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**ICRF Heating and Current Drive in TFTR Supershot Plasmas:
Data Analysis and Interpretation of ICRF/Edge Interactions**

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ABSTRACT

The relevance of rf-sheath-plasma interactions to ICRF operation in TFTR has been studied. Screen-screen and screen-limiter rf sheaths have been identified and analyzed for the old and new Bay M geometries on TFTR, including sheath voltages driven by both feeders and the central antenna conductor. Calculations have been carried out to determine the effects of ICRF on edge transport (profile flattening by $\mathbf{E} \times \mathbf{B}$ convection), impurity influx (δZ_{eff}) and edge electron heating (FS glow phenomena) as a function of edge plasma parameters, rf power and antenna phasing. It was found that many of the experimentally observed ICRF-edge plasma interactions on TFTR are consistent with the predictions of rf sheath theory.

PROGRESS REPORT

Background

The ability of ICRF systems to effectively heat tokamak plasmas has been well established experimentally, and it has been shown on many tokamaks that ICRF-edge interactions due to rf sheaths can be reduced to negligible levels by the use of two-strap antennas with π phasing between the straps. There is now considerable interest in employing ICRF for current drive and stabilization. For example, control of the sawtooth instability is important to achieve maximum fusion power, Q_{DT} and β_α (alpha particle pressure). Sawtooth stabilization by ICRF has been demonstrated experimentally by both fast ion^{1, 2} and ion current drive^{3, 4} (q profile control) mechanisms. The new applications of ICRF power require multiple-strap antennas with a variety of phasings, and rf sheath-plasma interactions are expected to be important. Upcoming TFTR program priorities in preparation for and during D-T operation^{5, 6} will explore ICRF operation in these more challenging regimes, which motivates the present study of ICRF-edge interactions on TFTR.

The importance of rf-sheath-plasma interactions,^{7, 8} has been confirmed by both experiment and theory in recent years. Lodestar has spent several years studying rf sheath physics,⁸⁻¹⁶ developing appropriate numerical models and simulation codes (for rf sheath potentials,⁸ rf-enhanced impurity sputtering,⁹⁻¹² rf convective cells,¹³⁻¹⁴ estimates of impurity radiation and Z_{eff} ,¹⁵ and far field sheath formation¹⁶). This work has previously been applied to understand ICRF-edge interactions during L-mode and H-mode operation on JET in collaboration with M. Bures and J. Jacquinet.

In the past year we have tested the validity of these concepts to ICRF operation during supershots on TFTR in collaboration with R. Majeski and J. R. Wilson. It was found that rf sheath theory is consistent with the edge physics and impurity data on TFTR, and there are some interesting differences from JET. This work has been reported in a recent EPS paper¹⁷ and more details will be discussed in two upcoming APS papers.¹⁸⁻¹⁹ Future work with the TFTR ICRF team and the ORNL reflectometer group will concentrate on data analysis and optimization studies relevant to the current TFTR D-T campaign.

The following sub-sections report on our progress to date.

Rf sheath geometry

We have identified the relevant rf sheath mechanisms on TFTR. Rf sheath formation requires a field line connection between conductors (e.g. the Faraday screen and limiters) on which a substantial rf voltage is induced. Therefore, the magnitude and location of rf sheaths depend on the field line connections in the vicinity of the antenna. We have compared several types of connections for the old and new Bay M geometry on TFTR, including sheath voltages driven by both feeders and the central antenna conductor. In

each case the sheath voltage and effective surface area was estimated. Subsequent calculations determined the effects of ICRF on edge transport (profile flattening by $\mathbf{E} \times \mathbf{B}$ convection), impurity influx (δZ_{eff}) and edge electron heating (FS glow phenomena) as a function of edge plasma parameters, rf power and antenna phasing.

It is useful to distinguish between two types of sheaths on TFTR: screen-limiter (SL) sheaths (linking the FS to the rf limiter 1.7 m downstream along the field line) and screen-screen (SS) sheaths (linking the front faces of two "Vee shaped" FS elements). Many of the differences between the old and new Bay-M configurations can be attributed to the elimination of the SL sheaths in the new Bay-M geometry by re-positioning the antenna bumper tiles. We have found that rf sheath theory gives a qualitative, and sometimes quantitative, understanding of many of the features of the experiments reported in Refs. 20-21.

ICRF convective cells

The rf sheaths cause rectification or self-biasing of the field lines on which they exist. Poloidal and radial variations in this dc voltage lead to $\mathbf{E} \times \mathbf{B}$ plasma convection^{13,14} which works to flatten the density profile, increasing plasma density on the screen. This enhanced density increases the impurity production, local power dissipation, and other sheath effects. It may also play a role in the plasma glow observed on the old Bay M. For typical TFTR parameters, we have calculated the effective perpendicular transport driven by the SS sheaths to be about 10-20 times Bohm in 0-0 phasing, so that the density at the screen is large compared to the value predicted for Bohm diffusion. In 0- π phasing, the effective $D_{\perp}$ is about twice Bohm and is due to the SL sheaths. The enhanced perpendicular transport coefficient is used in the impurity calculations described below.

Impurity production

Employing our rf sheath impurity influx model,¹⁰ modified to take into account TFTR geometry, we have estimated the sheath driven impurity influxes including sputtering of both D and C on Ti and summing the contributions of both SS and SL sheaths. For old Bay-M, the model predicts an influx $\Phi \sim 2 \times 10^{19}$ Ti atoms s^{-1} in 0-0 phasing and $\Phi \sim 3 \times 10^{18}$ Ti atoms s^{-1} in 0- π phasing for 1 MW rf power. The factor of 6 difference between the two phasings is consistent with the experimental results.^{20,21} A 1D transport calculation¹⁵ of the impurity penetration corresponding to the calculated influx yields $\delta Z_{\text{eff}}(\text{Ti}) \sim 0.02$ for 0-0 phasing, which agrees to within a factor of 2 with the measured values. For the new Bay-M, the model predicts a greatly reduced influx in 0-0 phasing, $\Phi \sim 6 \times 10^{18}$ Ti atoms s^{-1} , and a negligible influx in 0- π phasing because of the cancellation of the rf flux from the antenna current straps in this case. Thus, our

calculations of impurity influxes agree qualitatively with the observed phasing dependence on TFTR and correspond to a $\delta Z_{\text{eff}}(\text{Ti})$ in reasonable agreement with the data.

Plasma glow and Fermi acceleration

We have found that the rf sheaths also provide a promising candidate for explaining the FS glow phenomena observed in old Bay M. The calculated spatial dependence of the SL sheath voltage predicts a maximum sheath potential at the spatial location where the glow was observed, and the mechanism of Fermi acceleration^{22,23} of electrons by the sheaths provides a means for increased ionization and excitation of atoms in the SOL. For the SL sheaths, the B-field line intersects the FS face at a near glancing angle ψ so that the sheath can cause electron edge heating by an analog of the usual Landau damping mechanism. Calculations in progress describe the electron rf-sheath interaction in the small ψ regime. The net electron heating depends on the competition of Fermi acceleration with electron losses including perpendicular transport (e.g. rf convection) and parallel losses through the sheath. This work will be completed in the next year.

In summary, we have identified the relevant rf sheath mechanisms and verified that the experimentally observed ICRF-edge plasma interactions are consistent with the predictions of rf sheath theory. More detailed modeling and analysis of experimental data will be carried out in the next contract year to confirm this picture, and optimization studies for present TFTR experiments will be carried out.

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