Measurements of the effect of the plasma density step on electron energy gain

AWAKE Collaboration Meeting
06.11.24

F. Pannell and the AWAKE Collaboration

Introduction

The magnetic spectrometer

Design recap, optics upgrades

Acceleration with density steps

The plunger experiment, requirements

First look: Preliminary results 2024

Energy gain with uniform and steps

The magnetic spectrometer

Design recap

The main diagnostic to study the accelerated electrons

Quadrupole doublet → electron bunch focusing

C-shaped dipole → separate electrons from protons

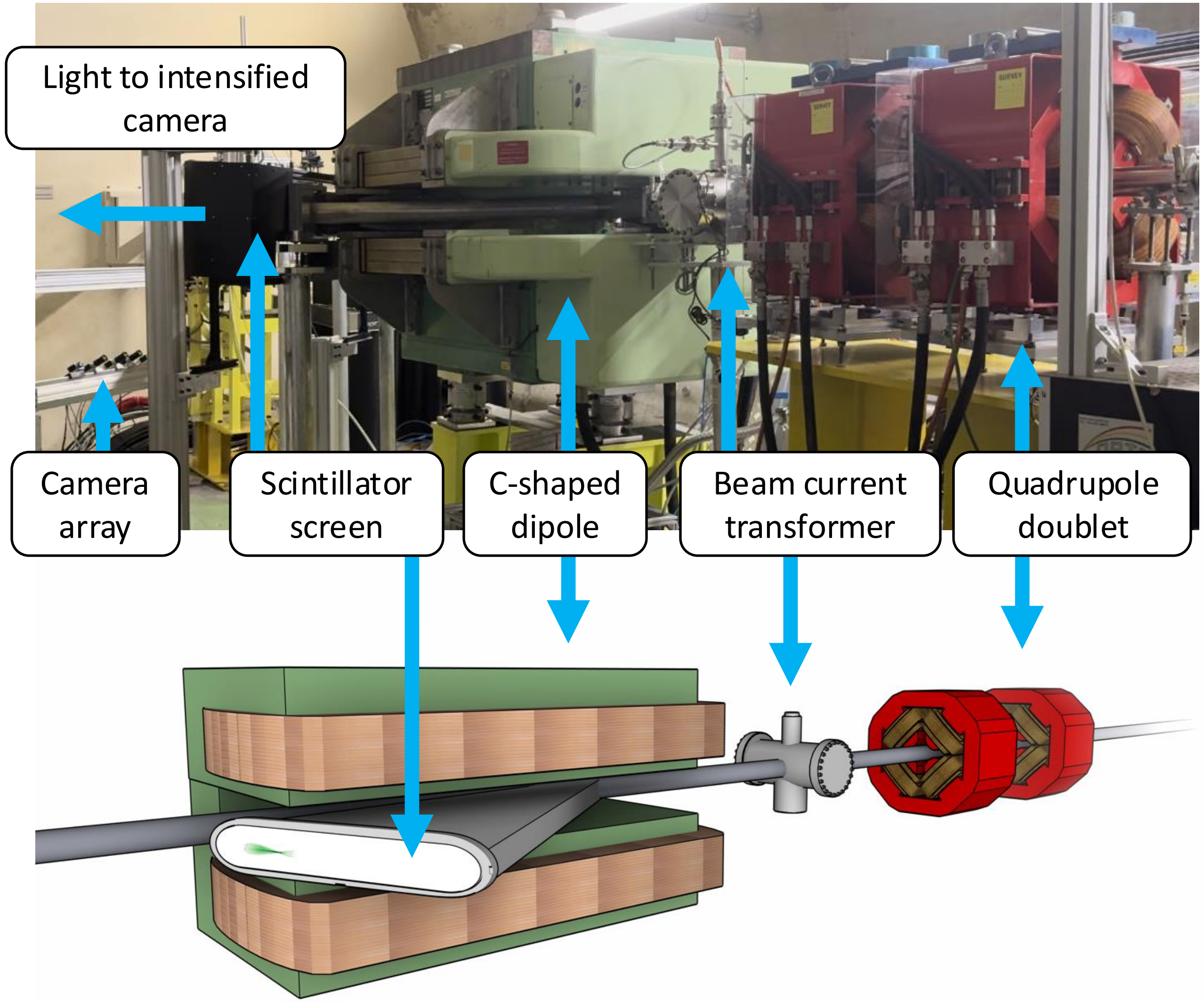
Scintillator screen → electron impact causes scintillation

Camera systems → capture the scintillation light

Integrating current transformer → charge calibration

Measurements of the energy, energy spread, charge

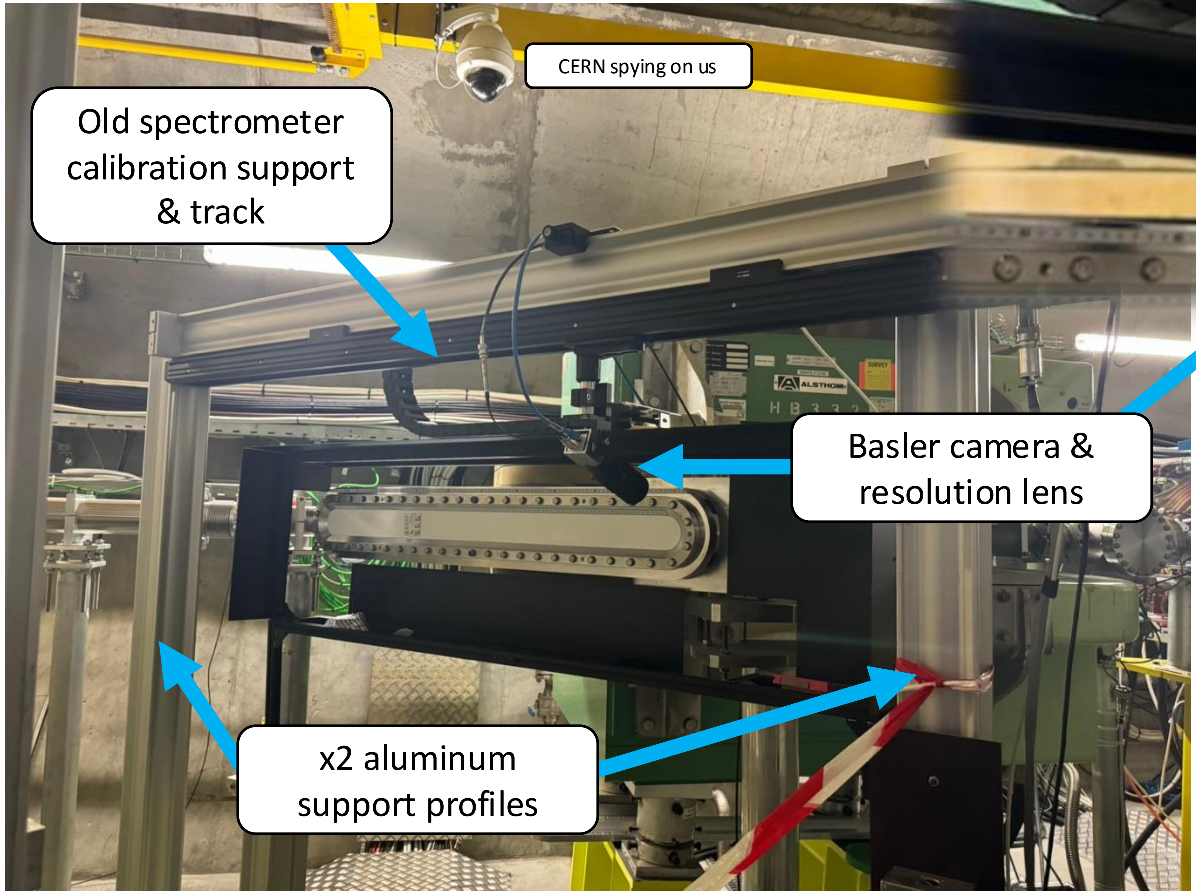
Run 2b: Upgrades to the imaging systems for measurements of the transverse emittance

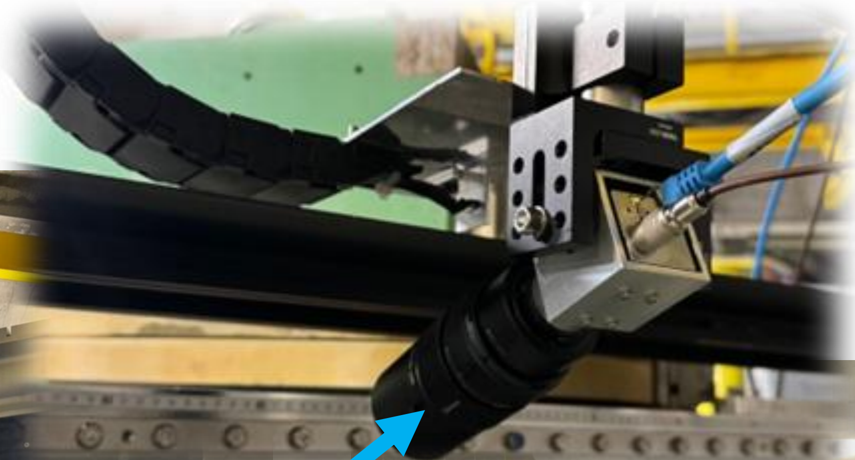


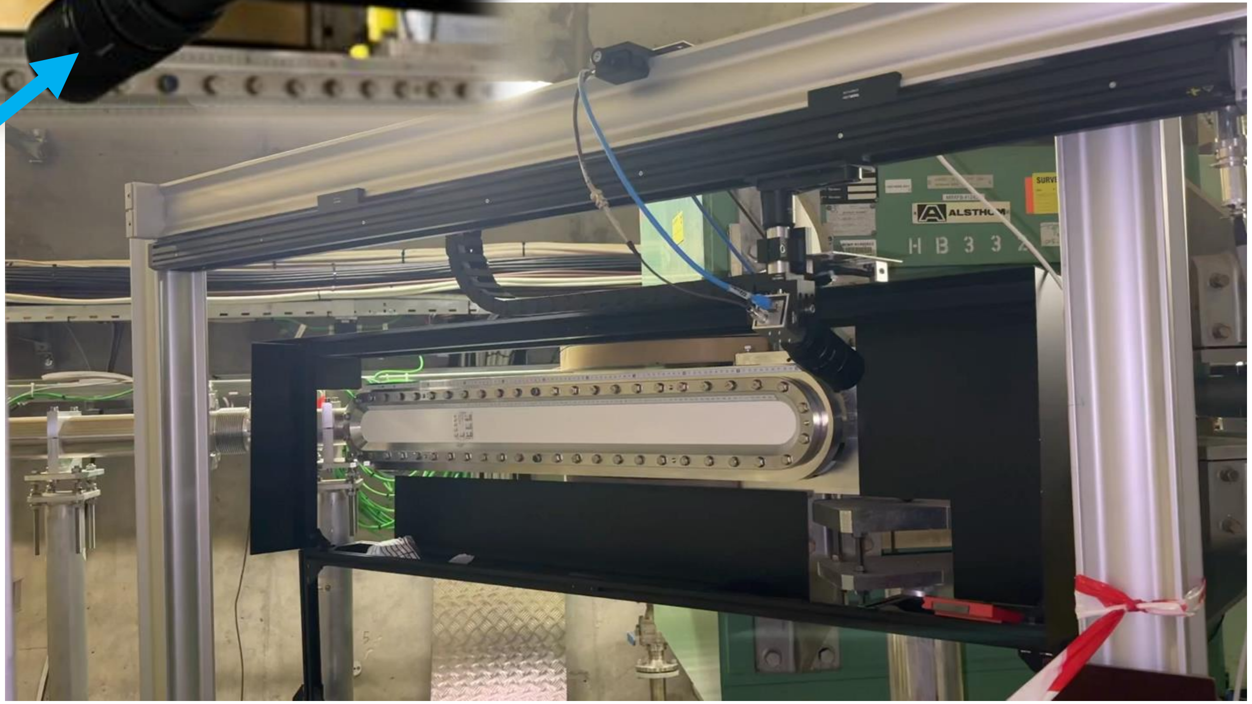
New installation: High resolution camera

