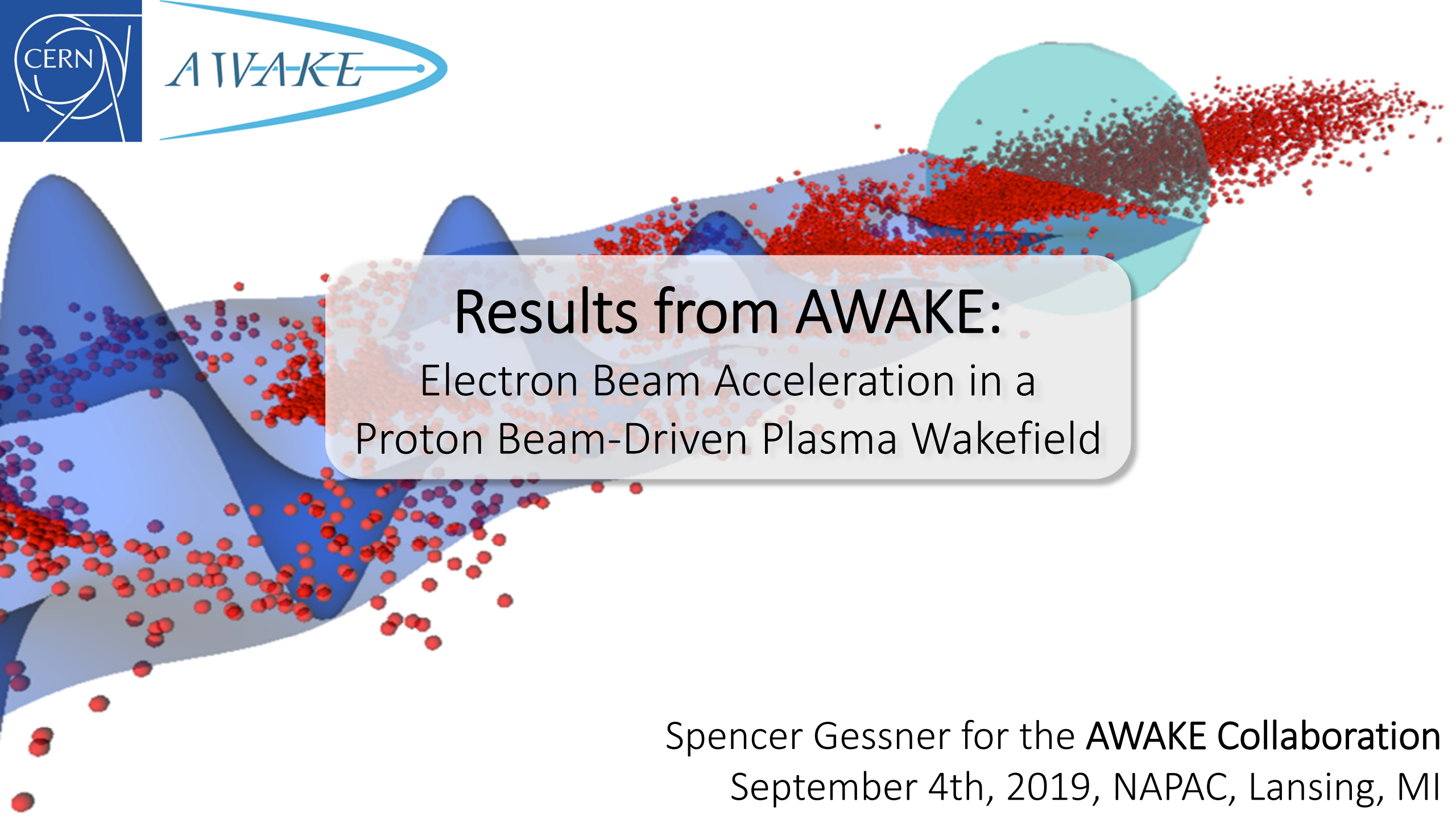




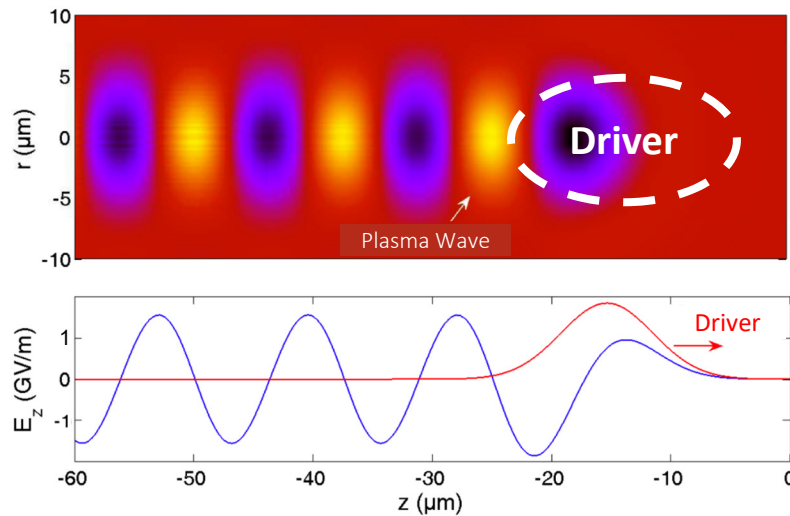
Results from AWAKE:

Electron Beam Acceleration in a
Proton Beam-Driven Plasma Wakefield

Spencer Gessner for the AWAKE Collaboration
September 4th, 2019, NAPAC, Lansing, MI

Why Plasma Wakefield Acceleration?

Plasma wakefield acceleration is a novel method for accelerating particles using *extremely* large fields:



$$E_0 \approx 0.96 \sqrt{n(10^{14} \text{ cm}^{-3})} [\text{GV/m}]$$

Note, the density of air in the room is:

$$n_{air} = 2.69 \times 10^{19} \text{ cm}^{-3} \Rightarrow E_0 \approx 500 \text{ GV/m}$$

Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.

Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

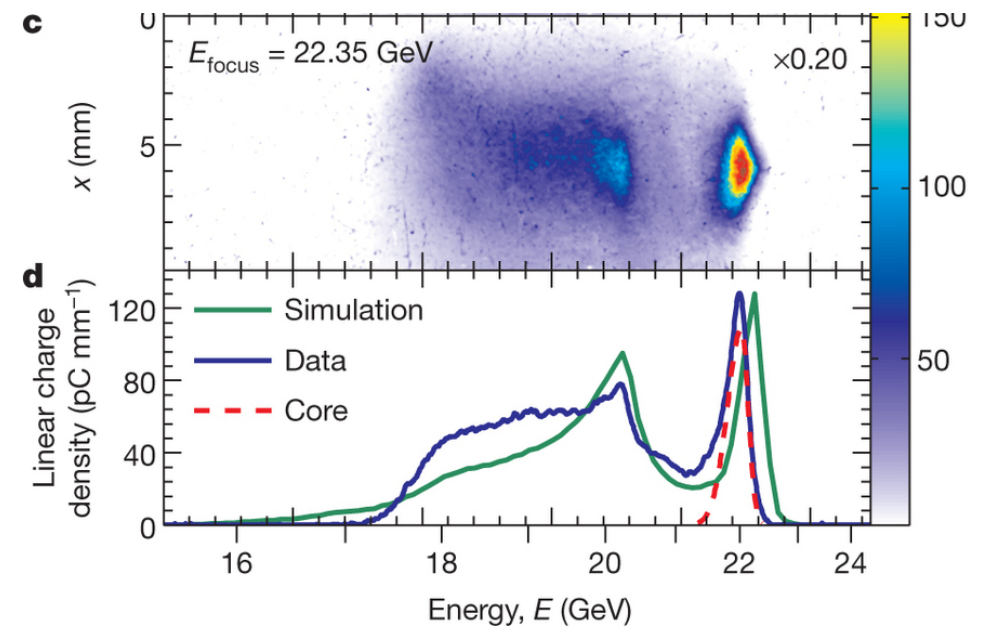
1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.

LETTER

doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

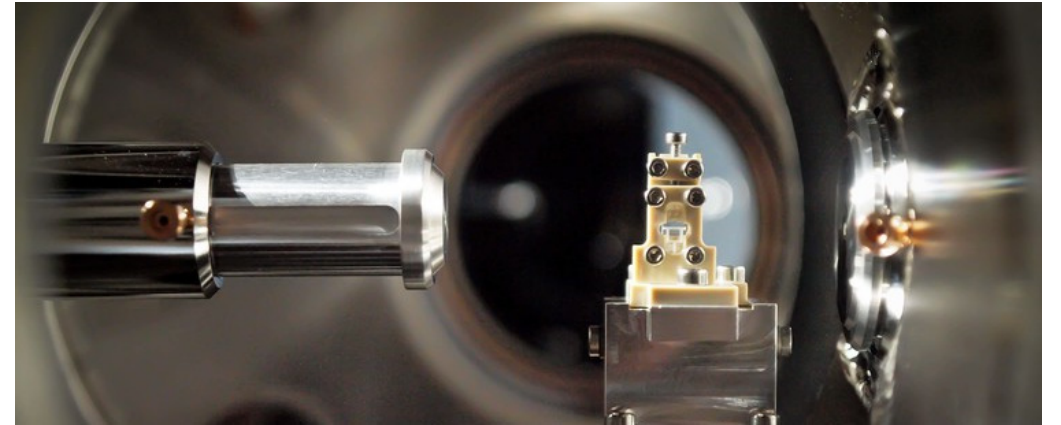
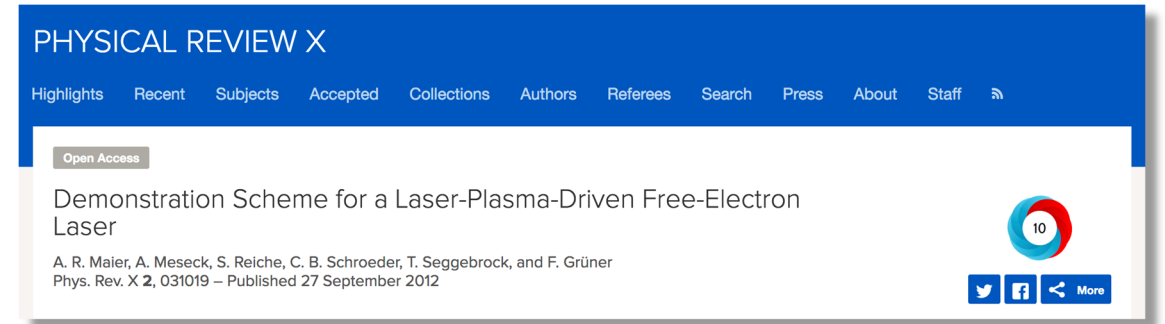
M. Litos¹, E. Adli^{1,2}, W. An³, C. I. Clarke¹, C. E. Clayton⁴, S. Corde¹, J. P. Delahaye¹, R. J. England¹, A. S. Fisher¹, J. Frederico¹, S. Gessner¹, S. Z. Green¹, M. J. Hogan¹, C. Joshi⁴, W. Lu⁵, K. A. Marsh⁴, W. B. Mori³, P. Muggli⁶, N. Vafei-Najafabadi⁴, D. Walz¹, G. White¹, Z. Wu¹, V. Yakimenko¹ & G. Yocky¹



Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.



LUX interaction chamber.



@



Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.

Plasma Physics and Controlled Fusion

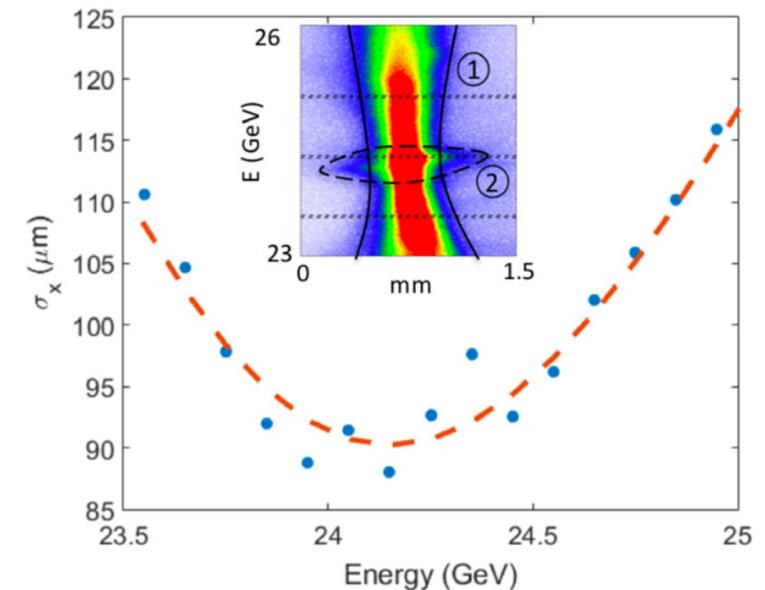
PAPER

Evidence for high-energy and low-emittance electron beams using ionization injection of charge in a plasma wakefield accelerator

N Vafaei-Najafabadi¹, W An¹, C E Clayton¹, C Joshi¹, K A Marsh¹, W B Mori¹, E C Welch¹, W Lu², E Adli^{3,4}, J Allen³, C I Clarke³, S Corde^{3,5}, J Frederico³, S J Gessner³, S Z Green³, M J Hogan³, M D Litos³ and V Yakimenko³ [Hide full author list](#)

Published 9 February 2016 • © 2016 IOP Publishing Ltd

[Plasma Physics and Controlled Fusion, Volume 58, Number 3](#)



Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

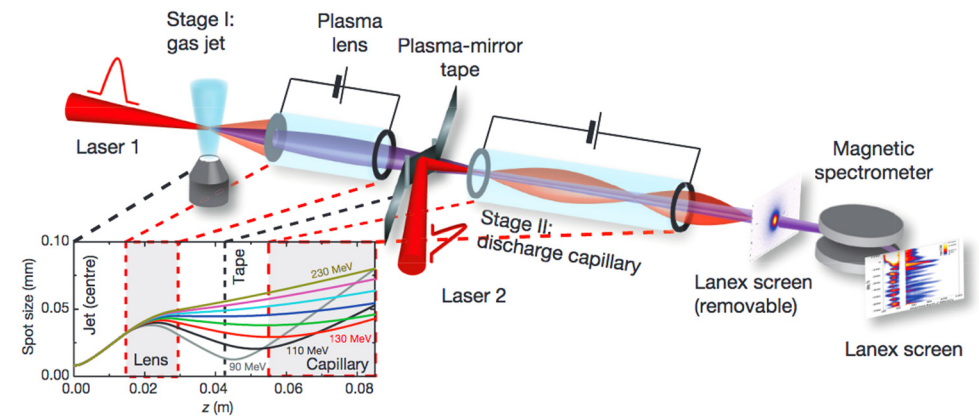
1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.

