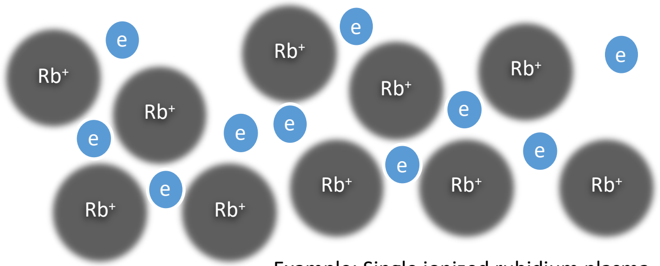
Plasma Wakefield Acceleration and the AWAKE Experiment at CERN

Edda Gschwendtner, CERN

LISA Conference
1 – 4 September 2024


Bruce Marsh
In loving memory

Plasma Wakefield Acceleration



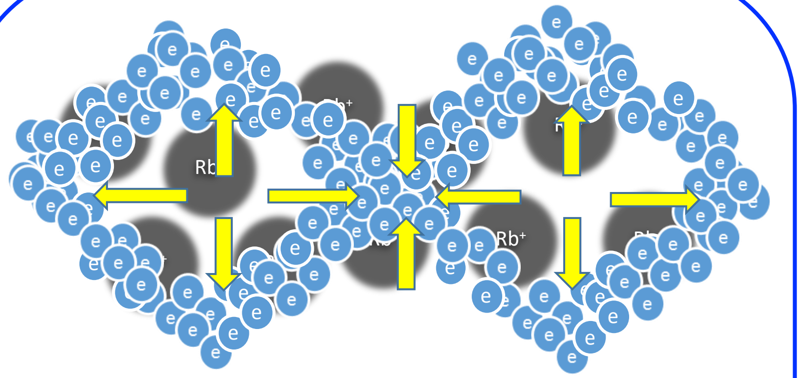
Example: Single ionized rubidium plasma

PLASMA is the 4th state of matter

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.

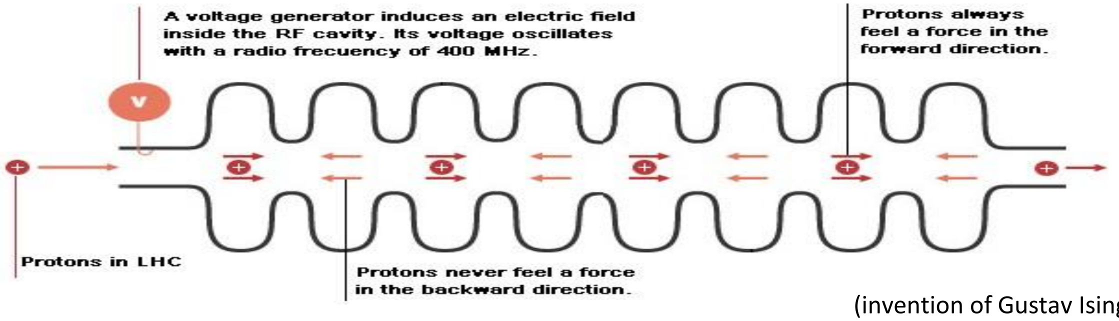
Electrostatic interactions dominate over collisions or ordinary gas kinetics.



Plasma WAKEFIELDS are the fields created by collective motion of plasma particles are called.

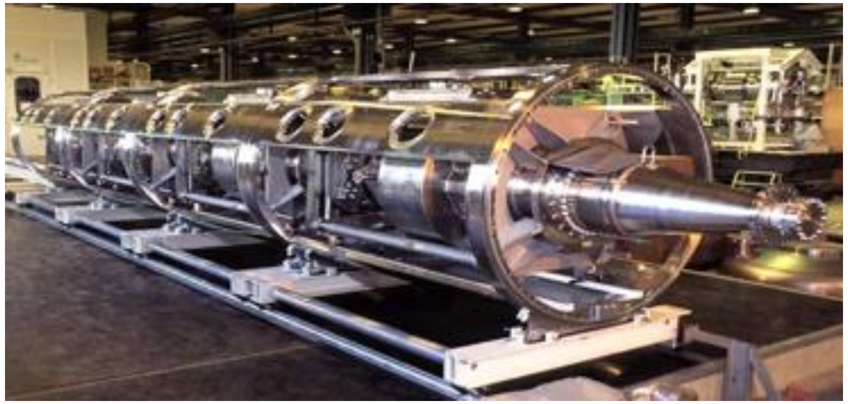
ACCELERATION of charged particles when they experience an electric field.
Strength of the acceleration:
'Accelerating gradient' : ~MV/m

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity



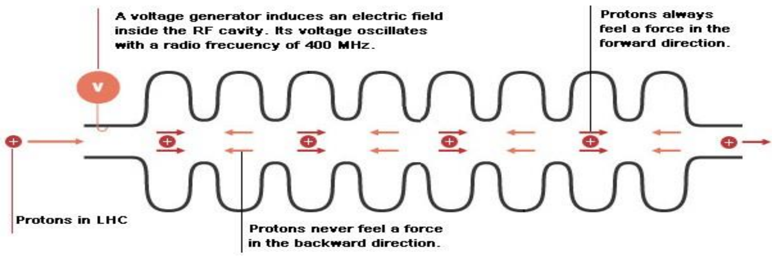
Typical gradients:

LHC: 5 MV/m
ILC: 35 MV/m
CLIC: 100 MV/m

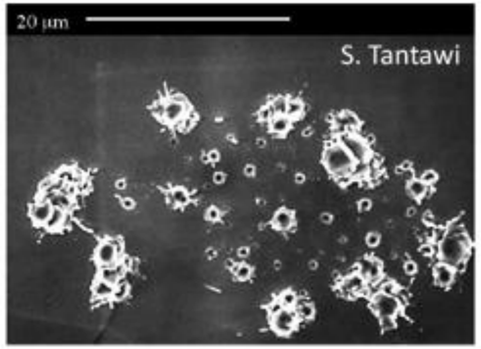
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

Accelerating Gradient

Conventional RF Cavities



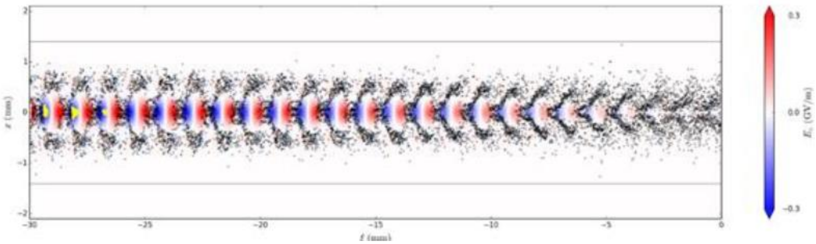
Surface of Copper Cell After Breakdown Events

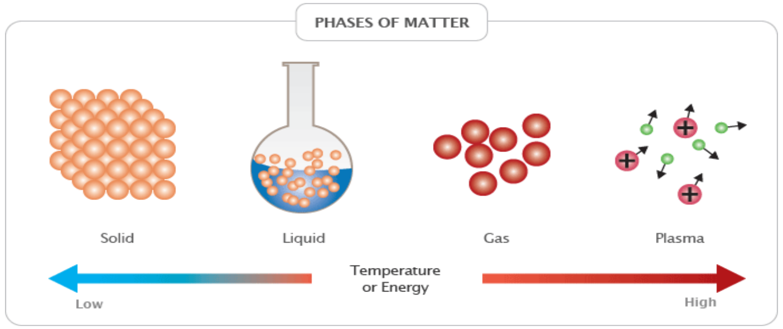


Accelerating fields are **limited to <100 MV/m**

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.

Plasma Acceleration





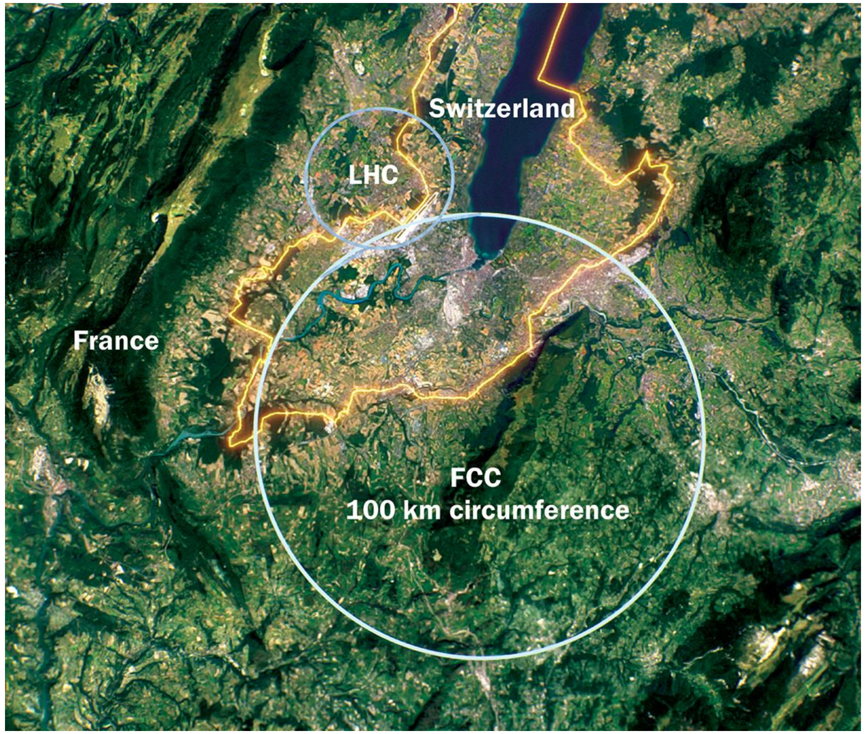
Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

→ **order of 100 GV/m.**

→ **~1000 factor stronger acceleration!**

Circular Accelerators

To discover new physics: accelerate particles to even higher energies



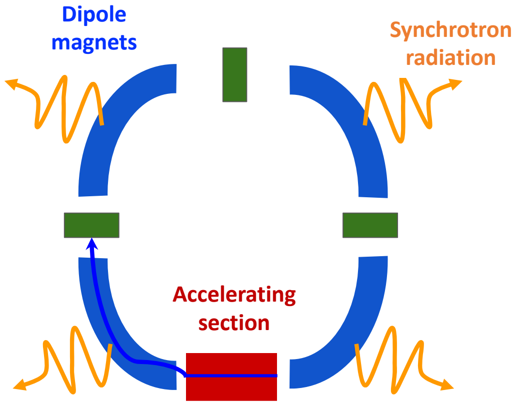
Conventional RF cavities ok for circular colliders:

👍 beam passes accelerating section several times.

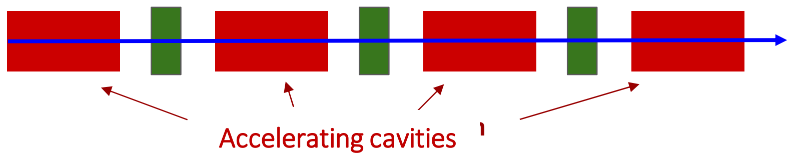
👎 **Limitations of electron-positron circular colliders:**

- 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.

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



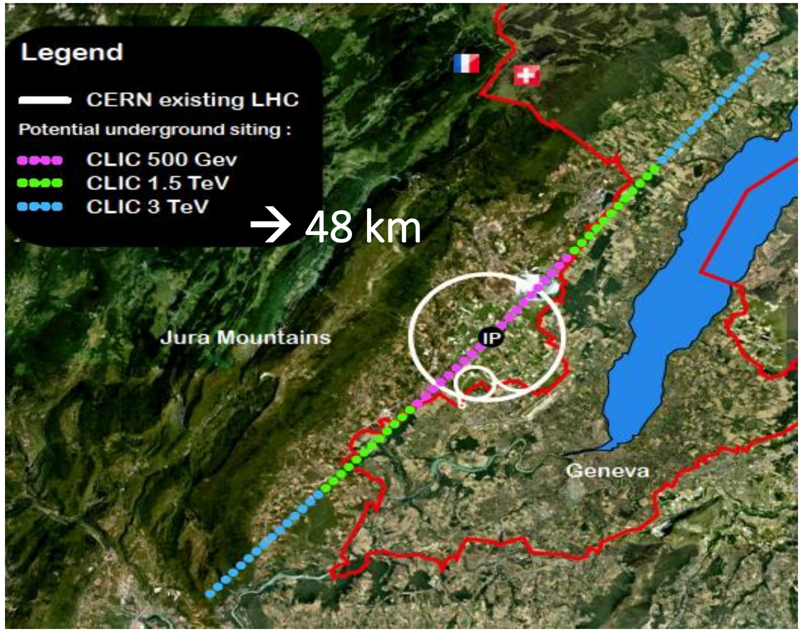
Linear Colliders



Favorable for acceleration of low mass particles to high energies.

Limitations to linear colliders:

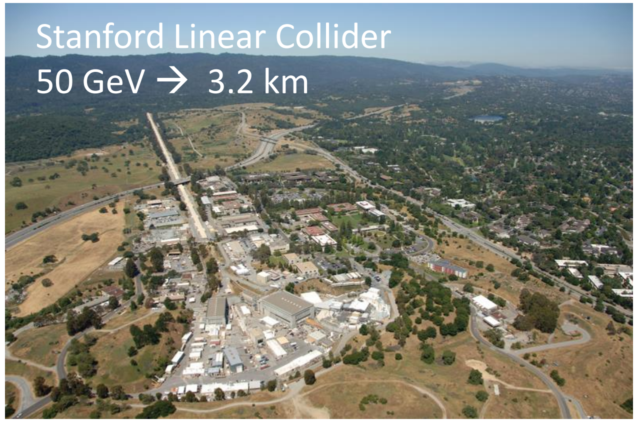
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.



CLIC, electron-positron collider with 3 TeV energy

Particle energy = accelerating gradient*distance

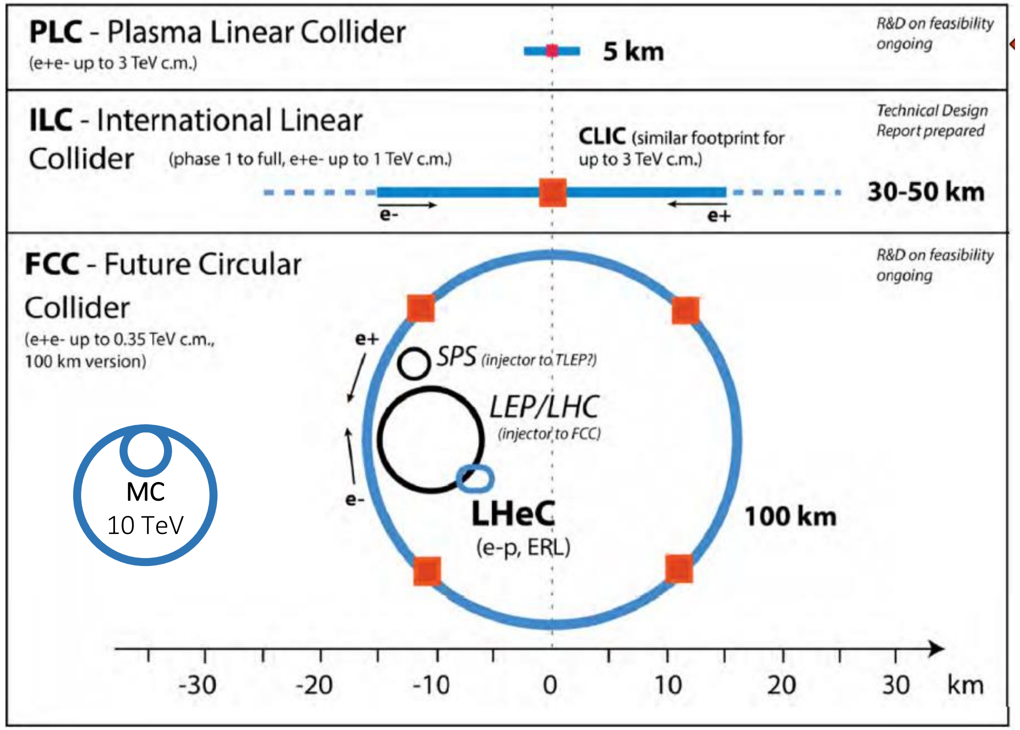
e.g. accelerate electrons to 1 TeV (10^{12} eV):
100 MeV/m x 10000 m or
100 GeV/m x 10 m



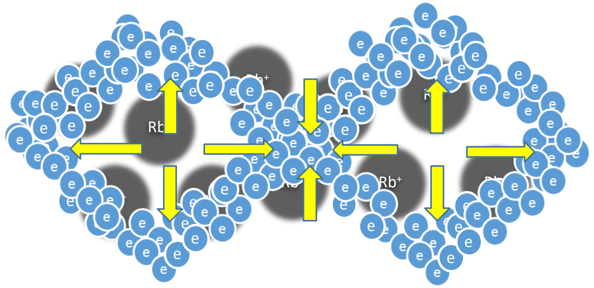
Plasma Wakefield Acceleration

The **high gradient of plasma wakefield acceleration** makes this technology very interesting for reducing the size (and cost) for future linear colliders.

