Department of Physics & Astronomy

UCL

Upgrading the magnetic spectrometer for electron bunch emittance and energy measurements at AWAKE

IOP Joint APP, HEPP and NP Annual Conference
8th – 11th April 2024

Fern Pannell and the AWAKE Collaboration

AWAKE

Introduction

Conventional Accelerator Physics

Plasma Wakefield Acceleration

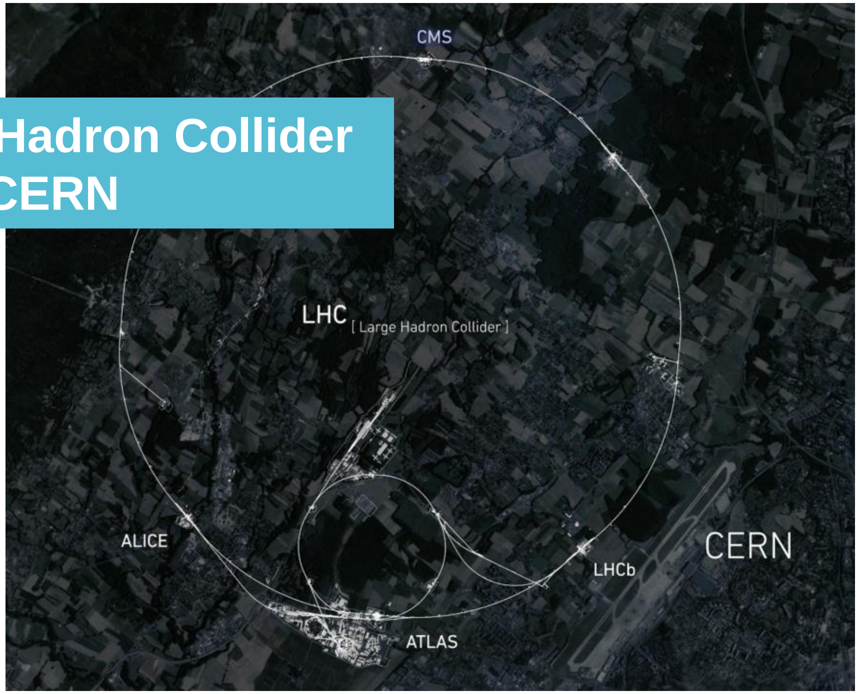
The AWAKE Experiment

Upgrading the Magnetic Spectrometer

Designing a Particle Accelerator

When designing the shape of a particle accelerator, you generally have two choices:

Circular



The Large Hadron Collider
CERN

27 km circumference synchrotron
6.5 TeV proton bunches

Linear

The Stanford Linear Collider
SLAC

3.2 km long linear accelerator
50 GeV electron/positron bunches

Image sources: CERN & SLAC

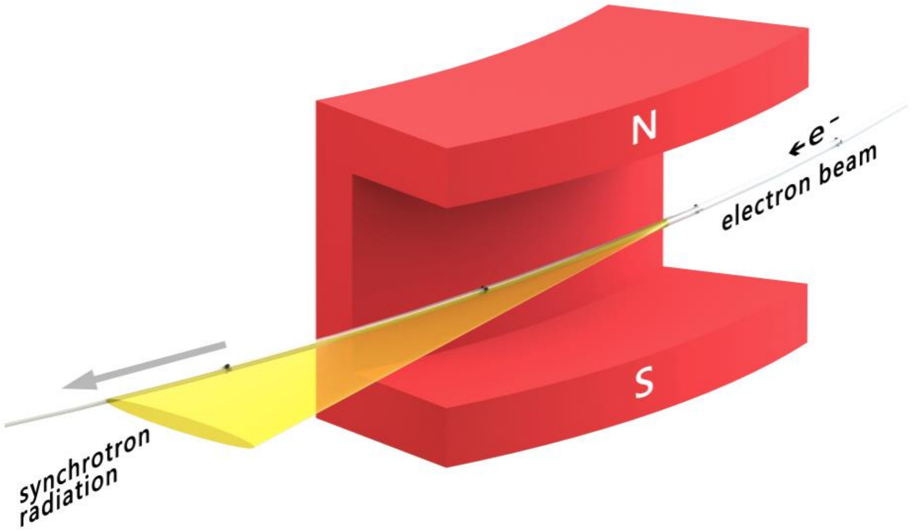
Designing a Particle Accelerator

Circular accelerators:

Particles can repeatedly pass through accelerating structures

Circular trajectory leads to energy loss via synchrotron radiation

- Losses proportional to $1/m^4$ → lighter particles suffer more



Linear accelerators:

Straight trajectory avoids synchrotron radiation losses

Single shot → particles can only pass through cavities once

RF strength limitation (av. 30 MV/m) → Very long accelerators

- Breakdown of metallic walls prevents strong fields

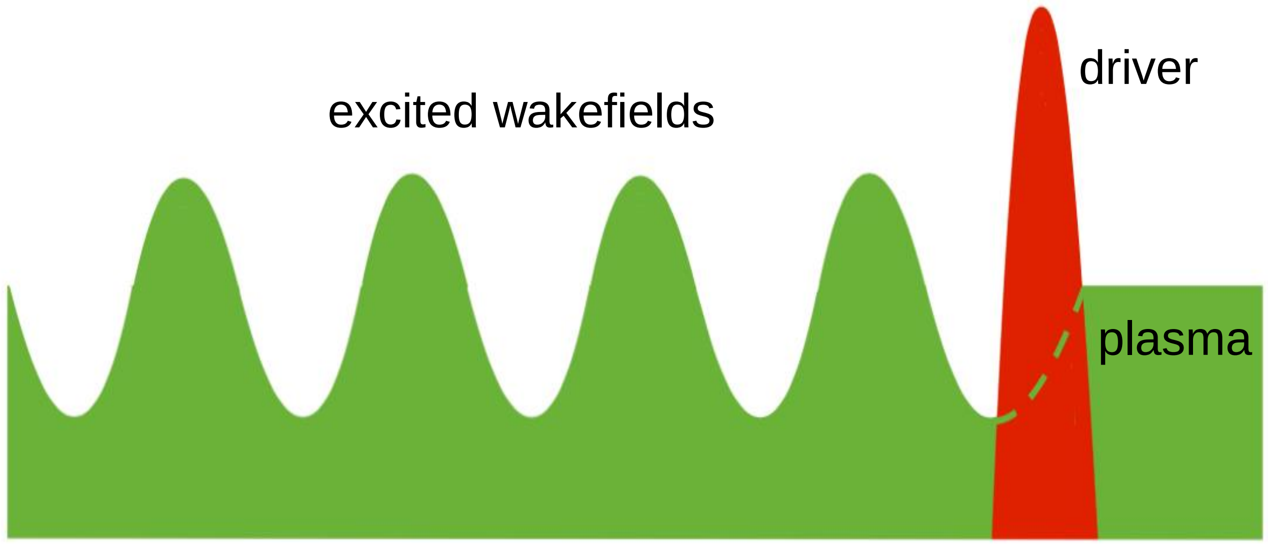
Motivation for a compact, linear accelerator

Image source: https://www.nsrrc.org.tw/English/lightsource.aspx

Plasma Wakefield Acceleration (PWFA)

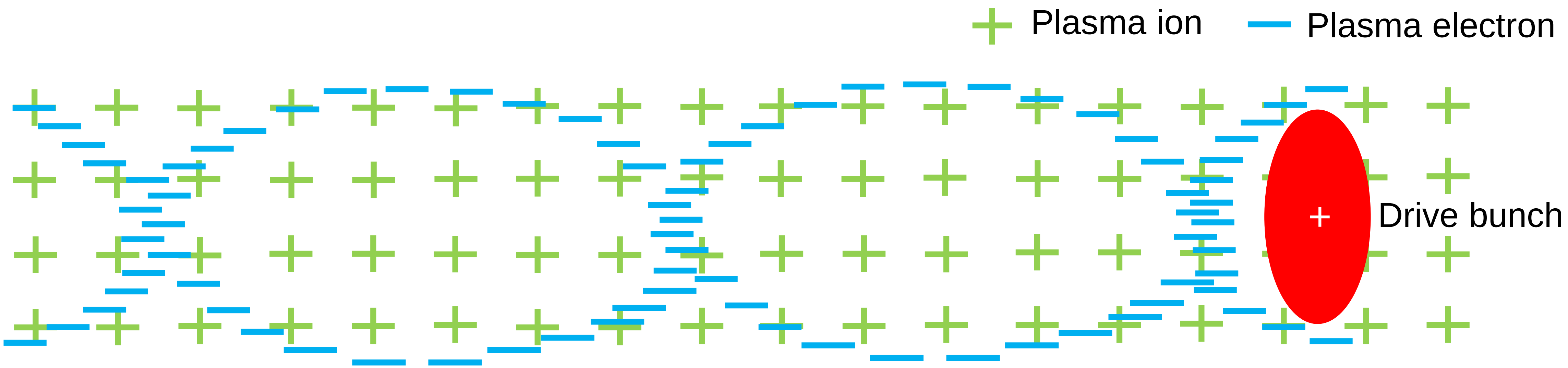
Plasma is a material which is already "broken down"

- Removes issue of damage threshold → can withstand stronger electric fields
- Potential for a higher accelerating gradients
- Reduces the required length of an accelerator to reach a given design energy



- Accelerating particles in a plasma wave (wakefield)
- Driver (laser pulse or relativistic particle bunch) creates plasma wave
- Injected "witness" bunch "surfs" the wave and is accelerated

Plasma Wakefield Acceleration (PWFA)



