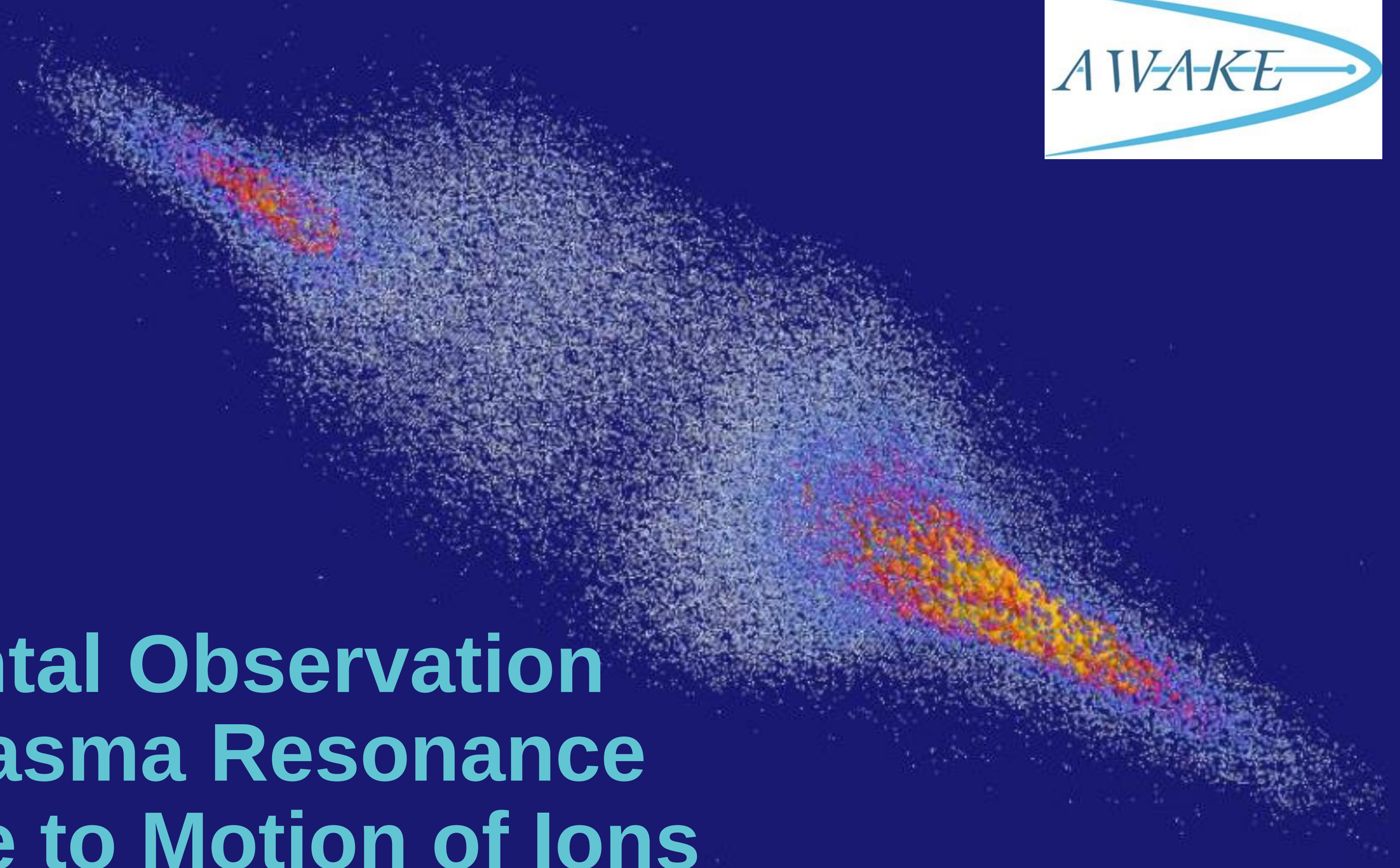


Experimental Observation of Beam-Plasma Resonance Detuning due to Motion of Ions

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

Ion Motion in Plasma Wakefields

Ions assumed to be immobile

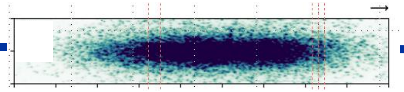
Ion motion in plasma wakefields may originate from:

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)

Experimental Setup

Driver



$n_b << n_{pe}$

N_b = 3e11 protons / bunch,
σ_z = 170 ps, σ_r ~ 160 um,
E_b = 400 GeV, provided by
CERN SPS, E_t=19 kJ
Rep. rate: every ~25 s

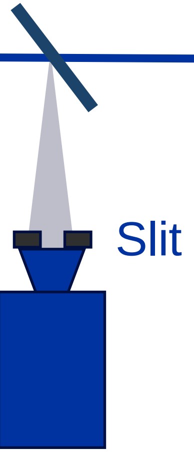
Discharge Plasma Source

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

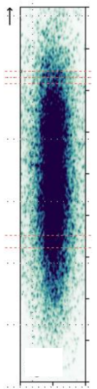
SMI development, formation of bunch train

