AWAKE:
A Proton Driven Plasma Wakefield Experiment at CERN

Edda Gschwendtner, CERN

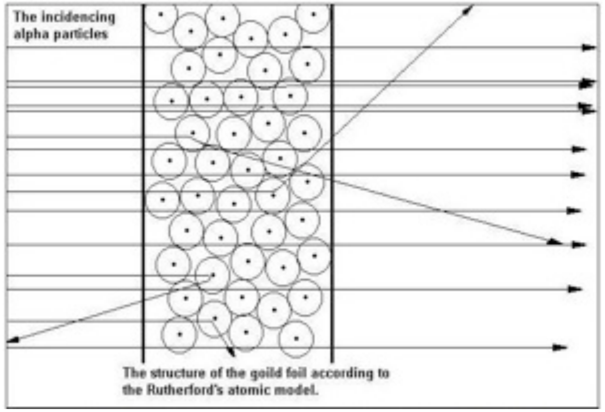
CEA, Saclay, 10 December 2018

Outline

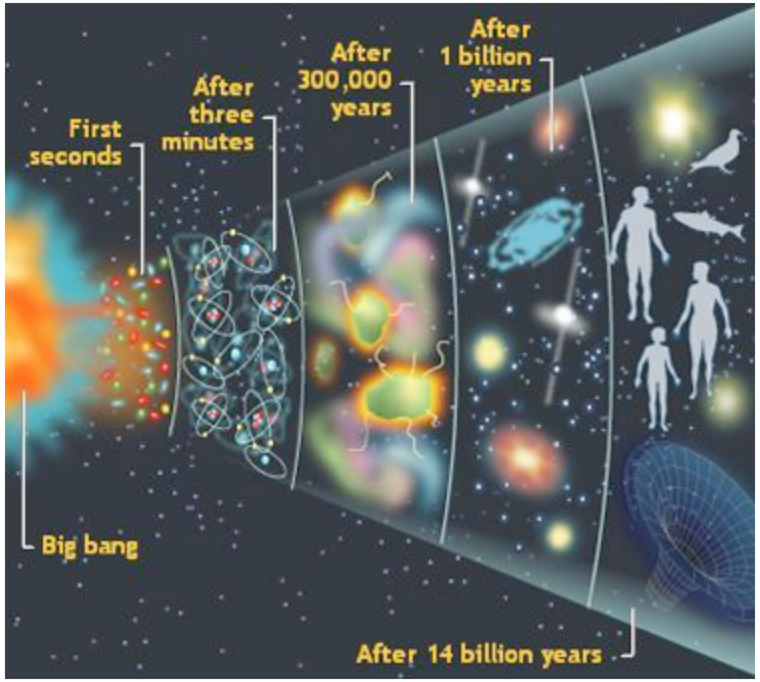
- Motivation
- Plasma Wakefield Acceleration
- AWAKE
- Outlook

Motivation: Increase Particle Energies

- Increasing particle energies **probe smaller and smaller scales of matter**
  - **1910:** Rutherford: scattering of MeV scale alpha particles revealed structure of atom
  - **1950ies:** scattering of GeV scale electron revealed finite size of proton and neutron
  - **Early 1970ies:** scattering of tens of GeV electrons revealed internal structure of proton/neutron, ie quarks.



- Increasing energies **makes particles of larger and larger mass accessible**
  - GeV type masses in 1950ies, 60ies (Antiproton, Omega, hadron resonances…
  - Up to 10 GeV in 1970ies (J/Psi, Ypsilon…)
  - Up to ~100 GeV since 1980ies (W, Z, top, Higgs…)



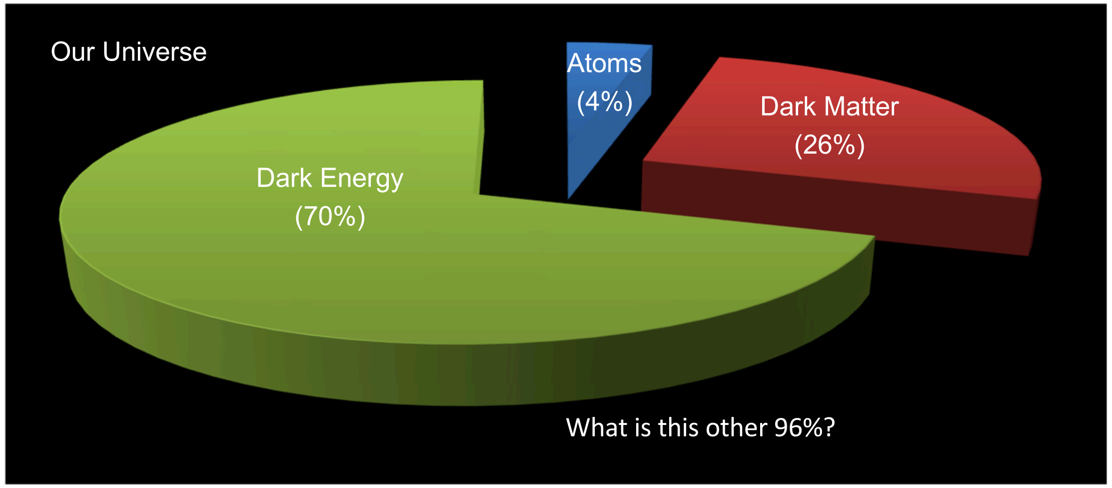
- Increasing particle energies **probe earlier times in the evolution of the universe.**
  - Temperatures at early universe were at levels of energies that are achieved by particle accelerators today
  - Understand the origin of the universe

- Discoveries went hand in hand with theoretical understanding of underlying laws of nature

  → **Standard Model** of particle physics

Motivation: High Energy Accelerators

- Large list of unsolved problems:
  - What is dark matter made of? What is the reason for the baryon-asymmetry in the universe? What is the nature of the cosmological constant? …

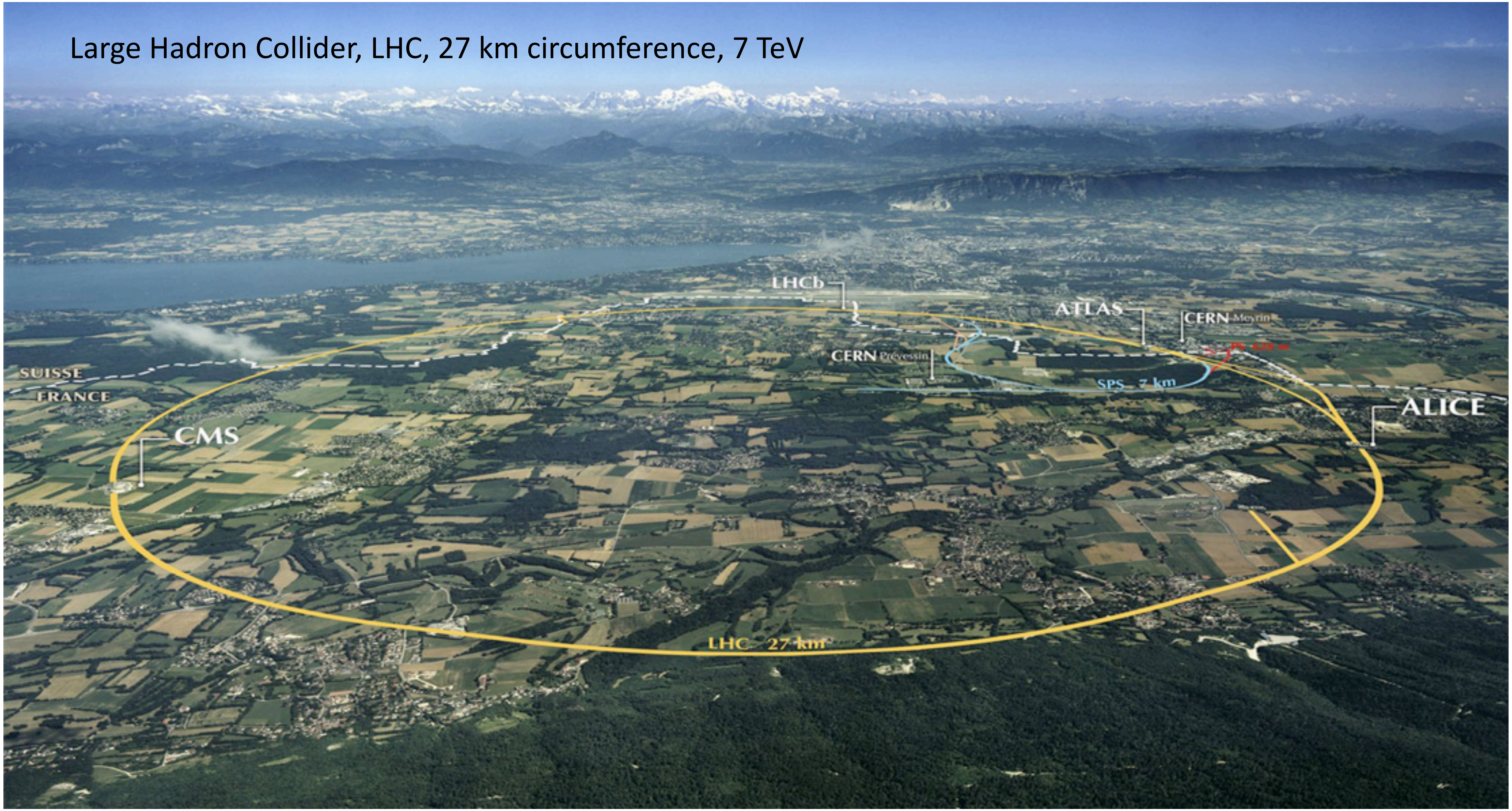


- **Need particle accelerators with new energy frontier**

➔ 30’000 accelerators worldwide!

Also application of accelerators outside particle physics in medicine, material science, biology, etc…

LHC



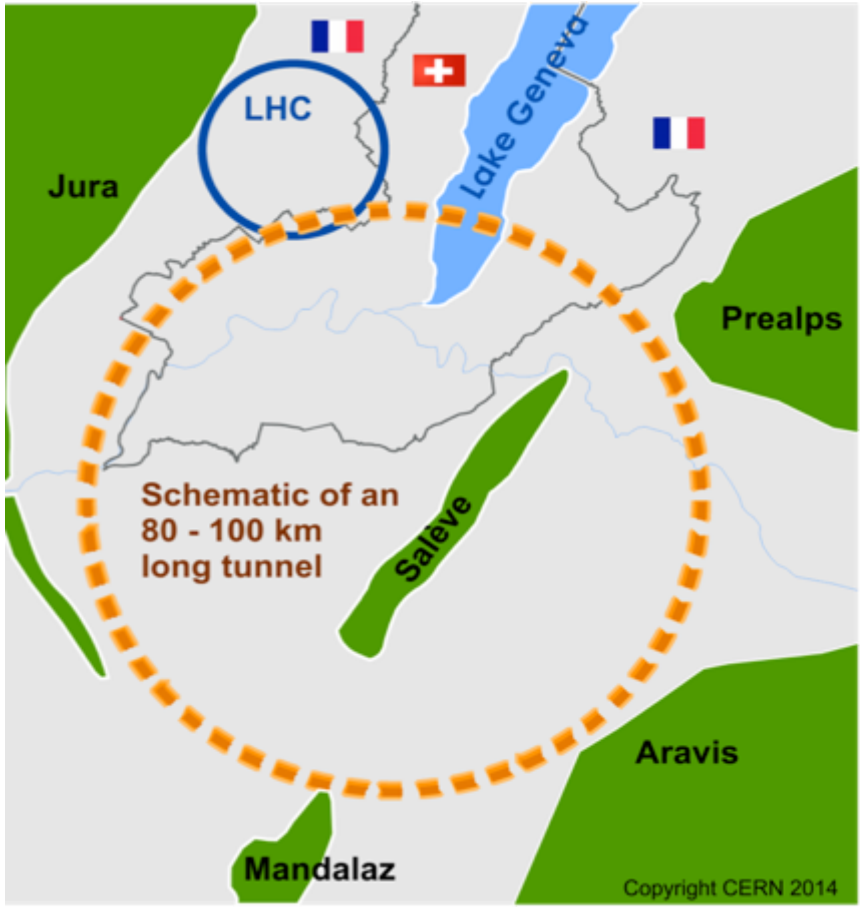
Large Hadron Collider, LHC, 27 km circumference, 7 TeV
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators**

Future Circular Collider FCC



Limitations of conventional circular accelerators:

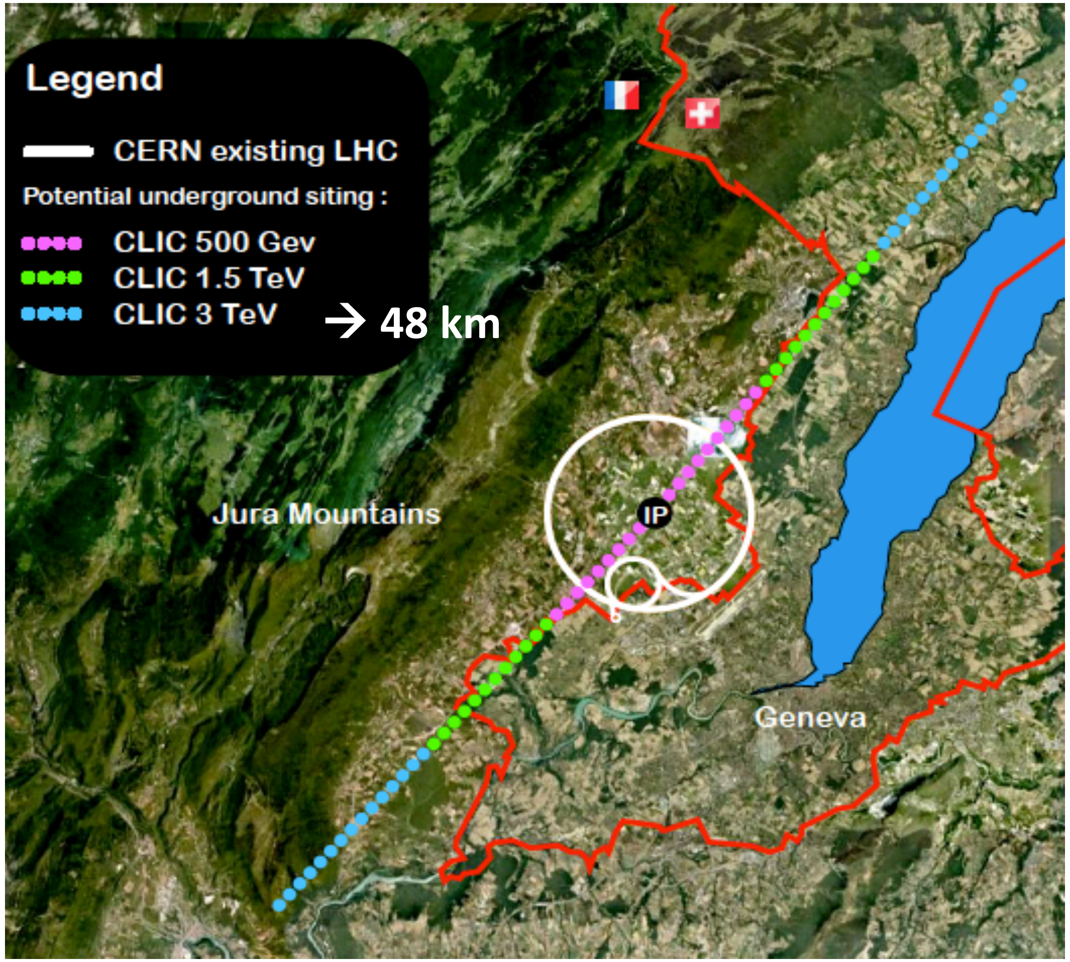
- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of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

$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$

Discover New Physics

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

CLIC, electron-positron collider with 3 TeV energy

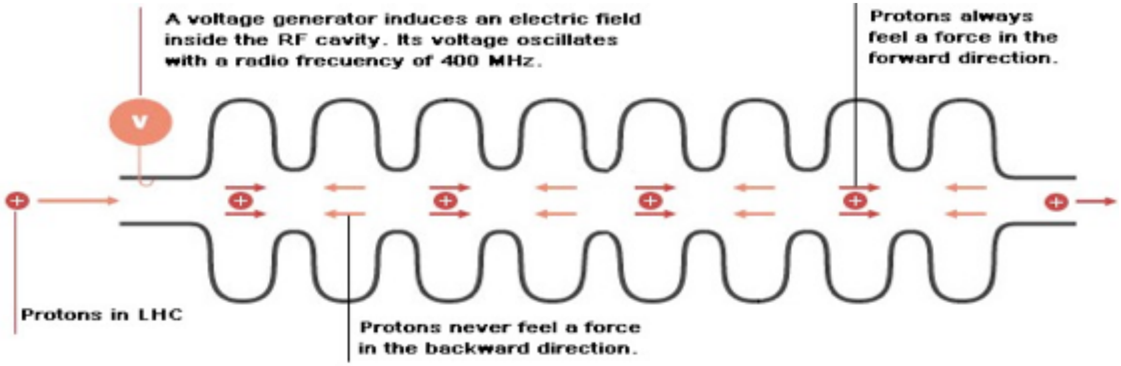


Limitations of linear colliders:

- 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.

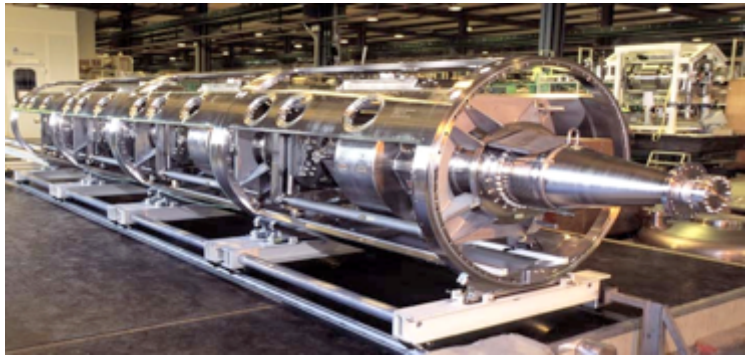
Conventional Acceleration Technology

Radiofrequency Cavities

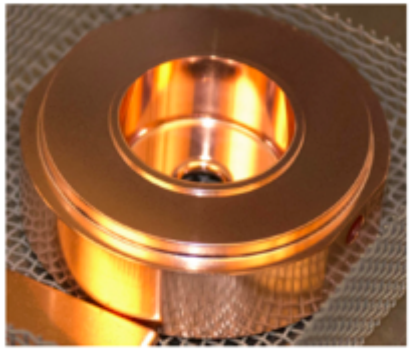


(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity



New RF Copper Cell



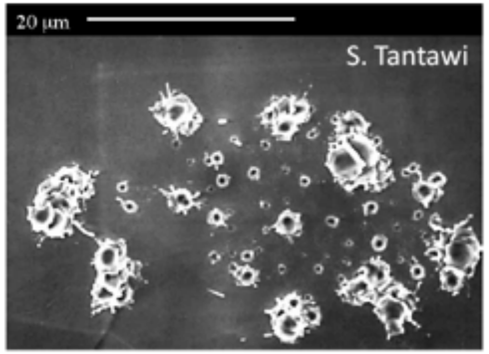
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

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

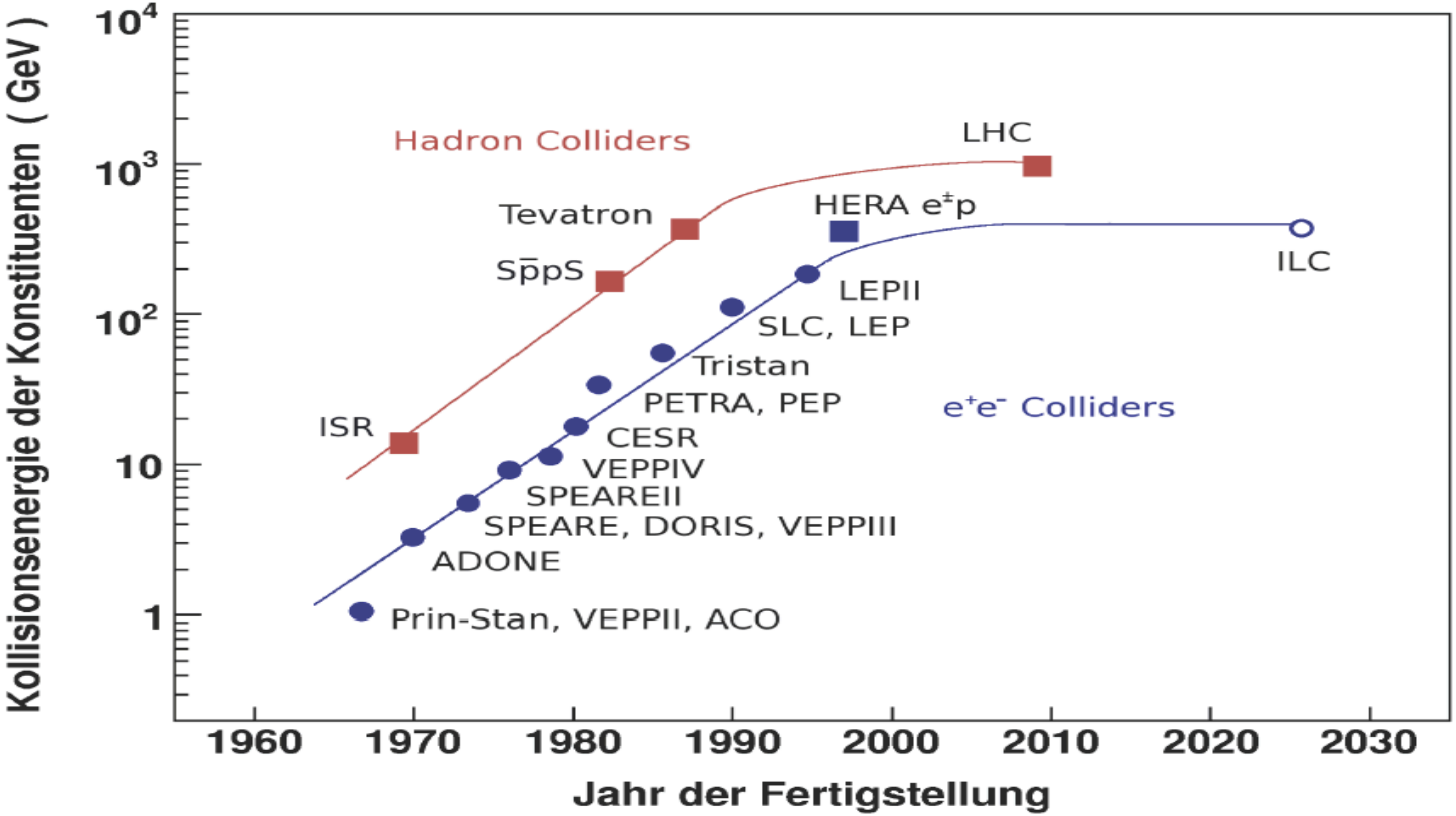
- In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge.
- Fields cannot be sustained, structures might be damaged.

