CQL3D-GENRAY Simulations of Suppression of Impurity-Induced Current Quench Using LH Cuurent Drive in C-Mod

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In C-Mod lower hybrid current drive experiments (LHCD), Reinke [1] has examined rare lower hybrid driven discharges which undergo an abrupt thermal quench (TQ) to low Te due to radiation from incoming tungsten flake material. Surprisingly, cases are found for which the TQ does not lead to a runaway electron (RE) current quench (CQ), normally expected to follow the TQ. Rather, the toroidal current continued at its pre-TQ value without very large enhancement of the toroidal electric field, implying that the LH is instrumental in maintaining the current. We simulate the driven LHCD and compare with experiment using the coupled CQL3D Fokker-Planck [2] and GENRAY ray tracing codes, based on experimental traces of the background densities and temperatures. The toroidal voltage boundary condition for a self-consistent solution of the Ampere-Faraday equations[3] is shown in Fig. 1, which also indicates at the bottom phases of the discharge which we aim to model. Further shot data is in [1].

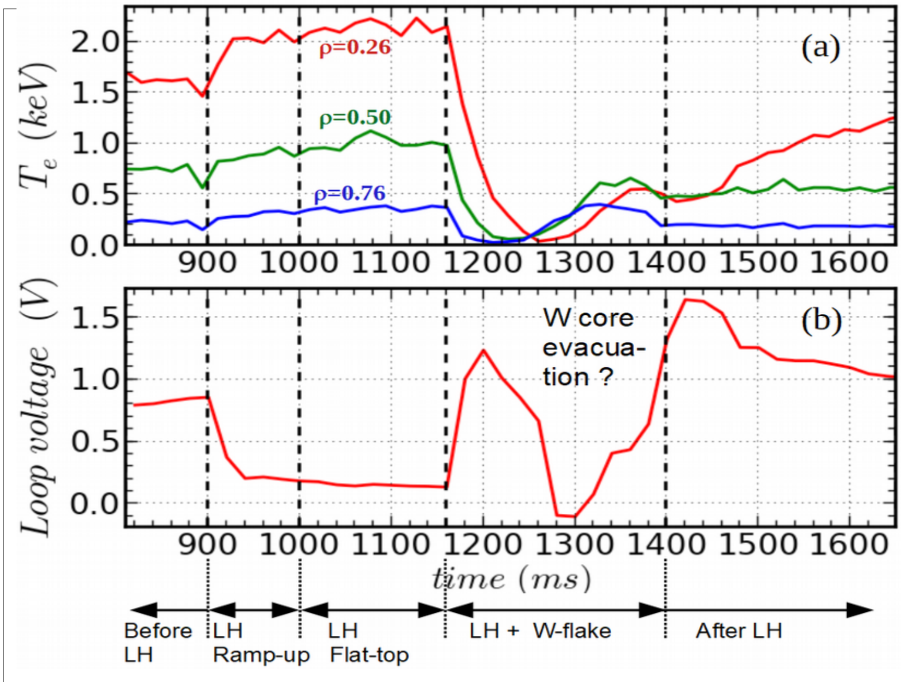

Fig.1. As indicated at the bottom, LH is ramped up from 400 to 725 kW giving most of the plasma current Ip=425 kA, which is maintained constant over this period. Voltage drops and Te increases. A W-flake enters the plasma at 1160 ms, Te drops, and Vloop jumps up. Then runaway current takes over at 1230 ms. Vloop drops to zero, and the plasma begins to recover (Te grows, j(rho) broadens, and the plasma position is maintained).

CQL3D computes the bounce-average electron distribution function f_e(upar,uperp,rho,t) using the above plasma data. The (upar,uperp) are momentum-per-mass, rho is generalized plasma radius, and magnetic geometry is based on solution of the equilibrium equation. The effects of relativistic collisions, toroidal electric field, magnetic trapping, LH QL diffusion based on GENRAY[4] data, knockon collisions[5], and Hesslow[6] corrections of RE collisions are included in the calculations.

