AWAKE

Austrian Teacher Programme
29 November 2024

Edda Gschwendtner, CERN

Plasma Wakefield Acceleration and AWAKE

AWAKE

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

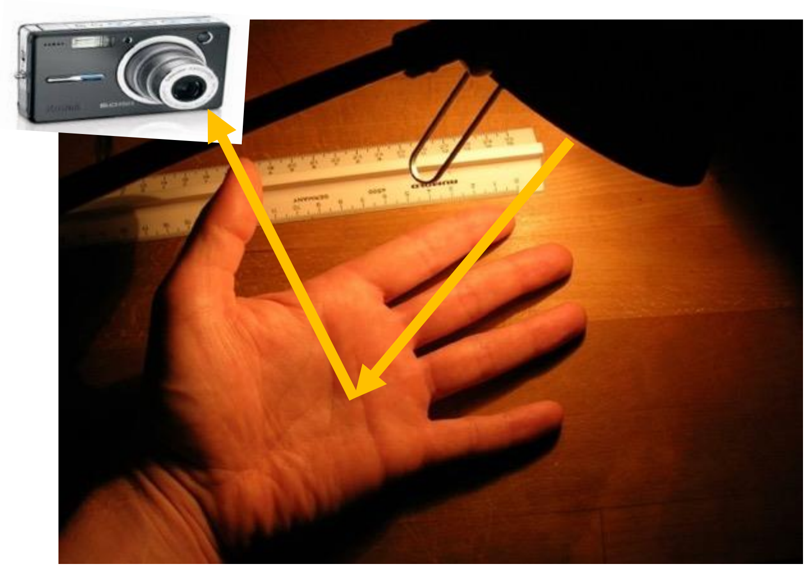
“Plasma Kielfeld Beschleunigungsexperiment, angetrieben durch einen Protonenstrahl”

- ➔**Plasma???**
- ➔**Kielfeld Beschleunigung???**
- ➔**Angetrieben durch einen Protonenstrahl???**

Und überhaupt: ➔ **Warum???**

Why Do We Need Particles at Even Higher Energies?

Pattern of the scattered light → structure of the hand.



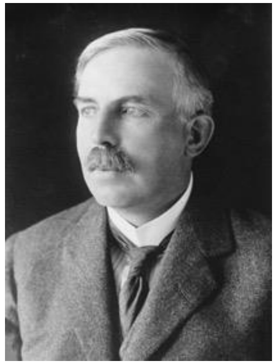
Visible light ~ 10^{-6} m = 1 micrometer = 0.001mm ~ size of a bacterium

Higher particle energy → smaller wavelength → smaller structures

Accelerators are Super-Microscopes !

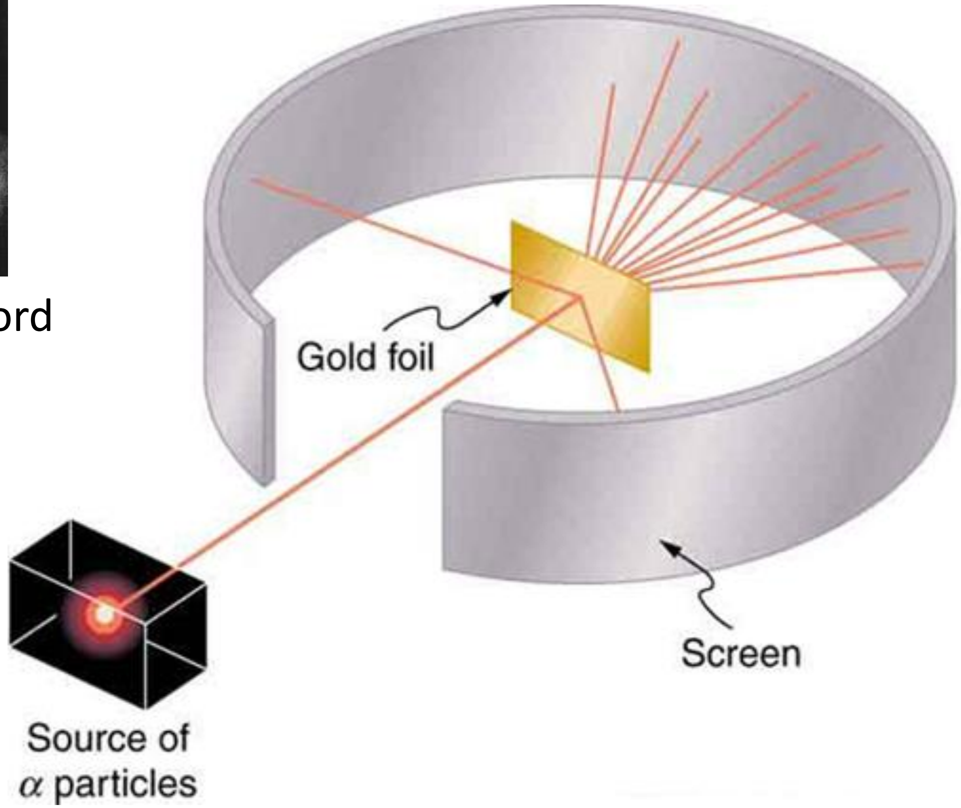
3

Rutherford Experiment, 1910

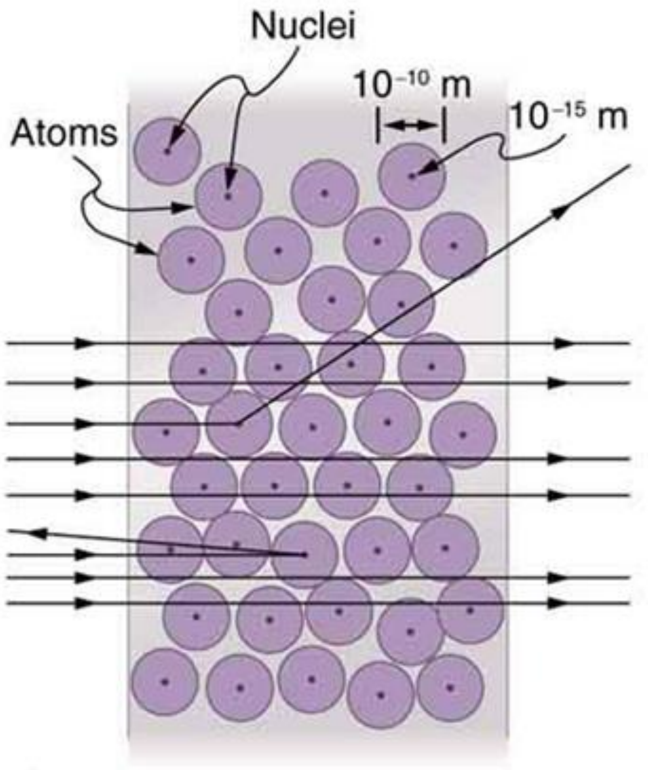


Ernest Rutherford

Alpha Particle Source

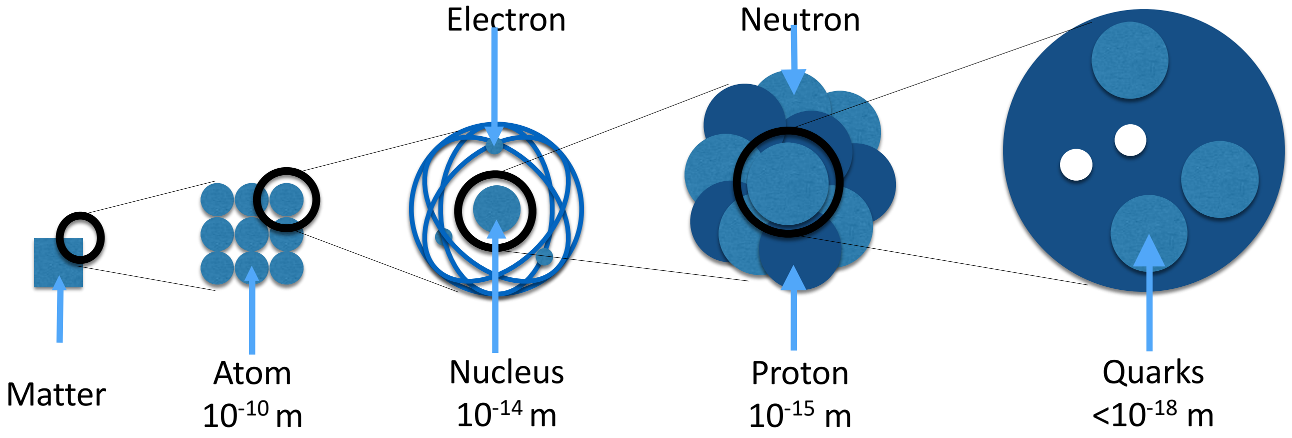


Pattern of scattered high energy particles
→ structure of the atom.



Atoms (10^{-10} m) consist of an extremely small Nucleus (10^{-15} m), electrons are moving around.

Why Do We Need Particles at Even Higher Energies?

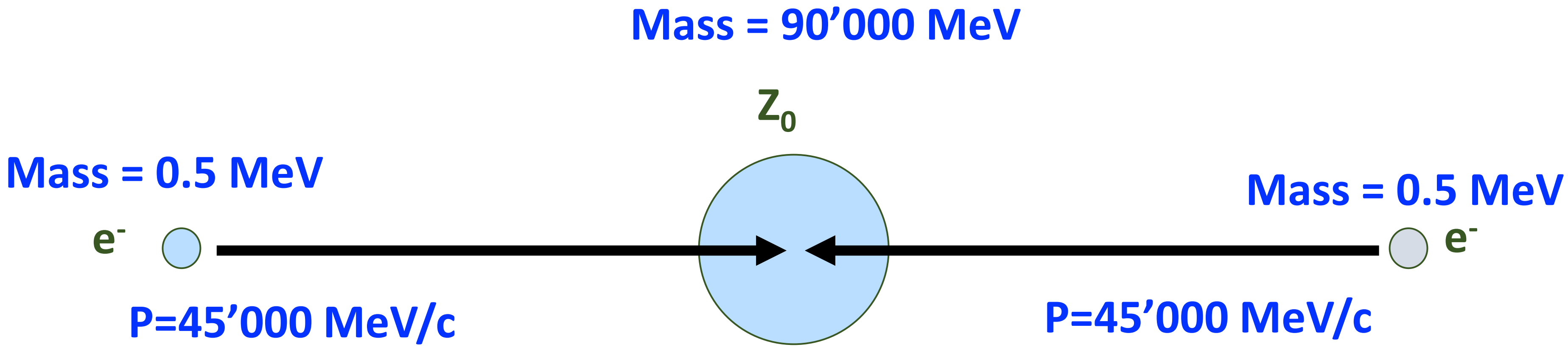


Optical Microscope: 10^{-6} m
Radioactive Source: 10^{-14} m
LHC: $<10^{-21}$ m

Particle Collisions and New Particles

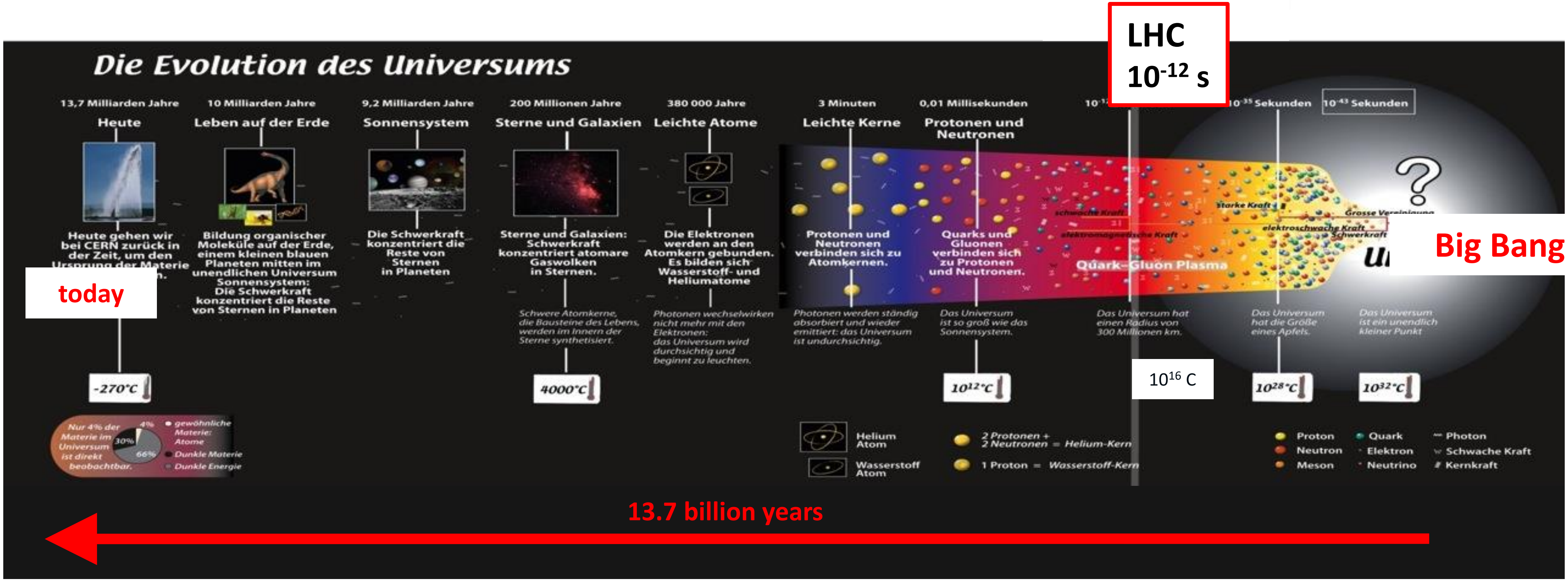
The study of the smallest building blocks of matter with high energy particle colliders and the production of new massive particles is connected:

$$E = mc^2$$



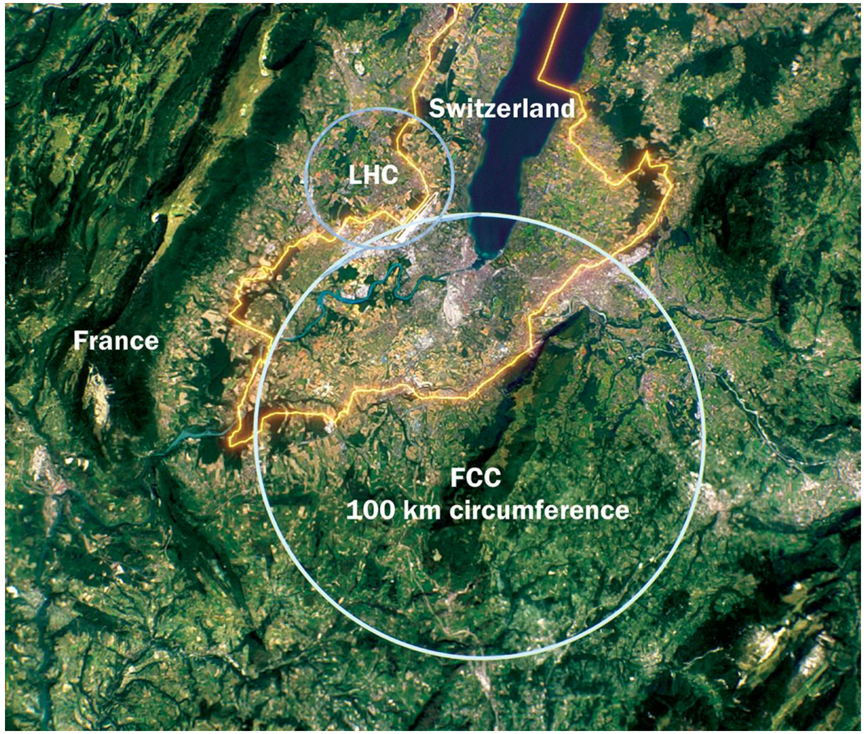
Higgs Boson Discovery at the LHC in 2012
Nobel Prize in 2013

What is the Origin of the Universe?



To discover new physics: accelerate particles to even higher energies

Circular Accelerators

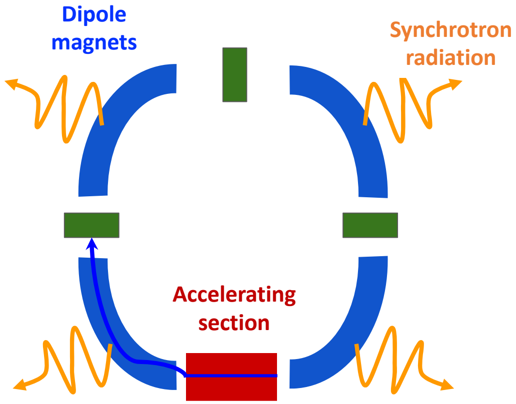


Conventional RF cavities ok for circular colliders:
👍 beam passes accelerating section several times.