➔ **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**

Motivation

New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

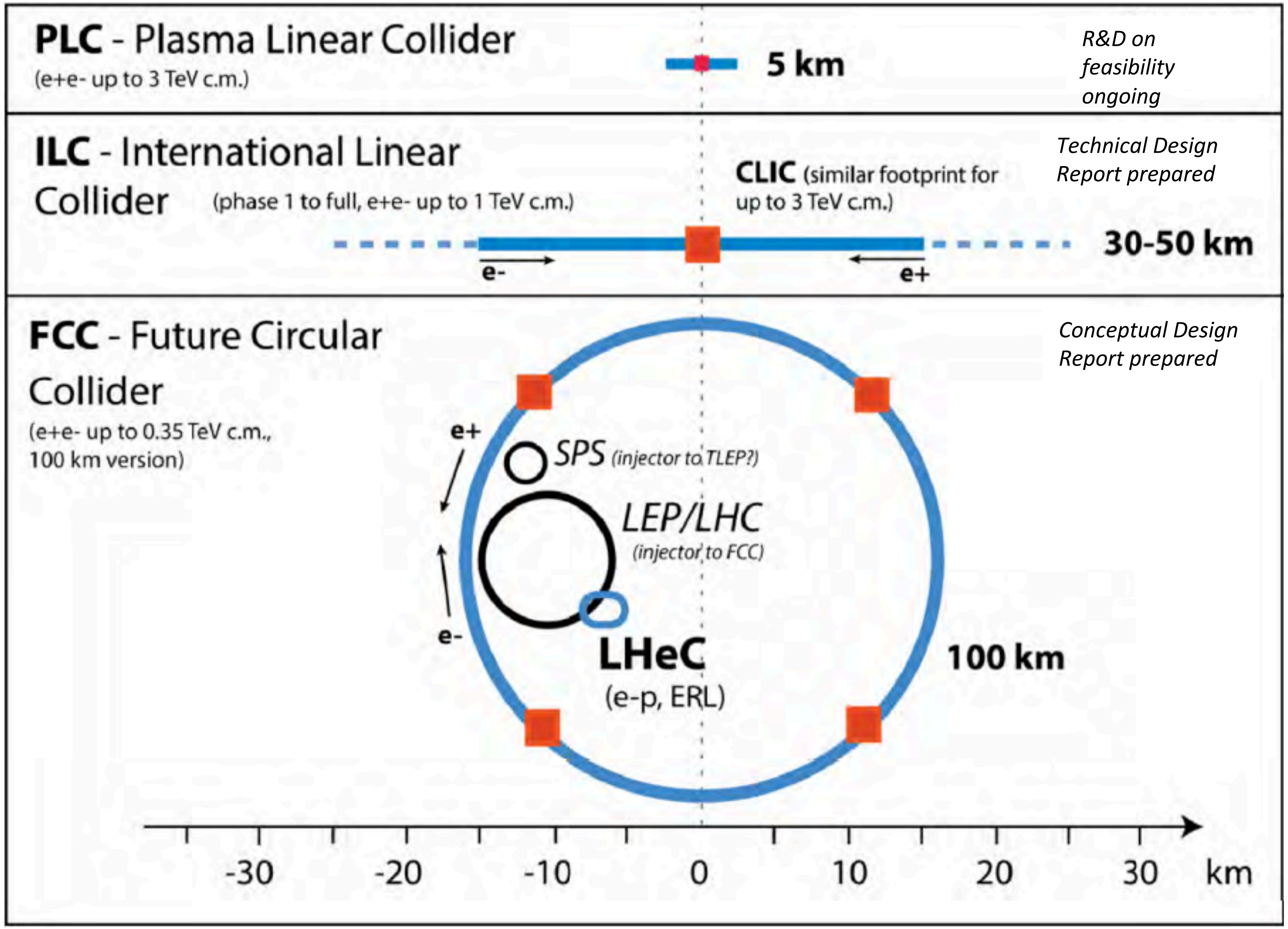
The effect of a tool-driven revolution is to discover new things that have to be explained.

From Freeman Dyson 'Imagined Worlds'

Plasma Wakefield Acceleration

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

Conventional vs. Plasma



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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 Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2.

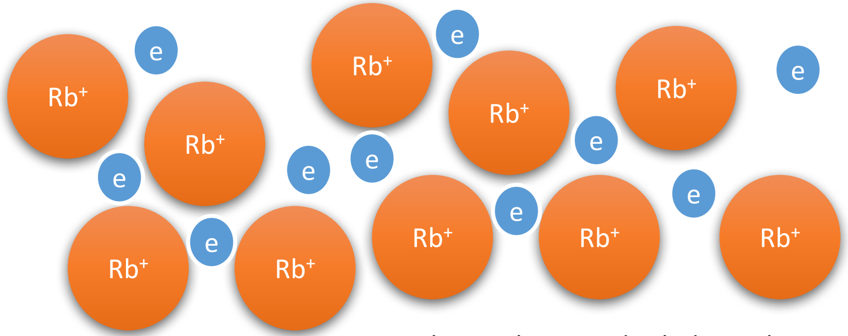
the wavelength of the plasma waves in the wake:

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

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

Plasma Wakefield

What is a plasma?



Example: Single ionized rubidium plasma

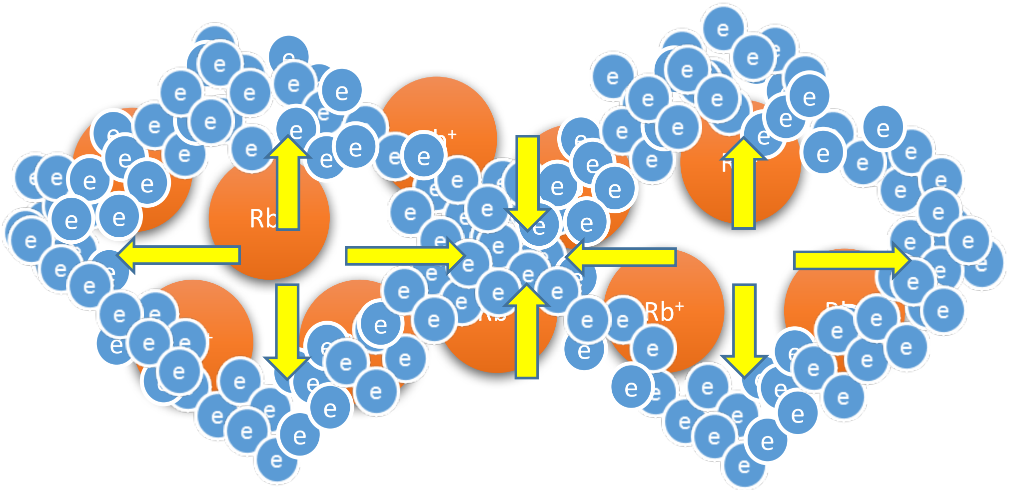
Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients** → order of **100 GV/m.**

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



Fields created by collective motion of plasma particles are called plasma wakefields.

Plasma Baseline Parameters

- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

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

- This translates into a wavelength of the plasma oscillation

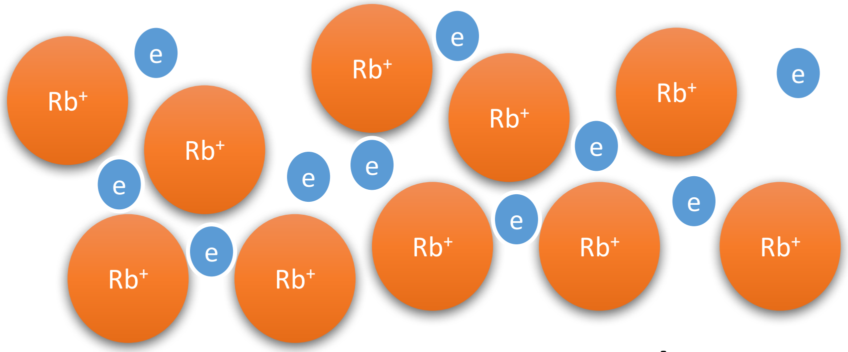
$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \quad \rightarrow \quad \lambda_{pe} \approx 1\text{ mm} \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$

$\boxed{\lambda_{pe} = 1.2\text{ mm}}$ → **Produce cavities with mm size!**

How to Create a Plasma Wakefield?

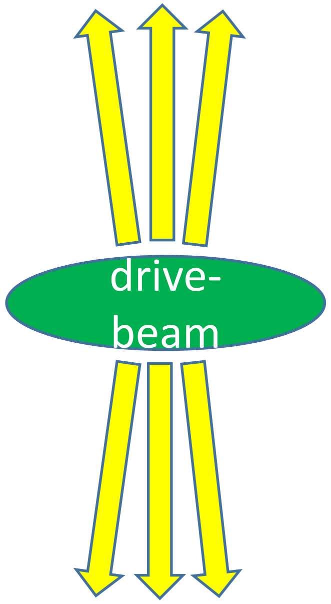
What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



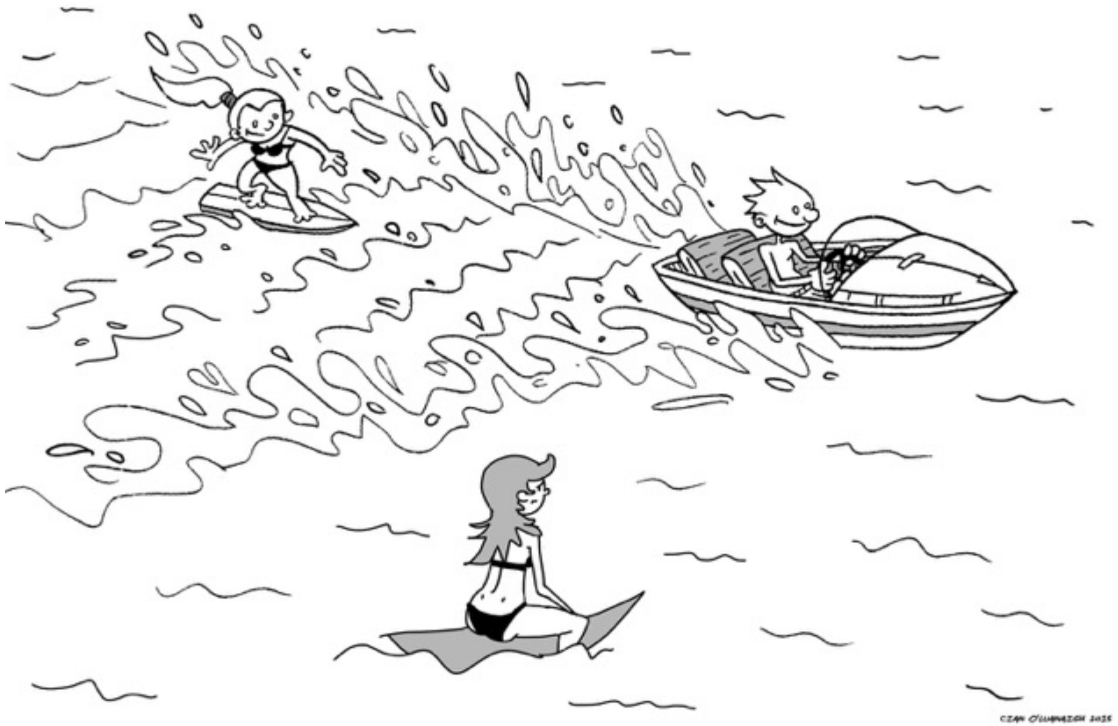
Single ionized rubidium **plasma**

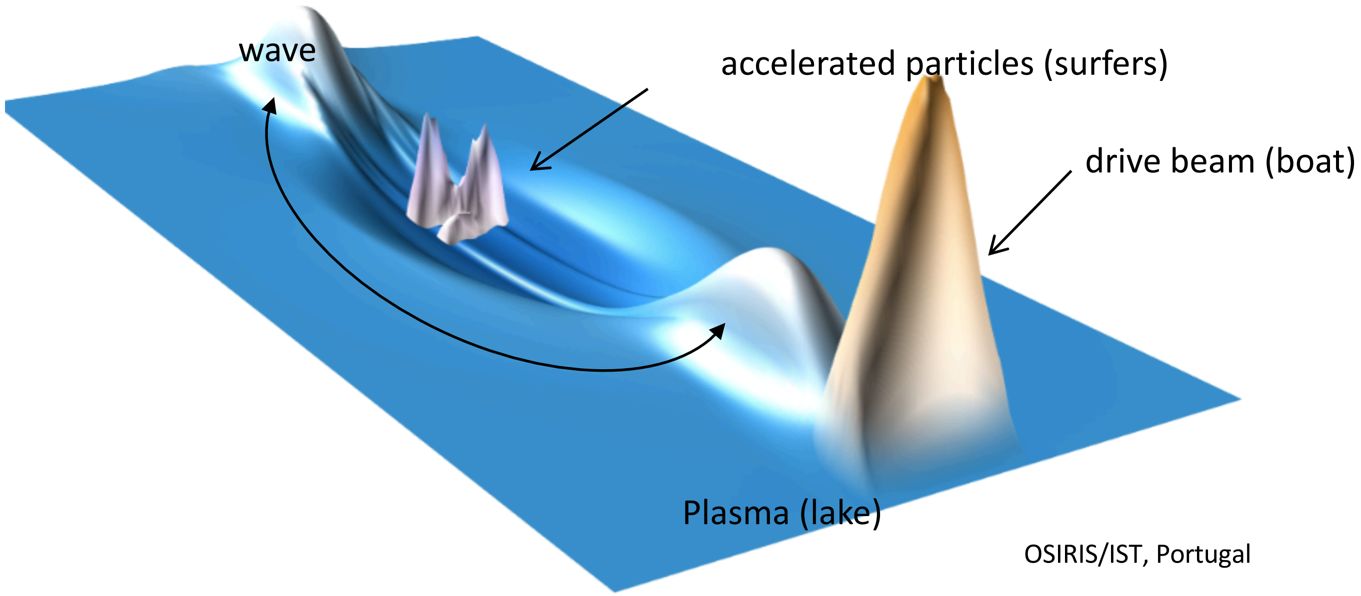
Charged particle bunches carry almost purely transverse electric fields.



Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.** The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

How to Create a Plasma Wakefield?

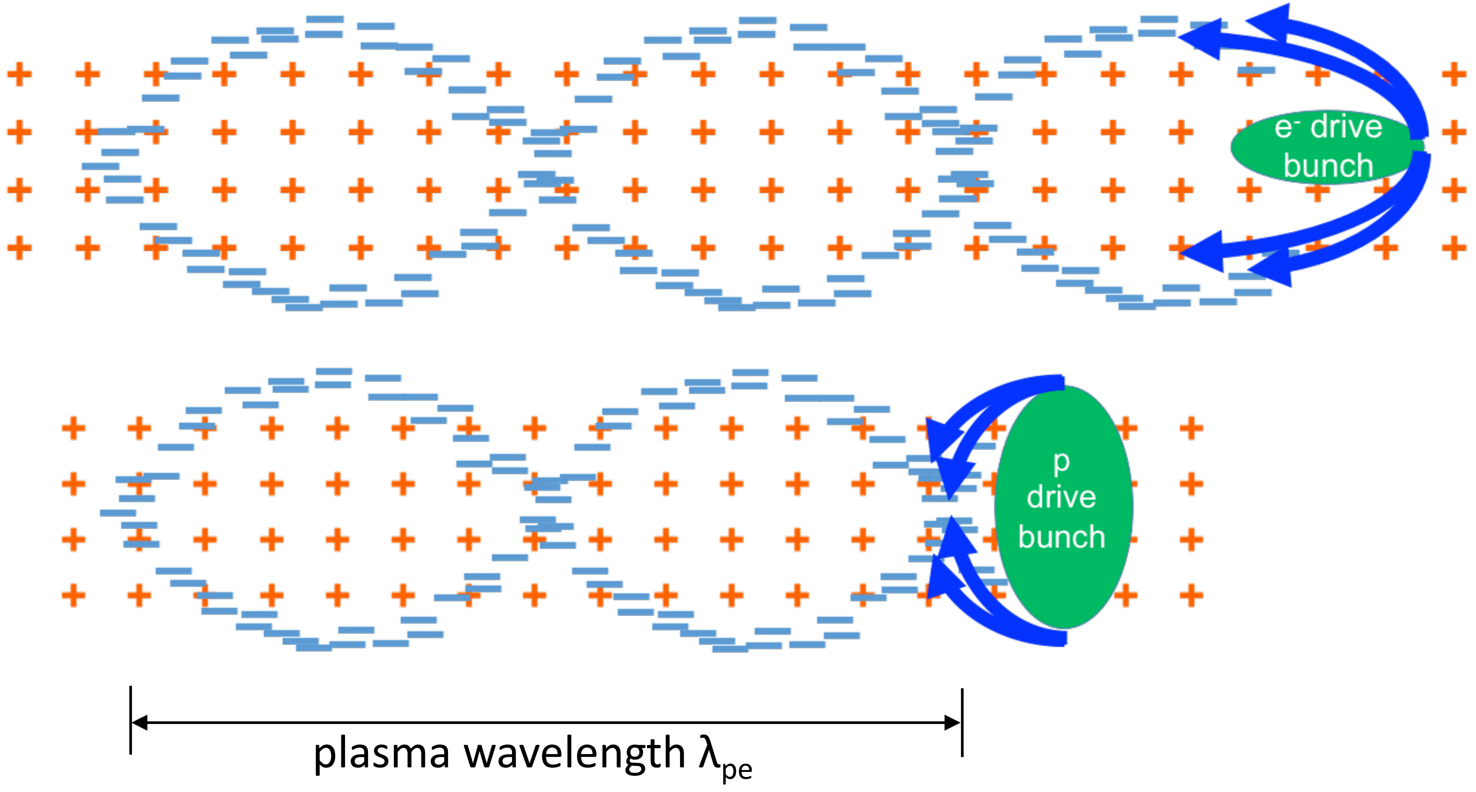




OSIRIS/IST, Portugal

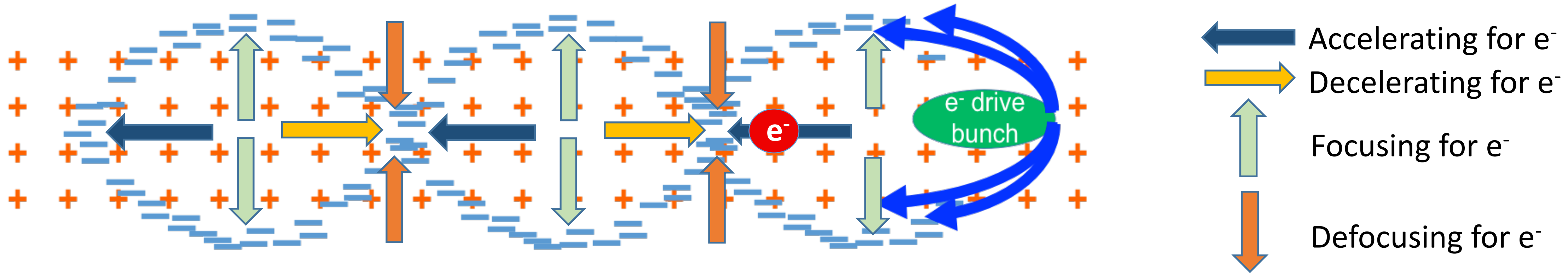
Principle of Plasma Wakefield Acceleration

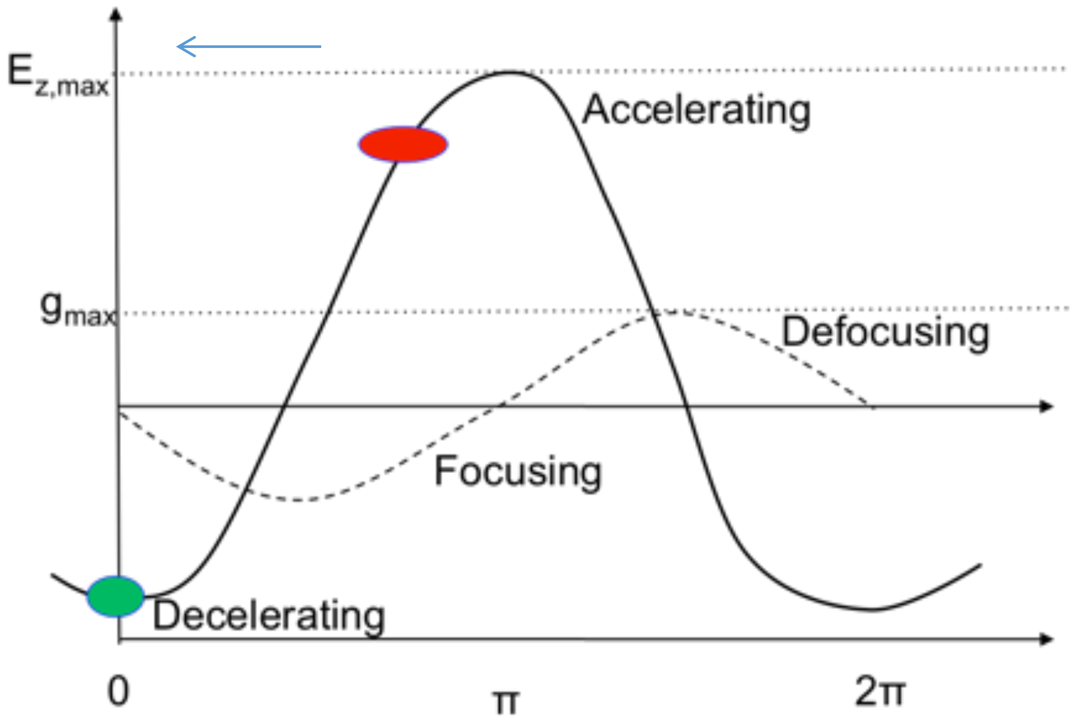
- **Laser drive beam**
  - ➔ Ponderomotive force
- **Charged particle drive beam**
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



- 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)?





