Weibel instability in astrophysical jets

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Nishikawa et al. 2006, ApJ 642, 1274
Ramirez-Ruiz, Nishikawa, & Hededal, 2007, in press (astro-ph/0707.4381)

Interdisciplinary Workshop/Foram on Magnetospheric Activities in Moon, Planets and Black Holes,

MSSL, September 18 – 20, 2007

Outline of talk

- **Motivations**
- **3-D particle simulations of relativistic jets**

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

  □= 5 (electron-ion), 15, 4 < □<100

  *** pair jet into pair and electron-ion ambient plasmas**

  □= 12.57, 1 < □<30
- **Evolution of the Weibel instability**
- **Particle Acceleration mechanism**
- **Summary of current 3-D simulations (Weibel Instability)**
- **Calculation of radiation based on particle trajectories**
- **Future plans of our simulations of relativistic jets**

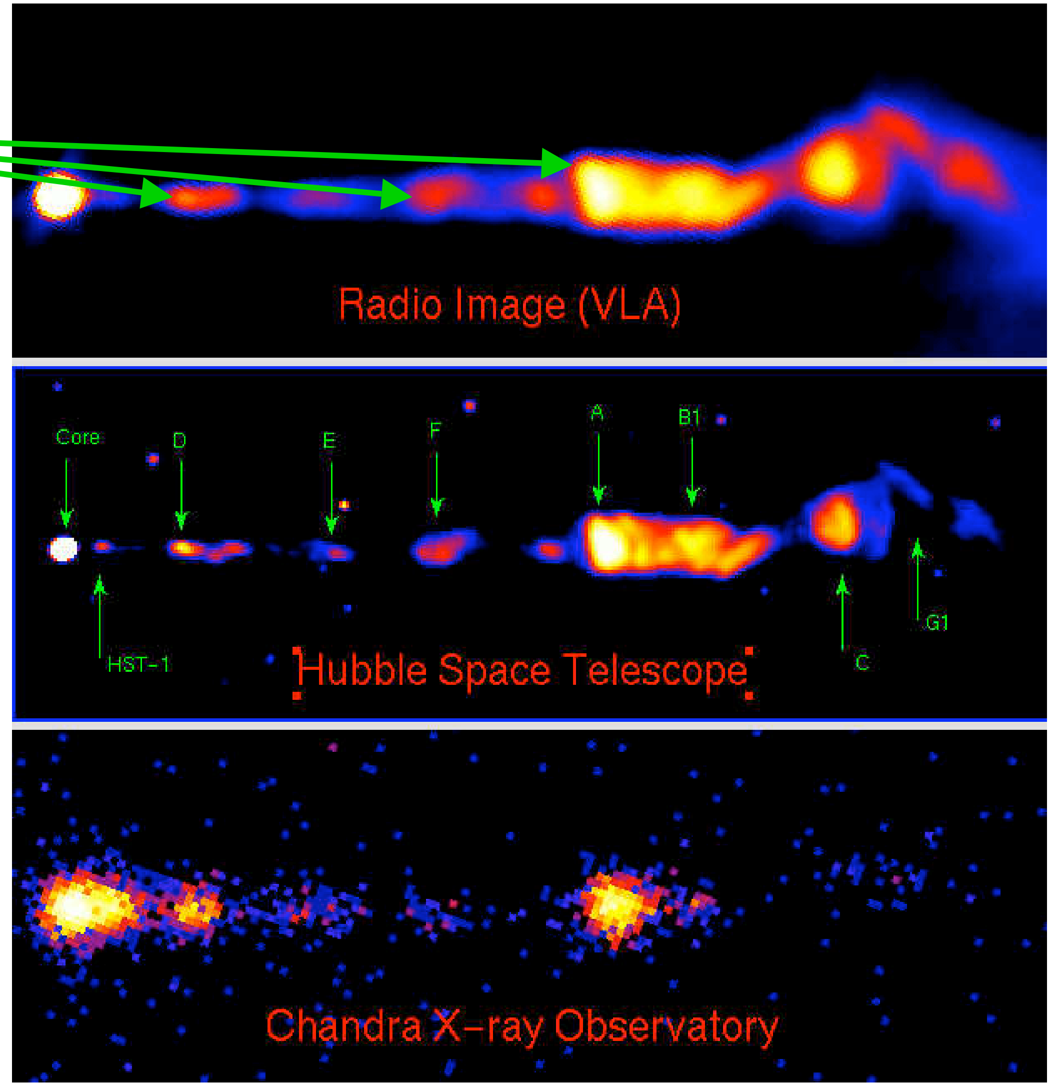
Motivations

- **Study particle acceleration at external and internal shocks in relativistic jets self-consistently with kinetic effects**
- **Study structures and dynamics of collisionless shocks caused by instabilities at the jet front and transition region in relativistic jets**
- **Particles acceleration and associated synchrotron/jitter radiation**
- **Examine possibilities for afterglows in gamma-ray bursts with appropriate ambient plasmas**

Observations of M87

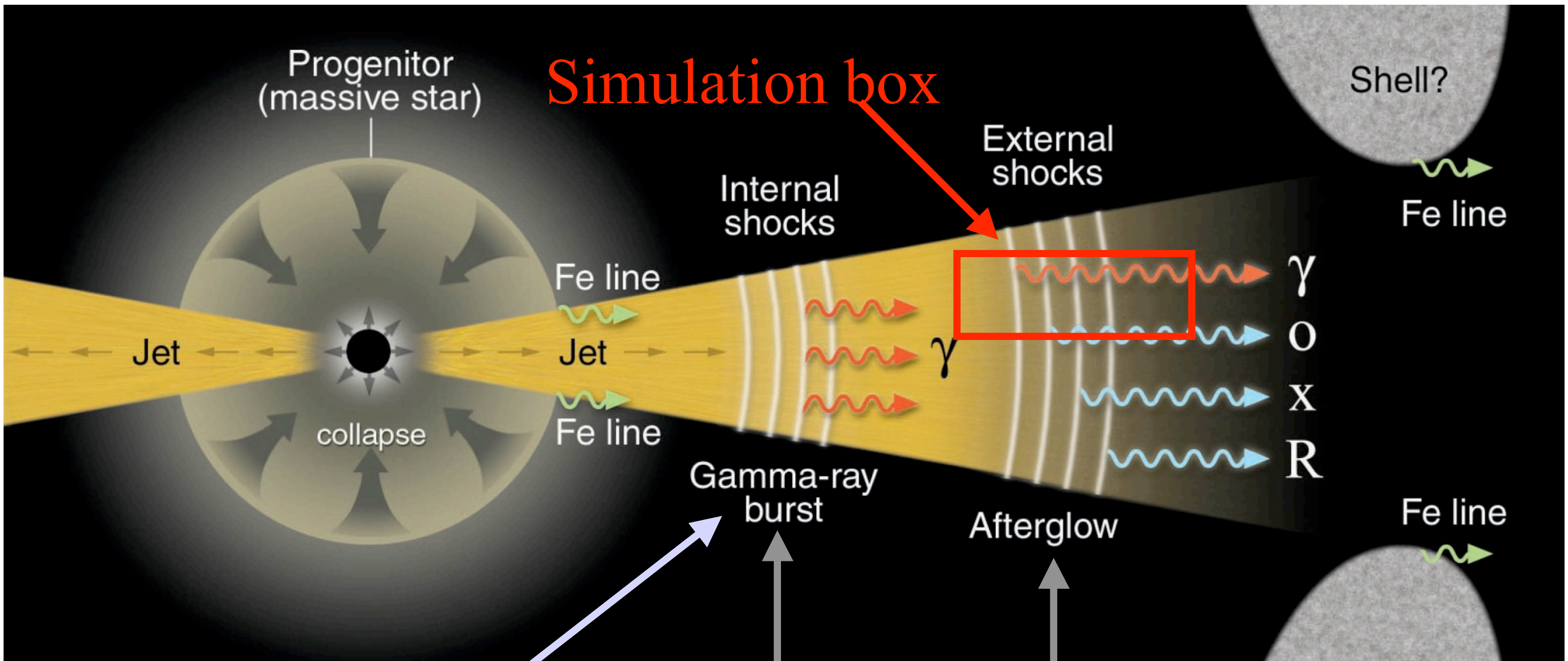
Shocks?

nonthermal electrons, enhanced magnetic field, jitter radiation (Medvedev 2000, 2006; Fleishman 2006)?



Schematic GRB from a massive stellar progenitor

(Meszaros, Science 2001)



Prompt emission

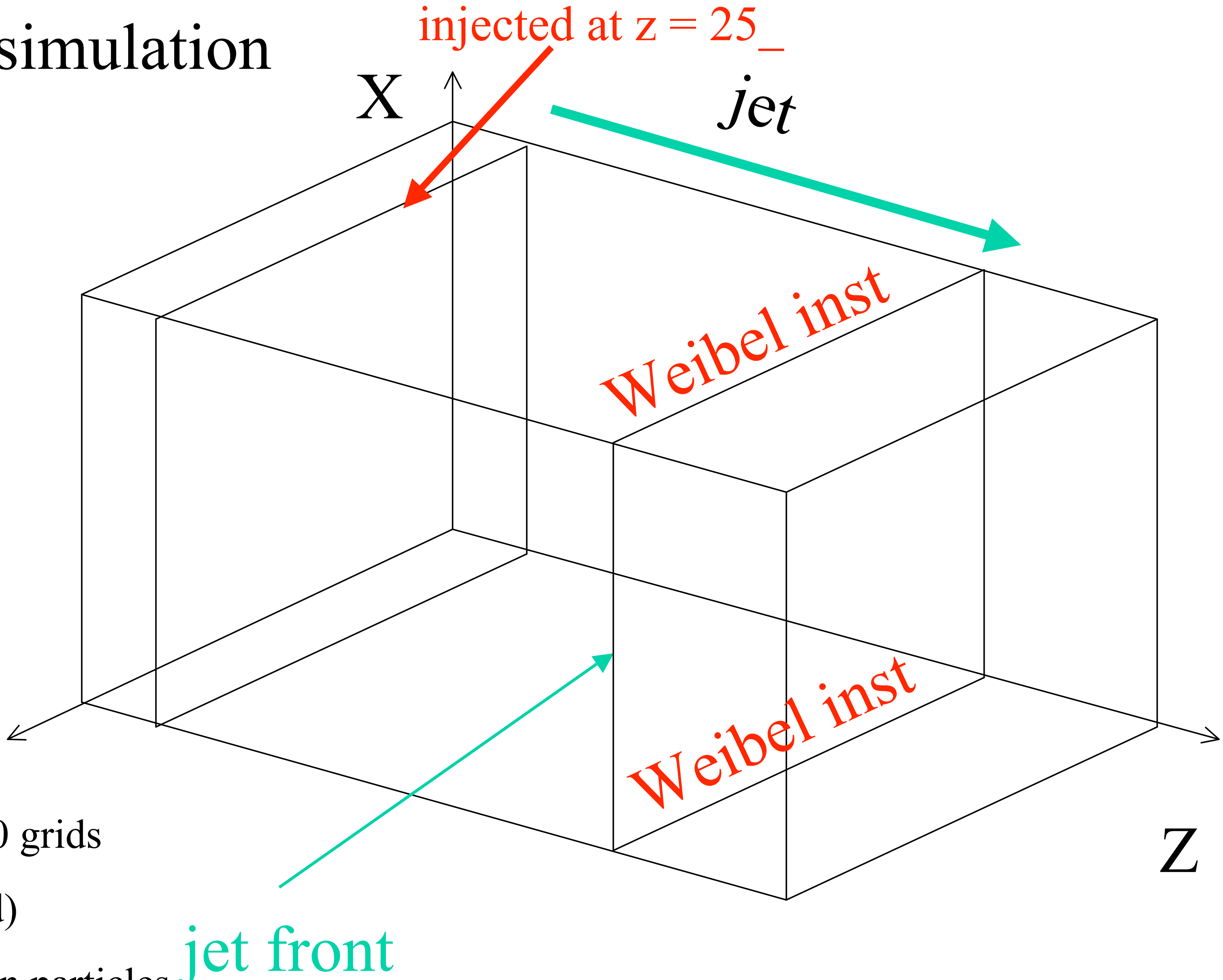
Polarization ?

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 (_) with ($\square_e$, $\square_B$) 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.**

3-D simulation



85_85_640 grids

(not scaled)

380 Million particles

Collisionless shock

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

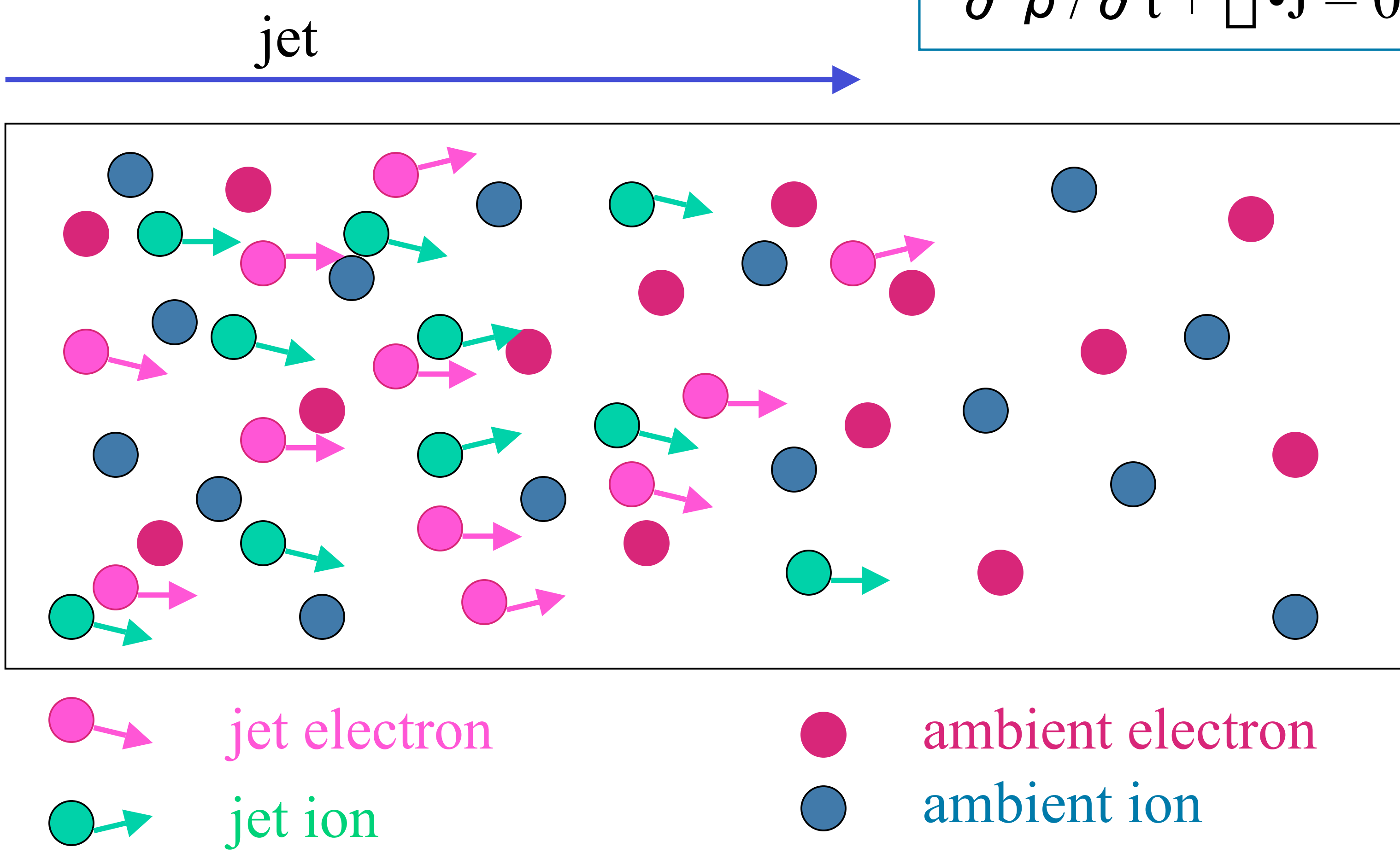
(Buneman 1993)

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

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

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

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



Weibel instability

current filamentation

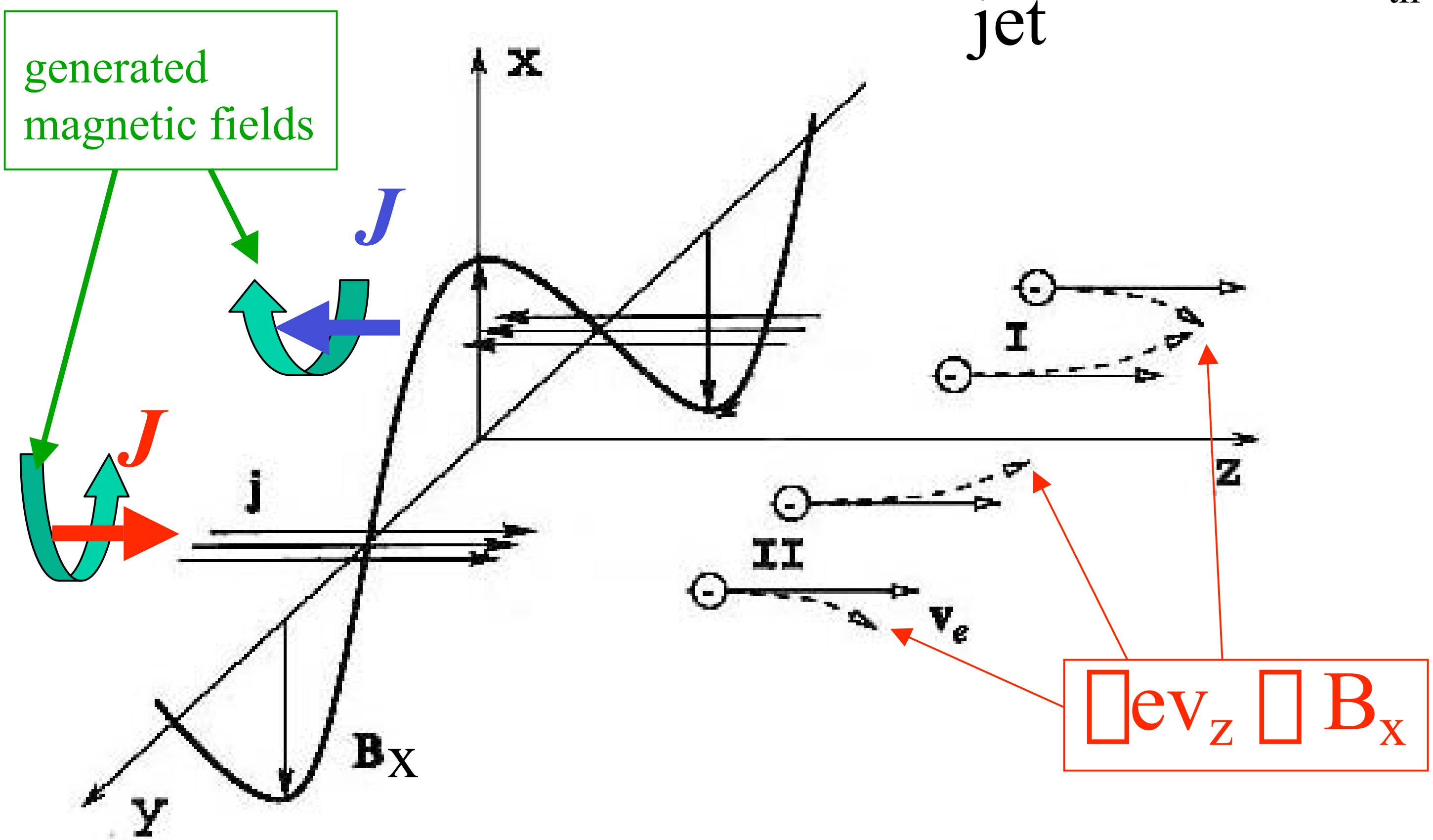
Time:

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

Length:

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

jet

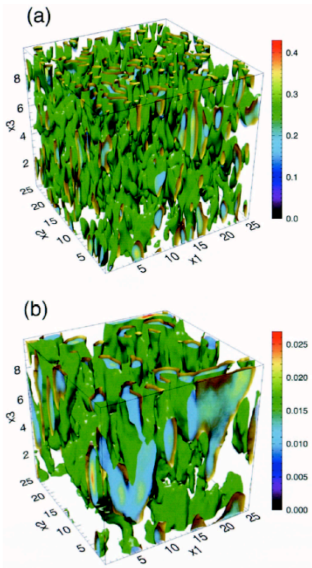


(electrons)

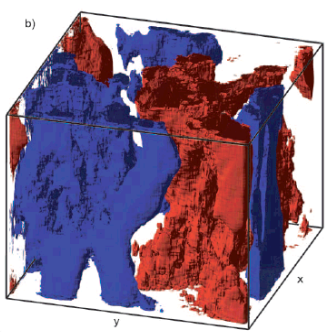
(Medvedev & Loeb, 1999, ApJ)

3-D Simulations of Weibel instability

Counter-steaming electron-positron shells

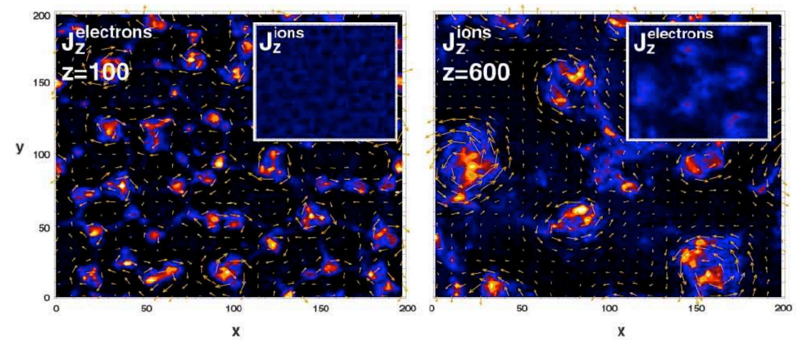


(Silva et al. 2003, ApJL)

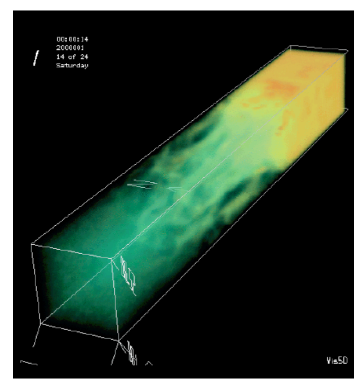


(Jaroschek, Lesch, & Treumann, ApJ, 2005)

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)

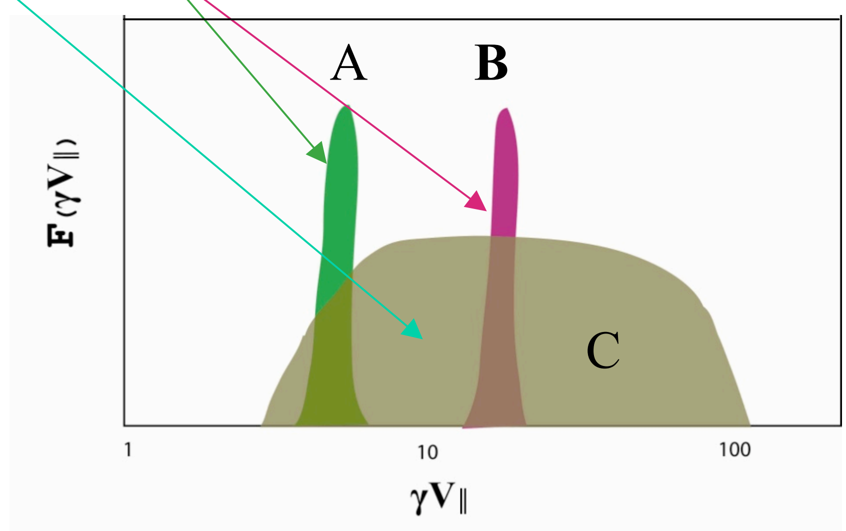
(pair jet created by photon annihilation, _+_□ $e^{\pm}$)

- A’: □= 5 (electron-ion)

Growth times of Weibel instability:

_ A ≪ τ A’ ≪ _B ≪ _C

Schematic initial parallel velocity distribution of jets



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

electron-positron $\gamma = 15$ (B) at Y = 43 Δ

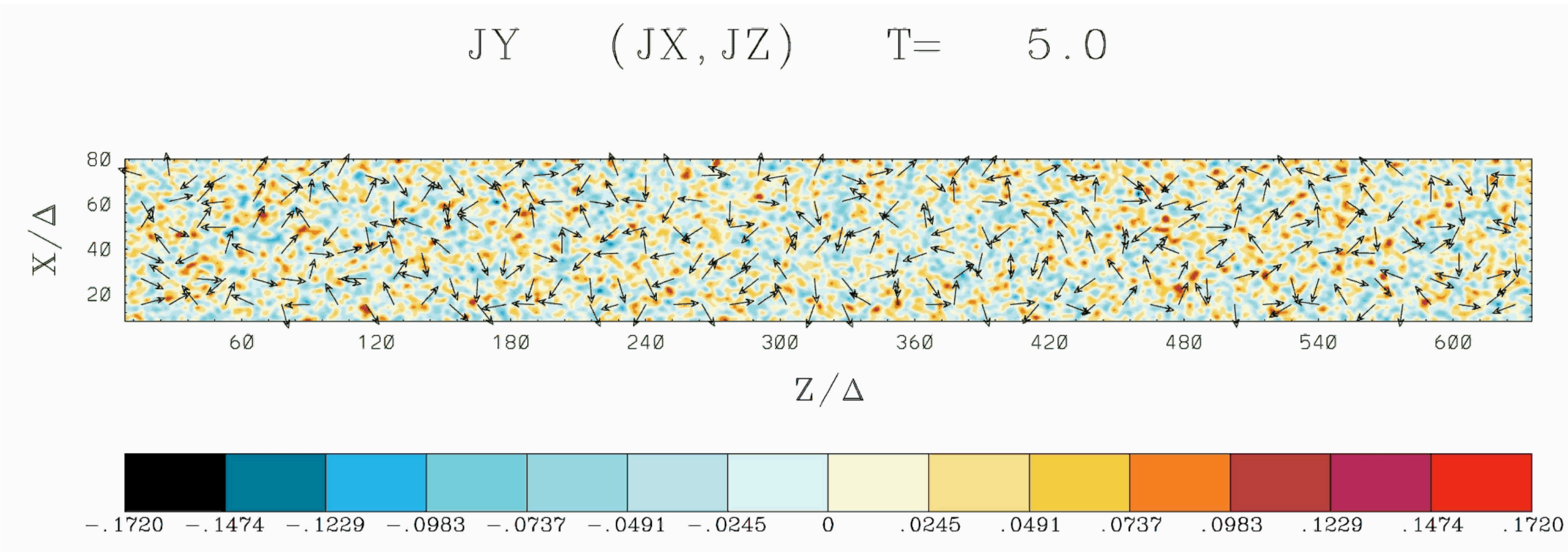
$$\omega_{pe}t = 59.8 \approx 6\text{msec}$$

$n_{ISM} = 1/cm^3$

_$_{pe}^{-1} \approx 0.1$msec

$c/\omega_{pe} = 5.3$ km

$L \approx 300$ km



Weibel instability

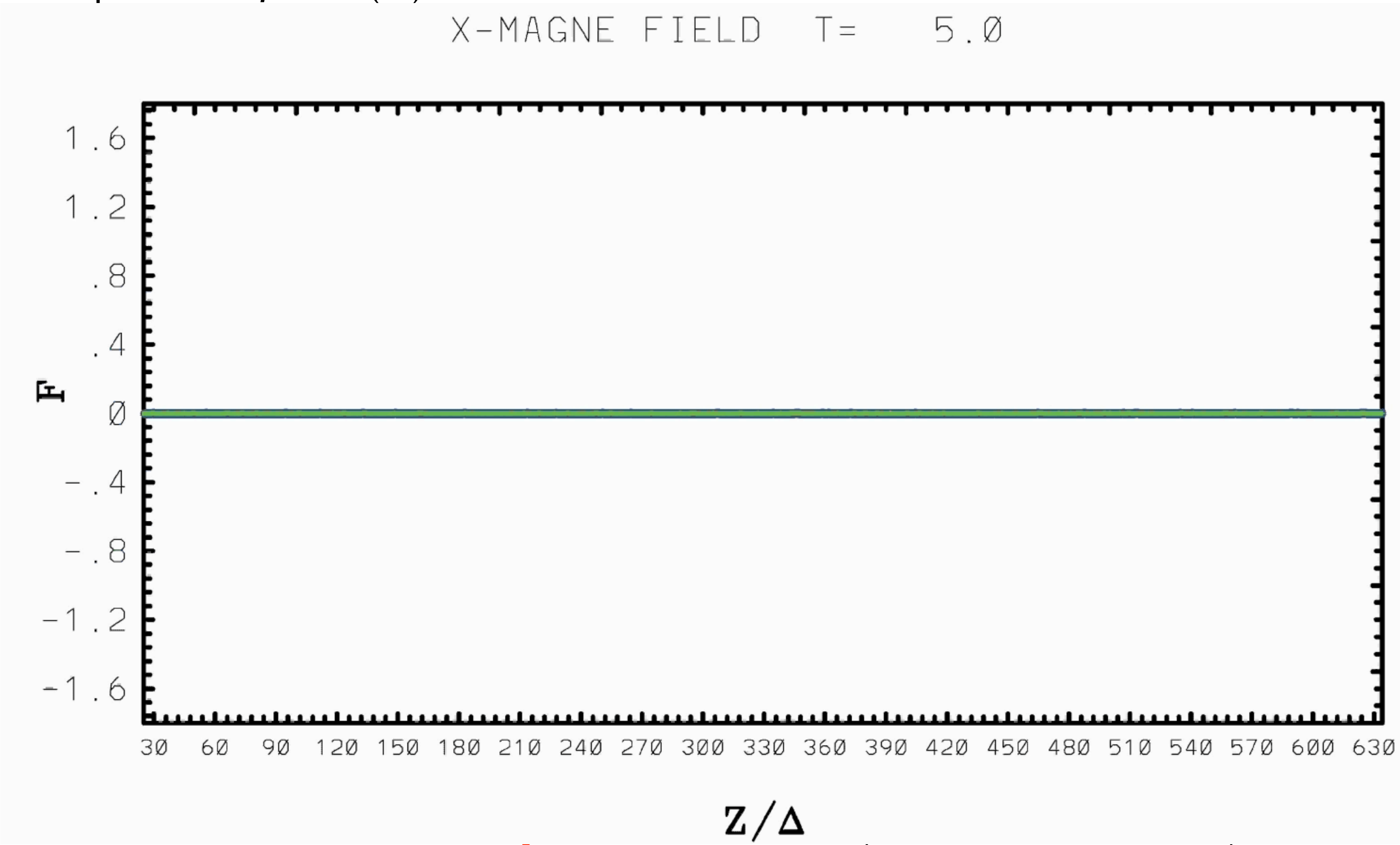
jet front

(Nishikawa et al. 2005)

Evolution of B_x due to the Weibel instability

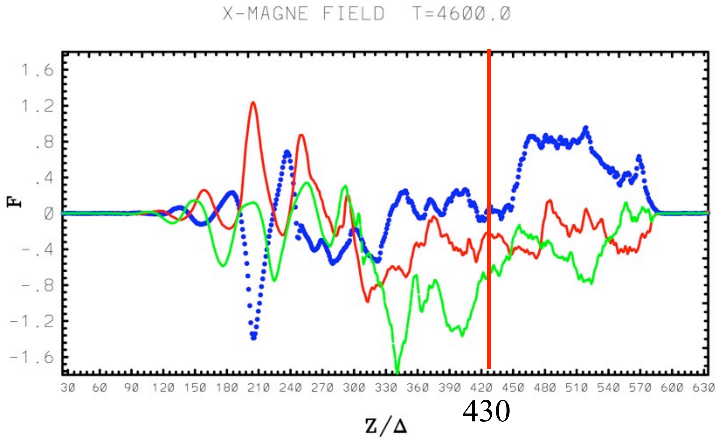
el-positron γ = 15 (B)

(convective instability)

