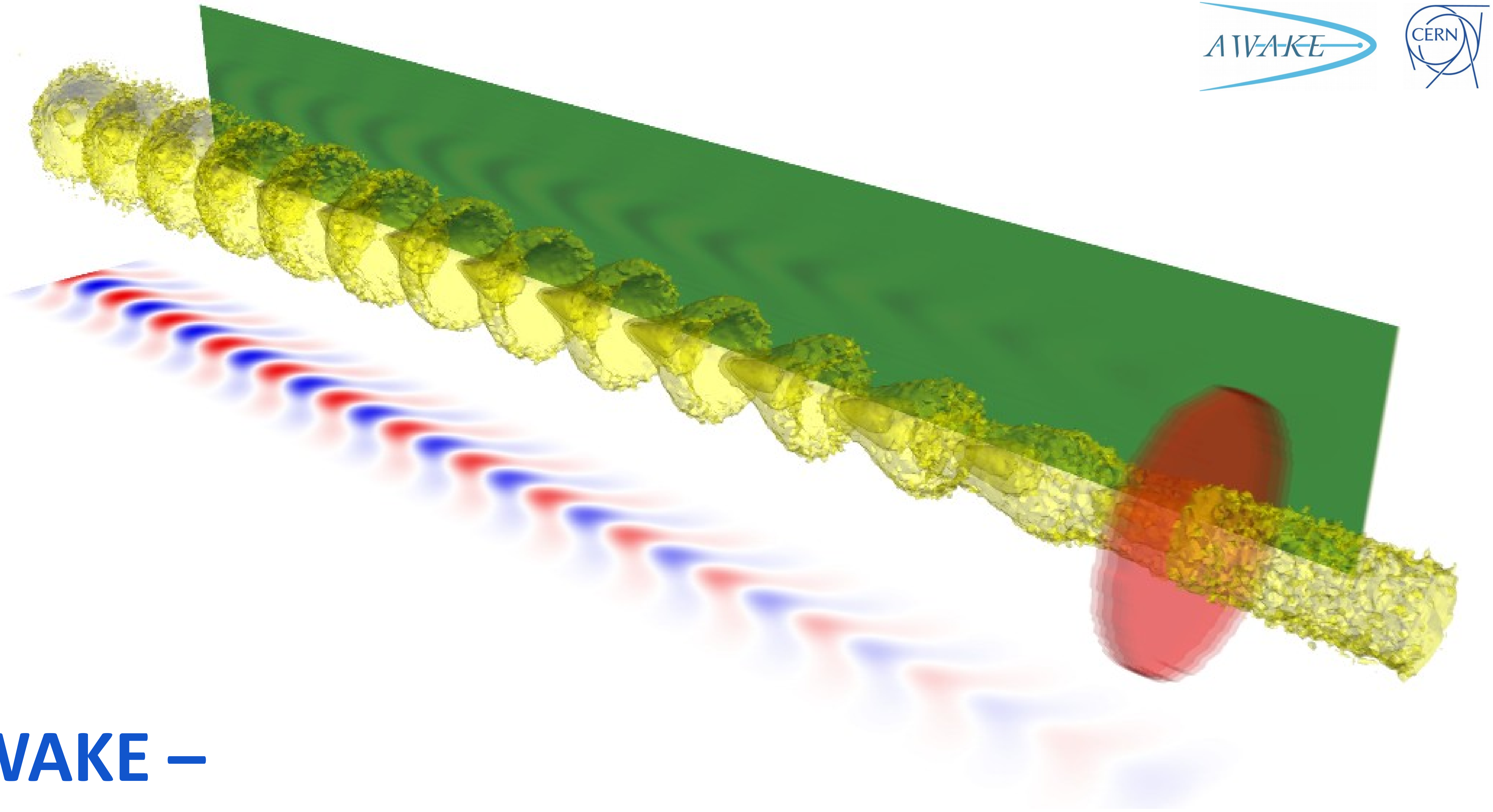


AWAKE –
Avanced WAKefield Experiment

John Farmer

Outline

Motivation and introduction

Run 1 (2016-2018)

Run 2 (2021 -2028)

Conclusions

Motivation

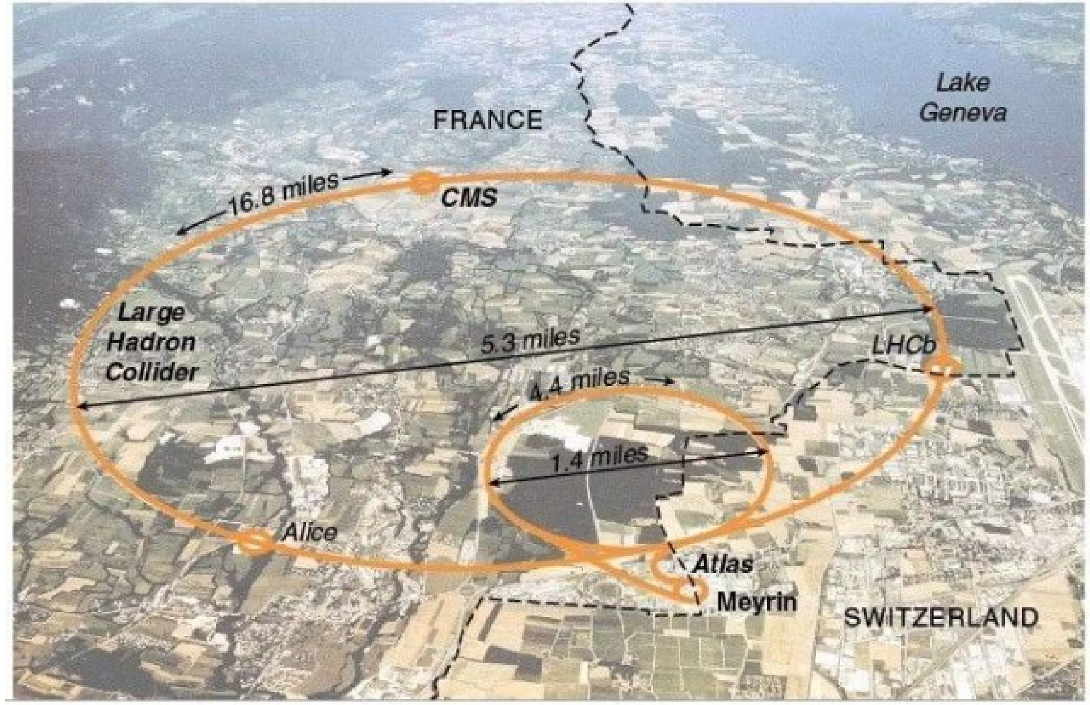
CERN is perhaps best known for the LHC

Why large?

Why hadrons?

Synchrotron radiation leads to energy loss

$$P_{rad} \sim \frac{\gamma^4}{\rho^2}$$



Großmutter, warum hast du so große Speicherringe?

Motivation

Alternatively, use linacs

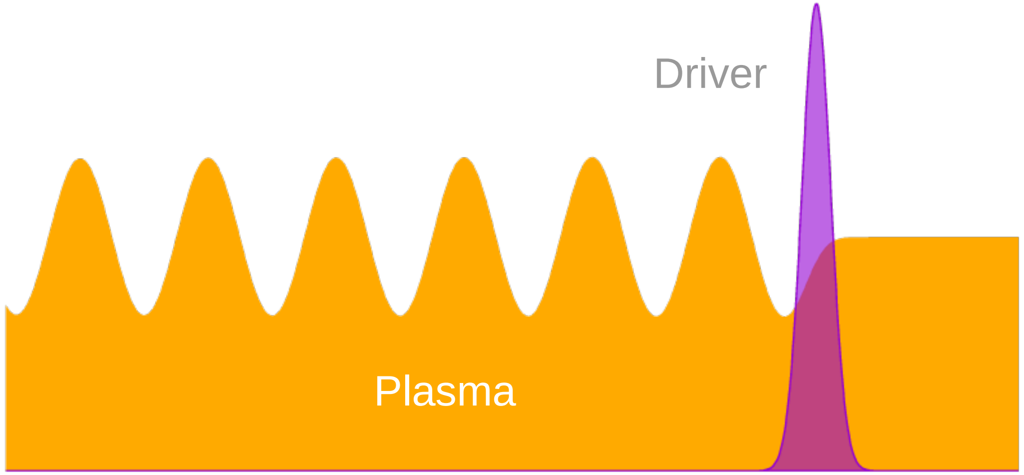
Energy gain limited by
length
acceleration gradient


SLAC used a 3.2 km linac

Acceleration gradient limited by damage threshold,
~ 100 MeV/m for conventional accelerators

Motivation

Damage threshold not a concern for plasma
– already "broken"



Accelerate particles on a wakefield
- driver generates plasma wave
- witness "rides" the wave

Plasma wakefield acceleration

Wakeboarding

Choice of drivers:

Laser pulse

Electron beam

Proton beam

Plasma wakefield acceleration

Of these, proton beams have by far the highest energy

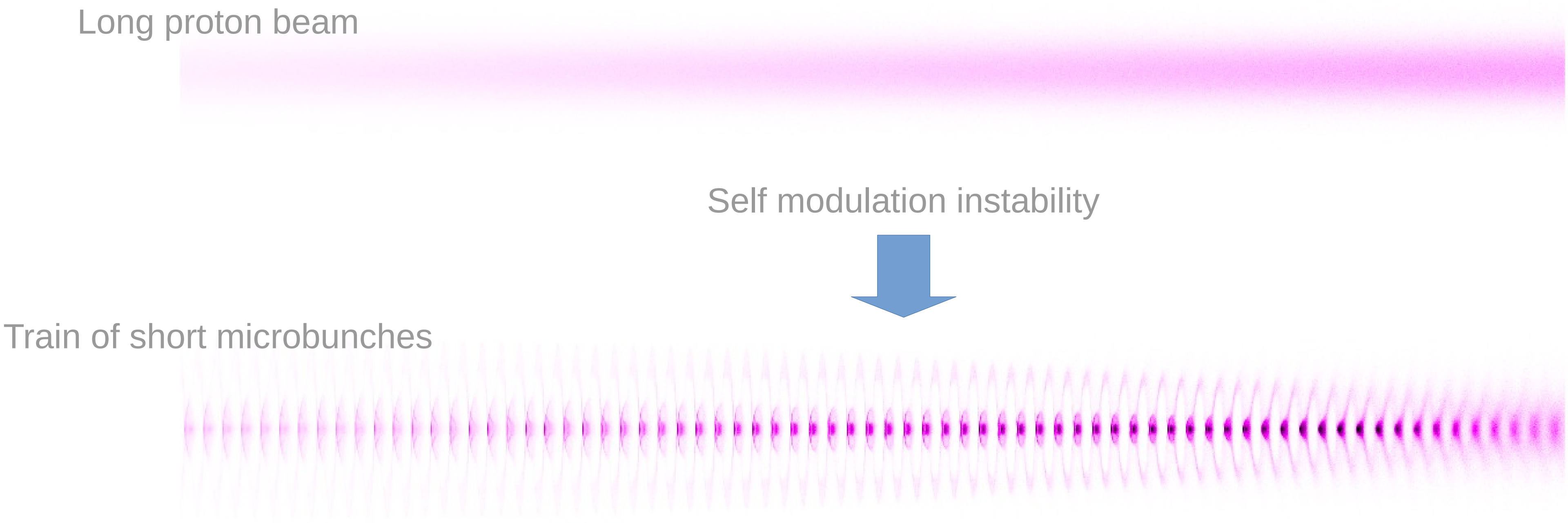
BUT available beams “too long” to efficiently drive a wake

