Radiation from accelerated particles in relativistic jets with shocks, shear-flow and reconnections

Ken Nishikawa ***UAH/CSPAR***

Collaborators:

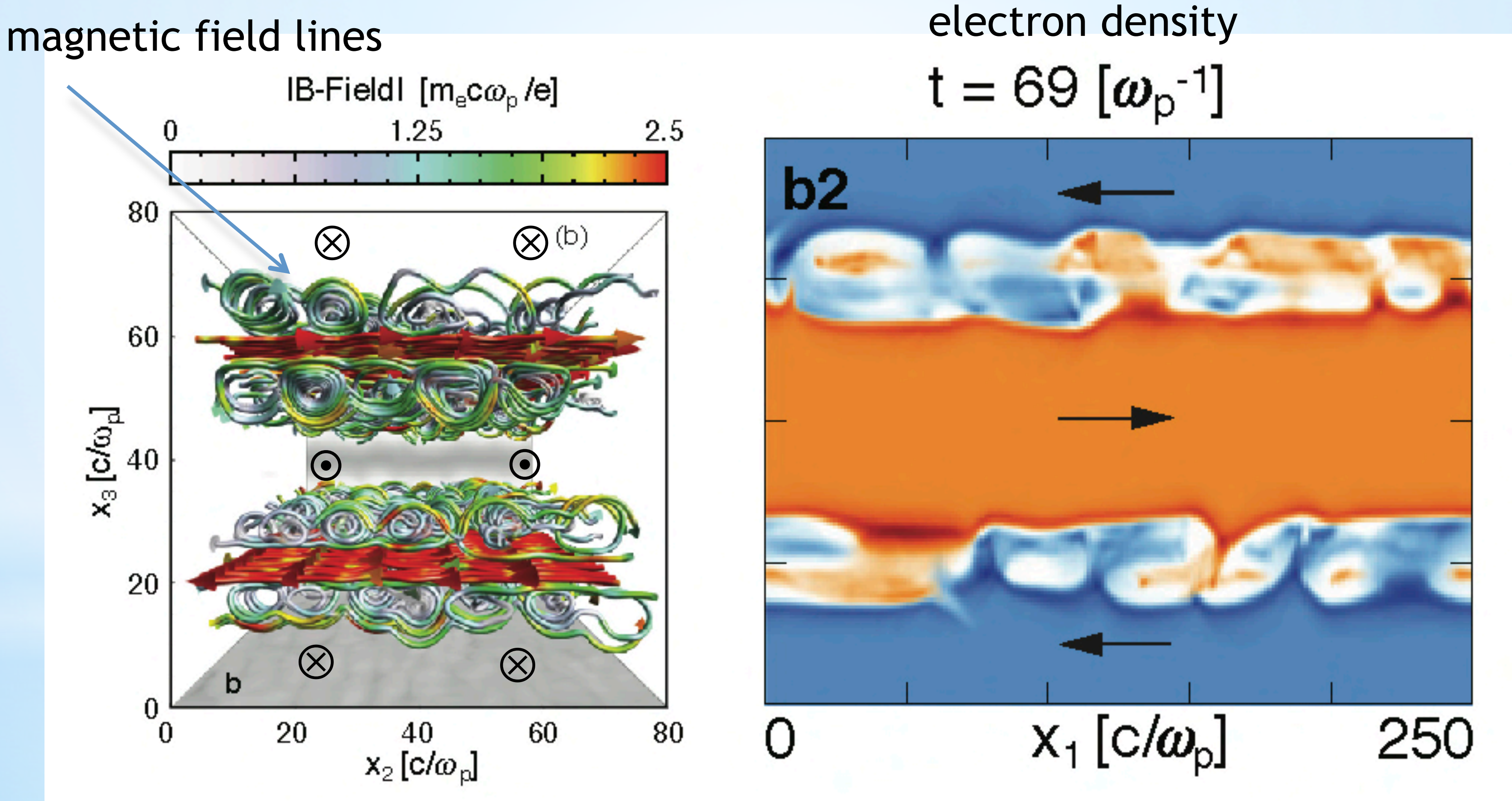
P. Hardee (*Univ. of Alabama, Tuscaloosa*)
Y. Mizuno (*National Tsing Hua University, Taiwan*)
I. Dutan (*Institute of Space Science, Rumania*)
B. Zhang (*Univ. Nevada, Las Vegas*)
M. Medvedev (*Univ. of Kansas*)
E. J. Choi (*KAIST*)
K. W. Min (*KAIST*)
J. Niemiec (*Institute of Nuclear Physics PAN*)
Å. Nordlund (*Niels Bohr Institute*)
J. Frederiksen (*Niels Bohr Institute*)
H. Sol (*Meudon Observatory*)
M. Pohl (*U-Potsdam/DESY*)
D. H. Hartmann (*Clemson Univ.*)
A. Marscher (*Boston Univ.*)
J. Gómez (*IAA, CSIC*)

The Innermost Regions of Relativistic Jets and Their Magnetic Fields
Granada, Spain, June 10 – 14, 2013

Outline

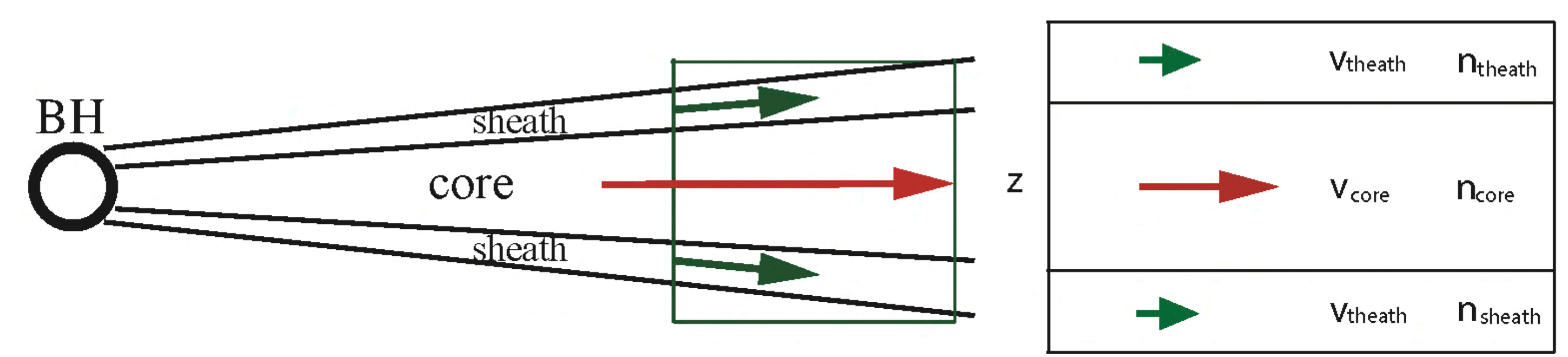
1. Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability
2. Self-consistent radiation method using PIC simulations
3. Synthetic spectra in shocks generated by the Weibel instability
5. Strong magnetic field amplification with colliding jets with magnetic fields
6. Acceleration in recollimation shock
7. Summary
8. Future plans

Simulations of Kinetic Kelvin-Helmholtz instability with counter-streaming flows (γ_0 = 3, m_i/m_e=1836)

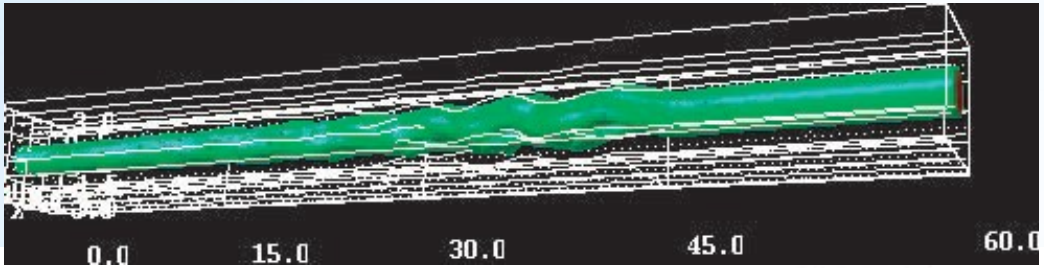


Alves et al. (2012)

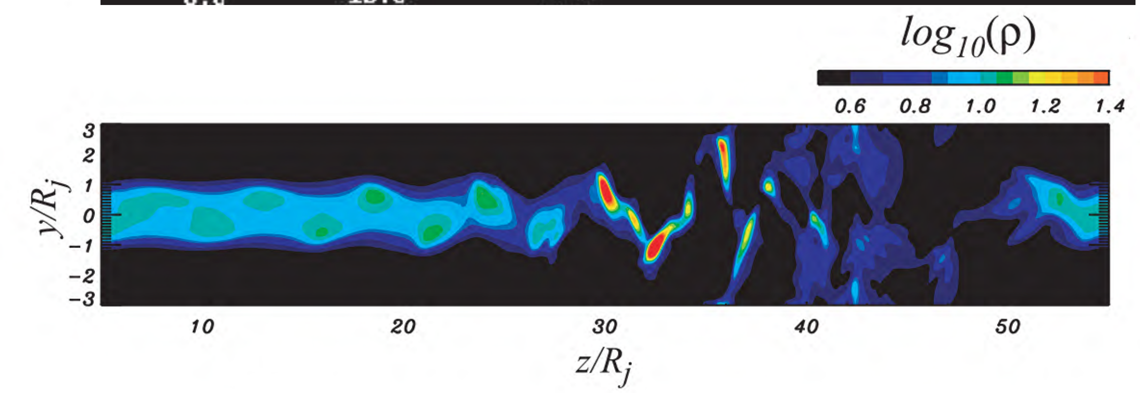
Simulations of KHI with core and sheath jets

