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Filamentation instability of counterpropagating charged particle beams: Statistical properties

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Overview

- Consider two counterstreaming beams of electrons.
- The electrostatic two-stream instability grows, if the beams move with a nonrelativistic relative speed v_b.
- *Cool* electron beams of infinite extent: Bulk electron density n_p, beam electron density n_b and $n_i = n_p + n_b$ is the density of the immobile ions.

➢ $v_b \approx c$ and $n_b \ll n_p$: Mixed modes grow fastest.

➢ $v_b \approx c$ and $n_b \approx n_p$: Filamentation modes win.

Overview

- Physical mechanism of the filamentation instability
- *1D particle-in-cell simulation:* Large domain, obtain size distribution of filaments just before mergers start.
- *2D particle-in-cell simulation:* Allows for filament mergers, obtain time-evolution of filament's mean size
- Conclusion

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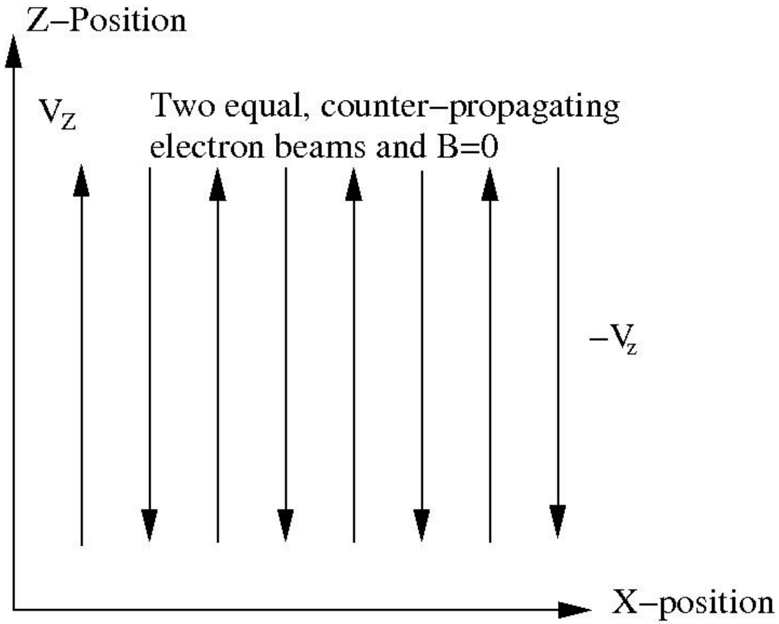
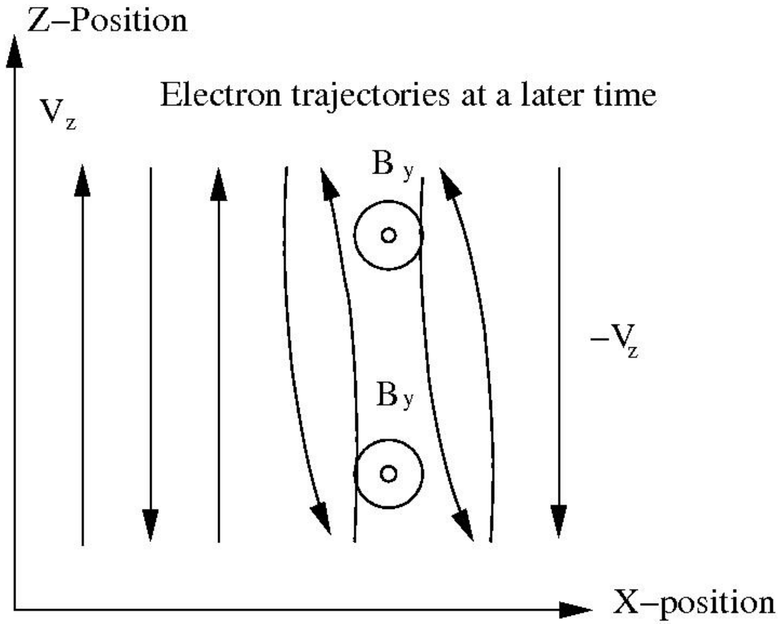
- *Co-workers:* P. K. Shukla, G. Rowlands, I. Lerche and L.O.C. Drury

The filamentation mechanism





•Initially, two symmetric beams counter-propagate and the current cancels → No net current and no magnetic field.
•A small magnetic field perturbation in z-direction separates the electrons moving in opposite directions → A net current grows, that amplifies the magnetic field.

