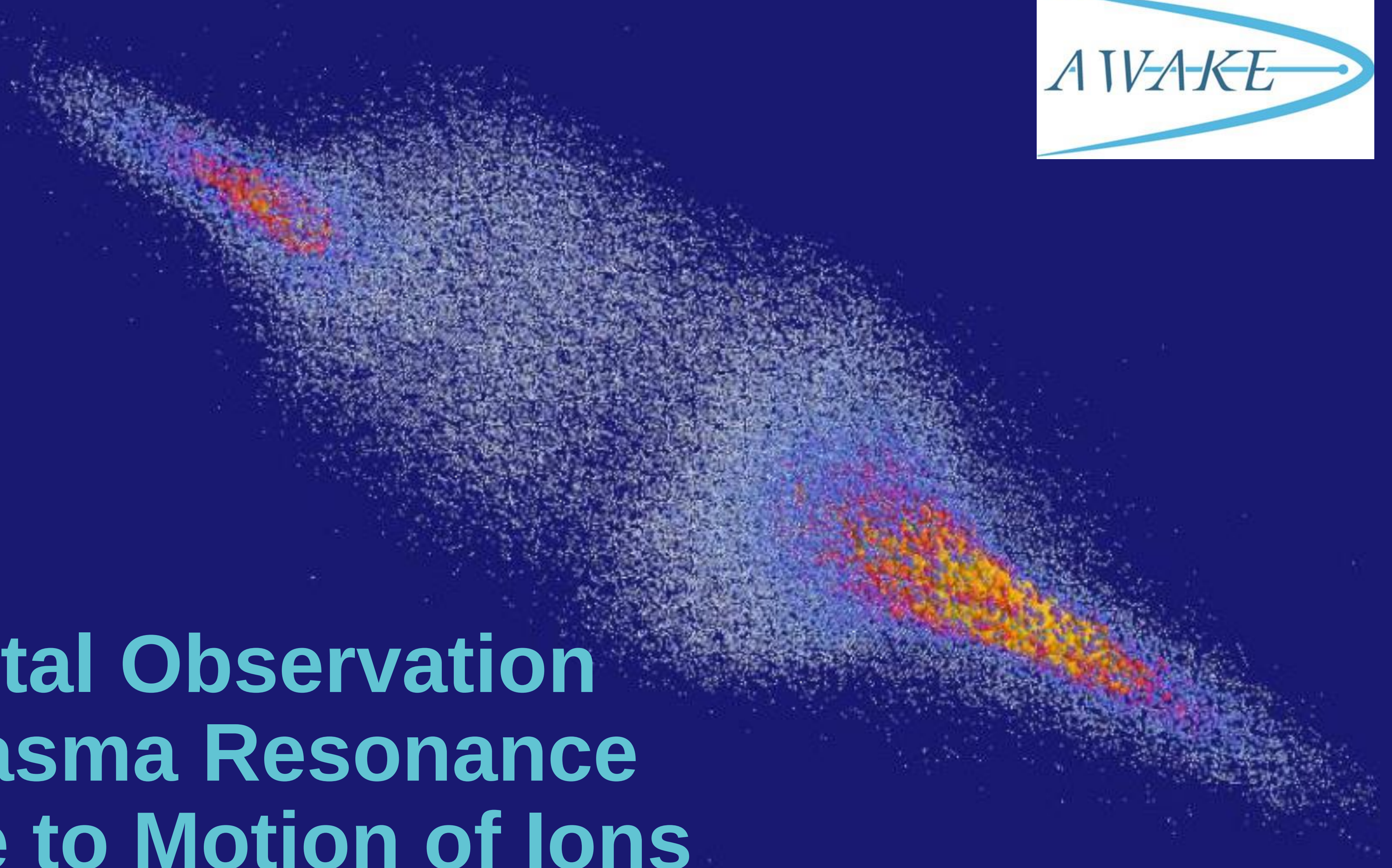


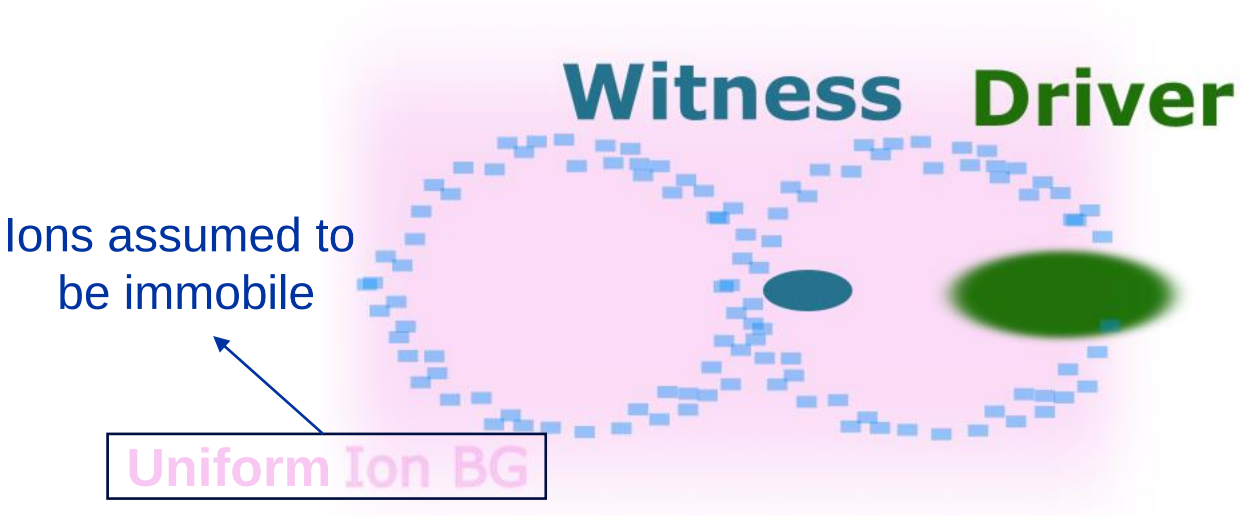
Experimental Observation of Beam-Plasma Resonance Detuning due to Motion of Ions

M. Turner, E. Walter, L. Verra, A. Clairembaud, C. Amoedo, E. Gschwendtner,
F. Pannell, G. Zevi Della Porta, J. Mezger, J. Pucek, J. Farmer, M. Bergamaschi,
N. Lopes, N.Z. van Gils, N. Torrado, A. Sublet, P. Muggli, AWAKE Collaboration

Outline

- Introduction, Previous Work
- AWAKE Experimental Setup and Results
- Scaling, Discussion
- Summary and Conclusions

Ion Motion in Plasma Wakefields



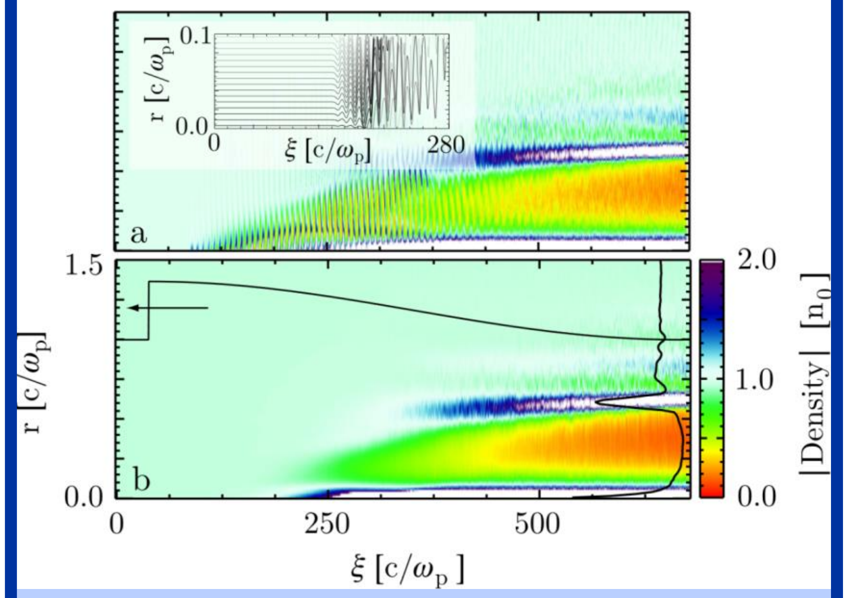
Ion motion in plasma wakefields may originate from:

1) Driver E-field (on itself or the witness)
2) Witness E-field (on itself, important for collider relevant beams)
   → Was proposed to be used to detune resonances
3) **Ponderomotive force of transverse wakefields**
   → Important when there is many oscillation periods

T. J. Mehrling, et al., Phys. Rev. Lett. 121, (2018)
C. Benedetti, et al., Phys. Rev. Accel. Beams 20, 111301 (2017)

Previous Work on Ion Motion Caused by the Ponderomotive Force

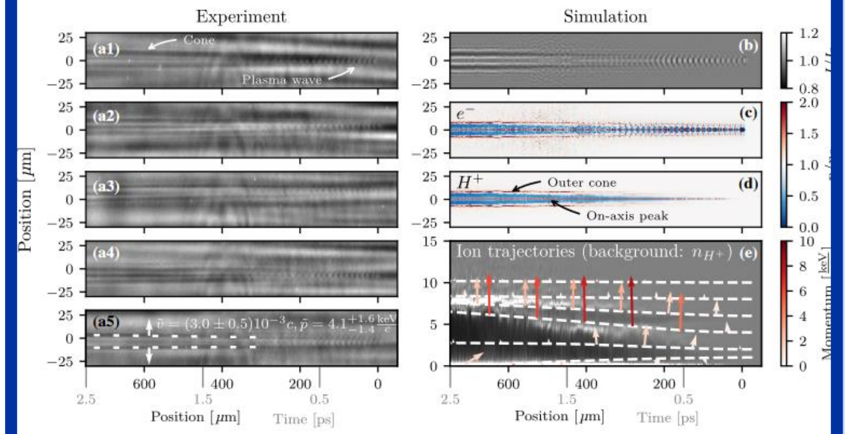
J. Vieira, et al., Phys. Rev. Lett. 109, 145005 (2012)



Ion Motion in Self-Modulated Plasma Wakefield Accelerators

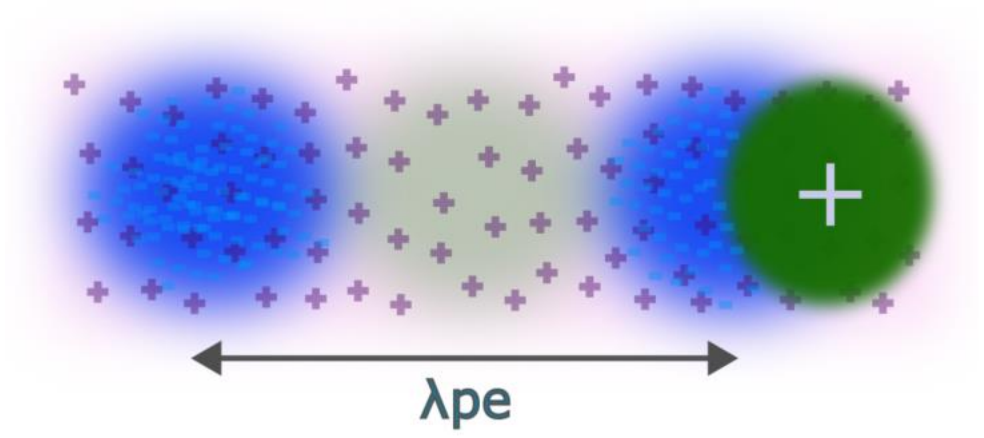
Direct Observation of Plasma Waves and Dynamics Induced by Laser-Accelerated Electron Beams

M. F. Gilljohann et al. Phys. Rev. X 9, 011046 (2019)



→ Observed cone like features due to ion motion after the passage of dense beams

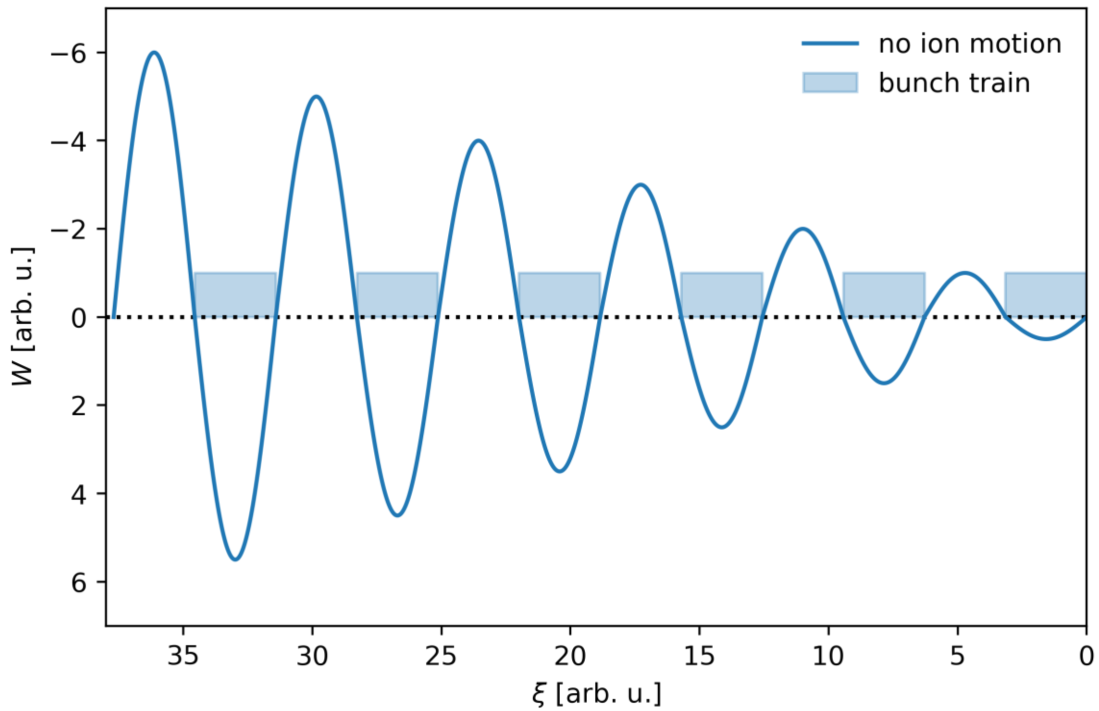
Ion Motion Effects on Plasma Wakefields



Ion column provides restoring force that leads to:

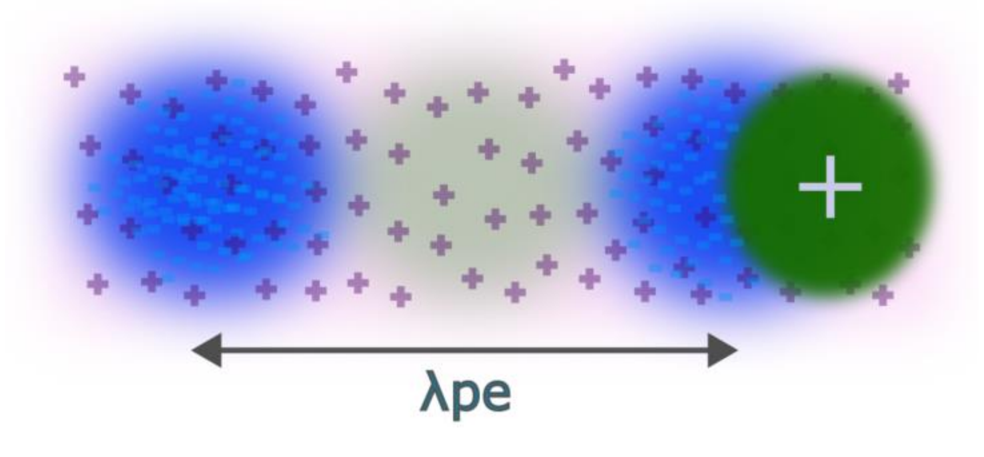
- Coherent electron oscillations
- Hosing

