Final Report of UT Austin of Project
PLASMA ENERGETIC PARTICLES SIMULATION CENTER (PEPSC)

DE-FC02-08ER54988; DOE- UTAUSTIN-ER54988

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Award Reporting Period 05/15/2008 - 01/14/2012

Final Report of UT Austin PEPSC grant (July 15, 2008 – January 14, 2012)

1. Introduction

The University of Texas SciDac groups worked with its partner groups at the Princeton Plasma Physics Laboratory (PPPL), where Guyong Fu was the principal PI of the entire project, and the University of Colorado, where Scott Parker was the PI. In this collaboration, the University group consulted with PPPL in the understanding of the benchmark physics simulations which were geared to demonstrating that saturation of single mode excitations is due to particle trapping, a prediction previously made by the Texas group. This scaling was indeed confirmed as demonstrated in work of both the PPPL and Colorado groups.

The main effort of the Texas group was to develop theoretical and simplified numerical models to understand chirping phenomena often seen for Alfven and geodesic acoustic waves in experimental plasmas such as D-III-D, NSTX and JET. Its main numerical effort was to modify the AEGIS code, which was originally developed as an eigenvalue solver. To apply to the chirping problem this code has to be able to treat the linear response to the continuum and the response of the plasma to external drive or to an internal drive that comes from the formation of phase space chirping structures. The theoretical underpinning of this investigation still needed to be more fully developed to understand how to best formulate the theoretical problem. Considerable progress was made on this front by B.N. Breizman and his collaborators and a new reduced model was developed by H. L. Berk and his PhD student, G. Wang which can be uses as simplified model to describe chirping in a large aspect ratio tokamak. This final report will concentrate on these two directions that were developed as well as results that were found in the work with the AEGIS code and in the progress in developing a novel quasi-linear formulation for a description of Alfvenic modes destabilized by energetic particles, such as alpha particles in a burning plasma.

II. Fundamental Progress in Frequency Chirping Theory

A basic mechanism for frequency chirping was discovered in previous IFS works [1, 2] for spontaneous frequency chirping which were found to arise in systems with a weak kinetic instability drive. The instability resulted from the formation of phase space structures (called holes and clumps) which in the presence in dissipation, move to lower energy regions of phase space, with the observed frequency locked into the linear resonance condition of the moving structure. The theory was developed for a paradigm model, the linear bump-on-tail instability, but the basic mechanism is fundamental, and is believed to be the mechanism responsible for numerous spontaneous chirping observations seen in many experiments and is particularly ubiquitous in tokamaks. The likelihood of such chirping phenomena arising in burning plasma experiments has motivated us to attempt to extend the chirping theory to be able describe realistic geometry.

One important element that appeared to disagree with experiment was the condition for chirping onset, which was not fulfilled in the original theory [1]. This disparity was resolved in joint work by Lilley, Breizman and Sharapov [3,4], where it was observed that particle drag, which was neglected in the original theory, had a profound effect on the condition for chirping. Figure (1) shows the expanded phase space region for where non-steady solutions arise. In this non-steady regions, especially to the lower right of the figure, chirping solution can arise. The figure shows that when diffusion, proportional to the parameter, $\hat{\upsilon}$, is dominant, the non-steady solution require a relatively small value for $\hat{\upsilon}$. However, if drag, which is proportional to the parameter, $\hat{\alpha}$, competes with $\hat{\upsilon}$, non-steady solutions, which can lead to a chirping response, can arise even for a relatively large diffusion parameter, $\hat{\upsilon}$ as is seen in this figure.

