Abstract
Using a three dimensional relativistic particle–in–cell code we have performed numerical experiments of plasma shells colliding at relativistic velocities. Such scenarios are found in many astrophysical objects e.g. the relativistic outflow from gamma ray bursts, active galactic nuclei jets and supernova remnants. We show how a Weibel like two–stream instability is capable of generating small–scale magnetic filaments with strength up to percents of equipartition. Such field topology is ideal for the generation of jitter radiation as opposed to synchrotron radiation. We also explain how the field generating mechanism involves acceleration of electrons to power law distributions ($N(p) \propto p^{-7}$) through a non–Fermi acceleration mechanism. The results add to our understanding of collisionless shocks.

Keywords: Collisionless shock waves, particle acceleration, gamma ray bursts, plasma instabilities

1. Introduction
Many astrophysical objects emit non–thermal radiation when expelled plasma interacts with the surrounding media. These objects include gamma ray bursts (GRBs) and their afterglows, the jets from active galactic nuclei, jets from quasars and supernova remnants. The non–thermal radiation is believed to be emitted in strong collisionless shocks. Despite the vast prevalence and wide astrophysical applicability, collisionless shocks remain poorly understood. The observed non–thermal emission suggests that strong particle acceleration and magnetic field generation takes place in these shocks. It was suggested by Medvedev and Loeb, 1999 that a Weibel–like two–stream instability is able to generate a strong magnetic field in the shock transition region. Recently, due to the increase in computer power, this has been verified with particle–in–cell
(PIC) simulations (Frederiksen et al., 2003, Frederiksen et al., 2004, Hededal et al., 2004, Medvedev et al., 2004, Nishikawa et al., 2003, Nishikawa et al., 2004, Silva et al., 2003). Still, today's computer power does not allow us to fully resolve the shock transition region. We can, however, explain the non-linear kinetic plasma dynamics that generate the electromagnetic fields needed for transmission of momentum between the colliding plasma populations. Here, we report on 3D PIC simulations of the shock formation in the counter-streaming region of two colliding plasma shells.

2. Numerical Experiments

We have performed numerical experiments using a three dimensional relativistic kinetic electromagnetic particle-in-cell code. The code works from first principles by solving the Lorentz force equation for the particles and the Maxwell’s equations for the electromagnetic fields.

We let two electron-proton plasma populations (with a density difference of a factor of three) collide in the reference frame of the denser population. In this frame we continuously inject the less dense population with a bulk Lorentz factor, \( \gamma = 15 \) in the \( z \)-direction. The computational box consists of 125 \( \times \) 125 \( \times \) 2000 gridzones or 37 \( \times \) 37 \( \times \) 600 \( \tau^* \) where \( \tau^* \) is the electron skin depth \( \tau^* = \sqrt{\frac{e}{\mathcal{E}}} \). Using 16 particles per cell this adds up to almost \( 10^9 \) particles. Both populations have a rest frame temperature corresponding to a thermal velocity \( v_{\text{th}} = 0.01c \). In order to be able to resolve both electron and ion dynamics the ion-electron mass ratio is \( \frac{M_i}{m_e} = 16 \). This is clearly a strong assumption but it allows us qualitatively to understand how particles with different mass affects the Weibel instability. In these experiments both populations are initially unmagnetized.

3. Results

When the simulation runs and the plasma populations stream through each other, we observe how the Weibel instability collects particles into current filaments (Medvedev and Loeb, 1999). First the electrons go through the instability and then further downstream the electrons thermalize to one single population and the heavier ions go through the instability. The ion filaments are more robust than the preceding electron filaments since the thermalized electron will Debye shield the ion filaments. Even further downstream the current filaments acts as 2D macro particles in the transverse plane and are themselves collected into larger filaments as explained by Frederiksen et al., 2004 and Medvedev et al., 2004. This behavior can be seen in fig. 1.