Resonant wakefield excitation

Diagnostic

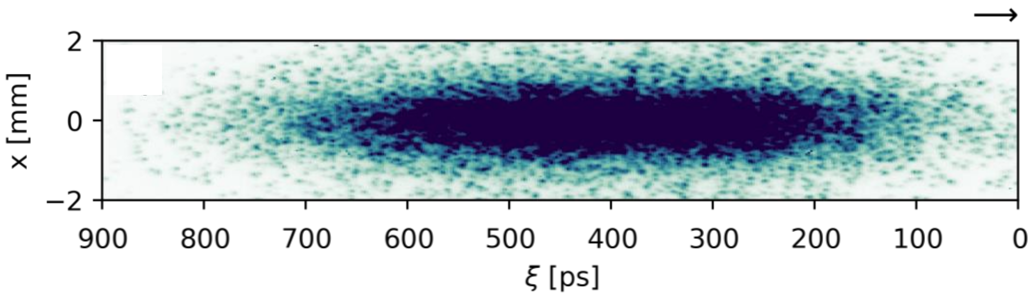


Streak camera (ps time-resolution)

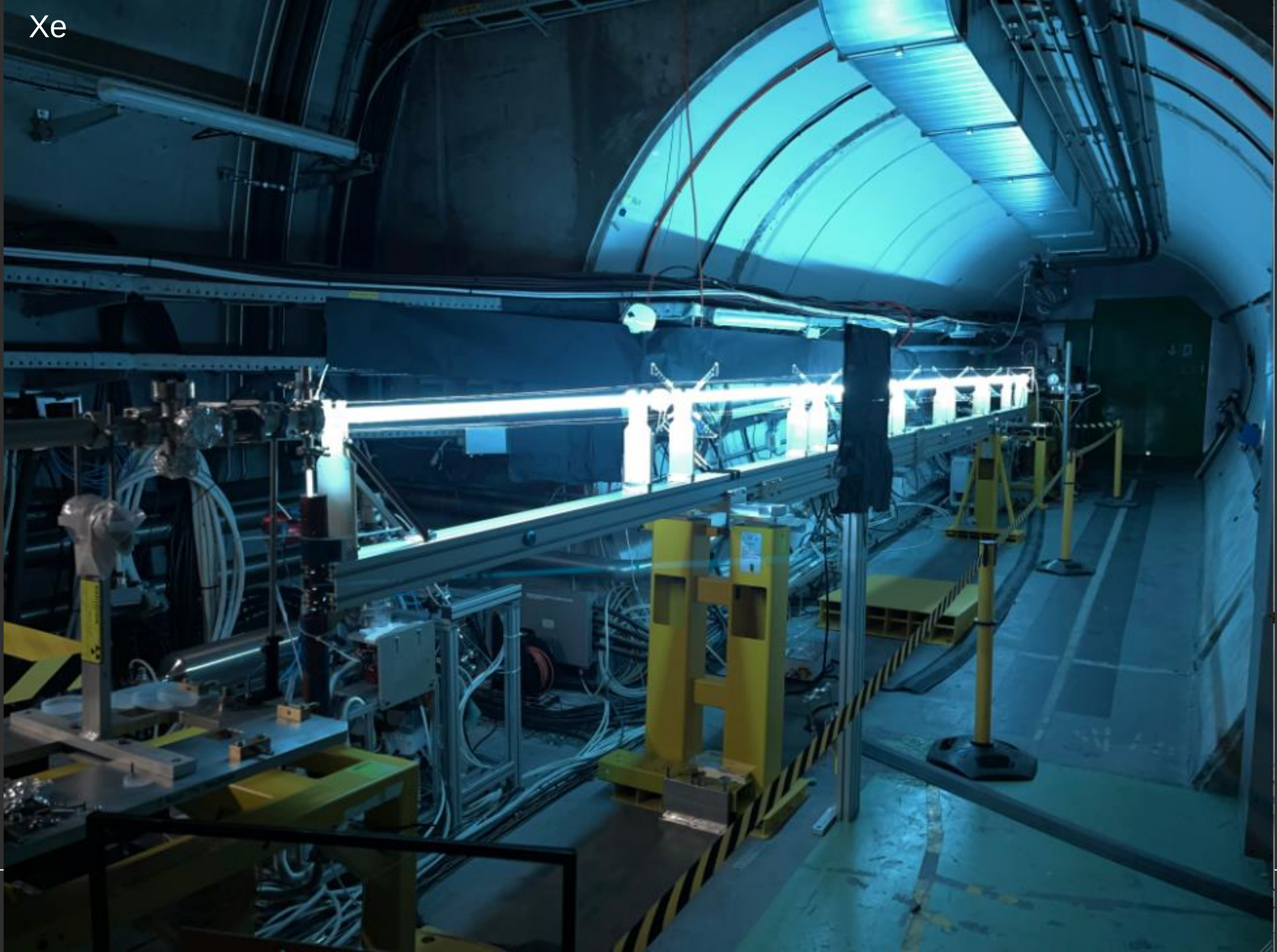


Experimental Results
Streak Camera Measurements

No Plasma



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

