NONDIMENSIONAL CONFINEMENT SCALING IN SIMILAR NEGATIVE TRIANGULARITY PLASMAS ON THE DIII-D AND TCV TOKAMAKS

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Similar experiments were performed on the DIII-D and TCV tokamaks to explore the scaling of energy confinement in negative triangularity plasmas in nondimensional units. Near up-down symmetric plasmas with large top-bottom averaged triangularity, $\delta_{avg} \sim -0.5$, were created in a lower single null configuration, displayed in Fig.1, with the shape of the separatrix being closely matched between the two devices. The normalized energy confinement is found to weakly improve at increasing collisionality and, between the two devices, shows a machine size scaling behavior between Bohm and gyroBohm.

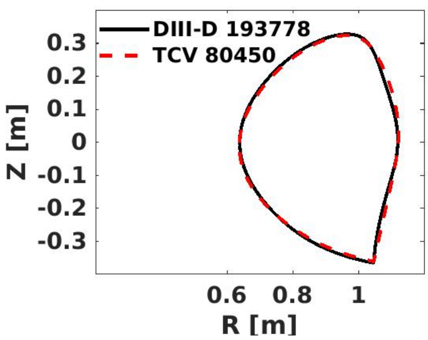

Figure 1. Comparison of the separatrix for TCV discharge #80450 (dashed red) and DIII-D discharge #193778 (full black) scaled to fit inside the TCV vessel.

Negative triangularity (NT) configurations are emerging as potentially viable solutions for future reactors thanks to their ability to sustain H-mode grade levels of confinement and pressure despite the absence of an edge pedestal. The latter property is beneficial in several aspects, such as eliminating the need for active mitigation or suppression of edge localized modes (ELMs), low impurity retention, a wider Scrape-Off Layer heat flux width, and the possibility of employing impurity induced mantle radiation to dissipate power from inside the last closed flux surface [1]. Although results in present devices are encouraging, the design of a prospective reactor operating with NT plasmas requires knowledge of how the energy confinement scales to reactor conditions. The operating point of future devices is commonly designed using formulas derived from engineering scaling of confinement which, however, require large multi-machine datasets because of large uncertainties in extrapolating results to reactor conditions and, in general, to issues associated to identifying the correct regression variables and to accurately determining the corresponding parametric dependencies [2]. In the case of NT configurations, such uncertainties are even greater because of the paucity of devices that are able to properly execute the experiments, which severely curtails the variable space usable for the regression analysis. In contrast, non-dimensional analysis [3] offers a theory-based tool that can be used in a more straightforward way to quantitatively compare results to state of the art numerical models. Once the models recover the experimental measurements, they can be used to confidently extrapolate fusion performance in future reactors.

This work reports the first sedulous experimental investigation of NT confinement scaling across multiple machines, attempting to determine the dependence of the energy confinement on normalized collisionality, ν_*, and on the Larmor radius normalized to machine size, ρ_*. The dependence on the normalized plasma pressure, β, and on ratios of like quantities was not probed due to their lower importance within the experimental resources available to this study. On both devices, magnetic field, auxiliary power, plasma current and density were altered in such a way as to individually vary the two normalized quantities above while maintaining fixed the other quantities of interest over most of the normalized minor radius. More specifically, experiments were designed to explore primarily beam-heated plasmas without radio-frequency (RF) heating to avoid inconsistencies when exploring low-field discharges for which RF auxiliary power would not be effectively coupled. This resulted in plasmas with electron to ion temperature ratio near unity and effective charge below two throughout most of the plasma volume. Since NT plasmas routinely operate with the highest confinement at edge safety factor less than three and the energy confinement is observed to strongly improve with increasing plasma current, all discharges on both devices were executed near the lowest achievable edge safety factor which, owing to the constraints of the joint experiment, corresponds to $q_{95} = 2.8$; the value of the safety factor on axis was maintained near unity by sawteeth, thereby making the magnetic shear over radius similar among all cases. Given operational difficulties with obtaining quiescent discharges at reduced field, near balanced beam torque plasmas were not executed.

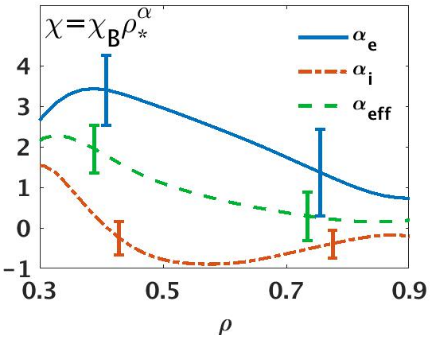

Figure 2. Radial dependence of the exponent determining the ρ_* scaling for electron (full blue), ion (dash-dotted red) and effective (green dashed) energy conductivity for the DIII-D non dimensional experiment.

The normalized energy confinement shows a weak, though positive dependence on collisionality on both devices, $B_T\tau$ $\nu_*^{0.04\ +/-\ 0.05}$ on DIII-D and $B_T\tau$ $\nu_*^{0.09\ +/-\ 0.03}$ on TCV, which is understood in terms of collisionality quenching of micro-instabilities. The normalized energy confinement scales as gyro-Bohm (favorable) on TCV but scales as Bohm (unfavorable) at the lower ρ_* values of DIII-D. This counter-intuitive result might depend on different operational conditions on the two devices and is currently being investigated. More detailed transport analysis carried out with the TRANSP [4] code on the DIII-D experiment indicates that the near Bohm scaling of the energy confinement is due to a combination of Bohm scaling for ions and near Gyro-Bohm for electrons, as displayed in Fig. 2, with one fluid analysis showing an intermediate behavior. This is consistent with previous results in positive triangularity L-mode plasmas on DIII-D where ion and electrons share the total energy flux [5], and is indicative of differences in behavior for the two species from a turbulence standpoint. The Bohm and weak-collisional nondimensional scaling observed on DIII-D is consistent with an engineering regression carried out on many more discharges with the same plasma shape, when the exponents are converted to their nondimensional counterpart. Present work is finalizing the transport analysis for the most recent TCV experiments to compare results to those on DIII-D as well as to link non dimensional to engineering scaling results on both devices.

The confinement scaling results outlined in this work are important for the NT scenario and will motivate increased investigation and understanding of the fundamental turbulence scaling through detailed numerical modelling and validation. A complete characterization of the confinement scaling in NT plasmas will determine whether more advanced scenarios featuring improved confinement will need to be developed for reactors.

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