Linear Theory (P. Chen, R. Ruth 1986)

When drive beam density is smaller than plasma density (**n_b << n_p**) → **linear theory.**

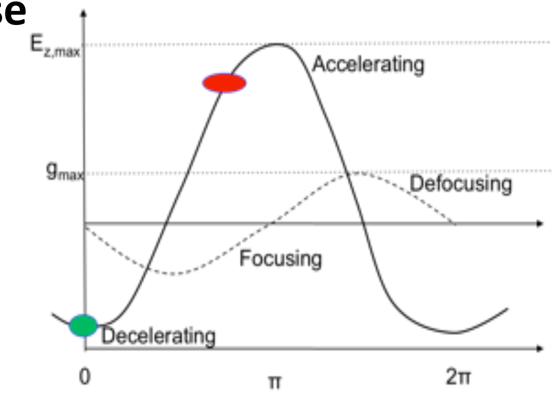
- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

$$eE_z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}\,k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

➔ **$eE_z \approx N/\sigma_z^2$**

B.E. Blue 2003

- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**



- The **accelerating field is maximized** for a value of

$$\mathbf{k_{pe}\,\sigma_z \approx \sqrt{2}}$$
$$\mathbf{k_{pe}\,\sigma_r \leq 1}$$

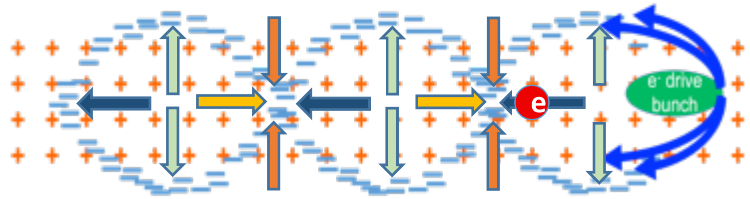
Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE), k_{pe} = 5 mm^{-1} ➔ drive beam: σ_z = 300µm, σ_r = 200µm

Linear Theory

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

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

Drive beam fulfills: $k_{pe} \, \sigma_z \approx \sqrt{2}$



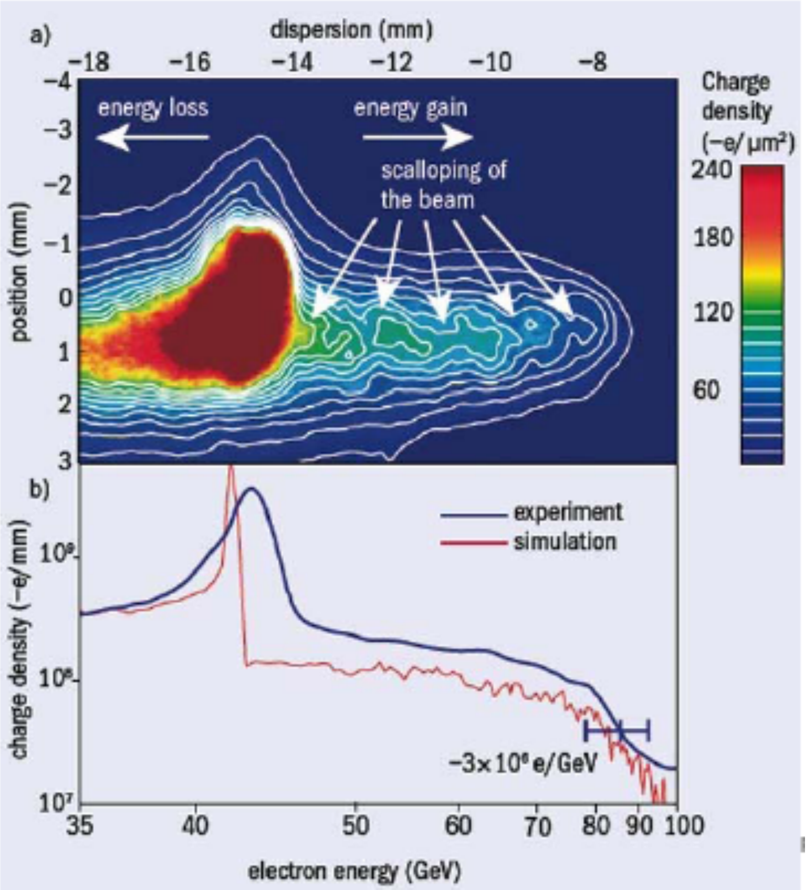
Examples of accelerating fields for different beam parameters and plasma parameters fields:

$N = 3\text{x}10^{10}$, $\sigma_z = 300\mu\text{m}$, $n_{pe} = 7\text{x}10^{14}$ cm^{-3} ➔ **E_{acc} = 600 MV/m**
$N = 3\text{x}10^{10}$, $\sigma_z = 20\mu\text{m}$, $n_{pe} = 2\text{x}10^{17}$ cm^{-3} ➔ **E_{acc} = 15 GV/m**

Experimental Results

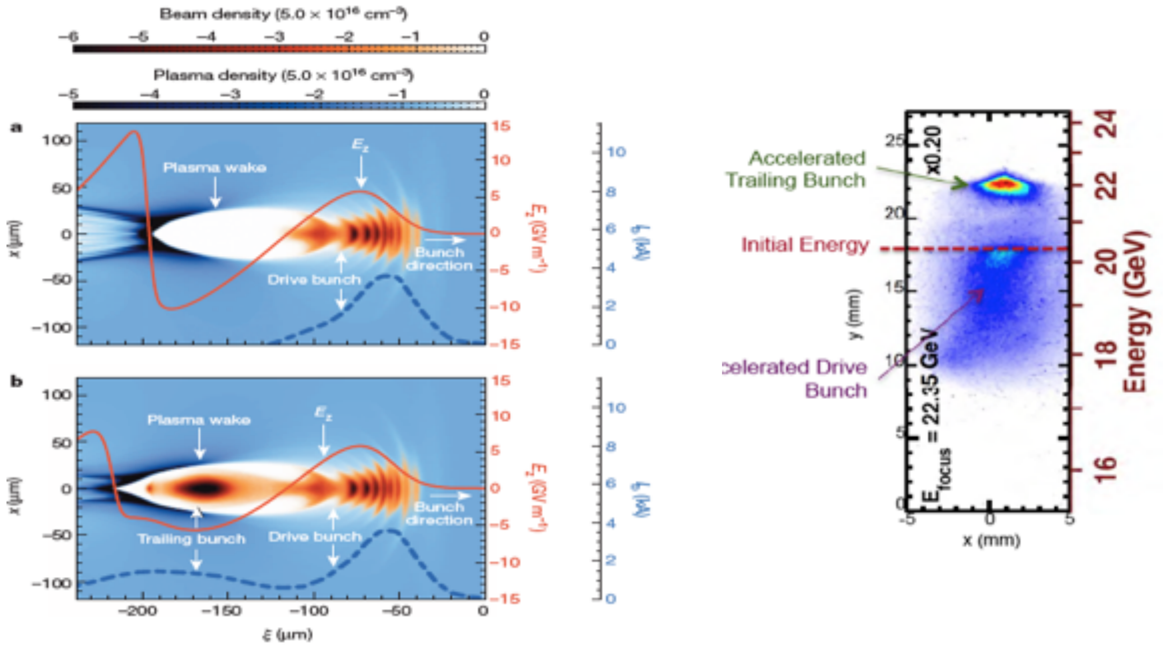
SLAC Experiment, I. Blumenfeld et al, Nature 455, p 741 (2007)

- Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, σ_x = 10µm, 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 <29.1%>** 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

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 15 MeV)	2016	2020+	**Use for future high energy e-/e+ collider.** - 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	- 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	- 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+	- **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		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV **electrons**	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments

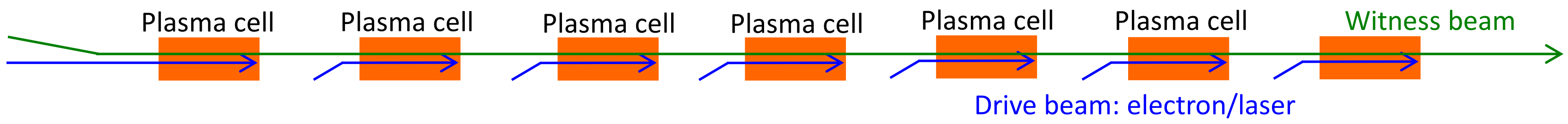
High Energy Plasma Wakefield Accelerators

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

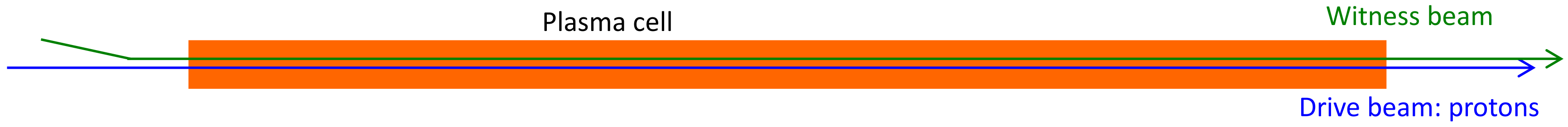
Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

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.

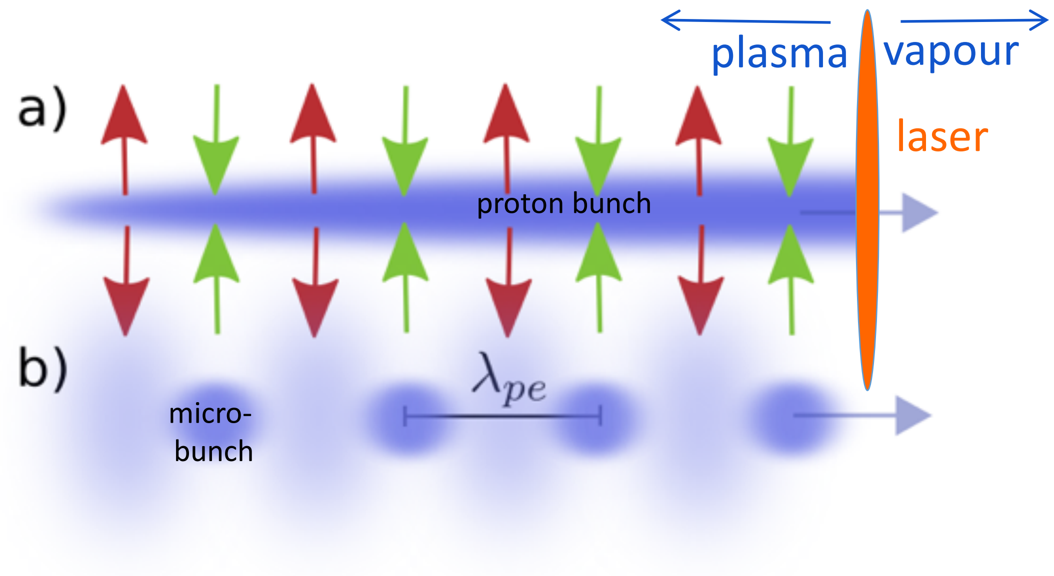
CERN SPS proton bunch: very long! (σ_z **= 12 cm**) → much longer than plasma wavelength (**λ = 1mm**)

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. → On-axis dens is modulated. → Contribution to the wakefields is $\propto n_b$.

b) Density modulation on-axis → **micro-bunches**.
   - Micro-bunches separated by plasma wavelength λ_{pe}.
   - drive wakefields resonantly.



⇒ **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
- → Seeding with ionization front

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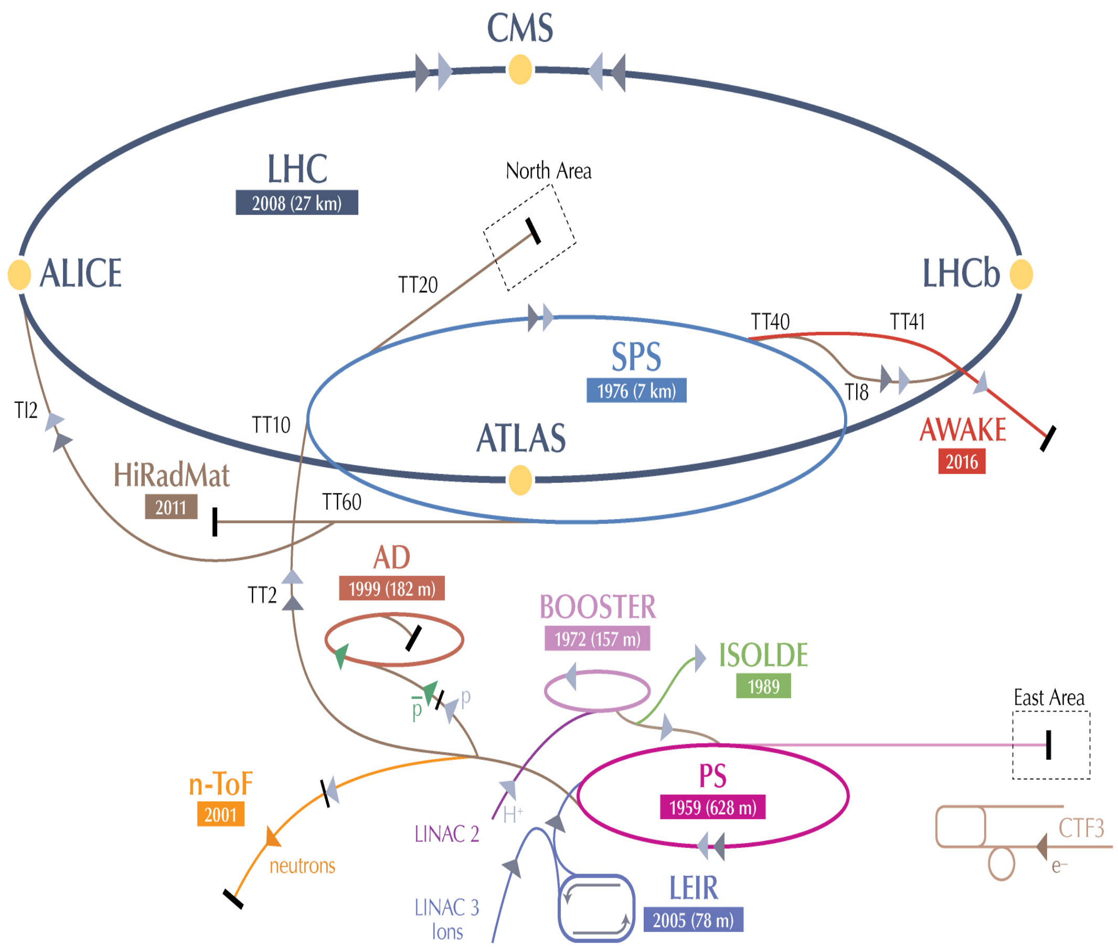
AWAKE at CERN



Advanced WAKEfield Experiment

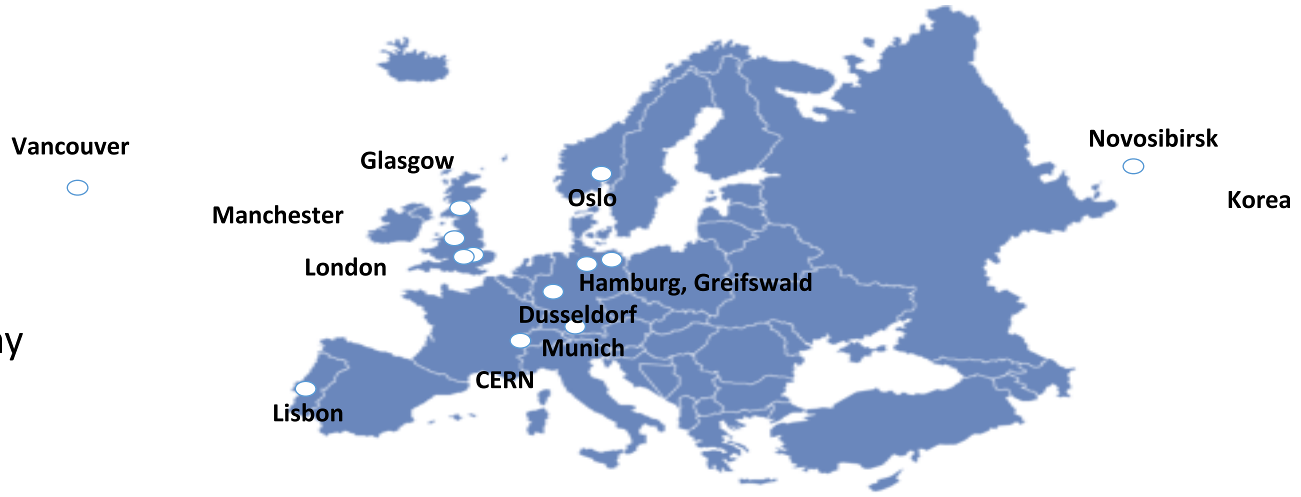
- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First beam end 2016

AWAKE

AWAKE Collaboration: 18+3 Institutes world-wide:

Collaboration members:

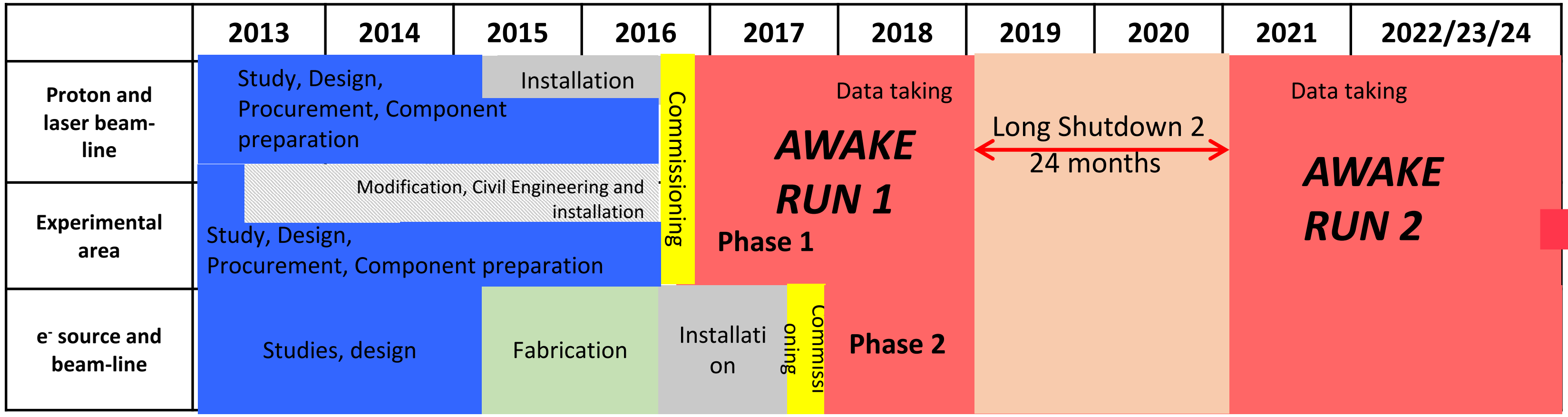
- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL,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