High resolution imaging of beam waist
Project completed May 2024

Many thanks to the support from SY-BI-ML with the construction

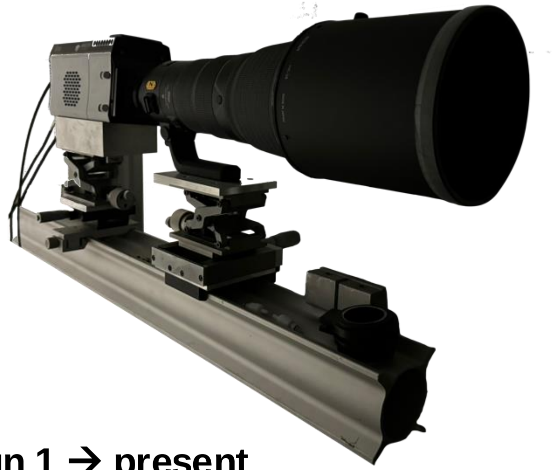






Camera systems

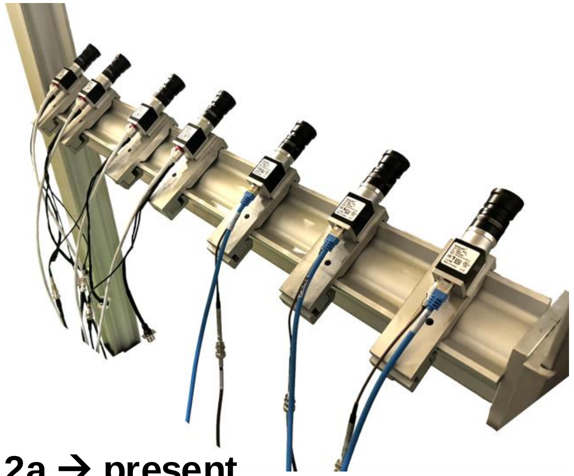
Intensified camera



Run 1 → present

Position from screen: 17m (via mirrors)
Camera: Andor iStar 340T
Lens: Nikon AF-S Nikkor
Focal length: 400mm
Field of view: ~1m
Pixel size (image): 13.5um
Pixel size (object): ~0.5mm

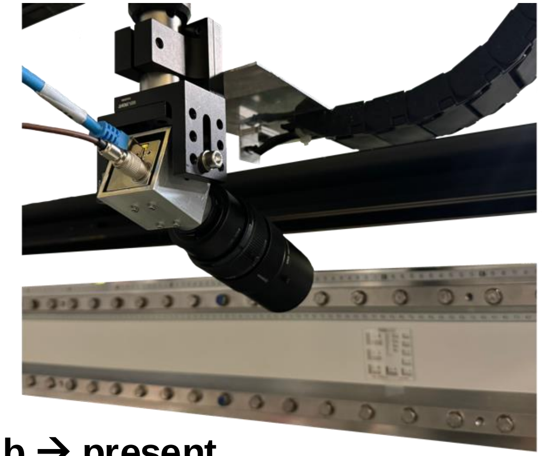
Camera array



Run 2a → present

Position from screen: 1.2m, -30°
Camera: Basler aCA 1920-40gm
Lens: Fujinon HF75HA-1S
Focal length: 75mm
Field of view: 0.15m
Pixel size (image): 5.86um
Pixel size (object): ~80um

High resolution camera

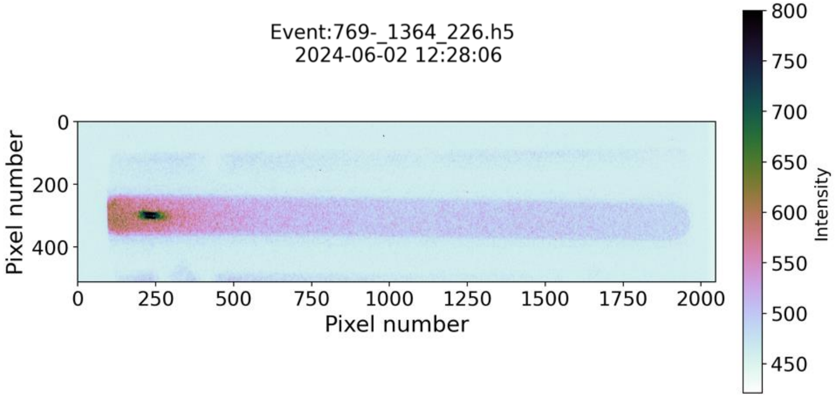


Run 2b → present

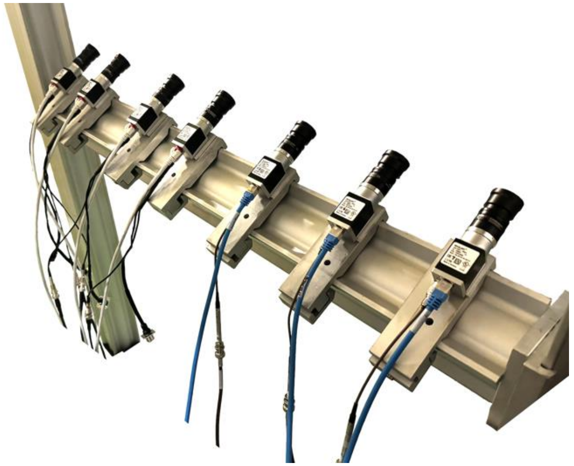
Position from screen: 0.25m, +40°
Camera: Basler aCA 1920-40gm
Lens: Edmund Optics DG
Focal length: 75mm
Field of view: ~0.02m
Pixel size (image): 5.86um
Pixel size (object): ~10um

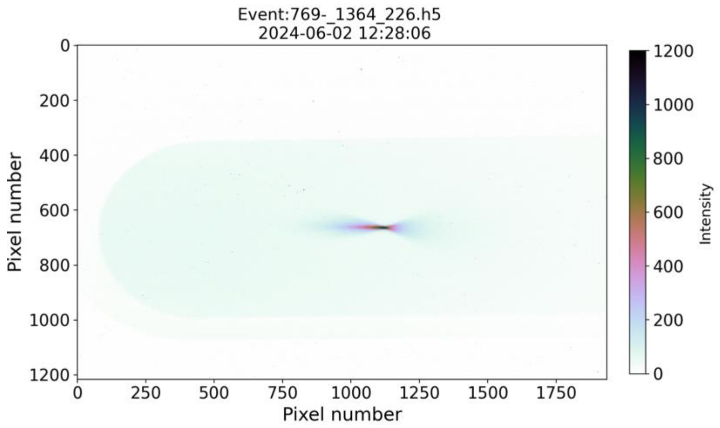
Camera systems

Intensified camera

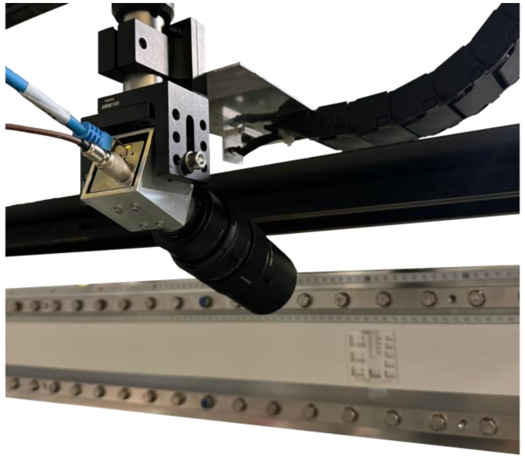


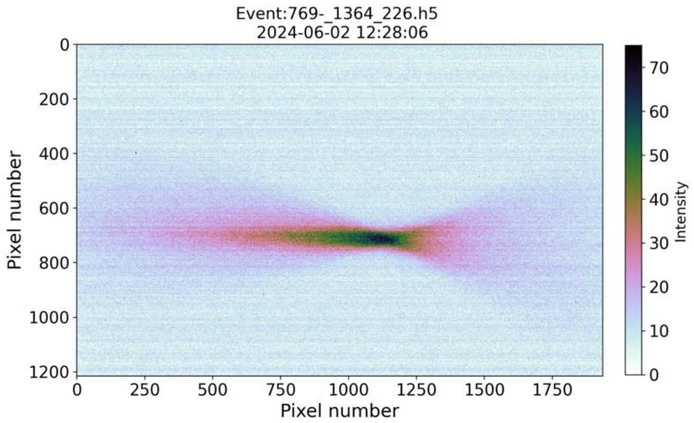
Camera array





High resolution camera





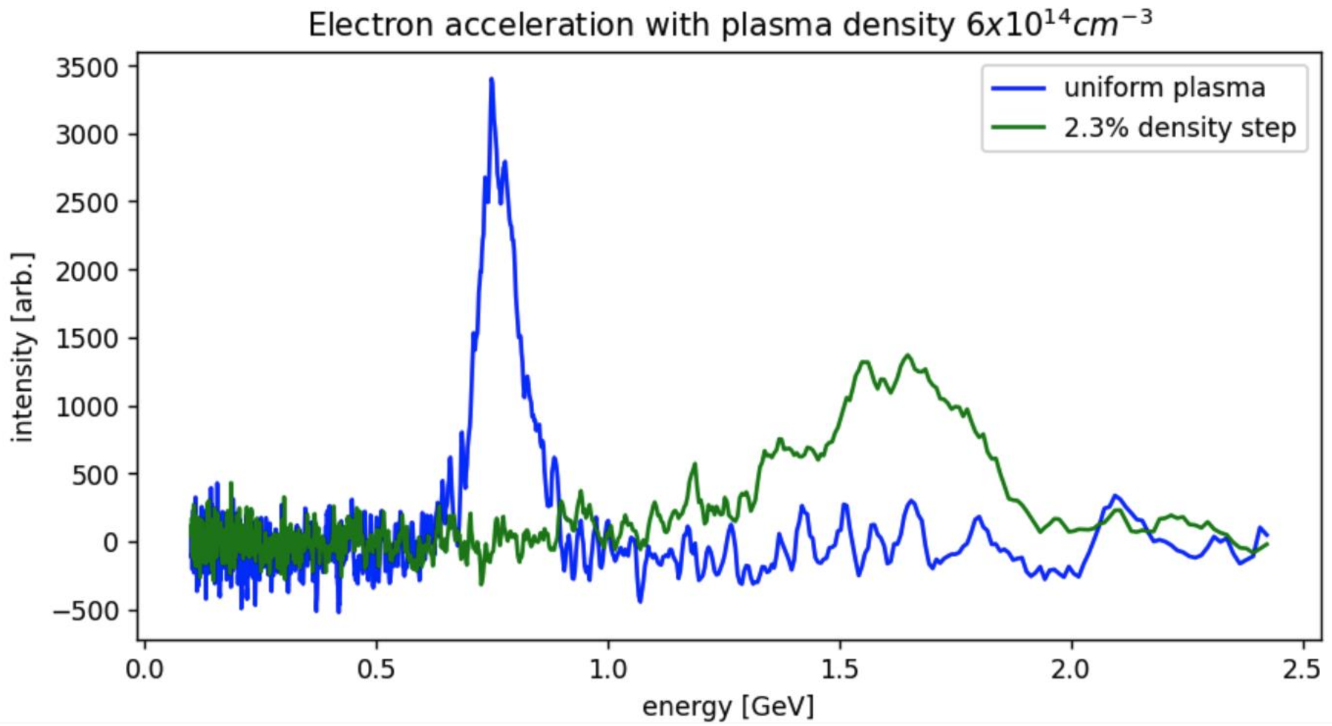
Acceleration with density steps

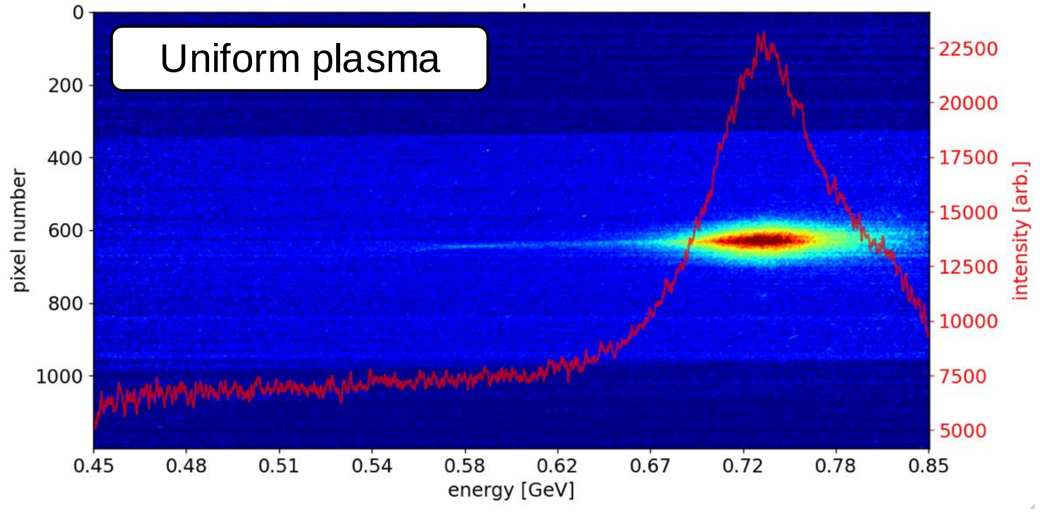
Reminder: First look at density steps (2023)

