Particle Acceleration, Magnetic Field Generation and Emission from Relativistic Jets

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Outline of talk

- **Scientific goals**
- **Observations of accelerated particles**
- **Recent 3-D particle simulations of relativistic jets**

  *** electron-positron, (a pair jet created by photon annihilation)**

  $\gamma = 5, 15, 4 < \gamma < 100$

  *** electron-ion ($\gamma = 5$)**

  *** particle acceleration with the radial electric field**
- **Calculation of radiation based on particle trajectories**
- **Summary of current 3-D simulations (Weibel Instability)**
- **Future plans of our simulations of relativistic jets**

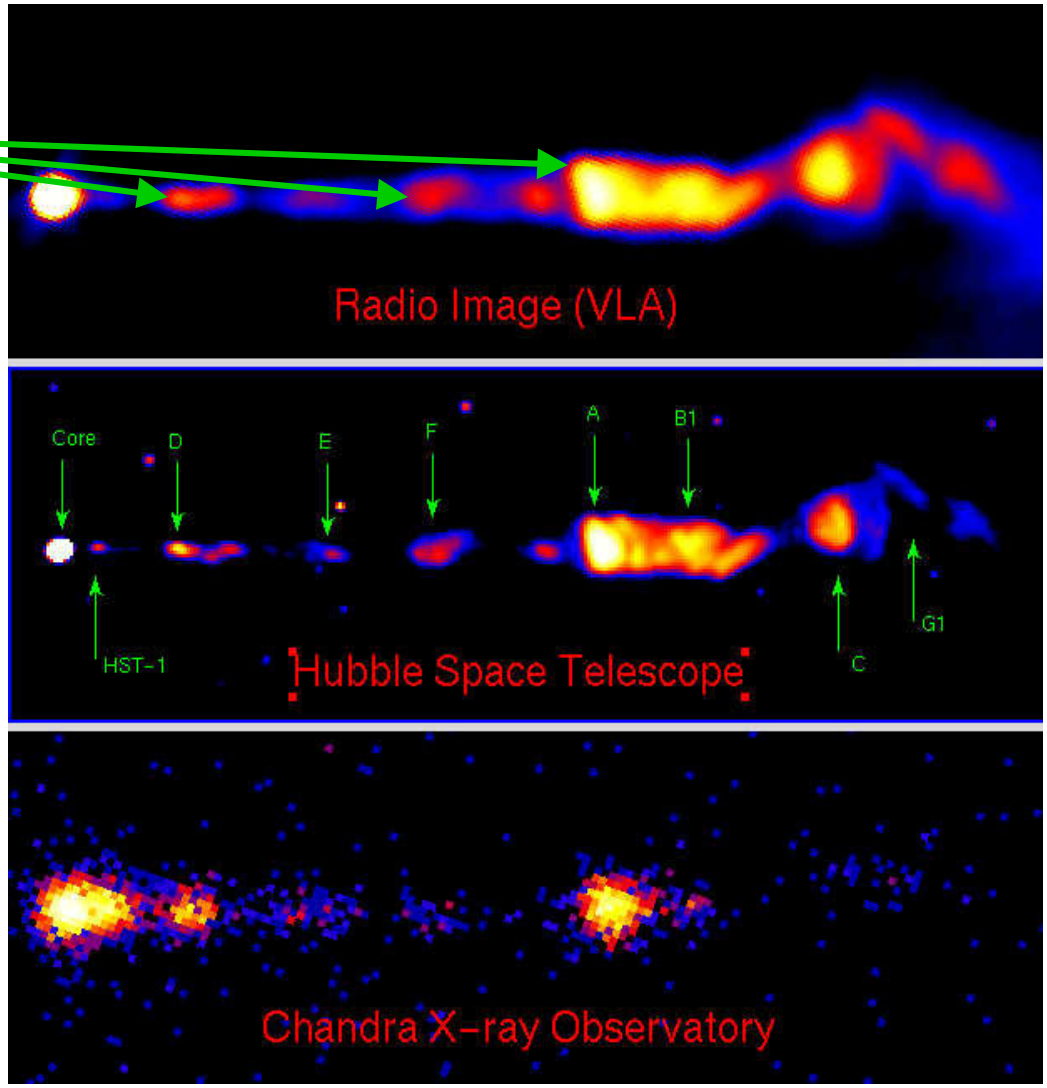
Motivations

- **Study particle acceleration at external and internal shocks in relativistic jets self-consistently with kinetic effects**
- **Examine the shock surfing acceleration in a 3-D system proposed in one-dimensional simulations including the dynamics of shock transition region**
- **Study structures and dynamics of shocks caused by instabilities at the shock front and transition region in relativistic jets**
- **Estimate synchrotron/jitter radiation from accelerated particles**
- **Examine possibilities for afterglows in gamma-ray bursts with appropriate ambient plasmas**

Observations of M87

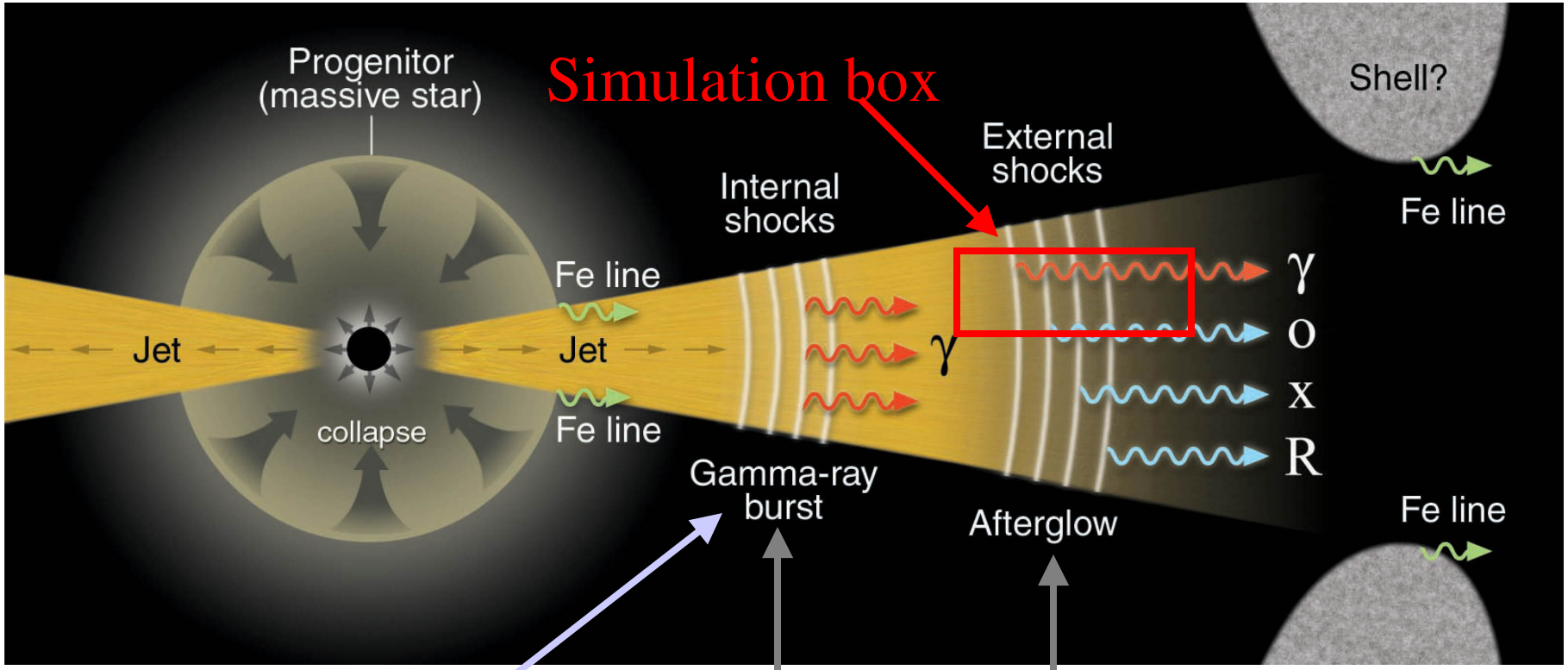
Shocks?

nonthermal electrons, enhanced magnetic field, jitter radiation (Medvedev 2000)?



Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



Prompt emission

Polarization ?

Accelerated particles emit waves at shocks

Necessity of 3-D full particle simulation for particle acceleration

- **MHD simulations provide global dynamics of relativistic jets including hot spots**
- **MHD simulations include heating due to shocks, however do not create high energy particles (MHD simulation + test particle (Tom Jones))**
- **In order to take account of acceleration, the kinetic effects need to be included**
- **Test particle (Monte Carlo) simulations can include kinetic effects, but not self-consistently**
- **Particle simulations provide particle acceleration (p) with (ε_e, ε_B) and emission self-consistently. However, due to the computational limitations, particle-in-cell (PIC) simulations covers only a small part of the full jet.**
- **Particle simulations can provide synchrotron and jitter radiation from ensemble of each particle (electron and positron) motion in electromagnetic fields.**

Collisionless shock

Electric and magnetic fields created self-consistently by particle dynamics randomize particles

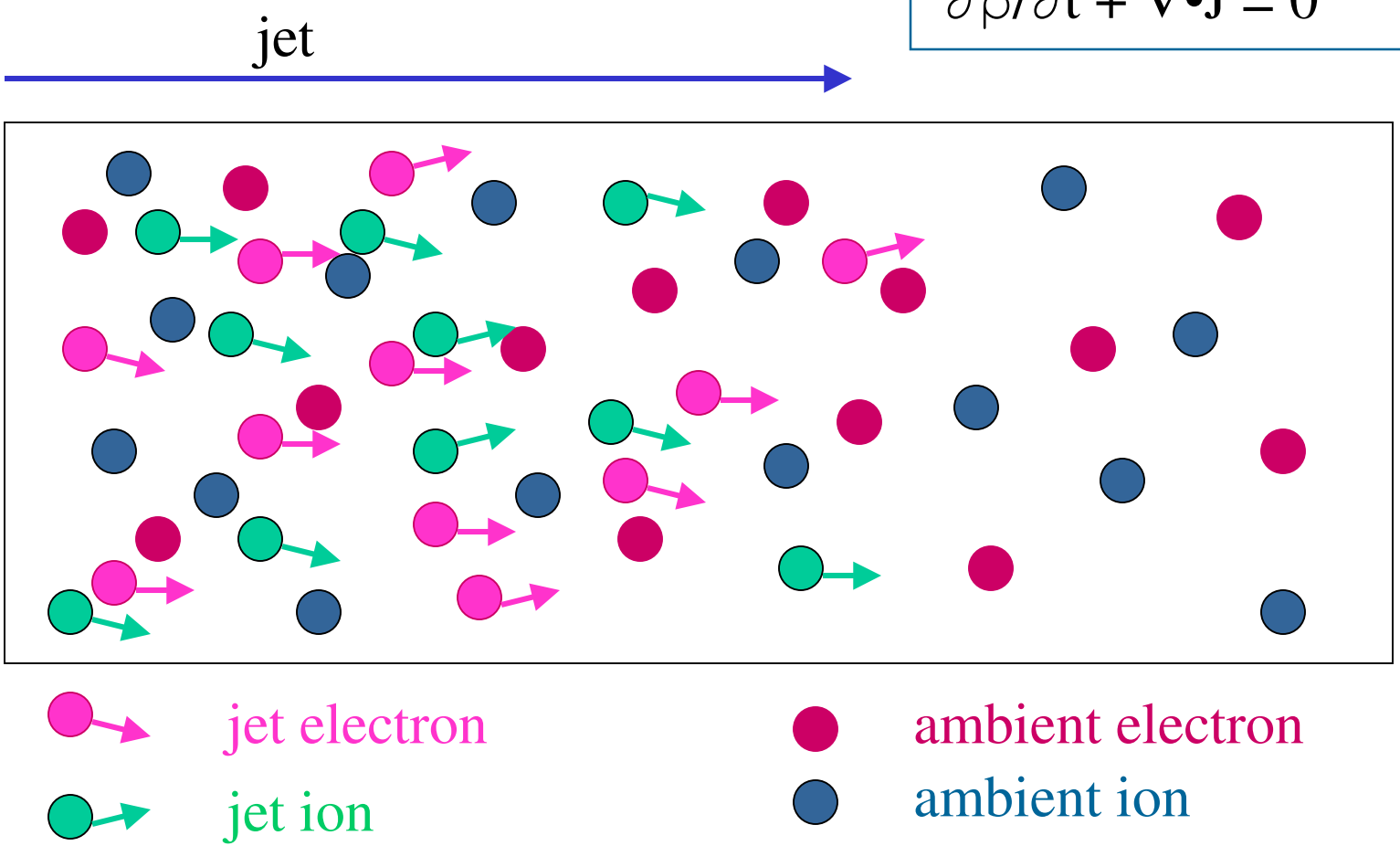
(Buneman 1993)

$$\partial B/\partial t = -\nabla\times E$$

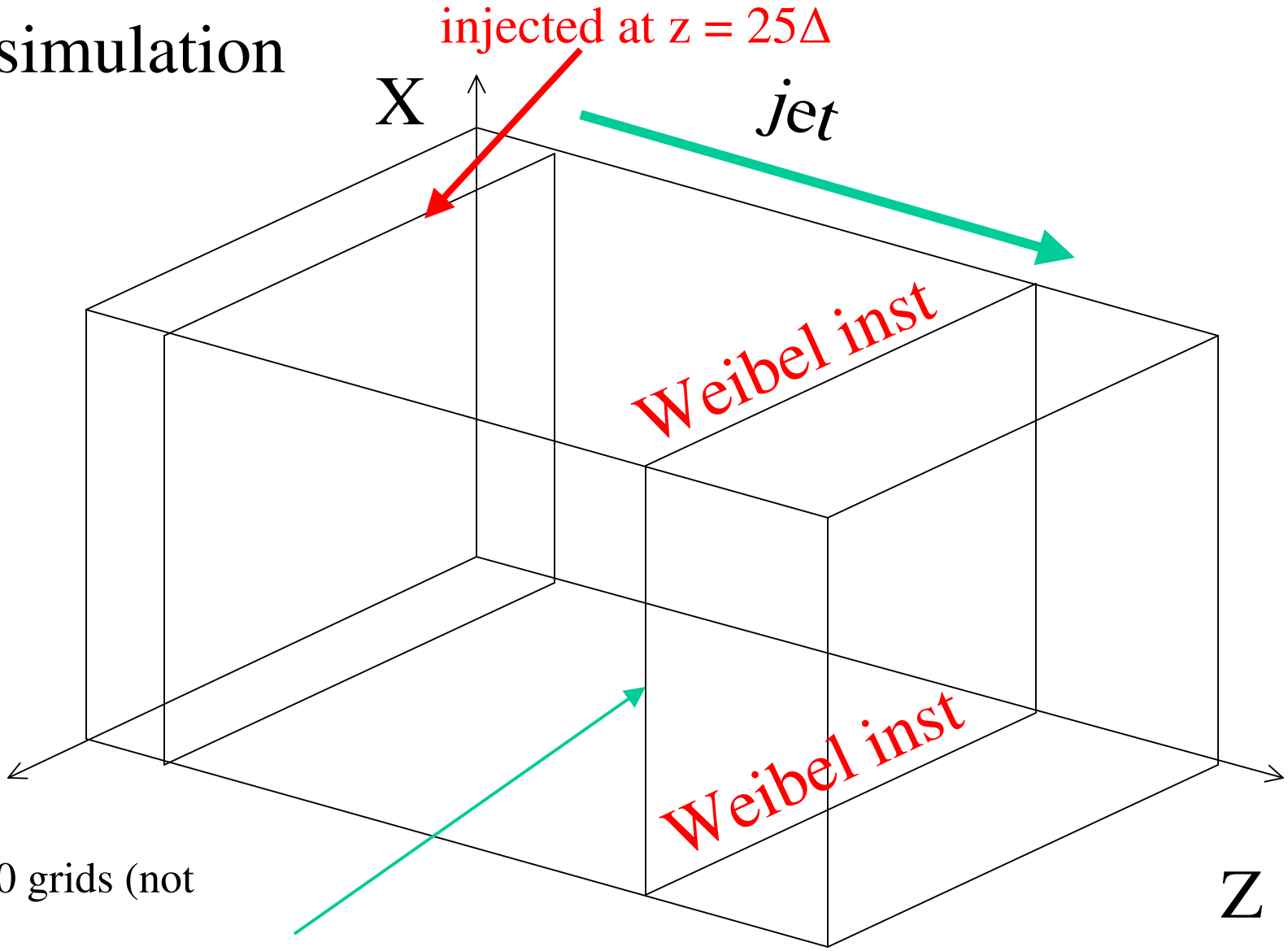
$$\partial E/\partial t = \nabla\times B - J$$

$$dm_0\gamma v/dt = q(E + v\times B)$$

$$\partial\rho/\partial t + \nabla\bullet J = 0$$



3-D simulation



85×85×640 grids (not scaled)

