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A conceptual design for the ECH launcher is being developed. The physics for ITER requires that the ECH beam be steerable from 15 deg to 45 deg in the toroidal direction. A system using a rotating final mirror can meet all the requirements. Bearings, linkages, and cooling issues are addressed. An alternate system in which the steering is performed from outside the cryostat and all internal components are stationary also appears feasible.

Introduction

The Design Description Document for ITER calls for 50 MW of electron cyclotron power at a frequency of 170 GHz, upgradeable to 100 MW. This power is intended to heat the plasma from Ohmic temperatures to ignition, in concert with power from some combination of neutral injection and/or ICRF heating. The pulse length is 50 to 100 sec, and the central heating is required to be effective for a toroidal field range of 4.0 to 5.7 . The reference scenario is that the auxiliary heating provide sufficient heating at low density, 3×10^{19} m^{-3}, to access the H–mode and continue heating through an ELMing edge to ignition.

The second major application of ECH power is current drive. In the advanced steady-state scenarios, the total current is 12 to 16 MA, of which 75% is driven by bootstrap effects. The current drive requirement is 2 to 3 MA at a relative minor radius of 0.7, plus a small current near the center of the discharge. ECH power is also used for plasma initiation and startup, using a separate ECH system of two fixed frequencies between 90 to 140 GHz and total power to 6 MW.

Suppression or control of MHD instabilities like neoclassical tearing modes, sawteeth, ELMs, and locked modes are also important objectives for the ECH systems. However, the launching and power characteristics of the ECH for these applications is highly specialized. The ability to modulate at high frequency (at least several tens of kHz), the ability to redirect the beams with precision at relatively high speed, and the requirement that the stabilization be carried out at the same time as the bulk heating and current drive imply that separate and specialized ECH systems are needed for the stabilization activities. For example, for stabilization of neoclassical tearing modes current must be driven inside the islands near the $q = 2$ surface. If this is done near the outboard mid plane, a system with optimized frequency might be much more effective than what could be done with the main 170 GHz system. This paper does not treat the launchers for the stabilization systems.

Physics Requirements

ECH is well adapted to the heating and current drive applications on ITER. Taking advantage of the propagation of the wave in free space, the antennas can be located far from the plasma, which protects the mirrors from direct damage by the plasma, greatly reduces the neutron flux down the waveguides, and reduces the forces and heat fluxes on the mirrors when disruptions occur. The density variations associated with the transition to H–mode and the subsequent ELMs should not much affect the wave propagation. The Greenwald density limit for ITER is about $1.1\times10^{20}\ \mathrm{m}^{-3}$, so even at the nominal operating point of 1.5 times the Greenwald limit the electron density is well below the cutoff density of $3.5\times10^{20}\ \mathrm{m}^{-3}$ for the O–mode at 170 GHz.

Radial control of the location of the deposition is obtained through steering the wave launch in the toroidal direction. The resonance condition for the fundamental mode, $\omega = \Omega_\mathrm{e}/\gamma + k_\| v_{\mathrm{e}\|}$, where the cyclotron frequency $\Omega_\mathrm{e}(R)$ is proportional to $1/R$ and γ is the relativistic mass factor, shows that the resonance can be shifted in space toward the low field side by increasing $k_\|$. The resonance can be moved in this way by a large fraction of the minor radius [1]. However, the shift in minor radius cannot be made too large due to relativistic effects or introducing inadequate wave damping.

Figure 1 shows the current density calculated for the ITER reference scenario. The ray tracing code TORAY was used to generate rays along which the absorption was calculated using the CQL3D Fokker-Planck code with momentum conserving electron collisions. The total injected power is 50 MW at 170 GHz for the calculation, using the idealized case of a single ray launched from the mid plane

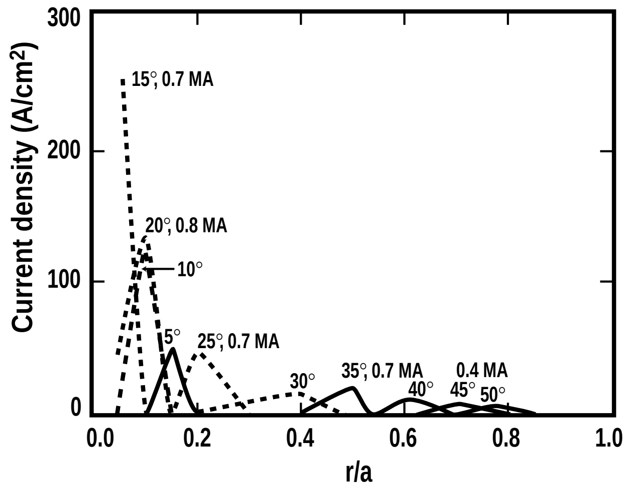

Figure 1. Current density as a function of minor radius, for 50 MW of ECH power. The curves are parameterized by the angle in degrees between the wave normal and the major radius. The plasma current is 21 MA, the toroidal field is 5.7 T, the plasma density is $1.7\times10^{20}\ \mathrm{m}^{-3}$, and the central electron temperature is 30 keV. The density profile is assumed nearly flat and the electron temperature is parabolic. Also shown for some of the curves are the integrated total driven currents.

