Long term wake evolution: heating & ion wakes

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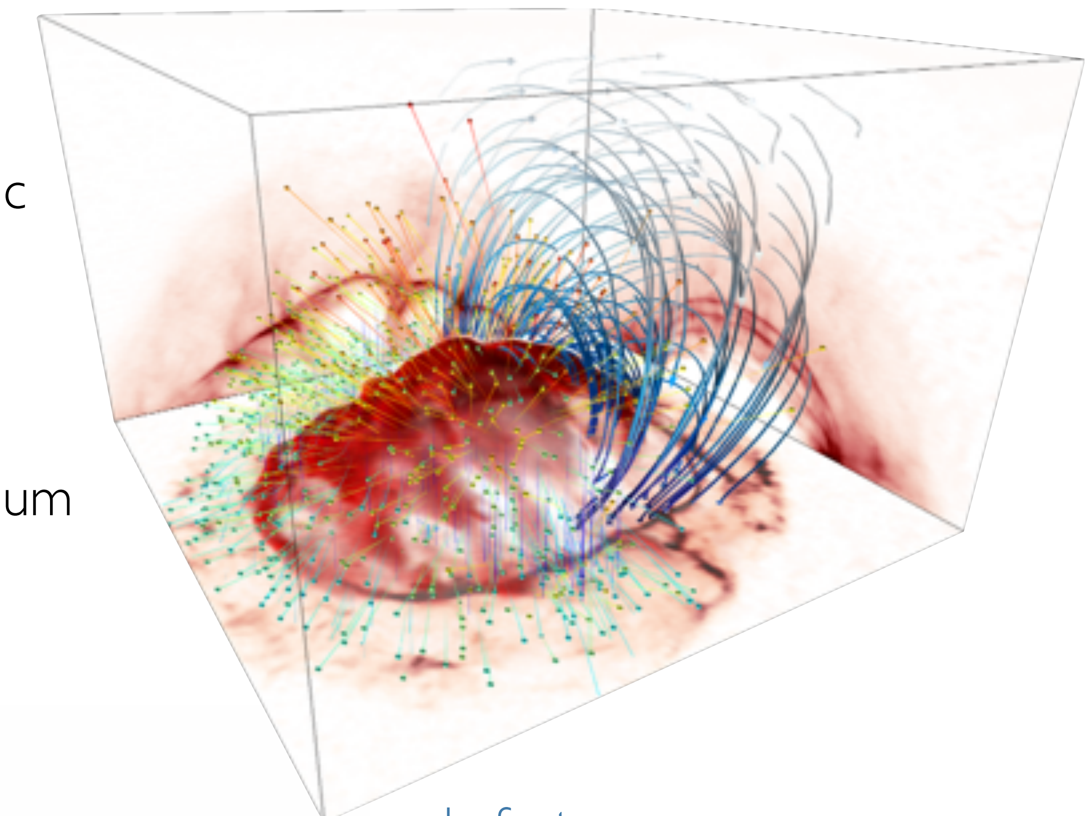
INVESTIGADOR FCT

OSIRIS 3.0

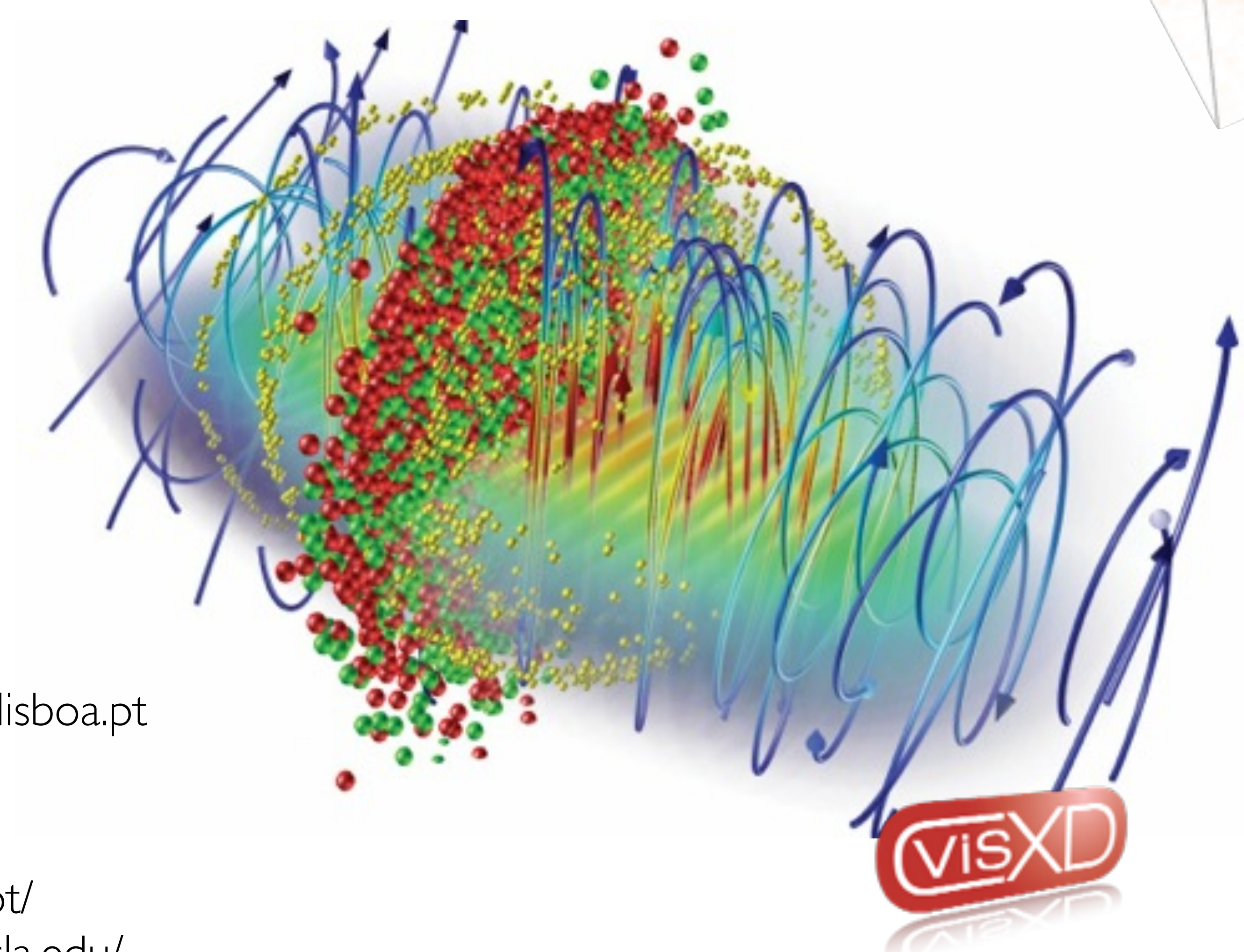
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  - ⇒ UCLA + IST



code features

- Scalability to ~ 1.6 M cores
- Dynamic Load Balancing
- GPGPU and Xeon Phi support
- Particle merging
- QED module
- Quasi-3D
- Current deposit for NCI mitigation
- Collisions
- Radiation reaction
- Ponderomotive guiding center



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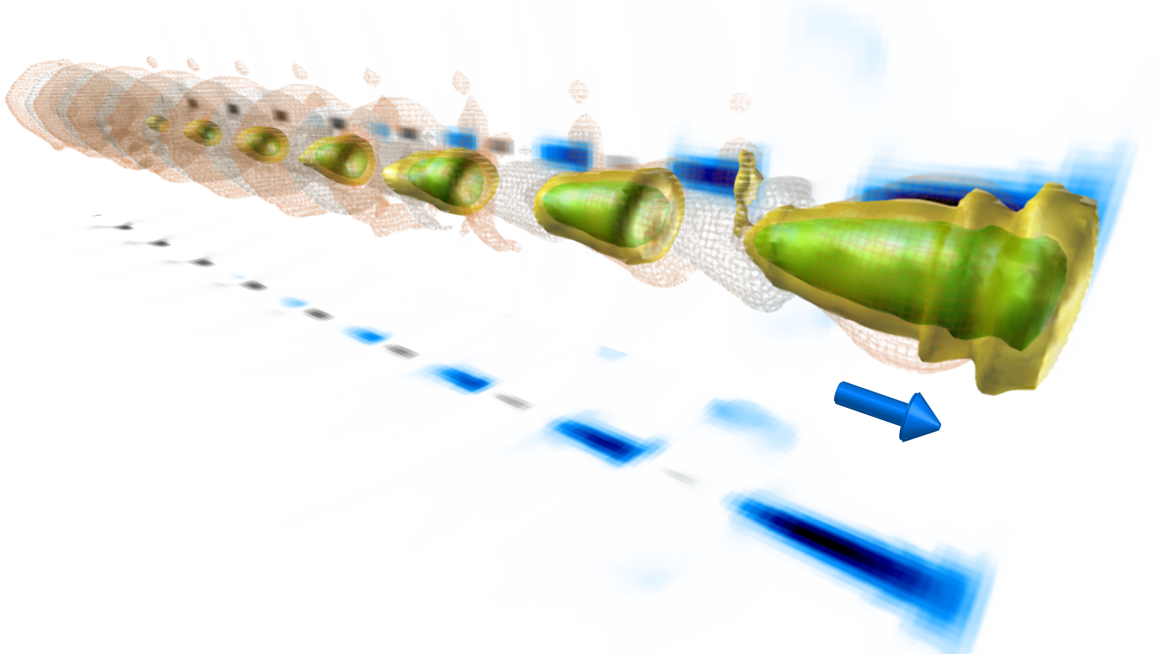
Ion motion in plasma wakefield accelerators

