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FÜR PLASMAPHYSIK

Filamentation in AWAKE

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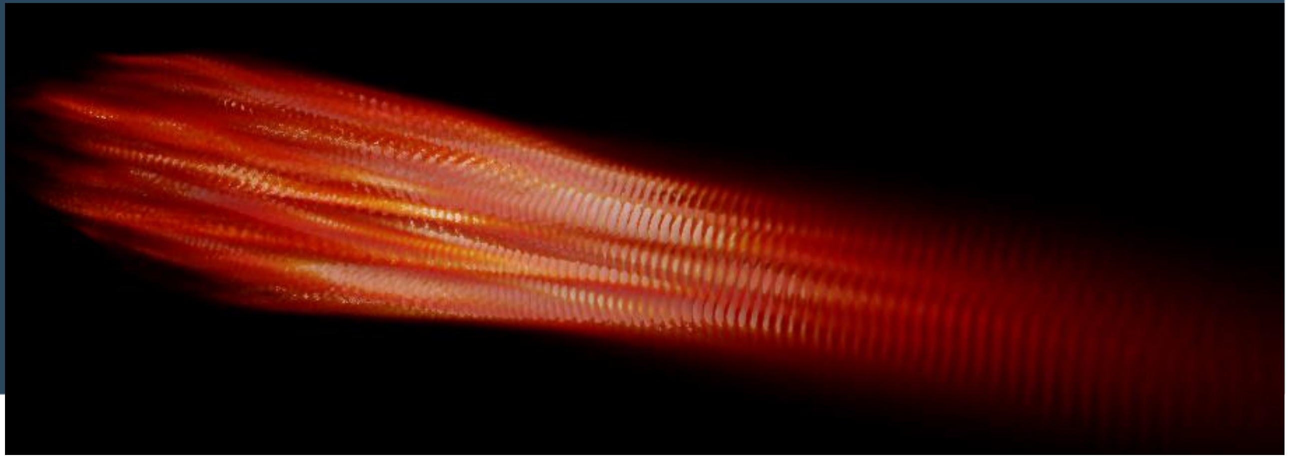

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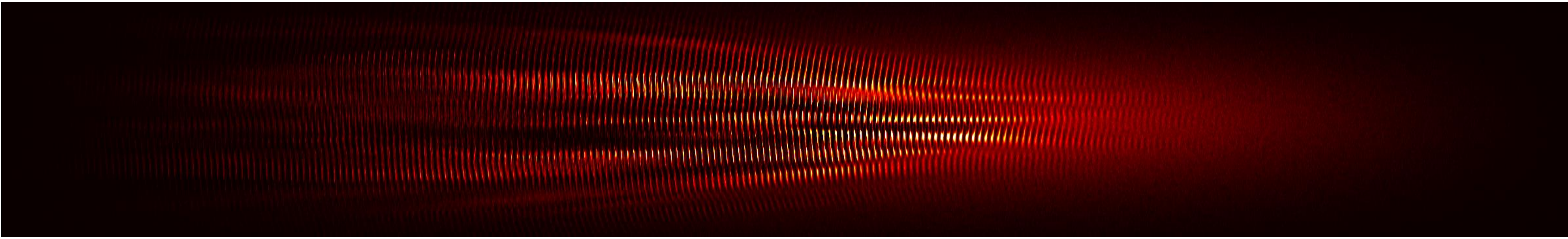
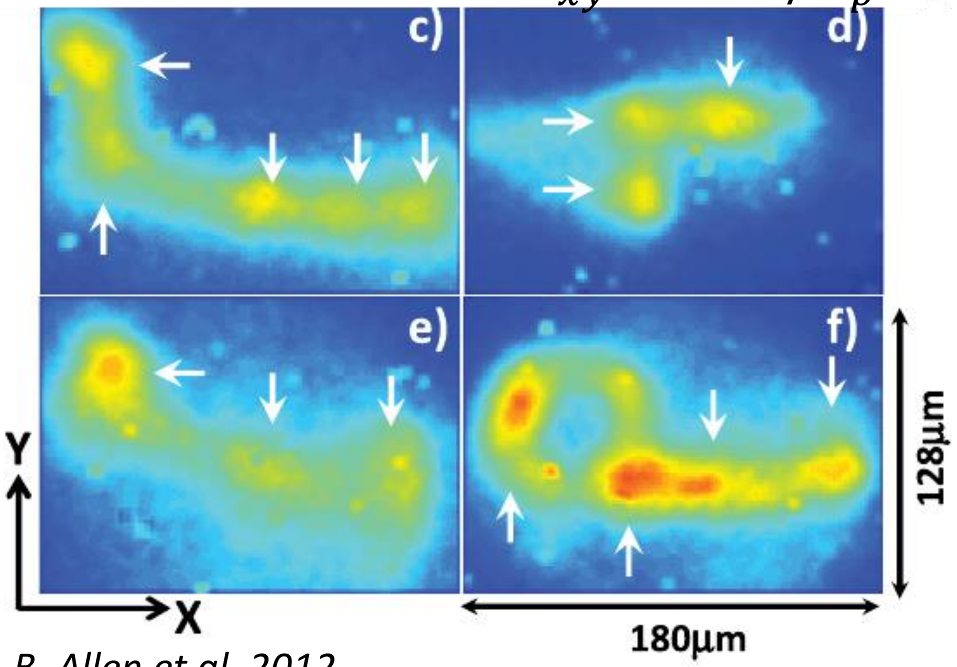


Introduction

Previous work

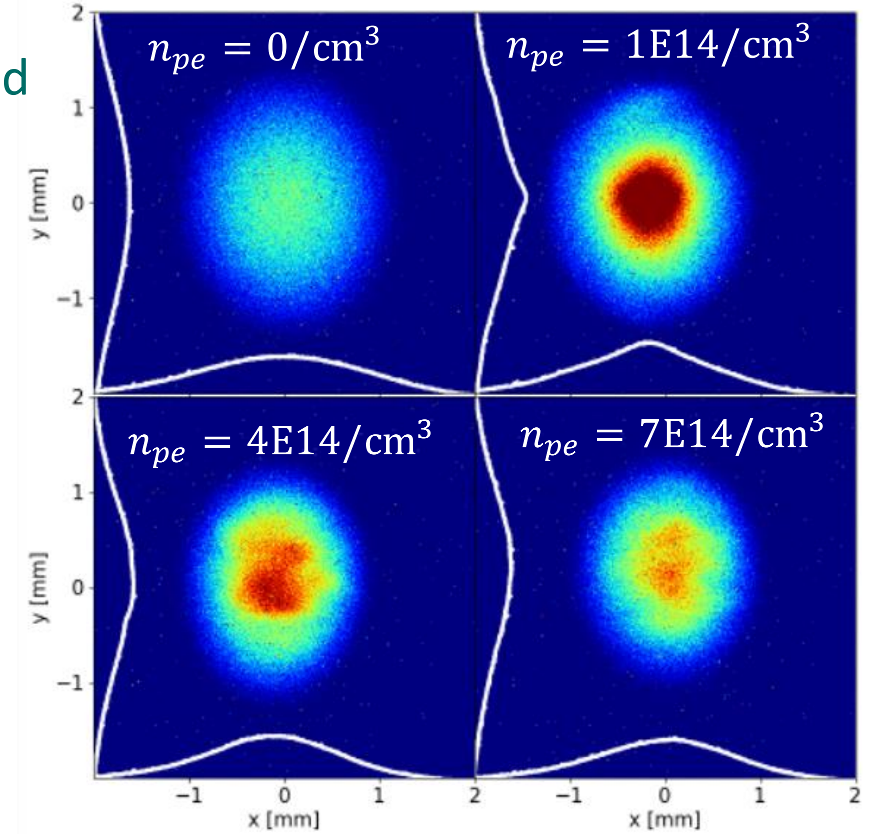
- Beam filamentation has been studied in previous experiments (B. Allan et al. 2012, F. Fiuza 2020, C. Zhang 2022)
- Some evidence of filamentation in previous AWAKE run 2ab
- Experimental study of filaments at AWAKE with DPS planned

Minimum beam width $\sigma_{xy} > 2.2\ c/\omega_p$



B. Allen et al, 2012

AWAKE Run 2ab

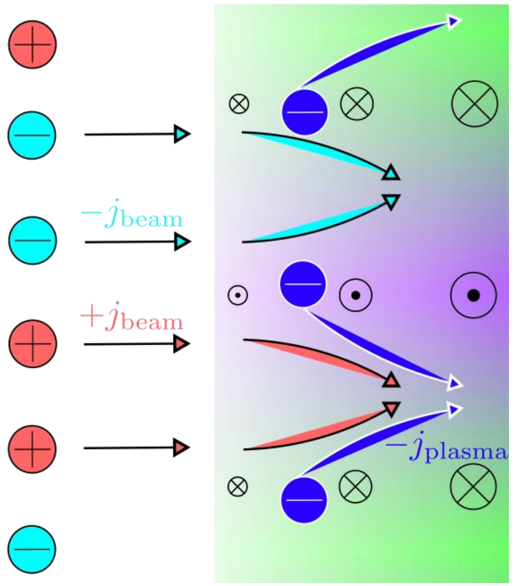


L. Verra, P. Muggli et al (AWAKE collaboration)

Introduction

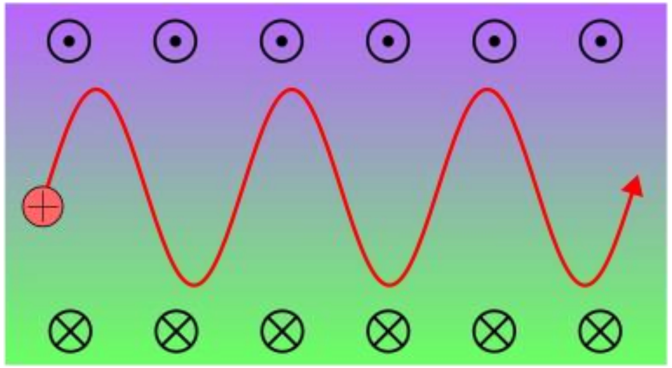
Current Filamentation Instability (CFI) of Fireball - *B. D. Fried (1959)*

Mechanism



- Transverse fireball beam particles separation
- Electromagnetic

Saturation



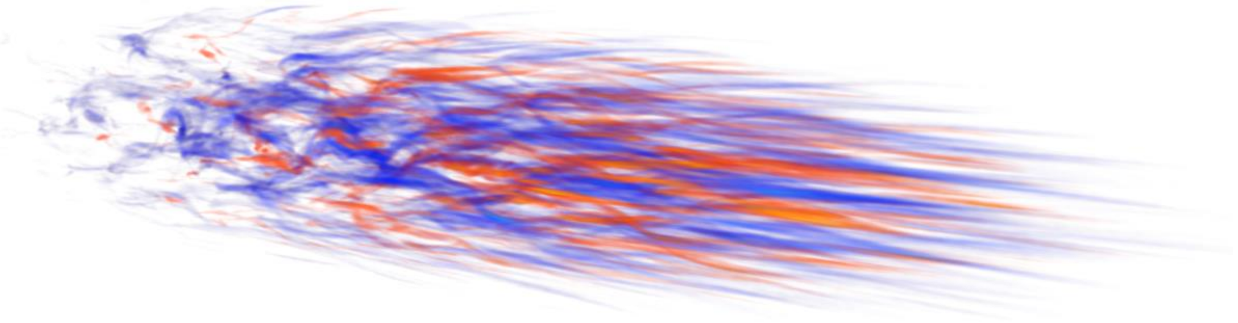
- Magnetic trapping with $\omega \sim \Gamma_{\text{CFI}} \sim \sqrt{\frac{n_b/n_p}{\gamma M_b/m_e}}\,\omega_p$ (*R.Davidson 1972, A. Bret 2004*)
- **Filaments merge**

Goal

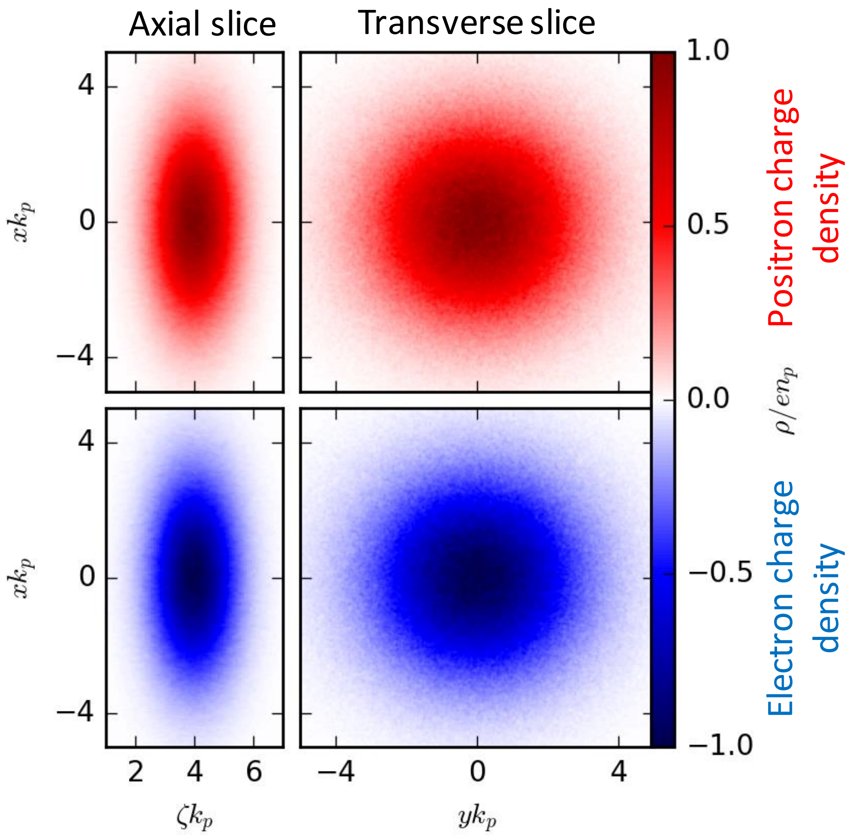
Observe spatial evolution of filamentation along proton beam.

