AWAKE

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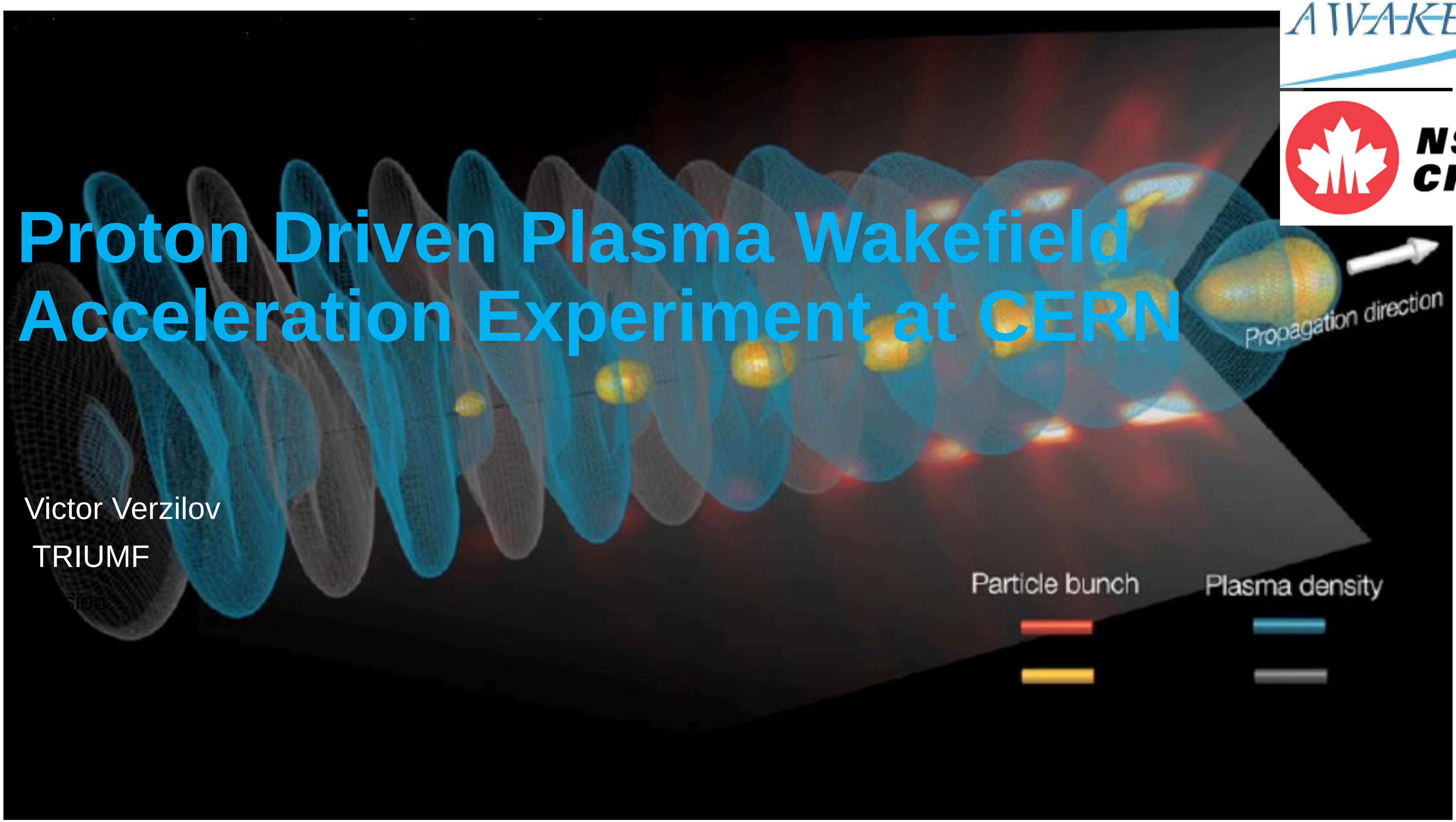
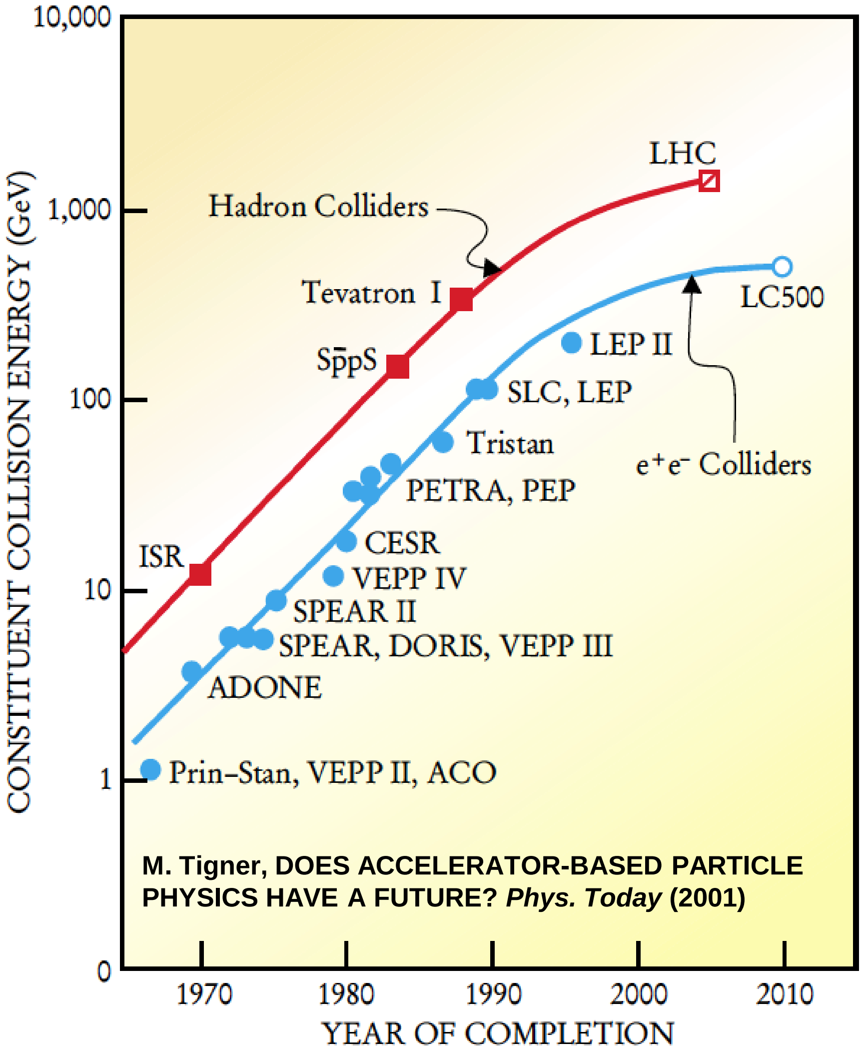


Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Victor Verzilov
TRIUMF

2022-06-06

DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE?

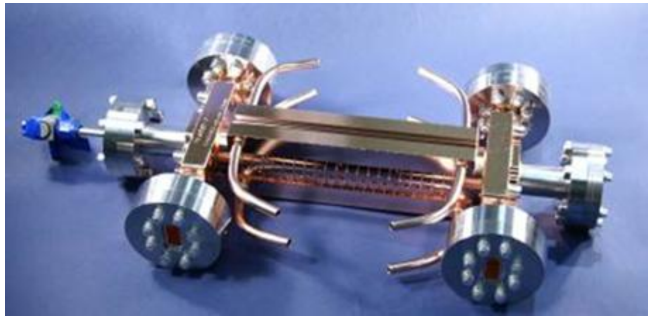


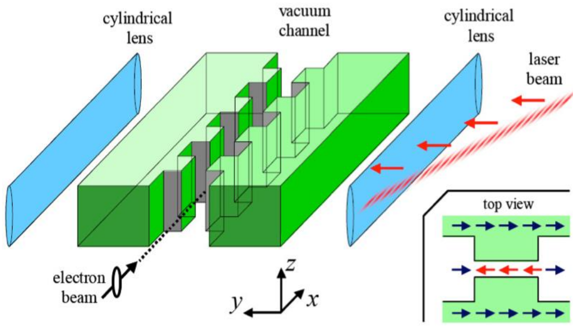
M. Tigner, DOES ACCELERATOR-BASED PARTICLE PHYSICS HAVE A FUTURE? *Phys. Today* (2001)

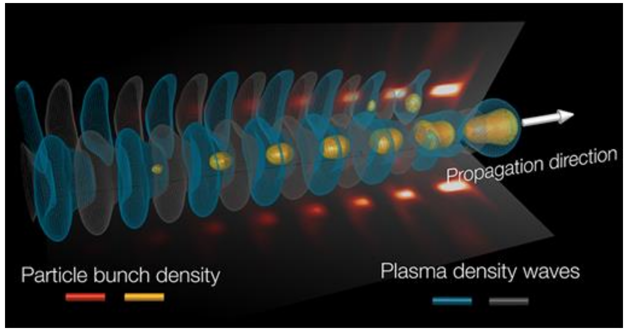
- Conventional high-energy accelerators approaching limits due to complexity, size and costs
- Any future TeV (>TeV) collider is a massive (to ultra-massive) project

Can new approaches and new acceleration concepts reduce the size (and, hence, cost) of a future accelerator?

