



AWAKE: Accelerating Electrons to GeV in a Proton Driven Plasma Wakefield Experiment

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Outline

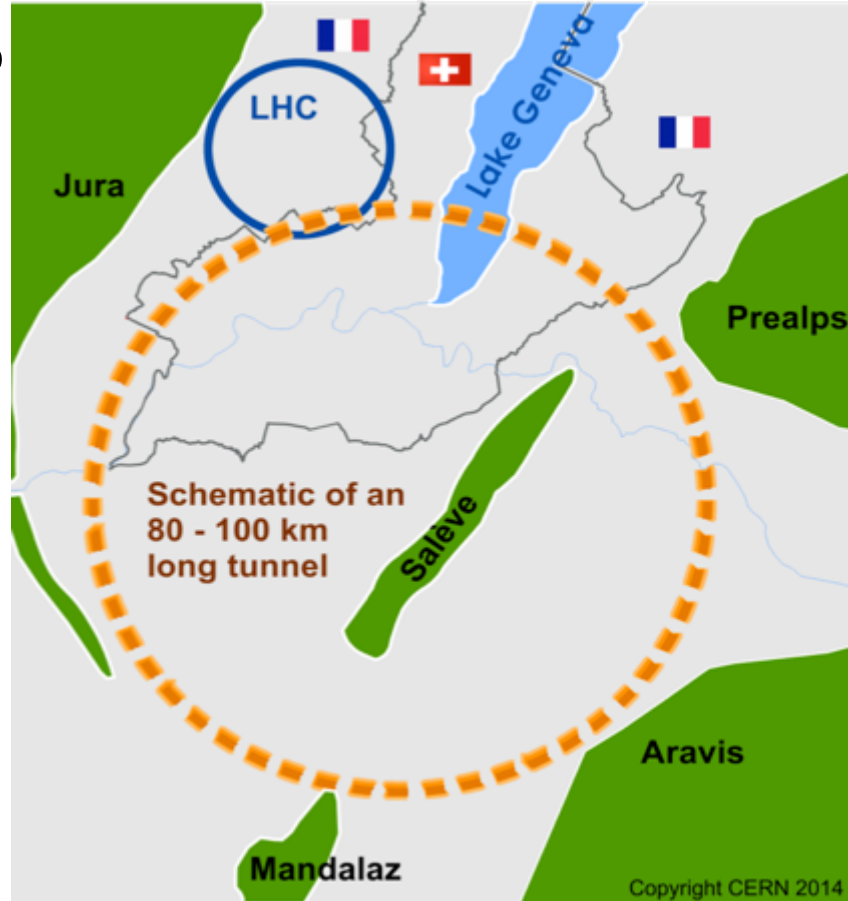
- Plasma Wakefield Acceleration
- AWAKE, The Advanced Wakefield Experiments
- AWAKE Results
- What's Next

Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

Future Circular Collider: FCC



Limitations of conventional circular accelerators:

- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

$$P_{synchr} = \frac{e^2}{6\pi\epsilon_0 c^7} \frac{E^4}{R^2 m^4}$$

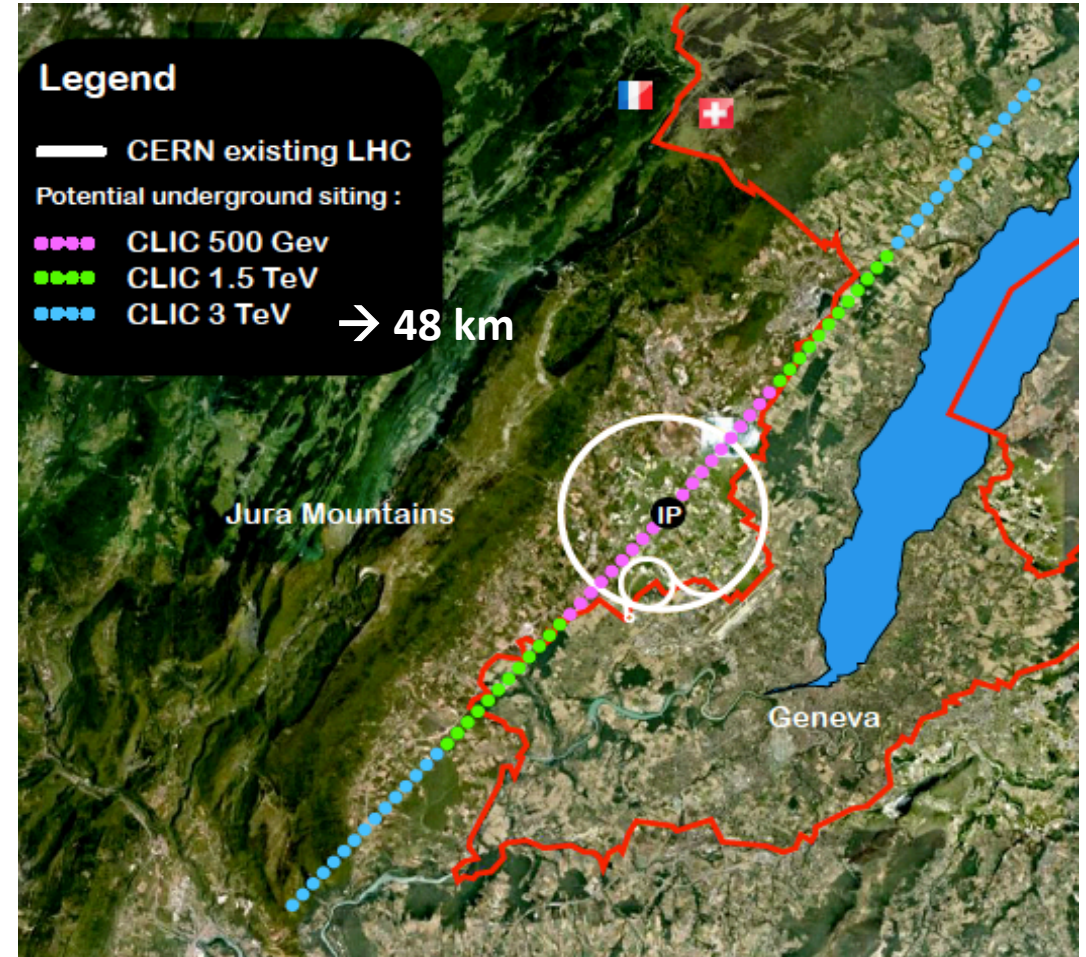
Discover New Physics

Linear colliders are favorable for acceleration of low mass particles to high energies.

CLIC, electron-positron collider with 3 TeV energy

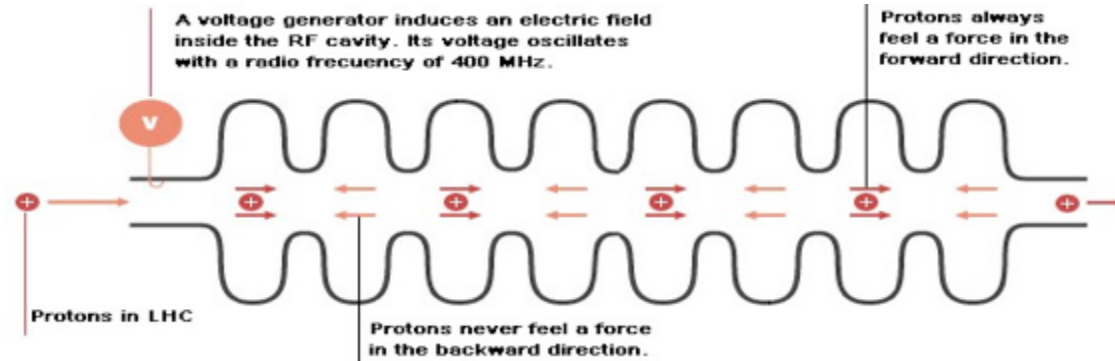
Limitations of linear colliders:

- Linear machines accelerate particles in a **single pass**. The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.



Conventional Acceleration Technology

Radiofrequency Cavities

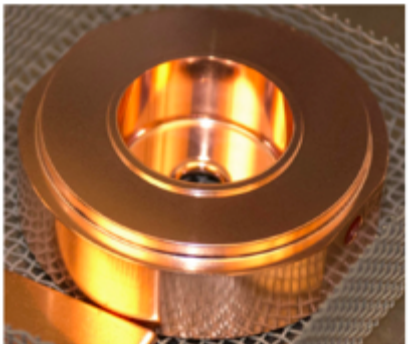


(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity



New RF Copper Cell



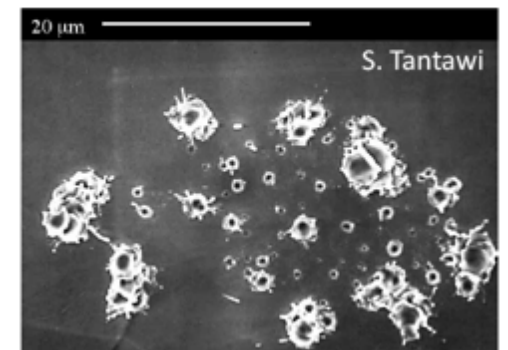
Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.

Accelerating fields are **limited to <100 MV/m**

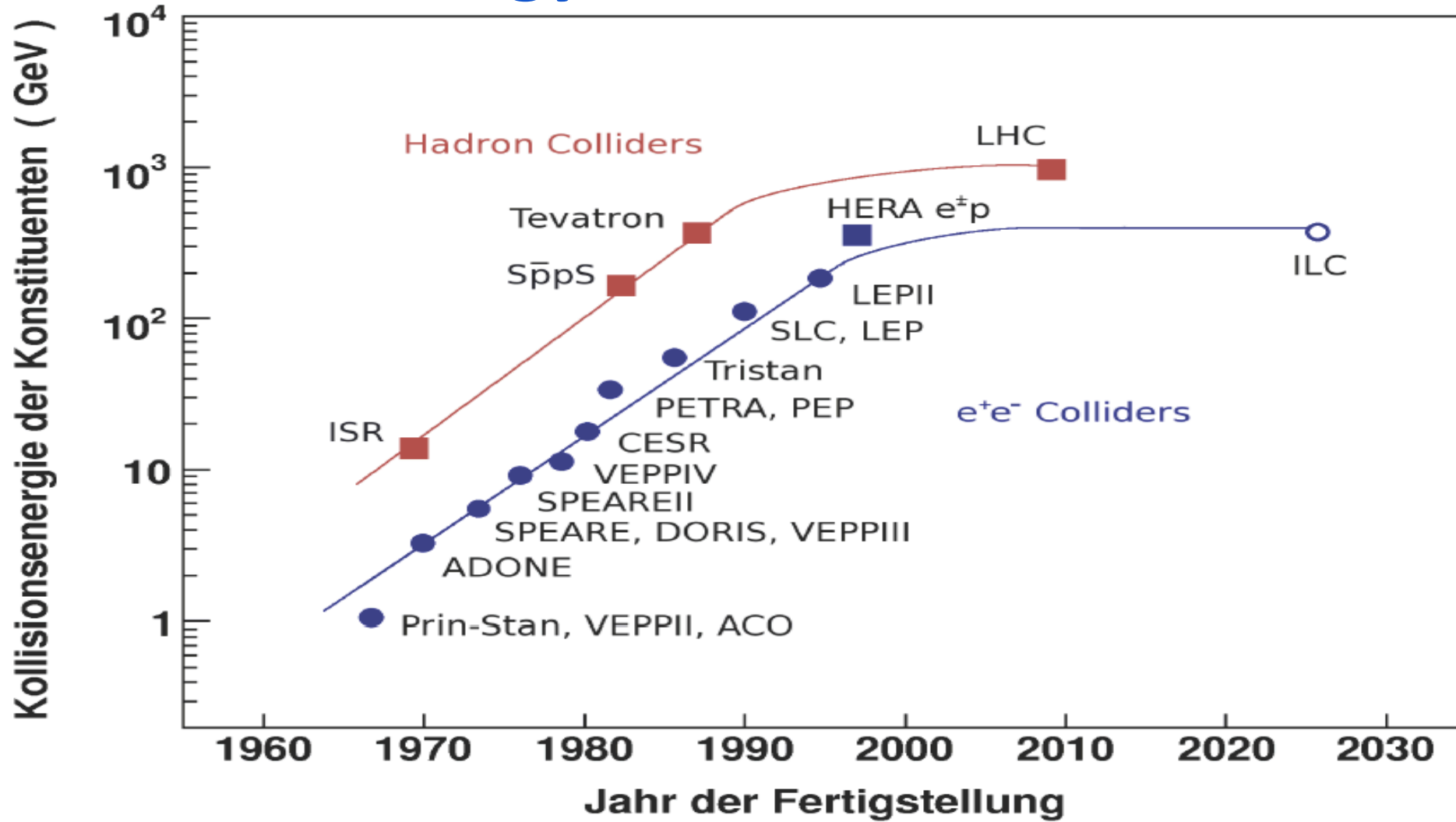
- In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge.
- Fields cannot be sustained, structures might be damaged.

➔ **several tens of kilometers for future linear colliders**

Surface of Copper Cell After Breakdown Events



Saturation at Energy Frontier for Accelerators



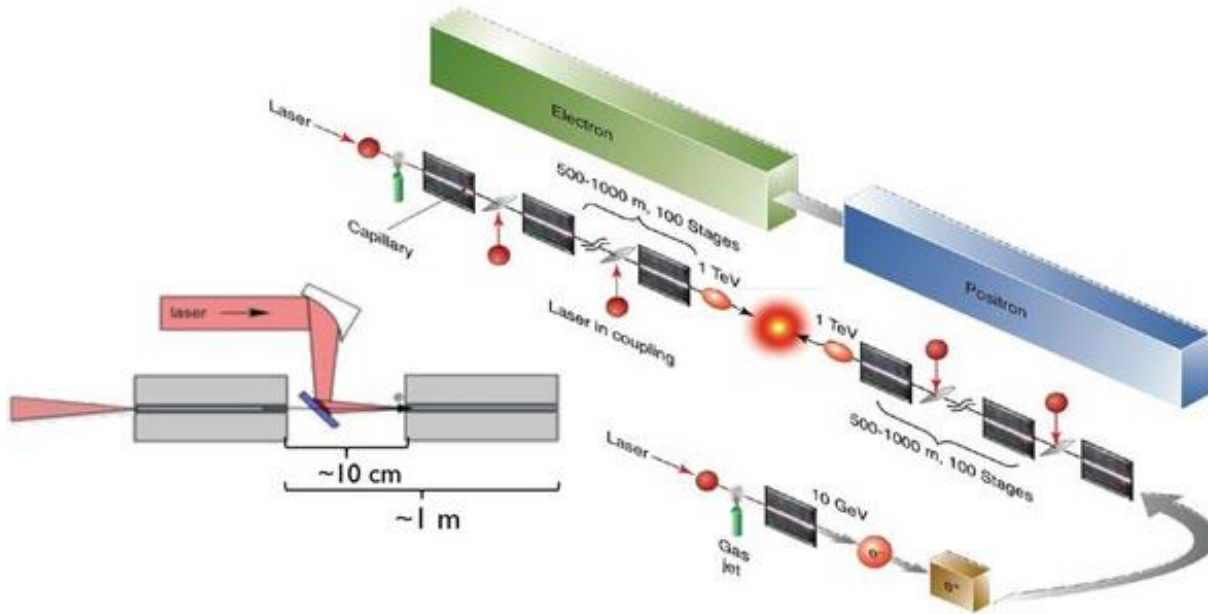
➔ Project size and cost increase with energy

Plasma Wakefield Acceleration

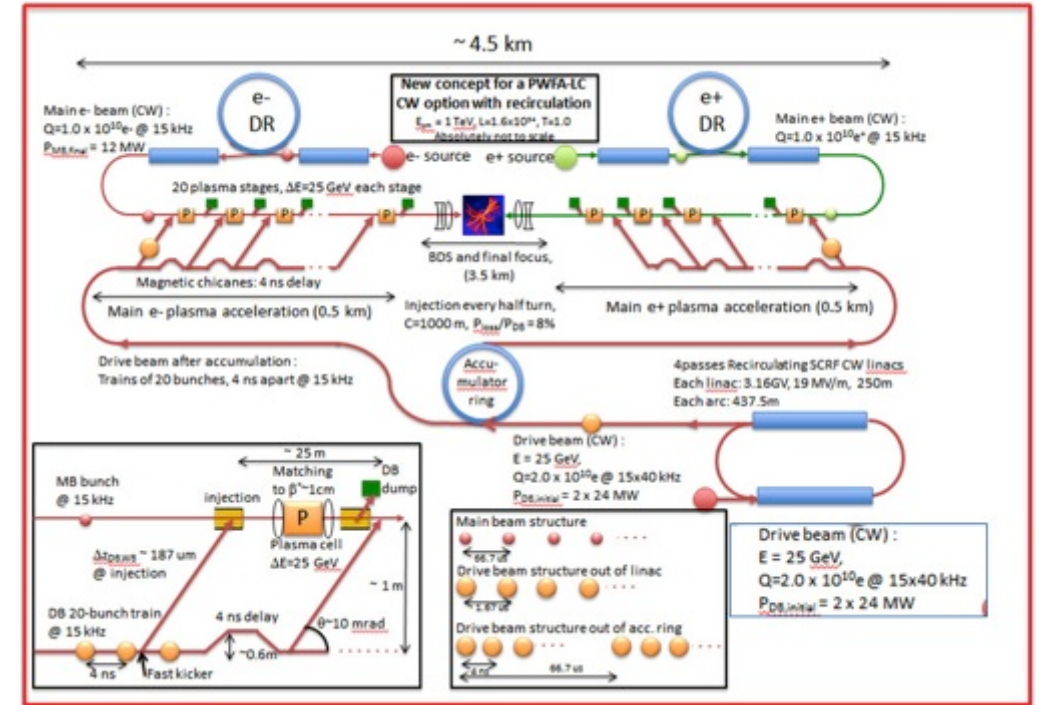


➔ Acceleration technology, which obtains ~ 1000 factor stronger acceleration than conventional technology.

