Drift surface solver for runaway electron current dominant equilibria

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Runaway electron current generated during the Current Quench phase of tokamak disruptions could result in severe damage to future high-performance devices [1]. In the most disastrous scenario, significant portion of the original plasma current could be converted into runaway electron current, and all of their kinetic energy as well as a large portion of the magnetic energy it carries could be unleashed locally [2]. To control and mitigate such runaway electron current, it is important to accurately describe the runaway electron current dominated equilibrium first, based on which further stability analysis could be carried out. This could not be done with traditional Grad-Shafranov equation, since the current carrier is not following the magnetic field line and the current no longer flow along the flux surfaces. Instead, the current will follow the drift surface of the runaway electrons, which is essentially the constant canonical angular momentum surface in the axisymmetric geometry [3,4].

To resolve this problem, we derive a Grad-Shafranov-like equation solving for the axisymmetric drift surfaces of the runaway electrons instead of the magnetic flux surfaces for the simple case that all runaway electron shares the same parallel momentum and is the dominant current carrier. This new equilibrium equation is obtained by considering the toroidal symmetry and the new force balance equation of the runaway electron fluid, which in turn is obtained from the Euler-Lagrangian equation of the strongly passing runaway electrons [3]. This new equilibrium equation is then numerically solved with given right hand side profiles as well as given boundary conditions.

In this study, we look at simple rectangular wall cases with both ITER-like and MAST-like geometry parameters. We first show that we obtain exact the same equilibrium compared with the traditional Grad-Shafranov solution in the negligible parallel runway electron momentum limit. The deviation between the drift surfaces and the flux surfaces is then readily obtained in the finite runaway electron momentum cases, and they are found to be well confined even in regions with open field lines. Any change of the runaway electron parallel momentum, such as those caused by collision with background species [5], radiative drag [6], kinetic instabilities [7] or toroidal electric field is found to result in a horizontal current center displacement even without any changes in the total current or the external magnetic field. The runaway current density profile is found to affect the susceptibility of such displacement, with flatter profiles result in more displacement by the same momentum change. It is found that this effect is more pronounced in smaller, compact device and weaker poloidal field cases.

Another interesting finding is that, with up-down asymmetry in the external poloidal field, the aforementioned horizontal displacement is accompanied by a vertical displacement of runaway electron current, which could contribute to the VDE of the runaway electron current during the current quench phase.

The above results demonstrate the dynamics of current center displacement caused by the momentum space change in the runaway electrons, and pave way for future, more sophisticated runaway current equilibrium theory with more realistic consideration on the runaway electron momentum distribution. This new equilibrium theory also provides foundation for future stability analysis of the runaway electron current.

References

[1] Lehnen M, Aleynikova K, and Aleynikov P B et al. 2015 J. Nucl. Mater 463 39-48
[2] Martín-Solís J R, Loarte A, and Lehnen M 2017 Nucl. Fusion 57 066025
[3] Cary, John R, Brizard, and Alain J 2009 Rev. Mod. Phys 81 693-738
[4] Liu C, Qin H, Eero Hirvijoki,Wang Y L, and Liu J 2018 Nucl. Fusion 58 106018
[5] Hesslow L, Embréus O, Stahl A , DuBois T C, Papp G, Newton S L, and Fülöp T 2017 Phys. Rev. Lett 118 255001
[6] Martín-Solís J R, and Sánchez R 2008 Phys. Plasmas 15 112505
[7] Liu C, Eero Hirvijoki, Fu G Y, Brennan Dylan P, Bhattacharjee Amitava, Paz-Soldan Carlos 2018 Phys. Rev. Lett 120 265001