AWAKE

Austrian Teacher Programme
11 November, 2022

Edda Gschwendtner, CERN

Plasma Wakefield Acceleration and AWAKE

AWAKE:

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

“Plasma Kielfeld Beschleunigungsexperiment, angetrieben durch einen Protonenstrahl”

→Plasma???
→Kielfeld Beschleunigung???
→Angetrieben durch einen Protonenstrahl???

Und ueberhaupt: → **Warum???**

Why?

We need huge accelerators…

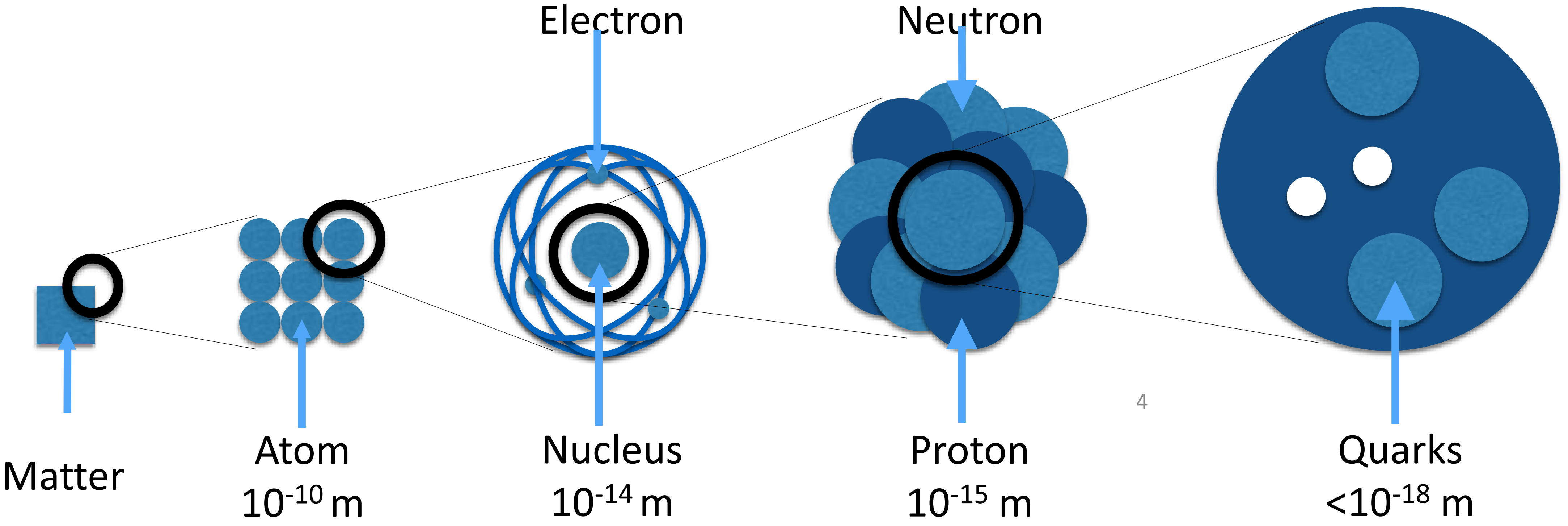
… to study the smallest building blocks of matter
… to study the origin of the Universe

Higher particle energy → smaller wavelength → smaller structures

Accelerators are Super-Microscopes !

What is Matter?

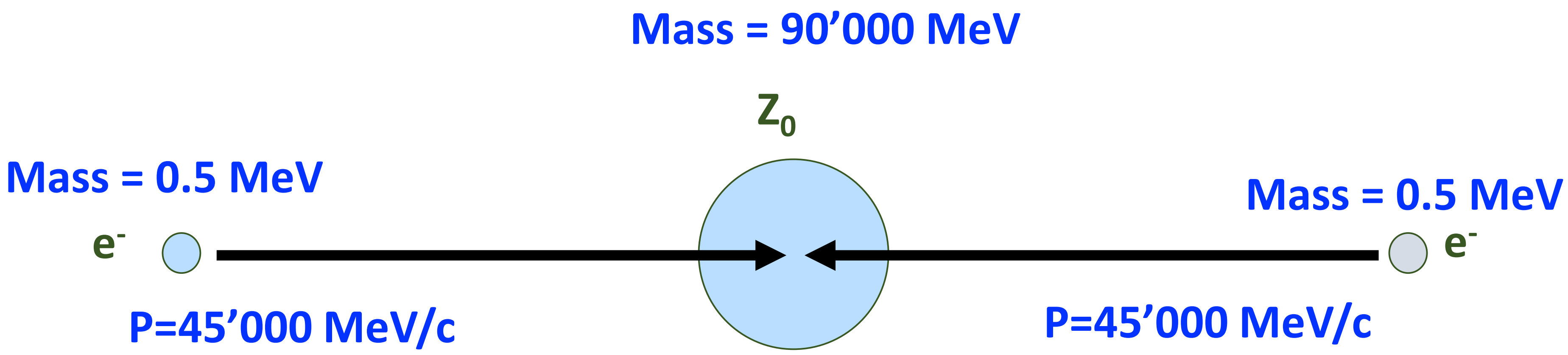
Optical Microscope: 10^{-6} m
Radioactive Source: 10^{-14} m
LHC: $<10^{-21}$ m



Particle Collisions and New Particles

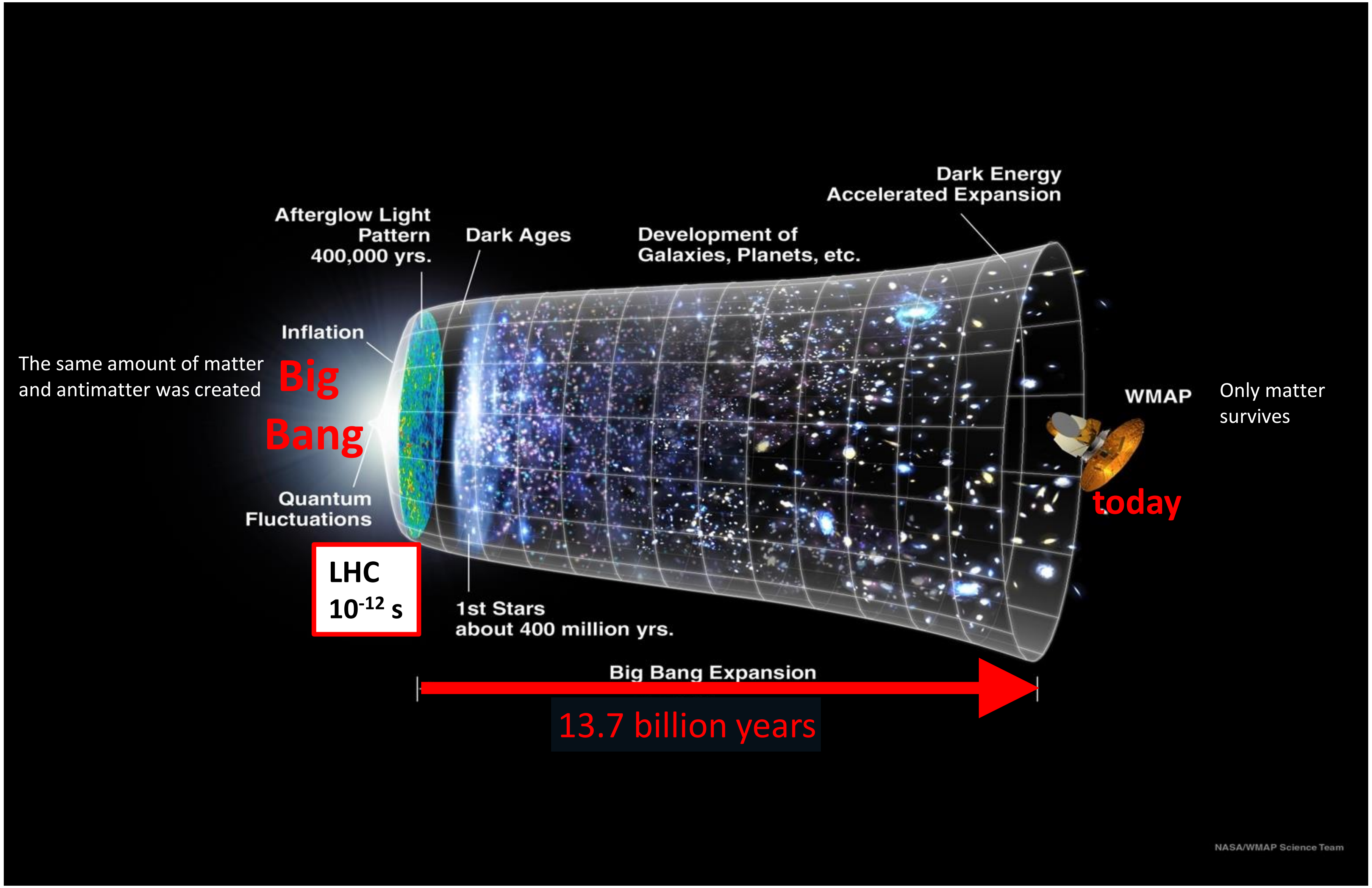
The study of the smallest building blocks of matter with high energy particle colliders and the production of new massive particles is connected:

$$E = mc^2$$



Higgs Boson Discovery at the LHC in 2012
Nobel Prize in 2013

What is the Origin of the Universe?

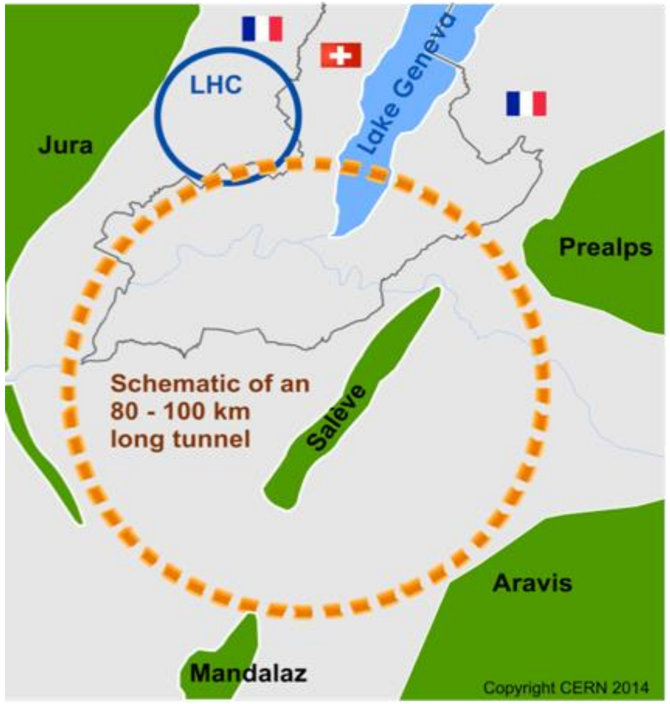


Discover New Physics

→ Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

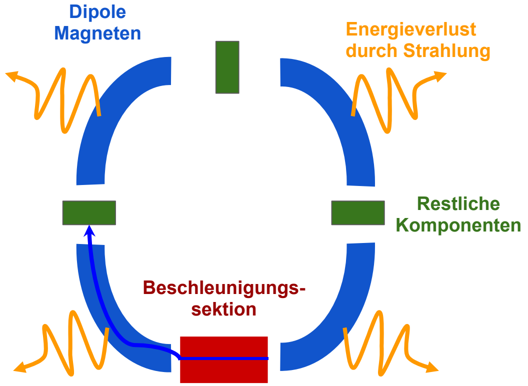
Future Circular Collider: FCC



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**.

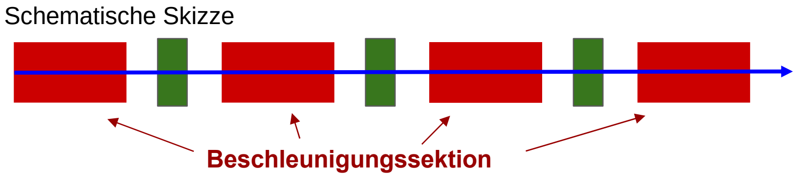
$$P_{synchr} = \frac{e^2}{6\pi\varepsilon_0 c^7}\frac{E^4}{R^2 m^4}$$



Discover New Physics

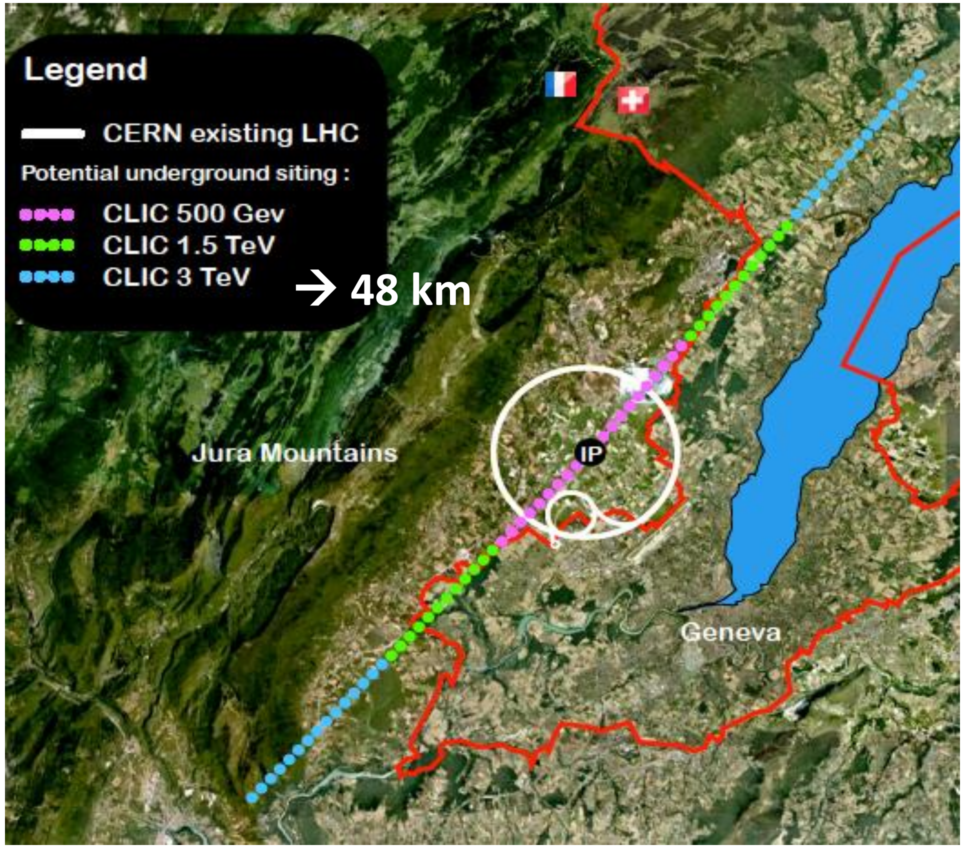
Linear colliders are favorable for acceleration of low mass particles to high energies.