Paths towards higher gradient accelerators







- RF-source driven microwave structures
- Beam-driven microwave structure

~100MV/m

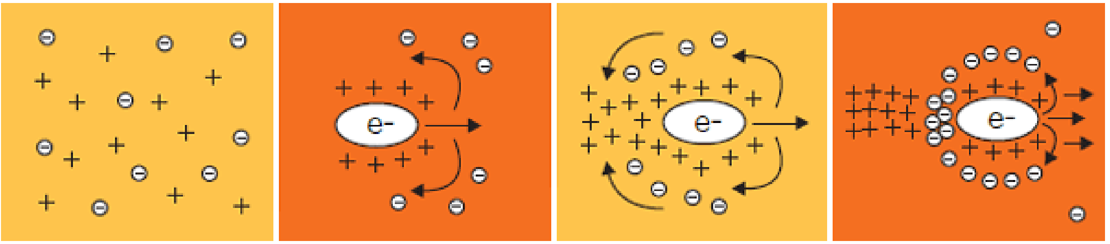
- Laser-driven dielectric structures
- Beam-driven dielectric structures

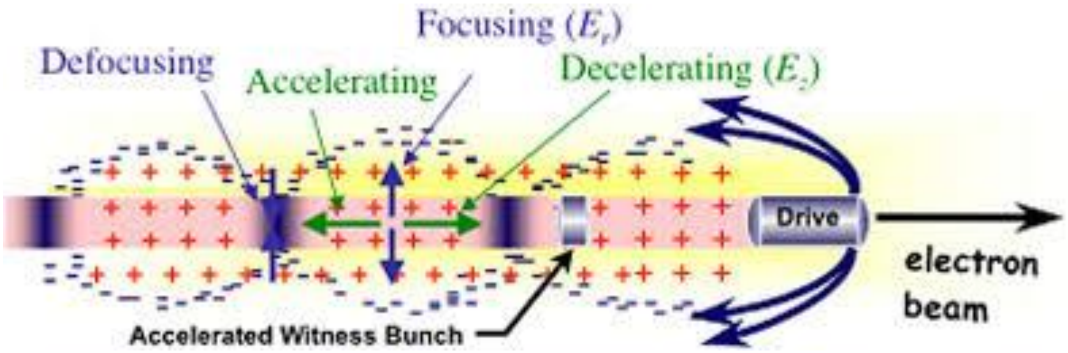
~1GeV/m

- Laser-driven plasma wakefields
- Beam-driven plasma wakefields

10 GeV/m and beyond

Plasma Acceleration



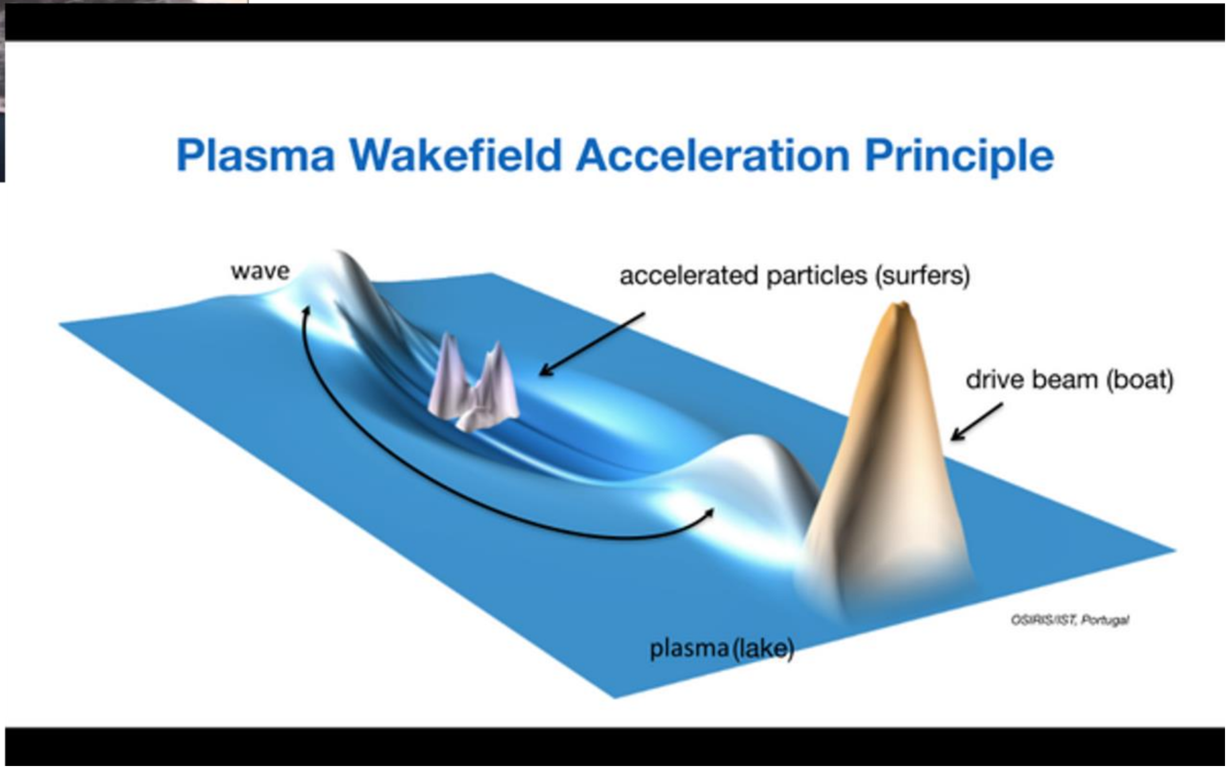


$$\boxed{E_z \sim \left(\frac{mc\omega_p}{e}\right) \approx (96V/m)\sqrt{n_0[cm^{-3}]}}$$

$$n_0 \sim 10^{14} - 10^{18} [cm^{-3}]$$

- Laser or charged particles beams drive time-varying electrical fields (wakefields) in plasmas by displacing plasma electrons.
- Electron density perturbation follows the drive beam in a form of plasma waves with a plasma frequency $\omega_p = \sqrt{4\pi n_0 e^2/m_e}$
- Both longitudinal and transverse field components are formed. A witness beam has to be properly placed into the wave.
- Practically, driver and witness beams have to be small compared to the plasma wave wavelength.
- The maximum longitudinal electric field is of the order of the wave-breaking limit ~1-100 GV/m depending on the plasma density.

Picturized

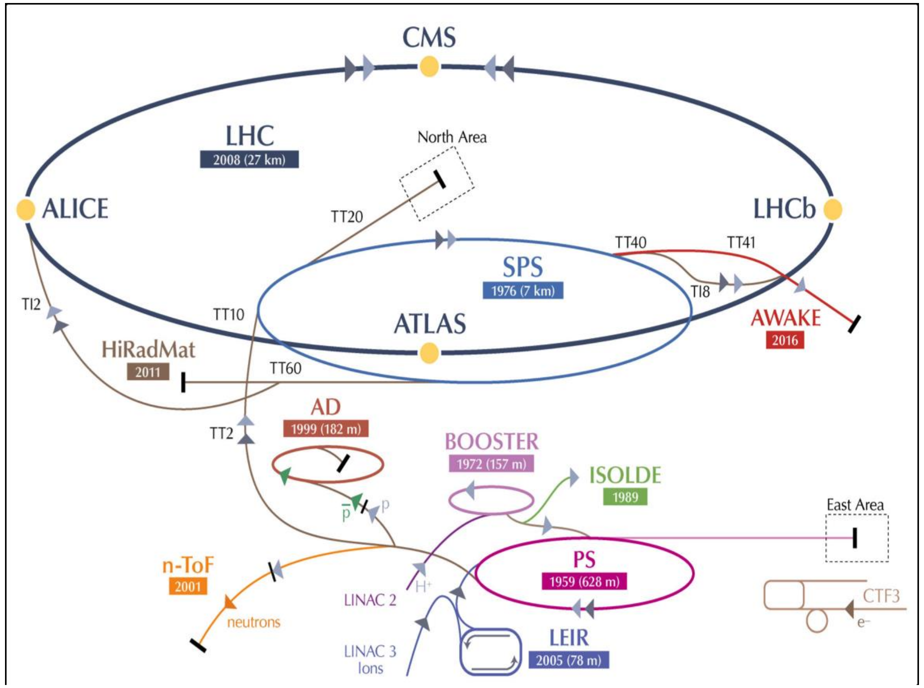


Plasma Wakefield Acceleration Principle

OSIRIS/IST, Portugal

What is AWAKE

- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - First proton driven plasma wakefield experiment
  - The AWAKE facility is installed in the former CNGS (CERN Neutrinos to Gran Sasso)
  - Use SPS proton beam as a drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject external electron beam as witness beam
  - Develop technology for particle physics applications



AWAKE collaboration

AWAKE

AWAKE Collaboration: 18+3 Institutes world-wide:

Collaboration members:

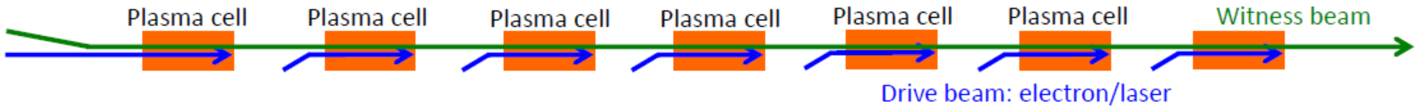
- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, 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 Universitéario 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

Associated members:

- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

Why protons?

