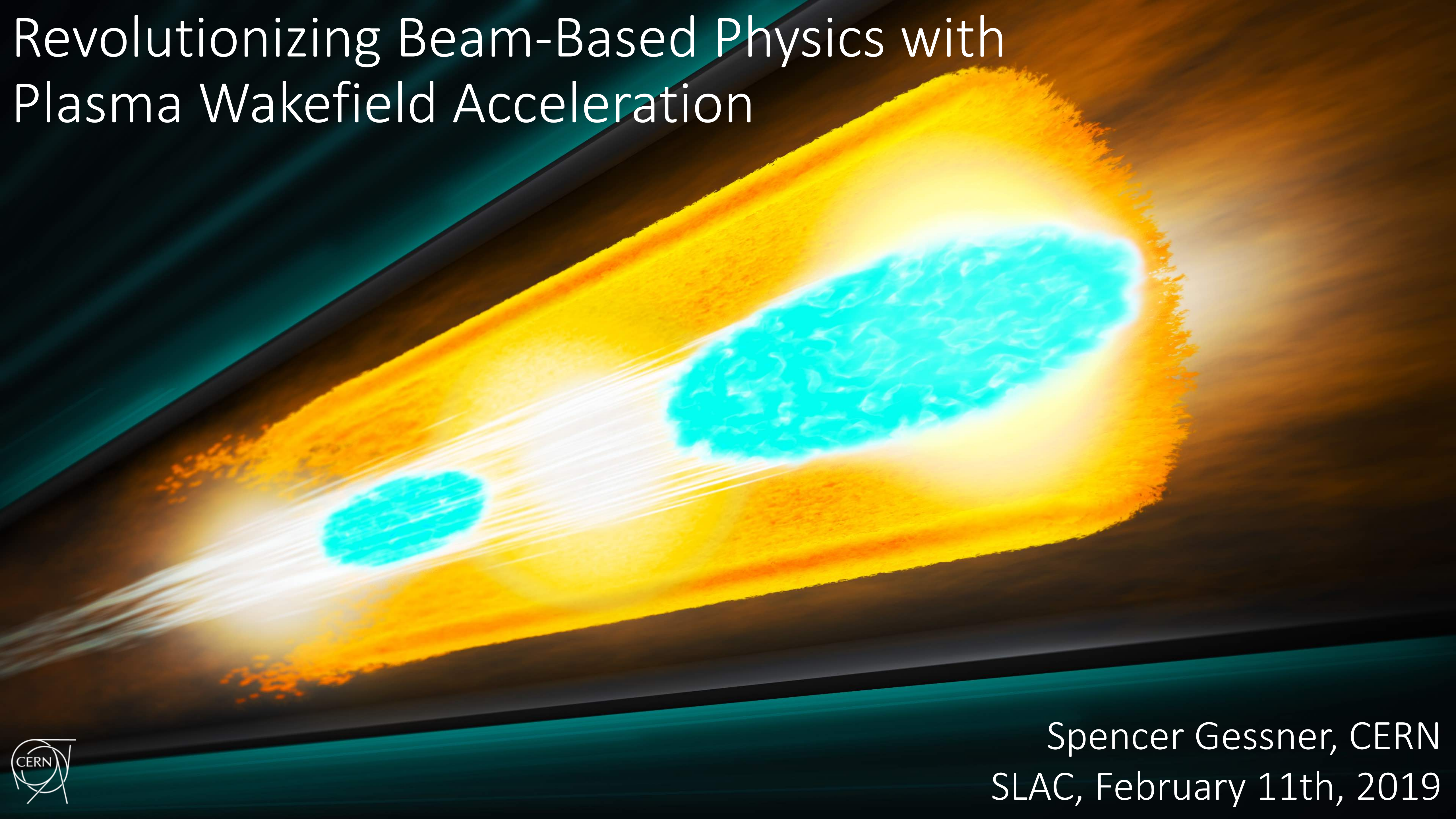
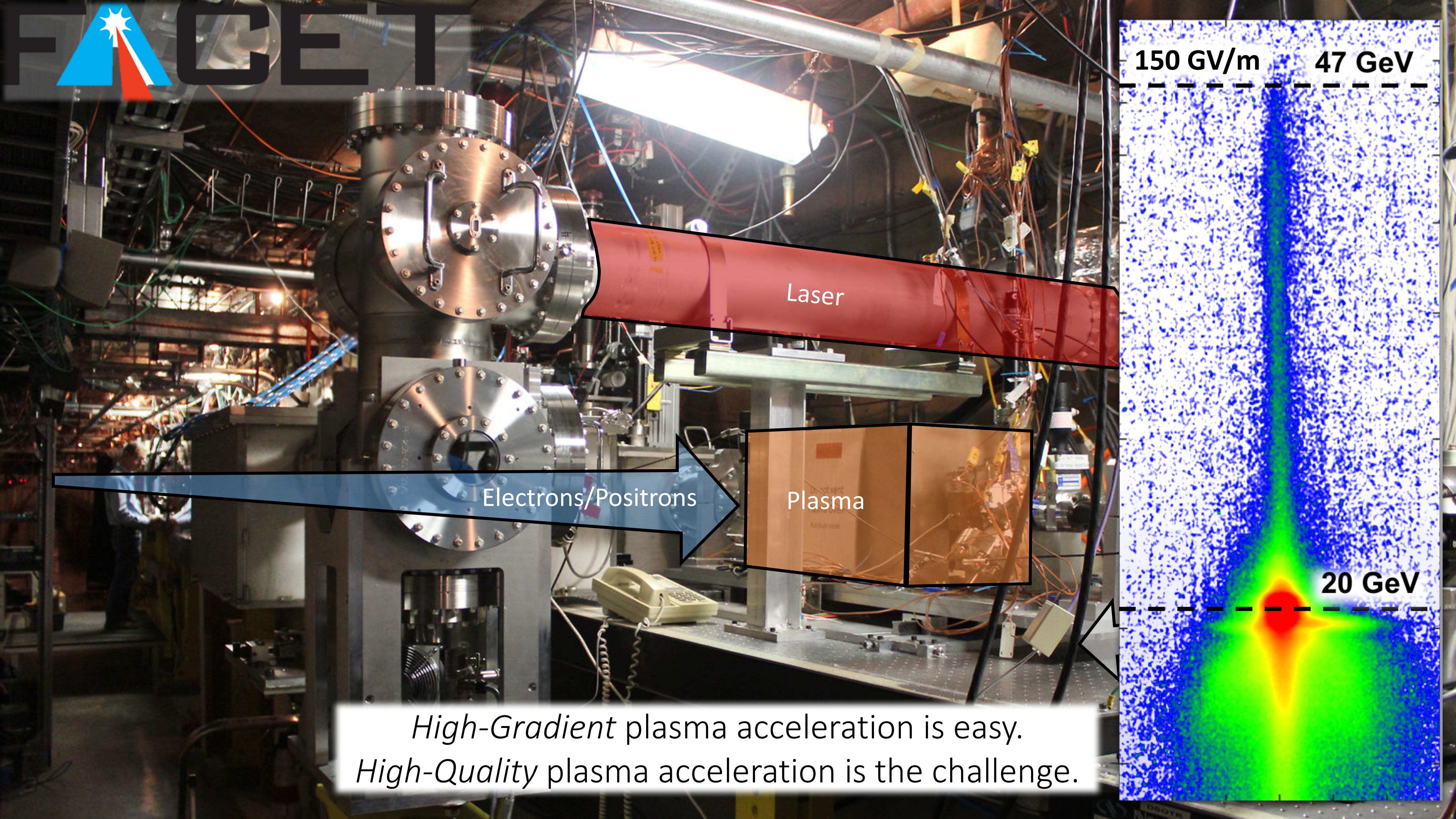
Revolutionizing Beam-Based Physics with Plasma Wakefield Acceleration



Spencer Gessner, CERN

SLAC, February 11th, 2019

CERN



High-Gradient plasma acceleration is easy.
High-Quality plasma acceleration is the challenge.

Outline

1. Efficient, high-quality acceleration of electrons in plasma.

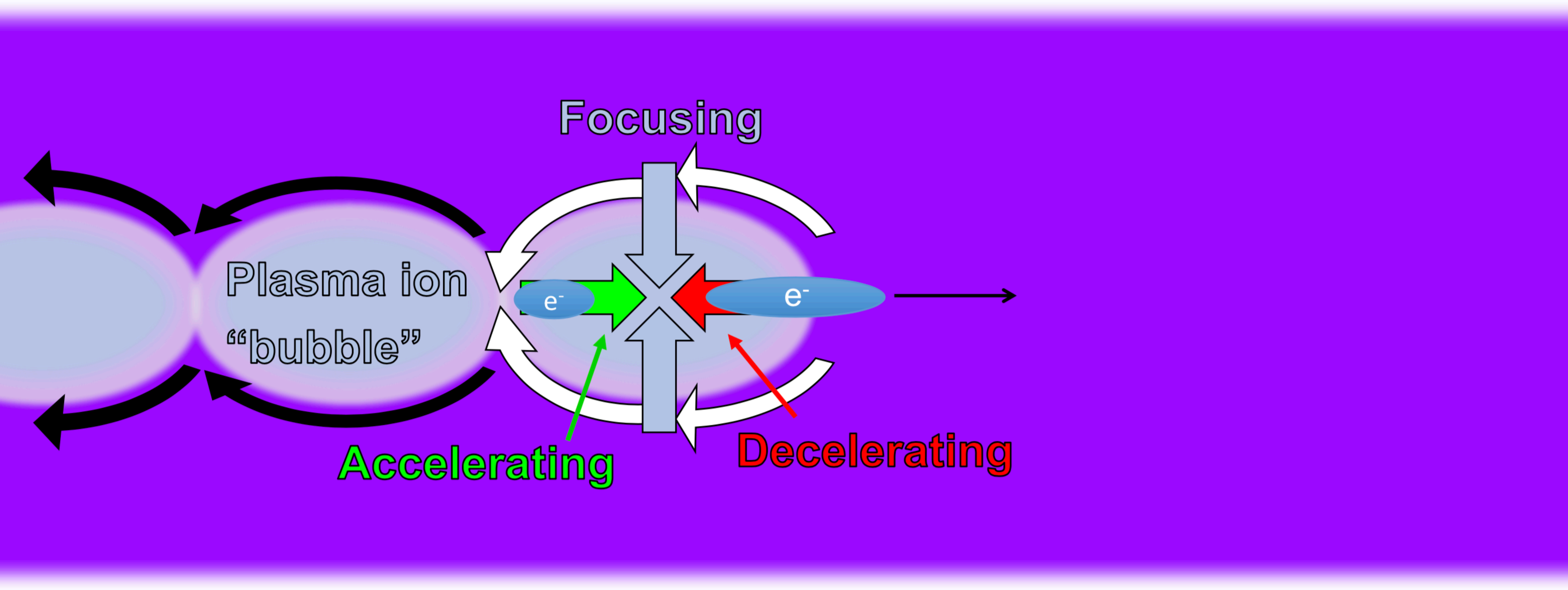
2. The unsolved problem of positron acceleration in plasma.

3. Proton beam-driven acceleration results from AWAKE.

4. Applications for light-sources and high energy physics.

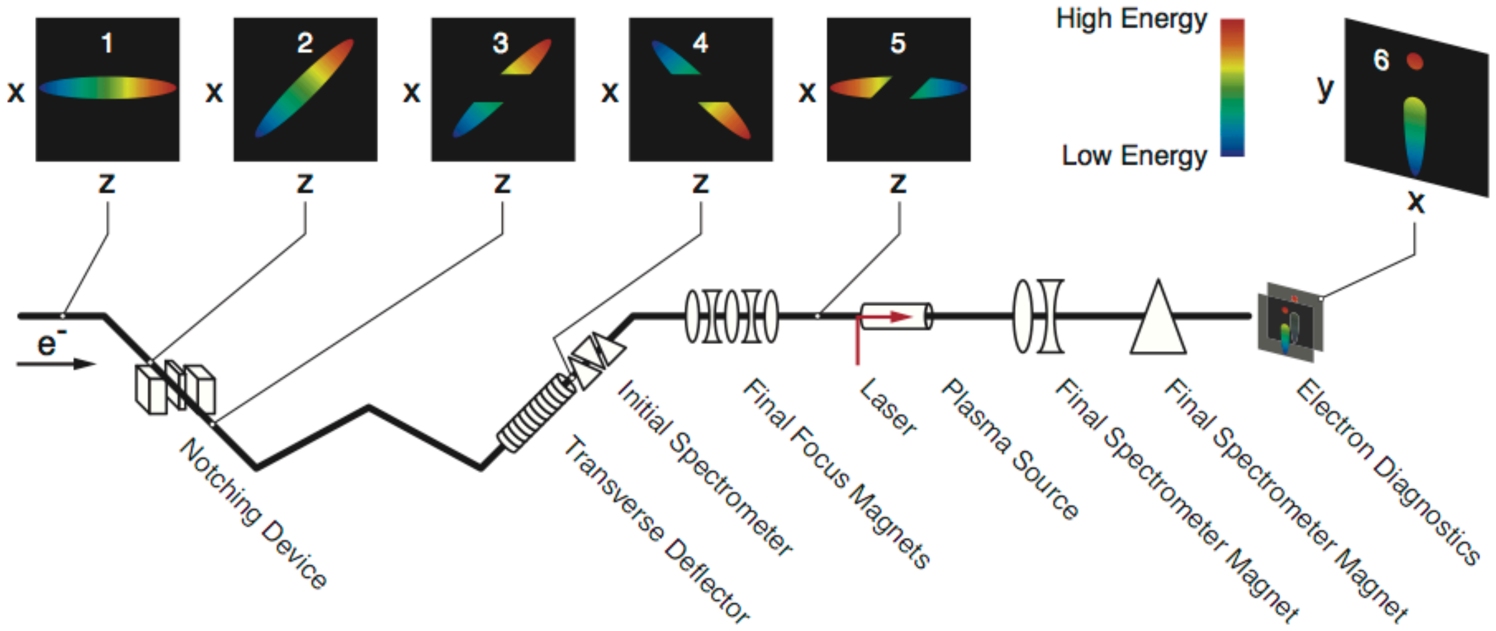
Efficient, High-Quality Acceleration

Beam-Driven Plasma Acceleration



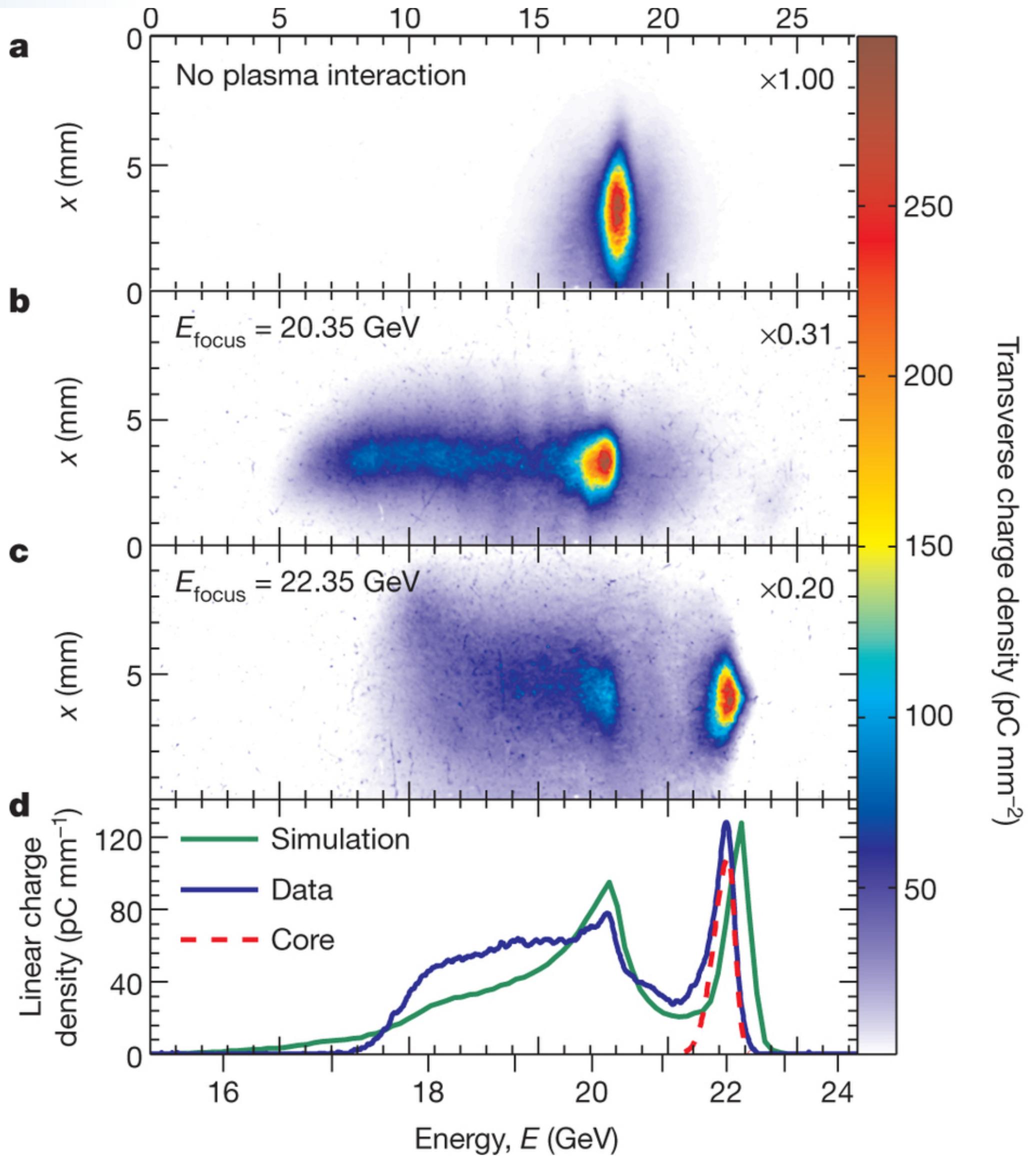
The field is accelerating in the back half of the bubble. Beam electrons can extract energy from the plasma wake in this region.

Two-Bunch Experiments at FACET



Two-Bunch Experiments at FACET

- First demonstration of a high-efficiency, low energy-spread plasma wakefield acceleration:
  - 70 pC of charge accelerated
  - 2 GeV energy gain
  - 5 GeV/m gradient
  - **Up to 30% transfer efficiency**
  - ~2% energy spread



M. Litos et. al. *Nature* **515**, 92-95 (2014)

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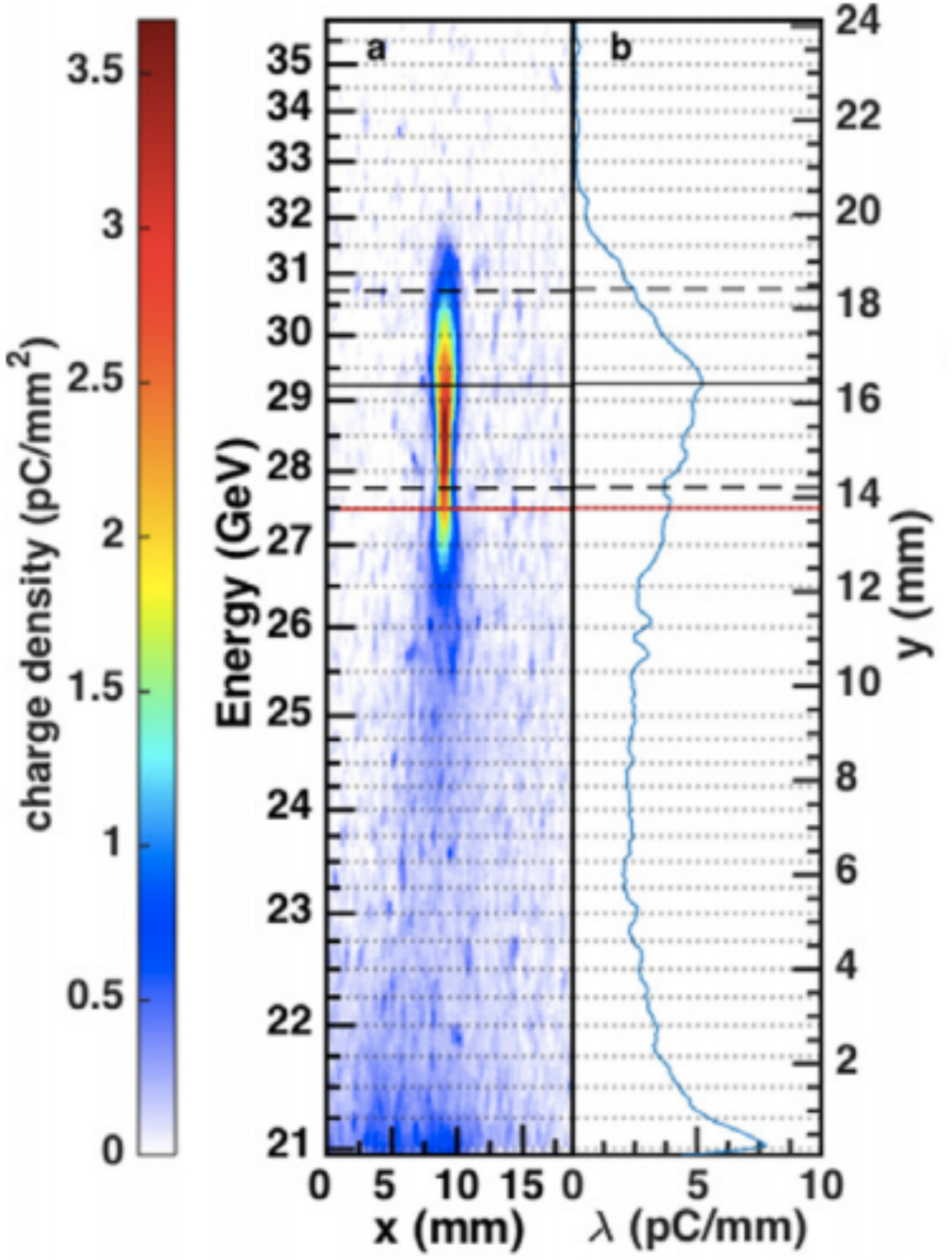
- A high-impact result!