Long drivers

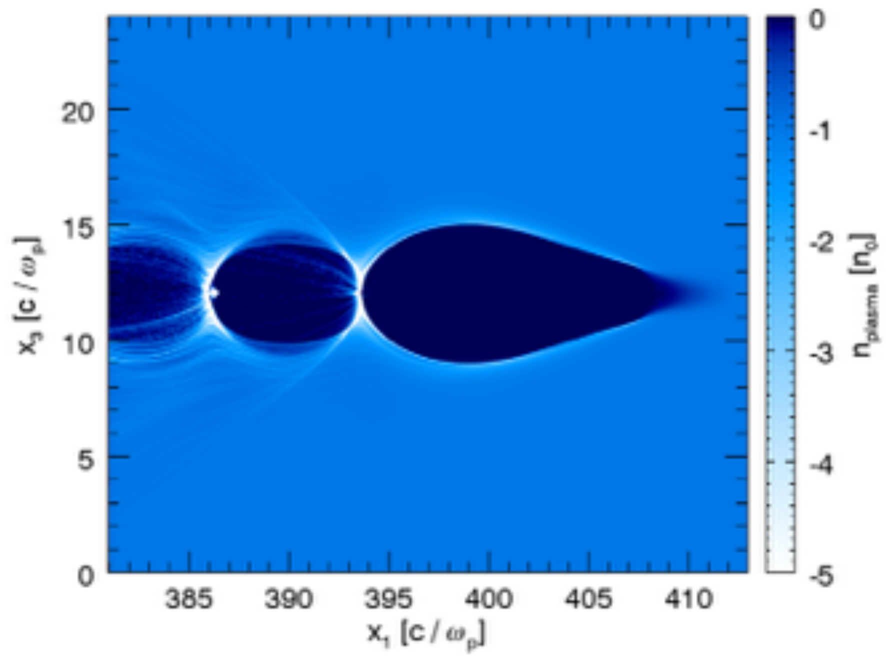
self-modulated proton driven wakefield accelerator



- important when beam length (σ_z) is comparable to ion skin depth (c/ω_{pi})
- disrupts acceleration structures
  J.Vieira *et al.* PRL 2011
- may have strong impact on repetition rate
  A. Sahai *et al.* 2017

Short drivers

plasma wakefield accelerator in the blowout regime



- influences emittance evolution for tightly focused drivers plasma accelerators
  W. An *et al.* PRL 2017
- may have strong impact on repetition rate

Need to explore the physics of ion motion experimentally and theoretically.

Outline

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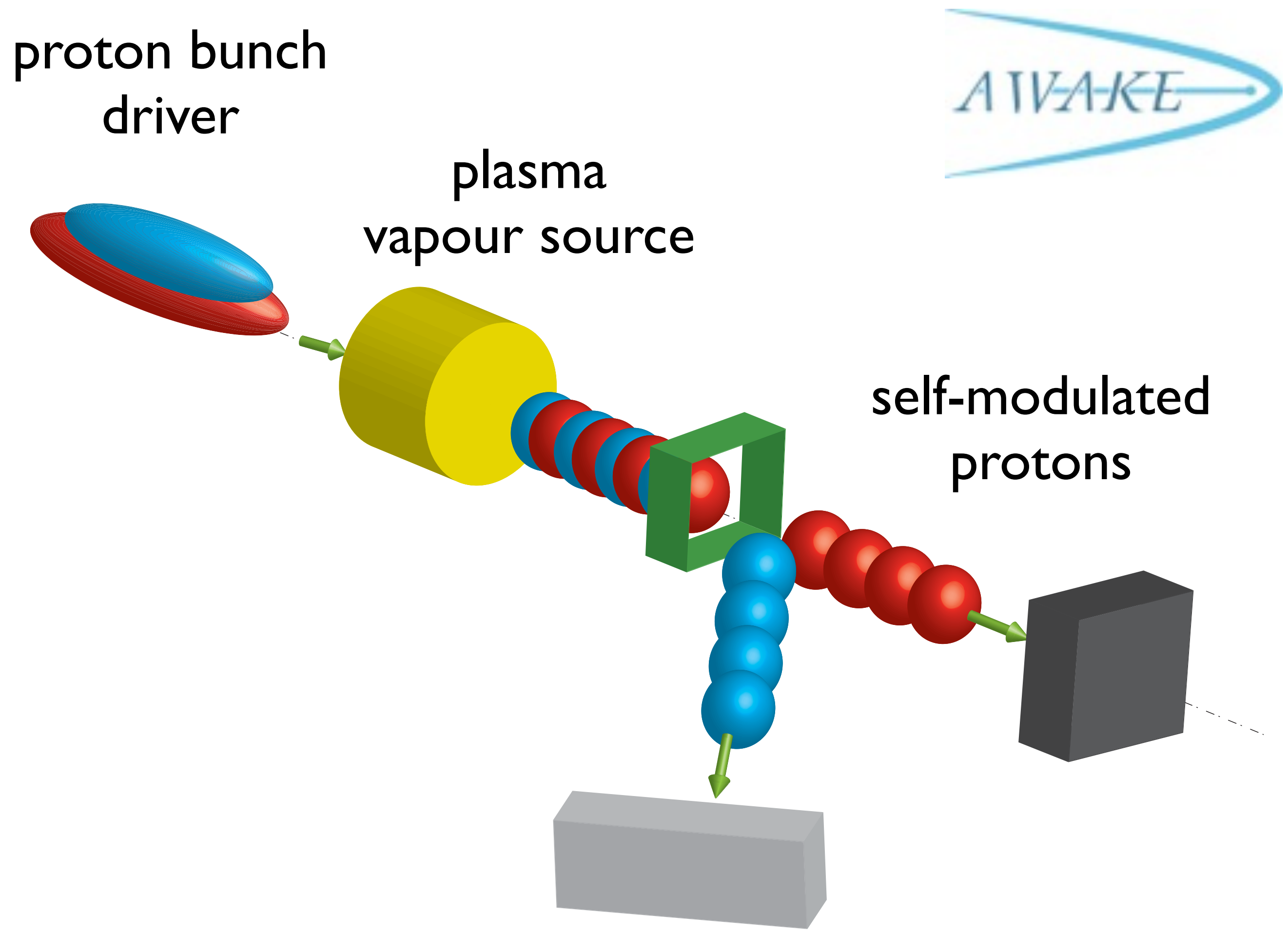
- Ion motion in the proton driven plasma wakefield accelerator
- Ion motion in the nonlinear blowout regime
- Conclusions & future directions

AWAKE experiment at CERN

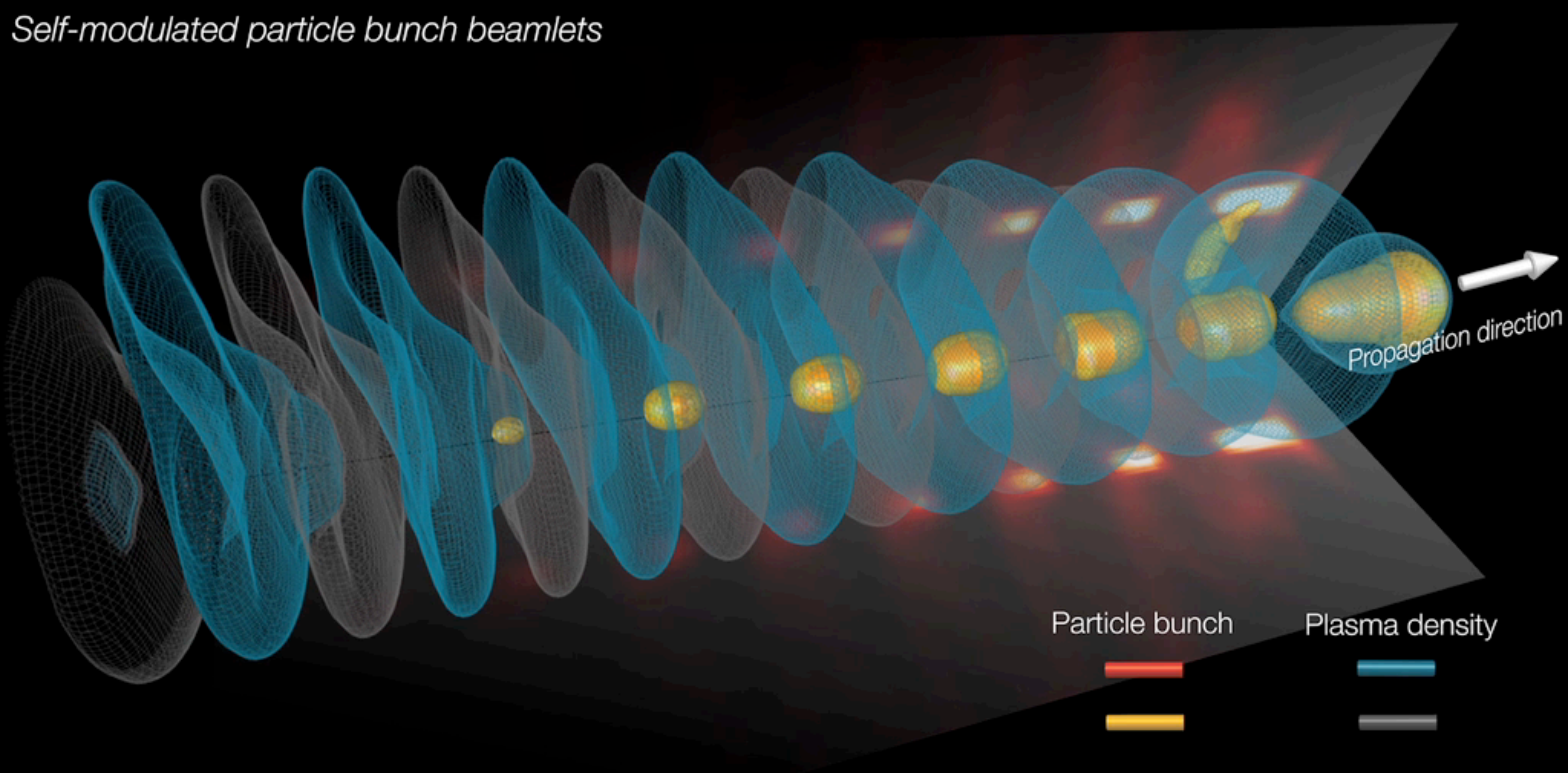
ion motion can suppress plasma wakefields in the linear regime

