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TRANSP Modeling of Minority Ion Sawtooth Mixing in ICRF + NBI Heated Discharges in TFTR

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ABSTRACT. Time independent code analysis indicates that the sawtooth relaxation phenomenon affects RF power deposition profiles through the mixing of fast ions (1,2). Predicted central electron heating rates are substantially above experimental values unless sawtooth relaxation is included. The PPPL time dependent transport analysis code, TRANSP, currently has a model to redistribute thermal electron and ion species, energy densities, plasma current density, and fast ions from neutral beam injection at each sawtooth event using the Kadomtsev (3) prescription. Results are presented here in which the set of models is extended to include sawtooth mixing effects on the hot ion population generated from ICRF heating. The ICRF generated hot ion distribution function, $f(v_{||}, v_{\perp})$, which is strongly peaked at the center before each sawtooth, is replaced throughout the sawtooth mixing volume by its volume averaged value at each sawtooth. The modified $f(v_{||}, v_{\perp})$ is then used to recalculate the collisional transfer of power from the minority species to the background species. Results demonstrate that neglect of sawtooth mixing of ICRF-induced fast ions leads to the prediction of faster central electron reheat rates than are measured experimentally.

INTRODUCTION

Comparisons of inferred central electron heating rates following a sawtooth crash do not agree with the predictions of wave damping codes unless some broadening mechanism is included in the power deposition profiles predicted by the codes. ECE measurements can be performed of the rate of rise of the central electron temperature. This method has been used in power modulation experiments, and directly after a sawtooth crash, to infer the net power deposited to electrons on axis. When compared to the RF power deposition profiles predicted by wave damping codes, experiments yield heating rates that are broader with a lower central value.

TRANSP currently has models which use the Kadomtsev prescription for simulating the sawtooth event for the thermal species, as well as Monte Carlo models for fast ions (beam ions as well as fusion products). The existing set of sawtooth models in TRANSP has been expanded to include a sawtooth simulation for the hot ion tail of the minority species. The fast ions lie far above

* Work supported by U. S. DOE Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.
** Work supported by U. S. DOE Contract No. DE-AC02-76-CHO-3073

the critical energy of the thermal plasma and hence their behavior will strongly affect electron heating. As expected, inclusion of a radial redistribution of the minority ion energy density strongly affects the electron reheat rate following a sawtooth. Indirect confirmation of this model is demonstrated by showing that it provides a more accurate power balance for electrons. Application of the model to two TFTR supershots is presented.

The ICRF heating in TRANSP is treated with a full wave code, SPRUCE (4), coupled to a Fokker-Planck package, FPPRF (5). Recently, FPPRF/TRANSP was modified to include a phenomenological model for sawtooth mixing of minority ions. At each sawtooth event during ICRF heating, the bounce-averaged minority ion distribution function, f , is replaced by its volume average, \tilde{f} , inside the mixing radius (as determined by the zero of the helical flux function), and is unchanged outside:

$$\tilde{f} = \frac{\int_0^{r_{mix}} dr r f(E, \xi, r, t) J(\xi, r)}{\int_0^{r_{mix}} dr r J(\xi, r)} \quad \text{for } r \leq r_{mix} \quad (1)$$

where r , E , and ξ are minor radius, energy and midplane pitch angle, respectively. The effect of the above action is to spatially flatten the minority ion energy distribution within the mixing radius volume.

Results

The first application of the new sawtooth model is to TFTR shot 54309, a ^3He minority supershot with a sawtooth at 3.924 secs during the ICRF. The electron temperature input data and the concomitant effect of the model on the minority energy density are shown in Fig. 1.

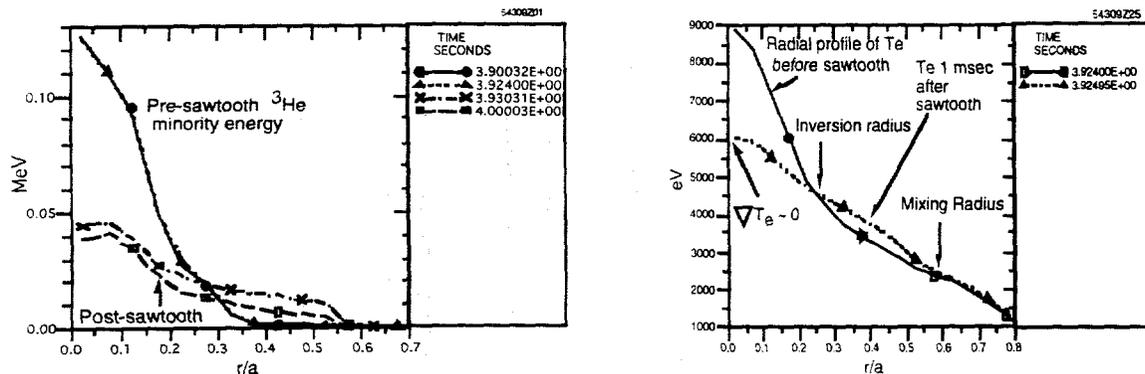


FIGURE 1. a) ^3He temperature profiles using the model and b) T_e data from ECE.

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Figure 2 shows that the calculated central minority heating of electrons, PEICH, drops after the sawtooth by ~40% to 0.3 W/cm^3 when the minority sawtooth model is 'on'. Beam heating, PBE, is ~ 50% of PEICH. When the same simulation is performed with the sawtooth model 'off', central heating of electrons by minority ions is calculated to be more than two times higher. This has a significant effect on the electron power balance and the inferred heat conduction.