PIC simulations of filamentation instability

- Counterstreaming beams with velocity $\pm v_b$ **z**
- Filamentation instability grows fastest if $k_z = 0$
- Magnetic / electric field growth in *x-y* plane
- Modulation in *x-y* of current j_z and charge ρ
- *Morse and Nielson, Phys Fluids 14, 830, 1971*

  1D simulation: (x) *2D simulation:* (x,y)
- Now we can redo this and model *many* flux tubes to get some of their statistical properties.

Simulation setup

- Initially $E = 0$, $B = 0$

- *1D simulation*
- $v_b = 0.3\, c$ and $v_b / v_{th} = 18 \rightarrow$ Beams are cool.
- Box length: 444 (6600) electron skin depths c / ω_p

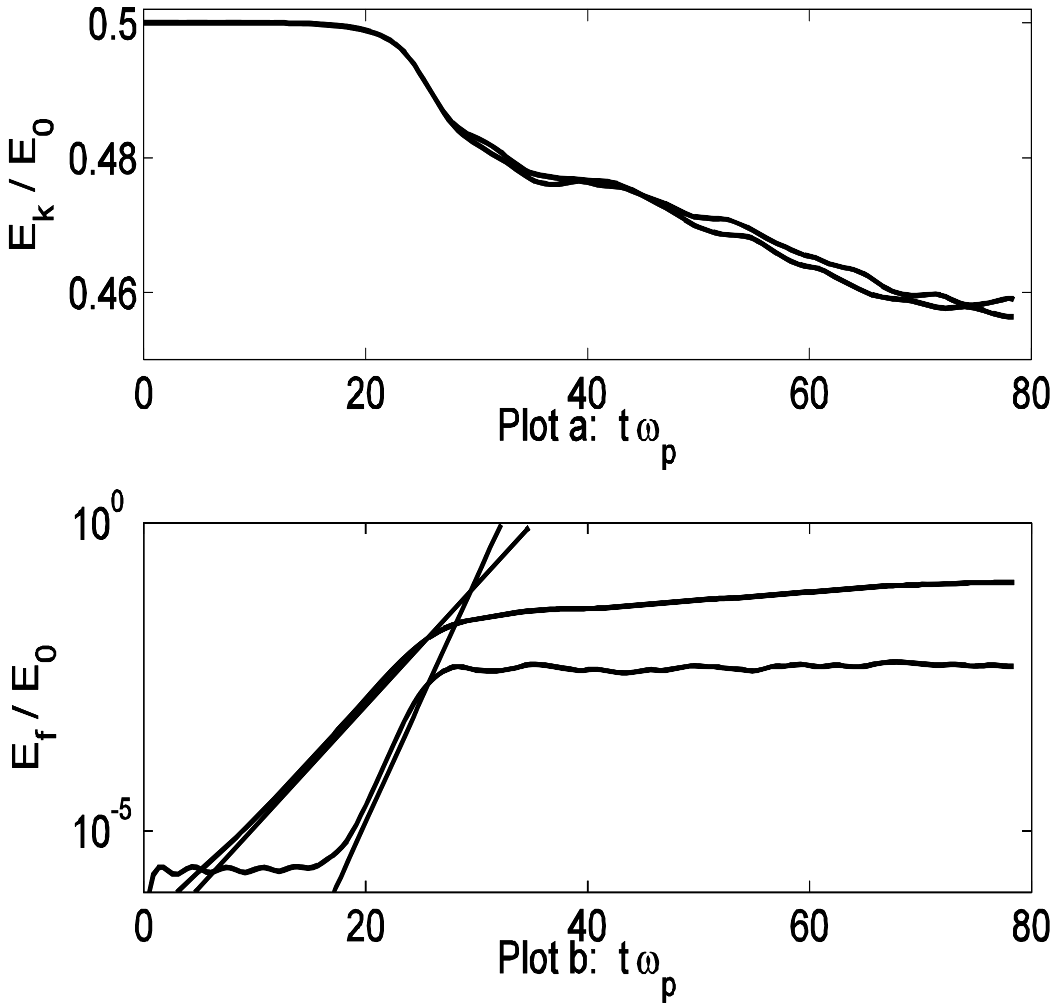
- *2D simulation*
- $v_b = 0.7\, c$ and $v_b / v_{th} = 5 \rightarrow$ Beams are warm
- Quadratic box with side length 100 c / ω_p