Experimental setup



- proton bunch length is σ_z = 10 cm long
- plasma density is $n_0 \sim 10^{14}\text{-}10^{15}$ cm^{-3}
- For a hydrogen plasma: **σ_z = 2-7 ion skin-depths**

Stable, hosing free self-modulation of long particle bunches

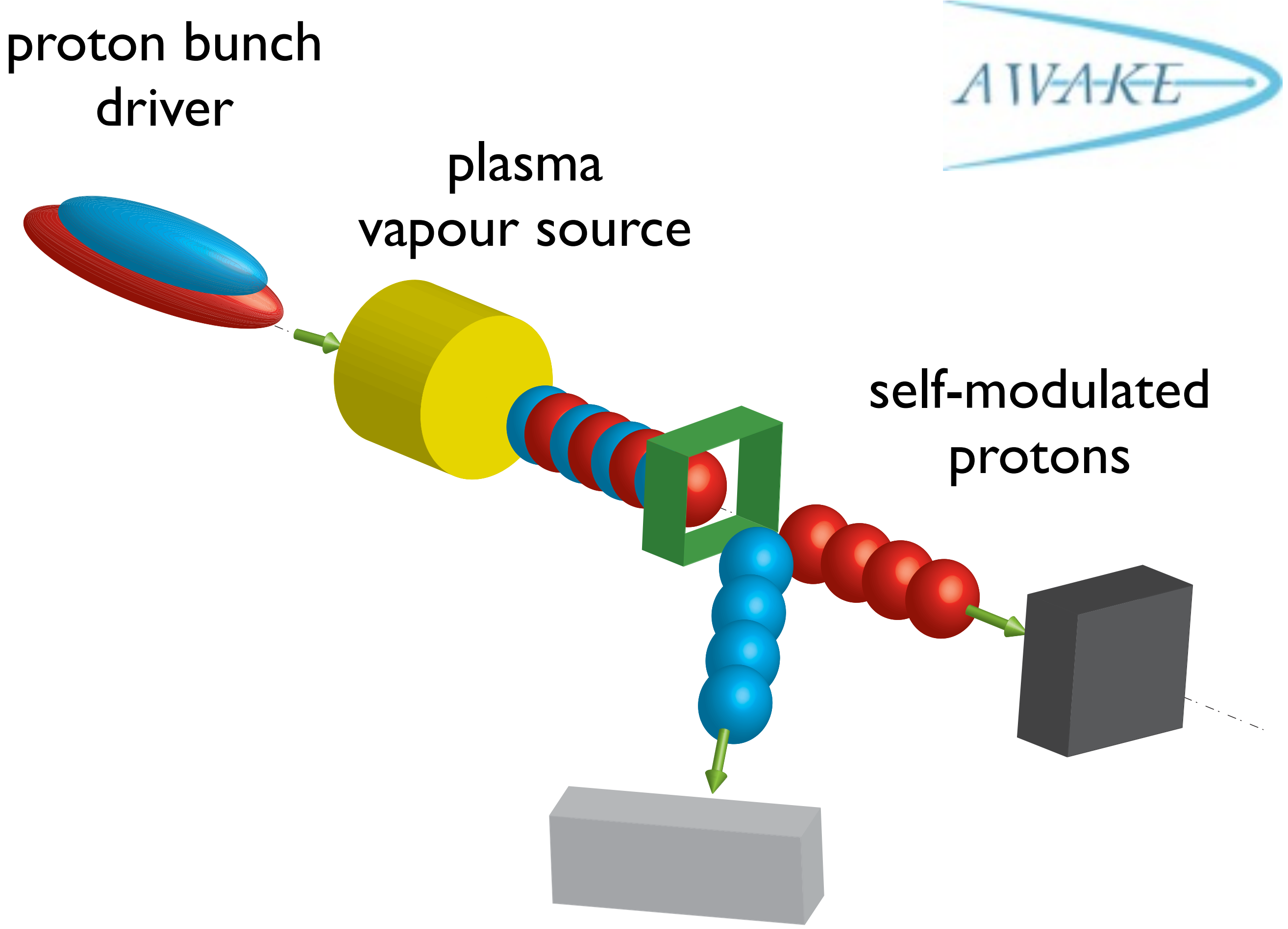


J. Vieira *et al.* PRL **112** 205001 (2014)

AWAKE experiment at CERN

ion motion can suppress plasma wakefields in the linear regime

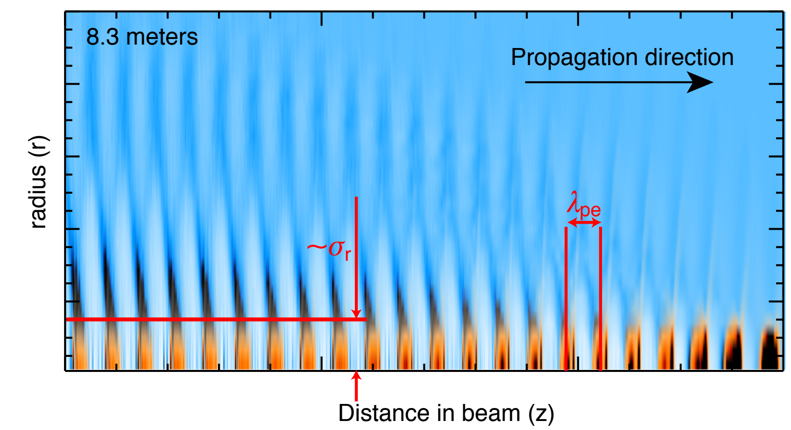
Experimental setup



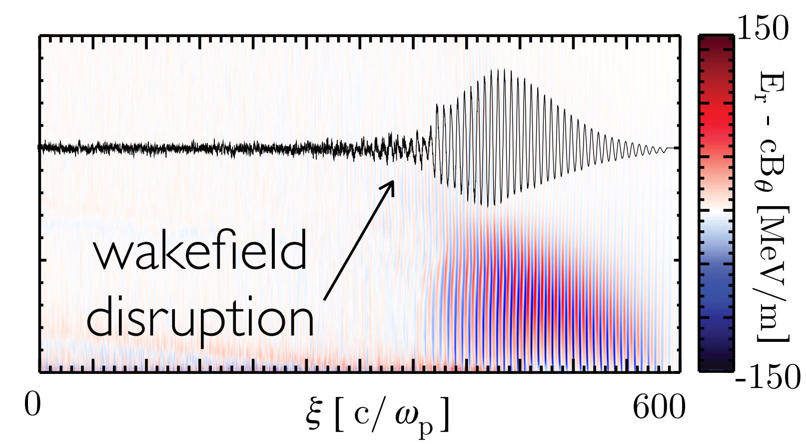
- proton bunch length is σ_z = 10 cm long
- plasma density is $n_0 \sim 10^{14}$-10^{15} cm^{-3}
- For a hydrogen plasma: **σ_z = 2-7 ion skin-depths**

Role of ion motion

Infinitely heavy ions



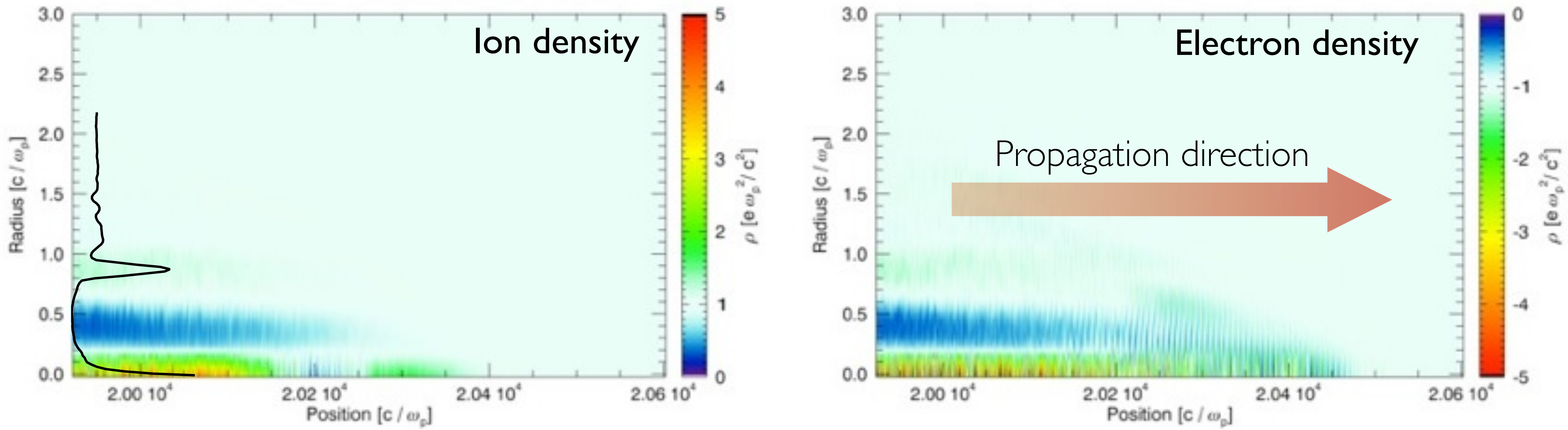
Hydrogen ions



J.Vieira *et al.* PRL **109** 145005201 (2012)

Ion motion suppresses space charge fields

Nearly hollow plasma channel driven by the ion dynamics



- ion/electron filament on axis
- generation of a near hollow plasma channel
- ion accumulation off-axis

J.Vieira *et al.* PRL **109** 145005201 (2012)

How do ions move?

