Simulation of Relativistic Jet-Plasma Interactions

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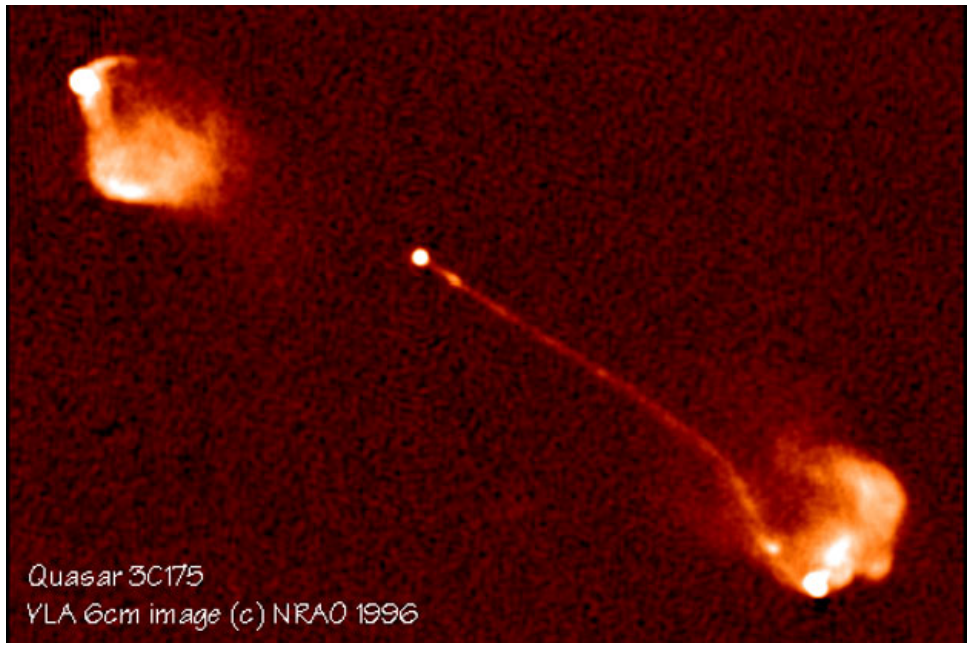
SABER Workshop, Laboratory Astrophysics WG
SLAC, March 15-16, 2006

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 with particle-in-cell code.**
- **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 can explore this physics, benchmark the codes, and connect this plasma physics to the astrophysical observations?

- Real astrophysical outflows are larger than anything we can simulate with a PIC code. We are not simulating the full jet, only physics at the **plasma wavelength scale**.

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– Weibel 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
- e+e- jet propagating in unmagnetized, stationary ion-electron plasma
- Narrow jets several skin-depths 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 may cause particle acceleration in jet-plasma interactions at the plasma wavelength scale.

