Energy gain with plasma density steps

AWAKE Collaboration Meeting
15.10.25

F. Pannell and the AWAKE Collaboration

Motivation for acceleration in Run 2b
Plasma density steps

The plunger experiment
Method and 2024 results

Linking experiment with simulation
LCODE 2D

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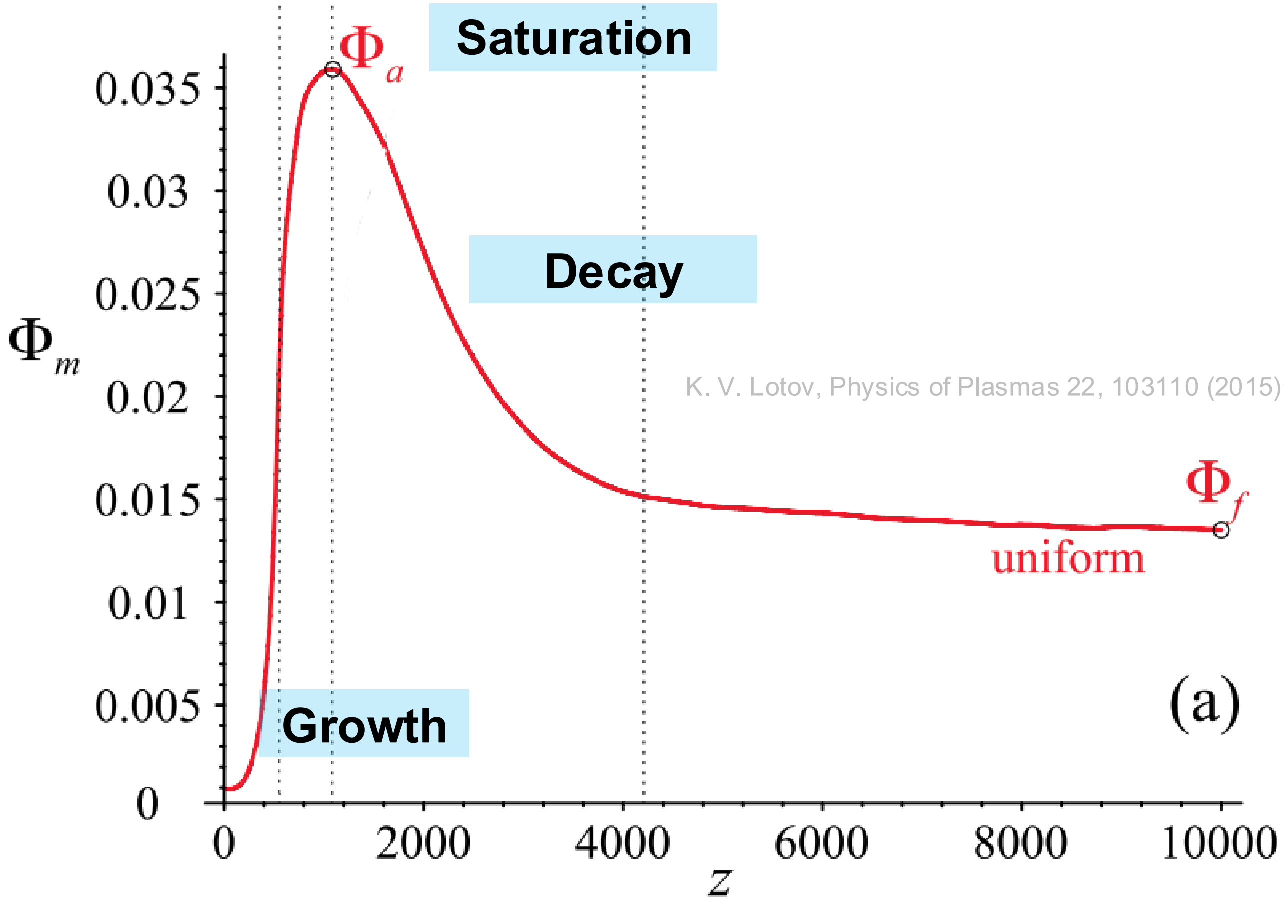
AWAKE Run 2b

AWAKE transition: From proof-of-concept towards acceleration quality and scalability

We know that, in a uniform plasma, the accelerating field decreases after the saturation of SSM

Microbunch train continues to evolve after saturation → decay in wakefield amplitude

Scaling in a uniform plasma is challenging → accelerating gradient quickly drops off after a few meters



K. V. Lotov, Physics of Plasmas 22, 103110 (2015)

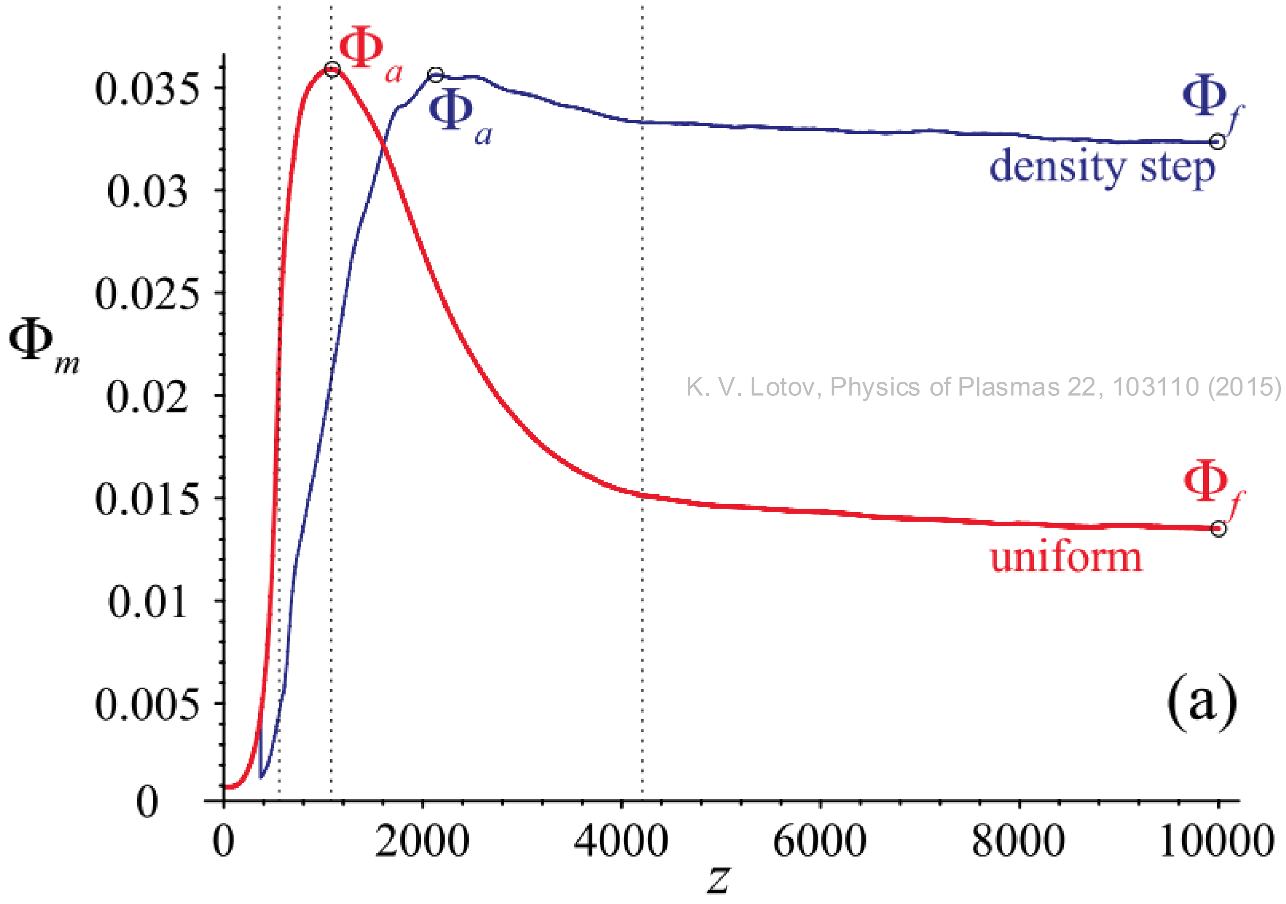
AWAKE Run 2b

Numerical simulations:

- Small, positive density step in the growth region
- Wakefields maintain large amplitude beyond saturation point

This is vital for **scalability** → maintaining high gradients over long distances.

We can use the **acceleration** of externally injected electrons to probe the longitudinal wakefield amplitude



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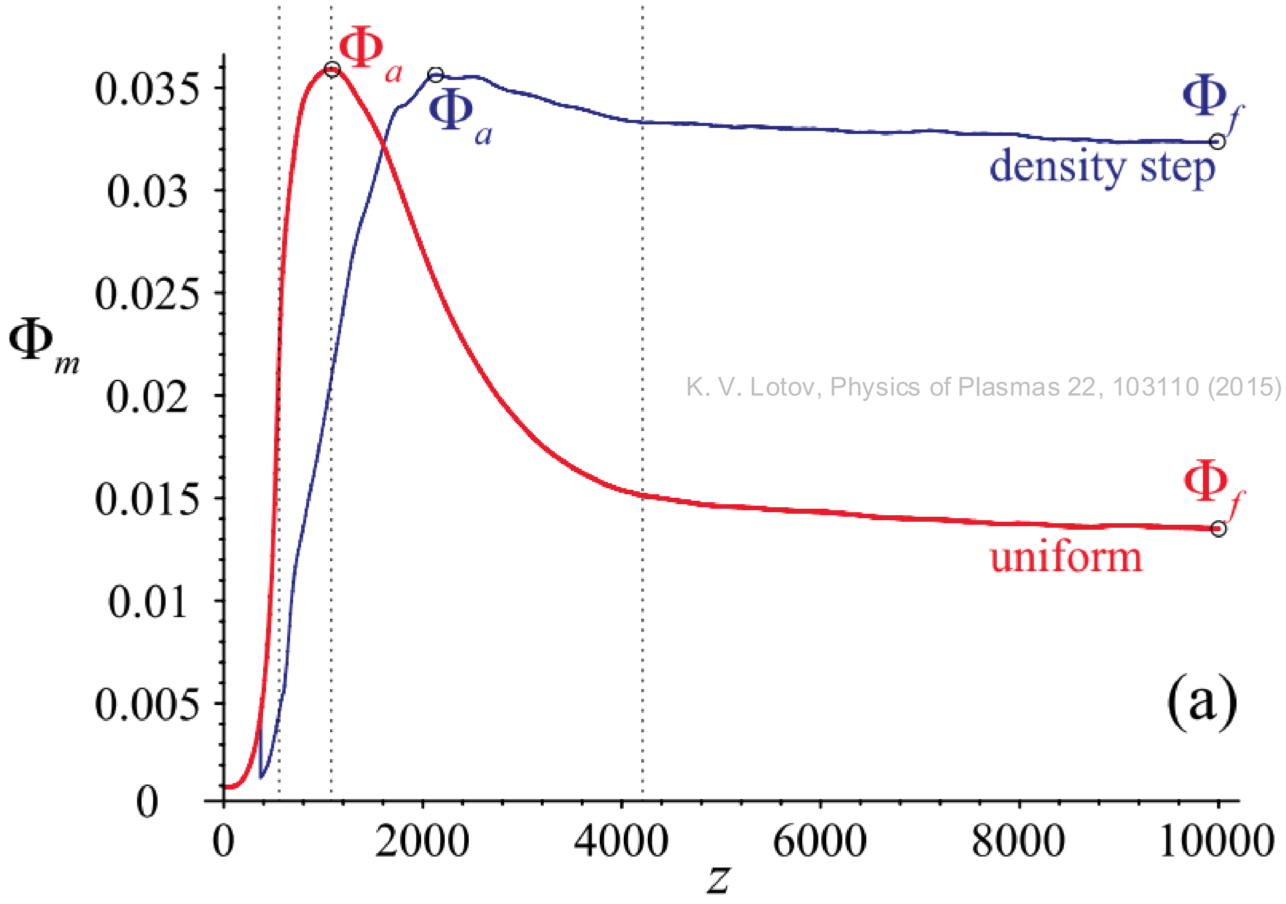
Key goal of AWAKE Run 2b:

Demonstrate an experimental understanding of the effect of plasma density steps on energy gain



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We can attempt to perform a direct measurement on the accelerating gradient (dE/dz)

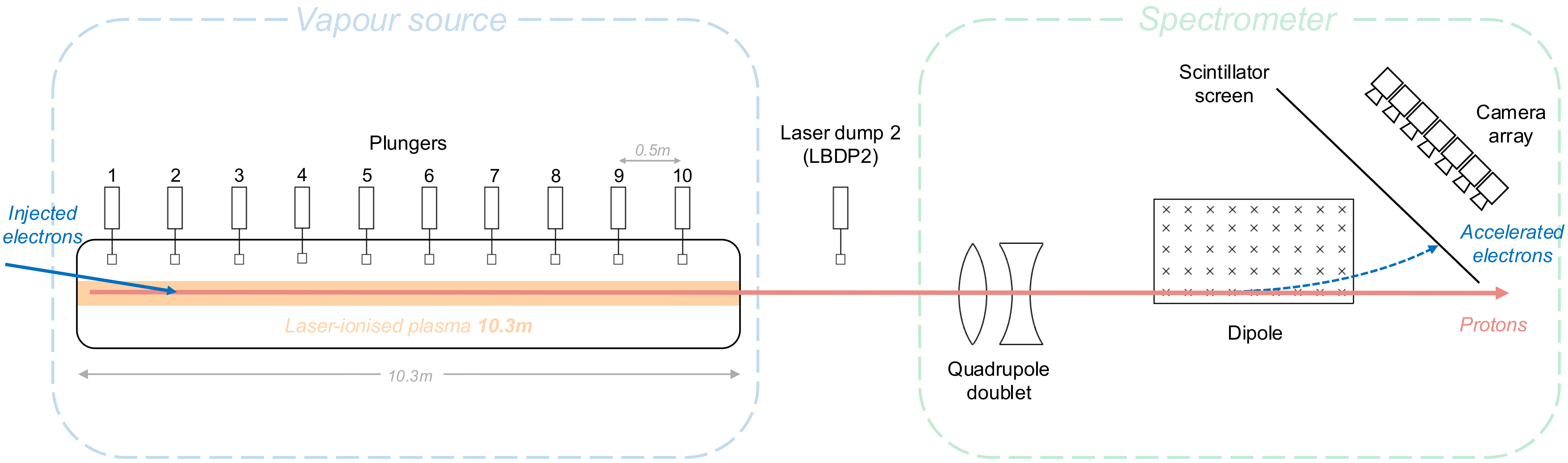


Diagram not drawn to scale

Requirement 1: Consistent acceleration

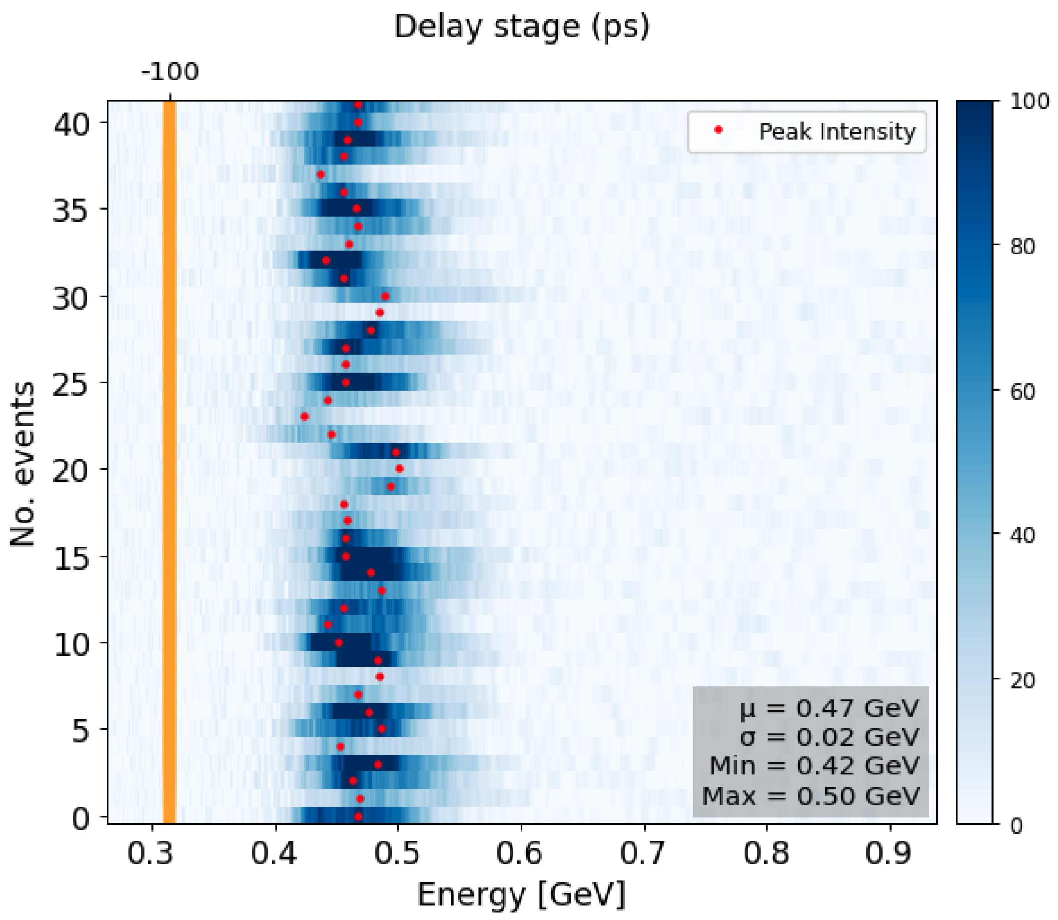
Limited number of shots of laser pulse onto foil (~500)

Must limit the shots on each plunger (~10 per foil).