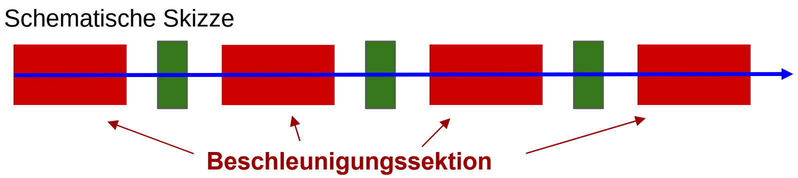
👎 **Limitations of electron-positron circular colliders:**

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

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



Linear Colliders



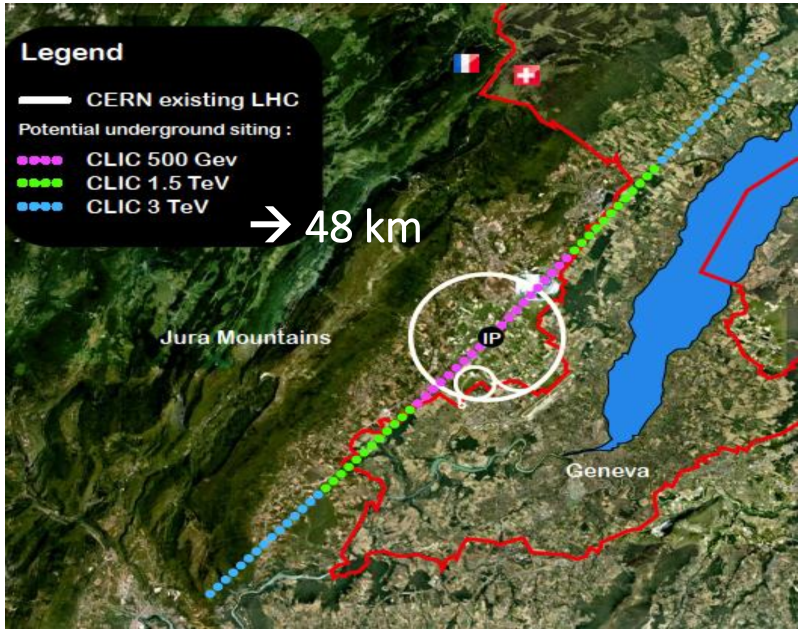
Favorable for acceleration of low mass particles to high energies.

Limitations to linear colliders:

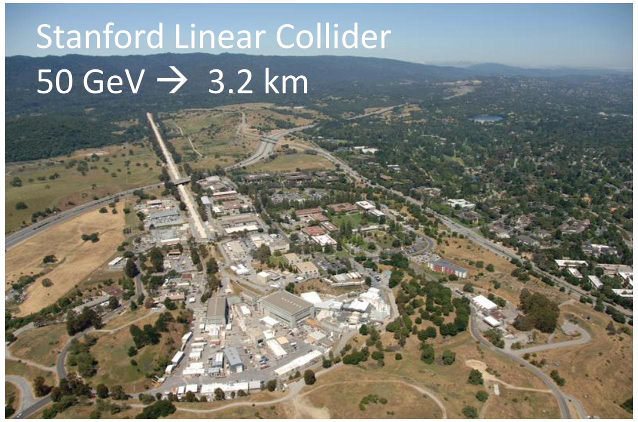
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.

Teilchenenergie = Beschleunigungsgradient x 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



CLIC, electron-positron collider with 3 TeV energy



Motivation:

- **Investigate the smallest building blocks of matter.**
- **Produce massive particles that are either unknown or predicted by theories.**

How?

- **Explore particle collisions at even higher energies.**

➔ *Darum!*

Plasma Wakefield Acceleration and AWAKE

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- ➔ **Plasma???**
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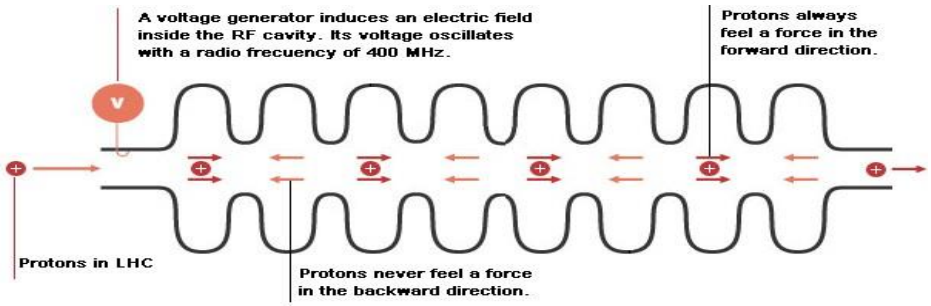
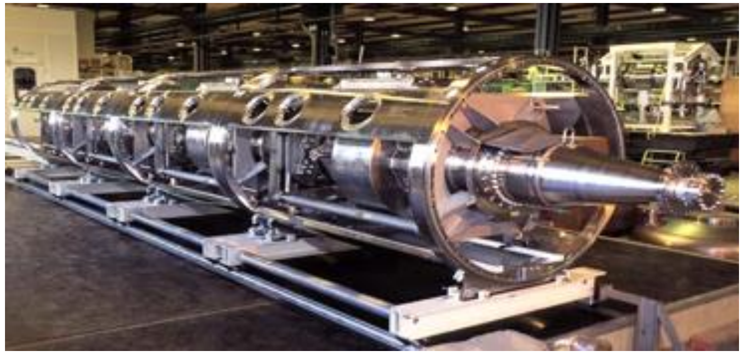
Und ueberhaupt: ➔ **Warum** 

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity



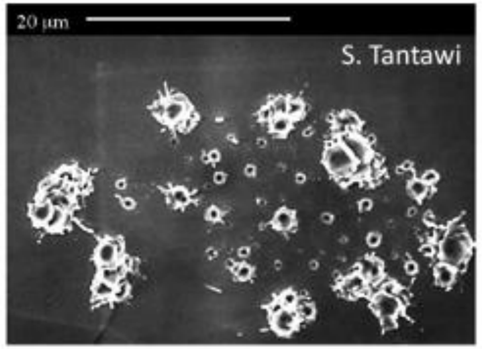
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

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

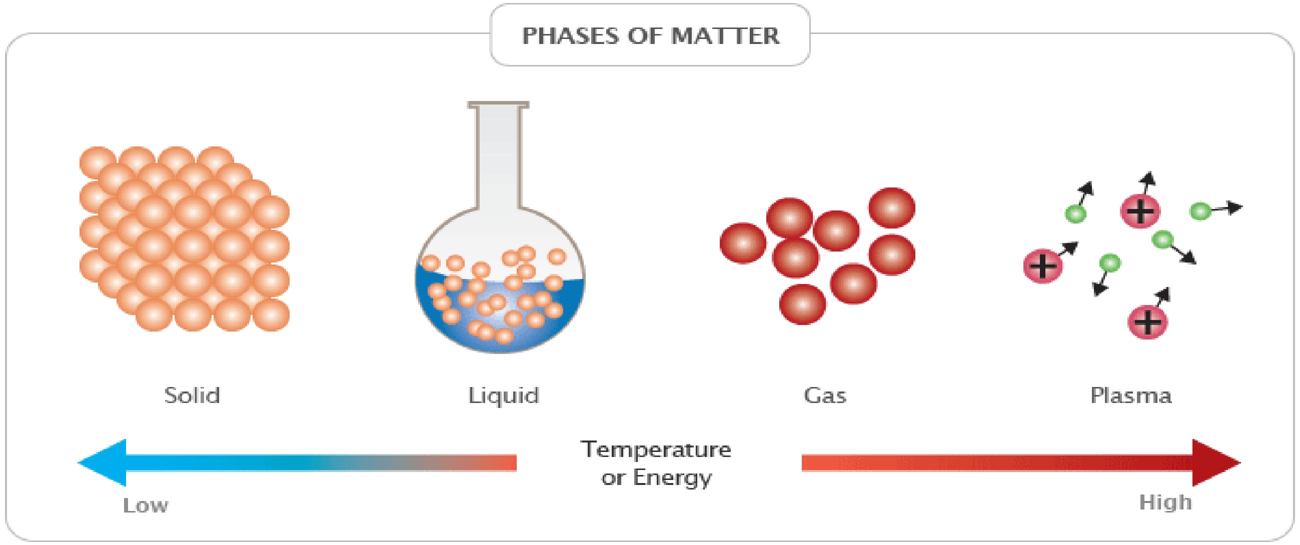
In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge.
Fields cannot be sustained, structures might be damaged.

➔ **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

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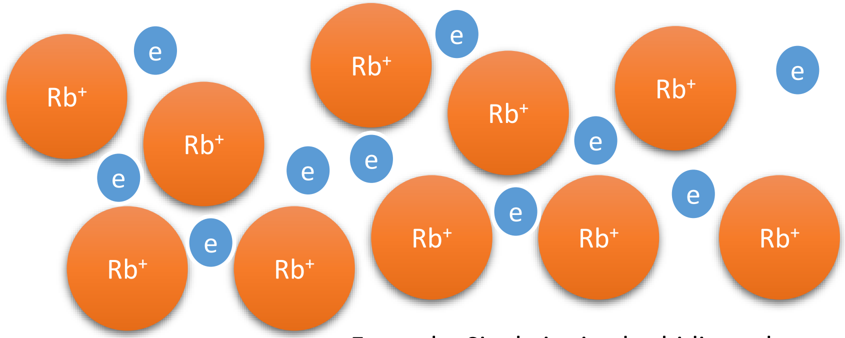
Plasma Wakefield

What is a plasma?



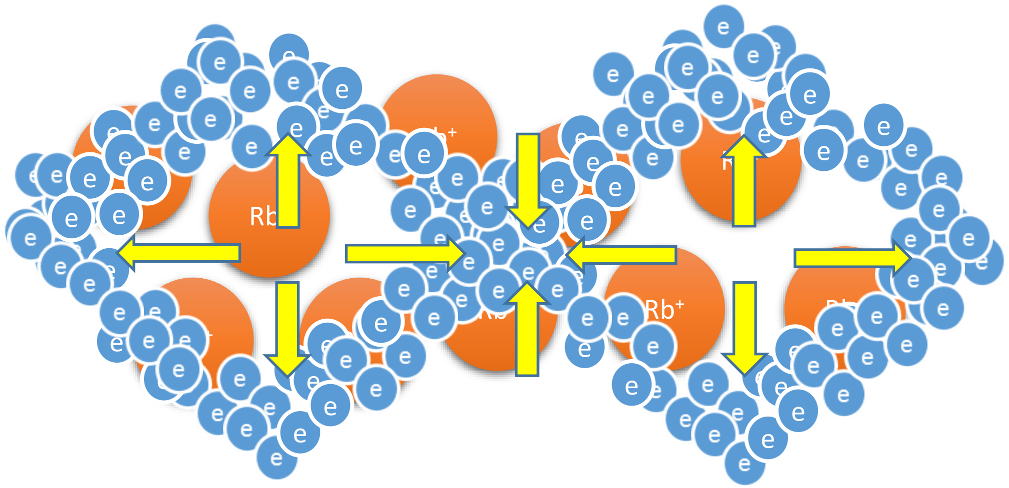
Example: Single ionized rubidium plasma

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.

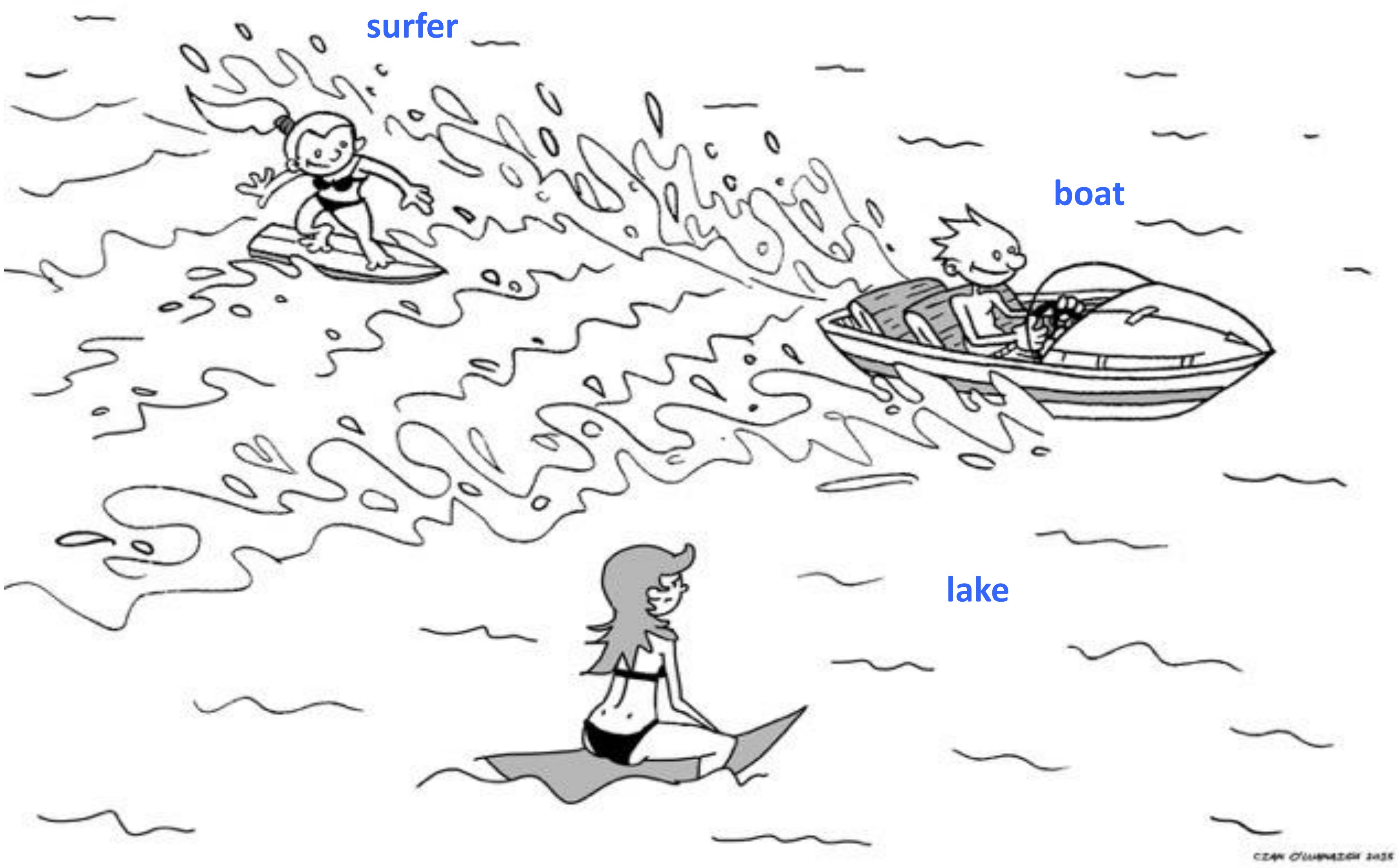
Electrostatic interactions dominate over collisions or ordinary gas kinetics.

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

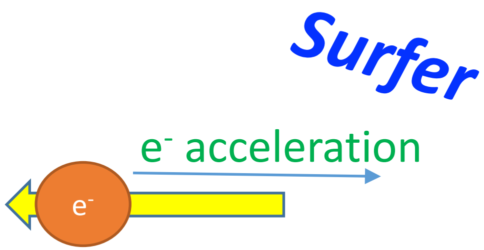
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

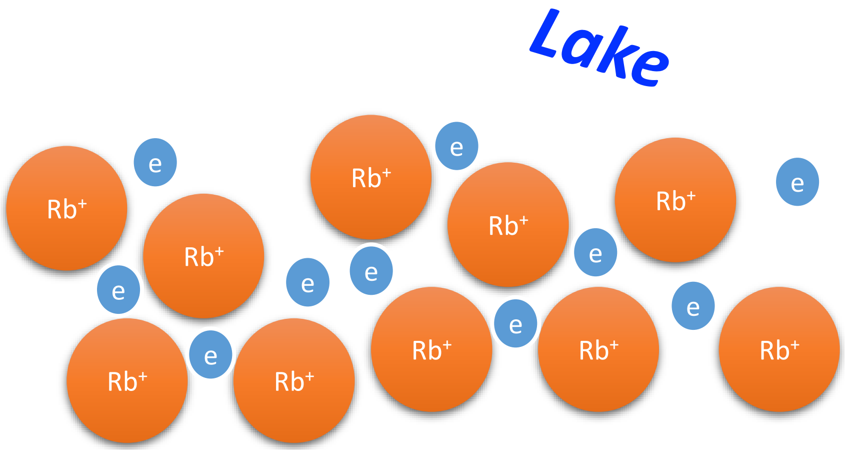
How to Create a Plasma Wakefield?