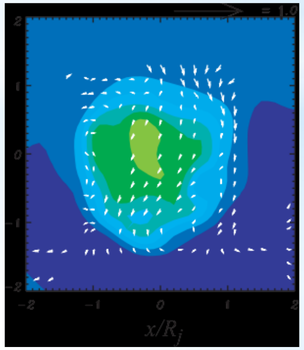


RMHD, no wind ω=0.93, time=60.0

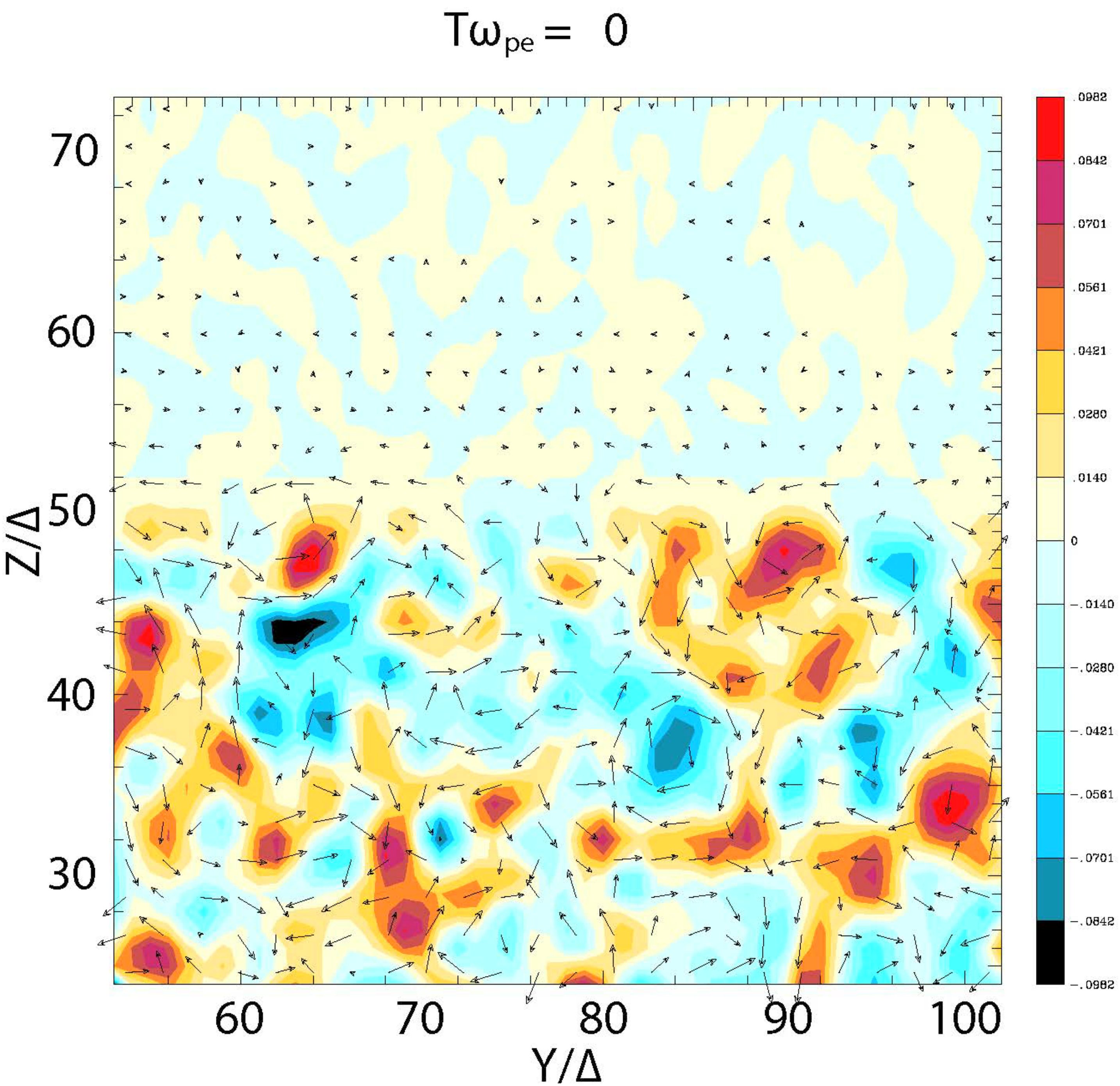


case of V_{theath} = 0



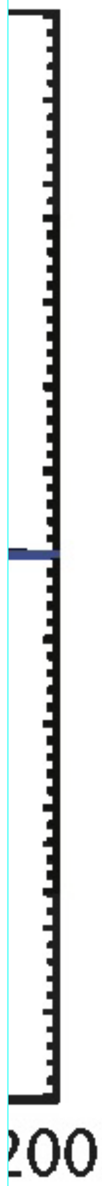


Mizuno, Hardee & Nishikawa, ApJ, 662, 835, 2007



ry

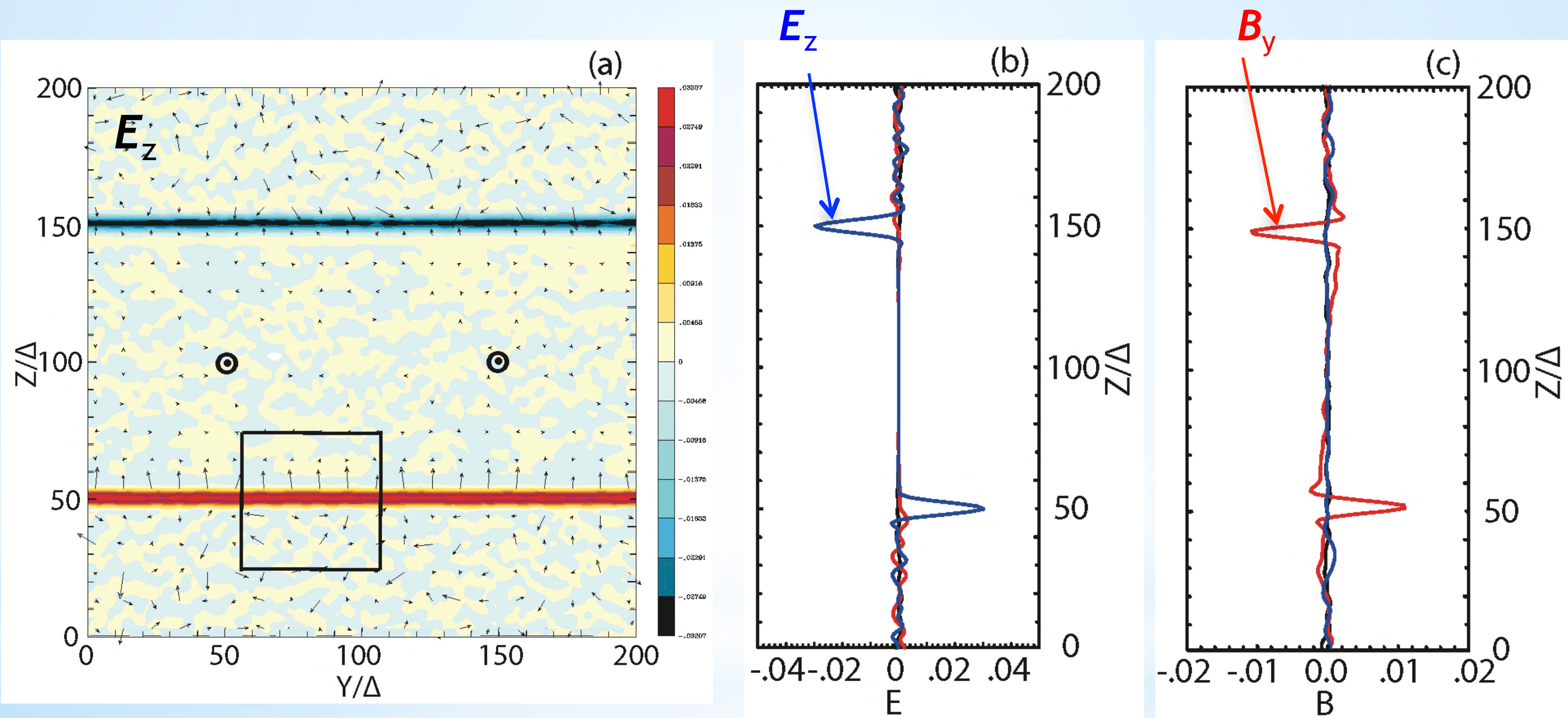
. al. 2013
28
2569)