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

This includes:

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



Requirement 2: Sufficient charge capture

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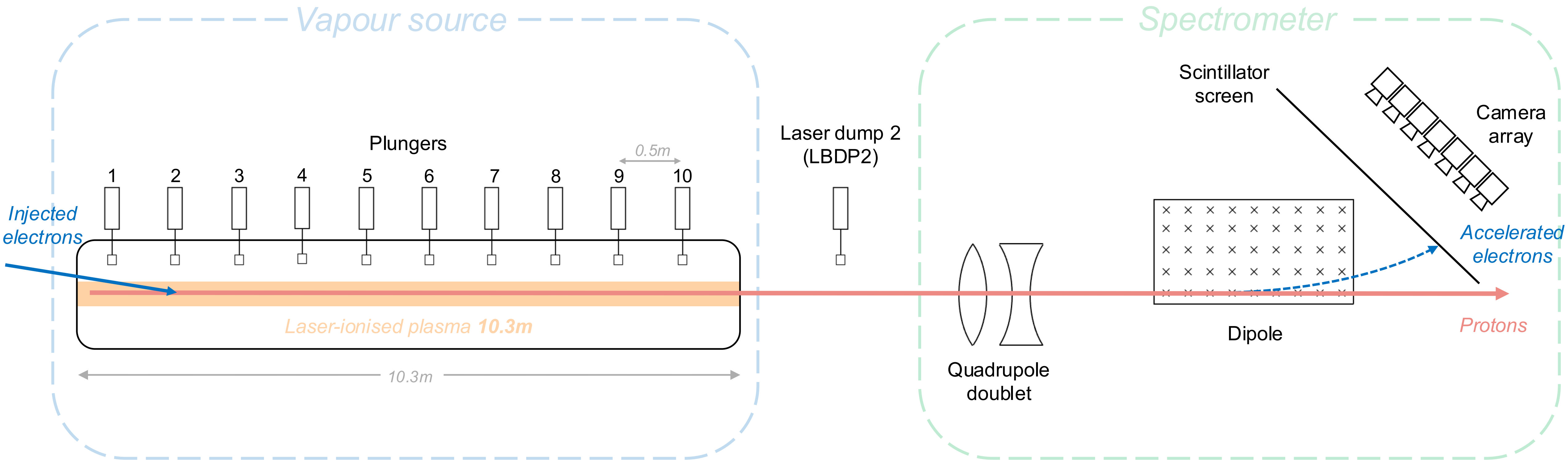

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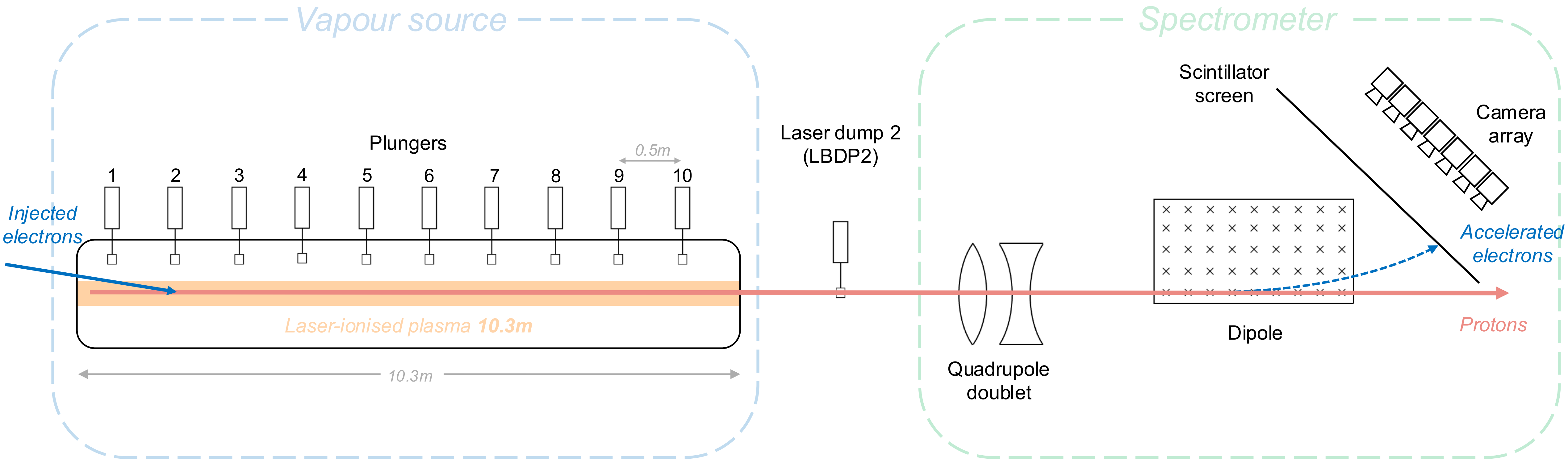

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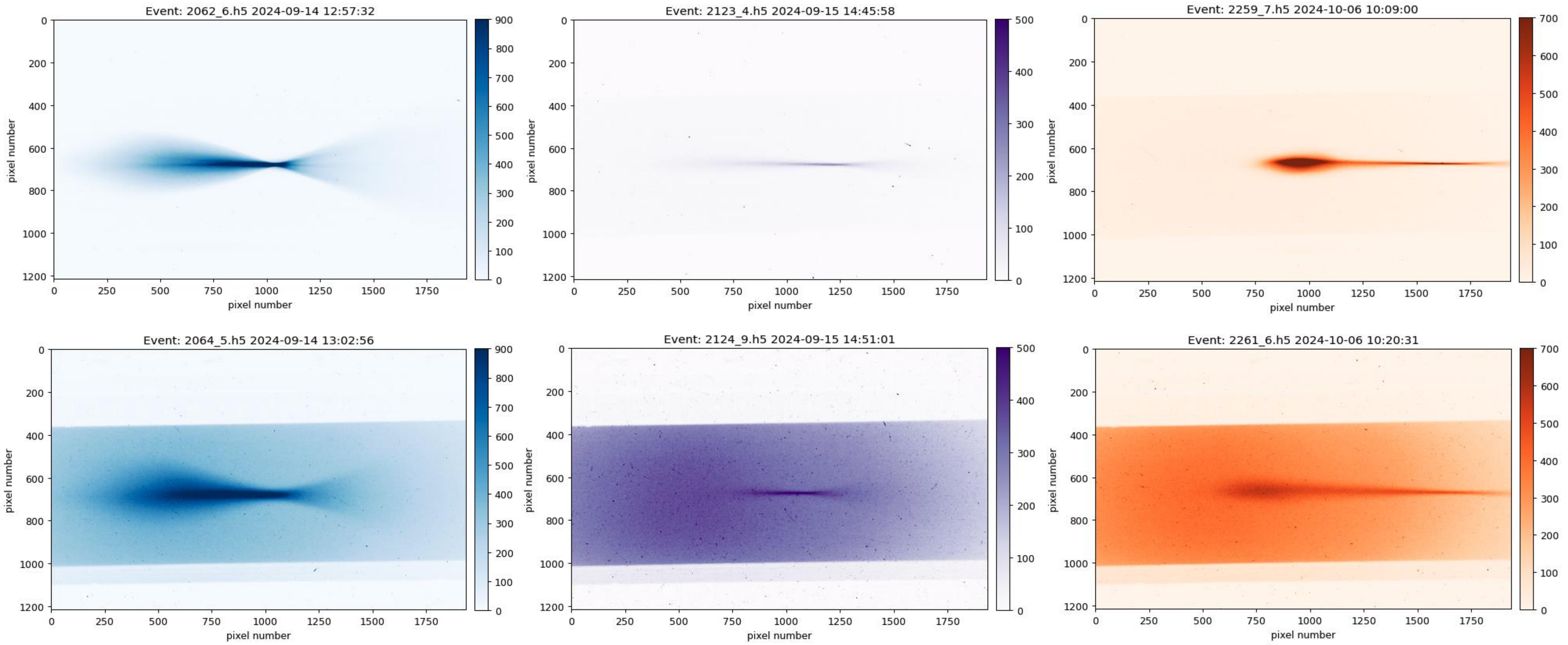
Requirement 2: Sufficient charge capture

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

Standard acceleration

Through Laser dump



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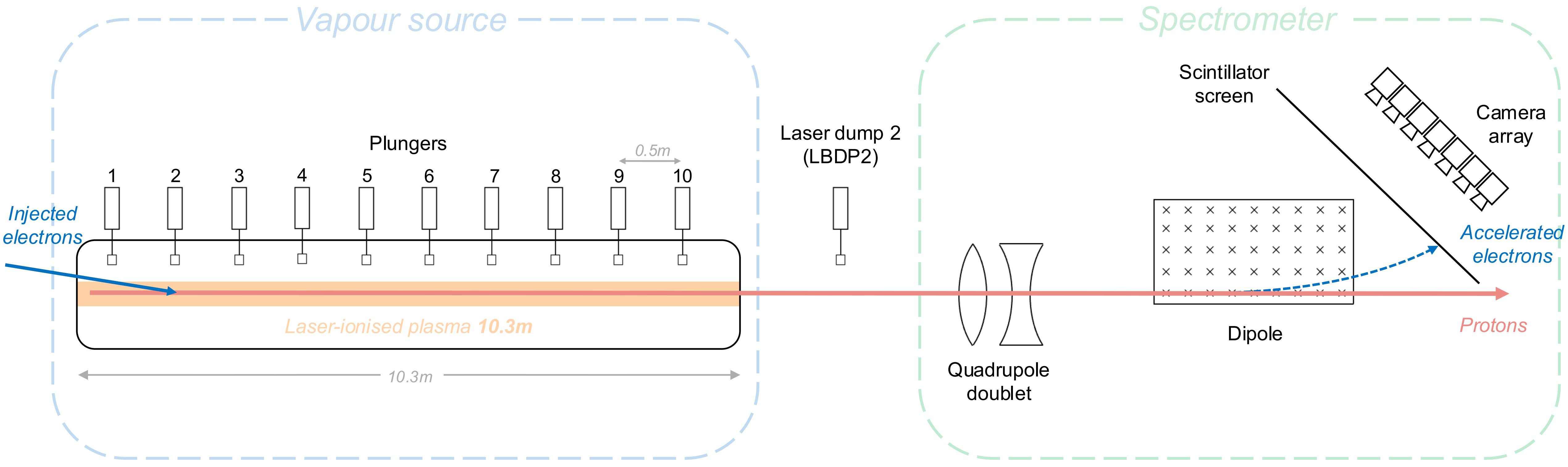

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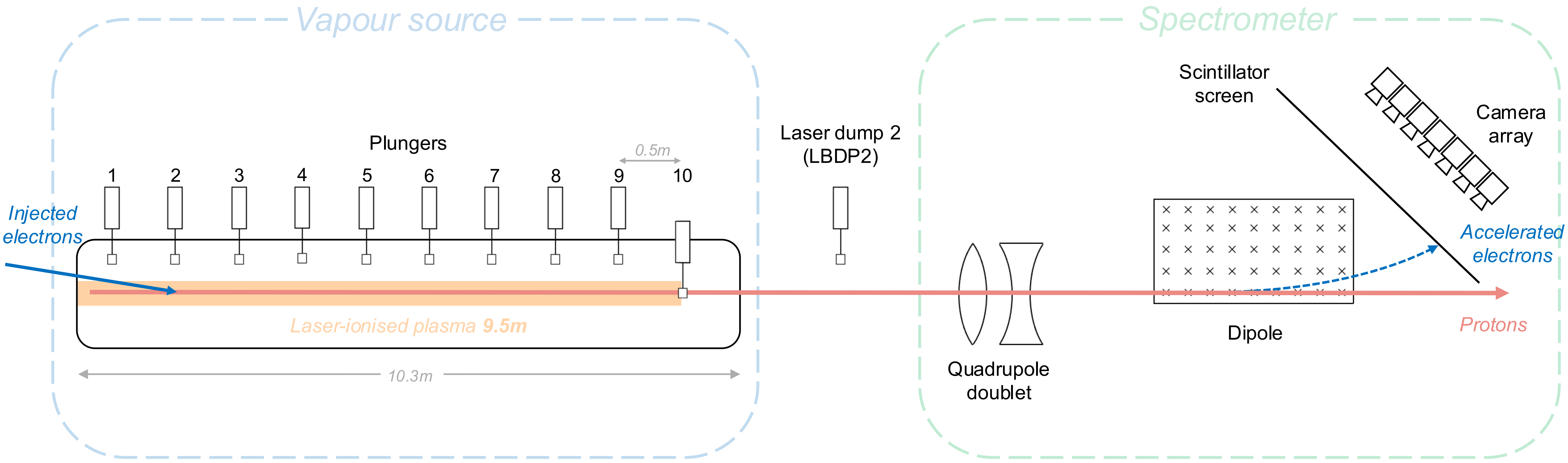

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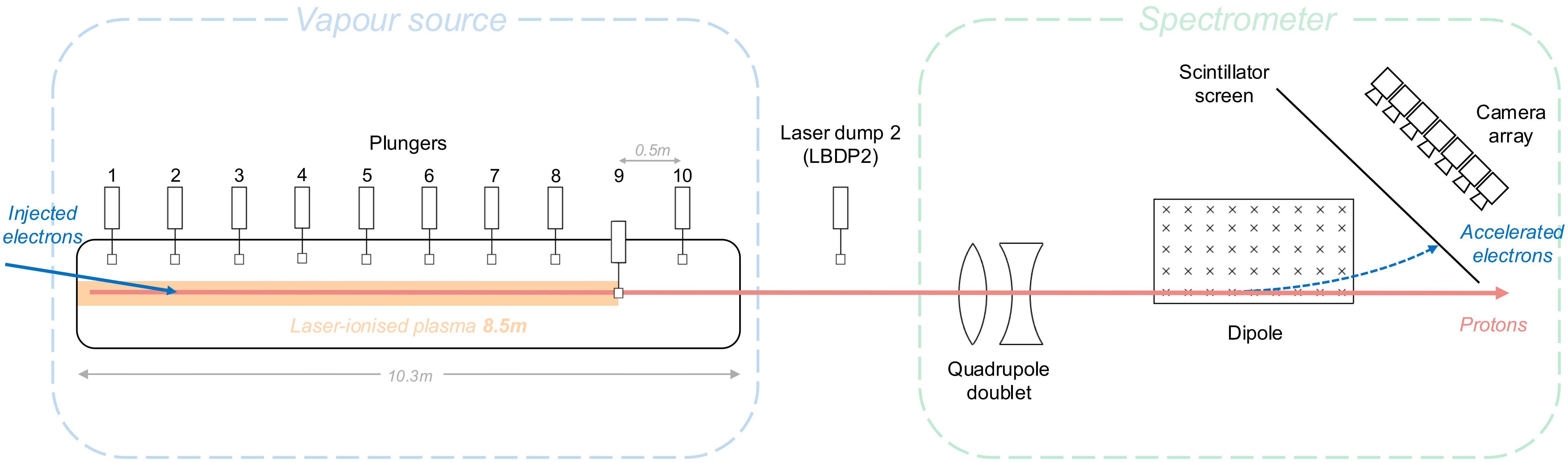