Field / particle energies in 1D

- Upper plot: Kinetic energy of each beam
- Lower plot: Energy in B_y and in E_x
- Electric energy grows *twice* as fast as the magnetic, suggesting

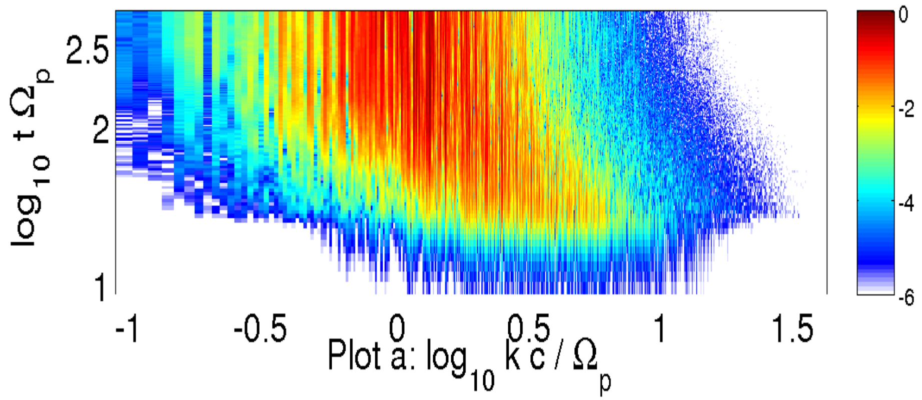
  $E_x(t) \sim B_y\,(dB_y / dx)$

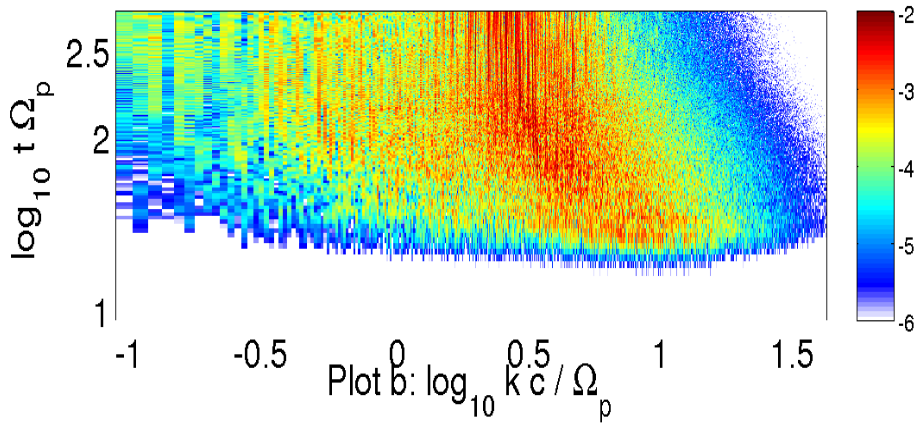
Quenching by magnetic pressure gradient