AWAKE Timeline

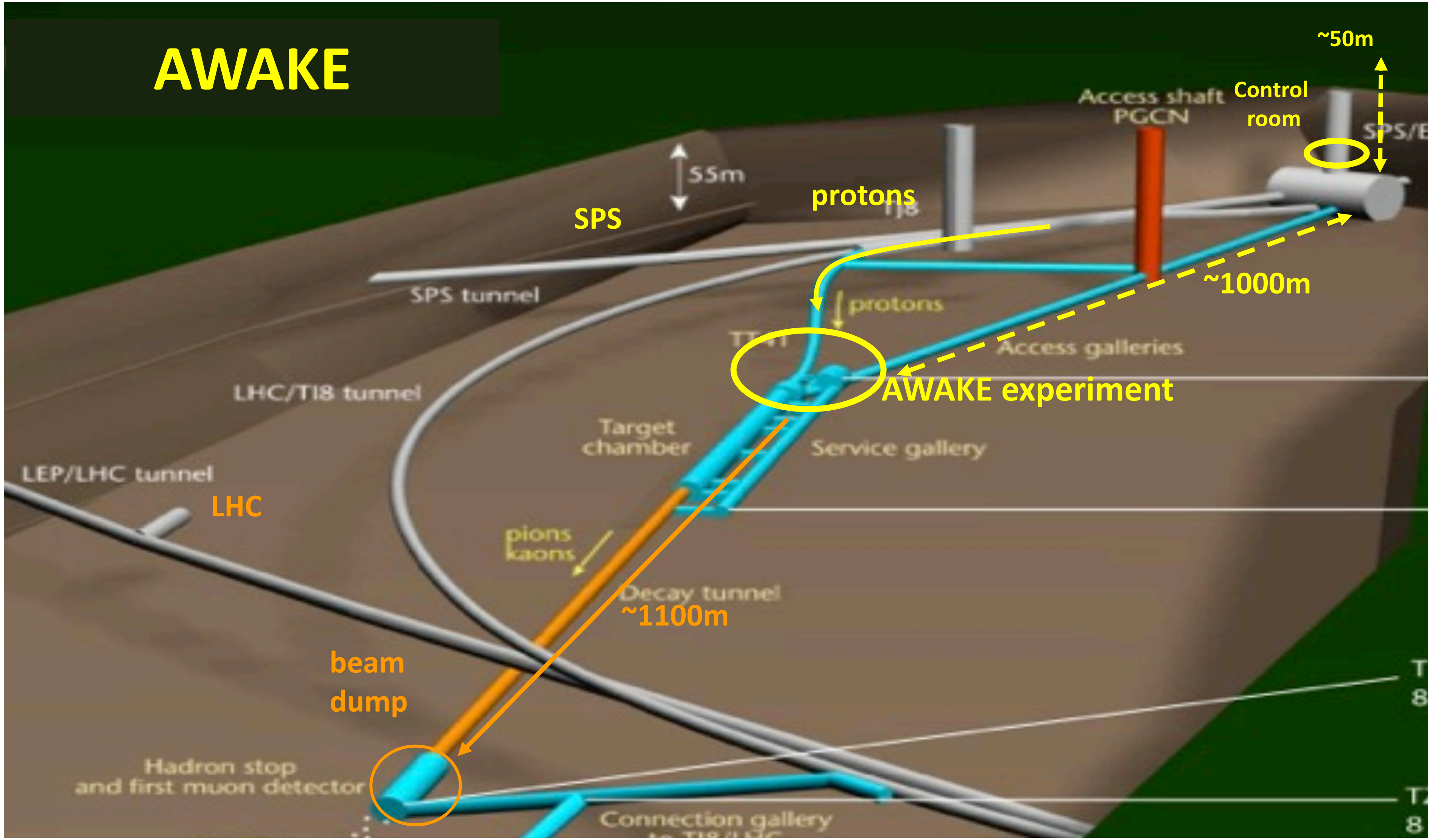


AWAKE++: After Run 2:
kick-off particle physics driven applications

AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

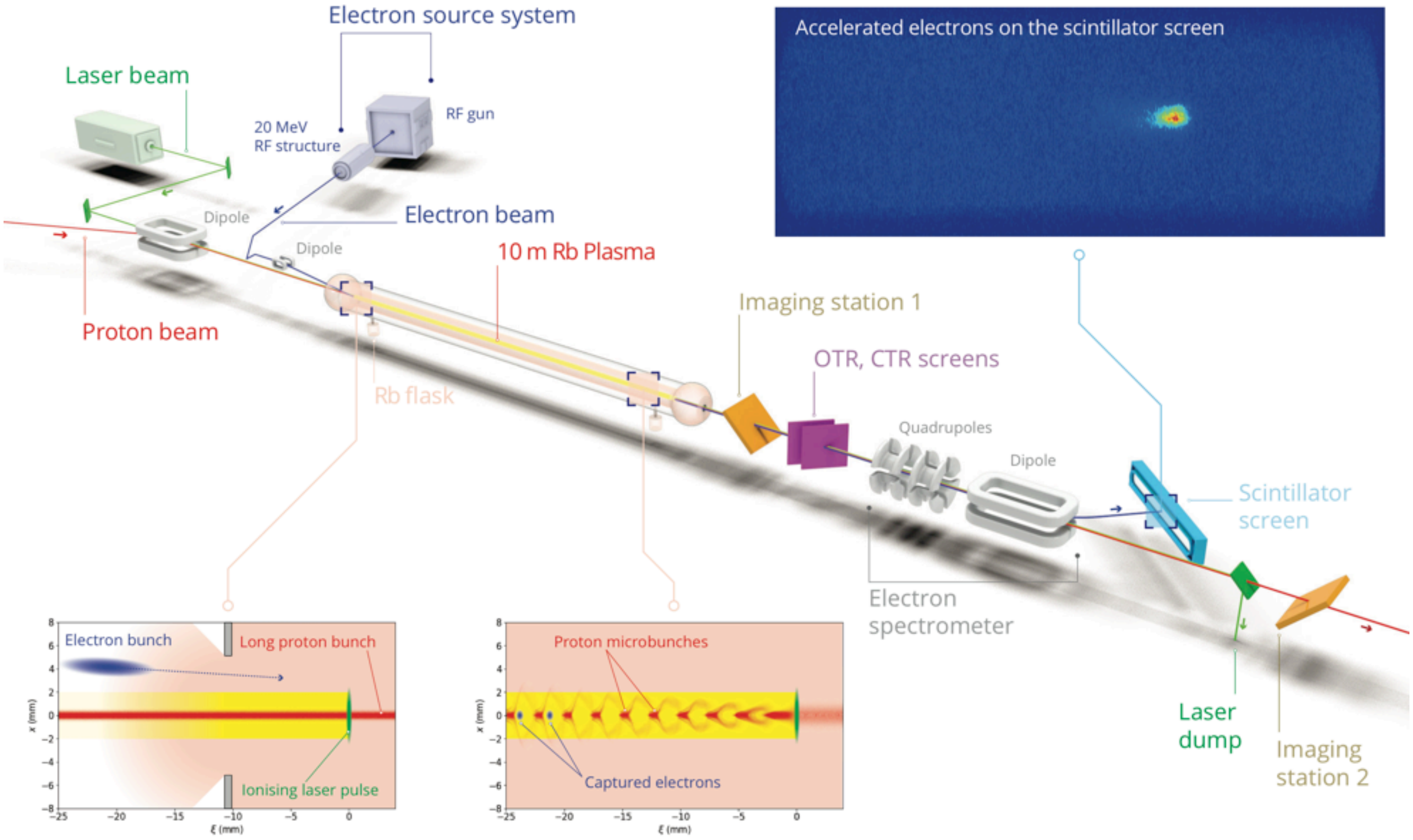
AWAKE Run 2:
After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

AWAKE at CERN



AWAKE installed in CERN underground area

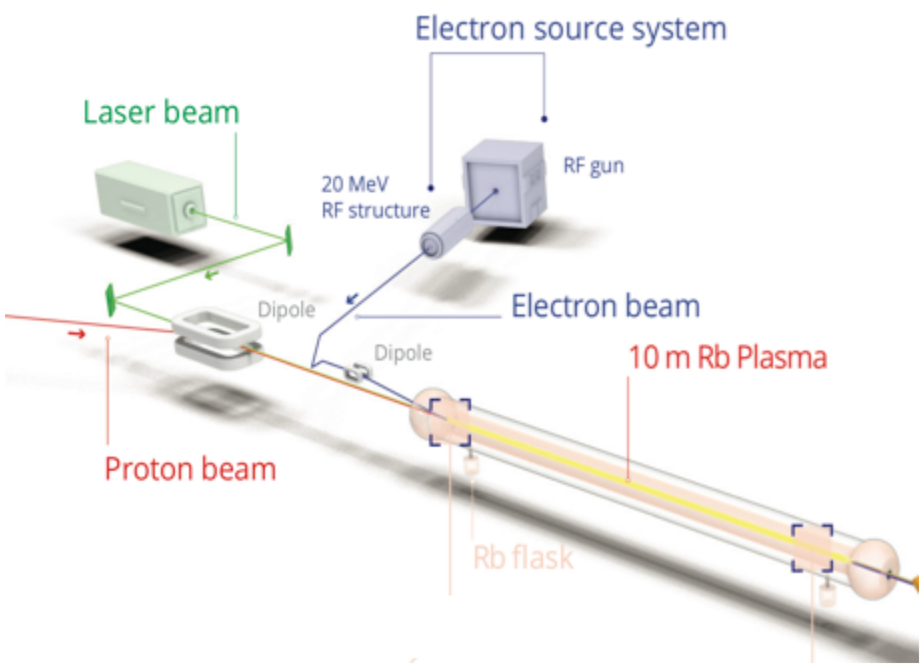
AWAKE Experiment

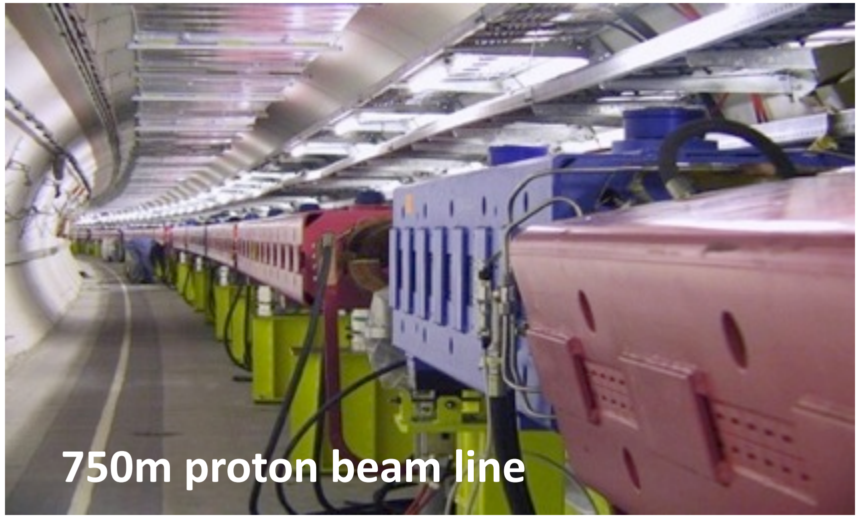


AWAKE Proton Beam Line

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 $\boldsymbol{\sigma_r}$ **= 200 µm**
$k_{pe} = \omega_{pe}/c = 5\ \mathrm{mm}^{-1}$
➔ $\mathbf{n_{pe} = 7 \times 10^{14}\ cm^{-3}}$

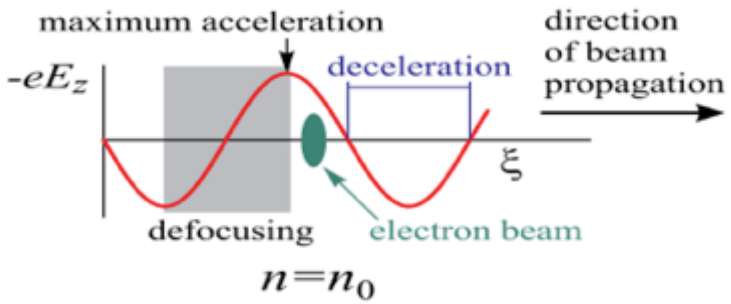


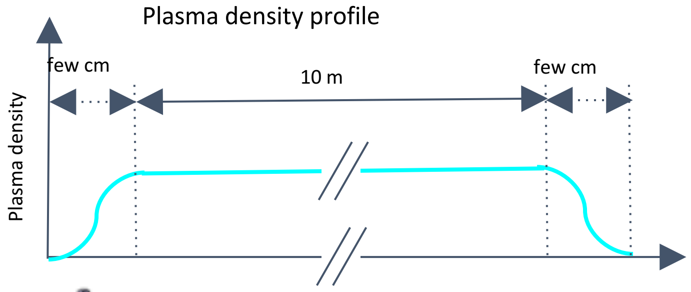


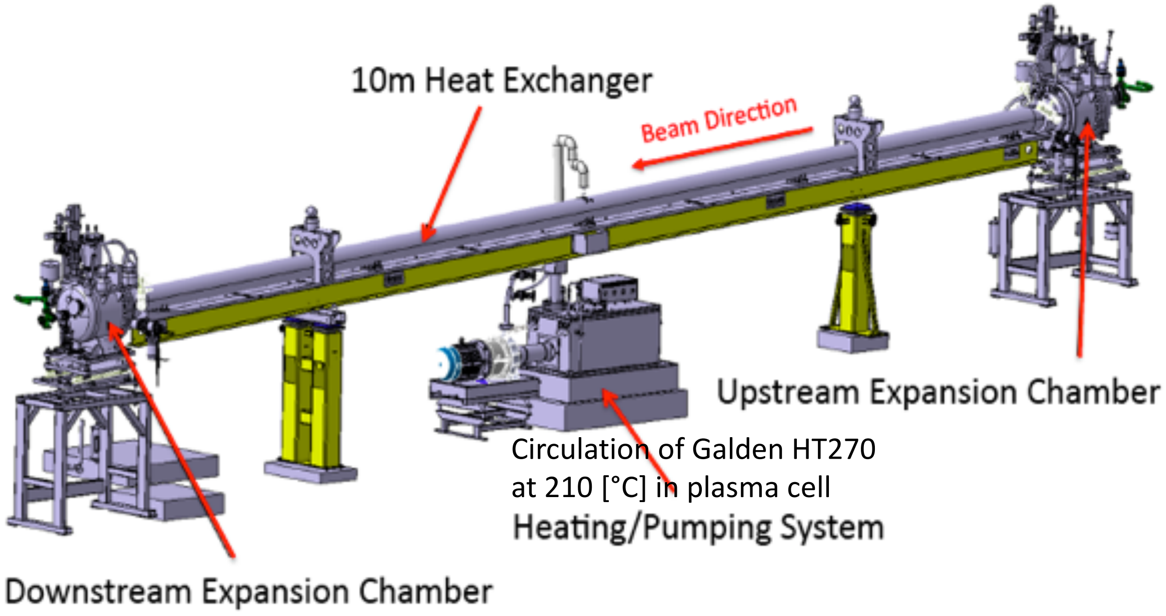
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, a **trailing electron beam** will injected into the same beamline.

AWAKE Plasma Cell

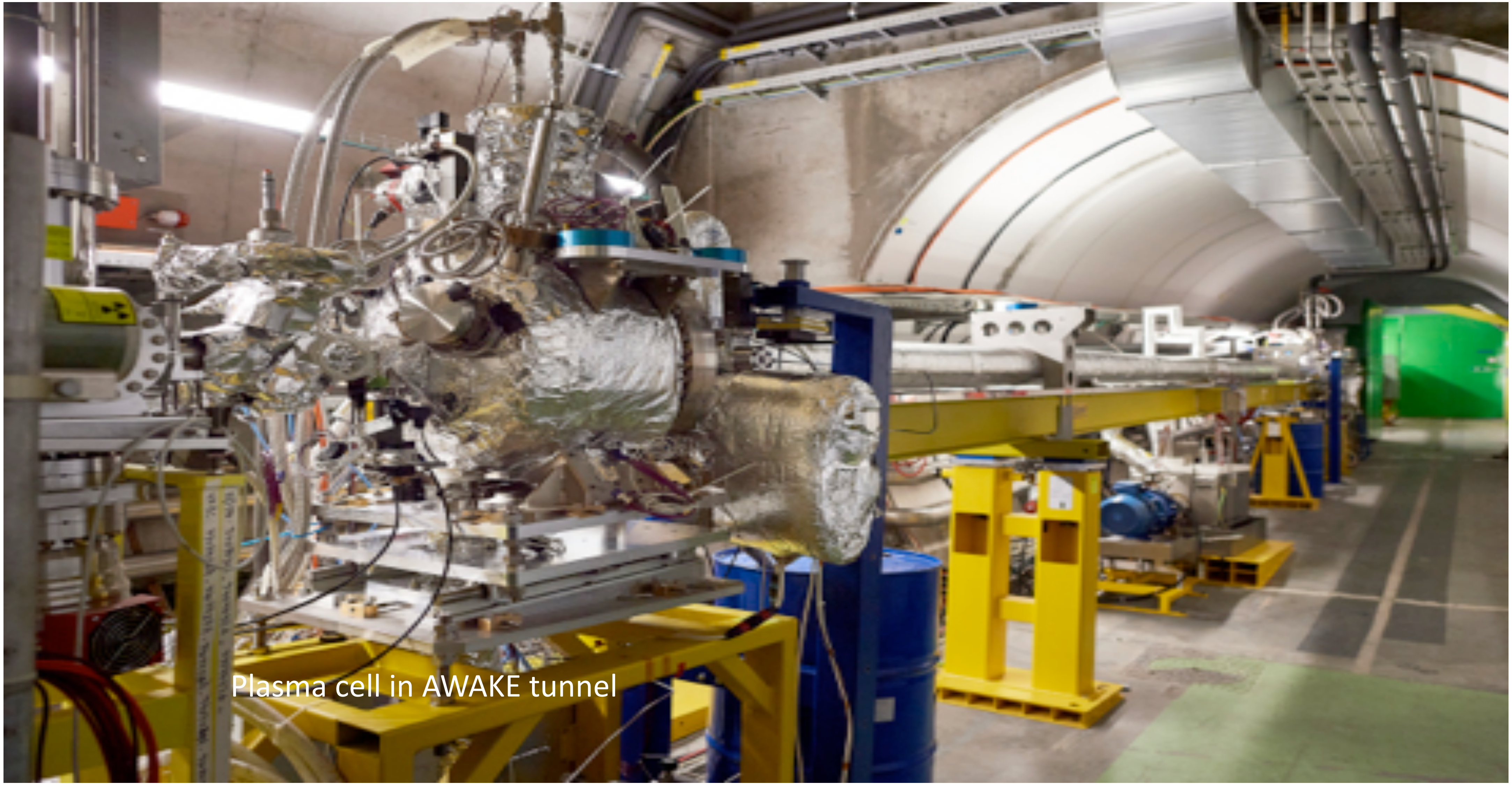
- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (˜220 deg)
    - Complex control system: 79 Temperature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







AWAKE Plasma Cell



Plasma cell in AWAKE tunnel

Laser and Laser Line

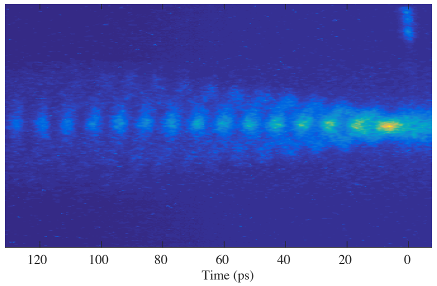
Ti:Sapphire laser system

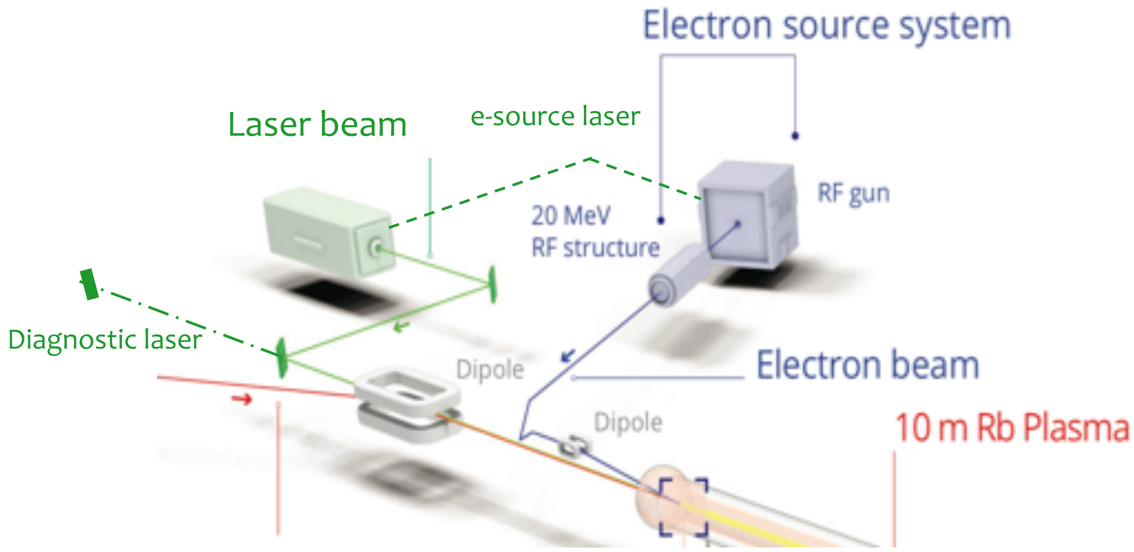
- Laser beam to the plasma cell → ionizes vapor and is used for seeded self-modulation

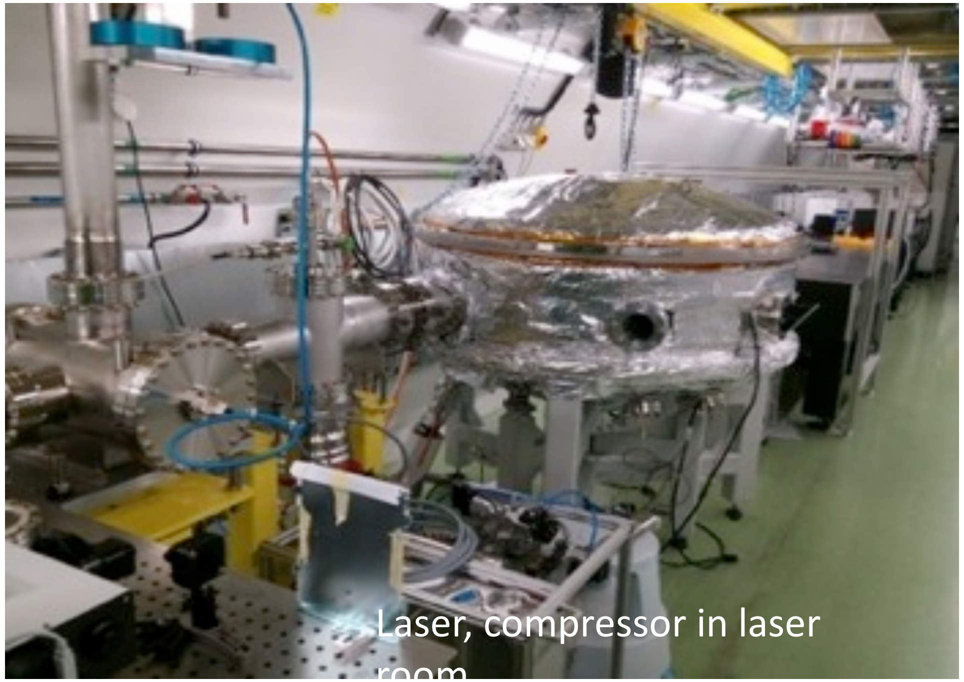
  λ = 780 nm, t_{pulse} = 100-120 fs, E = 450mJ

- Diagnostic beam line (virtual laser)
- Laser beam line to electron source

  λ = 260 nm, t_{pulse} ~8ps, E = 0.5 mJ

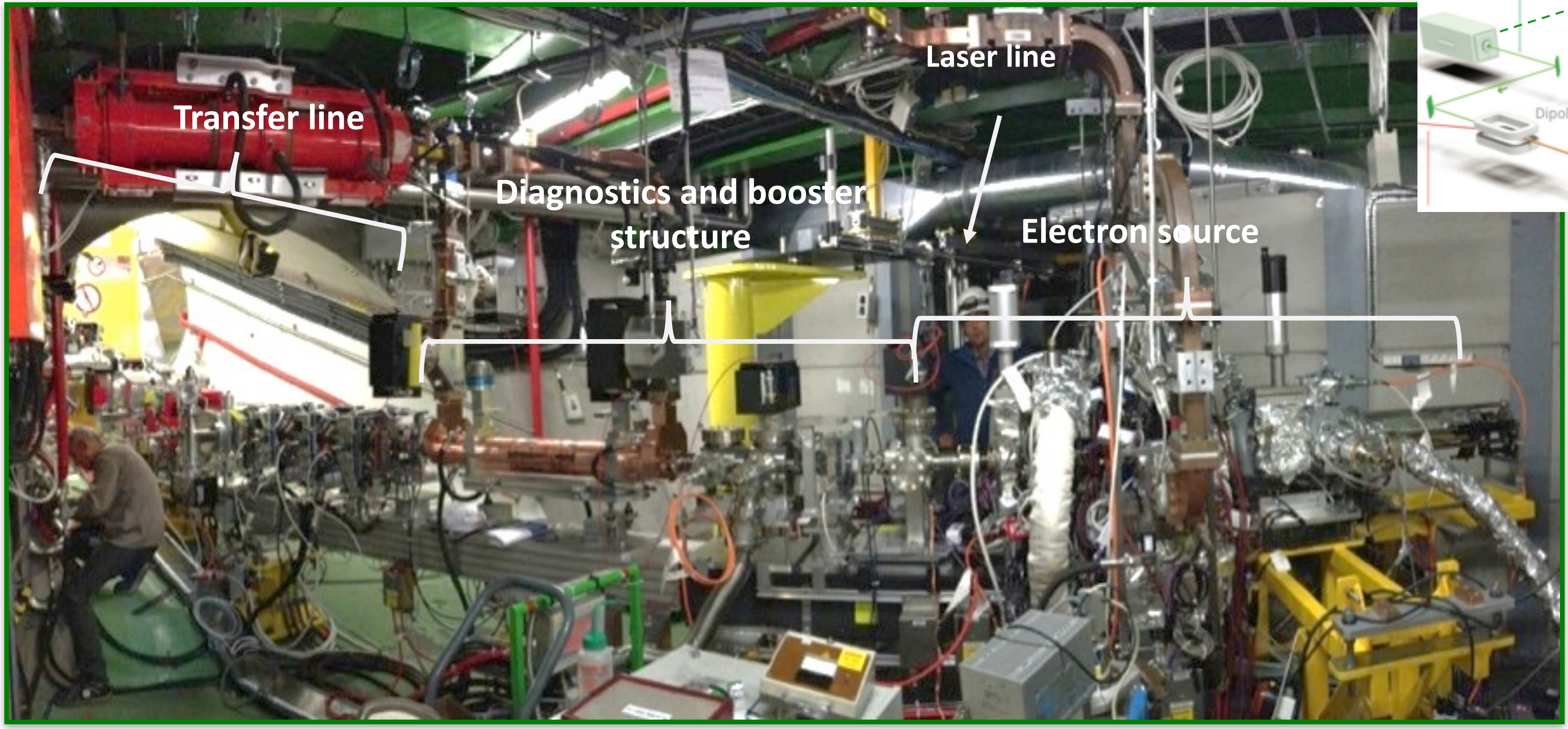


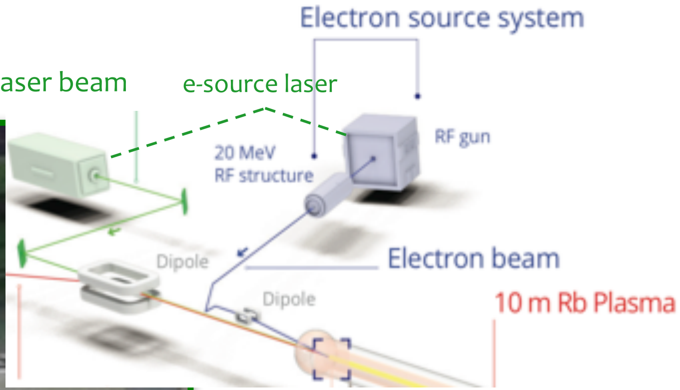




AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.