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.

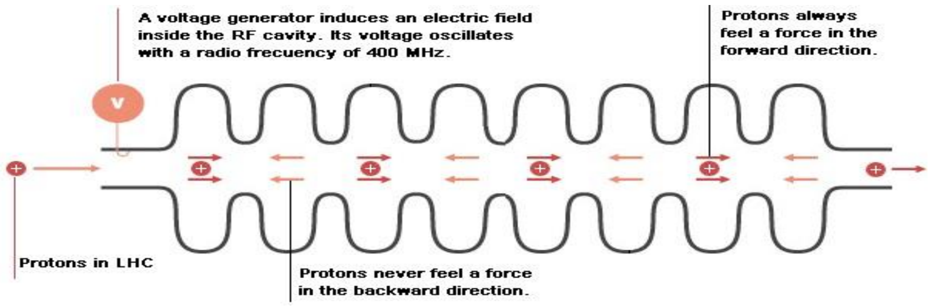


Teilchenenergie = Beschleunigungsgradient*Beschleunigungsdistanz

zB. um Elektronen auf 1 TeV zu beschleunigen (10^{12} eV):
100 MeV/m x 10000 m oder
100 GeV/m x 10 m

→ *Warum!*

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity

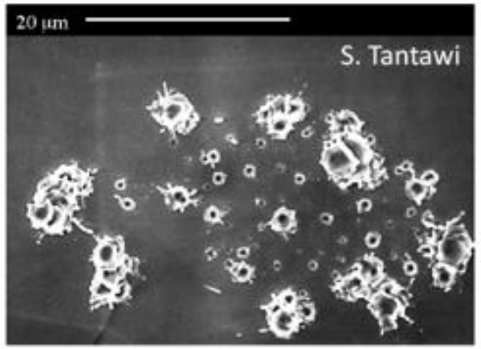
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

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

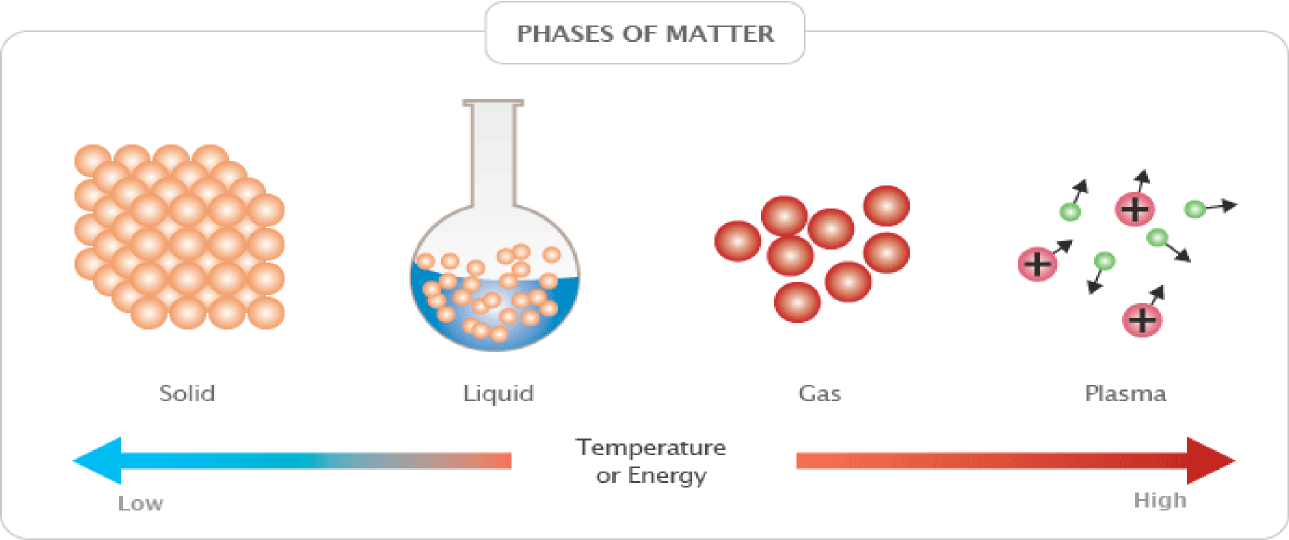
In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge.
Fields cannot be sustained, structures might be damaged.

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

Surface of Copper Cell After Breakdown Events



Plasma Wakefield Acceleration



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.**
→ ~1000 factor stronger acceleration!

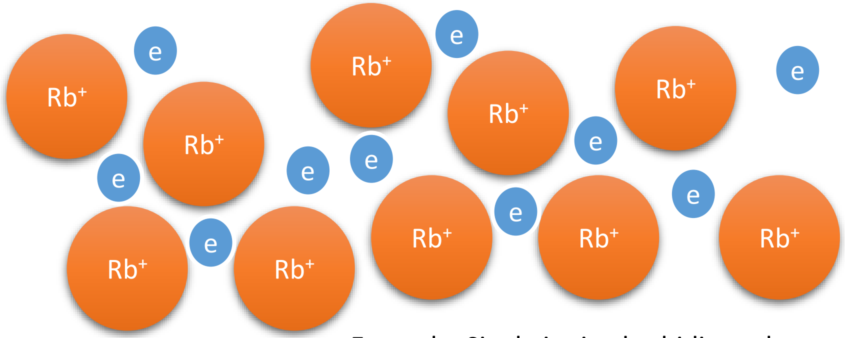
→ *Plasma!*

→ Use plasma as accelerating 'cavity'

→ Much shorter linear colliders

Plasma Wakefield

What is a plasma?



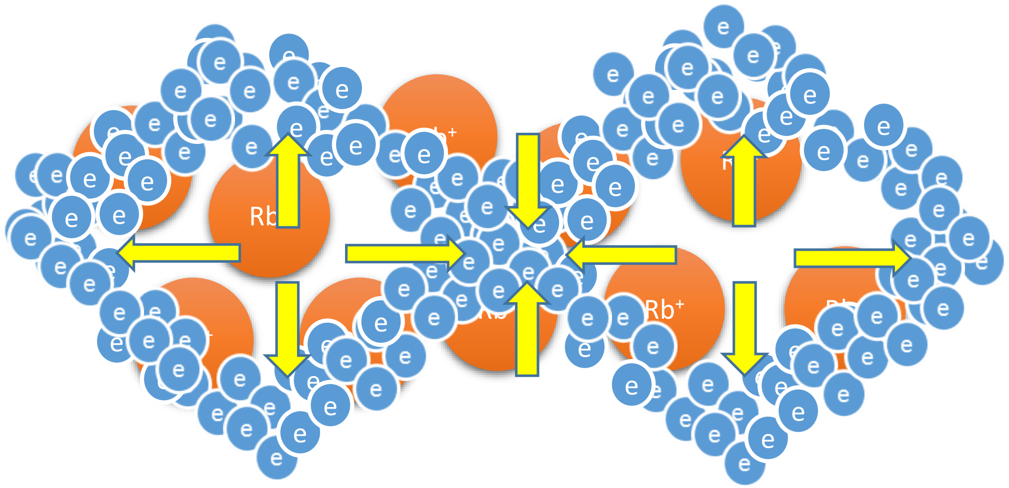
Example: Single ionized rubidium plasma

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.

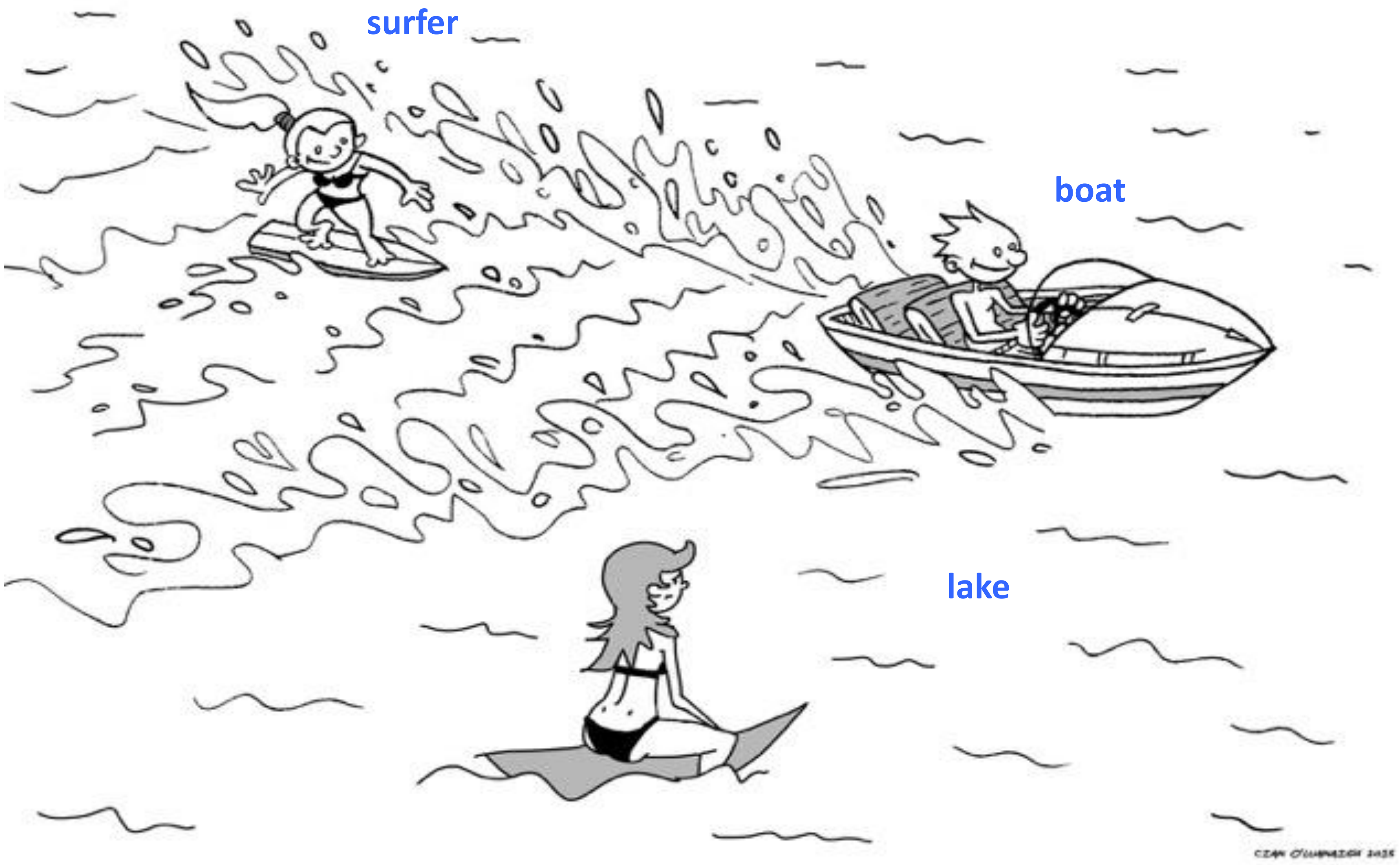
Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



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

How to Create a Plasma Wakefield?



Analogy:
lake → plasma

Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

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

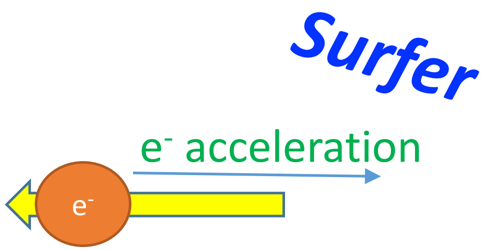
Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment

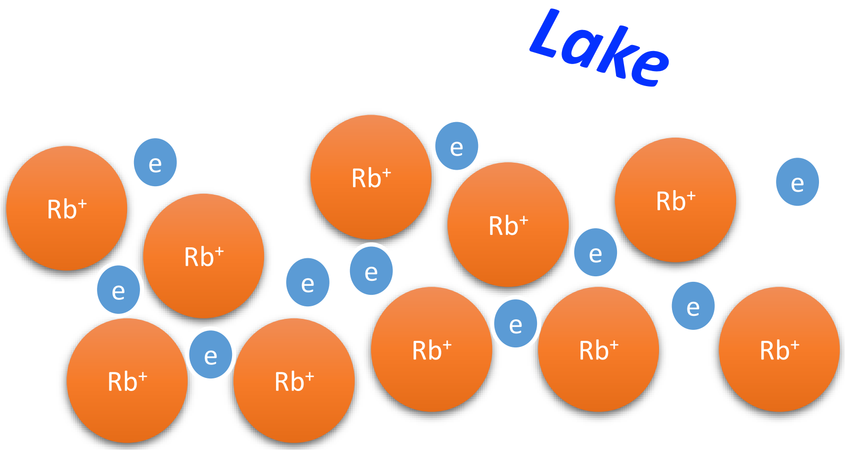
How to Create a Plasma Wakefield?

