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THE ION CYCLOTRON RESONANCE HEATING (ICRH) START UP ANTENNA FOR THE MIRROR FUSION TEST FACILITY (MFTF-B)

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Abstract

The purpose of the ICRH start up antenna on MFTF-B is to heat the plasma and control the ion distribution as the density increases during start up. The antenna, consisting of two center fed half turn loops phased 180^0 apart, has been designed for 1 MW of input power, with a goal of coupling 400 kW into the ions. To vary the heating frequency relative to the local ion cyclotron frequency, the antenna is tunable over a range from 7.5 to 12.5 MHz. The thermal requirements common to low duty cycle ICRH antennas are especially severe for the MFTF-B antenna. The stress requirements are also unique, deriving from the possibility of seismic activity or JxB forces if the magnets unexpectedly quench. Considerable attention has been paid to contact control at high current bolt-up joints, and arranging geometries so as to minimize the possibility of voltage breakdown.

Introduction

The ICRH start-up antenna design for MFTF-B represents an important advance towards the plasma heating technology needed to support commercial fusion applications.[1] In addition to the usual physics performance issues, the experiment requirements encompass engineering design issues such as long pulse thermal effects, neutron activation, and high reliability. The physics basis for the ICRH start-up system on MFTF-B has been reviewed elsewhere, along with a synopsis of relevant analytical tools and supporting experiments.[2] This paper will emphasize the engineering design issues.

The primary mission of the ICRH start up antenna is to heat plasma ions as the density is building up, during which period the density is too low for neutral beam heating to be effective. The antenna must couple 300 kW of power to the ions as the density builds up from 5×10^{11} to $5 \times 10^{12}/cm^3$ in the first 0.5 s of a shot. Anticipating an ion coupling efficiency of 33%, the rf power into the antenna is 1 MW. Power not coupled into the ions heats either electrons or metal surfaces. In order to not fill up potential wells established in the end cells, the ions must be heated in a manner so as to maintain constant collisionality, which is proportional to $n_i T^{-3/2}$. This is done by varying the input power in a predetermined and programmed manner. During the first 0.5 s the density becomes high enough for the 7.5 MW of available beam power to take over the ion heating function.

After neutral beams become the primary method of heating ions in the 25 cm radius core, the ICRH antenna performs a secondary role of heating the 15 cm thick halo plasma. Heating the halo improves energy confinement in the core by reducing the charge exchange loss rate with background neutrals. To meet future requirements of the MFTF-B experiment, the antenna must provide power for up to 30 s. The experiment cycle calls for one shot every 5 minutes. This relatively high average power, along with other unique features of the MFTF-B experiment, drive the design features described below.

The Antenna Concept

An artists rendition of the antenna is shown in Figure 1. An aluminum truss assembly supports the antenna from the bottom of the 4 m radius vacuum vessel. The housing surrounding the radiating elements consists of six copper coated stainless steel segments bolted into a cylindrical geometry. The segments are sized to pass through a 2' x 4.5' access door of the MFTF-B vessel. Two 180^0 half turn loop antennas reside inside the housing, a portion of which is shown in Figure 1. The loops themselves are made of OFHC copper. The current paths on the radiating elements and housing are shown in Figure 2. Power is provided to the center of each half turn loop by a transmission line, which also resides inside the vacuum vessel. The transmission lines transfer power from tuning and matching networks residing outside the vacuum vessel. Both the transmission lines and the tuning and matching networks are discussed in companion papers.[3,4]