Compliment upcoming experimental results with simulations to deepen understanding

Fireball



Parameter	**Fireball**
Plasma wavelength	$64.3\,\mu$m
Beam gamma	567.5
B. charge	2.92 nC
B. norm. emittance	$2.05\,\mu$m
B. length	$1 - 14\,c/\omega_p$
B. width	$2\,c/\omega_p$
B. macroparticles	32E6
Spatial resol. $(\Delta\zeta, \Delta\perp)$	$(0.25, 0.5)\,c/\omega_p$
Prop. distance	$1400\,c/\omega_p$

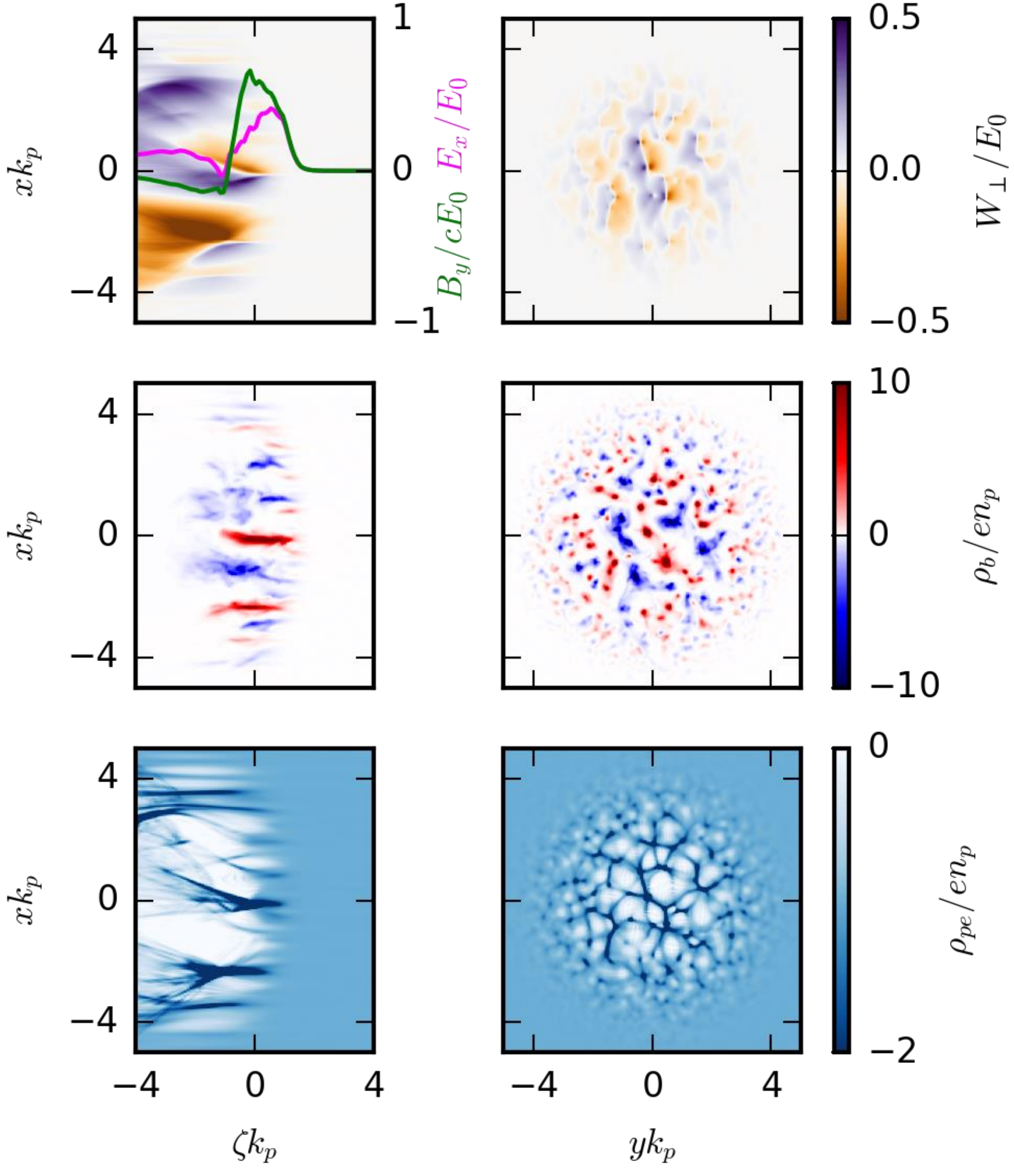


- Finite, quasineutral beam consisting of electrons and positrons
- Broadly studied (N. Shukla 2020, A. Spitkovsky 2008) model in gamma-ray burst research
- Convenient model for CFI studies (high growth rate, short beam)
- Expect same spectrum of instabilities compared to single species beam

Fireball

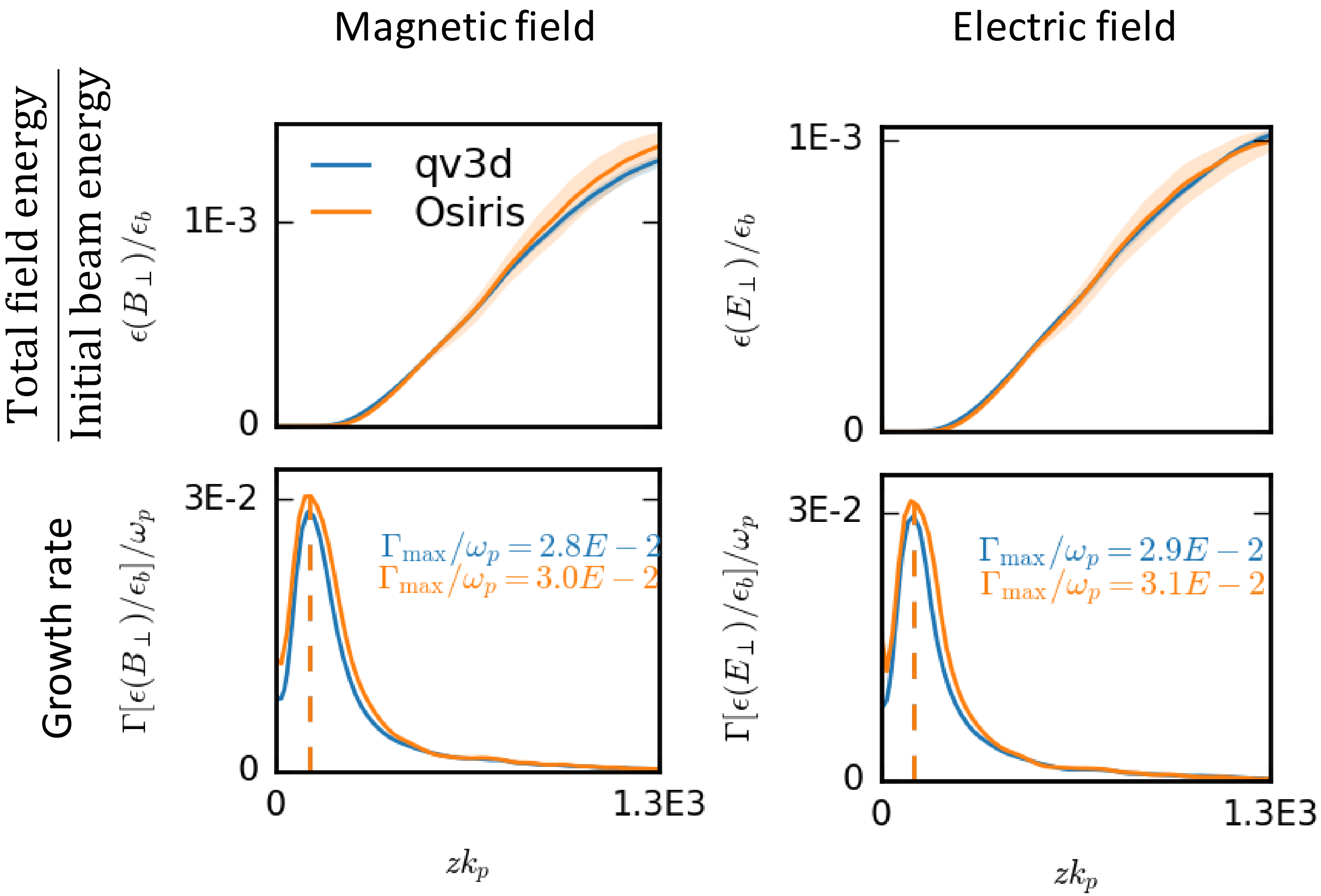
Short / dense

- Transverse filamentation mode dominant
- Plasma return current tends to cancel beam generated magnetic field
- Saturation: Betatron oscillation
- Growth along propagation distance and along beam



Fireball

Field energy comparison: Temporal evolution

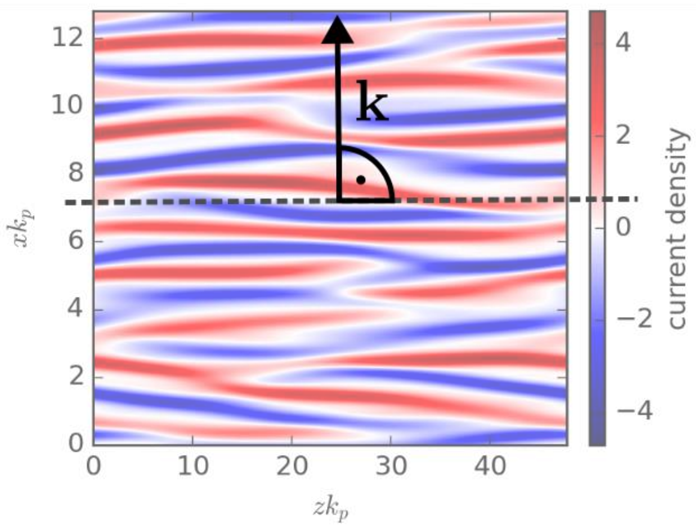


Electromagnetic instability requires benchmark

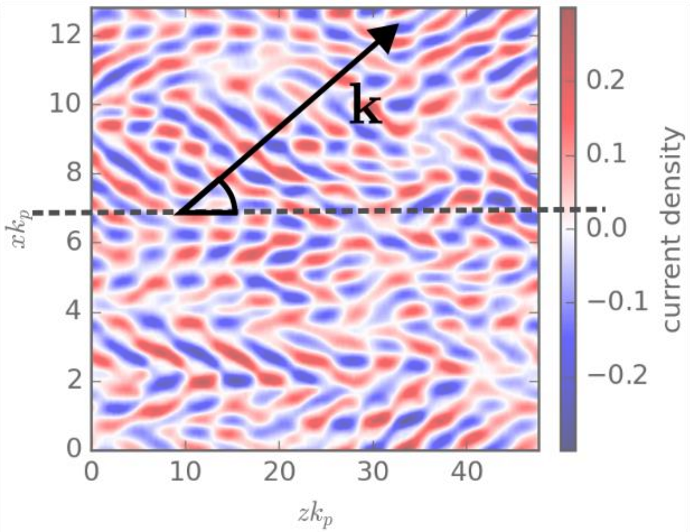
Good agreement in energy and growth rate of the perpendicular field components

