Simulation Study of Magnetic Fields generated by the Electromagnetic Filamentation Instability

K.-I. Nishikawa (*NSSTC/UAH*), E. Ramirez-Ruiz (IAS/UCSC), P. Hardee (*Univ. of Alabama, Tuscaloosa*),
C. Hededal (Niels Bohr Inst.), Y. Mizuno (NPP/*MSFC*), G.J. Fishman (*NASA/MSFC*)

Shock acceleration is a ubiquitous phenomenon in astrophysical plasmas. Plasma waves (e.g., Buneman, Weibel, other two-stream instabilities) created in the shock are responsible for particle (electron, positron, and ion) acceleration. Using a 3-D relativistic particle-in-cell (RPIC) code, we investigate particle acceleration in relativistic jets. Simulations show that the Weibel instability created at the shock front accelerates particles perpendicular and parallel to the jet propagation direction. This instability is also responsible for generating magnetic fields in the relativistic jets. The simulations show that the growth rate of the Weibel instability depends on the Lorentz factor and composition of the jet, as well as the orientation and strength of the ambient magnetic field. The magnetic fields generated by the Weibel instability create highly nonuniform, small-scale magnetic fields, which contribute to the electron's transverse deflection. The radiation from electrons in these environments (jitter radiation) is different from synchrotron radiation.

Key Scientific questions

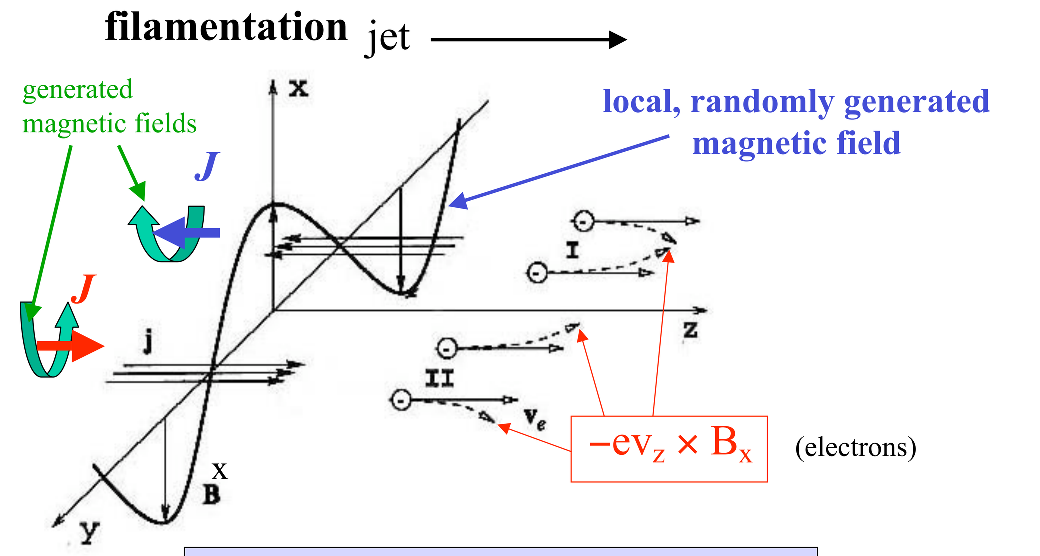
- **How do shocks in relativistic jets evolve?**
- **How are particles accelerated?**
- **What are the dominant radiation processes?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock fronts and transition regions?**
- **How do shocks in relativistic jets evolve under various ambient plasma and magnetic fields?**
- **How do magnetic fields generated by the Weibel instability contribute to jitter radiation?**

-- for some answers see Nishikawa et al. 2006, ApJ, 642, 1267 --

Ramirez-Ruiz, Nishikawa & Hededal, 2006 ApJL, submitted
Ramirez-Ruiz et al. 2006, ApJ, in preparraion