Model for the ion motion in narrow wakefields

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Evolution of the ion density

ion motion equation (momentum+continuity eqs)

$$m_i\left[c^2\frac{\partial^2}{\partial\xi^2}-c_s^2\nabla^2\right]n_i=-n_0Z\nabla\cdot\mathbf{F}_p$$

- speed of light frame: ξ=x-ct
- $\mathbf{F}_{p\perp} \gg \mathbf{F}_{p||}$ since $\sigma_z \gg \sigma_r$ ($\partial_r \gg \partial_z$)
- ions move radially: $\mathbf{F_p}$=<$\mathbf{E}_\perp$>
- Neglect temperature (c_s=0)

simplified model for ion response

$$m_ic^2\frac{\partial^2 n_i}{\partial\xi^2}=-\frac{n_0Ze^2}{4m_e\omega_p^2}\nabla^2\langle E_r\rangle^2$$

$\mathbf{\hat{E}_r}$ is the envelope of the plasma radial electric field

Analytic formulas at early times

leading order expansion O(ξ^3)

$$n_i=n_{i0}\left[1-\frac{Ze}{m_ic^2}\frac{\xi^2}{2}\nabla\cdot\langle E_r\rangle+\mathcal{O}(\xi^3)\right]$$

ion motion determined by E_r averaged over the fast (electron) time scales

nonlinear wakefield theory for narrow beams

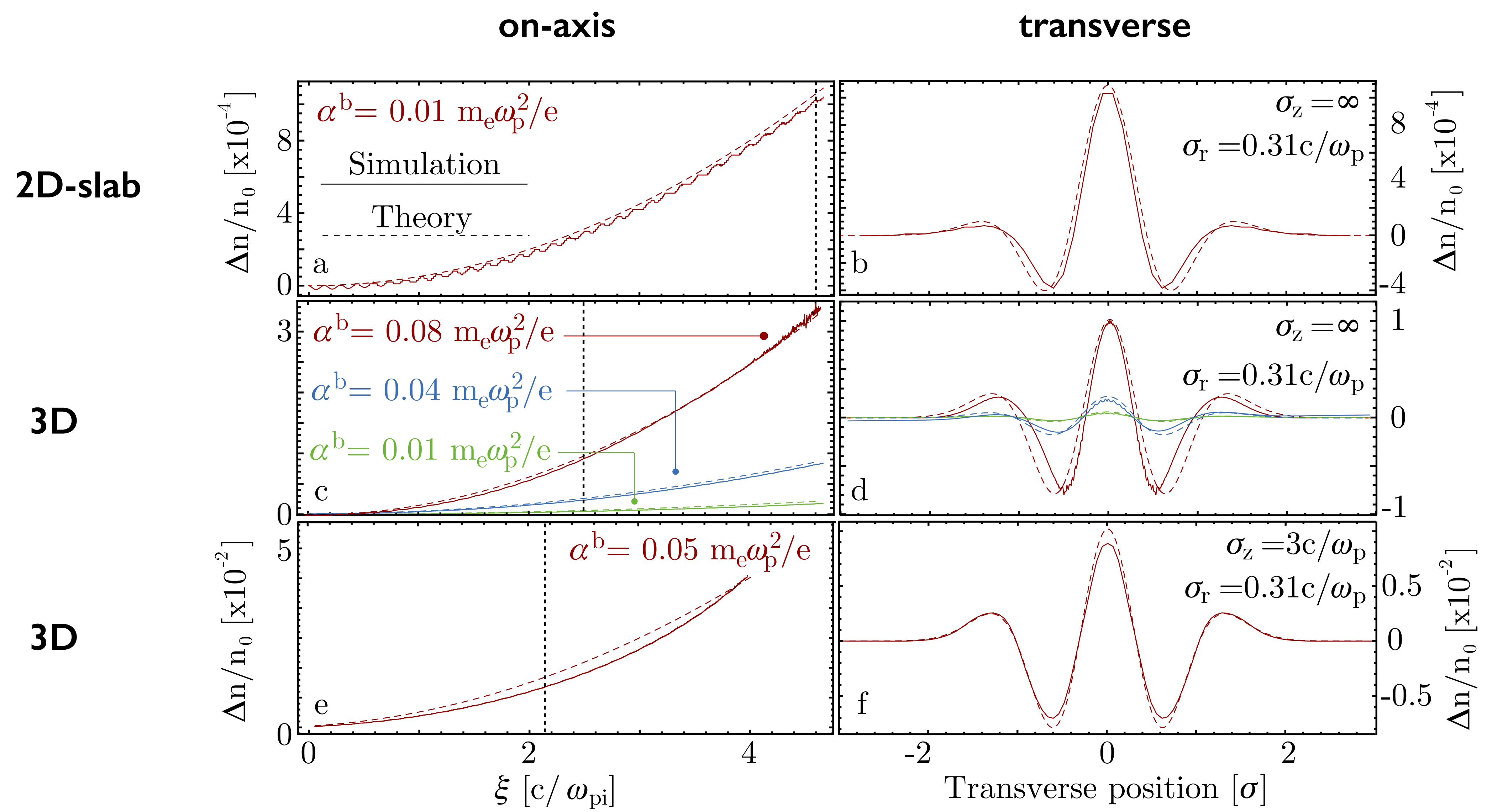
$$E_r^{\xi>\sigma_z}=\frac{\hat{E}_r\cos\phi}{1+\nabla_r[e\hat{E}_r/(m_e\omega_p^2)]\cos\phi}$$

- $\hat{E}_r[n_b(r)]$ is the wakefield amplitude
- Dawson sheath model in cylindrical geometry
- phase $\Phi = \omega_p\xi/c$

Osiris simulations confirm model

Proton density evolution

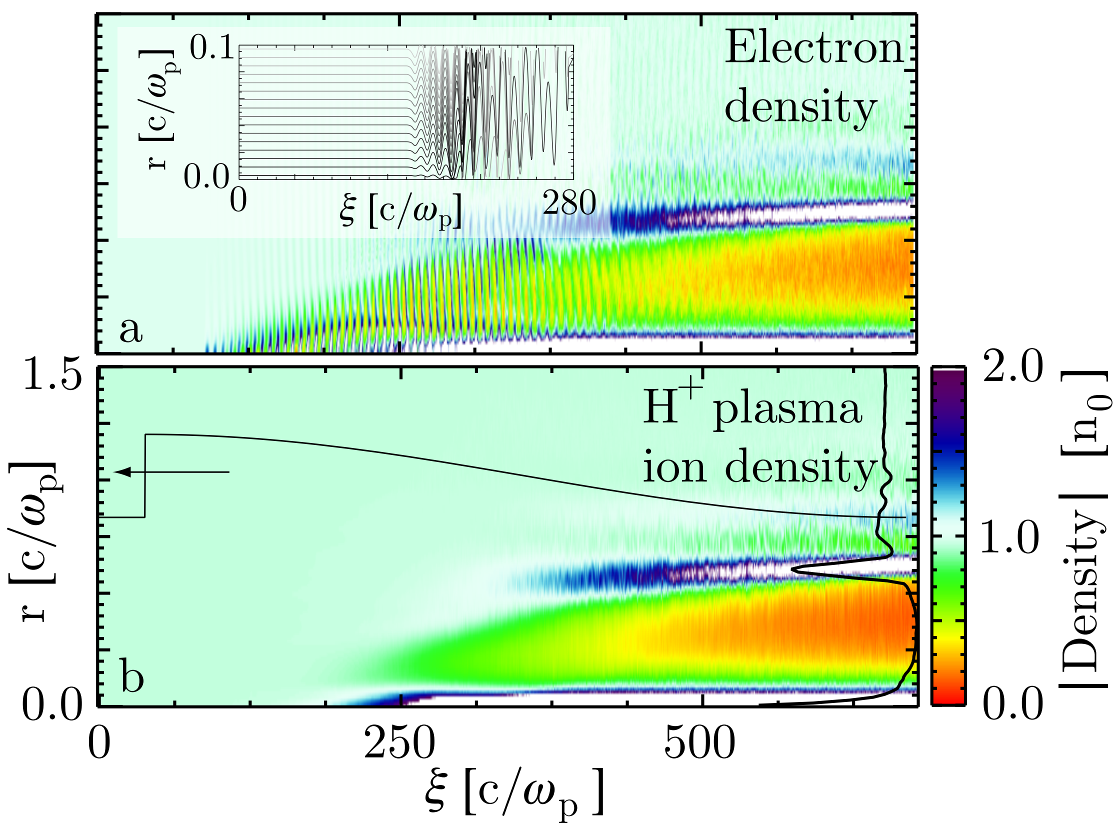
external electric field is the driver in the Osiris simulations