Plasma Based Linear Colliders



C. B. Schroeder *et al.* Phys. Rev. ST Accel. Beams **13**, 101301



E. Adli *et al.*, arXiv:1308.1145 [physics.acc-ph]

In 2011 and 2013, the plasma acceleration groups from Berkeley and SLAC put forward white papers for laser and beam-driven plasma-based linear colliders. → **3 TeV in ~5km.**

Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4

PHYSICAL REVIEW LETTERS

23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18} W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

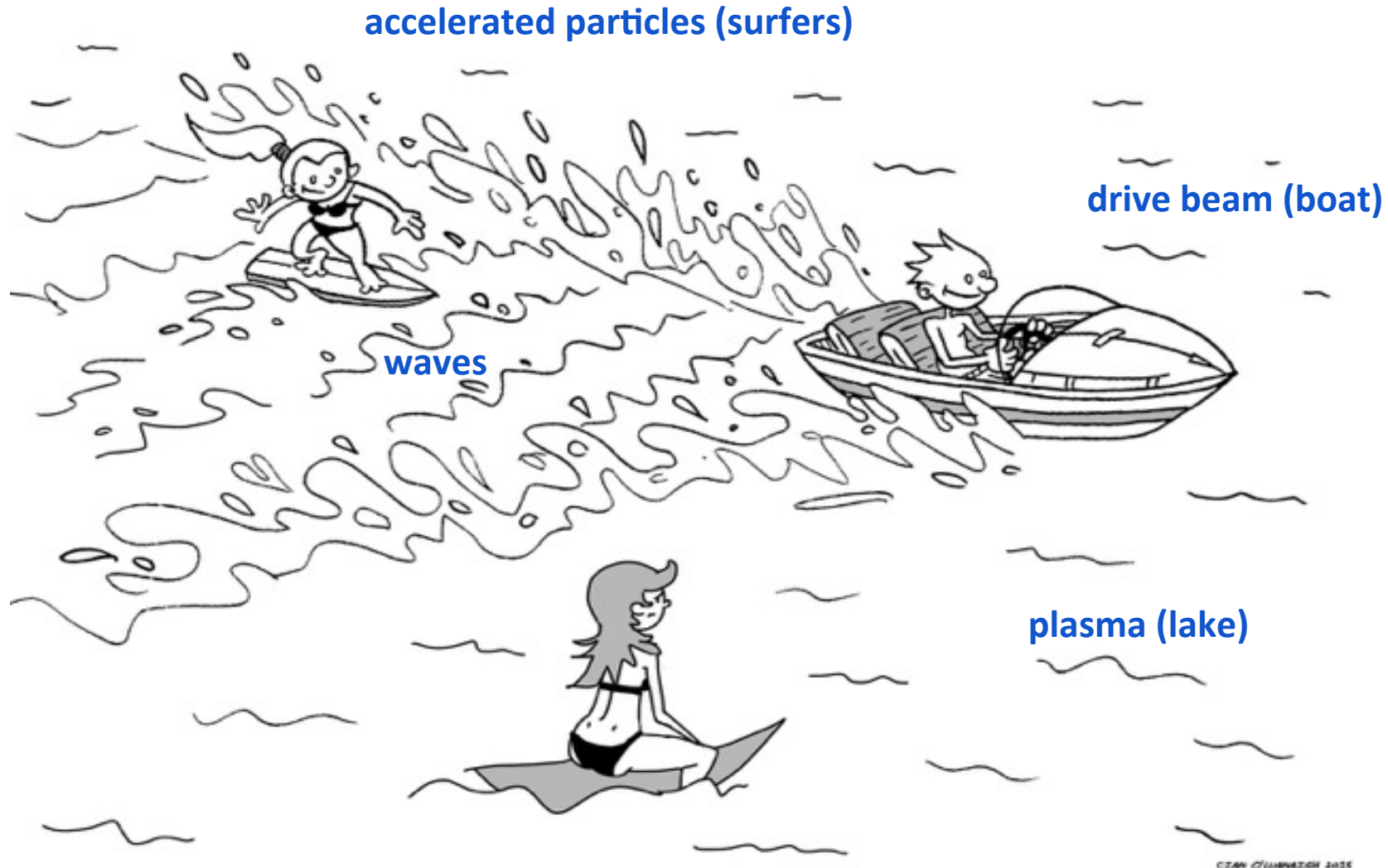
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi¹ and McMillan² considered cosmic-ray particle acceleration by moving magnetic fields¹ or electromagnetic waves.² In terms of the realizable laboratory technology for collective accelerators, present-day electron beams³ yield electric fields of $\sim 10^7 \text{ V/cm}$ and power densities of 10^{13} W/cm^2 .

the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \quad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes can be simply seen by the following approximate

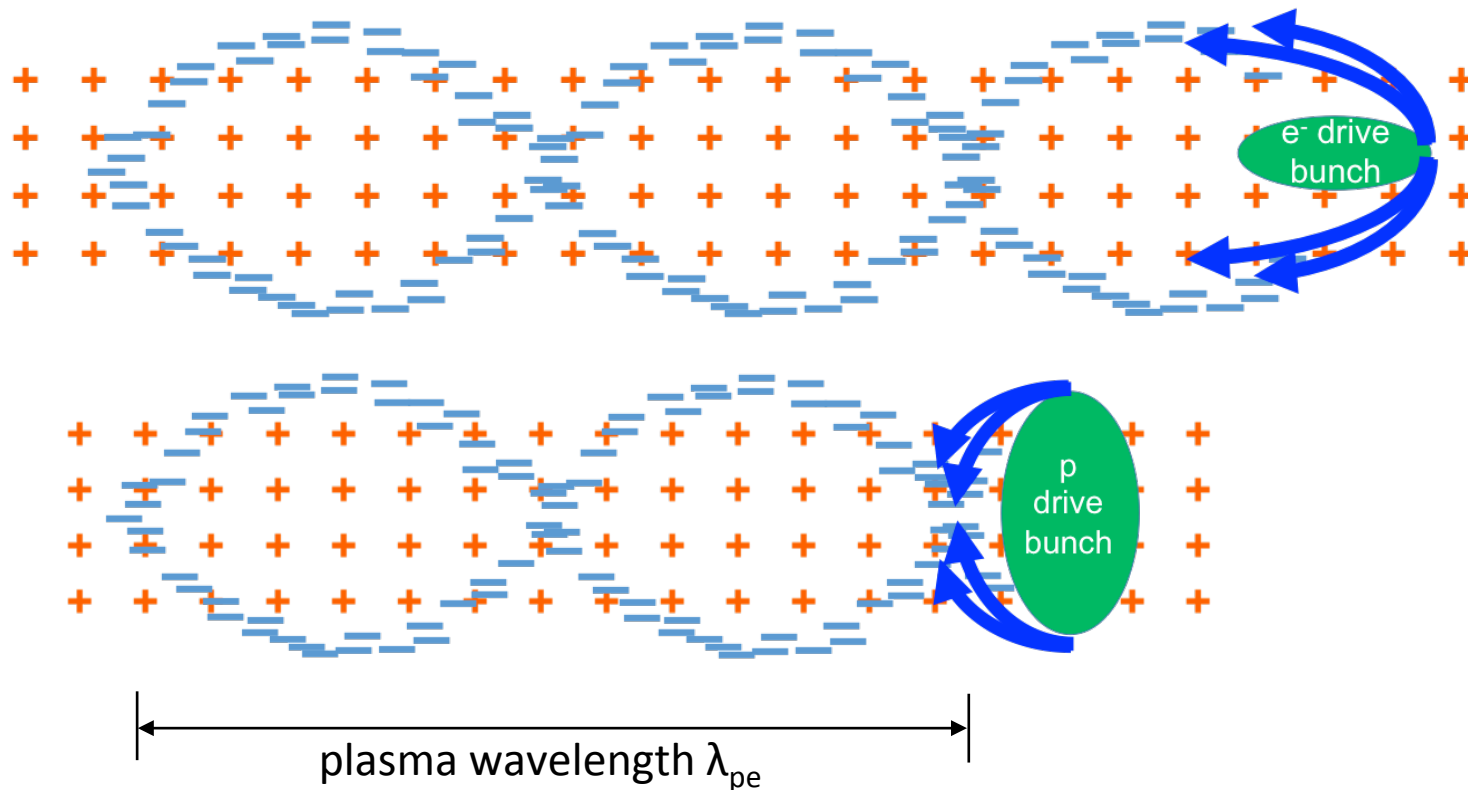
How to Create a Plasma Wakefield?



Principle of Plasma Wakefield Acceleration

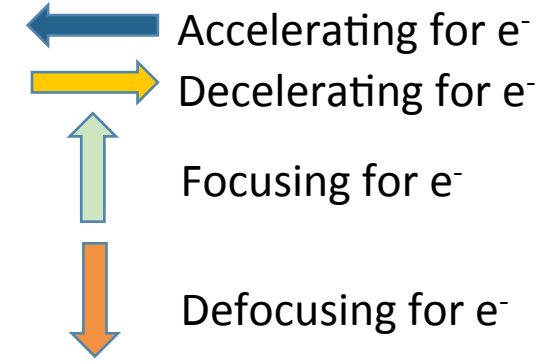
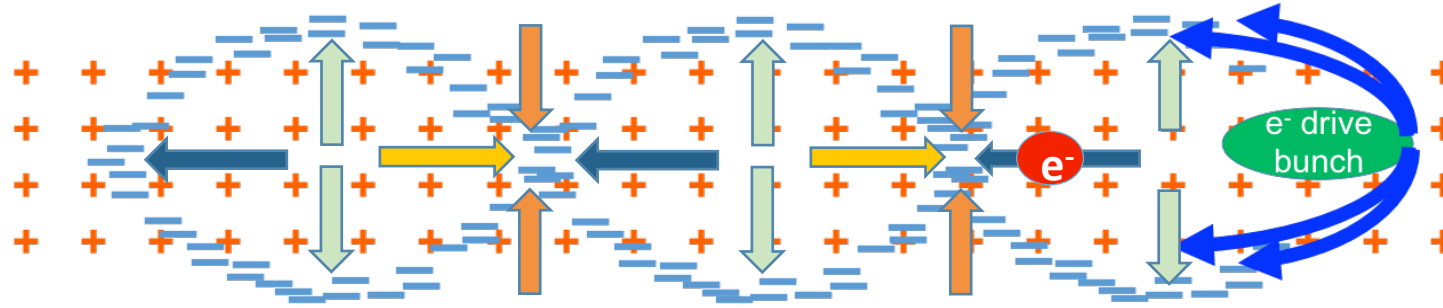
Different ways to excite the wakes - most commonly used:

- Laser bunches
- Electron beams
- **Protons bunches (first time done at CERN)**



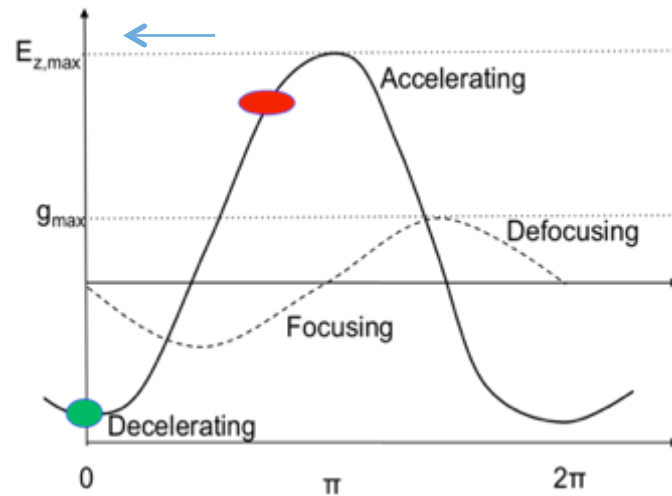
- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?



Maximum accelerating electric field reached with drive beam of N and σ_z :

$$E_{\text{acc}} = 110 \frac{\text{MV}}{\text{m}} \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6 \text{mm})^2}$$



Examples of accelerating fields for different beam parameters and plasma parameters fields:

$$\begin{aligned} N = 3 \times 10^{10}, \sigma_z = 300 \mu\text{m}, n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} &\rightarrow E_{\text{acc}} = 600 \text{ MV/m} \\ N = 3 \times 10^{10}, \sigma_z = 20 \mu\text{m}, n_{pe} = 2 \times 10^{17} \text{ cm}^{-3} &\rightarrow E_{\text{acc}} = 15 \text{ GV/m} \end{aligned}$$

Plasma Baseline Parameters

- Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m**.
- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \epsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \quad k_{pe} = \frac{\omega_{pe}}{c}$$

$$\text{Example: } n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \text{ (AWAKE)} \rightarrow \omega_{pe} = 1.25 \times 10^{12} \text{ rad/s} \rightarrow \frac{c}{\omega_{pe}} = 0.2 \text{ mm} \rightarrow k_{pe} = 5 \text{ mm}^{-1}$$

- This translates into a wavelength of the plasma oscillation

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \quad \rightarrow \quad \lambda_{pe} \approx 1 \text{ mm} \sqrt{\frac{10^{15} \text{ cm}^{-3}}{n_{pe}}}$$

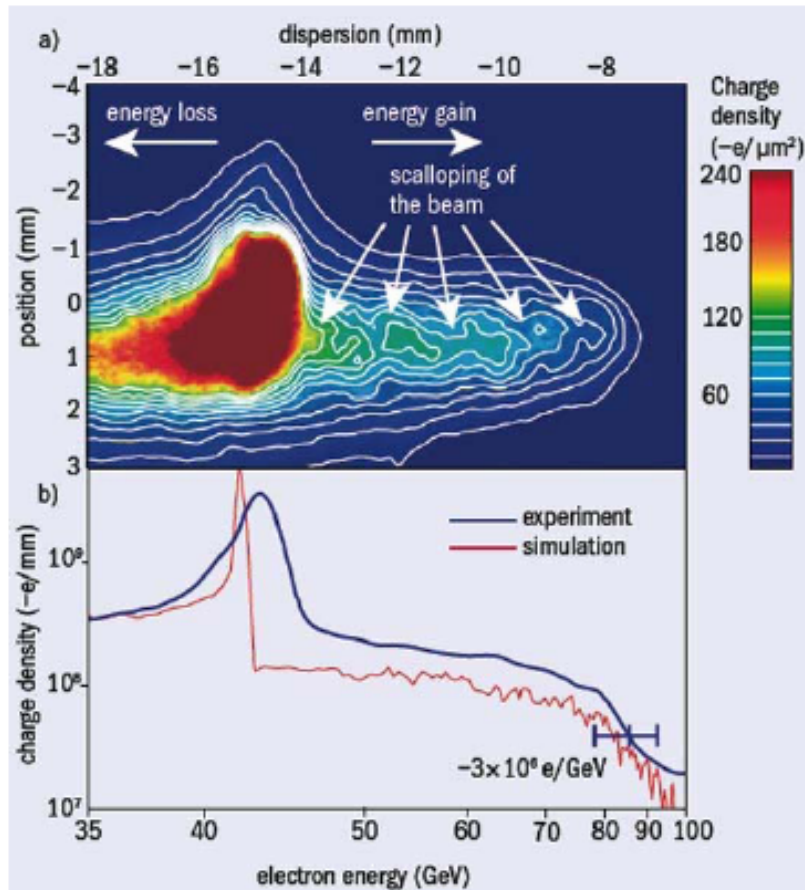
$$\lambda_{pe} = 1.2 \text{ mm}$$

→ Produce cavities with mm size!

Experimental Results

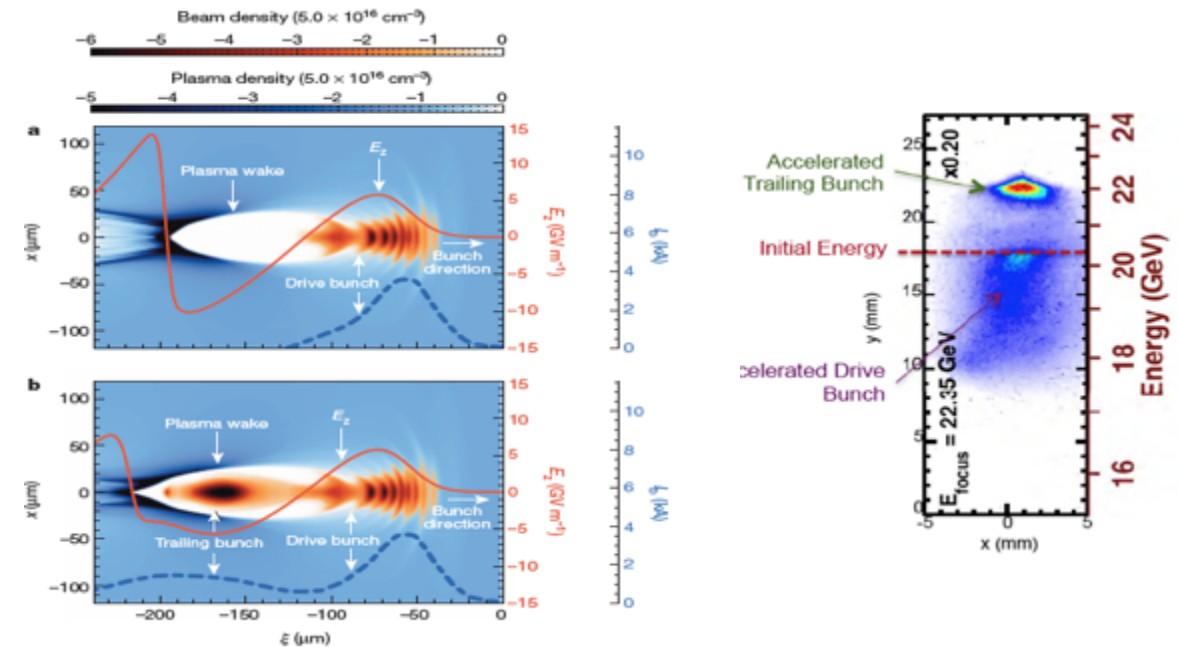
SLAC Experiment, I. Blumenfeld et al, Nature 455, p 741 (2007)

- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, $\sigma_x = 10\mu\text{m}$, 50 fs
- Reached accelerating gradient of **50 GeV/m**
- Accelerated electrons from 42 GeV to 85 GeV in 85 cm.



High-Efficiency acceleration of an electron beam in a plasma wakefield accelerator, M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

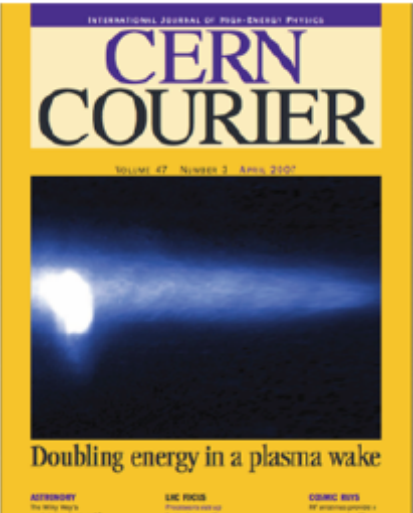
- 1.7 GeV energy gain in 30 cm of pre-ionized Li vapour plasma
- 6 GeV energy in 1.3 m of plasma
- Total efficiency is $\langle 29.1\% \rangle$ with a maximum of 50%.
- Final energy spread of 0.7 % (2% average)



- Electric field in plasma wake is loaded by presence of witness bunch
- Allows efficient energy extraction from the plasma wake

Many, Many Electron and Laser Driven Plasma Wakefield Experiments...

