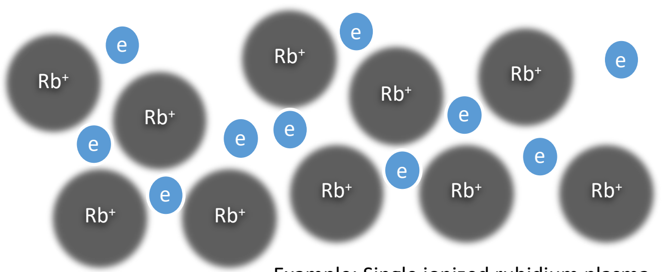
Plasma Wakefield Acceleration and the AWAKE Experiment at CERN

Edda Gschwendtner, CERN

Plasma Wakefield Acceleration



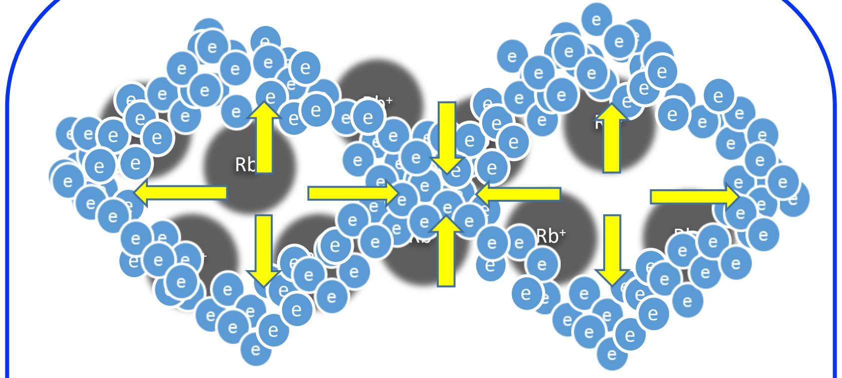
Example: Single ionized rubidium plasma

PLASMA is the 4th state of matter

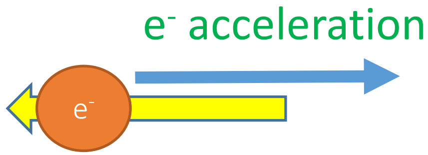
Quasi-neutrality: the overall charge of a plasma is about zero.

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.

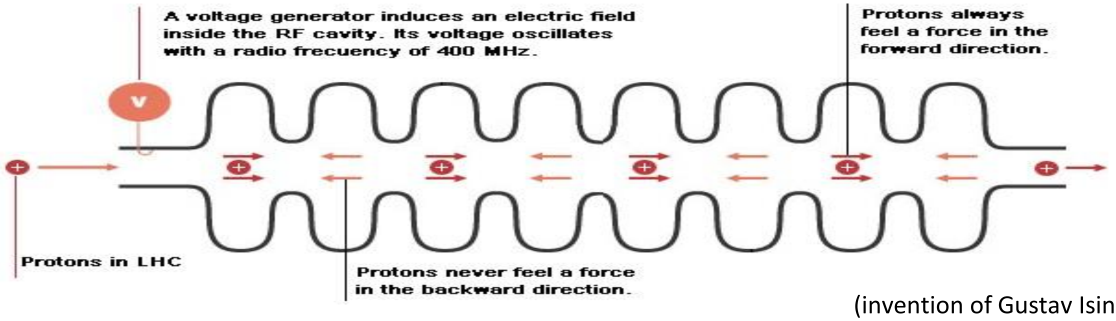


Plasma WAKEFIELDS are the fields created by collective motion of plasma particles are called.



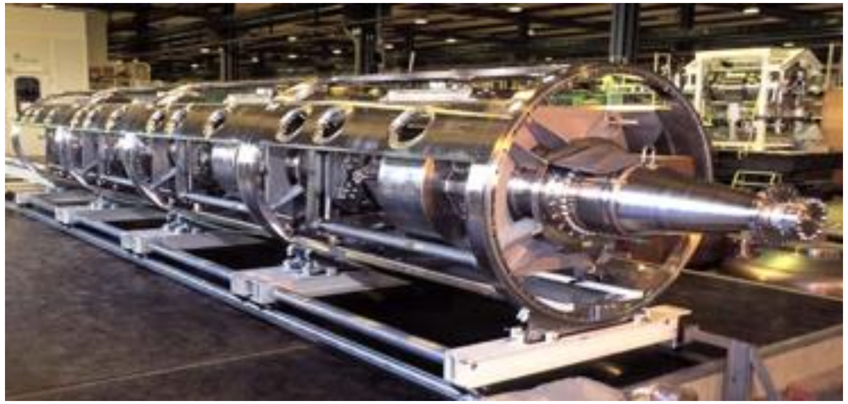
ACCELERATION of charged particles when they experience an electric field.
Strength of the acceleration:
'Accelerating gradient' : ~MV/m

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity



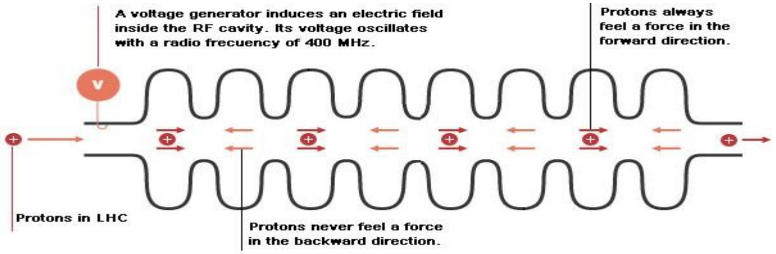
Typical gradients:

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

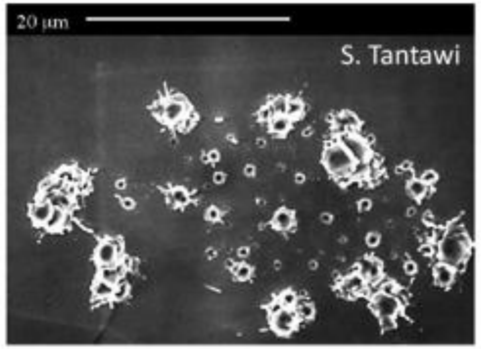
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

Accelerating Gradient

Conventional RF Cavities



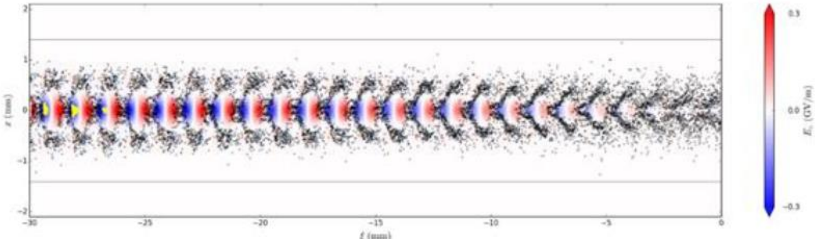
Surface of Copper Cell After Breakdown Events

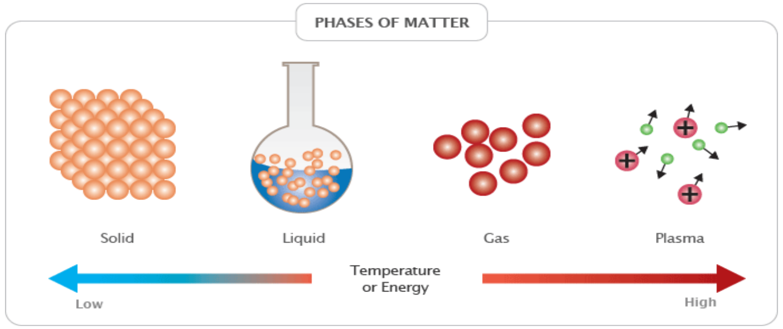


Accelerating fields are **limited to <100 MV/m**

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





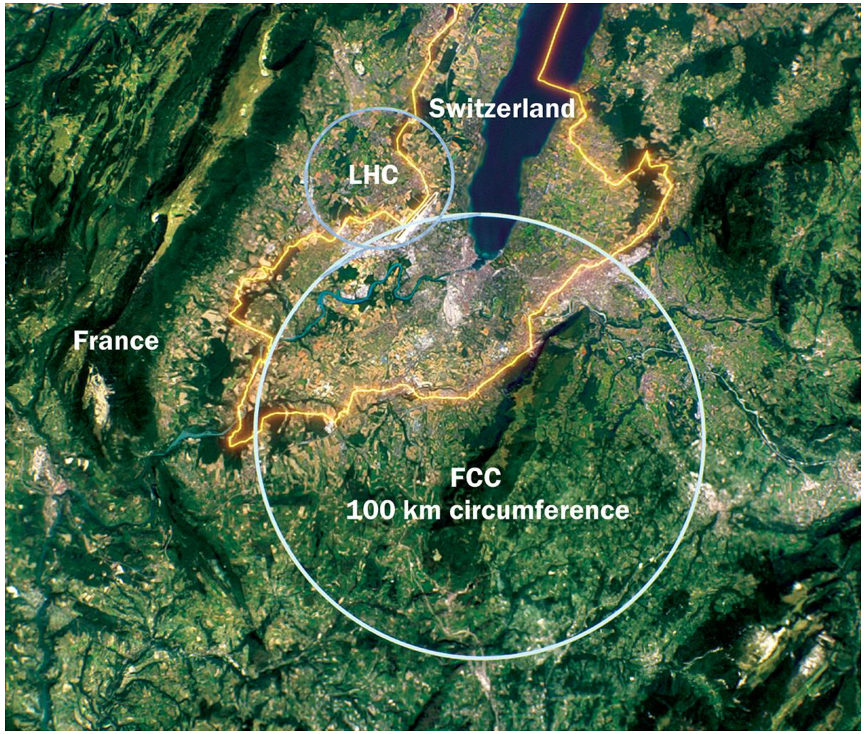
Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

→ **order of 100 GV/m.**

→ **~1000 factor stronger acceleration!**

Circular Accelerators

To discover new physics: accelerate particles to even higher energies



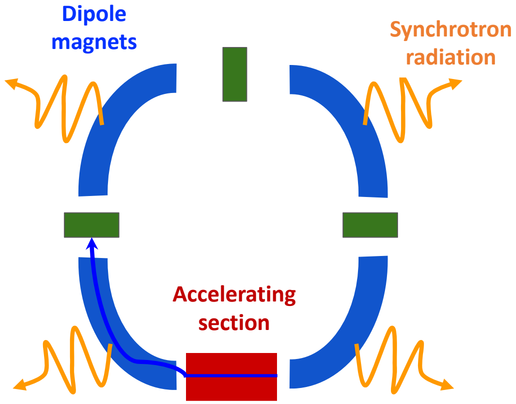
Conventional RF cavities ok for circular colliders:

👍 beam passes accelerating section several times.

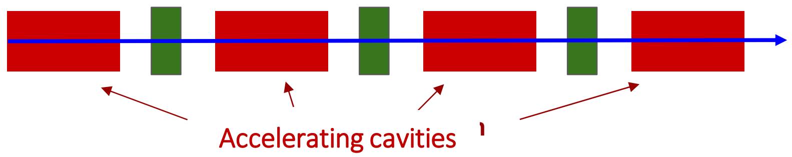
👎 **Limitations of electron-positron circular colliders:**

- 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.

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



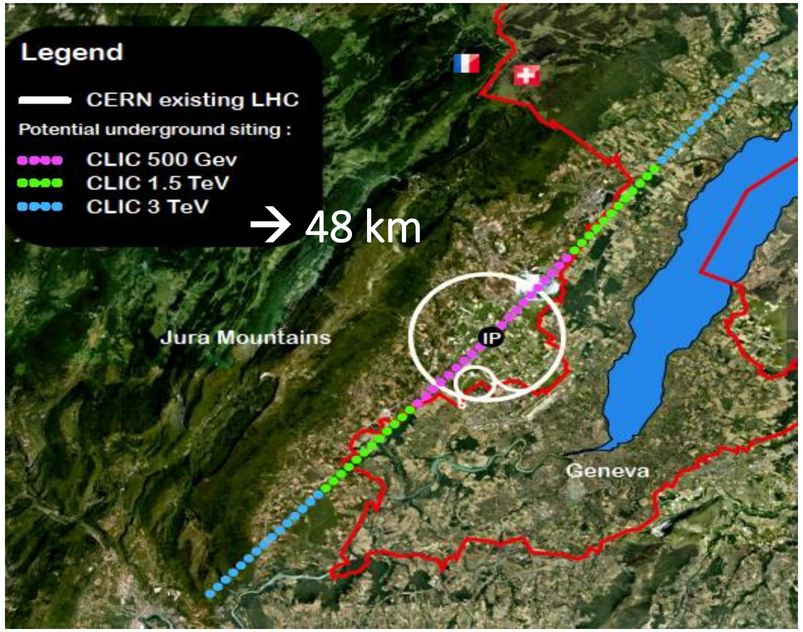
Linear Colliders



👍 Favorable for acceleration of low mass particles to high energies.

👎 **Limitations** to linear colliders:

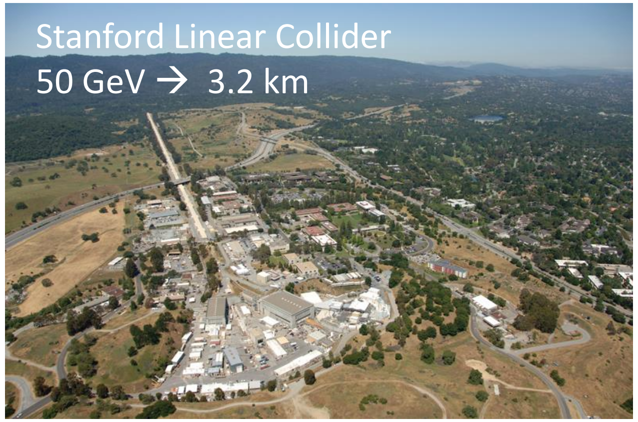
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.



