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# Design of the ICRH Antenna for TPX

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## ABSTRACT

A 6-MW ion cyclotron (IC) system for the Tokamak Physics Experiment (TPX) is in the preliminary design phase. In conjunction with the 3-MW Lower Hybrid system and the 8-MW neutral beam system, the IC system will provide heating and current-drive capabilities to explore advanced tokamak physics and long-pulse (1000 s) operation.

The IC launcher consists of six nickel-plated current straps arranged toroidally in pairs behind three water-cooled Faraday shields. The Faraday shields can be independently and remotely detached by cutting water lines at the back of the launcher and removing bolts at the front to free each shield. The antenna can be located at the +2 cm flux line and retracted 10 cm.

Faraday shields are usually copper- or nickel-plated stainless steel or inconel. Titanium is the preferred material to minimize activation without greatly decreasing electrical resistivity and therefore increasing disruption loads. The IC antenna research and development programs have provided data that confirm the feasibility of B<sub>4</sub>C-coated nickel-plated titanium alloy in the TPX environment.

## I. INTRODUCTION OSTI

The ion cyclotron (IC) system is part of an overall heating and current drive system for Tokamak Physics Experiment (TPX) that also includes neutral beam and lower hybrid systems. The IC system is required to provide electron heating and centrally peaked current drive. The first phase of the ion cyclotron resonant heating (ICRH) launcher system operation consists of one six-strap antenna in port G of the TPX vacuum vessel; the system can be upgraded to three antennas in adjacent ports. The most significant advancement at this stage of the design has been in research and development.

## II. DESIGN

The ICRH antenna is designed to bolt to the TPX vacuum vessel port flange forming a vacuum seal. It is sized to fit entirely within the envelope of the port and conform to the space constraints of any other hardware that shares the port. The antenna will be compatible with remote handling hardware for installation and safe removal of the contaminated equipment. Components of the ion cyclotron antenna are the Faraday shield, the current straps, the coaxial transmission lines, the cavity, the vacuum feedthrough, the shield box, and the drive and support system. Fig. 1 shows the antenna configuration.