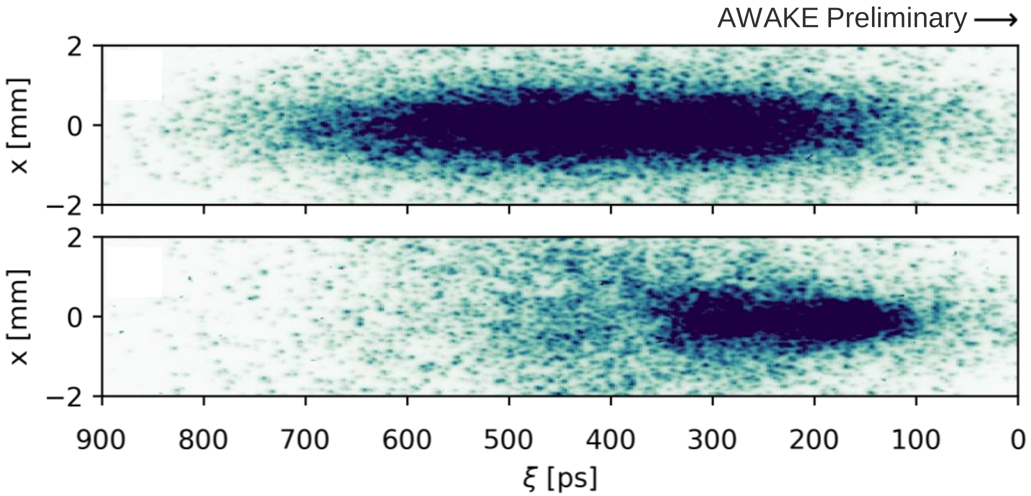


Xe
A = 131,
Single
ionisation

Experimental Results
Streak Camera Measurements

No Plasma

Xenon

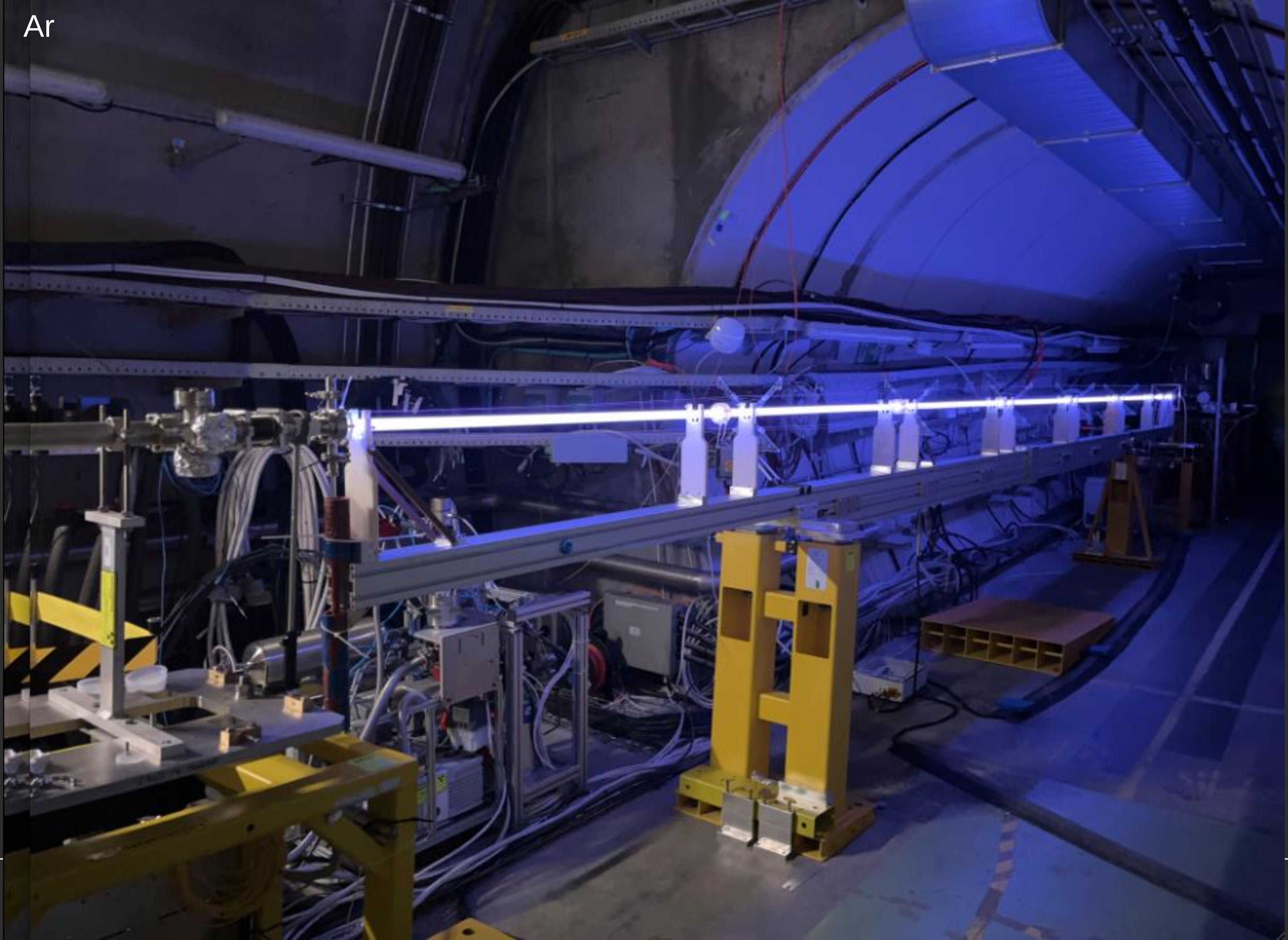


n_p = 3 x 10^{11} protons per bunch

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

- 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), Single ionisation