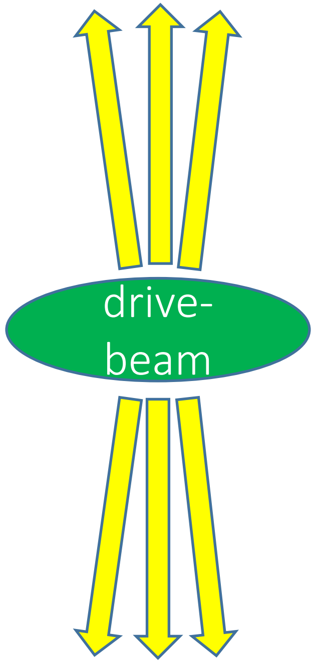
100 MV/m ➔ 100 GV/m



How to Create a Plasma Wakefield?



Energy source: the drive beam



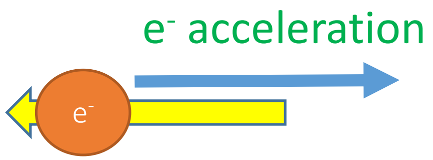
Charged particle bunches or laser bunches
→ carry almost purely transverse electric fields.

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

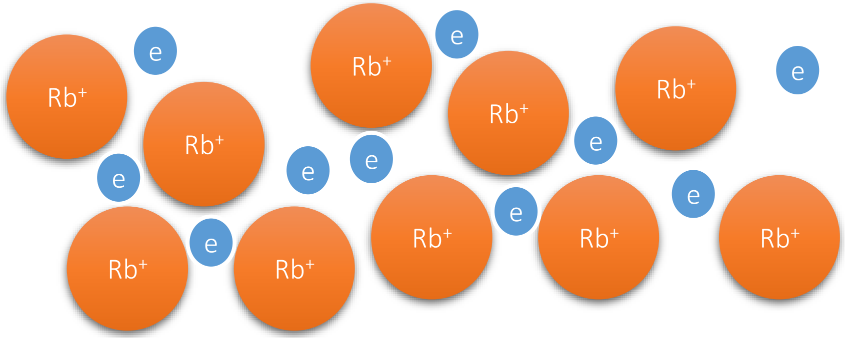
How to Create a Plasma Wakefield?

What we want:

Longitudinal electric field to accelerate charged particles.

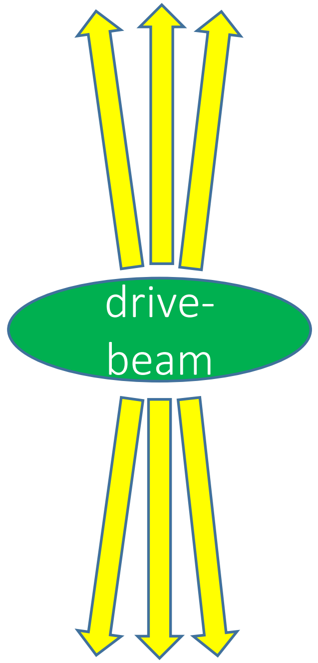


Our Tool:



Single ionized rubidium **plasma**

Energy source:



Charged particle bunches carry almost purely transverse Electric Fields.

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.

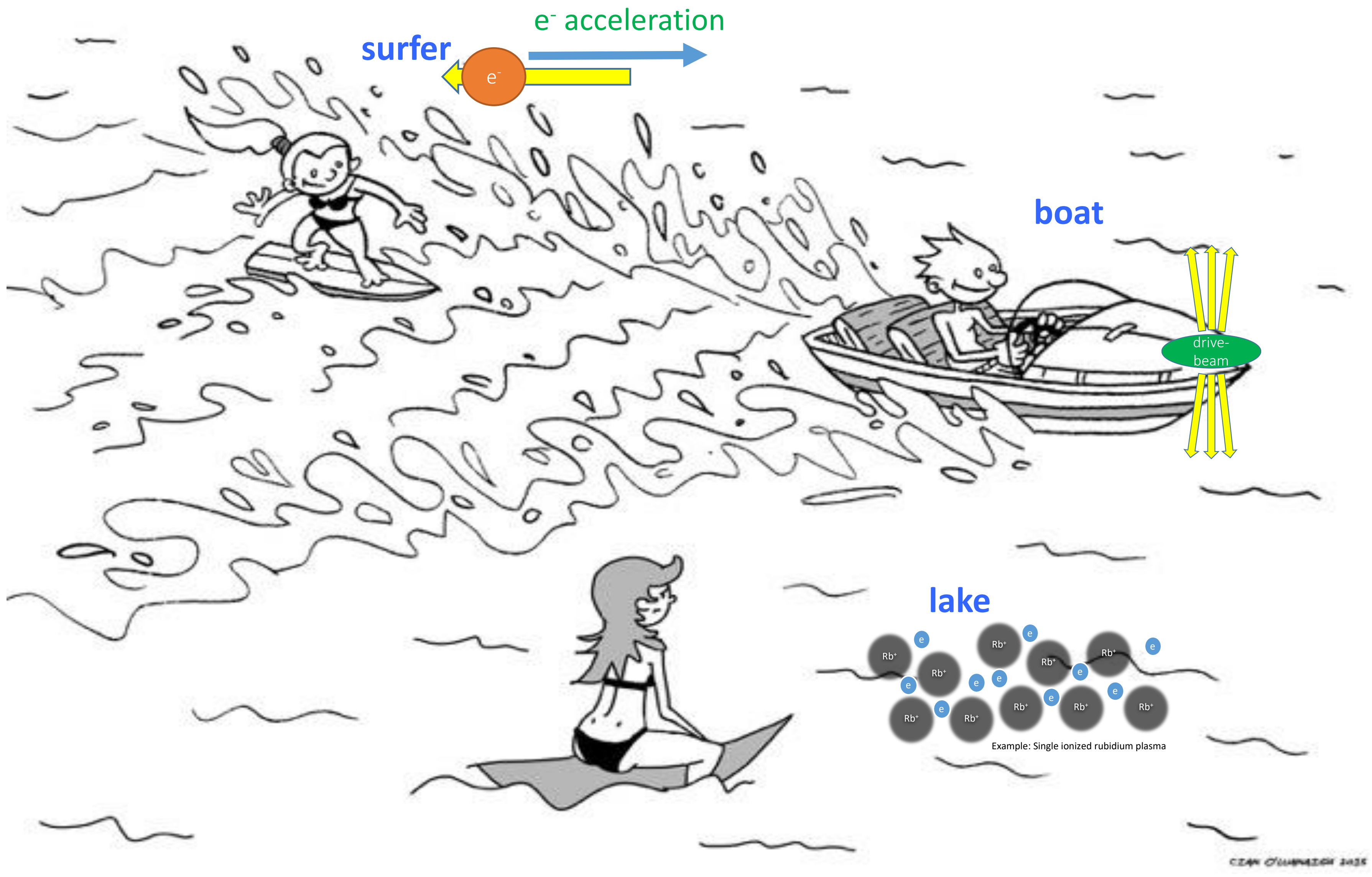
Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective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

How to Create a Plasma Wakefield?



Analogy:
lake → plasma

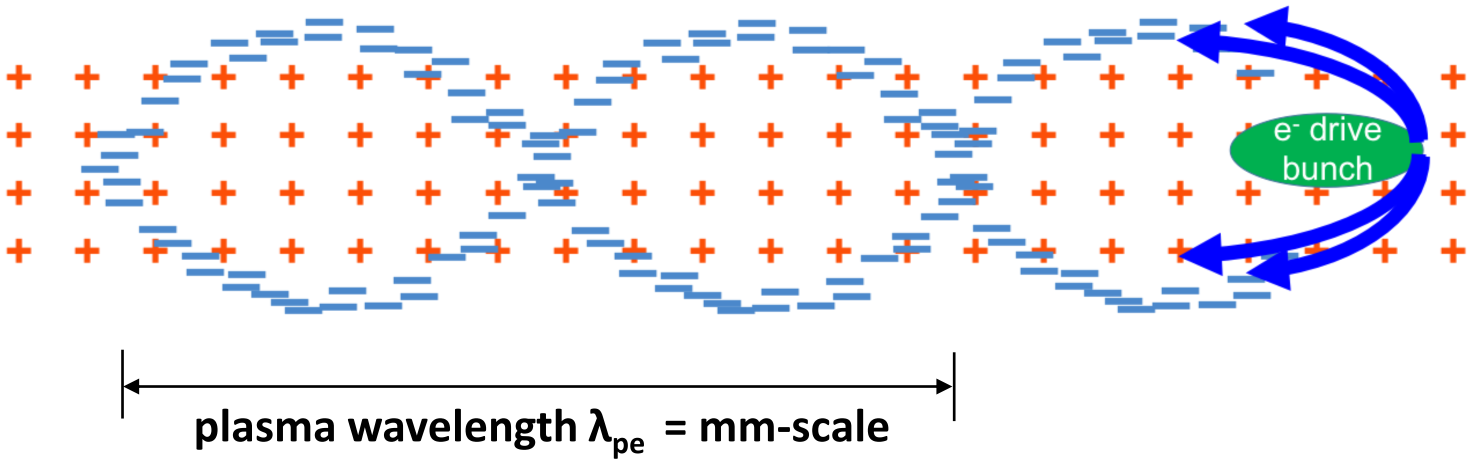
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Principle of Plasma Wakefield Acceleration

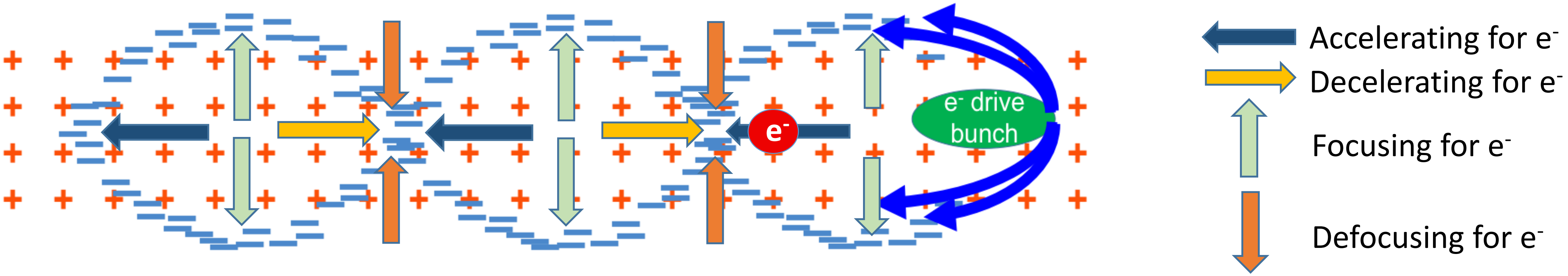
Boat:

- Laser drive beam
- Charged particle drive beam

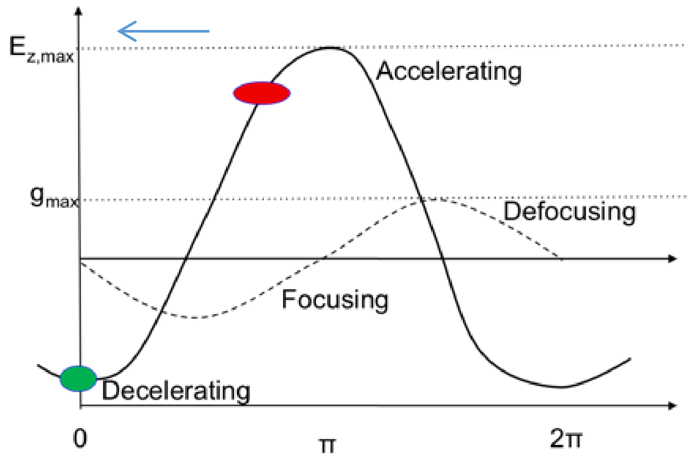


- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?



Longitudinal and transverse wakefields are π/2 out of phase
➔ Only ¼ of the electron oscillation length is focusing and accelerating for charged particles!




E. Gschwendtner, CERN

Plasma Wakefield, Density Scaling

Charged particle bunch traveling inside a plasma perturbs the plasma electron distribution

→ oscillation with $\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}}$ $\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}}$ → Plasma electron wavelength decreases with increasing plasma density

Example: $n_{pe} = 7 \times 10^{14}$ cm^{-3} (AWAKE). → **λ_{pe} = 1.2 mm** → Produce cavities with mm size!

The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

→ $E_{WB} = 96 \frac{V}{m} \sqrt{n_{pe}}$ → Maximum accelerating gradient increases with increasing plasma density

Example: $n_{pe} = 7 \times 10^{14}$ cm^{-3} (AWAKE) → E_{WB} = 2.5 GV/m
Example: $n_{pe} = 7 \times 10^{17}$ cm^{-3} → E_{WB} = 80 GV/m

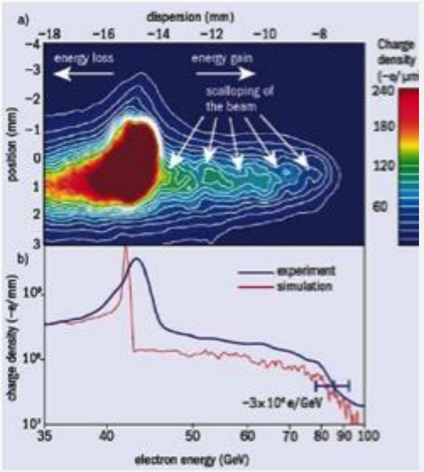
Some Highlights

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**

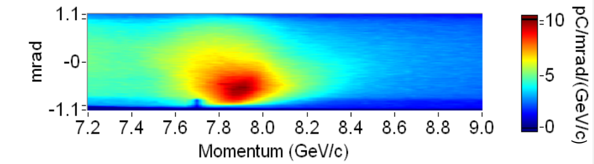


BELLA, Berkeley Lab, USA:
Laser-driven plasma wakefield acceleration Facility

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

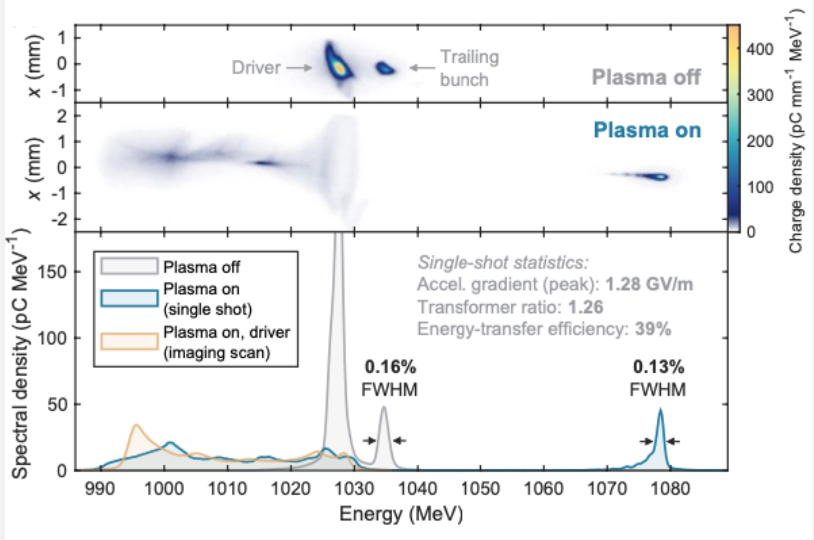
*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

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

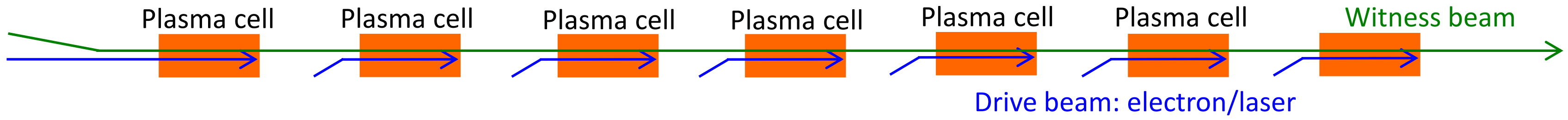
Plasma Wakefield Accelerators – Electron/Laser Drivers

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):

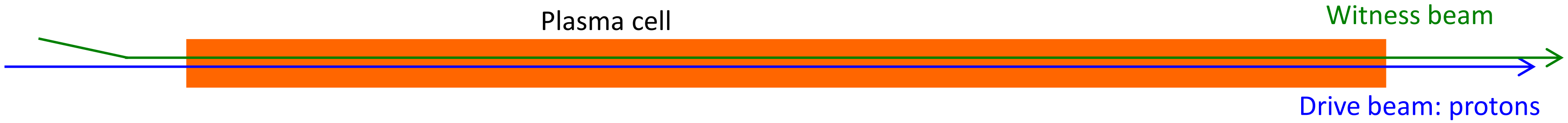
Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

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

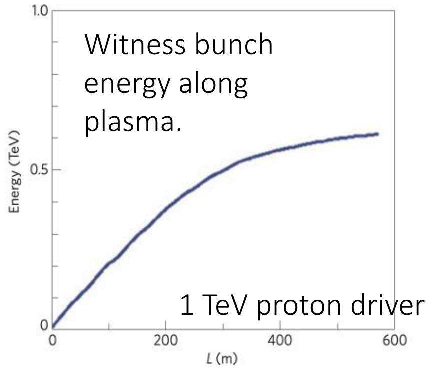
To reach TeV scale:

- **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)

The AWAKE Experiment

AWAKE is an International Collaboration

➔AWAKE is an international Collaboration, consisting of 22 institutes.