What we want:

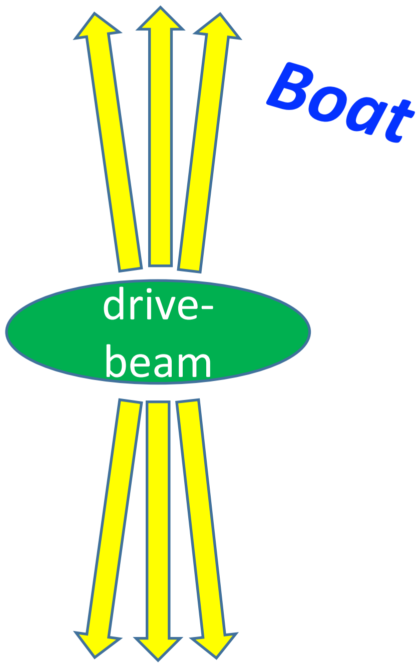
Longitudinal electric field to accelerate charged particles.



Our Tool:



Single ionized rubidium **plasma**



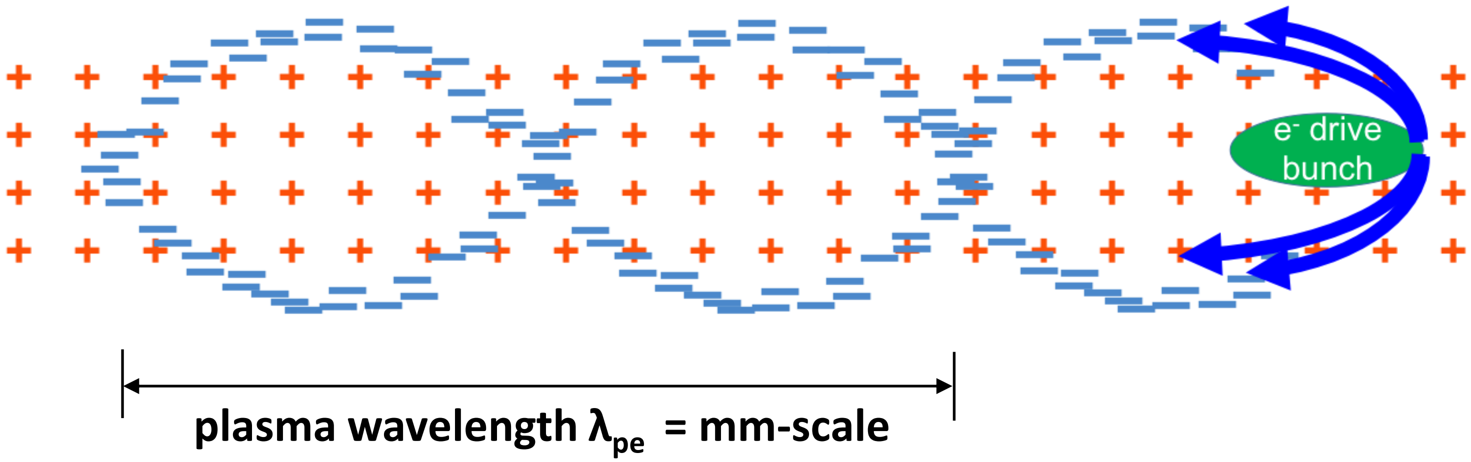
Charged particle bunches carry almost purely transverse Electric Fields.

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

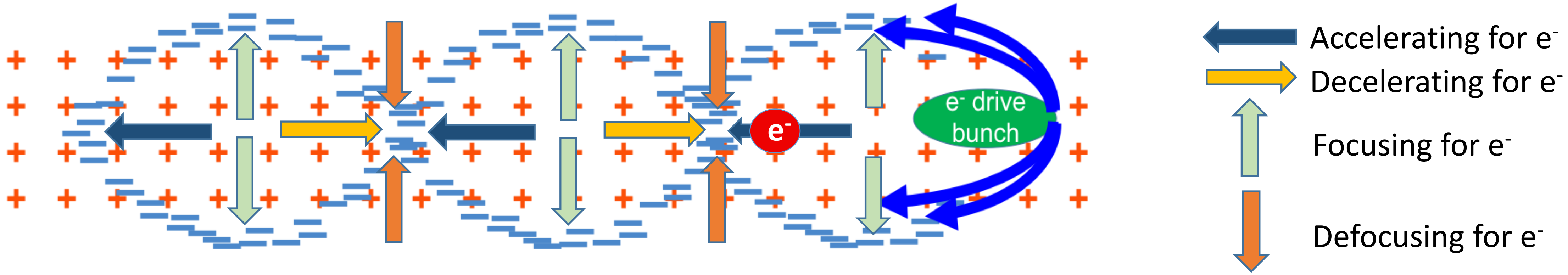
Boat:

- Laser drive beam
- Charged particle drive beam

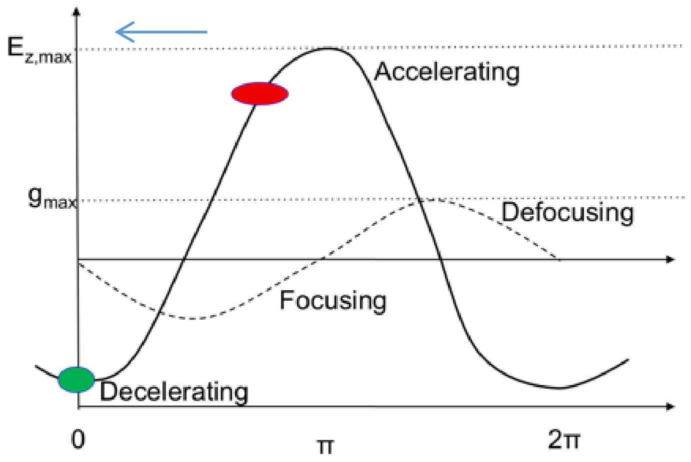


- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?



➔ *Kielfeld Beschleunigung!*



E. Gschwendtner, CERN

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Und ueberhaupt: → **Warum**

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:

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

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

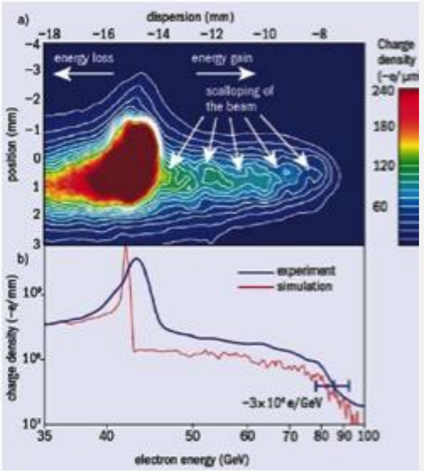
Some Highlights

FACET, SLAC, USA:
Premier R&D facility for electron-driven plasma wakefield acceleration: Only facility capable of e^+ acceleration

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**

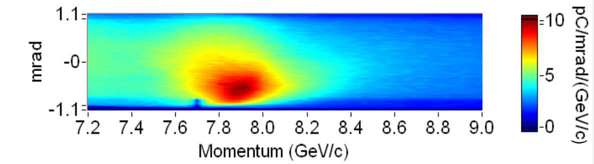


BELLA, Berkeley Lab, USA:
Laser-driven plasma wakefield acceleration Facility

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

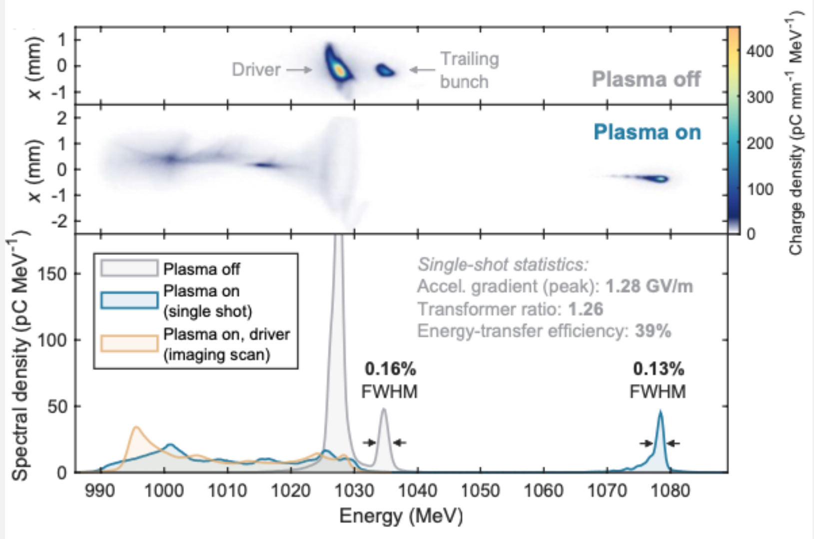
*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

20 cm-scale plasma



FLASHForward, DESY, Germany:
Electron-driven plasma wakefield acceleration facility

Energy-spread preservation and high efficiency in a plasma-wake-field accelerator
*C.A. Lindstrøm et al., Phys.Rev.Lett. **126**, 014801 (**2021**)*



Transfer efficiency **42+/-4%** with **0.2% energy spread**,
Up to **70%** when allowing energy spread increase

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

Now first Proton Driven Plasma Wakefield Experiment

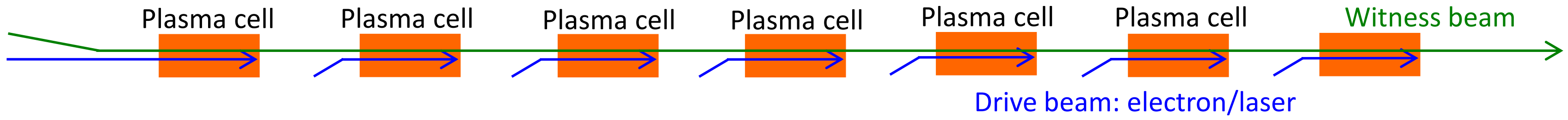
Plasma Wakefield Accelerators – Electron/Laser Drivers

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….



Plasma Wakefield Accelerators – Proton Drivers

Witness beams (Surfers):

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

Drive beams (Boat):

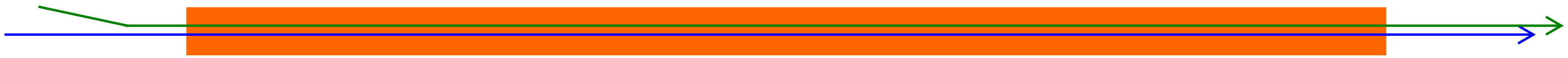
Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

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

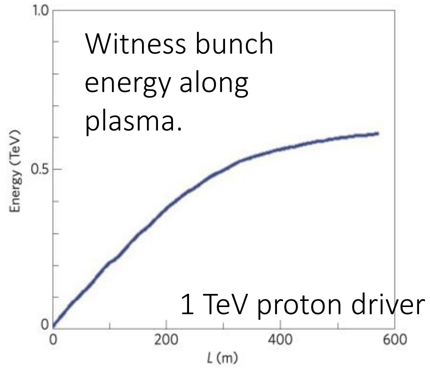
To reach TeV scale:

- **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.



With existing proton beams the energy frontier with electrons can be reached!

- SPS p^+ (450 GeV): accelerate to 200 GeV electrons.
- LHC p^+ can yield to 3 TeV electrons

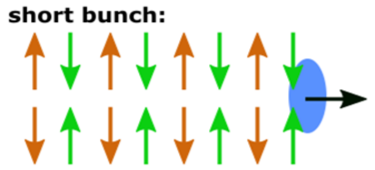


A. Caldwell et al., Nature Phys. **5**, 363–367 (2009)

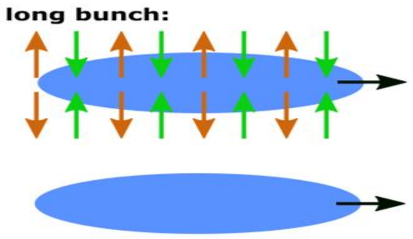
→ *Angetrieben durch einen Protonenstrahl!*

Seeded Self-Modulation of the Proton Beam

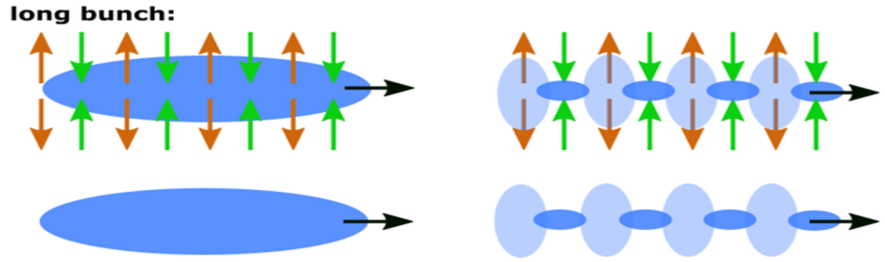
In order to create plasma wakefields efficiently, the drive bunch length must be in the order of the plasma wavelength.



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). These micro-bunches resonantly drive high wakefields! ➔ **immediate use of SPS proton bunch!**



➔ *Angetrieben durch einen Protonenstrahl!*

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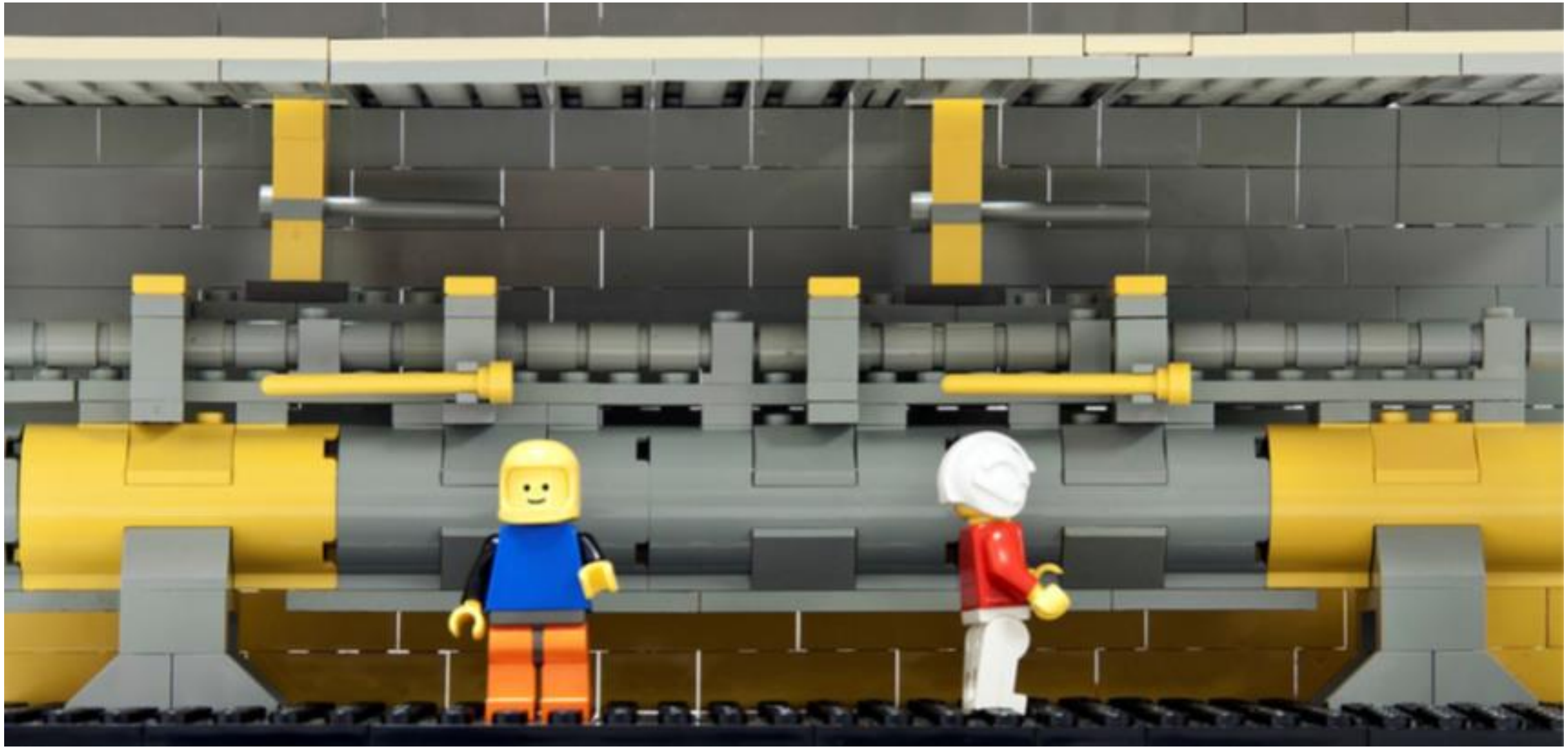
Und ueberhaupt: → **Warum**

The AWAKE Experiment

Experimenteller Aufbau des AWAKE Experiments am CERN



Von einer Idee zur Realität!