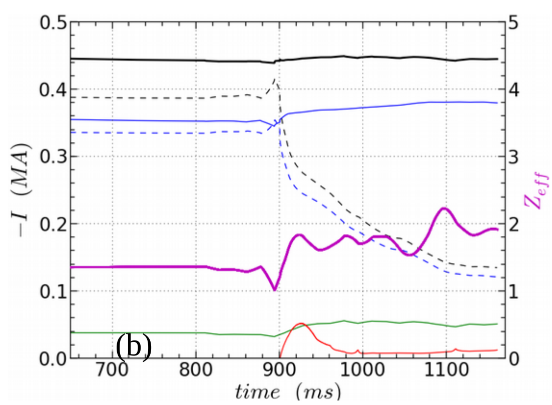

Fig. 2 Currents during Etor and Etor+LH phases. Solid black is total current for the Amp-Far equation. Solid blue from f_e. Black and blue dashed lines are Sauter formula at low and intermediate collisionality. Green line is bootstrap current. Red is runaway current. Purple is Zeff, on the right axis.

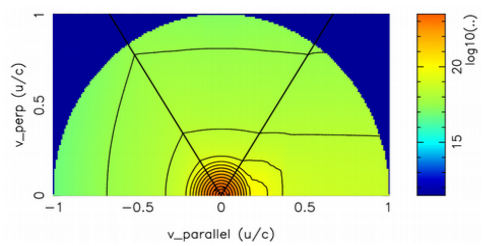

Fig. 3. Electron distribution at t=1160 ms, rho=0.5a, showing combined effects of LH and Etor.

We first examine the Ohmic and Ohmic+LH period of the discharge up to the flake event, that is, up to t=1160 ms. *New levels of fidelity between experiment and computed current are obtained (at least in this case).* CQL3D is run in a mode in which Zeff (taken to be radially uniform) is adjusted at each time step so that the total plasma current can be maintained at the experimental value of 425 kA. Results are shown in Fig. 2, which gives calculated total current Ip, the several Ip components, and the value of Zeff required to approximately maintain the target current. Note that in the Ohmic phase, Zeff~1.4. This is in general agreement with experiment, which was otherwise not well-matched in the past. In the presence of the LH, we obtain the usual 2D in velocity distributions, influenced primarily by the Etor and LH Dql (Fig 3). Fig. 4(a) and (b) give time history of the toroidal electric field and CQL3D current from the distribution functions, showing evolution on resistive time scales, and general broadening of the current density profile.

For driving the Ampere-Faraday equations, two new “currents” have been added to obtain the total CQL3D calculated current (solid black in Fig.2): (1) bootstrap (light green), and (2) the difference between the two dashed curves, the top/bottom being Ohmic current corrected finite/low collisionality [7]. CQL3D calculates the low collisionality Ohmic current (which is reasonably close to [7] although should be the same since the same code was used). We correct CQL3D Ohmic current to finite collisionality by adding the difference current. This current, plus the BSCD, make the difference between fitting the experimental current with reasonable Zeff (as shown) versus simulated Zeff being driven to an unreasonable value of 1.0 .

Simulations of the flake-period, beyond 1160 ms, *have thus far only proceeded to t=1240 ms.* Two approaches for modelling the flake are reported here. For the *first flake-model,* the above method of adjusting Zeff to maintain Ip is continued. For approach (1), we obtain the currents shown in Fig. 5, with CQL3D restarted in time from the pre-flake solution at t=1160ms. As Te drops from the W-radiation, the calculation gives that Zeff drops quite quickly (20 ms) to 1.0, trying to keep the total toroidal current constant but contrary to the flake effects. There is a prompt runaway electron (RE) current (red line) of about 1/3 of Ip , but it and the other currents are insufficient to support the observed 425 kA. Within 80 ms the RE current reaches about 2/3 of Ip. Knockon current can be expected to take over. *But, the model needs additional sources of current in order to match the experiment, a subject for future research.*

The *second flake-model* uses a pellet-like model for the incoming tungsten flake. The incidental W-flake hits the plasma edge at t=1160 ms, traveling at free-fall velocity from the upper vacuum vessel wall (which models reasonably well the progression of the observed cooling wave in to the plasma core. We use a simple ablation model