Now first Proton Driven Plasma Wakefield Experiment



Monoenergetic beams of relativistic electrons from intense laser-plasma interactions

S. P. B. Mangles¹, C. B. Murphy², J. H. Moore³, A. G. R. Thomas⁴, J. L. Collier⁵, A. E. Dangor⁶, E. J. Eves⁷, P. S. Foster⁸, J. G. Gallacher⁹, C. J. Hooker¹⁰, D. A. Jaroszynski¹¹, A. J. Langley¹², W. B. Mori¹³, P. A. Norreys¹⁴, P. S. Tseng¹⁵, B. Wilson¹⁶, B. W. Wilks¹⁷ & K. Krushelnick¹⁸

¹The Blackett Laboratory, Imperial College London, London SW7 2BZ, UK
²Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK
³Department of Physics, University of Strathclyde, Glasgow G4 8NG, UK
⁴Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. B. Mangles¹, C. B. Murphy², J. H. Moore³, E. E. Esarey⁴, G. B. Schroeder⁵, B. Wilson⁶, C. Hooker⁷, A. Cary⁸ & W. P. Leemans⁹

¹Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
²University of California, Berkeley, California 94720, USA
³University of California, Berkeley, California 94720, USA
⁴University of California, Berkeley, California 94720, USA
⁵University of California, Berkeley, California 94720, USA
⁶University of California, Berkeley, California 94720, USA
⁷University of California, Berkeley, California 94720, USA
⁸University of California, Berkeley, California 94720, USA
⁹University of California, Berkeley, California 94720, USA

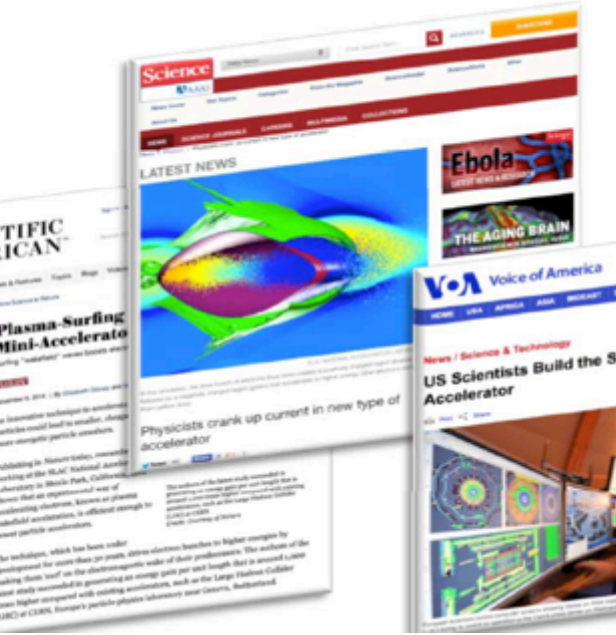
A laser-plasma accelerator producing monoenergetic electron beams

J. Faure¹, T. Gligos², A. Pukhov³, S. Kiselev⁴, S. Gordienko⁵, S. Lifshits⁶, J.-P. Rousseau⁷, F. Sauerbrey⁸ & V. Malka⁹

¹Université d'Orléans, Laboratoire d'Optique Appliquée, CNRS, 2007, 45071, France
²UMR 5076, CNRS, 45071, France
³Institut für Theoretische Physik 1, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
⁴Département de Physique Théorique et Appliquée, CEADAM, 91680 Bruyères-le-Châtel, France
⁵CEADAM, 91680 Bruyères-le-Châtel, France
⁶CEADAM, 91680 Bruyères-le-Châtel, France
⁷CEADAM, 91680 Bruyères-le-Châtel, France
⁸CEADAM, 91680 Bruyères-le-Châtel, France
⁹CEADAM, 91680 Bruyères-le-Châtel, France



Surfing wakefields to create smaller accelerators



Beam-Driven Wakefield Acceleration: Landscape

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV protons	Externally injected electron beam (PHIN 19 MeV)	2016	2020+	Use for future high energy e-/e+ collider. <ul style="list-style-type: none"> - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV electrons and positrons	Two-bunch formed with mask (e-/e+ and e--e+ bunches)	2012	Sept 2016	<ul style="list-style-type: none"> - Acceleration of witness bunch with high quality and efficiency - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV electron beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	<ul style="list-style-type: none"> - Study Self-Modulation Instability (SMI)
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type electron beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	<ul style="list-style-type: none"> - Application (mostly) for x-ray FEL - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV electrons	Several bunches, D+W formed with mask.	On going		<ul style="list-style-type: none"> - Study quasi-nonlinear PWFA regime. - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		<ul style="list-style-type: none"> - Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

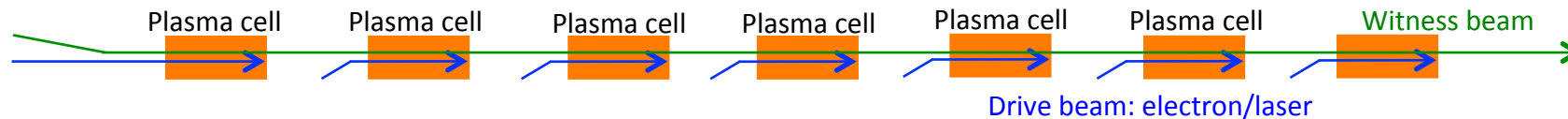
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:

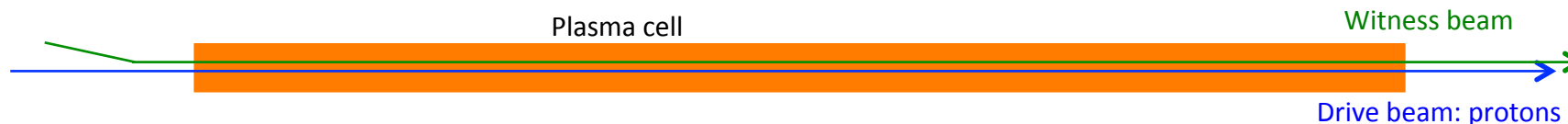
Electrons: 10^{10} particles @ 1 TeV ~few kJ

To reach TeV scale:

- **Electron/laser driven PWA:** need several stages, and challenging wrt to relative timing, tolerances, matching, etc...
 - effective gradient reduced because of long sections between accelerating elements....



- **Proton drivers:** large energy content in proton bunches → allows to consider single stage acceleration:
 - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.



Seeded Self-Modulation of the Proton Beam

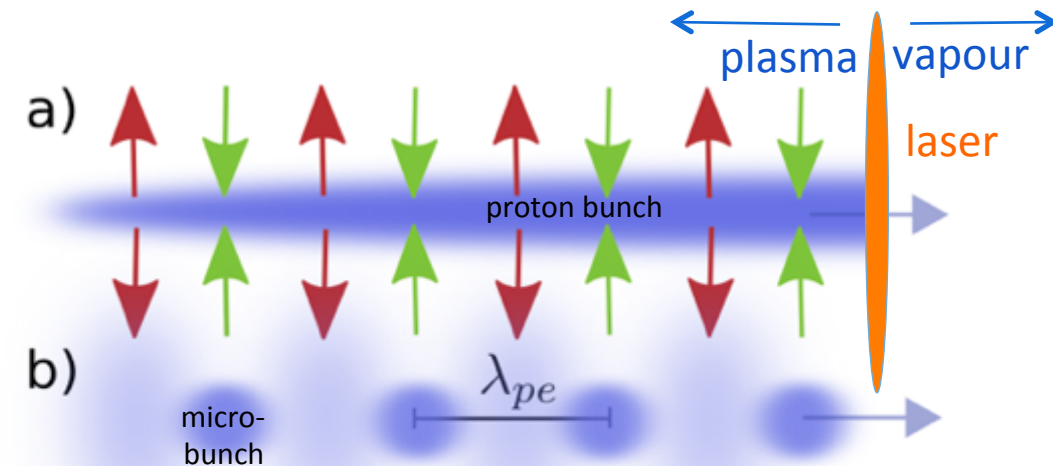
In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

CERN SPS proton bunch: very long! ($\sigma_z = 12 \text{ cm}$) \rightarrow much longer than plasma wavelength ($\lambda = 1 \text{ mm}$)

N. Kumar, A. Pukhov, K. Lotov,
PRL 104, 255003 (2010)

Self-Modulation:

- a) Bunch drives wakefields at the initial seed value when entering plasma.
 - **Initial wakefields act back** on the proton bunch itself. \rightarrow On-axis density is modulated. \rightarrow Contribution to the wakefields is $\propto n_b$.
- b) Density modulation on-axis \rightarrow **micro-bunches**.
 - Micro-bunches separated by plasma wavelength λ_{pe} .
 - drive wakefields resonantly.



\Rightarrow **Seeded self-modulation (SSM)**

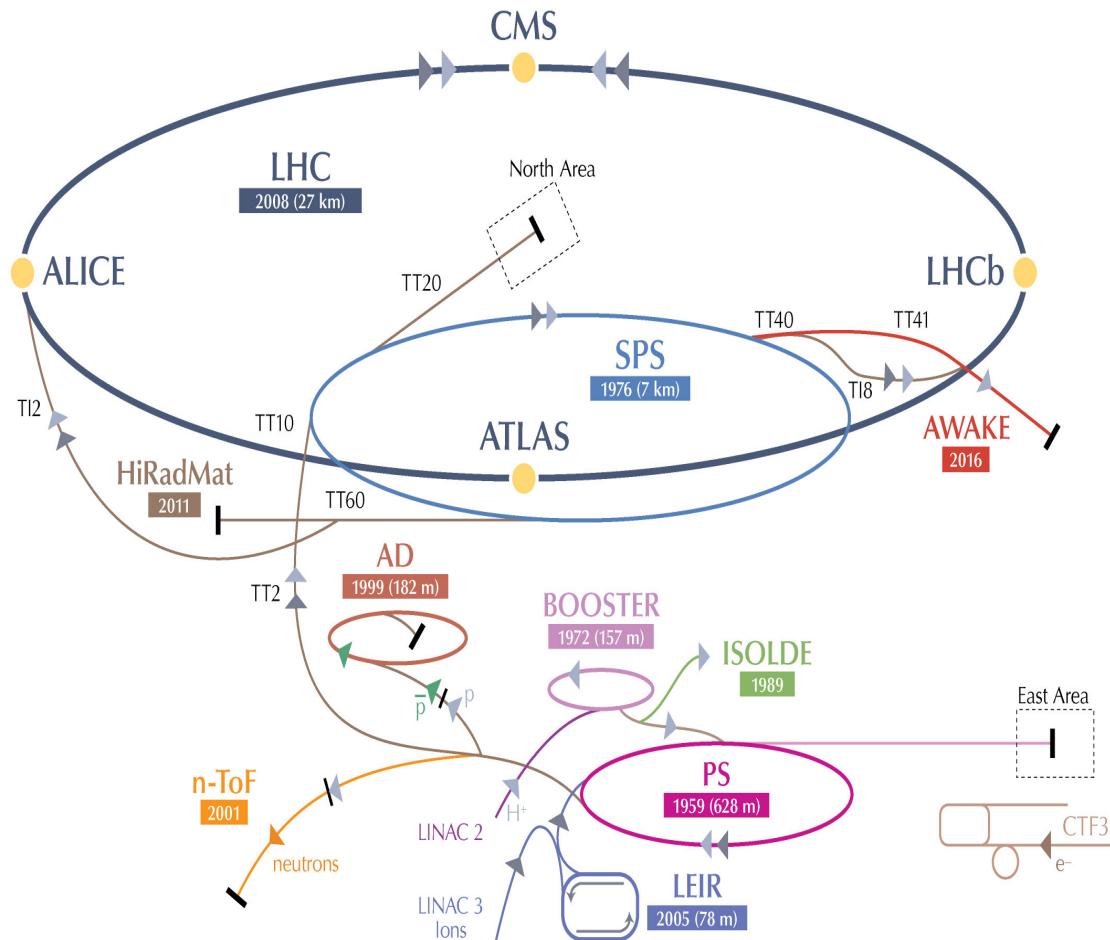
AWAKE: Seeding of the instability by

- Placing a **laser** close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- \rightarrow Seeding with ionization front

Outline

- Plasma Wakefield Acceleration
- **AWAKE, The Advanced Wakefield Experiments**
- AWAKE Results
- What's Next

AWAKE at CERN



Advanced **WAKE**field Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First beam end 2016

AWAKE

AWAKE Collaboration: 18+3 Institutes world-wide:

Collaboration members:

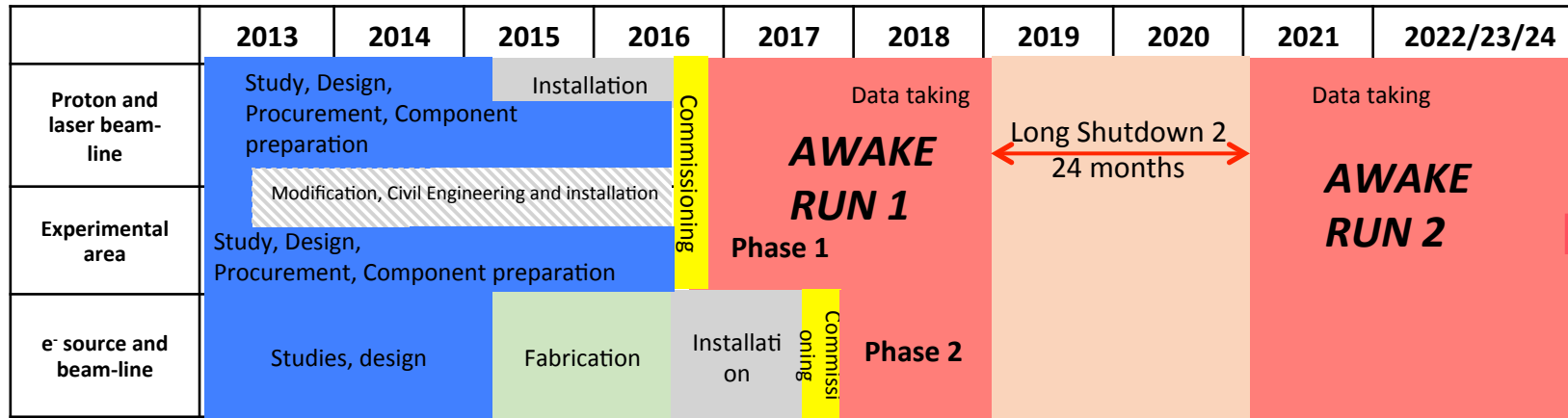
- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL,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



Associated members:

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

AWAKE Timeline



AWAKE++: After Run 2:
kick-off particle physics driven applications

AWAKE Run 1: Proof-of Concept

2016/17: Seeded Self-Modulation of proton beam in plasma

2018: Electron acceleration in plasma

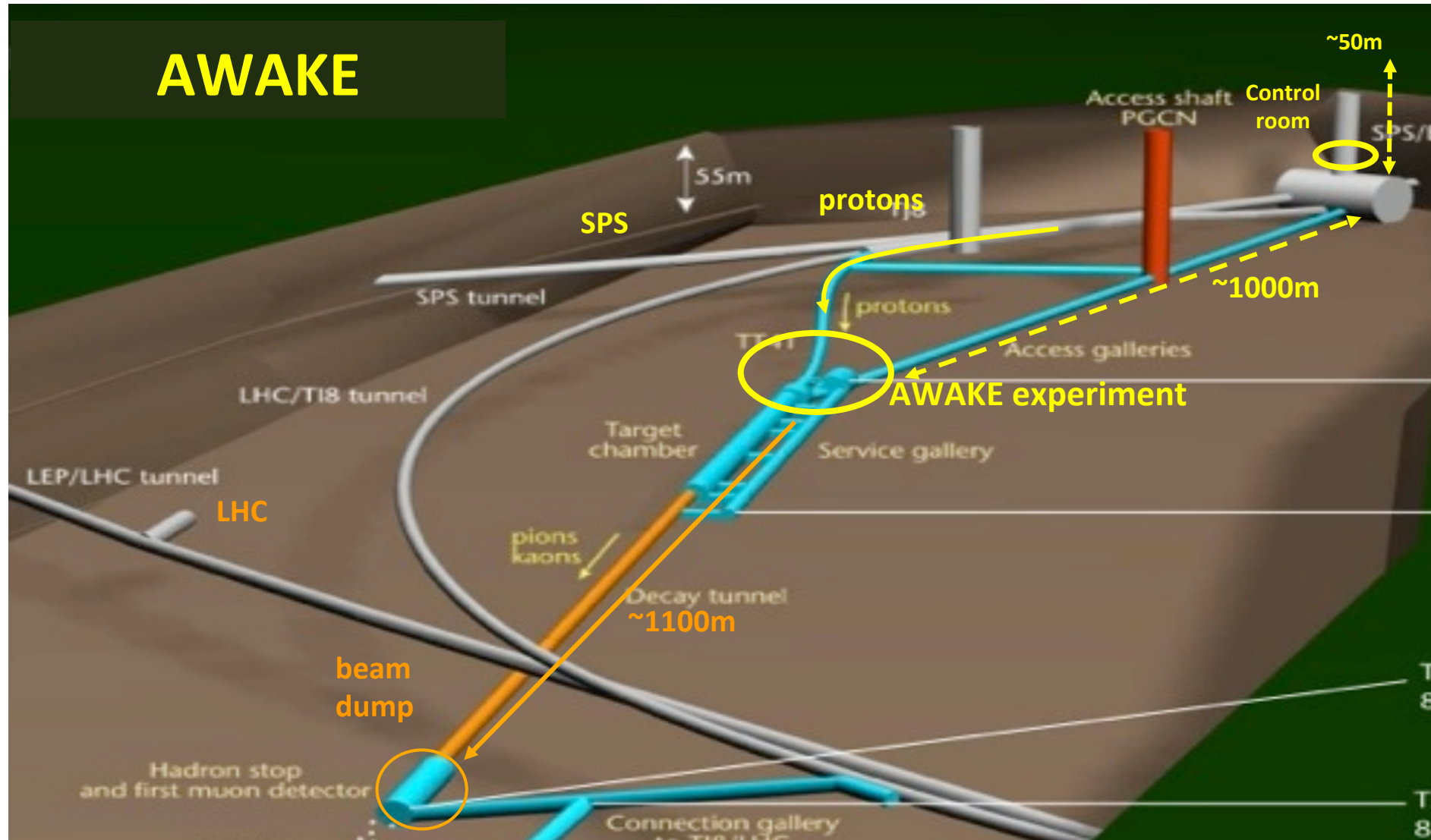


AWAKE Run 2: proposed for after LS2:

achieve high-charge bunches of electrons accelerated to **high energy, about 10 GeV**, while maintaining **beam quality** through the plasma and showing that the process is **scalable**.