- Generally speaking, plasma acts as an energy transformer; it transfers the energy from a driver to a witness bunch that is accelerated.
- A future linear electron accelerator, such as the ILC, will produce electron bunches **(0.5 TeV, 2e10 e+/e-)** carrying **1.6 kJ** each
  - Today's electron beams usually <100J (FACET beam is ~**60J**).
  - Most powerful BELLA laser ~ **40J**.



- Single SPS proton bunch **(0.4 TeV, 3e11 protons)**carries **19 kJ**
- Single LHC proton bunch **(7 TeV, 1.2e11 protons)**carries **120 kJ.** Full LHC beam carries about the same energy as a fully loaded A320 at a take-off speed

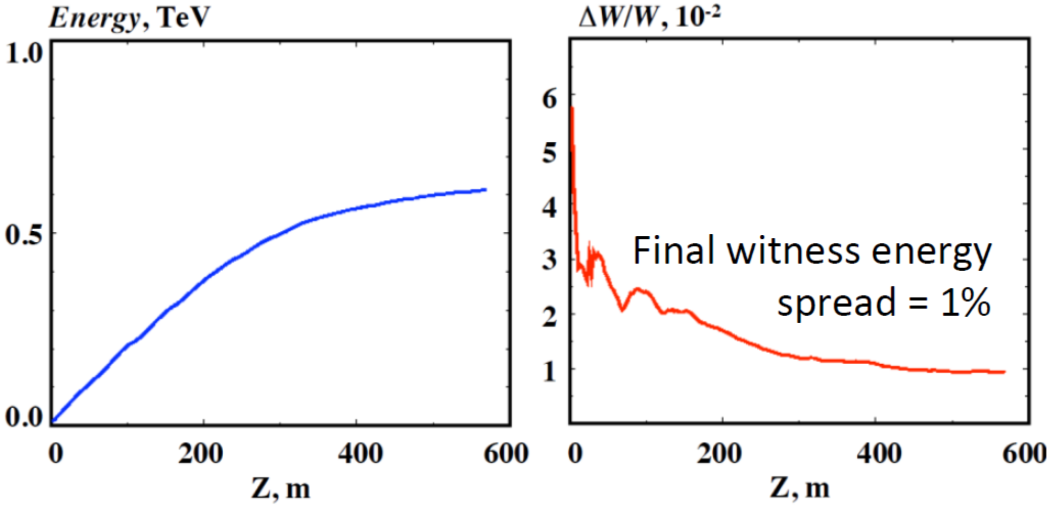
How the story started

Proof-of principle simulations

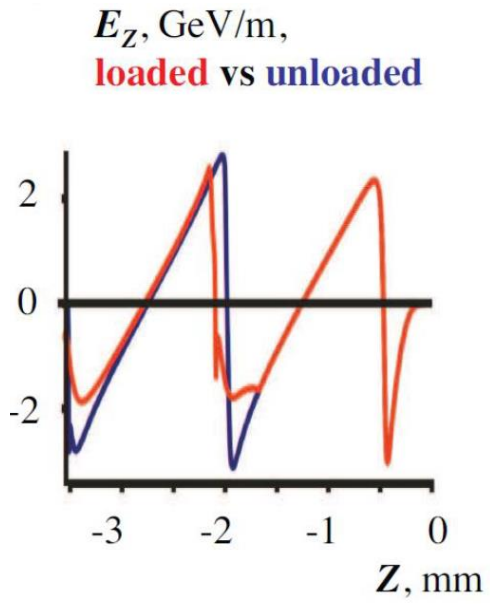
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics (2009)

Proton bunch driver: 10^{11} protons @ 1TeV, **σz = 0.1 mm**

Witness bunch of $1.5 \cdot 10^{10}$ electrons are accelerated to 650 GeV in 400 meters!



Final witness energy spread = 1%



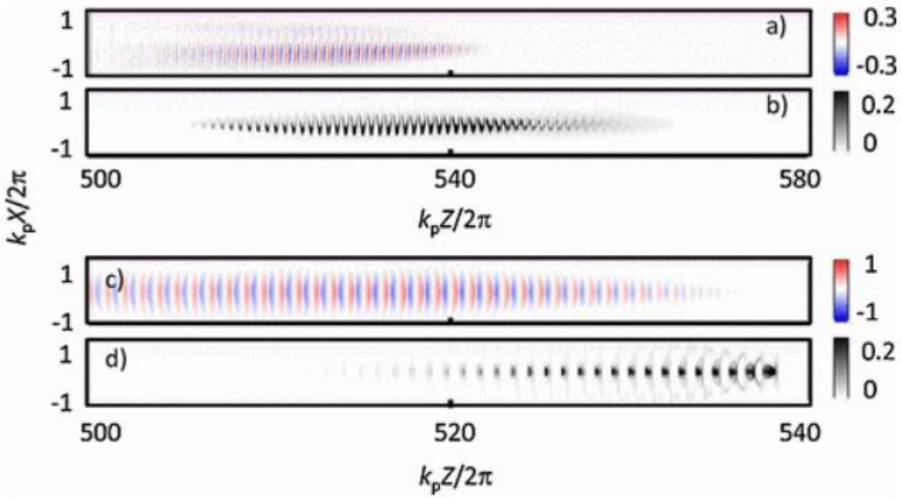
Unfortunately compressing 12 cm long LHC bunch down to **σz = 0.1 mm** is very challenging and expensive (although technically possible).

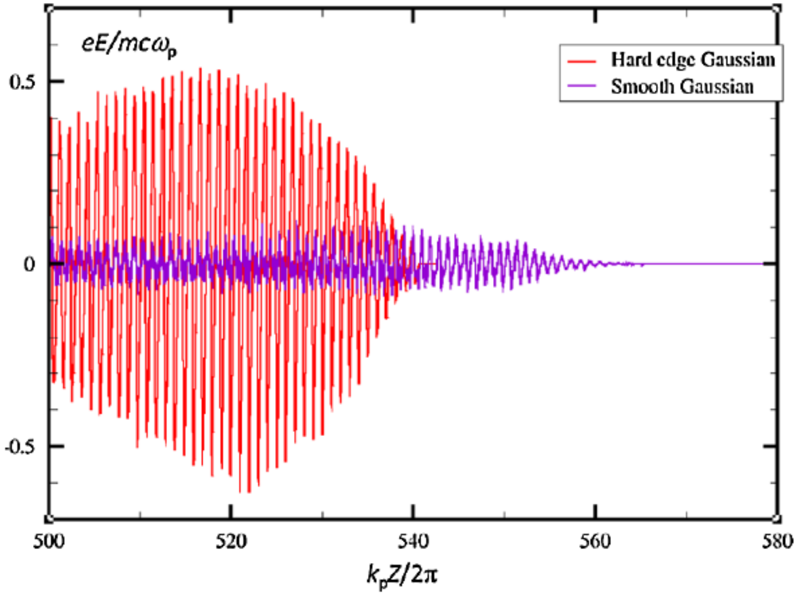
Self-modulation Instability (SMI)

N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010)

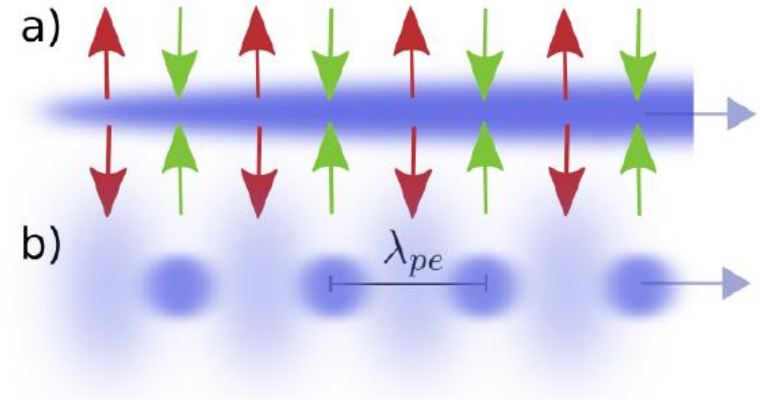
- A long proton bunch ($L > \lambda_p$) generates a wake within its body, which modulates the bunch itself.
- This self-modulation splits the long proton beam into ultrashort bunches of length λ_p.
- Remaining micro-bunches resonantly drive the plasma wake.

Hard edge beam is much more efficient than a smooth one.



