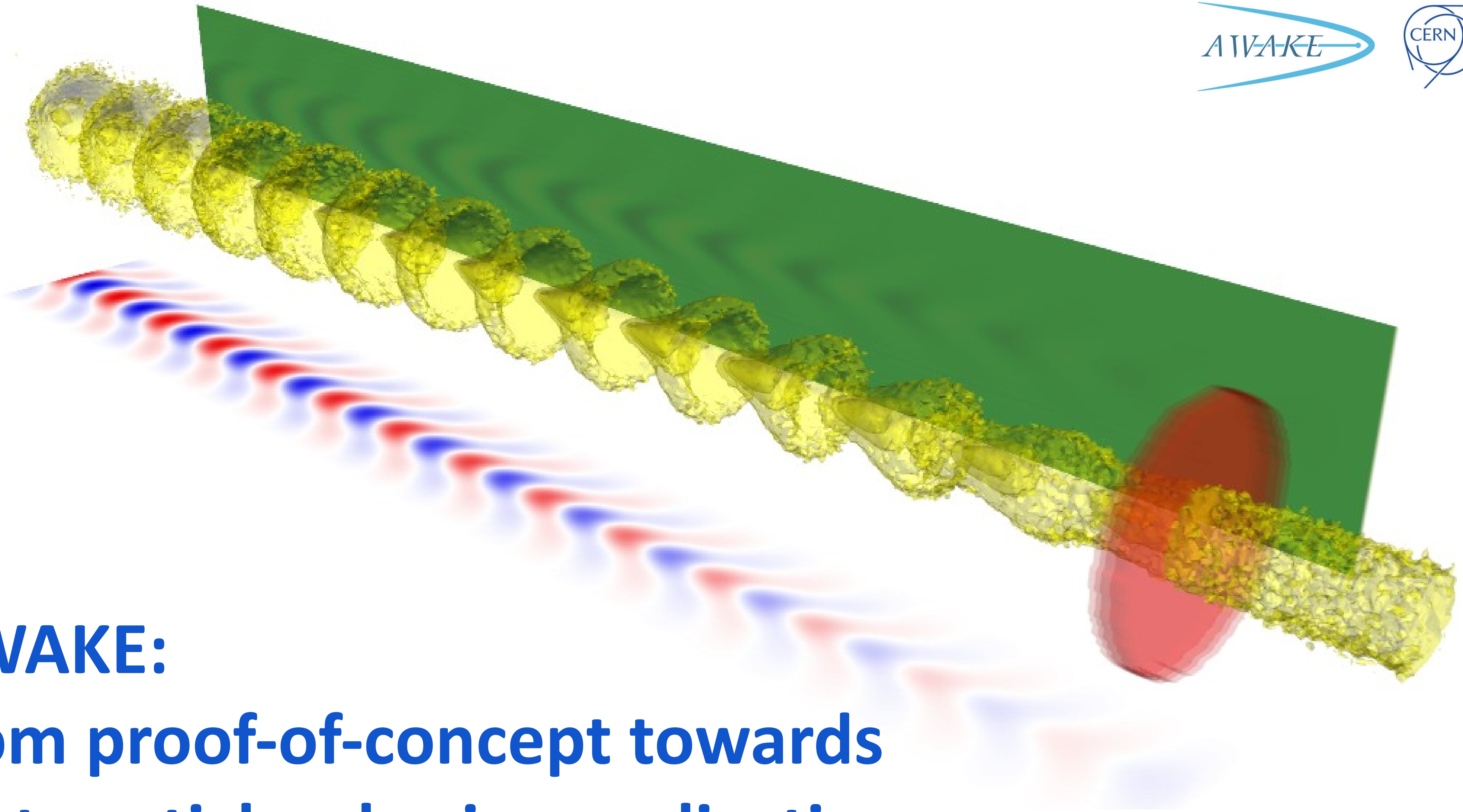


AWAKE:
from proof-of-concept towards first particle-physics applications

John Farmer

Outline

Motivation and introduction

Run 1 – Run 2ab (2016-2023)

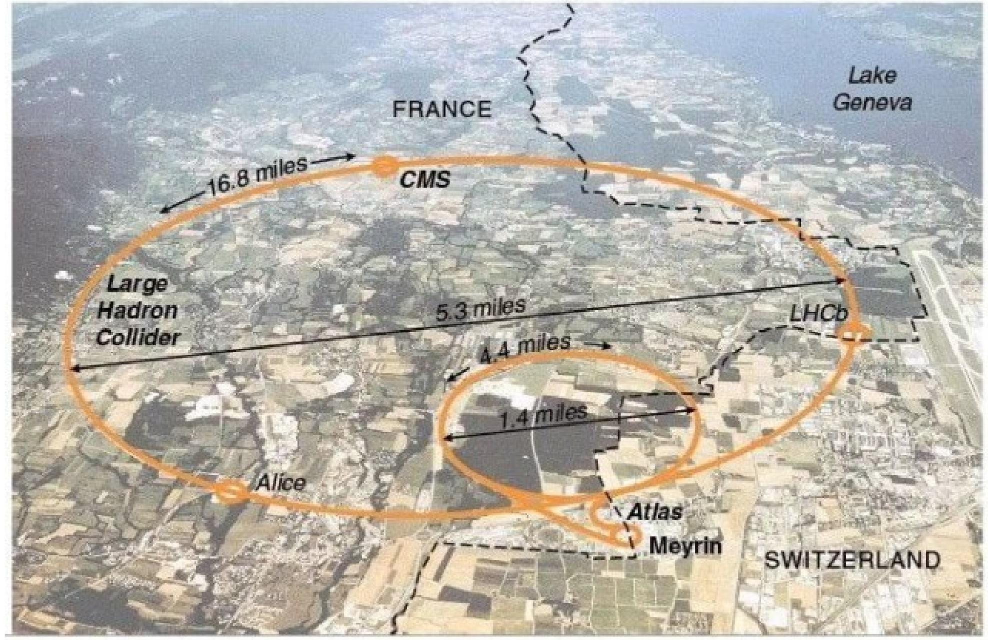
Run 2b – Run 2d (2023 -2032)

Towards Particle Physics

Beyond AWAKE

Motivation

Current state-of-the-art for accelerators is the LHC



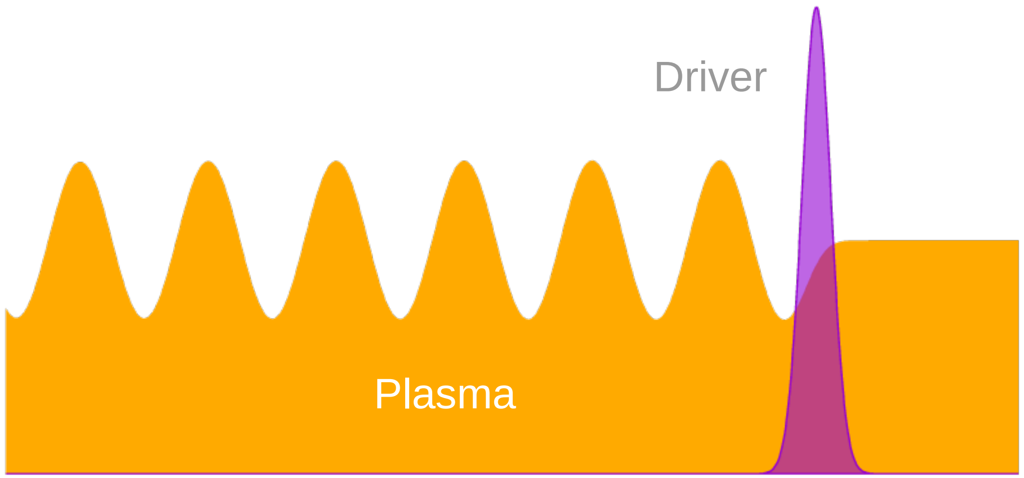
Why large?

Why hadrons?

Alternatively, use a linac. Size determined by acceleration gradient.

Plasma wakefield acceleration

Plasma supports high accelerating gradients (GV/m +).



Wakeboarding

Accelerate particles on a wakefield

- driver generates plasma wave
- witness “rides” the wave

Plasma wakefield acceleration

Choice of drivers:

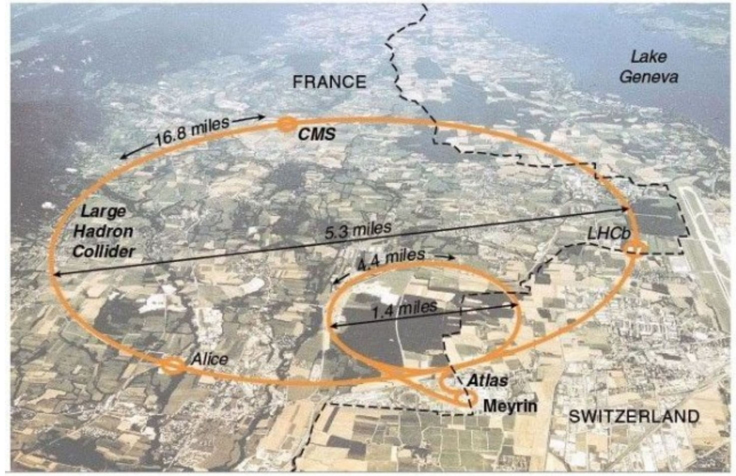
- Laser pulse
- Electron beam
- Proton beam

Not enough energy in laser/electron bunch to reach high witness energy. Solutions include

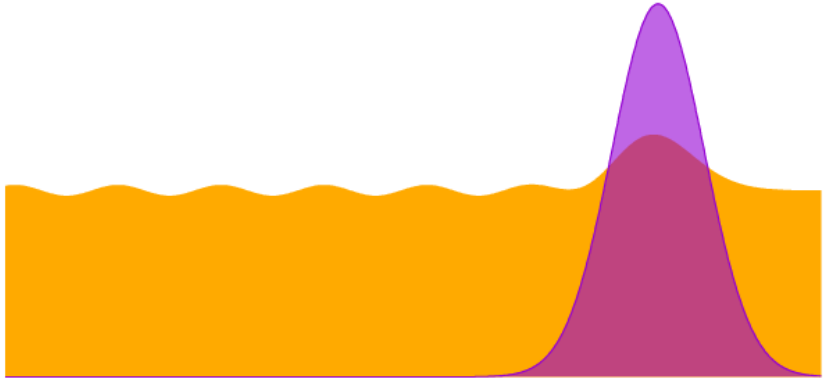
- structured driver (stability)
- staging (alignment, average gradient)

Plasma wakefield acceleration

Proton beams have plenty of energy
BUT available beams “too long”
to drive high-gradient wakefields



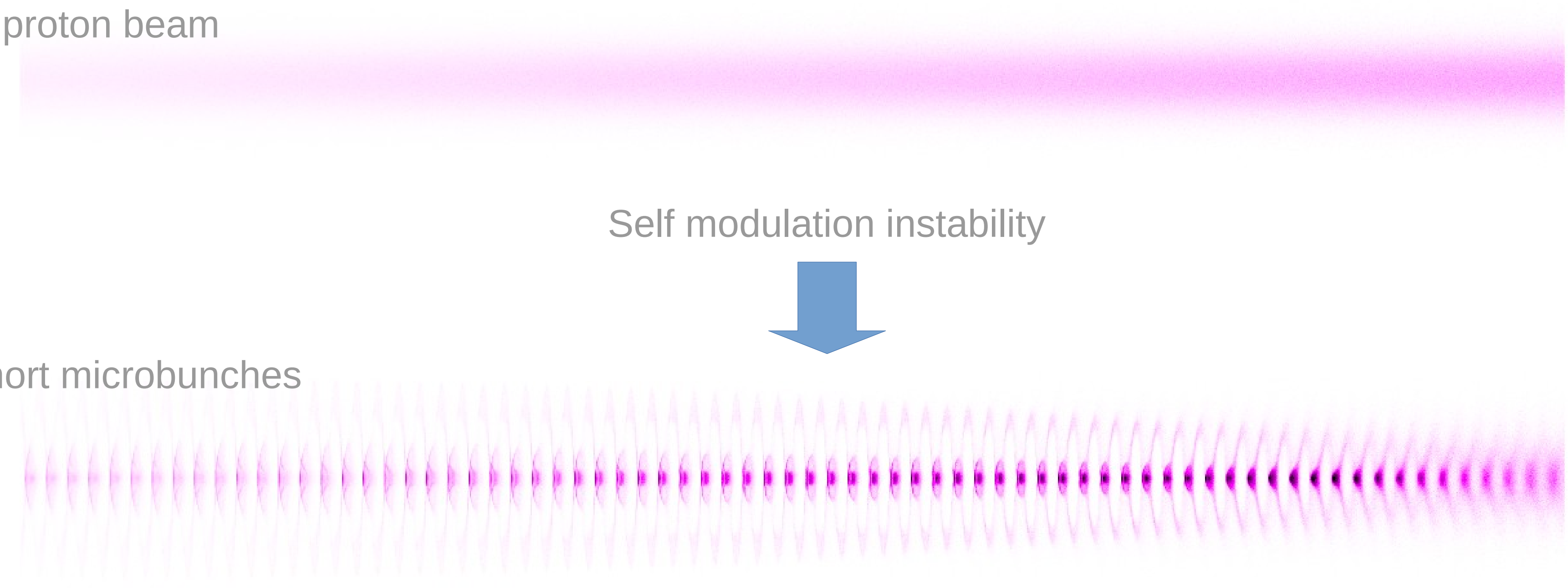
Short driver efficiently excites wakefield



