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Design and Construction of the JET ITER-Like ICRF High Power Prototype Antenna

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ABSTRACT.
A prototype of the JET ITER-like Ion Cyclotron Range of Frequencies (ICRF) launcher is presently being constructed by a collaboration between Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Laboratory (PPPL). The launcher is being designed to couple power at high density (8 MW/m^2, 7 MW total) into an ELMy H-mode plasma with a characteristic resistive loading > 2Ω/m. The two-strap High Power Prototype (HPP) closely approximates in geometry and materials the left upper quadrant of the actual antenna. High power tests will be performed in vacuum with the HPP installed in the Radio Frequency Test Facility (RFTF) at ORNL. These include long pulse (20 s) tests at the design current (920 A rms) and voltage (35 kV peak) limits, with shorter pulses (10 s) at currents up to 1250 A rms. The design of the HPP together with the set of diagnostics and test plan that will be employed are discussed.

1. INTRODUCTION
A collaboration between ORNL and PPPL is constructing a High Power Prototype (HPP) of a new ITER-like ICRF antenna that is planned for use in the JET tokamak [1]. The antenna will couple high power densities up to 8 MW/m^2 into H-mode plasmas. Its input impedance will be insensitive to increases in resistive loading caused by ELMs and other transients. The HPP consists of two vertically aligned current straps, and comprises one quadrant of the actual launcher. It will replicate very closely the geometry of the final antenna, and will be tested in a vacuum chamber at ORNL at the full design values of voltage (35 kV peak for 20 s, 37 kV peak for 10 s) and current (920 A RMS for 20s, 1250 A RMS for 10 s).

2. DESIGN OF THE HIGH POWER PROTOTYPE
The current strap configuration and internal matching network of the HPP is designed to minimize both the magnitudes of voltages and electric fields on launcher structures, and the physical extent over which high values of these quantities are present. The largest electric fields are confined to internal electrodes in the matching capacitors. They are located inside a private vacuum envelope, and thus shielded from free electron sources associated with plasma and ultraviolet light. Figures 1 and 2 show the principle components of the device. Two electrically short current straps, grounded at one end, are each connected in series to a matching capacitor. The other ends of the capacitors are connected in parallel to form a resonant double loop configuration [2]. During operation, the capacitors are adjusted to produce complex-conjugate admittances having a small real part at the connection (feed) point. The vacuum transmission line (VTL) feeding these capacitors consists of a rectangular outer conductor (shown partially cut away in Figure 1) and an inner conductor with a racetrack shaped cross-section. It serves as a $\lambda/4$ impedance transformer, transforming the low, real impedance at the feedpoint to the 30Ω characteristic impedance of the main transmission line. In this configuration, the voltage standing wave ratio (VSWR) at the input to the impedance transformer is insensitive to increases in resistive loading over a large range [3].

Several novel features of the ITER-like antenna design will be tested on the HPP. Unlike previous RDL implementations, the variable ends of the tuning capacitors are not grounded, and are exposed to machine vacuum. This requires a double bellows arrangement [1]. In addition, it is required that the capacitors be easily replaced in case of malfunction. The solution chosen was to make the entire VTL inner conductor removable, with the capacitors ‘plugged in’ to the current strap feeds. This cannot be done while still actively cooling the fixed ends of the capacitors, as is typical. Instead, the fixed end electrodes are cooled by conduction through the capacitor ceramics between pulses. Figure 3 shows the connectors that have been developed to implement the plug-in feature. The current is carried through silver plated copper-beryllium Multilam® contacts (type LA-CUT) between flanges. The ball and socket are designed to align the flanges to prevent crushing of the contacts during installation, while allowing the capacitors to rotate relative to the straps to facilitate assembly and accommodate thermal expansion.

Another unusual feature is the low characteristic impedance ($Z_0 = 9.4\Omega$) quarter-wave impedance transformer. The inner conductor is large enough to contain the capacitor drive motors, which are located in a separate vacuum interspace. The low Z_0 requires a minimum gap between inner and outer conductors of only 30 mm. Elongated pumpout holes are present in both inner and outer conductors to maintain good pumping speed in this region of low vacuum conductance.

Electrical modeling has played an important role in the design of the HPP. Transmission line models of the antenna and internal matching network have been used to calculate currents and voltages in these regions, as well as the antenna tuning range. Figure 4 shows voltages and currents on the current straps and leads for a representative case. Additional modeling has included use of a 2-D electrostatic solver to design the quarter-wave transformer and capacitor corona rings. An example of a design problem requiring higher level modeling arises from the fact that the capacitor ends nearest the current straps are not actively cooled. It is important to ensure even current distribution in this region to avoid thermal damage to the capacitor electrodes or adjacent braze joint. The current distribution has been determined using a commercial 3-D electromagnetic package, Microwave Studio by Computer Simulation Technology (www.cst.de). Results show that by changing the geometry slightly so that a thermal shield, which reduces line-of-site between the plasma and capacitors, is attached to the current strap leads (see Figure 1) rather than the antenna box, the azimuthal symmetry of the current density at the capacitor is markedly improved. A simplified geometry is used in the model, as shown in Figure 5. There is a cylindrical conducting boundary (not shown) surrounding open space (light gray cylinder). An internal conducting cylinder represents the capacitor, attached to a thin plate representing the current strap lead. In the first case (top), a semi-circular shield is attached to the outer conducting boundary. In the second case (bottom), a nearly circular shield is attached instead to the strap lead. It is assumed that pure TEM modes exist at the ends of the cylinders. The results are shown in Figure 6, which is a plot of current density as a function of angle around the capacitor cylinder. It can be seen that the variation in current density is greatly reduced for the second case.