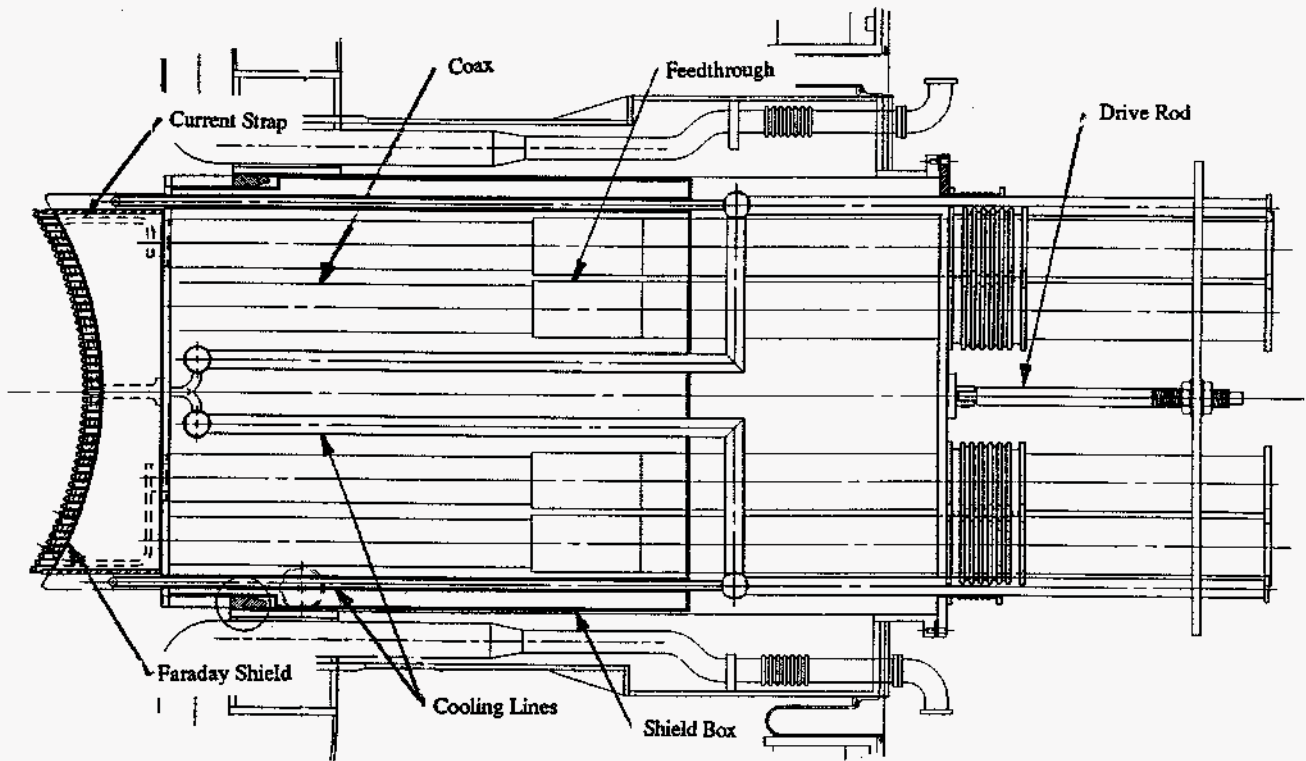


Fig. 1 Elevation of the ICRH antenna on TPX

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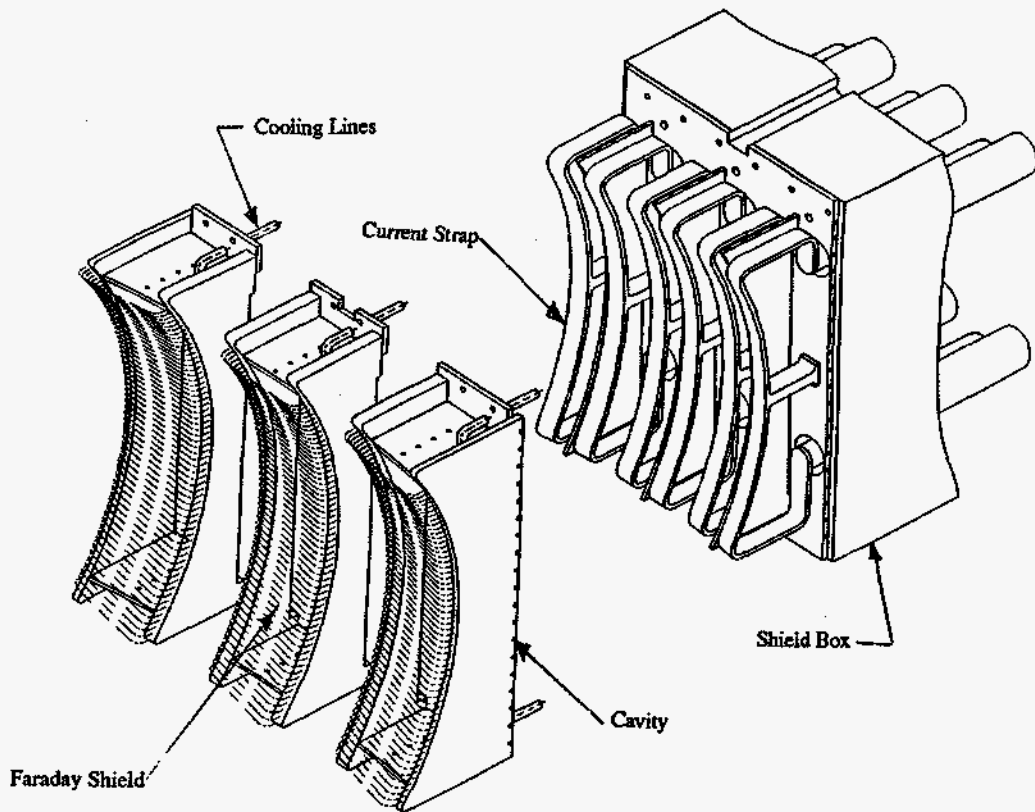


Fig. 2 Removable Faraday shields

#### A. Faraday Shield

Three nickel-plated titanium Faraday shields span each antenna (Fig. 2). Each Faraday shield covers two current straps. Its 47 tubes are single layer, slanted 12 degrees, and approximately 30 percent transparent. The tubes are coated with  $B_4C$ , and tube dimensions are 15.9 mm OD X 12.7 mm (0.625 in. OD X 0.5 in ID.)