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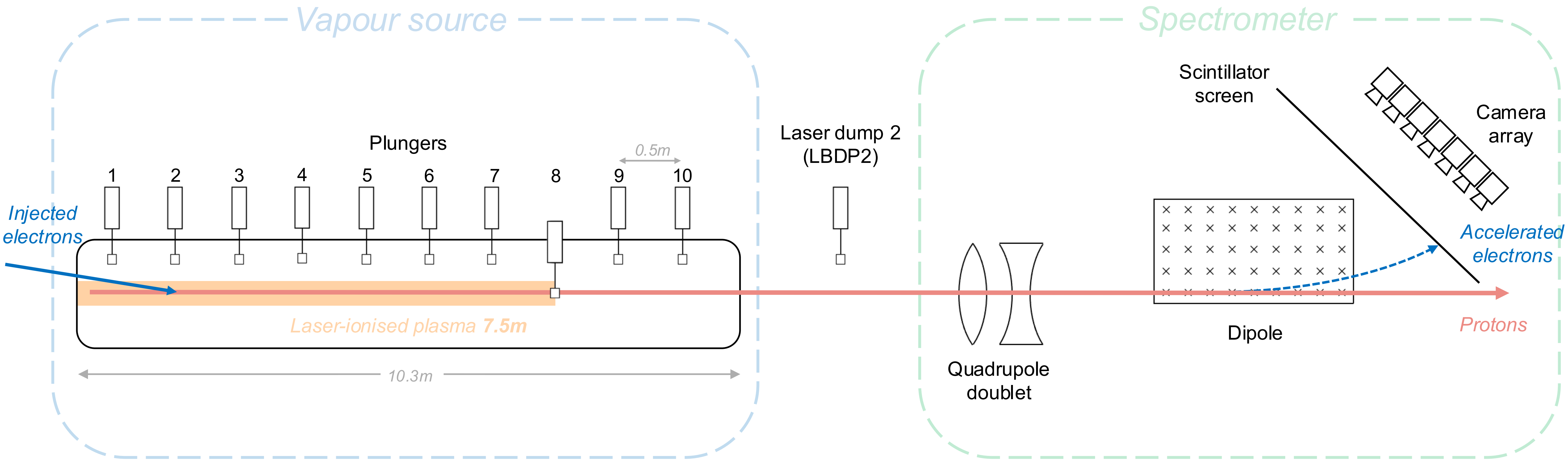

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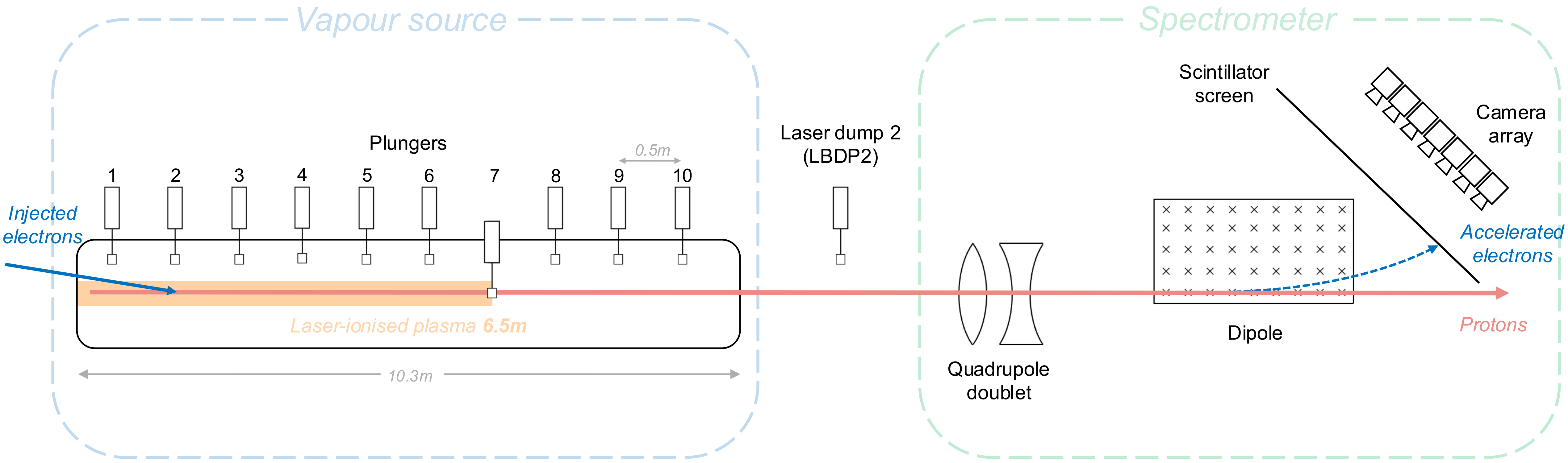

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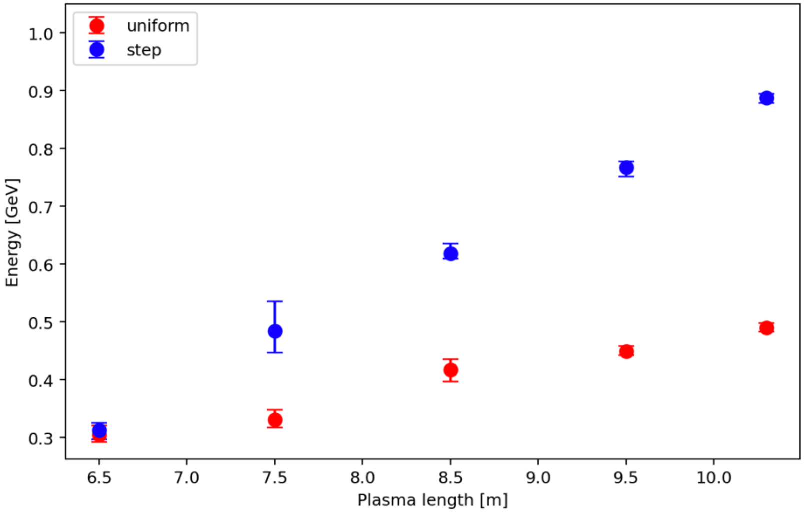
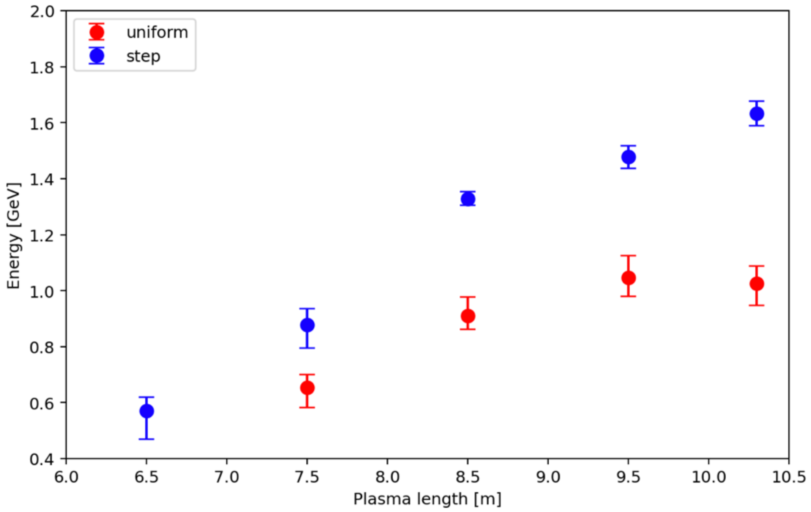
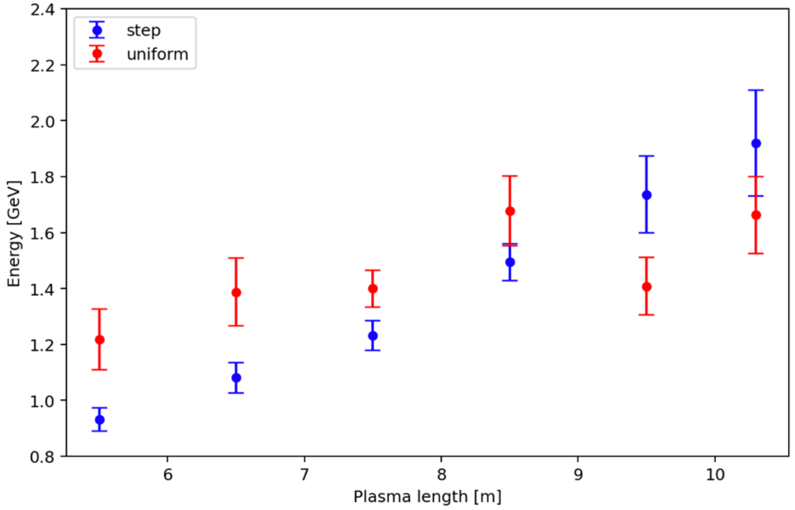
Plunger scans

The plunger scan results for 3 different densities







Parameter	Uniform	Step
Plasma density	$2.0 \times 10^{14} cm^{-3}$	$1.9 \times 10^{14} cm^{-3}$
Proton RIF	+100ps	+100ps
Electron delay	-100ps	-200ps
Injection z	1.5m	1.5m
Step height	-	3.9%
Step z	-	1.25m

Parameter	Uniform	Step
Plasma density	$3.8 \times 10^{14} cm^{-3}$	$3.8 \times 10^{14} cm^{-3}$
Proton RIF	+200ps	+200ps
Electron delay	-400ps	-400ps
Injection z	1.5m	1.5m
Step height	-	2.3%
Step z	-	1.25m

Parameter	Uniform	Step
Plasma density	$7.4 \times 10^{14} cm^{-3}$	$7.3 \times 10^{14} cm^{-3}$
Proton RIF	0ps	+200ps
Electron delay	-320ps	-300ps
Injection z	1.5m	1.5m
Step height	-	1.8%
Step z	-	1.25m

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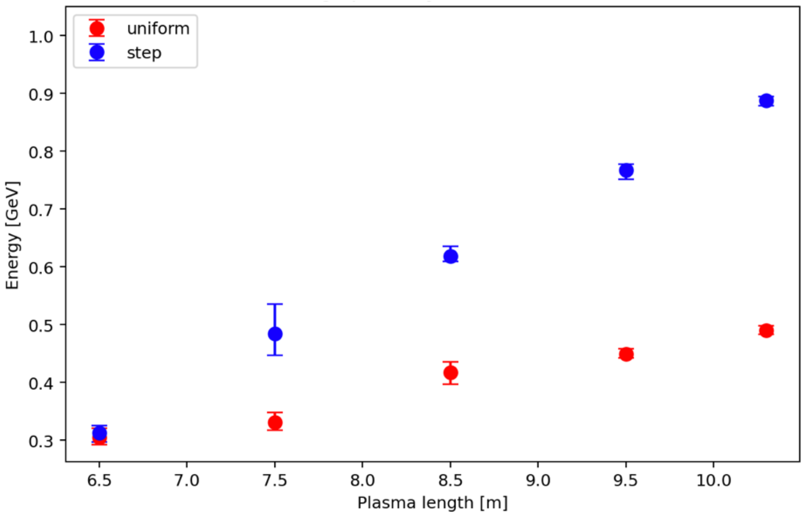

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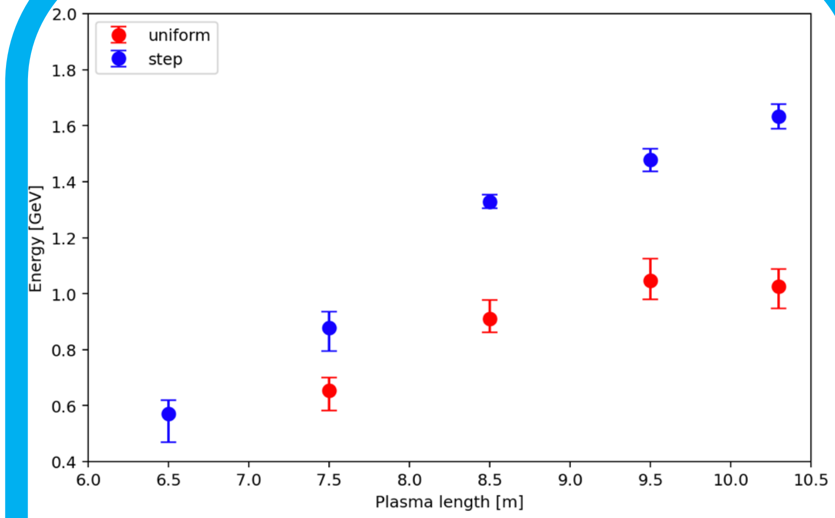

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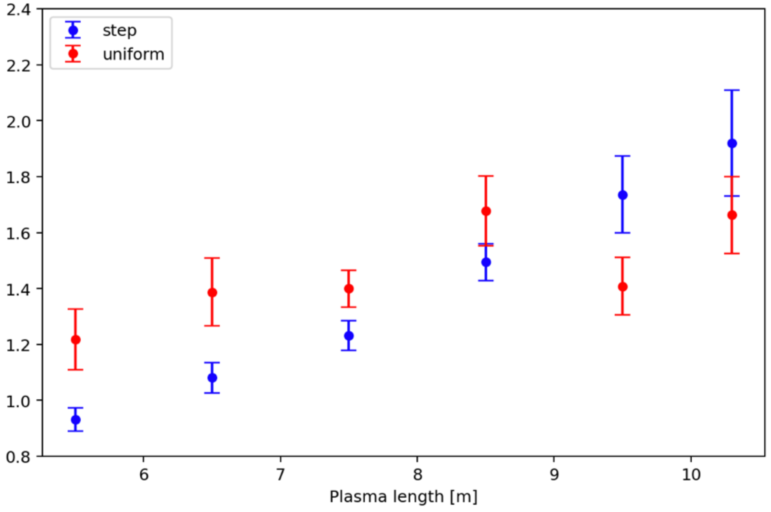

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Using LCODE 2D (K. Lotov et. al)

https://lcode.inp.nsk.su/site-files/manual.pdf

and Generalized LCODE Seeder for Protons, GLSP (J. Farmer)

https://indico.cern.ch/event/1498727/

Simulations with only the fields, no work with test particles (shown here)

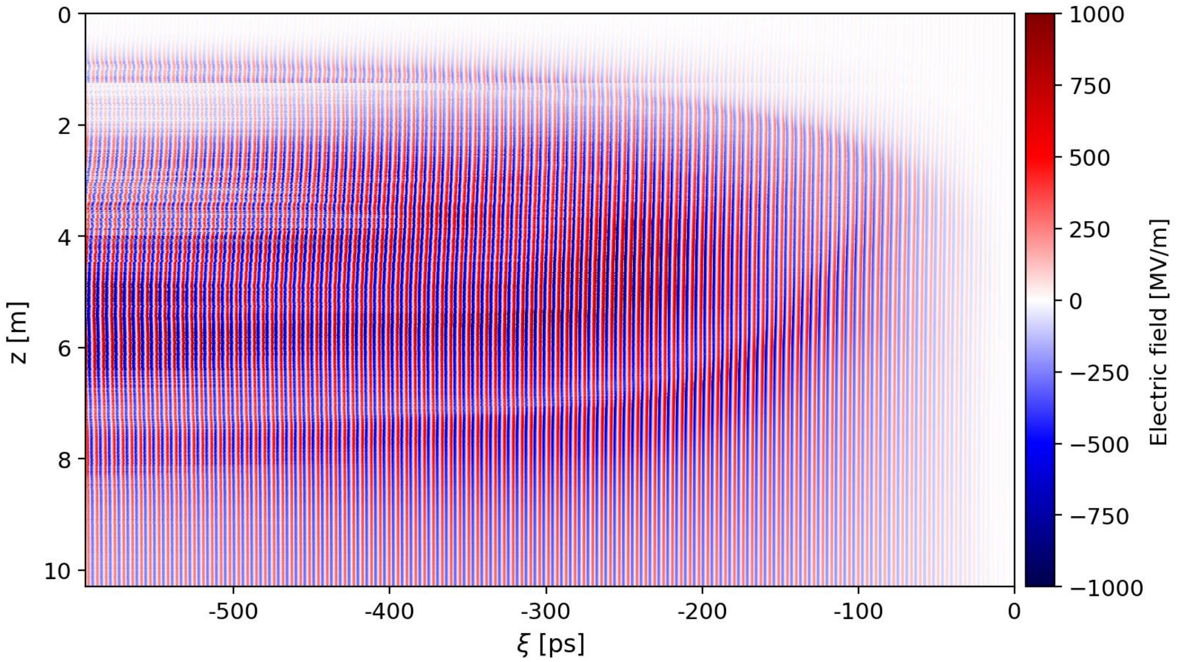
First-order approximation

Work is ongoing !

