DE89 011579

CONF-8905120--4

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ICRF ANTENNA DESIGNS FOR CIT AND ALCATOR C-MOD*

R. H. Goulding, F. W. Baity, P. L. Goranson, D. J. Hoffman, P. M. Ryan, D. J. Taylor, and J. J. Yugo
Oak Ridge National Laboratory, Oak Ridge, TN 37831-8071

ABSTRACT

An ion cyclotron range of frequencies (ICRF) launcher for the Compact Ignition Tokamak (CIT) has been designed. This launcher incorporates four current straps in a 2 × 2 configuration. The current straps consist of end-fed loops that are grounded in the middle. An antenna similar in geometry, size, and feed configuration to a single strap of the CIT launcher will be built for use on Alcator C-Mod. The design must provide maximum power levels of 4 MW/port for CIT and 2 MW/port for C-Mod, pulse lengths of 5–10 s for CIT and 1 s for C-Mod, and power densities up to 2 kW/cm^2. The design uses a Faraday shield consisting of Inconel rods with mechanically attached graphite tiles; the shield and the current strap are cooled by radiating to a gas-cooled backplane. A feed configuration compatible with the end-fed antenna design has been developed and features tunability in three bands in the range 65–130 MHz. It uses an external resonant loop with integral tuning elements. It has been designed to maximize power handling capabilities, minimize space requirements, and facilitate remote handling.

INTRODUCTION

The initial ICRF system for CIT will provide 25 MW of power to the plasma, utilizing a total of 16 radio frequency (rf) power units feeding 32 current straps in 8 ports. The proposed antenna is an end-fed loop, grounded in the middle, with matching elements in an external resonant loop outside the vacuum boundary. The antennas are of modular, compact construction for installation and removal through the midplane port. Remote maintainability plus the reactor-like operating environment have a major impact on the design of the launcher for this machine. An antenna that is being designed for Alcator C-Mod will have a single strap and will be similar in size, geometry, and feed configuration to a single strap of the CIT launcher.

SYSTEM OVERVIEW

The baseline CIT antenna design consists of four end-fed loop antennas in a single port (101.6 cm × 37.5 cm), which form one module as shown in Figs. 1 and 2. The antenna is tuned and impedance matched with capacitive elements in an external resonant loop outside the vacuum boundary. RF power is provided by 16 modified surplus Fusion Materials Interaction Tests (FMIT) rf transmitter units, with Varian X-2242 tetrodes or an improved equivalent, for an output power of 2 MW per transmitter at 95 MHz.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

LAUNCHER MECHANICAL DESIGN

The antenna system interfaces with the feed line at a constant-impedance vacuum feedthrough with a brazed alumina dielectric separating the pressurized 9-in. transmission line from the evacuated 5-in. antenna feed line. Figures 1 and 2 show the details of the side and top views of the baseline antenna configuration.

Each antenna strap has a center ground, which is securely bolted to the cavity back wall. This ground connection also reacts any disruption loads on the current strap into the wall. The antenna position within the port is adjusted by twin threaded shafts. Vacuum bellows, metal seals, and the brazed alumina dielectric in the feedthrough provide the vacuum boundary.

A remotely actuated flange is used to couple the impedance-matching and transmission line components to the antenna. The impedance-matching assembly for all four straps is disconnected as a unit from the antenna by an automated sequence of operations, and the assembly can then be removed by the overhead crane and remote manipulator.

Disruption forces are reacted into the vacuum vessel through keyways at the top and bottom of the antenna module. Acceleration of the antenna module through a 0.32-cm gap between the keyway and the module has been calculated to cause an impact load a factor of nine times larger than the applied load. Such a force magnification is unmanageable and requires eliminating the gap in the keyway and incorporating elastic materials as shock absorbers to decelerate the antenna. The solution of this design problem will await modeling of the disruption loads.

The Faraday shield is constructed of copper-plated Inconel rods (0.5 in. o.d.) in a staggered double row. Graphite tiles are mechanically attached to the plasma side of the tubing. The shield is cooled by radiation to the cavity back wall which is cooled with nitrogen gas at 200–350^{o} C between shots.

A one dimensional model of the Faraday shield has been used to evaluate the temperature evolution of the graphite tiles and Inconel rods. The model includes a time-dependent heat flux and models cooling by radiation and conduction to the surrounding structure. For an rf power density through the Faraday shield of 1.0 kW/cm^2, 50 W/cm^2 is assumed to be deposited in the Faraday shield for 10 s. Plasma radiation and neutrons deposit 30 W/cm^2 during 4 s of the plasma burn and 150 W/cm^2 during 6 s of field ramp-up where the plasma is limited by the outboard wall. For this case the peak graphite temperature is 1220^{o} C, and the peak Inconel temperature is 667^{o} C. The peak temperature in the Inconel is reached approximately 3.2 s after the end of the shot.

FEED SYSTEM ELECTRICAL DESIGN

The feed system for the CIT antenna has been designed to meet several objectives, including pulse lengths of 10 s, power levels of 1 MW per strap (2 MW for C-Mod), phasing of currents in toroidally adjacent straps at 0^{o} or 180^{o}, and tuning between 65 and 130 MHz. It uses an external resonant loop with integral tuning elements for each current strap, and is a modification of a Princeton design, used for an ICRF antenna now installed on TFTR.

The system, shown schematically in Fig. 3, is band tunable, with three bands approximately 10 MHz wide between 65 and 130 MHz. It can be adjusted to allow for variations in plasma resistive and reactive loading, changes in coupling between straps due to plasma effects, and changes in phasing of toroidally adjacent current straps. The resonant loop is matched to 50 Ω at the feed point, minimizing current and voltage amplitude on the feed lines.