AWAKE is an International Collaboration

Wigner

clear

UPPSALA UNIVERSITET

The Cockcroft Institute of Accelerator Science and Technology

Lancaster University

UNIVERSITY OF OXFORD

MAX-PLANCK-INSTITUT FÜR PHYSIK

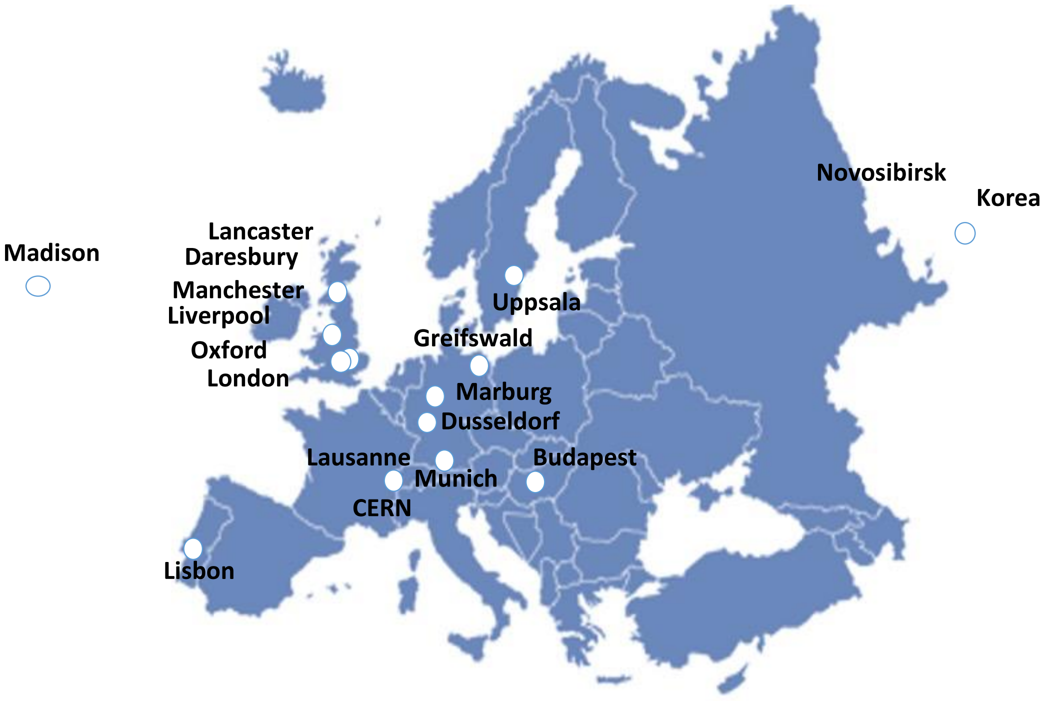
Philipps Universität Marburg

MAX PLANCK INSTITUTE FOR PLASMA PHYSICS

EPFL

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Strong Commitment from 21 Institutes



CERN

UKRI Science and Technology Facilities Council

MANCHESTER 1824 The University of Manchester

UNIVERSITY OF LIVERPOOL

Imperial College London

UCL

hhu Heinrich Heine Universität Düsseldorf

TÉCNICO LISBOA

UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY 2007

Novosibirsk State University *THE REAL SCIENCE

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AWAKE's Strong Scientific and Educational Output

22 AWAKE Collaboration papers in high-level journals

Authors	Title	Journal	Year
L. Verra, et al. (AWAKE Collaboration)	Filamentation of a Relativistic Proton Bunch in Plasma		2023
T. Nechaeva, et al. (AWAKE Collaboration)	Hosing of a long relativistic particle bunch in plasma		2023
L. Verra, et al. (AWAKE Collaboration)	Development of the Self-Modulation Instability of a Relativistic Proton Bunch in Plasma	PoP	2023
E. Gschwendtner, et al. (AWAKE Collaboration)	The AWAKE Run 2 programme and beyond	Symmetry	2022
L. Verra, et al. (AWAKE Collaboration)	Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma	PRL	2022
S. Gessner, et al. (AWAKE Collaboration)	Evolution of a plasma column measured through modulation of a high-energy proton beam		2020
V. Hafych, et al. (AWAKE Collaboration)	Analysis of Proton Bunch Parameters in the AWAKE Experiment	JINST	2021
P.I. Morales Guzman, et al. (AWAKE Collaboration)	Simulation and experimental study of proton bunch self-modulation in plasma with linear density gradients	PRAB	2021
F. Batsch, et al. (AWAKE Collaboration)	Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma	PRL	2021
J. Chappell, et al. (AWAKE Collaboration)	Experimental study of extended timescale dynamics of a plasma wakefield driven by a self-modulated proton bunch	PRAB	2021
F. Braunmüller, et al. (AWAKE Collaboration)	Proton Bunch Self-Modulation in Plasma with Density Gradient	PRL	2020
A. A. Gorn, et al. (AWAKE Collaboration)	Proton beam defocusing in AWAKE: comparison of simulations and measurements	PPCF	2020
M. Turner, et al. (AWAKE Collaboration)	Experimental study of wakefields driven by a self-modulating proton bunch in plasma	PRAB	2020
E. Gschwendtner, et al. (AWAKE Collaboration)	Proton-driven plasma wakefield acceleration in AWAKE	PTRSA	2019
M. Turner, et al. (AWAKE Collaboration)	Experimental Observation of Plasma Wakefield Growth Driven by the Seeded Self-Modulation of a Proton Bunch	PRL	2019
AWAKE Collaboration	Experimental Observation of Proton Bunch Modulation in a Plasma at Varying Plasma Densities	PRL	2019
AWAKE Collaboration	Acceleration of electrons in the plasma wakefield of a proton bunch	Nature	2018
P. Muggli, et al. (AWAKE Collaboration)	AWAKE readiness for the study of the seeded self-modulation of a 400 GeV proton bunch	PPCF	2018
E. Gschwendtner, et al. (AWAKE Collaboration)	AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN	NIMA	2016
A. Caldwell, et al. (AWAKE Collaboration)	Path to AWAKE: Evolution of the concept	NIMA	2016
C. Bracco, et al. (AWAKE Collaboration)	AWAKE: A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN	NPPP	2016
AWAKE Collaboration	Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics	PPCF	2014

> 70 papers related to AWAKE

> 90 Conference proceedings and papers

AWAKE courses and seminars

EPFL

John Adams Institute for Accelerator Science

CERN Teacher Program

USPAS, JUAS, CAS

➔ 4 doctoral thesis prizes, 2 early career awards!

> 28 PhD students

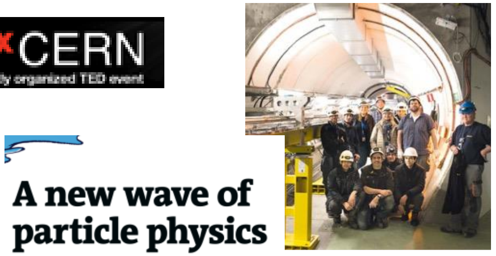
> 11 Master students

> 20 Post-docs

Outreach: Newspapers, TEDX, …

TEDxCERN

ask symmetry



AWAKE at CERN

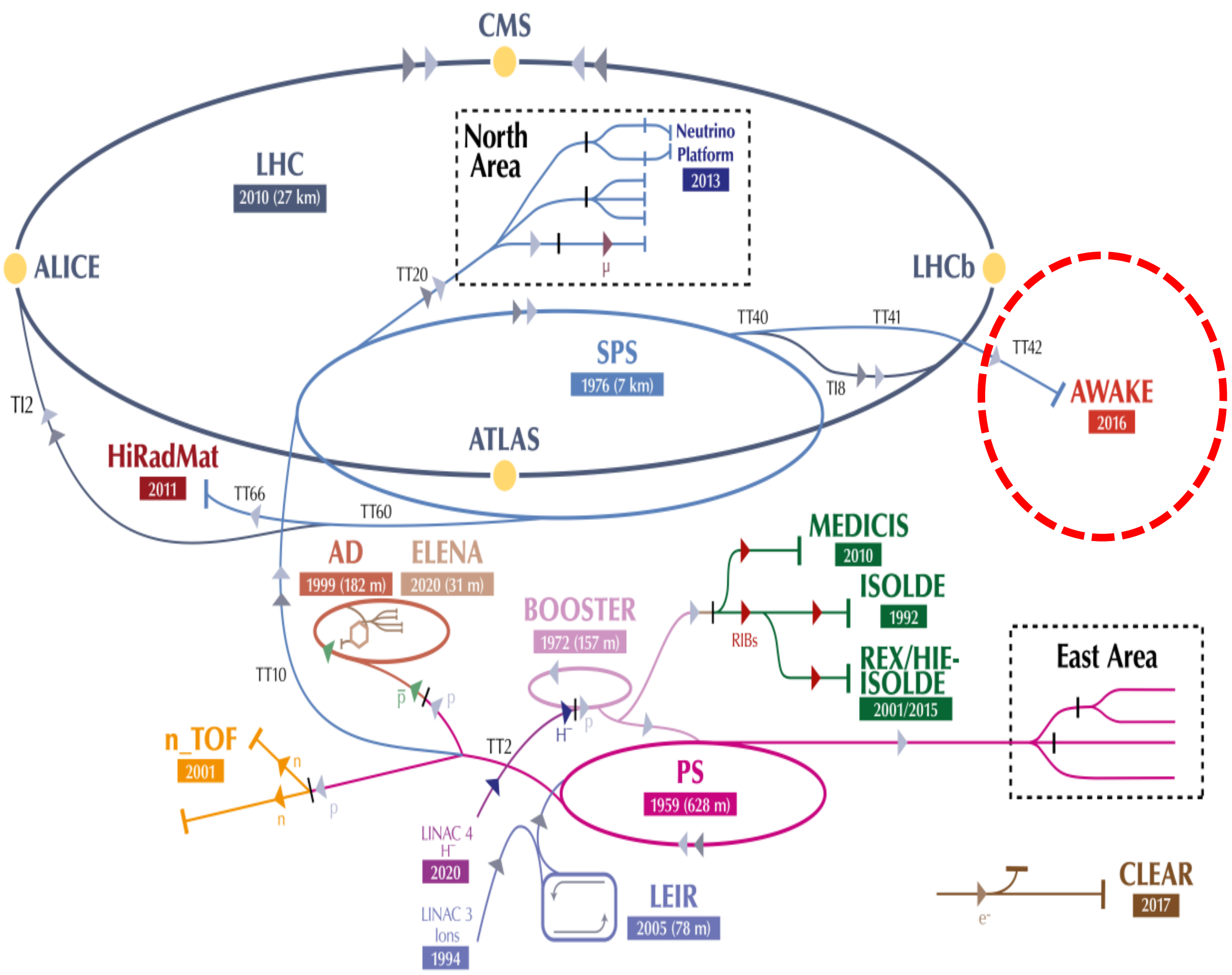
Advanced WAKEfield Experiment

➔Accelerator R&D experiment at CERN.

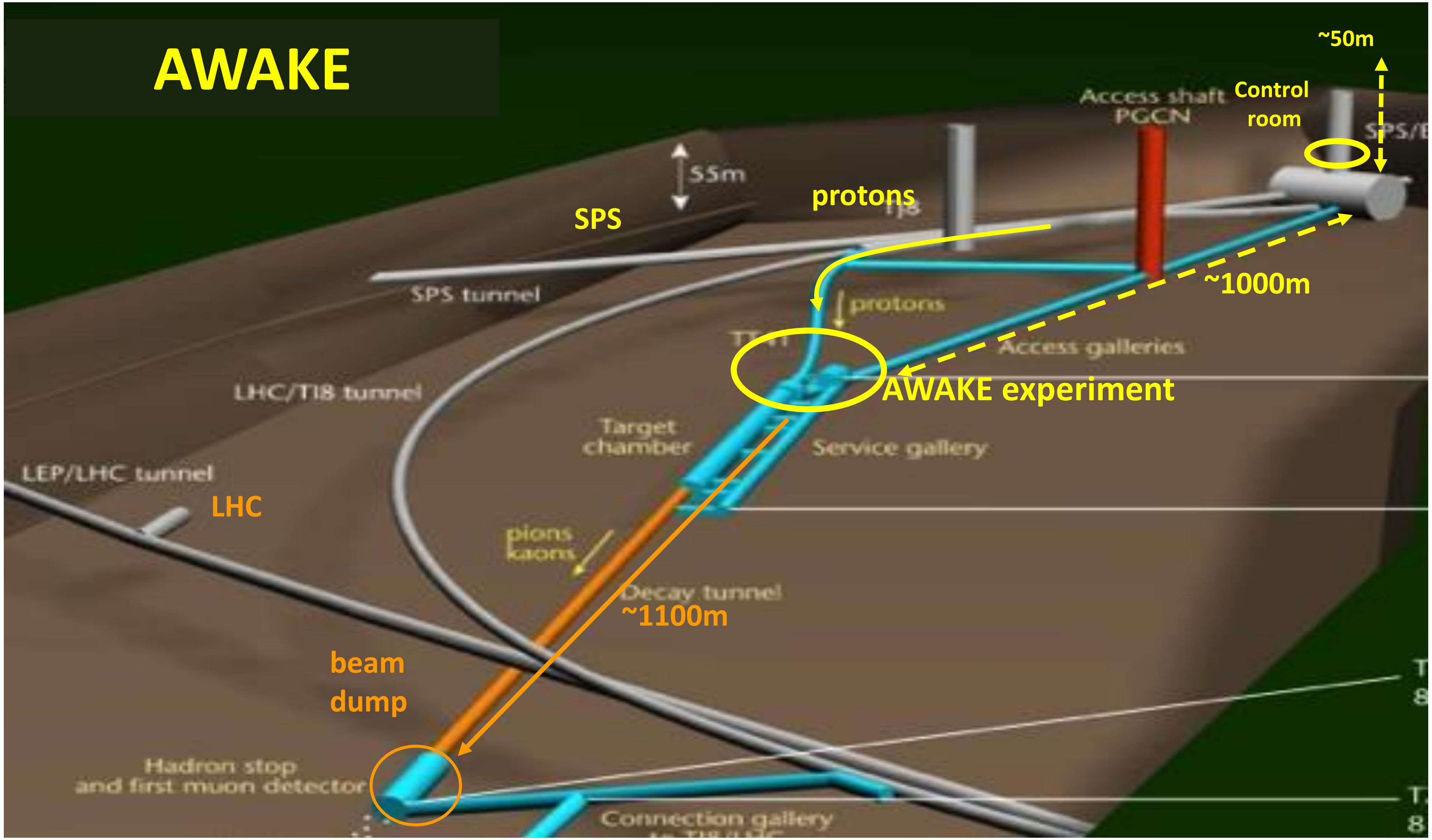
➔Unique facility driving wakefields in plasma with a proton bunch.

- ➔ At CERN highly relativistic protons with high energy (> kJ) available

➔Accelerating externally injected electrons to GeV scale.