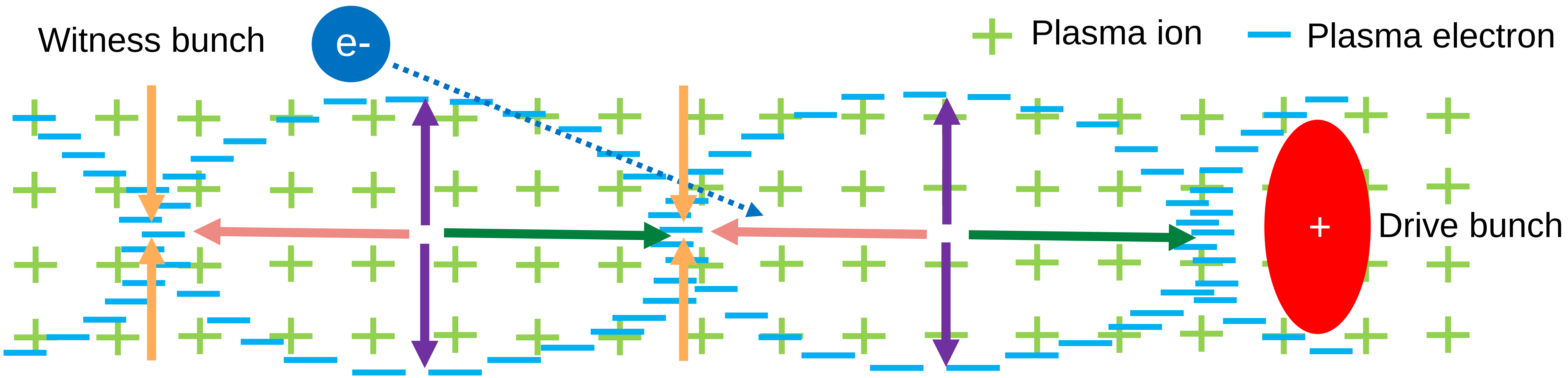
Drive bunch enters plasma

Space charge separation of plasma electrons and ions

Electrons attracted back to axis but overshoot

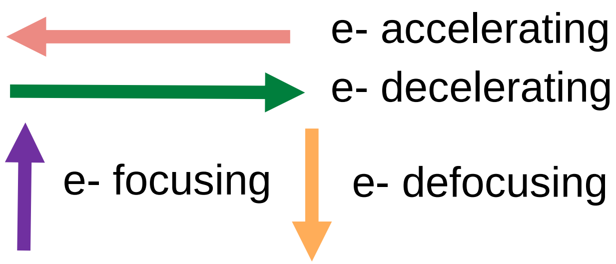
Periodic structures → plasma waves

Plasma Wakefield Acceleration (PWFA)



Electrons externally injected into the plasma wave

Plasma allows for energy transfer from the drive to witness bunch



The greater the energy of the drive bunch, the more energy available for transfer to the witness bunch

field lines → conventional current
electron motion opposes field line direction

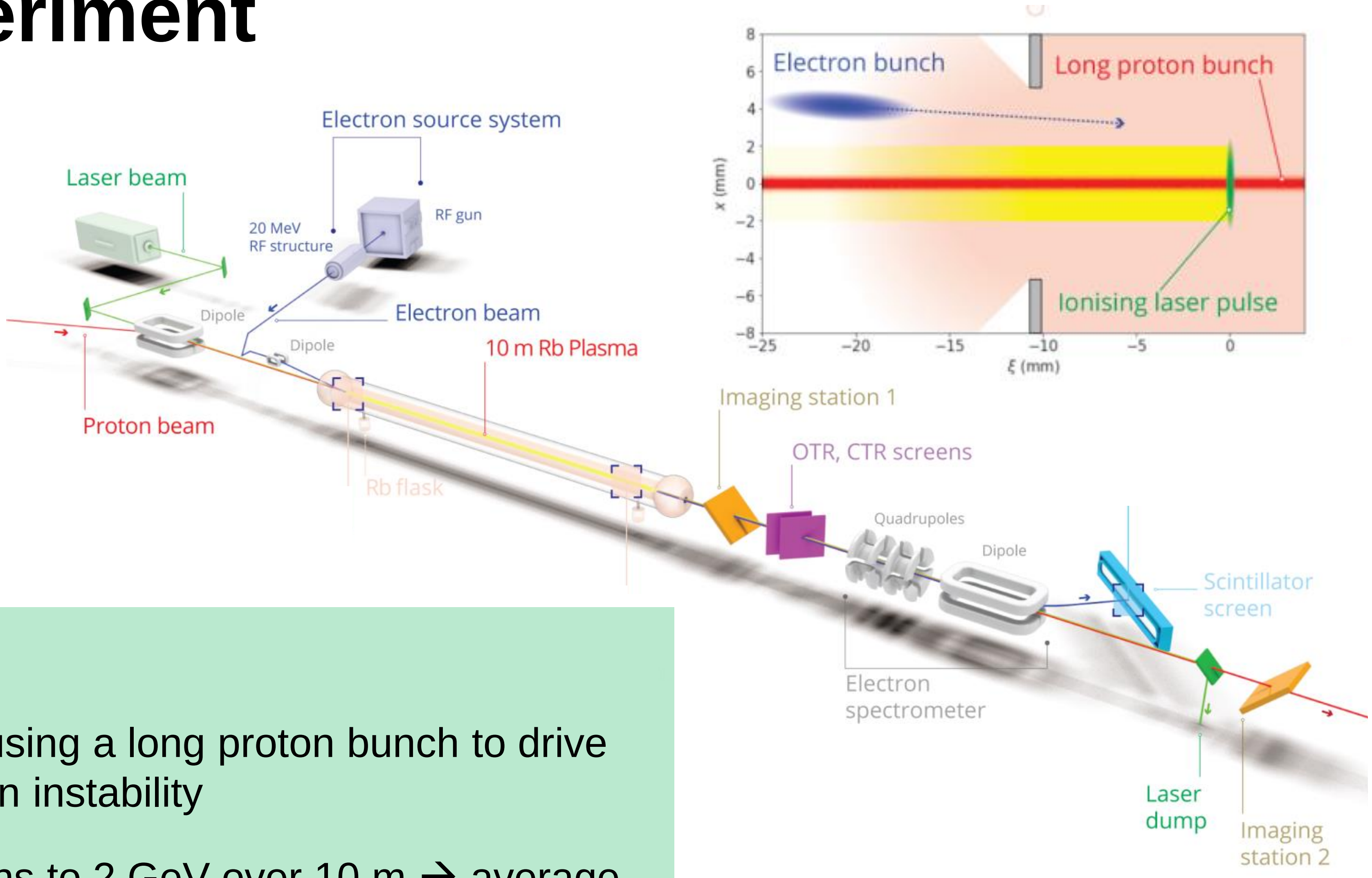
The AWAKE Experiment

10 m rubidium vapour source

Laser pulse ionises the vapour to create plasma

400 GeV proton driving beam from the SPS

Externally injected 20 MeV electrons for acceleration



AWAKE Run 1: 2017 – 2021

Demonstrated the possibility of using a long proton bunch to drive wakefields via the self modulation instability

Achieved acceleration of electrons to 2 GeV over 10 m → average accelerating gradient of 200 MV/m

The AWAKE Experiment

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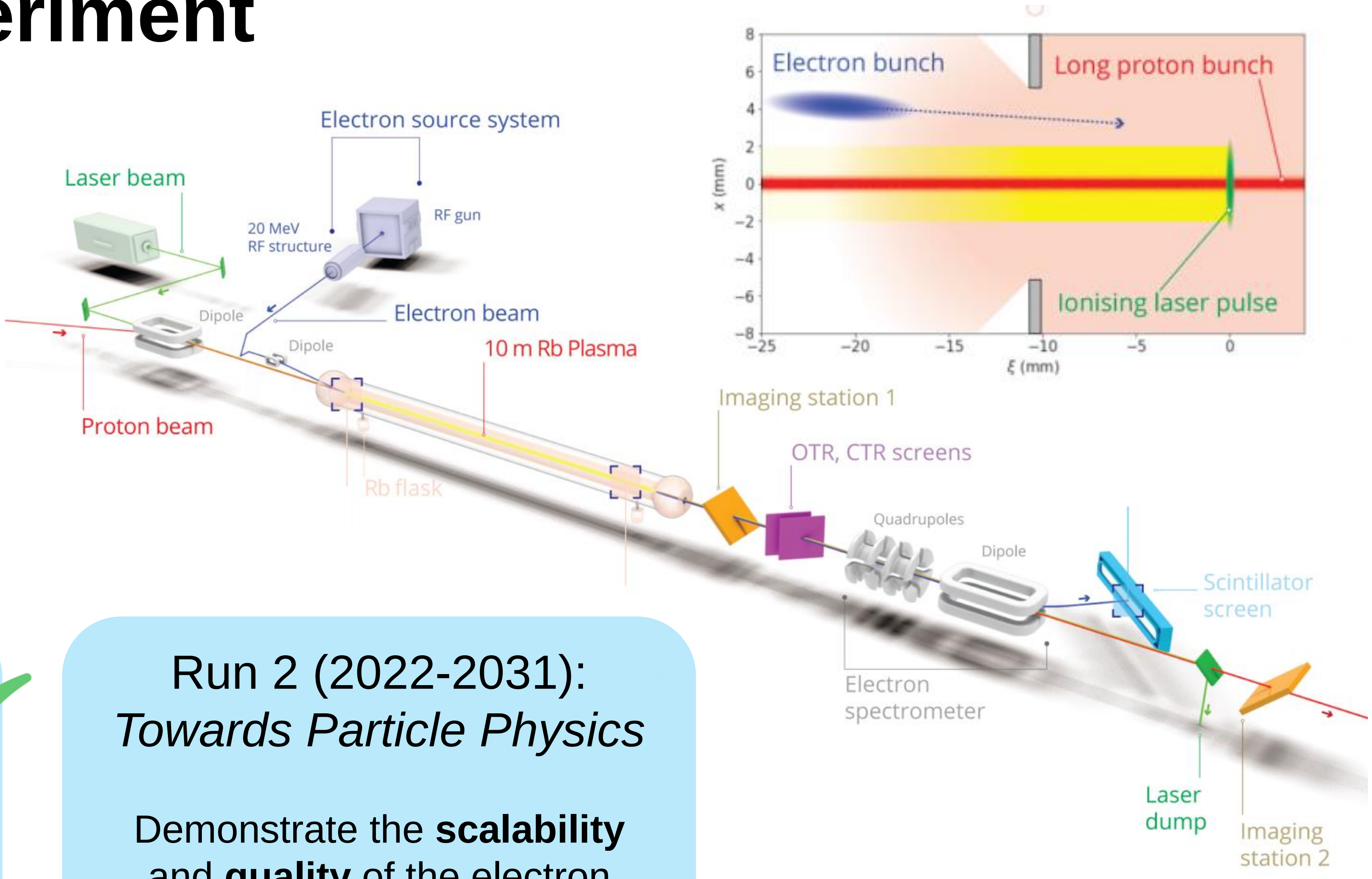