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

➔ Benefit from expertise from collaborating institutes.

AWAKE at CERN

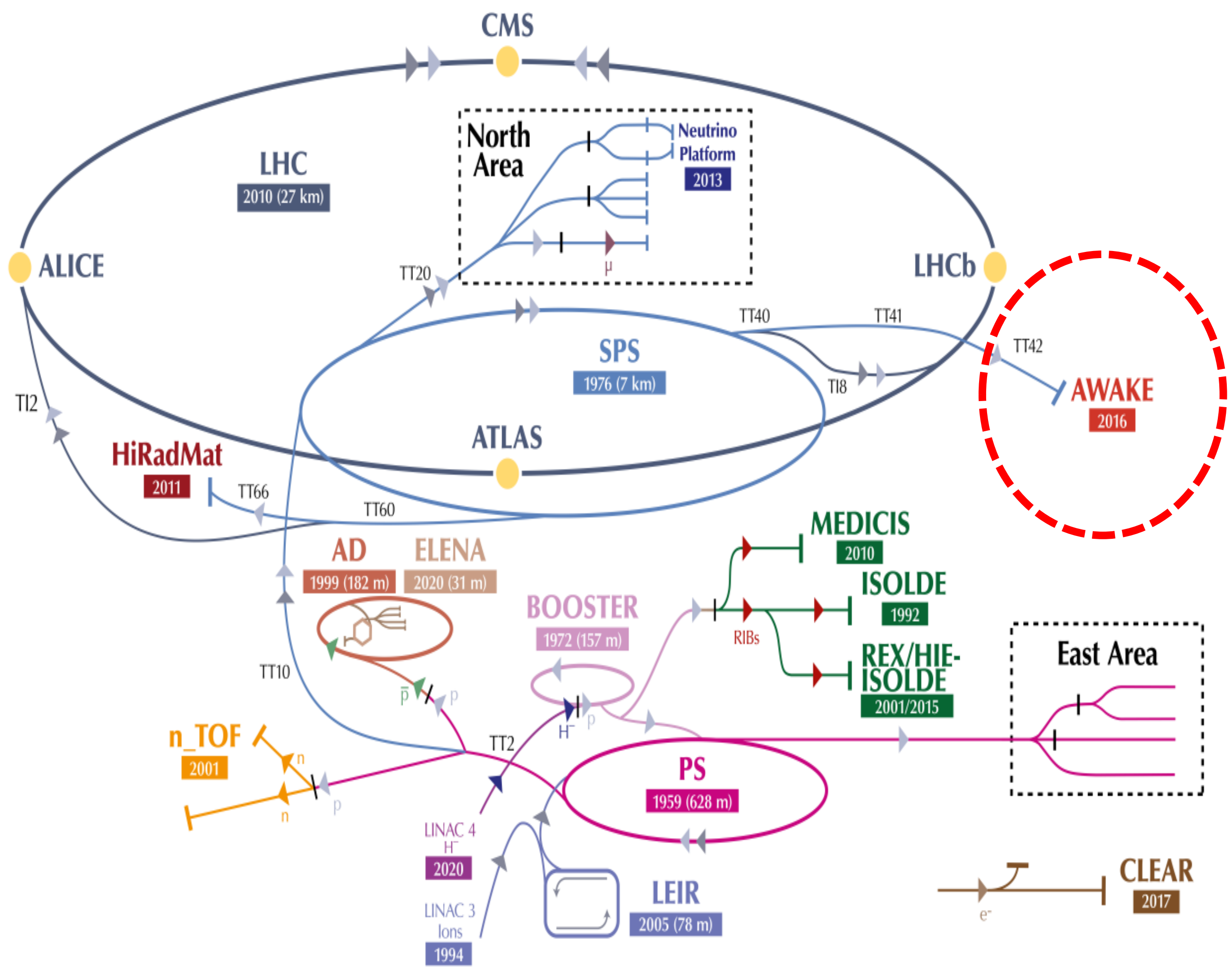
Advanced WAKEfield Experiment

➔Accelerator R&D experiment at CERN.

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

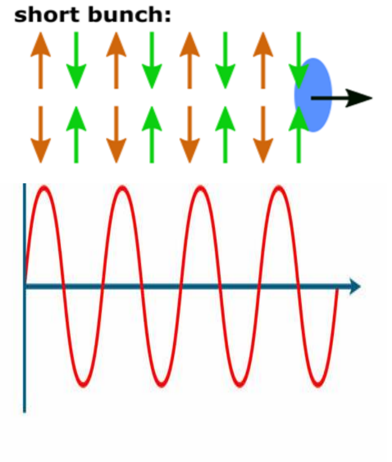
- ➔ At CERN highly relativistic protons with high energy (> kJ) available

➔Accelerating externally injected electrons to GeV scale.

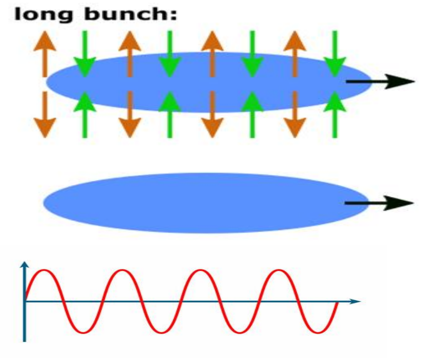


Proton Bunch as a Drive Beam

In order to create high wakefield amplitudes, the drive bunch length must be in the order of the plasma wavelength.

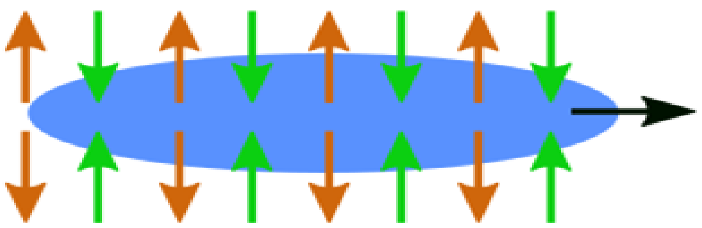


CERN SPS proton bunch: very long! (σ_z **= 6 - 10 cm**) → much longer than plasma wavelength (λ **= 1mm**)
→ Would create only small wakefield amplitudes



Self-Modulation of the Proton Bunch

Self-Modulation Instability:



p^+ bunch

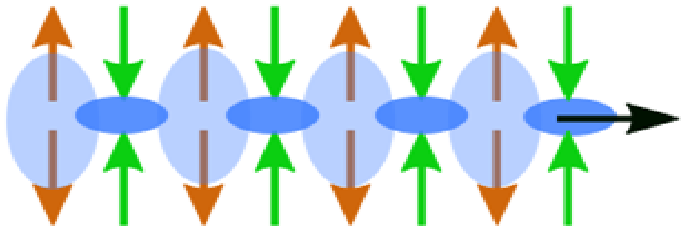
Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

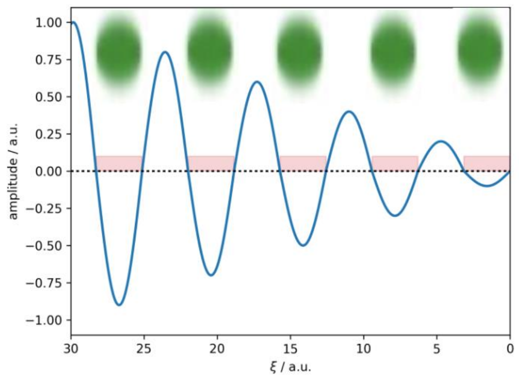
Stronger wakefields

Full modulation



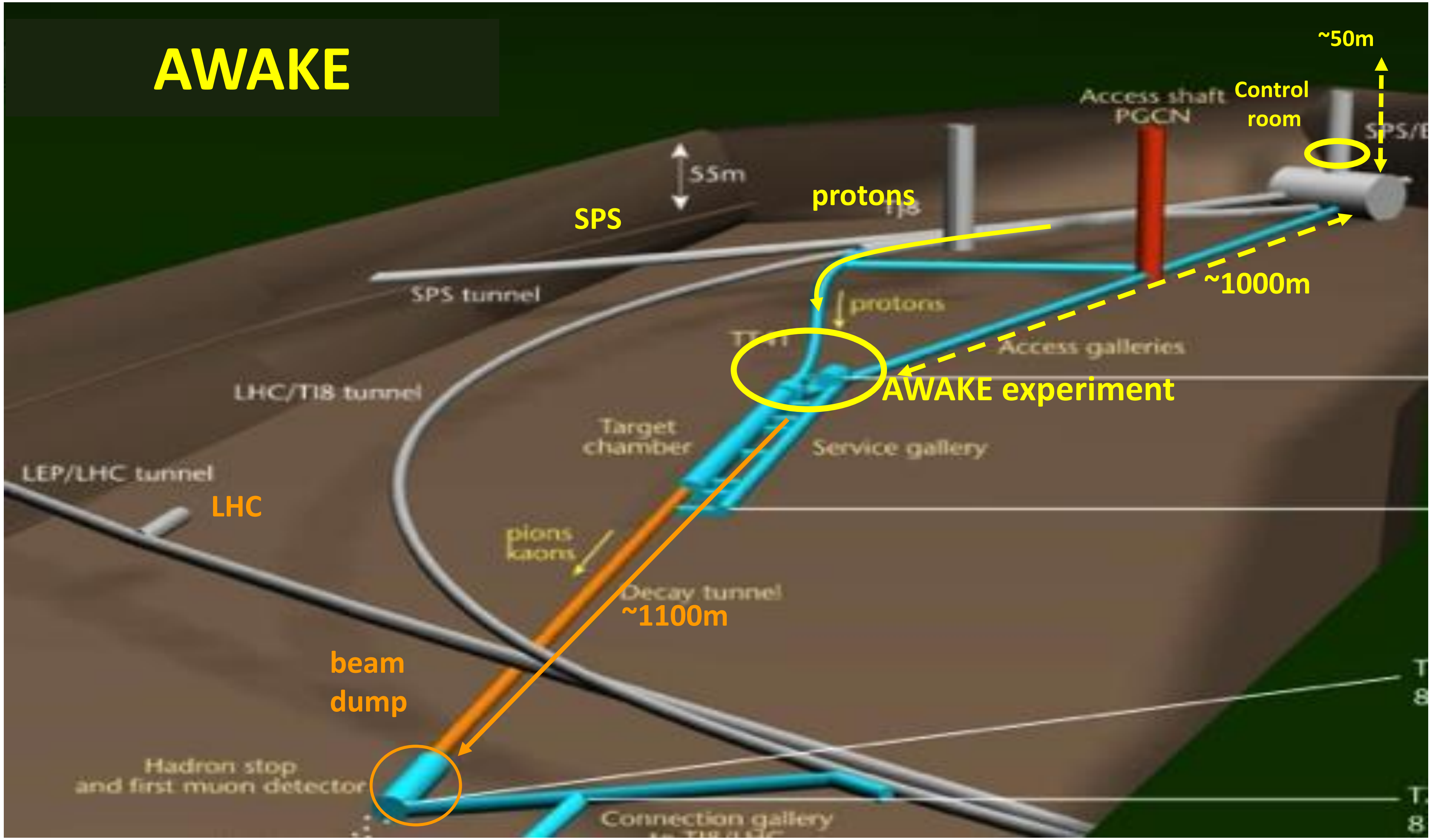
Density modulation on-axis → micro-bunches.

- Micro-bunches separated by λ_{pe}.
- Resonant wakefield excitation
- Large wakefield amplitudes



→ Immediate use of SPS proton bunch for driving strong wakefields!

AWAKE at CERN



AWAKE installed in CERN underground area

AWAKE has a Well-Defined Program

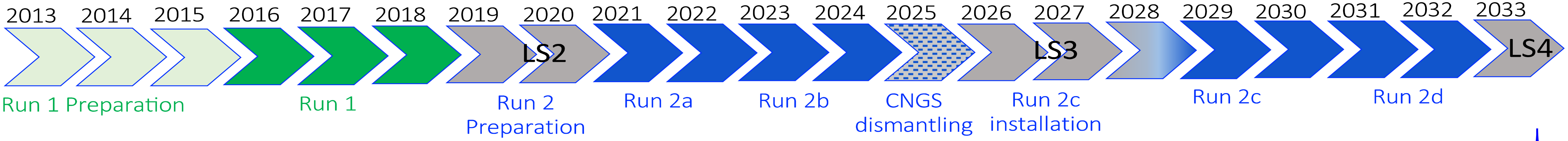
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

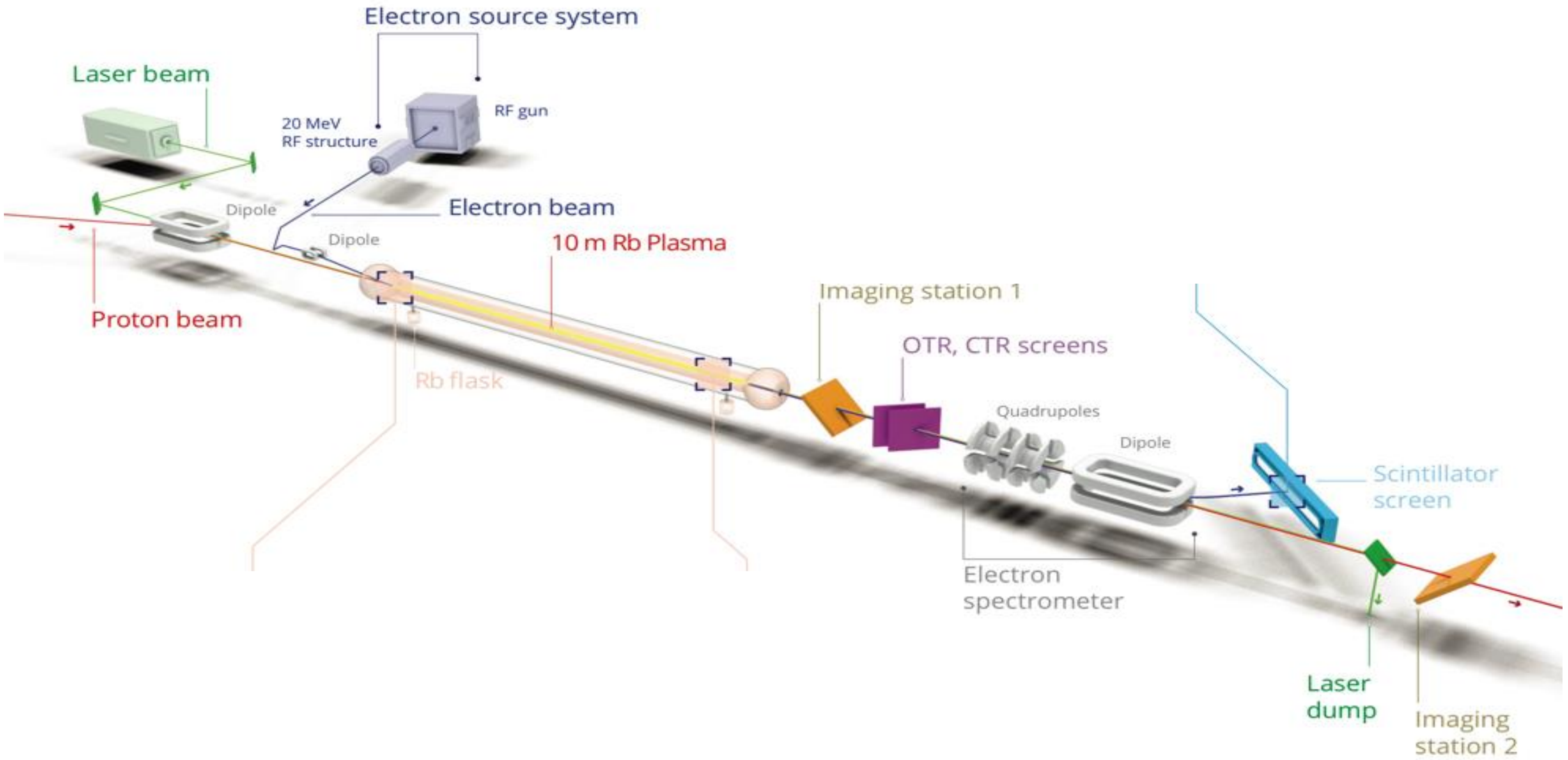
RUN 2 (2021-2032)

