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THE PRODUCTION AND CONFINEMENT OF RUNAWAY ELECTRONS WITH IMPURITY "KILLER" PELLETS IN DIII–D*

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Abstract

Prompt runaway electron bursts, generated by rapidly cooling DIII–D plasmas with argon "killer" pellets, are used to test a recent knock-on avalanche theory describing the growth of multi-MeV runaway electron currents during disruptions in tokamaks. Runaway current amplitudes, observed during some but not all DIII–D current quenches, are consistent with growth rates predicted by the theory assuming a pre-current quench runaway electron density of approximately 10^{15} m^{-3}. Argon "killer" pellet modeling yields runaway densities of between 10^{15}–10^{16} m^{-3} in these discharges. Although knock-on avalanching appears to agree rather well with the measurements, relatively small avalanche amplification factors combined with uncertainties in the spatial distribution of pellet mass and cooling rates make it difficult to unambiguously confirm the proposed theory with existing data. Additional measurements are proposed which should enable us to definitively test the theory.

1. INTRODUCTION

A basic issue for magnetic fusion devices with large toroidal plasma currents (I_P) is how best to dissipate the energy stored in the poloidal magnetic flux (ψ_θ) during a disruption. The rapid decay of ψ_θ following a thermal quench results in a toroidal electric field (E_ϕ) which can convert a substantial fraction of plasma current into a multi-MeV runaway electron current (I_R). This runaway current can damage wall components unless its energy is dissipated prior to reaching the plasma edge. In ITER, a pre-disruptive ohmic flux $\psi_\theta \approx 214$ Wb produces an average toroidal electric field $< E_\phi> = \psi_\theta(2\pi R\Delta t_q)^{-1} \approx 8.4$ V/m over a current quench time $\Delta t_q = 0.5$ s. This will not generate Dreicer runaways since it is only about 2% of the Dreicer electric field E_{DR} in post-thermal quench ITER plasmas. Alternatively, a small population of high energy electrons may grow exponentially via a knock-on avalanche process during an ITER disruption [1]. An estimate of the number of avalanche e-folds $\gamma_{RA}t \approx eI_P/mc^3\ln\Lambda$ in a 23 MA ITER discharge gives an amplification factor $A_{RA} = e^{\gamma_{RA}t} \approx e^{64}$. Thus, the prevailing theoretical view is that a substantial fraction of ITER's pre-disruptive I_P will be unavoidably converted into runaway current with an average electron energy of 10–20 MeV during disruptions [1]. In fusion devices Compton scattered electrons, produced by high-energy gamma radiation from wall activation, provide a sufficient seed population to generate multi-MA knock-on avalanche runaway currents assuming amplification factors similar to those predicted for ITER.

Since disruptive runaway avalanches may be unavoidable in tokamak reactors, it is imperative to confirm the details of knock-on theory during disruptions in existing tokamaks. In devices such as DIII–D, with $I_P \approx 1.5$ MA, avalanche e-folding times are expected to exceed 25%–30% of the I_P quench time. While this produces relatively small avalanche amplification factors (*i.e.*, $A_{RA} \approx 55$ with $\gamma_{RA}t \approx I_P/0.02\ln\Lambda \approx 4$ [1]) it can result in measurable I_R levels given a sufficient pre-I_p quench runaway electron seed density. In DIII–D, some types of "killer" pellets (KP) appear to produce seed densities of sufficient size to test knock-on avalanche theory. This paper describes recent DIII–D KP experiments carried out to better understand knock-on avalanching during disruptions.

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2. EXPERIMENTAL BACKGROUND AND OBSERVATIONS

Recent experimental and theoretical impurity KP results have substantially enhanced our understanding of the physics involved in the mitigation of disruptions as well as the generation and confinement of runaway electrons during and immediately following the pellet ablation phase [2–4]. Experiments with cryogenic neon, argon and methane KPs have been carried out in DIII–D and an ablation/radiation model (KPRAD) has been developed for the analysis of these experiments. Our experimental results demonstrate that KPs reduce local Vertical Displacement Event (VDE) vessel forces on average by about a factor of two and divertor heat loads by a factor of two [2–4]. We also find that some KPs produce prompt runaway electron bursts which are often correlated with fast ablation spikes and large MHD events. These prompt runaway bursts are generated at least 1 ms prior to the onset of the I_p quench and appear to be confined on some surfaces long enough to act as a seed population for knock-on avalanching during the remainder of the discharge.