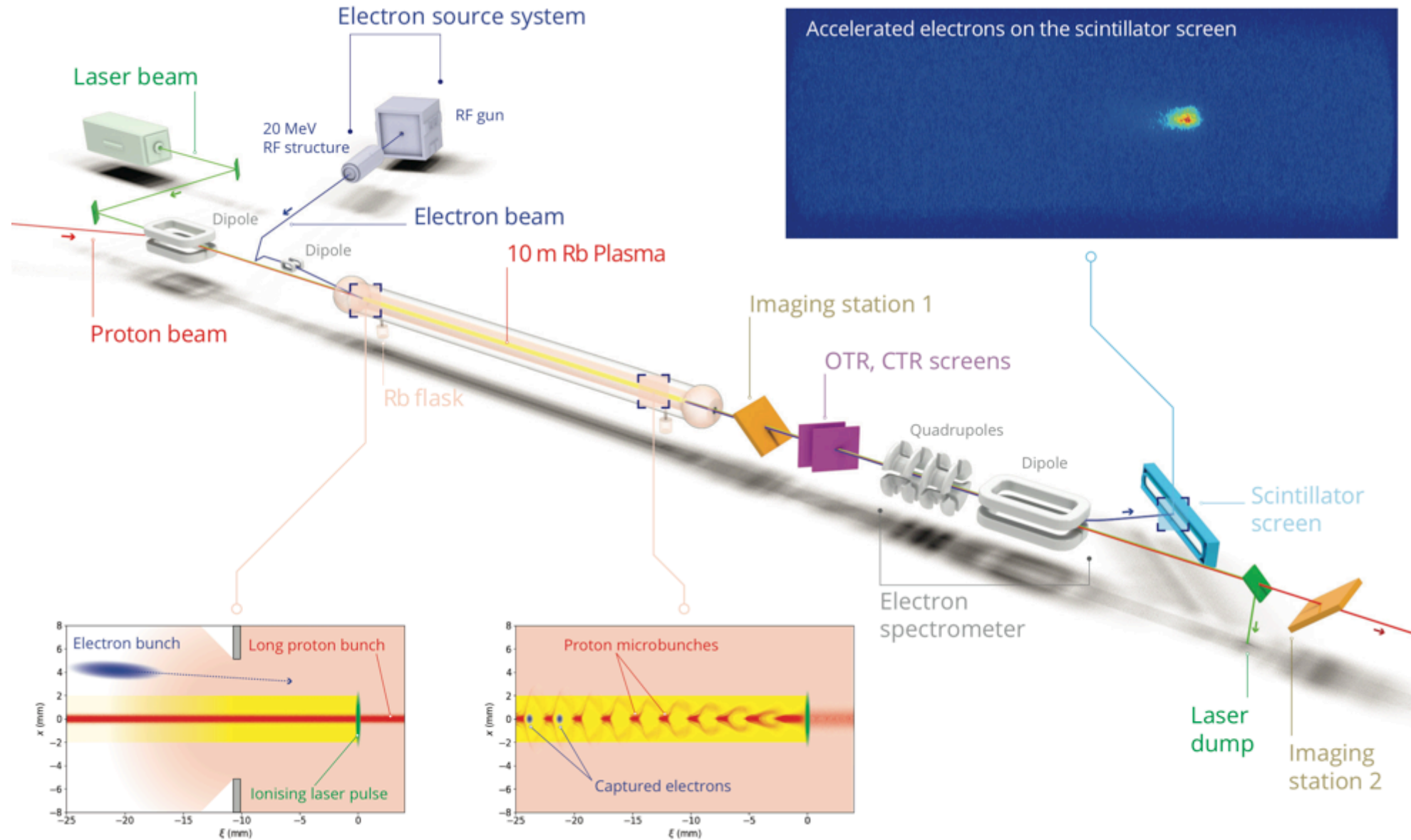


AWAKE at CERN



AWAKE installed in CERN underground area

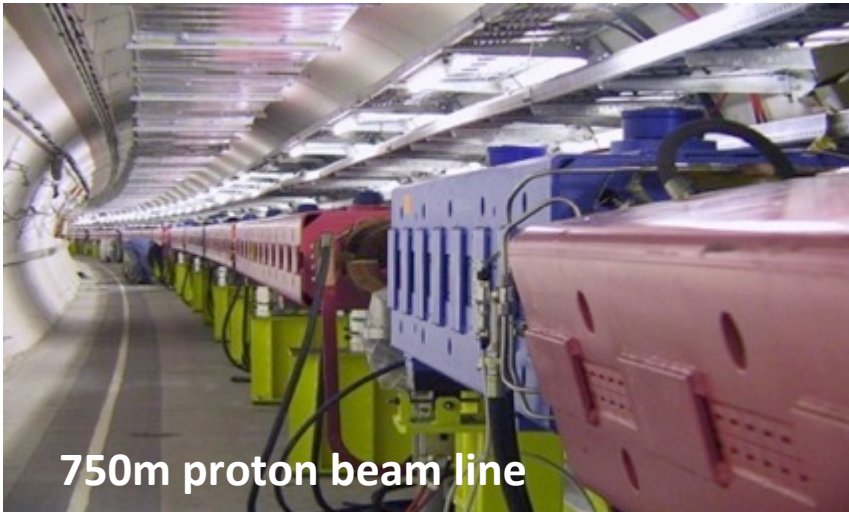
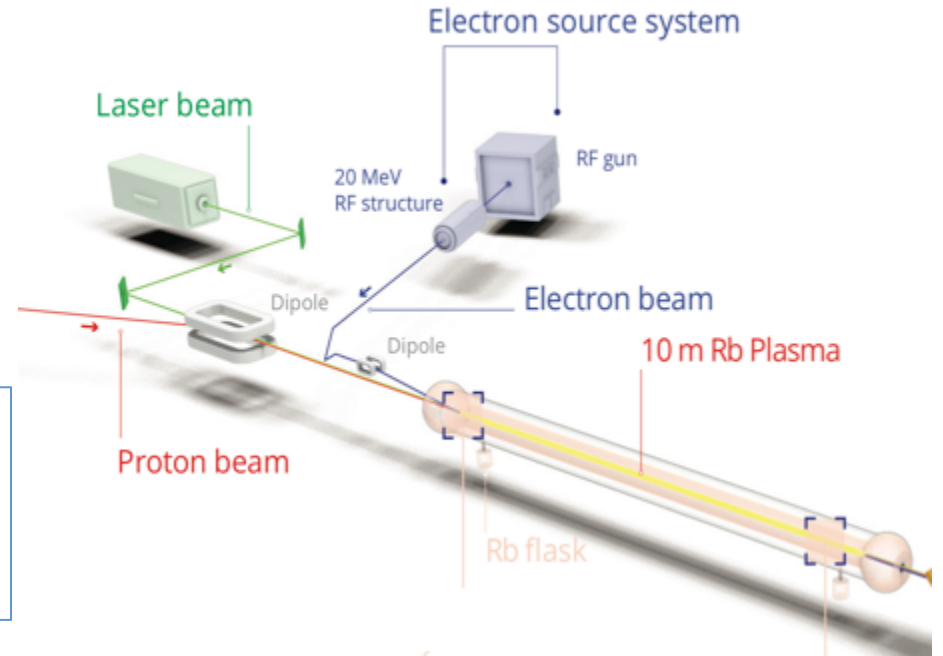
AWAKE Experiment



AWAKE Proton Beam Line

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	± 0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ± 20
β -function at focal point [m]	5
Dispersion at focal point [m]	0

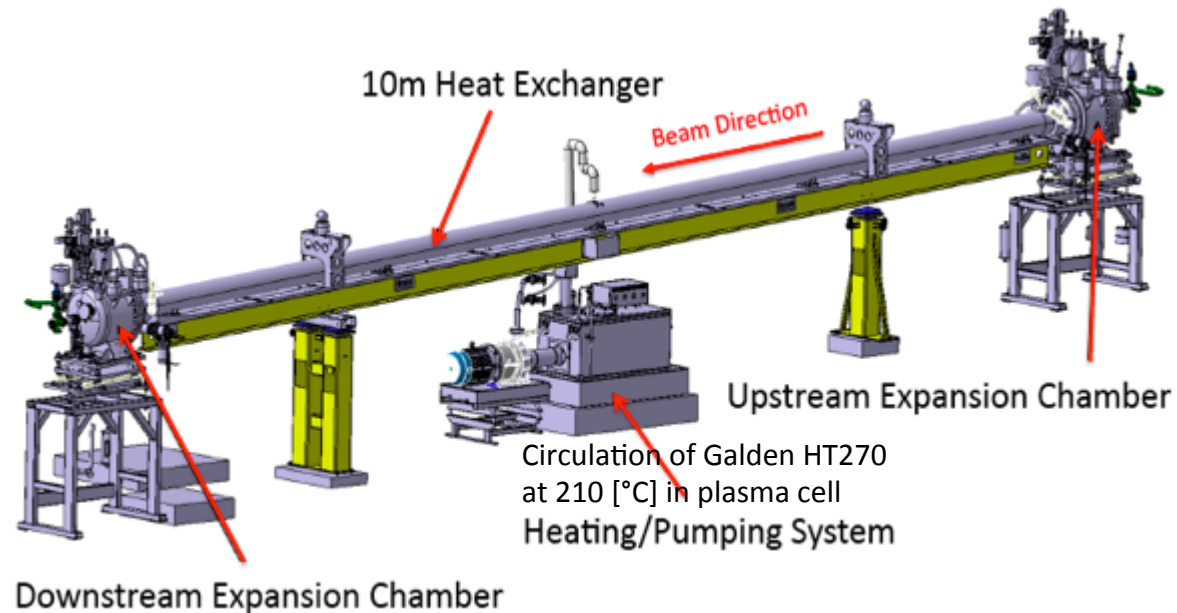
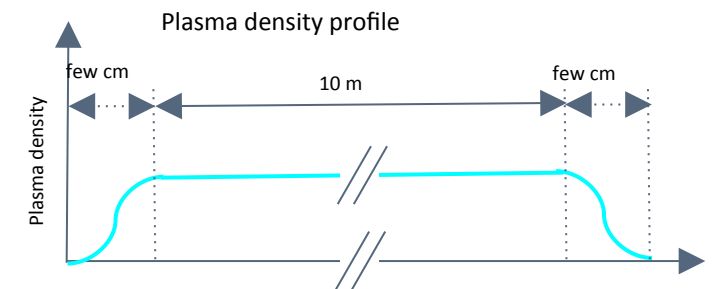
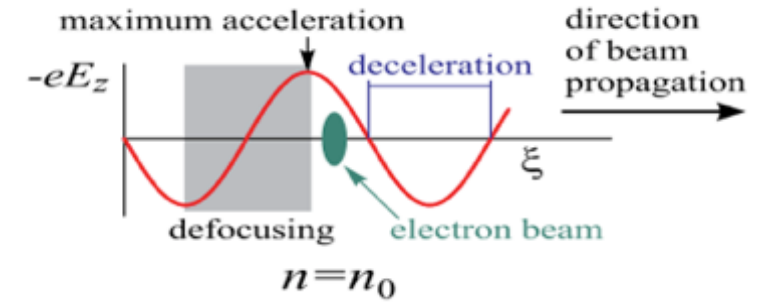
Plasma linear theory: $k_{pe} \sigma_r \leq 1$
 With $\sigma_r = 200 \mu\text{m}$
 $k_{pe} = \omega_{pe}/c = 5 \text{ mm}^{-1}$
 $\rightarrow n_{pe} = 7 \times 10^{14} \text{ cm}^{-3}$



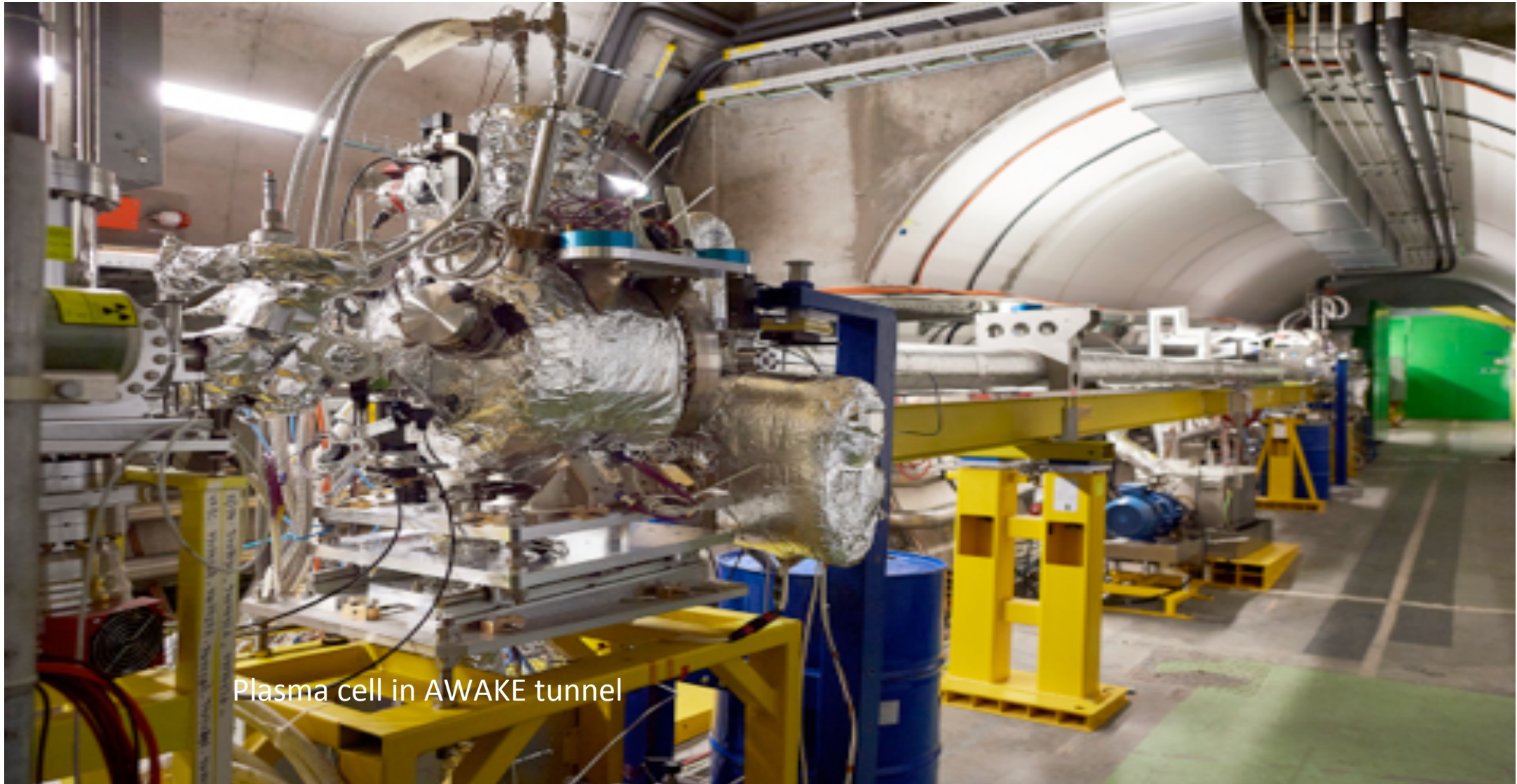
The AWAKE beamline is designed to deliver a **high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline. Further downstream, a **trailing electron beam** will be injected into the same beamline.