Onset of the ion motion and wavebreaking

Ion motion induces wavebreaking

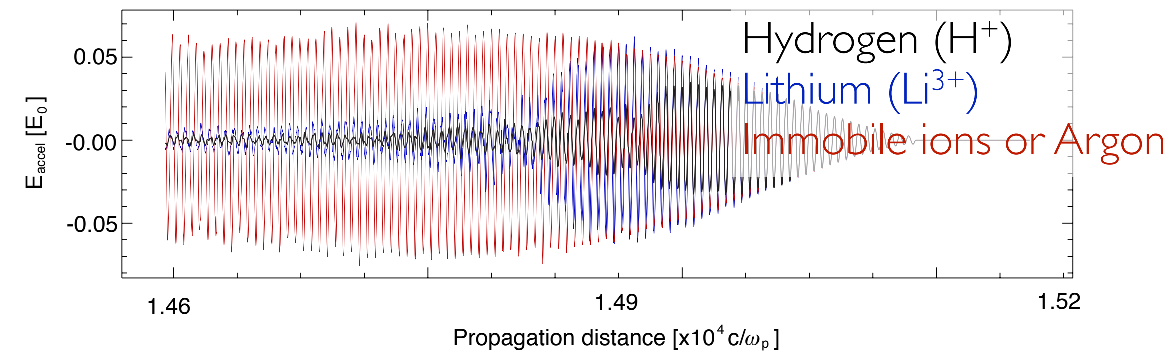
electron and ion density from OSIRIS simulations



- trajectory crossing occurs when ion motion becomes significant
- electron heating and wakefield suppression
- wavebreaking time ~ $(m_i/m_e)^{1/2}$

Ion motion mitigation

longitudinal electric fields



position ξ_{crit} is where the ion density becomes twice the background plasma

$$\frac{\xi_{\text{crit}}}{\sigma_z} = \frac{c^2}{\omega_p^2\sigma_z^2}\left(\frac{m_i}{2m_eZ}\right)^{1/2}\left[\frac{4\pi m_e\omega_p^2}{e\nabla_r\langle E_r\rangle} + \mathcal{O}(\nabla_r\langle E_r\rangle)\right]$$

- $n_b/n_0 \sim 10^{-2}$ and $eE_r/m_e\omega_p \sim 10^{-2}$
- $m_i/m_e = 1836$ and $Z = 1$
- **Ion motion is important:** $\xi_{crit} \sim 200c/\omega_p \sim \sigma_z$

Ion motion mitigation strategy: use heavier ions

Outline

Ion motion in the proton driven plasma wakefield accelerator

Ion motion in the nonlinear blowout regime at SLAC FACET

Conclusions & future directions

T. Silva *et al.* (2017)

Ion motion at SLAC FACET

Regimes differ drastically

SLAC electron and plasma parameters

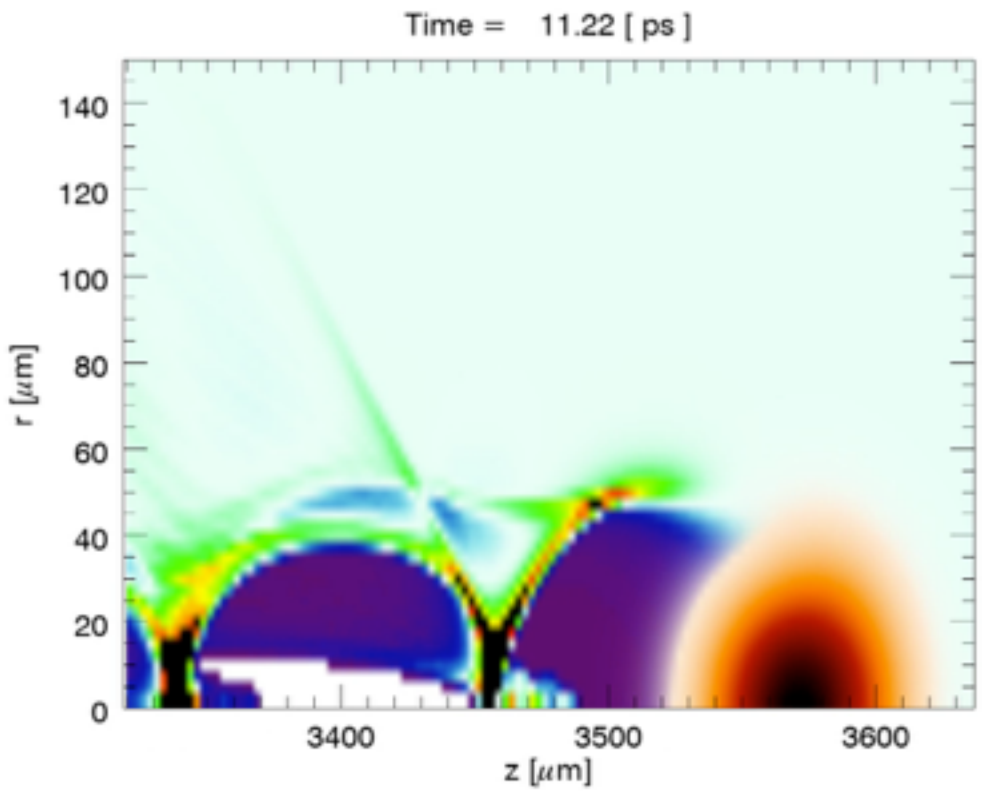
- Energy: 10 GeV
- σ_r ~ 10's μm (~1 c/ω_p)
- σ_z ~10's μm (a few c/ω_p)
- n_b/n_0 ~ 1

CERN self-modulated proton driven wakefields

- Energy: 500 GeV
- σ_r ~100's μm (less than 1 c/ω_p)
- σ_z ~10 cm (a few 100's c/ω_p)
- n_b/n_0 ~ 10^{-2}

Plasma wakefields at SLAC

strongly nonlinear blowout regime



ion motion is absent within the first few plasma wavelengths

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Ion motion at SLAC FACET

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Regimes differ drastically

SLAC electron and plasma parameters

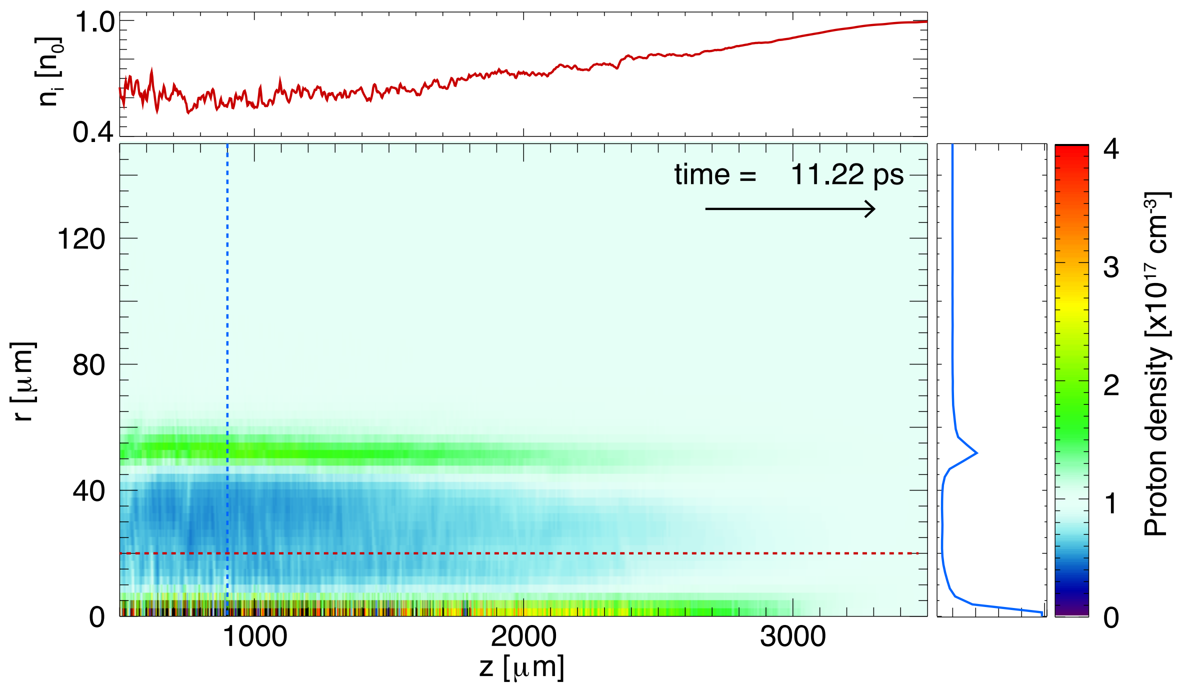
- Energy: 20 GeV
- $\sigma_r \sim$ 10's μm (a few c/ω_p)
- $\sigma_z \sim$ 10's μm (a few c/ω_p)
- $n_b/n_0 \sim 1$

CERN self-modulated proton driven wakefields

- Energy: 500 GeV
- $\sigma_r \sim$ 100's μm (less than 1 c/ω_p)
- $\sigma_z \sim$ 10 cm (a few 100's c/ω_p)
- $n_b/n_0 \sim 10^{-2}$

