Interaction of runaway populations with fast particle driven modes

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Introduction Reliable runaway electron (RE) mitigation after disruptions is one of the most important challenges for safe ITER operation. A proper understanding of the generation and losses of REs is therefore essential. The possibility of passive RE suppression by RE induced instabilities would ease the task of active mitigation systems and increase the overall safety of operation. Several tokamaks (TEXTOR, JET, EAST, HT-7, etc.) have reported the existence of various transient plasma waves connected to runaway formation and/or enhanced losses in both post-disruption and ramp-up cases. This paper investigates the interaction of runaway populations with fast particle driven modes.

Data analysis TEXTOR has recently reported magnetic turbulence [1] and wave phenomena connected to enhanced post-disruption runaway losses. We focus on the case of TEXTOR shots #115207-8 (figure 1a). These two shots had identical plasma parameters except for a difference in the toroidal magnetic field, $B_\mathrm{T} = 2$ T for #115207, $B_\mathrm{T} = 2.1$ T for #115208. In both cases the shot was terminated by the injection of 0.021 bar·l argon ($\sim 6 \cdot 10^{20}$ atoms). Shot #115207 observed no runaway plateau formation while #115208 formed a runaway plateau of ~ 100 kA. Meanwhile, the shot which had no plateau formed, registered strong coherent magnetic oscillations during the current quench phase, in contrast to the case with the significant RE plateau.

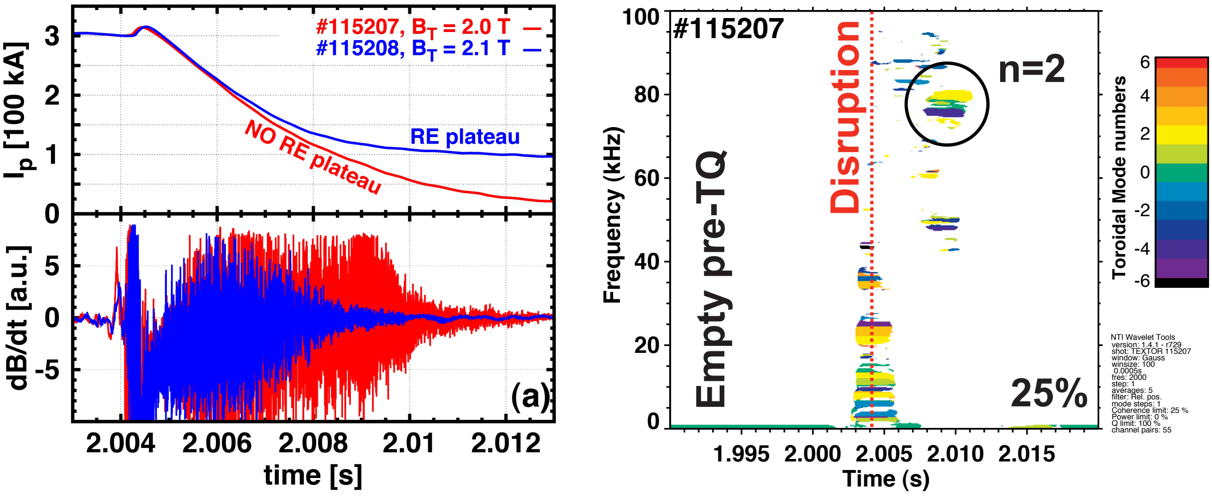

Figure 1: *(a) Evolution of plasma current and Mirnov coil signal in shots #115207-8 of the TEXTOR tokamak. #115207 shows large oscillations and the lack of RE plateau, #115208 is the opposite. (b) A globally coherent,* $(m,n) = (4,2) - (5,2)$ *mode was identified at 80 kHz, toroidal mode number analysis shown here with 25% coherence filtering.*

Through the detailed time-frequency analysis of magnetic signals after the disruption (using the NTI Wavelet Tools [2]), we have found a globally coherent mode with ~80 kHz frequency, typical of Toroidal Alfvén Eigenmodes (TAE). The mode structure analysis indicates the existence of $(m,n) = (4,2)$ and $(5,2)$ harmonics, propagating in the electron diamagnetic direction. When these modes were present in the post-disruption plasma, no runaway plateau formation was observed. Shot #115208 showed no globally coherent modes. To determine if our working hypothesis of this mode being a TAE is sound, we required knowledge of the plasma equilibrium in the stage of the mode formation.

Equilibrium Post-disruption equilibrium reconstruction is a highly complicated task, even if equilibrium codes (such as EFIT) manage to converge, the obtained plasma current profile in most cases cannot be used. To overcome this issue we chose to simulate the disruption phase. Even though an extremely precise reconstruction of the thermal- and current quench phases is not possible, this approach provides us with an evolution of plasma parameters that is consistent with the basic physics governing the quench phase. We chose to simulate the disruption using the GO code [3]. GO uses a self-consistent, one-dimensional model to calculate the evolution of electric field, plasma parameters and runaway current taking into account the argon injection and other possible impurities. It has a complete atomic physics model based on ADAS data, that evolves all charge states of every ion species self-consistently with the evolution of plasma parameters. We used the predisruption temperature (based on ECE) and density (based on interferometry) profiles as input parameters for the simulations. The free parameters for the GO simulations are the impurity accumulation ratio and the characteristic impurity transport time. By scanning through these parameters, we found good agreement between the measured and simulated plasma current and runaway evolution (figure 2).