AWAKE Plasma Cell

- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold $\sim 10^{12} \text{ W/cm}^2$
- Density adjustable from $10^{14} - 10^{15} \text{ cm}^{-3} \rightarrow 7 \times 10^{14} \text{ cm}^{-3}$
- Requirements:
 - **density uniformity better than 0.2%**
 - Fluid-heated system ($\sim 220 \text{ deg}$)
 - Complex control system: 79 Temperature probes, valves
 - **Transition between plasma and vacuum as sharp as possible**



AWAKE Plasma Cell



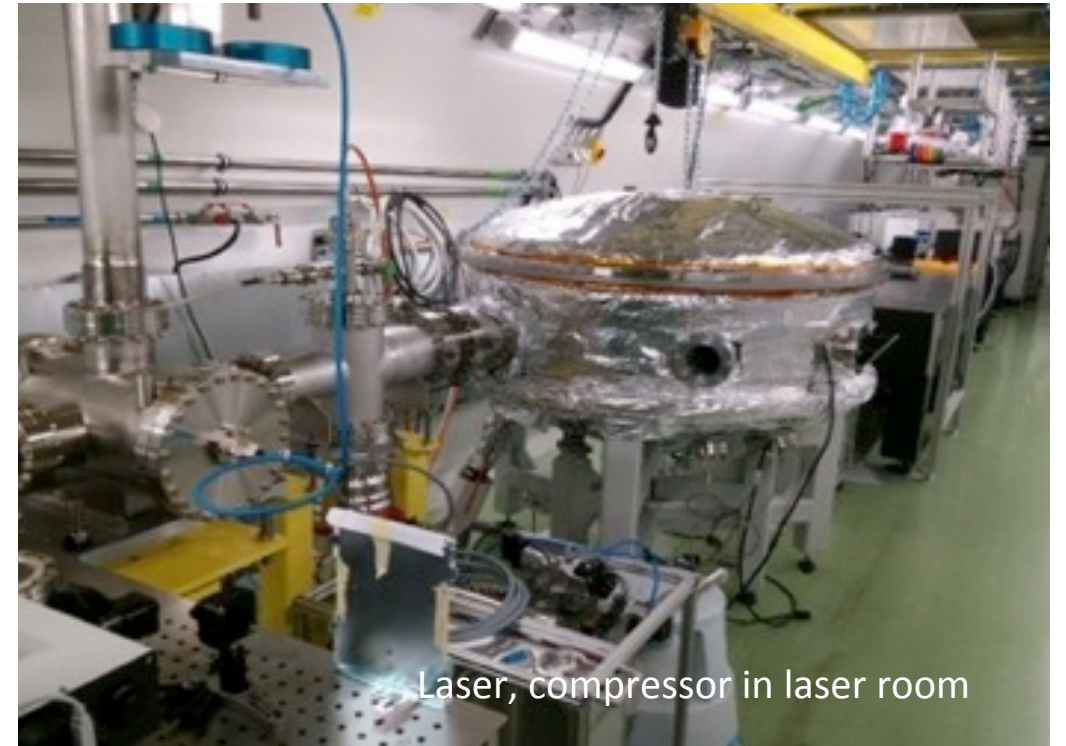
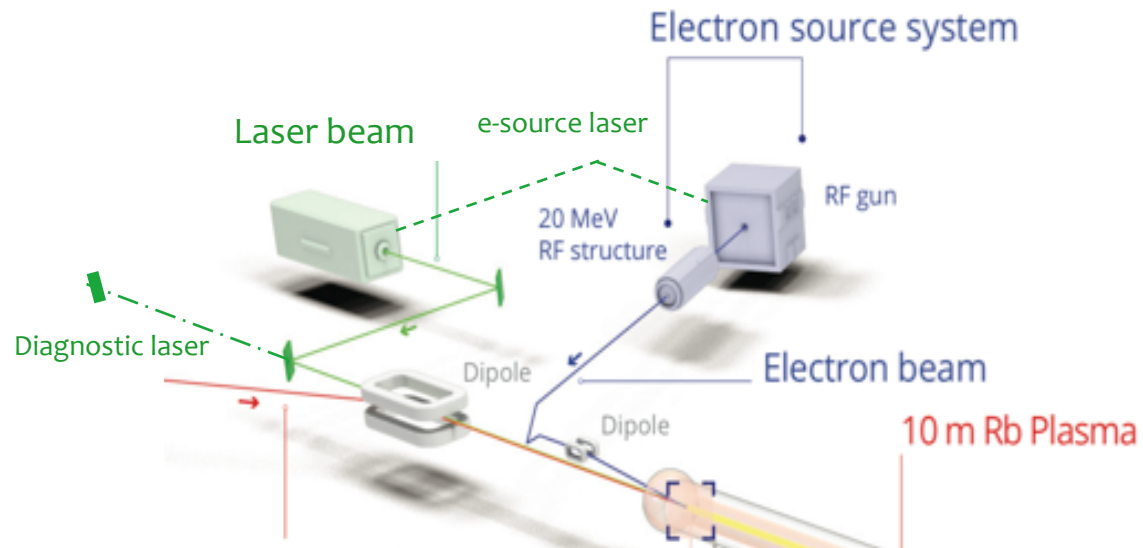
Plasma cell in AWAKE tunnel

Laser and Laser Line

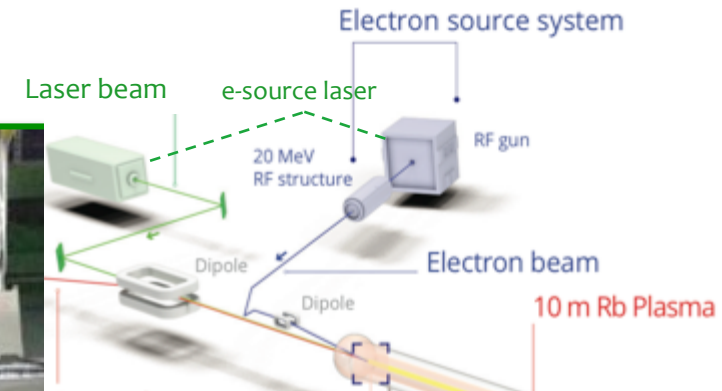
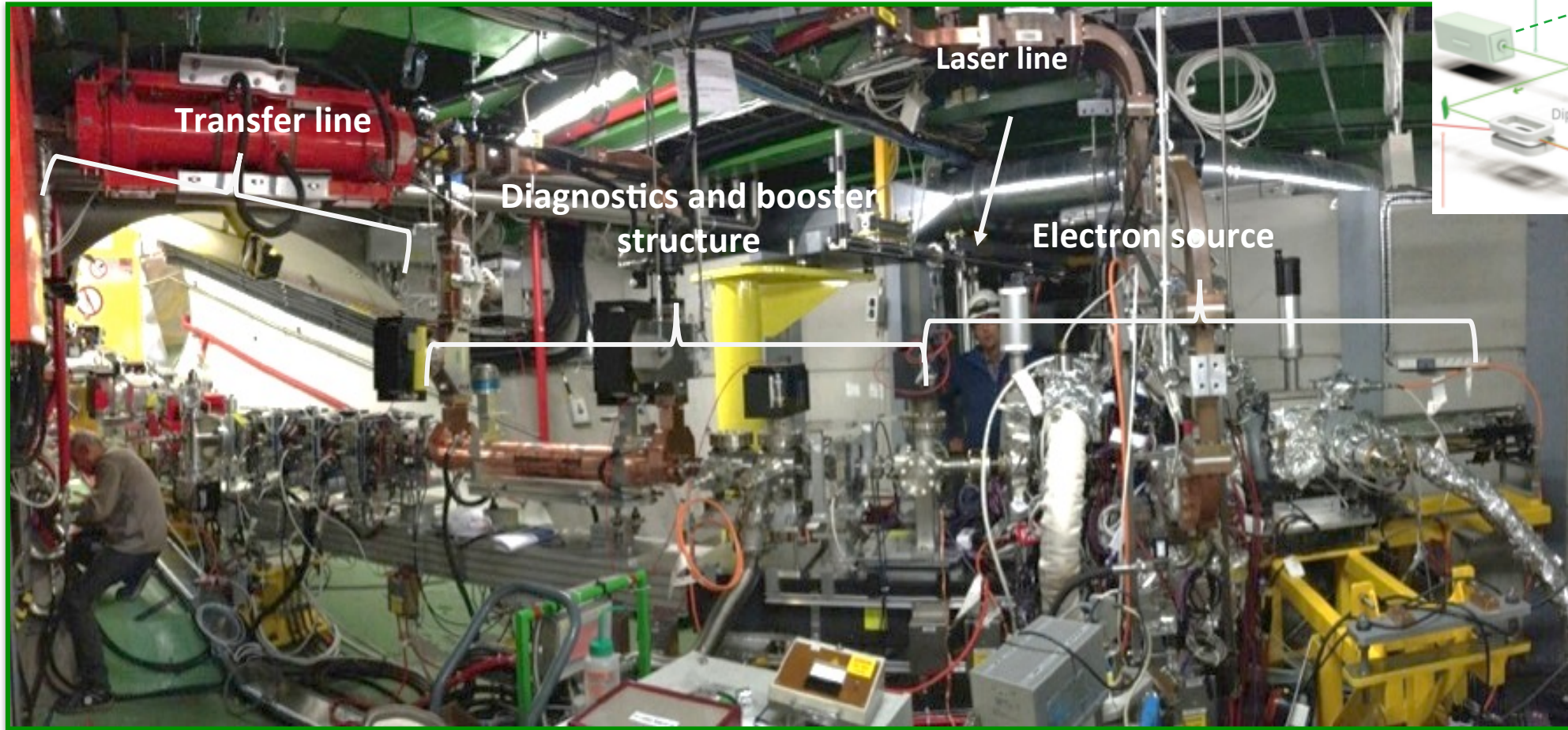
AWAKE uses a short-pulse **Titanium:Sapphire laser** to ionize the rubidium source.

→ Seeding of the self-modulation with the ionization front.

The laser can deliver up to **500 mJ** in a **120 fs pulse envelope**.



Electron Beam System



A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~ 20 MeV/c**.

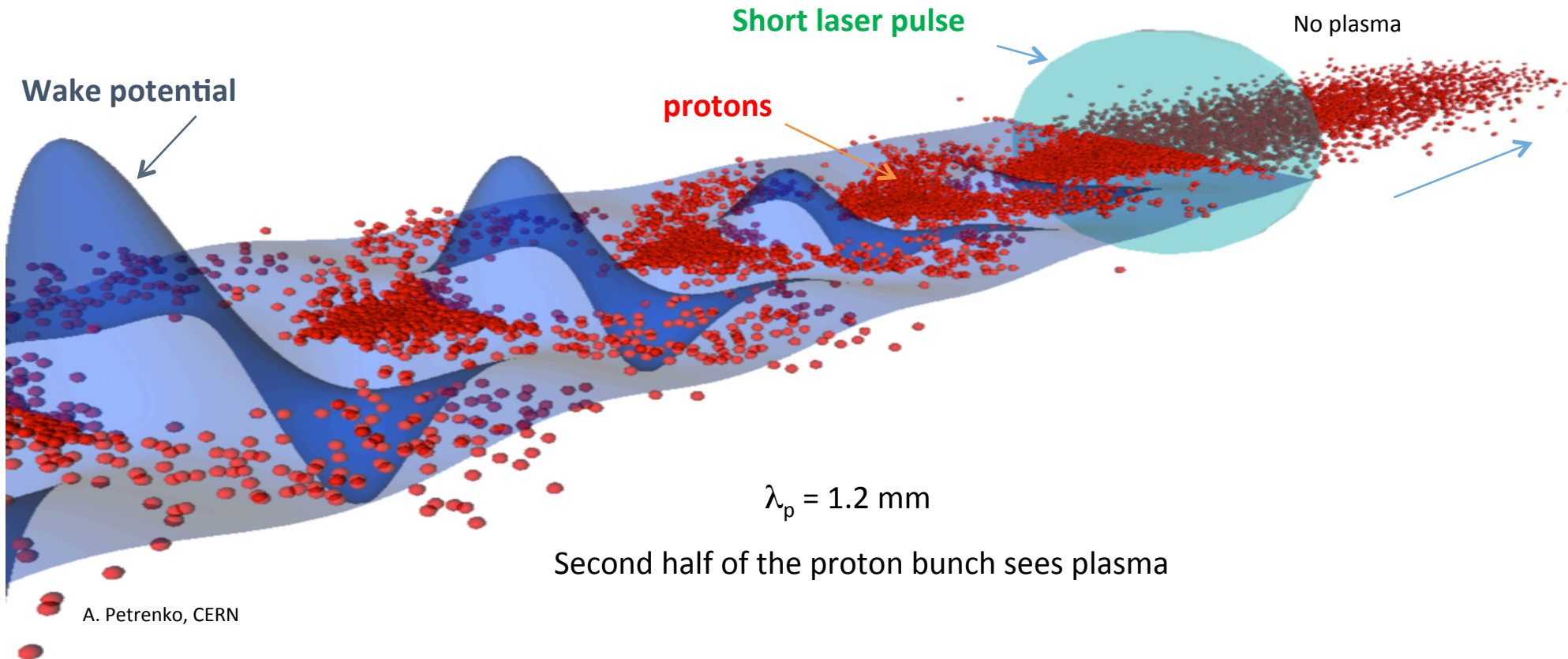
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

Challenge: cross the electron beam with the proton beam inside the plasma at a precision of $\sim 100 \mu\text{m}$.

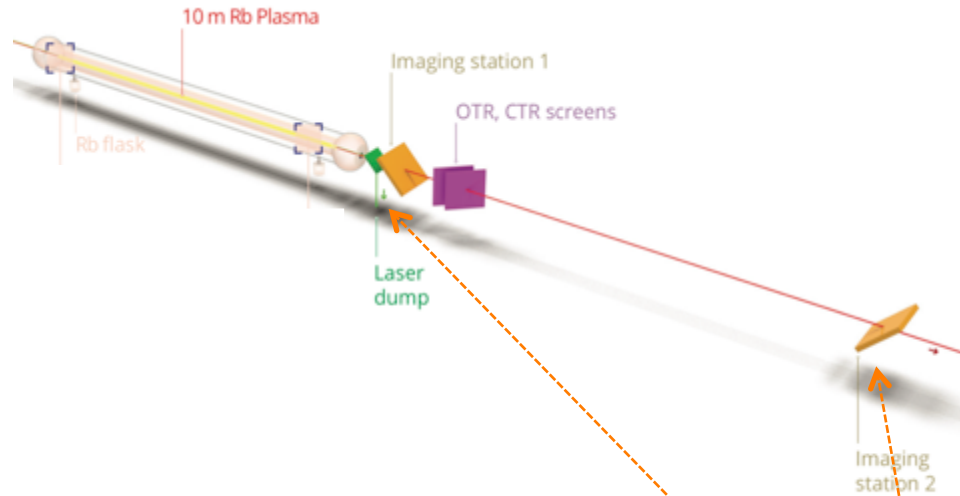
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Seeded Self-Modulation Results



Diagnostics for Seeded Self-Modulation

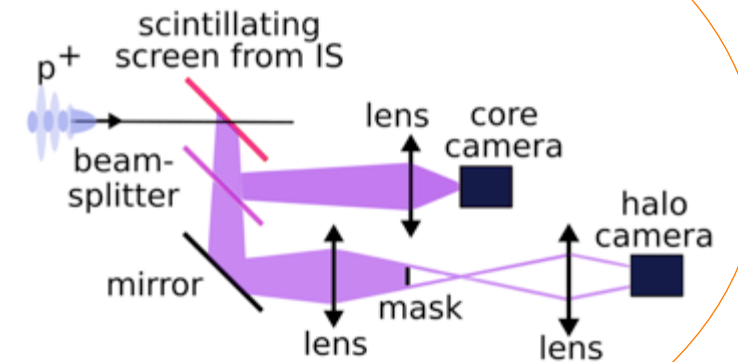


Indirect SSM Measurement:

Measure time integrated transverse bunch distribution.

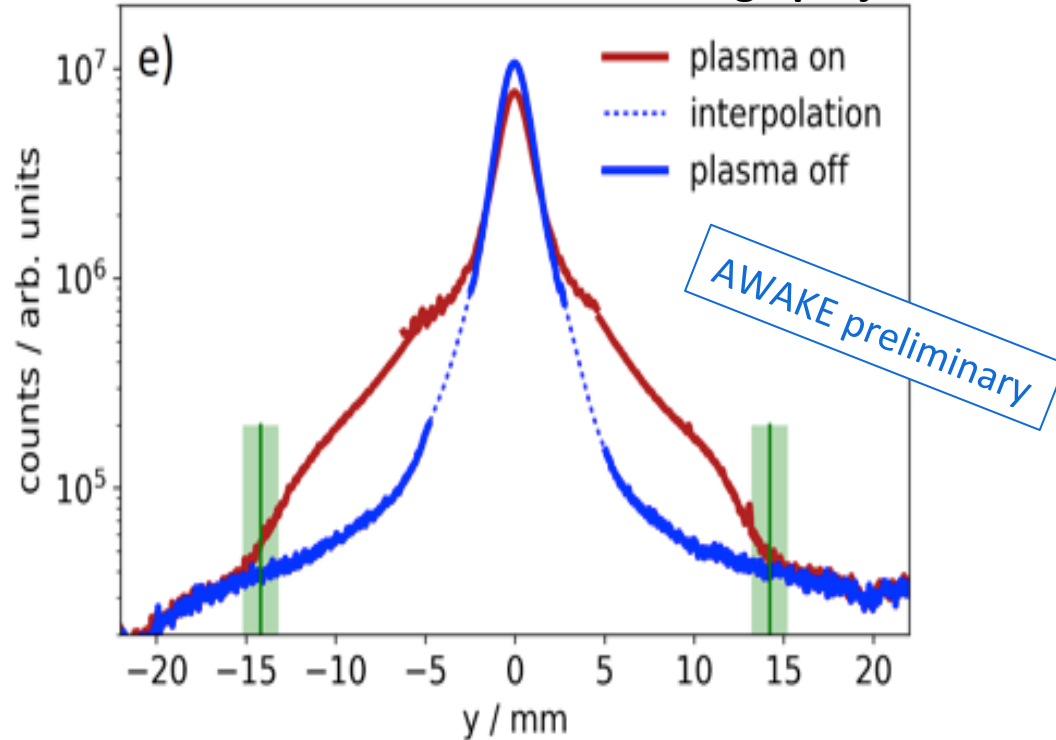
- Image protons defocused by the strong plasma wakefields
- Scintillation light from screen measured with digital camera.

Imaging station

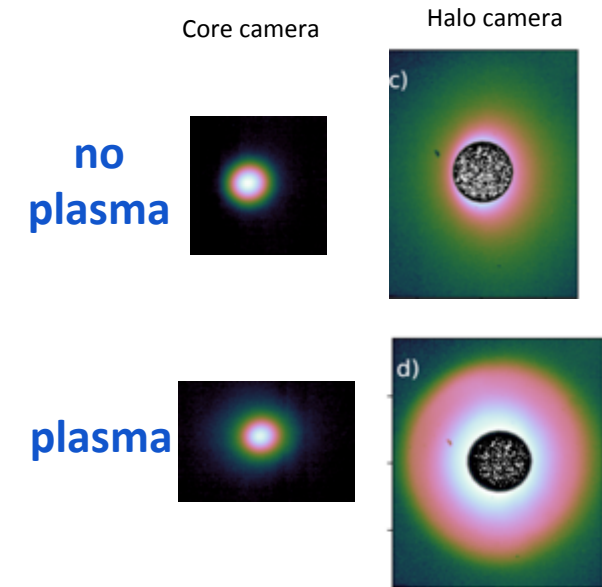


Results: Indirect Seeded Self-Modulation Measurement

Combination of core and halo image projections



From the **radial distribution** of the defocused protons, we learn about the **transverse effects** of SSM



- Protons are **defocused by the transverse wakefield (SSM)** and form a halo
- Proton density in core **decreases**, proton density at large radii **increases** (appearance of halo).
- Protons get defocused up to a **maximum radius of 14.5 mm for a plasma density of $7.7\text{e}14/\text{cm}^3$** .
- **Halo symmetric \Rightarrow no hose instability.**
- Estimate of the **transverse wakefields amplitude ($\int W_{\text{per}} dr$)**

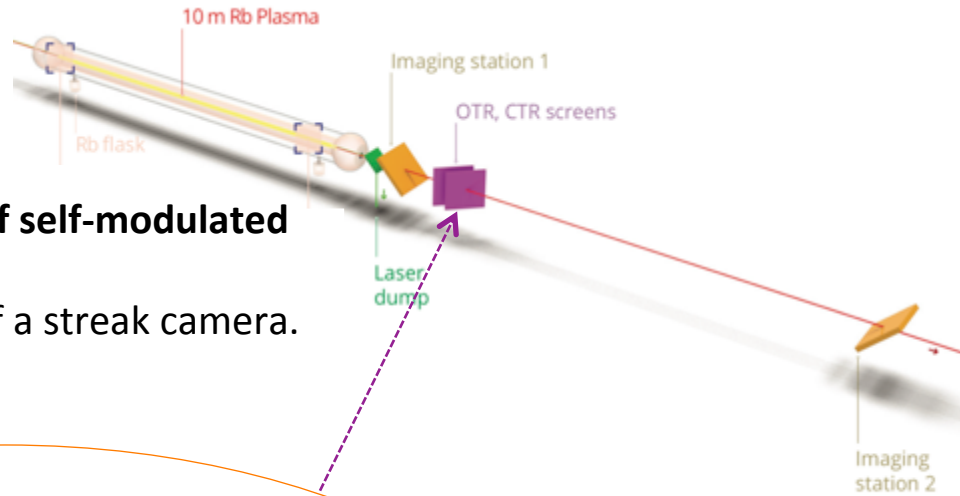
M. Turner et al. (AWAKE Collaboration), 'Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch'. **Phys. Rev. Lett.** **122**, 054801 (2019).