Electric field generation by KKHI

$\gamma_j = 15$, $m_i/m_e = 1836$, $t = 30/\omega_{pe}$

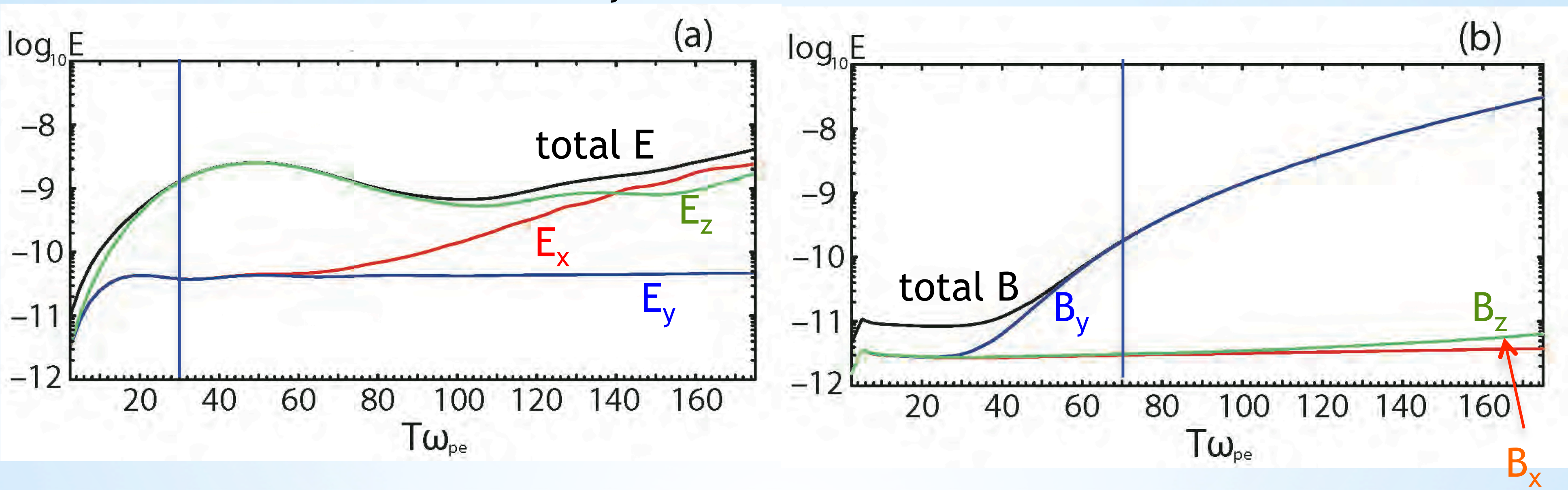
$t = 70/\omega_{pe}$

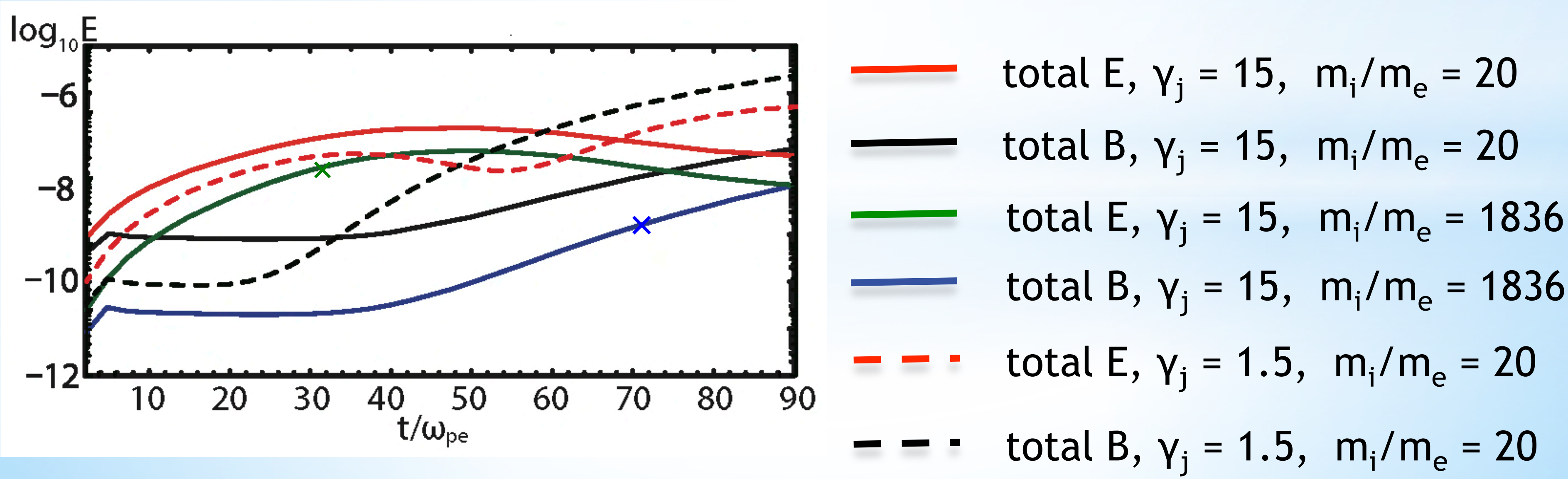


(Nishikawa et al. 2013)

Evolution of electric and magnetic field energy

$\gamma_j = 15, \quad m_i/m_e = 1836$

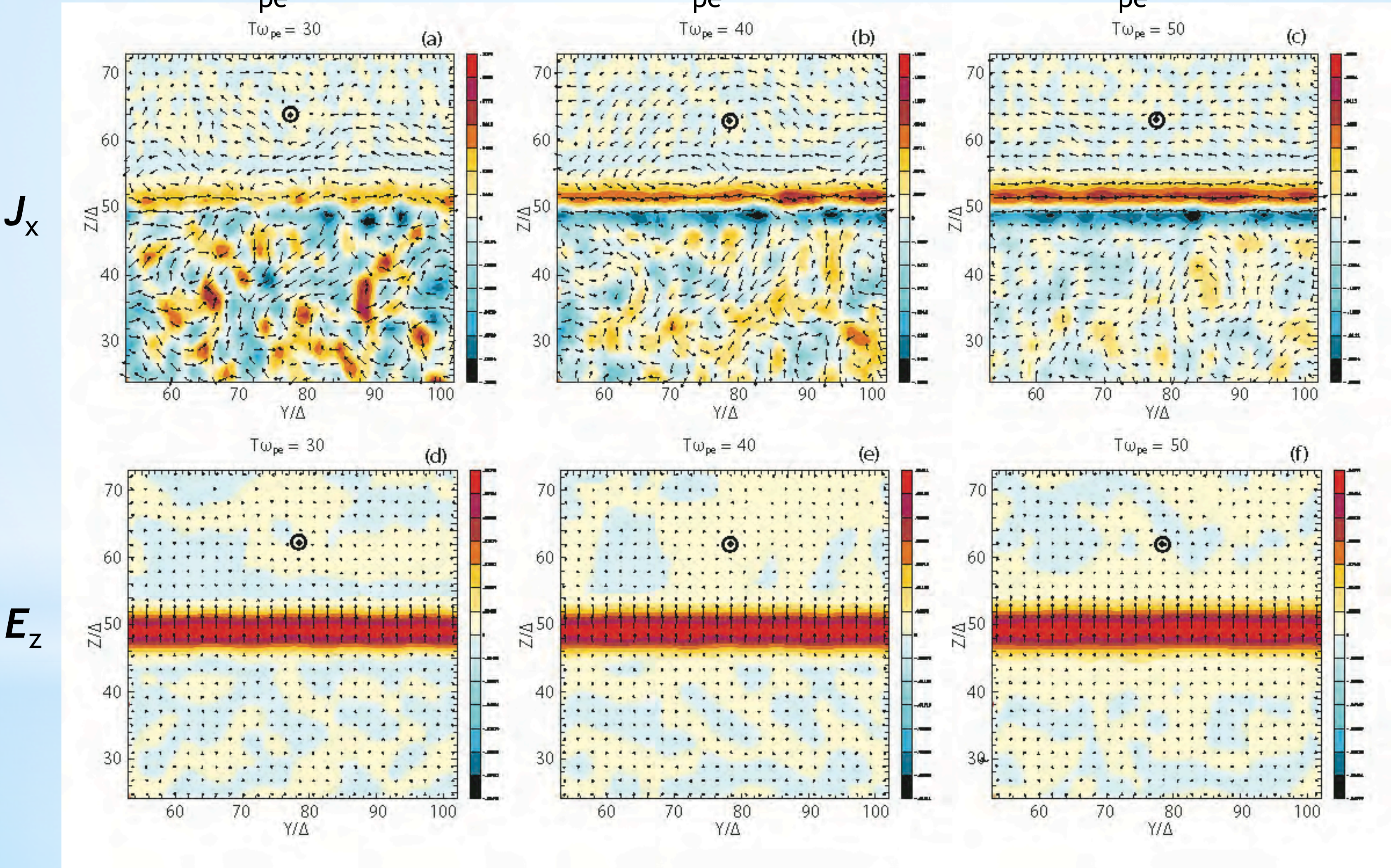




Evolution of current filaments (J_x) and electric field (E_z)

