Proton Beam Weibel Instability Simulations of Energy Transfer in Gamma-ray Bursts

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Abstract. Proton beam Weibel instability may explain key ingredients for Gamma-Ray Bursts (GRBs): amplified magnetic field, relativistic electron production and a power law energy distribution. By using particle-in-cell simulations, we demonstrate that a part of the directed kinetic energy of a proton beam is converted into kinetic energy of electrons, ions, electric and magnetic fields. A finite lifetime for the magnetic field is demonstrated, indicating a maximum for the GRB duration. An experiment probing the GRB environment is proposed.

1. Introduction

Historically, Gamma-ray bursts (GRBs) - short, intense pulses of γ rays, were discovered serendipitously by orbiting Vela satellites in 1963. Today, GRB are known to consist of both γ rays and any lower-energy emission that occurs simultaneously with them. The x-ray emission usually accompanies the γ-ray emission as a low-energy tail [1]. GRBs are observed almost daily with satellites and ground-based instruments. Their isotropic distribution across the sky indicates a cosmological origin. GRB observations in the radio, infrared, optical and x-ray domain have been reported [1]. The measured energy fluxes are of the order of $10^{41}$ J/cm$^2$ along with estimated distances up to 3 Gpc (distance of $10^{23}$ km corresponding to the optical red shift $Z \sim 5$), providing an estimated isotropic electromagnetic energy release of $\sim 10^{50}$ J. The total GRB duration is typically less than 100 s. Some of them are accompanied by a weaker afterglow that continues for as long as a few days. GRBs consist of a series of ms pulses with the majority of photons between 100 keV and 1 MeV; some up to GeV. GRB spectra have a broad power law tail, $dN/\epsilon \sim \epsilon^{-s}$. Breaks in GRB spectra indicate a structure of the source of radiation consisting of jets and dense bulk material moving with relativistic velocities [2].

The GRB origin is related to the explosion of a central engine with energy release in the form of two relativistic jets. As reviewed in [1], the central engine is jet-like consisting of a baryon–dominated or a lepton–dominated relativistic plasma flow. The fireball (internal-external shocks) model [1, 3] describes the GRB phenomenology and its principle parameters, although it does not define the inner engine that produces GRBs [1]. In this investigation, we assume baryon flux dominated jets from the central engine. The jets have relativistic velocities with an effective relativistic factor $\Gamma \sim 10 – 100$. The jet deceleration, heating of electrons and ions with magnetic field generation is due to: (1) the internal collisions of dense globules in the flying ejecta and (2) the interaction of jets with the interstellar medium (ISM). The electromagnetic radiation is explained by the synchrotron emission of relativistic electrons in a strong magnetic field and by Compton scattering. The fireball model relies on the hypothesis of energy equipartition: the total energy released in a form of directed kinetic energy of ions is evenly distributed between electrons, ions and magnetic field.

The fact that the jets are relativistic allows reconciling a very short duration GRB recorded on the Earth with a very long slowing down length that cannot be less than $10^{10} – 10^{12}$ km. The difference between the slowing down time of $\sim 10^5$ s and the GRB duration of $\sim 100$ s is explained by relativistic compression by a factor of $2\Gamma^2$ of a signal emitted from the source moving towards the observer. Moreover, such a large propagation length makes it evident that the slowing down process has to be collisionless and the directed kinetic energy of the jet is transformed into the energy of electrons, ion and electromagnetic fields via plasma instabilities. The Weibel-type instabilities are considered to be viable candidates [4]. However, theoretical arguments [5] predict a protracted distance for the proton energy exchange with the mechanisms for strong electron heating and strong magnetic field generation.
remaining unclear. Recent numerical simulations with particle-in-cell (PIC) codes address the issues of the development of ion Weibel instabilities in relativistic proton streams with formation of collisionless shocks [6 - 8]. However, the simulation results are contradictory and incomplete. Hence, the problem of energy dissipation by collisionless plasma flows within the context of the Fireball Model remains unresolved. Furthermore, it is advantageous to define the conditions whereby the main features of the model are verified to scale under controlled conditions in laboratory experiments.