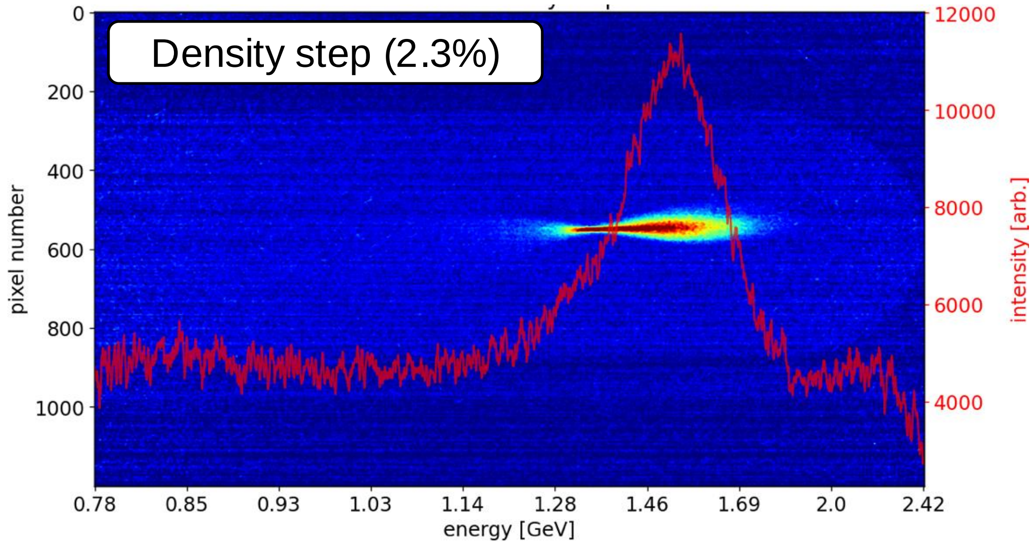
Plasma density: 6x10^{14} cm^{-3}(step 2.3% at 1.75m)

Proton bunch population: 3e11

RIF -100ps, electron delay -300ps, injection 2m







The plunger experiment

The ‘plungers’ (laser dumps) allow us to study the acceleration as a function of the plasma length
We can attempt to perform a direct measurement on the accelerating gradient (dE/dz)

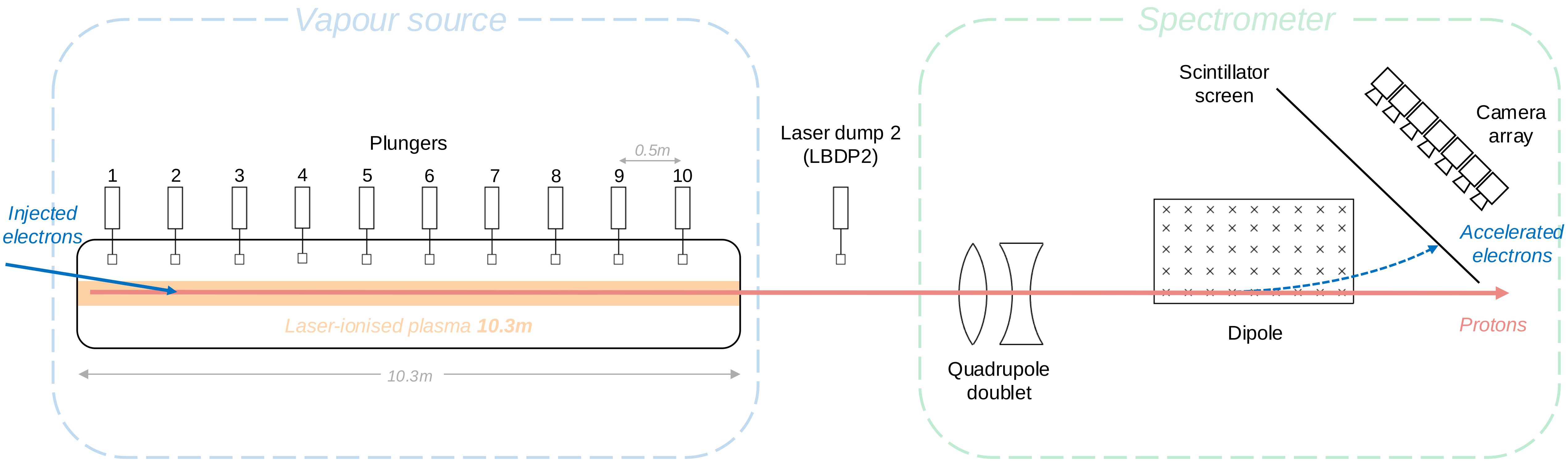


Diagram not drawn to scale

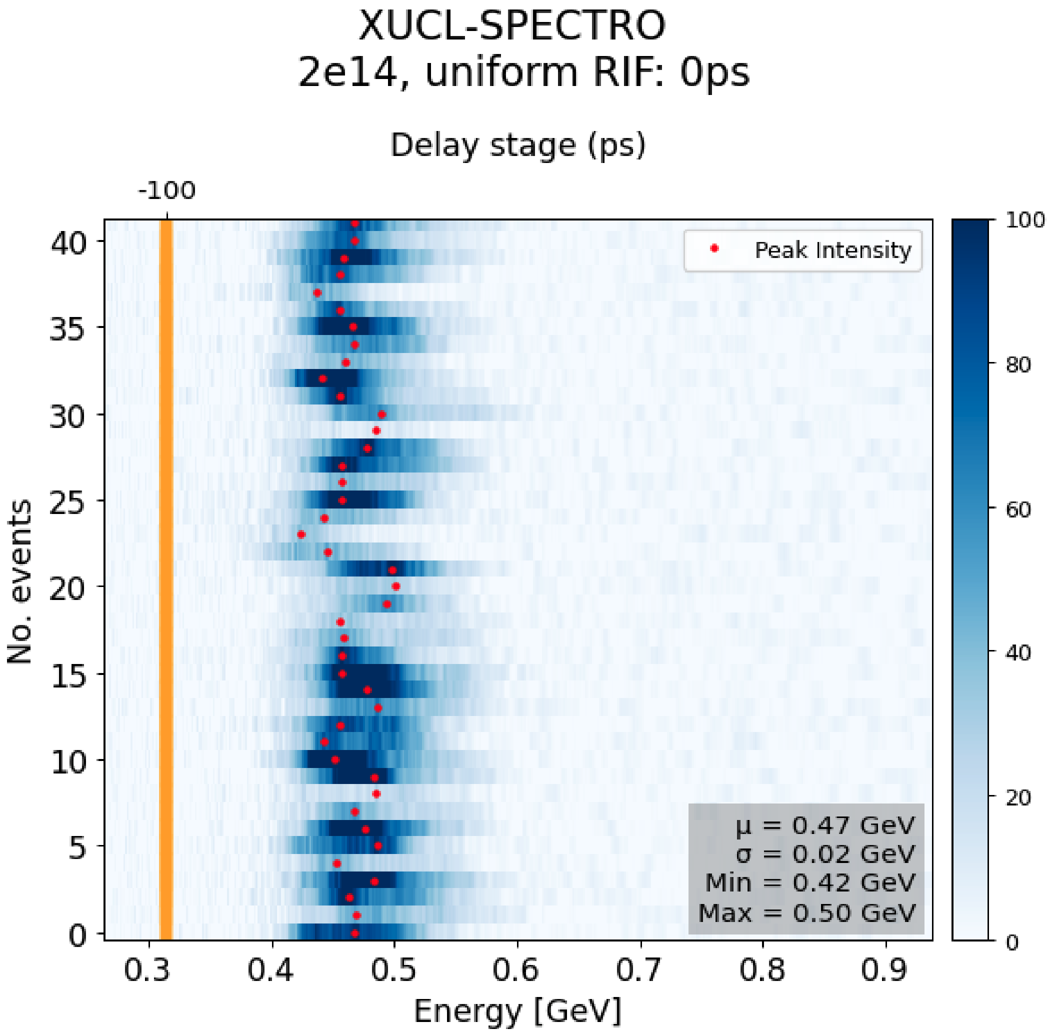
Requirements: Consistent acceleration

Due to the number of shots of the laser pulse onto the foil (~500), we must limit the shots on each plunger (10 per experiment).

We must be in as **stable** a configuration as possible

This includes:

- Capture **frequency** as close as possible to 100%
- Minimal shot-to-shot energy variation



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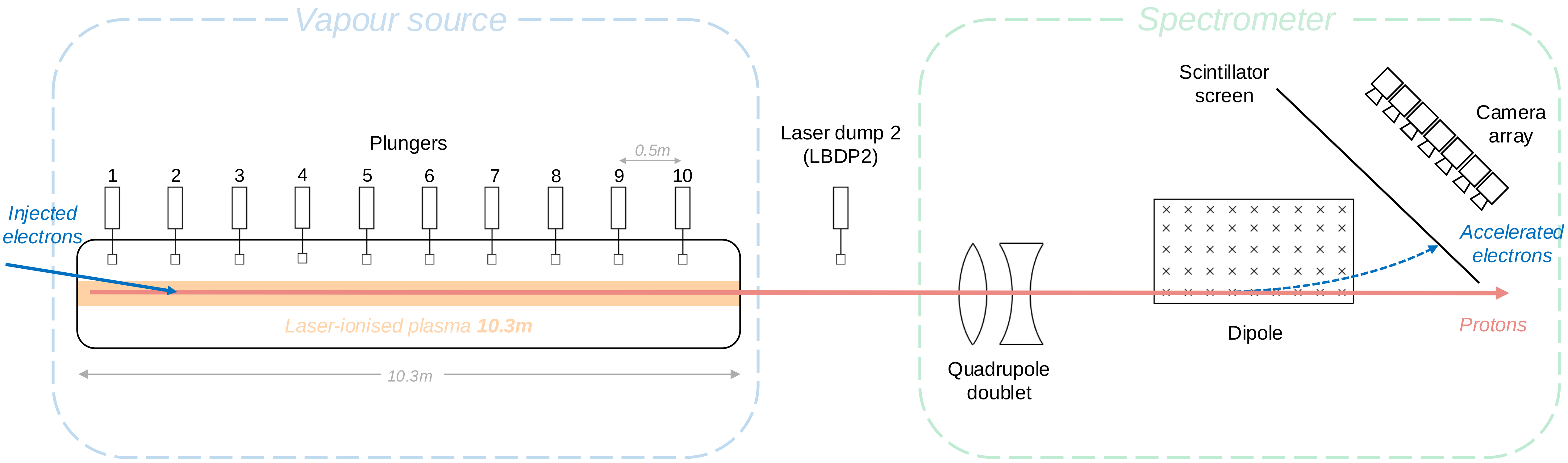

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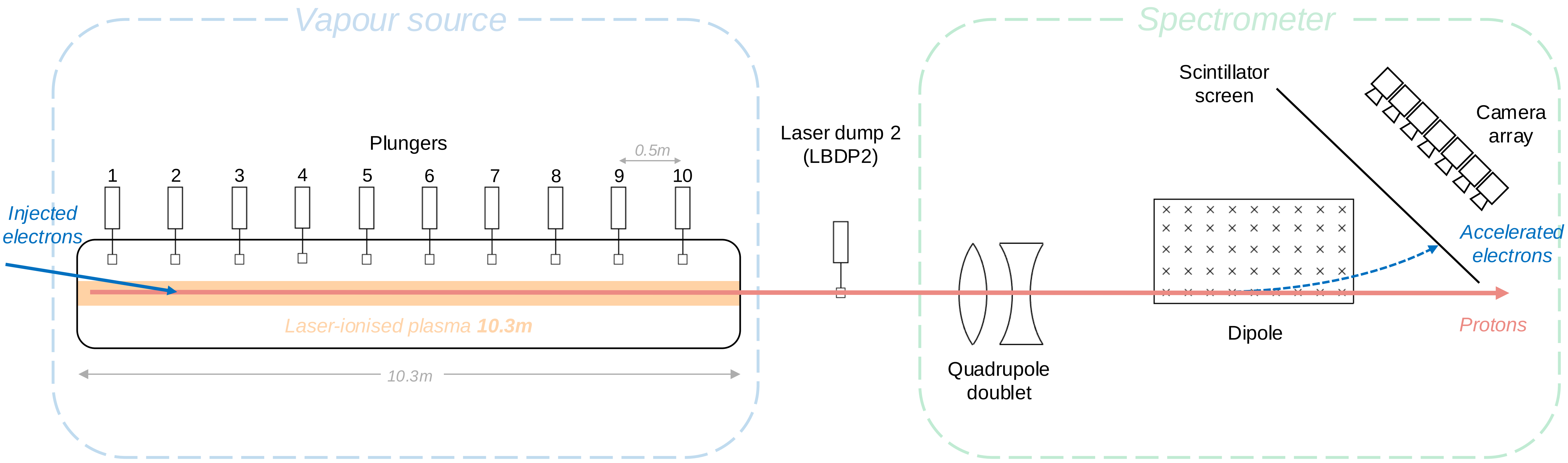


