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Design Options for an ITER Ion Cyclotron System*

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Abstract. Recent changes have occurred in the design requirements for the ITER ion cyclotron system, requiring in-port launchers in four main horizontal ports to deliver 50 MW of power to the plasma. The design is complicated by the comparatively large antenna-separatrix distance of 10–20 cm. Designs of a conventional strap launcher and a folded waveguide launcher that can meet the new requirements are presented.

IN-PORT STRAP ANTENNA

The ITER port size has recently increased because of a change from 24 TF coils to 20 in the ITER design. Figure 1 shows a view from the plasma of an antenna that can fit in the new port. Each current strap is grounded at its center, and each end is independently fed by vacuum coax. There are four straps toroidally, and four straps (counting each end as an independent strap) poloidally.

An electrical analysis has been done using a lossy transmission line model for the current straps (assumed to have a characteristic impedance of 40 Ω and phase velocity 0.7c) and for the vacuum transmission lines (30 Ω characteristic impedance) (1). The plasma coupling resistance R' was computed using the

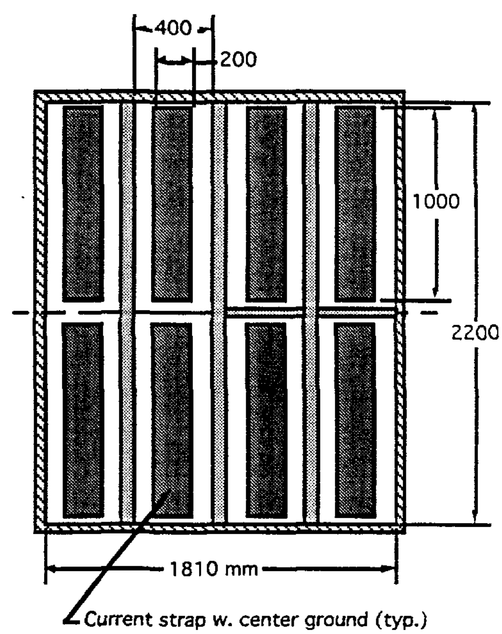

FIGURE 1. View from the plasma of the ITER in-port antenna.

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DISCLAIMER

RANT3D code, which has had significant success calculating the R' values measured on TFTR and DIII-D using measured density profiles (2). The plasma density profile used is typical of the ITER ignited plasma case (3): inside the separatrix $n(r) = (n_{eo}-n_{edge})[1-(r/a)^2]^{0.15} + n_{edge}$; outside the separatrix $n(r) = n_{edge} \exp[-(r-a)/\lambda]$. For the results presented here, $n_{eo} = 1.25 \times 10^{20}$ m^{-3}, $n_{edge} = 0.8 \times 10^{20}$ m^{-3}, and $\lambda = 0.02$ m.

Figure 2 shows the results of these calculations. The left figure is a plot of R' vs. the gap between the plasma separatrix and the first wall, for π and $\pi/2$ phasing between adjacent current straps. The right figure shows the maximum voltage in the rf system that is required to deliver 50 MW through four ports vs. gap, for π and $\pi/2$ phasing. For a 15 cm gap, the maximum voltages required to deliver 50 MW to the plasma are 40 kV for $\pi/2$ phasing and 54 kV for π phasing.

Operation with $V_{rfmax} \approx 30$–35 kV appears well within present-day state of the art. Some experiments report reliable operation up to $V_{rfmax} = 40$ kV (C-Mod) or 45 kV (Tore Supra). Thus, the rf voltages needed for $\pi/2$ operation are within the operating envelopes of some present-day tokamaks. Operation with π phasing would require higher voltages than are presently used, but may be achievable with a reasonable R&D effort. From the figure, reducing the gap from 15 to 10 cm would allow operation of the system at the 50 MW level with voltages approximately equal to those in use on some present-day systems.

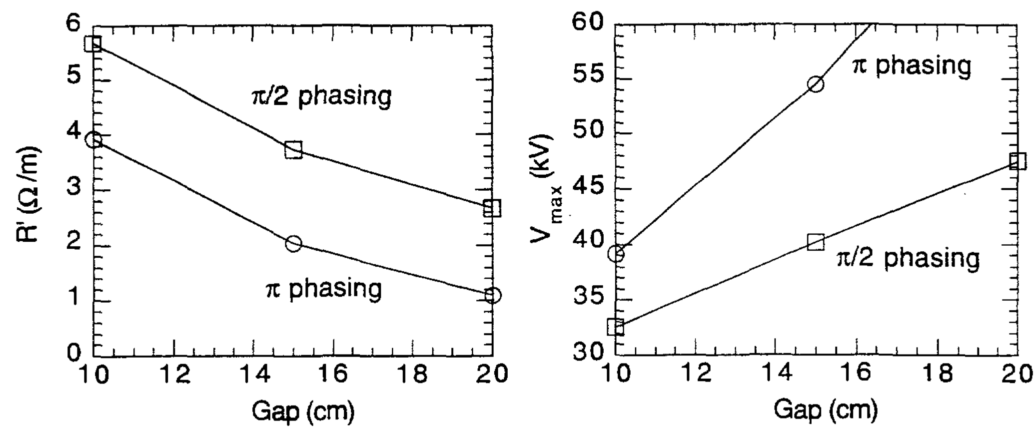

FIGURE 2. Loading resistance vs. separatrix-first wall gap (left), and maximum rf voltage vs. gap (right) for phasings of π and $\pi/2$ between adjacent current straps.