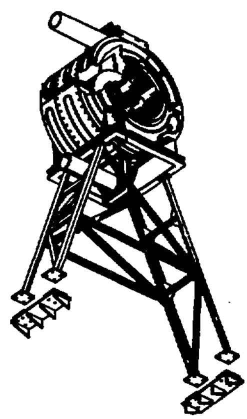

FIGURE 1 THE START-UP ANTENNA DESIGN

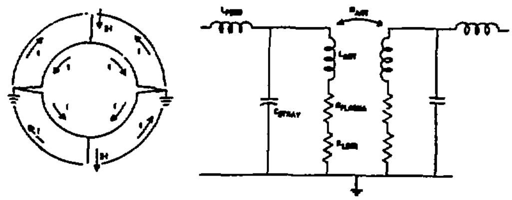

FIGURE 2 SCHEMATIC OF AN EQUIVALENT ELECTRICAL CIRCUIT

Between the radiating elements and the plasma is a Faraday shield comprised of a cylindrical array of 1/2" OD copper coated stainless steel tubes. The geometry is schematically indicated in Figure 3. The ends of each tube are welded into water cooling manifolds, which in turn are bolted to the housing. The cylindrical Faraday shield is divided into four 90^0 segments to facilitate installation. The shield is only intended to electrostatically decouple the radiating element from the plasma, and does not constitute an optically thick barrier.

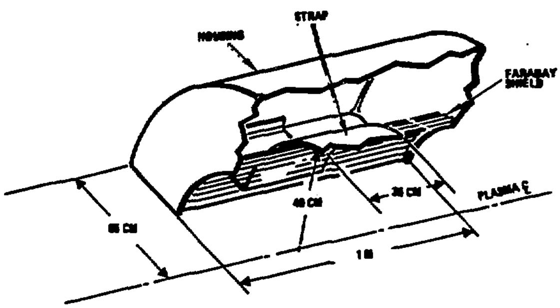

FIGURE 3 DIMENSIONS OF THE START-UP ANTENNA

Electrical Design Issues

Antenna voltages and currents are determined by the power input (500 kW/half loop) and the impedance of antenna and plasma. A circuit model is shown in Figure 2. Electrical stress is reduced by minimizing the reactive impedance, and maximizing plasma resistance. The geometry shown in Figure 3 was selected using computer models of the electromagnetic interaction with the plasma. The impedance seen by a power feed line is shown in Figure 4 over the density range of interest. With this impedance the current into a half turn loop will be 900 amps, and the voltage will be 12 kV. Measurements made on a full scale mock up built to benchmark the computer models in the no plasma case supports these estimates.

The peak voltage stress occurs where the vacuum transmission lines connect to the element feeding power to the loops. The voltage falls off to zero at the point where the loops bolt up to the housing. The propensity for arcing is minimized by arranging surface curvature and voltage stand off distances in a manner that limits the peak fields to 10 kV/cm, which is a factor of five to ten below the break down limit. Limiting the surface finish to 125 microns also helps avoid breakdown.

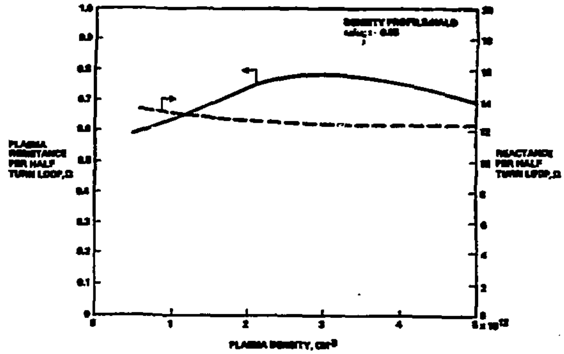

FIGURE 4 ANTENNA IMPEDANCE FOR THE OPTIMIZED GEOMETRY

Special measures have been taken to facilitate control of surface contact at bolt up joints carrying high current. The copper washers shown in Figure 5 provide firm contact at the area around each bolt. This arrangement provides for repeatable contact resistance, and reduces electrical noise. The part of the antenna shown in Figure 5 is where two ends of the half turn loops are bolted to the housing.

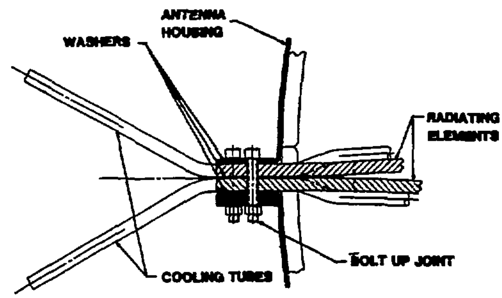

FIGURE 5 COPPER WASHERS CONTROL CONTACT RESISTANCE AT BOLT UP JOINTS

Thermal Design Issues

The heat sources acting on each antenna component are listed in Table 1, along with the magnitude of each source. The scraper referred to in the table is the edge of the Faraday shield manifold that is closest to the plasma. It is referred to as a separate component because the convective heat flux there is particularly high. The cooling requirements are also listed in Table 1. The cooling rate of some components is less than the instantaneous heating rate because the thermal inertia of the structure and the time between shots is utilized. Except for the Faraday shield, cooling of each component is facilitated by welding cooling tubes to the sheet metal structure.