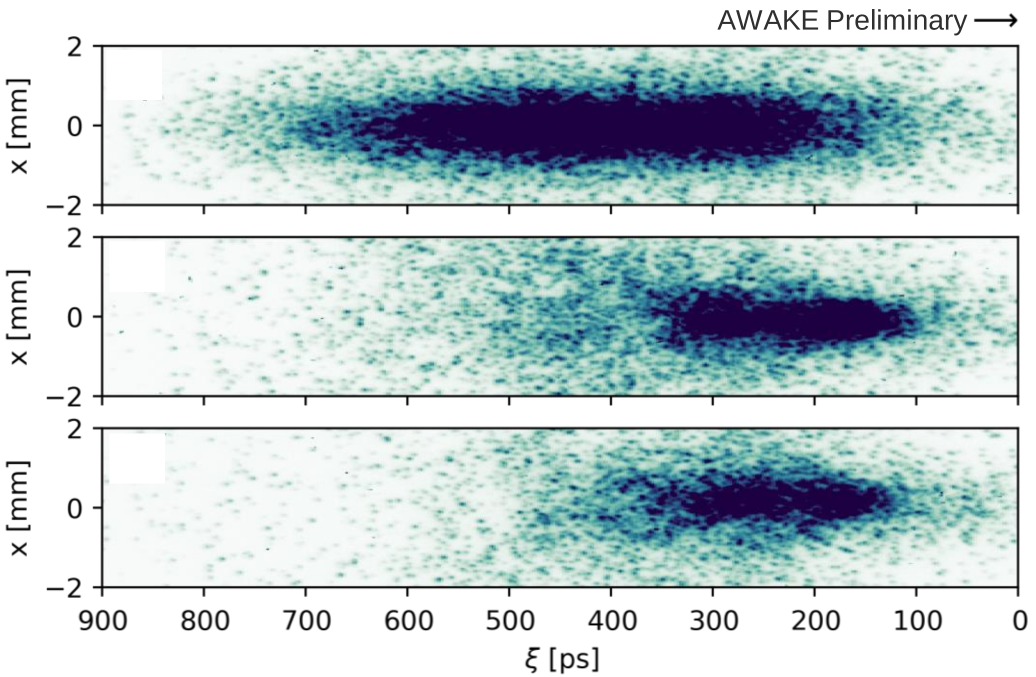


Experimental Results
Streak Camera Measurements

No Plasma

Xenon

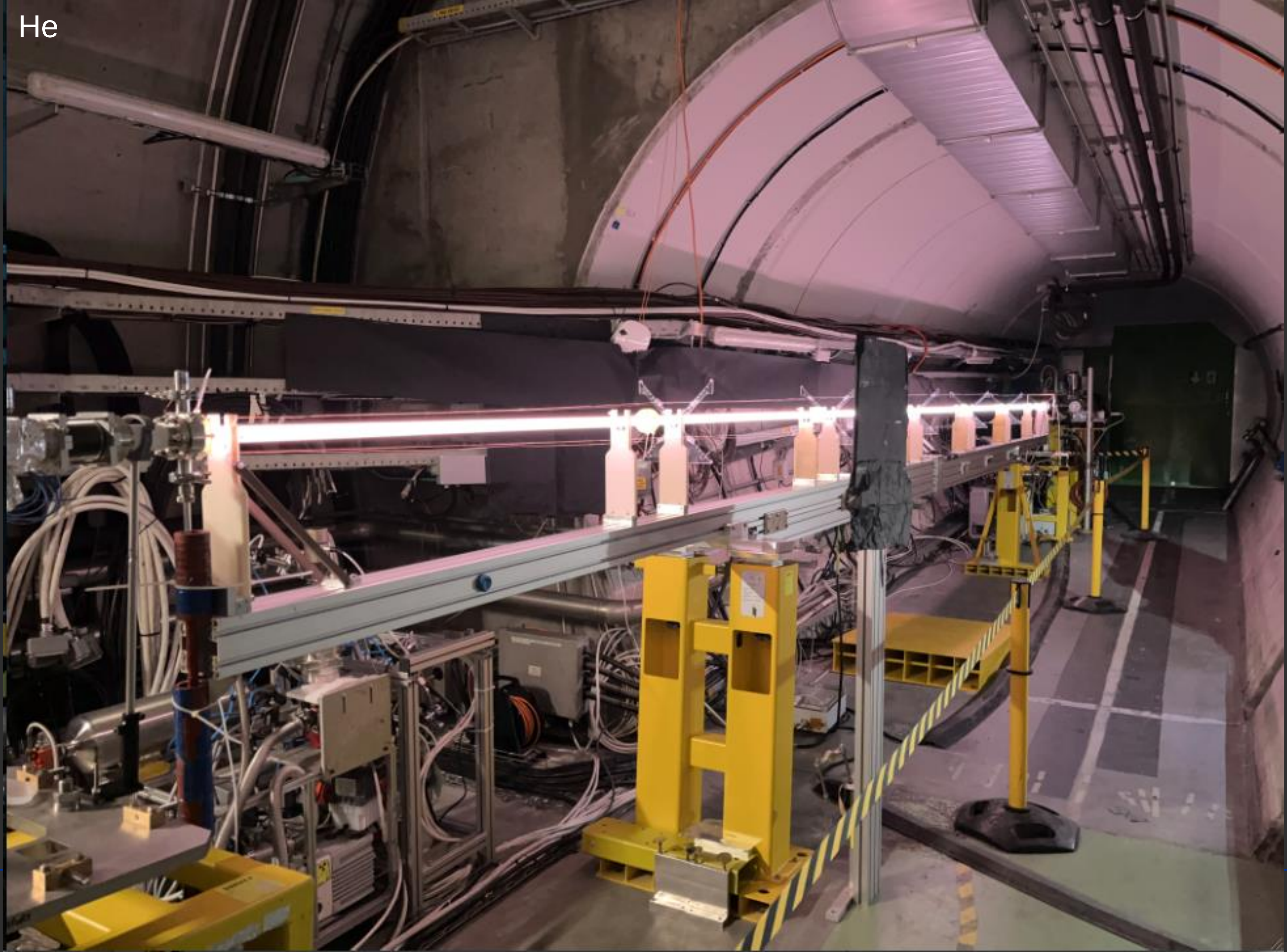
Argon



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),
Single
ionisation

Experimental Results