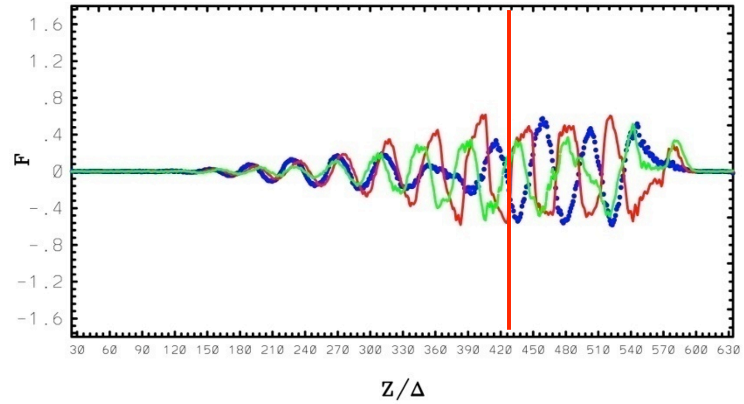


B_x *component generated by current channels at* $t = 59.8\,\omega_{pe}$

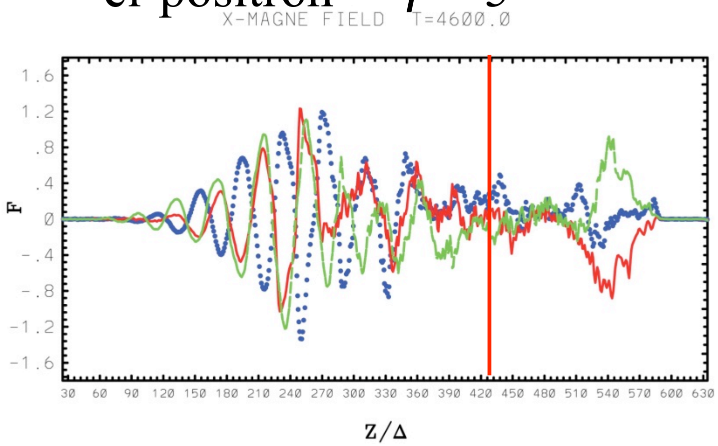
el-ion $\gamma = 5$



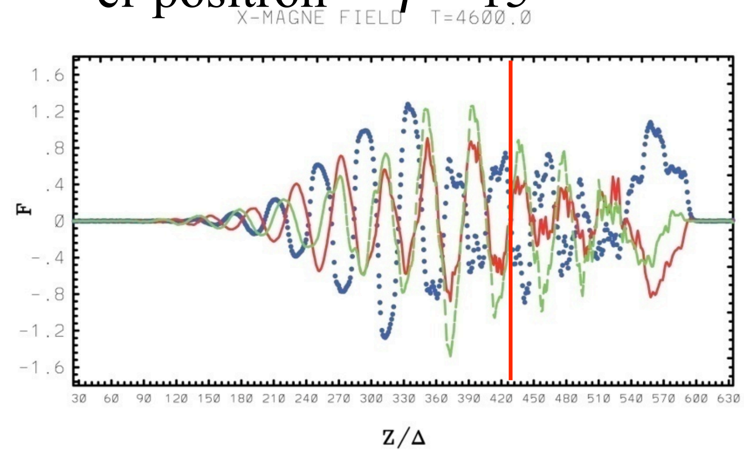
el-positron $4 < \gamma < 100$



el-positron $\gamma = 5$

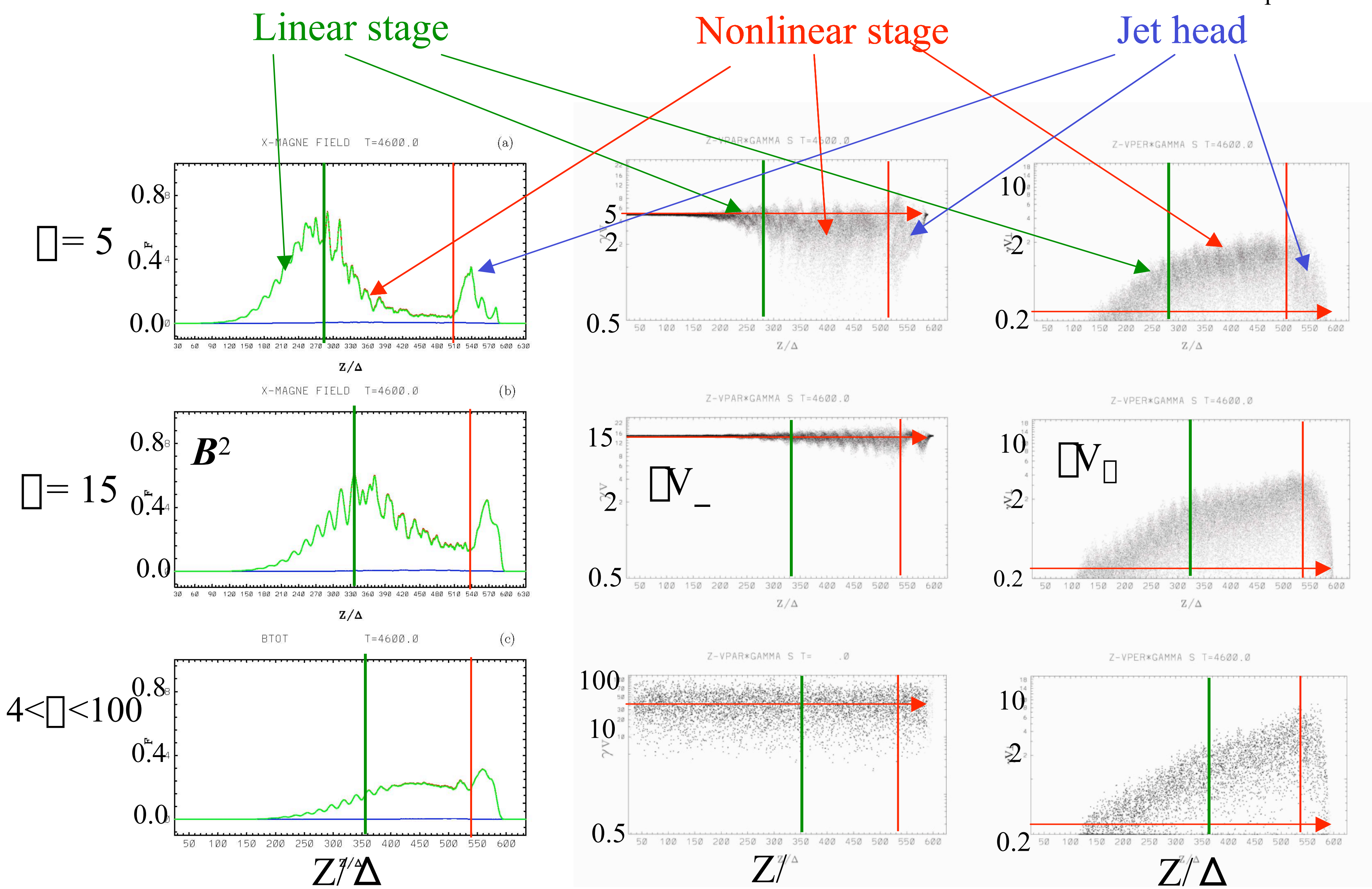


el-positron $\gamma = 15$



Magnetic field energy and parallel and perpendicular velocity space along Z

$\omega_{pe}t = 59.8$

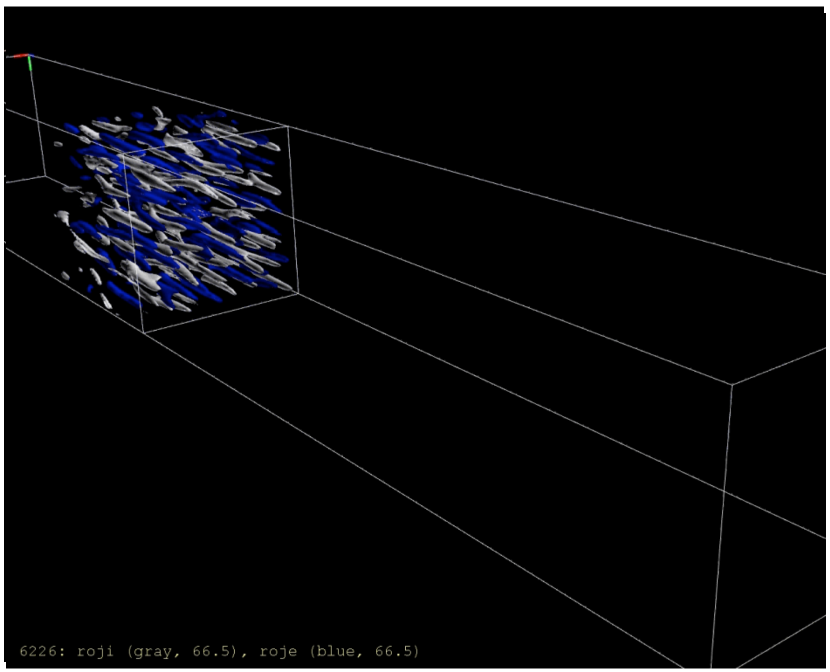


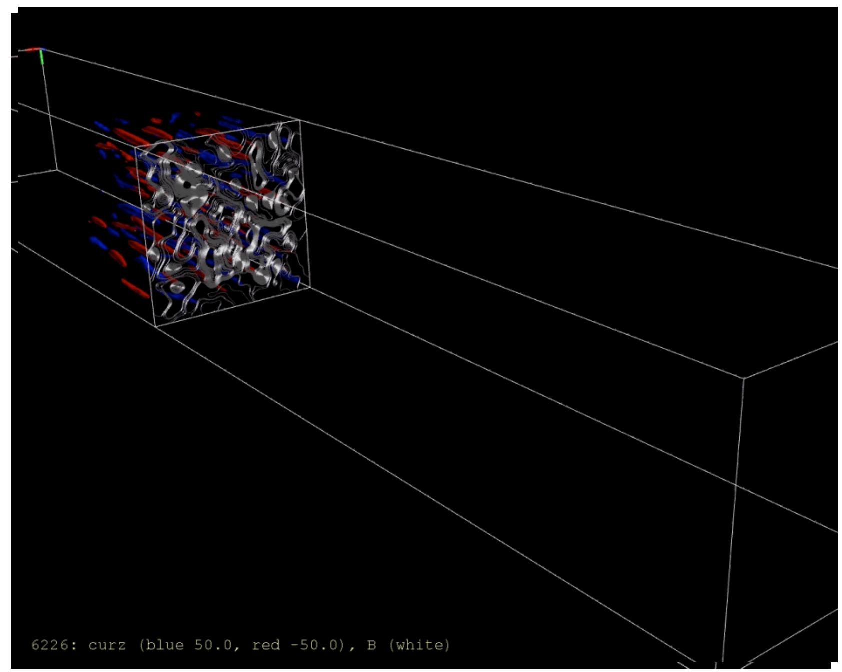
Isosurfaces of jet particles and z-component of current density injected into electron-ion ambient plasma

_v$_{||}$= 12.57

(electron: blue, positron: gray)

(+J_z: blue, -J_z:red)



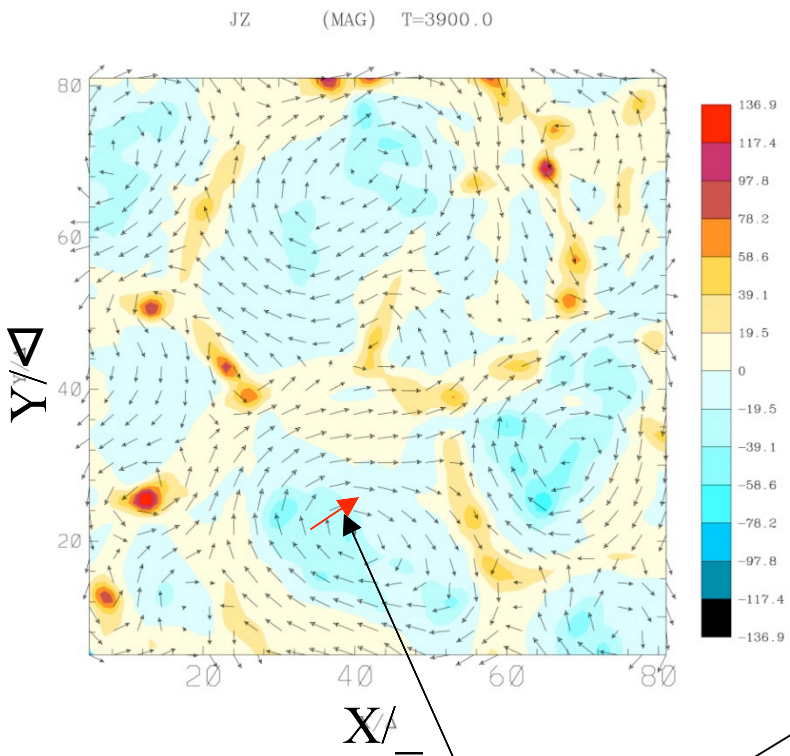


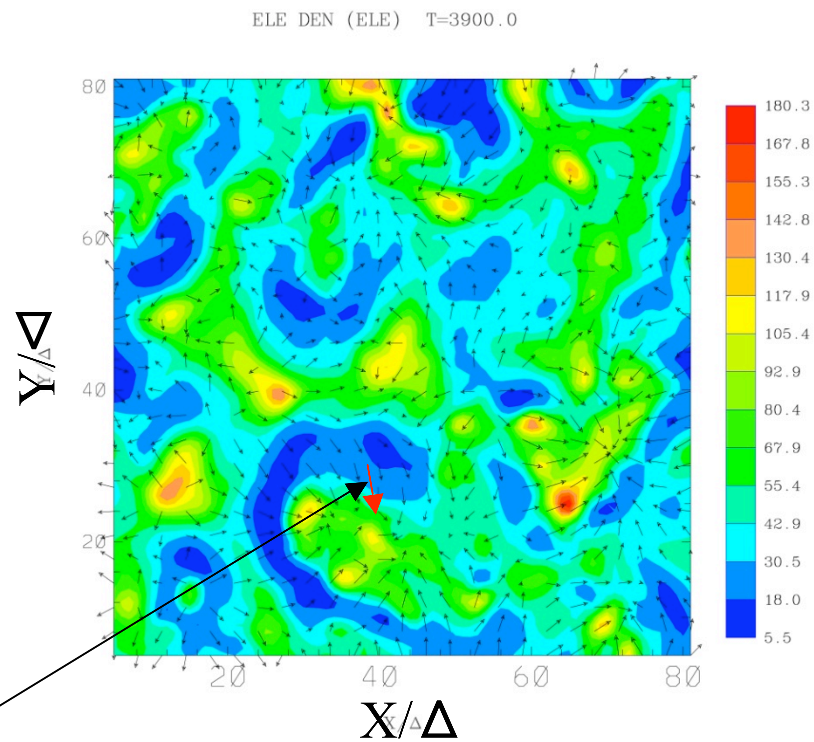
(local magnetic filed lines: white)

E_B acceleration due to the current channel (Z/_= 430)

t = 50.7_pe *electron-ion jet* γ = 5

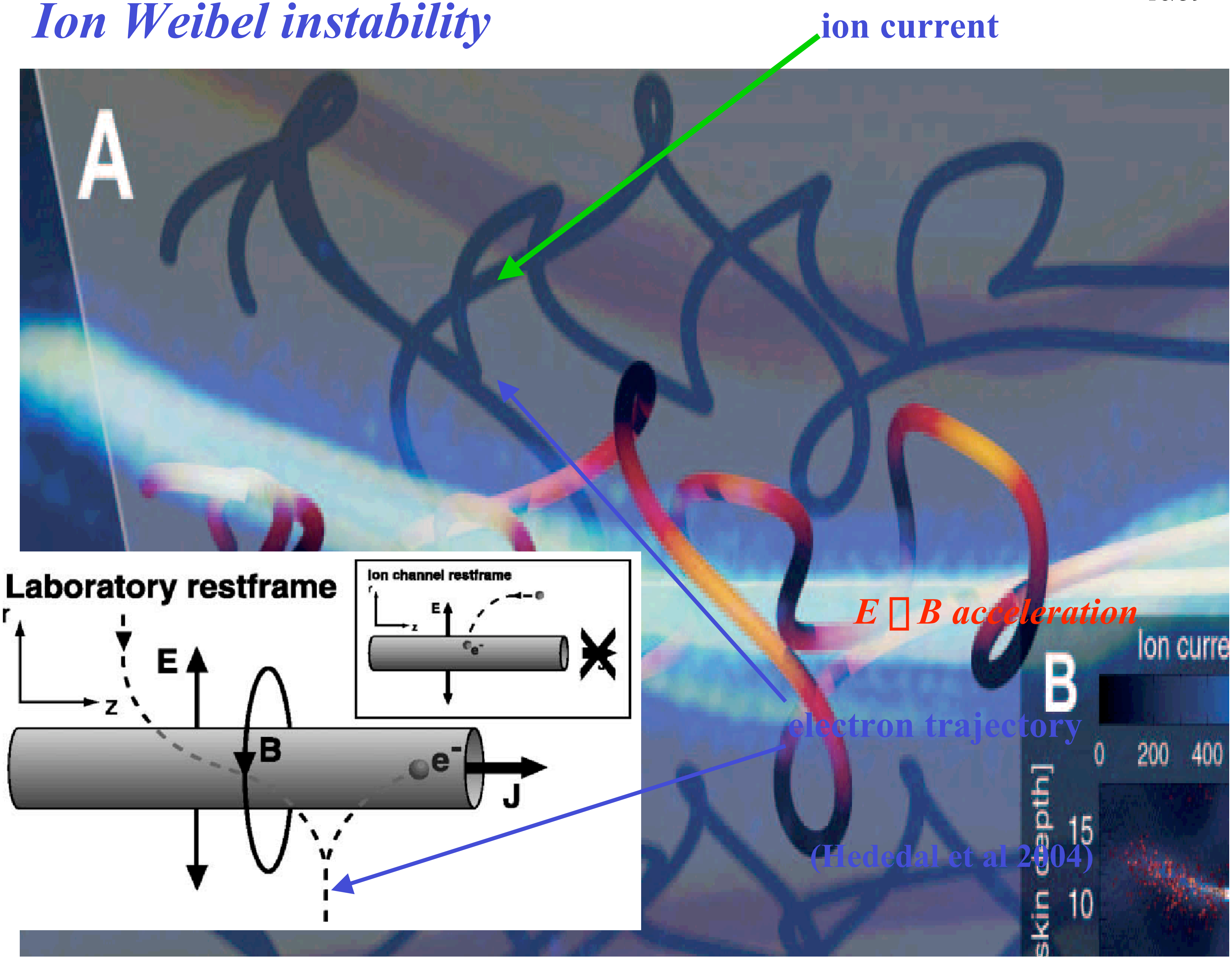
J_z arrows: B_x, B_y n_e arrows: E_x, E_y





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

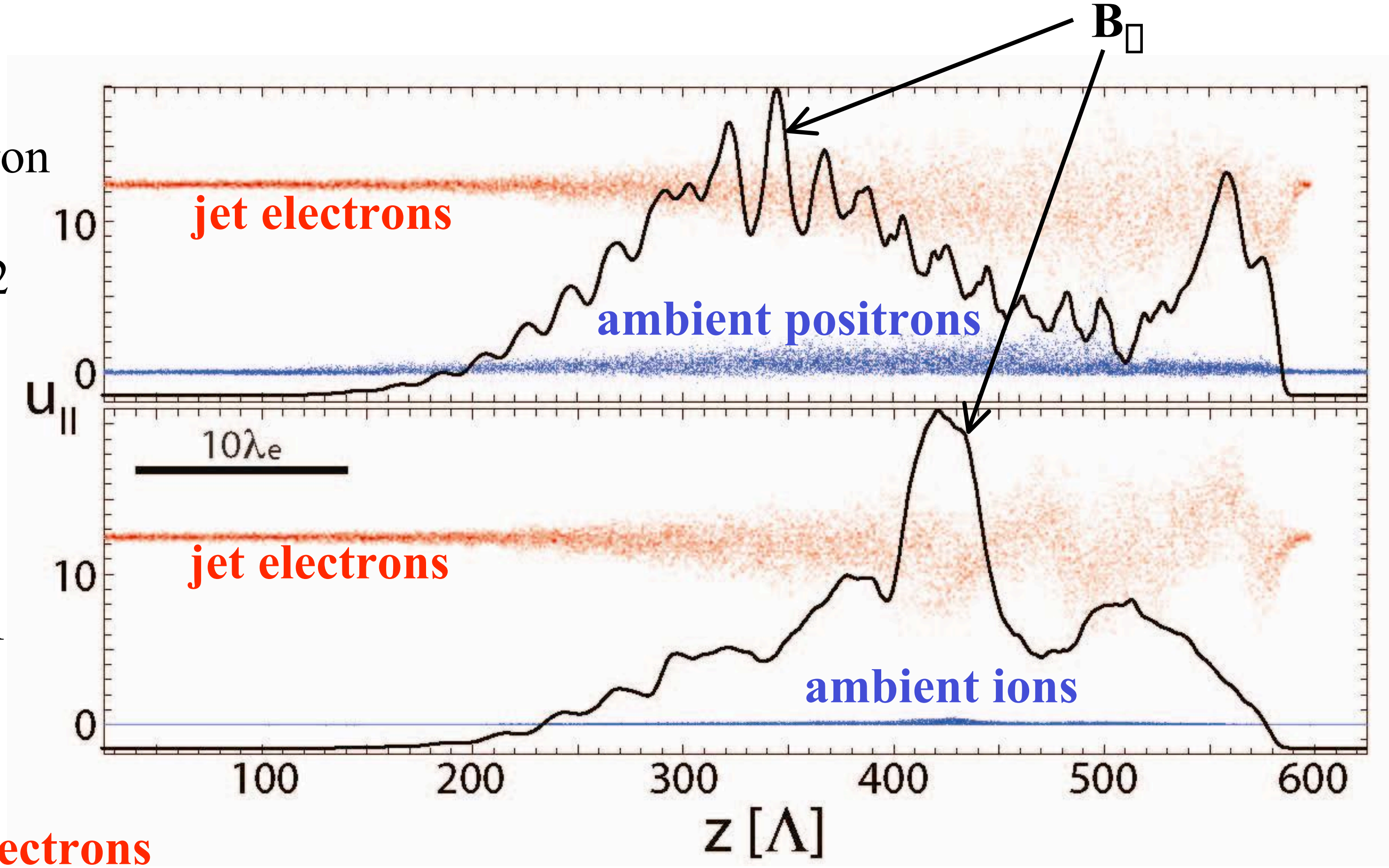
Ion Weibel instability



Magnetic field generation and particle acceleration with narrow jet ($u_{||} = \gamma v_{||} = 12.57$)

electron-positron ambient
$\varepsilon_{Bmax} = 0.012$

electron-ion ambient
$\varepsilon_{Bmax} = 0.061$



red dot: jet electrons
blue dots: ambient (positrons and ions)

(Ramirez-Ruiz, Nishikawa, Hededal 2007)

Present theory of Synchrotron radiation

- Fermi acceleration (not self-consistent simulation)
  (particles are crossing at the shock surface many times and
  accelerated, the strength of turbulent magnetic fields are assumed)
- The strength of magnetic fields is assumed based on the equipartition (magnetic field is similar to the thermal energy) ($\square_B$)
- The density of accelerated electrons are assumed by the power low ($F(\square) = \square^{p}$; $p = 2.2$?) ($\square_e$)
- Synchrotron emission is calculated based on p and $\square_B$
- There are many assumptions in this calculation

Self-consistent calculation of radiation

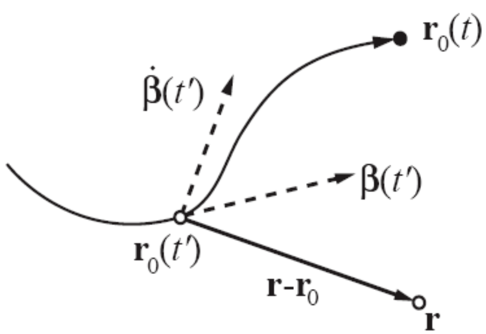
- Electrons are accelerated by the electromagnetic field generated by the Weibel instability (without the assumption used in test-particle simulations for Fermi acceleration)
- Radiation is calculated by the particle trajectory in the self-consistent magnetic field
- This calculation include Jitter radiation (Medvedev 2000, 2006) which is different from standard synchrotron emission

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, β the velocity and $\dot{\beta}$ the acceleration



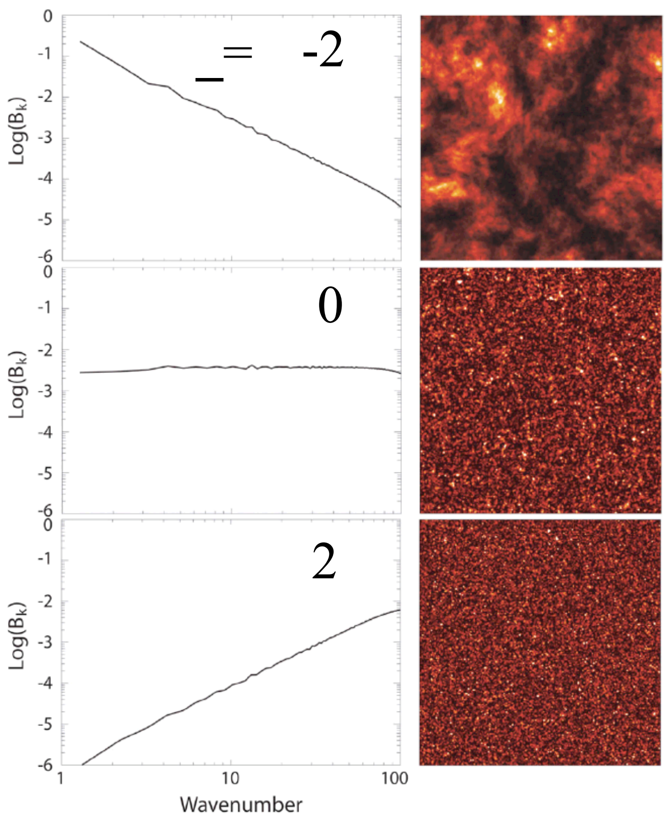
New approach: Calculate radiation from integrating position, velocity, and acceleration of ensemble of particles (electrons and positrons)

Hededal, Thesis 2005 (astro-ph/0506559)

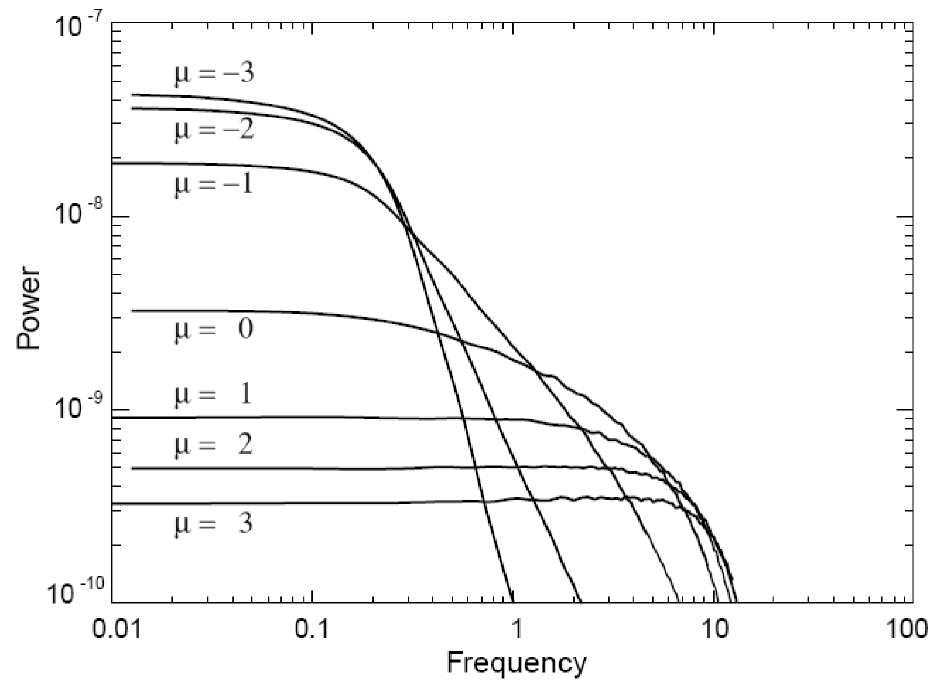
3D jitter radiation (diffusive synchrotron radiation) with a ensemble of mono-energetic electrons (□= 3) in turbulent magnetic fields (Medvedev 2000; 2006, Fleishman 2006)

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

2d slice of magnetic filed



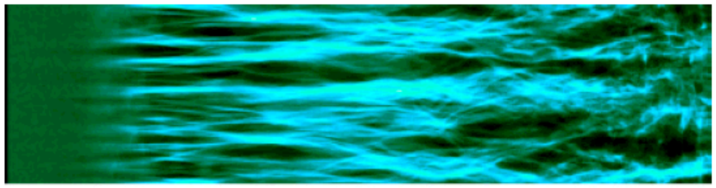
3D jitter radiation with □= 3 electrons



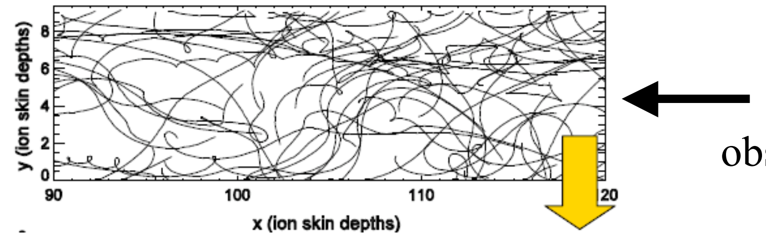
Hededal & Nordlund (astro-ph/0511662)

Radiation from collisionless shock

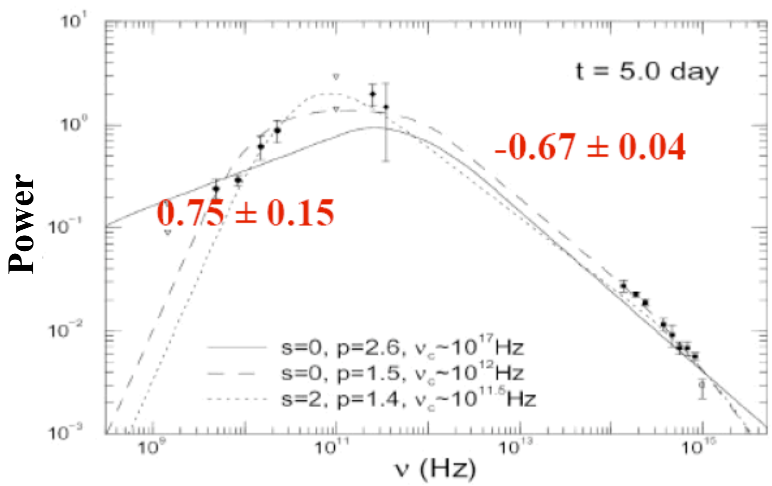
Spectrum obtained directly from shock simulations

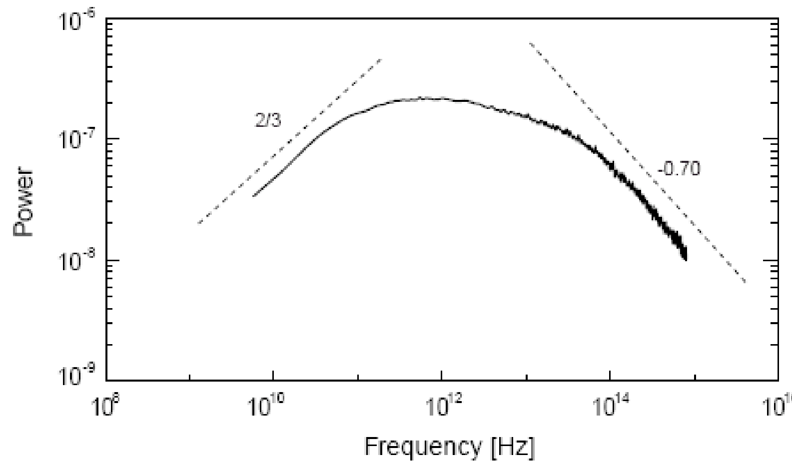


+



observer





GRB 000301c (Panaitescu 2001)

Shock simulations

Hededal Thesis: http://www.astro.ku.dk/~hededal

Hededal & Nordlund 2005, submitted to ApJL (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).**
- **For details see Nishikawa et al. ApJ, 2003, 2005, 2006, Hededal & Nishikawa ApJ, 2005, and proceeding papers (astro-ph/0503515, 0502331, 0410266, 0410193)**

Future plans for particle acceleration in relativistic jets

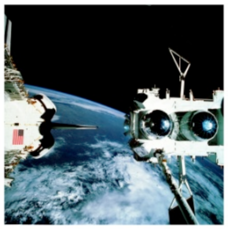
- **Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics**
- **In order to investigate shock dynamics further diagnostics will be developed**
- **Simulations with large systems will be performed with the codes parallelized with OpenMP and MPI**
- **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 and/or inverse Compton scattering**

Gamma-Ray Large Area Space Telescope (GLAST)

(will be launched in early 2008)

http://www-glast.stanford.edu/

Compton Gamma-Ray Observatory (CGRO)



Burst And Transient Source Experiment

(BATSE) (1991-2000)

PI Jerry Fishman

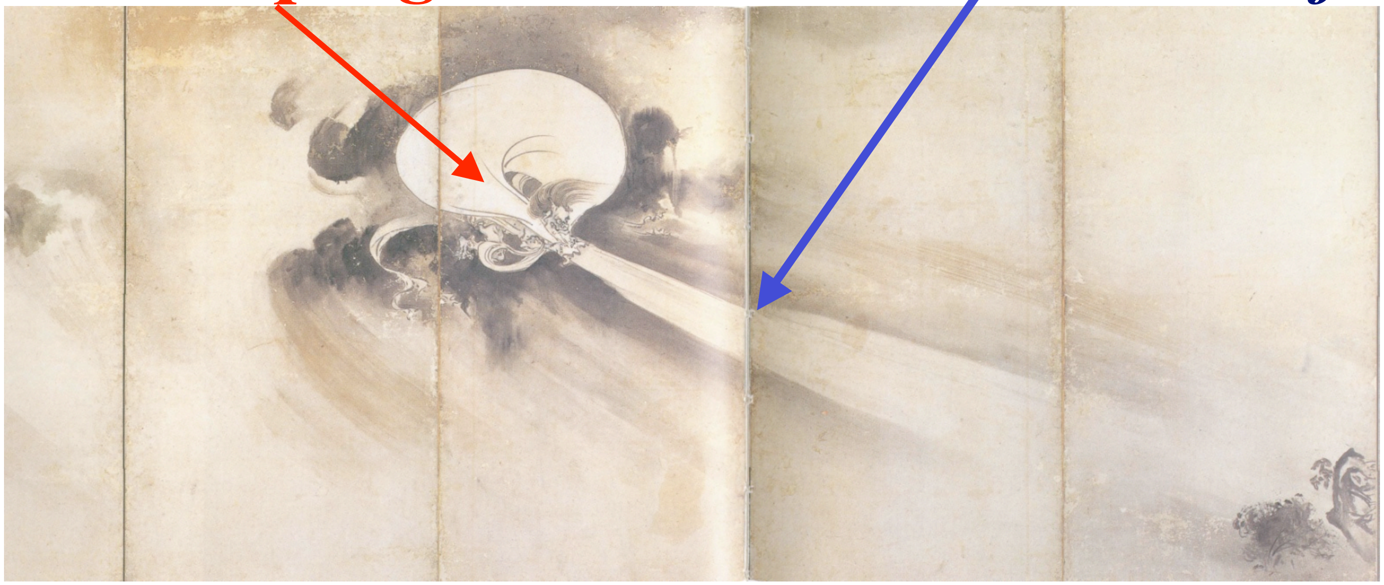
→

- **Large Area Telescope (LAT) PI Peter Michaelson:**
  20 MeV to about 300 GeV
- **GLAST Burst Monitor (GBM) PI Chip Meegan (MSFC):**
  X-rays and gamma rays with energies between 5 keV and 25 MeV (http://gammaray.nsstc.nasa.gov/gbm/)

The combination of the GBM and the LAT provides a powerful tool for studying gamma-ray bursts, particularly for time-resolved spectral studies over a very large energy band.

GRB progenitor

relativistic jet



Fushin

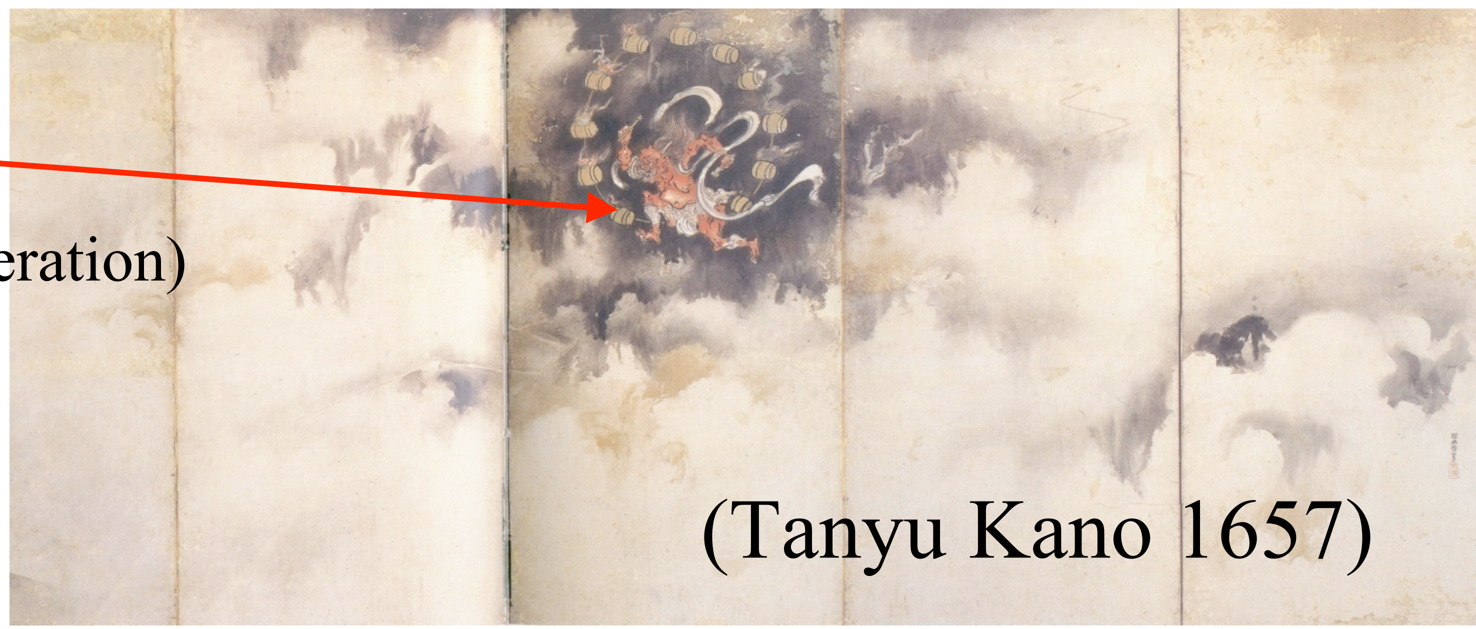
(god of wind)

emission

(shocks, acceleration)

Raishin

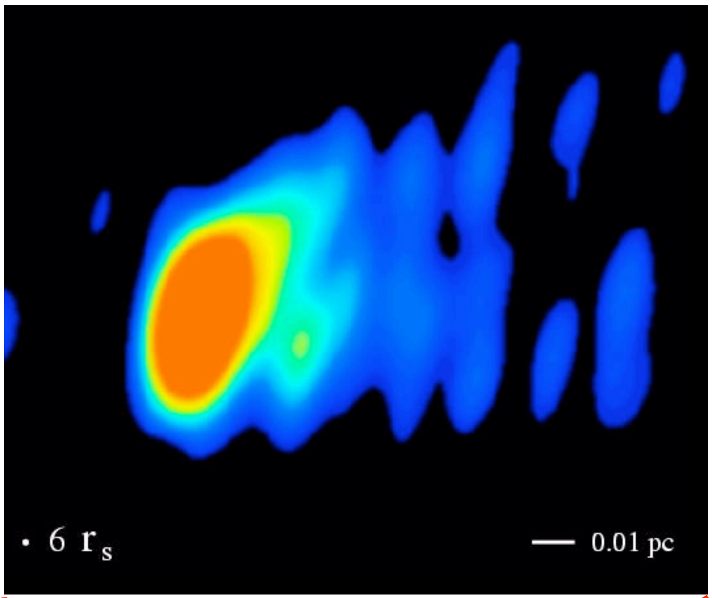
(god of lightning)

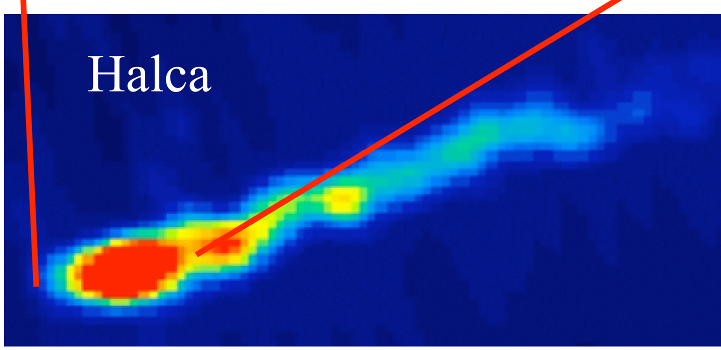


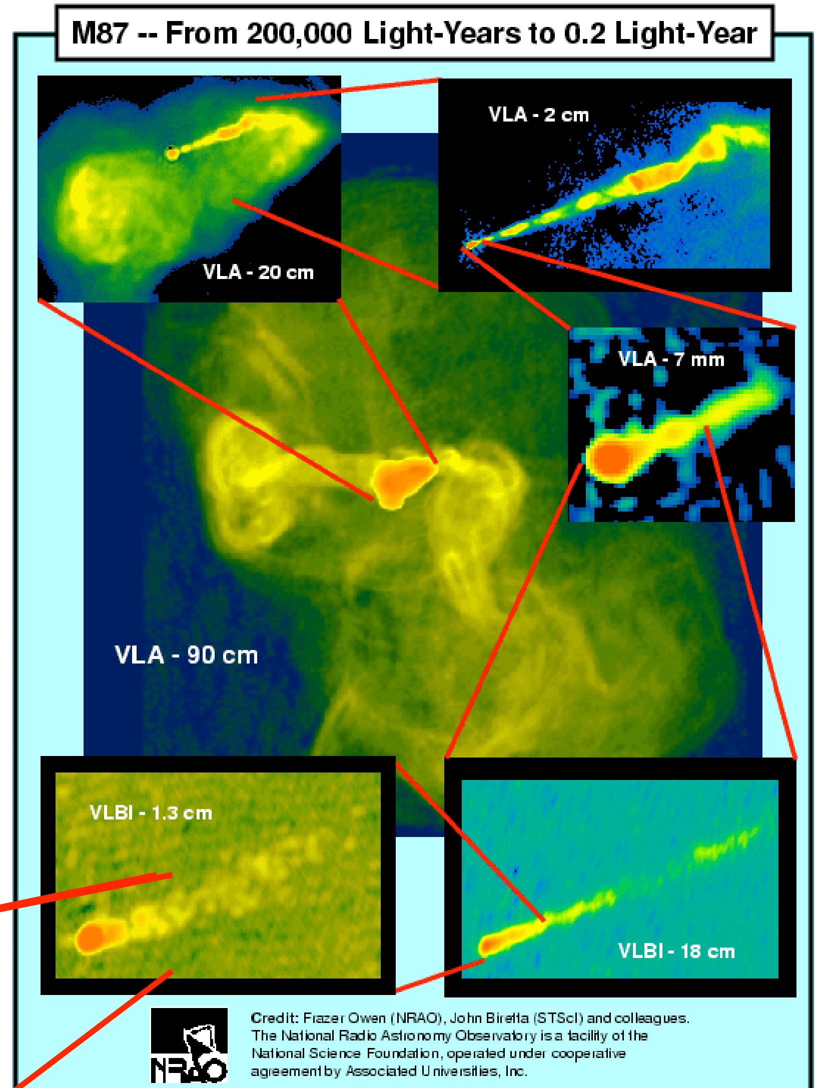
(Tanyu Kano 1657)

M87

Mass of black hole:
3 billion solar masses
Resolve ~ 100 m







Three-dimensional GRPIC Simulation of Jets from Accretion Disks

Background:

Accrete3D was developed to study the self-consistent evolution of the jet from the accretion disk.