with no vertical component. For a wave launched 15 degrees from normal, the wave power and current is deposited near the magnetic axis. The total driven current is 0.7 MA, for a current drive figure of merit of 0.19×10^{20} A/W m^2. This figure of merit increases only weakly as the electron temperature is raised above 20 keV. The density, however, scales approximately as the plasma current (for fixed ratio to the Greenwald density), so the advanced steady-state scenarios will have about double the driven current for the same power.

The peak in wave absorption can be moved outward by steering the beam away from normal, as far as r/a=0.8 for a beam 50 degrees from normal. The code results show that there is almost no loss in the driven current out to a normalized minor radius of 0.5. Beyond $r/a = 0.5$, the current drive efficiency decreases, by a factor 2 at $r/a = 0.7$ The time scale required for rotating the beams is approximately the flux diffusion time in ITER, which should be of order 10s of seconds. The same effect that produces off-axis current drive by steering the in poloidal direction can be used to provide nearly central heating over the required range in toroidal magnetic field.

The ECH launcher system is spread over a vertical distance of about 2 m and a horizontal distance of about 1 m. Because the source is so diffuse, there is no advantage to focusing the individual beams.

Engineering Design-Reference System

In the basic design for ITER the ECH mirrors are located more than 80 cm behind the front surface of the first wall, with the power passing through narrow slots in the first wall [2]. Figure 1 shows that the ECH beam must be steered between 15 degrees and 45 degrees from radial in order to meet the physics requirements. This steering can be accomplished by making the first (fixed) mirror reflect the beam directly down and placing a second mirror to reflect the beam in a horizontal plane. The steering is performed by rotating the second mirror about a vertical axis by ±15 deg from a neutral orientation of 30 deg from radial.

The decision was made in this design study to implement the system with moderate modularity. For example, it seems infeasible to provide a steering control system for each of the 56 mirrors independently, due to the great complexity involved. On the other hand, a single steering system for all mirrors is subject to complete failure if any single component fails. We have adopted the concept that each row of 8 launchers should be independent of the others, so that for each of the seven modules the steering controls, coolant feeds, and instrumentation will be independent of the others.

The ECH launching port contains 7 stacked rows of 8 launchers each. In order to obtain the space needed to launch the rays with a toroidal component, the launching mirrors are placed to one side of the port with 10 cm between mirror centerlines. The circular corrugated waveguides of inside diameter 6.0 cm converge in straight lines from the cryostat wall, where the distance between waveguide centerlines is 32 cm to accommodate the windows and support structure.

All components of the launcher structure must be cooled from a neutron heat load of about 1 W/cm^3 at the mirrors. The mirrors have an additional peak heat load of no greater than 350 W/cm^2 due to rf losses (even assuming partial coating of the mirror surface with beryllium), and waveguide walls have an rf loss which is small compared to the neutron heating. The thermal heat load on the mirrors from the plasma is also small, about 0.1 W/cm^2, since they are placed behind narrow slots in the first wall. The coolant is water with an inlet temperature of 150°C, an inlet pressure 4.5 MPa, and outlet pressure of 4 MPa. All reactor components must have active cooling.

Steerable mirror

The surface of the mirrors must be copper or a high copper alloy, in order to minimize rf dissipation. The material behind the mirror surface should have high thermal conductivity to facilitate heat removal from the surface. For this study, we choose Glidcop (an alumina dispersion in copper) for the body of the mirror due to its high electrical and thermal conductivity. Water passages can be formed in the bulk metal, providing highly efficient heat removal. Induced forces on the mirrors due to disruptions are modest [2].

Bearings for the steering mirror are a difficult design issue. Ball or roller bearings have the advantages of low friction and good stability. However, metal balls on metal races have significant potential for self-welding, while ceramic balls on metal races are subject to damage due to shock or vibration, especially if differential thermal expansion loosens or tightens the fit. Cooling the balls is also difficult, since the only contact with the races are point contacts. It is possible that some ceramics may come to a radiative equilibrium, especially if their thermal emissivity can be enhanced with surface treatment.

