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CURRENT DRIVE AND HEATING SYSTEMS FOR AN ITER HARD OPTION

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Abstract

A conceptual design has been developed for a reference current drive and heating system for a HARD (High Aspect Ratio Design) option for ITER [1]. Twelve neutral beam modules, each rated at 1.3MeV and 9.2MW, perform plasma heating and current drive. An electron cyclotron system is used for initiating the plasma and for disruption control. An alternate system has been defined which is comprised of a lower hybrid and ion cyclotron system for heating and current drive, augmented by the same electron cyclotron system proposed for the reference system.

Introduction

The U.S. home team has evolved a conceptual design for a HARD option for ITER in an attempt to improve the steady state operational scenario of the ITER device [2]. The general design philosophy was to maintain as much of the CDA (Conceptual Design Activity) design as practical. The most demanding task for the current drive and heating system, as in the CDA ITER design, remains steady state operation, specifically driving the full plasma current [3]. The injected power into the plasma was minimized to minimize the power loading on the divertor. A second consideration was to achieve sufficient plasma internal inductance to ensure plasma stability. An iterative design process was executed wherein machine performance was predicted using the ACCOME code [4], given different system design concepts [5]. In parallel, the conceptual design for the electron cyclotron system developed for the CDA was evaluated, using more sophisticated tools than were available during the CDA, and new requirements were established for the HARD option [6].

Requirements

The requirements, for steady state operation, that affect the design of the current drive and heating systems and which have changed significantly from the CDA are shown in Table I. The total injected power to drive current for the HARD option is about the same as required for the CDA, $P_{TOT} = 110 - 120$ MW compared with 135 MW.

To ensure plasma stability and control, the vertical separation between the centers of the poloidal magnets nearest the equatorial plane has been chosen to be 5m. This allows a port height of 2.3m between the magnets versus 3.4m for the CDA. Also, the vertical spacing between the passive coils in the first wall has been maximized to allow a port height of 2.9m at the first wall versus 3.4m for the CDA. The reduced height of the port disallows stacking 3 neutral beam modules in a vertical array as was done in

the CDA. In addition, the higher internal inductance requirement in HARD (more peaked current profile), versus a broader profile for the CDA, impacts the utility of lower hybrid for the HARD application.

Table I. CDA versus HARD Parameters

	CDA	HARD
Aspect ratio	2.79	4.00
Major radius (m)	6.0	6.33
Minor radius (m)	2.15	1.58
Magnetic field (T)	4.85	7.11
Plasma current (MA)	18.9	11.1
Bootstrap fraction (%)	29	50
Plasma density(10^{20}m^{-3})	0.64	1.12
Plasma temperature (keV)	20	15
Nominal plasma internal inductance	0.65	0.75

Design

As a result of the iterative design process, using the ACCOME code to predict plasma performance as a function of current drive and heating systems, a reference design has been developed. All the current drive is accomplished with neutral beams and bootstrap. Lower hybrid is not used because it is absorbed in the outer 1/3 of the plasma which tends to broaden the current profile, thereby leading to plasma internal inductance below the requirement. Also the HARD option has sufficient volt-seconds that current ramp up assist by LH, required in the CDA, is not required in HARD. It has been determined that 110MW of neutral beam power will drive the required current.

Neutral Beam System

Though the plasma density is higher for the HARD option, which decreases neutral beam penetration, the neutral beam energy is maintained at 1.3MeV to adhere to the design philosophy of making minimum changes to the CDA design. Rather than increase energy, the majority of the beams are aimed inboard of the magnetic axis, which decreases current drive efficiency but improves penetration and the ability to produce a peaked profile. The peaked profile increases the plasma internal inductance which is necessary to achieve plasma stability at the higher aspect ratio in HARD.

A neutral beam power of 110MW is required versus the 75MW required for the CDA. To ensure adequate availability, 12 modules are used versus the 9 employed for the CDA. The modules are rated at 9.2MW nominal and 11.0 MW maximum to allow 2 units to fail, versus 1.5 for the CDA design, and still inject the required neutral beam

power into the plasma. The nominal and maximum rating of a module has been increased by 10%, over the rating used for the CDA, by increasing the number of beamlets from 16 to 18 per module.