Run 1 (2017-2021):
Proof-of-concept

Demonstration of wakefields with long proton drive bunch and electron acceleration

Run 2 (2022-2031):
Towards Particle Physics

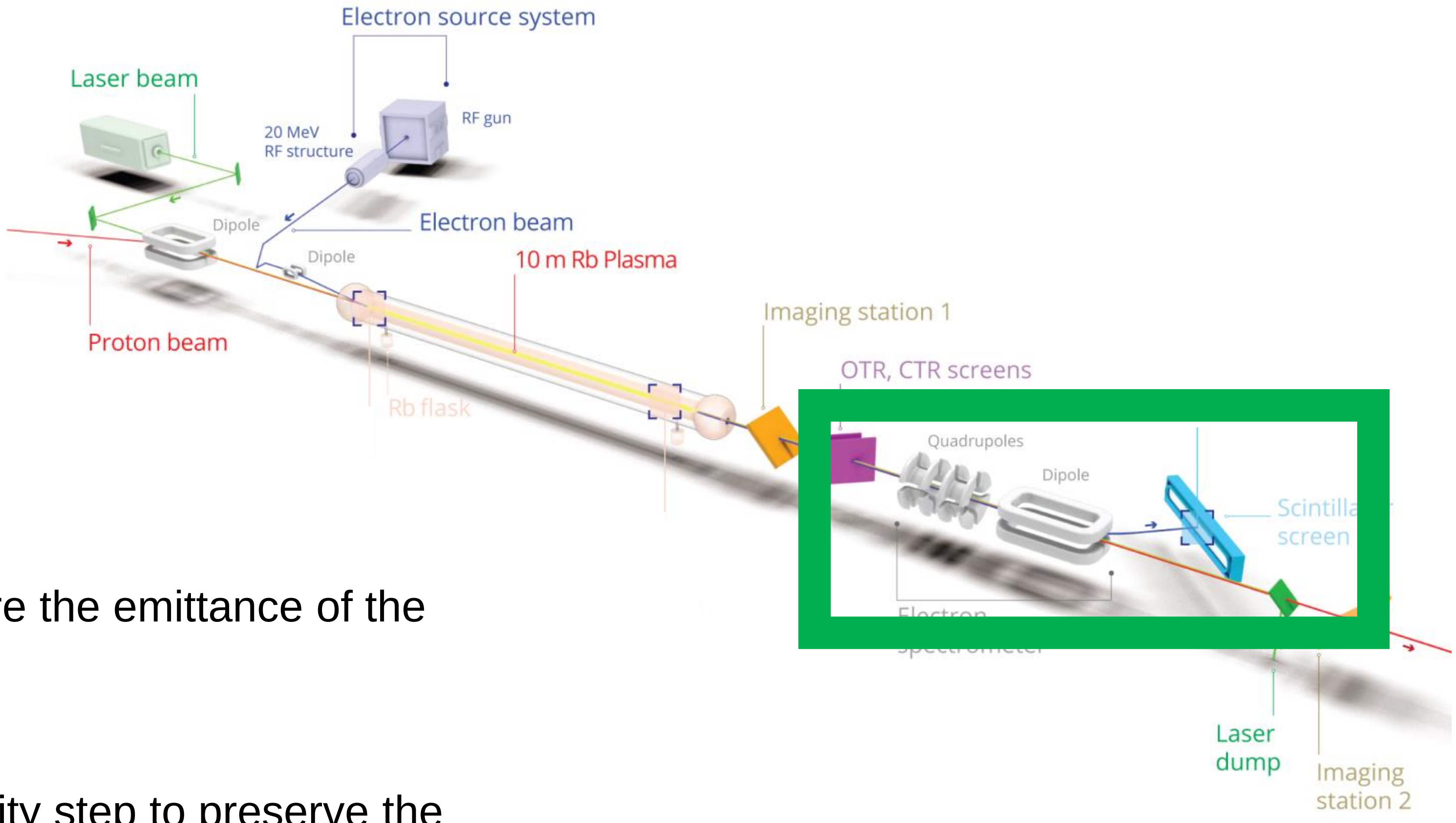
Demonstrate the **scalability** and **quality** of the electron acceleration

The Magnetic Spectrometer

Measures the acceleration of the injected electrons

Must be upgraded for AWAKE to achieve the early Run 2 goals

Early Run 2 experiments are dedicated to taking the first step towards:



Quality

Demonstrate the ability to measure the emittance of the accelerated electrons

Scalability

Explore the use of a plasma density step to preserve the wakefield amplitude over longer distances

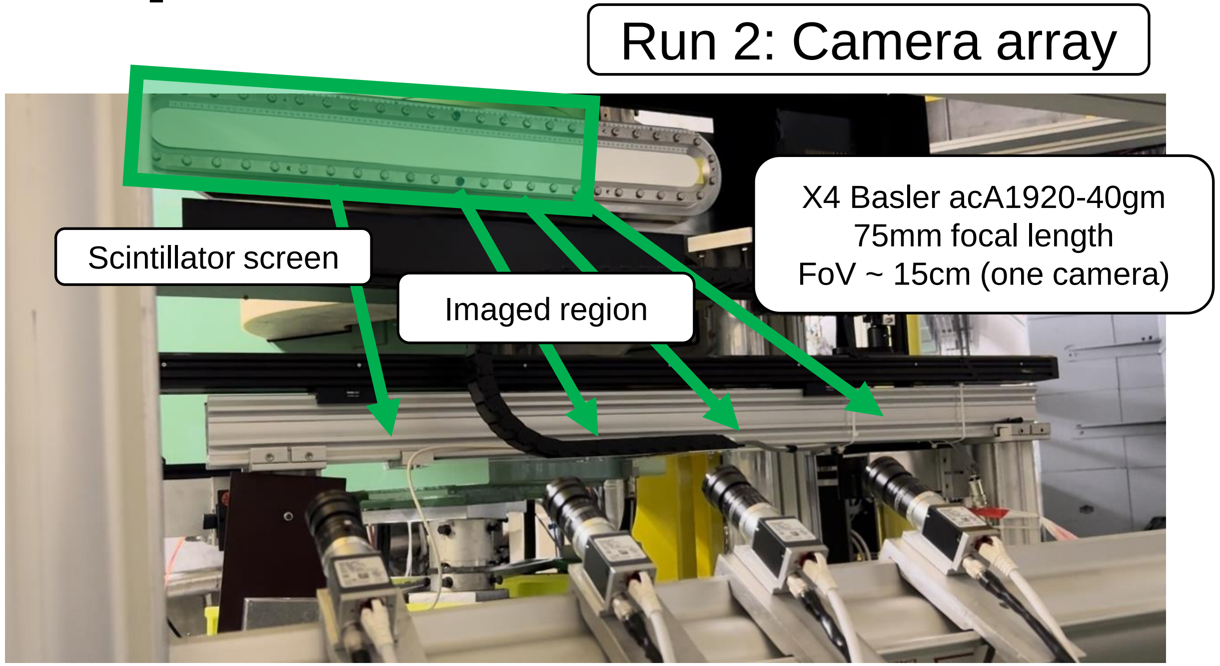
Upgrading the Spectrometer Optics

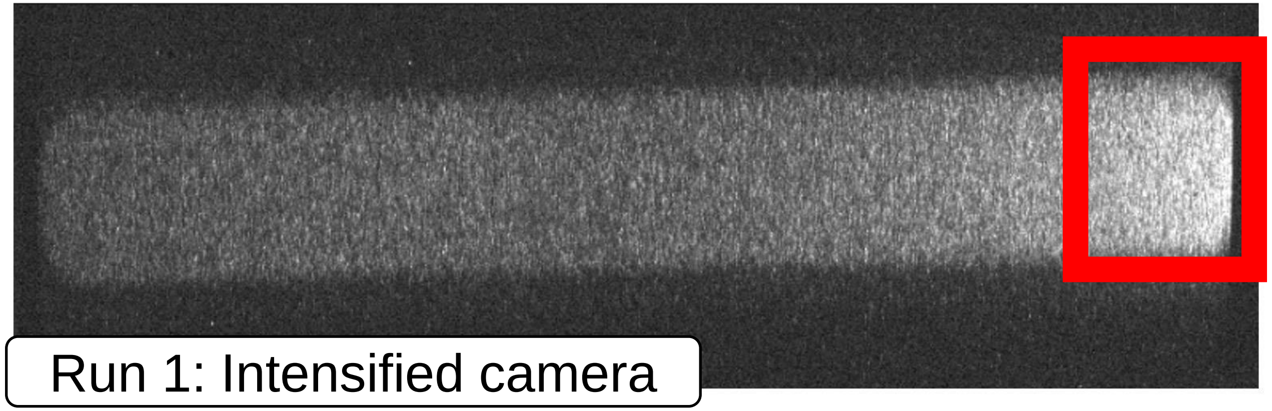
Run 1 (2017 - 2021):

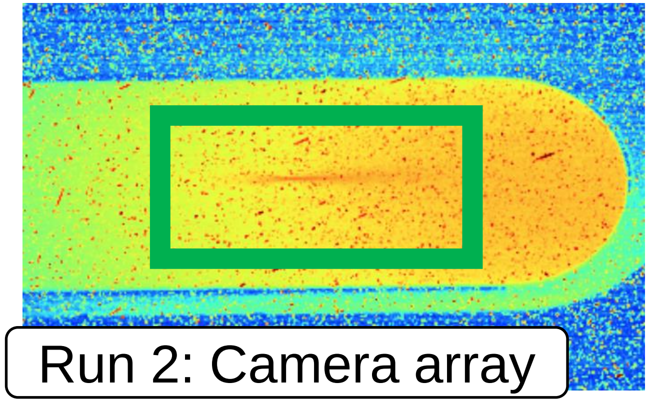
Intensified camera, 17m from screen, light transported through 3 mirrors.