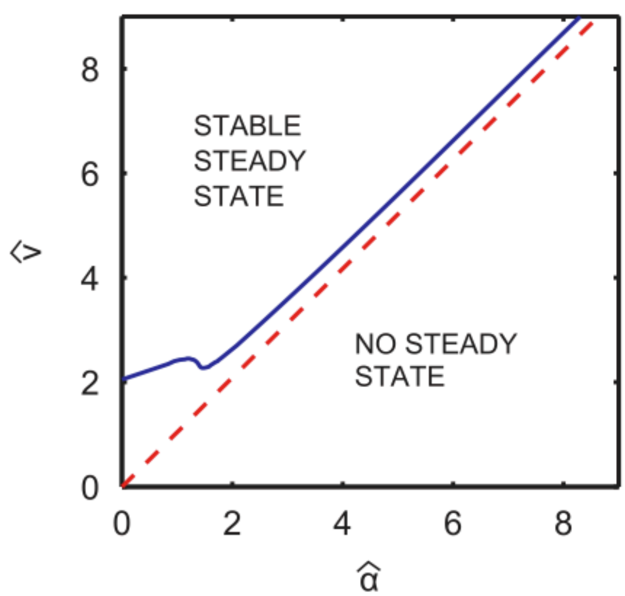

FIG. 1 (color online). Displays the boundaries in parameter space that give stable, unstable and no steady-state solutions to Eq. (4). The unstable solution lies in between the solid and dashed lines.

Another important extension to the chirping theory was to be able describe long range chirping. The validity of the original theory was limited is chirping range, as the spatial structure of the wave was fixed to the eigenfrequency of the background plasma. However, as chirping evolves the spatial structure of the wave needs to be taken into account. A analytic solution to this problem for the bump-on-tail problem was obtained by Breizman [5]. This theory was extended to a general numerical procedure by Nyqvist, Lilly and Breizman [6] and applied to the bump-on-tail instability. This theory incorporated the transport mechanism of drag and diffusion, which resulted in some interesting effects that enables upward chirping holes to change its chirping direction as has been seen in experiment (hooks) or even relax to a steady oscillation. Another important result was the explanation by Lilly and Breizman [7] of persistent chirping as shown in figure (2). It turns out that the mechanism of relaxation when the chirping of a phase space structure is launched, maintains the destabilizing gradient, as is indicated in figure (3), so that continuous triggering of the phase space structure arises . When diffusive and drag processes are absent, relaxation only occurs after the phase space structures sweep through the entire destabilizing region and then erosion of the entire plateau results, with a large release of free energy.

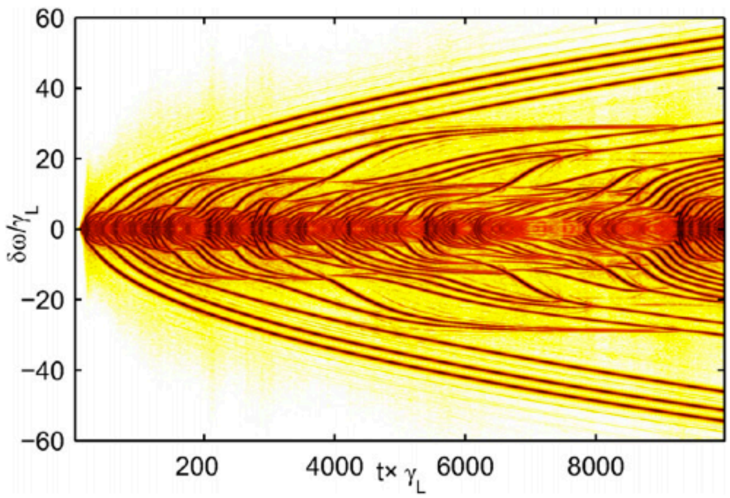

Figure 2. Modes with time-dependent frequencies in nonlinear simulations of the bump-on-tail instability [5]. Fourier analysis of the mode amplitude shows that waves are continuously produced at the resonance $v_p \equiv \omega_p/k$ if the initial distribution function has a constant slope.

