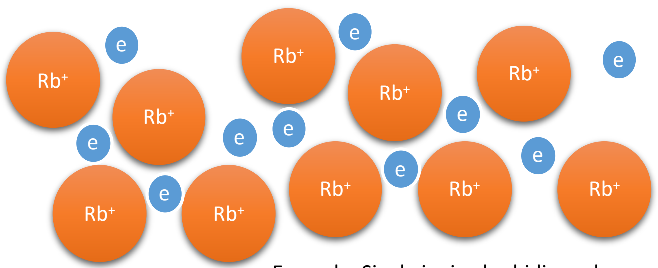
Plasma Wakefield Acceleration and the AWAKE Experiment at CERN

Edda Gschwendtner, CERN

7 June 2024
NIKHEF, Amsterdam, Netherlands

Plasma Wakefield Acceleration



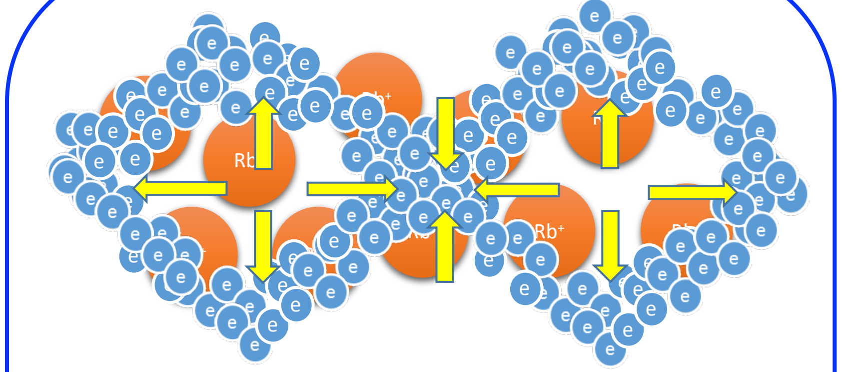
Example: Single ionized rubidium plasma

PLASMA is the 4th state of matter

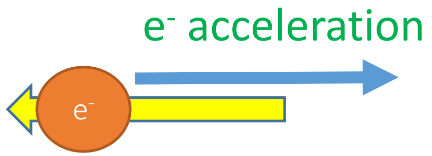
Quasi-neutrality: the overall charge of a plasma is about zero.

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.

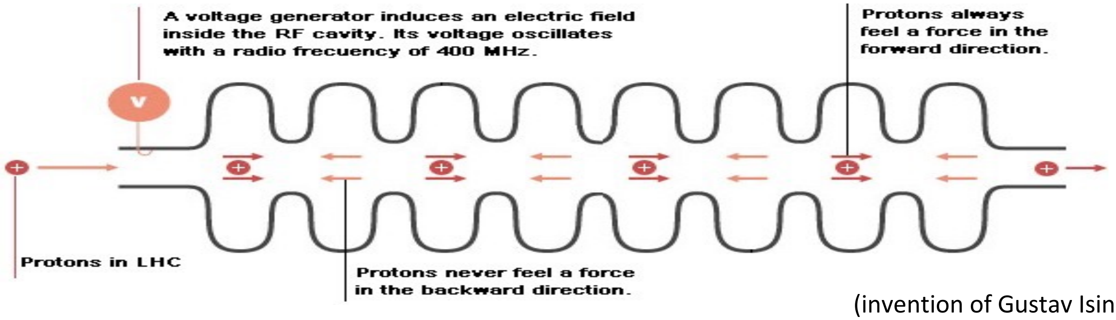


Plasma WAKEFIELDS are the fields created by collective motion of plasma particles are called.



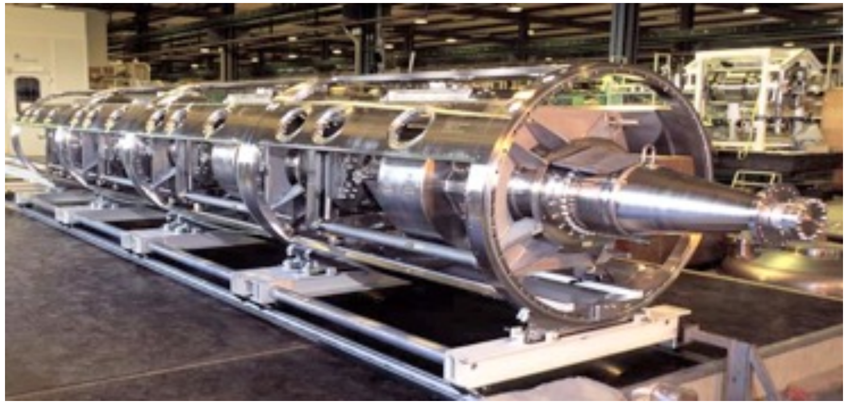
ACCELERATION of charged particles when they experience an electric field.
Strength of the acceleration:
'Accelerating gradient' : ~MV/m

