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ION CYCLOTRON RESONANT HEATING (ICRH) 2 X 170° LOOP ANTENNA FOR THE TANDEM MIRROR EXPERIMENT UPGRADE (TMX-U)

C. A. Brooksby
S. W. Ferguson
A. W. Molvik
J. Barter

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ION CYCLOTRON RESONANT HEATING 2 X 170° LOOP ANTENNA FOR THE TANDEM MIRROR EXPERIMENT-UPGRADE*

C. A. Brooksby, S. W. Ferguson, A. W. Molvik, J. Barter**
Lawrence Livermore National Laboratory
P.O. 5511, L-540
Livermore, CA 94550

Abstract

This paper reviews the mechanical design and improvements that have taken place on the loop type ion cyclotron resonance heating (ICRH) antennas that are located in the center cell region of the Tandem Mirror Experiment-Upgrade (TMX-U).

The west ICRH loop antenna consists of two kidney shaped antennae that each subtend an arc of approximately 170 degrees around the plasma. Each kidney shaped element consists of three turns. This antenna mounts to the capacitor matching network that was built by McDonnell Douglas and replaces the original 90-degree loop antenna. The antenna is surrounded by a grounded copper box on all sides with a cylindrical Faraday shield between the antenna and the plasma. An opaque Faraday shield and a 50% transparent shield have been designed and used. Two different electrical hook-ups have been used. One is a balanced mode with a virtual ground near the center, and the other is grounded in the middle.

A computer code (JASON) was used to design getter-shielded antenna supports that will hold off very high voltages (83 kV, DC) over a small insulator distance (2.25 inches) in a vacuum of 10^{-5} Torr. We also added corona shields on the ceramic-to-metal joints of the matching network capacitors. The system now operates reliably with peak radio frequency (RF) voltages of 40 kV at 2-to-4-MHz frequency and power levels up to 200 kW.

We have just installed a new loop antenna in the east part of the central cell where the slot antenna was located. This antenna uses two of the slot's internal coax lines and the external matching network. The feedthroughs designed by Lawrence Livermore National Laboratory (LLNL) were replaced with two high-voltage RF feedthroughs designed by Oak Ridge National Laboratory (ORNL).

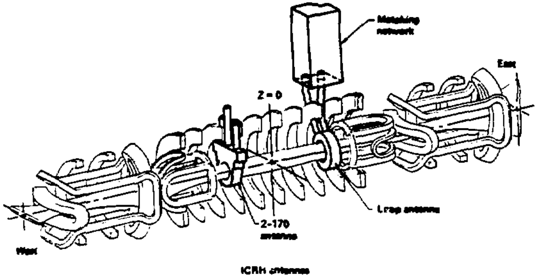
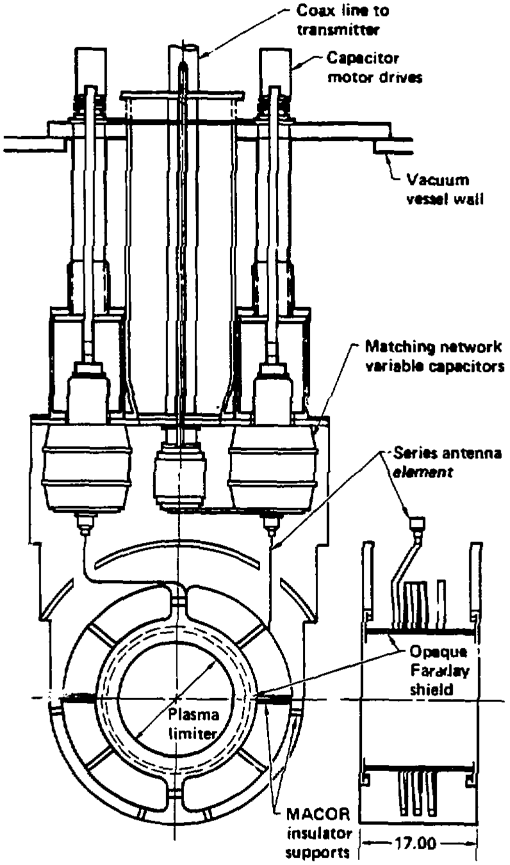