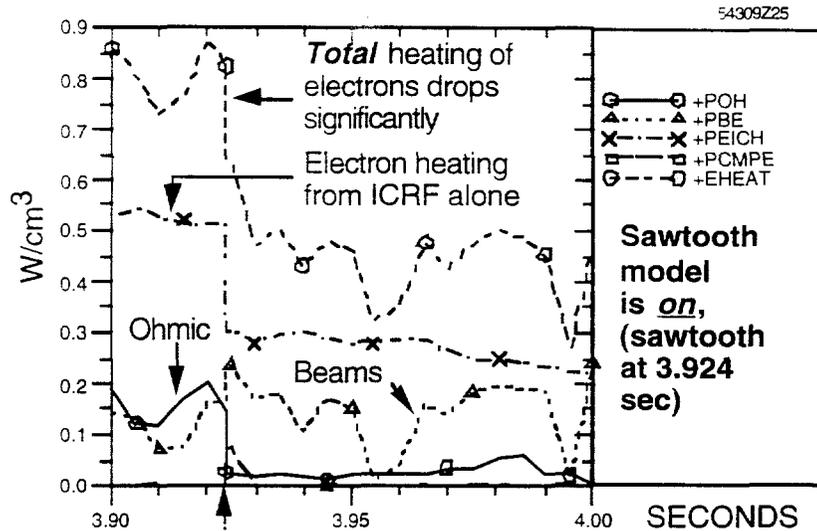


FIGURE 2. Sources of central electron heating around the time of the sawtooth in shot 54309.

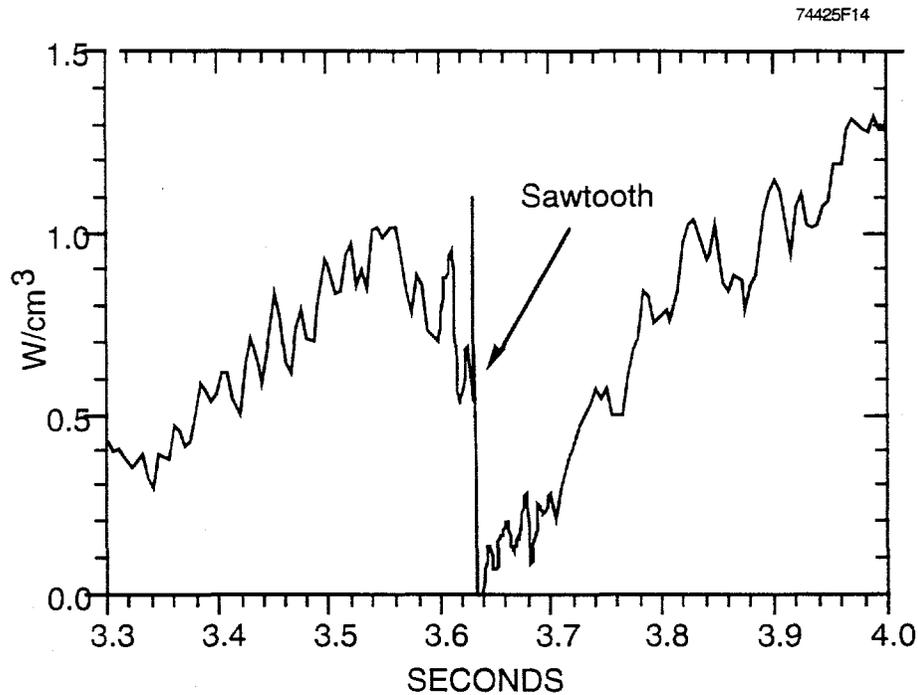


FIGURE 3. Computed central heat conduction for shot 74425. At the time of the sawtooth when the T_e gradient flattens, the heat conduction vanishes.

The second example is shot 74425 which is from the recent run series after the commencement of deuterium-tritium experiments. For this shot, the injected neutral beam species is pure deuterium and 1% was taken as the recycling fraction of tritium from the limiter. Figure 3 shows a TRANSP simulation in which the sawtooth model is used. The central electron heat conduction drops to zero immediately after the sawtooth and slowly rises to $\sim 1 \text{ W/cm}^3$ afterwards. This is consistent with the flattening of the central temperature in Fig. 1b, which should cause the inferred heat flux, $\Gamma_e \propto \chi_e \nabla T_e$, to vanish. In contrast, a simulation done with the sawtooth mixing model 'off' causes the computed heat conduction to be essentially unchanged through the sawtooth - a clear indication of inconsistency with the T_e data.

Conclusion

A model has been developed for TRANSP which extends the existing set of sawtooth models to include the ICRF accelerated minority species. This is accomplished by flattening the minority distribution function immediately after a sawtooth within the mixing radius, and then integrating the result with the FPPRF Fokker-Planck package in TRANSP.

This model is applied to simulations of two TFTR deuterium majority / ^3He minority supershots: 54309 and 74425. Because ICRF heating tends to be rather localized at the center, this causes the FWHM of the minority energy density profile to increase by approximately a factor of three and the central minority heating of electrons to drop by a similar amount. An analysis of the central electron power balance soon after sawtooth crashes demonstrates that the predictions of the new model have a significant effect on calculated quantities leading to better agreement with input data. The effect of the model is to decrease the central minority energy density after each sawtooth which leads to a lower calculated electron re-heat rate. This, in turn, gives a lower calculated heat conduction - in agreement with the experimentally observed drop in central ∇T_e . On the other hand, neglecting minority ion sawtooth mixing causes the calculated electron heat conduction and thermal diffusivity to remain implausibly high after sawteeth.

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