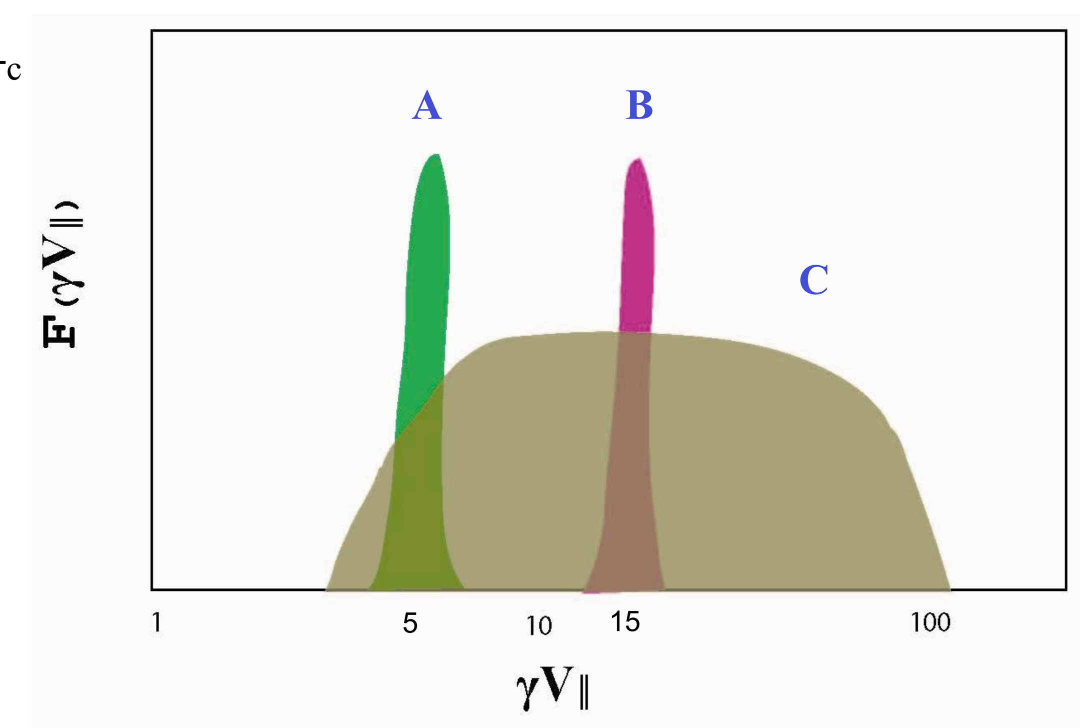
Weibel instability

Growth time:
$\tau_{growth} = \gamma_{sh}^{1/2}/\omega_{pe}$
Length:
$\lambda = \gamma_{th}^{1/2}c/\omega_{pe} = (\gamma_{th}/\gamma_{sh})^{1/2}\,\tau c$