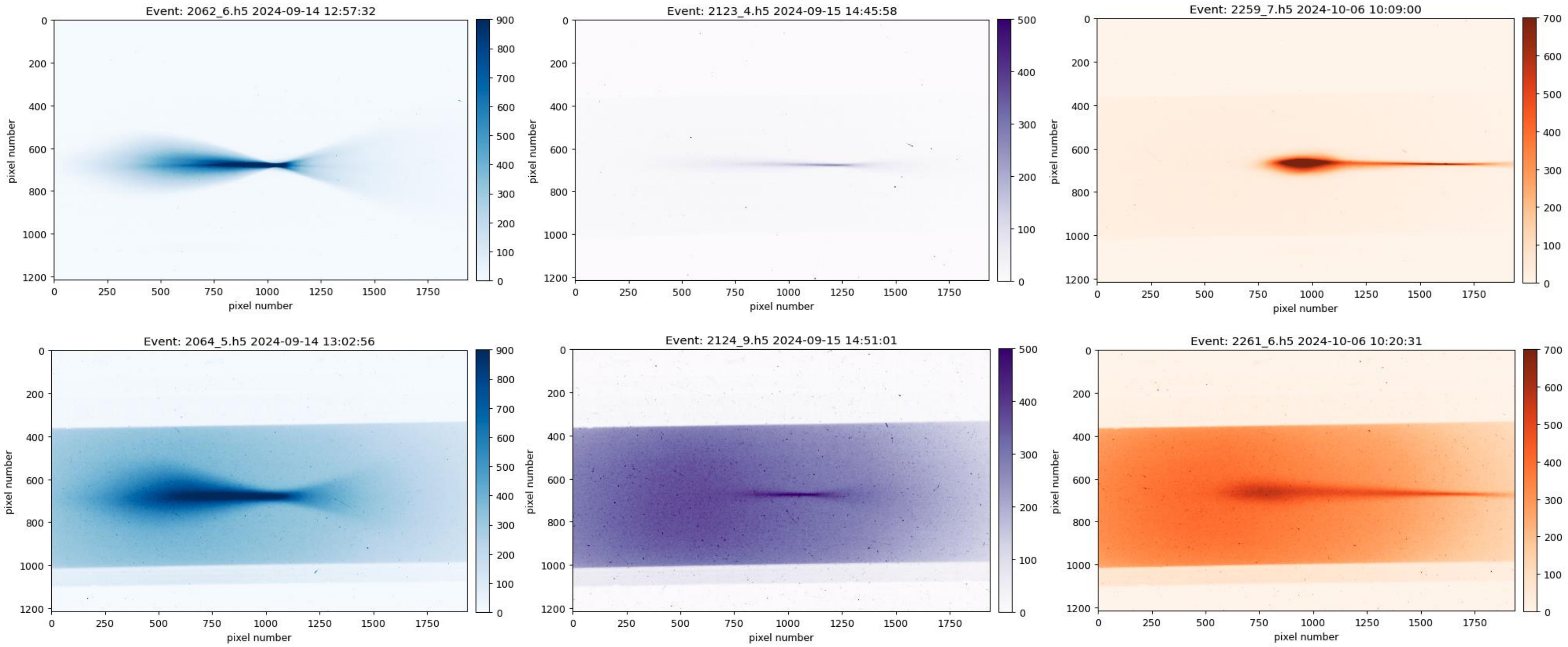
Diagram not drawn to scale

Requirements: Sufficient charge capture

$2 \text{x} 10^{14}\ \text{cm}^{-3}$ | $4 \text{x} 10^{14}\ \text{cm}^{-3}$ | $7 \text{x} 10^{14}\ \text{cm}^{-3}$

Standard acceleration

Through Laser dump



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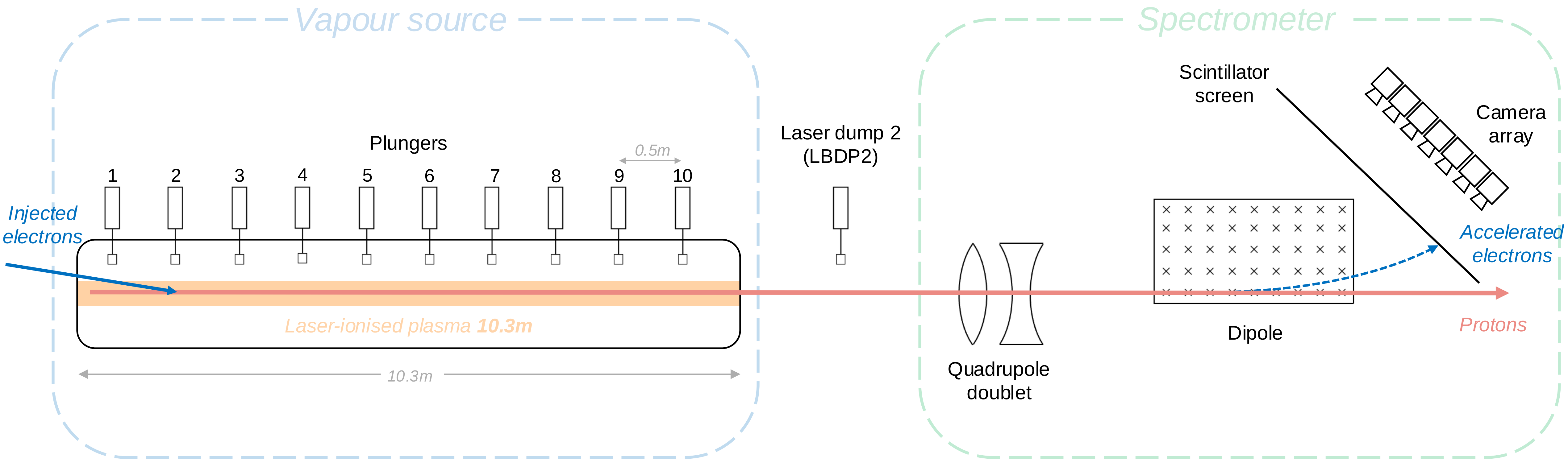

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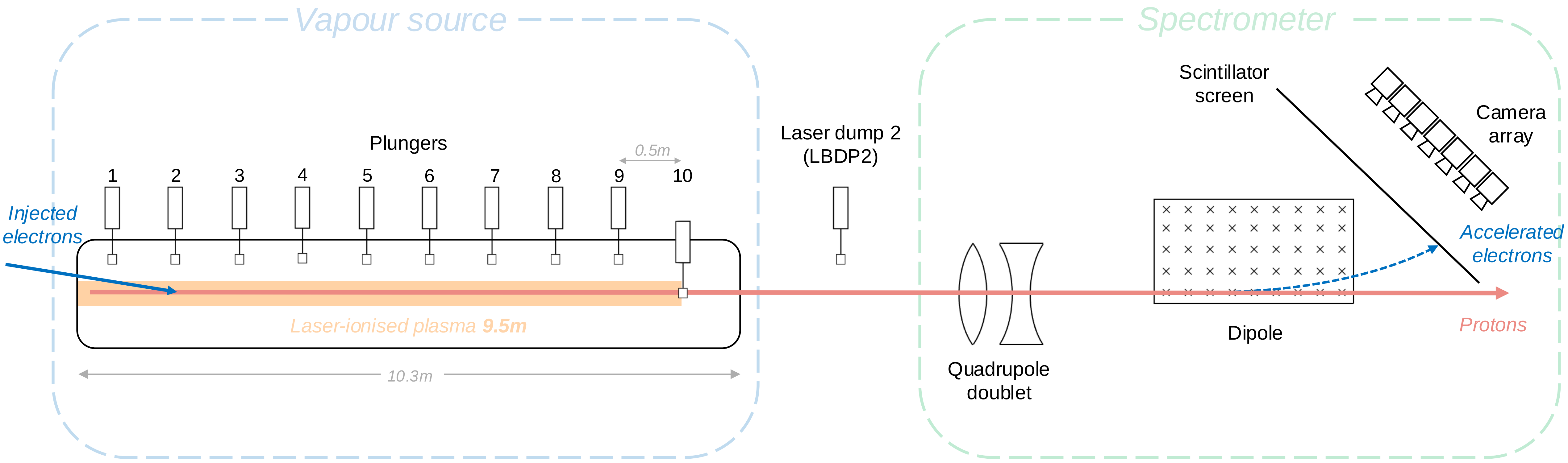

Diagram not drawn to scale

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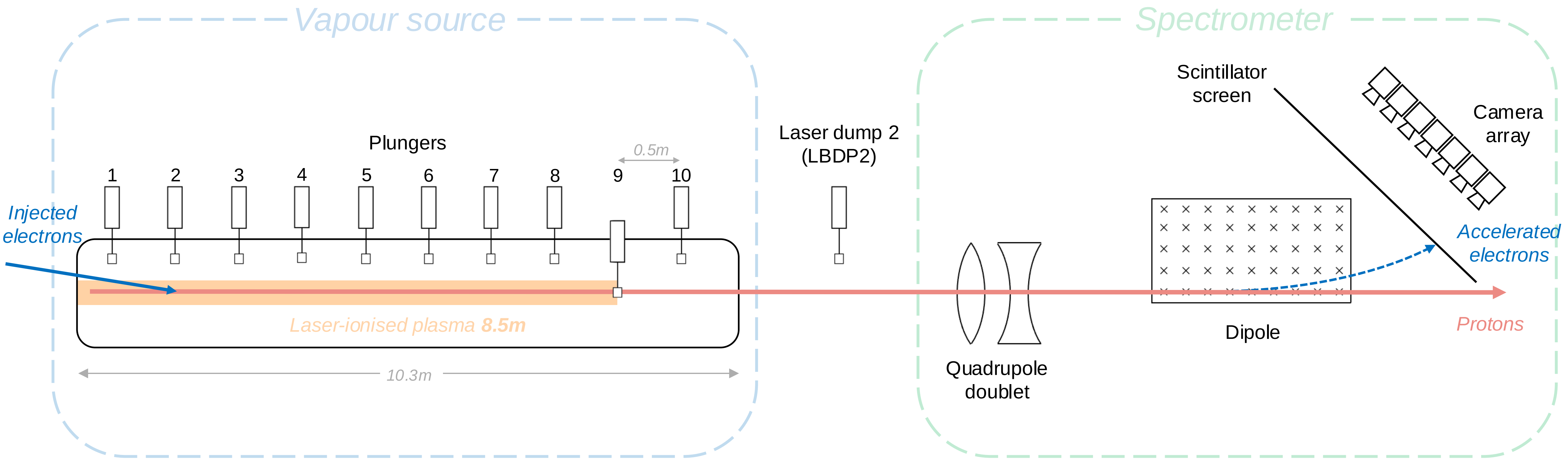

Diagram not drawn to scale

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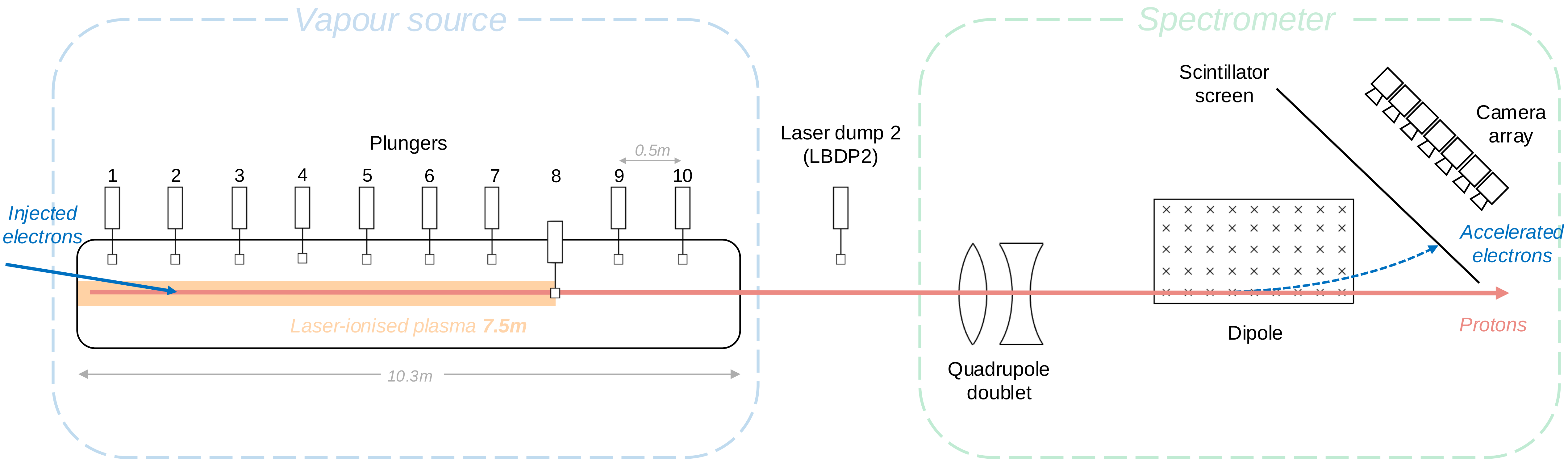