When ion motion becomes significant, there is a local change in:
→ Ion density → Restoring force → Electron motion (plasma and witness)

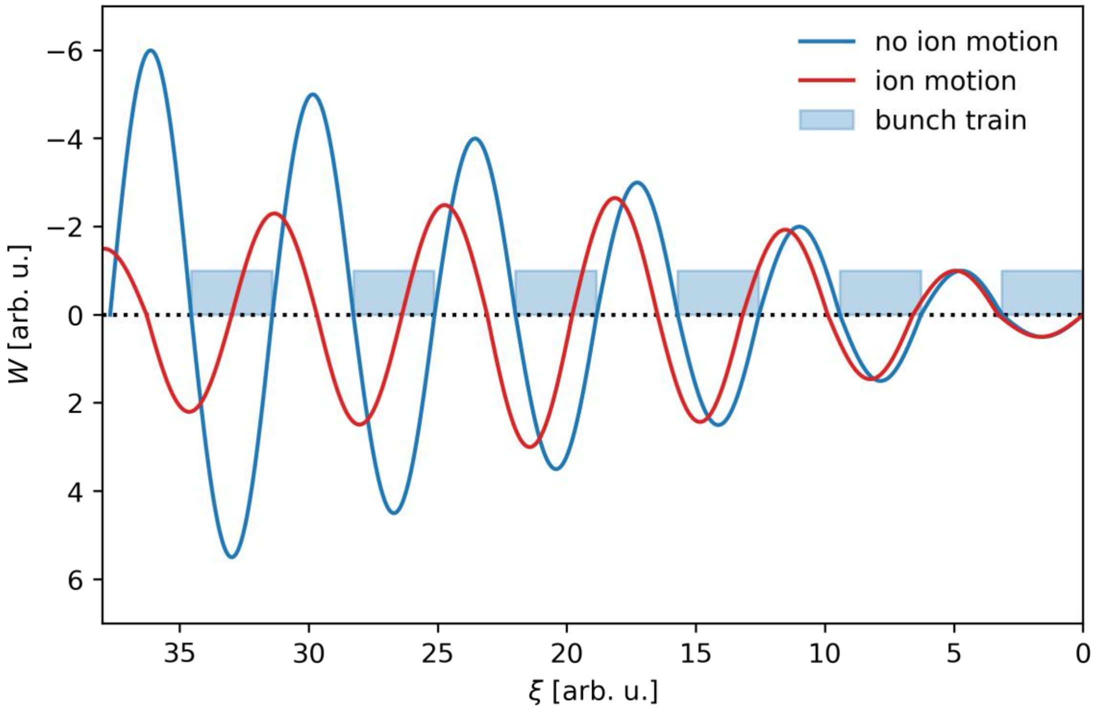


→ Especially important for wakefields accelerators driven resonantly

Ion Motion Effects on Plasma Wakefields



Simplistic picture, reality is more complex.



Plan: change the ion mass and wakefield strength in the experiment to see if the effect can be observed in a wakefield accelerator driven resonantly with multiple bunches.

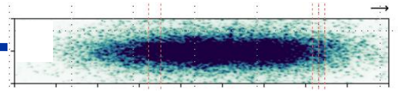
Experimental Setup

Experiments were performed at the **AWAKE facility**

See Plenary Talk from E. Gschwendtner Tuesday

See Talk from A. Sublet in WG 8, Wed 17:45
Poster from C. Amoedo and N. Torrado, WG 8

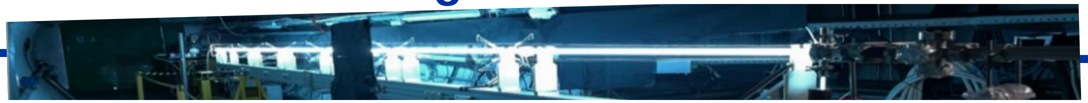
Driver



$n_b << n_{pe}$

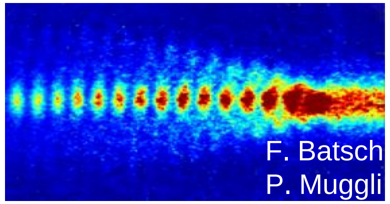
N_b = 3e11 protons / bunch,
σ_z = 185 ps, σ_r ~ 150 um,
E_b = 400 GeV, provided by CERN SPS, E_t=19 kJ
Rep. rate: every ~25 s

Discharge Plasma Source



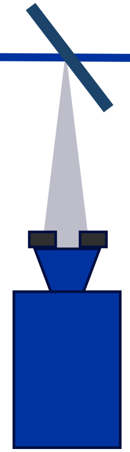
L = 10 m, r = 2.5 cm
n_{pe} = 0.1-10^{15} / cm^{-3}

SMI development, formation of bunch train



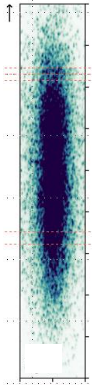
Resonant wakefield excitation

Diagnostic



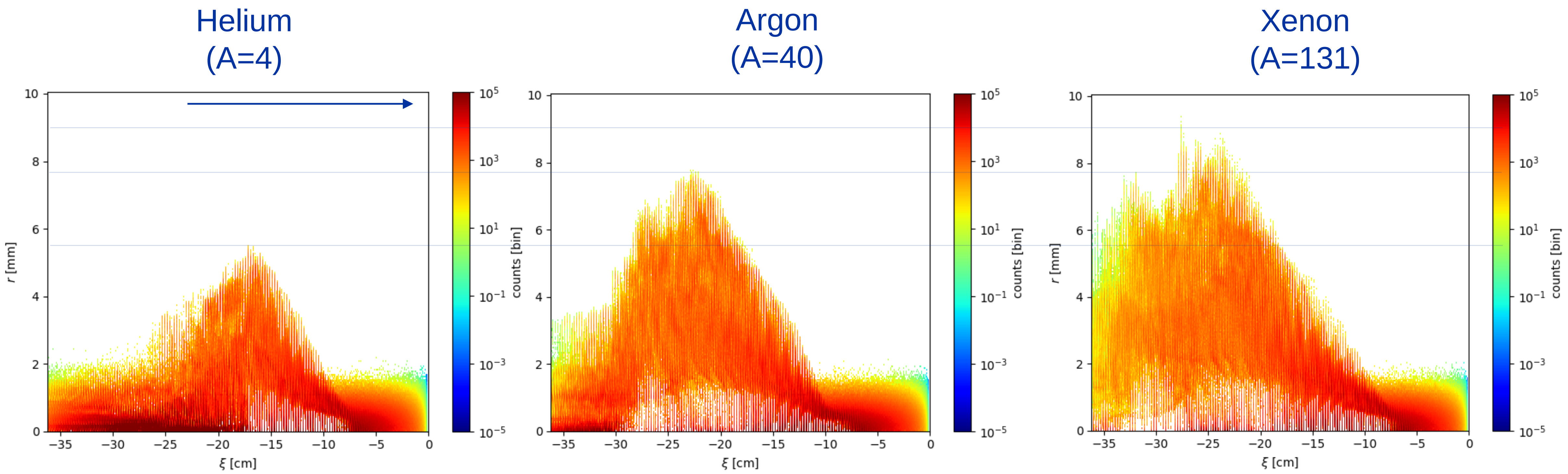
Slit

Streak camera (ps time-resolution)



Gas Species Affects SMI Development

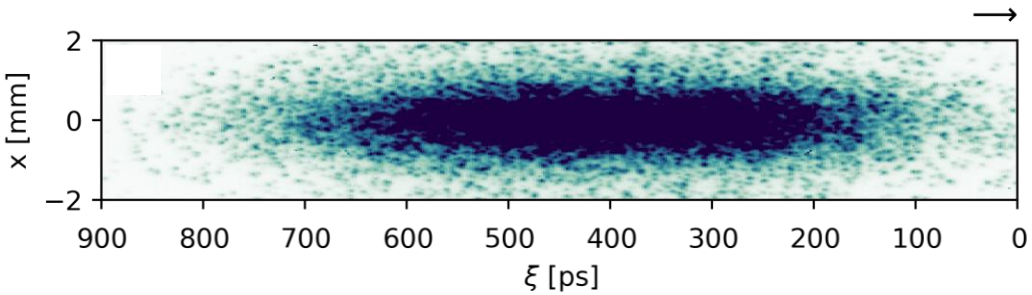
LCODE Simulation Results



- Higher ion mass allows for **longer wakefield growth** along the bunch and higher field amplitudes at large xi
- Experimental signature on the streak camera: longer bunch trains for higher ion masses, appearance of a **bunch tail** when ion motion becomes significant