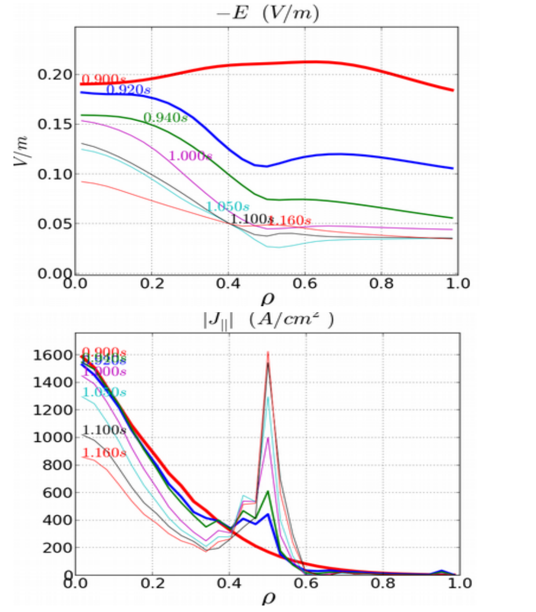

Fig. 4(a). Toroidal electric field versus radius for times from the beginning of the RF on to the beginning of the flake. Edge values are from data. 4(b): Calculated electron current from the distribution functions. The current profile broadens.

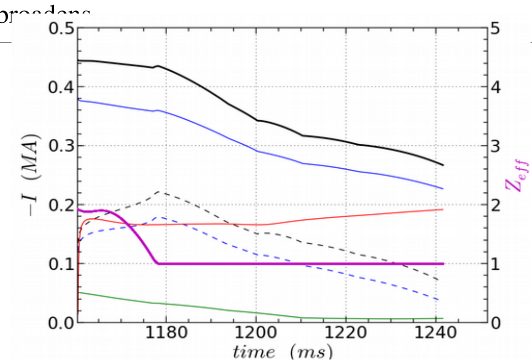

Fig. 5. Toroidal currents versus time. Curves are as described for Fig. 2. This is for the Zeff adjustment model. But Zeff moves quickly to 1.0, and current continues to drop below the experimental value.

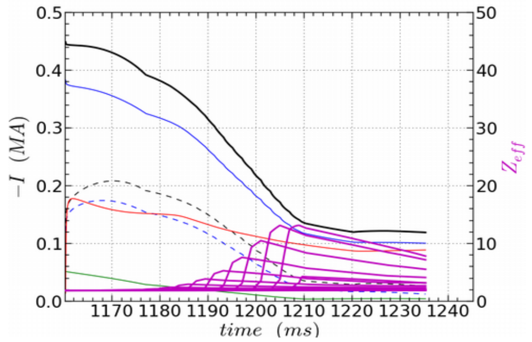

Fig. 6. Same as Fig. 5, except from the pellet-like model for the W-flake.

(Parks, personal communication, 2020; pellet size is chosen so that it just makes it to the plasma center. Results are shown in Fig. 6. The magenta lines reflect the progress of the W-flake in to the plasma, since Zeff varies with radius in this second model. The background ion density is varied so that electron density is kept constant. Most of the RF power is collisionally damped, as shown in Fig. 7. There is an interesting negative QL RF absorption (unstable LH, damped elsewhere) in the top plot, but here it is small. The bottom plot shows most of the power is collisionally damped, a robust effect. This will heat the plasma edge and broaden the Ohmic and runaway electron current. We have varied Zeff used in the collisional damping from 4 to 2, in GENRAY, but the total driven current only increased about 15%. The overall result is that the pellet-like model gives even less total Ip than the varying-Zeff model; Ip drops to about a 1/4 of the experimental value.

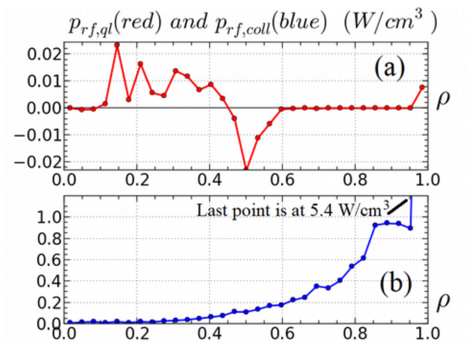

Fig. 7(a). Resonant QL LH power absorbed at t=1240ms 7(b). Collisional absorption is 50X greater.

Our conclusion regards the flake modeling is that most of the LH power ends up being absorbed collisionally towards the plasma edge, and should contribute to a broadened plasma current profile. This off-axis driven current is similar to recently reported TQ in DIII-D discharges due to error magnetic field stochasticity, followed by discharge healing due to sudden off-axis confinement improvement in a large 1/1 island, and off-axis Te-increase[8]. The above LH C-Mod interpretation further supports a new, hopefully robust, LH disruption control approach.

The current drive modeling of the LHCD before the flake appears to accurate. Future work will investigate modeling of methods and refinements to account for the markedly smaller model driven toroidal current during the flake event compared to the experiment.

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