Diagram not drawn to scale

The plunger experiment

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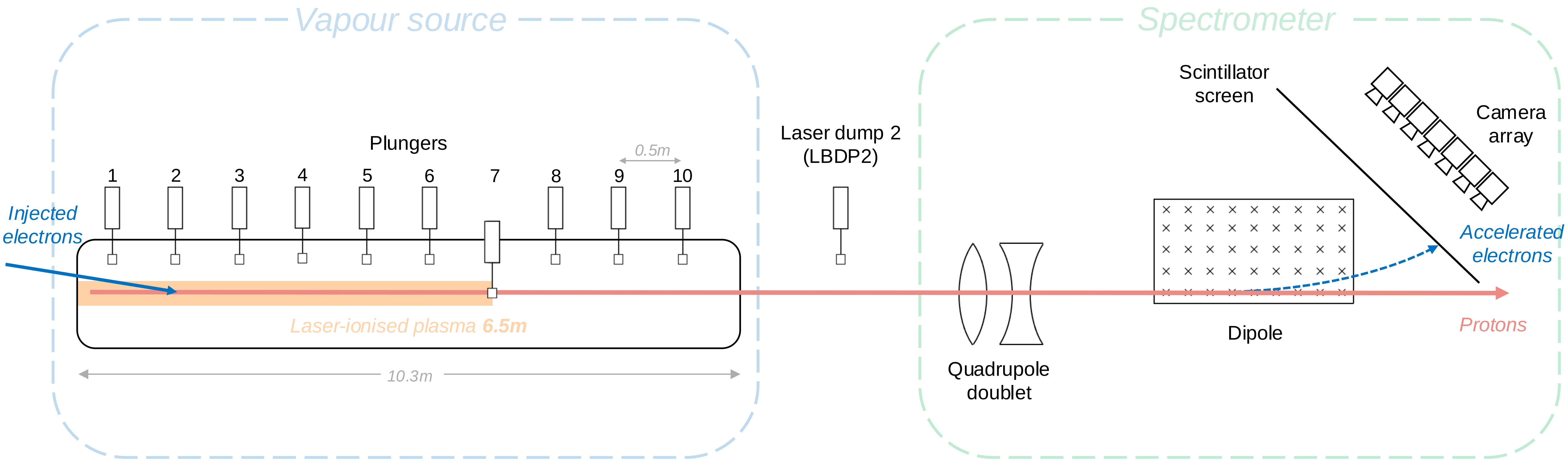


Diagram not drawn to scale

First look: Preliminary results 2024

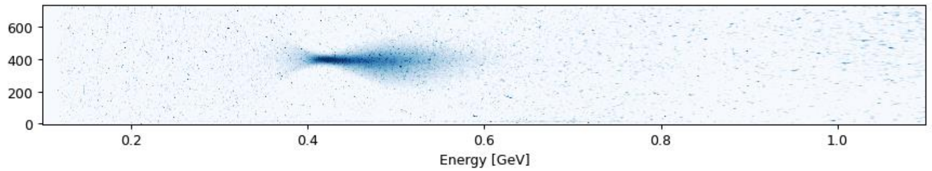
Disclosure: Very fresh results!!

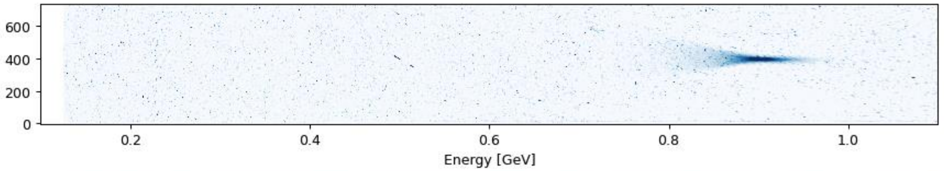
Example signals across the scans

$2\text{x}10^{14}\ \text{cm}^{-3}$, uniform

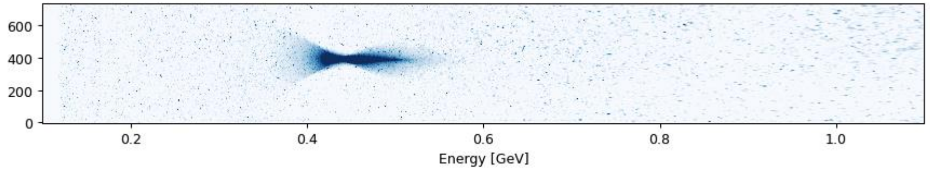
$2\text{x}10^{14}\ \text{cm}^{-3}$, 4% @ 1.25m

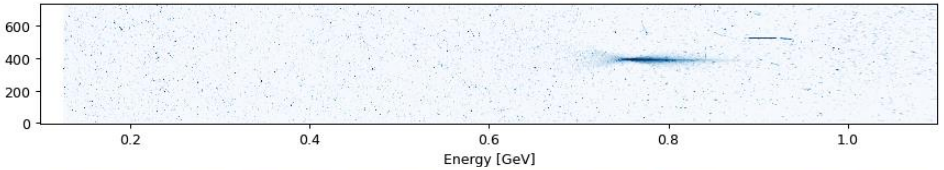
LBDP2
(10.3m)



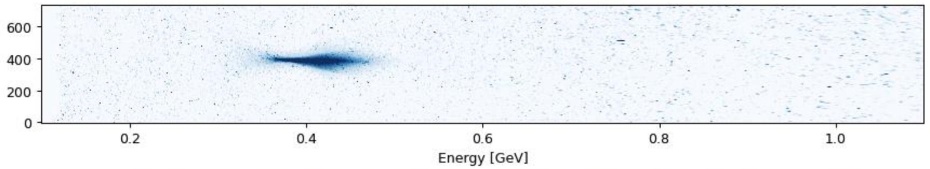


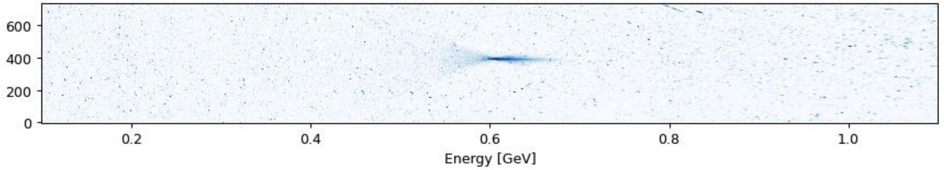
Plunger 10
(9.5m)



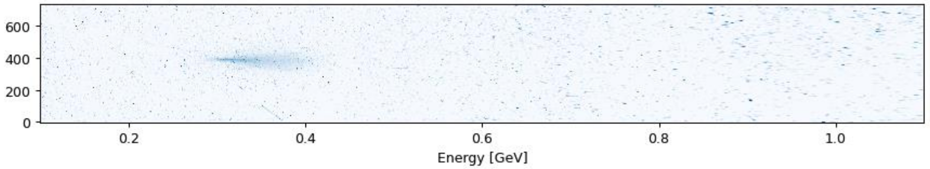


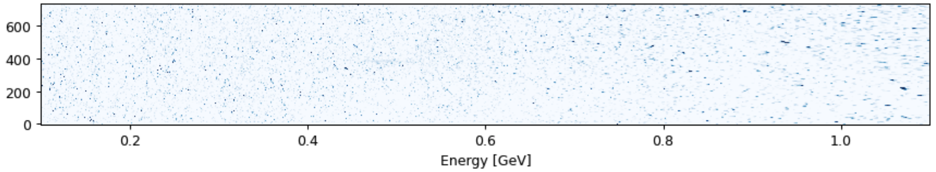
Plunger 9
(8.5m)



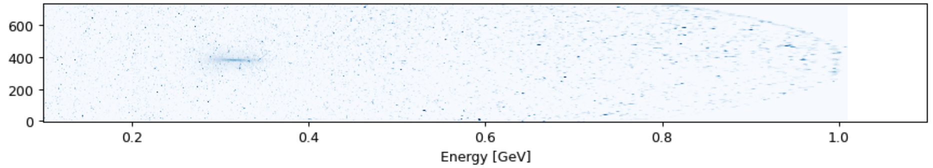


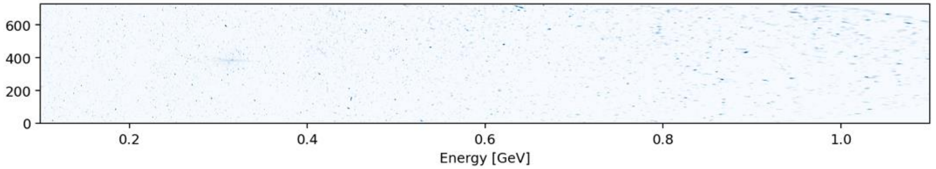
Plunger 8
(7.5m)



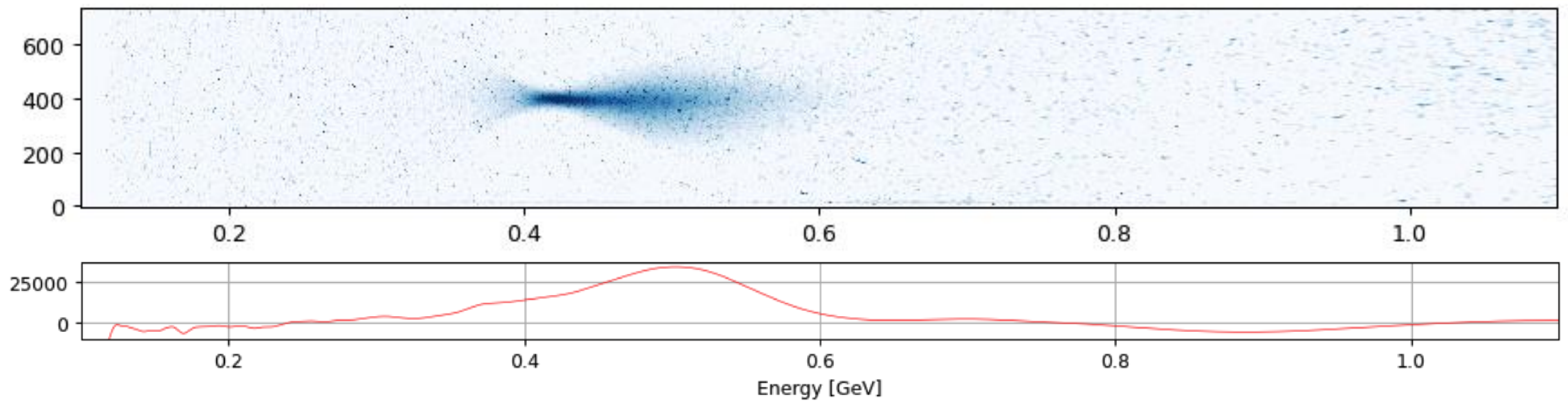


Plunger 7
(6.5m)





Analysis approach



There are multiple ways to approach this analysis:

- Observing the energy of the charge peak (done here)
- Observing the peak (e.g. 95th percentile) in the energy distribution
- Observing the mean and rms of the energy distribution (charge weighted)

All analysis approaches will be completed and compared.

Looking at the charge peak was chosen first, as it is the least sensitive to background subtraction techniques.