Ohmic heating losses from each component follows from the known currents, skin depth, and component geometry. Calculating losses from the Faraday shield is somewhat complicated because there is both an axial and aximuthal image current around each tube. These image currents have been estimated by estimating the direction and magnitude of the

TABLE I HEATING SOURCES AND COOLING REQUIREMENTS

COMPONENT	HEAT SOURCE, W/cm^2					COOLING REQUIRED W/cm^2
	OHMIC	BACK-GROUND CX	BEAM CX	CONVECTION	RADIATIVE COOLING	
Housing	0.5	1	1	---	-.04	0.2
Loops	0.5	2	---	---	---	0.5
Feed Element	5	---	---	---	---	2.0
Faraday Shield	3	4	---	.01	---	7
Scraper	---	4	1	10	---	15
Support Structure	---	2	1	---	-.001	0

magnetic field.

The background charge exchange heat flux refers to the energetic neutrals eminating from the plasma core as a result of charge exchange with the cold background gas in the vessel. For a background gas pressure of 10^{-6} Torr the heat flux eminating from the plasma surface is estimated at 4 W/cm^2. The heat flux on individual structures follows from the view factor with the plasma surface.

Beam charge exchange refers to the flux of energetic neutrals radiating from the plasma as a result of plasma ions undergoing charge exchange with the neutrals injected for heating purposes. Neutrals are injected at a number of positions along the plasma axis, the closest injection point around the antenna being 1 m away. The heat flux falls off as the square of the distance to the injection point.

Convective heat flux originates from plasma that has diffused radially outward in its journey from a limiter to the antenna scraper. There are two limiters in the MFTF-B experiment, one in each magnetic choke coil. The antenna is 0.5 m from the west choke coil, and 13 m from the east coil. The heat flux quoted in the table refers to that on the east scraper, which is far more significant than that on the west due to the distance over which diffusion can occur. Bohm diffusion is the basis of these estimates.

The outer casing of the super-conducting magnets inside the MFTF-B vessel are at liquid nitrogen temperatures. The magnet geometry relative to the support structure is indicated in Figure 6. Radiative cooling of the antenna to the magnets has a number of implications. First, water in cooling tubes must flow continuously to avoid freezing. Should the lines freeze, weeks of down time would be lost in bringing the vessel to air to warm the lines. A second consequence is that special measures must be taken to avoid thermal displacement of the antenna support structure. The antenna must remain aligned relative to the plasma centerline within 3 mm, implying the support structure must remain near room temperature. Figure 1 shows water lines welded to the support structure to control the temperature. In a more recent scenario the cooling tubes are replaced by multiple layers of aluminum coated kapton

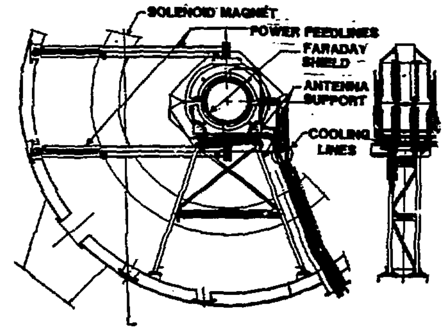

FIGURE 6 INSTALLATION DRAWING OF THE ICRH ANTENNA

which will be wrapped around the support structure to reduce the radiation cooling rate. This approach has been developed and used by TRW in spacecraft applications.

Structural Design Issues

The sources of significant stress and deflection on the antenna components are indicated in Table II. Some components are shell like structures inherently weak to membrane loads produced by gravity. For example, the 200 lb. weight of the vacuum transmission on the antenna housing will permanently deform the housing without additional support. Additional support has been provided using members that distribute the weight to the sides of the housing. The sides of the housing support the weight by reacting in tension and compression.