Theory

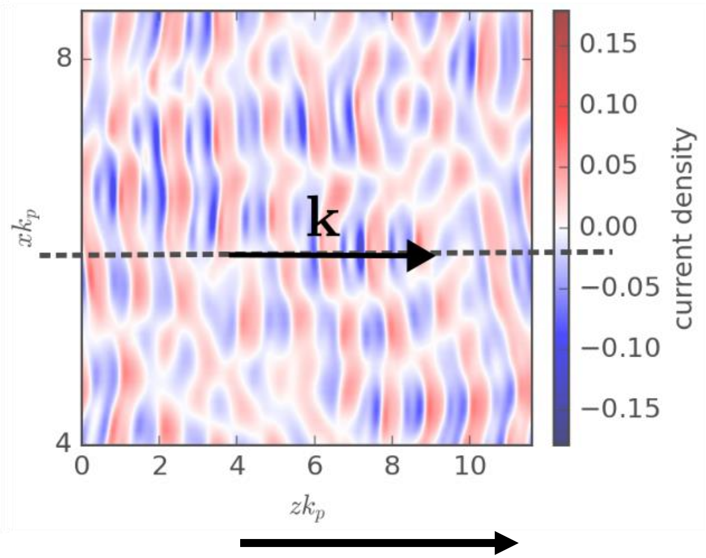
Oblique filamentation (OF) - *Bret (2004)*



CFI



OF



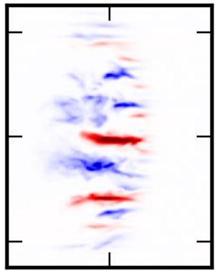
Two-stream

Propagation direction

- Superposition of transverse and longitudinal modes
- Wavevector $\boldsymbol{k} = \boldsymbol{k}_{\parallel} + \boldsymbol{k}_{\perp}$ of growing mode tilted
- Electrostatic instability → $E_{\parallel}, E_{\perp}, B_{\perp}(j_b)$

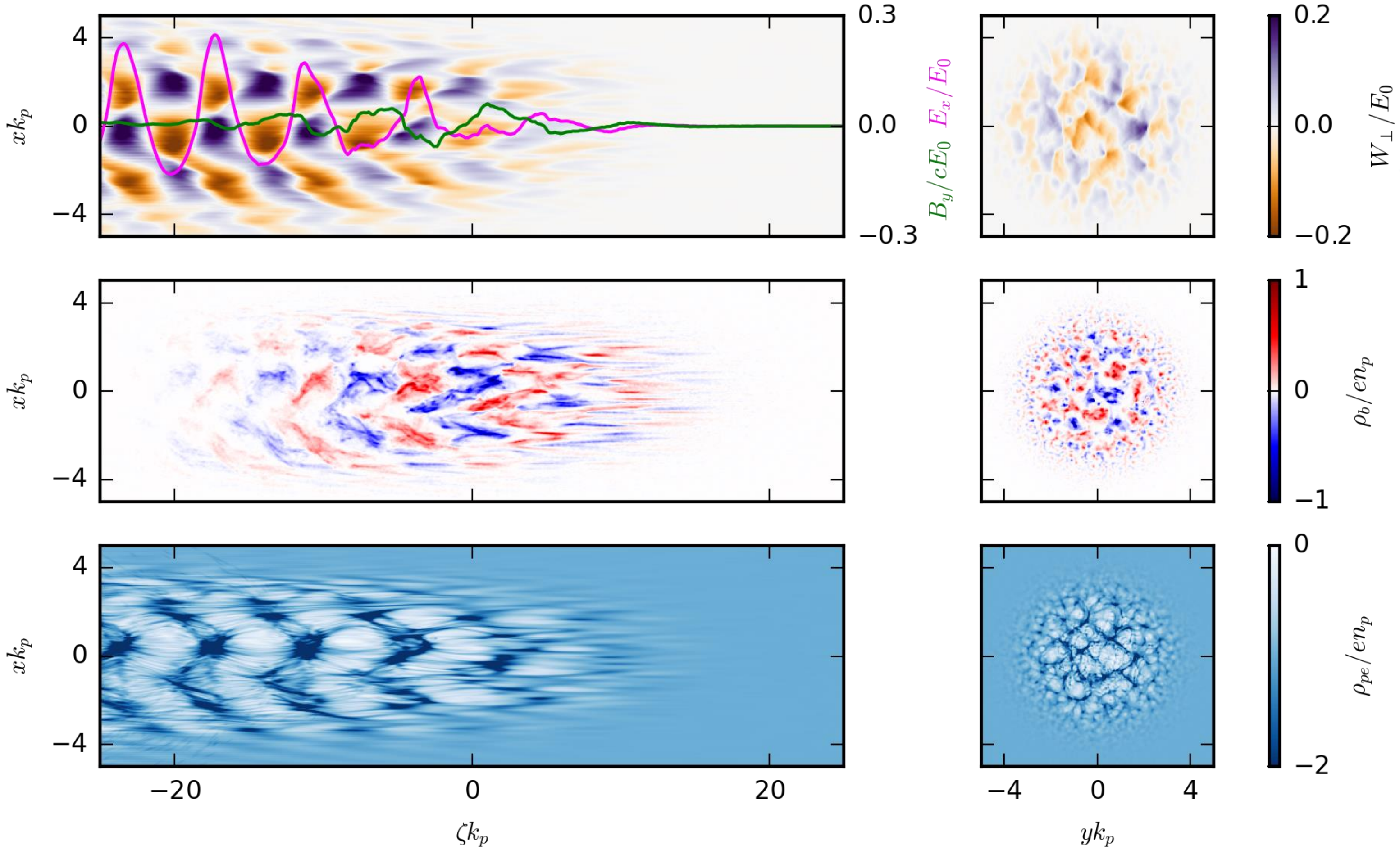
Fireball

Long / dilute



Constant beam charge

Increased beam length

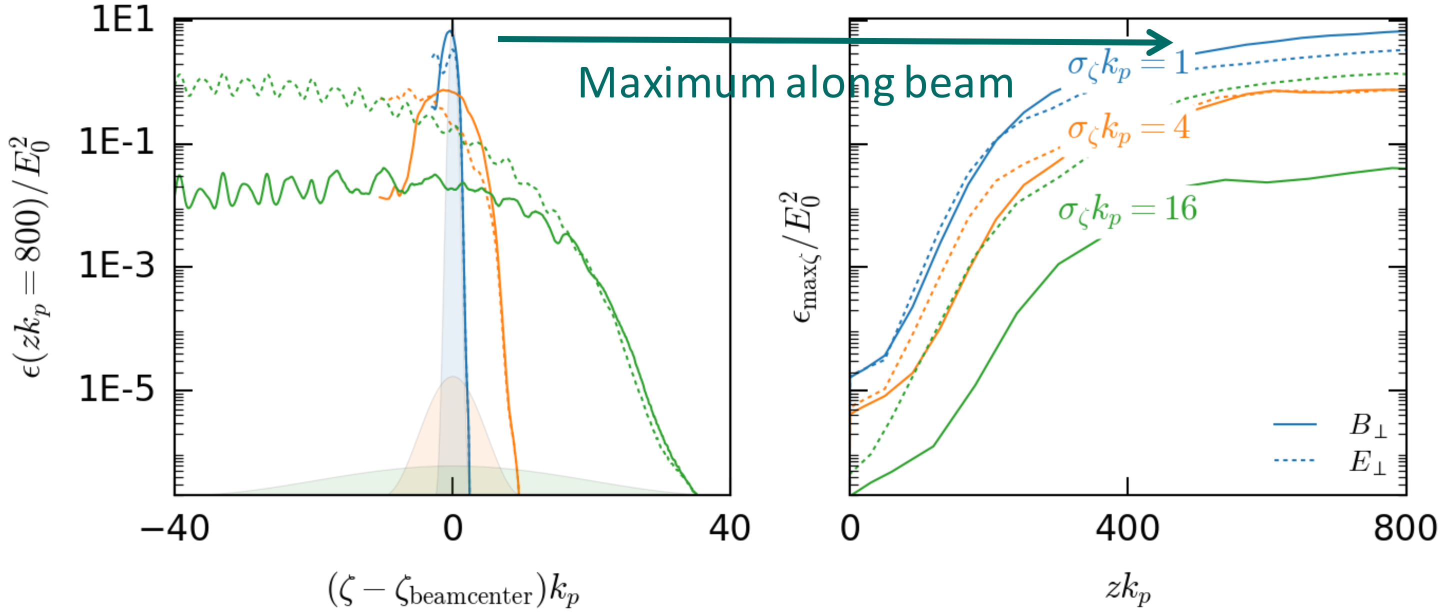


- Beam filamentation + self-modulation
- Transverse (de-)focussing of beam

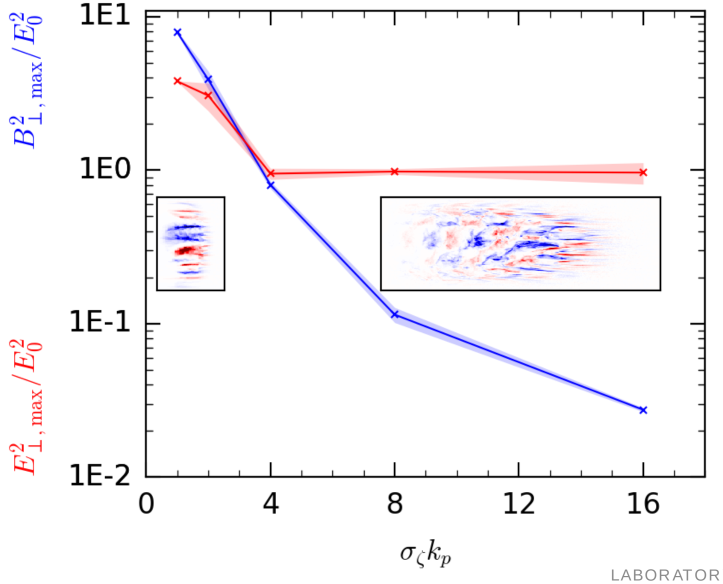
Fireball

Electromagnetic field

Magnetic field dominant within first plasma wavelength as plasma oscillation weak / not completed



- Magnetic field decrease: Lower beam density + detrapped particles
- Constant electric field: Bunched beam constructively adds to wakefield



Fireball

Growth rates

- Growth rates scale differently between current filamentation and two-stream
- Varying plasma parameters under constant total beam charge hints the filamentation mode

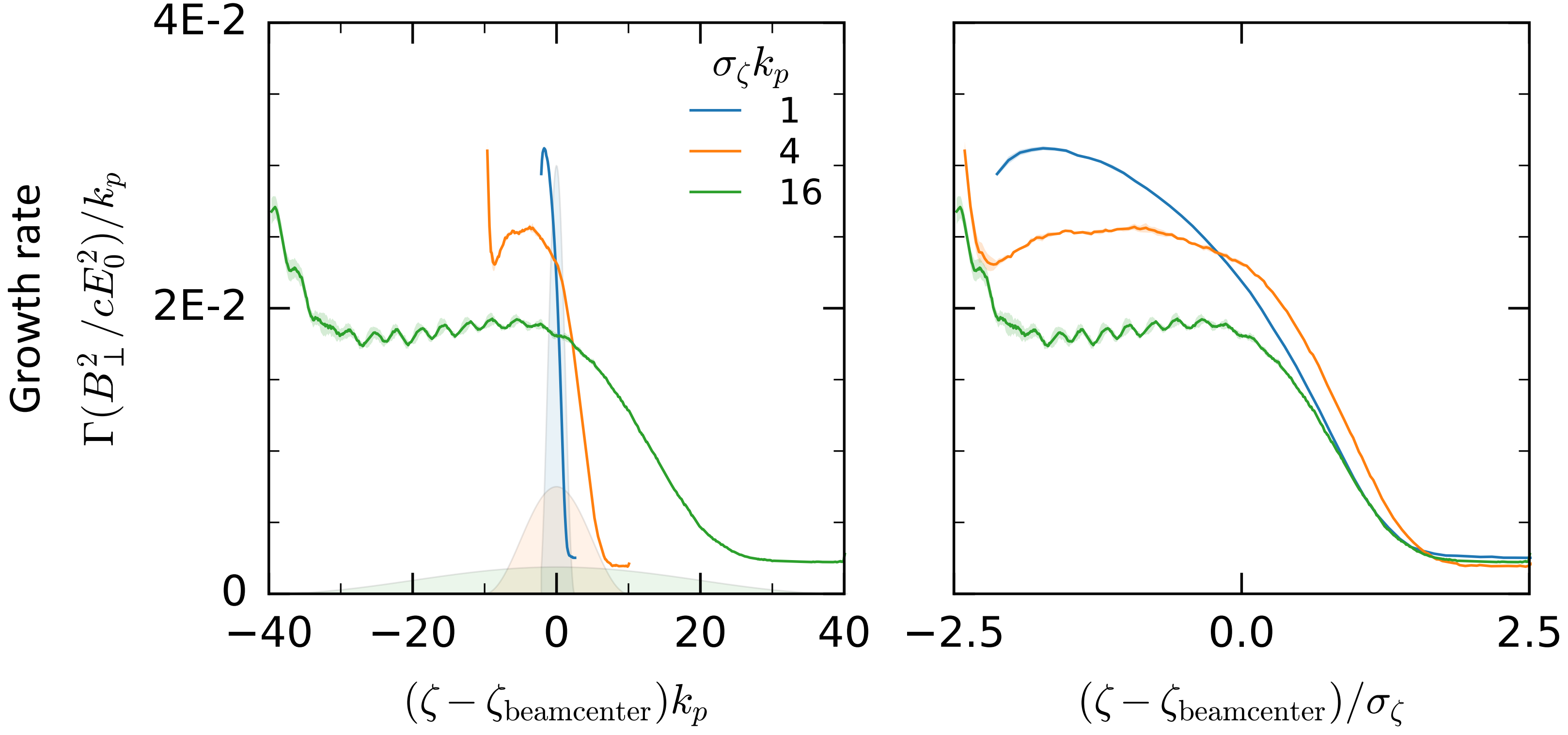
$$W_{\perp}(z,\zeta) = W_{\perp 0}(\zeta) e^{\Gamma(z,\zeta) z}$$

