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Spatially Dependent Simulations and Model Validation of Runaway Electron Dissipation Via Impurity Injection in DIII-D and JET Using KORC

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The Kinetic Orbit Runaway electrons Code (KORC) {1} has been extended to model post-disruption runaway electron (RE) dissipation by impurity injection incorporating state-of-the-art collisional models for partially ionized impurities {2} and models of thermal electron and impurity spatiotemporal dynamics. We fit these models to data from the DIII-D and JET tokamaks, exploring the role of spatial effects as compared to previous studies (e.g. Ref. {3}). This work presents model validation through detailed comparisons of shattered pellet injection (SPI) and massive gas injection (MGI) dissipation of REs and a detailed study of different collisional dissipation models. We find that the evolution of the spatiotemporal electron and impurity density profiles due to impurity injection and interaction with REs plays a significant role in the dissipation process and is an outstanding and critical modeling need. Additionally, we find that the dissipation timescale is fundamentally sensitive to the initial RE energy distribution. Beyond validation, this work allows for comparing and optimizing different impurity-based mitigation scenarios and their scaling towards ITER.

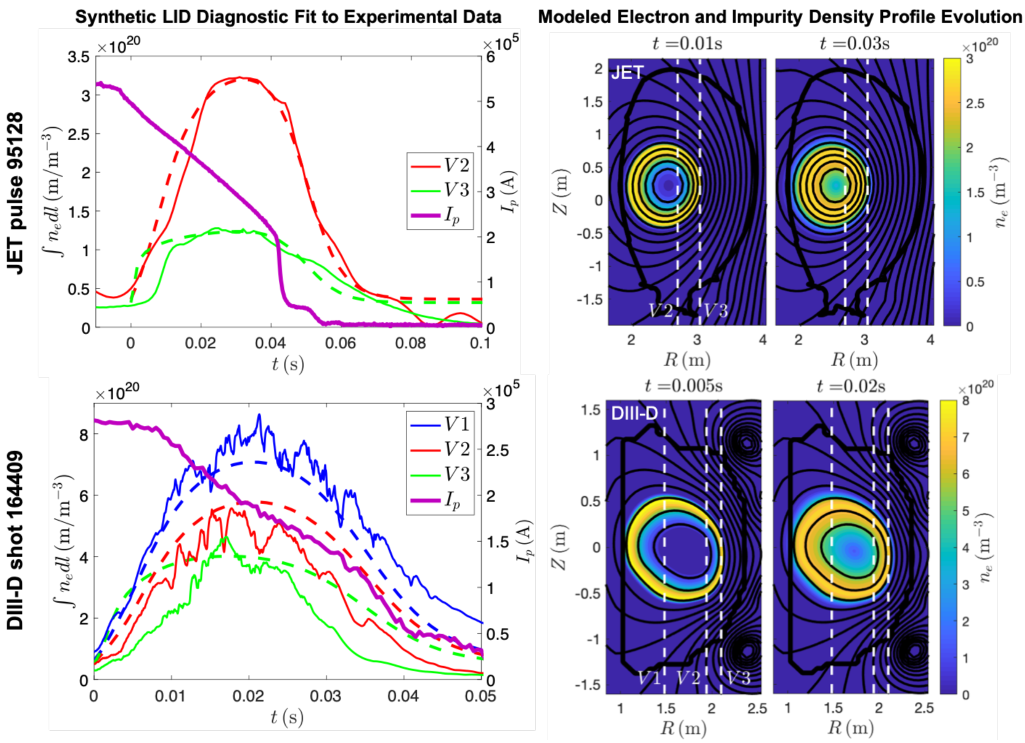

Figure 1: Top row panels correspond to JET pulse 95128 with Ar SPI and bottom row panels correspond to DIII-D shot 164409 with Ne MGI. Solid traces in the left panels show experimental plasma current and LID diagnostics, and dashed traces show synthetic LID diagnostics of the fitted model used in KORC calculations. The right panels show the evolution of the model spatiotemporal electron density profile corresponding to the synthetic LID diagnostics displayed in the left panels.

KORC has been extended to serve as a general framework for simulating RE physics, including validation and verification of the theoretical models needed to understand RE dissipation by impurity injection. To make calculations of RE dissipation numerically feasible, the RE guiding center orbit equations of motion have been implemented and are evaluated from experimental fields and plasma profile information via interpolation. The magnetic field configuration is held fixed and taken from experimental reconstructions, with EFIT used for JET and JFIT for DIII-D, as seen in overlaid (black) contours in the rightmost panels of Fig. 1 for JET pulse

95128 and DIII-D shot 164409. The toroidal electric field uses a 1/R spatial model fit to multiple experimental loop voltages. Initial RE distributions are initialized using a flexible sampling algorithm to initialize desired multidimensional distributions. The electron and impurity density profiles are taken from ad hoc models with a variable impurity charge state ratio that are fitted to experimental data using a synthetic line-integrated electron density (LID) diagnostic at multiple locations. The solid traces in the left panels of Fig. 1 correspond to experimental data from JET pulse 95128 with Ar SPI (top) and DIII-D shot 164409 with Ne MGI (bottom), and dashed traces correspond to synthetic LID signals for the profile shown in the right panels of Fig. 1 that are used in KORC calculations. A linearized, relativistic, Coulomb collision operator has been implemented via a Monte Carlo approach, where the effects due to bound electrons of partially ionized impurities are implemented through various models {2}. Additionally, synchrotron and bremsstrahlung radiation are included through additions to the guiding center orbit equations of motion.