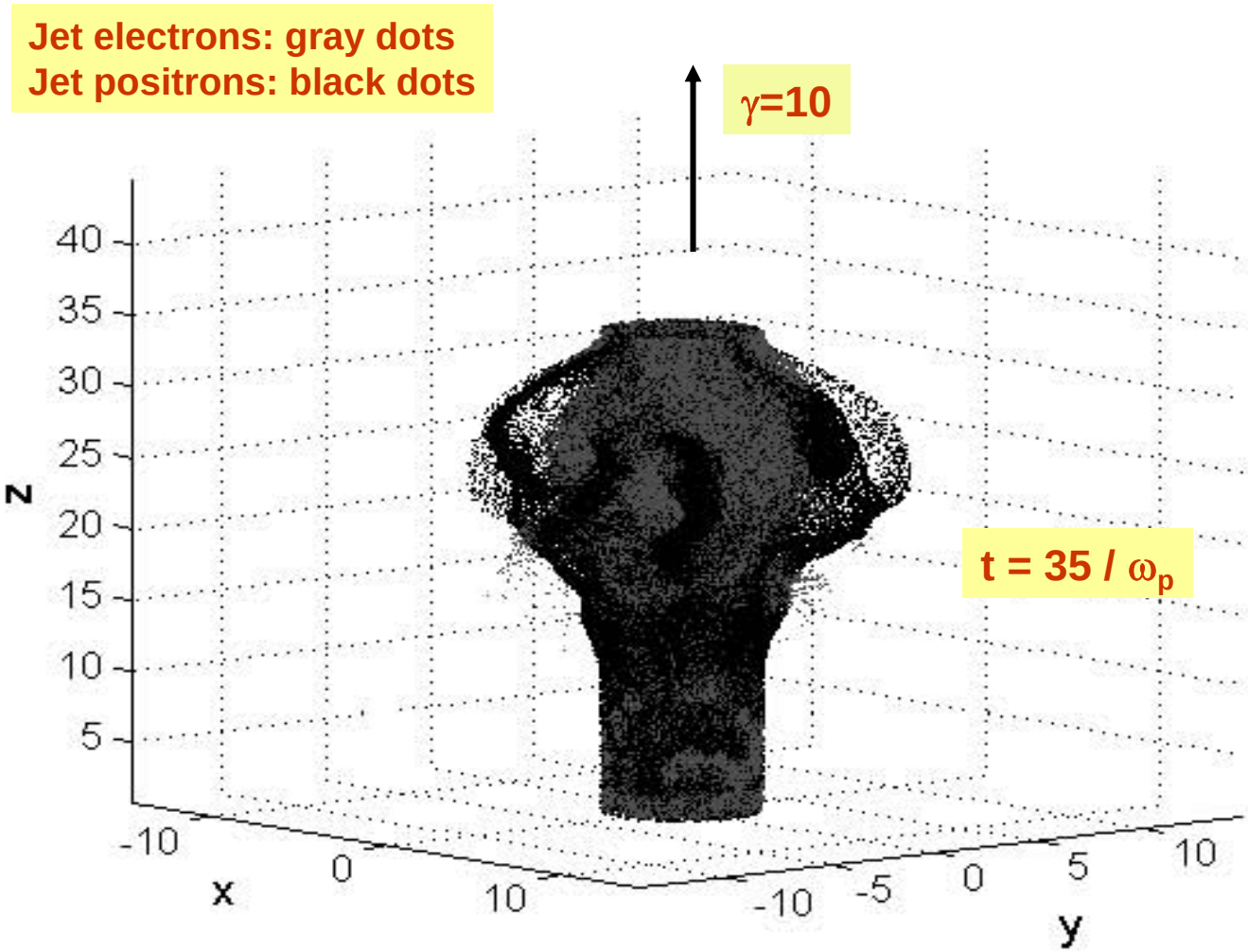
Simulation Parameters and Stability

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

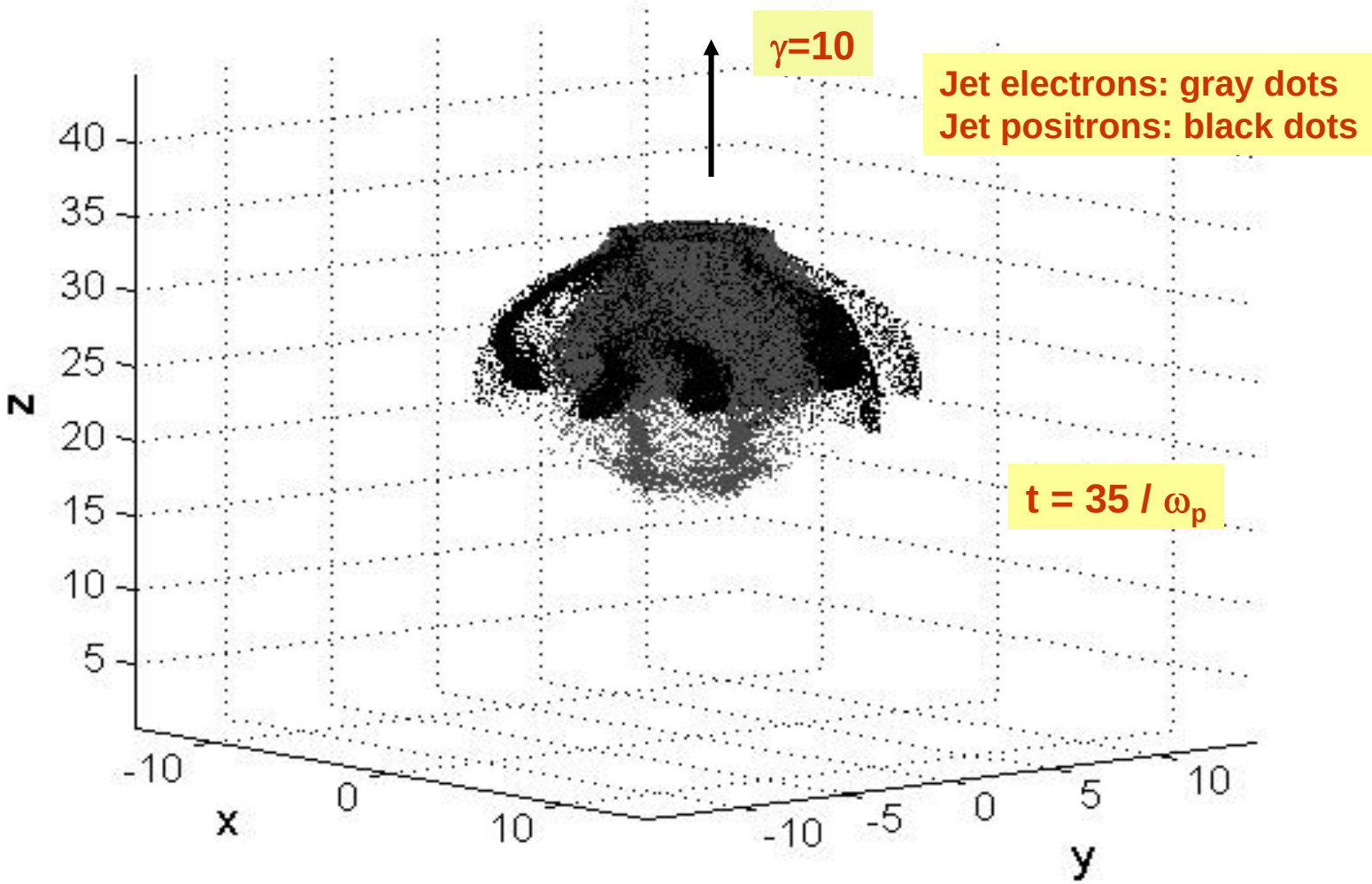
Stability checks:

- Time scale: dynamics occur within 45 /ω_{pe}; confirm physics was adequately resolved by runs with 0.05/ω_{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 in unmagnetized ion-electron plasma (not shown).