CLIC, electron-positron collider with 3 TeV energy

Particle energy = accelerating gradient*distance

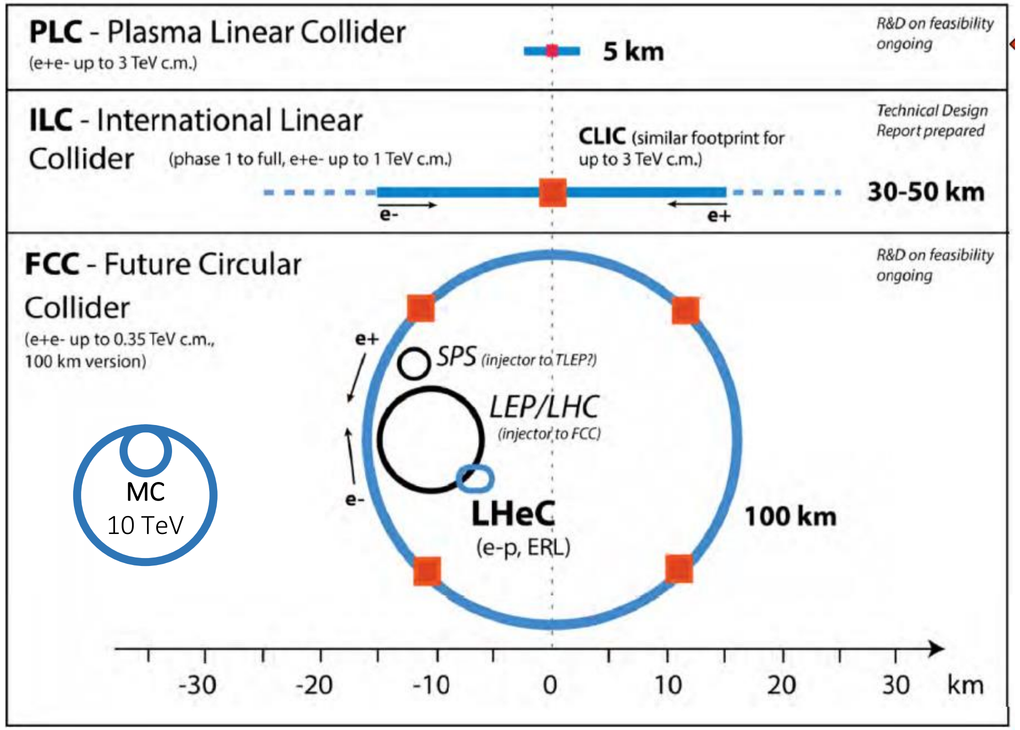
e.g. accelerate electrons to 1 TeV (10^{12} eV):
100 MeV/m x 10000 m or
100 GeV/m x 10 m



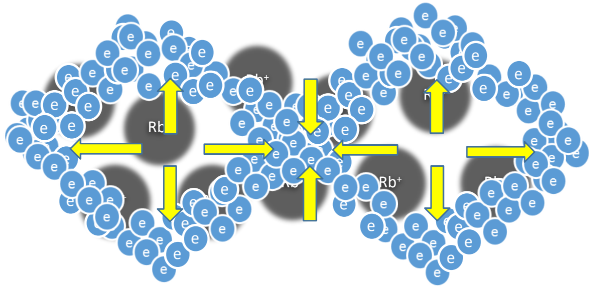
Plasma Wakefield Acceleration

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

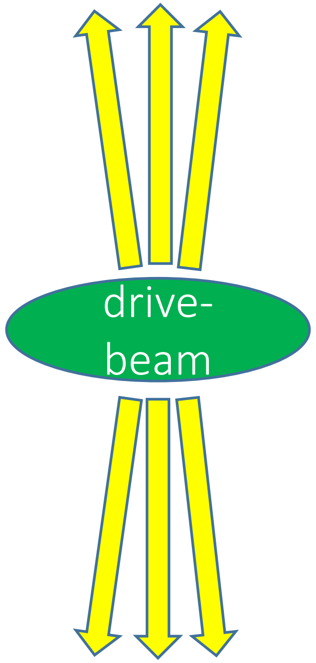
100 MV/m ➔ 100 GV/m



How to Create a Plasma Wakefield?



Energy source: the drive beam



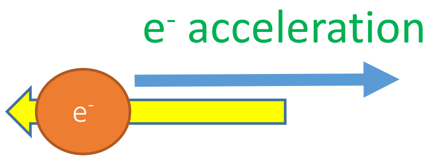
Charged particle bunches or laser bunches
→ carry almost purely transverse electric fields.

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.

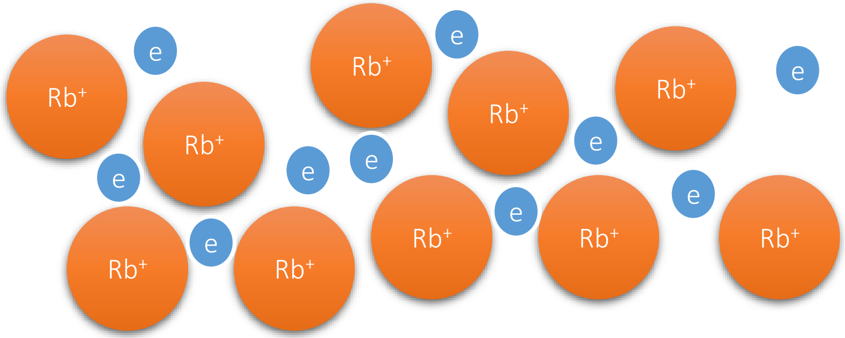
How to Create a Plasma Wakefield?

What we want:

Longitudinal electric field to accelerate charged particles.

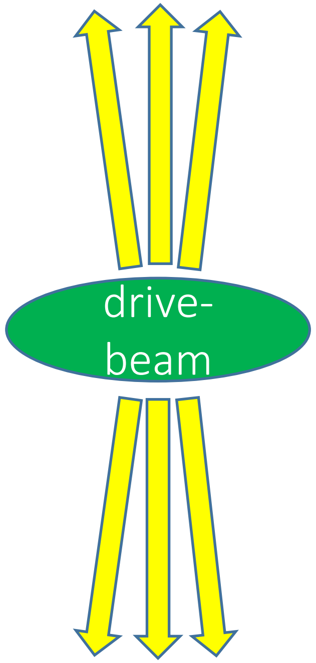


Our Tool:



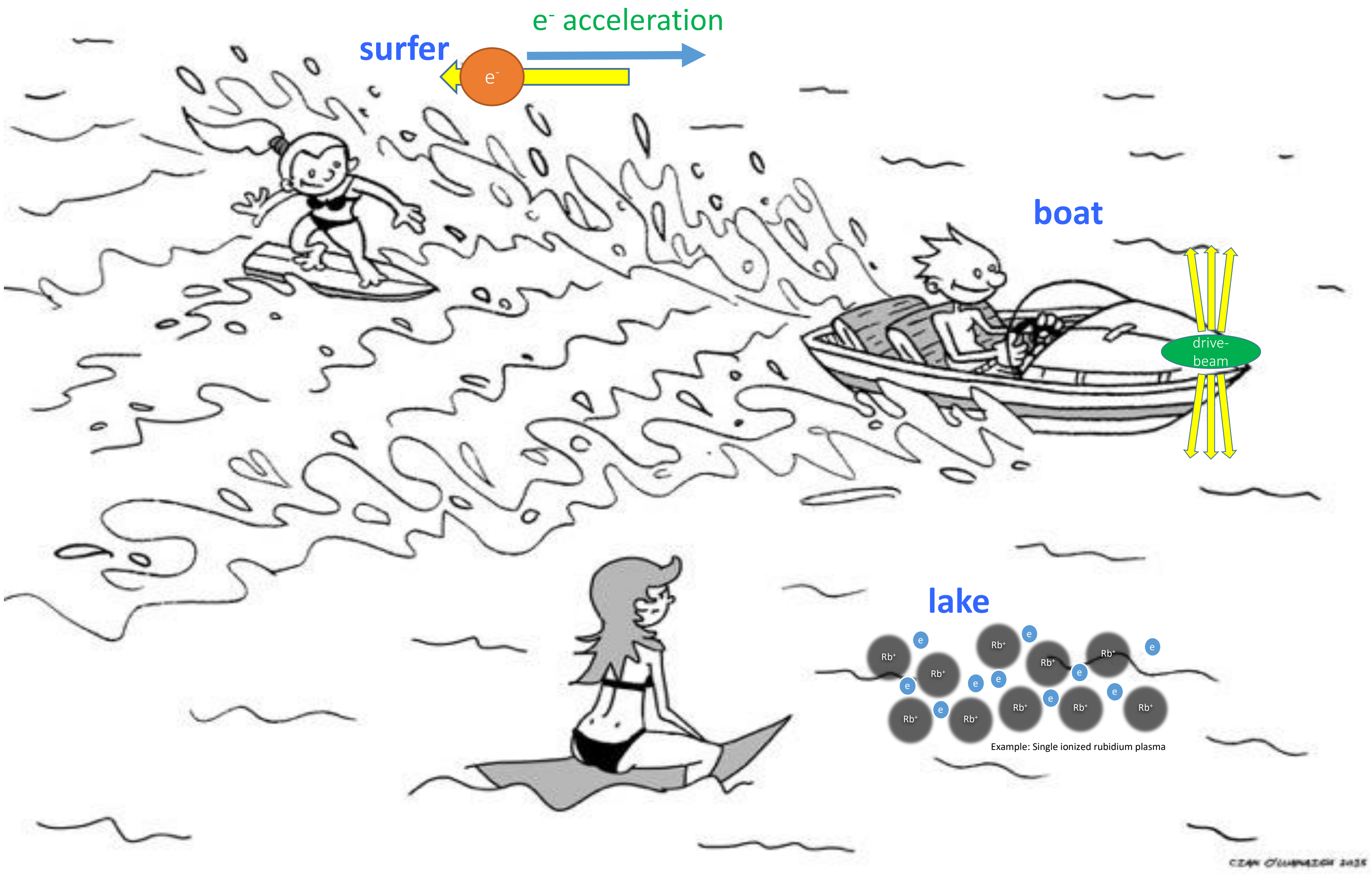
Single ionized rubidium **plasma**

Energy source:



Charged particle bunches carry almost purely transverse Electric Fields.

How to Create a Plasma Wakefield?



Analogy:
lake → plasma

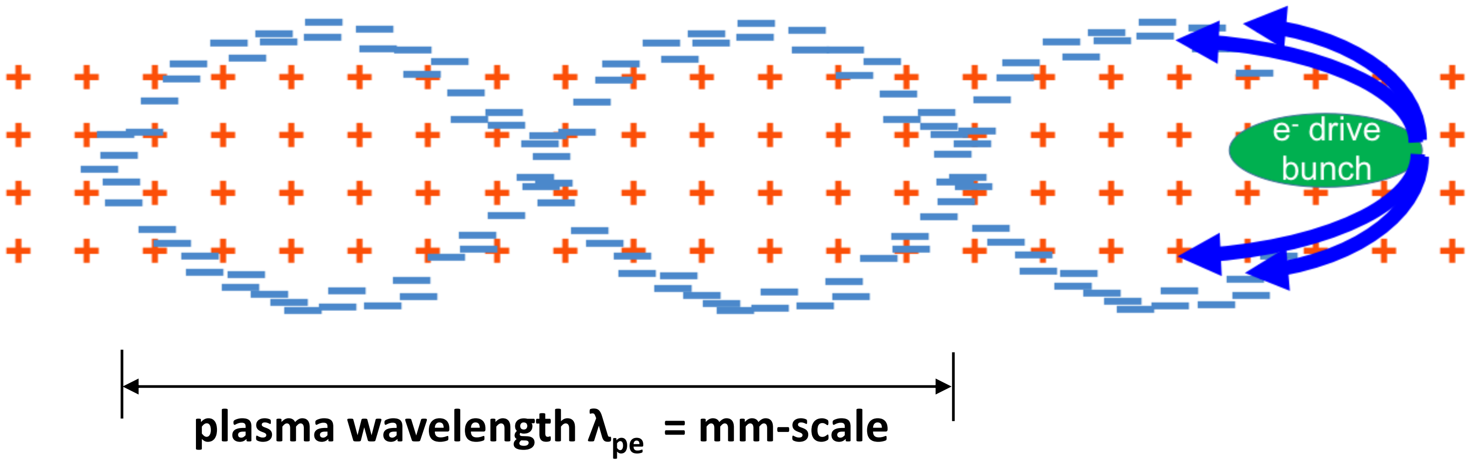
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Principle of Plasma Wakefield Acceleration

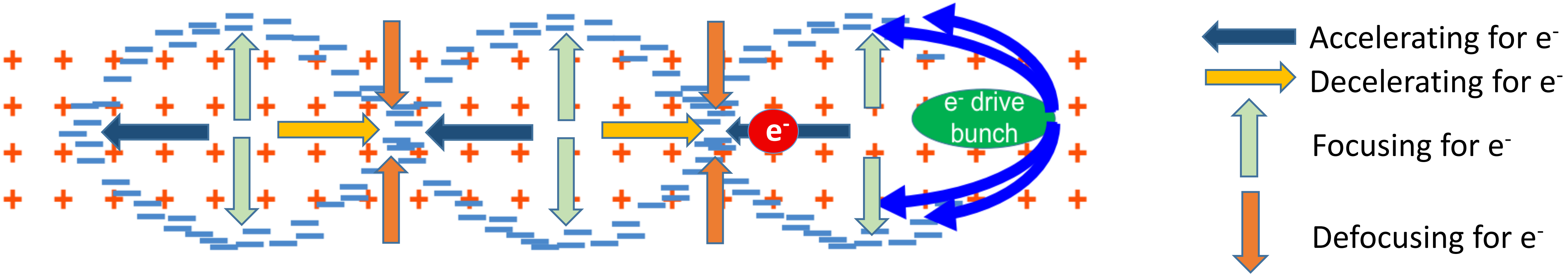
Boat:

- Laser drive beam
- Charged particle drive beam

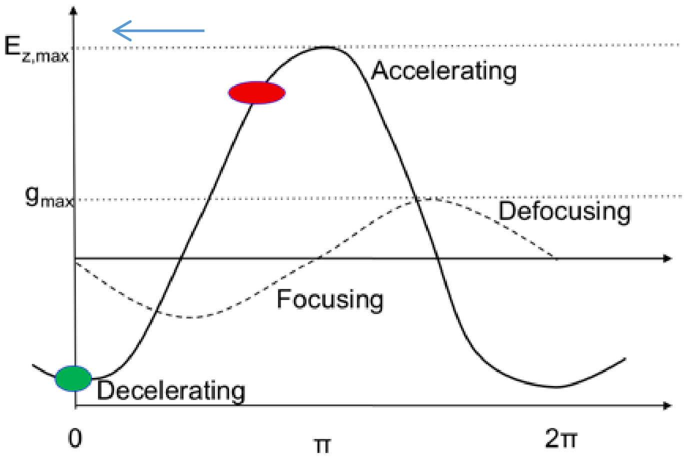


- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

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!

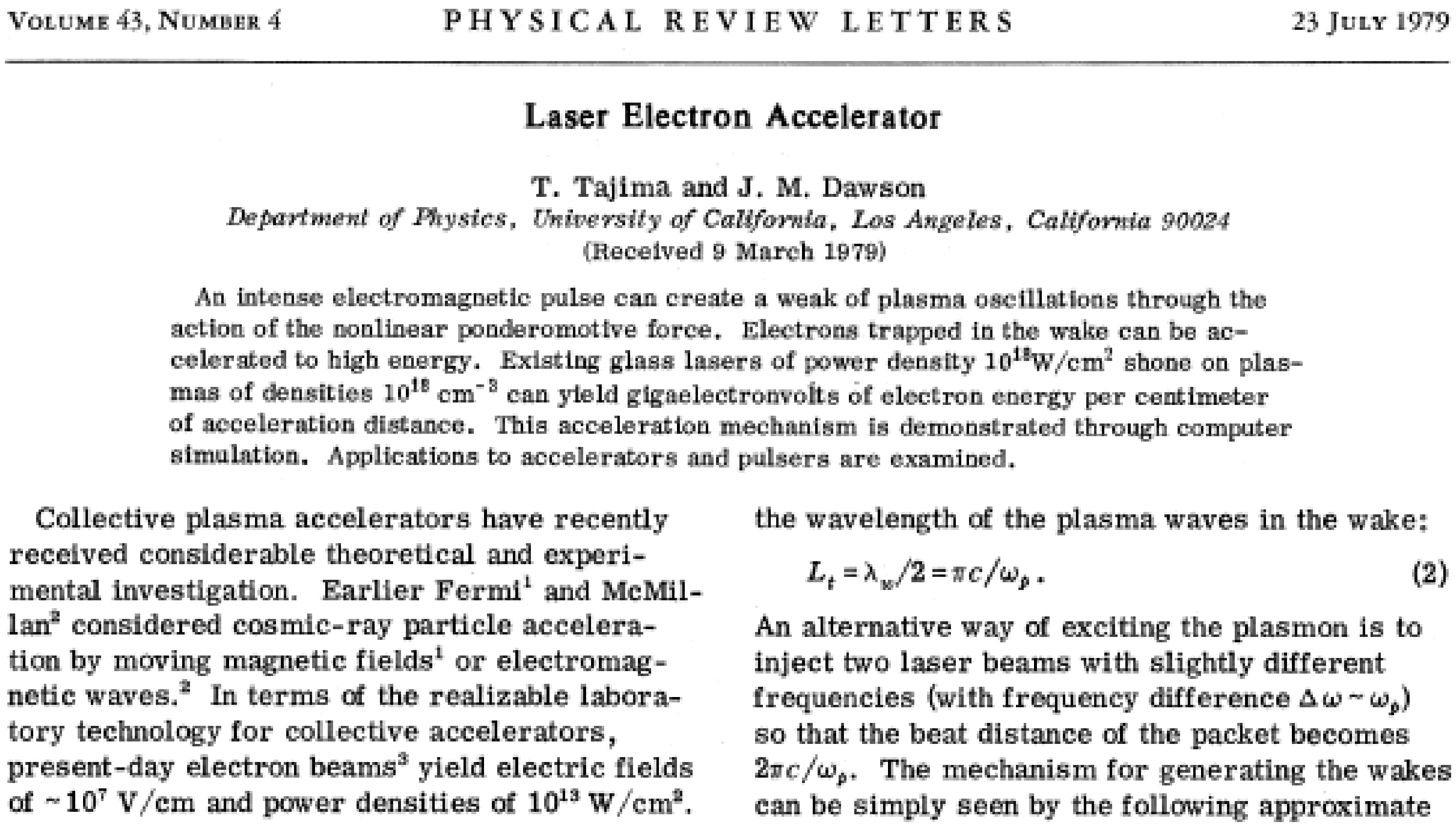
The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

→ $E_{WB} = 96 \frac{V}{m} \sqrt{n_{pe}}$ → 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

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.