$$\Gamma_{\mathrm{CF}} \backsim \sqrt{\frac{n_b/n_p}{\gamma\, M_b/m_e} \frac{\zeta}{z}}$$

V. B. Pathak (2015)

$$\Gamma_{\mathrm{OF}} \backsim \sqrt[3]{\frac{n_b/n_p}{\gamma\, M_b/m_e} \frac{\zeta}{z}}$$

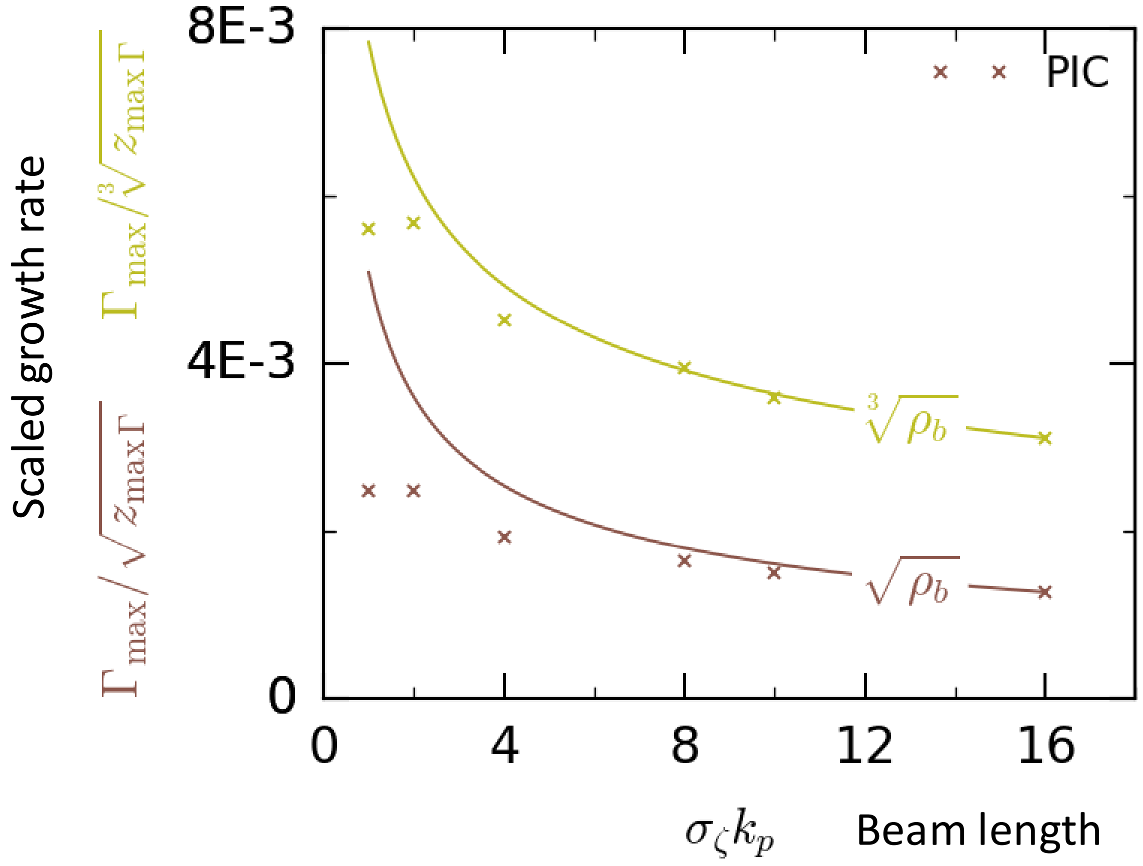
P. S. Claveria (2022)



Fireball

Growth rates

- Long fireball: growth rate scales like OF mode
- Short fireball: Nonlinear effects for short beams



$$\Gamma_{\mathrm{OF}} \sim \sqrt[3]{\frac{n_b/n_p}{\gamma\, M_b/m_e}\,\frac{\zeta}{z}}\; z$$

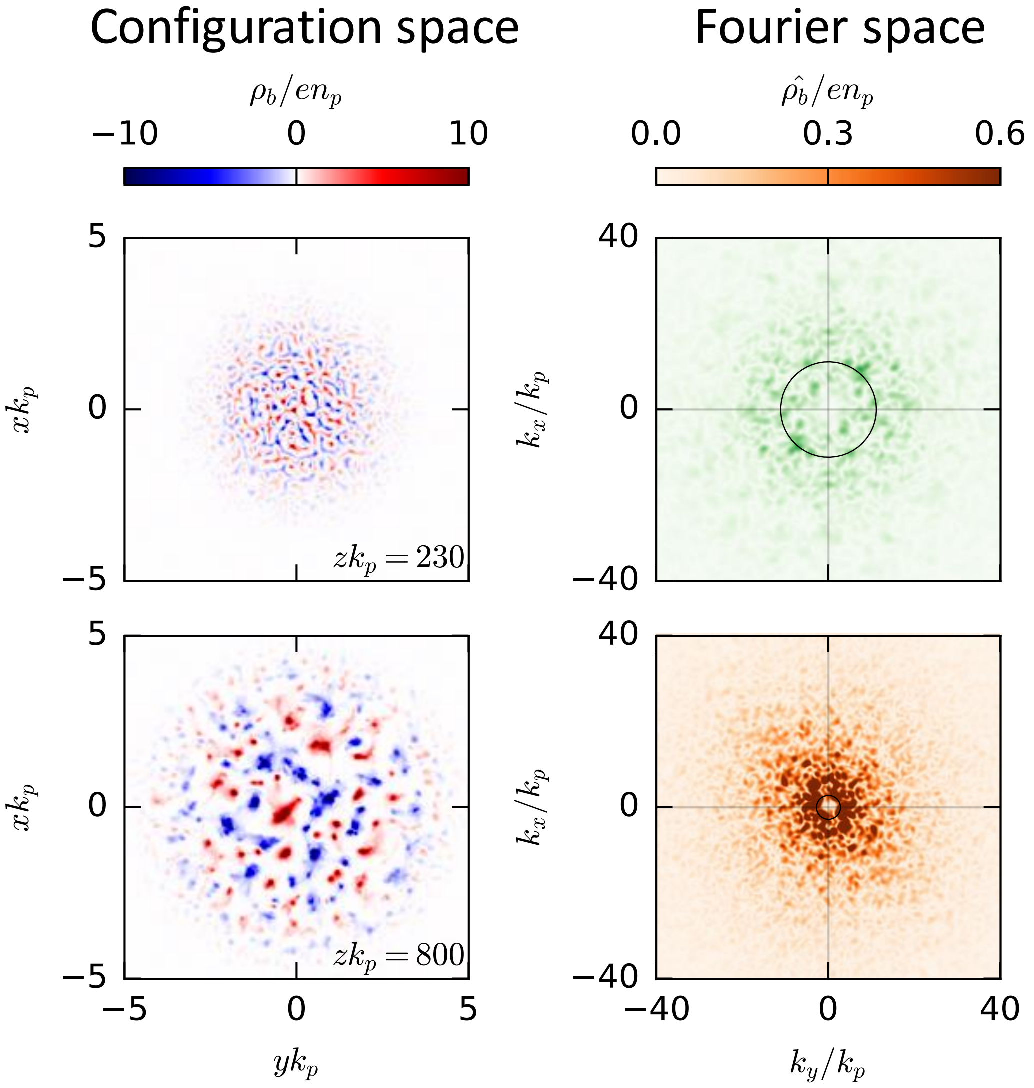
P. S. Claveria (2022)

$$\Gamma_{\mathrm{CF}} \sim \sqrt{\frac{n_b/n_p}{\gamma\, M_b/m_e}\,\frac{\zeta}{z}}\; z$$

V. B. Pathak (2015)

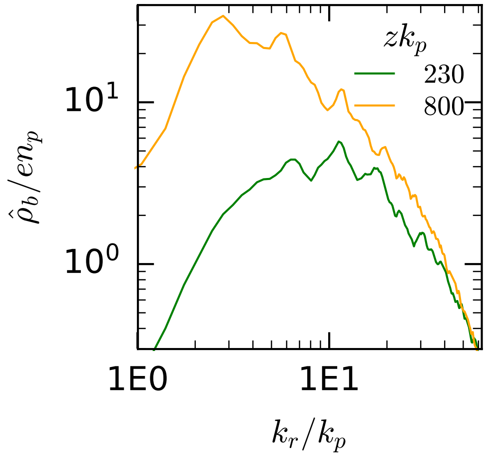
Fireball

Fourier Modes



- Instability: Random distribution
- Mean filament distance given by polar transformation $(k_x, k_y) \rightarrow (k_r, k_\varphi)$
- Relevant modes in interval $(1{,}30)\ k_p$