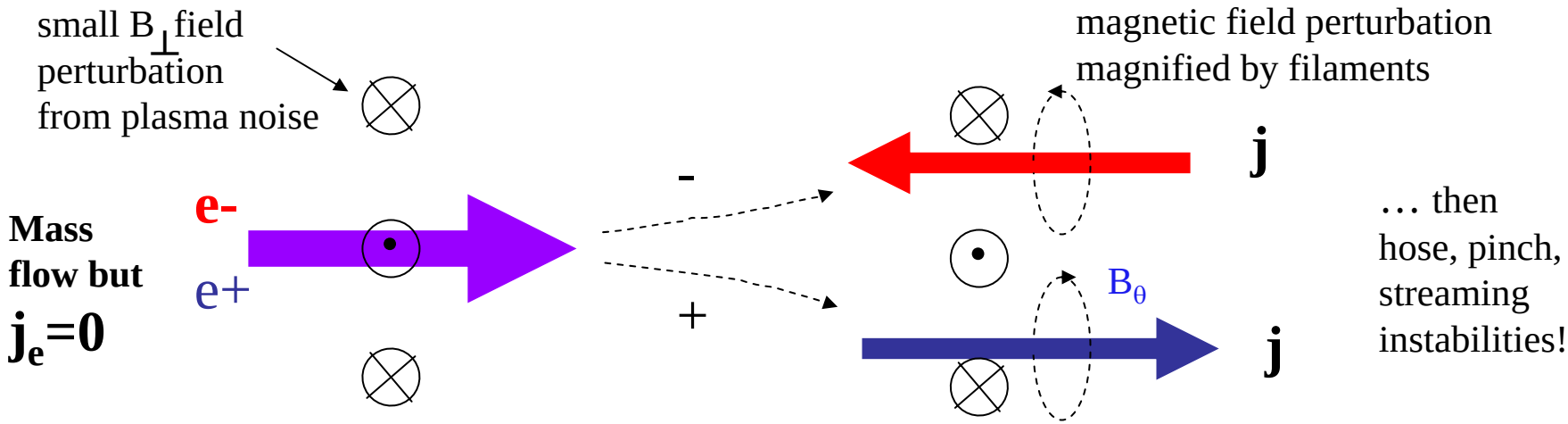


Simulation geometry: Finite-length (10 c/ω_{pe}) jet.



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 rate:

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

$$\sim (n/\gamma)^{1/2}$$

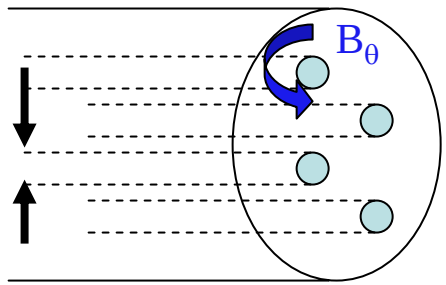
typ. $f \leq 1$

Transverse scale size:

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

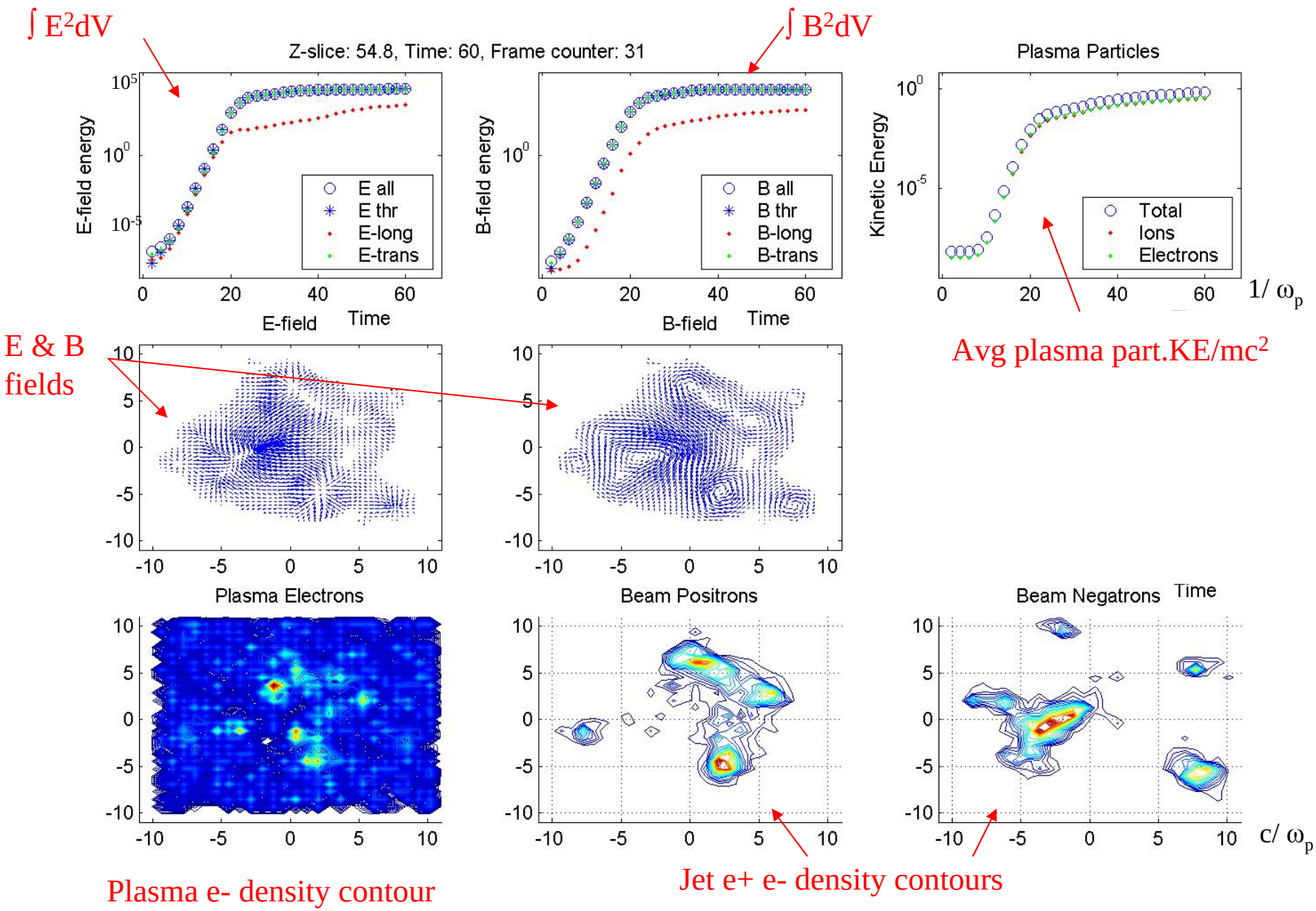
$$\sim (1/n)^{1/2}$$

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:

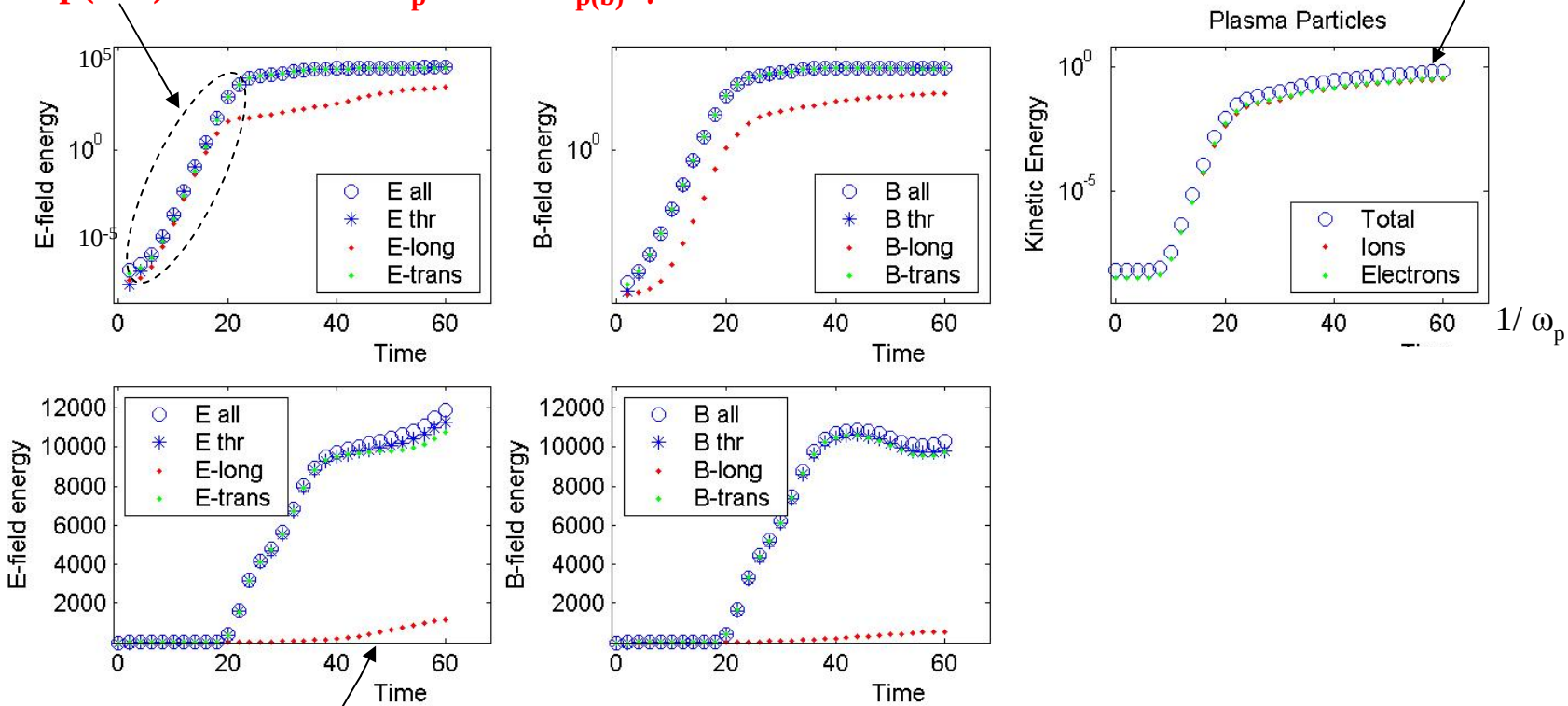
Growth rate:

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

Strong plasma heating of order $m_e c^2$

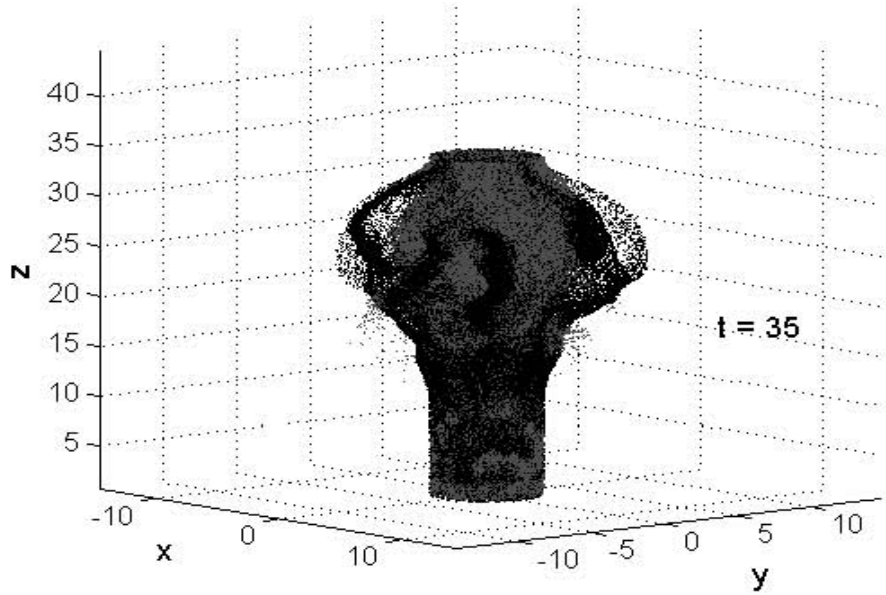
Log plot

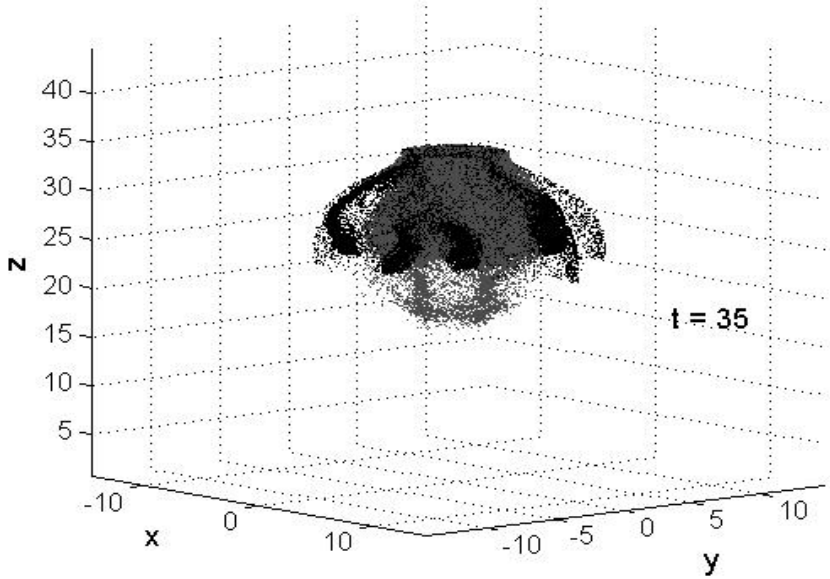
Linear plot



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 E_z
   - Positron acceleration; electron deceleration