- Later, we extended the plasma oven from 0.3 to 1.3 meters long. The accelerated beam had a spectral peak at 9 GeV energy gain.

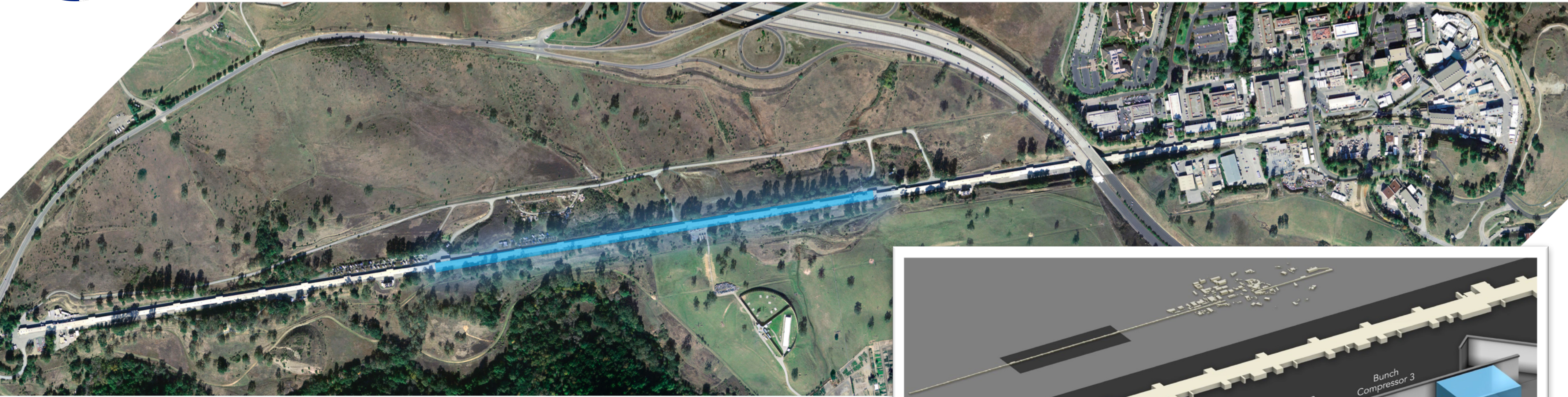


M. Litos et. al. *PPCF* **58**, 034017 (2016)

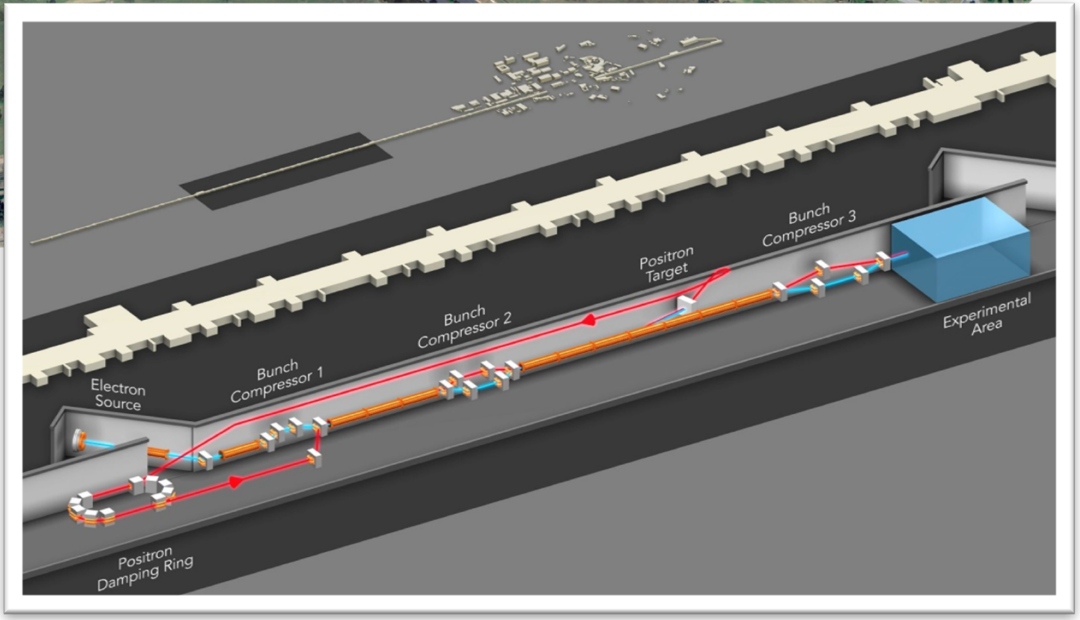
The Next Step: High-Quality Beams

FACET·II

Facility for Advanced Accelerator Experimental Tests



Operations begin in 2019!



How do we define beam quality?

Emittance ε: The volume of phase space occupied by beam particles.

FEL Brightness:

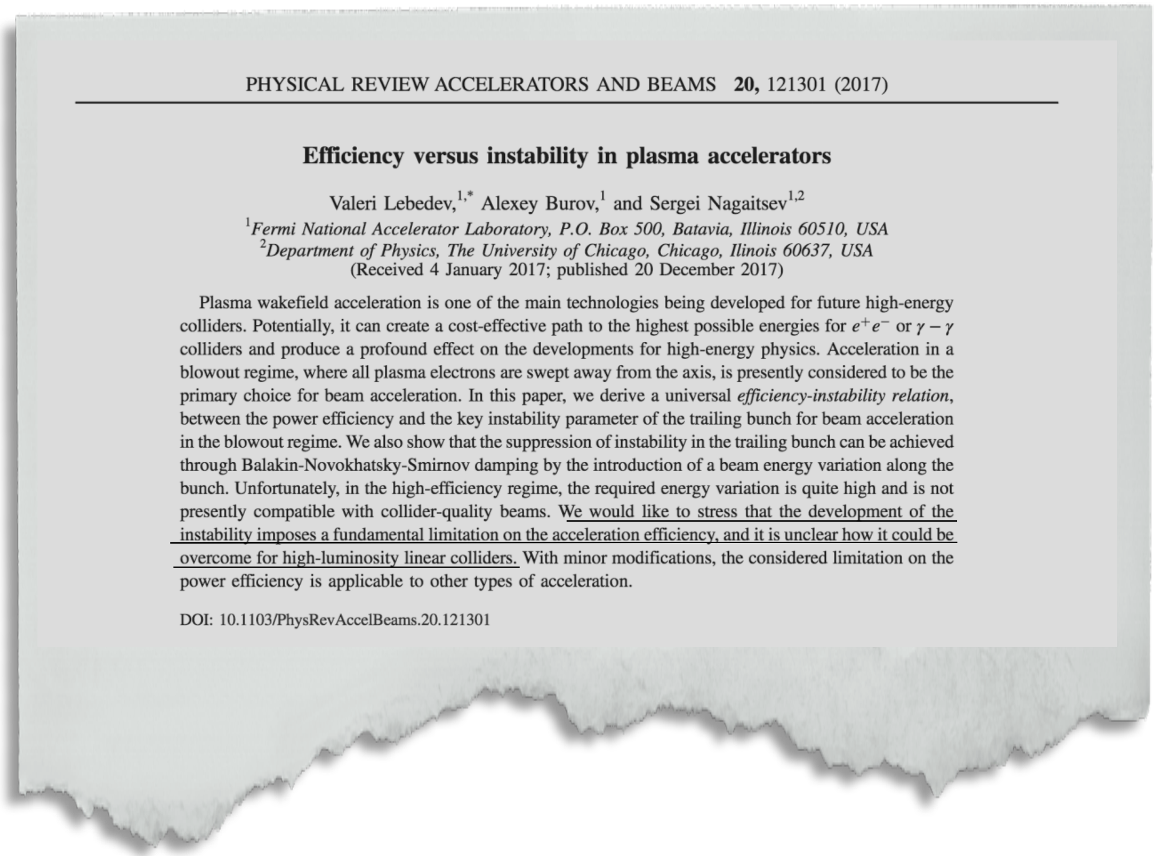
$$B \propto \frac{1}{\varepsilon_x \varepsilon_y \varepsilon_z}$$

Collider Luminosity:

$$\mathcal{L} \propto \frac{1}{\sqrt{\varepsilon_x \varepsilon_y}}$$

	Machine	ε_y [m·rad]
FELs	LCLS	$0.3\text{-}1.6 \times 10^{-6}$
	XFEL	1.4×10^{-6}
	LCLS-II	0.6×10^{-6}
LCs	ILC	35×10^{-9}
	CLIC	20×10^{-9}
AAs	PWFA (ext. inj.)	$> 100 \times 10^{-6}$
	PWFA/LFWA (int. inj.)	0.5×10^{-6} (slice emittance)

Challenges in Producing High Quality Beams


PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 121301 (2017)

Efficiency versus instability in plasma accelerators

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(Received 4 January 2017; published 20 December 2017)

Plasma wakefield acceleration is one of the main technologies being developed for future high-energy colliders. Potentially, it can create a cost-effective path to the highest possible energies for e^+e^- or $\gamma-\gamma$ colliders and produce a profound effect on the developments for high-energy physics. Acceleration in a blowout regime, where all plasma electrons are swept away from the axis, is presently considered to be the primary choice for beam acceleration. In this paper, we derive a universal *efficiency-instability relation*, between the power efficiency and the key instability parameter of the trailing bunch for beam acceleration in the blowout regime. We also show that the suppression of instability in the trailing bunch can be achieved through Balakin-Novokhatsky-Smirnov damping by the introduction of a beam energy variation along the bunch. Unfortunately, in the high-efficiency regime, the required energy variation is quite high and is not presently compatible with collider-quality beams. We would like to stress that the development of the instability imposes a fundamental limitation on the acceleration efficiency, and it is unclear how it could be overcome for high-luminosity linear colliders. With minor modifications, the considered limitation on the power efficiency is applicable to other types of acceleration.

DOI: 10.1103/PhysRevAccelBeams.20.121301

We would like to stress that the development of the instability imposes a fundamental limitation on the acceleration efficiency, and it is unclear how it could be overcome for high-luminosity linear colliders.

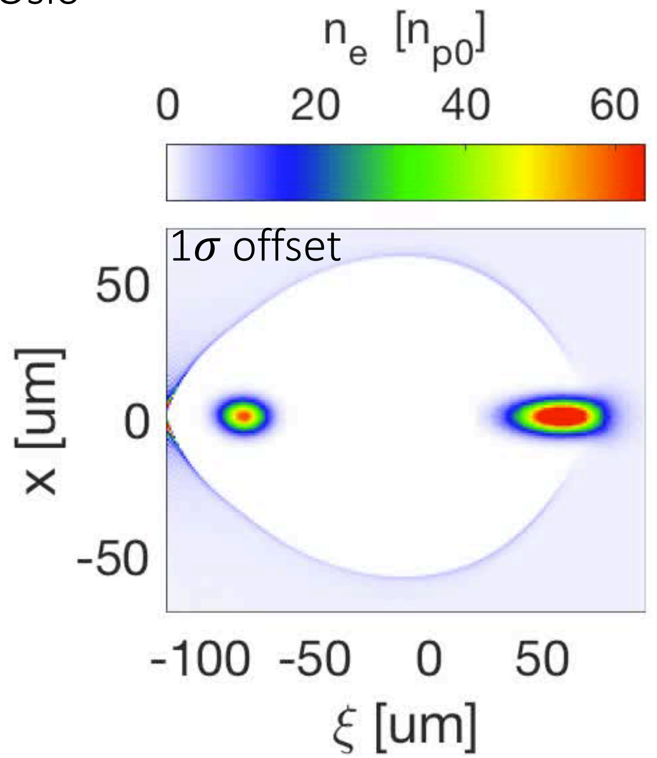
Wake-to-beam power coupling efficiency

Instability growth rate

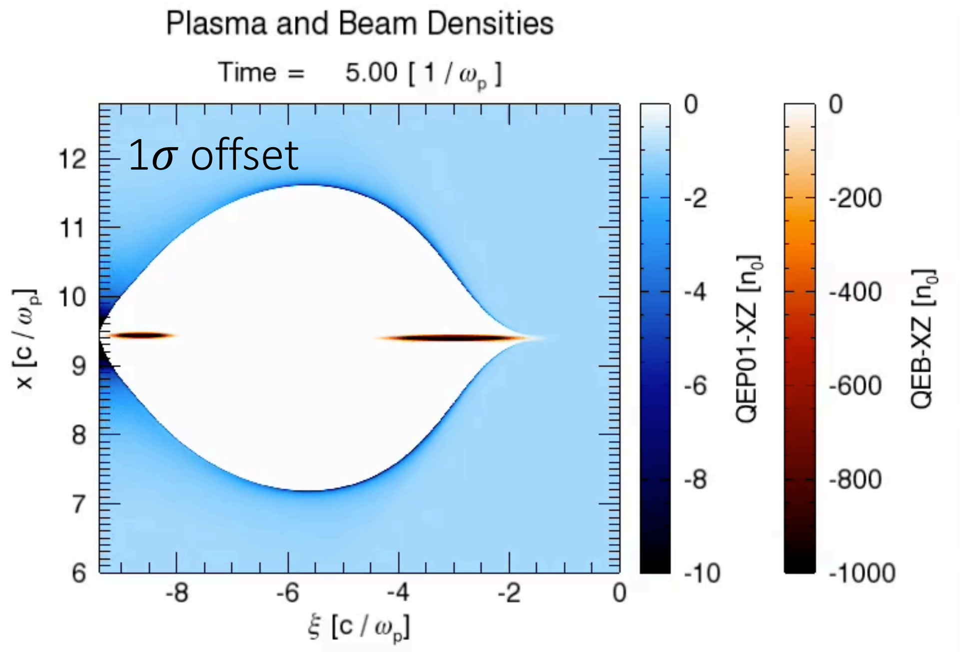
$$\eta_t \approx \frac{\eta_p^2}{4(1-\eta_p)}$$

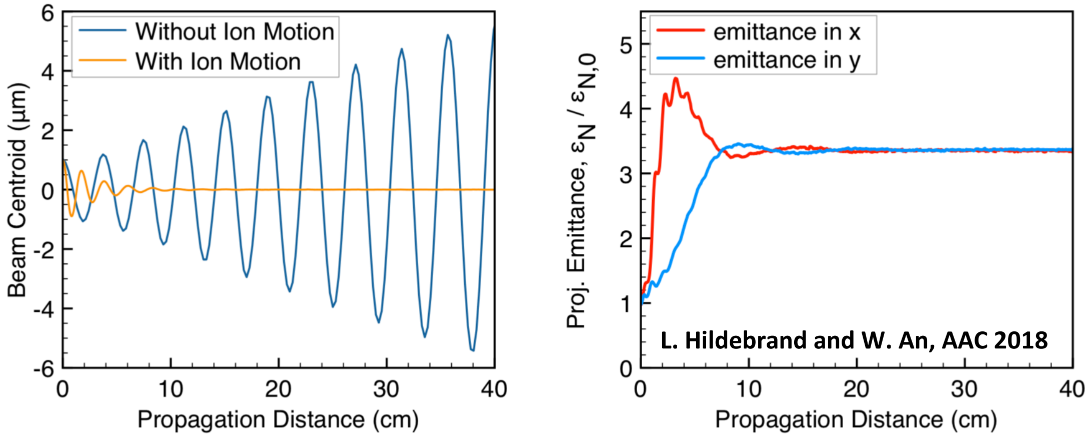
Plasma offers a unique solution!

E. Adli, U. of. Oslo



W. An, UCLA



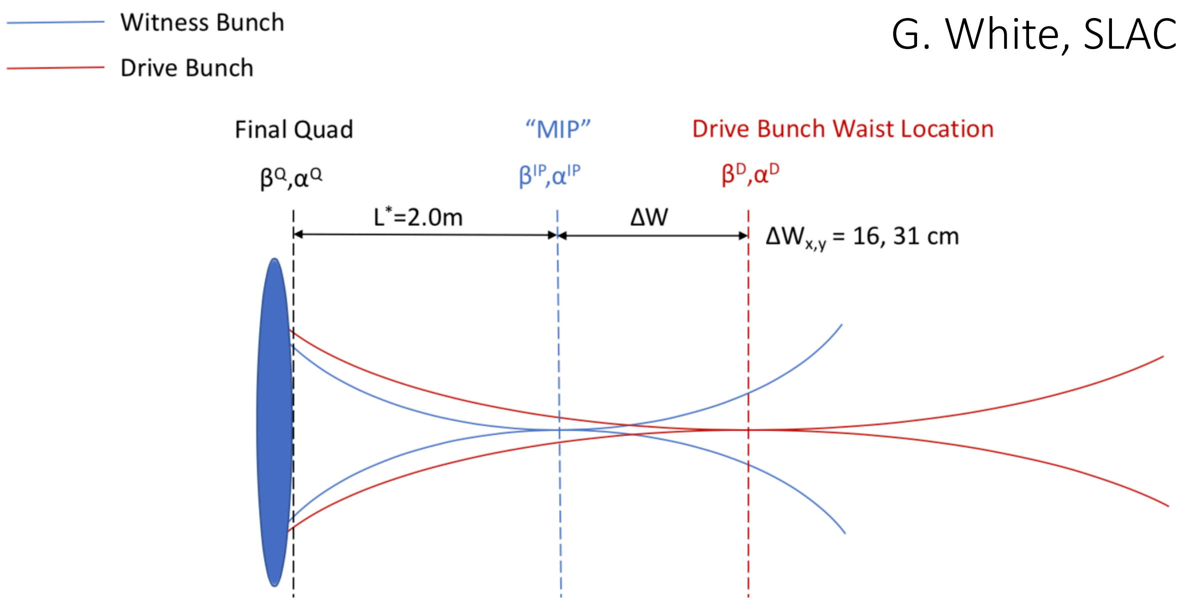


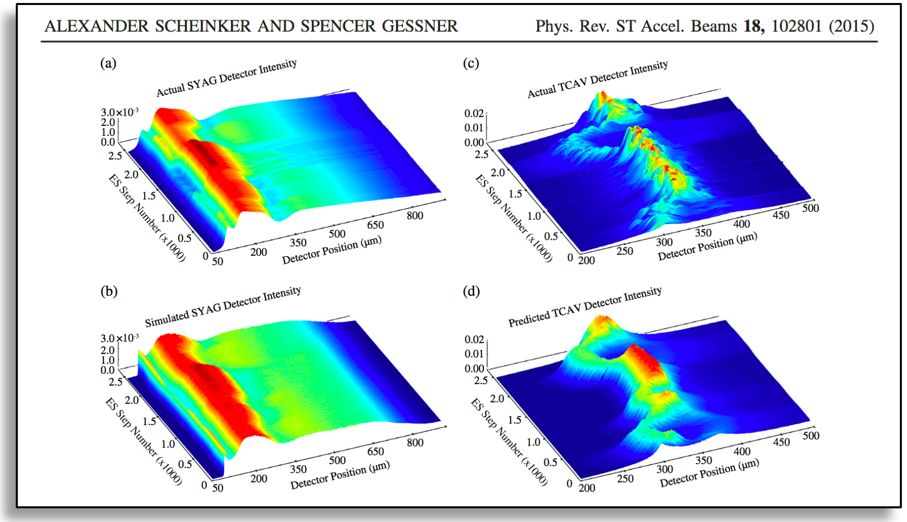
Ion motion in plasma is a *natural* mechanism for suppressing transvers instabilities.