Each poloidally adjacent strap (Fig. 3) is fed through a hybrid power splitter. The splitters are fed by separate transmitters with equal power to each splitter and with the forward voltage phase difference between splitters fixed at either 0^{o} or 180^{o}.

CIRCUIT MODELING

The circuit has been modeled using lossy transmission lines with distributed coupling between lines 1 and 3, and between lines 2 and 4, assumed constant along the line; coupling between other line combinations is ignored. For the results shown, the characteristic impedance of the current straps (neglecting coupling) is assumed to be 60 Ω, and the phase velocity to be 0.82 c. These values are typical of similar antennas that have been built previously, such as the ORNL antenna for TFTR.[1] The resonant loop transmission lines are assumed to have a characteristic impedance of 30 Ω and a phase velocity of 1.0 c.

Figure 4 shows the capacitances required to match to 50 Ω at the tee as a function of frequency for a 180^{o} phasing case. The operating bands are also shown. The center frequencies of these bands can be modified by changing the line lengths between the straps and capacitors. The values of C_3 and C_4 (not shown) correspond to those of C_1 and C_2 for 180^{o} phasing.

Figure 5 shows the sensitivity of the match at the input to tee 1 as the capacitances are varied over a range of ±10% at the same frequency. Capacitors C_3 and C_4 have relatively little effect on the match, which suggests that an iterative technique can be used to tune the antennas in practice. Figure 6 shows contours of constant maximum input power per strap as a function of resistive loading and the feed point α (see Fig. 3) for f = 95 Mhz. For 6-Ω/m loading, the maximum power is approximately 1.8 MW. This calculation assumes a maximum voltage of 50 kV on the resonant lines and maximum rms currents of 1200 A on the resonant lines and 1100 A on the capacitors.

CONCLUSIONS

An ICRF heating system designed for CIT features a Faraday shield with mechanically attached graphite tiles, which is cooled by radiating to a gas-cooled back plane. A tuning and matching system has been developed with a tuning range of 65–130 MHz in three bands that can operate at power levels greater than 1 MW with 6-Ω/m loading.

REFERENCES

1. D. J. Hoffman et al., "Coupling of ICRF Power with the TFTR ORNL Antenna," Bull. Am. Phys. Soc. **33**, 2094 (1988).

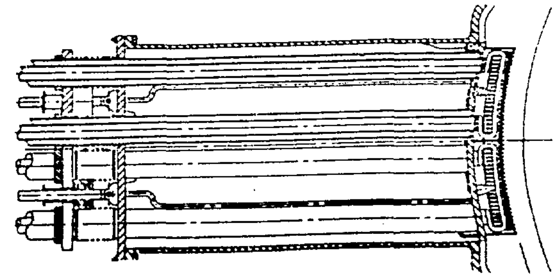

Fig. 1. Cut away side view of the four-strap, end-fed CIT antenna.

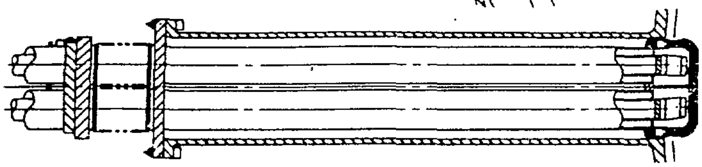

Fig. 2. Cut away top view of the four-strap, end-fed CIT antenna.

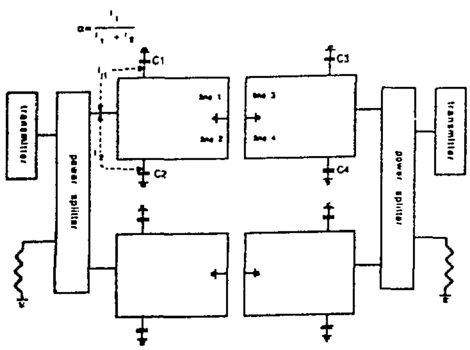

Fig. 3. Schematic of the four-strap array and feed system.

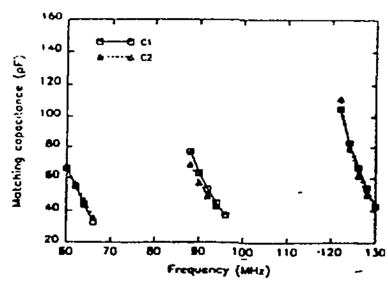

Fig. 4. Capacitances required to match to 50 Ω at the feed point as a function of frequency for 6-Ω/m resistive loading and 180° phasing.

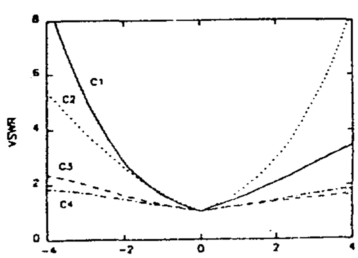

Fig. 5. Sensitivity of the match to changes in tuning capacitance with $f = 95$ MHz, $R_p = 6$ Ω/m.

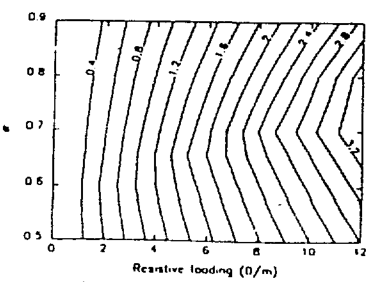

Fig. 6. Maximum input power per strap as a function of loading resistance and the feed point α for $f = 95$ MHz.