# Inductive and Electrostatic Acceleration in Relativistic Jet-Plasma Interactions

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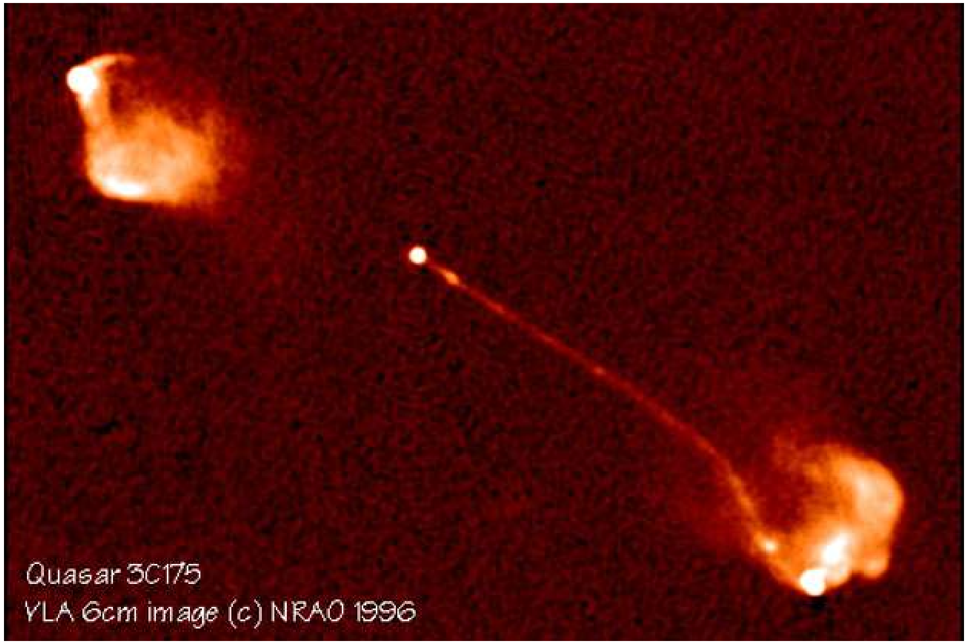
# Motivations

- High energy astrophysics phenomenon involve interactions of relativistic (bulk $\Gamma$>>1) plasma with ambient plasma, for example:
  - **GRB: colliding plasma shells**
  - **AGN jets: bow-shocks**




- Strong non-linear dynamics can produce:
  - **highly non-thermal radiation**
  - **particle acceleration – perhaps even ultra-high energy cosmic rays.**

⇒ **Simulate jet-plasma interactions: detailed microphysics**
**Design a laboratory relativistic "jet" dynamics experiment**

# Issues and Questions

What are the plasma microphysics that cause particle acceleration and deceleration, and radiation in jet-plasma interactions?

What are the parameters for scaled lab experiments that explore this physics, benchmark the codes, and connect this plasma physics to the astrophysical observations of AGN's and micro-quasars?

# Possible Laboratory Astrophysics Experiments

**Suggested in Oct. 2001 Workshop on Laboratory Astrophysics at SLAC:**

| | |
|---|---|
| 1. Cline (UCLA): | Primordial Black Hole Induced Plasma Instability Expt. |
| **2. Sokolsky (Utah):** | **High Energy Shower Expt. for UHECR SLAC E-165** |
| 3. Kirkby (CERN): | CLOUD Expt. on Climate Variation |
| 4. Chen-Tajima (SLAC-Austin): | Ponderomotive Acceleration Expt. for UHECR and Blazars |
| 5. Nakajima (KEK): | Laser Driven Dirac Acceleration for UHECR Expt. |
| 6. Odian (SLAC): | Non-Askaryan Effect Expt. |
| 7. Rosner (Chicago): | Astro Fluid Dynamics Computer Code Validation Expt. |
| 8. Colgate-Li (LANL): | Magnetic Flux Transport and Acceleration Expt. |
| 9. Kamae (SLAC): | Photon Collider for Cold $e^+e^-$ Plasma Expt. |
| 10. Begelman-Marshall (CO-MIT): | X-Ray Iron Spectroscopy and Polarization Effects Expt. |
| 11. Ng (SLAC): | Relativistic $e^+e^-$ Plasma Expt. |
| 12. Katsouleas (USC): | Beam-Plasma Interaction Induced Photon Burst Expt. |
| 13. Blandford (CalTech): | Beam-Plasma Filamentation Instability Expt. |
| 14. Scargle (NASA-Ames): | Relativistic MHD Landau Damping Expt. |

Pisin Chen (10-22-01)

# PIC Simulation – Very Brief Intro.

- Particle-in-cell (PIC) simulation

  [J. Dawson, Rev. Mod. Phys. 55, 403 (1983);  Birdsall and Langdon, "Plasma Physics via Computer Simulation", IOP Publishing Ltd 1991]

- Follow assembly of charged particles in their self-consistent electric and magnetic fields
- Find solutions to equations of motion and Maxwell's equations
- Numerical solutions on discrete spatial grids
- Practical limitation: a particle respresents many real plasma particles (macro-particles.)   Typically follow 10's to 100 millions of macro-particles in a PIC simulation.

⇨ Well-suited to study complex plasma dynamics problems

# PIC Code: TRISTAN Package

TRISTAN (Tri-dimensional Stanford code:
O. Buneman, T. Neubert, K.-I. Nishikawa, 1990)

3-D electromagnetic, relativistic, particle-in-cell code.
originally written under NASA grant to study interaction of the solar wind and Earth's magnetosphere
used by A. Spitkovsky for magnetosphere physics of neutron stars (mid- 1990's onward).
K. Nishikawa reported initial TRISTAN simulations of astro-jets impinging upon background plasma (ApJ, 595:555,2003; ApJ 622:927,2005)

# Recent PIC Simulations of Jet-Plasma Systems

- K.-I. Nishikawa *et al.* : astro-jets impinging upon background plasma– Weible instability (ApJ, 595:555,2003; ApJ 622:927,2005)

- Silva *et al.* have used OSIRIS to study the plasma micro-physics relevant to GRB models (ApJL, 596: L121, 2003)

- Frederiksen *et al.* used another 3D code to study collisionless shocks (ApJL, 608: L13, 2004).

These studies concentrated on wide jets using periodic boundary conditions to study the interior dynamics

# Objectives of This Work

Kinetic energy transfer via plasma instabilities: elucidate acceleration mechanisms

Narrow jets several skin-depth wide: dynamics in the jet interior ("spine"), as well as the jet-plasma interface region ("sheath")

Continuous as well as finite-length jets: different longitudinal dynamics

Simple system: to shed light on the processes that cause particle acceleration in jet-plasma interactions.