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

Inductive "Faraday Acceleration"

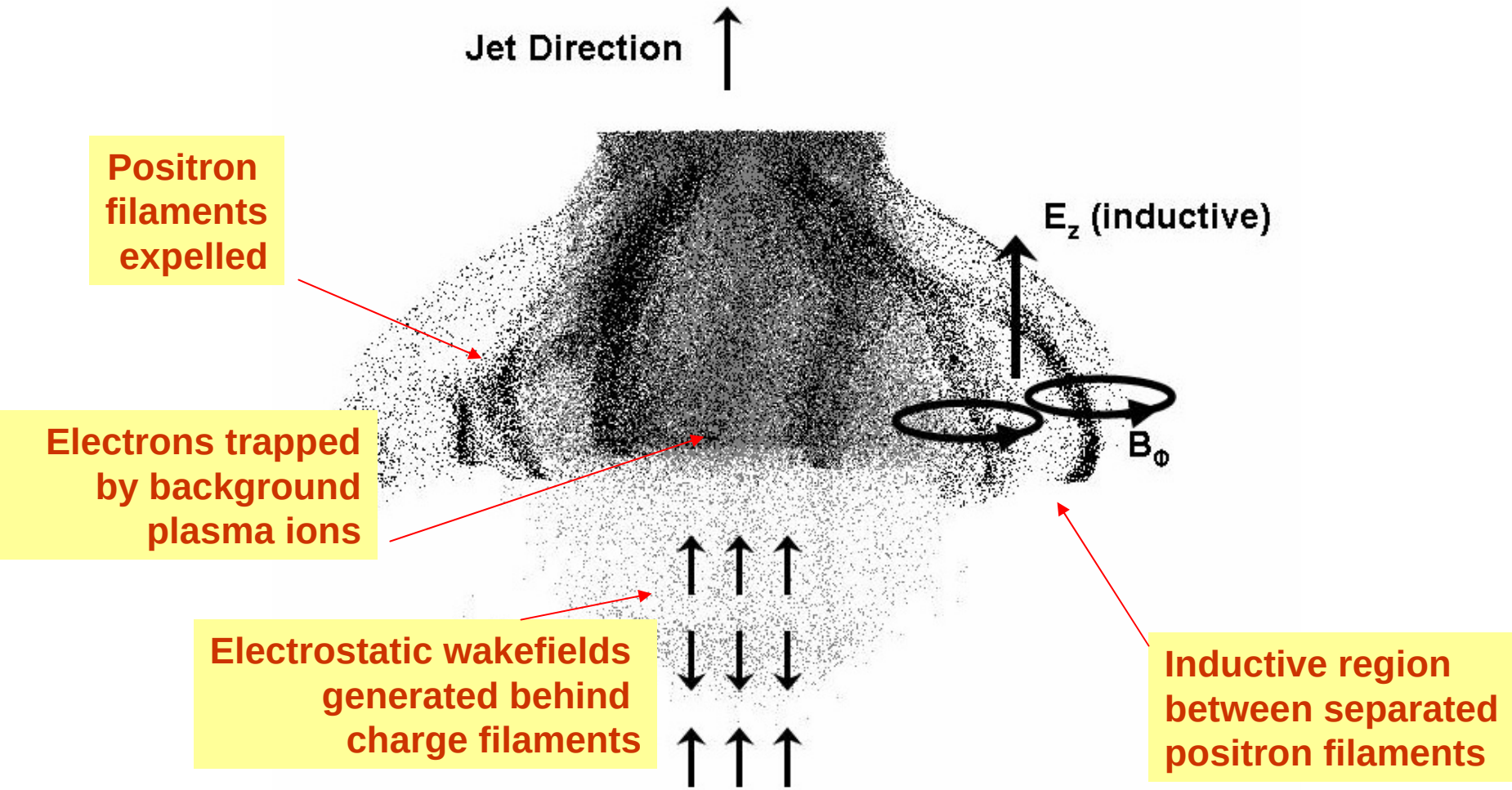
- Lorentz force: electron and positron filaments separate
- Electron filaments are confined by the electrostatic channel formed by the heavier plasma ions
- Positron filaments are preferentially expelled

⇨ Rapid decrease in B_ϕ associated with positron filaments

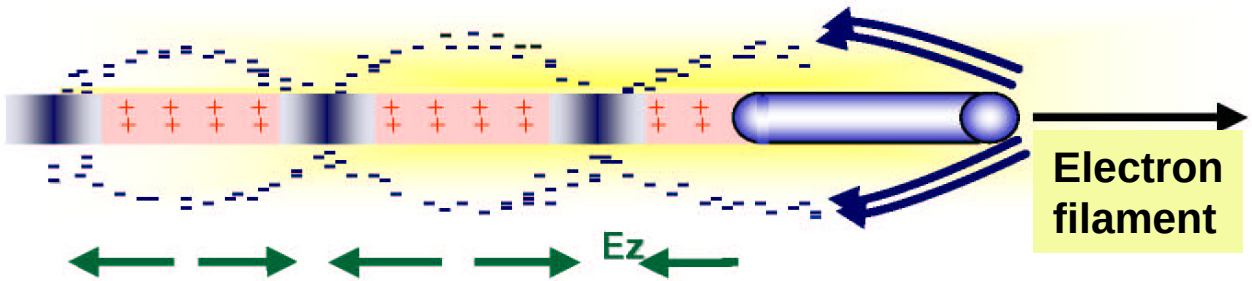
⇨ Locally induces a large and positive longitudinal electric field E_z, travelling with the filaments

