First Electron Acceleration in AWAKE

Joint Annual Swiss and Austrian Physical Society Meeting
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Edda Gschwendtner, CERN

Outline

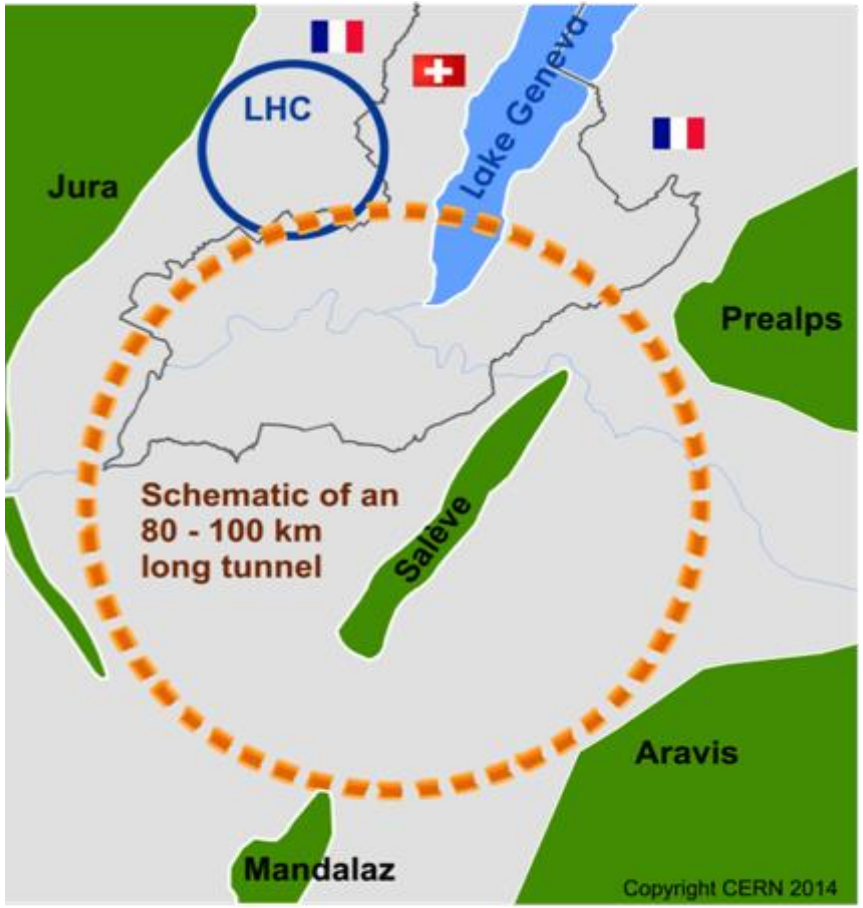
- Introduction to Plasma Wakefield Acceleration
- AWAKE, The Advanced Wakefield Experiment
- AWAKE Results
- What’s Next

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.

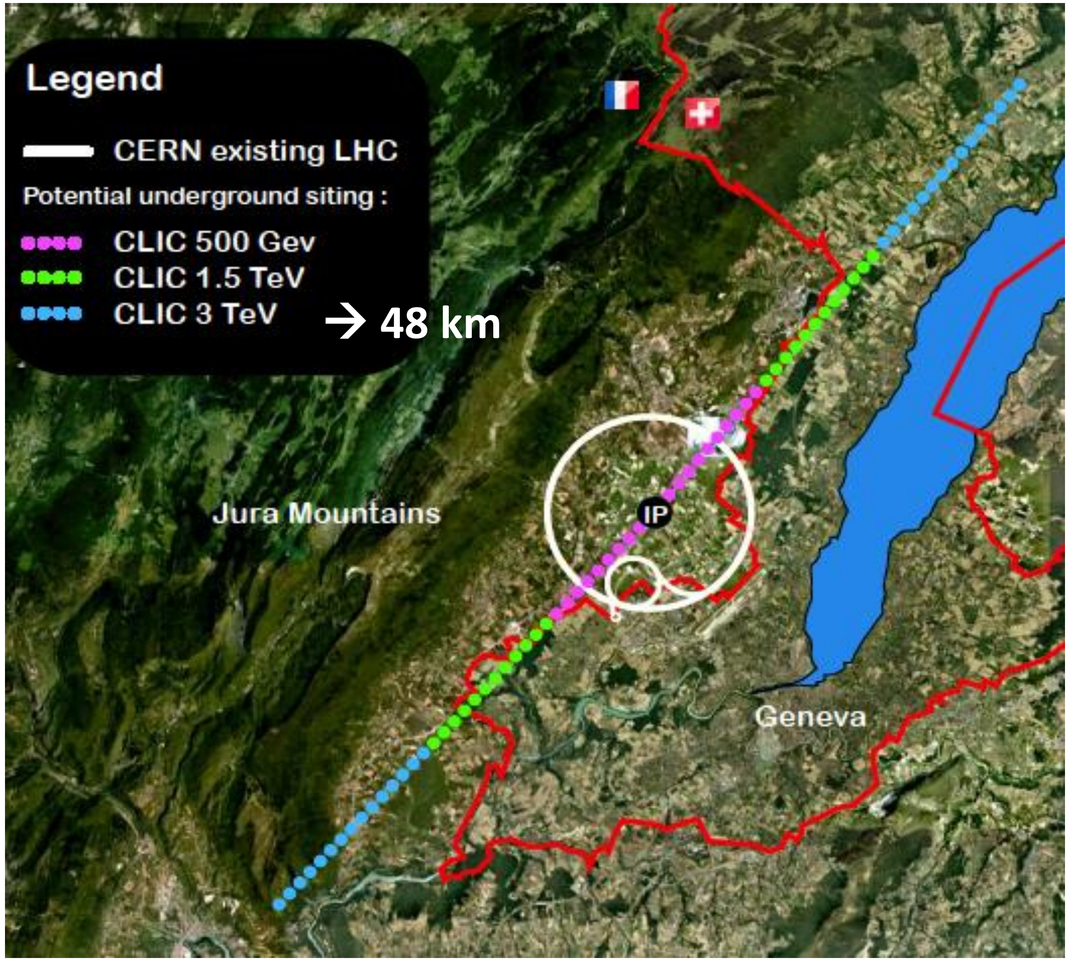
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

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

Discover New Physics

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

CLIC, electron-positron collider with 3 TeV energy

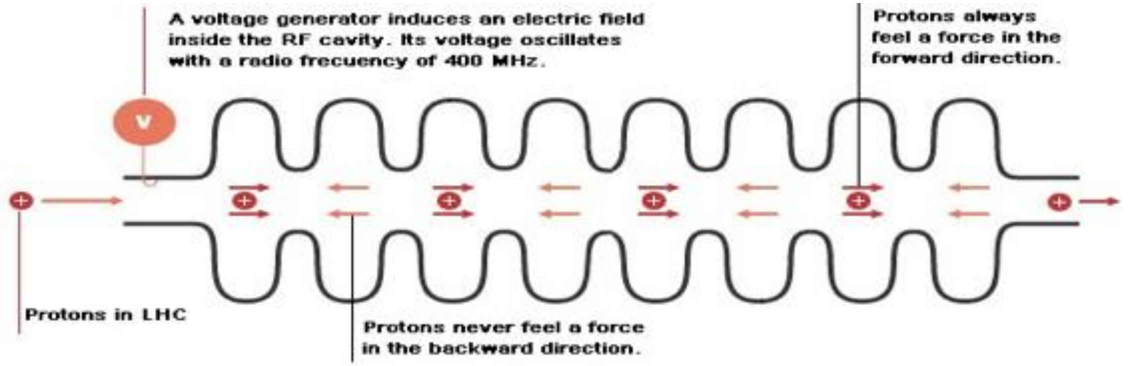


Limitations of linear colliders:

- 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.

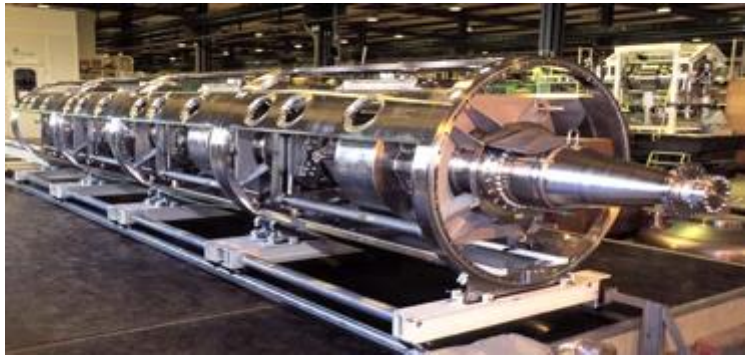
Conventional Acceleration Technology

Radiofrequency Cavities

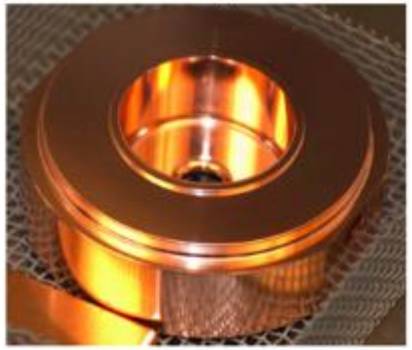


(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity



New RF Copper Cell



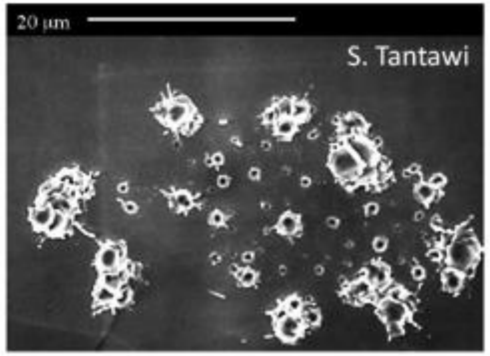
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

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



Plasma Wakefield Acceleration

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

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.

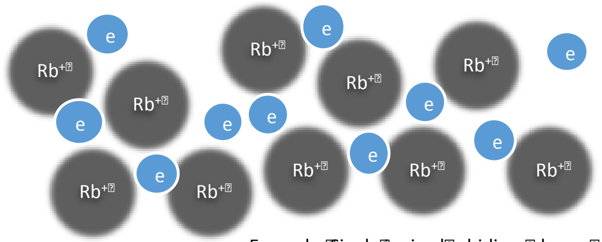
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective 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

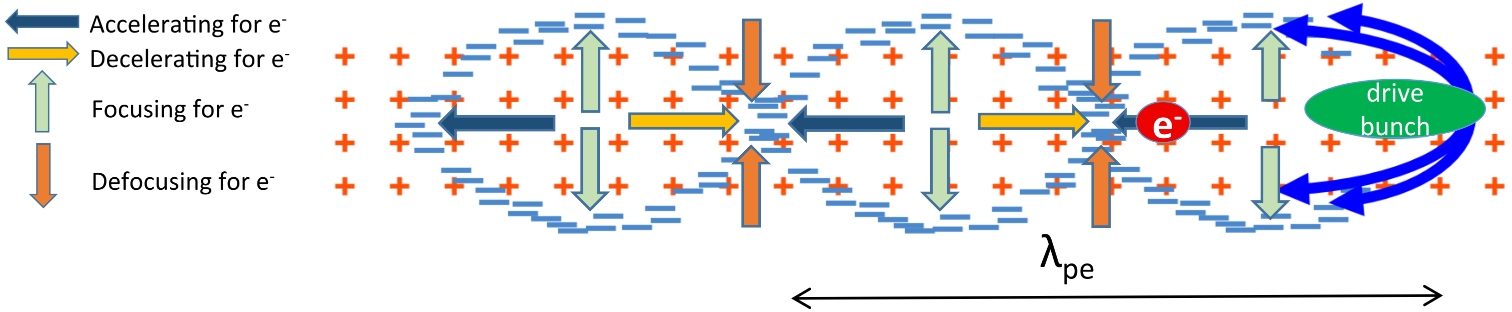
Introduction – Plasma Wakefield Acceleration, PWFA



Example: Single ionized rubidium plasma

Plasma is ionized and can sustain **electric fields up to three orders of magnitude higher** than conventional accelerator technologies**.**
Reach gradients → order of **100 GV/m.**

Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.**



Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam
Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \rightarrow \lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \rightarrow \lambda_{pe} \approx 1\ \mathrm{mm} \sqrt{\frac{10^{15}\ \mathrm{cm}^{-3}}{n_{pe}}}$$

Example: $n_{pe} = 10^{16}$ cm^{-3}
→ λ_{pe} = 0.3 mm

→ Cavities with mm size!