Run 2 (2022 +):

Addition of camera array for direct imaging. Angled -30º below horizontal to reduce radiation exposure.







Optical resolution increased with upgrade

Reveals acceleration events previously hidden

Accelerated Electron Bunch Emittance

A measure of the **transverse size** of the beam and the **divergence**

Run 1: Optics too resolution-limited for vertical size measurements

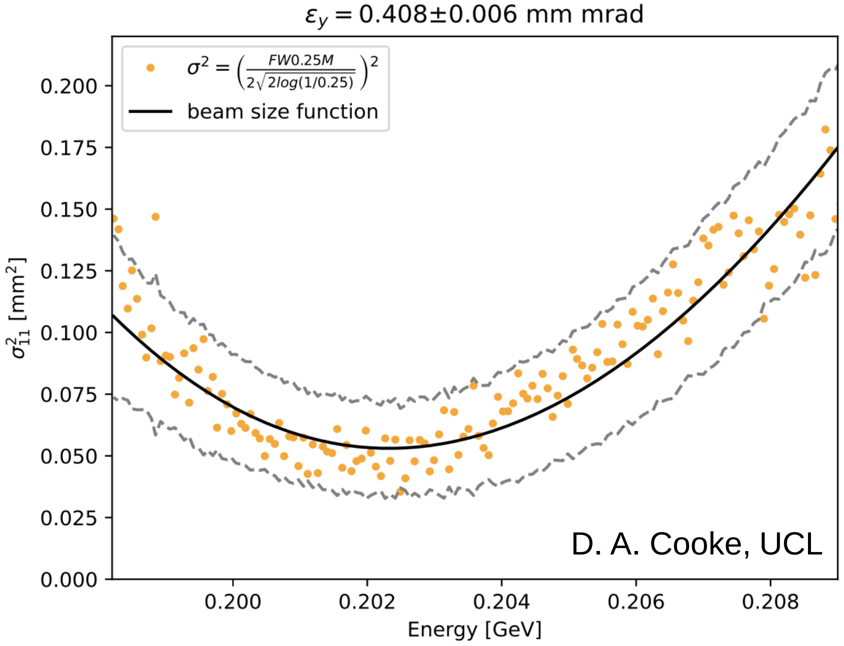
Run 2: Optics reveal shape and size of accelerated electron bunches

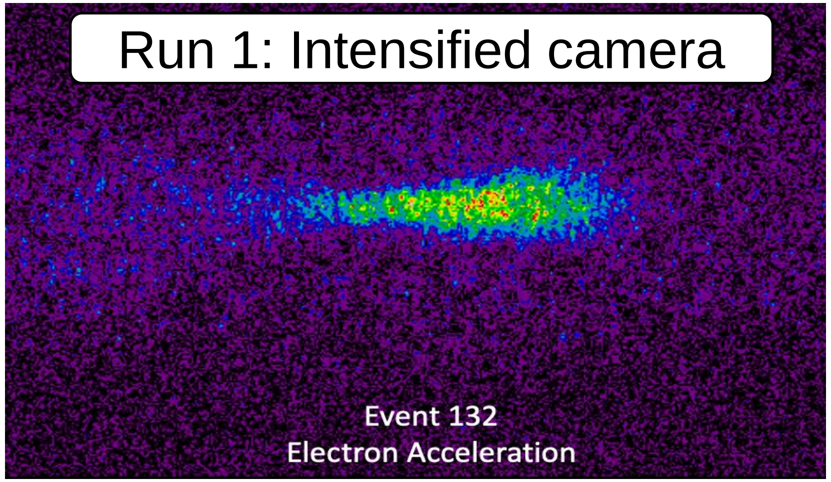
Variety of methods used to determine emittance:

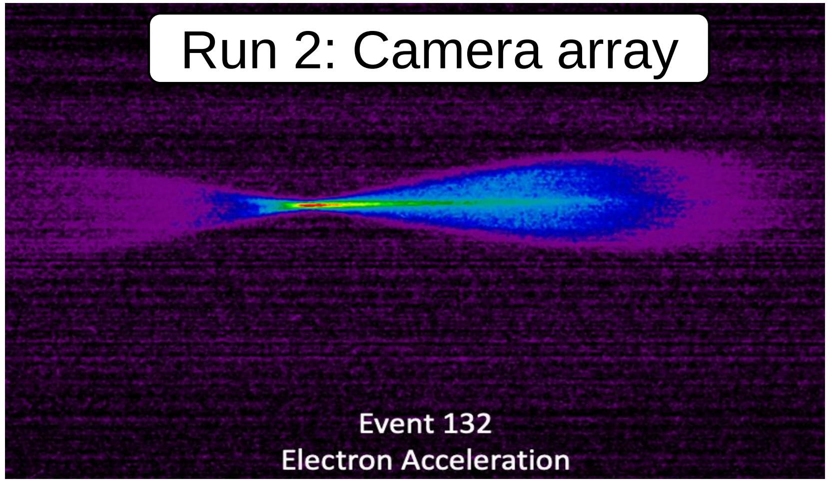
- Multi-shot quad scans
- Single-shot "butterfly" technique
- Single-shot tomography

Reasonable **agreement** between all methods.

Proof-of-principle measurement: AWAKE can now assess bunch quality via transverse emittance