Stalling of 1D filamentation

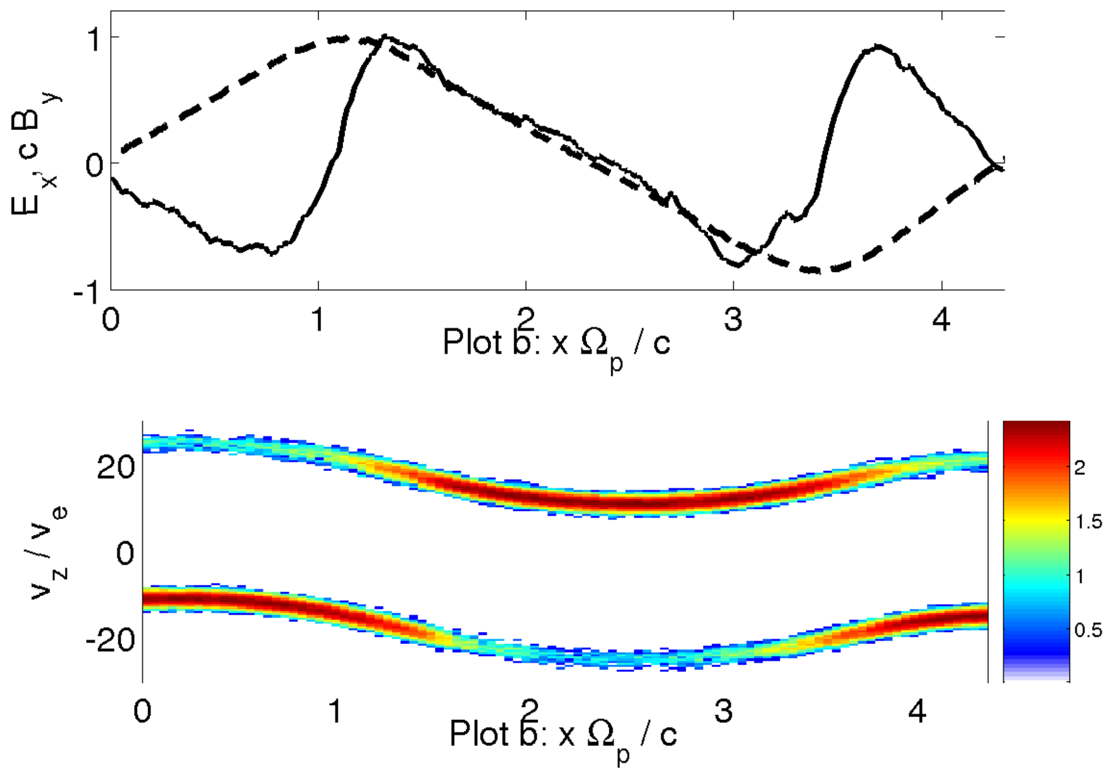
- $B_y^2(k_x,t)$ grows at high k_x and shifts to lower wavenumbers in time
- $E_x^2(k_x,t)$ grows later and at higher k_x
- The late power spectra are time-stationary
- The time-stationarity reflects the stalling of the electron distribution