Applicable to narrow jets of micro-quasars or the interface region of wide jets.

# Simulation Parameters and Stability

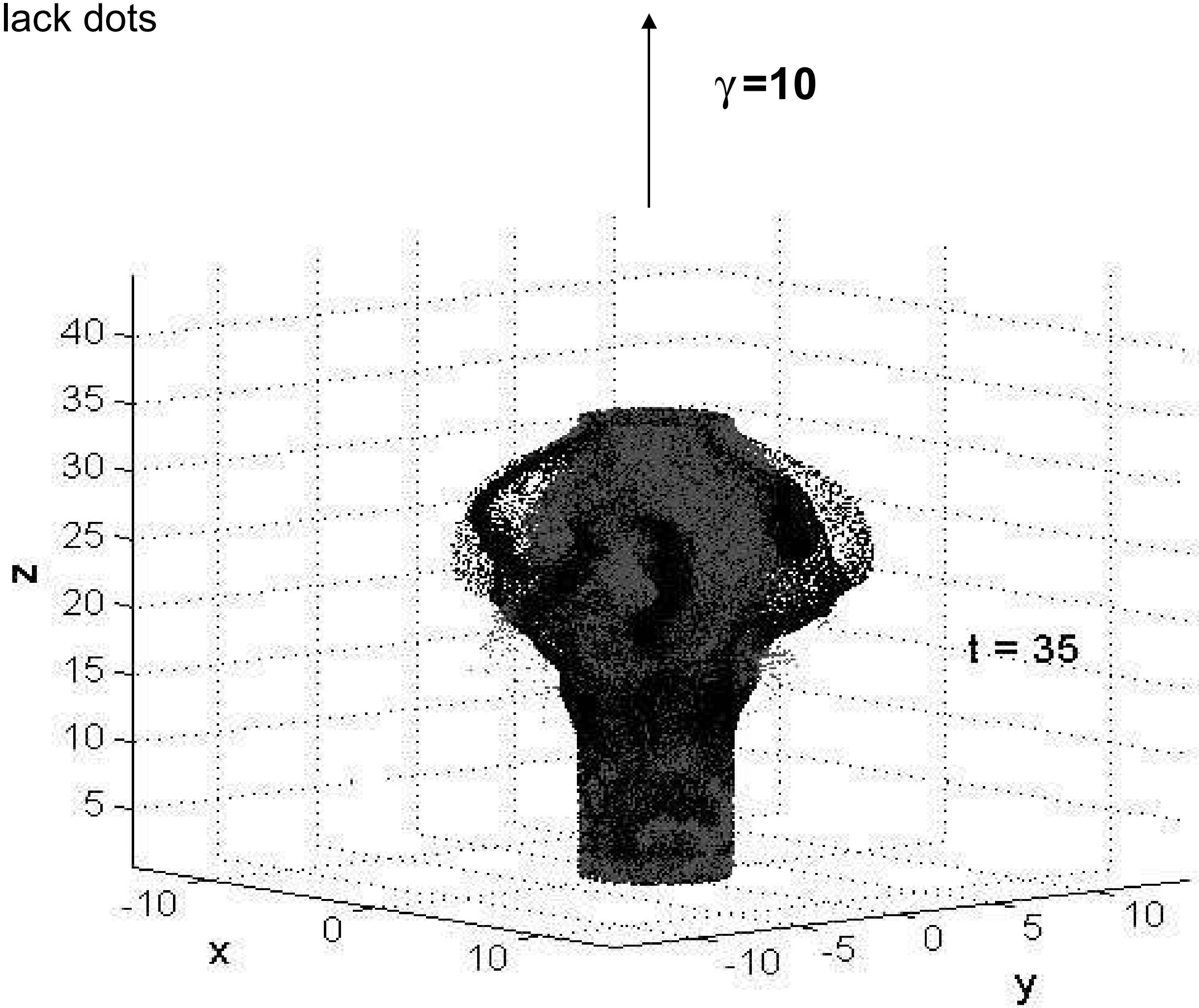
- Simulation performed on a 150x150x225 grid, with a total of ~40 million macro-particles
- Time step size=$0.1/\omega_{pe}$; Courant parameter=0.5: mesh size=0.2 $c/\omega_{pe}$
- Jet $\gamma$=10, spread=0.1%; jet-plasma density ratio:10
- Jet diameter=6 $c/\omega_{pe}$, length: 10 $c/\omega_{pe}$ or continuous
- Macro-particle density: 4/cell (background plasma), 32/cell (Jet).
- Boundary condition: absorbing; simulate free space; no reflections.

## Stability checks:

- Time scale: dynamics occur within 45 $/\omega_{pe}$; confirm physics was adequately resolved by runs with $0.05/\omega_{pe}$ time-steps
- Simulation box size: <0.5% of jet energy carried away in total; results not sensitive to reasonable variation of box size.
- Macro-particle density: insensitive in the range 4-8/cell.