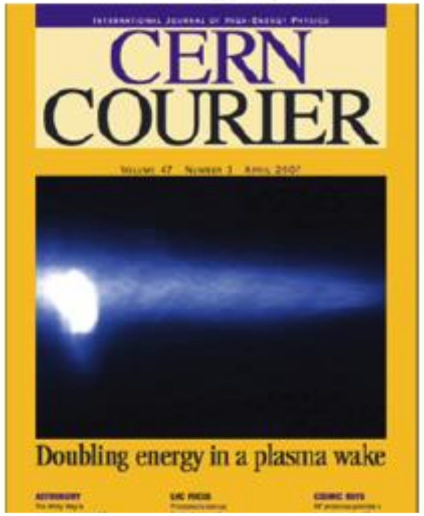
the wavelength of the plasma waves in the wake:

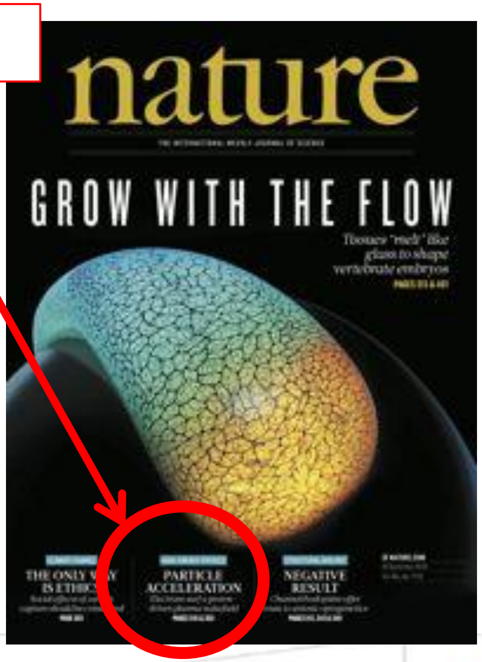
$$L_t = \lambda_w/2 = \pi c/\omega_p . \qquad (2)$$

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 Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment






Monoenergetic beams of relativistic electrons from intense laser–plasma interactions

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

A laser–plasma accelerator producing monoenergetic electron beams


NBC NEWS

Not-So-Large Colliders Cou
Revolutionize Physics

LETTER

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

SCIENTIFIC AMERICAN

Plasma-Surfing Mini-Accelerato

Science

LATEST NEWS

Physicists crank up current in new type of accelerator

Voice of America

US Scientists Build the Sma
Accelerator

Scienze

Gli acceleratori di particelle saranno più "piccoli" e low cost

welt der physik

Fortschritte in der Kielfeld-Beschleunigung

COMILLAS

ciencia plus.com

Proyectan aceleradores de partículas con plasma de bajo coste

Surfing wakefields to create smaller accelerators

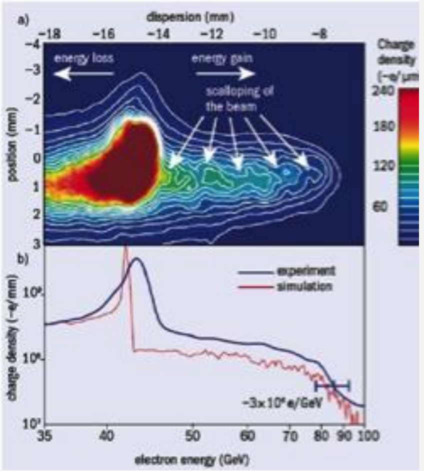
Some Highlights

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**

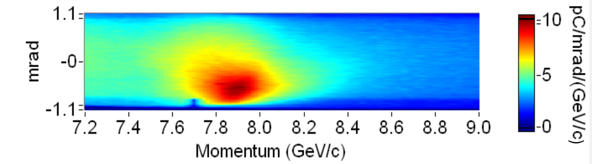


BELLA, Berkeley Lab, USA:
Laser-driven plasma wakefield acceleration Facility

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

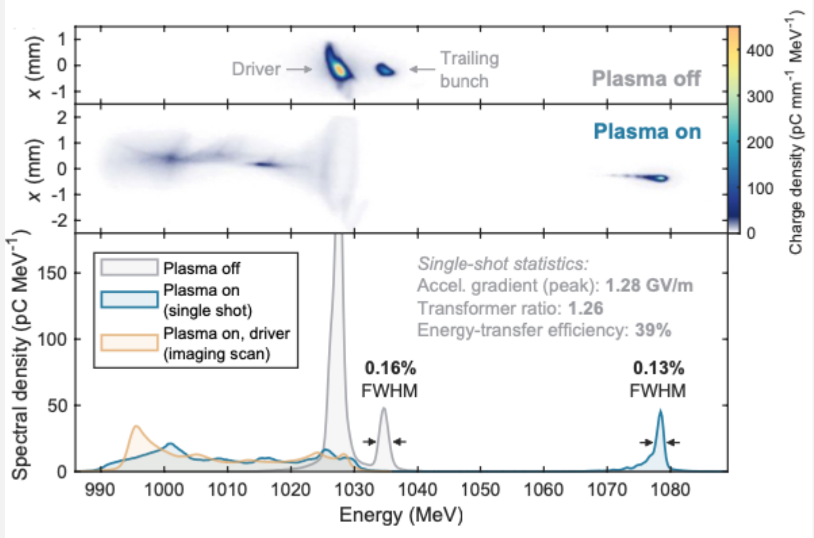
*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

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

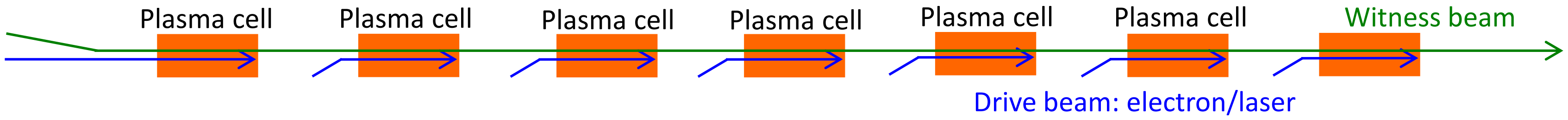
Drive beams (Boat):

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):

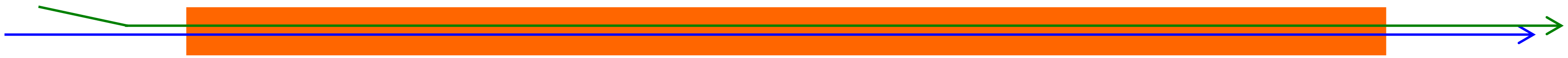
Lasers: ~40 J/pulse

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.



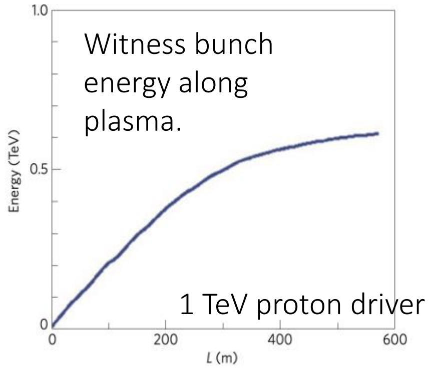
Plasma cell

Witness beam

Drive beam: protons

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



Witness bunch energy along plasma.

1 TeV proton driver

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

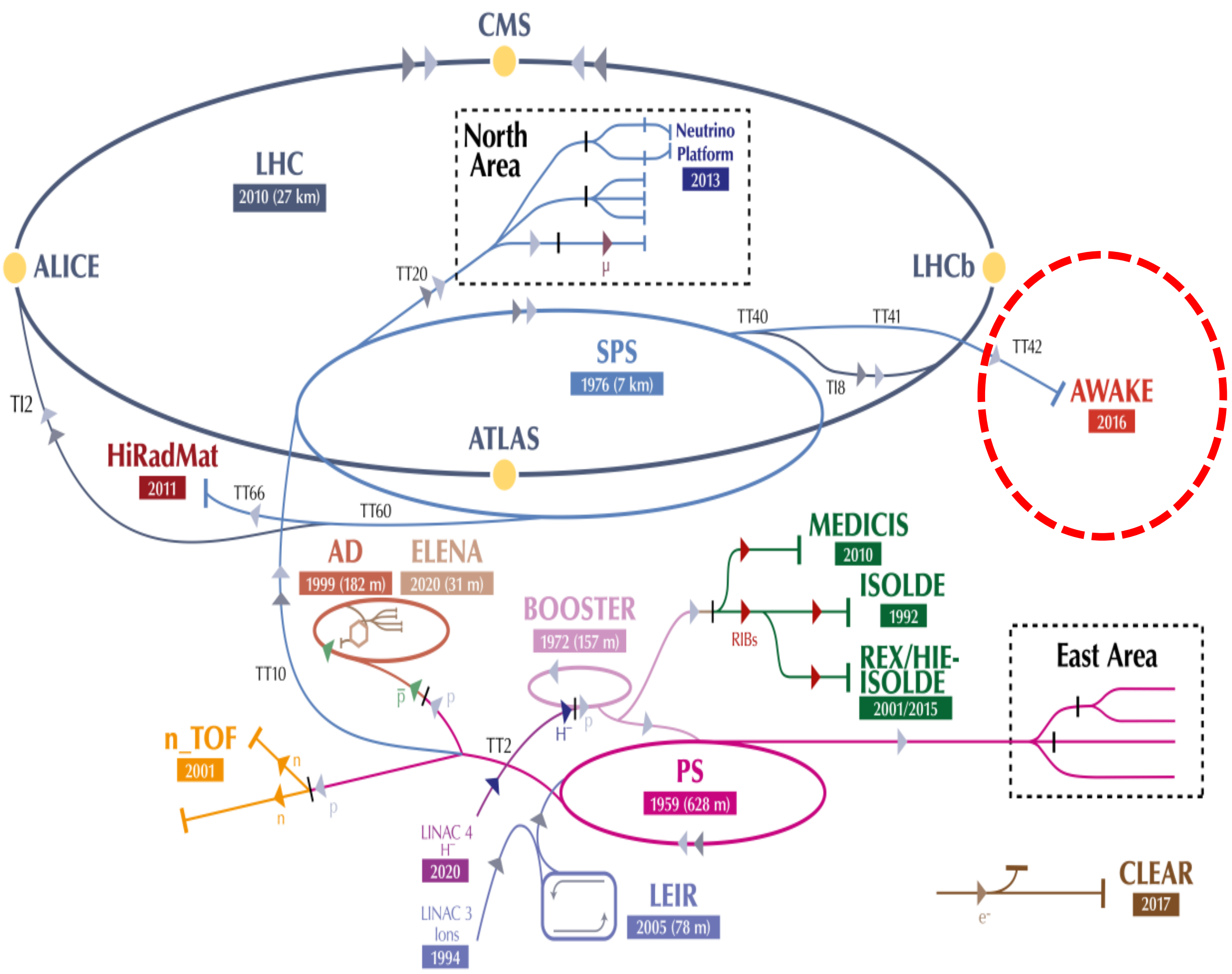
Advanced WAKEfield Experiment

➔Accelerator R&D experiment at CERN.

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

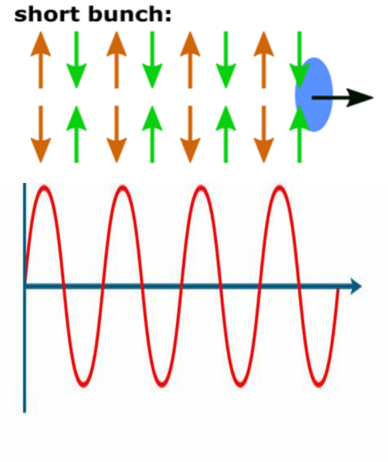
  ➔ At CERN highly relativistic protons with high energy (> kJ) available

➔Accelerating externally injected electrons to GeV scale.

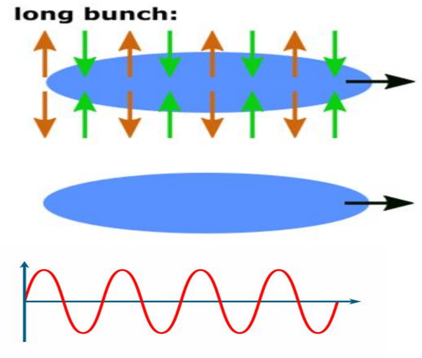


Proton Bunch as a Drive Beam

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

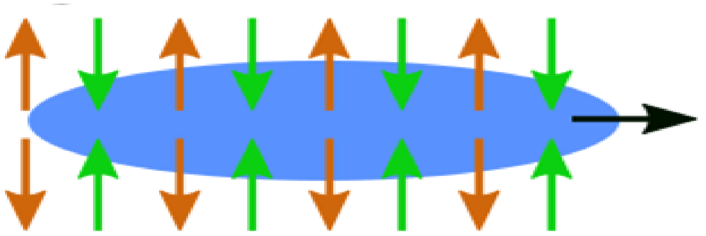


CERN SPS proton bunch: very long! (σ_z = **6 - 10 cm**) → much longer than plasma wavelength (λ = **1mm**)
→ Would create only small wakefield amplitudes

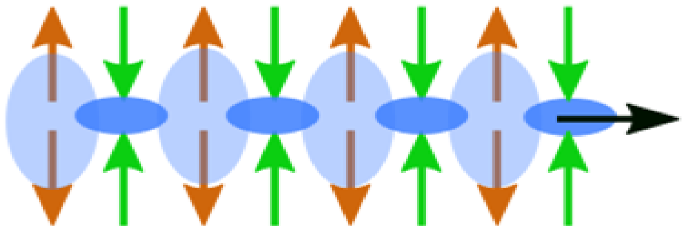


Self-Modulation of the Proton Bunch

Self-Modulation Instability:

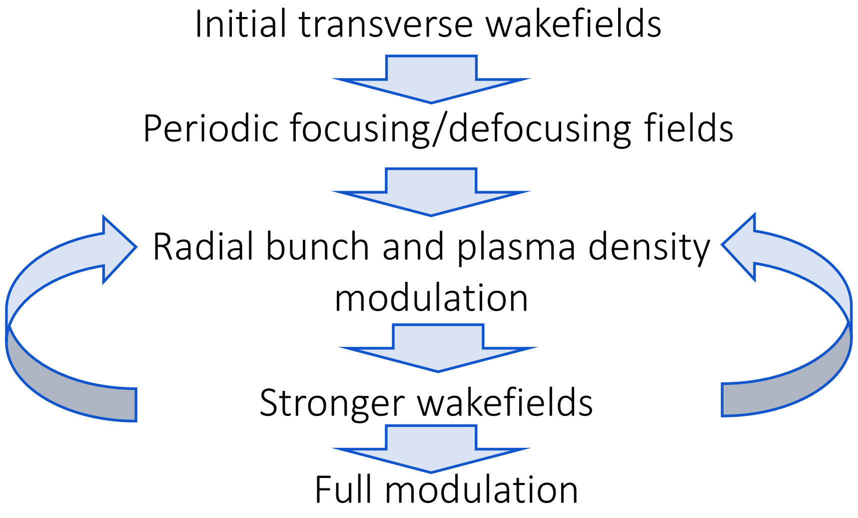


p^+ bunch



Density modulation on-axis → **micro-bunches**.