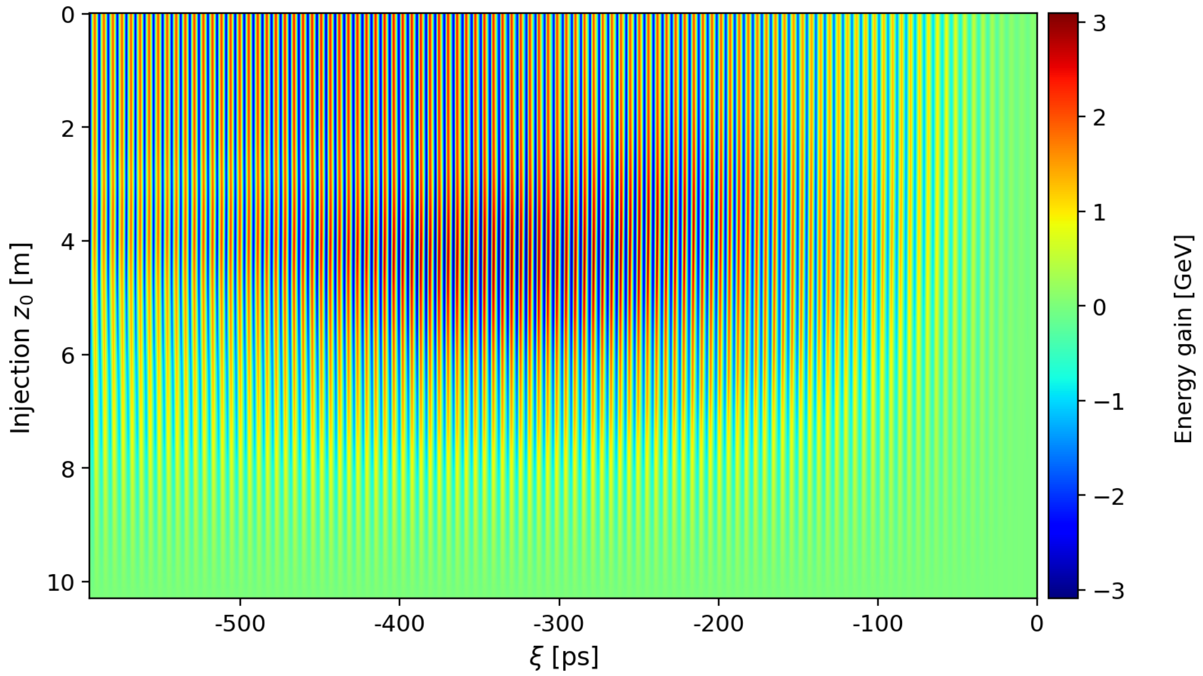
Ez on-axis fields for energy gain

ξ = xi = electron delay = delay of bunch centre behind RIF

Simulation of the experiment: $3.8\times 10^{14}\ \mathrm{cm}^{-3}$, 2.3% @ $1.25\mathrm{m}$, $\sigma_{p+} = 170\mathrm{ps}$, $\mathrm{RIF} = 200\mathrm{ps}$



Longitudinal electric field, Ez

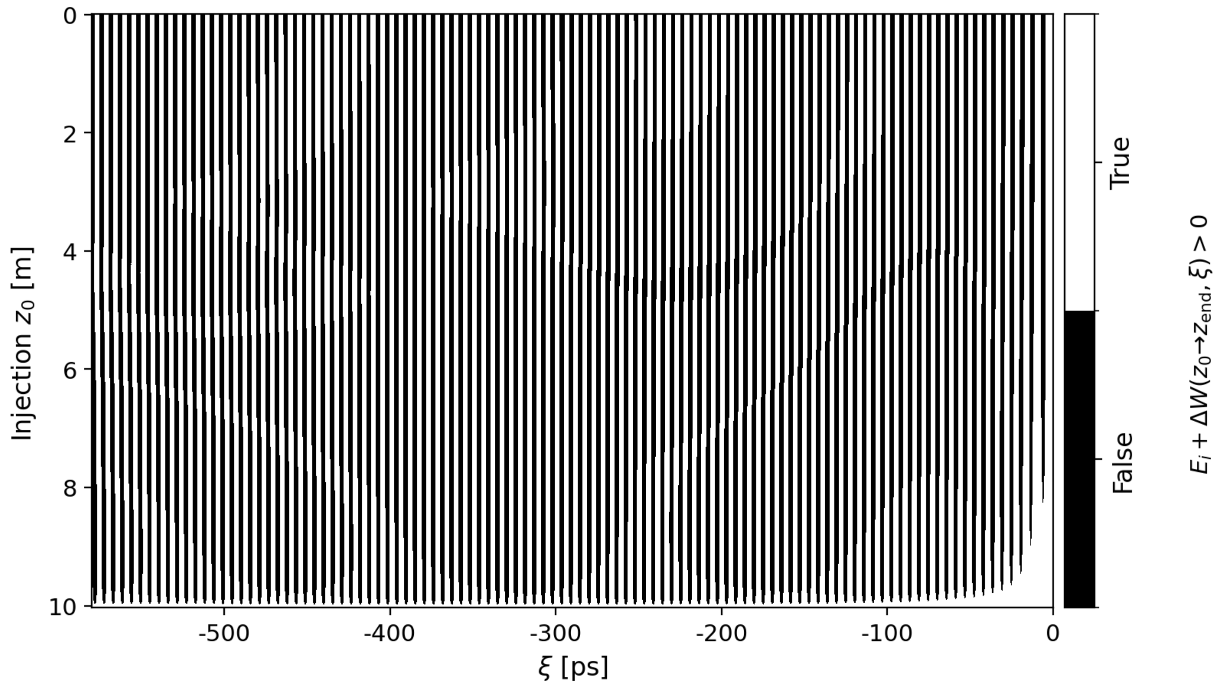


Ez cumulative sum

Energy gain/loss map

Masking for accelerating and focusing

Accelerating mask

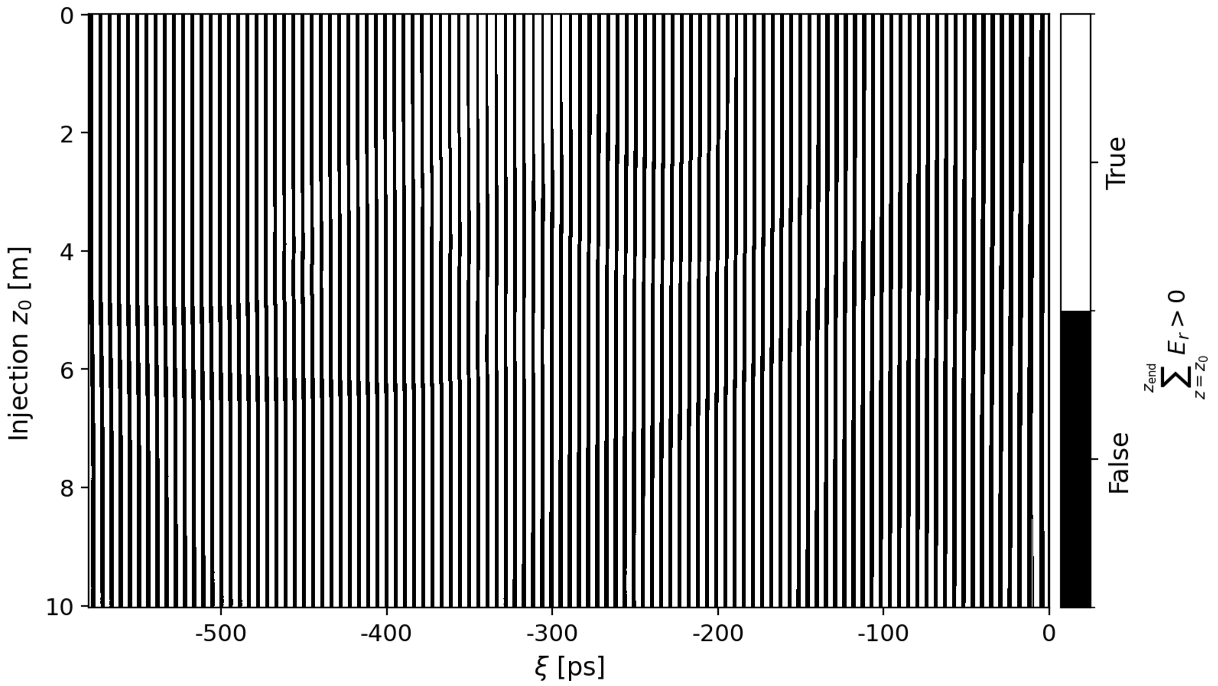


Energy has not fallen to 0 by the end of the plasma

(including Ei = 18 MeV)

$$E_i + \Delta\mathcal{E}_e(z_0, \xi) \; > \; 0$$

Focusing mask



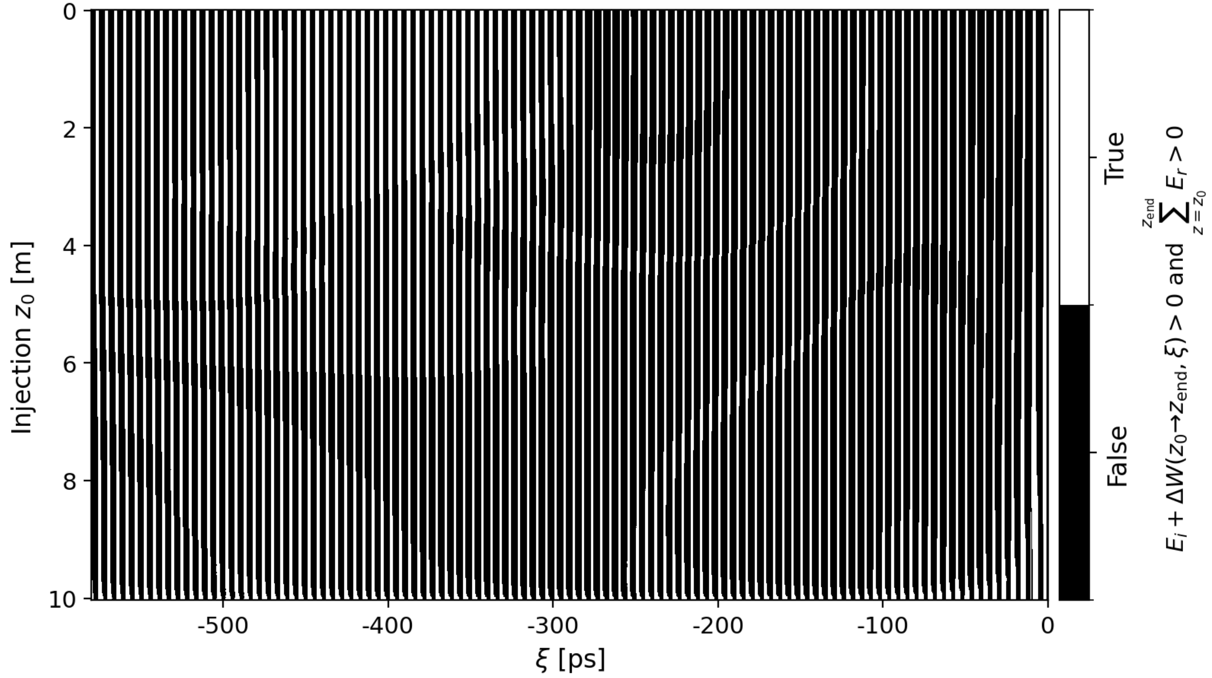
Particles are globally, transversely focused by the end of the plasma

$$\int_{z_0}^{z_{\mathrm{end}}} E_r(z, \xi)\, \mathrm{d}z \; > \; 0$$

Masking for accelerating and focusing

Accelerating mask

Focusing mask



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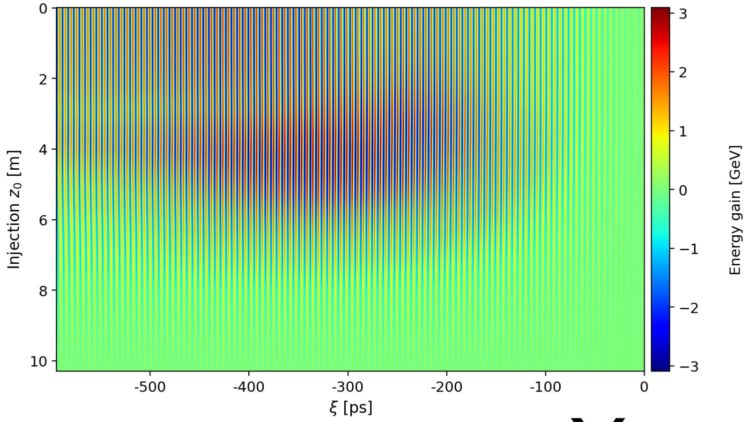
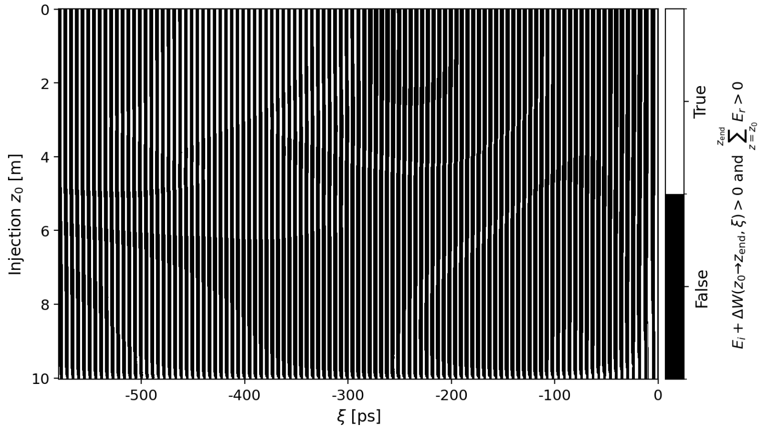
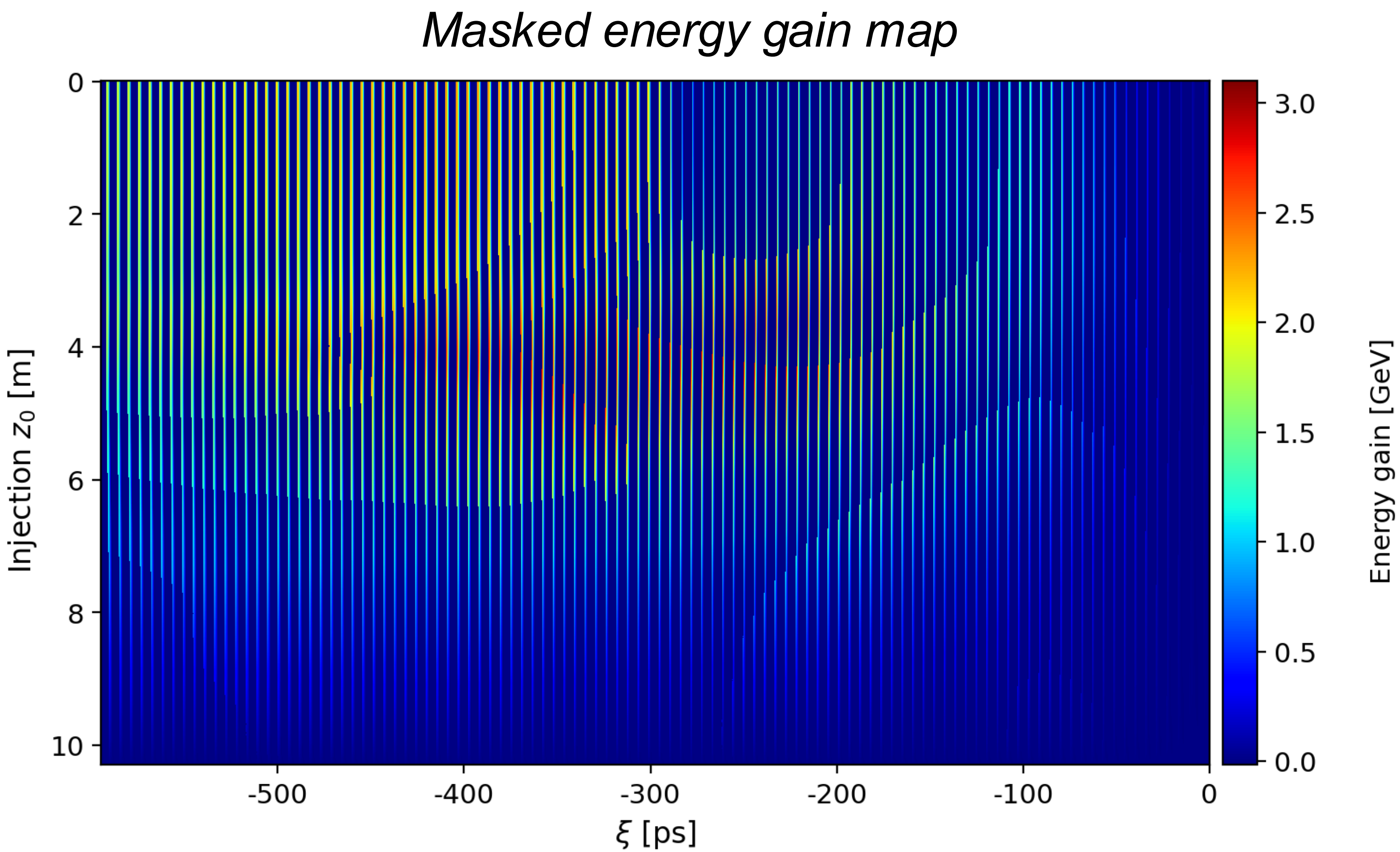