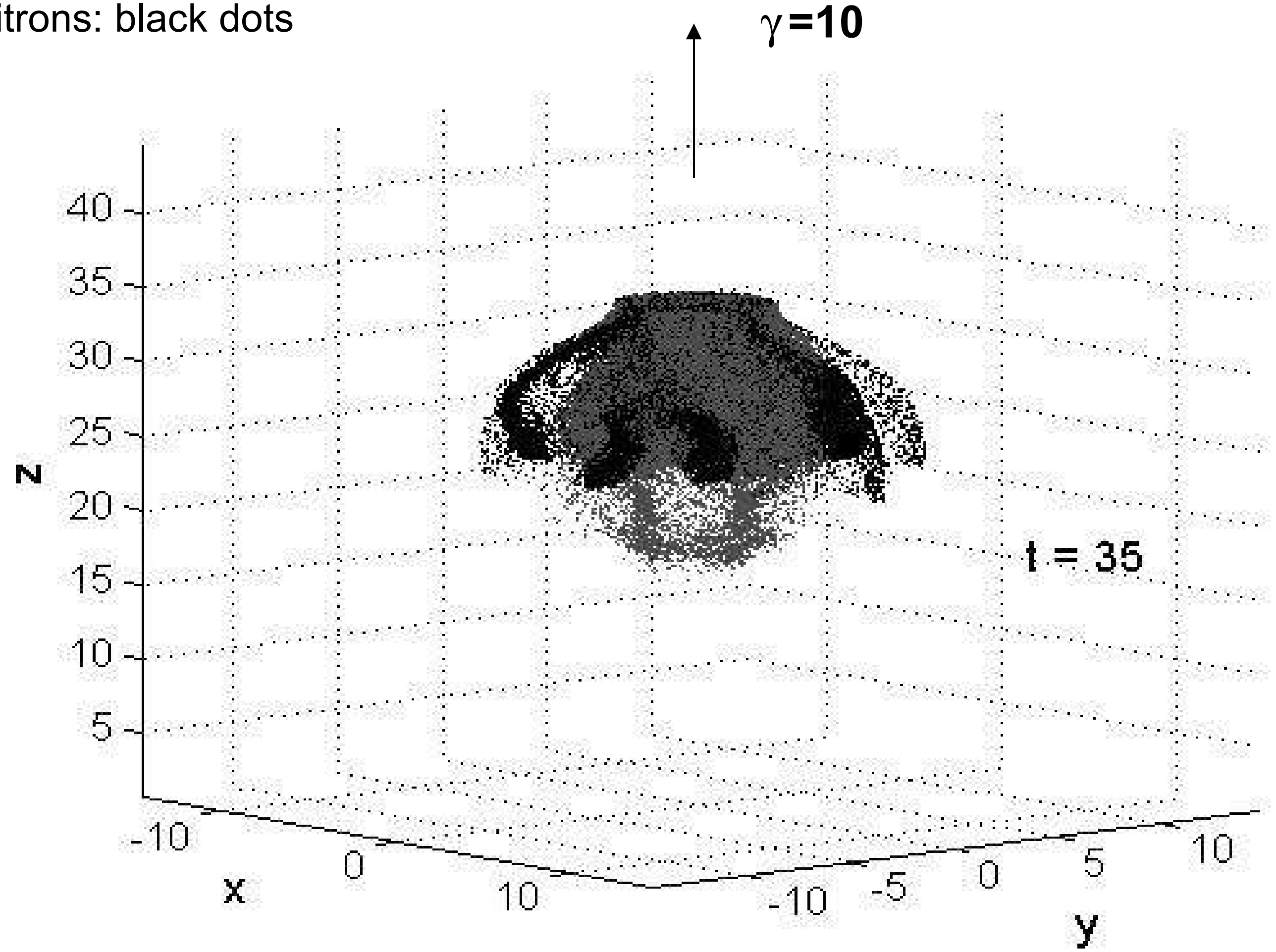
# Simulation geometry: continuous jet.

Jet electrons: gray dots
Jet positrons: black dots



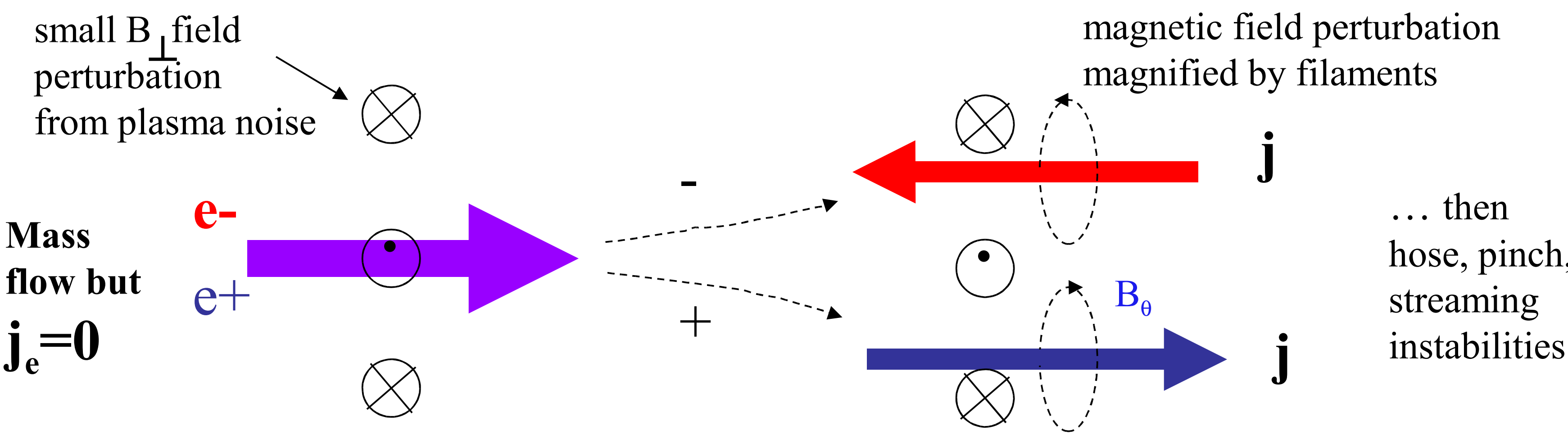
# Simulation geometry: finite-length (10 $c/\omega_{pe}$) jet.

Jet electrons: gray dots
Jet positrons: black dots



# Streaming Neutral Plasma Systems: Plasma Filamentation

Weibel instability (1959) is the spontaneous filamentation of the jet into separate currents and the generation of associated azimuthal magnetic fields.




Davidson and Yoon (1987)
Weibel growth time:

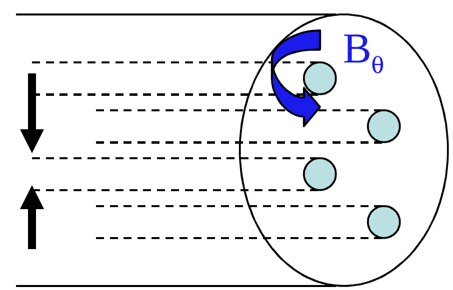
$$\Gamma = f(\beta_\perp, \beta_z)\ \omega_{p(b)} / \gamma^{1/2}$$

$\sim (n/\gamma)^{1/2}$ typ. $f \leq 1$

Transverse scale size:

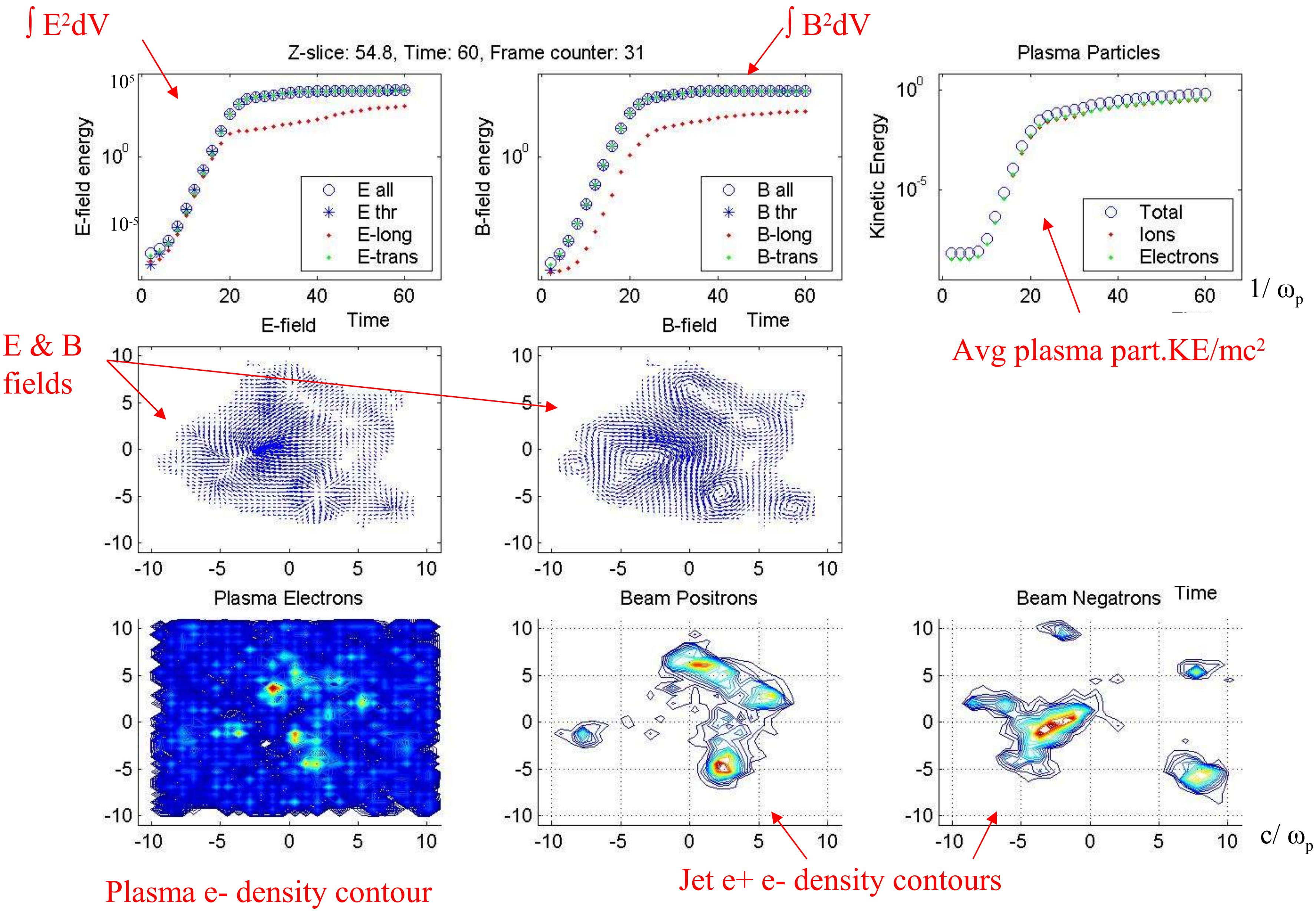
$$d = g(\beta_\perp, \beta_z)\ c/\omega_{p(b)}$$

$\sim (1/n)^{1/2}$ typ. $g \geq 1$




Past simulations: Saturated EM energy density/particle KE density ~ 0.01 – 0.1

# Illustrative Case: gamma =10, jet/plasma density = 10



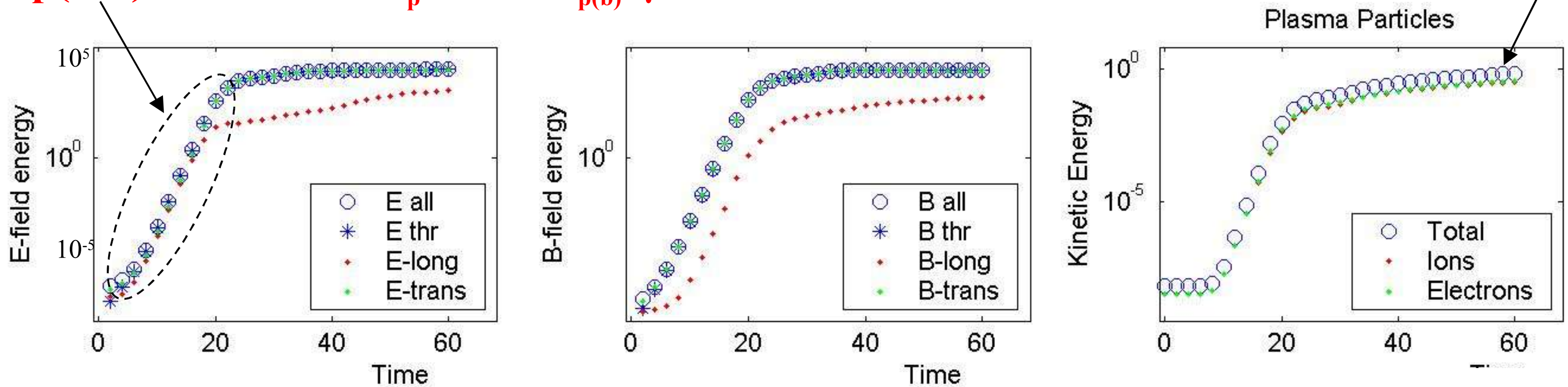
# Some Results from this Illustrative Case:

**Growth rate:**

**$E^2 \sim \exp(2\Gamma t) \rightarrow \Gamma \approx 0.85\ \omega_p = 0.85\ \omega_{p(b)}/\gamma^{1/2}$**

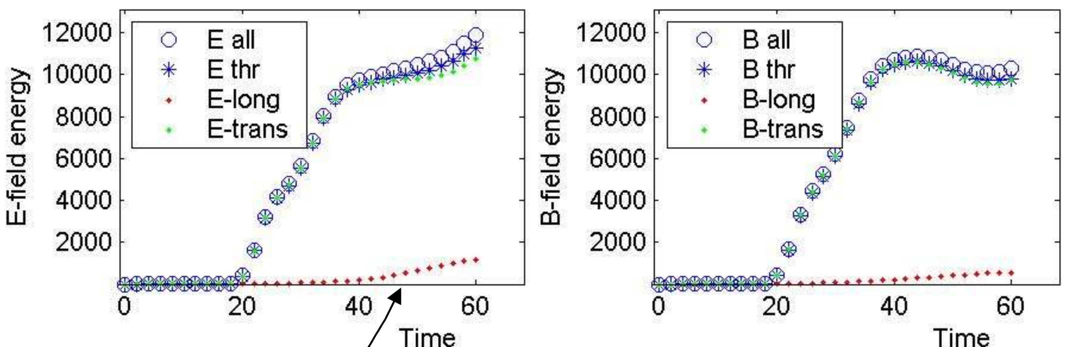
Strong plasma heating of order $m_e c^2$

