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FINAL REPORT

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Gregory Benford, Principal Investigator

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Abstract

We summarize advances in the general understanding of strong plasma turbulence, with special application to the mechanisms for powerful microwave emission. Principally, we developed an optical diagnostic system which permits *simultaneous* measures of the turbulent Langmuir fields (at the plasma frequency) in the plasma, plus the microwaves emitted by the plasma. This has allowed us to develop a complete inventory of energy transport, power production, losses and emissions. We then compare with the models we have developed. Agreement is good, and we now pursue fundamental aspects of the microwave emission processes.

ONR FINAL REPORT

Publications for Gregory Benford

Electric Field Spectra Beyond the Strong Turbulence Regime of Relativisitic Beam-Plasma Interactions (with Levron, D. and Tzach, D.), Phys. Rev. Letts., 58 13 (1987).

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Stability of Luminous Discharges in Strong Fields, IAU Symposium 140, Heidelberg, 1989, R. Beck et al. (eds.), Galactic and Intergalactic Magnetic Fields, 401-402, printed in the Netherlands (1990).

RESEARCH SECTION

A: 1987-89

INTRODUCTION

We have made substantial progress toward our goal of a general understanding of very strong plasma turbulence. In the past year we carried out a coordinated program of closely linked experiment and theory. Contemplated new measurements and modeling will complement each other. We plan to continue in this direction, with emphasis on new diagnostic techniques and extensive, computer-assisted modeling.

During this last year the group produced one PhD thesis (Ami Dovrat). A visiting scholar, David Tzach, is carrying forward extensive experimental research. We continued our collaboration with the high power microwave group at General Dynamics, sharing equipment and experiments.

Review of General Program

Over the last five years our program has broken new ground in the study of strong turbulence. To review briefly, we have used Stark effect diagnostics in the noisy environment of a relativistic beam-plasma system, achieving sensitivities and resolutions in time and space which considerably exceed earlier methods. Using observations of allowed helium lines, and satellites of forbidden lines, we found very strong Langmuir fields oscillating at the plasma frequency.

These fields of >10 kV/cm apparently derive from powerful instabilities. They are generated by passing a 10 kA, 800 kV electron beam through a background helium plasma of density in the 10^{13}/cc range. We find that the chance of seeing a given field strength E follows a probability distribution $\exp(-E^2)$, with at least 1% of the plasma volume experiencing $E^2 > 4\pi nT$. There is strong inferred evidence that turbulent fields are not smoothly distributed through the beam-plasma volume.

We have proposed detailed mathematical models to explain the chacteristic $\exp(-E^2)$ shape and the strong mean fields. Our observations can be described by either a model invoking strong wave correlations over ranges exceeding a Debye length, or by a picture requiring that strong cavitons interact to form a statistical ensemble on times shorter than the average caviton decay time. Other pictures will no doubt emerge as computer simulations of strong turbulence allow study of the long time scales of experiments such as ours. (Current simulations run for at most 0.1 % of the equivalent duration of our experiments, and thus do not follow the approach to a global steady state dynamical regime in which dissipation offsets the driver electric fields.)

Our experiments can also yield spatial measures of $\langle E^2 \rangle$ as a function of r and z in a cylindrical geometry, inside and outside the beam, as a function of time. This bears on questions of turbulent wave convection.

Further, we have analytically modeled production of strong electric fields by beam-plasma instability, including modulational transfer in $\vec{k}$-space, plasma heating, radiation, and wave convection. We compared in detail the results of this numerically integrated model with direct observations of $\langle E^2(r,z,t)\rangle$, using beam voltage and current as input and requiring no fitting parameters.

A detailed physical picture emerges of the strongly interacting regime of plasma turbulence, at both microscopic and macroscopic levels. Such turbulence may provide a powerful means to stop electron-neutralized ion beams which penetrate plasmas. Some theory describing this yields stopping lengths much shorter than classical collision lengths in a variety of conditions.

PROGRESS IN THE LAST YEAR

A. Measurement of detailed electric field behavior.

We developed a more sensitive Stark effect diagnostic, using laser-stimulated lines. ~~(Appendix A)~~ This was the basis of a thesis by Ami Dovrat. Careful study of the time evolution of $\langle E^2(r,t)\rangle$ in a cylindrical, beam-driven plasma allowed us to compare with an extensive numerical model, with very good agreement. The predicted electric field strength is within 30% of the observations, and displays the same general pattern of time dependence. This measurement resolves a $(mm)^3$ volume in the plasma, giving good spatial analysis of electric field. We find that the field falls with radius $\underline{r}$ in a manner compatible with Langmuir wave transport. These results fullfill the first major goal described in our proposal last year.

B. Forbidden Line measurements.

We have used the enhanced sensitivity of forbidden helium lines to probe the structure of strongly turbulent zones within the plasma. Using indirect deductive methods, we inferred that a substantial fraction of the plasma (> 1%) experiences high fields. This high density means that caviton "collisions" may be important. Such an effect may form the characteristic $\exp(-E^2)$ distribution we observed earlier if they can persist long enough to interact and form a statistical ensemble. These results are described in Appendix B, a reprint from Physics of Fluids.

C. Ion scattering by super-strong turbulence.

As described in our previous proposal, we have carried out a theoretical study of how a super-strong ensemble of nugget-like cavitons, with $\langle E^2\rangle/4\pi nT > 0.1$, could scatter ions and greatly enhance the interaction of colliding plasmas. We find that ordinary laboratory plasmas generated from ion beams will not display much anomalous stopping. However, plasmas of lower density and higher temperature will be dominated by these effects, as long as the source of energy for caviton formation persists (i.e., a strong driver electric field). This means that in magnetospheric or solar conditions this effect should dominate classical ion scattering by the dense background plasma. We worked out the stopping length for the solar coronal case, considering a slug of plasma striking the foot of a solar arch. Remarkable enhancement occurs, since the nuggets of intense electric fields scatter effectively. This work is detailed in Appendix C.

4. Circuit Analogy for Turbulent Systems

This theoretical work proposes a simple picture for naturally occurring regions where inductive processes can make turbulent plasma mechanisms prominent. In this picture, partlly ionized clouds moving across an imposed strong magnetic field can induce strong electric fields, $\vec{E}=\vec{v}x\vec{B}$. The magnetic field then forces a fixed geometry on the resulting currents. Since other dissipative processes will be typically much weaker, induced plasma turbulence will dominate the luminosity of such regions. This formulation allows a variety of applications. The region treated in Appendix D is our own galactic center, which displays highly organized filaments, over a hundred times longer than their one-light-year diameter, which radiate strong synchrotron spectra. This spectacular case promises to illuminate the general processes involved. More subtle current systems such as those of the near-Earth environment will be studied in future.

PUBLISHED PAPERS

1. Electric Field Spectra Beyond the Strong Turbulence Regime of Relativistic Beam-Plasma Interactions (with Levron, D. and Tzach, D.), Phys. Rev. Letts., 58 13 (1987).

2. The Collective Emission of Electromagnetic Waves from Astrophysical Jets: Luminosity Gaps, BL Lacertae Objects, and Efficient Energy Transport, (Benford, G., et al), Astrophys. J. 326 110-124 (1988).

3. A Circuit Analogy for Active Galactic Nuclei in Active Galactic Nuclei, Benford, G. Miller, H.R., and Wiita, P.J., eds., Springer-Verlag, New York, p. 370-374, (1988).

4. Diagnosing Superstrong Turbulence in Plasmas by Forbidden Line Measurements, Benford, G., Levron, D., Baranga, A. B.-A. and Means, J., Physics of Fluids, 31, 2026, (1988).