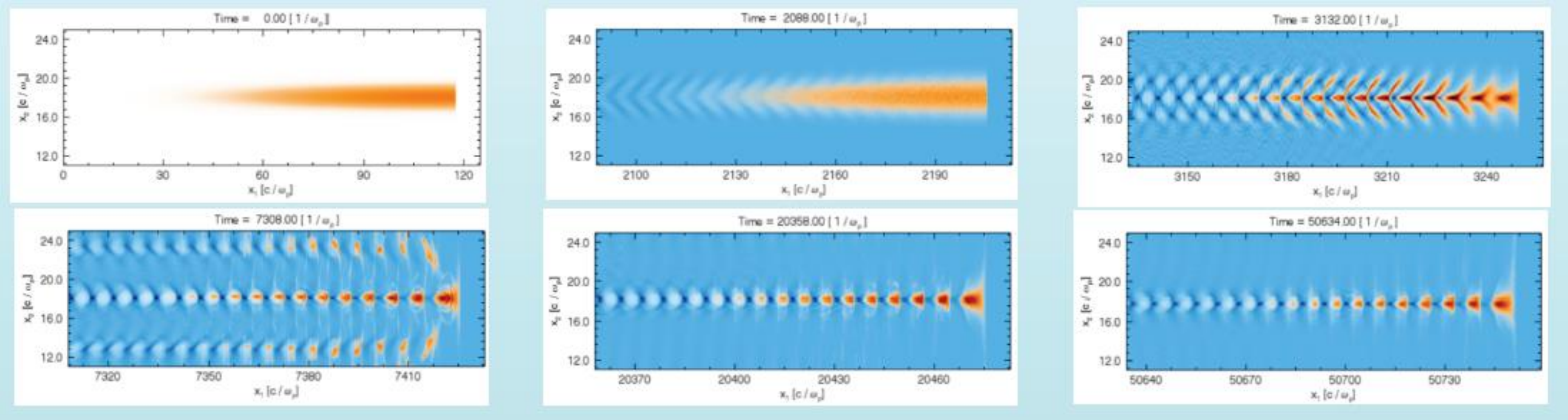


Self-modulation instability continued



- Self-modulation is a transverse effect. Different slices of the particle bunch are focused or defocused by generated wake-fields.

Vieira et al., Phys. Plasmas 19, 063105 (2012).



AWAKE experiment baseline parameters

SMI and seeding opened a possibility for the first proof-of-principle proton driven plasma wakefield experiment.

A short laser pulse seeds the SMI simulating hard edge bunch effect and ionizes plasma at the same time.

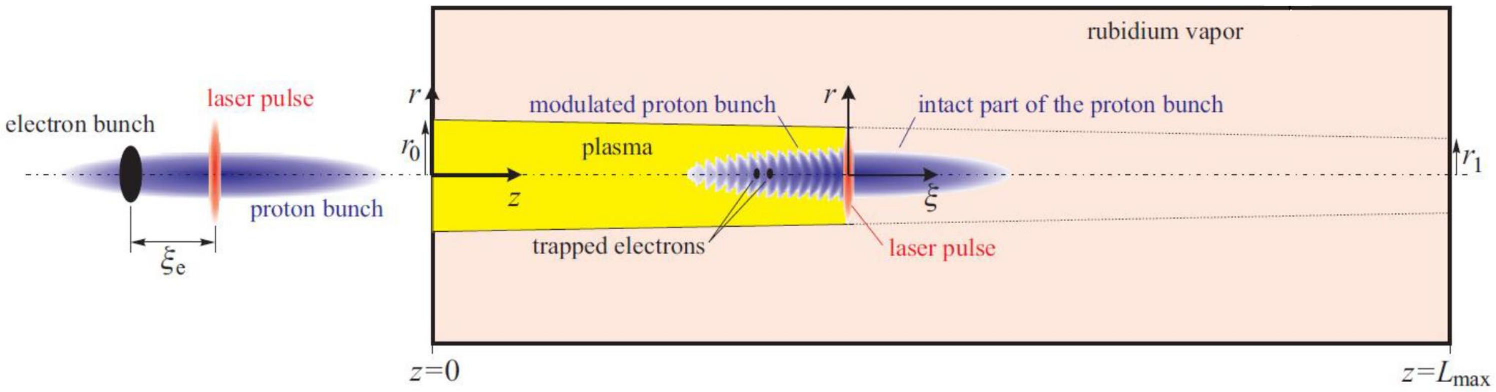
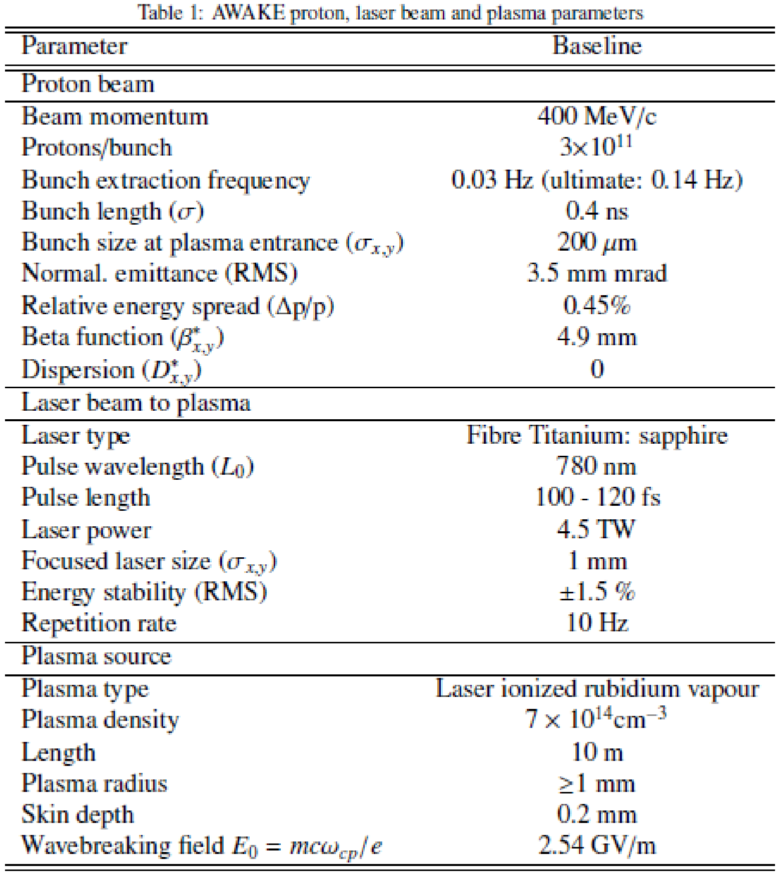
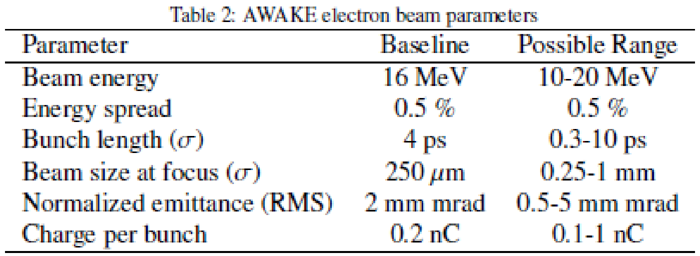