Figure 1.
2 x 170 Degree Antenna Design

This antenna is positioned at the 3.85 kG point in the west central cell region of TMX-U (Fig. 1). The antenna and matching capacitors are inside the vacuum vessel. McDonnell Douglas designed and built the matching network and its support hardware. The initial antenna was one that subtended an arc of 90 degrees about the plasma. This antenna produced unacceptable asymmetries in the plasma as indicated by a reduction in central cell density. It was replaced with two 3-turn loop antennas, which each subtend an arc of 170 degrees around the plasma as discussed in Moore [1] and Molvik [2]. These two loops were connected in series and mounted directly to the capacitors of the matching network. (See Fig. 2 for antenna and matching network assembly.) The first material used for the antenna element was 3/4-inch-OD, 0.065-wall, copper tubing that we flattened and then drilled holes in for vacuum pumpout. Without machining, this configuration gave nice rounded edges for the voltage holding that is required. However, this material proved to be hard to wind onto the kidney-shaped antenna form. Also, the inside of the tube could not



West ICRH 2 × 170° Antenna Assembly

Figu

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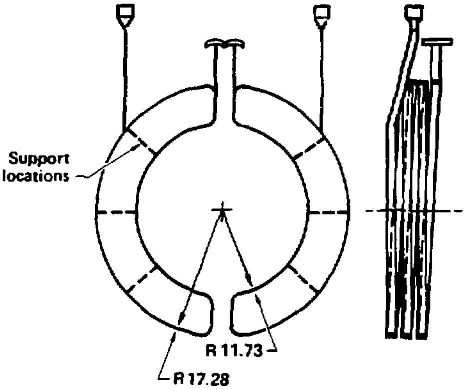
** TRW, Inc., Redondo Beach, CA

be cleaned properly after handling. For these reasons, the second antenna we made was constructed of 1.25- by-0.187-inch copper bar stock. A full radius was machined on each edge for voltage holding and then the material was annealed. This material was easier to wind on the form and, therefore, gave a more accurate antenna configuration. The vacuum problems were also eliminated.

This series antenna was later replaced with the parallel antenna of Fig. 3. Solid copper bar stock (1.25- by-0.187-inch cross section) was also used with this antenna. The connections in the middle were bolted to the grounded box structure. The copper strap plate from the small capacitor in Fig. 2 was also connected to both of the large capacitors instead of to just the one. The new cupped supports were used to support this antenna.

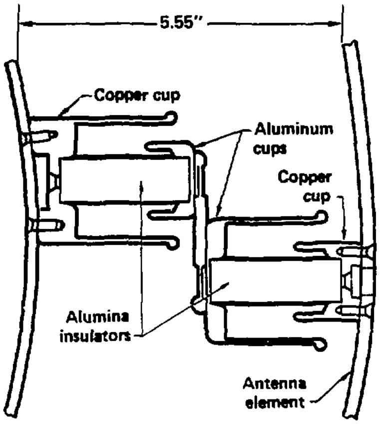


2 × 170° **Parallel Antenna Element**
Figure 3.

Insulator Cup Design

The 2 x 170 degree antenna was first supported between turns, and away from the grounded box, by MACOR (machinable ceramic) insulators (Fig. 2). This material was chosen because of its ease of machining to odd shapes, the ability to tap directly into it for mounting, and its good vacuum outgassing characteristics for an insulator that can hold off high voltages. The RF voltages expected on the antenna were from 20 to 40 kV. With a design voltage-holding capability of 10 kV/inch along an insulator surface, and the short spacings involved, it seemed necessary to span the gaps with only an insulator material. However, the MACOR was not able to withstand the forces of assembly and installation in the antenna box. It would chip at the edges and break at the tapped holes where it was attached to the antenna turns. These sharp and ragged edges could then develop high voltage stresses during operation and initiate breakdown.