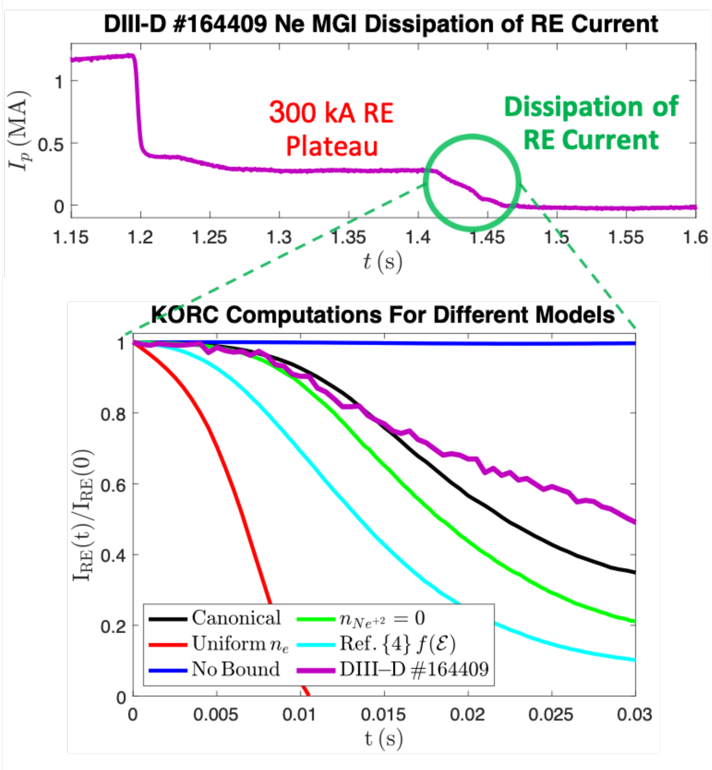

Figure 2: Top panel, DIII-D shot 164409 showing the dissipation of RE current resulting from Ne MGI. Bottom panel, KORC simulation results compared to DIII-D (violet trace). The critical importance of including bound electron physics and a spatiotemporal density profile for accurate modeling is evident (black trace) compared to without bound electrons (dark blue trace) or constant and uniform density (red trace). The dependence on different impurity charge state mix (green trace) and different initial energy distribution (cyan trace) is also shown.

The flexibility of KORC allows for simulations employing a hierarchy of models. Fig. 2 shows experimental plasma current from DIII-D shot 164409 with Ne MGI (top panel) and corresponding modeling results from KORC (bottom panel). The canonical case (black trace) includes bound electron physics, spatiotemporal electron and impurity density profiles fitted according to Fig. 1, a mix of singly and doubly ionized Ne, and an initial 10 MeV monoenergetic RE distribution. The critical importance of including bound electron collisional effects is evident from the different timescales of the without bound electrons (dark blue trace) and canonical cases. This physics is not only important for capturing accurate dissipation rates, but also the difference in dissipation rates for different injected impurities (not shown) and impurity charge state ratios (green trace). The KORC simulations also show a significant importance on the inclusion of a spatiotemporal density profile, as indicated by the difference between the constant and uniform density (red trace) and canonical cases. The initial energy distribution also plays an important role in the simulated dissipation timescale, shown by the difference between the canonical case and a case using an energy distribution inferred from a separate DIII-D study {4} (cyan trace). Interestingly, in the present work we find that for RE dissipation, as opposed to RE generation, the toroidal electric field plays a smaller role even when scaled (not shown), albeit a role that increases as the dissipation timescale increases. We additionally find that synchrotron and bremsstrahlung radiation have a comparatively minor effect (not shown). These results indicate the importance of including bound electron physics and spatiotemporal density evolution for assessing the efficacy and optimization of

RE dissipation strategies for ITER.

{1} Carbajal et al., Phys. Plasmas 24, 042512 (2017)
{2} Hesslow et al., Phys. Rev. Lett. 118, 255001 (2017)
{3} Martin-Solis et al., Nucl. Fusion 57, 066025 (2017)
{4} Hollmann et al., Phys. Plasmas 22, 056108 (2015)

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