GRPIC Considerations

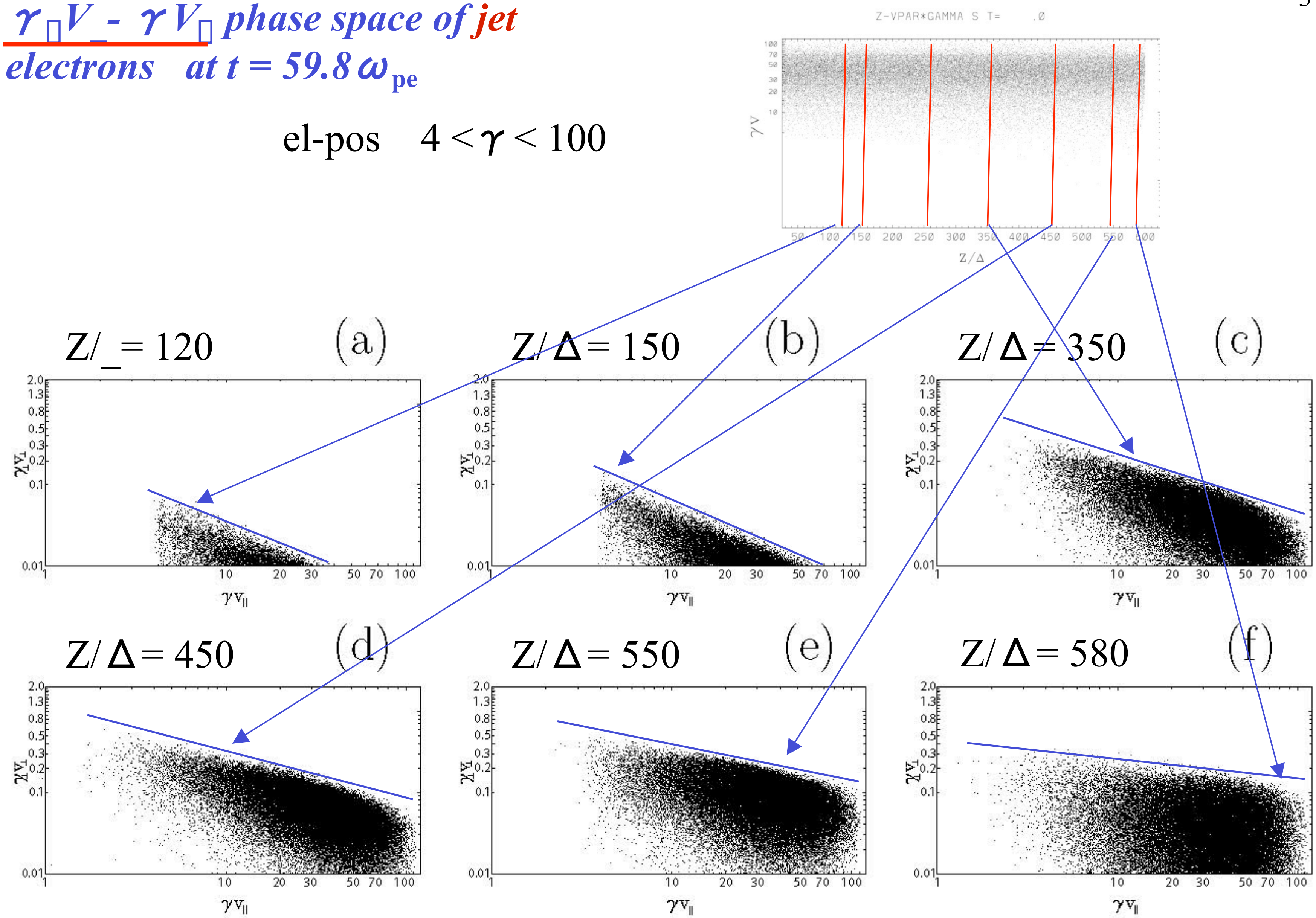
- GRMHD is a fluid approximation
- Particle motion is self-consistent (not ideal fluid)
- Dynamics of charged particle separation (not frozen)

Questions in Disk-Jet Dynamics/Simulation

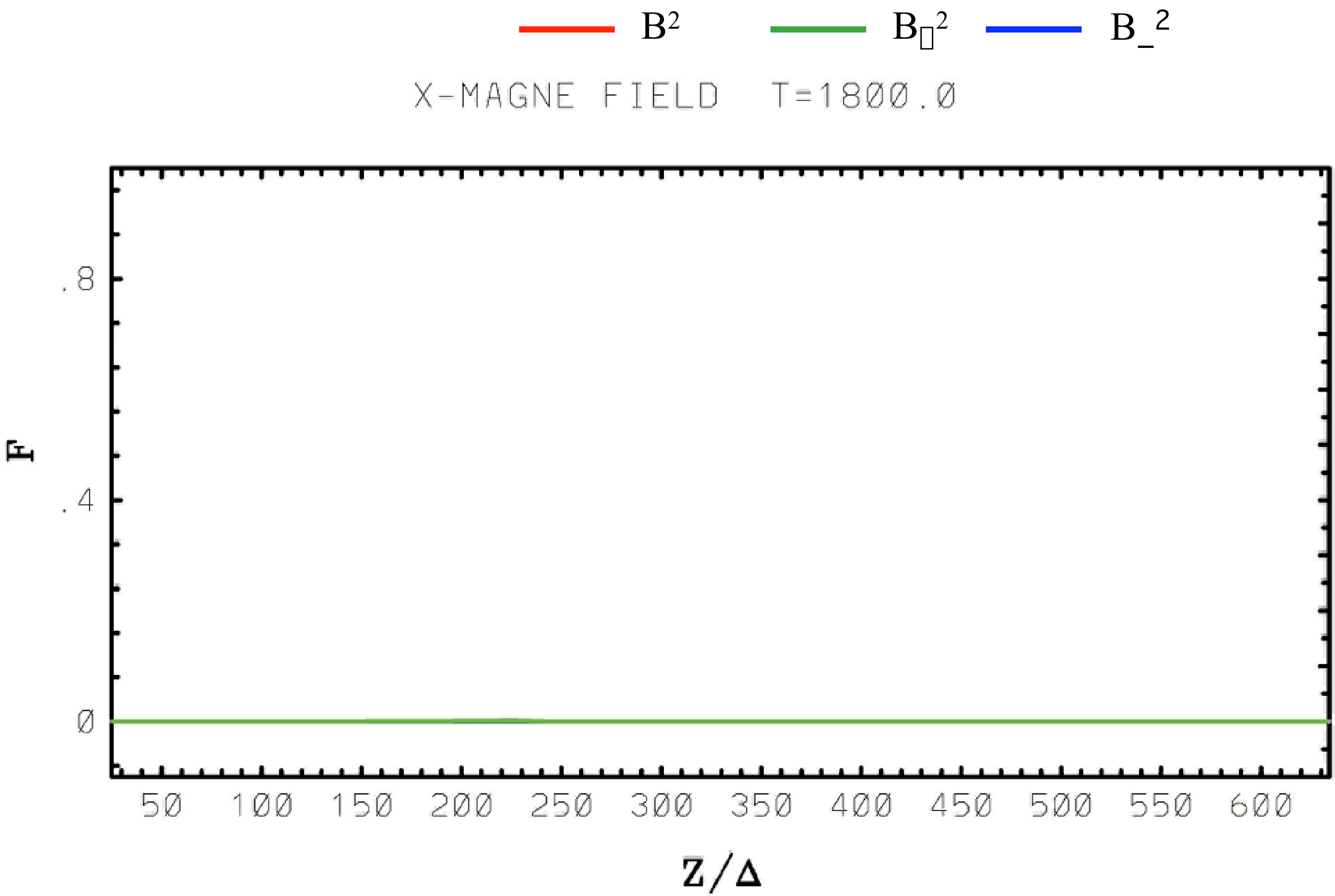
- What is the acceleration mechanism?
- Why is the jet collimated?
- Can the disk-jet system become steady self-consistently?

$\gamma_{\perp}V_{\perp}$ - $\gamma V_{\parallel}$ phase space of *jet* electrons at $t = 59.8\,\omega_{pe}$

el-pos $4 < \gamma < 100$

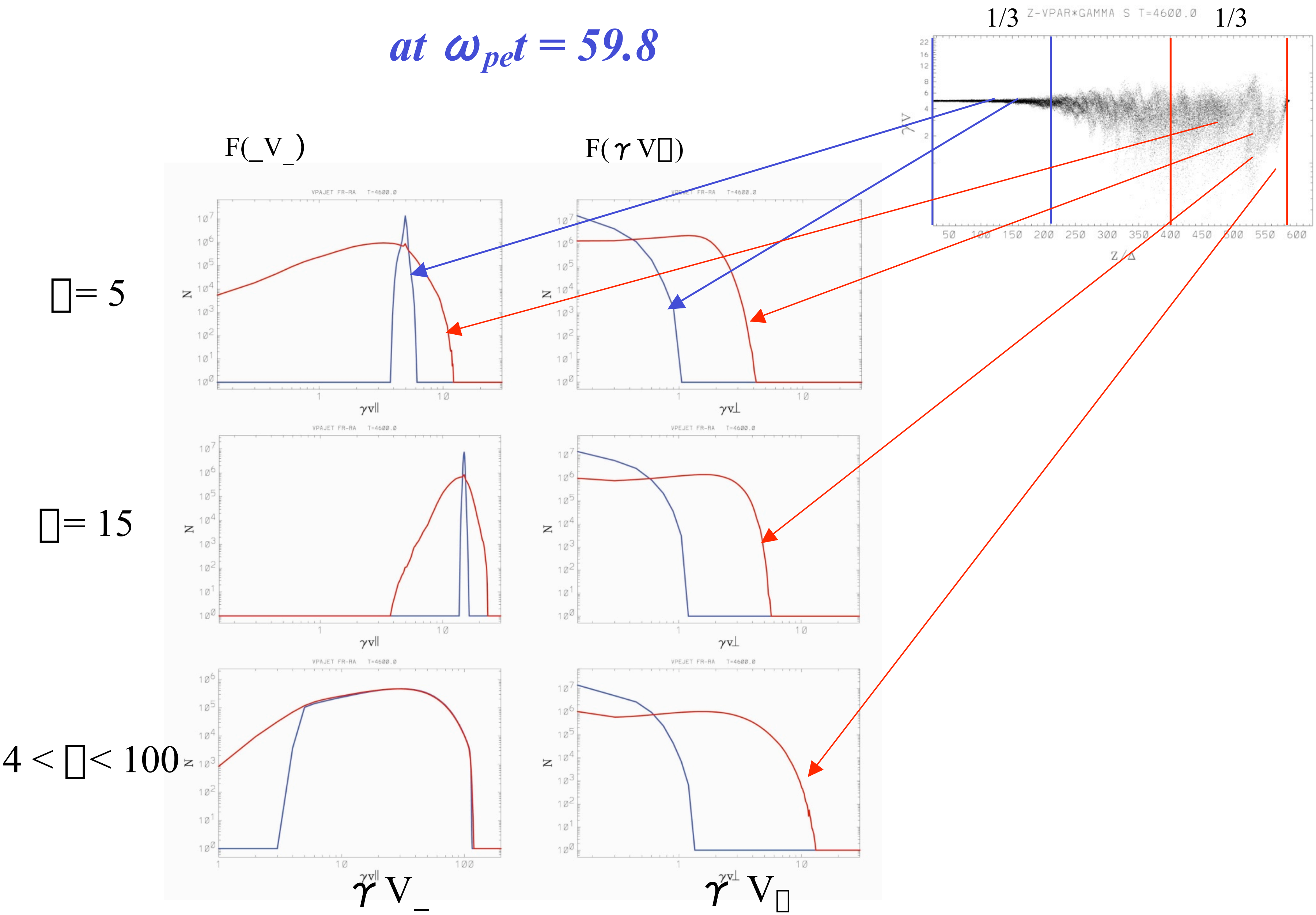


Total magnetic field energy (Bx2 +By2 +Bz2) averaged in the x-y plane



Parallel and perpendicular velocity distributions

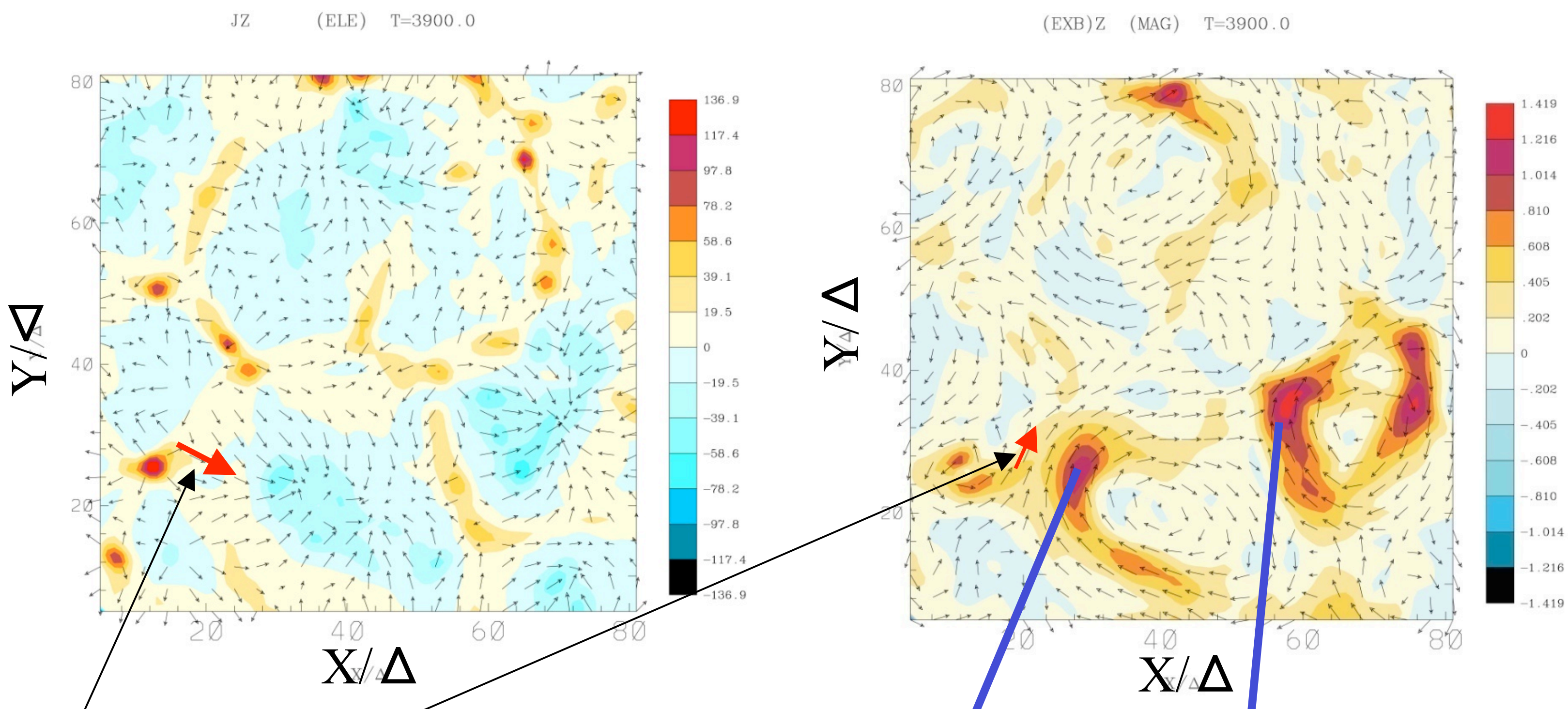
at $\omega_{pe}t = 59.8$



E_B acceleration and deceleration (Z/ Δ = 430)

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

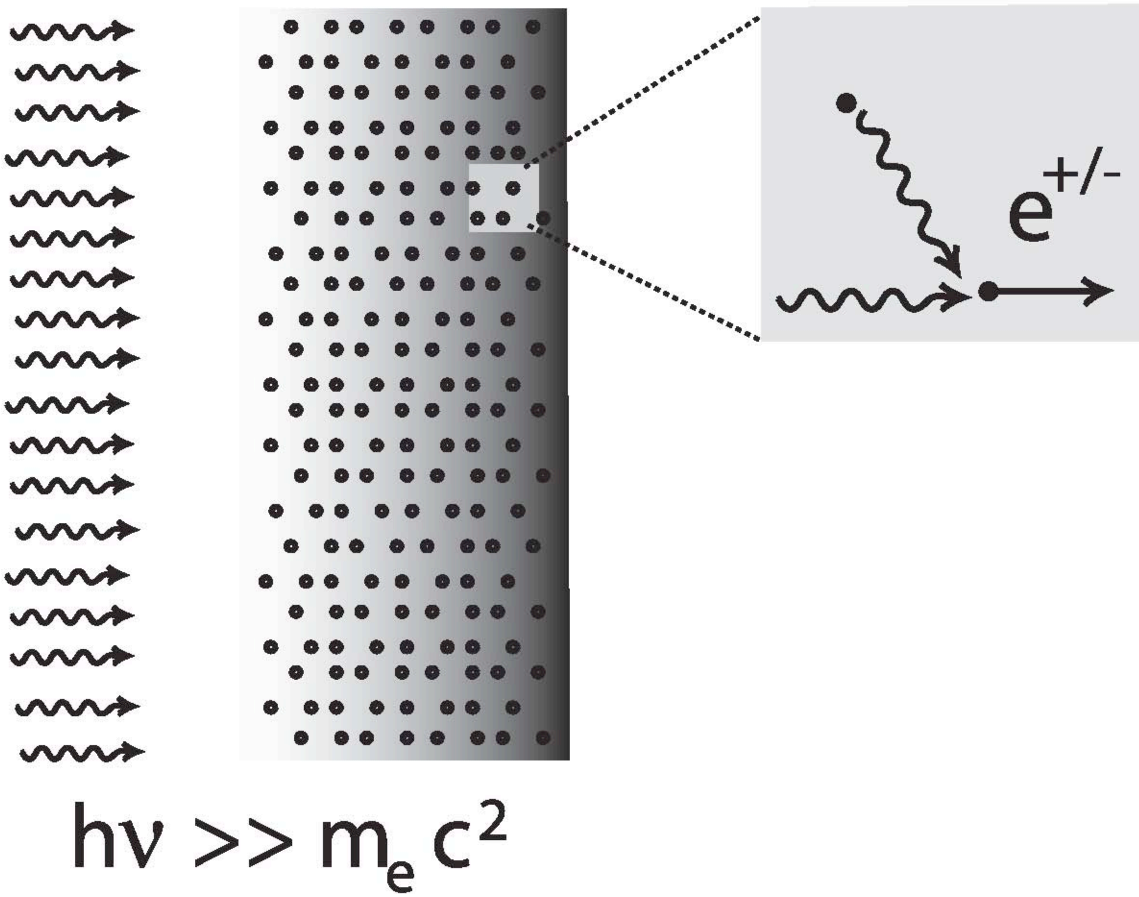
J_z arrows: E_x, E_y $(E\_B)_z$ arrows: B_x, B_y



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

both electrons (and positrons) are accelerated in this region

Pair-creation by collisions with lower energy photons: $\gamma\gamma \rightarrow e^+e^-$



Schematic plot of $e^{\pm}$ pair cascades triggered by the back-scattering of seed γ-ray photons on the external medium.

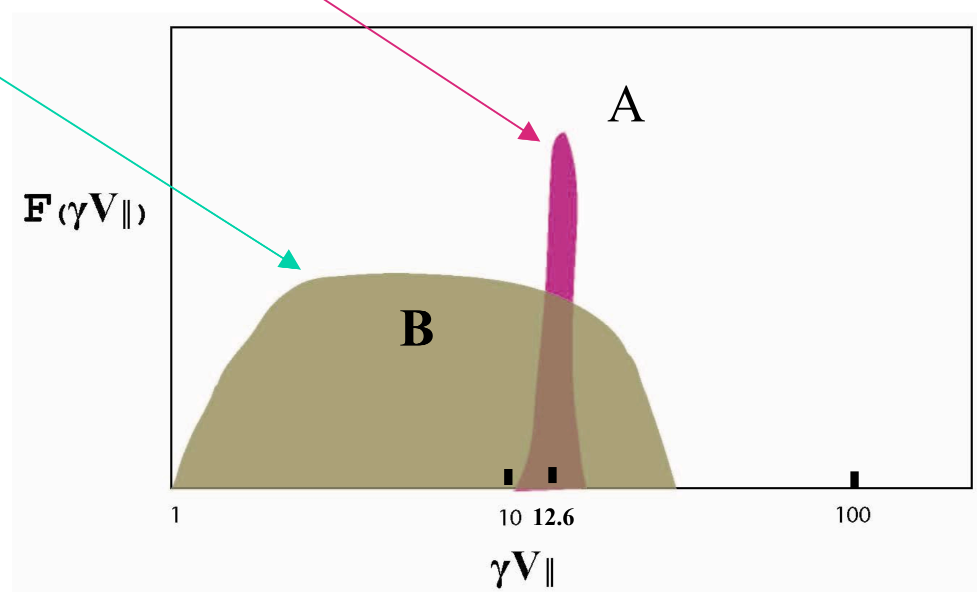
Initial parallel velocity distributions of pair-created jets (e±) (into ambient pair plasma)

- A: $\gamma = (1-(v_j/c)^2)^{-1/2} = 12.57$
- B: $1 < \gamma < 30$

  (distributed cold jet)

  (pair jet created by photon annihilation, _+_□ e±)
- A'and B': injected into ambient electron-ion plasma

Schematic initial parallel velocity distribution of jets



Growth times of Weibel instability:

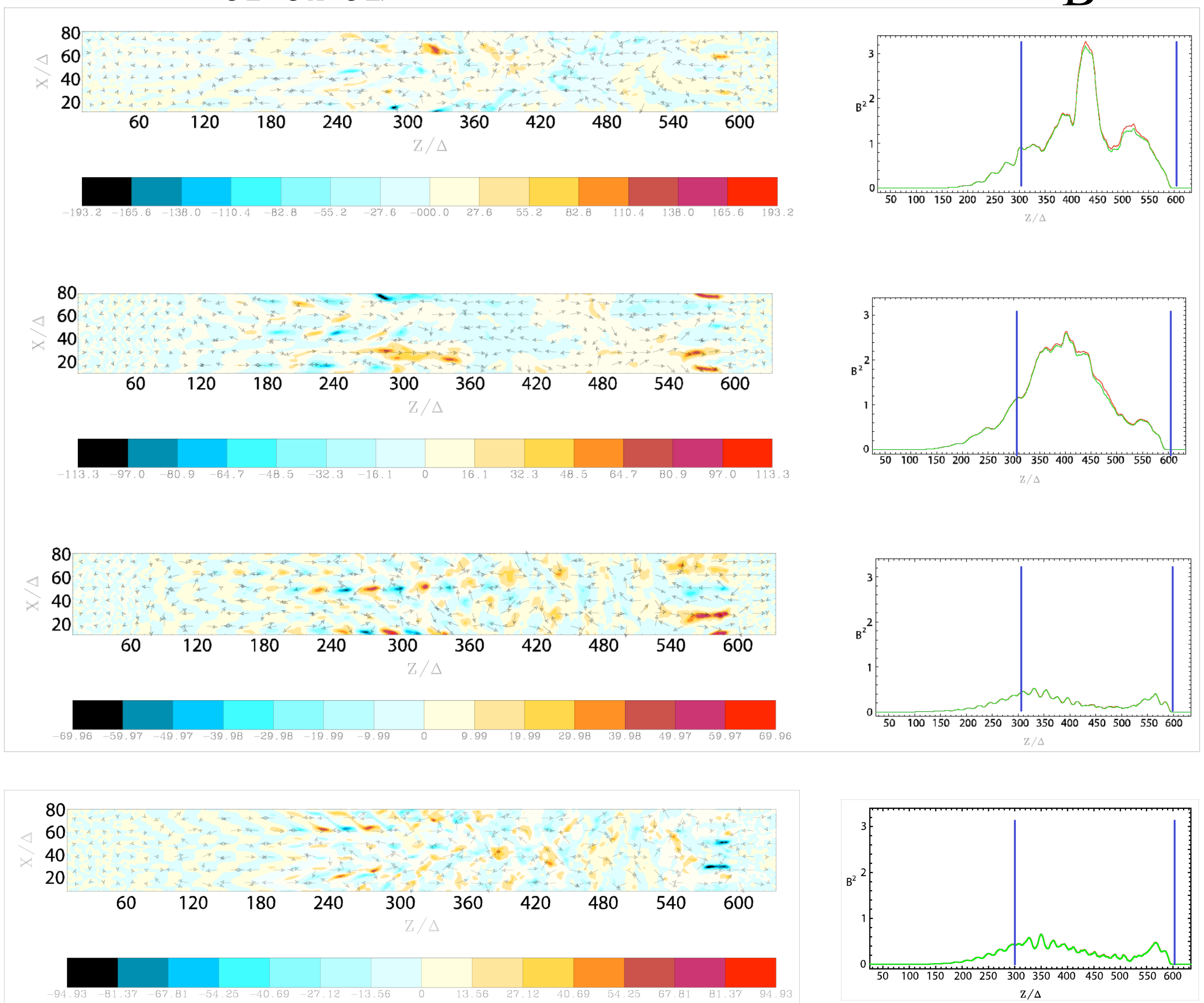
_ $_{B'} \ll \tau_{A'} \ll$ _$_{B} \approx$ _$_{A}$

Comparisons among four cases

□B
(shocked region: 300<z<600)

j_z (j_x, j_z)

B^2



A'
narrow
el-ion

2.57%
(1.38%)

B'
broad
el-ion

2.75%
(1.54%)

A
narrow
el-po

0.60%
(0.38%)

B
broad
el-po

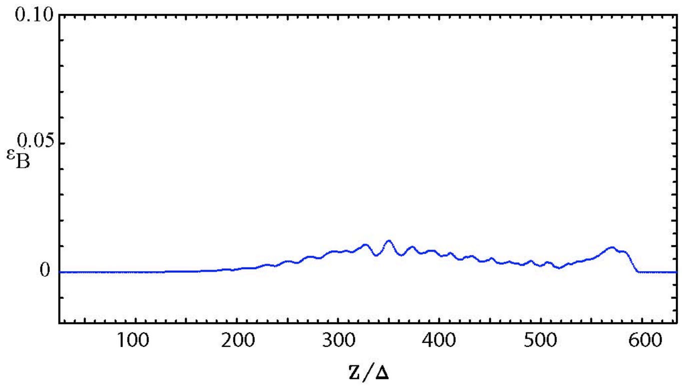
0.45%
(0.30%)

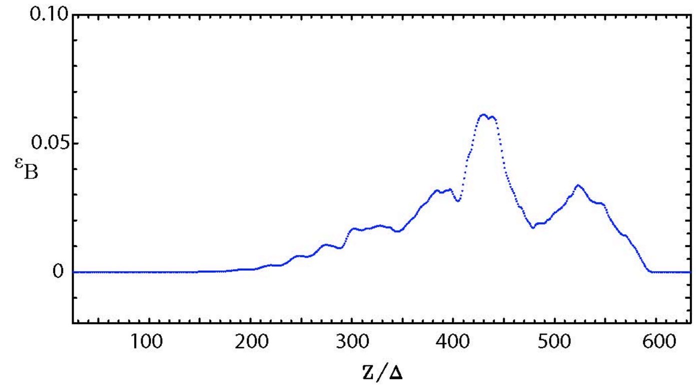
ϵ_B *along the jet for four different cases*

