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A PRELIMINARY ENGINEERING ASSESSMENT OF THE ITER CDA ECH LAUNCHER*

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ABSTRACT

A preliminary engineering study of the ITER electron cyclotron heating (ECH) launcher configuration proposed by the ITER Conceptual Design Activity (CDA) team¹ has been performed to assess its survivability in the ITER nuclear environment. Potential problem areas are with the vacuum windows, the plasma-facing mirrors, and some of the other high-power waveguide components that are untested in a reactor environment. The study indicates that the CDA design is quite robust, since the mirror power density is relatively low and the windows are well shielded. Although the CDA ECH system is unlikely to be built as proposed, most analysis techniques developed to study this system will apply to future ITER ECH system configurations. The vacuum window is likely to be the most difficult launcher component to develop. Design for a proposed resonant ring for high-power testing of windows using existing lower-power gyrotrons is presented.

INTRODUCTION

ECH was proposed for use on ITER primarily as a tool for plasma disruption suppression by locally controlling the plasma current profile near the $q = 2$ surface. A power level of 20 MW at a frequency of 120 GHz is required for this task. Power is generated by 28 gyrotrons with 1-MW cw capability and is transmitted to the tokamak through corrugated waveguide quasi-optical transmission lines. Local current drive at the moving $q = 2$ surface is possible using a fixed-frequency power source by varying the toroidal launch angle with a rotating mirror. To avoid locating a moving mirror in a plasma-facing nuclear environment, the CDA launcher design uses additional oversized mirrors between the moving mirror and the plasma. There has been some criticism of the CDA launcher design due to the large mirror cross-section and the relatively low power density, which violate one of the traditional claims for ECH system capabilities.

The inherent separation between ECH launcher components and the plasma is one of the principal advantages of ECH in a reactor environment. The potential problems that do exist for an ECH launcher on ITER are primarily with the mirrors and windows, as summarized in Table 1.

LAUNCHER MIRRORS

The proposed CDA launcher combines 28 Gaussian beams launched from a 4×7 array of corrugated waveguides that are located >14 m from the plasma edge and around several bends, as shown in Fig. 1. Power is beamed toward the plasma by a series of four mirrors. Mirrors M1 and M4 are ellipsoidal to provide focusing. Mirror M2 is flat and has a $\pm 5^\circ$ rotation capability that is motorized for high-speed remote operation. The 28 beams have arbitrary phasing so that they propagate incoherently through the launcher. Because of adjacent launch locations and beam diffraction, the beams partially overlap at the plasma edge. Gaussian beam analysis through the launcher indicates that an individual beam will expand by a factor of 2.64 from the input waveguide to the plasma edge, where the beam waist is ~ 75 mm. The last mirror, M4, is a large (1860×2660 mm) ellipsoidal-shaped surface. All mirrors require a surface accuracy of <0.1 mm to provide maximum launched beam quality. A potentially significant problem in the ITER launcher is distortion of mirror surfaces caused by non-uniform thermal expansion from non-uniform power deposition and by surface erosion from neutral particle flux. As indicated in Table 1, there are several sources of power deposition on the mirrors, especially in the plasma-facing mirror M4. Calculations show that microwave loss is the largest power flux into the mirror

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Table 1 ITER environmental effects on the ECH launcher components

ITER environmental factor	Launcher component affected	Potential complications
High frequency, high microwave power density, and long pulse operation	Mirrors	High and uneven power deposition; surface distortion
	Windows	Thermal stress from power absorption; complicated window design, possibly cryogenic or distributed
Fast and thermal neutrons	Mirrors	Power deposition; activation; material property degradation
	Windows	Material properties degradation; higher loss tangent; etc.
Plasma radiation	Mirrors	Power deposition
α , β , γ flux	Mirrors Windows	Power deposition Material properties degradation; higher loss tangent
Neutral particle flux	Mirrors	Surface erosion
Radioactive dust	Windows and mirrors	Contamination

surface. A reduction in particle and plasma radiation flux by a factor of ~ 200 is provided by the large distance to the plasma and beam duct shielding. Microwave power deposition ranges from 3 W/cm^2 on M4 to 115 W/cm^2 on the rotating mirror M2. Power non-uniformity occurs as a result of the multiple-beam configuration and beam motion as the launch angle is varied. The non-uniformity problem is solved by providing sufficient coolant flow to maintain

Fig. 1. ITER ECH launcher mirror optics.

uniform temperature across the mirror. A rather large thermal gradient is required to produce a significant change in the mirror focal length in the region of a single beam. A complicated variable temperature cooling system is proposed to maintain the surface temperature above 200°C for optimum vacuum conditions.¹ More detailed thermal stress and beam analyses are desired for the final mirror configuration.

Surface erosion due to sputtering of the last mirror will be caused by energetic neutral particles emitted from the plasma edge. The erosion rate was previously estimated¹ to be relatively small and is likely to be uniform, since the direct particle flux is uniform. Reflector

distortion due to neutron damage is also very small due to the large separation from the plasma.