Long driver suppresses its own wake

Self Modulation instability

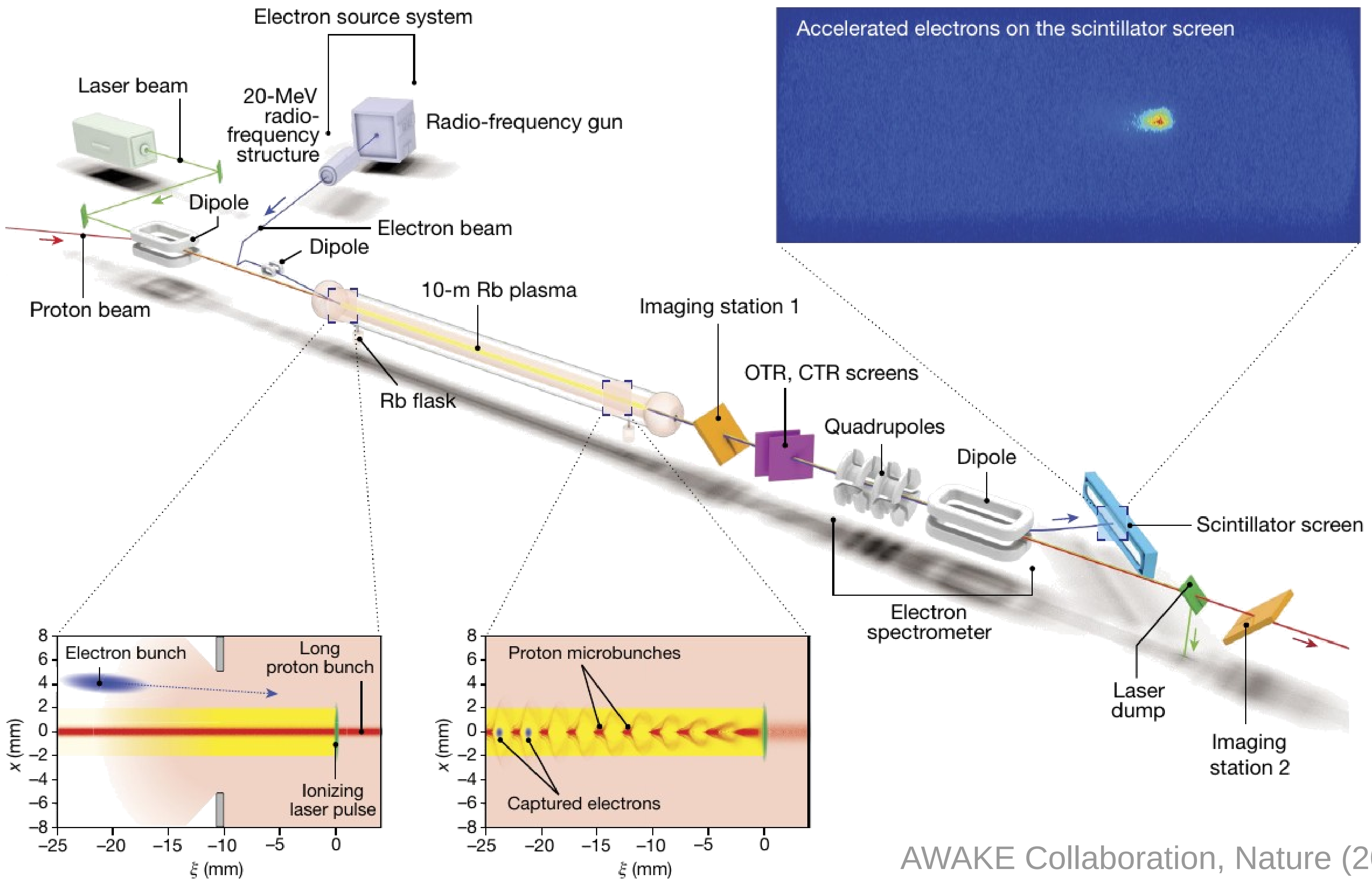
Plasma wake additionally provides focussing/defocussing fields



Resulting train of microbunches can drive large wakefields

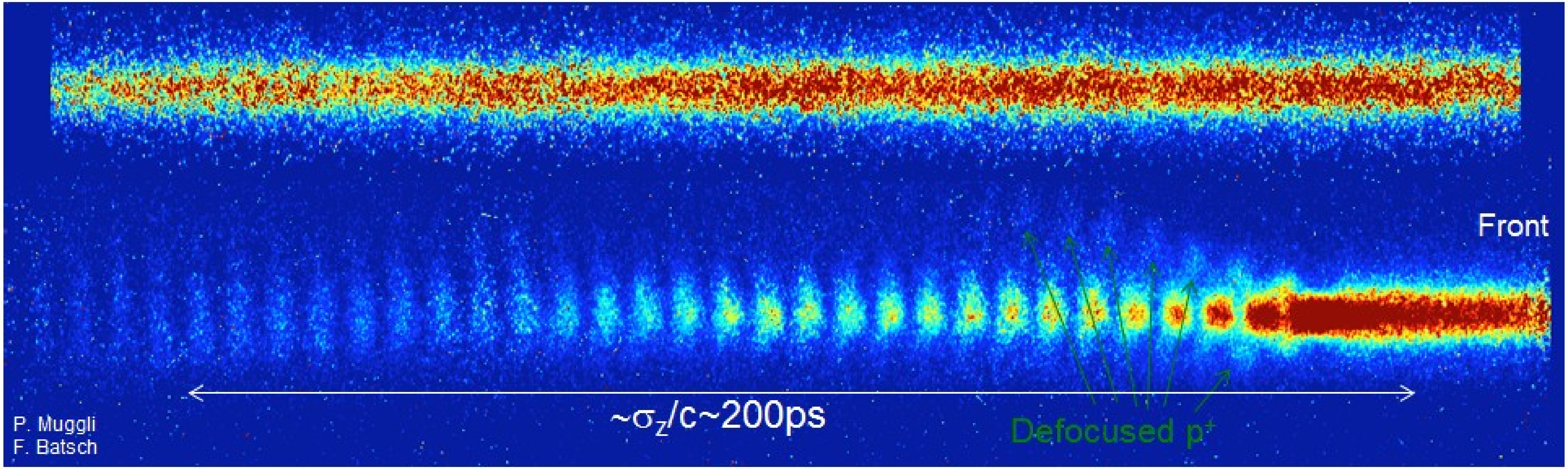
AWAKE Run 1 – Run 2ab (2016 – 2023)

AWAKE Run1 – Run 2a (2016-2022)



AWAKE Collaboration, Nature (2018)

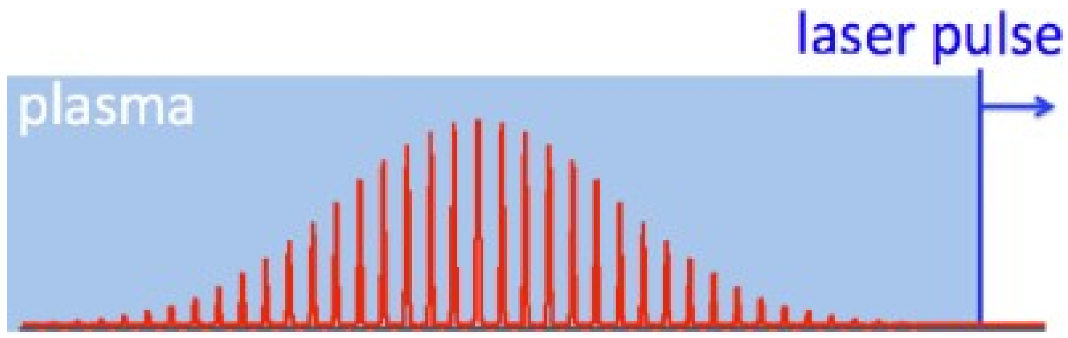
Self-modulation of the proton bunch

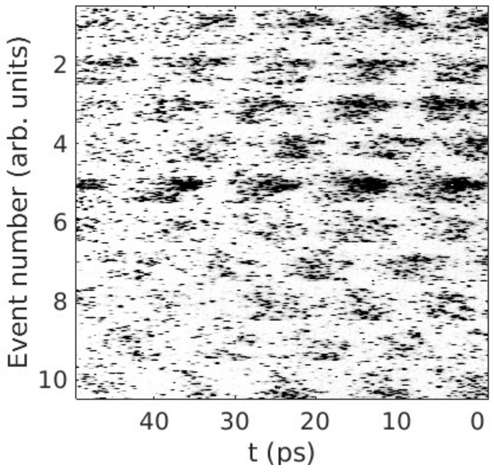


Proton bunch is modulated by the plasma

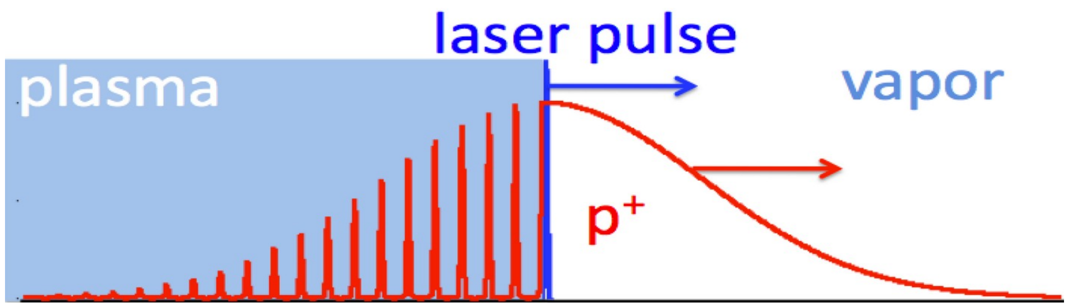
Seeded self-modulation

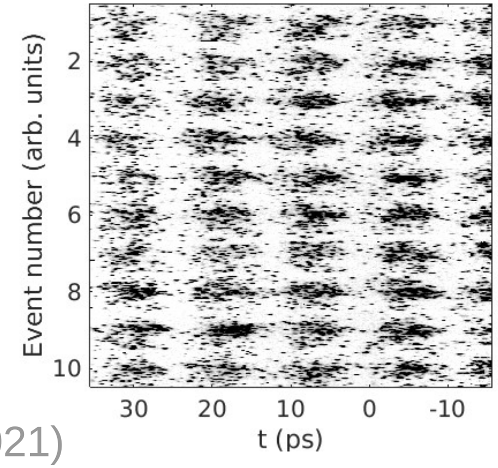
Relative laser timing affects self-modulation





Self-modulation instability: random phase





Seeded self-modulation: reproducible

F. Batsch *et al.* (AWAKE Collaboration), Phys. Rev. Lett. (2021)

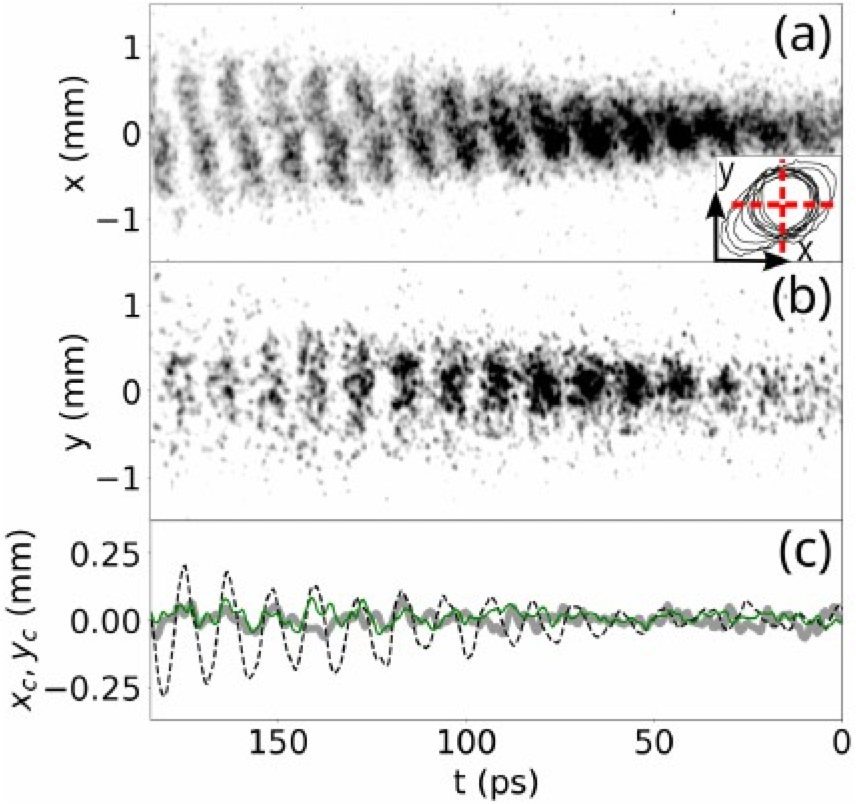
Seeded Hosing

Self-modulation can also be seeded by an electron bunch.

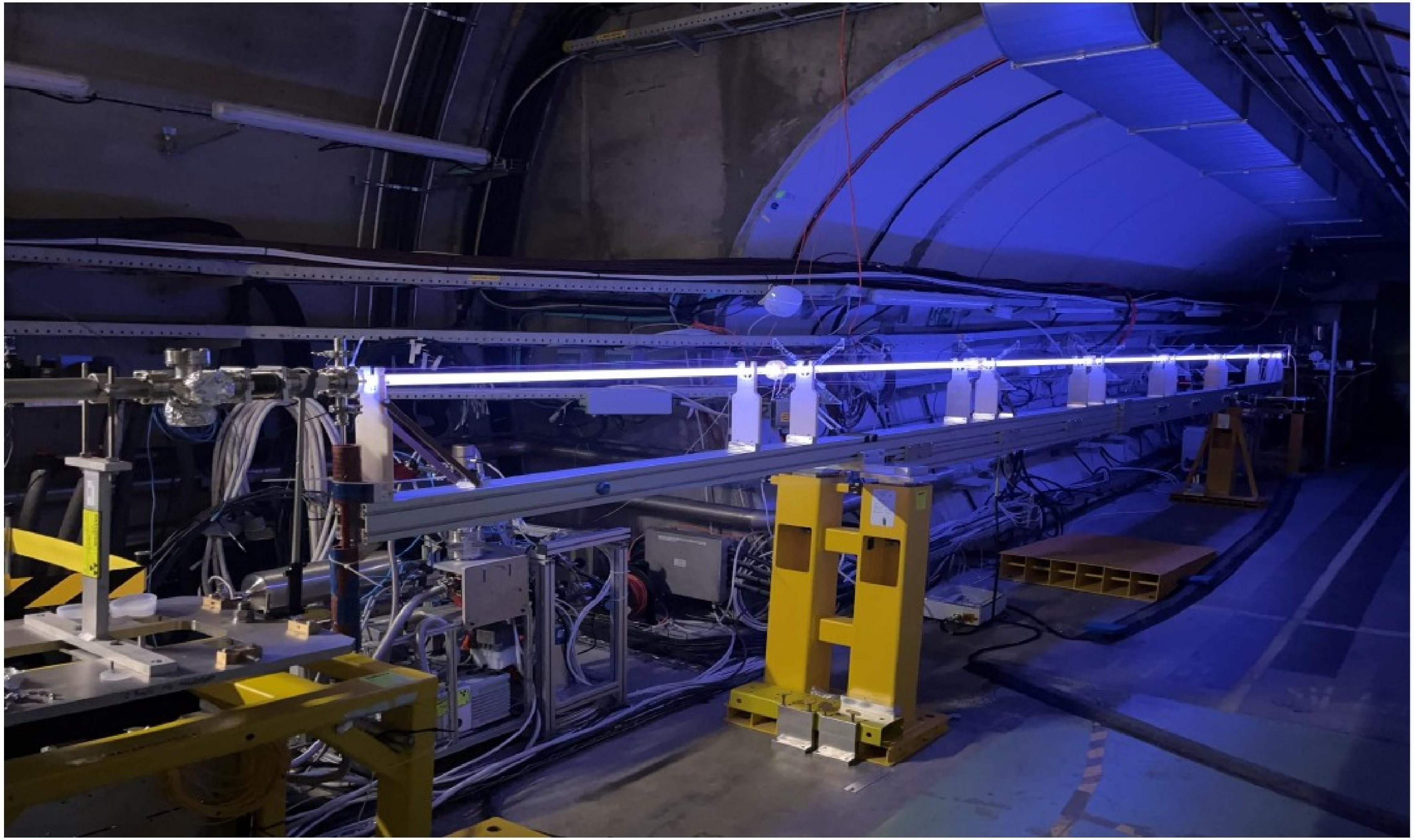
L. Verra *et al.* (AWAKE Collaboration),
Phys. Rev. Lett (2022).