Table 1: AWAKE proton, laser beam and plasma parameters



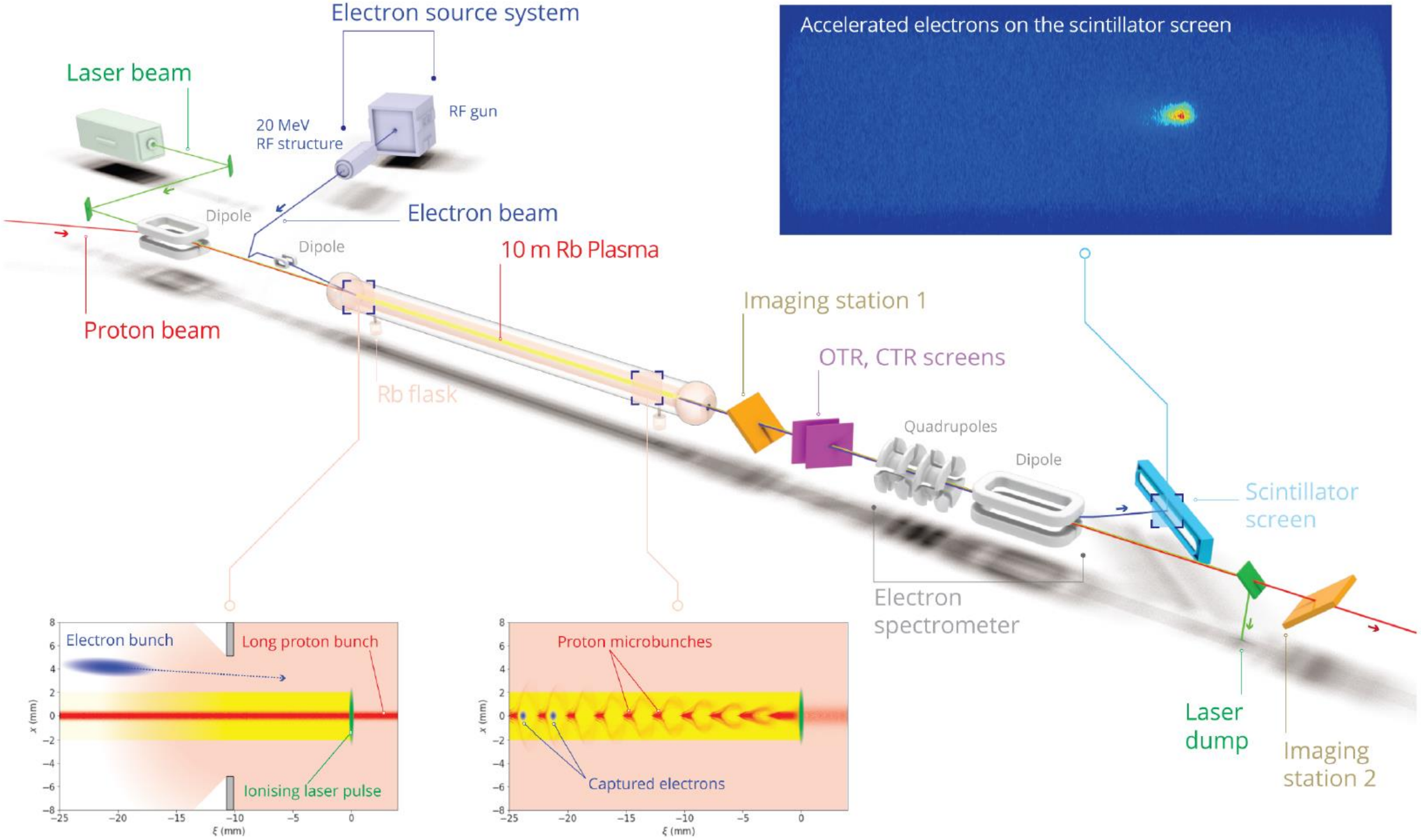
Parameter	Baseline
Proton beam	
Beam momentum	400 MeV/c
Protons/bunch	3×10^{11}
Bunch extraction frequency	0.03 Hz (ultimate: 0.14 Hz)
Bunch length (σ)	0.4 ns
Bunch size at plasma entrance ($\sigma_{x,y}$)	200 μm
Normal. emittance (RMS)	3.5 mm mrad
Relative energy spread (Δp/p)	0.45%
Beta function ($\beta^*_{x,y}$)	4.9 mm
Dispersion ($D^*_{x,y}$)	0
Laser beam to plasma	
Laser type	Fibre Titanium: sapphire
Pulse wavelength (L_0)	780 nm
Pulse length	100 - 120 fs
Laser power	4.5 TW
Focused laser size ($\sigma_{x,y}$)	1 mm
Energy stability (RMS)	±1.5 %
Repetition rate	10 Hz
Plasma source	
Plasma type	Laser ionized rubidium vapour
Plasma density	$7\times10^{14}\mathrm{cm}^{-3}$
Length	10 m
Plasma radius	≥1 mm
Skin depth	0.2 mm
Wavebreaking field $E_0 = mc\omega_{cp}/e$	2.54 GV/m

Table 2: AWAKE electron beam parameters

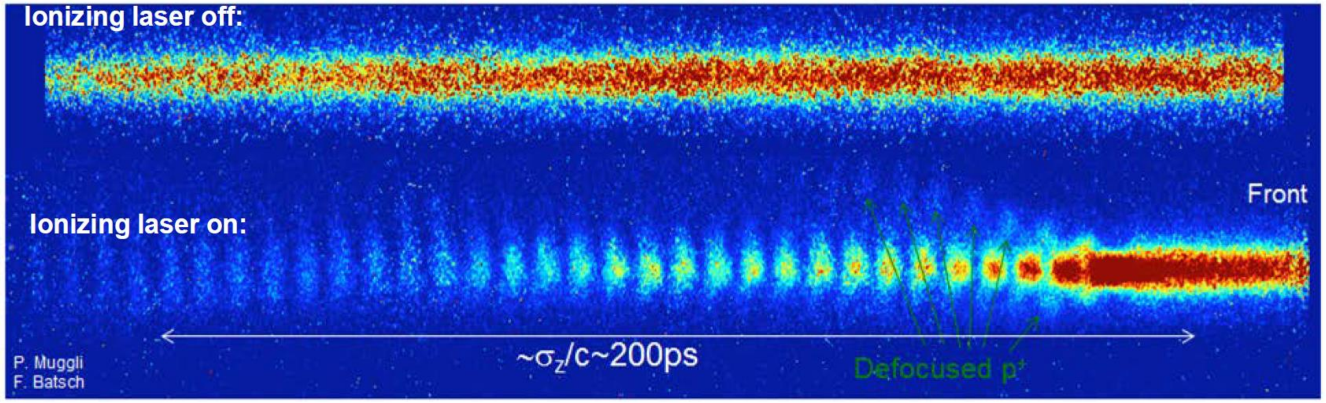


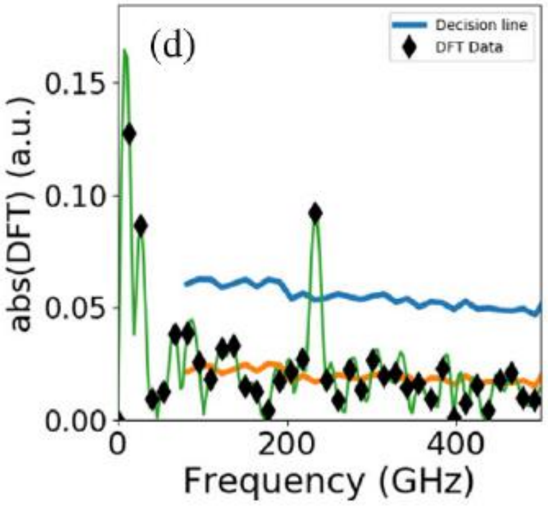
Parameter	Baseline	Possible Range
Beam energy	16 MeV	10-20 MeV
Energy spread	0.5 %	0.5 %
Bunch length (σ)	4 ps	0.3-10 ps
Beam size at focus (σ)	250 μm	0.25-1 mm
Normalized emittance (RMS)	2 mm mrad	0.5-5 mm mrad
Charge per bunch	0.2 nC	0.1-1 nC

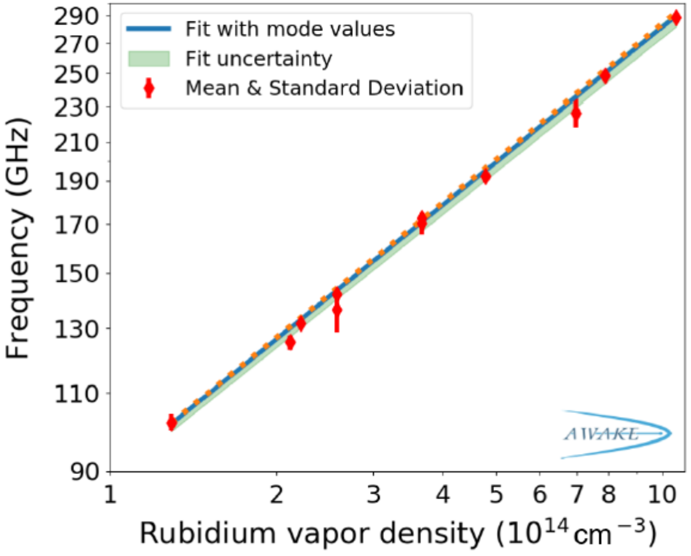
AWAKE Experiment Layout. Run 1



Experimental results. Observation of SSMI

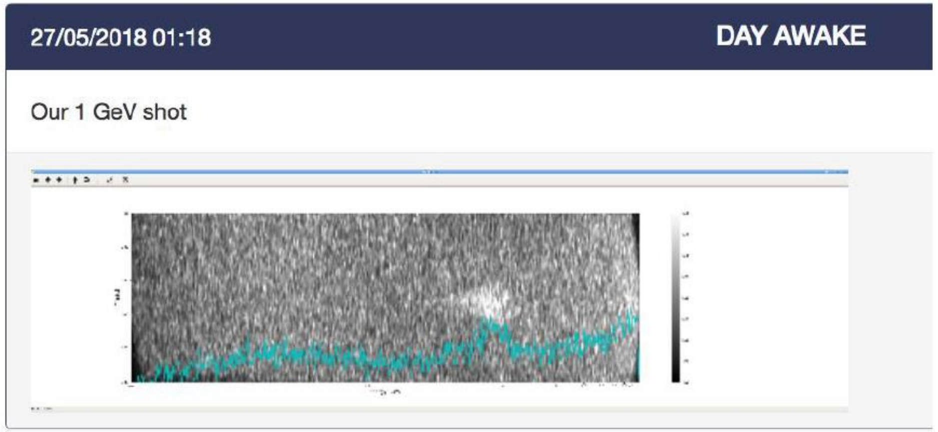






- First beam received in 2016
- Seeded self-modulation of the proton bunch observed in 2017
- Excellent agreement with theory