2.1. Generation of runaway seed currents with killer pellets

In DIII–D, KP's are injected from the low field side with velocities of 400–600 m/s. The duration of the ablation phase is 0.5-0.6 ms with a typical normalized pellet burnout radius $\rho_{PB} \approx 0.4$ where $\rho = r/a$ is referenced to the seperatrix radius $r_{SEP} = a$ at the time the pellet is injected. In the pellet ablation zone $\rho_{PB} \leq \rho \leq 1$ where T_e is small and n_e is large, $E_\phi << E_{DR}$ requiring a new mechanism to account for runaway generation in this region. Two distinct dynamical processes involving rapid non-adiabatic impurity radiation cooling have been proposed. The first of these is due to a rapidly growing $\nabla_r P_e$ instability on flux surfaces intersecting the active pellet ablation zone [4]. Calculations with the DIII–D KPRAD code show that T_e is reduced from 2500 eV to 30 eV within 20 μs after the arrival of a neon KP at $\rho = 0.5$ and then falls to a steady state value of ≈ 10 eV by about 100 μs. Thomson scattering measurements, made 500 μs after a neon pellet reaches $\rho = 0.5$, yield 10 eV and thus are in good agreement with the KPRAD calculations. KP's move about 10 mm in 20 μs implying $\nabla_r T_e \approx 2 \times 10^5$ eV/m. During this time n_e increases <50% producing a large increase in $\nabla_r P_e$. Ideal ballooning mode growth rates exceed $5 \times 10^5\ s^{-1}$ in this case implying the destabilization of MHD modes as the pellet approaches ρ_{PB}. Large δb_θ spikes observed during the ablation of neon and argon pellets appear to be related to these unstable MHD modes. In the region behind the pellet KPRAD is used to calculate $E_\phi = \eta j_\phi \approx 90$ V/m. Here η is calculated using Z_{eff}'s and T_e's determined in KPRAD assuming j_ϕ = const. during the 20 μs cooling time. While the cold electrons behind the pellet $\rho \geq \rho_{PB}$ are below the Dreicer threshold energy, keV electrons supplied from the region $\rho < \rho_{PB}$ by the MHD instantaneously runaway in the 90 V/m electric field.

The second mechanism proposed for generating prompt runaways in the cold region results from the Maxwellian nature of the electron distribution function (*i.e.*, a velocity space source involving electrons in the high energy wing of the distribution) and the rapid radiative cooling of the thermal part of the electron distribution compared to the high energy electrons. Calculation of electron cooling rates as a function of energy are used to estimate runaway production rates at each flux surface [5,6]. The model predicts a sharp jump in the runaway current density from essentially zero to $j_R \approx 75$ kA/m^2 as a neon pellet crosses a threshold radius $\rho_{TH} \approx 0.7$. During the rest of the pellet's flight $(0.7 \geq \rho \geq 0.5)$ j_R increases linearly to ≈ 95 kA/m^2. At $\rho = 0.5$ the crossover energy for converting Maxwellian tail electrons to runaways is about twelve times thermal T_e and the integrated runaway current across this region is approximately 25 kA. With argon pellets KPRAD predicts a more rapid radiation cooling rate thus runaway currents may be significantly larger in the ablation region. On the other hand, larger δb_θ spikes are observed with argon pellets as compared to neon so runaway losses from this region may be larger with argon. A Fokker-Planck code, CQL3D, has also been used to estimate runaway currents generated by the dynamical hot tail conversion mechanism and finds relatively large conversion factors unless losses due to magnetic fluctuations are included [6]. It is important to note that these models nominally only account for runaway generation during the pellet ablation phase on flux surfaces located a few mm inside ρ_{PB} out to ρ_{TH}. On the other hand, pellet driven $\nabla_r P_e$ instabilities near ρ_{TH} are expected to mix and drag some of the pellet's mass inward resulting in runaway generation near the center of the plasma via the Maxwellian tail electron conversion process. Experimental measurements confirm the existence of a rapid inward particle pinch with neon pellets along with an increase in the central density that is consistent with an inward redistribution of pellet mass [7].

