ADVANCED ICH ANTENNA DESIGNS FOR HEATING AND CURRENT DRIVE ON ITER AND NSTX*

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Abstract

Advanced physics scenarios need radiofrequency (rf) systems to heat either ions or electrons, to drive current at the center of high density discharges, to control plasma conditions by manipulation of the heating and current profiles, and possibly to establish rf-driven transport barriers. Operationally, the systems must deliver high power into rapidly varying plasma loads, with good performance over a wide range of plasma density and magnetic field strengths, and both high reliability and efficient use of installed power capability. Other important features are high power density to decrease port space, long-pulse or steady state operation, and compatibility with a reactor environment. Two programs in which ORNL is helping to advance the level of rf system development are the ICRF antenna design for ITER and the high harmonic fast wave (HHFW) antenna array for NSTX. The ITER antenna array is designed to heat both ions and electrons and to drive current over a frequency range of 40-70 MHz. An ITER prototype antenna (Fig. 1) has been fabricated and is undergoing vacuum testing at ORNL. Initial test results are presented. The NSTX HHFW 12-strap array has been designed to launch a highly directional wave spectrum for non-inductive current drive. We report on the antenna and feed system design, measurements on a mockup antenna, and physics modeling used in the design process.

1. HIGH POWER DENSITY ITER PROTOTYPE ANTENNA

1.1 Description

A high power density research and development (R&D) antenna with ITER relevant dimensions and voltage handling capability has been designed, built, and undergone initial testing [1]. The antenna is a resonant double loop (RDL) design (Fig. 1) with internal matching elements. This configuration provides a match to the characteristic impedance of the feed line at the antenna feed point, which minimizes the voltage and current on the transmission line and vacuum feedthrough [2]. The current strap is 1.18 m long and 0.22 m wide. The distance from the current strap to the cavity box sidewalls is 0.04 m, and the distance between the leads feeding the strap and the top and bottom of the cavity is adjustable, and is typically 0.02m. The current strap is made of OFHC copper, and the cavity box is Ni-plated 304 stainless steel. There are 12 equally spaced Cu Faraday shield elements that are each 0.05m in height. There is an adjustable gap between the current strap front surface and Faraday shield element rear surfaces, which is fixed at 0.015 m for the tests reported here. The antenna is matched using two manually adjustable shorted stubs which consist of Ni-plated 304 SS inner and outer conductors, and Cu annular shorting rings with Multilam type LA contactors on the inner and outer surfaces. The stub inner conductors are water-cooled up to the current strap leads, and there are trace water cooling lines on the cavity top, bottom, and sidewalls. The stubs are designed to be replaced by an advanced short-stroke design developed by the EU as an ITER development task[1], which will be tested when available. Finally, there are several diagnostic ports in the antenna port cover and matching stubs. Capacitive probes are mounted in the stub ports immediately behind the port cover plate (Fig. 1) in order to measure voltages during high power operation.

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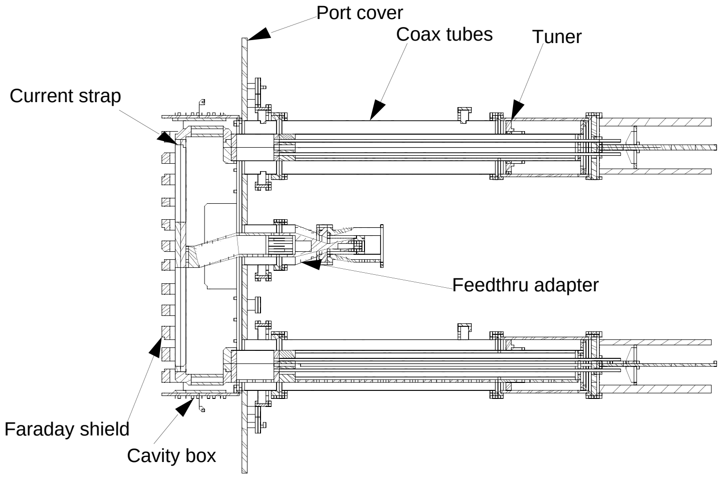

FIG. 1. The ITER prototype R&D antenna

1.2 Low power measurements

A set of measurements was made with the R&D antenna in air, including rf magnetic field profiles and swept frequency measurements of the quality factor (Q). RF magnetic field profiles were made using loop probes mounted on a computer controlled measurement frame. Measurements of the toroidal rf magnetic field component were compared with 2D and 3D magnetostatic models. It was found that accurate profile modeling in the vicinity of the antenna sidewalls required use of the 3D code [1]. This is likely due to currents flowing through the Faraday shield elements, which cannot be directly represented in the 2D code.

