Chirping in Plasmas; test of criterion for chirping onset and simulation of explosive chirping[1]

H. L. Berk, B. N. Breizman (presenter), G. Wang, L. Zheng;
University of Texas at Austin, Austin, Texas 78723, USA
V.N. Duarte[2], N. N. Gorelenkov, G. Kramer, N. Nazikian, M. Podesta, B. J. Tobias;
Princeton Plasma Physics Laboratory, Princeton, N.J. 08543, USA
W. W. Heidbrink; University of California Irvine; Irvine, CA, 92697 USA
D.C. Pace, M.A. Van Zeeland; General Atomics, San Diego 92186 CA USA

Overview of paper: When plasmas have a sufficient number of energetic particles to induce instability, such as may occur in burning plasmas, it is important to have a reliable method of predicting the nature of the unstable state that will arise. Two extreme scenarios scenarios for the TAE frequency, ω_{TAE} arises: relatively steady oscillations at one extreme and chirping oscillations at the other extreme. This work uses the generalized form of a criterion found by Lilley et.al. [1] that indicates, whether marginally unstable Alfvenic modes destabilized by energetic particles are more likely to chirp or more likely to remain as steady oscillations. This criterion has been applied to data in NSTX and DIII-D and it successfully predicts the parameters that produce either chirping or steady Alfvenic oscillations. Chirping arises in DIII-D when background turbulence markedly decreases.

As the strength of the driving source of energetic particles increases, instability may emerge from the continuum to form what has been called energetic particle modes (EPM)[4]. Here we describe a new way of simulating an EPM which enables a significantly increased time-step for the numerical simulations. This study simulates, we believe for the first time, a chirping avalanche that is triggered by an EPM excitation and explains the dynamics with a new analytic theory.

### Part I. Application of the chirping criterion to NSTX and DIII-D

The criterion, for whether chirping or steady oscillations arise is related to whether stochastic diffusive or drag processes dominate the nonlinear response of energetic particles near marginal instability. Stochasticity promotes steady behavior, while drag promotes chirping. It is often essential to use the detailed criterion, rather than an approximate form, to obtain a criterion that agrees with experimental data. Hence, NOVA and NOVA-K eigenmode codes are used to calculate mode structure, the wave-particle interaction strength and the pitch angle and drag contributions from the resonant regions of phase space. In addition, the scattering of energetic particles due to micro-turbulence is a significant stochastic diffusion source to consider even though the macroscopic energetic particle equilibrium distribution is hardly affected by ion micro-turbulence. In addition, TRANSP is used to infer the ion micro-turbulent diffusion coefficient. Since the micro-turbulent space scale is typically much less than the energetic particle Larmor radius, the large energetic particle orbit has substantially less diffusion from this turbulence than the background plasma. A kinetic theoretical model [2] is used to estimate this reduction. In NSTX, the micro-turbulence contribution is found to be insignificant. As a result the generalized chirping criterion for NSTX experiments predicts that chirping should arise for the shots that were analyzed and this prediction is in agreement with the experimental observation in NSTX [3]. In DIII-D, ion micro-turbulence is often at a high enough level so that induced stochastic diffusion from ion micro-turbulence needs to be accounted for. This contribution is typically large enough to prevent chirping from arising. However, the few cases that chirping is observed on DIII-D correlates closely with a marked reduction in the experimental ion micro-turbulence, as shown in fig. 1. Thus, this theory together with the observed data, appears to answer a puzzle as to why chirping is so rarely observed in DIII-D and so ubiquitous in NSTX.

### Part II: Simulation of the Energetic Particle mode and Induced TAE Avalanche

TAE and related instability growth rates are relatively slowly growing and require many transit times of the particles around a tokamak before instability causes significant orbit deviation. The main nonlinearity is due to the wave-particle interaction on energetic particles, while the response from the non-resonant energetic particles is small and is neglected. The disturbances of the background plasma are assumed to remain linear. The basic time step of the problem is determined by the relatively weak strength of the wave-particle interaction and the frequency width of the gap, rather than the transit time around the machine. Presently the study is confined to large aspect ratio, $1/\epsilon \gg 1$, tokamaks with passing particle interactions. As a result of the interaction, a