Short driver efficiently excites wakefield

Long driver suppresses its own wake

Self Modulation instability

Focussing/defocussing fields in plasma



Resulting train of microbunches can drive large wakefields

MPP · AWAKE

Masters Students

Matthias Kerscher

PhD Students

Fabian Batsch
Anna Maria Bachmann
Vasyl Hafych
Pablo Irael Morales Guzmàn
Jan Pucek
Livio Verra
Tatiana Nechaeva

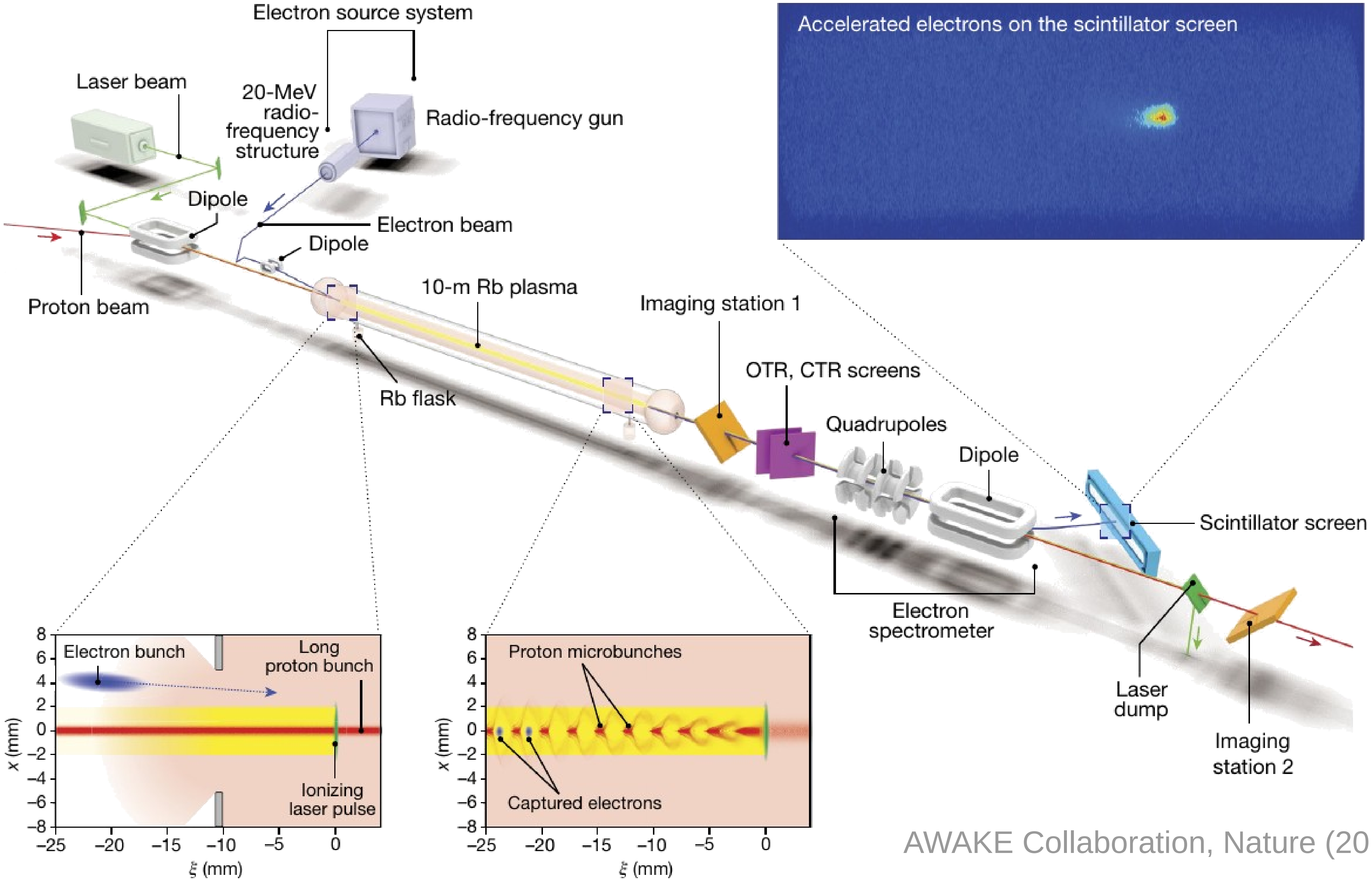
Postdocs

Joshua Moody
John Farmer
Mathias Hüther
Michele Bergamaschi

Faculty

Patric Muggli
Allen Caldwell

AWAKE Run1 (2016-2018)



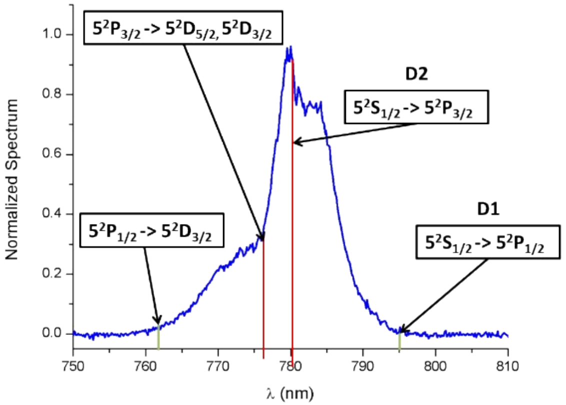
AWAKE Collaboration, Nature (2018)

Plasma Source: Ionization and Propagation

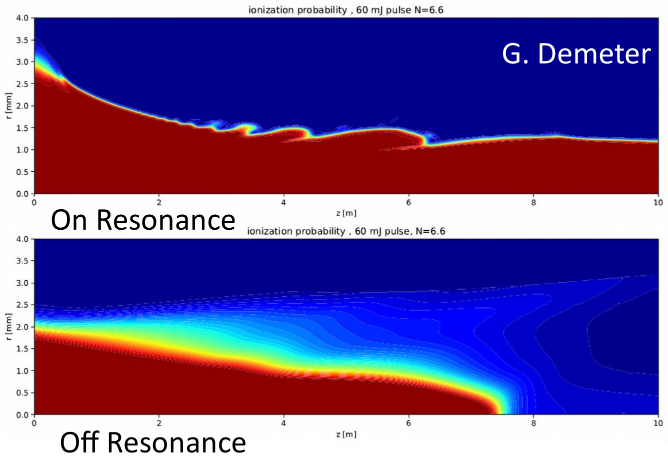
Significant differences from other laser-ionized plasma sources

- Long source (10m)
- Low ionization energy 4.2 eV
- Resonances within laser bandwidth

Josh Moody



Resonances within laser bandwidth



Ionization simulations

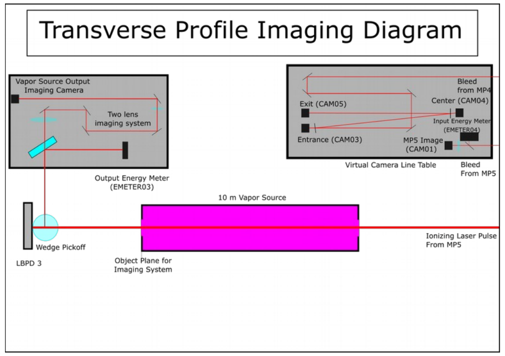
Simulations performed by collaborator G. Demeter from Wigner Institute suggest resonances significantly help ionization

Ionization Propagation Experiments

Transverse Profile and Energy Loss

M. Á. Kedves, B. Ráczkevi, M. Aladi, G. Demeter, J. Moody

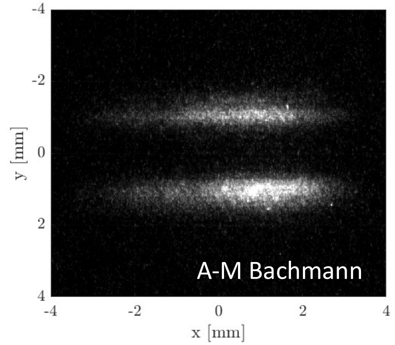
- Use series of virtual cameras and image of exit of vapor source
- Energy in vs Energy out
- Compare output laser profile and energy to simulation
- **Preliminary publication being worked on**


Transverse Profile Imaging Diagram

Schlieren Measurements

A.M. Bachmann, M. Kerscher, J. Moody

- Probe beam tuned close to Rb D2 resonance
- Use High pass mask in fourier plane for transverse phase contrast at imaging plane
- Can measure channel width and sharpness

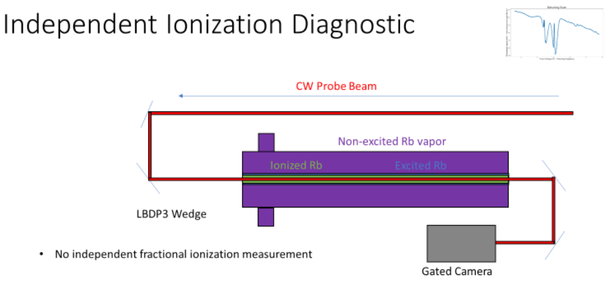


A-M Bachmann

Longitudinal narrowband probe loss measurements

M. Á. Kedves, B. Ráczkevi, M. Aladi, G. Demeter, J. Moody

- Narrowband probe laser back propagates
- Close to resonance follows Lambert
- In plasma losses are reduced based on ionization fraction
- 420 nm laser can be used for better overlap with plasma column

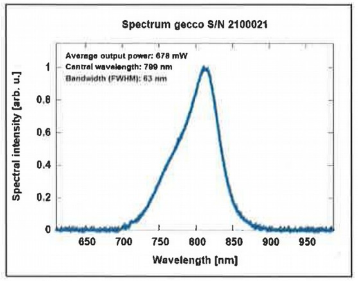

Independent Ionization Diagnostic

- No independent fractional ionization measurement

Resonant vs Nonresonant spectrum

M. Á. Kedves, B. Ráczkevi, M. Aladi, G. Demeter, E. Granados, J. Moody

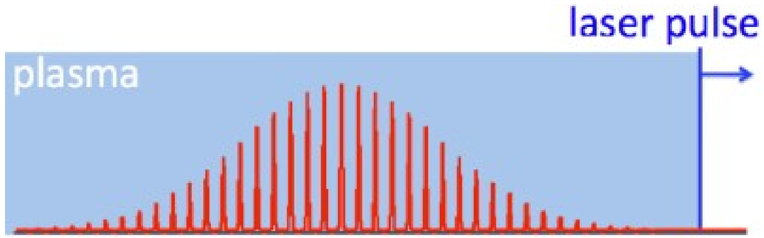
- Repeat other three experiments but:
  - Use TiSa oscillator with 80 nm bandwidth, instead of 20 nm fiber oscillator
  - Shape spectrum to move central wavelength away from 780 but keep pulse length and energy same as fiber oscillator

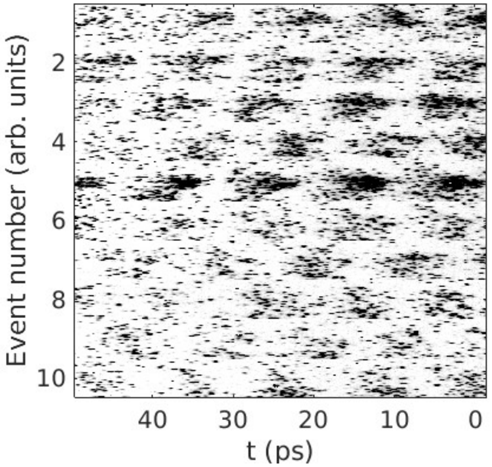


Some measurements completed, others delayed due to Covid and technical issues, plan to continue in 2021.