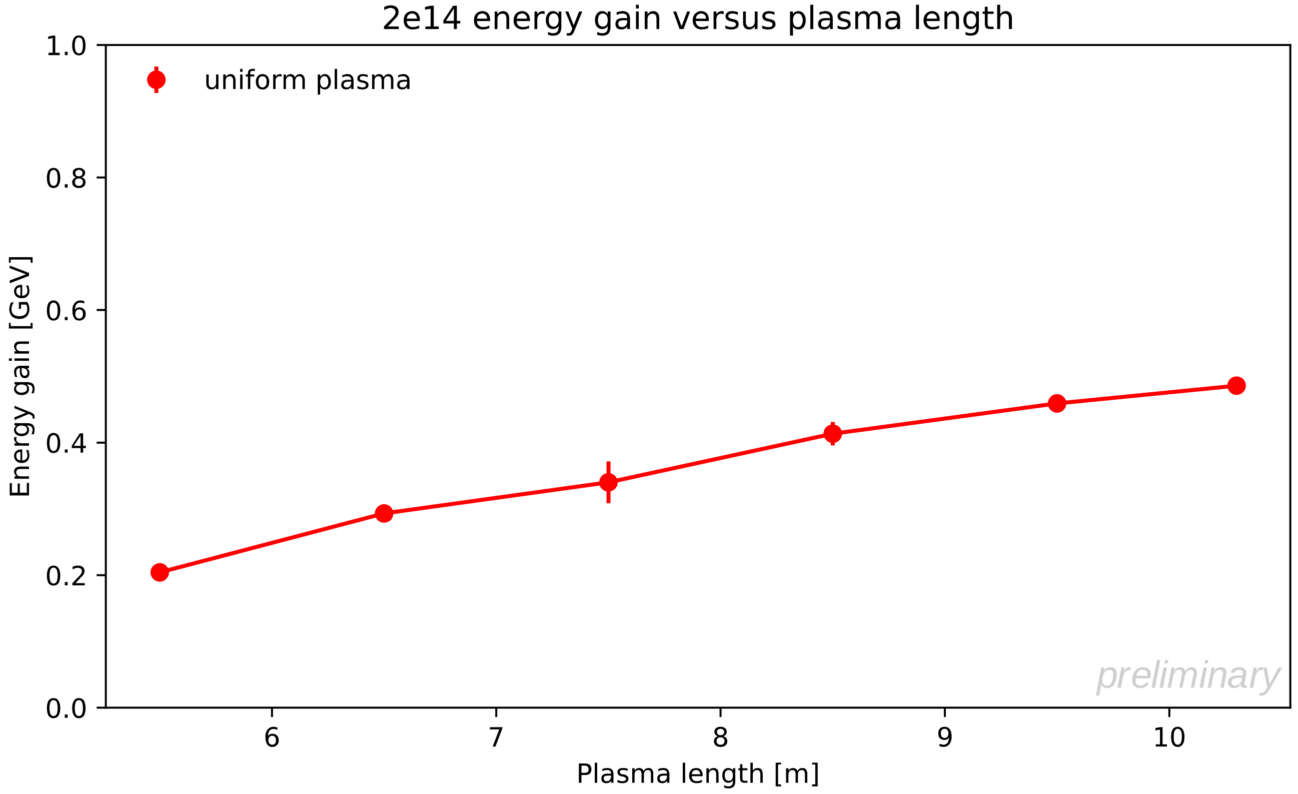
Acceleration at $2\text{x}10^{14}\ \text{cm}^{-3}$

Parameters for this experiment:

- Plasma density $2\text{x}10^{14}\ \text{cm}^{-3}$
- Proton RIF: +100ps
- Electron delay: -100ps (uniform) -200ps (step)
- Injection z: 1.5m
- Density step: ~4% at 1.25m

Clear signal seen up to plunger 6 (5.5m)

Very consistent acceleration, charge peak energy jitter is minimal



Preliminary data analysis:

- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Acceleration at 2x10^{14} cm^{-3}

Parameters for this experiment:

- Plasma density 2x10^{14} cm^{-3}
- Proton RIF: +100ps
- Electron delay: -100ps (uniform) -200ps (step)
- Injection z: 1.5m
- Density step: ~4% at 1.25m

Clear signal seen up to plunger 6 (5.5m)

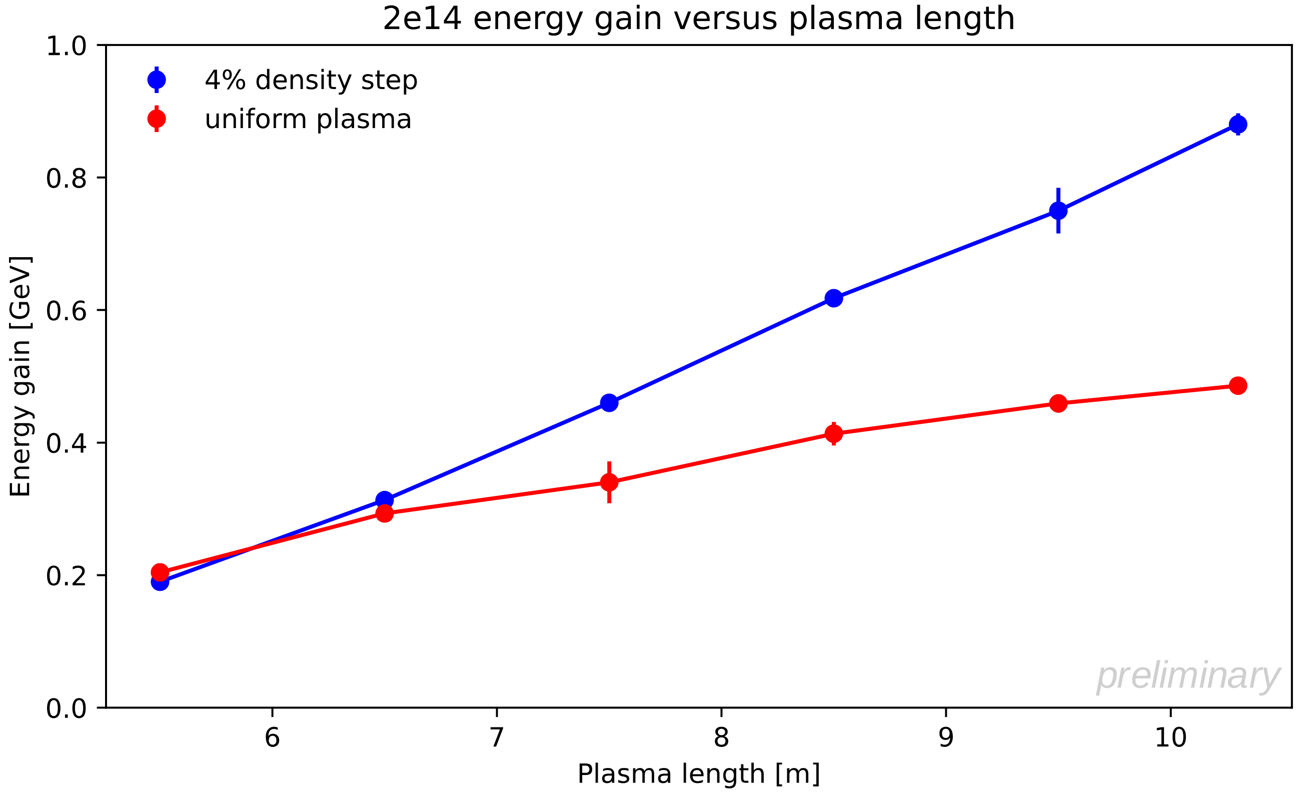
Very consistent acceleration, charge peak energy jitter is minimal

With the density step, the overall energy gain is greater

Seems consistent with theory and 2023 observations

The gradient at uniform *could* be tapering, but it's unconvincing for now

The gradient *appears* constant with the step



Preliminary data analysis:

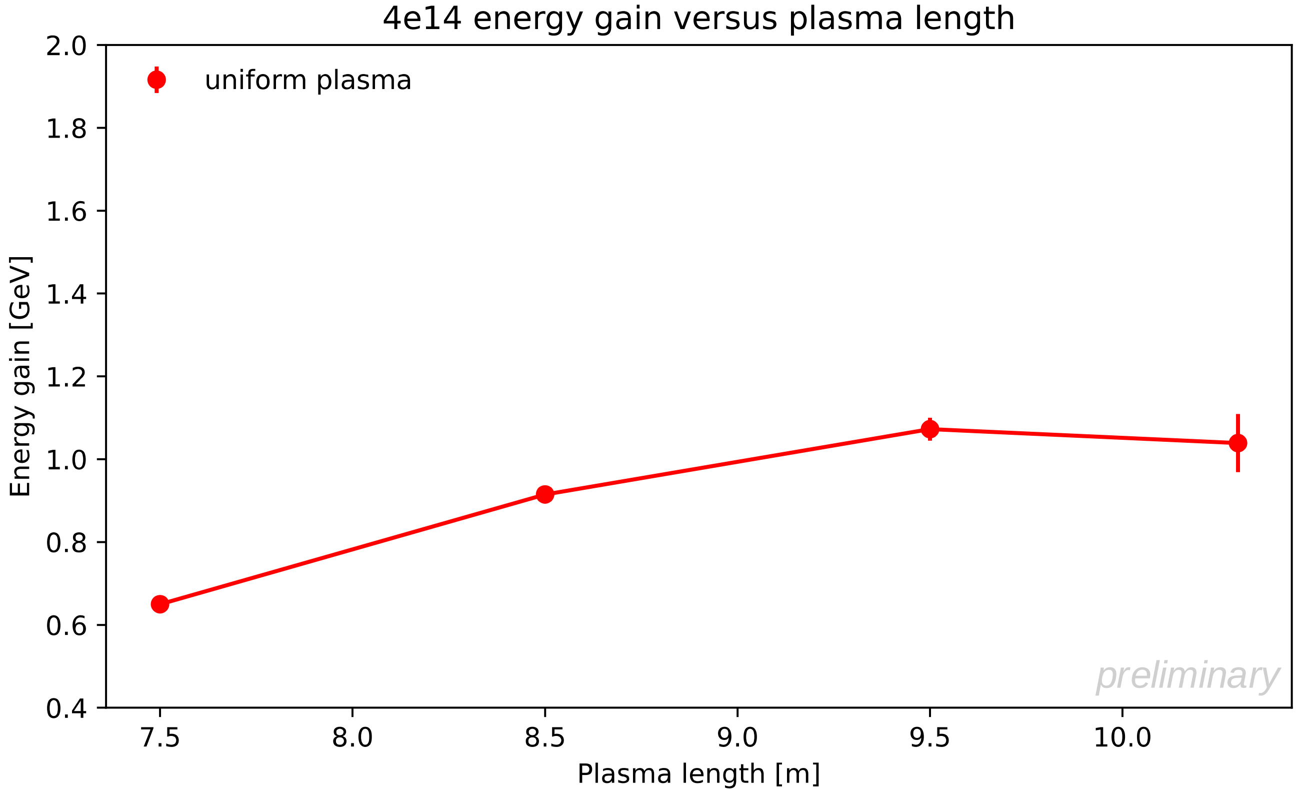
- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Acceleration at 4x10^{14} cm^{-3}

Parameters for this experiment:

- Plasma density 4x10^{14} cm^{-3}
- Proton RIF: +200ps
- Electron delay: -400ps
- Injection z: 1.5m
- Density step: ~2% at 1.25m

Clear signal seen up to plunger 8 (7.5m) in uniform
Acceleration reasonably consistent, charge peak jitter still small
Higher energy gain than 2e14
Tapering of the gradient is more convincing



Preliminary data analysis:

- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Acceleration at $4\text{x}10^{14}\ \mathrm{cm}^{-3}$

Parameters for this experiment:

- Plasma density $4\text{x}10^{14}\ \mathrm{cm}^{-3}$
- Proton RIF: +200ps
- Electron delay: -400ps
- Injection z: 1.5m
- Density step: ~2% at 1.25m

Clear signal seen up to plunger 8 (7.5m) in uniform

Acceleration reasonably consistent, charge peak jitter still small

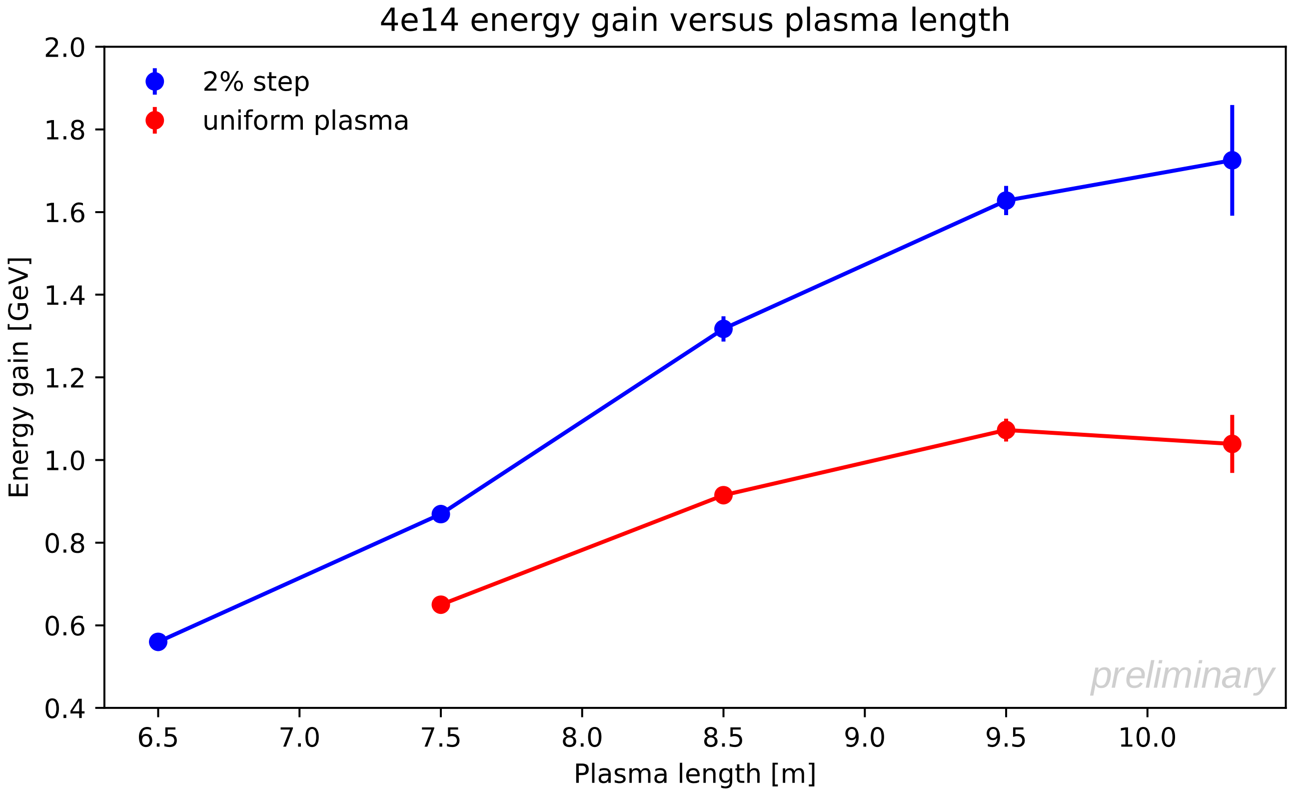
Higher energy gain than 2e14

Tapering of the gradient is more convincing

Clear signal seen up to plunger 7 (6.5m) with a step

With the density step, the overall energy gain is again greater

The gradient with the density step is also tapering similarly to uniform, which may suggest an alternative step would be better