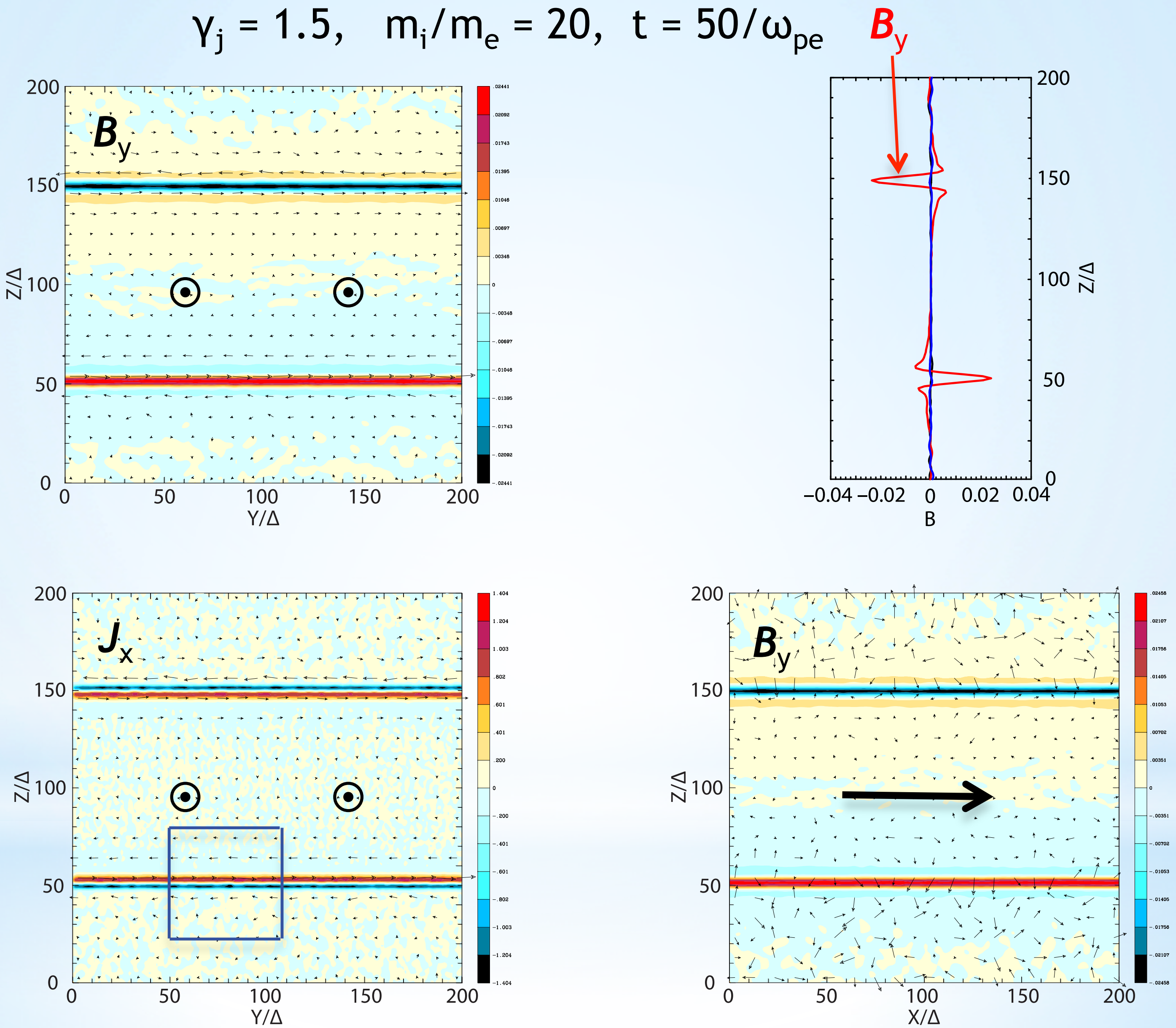
$\gamma_j = 15, \quad m_i/m_e = 1836$

$t\omega_{pe} = 30$ $t\omega_{pe} = 40$ $t\omega_{pe} = 50$



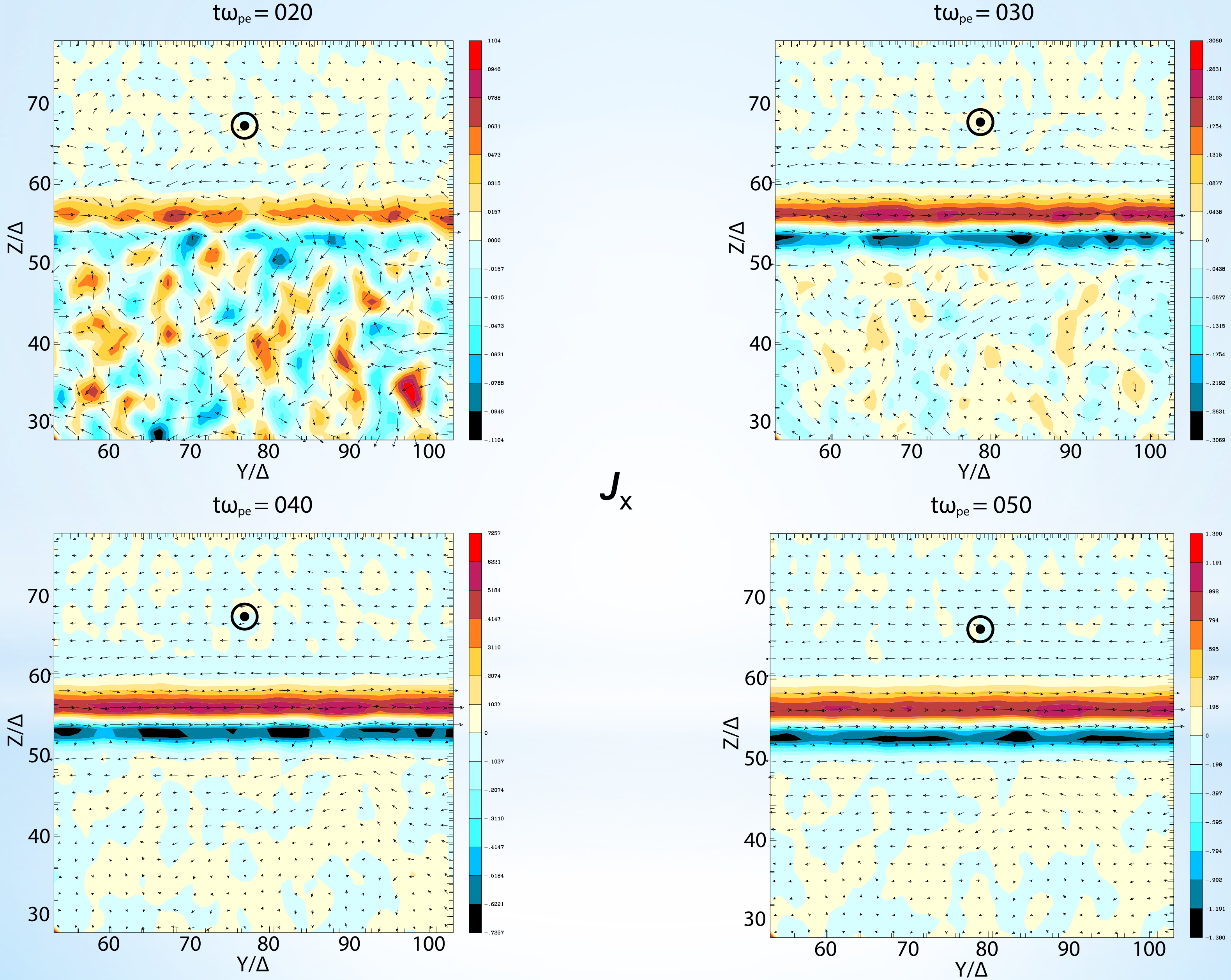
KKHI simulation of core jet-stationary sheath plasma

γ_j = 1.5, m_i/m_e = 20,   t = 50/ω_{pe}



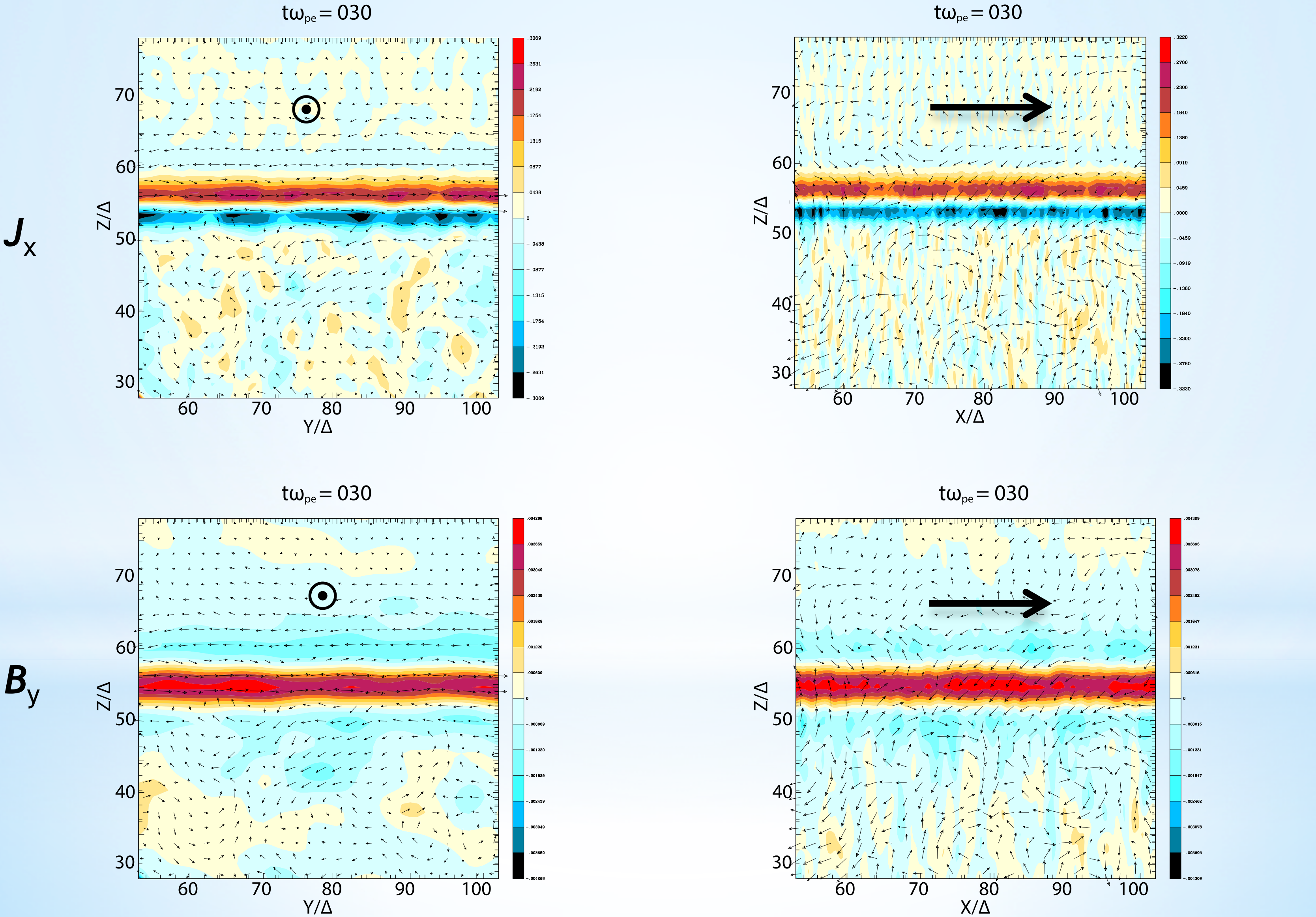
Time evolution of current filaments (J_x) generated by KKHI in the small box in y - z plane

$\gamma_j = 1.5, \quad m_i/m_e = 20$



Motion of the electrons across the shear surface produce electric currents which generate magnetic field

$t = 30/\omega_{pe}$ $\gamma_j = 1.5$, $m_i/m_e = 20$



Kinetic Kelvin-Helmholtz Instability

1. Static electric field grows due to the charge separation by the negative and positive current filaments
2. Current filaments at the velocity shear generate magnetic field transverse to the jet along the velocity shear
3. Jet with high Lorentz factor with core-sheath case generate higher magnetic field even after saturated in the case counter-streaming case with moderately relativistic jet
4. Non-relativistic jet generate KKHI quickly and magnetic field grows faster than the jet with higher Lorentz factor
5. For the jet-sheath case with Lorentz factor 15 the evolution of KKHI does not change with the mass ratio between 20 and 1836
6. Strong magnetic field will affect electron trajectories and create synchrotron-like (jitter) radiation which will be investigated
7. KKHI need to be investigated with shocks

Self-consistent calculation of radiation

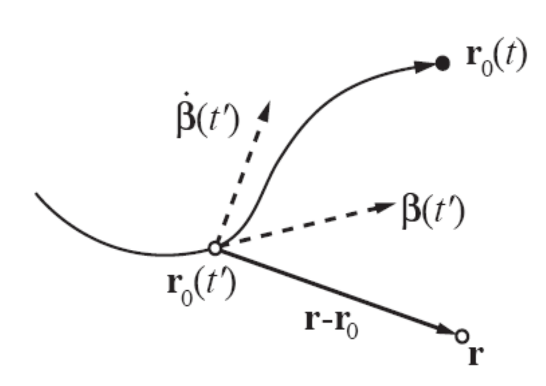
- Electrons are accelerated by the electromagnetic field generated by the Weibel instability and KKHI (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated using the particle trajectory in the self-consistent turbulent magnetic field
- This calculation includes Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission
- Radiation from electrons in our simulation is reported in Nishikawa et al. Adv. Sci. Rev, 47, 1434, 2011.