Conventional Acceleration Technology



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC cavity



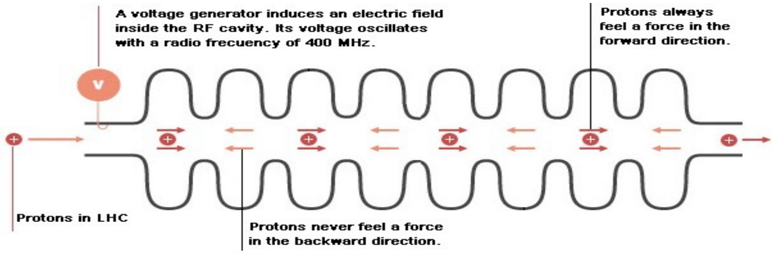
Typical gradients:

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

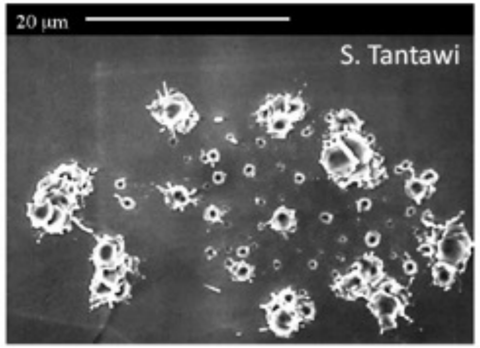
Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

Accelerating Gradient

Conventional RF Cavities



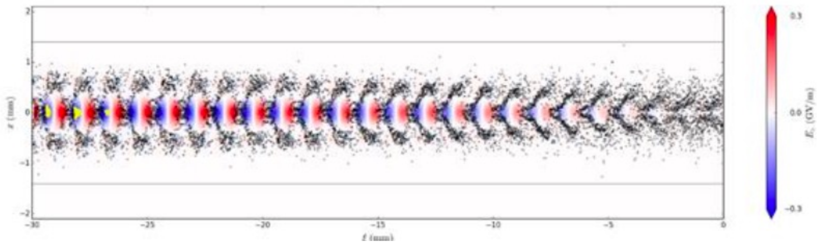
Surface of Copper Cell After Breakdown Events

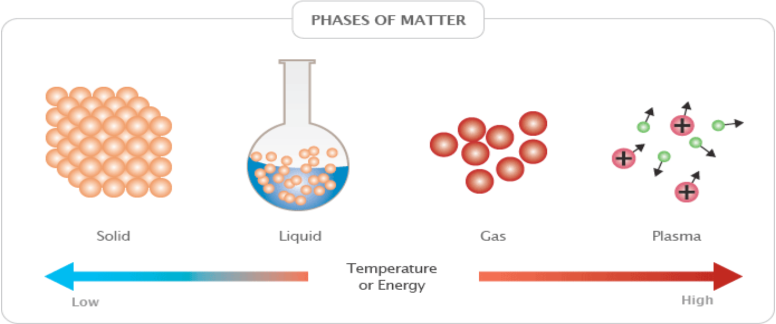


Accelerating fields are **limited to <100 MV/m**

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





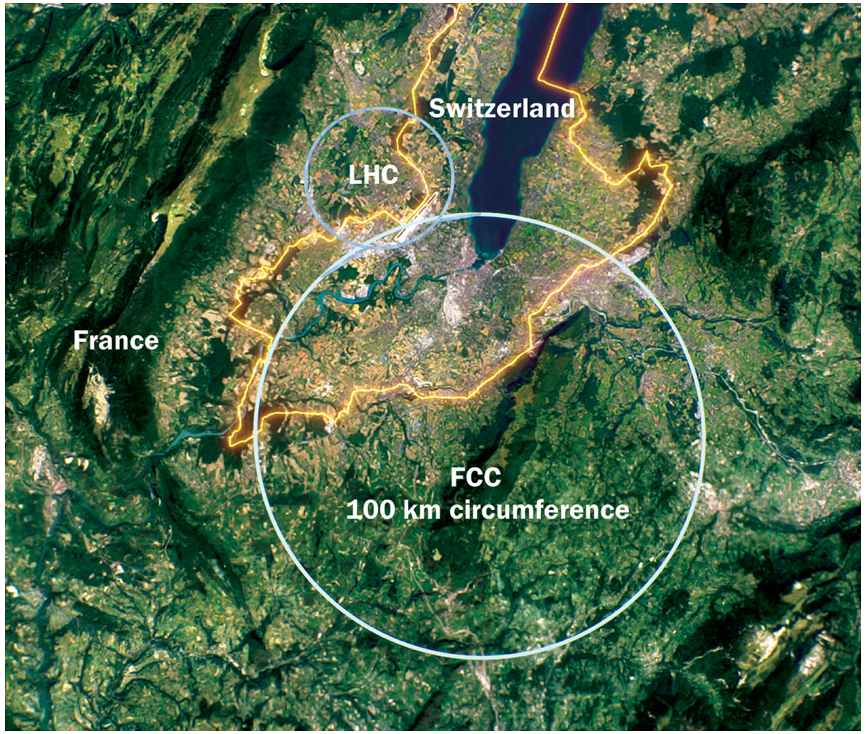
Plasma is already ionized or "broken-down" and can sustain **electric fields up to three orders of magnitude higher gradients**