Diagnostics for Seeded Self-Modulation

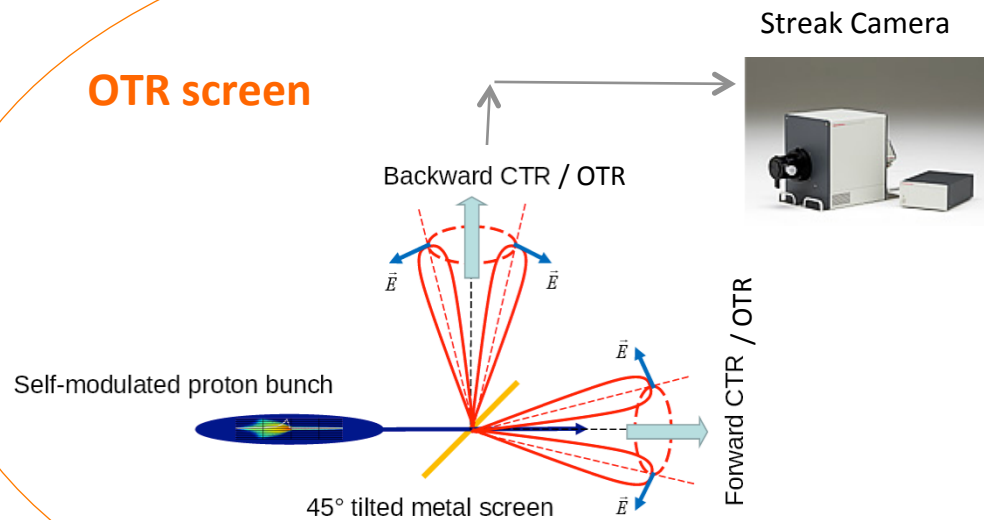
Direct SSM Measurement:

Measure longitudinal structure of self-modulated proton bunch.

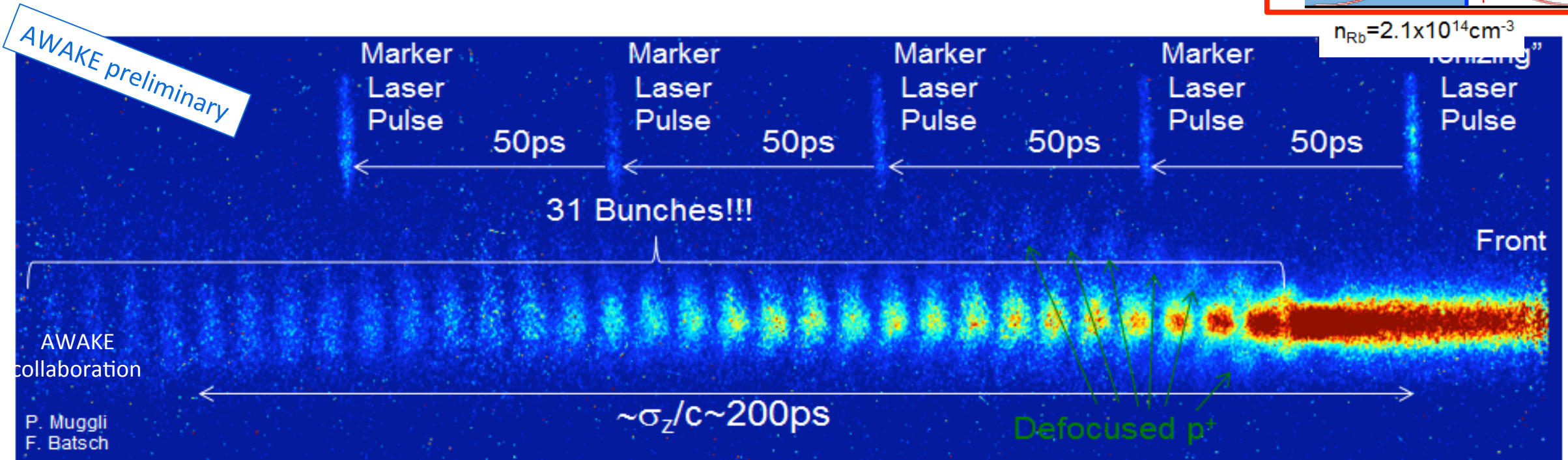
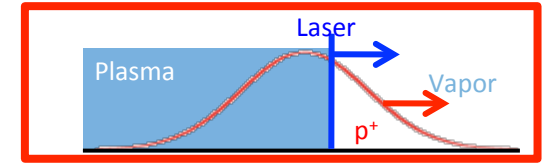
- Image OTR light onto the slit of a streak camera.
- Time resolved measurement.



OTR screen



Results: Direct Seeded Self-Modulation Measurement



- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the μ -bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

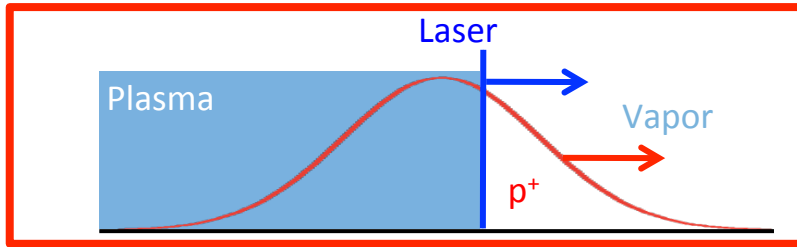
→ **1st AWAKE Milestone reached**

AWAKE Collaboration, 'Experimental observation of proton bunch modulation in a plasma, at varying plasma densities'. **Phys. Rev. Lett.** **122**, 054802 (2019).

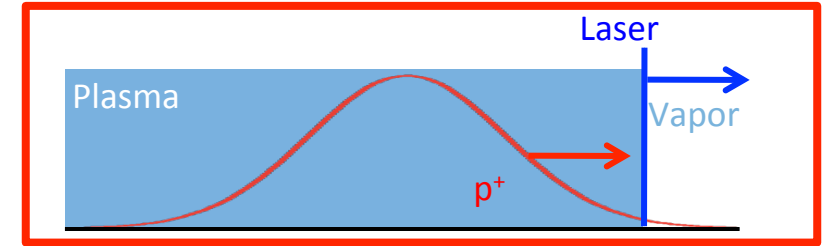
M. Turner et al. (AWAKE Collaboration), 'Experimental observation of plasma wakefield growth by the seeded self-modulation of a proton bunch', **PRL**, **122**, 054801 (2019).

Other Studies

- Seeded Self-Modulation (not) stability



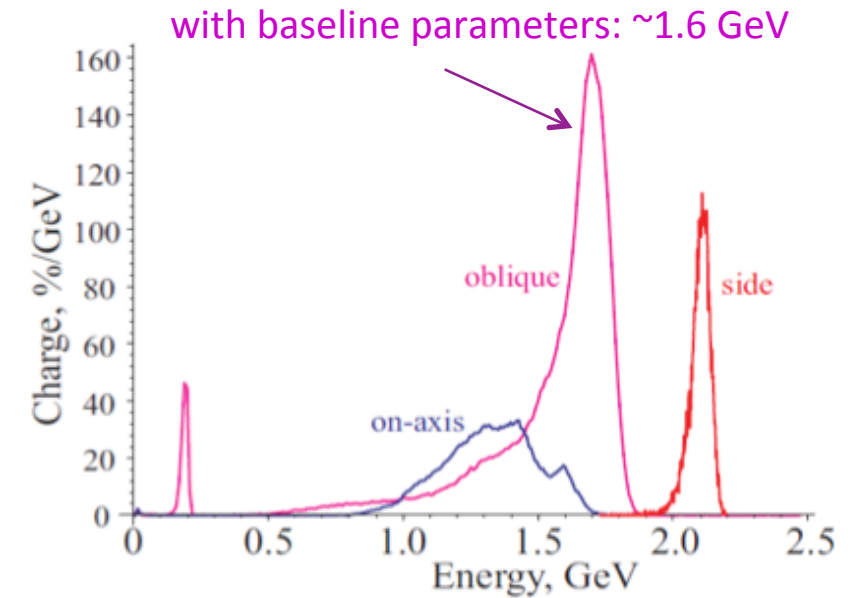
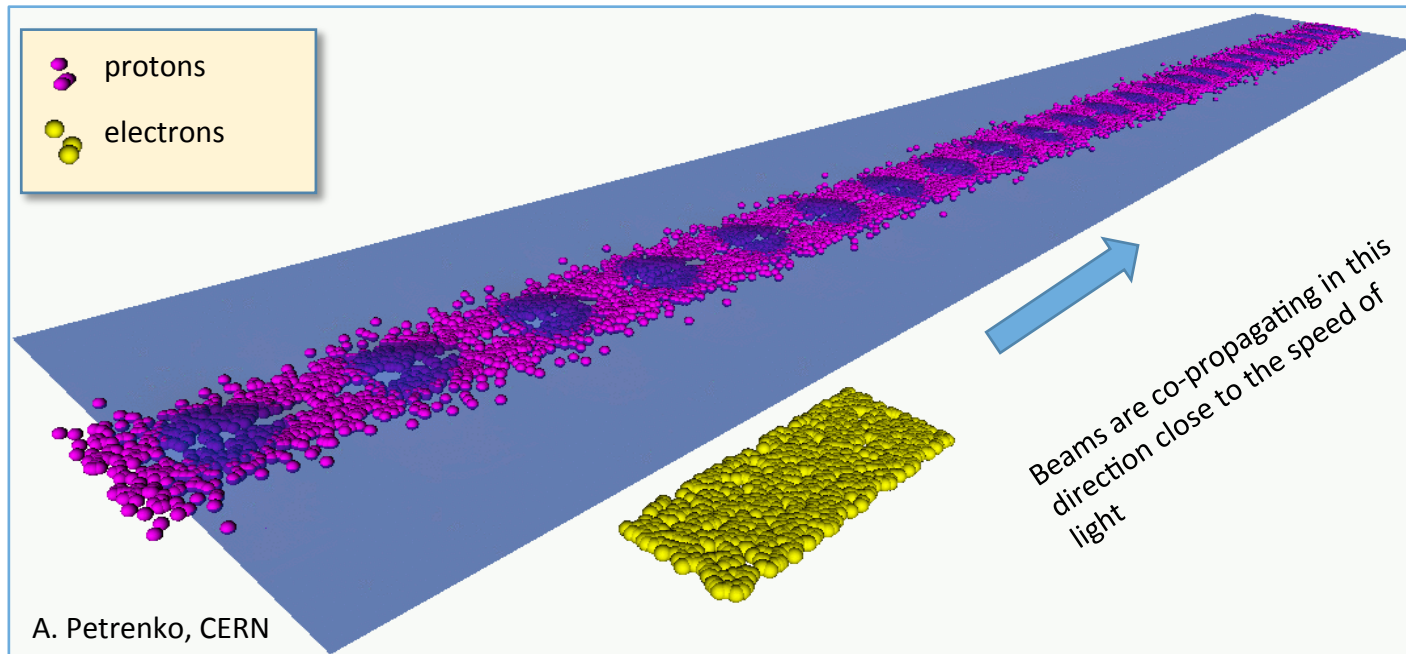
← ?? →



- Hosing Instability

Electron Acceleration Results 2018

Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:

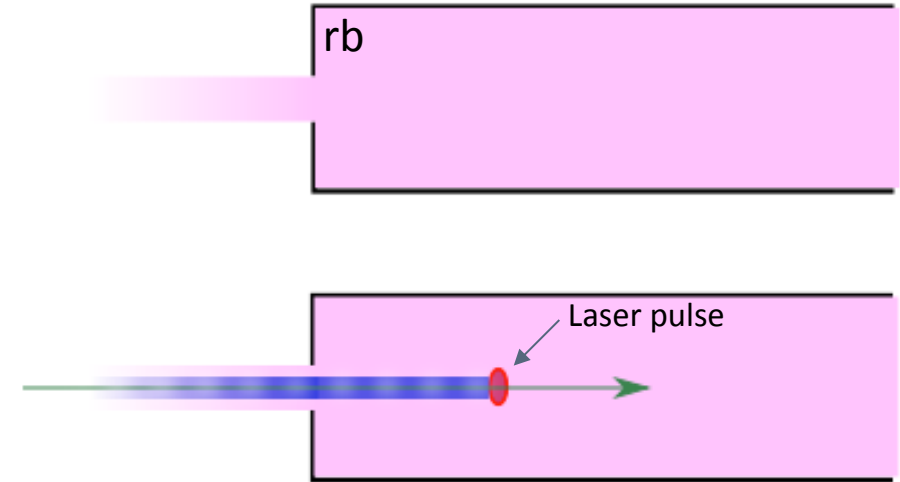


A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Electron Acceleration – Injection into Plasma

Challenge:

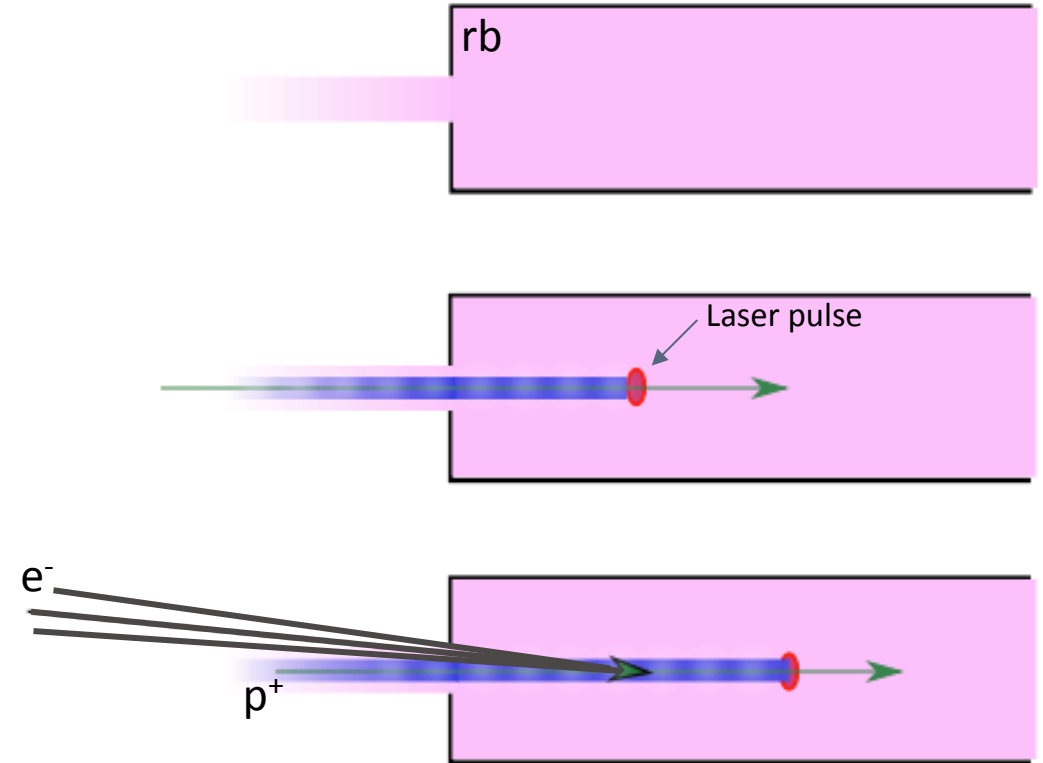
- During the Seeded Self-Modulation the proton bunch distribution **evolves**.
- Short density ramp at the entrance of the plasma → **change of wakefield phase**



Electron Acceleration – Injection into Plasma

Challenge:

- During the Seeded Self-Modulation the proton bunch distribution **evolves**.
- Short density ramp at the entrance of the plasma → **change of wakefield phase**.
- Instead of injecting bunches co-linear → **cross the electron** and proton bunch at a defined location inside the plasma.