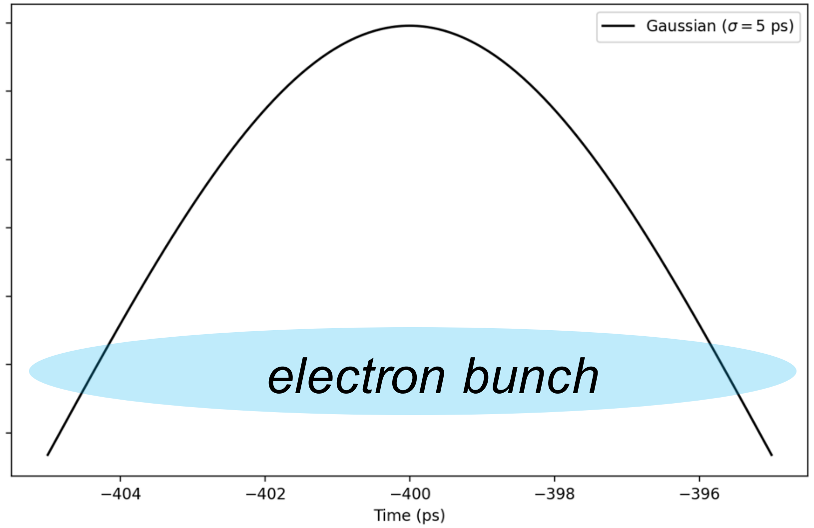
X





Considering our electron bunch…

We inject a long electron bunch: rms size of 5ps

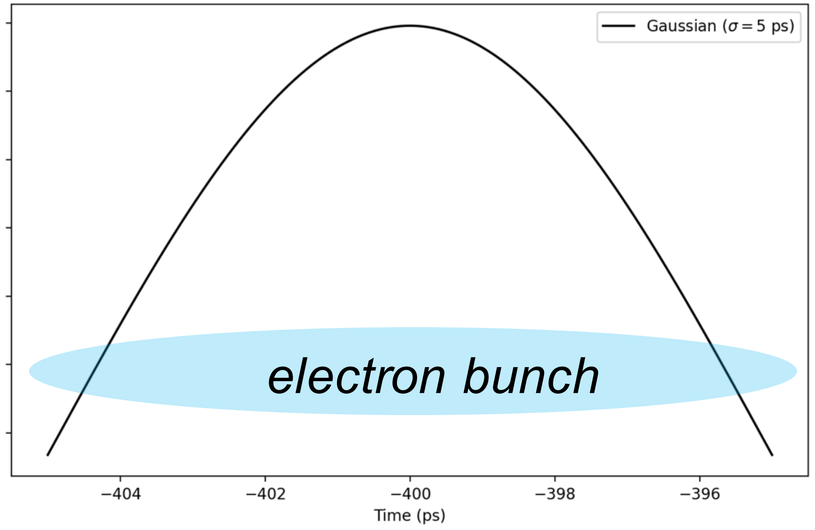


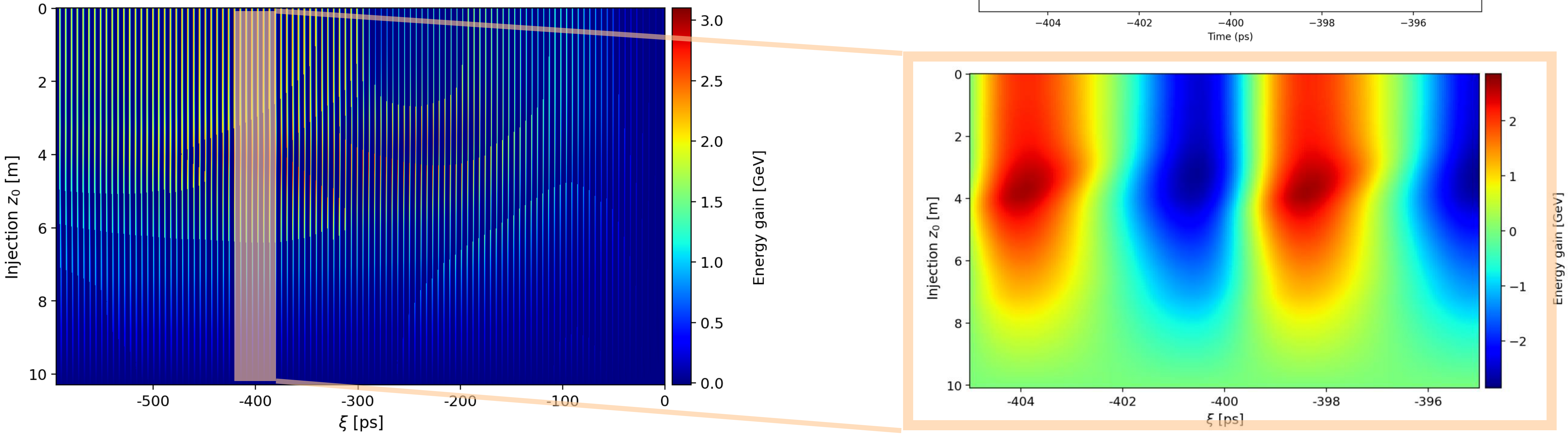
Considering our electron bunch…

We inject a long electron bunch: rms size of 5ps

Experimentally, we observe the effect of spanning multiple delays

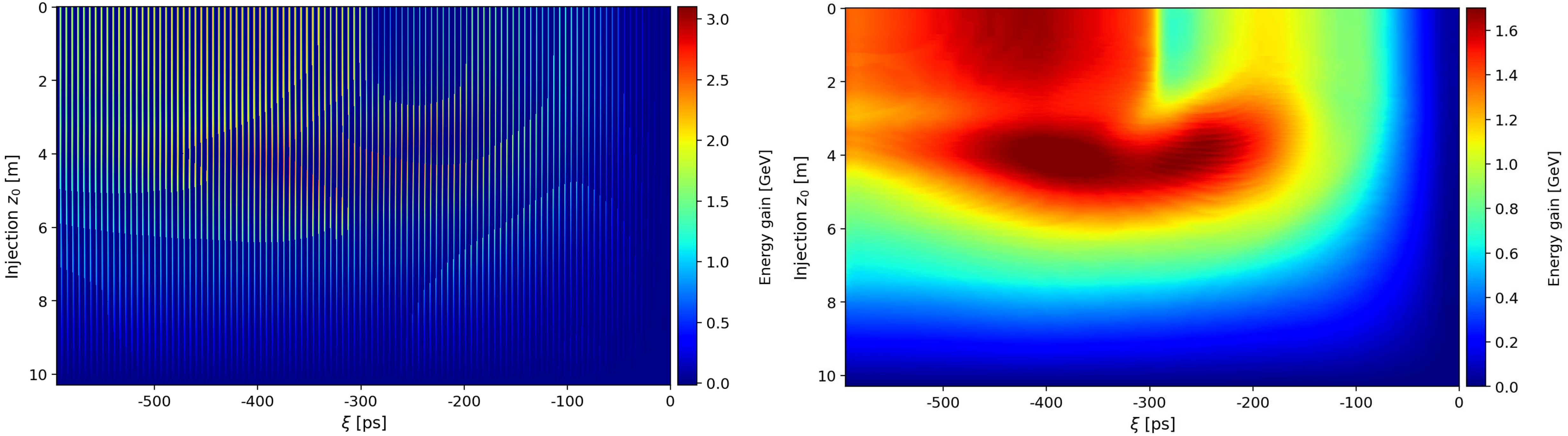
Apply a convolution (gaussian with sigma 5ps) to smooth





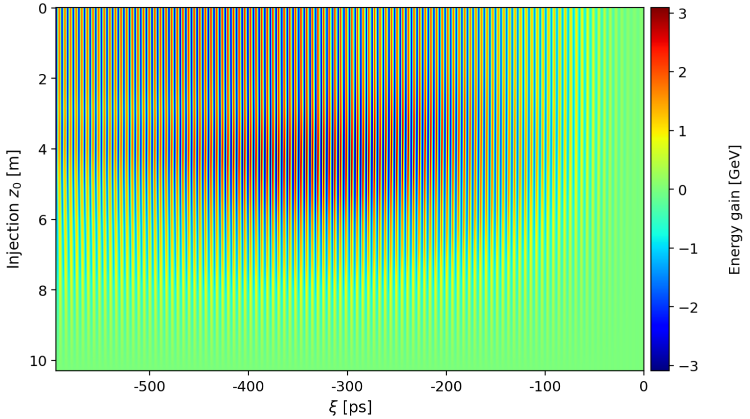
Considering our electron bunch…

Measure of the average energy experienced by the accelerated bunch



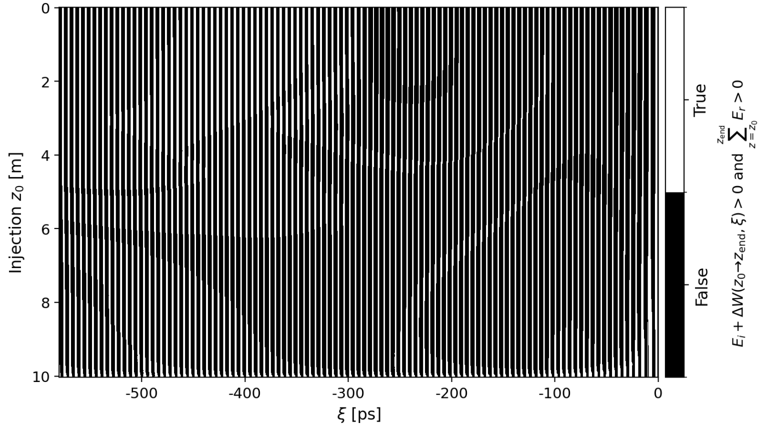
Simple workflow

1



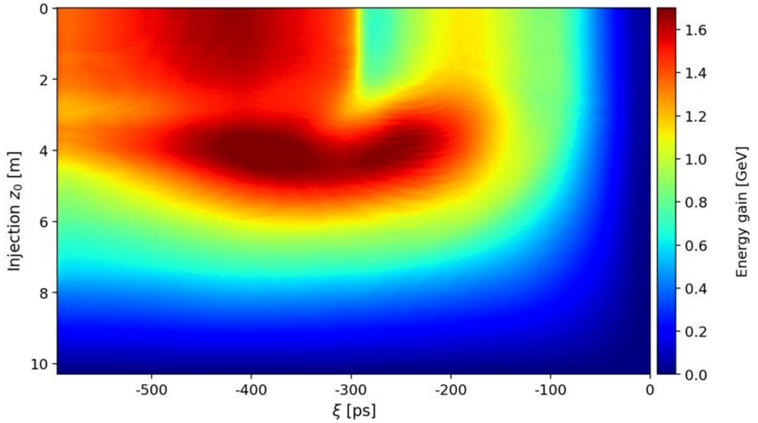
Sum the Ez fields

2



Mask for accelerating and focusing regions

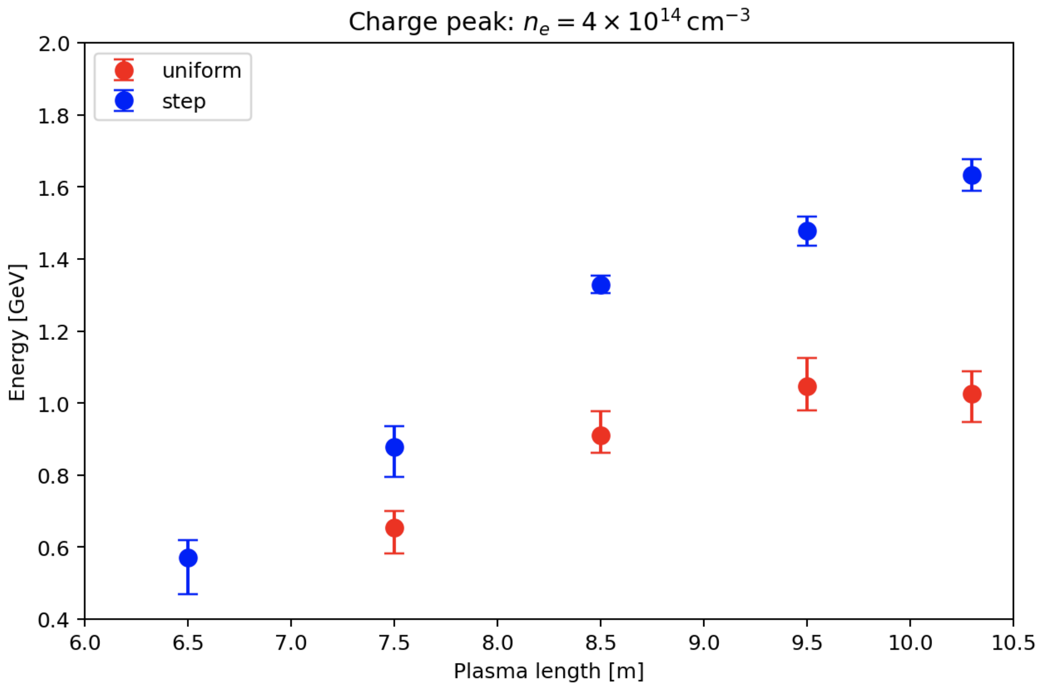
3

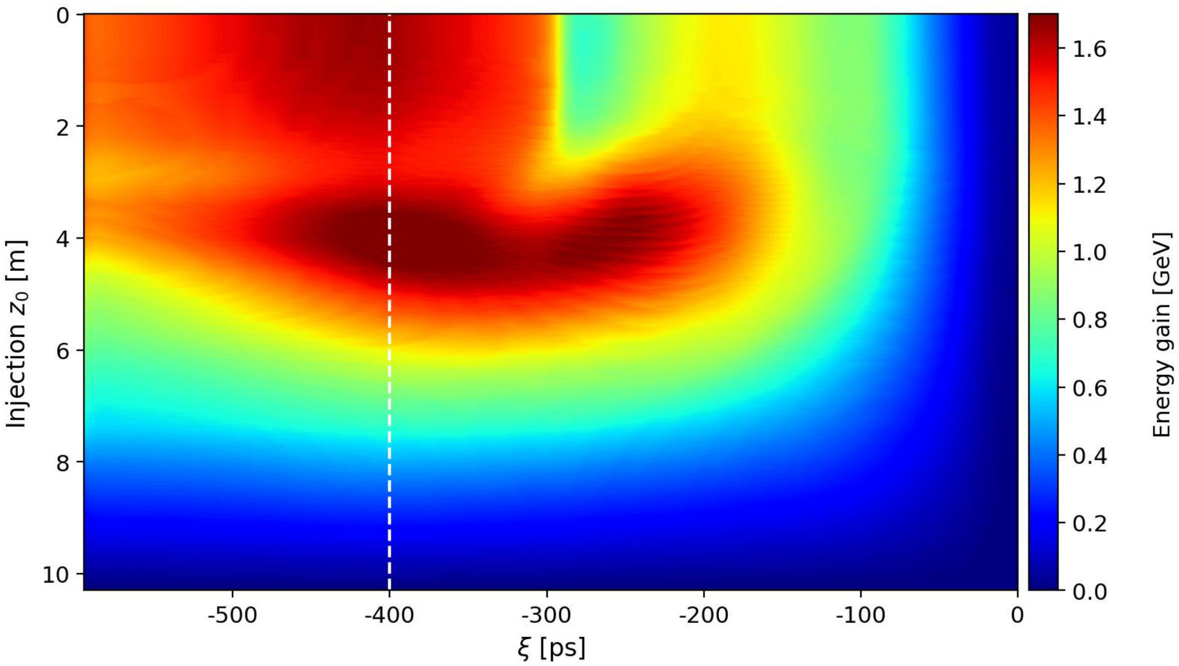


Weighted for electron bunch distribution

Linking to the experiment…

Heatmap shows the expected energy gain after 10m, for various injection positions and delays