→ **order of 100 GV/m.**

→ **~1000 factor stronger acceleration!**

Circular Accelerators

To discover new physics: accelerate particles to even higher energies



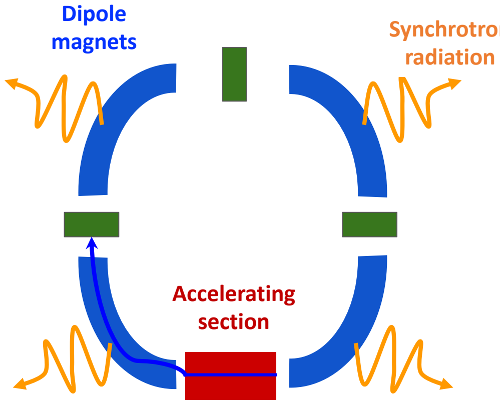
Conventional RF cavities ok for circular colliders:

👍 beam passes accelerating section several times.

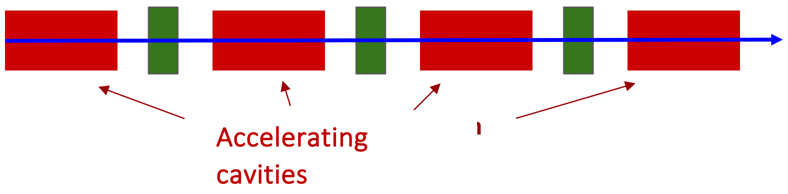
👎 **Limitations of electron-positron circular colliders:**

- 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



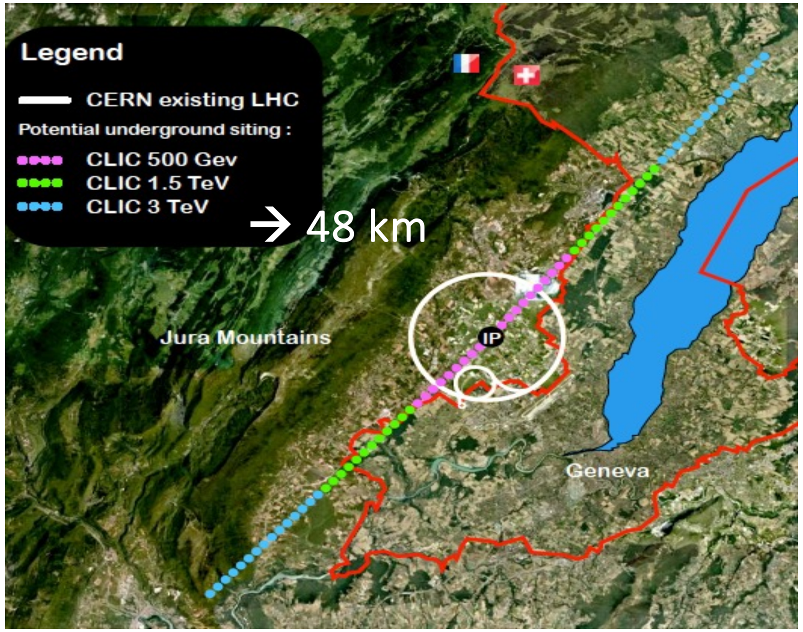
👍 Favorable for acceleration of low mass particles to high energies.

👎 **Limitations** to linear colliders:

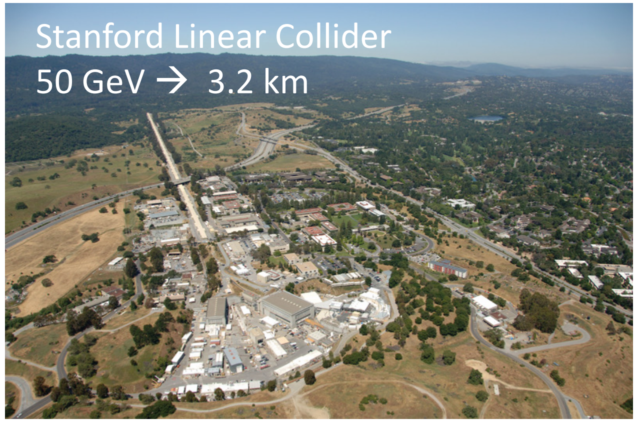
- Linear machines accelerate particles in a **single pass.** The amount of acceleration achieved in a given distance is the ***accelerating gradient***. This number is **limited to 100 MV/m** for conventional copper cavities.