380 Million particles jet front

Weibel instability

current filamentation

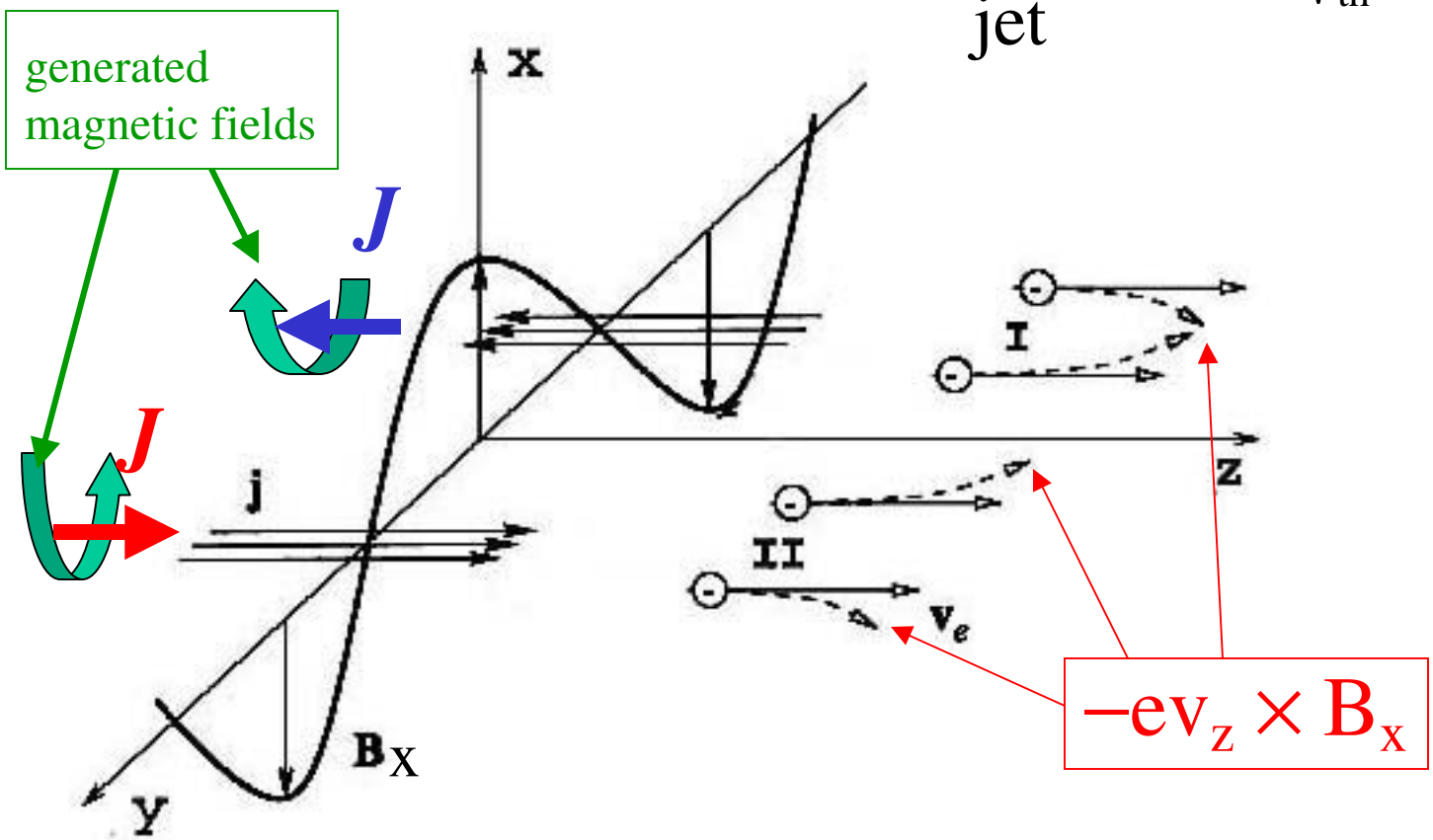
Time:

$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$

Length:

$\lambda = \gamma_{th}^{1/2} c/\omega_{pe} \approx 9.6\Delta$

jet

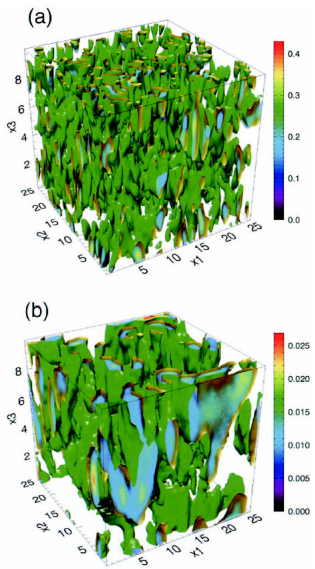


$-ev_z \times B_x$ (electrons)

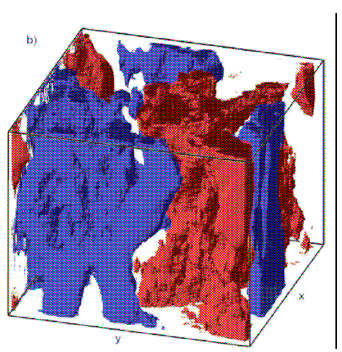
(Medvedev & Loeb, 1999, ApJ)

3-D Simulations of Weibel instability

Counter-steaming electron-positron shells

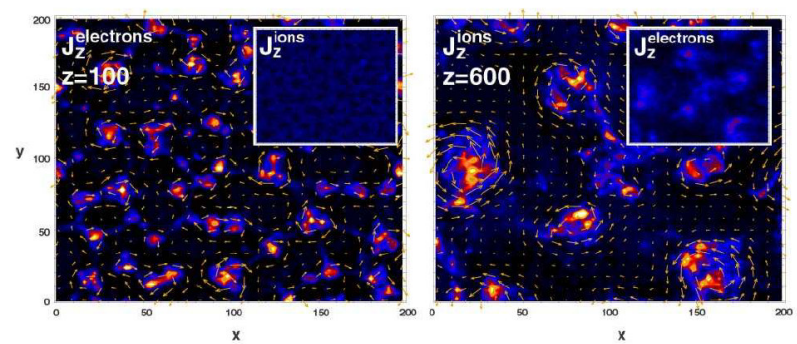


(Silva et al. 2003, ApJL)

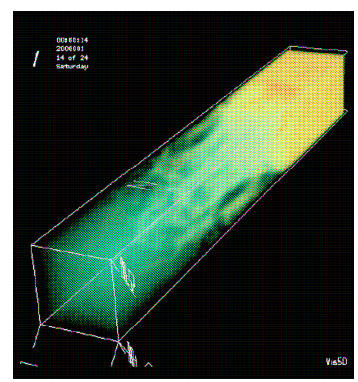


(Jaroschek, Lesch, & Treumann, ApJ, 2005)

Electron-ion plasma for a long time for nonlinear stage (Frederiksen at al. 2004, ApJL; Hededal et al. 2004, ApJL)



electrons ions



(Spitkovsky 2006)

Initial parallel velocity distributions of pair-created jets

- A: $\gamma = (1-(v_j/c)^2)^{-1/2} = 5$
- B: $\gamma = (1-(v_j/c)^2)^{-1/2} = 15$
- C: $4 < \gamma < 100$ (distributed cold jet)

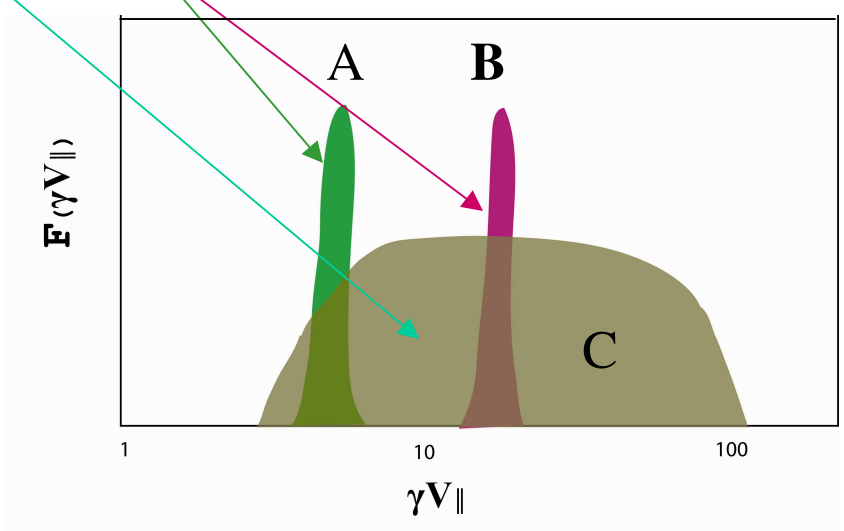
(pair jet created by photon annihilation, $\gamma+\gamma \rightarrow e^{\pm}$)

- A': $\gamma = 5$ (electron-ion)

Growth times of Weibel instability:

τ_A. $\tau_{A'}$.τ_B . τ_C

Schematic initial parallel velocity distribution of jets



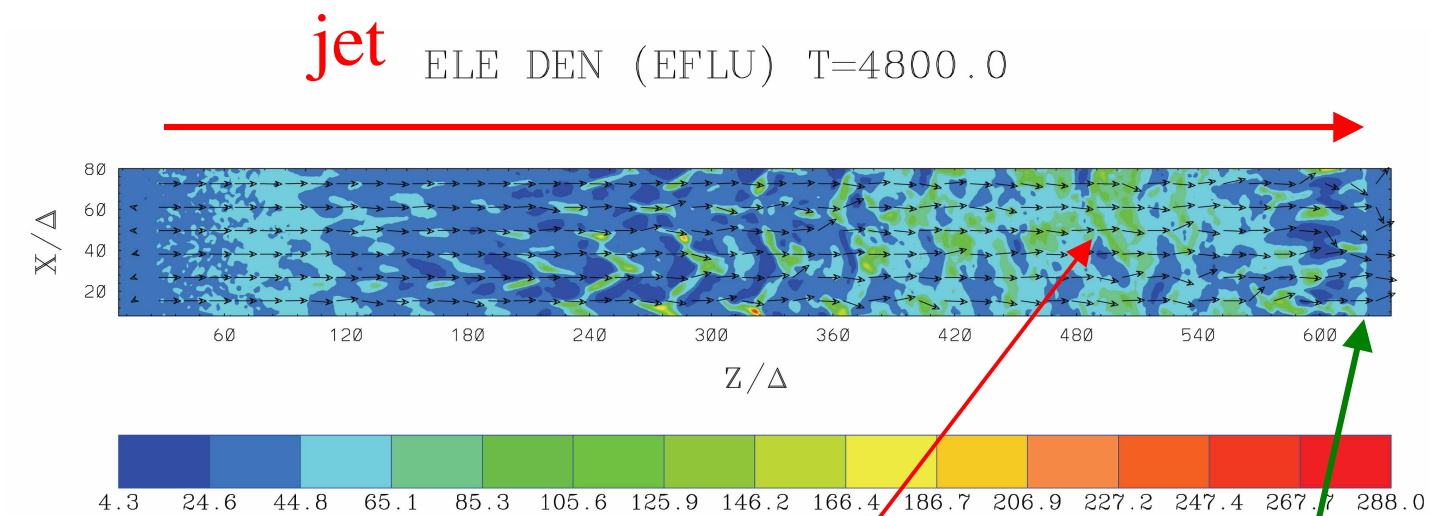
Electron density (arrows: B_z, B_x)

$n_{ISM} = 1/cm^3$
$\omega_{pe}^{-1} = 0.1$msec

$c/\omega_{pe} = 5.3*10^3$ km

electron-positron jet (γ= 15) (B)

$\omega_{pe}t = 62.4$



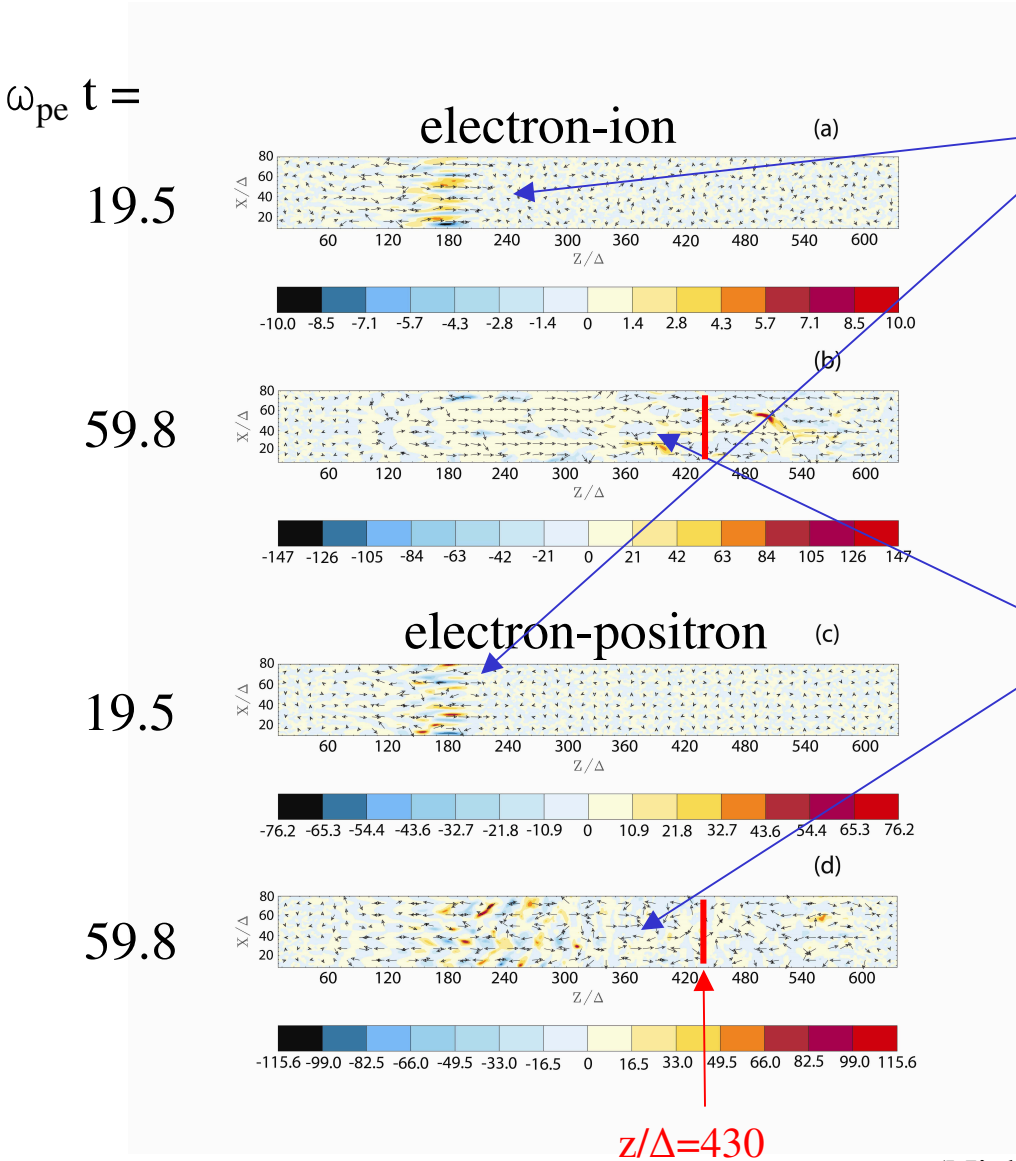
Weibel instability

jet front

(Nishikawa et al. 2005)