Plasma wakefields at SLAC

deep ion channel formation over the entire plasma length



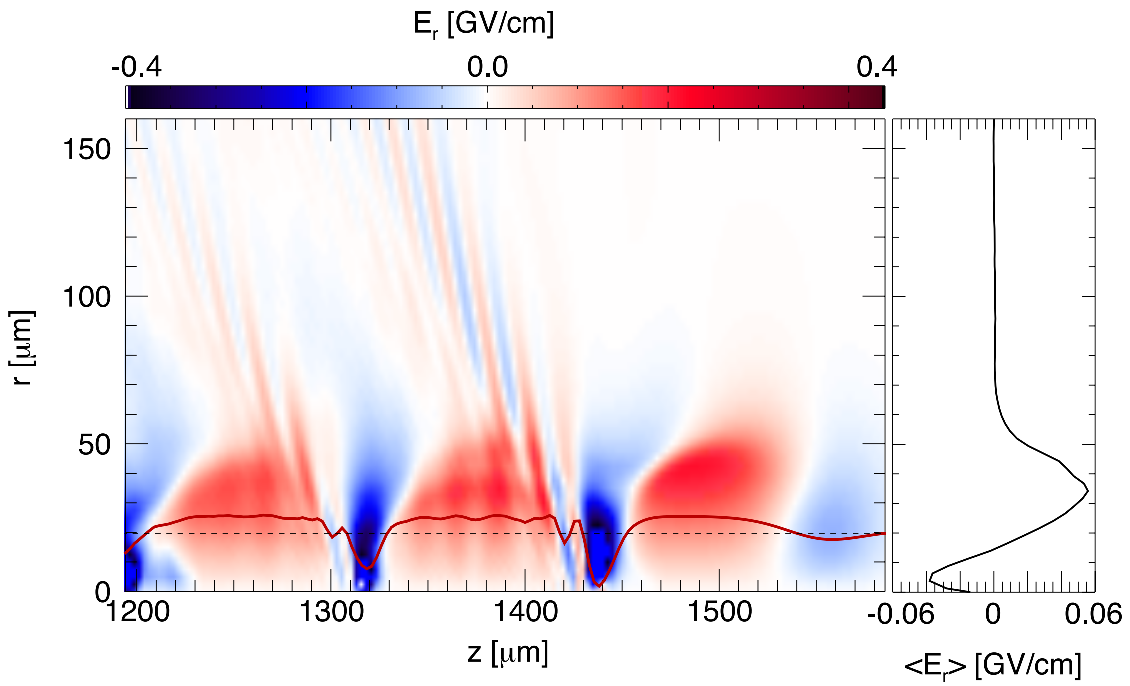
- ion filament on axis
- near hollow plasma channel
- ion structures similar to proton driven wakefield case

T. Silva *et al.* (2017)

Onset of the ion motion

Evolution of the ion density

Radial electric fields are strongly nonlinear

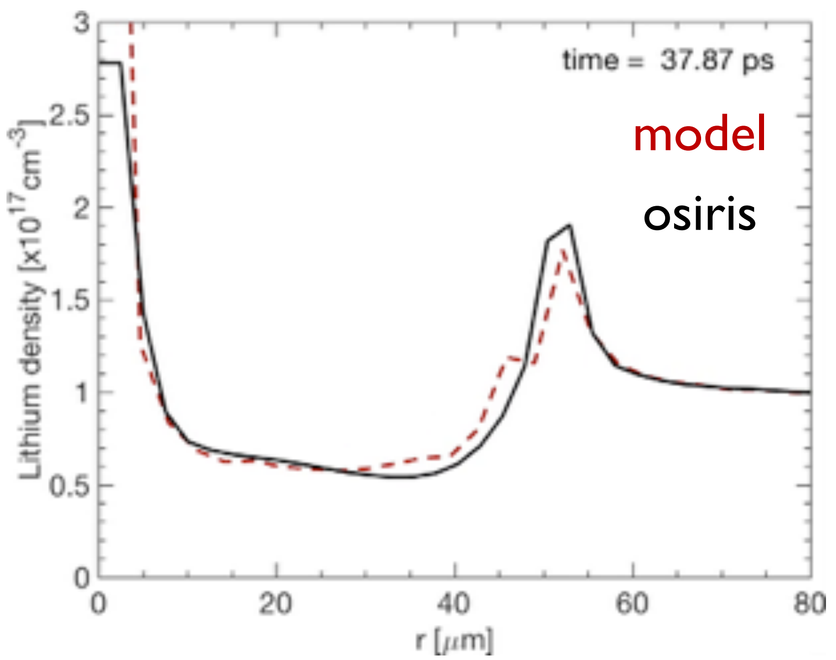


the average $\langle E_r \rangle \neq 0$ drives the ion motion

Numerical model

advance particles with average radial electric field

$$m_i \frac{d^2 r_i}{dt^2} = eZ\langle E_r \rangle$$



Key structures:

- generation of nearly hollow channel off-axis
- plasma filament on-axis

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Expansion dynamics

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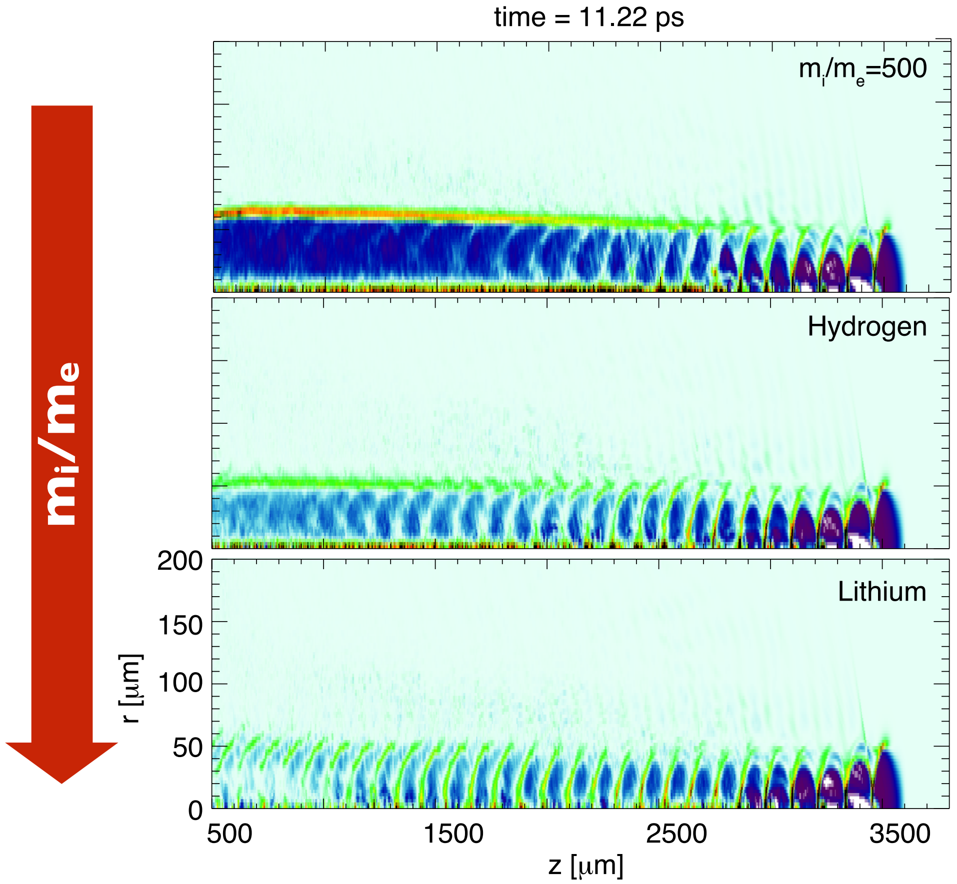
Expansion velocity - wave breaking

ion expansion velocity is related
to the onset of wave breaking



- T_{W-B} dominated by ion motion time (lower mass ratios)
- T_{W-B} due to nonlinear e- oscillations (higher mass ratios)

Late times - shock(shell) formation

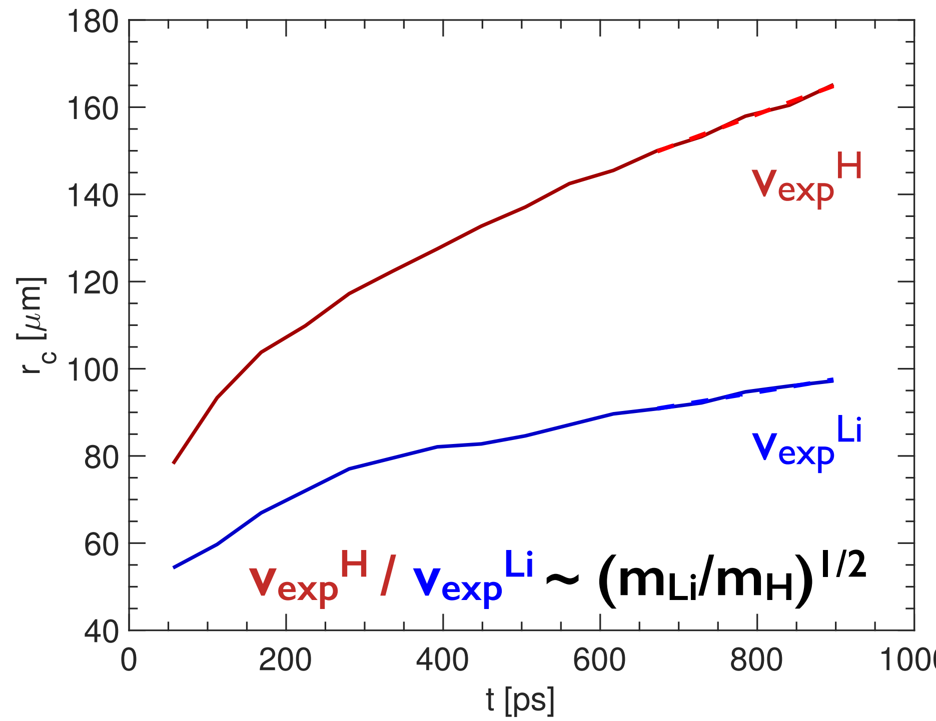
When wave breaking is
dominated by the ion motion:

$$T_{W\text{-}B} \sim (m_i/m_e)^{1/2}$$

Ion expansion velocity estimate:

$$v_{exp} \sim \langle E_r\rangle (m_e/m_i) T_{W\text{-}B} \sim \langle E_r\rangle (m_e/m_i)^{1/2}$$