What we want:

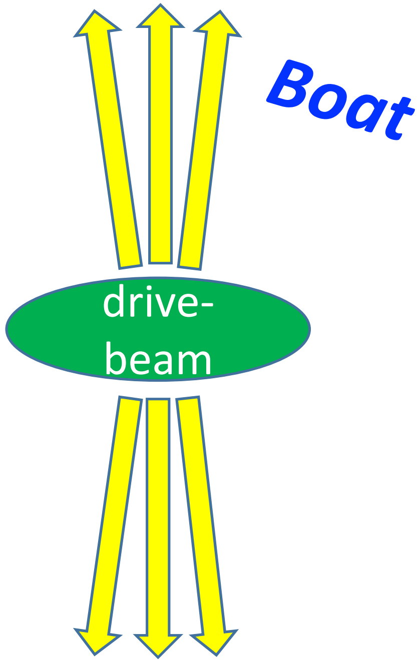
Longitudinal electric field to accelerate charged particles.



Our Tool:



Single ionized rubidium **plasma**



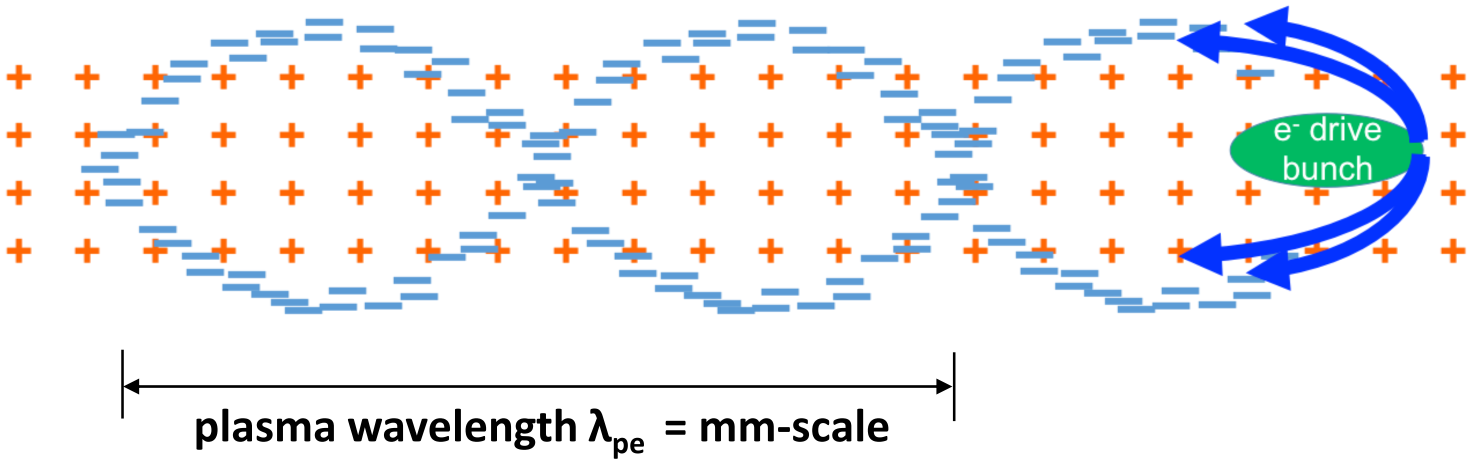
Charged particle bunches carry almost purely transverse Electric Fields.

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.

Principle of Plasma Wakefield Acceleration

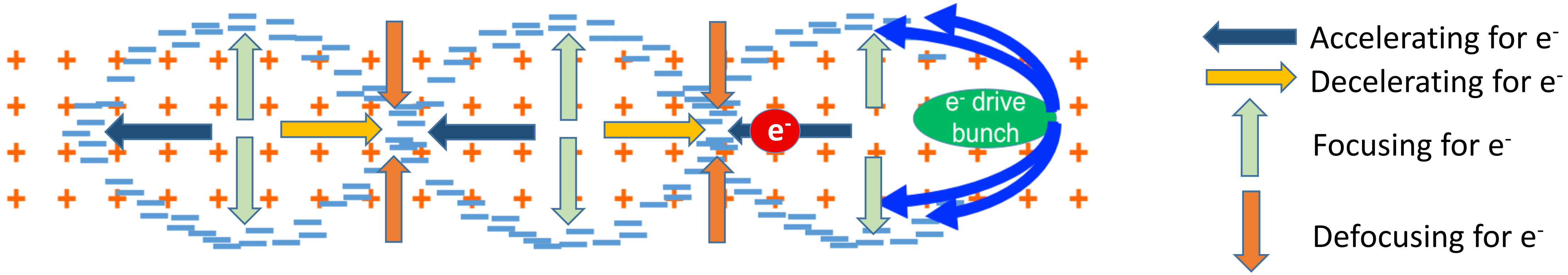
Boat:

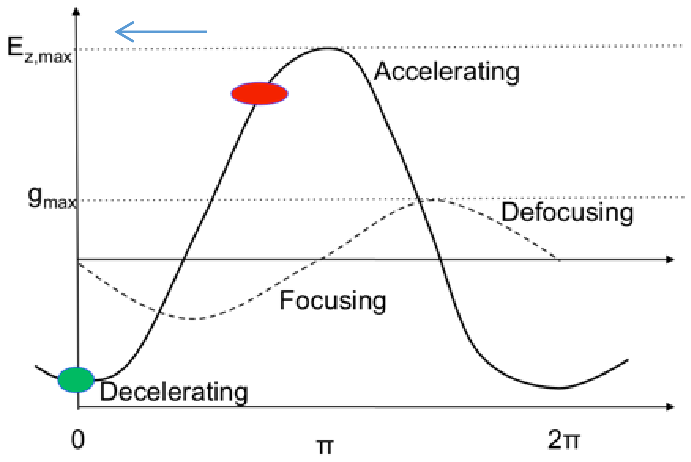
- Laser drive beam
- Charged particle drive beam



- 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)?





➔ *Kielfeld Beschleunigung!*

E. Gschwendtner, CERN

Why Protons?
Energy Budget for High Energy Plasma Wakefield Accelerators

Witness beams (Surfers):

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

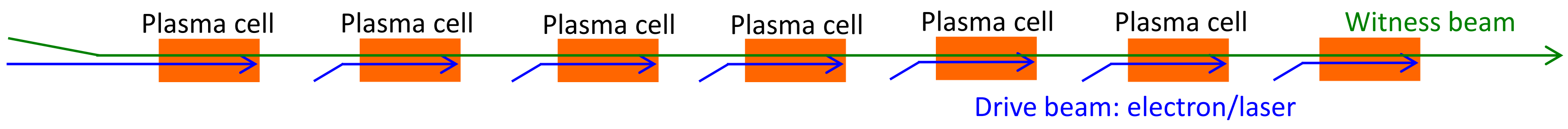
Drive beams (Boat):

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

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….



Why Protons?
Energy Budget for High Energy Plasma Wakefield Accelerators

Witness beams (Surfers):

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Drive beams (Boat):

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

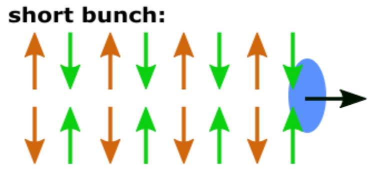
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

To reach TeV scale:

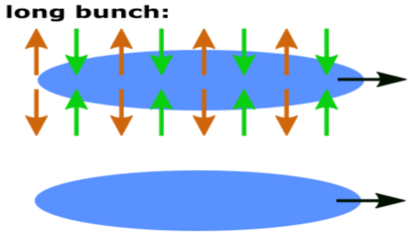
- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

Seeded Self-Modulation of the Proton Beam

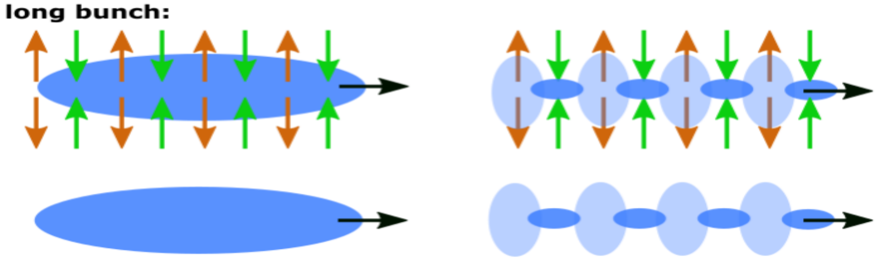
In order to create plasma wakefields efficiently, the drive bunch length must be in the order of the plasma wavelength.



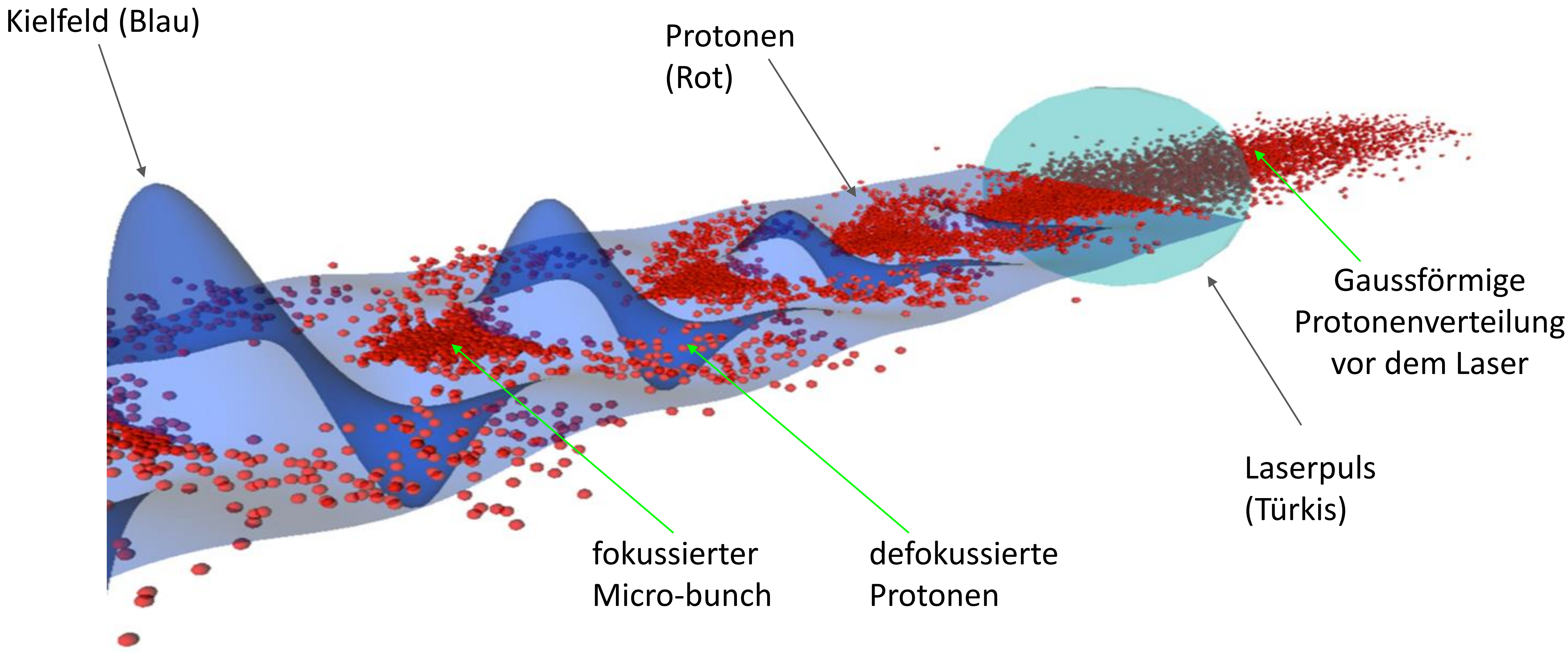
CERN SPS proton bunch: very long! (σ_z **= 12 cm**) → much longer than plasma wavelength (λ **= 1mm**)



The experiment induces a plasma instability, this instability modulates the long proton beam into a sequence of short beams (micro-bunches).