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



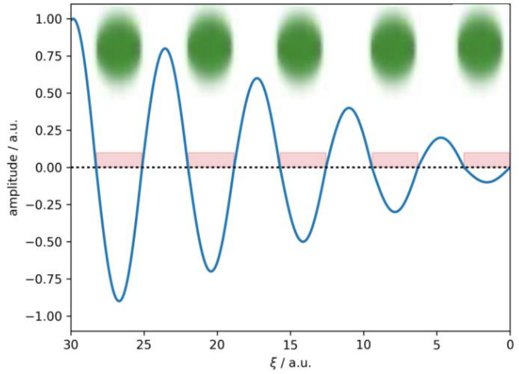
Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

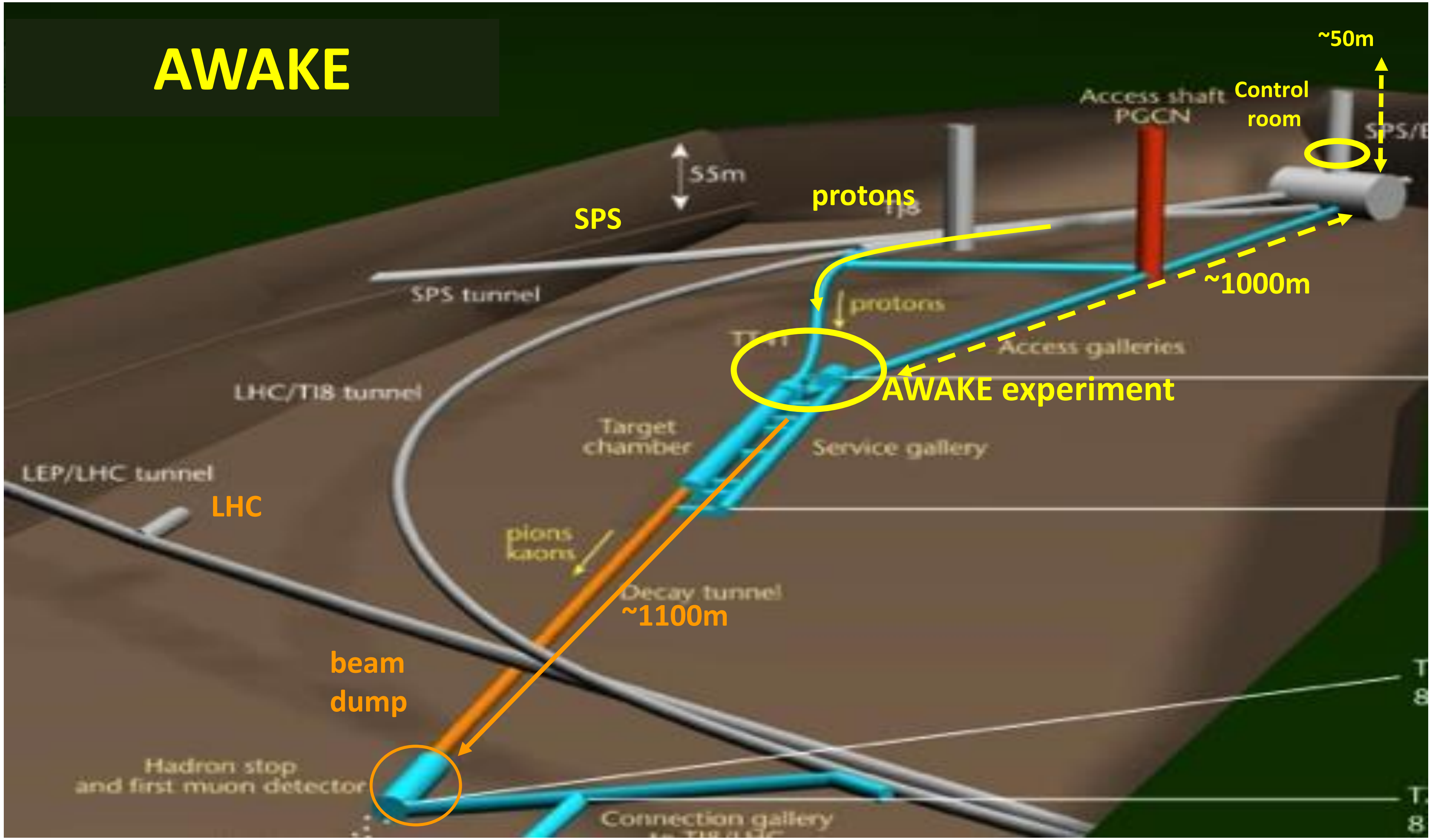
Stronger wakefields

Full modulation



➔ 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

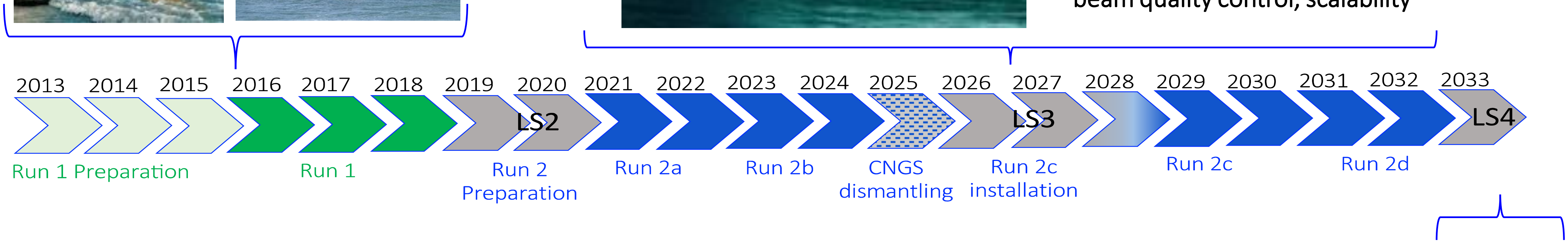
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2032)

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



2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2

LS3

LS4

Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

Run 2c installation

Run 2c

Run 2d

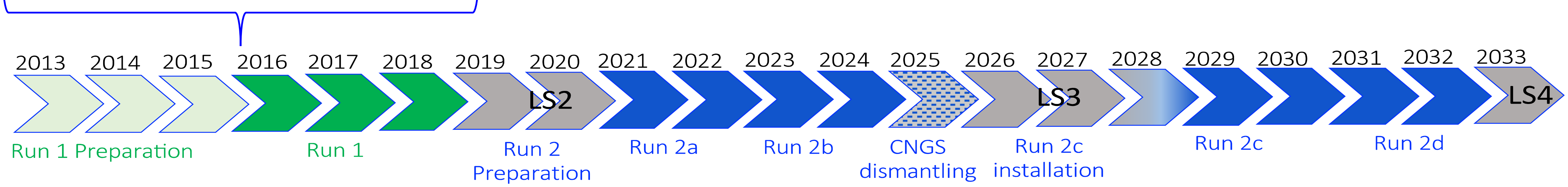
➔First applications >2033

AWAKE Program

RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration



Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

Run 2c installation

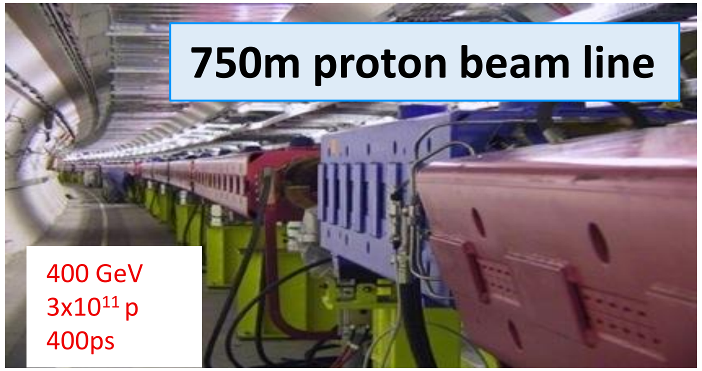
Run 2c

Run 2d

AWAKE Experiment and Run 1 Results

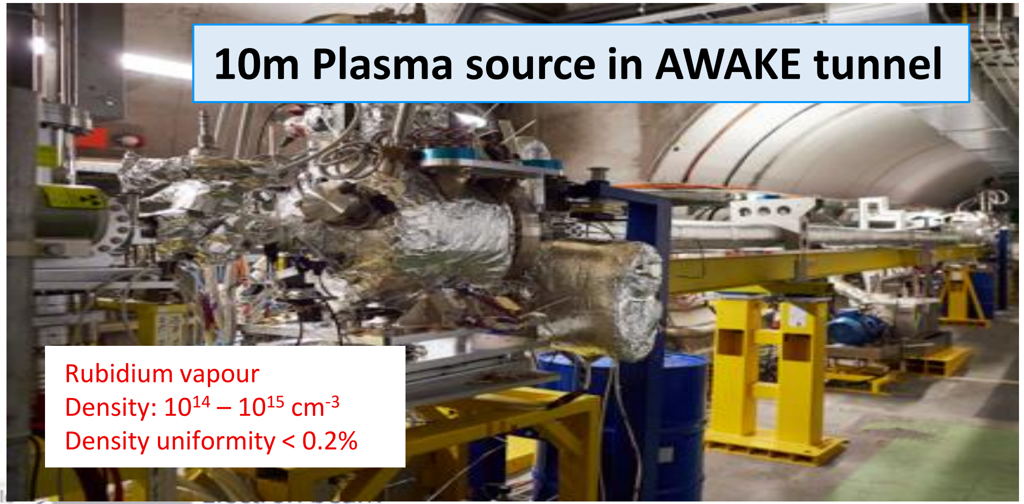
Ti: Sapphire Laser

Ti:Sapphire
500mJ
120 fs



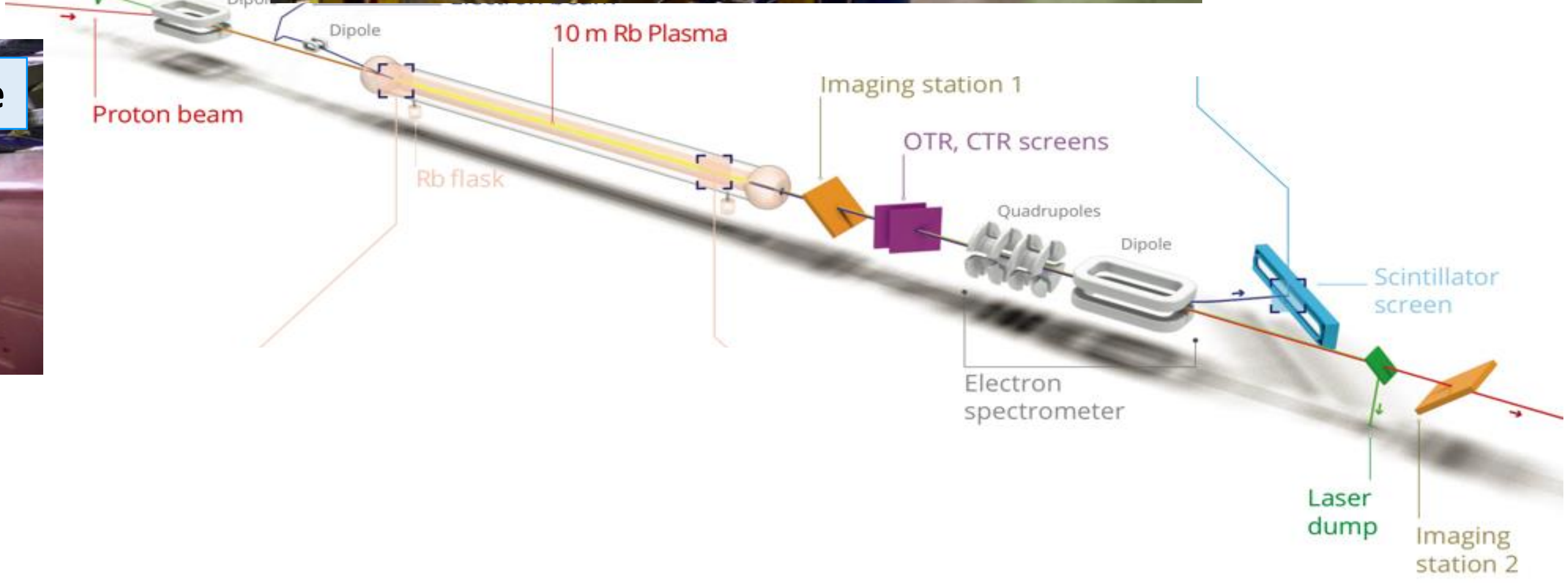
750m proton beam line

400 GeV
3×10^{11} p
400ps



10m Plasma source in AWAKE tunnel

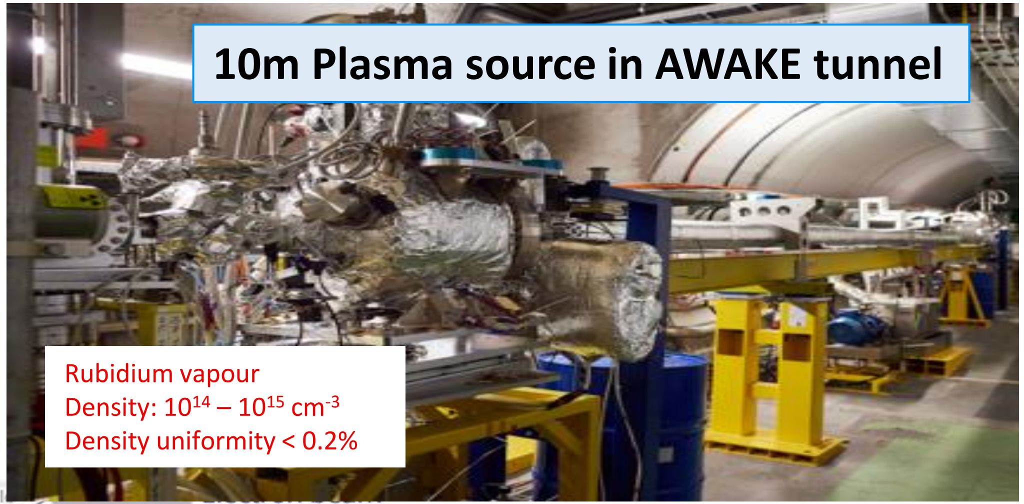
Rubidium vapour
Density: $10^{14} - 10^{15}$ cm^{-3}
Density uniformity < 0.2%