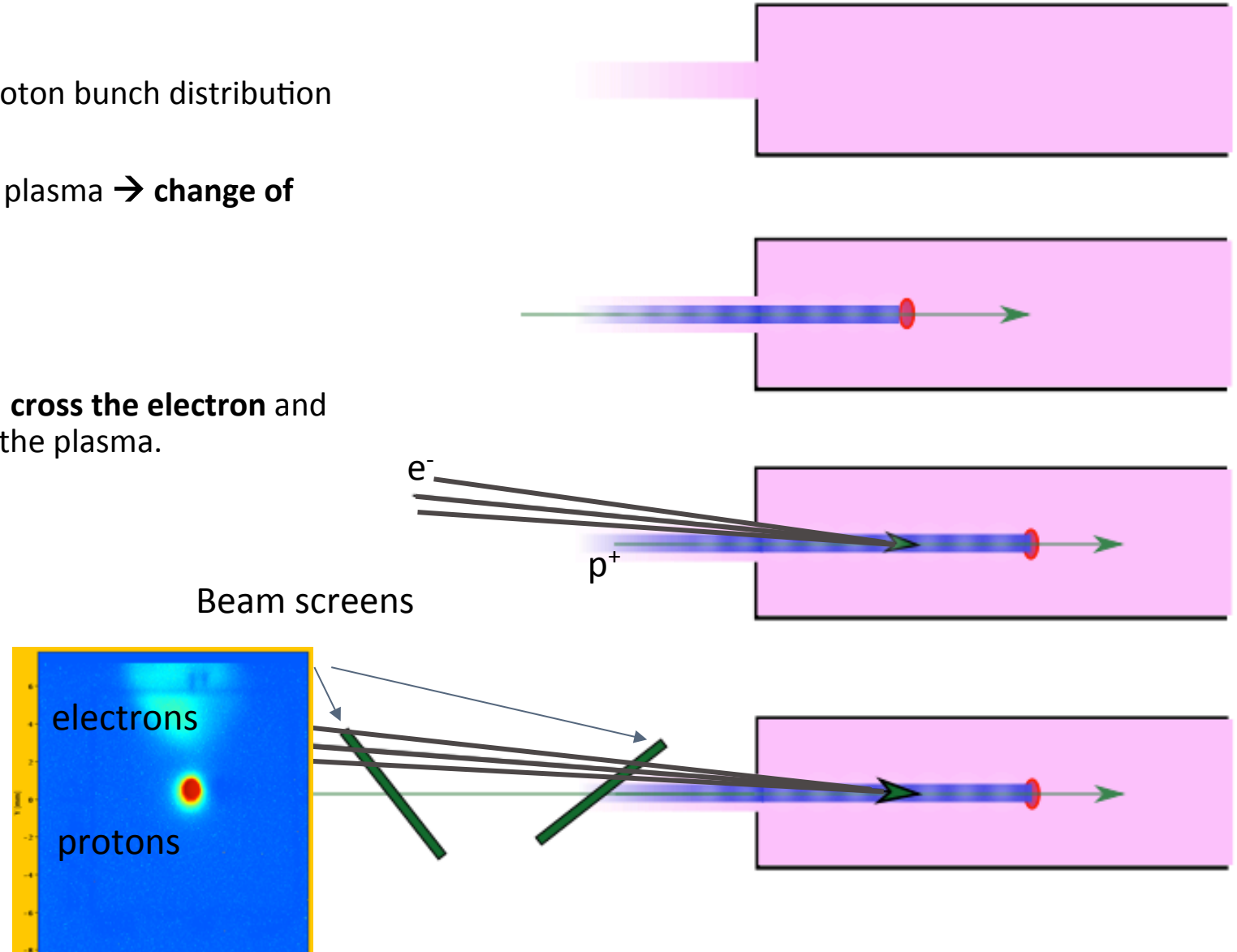
Electron Acceleration – Injection into Plasma

Challenge:

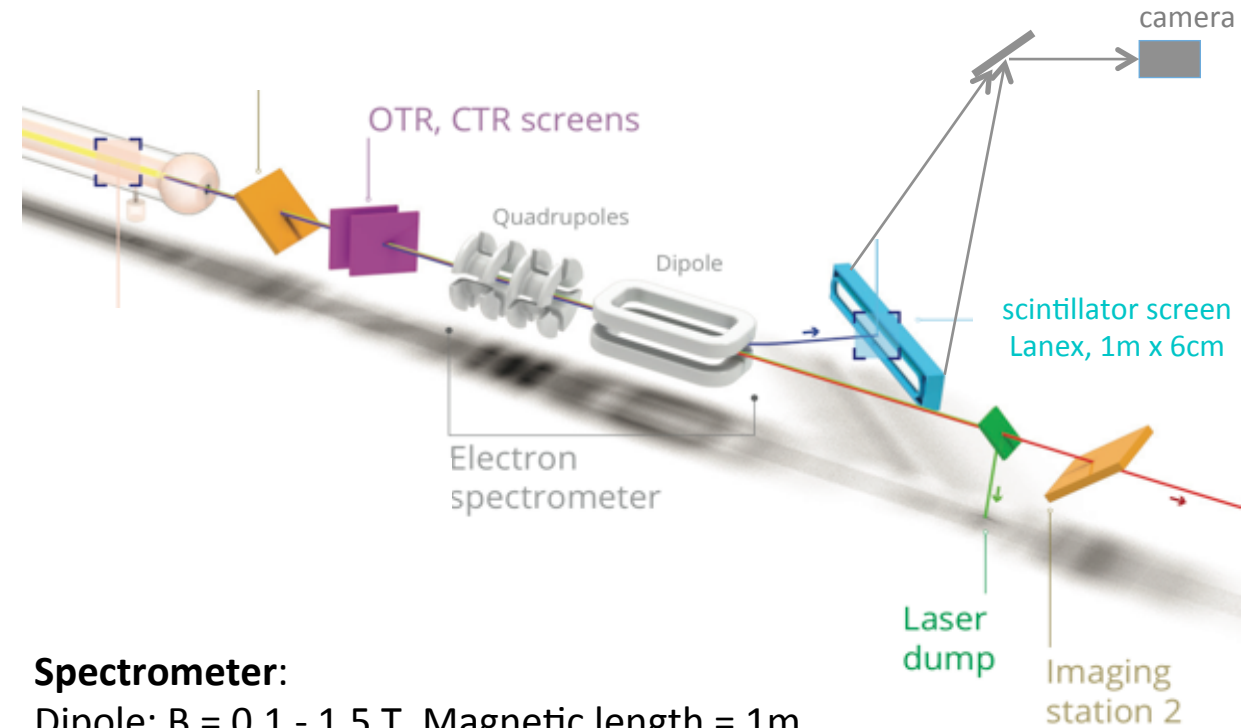
- During the Seeded Self-Modulation the proton bunch distribution **evolves**.
- Short density ramp at the entrance of the plasma → **change of wakefield phase**.
- Instead of injecting bunches co-linearly → **cross the electron** and proton bunch at a defined location inside the plasma.

May Run 2018: electron beam:

- 19 MeV
- 14mm mrad
- 650 pC at source
- FWHM = 5.2 ps.



Electron Acceleration Diagnostics



Spectrometer:

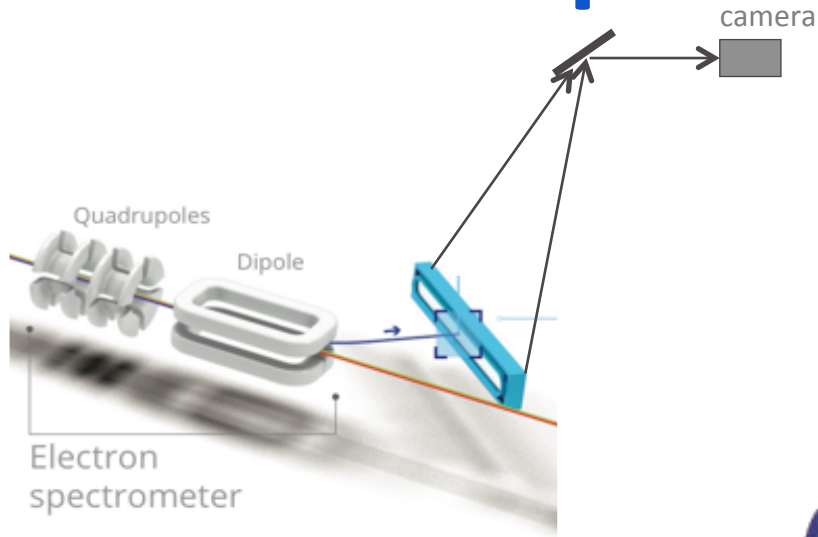
Dipole: $B = 0.1 - 1.5 \text{ T}$, Magnetic length = 1m

→ detect electrons with energies ranging from 30MeV - 8.5 GeV

Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a **dipole spectrometer** and the **dispersed electron impact on the scintillator screen**.

The resulting light is collected with an intensified CCD camera.

Electron Spectrometer Image Analysis



Charge response calibration

Screen and camera calibrated at the CLEAR Facility at CERN

Optical line corrections

1000 mm

Background subtraction

60 mm

Position \leftrightarrow Energy conversion

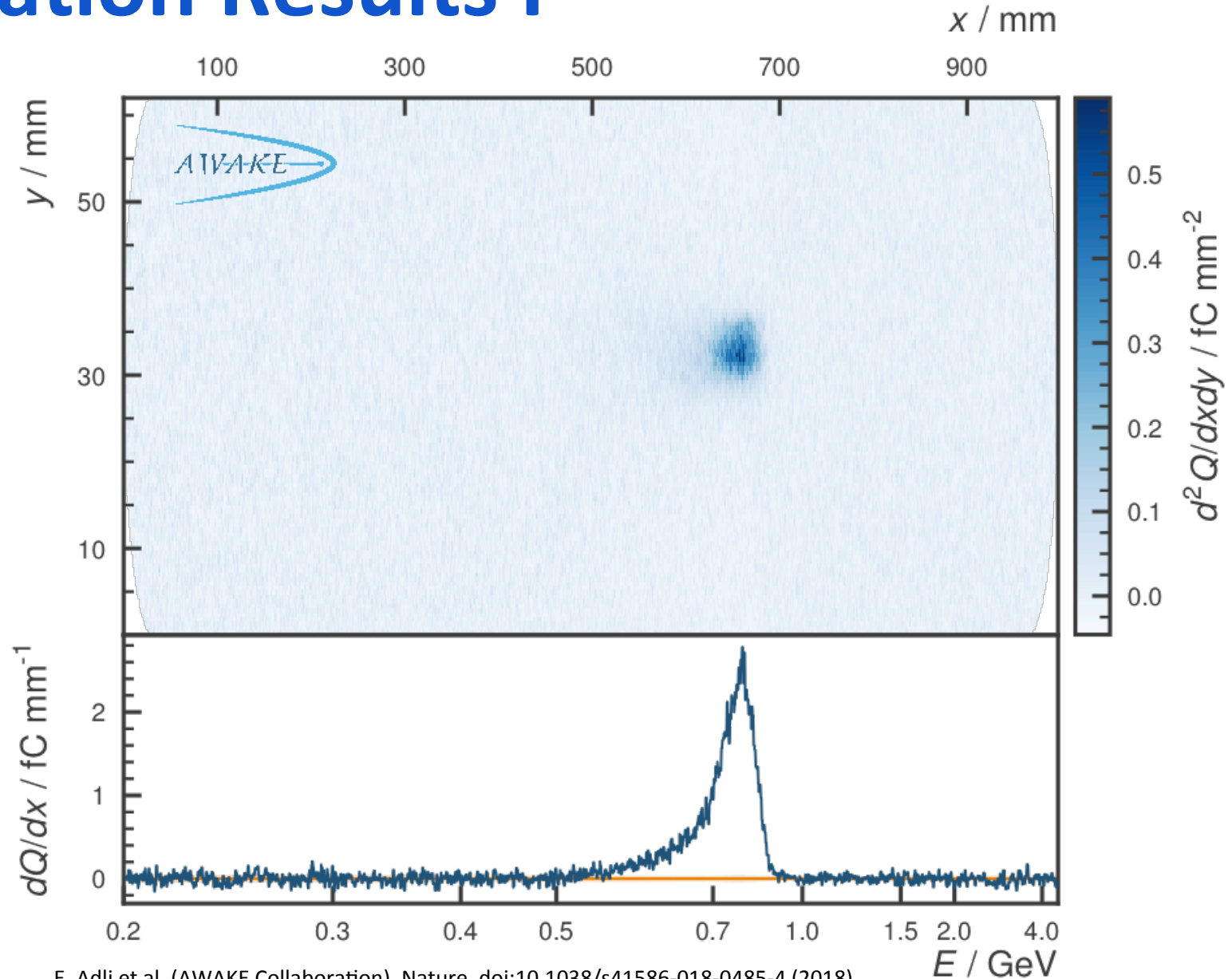
Electron Acceleration Results I

Results from May 2018 Run

Event at $n_{pe} = 1.8 \times 10^{14} \text{ cm}^{-3}$ with 5%/10m density gradient.

- Acceleration to **800 MeV**.
- **Accelerated bunch charge** of 0.2pC → Capture efficiency not yet optimized.

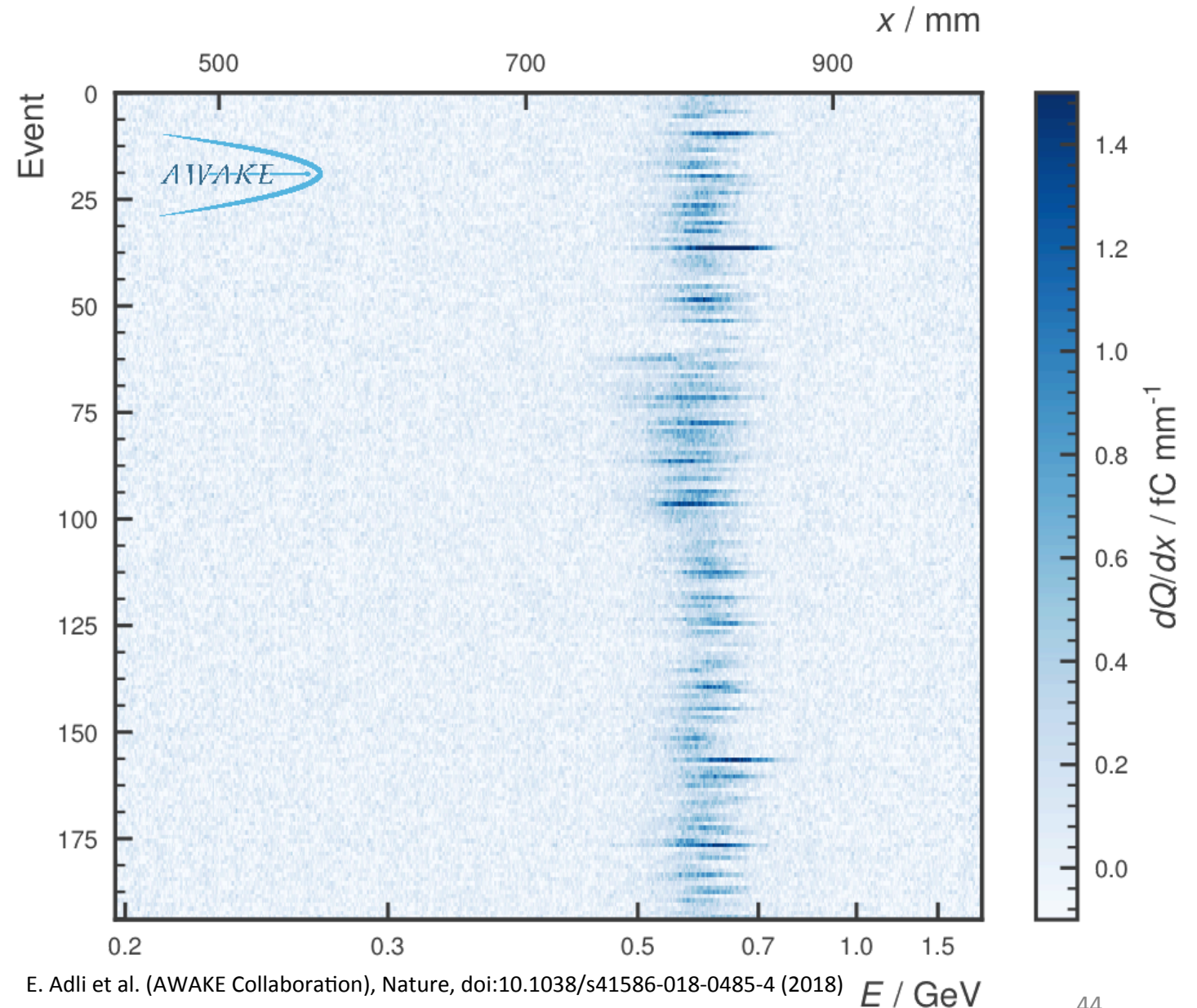
➔ recent measurements factor 50-100 higher capture efficiency!!



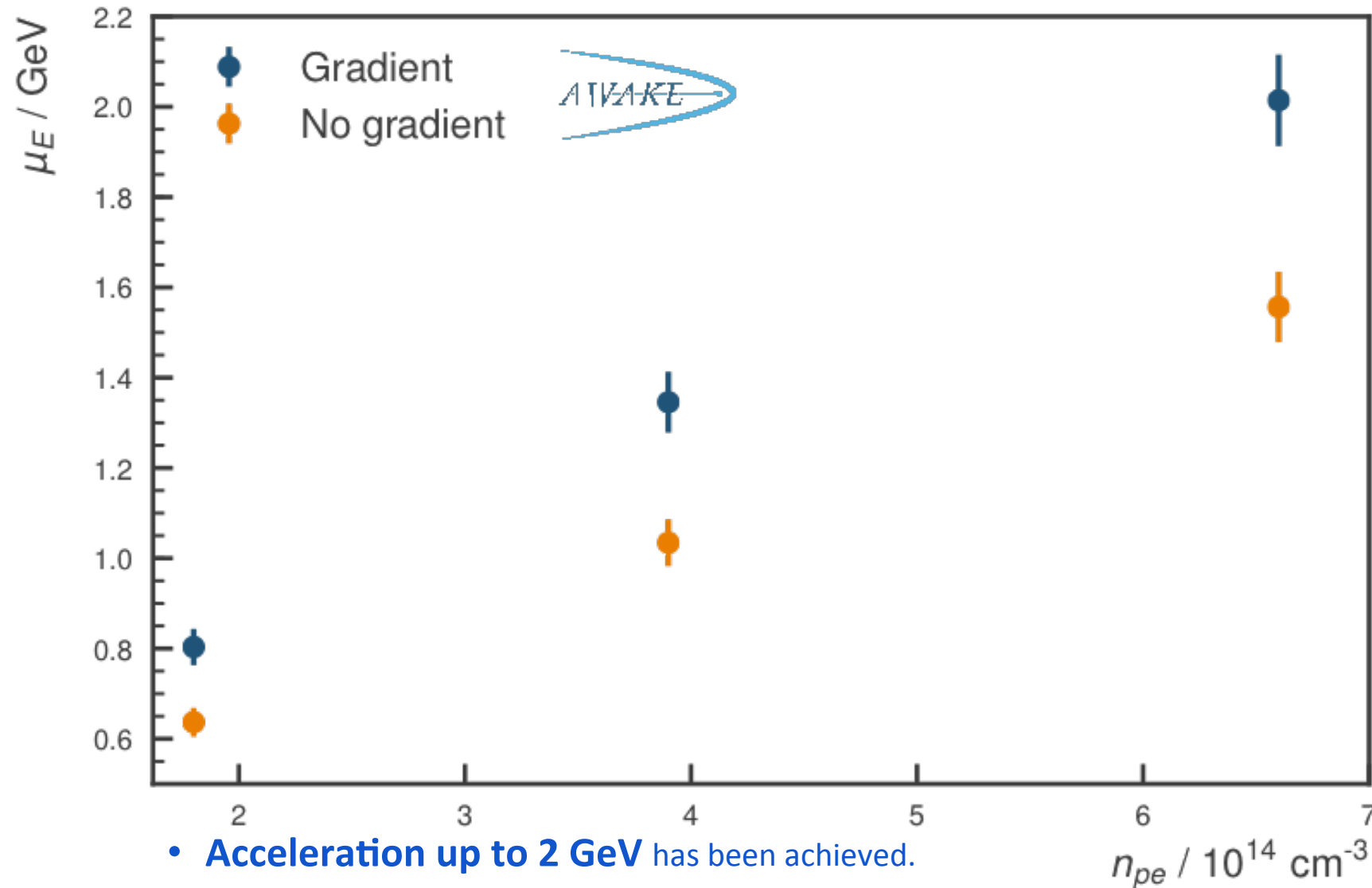
E. Adli et al. (AWAKE Collaboration), Nature, doi:10.1038/s41586-018-0485-4 (2018)

Electron Acceleration Results II

- **Consecutive electron injection** events at $n_{pe} = 1.8 \times 10^{14} \text{cm}^{-3}$.
- **Quadrupole scan** performed over this period.
- **Stability** crucial for further development.