Hosing can be seeded by deliberately misaligning the electron and proton bunches.

T. Nechaeva *et al.* (AWAKE Collaboration),
Phys. Rev. Lett (2024).



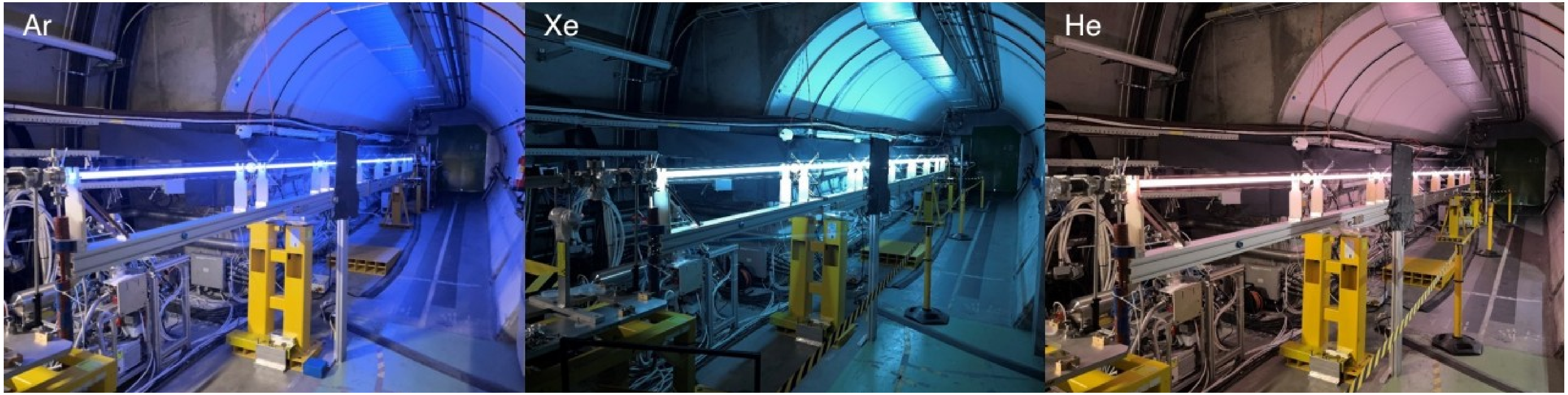
AWAKE Run 2ab (2023)



Development of a new discharge source

N. E. Torrado *et al.*
IEEE Trans. Plas. Sci. (2023)

Tolerances: Ion motion



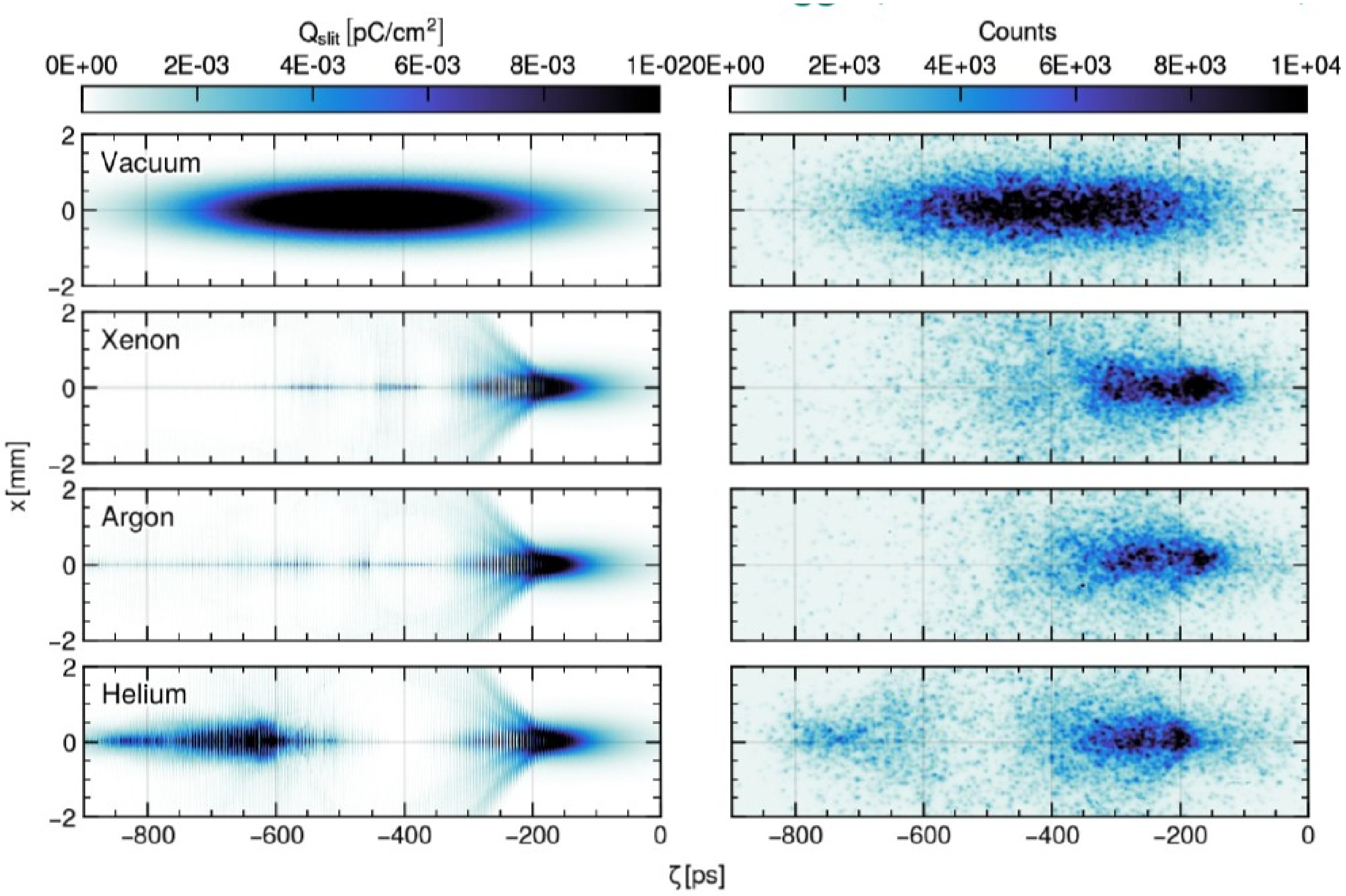
N. E. Torrado *et al.* IEEE Trans. Plas. Sci. (2023)

Allows the use of different ion species

Tolerances: Ion motion

Heavy ions:
full self-modulation
of the proton beam.

Lighter ions:
ion motion suppresses
self-modulation.



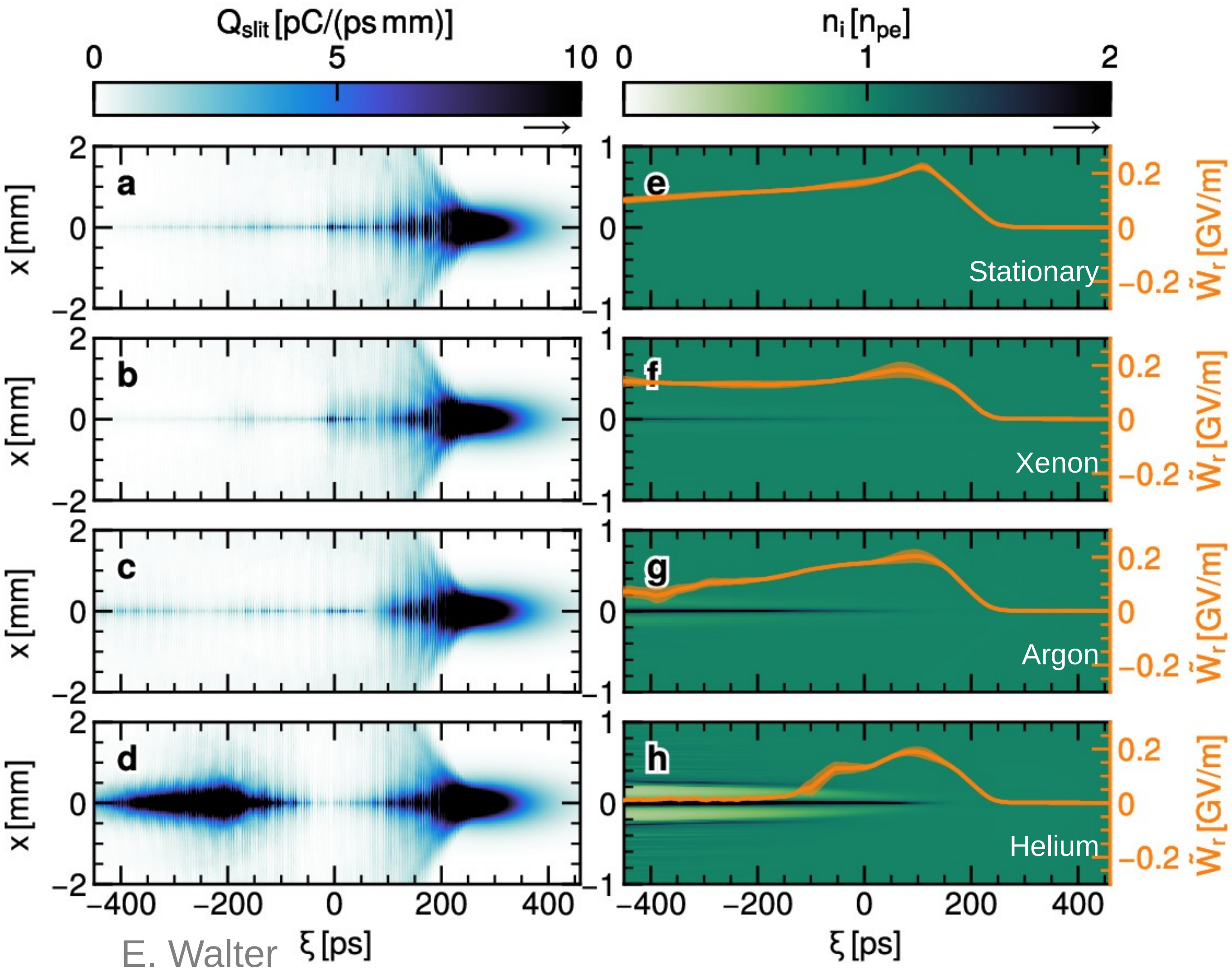
AWAKE preliminary
M. Turner *et al.* (AWAKE Collaboration), *in preparation*

Tolerances: Ion motion

Simulations allow ion dynamics to be tracked.

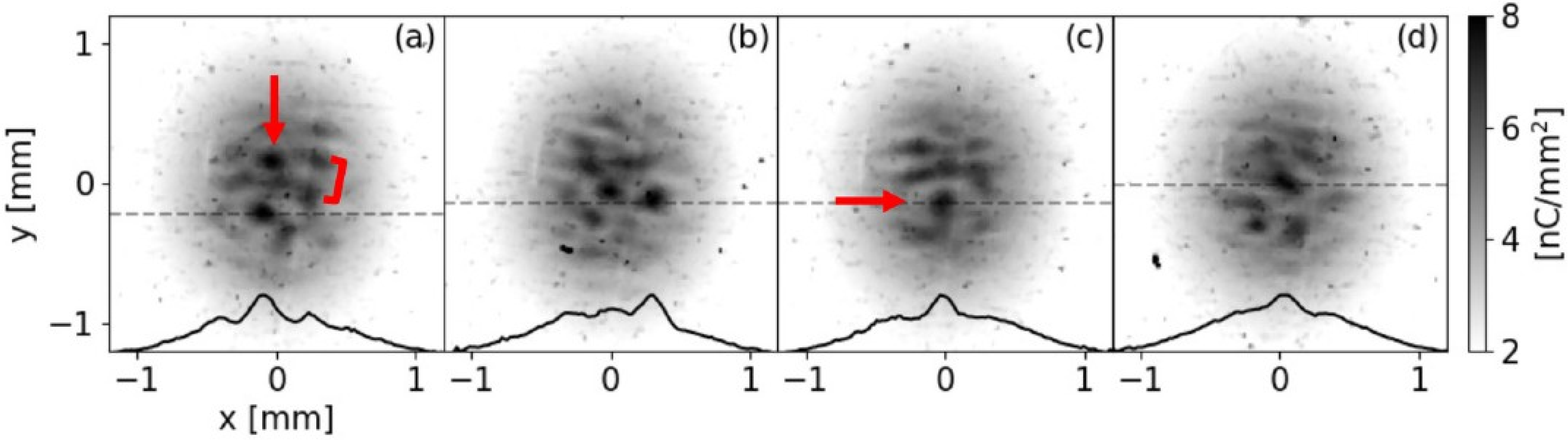
Ions are pushed by the ponderomotive force of the plasma electron wave.

Allows decisions to be made for future runs.