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



➔First applications >2033

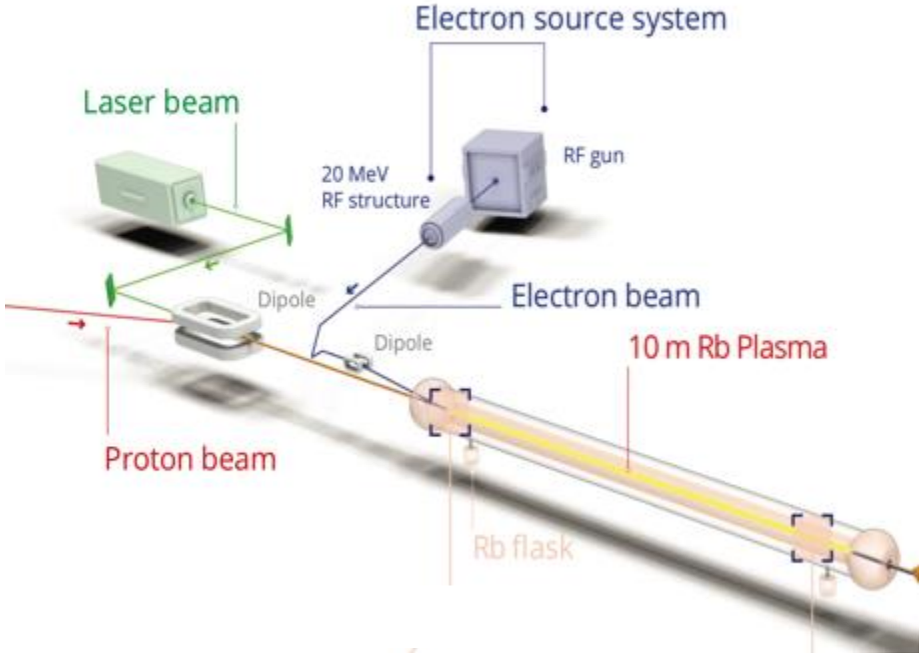
AWAKE Experiment

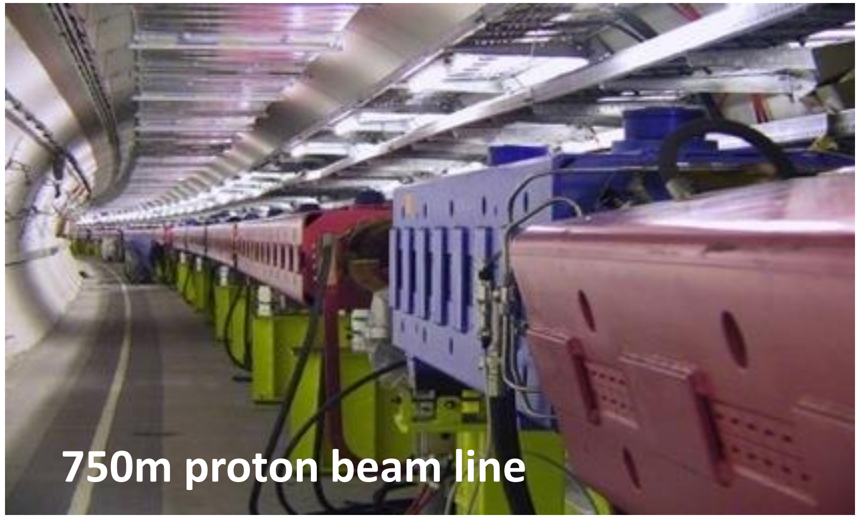


AWAKE Proton Beam Line

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

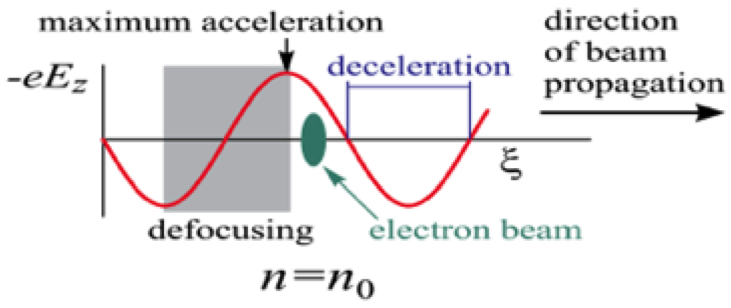


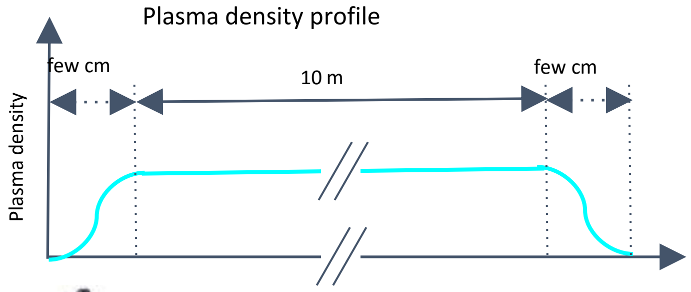


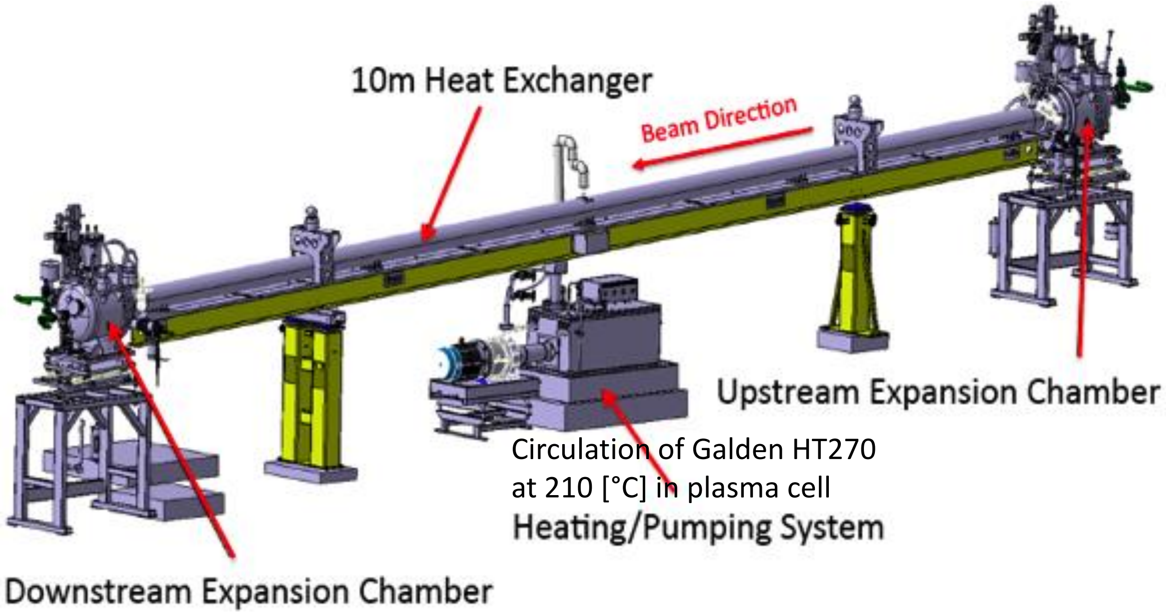
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will injected into the same beamline.

AWAKE Plasma Cell

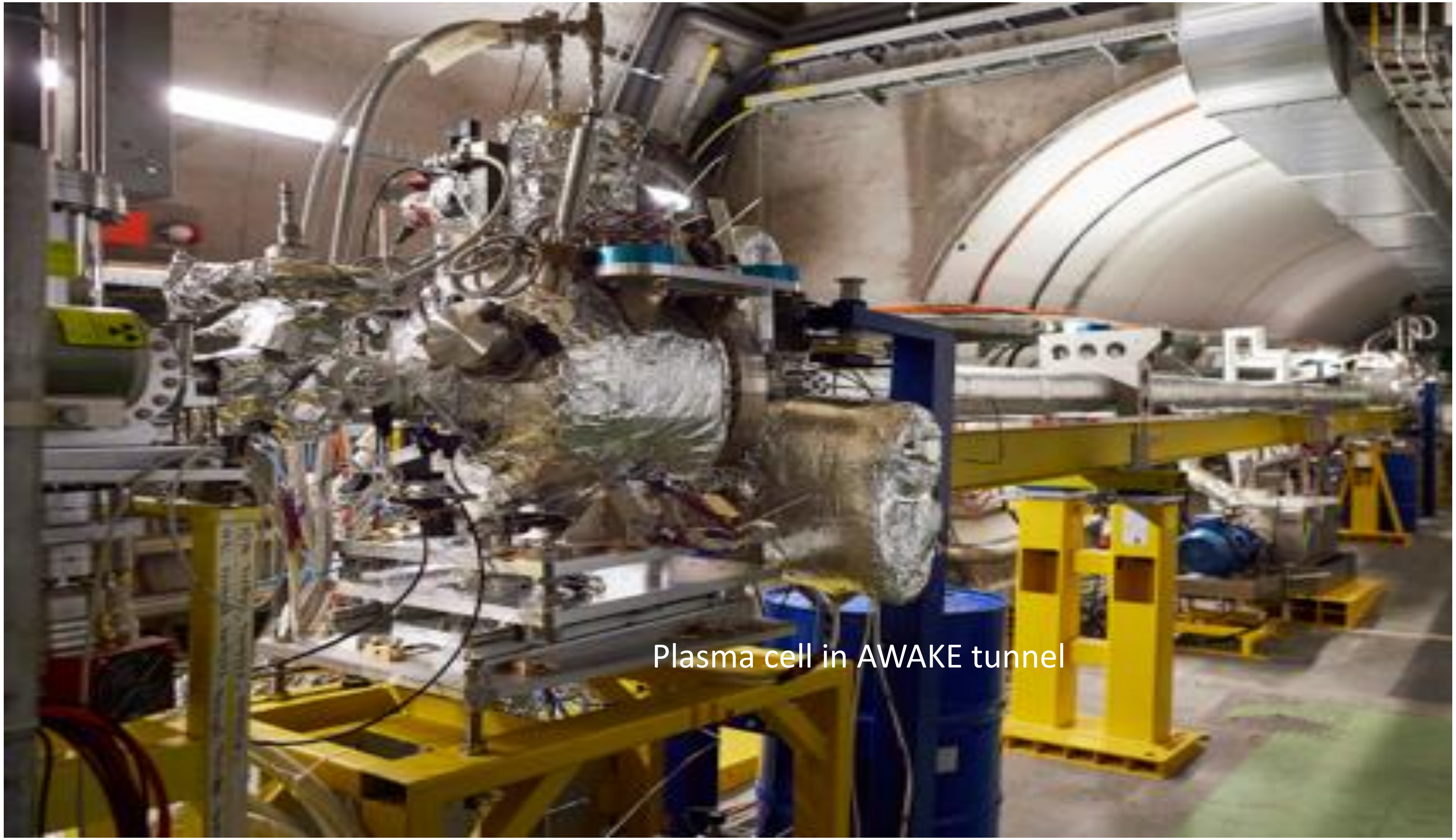
- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (~220 deg)
    - Complex control system: >80 temperature probes, valves
  - **Transition between plasma and vacuum as sharp as possible**





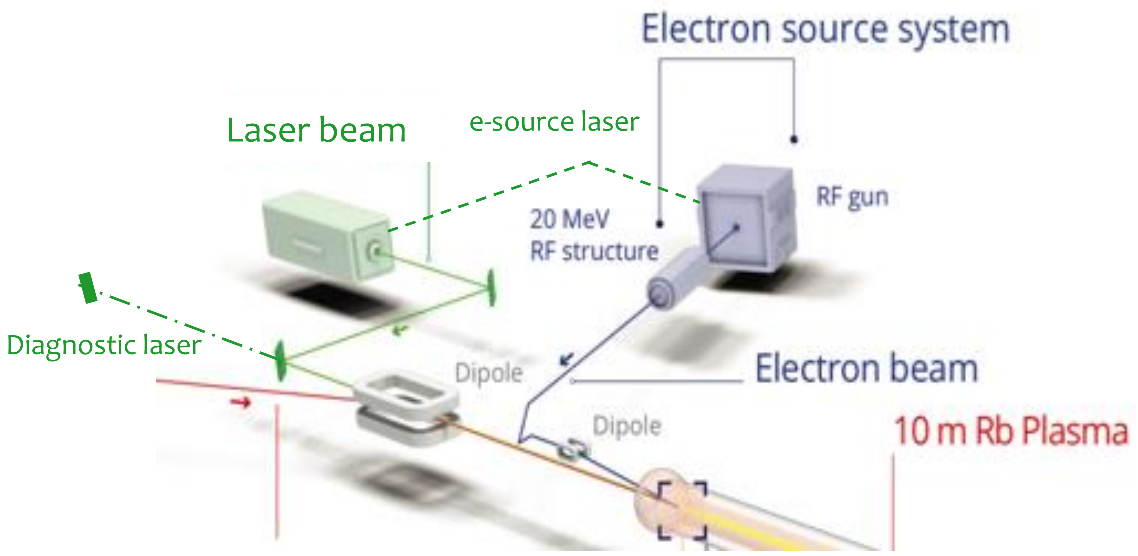


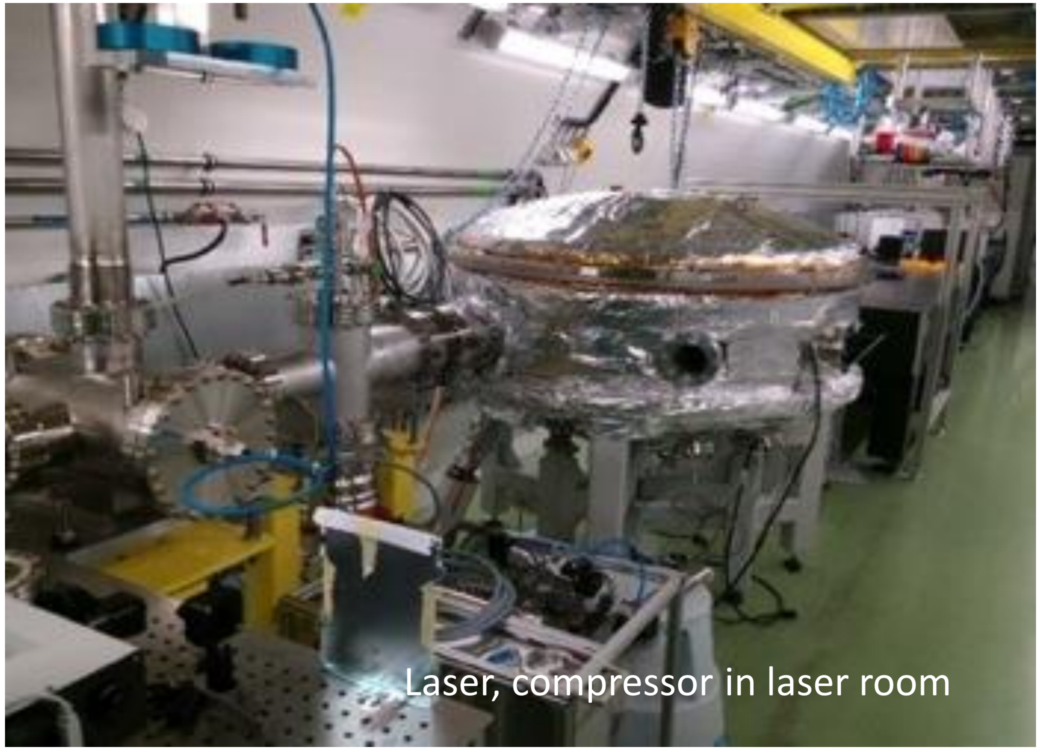
AWAKE Plasma Cell



Laser and Laser Line

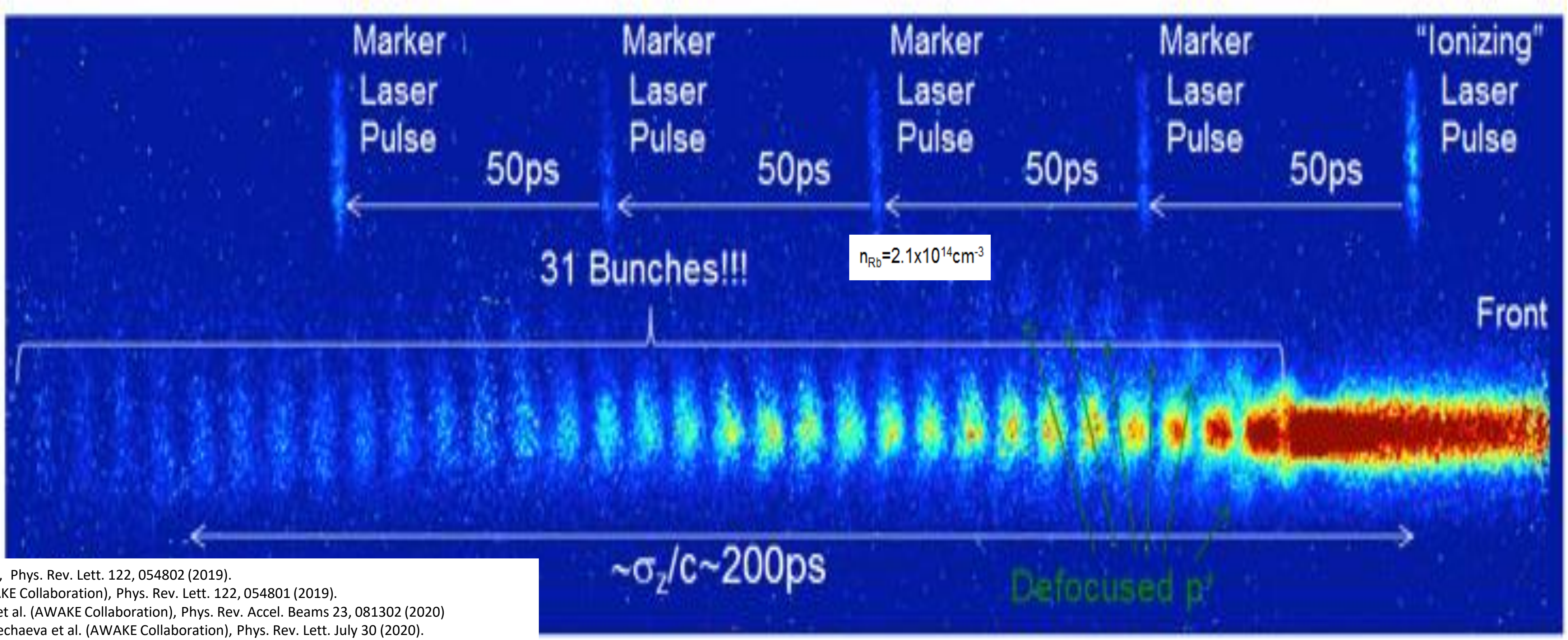
AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