FOLDED WAVEGUIDE

The change to an in-port antenna design has led us to do a preliminary study of using a folded waveguide (FWG) array as an IC launching structure for ITER. The FWG array has the potential for delivering significantly higher power per port than the conventional strap launcher described above (4). Figure 3 shows a layout for a FWG array suitable for installation in an ITER-sized port.

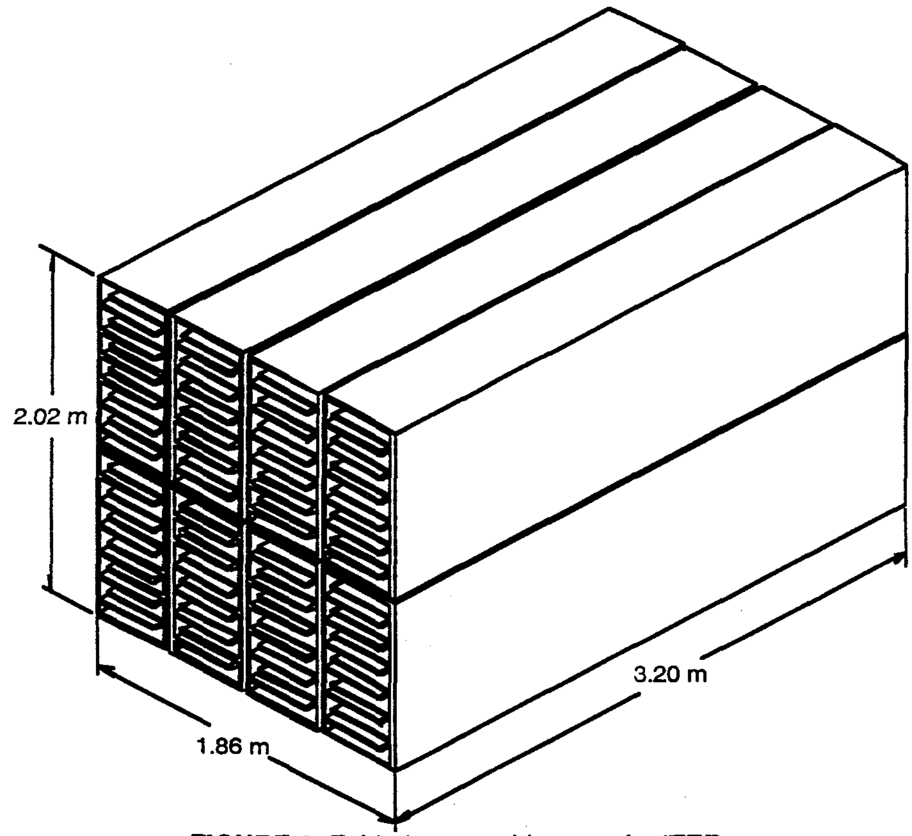

FIGURE 3. Folded waveguide array for ITER

The array consists of a 4 (toroidal) x 2 (poloidal) array of individual folded waveguides. The guides as shown are chosen to resonate at 55 MHz; by changing the length of the 3.2 m side, the resonance frequency can be adjusted to up to about 100 MHz. Each FWG is independently driven by a coax line. The magnetic field pattern from a FWG is very similar to that of an ordinary current strap antenna that fits in the same space, so the physics of the launched fast wave should be the same as the physics of waves launched with strap launchers.

For a FWG, the power that can be delivered to the plasma depends on the maximum electric field that can be sustained in the FWG, and on the loading of the FWG by the plasma. A development FWG has been operated on a test stand with electric fields inside the launcher of up to 50 kV/cm in the presence of a plasma and static magnetic field (5); we take *half* this value, 25 kV/cm, as the maximum electric field for FWG operation on a fusion device. An electromagnetic model of the FWG is used to relate the maximum electric field (in the center of the FWG) to the maximum magnetic field (at the plasma-facing end of the box).

The antenna coupling code RANT3D is used to calculate the power that can be coupled to the plasma from an antenna structure that generates such a surface magnetic field. To do this, the field pattern of a FWG array is simulated by a series of short current straps stacked poloidally, with currents on each strap chosen to give a magnetic field pattern similar to that produced by a FWG. For the array of eight FWG's shown in Fig. 3, with π phasing between adjacent toroidal waveguides, and a nominal separatrix-first wall distance of 15 cm, the total power per port is calculated to be $P_{port} \approx 32$ MW.

For different parameters, the power should scale approximately as the values of R' shown in Fig. 2. For example,

$$\frac{P_{port}(\pi/2)}{P_{port}(\pi)} = \frac{R'(\pi/2)}{R'(\pi)} \approx 1.8,$$

yielding $P_{port} \approx 58$ MW for the power that can be delivered from one port with π/2 phasing between adjacent FWG's with a 15 cm gap.

CONCLUSIONS

The conclusions of this study are cautiously optimistic. With π/2 phasing between adjacent current straps, 50 MW can be coupled to the plasma through four ports with a maximum voltage in the rf system of ≈ 40 kV. This voltage is within the operating regime of some present-day experiments, and should be achievable in ITER. For π phasing, R&D to develop rf systems that can be operated at ≥ 50 kV will be needed.

A preliminary assessment of a FWG launcher for ITER looks exceptionally promising. For a 4 x 2 array of folded waveguides operating at 60 MHz with π/2 phasing between adjacent toroidal waveguides, the full 50 MW could be delivered to the plasma from a single port. In addition, the FWCD current drive capability should be as good as that from a conventional strap array. The FWG can only operate at a fixed frequency, unless mechanical tuning elements are introduced into the vacuum (an undesirable option). However, the significant increase in power-handling capability with a FWG array could offset the disadvantage of single-frequency operation.

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