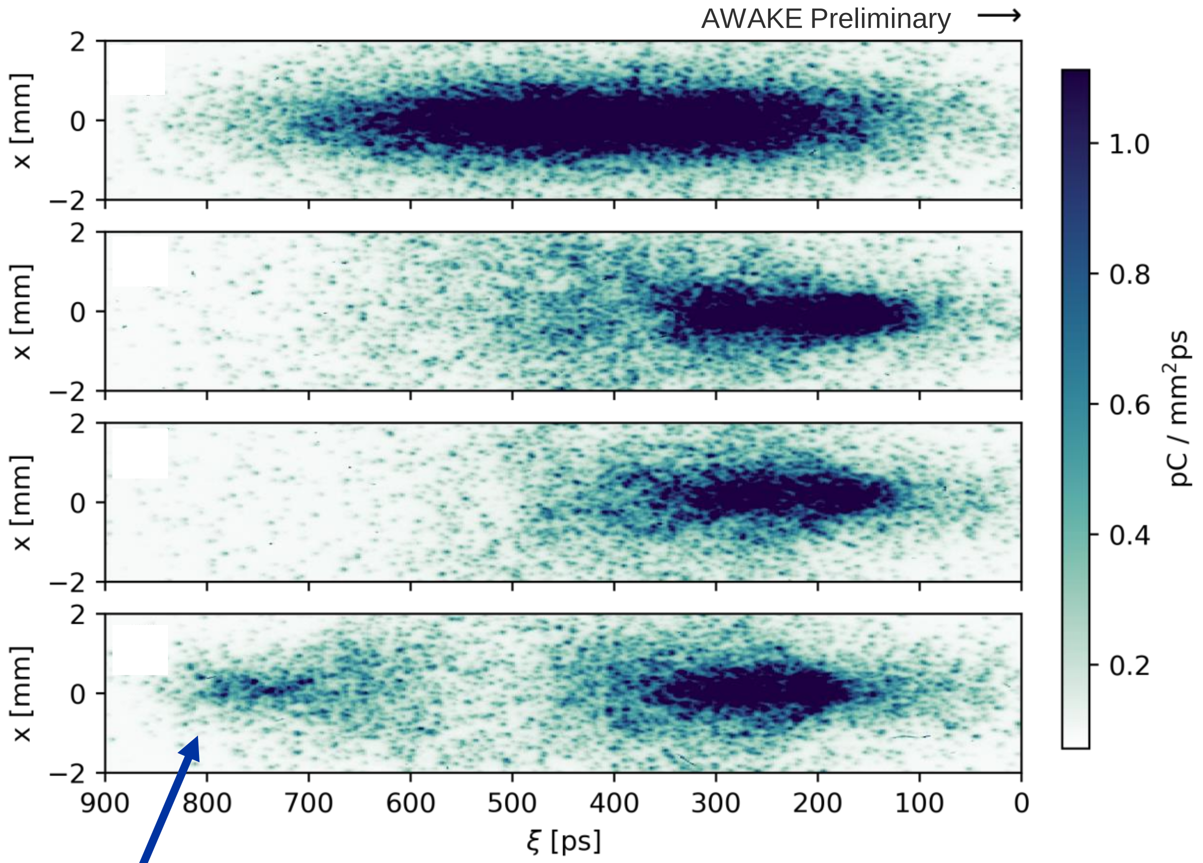
Streak Camera Measurements

No Plasma

Xenon

Argon

Helium



Beam Tail

$n_p = 3 \times 10^{11}$ protons per bunch

$n_{pe} = 4.8 \times 10^{14}$ cm^{-3}

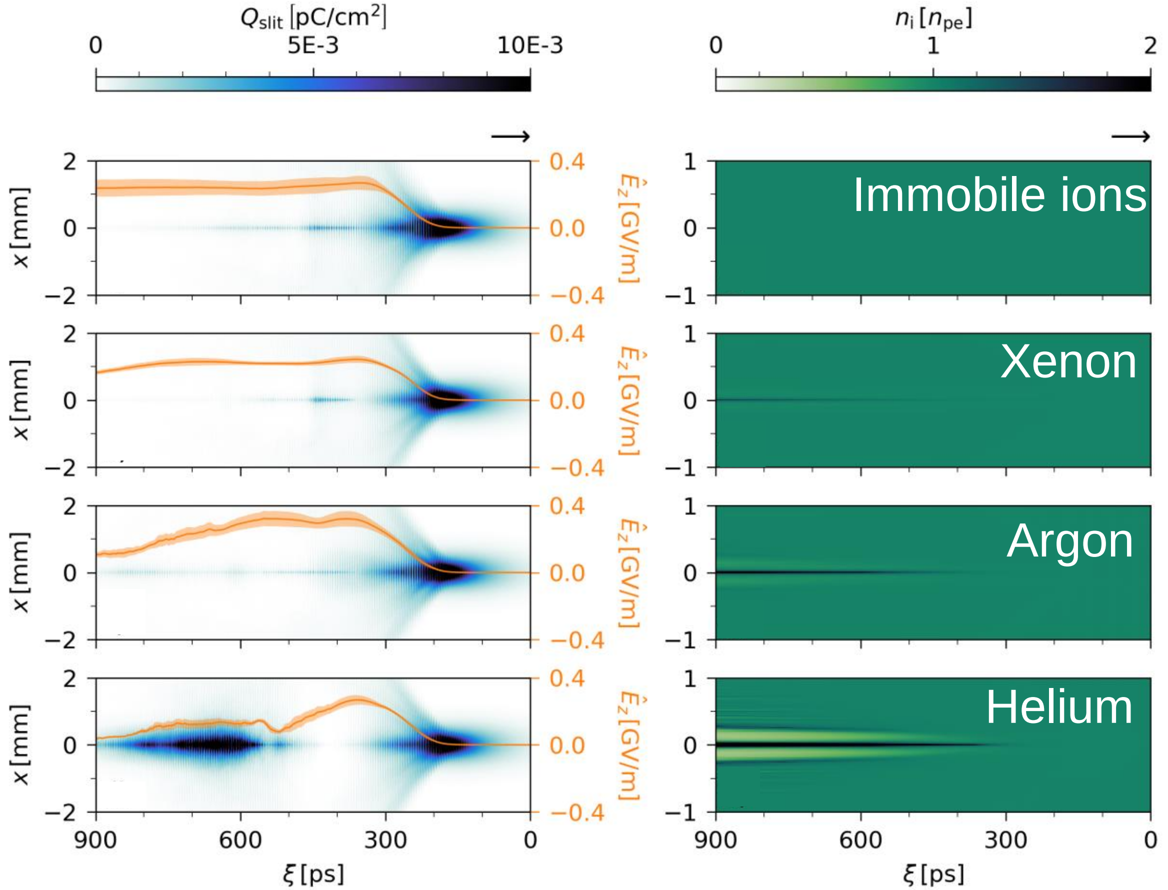
- Appearance of a beam tail (increase of proton bunch charge later along the bunch) when using Helium.