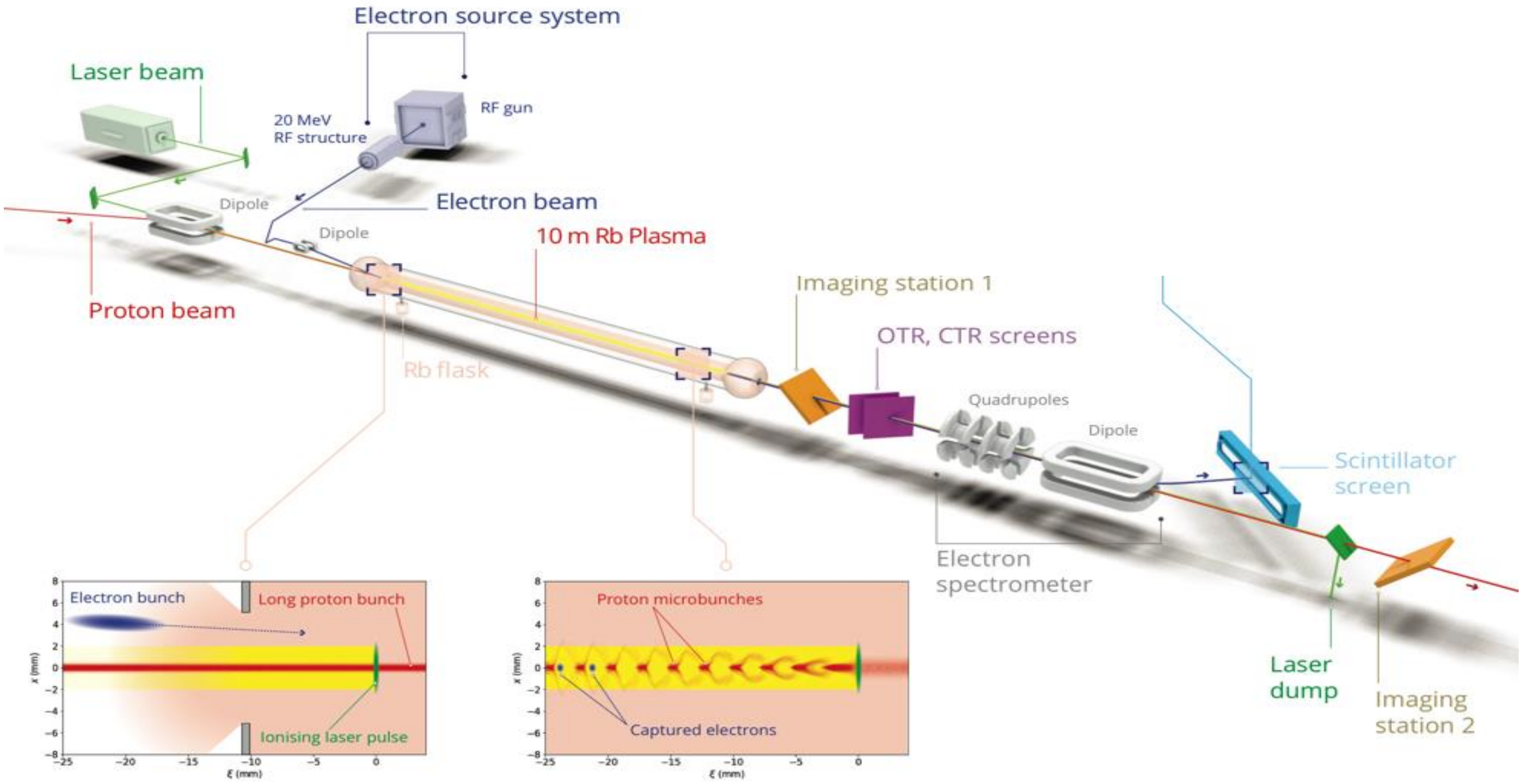
AWAKE Run 1: Proton Self-Modulation Results

#1: Demonstration of Seeded Self-Modulation of the Proton bunch

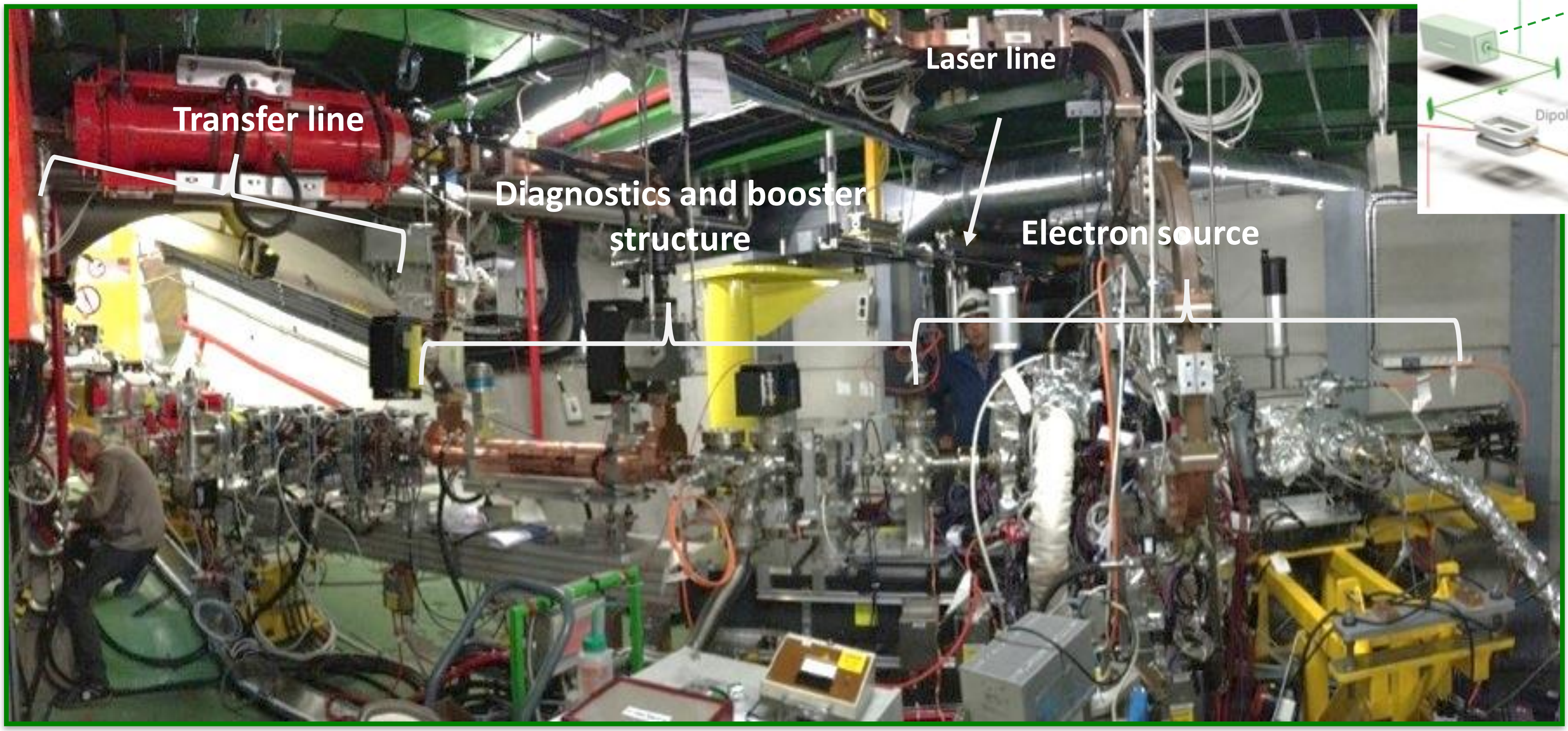


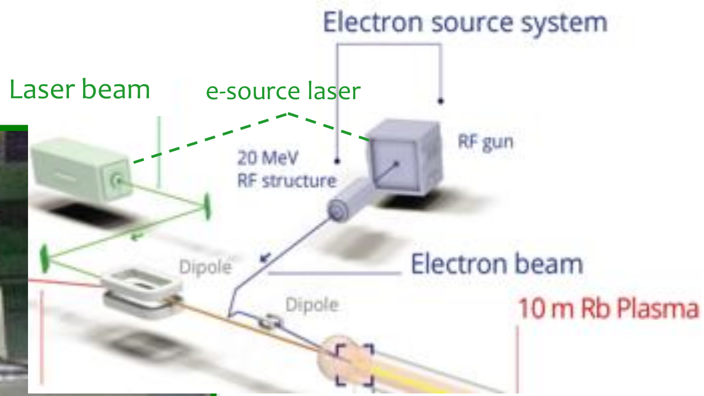
WAKE Collaboration, Phys. Rev. Lett. 122, 054802 (2019).
I. Turner et al. (AWAKE Collaboration), Phys. Rev. Lett. 122, 054801 (2019).
I. Turner, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Accel. Beams 23, 081302 (2020)
Braunmueller, T. Nechaeva et al. (AWAKE Collaboration), Phys. Rev. Lett. July 30 (2020).
.A. Gorn, M. Turner et al. (AWAKE Collaboration), Plasma Phys. Control Fusion, Vol. 62, Nr 12 (2020).
Batsch, P. Muggli et al. (AWAKE Collaboration), accepted in Phys. Rev. Lett. (2021)

AWAKE Experiment



Electron Beam System



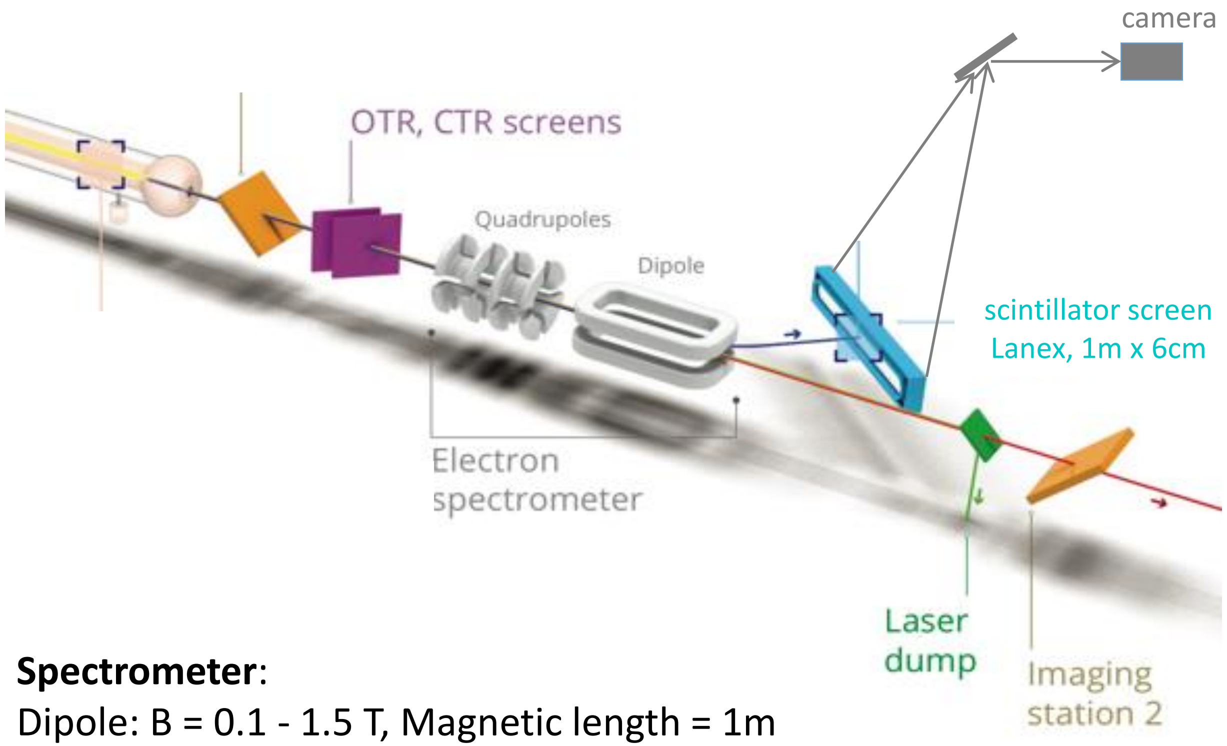


A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**

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



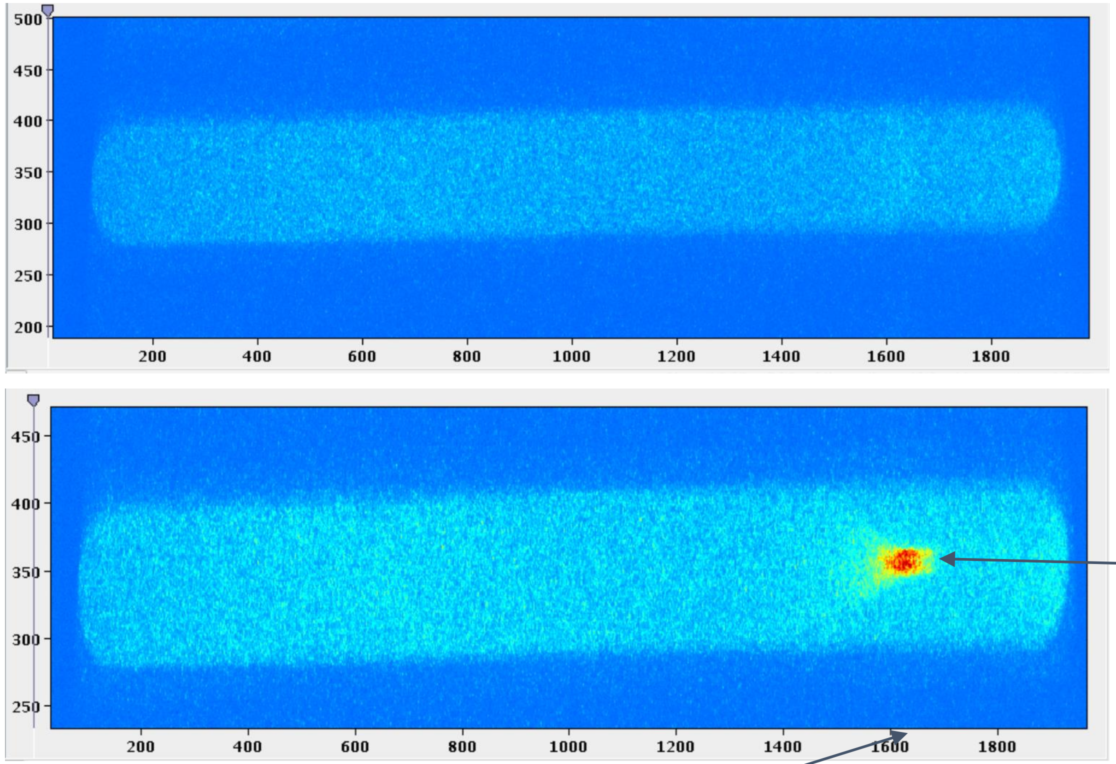
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

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.