2.2. Runaway current growth during disruptive plasma current quenches

We now turn to observations of growing runaway currents following some argon killer pellet injection. Figure 1(a) shows an argon KP (refer to P01HA1 for the ablation signal) induced prompt runaway burst on an ECE signal (ECEF1) followed by an exponential I_P quench 1720 ms $\leq t \leq$ 1722 ms then a flattened region in I_P 1722 ms $< t \leq$ 1729.5 ms and finally a second exponential decay $t >$ 1729.5 ms. This ECE burst is believed to be caused by runaway acceleration near the center of the plasma following a pellet induced MHD instability. We approximate the ohmic part of the I_P quench with an exponential function, fit to I_P between 1720 ms $\leq t \leq$ 1722 ms, where $\tau_{L/R}$ = 4.5 ms then extend this to t = 1735 ms [refer to the dashed line in Fig. 1(a)]. A rough approximation of I_R, as shown in Fig. 1(c), is taken as the difference between I_P and the dashed line. The assumption that the ohmic L/R time remains constant is a weak point in this approach but until we understand the detailed evolution of E_ϕ, T_e and Z_{eff} in these discharges we must accept this uncertainty in the analysis. A detailed evaluation of $E_\phi(t)$ during the I_P quench is underway and will be reported in a subsequent paper [8].

In Fig 1(b) the signal from one channel of a soft x-ray detector array shows a representative increase with I_R. This array does not have a direct view of the plasma after t = 1723 ms but is known to be sensitive to hard x-rays produce by runaway electrons interacting with carbon tiles at the top of the vessel. The base level increase in this signal is thought to be due to a loss of runaways as the flux surfaces between $0.7 \geq \rho \geq 0.25$ are scraped off by these carbon tiles while the spikes may be due to the interaction of runaways confined to isolated stochastic layers spread across this region. Figure 2 shows the position of the plasma and the loss of the outer flux surfaces at 2 ms intervals during the I_P quench. We see from Fig. 2 that at the peak in I_R all the runaways are confined to $\rho \leq 0.25$ well inside ρ_{PB}. We assume the central flux surfaces remained closed (*i.e.*, are not stochastic) during the time between the pellet injection and the peak in I_R (Δt_{RA} = 10.8 ms) and calculate an average avalanche growth rate inside $\rho = 0.25$. $E_\phi(t)$ is calculated from an analytic model of $\partial_t\psi_\theta$ and $n_e(t)$ is obtained from experimental data. We estimate the free and bound electron populations produced by the mixing process discussed above and calculate the critical electric field $E_c(t) = 0.092\, n_e \times 10^{-20}\ \mathrm{m}^{-3}$ [1]. E_ϕ/E_c varies with time so we estimate the knock-on growth rate using the average $\langle E_\phi/E_c \rangle = 300$ over Δt_{RA}. This results in an approximate amplification factor of 18.2 based on Eq. (18) in Ref. 1. Thus, a KP induced seed density of $1.6 \times 10^{15}\ \mathrm{m}^{-3}$ (*i.e.*, a 17.6 kA runaway seed current contained inside ρ = 0.25) can roughly account for the 320 kA peak in I_R observed in Fig. 1(c). Projecting the neon hot tail conversion results given above into $\rho \leq 0.25$ we find a runaway current of about 12 kA. Since argon cooling is known to be more rapid than neon from KPRAD modeling in the ablation zone, we expect that the argon seed population inside ρ = 0.25 could be significantly larger than that produced by neon.