A better choice may be sleeve type bearings. Sleeve bearings have the advantages of simplicity, greater resistance to vibration, and ease of cooling, but they are higher in friction and backlash. Candidate material combinations are metal on metal, such as stainless steel on beryllium-copper, Nitronic 60 (a surface nitrided stainless steel), or copper-aluminum; metal on ceramic, such as stainless steel on fine-grained alumina or toughened zirconia; or metal on polymer. Metal on metal has high friction and significant (at least non-zero) potential for welding and seizing over the required lifetime of the system. Tests by Trester *et al.* [3] on nitride-surface-hardened 316 stainless steel coupled against like material yielded coefficient of friction values of 0.37 and 0.67 for sliding rates of 7.1×10^{-3} and 7.1×10^{-4} ms^{-1}, respectively (tests conducted at 2.76 MPa contact pressure, 10^{-5}–10^{-6} Torr vacuum, and no lubrication). Metal on ceramic also has high friction and very significant wear and galling issues. The same study by Trester [3] tested an Al_2O_3-15 wt% TiO_3 (METCO 130SF) coating against Nitronic 60 in a vacuum (10^{-5}–10^{-6}), at 6.89 MPa contact pressure, and without lubrication. Sliding tests yielded coefficient of friction values of 0.52 and 0.56 for sliding rates of 7.1×10^{-3} and 7.1×10^{-4} ms^{-1}, respectively.

Metal on polymer is a better choice for a sleeve bearing. It can have relatively low friction, essentially zero probability for seizing, galling or welding, and a high degree of mechanical stability and robustness. Polymers and ceramics also provide electrical insulation, which is very desirable to avoid forces and other problems associated with the flow of electrical currents. Polybenzimidazole (PBI), an unreinforced polyimide alloy (trade name Celazole, produced by Hoechst-Celanese), is a polymer with high mechanical strength and capable of continuous operation at temperatures as high as 500°C in vacuum and stability to 760°C for short periods. Its valuable design characteristics are low coefficient of friction (unlubricated) versus steels (0.24), highest strength of all unreinforced plastics, (tensile strength of 159 MPa, compressive strength of 345 MPa, and flexural modulus of 6.55 GPa), with dimensional stability, high resistance to radiation, and virtually no outgassing in ultra high vacuums. PBI's strength properties generally exceed those of well known polyimides such as Vespel and Moldin by a factor of 2–3. As a sleeve bearing, PBI's coefficient of thermal expansion of 23.4 μm/m·°C is the closest match to 316 LN stainless steel (~16 μm/m·°C) of all unreinforced polymers. Its properties under neutron radiation are not specifically known, but the polyimide class has generally excellent resistance to nradiation damage as well as low absorptivity for millimeter wave power. It also has excellent dielectric strength.

Steering System

The concept for the steering system is that each mirror housing will have an arm which is connected mechanically through a pin-sleeve (PBI) joint to a common tie rod. By pinning each mirror to a common tie rod, accumulation of mechanical error in individual mirror bearings can be avoided. The tie rod is translated laterally to steer the mirrors. Motion of the tie rod is controlled at both ends by pull rods that extend to the outside of the cryostat. Some redundancy comes from the dual pull rods, since pulling on one will cause the other pull rod to retract, verifying motion of the tie rod. Some pushing force can also be applied with the second pull rod, especially if intermittent sliding supports with PBI sleeves are used to eliminate buckling. The tie rod is made of Glidcop for its superior thermal conductivity (365 W/m-K versus 16 for 316 LN stainless steel), and cooling of the rod is by straps of copper alloy braid connected to a stationary water coolant manifold parallel to the tie rod. Alternatively, the tie rod could be made of stainless steel and cooled by a brazed water tube, but the water connections to the tie rod would substantially increase the resistance to motion.

Cooling System

The greatest design cooling challenge for primary cooling is the steering mirrors. The required heat transfer coefficient of 25,000 to 50,000 W/m^{2}K can be achieved with a coolant flow velocity of 5 m/sec, which can be obtained without excessive pressure drop in tubes of diameter 4 to 8 mm. The same cooling requirement applies to all of the mirrors in the waveguide system, but the particular difficulty of the steering mirrors is ducting the coolant to rotating parts. Major concerns are the integrity of the coolant ducts, addition of resistance to turning motion of the mirrors due to the high pressure coolant lines, and fatigue of the attachment points of the coolant tubes with the mirror bodies. Modularity requires use of a single manifold for the inlet and outlet coolant loops for each row of mirrors, with temperature monitoring of each individual mirror circuit. Work is in progress to further define this system.

Engineering Design-Alternate Remote Steering System

Having movable parts inside the vacuum vessel raises many potential issues, including lifetime of bearings, vulnerability of coolant ducts to rupture and fatigue, and maintenance and repair. These concerns motivate a search for steering systems in which all moveable parts can be placed outside the cryostat.

An approach to remote steering is to note that a wave emanating from a waveguide at an angle can be synthesized as a sum of waveguide normal modes at the mouth of the waveguide. Fourier analysis shows that for a given angle only three to five modes of the correct amplitude and phase are needed to generate the desired wave with a high degree of accuracy. The mode numbers, amplitudes, and phases change, of course, as a function of the angle of launch. The problem then becomes one of launching an array of modes at the input of the waveguide in such a way that they match the desired mode set at the output.