As the plasma current is continuously evolving, we fitted a general plasma current shape during the current quench phase in a function form which depends only on the plasma current. This way we can select specific stages of the quench which we want to study. Our equilibrium reconstruction (using VMEC and HELENA) is based on the plasma profile evolutions taken from the GO simulations.

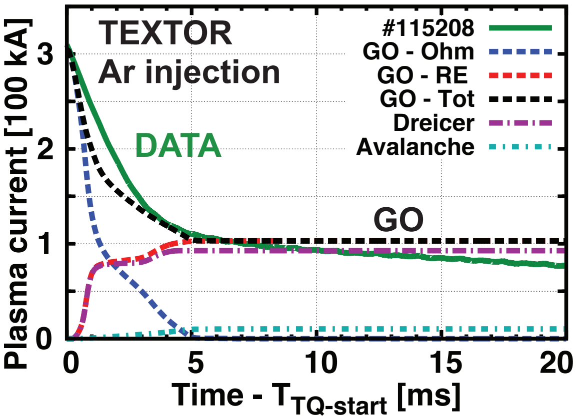

Figure 2: *Good agreement between the simulated and measured plasma current evolution.*

Mode analysis The frequency, damping/drive and structure of the modes in the post-disruption equilibrium were calculated using the LIGKA code [4]. In order for any mode to be driven, we required to insert a warm Maxwellian particle population with the characteristic density of $n_0 \simeq 10^{17}$. This population has a negative density gradient in the $\rho_p = 0.1 - 0.3$ radial region. Such population can exist 1) during the penetration of the cold gas from the inside towards the outside or 2) during core-localised runaway formation (the existence of non-monotonic background plasma density profiles as well as possible runaway electron non-monotonicity is generally supported by GO calculations). The ideal MHD spectrum allows the existence of n=2,6 and n=10 modes in the TAE gap with frequencies of ∼ 80 kHz, in good agreement with the experimental result. In the core, where the driving negative gradient is localised,

$m = 2,3$ harmonics are present (figure 3a). These are coupled to higher order harmonics towards the plasma edge, which explains the measured $m = 4,5$ poloidal mode numbers. The on-axis electron Landau damping is below 1%. The resistive/collisional damping for the $n = 2$ harmonic is in the order of $\gamma_d/\omega < 2\%$. The damping is a factor of 3-4 higher for $n = 6$, and almost a factor of 10 higher for $n = 10$. We found that with a sufficiently large fast particle β, the $n = 2$ can be the most easily driven, which explains why the $n = 2$ harmonic is measured in the experiment. There is a dependence of the ratio of drive / damping on B_T, the mode is more easily driven if the magnetic field is low. However, at this point, quantitative conclusions cannot be drawn in order to explain the difference of the $B_T = 2$ T and $B_T = 2.1$ T cases.

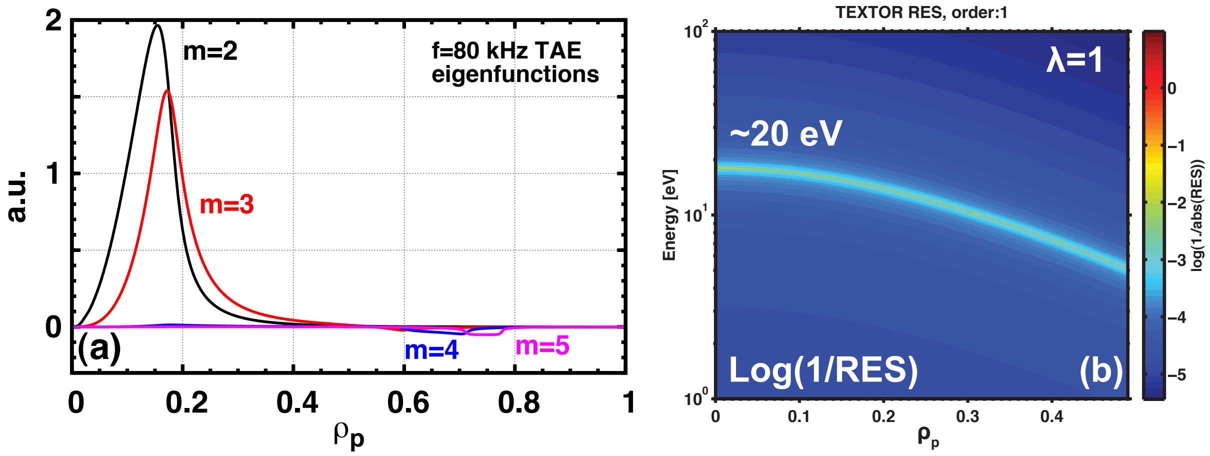

Figure 3: *(a) Eigenfunctions of the* $f \simeq 80$ *kHz,* $n = 2$ *TAE mode harmonics. (b) An example of thermal particle resonance at* $\mathscr{E} = 20$ *eV,* $v_\parallel/v = 1$*. The color scale shows* $\log_{10}(1/|R|)$*, where* R *is the right hand side of equation (1).*

Fast particle – wave interaction is modelled with the HAGIS code [5], which has recently been extended to relativistic physics, using the relativistic equations of motion in Boozer coordinates. The relativistic implementation was thoroughly benchmarked against the ANTS code [6], which is a full-f, 3D, test particle Monte Carlo code. The benchmarking found good agreement between the two codes in a wide range of particle charges, masses, pitches and energies (up to 200 MeV – confined by an ITER equilibrium).