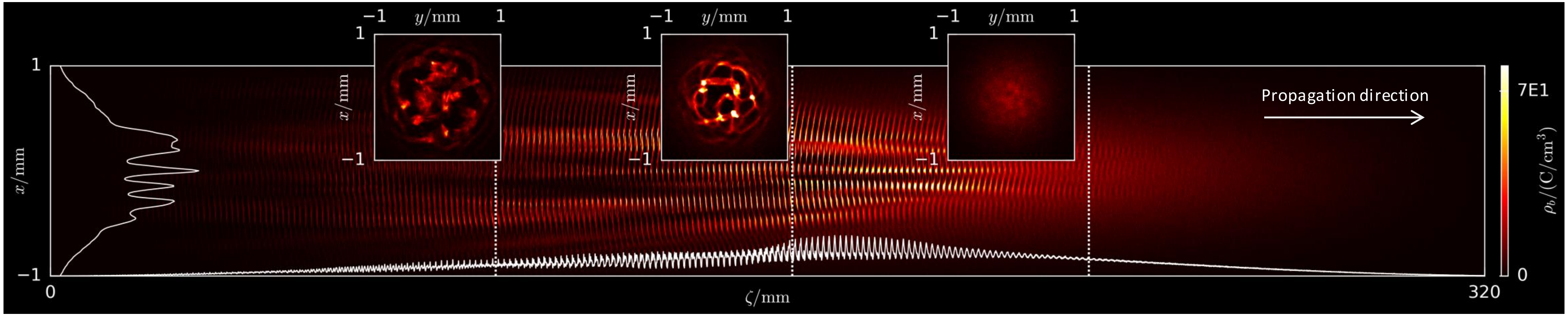
Sum over k_φ



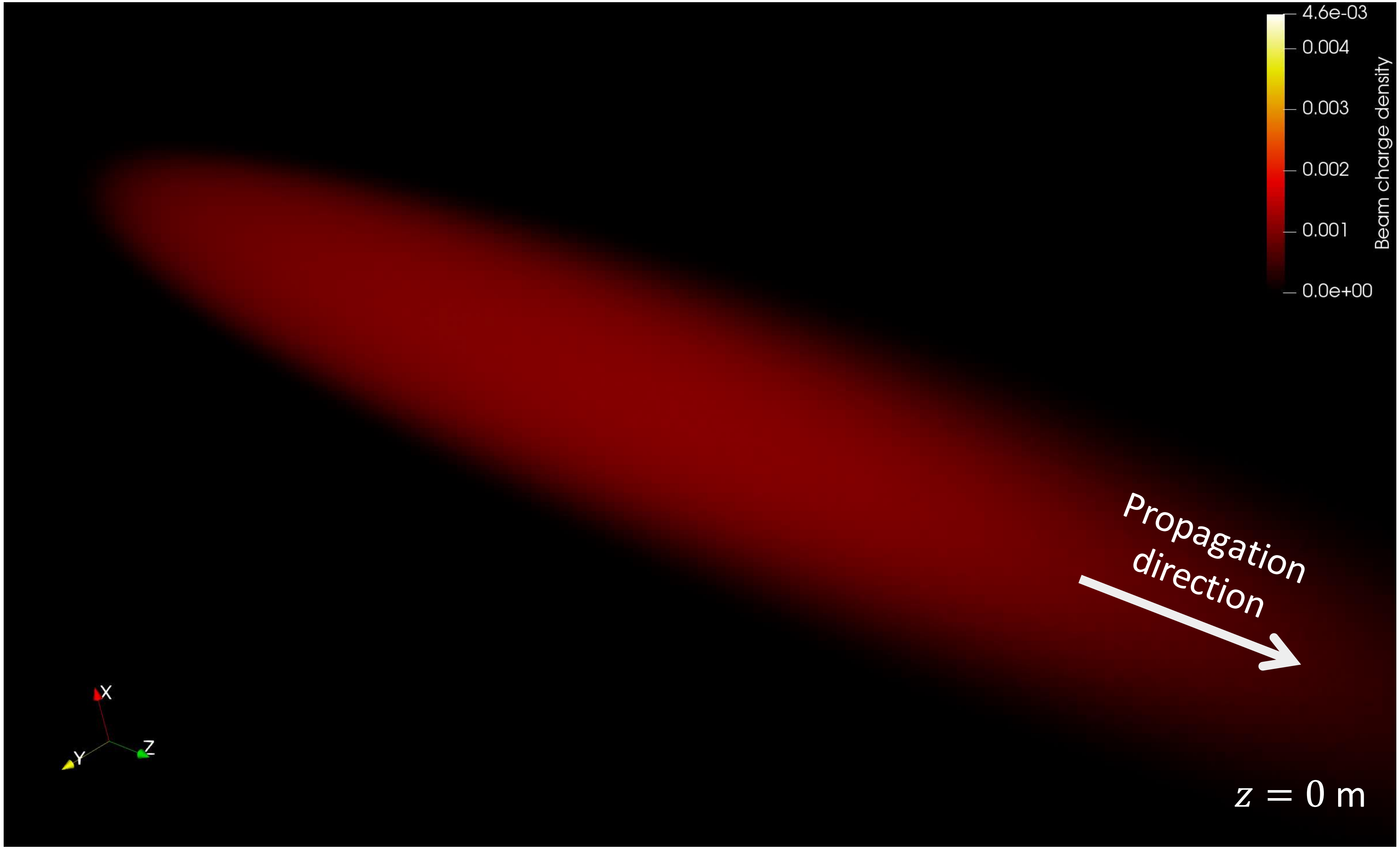
Filamentation in AWAKE?

- Beam/plasma parameters achievable within AWAKE
- Longitudinal + transverse beam modulation with filaments evolving along beam and propagation
- Average filament distance: 0.3-0.4 mm

Parameter	**Proton beam**
Plasma wavelength	1.26 mm
Beam gamma	426.4
B. charge	48 nC
B. norm. emittance	2.5 μm
B. length	220 ps
B. width	440 μm
B. macroparticles	1.18E9
Spatial resol. $(\Delta\zeta, \Delta\perp)$	$(0.25, 0.5)\, c/\omega_p$
Prop. distance	10 m

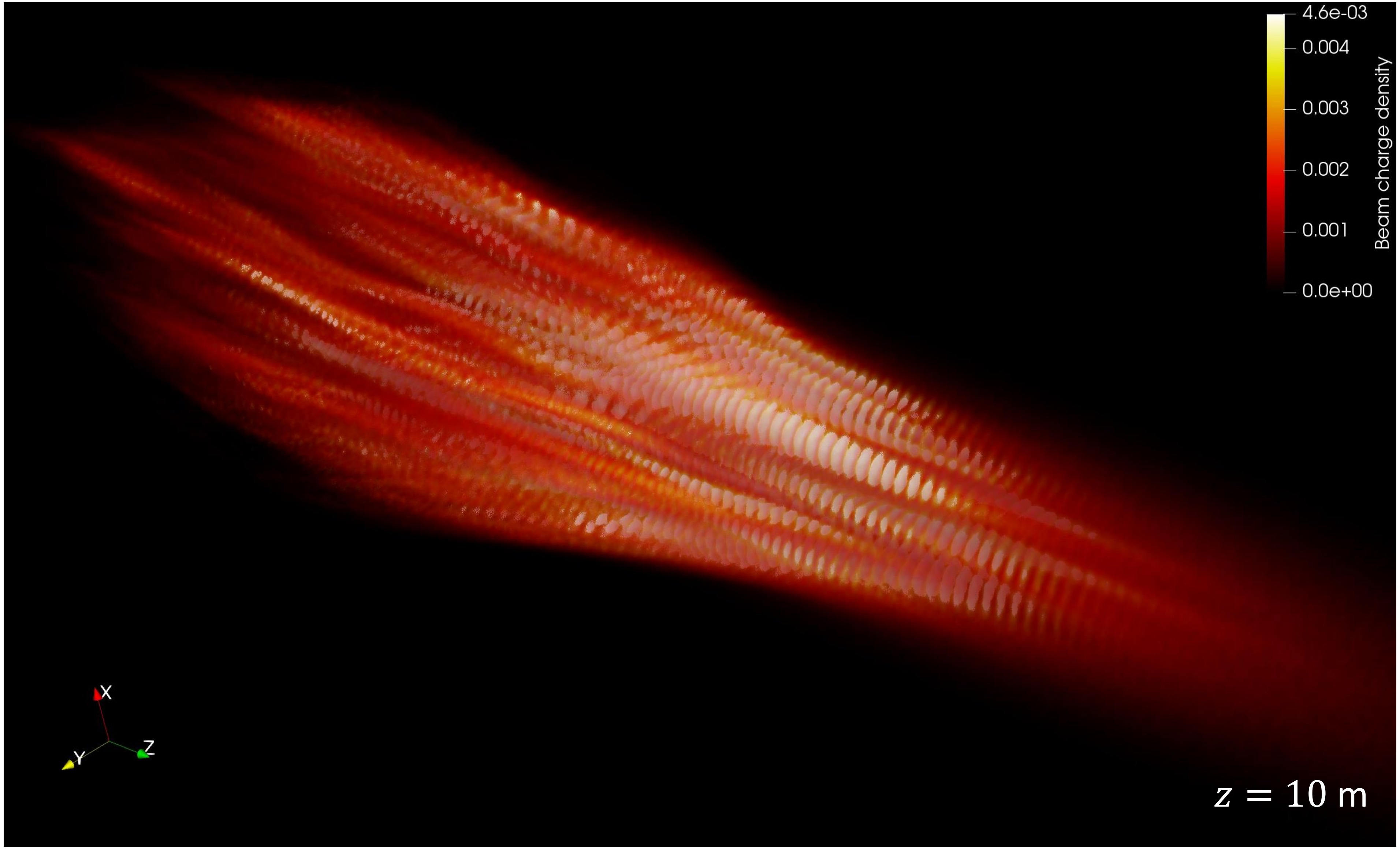


Filamentation in AWAKE?



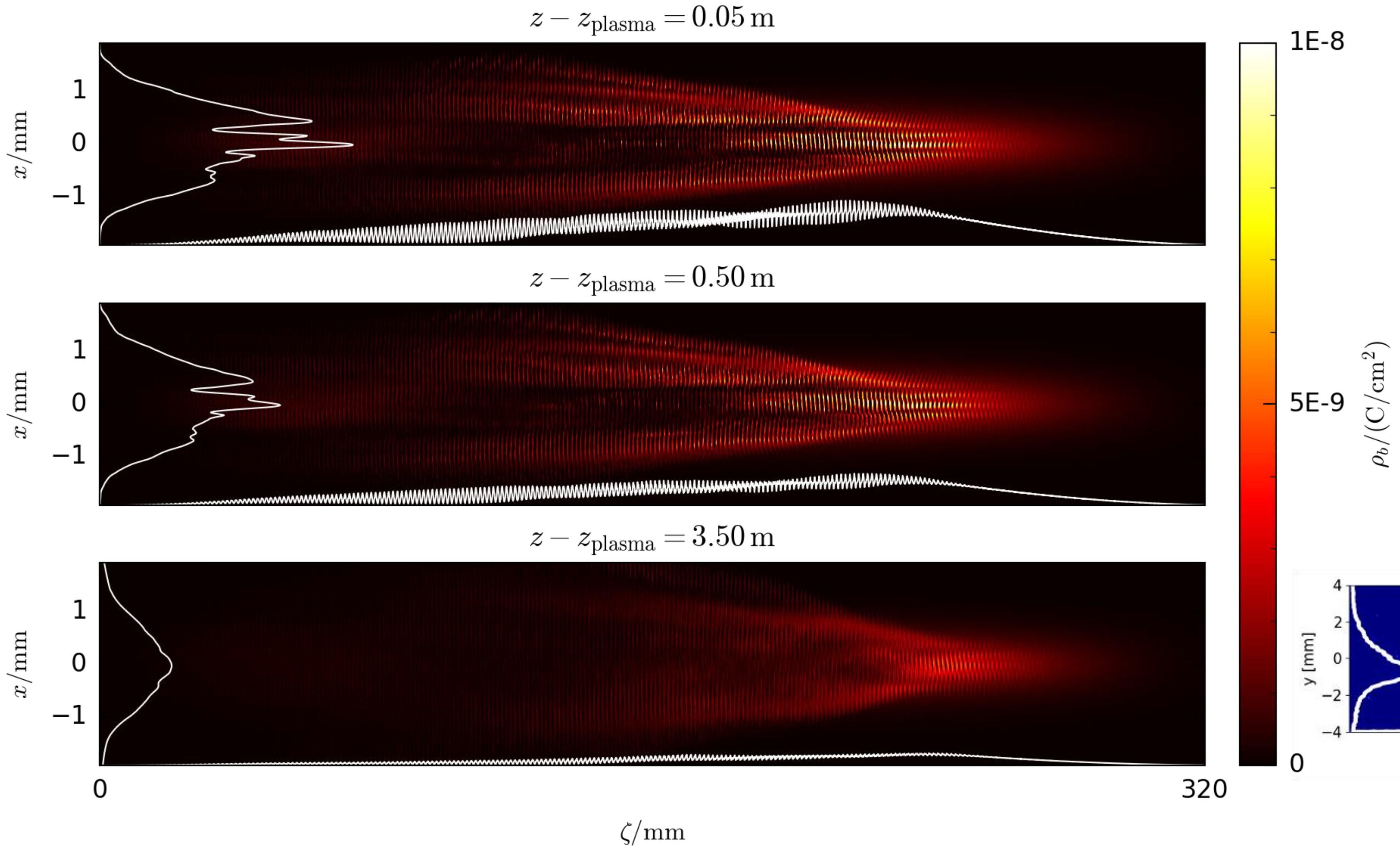
Filamentation in AWAKE?

Filamentation in AWAKE?