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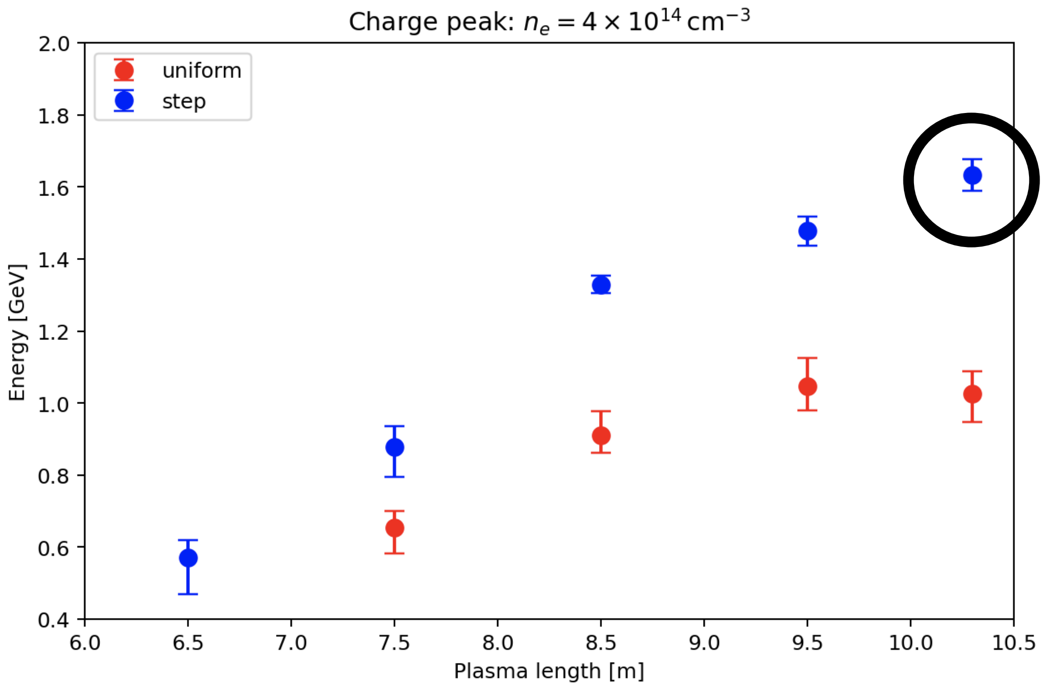
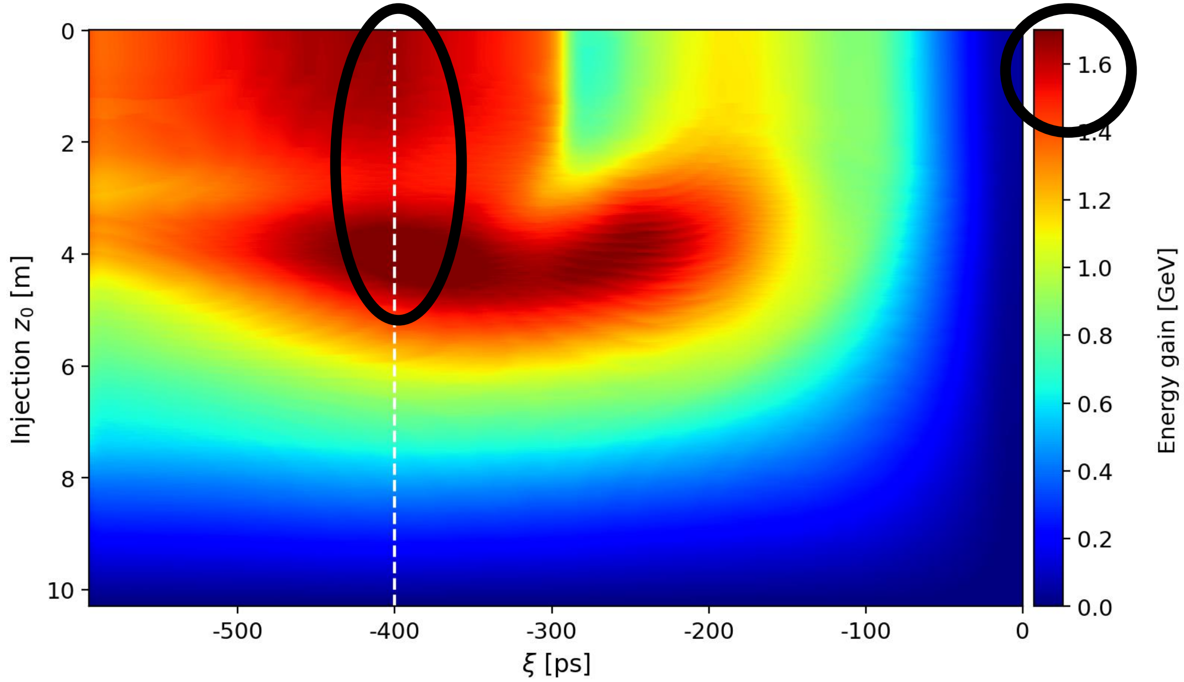
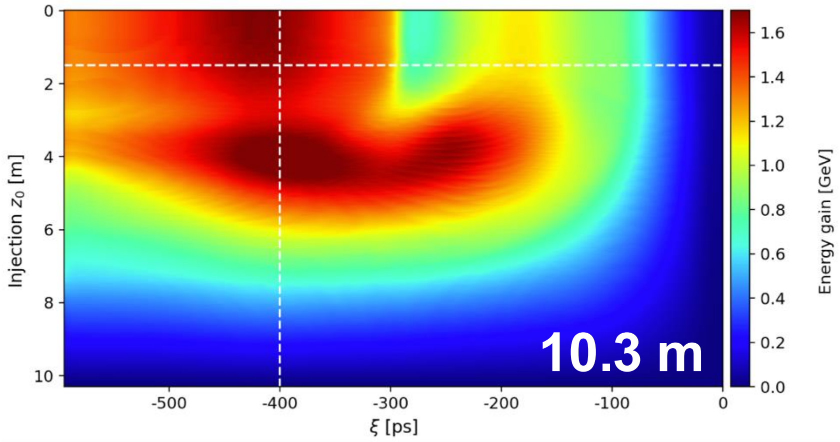


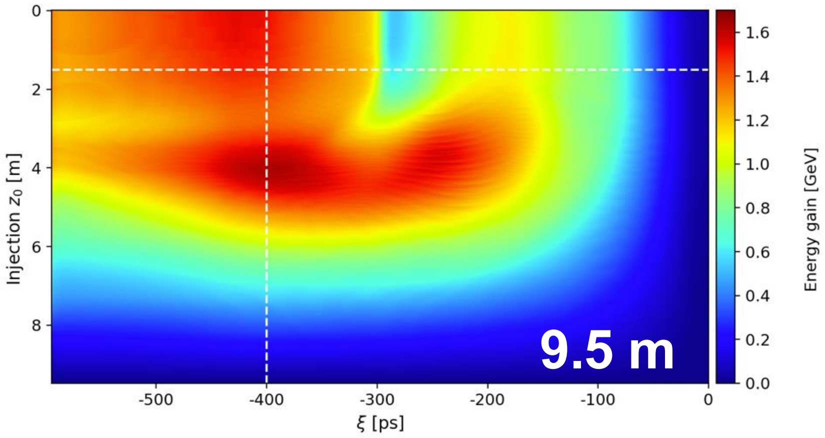


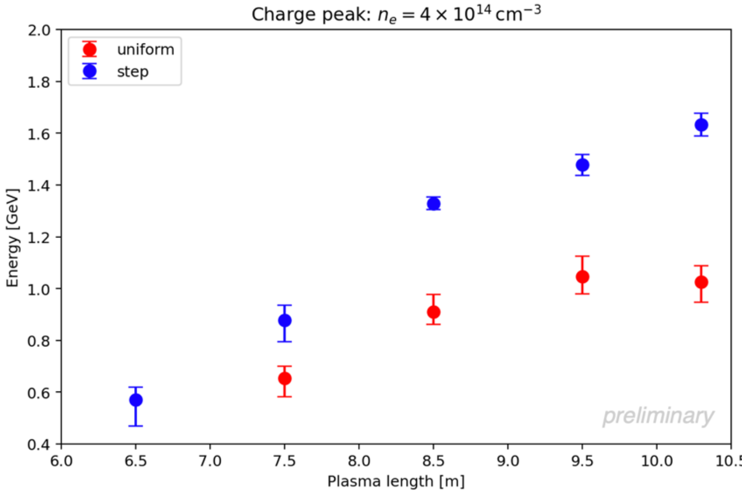
Linking simulation and experiment

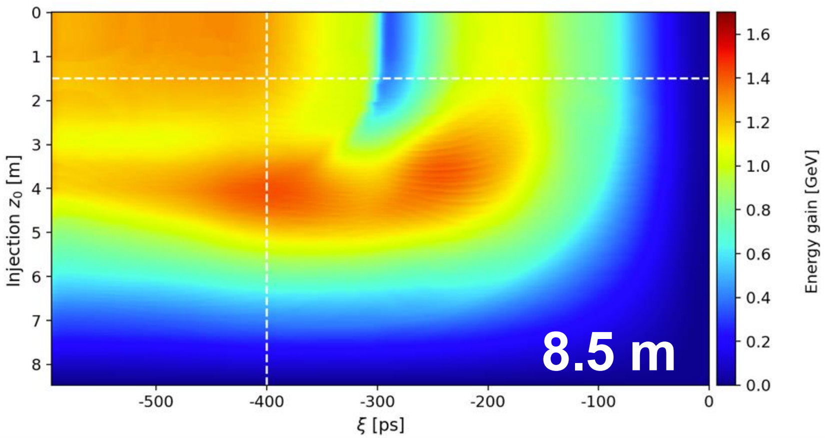
So, we can make the same heatmaps at every plunger position

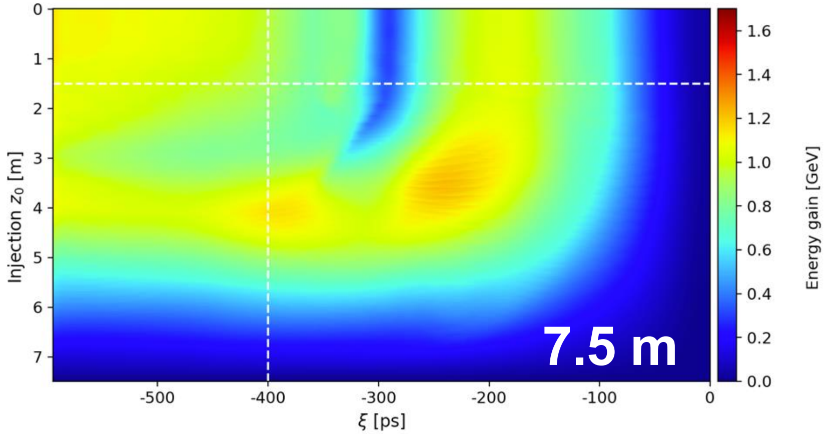
We want to compare these simulations of the experiment, to the experiment!

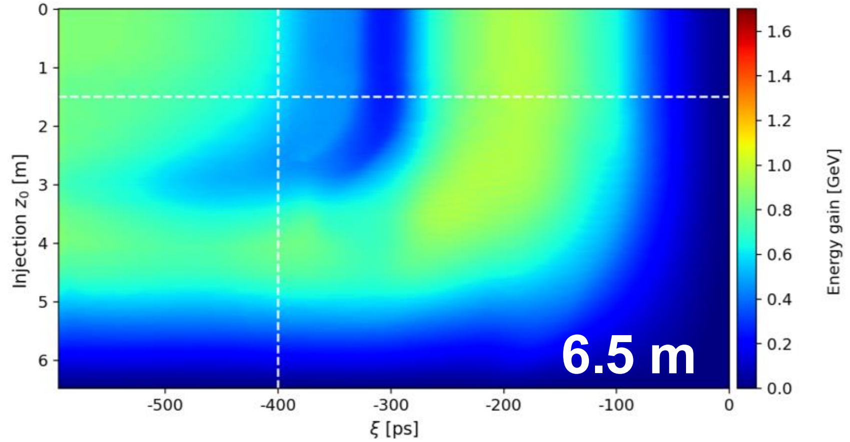










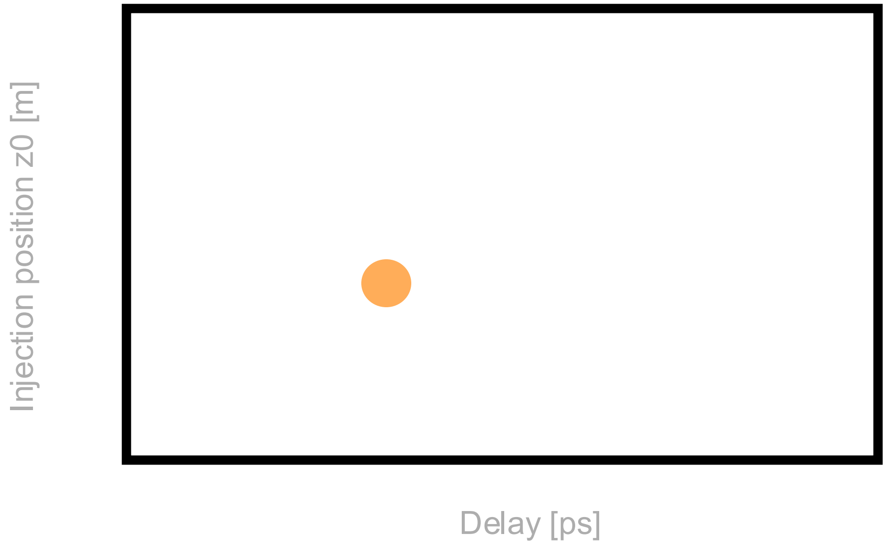


Searching for the best fit

We have experimental curves of energy gain versus plasma length

Each 2D simulation map shows predicted energy gain for injection vs. delay

- Fix the injection point and delay



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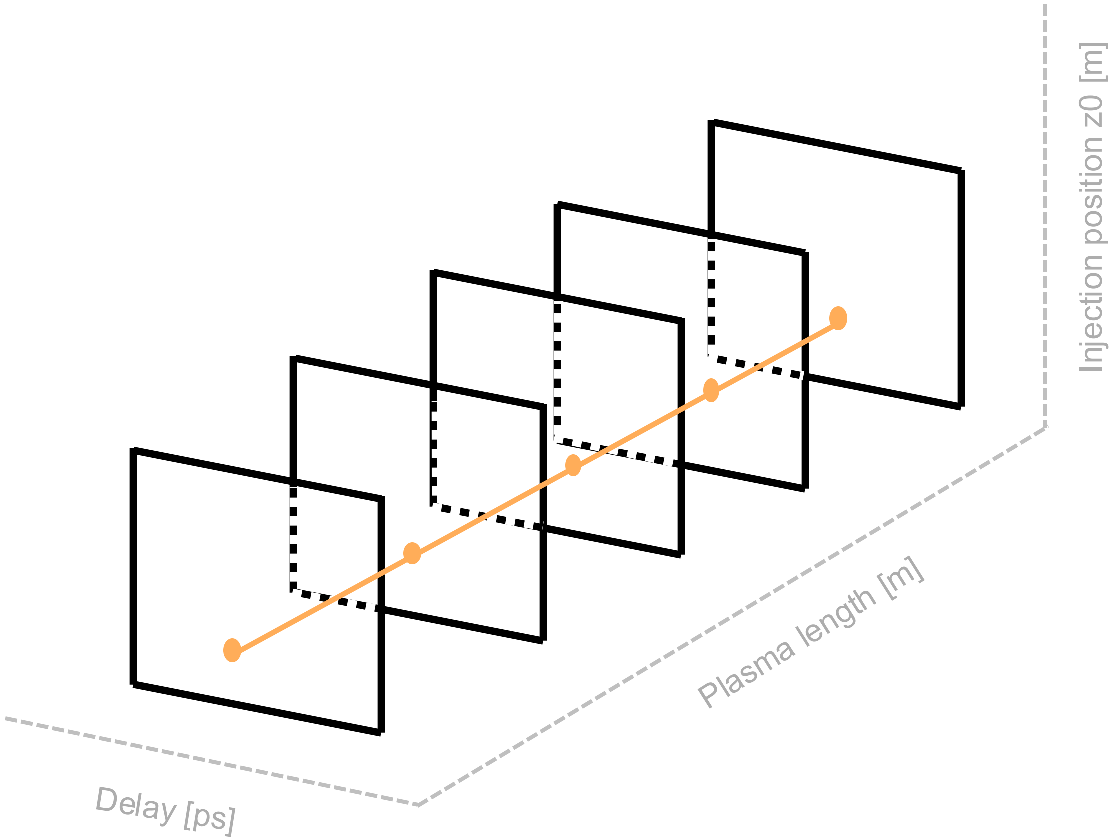