Simulations



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Expansion dynamics

Expansion velocity - wave breaking

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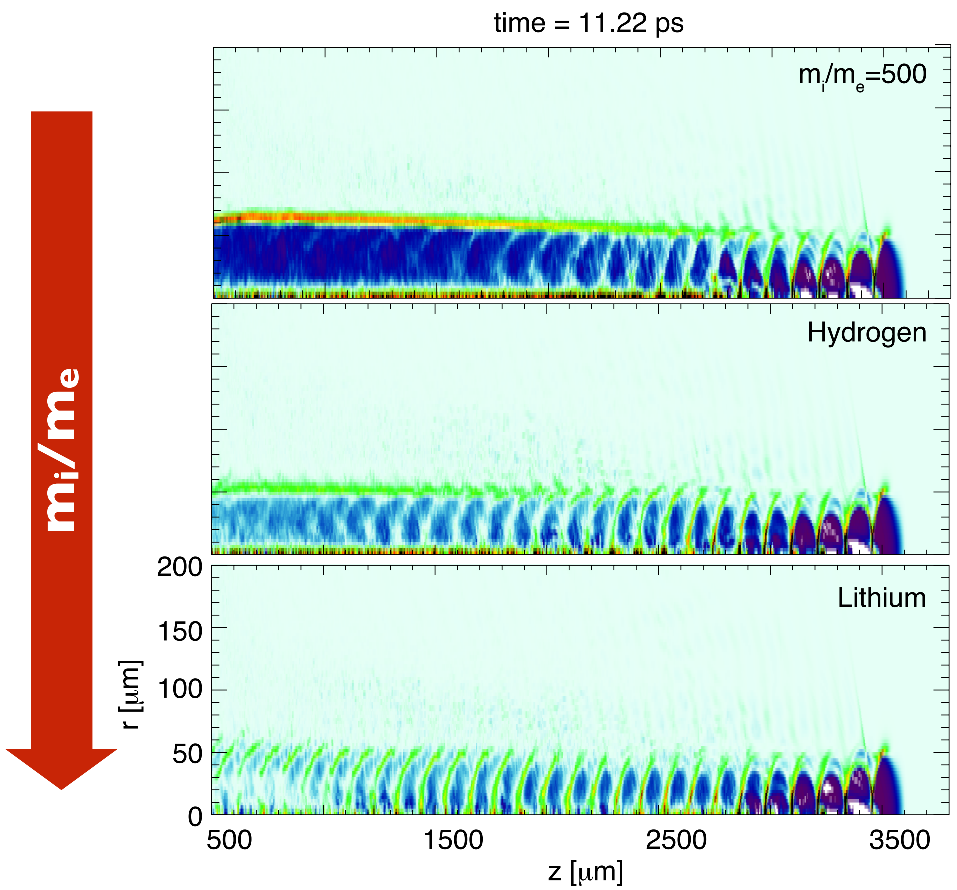
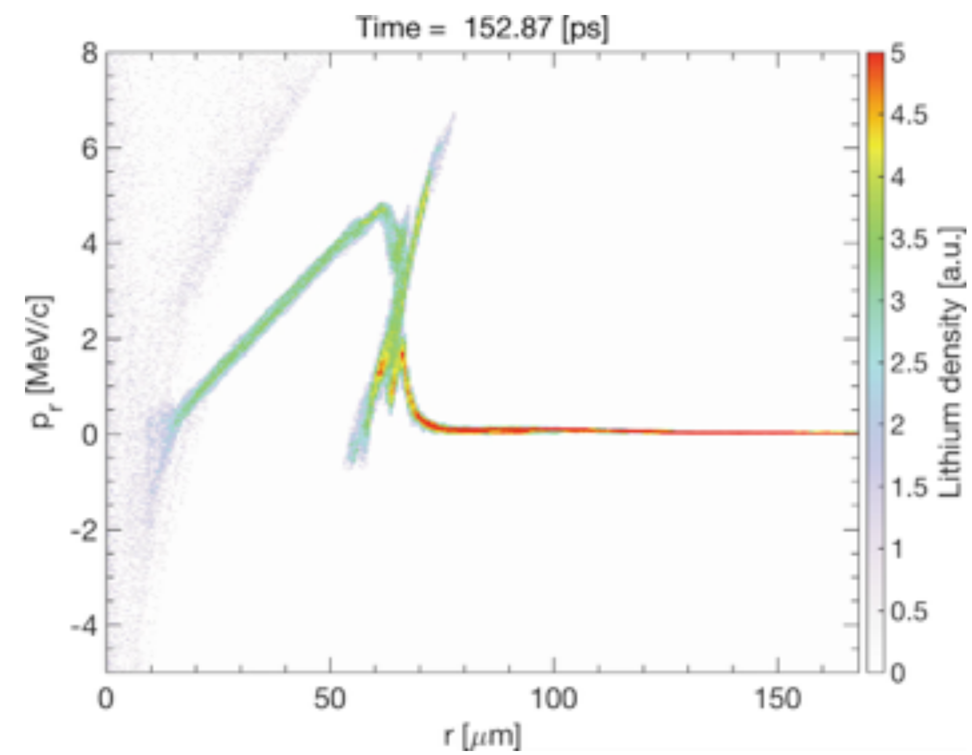


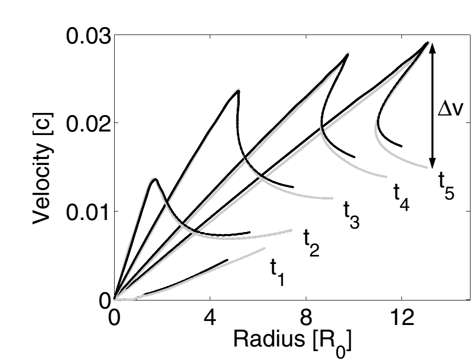
- $T_{W\text{-}B}$ dominated by ion motion time (lower mass ratios)
- $T_{W\text{-}B}$ due to nonlinear e- oscillations (higher mass ratios)

Late times - shock(shell) formation

gradual steepening of ion phase
space results in a shock structure



may be similar to the explosion of clusters
[F. Peano *et al.*, PRL **94** 033401 (2005).]



T. Silva *et al.* (2017)

Experiments at SLAC FACET

ion expansion times are at the ns time scales for Hydrogen and Lithium consistent with theory and simulations

Hydrogen

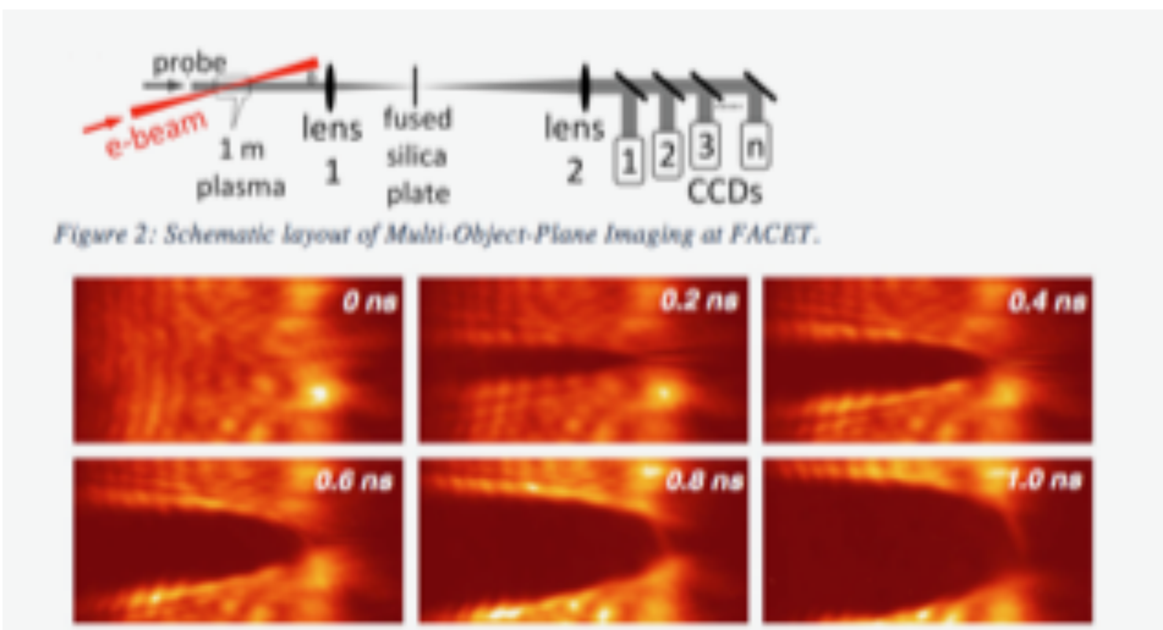
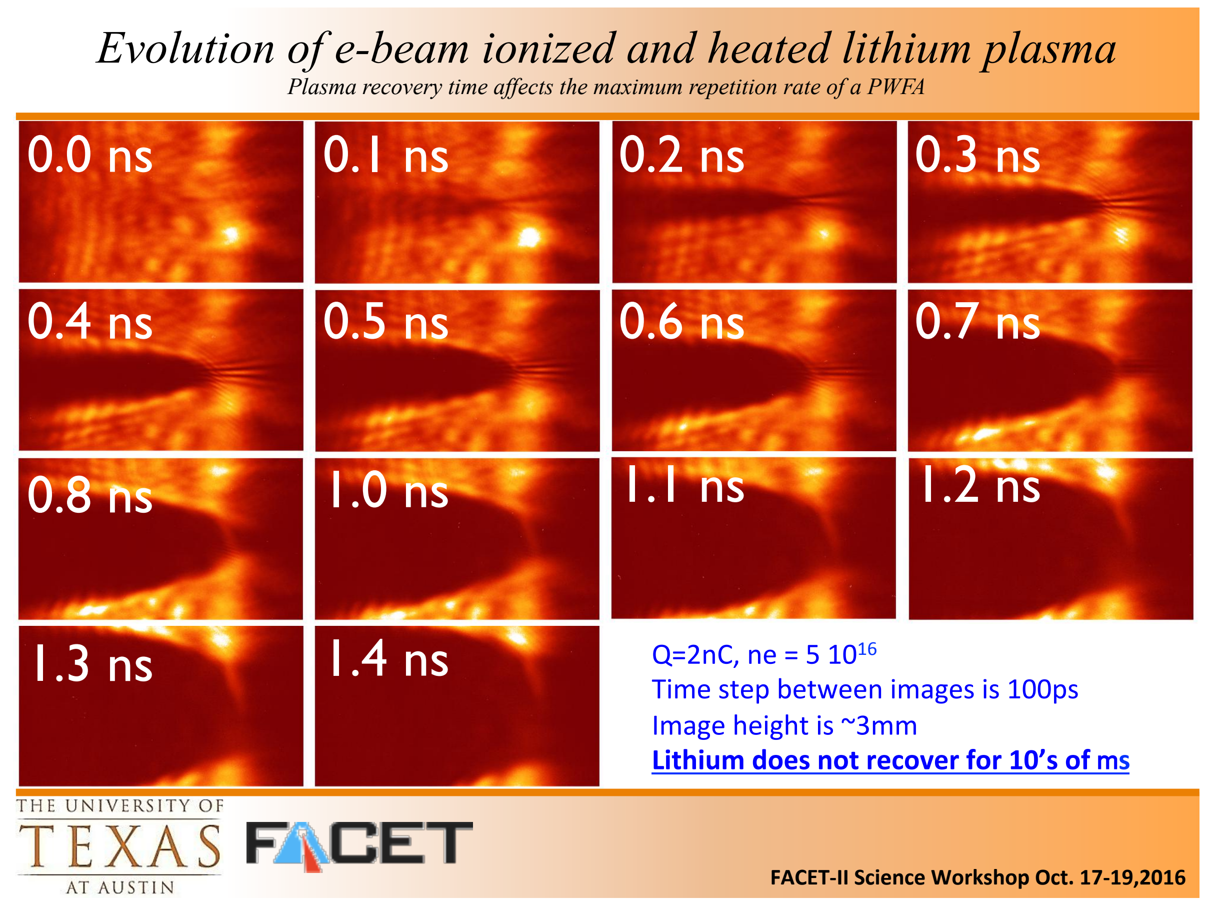