Radiation from particles in collisionless shock

To obtain a spectrum, "just" integrate:

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

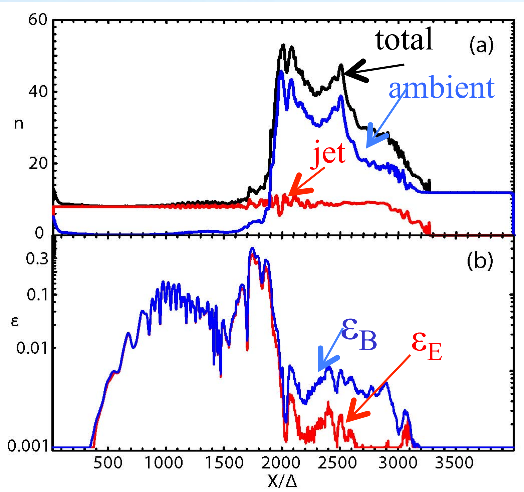
where $\mathbf{r}_0$ is the position, β the velocity and $\dot{\beta}$ the acceleration



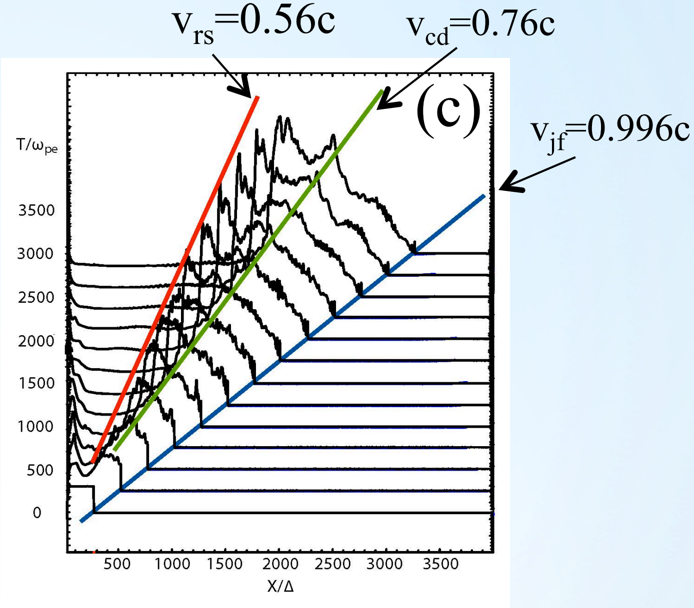
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Hededal, Thesis 2005 (astro-ph/0506559)
Nishikawa et al. 2008 (astro-ph/0802.2558)
Sironi & Spitkovsky, 2009, ApJ
Martins et al. 2009, Proc. of SPIE Vol. 7359
Frederiksen et al. 2010, ApJL

Shock formation, forward shock, reverse shock



(a) electron density and (b) electromagnetic field energy (ε_B, ε_E) divided by the total kinetic energy at $t = 3250\omega_{pe}^{-1}$



Time evolution of the total electron density. The velocity of the jet front is ~c, the predicted contact discontinuity speed is 0.76c, and the velocity of the reverse shock is 0.56c.

(Nishikawa et al. ApJ, 698, L10, 2009)

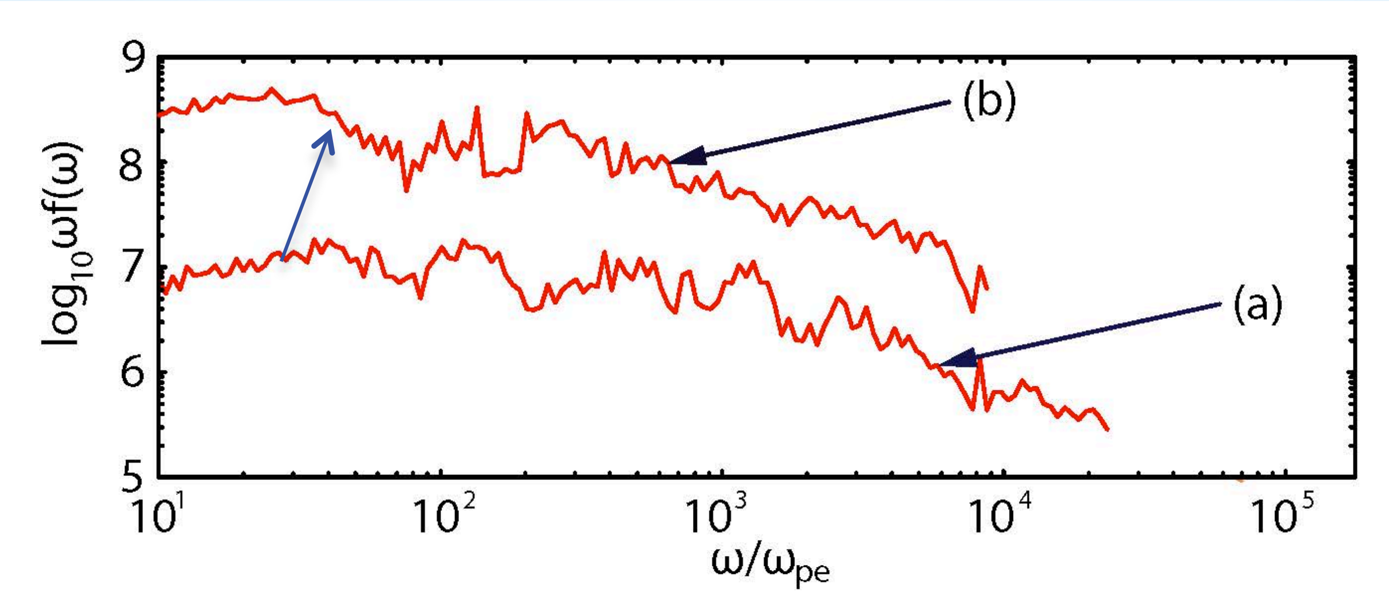
Radiation in a larger system at early time

System size: 8000 × 240 × 240
Electron-positron: $\gamma = 15$

Sampled particles 115,200

(a) $150\,\omega_{pe}^{-1} \leq t \leq 225\,\omega_{pe}^{-1}$

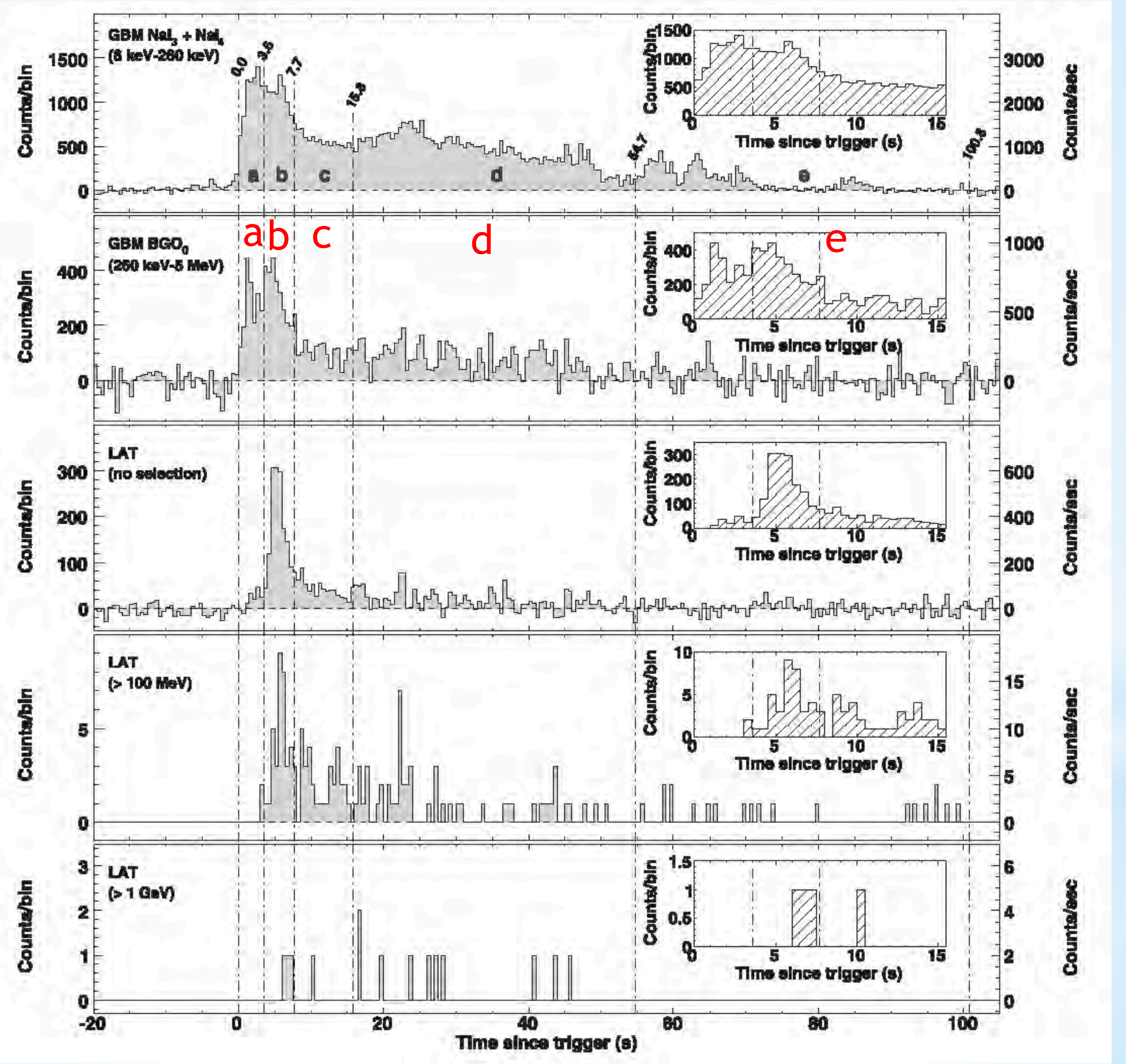
(b) $200\,\omega_{pe}^{-1} \leq t \leq 275\,\omega_{pe}^{-1}$



Nishikawa et al. in progress

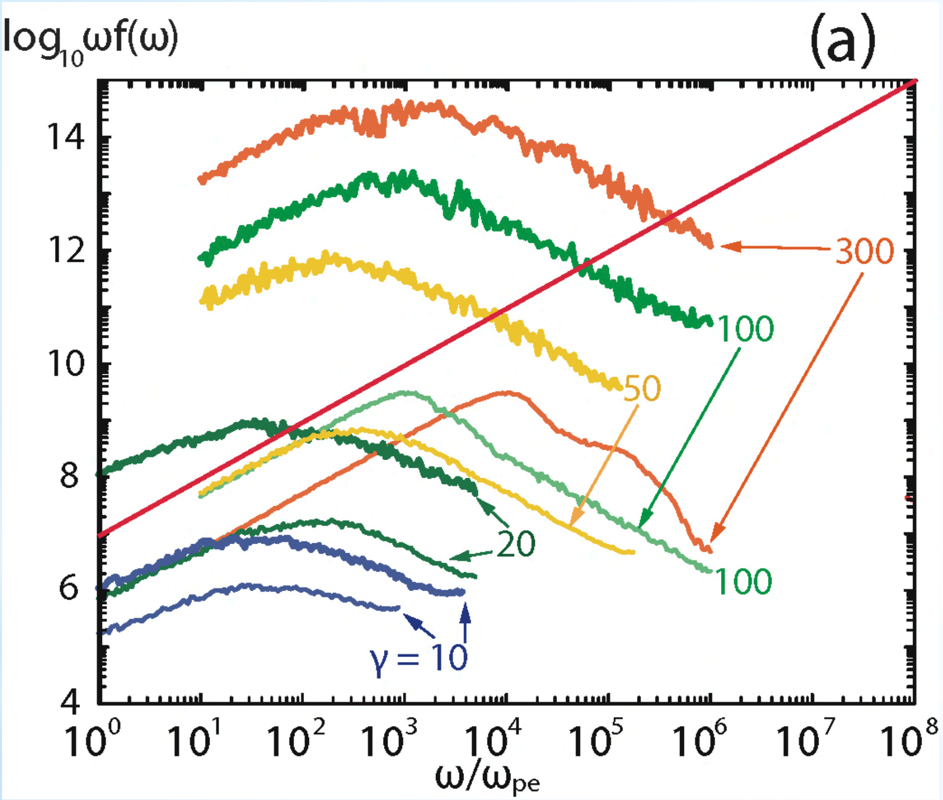
Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C