Run 1 Results: Electron Acceleration

#2: Demonstration of Electron Acceleration in Plasma Wakefield

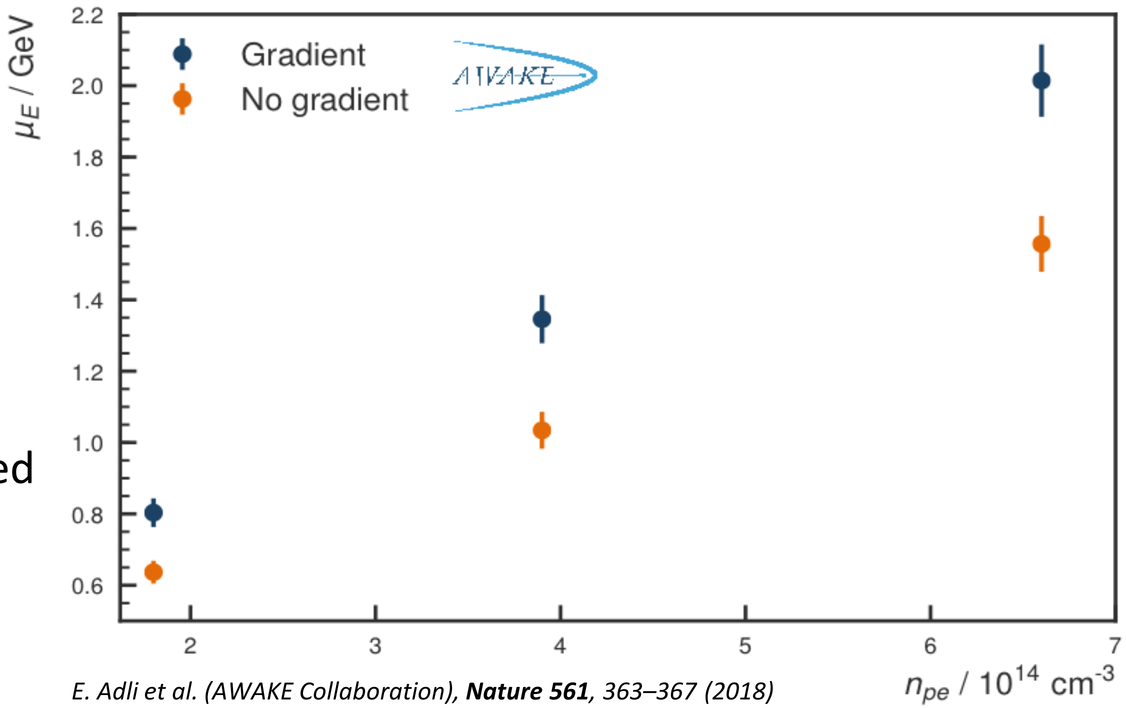
- **Acceleration up to 2 GeV** has been achieved.
- Charge capture up to 20%.



No accelerated electrons

Accelerated electrons

Convert pixel-size and dipole setting to energy

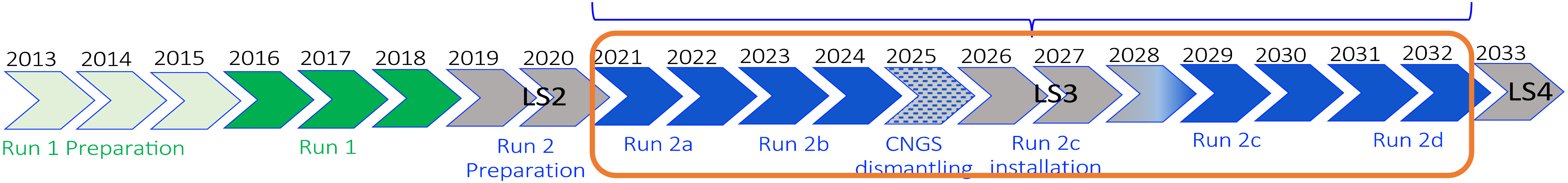


*E. Adli et al. (AWAKE Collaboration), **Nature 561**, 363–367 (2018)*

AWAKE Program

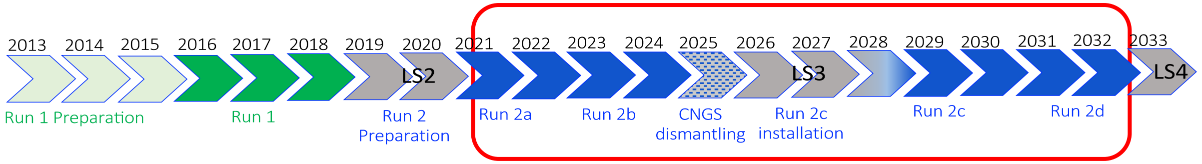
RUN 2 (2021-2032)

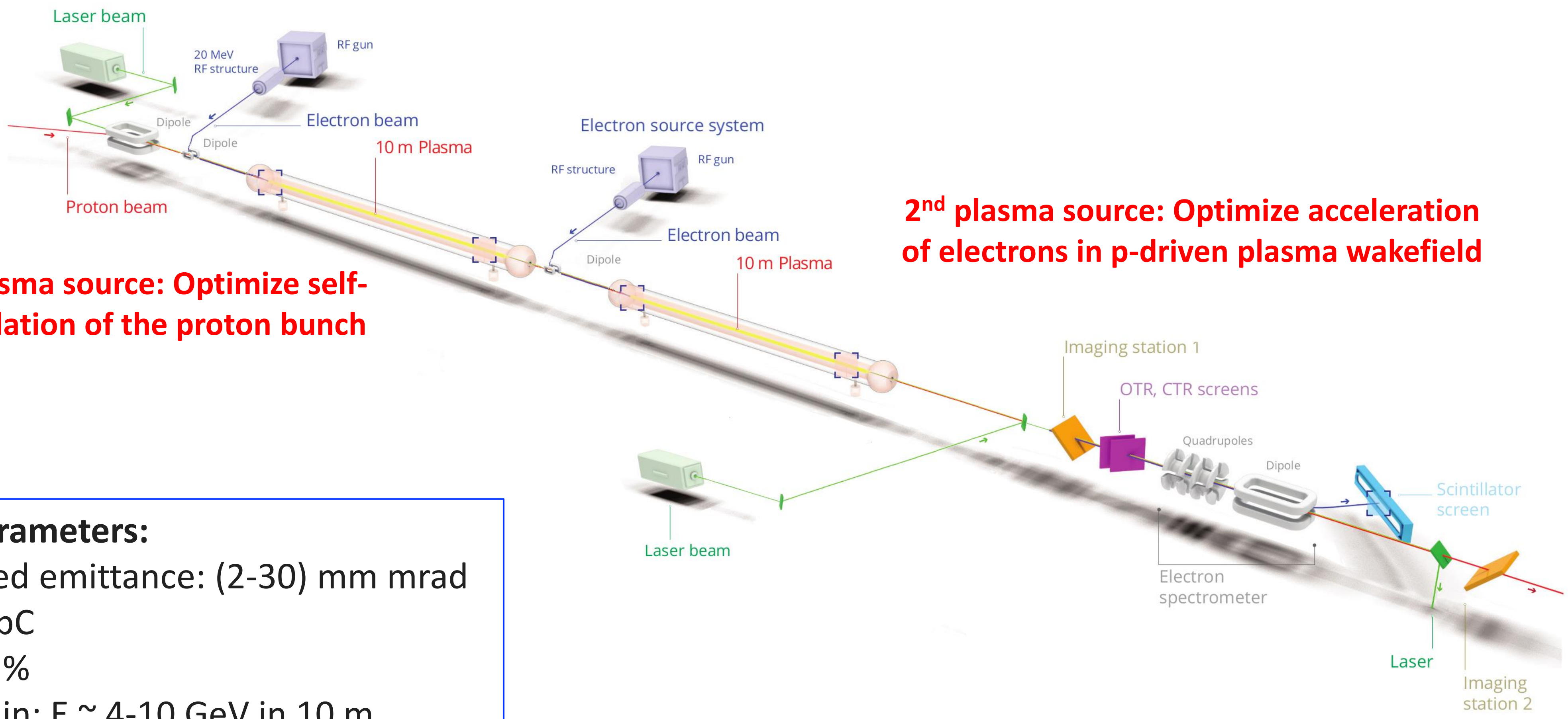
e- acceleration to several GeV,
beam quality control, scalability



AWAKE Run 2

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





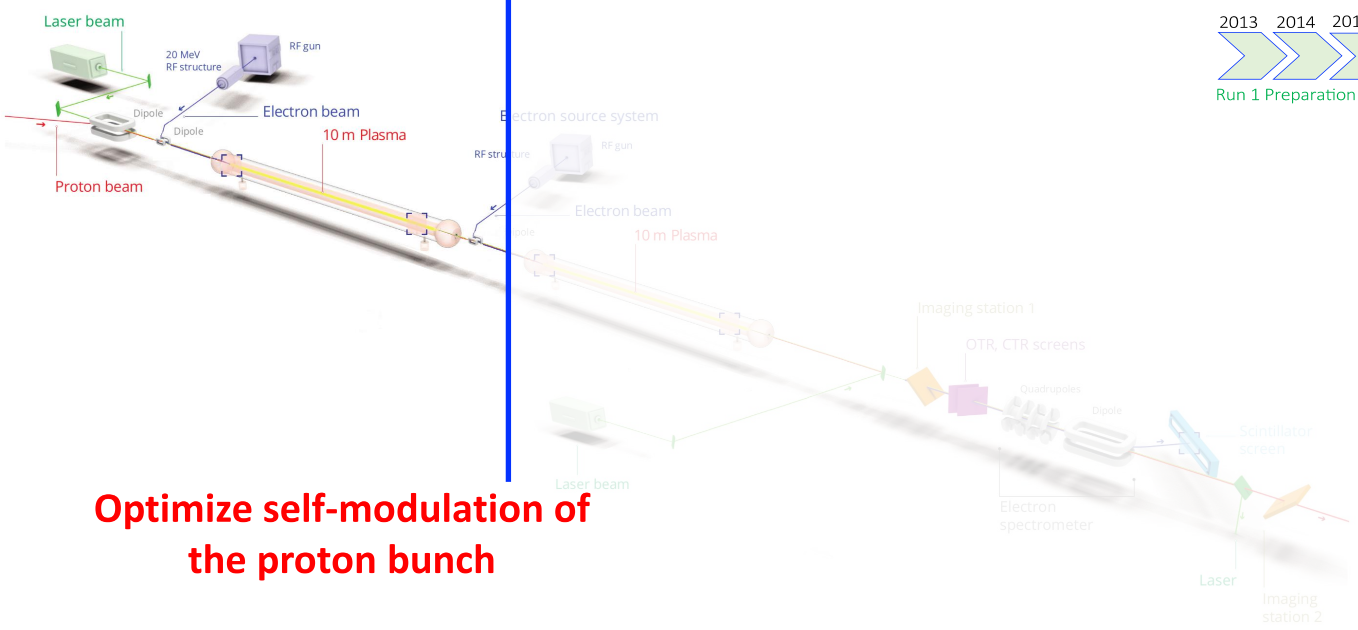
1st plasma source: Optimize self-modulation of the proton bunch

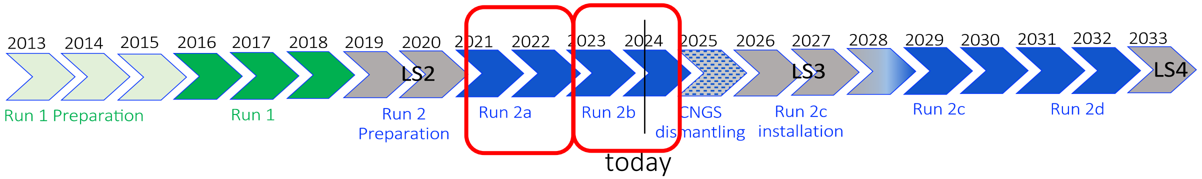
2nd plasma source: Optimize acceleration of electrons in p-driven plasma wakefield

Expected parameters:

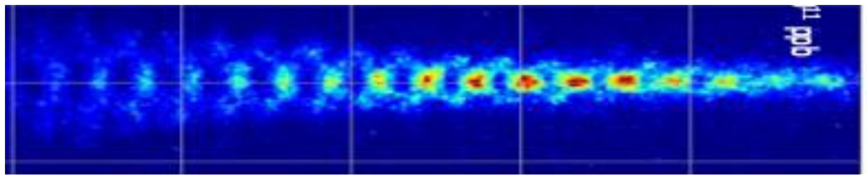
- Normalized emittance: (2-30) mm mrad
- Q_e = 100 pC
- dE/E: 5-8 %
- Energy gain: E ~ 4-10 GeV in 10 m

AWAKE Run 2a and Run 2b





Optimize self-modulation of the proton bunch



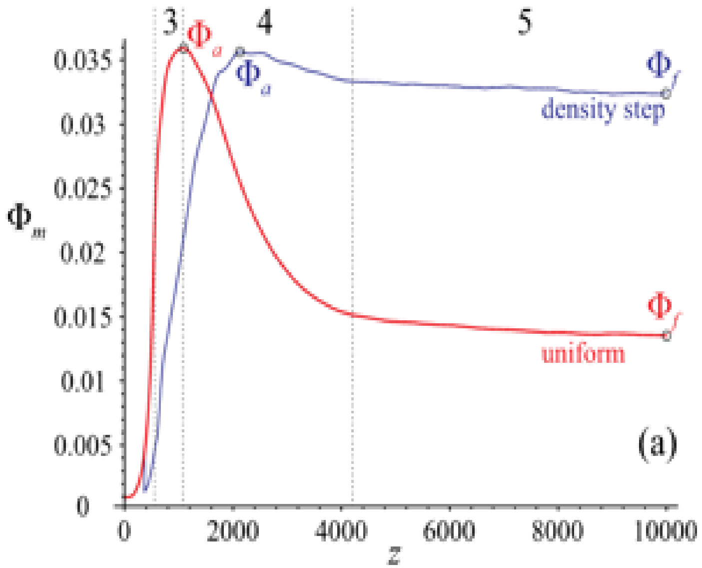
L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

✓ Run 2a (2021-2022): **CONTROL:** demonstrate the ***seeding of the self-modulation of the entire proton bunch with an electron bunch***

now ➔ **Run 2b (2023-2024): STABILIZATION:** ***maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

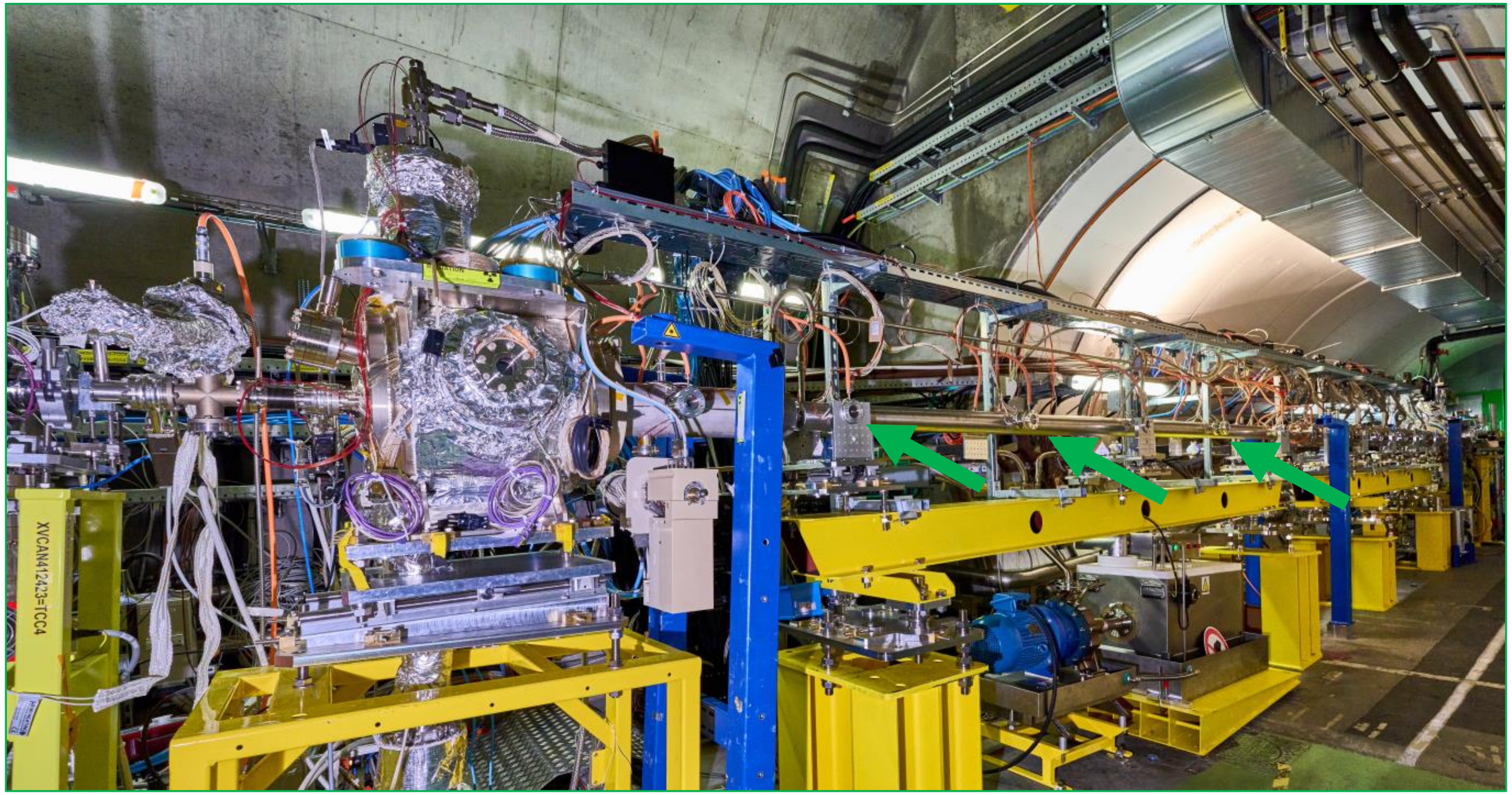
Run 2b – Stabilizing Large Wakefield Amplitudes

Introducing a density step in the plasma cell
➔ stabilization of the micro-bunches
➔ Increased wakefield amplitudes after SSM saturation