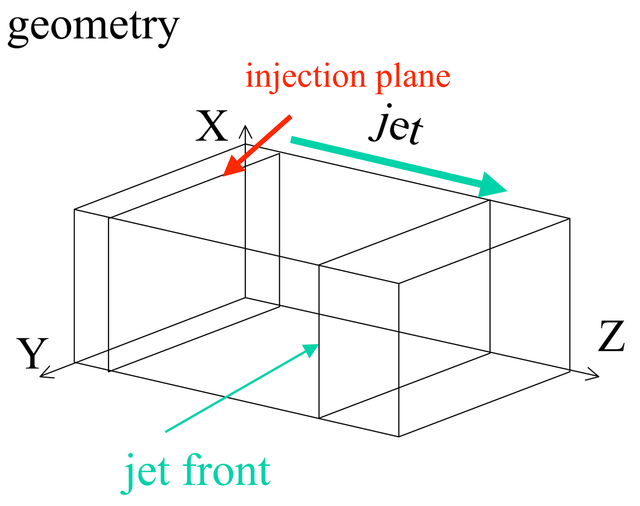


adapted from Medvedev & Loeb, 1999, ApJ 526, 697

Schematic Jet velocity distributions

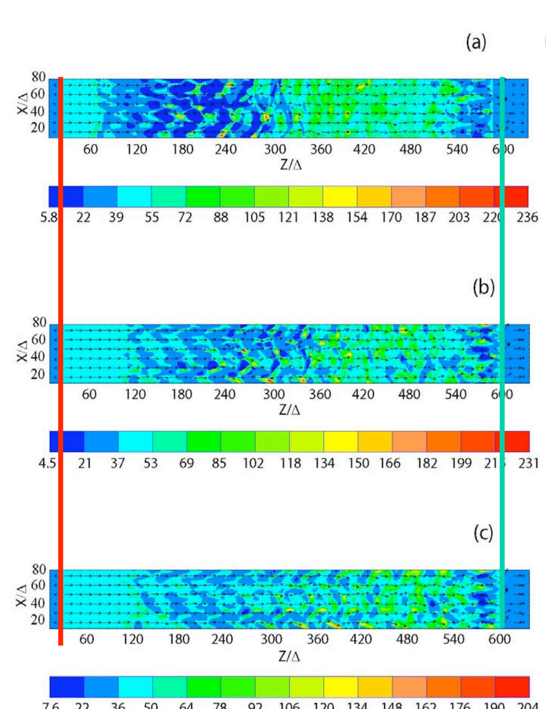


3-D RPIC simulation geometry



Growth times of Weibel instability:
$\tau_A < \tau_B < \tau_C$

Density perturbation by the Weibel instability



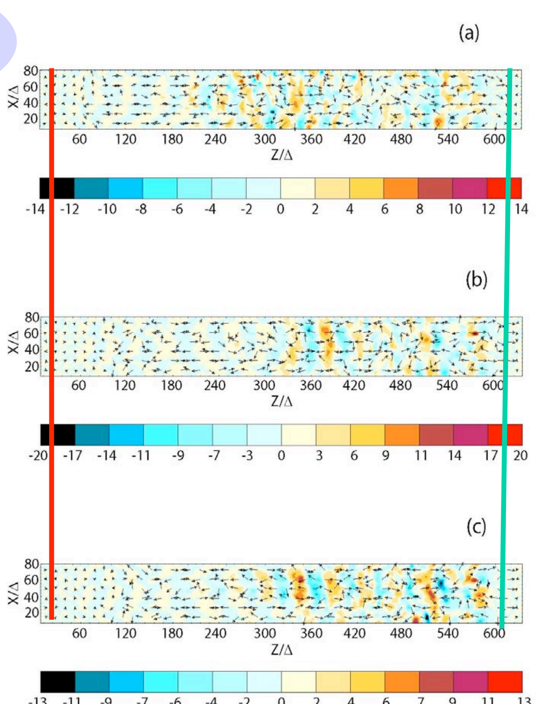
Electron-positron jet
$\omega_{pe}t \sim 4\,\tau_{growth}$