An interesting result is shown in Fig. 2, which is a graph of reflection coefficient magnitude vs. frequency, which is used to determine Q. This measurement was made in order to estimate the intrinsic losses in the antenna and tuning stub. The solid line resulted from a measurement made with the antenna mounted on the Radio Frequency Test Facility (RFTF) vacuum chamber, and the dashed line was obtained with the antenna located in an open room with no metallic objects closer than 3m from the front surface. The two conditions gave very different results, with Q=98 for the antenna in air, and Q=336 for the antenna mounted on the chamber, a factor of ~3 reduction in apparent losses. It is believed that radiation resistance is partially responsible for the low Q in the former case, and that the latter case more accurately reflects the launcher internal dissipation. Approximately the same Q value was obtained as in the latter case when the Faraday shield was covered with metal foil.

1.3 High Power tests

Initial high power tests have been run with the antenna operating in vacuum on the RFTF test stand. Before high power was applied, several steps were taken to condition the antenna. The matching stubs and feedthrough were first baked to approximately 150 °C for 8 hours using heating tapes wrapped around the outer conductors. Then a multipactor discharge was initiated by running 2 kW of continuous power, and maintained until it self-extinguished. The power was then reduced slightly until multipactoring was re-established, and again was maintained until the discharge extinguished. This process was repeated until the power level was reduced to ~ 50 W. Next, rf power levels up to ~ 5 kW were applied continuously for several hours with the heating tapes turned on in order to bake as many regions of the antenna structure as possible.

Following the conditioning process, it was possible run pulses of 0.1 s duration at voltages greater than 50 kV with essentially no arcing. After ~2 hours of high power conditioning, a maximum voltage of 72 kV was achieved for 0.1s pulses (corresponding to 2 kA peak current at the current maximum on the strap), 65-70 kV for 1.0 s pulses (fig. 3), and 62 kV for 2 s pulses. For operation in plasma, assuming moderate plasma loading of 4 Ω/m, the highest voltage achieved corresponds to a power density of ~ 15 MW/m^2. During long pulse operation, it appeared that the decrease in voltage limit was due to heating of internal surfaces accompanied by outgassing, with chamber pressure increasing more than an order of magnitude during a 2 s pulse to

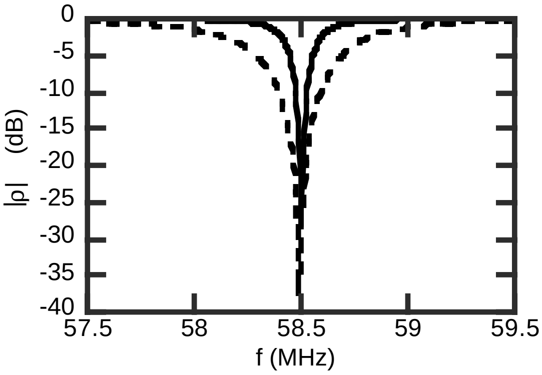

FIG 2. Swept frequency Q measurement.

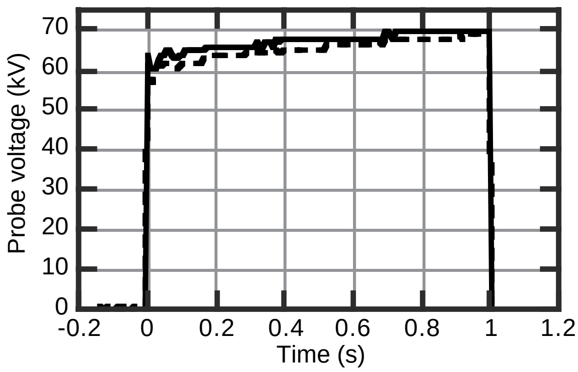

FIG 3. Voltage at capacitive probe during 1s pulse.

a maximum of ~7×10^{-3} Pa. The pressure was not measured in the stubs, but was likely to be significantly higher in these regions due to their low conductance.

Future tests will include an attempt to identify breakdown locations using optical sensors in the antenna and stub diagnostic ports, and an investigation of the dependence of voltage limits on the current strap to Faraday shield separation distance, the characteristic impedance of the antenna leads, and presence of a static magnetic field. Improvements in performance could likely be obtained by silver plating the stub regions to reduce rf dissipation, and actively cooling the current strap and increasing cooling of the antenna box. Active pumping of the stub regions may also be beneficial.