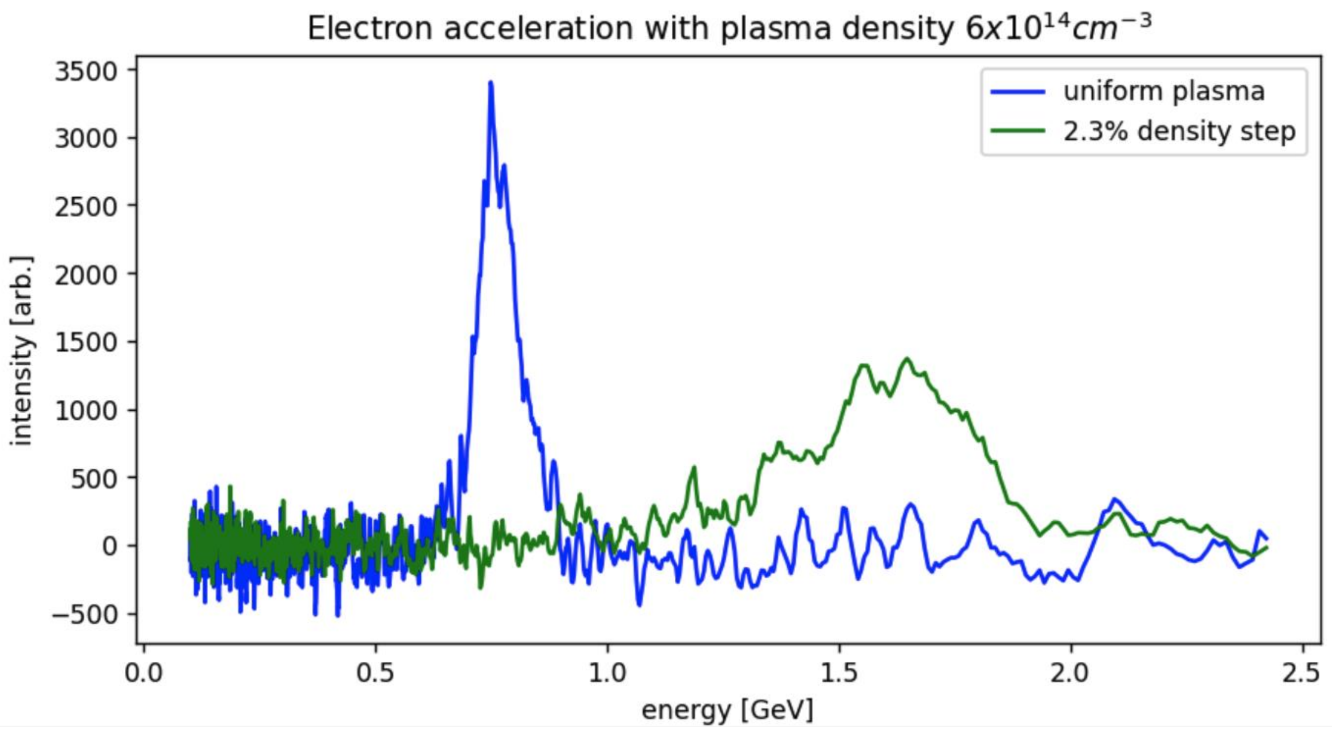


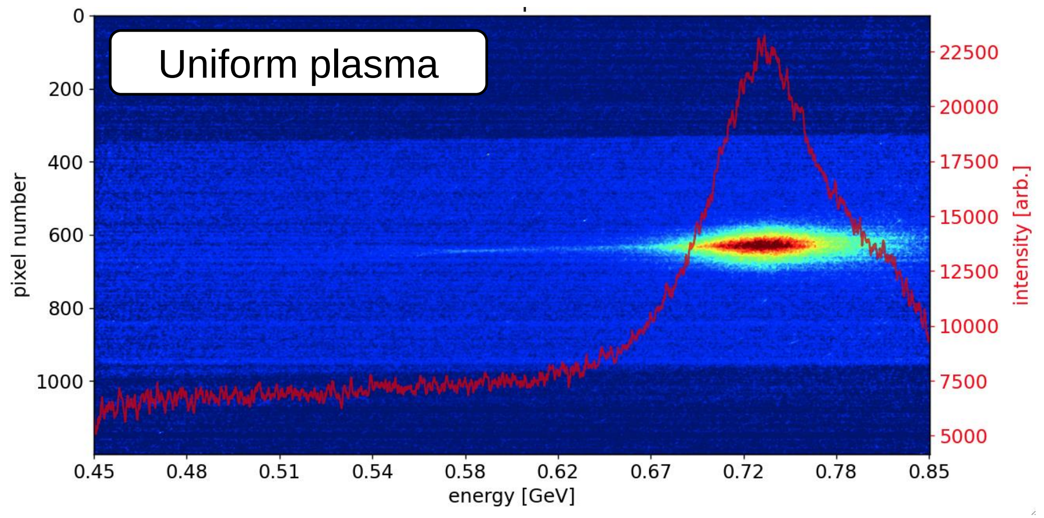
First Energy Gain with Density Steps

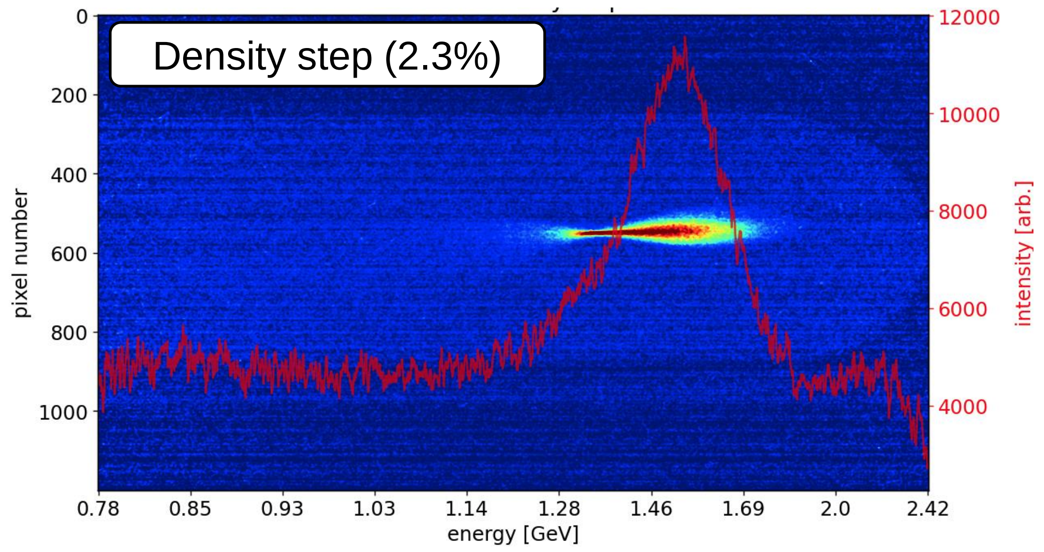
Preliminary

Plasma density: $6\times 10^{14}\mathrm{cm}^{-3}$(step 2.3% at 1.75m)