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



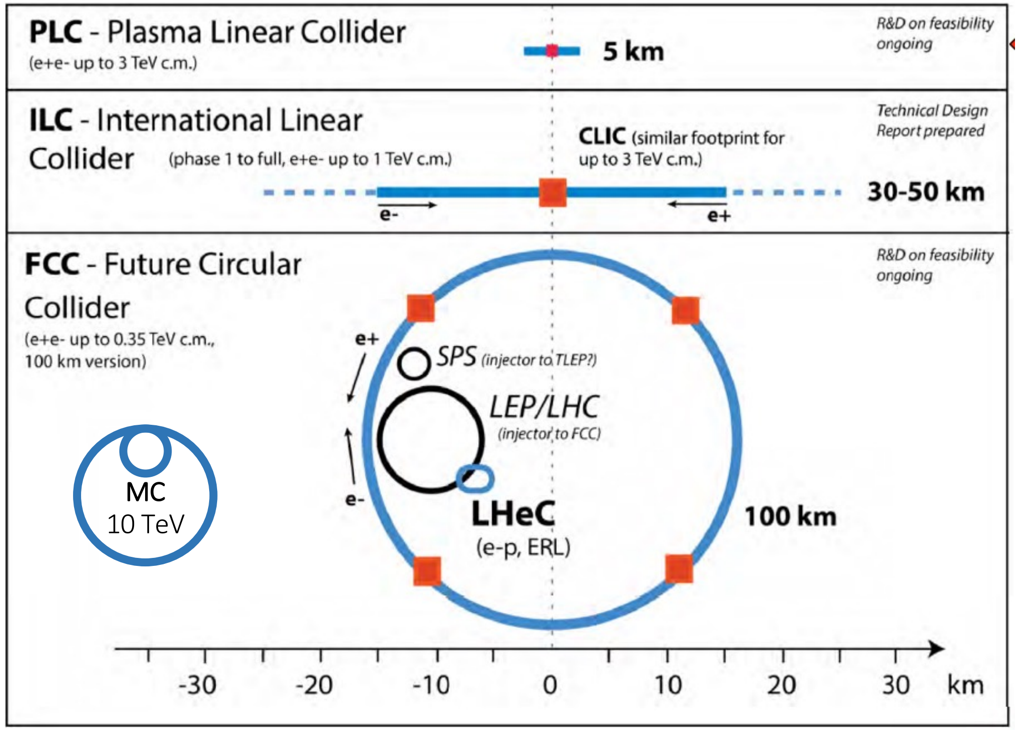
CLIC, electron-positron collider with 3 TeV energy



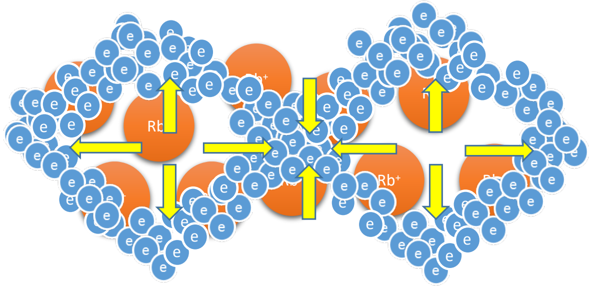
Plasma Wakefield Acceleration

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

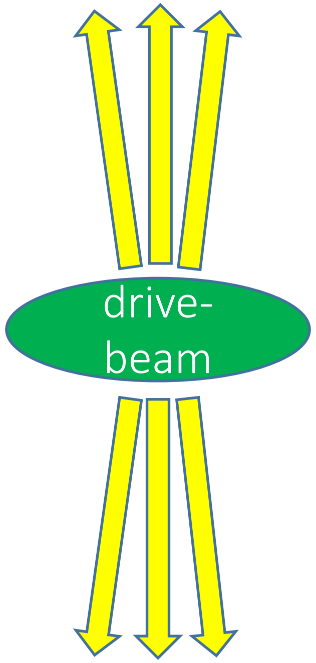
100 MV/m → 100 GV/m



How to Create a Plasma Wakefield?



Energy source: the drive beam



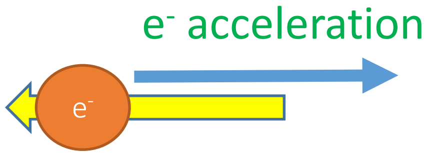
Charged particle bunches or laser bunches
→ carry almost purely transverse electric fields.

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.

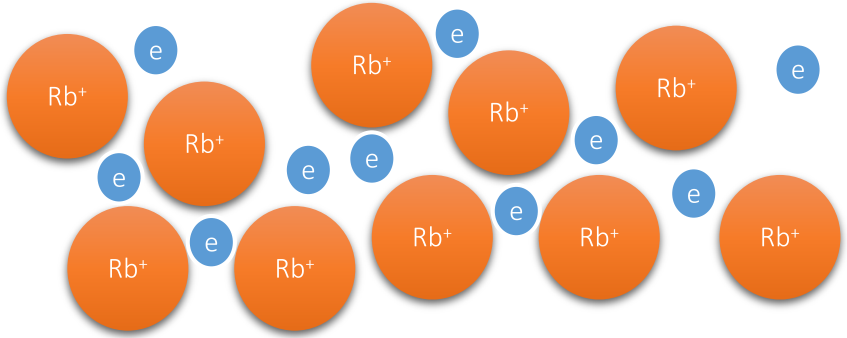
How to Create a Plasma Wakefield?

What we want:

Longitudinal electric field to accelerate charged particles.