Electron Acceleration Results III



- **Acceleration up to 2 GeV** has been achieved.
- Charge capture decreases with plasma density n_{pe} .

Electron Acceleration Results III



ent
radient



nature

Accelerated Article Preview

LETTER

doi:10.1038/s41586-018-0485-4

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli, A. Ahuja, O. Apsimon, R. Apsimon, A. – M. Bachmann, D. Barrientos, F. Batsch, J. Bauche, V.K. Berglyd Olsen, M. Bernardini, T. Bohl, C. Bracco, F. Braunmüller, G. Burt, B. Buttenschön, A. Caldwell, M. Cascella, J. Chappell, E. Chevallay, M. Chung, D. Cooke, H. Damerau, L. Deacon, L.H. Deubner, A. Dexter, S. Doeber, J. Farmer, V.N. Fedosseev, R. Fiorito, R.A. Fonseca, F. Friebe, L. Garolfi, S. Gessner, I. Gorgisyan, A.A. Gorn, E. Granados, O. Grulke, E. Gschwendtner, J. Hansen, A. Helm, J.R. Henderson, M. Hüther, M. Ibison, L. Jensen, S. Jolly, F. Keeble, S.–Y. Kim, F. Kraus, Y. Li, S. Liu, N. Lopes, K.V. Lotov, L. Maricalva Brun, M. Martyanov, S. Mazzoni, D. Medina Godoy, V.A. Minakov, J. Mitchell, J.C. Molendijk, J.T. Moody, M. Moreira, P. Muggli, E. Öz, C. Pasquino, A. Pardons, F. Peña Asmus, K. Pepitone, A. Perera, A. Petrenko, S. Pitman, A. Pukhov, S. Rey, K. Rieger, H. Ruhl, J.S. Schmidt, I.A. Shalimova, P. Sherwood, L.O. Silva, L. Soby, A.P. Sosedkin, R. Speroni, R.I. Spitsyn, P.V. Tuv, M. Turner, F. Velotti, L. Verra, V.A. Verzilov, J. Vieira, C.P. Welsch, B. Williamson, M. Wing, B. Woolley and G. Xia



Media and Press Relations



AWAKE achieves first ever acceleration of electrons in a proton-driven plasma wave

29 Aug 2018



4

✓ has been achieved
plasma density n_{pe} .

Outline

- Plasma Wakefield Acceleration
- AWAKE, The Advanced Wakefield Experiments
- AWAKE Results
- What's Next

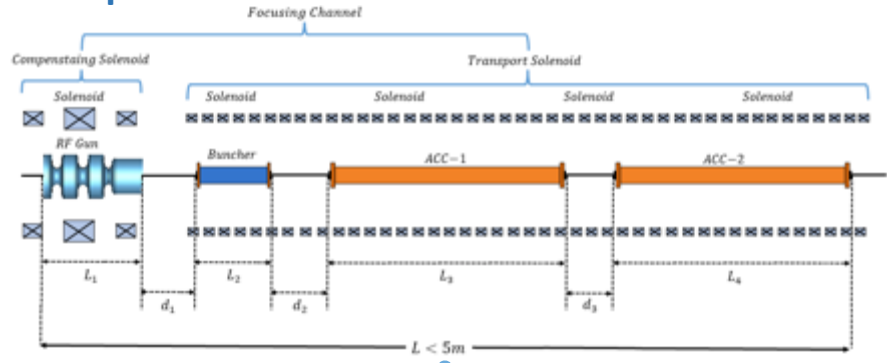
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

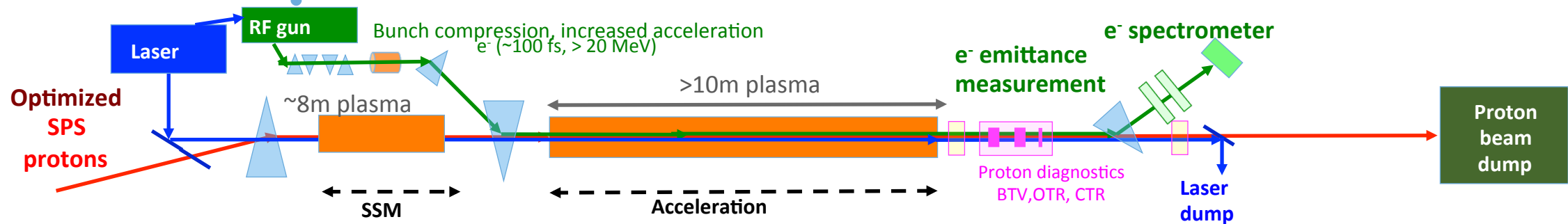
Goals:

- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
- Demonstrate scalability of the AWAKE concept (R&D plasma sources)

Proposal: X-band electron source



Preliminary Run 2 electron beam parameters	
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim 50$ MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim 10$ μm

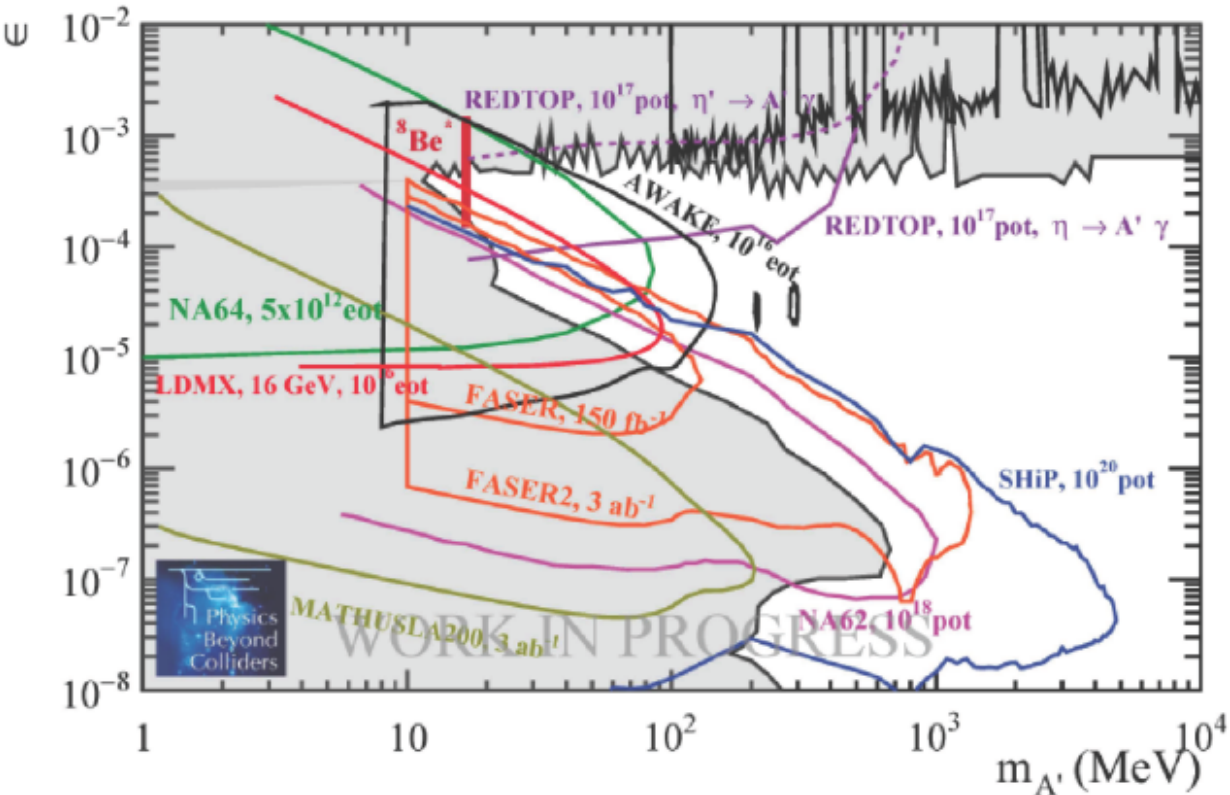


Application: Fixed Target Experiments

- **Fixed target test facility:** Use bunches from SPS with 3.5 E11 protons every ~5sec,
 → electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons**
- deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**

Parameter	AWAKE-upgrade-type	HL-LHC-type
Proton energy E_p (GeV)	400	450
Number of protons per bunch N_p	3×10^{11}	2.3×10^{11}
Longitudinal bunch size protons σ_z (cm)	6	7.55
Transverse bunch size protons σ_r (μm)	200	100
Proton bunches per cycle n_p	8	320
Cycle length (s)	6	20
SPS supercycle length (s)	40	40
Electrons per cycle N_e	2×10^9	5×10^9
Number of electrons on target per 12 weeks run	4.1×10^{15}	2×10^{17}

NA64 experiment: $\sim 3 \times 10^{12}$ electrons on target



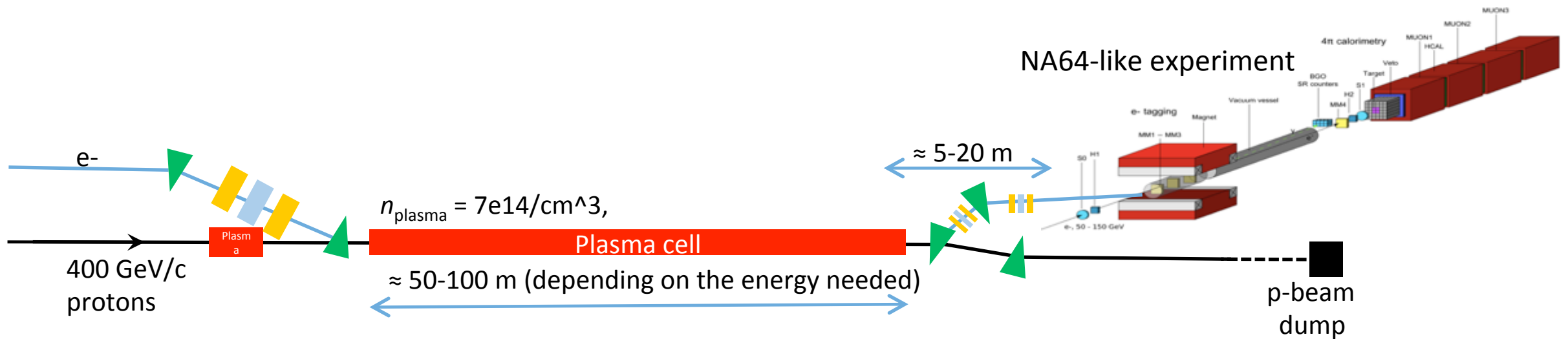
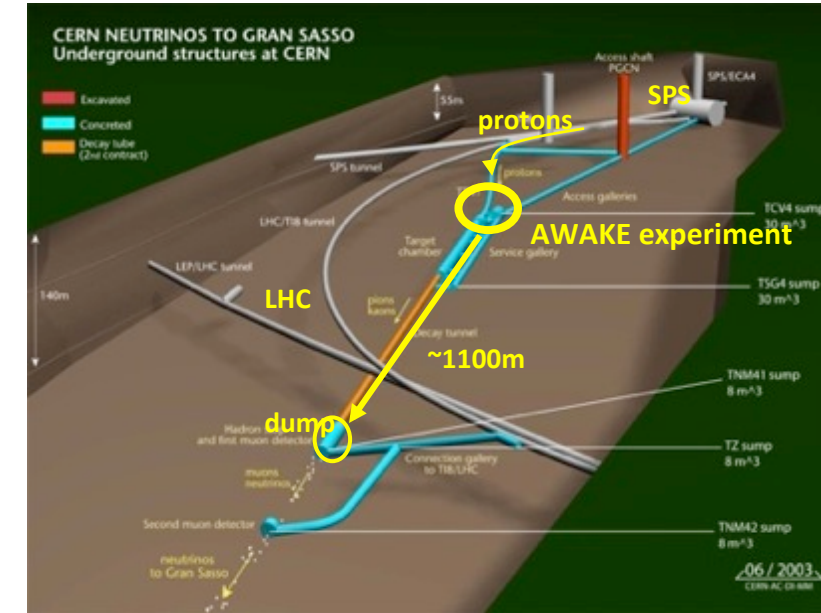
Projected sensitivities to the dark photon visible mode

Application: Fixed Target Experiments

Install in the current AWAKE facility, empty old CERN Neutrinos to Gran Sasso Area

Baseline scenario (based on AWAKE Run 2 parameters)

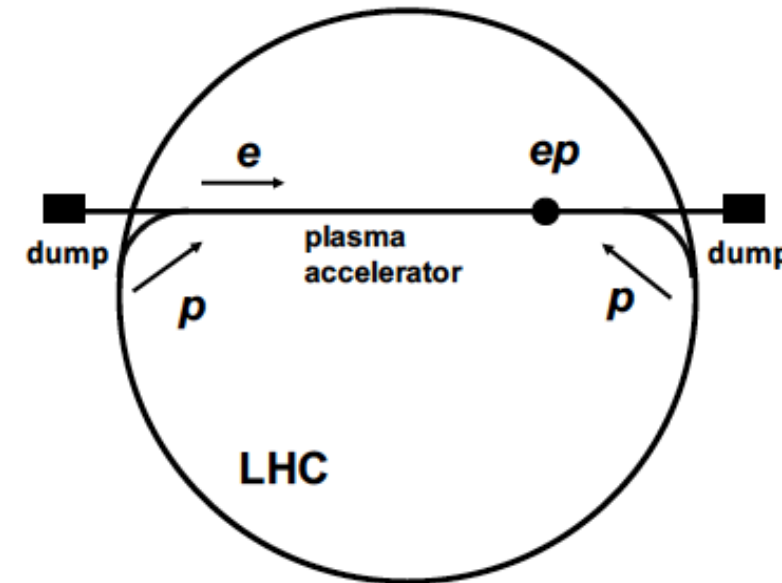
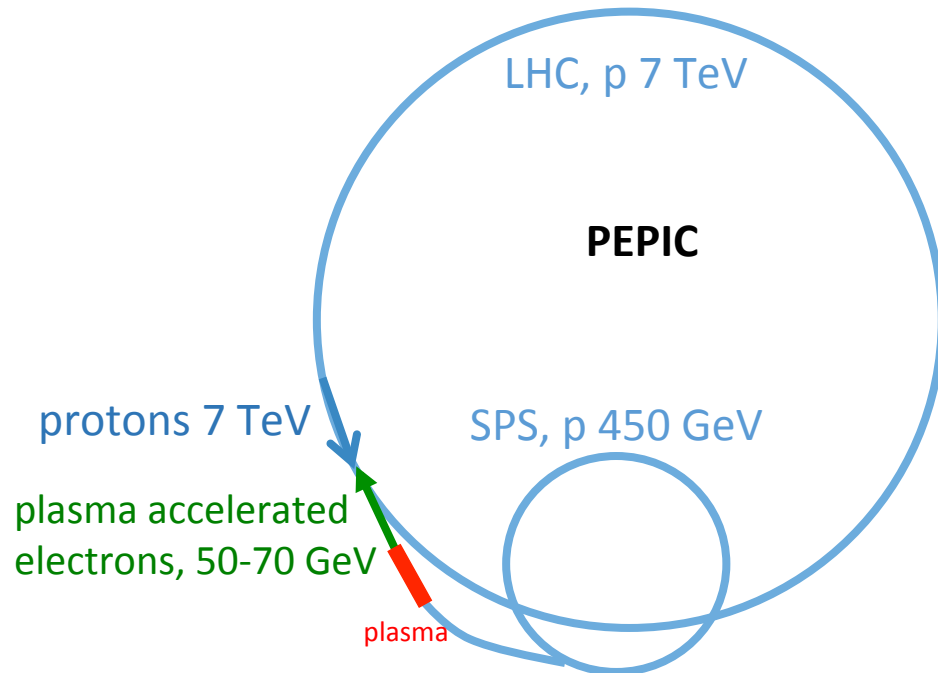
- 50 m long plasma accelerator
- 33 GeV/c electrons, $\Delta E/E = 2\%$, ~ 100 pC
- For 100 m accelerator: 53 GeV/c e, $\Delta E/E = 2\%$, ~ 130 pC



Application: Colliders

Using **the SPS or the LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider

- **PEPIC**: LHeC like collider: E_e up to O (70 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy
- **VHPEc**: choose $E_e = 3$ TeV as a baseline and with $E_p = 7$ TeV yields $\sqrt{s} = 9$ TeV. → CM ~30 higher than HERA. Luminosity $\sim 10^{28} - 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ gives $\sim 1 \text{ pb}^{-1}$ per year.



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

Summary

- Many encouraging results in the plasma wakefield acceleration technology. Plasma wakefield acceleration is an exciting and growing field with a huge potential.
- **AWAKE**: Proton-driven plasma wakefield acceleration interesting because of large energy content of driver. Modulation process means existing proton machines can be used.
- **AWAKE has for the first time demonstrated proton driven plasma wakefield acceleration of externally injected electrons.**
- **AWAKE Run 1** was a proof-of-concept experiment. → **DONE!**
- Aim of **AWAKE Run 2** starting 2021 after CERN's Long Shutdown 2 is to achieve high-charge bunches of electrons accelerated to **high energy, about 10 GeV**, while maintaining **beam quality** through the plasma and showing that the process is **scalable**.
- Use the **AWAKE** scheme for **particle physics applications** such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.