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:

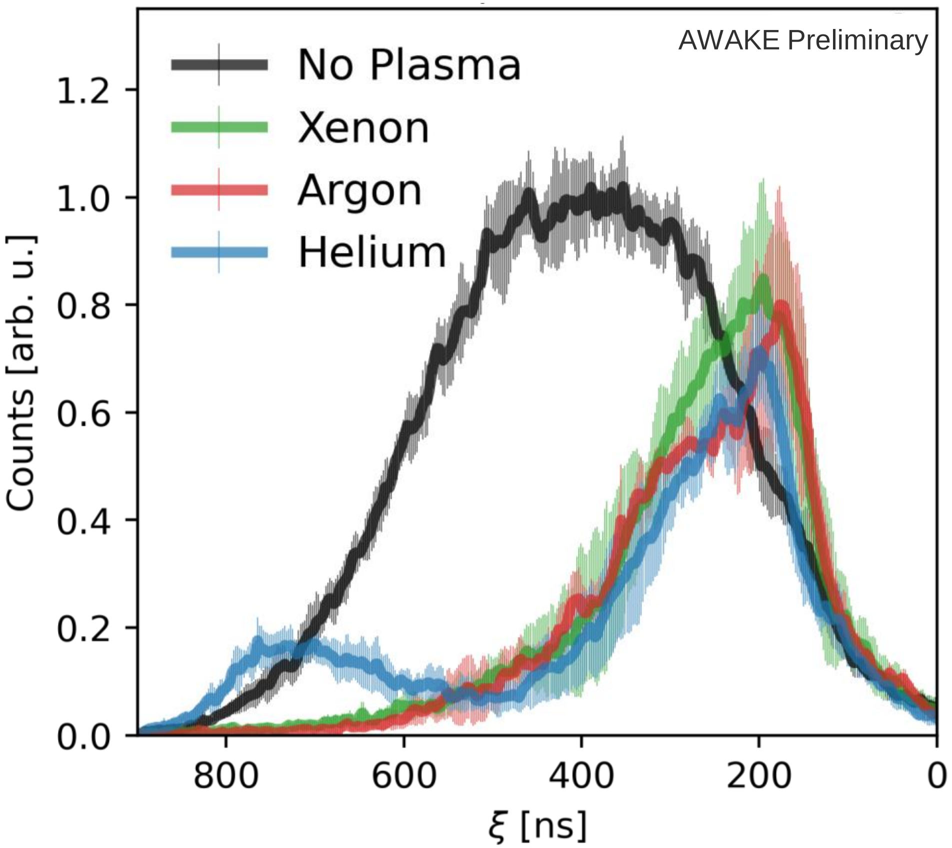
- Locally reduced ion density leads to longer oscillation period (less restoring force)
- Radially varying ion density leads to radially varying restoring force