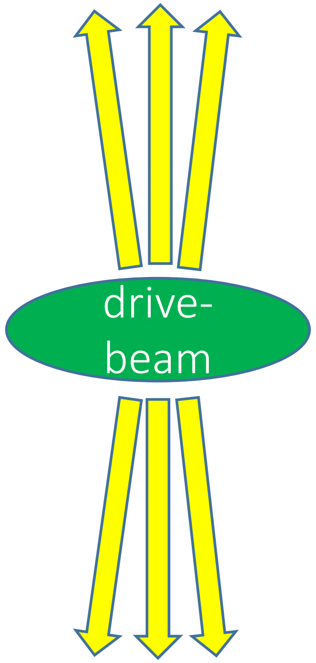


Our Tool:



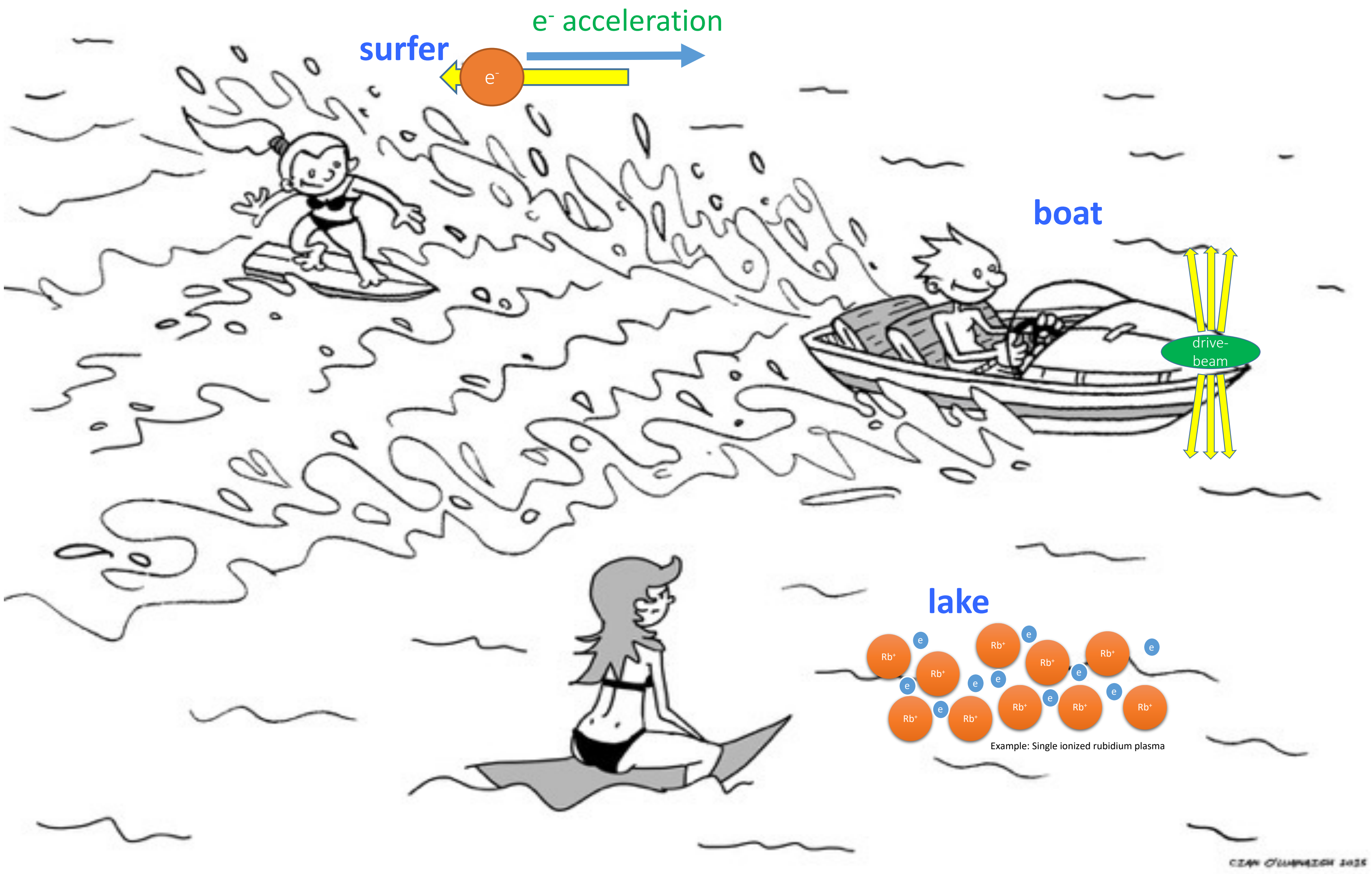
Single ionized rubidium **plasma**

Energy source:



Charged particle bunches carry almost purely transverse Electric Fields.

How to Create a Plasma Wakefield?