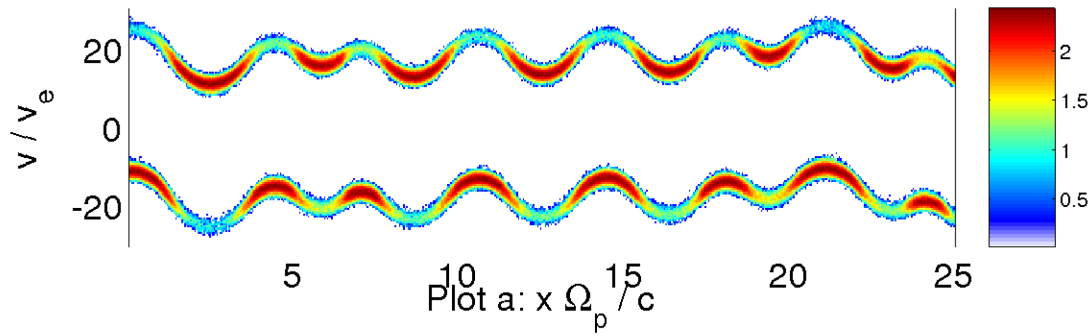
Field distribution

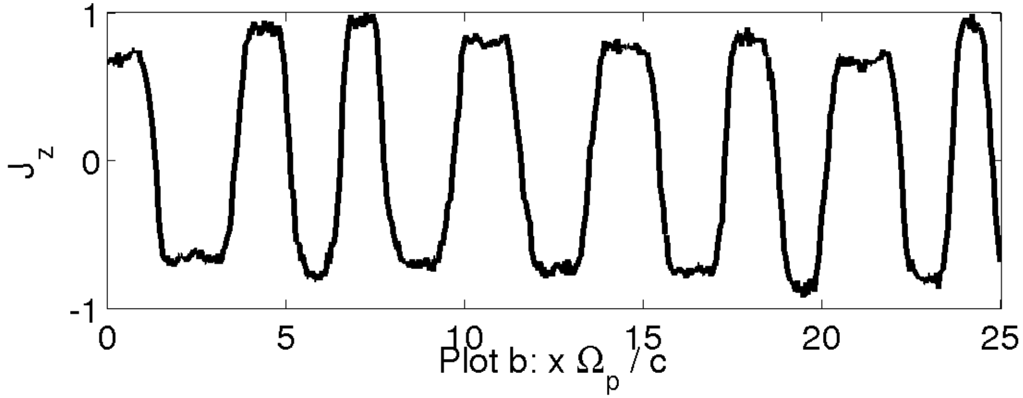
- Dashed line: cB_y
- Solid line: $5E_x$
- Steady state involves field distributions with a constant slope
- Fourier transform of a constant slope gives power-law



Current distribution

- Upper plot: 10-log of electron phase space density.
- Lower plot: J_z current normalized to peak
- Zero crossings are filament boundaries





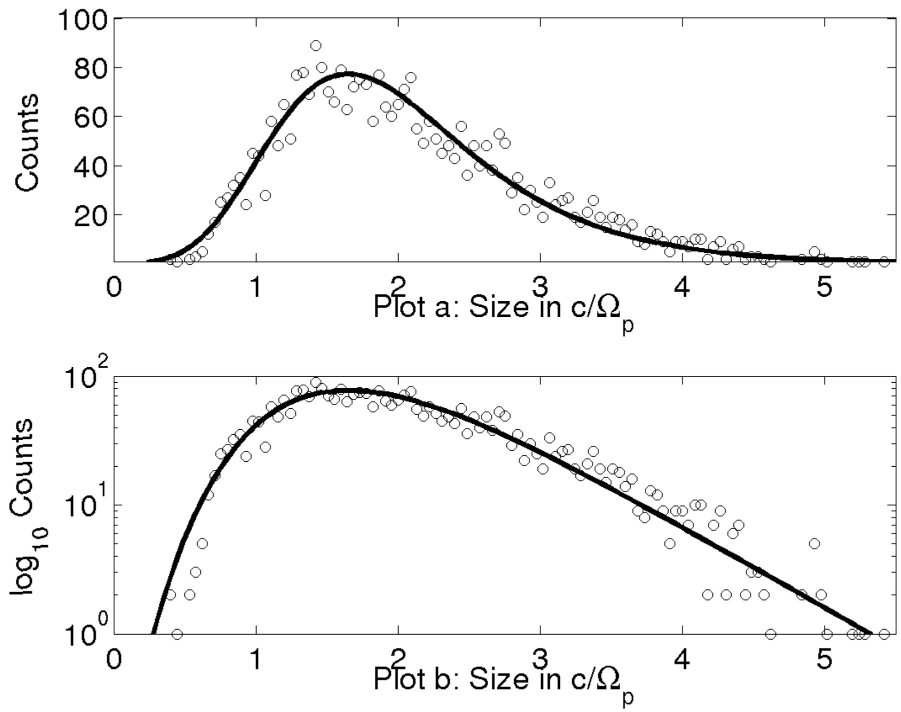
Gumbel distribution ~ exp(-u-exp[u])

•Measure distance between zero-crossings.

