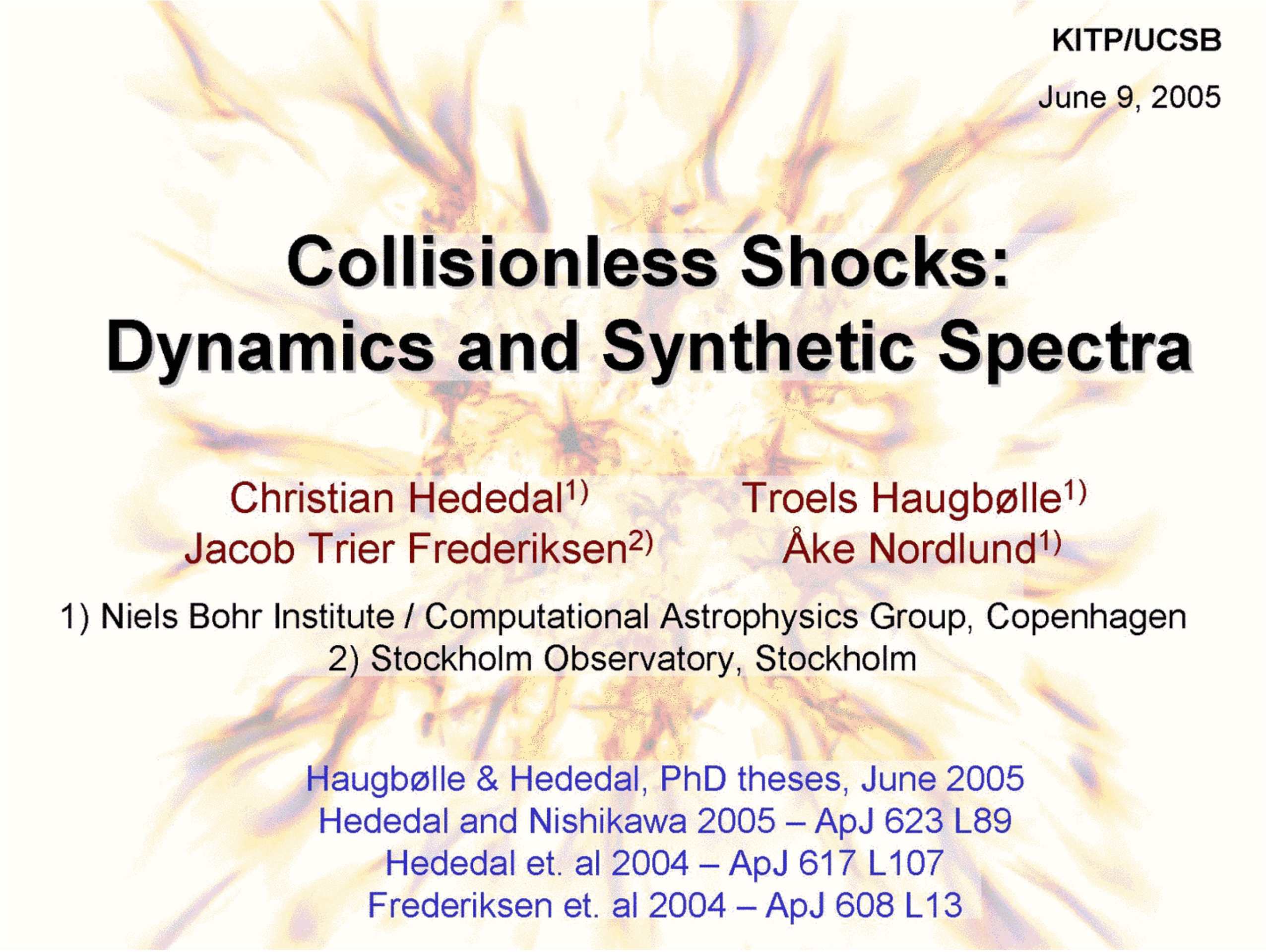


KITP/UCSB

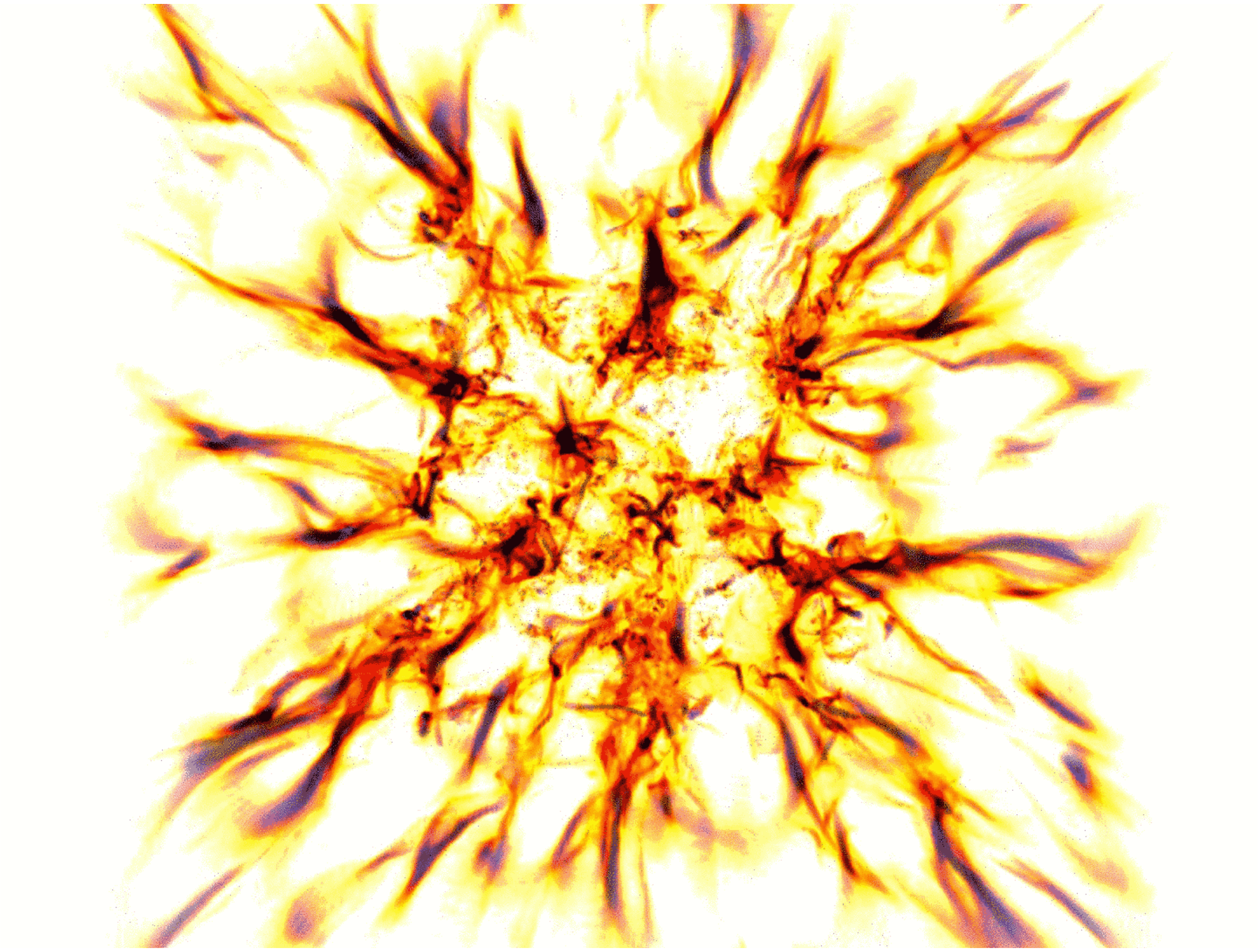
June 9, 2005

Collisionless Shocks: Dynamics and Synthetic Spectra

Christian Hededal[1)] Troels Haugbølle[1)]
Jacob Trier Frederiksen[2)] Åke Nordlund[1)]

1) Niels Bohr Institute / Computational Astrophysics Group, Copenhagen
2) Stockholm Observatory, Stockholm

Haugbølle & Hededal, PhD theses, June 2005
Hededal and Nishikawa 2005 – ApJ 623 L89
Hededal et. al 2004 – ApJ 617 L107
Frederiksen et. al 2004 – ApJ 608 L13



Overview

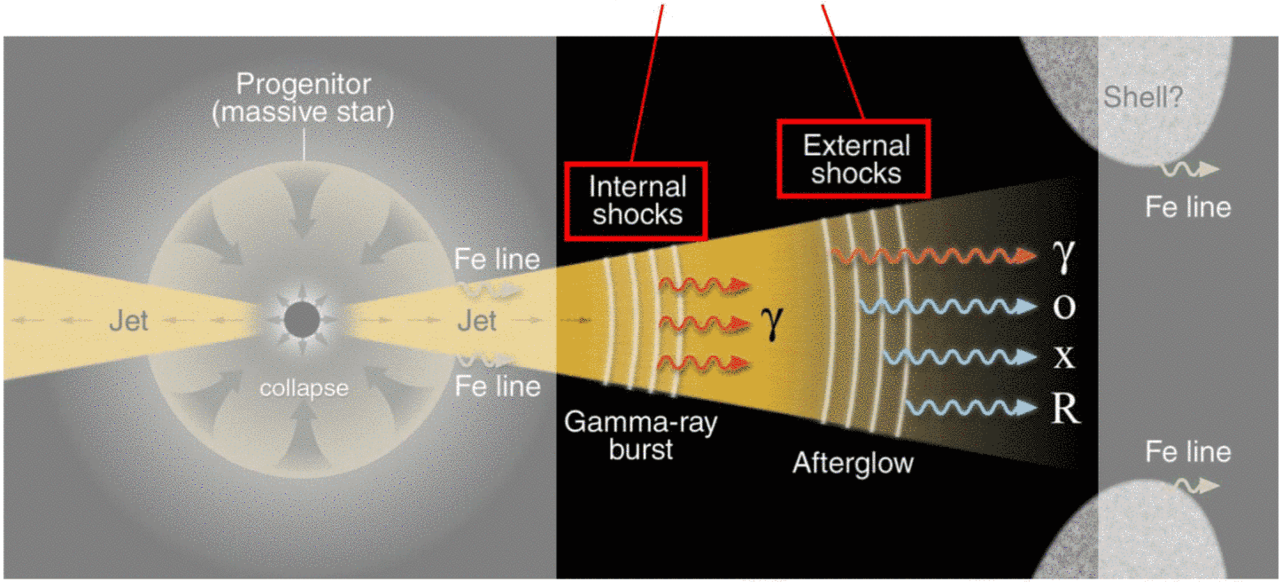
- About codes
- Structure formation in collisionless shocks
- Particle acceleration
- Radiation diagnostics

Overview & main points

- About codes
  - 3-D PIC codes are affordable!   Much more to come…
- Structure formation in collisionless shocks
  - Persistent structure growth is due to ion/electron asymmetry
- Particle acceleration
  - Other processes than Fermi-acc. may be at play
- Radiation diagnostics
  - Realistic synthetic spectra replaces std. models

Copenhagen context: Gamma-Ray Bursts

Collisionless plasma shocks!