Example: Single ionized rubidium plasma

Analogy:
lake → plasma

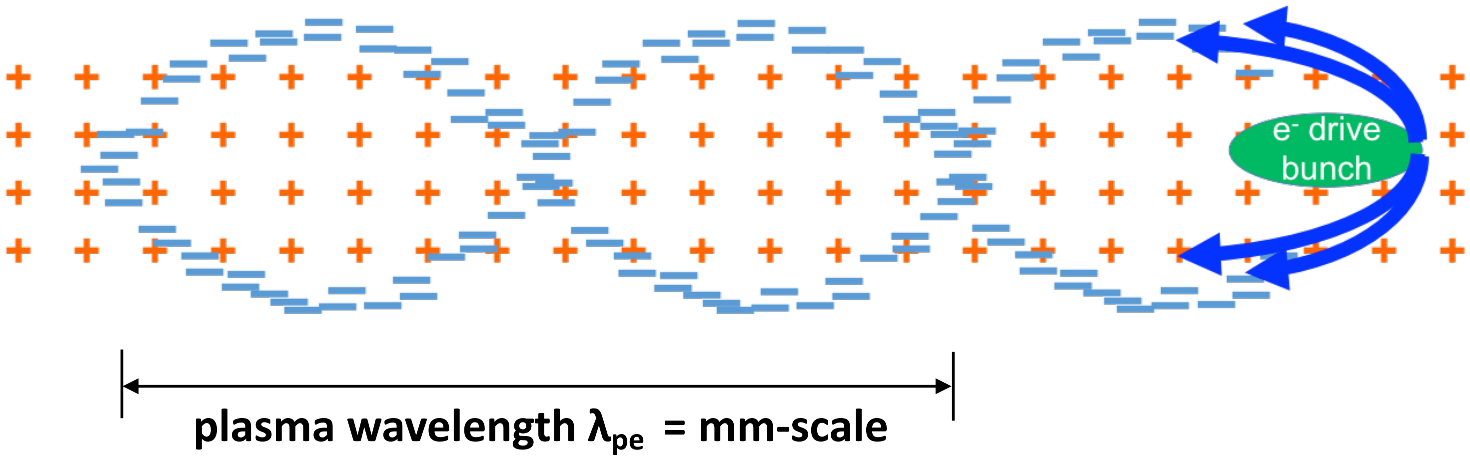
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Principle of Plasma Wakefield Acceleration

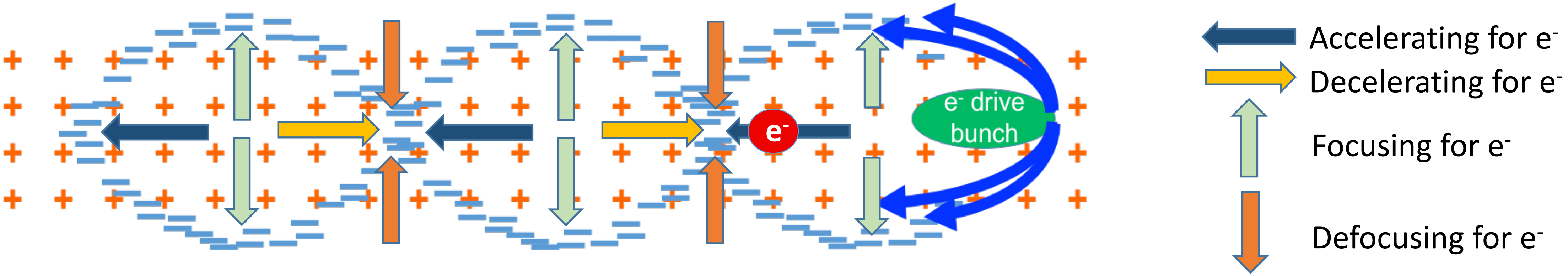
Boat:

- Laser drive beam
- Charged particle drive beam

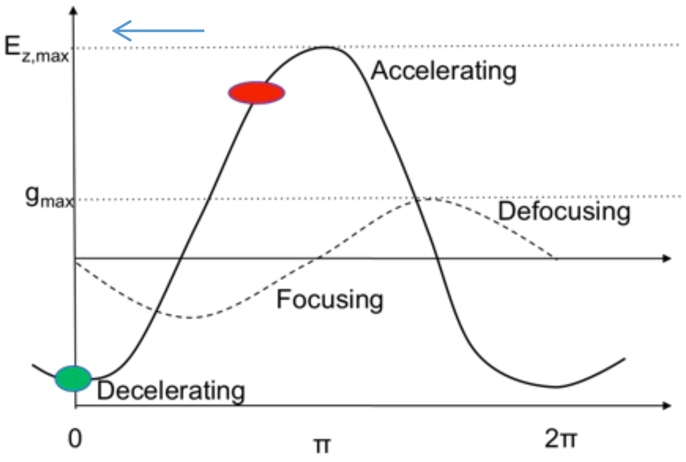


- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

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

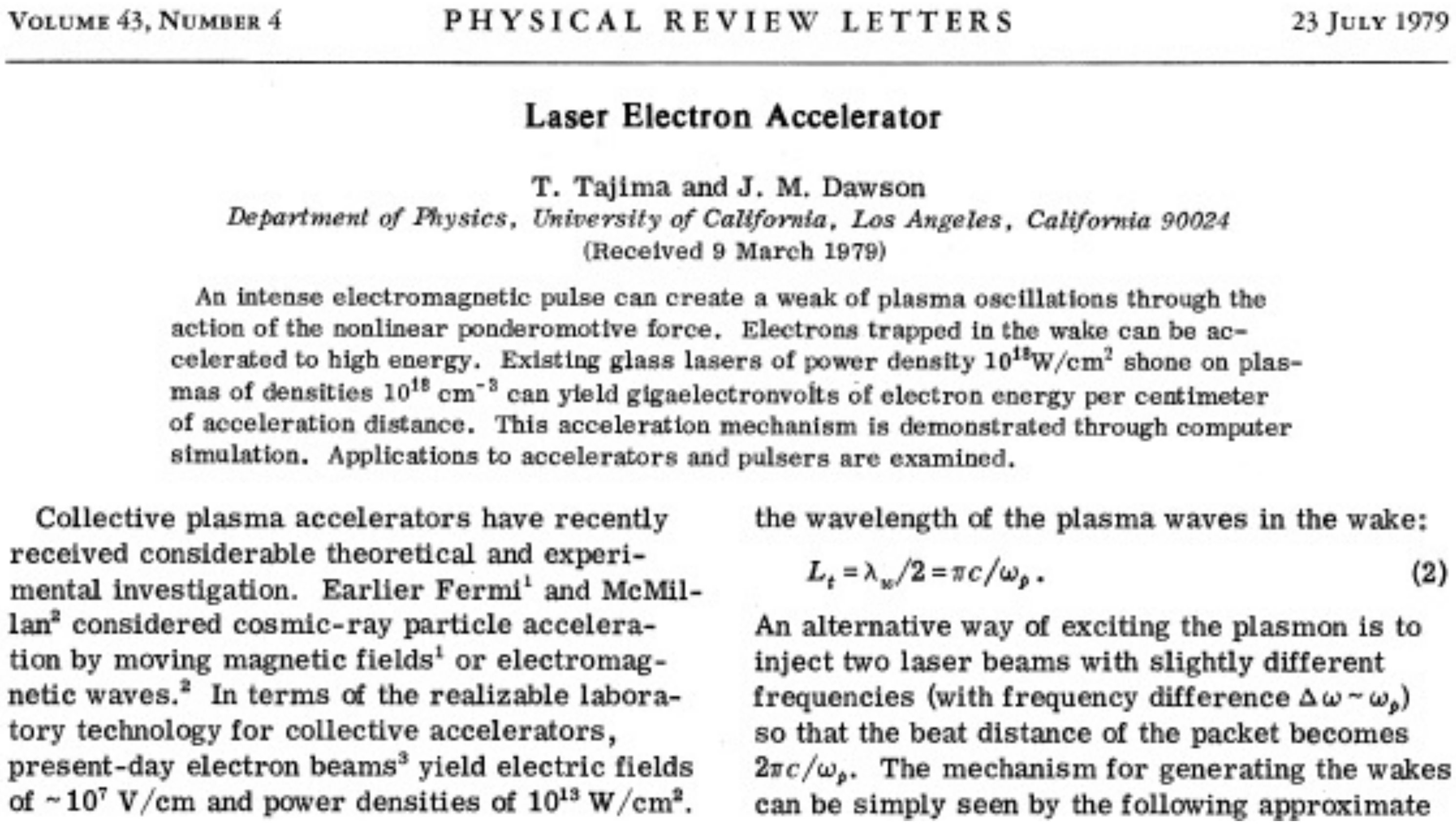
The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

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

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

$$L_t = \lambda_w/2 = \pi c/\omega_p . \tag{2}$$

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

CERN COURIER

Doubling energy in a plasma wake

nature

FULL SPEED AHEAD

nature

Dream beam

The dawn of compact particle accelerators

nature

GROW WITH THE FLOW

PARTICLE ACCELERATION

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

Not-So-Large Colliders Could 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