AWAKE Experiment and Run 1 Results

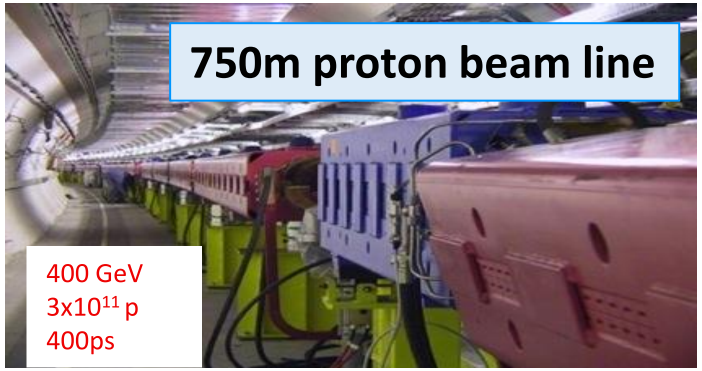
Ti: Sapphire Laser

Ti:Sapphire
500mJ
120 fs



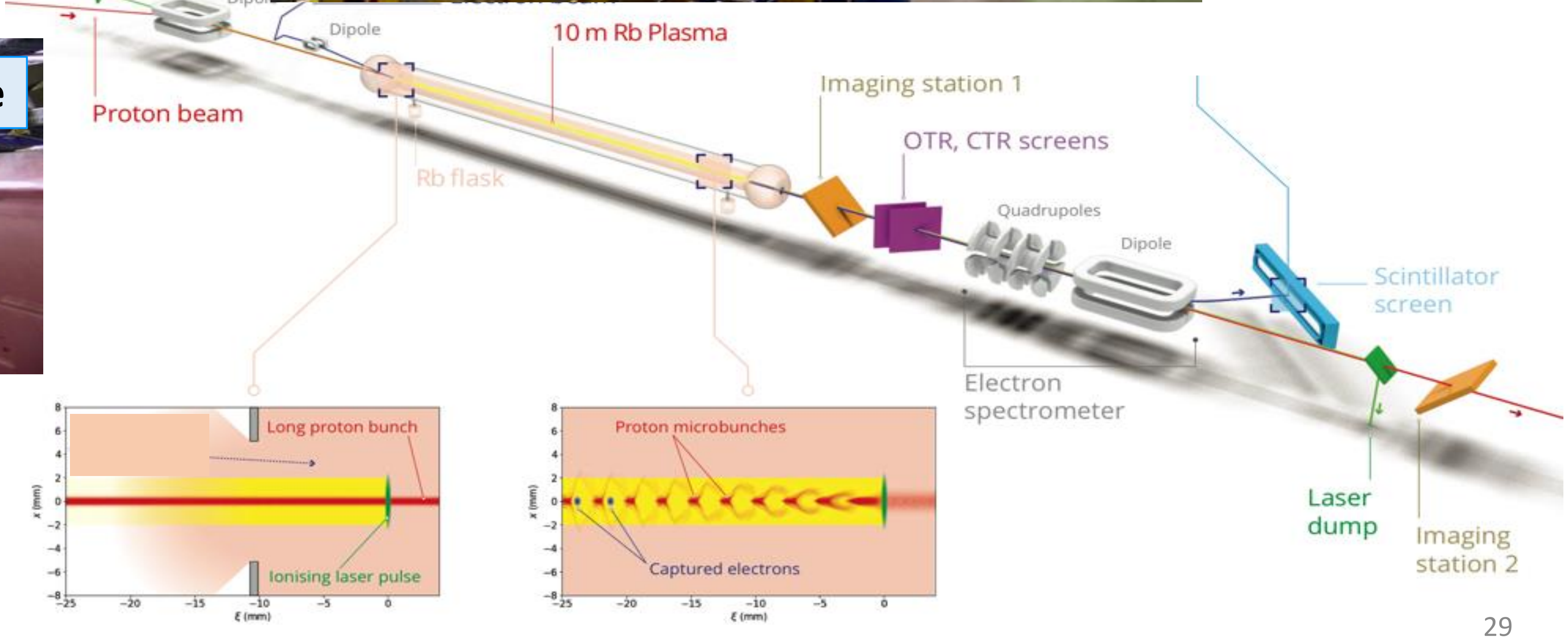
10m Plasma source in AWAKE tunnel

Rubidium vapour
Density: $10^{14} – 10^{15}$ cm^{-3}
Density uniformity < 0.2%



750m proton beam line

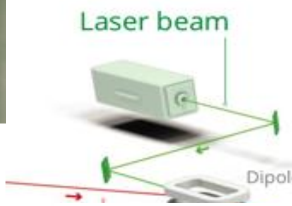
400 GeV
3x10^{11} p
400ps

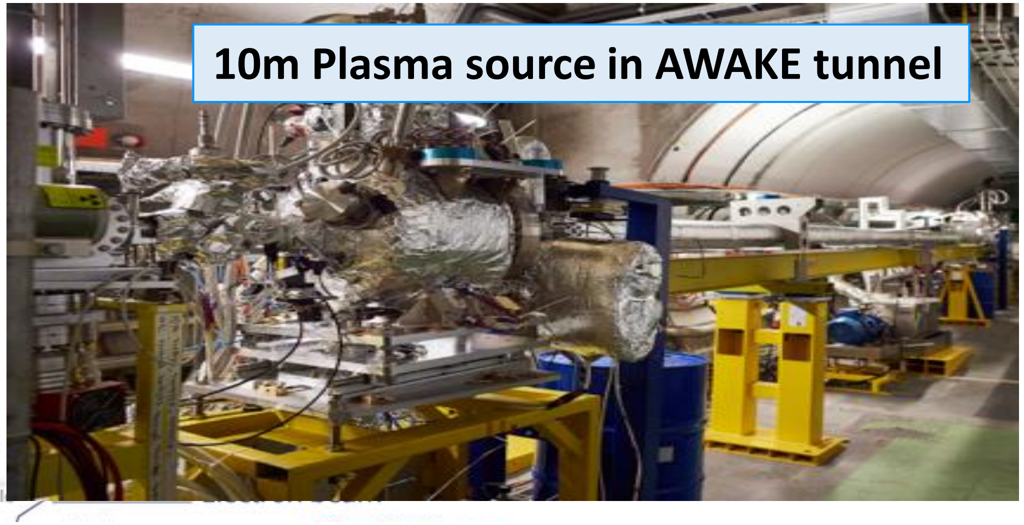


AWAKE Experiment and Run 1 Results

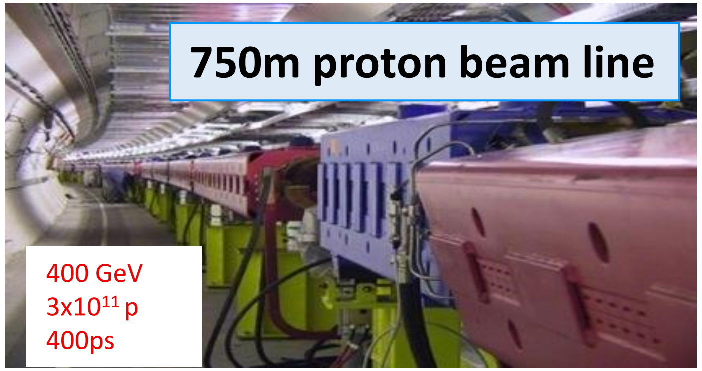
Ti: Sapphire Laser

Ti:Sapphire
500mJ
120 fs





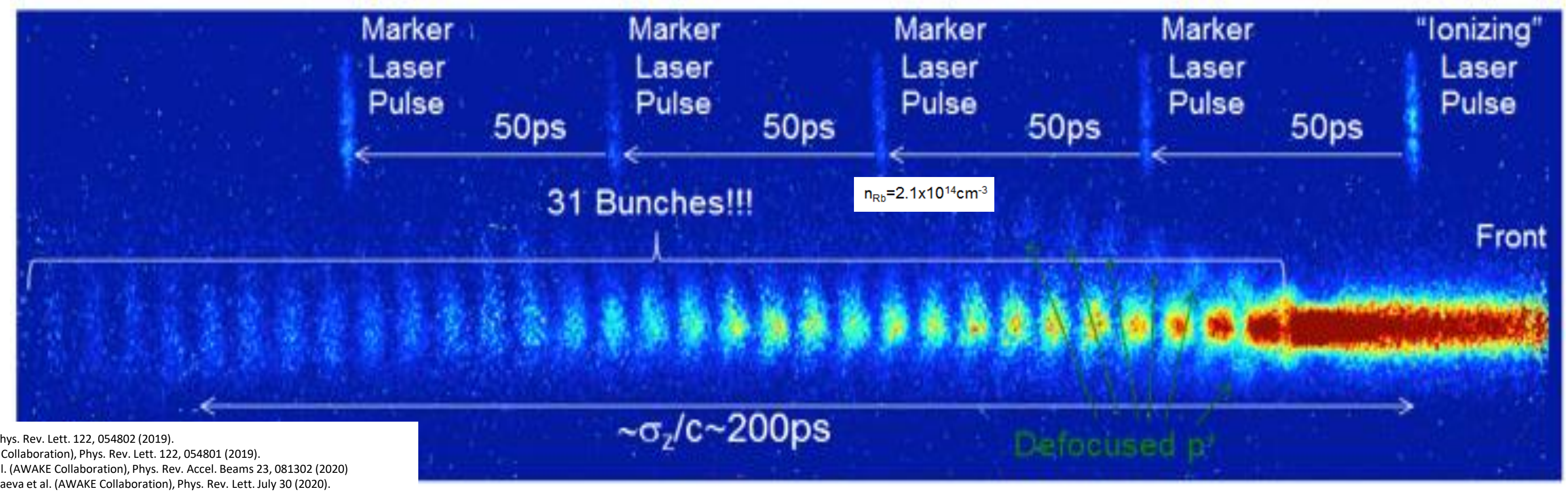
10m Plasma source in AWAKE tunnel



750m proton beam line

400 GeV
$3\text{x}10^{11}$ p
400ps

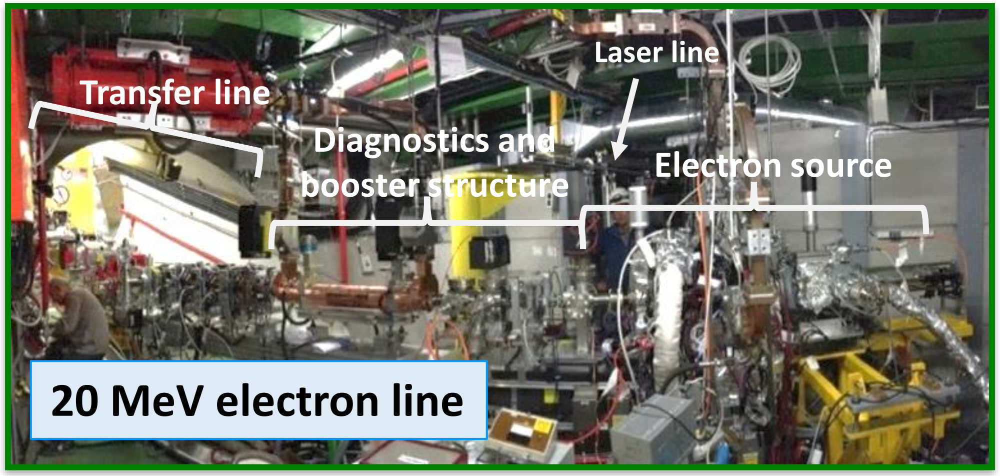
#1: Demonstration of Seeded Self-Modulation of the Proton bunch



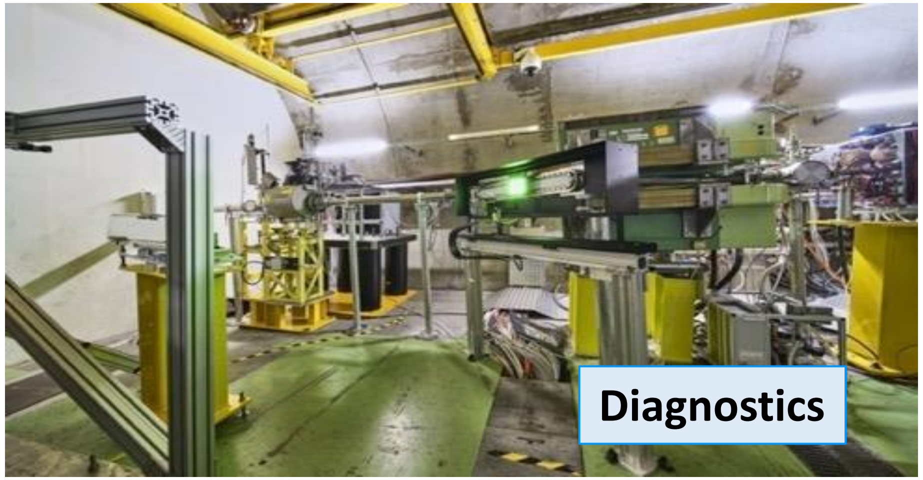
E. Gschwendtner, CERN

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), accepted in Phys. Rev. Lett. (2021)

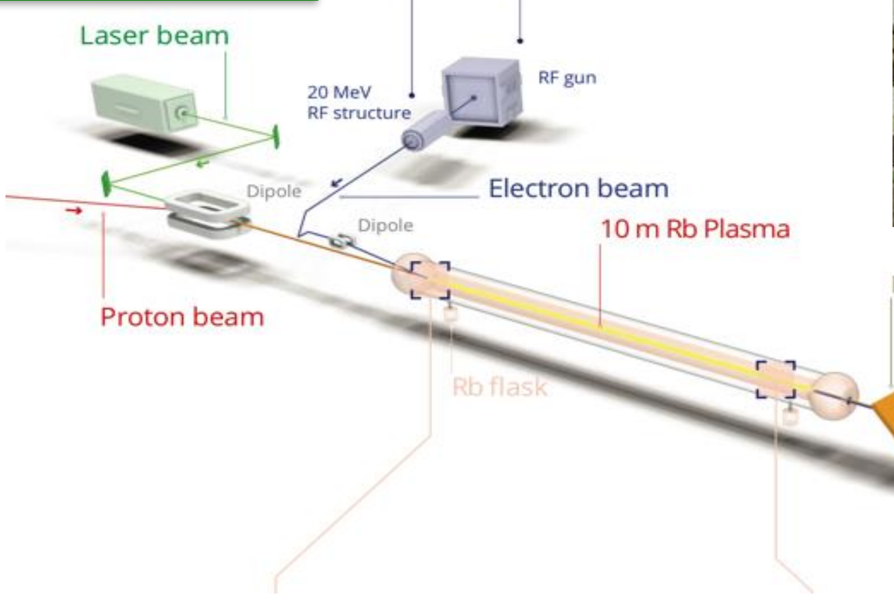
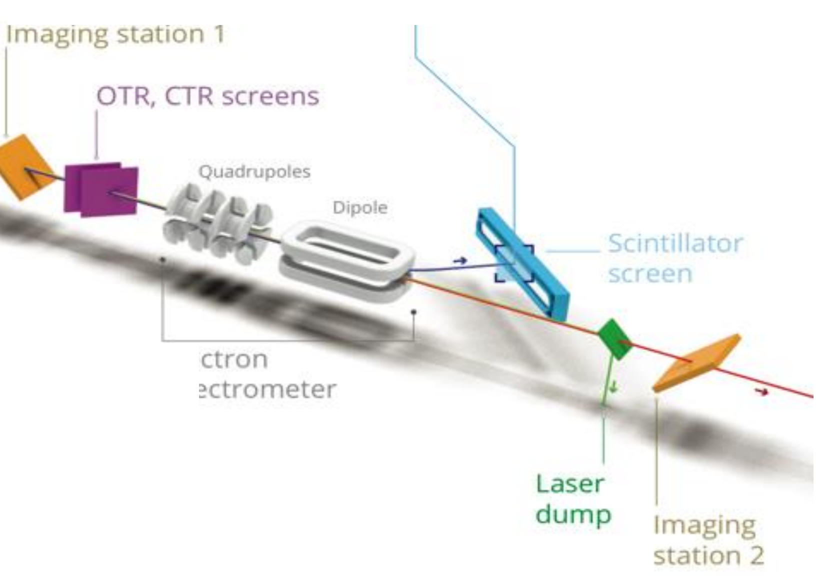
AWAKE Experiment and Run 1 Results