Filamentation in AWAKE

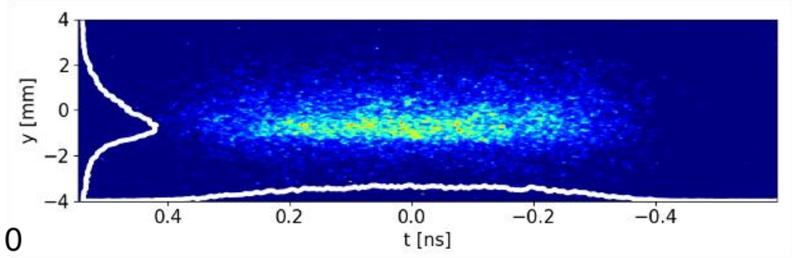
Beam propagates in vacuum



Bunches smear out

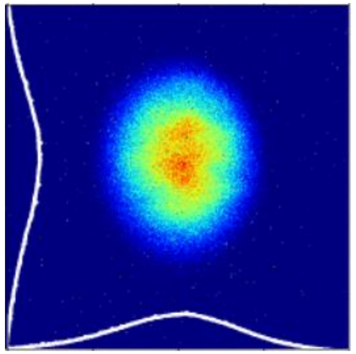
$T_p \approx 4.2$ ps

$\approx 2\Delta t$



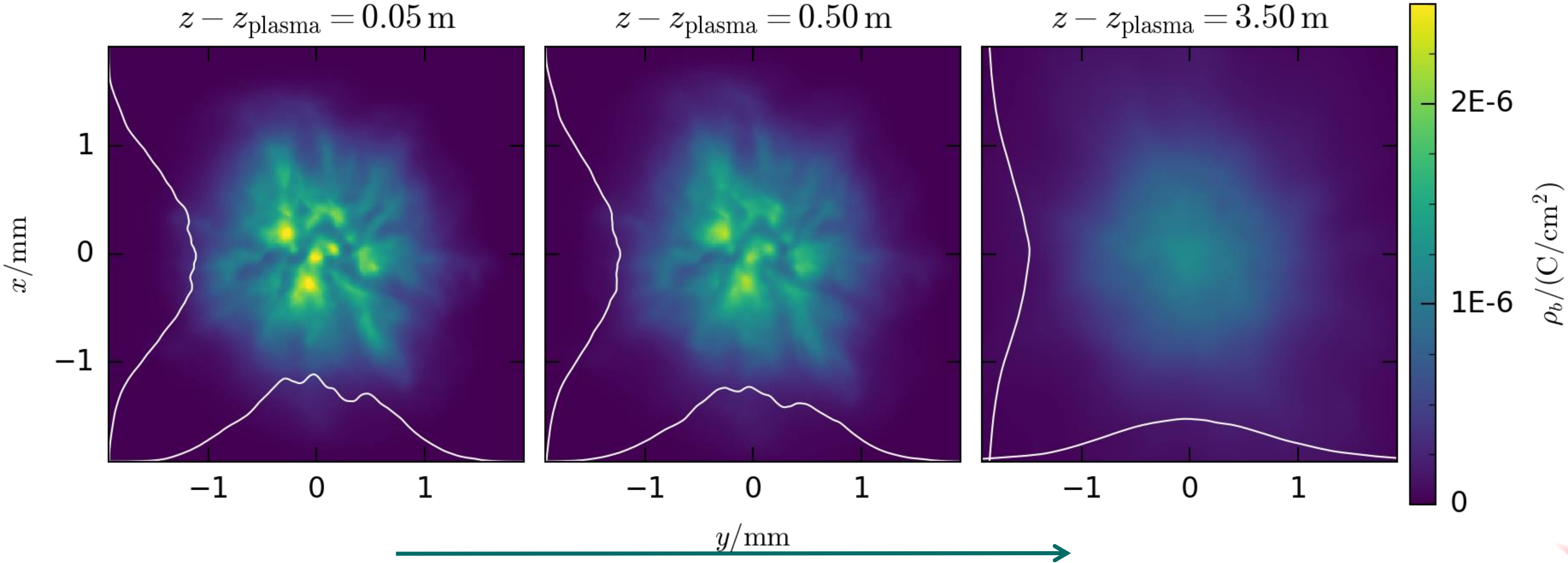
Filamentation in AWAKE?

Potential Screen Images



Run 2ab

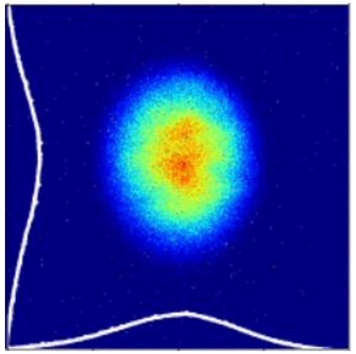
Beam propagates in vacuum



Filaments diverge / smear out

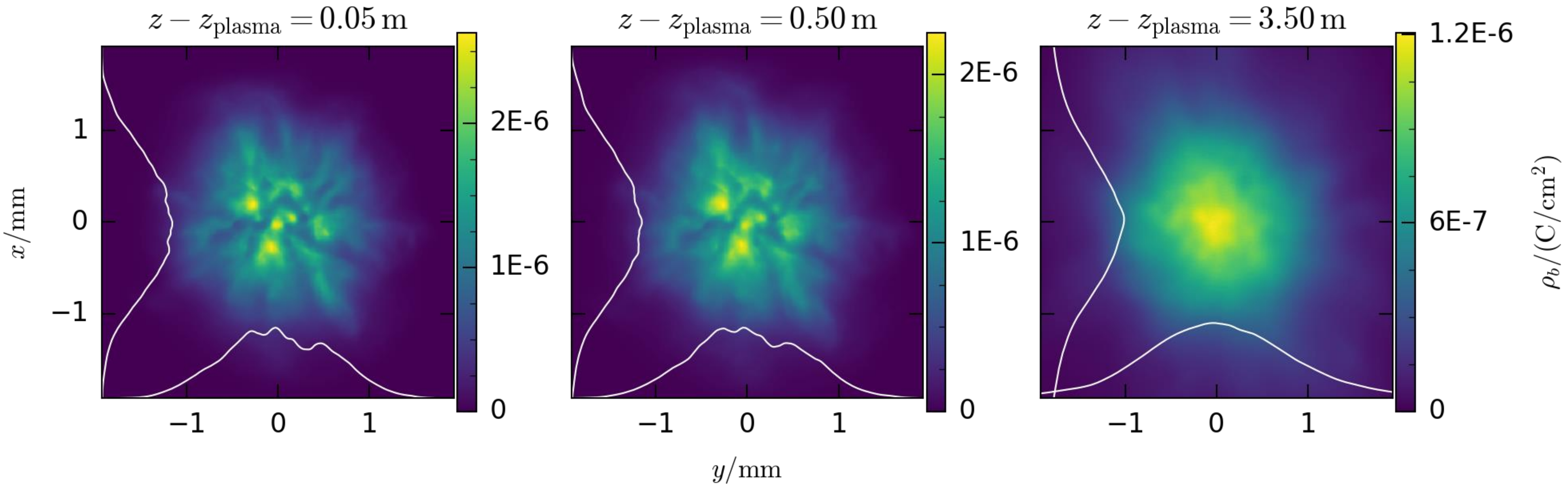
Filamentation in AWAKE?

Potential Screen Images



Run 2ab

Beam propagates in vacuum →

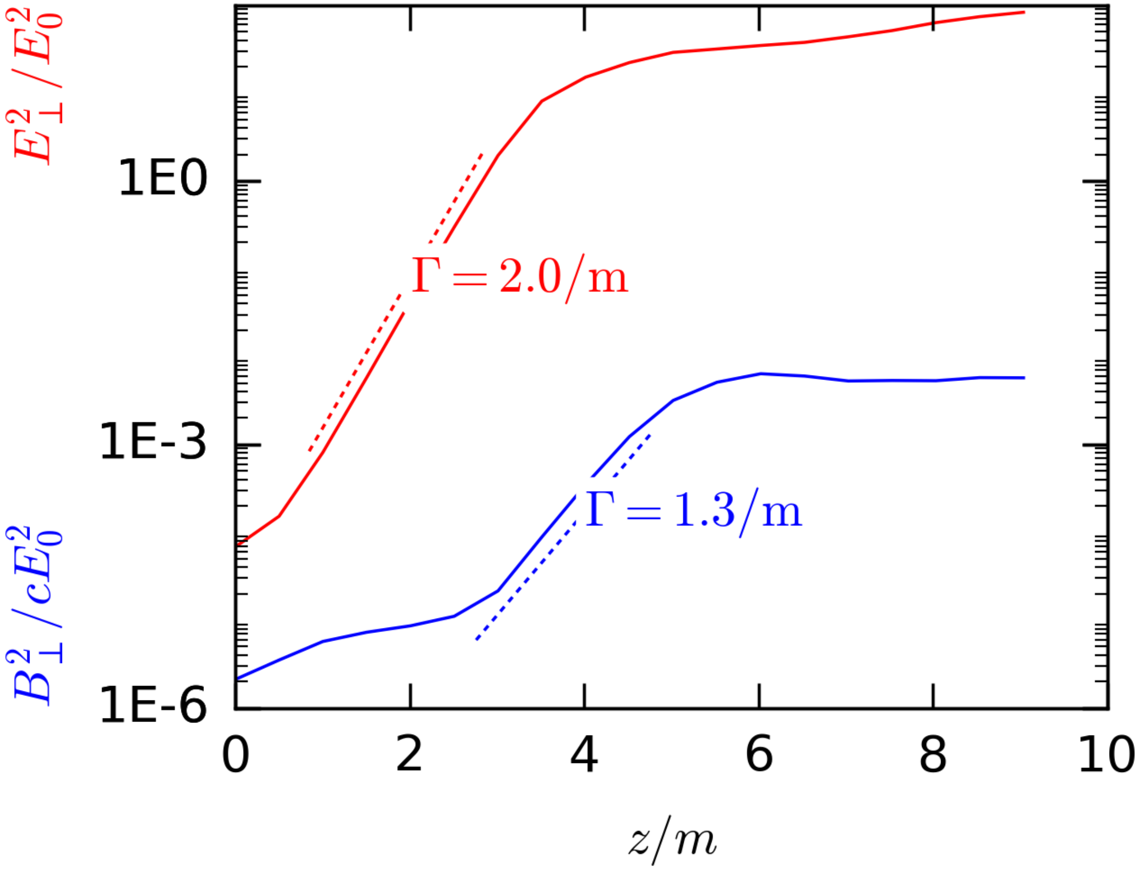


→ **Filaments diverge / smear out**

Filamentation in AWAKE

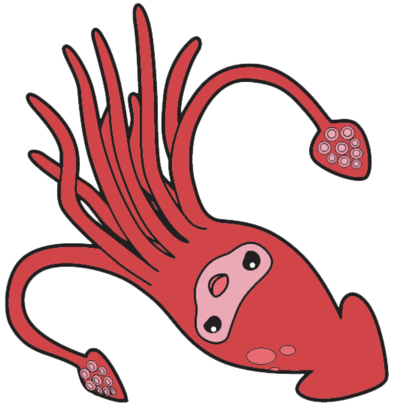
Electromagnetic Field Energy

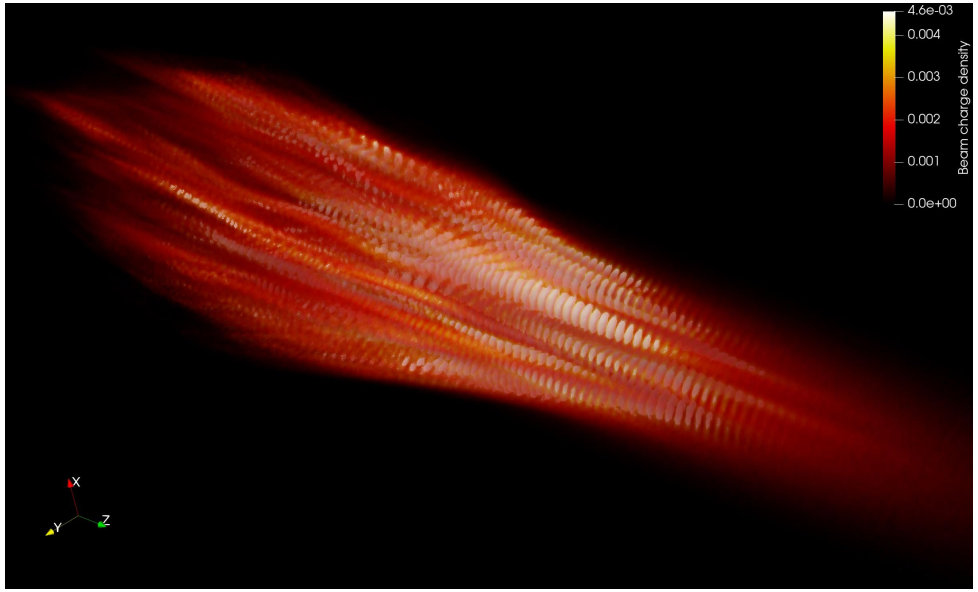
- Magnetic field orders of magnitudes smaller compared to electric field
- Saturation reached after 5m for $n_p = 7\mathrm{E}14/\mathrm{ccm}$
- Margin for different seed level



Summary

- Different filamentation modes observable for fireball beams.
- Simulations show beam filamentation for wide proton beam parameters achievable within AWAKE.
- Experimental results from DPS combined with simulations will help to improve understanding of filamentation modes achievable within AWAKE.