Jz at the linear and nonlinear stages

color: electron density



linear stage

elongated current channels are generated

nonlinear stage

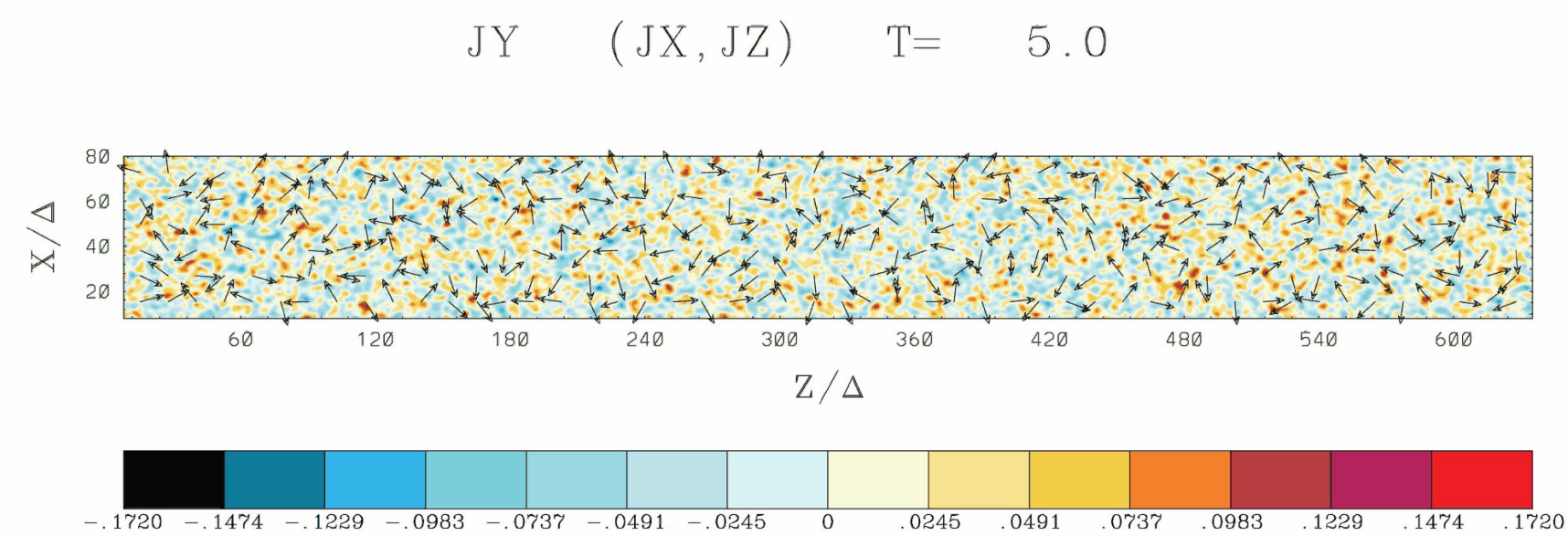
current channels are shorter and bent

arrows: electron flux

(Nishikawa et al 2005)

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

electron-positron γ= 15 (B) $\omega_{pe}t = 59.8$ at Y = 43Δ



Weibel instability

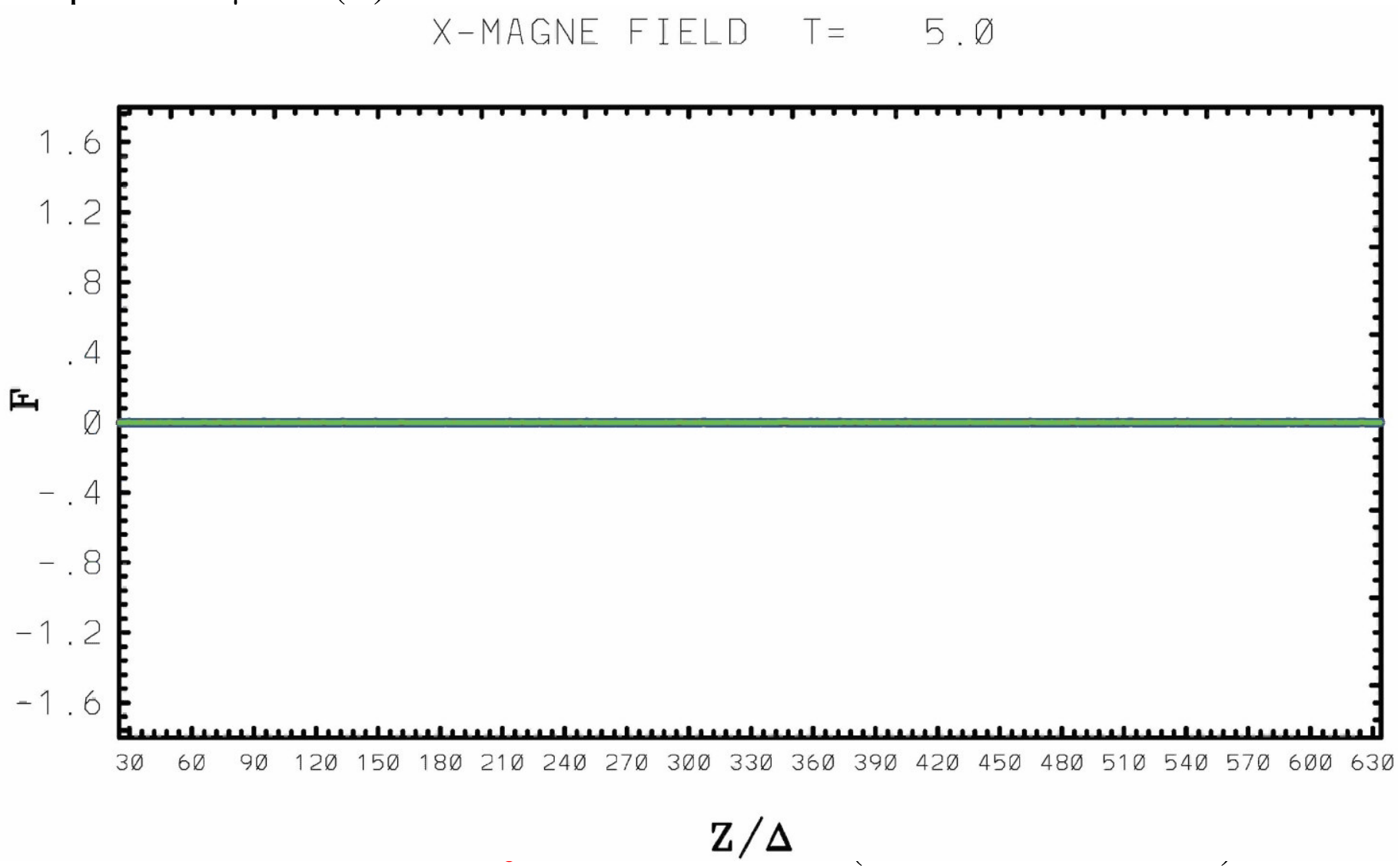
jet front

(Nishikawa et al. 2005)

Evolution of B_x due to the Weibel instability

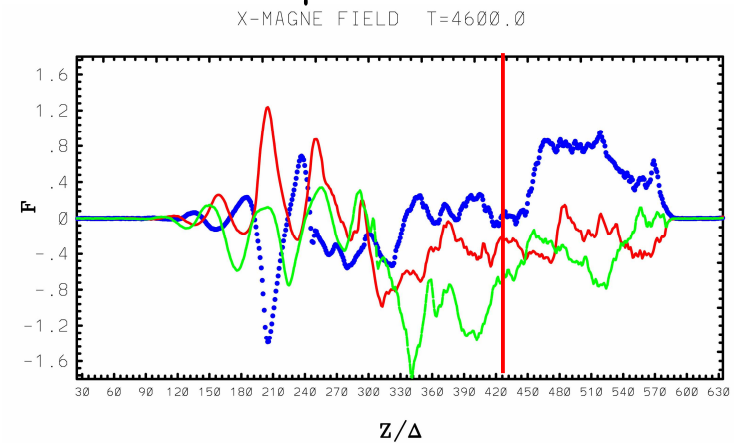
el-positron γ= 15 (B)

(convective instability)