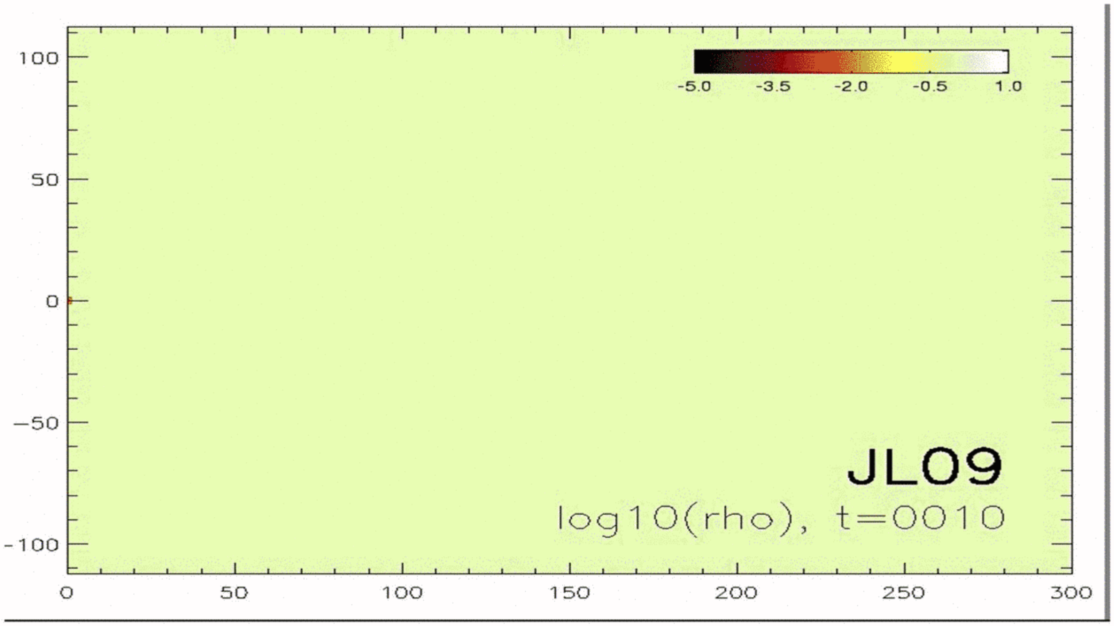
(Meszaros, Science 2001)

Magnetic fields in GRB shocks

- Required strength: e_B = 0.0001-0.1 ~ 10^{-4} T (Waxman, 1997; Wijers and Galama, 1999; Panaitescu and Kumar, 2002; Yost et al., 2003).
- Compression of ISM/wind field: 10^{-9} T
- Progenitor carried field too weak from flux-conservation (and hard to transport to and keep at the shock front)
- Magnetic field must be **generated** *in situ* in the shock.

Simulation tools …

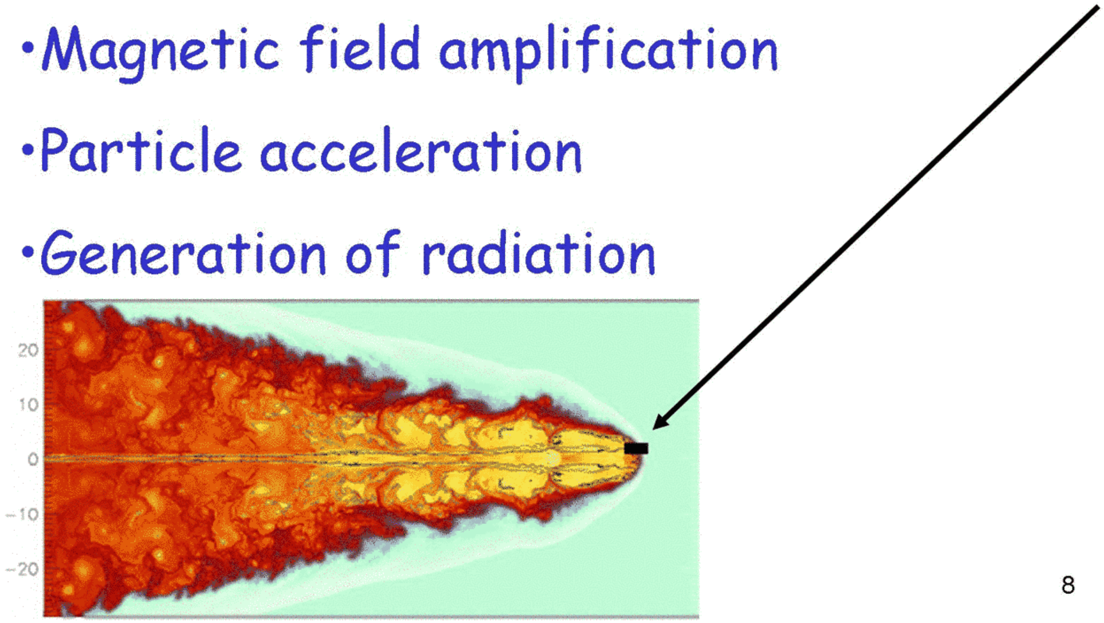
- Fluid simulations are nice for large scales…



(Scheck et. al, 2002)

Simulation tools …

- Fluid simulations are nice for large scale…
  …but cannot cover the shock microphysics:
  - •Magnetic field amplification
  - •Particle acceleration
  - •Generation of radiation



1. Particle-In-Cell Simulations

- Particle-In-Cell simulations are nice…
  …because they cover the shock microphysics:

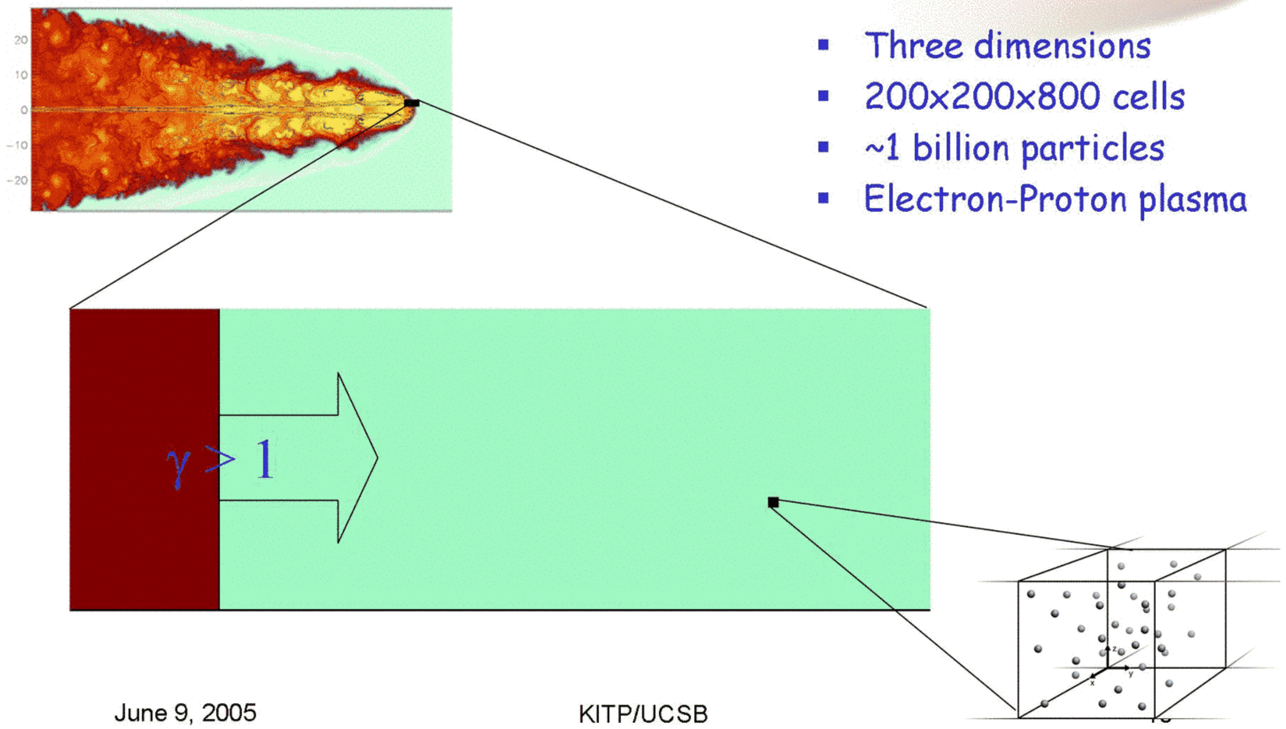
•Magnetic field amplification

•Particle acceleration

•Generation of radiation

...but they only cover a very small scale

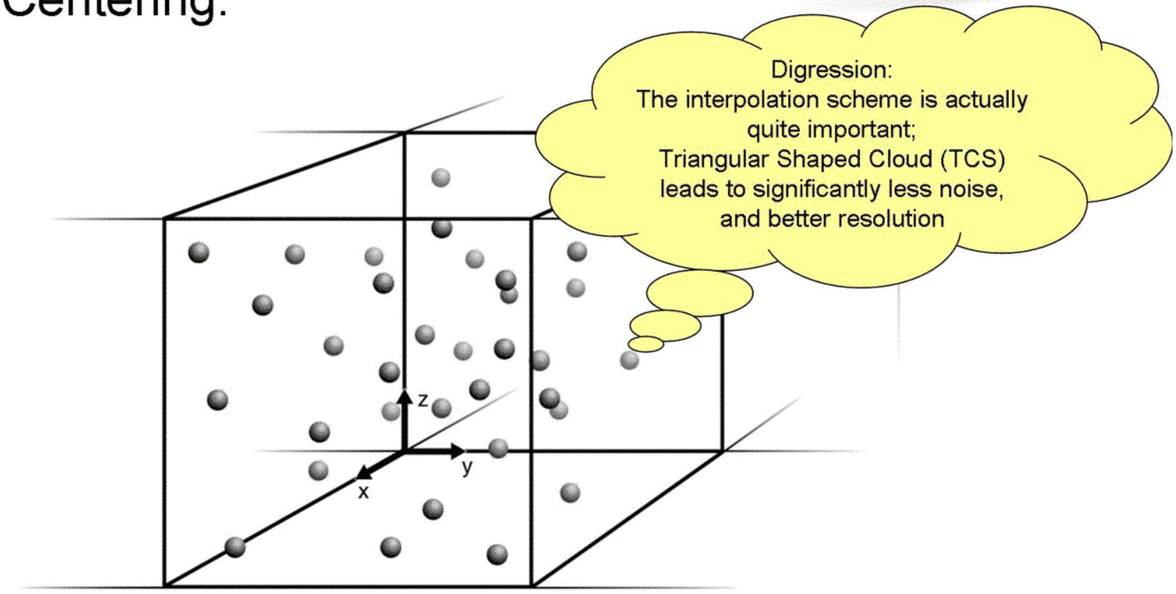
The experiment setup



- Three dimensions
- 200x200x800 cells
- ~1 billion particles
- Electron-Proton plasma