Because of the problems with the MACOR it became apparent that the antenna supports needed a new design. The double insulator and cup design of Figs. 4 and 5 was developed to reliably hold off higher voltages. This configuration was also chosen because the decision was made to go to the open (transparent) Faraday shield discussed later in this paper. This configuration required that the insulators be shielded from the titanium gettering. The other design criteria were: a) the breakdown, if it occurred, should be from metal to metal across a vacuum gap and removed from the insulator, thus reducing the problem of carbon arc tracking on the insulator, b) the electric field potential should be distributed along the insulator surface as uniformly as possible, c) the high electric fields at the ceramic-to-metal interface should be avoided, d) the strength-to-weight ratio of the support system should be maximized, e) the 5.5-inch gap between windings should be maintained, which meant using 2.25-inch-long insulators, and f) the DC hi-pot test should reach twice the maximum RF voltage of 40 kV.



Insulator & Cup High Voltage Antenna Supports

Figure 4.

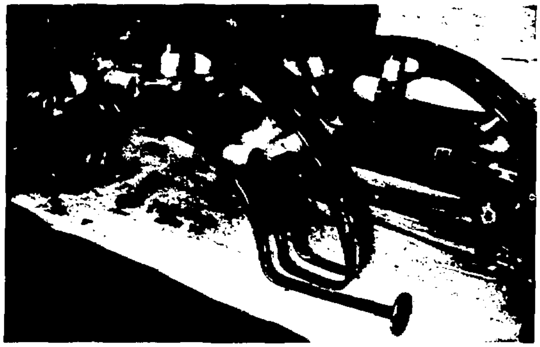


Figure 5.

The JASON computer code was used to model the electric field stresses that might be developed on the configurations chosen and to therefore minimize the iterations on testing of actual parts. James Barter (TRW) did the computer modeling and most of the testing at our facilities. In the first iteration (Fig. 6a), we used standard copper pipe caps with full radii on the edges and a standard 2-inch-long glazed steatite insulator assembled as shown. The model shown, however, uses a 2-inch-long alumina insulator. This was because we knew we wanted to go to a stronger insulator material than the MACOR. Alumina is approximately three times stronger than the steatite, and much stronger than the MACOR. See Table 1 for the test results.

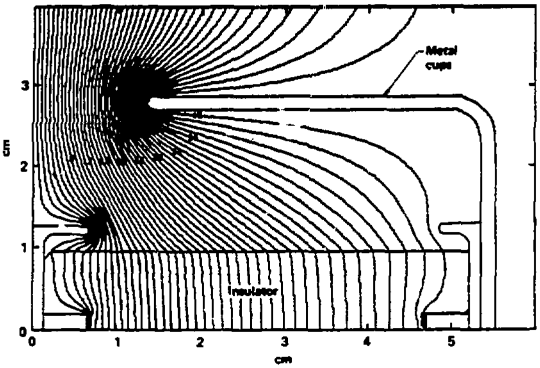


Figure 6a.

For the second iteration (Fig. 6b) the JASON model shown uses a 2-inch alumina insulator. However, the test (see Table 1) was conducted with a glazed 2.0-inch-long steatite insulator. Though the voltage holding in the first test was good, the reasons for going to this configuration were to provide better shielding from the gettering and to distribute the field stresses more uniformly along the insulator.

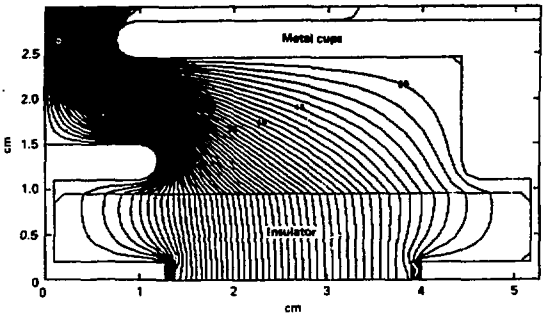


Figure 6b.

For the final iteration (Fig. 6c), the JASON model shown uses the 2.25-inch alumina insulator. The test (see Table 1) also used this 2.25-inch alumina insulator. No arcing was seen on the insulator. The reasons for this configuration were to gain more getter shielding, to gain even better uniformity of the field along the insulator, and especially to remove the breakdown point from the insulator to across the metal gap.