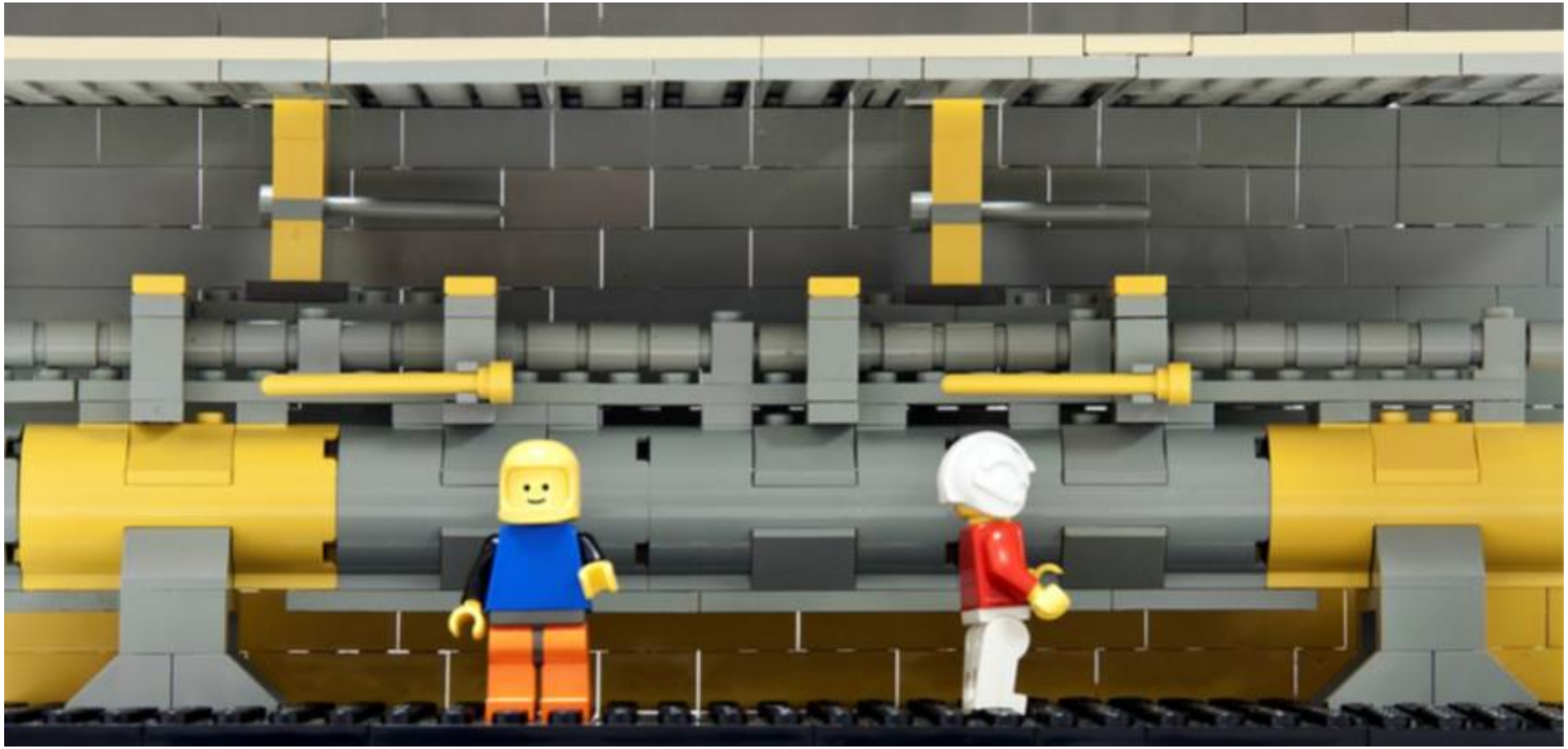
Simulationsergebnis



➔ **_Angetrieben durch einen Protonenstrahl!_**

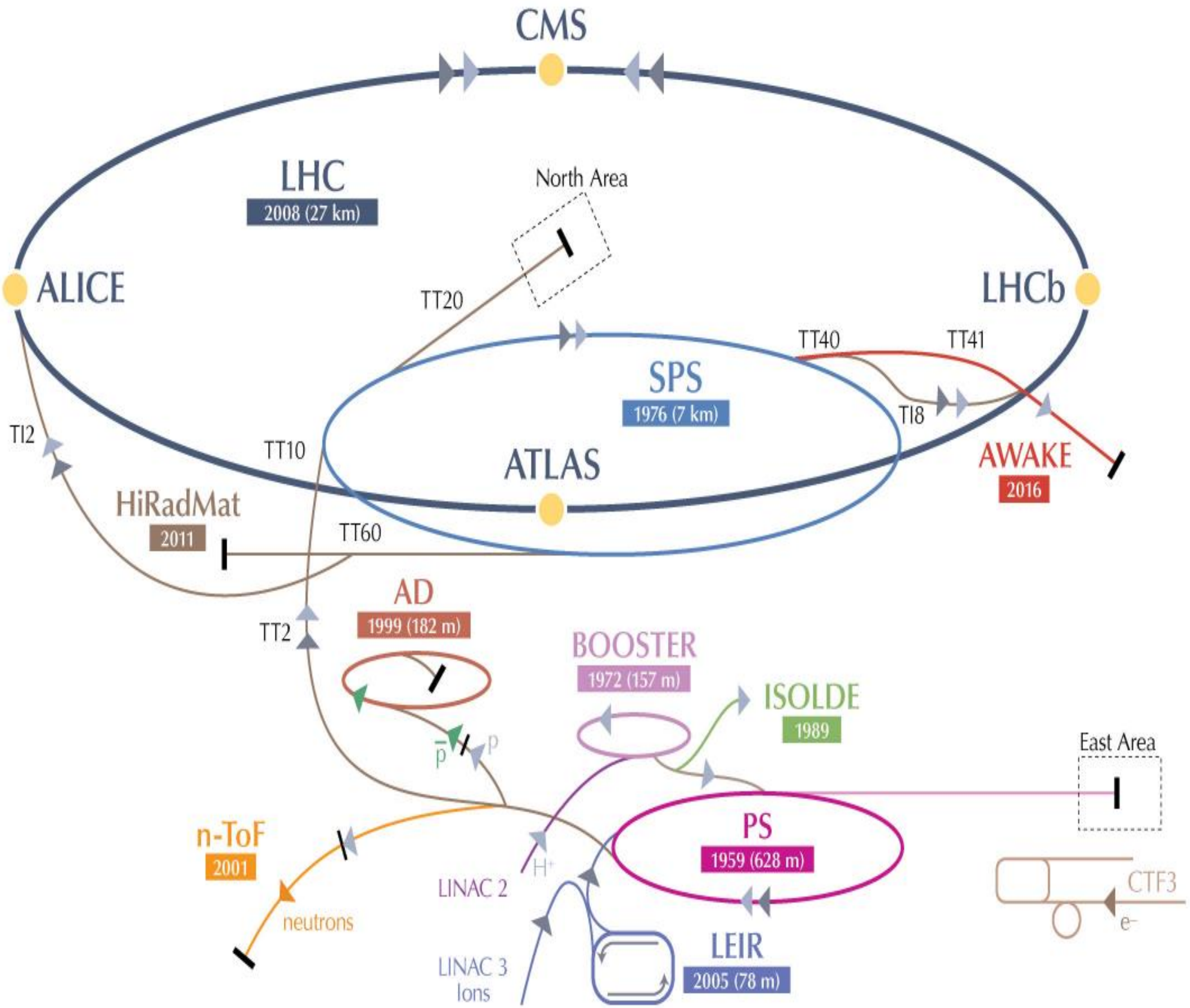
The AWAKE Experiment

Experimenteller Aufbau des AWAKE Experiments am CERN



Von einer Idee zur Realität!

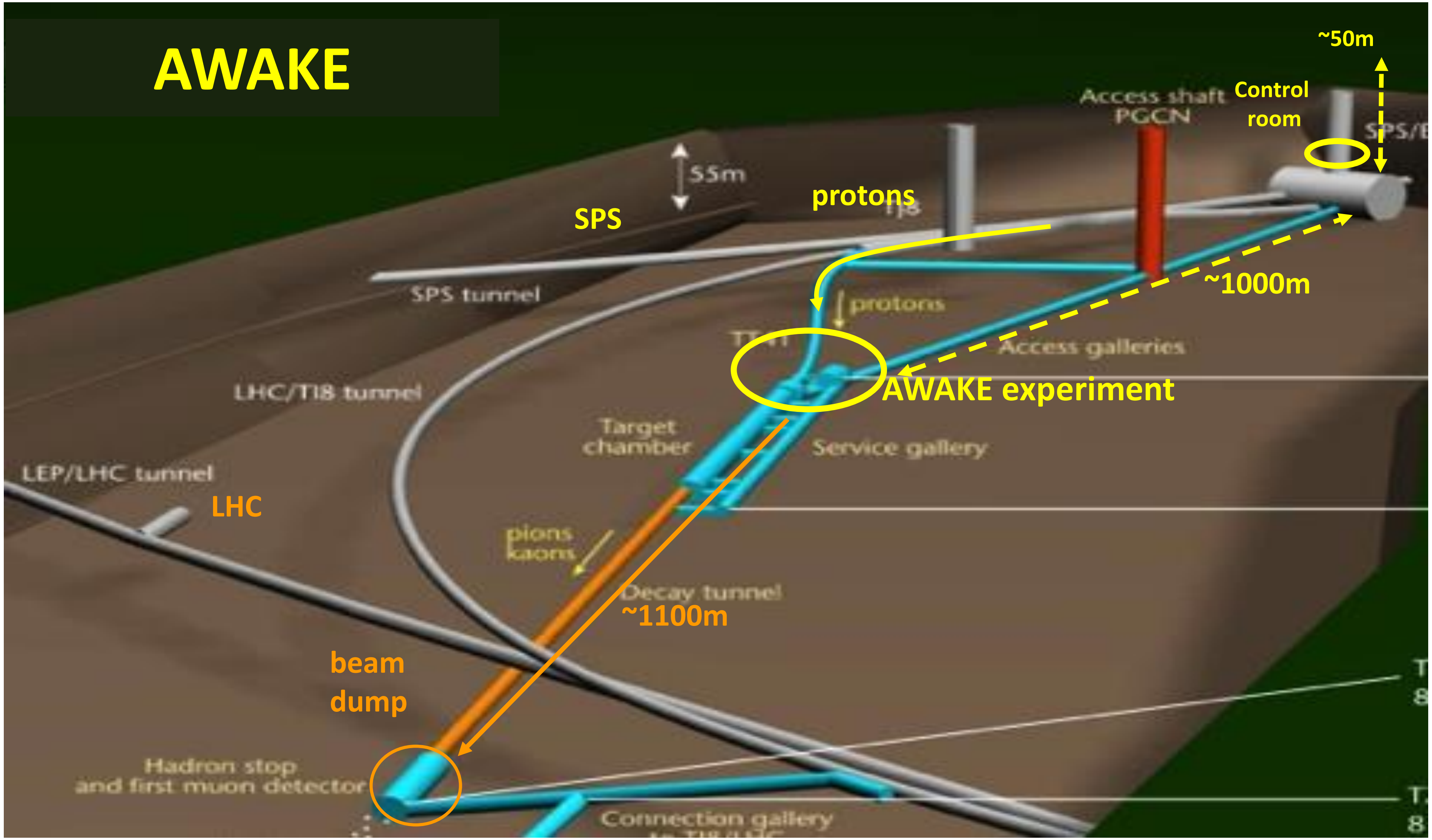
AWAKE at CERN



Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Collaboration of 23 institutes world-wide
- Approved in August 2013

AWAKE at CERN

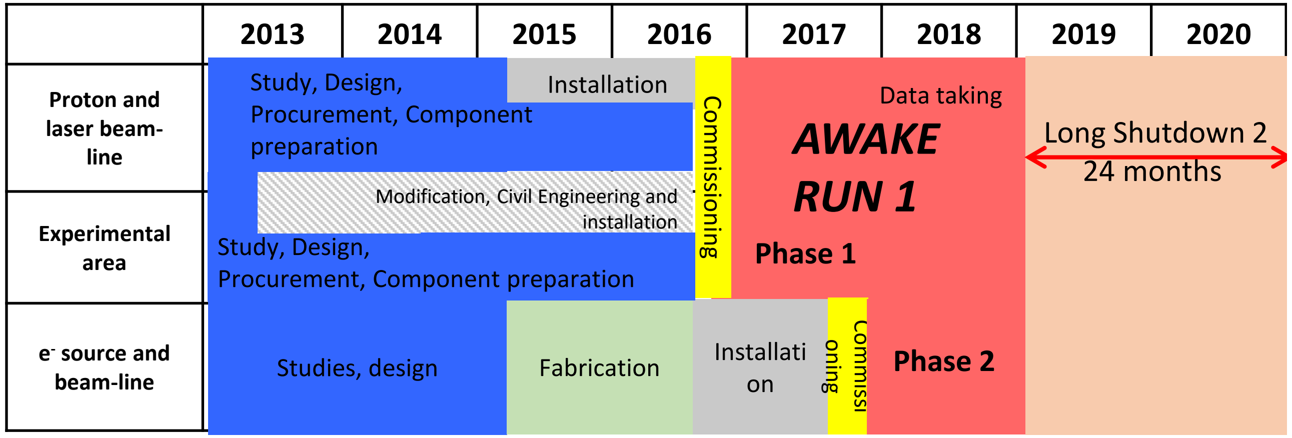


AWAKE installed in CERN underground area

AWAKE Collaboration: 23 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
- Uppsala University, Sweden
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

AWAKE Timeline



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

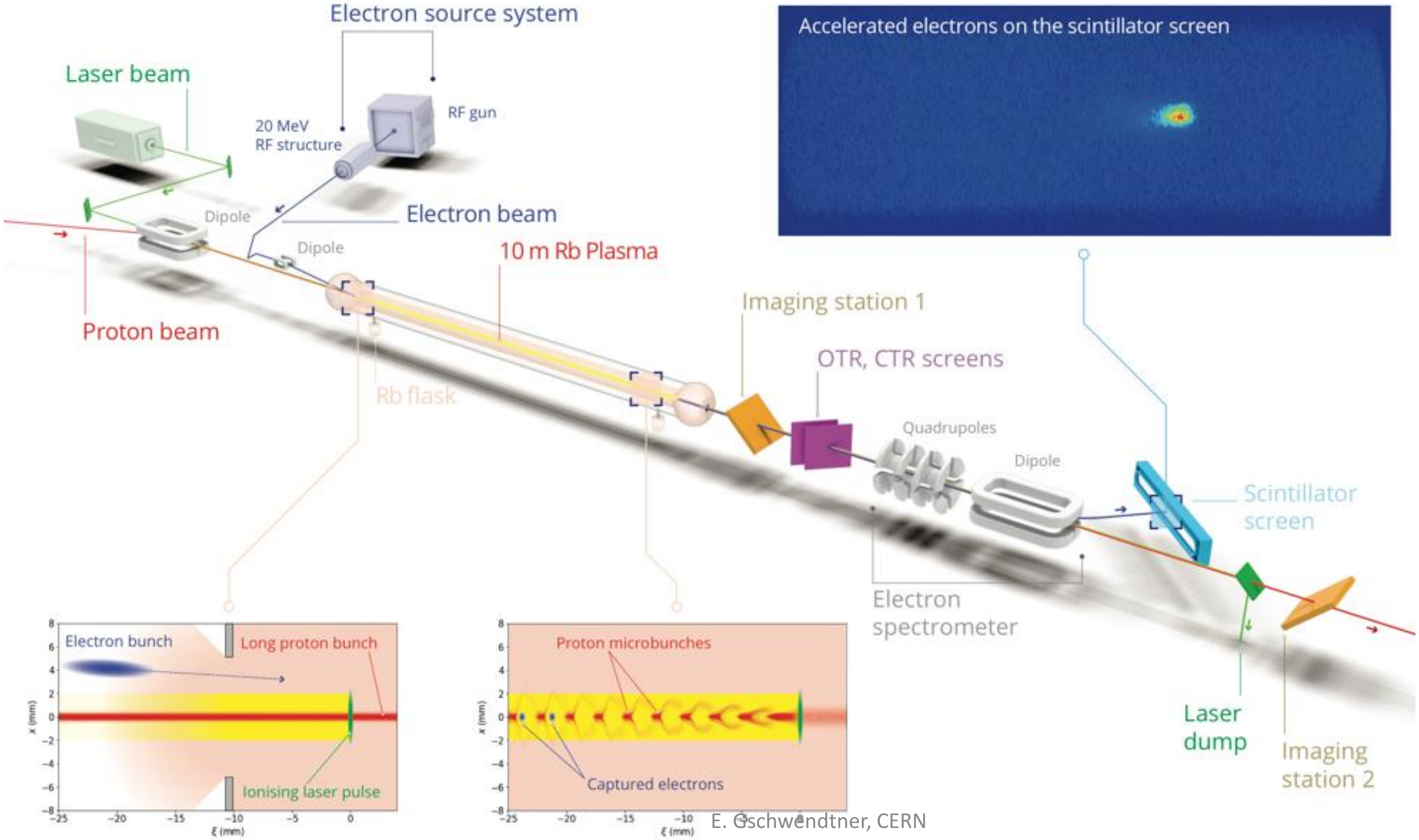
AWAKE Timeline

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

AWAKE Run 2: 'Accelerator':
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