Light curves for GRB 080916C observed with the GBM and the LAT (Abdo et al. 2009)

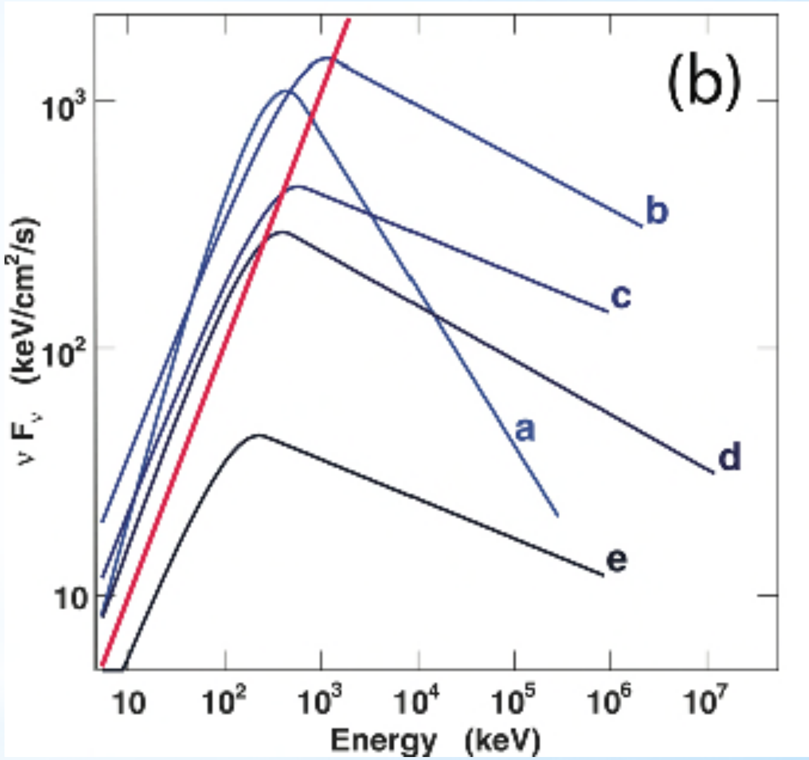


Synthetic spectra with different Lorentz factors with cold and warm thermal temperatures

synthetic spectra



modeled Fermi spectra in vF units

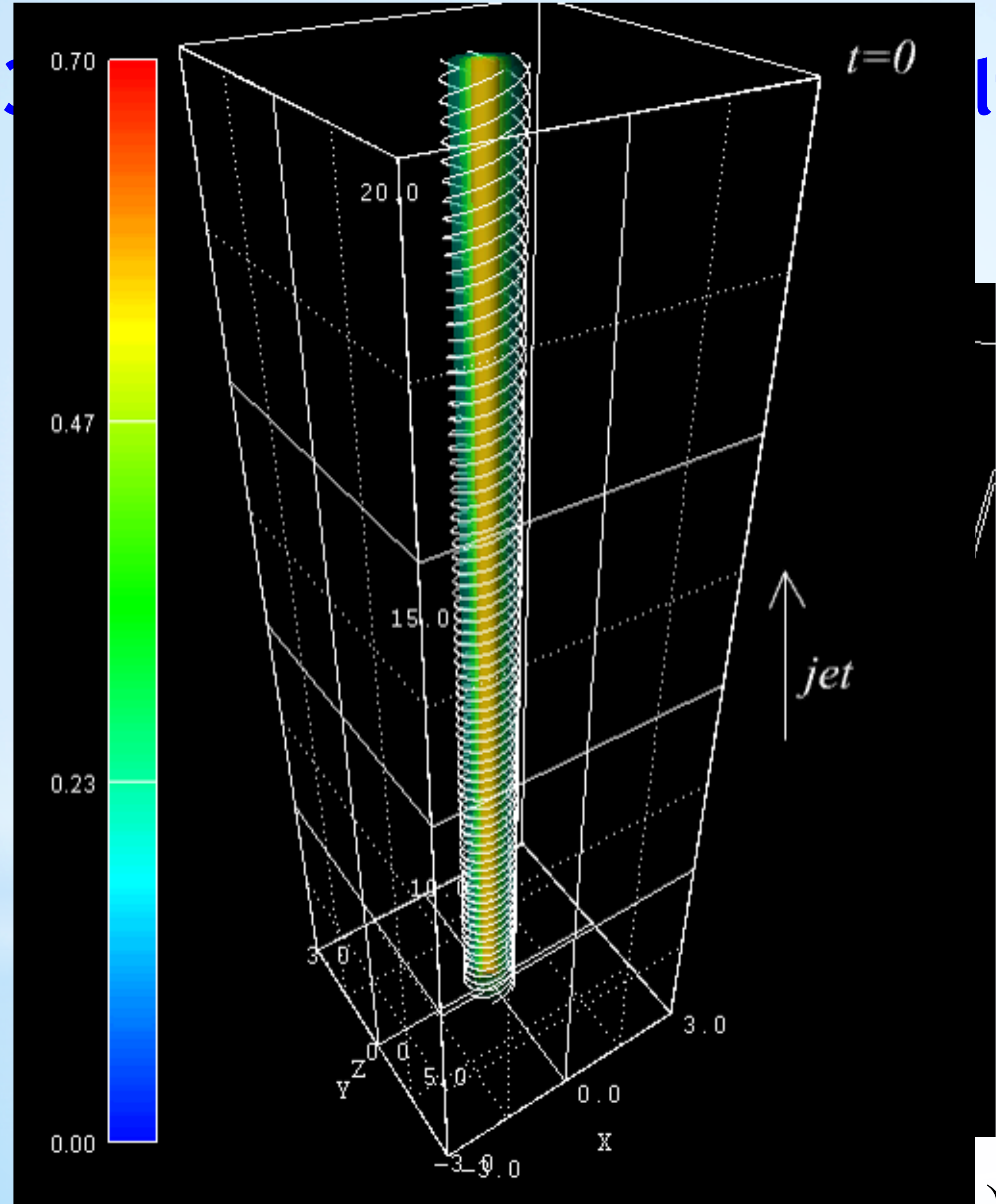


(thin lines) and warm (thick lines) electron jets.
The red lines indicate slope in vF ~ 1

(Nishikawa et al. 2012)

(Abdo et al. 2009)

…lical magnetic field

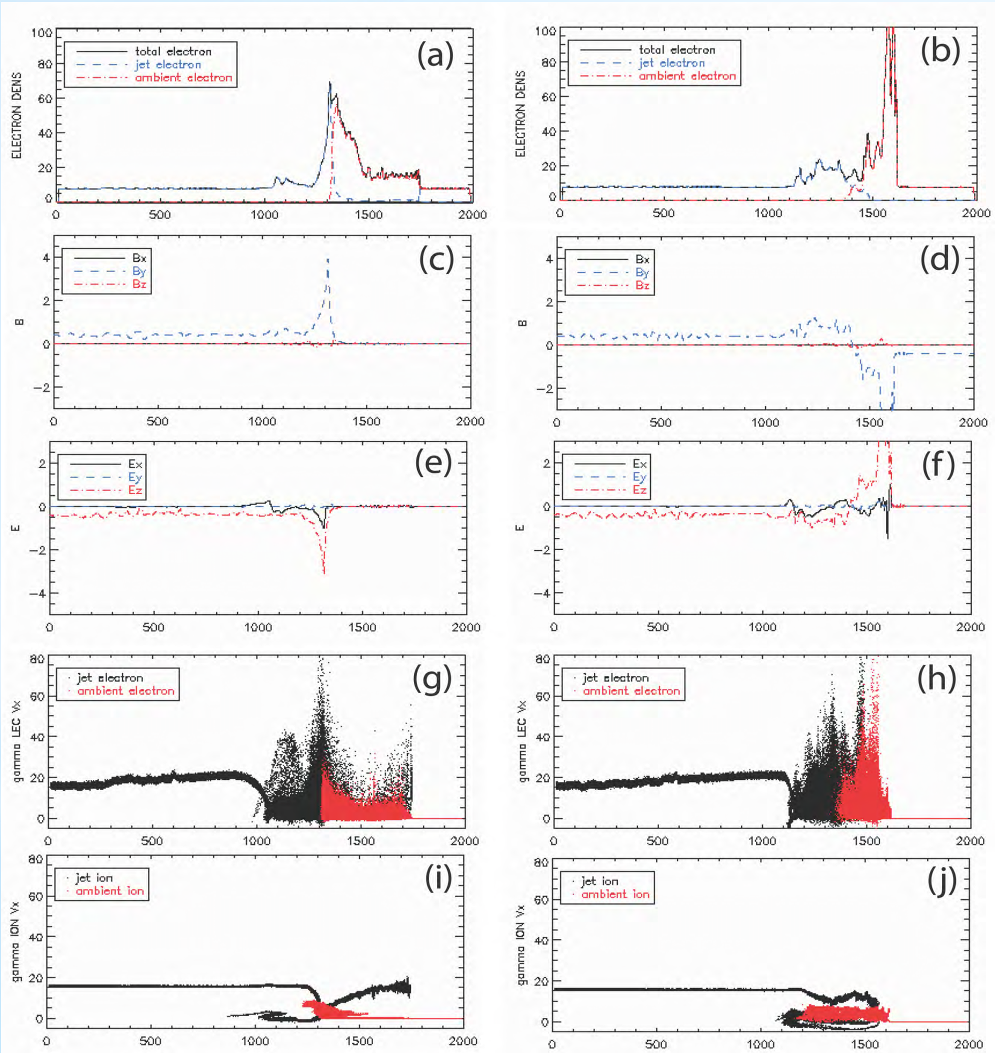


Relativistic jet with helical magnetic field, which leads to the kink instability and subsequent reconnection, can be simulated using resistive relativistic MHD (this simulation was performed with ideal RMHD code).