Experimental results. First acceleration



27/05/2018 01:18

DAY AWAKE

Our 1 GeV shot

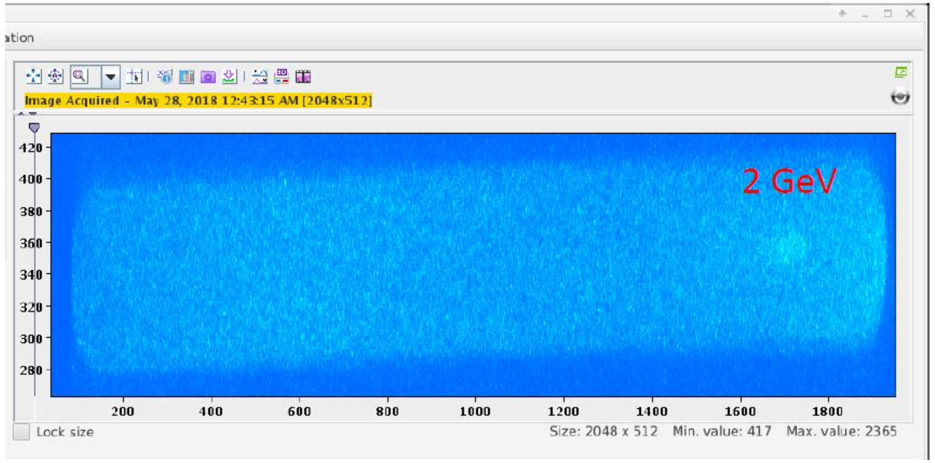
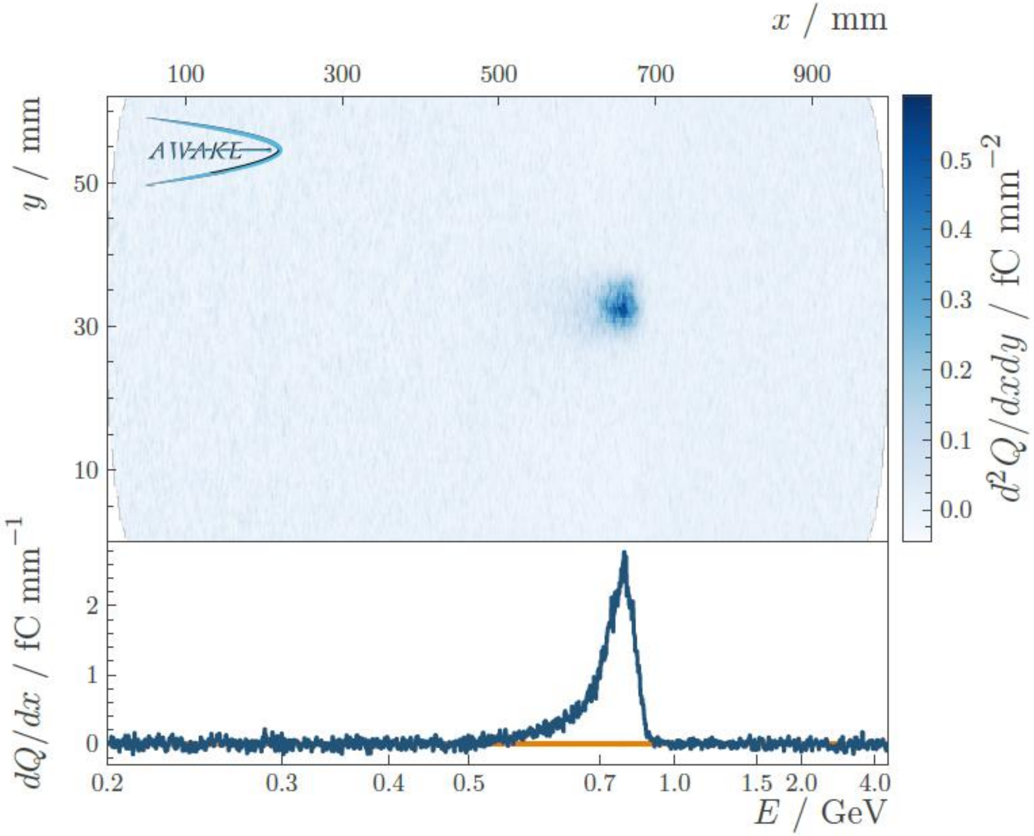


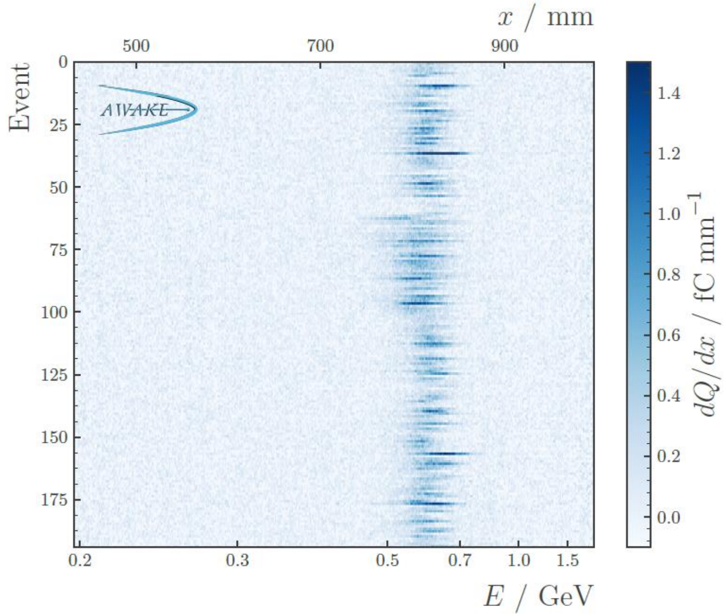
Image Acquired - May 28, 2018 12:43:15 AM [2048x512]

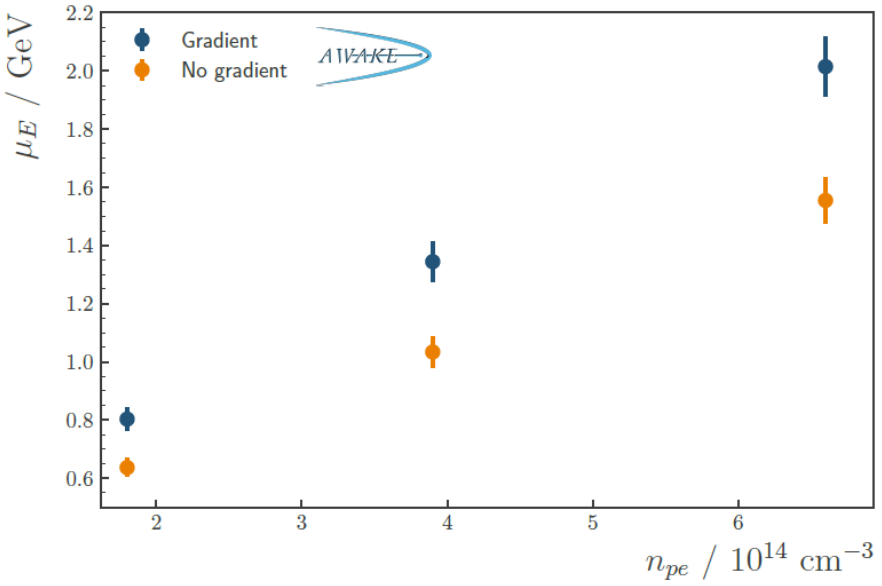
Size: 2048 x 512 Min. value: 417 Max. value: 2365

Experimental results. Electron acceleration summary.

AWAKE Collaboration, Nature 561, 363 (2018)



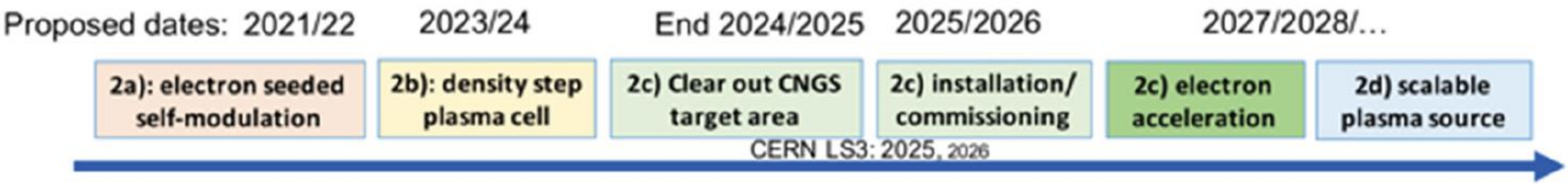




AWAKE Experiment. Run 2

- All goals for Run 1 were successfully completed.
- AWAKE Run 2 started in 2021 and aims to bring the technology to a point where particle physics applications based on the AWAKE scheme can be proposed and realized.
- For this purpose, the goals of Run 2 are to achieve high-charge bunches of electrons accelerated to high energy, at about ~1 GeV/m, while maintaining the beam quality through plasma and showing that the concept is scalable to long acceleration distance scales.