Electron Beam System

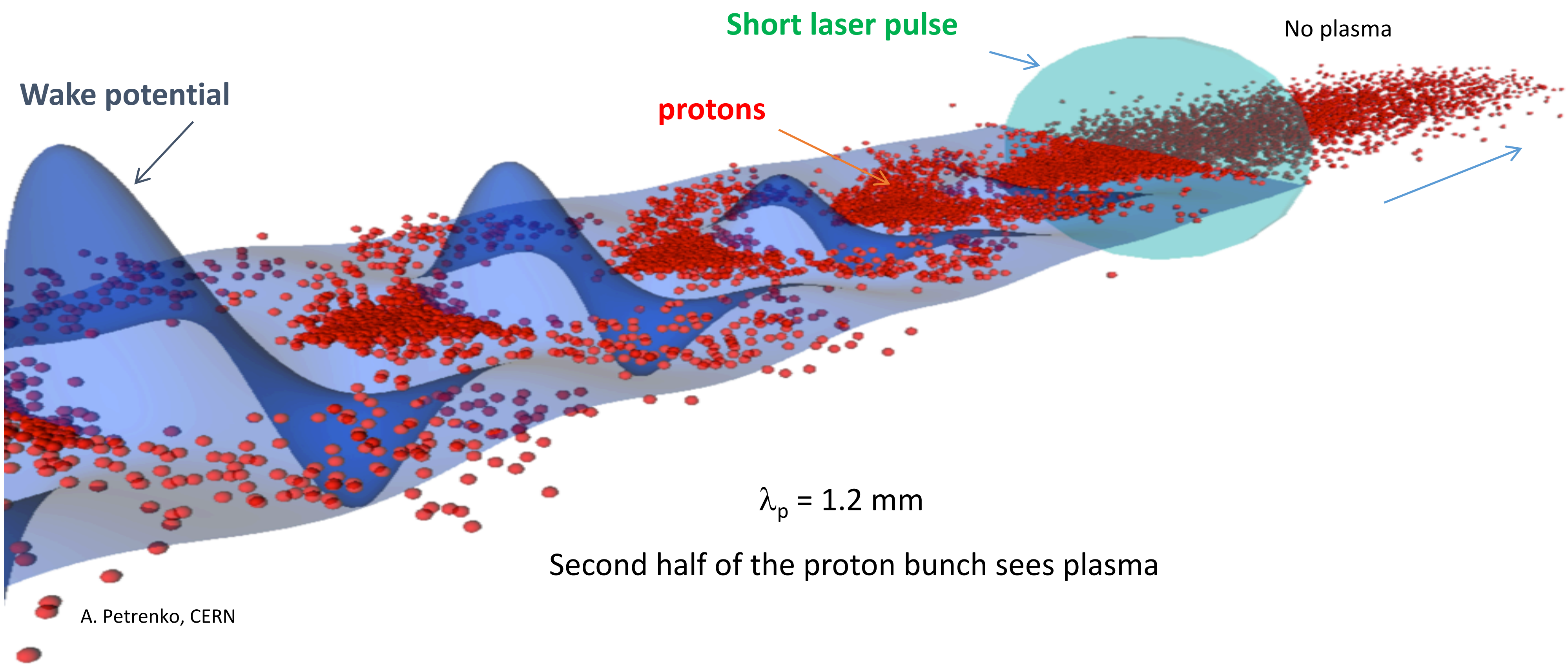




A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

Challenge: cross the electron beam with the proton beam inside the plasma at a precision of ~100 µm.

Seeded Self-Modulation Results



λ_p = 1.2 mm

Second half of the proton bunch sees plasma

A. Petrenko, CERN

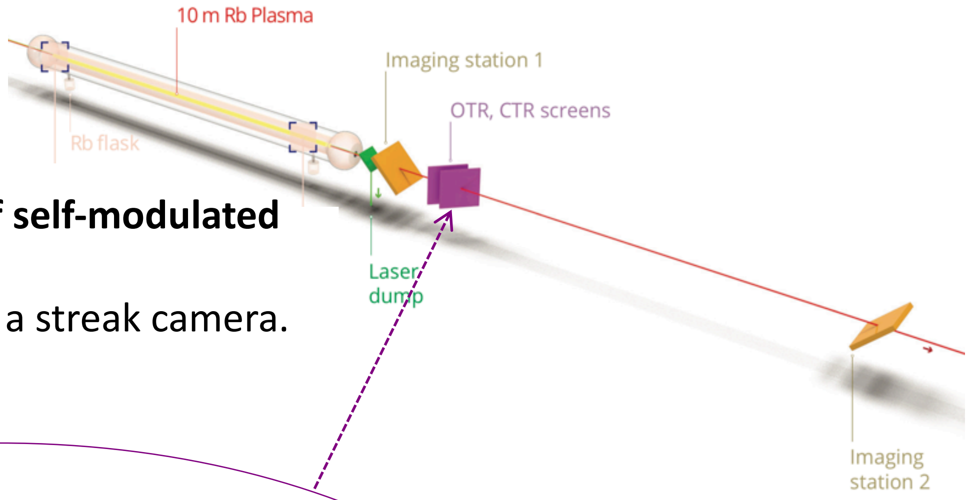
Diagnostics for Seeded Self-Modulation

Direct SSM Measurement:

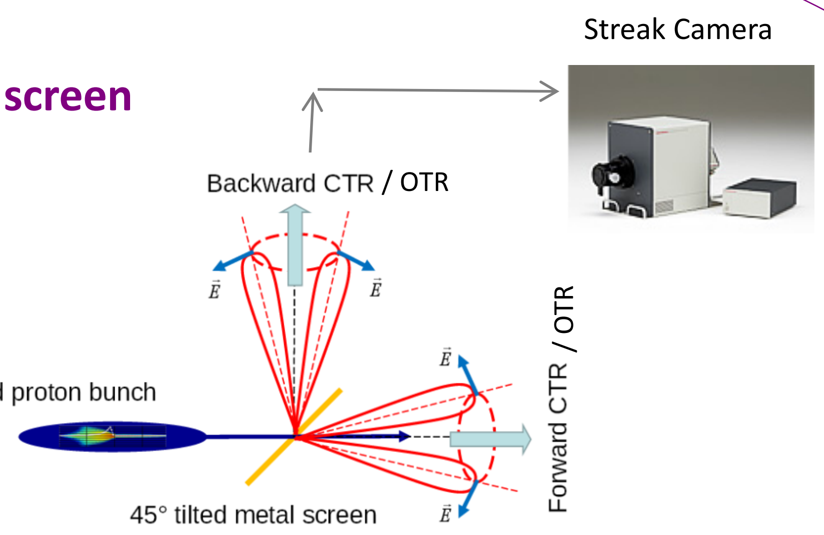
Measure longitudinal structure of self-modulated proton bunch.

→ Image OTR light onto the slit of a streak camera.

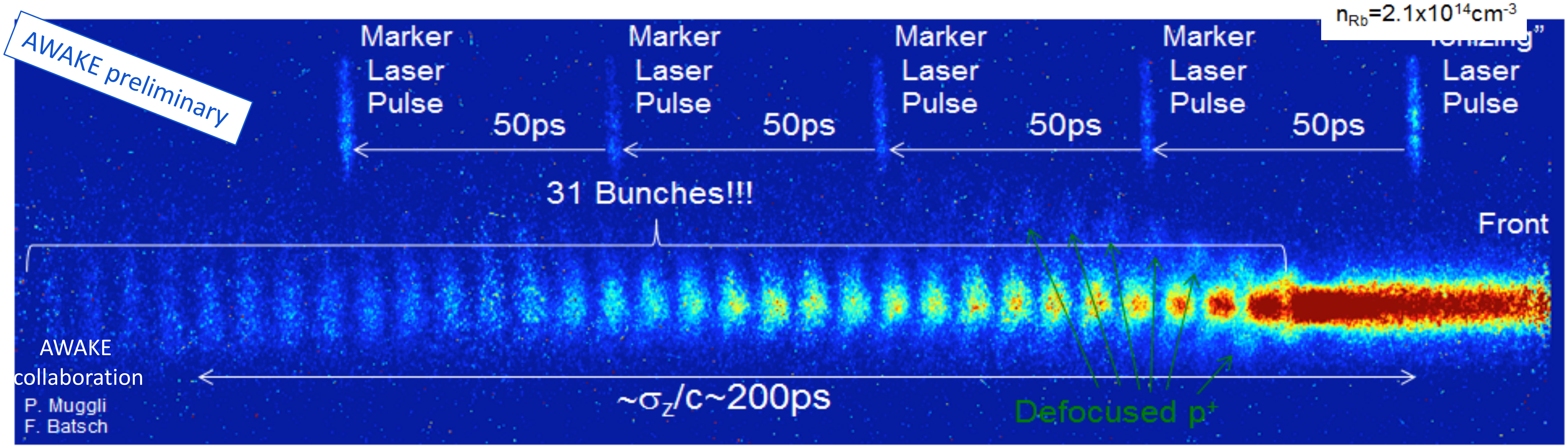
→ Time resolved measurement.



OTR screen



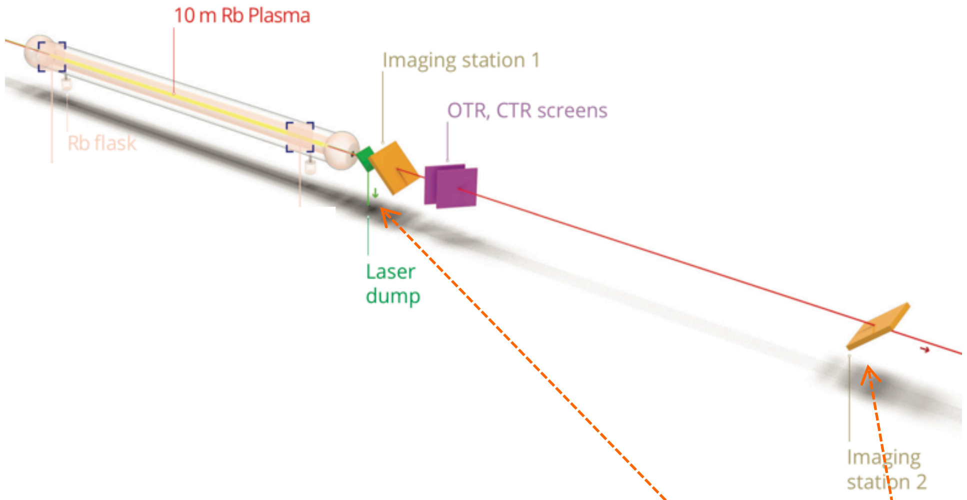
Results: Direct Seeded Self-Modulation Measurement



- Effect starts at laser timing $\rightarrow$ **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

Diagnostics for Seeded Self-Modulation

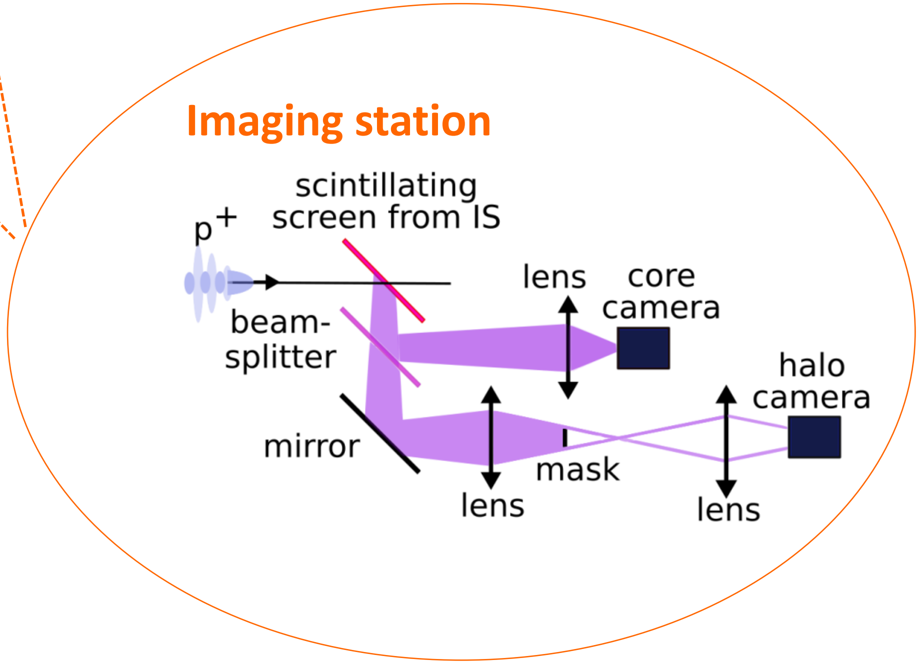


Indirect SSM Measurement:

Measure time integrated transverse bunch distribution.

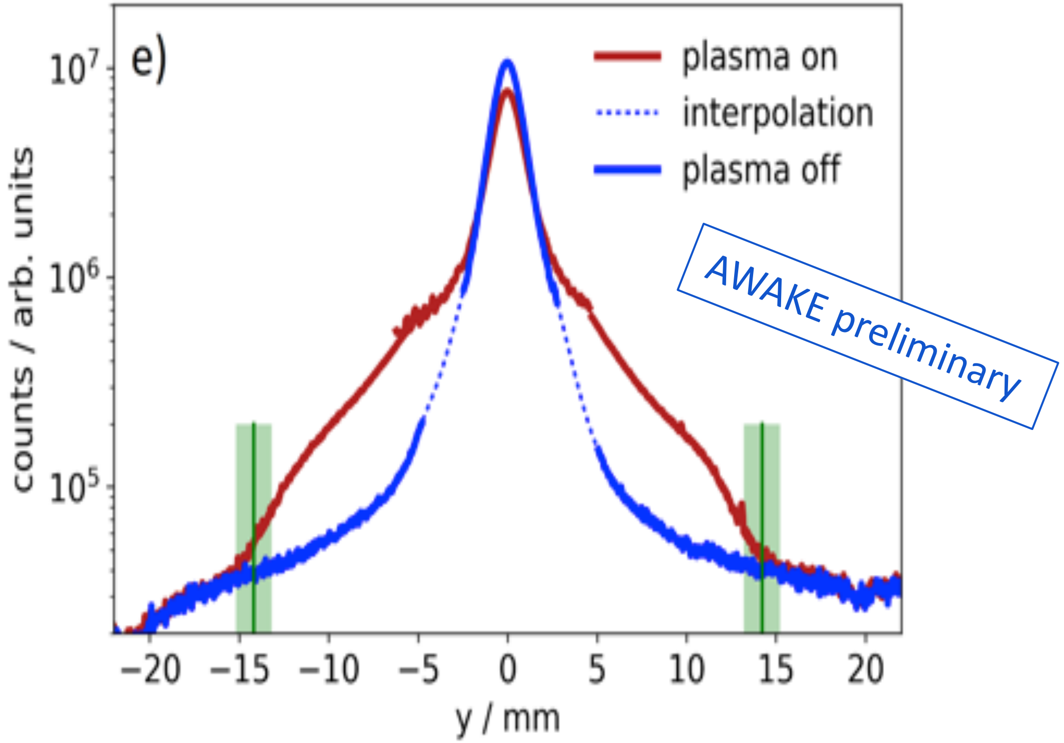
→ Image protons defocused by the strong plasma wakefields

→ Scintillation light from screen measured with digital camera.

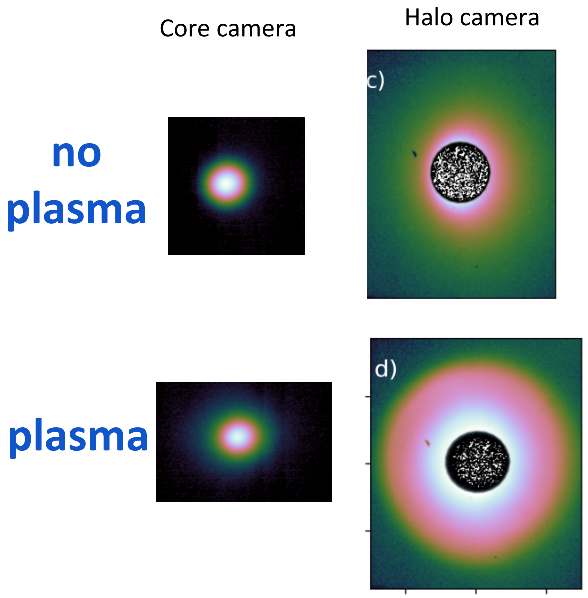


Results: Indirect Seeded Self-Modulation Measurement

Combination of core and halo image projections



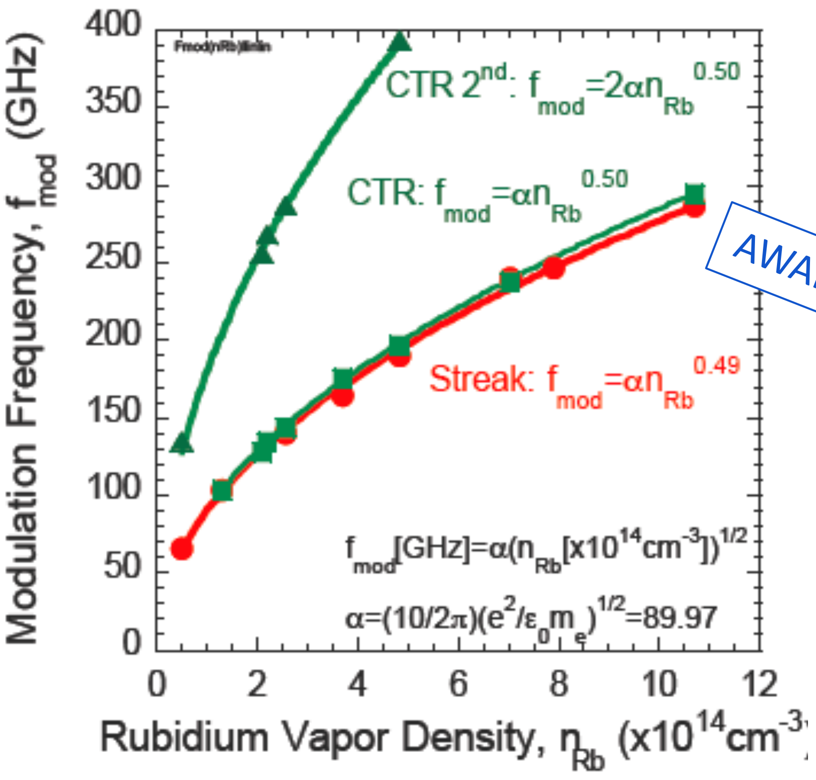
From the **radial distribution** of the defocused protons, we learn about the **transverse effects** of SSM



- 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 7.7e14/cm³**.
- **Halo symmetric ⇒ no hose instability.**
- Estimate of the **transverse wakefields amplitude ($\int W_{per} dr$)**