Thank you for your attention

For questions please contact me: erwin.walter@ipp.mpg.de

Literature

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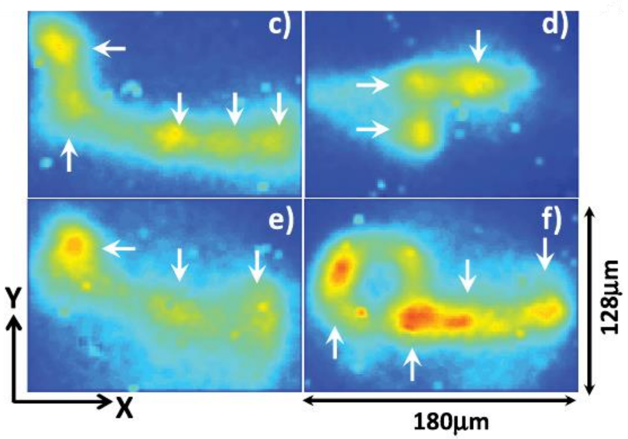
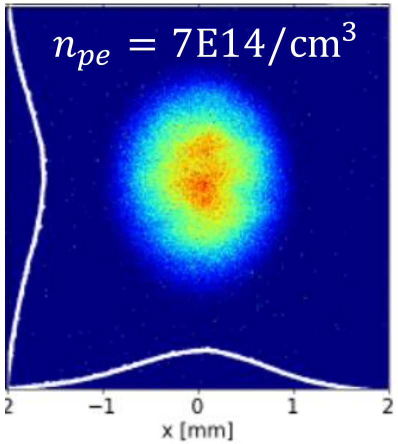
Introduction

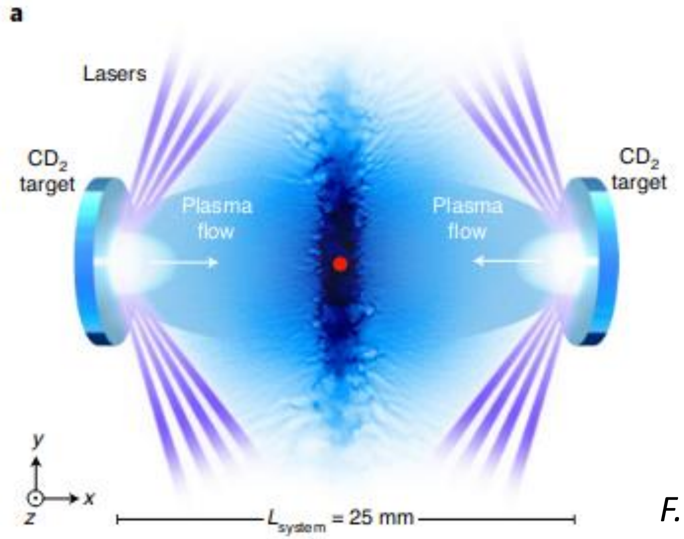
Previous work



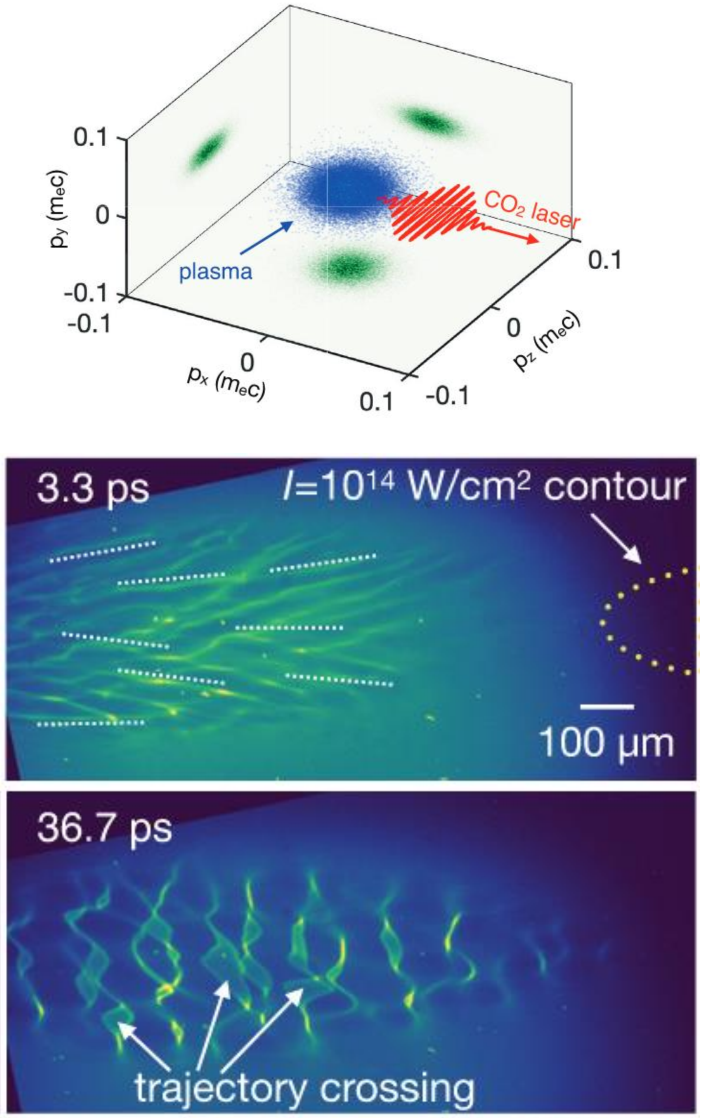
B. Allen et al, 2012



L. Verra, P. Muggli et al (AWAKE collaboration)



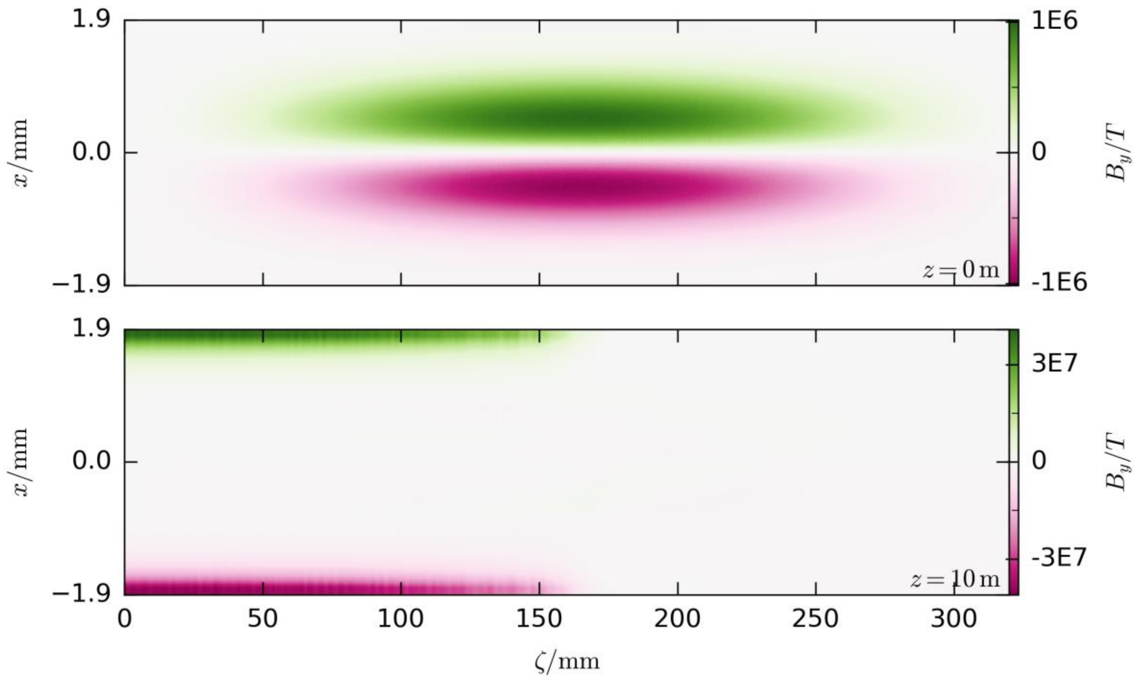
F. Fiuza et al. 2020

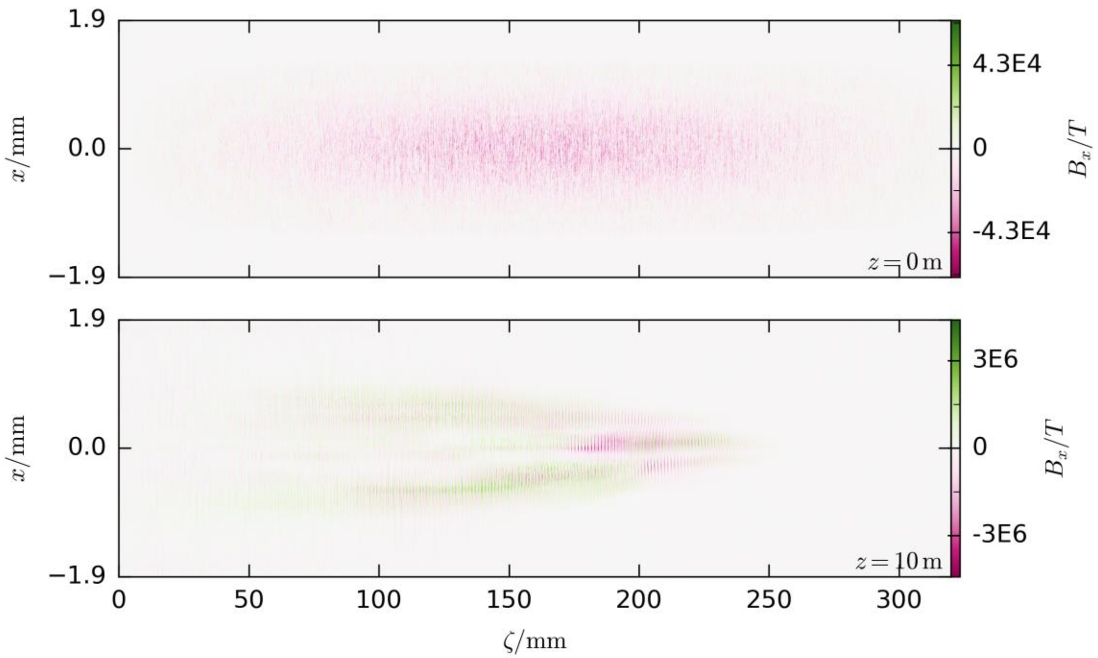


C. Zhang et al. 2022

Filamentation in AWAKE

Electromagnetic Field Energy

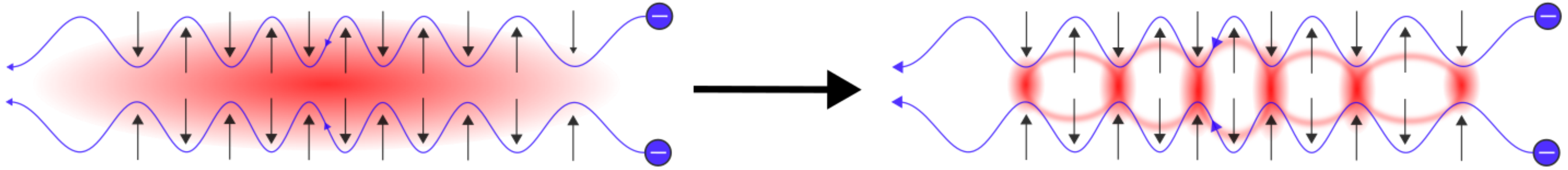




- Strong static magnetic field due to beam and plasma hides filamentation modes

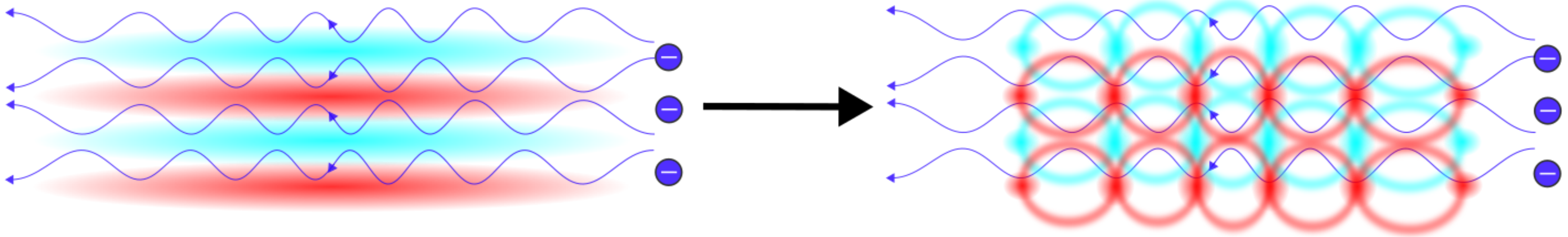
Extension of Theory

Transverse Two-Stream Instability (TTS)