The maximum accelerating field (wave-breaking field) is: $e\,E_{WB} = 96 \frac{\mathrm{V}}{\mathrm{m}} \sqrt{\frac{n_{pe}}{\mathrm{cm}^{-3}}}$

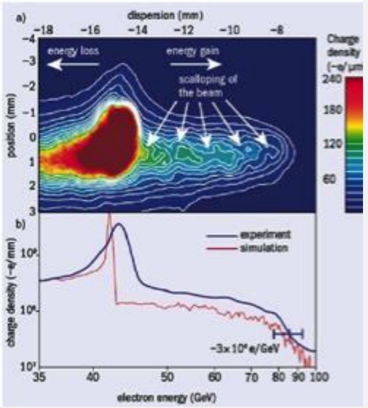
Example: $n_{pe} = 10^{16}$ cm^{-3} →
E_{WB} = 10GV/m

Some Highlight Results

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

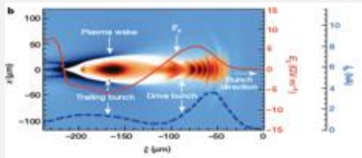
*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

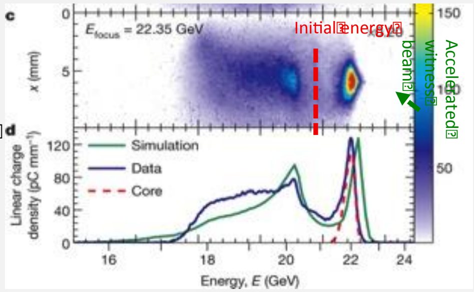
→ **gradient of 52 GV/m**



High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

*M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature13882*





70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient → **Up to** **30% transfer efficiency, ~2% energy spread**

Electron beam driven PFWA

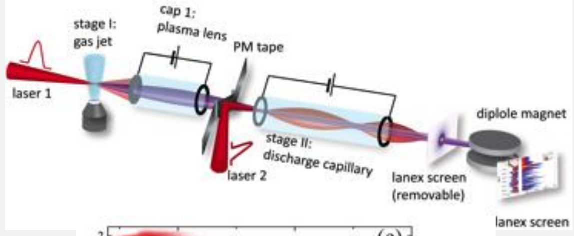
9 GeV energy gain in a beam-driven plasma wakefield accelerator

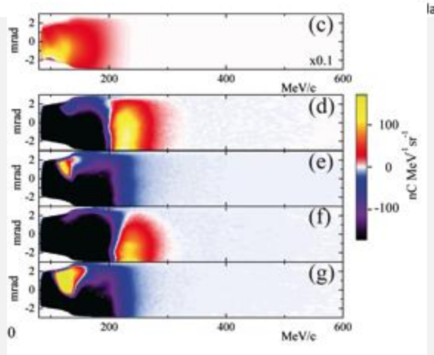
*M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017*

Laser driven LFWA

Multistage coupling of independent laser-plasma accelerators

*S. Steinke, Nature **530**, 190 (2016)*

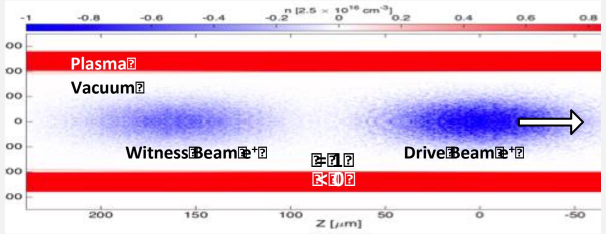




Staging demonstrated at 100MeVs level.

Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Positron acceleration with PFWA

Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

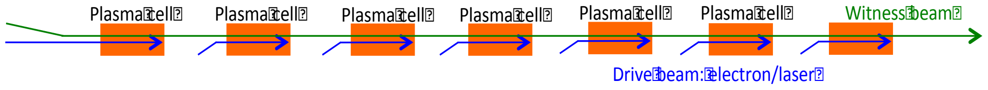
Now first Proton Driven Plasma Wakefield Experiment

Acceleration to HEP Energies

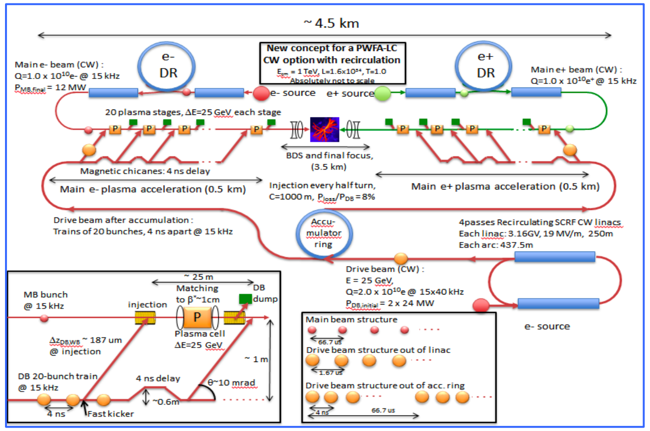
Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

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

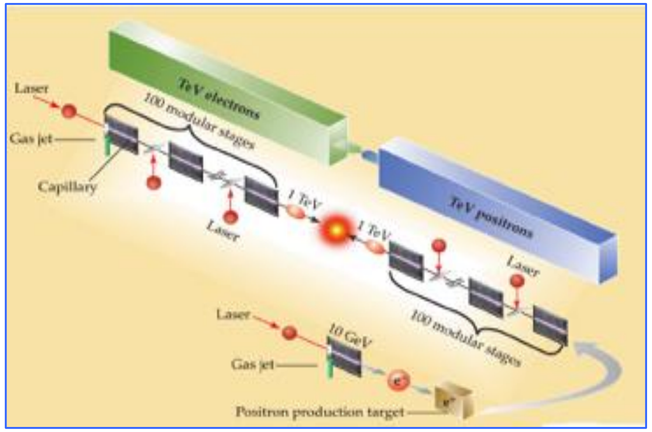
- **Electron/laser driven PWA**: need several stages
  - effective gradient reduced because of long sections between accelerating elements….



➔ Challenges: staging, matching, tolerances



E. Adli et. al.,arXiv:1308.1145 (2013)

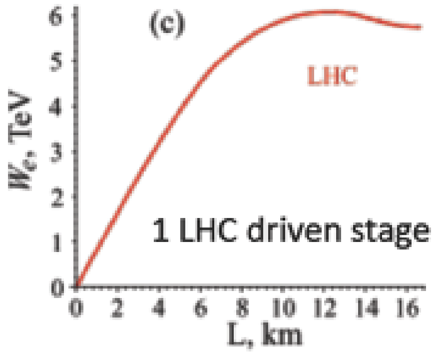


Leemans & Esarey, Phys. Today 63 #3 (2009)

- **Proton driven PWA**: 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.

➔ Challenges: long plasma sources

Dephasing:
SPS: ~70 m
LHC: ~few km
FCC: ~∞



A. Caldwell and K. V. Lotov, Phys. Plasmas **18,** 103101 (2011)

Drive Beams in Plasma Wakefield Acceleration

In order to create plasma wakefields efficiently, the drive bunch length has to be short compared to the plasma wavelength. → Relatively easy for **Laser** and **Electron** bunches.

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

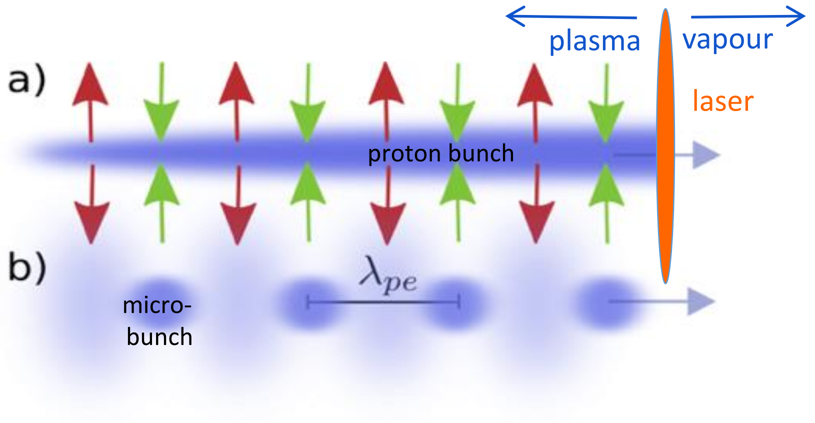
Proton beam as drive beam**:** CERN SPS proton bunch: very long! (σ_z = 12 cm) → much longer than plasma wavelength (λ = 1mm), but rely on self-modulation of the proton beam

Self-Modulation of a Long Proton Beam:

a) Bunch drives wakefields at the initial seed value when entering plasma.

- **Initial wakefields act back** on the proton bunch itself. → On-axis density is modulated. → Contribution to the wakefields is $\propto n_b$.

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



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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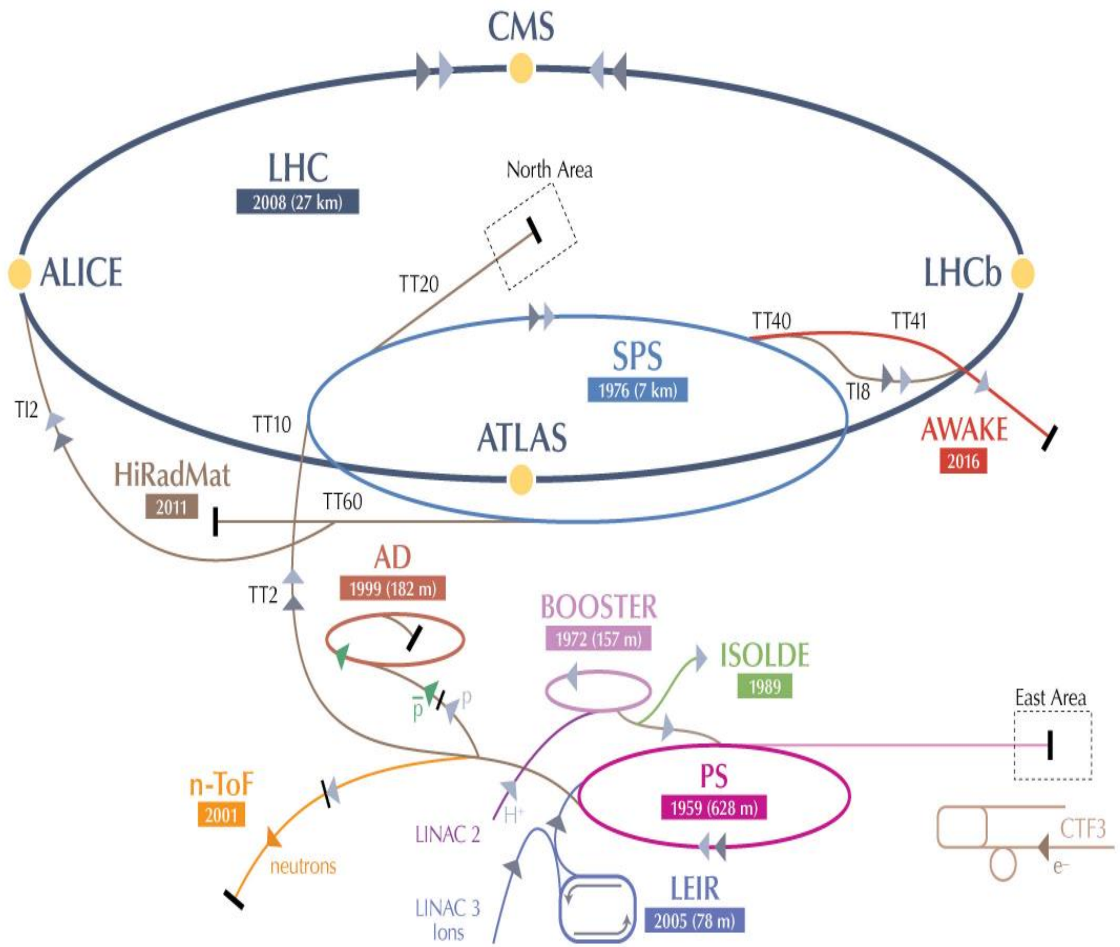
AWAKE at CERN