AWAKE at CERN



AWAKE installed in CERN underground area

AWAKE Program

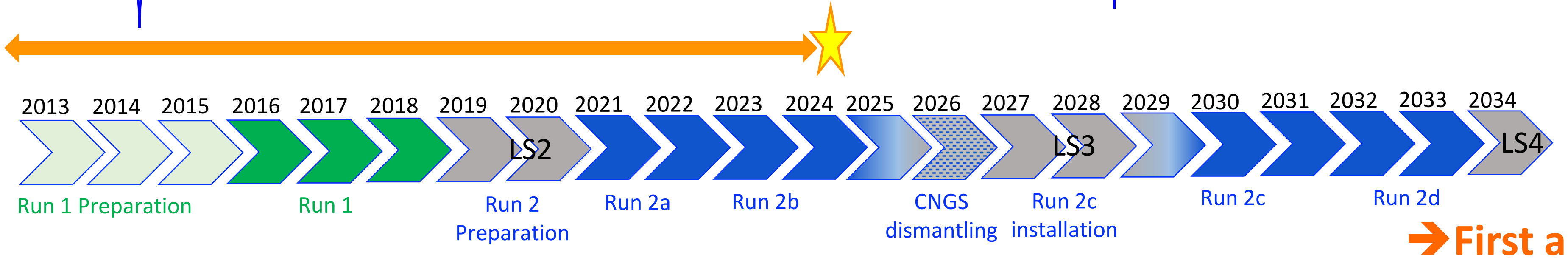
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

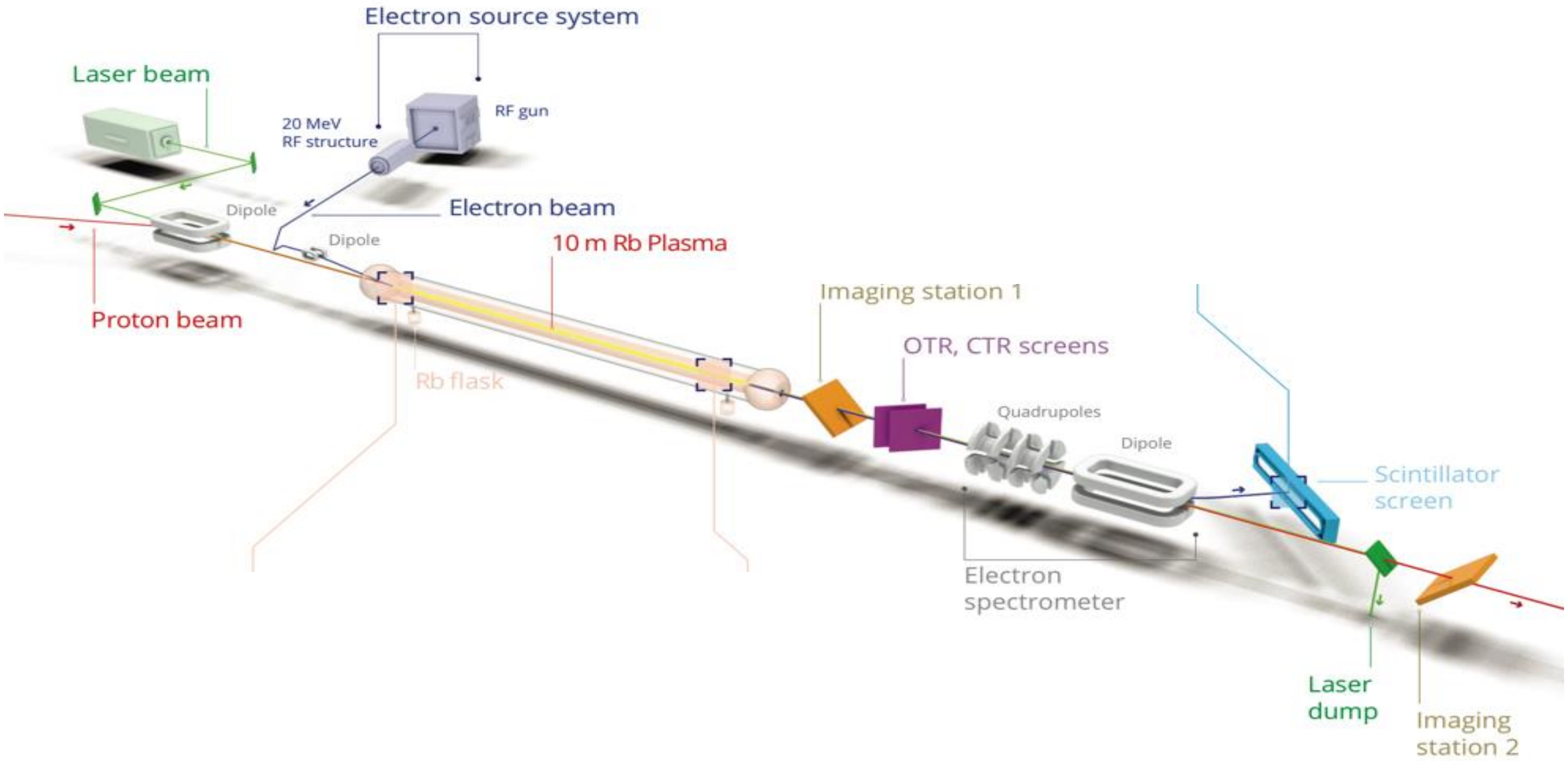
RUN 2 (2021-2033)

e- acceleration to several GeV,
beam quality control, scalability

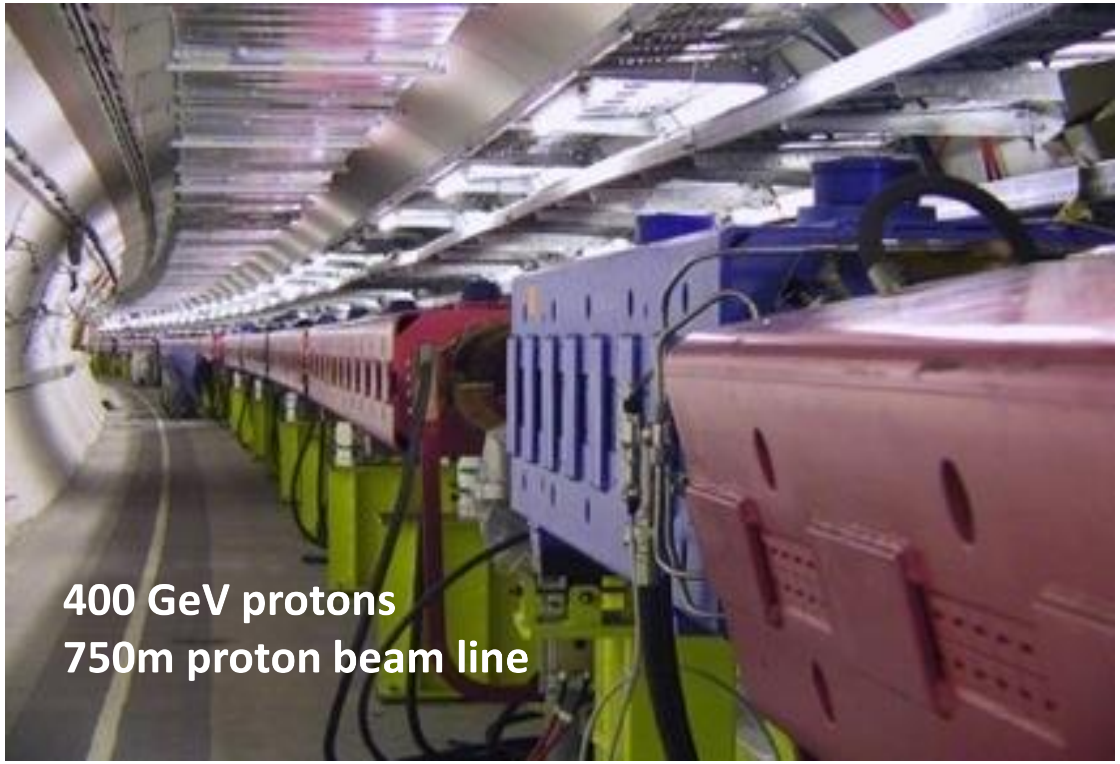


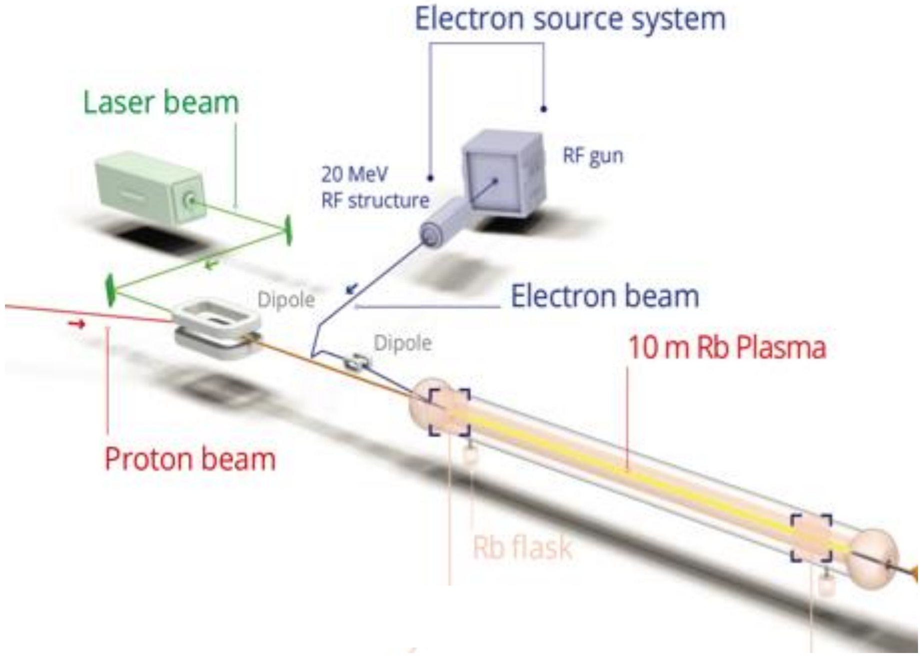
→ First applications >2034

AWAKE Experiment



AWAKE Proton Beam Line

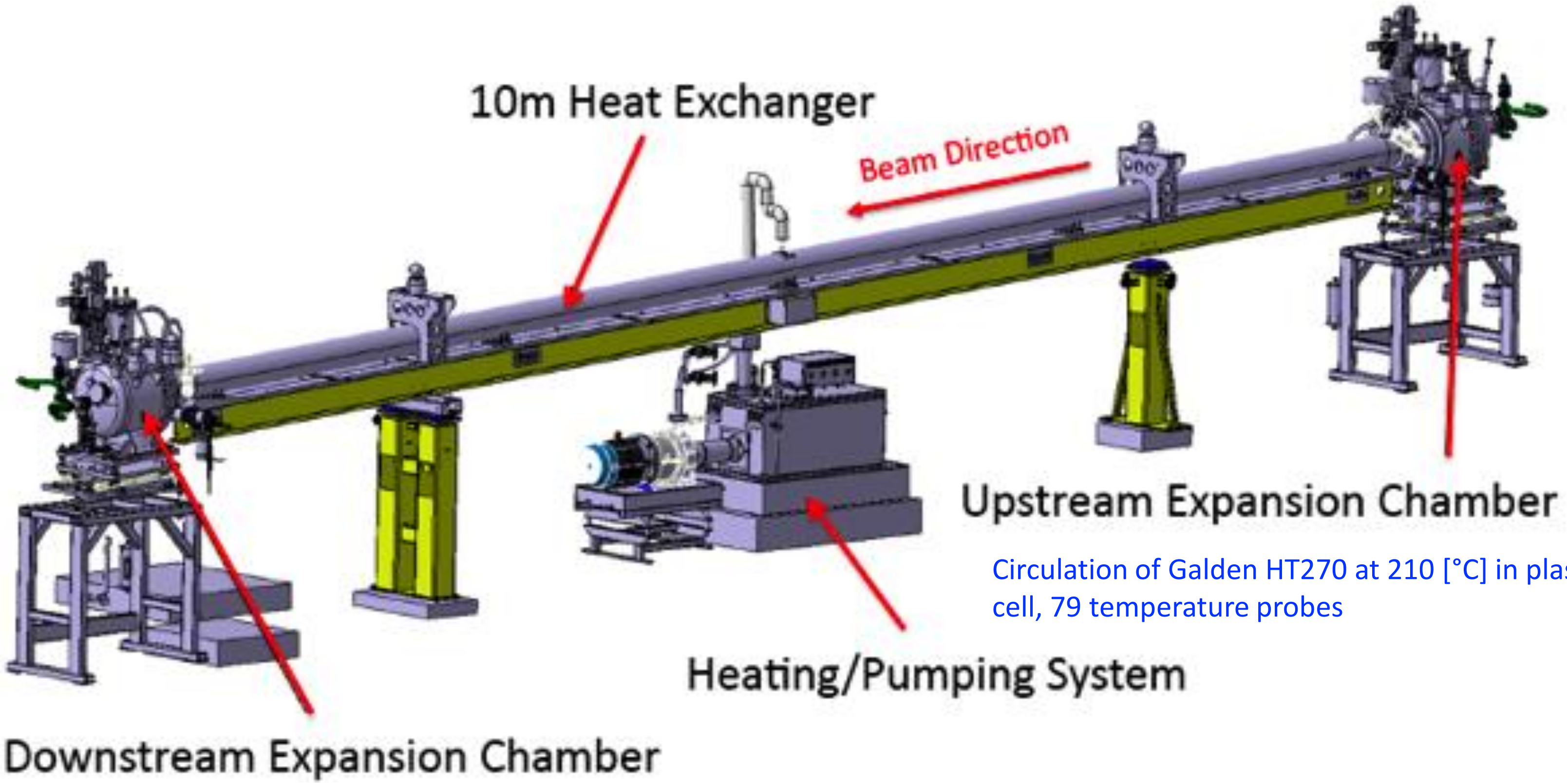




The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will injected into the same beamline.

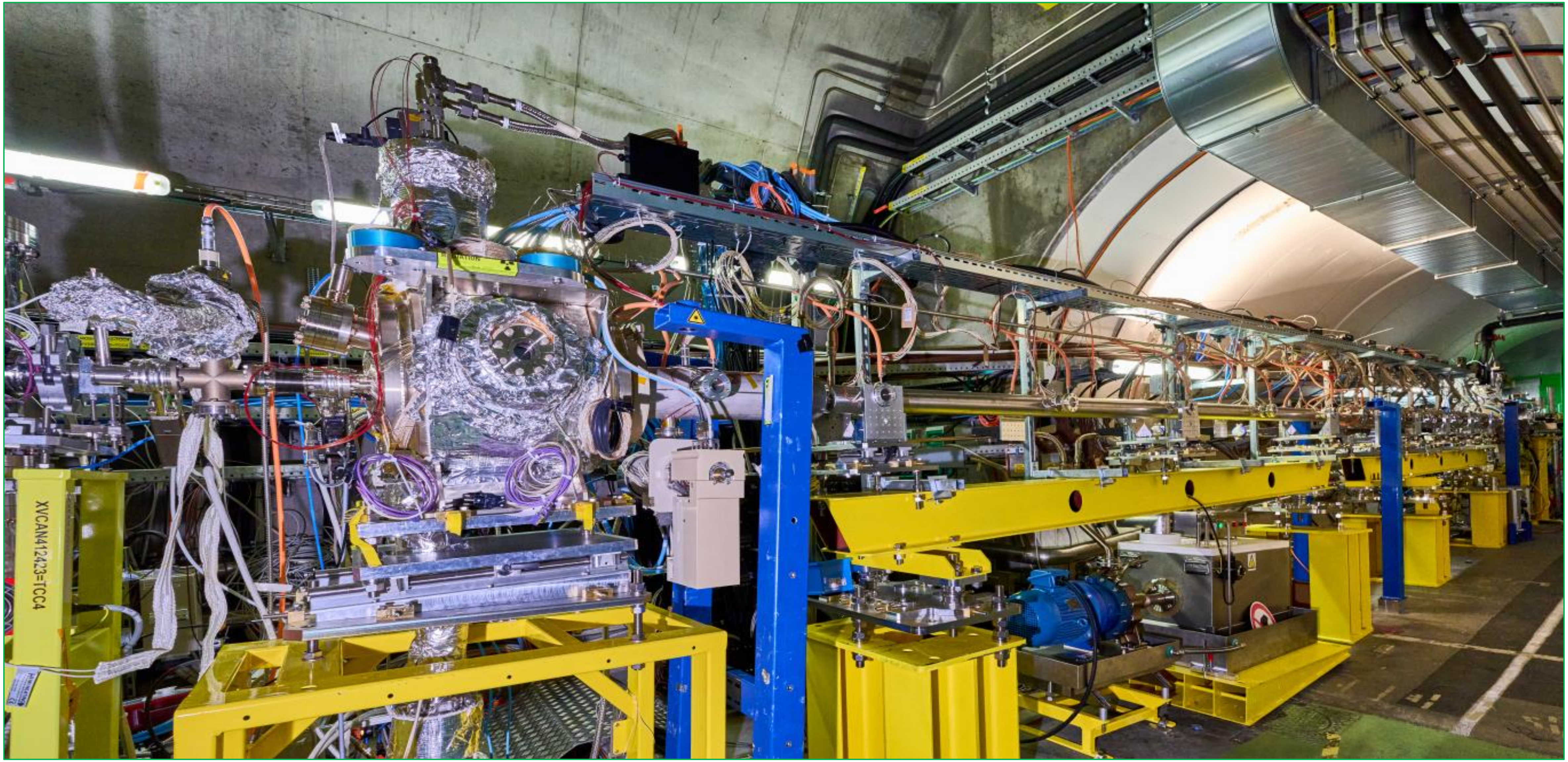
AWAKE Plasma Cell

- **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}



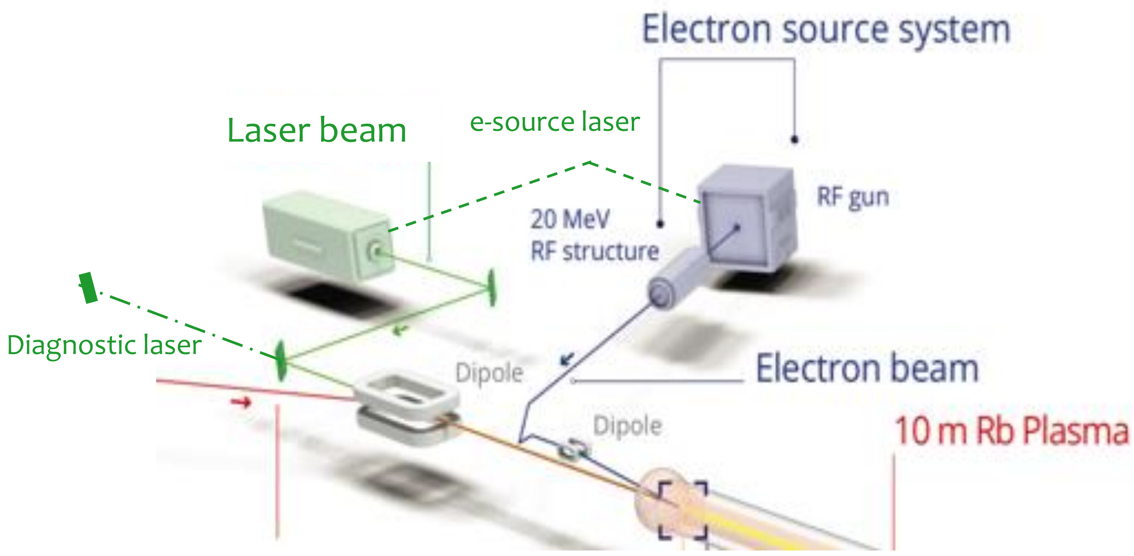
Circulation of Galden HT270 at 210 [°C] in plasma cell, 79 temperature probes