ele-pos ambient

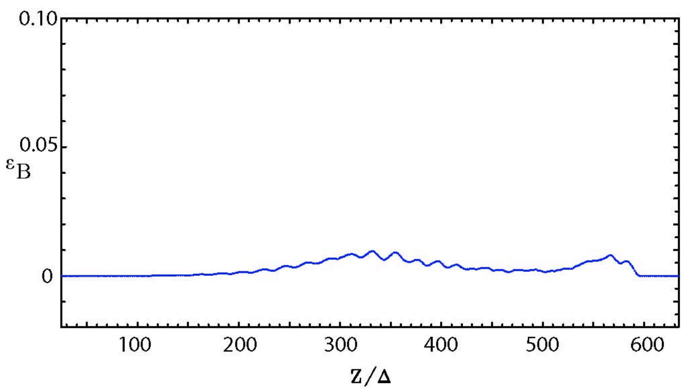
ele-ion ambient

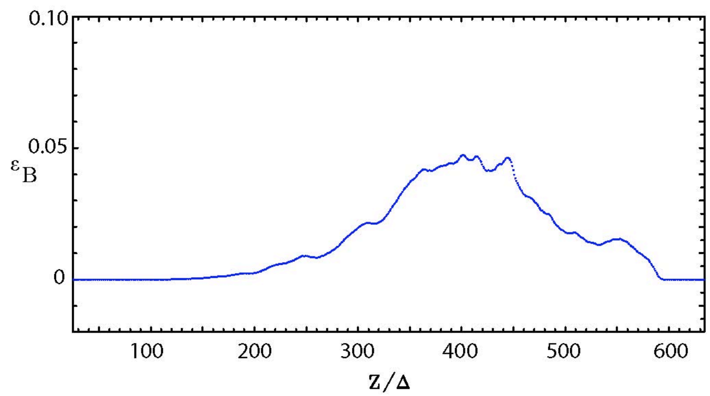
narrow





broad



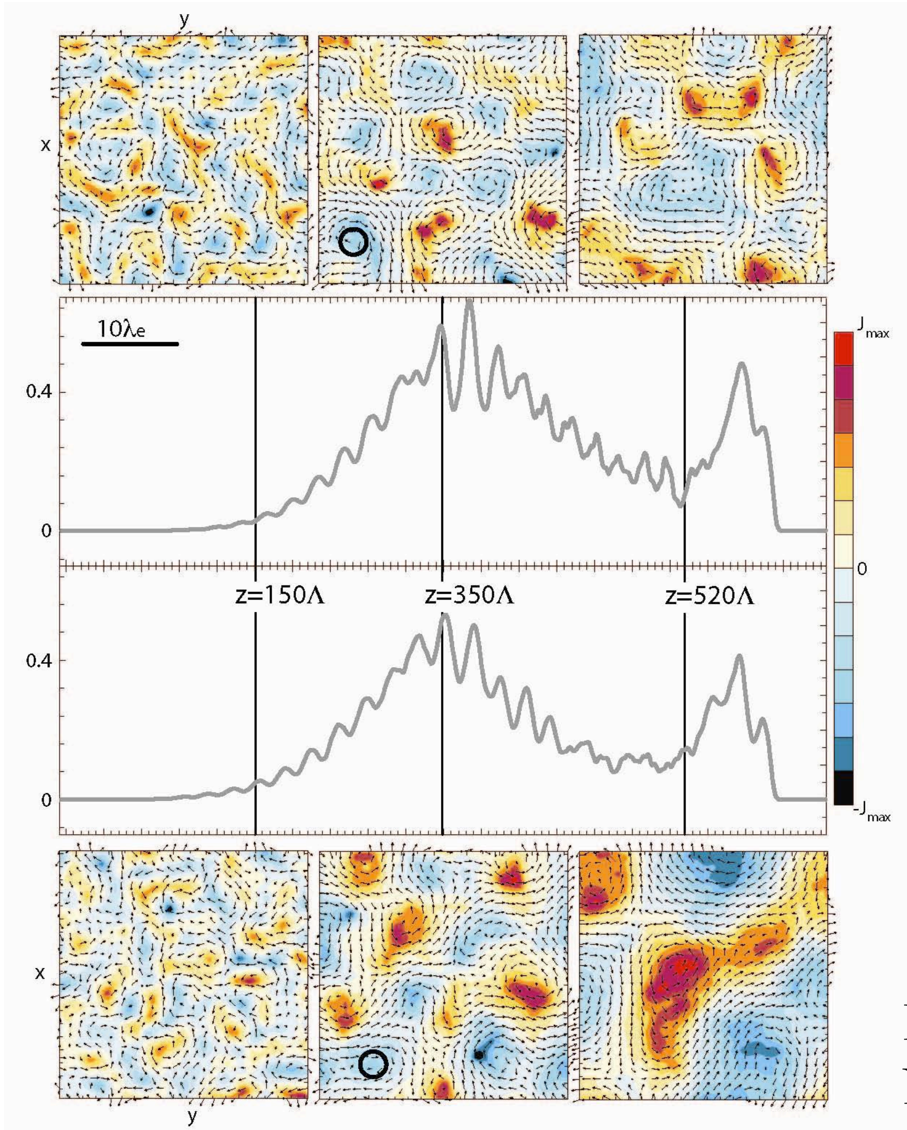


Growth of the two-stream instability at time t = 59.8_pe

J_

B

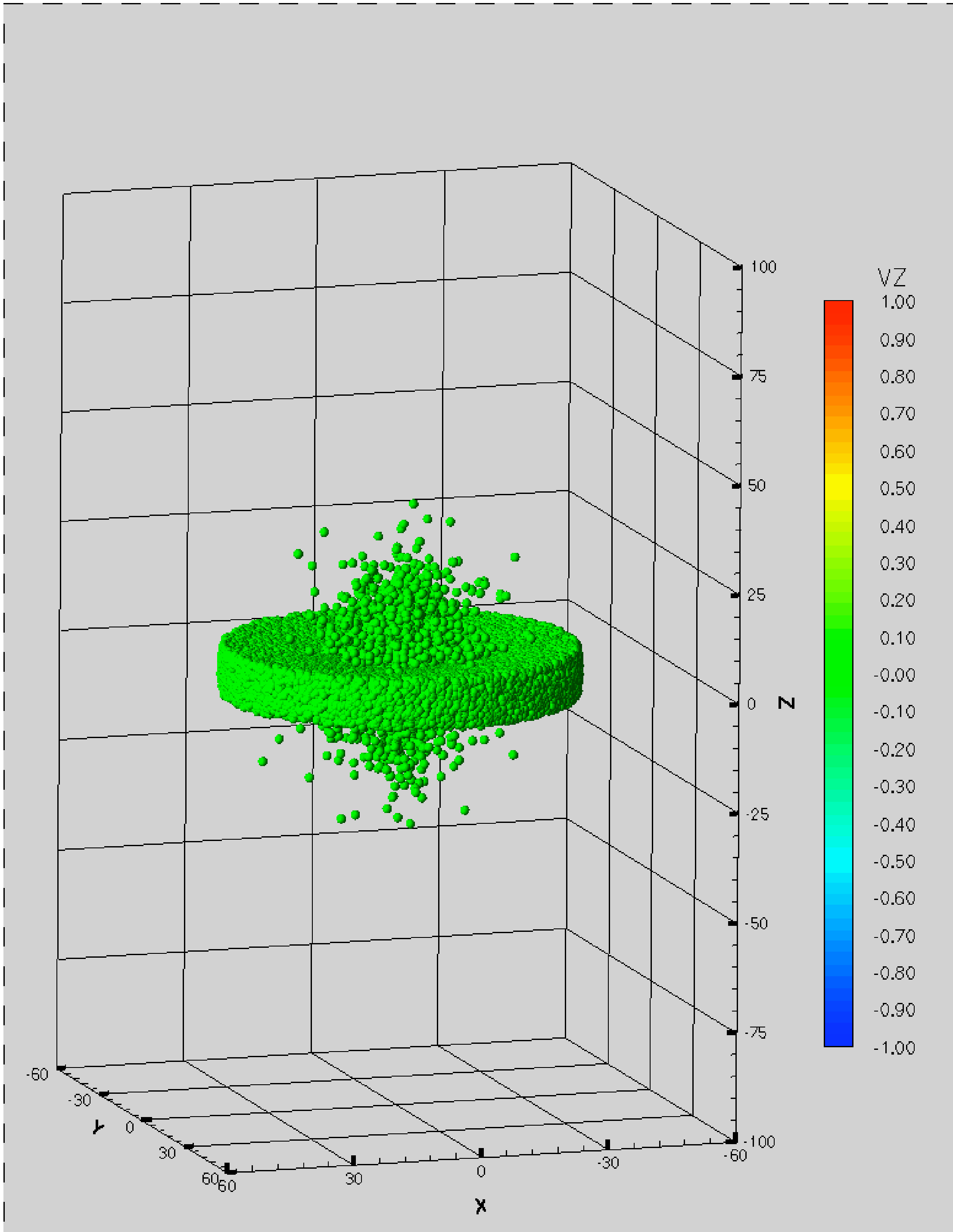
J_

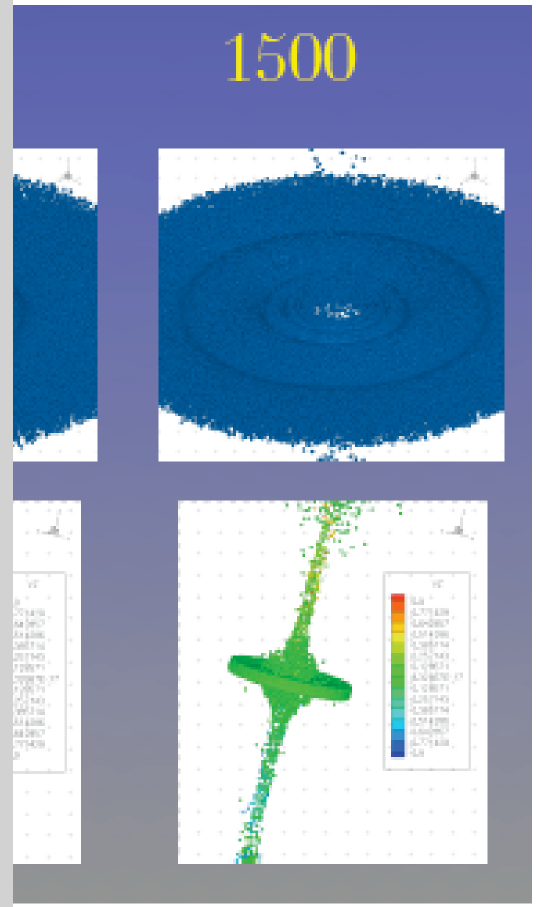


monoenergetic

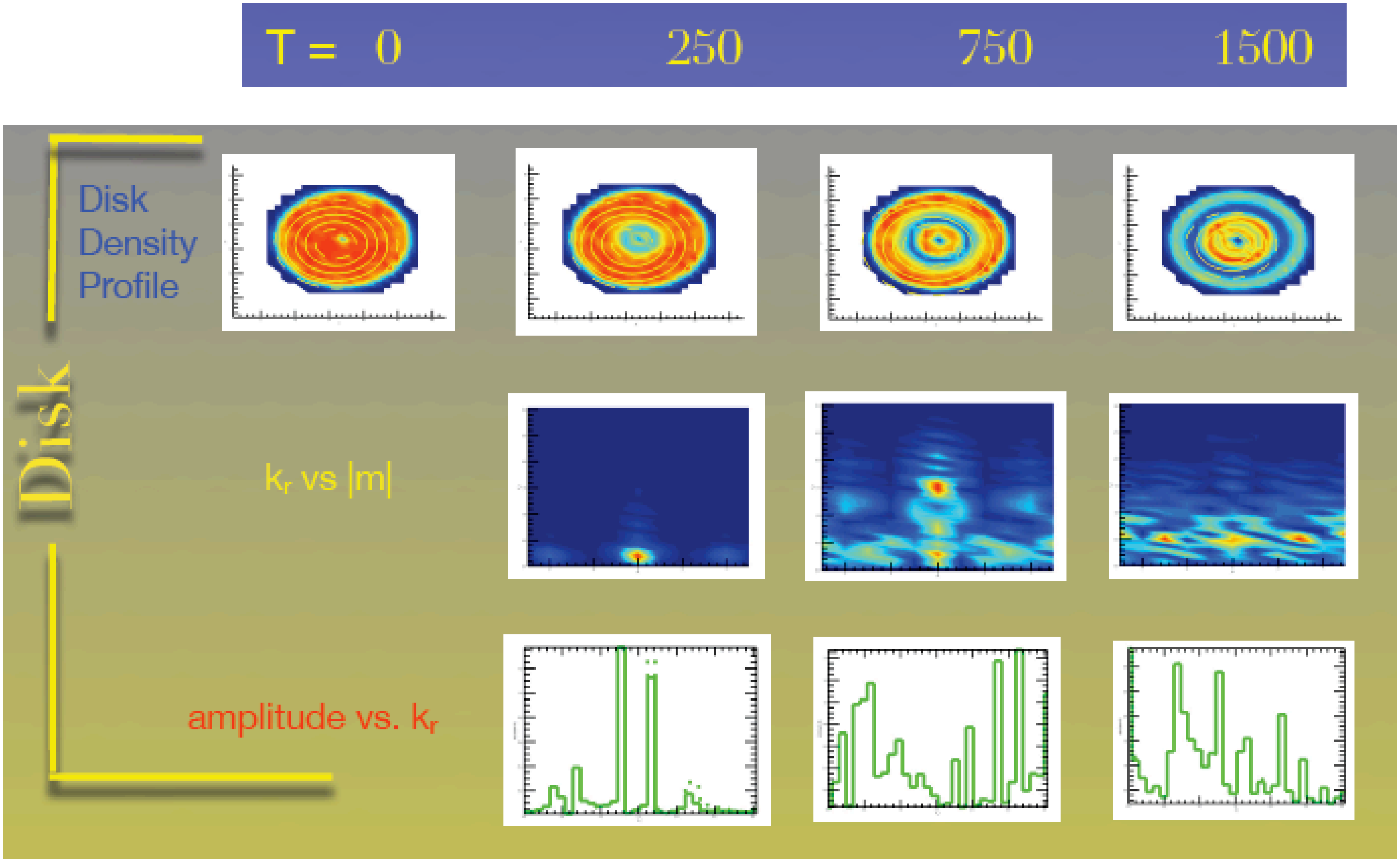
broadband

Ramirez-Ruiz, Nishikawa, Hededal (2007)


VZ
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
-0.90
-1.00
Z
100
75
50
25
0
-25
-50
-75
-100
Y
-60
-30
0
30
60
X
60
30
0
-30
-60


1500

Evolution of accretion disk with kinetic processes



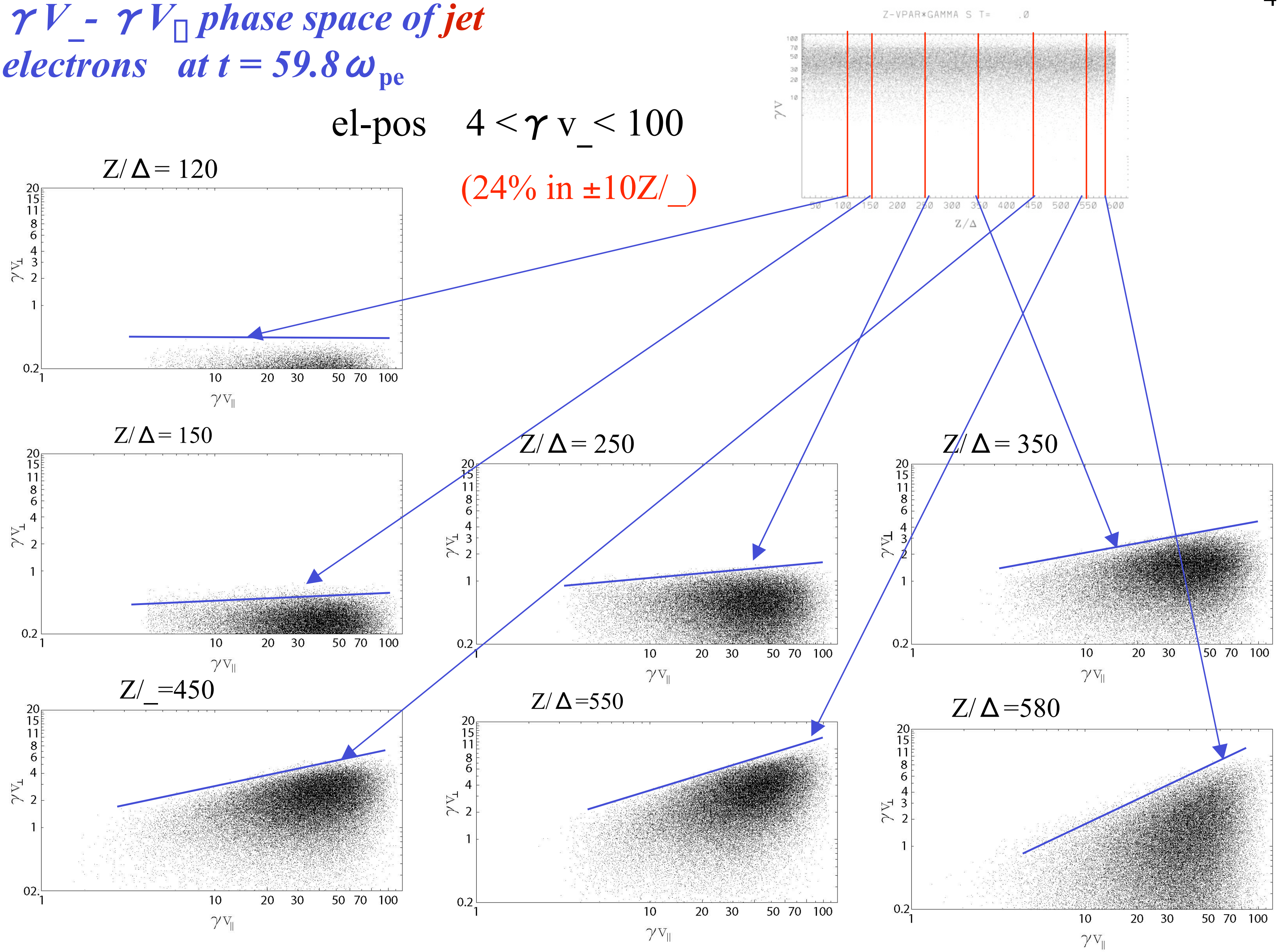
Disk Instabilities

- We have conducted a preliminary analysis on the plasma mode and density structure within the disk.
- There is no electric field at T = 0.
- The first row is the density profile within the disk. The density
structure develops waves as the jet develops.
- The second row shows the growth of |m| = 4 for the z-component of the electric field . As the jet fully develops the instabilities grow within the disk.
- The third row shows the mode amplitude of the instability.

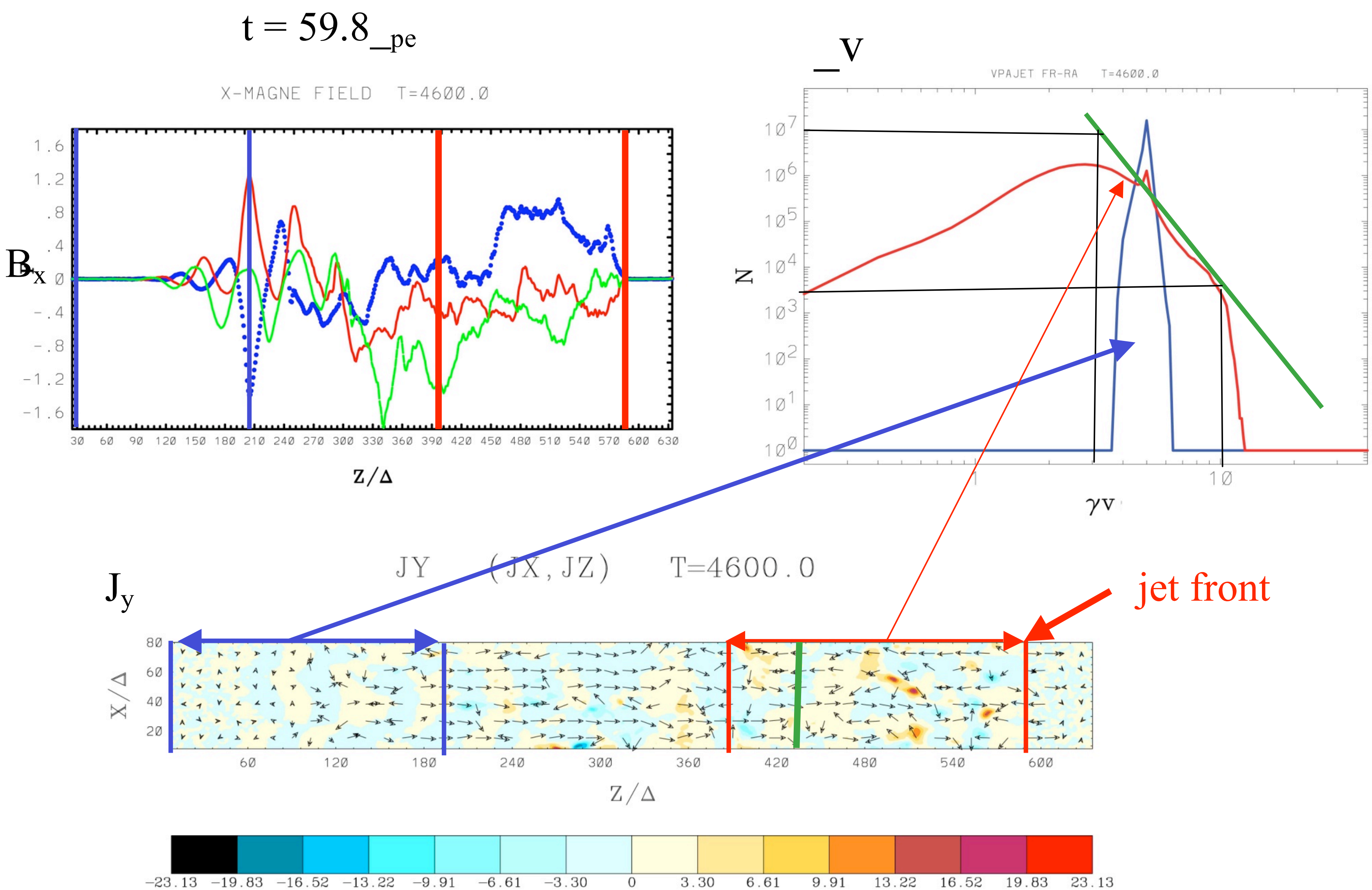
Summary and Further Development

• There appears to be mode coupling between the disk and the jet within the simulation. We see some of the same instabilities within the disk electric field within the jet region.
• The low grid resolution prevents an in-depth analysis of the density modes.
• We will increase the number of particles to study the density fluctuations and to test the correspondence with the field modes.
• We will include studies of the particle heating and work done by the field on the particles.
• Using MPI, we will make the code parallel.

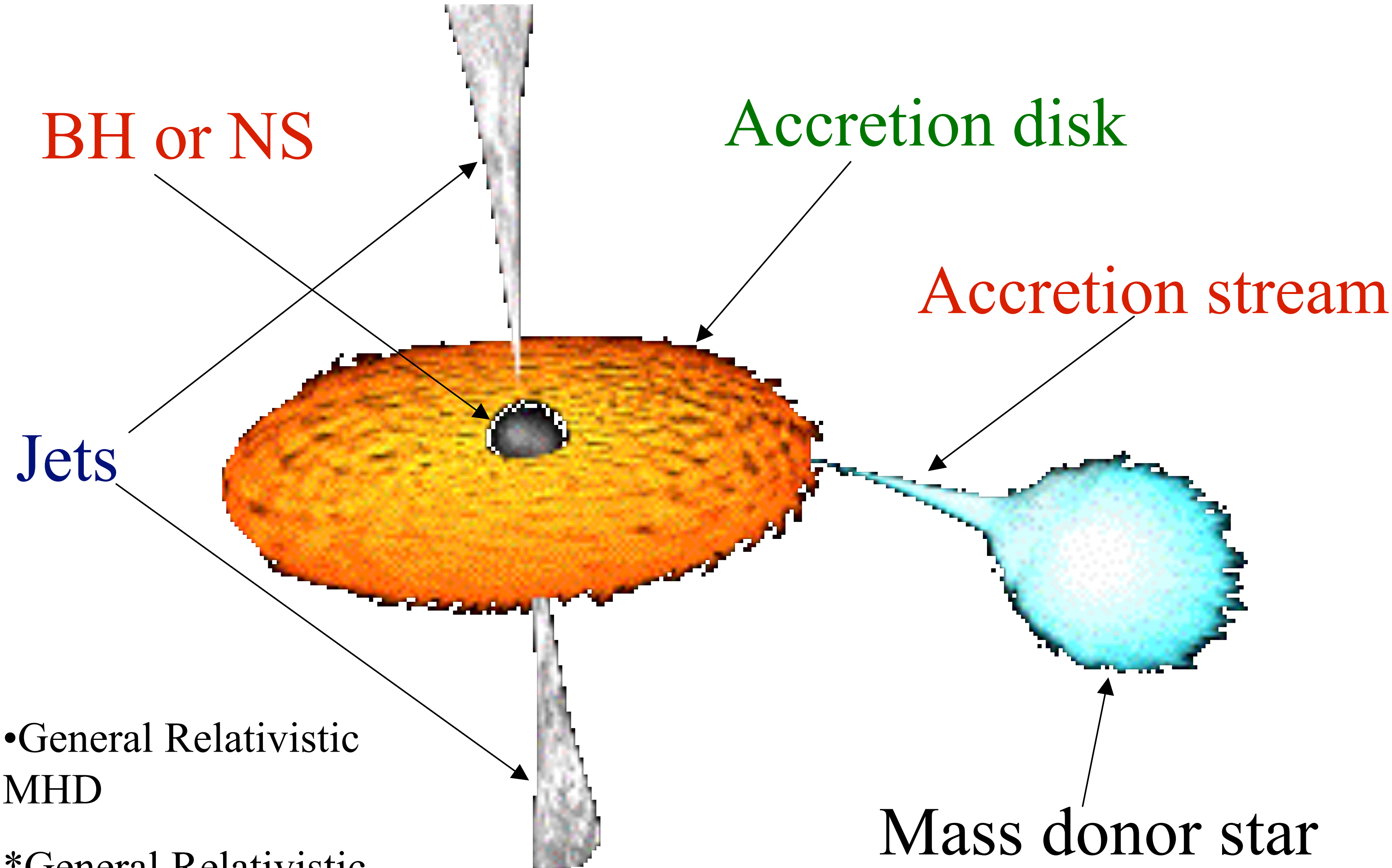
γ V_- γ V▯ phase space of jet electrons at t = 59.8 ω_{pe}



Longer simulation of electron-ion jet injected into unmagnetized plasma



Jets from binary stars (Schematic figure)



•General Relativistic MHD

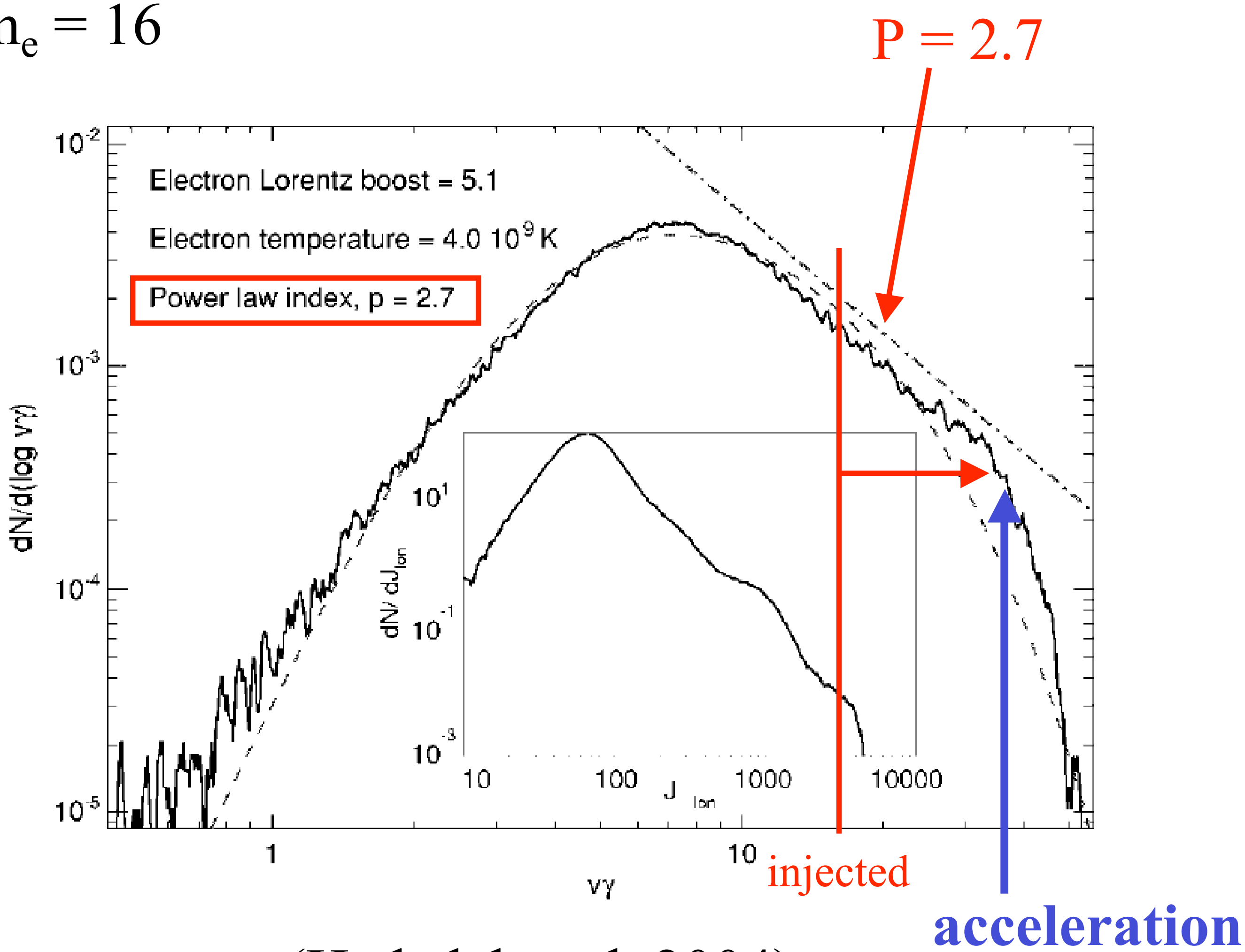
*General Relativistic PIC

Scientific objectives

- **How do shocks in relativistic jets evolve in accelerating particles and emission?**
- **How do 3-D relativistic particle simulations reveal the dynamics of shock front and transition region?**
- **What is the main acceleration mechanism in relativistic jets, shock surfing, wakefield, Fermi models or stochastic processes?**
- **Obtain spectra and time evolutions from simulations and compare with observations**
- **Understand observations from GLAST (GBM) based on simulation and theoretical studies**

Electron acceleration by ion Weibel instability

_=15, m_i/m_e = 16

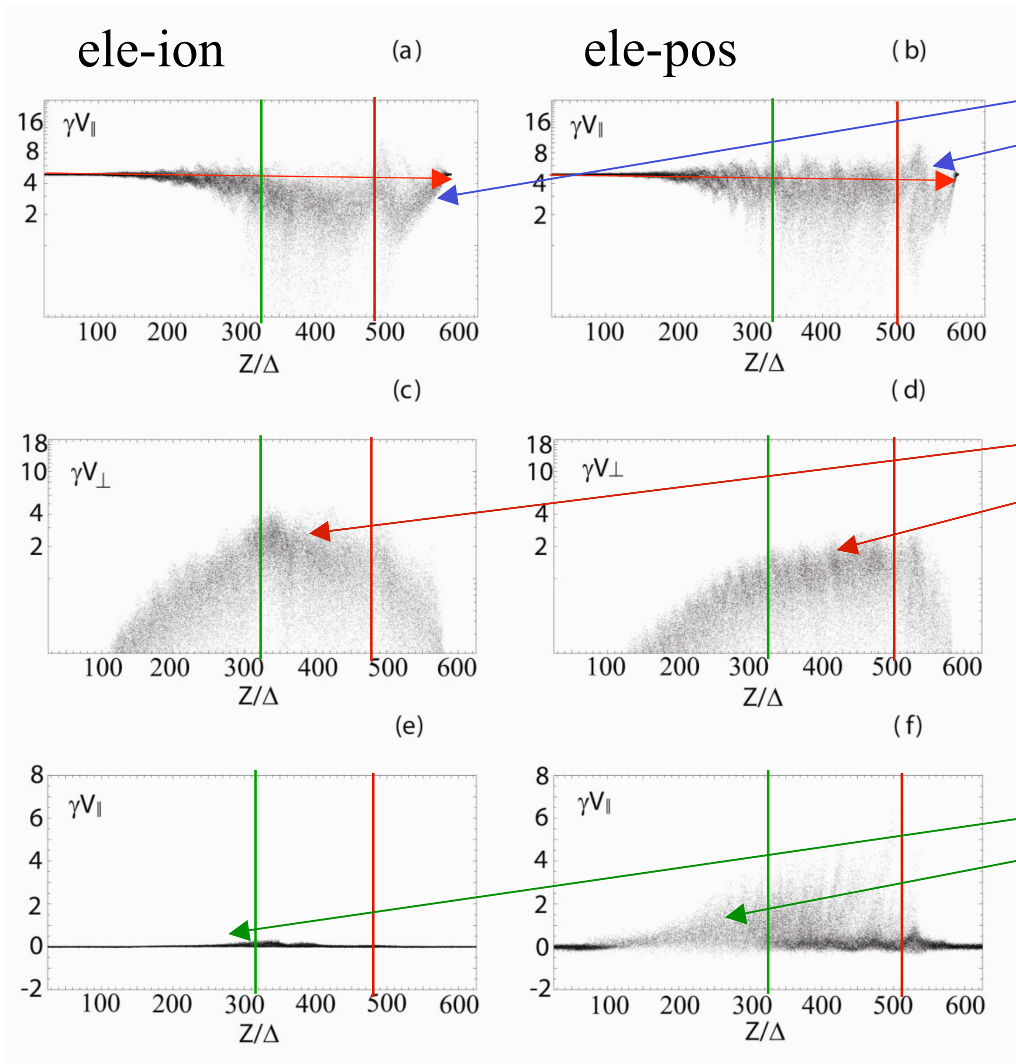


(Hededal et al. 2004)

Phase space distributions of elctrons

$\omega_{pe} t = 59.8$

jet



ambient

Jet head

Nonlinear stage

Linear stage

Parallel and perpendicular velocity space of ambient electrons along Z

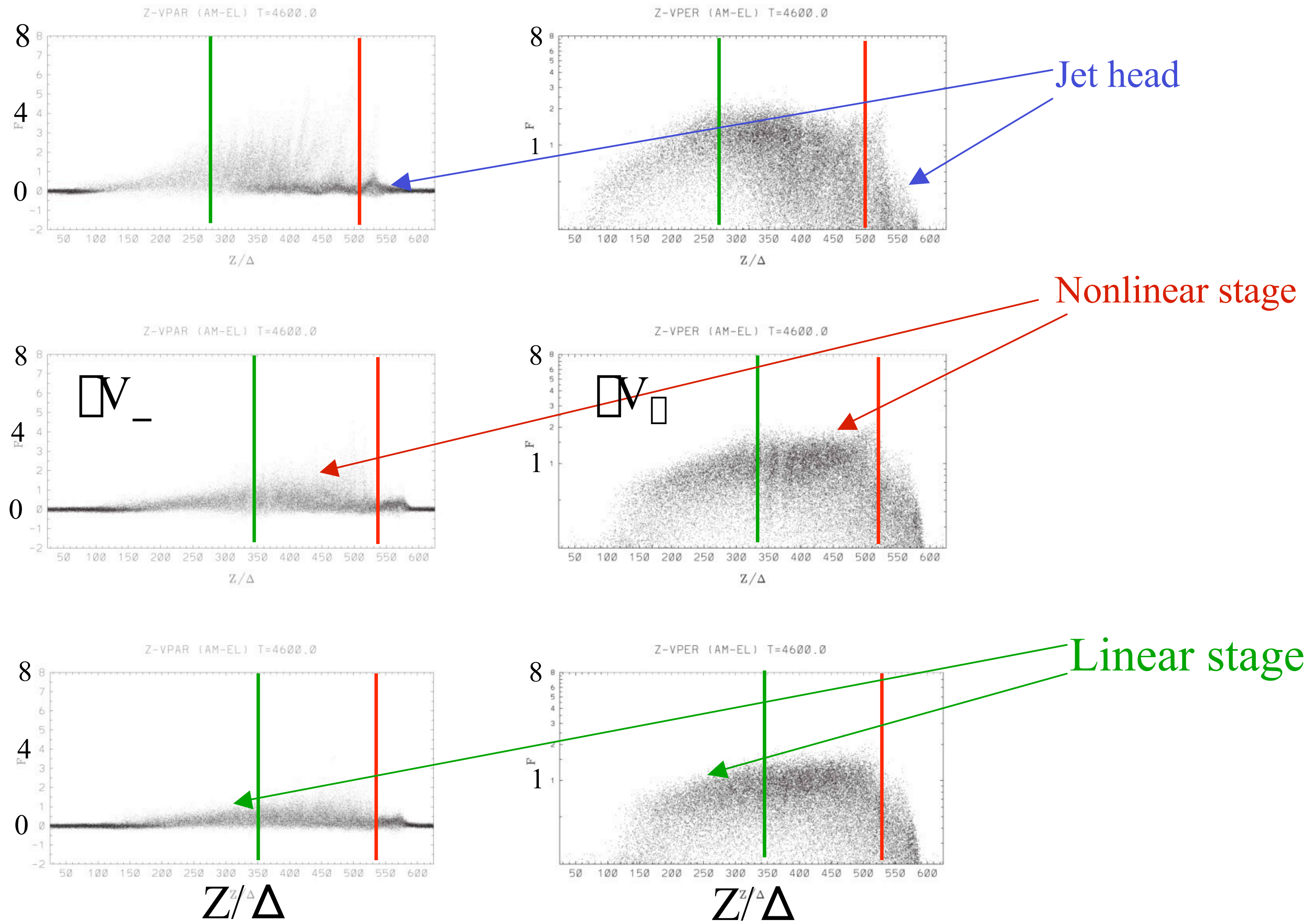
$\omega_{pe}t = 59.8$

parallel perpendicular

□= 5

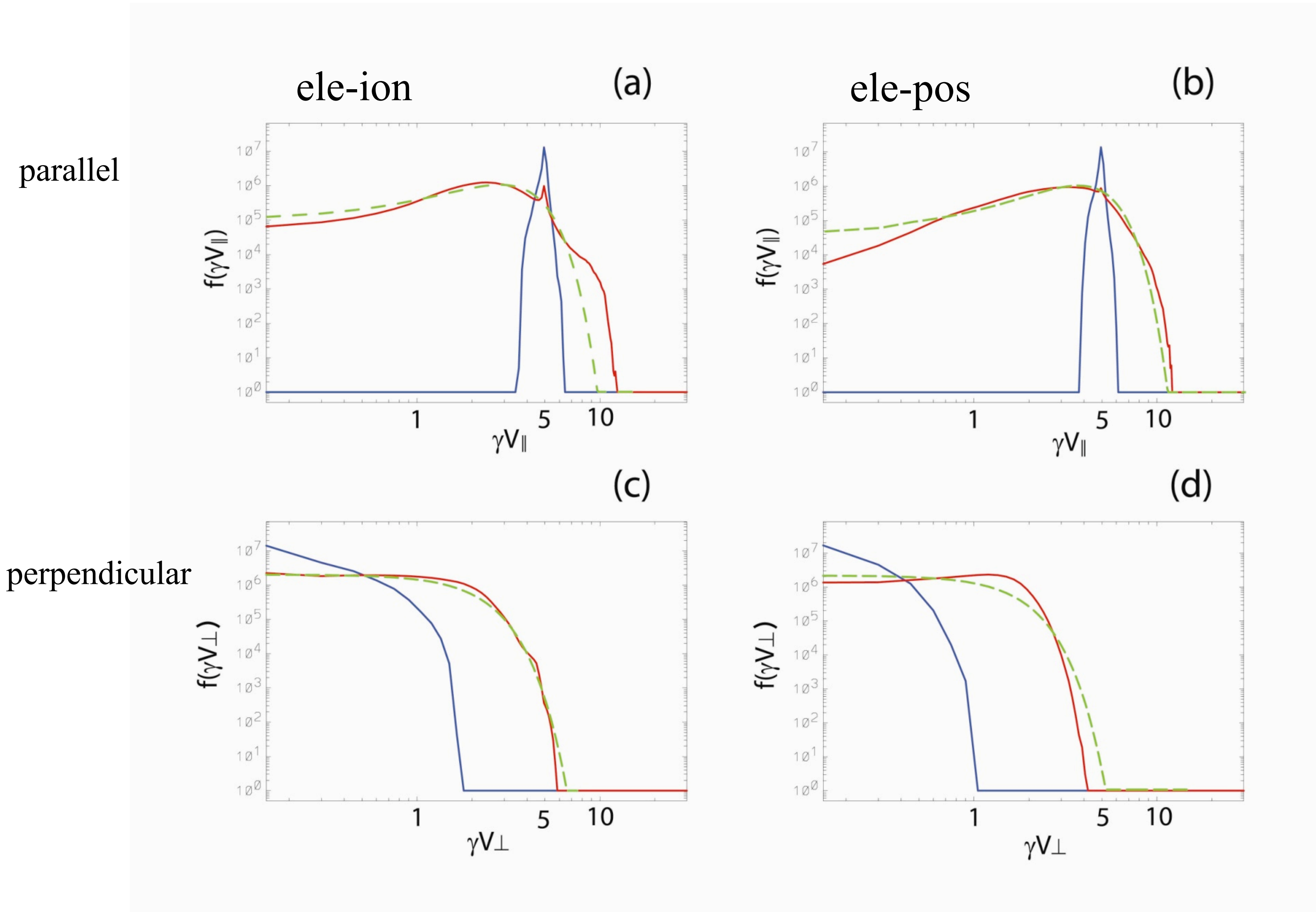
□= 15

4 <□<100



Electron jet velocity distributions

$\omega_{pe} t = 59.8$



Evolutions of magnetic fields

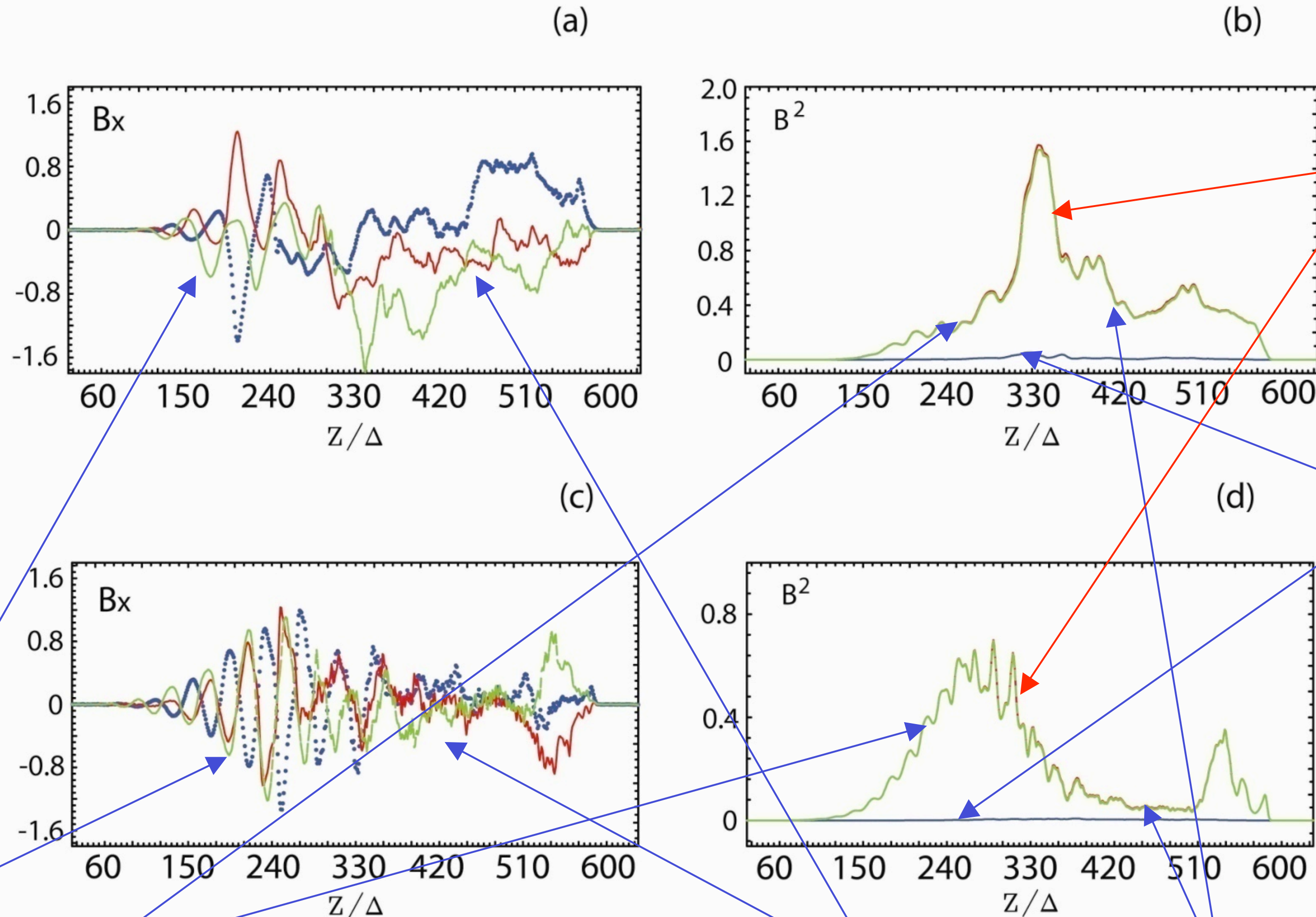
□= 5

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

x/_ = 38
y/_ = 33 (*blue*); 43 (*red*); 53 (*green*)