Advanced WAKEfield Experiment

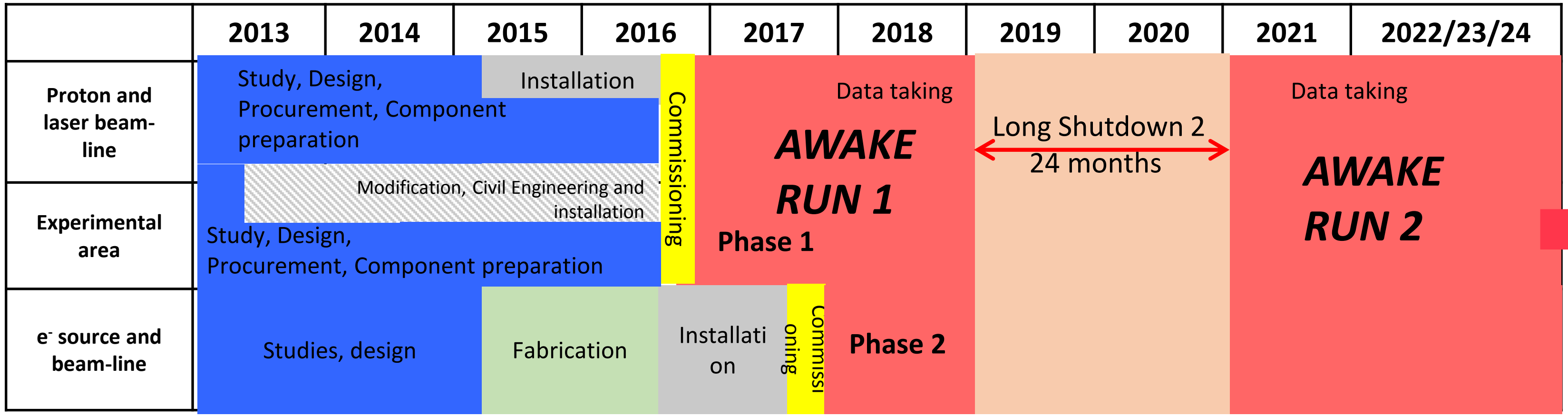
- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First proton beam sent to plasma end 2016
- First electron acceleration in 2018

AWAKE

AWAKE Collaboration: 22 Institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, 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
- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

AWAKE Timeline

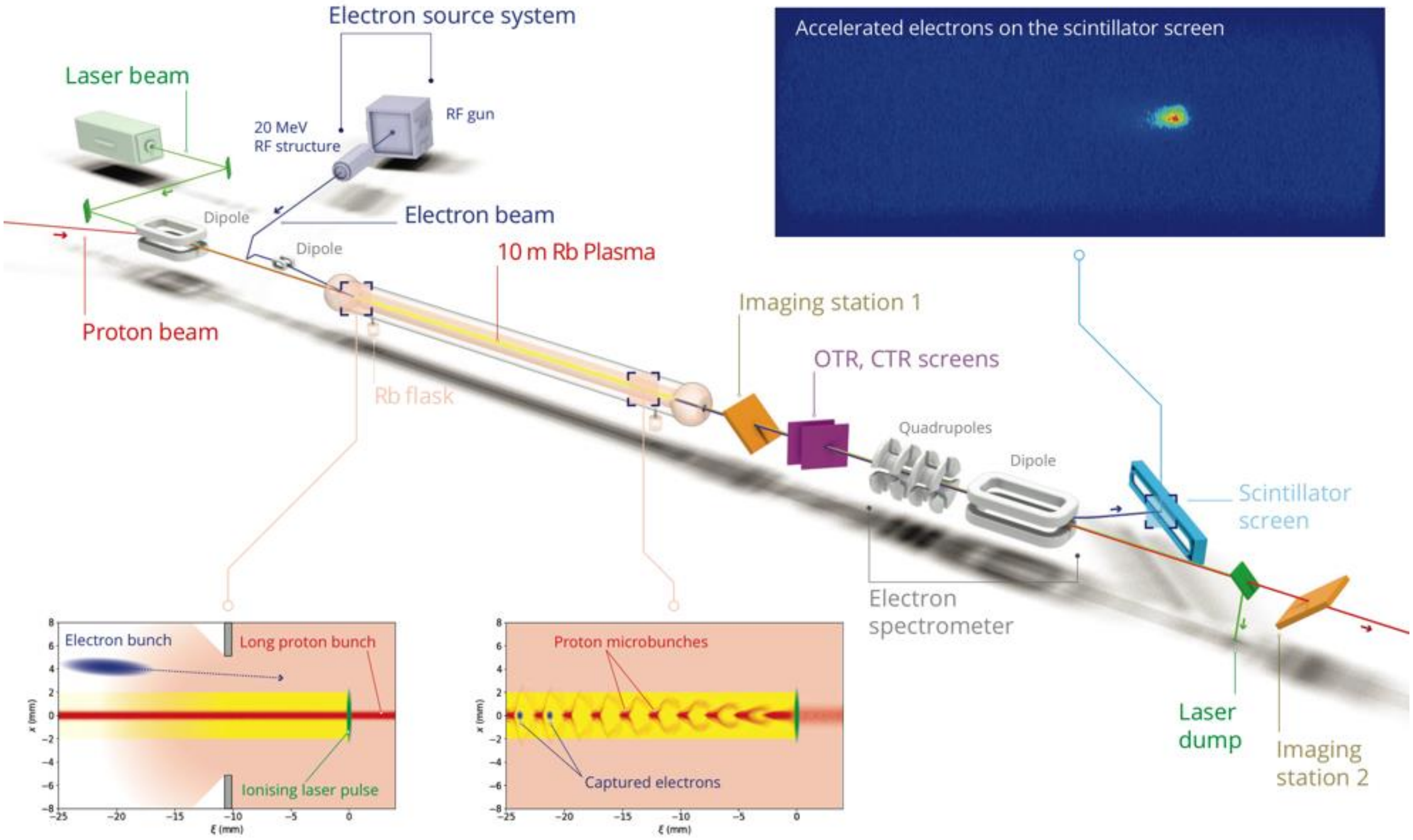


AWAKE++: After Run 2:
kick-off particle physics driven applications

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**.

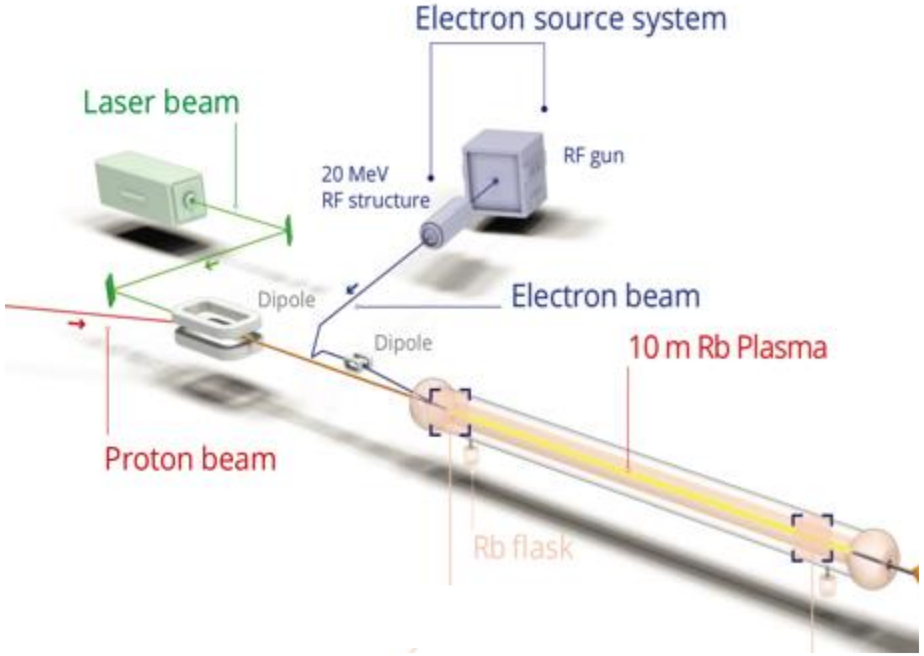
AWAKE Experiment

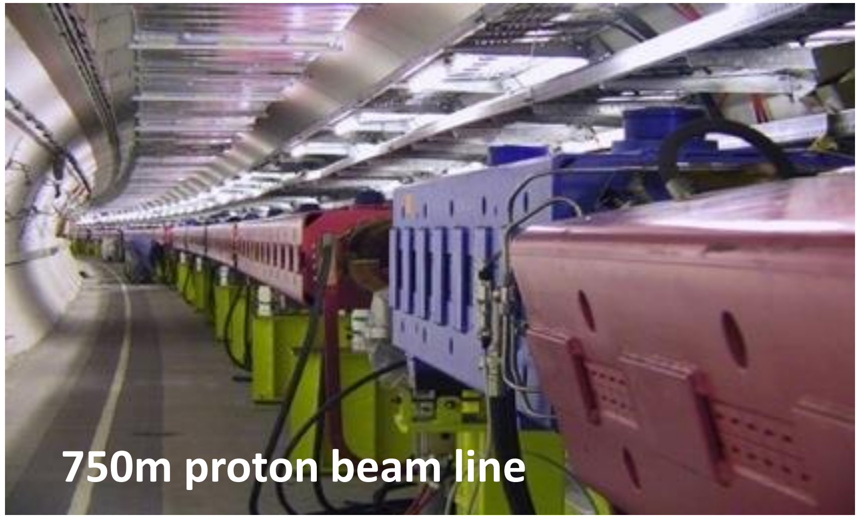


AWAKE Proton Beam Line

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

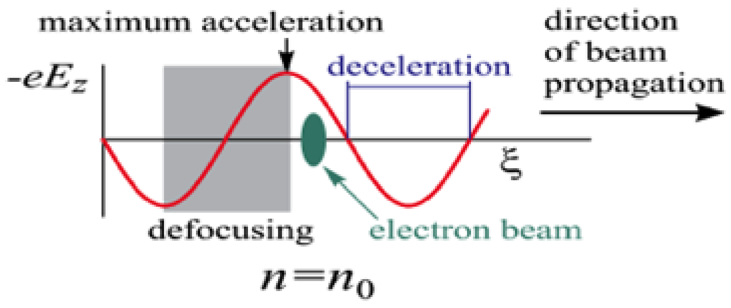


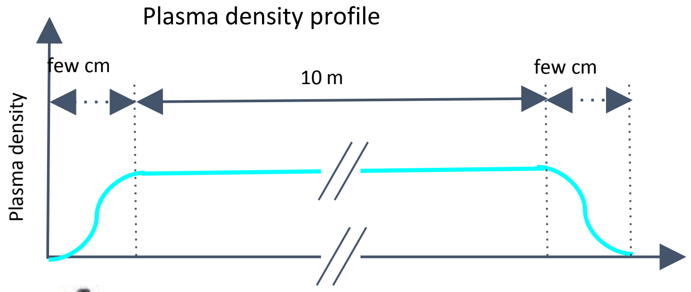


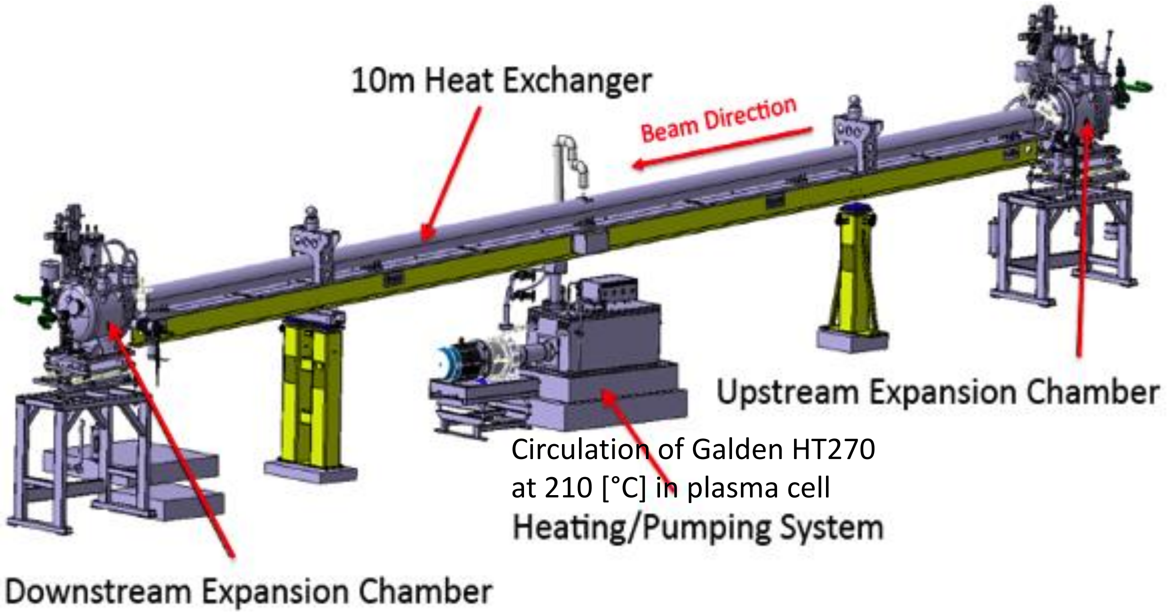
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will injected into the same beamline.