2. NSTX HIGH HARMONIC FAST WAVE SYSTEM

2.1 Description

The NSTX HHFW system consists of a 12 element phased antenna array (Fig. 4) and the associated feed network. The system is designed to deliver 6 MW of rf power at 30 MHz (during initial operation, some power will be injected at 41 MHz) in a high β, low toroidal B field (0.3T) device. Waves in the HHFW frequency range[3], in which the system will operate, are expected to damp primarily on electrons under these conditions, although the low value of B may also allow ion damping [4]. The system will be used to heat and drive current during the startup and steady-state phases of operation, and will be required to deliver full power over a large range of edge densities, electron temperatures, plasma β, and resistive loading (4-8 Ω/m). Given these requirements, it was decided to design an array that is conservative in terms of the specified power flux (3.5 MW/m^2). In addition, the feed network design allows real-time variation in current phasing on all 12 straps, permitting control of the toroidal wave spectrum in order to maximize single-pass damping and possibly provide some profile control[4].

The 12 straps are connected together in pairs by resonant coaxial transmission line loops that are 2λ in total length in such a way to provide π phasing between antennas in a pair. The

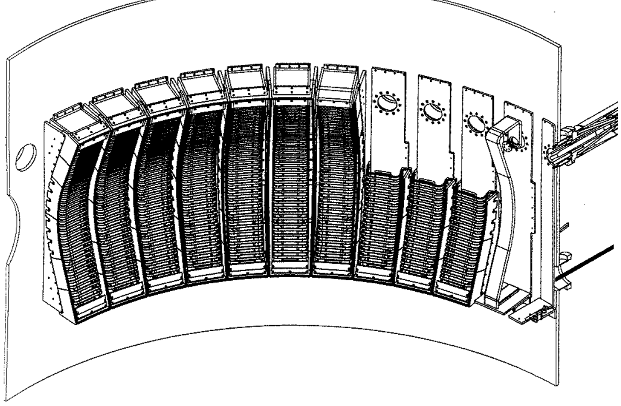

FIG. 4. 12-strap HHFW antenna array for NSTX.

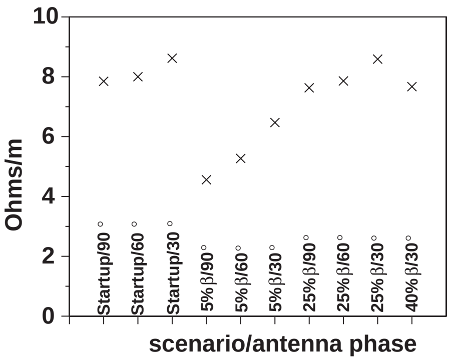

FIG 5. Plasma loading for various scenarios

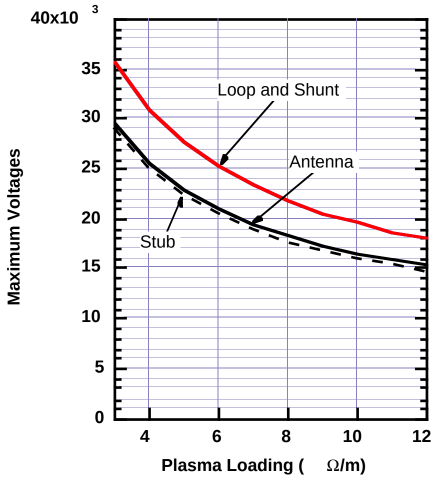

FIG. 6. Maximum system voltages as a function of plasma loading

first and sixth strap are connected together, as are the second and seventh, and so on for the remaining straps. Each pair is driven by a separate transmitter to allow rapid phase variation between pairs, and stub decouplers[5] are connected between the six feed lines so that the input impedance of each is independent of phasing. A more complete description of the somewhat complex feed network is given in reference [6].

2.2 **System modeling results**

A 3-D magnetostatic code was used to determine the antenna characteristic impedance (~52 Ω average) and phase velocity (0.6c). These calculated values compare well with measurements made on a full-scale mockup of a 2-strap section of the array of ~55 Ω and 0.62c respectively. Using the calculated antenna transmission line parameters, a model of the entire network was created using the FDAC[7] code. Loading predictions for a variety of operating conditions were obtained using The RANT3D[8], and GLOSI[9] codes (Fig 5.), allowing maximum voltages in the network to be calculated with FDAC (Fig. 6). Even at the lowest value of predicted loading (4 Ω/m), the maximum voltage for 6 MW total input power is predicted not to exceed ~32 kV. It can be seen from Fig. 5 that the loading always increases inversely with antenna phasing, as would be expected from the well understood dependence on the parallel wavenumber $k_{||}$. However, the faster toroidal phase velocity produced at low relative phasing also results in reduced single pass absorption at low T_{e},. making it important to retain spectral control capability. Another important modeling result is that although the magnetic field lines near the antenna array can be angled as much as 45° from the toroidal direction for large plasma current, higher loading is obtained with vertical current straps than with straps tilted 24°, the largest tilt allowed by the vacuum chamber ports, for all but the highest values of plasma β[4]. For this reason, it was decided not to tilt the current straps in the final design.

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