Particle-In-Cell Simulations

- Centering:



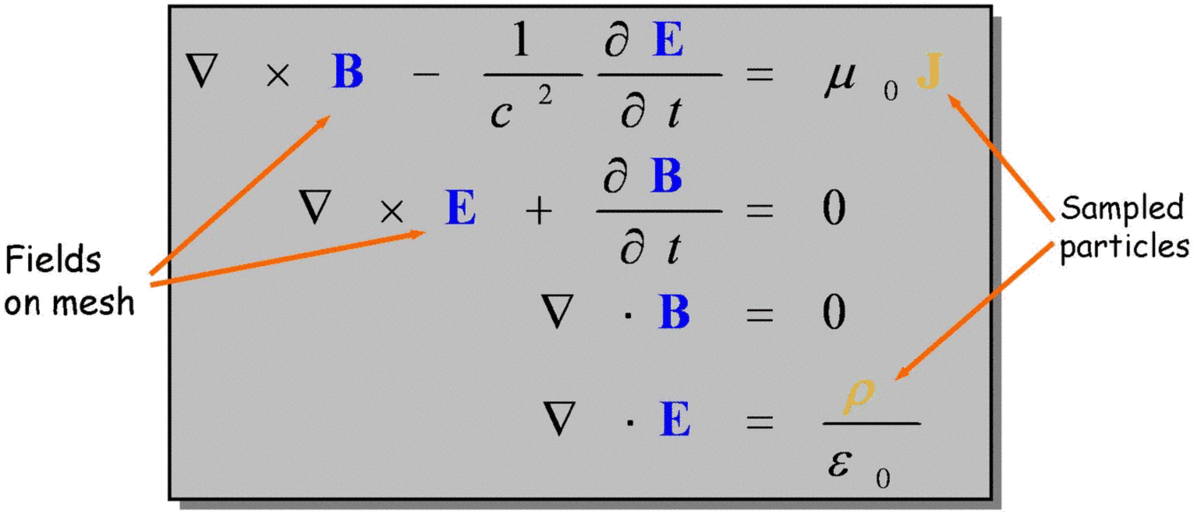
Digression:
The interpolation scheme is actually quite important;
Triangular Shaped Cloud (TCS) leads to significantly less noise, and better resolution

PIC code in use

Based on original 2-D, non-relativistic code by
Michael Hesse, GSF
3-D, relativistic version developed by
Jacob Trier Frederiksen, Stockholm University

- Steps
  - Relativistic particle move, using **B** & **E**
    - Uses $\beta\gamma$ - relativistic momenta
      - Up to ~ 2.5 10^7 particle updates / sec on 24CPUs (64-CPU Altix)
      - Parallelizes with OpenMP on Origin,UltraSparc,Power4,Itanium,…
  - Gather fields; n_i, n_e , $\mathbf{j}_i$, $\mathbf{j}_e$
    - 2nd order; Triangular Shaped Clouds (TSC)
  - Push **B** & **E** – staggered in space and time
    - Implicit B-solver
  - Optionally include radiative cooling of particles

PIC & Maxwell's Equations



$$\nabla \times \mathbf{B} - \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J}$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

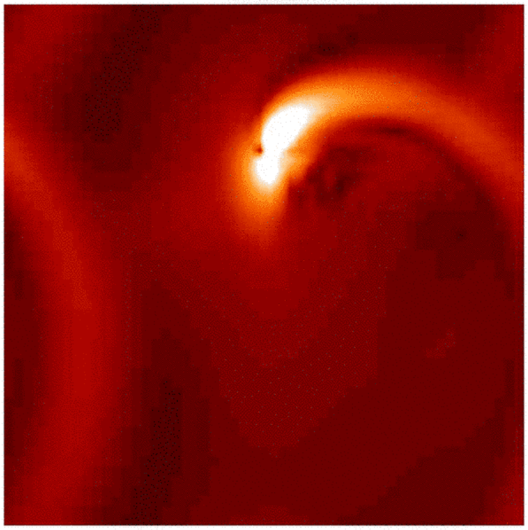
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

Basic tests: wave propagation, etc

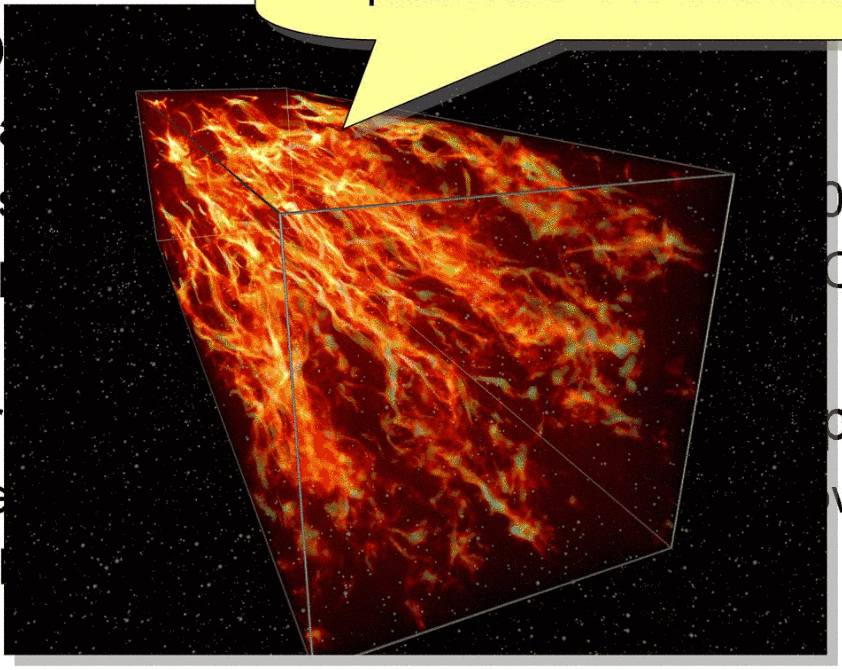
Example: Single electron

- Relativistic; γ=10
  - NOTE: resolution implications of high γ!
- Far field:
  - Synchrotron radiation



Affordabl

- 3-D
  - h
  - us 00
  - u CPU
- Per oh
  - te wer
  - p

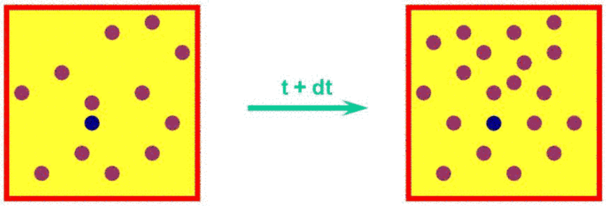


<u>Not</u> an artists rendering!
Shows ion-current filaments in a collisionless shock simulation with ~ 10^9 particles and ~ 3 10^9 mesh zones

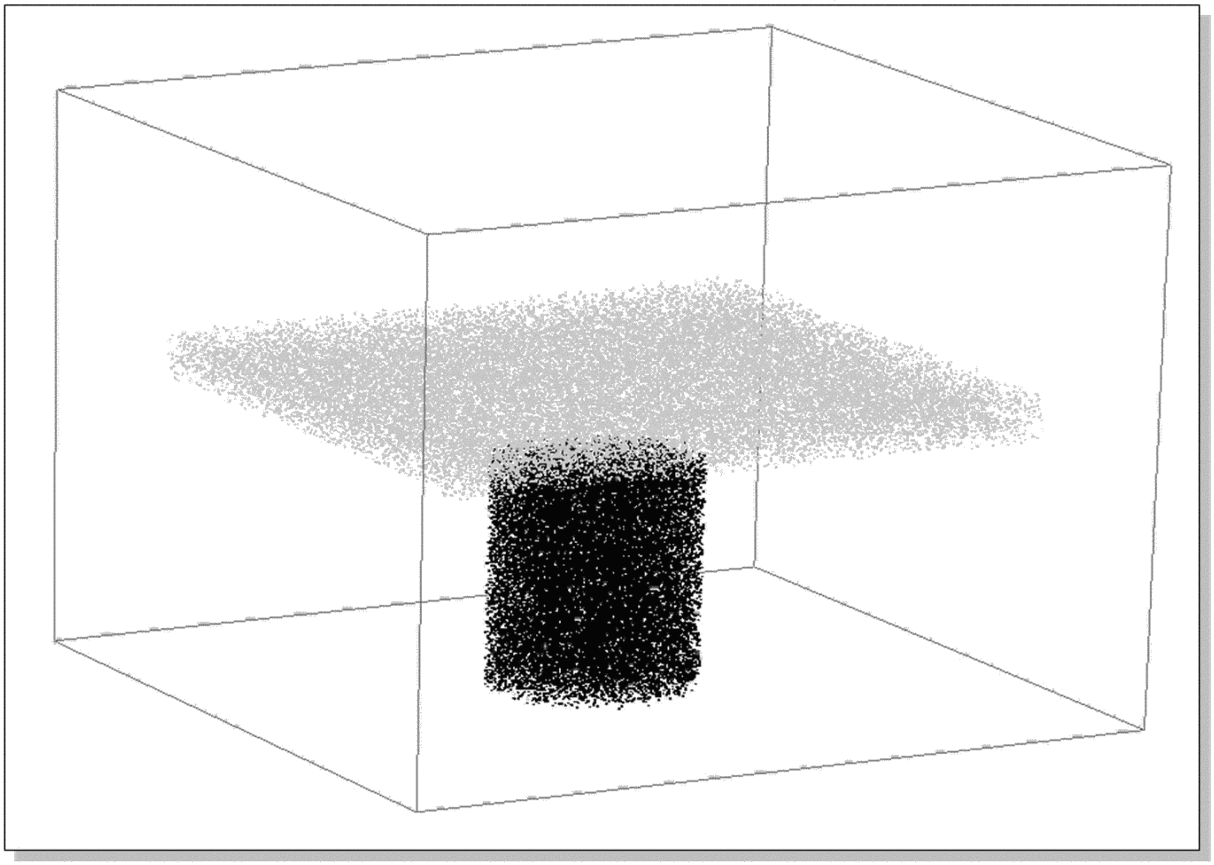
---

Photon-plasma PIC-code

- New code, in early stage testing
  - will be MPI-parallelized
- Create and destroy particles and photons
  - photon interactions; Compton, …
  - pair plasma