Additional Results and Studies

Modulation frequency versus vapour density results



Hosing Studies

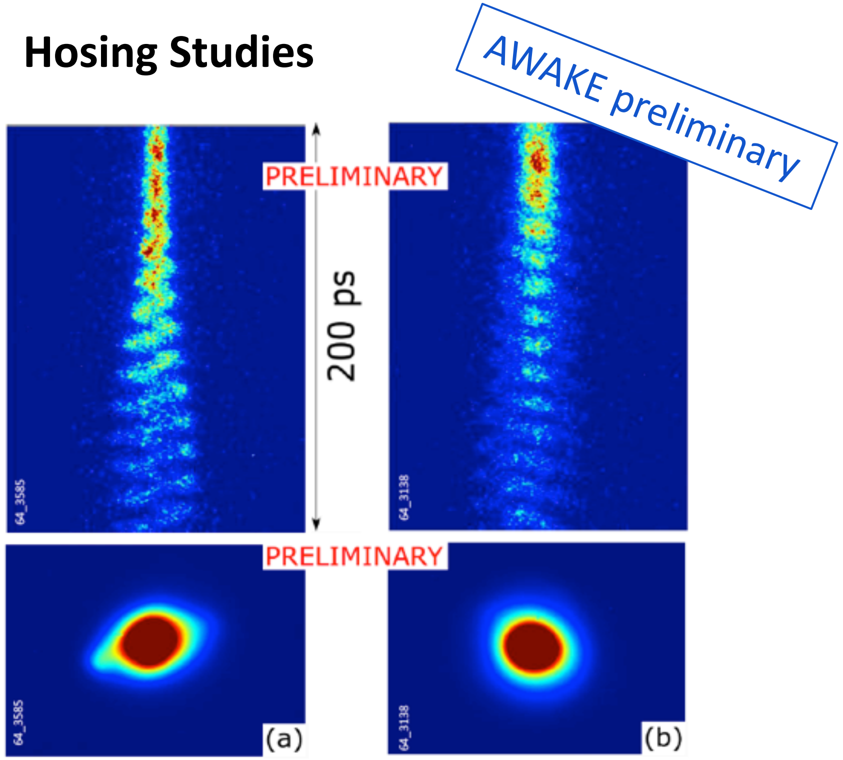
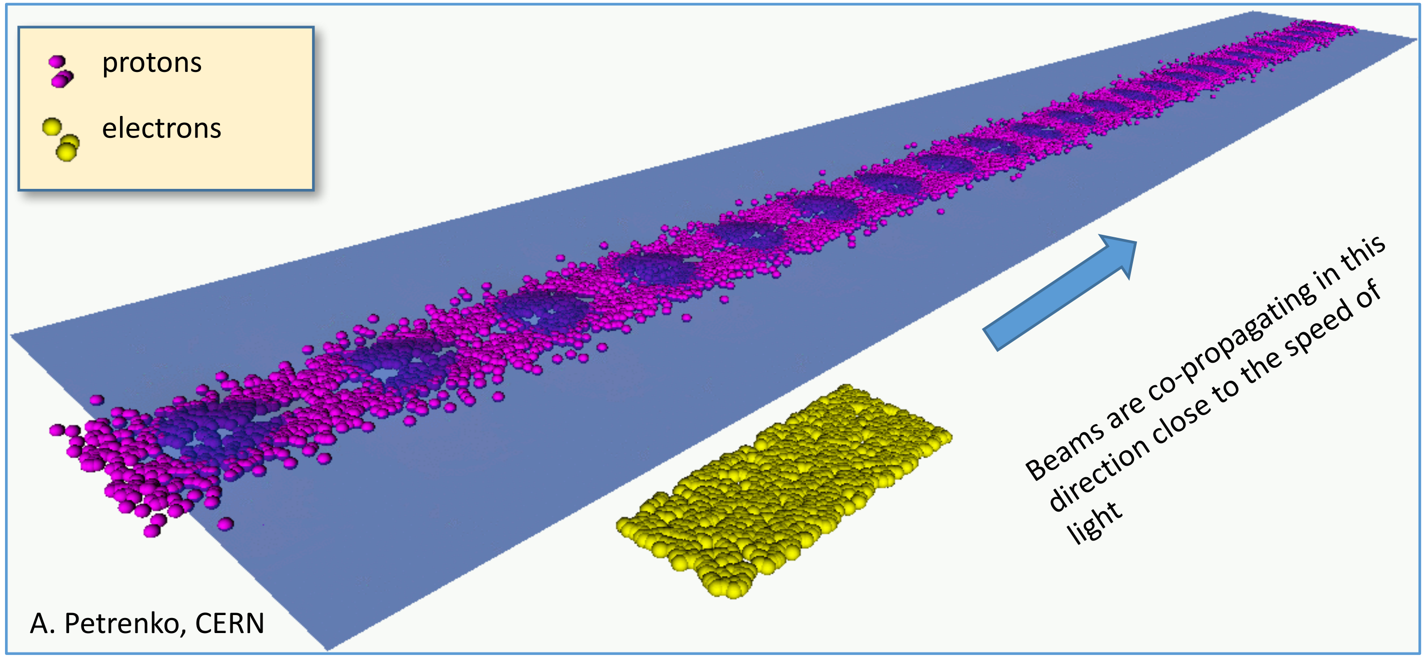
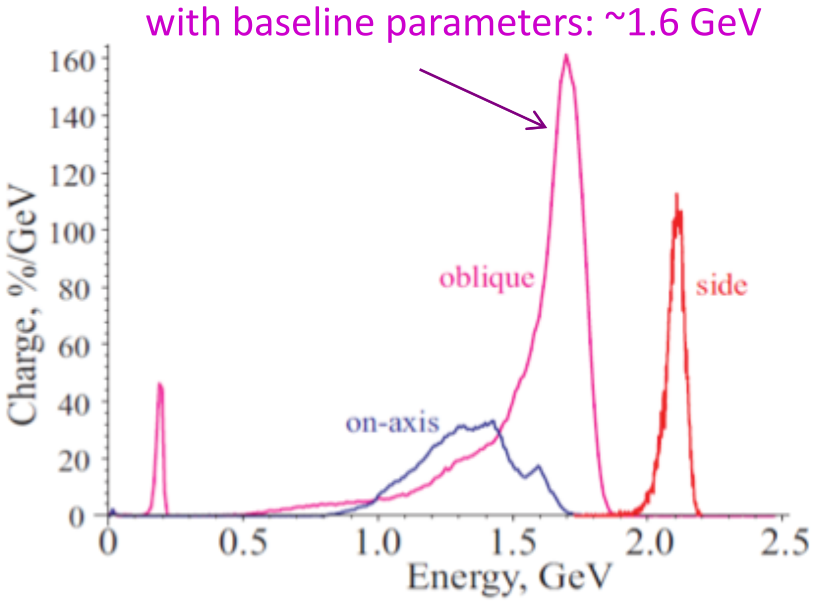


Fig. 3: Streak camera images (top images) and two-screen measurement [6] (bottom images) of an AWAKE proton bunch (plasma density $0.5 \cdot 10^{14}\mathrm{cm}^{-3}$):
(a) Hosing beam with periodic modulation of the beam centroid
(b) Periodic micro-bunching in a self-modulated beam

Electron Acceleration Results 2018

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



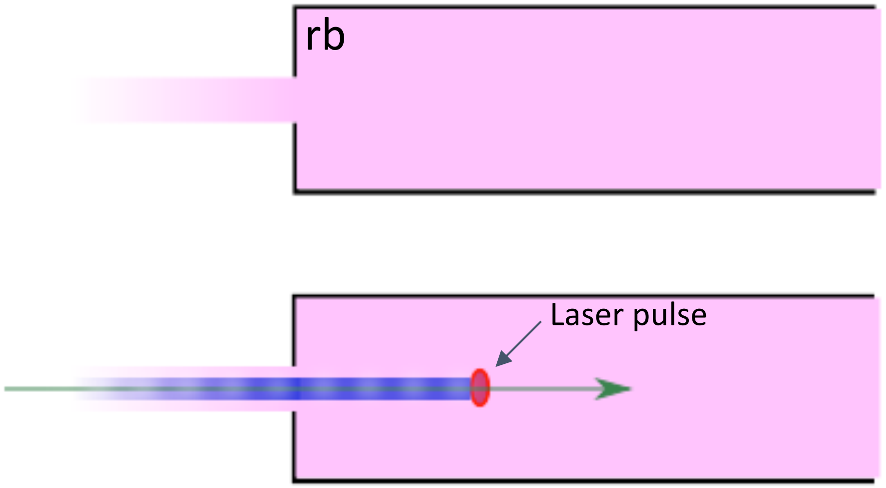


A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Electron Acceleration – Injection into Plasma

Challenge:

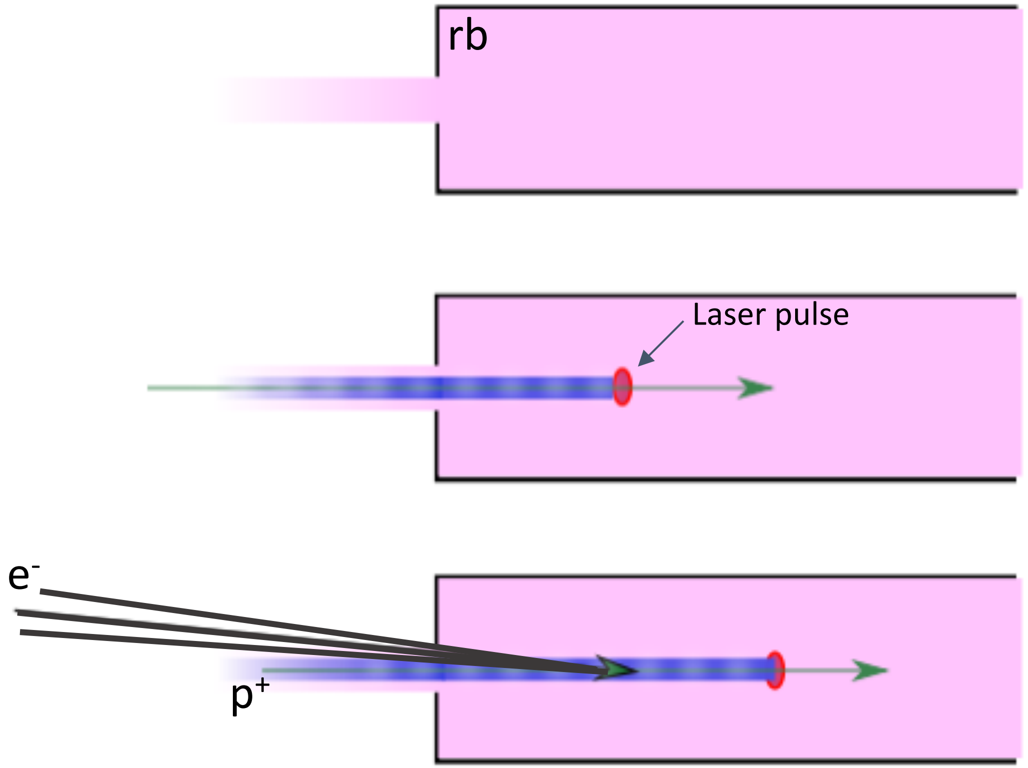
- During the Seeded Self-Modulation the proton bunch distribution **evolves**.
- Short density ramp at the entrance of the plasma → **change of wakefield phase**



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.



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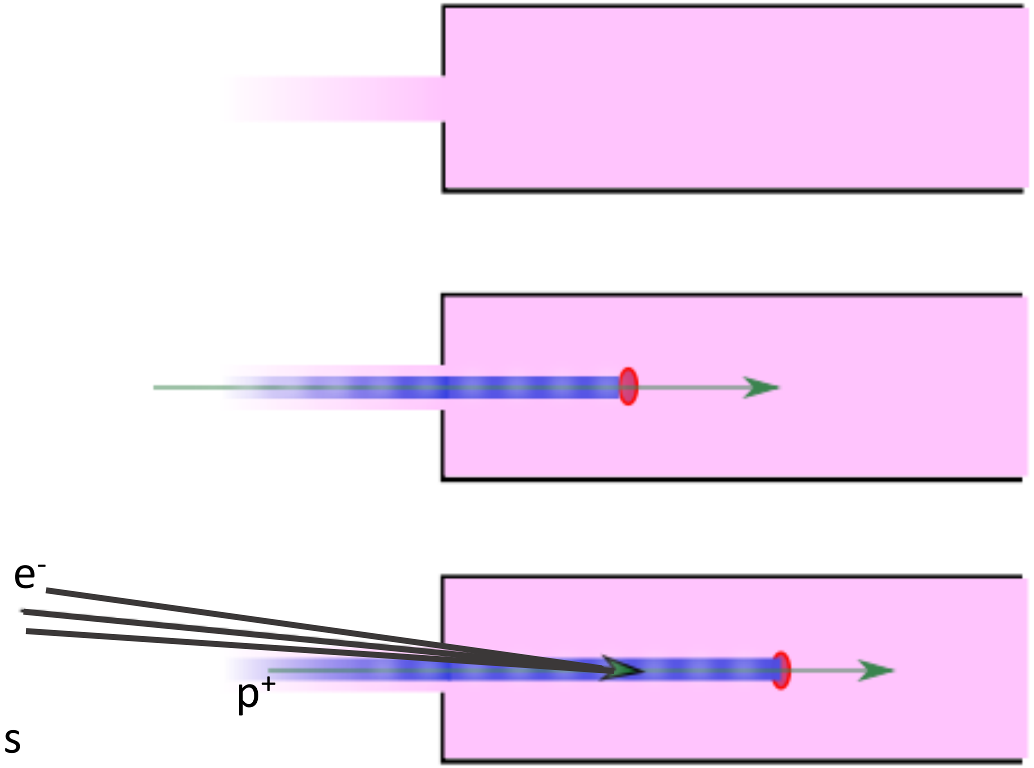
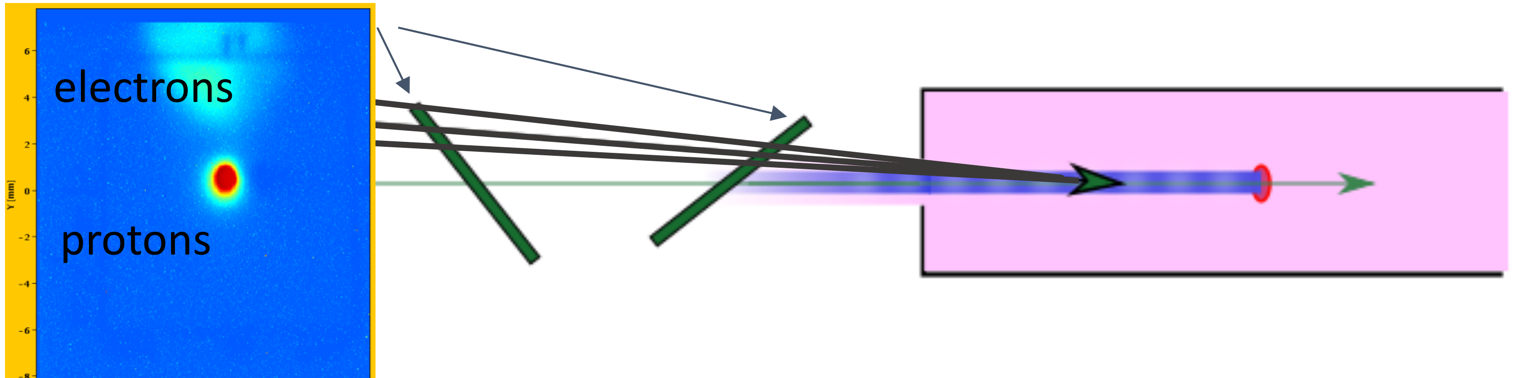


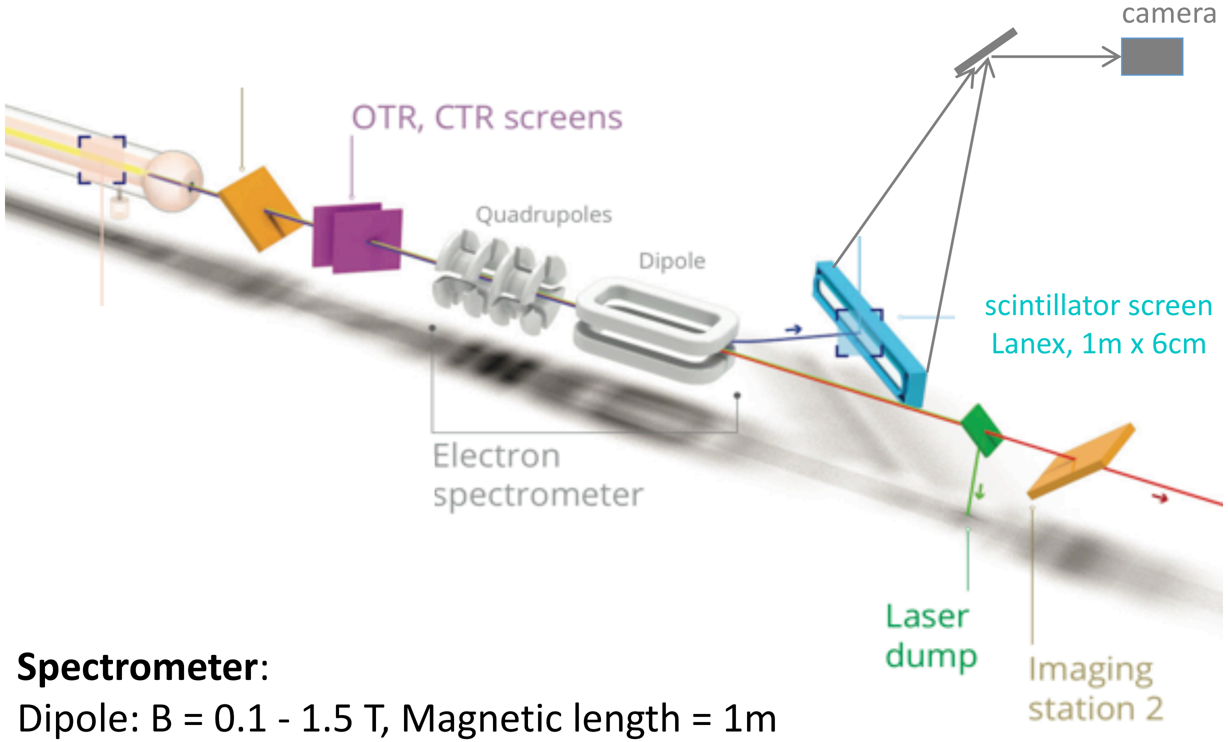
May Run 2018: electron beam:

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

Beam screens



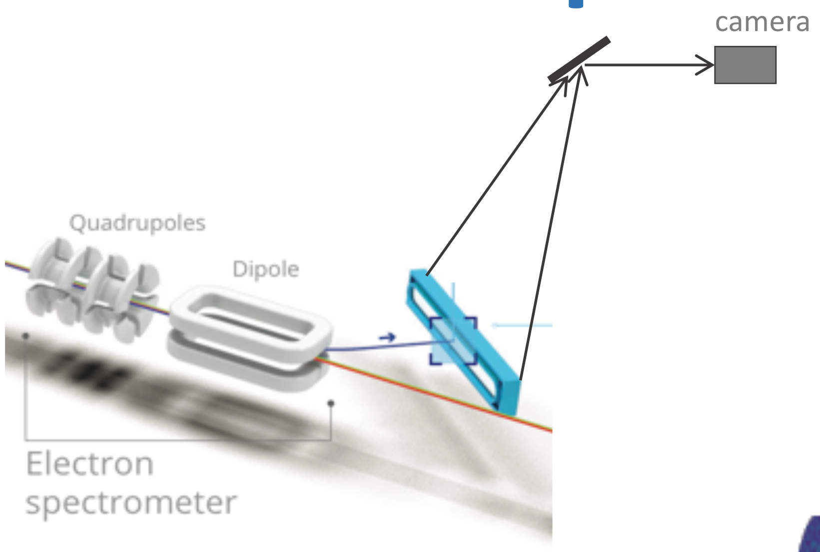
Electron Acceleration Diagnostics



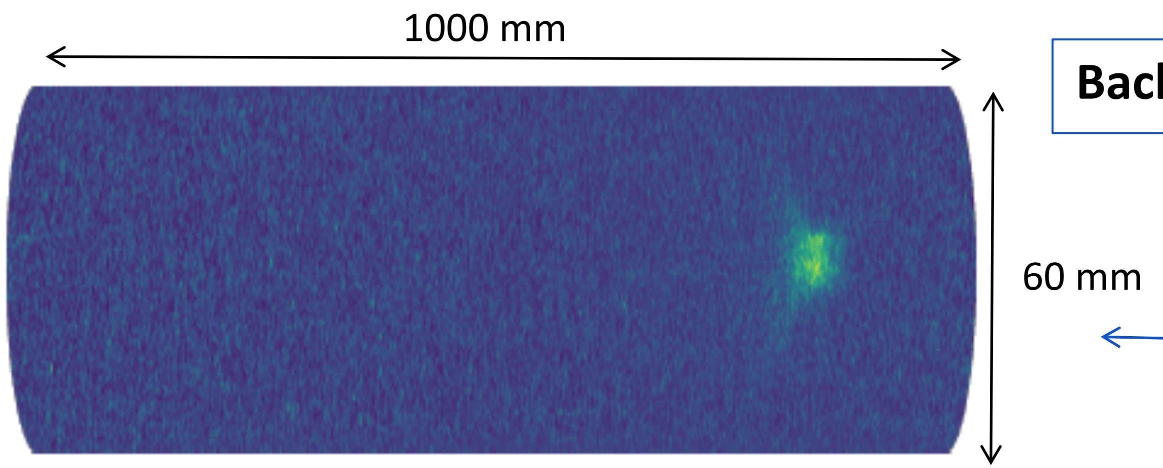
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

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



Optical line corrections



Background subtraction

Charge response calibration

Screen and camera calibrated at the CLEAR Facility at CERN

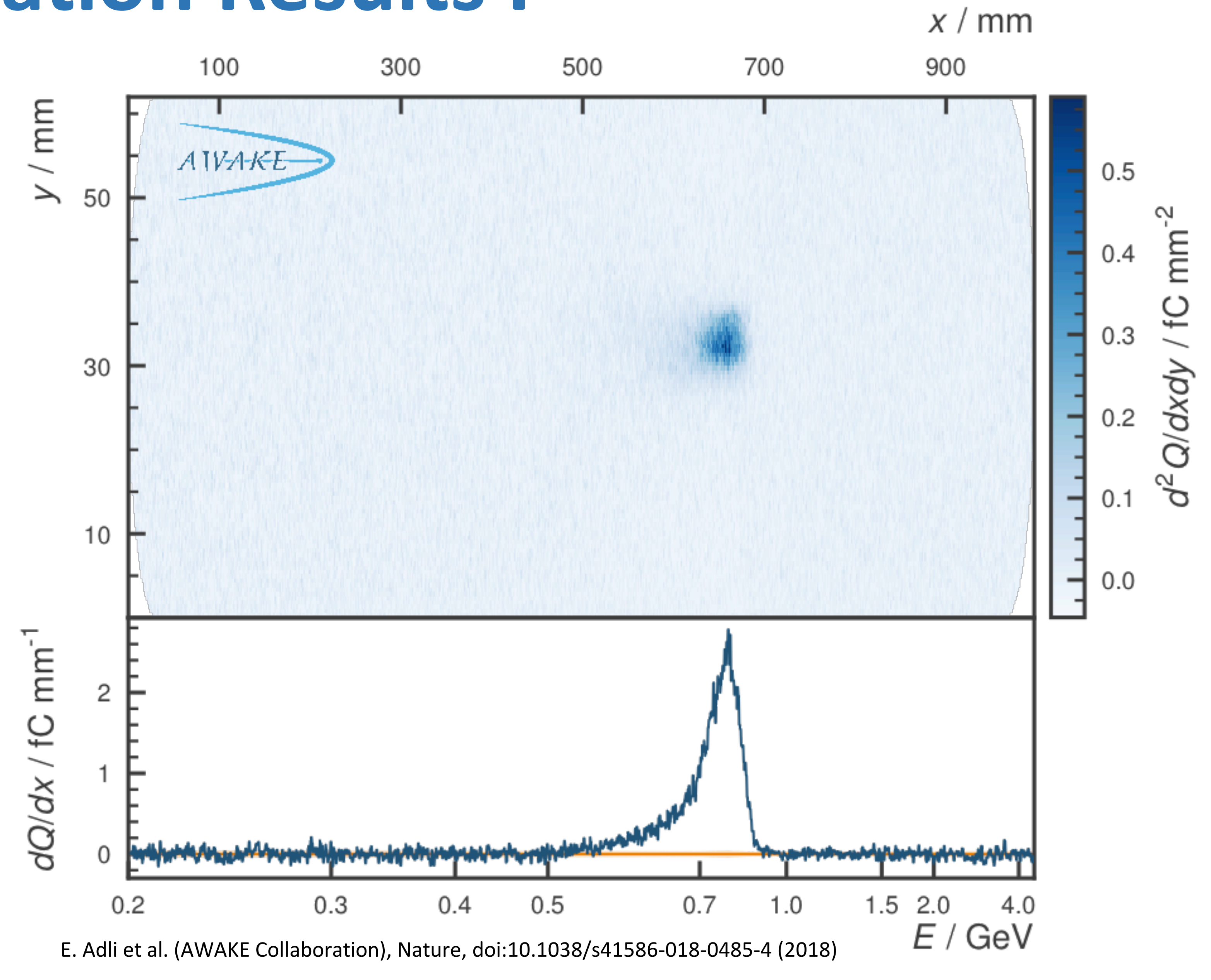
Position ← → Energy conversion

Electron Acceleration Results I

Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.