E. Walter

Tolerances: Filamentation



L. Verra *et al.* (AWAKE Collaboration), PRE (2024)

Transverse filamentation sets a limit on the driver radius:

$\sigma_r \leq 1/k_p$

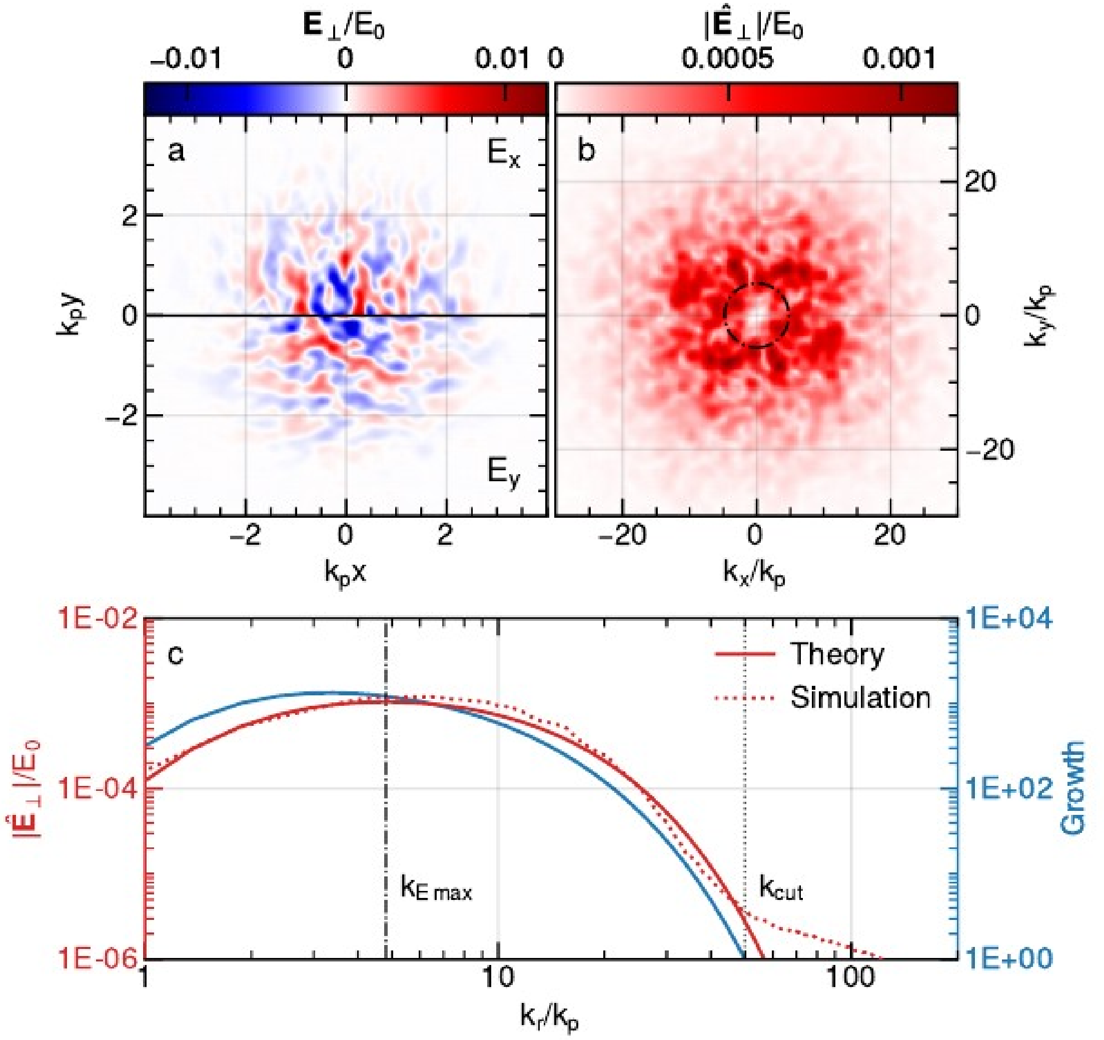
Deliberately choosing a wide beams lets us study this.

Tolerances: Filamentation

Development of a new analytical model for the filamentation of warm beams.

Correctly predicts threshold for filamentation and distance between filaments seen in experiments.

Relevant for astrophysics.

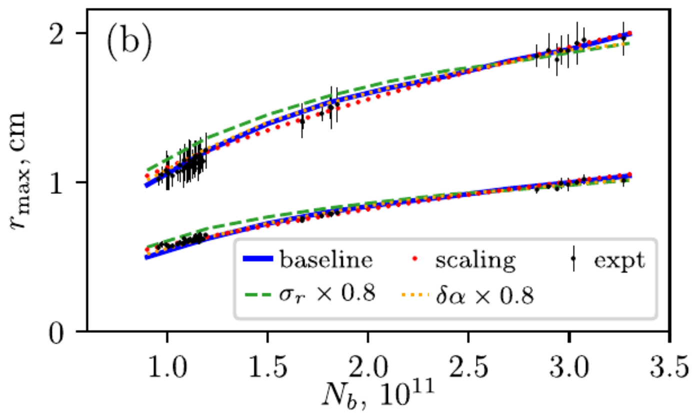


E. Walter *et al.*, *in preparation*

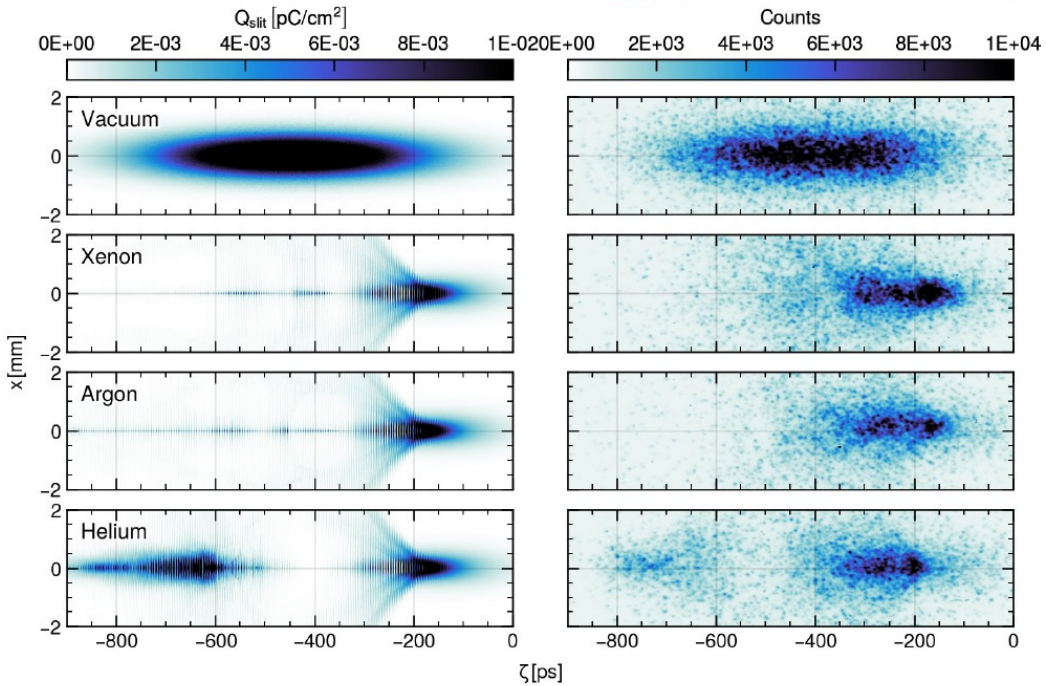
Agreement with Simulation

Beam radius after SMI at Imaging Station 2

A. Gorn, PPCF (2020)

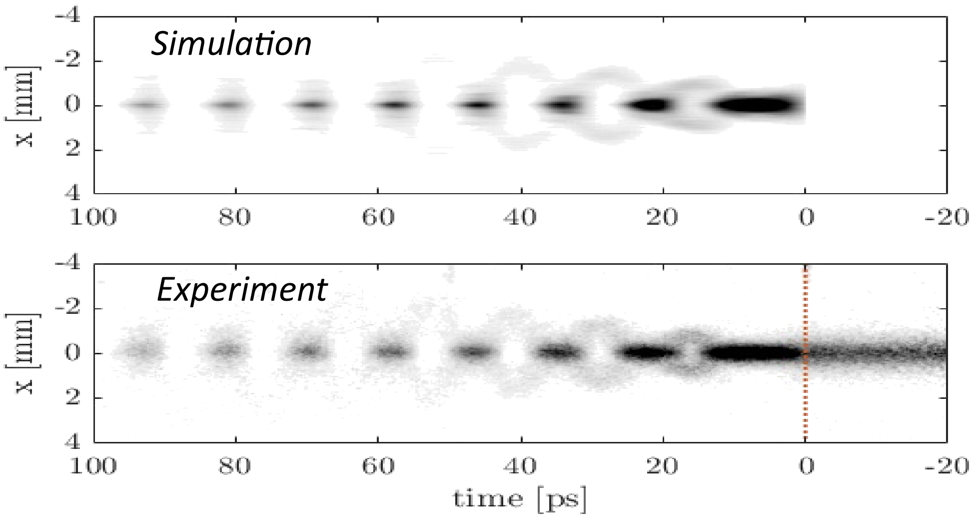


Impact of ion motion on SMI imaged at streak camera



AWAKE preliminary

M. Turner *et al.* (AWAKE Collaboration), *in preparation*



Microbunch structure at streak camera

A.-M. Bachmann, PhD thesis (2021)

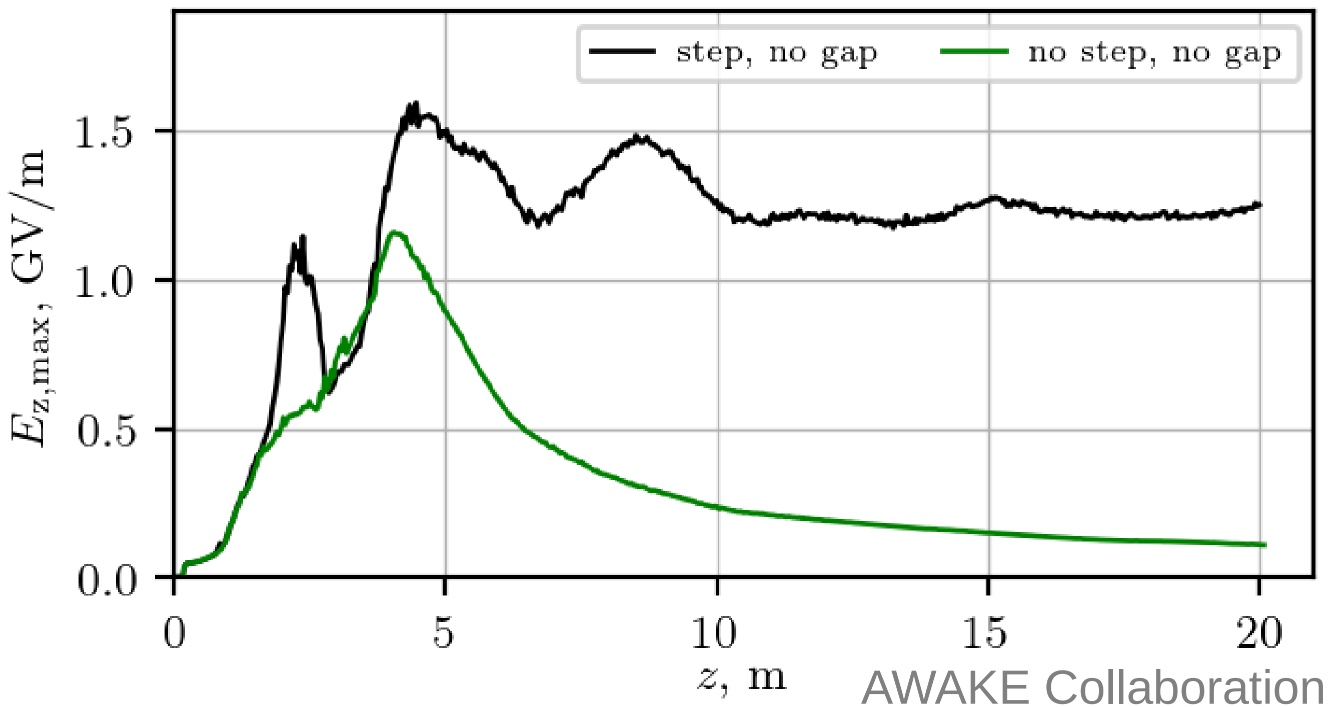
AWAKE Run 2b – Run 2d (2023 – 2032)

Controlling Self-modulation

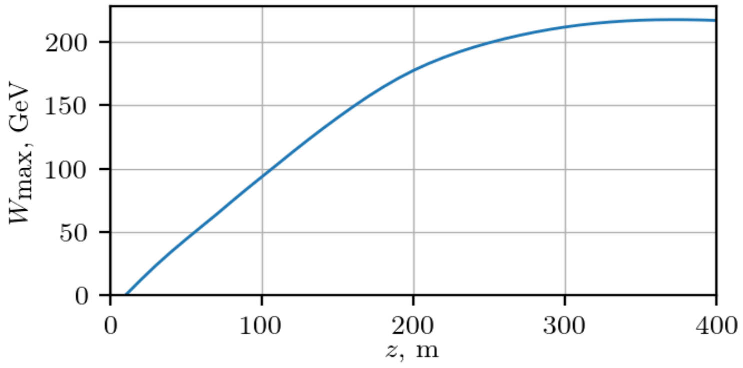
Wakefields initially grow, before decaying.

Plasma density step allows self-modulation to be controlled.

K Lotov, Phys. Plas. (2011)



AWAKE Collaboration, Symmetry (2022)



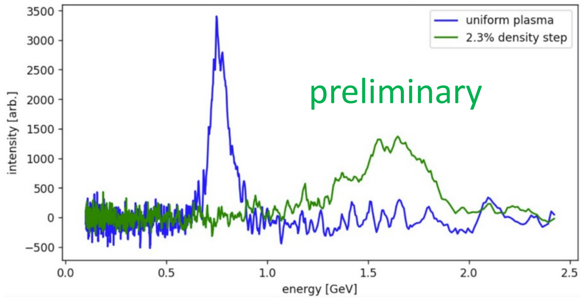
Wakefields maintain high gradients over hundreds of metres.