A: $\gamma = 5$

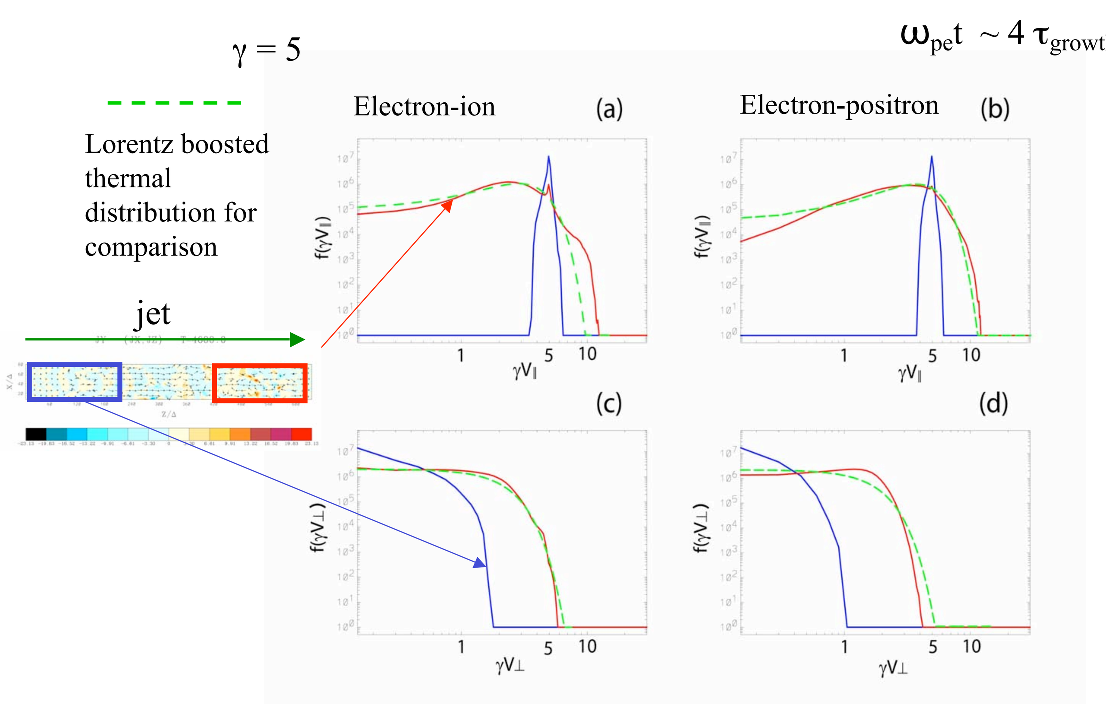
B: $\gamma = 15$

C: $4 < \gamma < 100$

Parallel current J_z (arrows: $J_{z,x}$)