AWAKE Plasma Cell

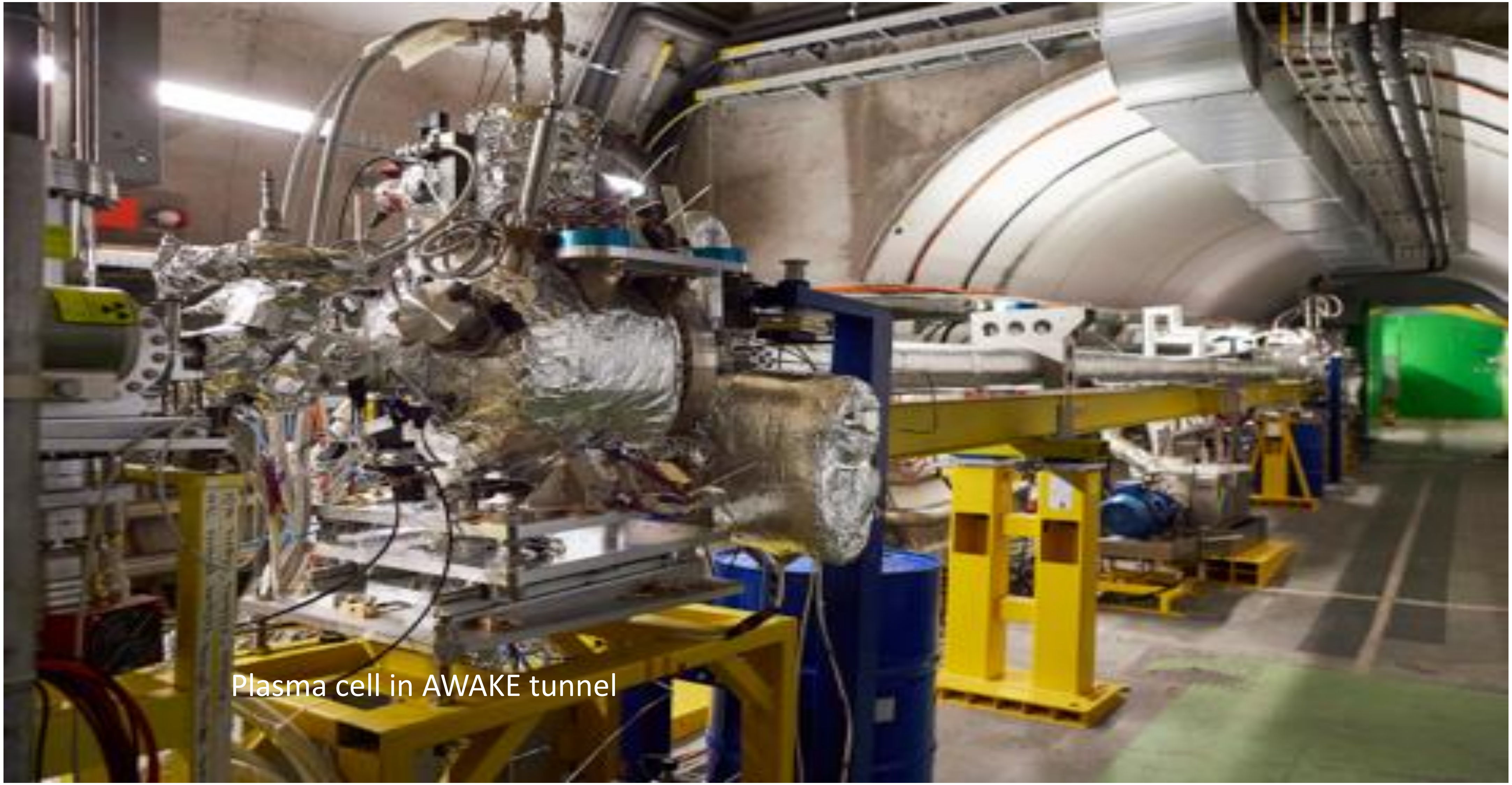
- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (˜220 deg)
    - Complex control system: 79 Temperature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





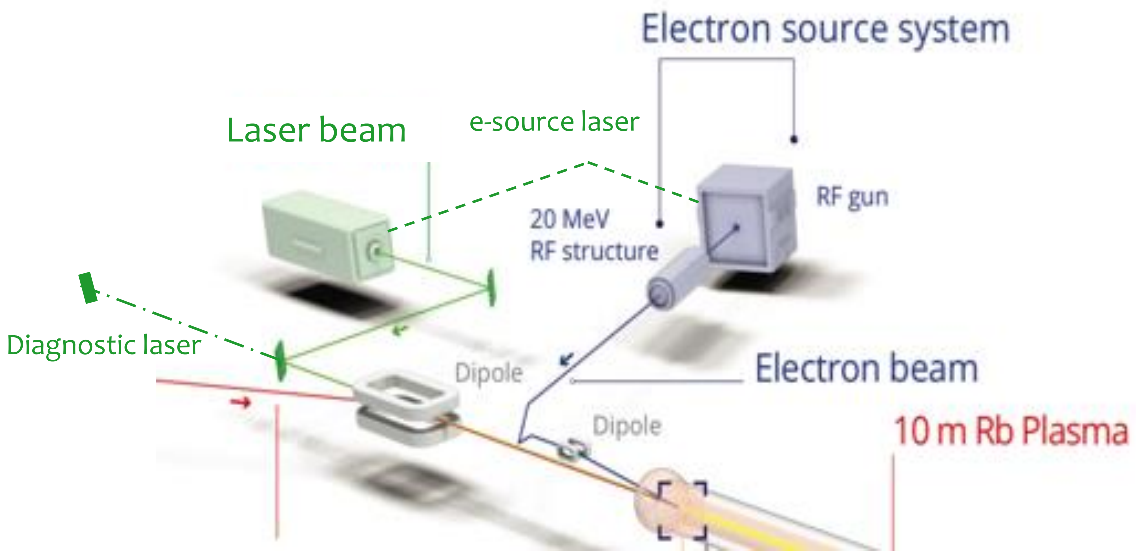


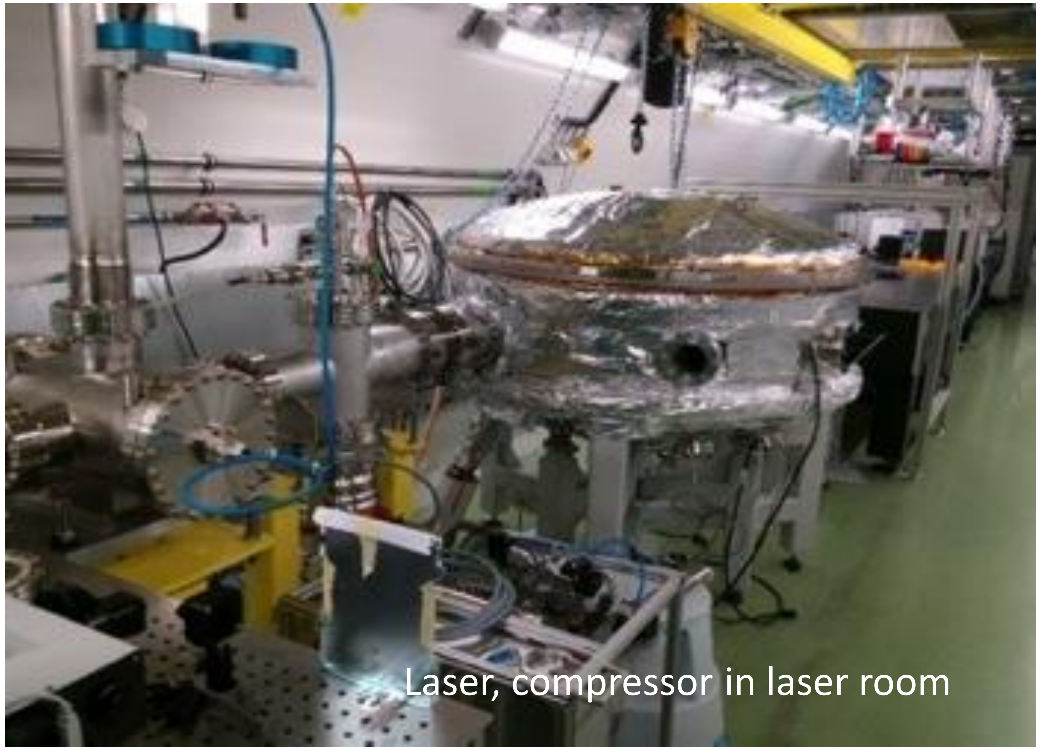
AWAKE Plasma Cell


Plasma cell in AWAKE tunnel

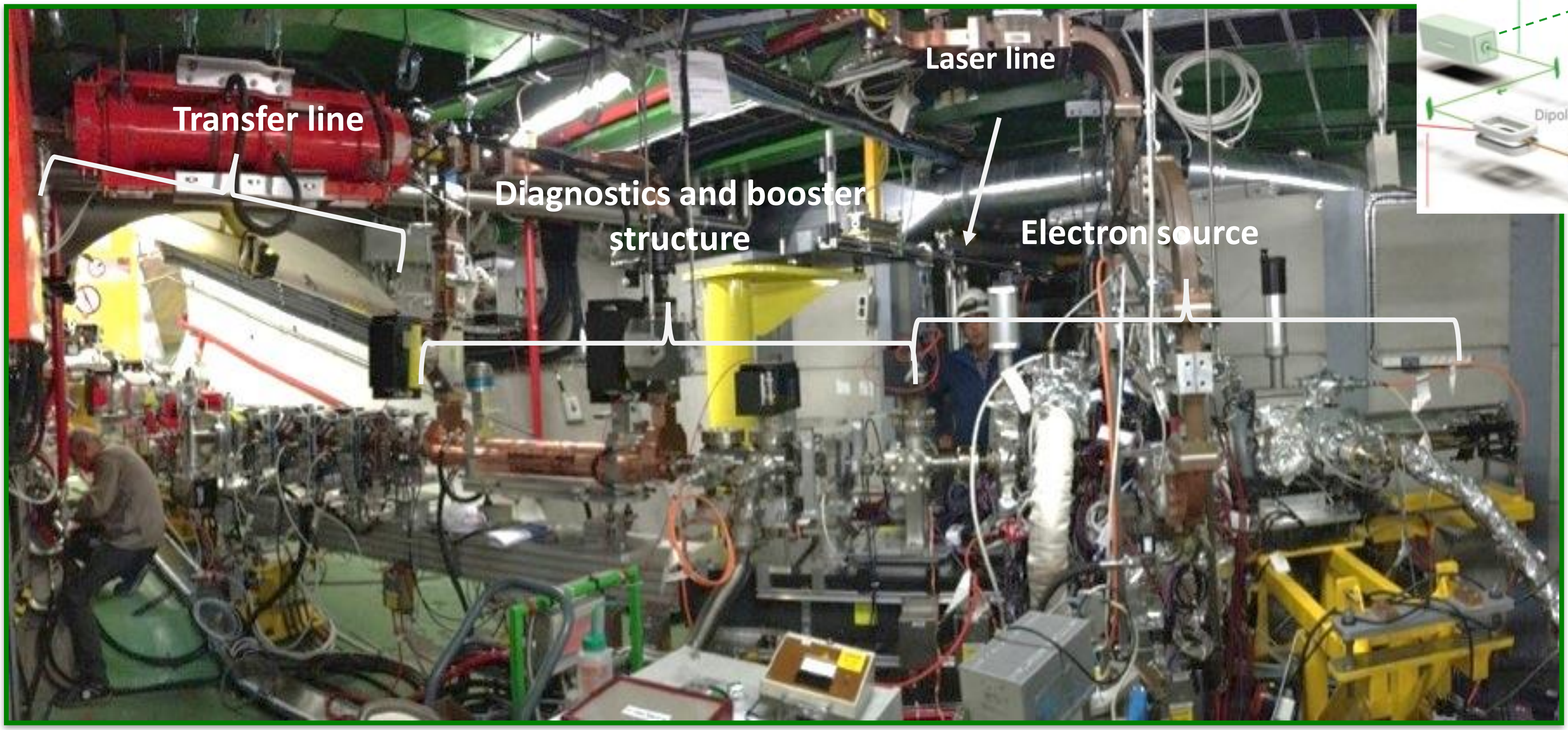
Laser and Laser Line

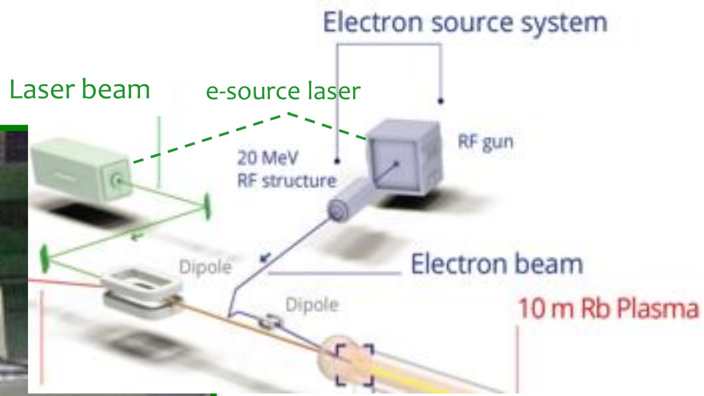
AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





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 ~100 µm.