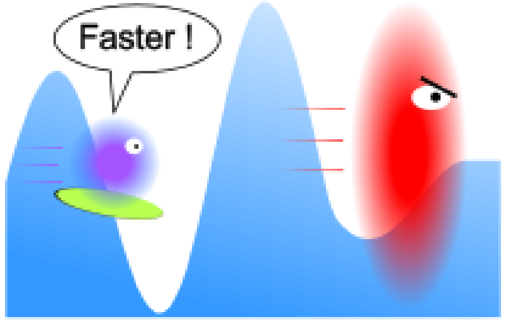
- Beam generates wakefields due to space-charge effect
- Wakefields act back on beam particles resulting in focussing / defocussing
- Electromagnetostatic → $E_{\parallel}, E_{\perp}, B_{\perp}(j_b)$

- Plasma electrons may oscillate for weak magnetic field
- Self-modulated beam filaments
- Spatiotemporal evolution of EM field



Motivation

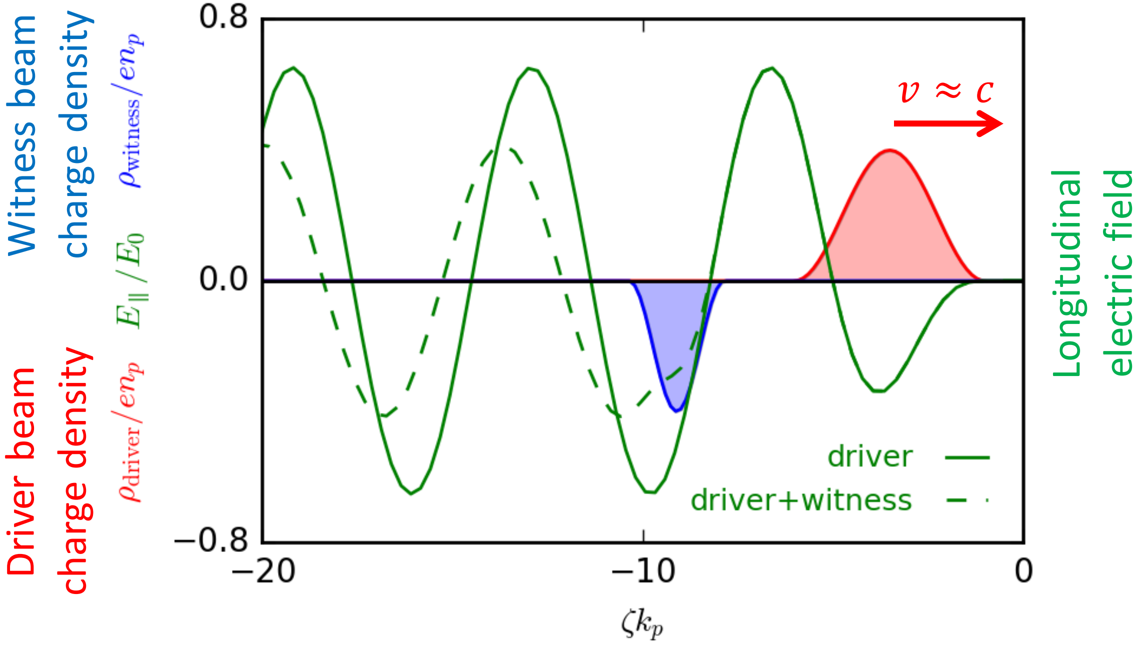
Plasma wakefield accelerators (PWFA)



Linear accelerators with high electric field (GV/m)

Basic concept: Transfer of kinetic energy (*P. Chen, 1985*)

- Charged beam drives wakefields
- Witness beam supresses wakefields



Wakefield: Electrostatic plasma response due to the beam

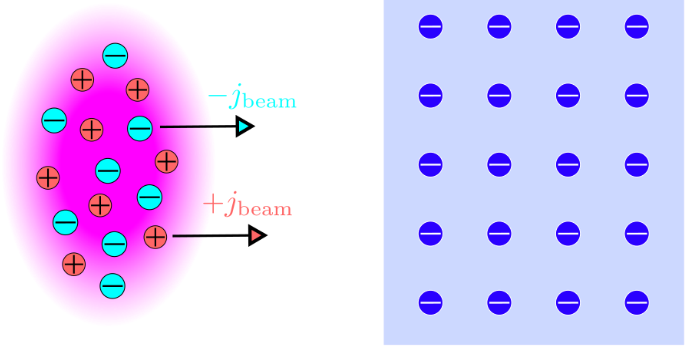
A relativistic beam in plasma may undergo current filamentation

Can we use existing experiments for astrophysical laboratory?

Introduction

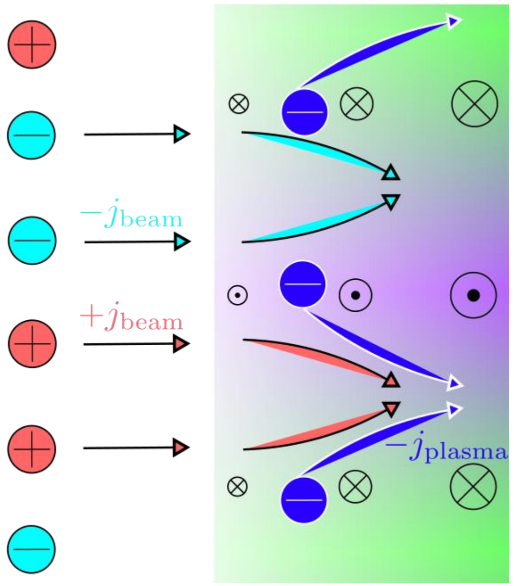
(Current) Filamentation Instability - *E. S. Weibel (1958)* , B. D. *Fried (1959)*

Requirement



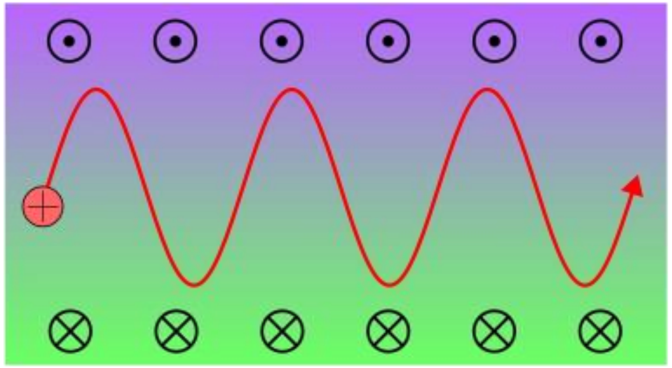
Velocity anisotropy of total system

Mechanism



- Transverse beam particles separation
- Electromagnetically dominant instability

Saturation



- Magnetic trapping with $\omega \sim \Gamma_{\mathrm{CFI}}$ (*R.C.Davidson, 1972*)
- **Filaments merge**

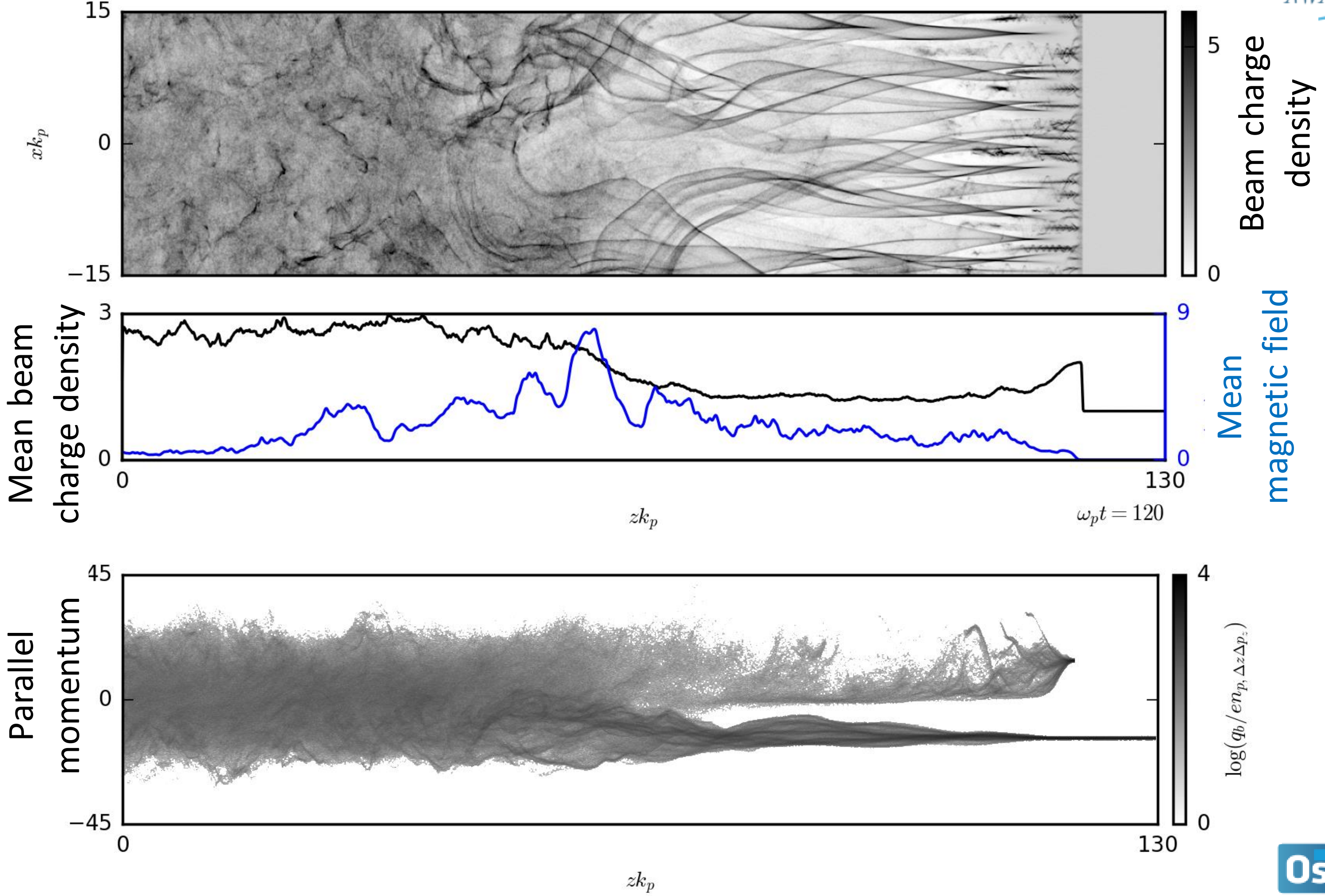
Motivation

Collisionless shock front

Candidate for cosmic acceleration

Characterization: Sudden change in momentum space and electromagnetic field

- Magnetic field growth due to **current filamentation instability (CFI)**

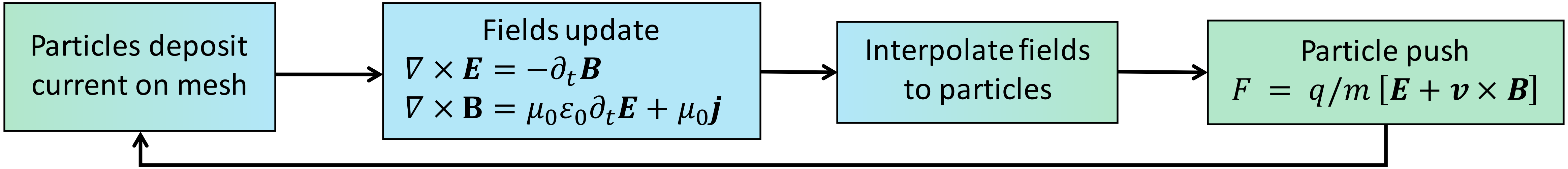


Methods

Fully electromagnetic particle-in-cell (PIC) method

Kinetic: Phasespace discretely resolved by macroparticles with charge, position and momentum

Interaction **in space and momentum**



Particles deposit current on mesh

Fields update

$$\nabla \times \boldsymbol{E} = -\partial_t \boldsymbol{B}$$

$$\nabla \times \mathbf{B} = \mu_0 \varepsilon_0 \partial_t \boldsymbol{E} + \mu_0 \boldsymbol{j}$$

Interpolate fields to particles

Particle push

$$F = q/m\,[\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}]$$