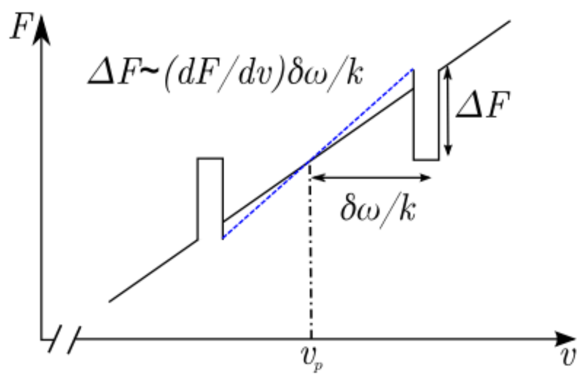

Figure 3. Cartoon illustrating the motion of holes and clumps and the wake (dotted line) that acts to steepen the distribution function, creating a favourable environment for instability.

III-TAE Reduced Model

The previous work on chirping was done for the paradigm bump-on-tail problem. A more sophisticated simplified model problem applicable to TAE modes, was developed by Wang and Berk [8,9]. The model applies the TAE model developed by Rosenbluth, et. al. ('tip model') which was developed to describe an eigenmode response, to obtain a time dependent response for the mode development in terms of a Volterra integral equation which can be processed extremely quickly. A toy self-consistent interaction between energetic particles and the waves governed by the tip model was developed (which showed how the waves are generated in a TAE gap and then proceeded to chirp into the lower continuum as shown in fig.(4). An appropriate adiabatic theory was developed which showed that the amplitude of the wave as a function of frequency shift coincided with the evolution of the dynamic code as is seen in the fig. (5). This was a very important development which indicates that the assumption that an semi-analytic approach to this problem using adiabatic and bounced averaged transport assumptions is a feasible way to predict and explain primitive (in the technical sense) simulations as well as experimental data. This work was presented by Wang at the IAEA Technical Workshop on Energetic Particles held Sept. 2011 in Austin, Texas.

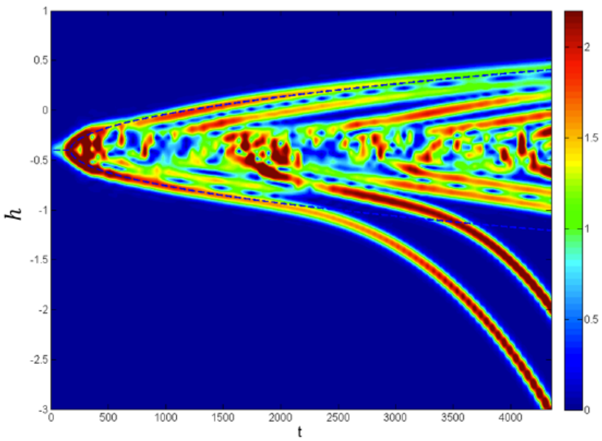

Fig. 4. Simulated chirping spectrum induced from reduced TAE model. TAE gap is between -1 < h < 1, with h the normalize frequency difference from the TAE frequency.

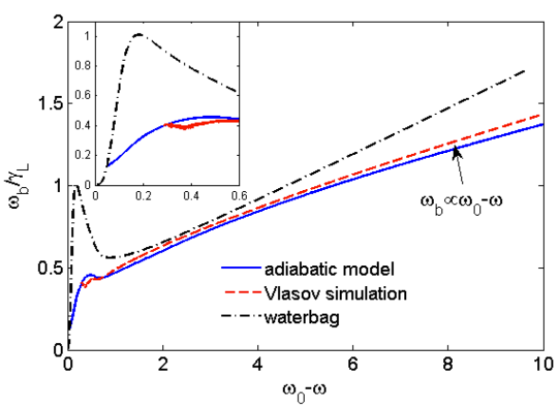

Fig. 5. Comparison of predictions of square root of mode amplitude (vertical axis) with frequency shift from the frequency predicted from linear theory for: the dynamical simulation (dotted red curve), the adiabatic theory of a self-consistent distribution (solid blue curve) and the prediction of a highly simplified waterbag model (dashed dotted blue curve) which can only produce qualitative similarity. Note long term overall agreement between the simulation and the detailed adiabatic model.