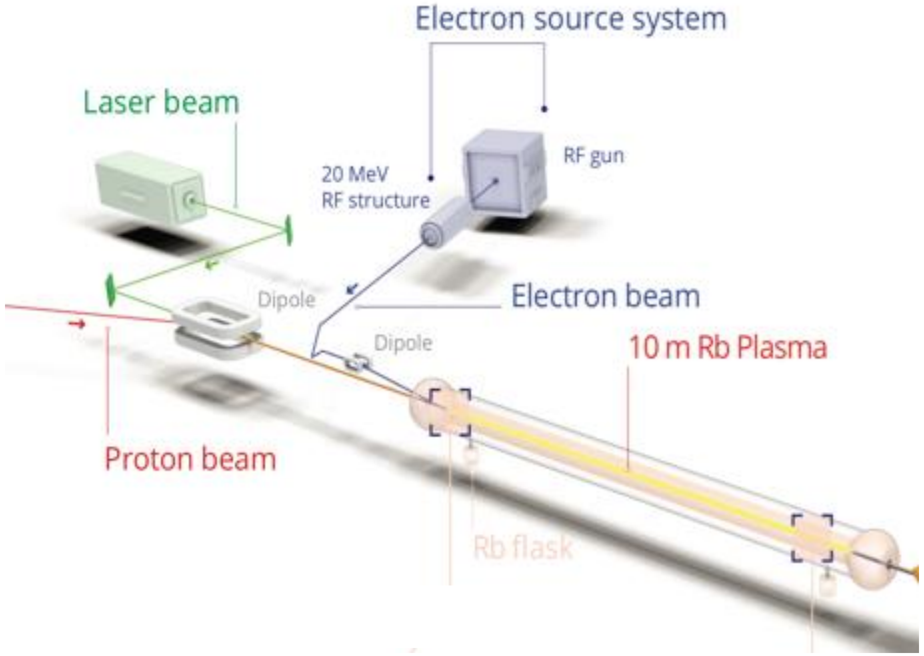
AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

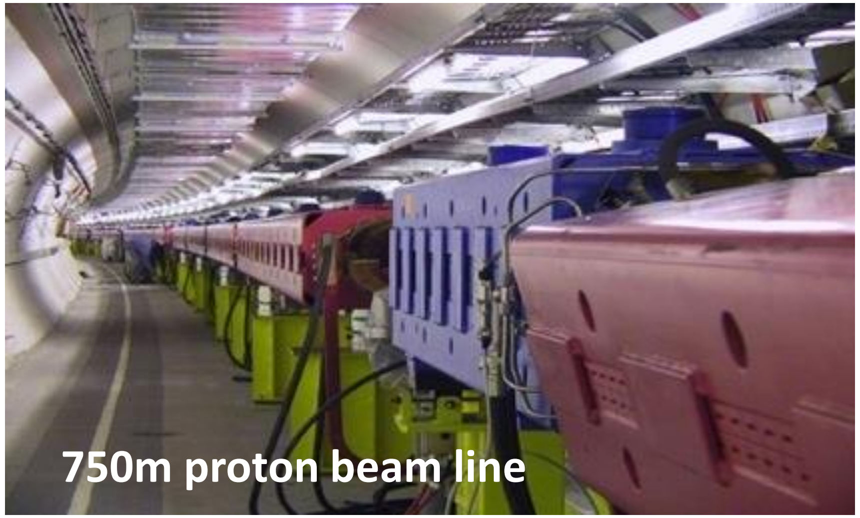


AWAKE Proton Beam Line

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**
$k_{pe} = \omega_{pe}/c = 5\ \mathrm{mm}^{-1}$
➔ $\mathbf{n_{pe} = 7\times10^{14}\ cm^{-3}}$

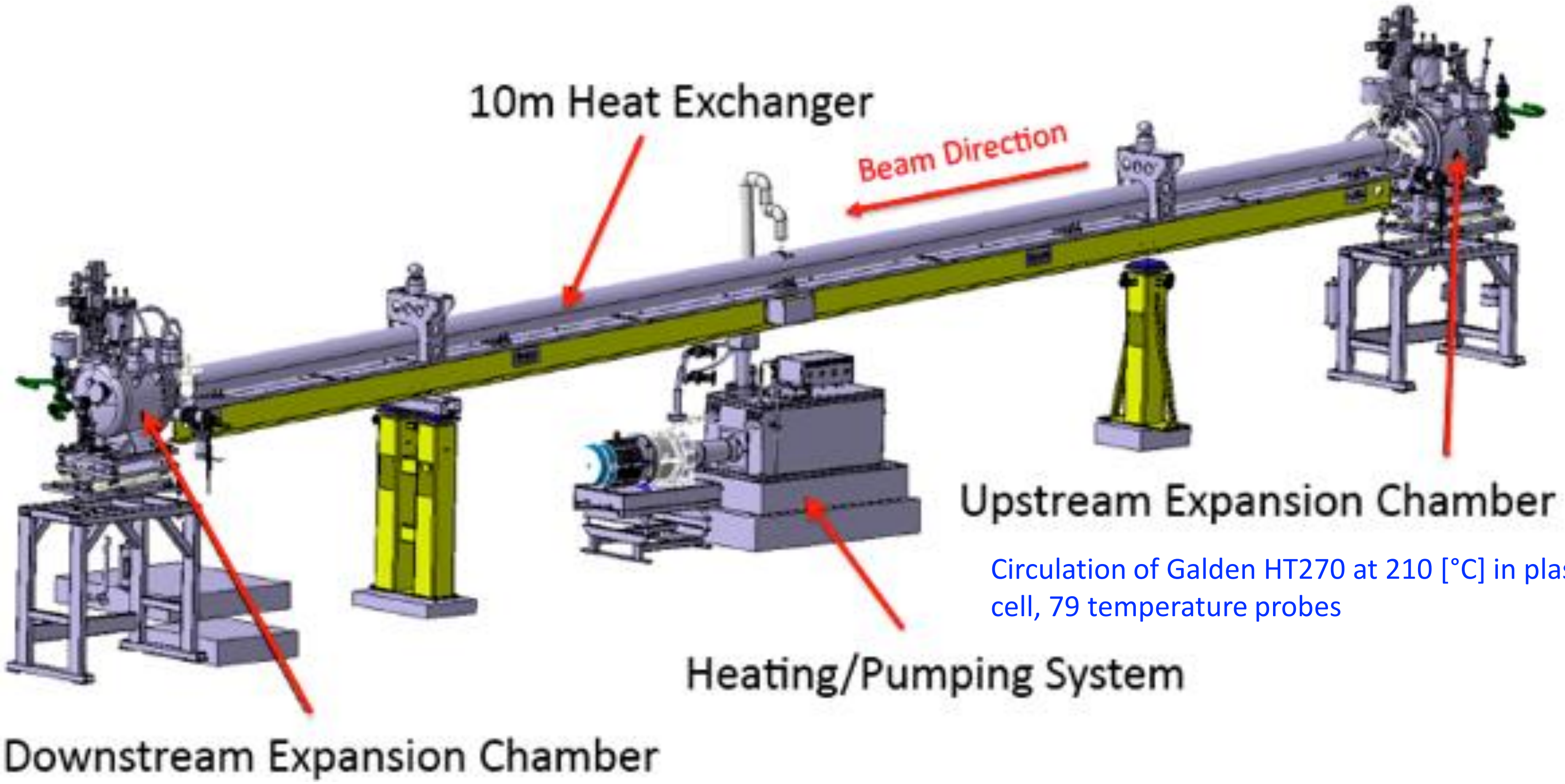



750m proton beam line

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.

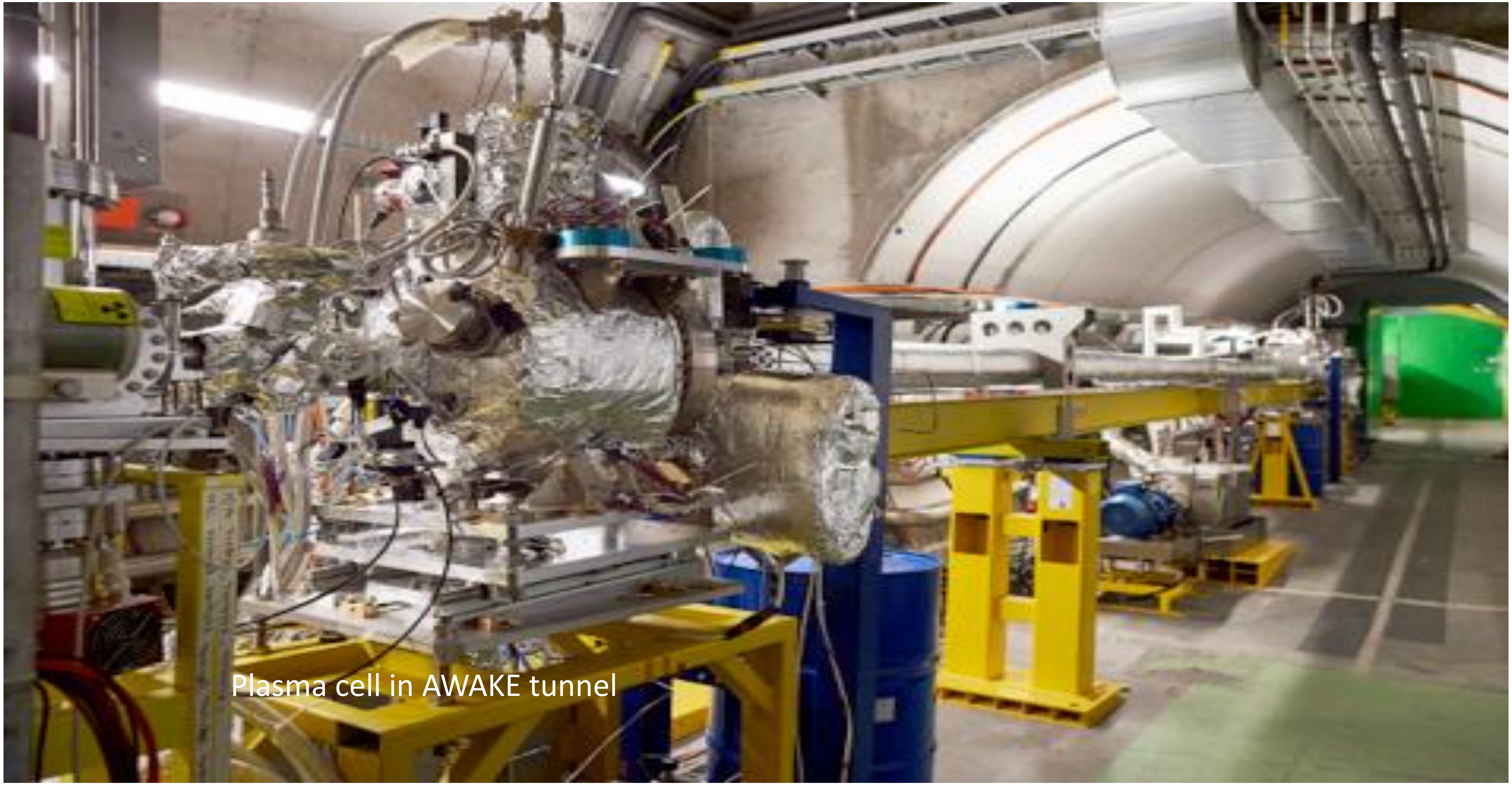
AWAKE Plasma Cell

- **10 m long**, 4 cm diameter **Rubidium** vapour source
- **Laser** ionizes Rb vapour to become Rb plasma.
- Density adjustable from $10^{14} - 10^{15}$ cm^{-3} ➔ desired: 7x 10^{14} cm^{-3}