W. An, et. al. Phys. Rev. Lett. 118, 244801 (2017)
T.J. Mehrling, et. al. Phys. Rev. Lett. 121, 264802 (2018)

Demonstrating High-Quality Acceleration at FACET-II

G. White, SLAC



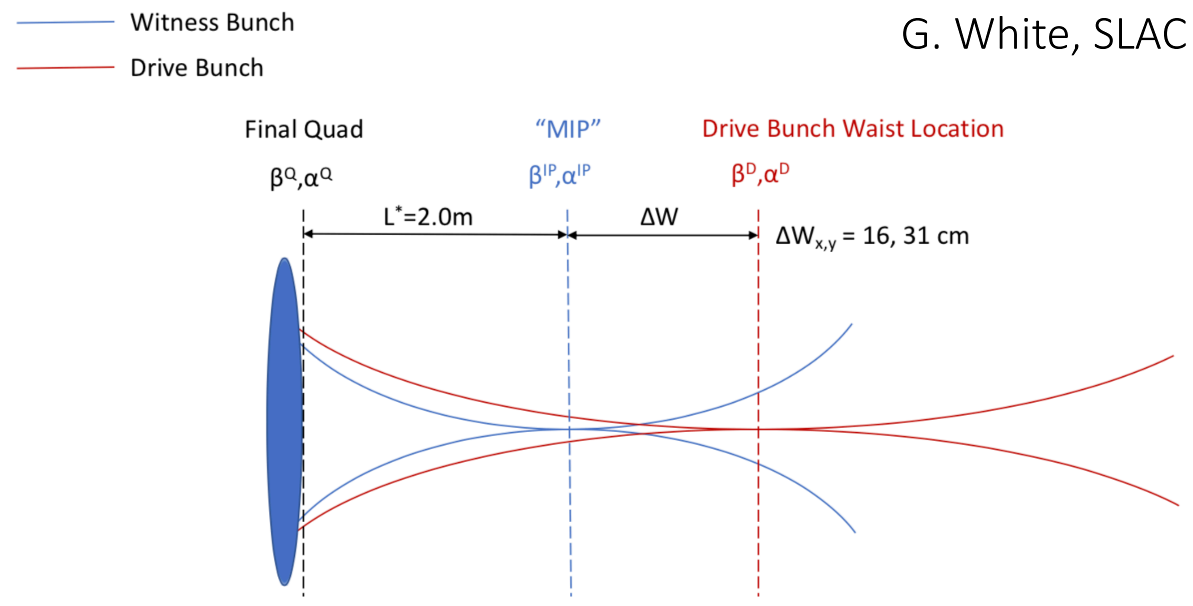


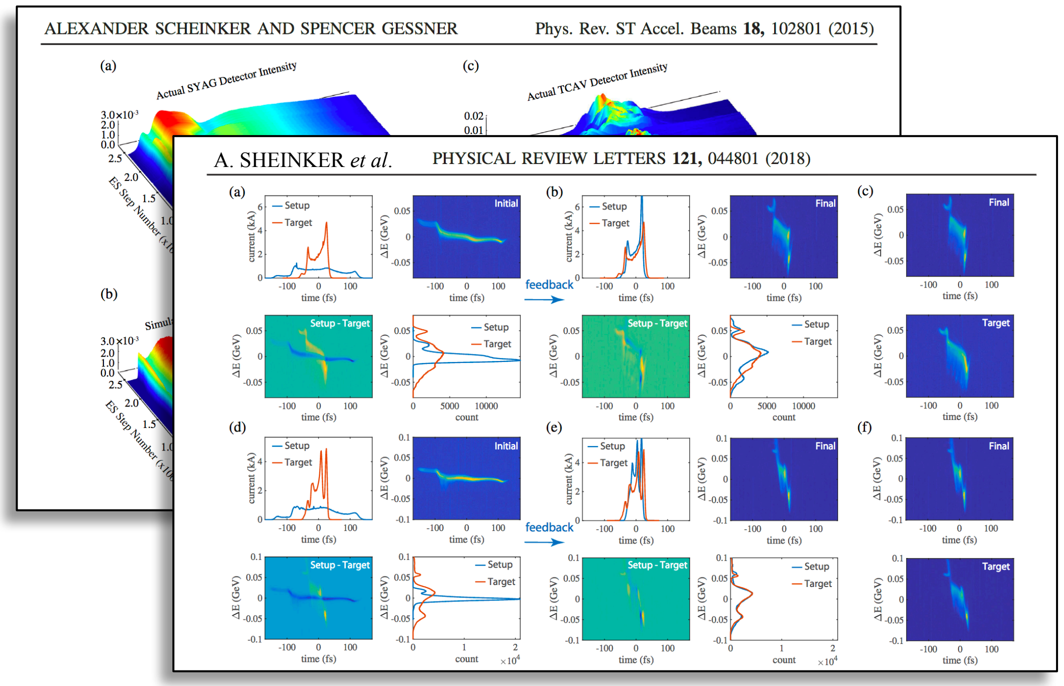
FACET-II will provide drive-witness bunch pairs with peak currents in the range of 10-100 kA and micron level spot sizes.

Advanced algorithms will be critical to optimizing and diagnosing the beams in PWFA experiments.

Demonstrating High-Quality Acceleration at FACET-II

G. White, SLAC





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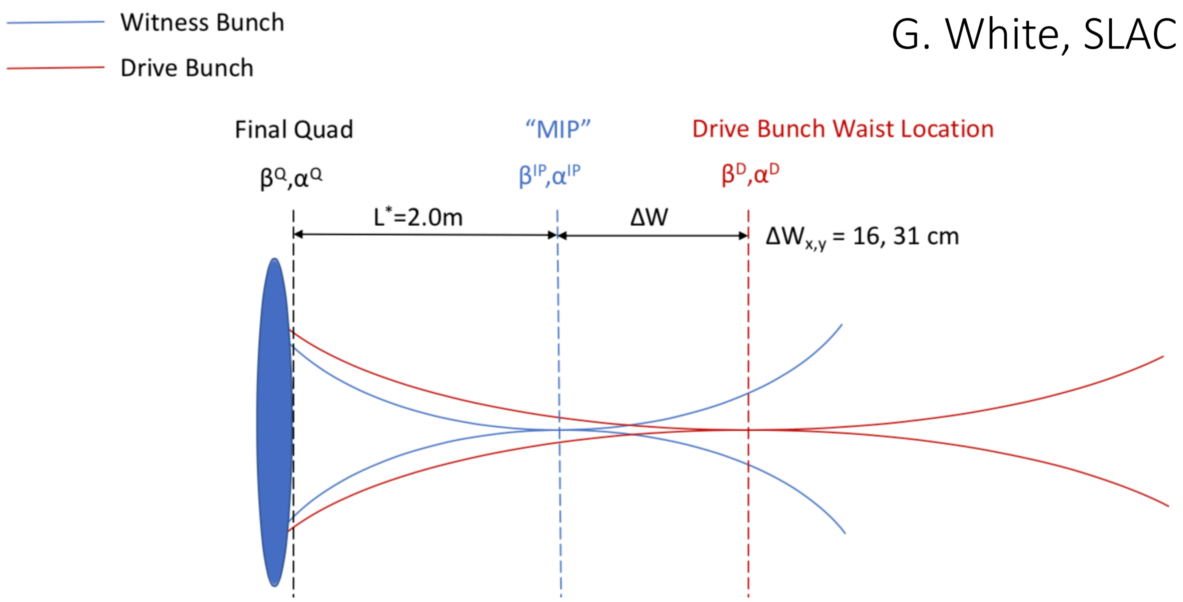

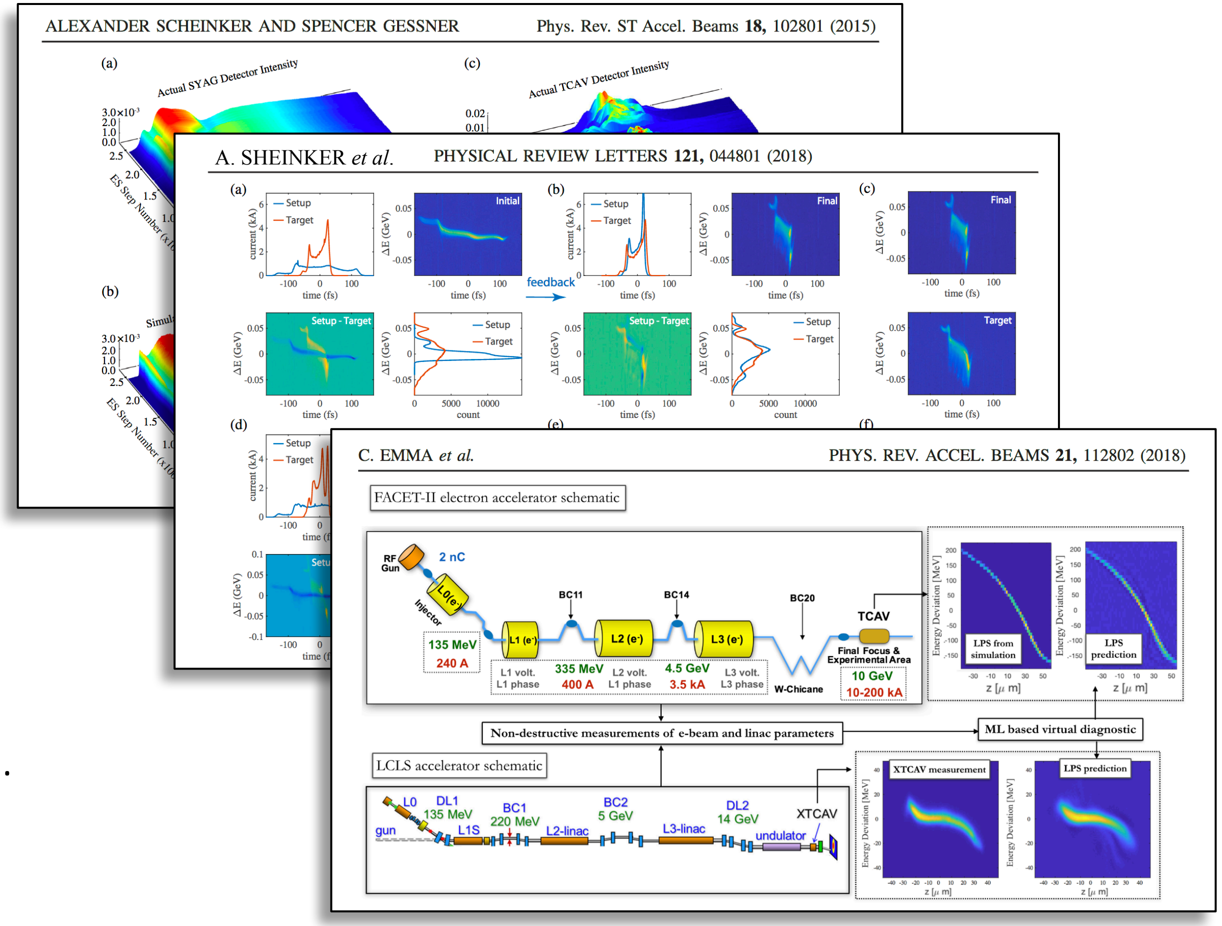

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Success at FACET-II Leads to Applications

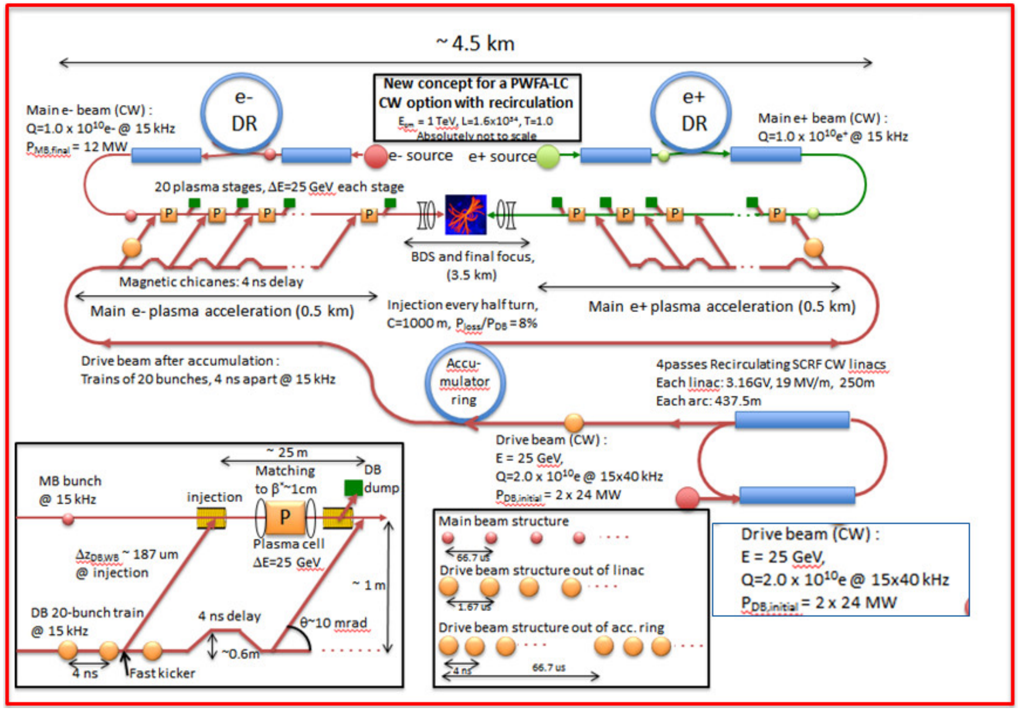
1. Demonstrate that highly-efficient acceleration of low-emittance electron beams is possible in a plasma wakefield accelerator.

2. How tight are the tolerances? What is the sensitivity of the beam emittance to each of the various parameters?

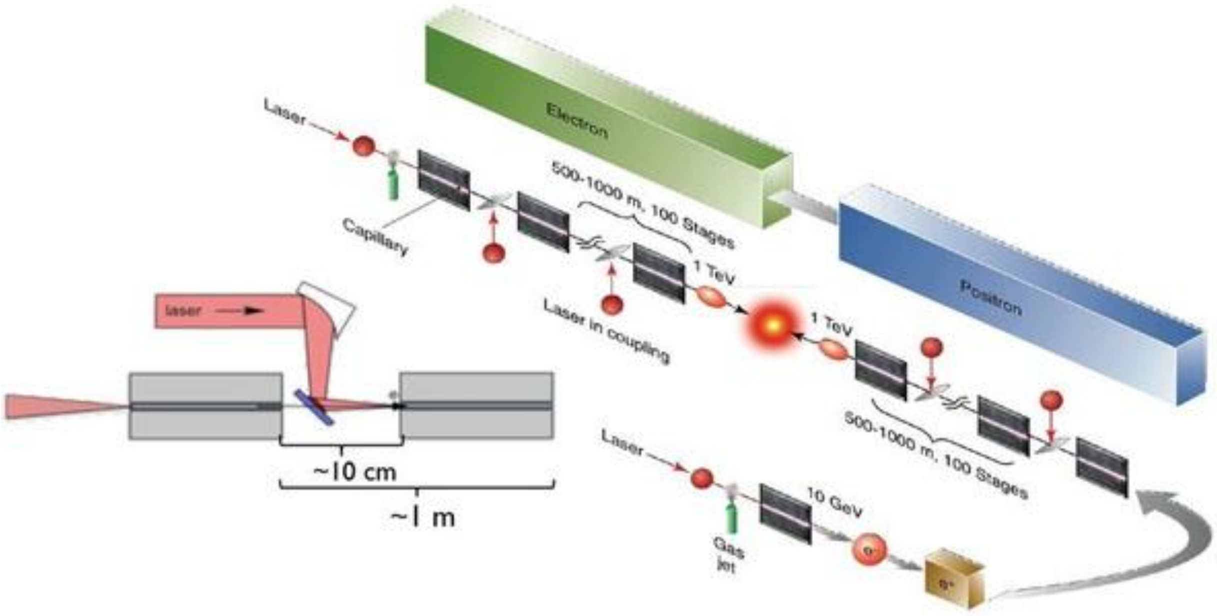
3. From our knowledge of tolerances/sensitivity, we can create a design for electron beam-driven plasma accelerator AND provide realistic estimate of the cost.

Plasma Acceleration of Positron Beams

Why Accelerate Positrons?



E. Adli, J.-P. Delahaye, S. J. Gessner, M. J. Hogan, T. Raubenheimer, W. An, C. Joshi, and W. Mori, arXiv:1308.1145 [physics.acc-ph]



C. B. Schroeder, E. Esarey, C. G. R. Geddes, C. Benedetti, and W. P. Leemans, Phys. Rev. ST Accel. Beams **13**, 101301

The most ambitious application of plasma wakefield acceleration is a plasma-based, electron-positron linear collider (PLC).

Positron PWFA Experiments by the Numbers

1 Laboratory: SLAC

3 Facilities: FFTB, FACET, FACET-II

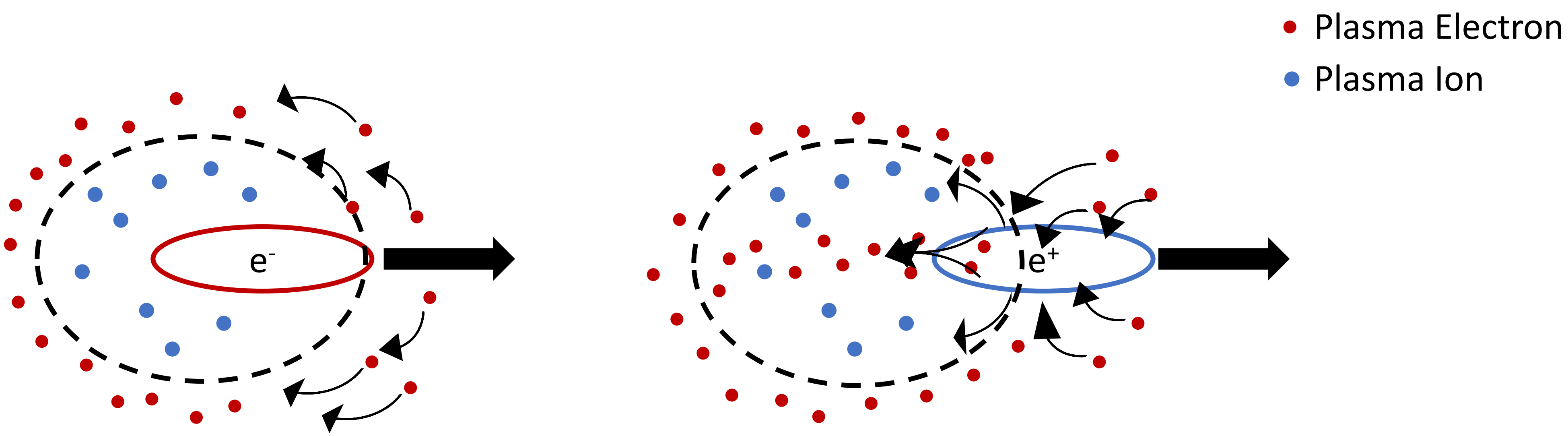
3 Experiments: E162, E200, E225

7 Publications:

- Ultrarelativistic-Positron-Beam Transport through Meter-Scale Plasmas, M. J. Hogan et. al. *Phys. Rev. Lett.* 90 205002 (2003).
- Plasma-Wakefield Acceleration of an Intense Positron Beam, B. Blue et. al. *Phys. Rev. Lett.* 90 214801 (2003).
- Halo Formation and Emittance Growth of Positron Beams in Plasmas, P. Muggli et. al. *Phys. Rev. Lett.* 101 055001 (2008).
- Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield, S. Corde et. al. *Nature.* 524 442445 (2015).
- Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator, S. Gessner et. al. *Nat. Comm.* 7 11785 (2016).
- Acceleration of a trailing positron bunch in a plasma wakefield accelerator, A. Doche et. al. *Nat. Sci. Rep.* 7 14180 (2017).
- Measurement of Transverse Wakefields Induced by a Misaligned Positron Bunch in a Hollow Channel Plasma Accelerator, C. A. Lindstrøm et. al. *Phys. Rev. Lett.* 120 124802 (2018).