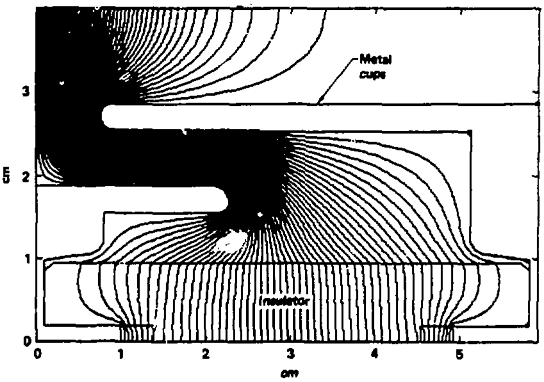


Figure 6c.

The relative dielectric constants that were used in the JASON models were 8.8 for the alumina, 5.77 for the steatite, and 1.0 for vacuum. These values are listed for these materials in the megahertz range. All the test data values listed in Table 1 were taken after several shots of conditioning. The difference seen by switching the polarity during the DC high pot tests was attributed to the electron emitter source, which initiates breakdown, being switched from the small-cup to the large-cup ends. The alumina insulator chosen was 99.4% and unglazed. The reason for choosing an unglazed insulator was to control the secondary emission that is produced by small surface irregularities. The glazed steatite provides smaller irregularities, and the higher dielectric alumina should create higher local fields at surface irregularities than steatite; however, the secondary emission of electrons is apparently less on the alumina since it tested slightly better than the steatite.

Table 1.

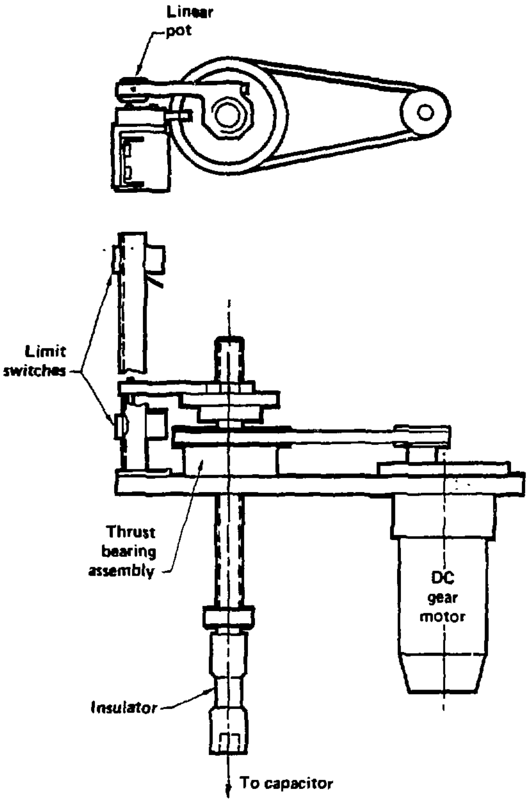
Iteration No.	Polarity (left/right in Fig. 6) +/-	-/+	DC Voltage Holding (kV)	Vacuum Pressure ($x10^{-5}$ Torr)
1 (Fig. 6a)	*		55	0.8
		*	80	2.9
2 (Fig. 6b)	*		70	1.0
		*	61	3.0
3 (Fig. 6c)	*		83	5.1
			85	1.3

Iteration No.	Location of Arcing
1 (Fig. 6a)	At small cup on left and along the insulator.
2 (Fig. 6b)	From large cup to ground with some along insulator.
3 (Fig. 6c)	0.7 cm gap between large and small cups and ground plane.

Capacitor Drive Design

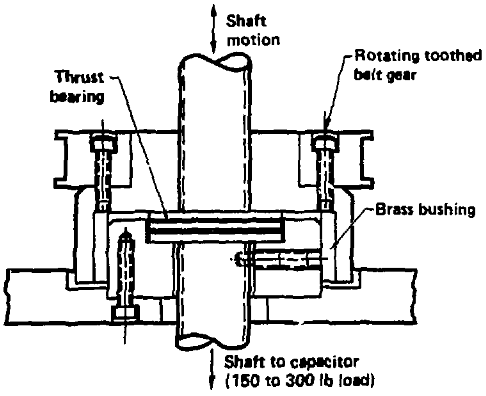
The variable capacitors used in the matching networks of both ICRH systems needed to be remotely variable. Since no standard design existed that we knew of, we designed a simple mechanism that uses basic parts (Fig. 7). All of the five variable capacitors have the same design so that the parts are standardized as much as possible. This simplifies operation, maintenance, and costs.