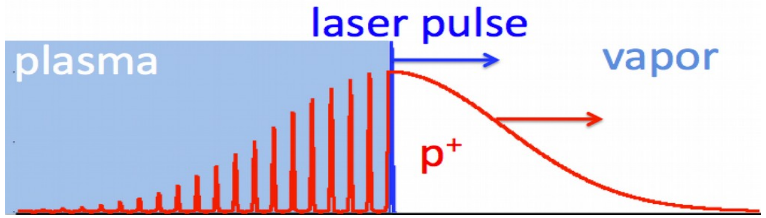
Ionization as a seed for self modulation

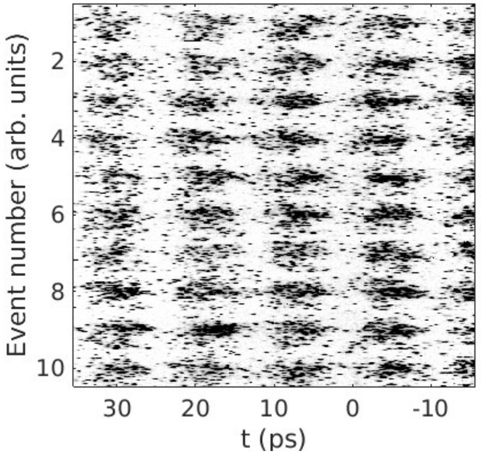
Relative laser timing affects self modulation





Fabian Batsch





Phase reproducibility vs RIF timing

Relativistic ionization front (RIF) controls starting point for wakefields

wakefield amplitude at RIF depends on local proton density

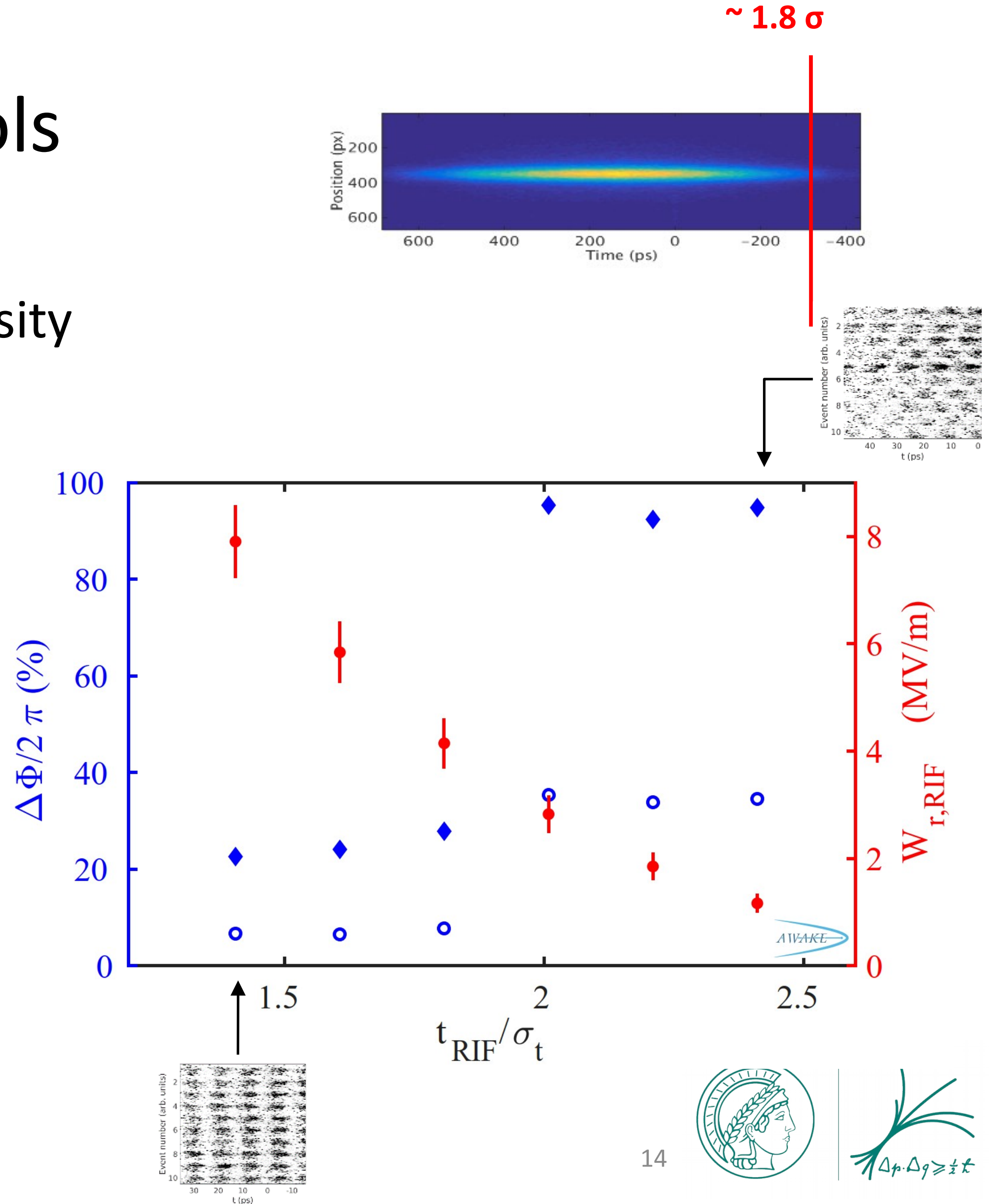
Clear transition
from self modulation instability (SMI)
to seeded self modulation (SSM)

Blue diamonds represent the full range of observed phases

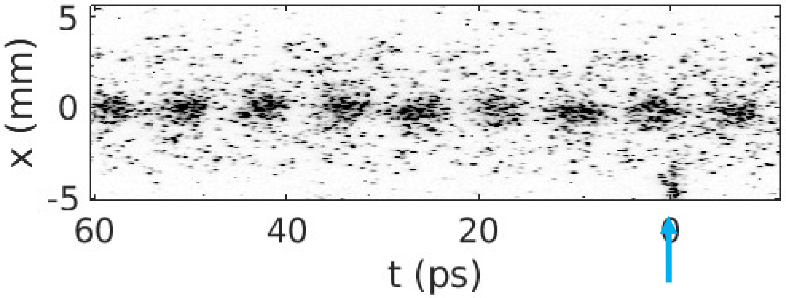
Blue circles show the rms variation

Calculated wakefield at RIF in red

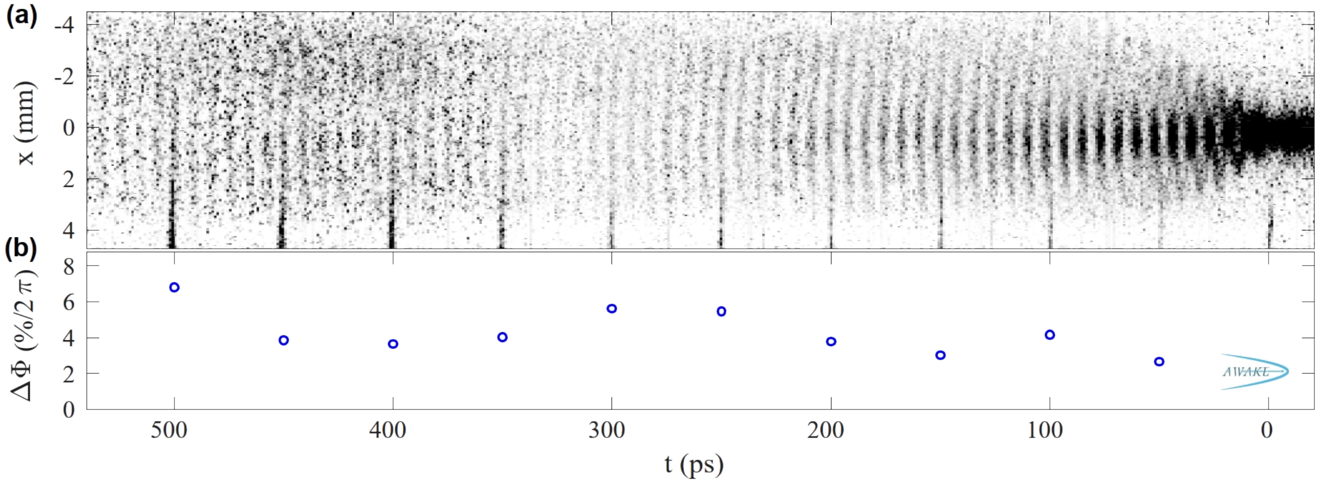
RIF varied from 350 ps (1.4 σt) to 600 ps (2.4 σt) ahead of the bunch center



Stitched images of SSM



LRS



“Transition between instability and seeded self-modulation of a relativistic particle bunch in plasma”

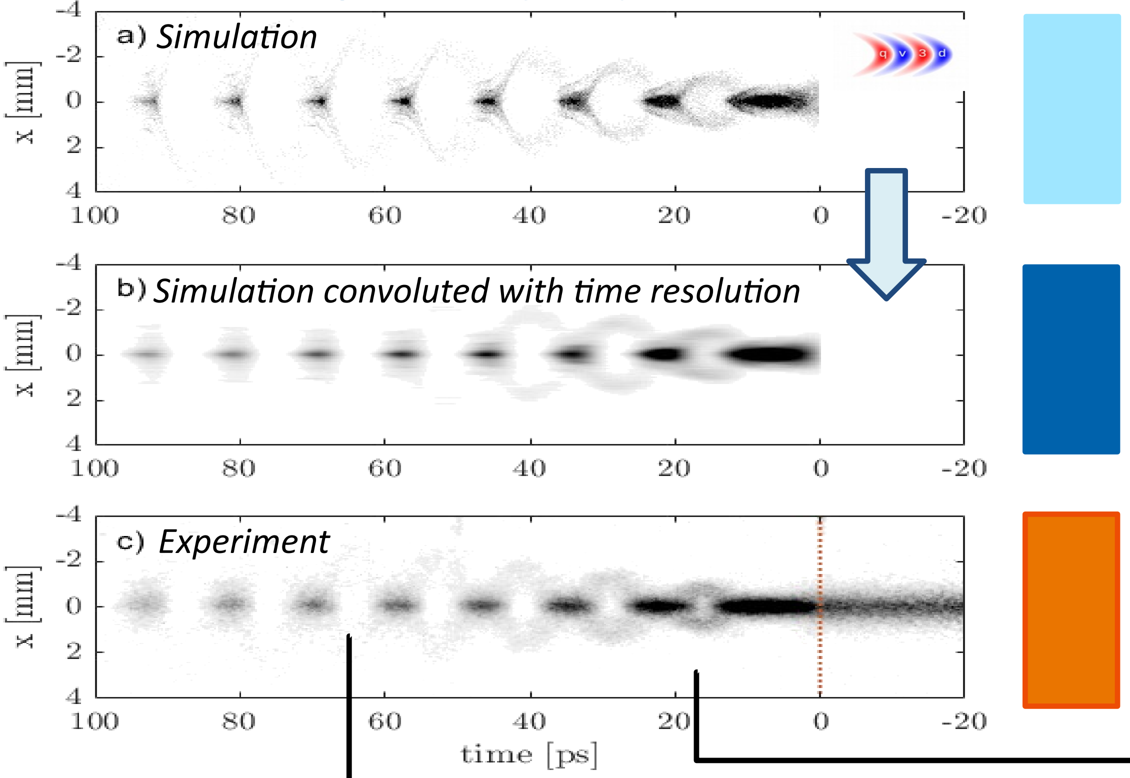
F Batch, P Muggli, *et al.* (AWAKE collaboration). To be submitted to PRL.