Proton bunch population: 3×10^{11}

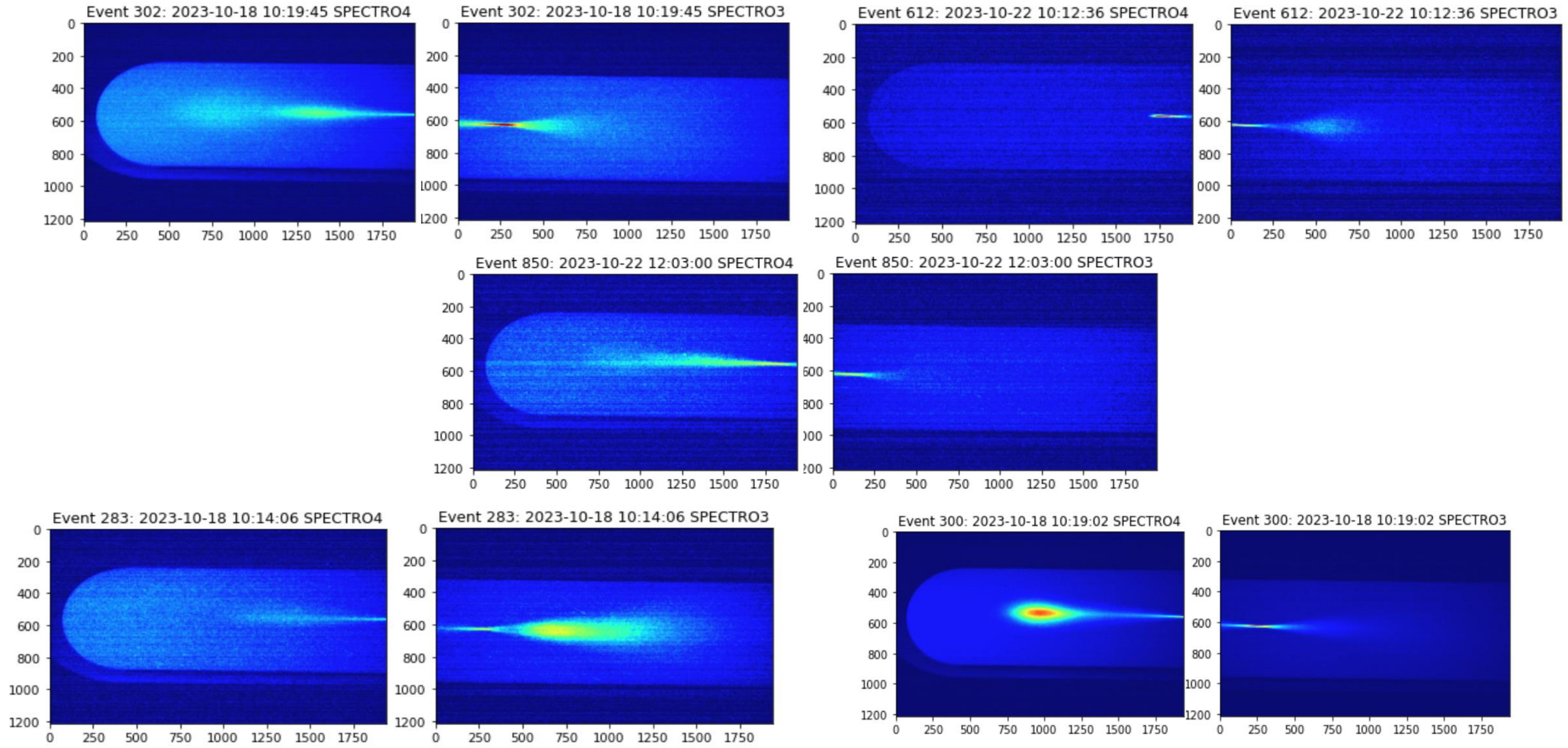






Upgrading the Spectrometer Optics

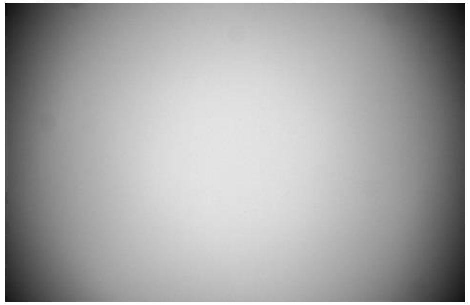
Imaging Stitching

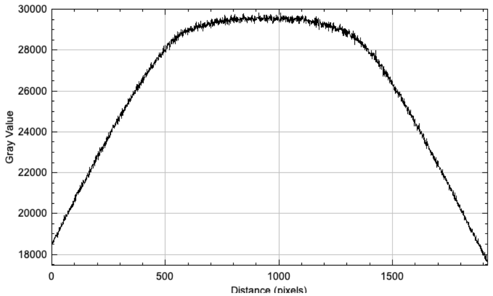


Upgrading the Spectrometer Optics

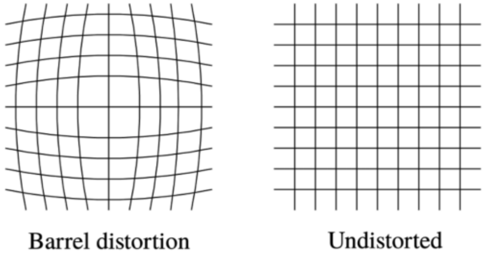
Imaging Stitching

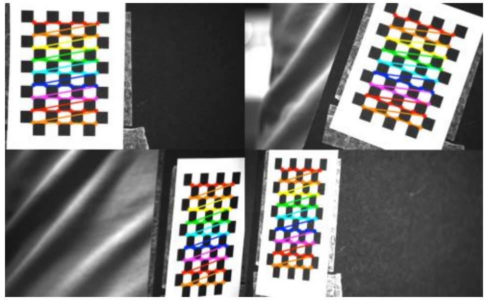
Vignetting correction





Lens distortion





Perspective correction

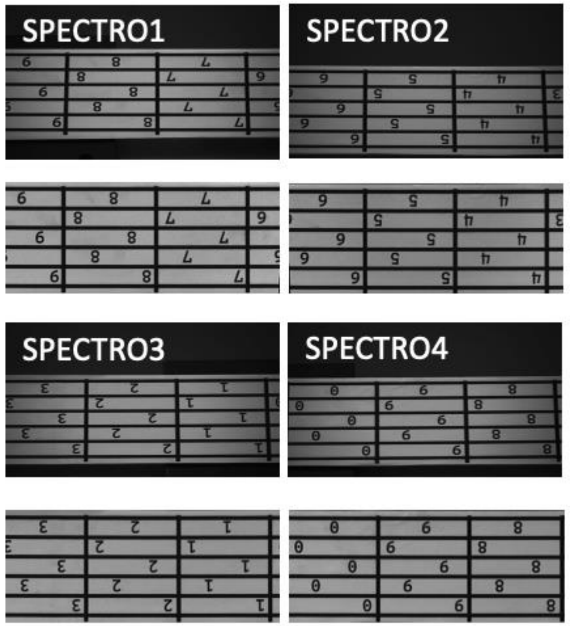
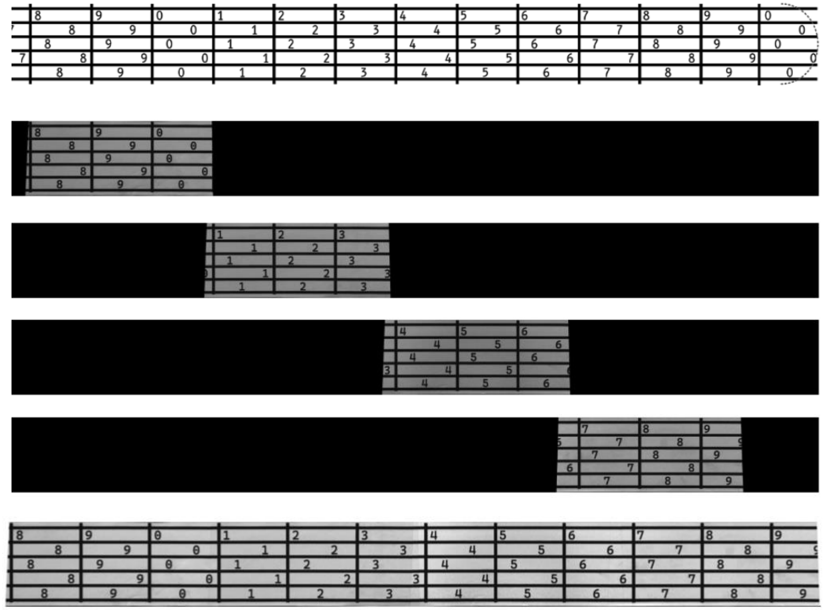
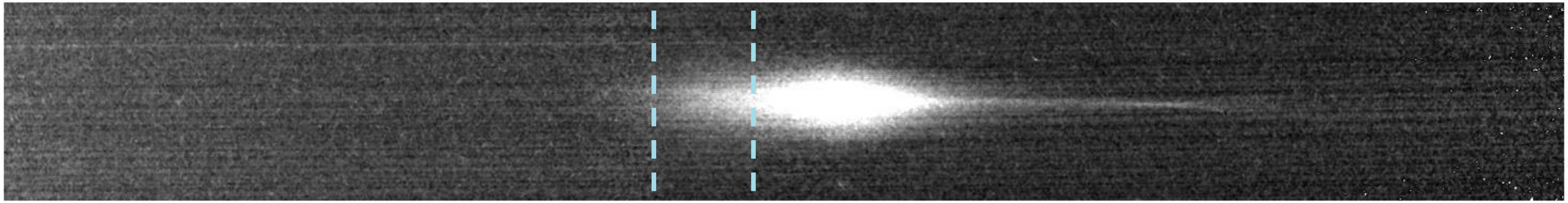


Image overlaying





Summary

AWAKE is a proton-driven plasma wakefield acceleration experiment at CERN

Run 1 demonstrated the feasibility of a long proton bunch drive beam and electron acceleration with high gradients

Scalability: Exploration of a plasma density step to scale the acceleration

- Preserves the wakefield amplitude for longer distances
- First results from 2023 look promising, 2024 dedicated to understanding and optimisation

Quality: Essential upgrades to the magnetic spectrometer have:

- Increased the number of events visible during live data collection
- Allowed for measurements of the transverse emittance of the accelerated electrons

The current AWAKE timeline predicts applications to HEP in the 2030's

- AWAKE goes into shutdown end of 2024 for expansion → Longer plasma acceleration & controlled emittance
- Predicted 50 – 200 GeV electron bunches via the use of scalable plasma sources

Thanks for listening!

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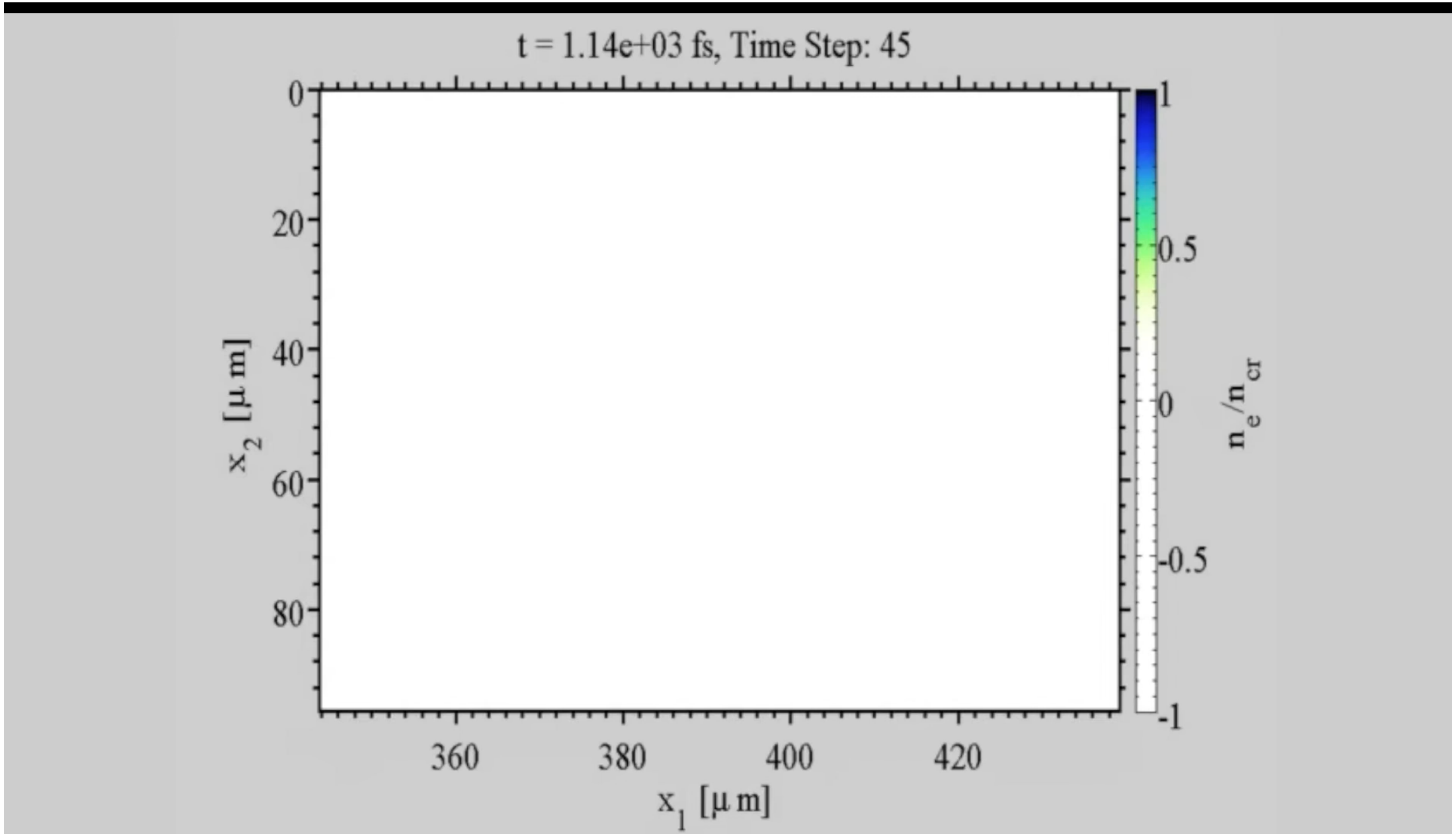
A massive thank you to my AWAKE colleagues at UCL and CERN supporting me during my PhD:

M. Wing, D. Cooke, G. Zevi Della Porta, S. Mazzoni, J. Farmer, M. Turner, V. Bencini, N. van Gils, C. Pakuza, L. Ranc, M. Bergamaschi, P. Muggli, E. Gschwendtner,

Backup

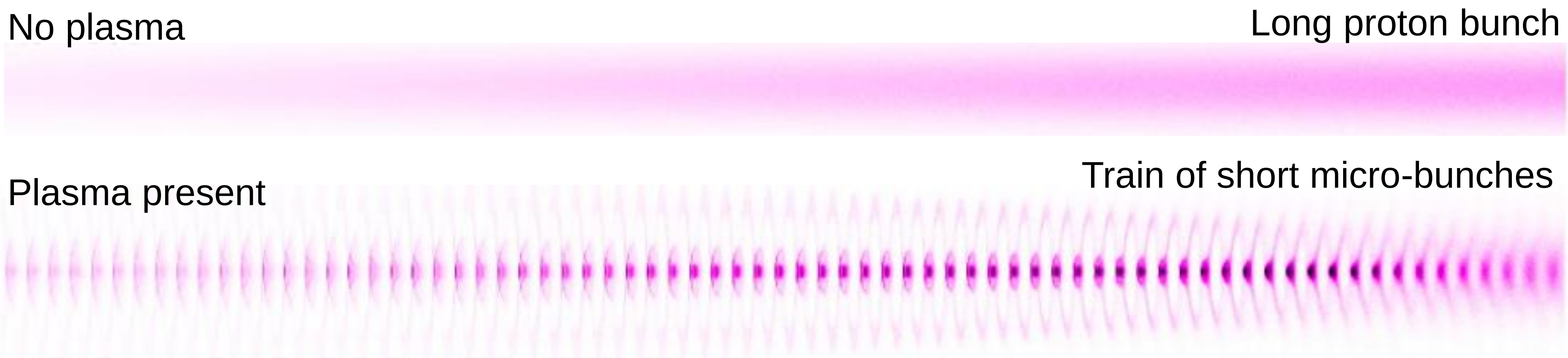
Plasma Wakefield Acceleration (PWFA)



