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Density Limits as Disruption Forecasters for Spherical Tokamaks

Jack Berkery[1], S.A. Sabbagh[2], C.J. Ham[3], M. Giacomin[4], V. Zamkovska[2], J. Butt[5], J. Riquezes[2], M. Tobin[2], S. Henderson[3], L. Kogan[3], B.S. Patel[3], R. Scannell[3], E. Trier[3] and B. LeBlanc[1]

[1] PPPL, [2] Columbia University, [3]UKAEA, [4]University of York, [5]Princeton University

e-mail (speaker): jberkery@pppl.gov

Fusion power output from spherical tokamaks would benefit from increased confined plasma density, but there exists a limit on the density before confinement is lost and the plasma current is disrupted. Understanding the physics of the density limit in spherical tokamaks (STs) by testing multiple theories and determining their utility for disruption forecasting is vital work to be carried out on present machines to have confidence in designs of stably operating future ST fusion pilot plants. This density limit has long been characterized by a simple, global Greenwald limit proportional to the plasma current and inversely proportional to the cross sectional area of the plasma. It is shown that in the database of discharges from the NSTX and MAST spherical tokamaks, the likelihood of disruption does increase above the Greenwald limit, and especially in the plasma current rampdown phase.

The physics of the density limit has been recently theoretically explored through local criteria. Several of these are now tested for STs [1] using the disruption event characterization and forecasting (DECAF™) code [2] for their potential effectiveness as disruption warning signals. The framework of the DECAF code, and its large database of discharge data from many machines, including these, represents an opportunity to test the density limit theories. For a limited set of NSTX discharges, a local island power balance criteria [3] was found to be less reliable, presently, than the Greenwald limit. An empirical critical edge line density (Bernert) [4] and a first-principles boundary turbulent transport limit (Giacomin) [5] have found some success in various conventional tokamaks. The Giacomin limit was derived from turbulent transport considerations at the separatrix, by balancing heat source and cross-field turbulent heat flux, derived from a quasi-linear non-local theory. In particular, turbulent transport is found to increase with edge collisionality, which increases with density. At high density, turbulent transport is catastrophically large, therefore causing a collapse of the edge pressure gradient, which is followed by the onset of MHD instabilities and the subsequent plasma disruption.

These limits were tested for MAST-U, which has a detailed electron density profile measurement. Both were found to have similar dependencies. MAST-U has mostly operated under the Greenwald limit so far [6], but in a limited set of MAST-U discharges that appear to disrupt due to rising density at values under the Greenwald limit, crossing of the Giacomin limit ($n_{e,edge,crit}$) occurred close to the time of disruption. Figure 1 shows the trajectories of MAST-U plasmas in the space of $n_e/n_{e,edge,crit}$ vs. n_e/n_{GW}, showing that many of the discharges cross the edge limit and disrupt before the Greenwald limit.

Finally, these limits were evaluated for their potential use in real-time, and it was found that with the necessary real-time inputs and with refinement through further testing, these limits could be implemented in a real-time disruption forecasting system.

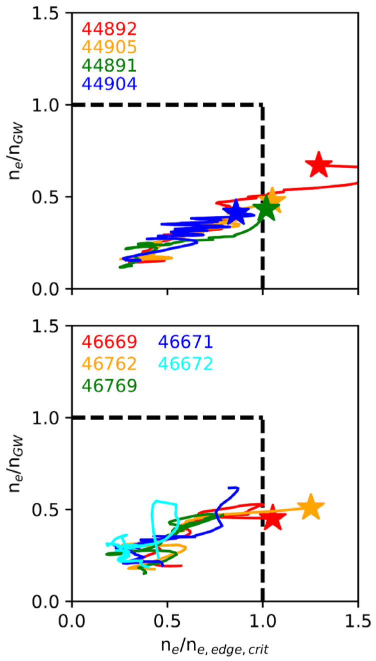

Figure 1: Plots of $n_e/n_{e,edge,crit}$ vs. n_e/n_{GW} for (top) four MAST-U Ohmic ~ 600 kA discharges, and (bottom) five beam heated ~750 kA discharges. Stars indicate disruptions.

References

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