20 MeV electron line



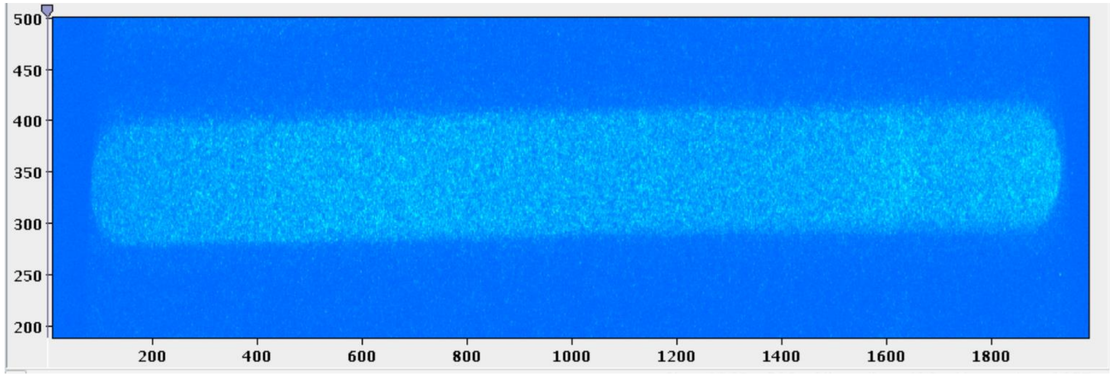
Diagnostics

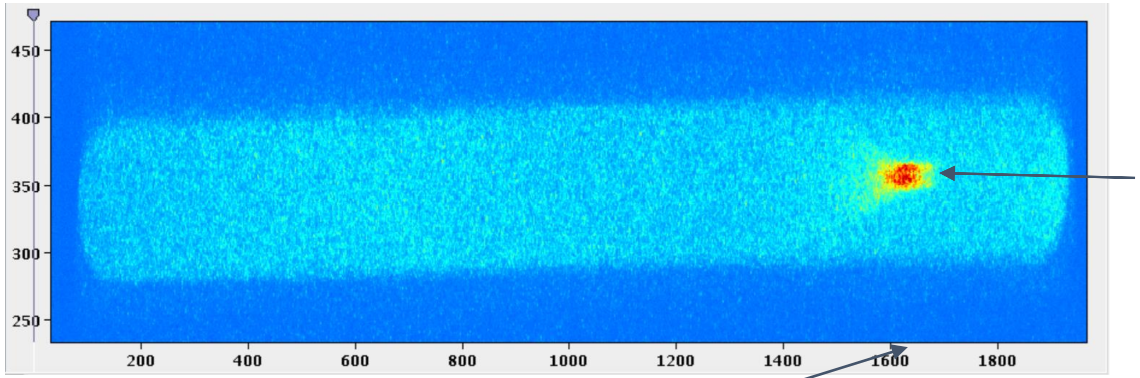
Run 1 Results: Electron Acceleration

#2: Demonstration of Electron Acceleration in Plasma Wakefield

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

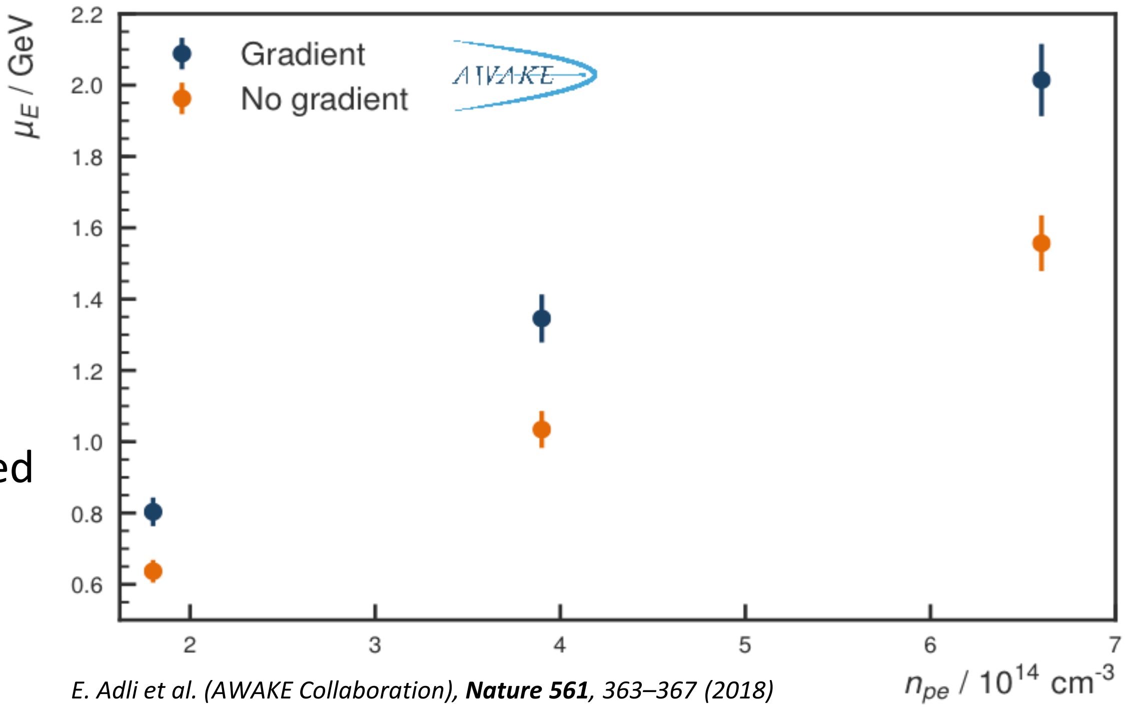


No accelerated electrons



Accelerated electrons

Convert pixel-size and dipole setting to energy

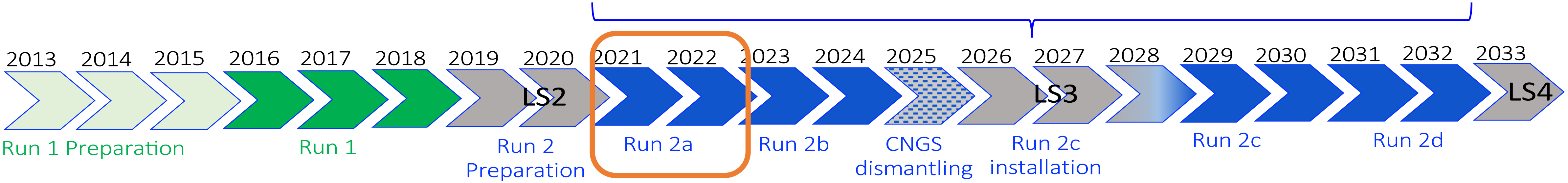


E. Adli et al. (AWAKE Collaboration), ***Nature 561****, 363–367 (2018)*

AWAKE Program

RUN 2 (2021-2032)

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



2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

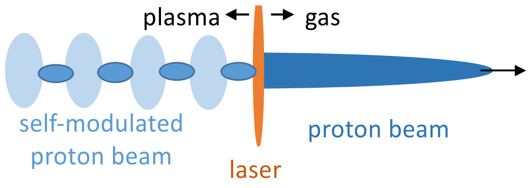
LS2
LS3
LS4

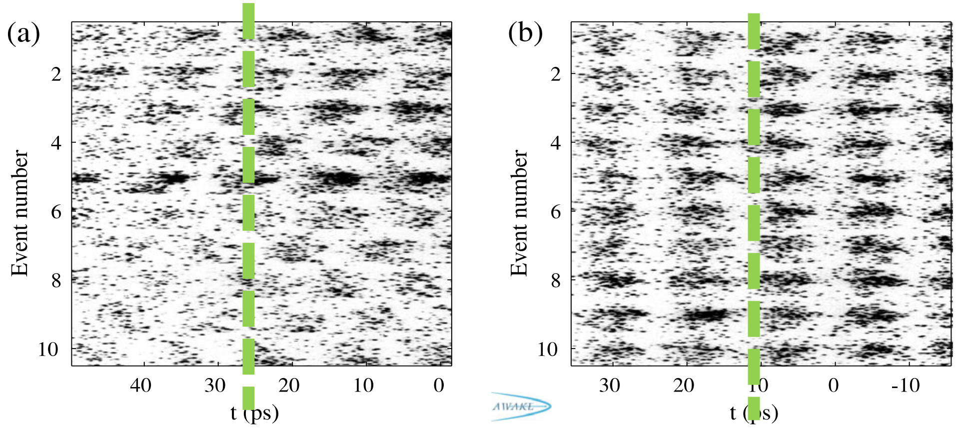
Run 1 Preparation
Run 1
Run 2 Preparation
Run 2a
Run 2b
CNGS dismantling
Run 2c installation
Run 2c
Run 2d

Run 2a Results – Seeding the Self-Modulation

➔ Proton-bunch self-modulation process must be reproducible, reliable and stable.

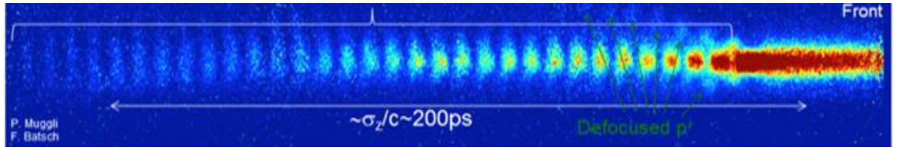
Seeding with the relativistic ionization front





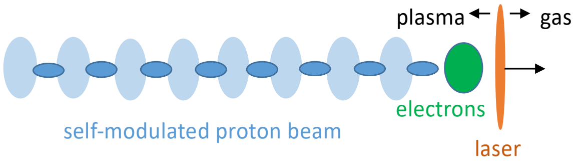
Unseeded: phase not reproducible

Seeded with laser ionization front



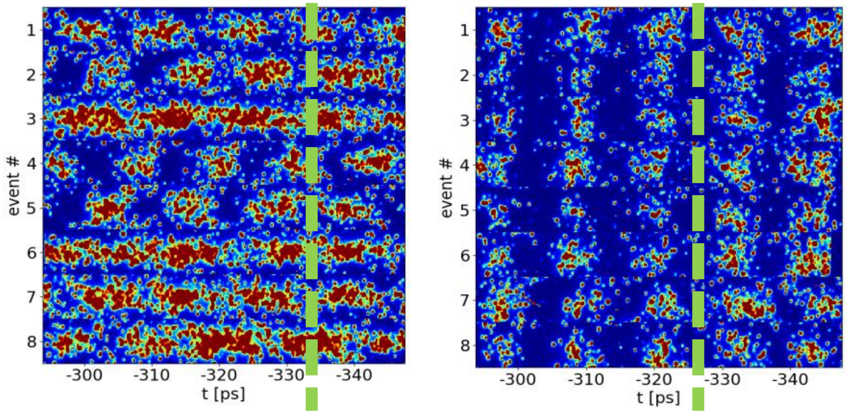
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

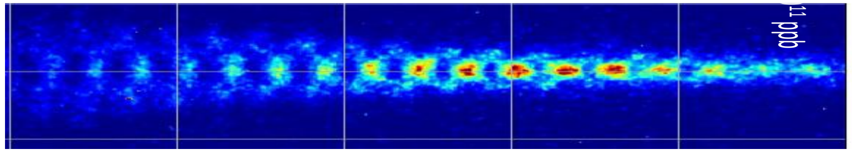
Seeding with the electron bunch



No e^- bunch → SMI

with e^- bunch → seeded SM



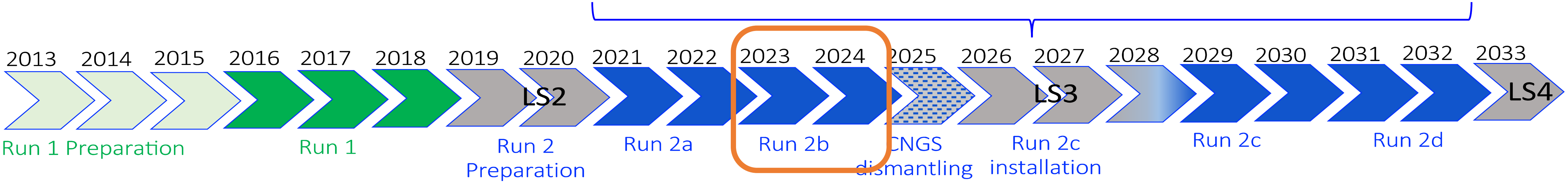


L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

AWAKE Program

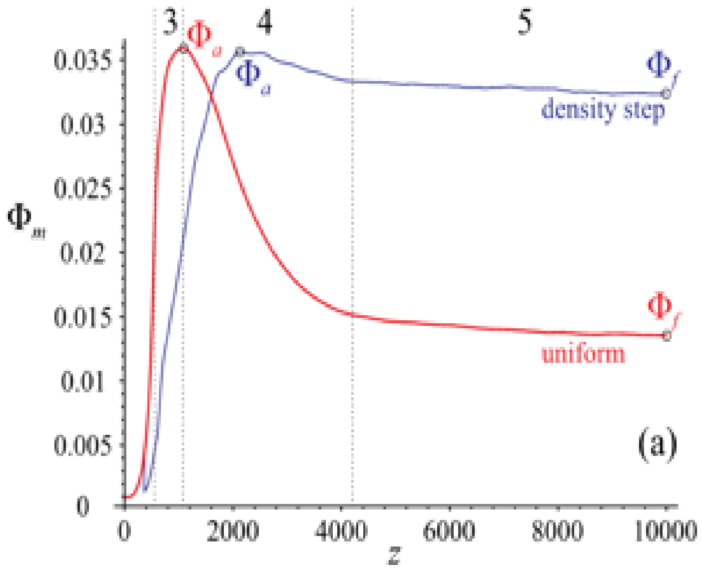
RUN 2 (2021-2032)