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

Mechanisms for Generating Longitudinal Electric Fields (E_z)



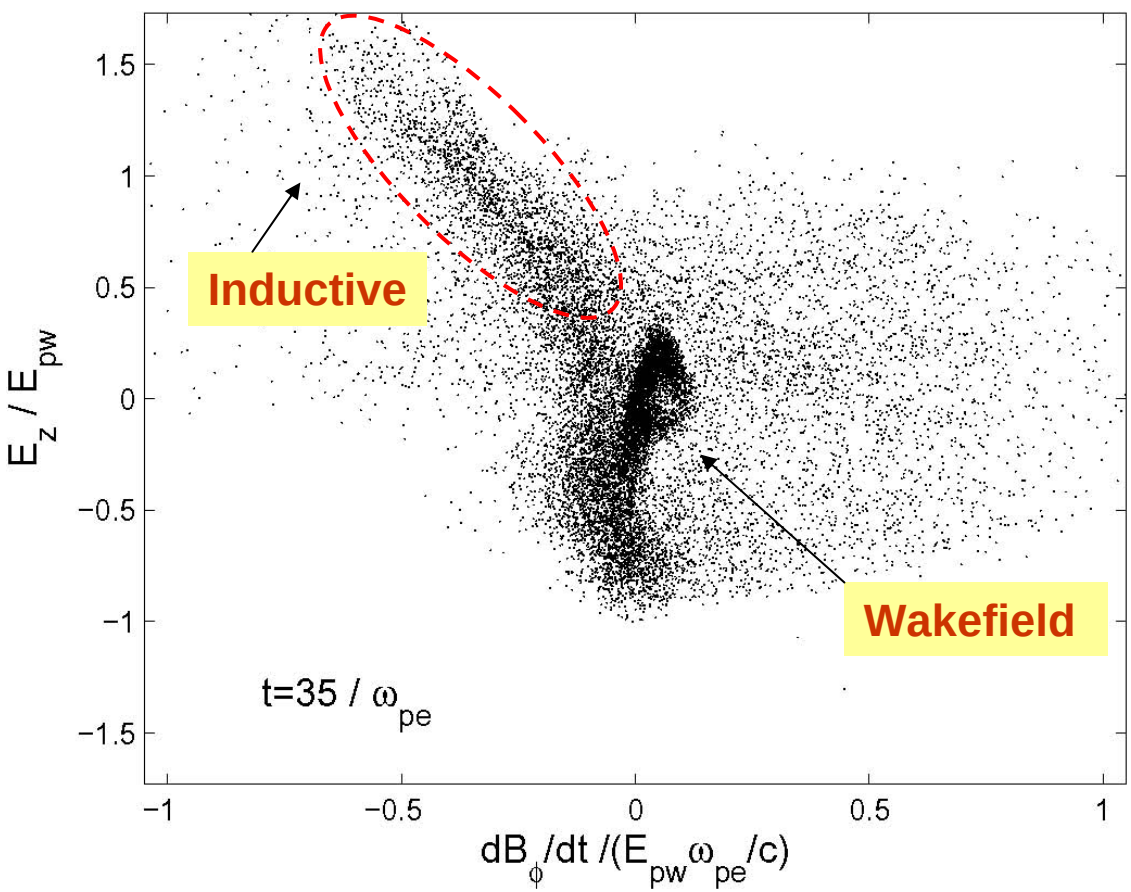
Electrostatic Plasma Wakefield Acceleration



- Filament separation results in charge separation in an initially neutral jet

- Separated charge filaments drive wakefields similar to beam-driven plasma wakefield acceleration