Water flow through the tubes is in series with supply and return manifolds in the sides of the cavity. The water headers penetrate the shield box through a sleeve. Use of the sleeve allows the Faraday shield to be removed by cutting the piping behind the shield box and sliding the freed header through and out of the sleeve.

Each Faraday shield can be installed independently by using bolts at the top, bottom, and sides (the center Faraday shield does not have side bolts) and welding the water lines. The Faraday shields can also be removed independently, but they are not interchangeable.

#### B. Current Strap

There are six nickel-plated titanium current straps per antenna in-line toroidally. The current straps in each pair behind a common Faraday shield are slightly closer together than adjacent current straps from different pairs. This placement is

necessary because of the space required in the cavity wall to accommodate the water manifolds. The "C"-shaped current straps are water-cooled via flow passages along the periphery. Each strap is grounded at the center where the water inlet and exit are located and is electrically fed at the ends where the inner conductor of the coax is bolted in place.

#### C. Coaxial Transmission Lines

Five-inch rigid vacuum coax connects each current strap end to a vacuum feedthrough. The center conductor is cooled with water fed through a squirt tube from the water-cooled transmission lines outside the vacuum vessel. The outer conductor is welded to the cavity back plate. Cooling for the outer conductor is provided by a low vapor pressure coolant (Dowtherm) surrounding the coaxes inside the shield box. Neutronics calculations show that the two right-angle bends in the coax assumed necessary to prevent excessive neutron streaming from the plasma to the exterior of the tokamak are in fact unneeded, and the straight coax simplifies welding. The coax extends through a bellows at the port flange. The bellows allows radial adjustment of the antenna assembly and forms the vacuum interface between the port cover and the coax.

#### D. Cavity

The cavity is composed of the cavity back plate with the three septa bolted on. Cavity walls are part of the Faraday shields.

The cavity back plate is the front plate of the shield box. Current strap water lines penetrate the cavity back plate and are welded onto headers on the other side.

#### *E. Vacuum Feedthrough*

The vacuum feedthrough separates the 6-inch ID pressurized transmission line input coax from the evacuated 5-inch ID antenna coax. The separation is achieved by a brazed alumina dielectric. The inner conductor component of the feedthrough provides passage of the inner conductor cooling water to and from the transmission line. The supply and return lines are coaxial in the coax and the transmission line, but they are parallel through the vacuum feedthrough.

#### *F. Shield Box*

The shield box houses the Dowtherm that provides neutron shielding. The box also serves as a mounting structure for the wheels, which carry the antenna on rails welded to the port side walls.

#### *G. Support and Drive System*

The launcher assembly is attached to the vessel at the vessel port flange. Radial movement is restrained by an adjustable drive screw mounted on the port cover. At installation, the Faraday shield is positioned by turning the drive screw that drives a plate attached to all twelve coaxes. This moves the entire launcher radially with its wheels riding on the rails. When the launcher is near its nominal position, the wheels do not take any load. Instead the horizontal surfaces of the key ways cut out on the top and bottom of the shield box slide against the stationary keys fastened to the vessel at the port opening. Vertical, horizontal, and torsional disruptive loads are also resisted by the engagement of the keys and the key ways.

### III. ANALYSIS

Stress and thermal analyses have been performed on the ICRH antenna. The stress analysis was performed for the conceptual design but has not been updated for the changes in configuration, material, and disruption loads. Details of the disruption analysis can be found in [1].

Thermal analysis was based on the upgraded case of 45 MW of total power to the plasma. Heat loads on the Faraday shield tubes are the sum of the plasma load, the radio frequency heat loss, and the beam particle ripple loss. The maximum heat flux is 233 W/cm<sup>2</sup> on the upper and lower tubes. Adequate cooling requires a flow velocity of 6 m/s (20 ft/s) for these tubes. The coolant flow is biased through the tube array using orifices to allow the high-velocity flow in the critical tubes while reducing the flow to the center tubes. Total pressure drop through the Faraday shield is 2.1 X 10<sup>5</sup> N/m<sup>2</sup> (30 psi).