3. DIAGNOSTICS AND TEST PLAN

The HPP diagnostic set includes: 1) voltage probes to monitor the voltage on the current strap end of each capacitor and the voltage waveform on the λ/4 transformer section (6 total), 2) directional couplers to determine the input impedance in the main transmission line, 3) infra-red thermocouples to monitor the temperature on the capacitor ceramics next to the current strap side braze joints, 4) an ionization gauge to measure pressure in the quarter-wave transformer region, 5) an IR camera to determine temperatures on Faraday shield elements and current straps, and 6) thermocouples to measure temperatures at these locations, as well as in the quarter-wave transformer sections. All data will be obtained using a system based on LABVIEW software and National Instruments controllers and digitizers.

The test plan is as follows:

- Capacitors will be high-potted prior to installation.
- Capacitor drive motors will be tested with shielding at magnetic field levels up to 0.3 Tesla (time permitting).
- Low power measurements will be used to determine the frequency tuning range and the quality factor (Q) of the antenna. Effects of varying resistive load on input impedance will be investigating using a method yet to be decided.
- 3-D maps of the rf magnetic field pattern in front of the antenna will be made at several frequencies and compared to theoretical predictions.
- The antenna will be leak tested, and then baked to 180ºC in vacuum, followed by low-voltage conditioning to eliminate multipactor and high voltage conditioning to increase voltage standoff.
- Voltage limits will be determined for 10 and 20s pulses, in the frequency range 42–55 MHz, with voltages and currents not to exceed those specified in section 1 above and capacitor braze joint temperatures not to exceed 130ºC.
- Mistuned high power pulses will be used examine voltage limits in the transformer/window region and effects of voltage levels on multipactor breakdown.
- A visual inspection will be made of all HPP structures.

CONCLUSIONS

The HPP is geometrically nearly identical to one quadrant of the JET ITER-like ICRF launcher, and is expected to provide accurate information on the tuning range and voltage handling in vacuum of the actual device. Its construction will allow tests of many advanced features of the antenna, including the plug-in capacitors and VTL inner conductor, and the low Z_0 impedance transformer. It will also be used to evaluate the performance of the internal capacitor actuators. It is anticipated that through these tests much information will be gained which will contribute to the optimization of the design and operation of the new ITER-like launcher for JET.

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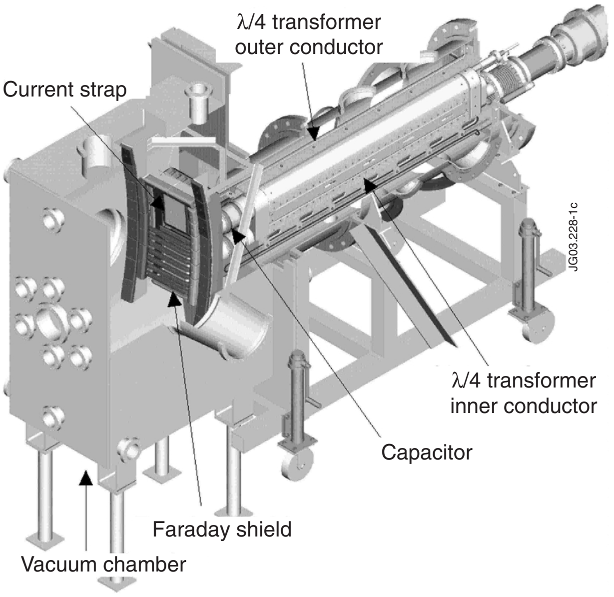


Figure 1: Cutaway view of the High Power Prototype antenna.

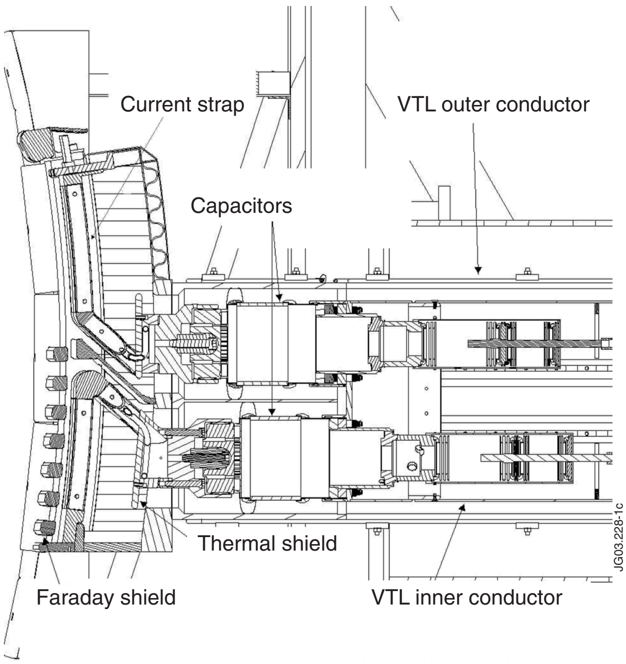


Figure 2: Side view showing current straps, Faraday shield, and capacitors.