Video source: https://www.youtube.com/watch?v=uYKIreP0iIo&t=93s

The Self Modulation Instability

1. Long charged particle bunch enters plasma
2. Separation of plasma electrons and ions
3. Initial (transverse) wakefields
4. Periodic focusing and defocusing along bunch
5. Modulation of the bunch density profile
6. Micro-bunch train separated by plasma period



Simulation shows a long proton bunch **can** be used for PWFA

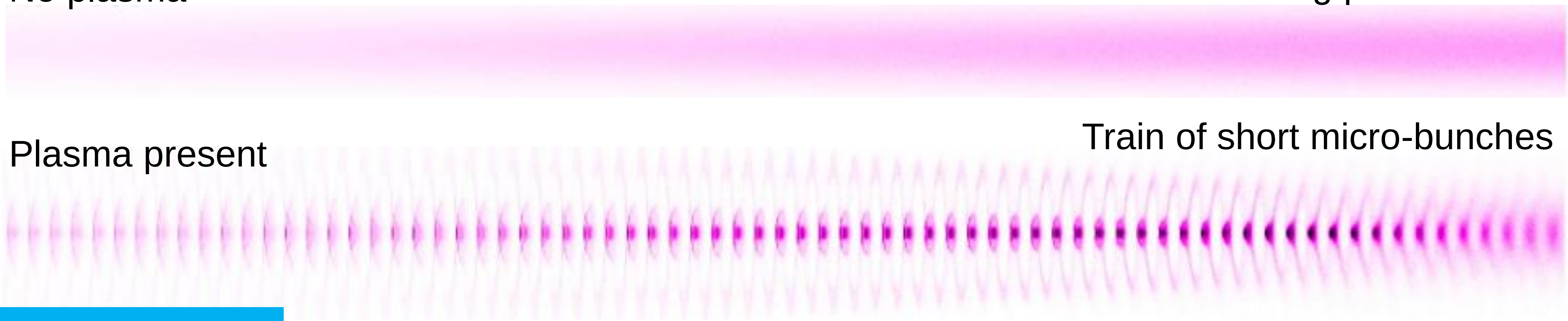
AWAKE Run 1: Self Modulation Instability

No plasma

Long proton bunch

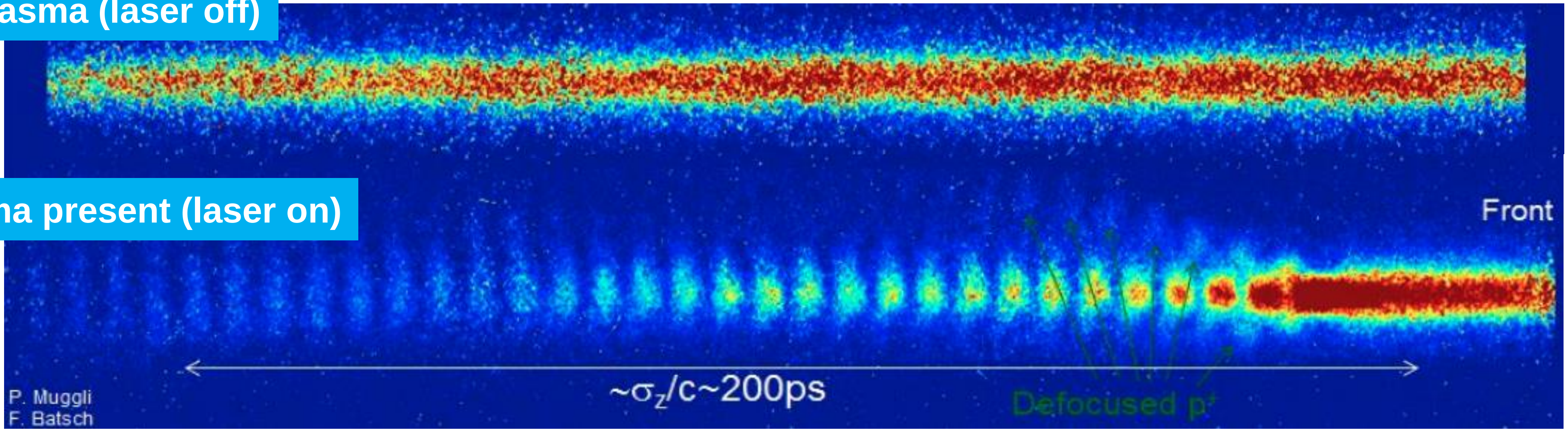
Plasma present

Train of short micro-bunches



No plasma (laser off)

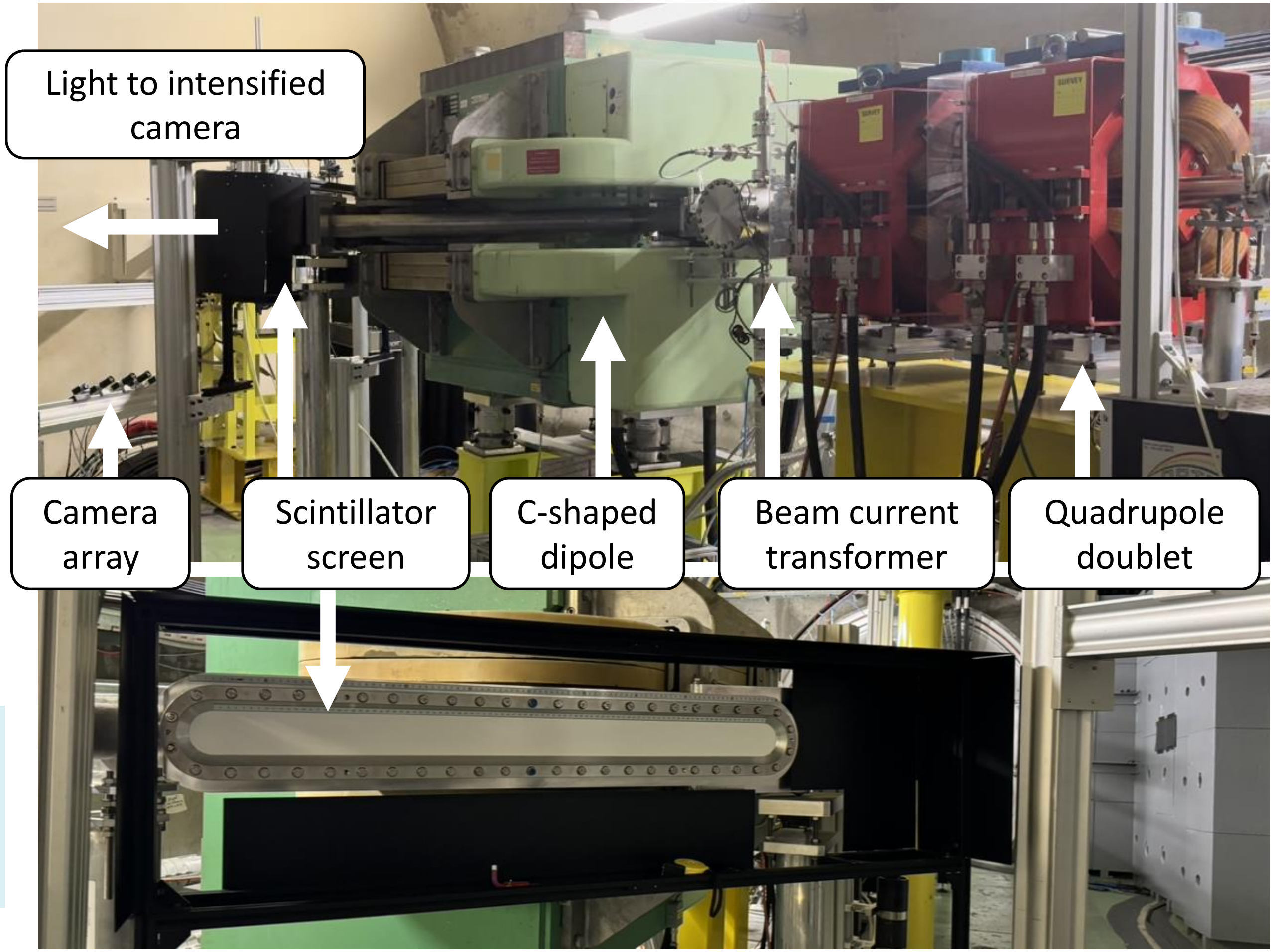
Plasma present (laser on)



The Magnetic Spectrometer

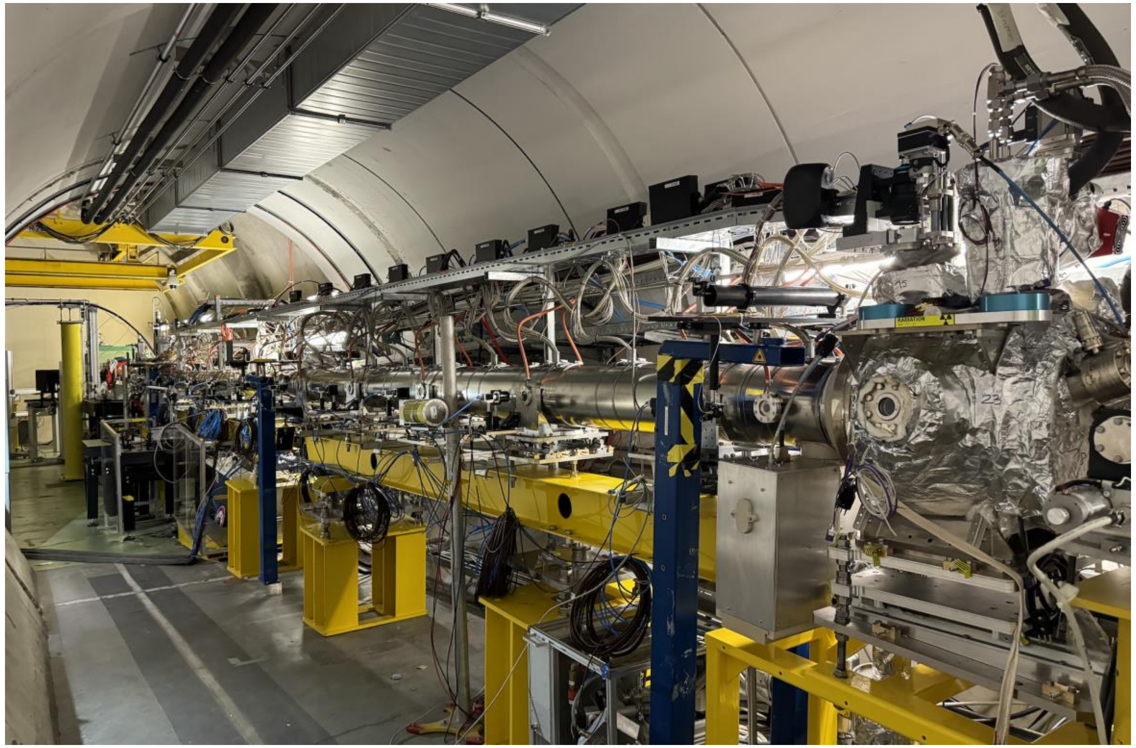
Design goals

- Separate electrons from proton drive beam
- Measure intensity of spatially distributed electrons
- Prevent significant beam loss of accelerated electrons prior to measurement
- Provide a sufficient dynamic range of measurable electron energies
- *Demonstrate the ability to measure the emittance of the accelerated electron bunches*