IV. Line Broadened Quasi-linear Model

Depending on the nature of background transport processes available, the response of resonant particle interactions may give rise to frequency chirping on one extreme when background stochastic transport of energetic particles are sufficiently small or to a response compatible with Quasilinear theory, if stochastic transport is sufficiently large.

Previously, such a line broadened theory in a toy model as well as in a tokamak plasma was developed in Joseph Fitzpatrick's PhD thesis (1999). This model assumed that the transport was only radial position, whereas it is important to take into account that this transport will occur in energy as well as momentum. The appropriate generalization was developed in a collaboration of H. L. Berk, N.N. Gorelenkov and his student, K. Ghantous.

It is important to emphasize that this model is novel in that it uses the Q.L. structure coupled with analytic theory to prediction the satuaration level of a single resonant mode and thus even without mode overlap, this quasilinear theory is able to predict accurate saturation levels. The theory presents a model for how the dynamics evolve when mode overlap begins, and when there is multiple mode overlap the new QL smoothly blends into the predictions of standard QL theory. The model can focus in on near marginal stability situations, which may become an essential area of interest in burning plasma situations and where one needs to know the deviations from the marginal stability conditions that are likely to arise (much like the various ELM regimes associated with edge tokamak operation).

This problem was K. Ghantous PhD thesis topic which she subsequently earned after the PEPSC project was terminated. The original Fitzpatrick work showed that the distribution response at a fixed energy, is basically a one dimensional phase space response in the distribution relaxation even when resonances overlapped. Ghantous' work demonstrated that the one dimensional response is still a valid picture if resonances do not overlap, as then one can use that for resonance there is an additional invariant, $E' = E - \omega P_\phi / n$, with E the energetic particle energy, ω the mode frequency and n the toroidal mode number. However, when modes overlap, one still needs to develop a suitable QL linear broadened code, whose details are still in the process of development. Some of Ghantous' work [10] has recently been published.

V. Upgrade of AEGIS Code

The AEGIS code is an MHD code developed by L. J. Zheng at IFS [11]. It is envisioned that this code can be the 'workhorse' for calculating the background plasma wave response for the plasma, that is then altered by the response of the energetic particles. The then existing AEGIS was eigenvalue solver that could not deal with obtaining 'quasi-modes' that arise when frequencies that cross continuum regions are important.

During the phase of the project covered the PEPSC grant, it was envisioned that AEGIS code would be able to calculate the linear response of the plasma to a phase space structure that forms and follow this response as the chirping evolves. To do this it was necessary to make two important modification of AEGIS. One is to be able to treat the response for frequencies in the continuum and the second is to develop a package that could respond to the source due to the resonant energetic particles. The first goal was fulfilled in the work of the post-doc, Eugene Chen, who enable AEGIS to treat the continuum response so that the mode structure and damping rates of the mode could be calculated. Indeed even a new mode associated with edge conditions in the TAE bandwidth was found in ref. [12]. Additional work by Chen discovered a mystery in the response of the wave to an external wave drive near the upper continuum that has not as yet been explained. It is particularly interesting as the response near the lower continuum was in accord with theoretical explanations.

The next step in this development was geared to start up at the end of the PEPSC funded period, which was to incorporate a source term inside AEGIS. Work on this goal was initiated with arrival of a new post-doc, Bo Zhang. Three months after Zhang's arrival, funding for Zhang's work was transferred to a SCIDAC grant.

VI. Interaction with PEPSC team

The major interactions of the IFS group with the PEPSC team was to consult on the validation points that were outputs of the M3D hybrid code run at Princeton and the GEM code run at Colorado. Points of validation that were discussed were predictions of single mode saturation in terms of drag and diffusion mechanisms that were present in these codes and the assessment of the roles of continuum and radiation damping. The other important region of overlap was the aforementioned mutual collaboration on developing a global machine Quasis-linear code to describe energetic particle diffusion. In addition, work began on a QL toy model to interpret D-III D data, that has subsequently been published in Phys Plasmas [13].