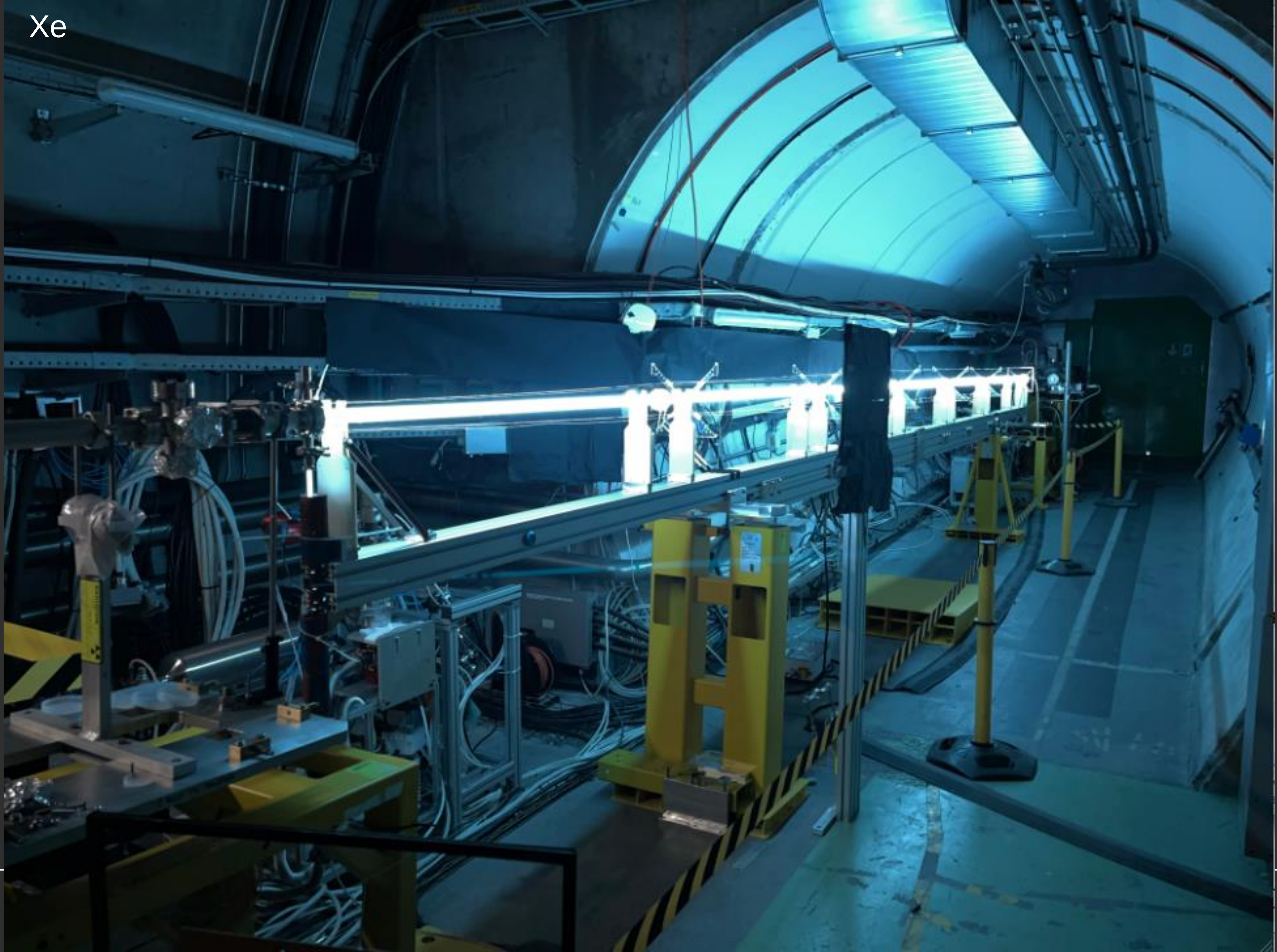
Experimental Results
Streak Camera Measurements

No Plasma



3.5 m of vacuum propagation downstream the plasma exit.
Approximately Gaussian in longitudinal and transverse direction