Compton scattering test

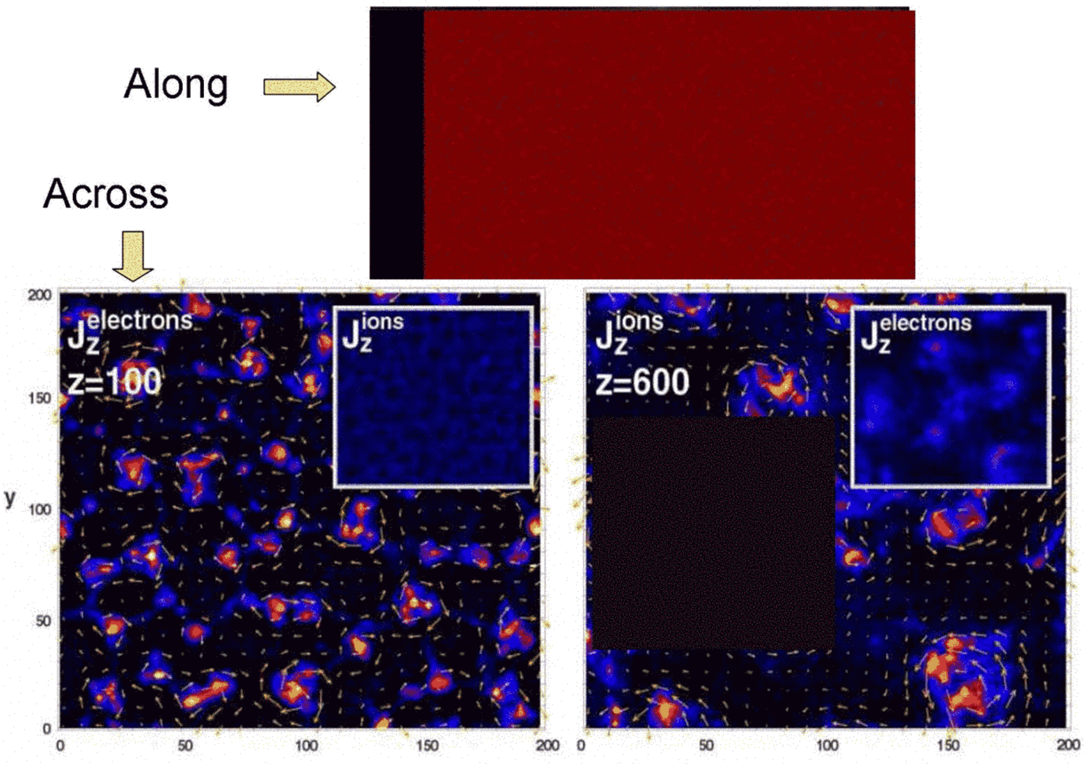


2. Structure formation and growth

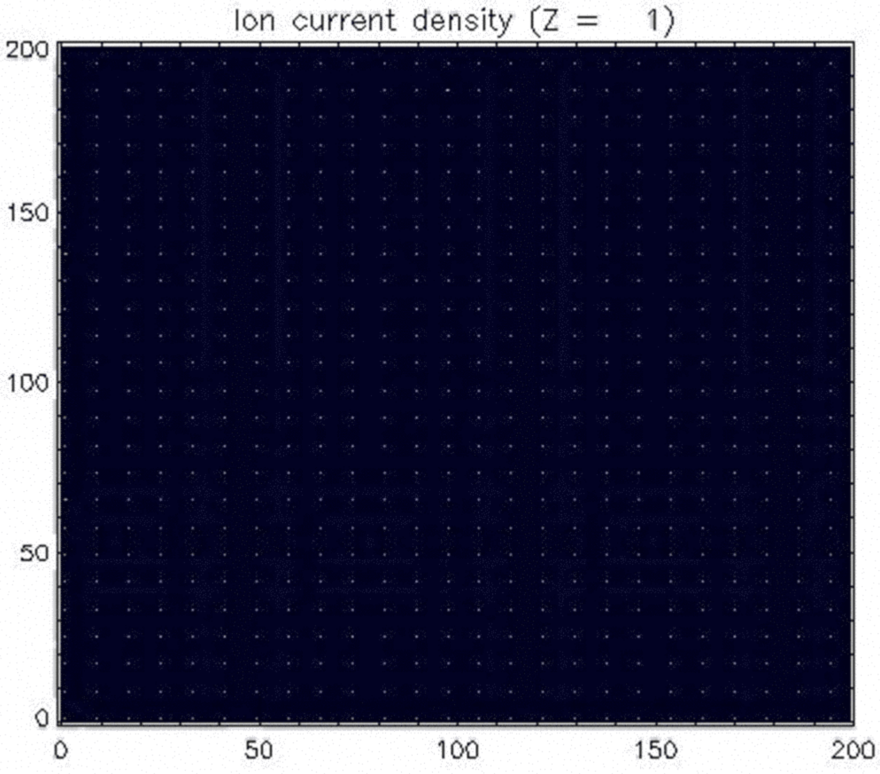
- Questions:
  - What's the physical cause?
  - What length scales develop?
  - How much energy goes into B?
  - And how much into e-acceleration?
  - Can we model it now?

Coherent Structures in Collisionless Shocks

- Electron and ion current channels



Ion-current density and B



Energy growth

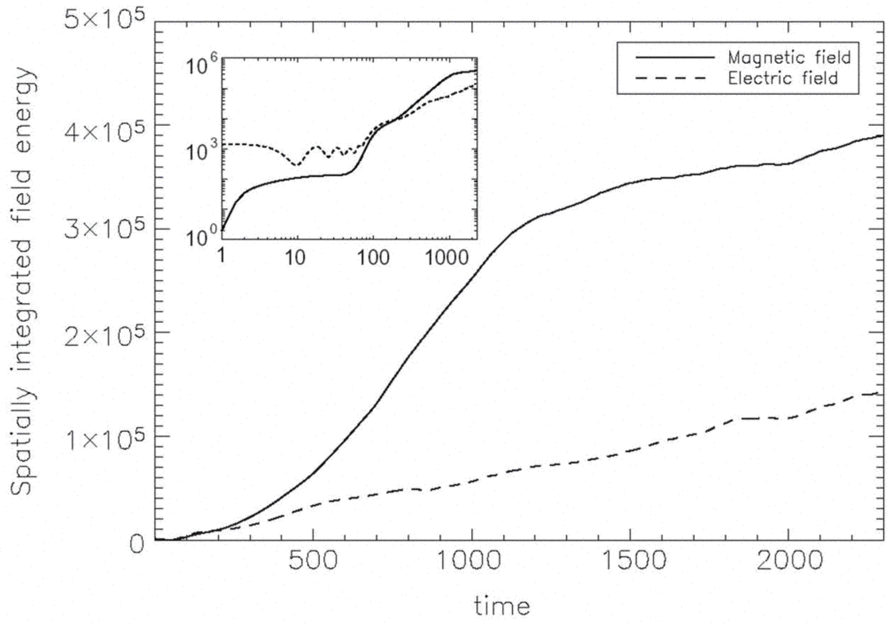


Figure 3.5: Total magnetic (full drawn) and electric (dashed) energy in the box as a function of time. The inset shows a log-log plot of the same data.

Hededal (phd-thesis 2005)

Electron thermalization

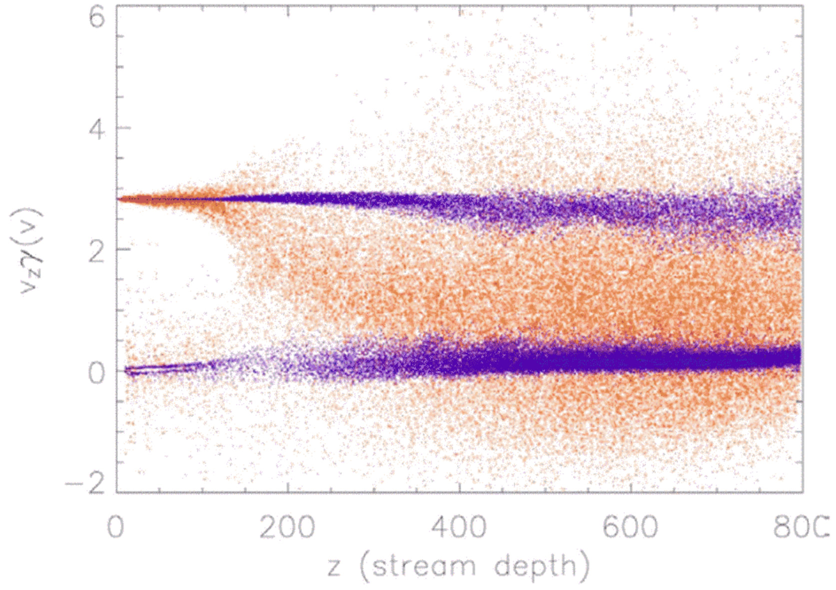


Figure 3.6: Thermalization and longitudinal acceleration, illustrated by scatter plots of the electron (orange) and ion (blue) populations. Note the back-scattered electron population ($v_z\gamma(v) < 0$). Hededal (phd-thesis 2005)