We use a relativistic ionization front to provide various initial transverse wakefield amplitudes for the self-modulation of a long proton bunch in plasma. We show experimentally that, with sufficient initial amplitude (≥ (4.1±0.4) MV/m), the phase of the modulation along the bunch is reproducible from event to event, with 3 to 7% (of 2π) rms variations all along the bunch. The phase is not reproducible for lower initial amplitudes. We observe the transition between these two regimes. Phase reproducibility is essential for deterministic external injection of particles to be accelerated.

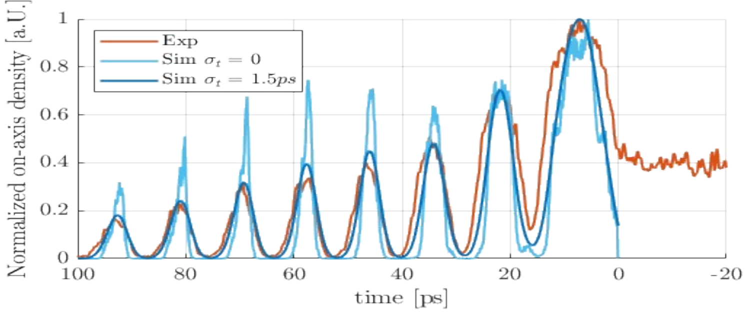
Fabian currently writing up

SSM: experiment vs simulation

Beam Charge Density Map

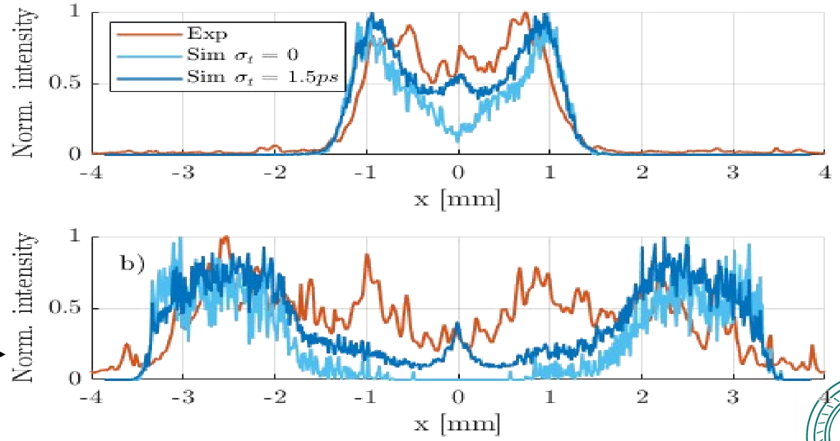


On-Axis Charge Density Profile



Anna-Maria Bachmann

Defocusing Profiles

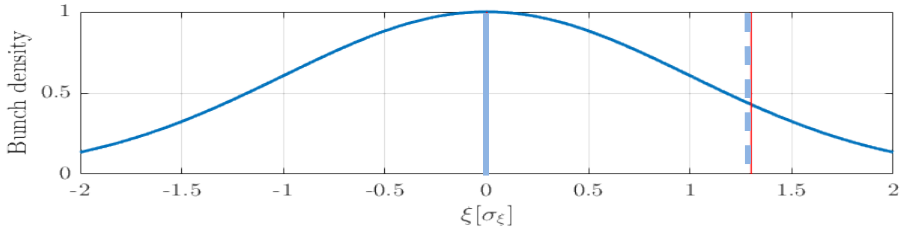


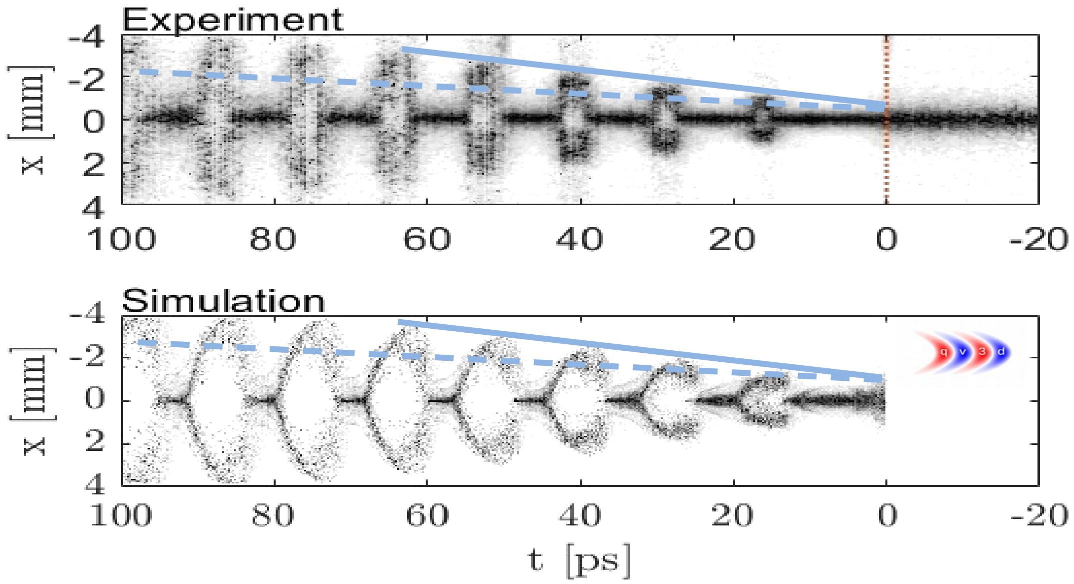
1st Period

5th Period

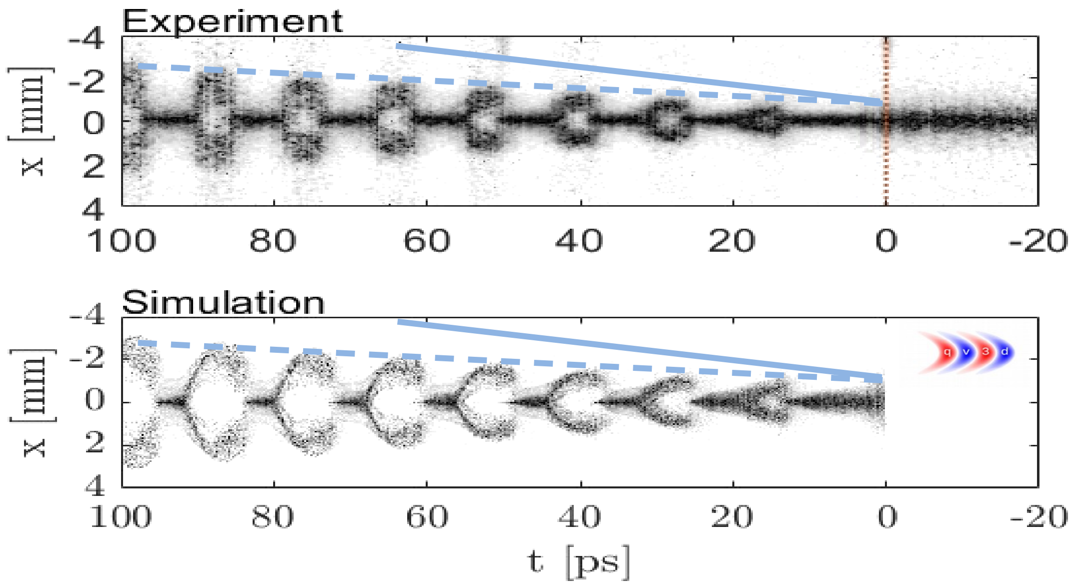
→ **Good agreement between simulation and experiment**

Defocusing for varying RIF position





Defocussing increases along bunch



More defocusing for higher density at RIF

→ **Stronger defocusing due to larger wakefield amplitudes**

Invited talk at IBIC 2020

Anna currently writing up

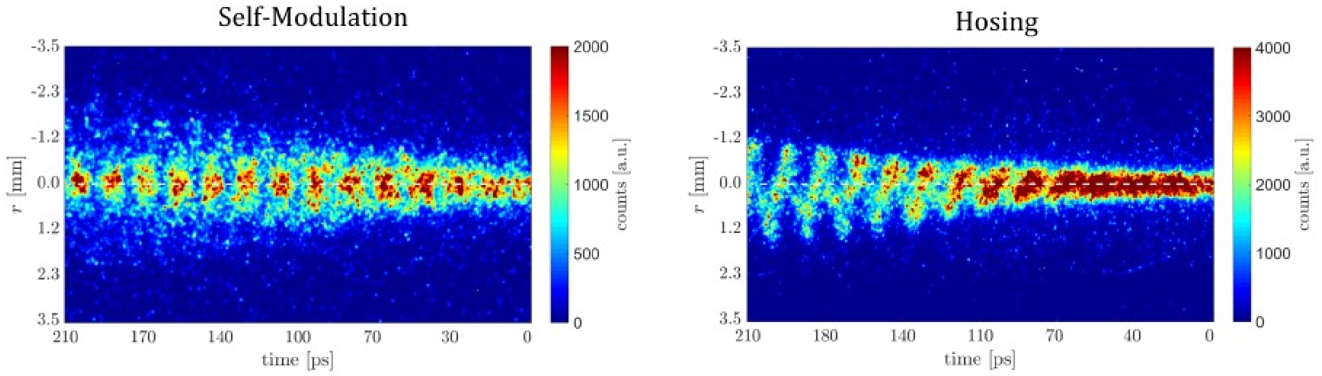
Results to be published

The Hosing Instability

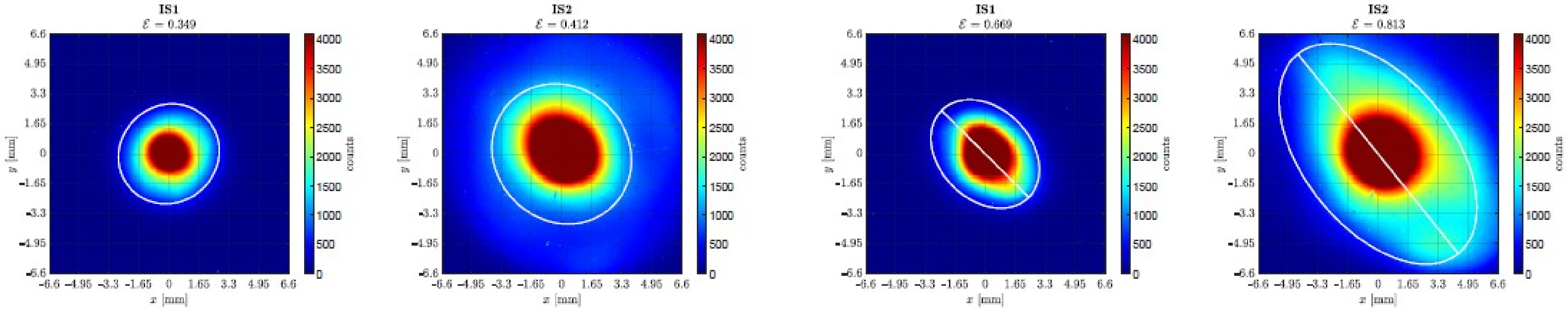
Hosing is a transverse beam/plasma instability