Lotov and Tuev, PPCF (2021)

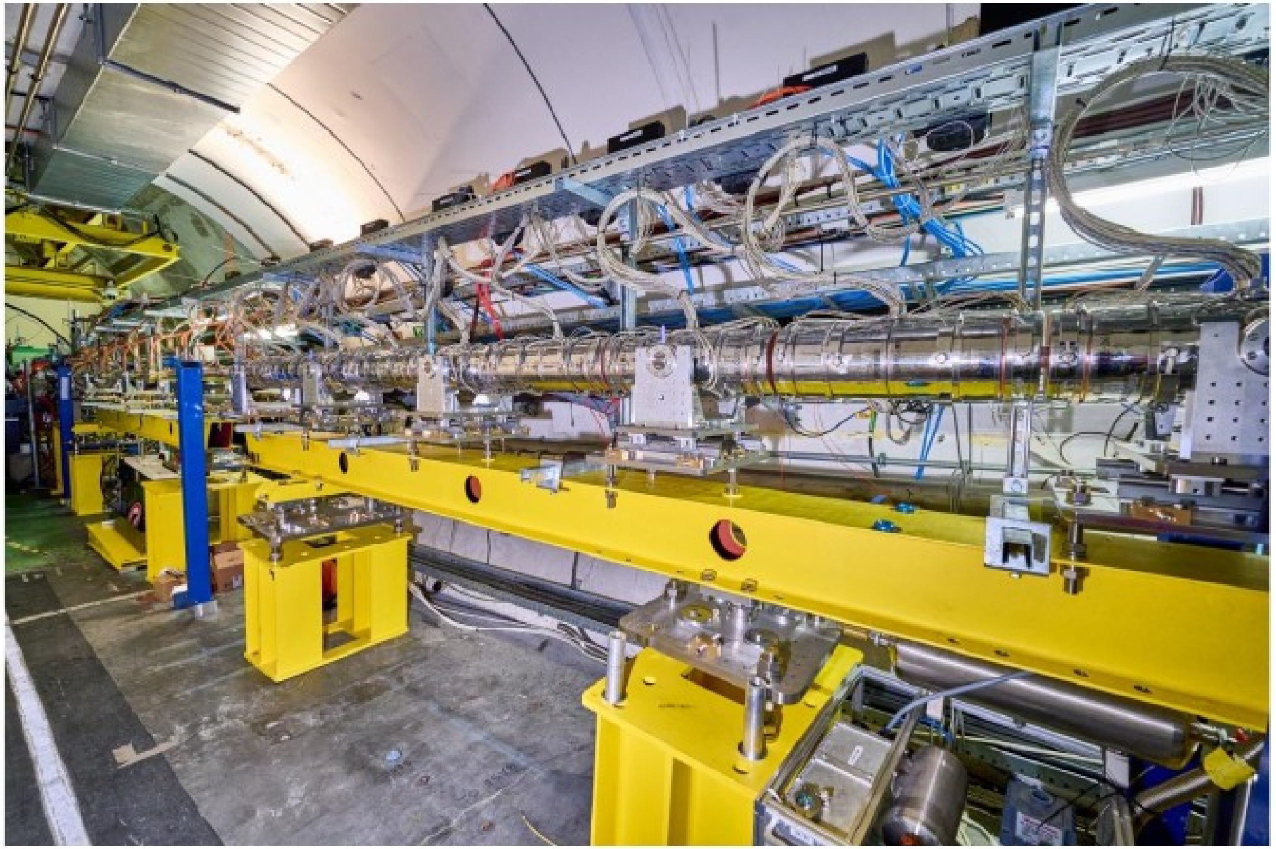
AWAKE Run 2b (2023-2024)

Wakefields initially grow, before decaying.

Plasma density step allows self-modulation to be controlled.



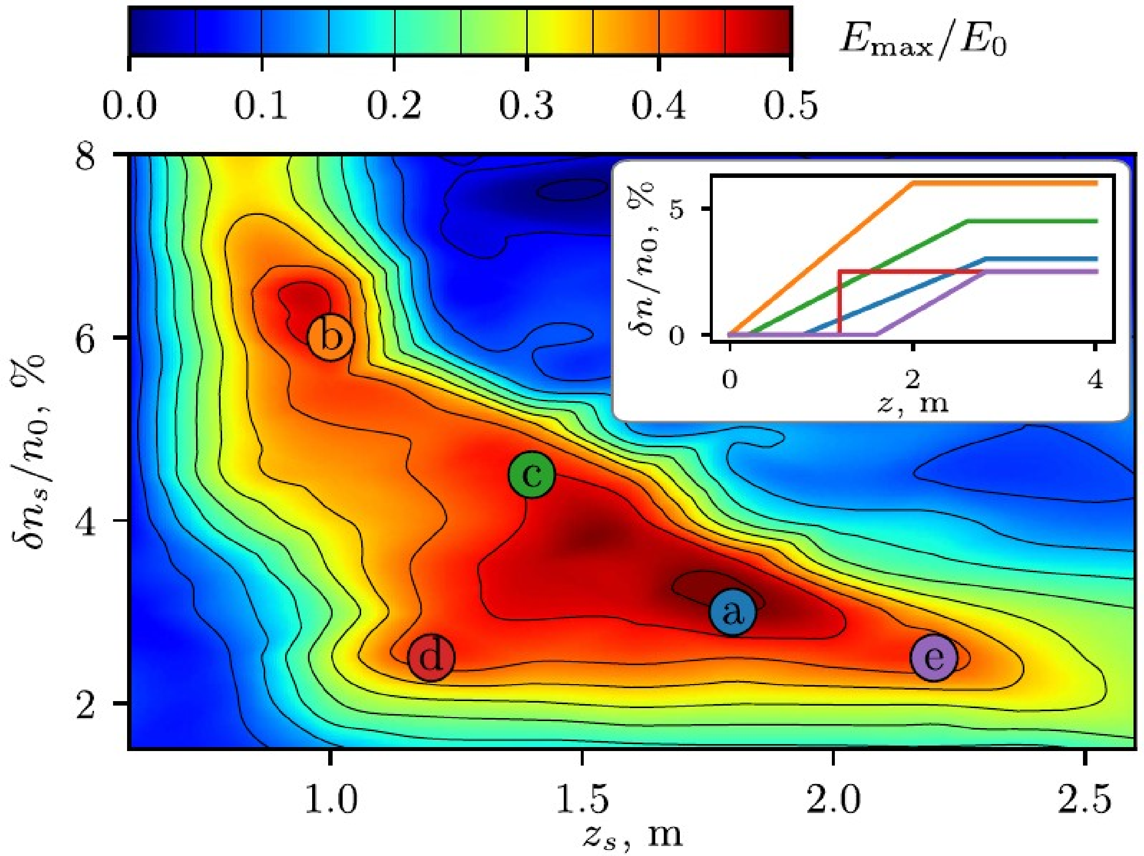
F. Pannell, UCL, AWAKE Collaboration



July 2023 – new vapour source installed

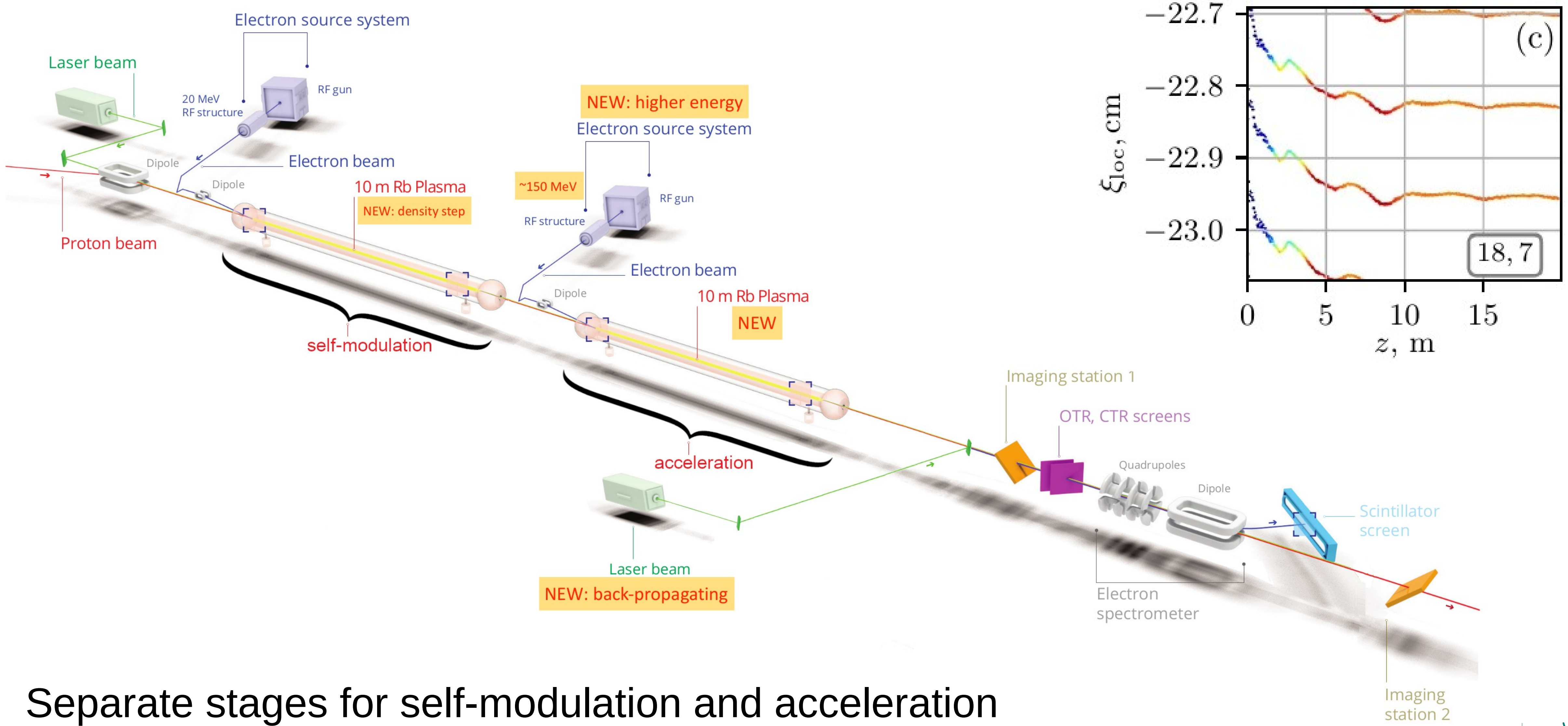
Controlling Self-modulation

Wakefields after 20 metres show broad tolerances for step position and height.



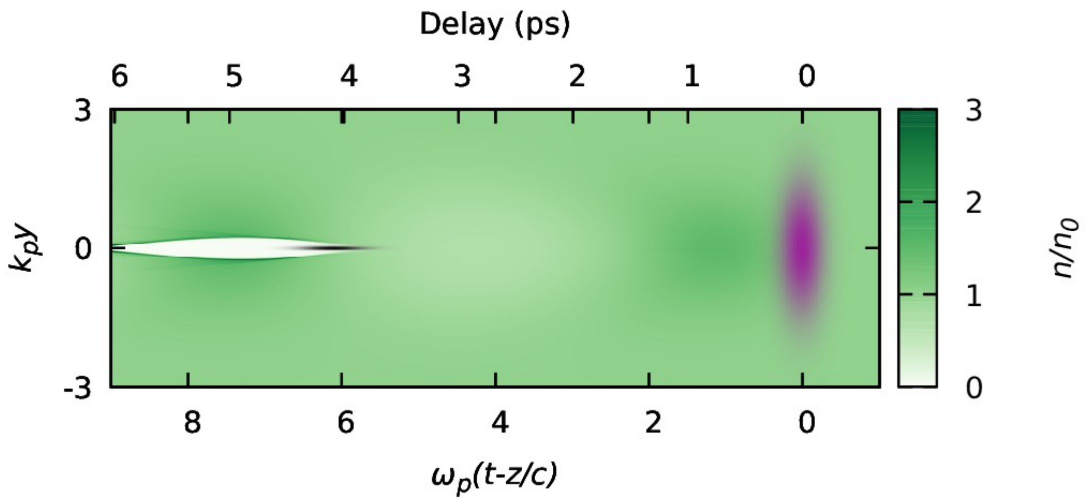
Lotov and Tuev, PPCF (2021)

AWAKE Run 2c (2028-)



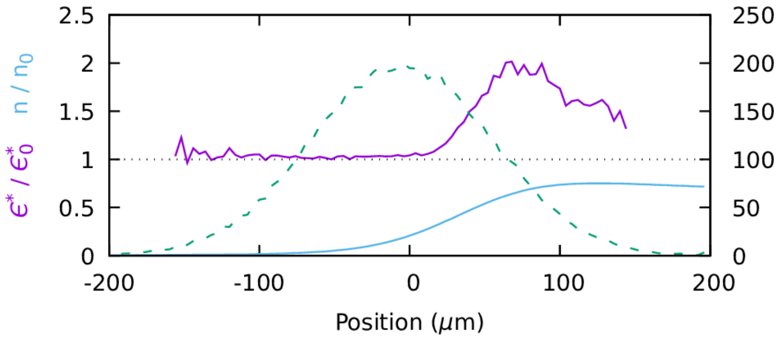
Separate stages for self-modulation and acceleration

Injection Studies



Conventional wisdom:
need a blowout to conserve emittance.

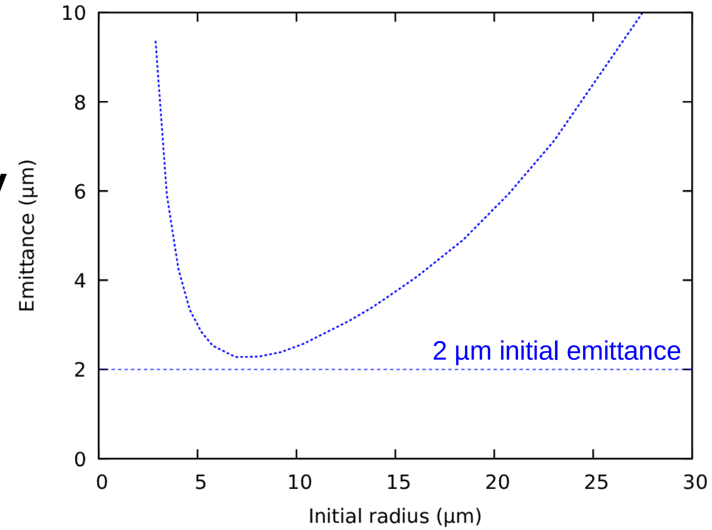
Low-emittance witness drives its own!



