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Abstract

The ICH system is required to deliver at least 20 MW of rf power to the BPX plasma for pulse lengths of up to 15 s over a range of plasma operating conditions (e.g., average plasma densities from 0.5 to $4.5 \times 10^{20} \text{ m}^{-3}$, toroidal fields from 5 to 8 T). The power must be delivered to the plasma over a range of frequencies corresponding to the different operating conditions. On the basis of calculations of the load resistance that the antennas will see because of the presence of the plasma, circuit analysis of the rf system indicates that the present ICH design should easily be able to deliver this amount of power to the plasma. Some research and development (R&D) must be done to provide a reliable system in the BPX radiation environment.

Introduction

ICH has been chosen to heat the BPX plasma to ignition based on the demonstrated capability of high-power cyclotron waves to penetrate to and heat the core of a large, hot plasma (e.g., JET, JT-60, TEXTOR, TFTR),¹ and the ready availability of high-power, long-pulse rf sources in this frequency range. The baseline scenario uses He^3 minority heating in the DT plasma, transferring to second-harmonic tritium (T) heating at high temperature.

The ICH system has two functions on BPX in the burning plasma phase of operation: it must heat the plasma to near ignition conditions, and then it must control the amount of fusion power produced by the plasma by controlling the plasma energy content and associated fusion reactivity. In the earlier phases of BPX operation, the ICH system must provide heating power over a range of plasma densities and density profiles, for operation both at full magnetic field and at reduced field (nominally 2/3 of the peak field), so that a full range of physics experiments can be carried out.

ICH works by injecting high-power rf waves into the plasma; the frequency is chosen so that the injected frequency equals the cyclotron frequency, or a harmonic of the cyclotron frequency, of an ion species in the plasma. Under proper circumstances, the rf waves are strongly absorbed by the ion species at the resonant location and the absorbed power heats the resonant ion species directly. Figure 1 shows the resonant frequencies of different ion species vs magnetic field.

Fig. 1. Operating frequencies vs magnetic field.

If the location of the ion cyclotron resonance is near the center of the plasma, well-localized heating near the plasma center can be

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obtained.²

The ICH system for BPX is designed to work in the two shaded frequency bands shown in the figure. For full-field operation at 8.1 T, the ICH frequency will be near 81 MHz and will heat a small concentration (1-4%) of He^3 (" He^3 minority heating"). The He^3 minority will then transfer its energy to the bulk ions by Coulomb collisions. If tritium is present, second harmonic absorption by that species will become important as the ion temperature increases. For lower-field (~5.5-T) operation, the ICH system will heat He^3 minority or second harmonic T at 55 MHz. In addition, it can heat H minority at 84 MHz at this field as an alternative mode of operation.

The conceptual design of the present ICH system is described, along with the R&D that will be needed to validate the design choices.

System Description

The overall ICH system consists of four antenna arrays (each consisting of four independently driven current straps) mounted in four of the main horizontal ports. The current straps are covered by a Faraday shield, as shown in Fig. 2. The present design uses either carbon-carbon composite for the shield rods, or has carbon-carbon composite tiles attached to Inconel rods (other options are also being considered). Each of the 16 current straps is driven through a tuning and matching network by an rf power unit that can deliver up to 3 MW into a matched load in the 50- to 90- MHz range, with reduced power output at higher frequencies. Each power unit can deliver 2.1 MW into a transmission line with a VSWR of 1.5, which corresponds to mismatches that could be caused by sudden changes in plasma properties. If the plasma loading resistance is high enough, the availability of this amount of power would deliver almost 30 MW to the plasma, well in excess of the minimum 20 MW requirements.

Fig. 2. Perspective view of an ICH antenna, showing the Faraday shield structure that mounts on the vacuum vessel wall, and the current strap and backplane that are inserted through a port.

A block diagram showing the power flow from the AC line to the plasma for one transmitter-transmission line-current strap system is shown in Fig. 3, with the approximate losses in each subsystem. It takes approximately 2.2 MW of AC power per current strap to deliver 1.25 MW to the plasma (20 MW total from all 16 straps) for the lowest values of plasma loading anticipated.

Input **Losses**

Component	Power (MW)	Losses (MW)
AC power	2.20	0.10
Power conversion equip.	2.10	
DC power	2.10	
RF generation equip.	1.35	0.75
RF power	1.35	
Transmission system	1.32	0.03
RF power	1.32	
Antenna system Matching circuit	1.27	0.043
RF power	1.27	
Antenna system Current strap	1.27	0.005
RF power	1.27	
Antenna system Faraday shield	1.25	0.018
RF power	1.25	
Plasma		

Mechanical Design of the Antenna

Figures 4 and 5 show the details of the antenna configuration. The center conductors of the coaxial transmission lines are supported by ceramic insulators/feedthroughs (not shown) in the transmission lines. The transmission lines feed both ends of the 47-cm-long current strap.