It appears that the reflectors are not likely to be a significant problem in the CDA launcher design, partly because of the large plasma-to-mirror separation used in the design and partly because of the large mirrors with low power density. The CDA team considered the launcher system (except for the windows) to be a very low maintenance item. Newer launcher configurations with reflecting mirrors located much closer to the plasma will require more work and careful design to avoid difficulty in these areas.

VACUUM WINDOWS

A vacuum barrier window is required to isolate the ITER vacuum chamber from the waveguide transmission and power generation portions of the ECH system. Since the window also serves as a tritium and radioactive particle containment barrier, a reliable, highly robust design is required. In the CDA system, a window and a second back-up window are included in each corrugated waveguide. The design of a reliable window that functions at 120 GHz, 1 MW cw for a HE_{11} Gaussian-like mode is a very difficult problem due to the high dielectric loss and centrally peaked power density. Sapphire, the window material of choice, has a loss tangent of ~ 0.0002 at 120 GHz and 27°C; a single 3.2-mm-thick disk of sapphire will absorb $< 0.1\%$ of the power at 120 GHz in a large waveguide size. Three categories of window design options are available: (1) face-cooled double disk, (2) edge-cooled cryogenic, and (3) distributed. The additional ITER environmental factors described in Table 1 (such as neutron flux) complicate the design by degrading the window material properties. Although the window design for ITER is not yet finalized, it is possible to analyze the effect of the ITER environmental factors on sapphire material to determine the safety factor required in the design.

Neutron flux onto sapphire will cause atomic displacement and ionization of the crystal structure and lead to increased dielectric loss. Gamma flux causes only ionization. Measurements of the alumina loss tangent after irradiation to 10^{20} n/cm² have shown a factor of 2–4 increase after irradiation.¹ Measurements during radiation have not been widely reported at 100 GHz, although recent tests have been performed at 100 MHz on several materials with both neutron and gamma irradiation.² Displacive and ionizing radiation were both found to effect on loss tangent at 100 MHz, and sapphire (which had the lowest loss tangent) actually showed the greatest increase of the materials tested. These tests clearly indicate the need for loss measurements at > 100 GHz under both types of irradiation.

Exact analysis of the neutron flux level that will exist at the window location is extremely difficult; however, an approximate numerical calculation of the flux and energy spectrum at the waveguide apertures was performed.³ The model indicates a reduction in flux from 10^{14} to 10^{10} n/cm² s between the ITER first wall to the window location. The neutron energy spectrum becomes thermalized due to the multiple reflections between the plasma and mirror M1. Additional neutron attenuation is provided by the corrugated waveguide length and bends. Although the waveguide could provide some ducting of lower-energy neutrons, there is attenuation at each reflection. Therefore, there is a flux reduction factor of approximately 10 due to the small window solid angle inside the waveguide and an additional factor of 10 for each miter bend (there are at least two bends per waveguide before the window). These conservative estimates indicate that neutron flux is reduced to $\sim 10^7$ n/cm² s at the window location, which gives a total fluence of $\sim 5 \times 10^{14}$ n/cm² after a full power year of ITER operation. Neutron irradiation does not appear to be a particularly bad problem for windows in the ITER launcher design. Other material properties such as thermal conductivity are also only slightly degraded by the predicted neutron flux levels. Additional measurements of dielectric loss data under irradiation at realistic levels are still necessary. There does appear to be a need to produce a window design with a conservative power safety margin, which implies the need to test to failure. A technique has been proposed that will allow window testing at power levels up to 10 times higher than available power sources. This

technique uses a resonant waveguide ring with a quasi-optical directional coupler, as shown in Fig. 2. This arrangement would allow window designs under development to be tested to

Fig. 2 HIGH POWER RESONANT RING TEST DEVICE

levels of nearly 2 MW with existing 200-kW cw gyrotrons.

ALTERNATE ECH APPLICATIONS ON ITER

There are several uses for ECH on ITER, shown in Table 2. For most applications, the launcher requirements are simpler than in the CDA design. A single system could be designed to provide many of these functions. The use of multiple launchers which are selectable with waveguide switches will provide optimum launch conditions for different applications.

Table 2. Possible applications of ECH on ITER

ECH application	Power level	Launcher requirements
Bulk plasma heating	>20 MW	Perpendicular low field launch
Plasma startup	2-4 MW	Perpendicular low field launch
Transport diagnostic	1 MW	Steerable low field launch
Alpha particle diagnostic	1 MW	Steerable top launch
Vacuum vessel conditioning	5 MW	Arbitrary launch
Edge heating	5 MW	Perpendicular low field launch
Disruption suppression with fixed launch angle	20 MW?	Fixed oblique launch

CONCLUSION

Several potential problems with the ITER CDA ECH launcher caused by the reactor environment have been investigated and found not to be severe because of the large separation between components and plasma. The window design appears to be the most significant problem at this time, and a concept for very high power testing was presented. This study has been useful in pointing out beneficial design features that could be incorporated into new designs.

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