In order for the TAE mode to be driven, the resonance condition of

$$0 = \omega_{\text{wave}} + n \cdot f_{\text{tp}} - (n \cdot q - m + k) \cdot f_{\text{b}} \tag{1}$$

has to be fulfilled. Here, f_{tp} is the toroidal precession frequency, f_{b} is the poloidal bounce / transition frequency and $k \in \mathbb{Z}$ is the bounce harmonic. For TAE modes at the resonance $n \cdot q - m = 0.5$. To illustrate possible resonances, we have scanned the particle phase space (ρ_p, p, λ) with $\mathscr{O}(10^6)$ test particles and extracted the $f_{\text{tp}}, f_{\text{b}}$ values using HAGIS. The post-disruption TEXTOR equilibrium can conveniently confine particles up to 30 MeV energy. While the resonance condition can be fulfilled by thermal electrons, we found no fast particle resonances with the 80 kHz $n = 2$ TAE mode. An example of thermal particle resonance is shown in figure 3b.

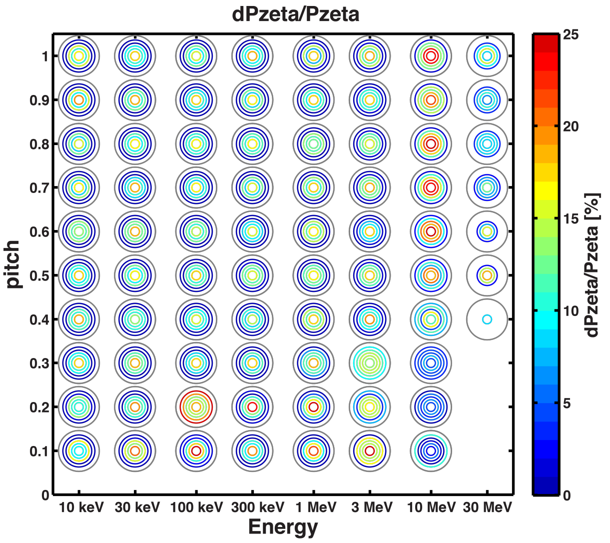

Figure 4: *$\delta P_\zeta / P_\zeta$ expressed in % over a grid in (ρ_p, p, λ) phase space. The radius of the circles represent the starting position in ρ_p.*

Due to the very small integration times and large number of test particles required for self-consistent calculations of the mode drive in the presence of relativistic particles, we have not yet been able to complete the convergence test in order to obtain the saturation amplitudes of the modes. However, as we could not find any fast particle resonances, the effect of the TAE mode on the runaway population at a prescribed perturbation strength can be calculated. Again, we set up an ensemble of $\mathcal{O}(10^6)$ test particles over a phase space grid in (ρ_p, p, λ) and varied the relative perturbation strength of the TAE to study its effect on the runaway electrons. In order to gain statistics, each (ρ_p, p, λ) point in phase space is represented by $\mathcal{O}(100)$ test particles scattered over an initial flux surface with uniform random distribution for starting angles (ϕ, ϑ). To express the effect of the TAE on the particles, we chose to plot the relative change in the canonical toroidal momentum given by $P_\zeta = p_\parallel g/B - e\psi_p/c + e\tilde{A}_\zeta/c$, normalized to the range of P_ζ for a given particle energy and pitch. As P_ζ is a function of parallel kinetic momentum and radial position, in a sense it represents the contribution to the change in the current profile of the given test particle. The relative changes in P_ζ as a function of (ρ_p, p, λ) are plotted in figure 4 for the case of $\delta B/B = 1\%$. We see that with a sufficiently strong perturbation the particle orbits can be displaced by as large as 25% of the normalized radius, which is the radial extent of the core localized $m = 2, 3$ harmonics. Further studies will be necessary to convert changes in P_ζ into transport coefficients do determine the effect of the TAE on the evolution of the runaway current.

Conclusions The presence of a 80 kHz, $n = 2$ TAE mode has been connected to the lack of RE plateau in the induced disruption of TEXTOR shot #115207. By modelling the quench phase with the GO code, we have been able to reconstruct the post-disruption equilibrium, which, according to the LIGKA code, can support an $n = 2$, 80 kHz TAE mode. We found that the mode is most probably driven by a particle population with slightly inverted core density profile. As modelled with the relativistic version of the HAGIS code, this mode can scatter runaways out of its radial presence, given a large enough mode amplitude.

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