Witness slice emittance after 10m acceleration

Projected emittance after 10m acceleration has only weak dependence on initial radius (5-15µm)

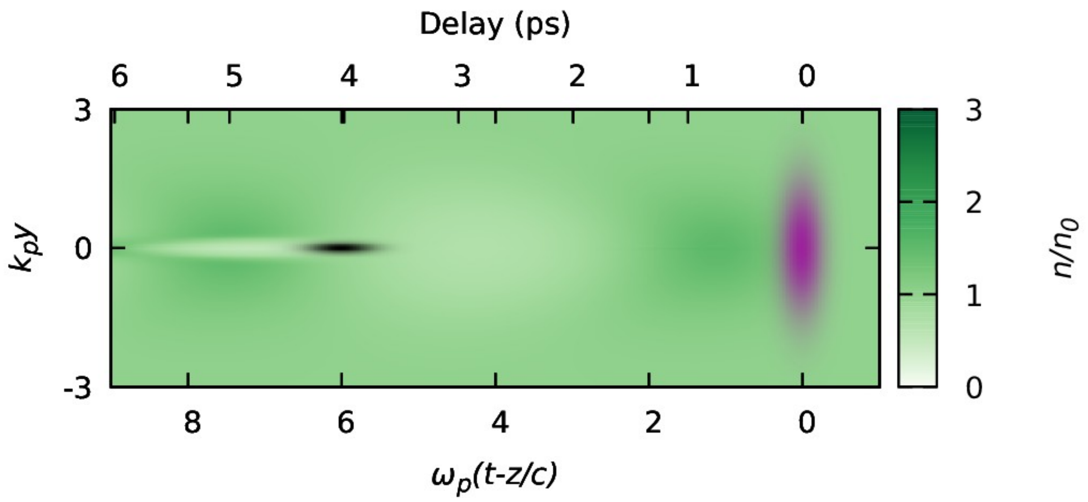
- broad tolerances



Witness projected emittance after 10m acceleration

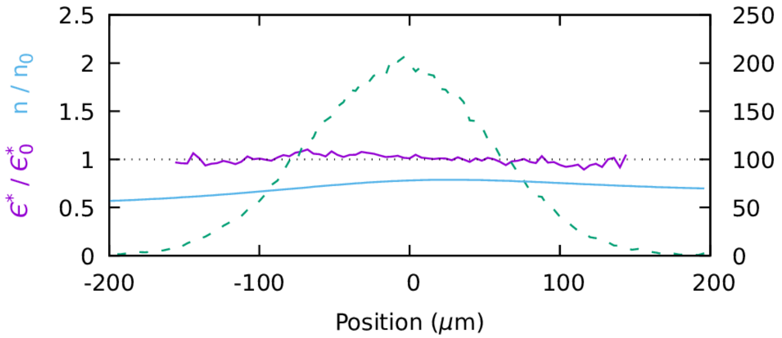
Farmer *et al.*, 2203.11622

Injection Studies



Conventional wisdom:
need a blowout to conserve emittance.

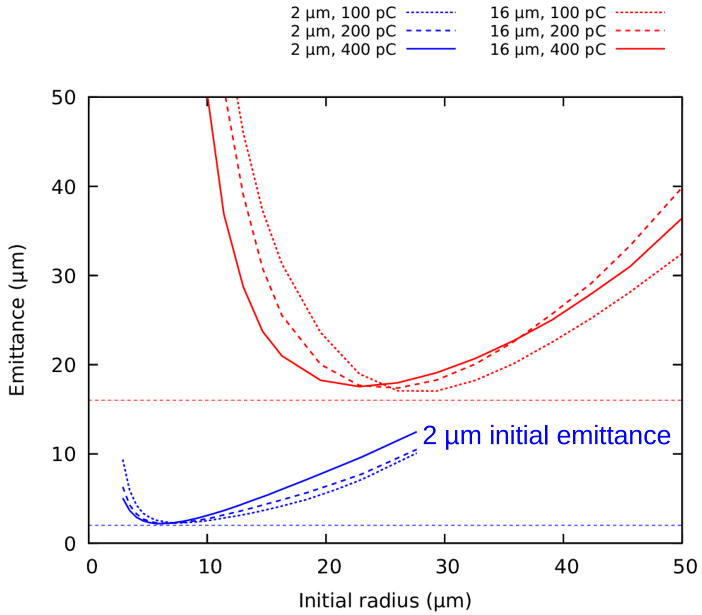
Higher-emittance witness can be matched to wakefields



Witness slice emittance after 10m acceleration

Projected emittance after 10m acceleration has only weak dependence on initial radius

- broad tolerances

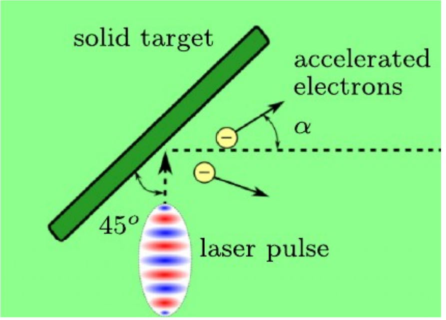


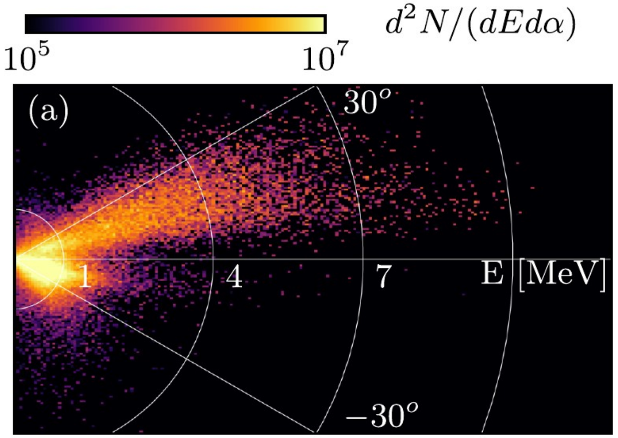
Witness projected emittance after 10m acceleration

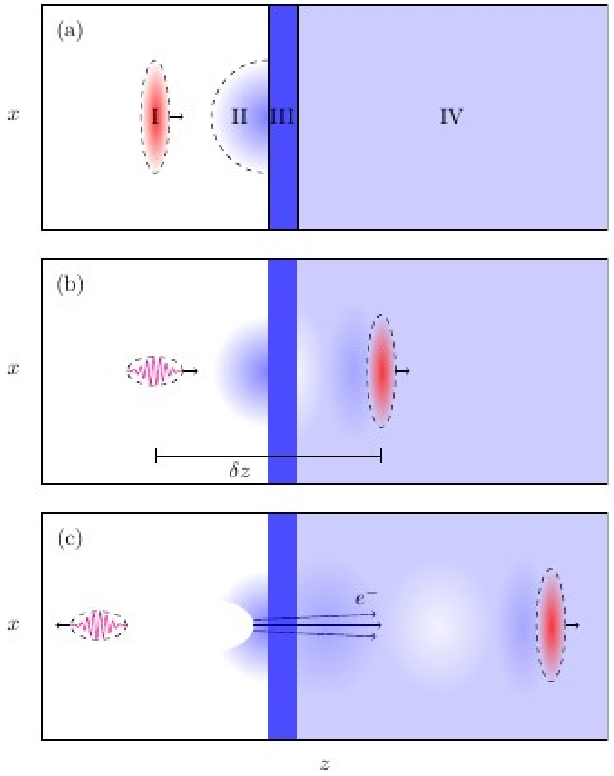
Farmer *et al.*, 2203.11622

Alternative Injection Schemes

Laser-foil injector



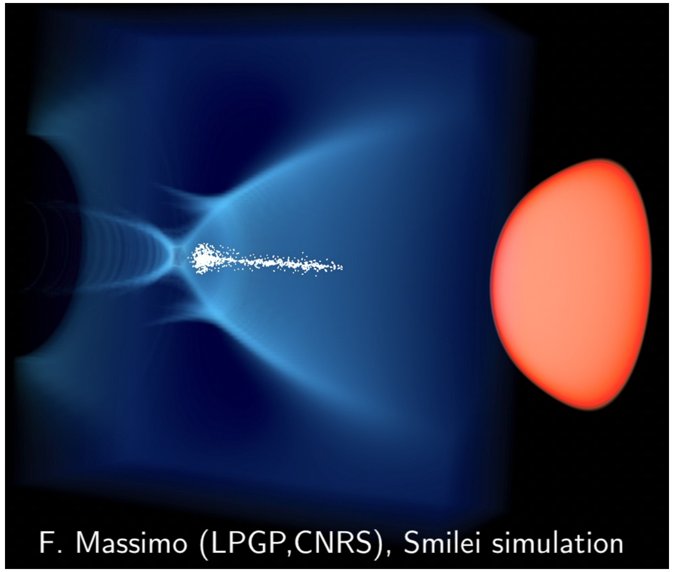




Khudiakov and Pukhov,
PRE (2021)

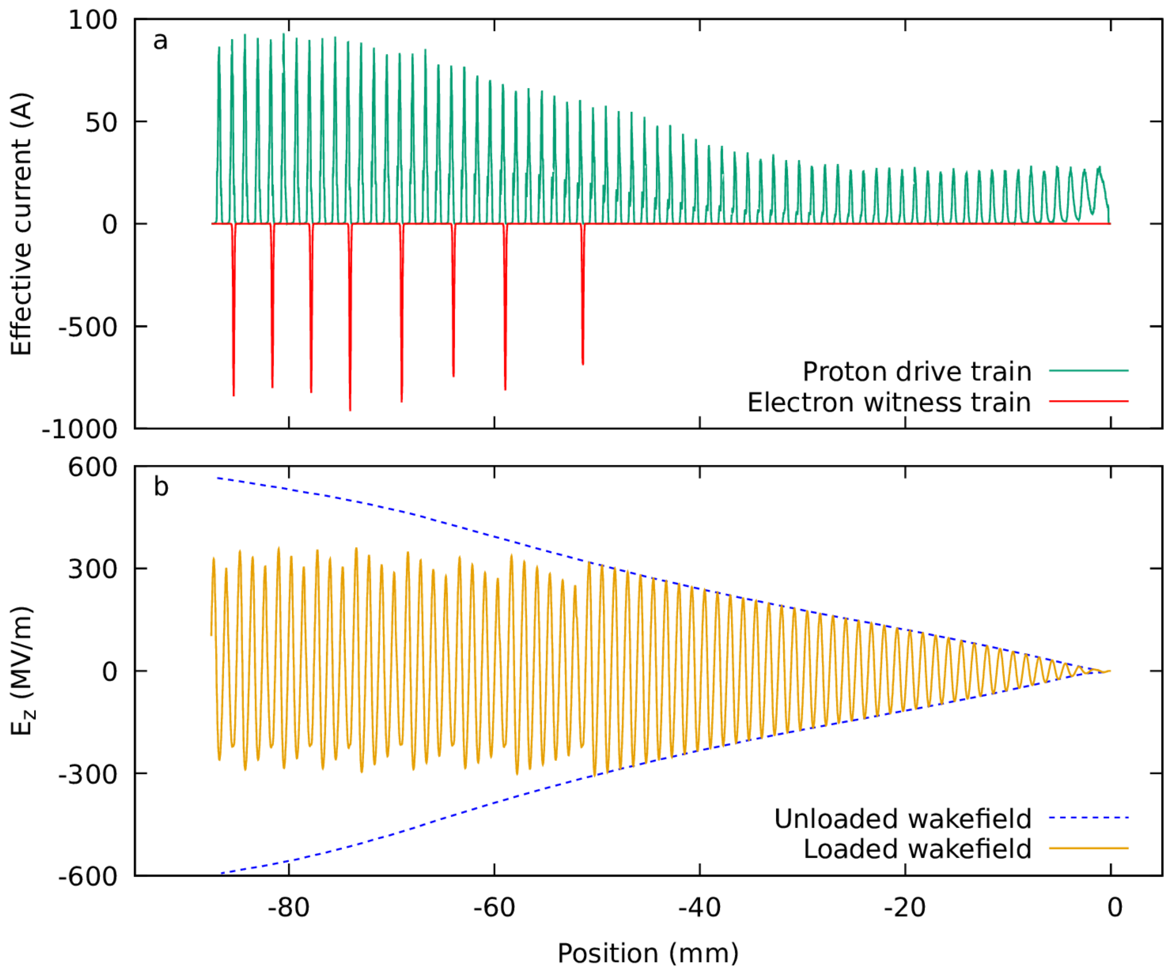
Wilson *et al.*
submitted.

Laser-plasma injector



Minenna *et al.*
(EARLI Collaboration),
In press.

Alternative Injection Schemes



J. Farmer and G. Zevi Della Porta, *2404.14175*

Wakefields are limited by the nonlinear plasma response.

Injecting multiple witness bunches allows the wakefield to regenerate, extracting more energy from the driver and accelerating more charge.

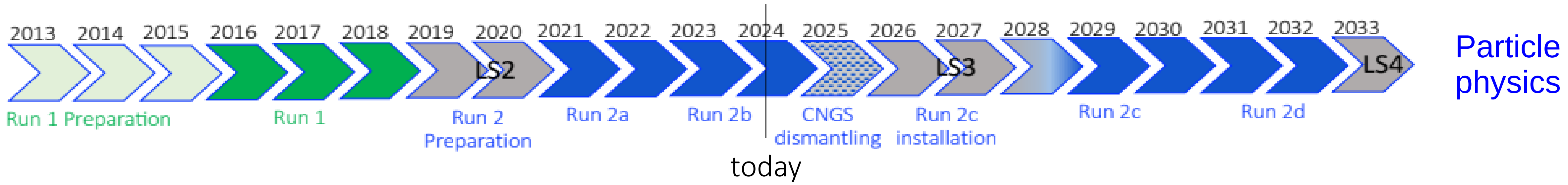
Associated Physics

AWAKE also contributes to general understanding of:

- beam–plasma instabilities (SMI/filamentation/hosing)
- plasma ion motion
- development of plasma sources
- external injection
- development and validation of simulation tools
- excellent test bed for global push towards High Performance Computing at the exascale

Towards particle physics applications

AWAKE Timeline



Run 1 demonstrated self-modulation and first acceleration.

Run 2a demonstrated electron seeding.

Run 2b to demonstrate sustained wakefield amplitude.

Run 2c to demonstrate emittance control.

Run 2d to demonstrate extensible plasma sources.