LETTER

doi:10.1038/nature16525

Multistage coupling of independent laser-plasma accelerators

S. Steinke¹, J. van Tilborg¹, C. Benedetti¹, C. G. R. Geddes¹, C. B. Schroeder¹, J. Daniels^{1,3}, K. K. Swanson^{1,2}, A. J. Gonsalves¹, K. Nakamura¹, N. H. Matlis¹, B. H. Shaw^{1,2}, E. Esarey¹ & W. P. Leemans^{1,2}



BELLA @



Challenges in Plasma Wakefield Acceleration

Plasma accelerators should:

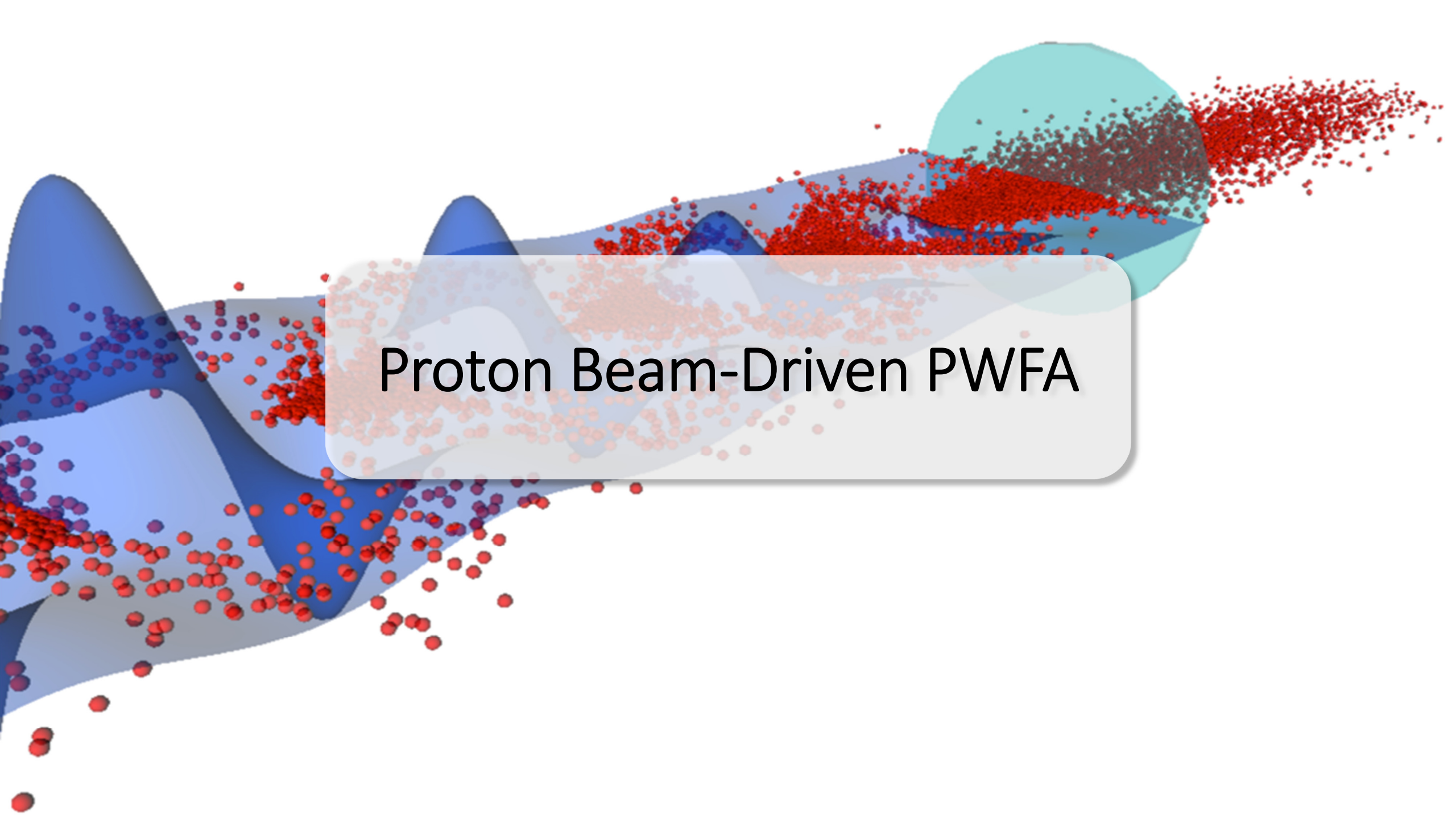
1. Be efficient.
2. Be stable.
3. Produce low emittance beams.
4. Reach extremely high energies.

AWAKE is a **proof-of-concept** experiment to show that **proton beam-driven PWFA** can be used to reach extremely high energies without the use of staging.



@





Proton Beam-Driven PWFA

Why Use Protons for PWFA?

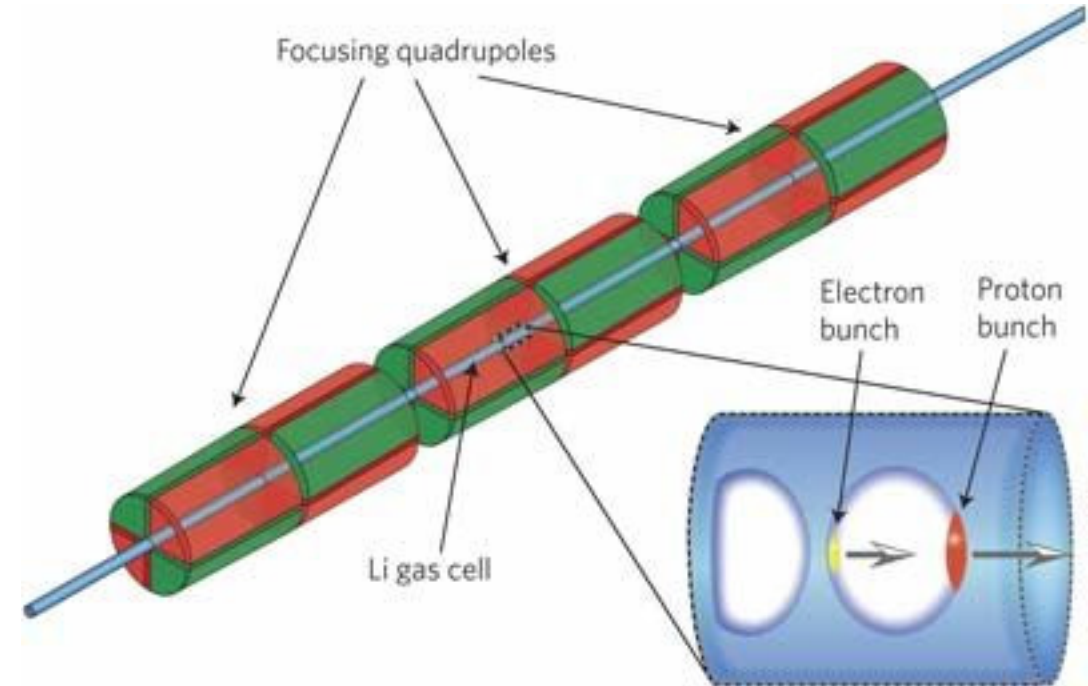
Proton beams store tremendous amounts of energy:

- Petawatt Laser Pulse ≈ 50 J
- FACET Electron Beam ≈ 65 J
- CERN SPS Proton Bunch $\approx 20,000$ J

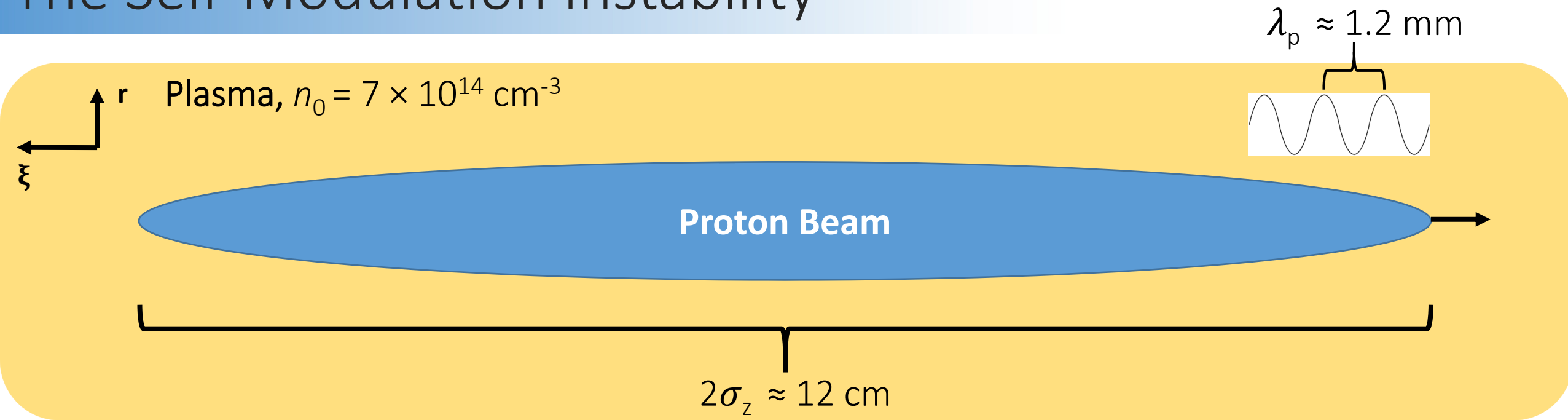
By transferring a significant amount of this energy to a trailing electron beam, we create a single-stage, high-energy, plasma accelerator.

But there's a catch . . .

The proton beam is **much longer** than the **plasma wavelength**.



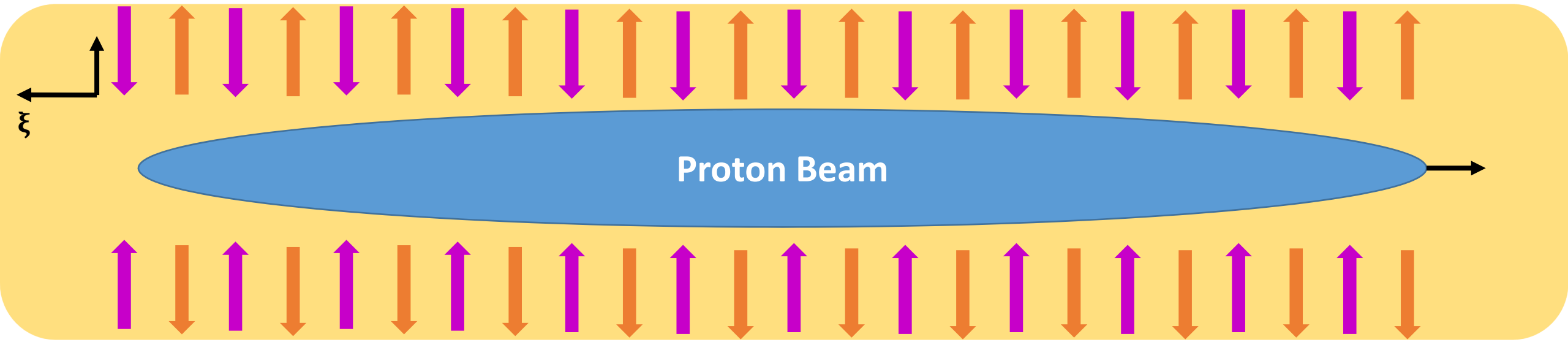
The Self-Modulation Instability



At a density of $7 \times 10^{14} \text{ cm}^{-3}$, the proton beam is hundreds of times longer than the plasma wavelength. As a result, the proton beam does not drive a large amplitude wakefield in the plasma.

The Self-Modulation Instability

N. Kumar, et. al. *PRL* **104**, 255003 (2010)

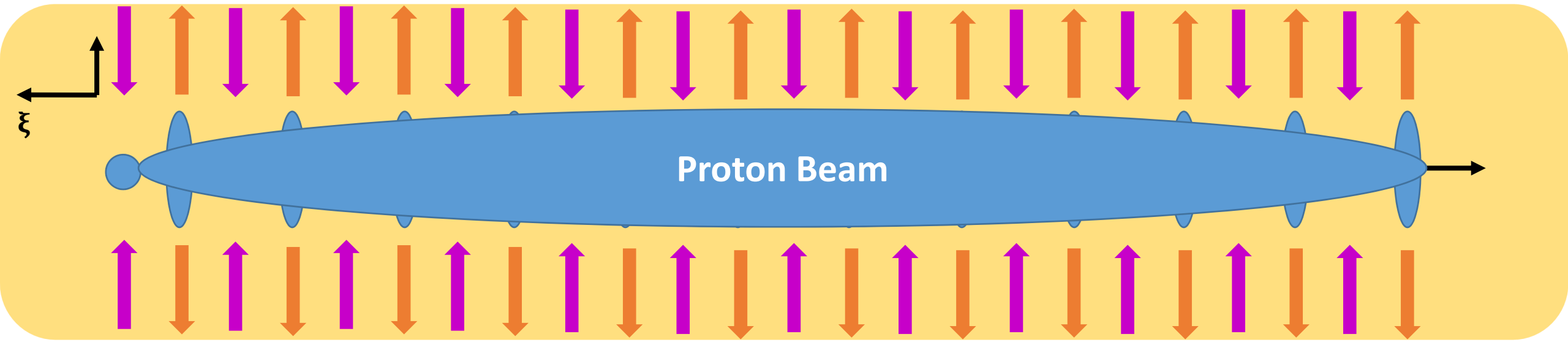


There is a small transverse force experienced by the beam as it propagates through the plasma. The force alternates between focusing and defocusing.

