It's the magnetic field, stupid!

Exploring an astrophysical plasma instability in the laboratory

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In Short

Plasma instabilities driven by an electron or proton beam play a crucial role in many astrophysical contexts. Using MHD theory, Bell found a new, purely aperiodic non-resonant instability driven by a proton beam. The non-resonant Bell instability has a wave vector parallel to the ambient magnetic field, and simulations suggest that it may be driven to amplitudes much larger than that of the ambient field and thus may provide the magnetic-field amplification needed at astrophysical shocks for further particle acceleration. The level of magnetic-field amplification may be explored in laboratory experiments, in which a relativistic electron rather than proton beam is directed into a magnetized plasma. We conduct particle-in-cell simulations to find parameters that permit studying Bell's instability in the laboratory. The initial idea was to use equipment originally developed for the injector of the XFEL. In any case, the scenarios have to be kinetically simulated before a significant investment in hardware can be justified. The main issue is to avoid other instabilities that grow faster than Bell's instability.

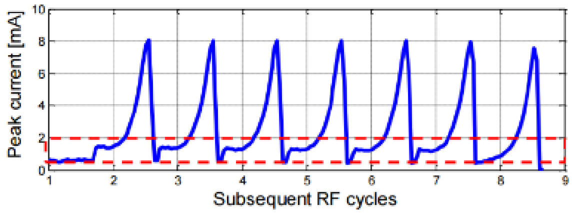

***Figure 1:** Peak electron beam current versus time in units of subsequent RF cycles of the PITZ gun at 1.3 GHz – simulated operation regime optimized for laboratory astrophysics experiments.*

The prime acceleration mechanism of cosmic rays is based on scattering by self-generated magnetic turbulence near astrophysical shock waves. If the cosmic rays would drive a turbulent magnetic field to an amplitude much larger than the homogeneous interstellar field, particle acceleration could be faster and extend to higher energies than conventionally estimated. We conduct large particle-in-cell (PIC) simulations of a specific plasma instability that is suspected to provides strongly amplified magnetic field.

In 2004, Bell noted that in the upstream region of astrophysical shocks the current carried by drifting cosmic rays along a background magnetic field B_0 should efficiently excite non-resonant, nearly purely growing ($\Re\,\omega = \omega_{\rm R} \simeq 0$) transverse modes of magnetic turbulence, rather than resonant Alfvén waves [1]. An open question is at what amplitude the mode saturates. An analytical treatment suggests that field amplification is possible. Kinetic simulation vary in their results and indicate that the amplification factor may be around 10, but with one exception they have only been conducted with periodic boundaries to date. A source of saturation is scattering and deceleration of the drifting, current-carrying particles. In the only simulation with open boundaries, we demonstrated that the bulk deceleration introduces a compression zone that may significantly impact the shock/precursor system [2].

Our goal in this project is to find parameters that permit studying this instability in the laboratory. Studying current-driven instabilities in the laboratory is a new, promising avenue of research that explores the saturation level and persistence of turbulent magnetic fields that can be related to analog astrophysical systems [3].

Studying Bell's instability in the laboratory sets requirements on the electron source and the plasma cell which includes crucial beam and plasma parameters such as (quasi-) continuous electron-beam temporal profile, mA-range beam current, a beam energy of a few MeVs, a plasma density of approximately $10^{13}\ \mathrm{cm}^{-3}$ for a duration of a millisecond, sufficiently long plasma, and many others. Real electron beams such as that produced by a modified injector to the X-ray free-electron laser, XFEL, have a beam profile as indicated in figure 1.

In any case, the scenario has to be kinetically simulated before a significant investment in hardware can be justified. The main issue is to avoid other instabilities that grow faster than Bell's instability. We will determine the requirements on the time profile and the angular and momentum distribution of the electron beam. The simulations, for which resources are requested here, are one pillar of the project, besides analytical studies of the linear growth rate of various wave modes and experimental efforts in shaping the electron beam. We will conduct a number of large and medium-size simulations designed to explore the nonlinear evolution of the system and in particular the interplay of physical interactions that the beam is subjected to. We analytically calculated the dispersion relation for transverse, electromagnetic waves driven by electron beams and found