AWAKE Experiment. Run 2 phases



Proposed dates: 2021/22 | 2023/24 | End 2024/2025 | 2025/2026 | 2027/2028/…

2a): electron seeded self-modulation

2b): density step plasma cell

2c) Clear out CNGS target area

2c) installation/ commissioning

2c) electron acceleration

2d) scalable plasma source

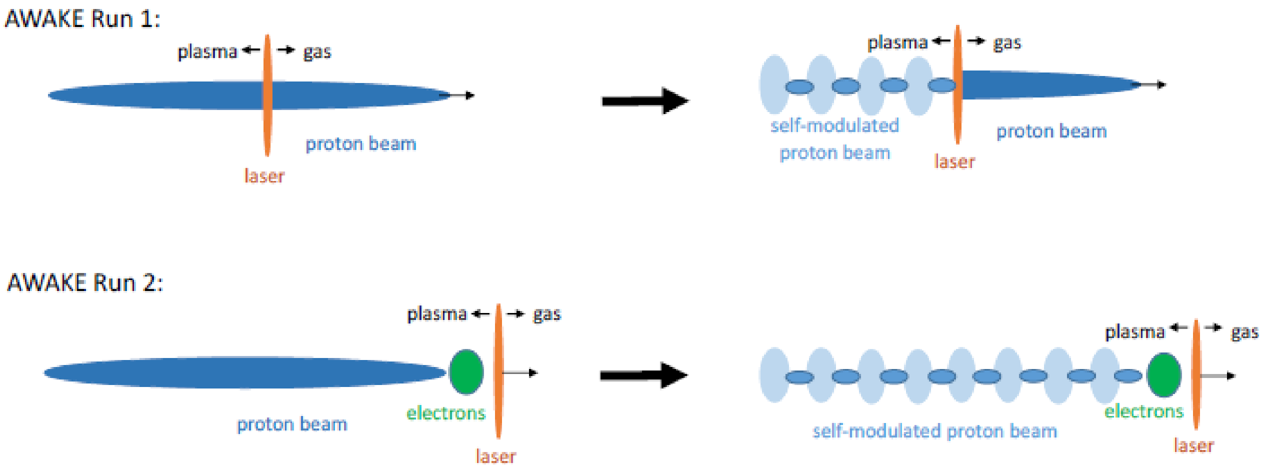
CERN LS3: 2025, 2026

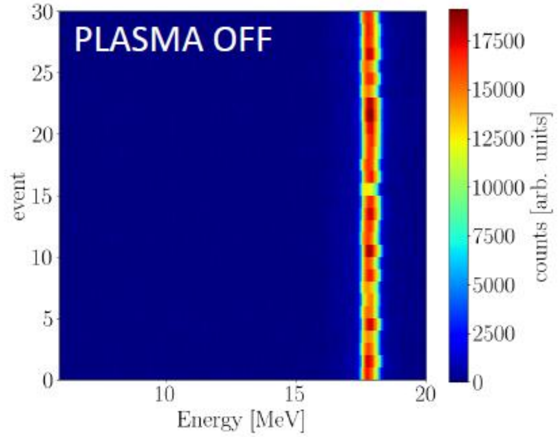
Following these goals, the AWAKE program of Run 2 is subdivided into four phases

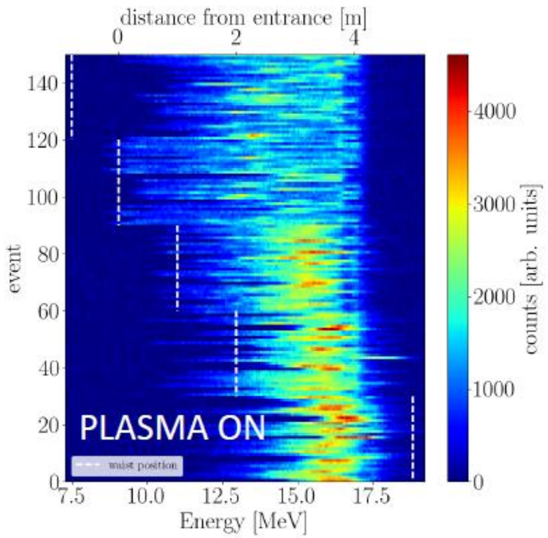
- Run 2a: Demonstration of the electron seeding of the proton bunch self-modulation in the first plasma source.
- Run 2b: Demonstration of the stabilization of microbunches with a plasma density step in the first plasma source.
- Run 2c: Demonstration of electron acceleration and emittance control.
- Run 2d: Demonstration of electron acceleration in scalable plasma sources.

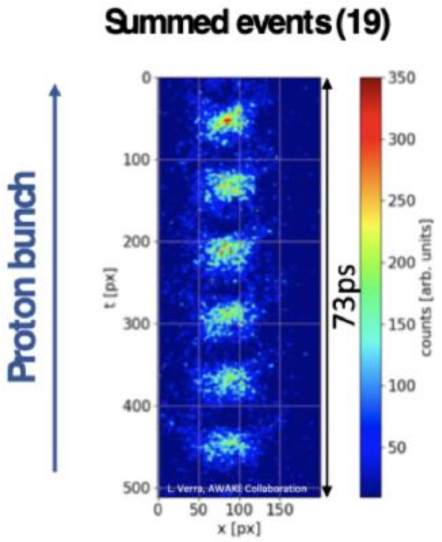
AWAKE Phase 2a

- To modulate the whole proton bunch wakefields have to be seeded ahead of it in pre-formed plasma.
- Seeding will be done by the existing electron beam.
- Initial results are encouraging.