TABLE II SOURCES OF STRESS AND DEFLECTION

COMPONENT	STRESS SOURCE			
	GRAVITY	SEISMIC	QUENCH	THERMAL
Housing (304 SS)	X		X	
Loops (OFHC Cu)	X		X	
Faraday Shield (304 SS)				
Scraper (304 SS)				X
Support Structure (6061 Al)		X		
Bolts (Grade 5 SS)	X	X		

Seismic loads are an important issue for the MFTF-B systems. The potential for seismic loads affects the support structure design. The support structure has purposely been designed with enough stiffness to keep its resonant frequencies below the peak of the anticipated spectral response function. By avoiding resonance conditions, stress and deflections can be kept within design limits.

The superconducting nature of the magnets introduces the potential for a unique loading contribution on the antenna. If the magnets all quench simultaneously the time rate of magnetic field change will be as large as 20 Gauss/s. Faraday's law dictates an aximuthal current on the antenna loops and housing on the order of a few hundred ampheres will be driven. These currents will interact with the remaining field to produce a radially outward pondromotive pressure force. Although the pressure will be less than 1 psi, the stress produced in structures with cantilever supports can be significant. The point where the antenna loops bolt to the housing shown in Figure 5 is an example. The thickness of such components is chosen to mitigate quench induced stress.

Sputtering

Material erosion due to sputtering can be a life limiting factor. There are three sources of particles that can sputter material from the antenna. Two arise as a result of charge exchange with the background gas. High energy (15 keV) neutrals are generated by the plasma core, which produces a flux of $2 \times 10^{15}/cm^2/s$ at the 45 cm radius plasma. A low energy current (20 eV) is generated by the cooler halo plasma, producing a flux of $1.5 \times 10^{17}/cm^2/s$. Taking the energy dependence of the sputtering yield into account, the erosion rate from the high energy component is 2 µm/yr, and an order of magnitude larger for the low energy component.

The third source of sputtering particles is from radially diffusing halo ions. These ions are intercepted by the Faraday shield scraper. The flux due to Bohm diffusion is $9 \times 10^{17}/cm^2/s$. The halo ions increase in energy from 20 eV to 80 eV as they accelerate through the sheath potential to the scraper, which increases the sputtering yield by an order of magnitude. The sputtering rate is 0.3 mm/yr, which limits the lifetime of a 1/2" thick scraper plate to 10 yrs.

Activation

An important requirement is that neutron activation shall result in personnel exposures less than 10 mrad/week. This constraint was met by calculating the limitations imposed by the constituent materials. For massive structures the maximum allowable isotope density is calculated assuming the structure is an infinite half space. This is a conservative estimate because the antenna components are not really massive. The limitations imposed by localized sources are indicated by calculating the size of a sphere that produces the limiting dose at its surface. Applying these two limiting cases, each component has been designed to satisfy the exposure constraints. One effect of this constraint is that the amount of silver braze material is restricted.

Availability

An important factor affecting the antenna design is that the availability must be greater than 0.997. Availability is defined here as the mean time between failure divided by the mean time between failure plus the mean time to repair. Given that the mean time to repair is 670 hours due to the time required to cycle the superconducting magnets, the mean time between failures must be less than 2×10^5 hours. This requirement led to selection of orbital welding techniques wherever possible at vacuum interfaces. Table III summarizes the availability analysis of the antenna.

TABLE III AVAILABILITY ASSESSMENT

COMPONENT	NUMBER	FAILURE RATE (Per Item*)	MTTR (Hr)	AVAILABILITY
Strap, Housing Cooling: Brazes	30	0.1	672	.9980
Faraday Shield:				
Stainless Tube Welds	216	0.001	672	.99986
Other Welds	905*	0.0004/in	672	.99976
In-Vessel Welds	15	0.01	672	.99990
Thermostats**	4	2	672	.99989
TOTAL		3.7	672	.9974

* Per 10**6 Hours

**Each Thermostat Has A Redundant Backup

Summary

The start-up antenna design for MFTF-B meets the requirements of the experiment. Particular attention has been paid to meeting the unique engineering design requirements that arise due to long pulse operation and the use of superconducting magnets. The experience attained in addressing these issues on MFTF-B will aid in addressing these issues on future generation devices.

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