ele-ion

ele-pos



B²≈ B□²

B_²

linear grow

nonlinear stage

Generated magnetic field Bx along Z direction

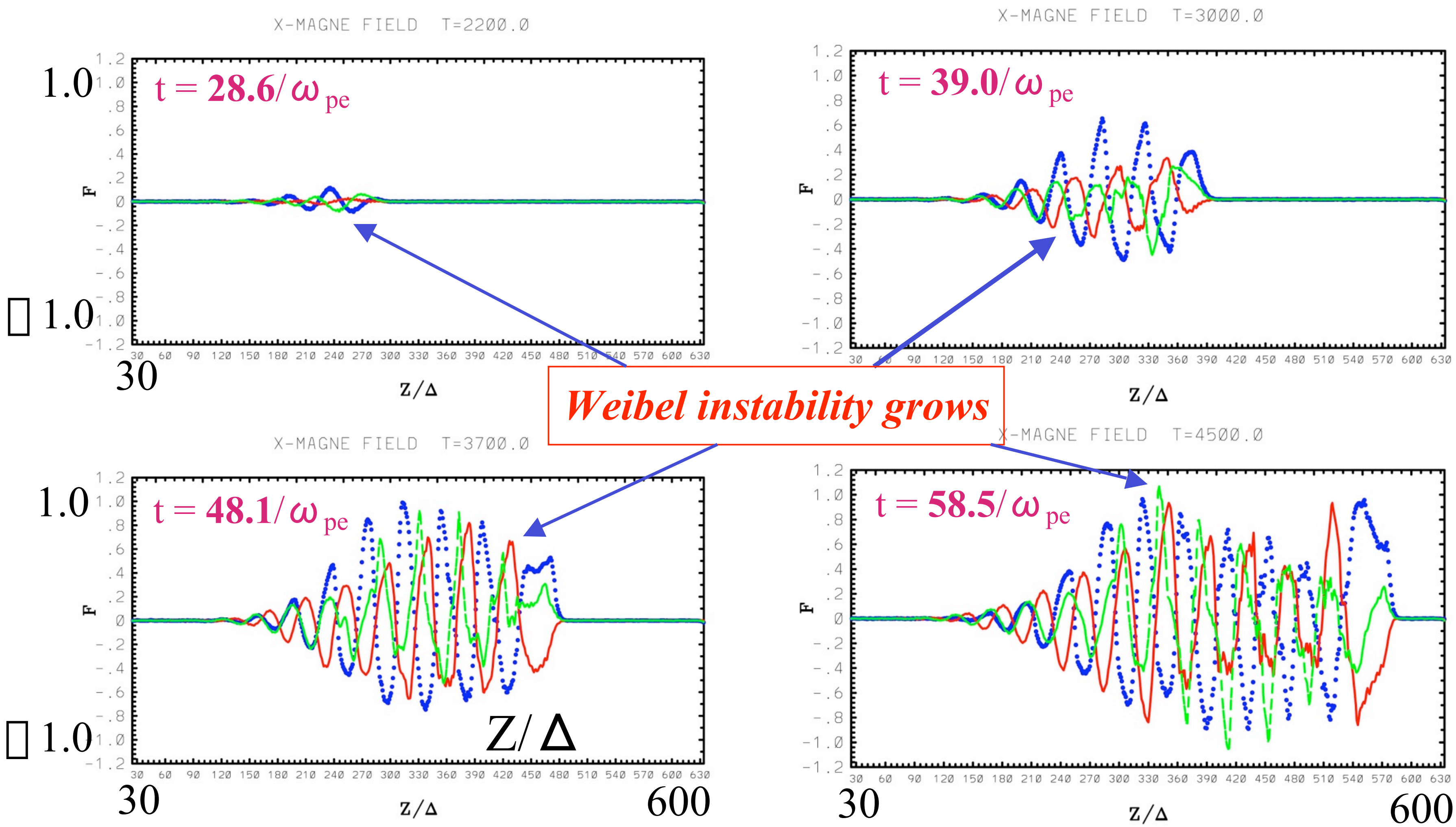
$4 < \gamma < 100$ (distributed cold jet)

at Y = 43 Δ

Blue X = 33 Δ

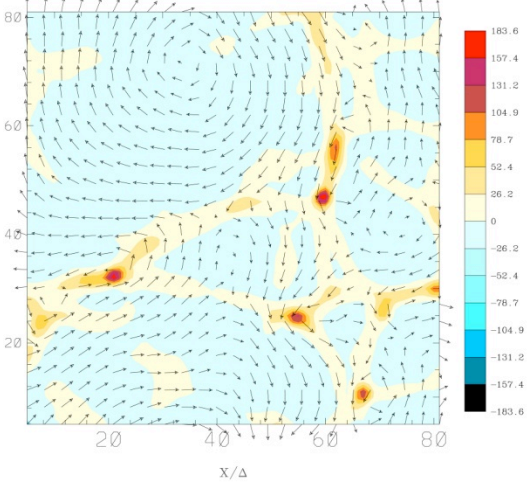
Red X = 43 Δ

Green X = 53 Δ

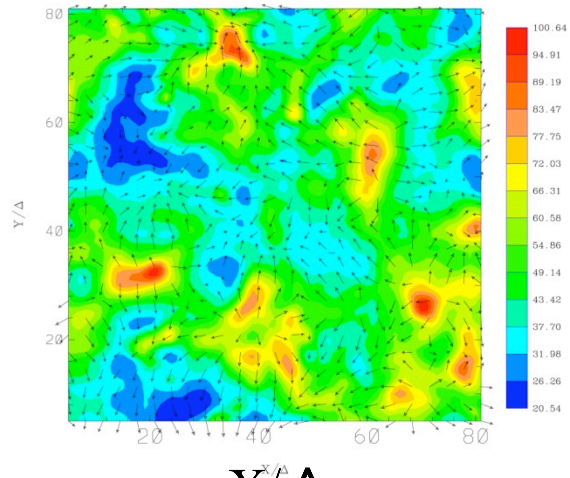


electron-ion jet $\gamma = 5$ $t = 59.8\,\omega_{pe}$ $(Z/\Delta = 430)$

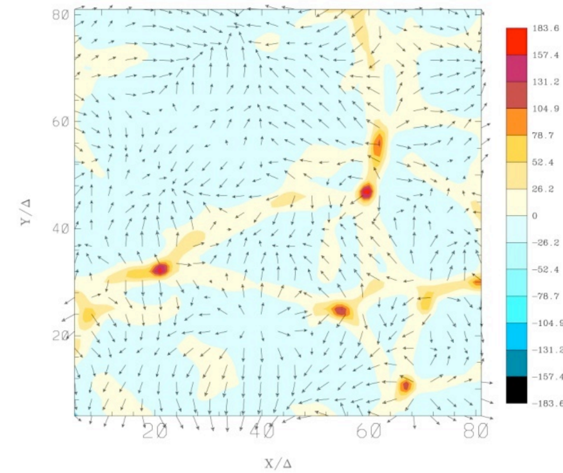
J_z arrows: B_x, B_y



n_e arrows: E_x, E_y



J_z arrows: E_x, E_y

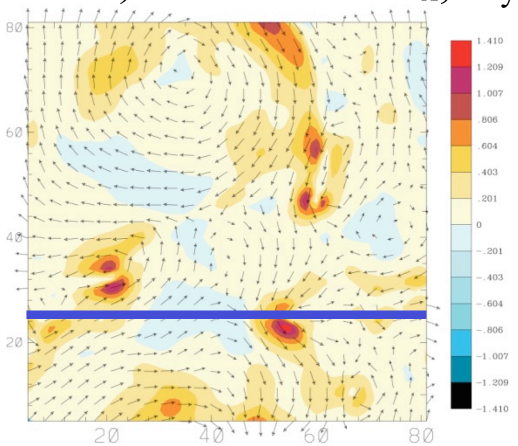


Y/Δ

X/Δ

jet ⎯

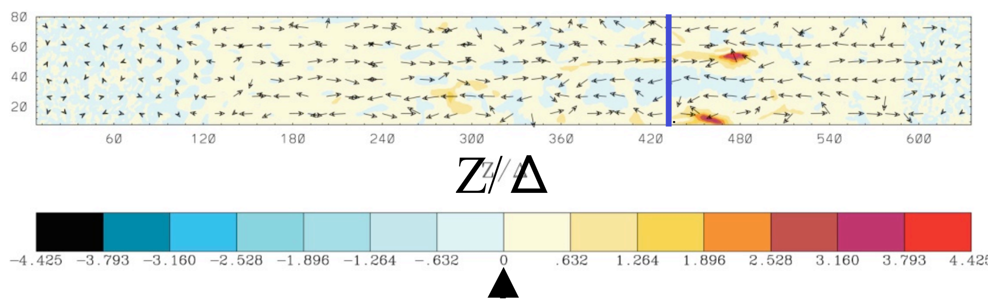
$(E \times B)_z$ arrows: B_x, B_y



Y/Δ

X/Δ

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



X/Δ

Z/Δ

0

Electron density (arrows: B_z, B_x)

electron-positron jet (_= 15) (B)

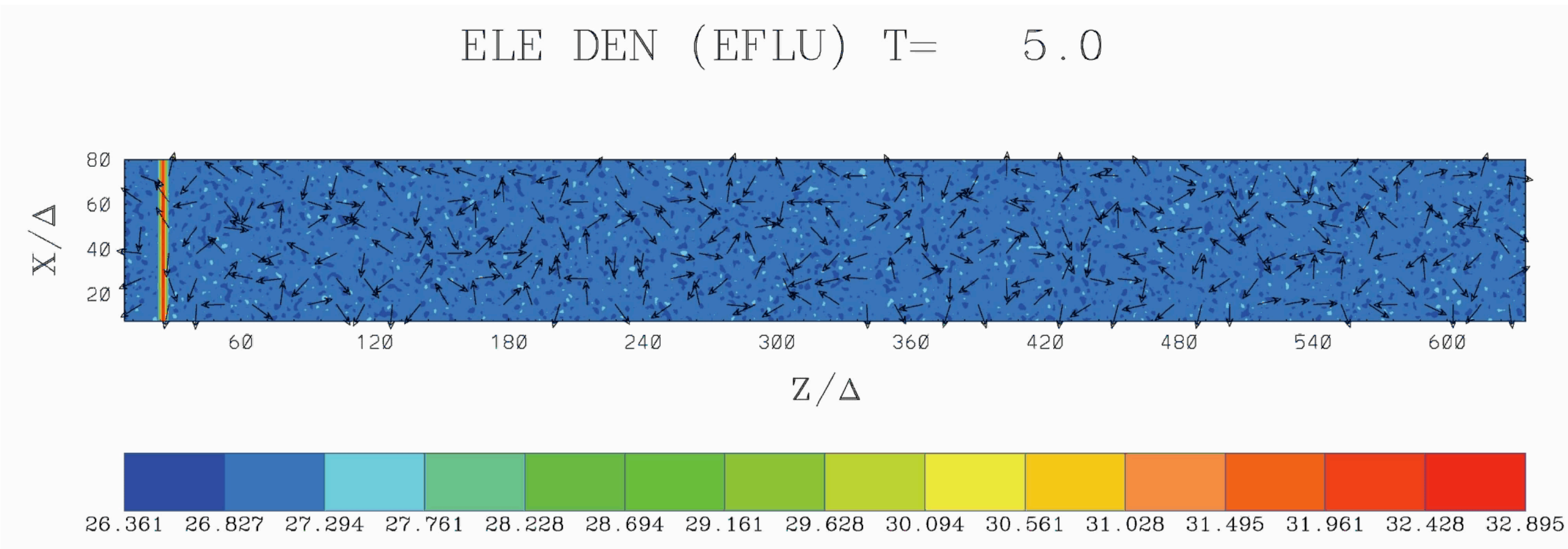
$\omega_{pe} t = 62.4$

$n_{ISM} = 1/cm^3$

$\_{pe}^{-1} = 0.1 msec$

$c/\omega_{pe} = 5.3$ km

$L \approx 300$ km



Weibel instability

jet front

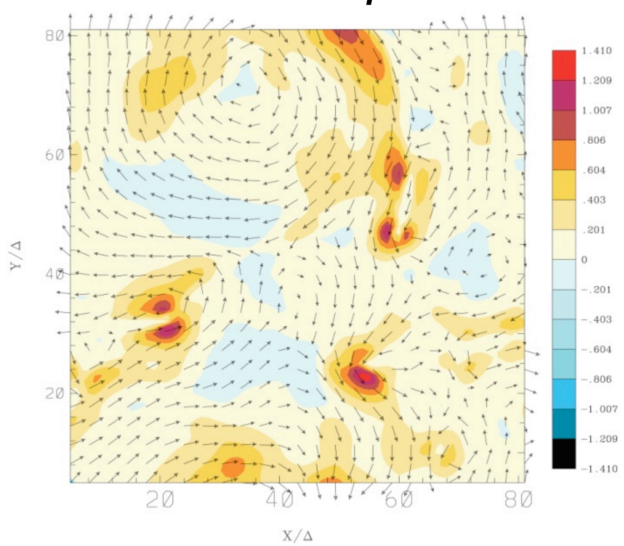
(Nishikawa et al. 2005)

E×B acceleration and deceleration in x-y plane (Z/Δ = 430)

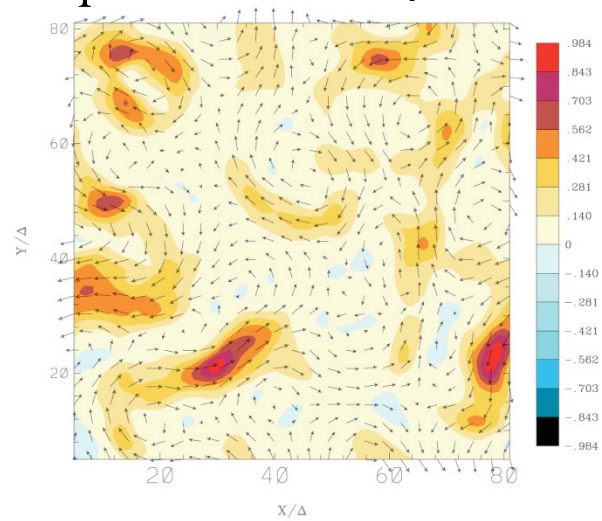
$(E\times B)_z$

arrows: Bx, By

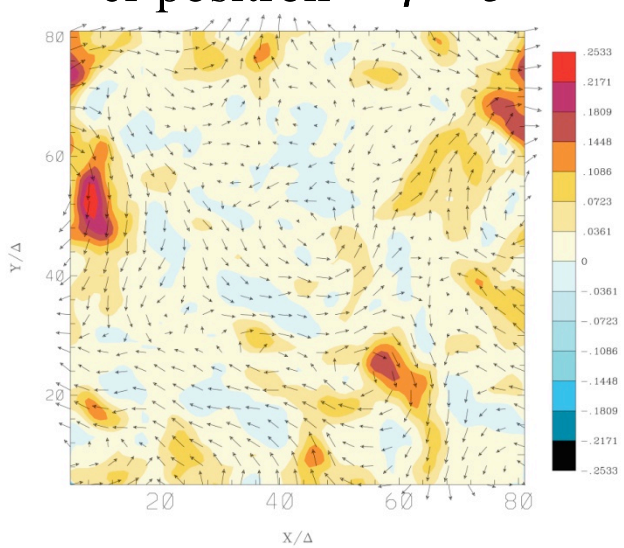
el-ion γ = 5



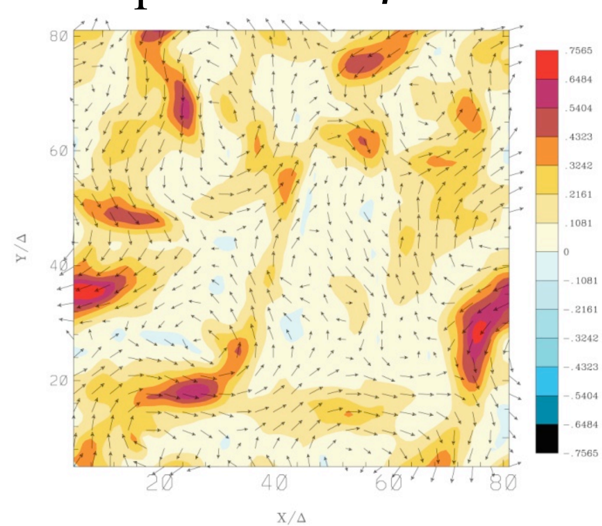
el-positron 10< γ <100



el-positron γ = 5



el-positron γ = 15



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

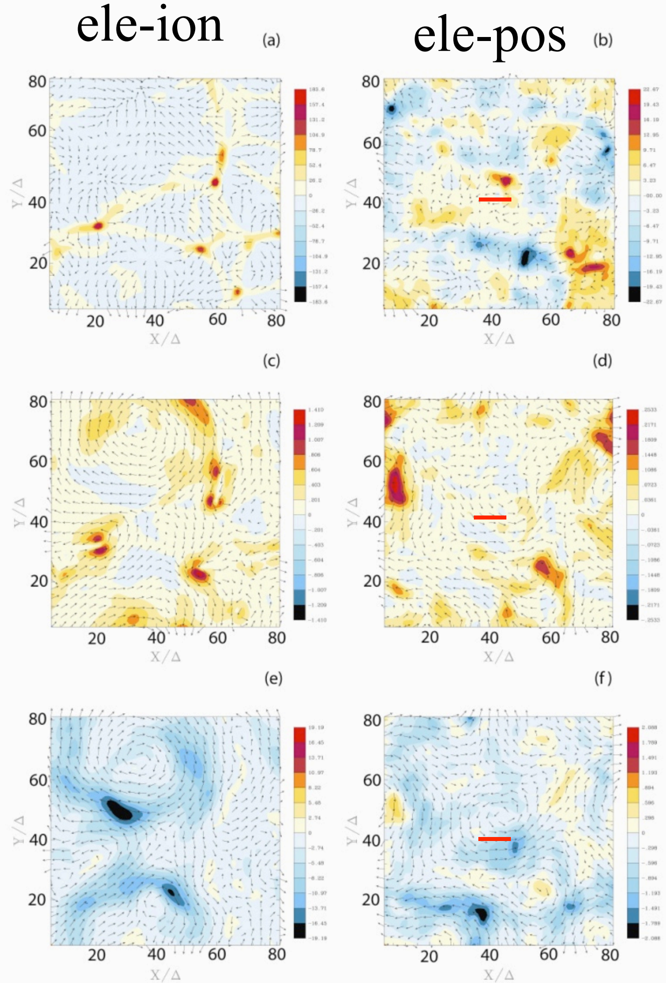
z/_=430 $\omega_{pe}\,t = 59.8$

ele-ion ele-pos arrows

J_z — E_x, E_y

$(E\_B)_z$ — B_x, B_y

$(E\times B)_z$ — B_x, B_y



__ = v_z/c

= 0.8

□= 5

ion current channel

_ electron current channel

***E_B* force accelerate and decelerate particles**

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

$\omega_{pe} t = 59.8$ □= 5

β _= v_z/c

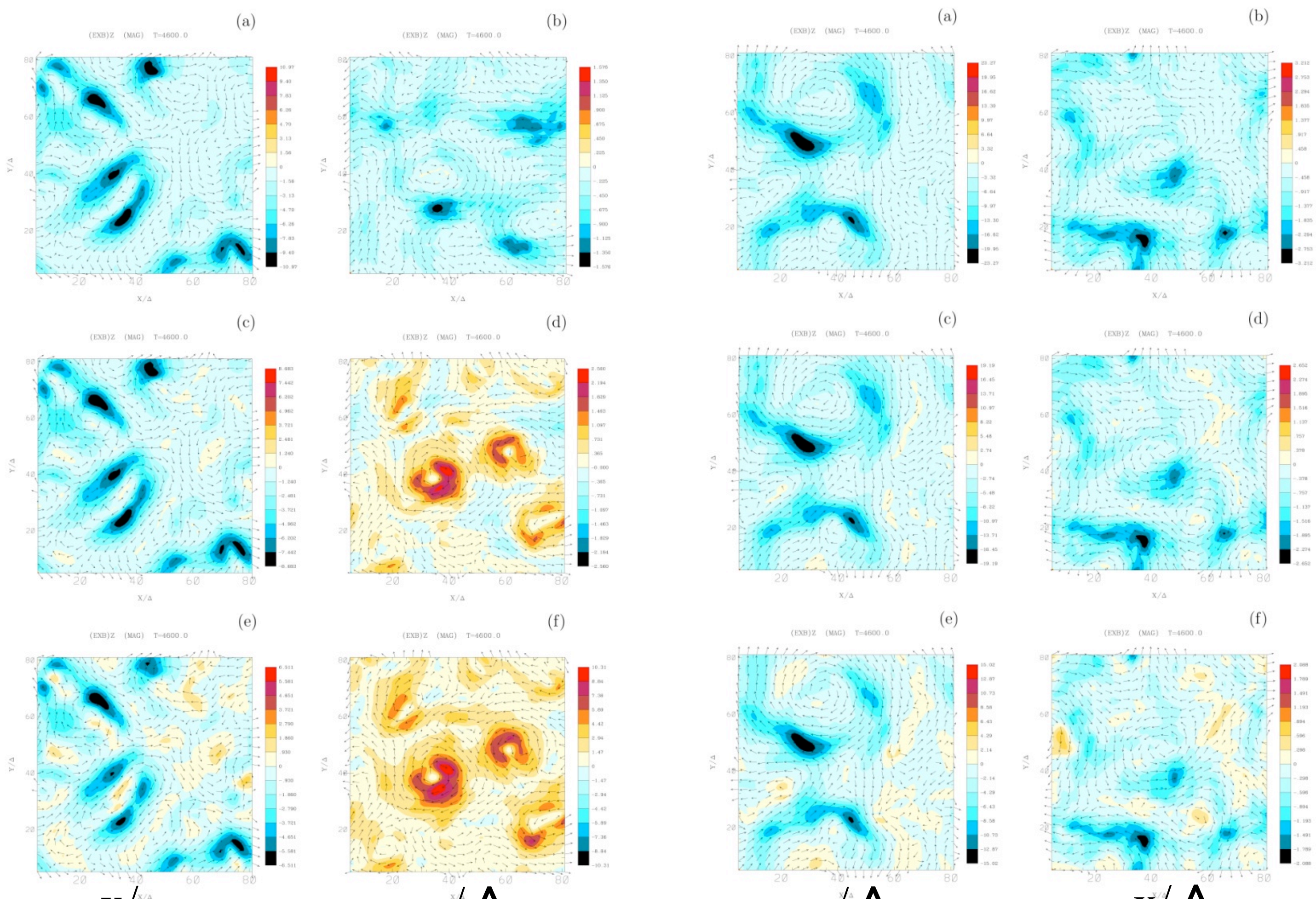
z/ Δ=250 — ele-ion, ele-pos

z/ Δ=430 — ele-ion, ele-pos

= 0.98

= 0.8

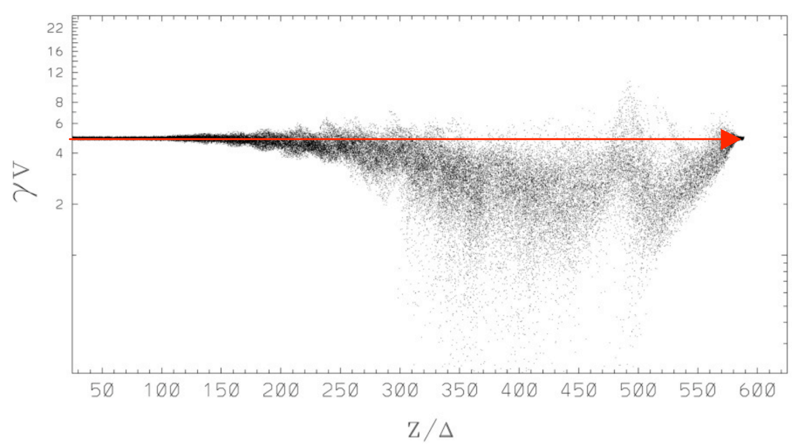
= 0.6



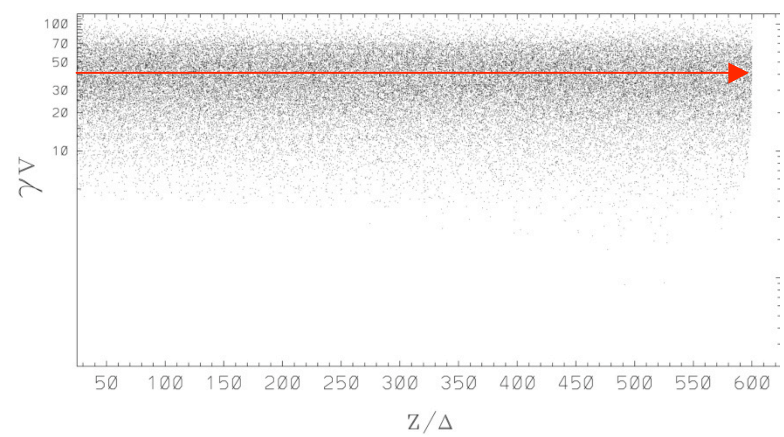
x/_ x/ Δ x/ Δ x/ Δ

*Z/_ - _V_phase space of **jet** electrons at $t = 59.8\,\omega_{pe}$*

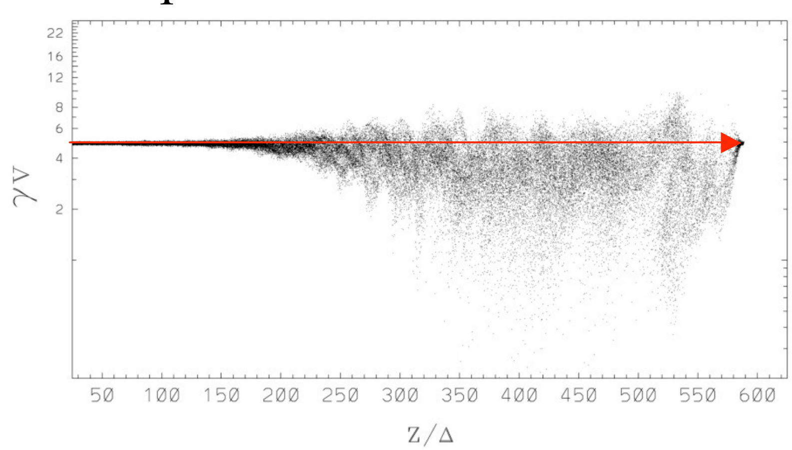
el-ion $\gamma = 5$



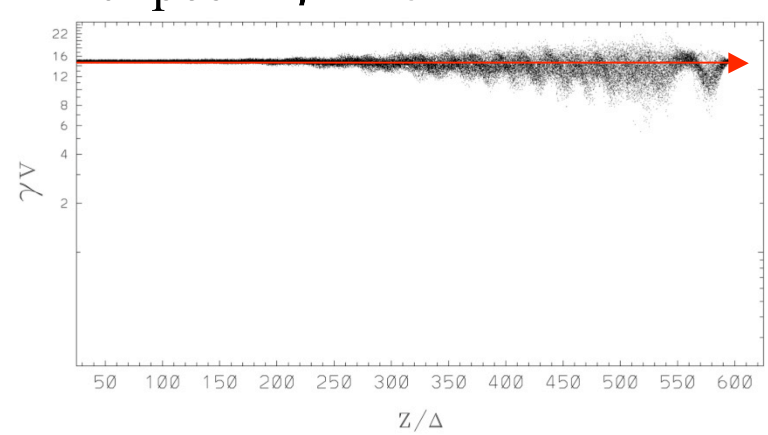
el-pos $4 < \gamma < 100$



el-pos $\gamma = 5$

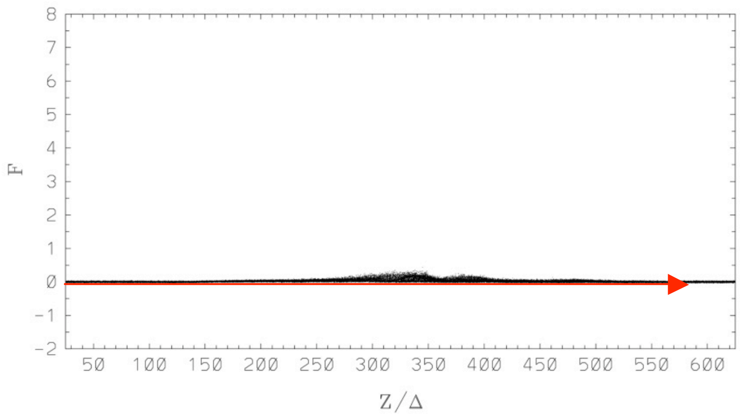


el-pos $\gamma = 15$

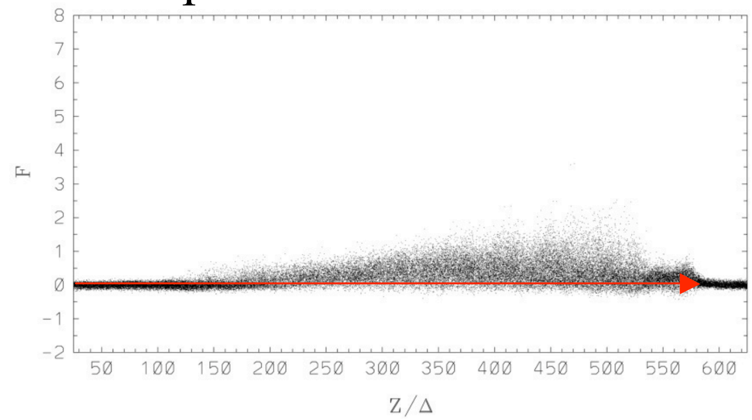


Z/Δ - γV_phase space of ambient electrons at t = 59.8 ω_{pe}

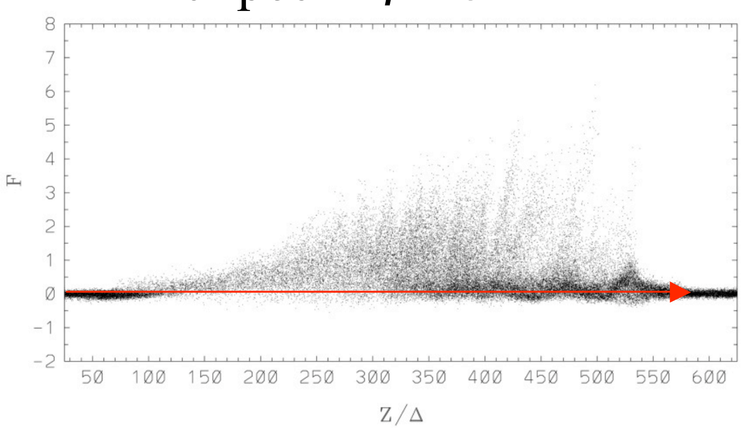
el-ion $\gamma = 5$



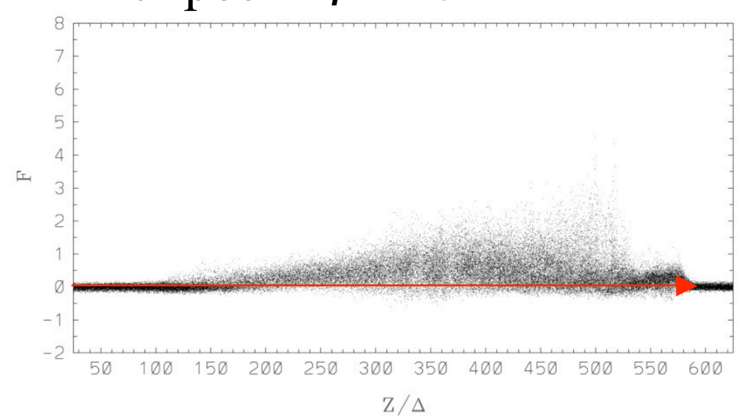
el-pos $4 < \gamma < 100$



el-pos $\gamma = 5$

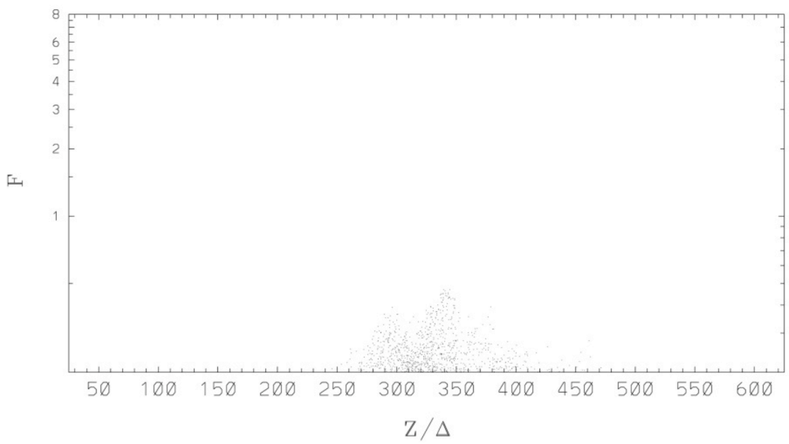


el-pos $\gamma = 15$

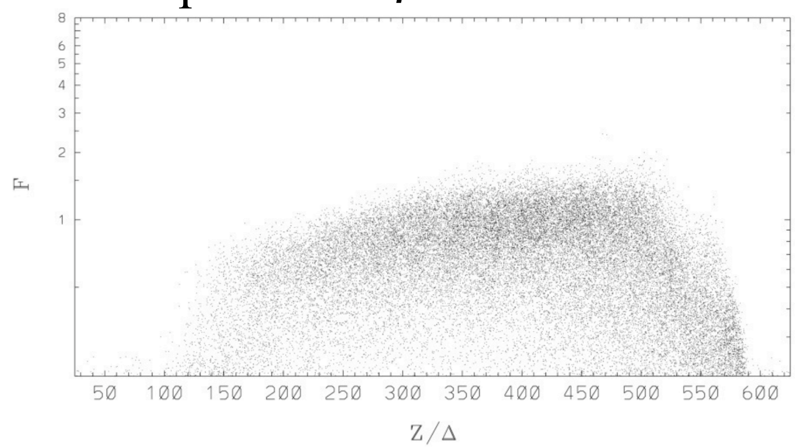


Z/Δ - $\gamma V_{\perp}$ phase space of **ambient** electrons at $t = 59.8\,\omega_{pe}$