Log plot



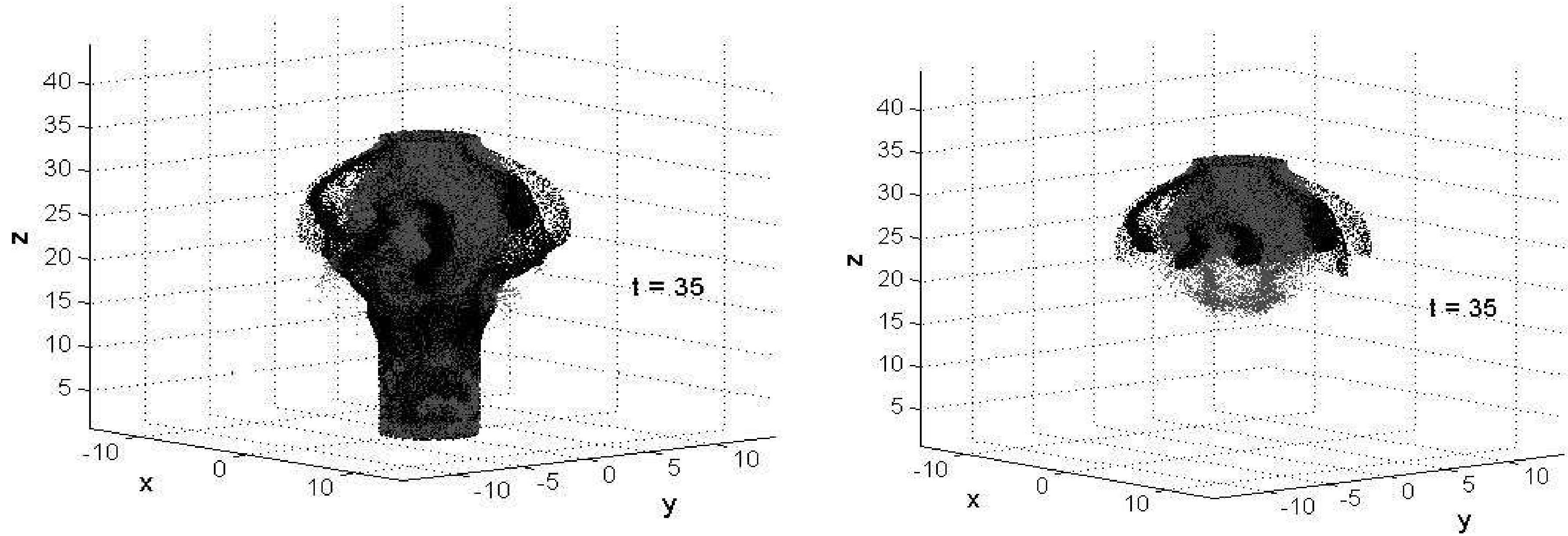

$1/\ \omega_p$

Linear plot




Longitudinal E fields
start building up
once the jet breaks up into
e+ and e- filaments

# Simulation Results: Overview




1. Transverse dynamics (same for continuous and short jets):
    Magnetic filamentation instability: inductive Ez
    Positron acceleration; electron deceleration

3. Longitudinal dynamics (finite-length jet):
    Electrostatic “wakefield” generation
    Persists after jet passes: acceleration over long distances.

# Inductive "Faraday Acceleration"

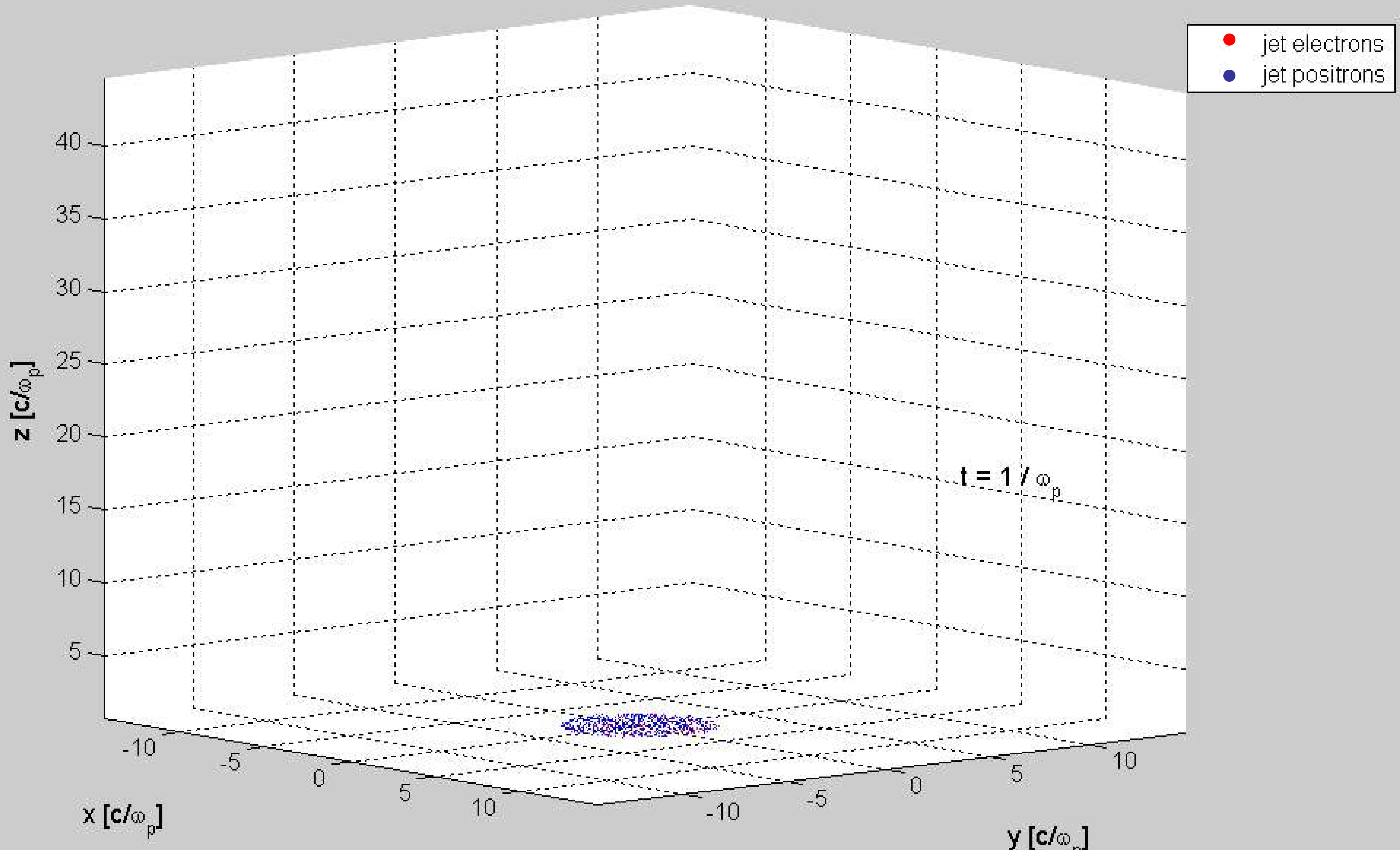
- Lorentz force: electron and positron filaments separate
- Electron filaments are confined by the electrostatic channel formed by the heavier plasma ions
- Positron filaments are preferentially expelled

