Generation and decay of the magnetic field in collisionless shocks

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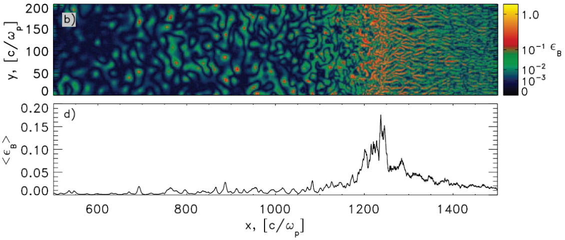
Relativistic shocks

- GRBs, AGNs, Microquasars
- Collisionless: the mean free path for Coulomb collisions is too large, often exceeding the size of the system
- Could generate strong magnetic field even when they propagate in unmagnetized media (e.g. Medvedev, Loeb (1999)) $\Rightarrow$ Sources of synchrotron emission

Main problem (Gruzinov, 2001; Sironi et al. 2015):



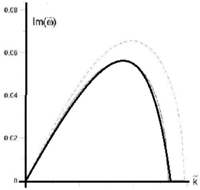
from Chang, Spitkovsky, Arons, 2008

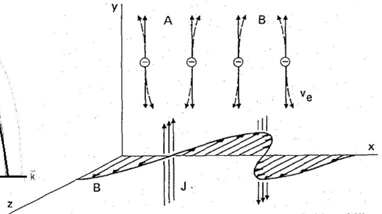
Weibel instability. Linear theory.

$$K = k\omega_p/c, \quad \Omega = \gamma/\omega_p,$$

$$\xi = c\Omega/(K * v_{T_\perp}),$$

$$A = \frac{T_\parallel}{T_\perp} - 1.$$





Physical mechanism of the Weibel instability.

PDF

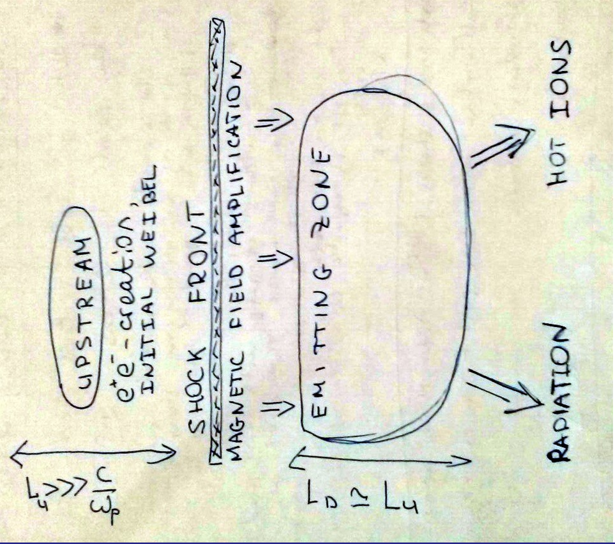
$$f(\mathbf{p}) \sim e^{-p_x^2/(2T_\parallel)-(p_y^2+p_z^2)/(2T_\perp)}.$$

Dispersion relation:

$$K^2 + \Omega^2 = -1 + (1+A)(1+\xi Z(\xi)) = A + (1+A)\xi Z(\xi).$$

$$K_{lim} \sim \sqrt{A}, \quad K_{max} \sim A^{3/2}, \quad \gamma_k \sim k^3$$

New model of a relativistic shock (Derishev, Piran 2016)



Simulation setup

Initial setup: box filled with isotropic e^-e^+ Maxwellian plasma with temperature $T = 50$keV. The injected plasma has two-temperature anisotropic distribution ($T_\perp = 50$keV, $T_\parallel = 200$keV). The number density of injected component is

$$N_a(t) = N_0\delta \begin{cases} \frac{t_i + t}{t_i}, & -t_i \leq t \leq 0, \\ 1, & t > 0. \end{cases}$$

In the talk I will use dimensionless times:

$$\tau = \int_{-t_i}^{t} \omega_p dt - \tau_i, \qquad \tau_i = \int_{-t_i}^{0} \omega_p \, dt\,.$$

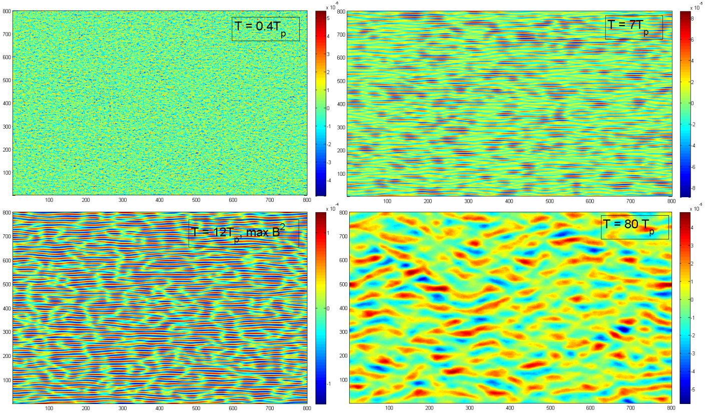
We performed two sets of simulations:

- After the injection we track the evolution of the field
- After the injection we model shock passage through the plasma by artificially stretching the PDF (doubling p_x component of each particle momentum) and letting system to evolve

Simulation parameters

- PIC-code (EPOCH), FDTD + Vay + 3rd order B-spline, 2D3V Geometry
- Conservation of energy $\delta e/e \lesssim 10^{-5}$
- Grid 1600 x 1600, periodic bc
- ~ 1000 ppc
- T_{sim} up to $20000/\omega_p$

Generation of the magnetic field via Weibel instability.