AWAKE Plasma Cell

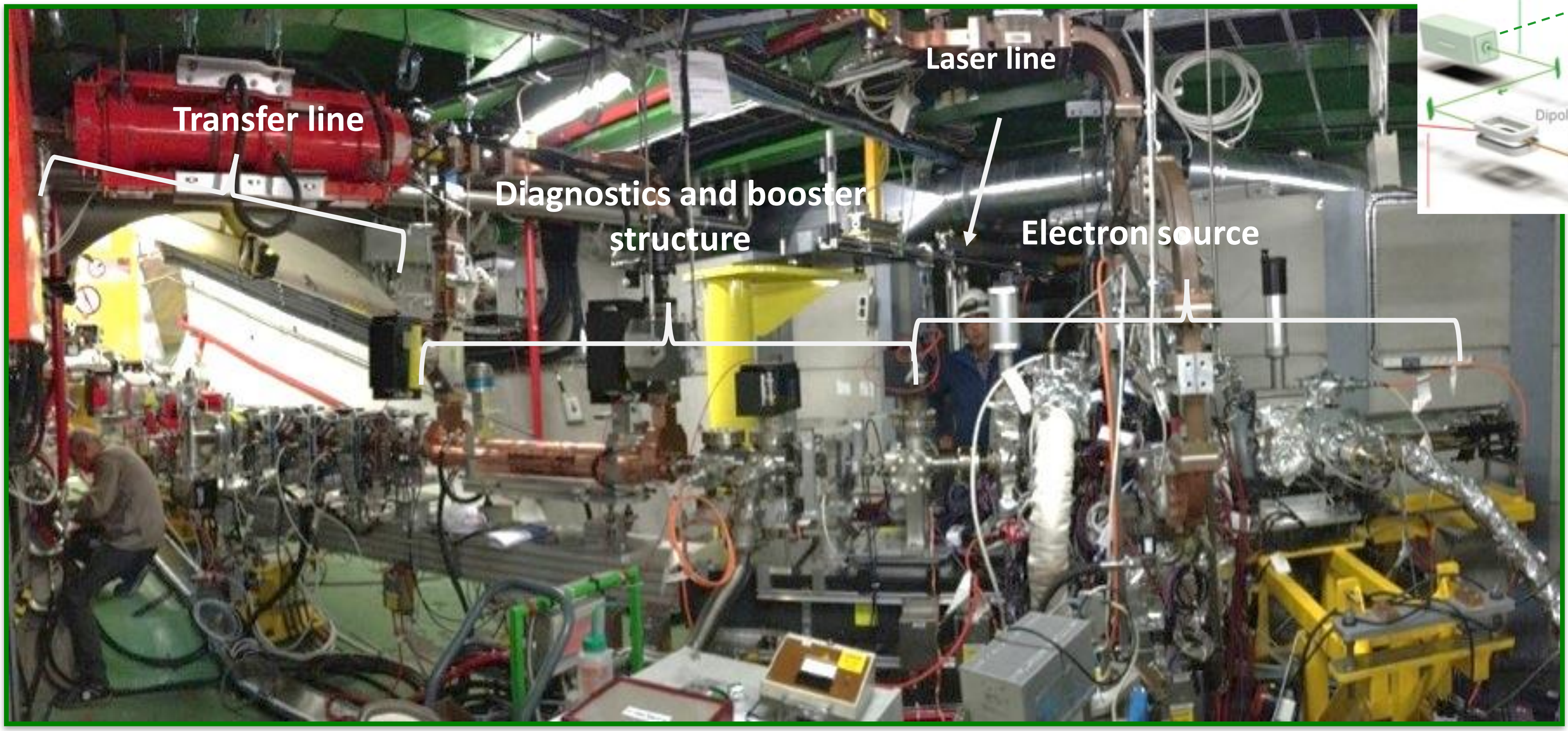


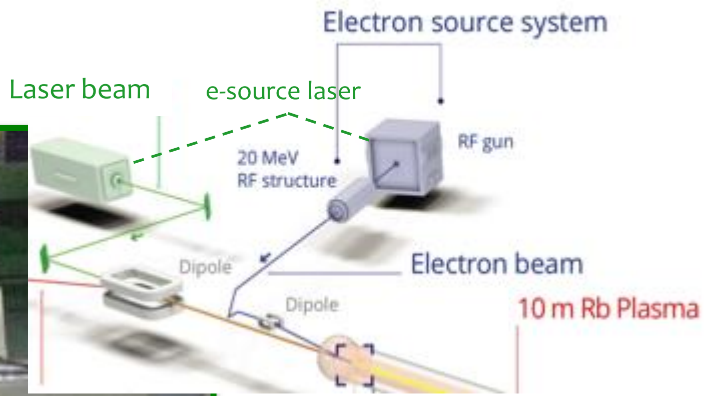
Laser and Laser Line

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**.



Electron Beam System

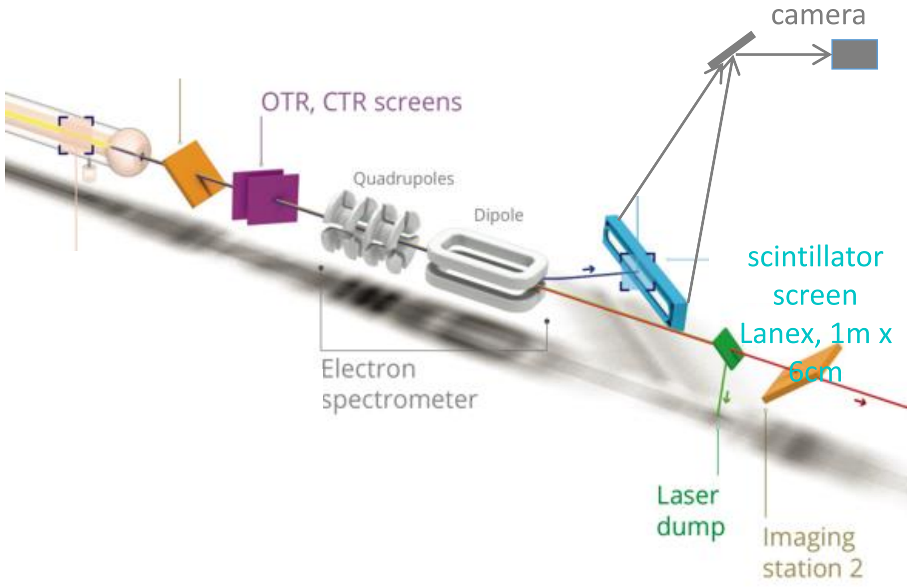




A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

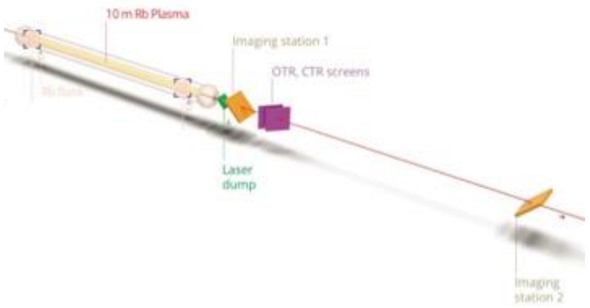
Challenge: cross the electron beam with the proton beam inside the plasma at a precision of ~100 μm.

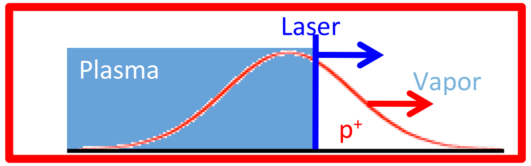
Electron Acceleration Diagnostics



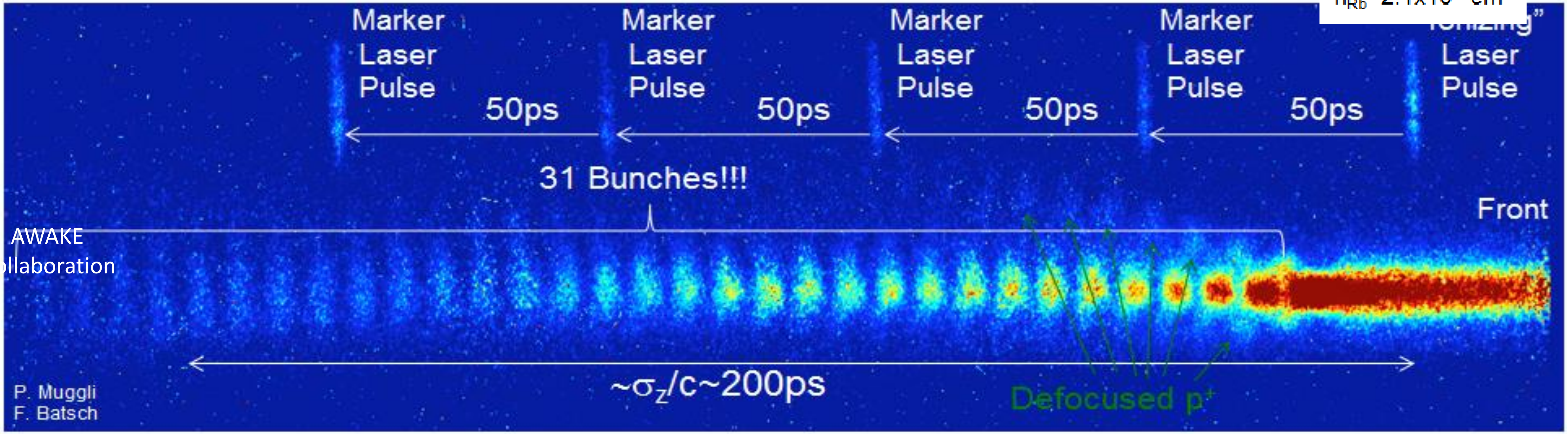
Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a **dipole spectrometer and the dispersed electron impact on the scintillator screen.**
The resulting light is collected with an intensified CCD camera.

Results Run 1: Direct Seeded Self-Modulation Measurement





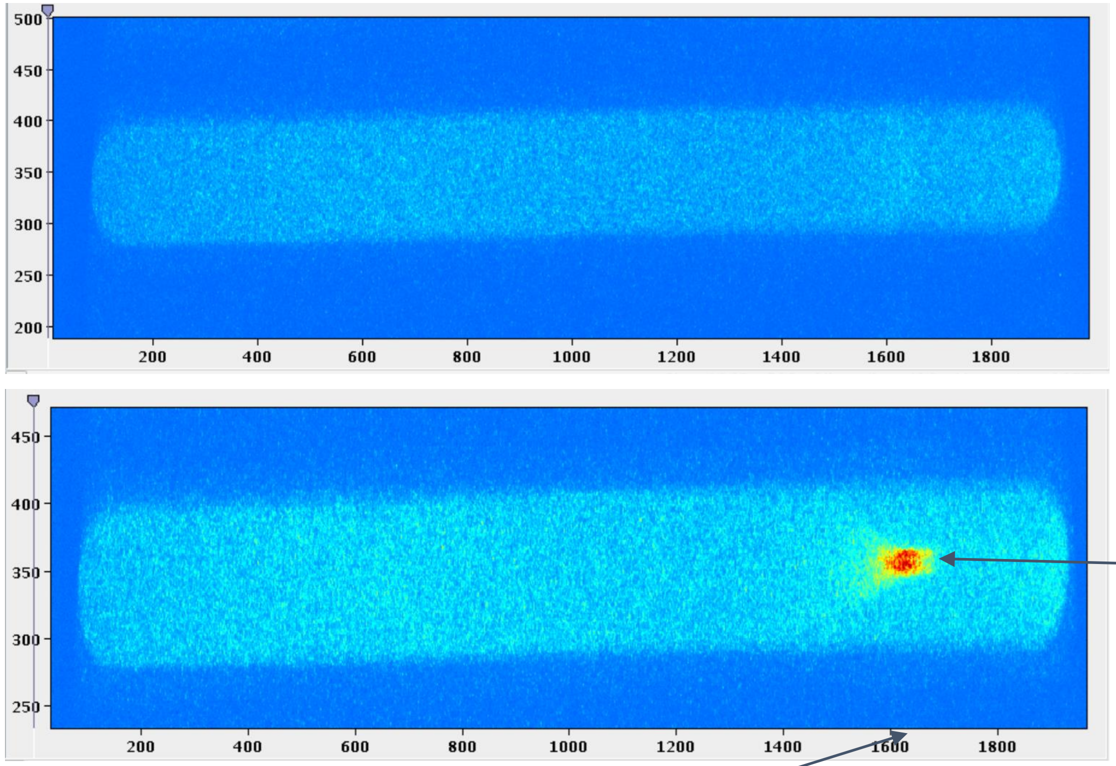
$n_{Rb}=2.1\times10^{14}cm^{-3}$



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).

Beschleunigung von Elektronen

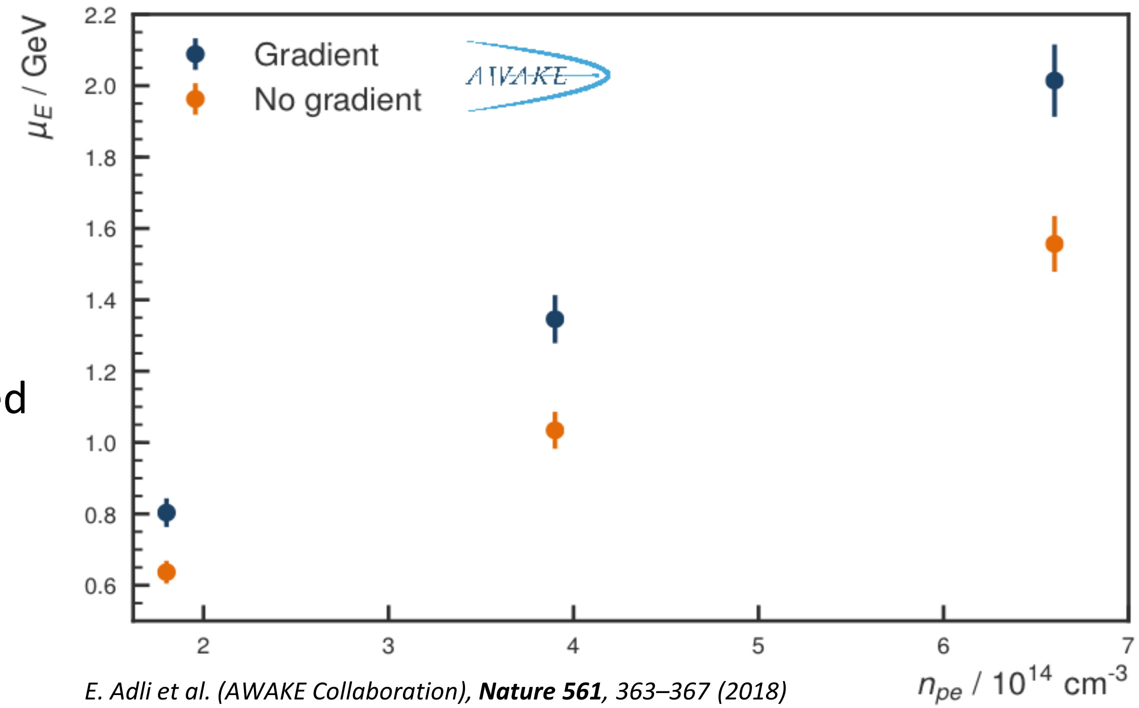
- **Acceleration up to 2 GeV** has been achieved.
- Charge capture up to 20%.



