Multi-dimensional collective effects in high-current relativistic beams relevant to High Density Laboratory Plasmas

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Summary:

Our theoretical/computational group is based in the Physics Department of the University of Texas at Austin. The PI (Dr. Shvets) and his team (research scientist Dr. Vladimir Khudik) are also affiliated (and physically located) at the Institute for Fusion Studies (IFS). The focus of our work is on studying the fundamental plasma physics of electron beam propagation through plasma, investigating collective phenomena responsible for deceleration of the beam and extraction of its kinetic energy by the plasma. The context of this research is on the dynamics of collisionless stopping.thermalization of relativistic electron beams via Weibel instability. The context is primarily astrophysical: generation of collisionless shocks via Weibel Instability. Stopping distance for a highly relativistic beam due to non-collective (collisional) processes scales as the square of the beam's energy, and can easily become larger then the target's radius. Therefore, collective instabilities may have to be invoked in order to extract the beam's energy. Understanding such collective stopping by instabilities such as the Weibel instability is the main focus of our proposal. Developing a reduced model of the Weibel instability and developing the appropriate numerical code has been the main task of our research during the first year of funding. This was a no-cost extension from June 1, 2012 to May 31, 2013 reporting period. We needed this funding to finish our work on a Physics of Plasma paper and to submit it for publication. The total amount of this no-cost extension was $2,611.

The main deliverable was the publication of the paper:
Vladimir Khudik, Igor Kaganovich, and Gennady Shvets, "Halo formation and self-pinching of an electron beam undergoing the Weibel instability", Physics of Plasmas 19, 103106 (2012).
The abstract of this paper is as follows:

The collisionless Maxwellization of the energy distribution of an electron beam undergoing Weibel filamentation instability in a dense background plasma is demonstrated. While binary collisions between discrete charged particles are usually responsible for establishing the Maxwell-Boltzmann distribution (MBD) of non-equilibrium plasmas, we demonstrate that the same effect is achieved through collective collisions between multiple beam filaments. The final state of the filaments' merger is a single pinched beam surrounded by a wide halo. An analytic model for the equilibrated beam is developed and used to estimate spatial profiles of the pinched beam and its halo, the temperature, and the magnetic field. Results of analytical theory agree well with those of particle-in-cell simulations. Deviations from the MBD are explained by incomplete Maxwellization of the electrons with high and low transverse energies.

In summary, an analytical model describing the self-pinching of a relativistic charge-neutralized electron beam undergoing the collisionless Weibel instability in an overdense plasma has been developed. The model accurately predicts the final temperature and size of the self-focused filament. It is found that the final temperature is primarily defined by the total beam's current, while the filament's radius is shown to be smaller than the collisionless skin depth in the plasma and primarily determined by the beam's initial size. The model also accurately predicts the repartitioning ratio of the initial energy of the beam's forward motion into the magnetic field energy and the kinetic energy of the surrounding plasma. The density profile of the final filament is shown to be a superposition of the standard Bennett pinch profile and a wide halo surrounding the pinch, which contains a significant fraction of the beam's electrons. PIC simulations confirm the key assumption of the analytic theory: the collisionless merger of multiple current filaments in the course of the Weibel Instability provides the mechanism for Maxwellization of the beam's distribution function. Deviations from the Maxwell-Boltzmann distribution are explained by incomplete thermalization of the deeply trapped and halo electrons. It is conjectured that the simple expression derived here can be used for understanding collsionless shock acceleration and magnetic field amplification in astrophysical plasmas.

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