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Issues Concerning the Simulation of the H-mode Pedestal and ELMs in Tokamaks

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Models have been developed for use in integrated simulations with the objective of predicting the height, width, and shape of the pedestal at the edge of H-mode plasmas in tokamaks. In addition, simulation models predict the frequency of the periodic Edge Localized Modes (ELMs) that occur in most H-mode discharges and the effects of the ELMs on the plasmas profiles. Predictive models for the pedestal and for the ELMs are needed in order to make accurate predictions for the performance of burning plasma experiments [1,2]. Our research on this topic is proceeding through the following stages:

In the first stage, stand-alone models were developed for the H-mode pedestal [3,4] and were used as the boundary conditions in a core integrated modelling code [1,2,5]. These simulations do not include a dynamic model for ELMs. It was found that the agreement between the results of these simulations and experimental data was similar to the agreement that was obtained in corresponding simulations that used experimental data for the boundary conditions at the top of the pedestal [5].

In the second stage, a continuous, self-consistent model is used for the core and pedestal, together with a time-dependent model for ELMs. This approach is currently used in the JETTO code [6,7,8,9] and in the ASTRA code [10,11]. At this stage of the research, relatively simple models are used for the suppression of anomalous transport in the steep gradient region of the pedestal and for the mechanisms that trigger ELM crashes.

For the third research stage, there is a need to develop more sophisticated models based on first-principle theory and computation of the pedestal and ELM crashes. Three of the issues that need to be resolved are outlined below.

1. Current density in the pedestal: A relatively high current density is driven in the pedestal by the bootstrap current, which, in turn, is the result of the steep temperature and density gradients in the pedestal. The high current density in the pedestal has a direct effect on peeling modes and on current-driven kink modes, which could initiate ELM crashes. The increased current density in the pedestal also has the effect of reducing the magnetic shear in the pedestal. The magnetic shear affects the stability condition for pressure-driven ballooning modes and these modes could also initiate ELM crashes. If the pedestal current density drives the magnetic shear to low enough levels, access to second stability could be achieved, and the pedestal pressure gradient could reach values that are several times higher than the pressure gradient allowed in the first stability region [8,9]. Hence, the current density that is driven in the steep gradient region of the pedestal plays a crucial role in determining the height of the pedestal and the conditions needed for ELM crashes.

JETTO and ASTRA simulations indicate that the current density in the pedestal decreases dramatically after each ELM crash [7,9,11] as shown in Fig. 1. The extent of the decrease in the current density during and immediately following each ELM crash has a significant effect on the length of time between successive ELM crashes. If the pedestal current density remains high immediately following an ELM crash, less time is required for the pedestal current density to build up to the level needed to trigger a peeling mode resulting in the next ELM crash. In addition, the pedestal current affects the magnetic shear, which, in turn, affects the stability condition for the pressure-driven ballooning modes.

At the present time, the models used in the JETTO and ASTRA codes compute the diffusion of current density using neoclassical electrical resistivity. Simulation results suggest that this current diffusion process does not remove the current density in the pedestal fast enough during an ELM crash to stabilize the current-driven peeling mode resulting in an unrealistically extended ELM crash [12]. The MHD stability analysis of the pedestal, just before an ELM crash, indicates that an instability with many poloidal harmonics becomes unstable near the edge of the plasma [13]. During the non-linear evolution of the instability that causes each ELM crash, it is likely that there are numerous fine-scaled magnetic reconnection layers that remove the pedestal current density on the time scale of an ELM crash, which is less than a millisecond. A model is needed for use within integrated modelling codes to predict the fraction of pedestal current density that is removed by these magnetic reconnection layers during each ELM crash. The model might be expressed in terms of a hyper-resistivity extension to the magnetic diffusion equation [14]. Non-linear simulations of ELM crashes could also be used to construct a model for the shapes of the temperature and density profiles immediately following each ELM crash.

In the JETTO and ASTRA simulations, the current that is removed from the pedestal during each ELM crash moves into the core of the plasma, as shown in Fig. 1, while the total toroidal current is held fixed or evolves slowly in time. In reality, it is likely that at least part of the current that is removed from the pedestal during an ELM crash goes to the scrape-off-layer or the first wall as an eddy current. The current then diffuses back into the pedestal region during the time between ELM crashes. It is likely that inductive/resistive time scales of the wall and edge plasma control the diffusion of the current into the pedestal and, consequently, influence the period between ELM crashes. If this logic is true, then the integrated modelling codes have to be modified to include the effect of the eddy currents within the first wall in response to ELM crashes.