---

[2]Institute of Physics, University of Sao Paulo, Sao Paulo, SP, 05508-090, Brazil
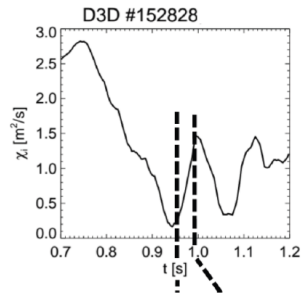
(a) Heat diffussivity vs. time, with window of low diffusivity.
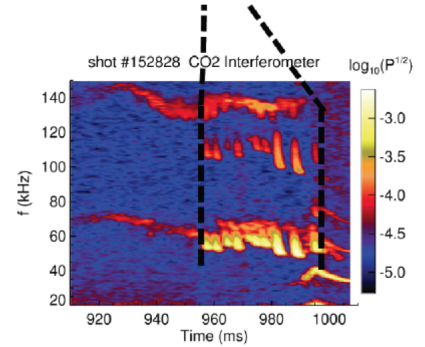
(b) Evolution of mode spectrum vs. time, with chirping in dashed time window.

Figure 1: Spectral evolution from steady to chirping with decrease of heat diffusivity.

particle can cross field lines, while its speed and magnetic moment do not change. The resulting equations have been simulated for the case of an excitation of a single component, core localized TAE mode, which consists of the excitation of an m and $m + 1$ poloidal harmonics, for a fixed toroidal mode number n, such that the gap position is located at $q(r_m) = (m+1/2)/n$ for relatively low magnetic shear. The method succeeds in simulating chirping behavior associated with a perturbative TAE mode. It's found that the generated chirping range of a perturbative mode remains small compared to the TAE gap width, $\sim \epsilon\omega_{TAE}$, and is confined to the gap. However, as the source strength of the energetic particles increases, it's found that an energetic particle mode (EPM) [4] is excited with a frequency that emerges from the continuum close to the gap. Nonlinearly, this mode promptly chirps down, moving deep into the continuum frequency below the gap. A simulation experiment is performed where a source is used to increase the instability drive with time. The resulting evolving spectra is shown in fig. 2. At first just the perturbative TAE instability is excited, with a limited chirping range. However, as the simulation continues, the energetic particle density builds up, until an EPM is excited in the continuum. The excitation of this mode then leads to a rapid frequency downshift (see fig. 2a) reminiscent of chirping that occurs in a frequency chirping avalanche that has been reported in experimental observations on NSTX [3]. Physically, this chirping is due to a phase space structure (a clump) moving across field lines, to the outer region of the plasma. When the chirping structure is followed in the frame of the structure, the detailed distribution of the trapped particles in phase space is observed as shown in fig. 2b. This chirping structure is embedded in the same shaped separatrix as is theoretically expected to arise from the observed field amplitude and chirping rate. Thus the shape of the separatrix is consistent with the theoretical prediction. A detailed analytic theory that reproduces the mode amplitude and chirping rate of the TAE avalanche will be discussed.
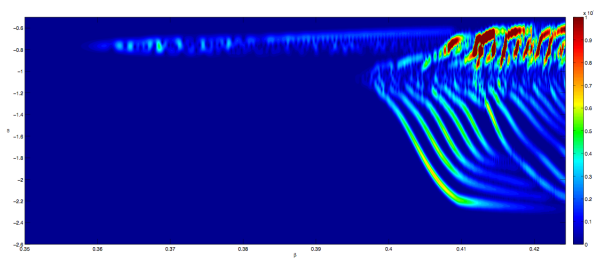
(a) Evolution of TAE and EPM mode spectrum with increasing source strength. The frequency region, $-1 < \omega < 1$, is the TAE gap width.
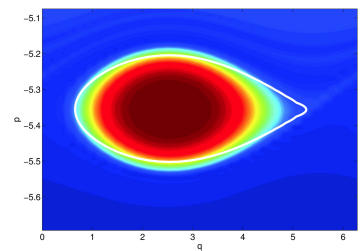
(b) Trapped particle distribution in phase space encompassed by inferred theoretical separatrix shape.

Figure 2: Frequency avalanche from EPM mode.

References

[1] M.K.Lilley, et. al. Phys.Rev.Lett., **102**, 195003 (2009)

[2] W. Zhang, et. al. Phys. Rev.Lett., **095001**, (2008)

[3] M. Podesta, et. al. Nuclear Fusion **52**, 094001, (2012)

[4] Chen, L., Phys. Plasmas **1**, 1519, (1994)