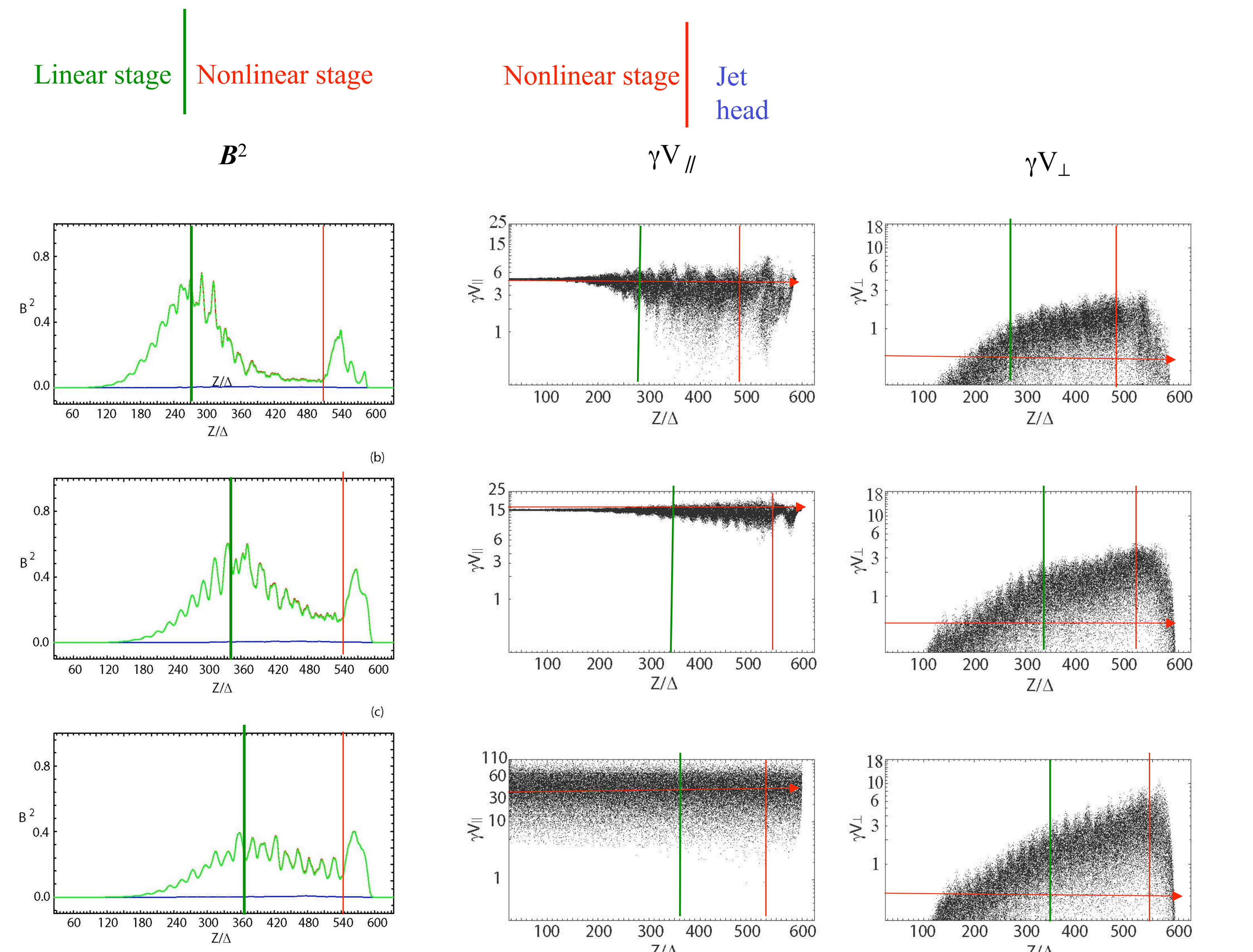


γV distribution functions (parallel, perpendicular to the jet)