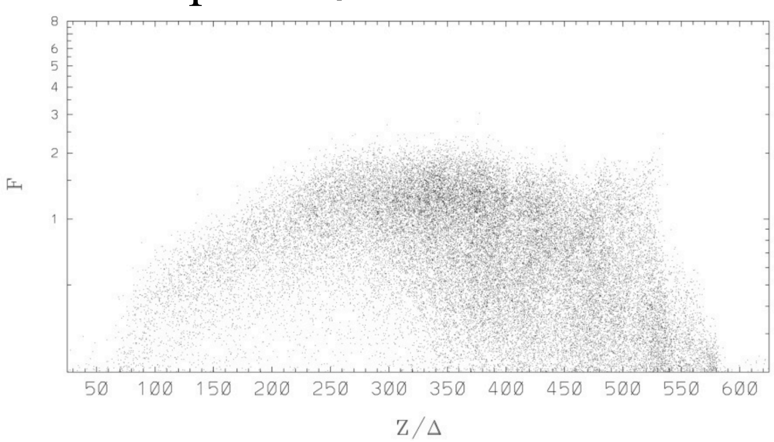
el-ion $\gamma = 5$



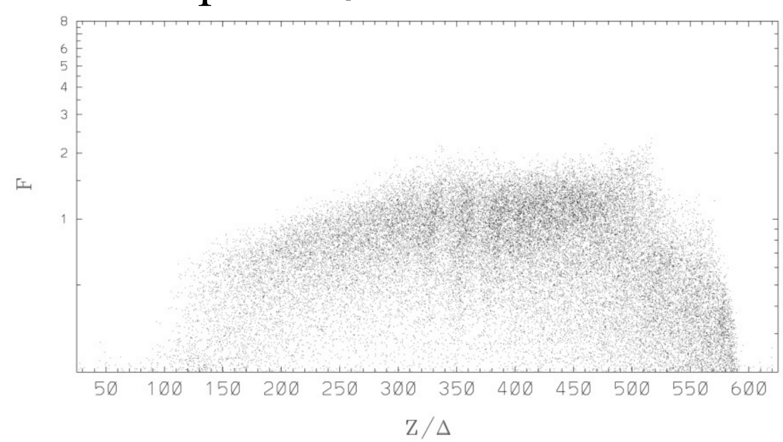
el-pos $4 < \gamma < 100$



el-pos $\gamma = 5$



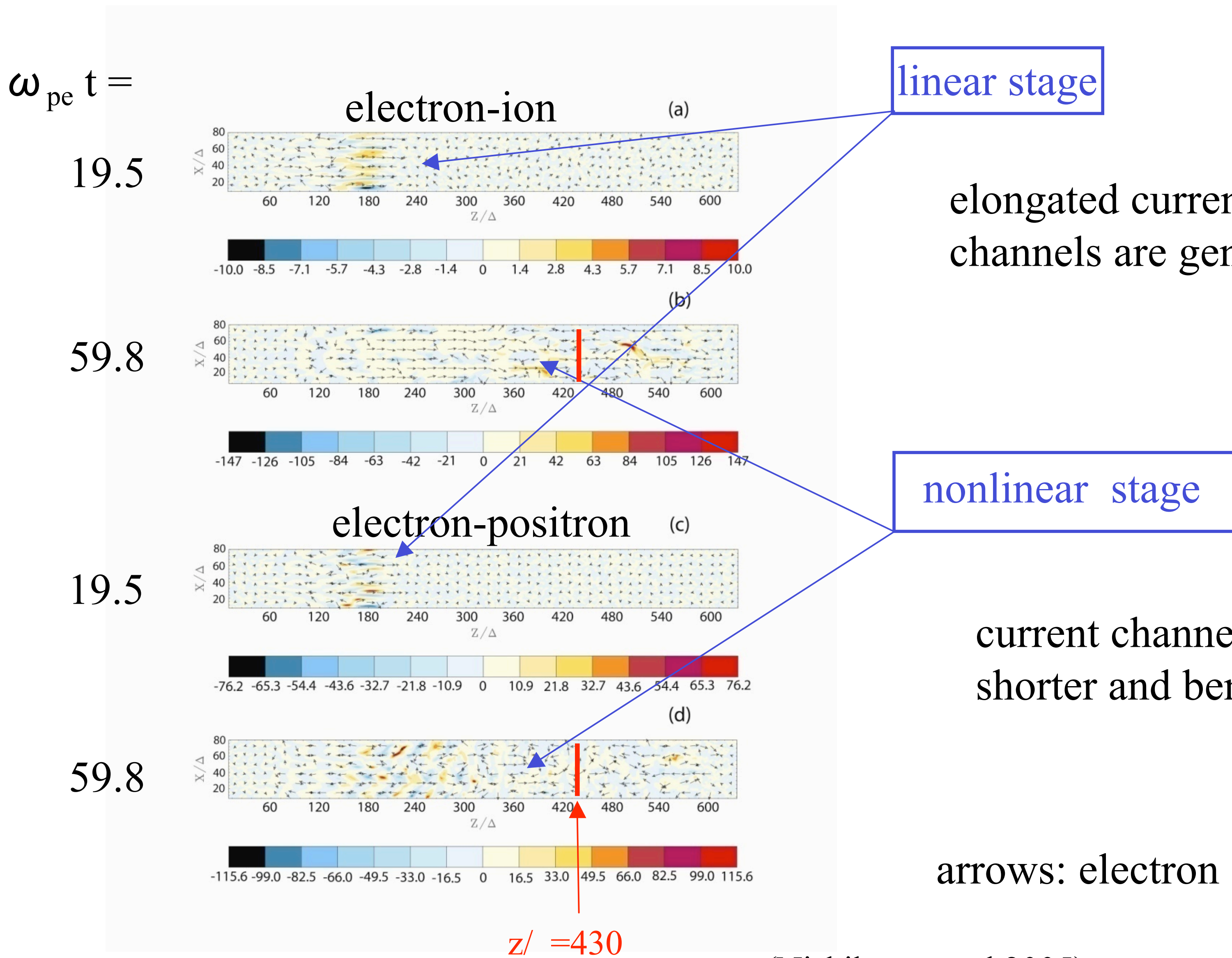
el-pos $\gamma = 15$



Jz at the linear and nonlinear stages

color: electron density

ω_{pe} t =



elongated current channels are generated

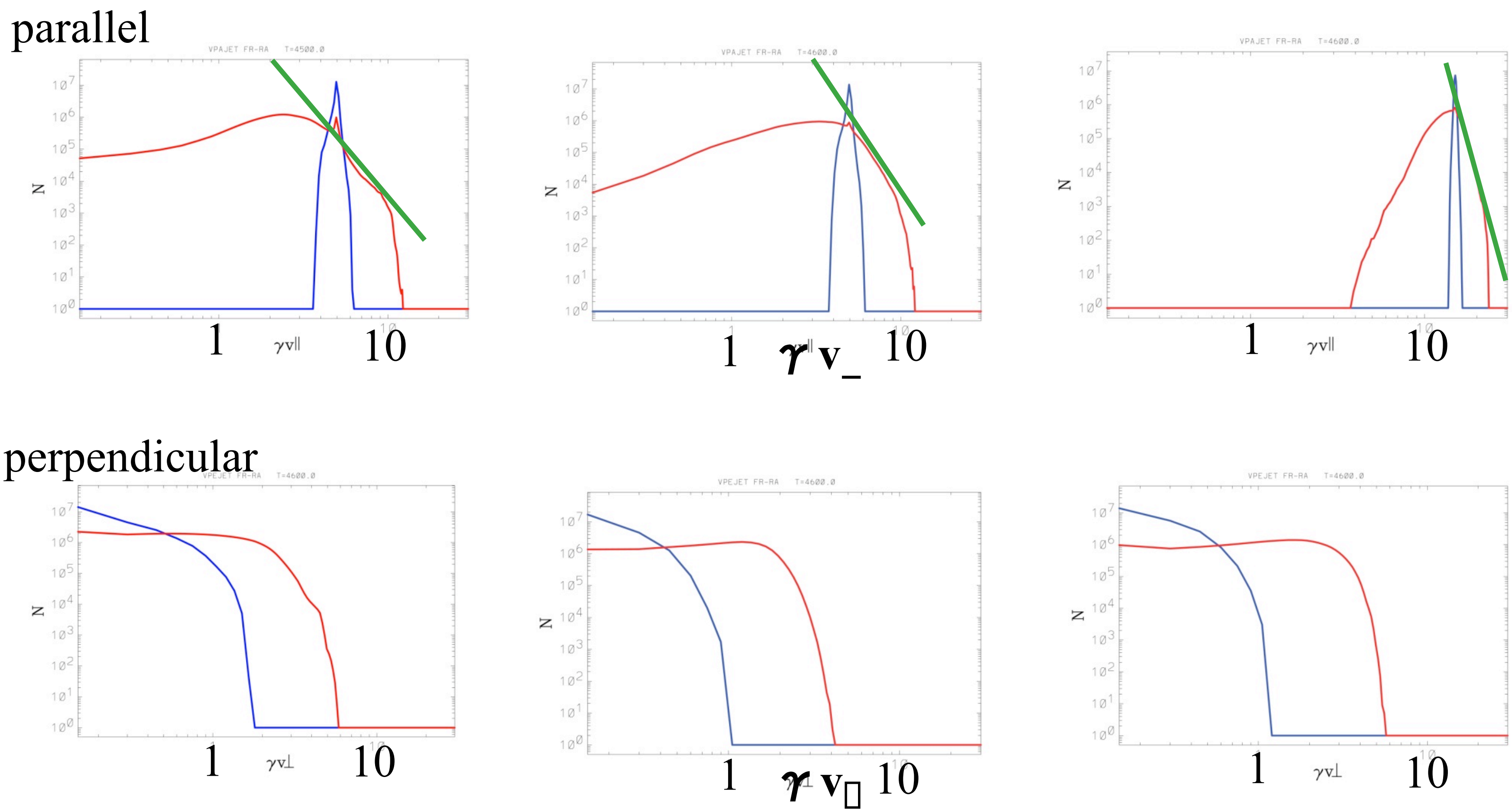
current channels are shorter and bent

arrows: electron flux

(Nishikawa et al 2005)

Electron acceleration at t = 59.8 ω_{pe}

el-ion _= 5 el-positron γ = 5 el-positron γ = 15

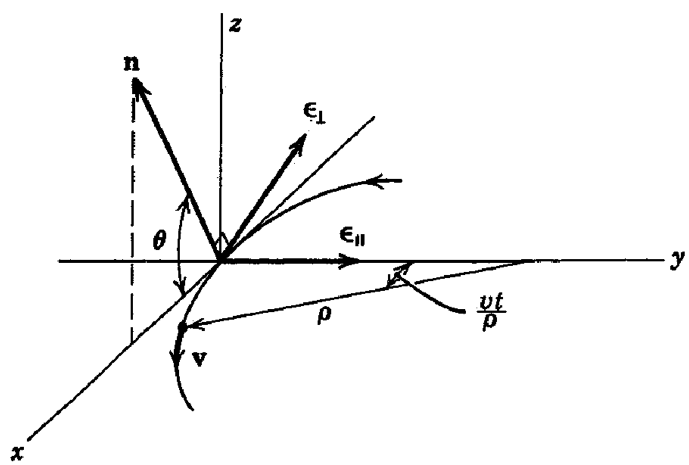


Frequency spectrum of radiation emitted by a relativistic electron

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

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

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



If $\gamma \gg 1$, $\omega \gg \omega_c$, $\theta = 0$

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

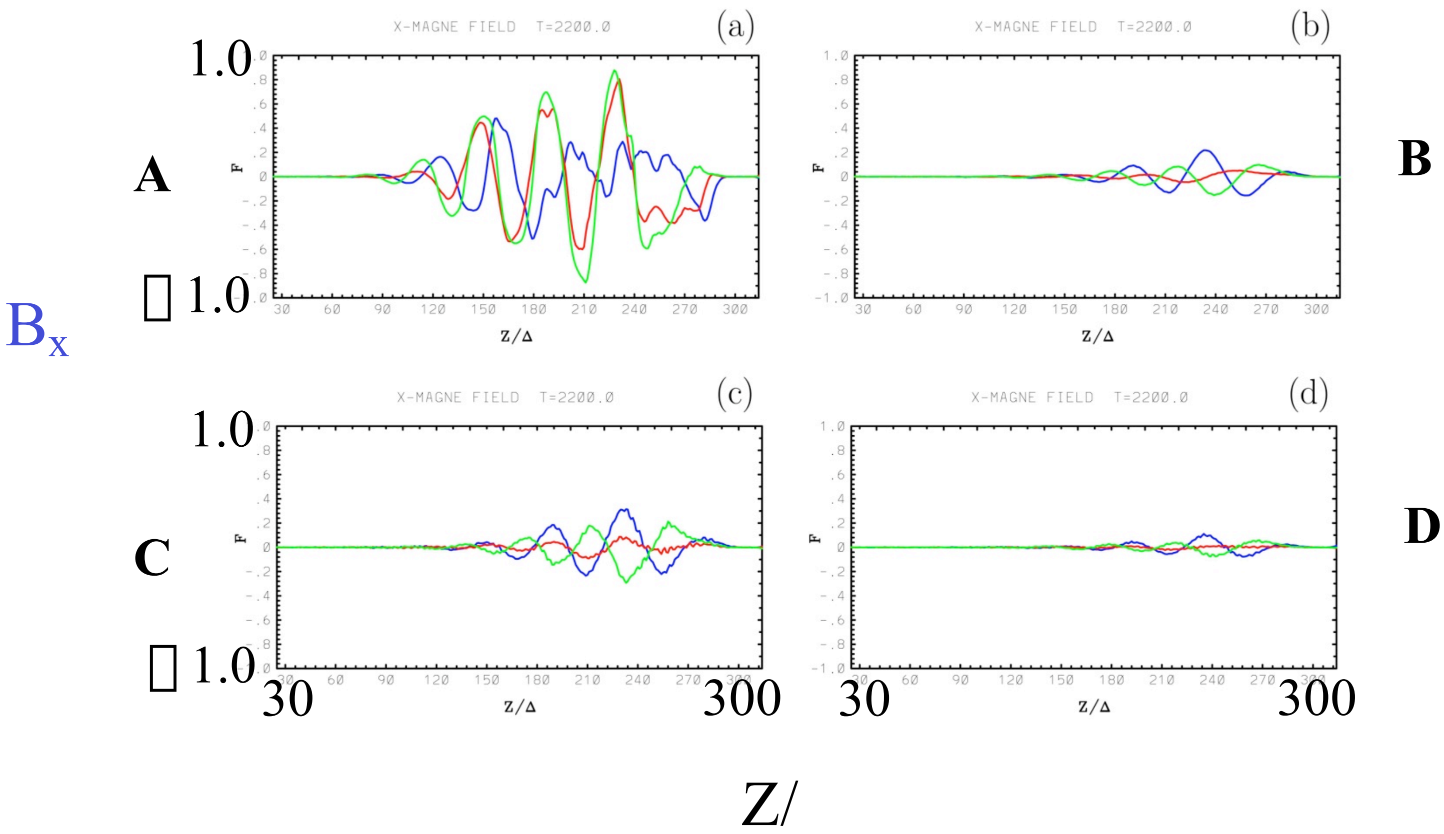
(Jackson 1999; Rybicki & Lightman 1979)

at Y = 43_

Generated magnetic field B_x along Z direction

Blue X = 33 Δ
Red X = 43 Δ
Green X = 53 Δ

$t = 28.6/\omega_{pe}$

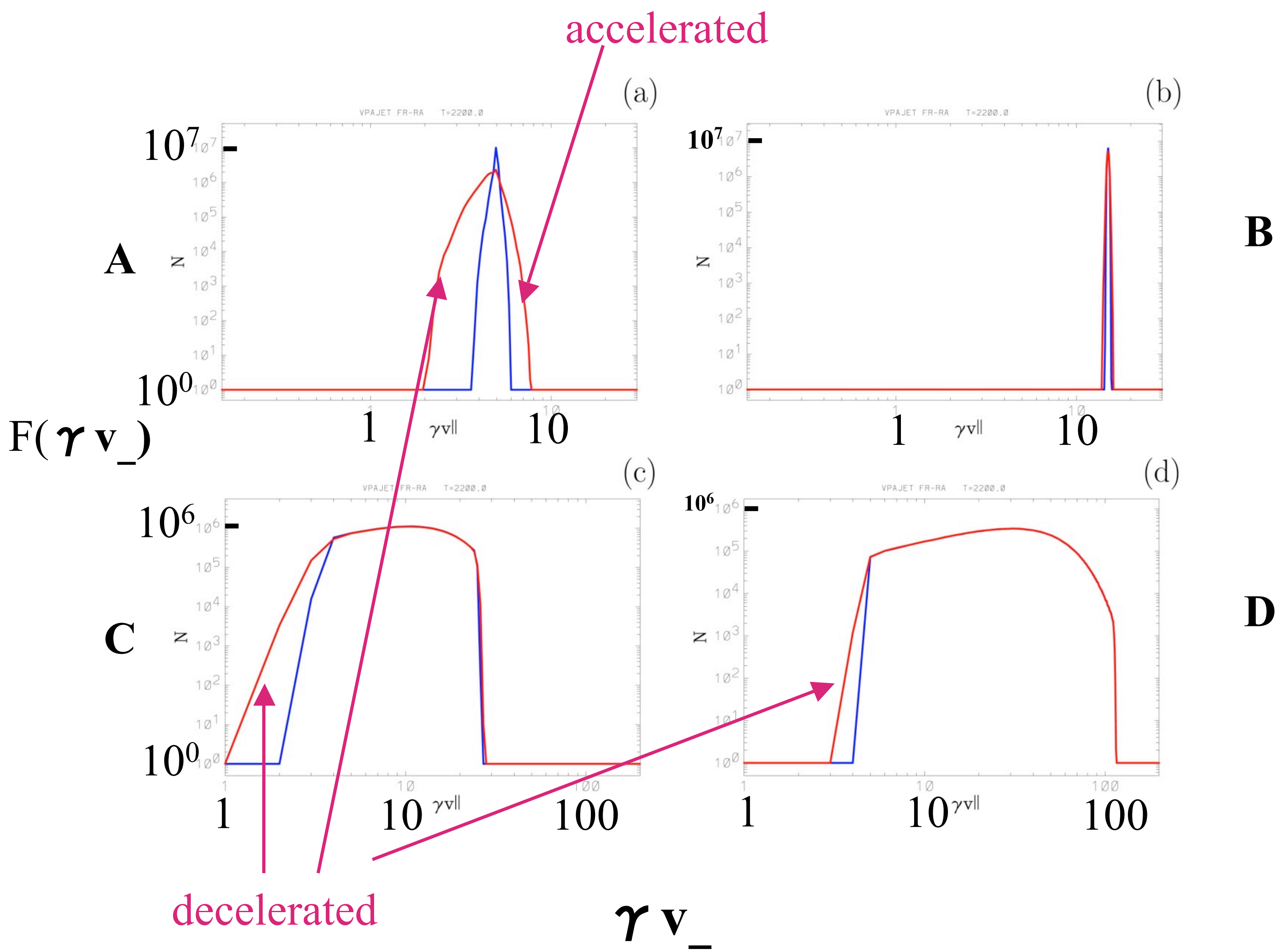


Parallel velocity distributions of jets (_v_)

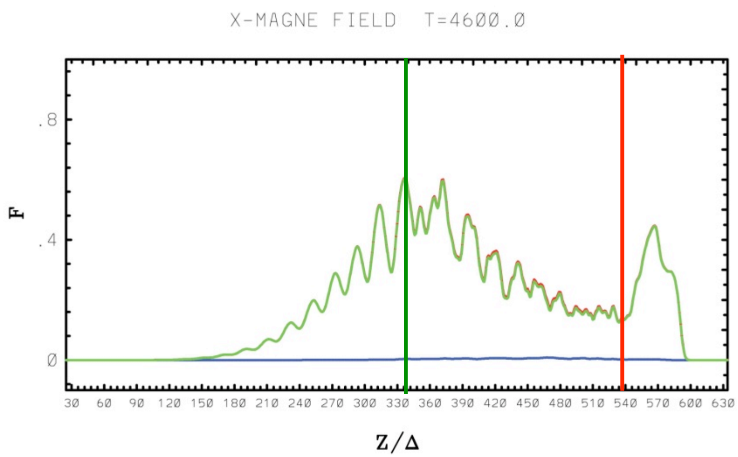
Red: front half

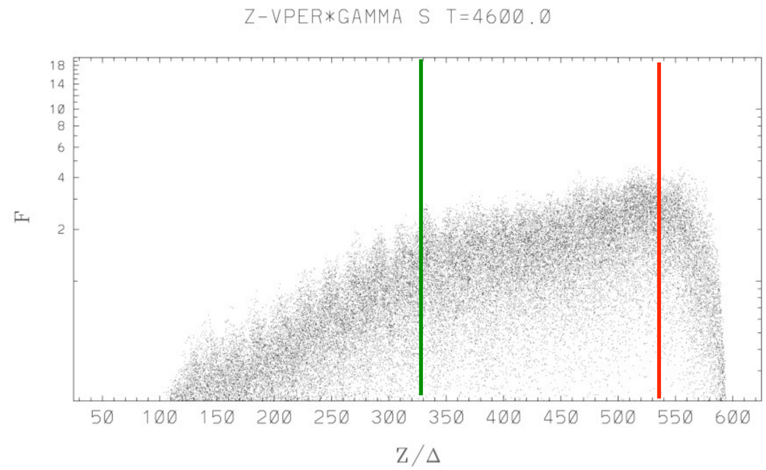
Blue: rear half

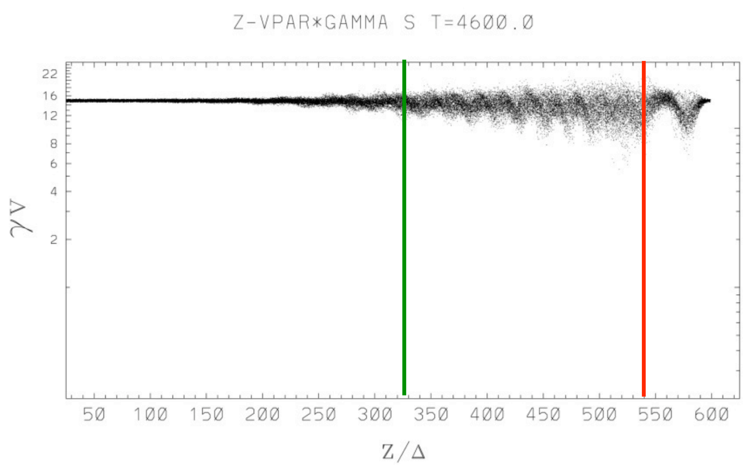
t = 28.6/ ω_{pe}

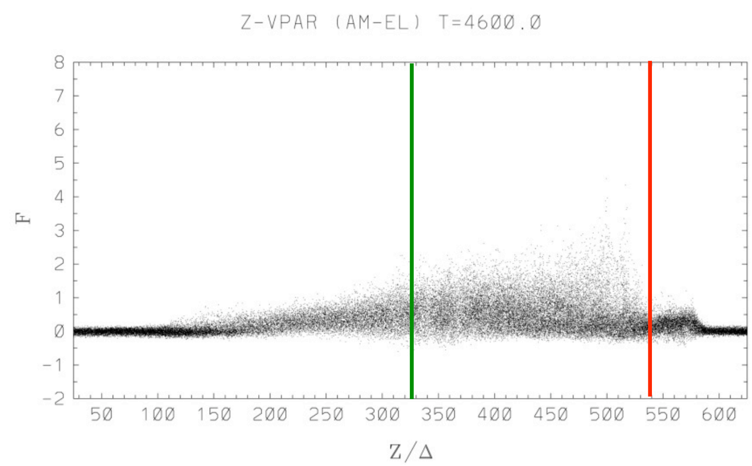


Relationship between the total magnetic field energy and particle acceleration

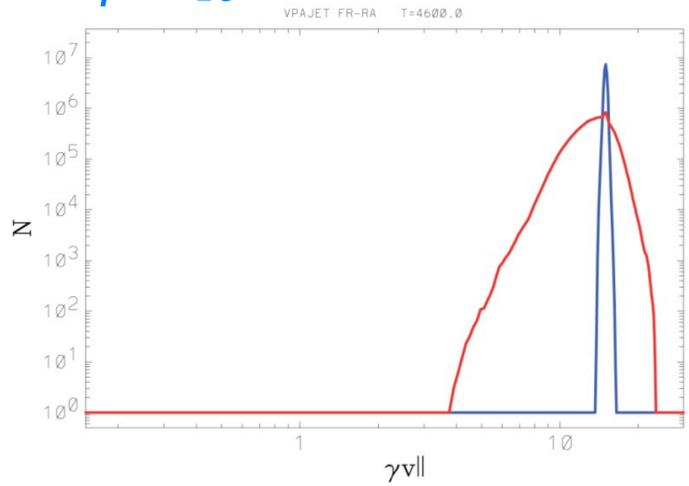


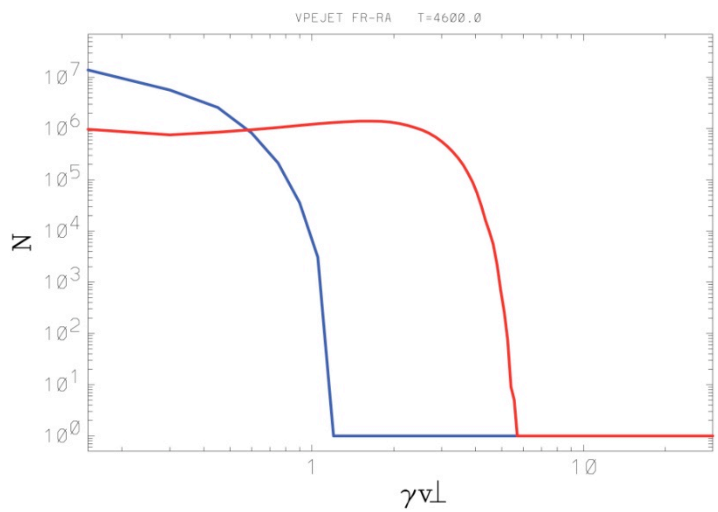




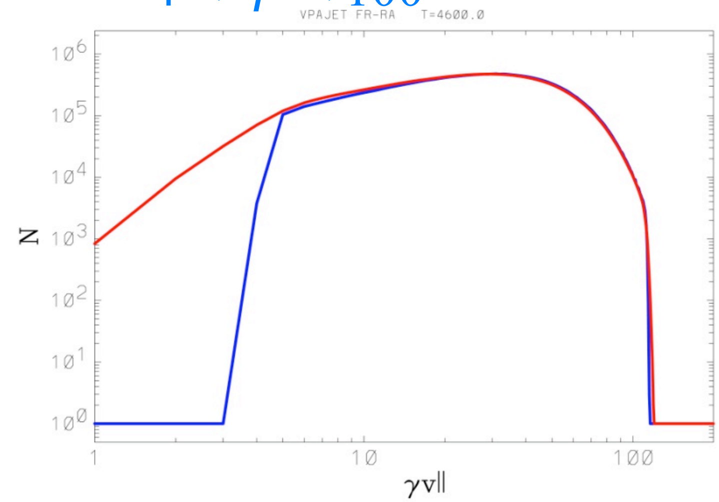


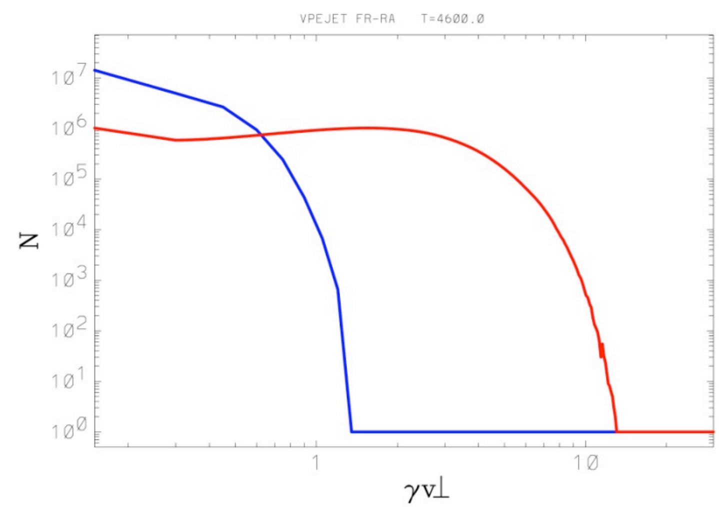
$\gamma = 15$





$4 < \gamma < 100$



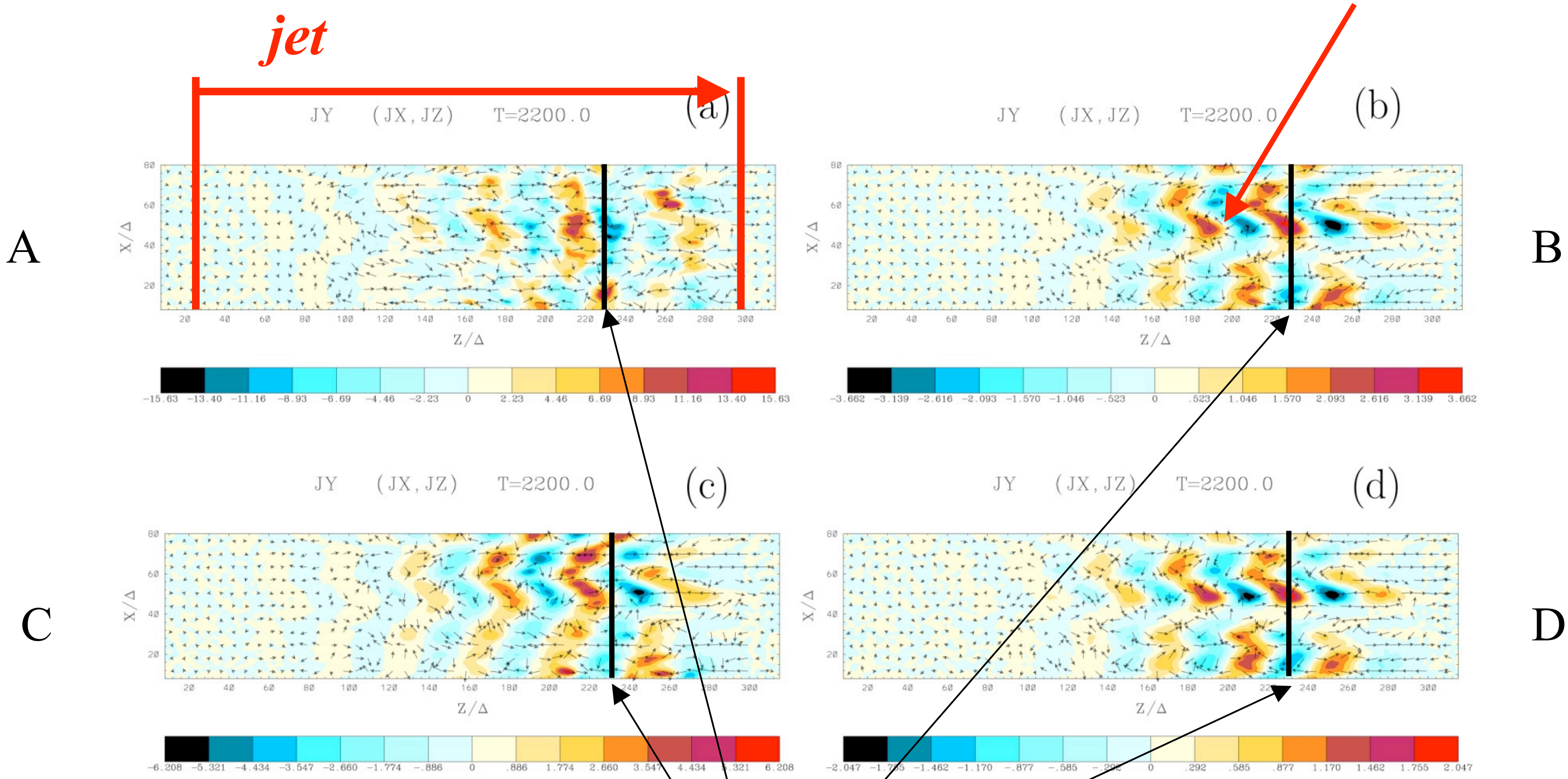


Perturbed current density J_y (Z – X plane)

t = 28.6/_pe

Arrows ($\boldsymbol{J_z}$, $\boldsymbol{J_x}$)

Weibel instability

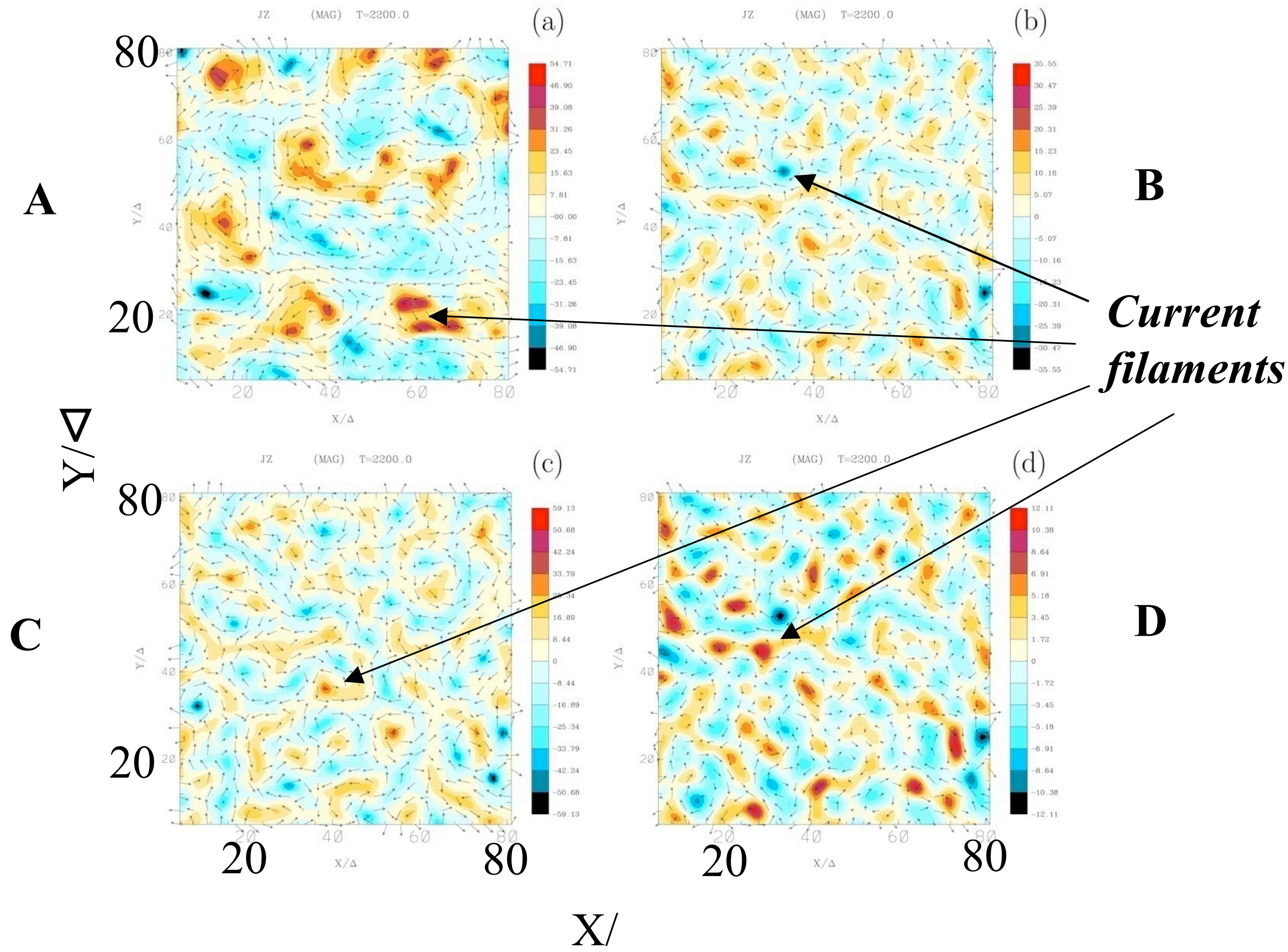


Z = 230 Δ (the next sheet shows J_z in the X – Y plane)

Perturbed current density J_z (X – Y plane)

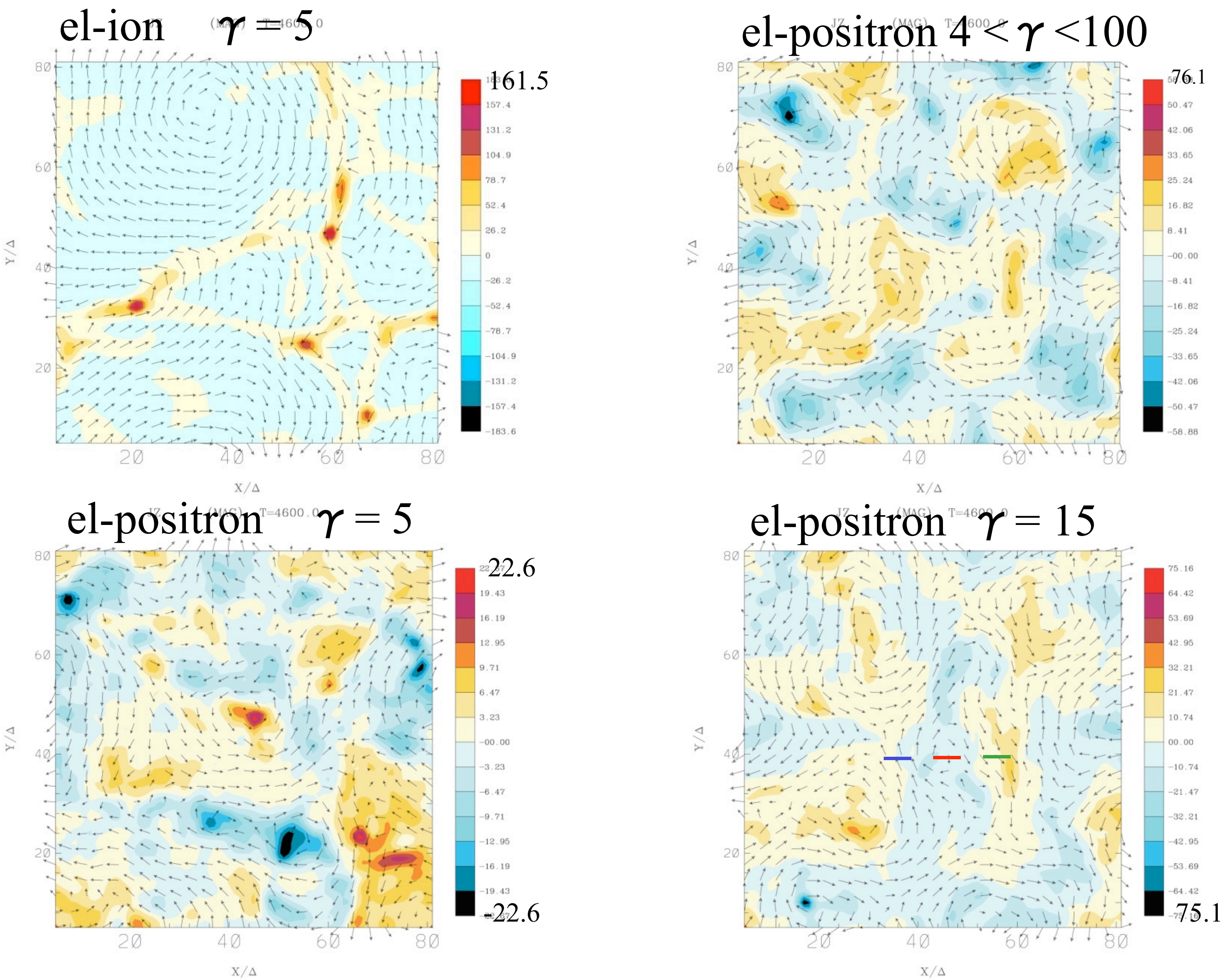
t = 28.6/ω_{pe} Arrows ($\boldsymbol{B_x}$, $\boldsymbol{B_y}$)