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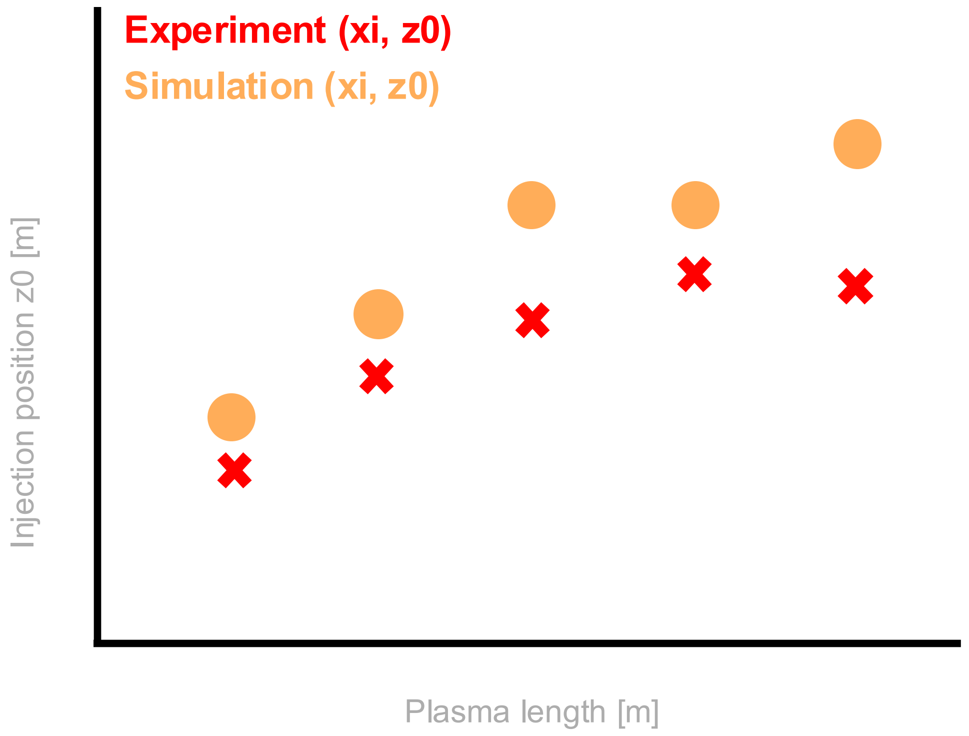

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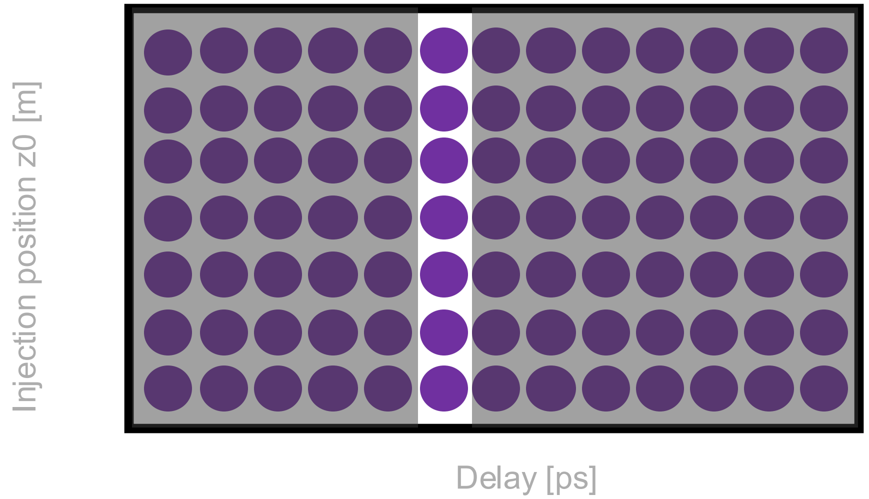

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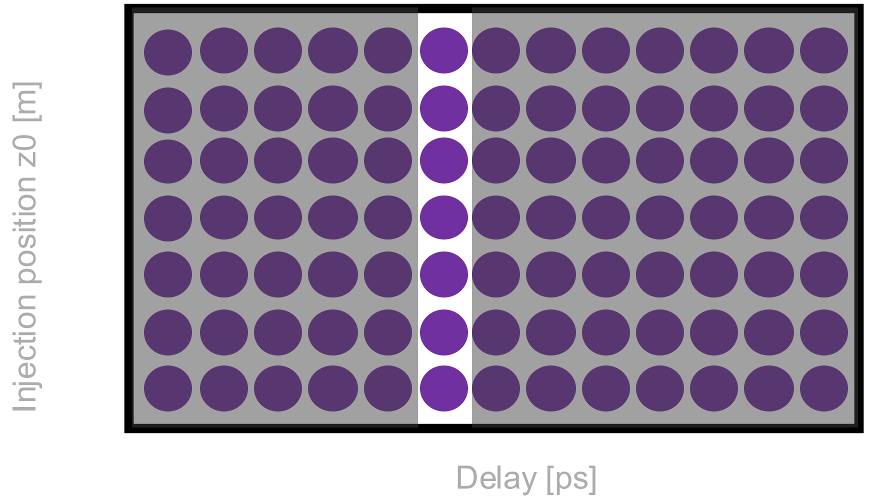
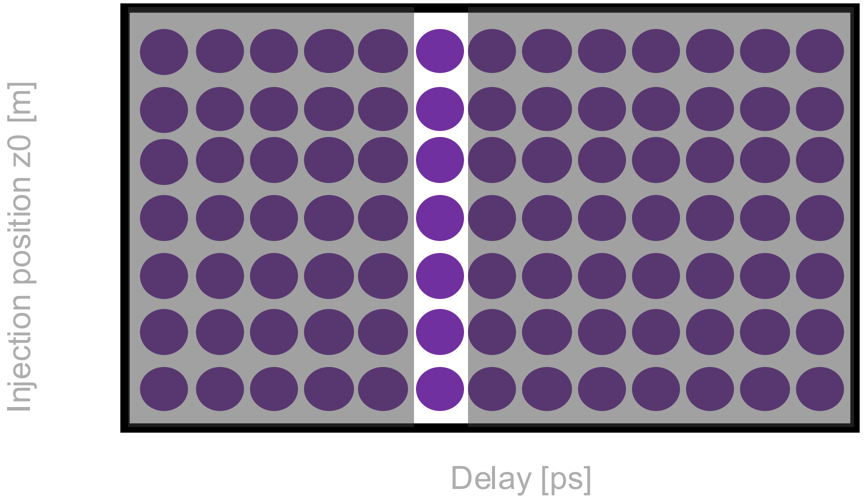
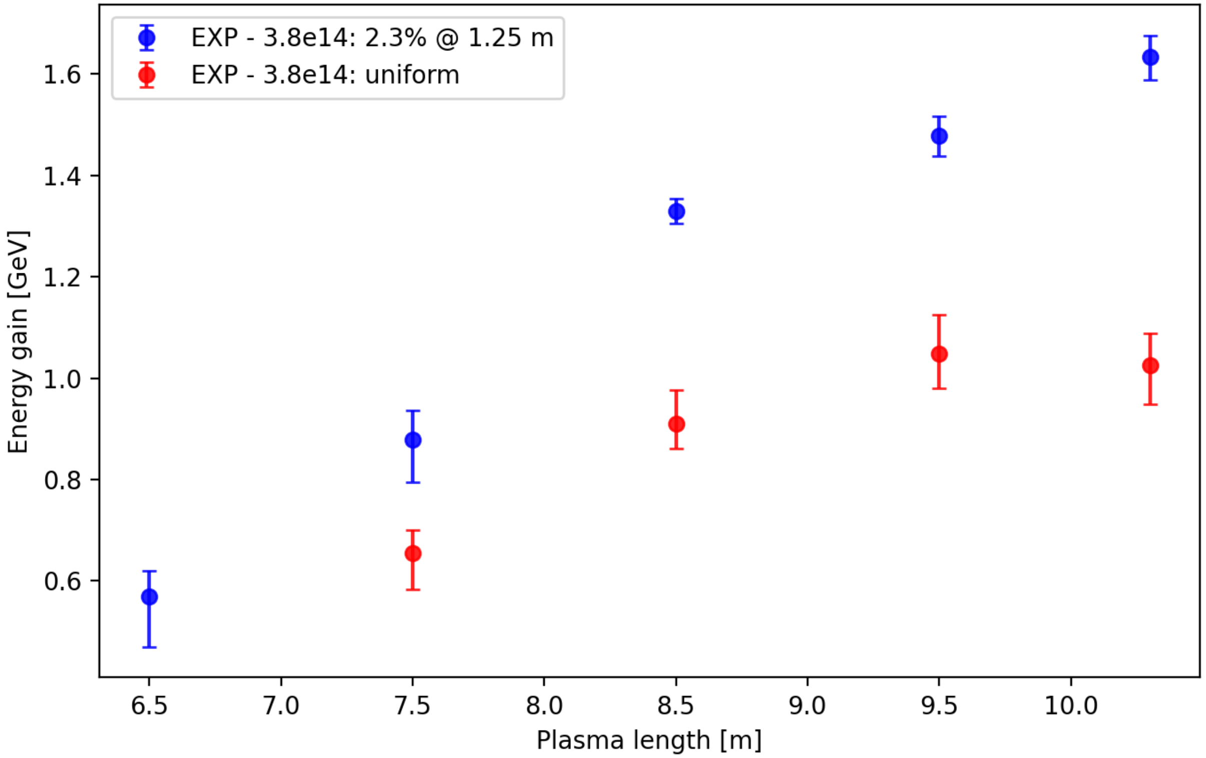
- Repeat for all possible xi, z0 points
- **Return xi z0 which produces the line in best agreement with experiment**



Linking to the experiment…

First look: Fix the delay to -400ps as we know this from the experiment

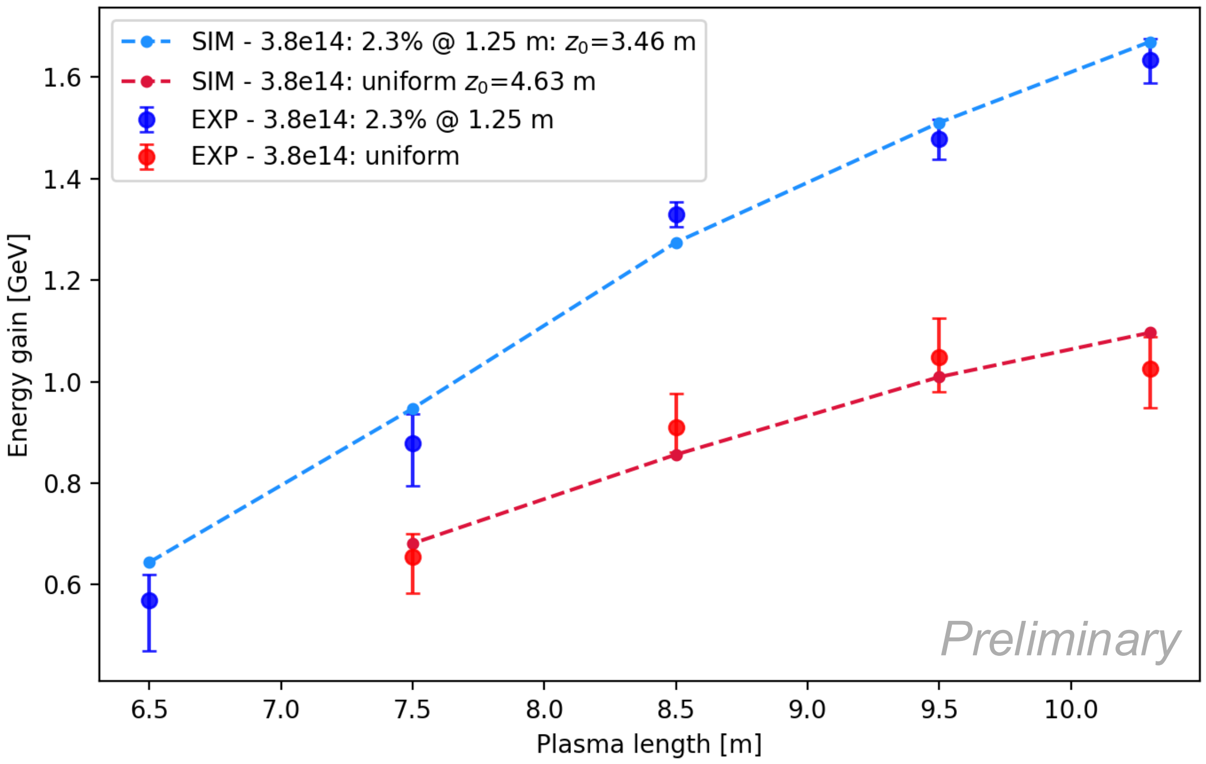




Linking to the experiment…

First look: Fix the delay to -400ps as we know this from the experiment

LCODE simulations are describing the experiment **extremely well**



Linking to the experiment…

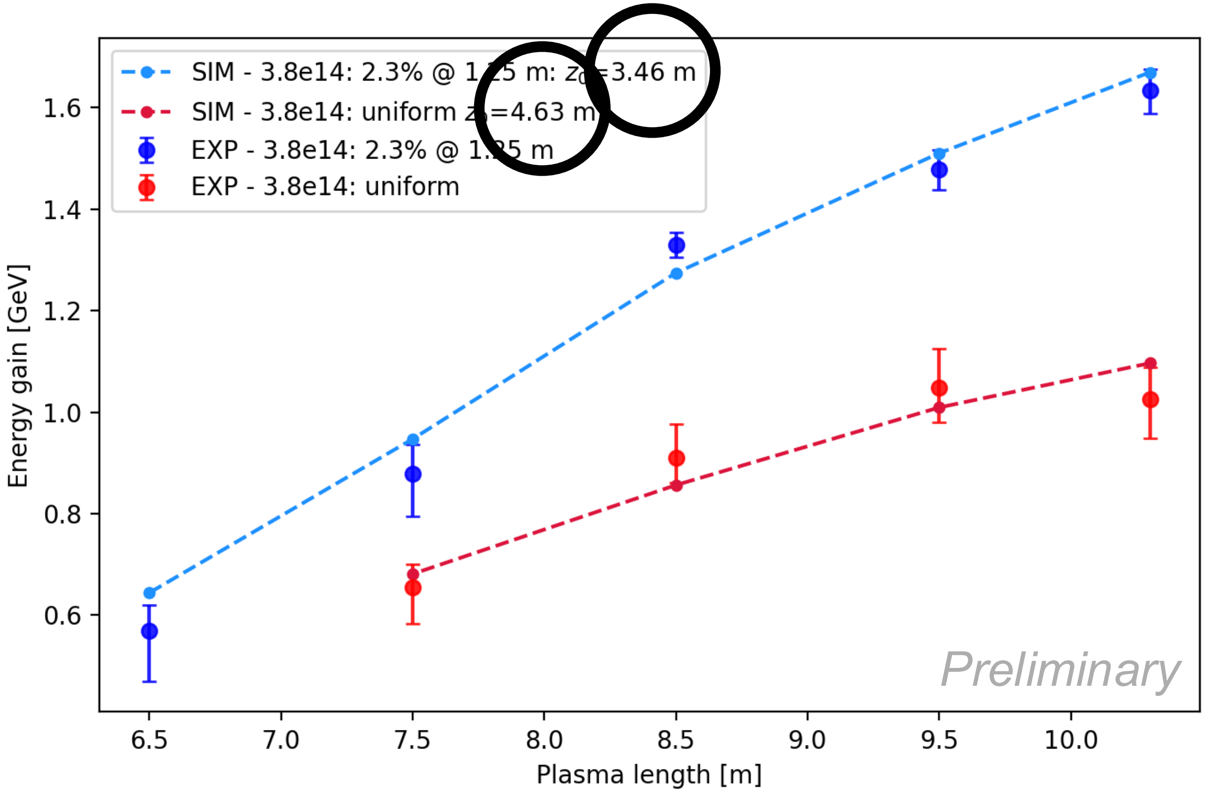
First look: Fix the delay to -400ps as we know this from the experiment