Xe



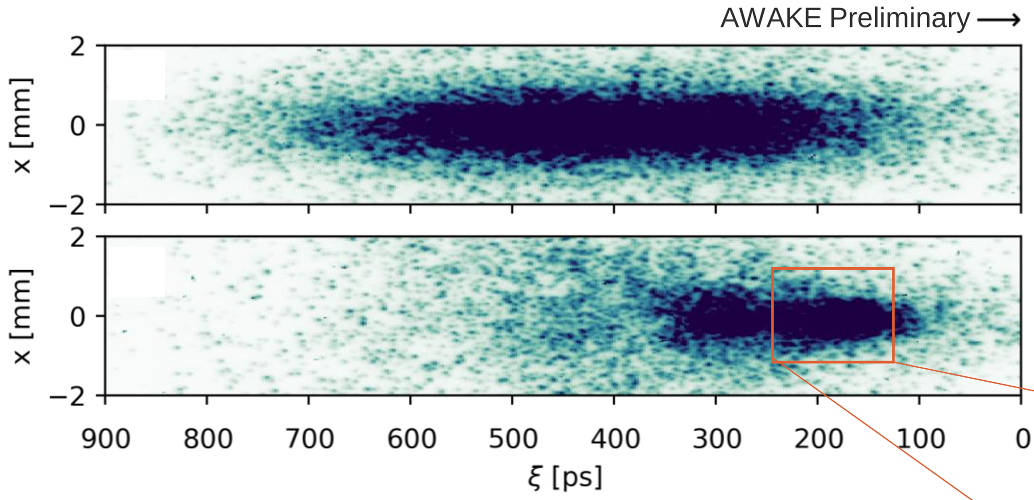
Xe
A = 131

Experimental Results

Streak Camera Measurements

No Plasma

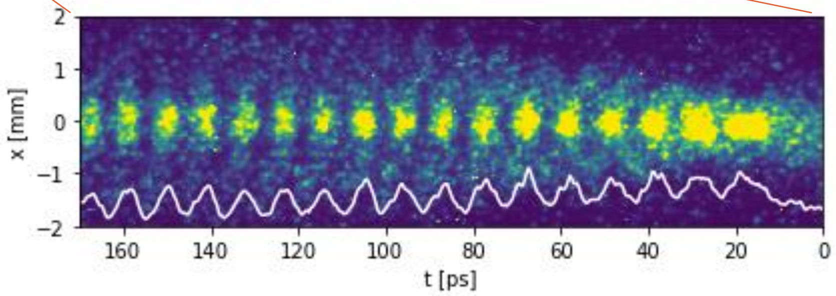
Xenon



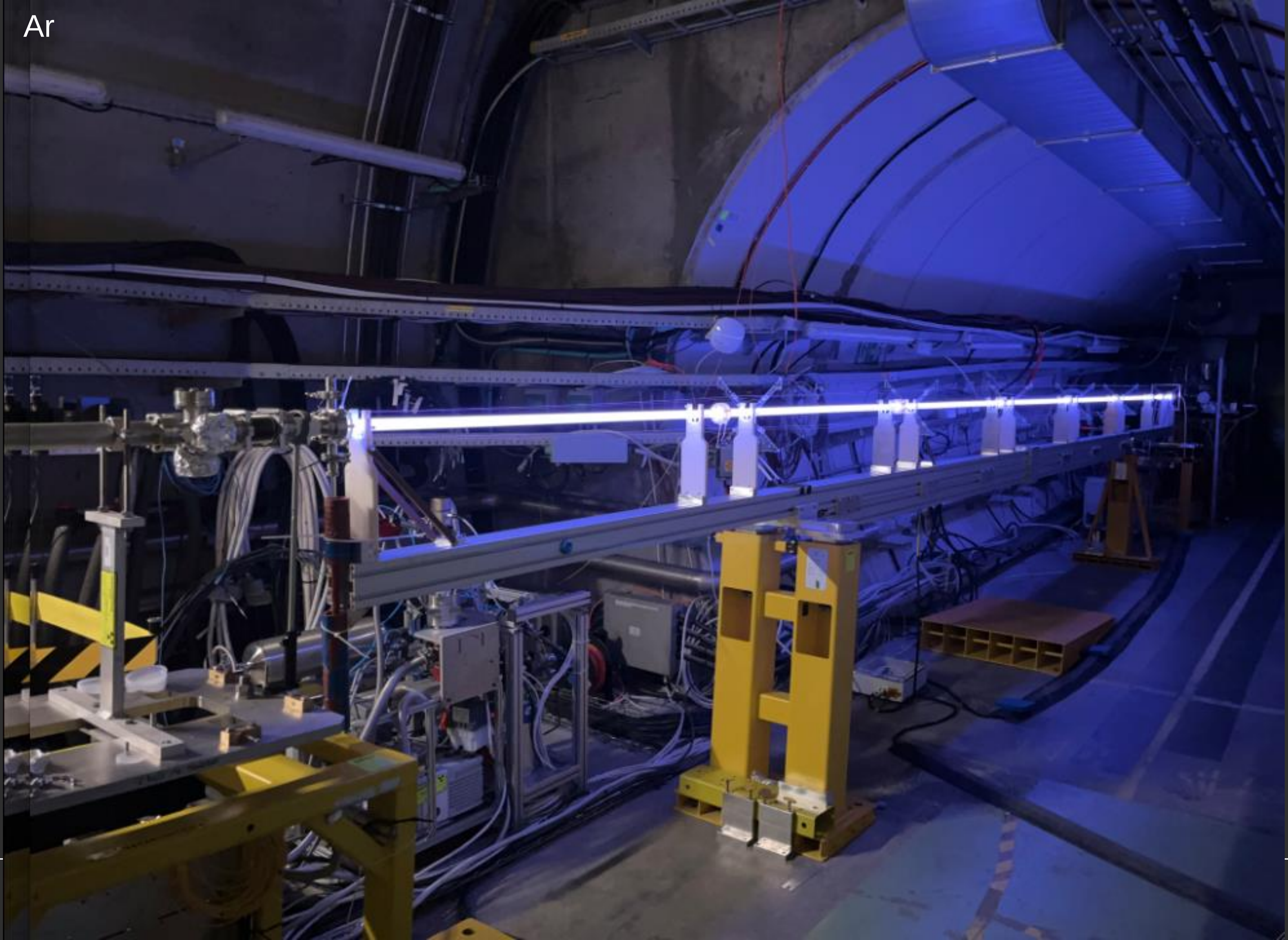
n_p = 3 x 10^{11} protons per bunch

n_{pe} = 4.8 x 10^{14} cm^{-3}

Measurement shows typical successful self-modulation on the ns scale



- Growth along the bunch, stronger wakefields lead to stronger focusing and defocusing
- Larger focusing wakefields lead to larger divergence downstream of the plasma exit.



Ar
(A=40)