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

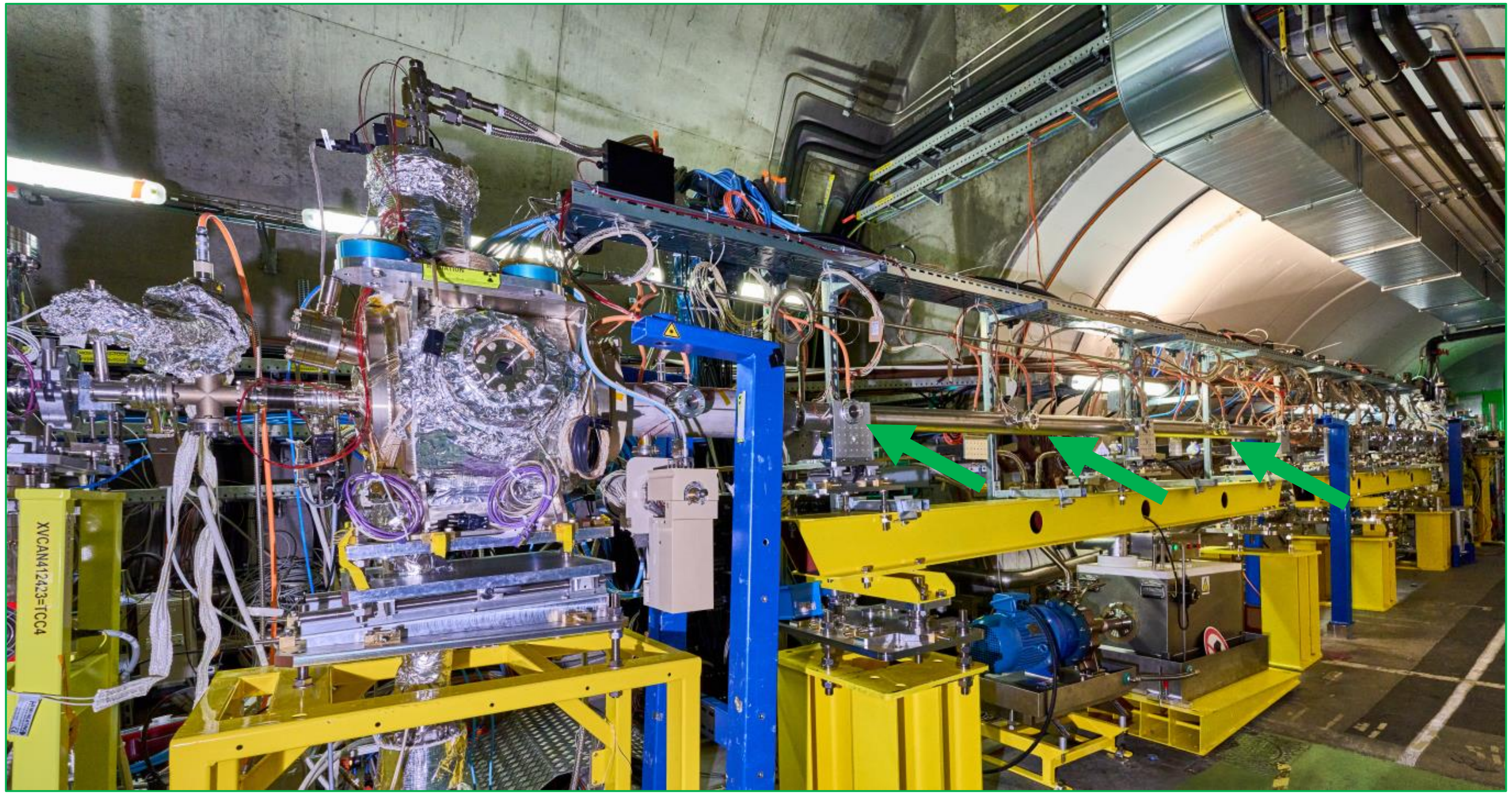


Run 2b Results – Stabilizing Large Wakefield Amplitudes

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



New Rubidium vapour source with density step installed in 2023

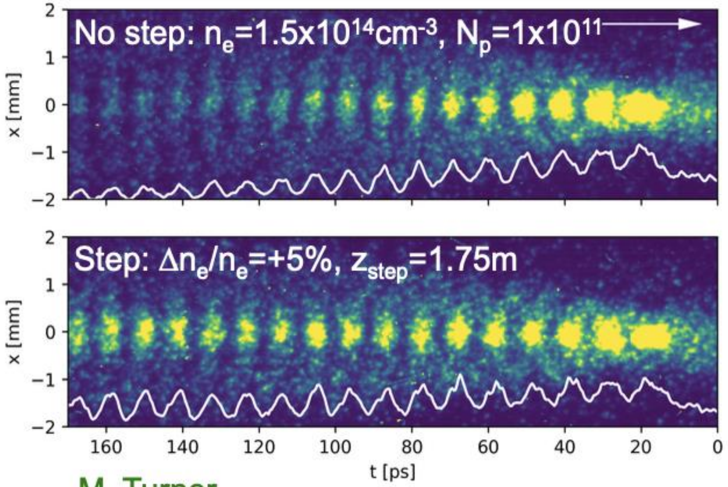


- Length: ~ 10 m, independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ to measure light emitted by wakefields dissipating after the passage of the proton bunch

Run 2b Results – Stabilizing Large Wakefield Amplitudes

Physics program: study the effect of the plasma density and test whether wakefields maintain a larger amplitude

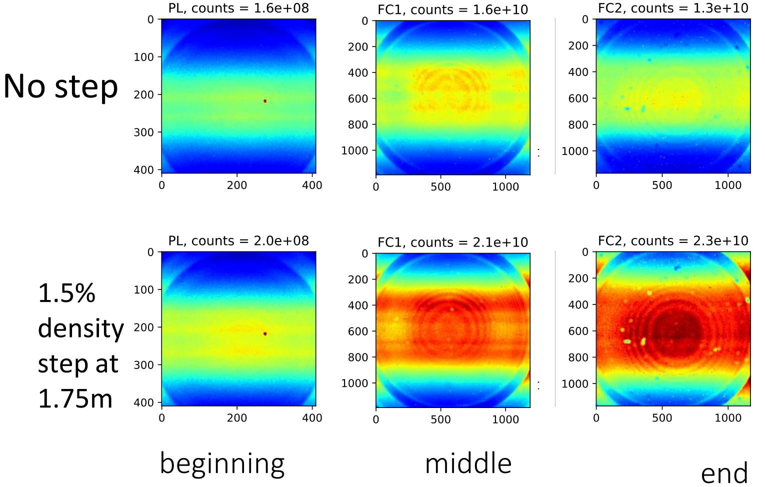
Proton Bunch Time-Resolved Images



M. Turner

➔ plasma density step clearly influences seeded self-modulation: Longer bunch train with more charge

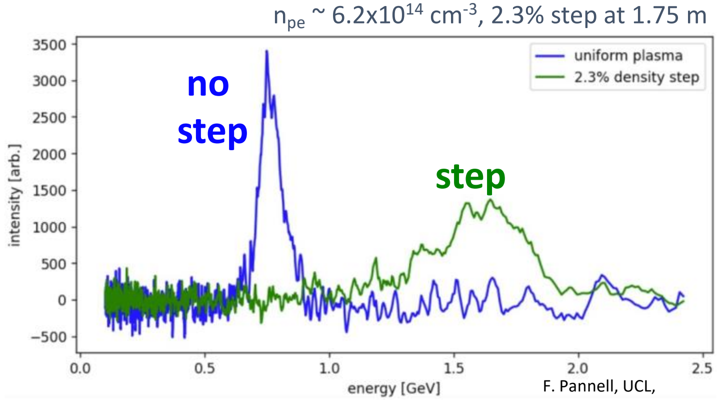
Plasma Light



➔ plasma density step clearly influences plasma light from dissipating wakefields

Electron Acceleration

External injection downstream of the density step



F. Pannell, UCL, AWAKE Collaboration

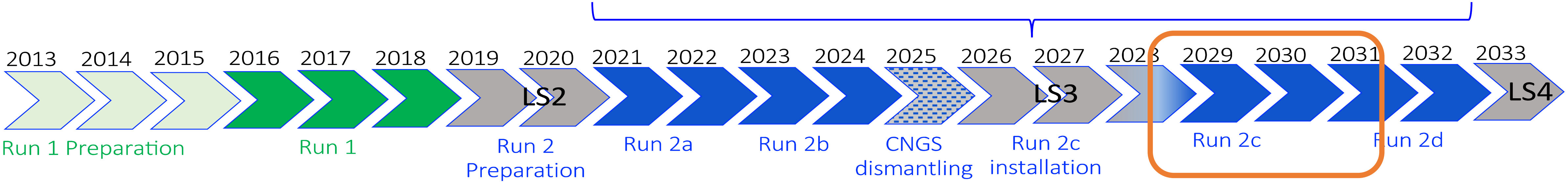
➔ Plasma density step clearly influences energy of the accelerated electrons: electron energy much higher

➔ Complete the measurements during 2024 run!

AWAKE Program

RUN 2 (2021-2032)

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



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

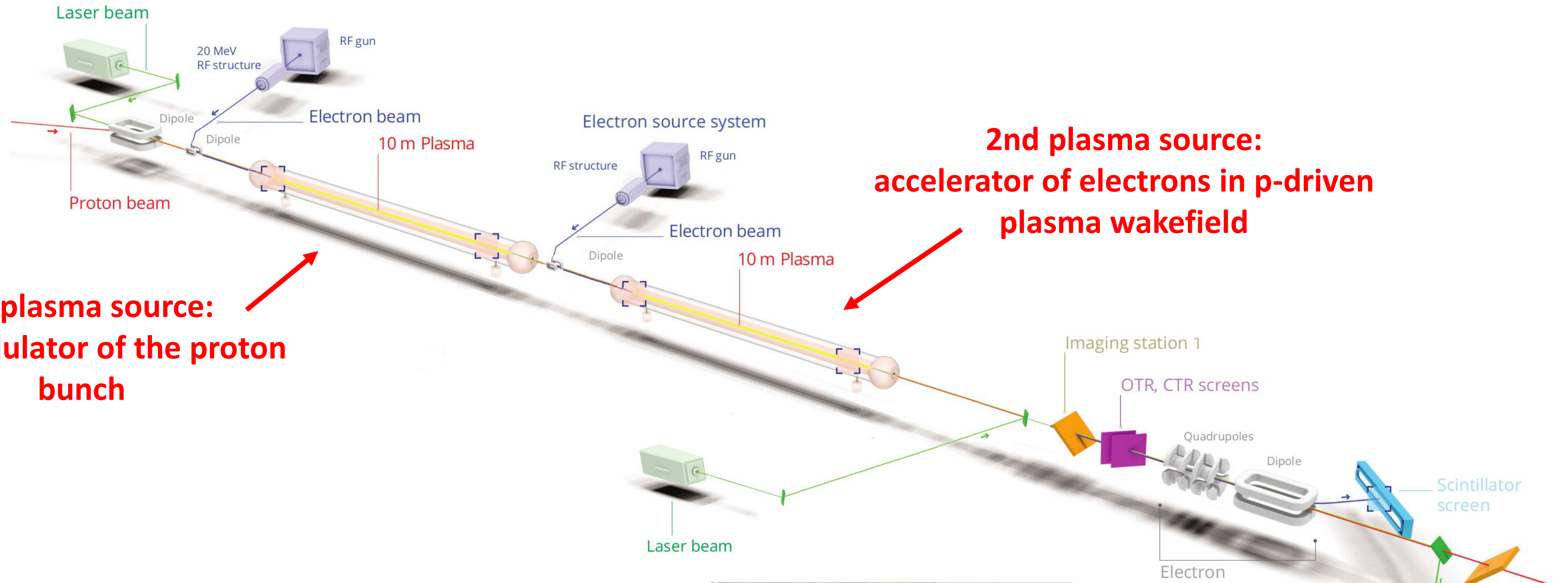
➔ **Run 2b (2023-2024): STABILIZATION: *maintain large wakefield amplitudes*** over long plasma distances by introducing a step in the plasma density

➔ *(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***.

AWAKE Run 2c – Start after LS3

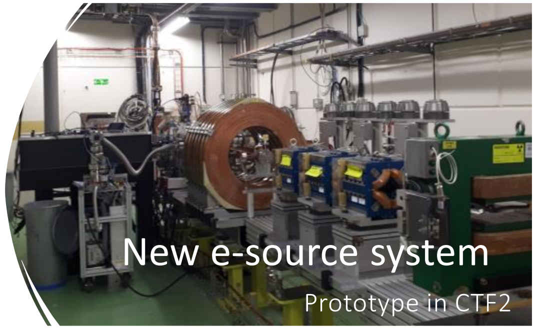
➔Accelerate an ***electron beam to high energies (gradient of 0.5-1GV/m)***
➔while controlling the ***electron beam quality (~10 mm-mrad emittance, 10% energy spread)***
➔demonstrate ***scalable plasma source technology.***



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

1st plasma source: self-modulator of the proton bunch

➔ Studies, design and prototyping already advancing well for several experimental elements of Run 2c



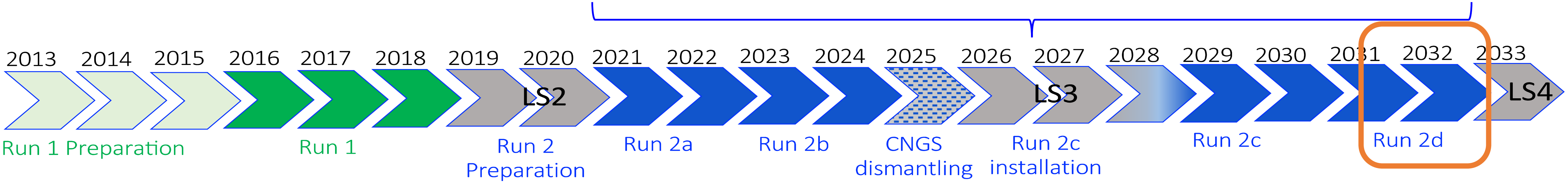
New e-source system

Prototype in CTF2

AWAKE Program

RUN 2 (2021-2032)

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



✓ **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

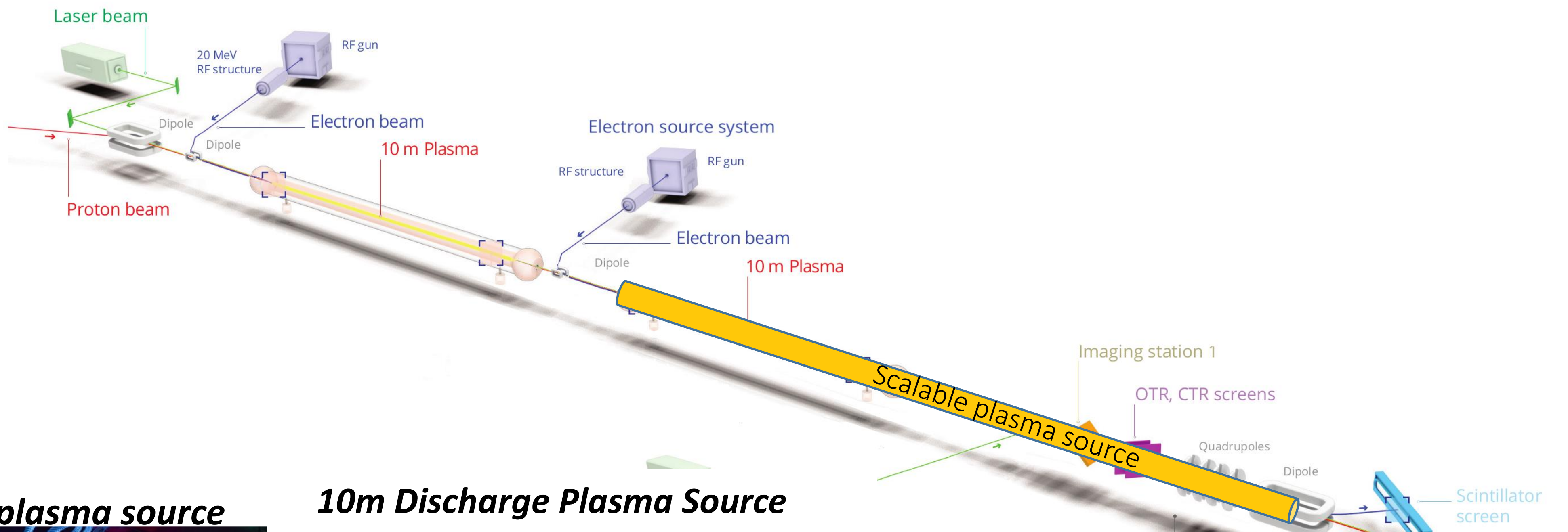
➔ *(2025-2027): CNGS dismantling, CERN Long Shutdown LS3, installation of Run 2c*

