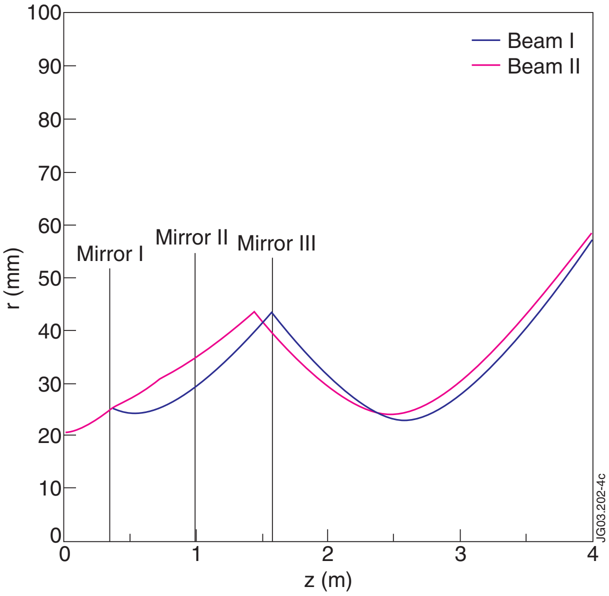

Figure 4: Beam radius (w) as a function of position along the beam lines.

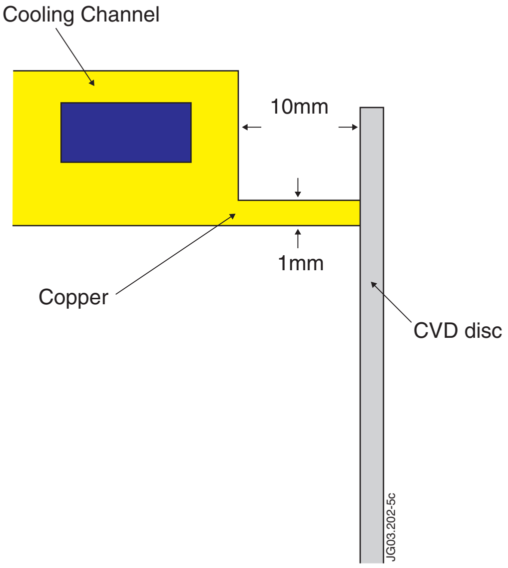

Figure 5: Schematic arrangement of the brazing geometry as performed at TED.

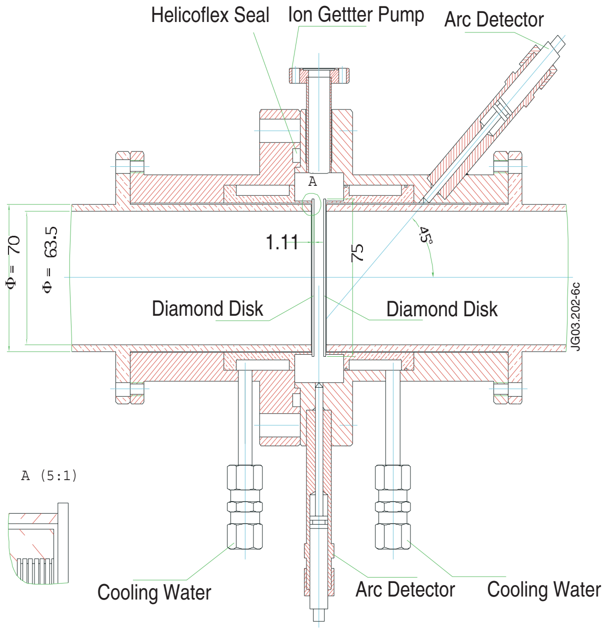

Figure 6: The double disk window unit.

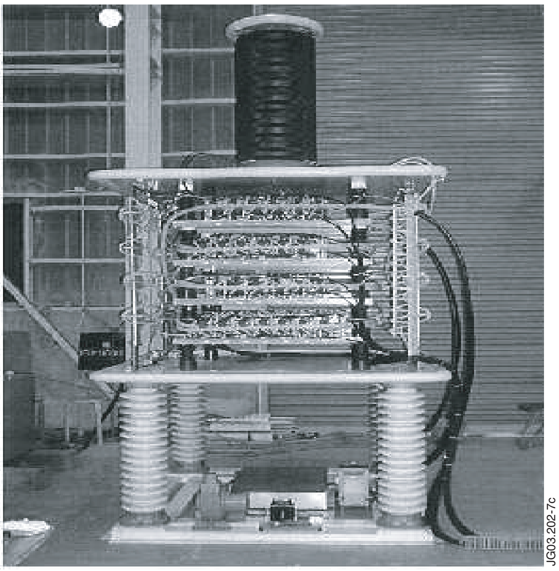

Figure 7: Test-circuit for 10 kHz modulation test.

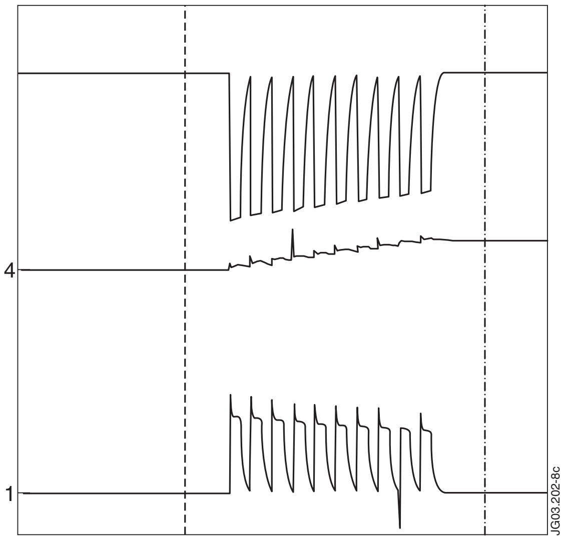

Figure 8: Top – voltage across load resistor with 70 kV amplitude; Bottom – load current with 35 A amplitude.