FAST-WAVE ICRF MINORITY-REGIME HEATING EXPERIMENTS ON THE
TORE SUPRA TOKAMAK*

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ABSTRACT

Up to 4 MW of rf power at 57 MHz has been coupled to Ohmic target plasmas during the first ICRF heating experiments on Tore Supra. A total of 12 MW of rf power will ultimately be available from six tetrode amplifiers and will be coupled to the plasmas using three ORNL/CEA-designed resonant double-loop antennas. During these first experiments, two antennas were used, with one or two energized at a time. The antenna loading with plasma was observed to be well over an order of magnitude greater than that without plasma. In addition, one kilo-electron-volt of electron heating, significant minority nonthermal ions, and significant increases in diamagnetic stored energy were observed. A comparison of in-phase and out-of-phase antenna operation showed the same increase in stored energy, less radiated power, and a larger drop in loop voltage for out-of-phase operation. Confinement scaling agrees with the ITER scaling law.

ICRF SYSTEM HARDWARE

The Tore Supra ICRF power system consists of six tetrode amplifiers supplied by Thomson Electronics, France, and three antennas designed jointly by ORNL and CEN-Cadarache. Each amplifier can produce 2 MW of ICRF power in 30-s pulses and can withstand up to 200 kW of reflected power. The frequency is adjustable within several 4-MHz-wide bands from 35 to 80 MHz. The three antennas are installed in non-adjacent, horizontal ports and can be remotely moved 300 mm in the horizontal direction to control the distance between the Faraday shields and the plasma. Each antenna is a two-strap resonant double loop with each loop fed by a separate amplifier (Fig. 1). Each loop is fed by a current tap offset slightly from the loop center, with vacuum-variable capacitors terminating each end of the loop. The capacitors can be remotely adjusted between plasma discharges to provide matched loads to the amplifiers.

The Faraday shield for each antenna consists of two layers of tubes, with the front face of the front layer protected by brazed-on carbon tiles. The top, bottom, and sides of each antenna are protected by graphite-armored bumper limiters, and the limiters and Faraday shield tubes are actively water cooled. There is a metallic septum between the two straps of each antenna whose purpose is to limit mutual inductive coupling between the two rf circuits. Very large surface currents flow in this septum and limit high-power operation of each antenna to a few seconds per pulse due to

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excessive septum heating. A design is under way for a new Faraday shield module that will incorporate an actively cooled septum to address this issue. The new Faraday shield will also have only a single layer of tubes to further reduce antenna losses by increasing radiation resistance and thus reducing the antenna current for a given power.

HEATING RESULTS WITH 4-MW OF ICRF POWER

Heating results from a discharge with almost 4 MW of ICRF power are shown in Fig. 2. This was a full-size plasma (minor radius 0.78 m, major radius 2.34 m) limited by both the inner wall and the outer horizontal limiter. The heating regime was hydrogen minority fundamental cyclotron absorption in a helium-4 majority plasma. The toroidal field was 3.86 T and the ICRF frequency was 57 MHz. A plasma current of 1.6 MA resulted in $q(a) = 3.6$ and distinct sawteeth in the measured electron temperature. Power was coupled using two antennas with overlapping 2-s rf pulses. Dipole phasing of the antenna conductors was necessary to achieve this power level. With monopole phasing a disruption always occurred for ICRF power levels greater than 1.5 MW. Electron temperature averaged over sawteeth increased by 500 eV and heating was centrally peaked. (Electron heating up to 1 keV was observed at lower density and with lower rf power.) The loop voltage decreased significantly, there was only a slight ICRF-induced perturbation in the density, and the poloidal beta measured via plasma diamagnetism increased significantly. The shape of the heating profile was found to depend on the position of the cyclotron resonance layer, and increases in the amplitude and period of sawteeth were seen for rf powers as low as 0.8 MW.

ANTENNA PHASING STUDIES

Discharges with antenna straps in phase and 180° out of phase are compared in Fig. 3. In a direct comparison of consecutive shots, the total heating power and stored energy were approximately the same, and thus the energy confinement times were the same, but the discharge with dipole phasing had significantly less radiated power and a larger drop in loop voltage than the discharge with monopole phasing. The increase in electron temperature was slightly higher for the discharge with dipole phasing. Although total radiated power always increased during injection of rf power, the fraction of total heating power radiated generally decreased during rf power injection. A comparison of our heating results with the ITER scaling law¹ shows very good agreement.

HEATING OF THE MINORITY ION SPECIES

So far, only very limited data are available from diagnostics of the resonant minority ion species. In an early discharge, with a hydrogen minority concentration of approximately 30% in a deuterium plasma and 0.9 MW of ICRF power, a straight-line fit to the highest-energy experimentally significant neutral particle analyzer channels (Fig. 4) yields a minority tail temperature of 2.2 keV. Fitting the isotropic Stix theory² to the same points yields a minority tail temperature of 3.6 keV, the implication being that the energy range over which the data were experimentally significant was not high enough to be in the tail of the distribution function.

For a later shot, with 1.5 MW of ICRF power in a plasma composed of helium-4 with residual amounts of hydrogen and deuterium, a high-energy charged-particle

diagnostic exhibited the two peaks at very high energy shown in Fig. 5. Our hypothesis is that the peak just below 2 MeV is caused by fundamental cyclotron heating of the residual hydrogen, while the peak just below 3 MeV is from protons produced by D-D fusion reactions of high-energy deuterons produced by second harmonic heating of residual deuterium. These high-energy charged particles were seen only with monopole antenna phasing.

SUMMARY

Up to 4 MW of ICRF power (one-third of the total ICRF generating capacity) has been injected into Ohmic target plasmas in the Tore Supra tokamak using two of the three antennas. Most of the experiments were performed in the hydrogen minority regime in helium plasmas, except for a few early experiments with deuterium majority ion species. Significant increases in electron temperature, sawtooth amplitude and period, and stored energy; generation of high-energy nonthermal ions; and decreases in loop voltage were observed. A comparison of in-phase and out-of-phase operation demonstrated significant reduction in radiated power fraction with 180° phasing, suggesting that 180° phasing results in reduced impurity production. An analysis of the electron energy balance shows agreement with the ITER scaling law.

REFERENCES

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Fig. 1. Antenna design for Tore Supra fast-wave ICRH.

Fig. 3. Comparison of monopole phasing (solid lines, circles) and dipole phasing (dashed lines, stars). For electron temperature measurements, top traces are during rf heating and bottom traces are during the Ohmic portion of the discharge before rf.

Fig. 4. Neutral particle analyzer spectrum with 0.9 MW of ICRF power, 30% hydrogen minority in deuterium.

Fig. 5. Energy spectrum of high-energy protons with 1.5 MW of ICRF power, He plasma.

Fig. 2. Heating results with 4 MW of ICRF power.