No accelerated electrons

Accelerated electrons

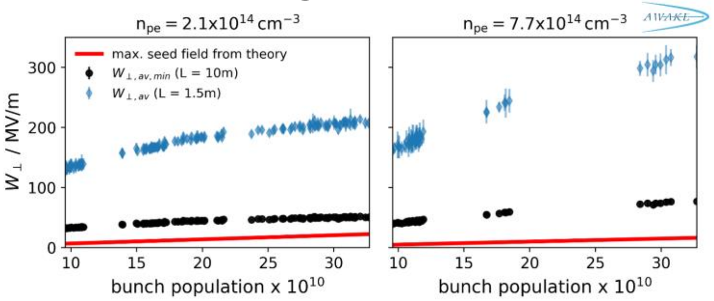
Convert pixel-size and dipole setting to energy



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

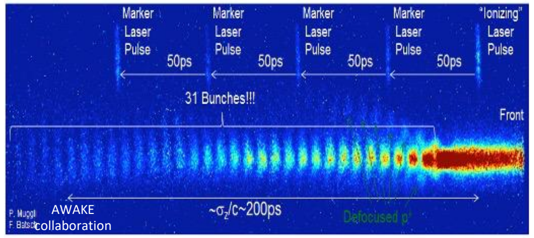
AWAKE Scientific Merit

Wakefield growth due to SM



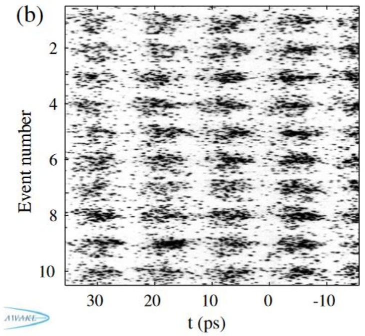
M. Turner et al. (AWAKE Collaboration), 'Phys. Rev. Lett. 122, 054801 (2019).

Proton bunch self-modulation



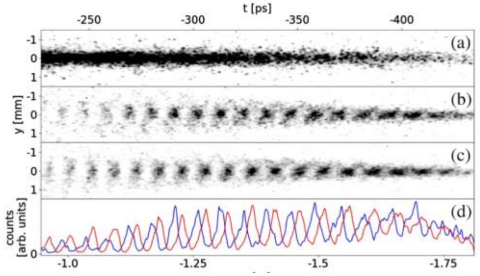
AWAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).

Seeding with relativ. ionization front



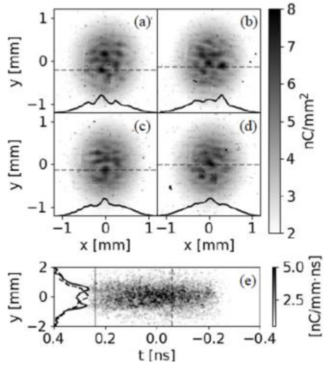
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

Seeding with electron bunch



L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

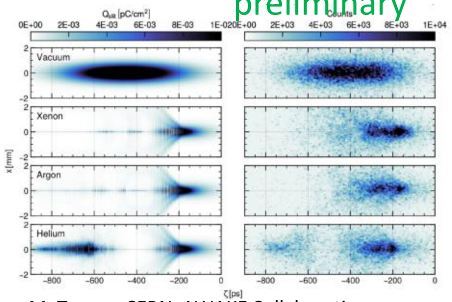
Filamentation instability



L. Verra, et al. (AWAKE Collaboration), Phys. Rev. E 109, 055203 (2024).

Ion motion, Sim/Meas

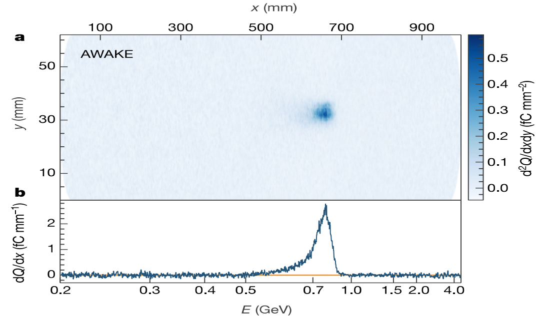
preliminary



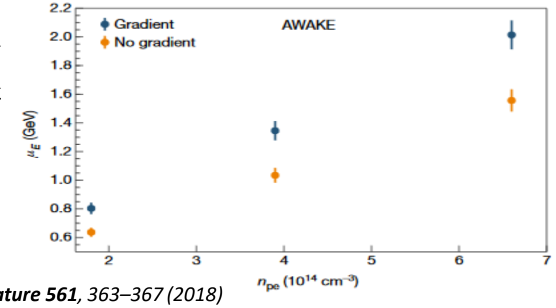
M. Turner, CERN, AWAKE Collaboration

- ✓ All milestones achieved – plus additional ones.
  - ✓ Relevant studies for general plasma wakefield acceleration concepts.
- ✓ Investing in young researchers.
- ✓ Many prizes, thesis and publications in high impact journals.

Accelerated electrons

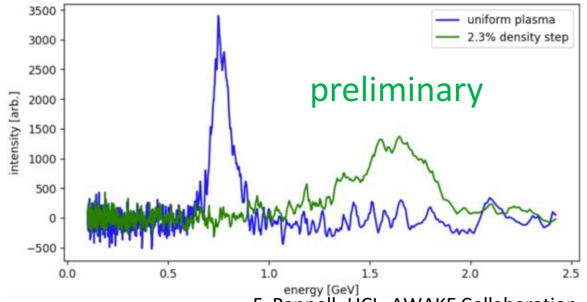


Increase e-energy with density gradients



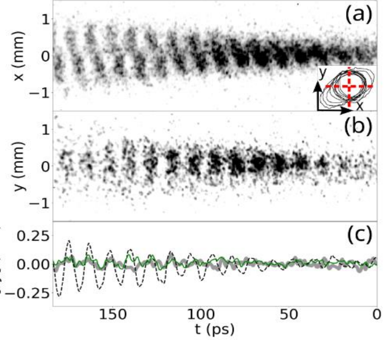
*AWAKE Collaboration, **Nature 561**, 363–367 (2018)*

Effect of density step on accelerated electrons



F. Pannell, UCL, AWAKE Collaboration

Beam-hose instability



T. Nechaeva, et al. (AWAKE Collaboration), Phys. Rev. Lett. 132, 075001 (2024).

AWAKE Program

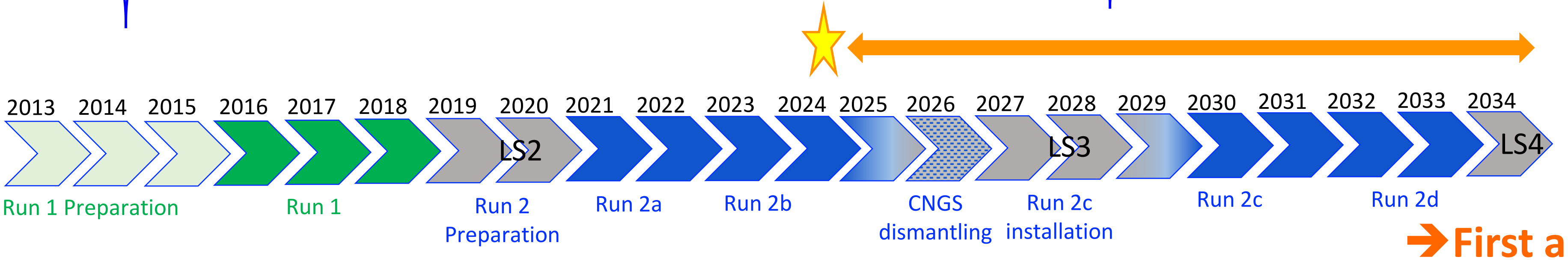
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2033)

e- acceleration to several GeV,
beam quality control, scalability



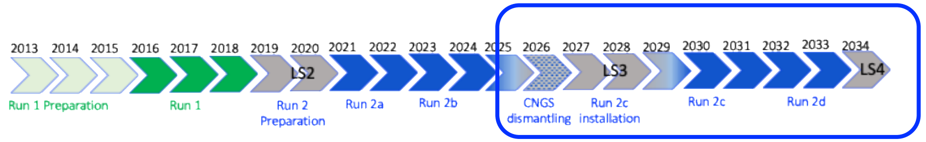
➔ **First applications >2034**

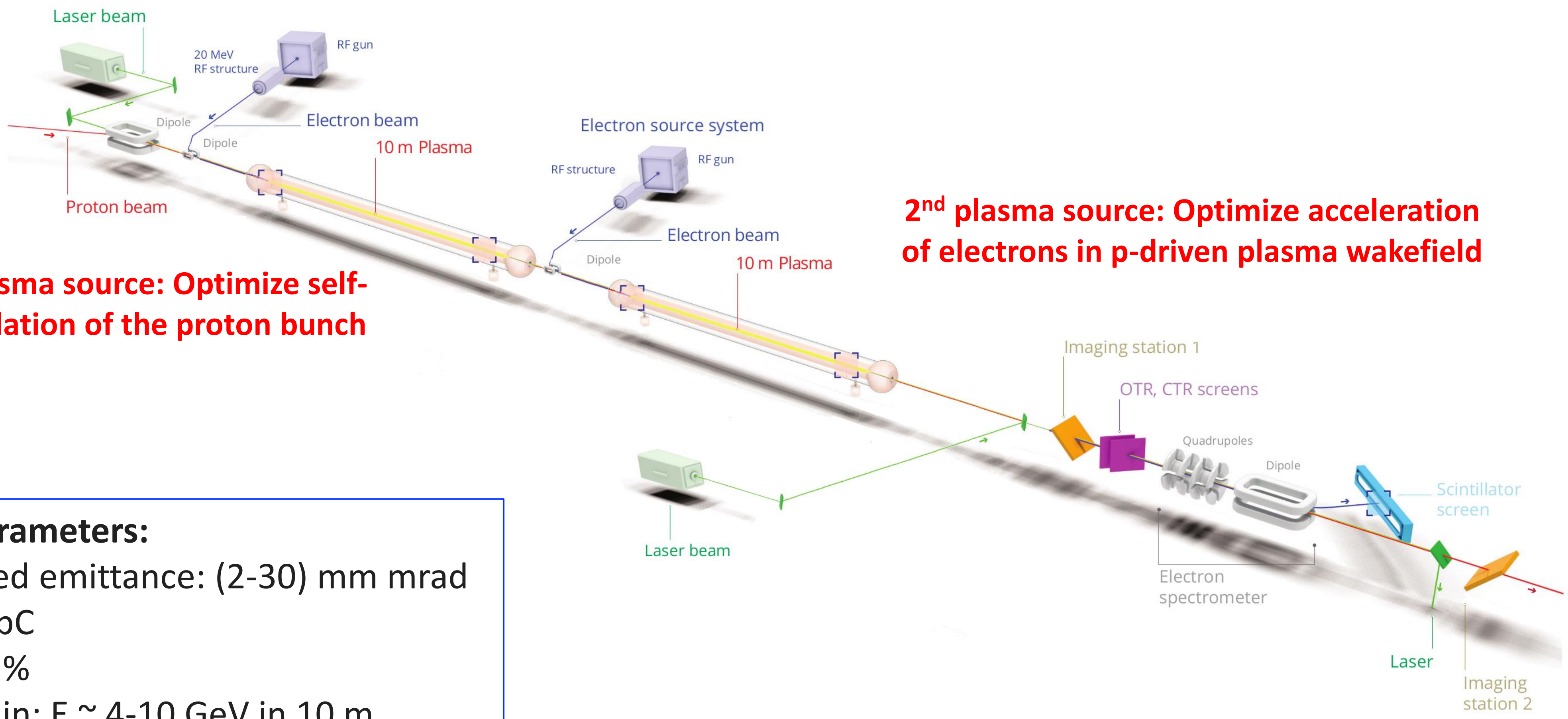
In Run 2: paradigm change:

➔ Move from 'acceleration R&D' to an 'accelerator'

AWAKE Run 2

Accelerate an electron beam to **high energies**, while controlling the electron **beam quality** and demonstrate **scalable plasma source** technology.





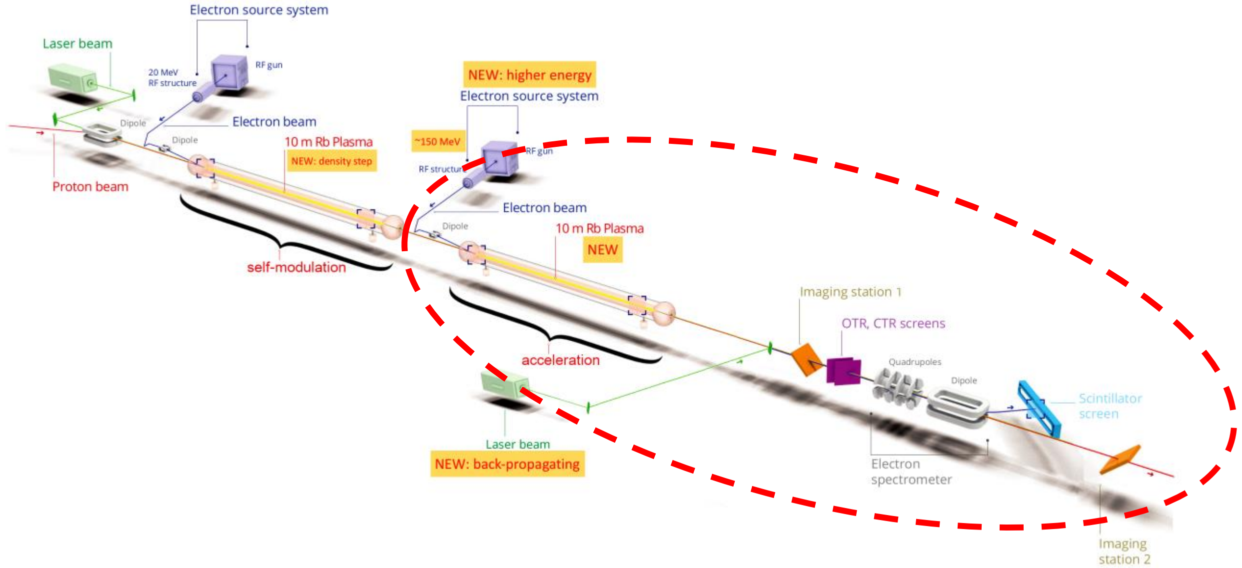
1st plasma source: Optimize self-modulation of the proton bunch

2nd plasma source: Optimize acceleration of electrons in p-driven plasma wakefield

Expected parameters:

- Normalized emittance: (2-30) mm mrad
- Q_e = 100 pC
- dE/E: 5-8 %
- Energy gain: E ~ 4-10 GeV in 10 m

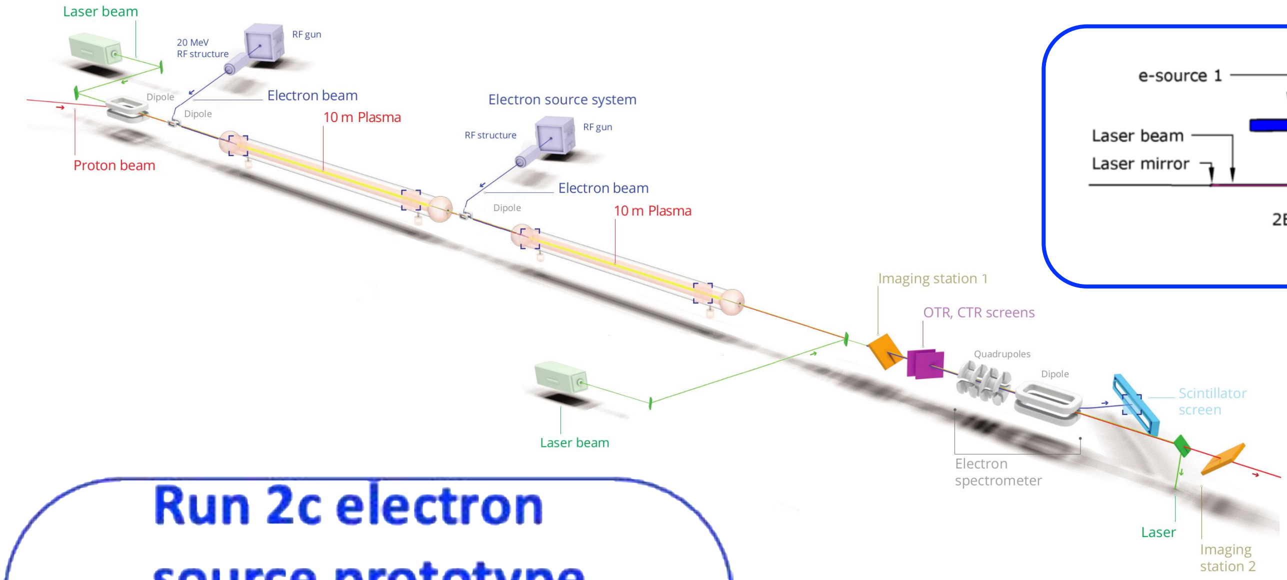
Preparing for AWAKE Run 2c/d during LS3

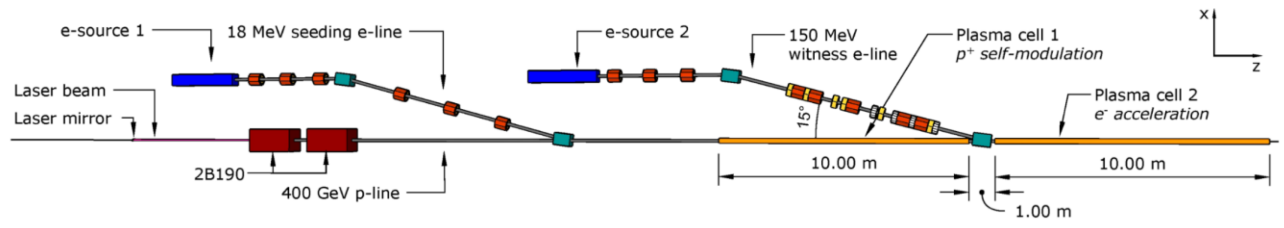


CERN Neutrino Gran Sasso area content (~600m^3):