VII. Interaction with Graduate Students

During the PEPSC funding cycle the following graduate students received their principal technical guidance and were on or chaired their PhD committer from either B. N. Breizman or H. L. Berk, in training them to earn their Ph. D. degrees on topics relevant to the PEPSC project. At the date of this report, each of these students have earned the Ph. D degree.

1. Tianchun Zhou, under H.L. Berk on the theoretical description of E-Gam modes. Ph. D. from the University of Texas obtained in 2010. See ref. [14]
2. Matthew Lilly under B. N. Breizman on the destabilization of a steady response of a saturated TAE mode. Ph. D. from Imperial College obtained in 2010.
3. Robert Nyqvist under B.N. Breizman on the prediction of self-consistent frequency chirping of phase space structures far from the eigenfrequency of a mode. Ph. D from University of Goteborg, obtained in 2011.
4. Ge Wang under H. L. Berk on a reduced model for chirping of a TAE mode. Ph. D from Univ. of Texas, obtained in 2013.
5. Katy Ghantous under H. L. Berk and N. Gorelenkov on the feasibility of applying Line- Broadened Quasi-Linear Theory to burning plasmas. Ph. D. degree from Princeton University, obtained in 2013.

IX. Project Associated Publications

All the references cited (except for the first two) are on topics associated with IFS's development of physics and numerical issues needed for the SCIDAC project and in which at least some of the work was performed during the time SCIDAC funded this project. The last two references [15,16] are review papers papers written at a time that overlapped with the SCIDAC support period.

References:

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4. Lilley, M. K., Breizman, B. N. and Sharapov, *Effect of dynamical friction on nonlinear energetic particle modes* S. E. Physics of Plasmas **17**, 092305 (2010)
5. Breizman, B.N. *Nonlinear travelling waves in energetic particle phase space* Nuclear Fusion **50**, 084014 (2010)
6. Nyqvist, R. M., Lilley, M. K., and Breizman, B. N., *Adiabatic description of long range frequency sweeping,* Nucl. Fusion **52**, 094020 (2012).
7. Lilley, M. K., and Breizman, B. N., *Convective transport of fast particles in dissipative plasmas near instability threshold,* Nucl. Fusion **52**, 094002 (2012).
8. Ge.Wang and H. L. Berk *Model for spontaneous frequency sweeping of and Alfven wave in a toroidal plasma* in Communications in Nonlinear Science and Numerical Simulation, **17**, no.5, 2179 (2012)
9. G. Wang and H. L. Berk *Simulation and theory of spontaneous TAE frequency sweeping* Nuclear Fusion **52** 094003 (2012)
10. Ghantous, K. , Berk H.L., Gorelenkov, N.N. *Comparing the Line Broadened quasilinear model to Vlasov Code* Physics of Plasmas, March 2014, vol.21, no.3, 032119
11. L. J. Zheng, M. T. Kotschenreuther, and J. W. Van Dam, "AEGIS-K code for linear kinetic analysis of toroidally axisymmetric plasma stability", J. Computational Phys. 229, 3605 (2010).
12. E.Y. Chen, H.L. Berk**,** B. Breizman, L.J. Zheng, in Physics of Plasmas, **18**, 052503 (2011)
13. K. Ghantous, N.N. Gorelenkov, H. L. Berk**,** W. W. Heidbrink, M. A. Van Zeeland, *1.5 quasilinear model and its application on beams interacting with Alfven eigenmodes in III-D* in*:* Physics of Plasmas. **19**, 092511, (2012)
14. H. L. Berk and T. Zhou Fast excitations of EGAM by NBI Nuclear Fusion 50, 035007 (2010)
15. Breizman, B.N. and Sharapov, S.E., *Major minority: energetic particles in fusionplasmas,* Plasma Phys. Control. Fusion **53**, 054001 (2011), Review Paper3.
16. H. L. Berk *Overview of nonlinear kinetic instabilities* in AIP Conference Proceedings **52** 094003 (2012)

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