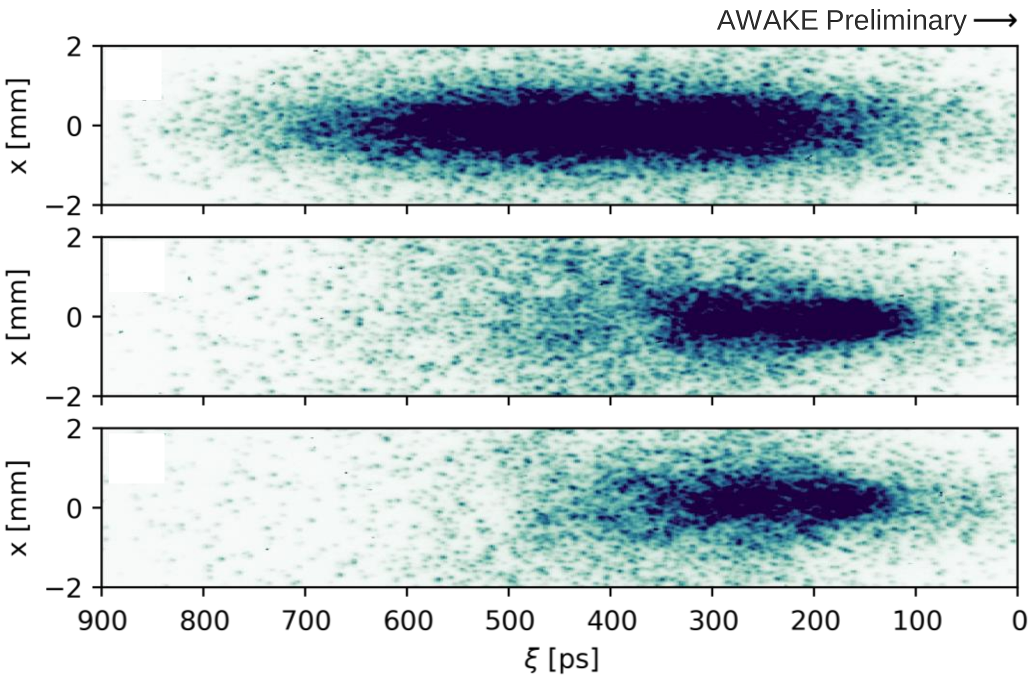
Experimental Results

Streak Camera Measurements

No Plasma

Xenon

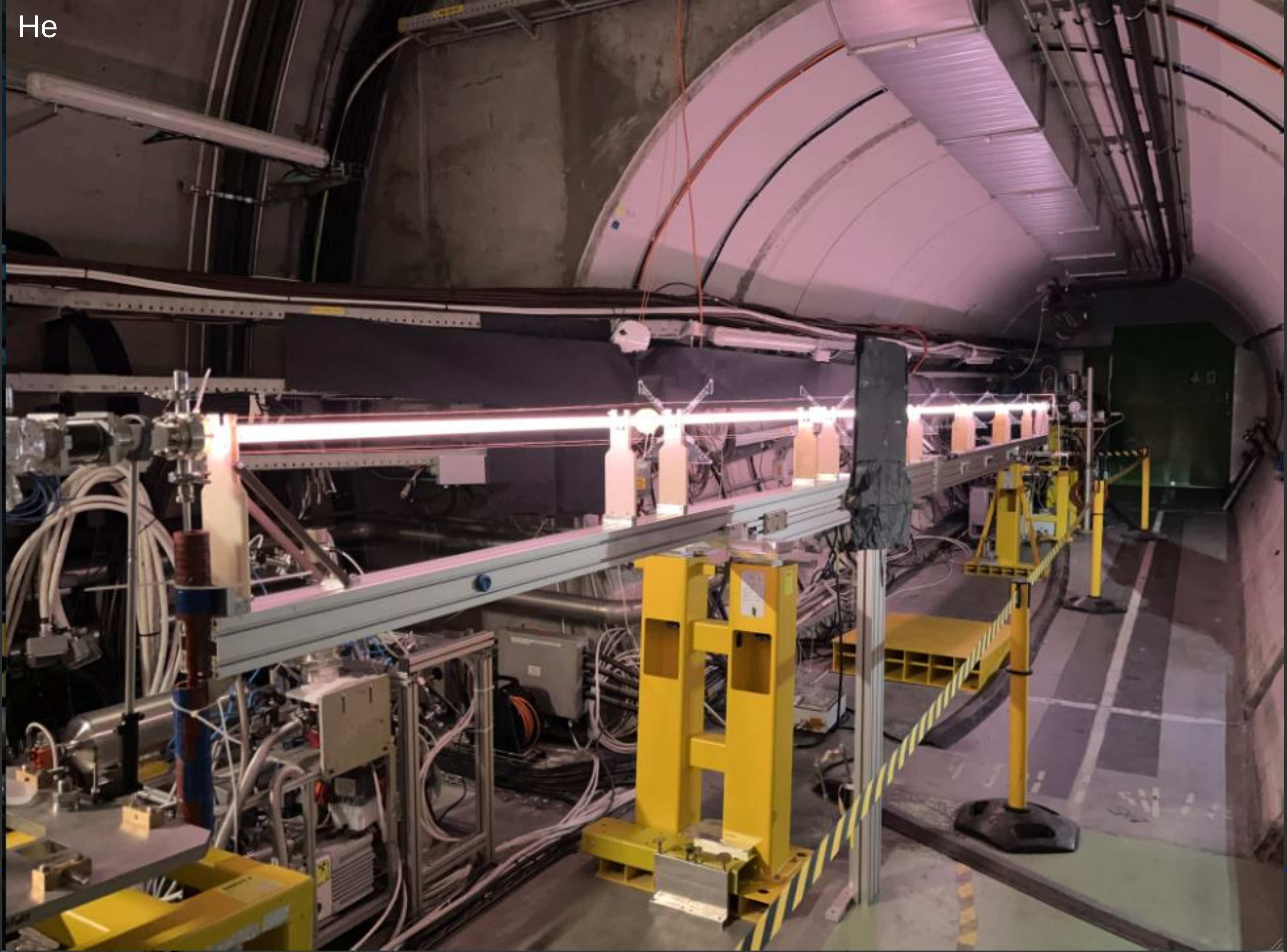
Argon



n_p = 3 x 10^{11} protons per bunch

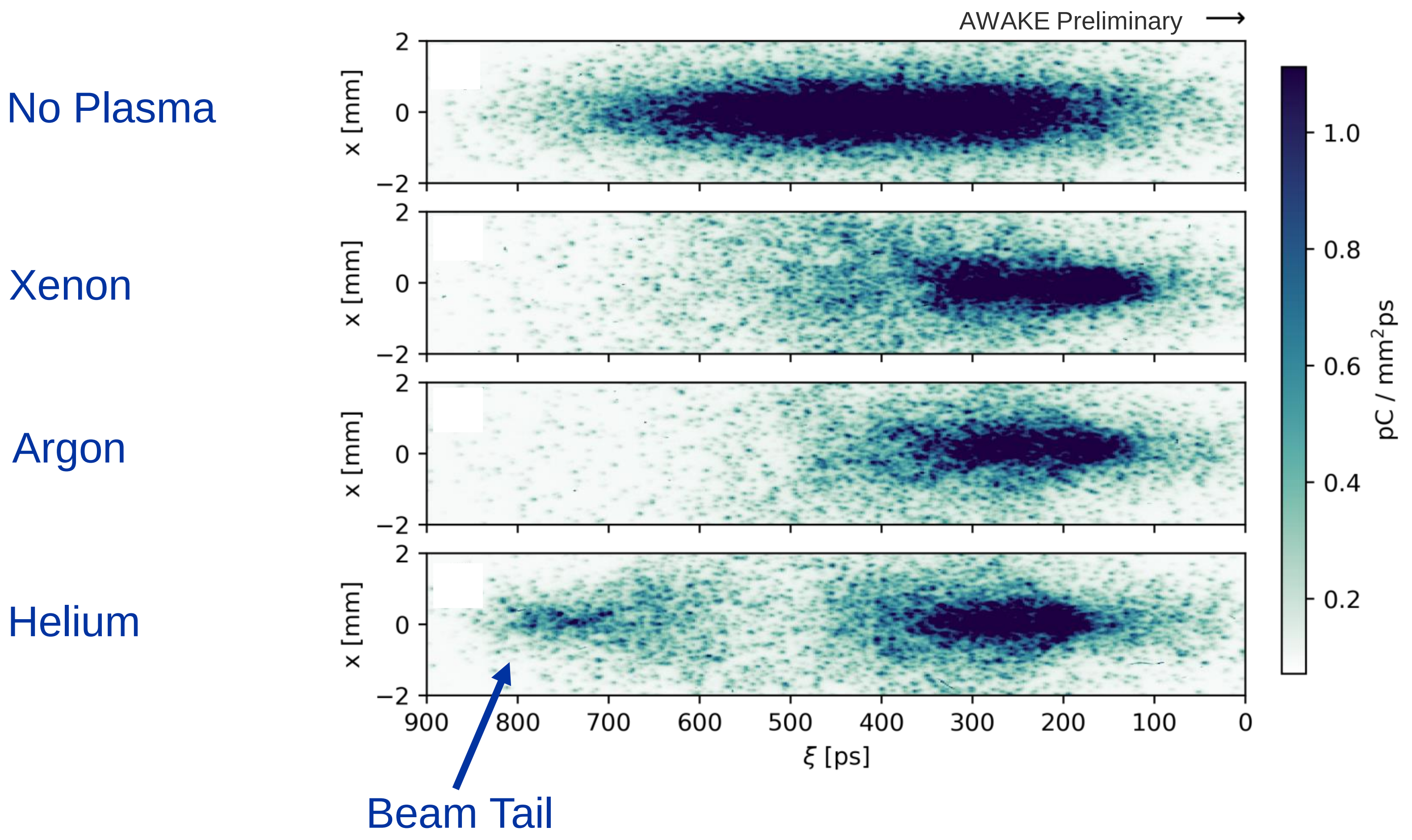
n_{pe} = 4.8 x 10^{14} cm^{-3}

- Single event measurements
- Measurements using Xenon and Argon plasma agree



He
(A=4)

Experimental Results
Streak Camera Measurements



n_p = 3 x 10^{11} protons per bunch

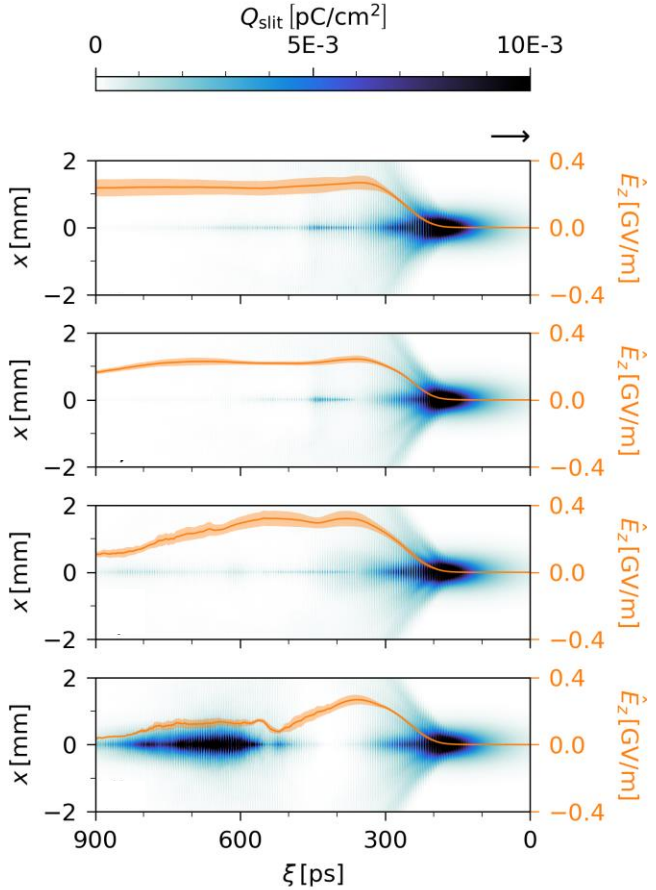
n_{pe} = 4.8 x 10^{14} cm^{-3}

- Appearance of a beam tail (increase of proton bunch charge later along the bunch) when using Helium.