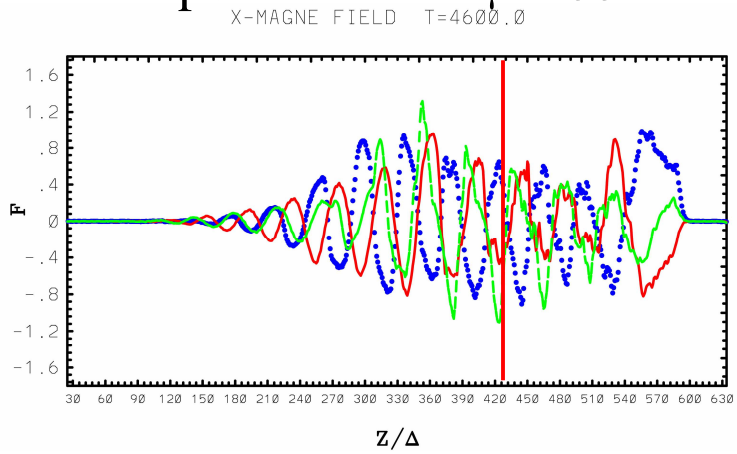


B_x component generated by current channels at $t = 59.8\,\omega_{pe}$

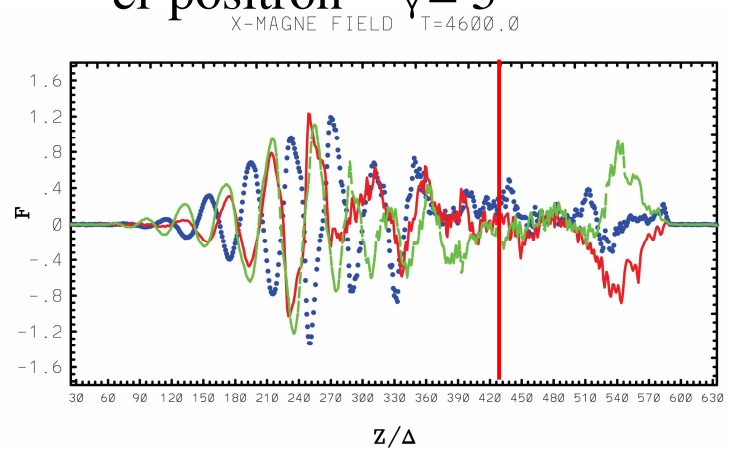
el-ion $\gamma = 5$



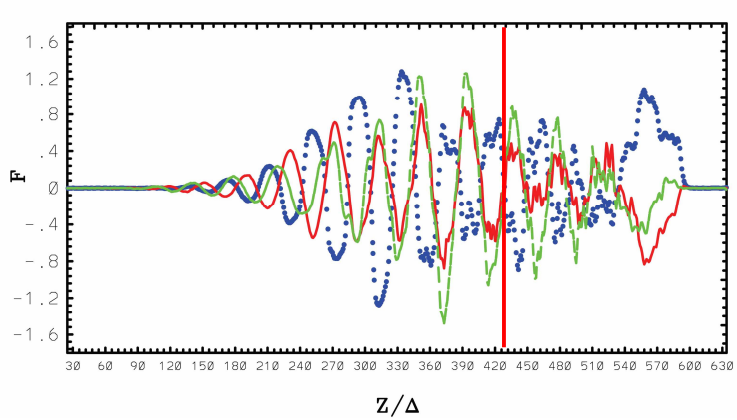
el-positron $4 < \gamma < 100$



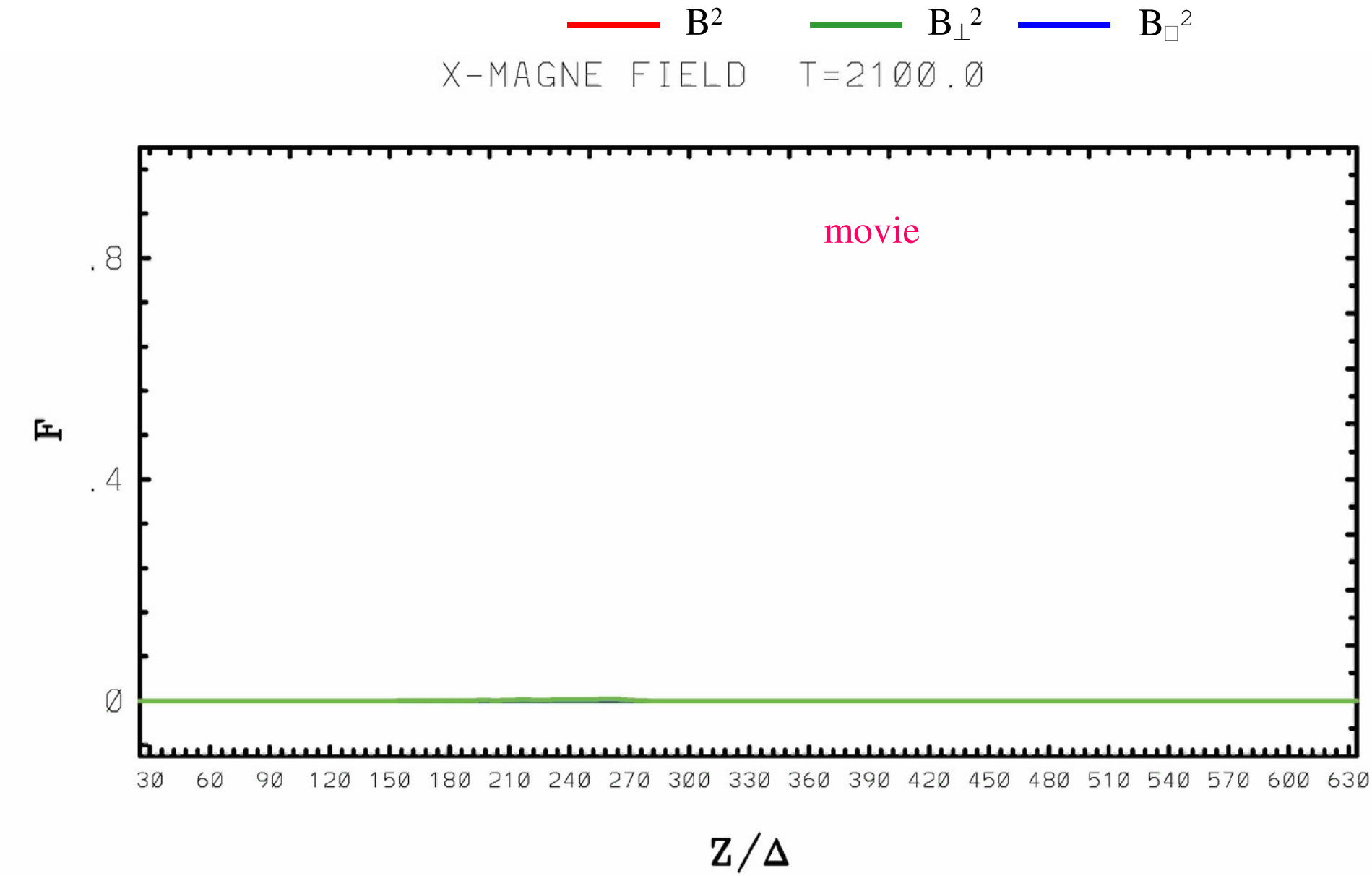
el-positron $\gamma = 5$



el-positron $\gamma = 15$

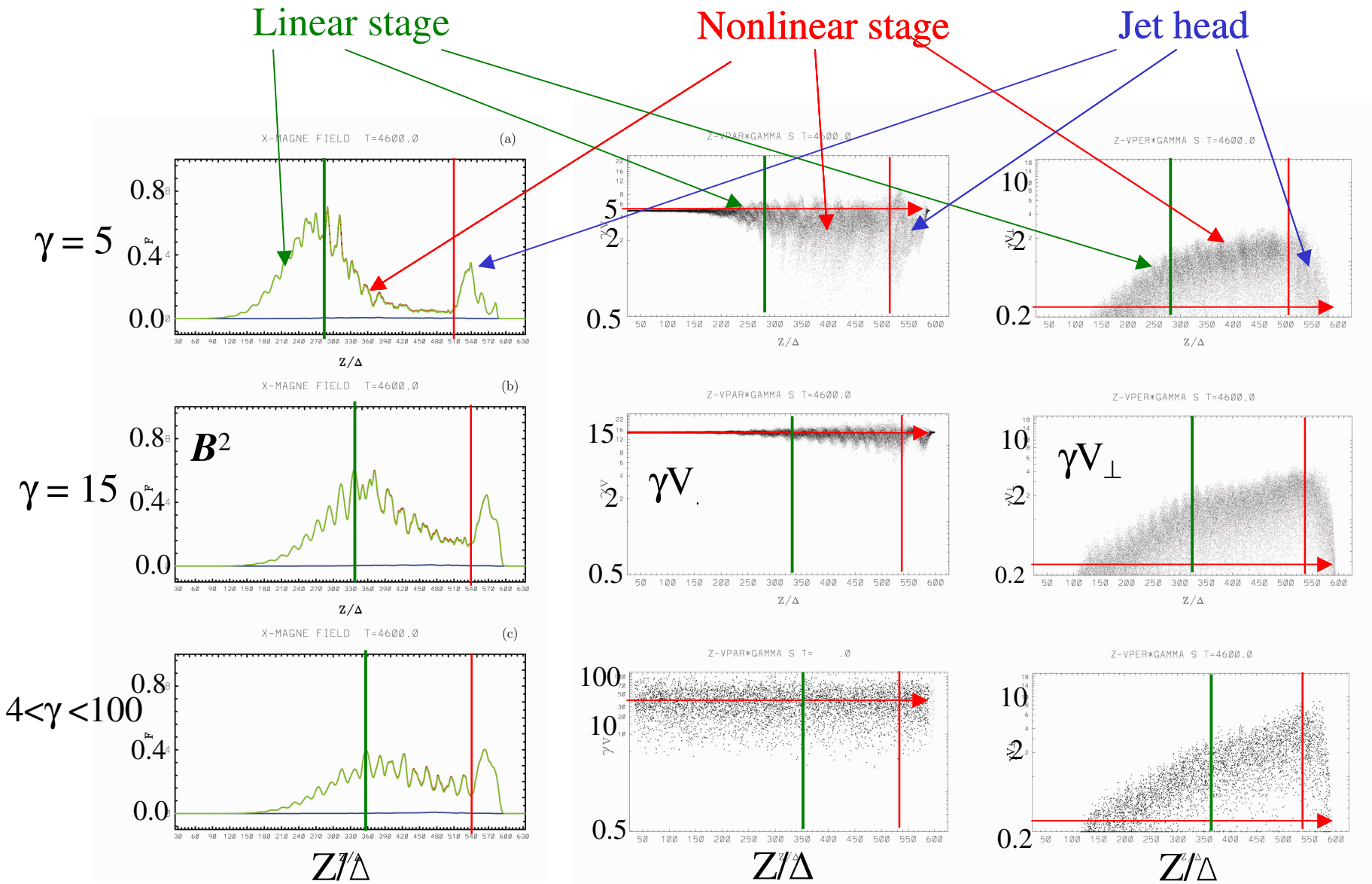


Total magnetic field energy ($B_x^2 + B_y^2 + B_z^2$) averaged in the x-y plane



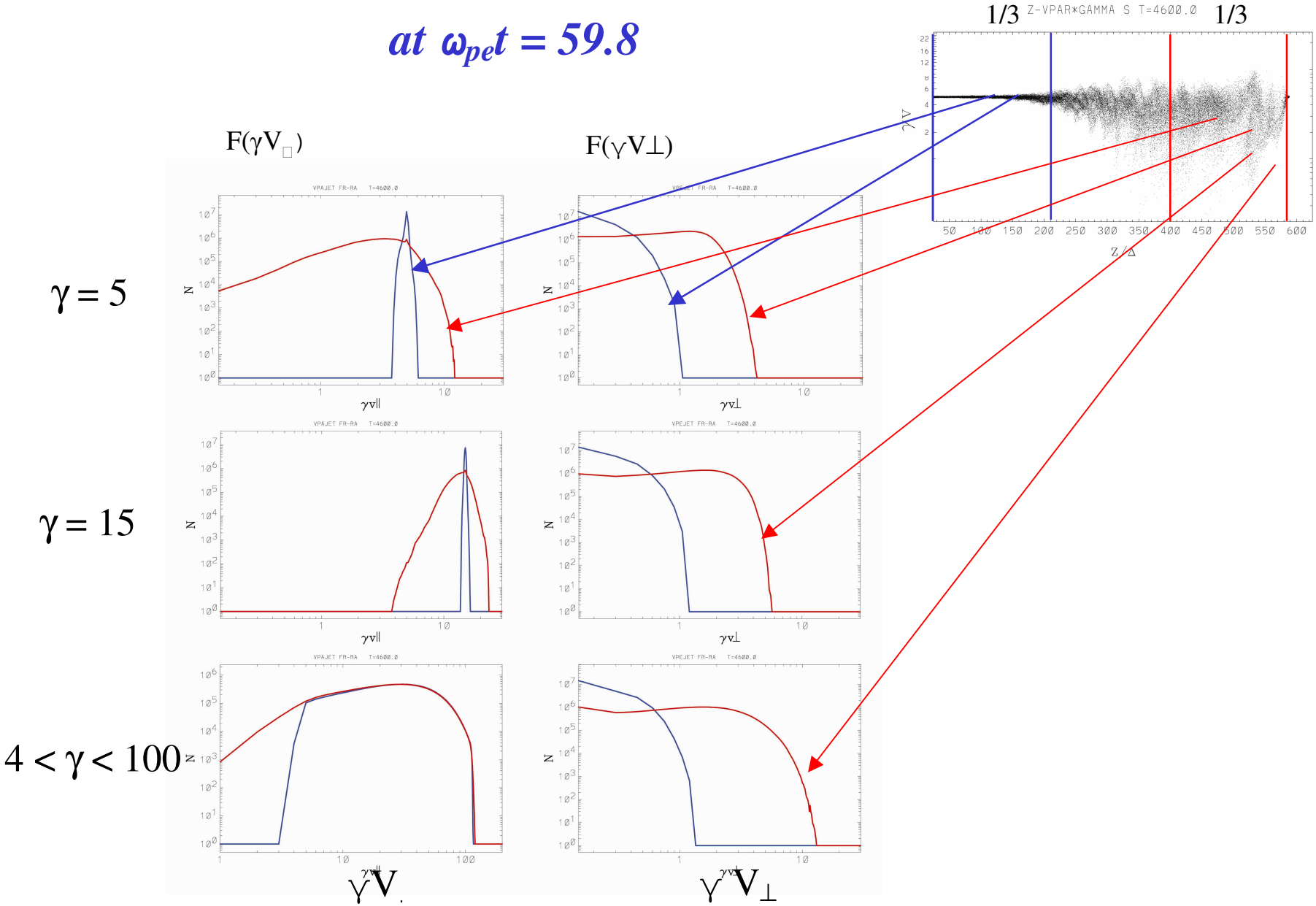
Magnetic field energy and parallel and perpendicular velocity space along Z

$\omega_{pe}t = 59.8$



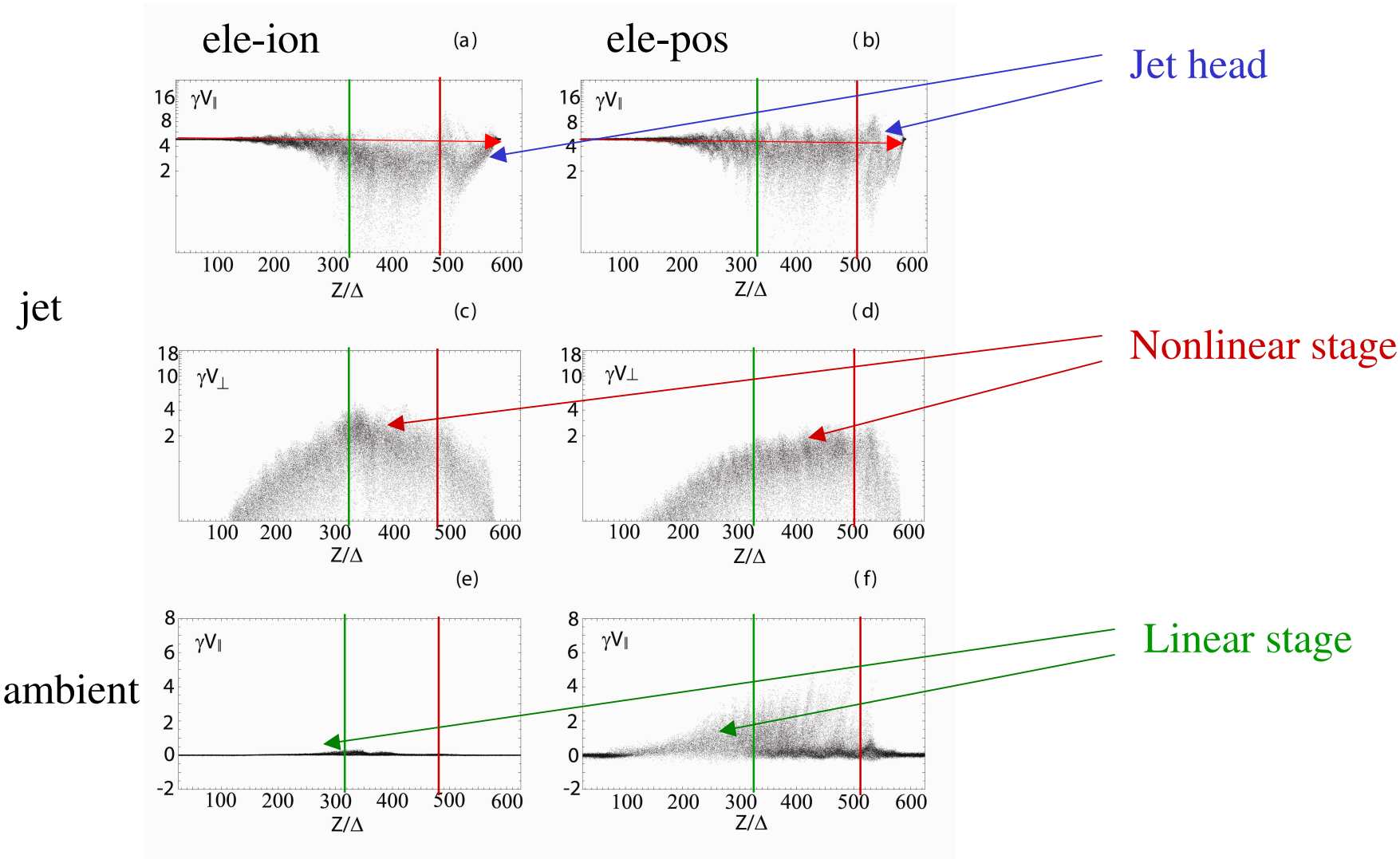
Parallel and perpendicular velocity distributions