•Count how many filaments have a given size

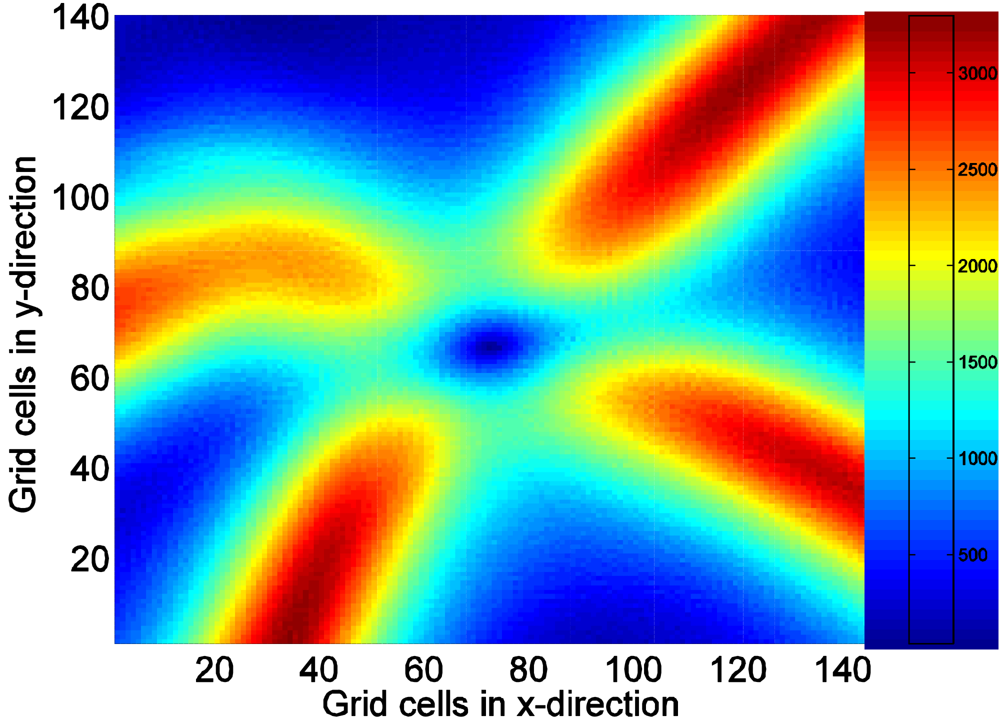
•The solid lines show the Gumbel distribution

•The circles give the number of filaments with a given size

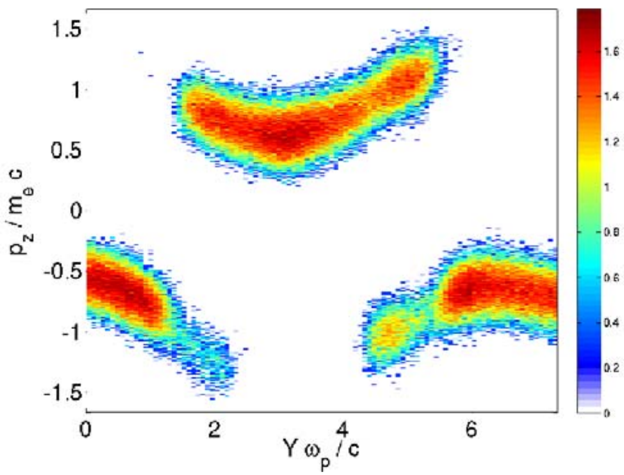


We go from 1D to 2D

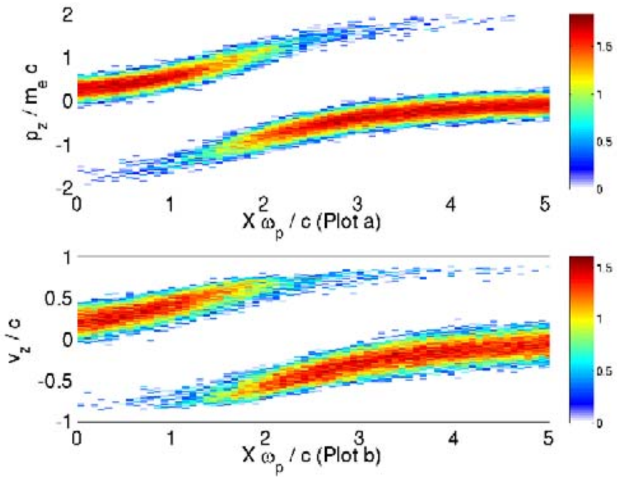
- Two flux tubes with electrons flowing in opposite directions repel each other
- 1D: The system locks up
- 2D: Flux tubes can go around each other
- 2D: Magnetic fields can reconnect, by which the flux tubes merge



