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# MHD-calibrated ELM model in simulations of ITER

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## INTRODUCTION

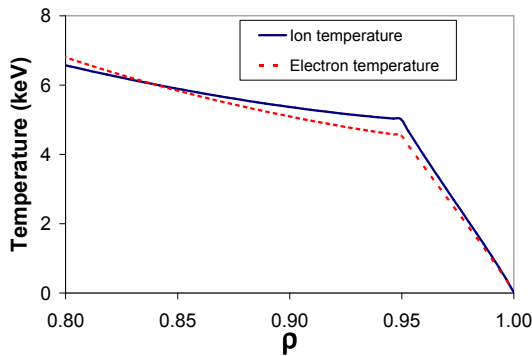
Self-consistent simulations of ITER are carried out using the JETTO predictive integrated modeling code [1] in which theory motivated models are used for the H-mode pedestal and for the stability conditions that lead to the ELM crashes. Each ELM crash results in a rapid loss of particles and energy from the edge of the plasma, which can reduce the average global energy content by 10-20%. In addition, ELMs play an essential role in the control of the height of the pedestal in H-mode plasmas. A stability analysis is carried out using the stability analysis codes, HELENA and MISHKA, to confirm the stability criterion used to trigger ELM crashes in the JETTO code. Possible access to second stability of the ballooning mode is investigated using the HELENA and MISHKA stability analyses. With access to second stability, the edge pressure gradient can increase to a higher level, which results in a higher temperature at the top of the pedestal and, consequently, better plasma performance. The issue of ELM behavior and access to second stability is important for the success of ITER.

## PREDICTIONS FOR ITER

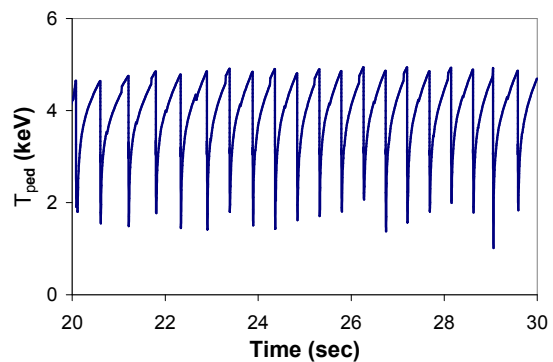
In this study, it is assumed that the ITER plasma is a type I ELMy H-mode discharge. The core transport is described by combining the Mixed Bohm/gyro-Bohm anomalous transport model with the NCLASS neoclassical transport model. In the pedestal region, it is assumed that all anomalous transport is completely suppressed and the ion neoclassical transport at the top of the pedestal is used to compute all channels of the transport within the pedestal. The reduction of transport within the pedestal results in a steep pressure gradient at the edge of the plasma, which, in turn, produces a large bootstrap current density in the pedestal. In the

simulation, an ELM crash is triggered by a pressure-driven ballooning mode if anywhere within the pedestal region the normalized pressure gradient exceeds the ballooning mode stability limit or by a current-driven peeling mode if the edge current density exceeds the critical edge current density of the peeling condition. During each ELM crash in the JETTO simulations, transport within the pedestal is increased significantly, resulting in the loss of plasma energy and particles. The transport model and instability criteria employed in this paper have been calibrated against JET H-mode experimental data [2].

Simulations are carried out for the baseline ITER parameters: major radius (6.20 m); minor radius (2.00 m); plasma current (15.0 MA); toroidal magnetic field (5.3 T); elongation at the separatrix (1.85); triangularity at the separatrix (0.48); electron line average density ( $1.05 \times 10^{20} \text{ m}^{-3}$ ), and effective charge (1.4). The effects of sawtooth oscillations, which periodically reduce the central plasma profiles, are also included. For simplicity, it is assumed that the mixing radius of each sawtooth oscillation extends from the plasma center to the  $q = 2$  radius, and that a sawtooth oscillation occurs every 10.0 s. Total plasma radiated power is assumed to be 30 MW and the radiated power density profile is taken from that for JET discharge 52009. In the JETTO simulation, it is assumed that the deuterium and tritium mix is 50:50 and that the fixed pedestal width is 6 cm.



**Figure 1:** The edge ion and electron temperature profiles are plotted at the time prior to an ELM crash from  $\rho = 0.80$  to the separatrix.



**Figure 2:** Ion temperature at the top of the pedestal is plotted as a function of time. A decrease in pedestal temperature indicates an ELM crash.