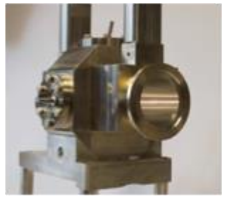
- **~500 large shielding blocks** (0,05-0,6 mSv/h)
- A few **high dose-rate elements** (50mSv/h)
- 70-meter-long aluminum **He-tank**
- **Various** supports, ducts…

AWAKE Run 2 Preparations





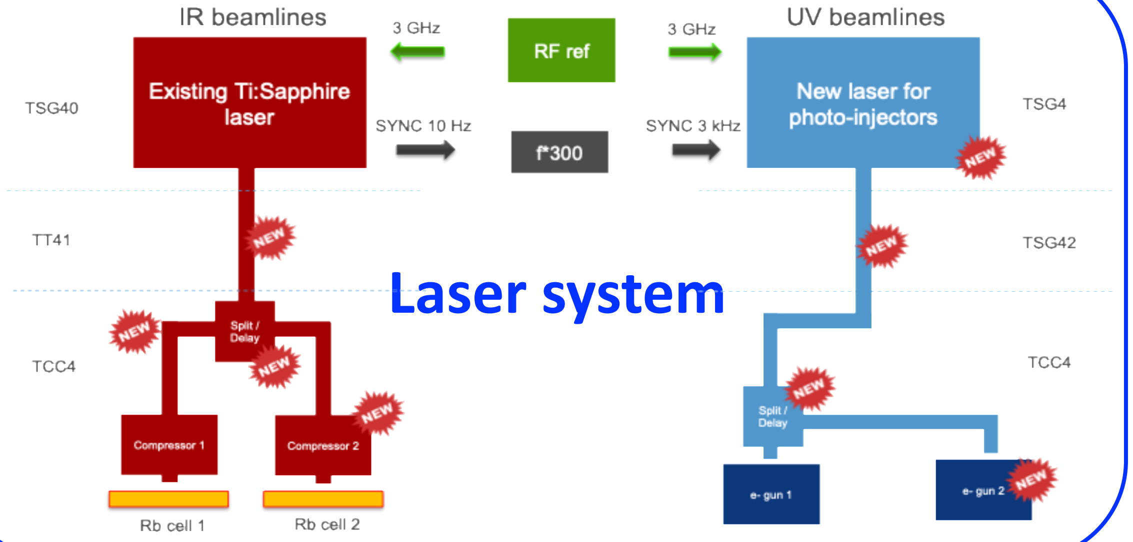
Beam instrumentation



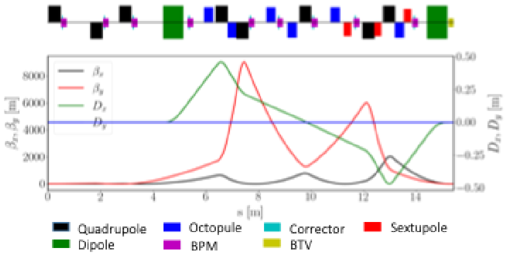
BPMs 10 µm resolution

Run 2c electron source prototype

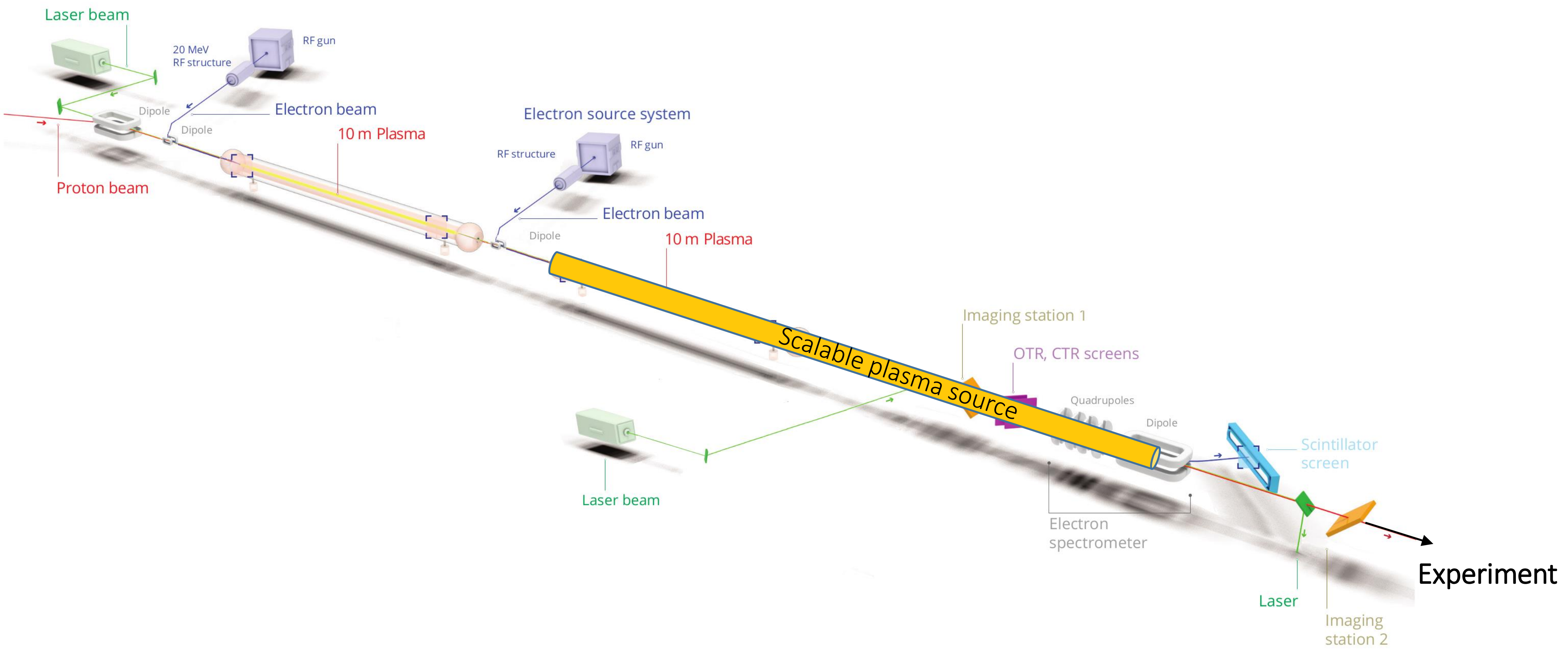
S-band e-gun (INFN) with
X-band accelerator (CLIC/CLEAR)



150 MeV beamline



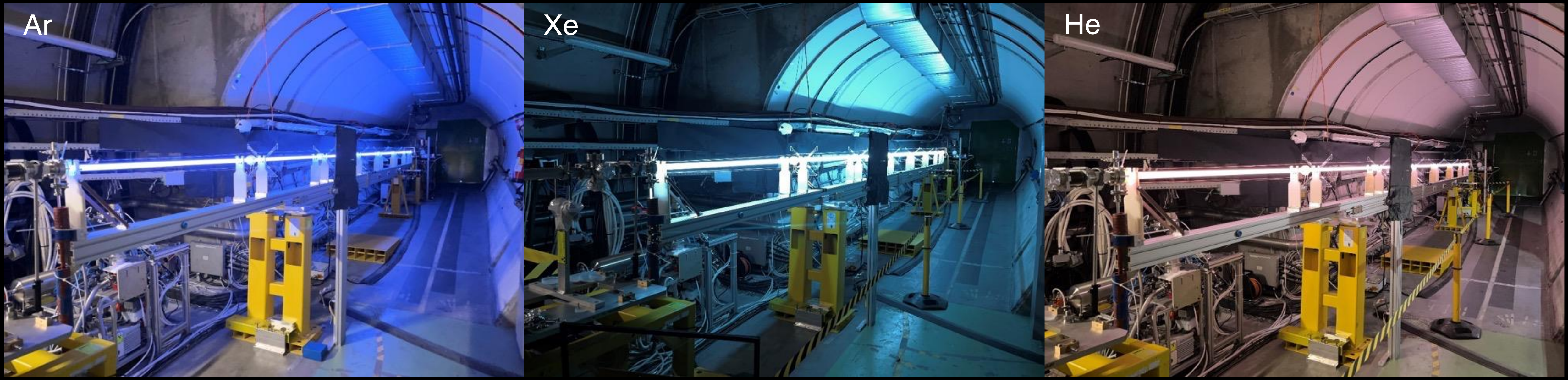
AWAKE Run 2: Demonstrate Scalable Plasma Sources



10 m Discharge Plasma Source in AWAKE

➔ Possible candidate for plasma source in Run 2c/d (2029-2034) and particle physics applications

Unique opportunity to test the discharge plasma source in May 2023 with protons in the AWAKE facility



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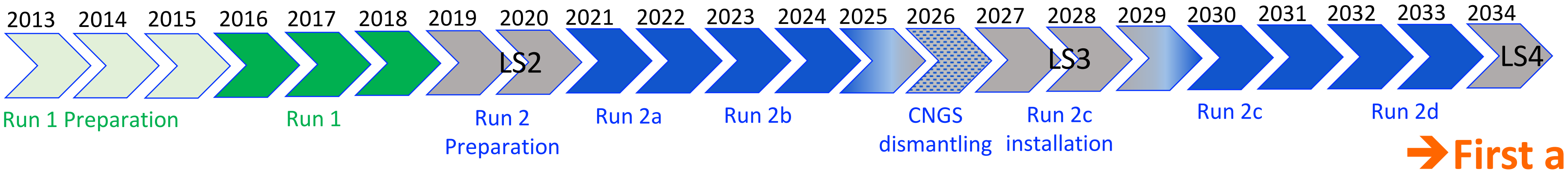
p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2033)

e- acceleration to several GeV,
beam quality control, scalability



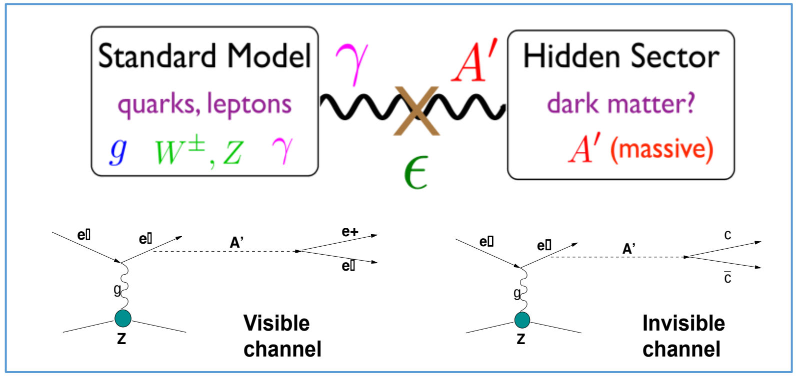
→ First applications >2034

Applications with AWAKE-Like Scheme

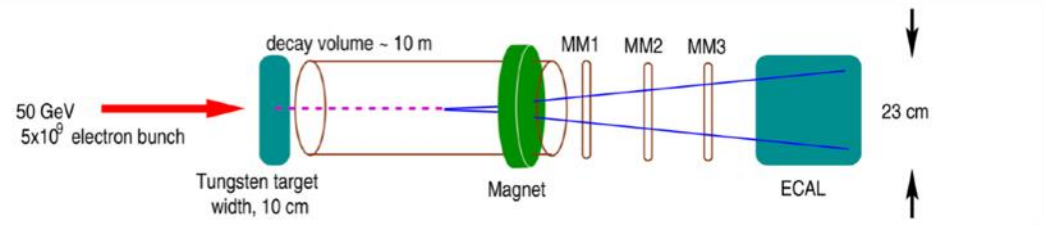
➔ **Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!**

First Application: Fixed target test facility:

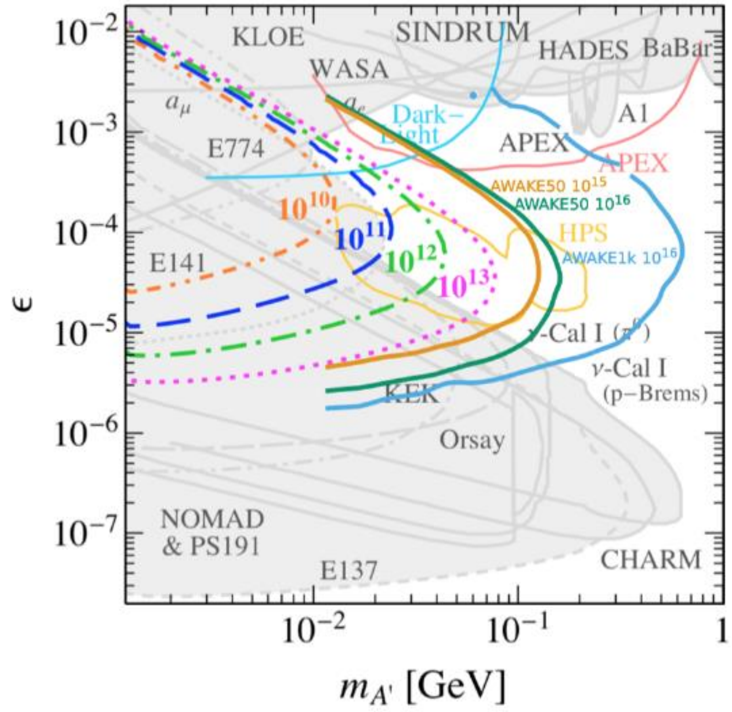
→ Deep inelastic scattering, non-linear QED, **search for dark photons**



→ 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.



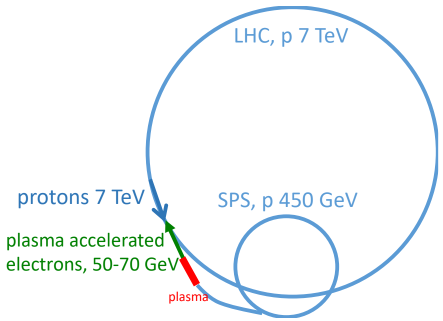
→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

10^{16} electrons on target with AWAKE-like beam (**Factor 1000 more than NA64)**

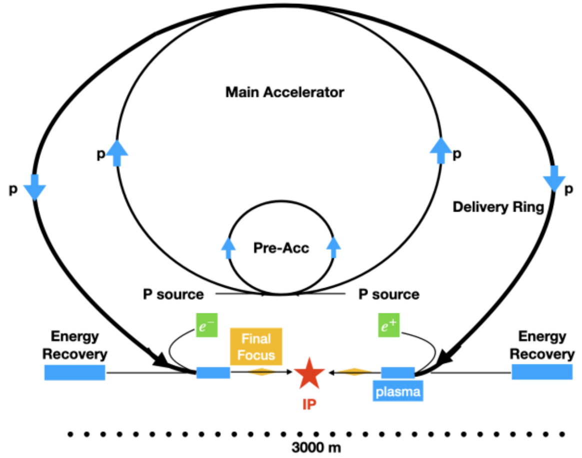
- **50 GeV e-beam**: Extend sensitivity further to ε~ 10^{-3} – 10^{-5} and to high masses~*0.1 GeV*.
- 1 TeV e-beam: : Similar ε values, approaching *1 GeV, b*eyond any other planned experiments.

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. 1pb^{-1}/yr.
  - New energy regime means new physics sensitivity even at low luminosities.
- **Fixed target** variants with these electron beams
- **Higgs factory: electron-positron collider 250 GeV c.o.m, proton driven**
  - J. Farmer, A. Caldwell, A. Pukhov, NJP**, DOI** 10.1088/1367-2630/ad8fc5 (2024)



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**

Vielen Dank fuer Ihre Aufmerksamkeit!