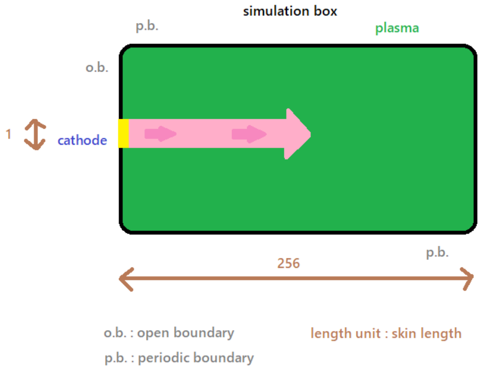

Figure 2: *Setup of test simulations.*

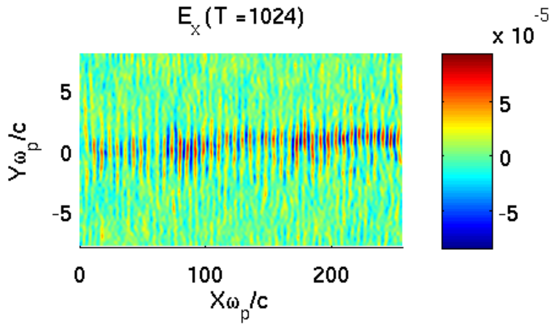

Figure 3: *Unwanted electrostatic instabilities can provide electric-field noise in test simulations with a bunched electron beam.*

that waves can be excited with frequencies up to the electron gyrofrequency, as opposed to the ion gyrofrequency that was deemed the limit in the original treatment of Bell's mode.

We investigate with particle-in-cell simulations the properties of Bell's instability induced with an electron beam. Our analytical studies gave us insight into the growth rate and the range of wave numbers, in which the mode would appear. The main challenge in the application to the laboratory experiment is that other instabilities with larger growth rate may deplete the beam energy in the early stage of evolution and suppress Bell's mode. Figure 2 displays the setup of a test simulation, in which a narrow beam is injected on one side and permitted to leave through open boundaries on the other side. Care must be exercised in keeping the wavenumber resolution of the grid large enough to capture the narrow resonance of the electrostatic foreground mode, the width of which is known from our analytical studies. The simulations may have to be larger than the plasma would be in the laboratory experiment, otherwise grid effects would deteriorate the usefulness of the numerical experiment. This restriction only applies in beam direction.

In homogeneous systems the ratio of the growth of Bell's mode to that of the unwanted electrostatic instability scales with the temperature and Lorentz factor of the beam. To understand the effect of the inhomogeneous beam structure and the size of the plasmas in our experiment, we also introduce the requirements for actual experiment in the simulation studies. Substructure in the electron beam may add complexity to the pattern of return current that the plasma sets up in compensation of the beam current, just like space plasma would. For non-uniform background plasma with density variations on scales larger than the electron skin length, we do not observe any feature in addition to those observed for homogeneous plasma. As for the inhomogeneous beam (cf. Figure 1), first simulation results indicate that the growth rate of the electrostatic foreground instability is commensurate with that corresponding to the average beam current density, provided bunches are injected with high frequency and smeared out in time.

Our simulations are divided into the categories "large" and "medium" solely on the basis of their duration. the simulation boxes will have a very similar size. The simulations are in particular needed to explore the impact of chirping in the phase-space distribution of the electron bunches in the beam. The exact parameters will be determined by modeling of the production of the beam and optional beam optics that would shape it. Likewise experimental efforts in developing the plasma cell will provide us with options for the plasma parameters that will need to be tested in simulations. The parameters of the simulation can then not be defined at this time, but will be developed in constant exchange with the experimentalists who derive direction from our simulations and analytical calculations.

Our simulations are scientifically important because the unknown saturation level of turbulent magnetic-field amplification near cosmic shock fronts is a critical ingredient in the theory of particle acceleration at shocks.

WWW

http://www-zeuthen.desy.de/ pohlmadq/

More Information

[1] Bell, A. R. 2004, MNRAS, **353**, 550

[2] Kobzar, O., Niemiec, J., Pohl, M., & Bohdan, A. 2017, MNRAS, **469**, 4985

[3] Warwick, J. et al. 2017, ArXiv e-prints 1705.08162

Project Partners

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