AWAKE Run 2(b)

Run 1: Installation of the first rubidium vapour source, 2016



Run 2b: Installation of the new rubidium vapour source, 2023

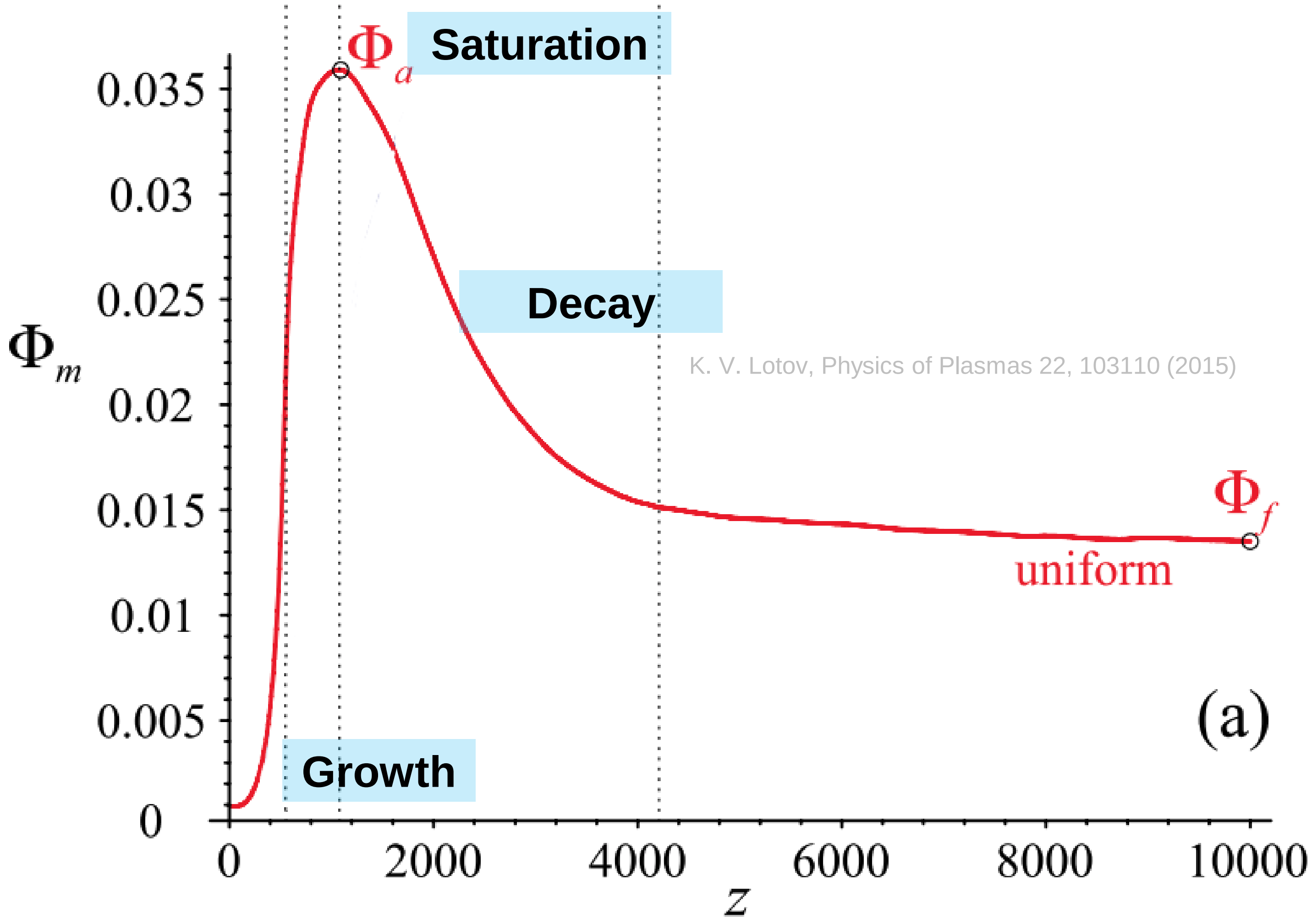
Plasma Density Steps

The amplitude of the wakefields correlates to the maximum accelerating gradient.

The growth of the wakefields happens early on, they then saturate and decay.

This makes scaling the plasma, in a single stage, for longer accelerators difficult.

Why study the effect of density steps?



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

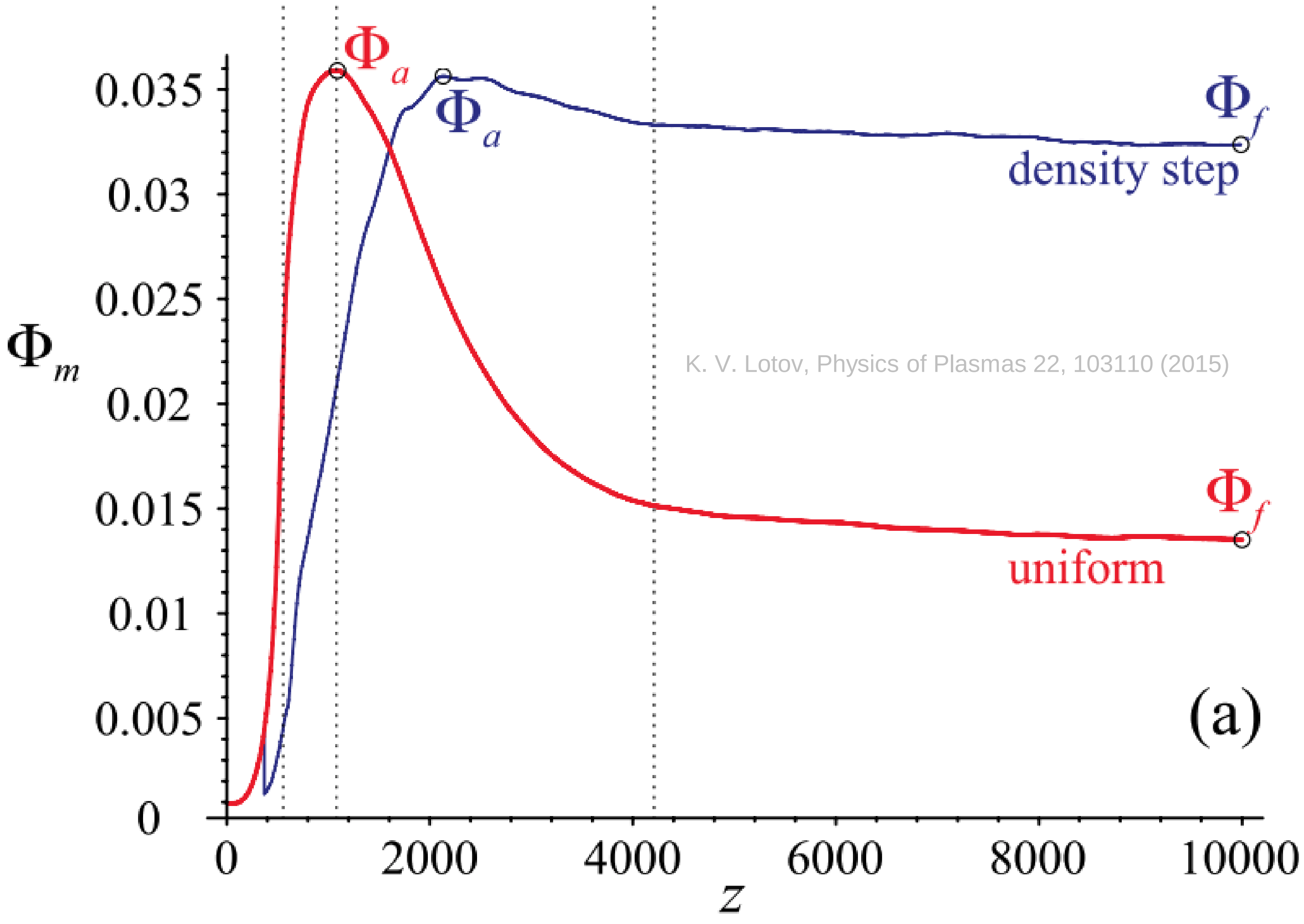
Plasma Density Steps

Simulations show the micro-bunch destruction can be 'cured' with the use of a small step in the plasma density

Wakefield amplitude can be preserved over a longer distance. This is **vital** for scalability → maintaining GV/m gradients over long distances.

AWAKE is using Run 2b to study and understand the effect of plasma density steps in experiment via:

- Measurements of the plasma light
- Injection and acceleration of electrons



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

AWAKE Run 2c: Separation of the Self Modulation and Acceleration