⇨ Rapid decrease in $B_\phi$ associated with positron filaments

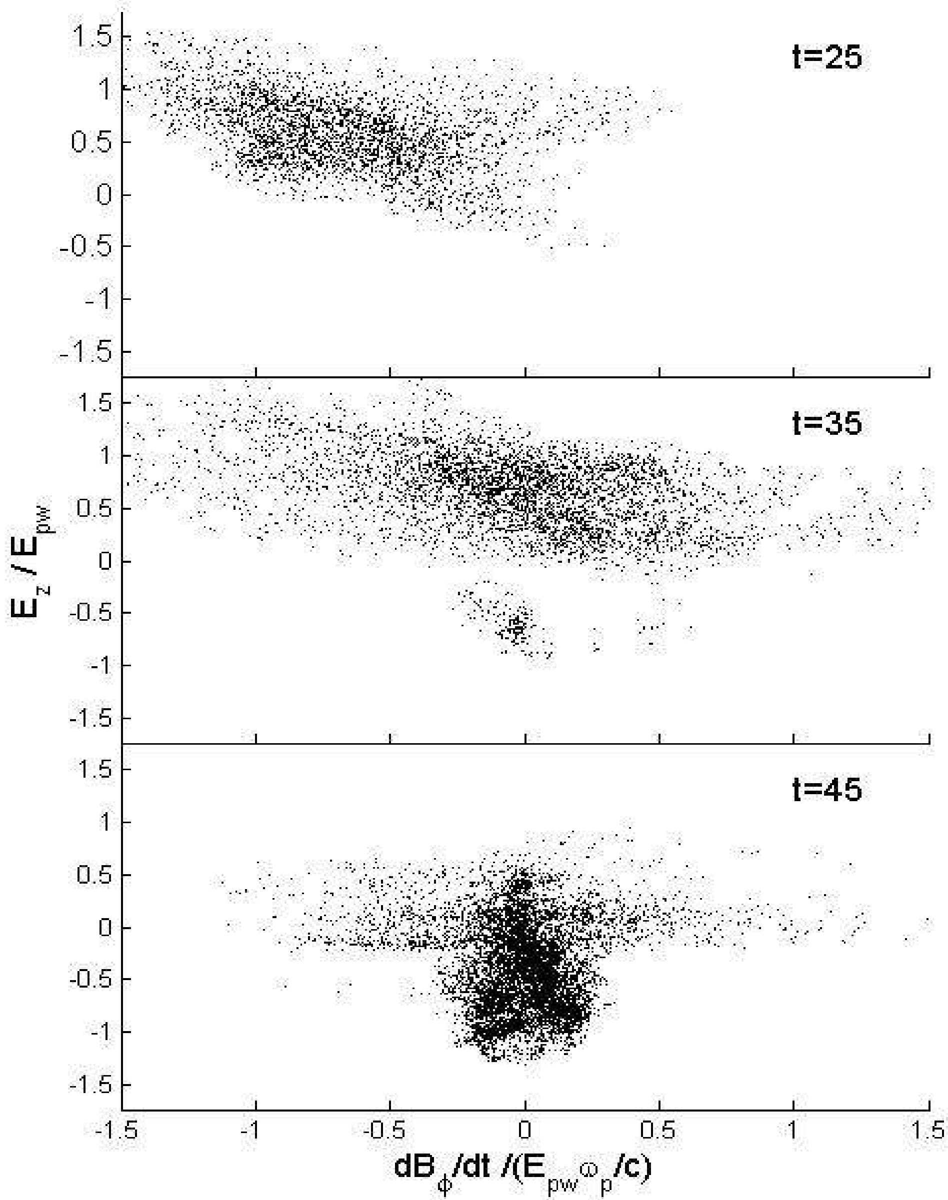
⇨ Locally induces a large and positive longitudinal electric field $E_z$, travelling with the filaments

⇨ Positrons accelerated, "surfing" on $E_z$ wave; electrons decelerated.

## Charge-neutral, electron-positron jet interacting with cold electron-ion background plasma (not shown)



# Inductive and Electrostatic Fields

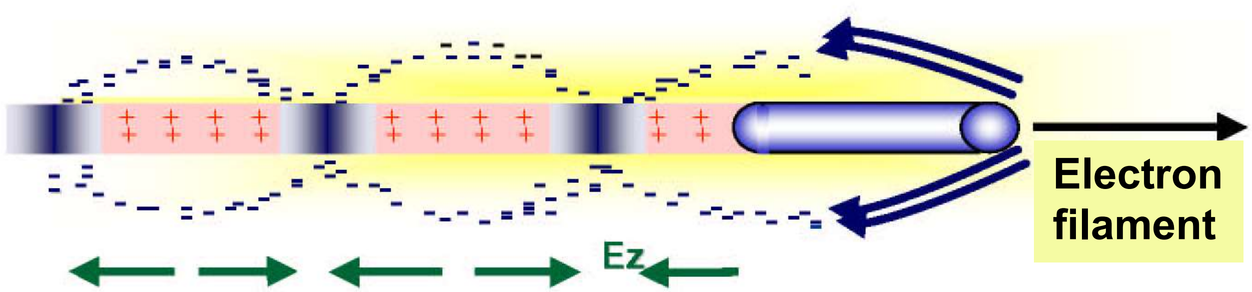



Correlation of longitudinal electric field with time variation of azimuthal magnetic field, in normalized units, for a finite-length jet.