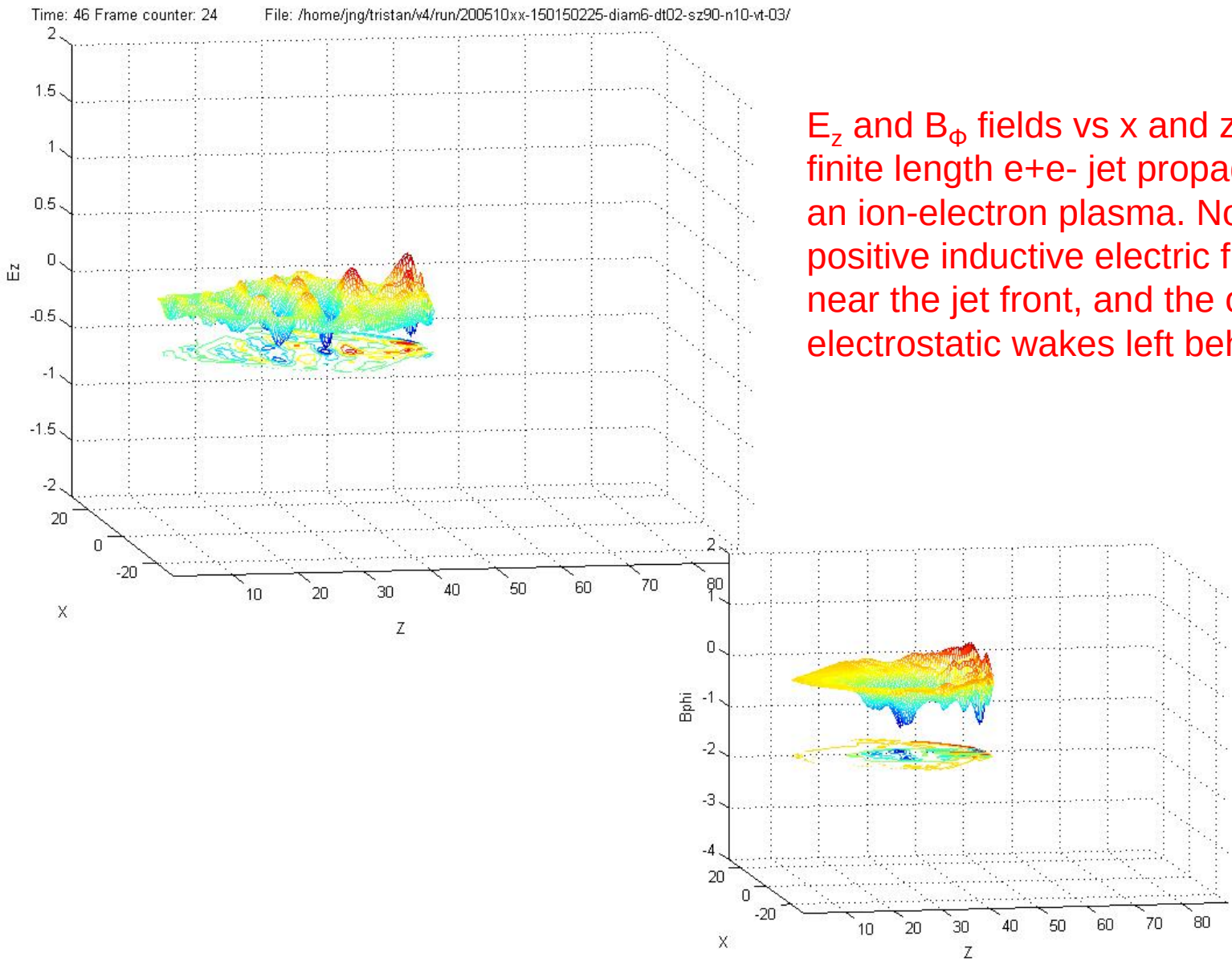
Inductive and Electrostatic Fields



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

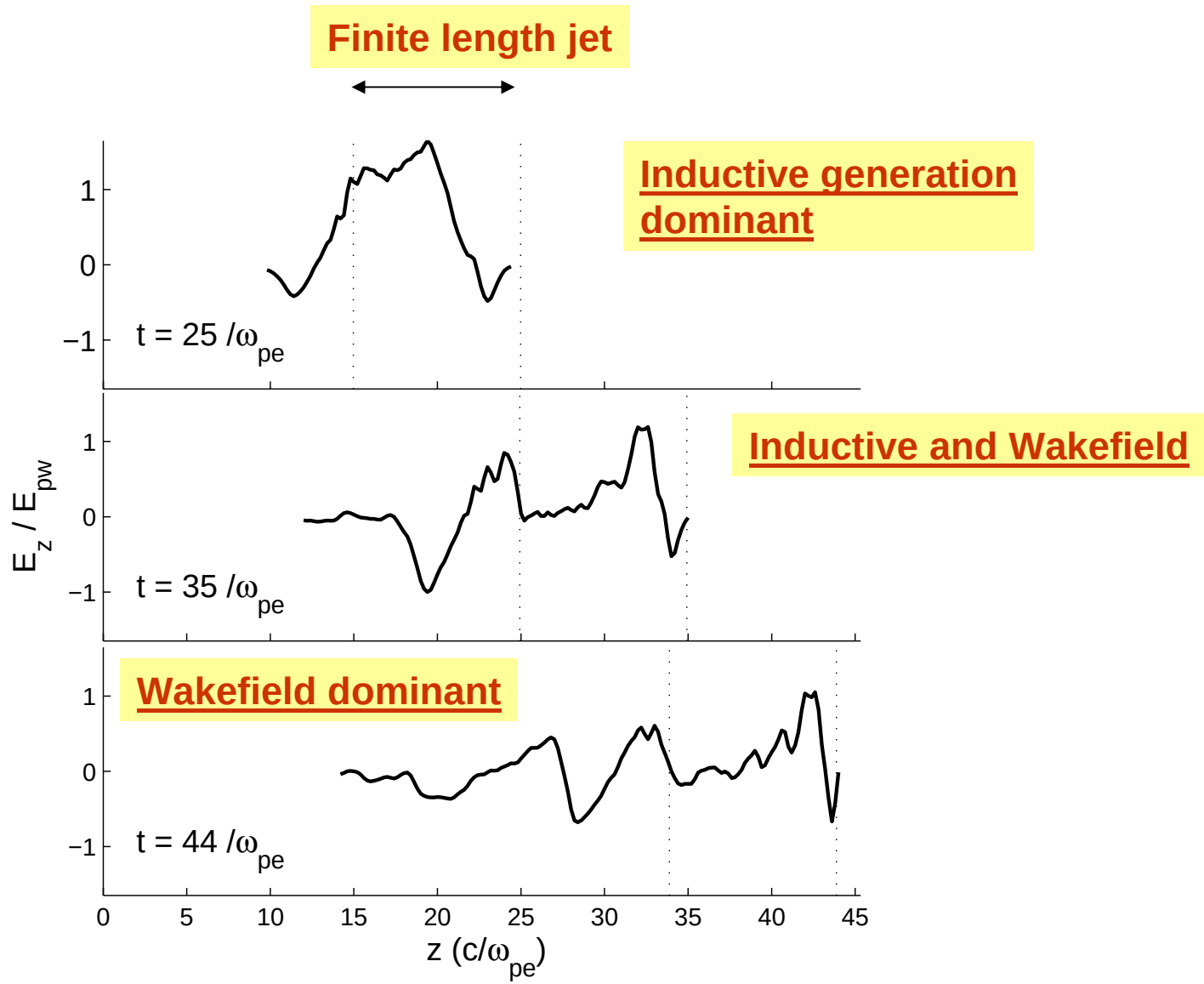
$$E_{pw} = m_e c \omega_p / e$$

t in units of $1/\omega_p$

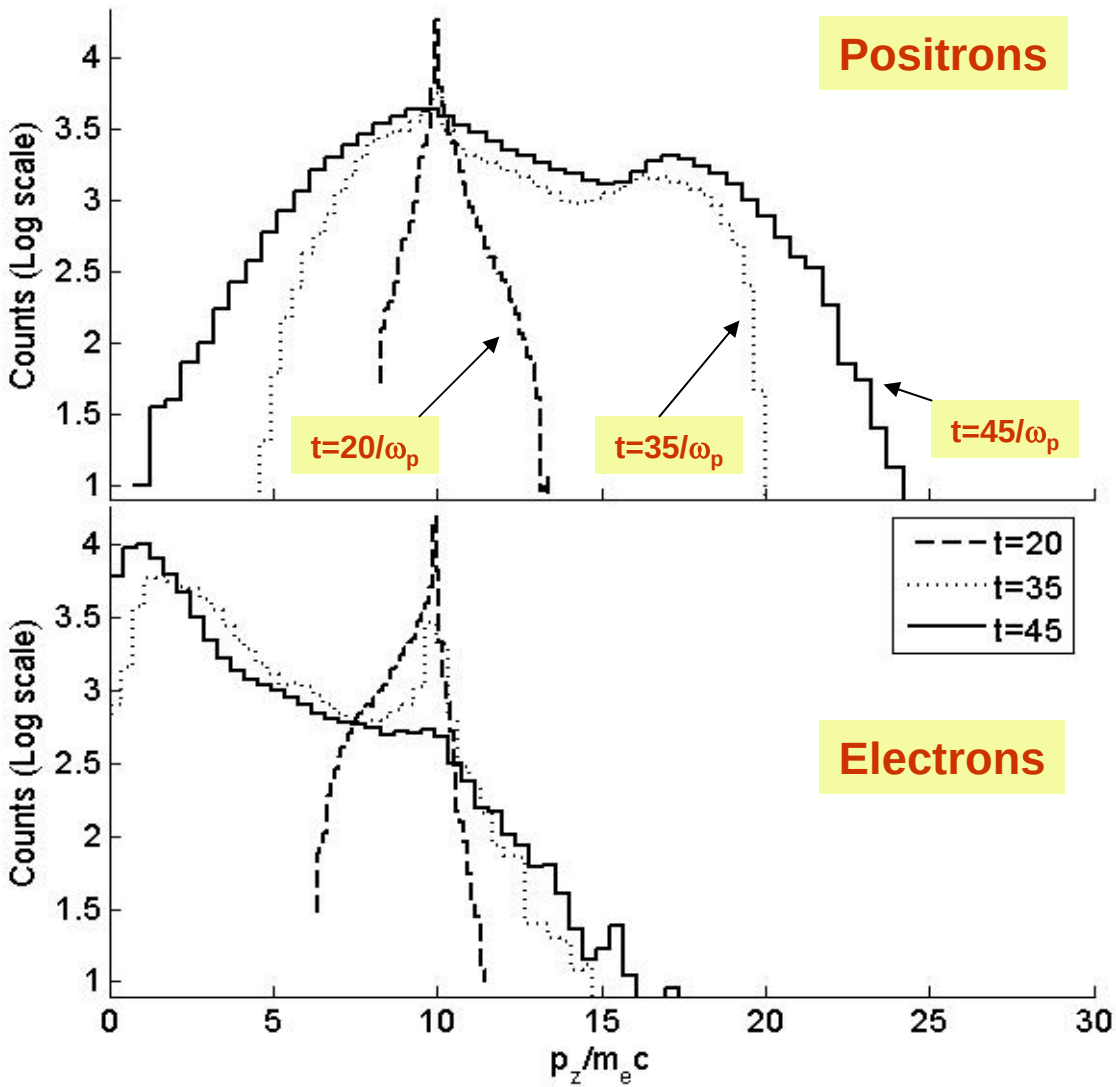


E_z and B_Φ fields vs x and z as a finite length e+e- jet propagates in an ion-electron plasma. Note the positive inductive electric field (red) near the jet front, and the oscillating electrostatic wakes left behind.

Waveforms: Inductive and Wakefield E_z



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)

Parameter Variation Studies

- Physical parameters:

  Relativistic factor: γ, jet diameter: D, Jet to plasma density ratio: α, RMS transverse velocity spread: $\Delta v_t/c = \Delta\beta_t$

- Jet parameters for earlier example:

  $\gamma = 10$, $\alpha = 10$, $D = 6\ c/\omega_p$, $\Delta\beta_t = 10^{-4}$

- Parameter variation range:

  $\gamma = 10 - 100$, $\alpha = 0.1 - 100$, $D = 6 - 60\ c/\omega_p$, $\Delta\beta_t = 10^{-4} - 10^{-1}$

⇒ Inductive and wakefiled acceleration observed when Weibel instability occurs

- Threshold condition: $\alpha > \gamma(\Delta\beta_t)^2$ [Silva et al.,2002]

⇒ Weibel filamentation suppressed for hot and tenuous jets (confirmed in our simulations)

Summary of Simulation Results

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 E_Z
   - Charge filaments excite longitudinal electrostatic plasma waves

❖ We observe two local acceleration mechanisms:
   - Inductive "Faraday acceleration"
   - Electrostatic Plasma Wakefield acceleration.

⇨ **Robust general result: only requires Weibel filamentation**

Implications for Future Work

- Include effect of background magnetic fields
- Extend length of simulation to study details of acceleration over long distances
- Implement particle radiation
- Detailed parameter variation studies and scalings, including different jet and plasma compositions.
- Design of laboratory jet-dynamics experiment using particle and/or photon beams, at SLAC for example. See Johnny Ng's talk next!

This work has been accepted for publication in Phys. Rev. Letters as of March 2006, under the title “Inductive and Electrostatic Particle Acceleration in Relativistic Jet-Plasma Interactions”.

Acknowledgements

We appreciate discussions with K.-I. Nishikawa, K. Reil, A. Spitkovsky, and M. Watson. We would also like to thank P. Chen, R. Ruth, and R. Siemann for their support and encouragement.

Work supported by the U.S. Department of Energy