The objective of the present paper is to propose a methodology and a preliminary design of an experiment whereby the collisionless slowing down processes of dense streams of high energy plasmas can be studied and test the major hypothesis of the fireball model. We focus exclusively on interacting shocks that expand into the surrounding ISM, and we investigate relativistic electrons accelerated within the shocks due to energy transfer from proton streams. The methodology incorporates the slowing down of relativistic proton streams, the repartition of the dissipated energy between the electrons, protons and magnetic fields; the electron heating mechanism, efficiency and spectrum of electromagnetic emission. In addition to its astrophysical goals, such an experiment is of interest for inertial fusion, whereby the method of fast ion ignition relies on the energy deposition of more than 10 kJ into the compressed fuel core at a time scale of a few ps. The role of collective processes in the transport and dissipation of such extremely high ion currents remains to be determined.

2. Scheme of laboratory experiment on the collisionless dissipation of fast ion beams

The experiments on ion acceleration with high intensity laser beams demonstrate a possibility of efficient proton acceleration to energies of several tens of MeV with pulse duration of several ps and a total charge of a few µC [9]. These proton beams have a very low emittance of less than 0.01 mm·mrad and can be transported over distances of a few mm. The proton density in such beams may exceed $10^{18} - 10^{19}$ cm$^{-3}$. We chose to investigate collisionless dissipation processes of such beams via interaction with plasma of comparable density. The estimates and numerical simulations shown below demonstrate that the collisionless shock might have a thickness of a few mm. Therefore, the experiment is feasible with present day plasmas and with lasers having pulse energy of a few kJ and petawatt power. The processes of energy conversion can be measured from the energy spectrum of the transmitted ion beam, from interferometric observations of the density distribution in the interaction zone, and from the spectrum and energy of soft x-ray emission.

Figure 1. Schematic of the experiment to probe the collective effects in ion beam collisions: 1 – a proton bunch is created from a thin foil irradiated by a high intensity short laser pulse, 2 – transport zone of the proton bunch to the interaction site, 3 – target plasma created by ionization of a gas jet with an auxiliary laser beam, and 4 – diagnostic equipment: ion energy detector, interferometer, x-ray detector.

Although the experiment proposed in Figure 1 is non-relativistic, it verifies the conditions of the proton Weibel instability and allows us to investigate electron heating and magnetic field generation that are the key descriptors of the GRB Fireball Model. Measurements for the proton beam slowing down length, x-ray emission and energy spectrum can be performed. The ion beam is created via interaction of a high intensity laser pulse with a thin solid foil made of plastic or metal. The laser and target parameters are discussed in the next section. A special target design may be used for controlling the proton energy spectrum, number of protons and their divergence. The secondary plasma is placed at a distance of ~ 1 mm, which is sufficiently far to avoid any parasitic coupling between the primary and secondary targets while maintaining a high ion density. The secondary plasma is created by an
auxiliary laser or an x-ray flash. The gas density and the size of the interaction region are chosen in order to optimize collective processes and to make visible the collisionless shock. The characteristics of the proton beam and its interaction with the secondary plasma are discussed below.

3. Ion acceleration in laser plasma interaction

Studies over the last ten years demonstrate efficient proton acceleration with laser pulses in thin solid foils. The model of target normal sheath acceleration (TNSA) [10] explains it as a three-step process: first, the laser pulse energy is converted into hot electrons with the energy of the order of the laser ponderomotive potential at the front side of the target. Then, these hot electrons cross the foil and create a strong electrostatic potential at the rear side. Because of an extremely steep density profile, the sheath electric field exceeds the values of 1 MV/µm and effectively ionizes and accelerates the ions from the surface. In our simulations with a one-dimensional version of the particle-in-cell code PICLS [11] we chose a 1 µm wavelength laser pulse with intensity of $10^{20}$ W/cm$^2$, and pulse duration of 0.3 ps. It interacts with a 5 µm thick CH foil (density $4 \times 10^{22}$ cm$^{-3}$) and accelerates electrons to the average energy of 16 MeV. The energy spectrum of protons accelerated from the rear side of the foil, their spatial and angular distributions are shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** Characteristics of the proton beam accelerated from the rear side of a 5 µm CH foil: a) energy spectrum at three time moments of 1, 1.3, and 1.5 ps; b) spatial distribution of fast protons for the same three time moments; the density is normalized to the critical density $n_c = 10^{21}$ cm$^{-3}$; c) velocity distribution of protons in the plane of laser polarization at 1.5 ps; the proton velocities in the normal direction, $v_x$, and in the target plane, $v_y$, are normalized to the light velocity, $c$.