Positron acceleration is 50% of a PLC but only a small fraction of PWFA research.

Plasma Response to Beams of Opposite Charge



$m_{ion} >> m_{elec}$

Plasma electrons are mobile but plasma ions are not. The plasma responds *asymmetrically* to beams of opposite charge. No other accelerating technology exhibits this behavior!

Positron Beam-Driven PWFA at FACET

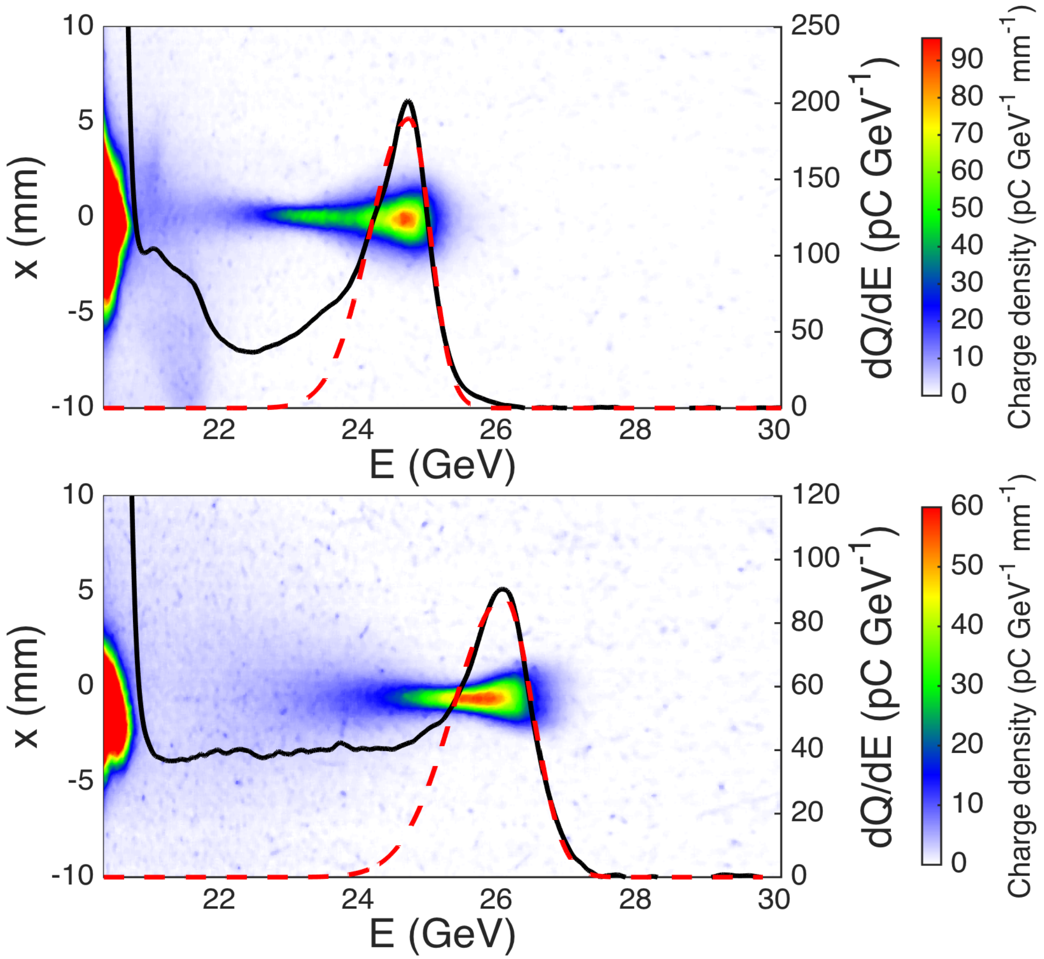
FACET was able to provide high-density, compressed positron beams for non-linear PWFA experiments.

This led to new observations:

- Accelerated positrons form a spectrally-distinct peak with an energy gain of 5 GeV.
- Energy spread can be as low as 1.8% (r.m.s.).

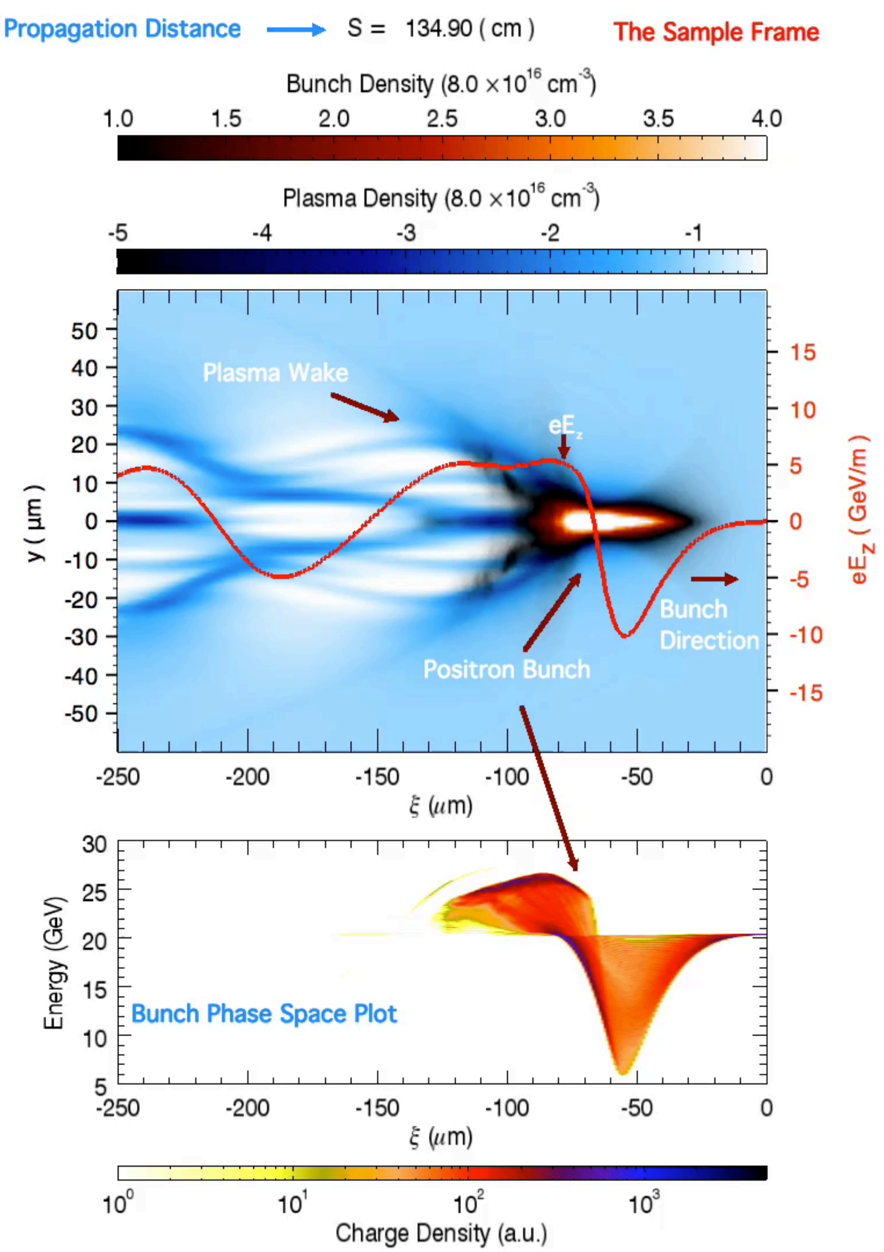
An unexpected result!

Experimental results in 1.3 m plasma



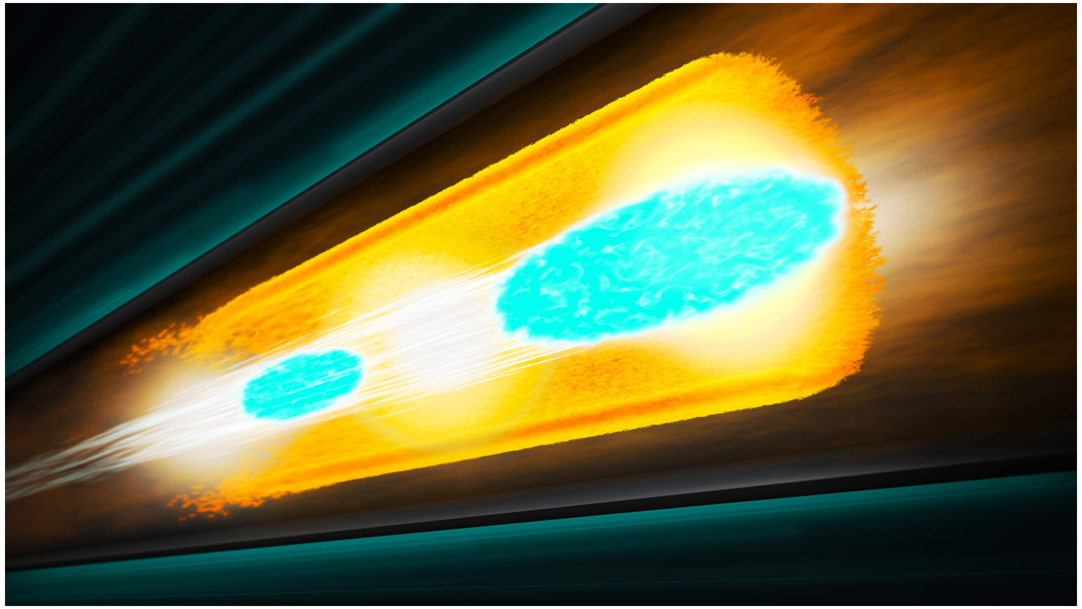
S. Corde *et al.*, Nature **524**, 442 (2015)

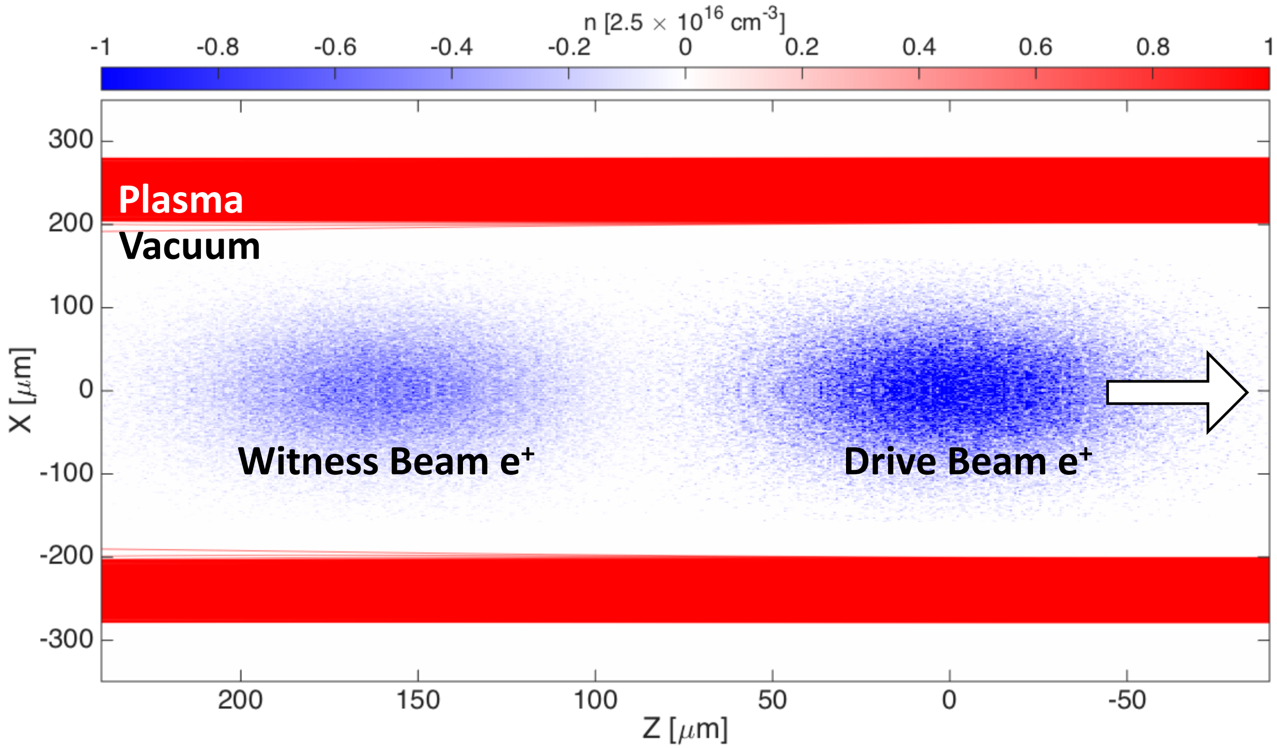
Positron-Plasma Equilibrium



S. Corde *et al.*, Nature **524**, 442 (2015)

The Hollow Channel Plasma Accelerator

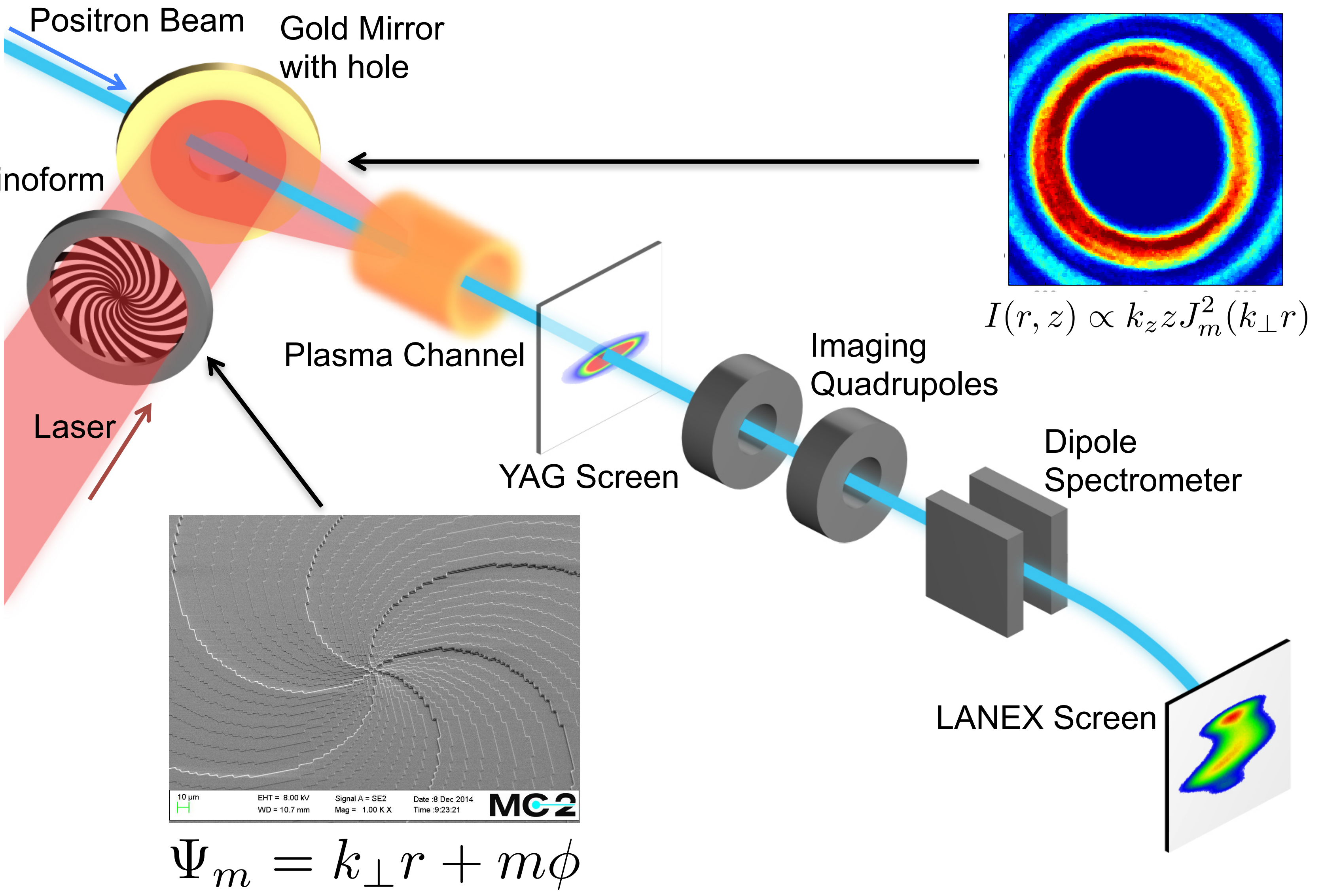




The Hollow Channel Plasma is a *structure* that symmetrizes the response of the plasma to electron and positron beams.

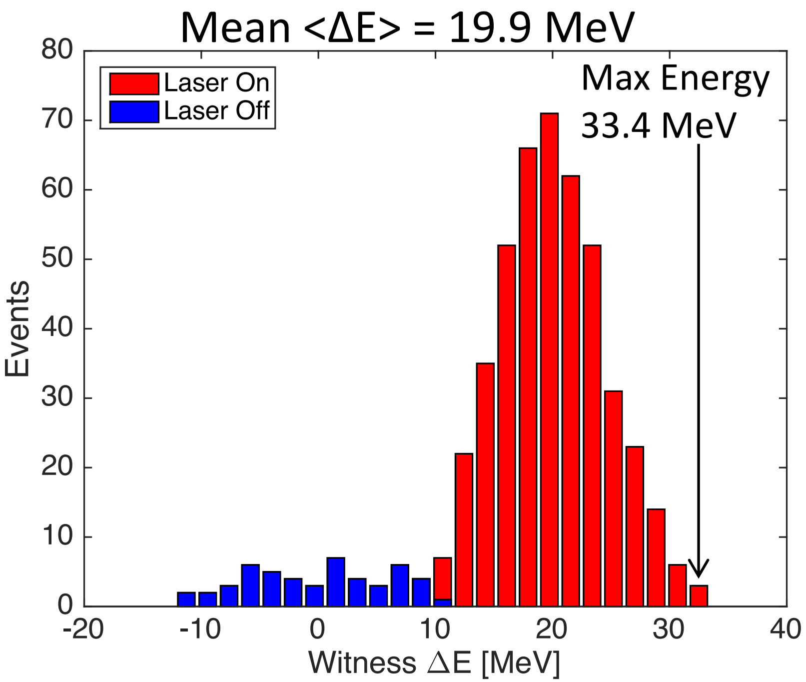
There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.

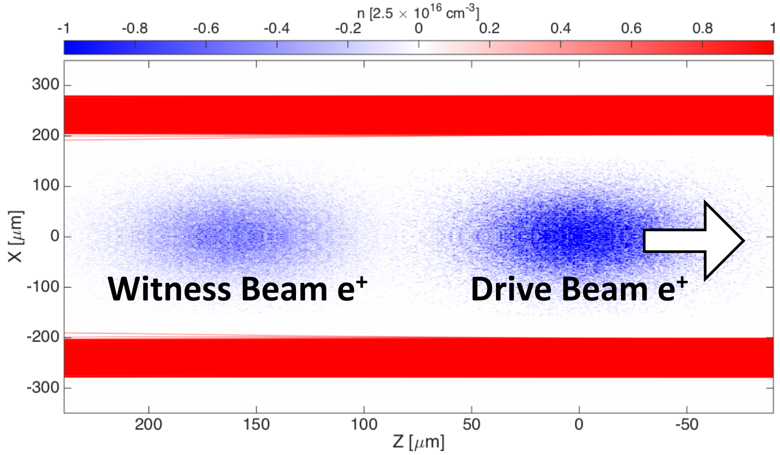
Creating a Hollow Channel Plasma

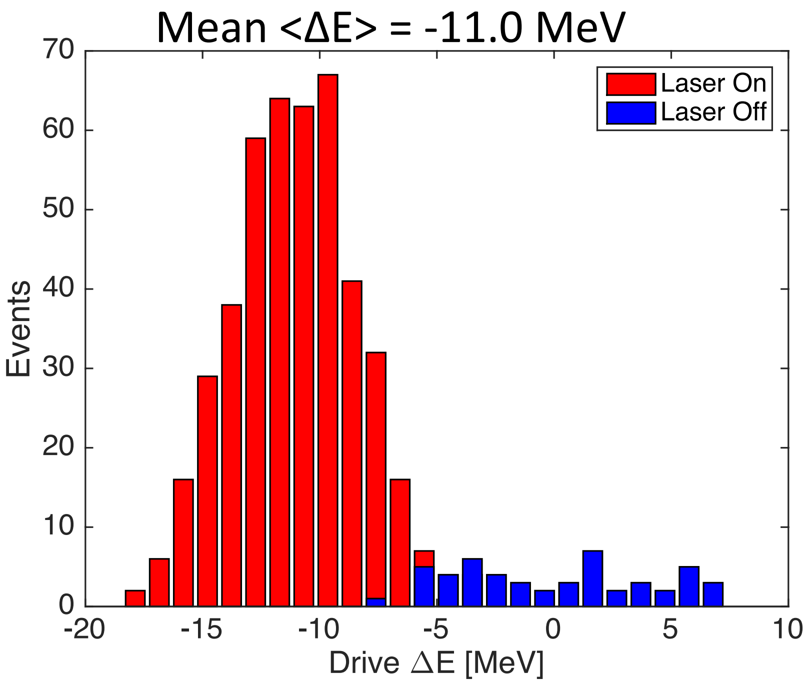


S. Gessner et. al. *Nat. Comm.* 7, 11785

Positron Acceleration in the Hollow Channel







Witness beam gains energy from the wake.