→ 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 ξ < 550 ps
- Visible beam tail for ξ > 600 ps

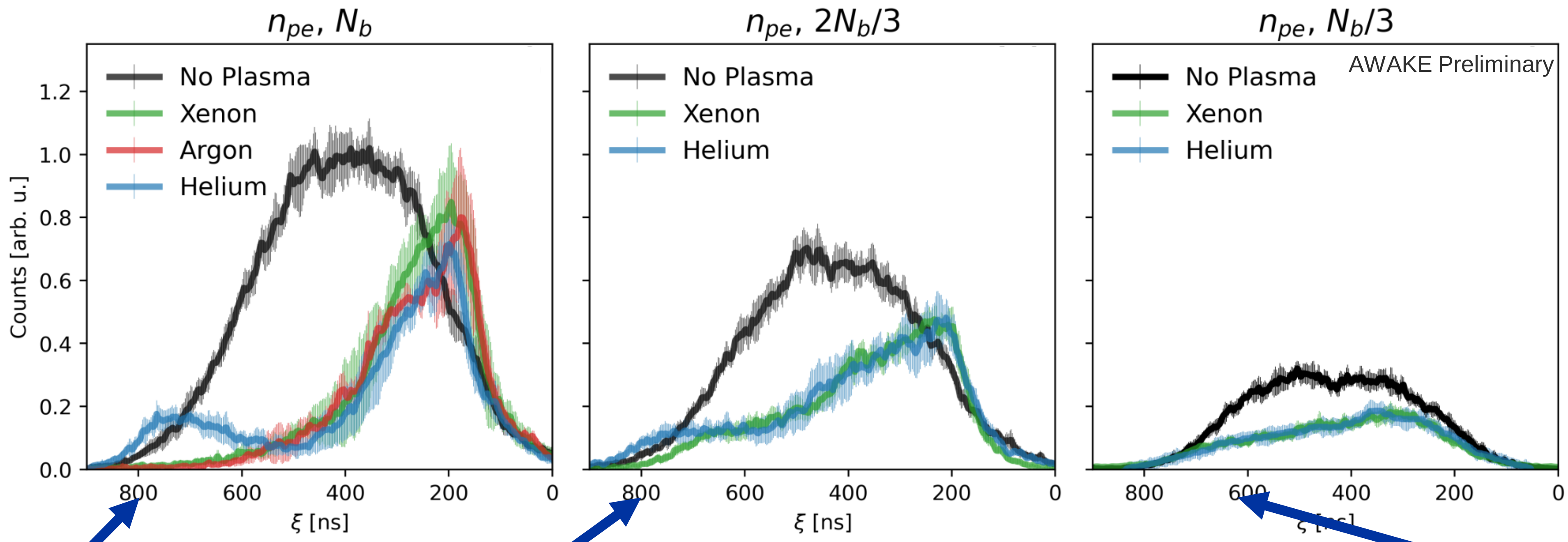
→ Scaling with ion mass
→ Effect visible with lighter ions

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



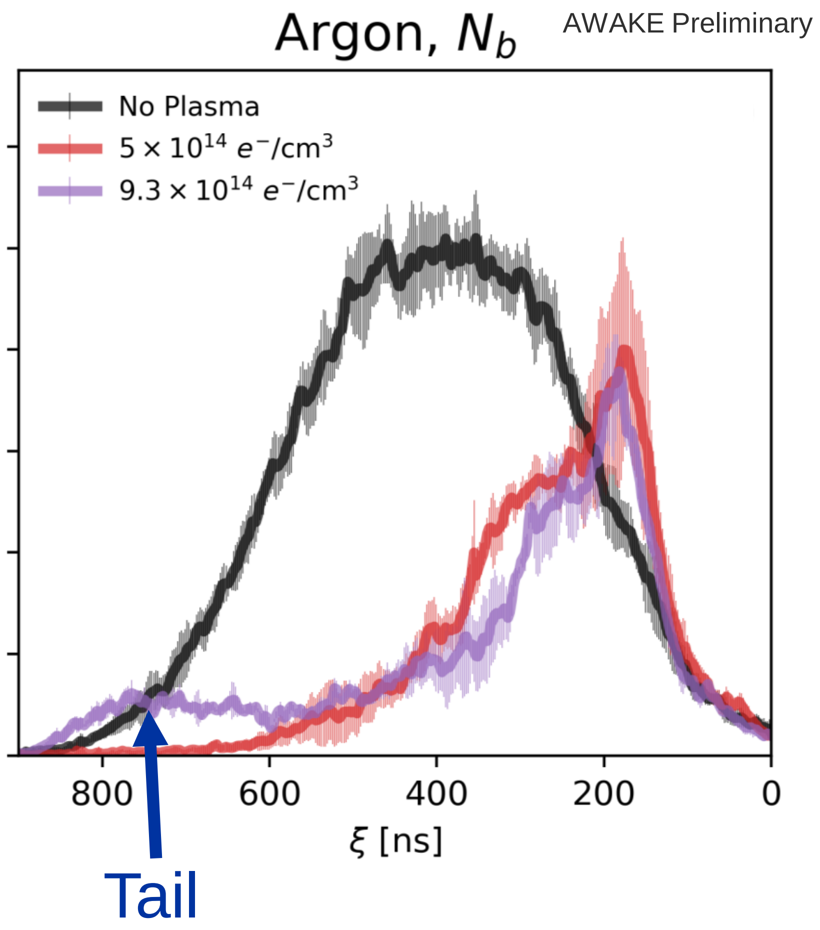
Largest Tail

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.