- Can couple to self modulation

Streak camera



Radial projections

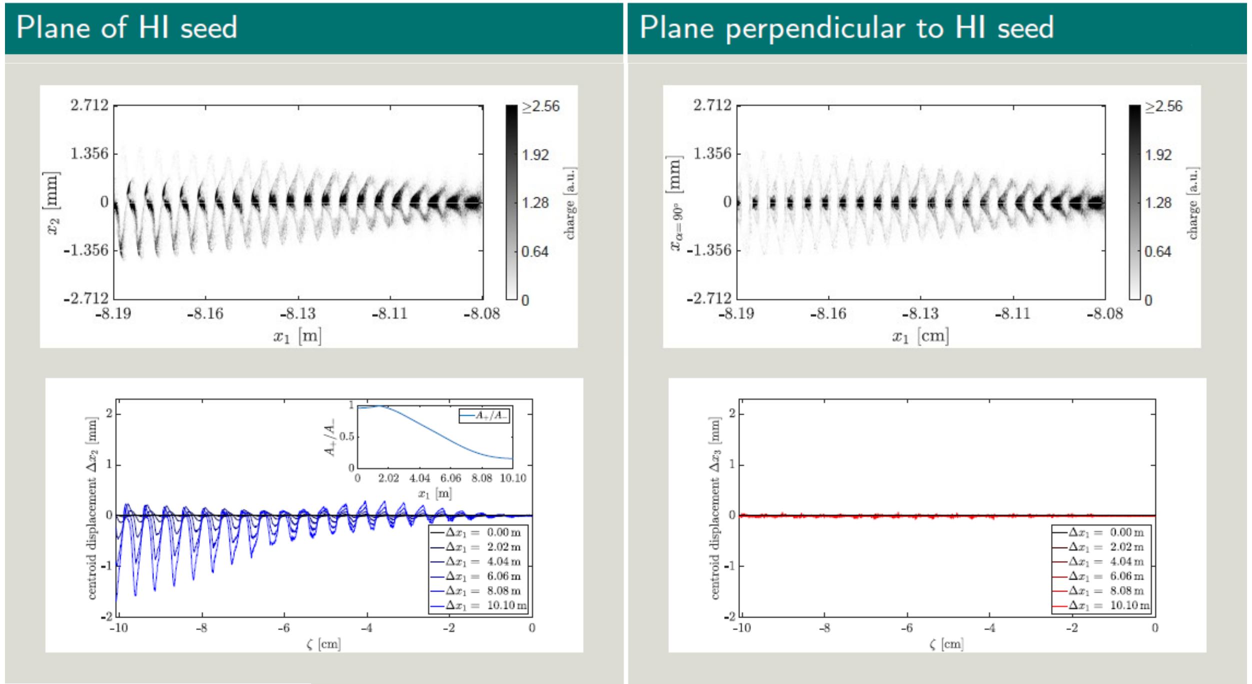


Mathias Hüther

Unwanted effect as the growth of the HI could severely limit acceleration length and energy gain in a PWFA

Only observed at lower plasma densities than used for acceleration

Comparison with theory and simulation

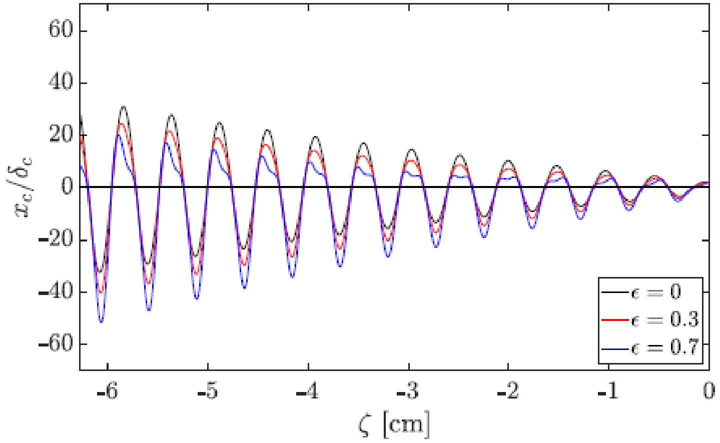


M. Moreira and J. Vieira, IST Lisbon

Full 3D simulations of an SPS-like bunch
HI seeded by small oscillation in initial bunch distribution

- Model of coupled beam hosing

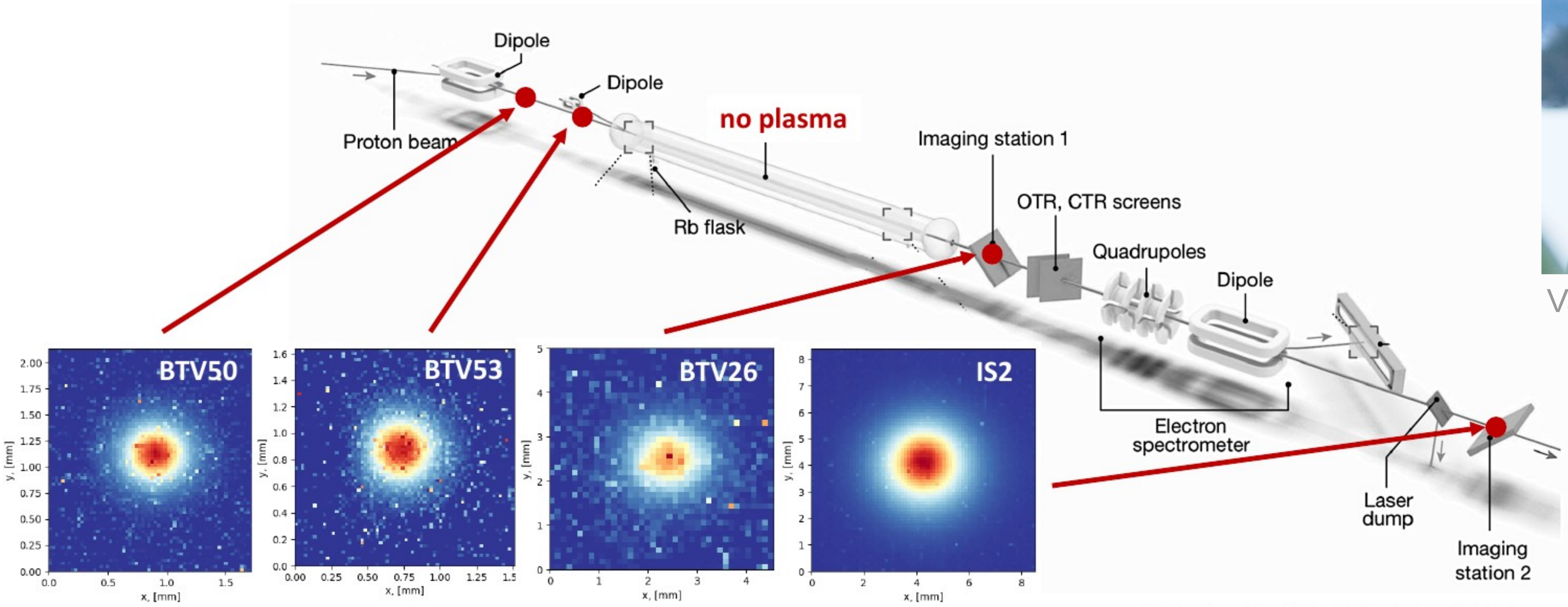
$$\left(\frac{x_c}{\delta_c}\right)_{coupled} = \left(\frac{x_c}{\delta_c}\right)_{uncoupled} \cdot [1 + \epsilon \cdot \sin(k_{pe}\zeta)]$$



Simulations and experiment both give good agreement with theory

Characterising the proton beam

Statistical modelling combing information from separate measurements can improve accuracy



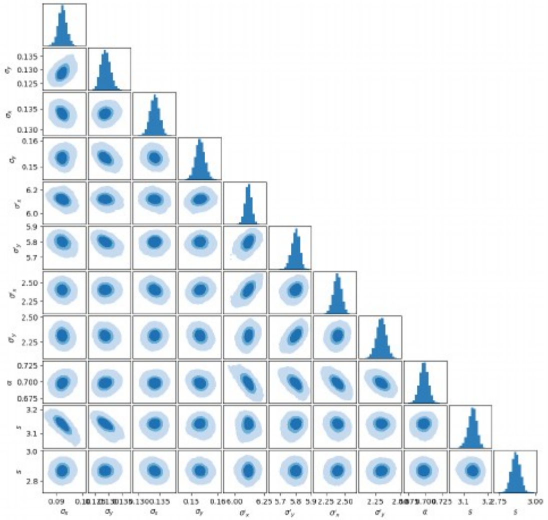
Retrieved from: https://doi.org/10.1038/s41586-018-0485-4