The antenna internal components are shielded from the plasma by a Faraday shield. The Faraday shield is constructed of copper-plated Inconel tubes (1.6 cm OD) in a single row. Tiles made of a high-electrical-conductivity graphite composite are mechanically attached to the plasma side of the tubing. The details of the attachment technique

must be developed and validated by testing. The shield is cooled primarily by radiation to the gas-cooled current straps and back plate between machine pulses, and also by conduction through the Faraday shield tubes and support frame to the vacuum vessel, which is also cooled by gas at 350° C.

The Faraday shield module, which includes the side walls of the antenna cavity, is installed through the ICH port (one of the large horizontal midplane ports) by ex-vessel remote maintenance equipment and is mounted by bolts to the vacuum vessel wall using the in-vessel manipulator. The current strap module, with associated transmission line feeds and the backplane of the antenna cavity, is installed in the ICH port from outside the tokamak. Forces induced in the Faraday shield tubes by plasma disruptions are transmitted through the Faraday shield frame to the vacuum vessel by the mounting bolts. Horizontal and vertical forces on the current strap assembly are transmitted to the vacuum vessel port through a sliding keyway. A drive screw mounted on the horizontal port flange will be used to react radial loads into the port.

The entire antenna system is supported by the vacuum vessel and port, which are in turn supported from the TF coil structure. Vacuum bellows, metal seals, and the brazed alumina dielectric in the feedthrough provide the vacuum boundary. A removable fixture is used to insert and withdraw the antenna from the port and to transport it remotely to maintenance areas.

Electrical Design and Analysis

Each current strap is grounded at the center for mechanical support. The ends of each strap are attached to 30- Ω , 6-in.-diam. vacuum coaxial lines. These lines extend beyond the port flange cover and are connected together to form a resonant loop circuit. The schematic of this circuit is shown in Fig. 6. Two vacuum capacitors allow for tuning the resonant frequency of the current strap-transmission line circuit, and also for adjusting the impedance of this circuit so that it appears close to a 50- Ω load to the rf transmission system.

Fig. 6. Schematic diagram of the antenna and the tuning and matching circuit.

The input impedance can be matched to the source impedance by adjusting the capacitors as the load resistance is varied. The resonant loop and variable capacitors restrict the high voltages associated with the unmatched impedances to the region of transmission line that is maintained at high vacuum, where the breakdown voltages are

adequate. Sections of the transmission line that are pressurized are maintained in an approximate impedance-matched condition (VSWR < 1.5). The antenna components within the vacuum envelope are simple and rugged and have no moving parts.

Results of Plasma Load Resistance Calculations

One of the most critical quantities that must be known in calculating the performance of a given ICH antenna is the plasma load resistance. Codes that yield good results for present tokamak experiments have been used to make calculations for BPX.³ The results are summarized here.

The plasma profile is a key factor in the calculation of the load resistance. Figure 7 shows two plasma profile models, with the density profile normalized to the central value. The solid curve is a step function profile, assumed to be an extreme case of the density profile in an H-mode discharge. The dashed curve, representative of a density profile typical of an L-mode discharge, is a square-root parabolic function that goes to 10% of the peak density value at the separatrix (located at $r/a = 1$). Beyond the separatrix, the density is assumed to decay exponentially with a decay length λ .

Fig. 7. Two plasma profiles used in the calculation of theoretical loading resistance, R' .

For the purposes of calculating system performance for a fixed separatrix-Faraday shield separation, the most stringent plasma conditions are a step function in density at the separatrix and no scrape-off plasma. At high density, the resulting plasma loading resistance is low. Figure 8 is a plot of the loading resistance R' in Ω/m calculated as a function of volume-averaged density $\langle n_e \rangle$ for 81 MHz. The solid curve corresponds to the step function profile, while the dashed curves are calculated for the square-root parabola profile with different values of λ . From this figure, it can be seen that the minimum loading resistance in the $0.5 - 4 \times 10^{20} \text{ m}^{-3}$ density range at 81 MHz is 8.3 ohms/m. This is the design value that will be used in subsequent calculations for the currents and voltages that will exist in the antennas.