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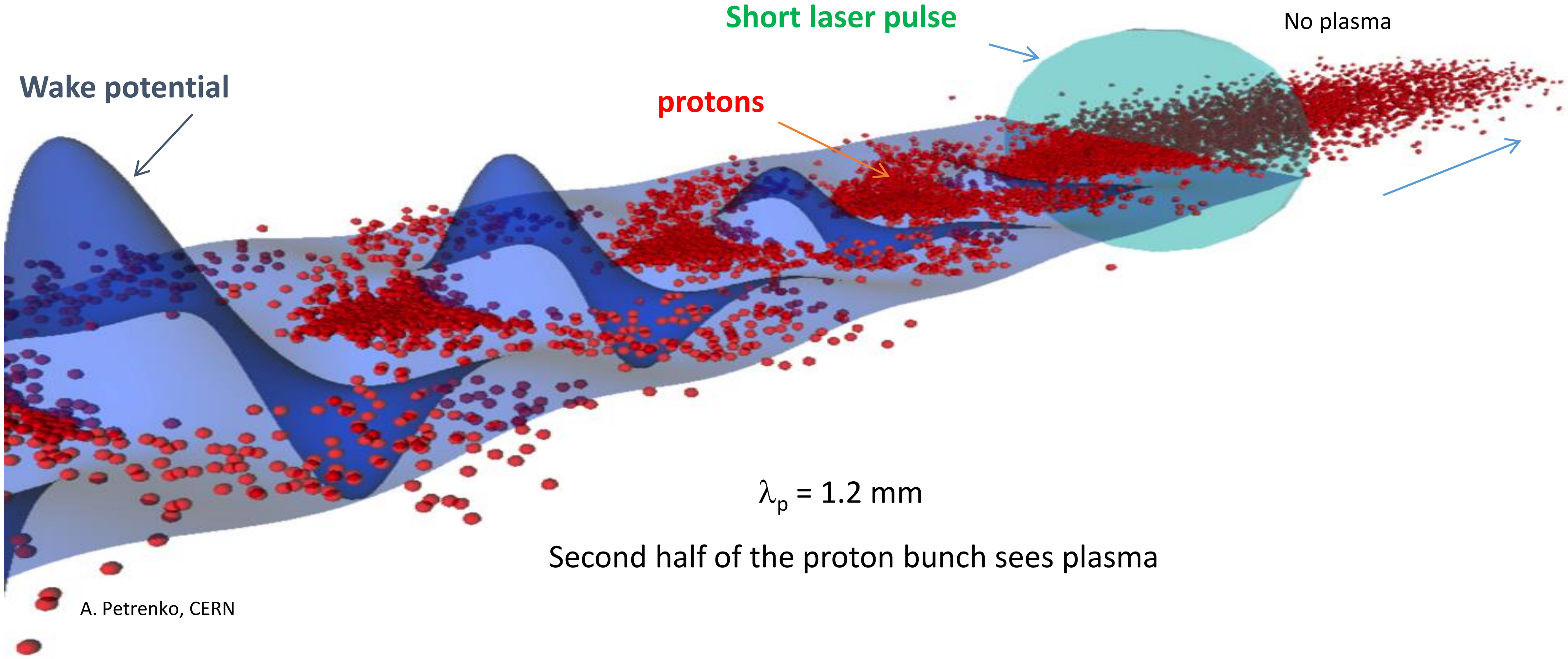
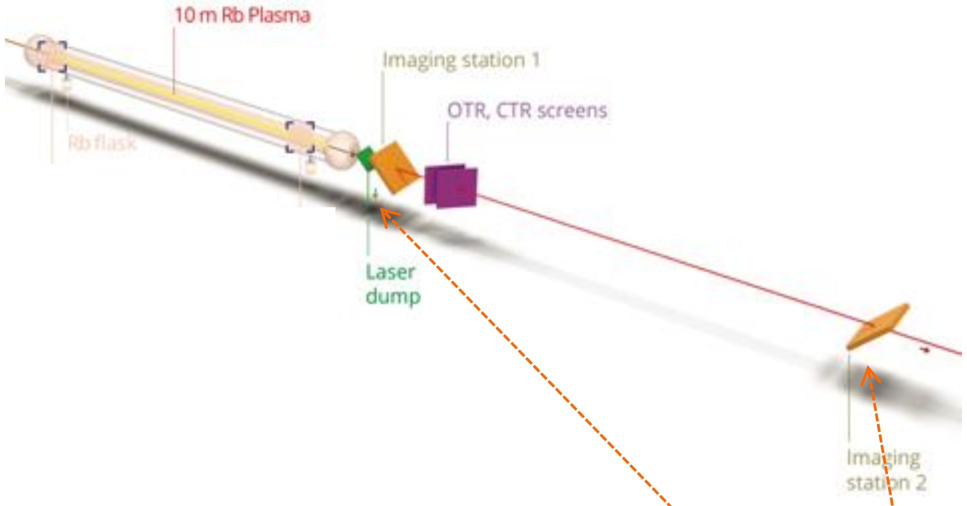
Seeded Self-Modulation Results



λ_p = 1.2 mm

Second half of the proton bunch sees plasma

Diagnostics for Seeded Self-Modulation



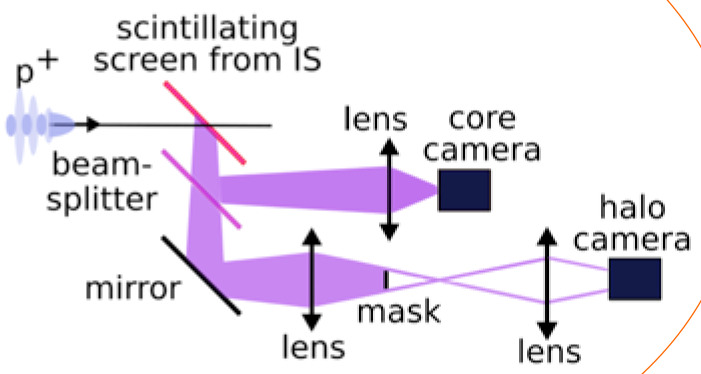
Indirect SSM Measurement:

Measure time integrated transverse bunch distribution.

→ Image protons defocused by the strong plasma wakefields

→ Scintillation light from screen measured with digital camera.

Imaging station



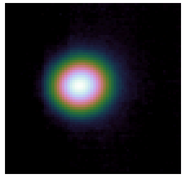
Results: Indirect Seeded Self-Modulation Measurement

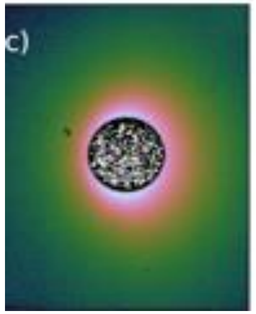
From the **radial distribution** of the defocused protons,
we learn about the **transverse effects** of SSM

Core camera

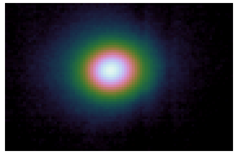
Halo camera

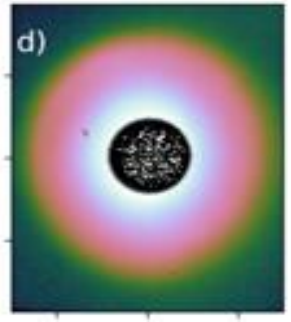
no plasma





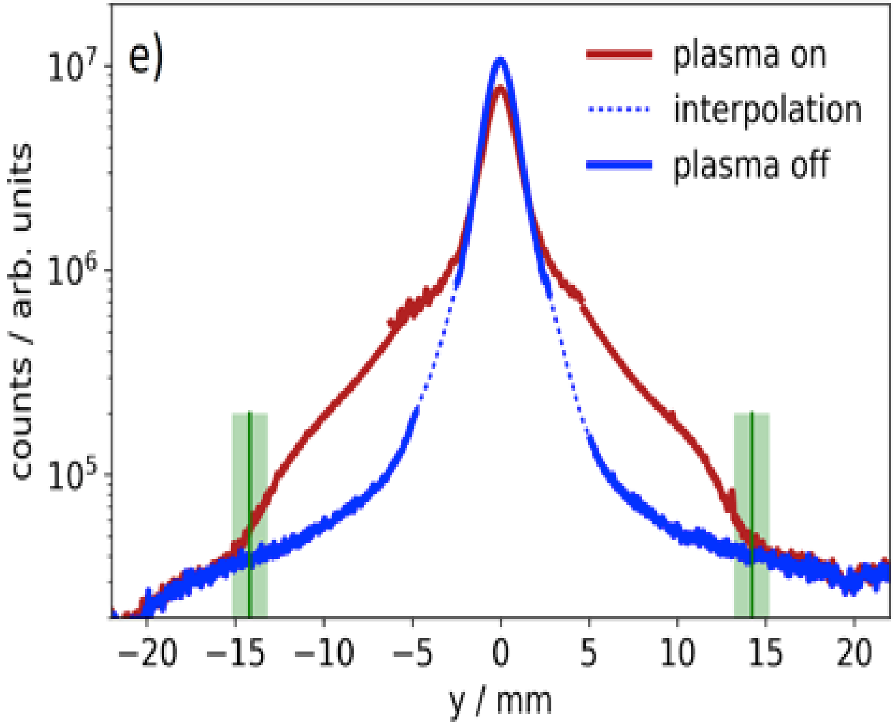
plasma





➔ **Victor Hess Prize 2019: Marlene Turner**

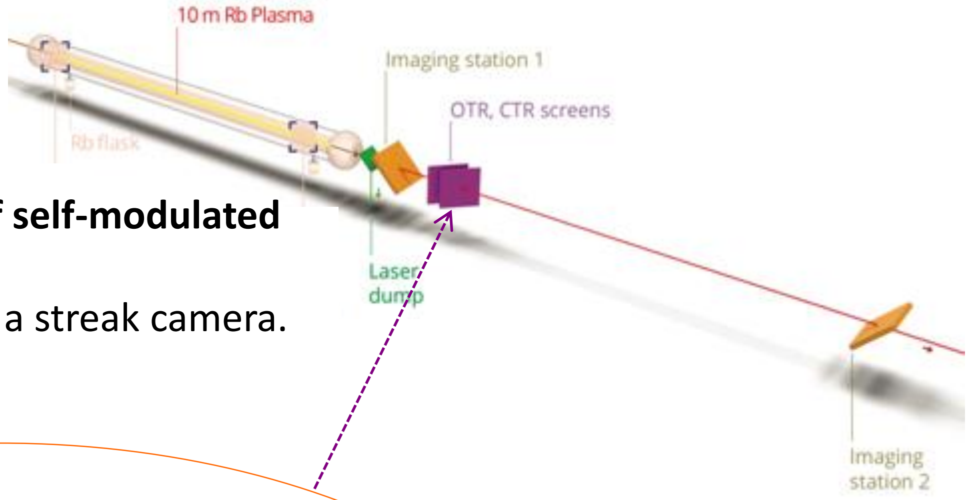
Combination of core and halo image projections