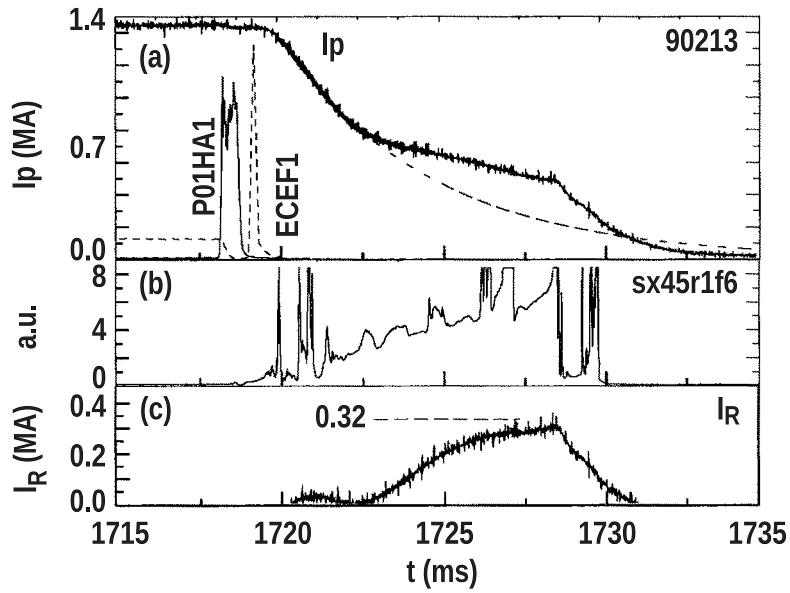

Fig. 1. (a) argon KP induced current quench showing the pellet ablation signal (P01HA1) and a fast response ECE radiation signal (ECEF1), (b) a central soft x-ray signal (sx45r1f6), (c) runaway current (I_R) growth.

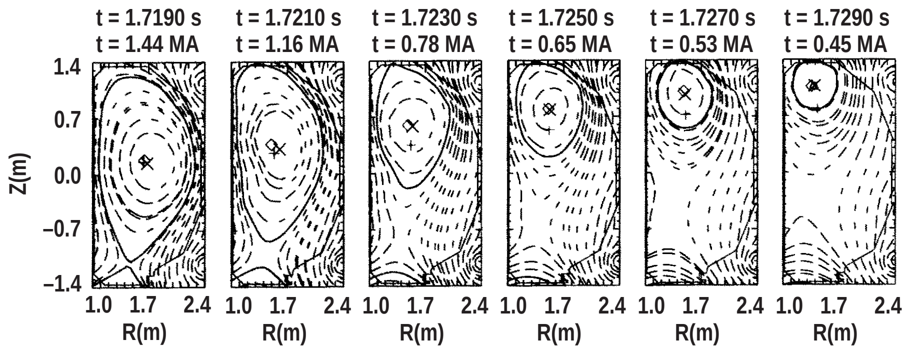

Fig. 2. Sequence of plasma equlibria during the I_P quench shown in Fig. 1.

Thus, if an argon pellet produces 50% more runaway seed current than neon it will result in the required 17.6 kA. On the other hand, given the uncertainties in the mixing process argon pellets could produce up to 100 kA of seed current in the core implying our simple estimate of the amplification factor would have to be reduced. We note that runaway currents similar to that shown in Fig. 1(a) have not been observed with neon or methane KP's. Additionally, we have identified an argon KP case which does not have this runaway current even though the seed population appears to be essentially identical to argon KP shots with these runaway currents. In this case it appears that an instability is triggered near the onset of the Ip quench which dumps all the runaways from the core plasma. Understanding this behavior may be beneficial for developing runaway electron mitigation techniques.

3. DISCUSSION

While the growth of knock-on avalanche runaways during the quiescent phase of the plasma appears to be relatively well established by experiments on TEXTOR [9], it is essential to understand the details of the avalanche process during disruptions in existing tokamaks. Based on our interpretation of existing DIII–D data, we believe runaway currents, such as the one shown in Fig. 1(c), can best be described by a growing population of relativistic electrons near the center of the discharge. The most plausible model requires a rapid inward transport of the argon from outside ρ_{PB} into the core which generates a sufficiently large density of well-confined seed runaways inside $\rho = 0.25$ in order to produce observable knock-on avalanche currents. Relatively low avalanche amplification factors along with uncertainties in the magnitude of the seed population, the temporal evolution of the toroidal electric field and the magnitude of the runaway current still need to be resolved. Detailed calculations of the toroidal electric field evolution in the core and the argon cooling rates based on inward transport estimates of the KP mass are underway and will be reported in a future paper [8]. Initial estimates of avalanche growth rates in discharges terminated by argon KP's suggest that it should be possible to definitively test the theory and develop avoidance or mitigation techniques in devices such as DIII–D. Methods for increasing seed densities and avalanche amplification factors while reducing the rate at which the outer flux surfaces are scraped off are being investigated for this purpose. Low Z (methane) and low concentration neon KP's as well as massive gas puffs and liquid jets are also being developed to mitigate avalanching in high current tokamaks.

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