$$E_{pw} = m_e c \omega_p / e$$

t in units of $1/\omega_p$

# Electrostatic Plasma Wakefield Acceleration

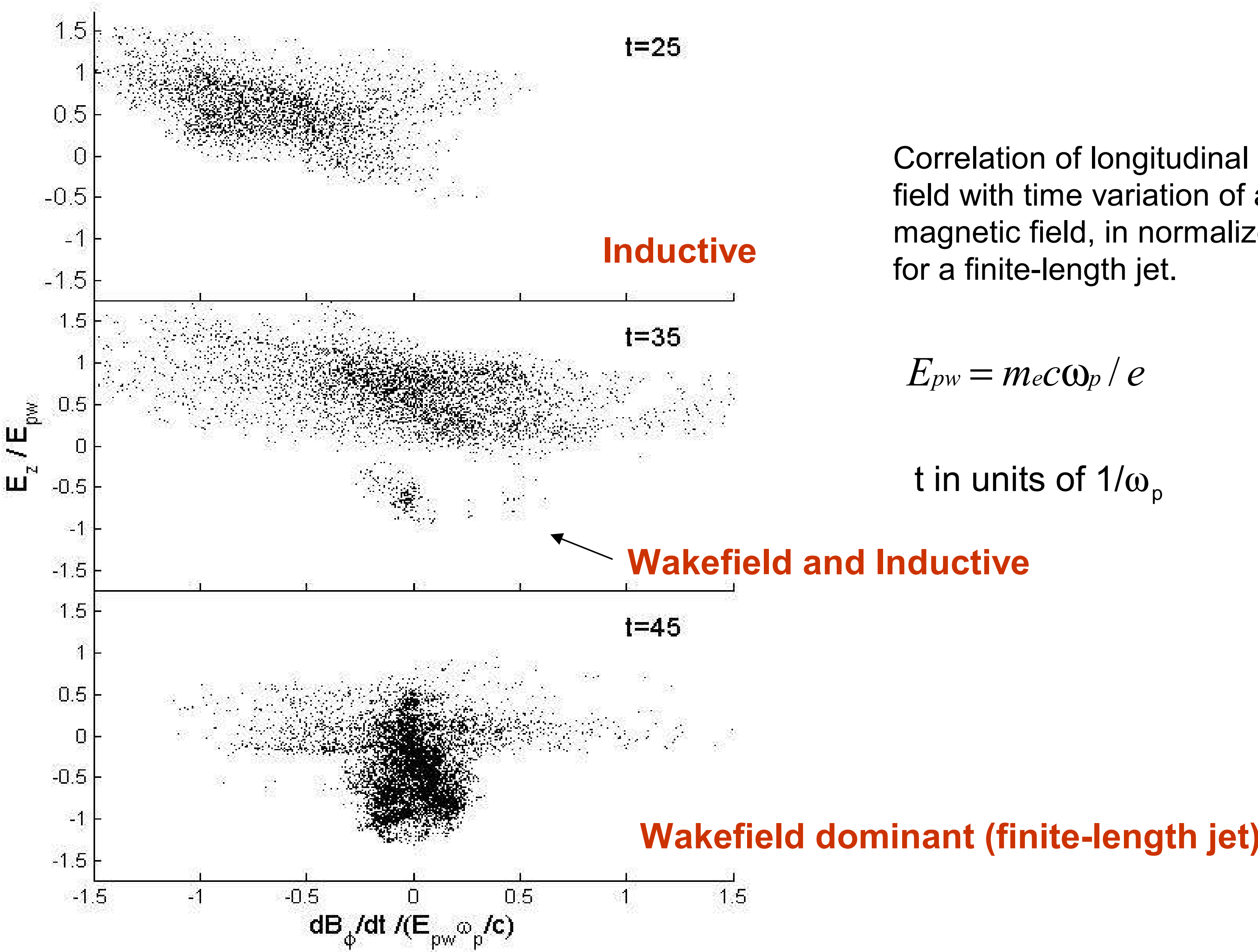



- Filament separation leaves behind electron "driver"-- a second field generation mechanism:
  - Displaces plasma electrons
  - Plasma ions try to restore neutrality: space charge oscillation
- "Wakefields" phase velocity same as drive jet
- Forms immediately behind the trailing edge
- Continues to oscillate after the jet passes: can accelerate particles over very long distances.

[See P. Chen *et al.,* Phys. Rev. Lett. 54, 693 (1985); talk at this Workshop]

# Finite-length, charge-neutral, electron-positron jet interacting with cold electron-ion background plasma – development of electric field $E_z$ is shown vs x and z.