at $\omega_{pe}t = 59.8$



Phase space distributions of electrons

$\omega_{pe}\, t = 59.8$



Parallel and perpendicular velocity space of ambient electrons along Z

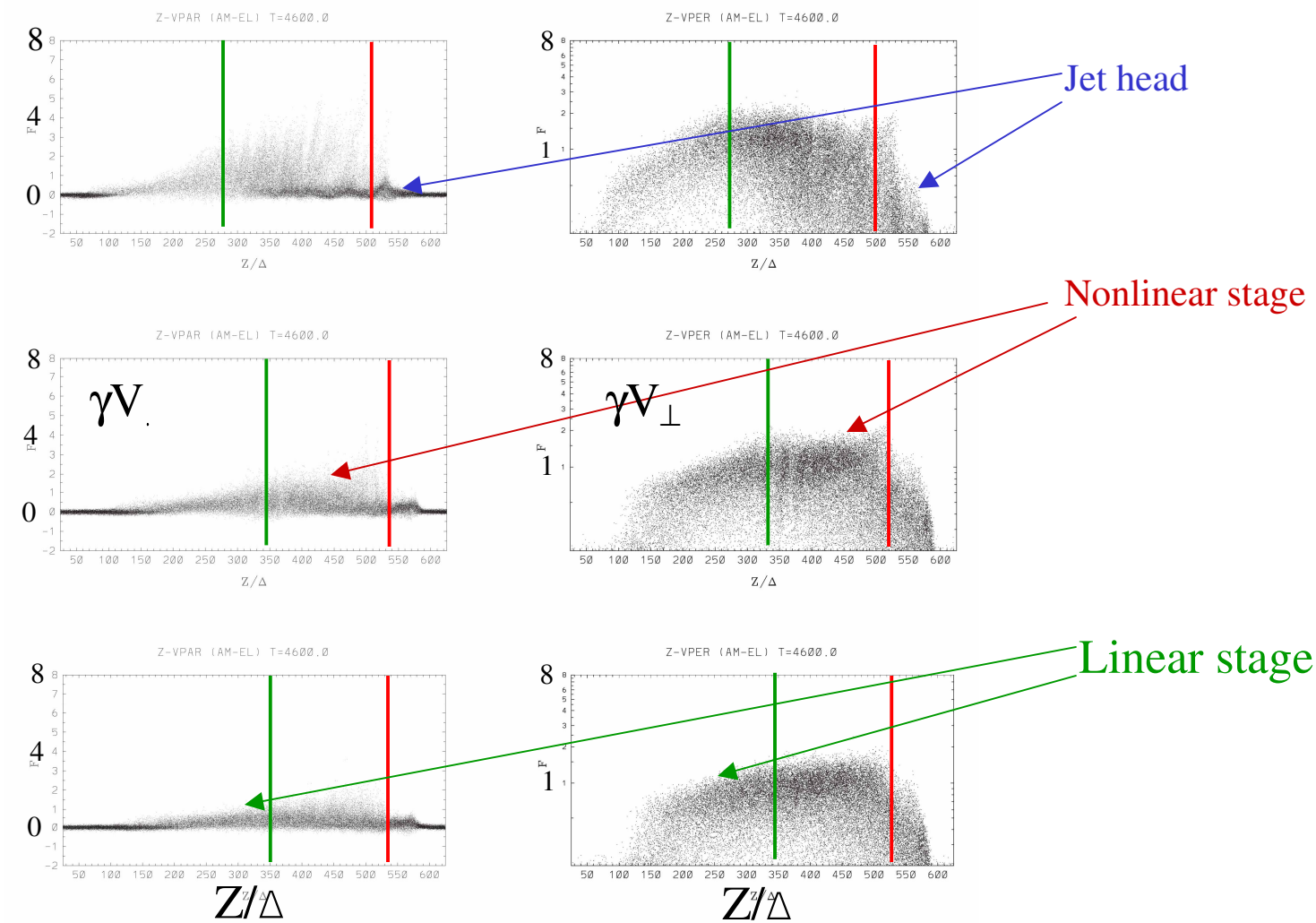
$\omega_{pe}t = 59.8$

parallel | perpendicular

$\gamma = 5$

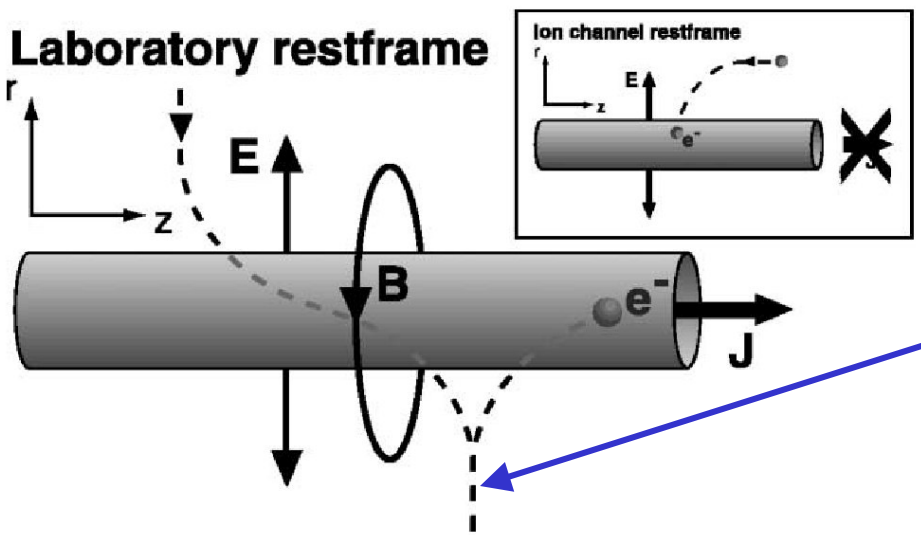
$\gamma = 15$

$4 < \gamma < 100$



Ion Weibel instability

ion current



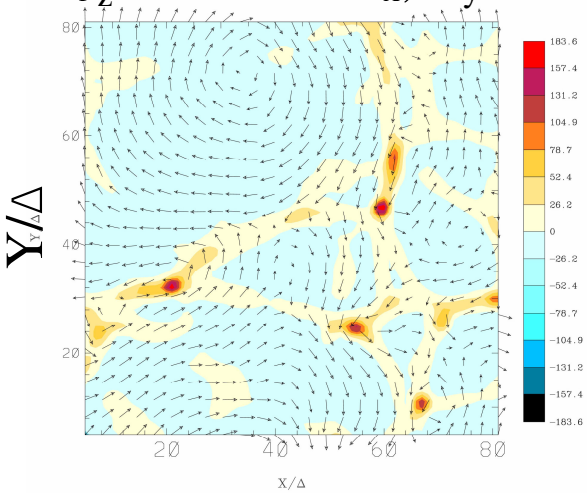
Radial E acceleration

electron trajectory

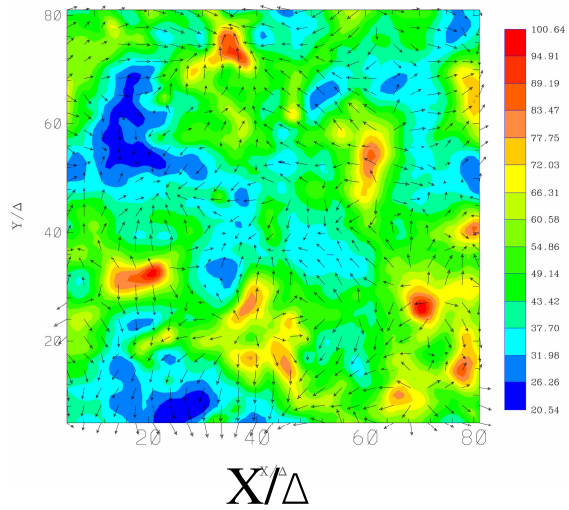
(Hededal et al 2004)

electron-ion jet $\gamma = 5$ $t = 59.8\omega_{pe}$ $(Z/\Delta = 430)$

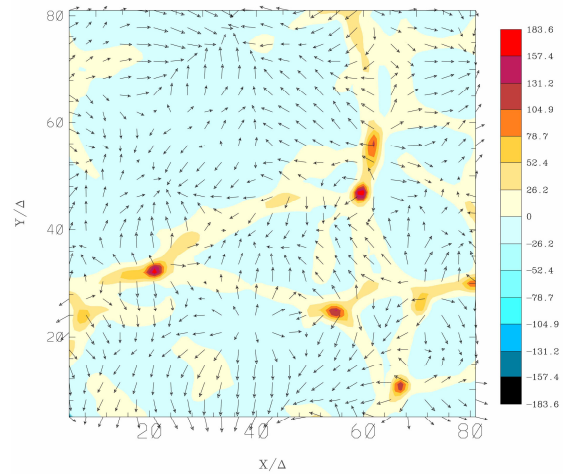
J_z arrows: B_x, B_y



n_e arrows: E_x, E_y

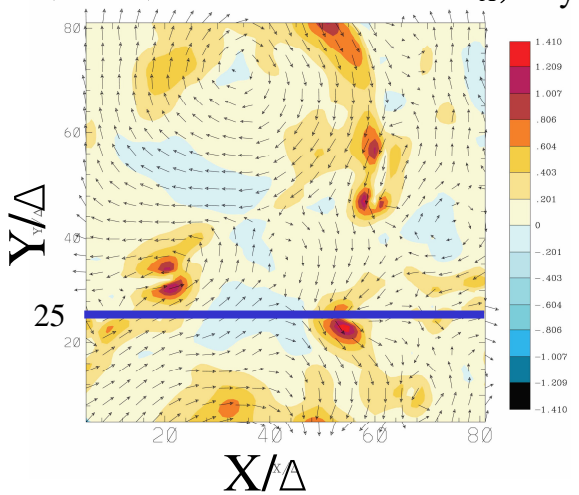


J_z arrows: E_x, E_y

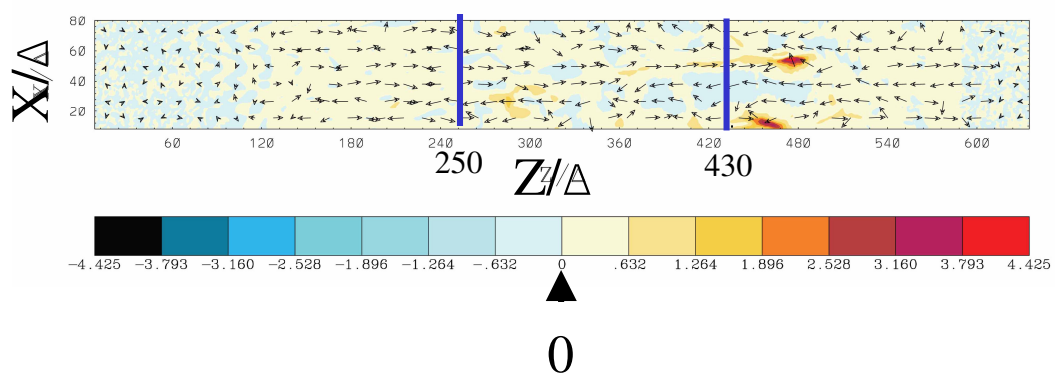


jet □

$(E\times B)_z$ arrows: B_x, B_y



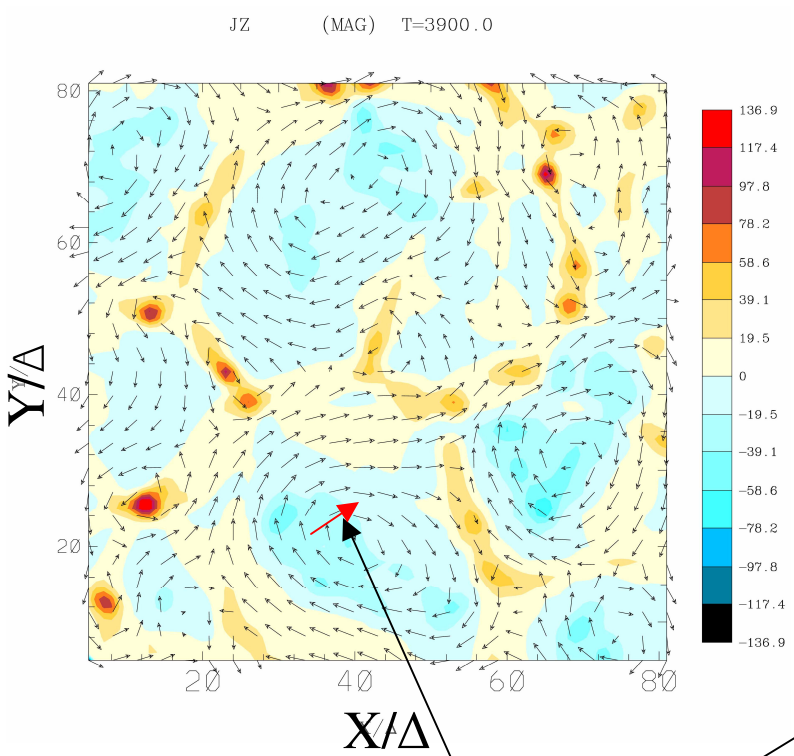
$(E\times B)_z$ arrows: J_x, J_z $(Y/\Delta = 25)$



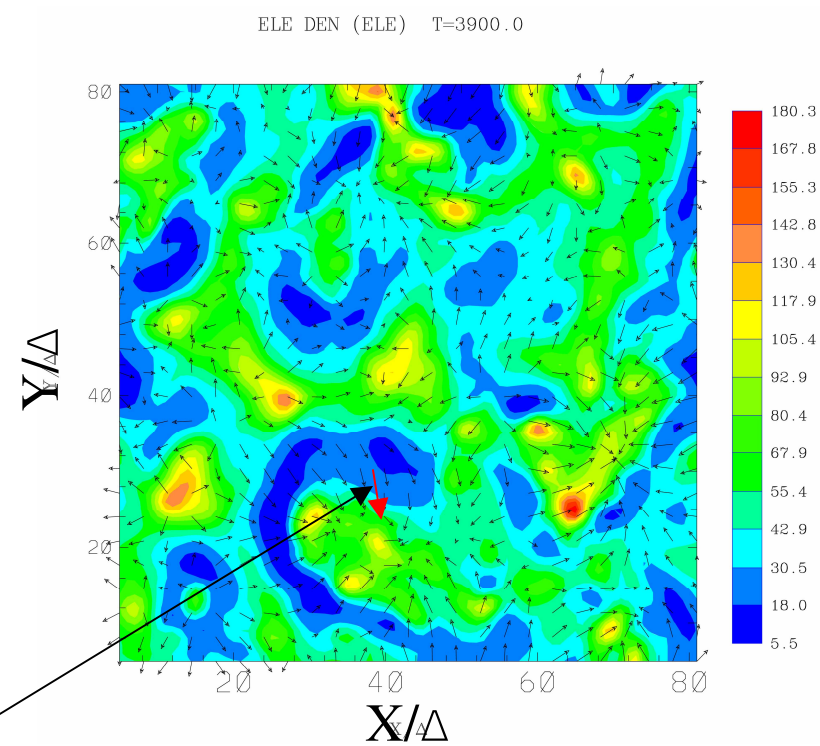
E×B acceleration due to the current channel (Z/Δ= 430)

$t = 50.7\omega_{pe}$ ***electron-ion jet*** $\gamma = 5$

J_z arrows: B_x, B_y



n_e arrows: E_x, E_y

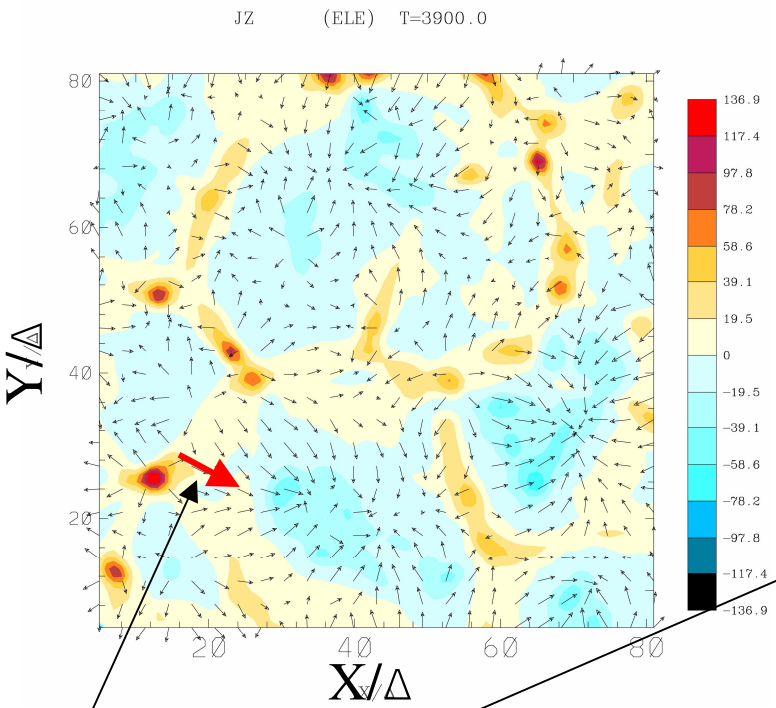


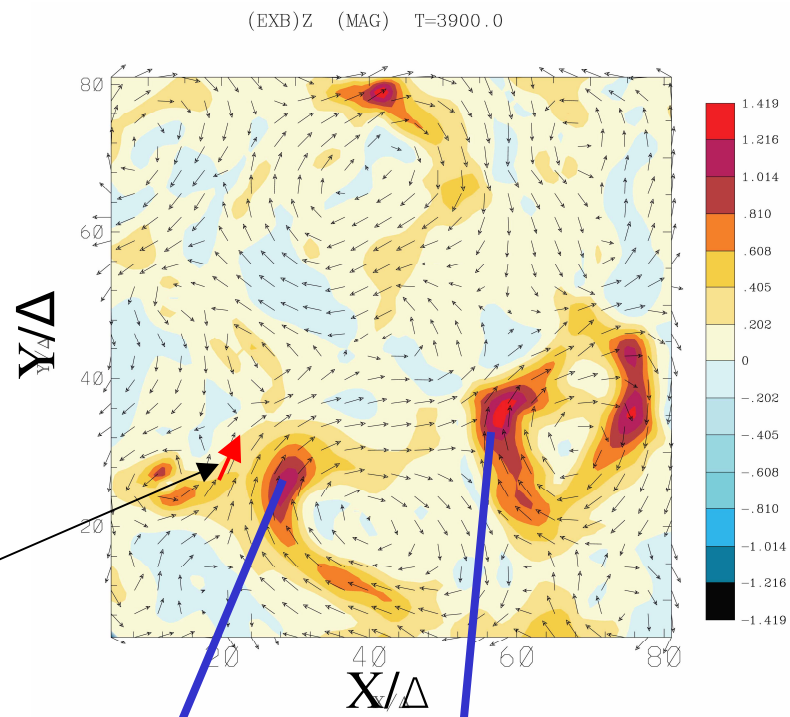
B and ***E*** are nearly perpendicular

E×B acceleration and deceleration (Z/Δ= 430)