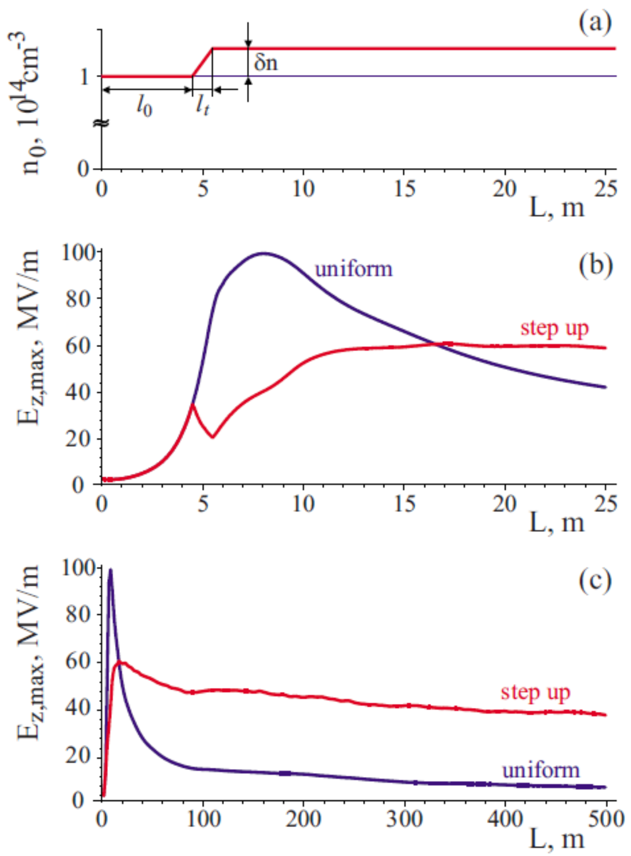


AWAKE Phase 2b

Controlled self-modulation of high energy beams in a plasma

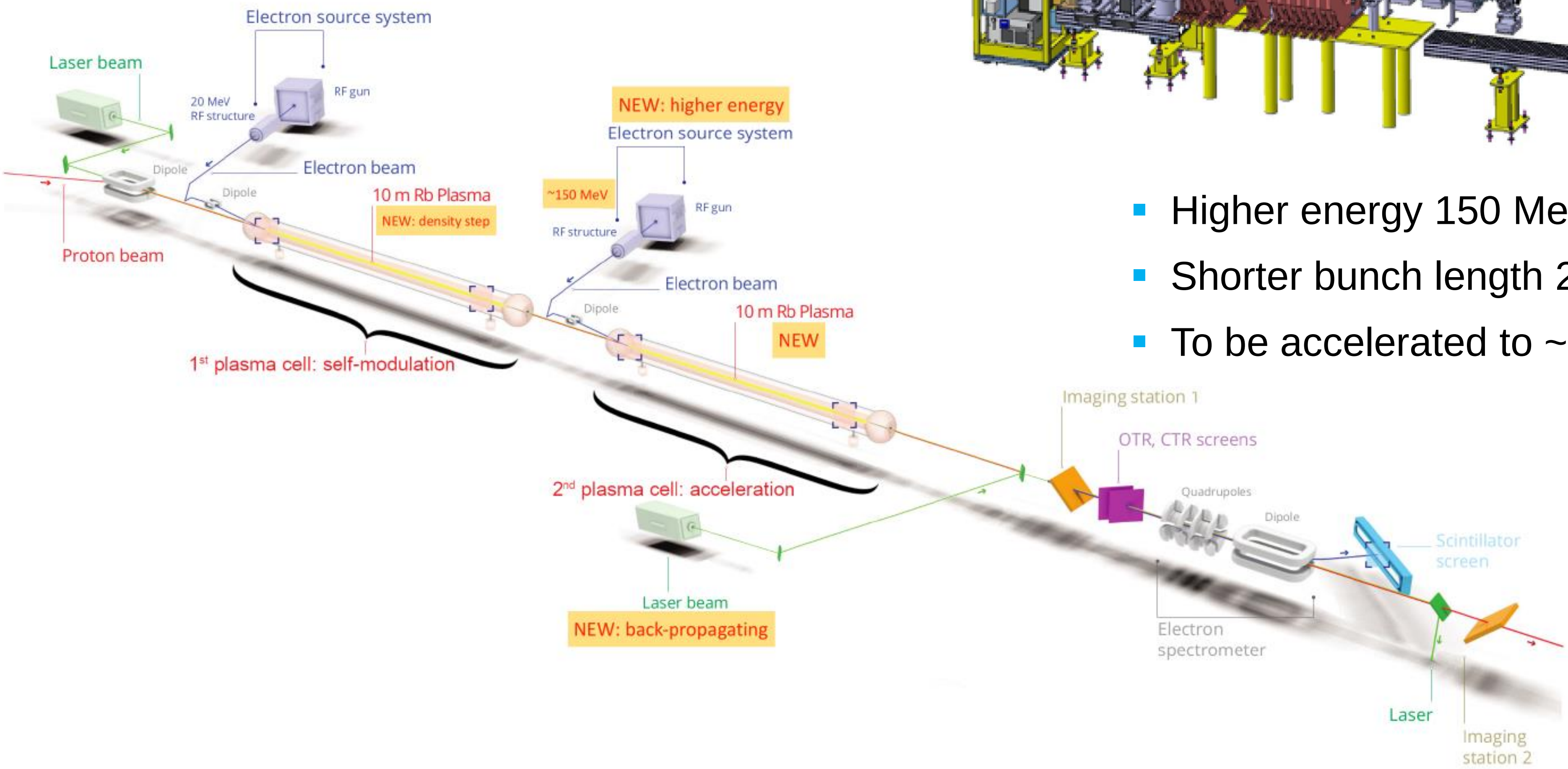
K. V. Lotov

Citation: Physics of Plasmas **18**, 024501 (2011); doi: 10.1063/1.3558697

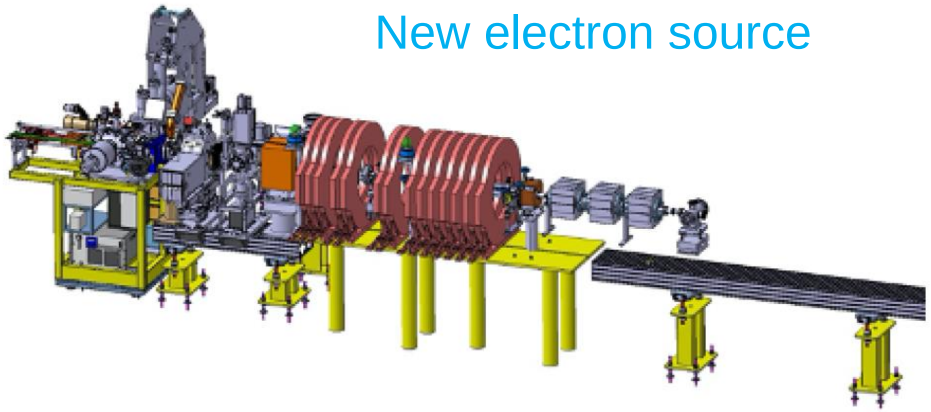


- Plasma waves move slower than protons
- A positive density step adjusts the phase velocity of plasma waves to control the SMI process
- In Rb plasma the density step is implemented as the temperature step

AWAKE Phase 2c and beyond



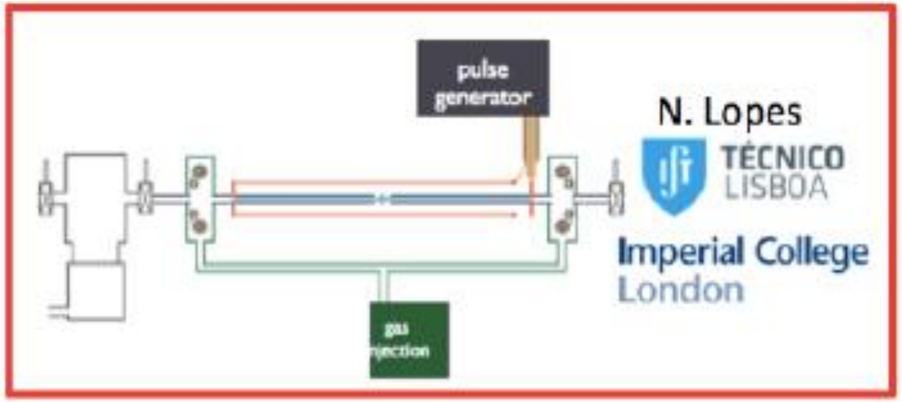
New electron source

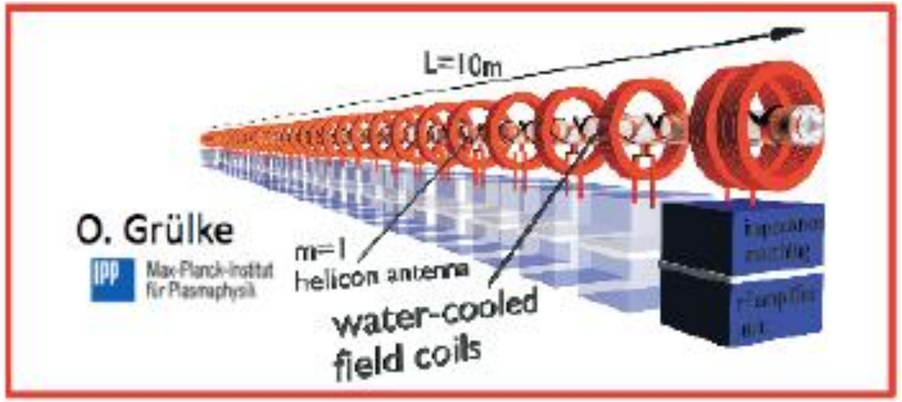


- Higher energy 150 Mev vs 18 Mev
- Shorter bunch length 200fs vs 3ps
- To be accelerated to ~ 10 GeV vs ~ 2GeV

Plasma scalability

- Laser pulse suffers from diffraction and energy depletion. Laser ionization is not scalable
- Discharge and Helicon plasma cell are considered as alternatives. However, the plasma uniformity is still to be proved.

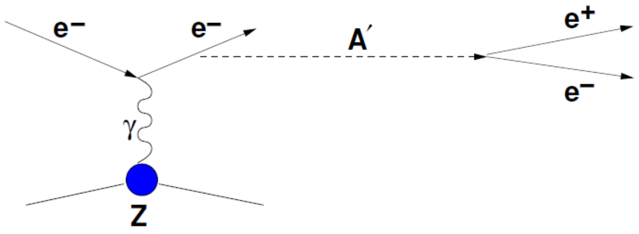


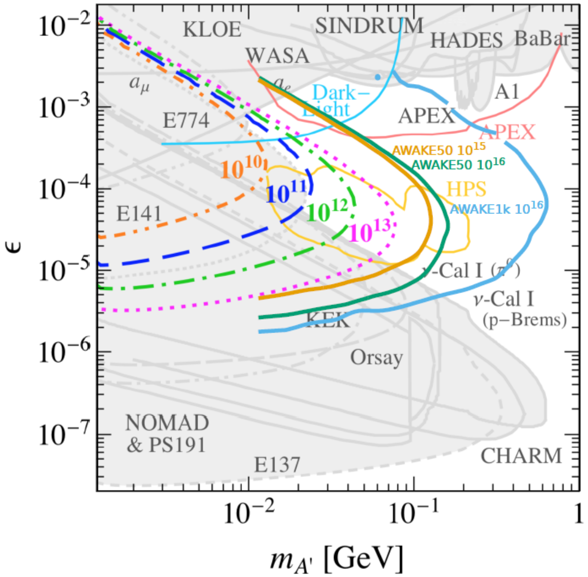


Particle Physics applications

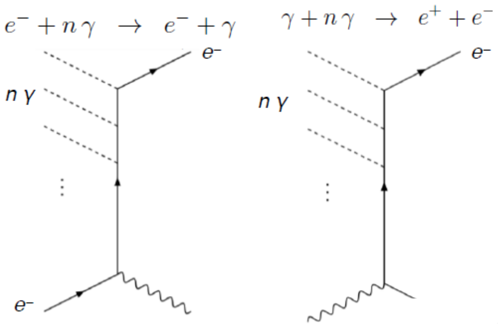
- 50 GeV with SPS and 3TeV in 4km with LHC

- Dark photon experiment

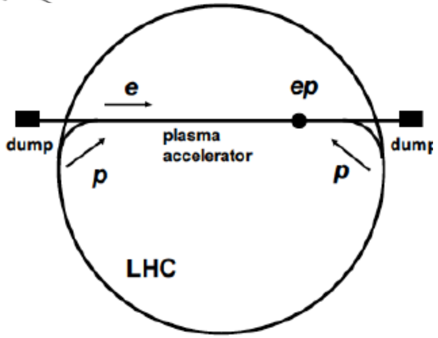


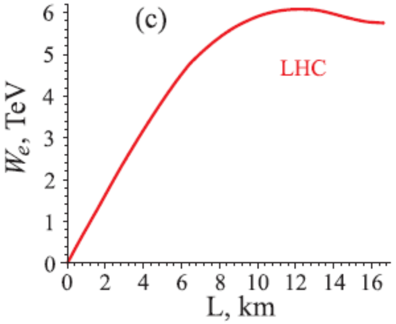


- Strong-field QCD near Schwinger critical field



- High-energy *ep/eA* collision





A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

Acknowledgements

- All presented results are obtained by collaborative efforts of > 100 scientists

AWAKE

- TRIUMF participation in the AWAKE experiment was made possible by NSERC

NSERC
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- TRIUMF management provided man-power and infrastructure

Thank you
Merci

Discovery, accelerated