Drive beam transfers energy to witness beam.

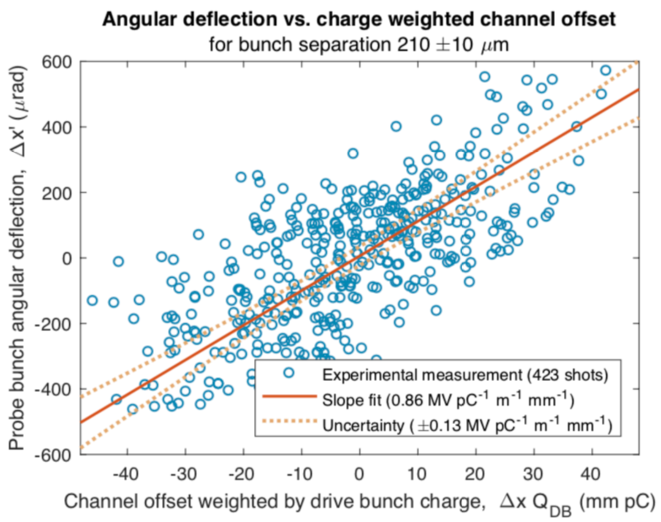
S. Gessner SLAC-R-1073

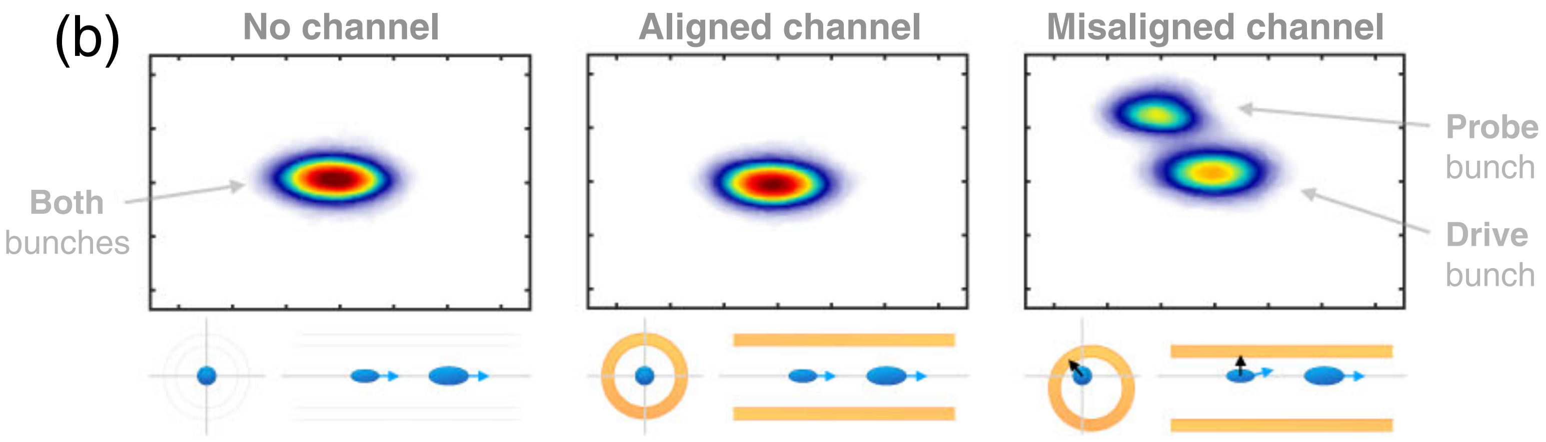
Transverse Wakefields in the Hollow Channel

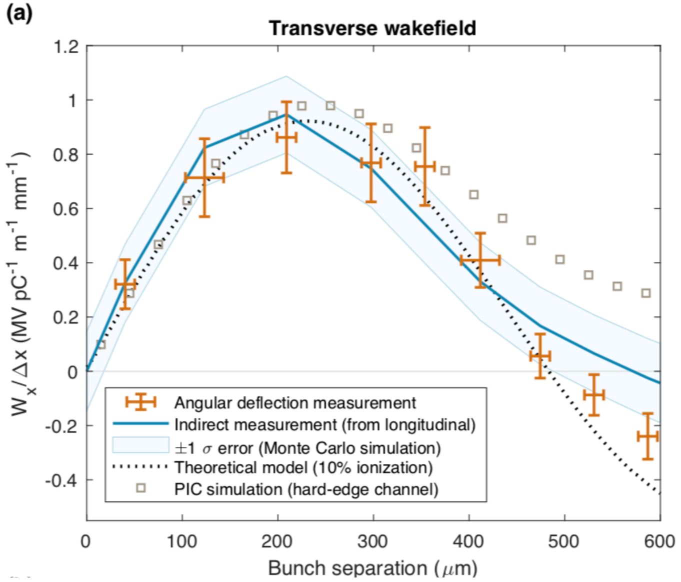
We measured the transverse wakefields in the hollow channel and the result agrees with our theoretical calculation:

$$10^6 \text{ V/(pC m mm)}$$

Or about 10,000 times stronger than the wakefields in CLIC!







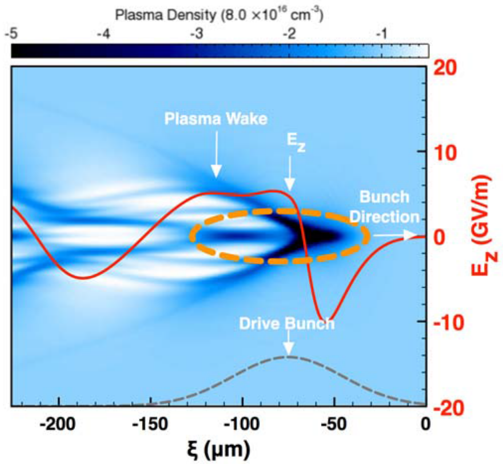
C. A. Lindstrøm et. al. *Phys. Rev. Lett.* 120 124802 (2018).

Positron PWFA Program at FACET-II

Non-Linear Regime

Investigate positron beam and plasma density profiles with the goal of finding low-emittance equilibrium conditions.

Plasma simulations will be key to this effort.

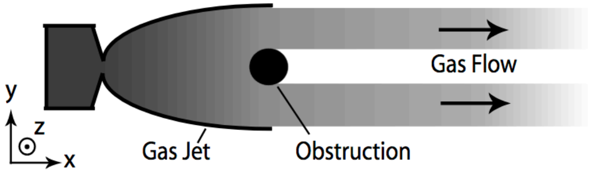


S. Corde *et al.*, Nature **524**, 442 (2015)

Hollow Channel

Develop techniques to mitigate the beam breakup instability.

Investigate slab-symmetric hollow channel plasmas. Can we use cryogenic gas jets to create channels with sharp features?

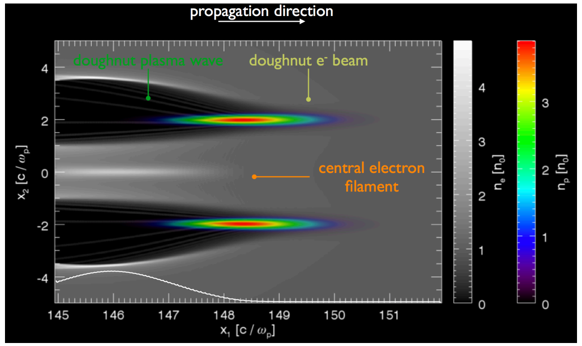


N. Kirby et. al. PAC '09

Novel Concepts

Recently, donut-shaped electron beams and high-order Laguerre-Gauss beams have been suggested to drive wakes that are optimal for accelerating positron beams.

Will these novel drivers maintain their symmetry in the plasma?



J. Vieira, et al. PRL 112 215001 (2014)

Plus: In-situ positron generation and acceleration experiments, and electron-based investigation of linear regime in uniform and hollow channel plasmas.

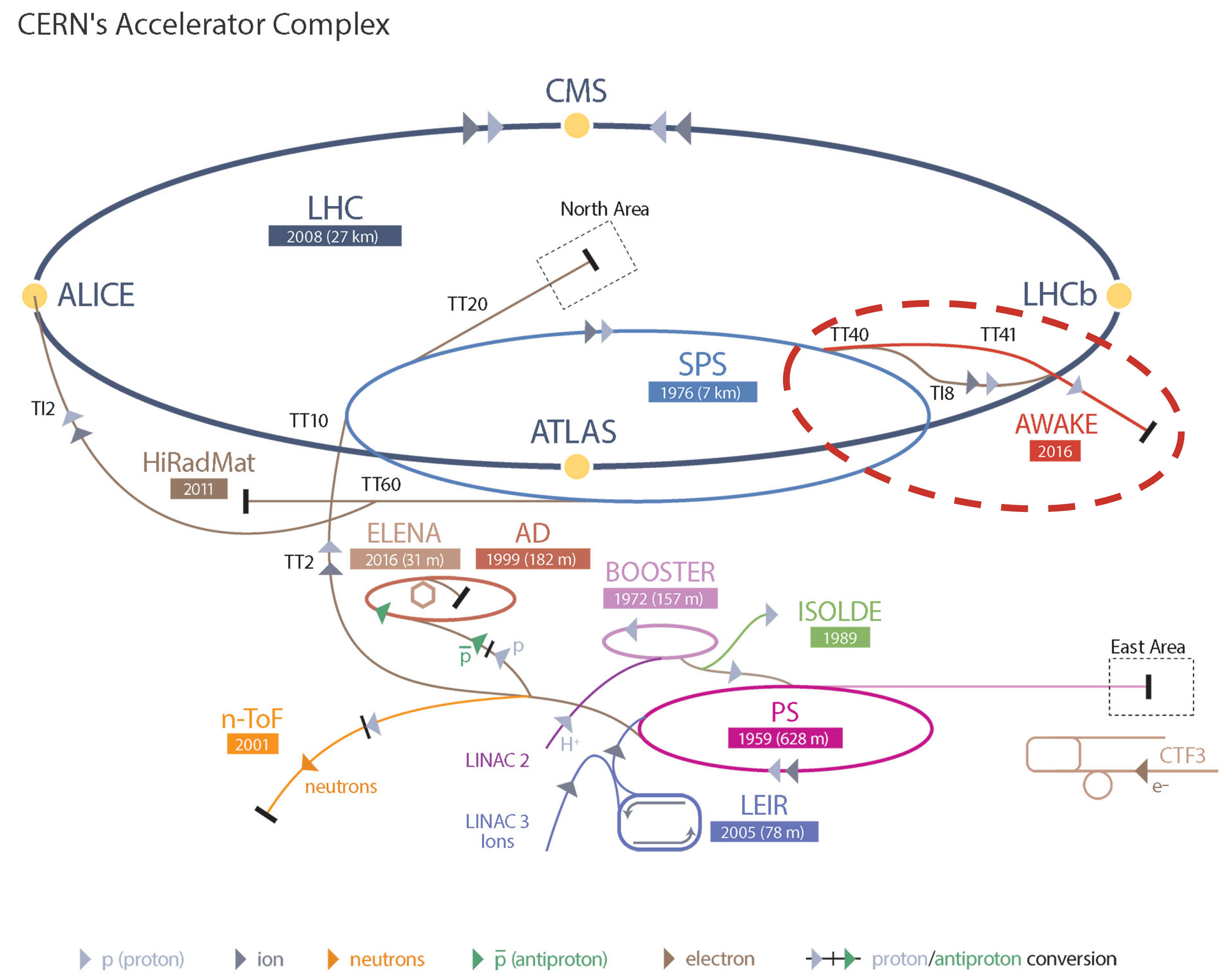
Recent Results from AWAKE

AWAKE @ CERN

The AWAKE experiment occupies the former CNGS target area, about 120 m underground.

The SPS sends a 400 GeV beam to AWAKE roughly once every 30 seconds.

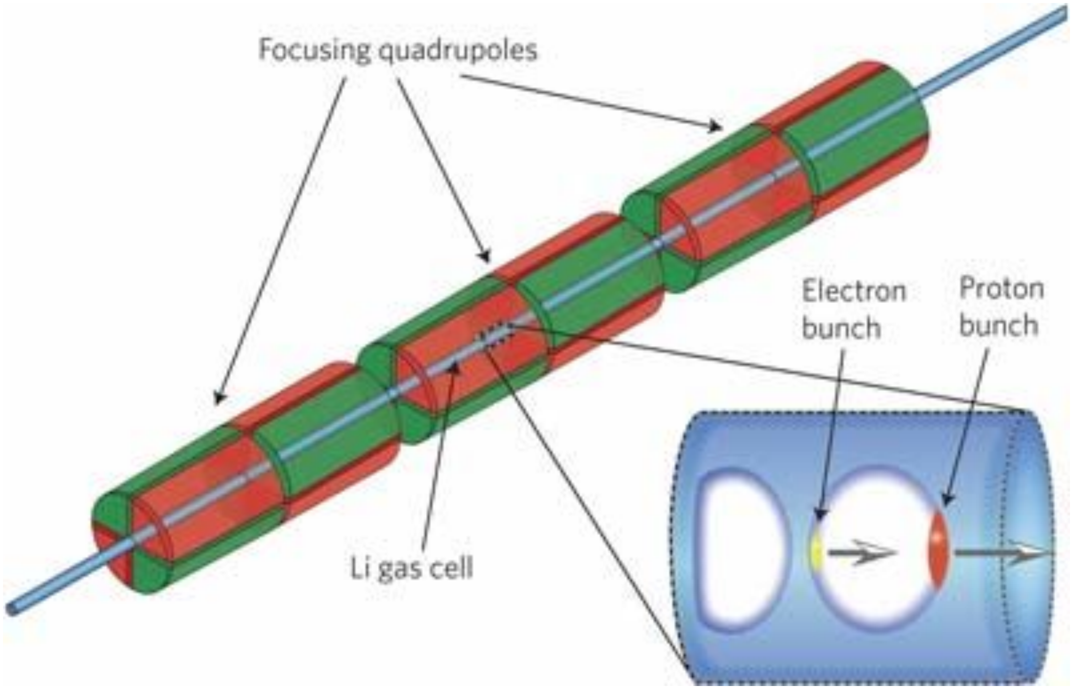
The proton beam is approximately 6 cm in length.



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 ≈ 20,000 J



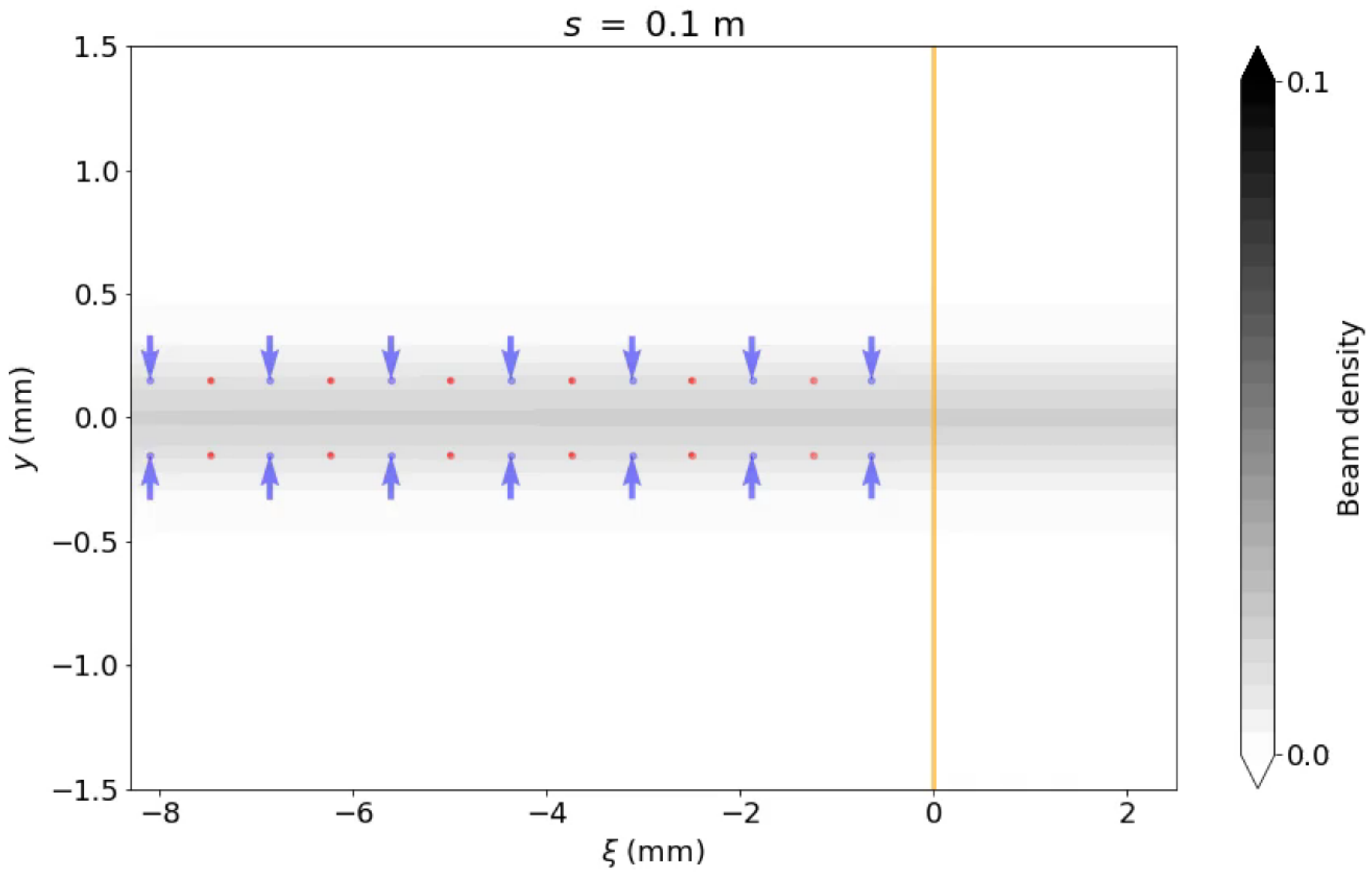
If we can transfer a significant amount of this energy to a trailing electron beam, we can create a simple, single-stage, plasma accelerator.

But there's a catch!