The system consists of a simple DC gear motor with a toothed belt drive to the capacitor shaft. The shaft is pinned so it will not rotate as the gear turns to raise and lower the shaft. A simple thrust bearing is required to allow the gear to pull against the 150 to 300 pound force produced by the vacuum loaded capacitor shaft (see Fig. 8). A bushing is required, however, to resist the side load produced by the belt drive. This system has worked quite well. The only problems experienced were with the side loading on the bearing assembly and the need for dissimilar metals and good lubrication between the shaft and thrust bearing gear. These problems were eliminated with the design shown in Fig. 8.



Capacitor Remote Control Motor Drive

Figure 7.



Capacitor Drive Thrust Bearing Assembly

Figure 8.

A simple disk attached to the top of the shaft actuates limit switches that are interlocked to control the maximum mechanical travel of the capacitors. An arm is also attached to the top of the shaft and extends to a linear potentiometer that allows the shaft position to be monitored (Fig. 7). This gives a linear correlation between the shaft position and the capacitance.

Corona Rings

One of the major problems with voltage holding experienced on the 2 x 170 degree matching network was arcing on the capacitors. The capacitors are ITT Jennings vacuum type and are located inside the vacuum vessel. The arcing has occurred at the interface between the insulator and the metal braze seal. These capacitors come with elastomer-type corona shields to protect this interface, but these are not vacuum compatible due to outgassing. To solve this problem, we installed copper corona rings as shown in Fig. 9. A good electrical joint is made between the ring and the irregular joint surface with either wire RF gasket or half-moon-shaped fingerstock.

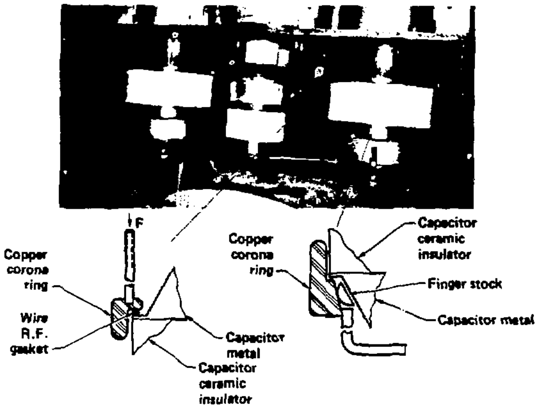


Figure 9.

Faraday Shields

We have used two types of Faraday shields on the 2 x 170 degree antenna. The first (seen in Fig. 2) was an opaque shield constructed of two concentric and slotted copper cylinders. A material thickness of 1/8 inch was chosen, with a spacing between cylinders of 3/8 inch. The slots were 3/16 inch wide on 1.33-inch centers. The slots were staggered to block a line-of-sight through the shield. This shield provides electrostatic shielding and environmental shielding of the antenna and matching network from charge exchange neutrals, uv radiation, and titanium gettering. This shield, however, attenuated the RF magnetic field by a factor of 1.7 and reduced the coupled power to the plasma by a factor of 3 from the maximum possible without a shield [2].

To increase the power to the plasma, a new 50% optically-transparent Faraday shield was made (Fig. 10.) This shield is made of 0.5-inch-OD copper tubing with 0.5-inch spacing between tubes. This shield provides the electrostatic shielding required with little environmental shielding. The power transmitted to the plasma was reduced by less than 10% of the maximum possible. The use of this open shield also required that we use the cupped insulator support design.