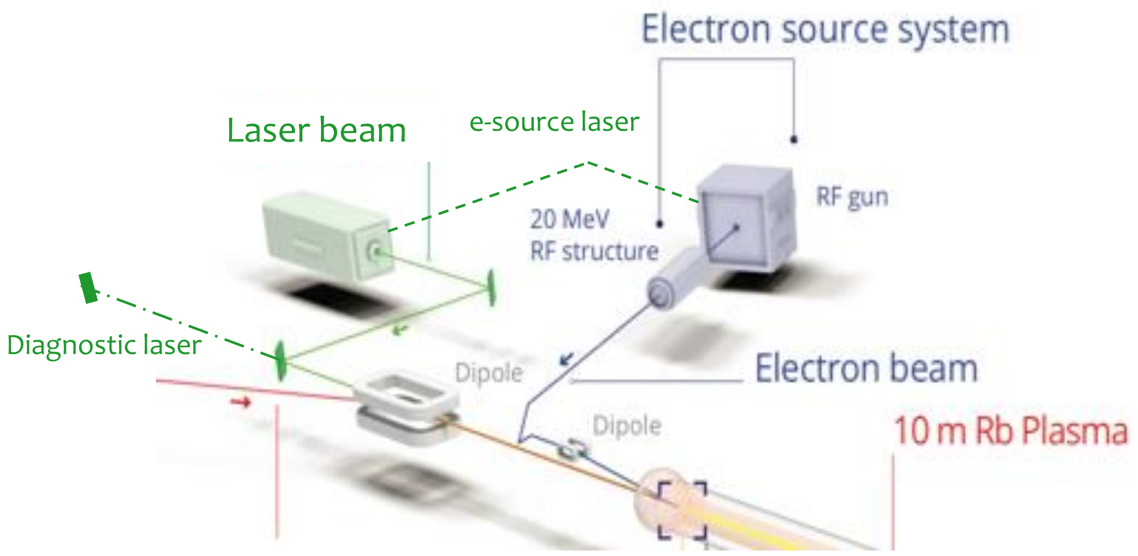
Circulation of Galden HT270 at 210 [°C] in plasma cell, 79 temperature probes

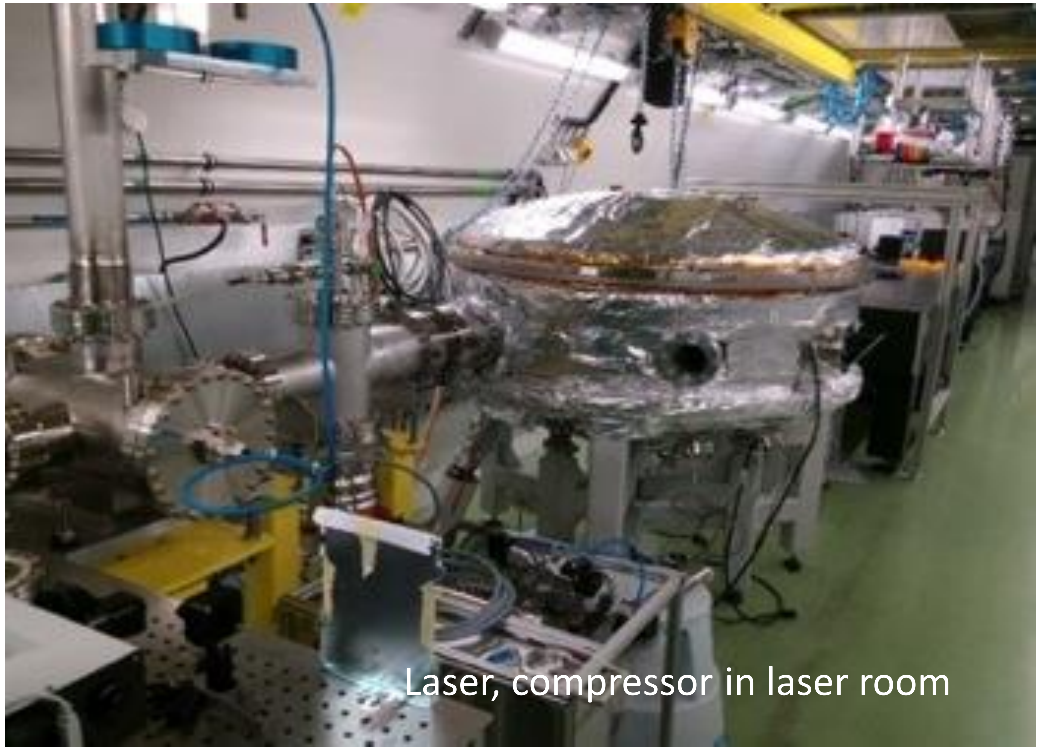
AWAKE Plasma Cell



Laser and Laser Line

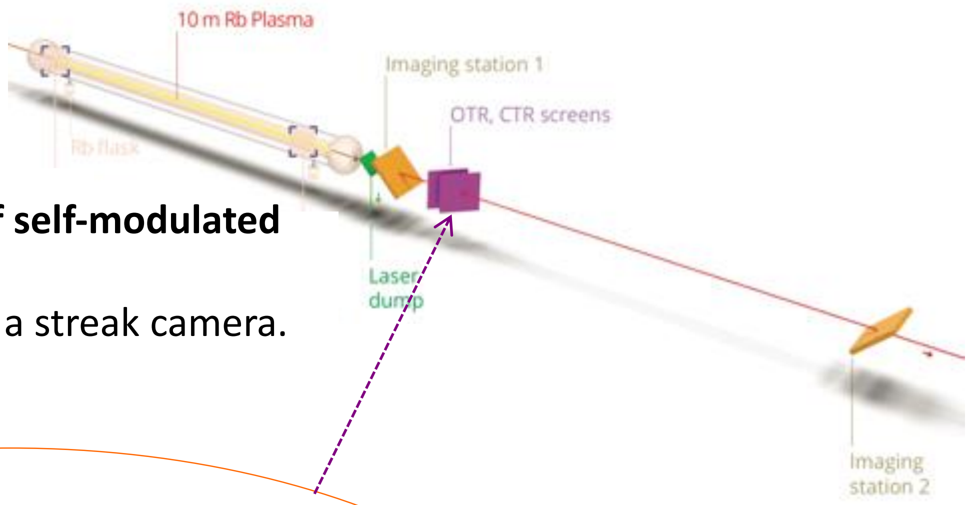
AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





Laser, compressor in laser room

Diagnostics for Proton Bunch Self-Modulation

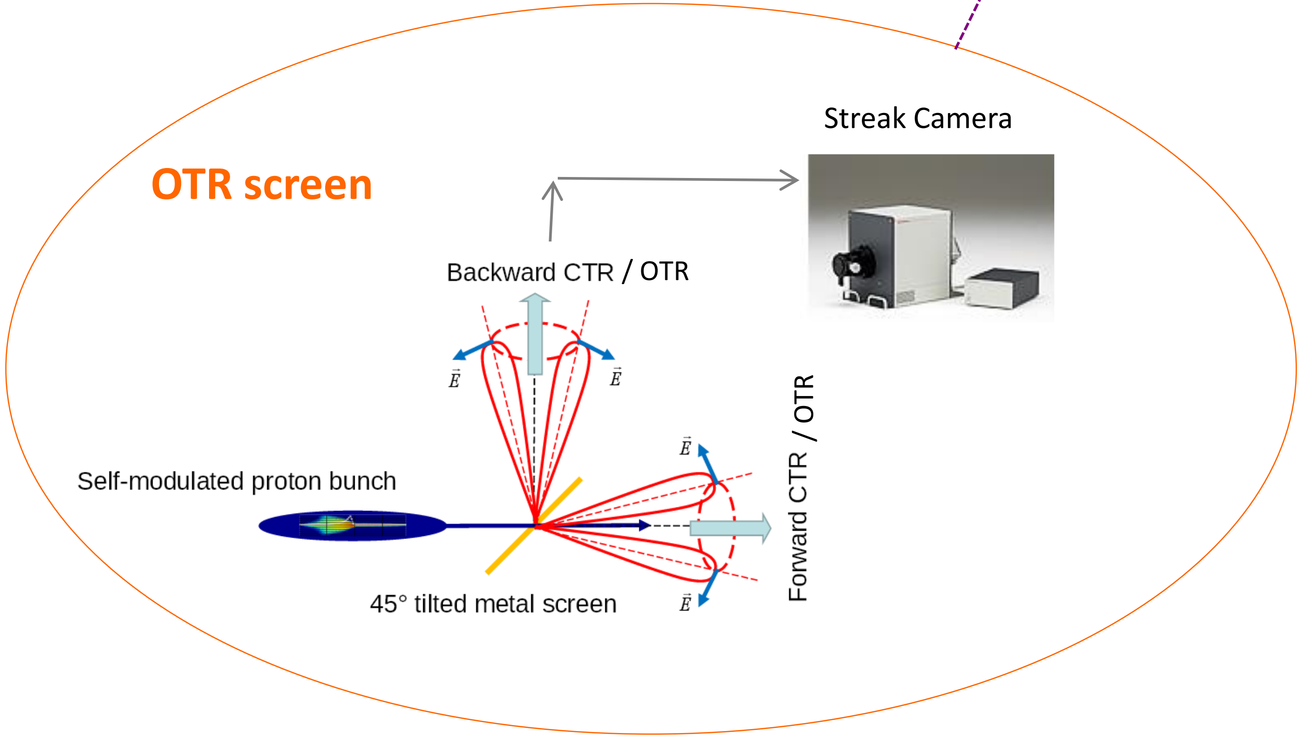


Direct SSM Measurement:

Measure longitudinal structure of self-modulated proton bunch.

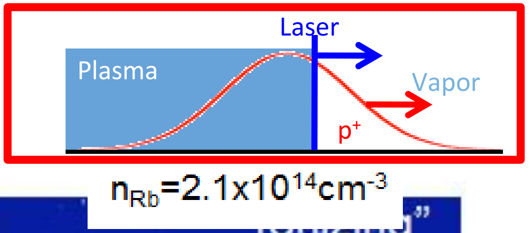
→ Image OTR light onto the slit of a streak camera.

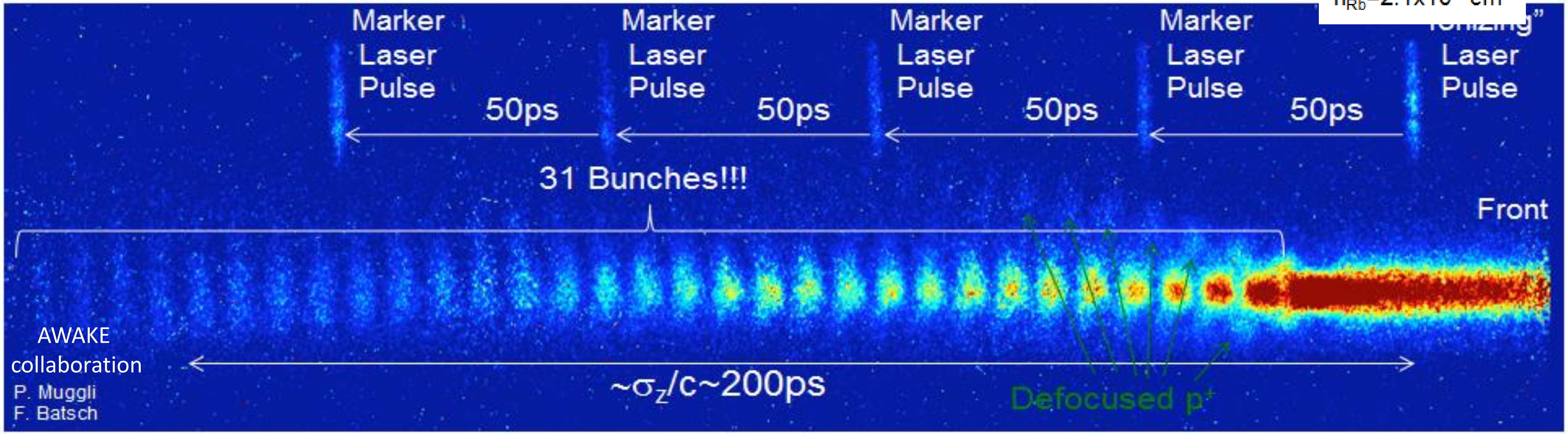
→ Time resolved measurement.



Metal foil emits electro-magnetic radiation with a maximal frequency corresponding to the plasma frequency