Z = 230_



J_z component generated by current channels (x-y plane) at $t = 59.8\,\omega_{pe}$

arrows: Bx, By

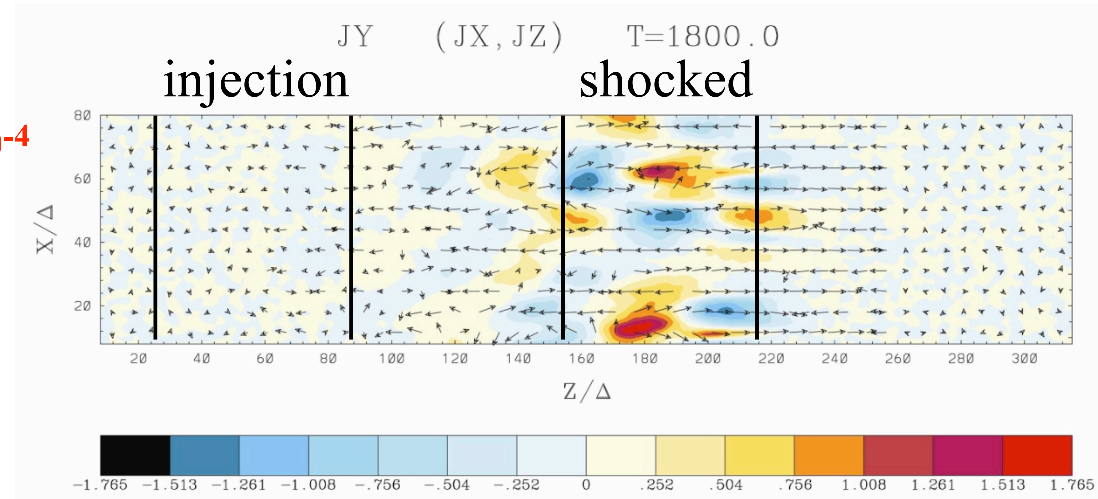


Comparison between electron-ion and electron-positron

no-ambient magnetic field $\omega_{pe}t = 23.4$

$\varepsilon_B^k = 0.45*10^{-4}$

ele-ion

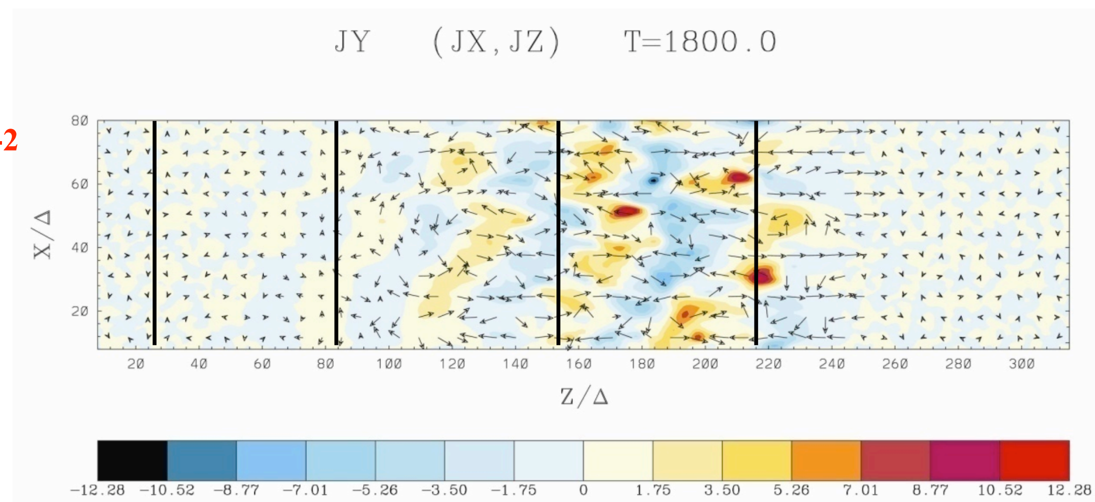


$U_B^{sh} / U_B^{in} = 1,140$

$U_{th}^{e,j,sh} / U_{th}^{e,j,in} = 1.02$

$\varepsilon_B^k = 1.02*10^{-2}$

ele-pos



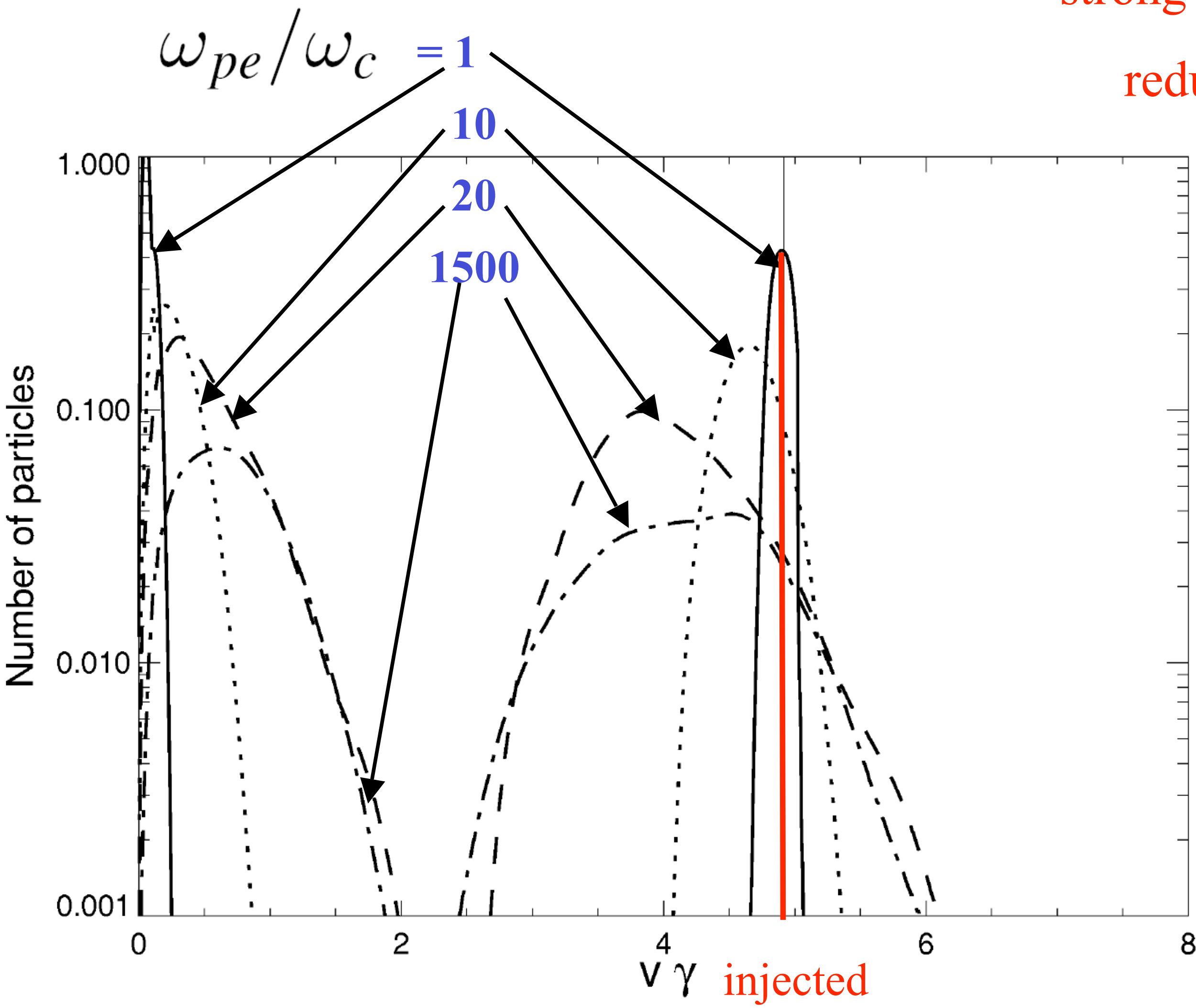
$U_B^{sh} / U_B^{in} = 6,080$

$U_{th}^{e,j,sh}/U_{th}^{e,j,in} = 2.12$

(Nishikawa et al. 2005)

Electron acceleration **(parallel injection)**

strong magnetic field reduces the growth rates



(Hededal & Nishikawa 2005)

Magnetosonic shock structure in 1-D system

ion

electron

motional electric field

$E_y = v_0 B_0$

U_{ix}/U_0

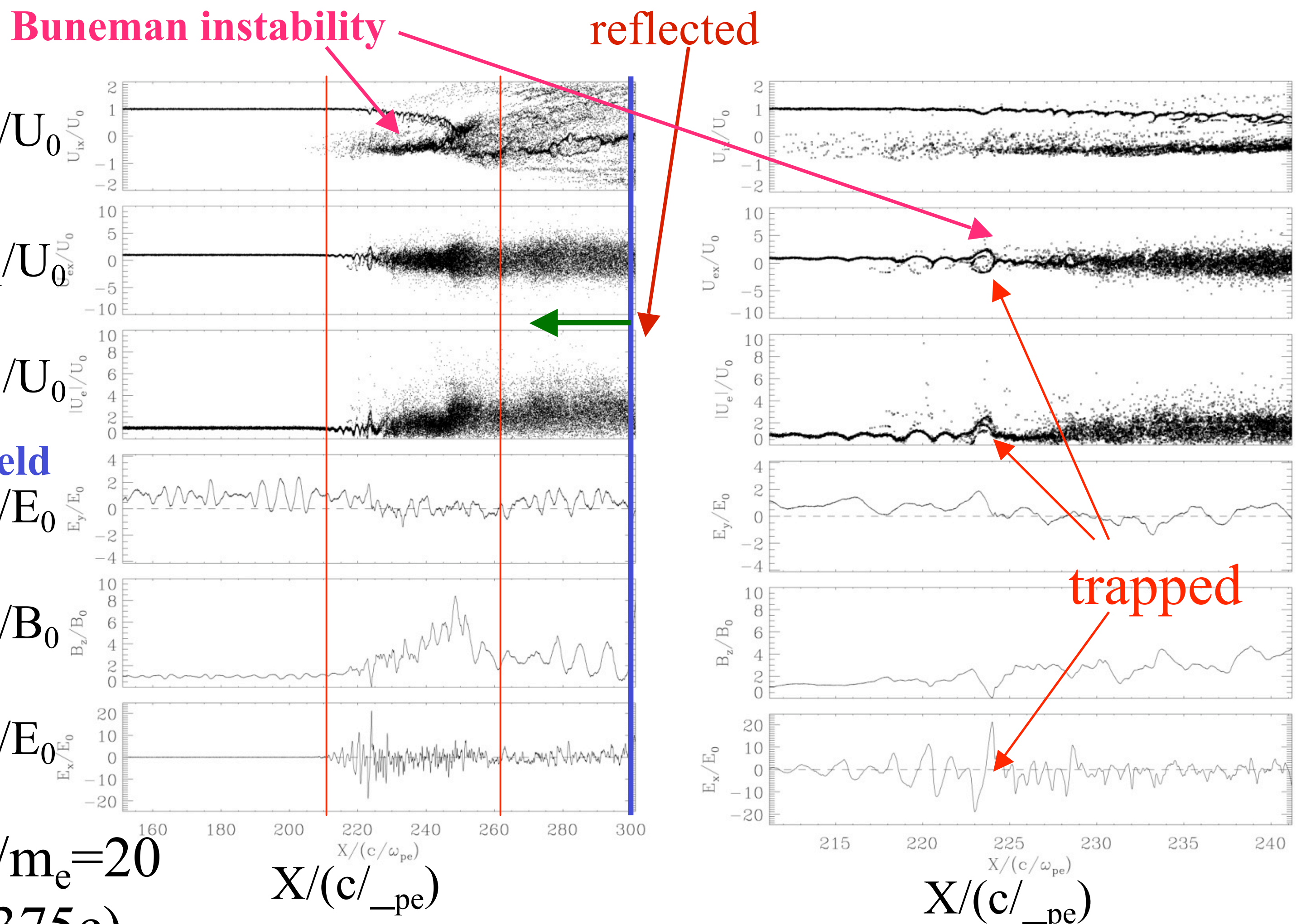
U_{ex}/U_0

$|U_{e|}/U_0$

E_y/E_0

B_z/B_0

E_x/E_0



$\beta_e = \beta_i = 0.01$

_pe/_ce =19 $m_i/m_e = 20$

U_0 =0.25c (0.375c)

$V_A/c = 0.012$

$M_A = 32$

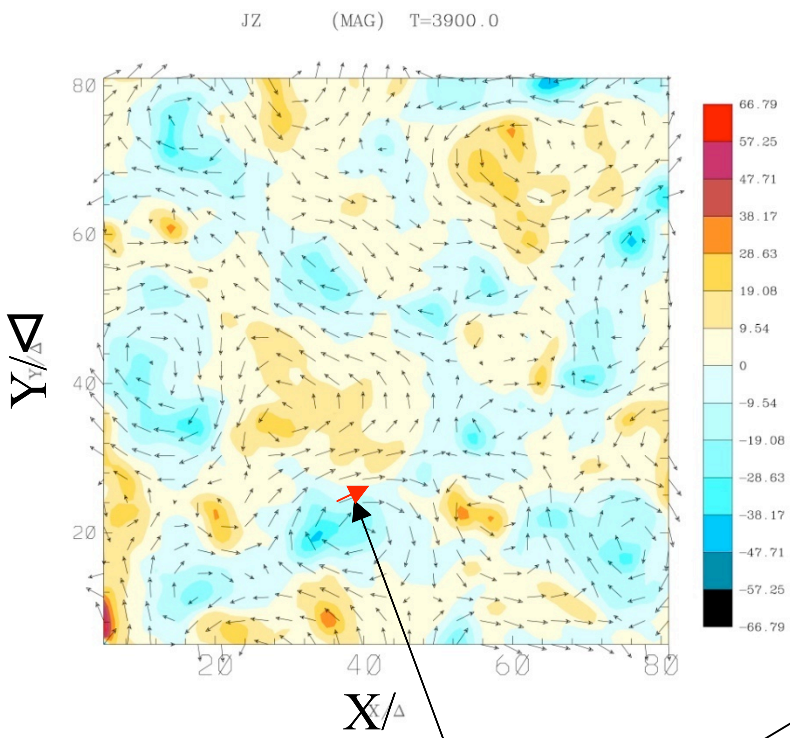
_0 ~ 1.03

(Hoshino & Shimada, 2002, ApJ)

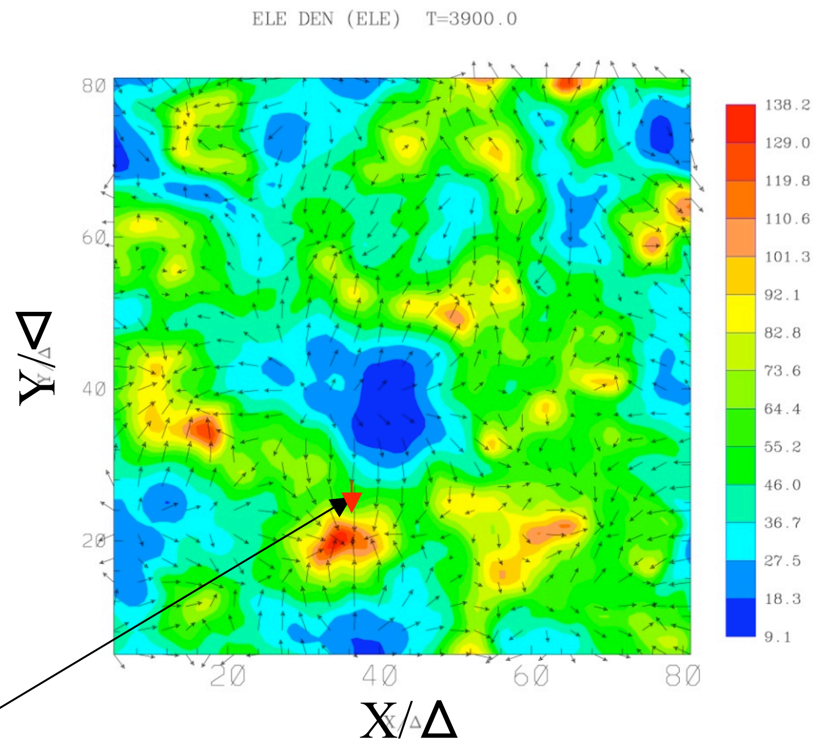
E_B acceleration due to the current channel (Z/_= 430)

t = 50.7_pe *electron-positron jet* $4 < \gamma < 100$

J_y arrows: B_x, B_y



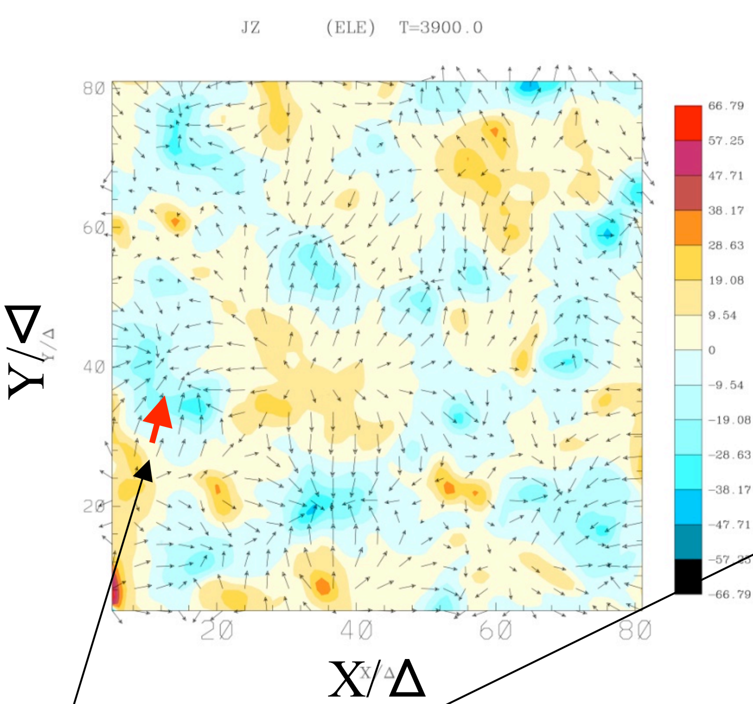
n_e arrows: E_x, E_y



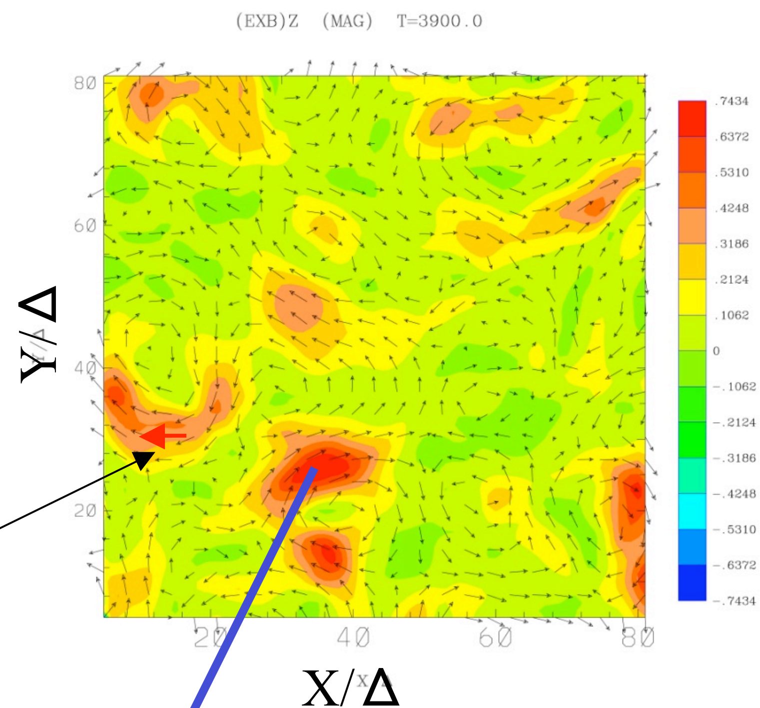
B and ***E*** are nearly perpendicular

E_B acceleration and deceleration (Z/Δ = 430)

J_z arrows: E_x, E_y



$(E\_B)_z$ arrows: B_x, B_y



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

both electrons and positrons are accelerated in this region

Schematic topology of magnetic field with current channel (xz- plane)

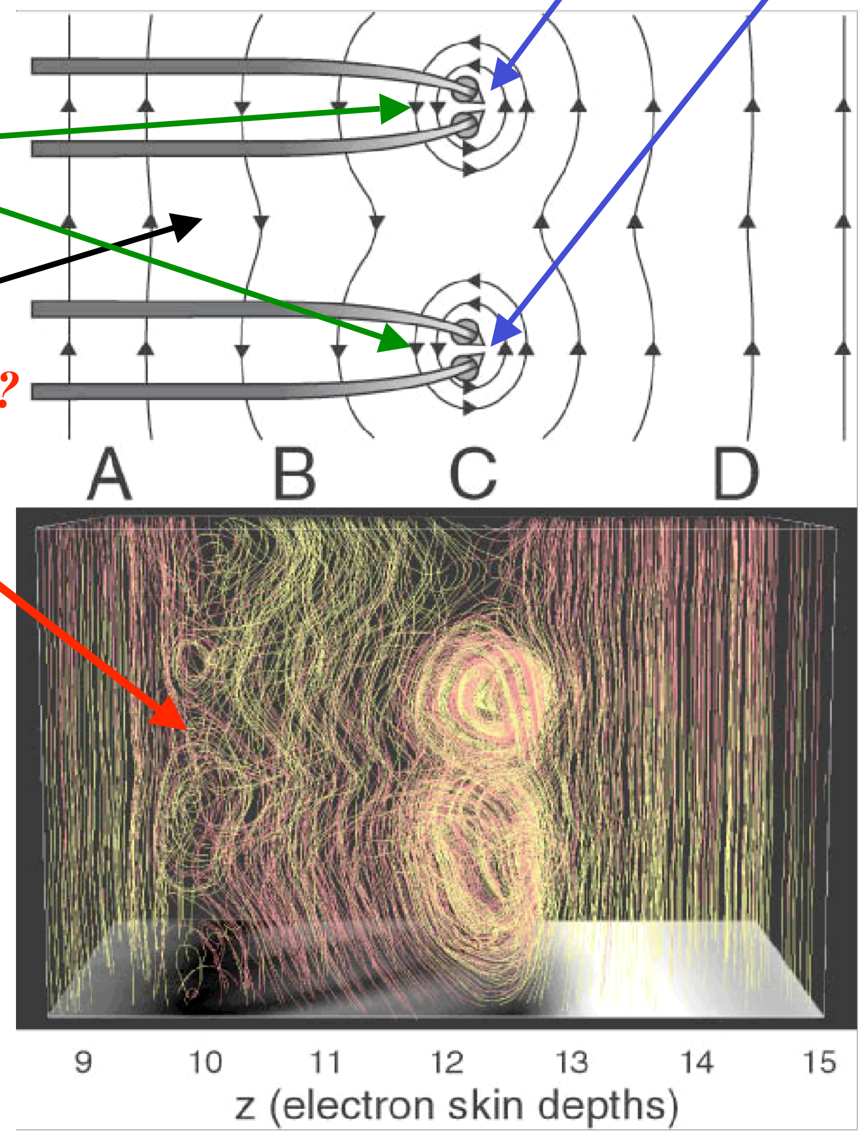
$t = 16/\omega_{pe}$

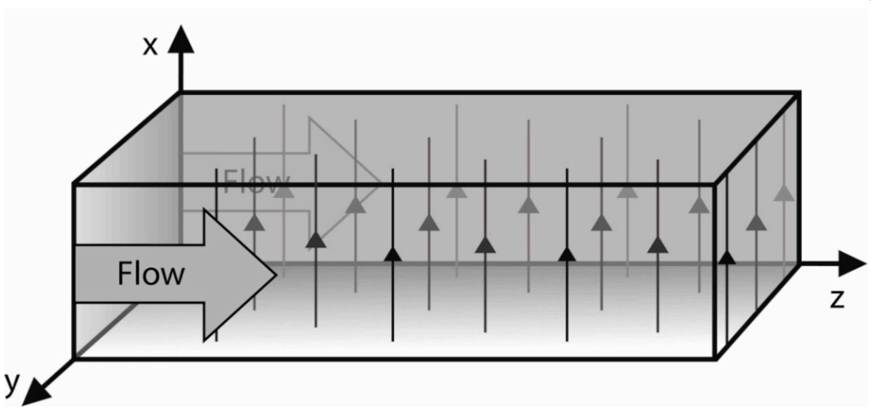
Deflected jet electrons

Weibel instability

Magnetic field lines with loops created by current channels

Reconnection ?



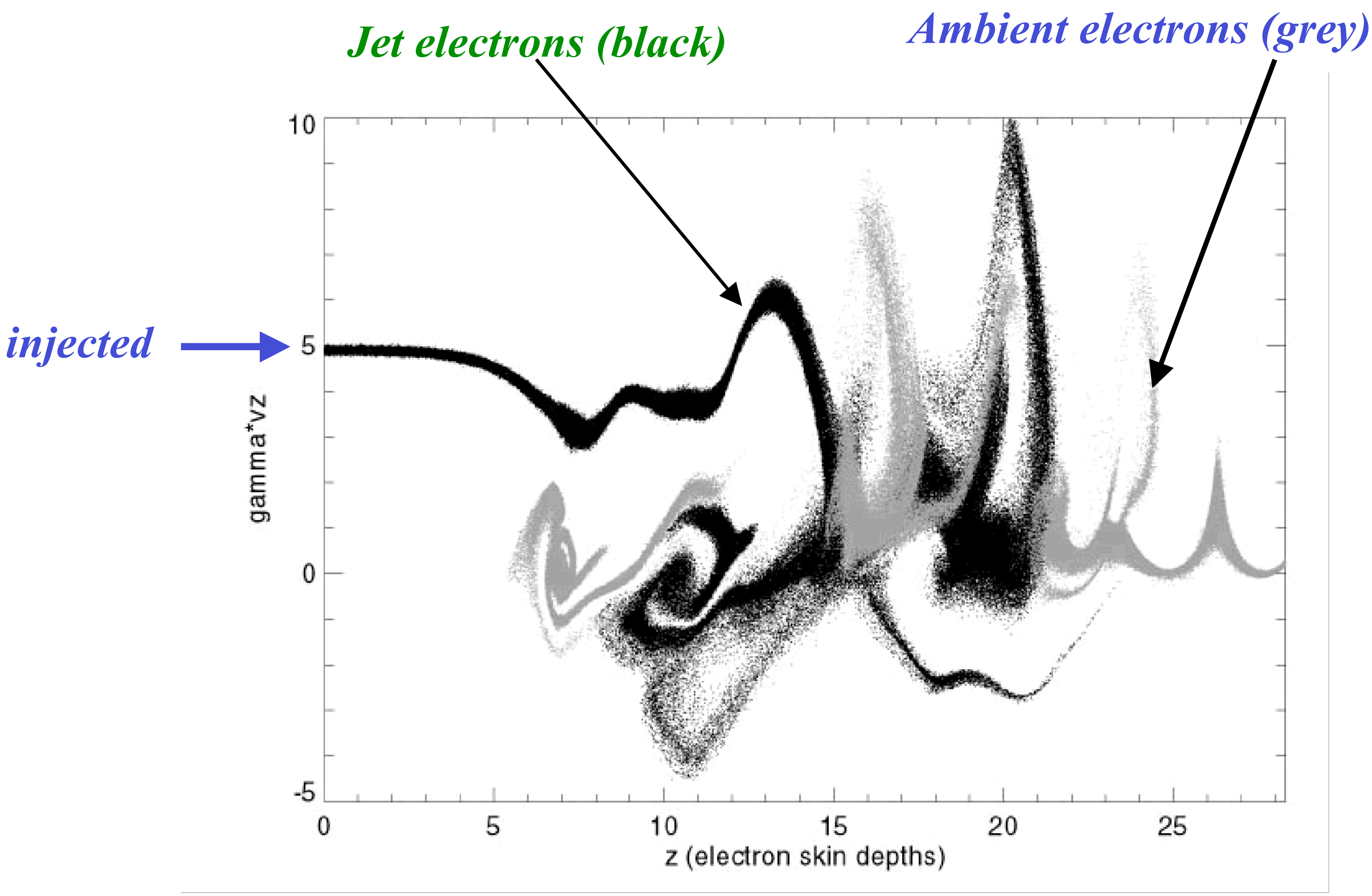


Initial setup

(Hededal & Nishikawa 2004)

Electron $v_z \gamma$ - z

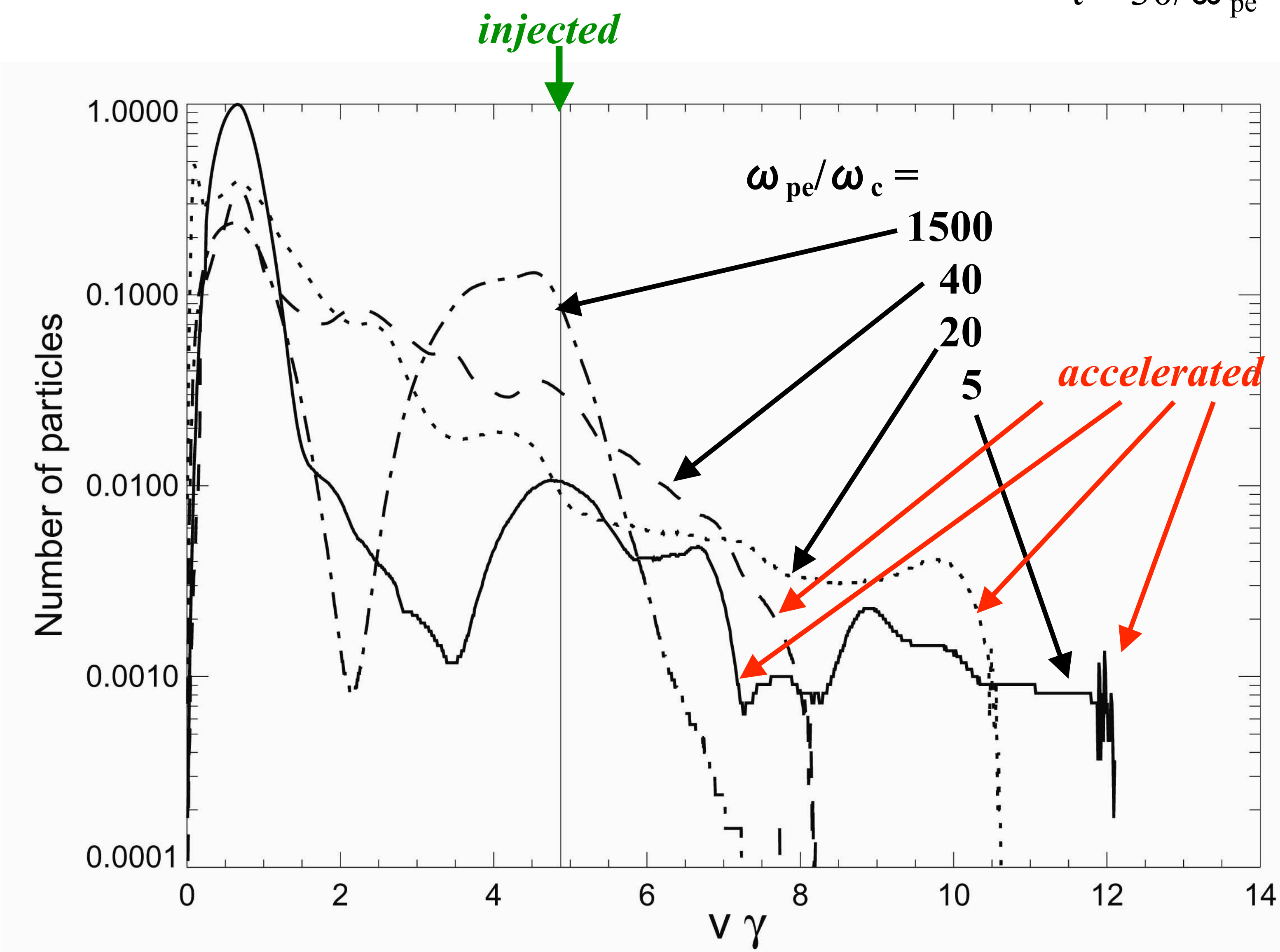
$t = 30/\omega_{pe}$ **$\omega_{pe}/\omega_c = 20$**



(Hededal & Nishikawa 2004)

Electron acceleration in perpendicular injection

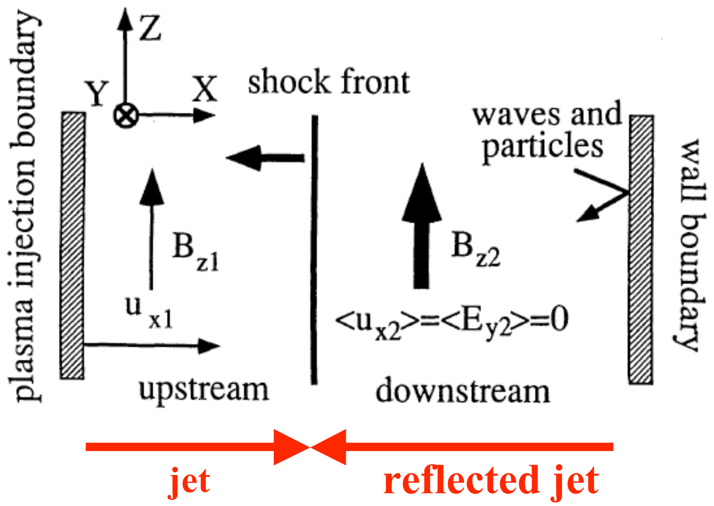
$t = 30/\omega_{pe}$



(Hededal & Nishikawa 2004)

1-D simulations of positron acceleration (Hoshino et al. 1992)

Maser instability



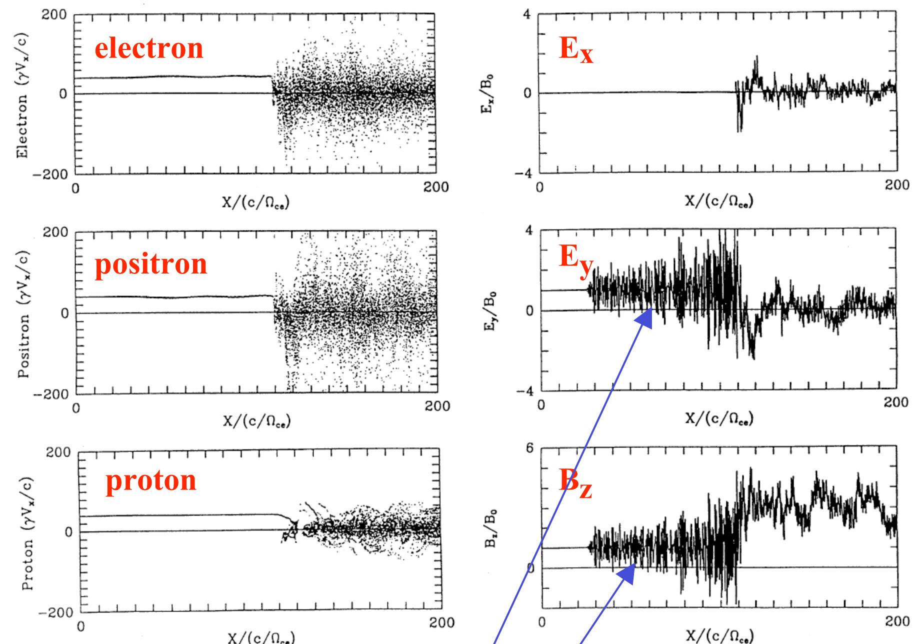
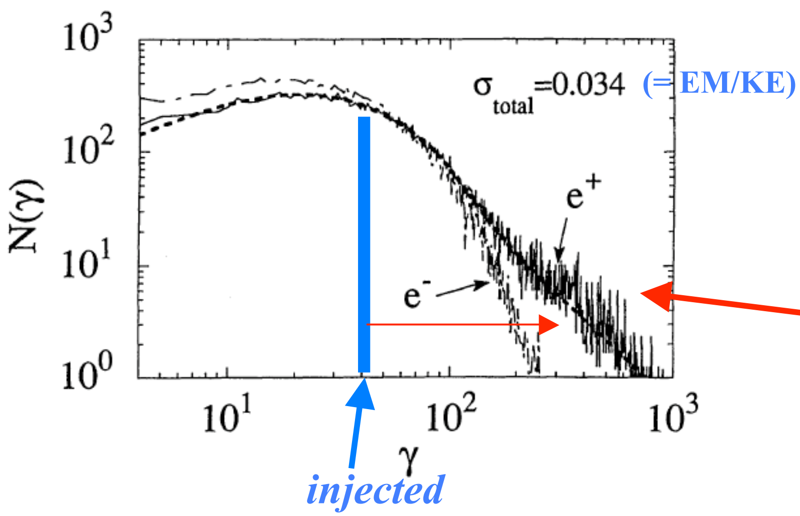
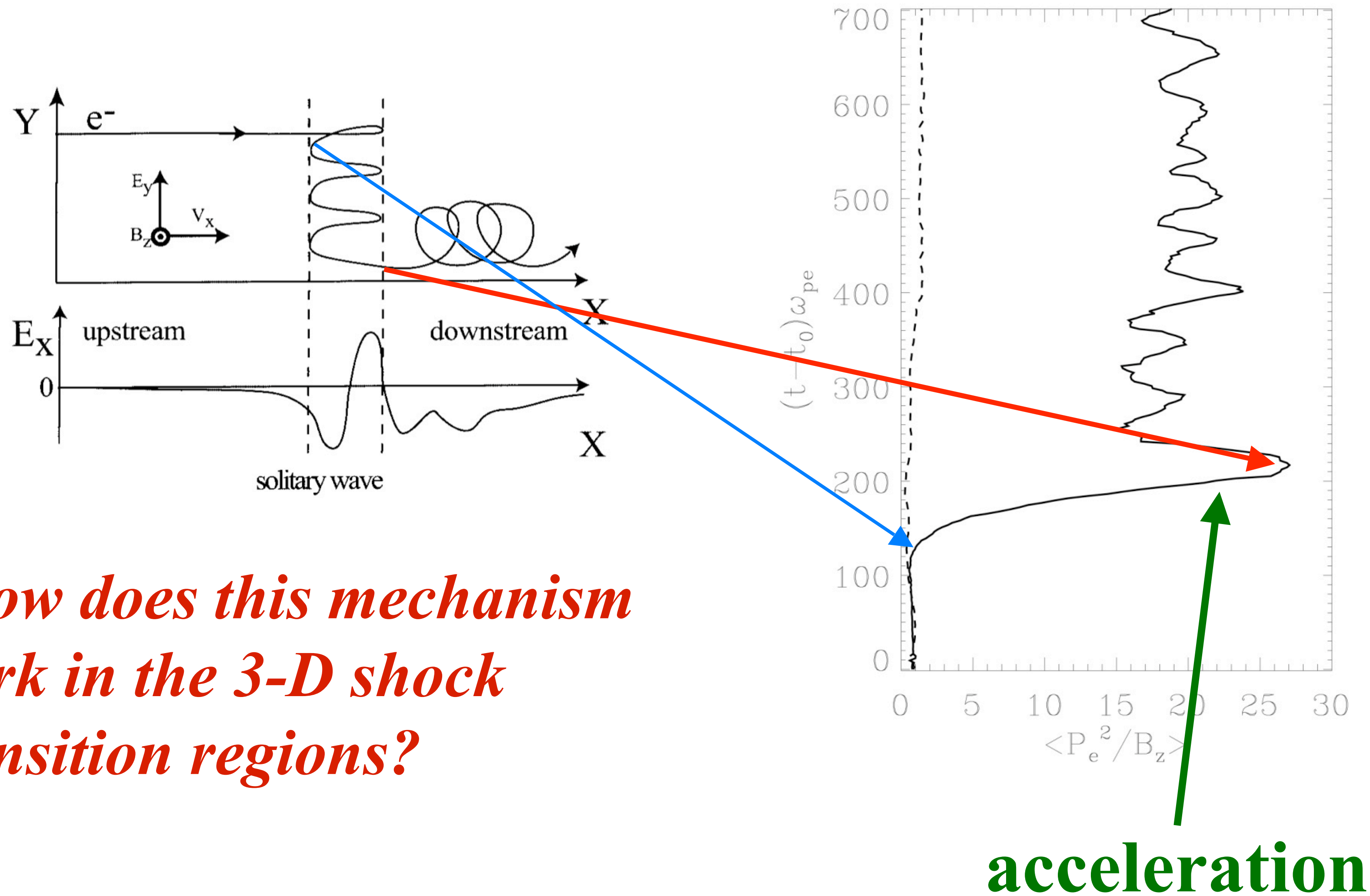


FIG. 13.—Phase space of particles and electromagnetic structure in low σ case. $\sigma_{e^-} = 0.2$, $\sigma_{tot} = 0.034$ and $\gamma_1 = 40$. Same format as Fig. 4.



positrons accelerated due to the resonance

Illustration of the electron surfing mechanism



•How does this mechanism work in the 3-D shock transition regions?