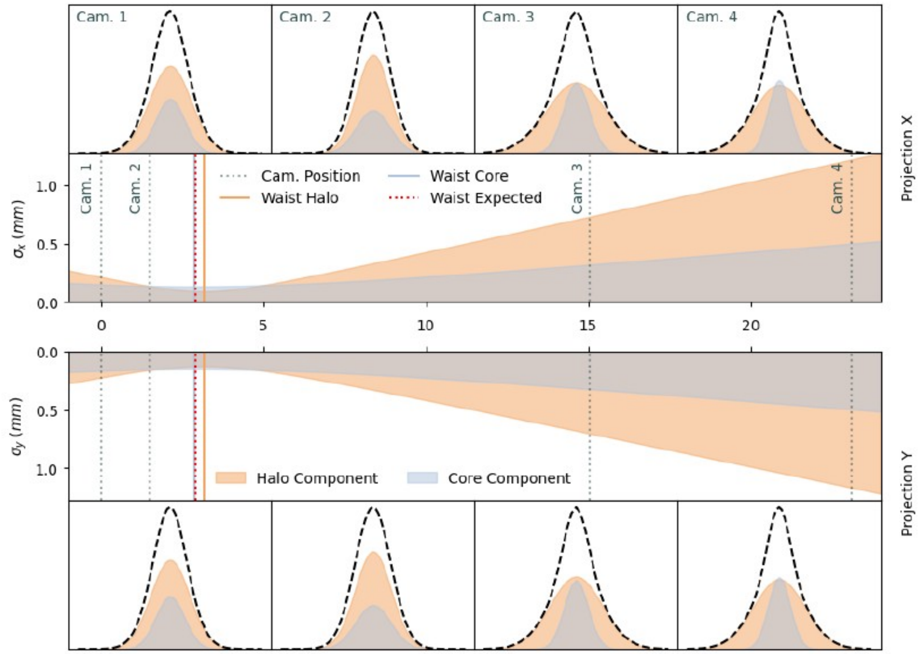
Vasyl Hafych

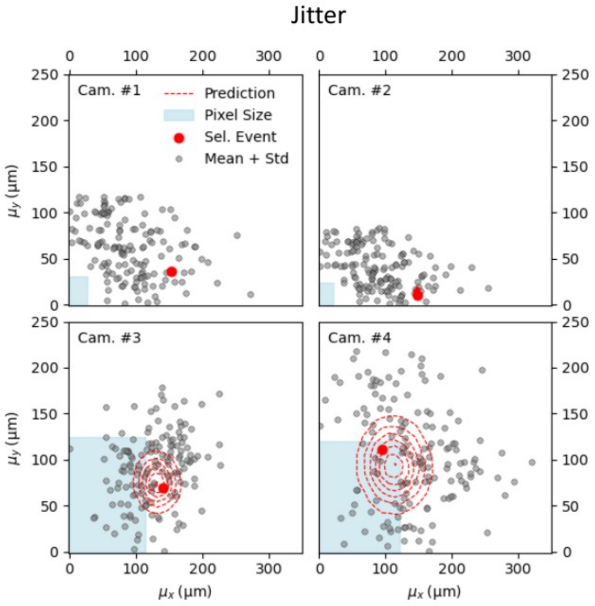
Characterising the proton beam

Model developed by considering many events

Analysis of 1 event using a double Gaussian model



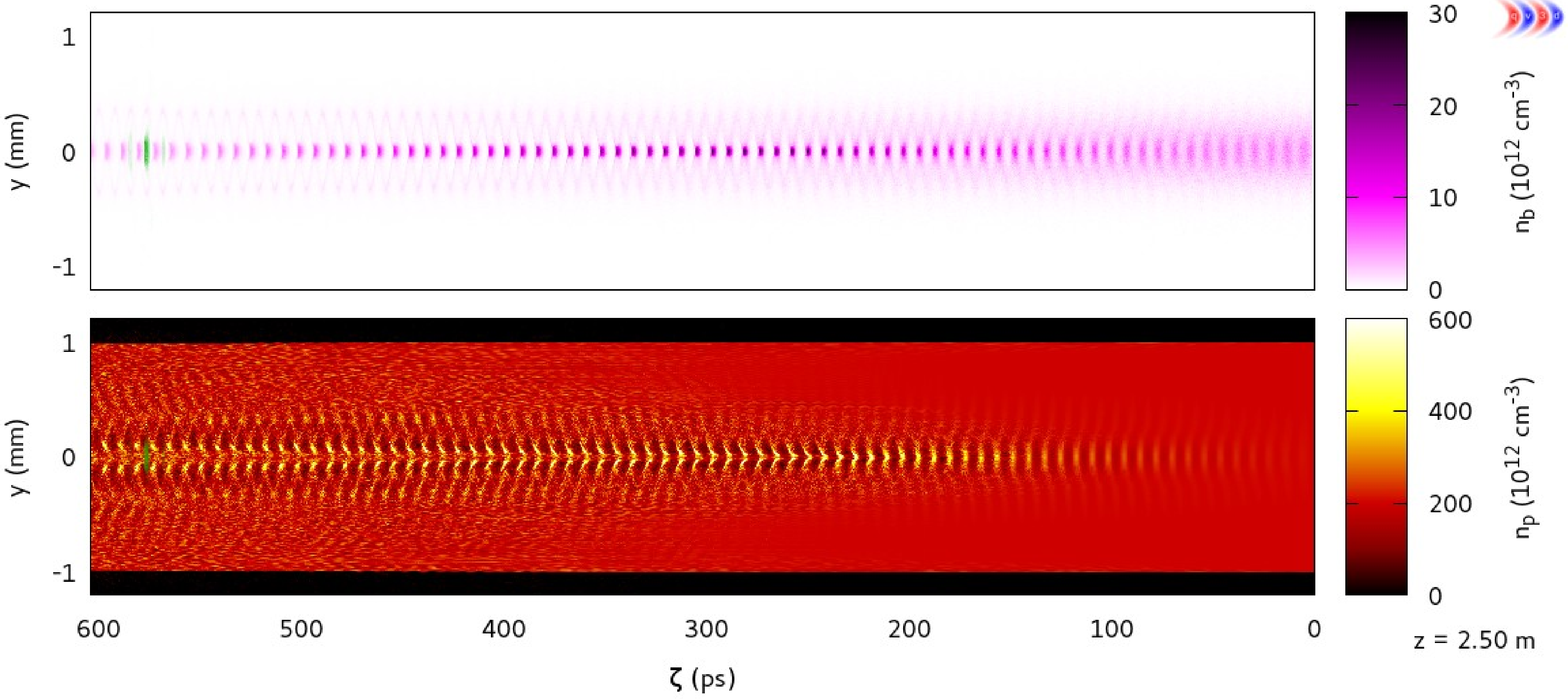




Allows determination of trajectories beyond single detector accuracy

Electron trapping and acceleration

Understanding injection requires simulations



John Farmer (i bims)

Wakefields grow as drive beam evolves

Electron trapping and acceleration

Understanding injection requires simulations

- Wakefield phase evolves during self modulation
- Full treatment requires 3D simulations

Disparate scales make simulations extremely challenging

- Plasma wavelength, electron and proton beam lengths
- Plasma frequency, electron and proton betatron frequencies

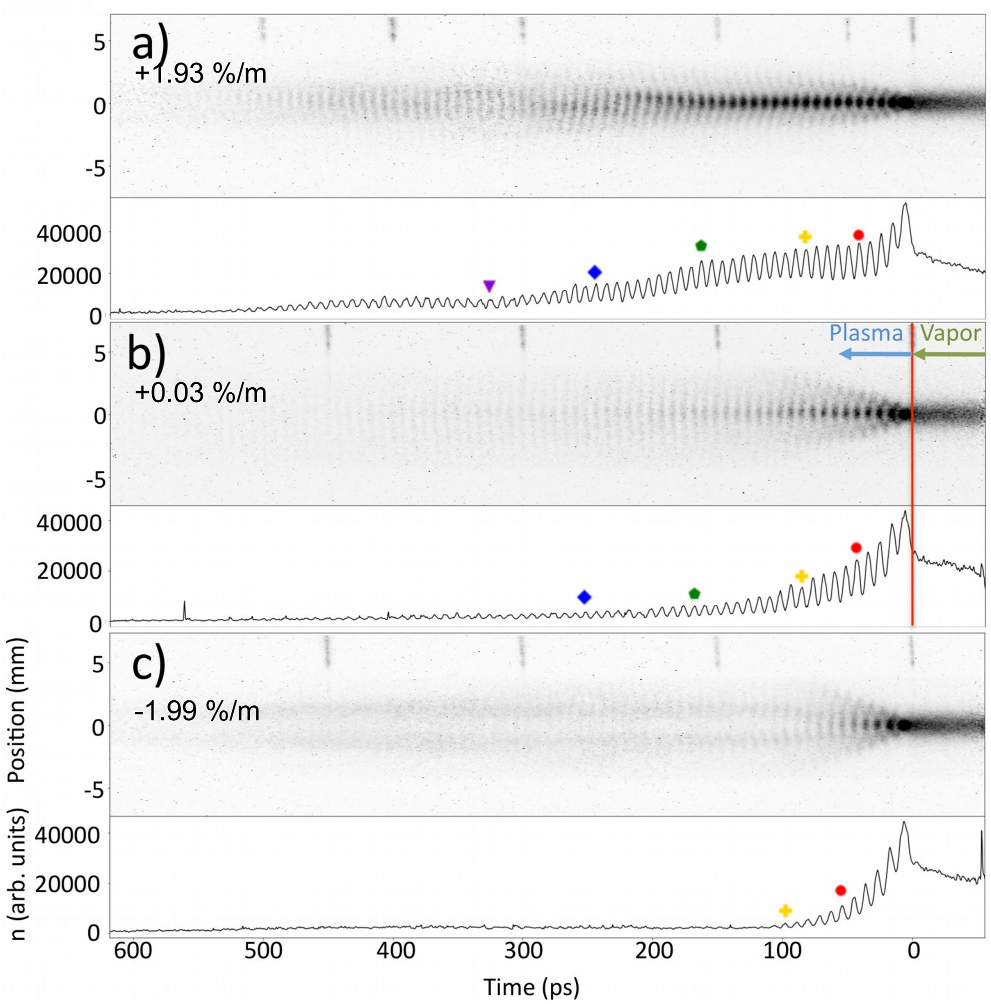
Parameter scans require new simulation techniques

Code and model development to separate scales

SM with plasma gradient

Falk Braunmüller,
Tatiana Nechaeva

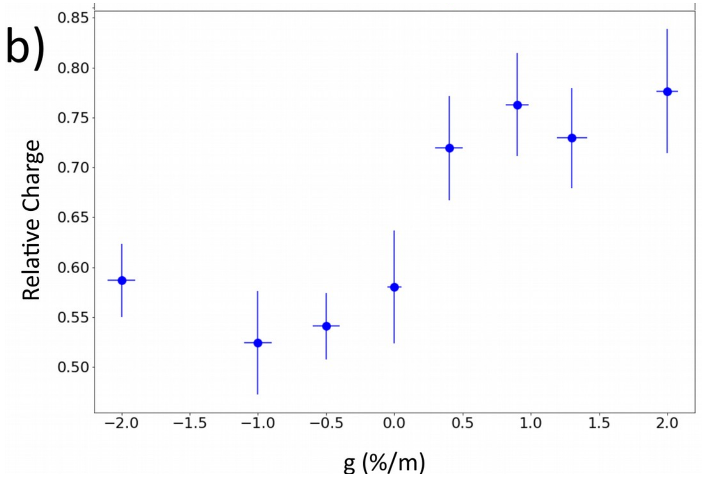
“Stitched” images of self-modulated bunch & time profiles



Plasma gradient can compensate dephasing during self modulation

Change in microbunch train observed experimentally

SM with plasma gradient



Positive gradient

- more microbunches
- longer bunch train
- more charge in core

Negative gradient

- fewer microbunches
- shorter bunch train
- less charge in core

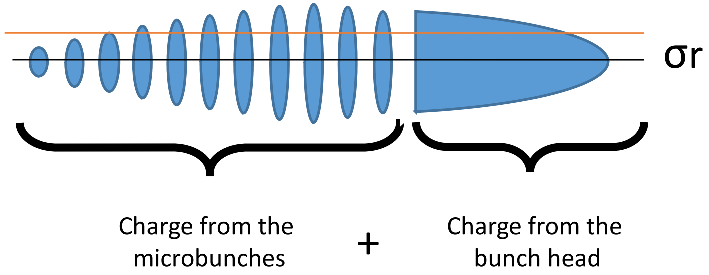
“Proton Bunch Self-Modulation in Plasma with Density Gradient”,
F. Braunmüller, T. Nechaeva *et al* (AWAKE collaboration), accepted by PRL (arXiv:2007.14894v2)

We study experimentally the effect of linear plasma density gradients on the self-modulation of a 400 GeV proton bunch. Results show that a positive/negative gradient in/decreases the number of micro-bunches and the relative charge per micro-bunch observed after 10 m of plasma. The measured modulation frequency also in/decreases. With the largest positive gradient we observe two frequencies in the modulation power spectrum. Results are consistent with changes in wakefields’ phase velocity due to plasma density gradient adding to the slow wakefields’ phase velocity during self-modulation growth predicted by linear theory.

