Long term wake evolution: heating & ion wakes

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OSIRIS 3.0

osiris framework

- Massively 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
Ion motion in plasma wakefield accelerators

**Long drivers**

- self-modulated proton driven wakefield accelerator
- important when beam length ($\sigma_z$) is comparable to ion skin depth ($c/\omega_{pi}$)
- 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.

Jorge Vieira | FACET ii Science workshop, SLAC | October 19, 2017
Outline

- 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 \( \sigma_z = 10 \text{ cm} \) long
- plasma density is \( n_0 \sim 10^{14}-10^{15} \text{ cm}^{-3} \)
- For a hydrogen plasma: \( \sigma_z = 2-7 \text{ ion skin-depths} \)
Stable, hosing free self-modulation of long particle bunches

Self-modulated particle bunch beamlets

J. Vieira et al. PRL 112 205001 (2014)
AWAKE experiment at CERN
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**Experimental setup**

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**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

How do ions move?

J. Vieira et al. PRL 109 145005201 (2012)
# Model for the ion motion in narrow wakefields

### Evolution of the ion density

**Ion motion equation (momentum+continuity eqs)**

\[
m_i \left[ c^2 \frac{\partial^2}{\partial \xi^2} - c_s^2 \nabla^2 \right] n_i = -n_0 Z \nabla \cdot F_p
\]

- speed of light frame: \(\xi = x-ct\)
- \(F_p \perp \gg F_p ||\) since \(\sigma_z \gg \sigma_r (\partial_r \gg \partial_z)\)
- ions move radially: \(F_p = <E_\perp>\)
- Neglect temperature \((c_s = 0)\)

**Simplified model for ion response**

\[
m_i c^2 \frac{\partial^2 n_i}{\partial \xi^2} = -\frac{n_0 Z e^2}{4 m_e \omega_p^2} \nabla^2 <E_r>^2
\]

\(\hat{E}_r\) is the envelope of the plasma radial electric field

### Analytic formulas at early times

**Leading order expansion \(O(\xi^3)\)**

\[
n_i = n_{i0} \left[ 1 - \frac{Ze}{m_i c^2} \frac{\xi^2}{2} \nabla \cdot <E_r> + O(\xi^3) \right]
\]

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**

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

**Ion motion mitigation**

- electron and ion density from OSIRIS simulations
- longitudinal electric fields
- position \(\xi_{\text{crit}}\) is where the ion density becomes twice the background plasma

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

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

**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
- $\sigma_r \sim 10$’s $\mu$m ($\sim 1 \ c/\omega_p$)
- $\sigma_z \sim 10$’s $\mu$m (a few $c/\omega_p$)
- $n_b/n_0 \sim 1$

### CERN self-modulated proton driven wakefields

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

## Plasma wakefields at SLAC

- **strongly nonlinear blowout regime**

  Ion motion is absent within the first few plasma wavelengths

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T. Silva et al. (2017)
Regimes differ drastically

SLAC electron and plasma parameters

- Energy: 20 GeV
- $\sigma_r \sim 10 \text{'s} \mu\text{m}$ (a few $c/\omega_p$)
- $\sigma_z \sim 10 \text{'s} \mu\text{m}$ (a few $c/\omega_p$)
- $n_b/n_0 \sim 1$

CERN self-modulated proton driven wakefields

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

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

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

T. Silva et al. (2017)
Expansion dynamics

**Expansion velocity - wave breaking**

Ion expansion velocity is related to the onset of wave breaking.

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

**Late times - shock(shell) formation**

When wave breaking is dominated by the ion motion:

$$T_{WB} \sim (m_i/m_e)^{1/2}$$

Ion expansion velocity estimate:

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

Simulations

$$v_{\text{exp}}^H / v_{\text{exp}}^\text{Li} \sim (m_{\text{Li}}/m_{\text{H}})^{1/2}$$

T. Silva et al. (2017)
Expansion dynamics

Expansion velocity - wave breaking

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- $T_{WB}$ 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

Lithium

Evolution of e-beam ionized and heated lithium plasma

Plasma recovery time affects the maximum repetition rate of a PWFA

Q=2nC, ne = 5 \times 10^{16}

Time step between images is 100ps

Image height is ~3mm

Lithium does not recover for 10's of ms

T. Silva et al. (2017)
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

Simulation using a smaller plasma radius ($r_p = 72/k_p$)

**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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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!