LCODE simulations are describing the experiment **extremely well**

Uniform: z0 = 4.63m, Step: z0 = 3.46m

We align in vapour to 1.5m, it is perhaps not unreasonable to see *capture* later than this…

…and different between uniform and step (different evolution)



Extending the experimental simulations

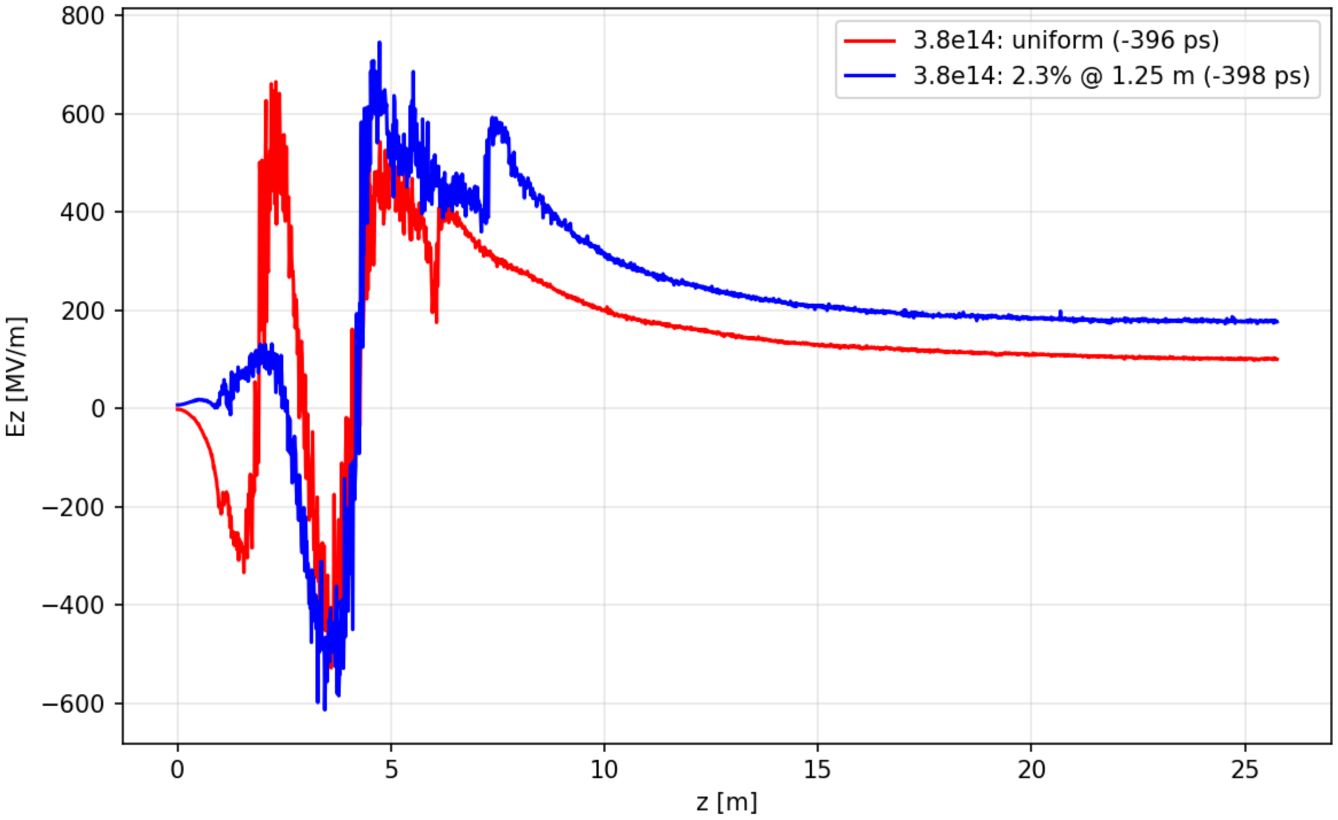
Let's return to a simple view on the effect of the density step

Looking at (predominantly) accelerating Ez for electrons, over longer distance

Density step: Increase the wakefield amplitude, and therefore accelerating gradient

Once stabilised, the accelerating gradient is **higher** with a density step than a uniform plasma

Even if experimentally we have not found the optimal density step for this configuration, we can still see the intended effect!



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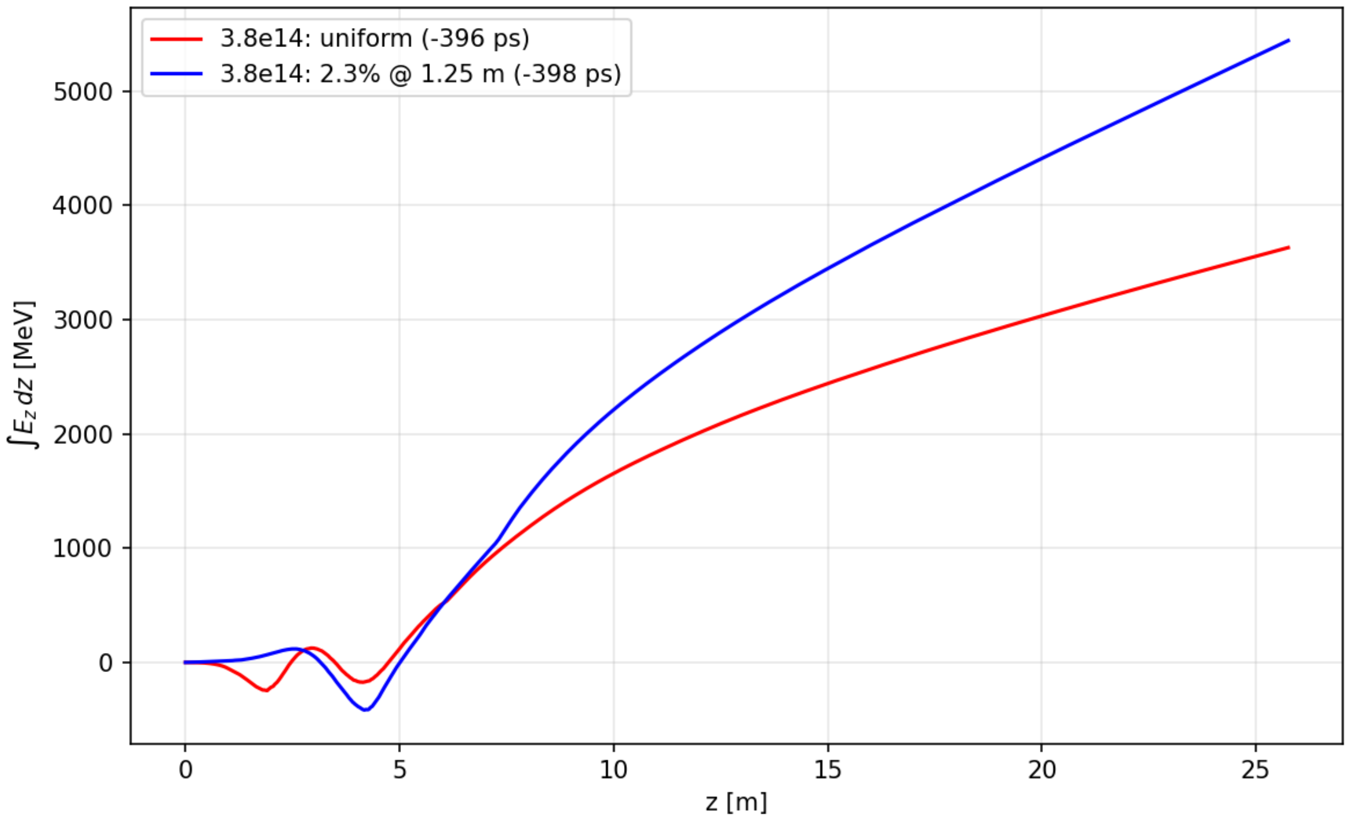


Summary

We have experimentally studied the effect of plasma density steps on accelerating gradients → vital for AWAKE Run 2c and beyond

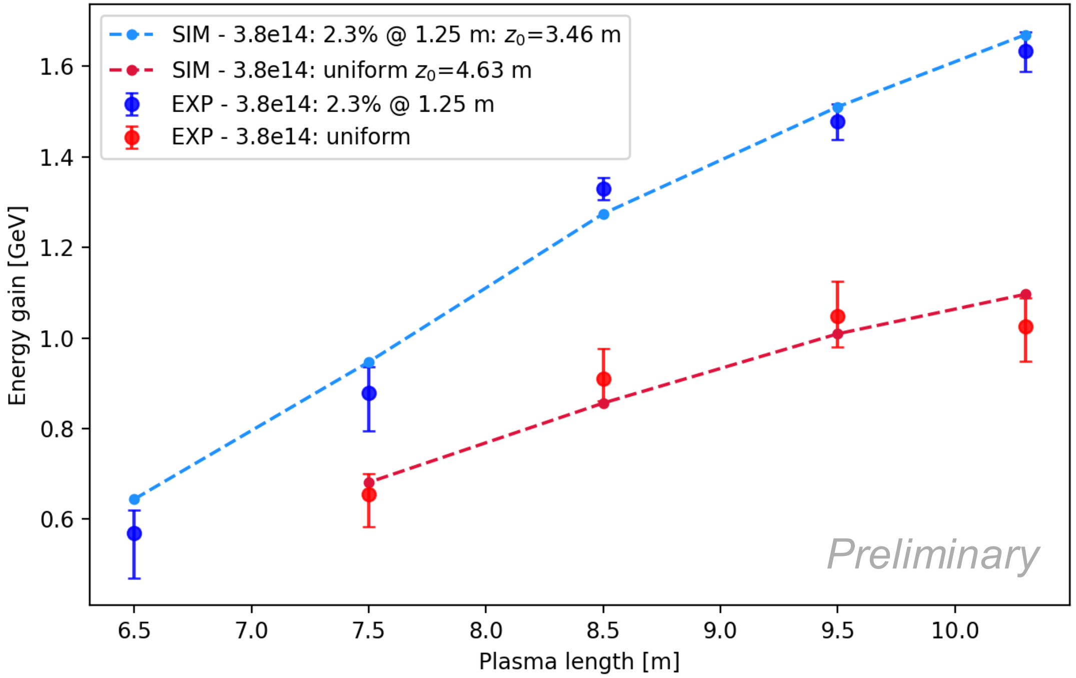
For lower plasma densities, a clear effect of the density step is observed

We are now turning to simple simulations to support our measurements

Simulations for the fields (LCODE 2D) show strong agreement with experiment

The accelerating gradient is improved with plasma density step, even if not at the optimal configuration

The team will start preparing a manuscript on this work



Backup

The magnetic spectrometer

The main diagnostic to study the accelerated electrons

Quadrupole doublet → electron bunch focusing

C-shaped dipole → separate electrons from protons

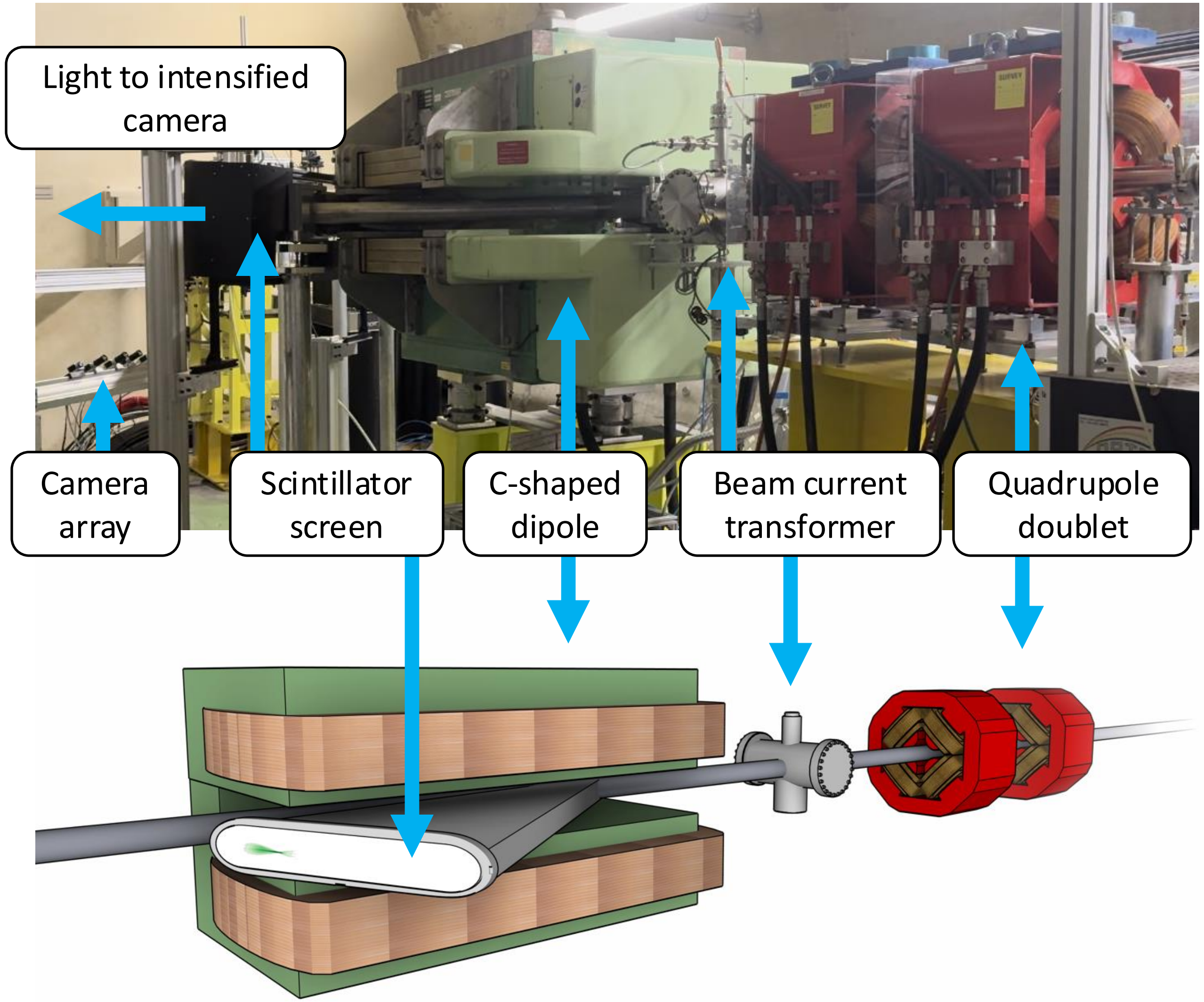
Scintillator screen → electron impact causes scintillation

Camera systems → capture the scintillation light

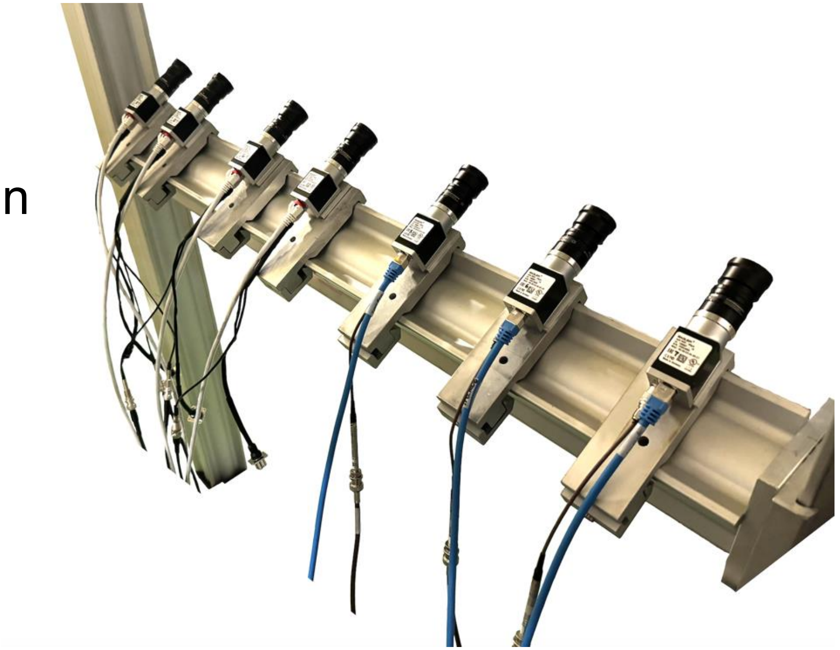
Integrating current transformer → charge calibration

Measurements of the energy, energy spread, charge

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



Imaging system



Camera array is the main imaging diagnostic for Run 2a & 2b acceleration

7 cameras cover entire screen, improved resolution over old system

The beam is rarely *fully* contained within a single camera

Need to view full beam → Capture full energy/charge distribution

Full screen → absolute position calibration