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Toroidal modeling towards understanding of ELM mitigation and suppression by RMP fields

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Edge localized modes (ELMs), in particular the so called type-I, have been the subject of decades long research. Significant progress has been made in theory and modeling, in particular in understanding the origin of these large bursts as the development of unstable, the peeling-ballooning modes [1]. The potential danger of ELMs to future large scale tokamak devices, in terms of causing severe material damages to plasma facing components, has only recently been realized [2]. This realization leads to extensive current research activities, aiming at finding good ways to control ELMs. Experimental efforts, utilizing various techniques such as resonant magnetic perturbations (RMP) [3], pellets injection [4], as well as vertical kicks [5], all show encouraging results. But the RMP so far appears to be the most successful technique for controlling type-I ELMs. In fact this technique has been tested essentially on all presently available major tokamaks where H-mode is achieved, including DIII-D, JET, MAST, ASDEX Upgrade, KSTAR, EAST and HL-2A. Either ELM mitigation, in which case the ELM bursting frequency is increased at the benefit of reduced amplitude per burst, or complete suppression of the instability, has been achieved depending on devices as well as on the plasma regimes in a given device.

Despite the huge experimental success in ELM control, theoretical understanding is still limited. This is of a particular concern for the RMP technique, which has been planned as the key ELM control approach in ITER. Lack of understanding, and lack of predictive capability for ITER, poses a severe challenge. Our work aims at improving theoretical understanding of the type-I ELM control using RMP fields, based on toroidal modeling. We use the single-fluid, resistive MHD code MARS-F [6] with toroidal flow to investigate certain key aspects associated with the ELM mitigation and suppression.

For ELM mitigation, we study the plasma response to the applied 3D RMP fields. By doing so, we find a correlation between different types of the plasma response, on one hand, and the experimentally observed controllability of ELMs on the other. More specifically, we find that the best ELM mitigation is achieved, when the applied vacuum RMP fields trigger the so called edge-peeling response from the plasma. This criterion, being now robustly validated against ELM control experiments in multiple devices [7], offers an alternative as opposed to the vacuum field based Chirikov criterion [8] that has previously been proposed and applied to various devices with mixed success. This contribution will show a systematic comparison, and the agreement obtained, between modeling and experiments in ASDEX Upgrade, using the new plasma response based criterion [9]. Furthermore, this new criterion also enables us to carry out detailed predictive study of the ELM control capabilities in ITER, by optimizing the RMP coil currents (both amplitude and phase) between different rows of coils [10].

Another key research topic that we pursued is closely related to the ELM suppression. There has been strong experimental evidence, at least in devices such as DIII-D [11], EAST [12] and recently ASDEX Upgrade [13], showing that ELM suppression is accompanied by the RMP field penetration near the pedestal top. This in turn is often associated with the observation of the plasma flow (often the perpendicular electron flow but sometimes also the ExB flow) being near or crossing zero at a rational surface near the pedestal top. This motivated us to perform a series of study on the plasma edge flow screening as well as the lack of screening (penetration) under the slow flow condition. We find that, at very slow flow, plasma enters into a new screening regime (referred to as GGJ-screening) [14], which is closely related to the average curvature physics that stabilize the tearing mode. In this regime, slower flow leads to stronger screening, as opposed to the conventional situation (e.g. the so called resistive-inertial regime), where faster flow leads to stronger screening. On the other hand, the presence of a relatively large magnetic island can eliminate the average curvature effect, by flattening the pressure profile inside the island. As a consequence, the GGJ-screening can be eliminated, leading to field penetration at slow flow [15].

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