Results Run 1: Direct Seeded Self-Modulation Measurement



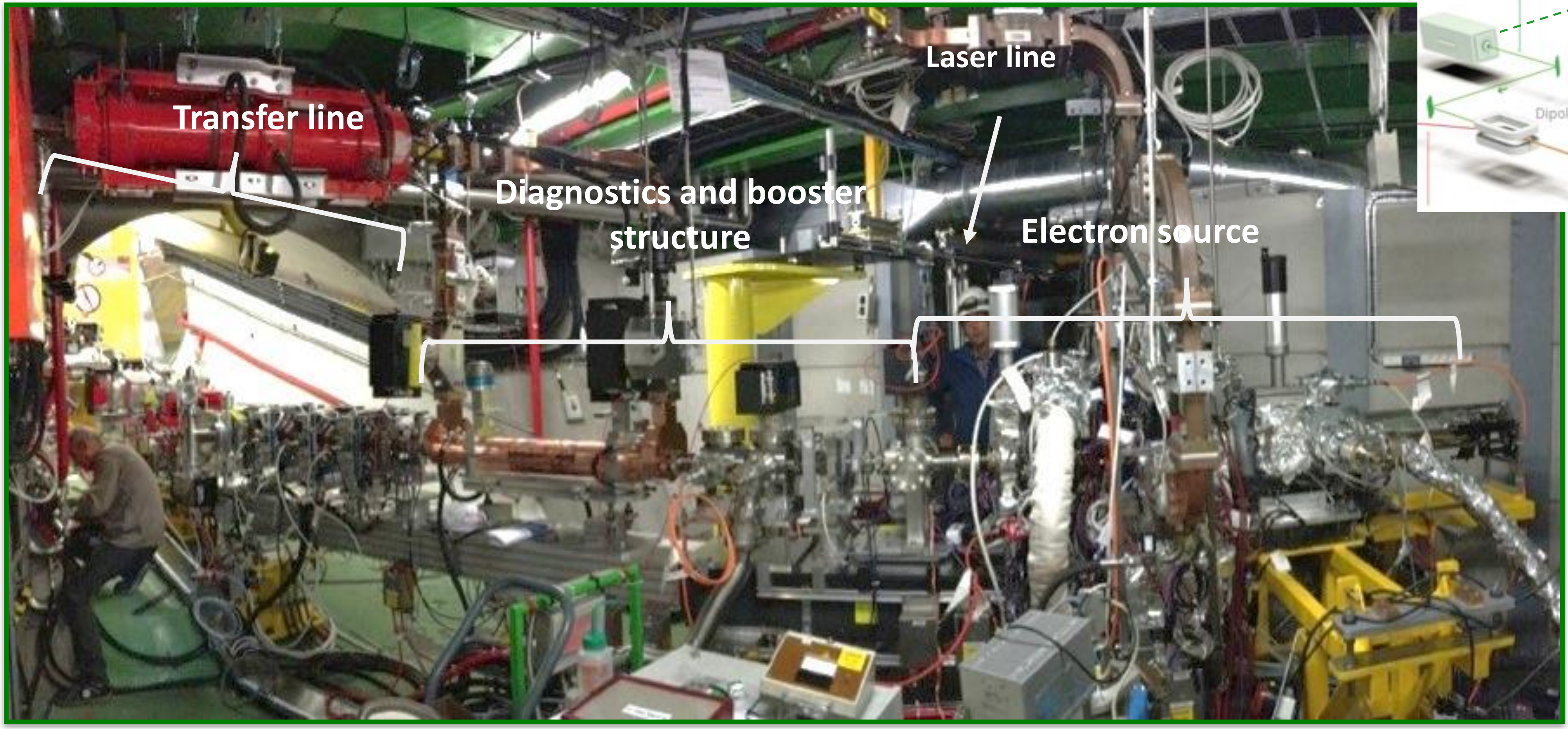


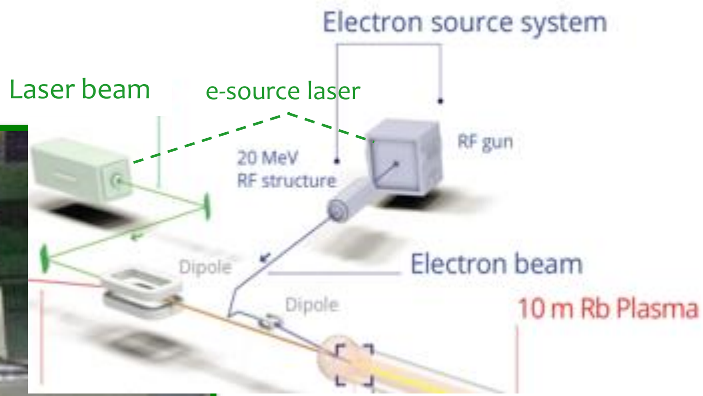
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e^- external injection.

→ 1st AWAKE Milestone reached

AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).
M. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
F. Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. July 30 (2020).
A.A. Gorn, M. Turner et al. (AWAKE Collaboration), Plasma Phys. Control Fusion, Vol. 62, Nr 12 (2020).
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

Electron Beam System

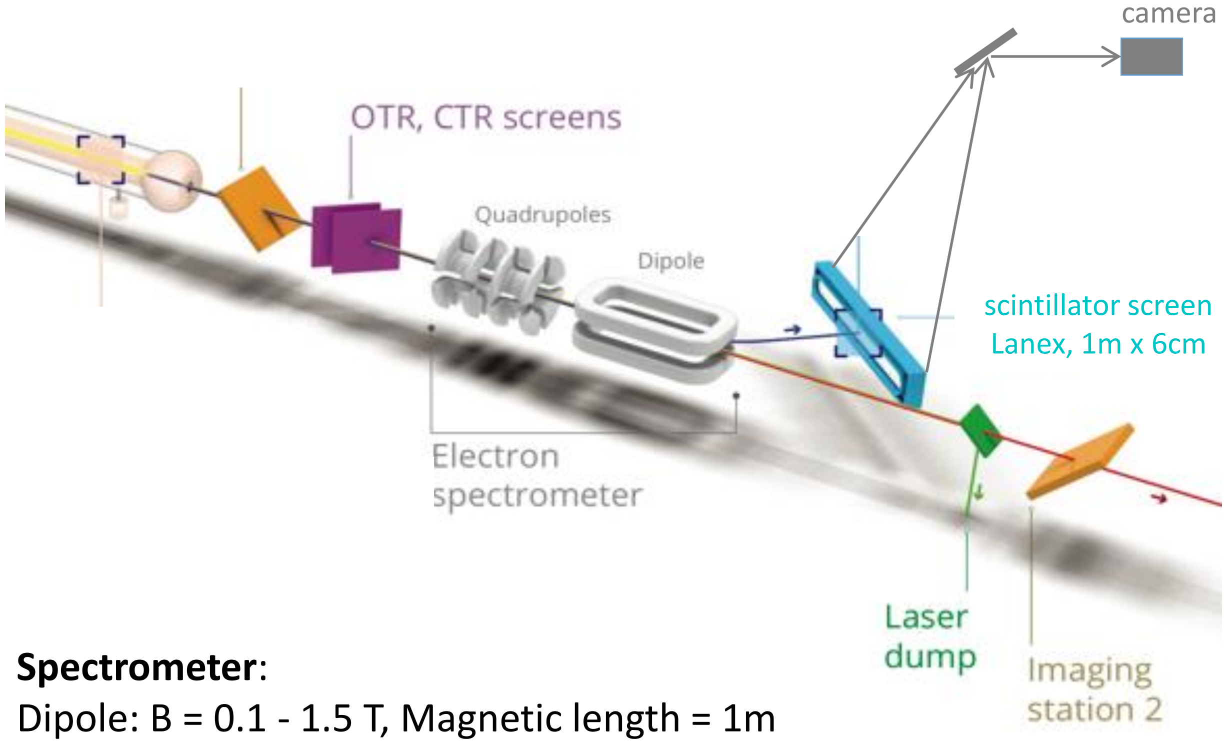




A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

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

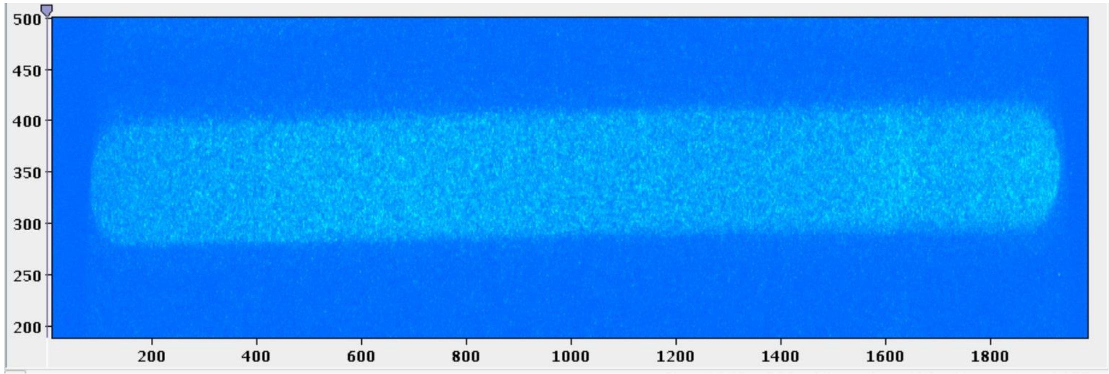
Electron Acceleration Diagnostics



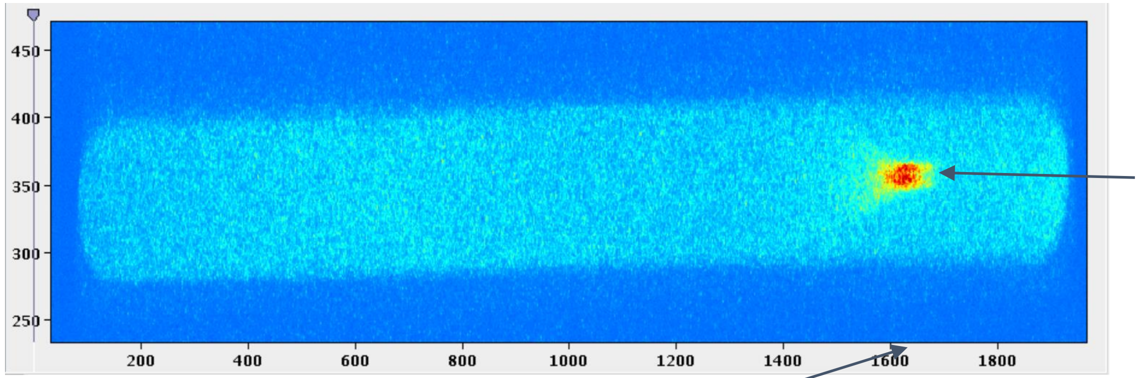
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

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.

Beschleunigung von Elektronen



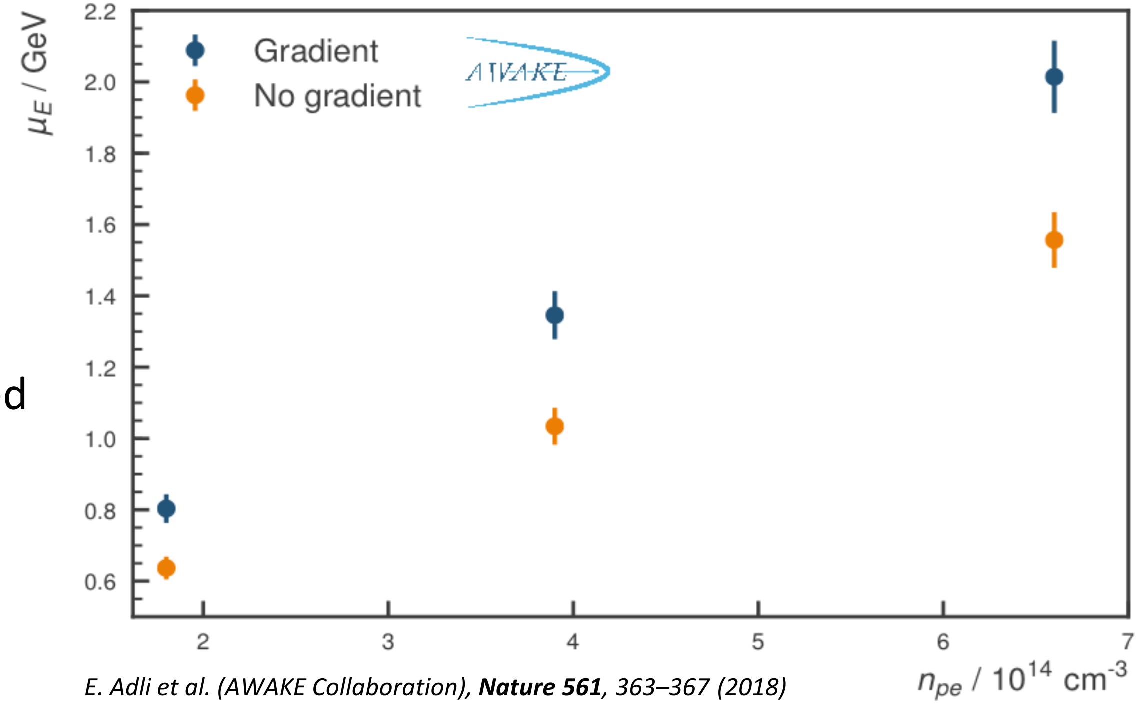
No accelerated electrons



Accelerated electrons

Convert pixel-size and dipole setting to energy

- **Acceleration up to 2 GeV** has been achieved.
- Charge capture up to 20%.



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

→ **2^{nd} AWAKE Milestone reached**

AWAKE Run 2 (2021– 2029)

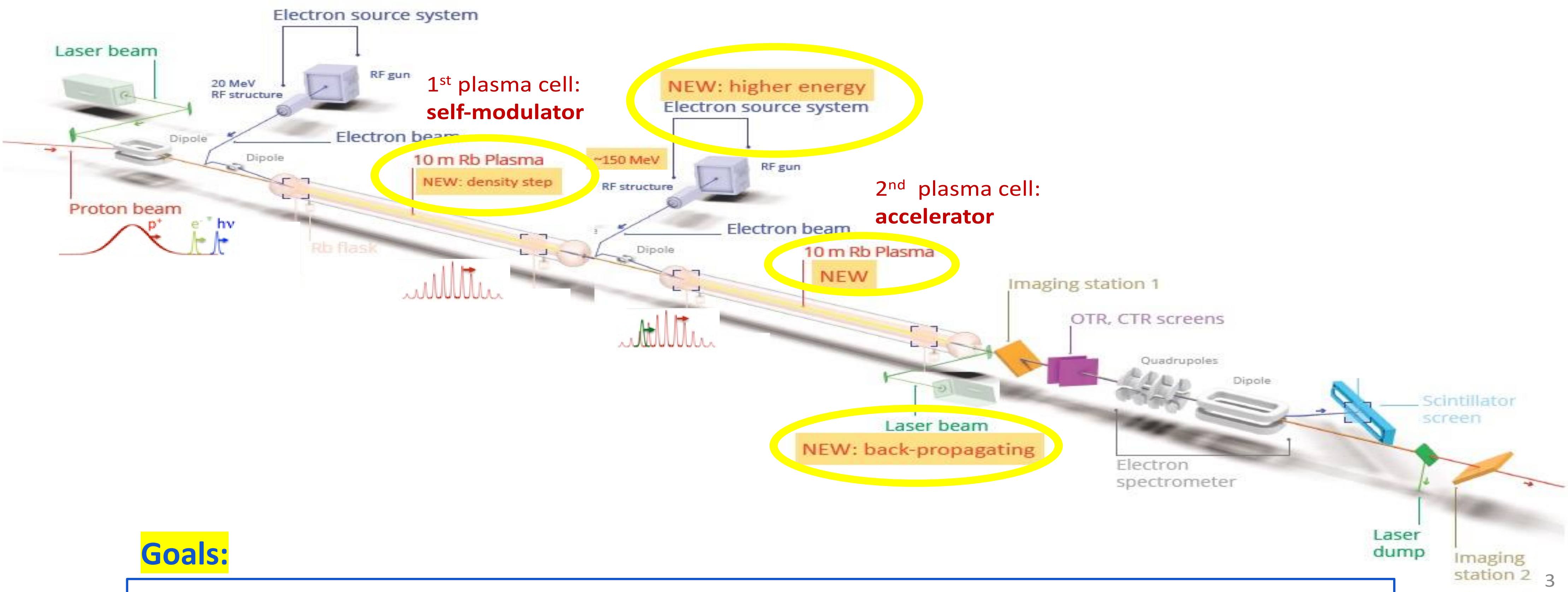
➔Has developed a clear scientific roadmap towards first particle physics applications within the next decade !