K. V. Lotov, Physics of Plasmas 22, 103110 (2015)
K. V. Lotov and P. V. Tuev 2021 PPFC ***63 125027***

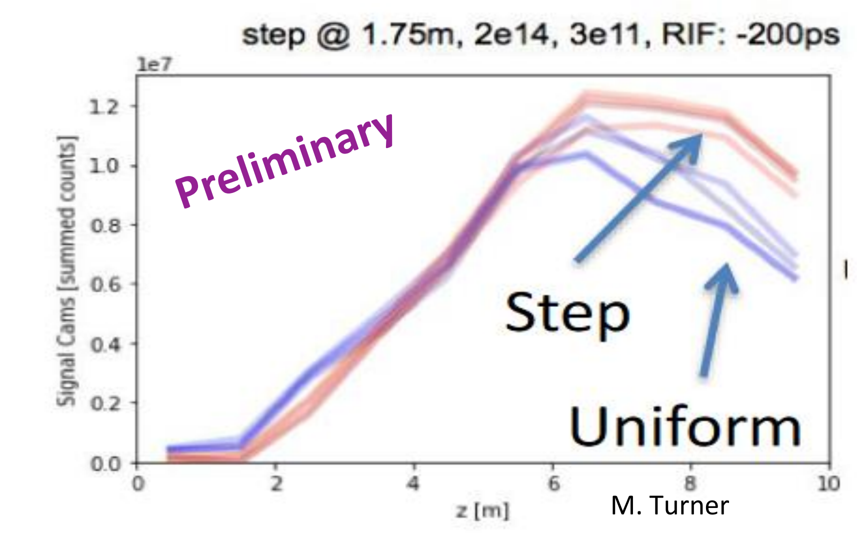
New Rubidium vapour source with density step installed in 2023



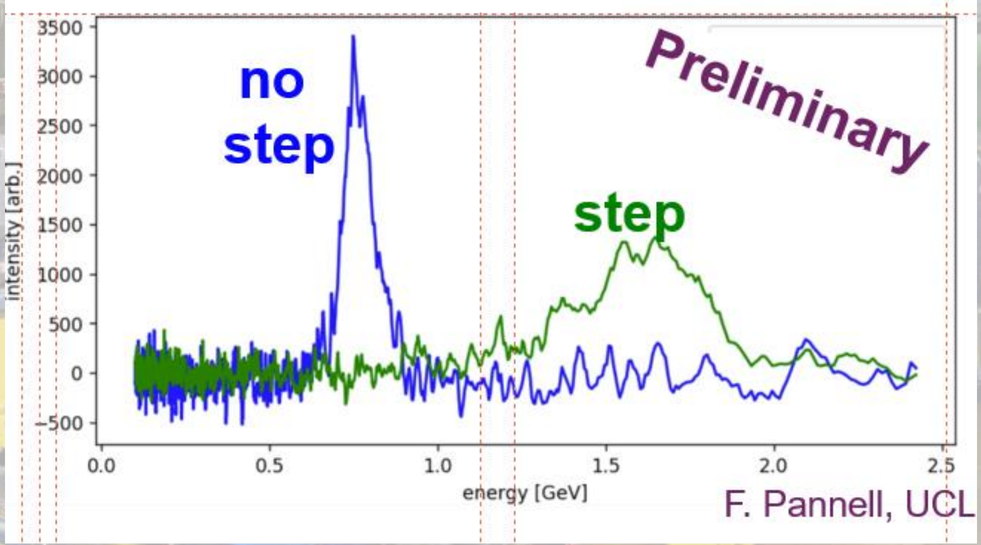
- Length: ~ 10 m, independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ to measure light emitted by wakefields dissipating after the passage of the proton bunch

Run 2b - Stabilizing Large Wakefield Amplitudes

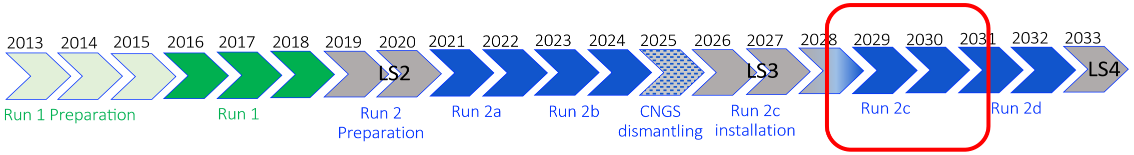
Wakefield light



Accelerated electrons



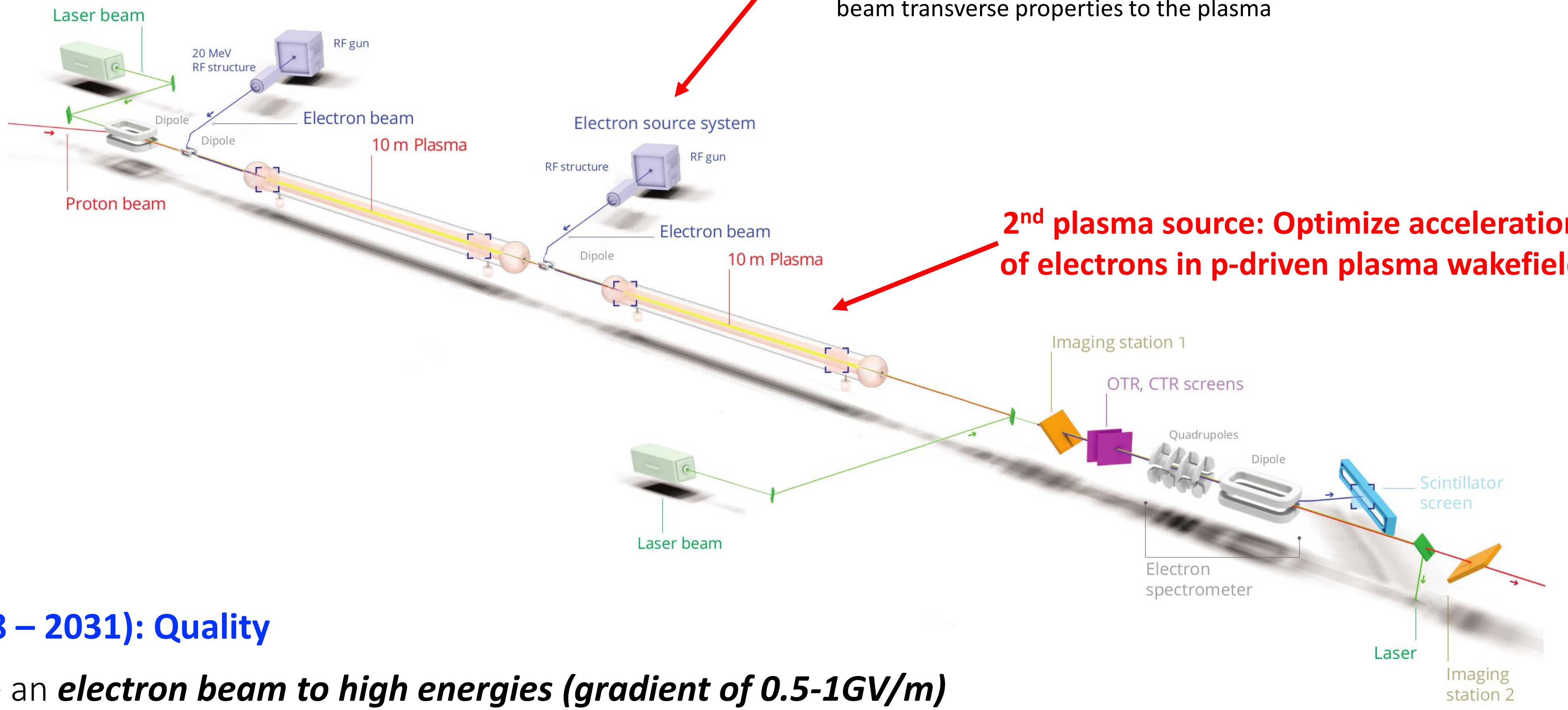
AWAKE Run 2c – Start after LS3 (2028



New electron beam: 150 MeV, 200 fs, 100 pC, σ = 5.75 µm

→ bunch length shorter than plasma wavelength

On-axis injection, Blow-out regime, **Beam loading**: reach small ∂E/E, **Match** electron beam transverse properties to the plasma



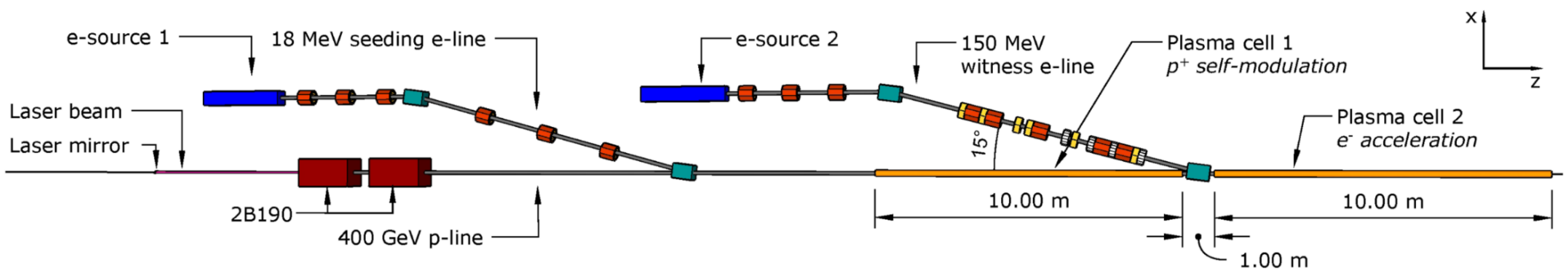
2[nd] plasma source: Optimize acceleration of electrons in p-driven plasma wakefield

Run 2c (2028 – 2031): Quality

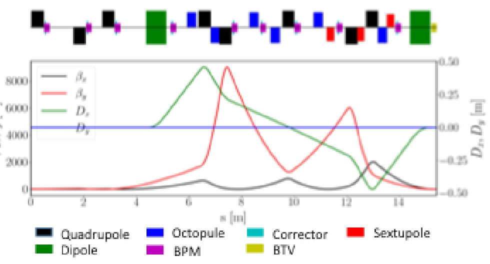
➔ Accelerate an ***electron beam to high energies (gradient of 0.5-1GV/m)***

➔ while controlling the ***electron beam quality (~10 mm-mrad emittance, 10% energy spread)***

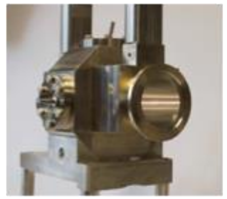
AWAKE Run 2c Studies and Prototyping Ongoing



150 MeV beamline



Beam instrumentation

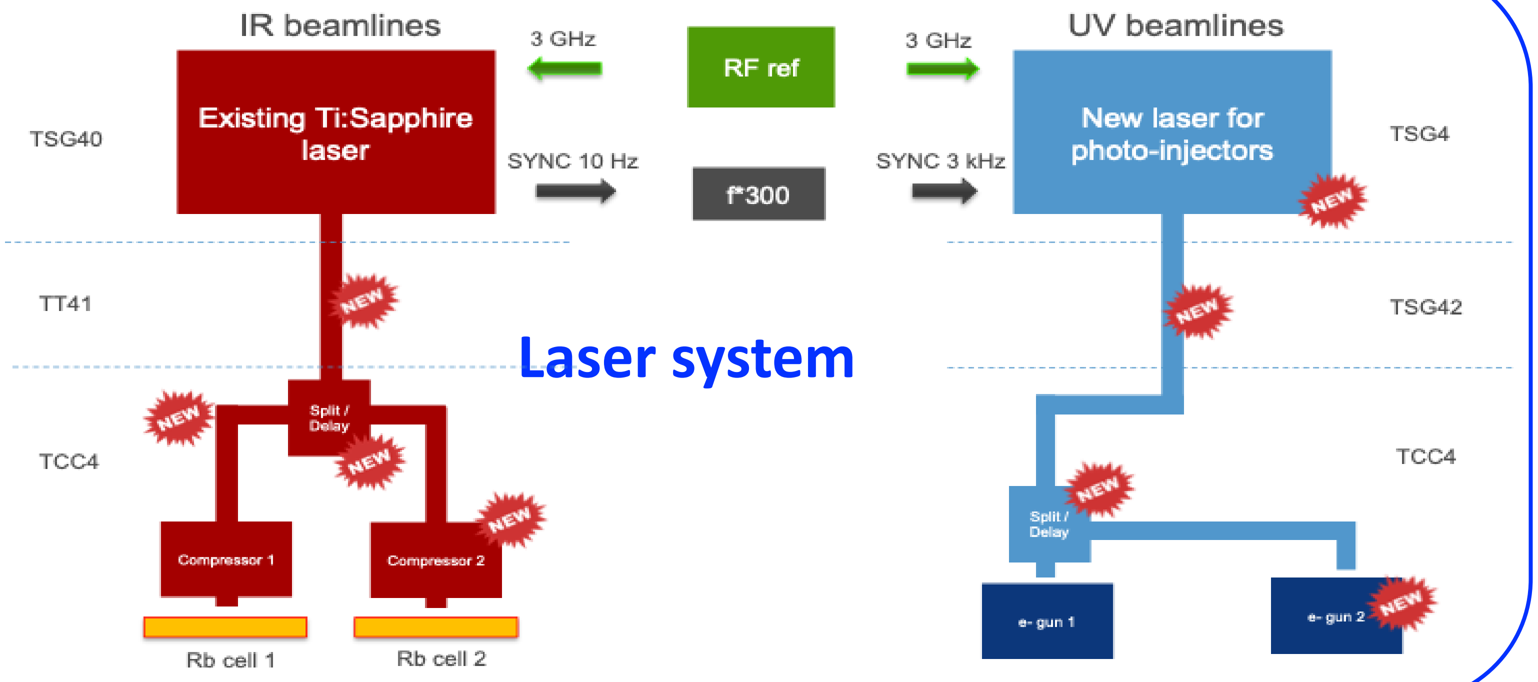


BPMs 10 μm resolution

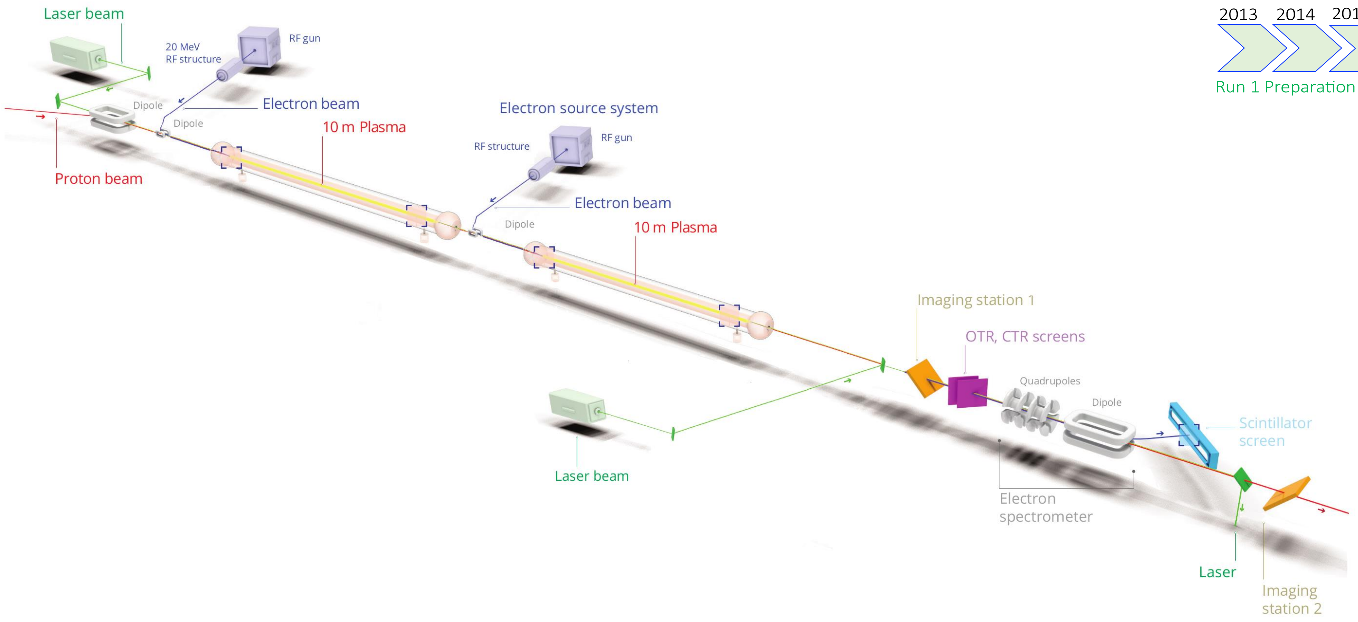
Run 2c electron source prototype

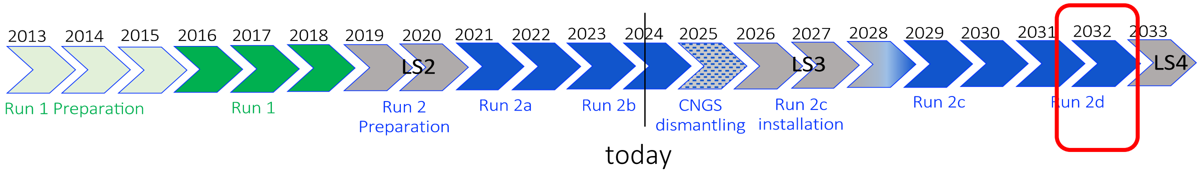
S-band e-gun (INFN) with
X-band accelerator (CLIC/CLEAR)