# Inductive and Electrostatic Fields

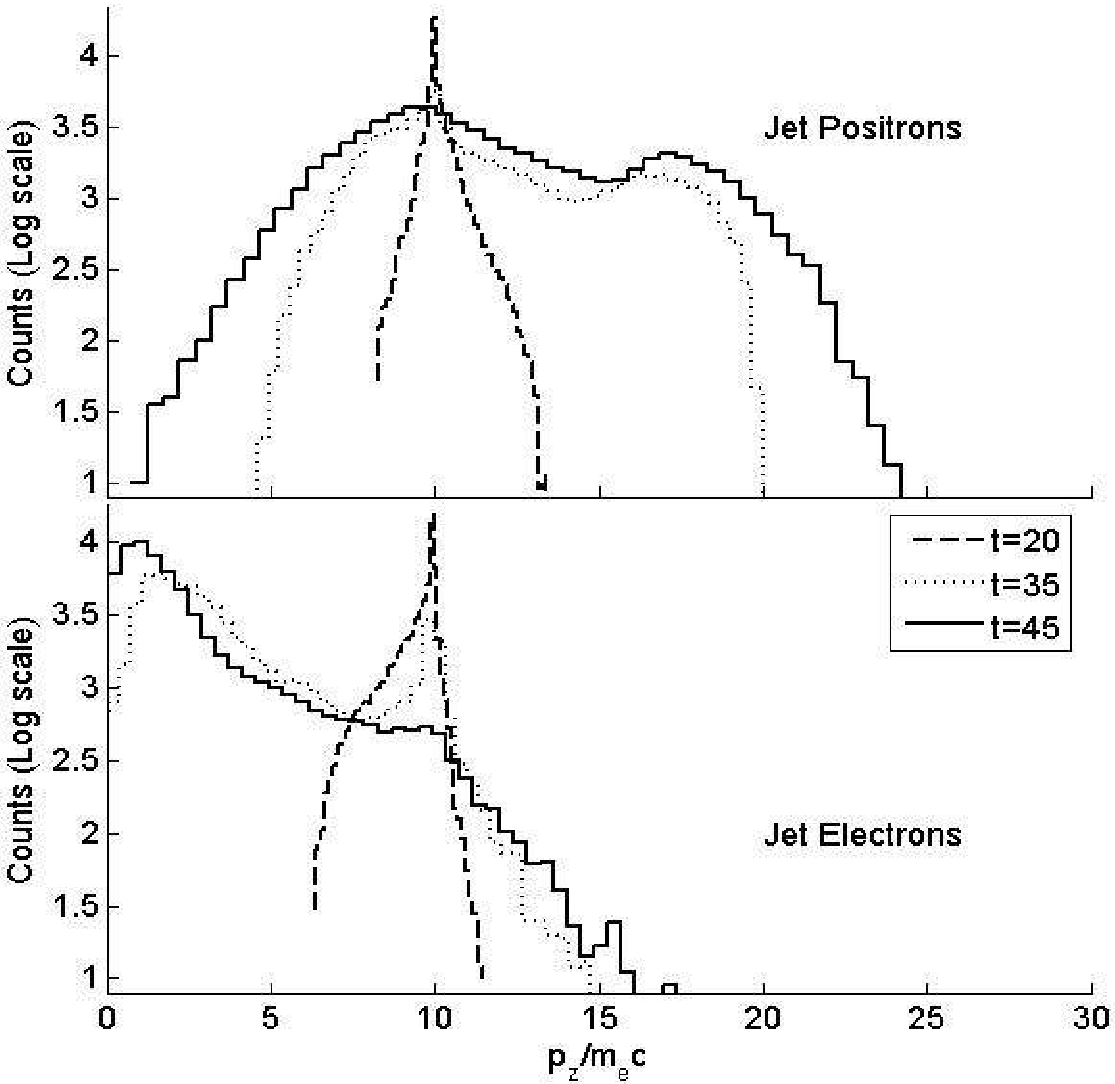



Correlation of longitudinal electric field with time variation of azimuthal magnetic field, in normalized units, for a finite-length jet.

$$E_{pw} = m_e c \omega_p / e$$

t in units of $1/\omega_p$

# Particle Acceleration and Deceleration




Longitudinal momentum distribution of positrons and electrons for a finite-length jet at three simulation time epochs.

t in units of $1/\omega_p$

~ 40% of positrons gained >50% In longitudinal momentum ($p_z$)

# Summary

1. General results:

   We observe the correct $(n/\gamma)^{1/2}$ scaling of the Weibel instability growth rate, transverse filament size of few skin depths, and approximately the correct absolute growth rate.

   Neutral jets in unmagnetized plasmas are remarkably unstable. One expects stability to improve if a background longitudinal B field existed.

2. Plasma filamentation sets up the jet for other instabilities.

   Separation of electron and positron filaments.
   Separating positron filaments generate large local Ez
   Finite-length electron filaments excite longitudinal electrostatic plasma waves

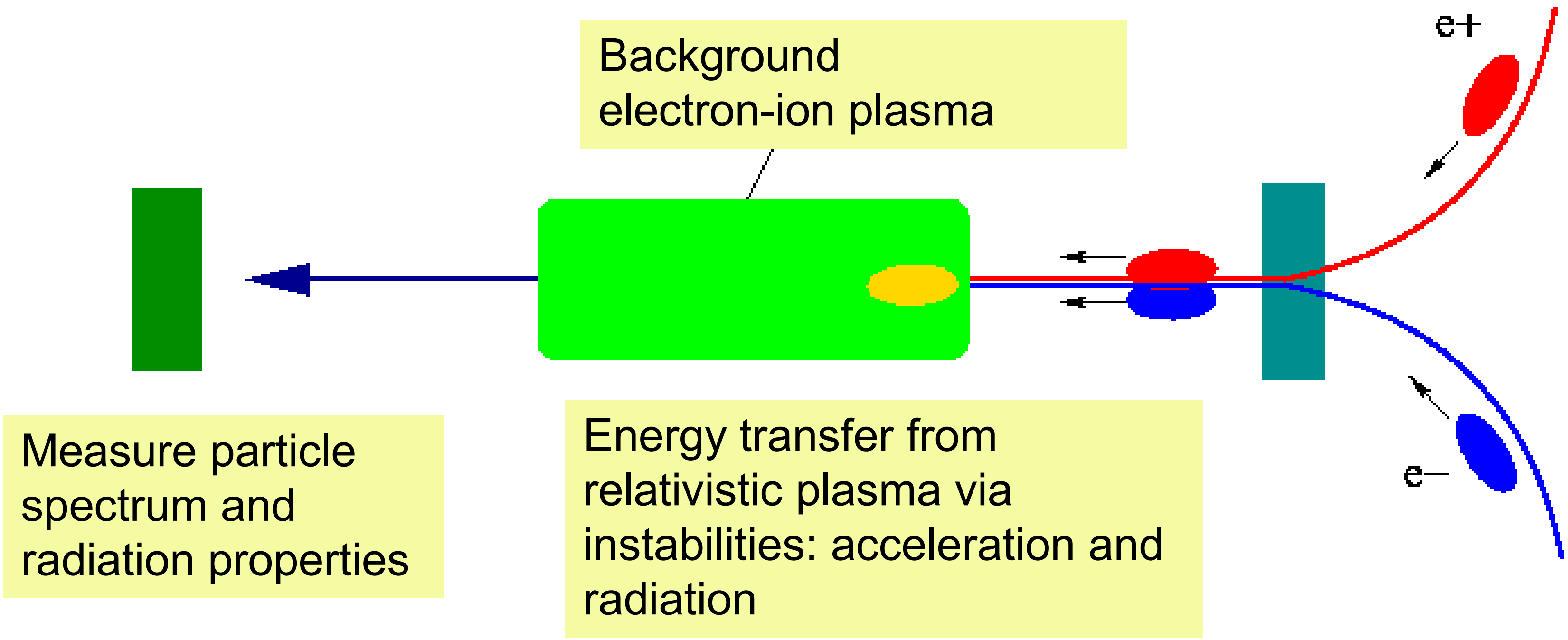
We observe:

Inductive “Faraday acceleration”
Electrostatic Plasma Wakefield acceleration.

# Outlook

Next:

Effect of background magnetic fields
Extend length of simulation to study details of acceleration
Implement particle radiation
Design of laboratory jet-dynamics experiment using particle and/or photon beams, at SLAC for example.



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