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

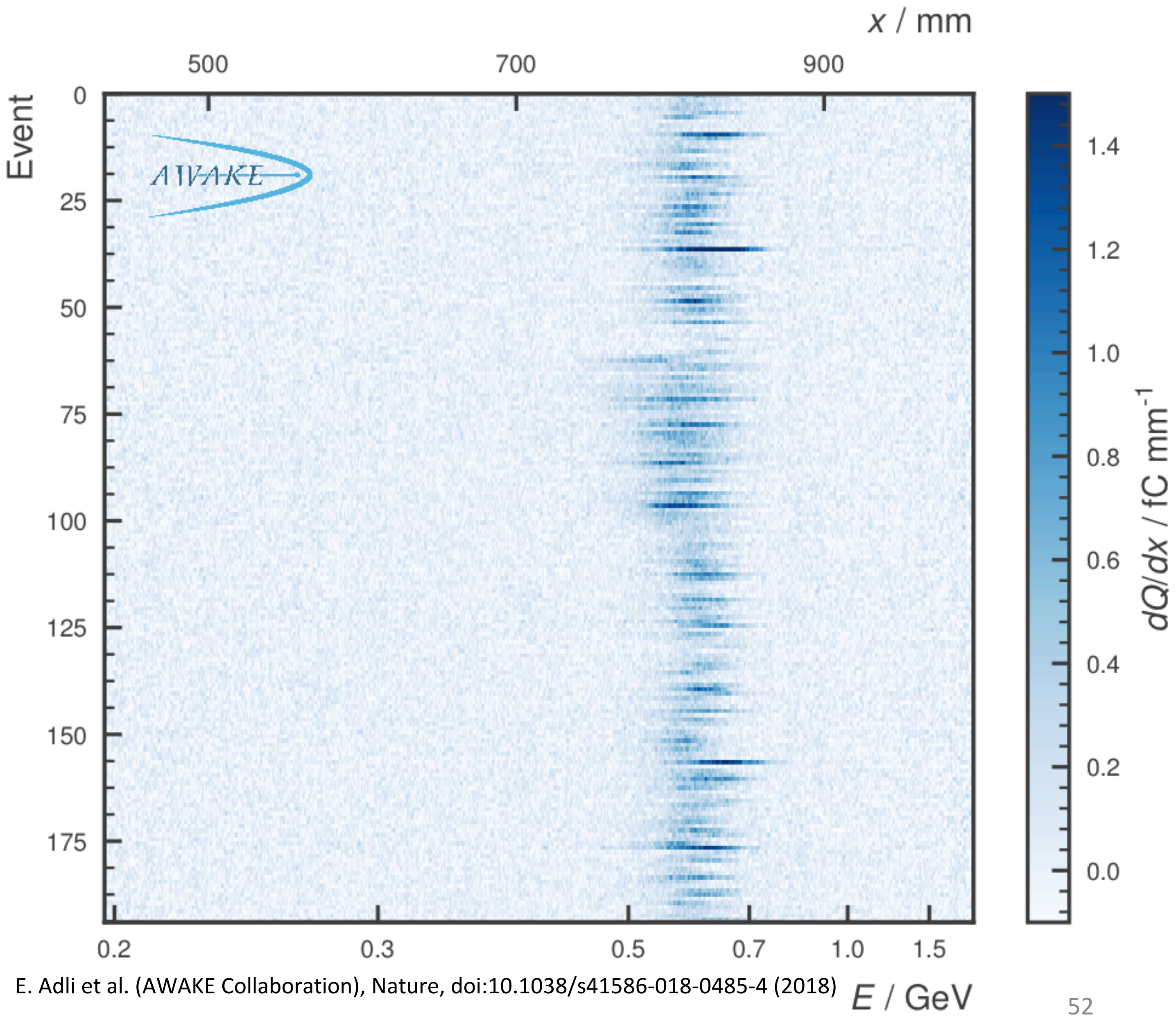
➔ recent measurements factor **50-100 higher** capture efficiency!!



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

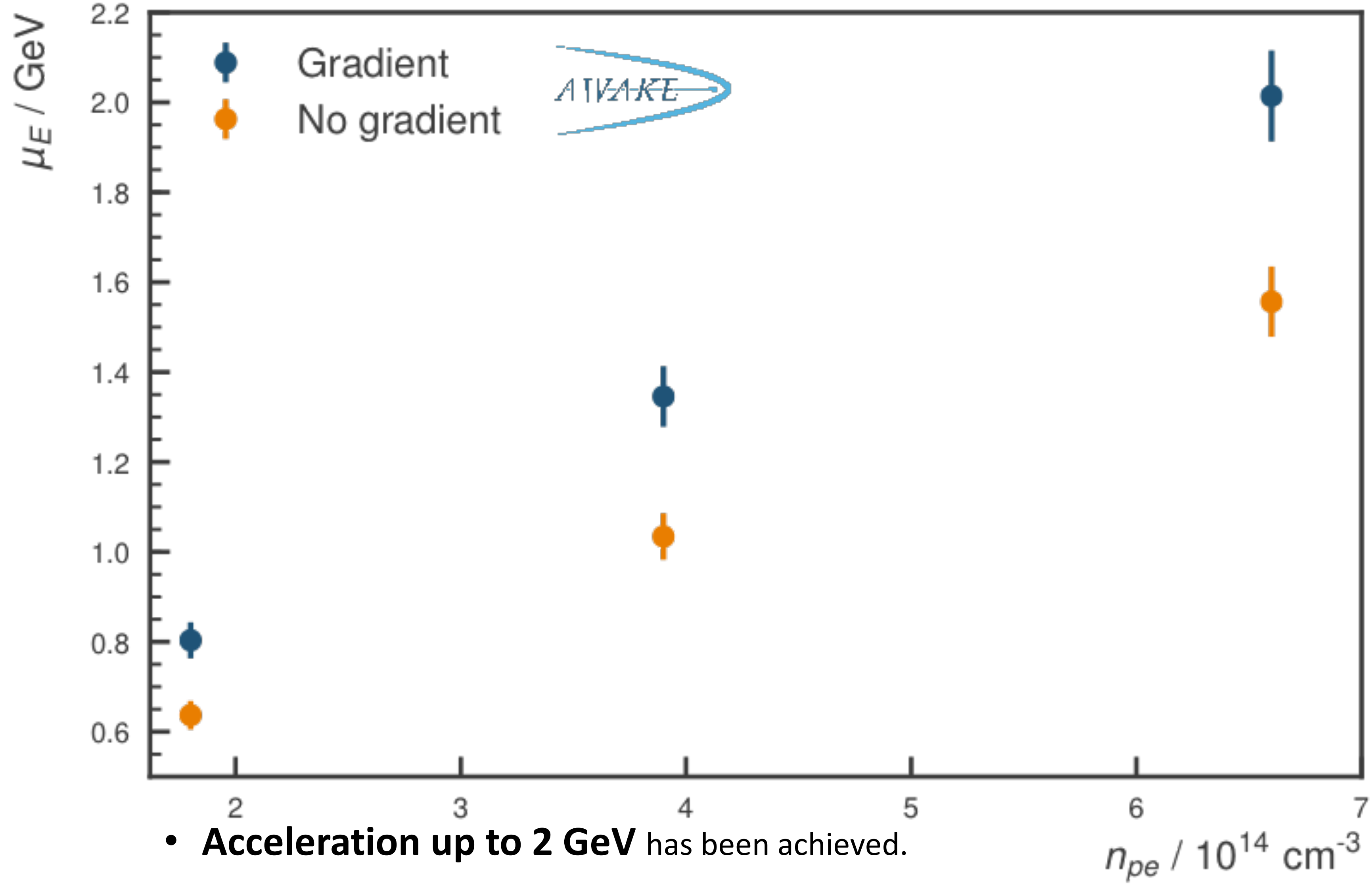
Electron Acceleration Results II

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



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

Electron Acceleration Results III



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

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

Electron Acceleration in AWAKE

nature Accelerated Article Preview

LETTER

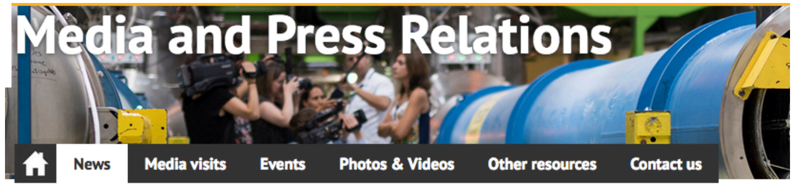
doi:10.1038/s41586-018-0485-4

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. Doebert, J. Farmer, V.N. Fedosseev, R. Fiorito, R.A. Fonseca, F. Friebel, 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. Tuev, M. Turner, F. Velotti, L. Verra, V.A. Verzilov, J. Vieira, C.P. Welsch, B. Williamson, M. Wing, B. Woolley and G. Xia

AWAKE Electron Acceleration Paper

- 22 June 2018: Paper submitted to Nature
- 14 August 2018: Paper accepted
- 29 August 2018: Press release
- 20 September 2018: Print issue published



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

29 Aug 2018

What’s Next?

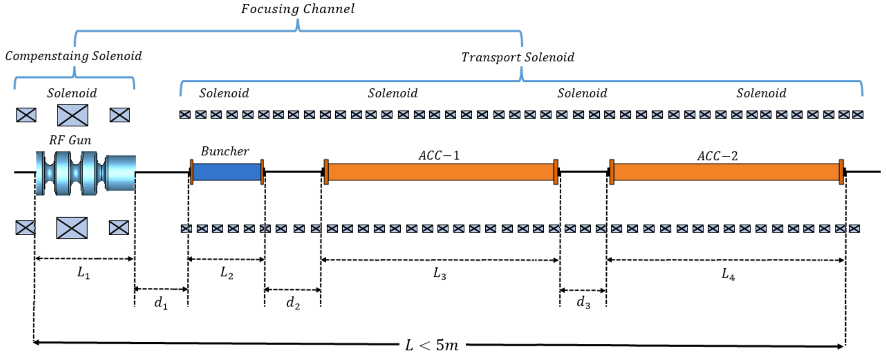
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

Goals:

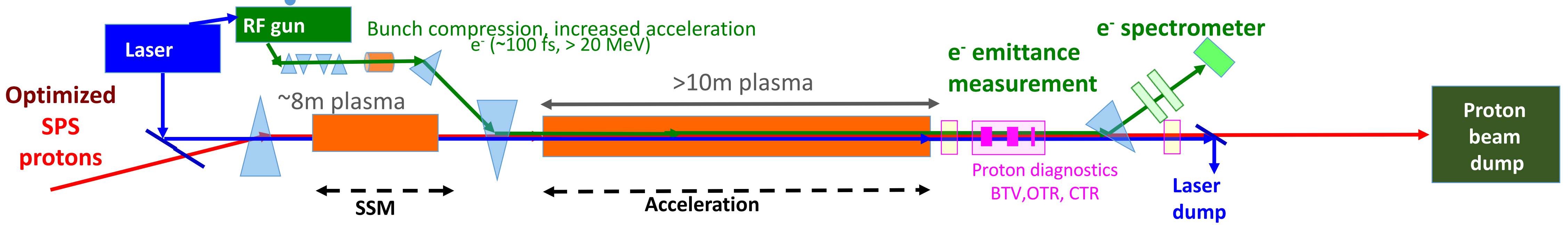
- **Accelerate an electron beam to high energy** (gradient of 0.5-1GV/m)
- **Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)
- **Demonstrate scalability** of the AWAKE concept

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



E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

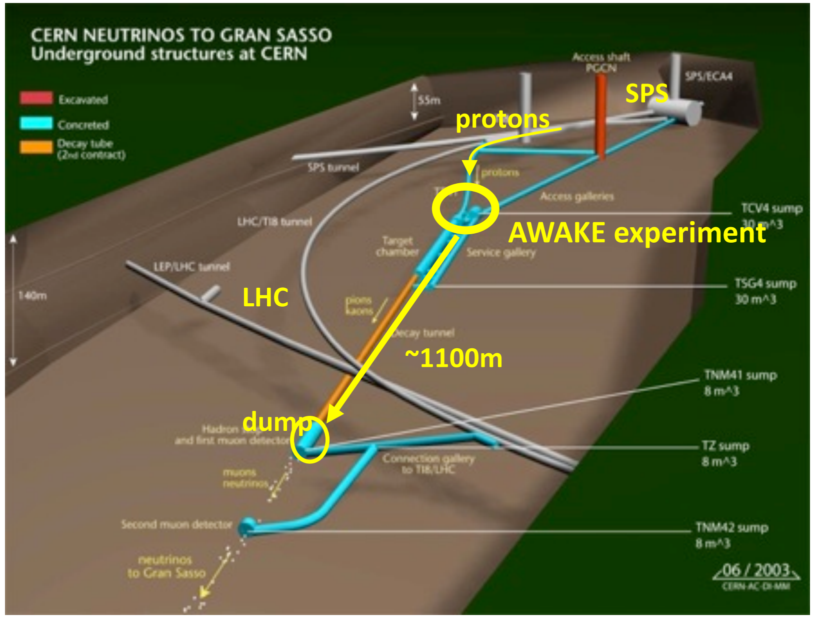
What's Next Next?

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**

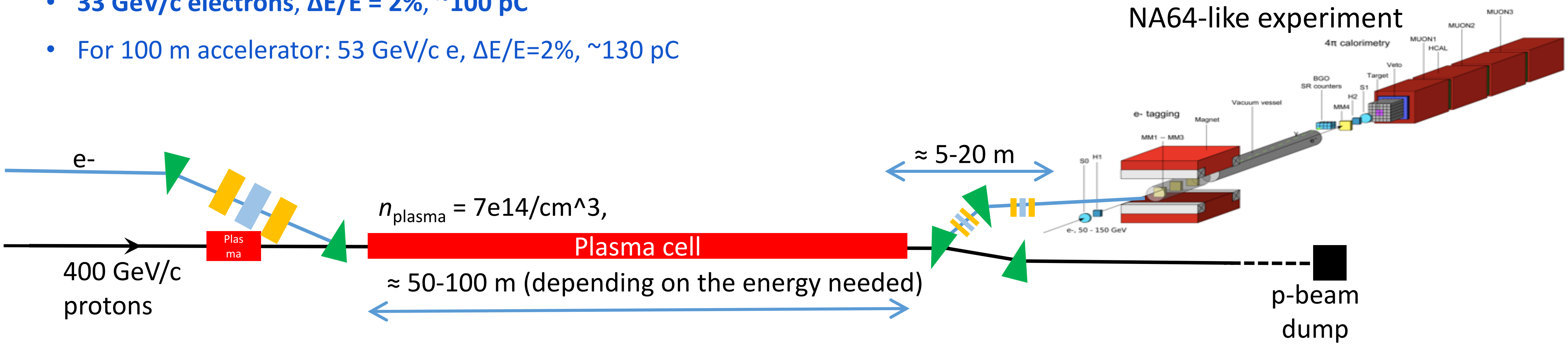
→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**

→ 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, ΔE/E = 2%**, **~100 pC**
- For 100 m accelerator: 53 GeV/c e, ΔE/E=2%, ~130 pC

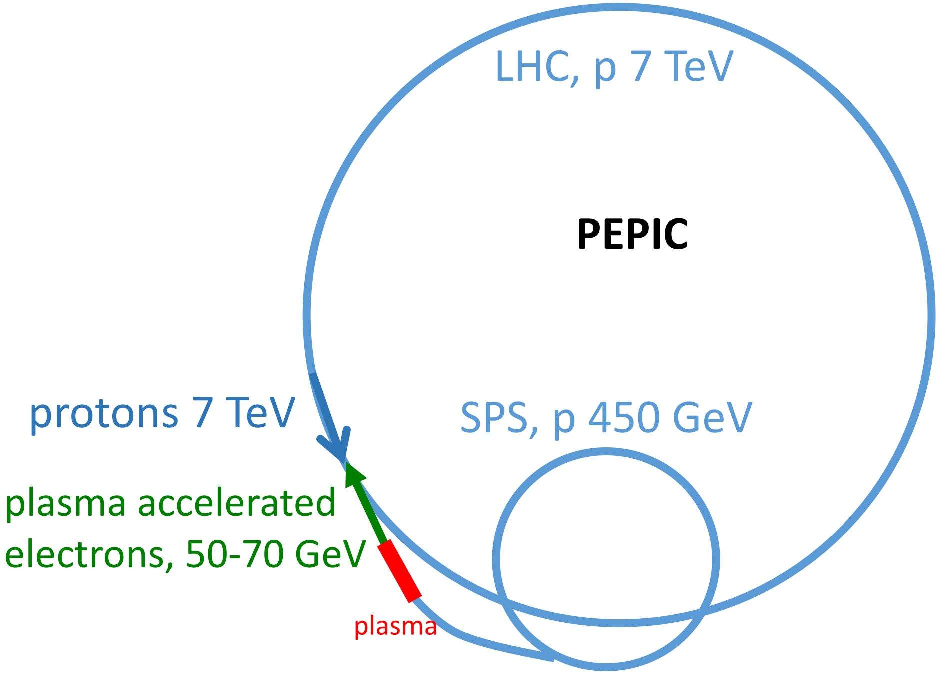


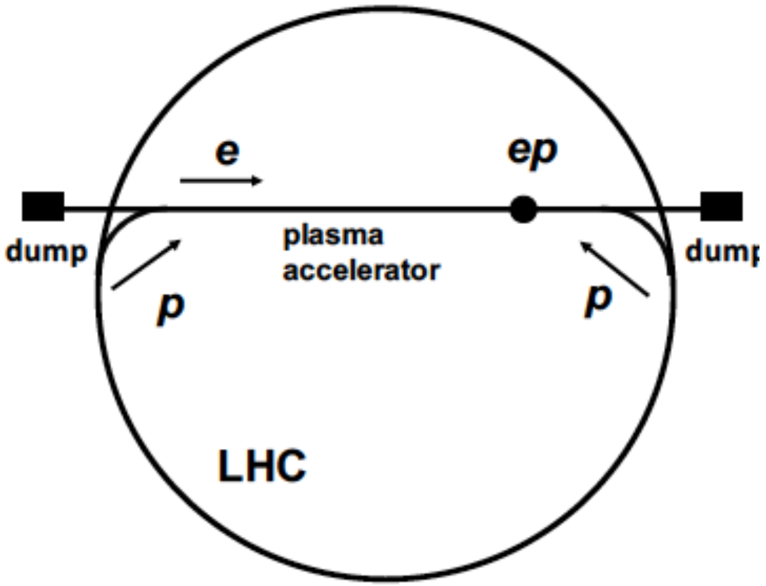
Application of Proton Driven Wakefield Acceleration Technology

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 ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 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.**

→Prepare AWAKE Run 2 starting 2021 after CERN's Long Shutdown 2 (2019/2020)

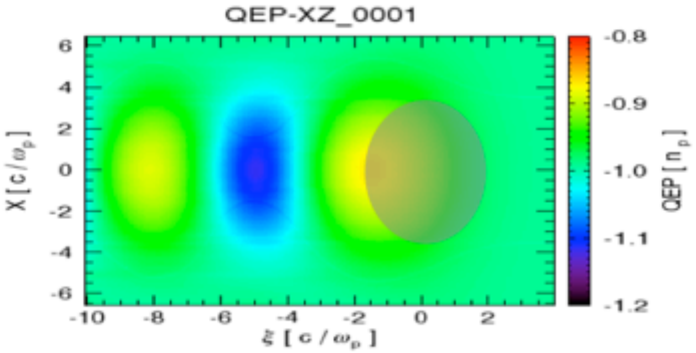
→High energy physics applications with this technology very interesting!