$t = 50.7\omega_{pe}$ ***electron-ion jet*** $\gamma = 5$

J_z arrows: E_x, E_y $(E\times B)_z$ arrows: B_x, B_y





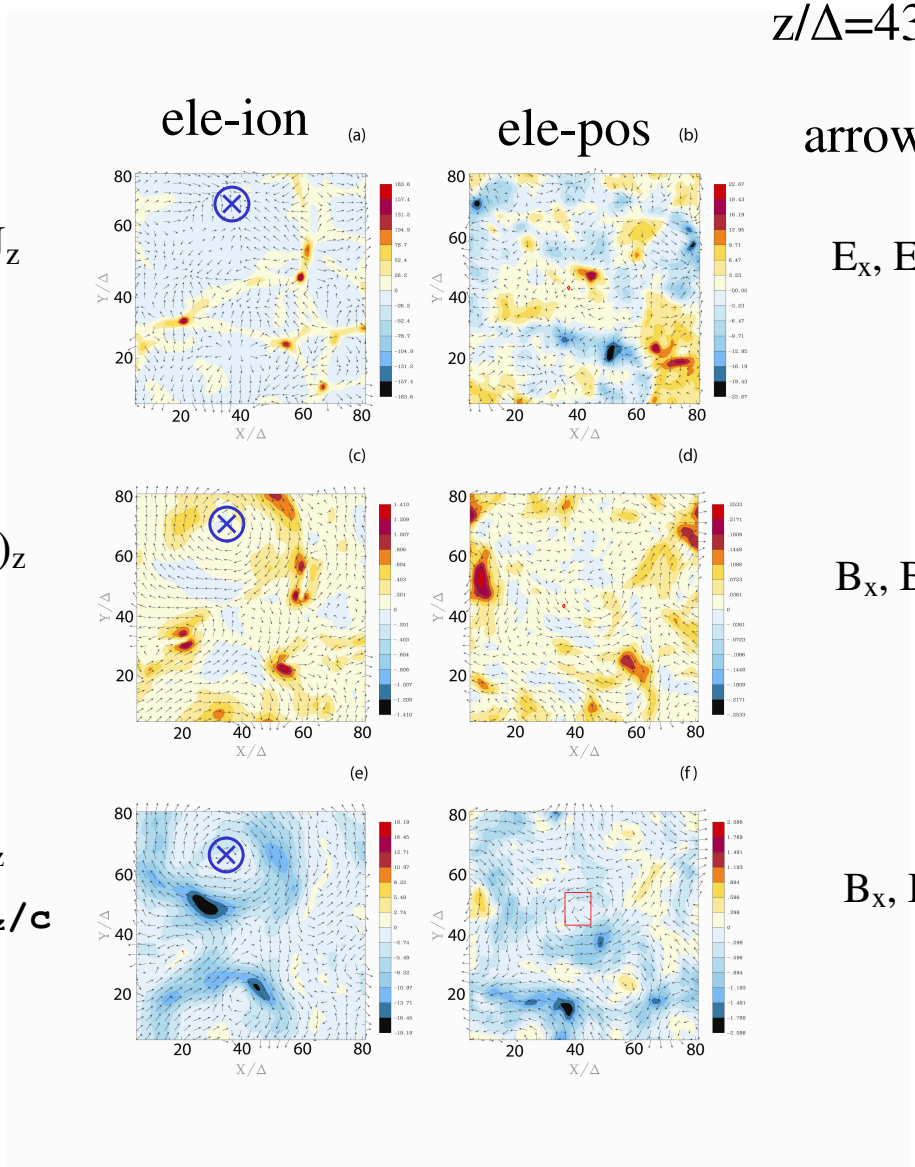
E and ***B*** are nearly perpendicular

both electrons (and positrons) are accelerated in this region

J_z and $(E\times B)_z$ in the nonlinear stage in the x-y plane

z/Δ=430

ω_{pe} t = 59.8



$\beta_z = v_z/c$

$= 0.8$

$\gamma = 5$

⊗ ion current channel

. electron current channel

Radial electric field *E* accelerate or decelerate particles along *z* direction depending on the sign of $(E \times B)_z$

$(E\times B)_z$ in the moving frames in the x-y plane

$\omega_{pe}\, t = 59.8 \quad \gamma = 5$

$\beta = v_z/c$

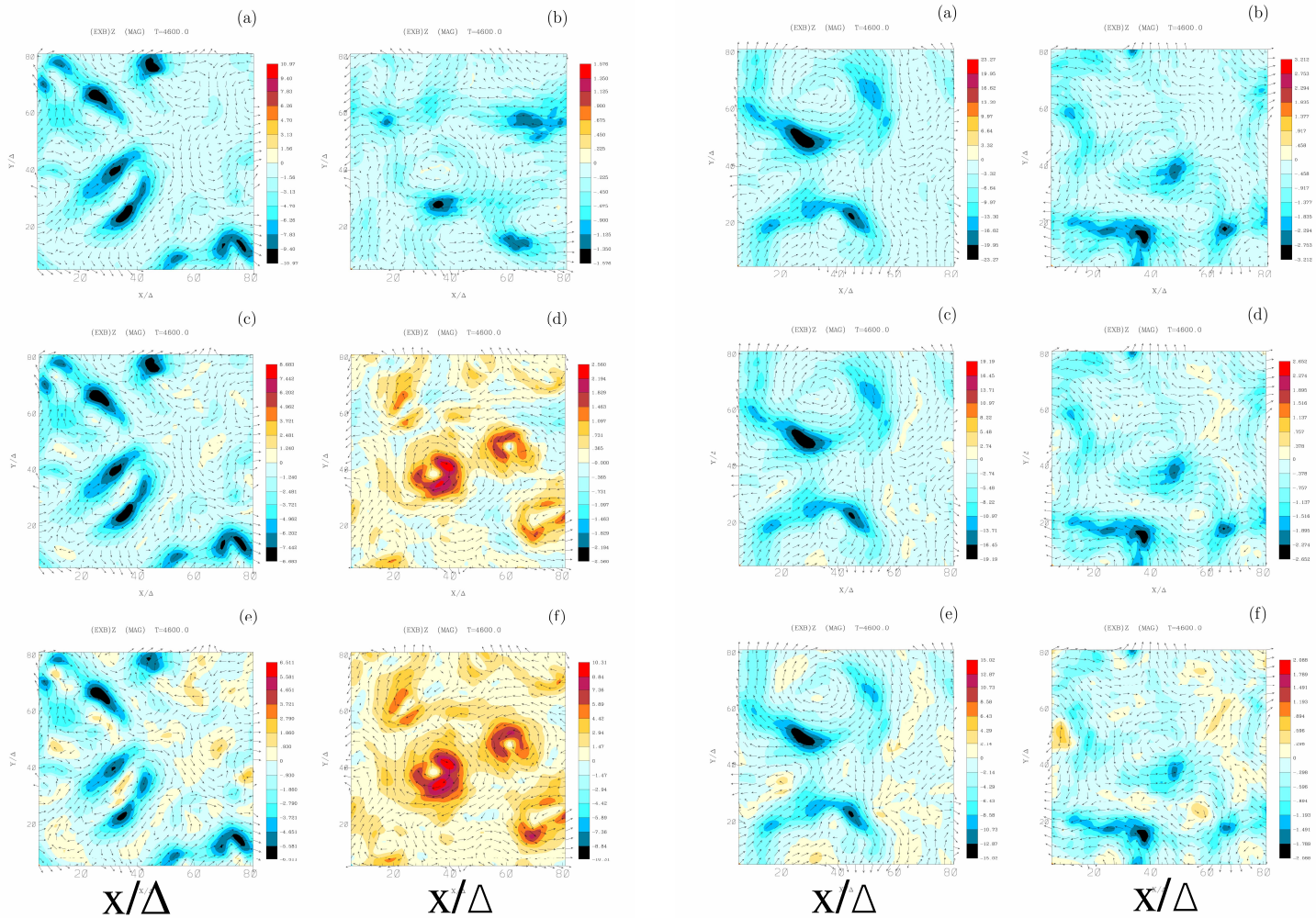
z/Δ=250 | z/Δ=430

ele-ion | ele-pos | ele-ion | ele-pos

= 0.98

= 0.8

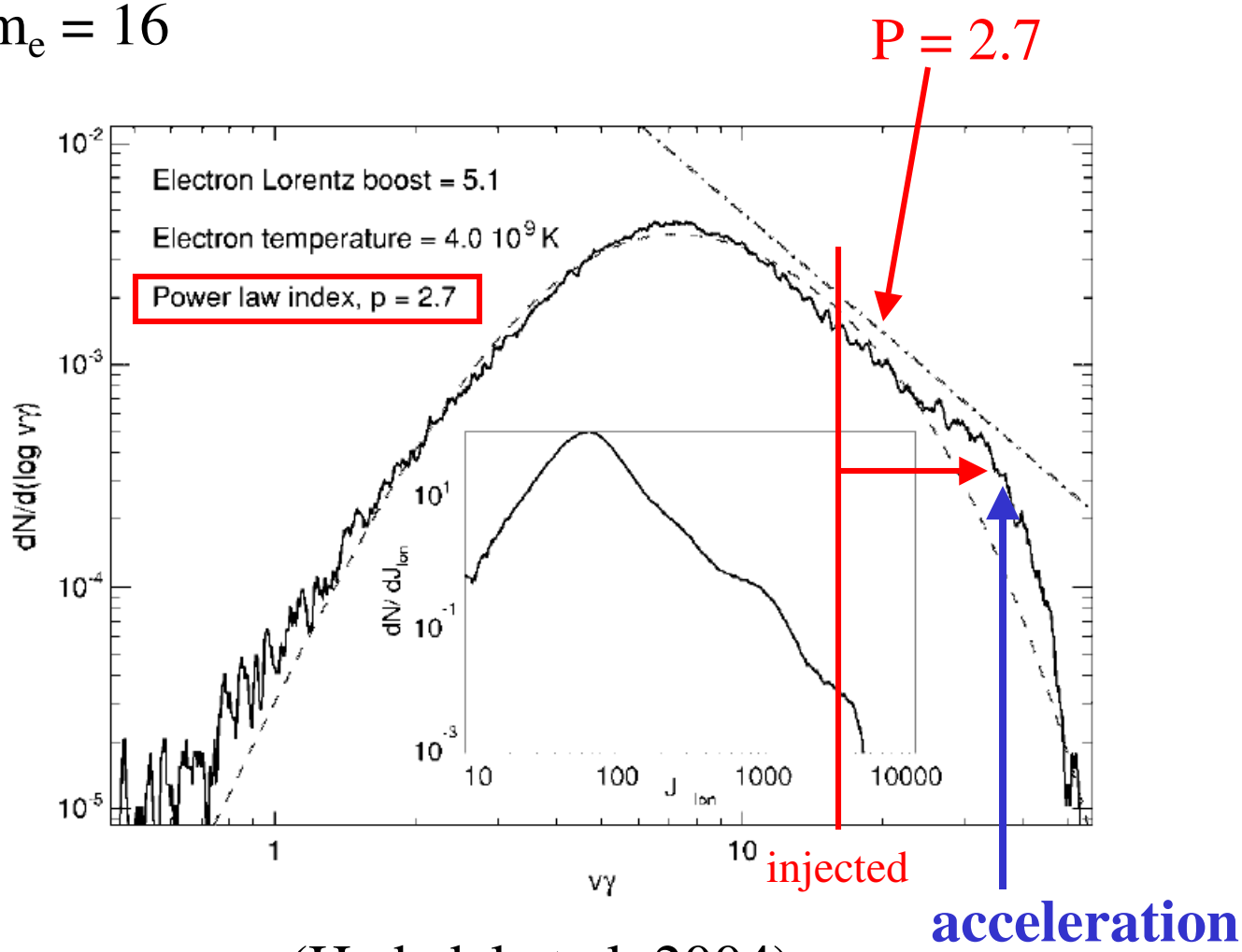
= 0.6



x/Δ | x/Δ | x/Δ | x/Δ

Electron acceleration by ion Weibel instability

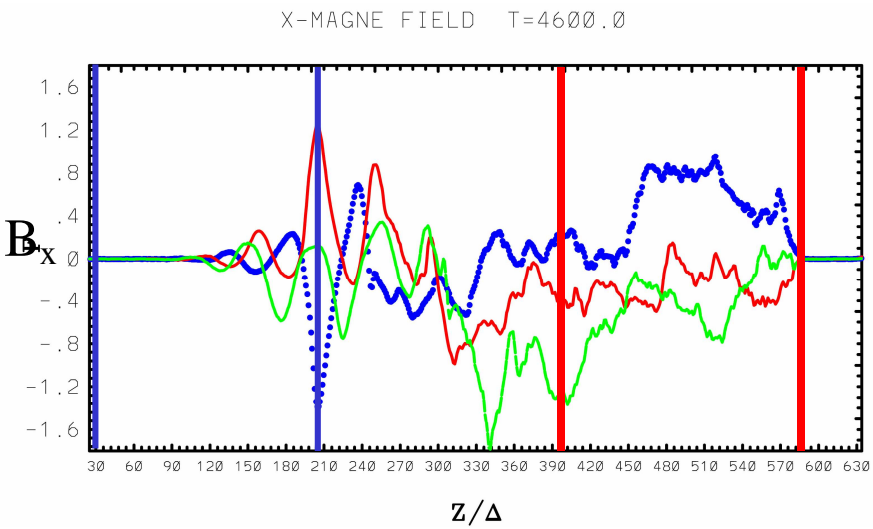
Γ=15, m_i/m_e = 16



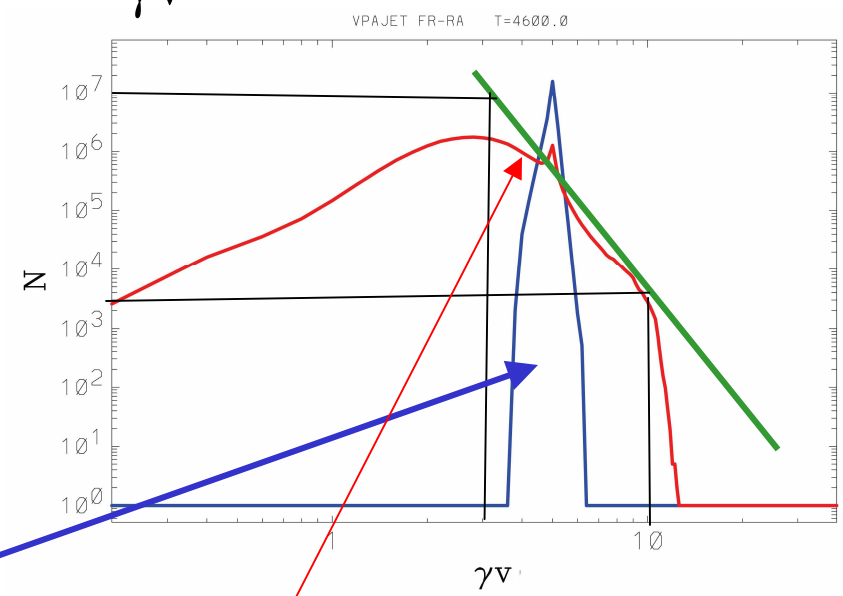
(Hededal et al. 2004)

