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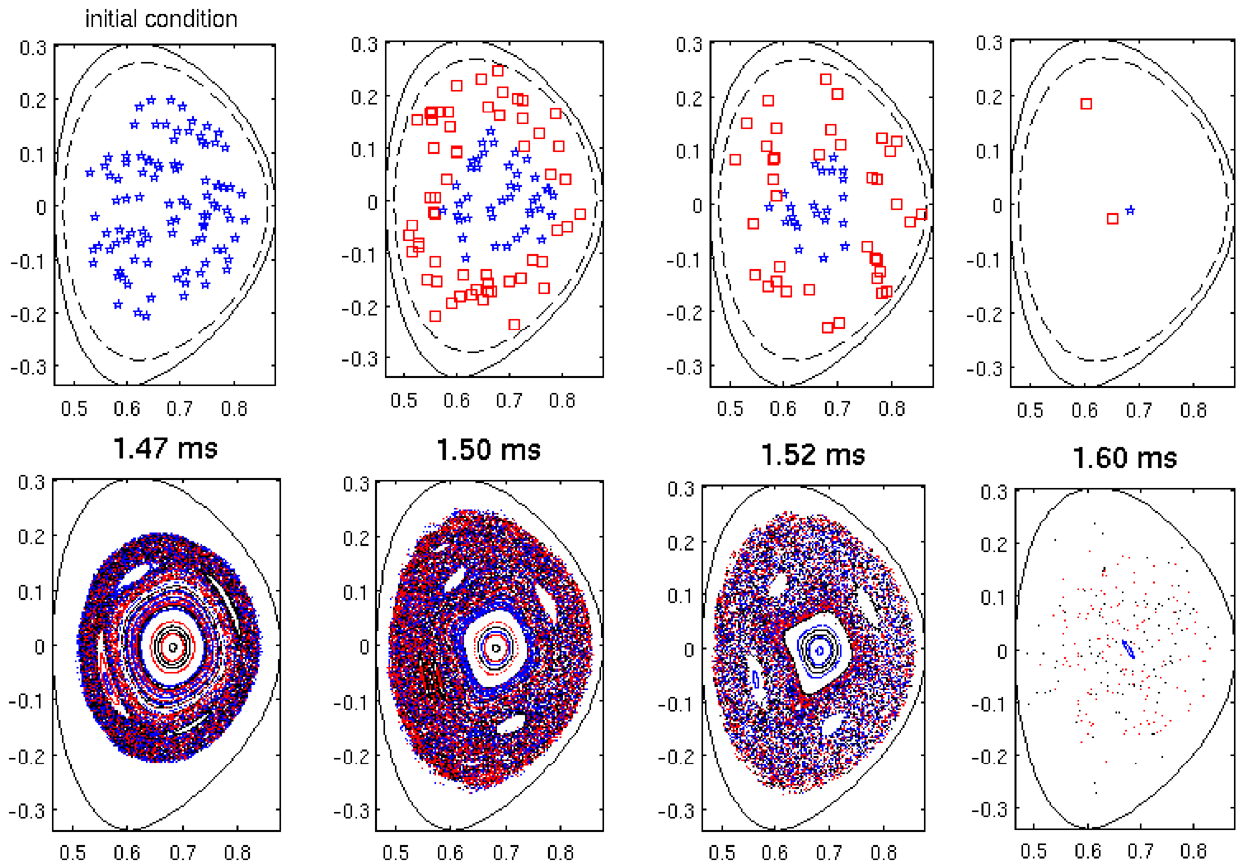
Mixing-up magnetic fields may solve a runaway problem for fusion walls

New results from the Alcator C-Mod tokamak suggests that a major concern for ITER, the generation of high energy electrons during plasma disruptions, may be mitigated by stochastic magnetic fields generated during the disruption process.

The goal of magnetic fusion is to confine very hot plasma with magnetic fields that circulate around a central axis forming a toroidally (donut) shaped geometry. However there is a case where good confinement is bad for the fusion device: runaway electrons. If the electric field around the torus is large enough so that electrons gain energy faster from the field than they lose it to collisions, they can be accelerated up to near the speed of light. This “runaway” condition is not met during normal operation, however during tokamak disruptions, rapid cooling of the plasma increases its electrical resistance and raises the electric field sharply. For very large devices like ITER, this could lead to massive generation of runaway electrons causing severe localized damage when they eventually impact material surfaces. Previous work on C-Mod and elsewhere established that other deleterious effects of disruptions can be mitigated by massive injection of impurities – which intensifies the cooling process. Unfortunately, this makes the runaway problem worse. The proverbial “rock and a hard place!”

Recent experiments and modeling on Alcator C-Mod indicate a possible solution to the problem. If the magnetic fields become disordered or “stochastic”, such that the electrons become poorly confined in the plasma, then the runaway process cannot be maintained. Alcator has been able to bring unique tools to bear on the problem of quantifying the stochastic losses. A key problem in studying runaways is that no present device is as large as ITER (C-Mod is $1/9^{th}$ the size) and so the runaway amplification factors are exponentially smaller. This shortcoming has been overcome in C-Mod by using a high-powered microwave heating system to produce a target plasma that is already seeded with a large population of hot electrons (not runaways), and then intentionally terminating the plasma with a massive gas injection to examine the runaway formation as it would happen in ITER. Calculations show that if the fast electrons were confined, that approximately half of the 1 million Amperes of plasma current, present before the disruption, would be converted into a runaway electron “tail” due to the hot electron acceleration. Indeed C-Mod diagnostics show the electrons becoming runaways, however these runaways are all lost by transport in a millisecond and are gone before the current decay phase of the disruption.

State of the art modeling using the 3-D NIMROD Magneto-hydrodynamic (MHD) code has been used to illuminate the issue of runaway confinement. A C-Mod / UCSD collaboration previously upgraded NIMROD to include impurity radiation physics to study disruption mitgation by massive gas injection. That work found that the mitigation is successful due to the evolution of vigorous MHD activity caused by the large edge cooling; this allows the impurities to access the energy of the plasma. Trace electrons were followed through the same 3-D code solution. The accompanying figure shows that the original fast electrons from LH are indeed accelerated to near the speed of light by the cooling-induced electric field. However, at the same time the field



Cross-sections of C-Mod from NIMROD MHD modeling in massive gas termination. Bottom row: magnetic flux surfaces becoming increasinly disordered as the impurity radiation forces cooling. Top row shows 100 trace suprathermal (blue) electrons accelerate to runaway electonrs (red) and then being lost by exiting across dashed line.

lines become "messy" (stochastic), allowing these electrons to leave the plasma in less than a millisecond, in agreement with the experimental results. While preliminary, these experiments and calculations strongly suggests that the same mechanism responsible for mititgation can suppress runaways. This is the first time that such a tool has been brought to bear on this problem and promises, with further refinement, the ability to predict runaway confinement and losses in ITER.

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