➔In AWAKE many general issues are studied, which are relevant for concepts that are based on plasma wakefield acceleration.

Paradigm change:
➔ Move from ‘acceleration R&D’ to an ‘accelerator’

AWAKE Run 2

➔ **Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!**
➔ **Start 2021, program goes beyond CERN Long Shutdown 3 (2027+)**!



Goals:

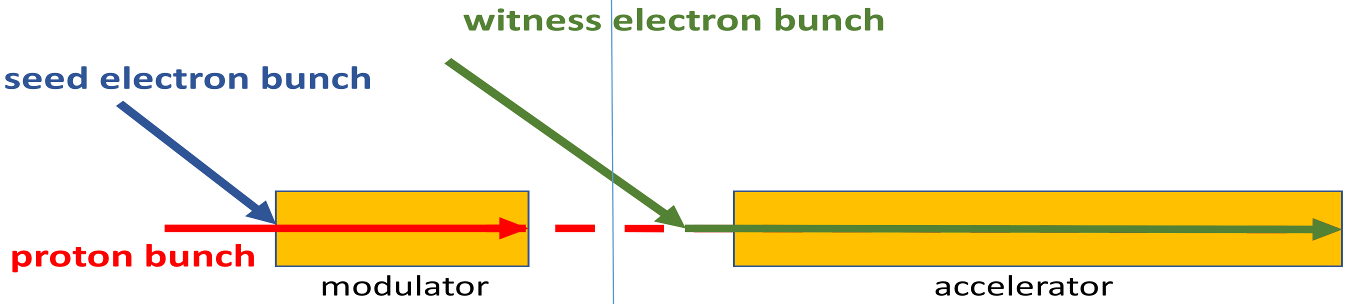
Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

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

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

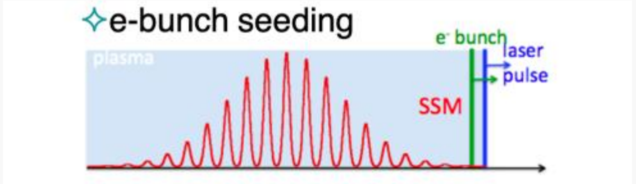
AWAKE Run 2

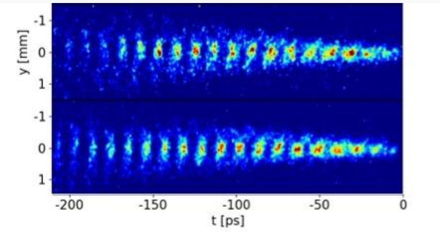
Optimize self-modulation of the proton bunch



Optimize acceleration of electrons in p-driven plasma wakefield

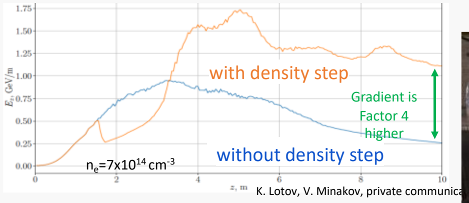
AWAKE Run 2a: self-modulation of entire p-bunch seeded with an e-bunch

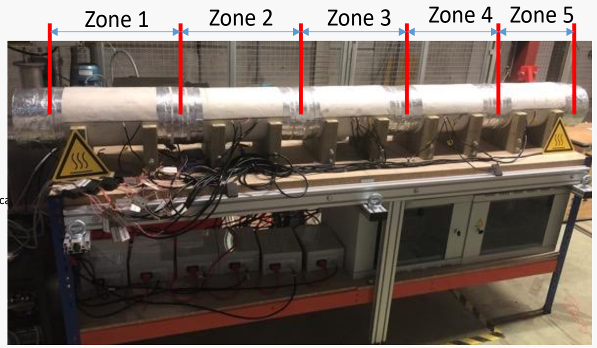




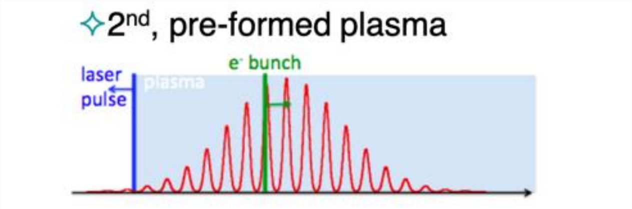
AWAKE Run 2b: stabilization of the micro-bunches with a density step in the plasma cell and maintain high gradient

Gradient in 1st plasma source (self-modulator)

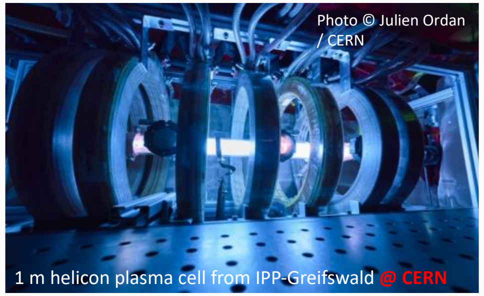




AWAKE Run 2c: electron acceleration and emittance control



AWAKE Run 2d: scalable plasma sources



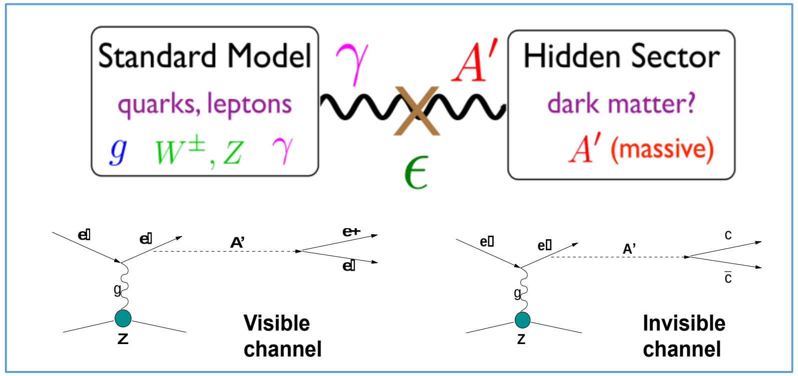
Applications with AWAKE-Like Scheme

Applications with AWAKE-Like Scheme

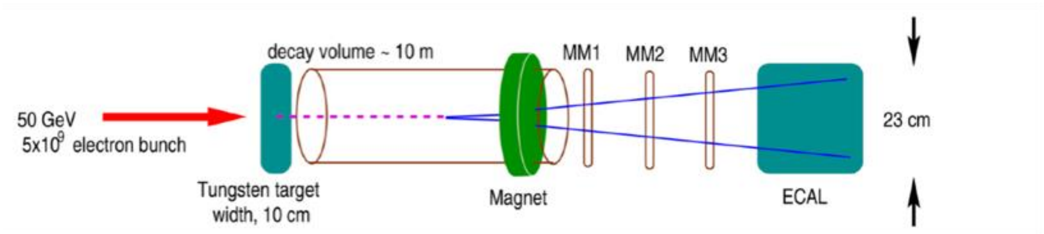
➔ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application: Fixed target test facility:

→ Deep inelastic scattering, non-linear QED, **search for dark photons**

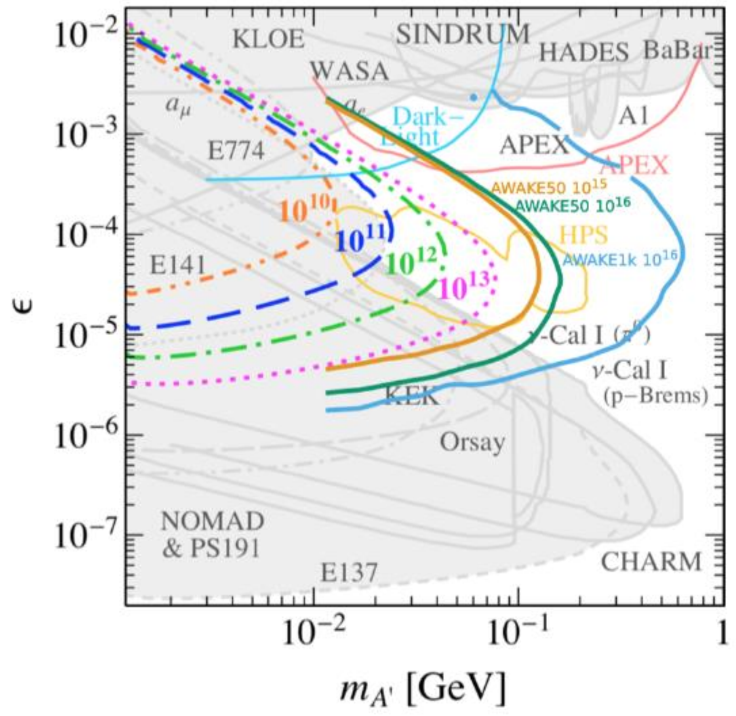


→ Decay of dark photon into visible particles (e.g. e+/e-)
→Energy and flux is important
→Relaxed parameters for emittance



Experimental conditions modeled on NA64 experiment.

→ 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)



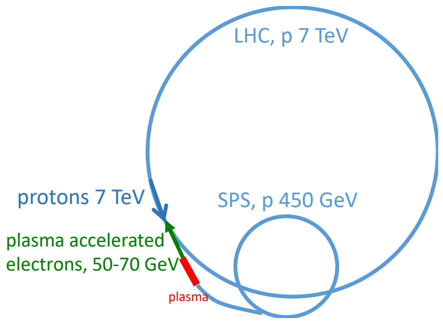
→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

Applications with AWAKE-Like Scheme

➔ Investigate non-linear QED in **electron- photon collisions**.

➔ Produce **TeV-range electrons with an LHC p_+ bunch:** use for lower luminosity measurements in electron-proton or electron-ion collisions.

- $\mathcal{L}$ Limited by proton accelerator repetition rate – look for high-cross-section processes to compensate.



- **PEPIC:** Low-luminosity version of LHeC (50 GeV electrons)
  - Use the SPS to drive electron bunches to 50 GeV and collide with protons from the LHC
  - Modest luminosity → only interesting should the LHeC not go ahead

- **EIC:**
  - use the RHIC-EIC proton beam to accelerate electron

- **3 TeV VHEeP**
  - use the LHC protons to accelerate electrons to 3 TeV and collide with protons from LHC with 7 TeV
  - Yields centre-of-mass energy of 9 TeV, Luminosity is relatively modest ~1028 – 10^{29} cm^{-2} s^{-1}, i.e. 1bp^{-1}/yr.
  - New energy regime means new physics sensitivity even at low luminosities.

- **Fixed target** variants with these electron beams

Summary and Outlook

→ Plasma wakefield acceleration is an exciting and growing field with many encouraging results and 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.

→ Current and planned facilities (Europe, America, Asia) explore different advanced and novel accelerator concepts and proof-of-principle experiments and address beam quality challenges and staging of two plasmas.

→ Coordinated R&D program for dedicated international facilities towards addressing HEP challenges are needed over the next 5 to 10 years.

  → As follow-up from the Update of the European Strategy on Particle Physics, the Plasma wakefield acceleration community has prepared a roadmap towards a high-energy collider based on advanced acceleration technologies.

Outlook:

→ **Near-term goals:** the laser/electron-based plasma wakefield acceleration could provide near term solutions for FELs, medical applications, etc.

→ **Mid-term goal:** the AWAKE technology could provide particle physics applications.

→ **Long-term goal:** design of a high energy electron/positron/gamma linear collider based on plasma wakefield acceleration.

Vielen Dank fuer Ihre Aufmerksamkeit!

State of the Art and Goals for HEP Collider

	Current	FEL (Intermediate Goal)	Collider (Final Goal)
Charge (nC)	0.01 – 0.1	0.01 – 0.1	0.1– 1
Energy (GeV)	9	0.1 – 10	1000
Energy spread (%)	0.1	0.1	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	0.1– 1	0.01
Staging	single, two	single, two	multiple
Wall plug efficiency (%)	0.1	<0.1 - 10	10
Rep Rate (Hz)	10	10^1 - 10^6	10^4 - 10^5
Avg. beam power (W)	10	10^1 - 10^6	10^6
Acc. Distance (m)/stage	1	1	1 – 5
Continuous run	24/1	24/1 – 24/7	24/365
Parameter stability	1%	0.1%	0.1%
Simulations	days	days - 10^7	improvements by 10^7
Positron acceleration	acceleration		emittance preservation
Plasma cell (p-driver)	10 m		100s m
Proton drivers	SSM, acceleration		emittance control

Various important milestones have been and will be achieved in internationally leading programmes at:
CERN, CLARA, CNRS, DESY, various centres and institutes in the Helmholtz Association, INFN, LBNL, RAL, Shanghai XFEL, SCAPA, SLAC, Tsinghua University and others.

New European research infrastructures involving lasers and plasma accelerator technology have been driven forward in recent years, namely ELI and EuPRAXIA, both placed on the ESFRI roadmap.

The distributed RI **EuPRAXIA** as well as the aforementioned internationally leading programmes **will pursue several important R&D milestones and user applications for plasma accelerators.**