It is found that the ion and electron temperature profiles are peaked at the center of the plasma while the electron density profile is relatively flat. The edge ion and electron temperature profiles prior to an ELM crash are shown in Fig. 1. The ion and electron temperatures at the top of the pedestal just prior to an ELM crash are found to be approximately 4.9 keV and 4.5 keV, respectively. It is also found in the simulations that as a result of the strong bootstrap current density within the edge barrier, the total current density has a local

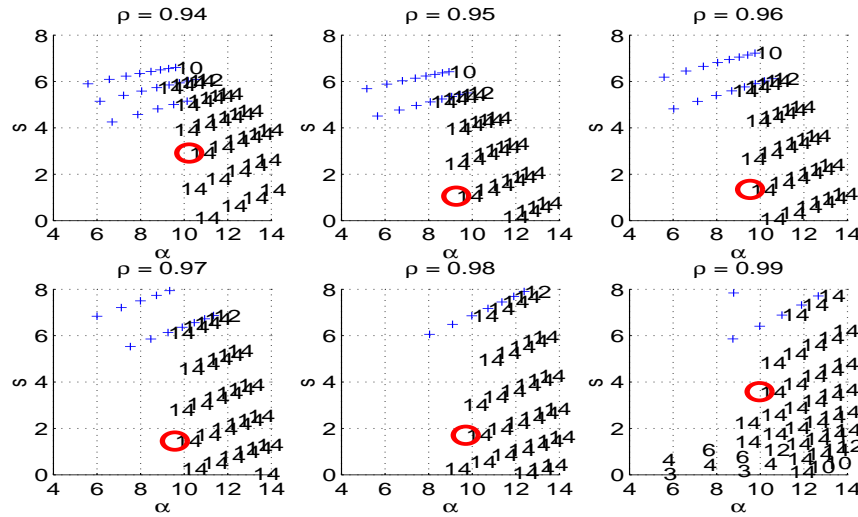
peak in the pedestal region. Because of the large current density near the edge of the plasma, the magnetic shear within the pedestal decreases to a low value, which can lead to access to the region of second stability on the  $s$ - $\alpha$  plane. In the JETTO simulations of ITER, it is found that the ELM frequency is about 2 Hz, as shown in Fig. 2. All ELM crashes appear as compound ELM crashes in which a pressure-driven ballooning mode is unstable first and then the current-driven peeling mode becomes unstable. These compound ELM crashes have been observed in previous JETTO simulations [3]. The current-driven peeling mode becomes unstable after the first part of the ELM crash because of the reduction in the pressure gradient associated with the initial ballooning mode instability. The reduced pressure gradient results in a reduction of the current density required in the pedestal region for the occurrence of a current-driven peeling instability. It is also found that associated with each ELM crash, the stored energy is reduced by approximately 10%. It's worth noting that such a high level of energy losses during each individual ELM crash can lead to a strong sputtering of target plate and, therefore, minimization of the ELM amplitude will be required in the ITER base scenario.

### STABILITY ANALYSIS

In order to confirm the validity of the criteria used to trigger ELM crashes in JETTO simulation, the JETTO results are evaluated using the HELENA and MISHKA MHD stability analysis codes. The HELENA code takes as input the self-consistent equilibrium produced by the JETTO code together with the corresponding magnetic configuration, at a time just prior to an ELM crash. The HELENA code then refines the equilibrium in order to provide the resolution required for the stability analysis. This refined equilibrium is then used in the HELENA code to generate a ballooning stability diagram of magnetic shear versus normalized pressure gradient ( $s$ - $\alpha$ ). The output of HELENA is also used in the MISHKA code to evaluate the stability criteria for finite- $n$  ballooning and low- $n$  kink/peeling modes, for toroidal mode numbers in the range of  $n = 1$  to  $n = 14$ .

Fig. 3 shows the stability  $s$ - $\alpha$  diagram computed using the HELENA and MISHKA codes for the ITER simulation. In the figure, the stability  $s$ - $\alpha$  diagram is plotted for the  $\rho = 0.94, 0.95, 0.96, 0.97, 0.98$  and  $0.99$  flux surfaces. The circle symbol represents the location of the operational point for the pressure gradient at that flux surface. The region of instability associated with the infinite- $n$  ideal ballooning modes is indicated with crosses and the numbers indicate the most unstable mode of finite- $n$  ballooning and low- $n$  kink/peeling modes at each location on the  $s$ - $\alpha$  plane. As shown in Fig. 3, the normalized edge pressure gradient appears to

be in the second stability region and to be limited by a finite- $n$  ballooning mode ( $n = 14$  toroidal mode). The access to the second stability region is probably a result of the strong shaping of the ITER plasma, particularly since the ITER design considered has a triangularity of 0.48 at the separatrix.



**Figure 3:** Stability results obtained using the HELENA and MISHKA stability codes are plotted on an  $s$ - $\alpha$  stability diagram at  $\rho = 0.94, 0.95, 0.96, 0.97, 0.98$  and  $0.99$  for ITER simulation.

### CONCLUSIONS

Self-consistent core-edge simulations of ITER are carried out using the JETTO integrated modeling code. In these simulations, ELM frequency is about 2 Hz. Each ELM crash appears as a compound ELM crash, where the first part of the ELM crash is triggered by a pressure-driven ballooning mode and the rest is triggered by a current-driven peeling mode. It is found that the ion and electron temperatures at the top of the pedestal prior to an ELM crash are 4.9 and 4.5 keV, respectively. The high values of the ion and electron pedestal temperatures mainly result from access to the second stability of ballooning modes, where the edge pressure gradient is limited by finite- $n$  ballooning modes.

### ACKNOWLEDGMENTS

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