If a wave is launched into an overmoded waveguide at the same angle as that desired for the output, the same set of modes will be generated in the waveguide. The waveguide is dispersive, however, so the different modes travel at different phase velocities. To an approximation the beat wavelengths of the relevant modes are commensurate, so picking the right length between the feed and the mouth can nearly reconstruct the desired pattern. Calculated power as a function of output angle is presented in Fig. 2 for the case of 170 GHz power in 6.35 cm square corrugated waveguides for three feed angles, with the feed point 18 m from the

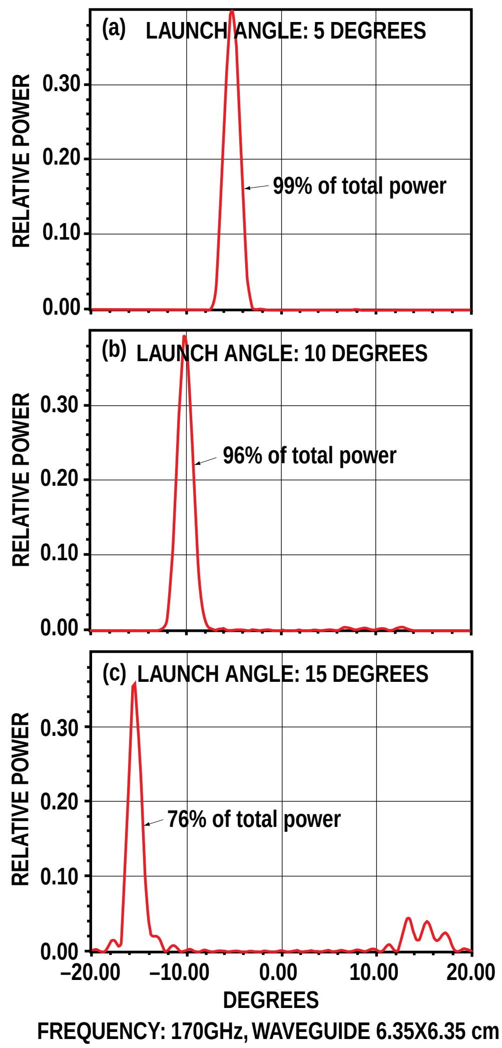

Figure 2. Calculated relative output power as a function of angle of launch to the plasma, using 170 GHz power in 6.35 cm square corrugated waveguide with a waveguide feeder which launches power at (a) 5 deg, (b) 10 deg, and (c) 15 deg from straight.

mouth. Figure 2 shows that small angular spread can be achieved with most of the power in the main lobe for exit angles up to 15 deg. This spread can probably be reduced.

Implementing this concept for ITER can be done using waveguide like that of the calculation in Fig. 2. In order to minimize the range of modes needed for the steering, the waveguide should launch the wave in the horizontal plane with a 30 deg offset, as shown in Fig. 3. This can be accomplished by using a 90 deg miter bend just inside the blanket, where the fixed mirror is located in the reference concept. By tilting the entire waveguide assembly around the axis of the waveguide by 30 deg, the beam exits the mitre bend with a 30 deg tilt from vertical, in the toroidal direction. Then a reflecting plane at the elevation of the slots in the first wall deflects the beam into the plasma. Steering the beam at the mouth of the waveguide via interference of modes then introduces the ±15 deg control of the launch angle.

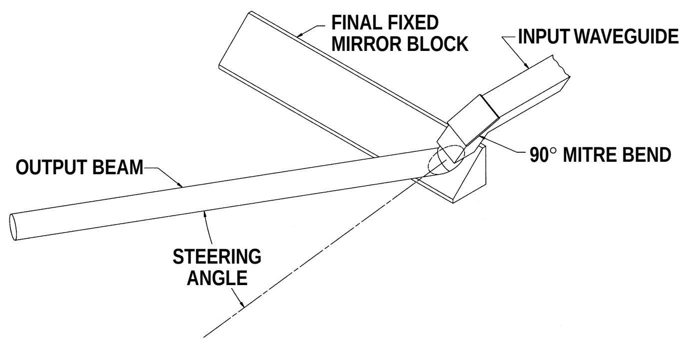

Figure 3. Layout of the remote steering geometry.

Considerable complication is introduced by the non-radial orientation of the feed waveguides. This causes the steered beam to travel radially across the final mirror and the exit angle to vary in the vertical direction. For the most oblique launcher, the average offset is 6 deg. This can be compensated by twisting the final mirror along its axis by about that angle.

This work suggests that a steerable launcher with no moving parts internal to the cryostat is feasible, but more research is required.

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