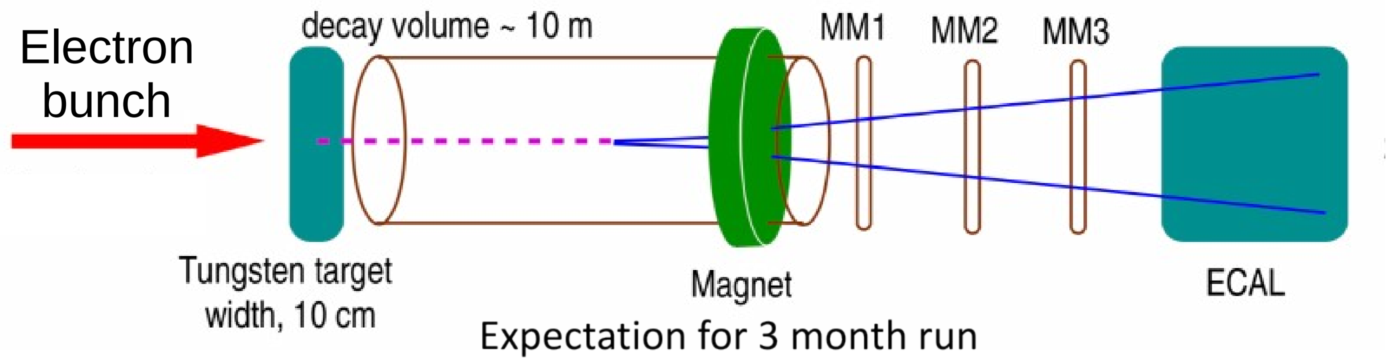
All technologies and beam parameters for a future particle physics experiment demonstrated by early 2030s.

Particle physics: dark photon search

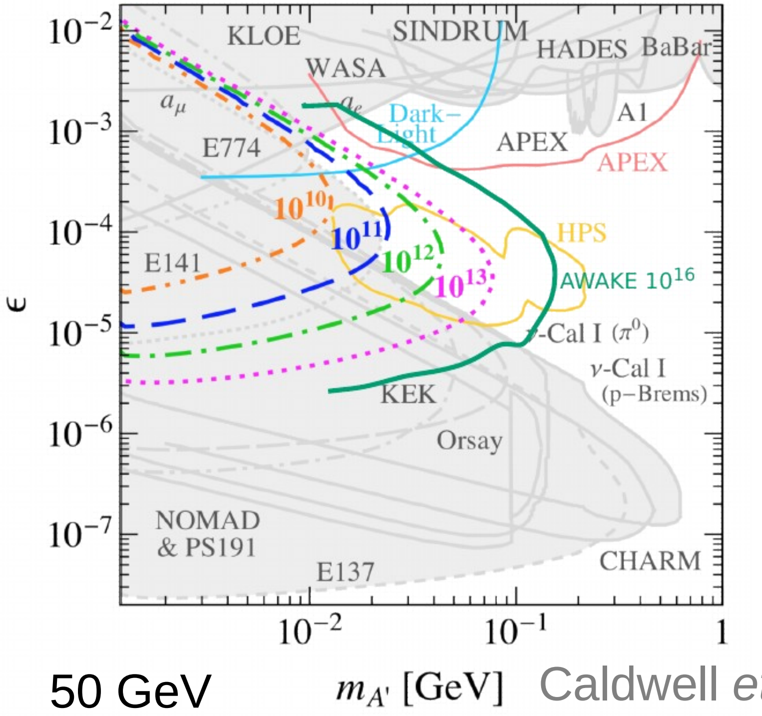
Beam dump experiment, similar to NA64.

AWAKE offers an electron beam with a few % energy spread.

Could offer significantly more electrons-on-target than secondary beam schemes.



Expectation for 3 month run

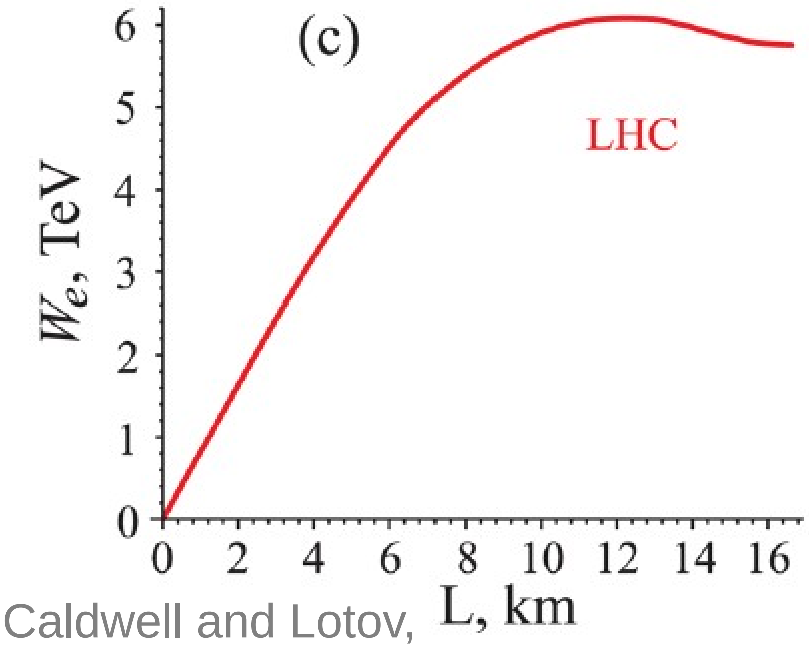


50 GeV electrons

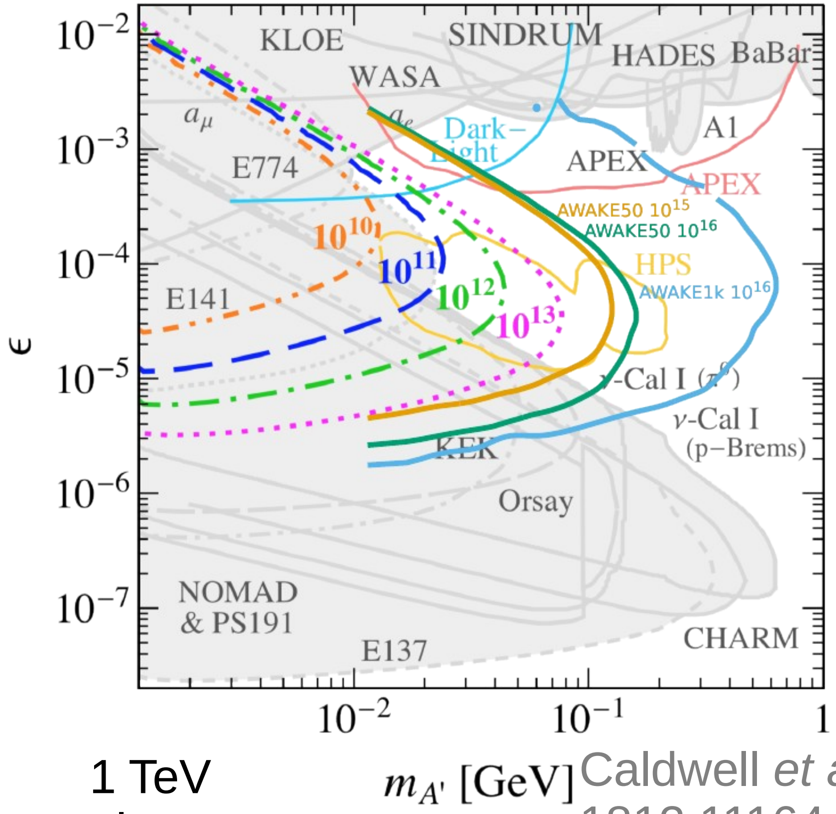
Caldwell *et al.*, 1812.11164

Beyond AWAKE

Using the LHC beam to drive wakefields would give much higher electron energies.



Caldwell and Lotov, Phys Plas. (2011)

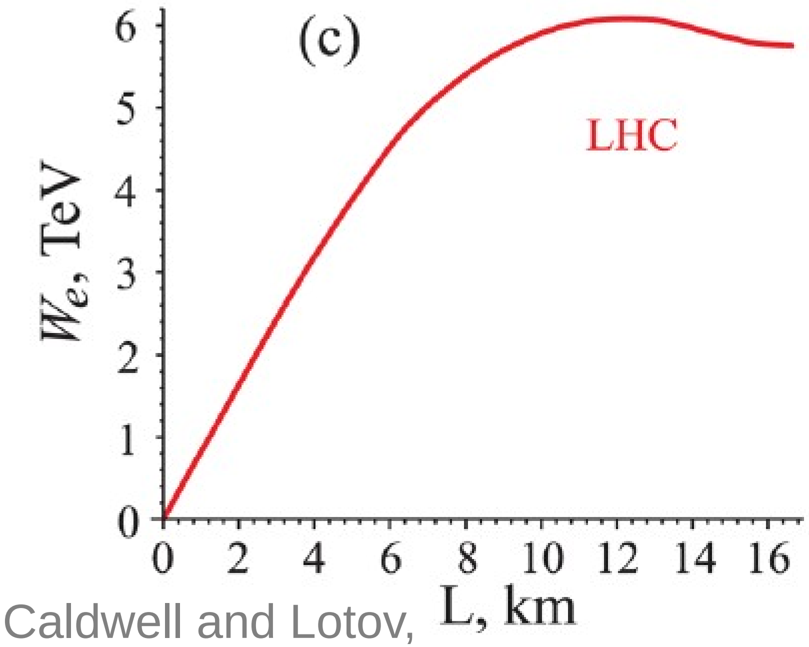


1 TeV electrons

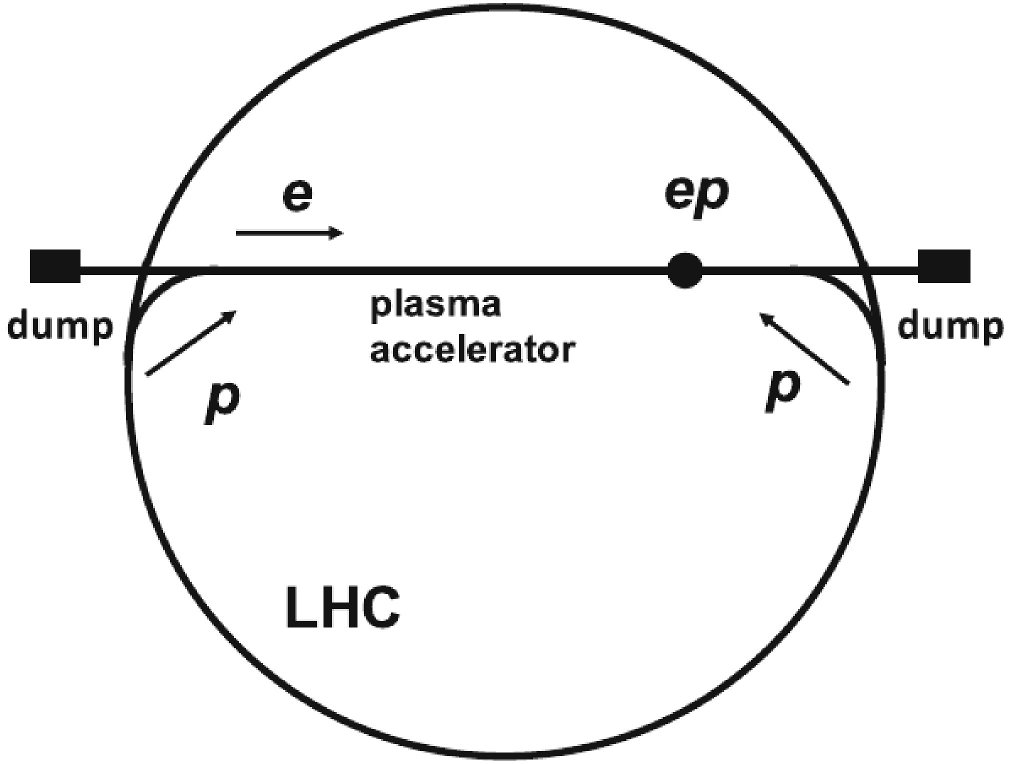
Caldwell *et al.*, 1812.11164

Beyond AWAKE

Using the LHC beam to drive wakefields would give much higher electron energies



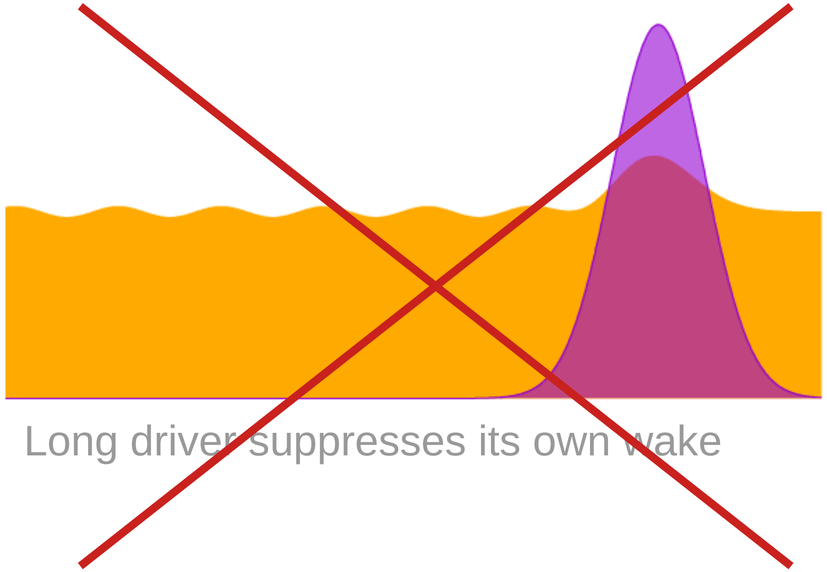
Caldwell and Lotov, Phys Plas. (2011)



Caldwell and Wing, Eur. Phys. J. C (2016)