(Mizuno et al. ApJ, 734:19 (18pp), 2011)

Simulations with magnetic field in jets

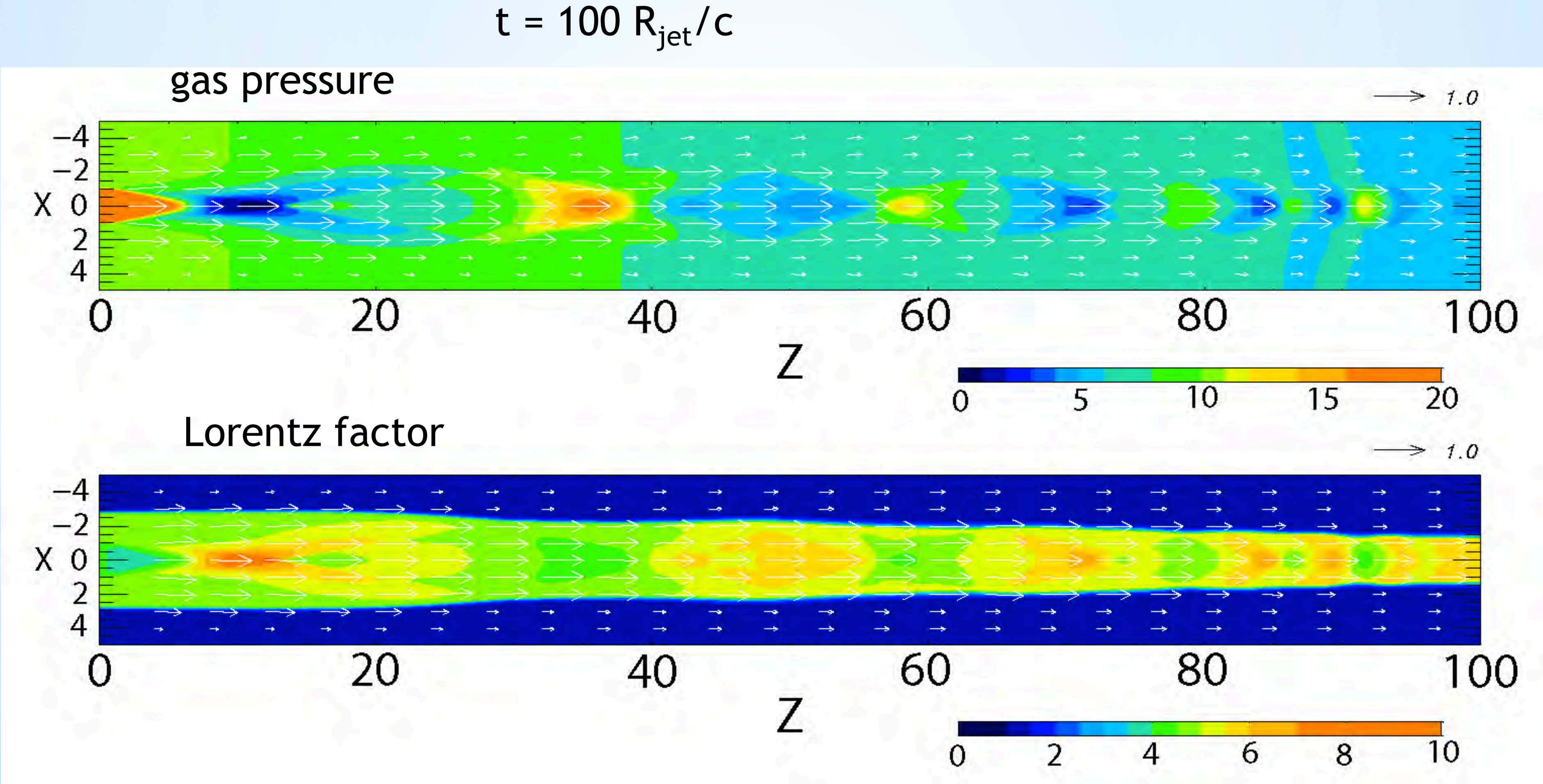
no magnetic field   anti-parallel magnetic field



Snapshots for unmagnetized ambient plasma (left column) and anti-parallel magnetic field in the ambient plasma (right column) at t = 1450 ω_{pe}^{-1} (Choi, Min, and Nishikawa, 2012). The averaged values of electron density (a) and (b), magnetic field (c) and (d), electric field (e) and (f), phase space of electrons (g) and (h), and phase space of ions (i) and (j). Reconnection occurs for the case of anti- parallel magnetic fields and is indicated by the positive E_y component in (f).

Choi, Min, KN, 2013 (in progress)

3D RHD simulation of recollimation shock similar parameters of Gómez et al. (1997)



Mizuno et al. in progress, 2013

Summary of 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.
- The presence of ions in the ambient plasma enhances the strength of the generated magnetic fields due to the excitation of the ion Weibel instability.
- This enhanced magnetic field with electron-ion ambient plasma may be the cause of large upstream magnetic fields in GRB shocks.
- 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.
- Spectra from two electrons were calculated for different conditions.
- The magnetic fields created by the Weibel instability generate highly inhomogeneous magnetic fields, which are responsible for Jitter radiation (Medvedev, 2000, 2006; Fleishman 2006; Frederiksen et al. 2010, Medvedev et al 2011).
- Our new numerical approach of calculating radiation from electrons based on self-consistent simulations provides more realistic spectra including jitter radiation.

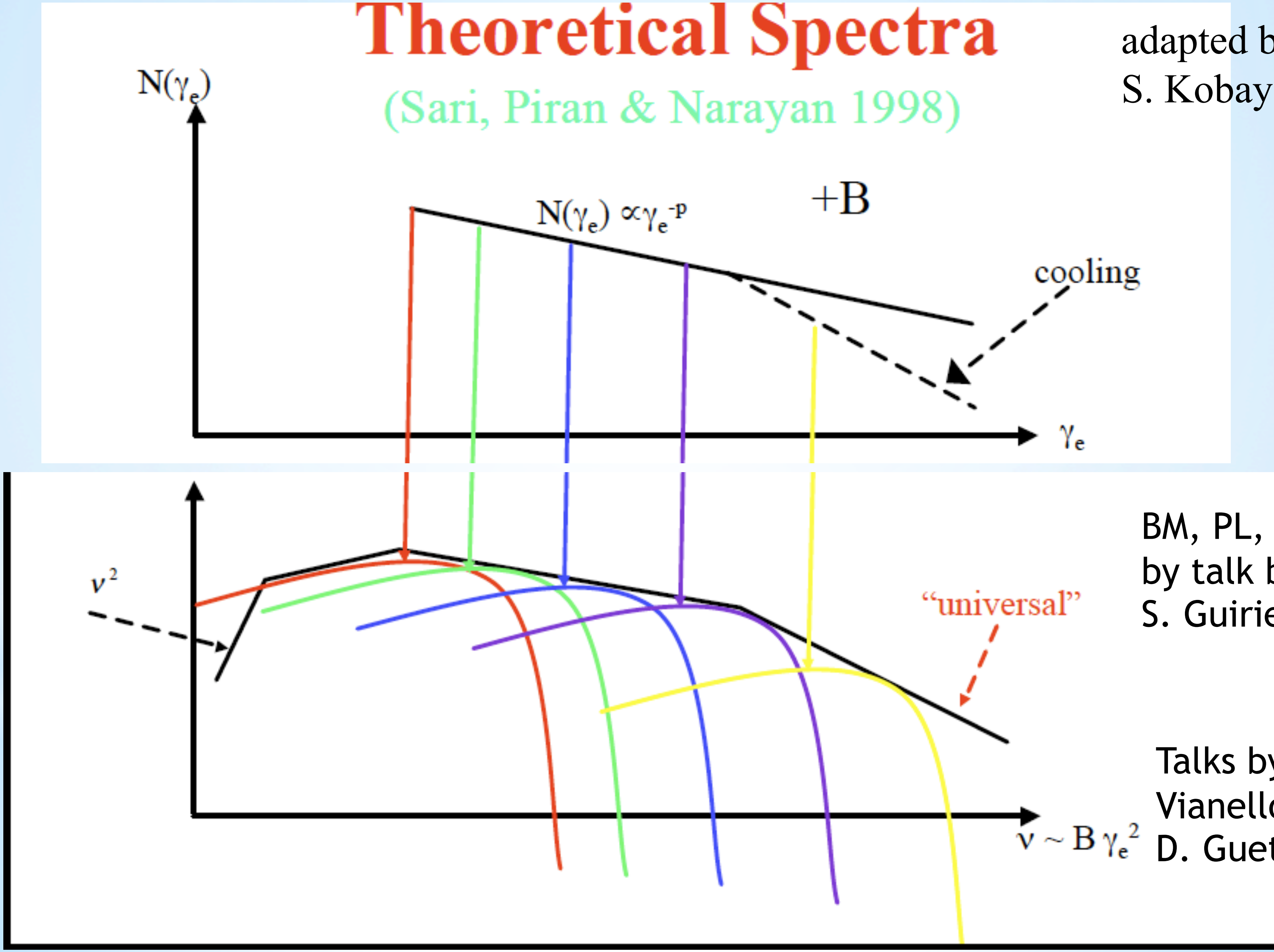
Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including reconnection and KKHI.
- Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability using larger systems.
- Investigate radiation processes from the accelerated electrons in turbulent magnetic fields and compare with observations (GRBs, SNRs, AGNs, etc).
- Particle acceleration and radiation in recollimation shocks

Present theory of Synchrotron radiation

- Fermi acceleration (Monte Carlo simulations are not self-consistent; particles are crossing the shock surface many times and remain accelerated, the strengths of turbulent magnetic fields are assumed), Some simulations exhibit Fermi acceleration (Spitkovsky 2008)
- The strength of magnetic fields is estimated based on equipartition - magnetic field energy is comparable to the thermal energy): $\varepsilon_B \sim u(T)$
- The distribution of accelerated electrons is approximated by the power law ($F(\gamma) = \gamma^{-p}$; $p = 2.2$?) (ε_e)
- Synchrotron emission is calculated based on p and ε_B
- There are many assumptions in this calculation!