Two-stream instability electron paths

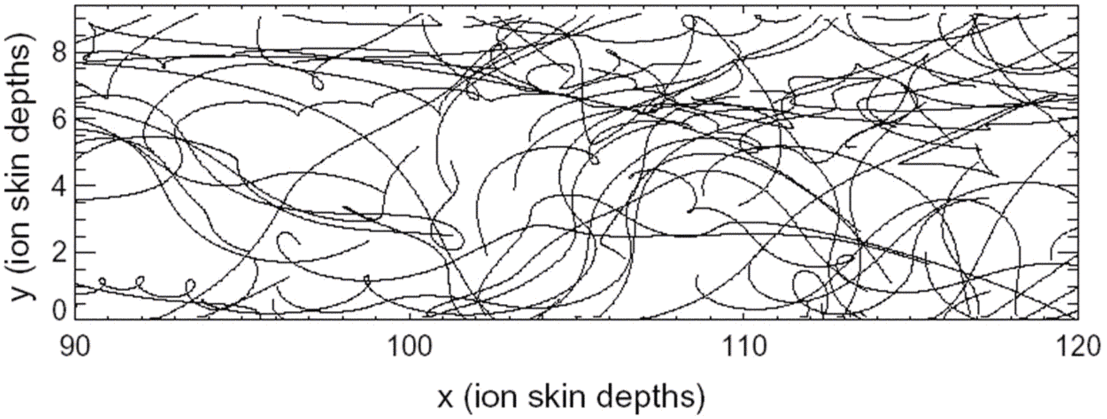


Figure 7.12: An example of the complicated paths of the electrons under the influence of electromagnetic field generated by the Weibel two-stream instability.

Hededal (phd-thesis 2005)

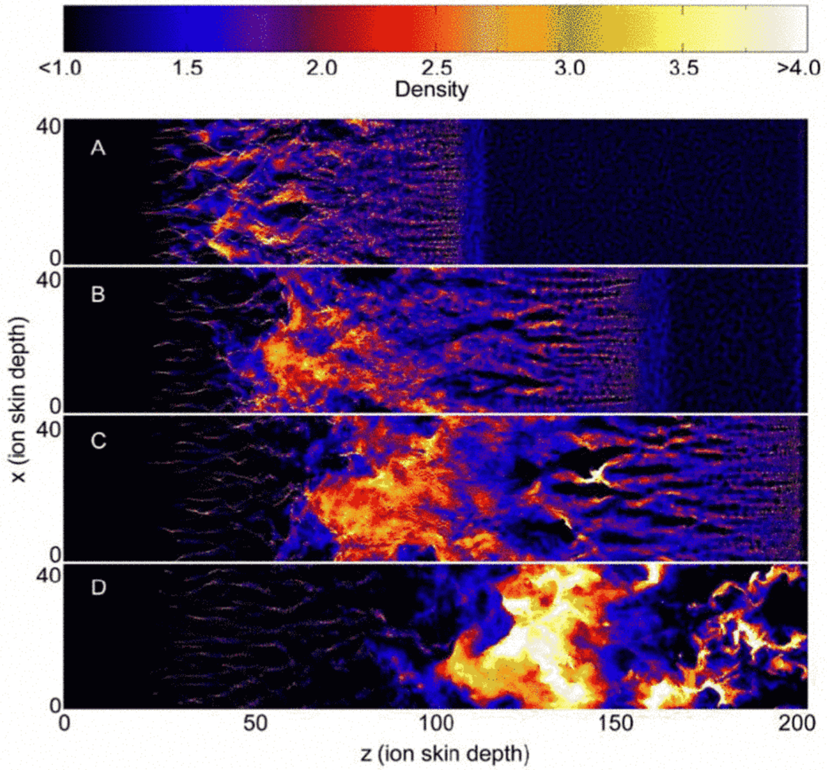
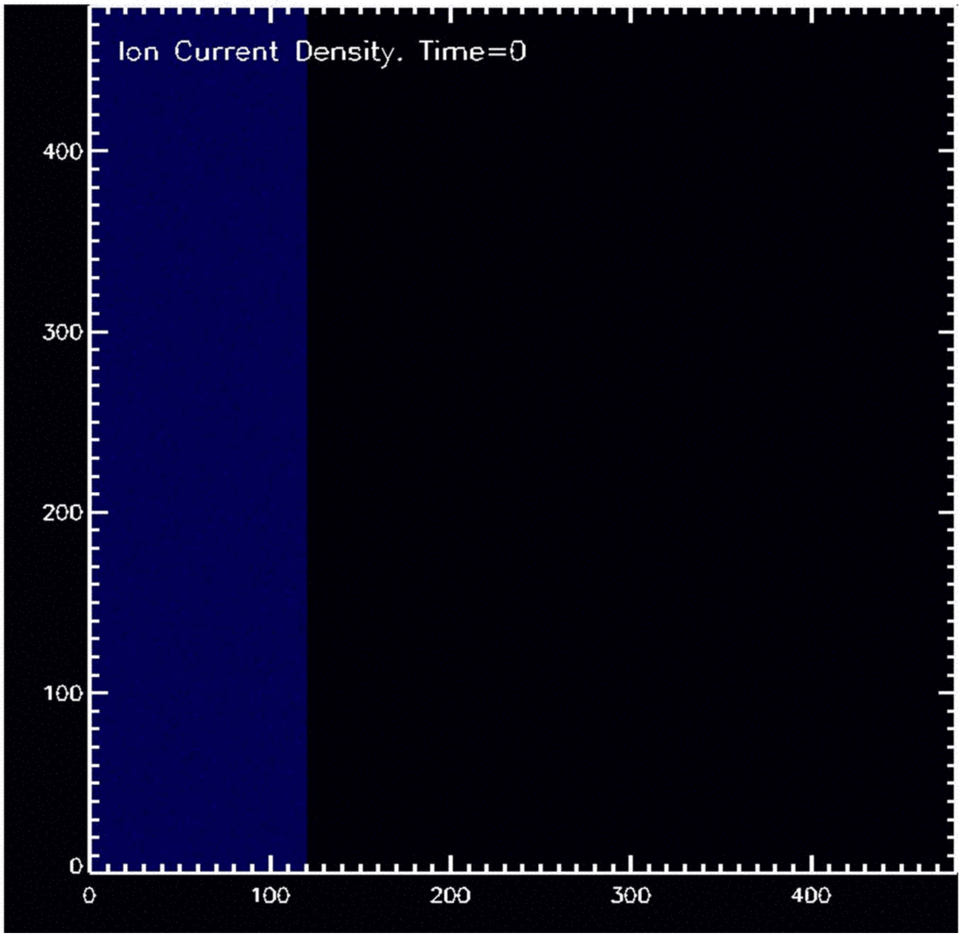


Figure 4.5: Plasma density contour plots at four different time levels A, B, C and D corresponding to $t = 100,\ 150,\ 200$ and $300\ \omega_{pi}^{-1}$

Hededal (phd-thesis 2005)

2.5-D vs. 3-D

- Questions:
  - Can one gain by going to 2.5-D?
  - Does the two-stream instab. still work the same?
  - Are particle distributions the same?



2.5-D vs. 3-D electron spectra

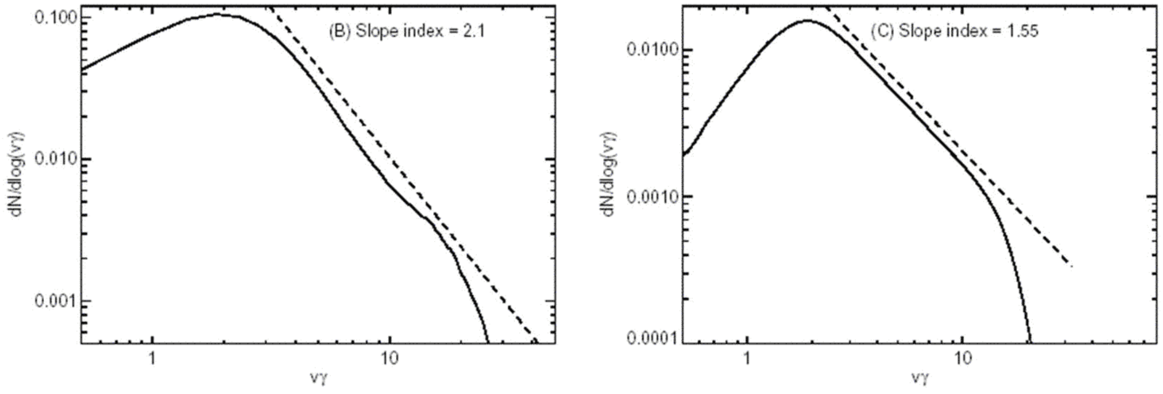
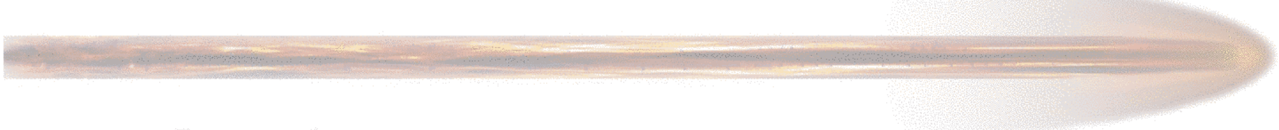


Fig. 1.7: Particle distribution function for the electrons in a slice indicated on Fig. 1.6. To the left is shown the PDF for the largest two-dimensional experiment, while to right the PDF for the three-dimensional experiment is shown.

Haugbølle (phd-thesis 2005)

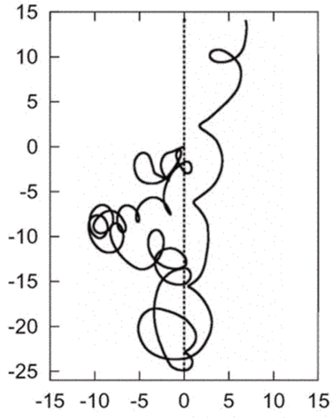
3. Particle Acceleration

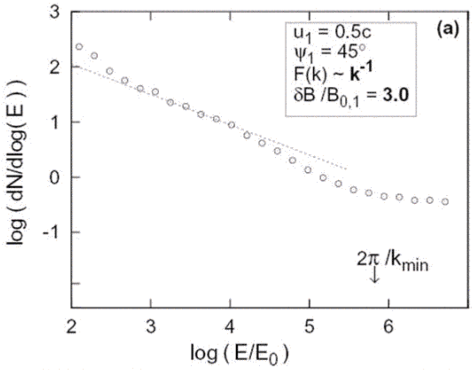


- Questions:
  - How does it occur?
  - Fermi / DSA?
  - If not, what so?