Transverse force felt by bunch

$$W_{\perp}(r, \xi) = -4\pi\rho_0 \int_0^{\xi} r_b(\xi') I_1\{k_p r(\xi')\} K_1\{k_p r_b(\xi')\} f(\xi') k_p \sin k_p(\xi - \xi') d\xi', \text{ Focusing oscillates along bunch}$$

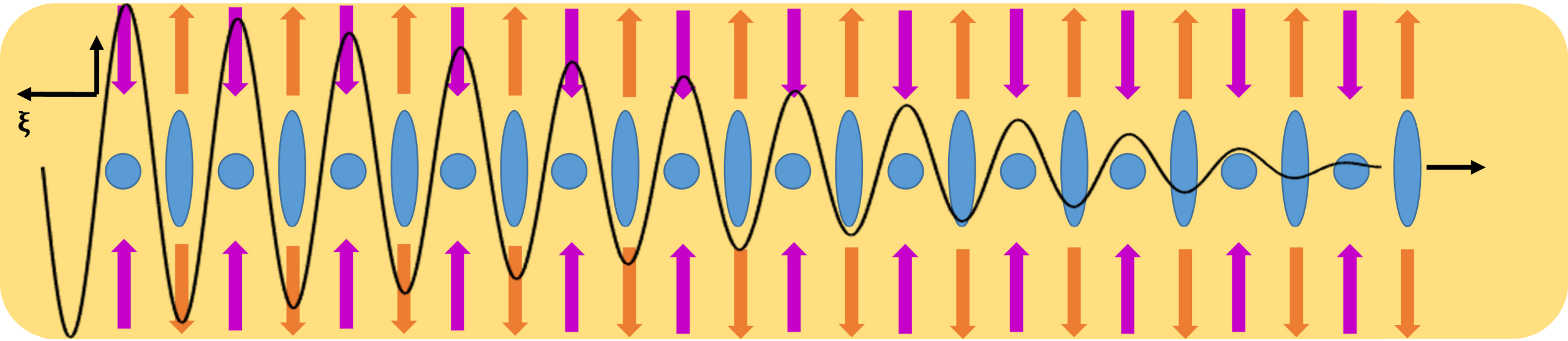
The Self-Modulation Instability



The transverse force alternately pinches and defocuses the beam which *enhances* the transverse force felt by the beam.

$$\underbrace{\frac{\partial^2 r_b}{\partial \tau^2} - \frac{\mathcal{M}^2}{r_b^3}}_{\text{Radial beam evolution}} = -\frac{\omega_b^2}{\gamma_0} \int_0^\xi r_b(\xi') I_1\{k_p r_b(\xi')\} K_1\{k_p r_b(\xi')\} \underbrace{f(\xi') k_p \sin k_p(\xi - \xi') d\xi'}_{\text{Transverse force felt by bunch}},$$

The Self-Modulation Instability



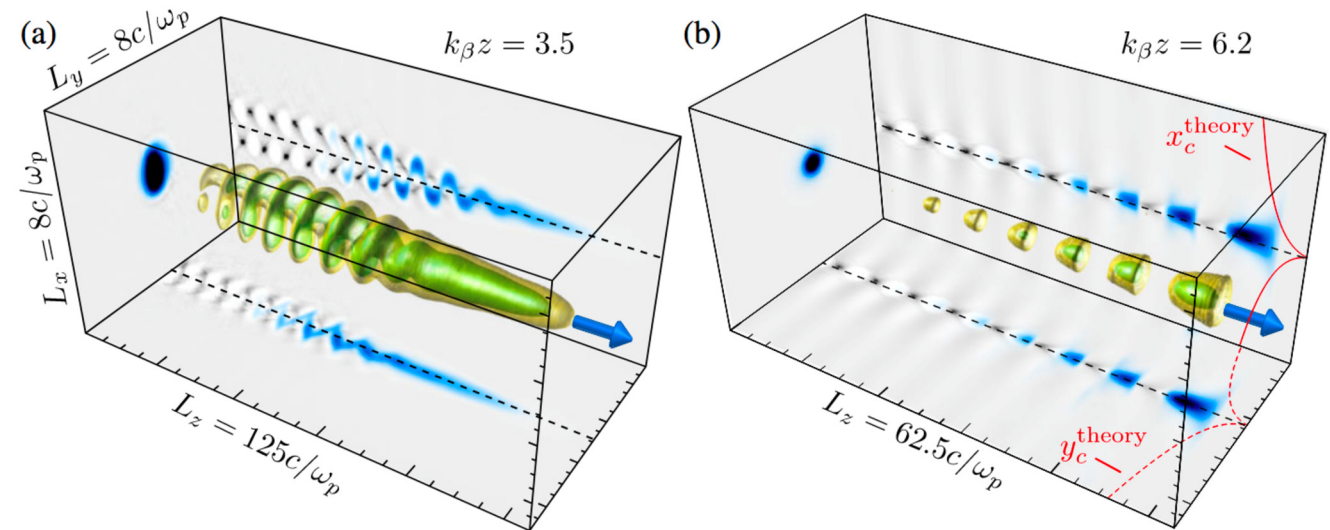
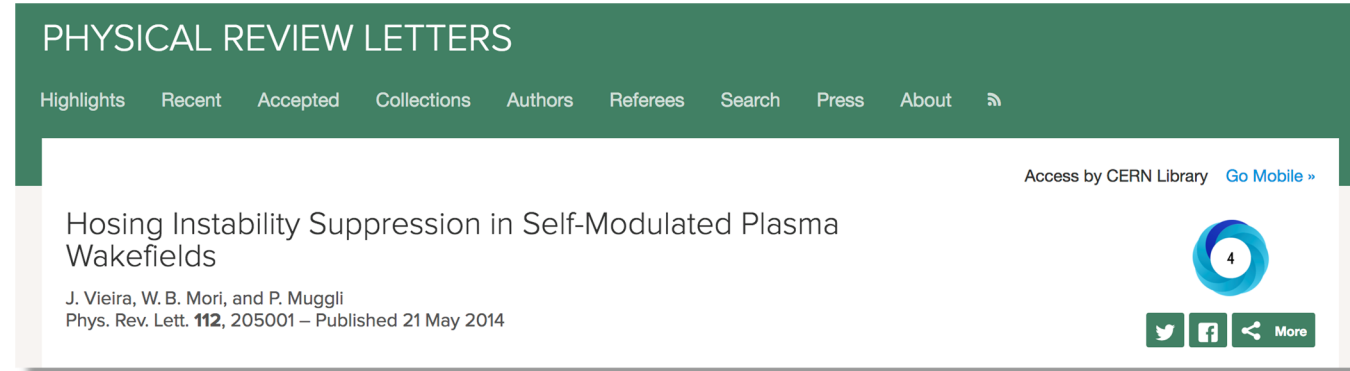
The strongly defocused protons exit the plasma, leaving behind a train of microbunches which *resonantly* excite a large amplitude plasma wakefield.

Seeded Self-Modulation (SSM)

The self modulation instability (SMI) is *useful* because it converts the long proton beam into a series of microbunches which resonantly excite the wake.

But other instabilities, like the hosing instability may also arise.

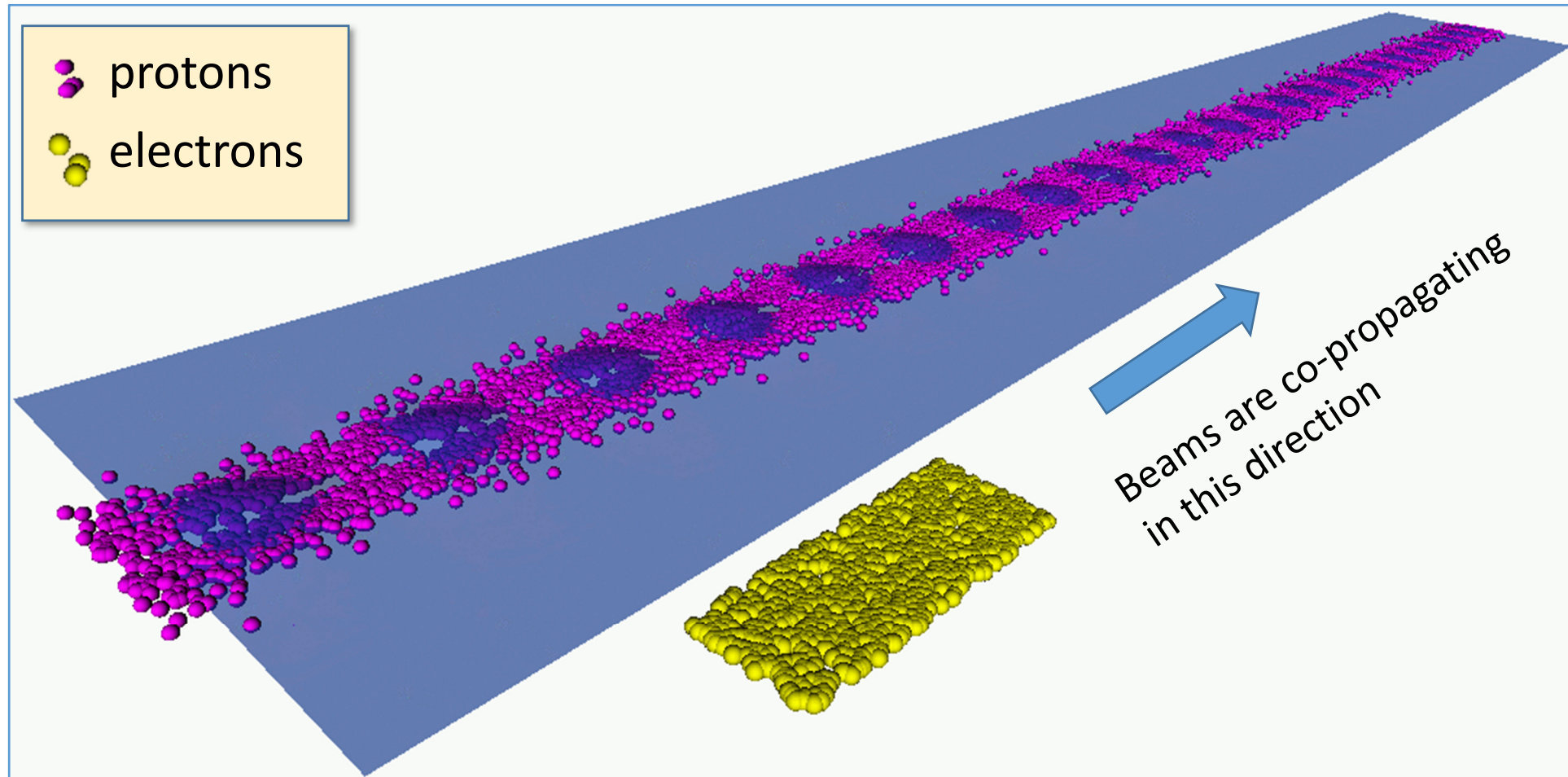
By *seeding* the SMI with a short laser pulse, we can suppress the hosing instability and control the phase of the wake.



Unseeded SMI and hosing instability.

Seeded SMI. No hosing.

Electron Capture and Acceleration



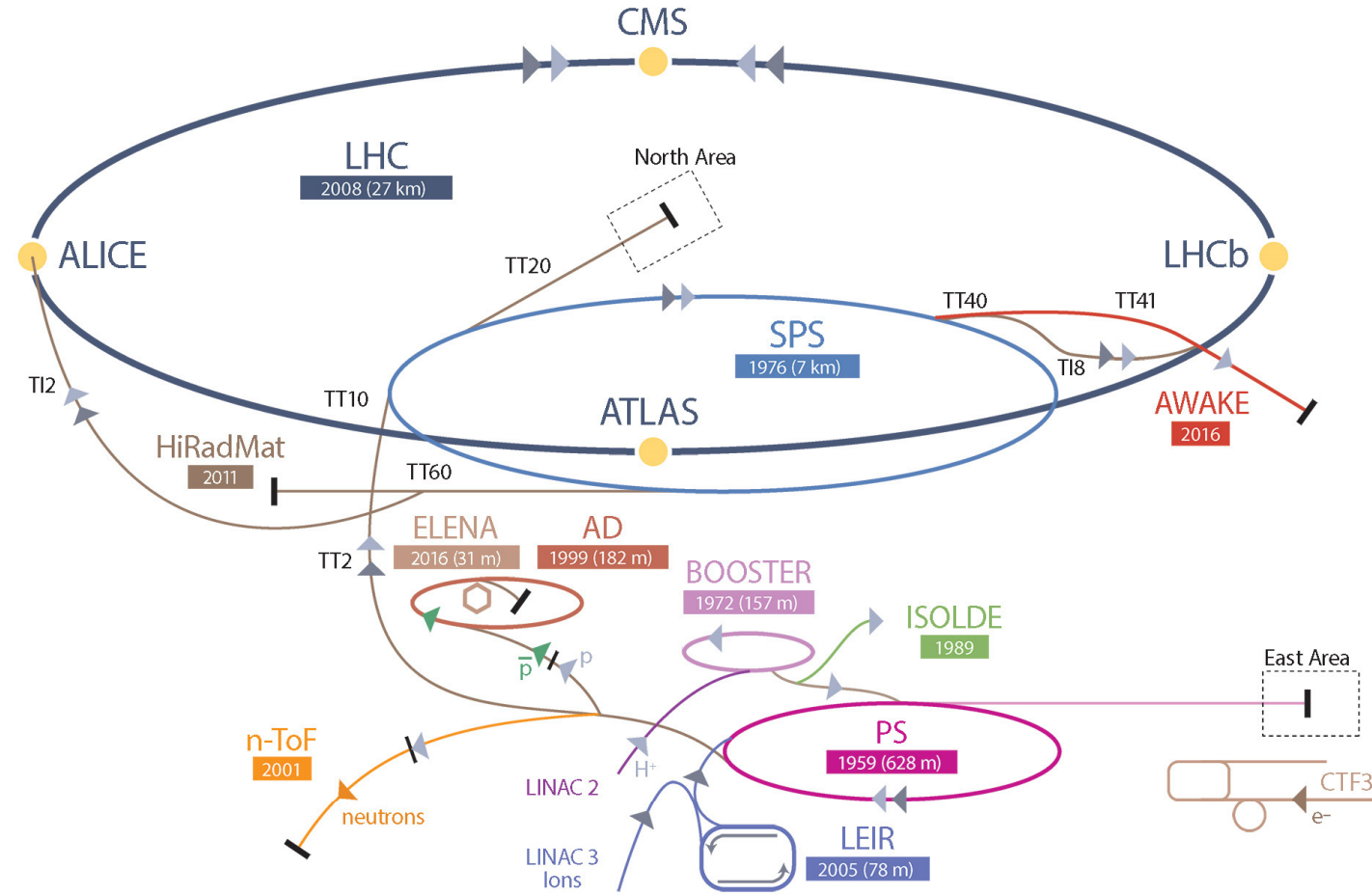
After seeding, the wakefield grows and we inject electrons into the high-amplitude part of the wake.