Synchrotron Emission: radiation from accelerated



adapted by
S. Kobayashi

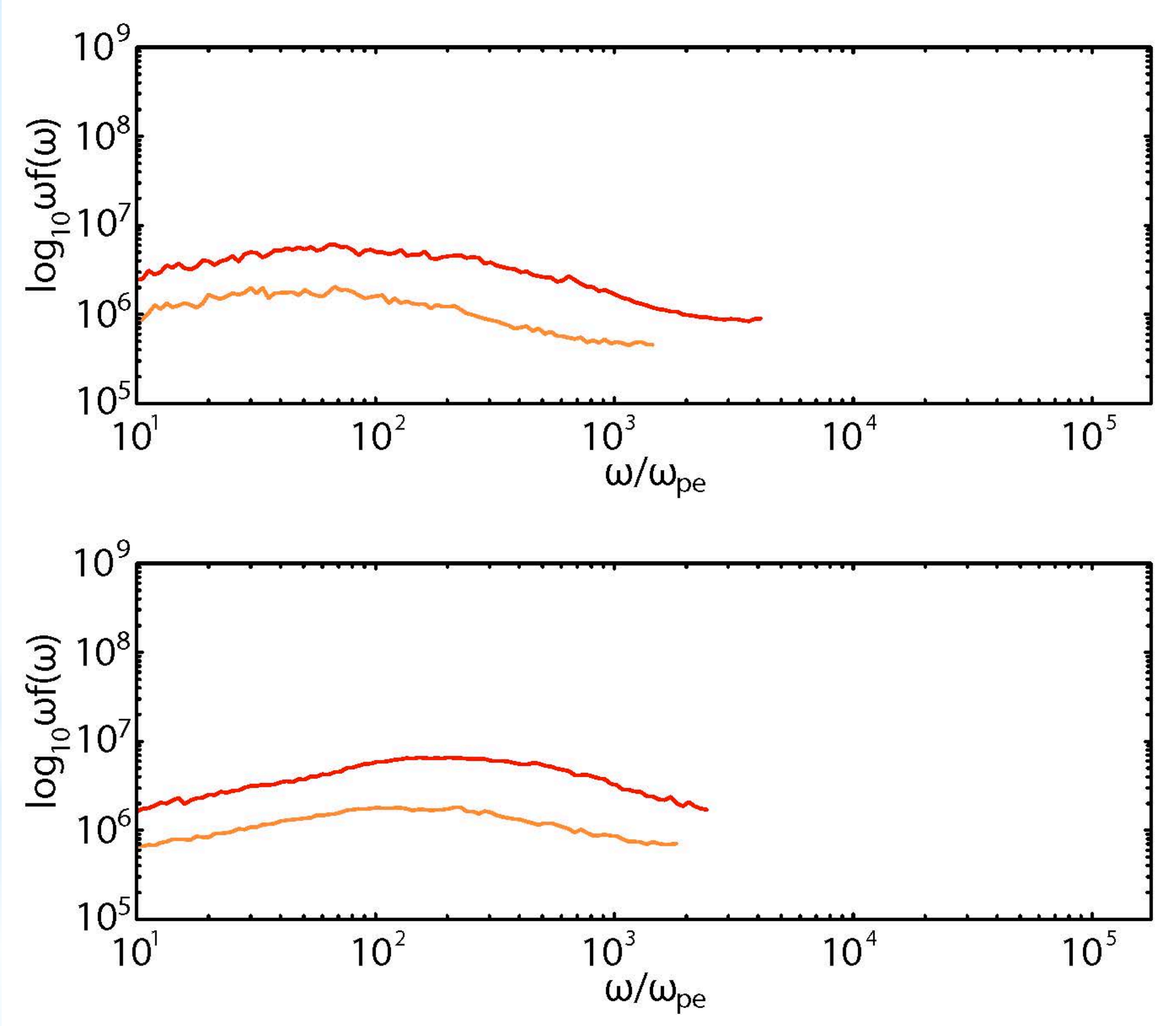
BM, PL, BB
by talk by
S. Guiriec

Talks by G.
Vianello and
D. Guetta

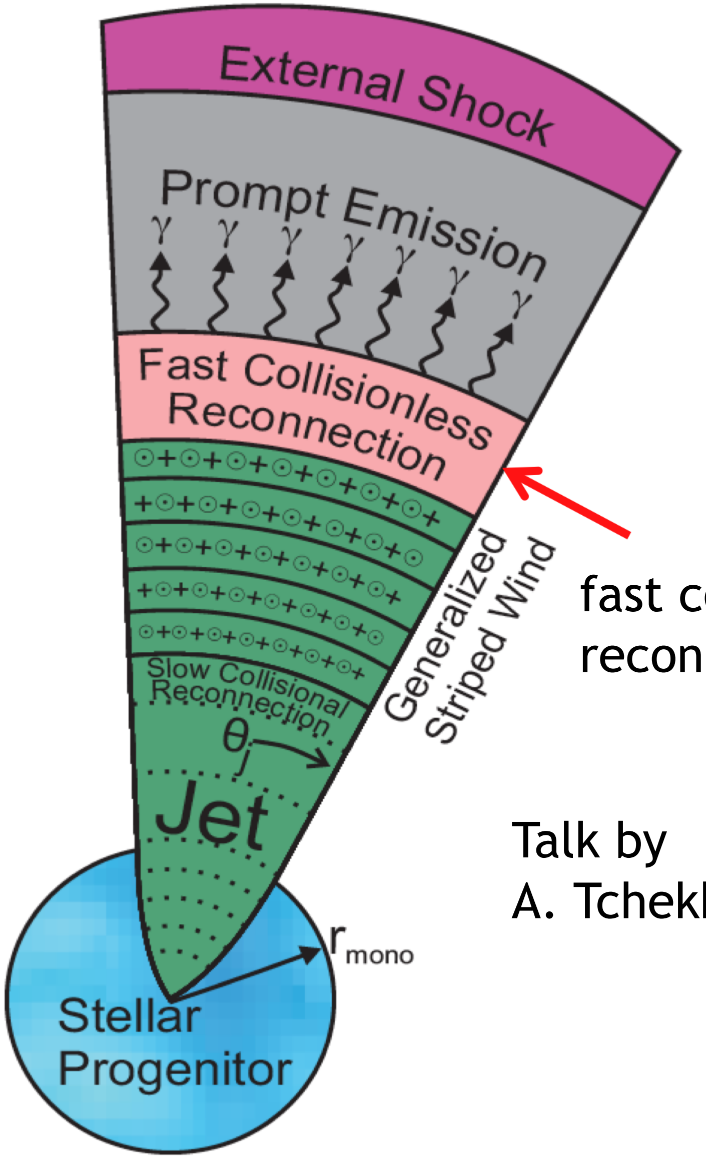
Radiation in a small system

without iteration

with iteration



Reconnection in jet



fast collisionless reconnection

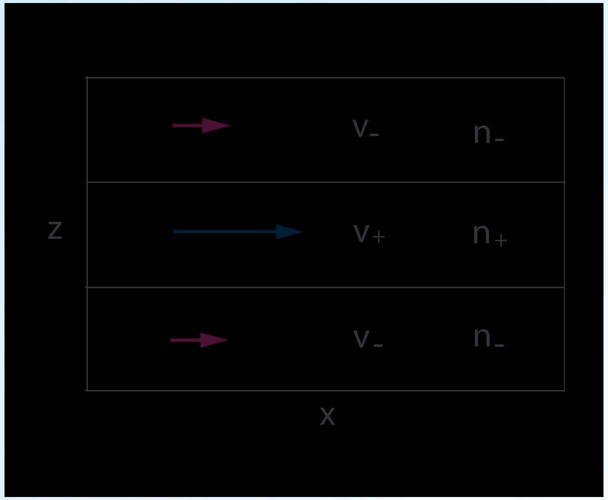
Talk by
A. Tchekhovskov

Reconnection switch concept: Collapsar model or some other system produces a jet (with opening half-angle θ_j) corresponding to a generalized stripped wind containing many field reversals that develop into dissipative current sheets (McKinney and Uzdensky, 2012, MNRAS, 419, 573). This reconnection needs to be investigated by resistive RMHD, which is in progress within our research effort.

Outline

1. Standard radiation mode
2. Self-consistent radiation method using PIC simulations
3. Synthetic spectra in shocks generated by the Weibel instability
4. Importance of reconnection in relativistic jet
5. Strong magnetic field amplification with magnetic fields
6. Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability
7. Summary
8. Future plans

Study of the relativistic velocity shear interface KKHI instability



$$\omega_p \equiv 4\pi n e^2/\gamma^3 m,$$

$$e^{i(ky-\omega t)}$$

$$(k^2c^2 + \gamma_-^2\omega_{p-}^2 - \omega^2)^{1/2}(kV_- - \omega)^2[(kV_+ - \omega)^2 - \omega_{p+}^2]$$
$$+(k^2c^2 + \gamma_+^2\omega_{p+}^2 - \omega^2)^{1/2}(kV_+ - \omega)^2[(kV_- - \omega)^2 - \omega_{p-}^2] = 0$$

Low-frequency limit (V_-=0)

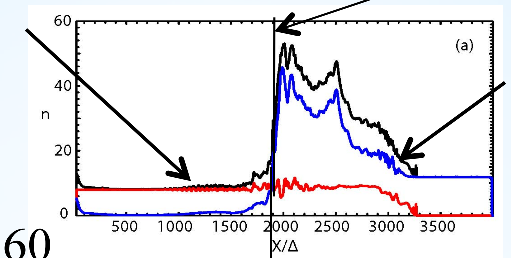
$$\omega \sim \frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt} \pm i\frac{(\gamma_{jt}\omega_{p,am}/\omega_{p,jt})^{1/2}}{(1+\gamma_{jt}\omega_{p,am}/\omega_{p,jt})}kV_{jt}.$$

Shock velocity and structure based on 1-D HD analysis

moving contact discontinuity (CD)

reverse shock

forward shock

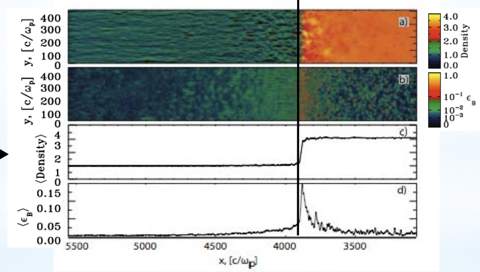


(Nishikawa et al. 2009)

$n_{sj}/\gamma'_{cd}n_j = 3.36$

$\beta_s = 0.417 \quad \gamma'_{cd} = 5.60$

$4/3 < \Gamma = 3/2 < 5/3$



fixed CD

0

Density →

$n_2/\gamma_0 n_1 = 3.13$

$\beta_c = 0.47$

$\gamma_0 = 15$

(Spitkovsky, ApJ, 682:L5, 2008 (adapted))