Evolution of the magnetic field

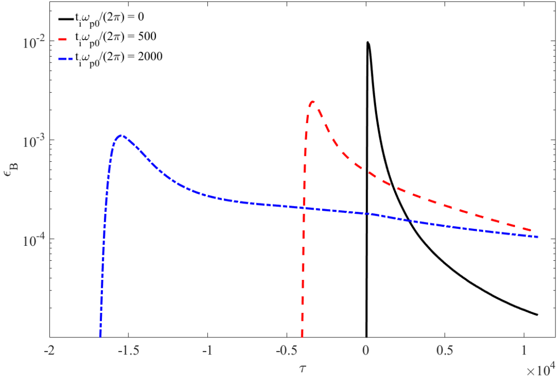


Figure: Evolution of magnetization for different durations of injection: instantaneous (black line), $\omega_p t_i/(2\pi) = 500$ (red line), $\omega_p t_i/(2\pi) = 2000$ (blue line).

Spatial scale evolution

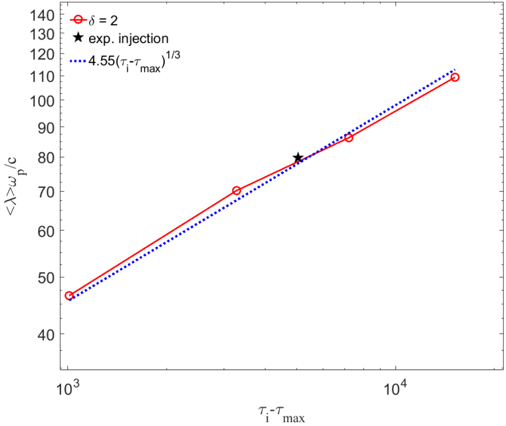


Figure: The average wavelength $\langle\lambda\rangle$ at the end of the injection as a function of $\tau_i - \tau_{max}$ where τ_{max} corresponds to the time, where maximum of the magnetic field energy is observed. Star represents a simulation with exponentially growing injection rate.

Decay of the magnetic field

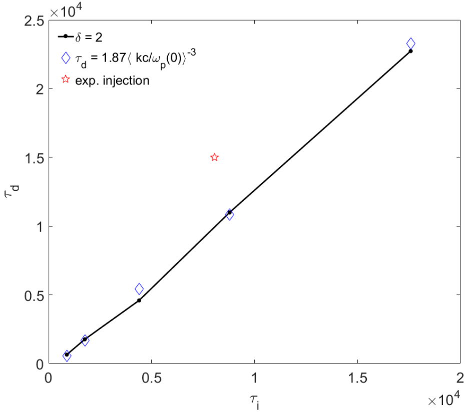


Figure: The magnetic field decay time scale as a function of injection duration. Diamonds show the decay time scale predicted theoretically in phase mixing model. Star represents a simulation with exponentially growing injection rate.

Evolution of the magnetic field at the shock.

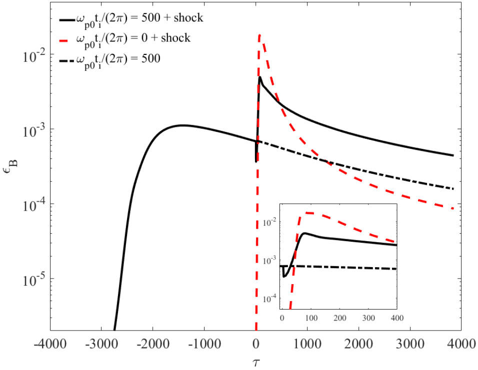


Figure: Solid line: the shock passage is preceded by injection of anisotropic plasma component with $\delta = 0.5$ and $t_i = 500 \cdot 2\pi/\omega_p$. Dashed line: the shock passes through plasma with zero magnetic field (no preceding injection). Dash-dotted: the decay of the field after injection without passage of the shock.

Power spectum of the magnetic field

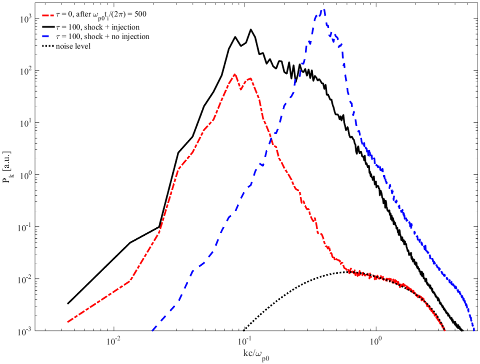


Figure: Power spectra $\mathsf{P_k}$ of the magnetic field just before the shock passame ($\tau = 0$) and shortly after the shock passage at $\tau = 100$, that approximately corresponds to the maximum of the magnetic field.

Main results.

- Weibel instability, when it develops in plasma with continuous supply of particles with anisotropic distribution, leads to generation of large-scale magnetic fields.

$$\langle \lambda \rangle \sim (\tau_i - \tau_{max})^{1/3}$$

- The field decay time is approximately equal to the injection duration, confirmed in simulation for τ_i up to $20000\omega_p^{-1}$
- This large-scale magnetic field could be amplified at the shock-front and then could survive for a long time in the downstream, explaining efficient synchrotron emission from relativistic shocks.