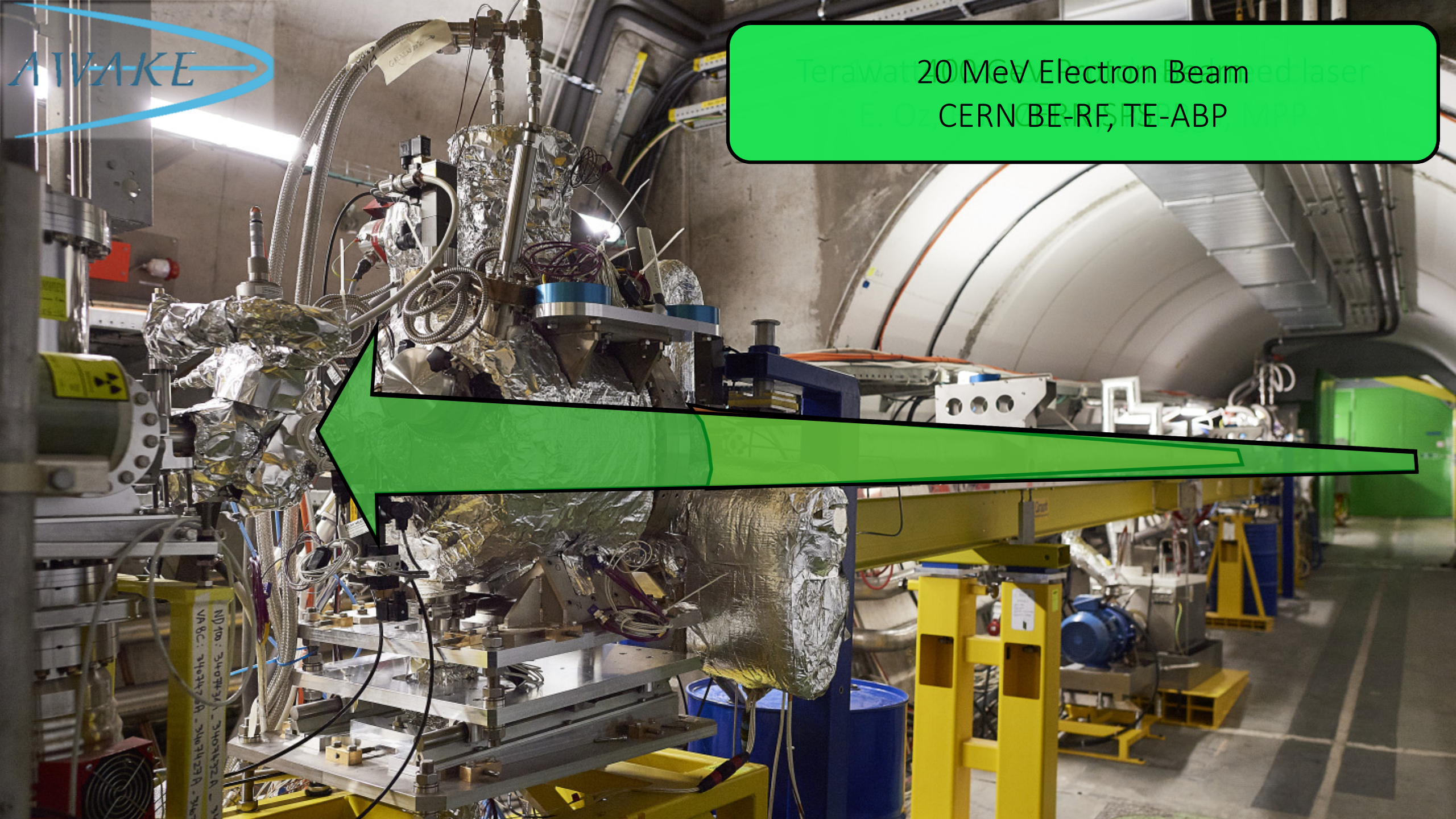
Results

AWAKE @ CERN

CERN's Accelerator Complex



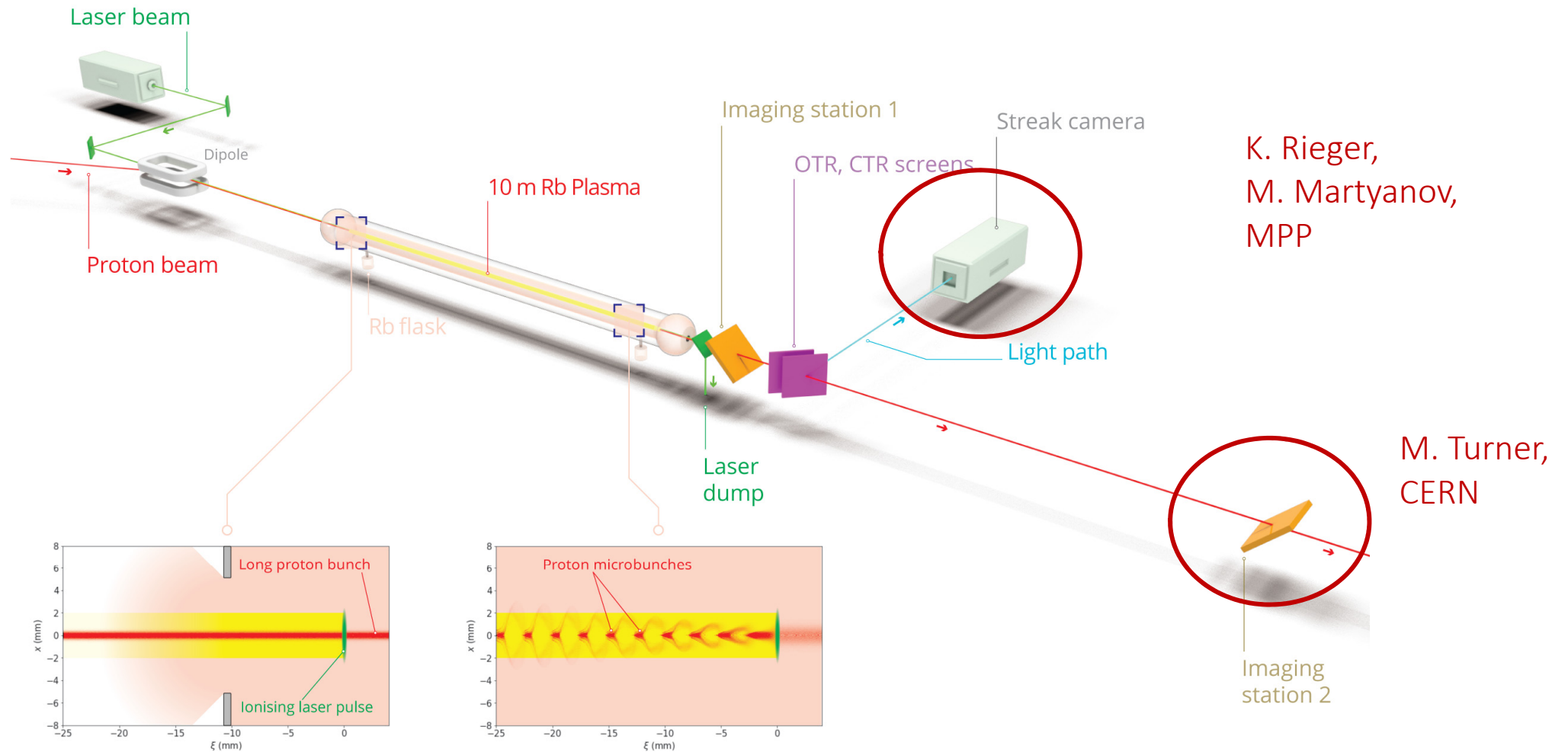
► p (proton) ► ion ► neutrons ► $\bar{p}$ (antiproton) ► electron ► proton/antiproton conversion



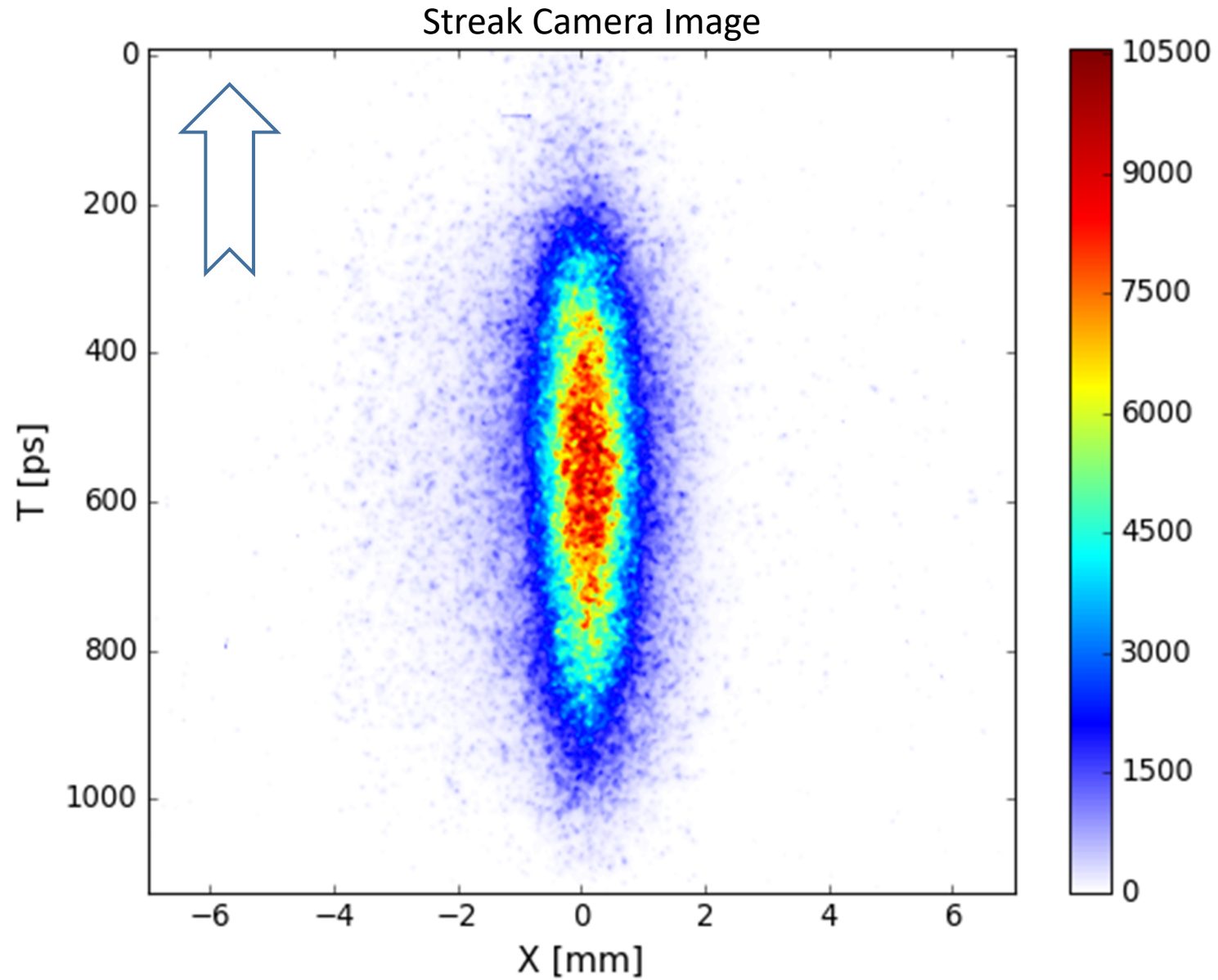
Terawatt 20 MeV Electron Beam driven laser
CERN BE-RF, TE-ABP



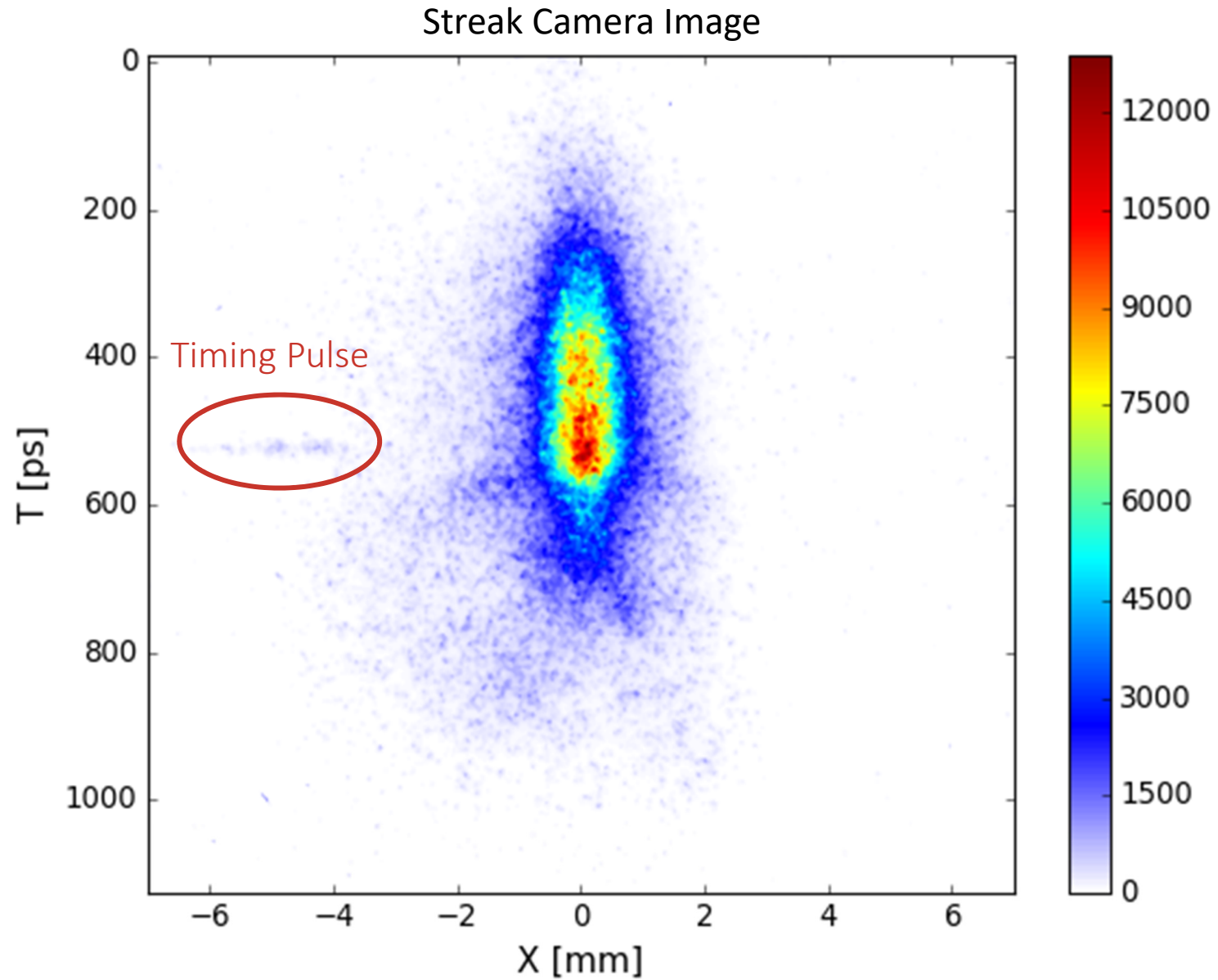
Experimental Schematic for SSM Measurements