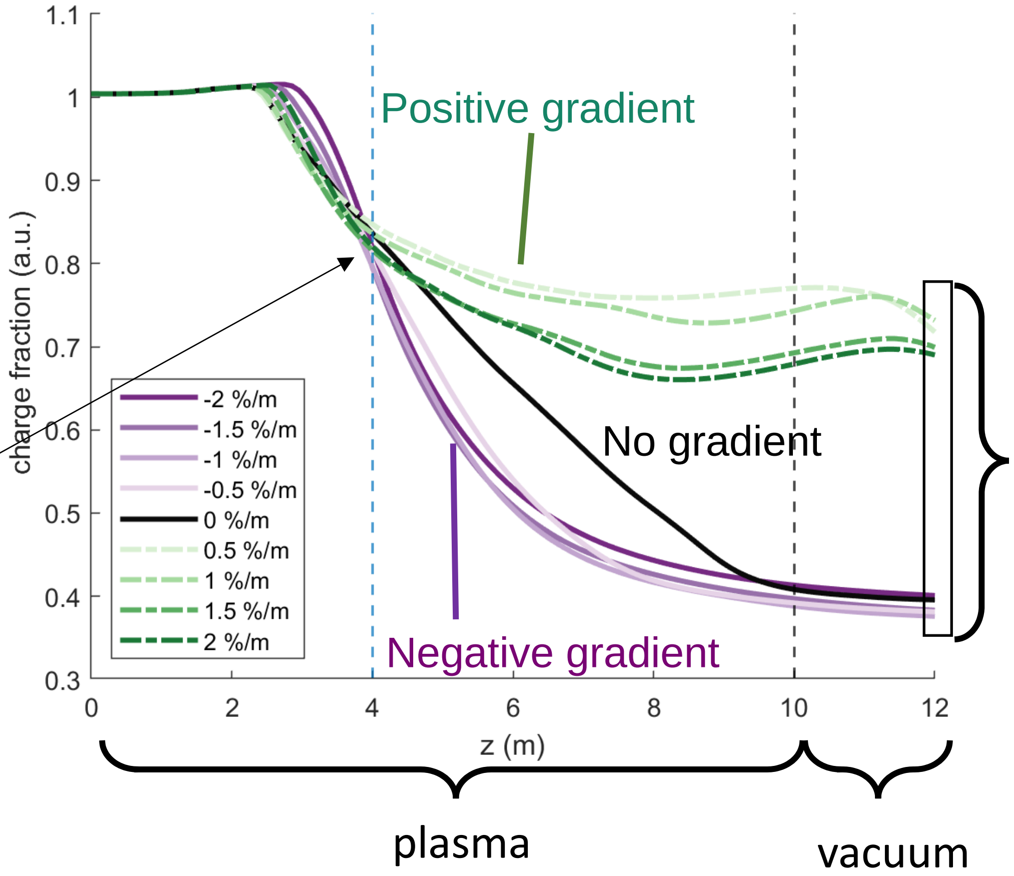
Tatiana starting PhD in the group

Simulation of density gradients

Charge fraction in the core of the modulated proton bunch

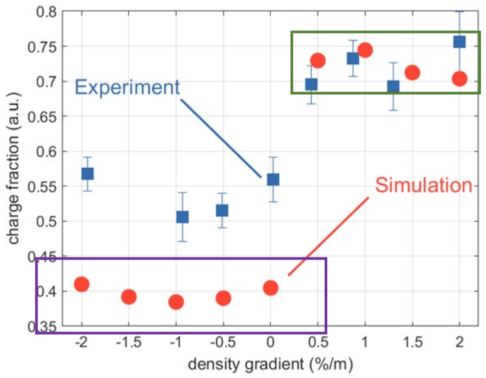


Two groups
- low charge fraction.
- high charge fraction.

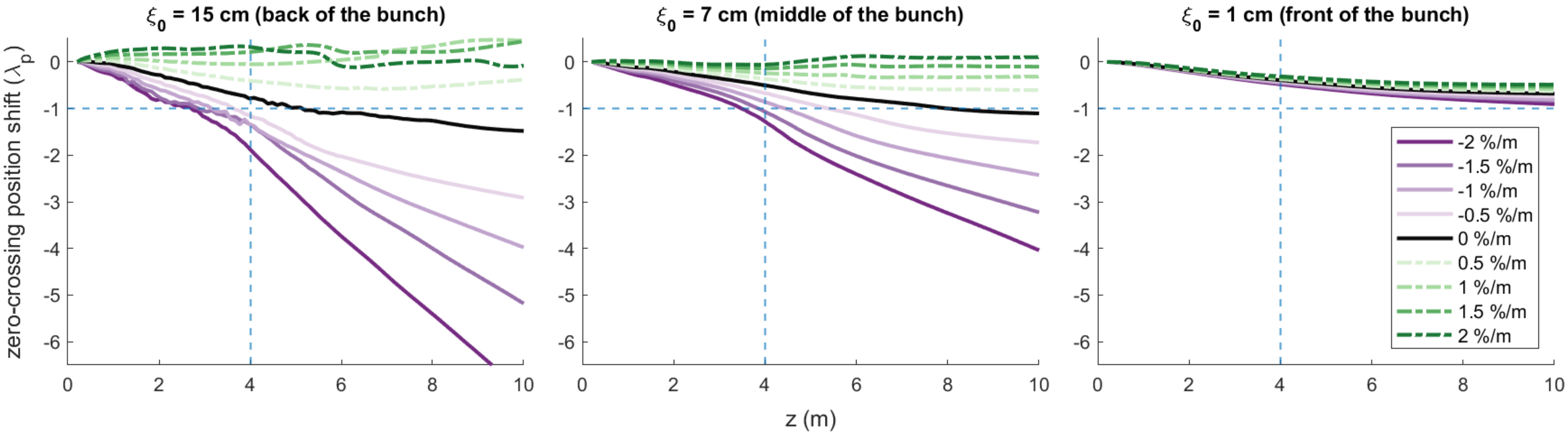


Positive and negative gradients separate at 4 m, constant density stays in between until just before the end of the plasma.

Pablo Israel Morales Guzmán



Simulation of density gradients

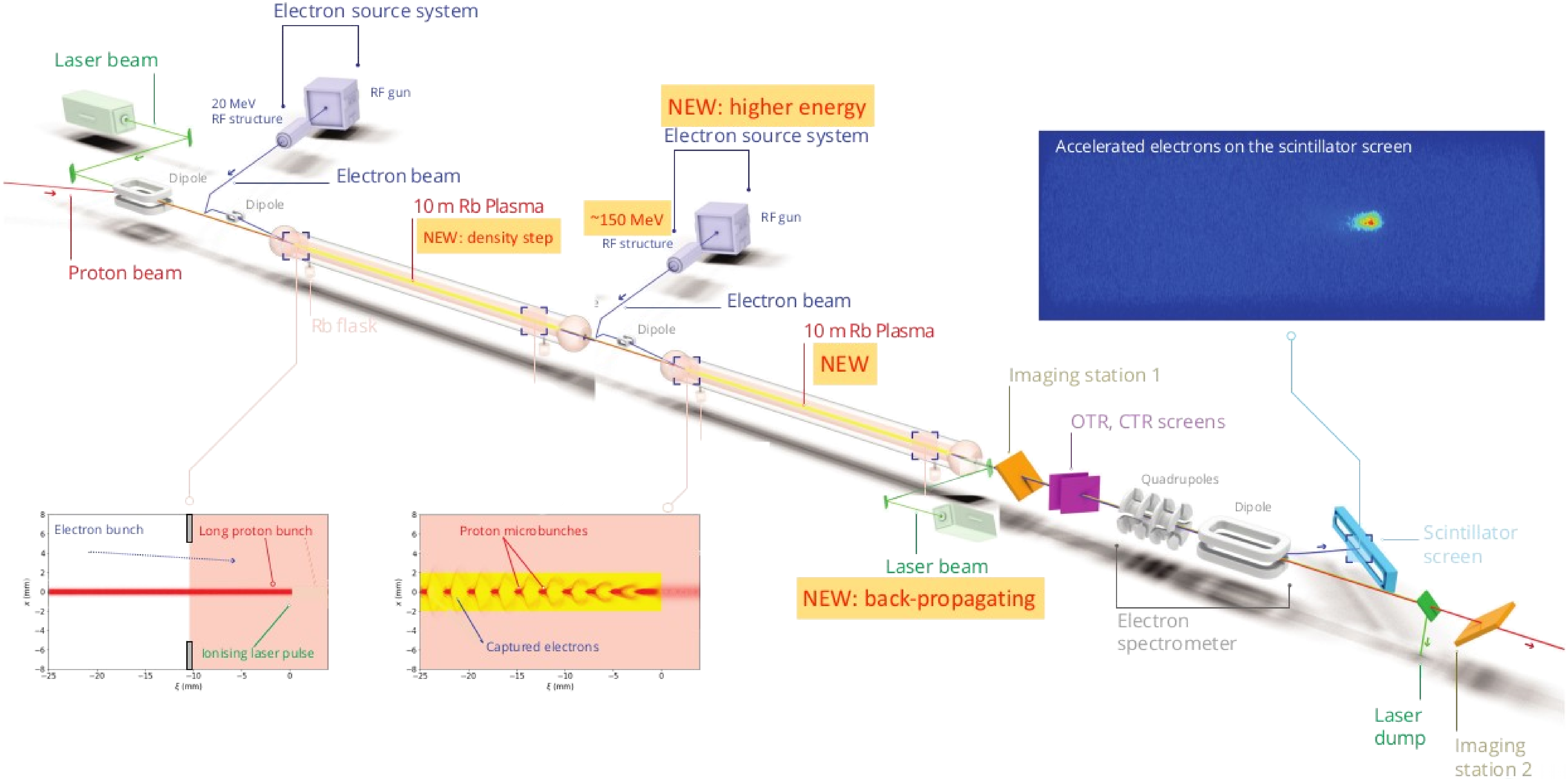


Phase calculated from zero-crossing close to ξ_0 from the longitudinal fields on axis.

Simulations allow phase evolution in plasma to be tracked

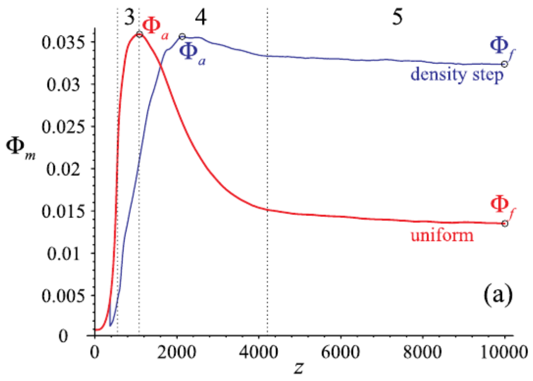
- Positive gradients give near constant phase
- Larger dephasing for decreasing gradients
  leads to sequential focussing/defocussing periods

AWAKE Run2 (2021-2028)



AWAKE Collaboration, Nature (2018)