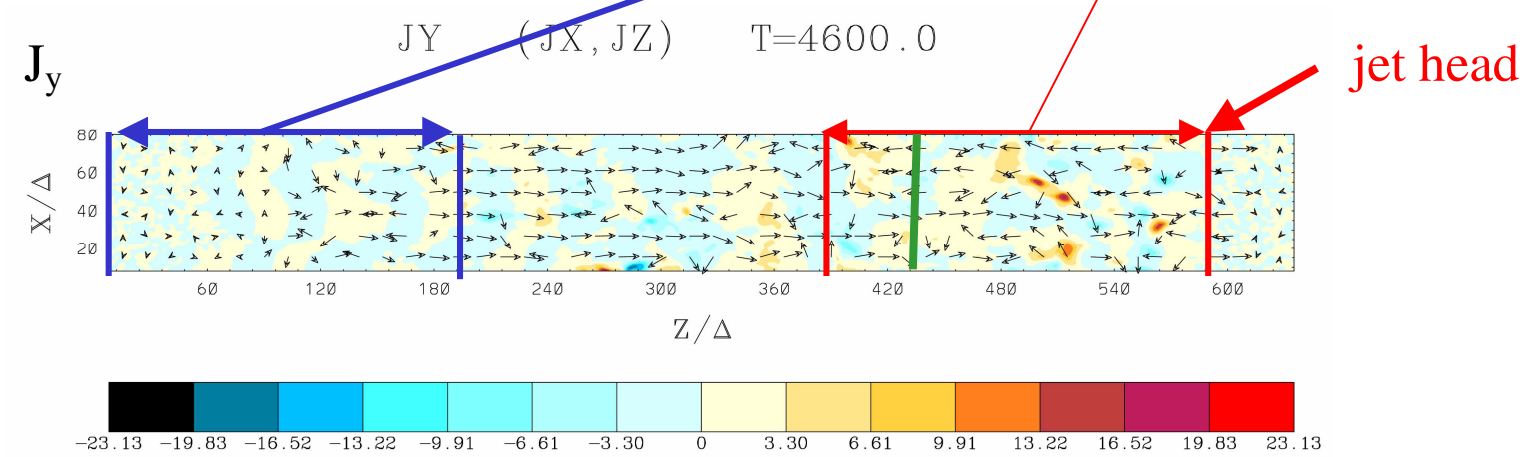
Longer simulation of electron-ion jet injected into unmagnetized plasma

$t = 59.8\omega_{pe}$



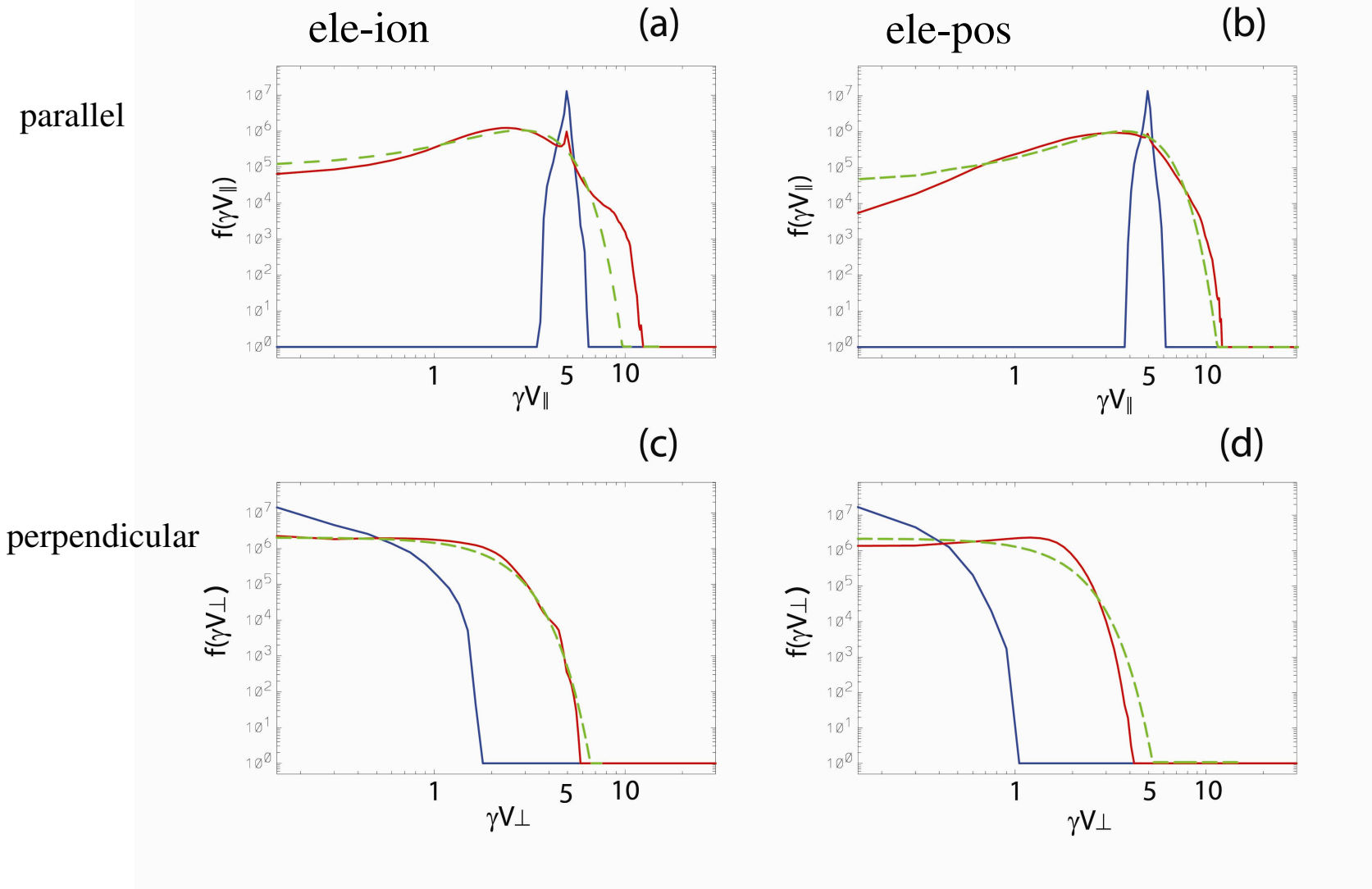
γv





Electron jet velocity distributions

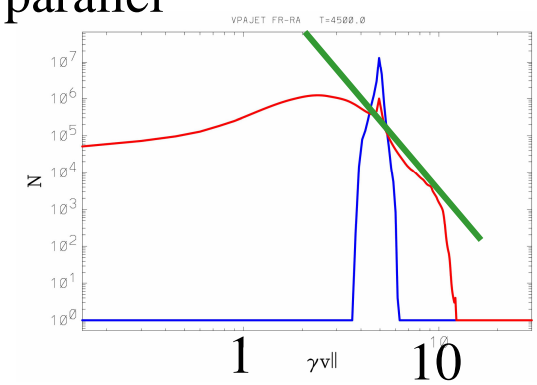
$\omega_{pe}\, t = 59.8$

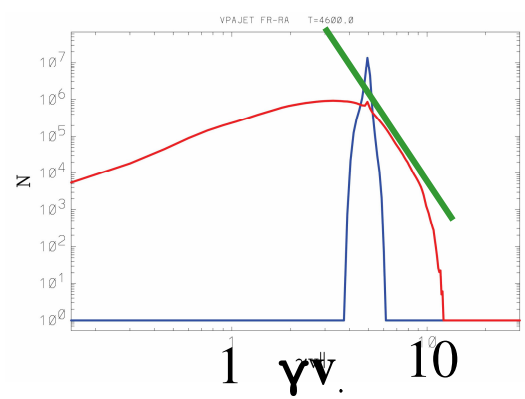


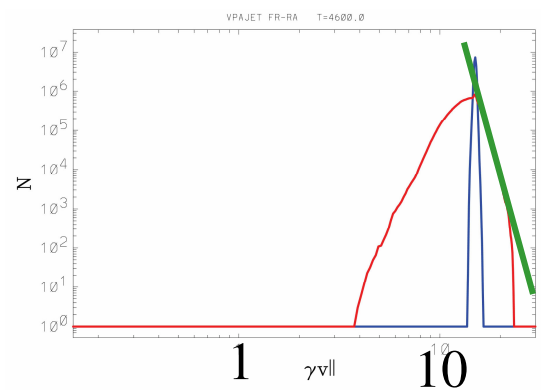
Electron acceleration at $t = 59.8\,\omega_{pe}$

el-ion $\gamma = 5$ | el-positron $\gamma = 5$ | el-positron $\gamma = 15$

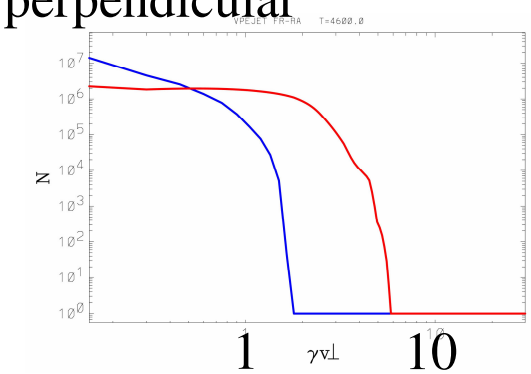
parallel

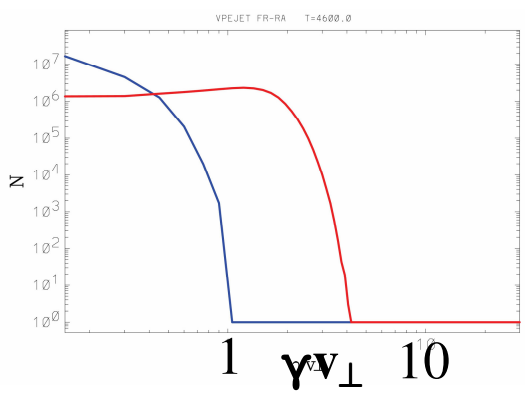


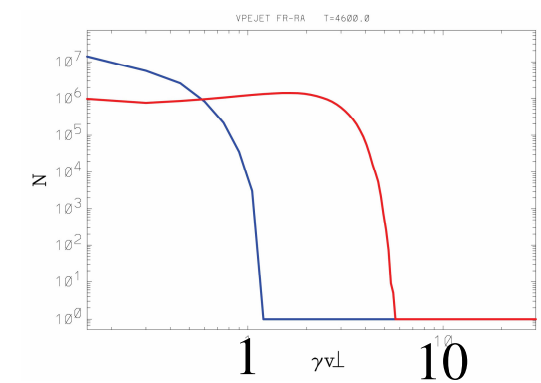




perpendicular







Calculation of synchrotron emission for afterglow (prompt emission)

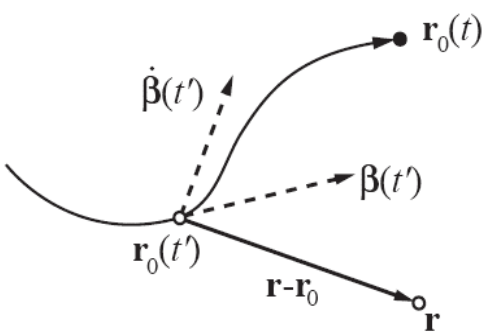
- Spectra from electron velocity distributions with assumed magnetic field strength with equipartitions
  - ► Distributions are obtained by the Monte Carlo simulations (theory)
  - ► assumed for $\varepsilon_e = 0.1$, $\varepsilon_B = 0.01$, $\xi=0.1$ (Fermi acceleration) $N(E_e)dE_e \propto E_e^{-p}dE_e$, $p \approx$ or < 2.2
- Calculate radiation from particle trajectories in the self-consistent inhomogeneous magnetic fields generated by the Weibel instability→ jitter radiation

Radiation from 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, $\boldsymbol{\beta}$ the velocity and $\dot{\boldsymbol{\beta}}$ the acceleration



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

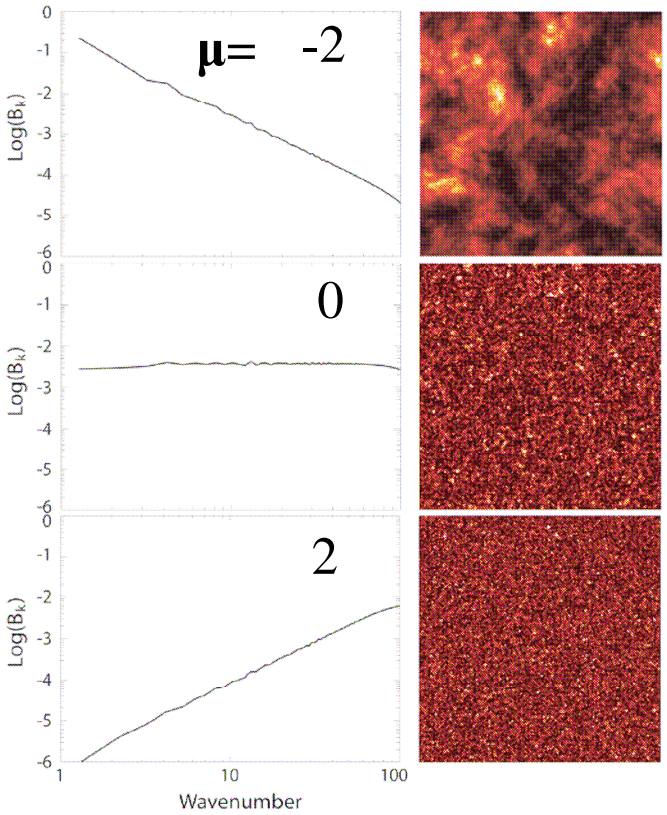
Hededal, Thesis 2005 (astro-ph/0506559)