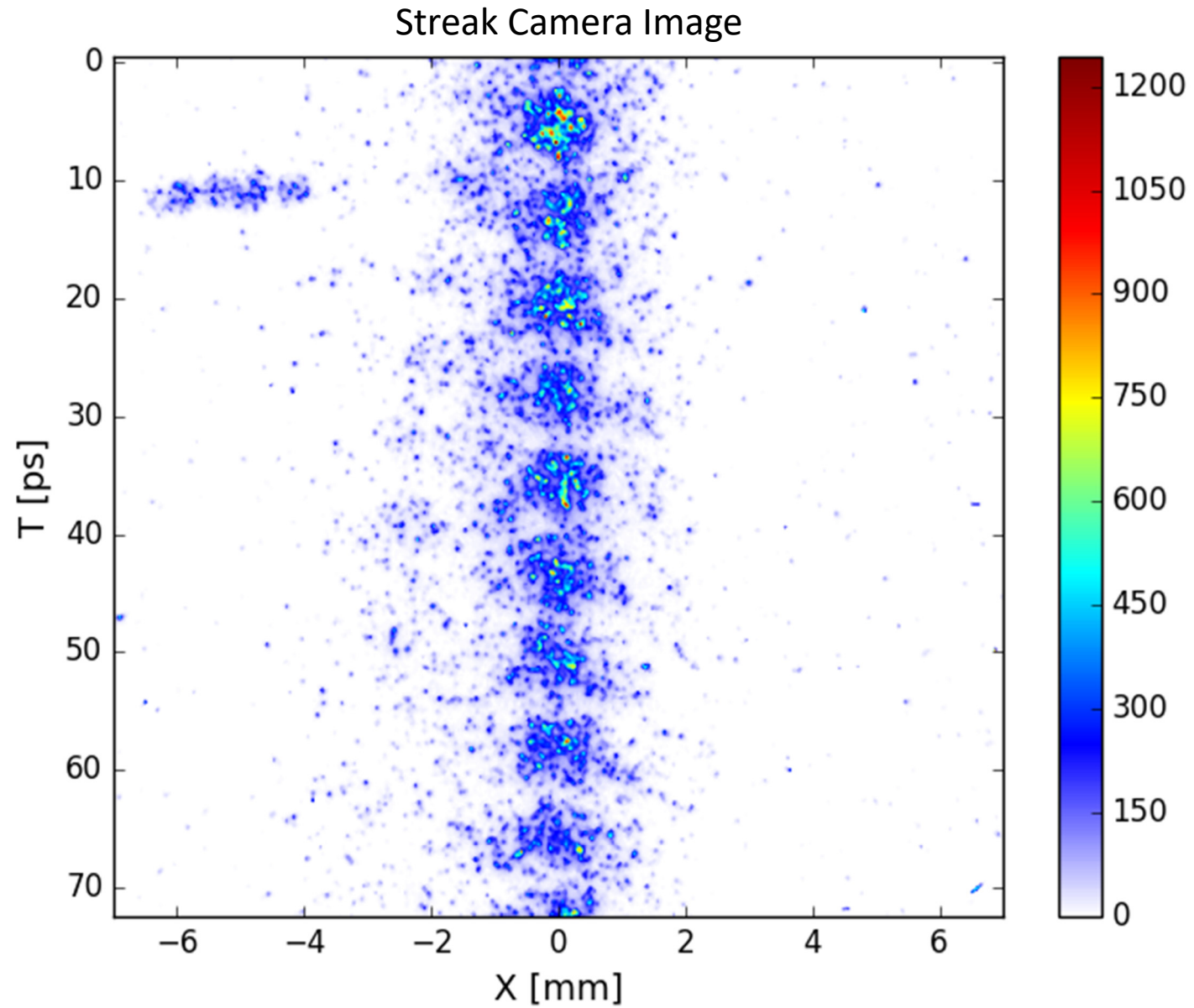
Demonstration of Seeded Self-Modulation



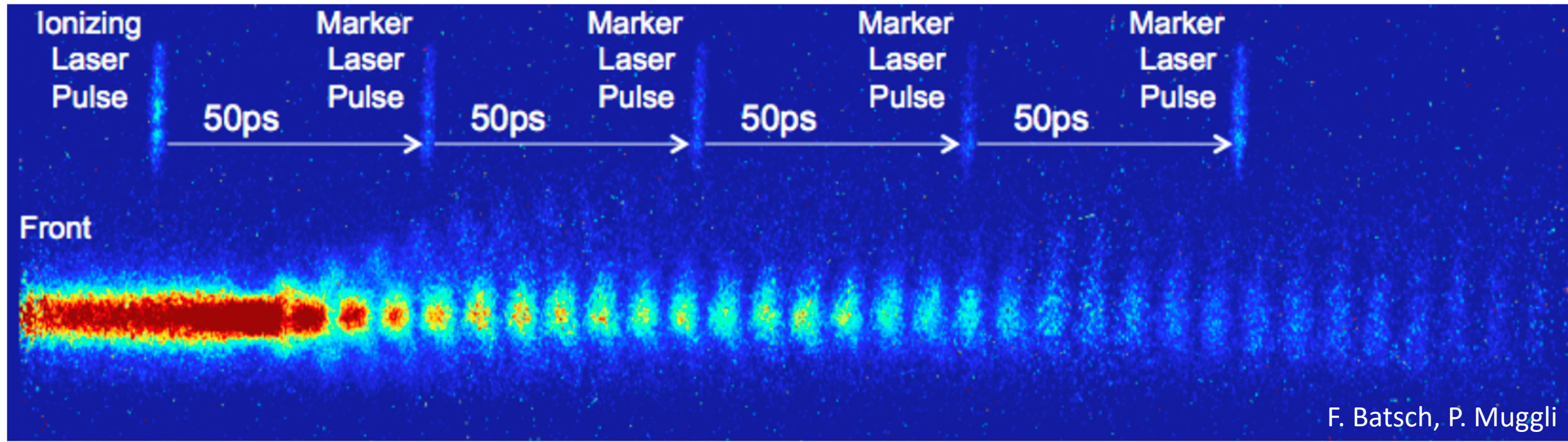
Demonstration of Seeded Self-Modulation



Demonstration of Seeded Self-Modulation



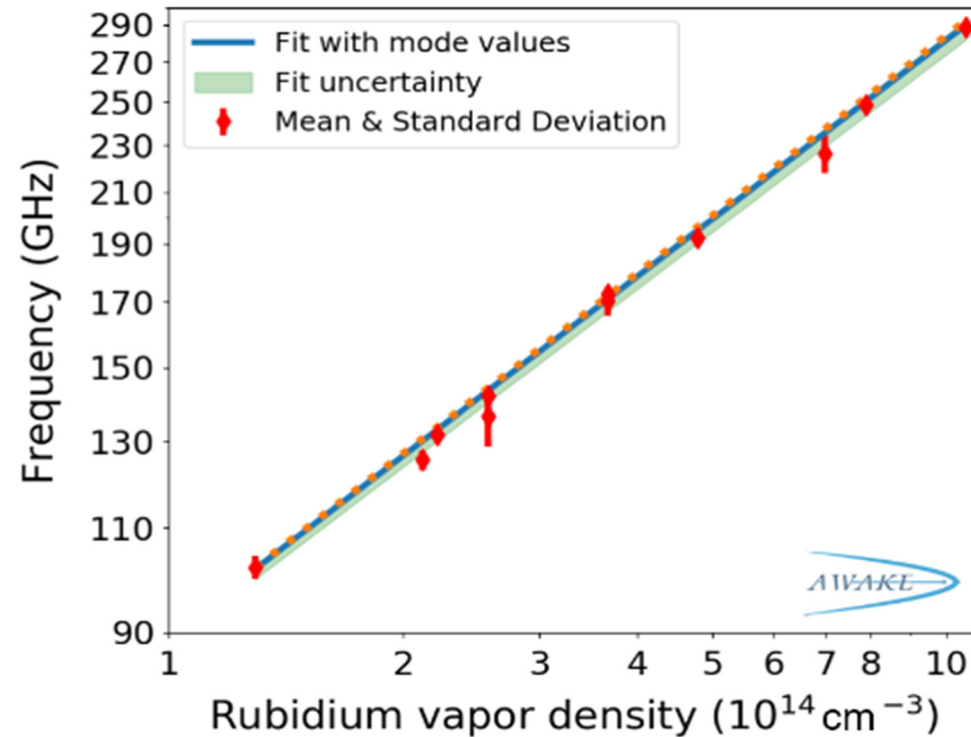
Demonstration of Seeded Self-Modulation



By “stacking” images together, we demonstrate that the proton bunch modulation is persistent and stable.

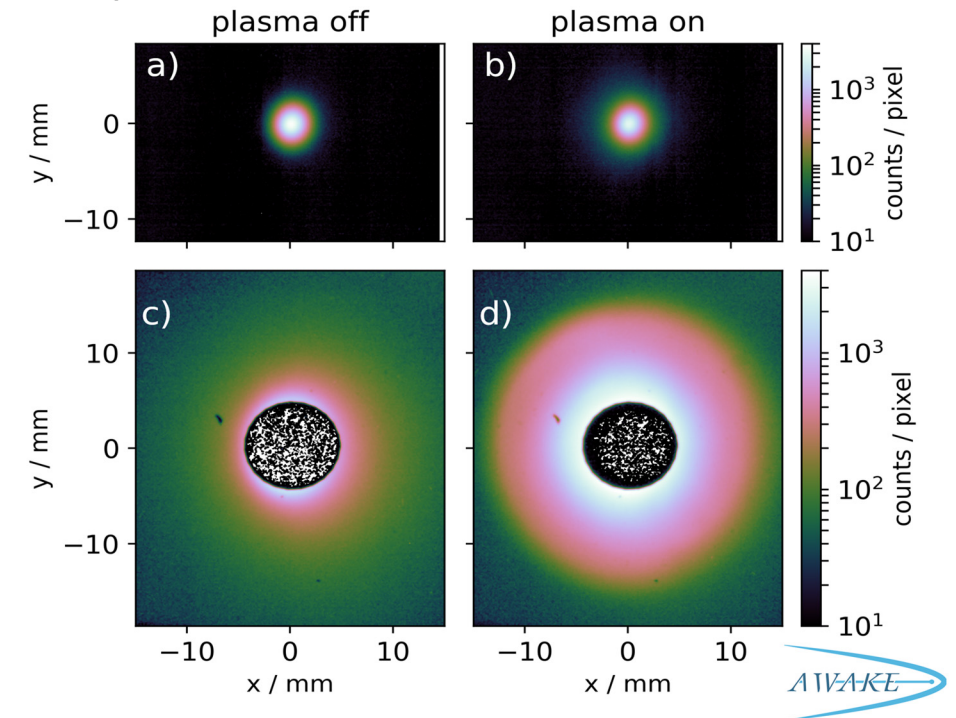
Seeded Self-Modulation Measurements

E. Adli, et. al. (AWAKE Collaboration) *PRL* **122**, 0548002 (2019)



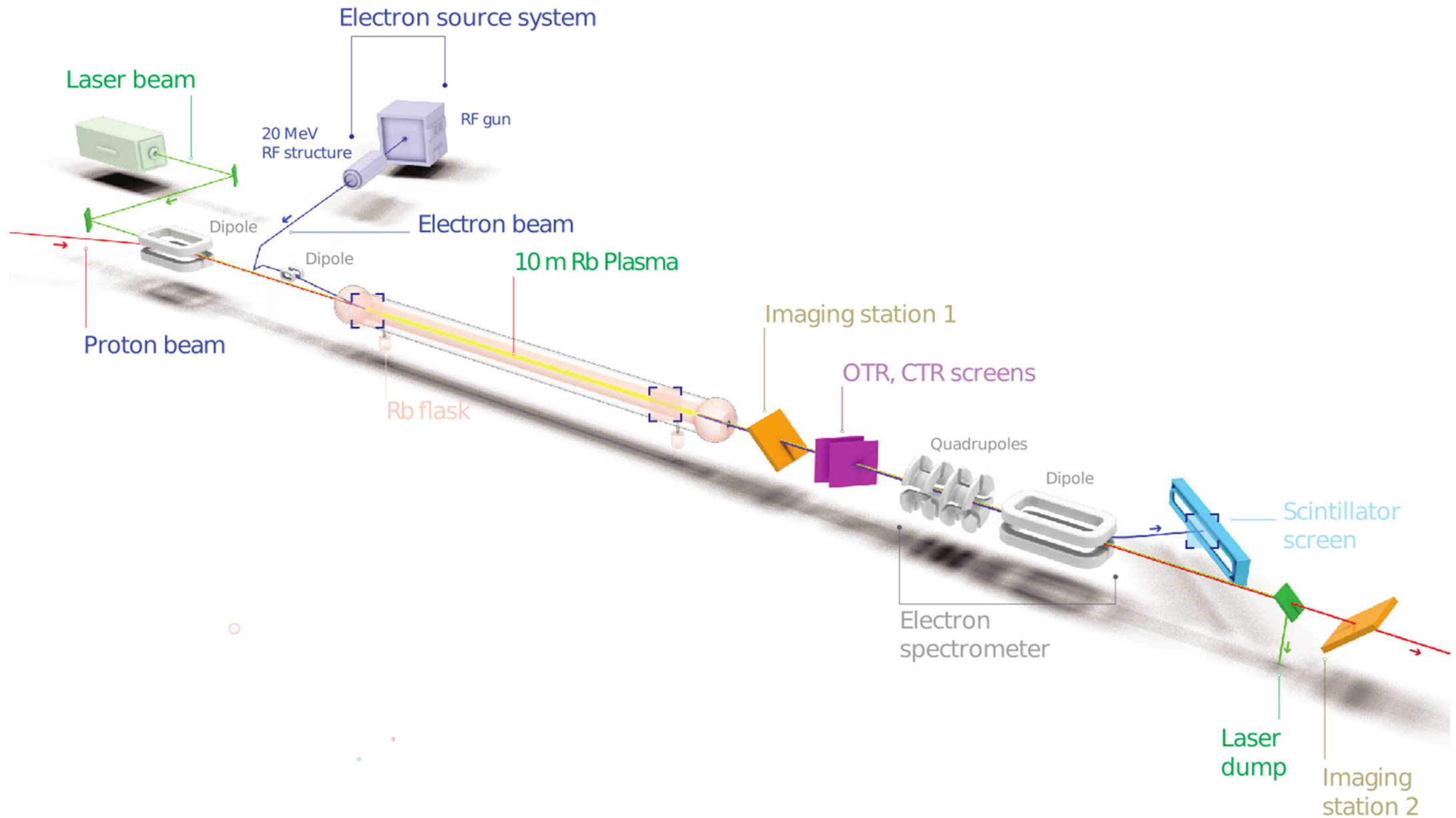
By measuring the frequency of modulation with the streak camera, we can verify that the proton bunch is modulated at the plasma frequency.