- 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/cm^3**.
- **Halo symmetric ⇒ no hose instability.**
- Estimate of the **transverse wakefields amplitude ($\int W_{per} dr$)**

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

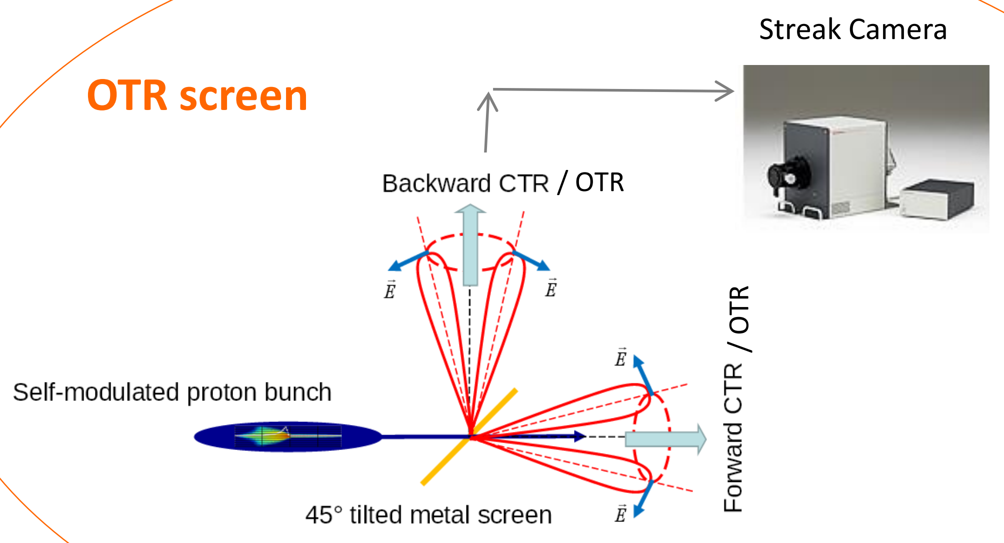


Direct SSM Measurement:

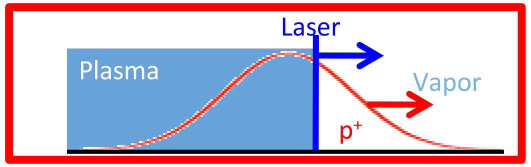
Measure longitudinal structure of self-modulated proton bunch.

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

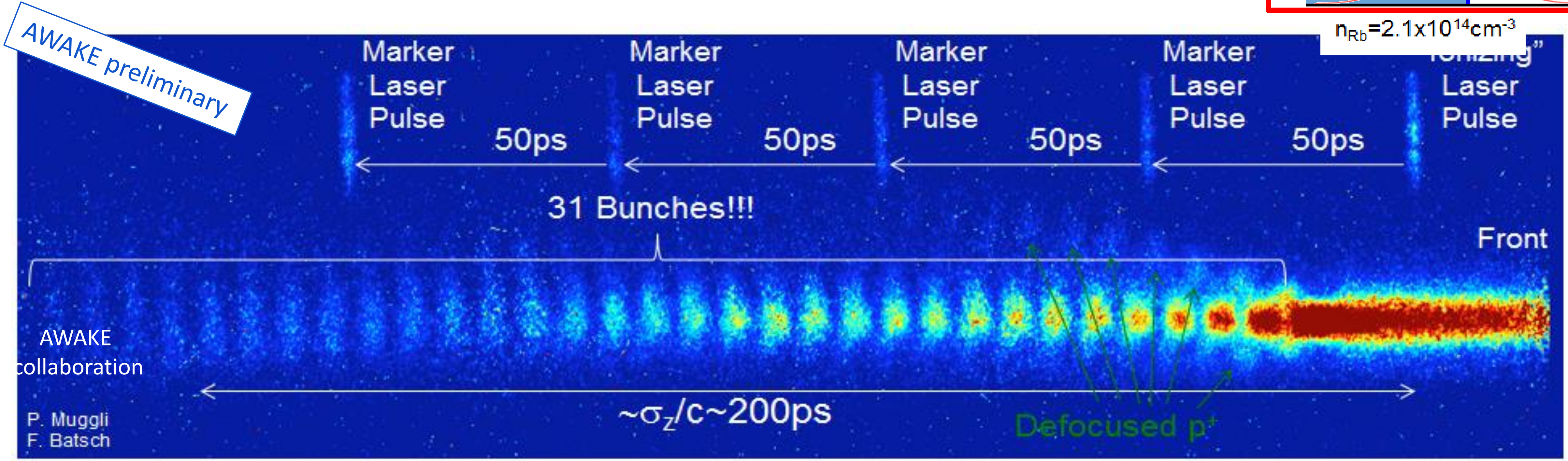
→ Time resolved measurement.



Results: Direct Seeded Self-Modulation Measurement



$n_{Rb}=2.1\times10^{14}cm^{-3}$



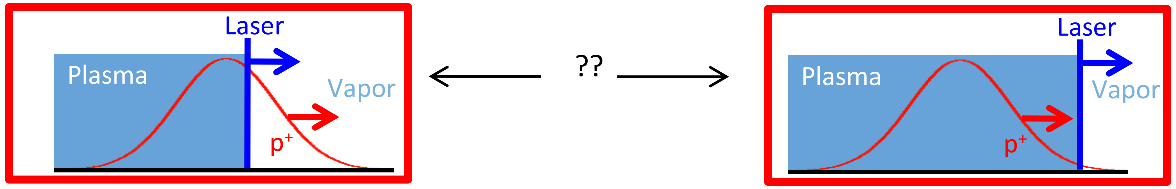
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the μ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

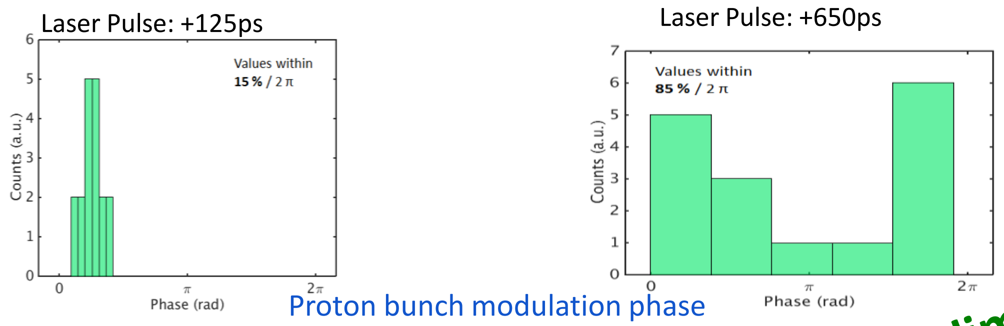
→ **1st AWAKE Milestone reached**

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

Other Studies

- Seeded Self-Modulation (not) Stability





F. Batsch

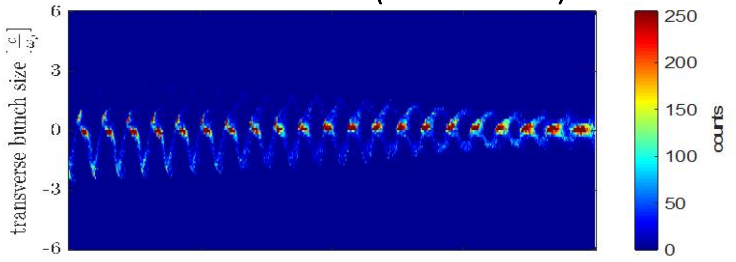
➔ Whether the phase is stable/not stable depends on the seed level

Preliminary!!!

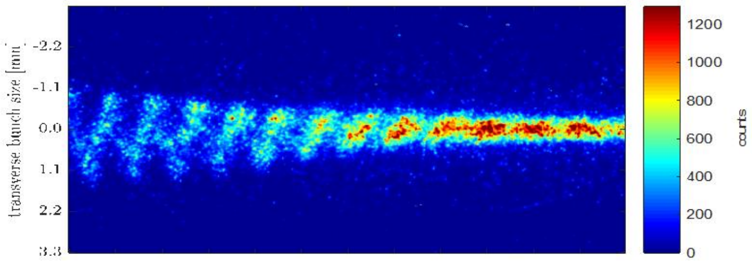
- Hosing Instability

Hosing is an asymmetric instability. → Important to understand!

Simulations: Osiris (M. Moreira)



Experiment (M. Huether)



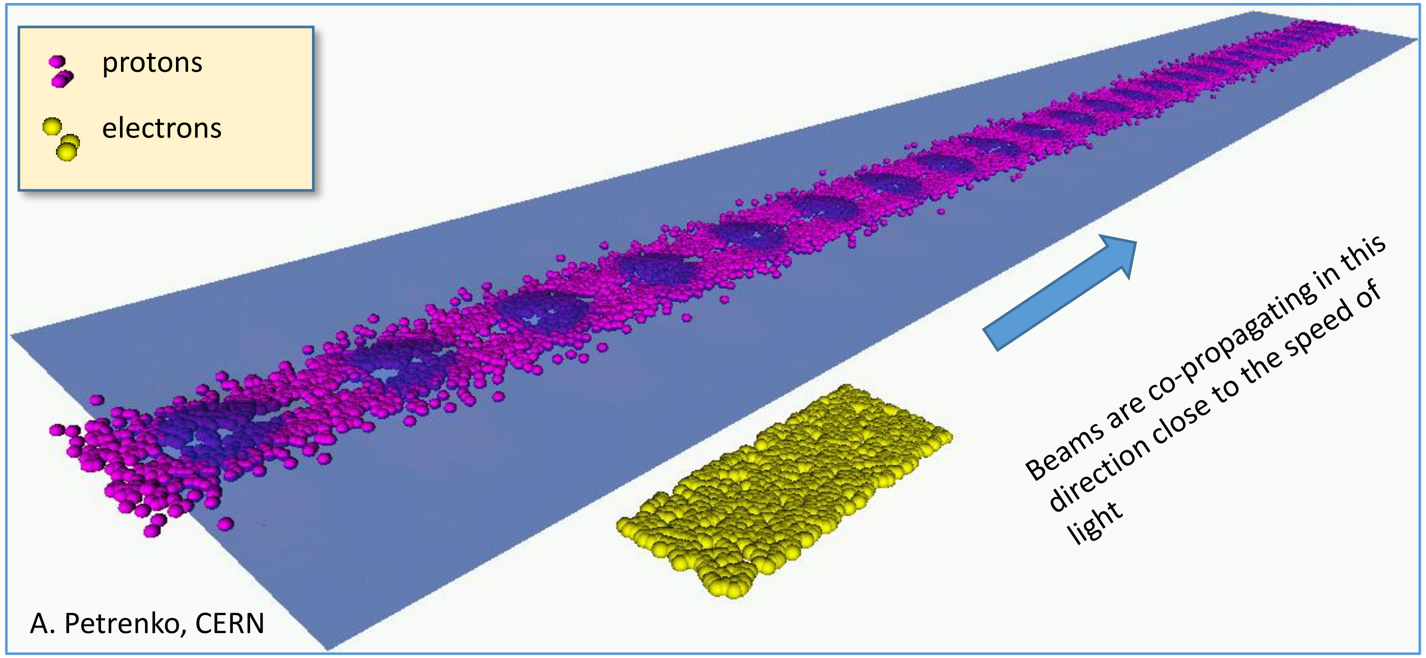
$N=1x10^{11}p^+$
$n_e=0.5x10^{14}cm^{-3}$
$\xi_{seed}=+100ps$
σ_z~190ps

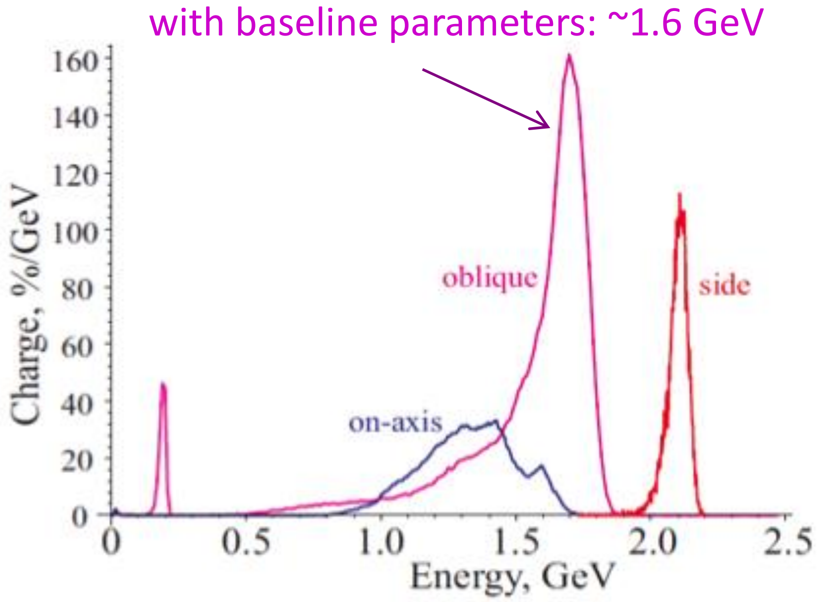
➔ Similarities in simulations and experiment
➔ Measurements show that HI appears only at low plasma density and proton bunch density.