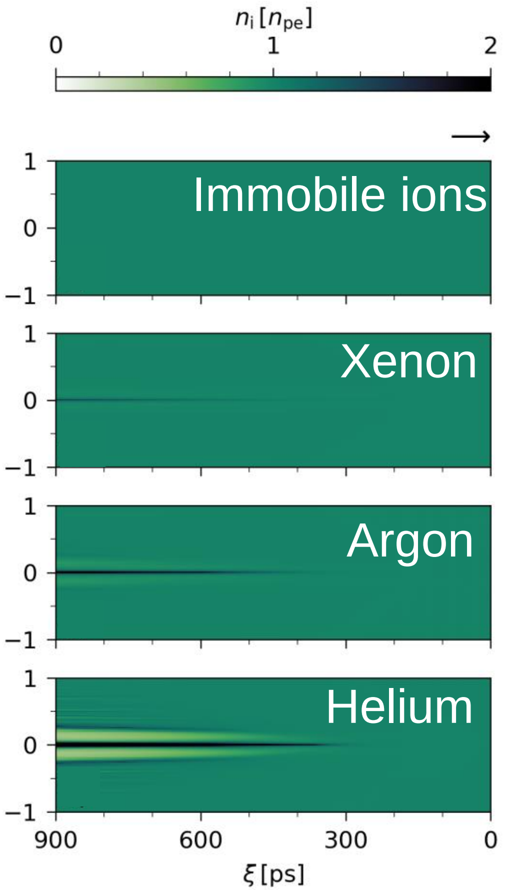
Simulation Results
LCODE

Simulations performed by E. Walter

Proton bunch density propagated to the streak camera location



Ion density @ 10m



Ponderomotive force of the wakefields causes ion motion → more significant later in the bunch (more time and higher wakefield amplitudes)

Two ways ion motion affects the wakefields:

Locally reduced ion density leads to longer oscillation period (less restoring force)

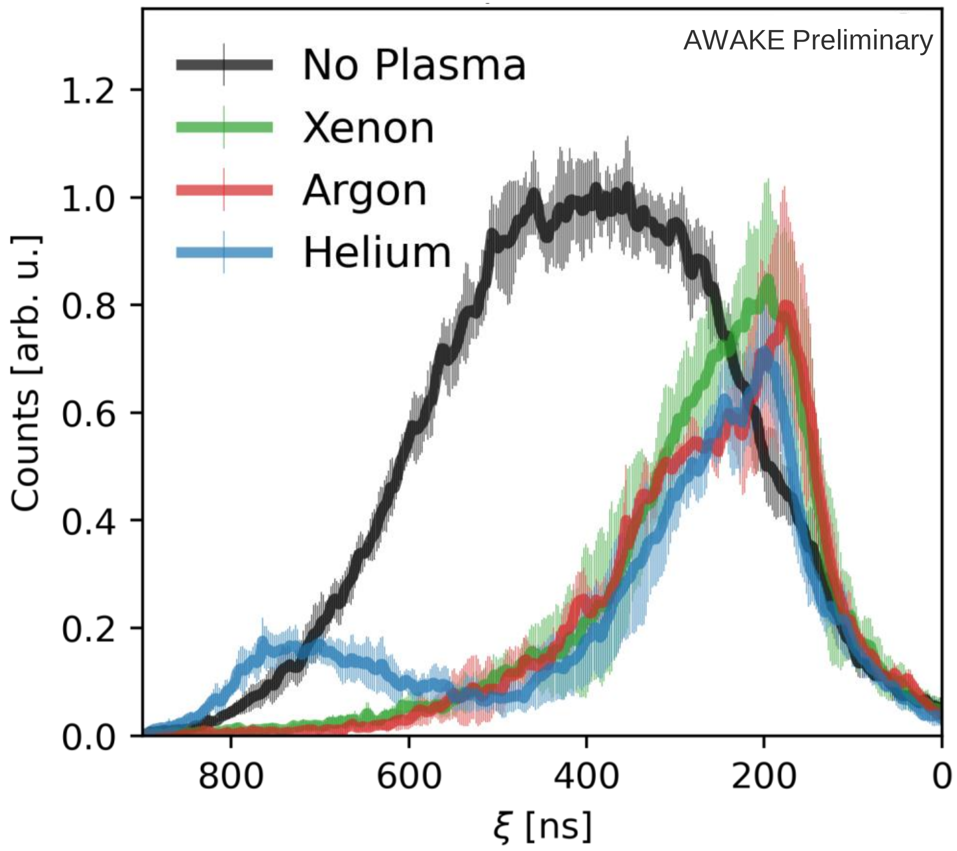
Radially varying ion density leads to radially varying restoring force

→ Decrease in wakefield amplitude due to decoherence later along the bunch

→ Hosing: also caused by the uniform focusing force from the ion column, proposed solution, detuning of resonance by ion motion

Comparison of Different Ion Species

Average of ~10 measurements and standard deviation



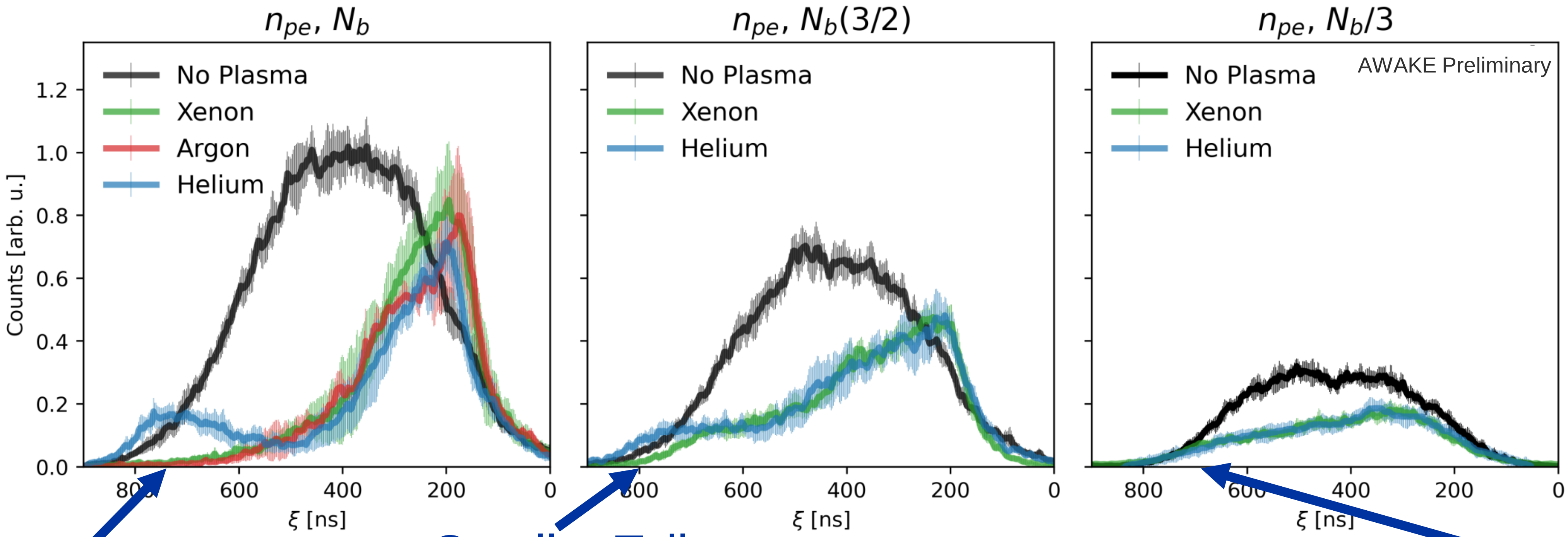
- Measured proton bunch density after propagation in Xenon and Argon Plasma (same n_{pe}) agree within the uncertainty
- Measurements using Helium agree for $\xi < 550$ ps
- Visible beam tail for $\xi > 600$ ps

To experimentally change the wakefield amplitude, we can change the:

1) proton bunch population
2) plasma electron density

Charge in Beam Tail Decreases with Lower Wakefield Amplitude

Lower bunch population → 1) lower SMI seed and 2) SMI growth rate



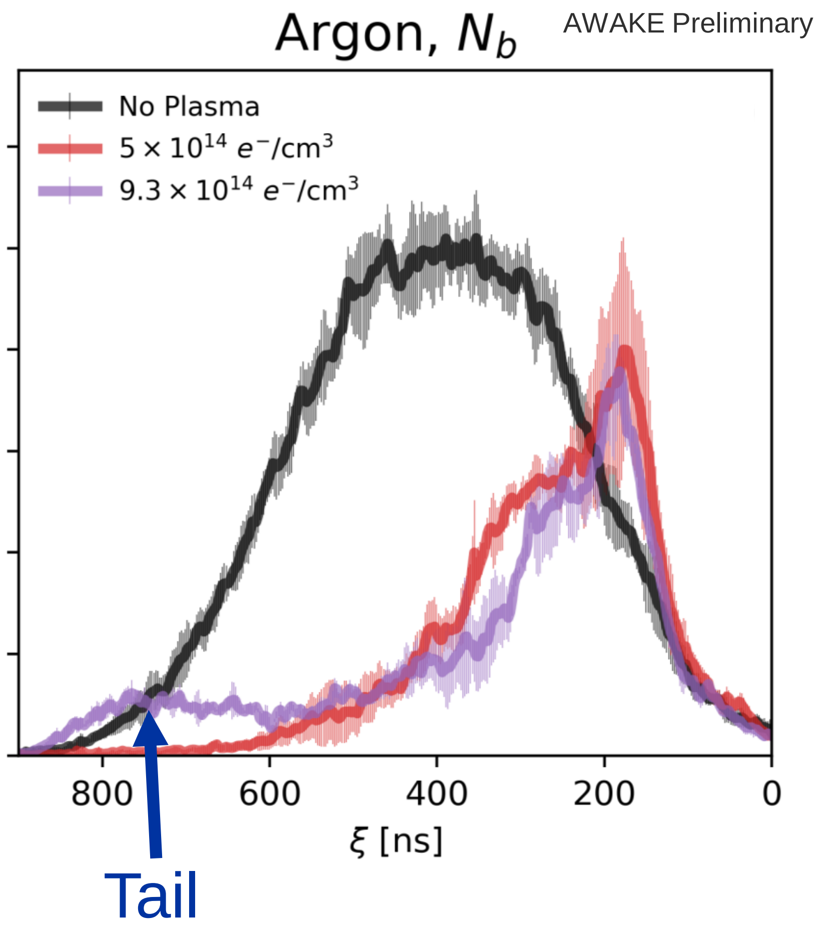
Largest Tail

Smaller Tail

No visible tail

Lower bunch population → lower wakefield amplitude
→ less effect of ion motion

Beam Tail Appears with Higher Wakefield Amplitude



Double plasma electron density in Argon.

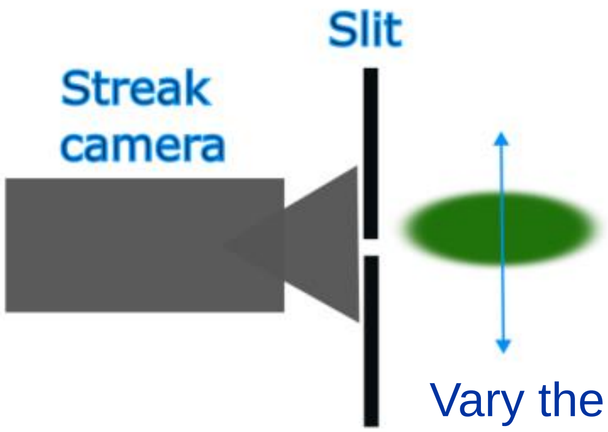
→ higher SMI growth rate.

In this case, higher average wakefield amplitude.

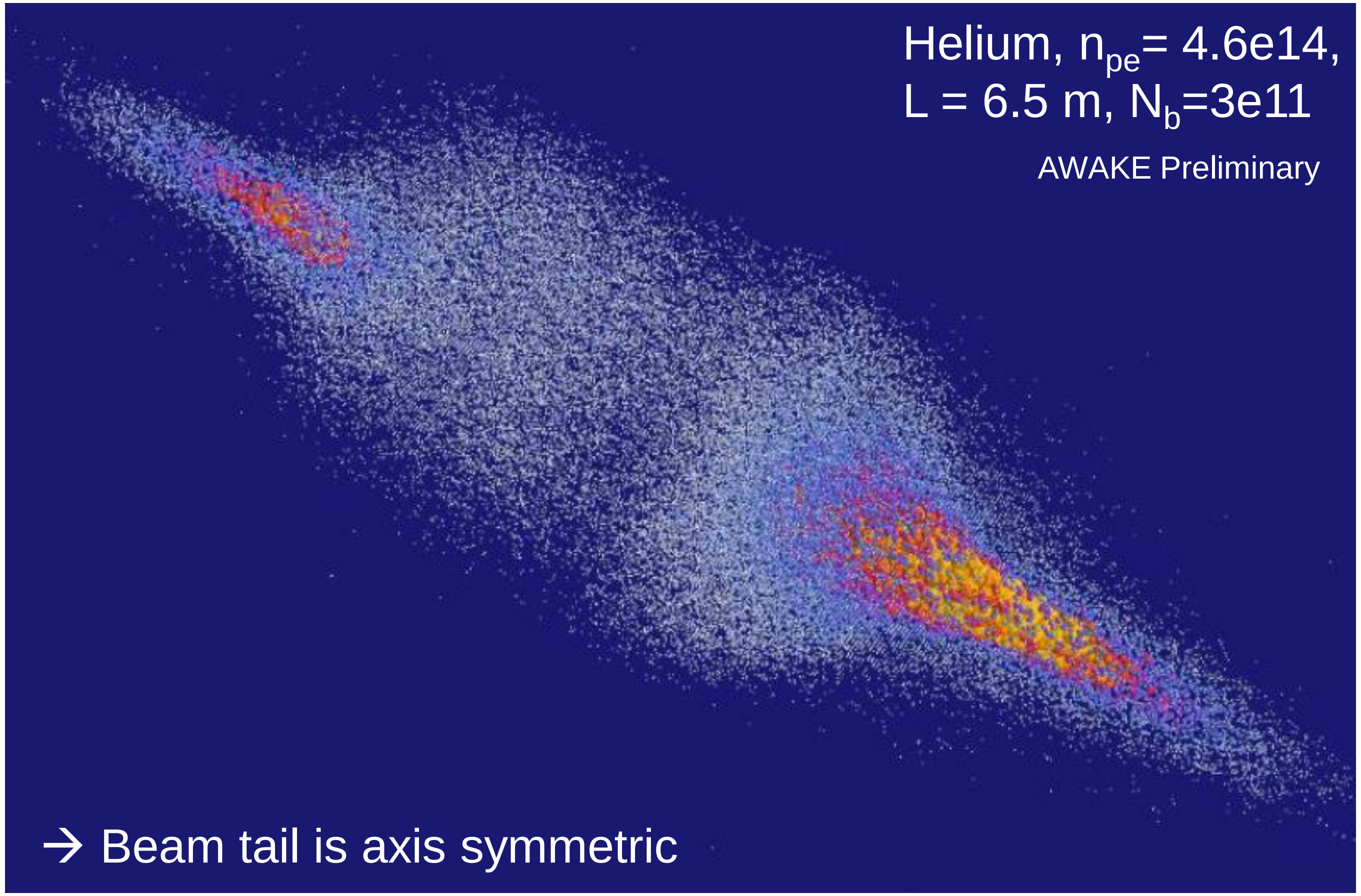
→ effect of ion motion (beam tail) appears

No effect of ion motion observed when using Xenon.

Tomographic Bunch Density Measurement and 3D Reconstruction



Vary the proton bunch slice that is imaged onto the streak camera



3D rendering by P. Blum

Summary & Conclusions

- We observed a clear effect of ion motion on a bunch train
  - Appearance of a bunch tail when ion motion caused wakefield decoherence
  - Ions moved due the ponderomotive force of transverse wakefields
  - Demonstrates resonance detuning due to ion motion

- The observed effect scales with expectations from wakefield theory and simulations
  - Appears first for ions with lower mass
  - Increases with wakefield amplitude
    - Higher proton bunch population
    - Higher plasma electron density
  - Good agreement with simulation results

- Effect needs to be taken into account for any wakefield accelerator that is driven with multiple bunches of pulses
  - AWAKE Baseline uses Rubidium (A=87), no effect of ion motion expected at nominal density ($7 \times 10^{14}/cm^3$)