Laser system



AWAKE Run 2d





✓ **Run 2a (2021-2022): CONTROL: demonstrate the *seeding of the self-modulation of the entire proton bunch with an electron bunch***

➔ **Run 2b (2023-2024): STABILIZATION: *maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

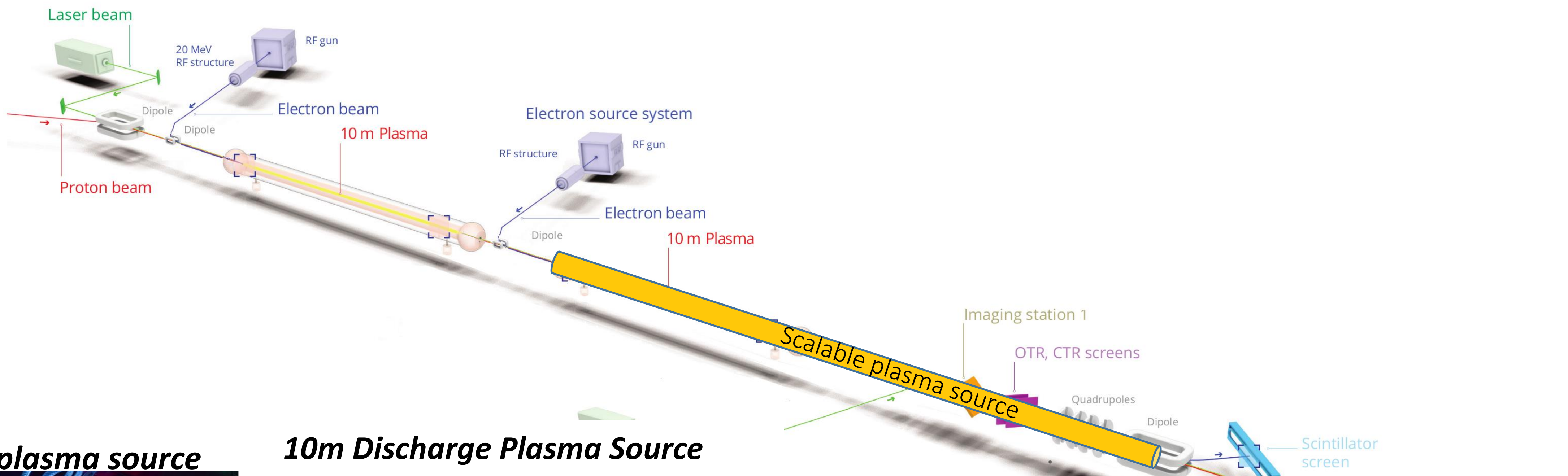
➔ *(2025-2027): CNGS dismantling, CERN Long Shutdown LS3, installation of Run 2c*

➔ **Run 2c (2028-2031): QUALITY**: demonstrate ***electron acceleration and emittance control of externally injected electrons***.

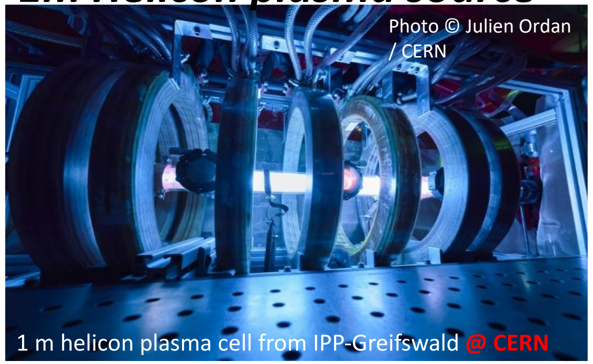
➔ **Run 2d (2032- LS4): SCALABILITY**: ***development of scalable plasma sources with sub-% level plasma density uniformity.***

AWAKE Run 2d: Demonstrate Scalable Plasma Sources

Today: Laboratory developments of scalable plasma sources in dedicated plasma labs
Aim: Propose a design for a scalable, several meter-long plasma cell for Run 2d.
Final Goal: Use this technology to build a 50-100m long plasma source for **first applications (>2033)**



1m Helicon plasma source



10m Discharge Plasma Source

10 m Discharge Plasma Source in AWAKE

➔ Possible candidate for plasma source in Run 2c/d and particle physics applications

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

Successfully installed, commissioned and operated the 10m long discharge prototype plasma source

➔ Demonstrated self-modulation of the proton bunch

➔ Flexible operation allowed to study various physics effects.

AWAKE as Part of the European Strategy Roadmap

	Timeline (approximate/aspirational) 0-10 years	10-20 years	20-30 years
Single-stage accelerators (proton-driven)	**Demonstration of:** Preserved beam quality, acceleration in very long plasmas, plasma uniformity (longitudinal & transverse)	**Fixed-target experiment (AWAKE)** Dark-photon searh, strong-field QED experiment etc. (50-200 GeV e-)	Legend: R&D (exp & theory); HEP facility
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

➔ AWAKE is part of the roadmap of the European Strategy for Particle Physics

e-p collider

	0-10 years
Single/multi-stage accelerators for light sources (electron & laser-driven)	**Demonstration of:** ultra-low emittances, high rep-rate/high efficiency e-beam and laser drivers, Long-term operation, potential staging, positrons (EuPRAXIA)

	Timeline (approximate/aspirational) 0-5 years	5 - 10 years	10-15 years	15-25 years	25+ years
Multi-stage accelerators (Electron-driven or laser-driven)	**Pre-CDR (HALHF)** Simulation study to determine self-consistent parameters (demonstration goals)	**Demonstration of:** scalabe staging, driver distribution, stabilisation (active and passive)	**Multistage tech demonstrator** Strong-field QED experiment (25-100 GeV e-)	Facility upgrade	Legend: Feasibility study; R&D (exp & theory); HEP facility (earlist start of construction)
		Demonstration of: High wall-plug efficiency(e- -drivers), preserved beam quality & spin polarization, high rep.rate, plasma temporal uniformity & cell cooling		**Higgs Factory (HALHF)** Asymmetric, plasma-RF hybrid collider (250-380 GeV c.o.m)	Facility upgrade
		Demonstration of: Energy-efficient positron acceleration in plasma, high wall-plug efficiency (laser-drivers), ultra-low emittances, energy recovery schemes, compact beam delivery systems			

R. Pattathil, presented at EAAC 2023

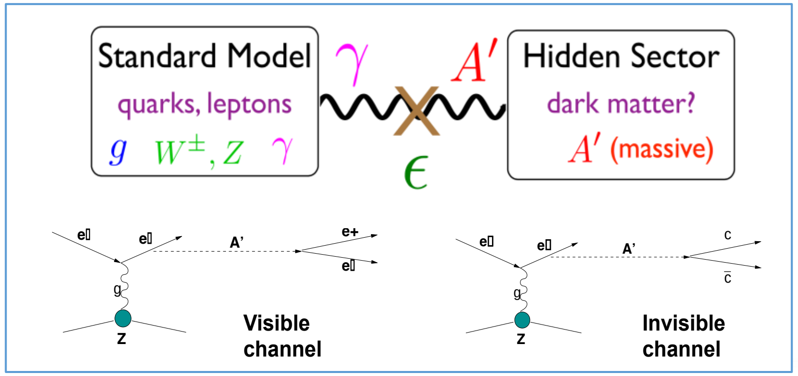
➔ AWAKE allows to bridge the gap between the PWFA development in general and a e+/e- collider.

Applications with AWAKE-Like Scheme

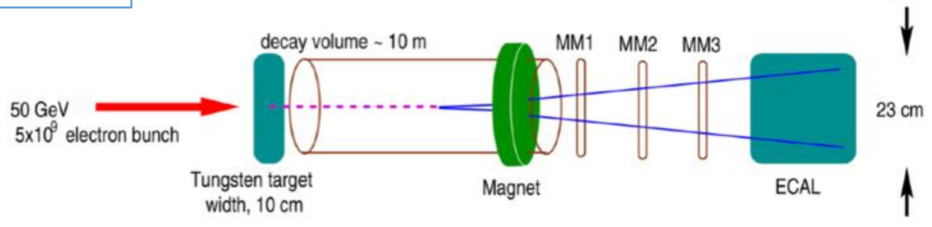
→ Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application: Fixed target test facility:

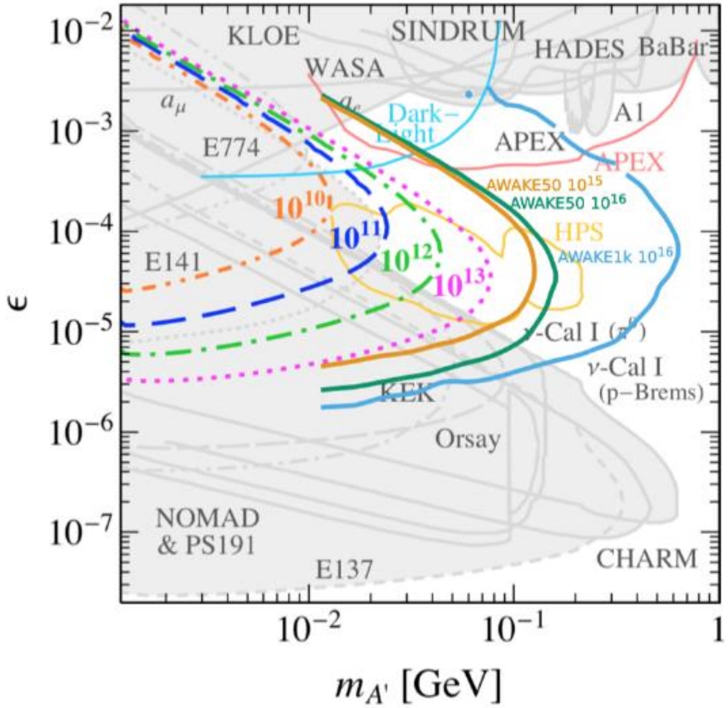
→ Deep inelastic scattering, non-linear QED, **search for dark photons**



→ 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.



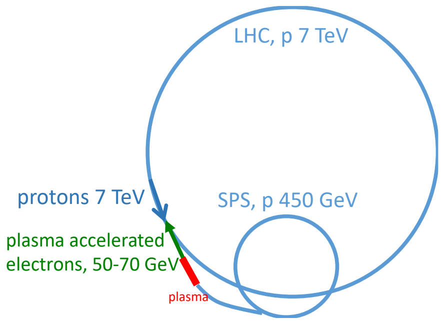
→ Extension of kinematic coverage for 50 GeV electrons and even more for 1 TeV electrons

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. $1bp^{-1}$/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.
  - → Acceleration with more than 50 GeV/m gradients have been achieved.
  - → Current and planned facilities (Europe, America, Asia) explore different advanced and novel accelerator concepts and proof-of-principle experiments and address beam quality challenges.

- AWAKE is a unique proton-driven plasma wakefield acceleration experiment at CERN
  - Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.
  - Modulation process means existing proton machines can be used.
  - AWAKE uses protons from CERN's SPS
  - Complex experiment, which capitalizes on CERN's accelerator technology expertise
  - AWAKE is an international collaboration with strong contributions from collaborating institutes

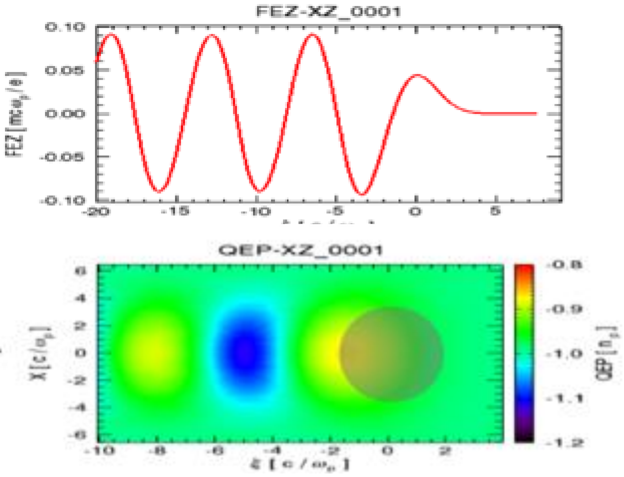
- AWAKE developed a well-defined plan towards first applications of particle physics experiments
  - AWAKE Run 2 is ongoing
  - AWAKE met all milestones to date

Back-Up

Introduction – *Beam Quality in PWA*

Different regimes:

Linear regime: $n_{beam} << n_{pe}$



- *lower wakefields*
- *transverse forces not linear in r*

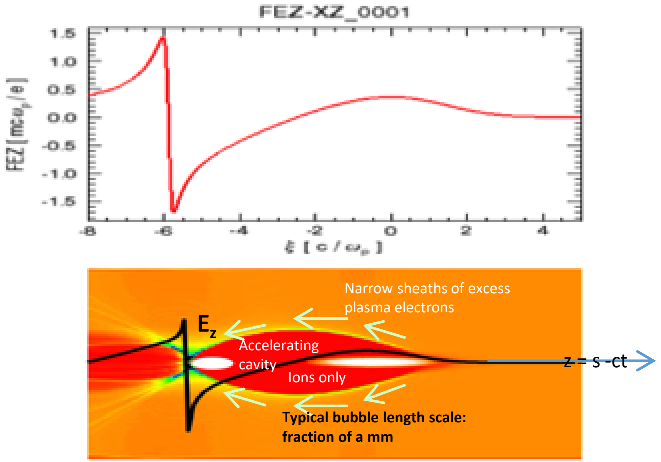
\+ Symmetric for positive and negative witness bunches

\+ Well described by theory

Accelerating field is maxi-mised for a value of

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

Blow-out regime: $n_{beam} >> n_{pe}$



\+ Higher wakefields

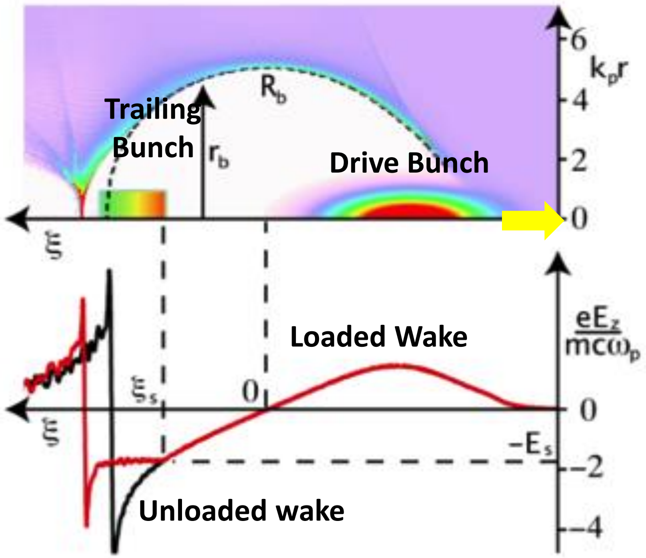
\+ transverse forces linear in r (emittance preservation)

\+ High charge witness acceleration possible

- *Requires more intense drivers*
- *Not ideal for positron acceleration*

Beam loading

Blown Out Wake

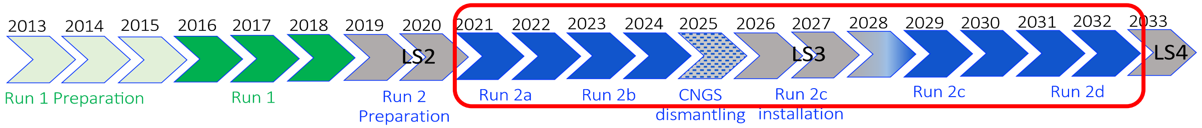


Sufficient charge in the witness bunch to flatten the accelerating field

→ **reduce energy spread**

Run 2 – Broader Impact

Examples of technological advancements



Machine Learning

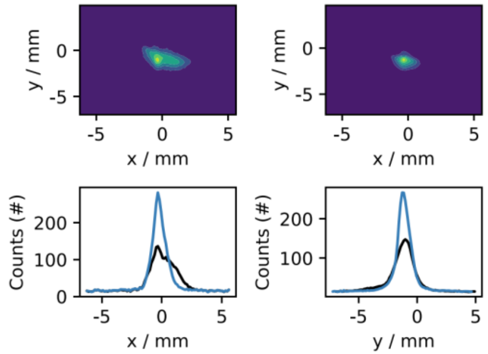
→ Running test-bed for operation efficiency studies and Machine Learning

Synergy with CERN and external institutes:

- Low energy e-beam line perfect for testing ML techniques
- Setup available in between runs used by users

Outcome:

- Development of beyond state-of-the art ML tools for accelerators
- 8 publications + proceedings



Velotti, F. M., et al. *Machine Learning: Science and Technology* 4.2 (2023): 025016.

Simulations

→ External injection of witness electron relevant for any plasma-based collider concept

→ Validation of simulation tools

Simulations predict broad tolerances for SMI control via a density step and for emittance control in quasilinear wakefield.