M. Turner, et. al. (AWAKE Collaboration) *PRL* **122**, 0548001 (2019)

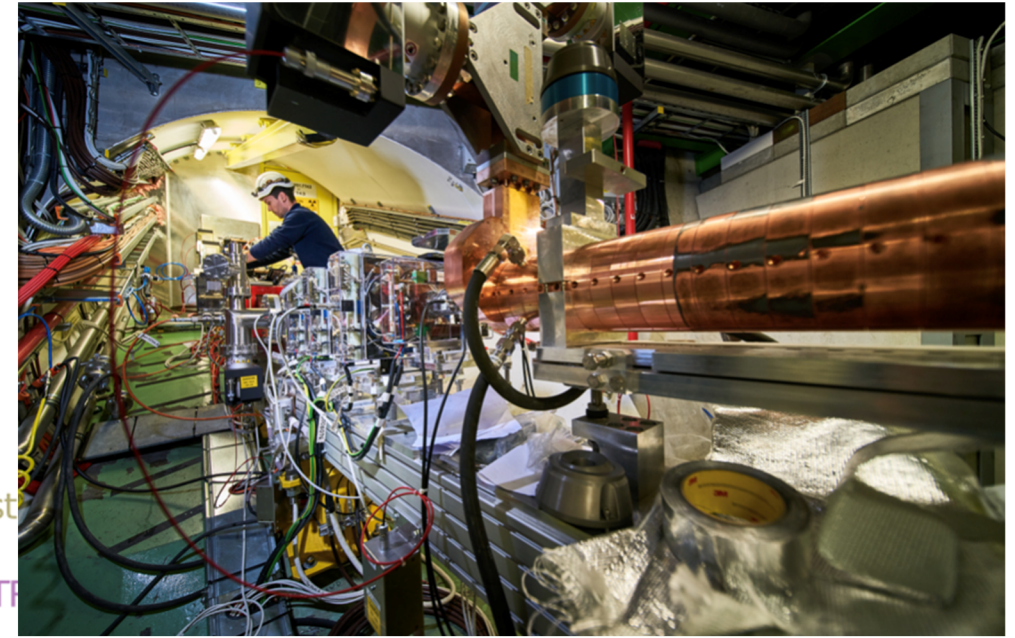
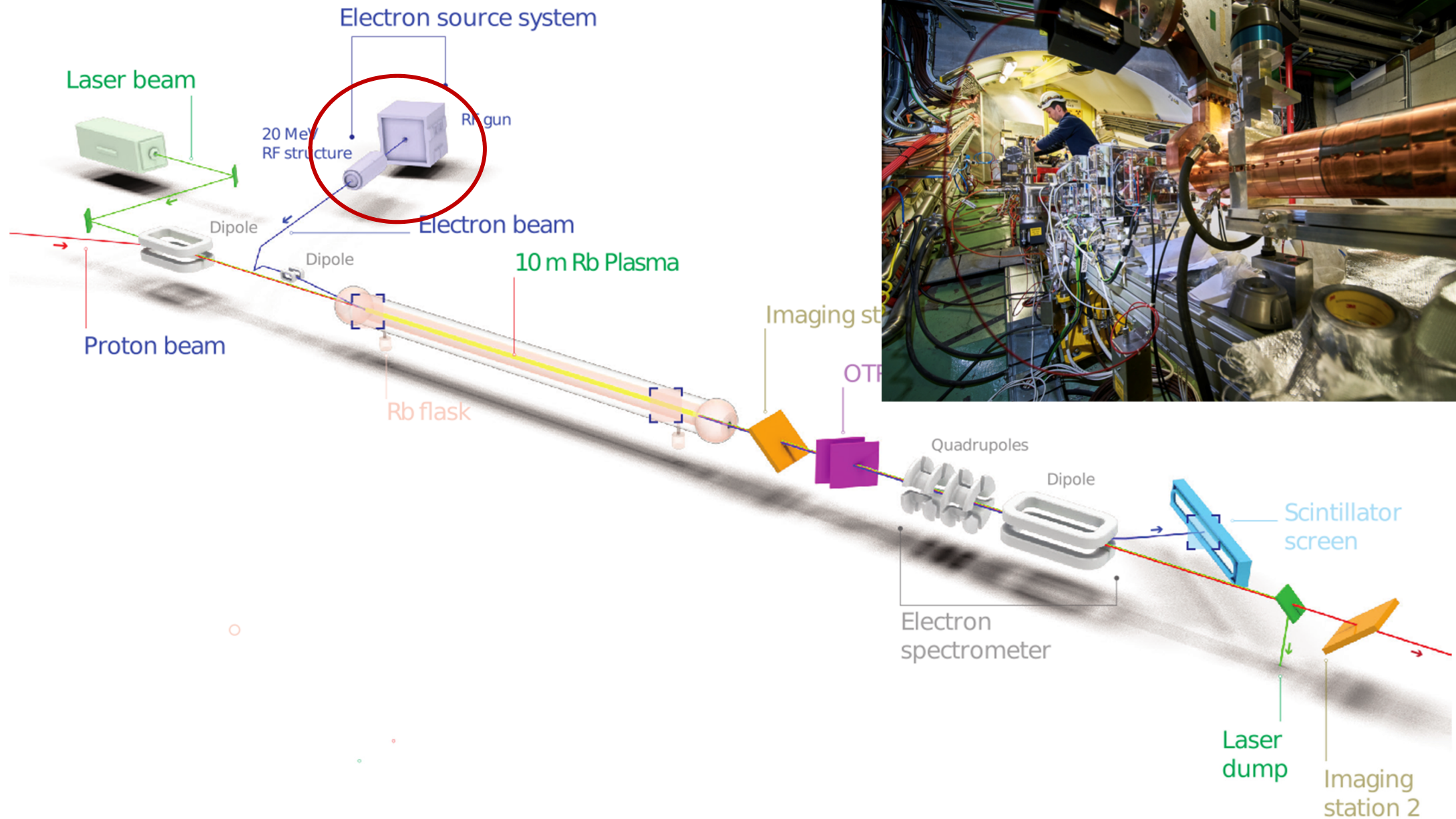


By measuring defocused protons that escape the plasma, we can infer the strength of the fields inside the wakefield.

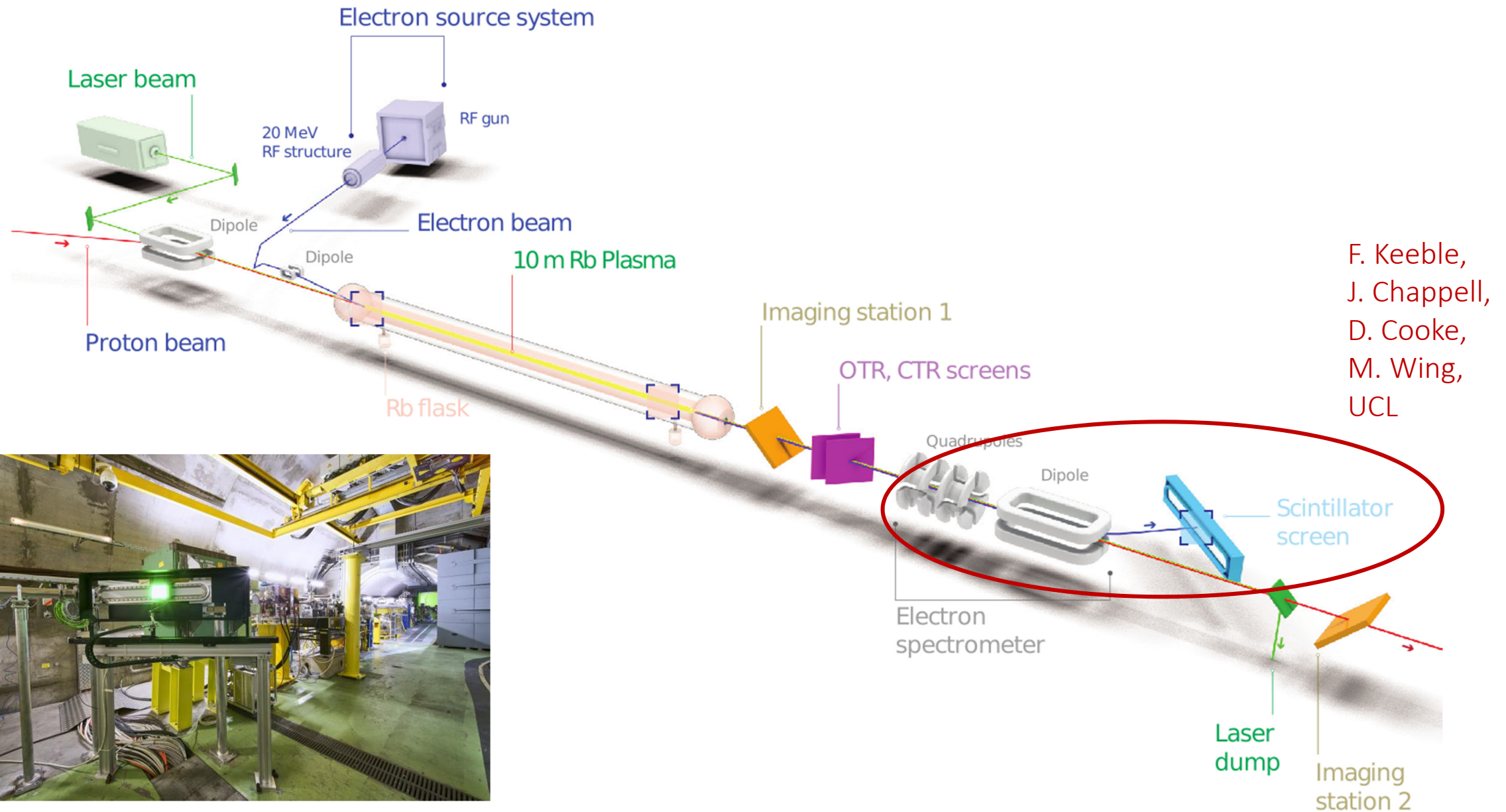
Experimental Schematic for Electron Acceleration



Experimental Schematic for Electron Acceleration

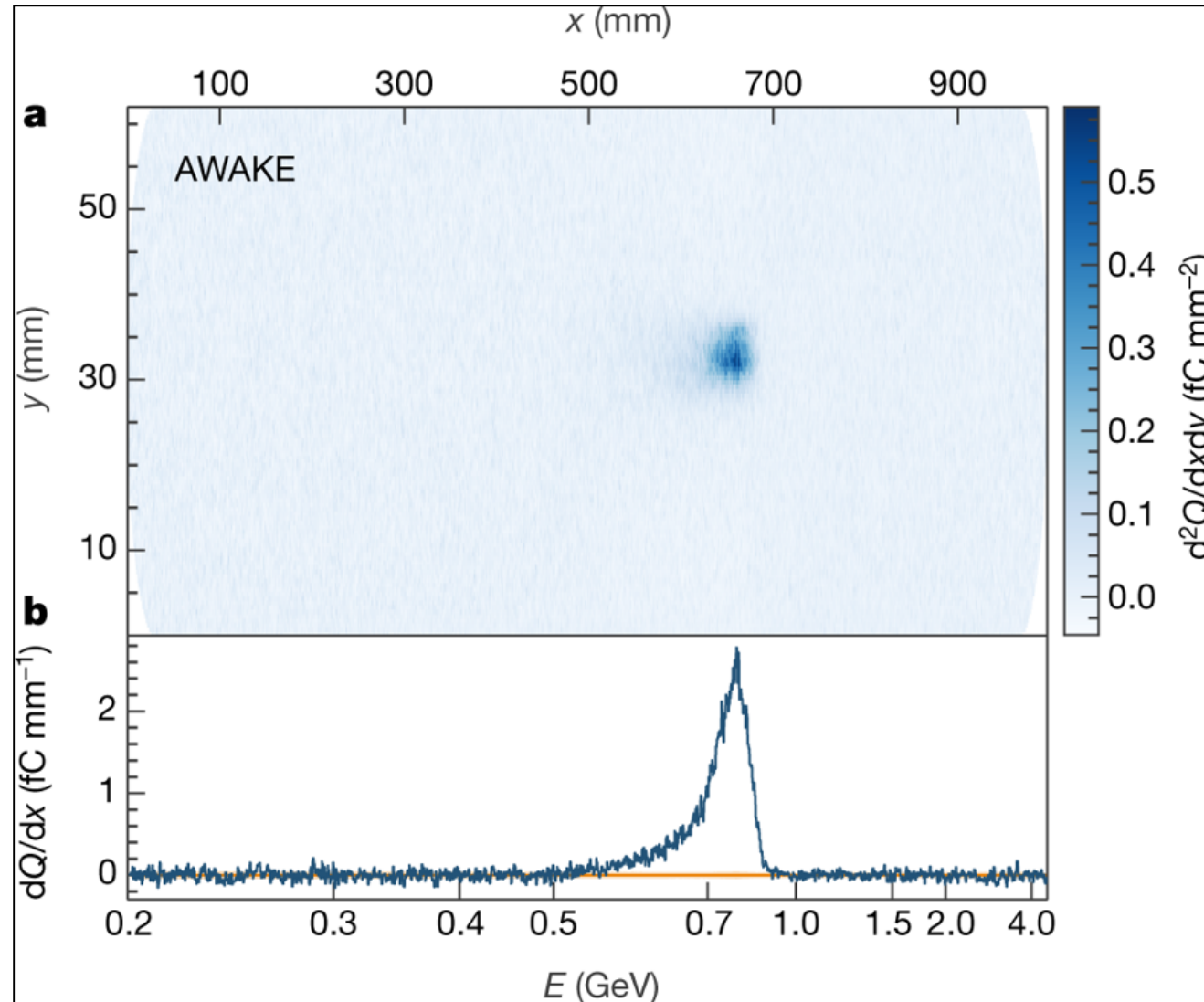


Experimental Schematic for Electron Acceleration



First Acceleration of Electrons at AWAKE!

E. Adli, et. al. (AWAKE Collaboration)
Nature **561**, 363 - 367 (2018)



First Acceleration of Electrons at AWAKE!