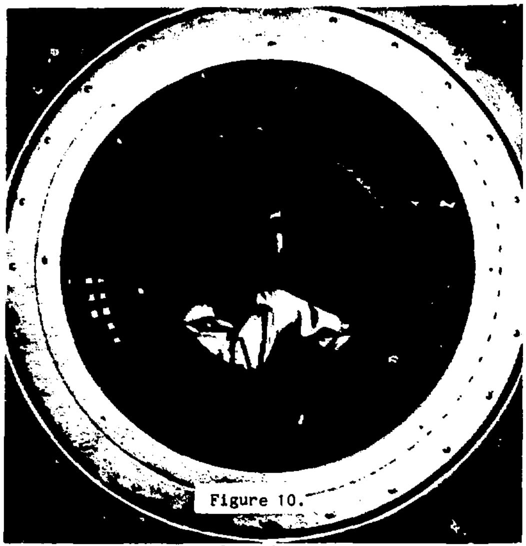
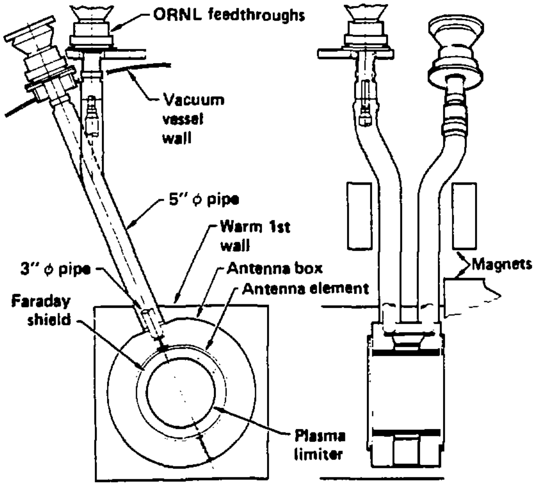


Figure 10.

East Loop Antenna

A new dual half-turn antenna has just been installed on TMX-U. (See Fig. 1 for the location on TMX-U and see Fig. 11 for the assembly.) It replaces the slot-type antenna on the east side of the central cell region and uses two of the 3- and 5-inch coax feedlines. The triaxial feedthroughs used with the slot antenna were replaced with two ORNL 9-inch RF high-voltage feedthroughs. The existing external matching network has also been used. The antenna element itself is a single-turn strap that goes completely around the plasma with a ground strap at the halfway point. The strap is constructed of 0.25-inch thick by 6.0-inch-wide copper bar stock that has had full radii milled on each edge. The loop is 22.25 inches in diameter and is self supporting. A 50% transparent tube-type Faraday shield, like the one on the west antenna, is also used on this antenna. The antenna is enclosed in a 1/16-inch-thick copper sheet metal box.



East IRCH Loop Antenna
Figure 11.

Silver Wire Joints

One of the items developed during the new east loop antenna design was the current joints between the antenna and coax feedlines and between the coax and the feedthroughs. In the design for the slot antenna coax lines these joints had 0.010-inch-thick silver-sheet rings pressed between two 0.065-inch-wide copper surfaces that had diameters of 1.5 to 5.0 inches. Even though the silver is a softer material than copper the forces of compression on these joints were distributed over too much surface area to produce good electrical contact all around the circumference. Slight inaccuracies in machining and joining the parts compounded the problem of getting a good current joint.

For the new antenna configuration, we reduced the contact surface area by using small (0.032 inch and 0.062 inch) diameter wire. This increased the force per square inch on the mating surfaces by approximately six. To reduce the effect of irregularities in the mating surfaces and misalignment, we wanted a "soft" metal. We performed compression tests of three different wire materials to obtain force versus deflection curves to determine the best material to use. The wires chosen were: a) annealed 0.031- and 0.051-inch-diameter copper, b) as drawn 0.032- and 0.062-inch-diameter silver, and c) annealed 0.0320- and 0.062-inch-diameter silver. The compressed lengths were 2.25 inches. It took 1/6 the force to straighten out the kinks in the wire with the annealed silver, as opposed to the annealed copper. After initial kink straightening, all of the types of wire took about 44 pounds per inch of wire length to compress the material 0.0002 inch. The annealed silver wire was, however, approximately 10% softer. As the forces increased above approximately 100 lbs per inch of wire length the annealed silver was almost 50% softer then annealed copper.

Summary

The west ICRH loop antenna has been improved in several ways during the past two years. We have gone from a series-3-turn-antenna element to a parallel configuration. The antenna supports have been improved with the high-voltage insulator and cup design. The remote control drives for the capacitors have been improved to operate reliably. Addition of copper corona rings to the matching capacitors have given improved voltage holding in this area. The new transparent Faraday shield has given increased power to the plasma.

We have recently added a new loop antenna to the east central cell which we hope will increase the RF power to the plasma. These antenna systems are also described in S. W. Ferguson's paper [3].

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