The protons in the interval from 10 to 30 MeV have a very small divergence of less than 1% (Fig. 2c). Their density just after the acceleration is $\sim 10^{19}$ cm$^{-3}$ and they are spread over the layer of thickness of $\sim 10$ µm (Fig. 2b). Assuming that they are accelerated from the spot of 100 µm in diameter, we estimate the total number of protons to be $\sim 10^{12}$ in the source region. These protons are spreading ballistically along the propagation direction. We estimate that at a distance of $\sim 1$ mm from the source the proton bunch will have a thickness of 100 µm and a density of $\sim 10^{18}$ cm$^{-3}$. These parameters are inputs for modeling of the proton bunch interaction with the secondary plasma.

4. Fast ion beam interaction with secondary plasma

The collisionless interaction of two plasmas is most efficient if both plasmas have similar densities. The simulations were conducted with the two-dimensional version of PICLS [11] in the center of mass reference system. Two quasineutral plasmas were colliding with equal bulk velocities $v_i = 0.2c$. The transverse temperature of the target plasma moving to the left is 100 eV. It plays role of the ISM in the GRB model. The transverse temperature of the plasma moving to the right is 10 keV. It plays the role of the external jet. The length of the simulation box in the propagation direction ($x$) is 1.2 µm, than is, about four ion inertia length, $c/\omega_{pi}$, the length in the perpendicular direction is $c/\omega_{pe}$ with periodic boundary conditions. The proton-to-electron mass ratio is 1836, the initial densities of both plasmas is $10^{18}$ cm$^{-3}$. Initially, each plasma occupies one-half of the simulation box.

The simulation results are presented in Figure. 3. The electron Weibel instability is excited immediately as the interpenetration begins and produces electron kinetic energy dissipation only. This results in minor electron heating and generation of a weak magnetic field with the energy of the order
of the initial electron kinetic energy. Large energy exchange begins after a few ion plasma periods followed by a rapid increase of the magnetic field, shock structure formation and coalescence of small-scale electron current filaments into larger scale structures with magnetic field of 400 – 500 T.

![Figure 3](image)

**Figure 3.** Simulation results of interaction of two colliding plasmas: a) temporal evolution of the electron energy and the magnetic field energy, b) proton density spatial distribution at the time of 3 ps when the ion Weibel instability is excited. Black is zero density and red is maximum density, which exceeds the average density by a factor of 3. c) The spatial structure of magnetic field (perpendicular to the simulation plane) at 3 ps. Orange – red color represents zero, bright yellow is for positive magnetic fields and blue is for negative magnetic fields; the maxima correspond to the fields of 500 T. The box size is $4c/\omega_{pi}$ in the horizontal direction and $c/\omega_{pi}$ in the vertical direction.

Similar results have been reported in previous publications [6, 8], which use smaller ion-to-electron mass ratio and different boundary conditions. More importantly, the collisionless shock structure found in our simulations has a finite extent of only a few ion inertial lengths. The continuing fusion of the current filaments leads to overall decrease of the magnetic energy and the interaction ceases after 4 – 5 ps, that is, after $\sim$ 10 ion plasma periods. Consequently, the energy dissipated in the plasma collision is about 3% of the ion directed kinetic energy, which agrees with the number reported in Ref. [8]. However, this is more than 10 times less than reported in Ref. [7]. This might be related to a lower proton energy and smaller simulation box in our case. The energy in our simulations is deposited mainly in the electron component. The electrons display an almost isotropic distribution function with a power law energy distribution $dN/\epsilon \sim \epsilon^{-3}$, up to the energy of 150 MeV.

5. Conclusions

An experiment for studying the collisionless mechanisms of fast ion dissipation in laboratory plasma is proposed. The laser pulse interaction with thin solid target enables creation of a dense proton beam with the energy flux exceeding $10^{17}$ W/cm$^2$ and the density more than $10^{18}$ cm$^{-3}$. The proton Weibel instability can develop on the length of 1 mm and generate a collisionless shock necessary for GRB emissions. About 2% of the directed proton energy is transformed into electrons and generated a flash of electromagnetic energy. Simulations of similar physical processes at the GRB scale are ongoing.

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