Preliminary data analysis:

- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Acceleration at $7x10^{14}$ cm^{-3}

Parameters for this experiment:

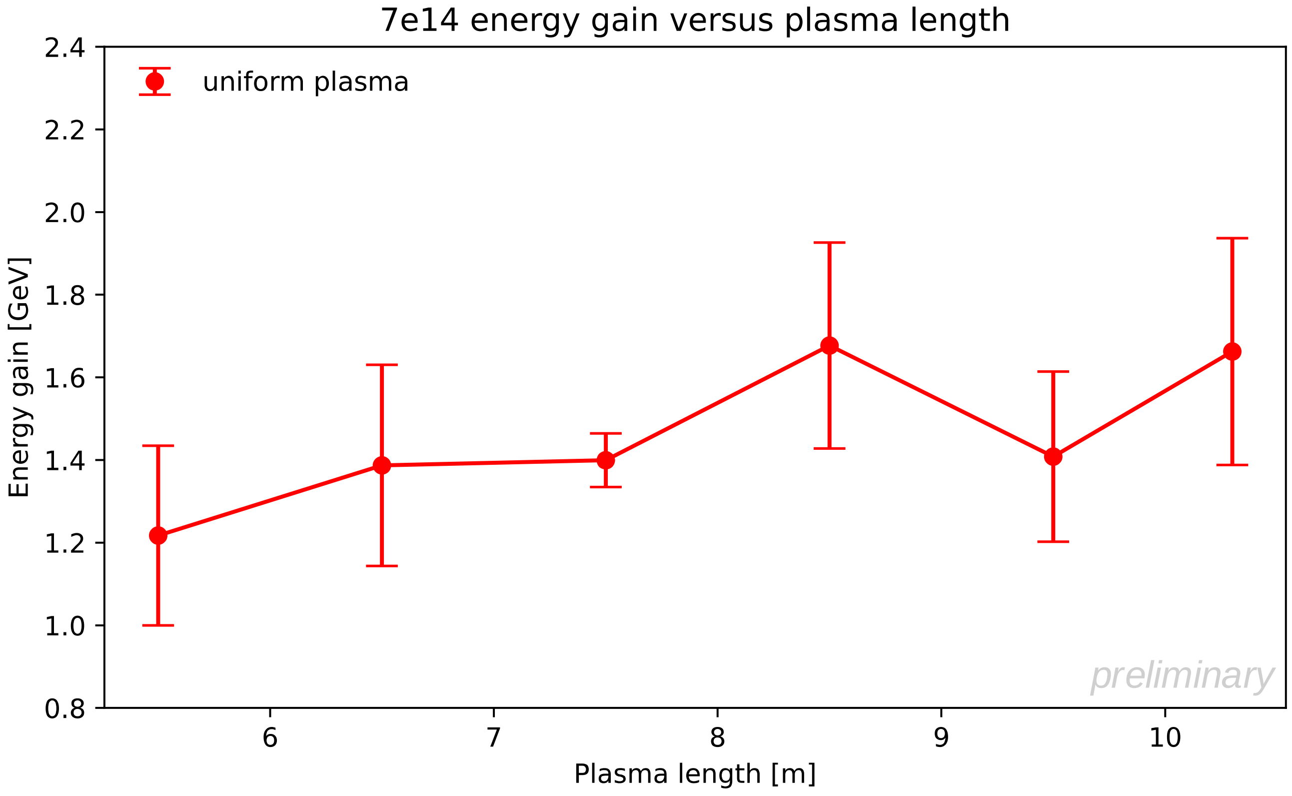
- Plasma density $7x10^{14}$ cm^{-3}
- Proton RIF: 0ps (uniform) +200ps (step)
- Electron delay: -320ps (uniform) -300ps (step)
- Injection z: 1.5m
- Density step: ~1.8% at 1.25m

Clear signal seen up to plunger 6 (5.5m) in uniform

Higher energy than 2e14 and 4e14

Acceleration is less consistent, charge peak energy jitters

There is little observed acceleration in the final ~5 meters of uniform plasma



Preliminary data analysis:

- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Acceleration at 7x10^{14} cm^{-3}

Parameters for this experiment:

- Plasma density 7x10^{14} cm^{-3}
- Proton RIF: 0ps (uniform) +200ps (step)
- Electron delay: -320ps (uniform) -300ps (step)
- Injection z: 1.5m
- Density step: ~1.8% at 1.25m

Clear signal seen up to plunger 6 (5.5m) in uniform

Higher energy than 2e14 and 4e14

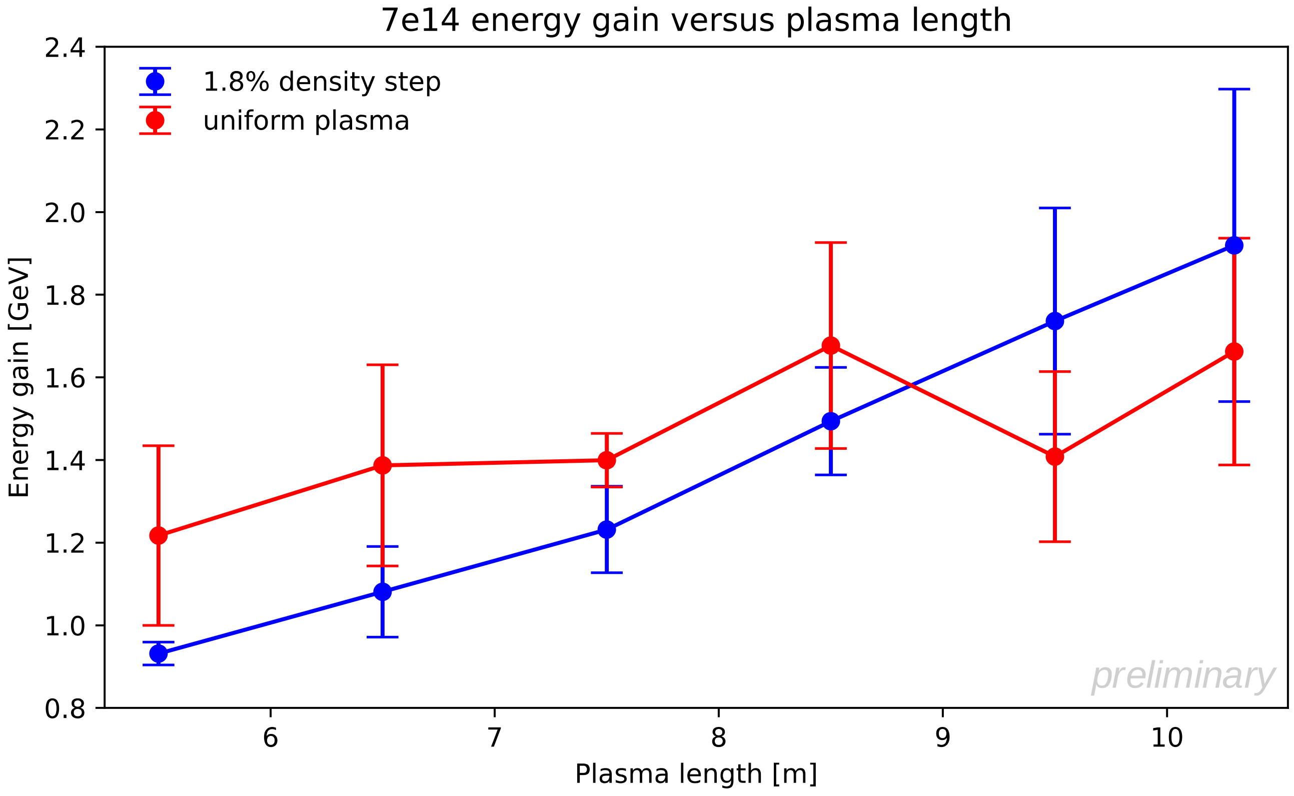
Acceleration is less consistent, charge peak energy jitters

There is little observed acceleration in the final ~5 meters of uniform plasma

With the density step, we have acceleration in the final ~5 meters of plasma, but the gradient is low

Looking to answer:

- Are the higher fields there, but we cannot inject into them?
- Or are the fields not higher with this chosen step?



Preliminary data analysis:

- 10 shots directed onto each plunger
- Data points: The mean of the charge peaks
- Error bars: Standard deviation of the charge peaks

Summary

A key goal for AWAKE Run 2b is to demonstrate the effect of the density step on the wakefield amplitude

The plunger experiments allow us to study the energy gain as a function of the plasma length:

- We have plunger scan results, comparing uniform and a density step, at three different plasma densities (2e14, 4e14, 7e14)
- Low density experiments seem more consistent with theoretical expectations
- High density experiments remain challenging, with greater variations in energy and charge capture

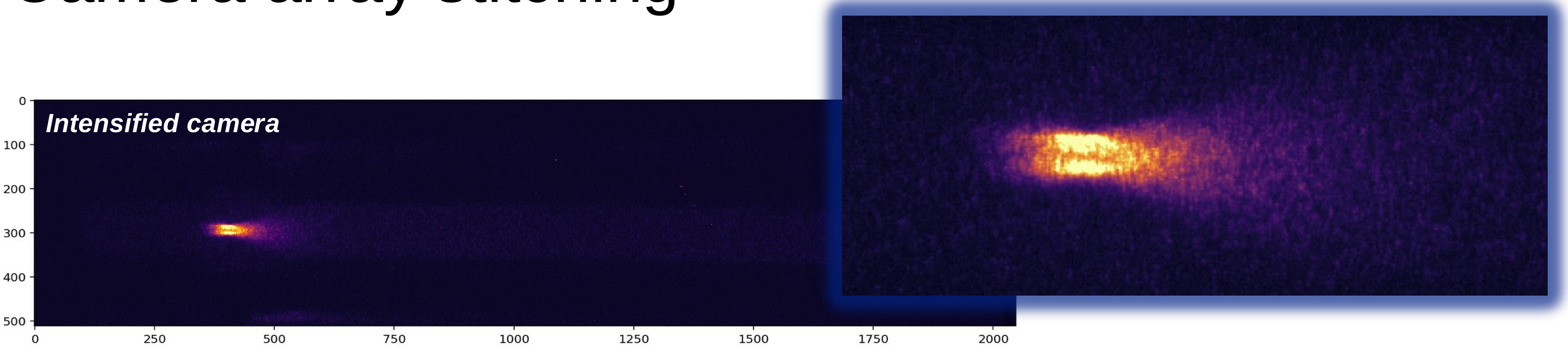
Analysis continues including:

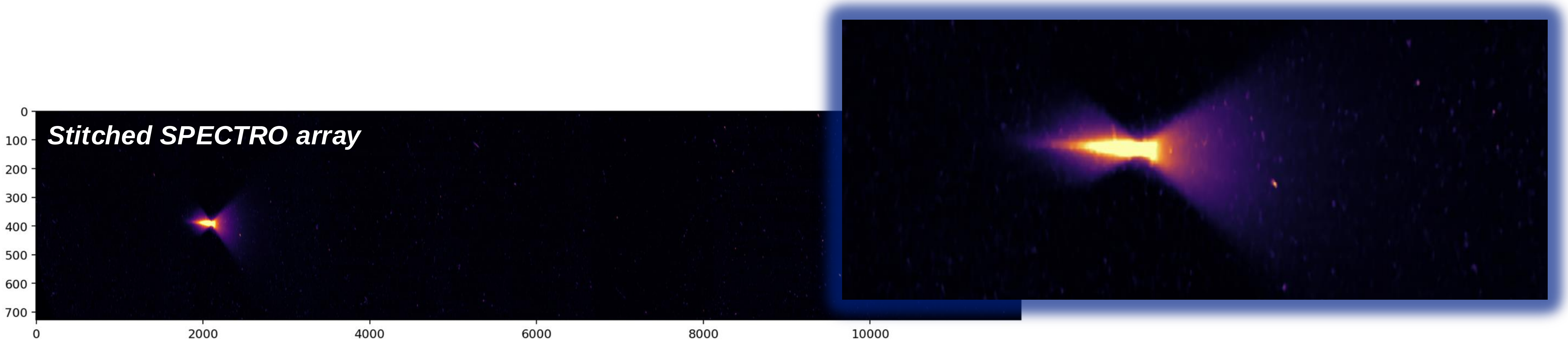
- Measurements of the energy gain with plasma length (peak charge, peak energy, mean energy)
- Accelerated charge over the plasma length
- Single shot emittance measurements, including the effect of the plasma exit ramp

Thanks for listening!