Density and J_z in x-y plane

$\omega_{pe}t = 23.4$

electron skin depth

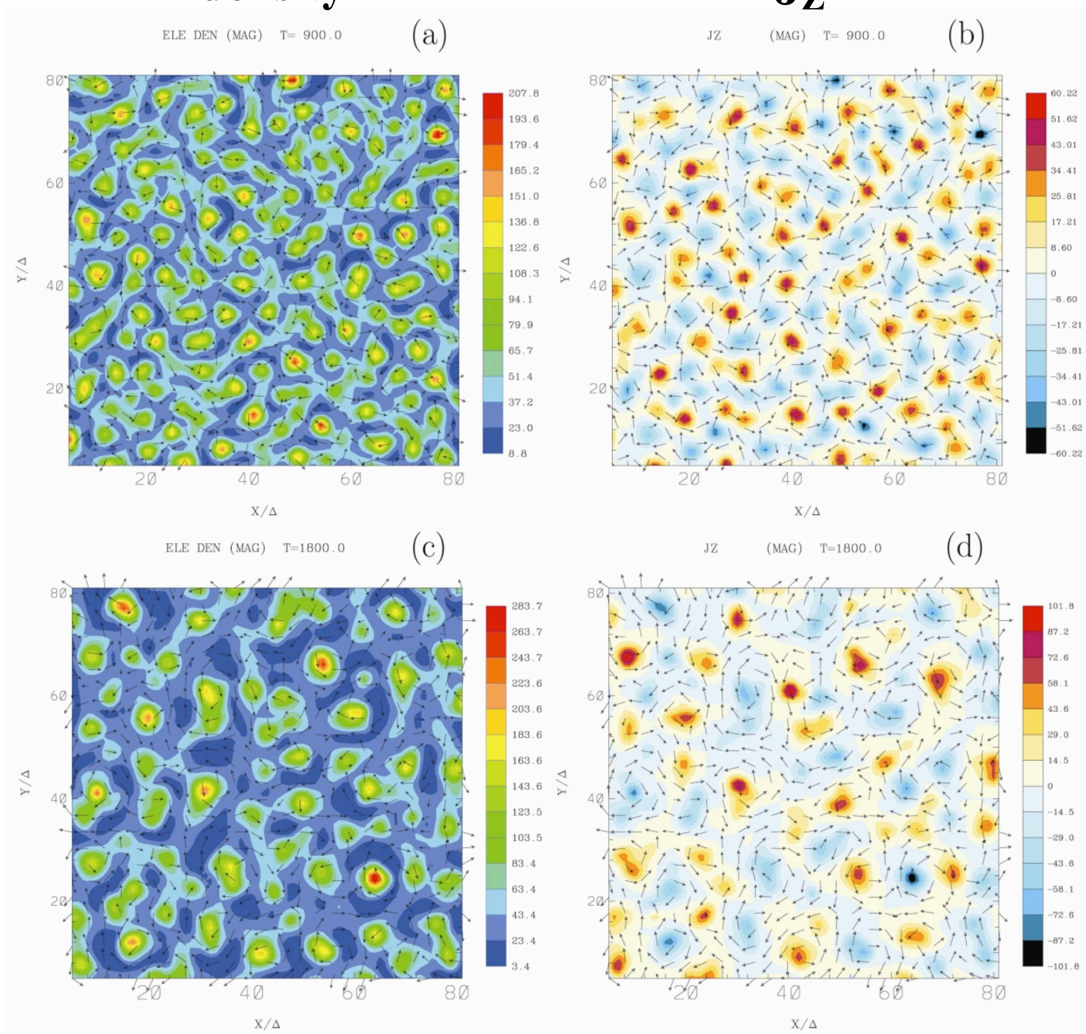
4.8 Δ

9.6 Δ

density

J_Z

Y/Δ



X/Δ

(Nishikawa et al. 2005)

Flat jet injected parallel to B

Electron-ion jet, $m_i/m_e = 20$

□= $v_j/c = 0.9798$, $v_{et}/c = 0.1$

_ = n_j/n_a □ 0.741

$\gamma = (1-(v_j/c)^2)^{-1/2} = 5$

$v_{je} = 3v_{et}$, $v_{ji} = 3v_{it}$, $v_{it}/c = 0.022$

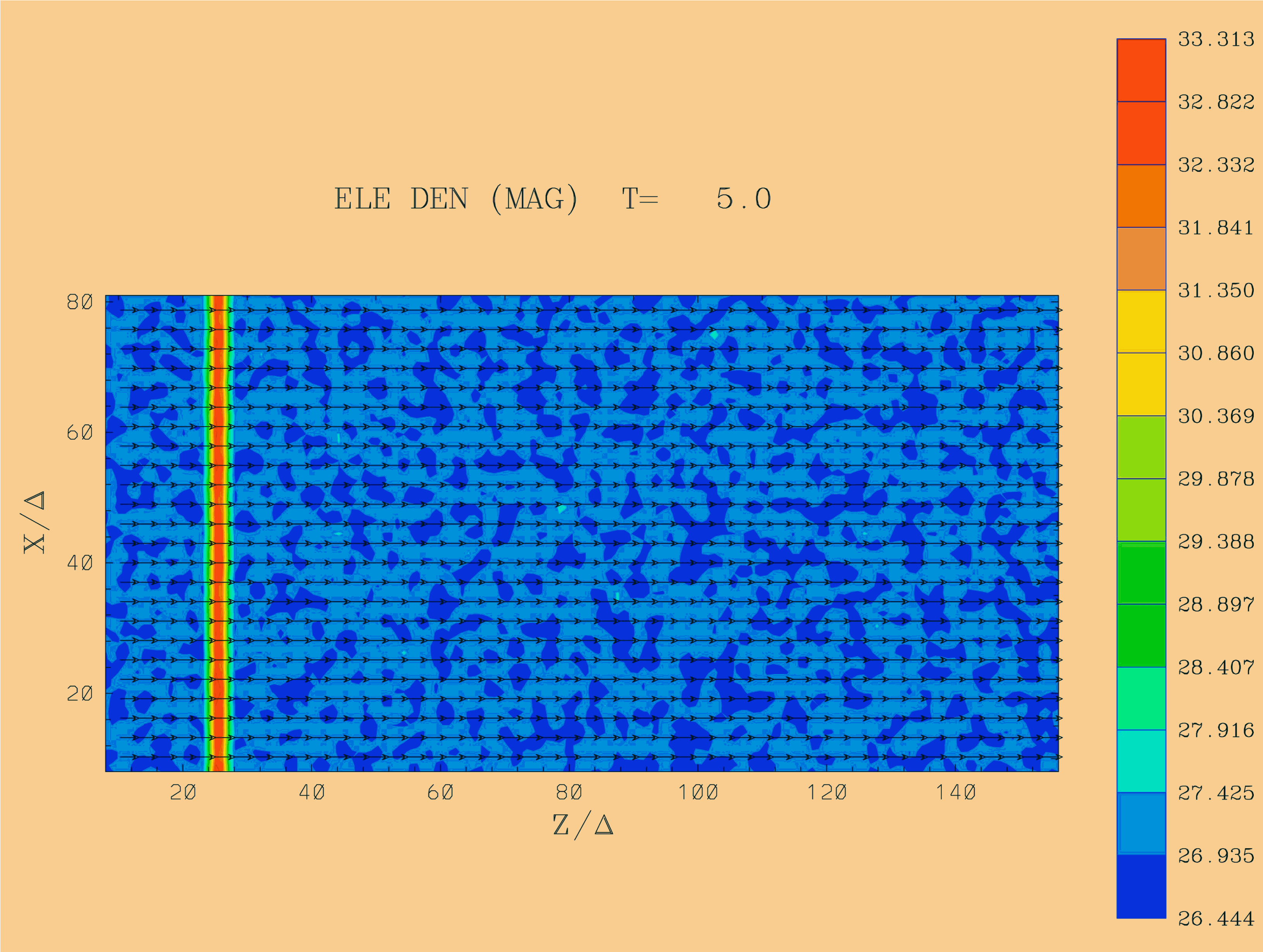
$\omega_{pe}/\_{e} = 2.89$, $V_A/c = 0.0775$, $M_A = 12.65$

□$_e$ $(=8\pi n_e T_e/B^2) = 1.66$

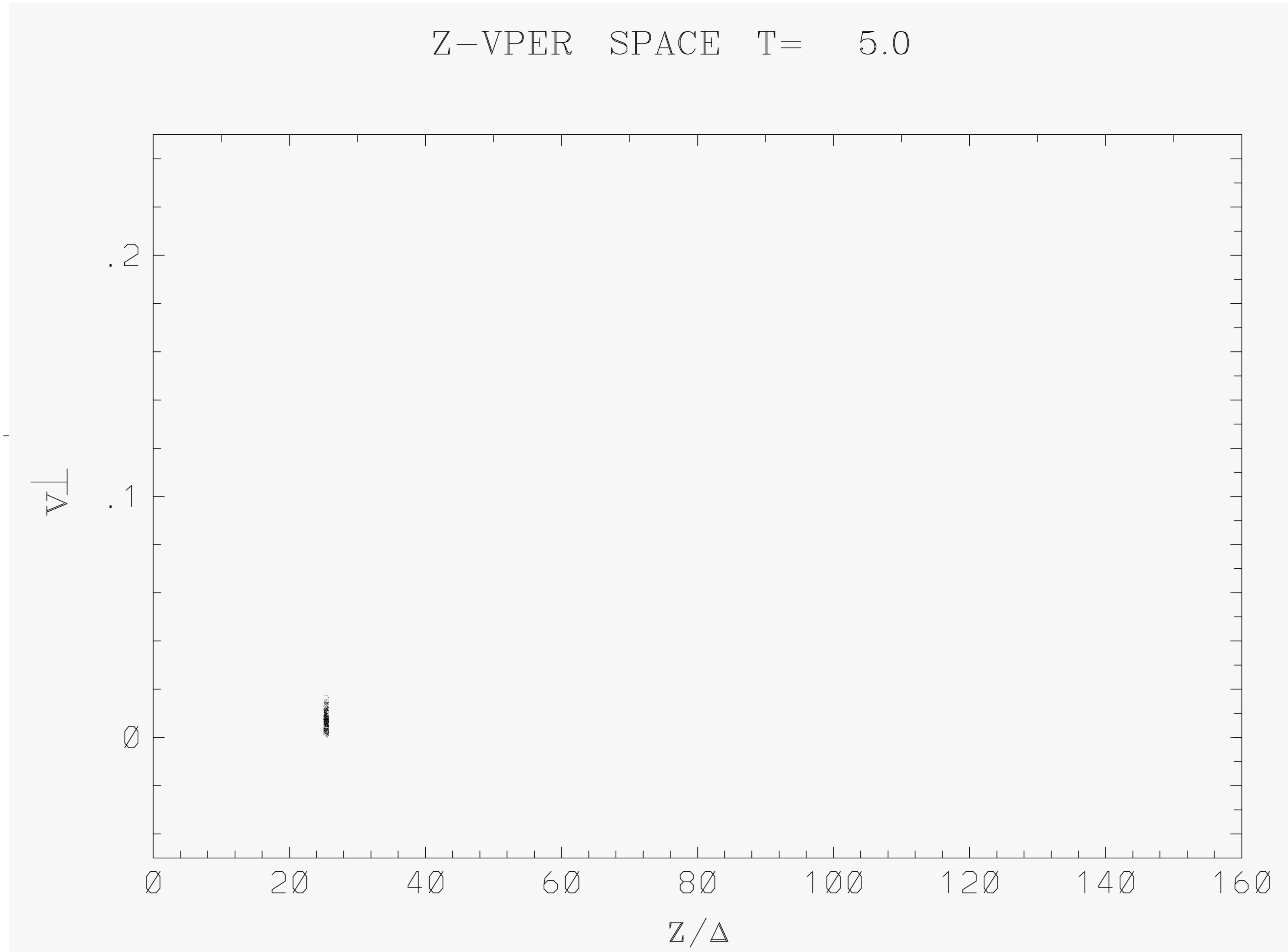
$\omega_{pe}\_t = 0.026$, $r_j = 40\,\_x$ □ $10\,\_{ce}$ (infinite)

$\_{e} = 1.389\_$, $\rho_i = 6.211\Delta$

Electron density (arrows: B_z, B_x)



Perpendicular acceleration of jet electron



A Flat jet injected into an unmagnetized plasma

Electron-positron jet, $m_p/m_e = 1$

□$= v_j/c = 0.9798$, $v_{et}/c = 0.1$

_ $= n_j/n_a$ □ 0.741

$\gamma = (1-(v_j/c)^2)^{-1/2} = 5$

$v_{je} = 0.1 v_{et}$, $v_{jp} = 0.1 v_{pt}$

ω_{pe}_$t = 0.013$

$\lambda_{ce} = c/\omega_{pe} = 9.6\Delta$, $\lambda_e = v_{et}/\omega_{pe} = 0.96\Delta$

A Flat jet injected into an unmagnetized plasma

Electron-positron jet, $m_p/m_e = 1$

_ = n_j/n_a □ 0.741, $v_{et} = v_{pt} = 0.1\ c$

$v_{je} = 0.1 v_{et}$, $v_{jp} = 0.1 v_{pt}$ (cold jet)

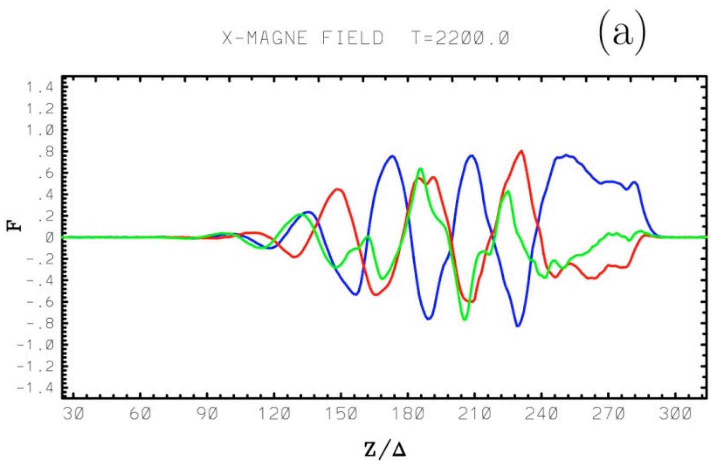
ω_{pe}_t = 0.013

$\lambda_{ce} = c/\omega_{pe} = 9.6\Delta$ (electron skin depth)

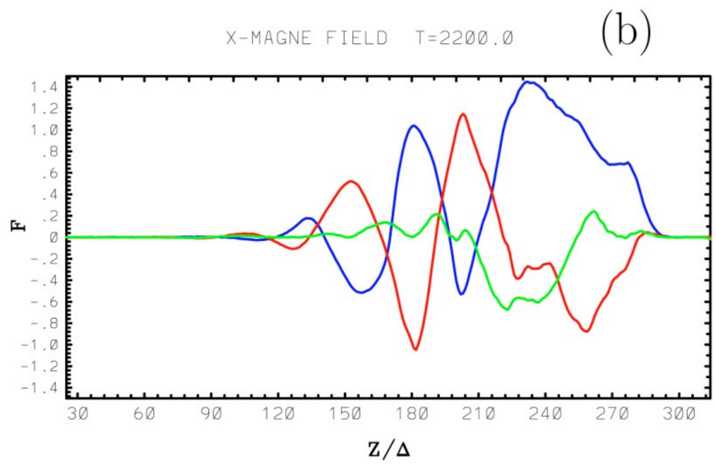
$\lambda_{e} = v_{et}/\omega_{pe} = 0.96\Delta$ (electron Debye length)

Δ: grid size (= 1)

Electron-positron jet injected

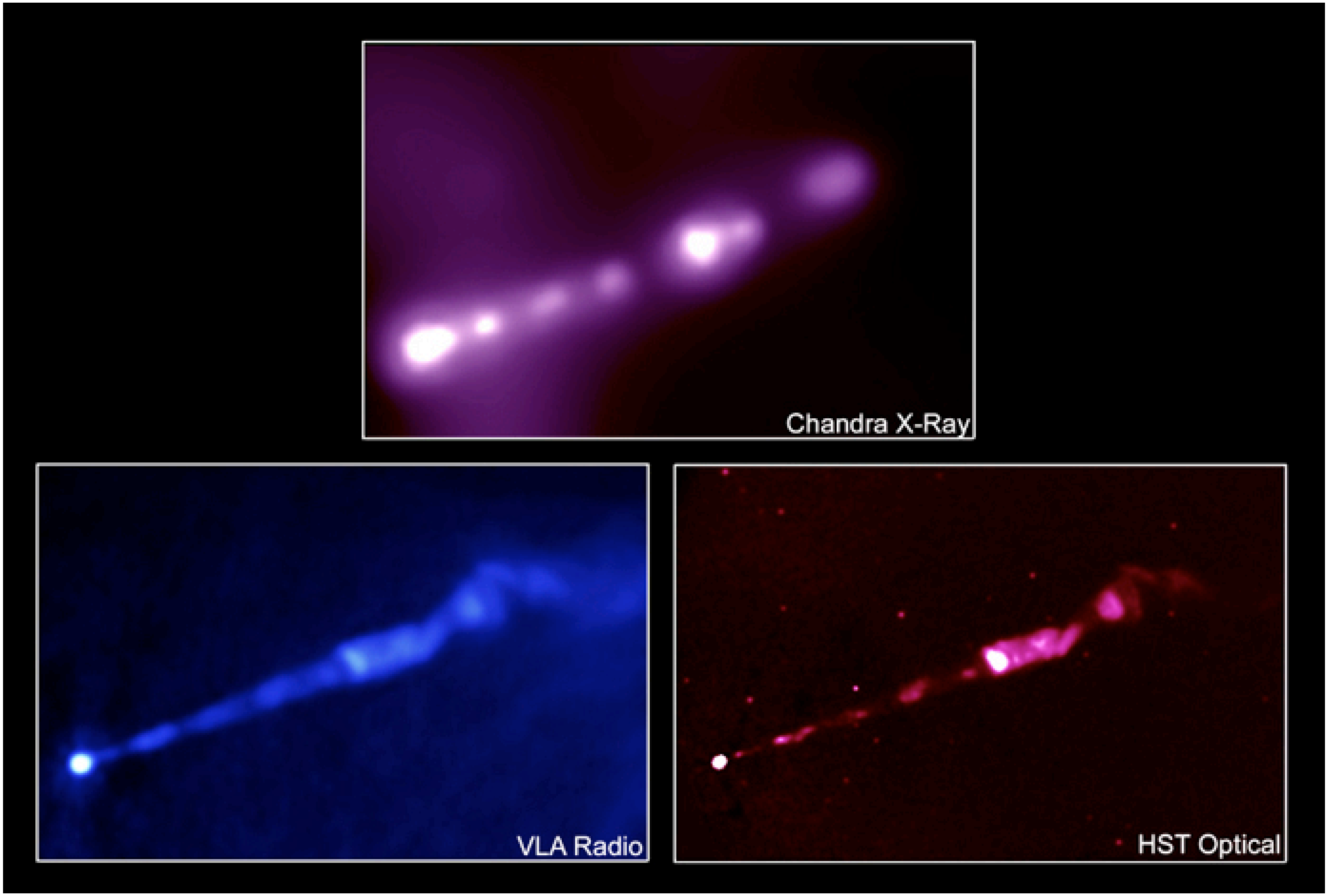


electron-positron ambient plasma



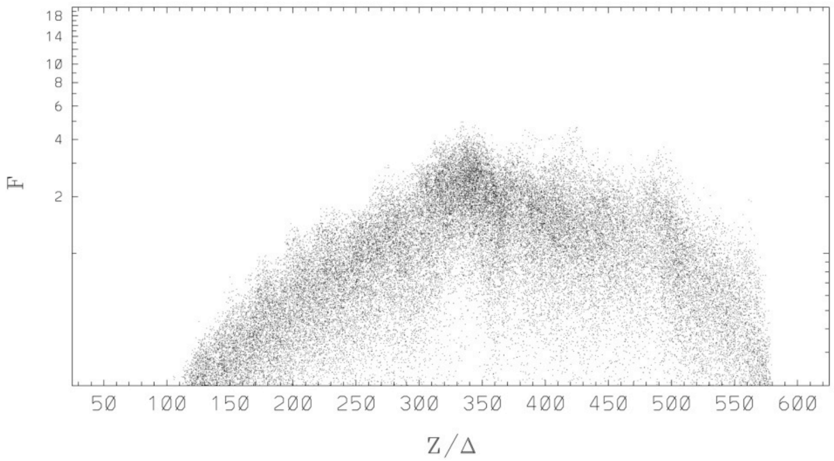
electron-ion ambient plasma

M87

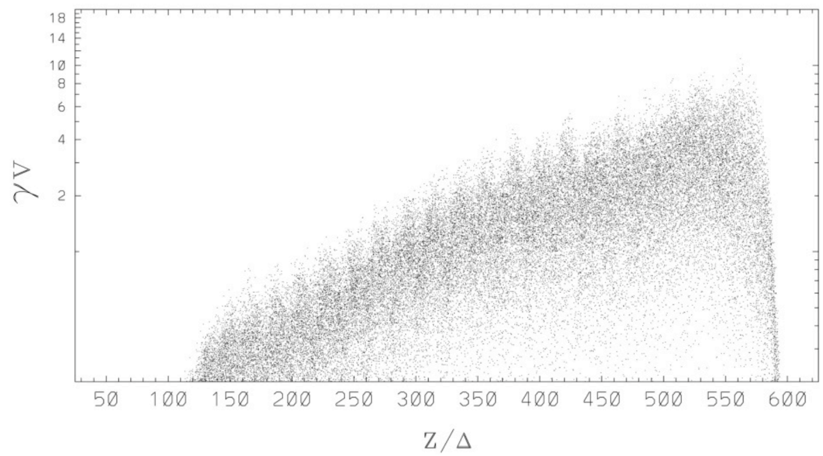


Z/_-_V□ phase space for jet electrons at t = 59.8 ω_{pe}

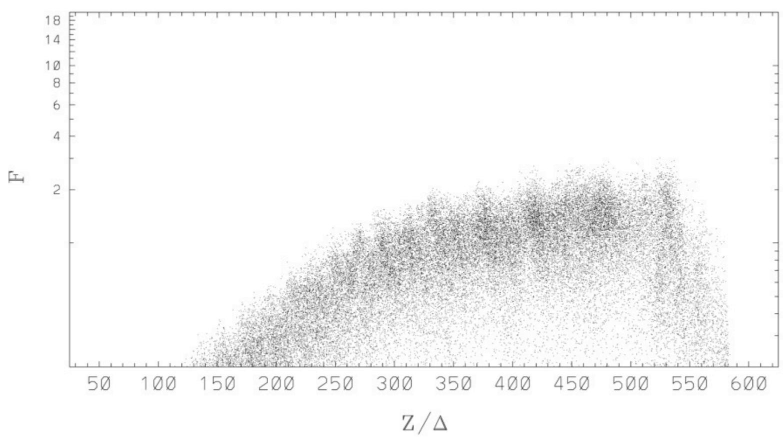
el-ion $\gamma = 5$



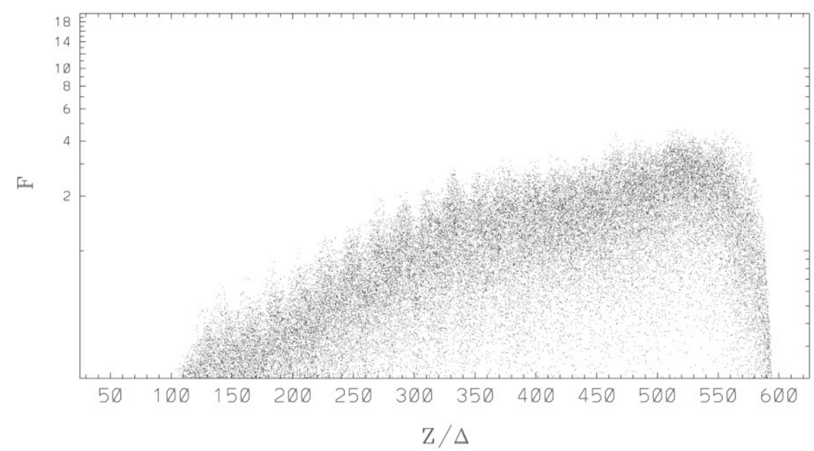
el-pos $4 < \gamma < 100$



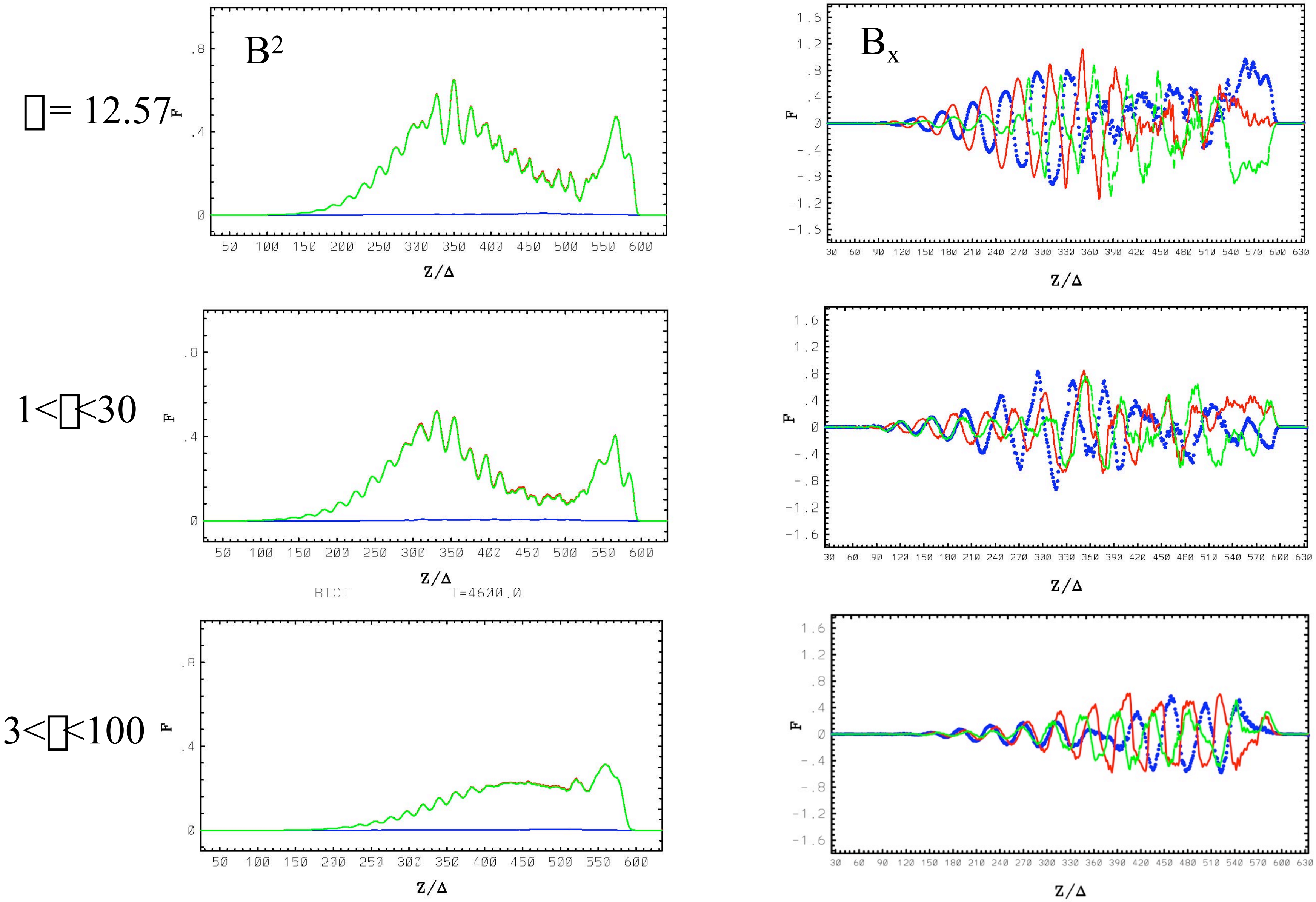
el-pos $\gamma = 5$



el-pos $\gamma = 15$



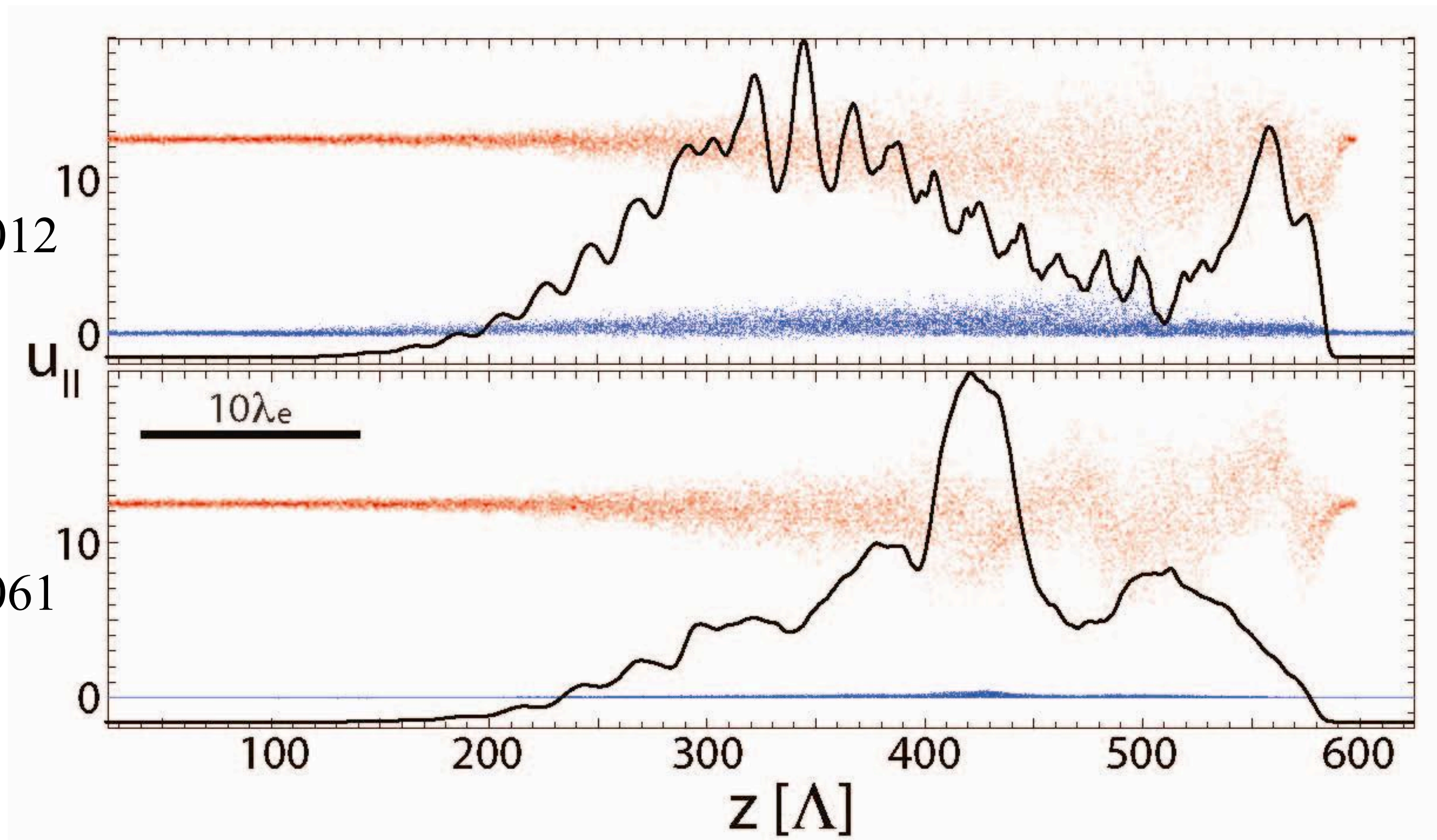
All pair plasmas



Magnetic field generation and particle acceleration with narrow injection

ele-pos
ambient
$\varepsilon_{Bmax} = 0.012$

ele-ion
ambient
$\varepsilon_{Bmax} = 0.061$



(Ramirez-Ruiz, Nishikawa, Hededal 2007)