Figure 2: Schematic layout of Multi-Object-Plane Imaging at FACET.

Figure 3: Images of ion wakes in H-plasma after passage of SLAC's 20 GeV e-bunch. These were measured with the E224 experiment.

Lithium



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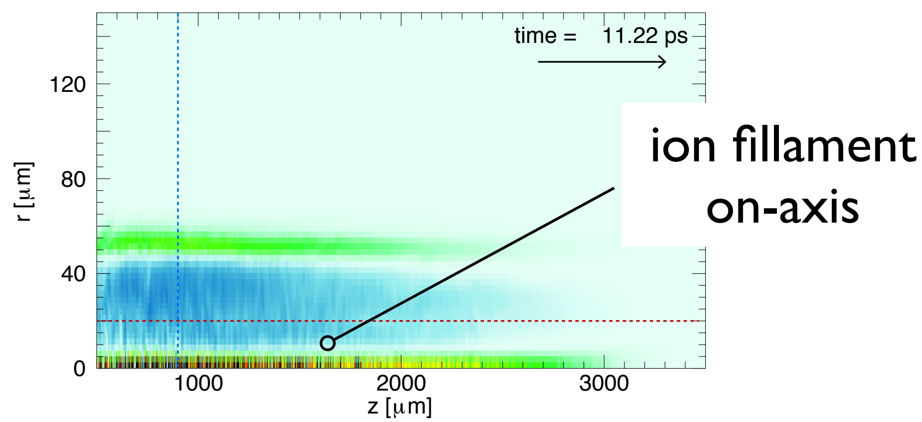
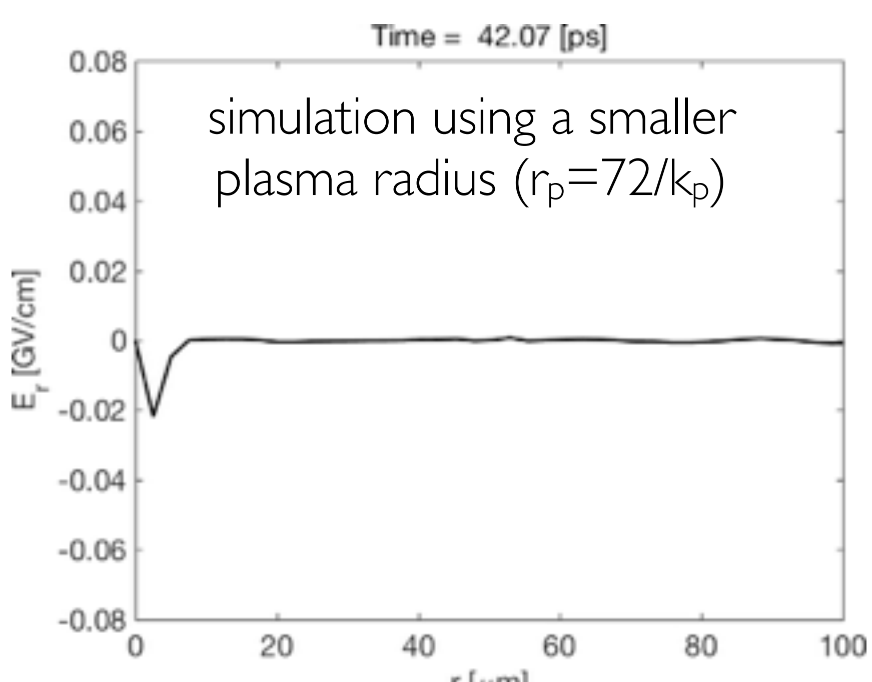
Formation of the on-axis plasma filament

Confinement of on-axis ion filament

stability of the on-axis plasma filament

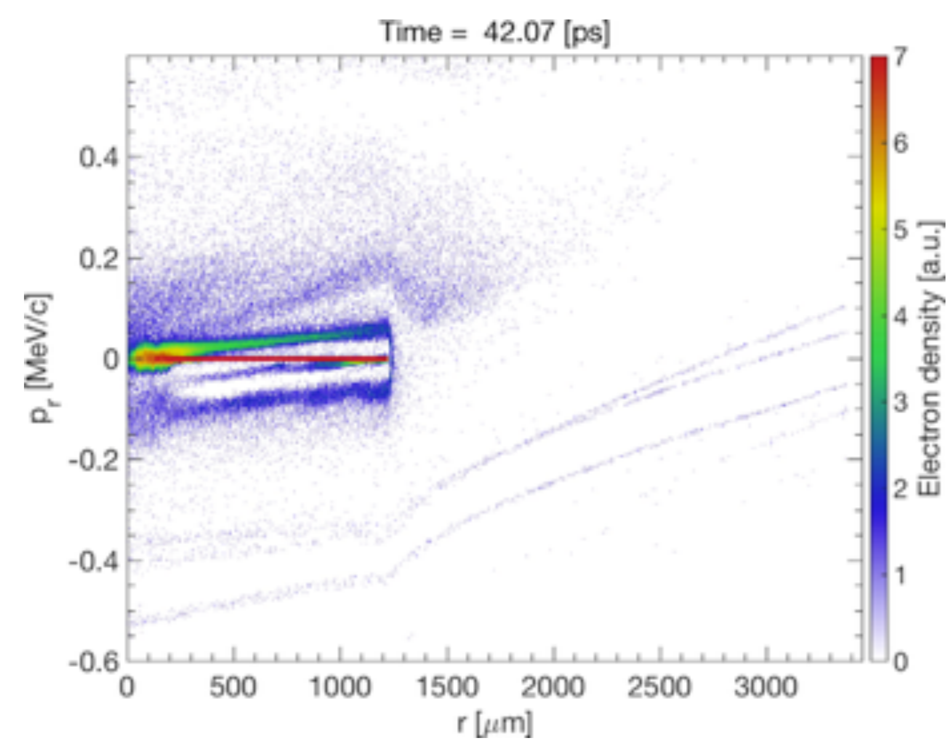


on-axis negative electric field may prevent on-axis ion filament defocusing



Electron re-circulation

electron phase-space distribution shows electron recirculation around the plasma



on-set of on-axis electric field coincides with electron recirculation around the plasma

T. Silva *et al.* (2017)

Outline

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- Ion motion in the proton driven plasma wakefield accelerator
- Ion motion in the nonlinear blowout regime
- Conclusions & future directions

Conclusions and future directions

Ion motion due to average radial plasma electric field

In the self-modulated wakefield accelerator the ion motion suppresses the instability and acceleration

In the plasma wakefield accelerator the ion motion can limit the maximum repetition rate

Future work

- effect of the plasma radius on the stability of the on-axis ion filament
- late time evolution of the ion channel expansion

Thank you!