Backup slides

Camera array stitching

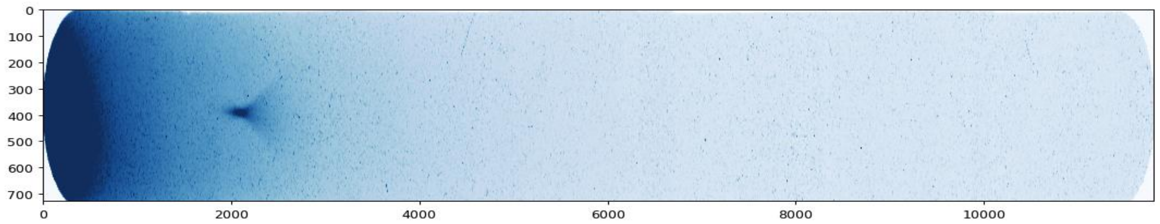




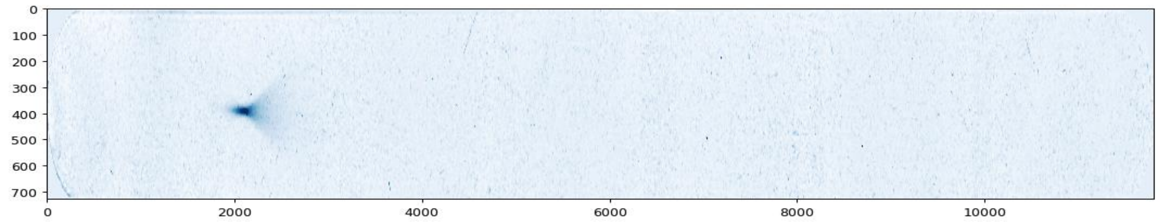
The analysis approach

Experimental update

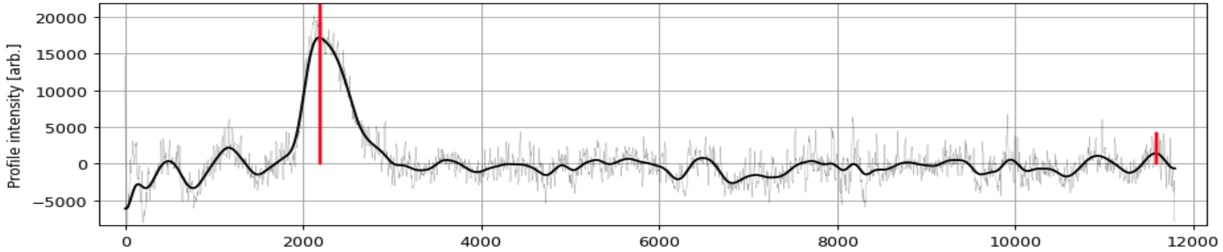
Obtain the 7-camera, corrected and stitched image of the acceleration event



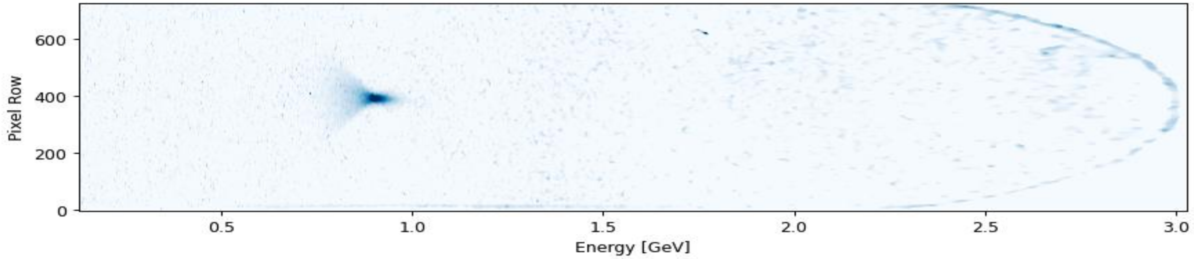
Apply a background subtraction to enhance the signal. Used here: strong background subtraction based off fits to various AWAKE proton conditions



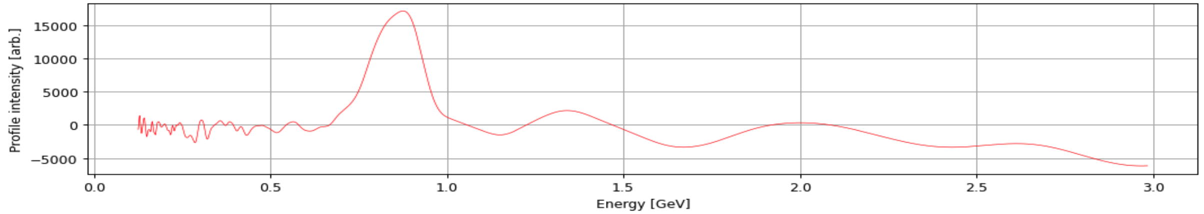
Identify location of peak in the image. Done here by sampling random intervals, optimising and binning.



Convert the image from pixels to energy via the spectrometer position to energy conversion model



Convert the 1D pixel array of the event into energy via the spectrometer position to energy conversion model



The experimental approach

Experimental update

Select the configuration (RIF and eDelay) that suits the uniform and density step case

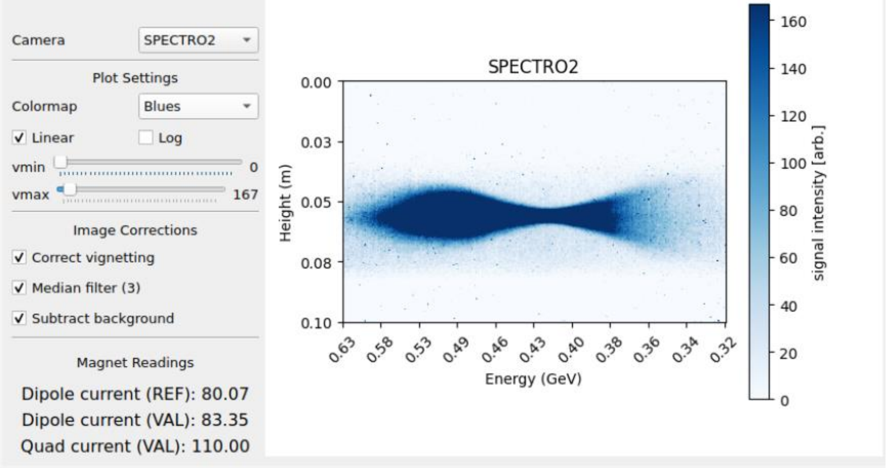
Check stability and reproducibility under standard accelerating conditions (no foils, full 10 meters)

Check charge capture through LBDP2, to assess how likely signal will be seen through a plunger

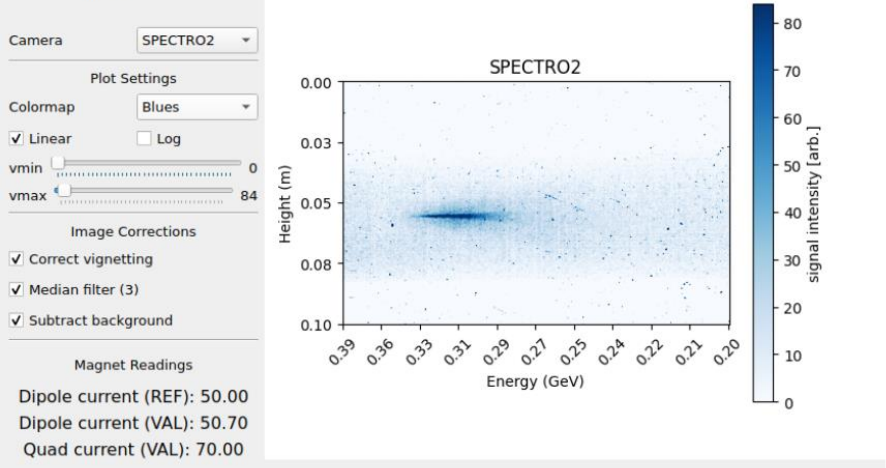
10 laser shots delivered on each plunger, until no hint of a signal remains. For each plunger:

- The spectrometer quadrupoles are shifted in accordance with the altered spectrometer geometry and predicted energy gain.
- The spectrometer dipole is moved to place the signal, regardless of energy, on SPECTRO2. This is to minimise over-dispersing weaker signals, as well as avoiding the highest radiation camera.

LBDP2 (10 meters acceleration)



Plunger 7 (6.5 meters acceleration)



Grid scans

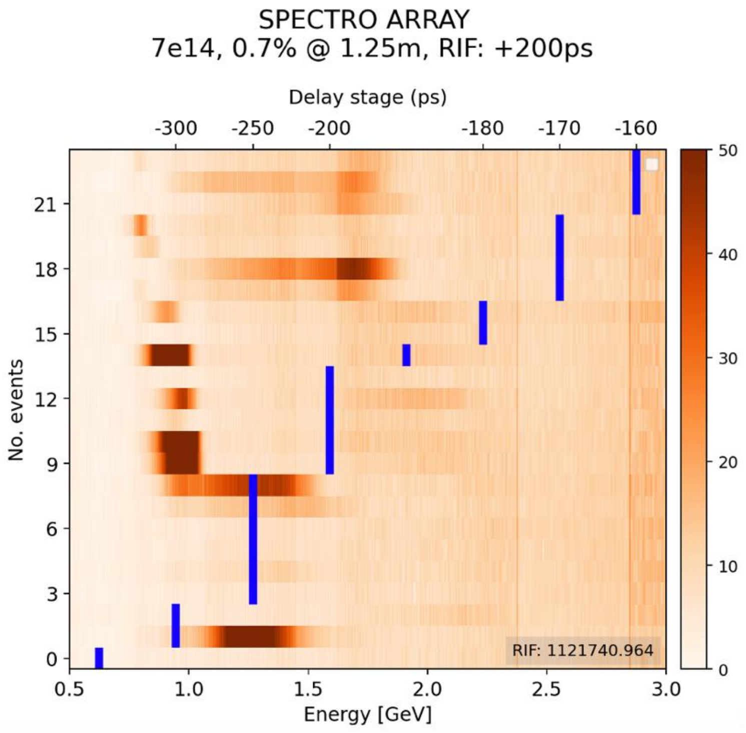
Summary: 7e14 *Note: vmax the same to allow for intensity comparison*

SPECTRO ARRAY

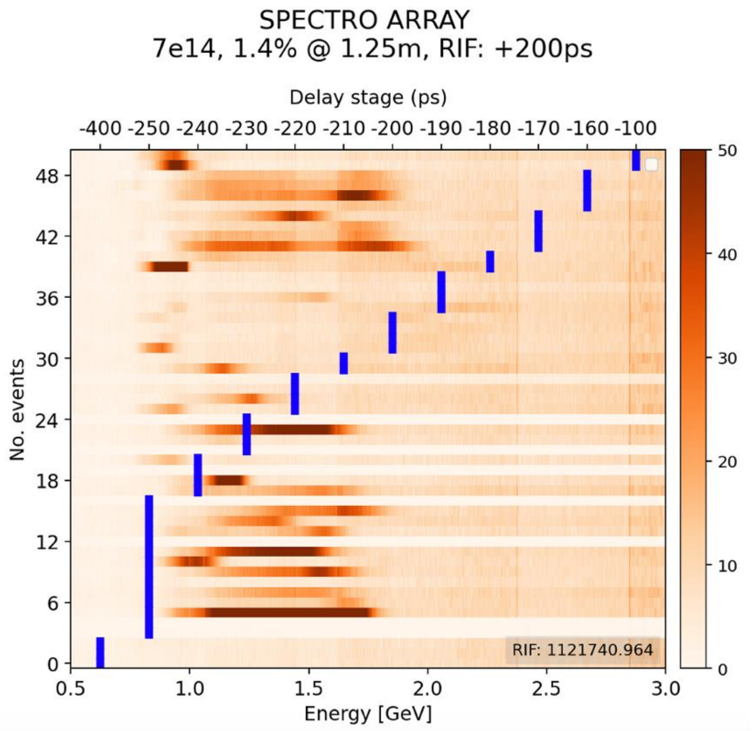
October 4th 2024

Injection 1.5m, RIF + 200

0.7% @ 1.25m



1.4% @ 1.25m



1.8% @ 1.25m