Fermi acceleration

- An iterative process in a competitive game between energy gain and escape.
- Test particle simulations: $p \sim 2.2$ (universal???)





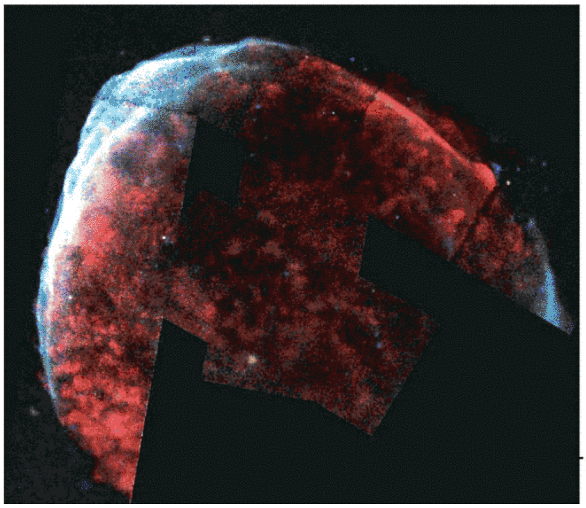
Niemiec and Ostrowski (2004)

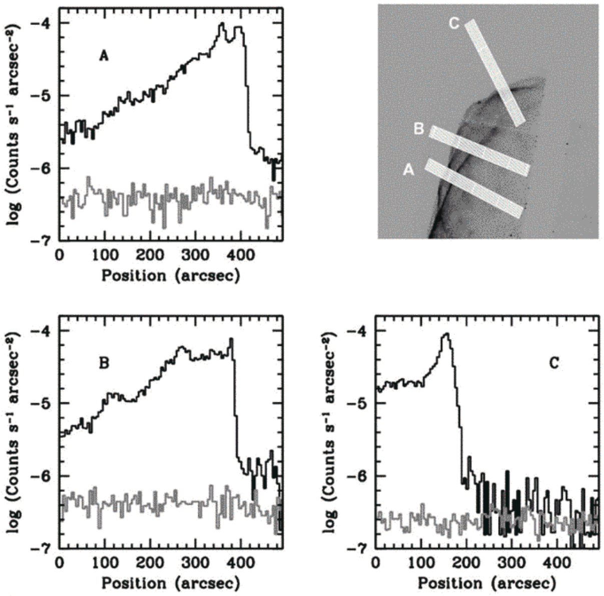
Fermi acceleration: Problem #1

- In the Crab Nebula, the ”low” energy electrons have a power-law distribution spectrum **$1.3 \geq p \geq 1.1$**. Much lower that the “universal” **$p = 2.2$**. (Weiler and Panagia, 1978).

Fermi acceleration: Problem #2

- With Fermi acceleration, one expects an X-ray halo around the shock. This is absent in Chandra observations of SN 1006. (Long et. al, 2003).





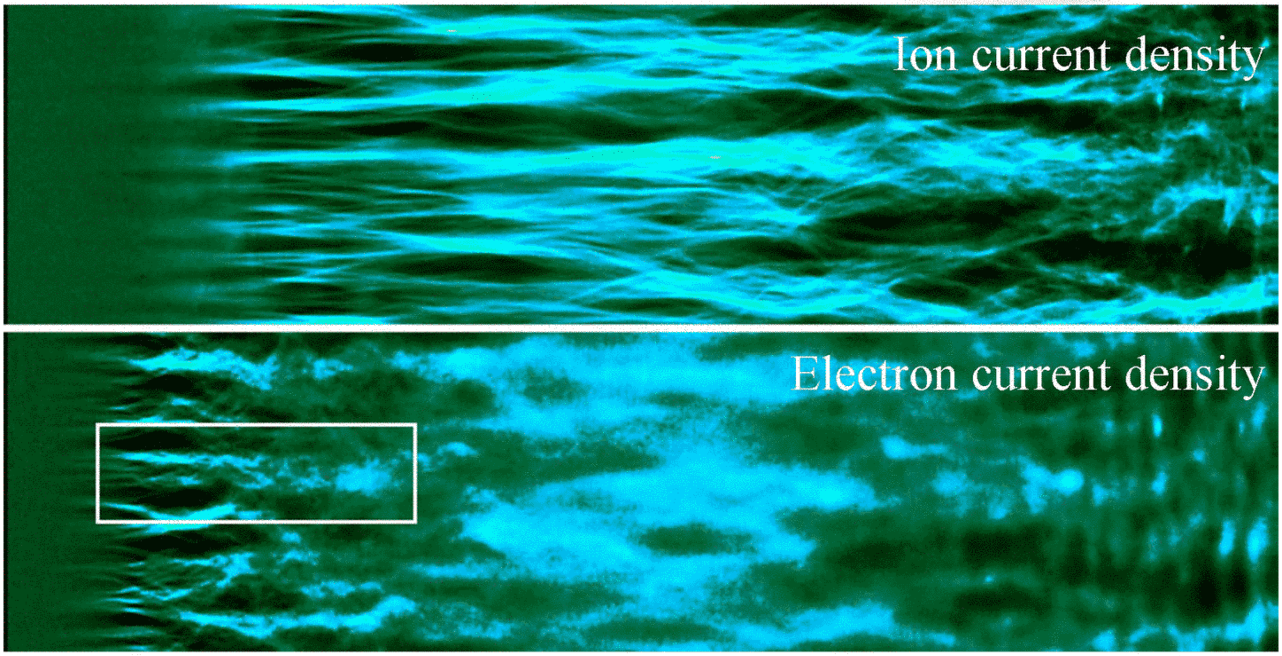
Fermi acceleration: Problem #3

- Particles need **pre-acceleration** to leave the thermal pool and enter the Fermi game.
  This mechanism remains unknown.
- How large a fraction of the electrons that are accelerated greatly affects our estimates of the total GRB energy.
  This fraction remains unknown.
- In the closest and best studied mildly relativistic shock (the Crab Nebula), most of the electrons radiate below this pre-acceleration threshold.
  (Eichler and Waxman, 2005).

Fermi acceleration: Problem #4

- Relativistic Fermi acceleration requires STRONG turbulence in downstream region.
(Ostrowski and Bednarz 2002).
- Test particle simulations show that the resulting spectrum of accelerated particles depends on the turbulent magnetic field structure considered.
(Niemiec and Ostrowski, 2004).
- What is the true nature of this turbulence???

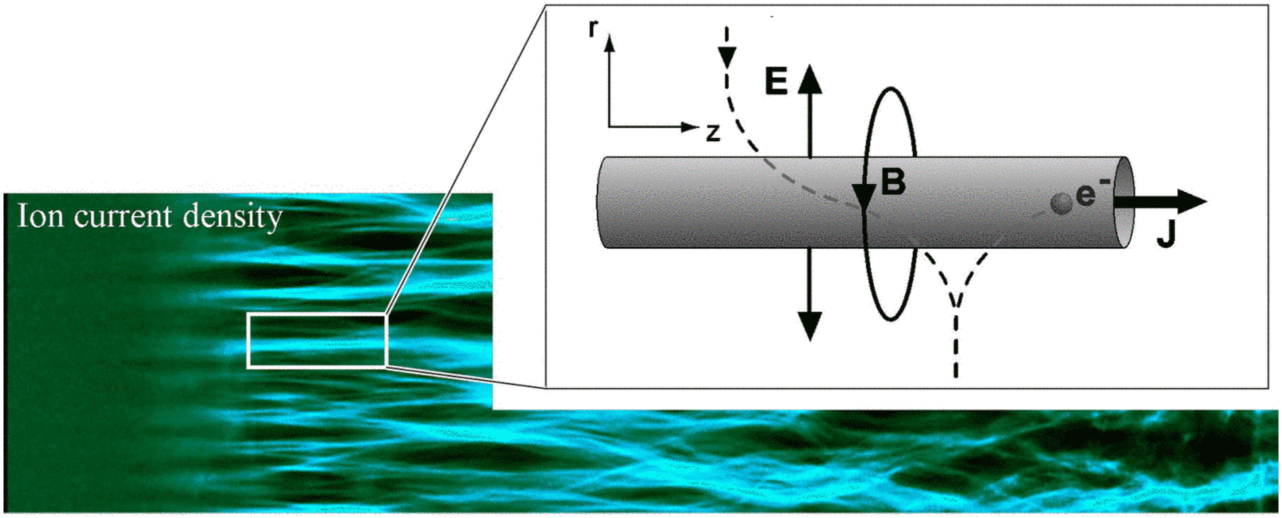
Simulation results



Non-thermal acceleration

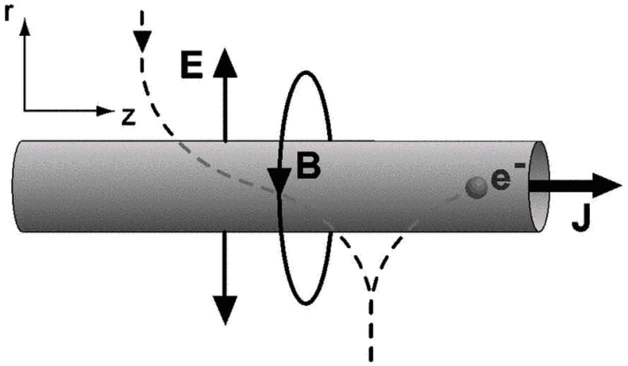
- Electrons are accelerated to a power law PDF directly due to the ion Weibel instability.