### IV. R&D

The research and development programs for the TPX ICRH antenna include the evaluation of the feasibility of nickel

plating titanium alloy 3Al-2.5V, the durability of B<sub>4</sub>C coatings under relevant heat fluxes, and hydrogen embrittlement of nickel-plated titanium. Results of these investigations indicate that B<sub>4</sub>C-coated, nickel-plated titanium alloy Faraday shield tubes can be fabricated and can endure the D-T environment of TPX.

#### *A. Nickel Plating*

Titanium alloy coupons as well as sample welded Faraday shield tube assemblies were successfully nickel plated independently by Oak Ridge National Laboratory and an industrial subcontractor. The plated coupons were thermally cycled and inspected. The plating survived the testing.

#### *B. B<sub>4</sub>C Coating*

Durability of the B<sub>4</sub>C coating on the nickel-plated 3Al-2.5V tube assemblies subjected to high heat fluxes was verified using a 30-kV neutral beam test facility. The plated tube assemblies were coated with 80-100 microns of B<sub>4</sub>C. The test was performed as follows:

- Units were actively cooled during tests. Water flow was maintained between 0.21 and 0.22 l/s (3.3 and 3.5 gpm).
- All testing was observed and recorded by infrared long wave video camera. At no time was the surface of coatings permitted to exceed 500°C-550°C.
- The front coated surface of the unit, from bend tangent to bend tangent, was exposed to the test beam as evenly as the test facility allowed. The profile was measured and mapped by a beam probe.
- A calorimetry device was used to monitor the heat input into the water circuit on runs longer than 5 seconds to determine whether steady state was achieved on the long (10 sec) pulses.
- Testing was started at 25 W/cm<sup>2</sup> and then increased to the full TPX exposure of 50 W/cm<sup>2</sup> by gradually increasing exposure duration to simulate increasing thermal load.
- After each run, the specimen was visually inspected through the observation port.

Results of the test showed that the B<sub>4</sub>C coating survived the 50 W/cm<sup>2</sup>. The tube temperature reached steady state within 5 seconds. The maximum wall temperature was 247°C, which is consistent with predicted temperatures. Additional testing performed with 5-second pulses at 100 W/cm<sup>2</sup> caused no visible degradation of the B<sub>4</sub>C coating.

#### *C. Hydrogen Embrittlement*

The resistance to hydrogen embrittlement of nickel-plated titanium alloy was tested using the following steps:

1. One sample in the unplated condition was heated in an outgassing furnace to a sufficient (800°C) temperature to

outgas all the entrapped hydrogen through a calibrated mass spectrometer.

2. One sample in the plated condition was subjected to the same outgassing procedure as in step [1]. The difference between the amount of hydrogen outgassed in steps [1] and [2] gives the approximate amount of hydrogen retention resulting from the plating/heat treatment process at Oak Ridge National Laboratory.

3. Three samples were simultaneously exposed to a 100-eV deuterium fluence of  $2 \times 10^{22}$  D/cm<sup>2</sup>-s: one unplated, one with 25 microns of nickel, and the third with 50-75 microns of nickel. The unplated sample was used to determine a baseline for hydrogen retention of unprotected alloy. The temperature of the specimens was dictated by the plasma.

4. After plasma exposure, the specimens were transferred to the outgassing furnace for processing as in step [1] to determine deuterium absorption.

5. Electron microscopy was used to examine the specimens for damaged and eroded surfaces.

Results of the test were as follows:

1. The nickel plating process introduced no additional hydrogen into the tube.

2. The unplated tube absorbed approximately 90 percent of the available deuterium.

3. The tube plated with 50-75 microns nickel absorbed no deuterium.

4. The tube plated with 25 microns nickel absorbed some deuterium. It is believed that the nickel sputtered and exposed the titanium alloy, which then allowed absorption.

## V. CONCLUSIONS

The design of the major components of the TPX ICH antenna has progressed. Had the project been continued, stress analysis and design iteration would have followed.

Design uncertainties of the TPX ICH antenna concerning the suitability of titanium for fabrication of major components have now been resolved.

## REFERENCES

[1] J. J. Yugo, C. H. Fogelman, P. L. Goranson, D. L. Conner, D. W. Swain, and R. O. Sayer, "Electromagnetic loads on ion cyclotron and lower hybrid launchers for TPX", *Proceedings of the IEEE/NPS Symposium on Fusion Engineering*, Champaign, Illinois, Oct. 1-5, 1995.

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