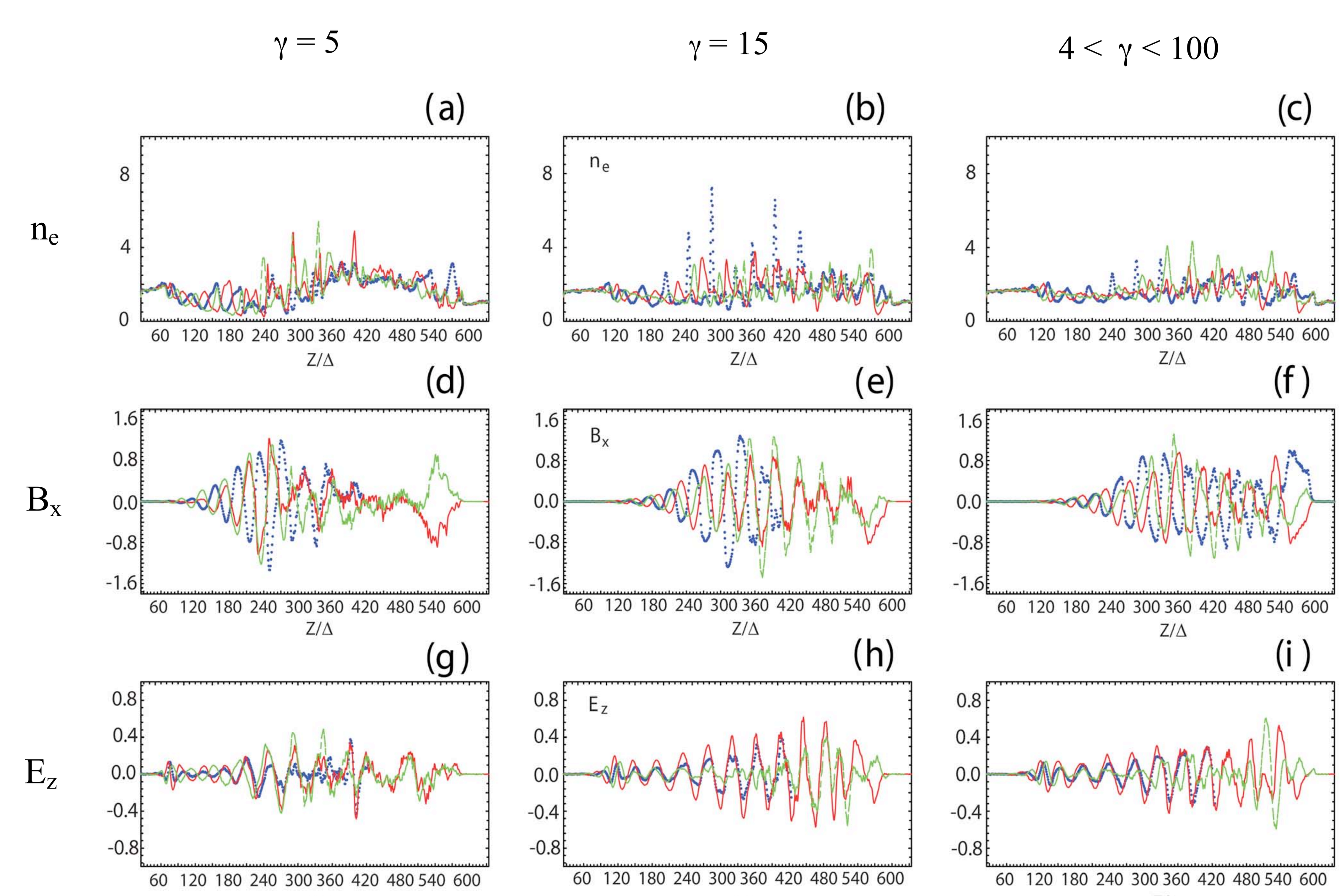


(Nishikawa et al. 2006)

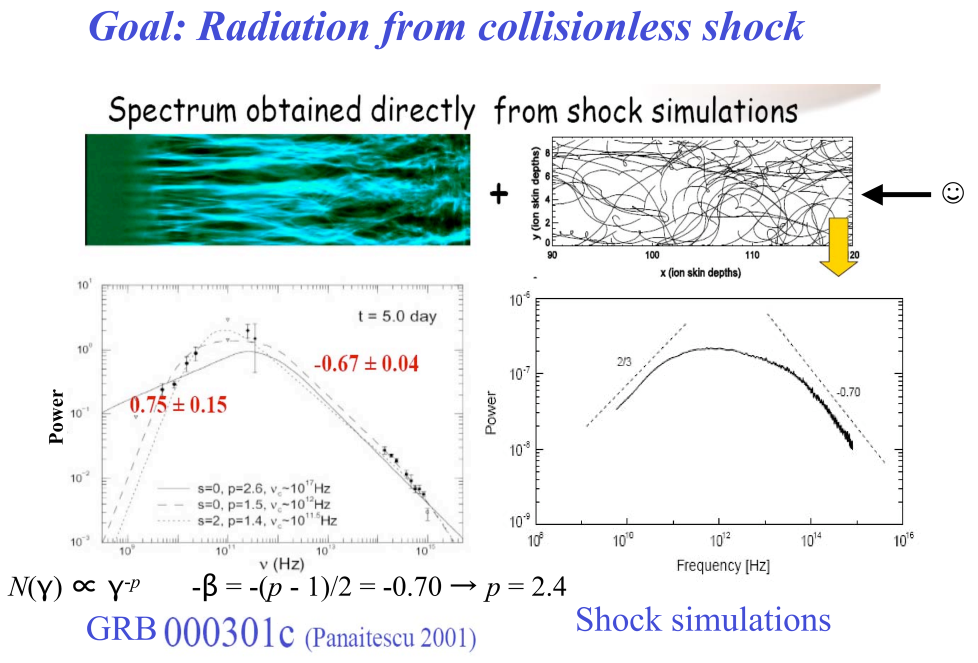
Magnetic field energy and parallel and perpendicular velocity space along Z with 3 stages



Properties along the jet for three slices in z



Goal: Radiation from collisionless shock



Hededal Thesis: http://www.astro.ku.dk/~hededal (astro-ph/0506559)

ala Hededal & Nordlund 2005 (astro-ph/0511662)

Results

- **The Weibel instability creates filamented currents and density structure along the propagation axis of the jet.**
- **The growth rate of the Weibel instability depends on the Lorentz factor, composition, and strength and direction of ambient B fields.**
- **In a one-dimensional system the Buneman instability is responsible for surfing acceleration.**
- **The Weibel instability is excited in the 3-D system.**
- **In order to understand the complex shock dynamics of relativistic jets, further simulations with additional physical mechanisms such as radiation loss and inverse Compton scattering are necessary.**
- **The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006).**

Future plans

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **Further diagnostics will be developed**
- **To improve the performance of the code, MPI is implemented and will be used for simulating a lager system**
- **Implement better boundary conditions at the free boundaries**
- **Investigate radiation processes from the accelerated electrons and compare with observations (GRBs, SNRs, AGNs, etc)**
- **Implement radiative losses into the dynamics**
- **Consider relevance to experiments at SLAC**

First GLAST Symposium, February 5 – 8, 2007
For further information: ken-ichi.nishikawa@nsstc.nasa.gov