➔ **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

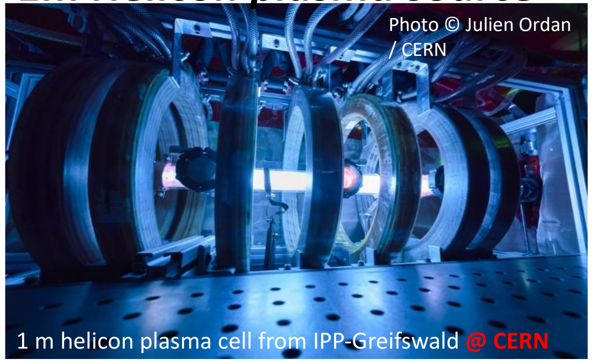


Photo © Julien Ordan / CERN

1 m helicon plasma cell from IPP-Greifswald @ CERN

10m Discharge Plasma Source

10 m Discharge Plasma Source in AWAKE

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

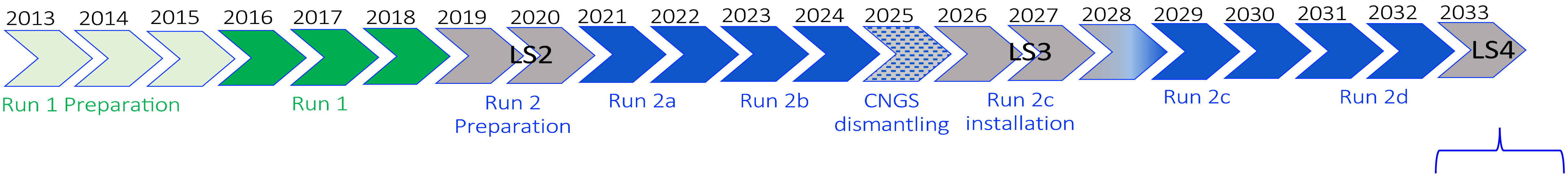
Unique opportunity to test the discharge plasma source in May 2023 with protons in the AWAKE facility

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 Program


2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

LS2

LS3

LS4

Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

Run 2c installation

Run 2c

Run 2d

→First applications >2033

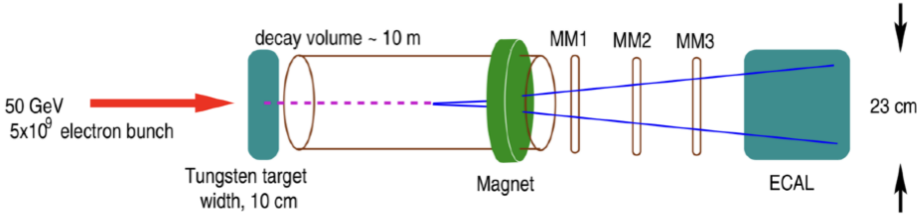
First Applications with AWAKE-Like Technology

➔ Within the context of the **Physics Beyond Colliders Project (PBC),** AWAKE performed preliminary studies on possible first particle physics applications in the nearer future.

Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
Search for dark photons using an AWAKE like electron beam:

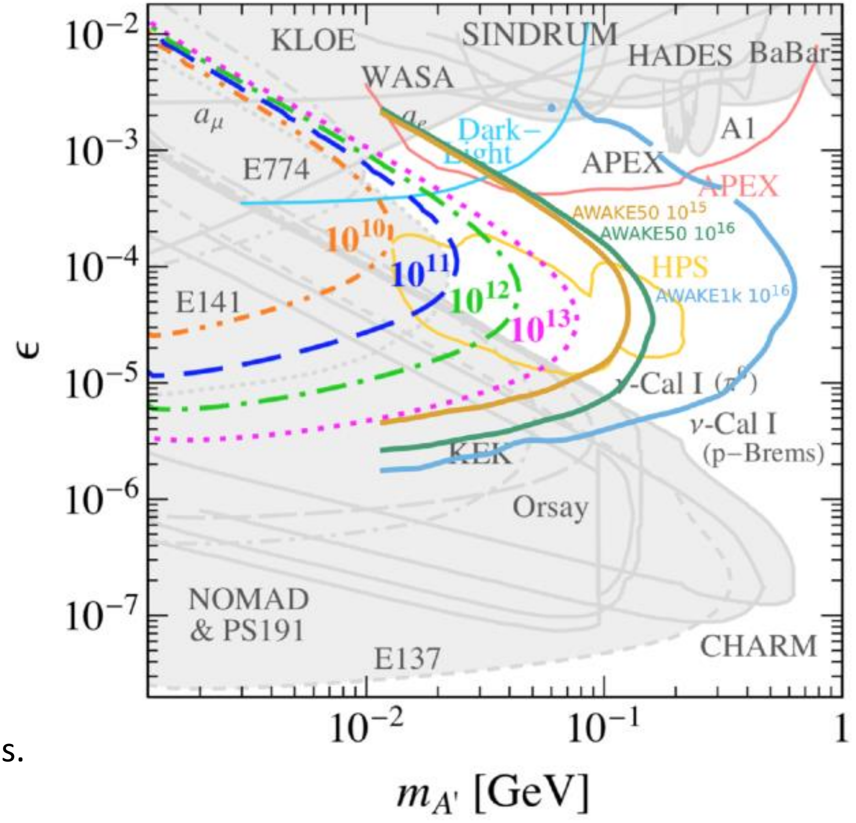
➔ Beam dump experiments

- Decay of dark photons into visible particles (e.g. e+/e-)
- Energy and flux is important, but relaxed parameters for emittance



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.



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.

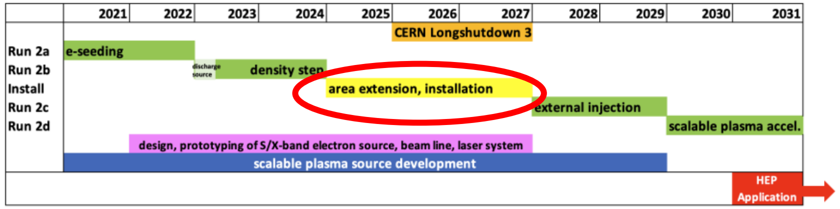
- AWAKE is a unique proton-driven plasma wakefield acceleration experiment at CERN
  - Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.
  - Modulation process means existing proton machines can be used.
  - AWAKE uses protons from CERN’s SPS
  - Complex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

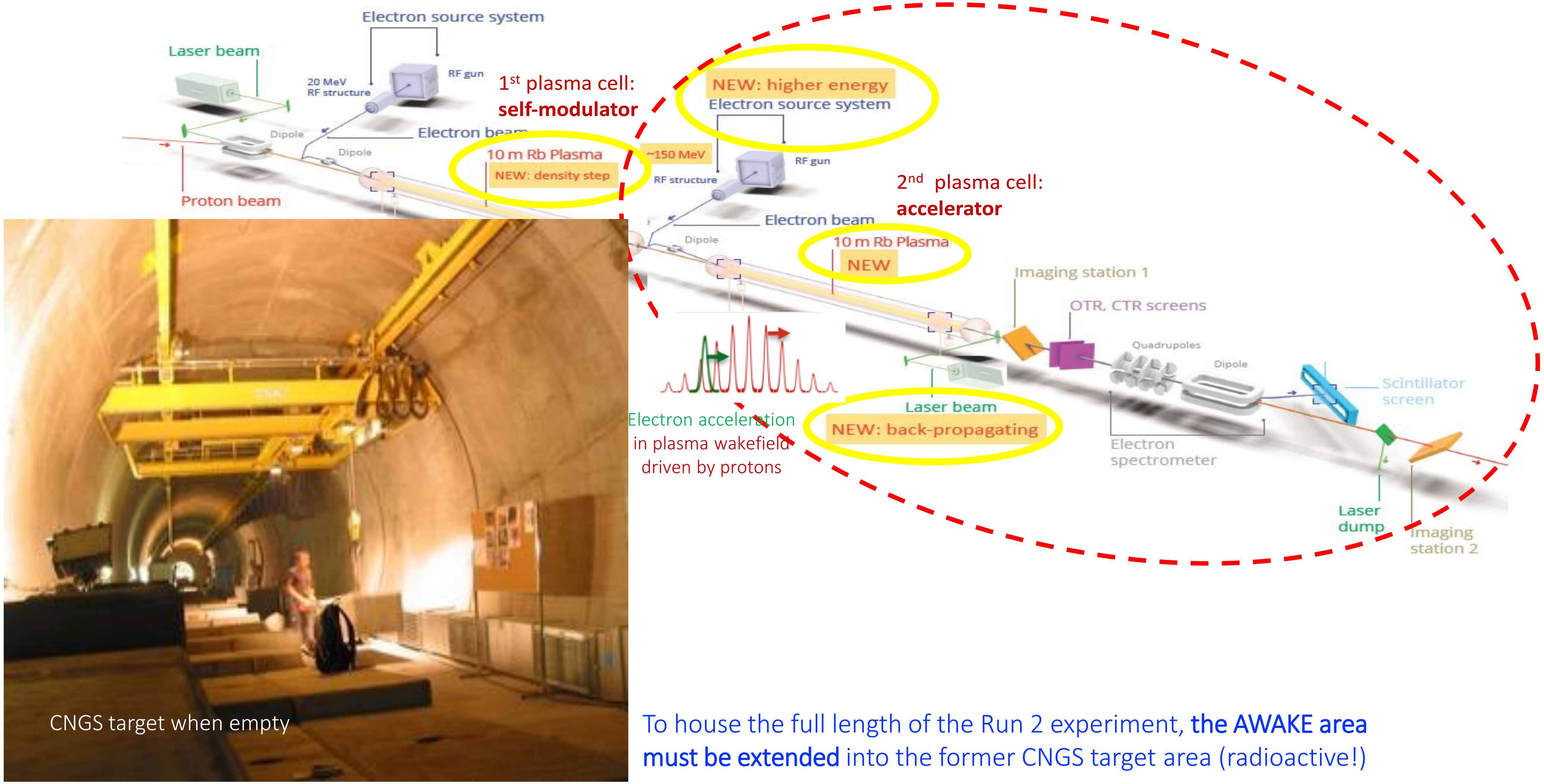
- AWAKE developed a well-defined plan towards first applications of particle physics experiments
  - AWAKE Run 2 is ongoing
  - AWAKE met all milestones to date

Back-Up

AWAKE Run 2c - Preparation

AWAKE Run 2c and Run 2d **after LS3 (2027+)** :
Optimize acceleration of electrons in p-driven plasma wakefield





1st plasma cell:
self-modulator

2nd plasma cell:
accelerator

Electron acceleration in plasma wakefield driven by protons

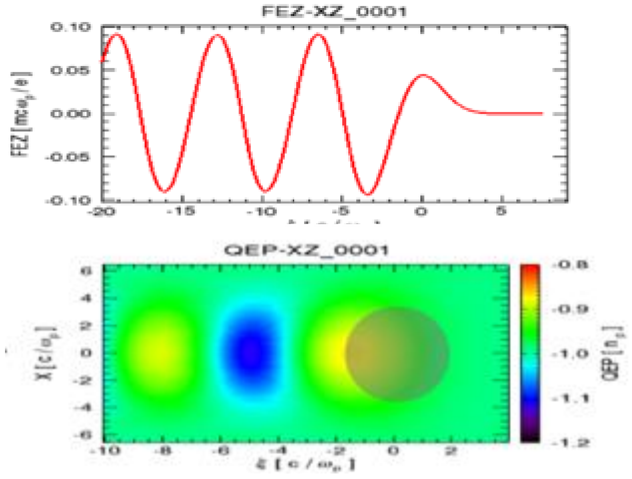
CNGS target when empty

To house the full length of the Run 2 experiment, **the AWAKE area must be extended** into the former CNGS target area (radioactive!)

Introduction – Beam Quality in PWA

Different regimes:

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

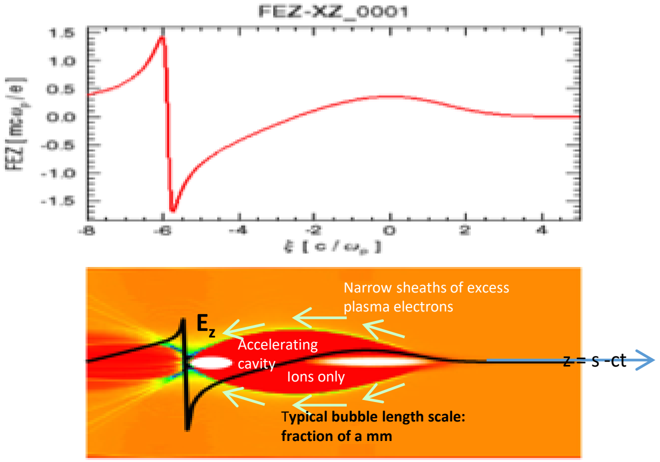


- *lower wakefields*
- *transverse forces not linear in r*
+ Symmetric for positive and negative witness bunches
+ Well described by theory

Accelerating field is maximised for a value of

$$\boxed{\begin{array}{l} k_{pe}\,\sigma_z \approx \sqrt{2} \\ k_{pe}\,\sigma_r \leq 1 \end{array}}$$

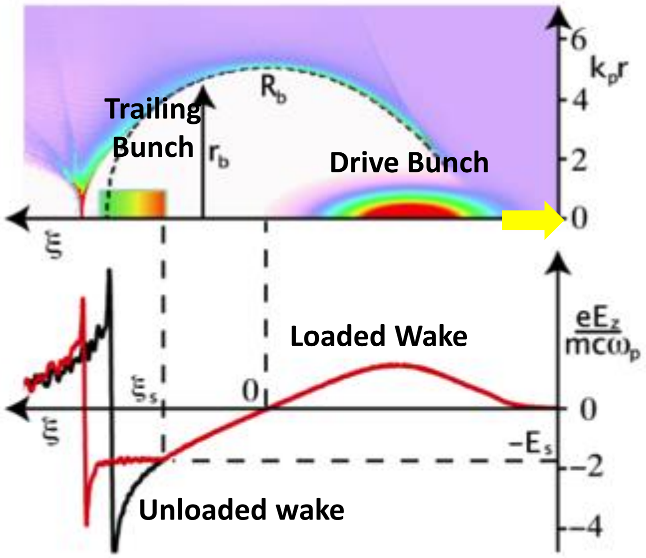
Blow-out regime: $n_{beam} >> n_{pe}$



+ 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**