Results of Electrical Circuit Analysis

The antenna and tuning circuit have been analyzed with a coupled lossy transmission line model to determine voltages, currents, and losses in the antenna structure. Table I gives results of the calculation for 81 MHz, $R' = 8.3 \text{ ohms/m}$, and 1.25 MW per strap to the plasma.

Figure 9 shows the rf peak voltage and rms current on the current strap and transmission line close to the antenna for the design frequency of 81 MHz, a total power to the plasma of 20 MW, and the design load of 8.3 Ω/m . The peak voltage is 33 kV and occurs approximately 50 cm down the 30- Ω transmission line. The system

should operate reliably at this voltage level, as it is within the operating voltage range of most tokamak rf heating experiments.

Fig. 8. Loading resistance vs volume-averaged density for three density profiles.

Table I. Calculated Antenna Voltages, Currents, and Losses.

Resonant Loop Characteristic Impedance	30	Ω
Current Strap Characteristic Impedance ^a	46.9	Ω
Current Strap Phase Velocity (v/c) ^a	0.67	
End-Effect Multiplier ^a	0.92	
Max Voltage (resonant circuit)	33	kV
Max rms Current (resonant circuit)	775	A
Max Voltage (current strap)	25	kV
Max rms Current (current strap)	623	A
RF Power Absorbed in Antenna Structure	18	kW/strap
RF Power Absorbed in Resonant Loop	43	kW/strap
Antenna Efficiency	95	%

^a Calculation by P. M. Ryan⁴

Fig. 9. Voltage and current vs distance along the current strap and transmission line.

As the plasma conditions change, the power that can be delivered to the plasma will change also. For a fixed maximum voltage in the transmission line, the power delivered to the plasma increases proportionally with R' , so that for $R' = 13 \Omega/\text{m}$ the system could deliver 30 MW to the plasma. As can be seen from Fig. 8, this value of loading resistance should be obtained for a substantial operating range in the density and profile space of the plasma.

At the higher values of plasma loading, the power output to the plasma will be limited by the transmitters. The ICH system is being designed to deliver full power with the transmitters operating into a transmission line with a VSWR of 1.5. This VSWR corresponds to a sudden change in R' by a factor of two. It is typical of the changes that are observed in present-day experiments and those that are calculated for BPX in the case of a sudden change in load resistance due to an L- to H-mode transition (for example). For these conditions, the maximum available power from the power units, based on presently available output tube characteristics, will be approximately 2.1 MW per transmitter, or a total power of 33 MW from the 16 transmitters. For $R' = 13 \Omega/\text{m}$, the power to the plasma will be reduced by losses in the transmission, tuning, and matching system to approximately 28 MW.

Research and Development

Significant R&D is required to develop and validate the Faraday shield concept and to test the capability of the vacuum transmission lines to withstand rf voltages up to 35 kV in the presence of the high neutron flux from the burning fusion plasma. The Faraday shield will be exposed to a plasma environment more severe than any present-day tokamak. Without careful design and analysis, plasma disruptions of the high-current BPX discharge could induce large eddy currents that might cause excessive forces in the Faraday shield structure in the presence of the high BPX toroidal field. In addition, the Faraday shield plasma-facing elements will be exposed to large heat fluxes from the plasma radiated power during normal operation, from plasma disruptions, and from heating by the large rf fields in front of the antenna. The design of the tiles that are mechanically attached to the front of the Faraday shield structure, must be analyzed and tested. Tests of the chosen concept in rf test facilities and in actual tokamak operation must be carried out to demonstrate the effectiveness and reliability of the design.

The 6-in. coaxial transmission line that will go from the current straps to the outside of the vacuum vessel will be evacuated to the ambient torus pressure. Ceramic spacers and vacuum feedthroughs will be required to hold the center conductor of the coax, and must operate in the neutron and gamma radiation flux from a plasma producing 500 MW of fusion power. For insulators located ~0.5 m behind the vacuum vessel wall, the gamma flux will be approximately $4 \times 10^{18}/\text{m}^2\text{-s}$, and the neutron flux will be $\approx 1 \times 10^{18}/\text{m}^2\text{-s}$.⁵ Although the total fluence should not cause significant damage to the ceramics (based on the total number of pulses and the pulse lengths anticipated for BPX), the transient effects during the pulse are largely unknown. Two effects that can occur are a change in the loss tangent of the ceramic during irradiation, thereby causing increased heating by the rf fields in the coax during the pulse, and a decrease in the holdoff voltage during irradiation. Experimental measurements of both effects must be made, and the system designed so that acceptable operation can be obtained.

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