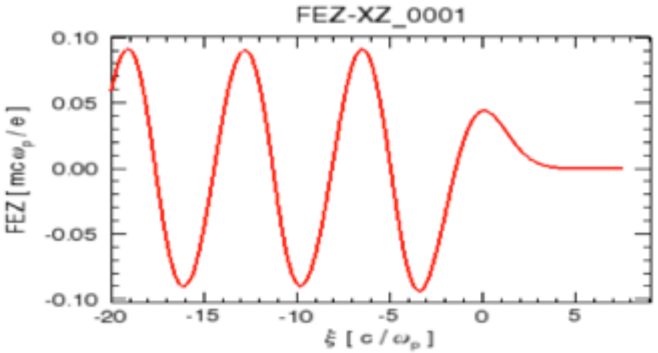
Extra slides

From Linear to Non-Linear

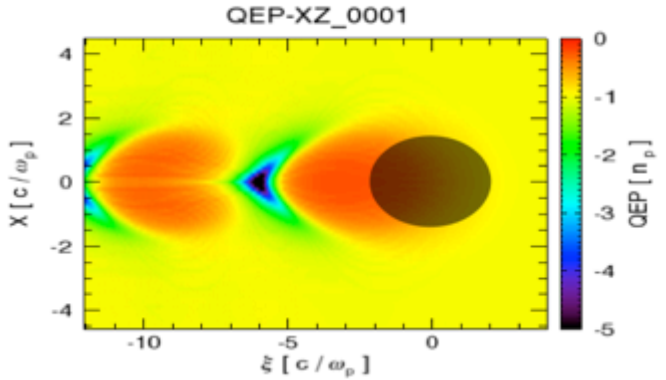
Electron density

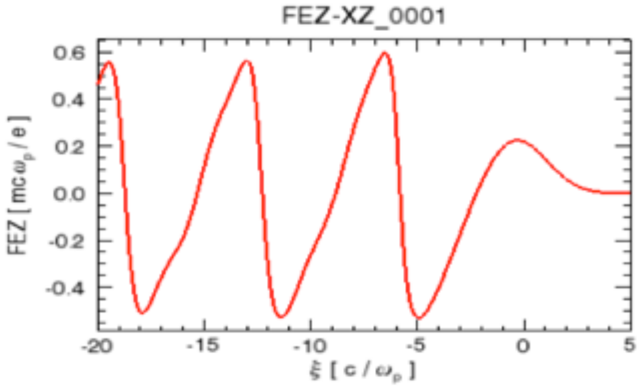
Longitudinal fields



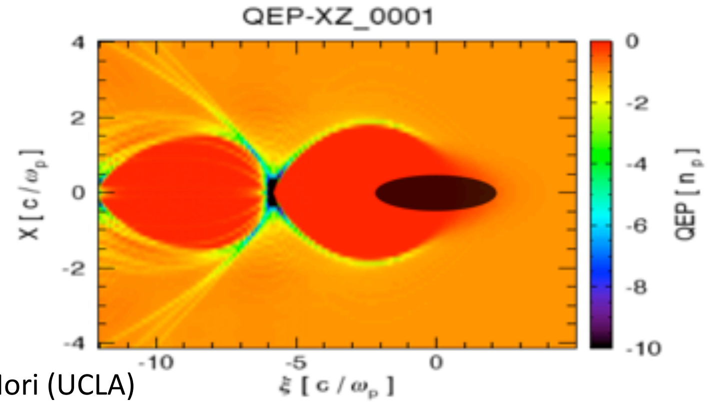


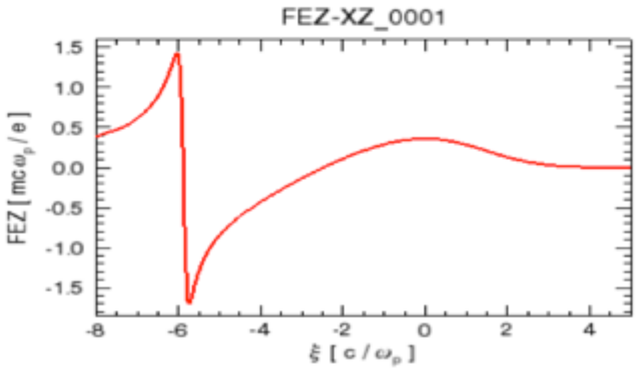
$n_b << n_{pe}$ – linear regime





$n_b \sim n_{pe}$ – non-linear wakes

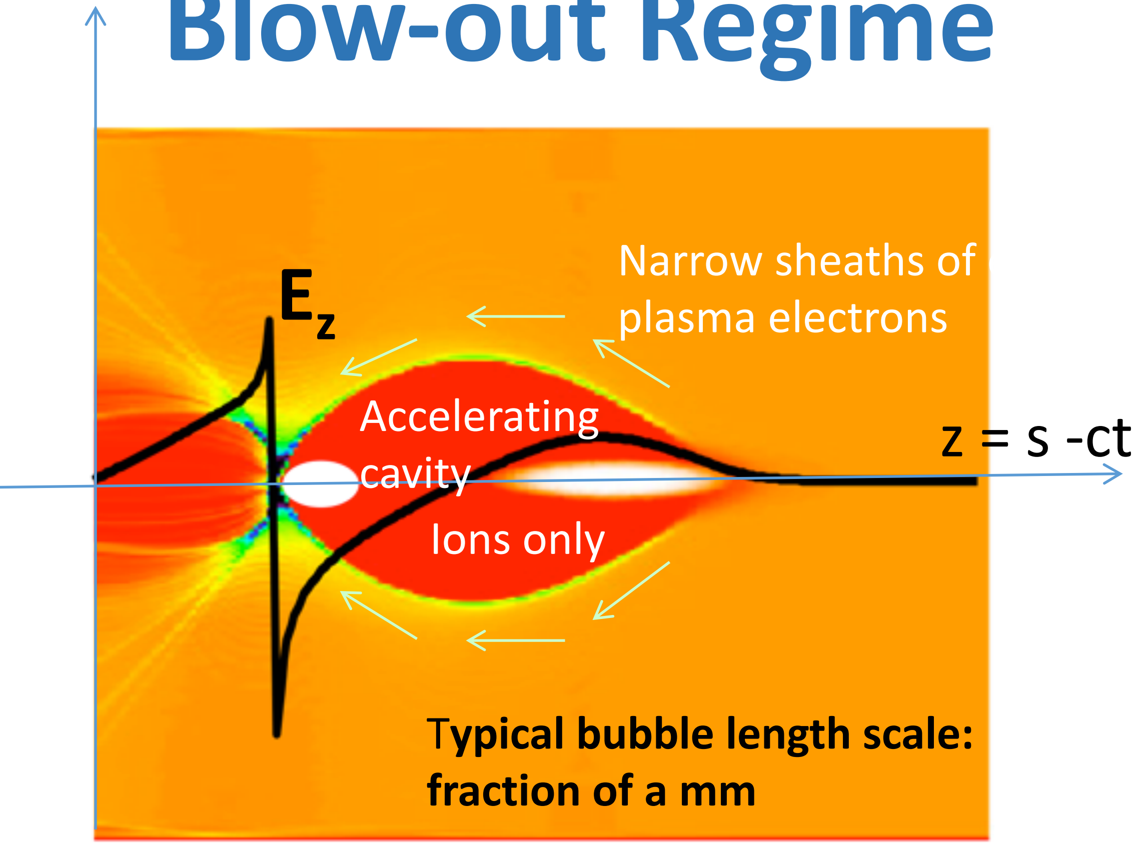




$n_b >> n_{pe}$ – **blow-out regime**

W. Mori (UCLA)

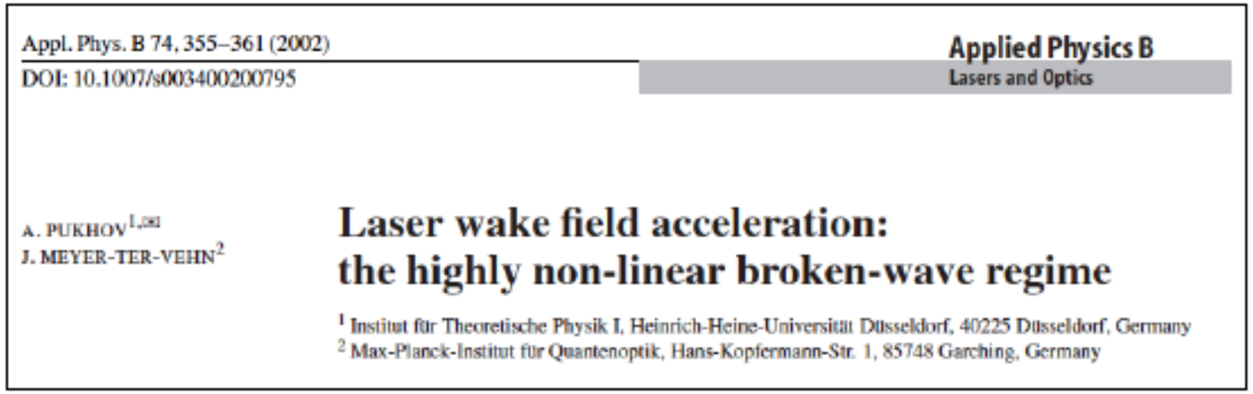
Blow-out Regime



- **Space-charge force** of the driver blows away **all the plasma electrons** in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a **narrow sheath** around the evacuated area, and are **pulled back by the ion-channel** after the drive beam has passed
- An **accelerating cavity** is formed in the plasma
- The back of the blown-out region: **ideal for electron acceleration**

→ **High efficiencies** for energy transfer from drive beam to loaded witness bunch (80-90% according to sim.)
→ **High charge witness** acceleration possible → charge ratio to witness of same order
→ **Linear focusing in r**, for electrons; very strong quadrupole (MT/m)
→ **High transformer ratios (>2)** can be achieved by shaping the drive bunch
→ **E_r independent of x**, can **preserve incoming emittance** of witness beam

Self-Injection Scheme



Appl. Phys. B 74, 355–361 (2002)

DOI: 10.1007/s003400200795

Applied Physics B

Lasers and Optics

A. PUKHOV[1,✉]

J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

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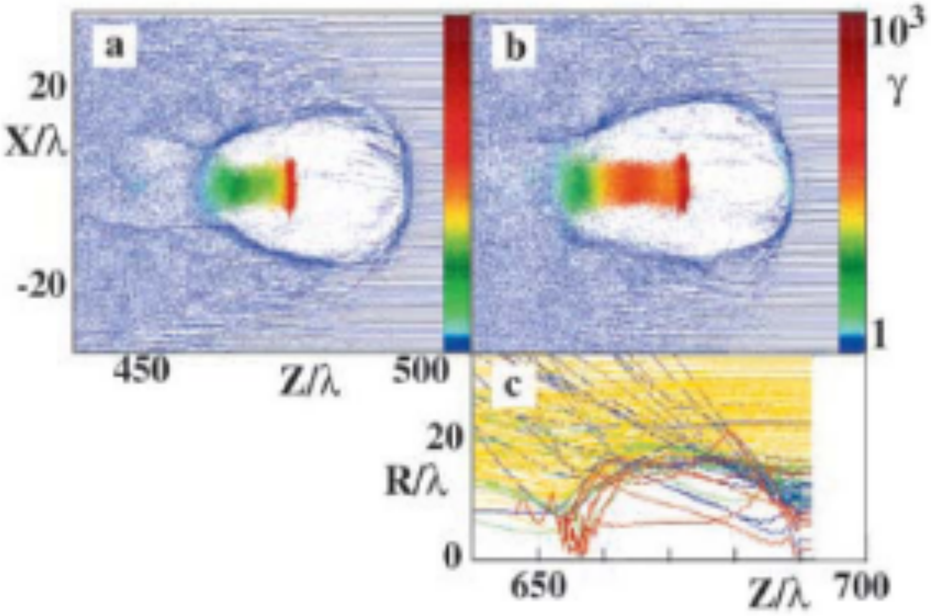
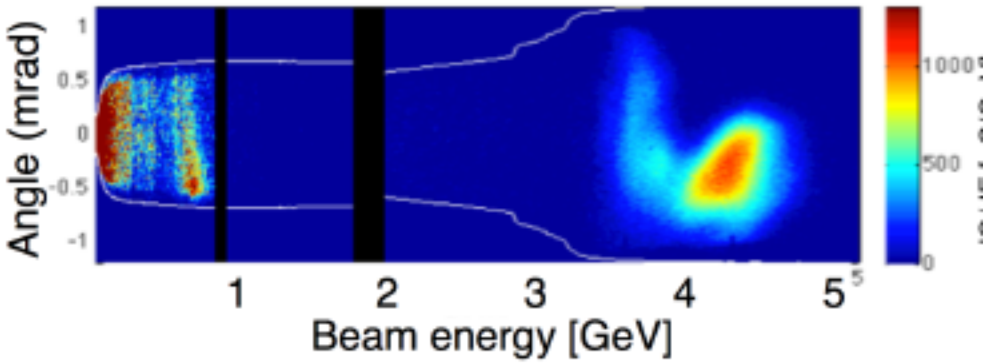
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany



Pukhov, ter-Vehn 2002

Electron beam spectrum



4.25 GeV beams obtained from 9cm plasma channel powered by 310TW laser pulse (15 J)

W.P.Leemans et al., PRL 2014

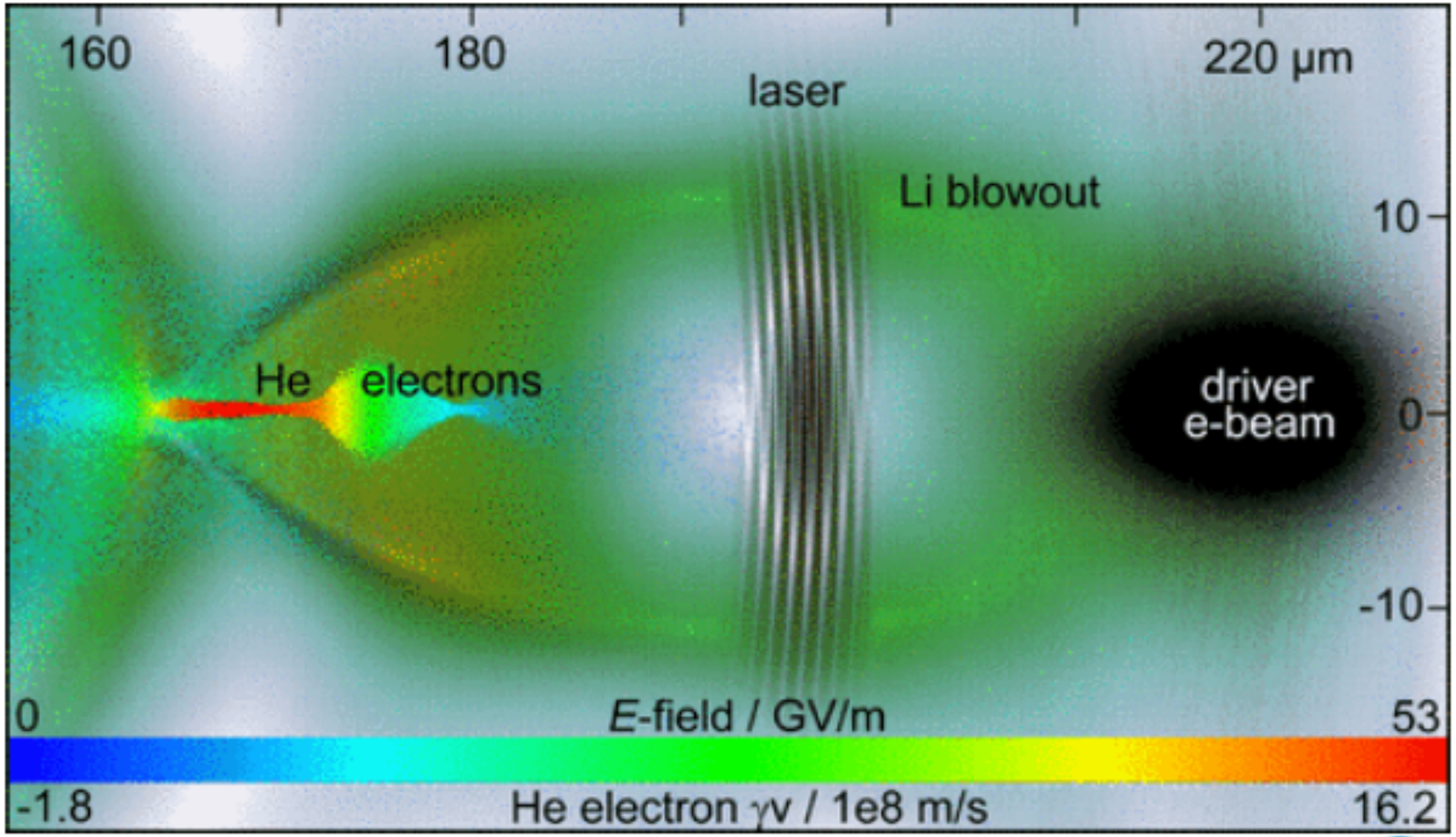
Hybrid Scheme

- **Beam-driven** plasma wakefield using low-ionization-threshold gas such as **Li**
- **Laser-controlled** electron injection via ionization of high-ionization threshold gas such as **He**

B. Hidding et al., PRL 108, 035001 (2012)

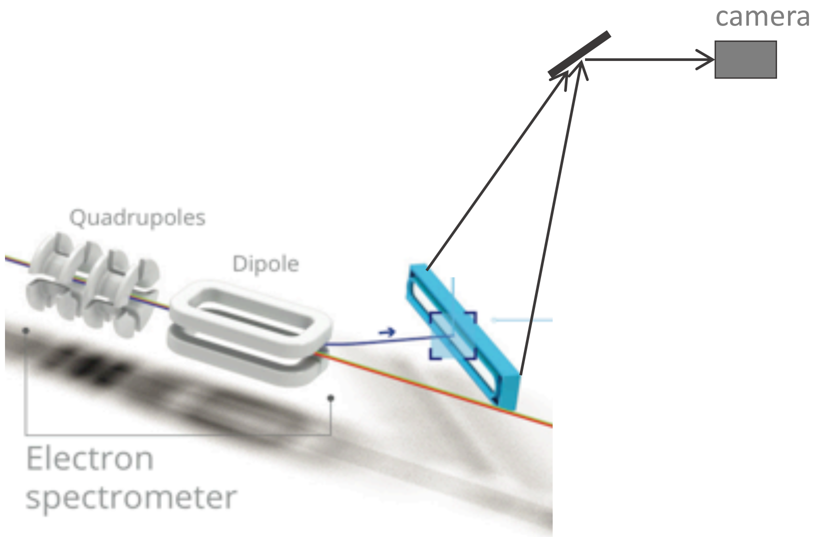
Ultra-high brightness beams:

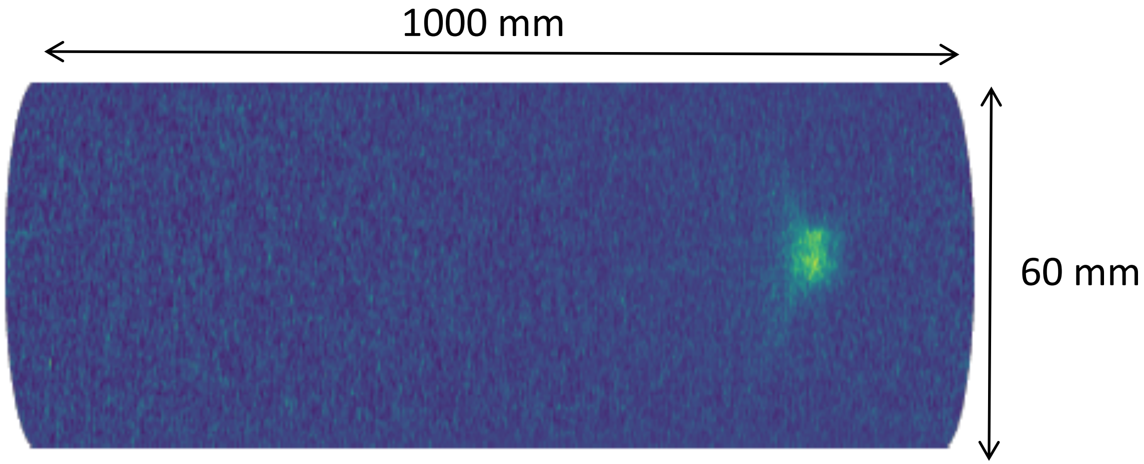
- Sub-µm spot size
- fs pulses
- Small emittance



He-electrons with low transverse momentum released in focus of laser, inside accelerating and focusing phase of the Li blowout

Electron Spectrometer Image Analysis



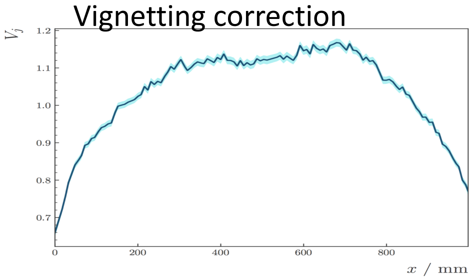


Charge response:

- Screen and camera calibrated at the CLEAR Facility at CERN
- Charge response corrected for AWAKE system (optical system, camera position)
- Charge response:
  6.9 ± 2.1 x 10^6 CCD counts/pC.

Optical line corrections:

- Incident angle corrections
- Vignetting correction: scanning a known light source across the screen



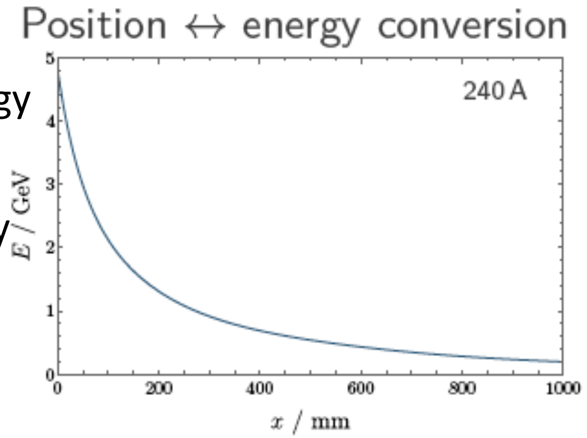
Background subtraction:

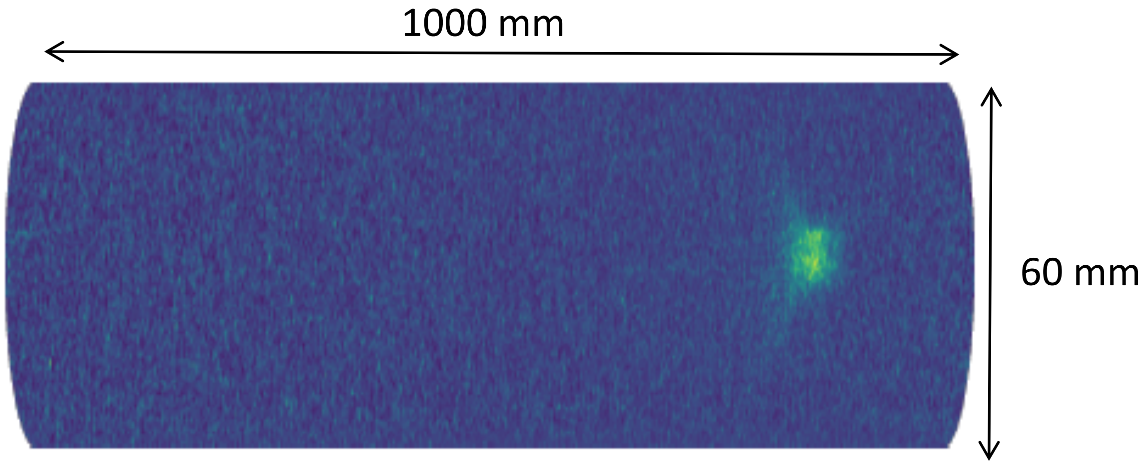
- Intrinsic contribution from camera noise
- Contribution from proton beam (SPS-AWAKE window, plasma iris) → dependent on bunch charge and plasma density

Electron Spectrometer Image Analysis

Position ← → Energy conversion

- Using measured dipole field maps and calculate conversion with BDSIM. →Energy uncertainty of 2%
- Overall uncertainty: higher: dominated by emittance of accelerated electron beam. But use of quads limits to ~5%.





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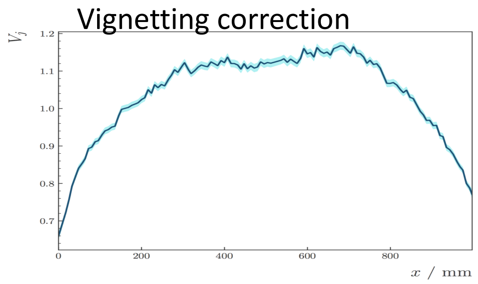

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