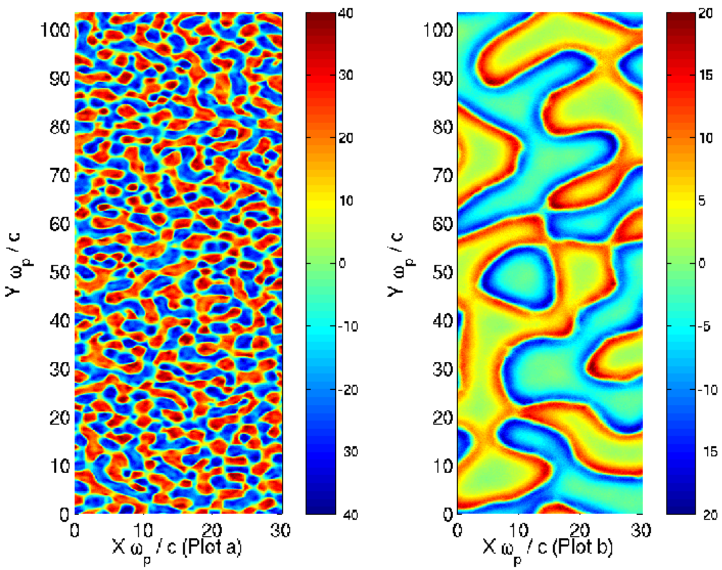
2D: Enabling flux tube merging



Phase space plots cut the distribution $J_z(x,y)$ below along one direction



Early time



Late time

Change of characteristic size

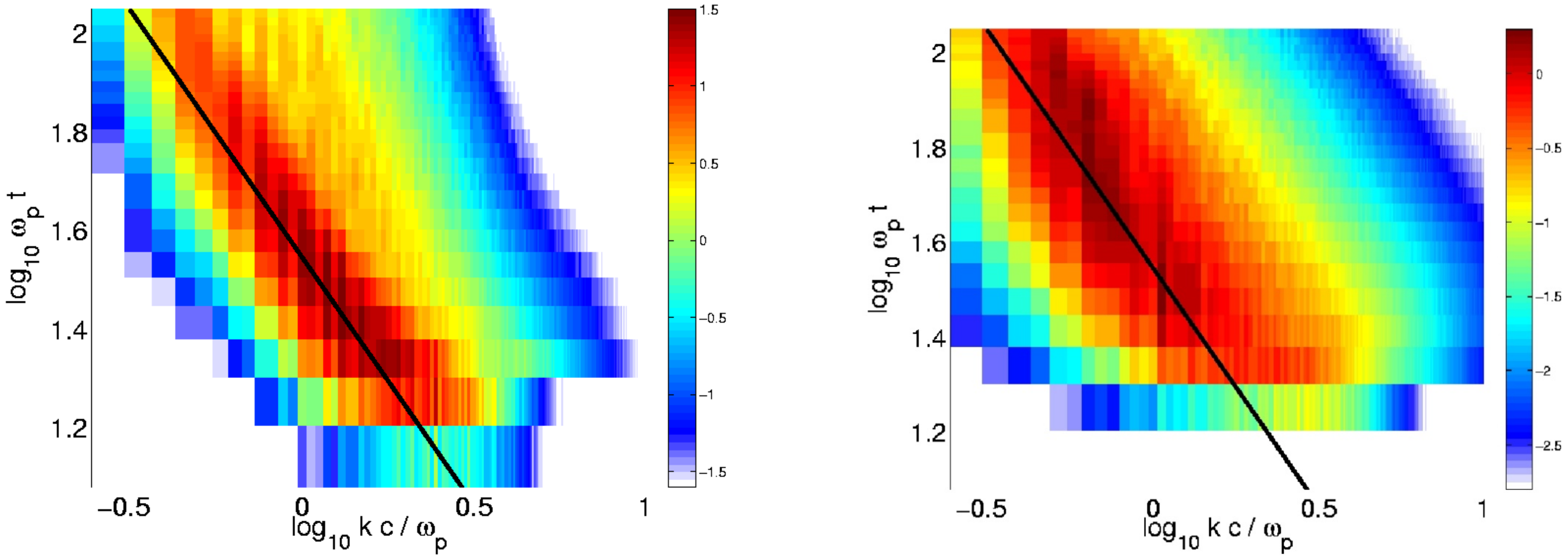
- The coherence length is difficult to quantify in x-y.
- Thus: 2D Fourier transform of $C(x,y)$ over x,y
- Get the power spectrum $C_z^2(k_x,k_y)$, $C_{x+iy}^2(k_x,k_y)$
- The system is symmetric around the z-direction