Surrounding the current filaments is generated a strong magnetic field with \( B_0 = 0.01 \). Here, \( B_0 \) is the field generation efficiency i.e. the amount of total injected kinetic energy that goes into magnetic field energy. It is important
Figure 1. This figure shows the generation of ion current filaments. Here we see the jet head on. The four slices show the ion current density at different depths of the shock at a fixed time. The different depths are $z=60, 100, 120, 160\,\text{g}\,\text{electron skin depths}$.

to realize that $B$ is not a simple parameter since it varies strongly along the flow-direction down through the shock.

Inside the Debye sphere, strong electron acceleration takes place. The electrical field that surrounds the ion current channel accelerates the electrons toward the filaments where they are deflected on the induced magnetic field. The scenario is depicted in fig. 2. It have previously been shown that the ion filaments are generated in a self-similar coalescence process (Medvedev et al., 2004) which implies that a spatial Fourier decomposition exhibits power law behavior. As a result, the electrons are accelerated to a power law distribution function (fig. 3) as shown by Hededal et al., 2004.

Figure 2. An ion current channel surrounded by an electric – and a magnetic field. Electrons in the vicinity of the current channels are thus subject to a Lorentz force with both an electric and magnetic component, effectively accelerating the electrons.

Figure 3. The normalized electron four velocity distribution function downstream of the shock. The dot–dashed line is a power law fit to the non–thermal high energy tail, while the dashed curve is a Lorentz boosted thermal electron population.
The electrons are trapped in the potential field of the ion channels and are repeatedly accelerated and decelerated. This means that energy losses due to escape are small, and that the electrons remain trapped long enough to have time to loose their energy via a combination of bremsstrahlung and synchrotron or jitter radiation. The fact that the electrons cannot escape the ion filaments without being decelerated also implies that they are not available for recursive acceleration as suggested in Fermi acceleration (Hededal et al., 2004).

4. Summary

We have performed numerical experiments of relativistic collisionless plasma shocks using a self-consistent three dimensional particle–in–cell code. We find that the Weibel instability is capable of generating turbulent magnetic fields with a strength up to percents of equipartition. The magnetic field is induced around ion current filaments. These filaments also accelerates electrons to power law distributions. The suggested acceleration scenario does not rule out ion Fermi acceleration but might overcome some of the problems pointed out by Baring and Braby, 2004 regarding the apparent contradiction between standard Fermi acceleration of electrons and spectral observations of GRBs.

The microphysics in the field generation and particle acceleration described here is clearly beyond the reach of the magneto hydrodynamic approximation. A parameter study utilizing a PIC code working from first principles is necessary to fully understand the interdependence between the relative bulk Lorentz factors of the colliding plasma shells, the power law index of the non–thermal electron population, $B$, and in a broader sense the detailed evolution and structure in collisionless shocks.

References

Baring, M.G. and Braby, M.L. (2004). ApJ, 613:460–476.
Frederiksen, J. T., Hededal, C. B., Haugboelle, T., and & Nordlund, Aa (2003). Proceedings of the 2002 Niels Bohr Summer Institute, ArXiv Astrophysics e-prints, astro-ph/0303360.
Frederiksen, J. T., Hededal, C. B., Haugboelle, T., and Nordlund, Aa. (2004). ApJL, 608:L13–L16.
Hededal, C. B., Haugboelle, T., Frederiksen, J. T., and & Nordlund, Aa (2004). Submitted to ApJL, astro-ph/0408558.
Medvedev, M. V., Fiore, M., Fonseca, R., Silva, L., and Mori, W. (2004). submitted to ApJ, astro-ph/0409382.
Medvedev, M. V. and Loeb, A. (1999). ApJ, 526:697–706.
Nishikawa, K.-I., Hardee, P., Richardson, G., Preece, R., Sol, H., and Fishman, G. J. (2003). ApJ, 595:555–563.
Nishikawa, K.-I., Hardee, P., Richardson, G., Preece, R., Sol, H., and Fishman, G. J. (2004). Submitted to ApJ, astro-ph/0409702.
Silva, L. O., Fonseca, R. A., Tonge, J. W., Dawson, J. M., Mori, W. B., and Medvedev, M. V. (2003). ApJL, 596:L121–L124.