Short proton driver

Short driver efficiently excites wakefield



Long driver suppresses its own wake

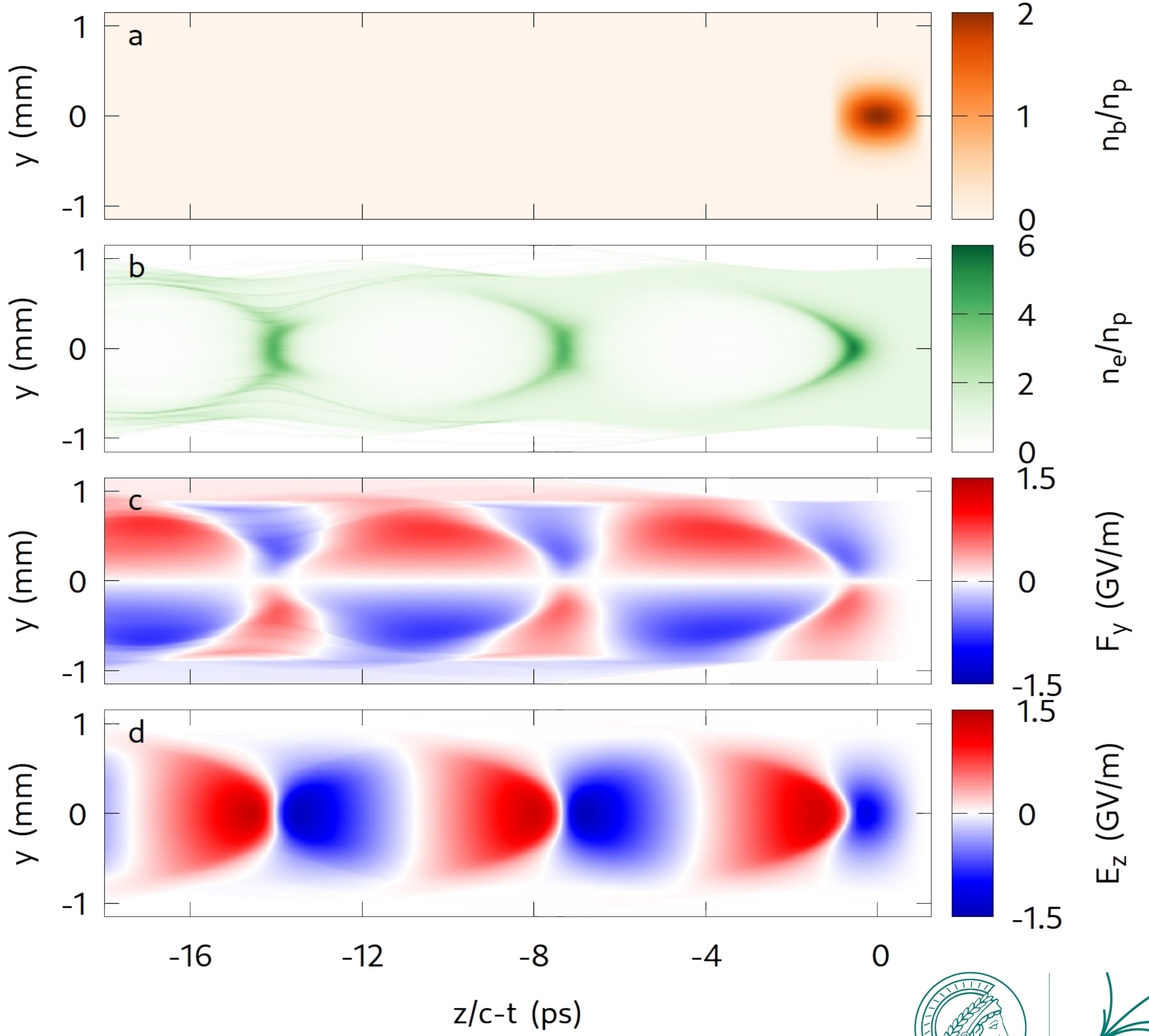
Acceleration gradient for a short driver ~ $\frac{511}{\sigma_z[\mu m]} GV/m$

Short proton driver

A *short* 400 GeV proton bunch can accelerate witness e^-/e^+ to 125 GeV.

Main challenges

- Fast-cycling short-bunch proton synchrotron.
- further development of e^+ acceleration in plasma.



Farmer, Caldwell and Pukhov, 2401.14765

Conclusions

AWAKE has a very successful experimental programme.

Simulations have proven ability to predict and reproduce experiment.

Provides confidence that Run 2c/d goals are achievable

Ready for first particle physics applications in early 2030s.

Thanks to all our collaborators

AWAKE CERN

Wigner
clear
UPPSALA UNIVERSITET
The Cockcroft Institute of Accelerator Science and Technology
Lancaster University
UNIVERSITY OF OXFORD
TRIUMF

MAX-PLANCK-INSTITUT FÜR PHYSIK

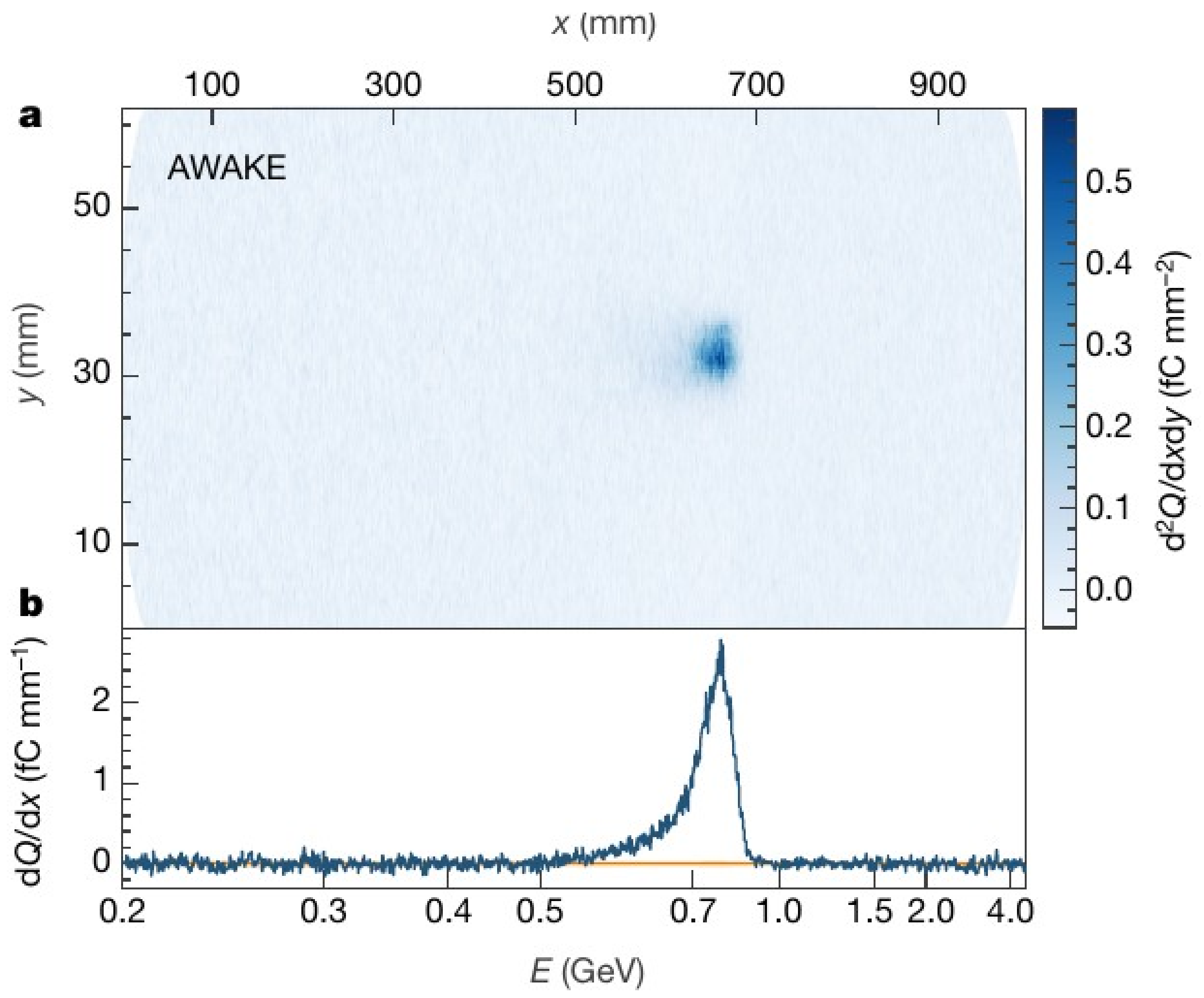
22 Institutes

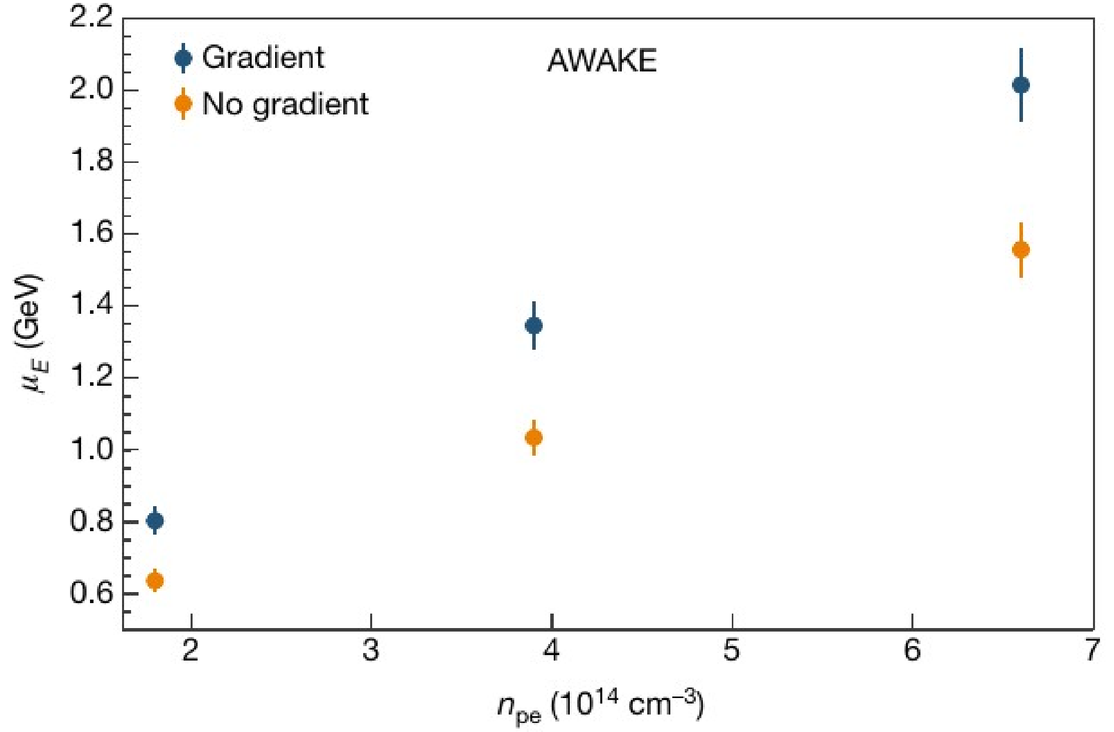
UKRI Science and Technology Facilities Council
MANCHESTER 1824 The University of Manchester
UNIVERSITY OF LIVERPOOL
Imperial College London
UCL

Philipps Universität Marburg
MAX PLANCK INSTITUTE FOR PLASMA PHYSICS
EPFL
WISCONSIN UNIVERSITY OF WISCONSIN–MADISON
hhu Heinrich Heine Universität Düsseldorf
TÉCNICO LISBOA
UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2007
Novosibirsk State University *THE REAL SCIENCE
clic

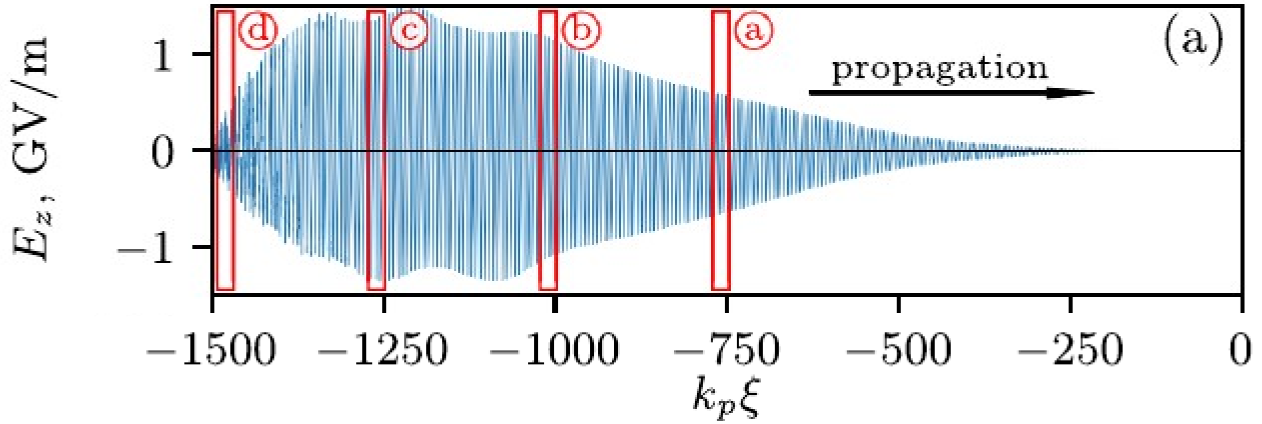
Thank you

Acceleration (Run 1)



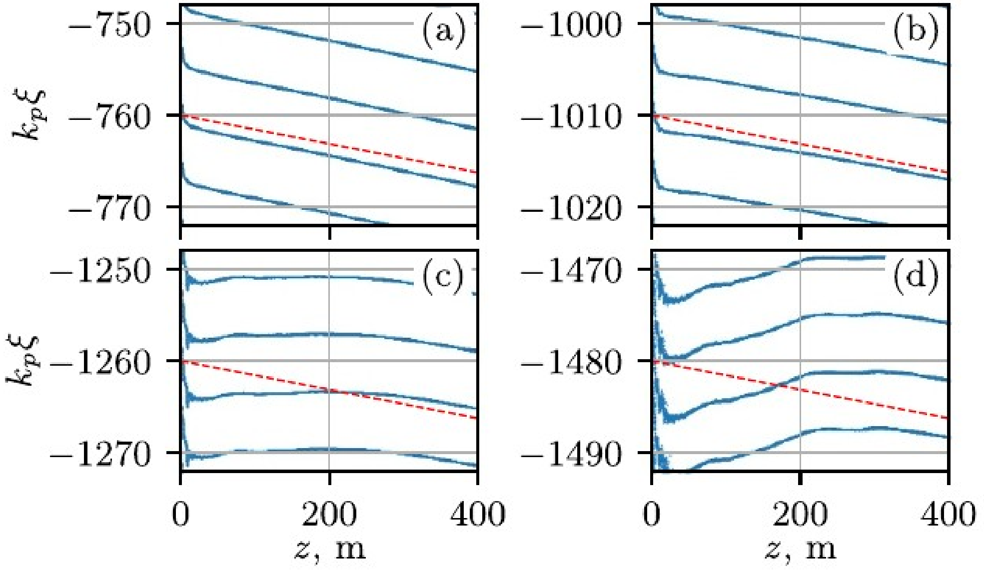


Injection Studies



SMI growth allows wakefields with luminal phase.

Lotov and Tuev, 2021



Blue – wakefield phase
Red – driver velocity

Injection Studies