Preliminary!!!

Electron Acceleration Results 2018

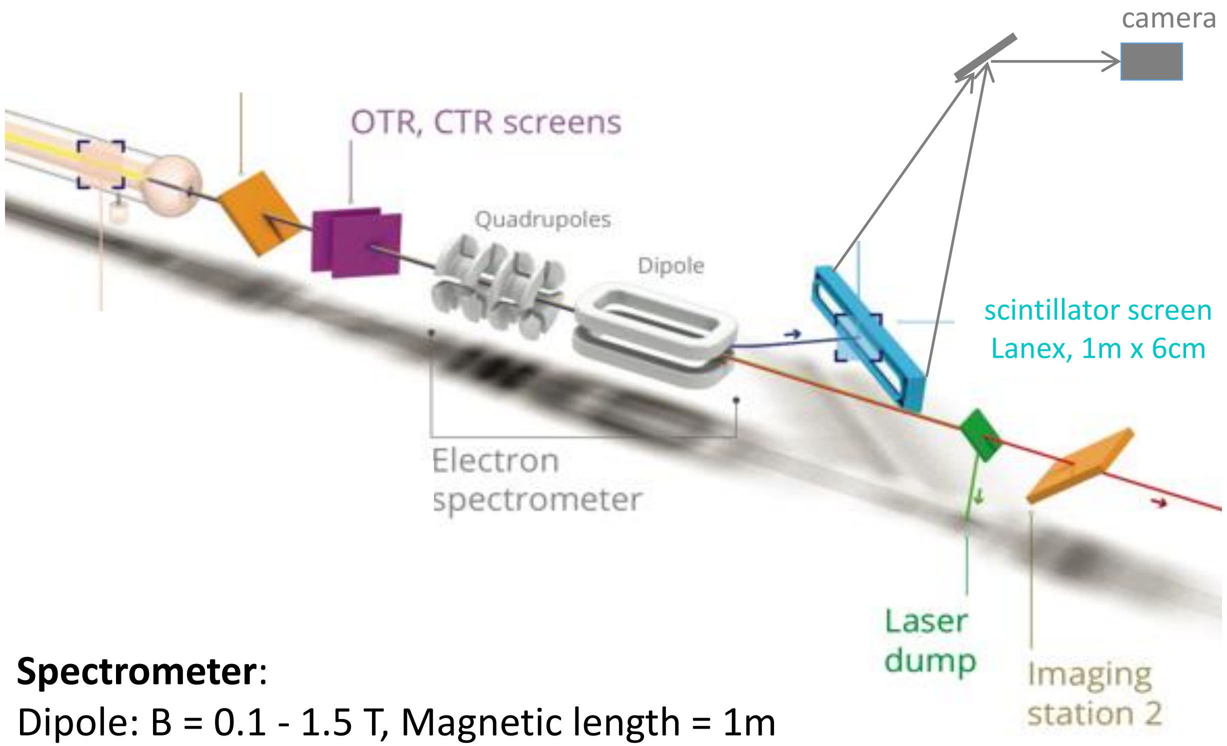
Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:





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

Electron Acceleration Diagnostics



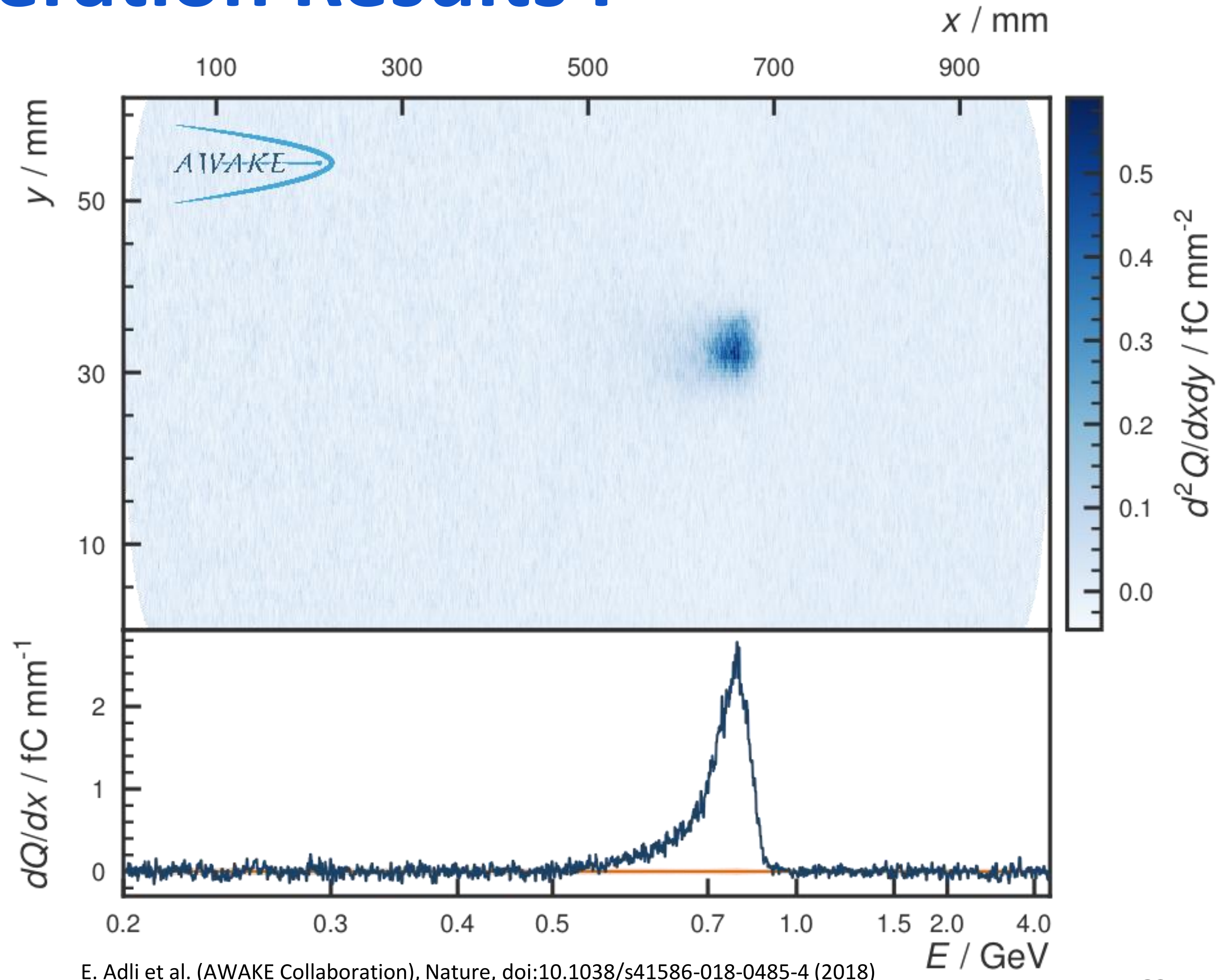
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

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 Acceleration Results I

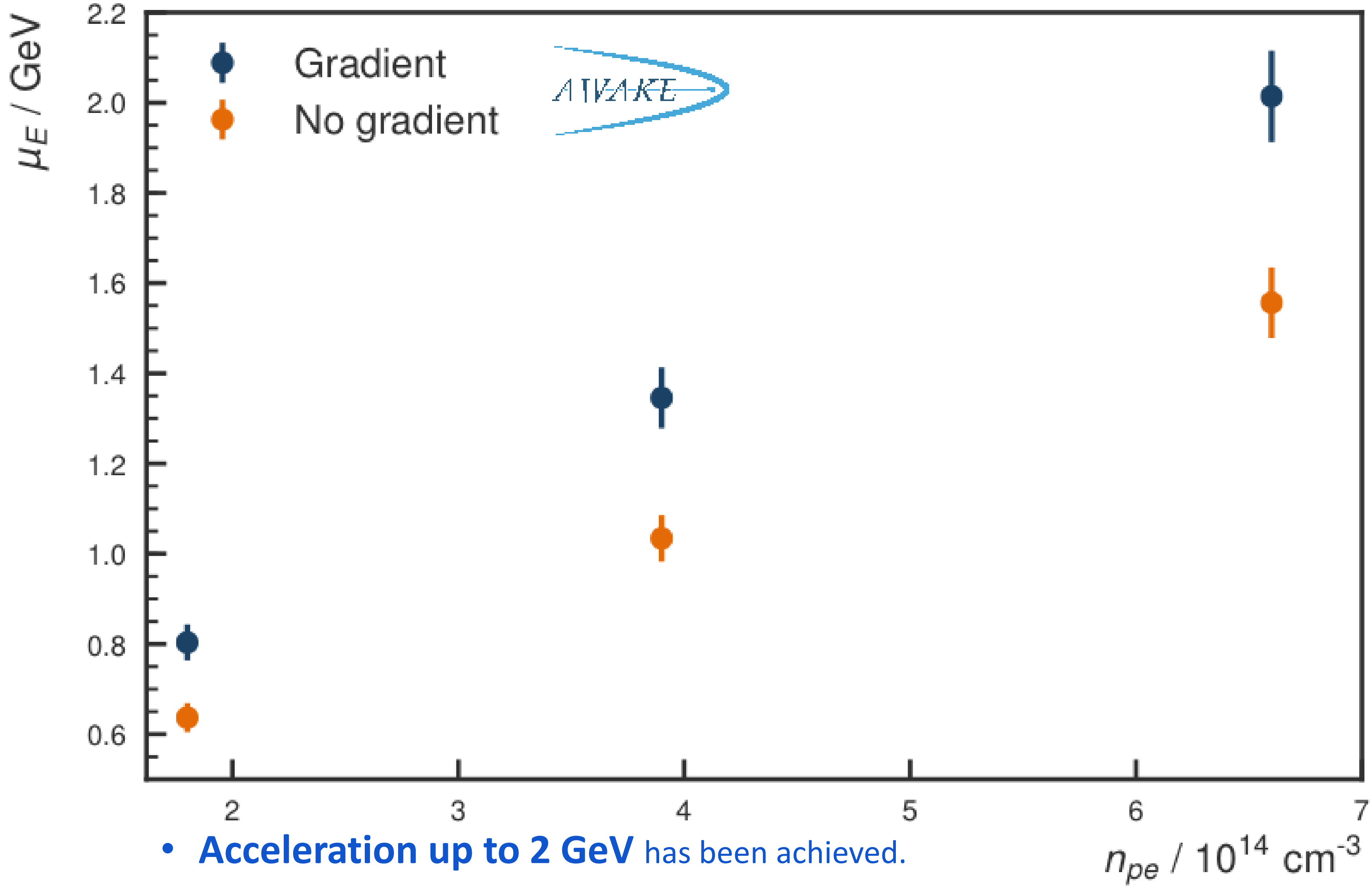
Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.

- Acceleration to **800 MeV**.