Three modules have been configured in a group, two in a vertical array and one nested to the side and between them, to minimize the number of ports required. The arrangement is shown in Fig. 1. The configuration of the three beam modules is constrained by: 1) the allowed port height at the cryostat and first wall, 2) the allowed port width between the toroidal magnets, and 3) the desired aiming radius. The beam centerlines and envelopes in the context of the machine constraints are shown in Figs 2 and 3. The two beams in a vertical array are aimed along a tangent to a radius of 5m. This is the minimum radius for which the beams do not shine directly on the inner wall. The third beam, the center module, is aimed at a radius as small as practical and is set back from the 2 modules in the vertical array to minimize the horizontal separation between the beams at the source. The layout of a beam set for one port in shown in Fig. 4. The port detail is shown in Figs. 5 and 6. The port is tapered at the entrance and exit in both the vertical and horizontal while maintaining a narrow cross section between the toroidal coils to comply with the magnet shielding requirements.

Though a peaked profile is desired, the capability for adjusting the current profile from peaked to flat is required. For the HARD design, current profile control can be accomplished in three ways: 1) by adjusting beam energy, 2) by changing the aiming of the beams in the vertical direction, and 3) by adjusting the relative power between the center beams and the beams in the vertical arrays. The energy of the beams can be adjusted from 1.3MeV, to 0.975MeV or 0.65MeV, which allows the average energy of the combined 12 beams to be adjusted in 3% increments. This affords precise current profile control via beam penetration. The center beams and the lower beamlet arrays of the upper modules and the upper beamlet arrays of the lower modules can be magnetically steered vertically, before the negative ions are neutralized, to aim the beams in the vertical direction. Beam footprints and power density profiles for the case where the beams all cross over at the same point in the port are shown in Figs. 7 and 8.

1. Three module arrangement

2. Beam layout, centerlines

3. Beam layout, envelopes

4. Elevation view of module group on tokamak

5. Plan view of port

6. Elevation view of port

7. Beam footprints

8. Power density profiles at plasma cross section

Electron Cyclotron System

The magnetic field for the HARD option is higher than for the CDA, 7.11T versus 4.85. The higher field requires the electron cyclotron system frequency to increase from 120GHz for the CDA to 175GHz for HARD. The increase in frequency, per se, should not significantly change the design concept developed for the CDA, though the rf source which is assumed to be a 1 MW gyrotron, will be more challenging to develop.

The analytical tools for designing an electron cyclotron system for current drive, which stabilizes tearing modes and provides for disruption control, have been improved since the CDA. The effect of beam divergence has now been included which suggests that the power required is a strong function of beam divergence. A nominal power of 25MW is required for the HARD option if the beam is assumed to have a vertical rms divergence of 0.5° and a horizontal rms divergence of 1° , which is a stringent requirement on divergence. A nominal power of 11MW would be required for a beam with zero divergence.

The CDA electron cyclotron system design used a set of mirrors to collect the outputs from an array of quasi-optic waveguides, each fed by a 1MW gyrotron, and transmit the combined beam into the plasma. The combined beam was injected at an angle of $20^\circ \pm 5^\circ$. The nominal injection angle for HARD is the same, 20° , but due to the lower divergence requirement, the mirror injection system should be reconsidered.

An alternate to sweeping the beam through an angle would be to adjust the frequency. Therefore, a variable frequency rf source should be considered for the HARD option which would eliminate the need for a sweeping mirror in the system. The desired flux surfaces could be accessed with a step frequency adjustment of 1Ghz over range from 173 to 177GHz [6].

Alternate System

An ion cyclotron system is well suited for driving current in the core of the plasma and producing peaked profiles in the HARD option. By adding a lower hybrid system, which preferentially drives current in the edge of the plasma, the current profile can be adjusted by adjusting the current driven by the respective systems. The combined power required for the alternate system is 140MW which is approximately 30% more power than the reference system injects to drive the same current. The design concepts for the ion cyclotron and lower hybrid systems for the HARD option are essentially the same as developed for the CDA.

Conclusion

An acceptable reference design concept has been developed for the HARD option which uses 12 neutral beam modules augmented by an electron cyclotron system. The neutral beam modules have been arranged in groups of three, two in a vertical array and one nested to the side. Four groups are required and thus four ports are required. Since a lower hybrid system is not needed for the HARD option, the two ports allocated for lower hybrid system in the CDA are available. Therefore, the total number of ports required for current drive and heating for the HARD option is five (4 neutral beams, 1 electron cyclotron) versus six (3 neutral beams, 2 lower hybrid and 1 electron cyclotron) for the CDA. Also the neutral beam modules have been configured in sets of three, 2 in a vertical array, which has significantly reduced the overall height of the system from the CDA design.

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