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

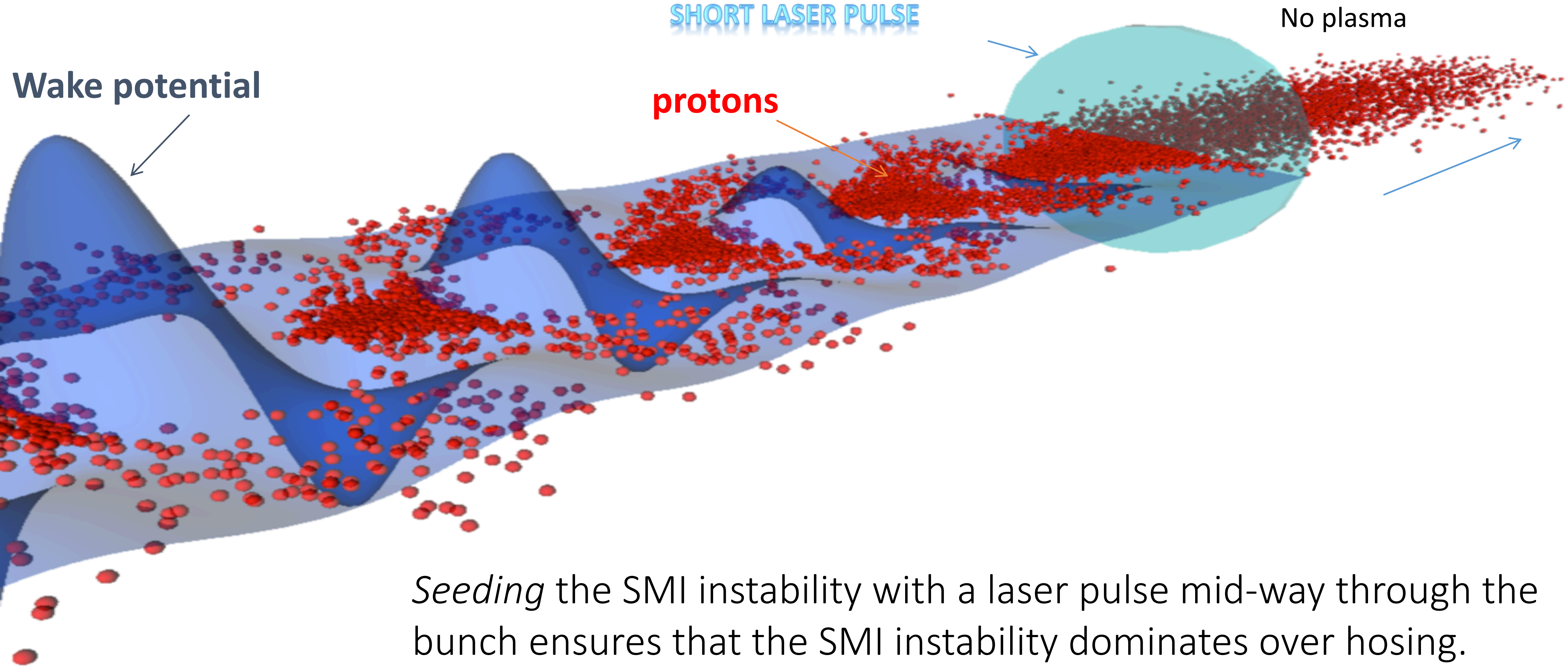
A. Caldwell, et. al. *Nat. Phys.* **5**, 363 - 367 (2009)

The Self-Modulation Instability

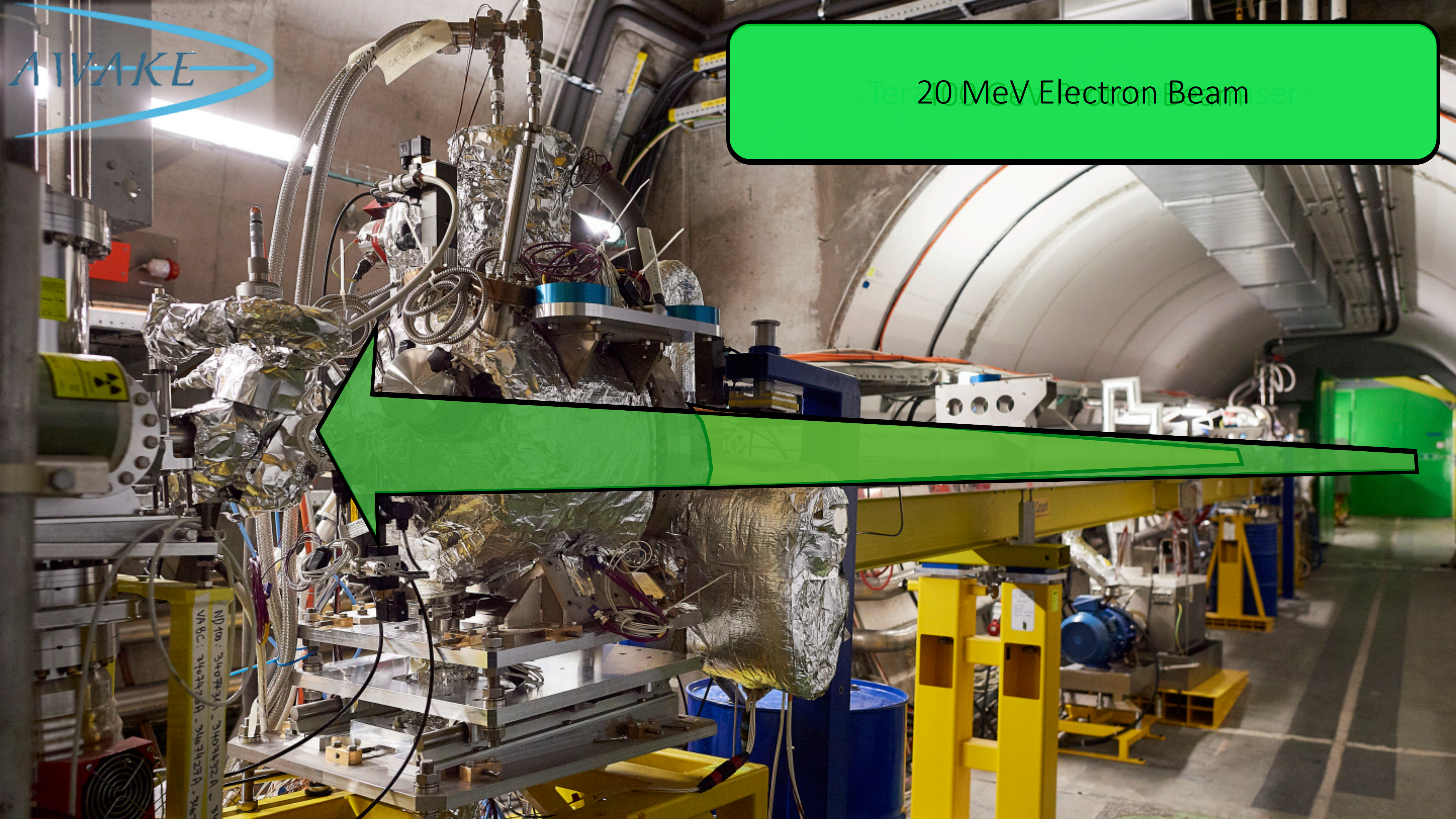


A. Petrenko, CERN

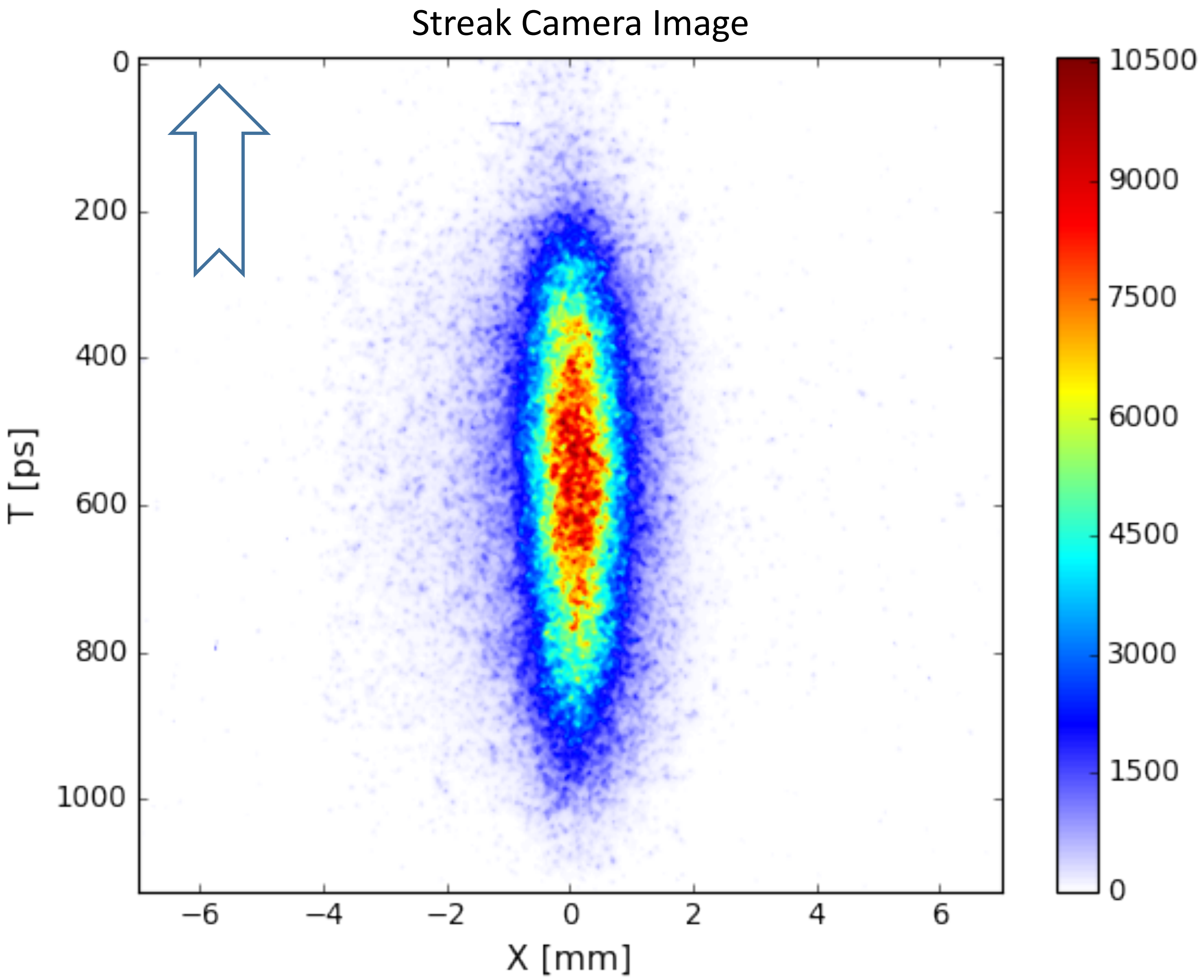
Seeded Self-Modulation



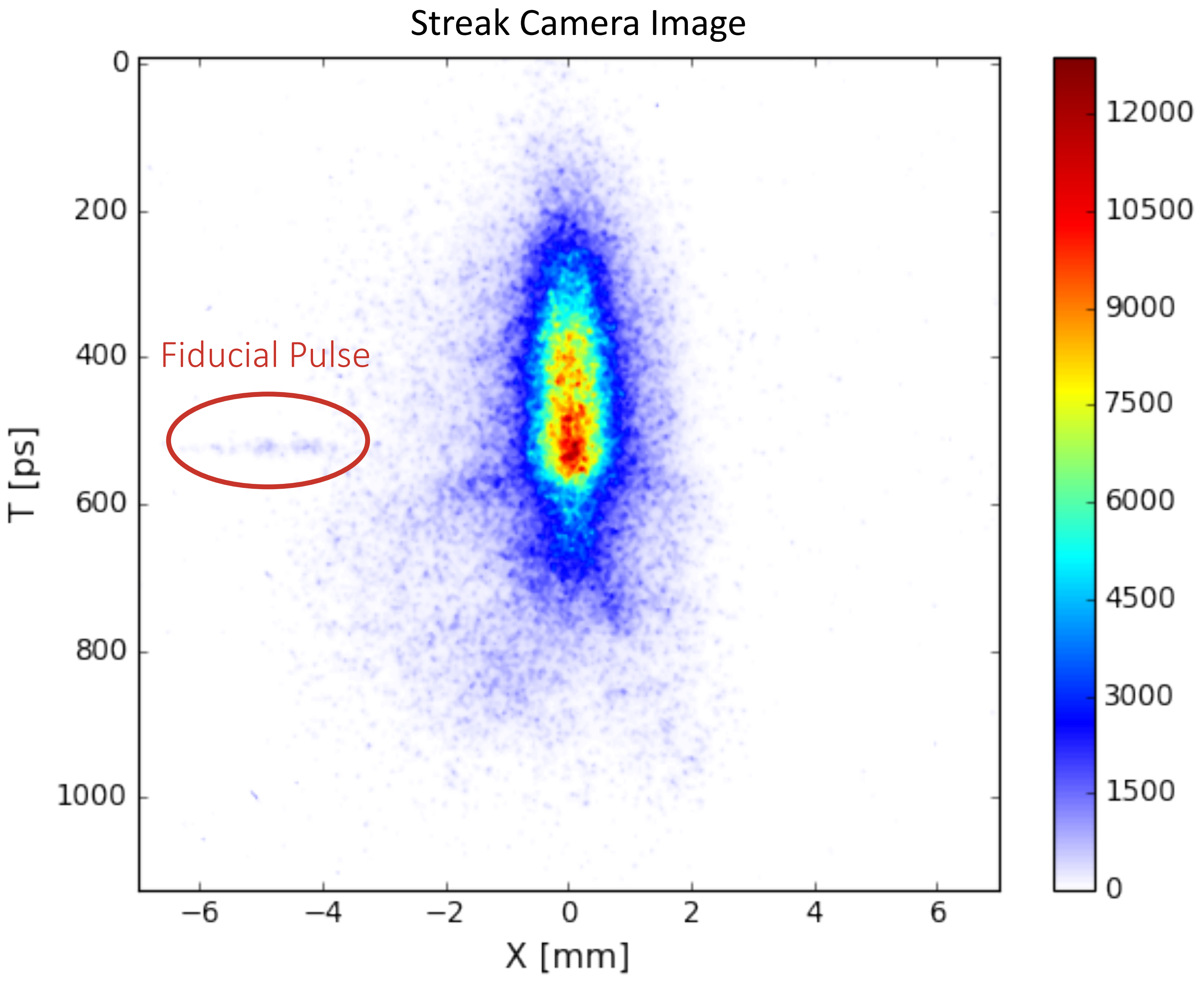
Seeding the SMI instability with a laser pulse mid-way through the bunch ensures that the SMI instability dominates over hosing.