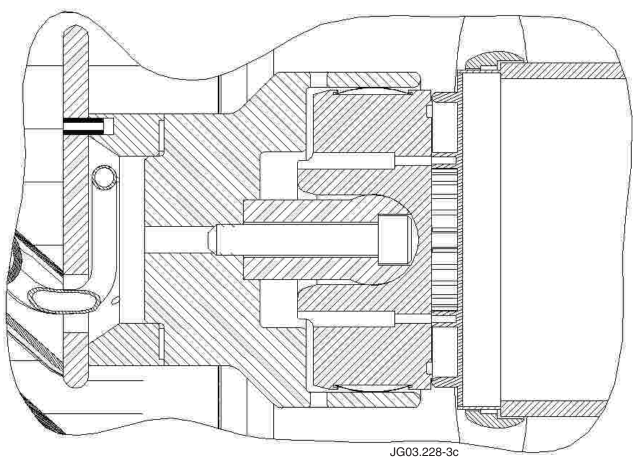


Figure 3: Plug-in capacitor connector.

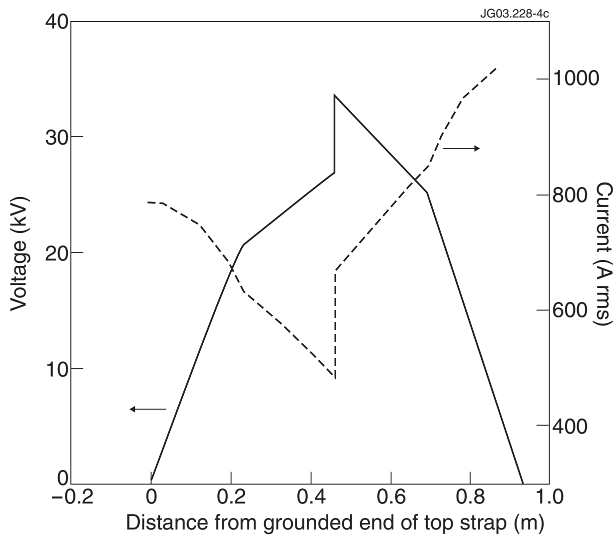
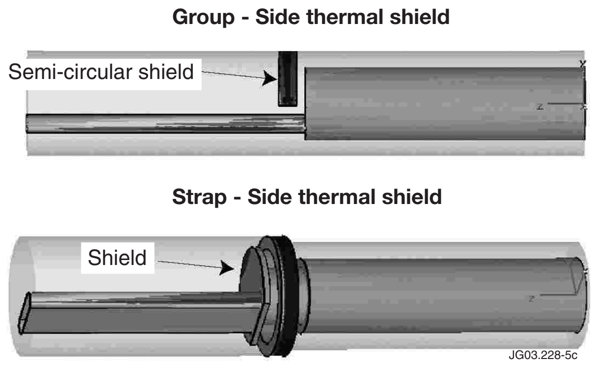


Figure 4: Voltage and current on current straps and leads for f = 55MHz, input power = 74kW, current strap lineic resistance R′ strap = 0.2Ω/m.



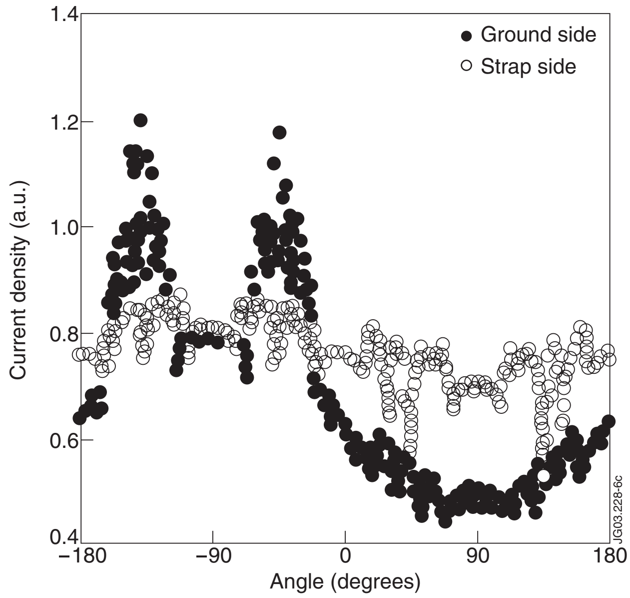


Figure 5: Simplified models of capacitor/current strap lead interfaces for estimation of azimuthal symmetry of current density.

Figure 6: Comparison of current density as a function of angle for thermal shield attached to the ground (antenna box) or current strap based on model of Figure 5. Position is immediately to the right of the capacitor cylinder – feed line transition.