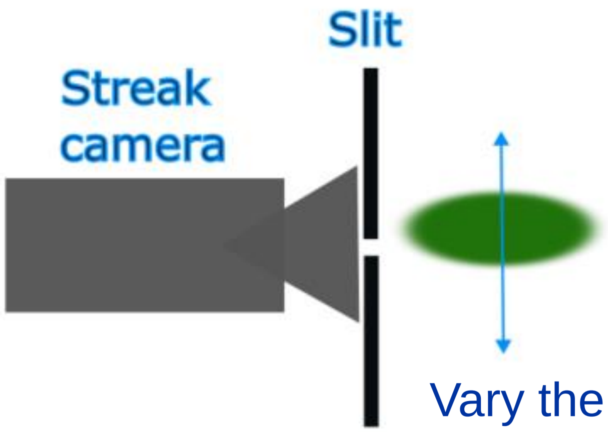
→ higher SMI growth rate.

In this case, higher average wakefield amplitude.

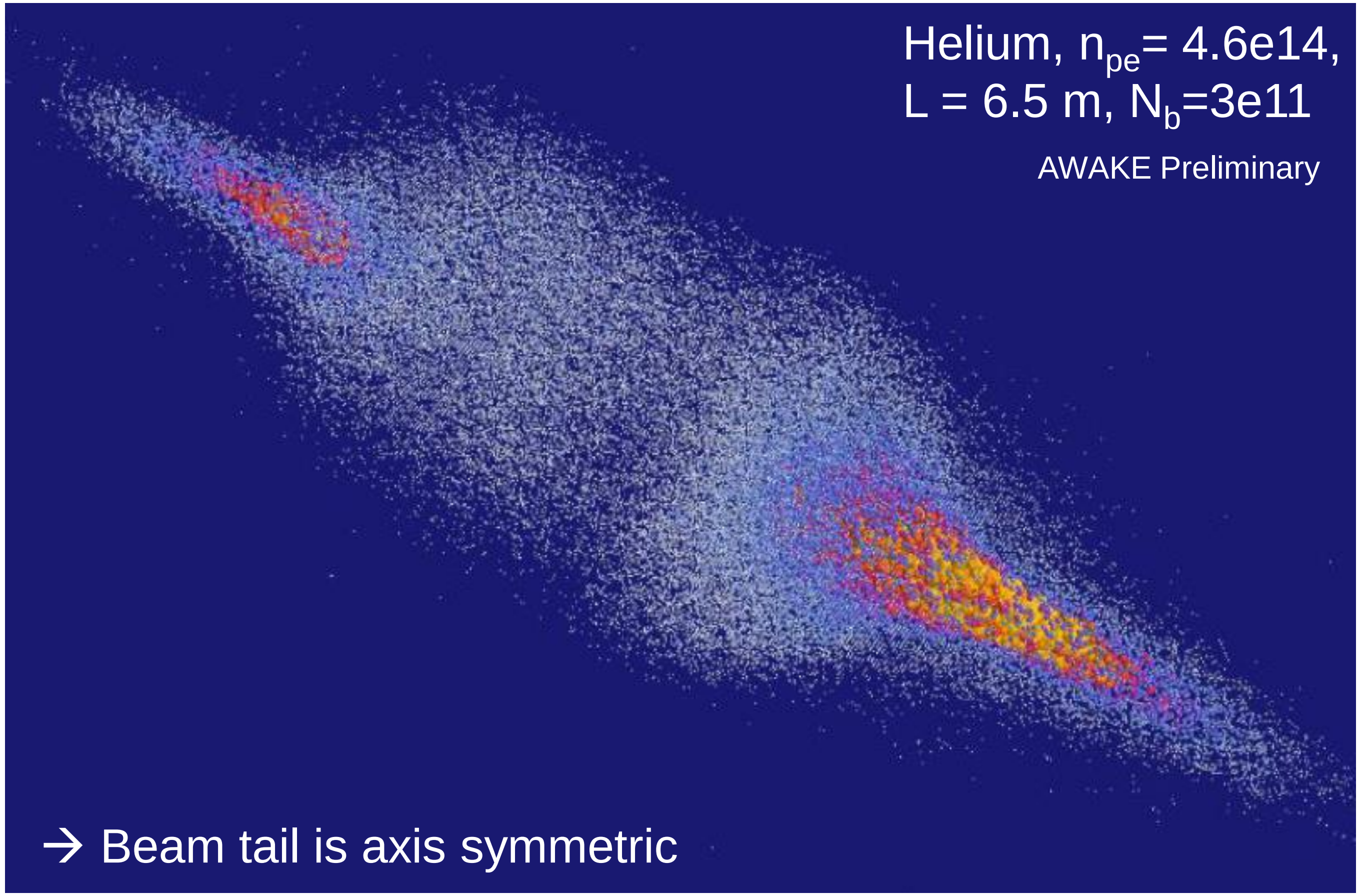
→ effect of ion motion (beam tail) appears

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 causes decoherence of electron motion
  - 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 ($7 \times 10^{14}/cm^3$)