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)

Outline

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

AWAKE Run 2

Goal:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

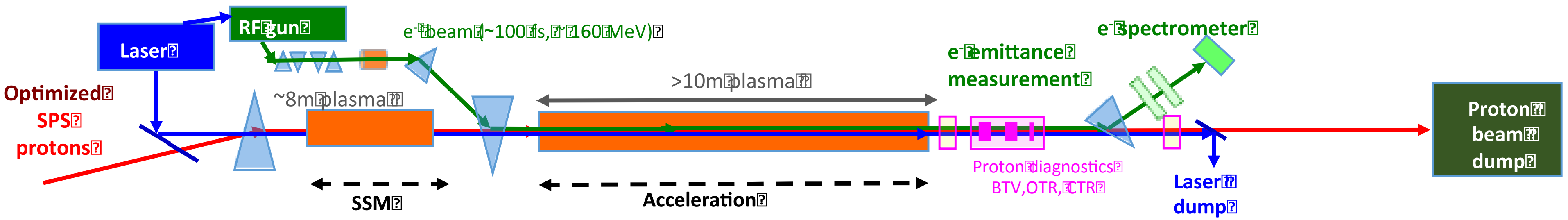
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

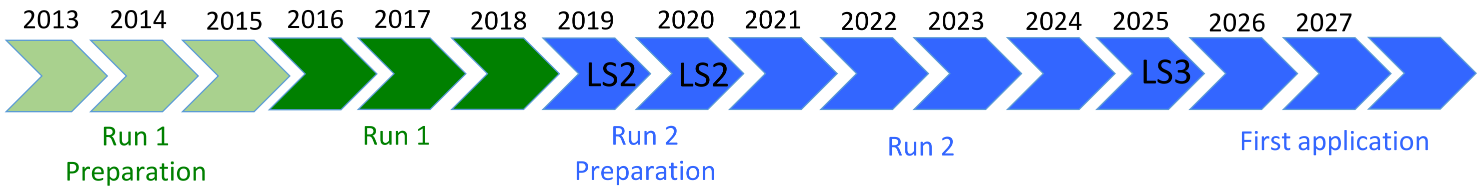
➔ Freeze the modulation with **density step** in first plasma cell

➔ For emittance control: need to work in **blow-out regime** and do **beam-loading**

➔ R&D on different **plasma source technologies**

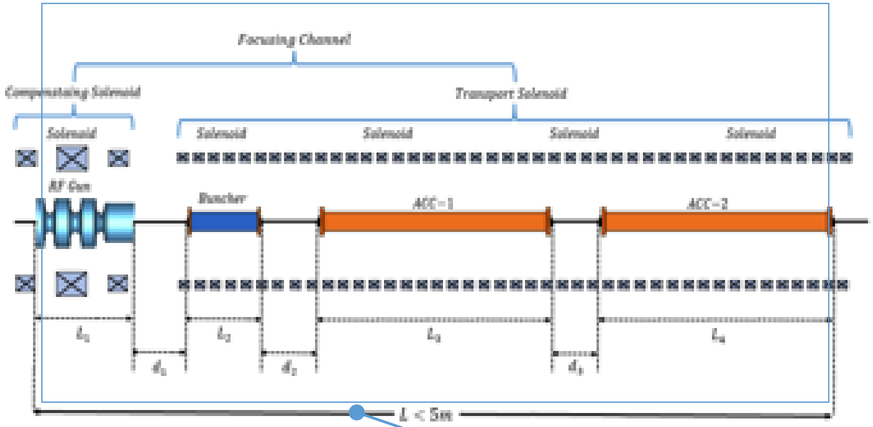


E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)



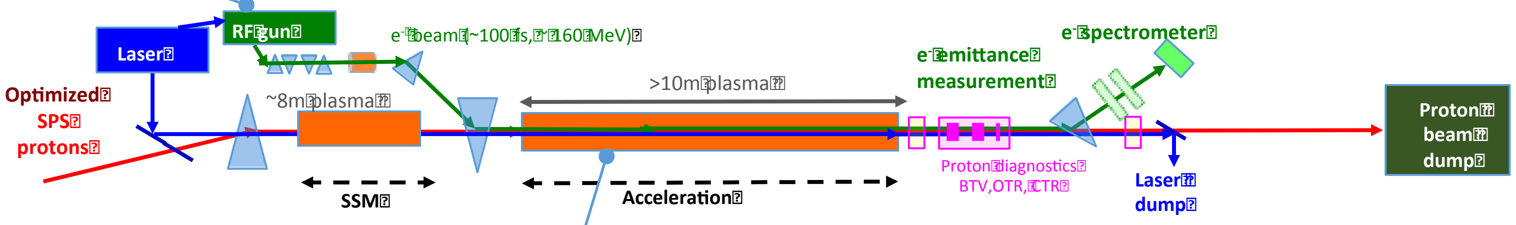
AWAKE Run 2

X-band electron source



Preliminary Run 2 electron beam parameters

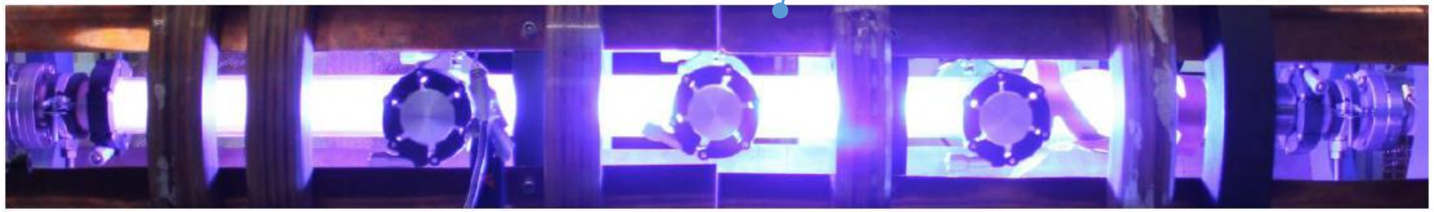
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

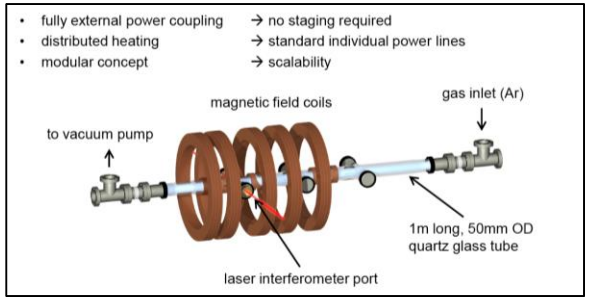


E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

Accelerating plasma cell

Helicon plasma cell





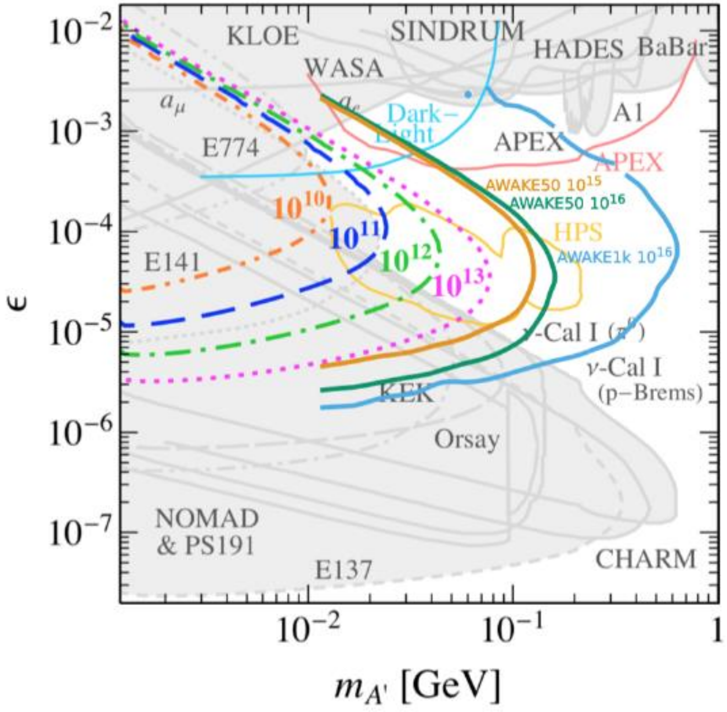
Applications with AWAKE-Like Scheme

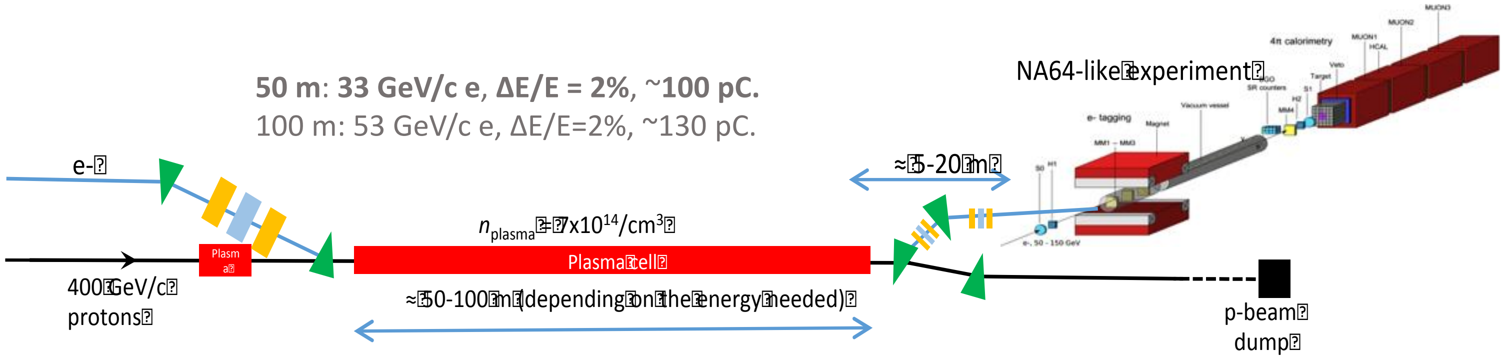
→ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application:

- → **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** (compared to NA64)
- → 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}



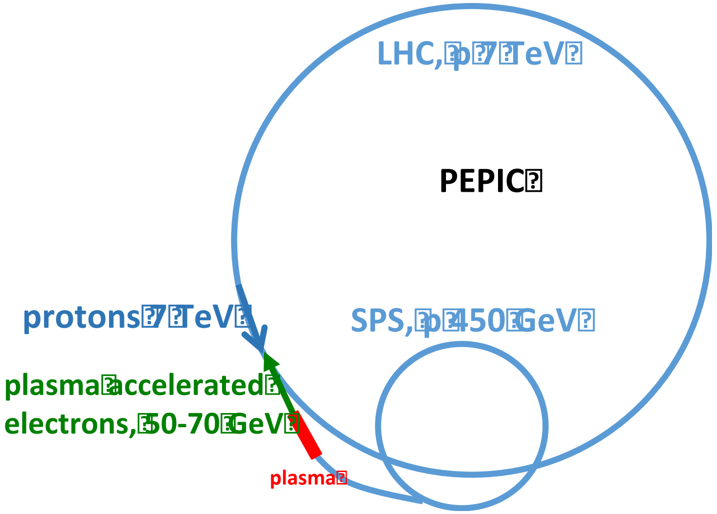


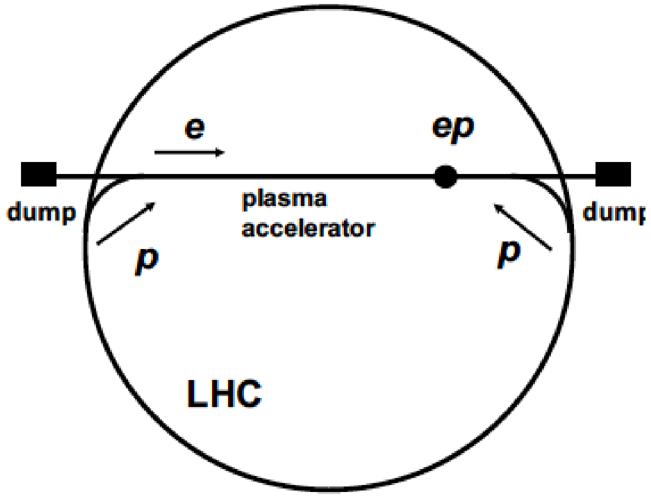
Applications with AWAKE-Like Scheme

➔ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

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
- **VHEeP:** 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}/yr.





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.

Extra slides

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	$<10^{-1}$
Staging	single, two	multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	Emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	Improvements by 10^7

Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges

Facility	Readiness	ANA technique	Specific Goal
kBELLA	Design study	LWFA	e-, 10 GeV, KHz rep rate
EuPRAXIA	Design study	LWFA or PWFA	e-, 5 GeV, reliability
AWAKE	Operating	PWFA	e^-/p^+ collider
FACET II	Start 2019	PWFA	e^-, 10 GeV boost, beam quality, e^+ acceleration
Flash FWD	Operating	PWFA	e-, 1.5 GeV, beam quality