Hededal et al., 2004 (**astro-ph/0408558**)



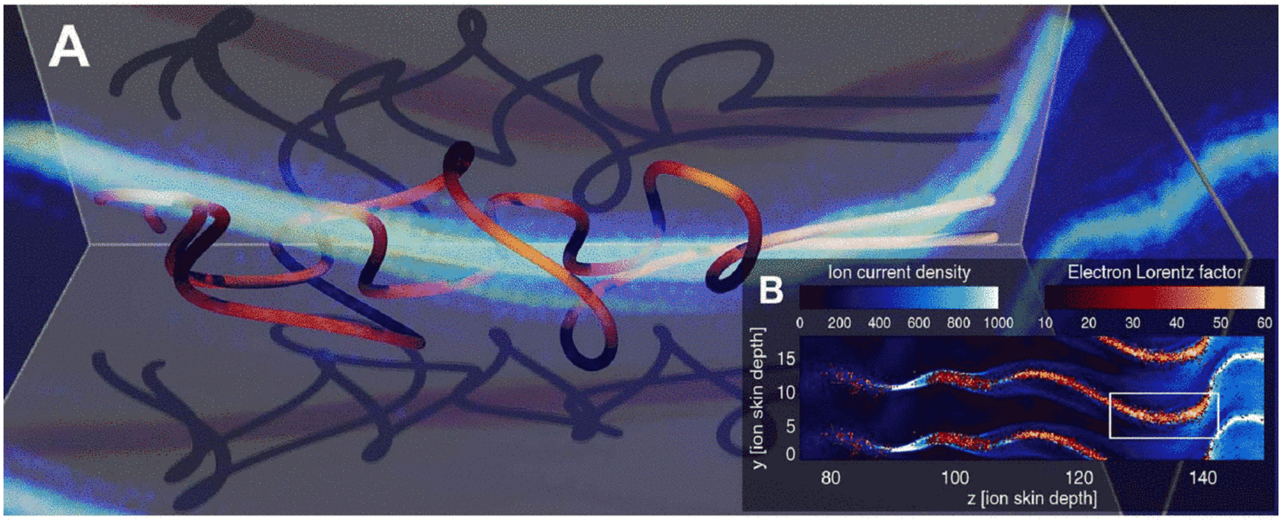
A non-Fermi acceleration scenario

- Electrons are accelerated instantaneously inside the Debye cylinder surrounding the ion current channels.



Hededal, Haugbølle, Frederiksen and Nordlund (2004)
astro-ph/0408558

A non-Fermi acceleration scenario



---

4. Synthetic Radiation Spectra

- Questions:
  - What is the nature of the radiation coming from collisionless shocks?
  - Can we extract spectra directly from the PIC-sims?
  - What about 'jitter-radiation'?

Hededal (phd-thesis 2005)

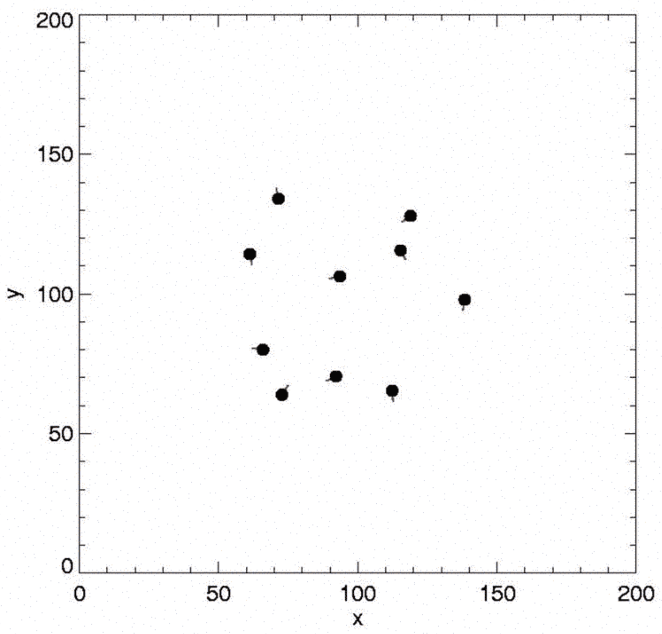
Radiation diagnostics from PIC-sims

- The far field from a PIC run is *not* an accurate representation of emitted ratioation
- May instead be obtained by direct integration of the (retarded) radiation formulae

Synchrotron radiation

Spectrum

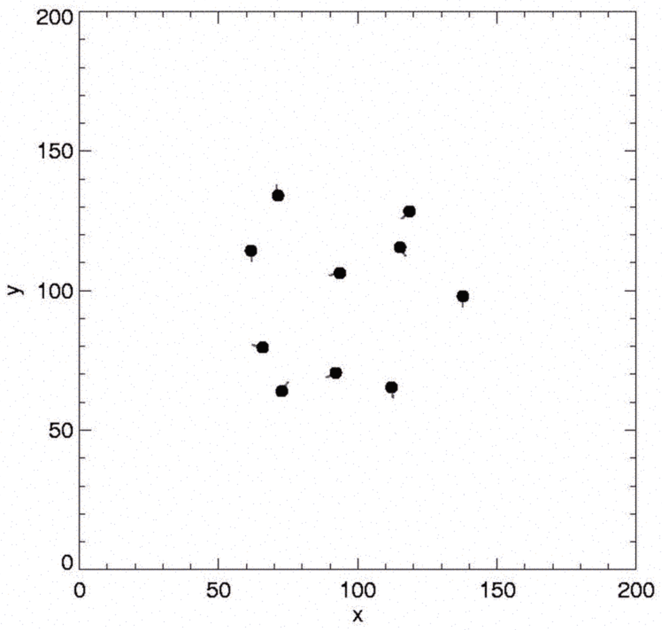
$B = B_0$



Synchrotron radiation?

Spectrum

$B(k) = B_0 + C_1\,k^{\mu}$

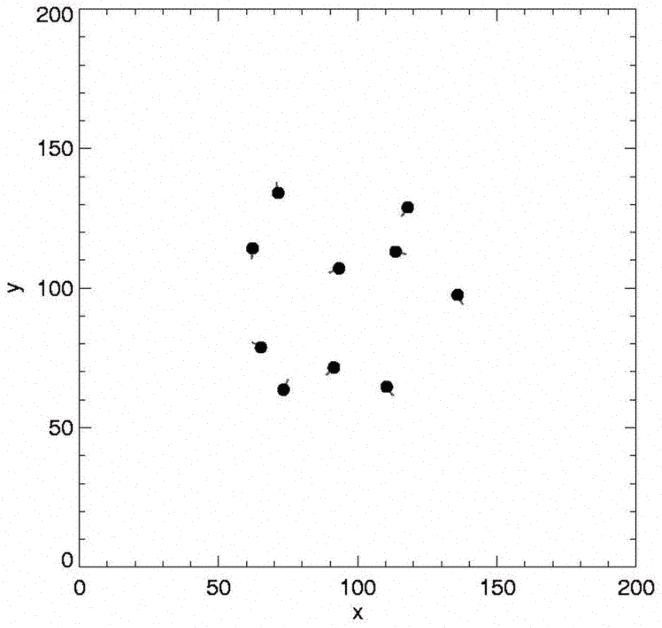


Synchrotron radiation???

$B(k) = C_2\,k^{\mu}$

Spectrum

?



Radiation from collisionless shocks

To obtain a spectrum, “just” integrate:

$$\frac{d^2W}{d\Omega d\omega} = \frac{\mu_0 c q^2}{16\pi^3}\left|\int_{-\infty}^{\infty}\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}]}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^2}\,e^{i\omega(t'-\mathbf{n}\cdot\mathbf{r}_0(t')/c)}dt'\right|^2$$

where $\mathbf{r}_0$ is the position, $\boldsymbol{\beta}$ the velocity and $\dot{\boldsymbol{\beta}}$ the acceleration

Analytical

- Possible for homogenous magnetic field (E=0)
- Impossible for tangled (realistic) electromagnetic field

New approach

- Get position, velocity and acceleration from simulations
- Integrate numerically.

Radiation from collisionless shocks

Test of the numerical spectrum generator:

Synchrotron spectrum

Radiation from collisionless shocks

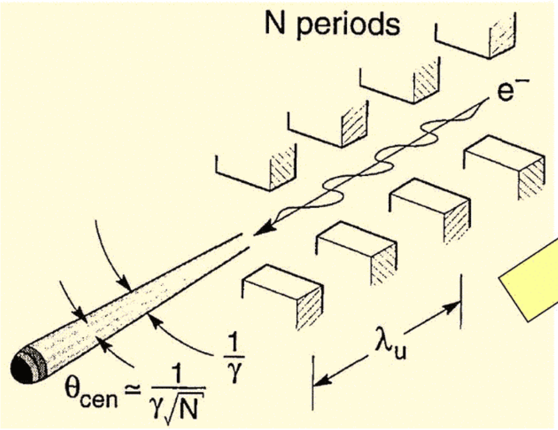
Test of the numerical spectrum generator:

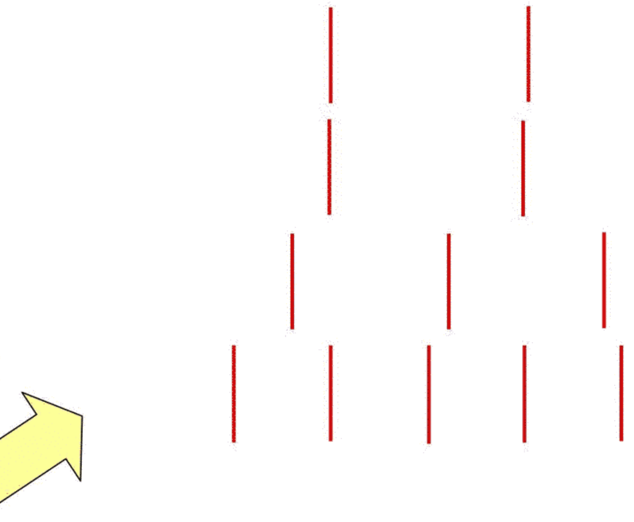
Bremsstrahlung spectrum

Radiation from collisionless shocks

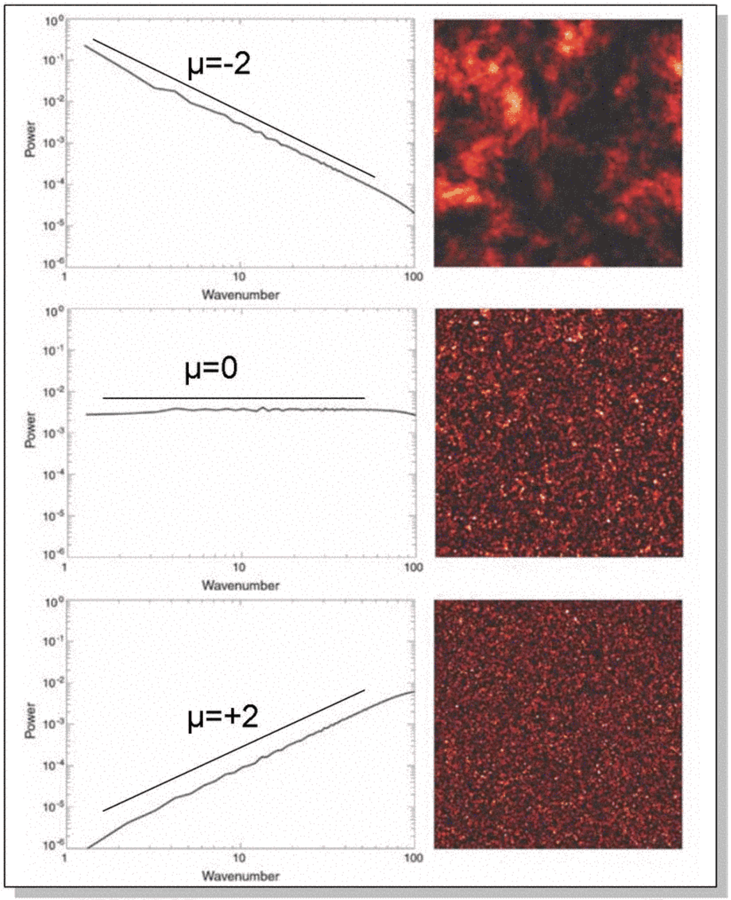
Test of the numerical spectrum generator:

Undulator spectrum





So, what is the (jitter – cf. Medvedev and others) radiation field from a ‘random’ B-field, and is the radiation from a PIC B-field the same as from a random B-field?



Hededal (phd-thesis 2005)

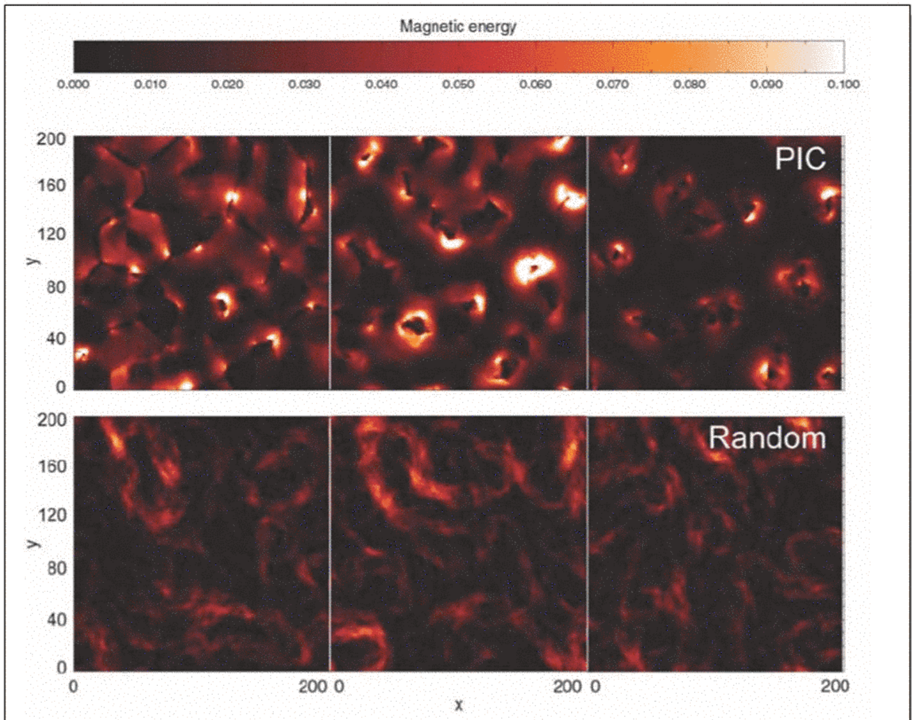


Figure 7.18: The spatial distribution of magnetic energy in three slices sampled at different depth in the plasma shock. The top panel shows $\mathbf{B}_0$ generated by the two-stream instability. The lower panel shows a random magnetic field $\mathbf{B}_1$ with the same spectral power distribution as $\mathbf{B}_0$.

Hededal (phd-thesis 2005)

Random vs. coherent (PIC) structures

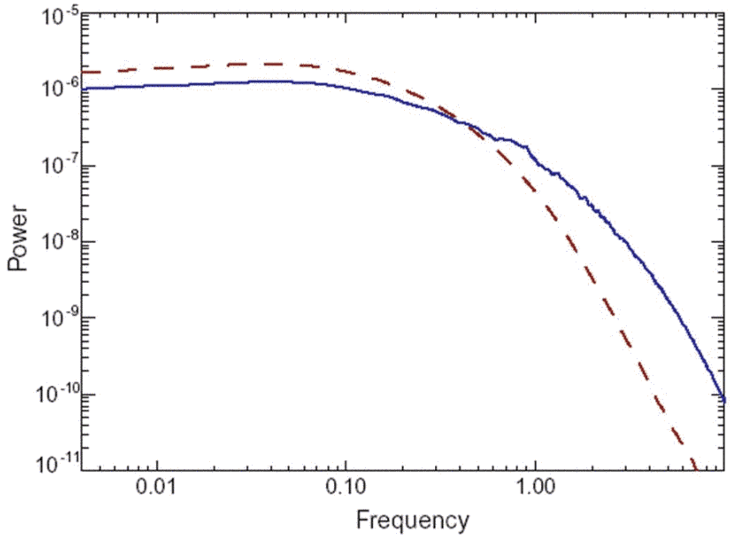
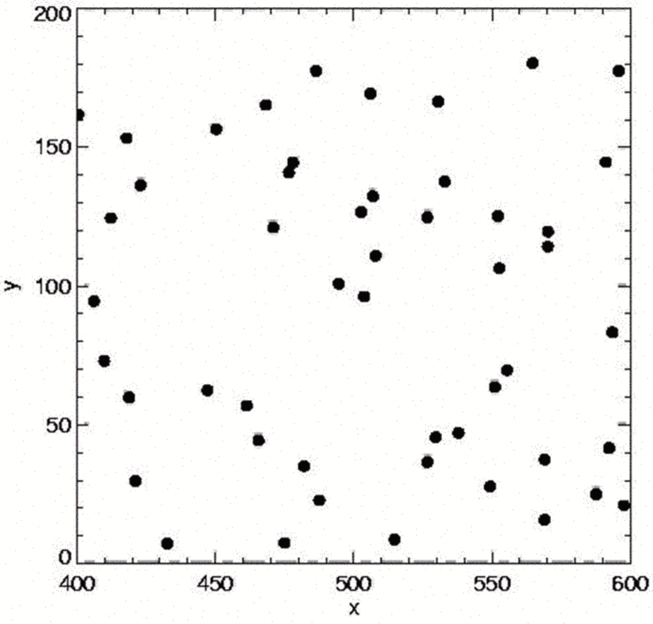


Figure 7.20: Radiation from PIC simulations (*solid blue*) compared to radiation from a random field with the same statistical properties (*dashed red*). Both spectra are generated by using the same ensemble of 20000 electrons. Hededal (phd-thesis 2005)

PIC-simulation jitter

B from PIC-sims

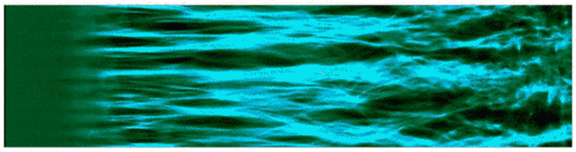


Spectrum

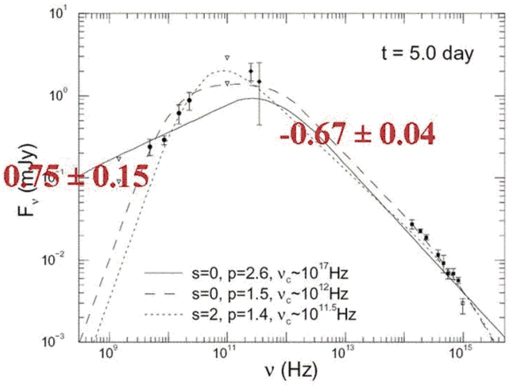
?

Synthetic radiation spectra

Spectrum obtained directly from shock simulations



+



Bulk Lorentz factor = 15

PDF: Thermal
+non-thermal (p=2.7)

GRB 000301c (Panaitescu 2001)

Shock simulations

PIC-results, collisionless shocks

From ‘first principles’ simulations:

- Magnetic field generation and **power law** particle acceleration are connected and unavoidable in weakly magnetized (ISM) relativistic collisionless plasma shocks.
- The non-thermal particle acceleration is instantaneously and local. This implies that the emitted radiation reflects the local plasma condition and the result is in contrast to recursive acceleration schemes (e.g. Fermi acceleration).
- ε_B, ε_e and p are highly interdependent and cannot be used as free parameters
- The radiation spectrum from the shock accelerated electrons in the shock generated electromagnetic field, shows promising resemblance with observations.

Summary & Conclusions

- About codes
  - 3-D PIC codes are affordable!   Much more to come…

Summary & Conclusions

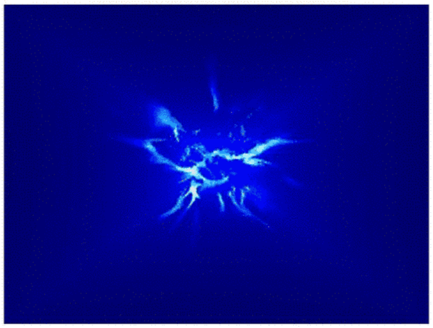
- About codes
  - 3-D PIC codes are affordable!   Much more to come…
- Structure formation in collisionless shocks
  - Persistent structure growth is due to ion/electron asymmetry

Summary & Conclusions

- About codes
  - 3-D PIC codes are affordable! Much more to come…
- Structure formation in collisionless shocks
  - Persistent structure growth is due to ion/electron asymmetry
- Particle acceleration
  - Other processes than Fermi-acc. may be at play

Summary & Conclusions

- About codes
  - 3-D PIC codes are affordable! Much more to come…
- Structure formation in collisionless shocks
  - Persistent structure growth is due to ion/electron asymmetry
- Particle acceleration
  - Other processes than Fermi-acc. may be at play
- Radiation diagnostics
  - Realistic synthetic spectra replaces std. models



The END …

… of e-p shocks has not been seen yet!
