Toward Understanding Runaway Electron Generation in Disruptions

A White Paper Submitted to the DOE Workshop on Integrated Simulation by

Dylan Brennan[1], Chang Liu[1], Allen Boozer[2]
Plasma Physics Laboratory, Princeton University
Department of Applied Physics and Applied Mathematics, Columbia University

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Introduction

Understanding the physics of the generation and dissipation of runaway electrons in magnetically confined plasmas is among the greatest important challenges for our field going forward. In addition to the importance for fusion experiments, there is pure scientific value in understanding the collective behavior of a population of relativistic runaway electrons, as it has applicability in other contexts, including astrophysical and solar plasmas.

Historically, runaway electrons have been easily generated or even hard to avoid in experiments with significant impurity content, but were relatively benign at moderate plasma current. Significant runaway currents can be driven in experiments such as DIII-D, but will be spontaneously driven to a destructive potential given a thermal collapse event in experiments with significantly more flux, as observed in TFTR, and expected in ITER [1].

In ITER, as the plasma current is raised to about 15 MA, the avalanche mechanism can quickly convert a large fraction of the plasma current into 10 MeV electrons if the plasma temperature drops well below 1 keV for any reason. Such a population would have a highly destructive potential. We must therefore build a good theoretical understanding of the physics of runaway generation and evolution, have a validated prediction of experimental outcomes in advance of operations, and thereby avoid intolerable damage to the device.

Recently, significant progress has been made in our understanding of the kinetic theory of runaway generation [1-3], specifically in the threshold electric fields, and effects on the distribution function from pitch angle scattering with bulk ions and high-Z impurities and radiation back-reaction force.

These are important steps, but much remains to be done. To credibly address runway mitigation and to assess the dangers to ITER, our quantitative, predictive understanding of runaway current generation in tokamak disruptions must rapidly advance. To achieve this goal we must develop critical computational tools to self consistently simulate the kinetic evolution of runaway electrons coupled with nonlinear MHD instabilities through the thermal collapse from various types of disruption events.

Important Open Questions

Experiments have shown a discrepancy in the threshold electric field [4, 5] from that expected in the simple theory. This has been qualitatively addressed [2, 3], but the importance of the threshold field in avoiding a runaway catastrophe in ITER makes a more complete simulation imperative. We must develop a quantitative, validated explanation of the experimental data via integrated simulation. Theoretical work to date has mainly focused on a specified static electric field, while in experiments the electric field varies significantly on a timescale comparable to the runaway growth time. The effect of the time history of electric field in combination with scattering and radiation may be required to quantitatively explain experimental observations.

Experimental observations of runaway beams have included crescent/ring shaped spatial distributions, curved both inward and outward, which rapidly redistribute to axisymmetric torus and back by some unknown mechanism. Some effort has been made [6] to understand the inward curved structure, but much more needs to be done.

An important mechanism which must be investigated is whistler wave scattering, which can be important in the decay phase of runaway beams [7, 8].

Also, the self-consistent interaction of runaway electrons with the plasma phenomena that are important in disruptions, such as tearing instabilities magnetic islands and magnetic field stochastization, must be understood. For example, TEXTOR experiments have indicated that magnetic fluctuations during the thermal collapse are related to a reduction in the amplitude of runaway current [9], a relation that is likely due to the destruction of magnetic surfaces [10].

Questions Only Integrated Simulation can Address

Some questions can only be answered by integrated simulation, in particular critical quantitative questions about runaway electron evolution during tokamak disruptions, the answers to which will elucidate mitigation strategies for ITER. Halo current mitigation, which results in a termination of the plasma current over about 150ms in ITER, can produce a runaway avalanche. In these quantitative studies, our scientific objectives must be focused on understanding how the runaway evolution is coupled to other plasma phenomena and quantitatively predicting what the experimental outcomes will be, to identify candidate mechanisms for controlled reduction in runaway current in ITER-like thermal quench scenarios.

An important research objective is to understand the sensitivity of the final runaway current to the initial seed distribution, and flux surface destruction due to MHD instability. As the runaway current grows the electric field will respond inductively, back reacting on the runaway current generation process, and the background current will evolve according to Ohm's law. Self-consistent simulations characterizing the n = 0 evolution of the runaway avalanche consumption of the full equilibrium current have been studied [11-13], along with candidate mitigation techniques. But much remains to be done to understand how 3D MHD instabilities of varying character evolve nonlinearly through the runaway avalanche.

There are various types of thermal collapse observed in tokamaks. Two key examples are that the temperature can collapse over the entire profile simultaneously, or a slowly inward propagating drop in Te can cause partial or full thermal collapse. Studying these thermal collapse events in existing experiments can tell a great deal about initial conditions for runaway current generation in ITER. This can only be done via integrated simulation.

The Need for Integrated Simulation

In summary, it is critical that we support the pursuit of integrated simulations of runaway electron generation coupled to MHD evolution to develop a validated predictive capability. We need to appropriately treat a relativistic kinetic population of runaway electrons coupled to nonlinear extended MHD to ultimately make quantitative predictions of the expected outcomes in ITER in advance of experimental operation. Comparison of simulations with experimental measurements of runaway generation and decay in existing experiments must be used to validate the models. This is a difficult task, that requires significant support and contribution from several leading experts in the relevant fields.

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