E. Adli, et. al. (AWAKE Collaboration)
Nature **561**, 363 - 367 (2018)

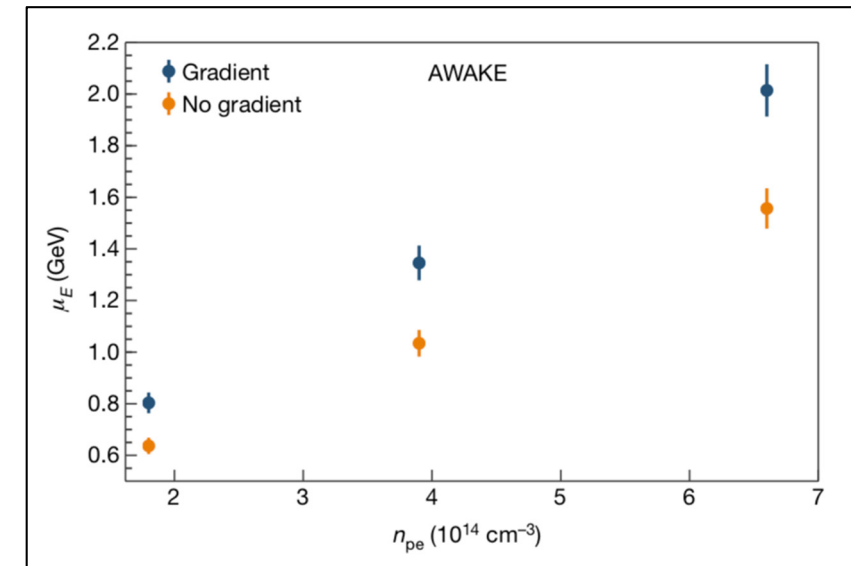
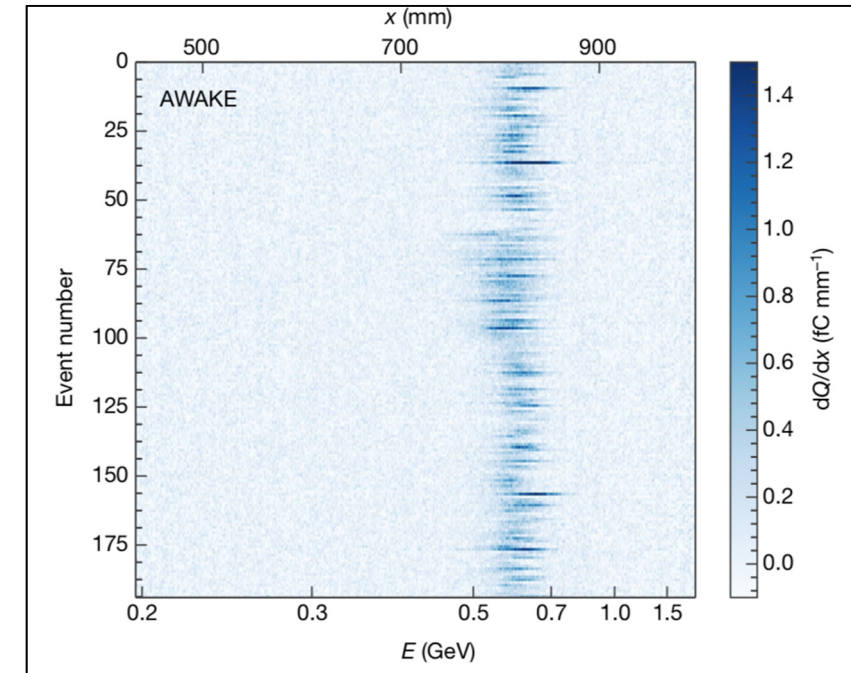
LETTER

OPEN

<https://doi.org/10.1038/s41586-018-0485-4>

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli¹, A. Ahuja², O. Apsimon^{3,4}, R. Apsimon^{4,5}, A.-M. Bachmann^{2,6,7}, D. Barrientos², F. Batsch^{2,6,7}, J. Bauche², V. K. Berglyd Olsen¹, M. Bernardini², T. Bohl², C. Bracco², F. Braunmüller⁶, G. Burt^{4,5}, B. Buttenschön⁸, A. Caldwell⁶, M. Cascella⁹, J. Chappell⁹, E. Chevallay², M. Chung¹⁰, D. Cooke⁹, H. Damerau², L. Deacon⁹, L. H. Deubner¹¹, A. Dexter^{4,5}, S. Doeber², J. Farmer¹², V. N. Fedosseev², R. Fiorito^{4,13}, R. A. Fonseca¹⁴, F. Friebe², L. Garolfi², S. Gessner², I. Gorgisyan², A. A. Gorn^{15,16}, E. Granados², O. Grulke^{8,17}, E. Gschwendtner², J. Hansen², A. Helm¹⁸, J. R. Henderson^{4,5}, M. Hüther⁶, M. Ibison^{4,13}, L. Jensen², S. Jolly⁹, F. Keeble⁹, S.-Y. Kim¹⁰, F. Kraus¹¹, Y. Li^{3,4}, S. Liu¹⁹, N. Lopes¹⁸, K. V. Lotov^{15,16}, L. Maricalva Brun², M. Martyanov⁶, S. Mazzoni², D. Medina Godoy², V. A. Minakov^{15,16}, J. Mitchell^{4,5}, J. C. Molendijk², J. T. Moody⁶, M. Moreira^{2,18}, P. Muggli^{2,6}, E. Öz⁶, C. Pasquino², A. Pardons², F. Peña Asmus^{6,7}, K. Pepitone², A. Perera^{4,13}, A. Petrenko^{2,15}, S. Pitman^{4,5}, A. Pukhov¹², S. Rey², K. Rieger⁶, H. Ruhl²⁰, J. S. Schmidt², I. A. Shalimova^{16,21}, P. Sherwood⁹, L. O. Silva¹⁸, L. Soby², A. P. Sosedkin^{15,16}, R. Speroni², R. I. Spitsyn^{15,16}, P. V. Tuev^{15,16}, M. Turner², F. Velotti², L. Verra^{2,22}, V. A. Verzilov¹⁹, J. Vieira¹⁸, C. P. Welsch^{4,13}, B. Williamson^{3,4}, M. Wing^{9*}, B. Woolley² & G. Xia^{3,4}



We observe electron acceleration up to 2 GeV.

First Acceleration of Electrons at AWAKE!

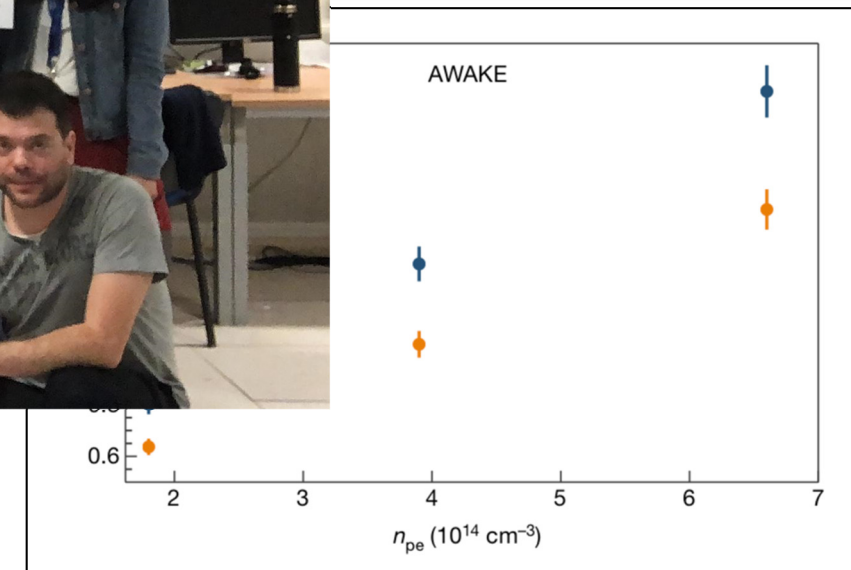
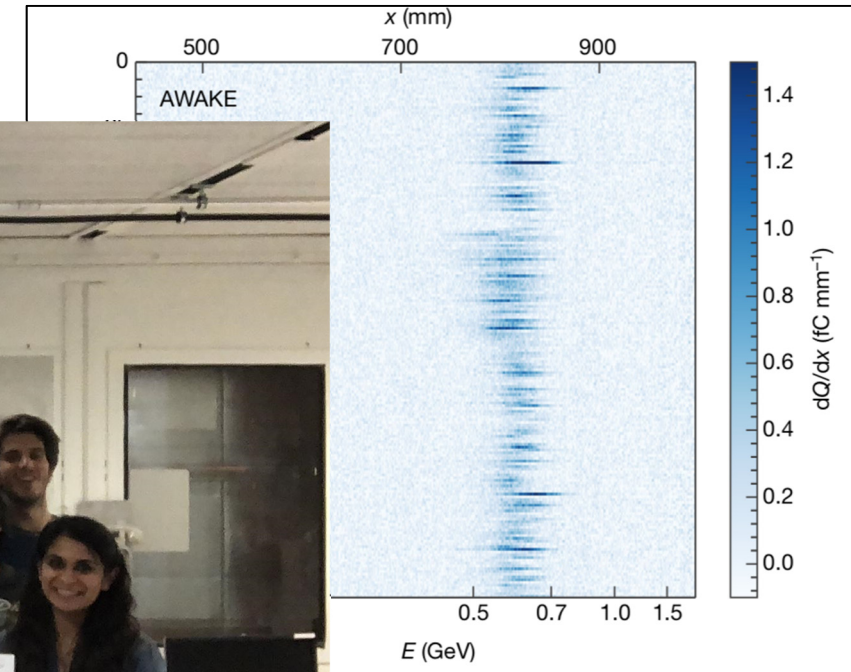
E. Adli, et. al. (AWAKE Collaboration)
Nature **561**, 363 - 367 (2018)

LETTER

Acceleration of electrons by a proton bunch

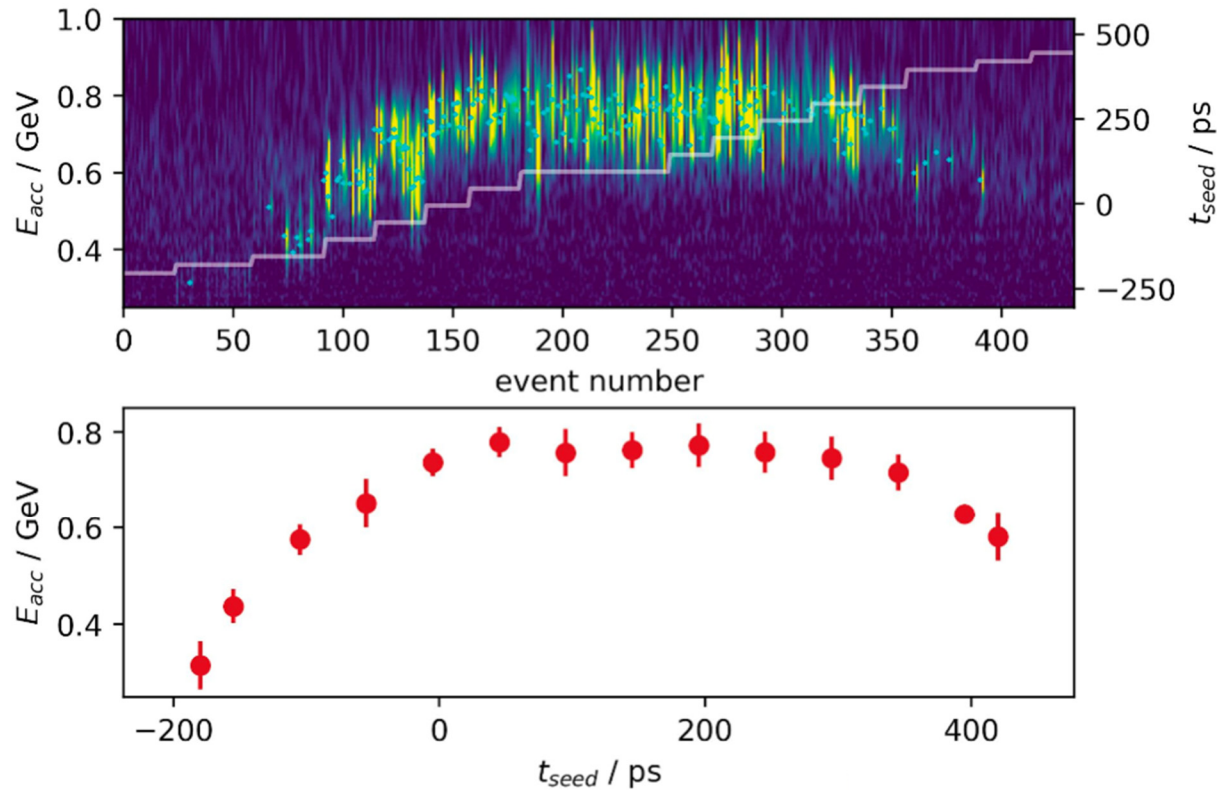
E. Adli¹, A. Ahuja², O. Apsimon^{3,4}, R. A. V. K. Berglyd Olsen¹, M. Bernardini², T. J. Chappell⁹, E. Chevallay², M. Chung¹⁰, J. Farmer¹², V. N. Fedosseev², R. Fiorito⁴, E. Granados², O. Grulke^{8,17}, E. Gschwend², S. Jolly⁹, F. Keeble⁹, S.-Y. Kim¹⁰, F. Krauss², S. Mazzoni², D. Medina Godoy², V. A. M. E. Öz⁶, C. Pasquino², A. Pardons², F. Perin², K. Rieger⁶, H. Ruhl²⁰, J. S. Schmidt², I. A. R. I. Spitsyn^{15,16}, P. V. Tuev^{15,16}, M. Turner², M. Wing^{9*}, B. Woolley² & G. Xia^{3,4}

We observe e

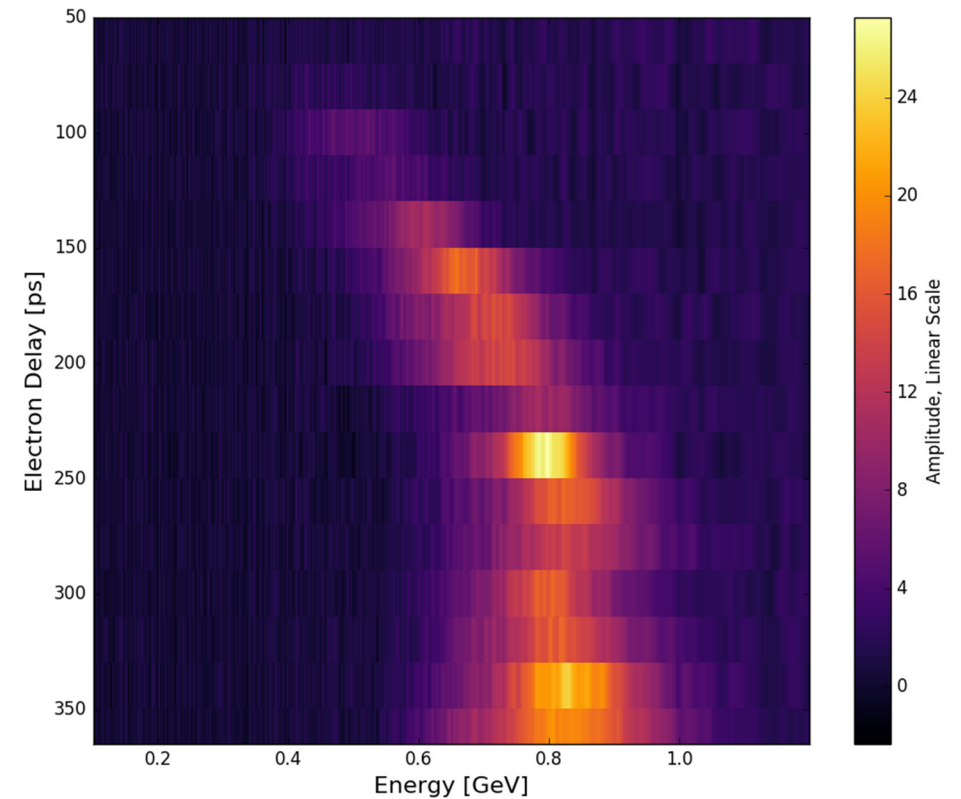


Electron Acceleration Results (PRELIMINARY!)