AWAKE
20 MeV Electron Beam

Demonstration of Seeded Self-Modulation

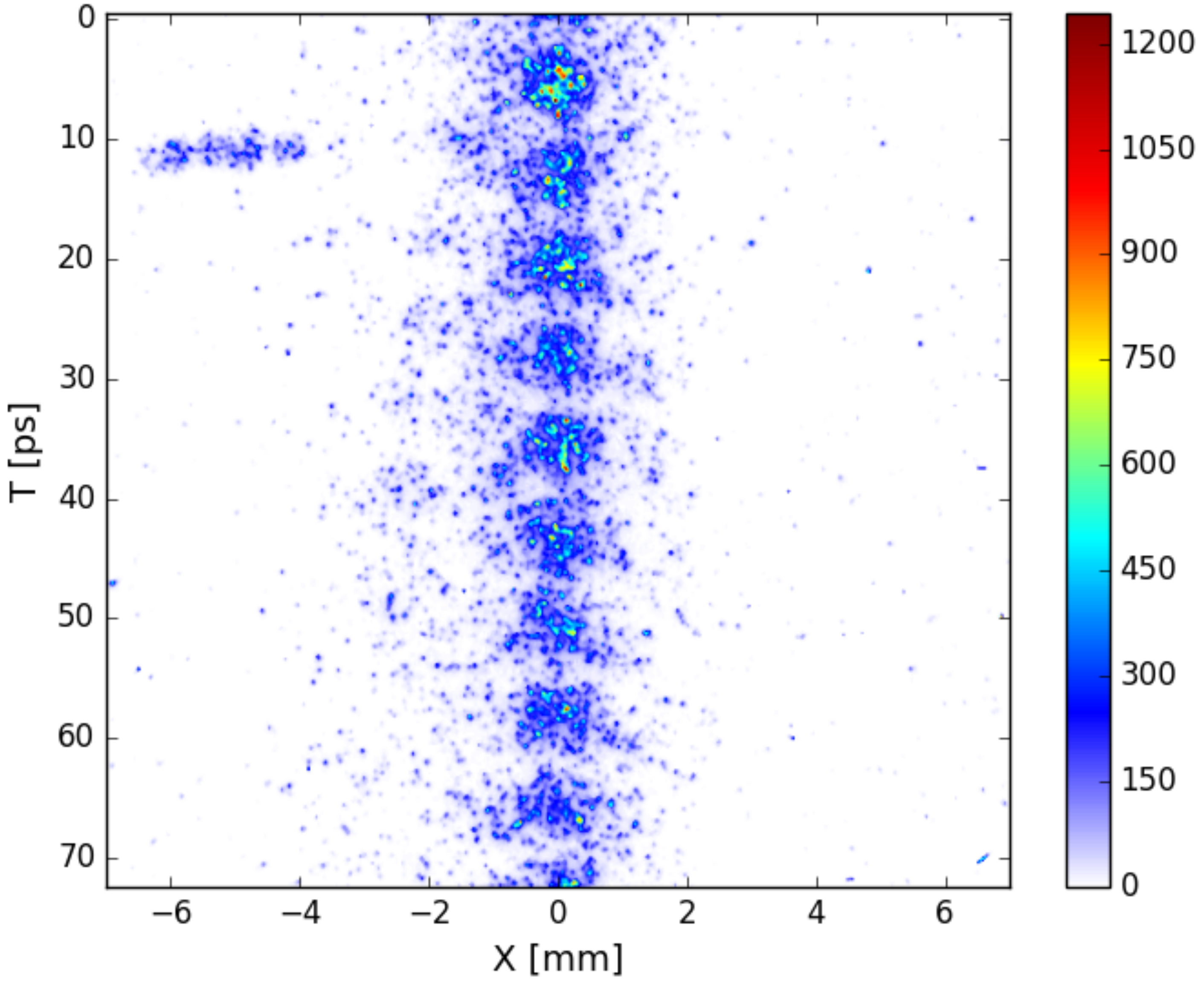


Demonstration of Seeded Self-Modulation

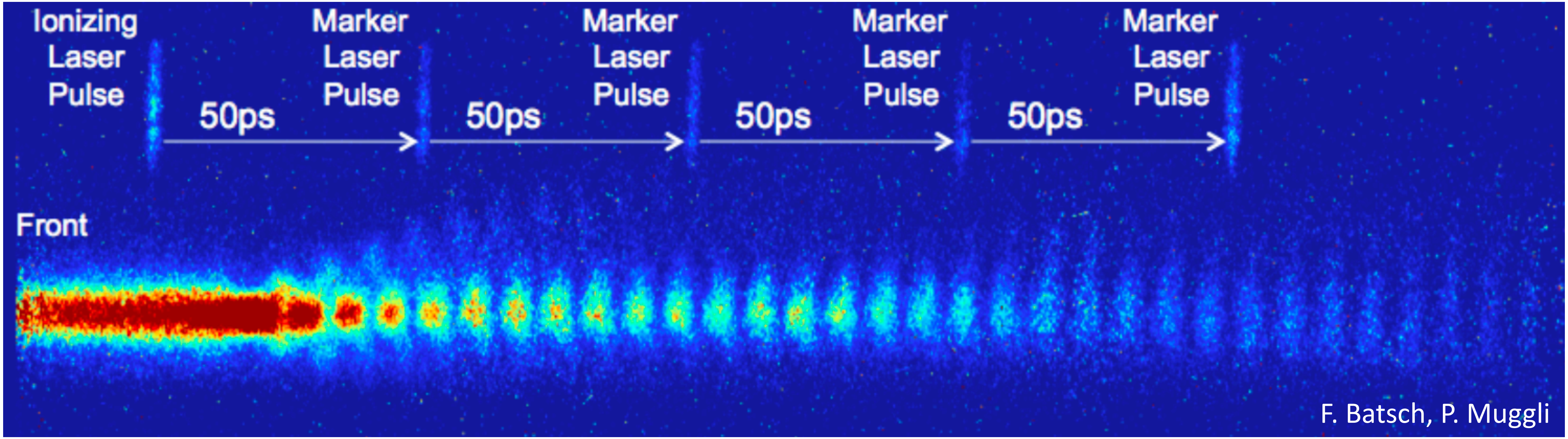


Demonstration of Seeded Self-Modulation

Streak Camera Image

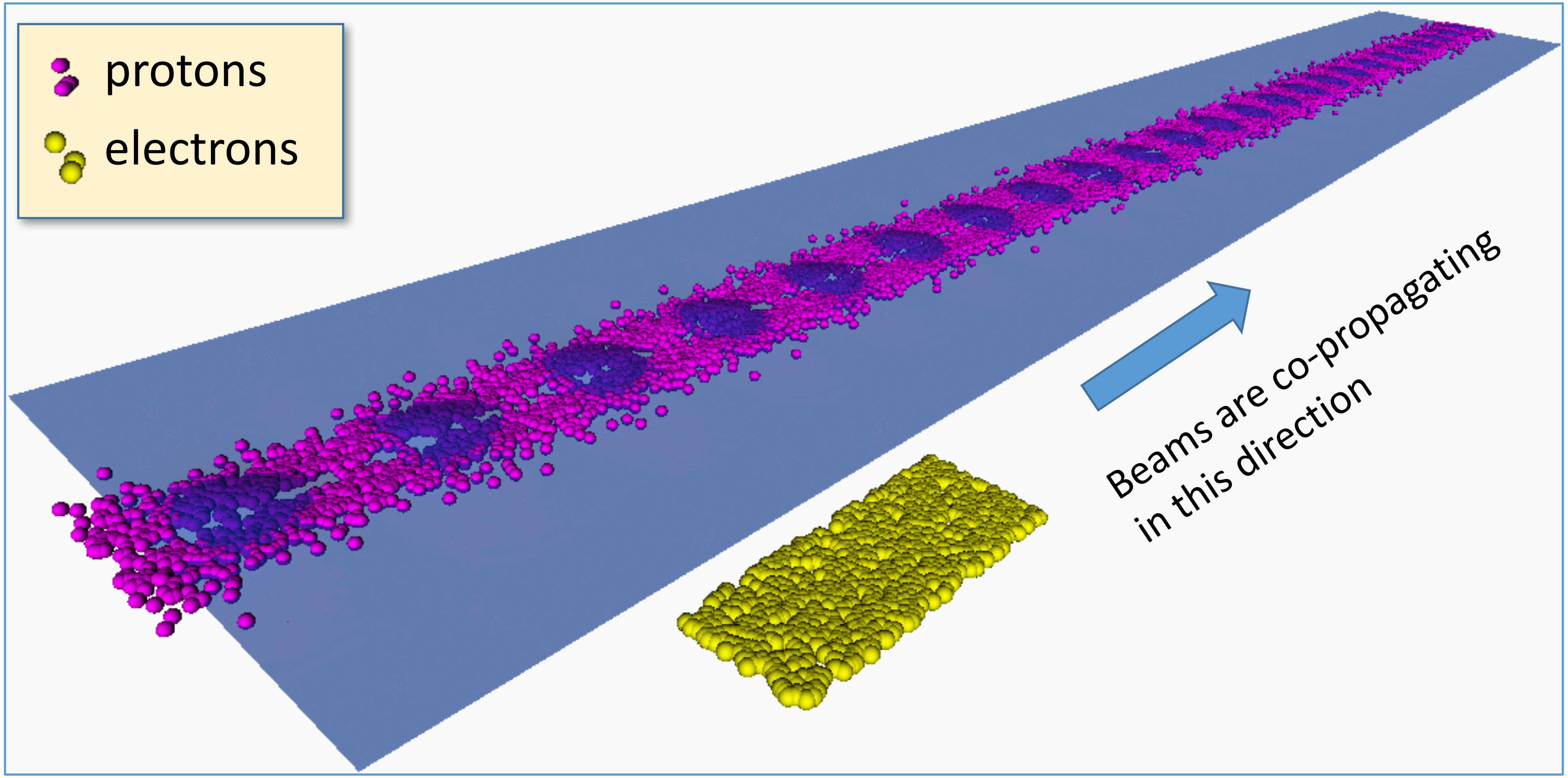


Demonstration of Seeded Self-Modulation



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

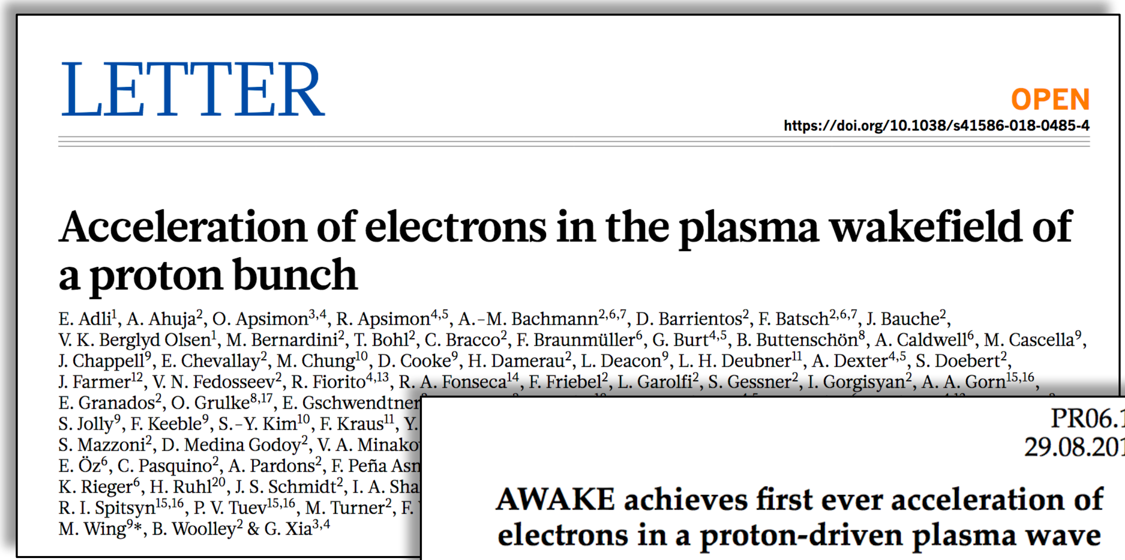
Injection of Electrons



The plasma wakefield forms via seeded self-modulation. In this process, roughly half of the protons are defocused by the plasma. The remaining protons form “micro-bunches” spaced at the plasma frequency.

A. Petrenko

First Acceleration of Electrons at AWAKE!


LETTER

OPEN

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Acceleration of electrons in the plasma wakefield of a proton bunch

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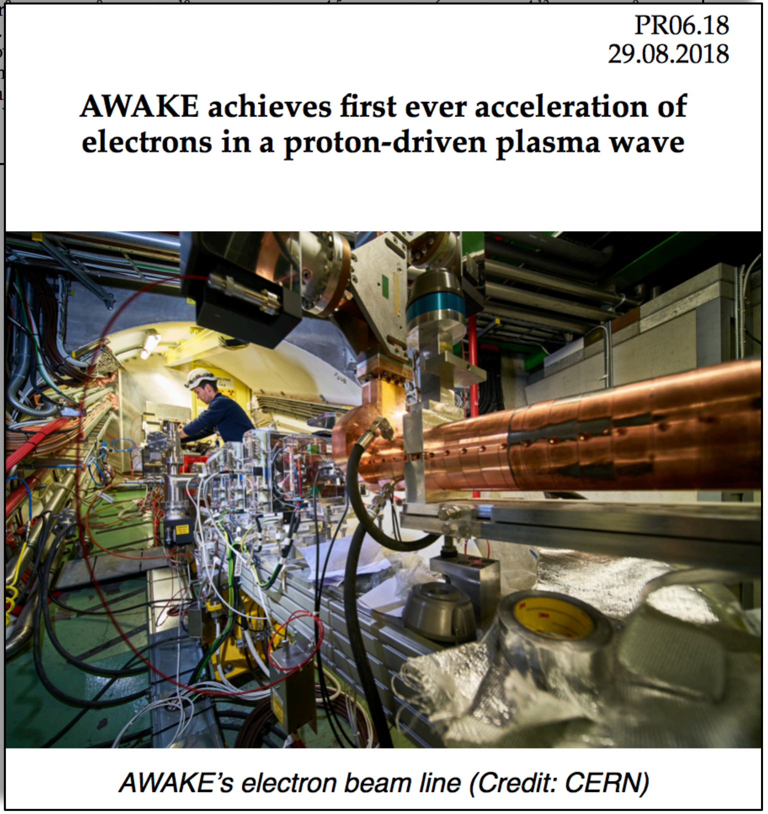
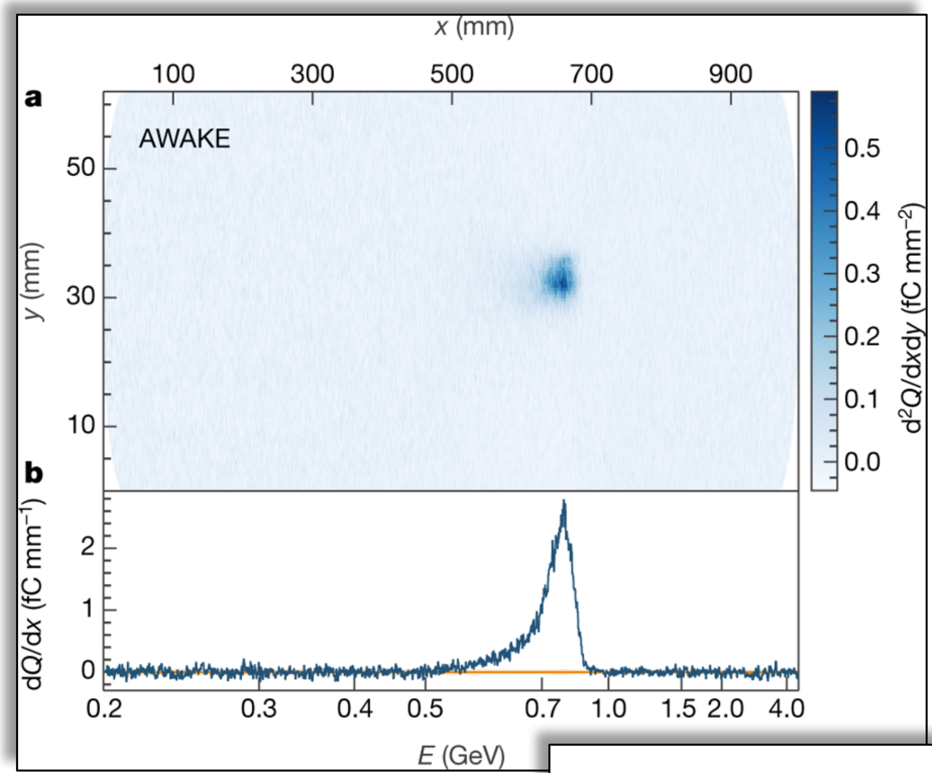
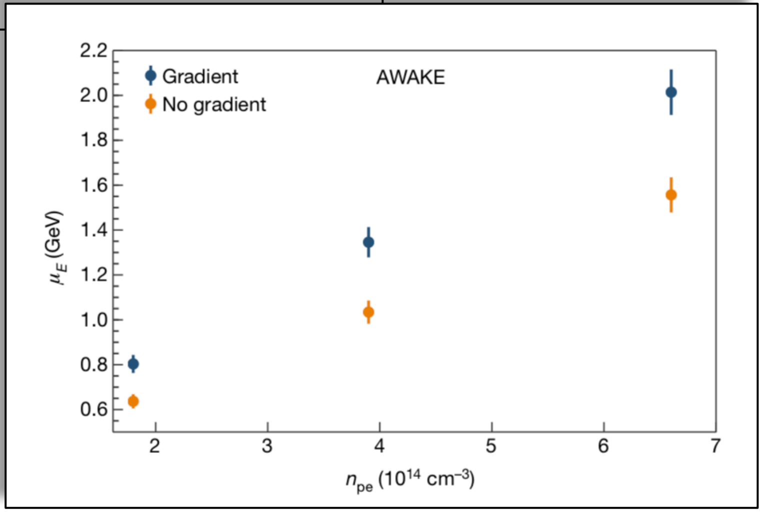


AWAKE's electron beam line (Credit: CERN)



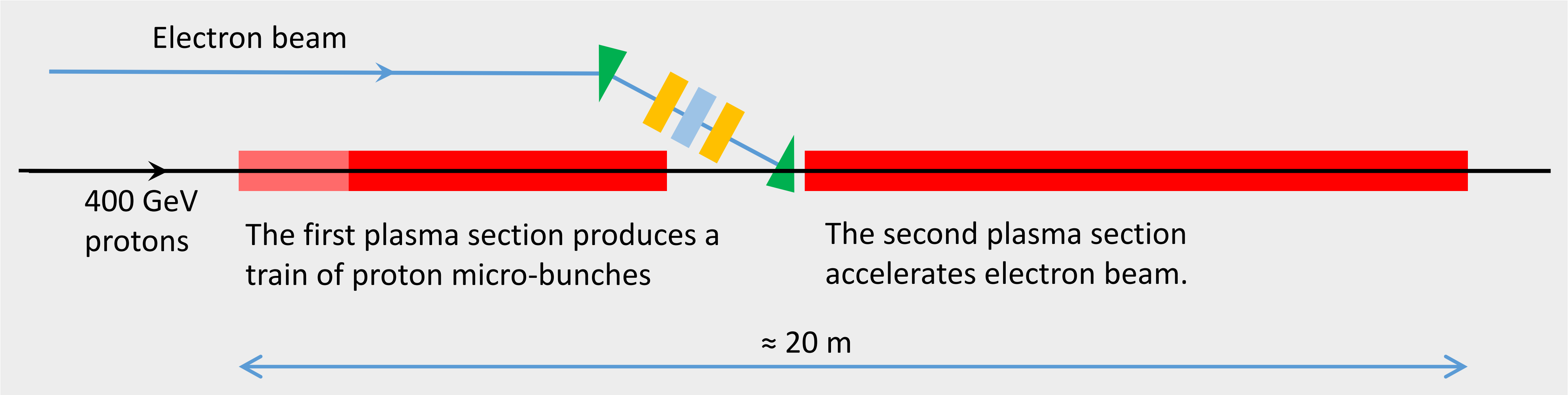


E. Adli, et. al. (AWAKE Collaboration) *Nature* **561**, 363 - 367 (2018)

Plans for AWAKE

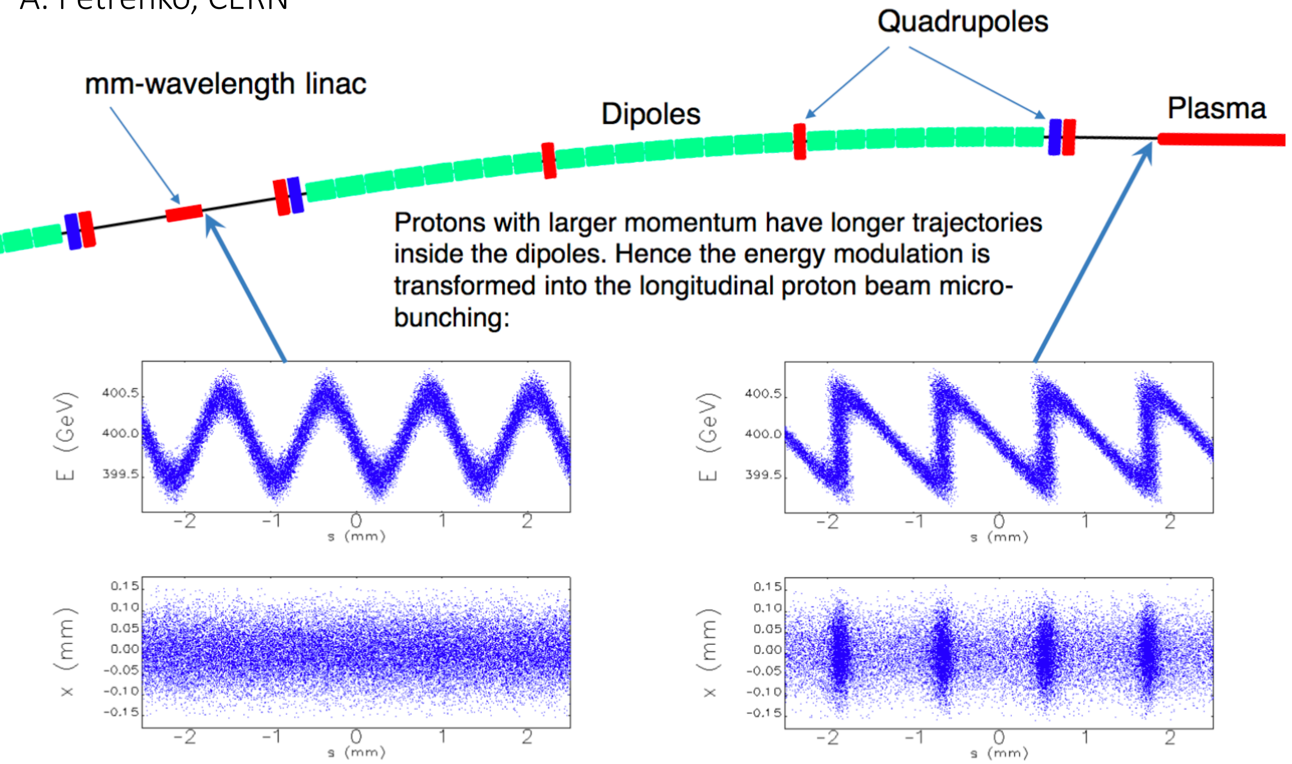
AWAKE wants to demonstrate increased charge capture and emittance preservation in future experiments.

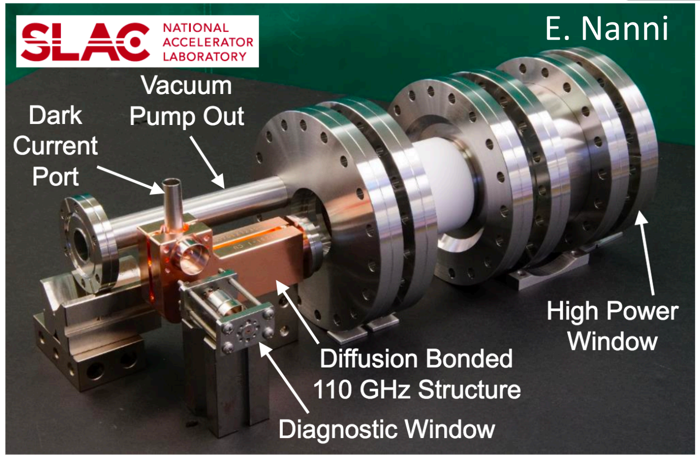
To do this, we will split the experiment in two: a modulation stage and an acceleration stage.

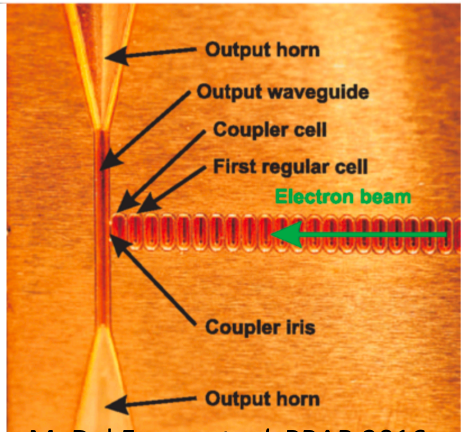


Applying SLAC Expertise to AWAKE

A. Petrenko, CERN







M. Dal Forno *et. al*. PRAB 2016

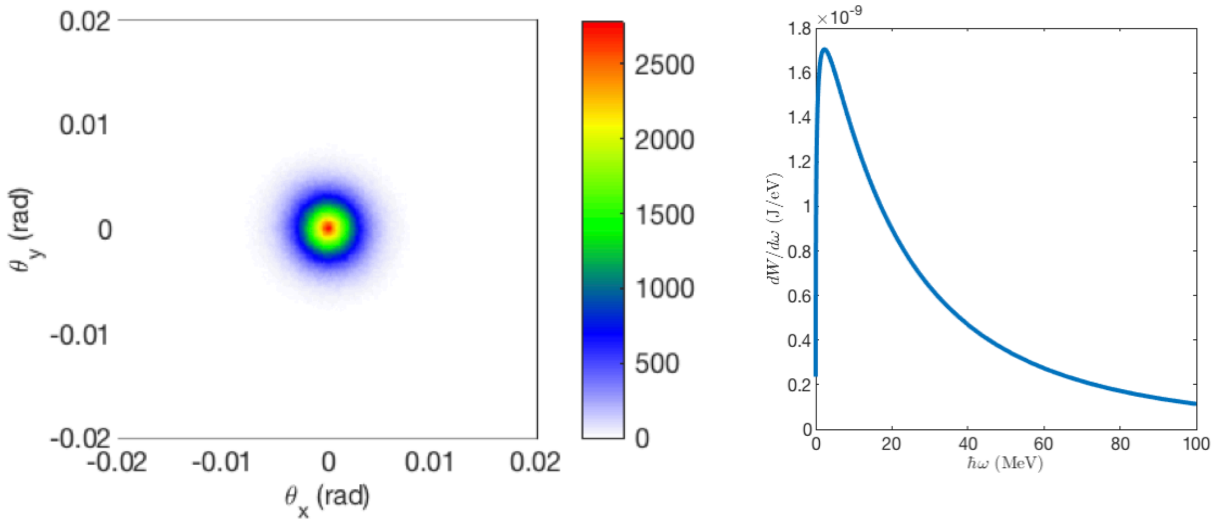
The self-modulation process is inefficient: 50% of the protons exit the wake! An alternative solution is to pre-modulate the protons at the plasma frequency.

Can we use mm-wave RF technology developed at SLAC to improve the AWAKE experiment?