→ Power spectrum is integrated over the azimuth

- We obtain $C_z^2(k)$ and $C_{x+iy}^2(k)$ for each simulation time slice

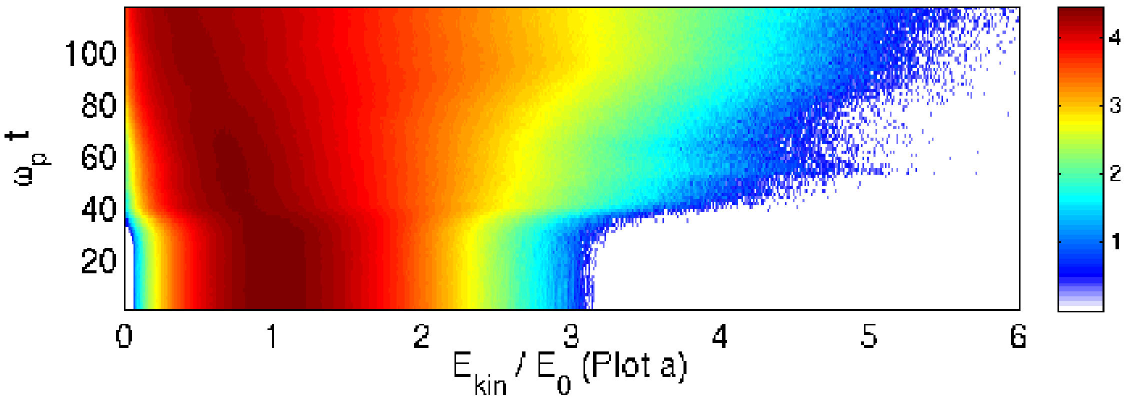
Filament size distribution

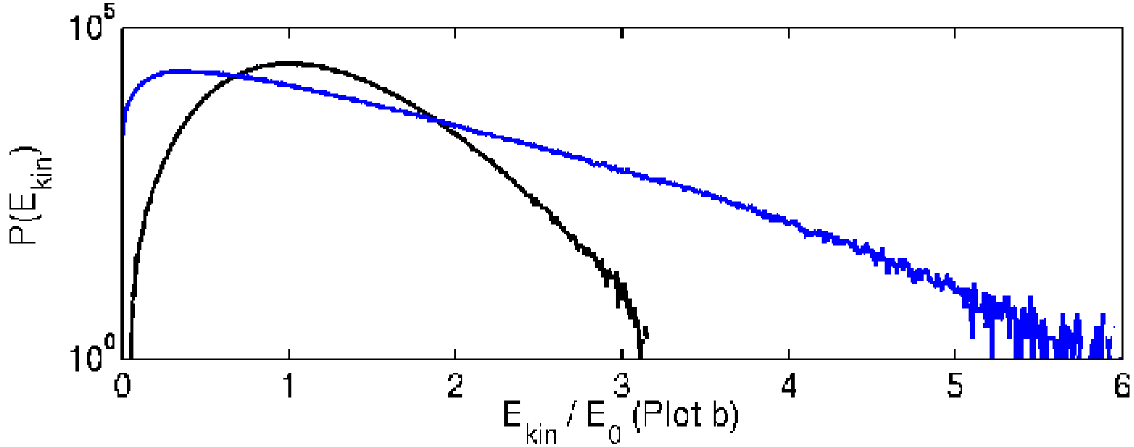
- The size is initially about an electron skin depth
- The peak power goes to lower wavenumbers as $k \sim t^{-1}$
- This resembles the vortex size evolution in fluid turbulence.
- Left: spectrum of C_z Right: spectrum of C_{x+iy}



Electron acceleration

- We compare initial electron energy distribution against final one.
- The peak electron energy increased by a few times.
- No substantial electron acceleration





Summary

- The filamentation instability generates magnetic fields through current separation
- The electric fields driven by the magnetic pressure gradient quench its growth
- The filament size distribution upon saturation decreases exponentially with increasing size
- Mergers let the filament size increase linearly with time. The size is limited by the number of mergers
- In 3D secondary instabilities may show up, destroying the flux tubes