Commissioning new plasma source



K. Lotov, PRAB (2015)

Heavy lifting: 500 kg of electrically-heated prototype

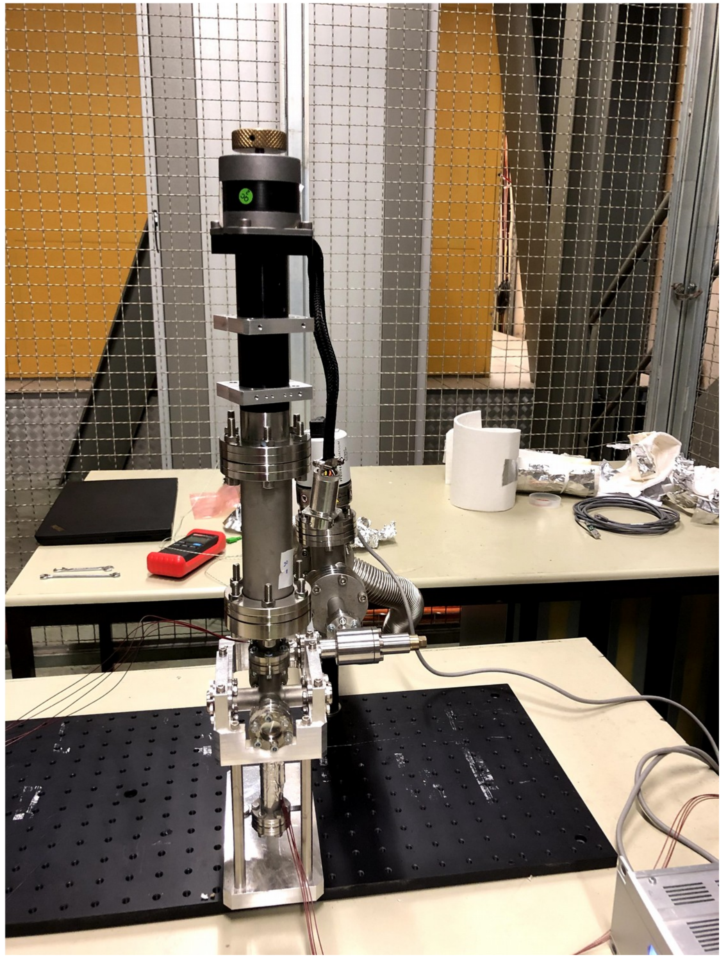
Jan Pucek

Michele Bergamaschi

Simulations show density step in modulator improves wakefields

- requires new plasma source

Developing diagnosics



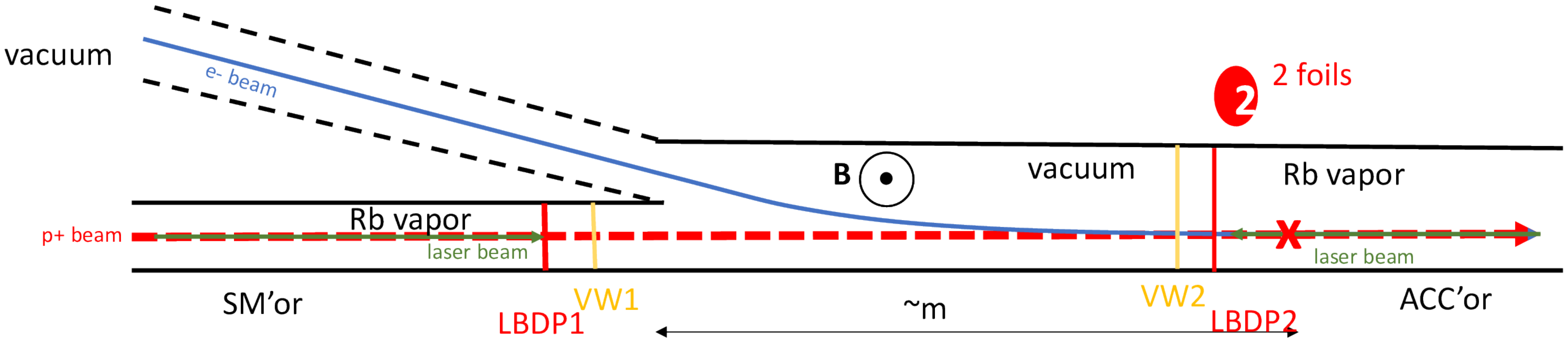
Testing beam screen performance in Rubidium vapour

Optical diagnostics for self modulation

- Commissioning
- Data analysis
- Simulation and theory

Jan Pucek

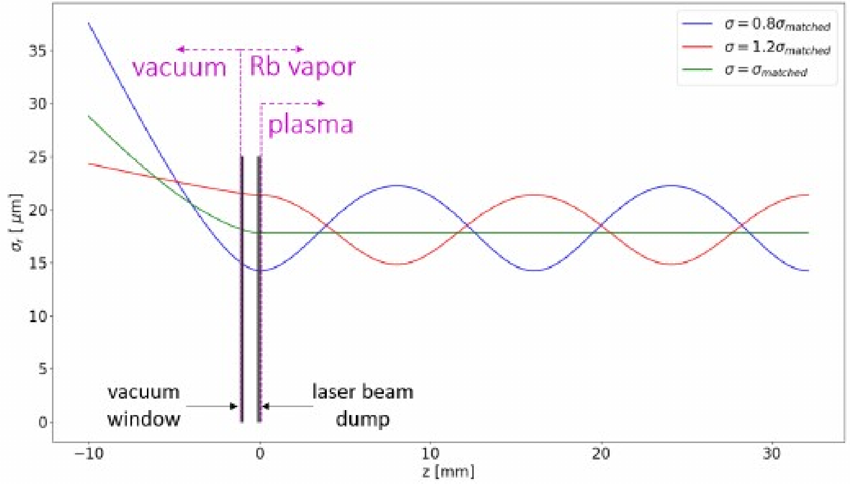
Electron injection for Run2



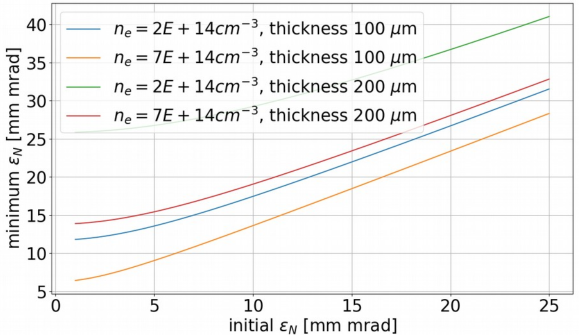
Livio Verra

Controlled electron injection

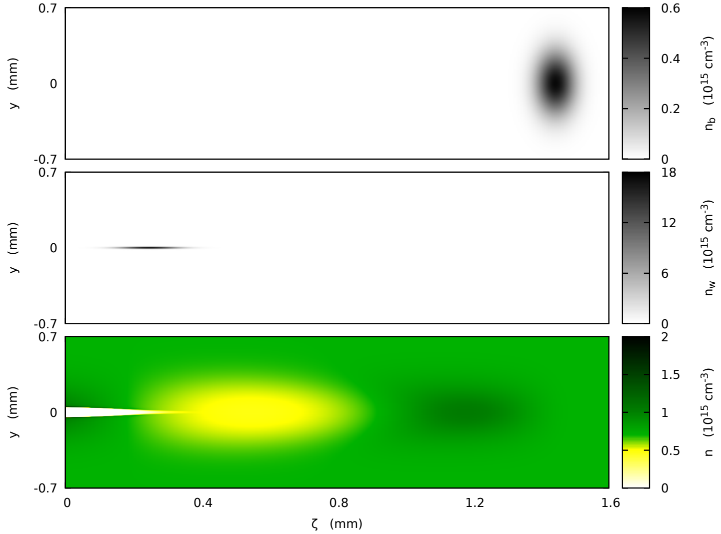
- On axis
- Matched spot size
- Must account for scattering



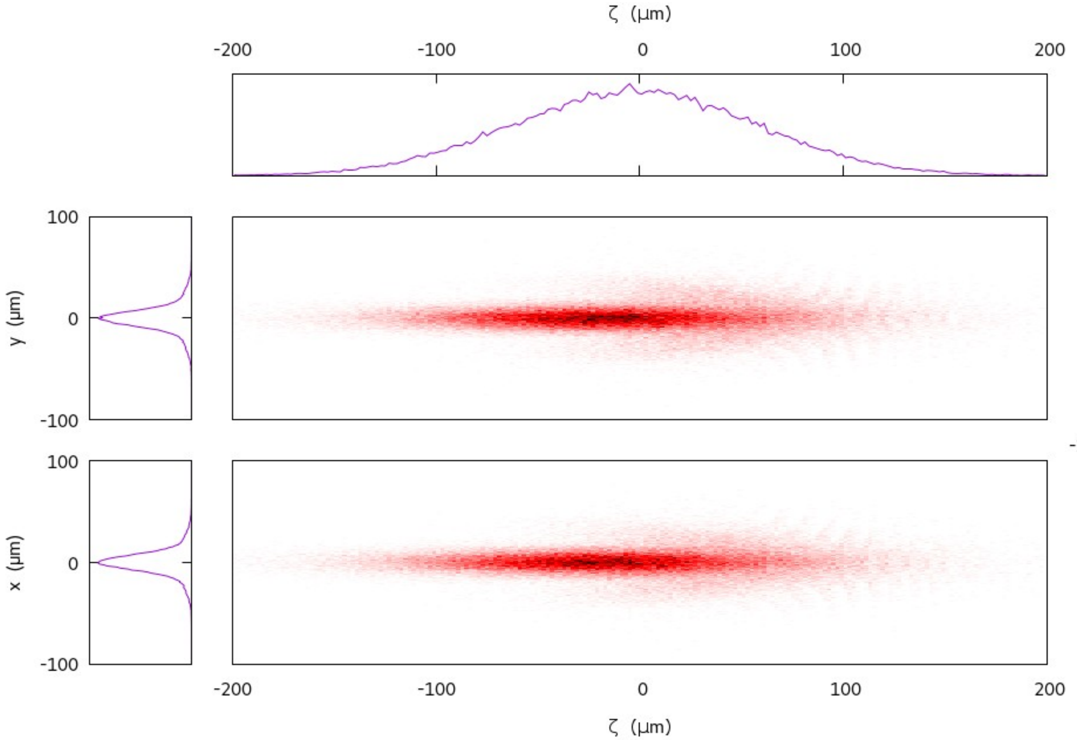
L. Verra *et al., J. Phys.: Conf. Ser.* **1596** 012007 (2020)

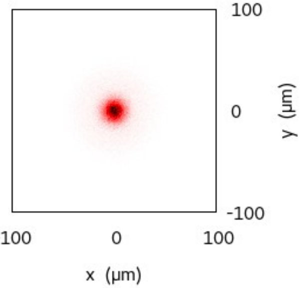


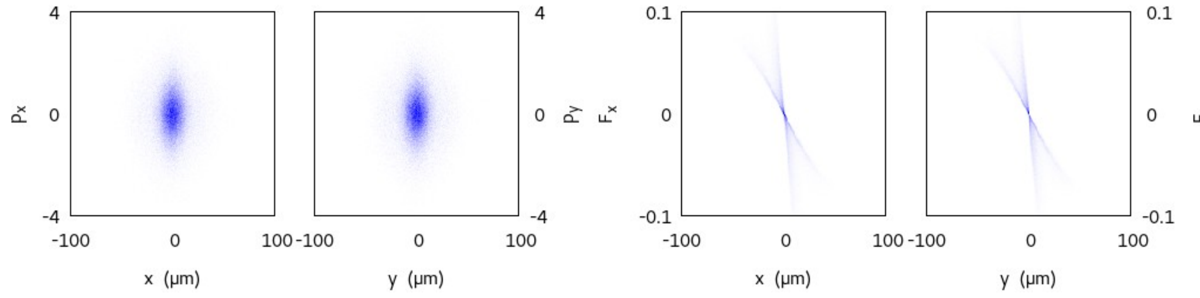
Injection tolerances for Run2



Toy model for injection







Z=200.0 cm

Phase space projections show variations along the bunch

John Farmer (again)

Not forgetting

Patric Muggli

Allen Caldwell

Conclusions

AWAKE Run1 was a great success, and continues to provide the basis for publications (and PhD theses)

Significant commissioning, diagnostic development and simulation effort to prepare for Run2

Controlled acceleration is an important step from proof-of-principle towards applications

Thanks

AWAKE Collaboration: 22 institutes world-wide:

- CERN, Geneva, Switzerland
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland
- University of Oslo, Oslo, Norway
- Wigner Institute, Budapest
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- Ludwig-Maximilians-Universität, Munich, Germany
- UCL, London, UK
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- TRIUMF, Vancouver, Canada
- University of Wisconsin, Madison, US
- UNIST, Ulsan, Republic of Korea

Associate members:

- Unversity of Jena, Germany

Thanks

To all of AWAKE, and to our collaborators