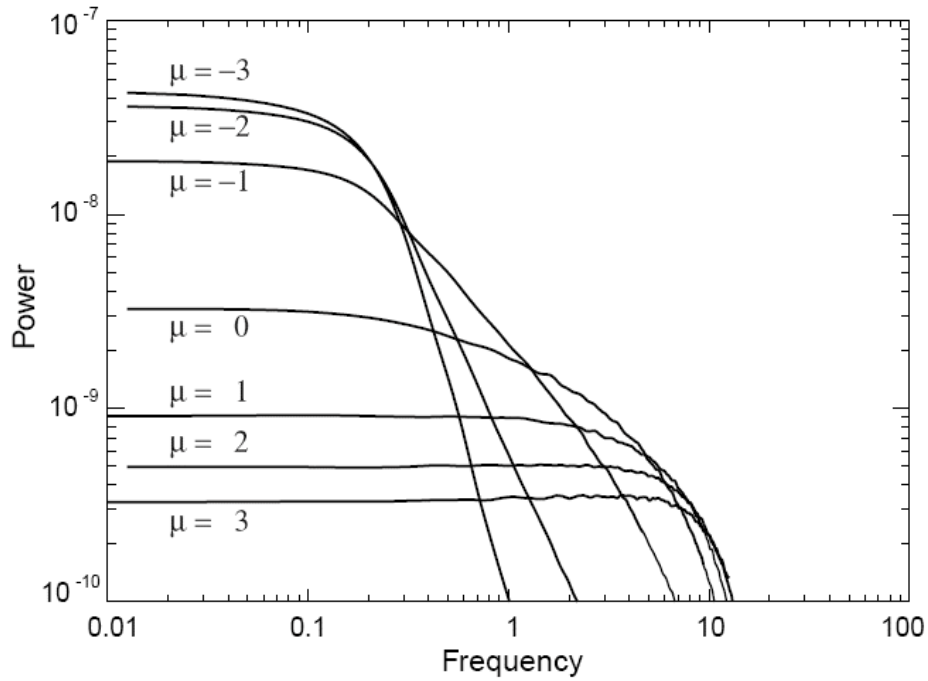
3D jitter radiation (diffusive synchrotron radiation) with a ensemble of mono-energetic electrons (γ= 3) in turbulent magnetic fields (Medvedev 2000; 2005, Fleishman 2005)

$P_B(k) \propto k^{\mu}$

2d slice of magnetic filed

3D jitter radiation with γ = 3 electrons

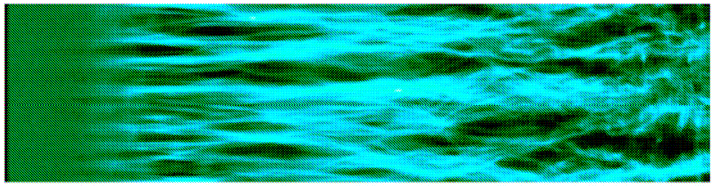


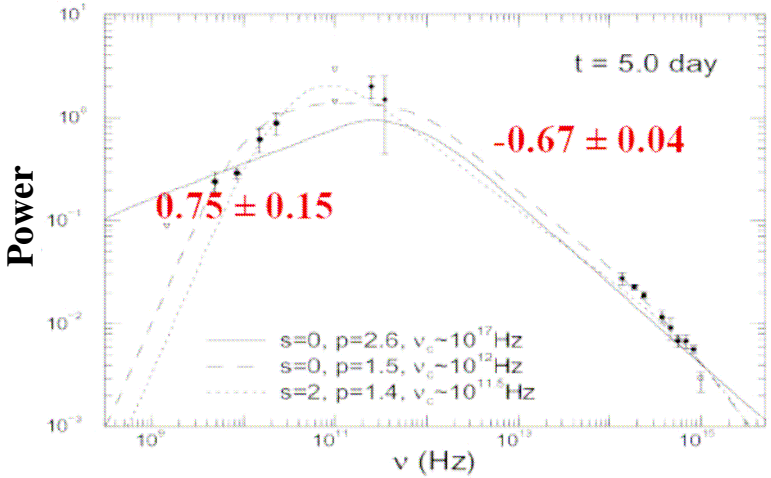


Hededal & Nordlund (astro-ph/0511662)

Radiation from collisionless shock

Spectrum obtained directly

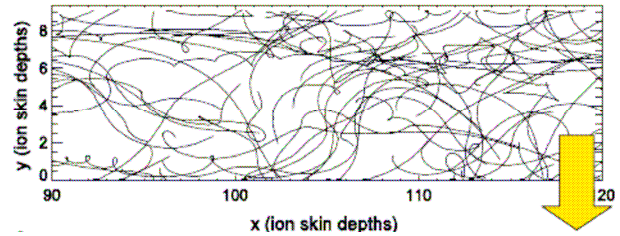




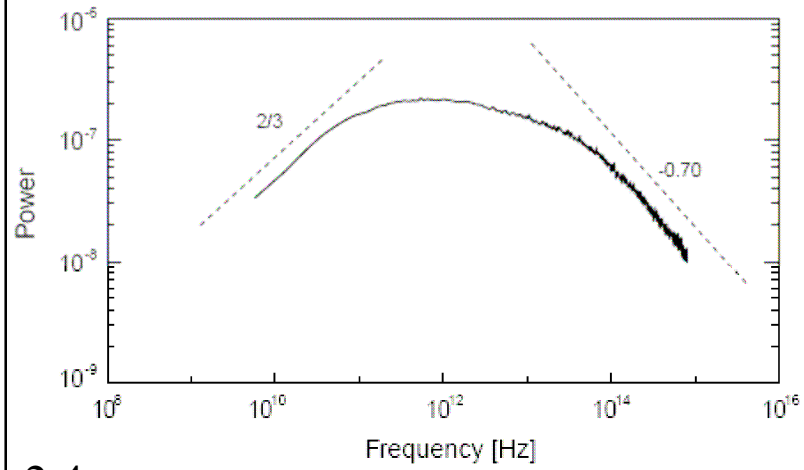
$N(\gamma) \propto \gamma^{-p}$ $\quad -\beta = -(p-1)/2 = -0.70 \rightarrow p = 2.4$

GRB 000301c (Panaitescu 2001)

from shock simulations (20,000 particles)



☺ observer



Shock simulations

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

Hededal & Nordlund 2005 (astro-ph/0511662)

Summary

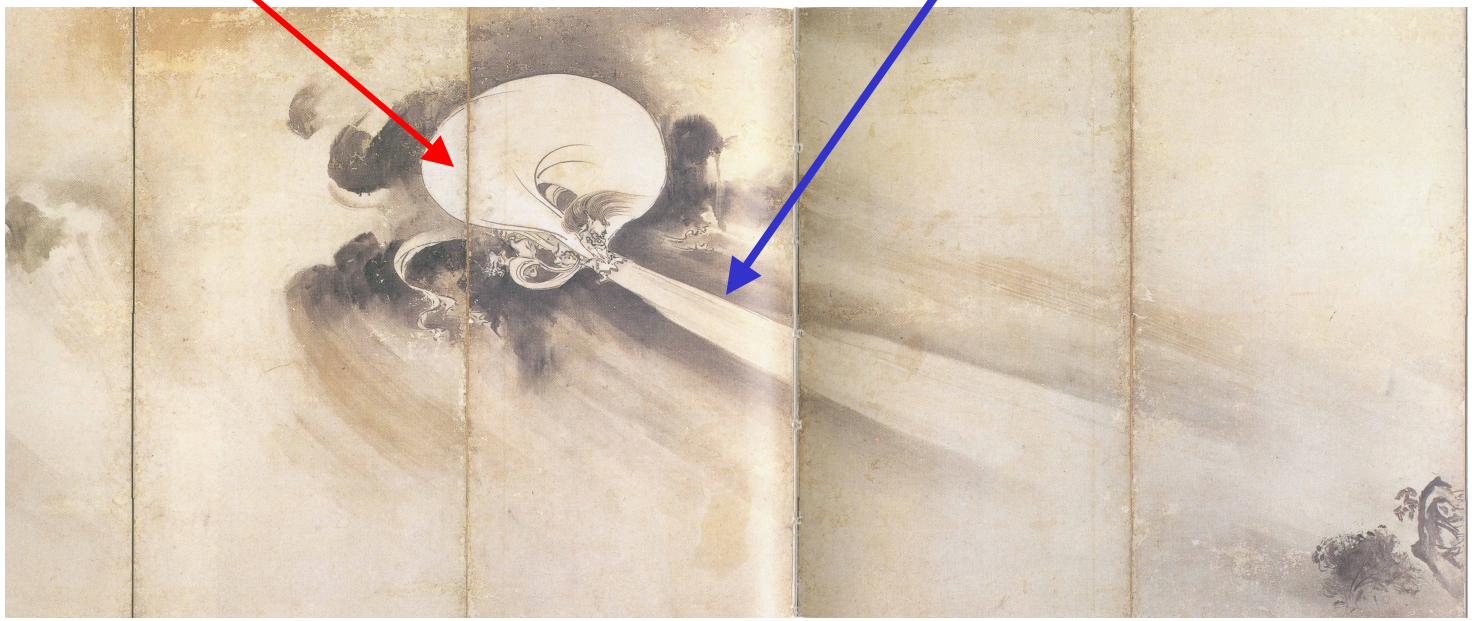
- **Simulation results show Weibel instability which creates filamented currents and density along the propagation of jets.**
- **Weibel instability may play a major role in particle acceleration in relativistic jets.**
- **The magnetic fields created by Weibel instability generate highly inhomogeneous magnetic fields, which is responsible for Jitter radiation (Medvedev 2000, 2006; Fleishman 2006).**
- **Spectra of jitter radiation depend on jet Lorentz factor and other parameters.**
- **For details see Nishikawa et al. ApJ, 2003, 2005 submitted to ApJ (astro-ph/0510590), Hededal & Nishikawa ApJ, 2005 and proceeding papers (astro-ph/0503515, 0502331, 0410266, 0410193), Hededal thesis (astro-ph/0506559), Hededal & Nordlund (astro-ph/0511662)**

Future plans for particle acceleration in relativistic jets

- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **In order to improve the performance of the code, High Performance Fortran (HPF) or Message Passing Interface (MPI) will be used (in progress)**
- **Investigate synchrotron (jitter) emission, and/or polarity from the accelerated electrons and compare with observations (Blazars and gamma-ray burst emissions)**
- **Develop a new code implementing synchrotron loss**

GRB progenitor

relativistic jet



Fushin

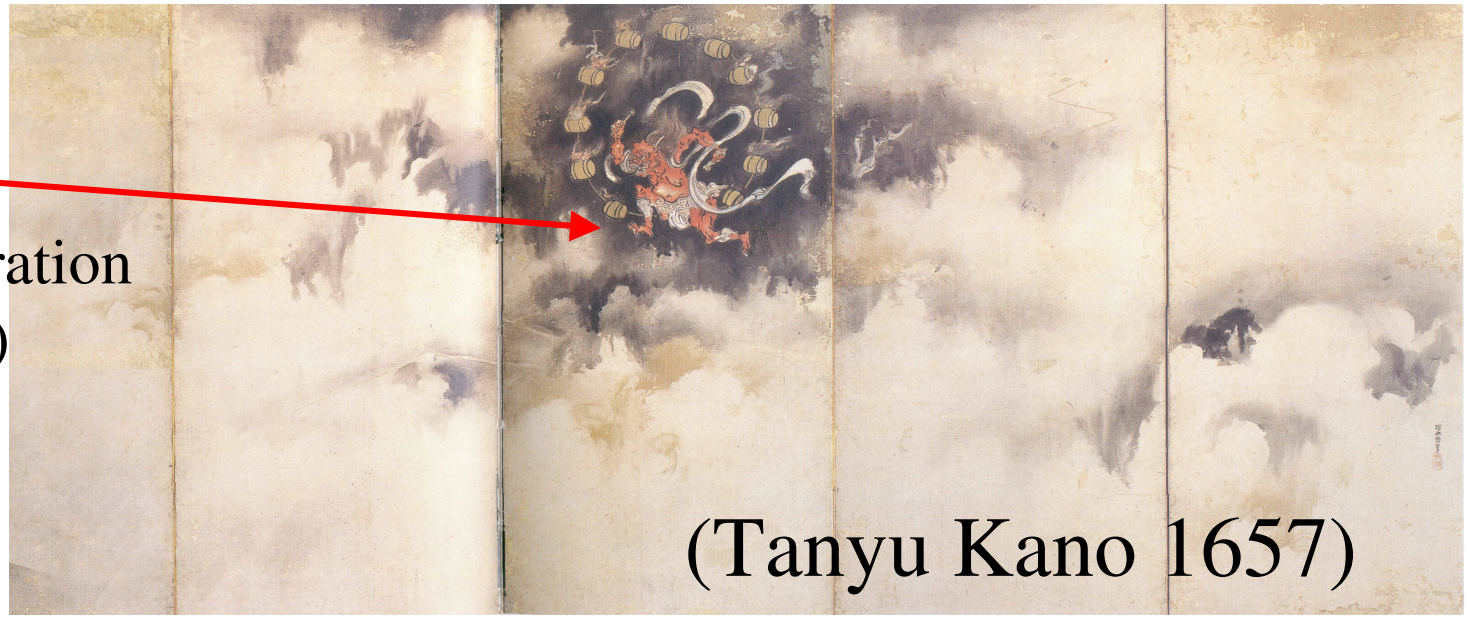
(god of wind)

emission

(shocks, acceleration
magnetic fields)

Raishin

(god of lightning)



(Tanyu Kano 1657)

Frequency spectrum of radiation emitted by a relativistic electron (approximation)

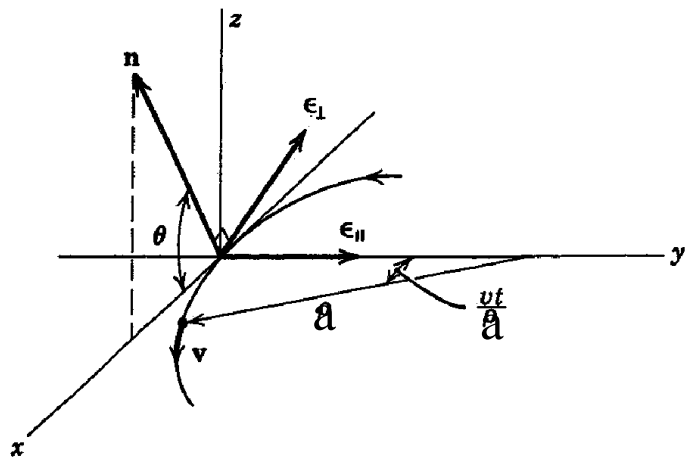
$$\frac{d^2W}{d\omega d\Omega} = \frac{d^2W_\perp}{d\omega d\Omega} + \frac{d^2W_\parallel}{d\omega d\Omega}$$
$$= \frac{e^2\omega^2}{3\pi^2 c}\left(\frac{a\theta_\gamma^2}{\gamma^2 c}\right)^2 K_{2/3}^2(\eta) + \frac{e^2\omega^2\theta^2}{3\pi^2 c}\left(\frac{a\theta_\gamma}{\gamma c}\right)^2 K_{1/3}^2(\eta)$$

$$\theta_\gamma^2 \equiv 1+\gamma^2\theta^2,\ \gamma = (1-v^2/c^2)^{-1/2} \text{ and } \eta = \frac{\omega a \theta_\gamma^3}{3c\gamma^3},\ \text{and } a = \frac{v^2}{\dot{v}_\perp} \simeq \frac{c^2}{\dot{v}_\perp}$$

$$\omega_c \equiv \frac{3}{2}\gamma^3\left(\frac{c}{a}\right) = \frac{3}{2}\left(\frac{E}{mc^2}\right)^3\frac{c}{a}$$

If γ. 1, ω.ω_c, θ= 0

$$\frac{d^2W}{d\omega d\Omega}\Big|_{\theta=0} \simeq \frac{3}{4\pi}\frac{e^2}{c}\gamma^2\frac{\omega}{\omega_c}e^{-\omega/\omega_c}$$



(Jackson 1999; Rybicki & Lightman 1979)