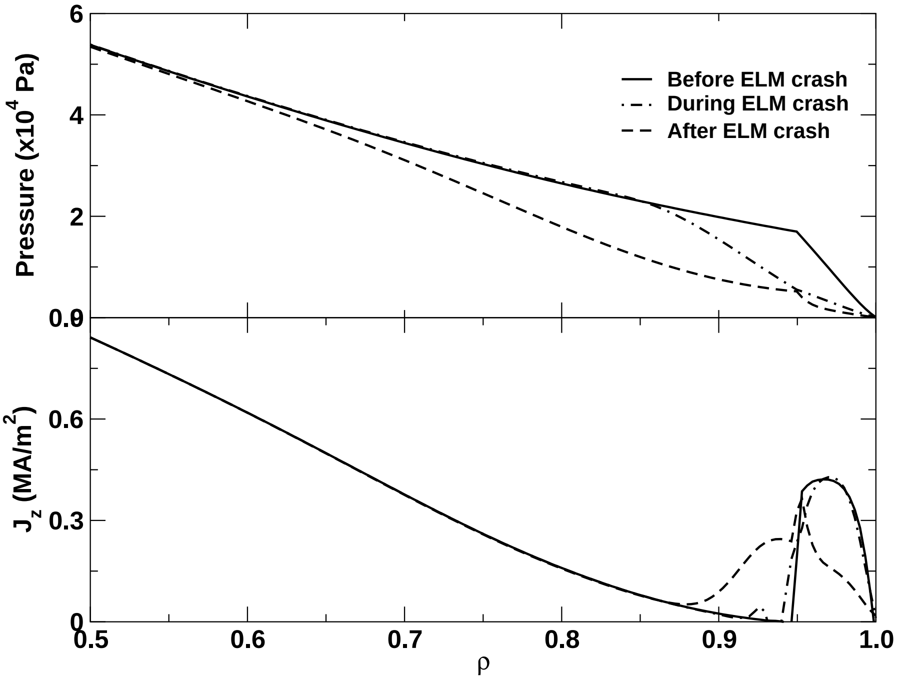

Fig. 1: Pressure and current density profiles from a simulation as a function of normalized minor radius before, during and after and ELM crash.

2. Channels of transport: If all the anomalous transport were completely suppressed by flow shear in the pedestal, then only neoclassical transport would remain. Ion thermal neoclassical transport is much larger than electron thermal neoclassical transport. As a result, when this assumption is used in simulations of low-density discharges, the electron temperature at the top of the pedestal becomes much larger than the ion temperature, in contradiction to experimental data [15]. Hence, the anomalous electron thermal transport must persist at some level while the anomalous ion thermal transport is reduced by flow shear. In general, it is likely that the different channels of transport are affected in different ways by the flow shear stabilization of the turbulence.

In the transport model currently used in our research [11], the Electron Temperature Gradient (ETG) mode contributes significantly to the electron thermal transport, but not to the ion thermal or particle transport. In that model, different flow shear stabilization rates are computed for the different modes that contribute to anomalous transport. It is assumed in that model that the ETG mode is not affected at all by flow shear, while the ion drift modes and the resistive ballooning modes are each affected by flow shear at rates that are computed using the de-correlation time scales for each mode of instability. The result is an ion temperature at the top of the pedestal that can be larger than the electron temperature. The model described here is currently being calibrated using the ASTRA code against experimental data by adjusting the coefficients of the flow shear rates for the different modes.

3. Edge Particle source: Experimental evidence indicates that the density profile is more perturbed by ELM crashes than the temperature profiles. Simulations indicate that the sources of ions are mostly localized near the pedestal, where neutrals from the walls are ionized. (The sources of heating power are more concentrated in the central part of the plasma.) Also, simulations indicate that gas puffing and the pedestal density profiles probably have a strong effect on the behaviour of ELMs [9]. An accurate modelling of the particle source requires an accurate modelling of the distribution of neutrals passing into the plasma through the separatrix. Hence, modelling of the neutrals, scrape-off-layer, and core plasma has to be integrated together.

With advances in understanding the evolution of the current density in the pedestal, the channels of transport, and how particle sources affect the density profile in the pedestal, improved pedestal and ELM models will be available for use within integrated fusion simulation modelling codes.

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