M. Turner, CERN



S. Gessner, CERN, J. Chappell, UCL, J. Moody, MPP



We study the longitudinal wakefield by varying the position of the seed pulse within the proton bunch, and the delay of the electron injection with respect to the seed pulse. **Analysis ongoing!**

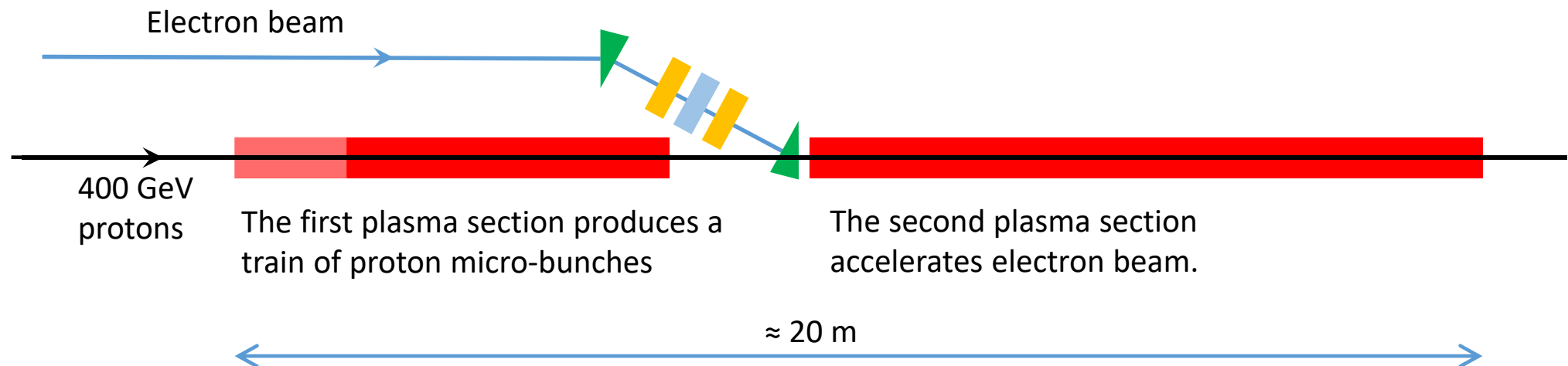
The background features a complex, abstract composition. On the left, there are several overlapping, wavy shapes in various shades of blue. A large, semi-transparent white rectangular box with rounded corners is positioned in the center, containing the text "The Next Steps". To the right of this box, a large, light blue sphere is visible. The entire scene is populated with numerous small, semi-transparent red spheres that are scattered across the image, with a higher concentration on the right side, appearing to trail off from the large sphere. The overall effect is one of dynamic movement and layered depth.

The Next Steps

Plans for AWAKE Run-II

AWAKE wants to demonstrate increased charge capture and emittance preservation in future experiments.

To do this, we will split the experiment in two: a modulation stage and an acceleration stage.



Plans for AWAKE Run-II

One concept for emittance preservation at AWAKE involves the dense electron witness bunch driving its own bubble wakefield.

In this technique, the electron beam is accelerated by the proton-driven wake, loads the wake, and experience a linear focusing force due to the ion bubble.

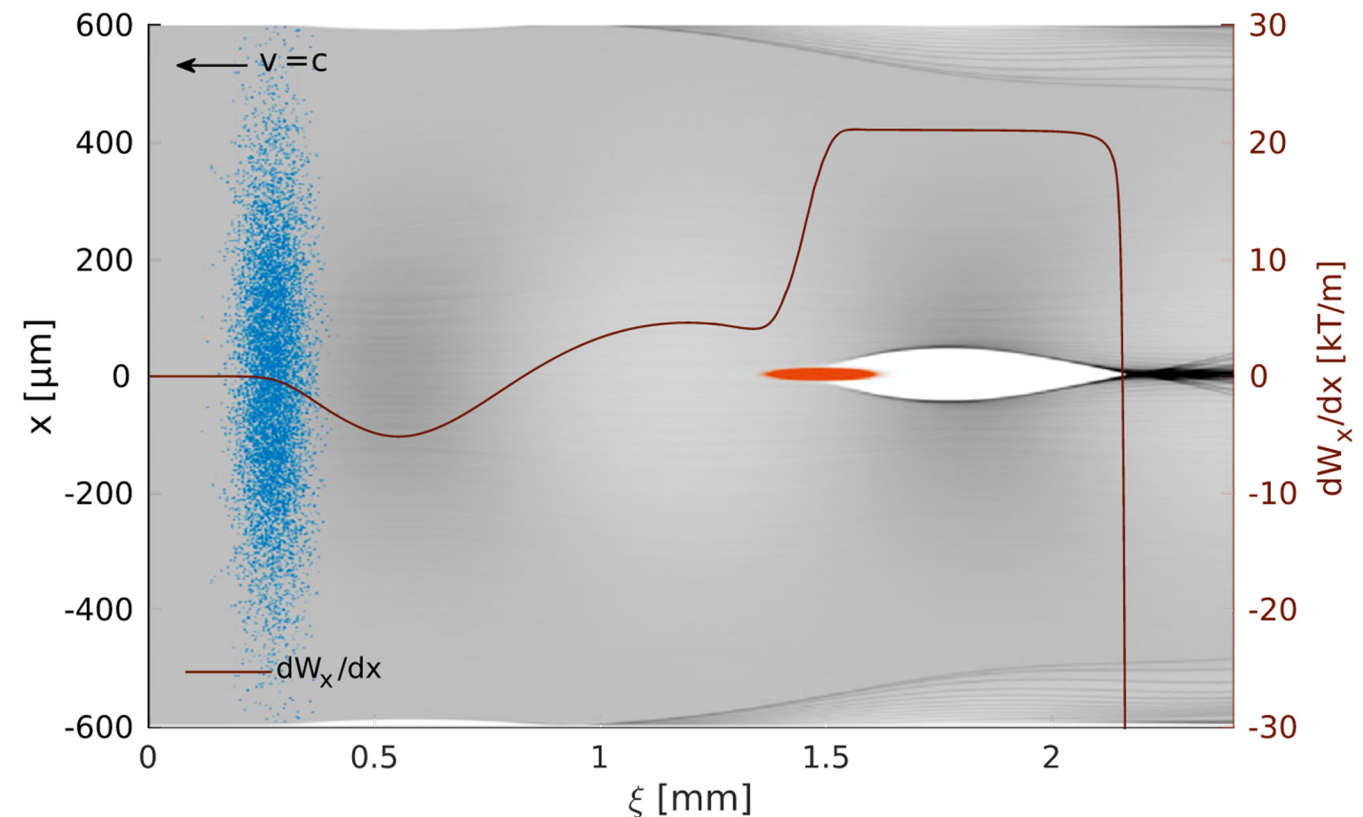
PHYSICAL REVIEW ACCELERATORS AND BEAMS

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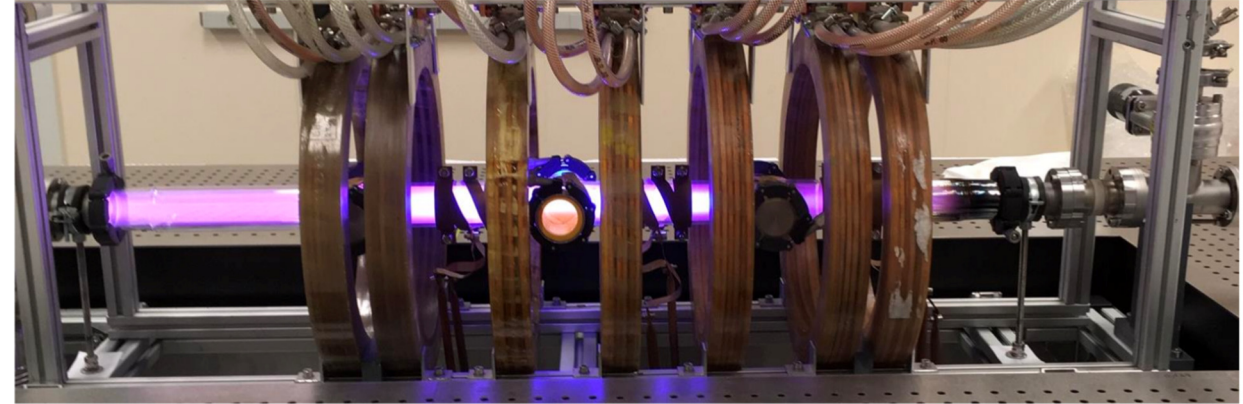
Emittance preservation of an electron beam in a loaded quasilinear plasma wakefield

Veronica K. Berglyd Olsen, Erik Adli, and Patric Muggli
Phys. Rev. Accel. Beams **21**, 011301 – Published 16 January 2018

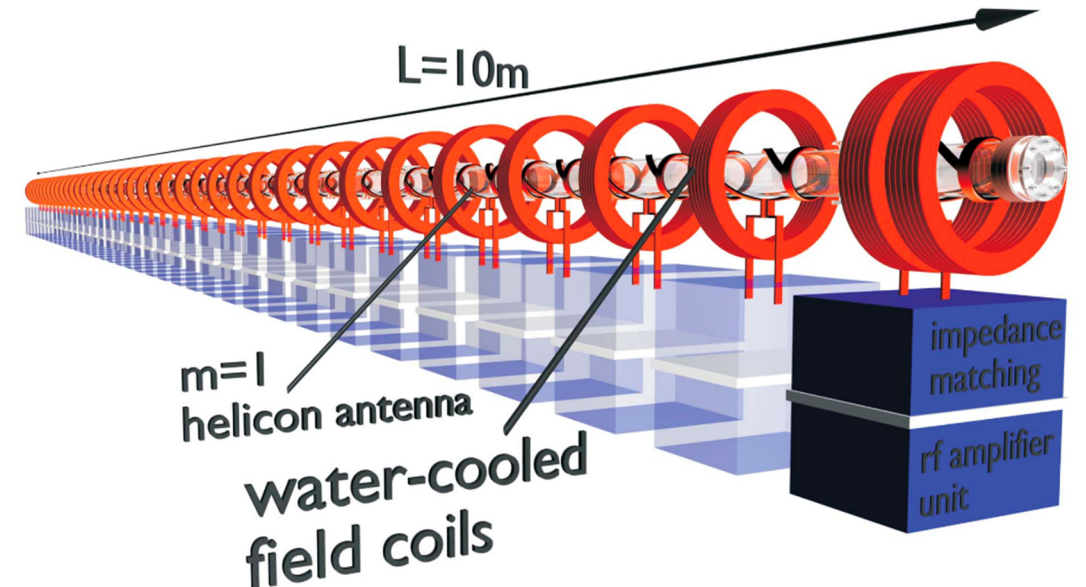


Beyond Run-II

Our long term goals include extracting a *significant fraction* of the energy from the proton beam. To do this we will need long (~ 100 meter) plasma stages. We are investigating helicon plasma sources as a possible solution.



Helicon plasma cell at CERN. Courtesy A. Sublet, CERN.



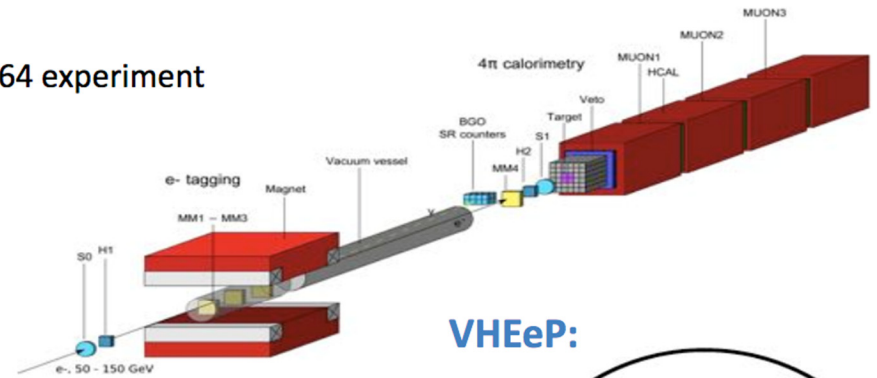
AWAKE TDR. CERN-SPSC-2013-013.

HEP Experiments

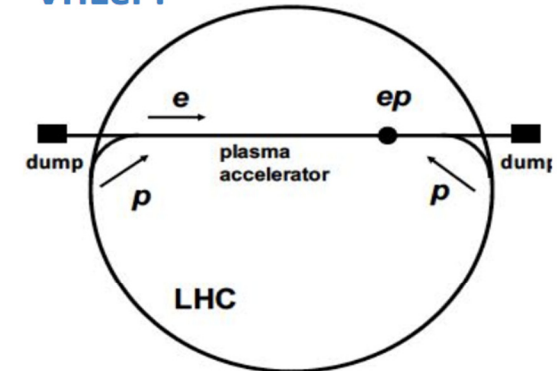
AWAKE is looking for *near-term* applications for electrons accelerated by protons in plasma. We are currently focusing on:

- Beam dump experiments
- Electron-proton collisions

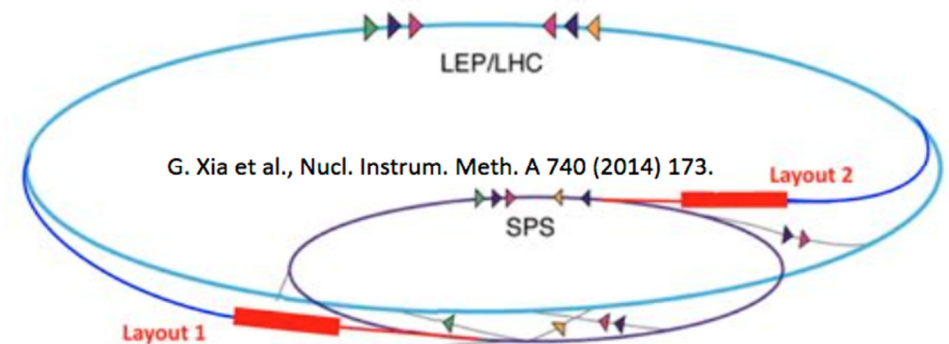
NA64 experiment



VHEeP:



VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463



G. Xia et al., Nucl. Instrum. Meth. A 740 (2014) 173.

Create ~50 GeV electron beam within 50–100 m of plasma driven by SPS protons, But luminosity $< 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

Conclusion

AWAKE Run-I was a success!

- Demonstration of Seeded Self-Modulation.
- Acceleration of an electron beam to 2 GeV.
- Many more studies I didn't have time to cover.

AWAKE Run-II is coming soon:

- Focus on emittance preservation of injected beam.

There is a lot more energy left in the proton beam:

- Future versions of AWAKE will aim for ultra-high energy by extending the plasma cell.

AWAKE Collaboration

AWAKE Collaboration: 21+2 Institutes world-wide:

Collaboration members:

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



Associated members:

University of Texas
Helmholtz Institut Jena

Thank You!

AWAKE Collaboration Meeting, Novosibirsk, 2017