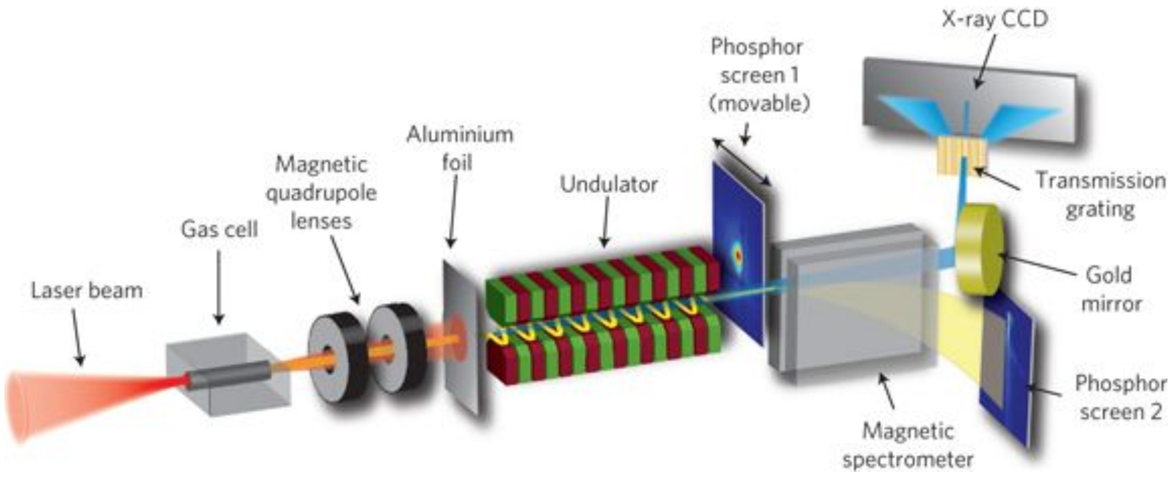
Applications

Light Sources

Gamma-ray spectrum produced by 10 GeV FACET-II electron beam.
S. Corde, K. Marsh, F. Fiuza, FACET-II proposal (2018).



Laser-driven soft-X-ray undulator source.
M. Fuchs et. al., *Nature Physics* 5, (2009)



Gamma-rays: Plasma accelerators naturally produce gamma-ray photons through betatron radiation and beam filamentation processes. These photon energies are not otherwise available at SLAC.

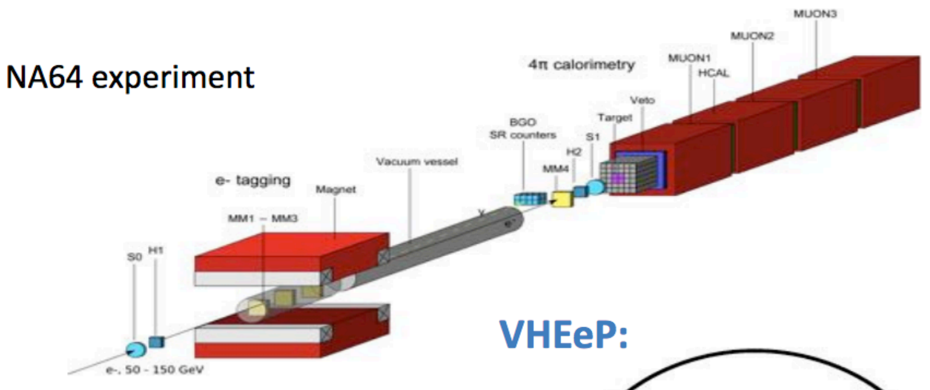
X-rays: Use the electron beam accelerated in the plasma to generate x-rays in an undulator. For an FEL, we need to minimize the 6D phase space ε_x, ε_x, *and* ε_z in order to have SASE.

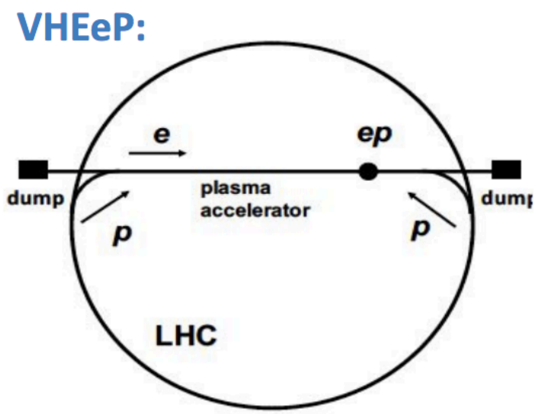
HEP Experiments

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

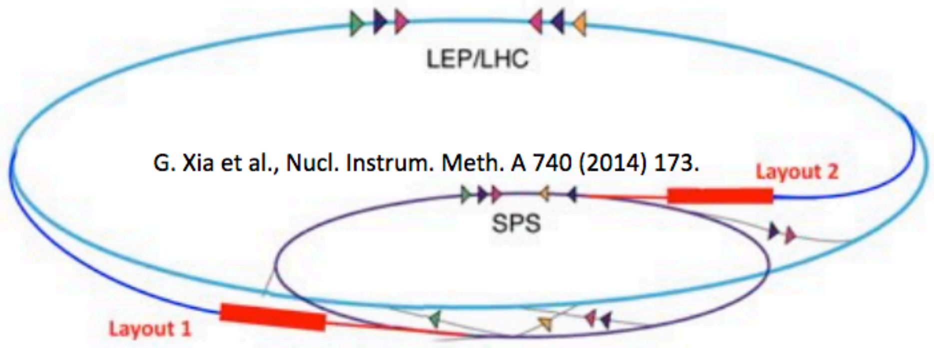
- Beam dump experiments
- Electron-proton collisions

Recently, we started investigating the use of protons beams to accelerate electrons for U.S. Electron-Ion Collider concept.





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} cm^{-2} s^{-1}.

Prospects for Future Colliders

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NEWS · 19 DECEMBER 2018

Plans for world's next major particle collider dealt big blow

Japanese science committee questions the project's multibillion-dollar price tag — but decision rests with the government.

Elizabeth Gibney

CLES

hrink plans for next major

"[the committee] stated that the scientific case for building the ILC was sound."

"The discoveries predicted to come out of the ILC would not fully warrant its nearly US $7-billion cost. Uncertainty about whether international partners would share the project's costs increased [the committee] concerns."

The New York Times

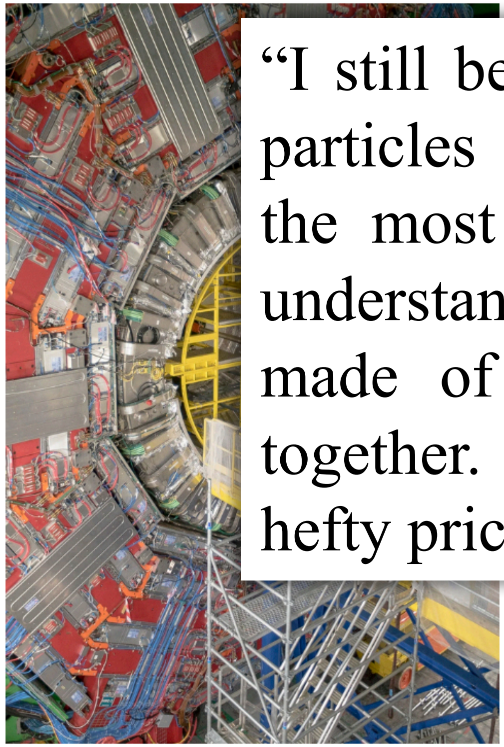
Opinion

The Uncertain Future of Particle Physics

Ten years in, the Large Hadron Collider has failed to deliver the exciting discoveries that scientists promised.

By Sabine Hossenfelder
Dr. Hossenfelder is a research fellow at the Frankfurt Institute for Advanced Studies.

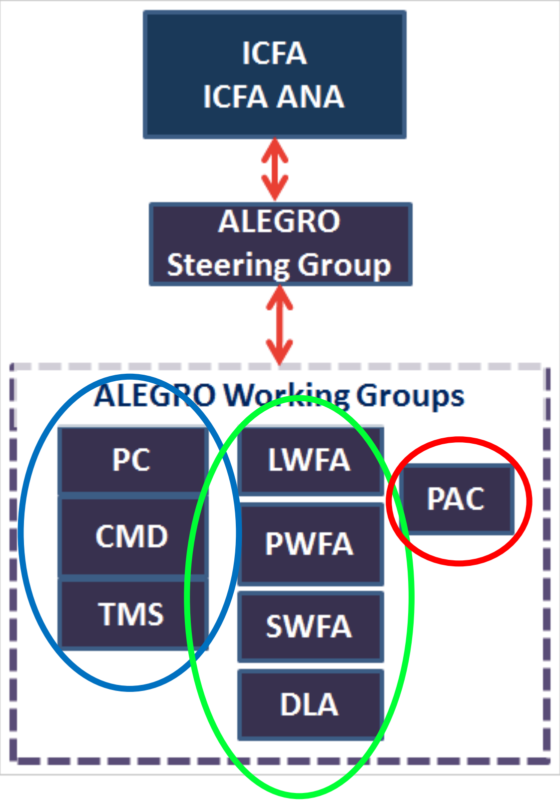
Jan. 23, 2019



"I still believe that slamming particles into one another is the most promising route to understanding what matter is made of and how it holds together. But $10 billion is a hefty price tag."

The Large Hadron Collider is the world's largest particle accelerator. It's a 16-mile-long underground ring, located at CERN in Geneva, in which protons collide at almost the speed of light.
Leslye Davis/The New York Times

ALEGRO: A Global Effort for an Advanced Linear Collider



The steering group is chaired by B. Cros, P. Muggli and C. Schroeder

ALEGRO is opened to interested scientists worldwide

ALEGRO WG titles and leaders:

PC: Physics Case (M. Peskin, J. Tian)

CMD: Collider Machine Design (A. Seryi, D. Schulte, H. Yamamoto)

TMS:Theory, Modelling, Simulations (JL. Vay, J. Vieira)

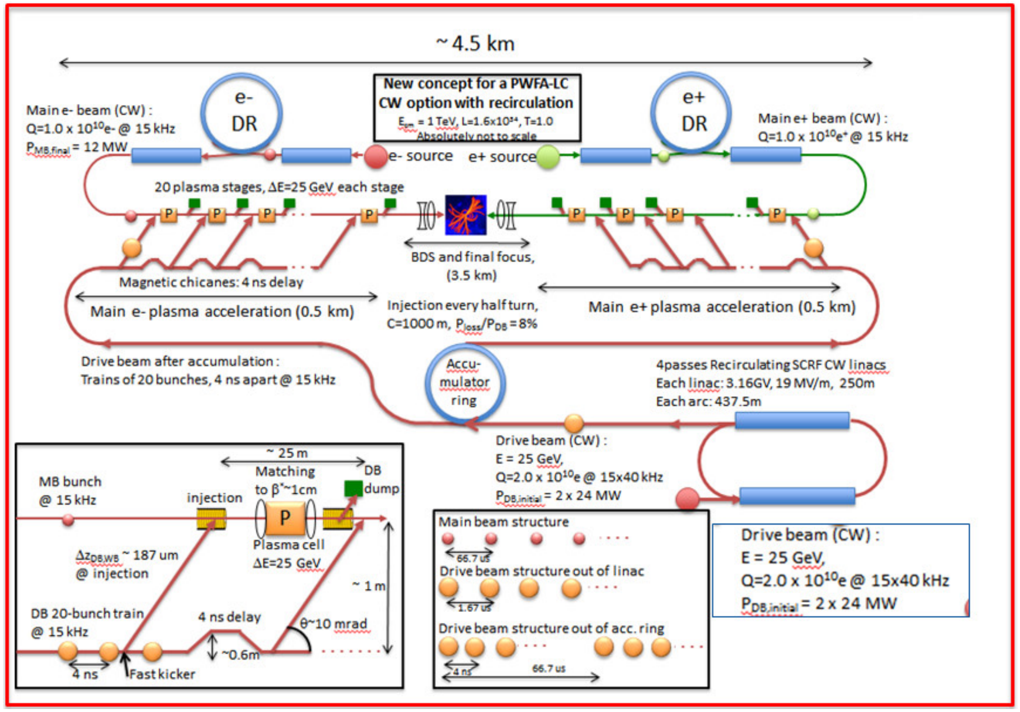
LWFA: Laser wakefield Accelerators (C. Schroeder, S. Hooker, B. Cros)

PWFA: Plasma wakefield Accelerators (J. Osterhoff, E. Gschwendtner, P. Muggli)

PAC: Positron acceleration (S. Gessner, S. Corde)

SWFA: Structure wakefield accelerator (P. Piot, J. Power)

DLA: Dielectric laser accelerator (J. England, B. Cowan)

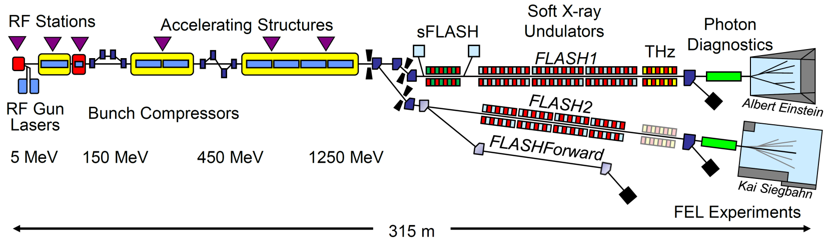


E. Adli, J.-P. Delahaye, S. J. Gessner, M. J. Hogan, T. Raubenheimer, W. An, C. Joshi, and W. Mori, arXiv:1308.1145 [physics.acc-ph]

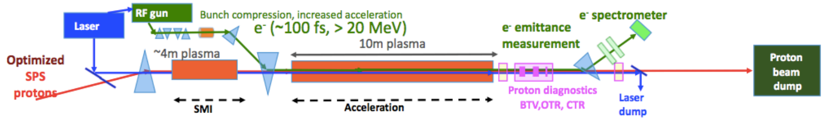
ALEGRO Mission: Identify and pursue the critical next steps on the path to an Advanced Linear Collider.

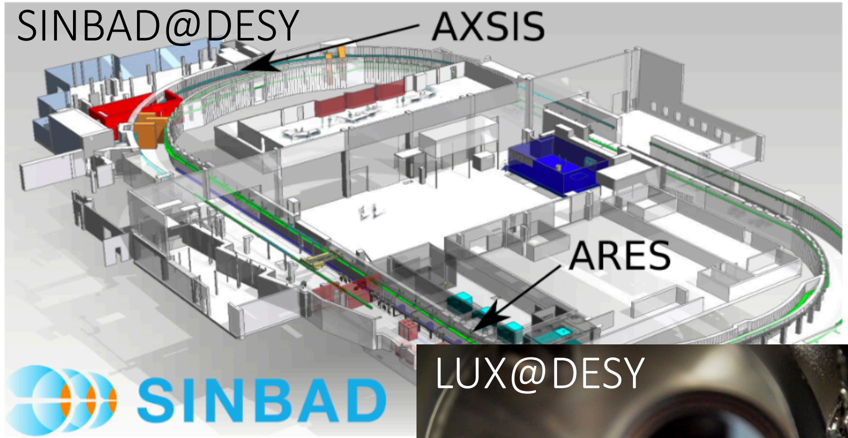
International Push for Plasma Acceleration Applications

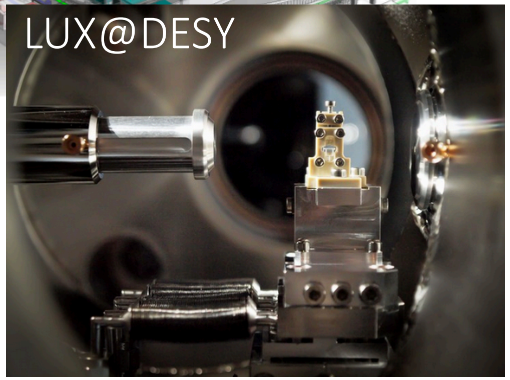
FLASHForward@DESY

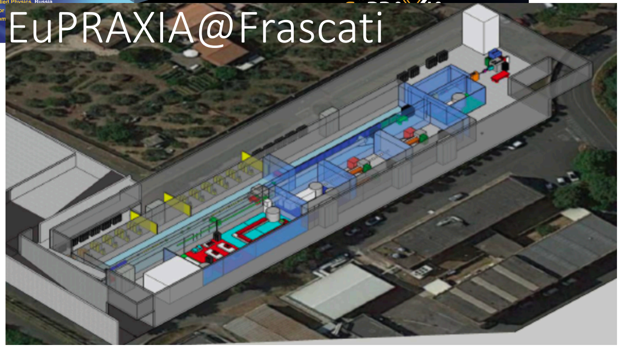


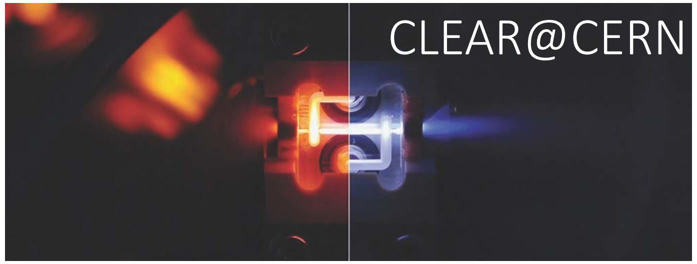
AWAKE Run-II@CERN



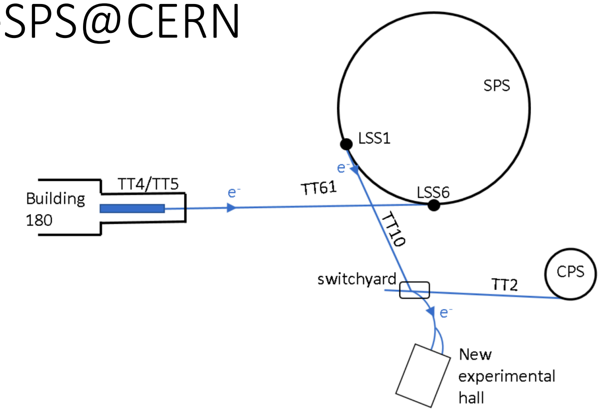




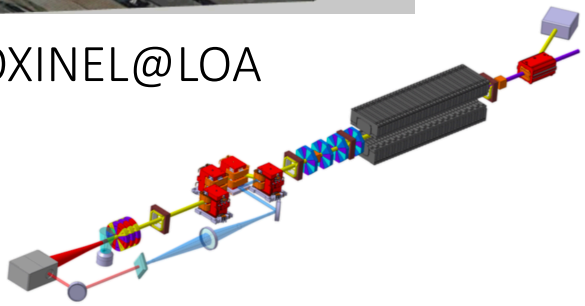




eSPS@CERN



COXINEL@LOA



The E.U., DESY, CERN, and others are pursuing projects on beam and laser driven plasma acceleration with an eye on near-term applications.

Conclusions

- SLAC is the birthplace of beam-driven Plasma Wakefield Acceleration.
- FACET-II aims to deliver high-quality beams from a plasma wakefield accelerator, and in doing so, will pave the way toward near-term applications of PWFA technology.
- FACET-II is the only facility that provides positron beams for PWFA experiments. The feasibility of plasma-based electron-positron linear collider will be determined by experiments carried out at FACET-II.

Thank You!

FACET End-of-Run Party 2016

AWAKE Collaboration Meeting, Novisibirsk, 2017

E200/E225 Collaboration (2016)

SLAC — J. M. Allen, C. I. Clarke, J.-P. Delahaye, J. Frederico, S. Gessner, S. Z. Green, M. Hogan, M. Litos, B. O'Shea, V. Yakimenko

UCLA — W. An, C. Clayton, C. Joshi, K. Marsh, W. Mori, N. Vafaei-Najafabadi

E. Adli, C. A. Lindstrom

S. Corde, A. Doche

W. Lu

PWFA Collaboration at FACET-II

SLAC — J. M. Allen, C. I. Clarke, C. Emma, S. Z. Green, M. Hogan, B. O'Shea, D. Storey, A. Sutherland, V. Yakimenko

UCLA — W. An, C. Clayton, H. Fujii, C. Joshi, K. Marsh, W. Mori, C. Zhang

E. Adli

École Polytechnique — S. Corde, P. San Miguel Claveria, O. Kononenko, G. Raj

M. Litos, R. Ariniello, C. Doss, K. Hunt-Stone

Stony Brook University — N. Vafei-Najafabadi, D. Amorim

W. Lu

CERN — S. Gessner, E. Gschwendtner

AWAKE Collaboration

AWAKE Collaboration: 18+2 Institutes world-wide:

Collaboration members:

- John Adams Institute for Accelerator Science
- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

Associated members:

- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

New Full members:

- Ulsan National Institute of Science and Technology (UNIST), Korea
- Phillipps-Universitaet Marburg, Germany