ciencia plus.com

Proyectan aceleradores de partículas con plasma de bajo coste

TEDxCERN

Surfing wakefields to create smaller accelerators

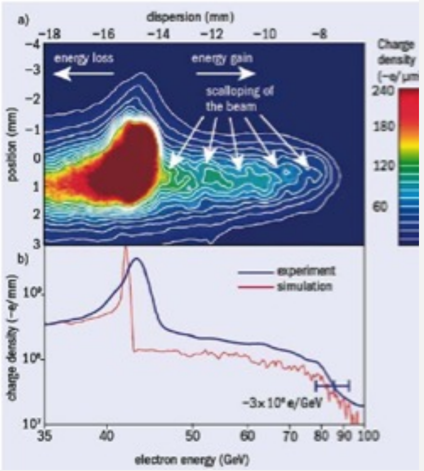
Some Highlights

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**

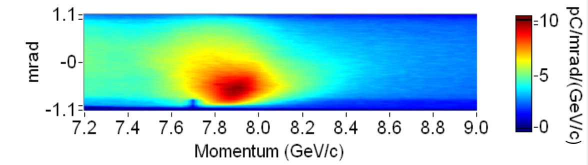


BELLA, Berkeley Lab, USA:
Laser-driven plasma wakefield acceleration facility

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

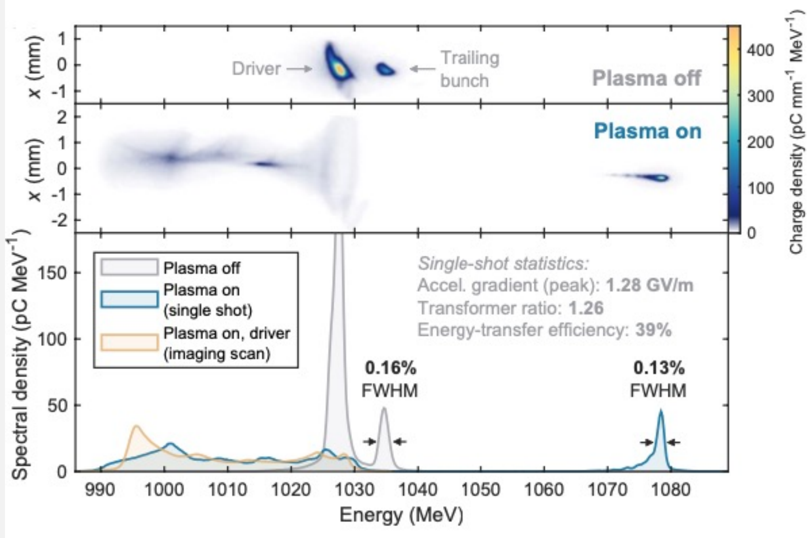
*A.J.Gonsalves et al., Phys.Rev.Lett. **122**, 084801 (2019)*

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

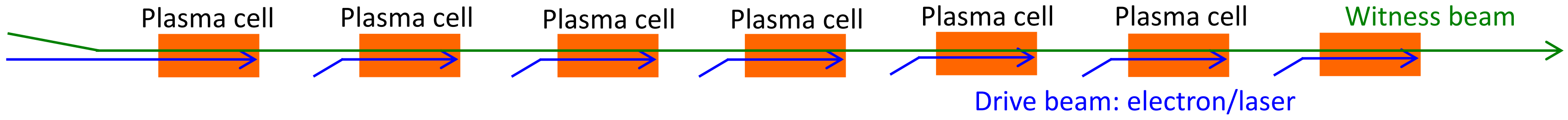
Drive beams (Boat):

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.

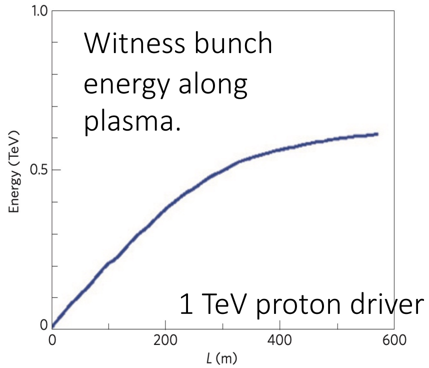

Plasma cell

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

wigner

clear

UPPSALA
UNIVERSITET

The Cockcroft Institute
of Accelerator Science and Technology

Lancaster
University

UNIVERSITY OF
OXFORD

TRIUMF

MAX-PLANCK-INSTITUT
FÜR PHYSIK

22 Institutes

CERN

Science and
Technology
Facilities Council

MANCHESTER
1824
The University of Manchester

Philipps Universität Marburg

UNIVERSITY OF
LIVERPOOL

MAX PLANCK INSTITUTE
FOR PLASMA PHYSICS

Imperial College
London

UCL

EPFL

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

hhu Heinrich Heine
Universität
Düsseldorf

TÉCNICO
LISBOA

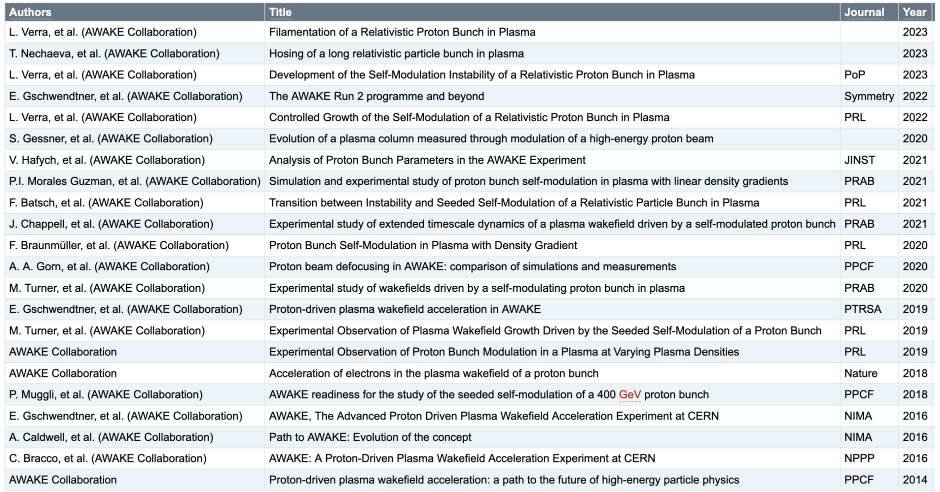
UNIST
ULSAN NATIONAL INSTITUTE OF
SCIENCE AND TECHNOLOGY
2007

Novosibirsk
State
University
*THE REAL SCIENCE

clic

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

Wakes

High Gradient Wakefield Accelerators

11–22 March 2019

Hotel Do Mar, Sesimbra, Portugal

EPFL

JAI 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 x = independently organized TED event

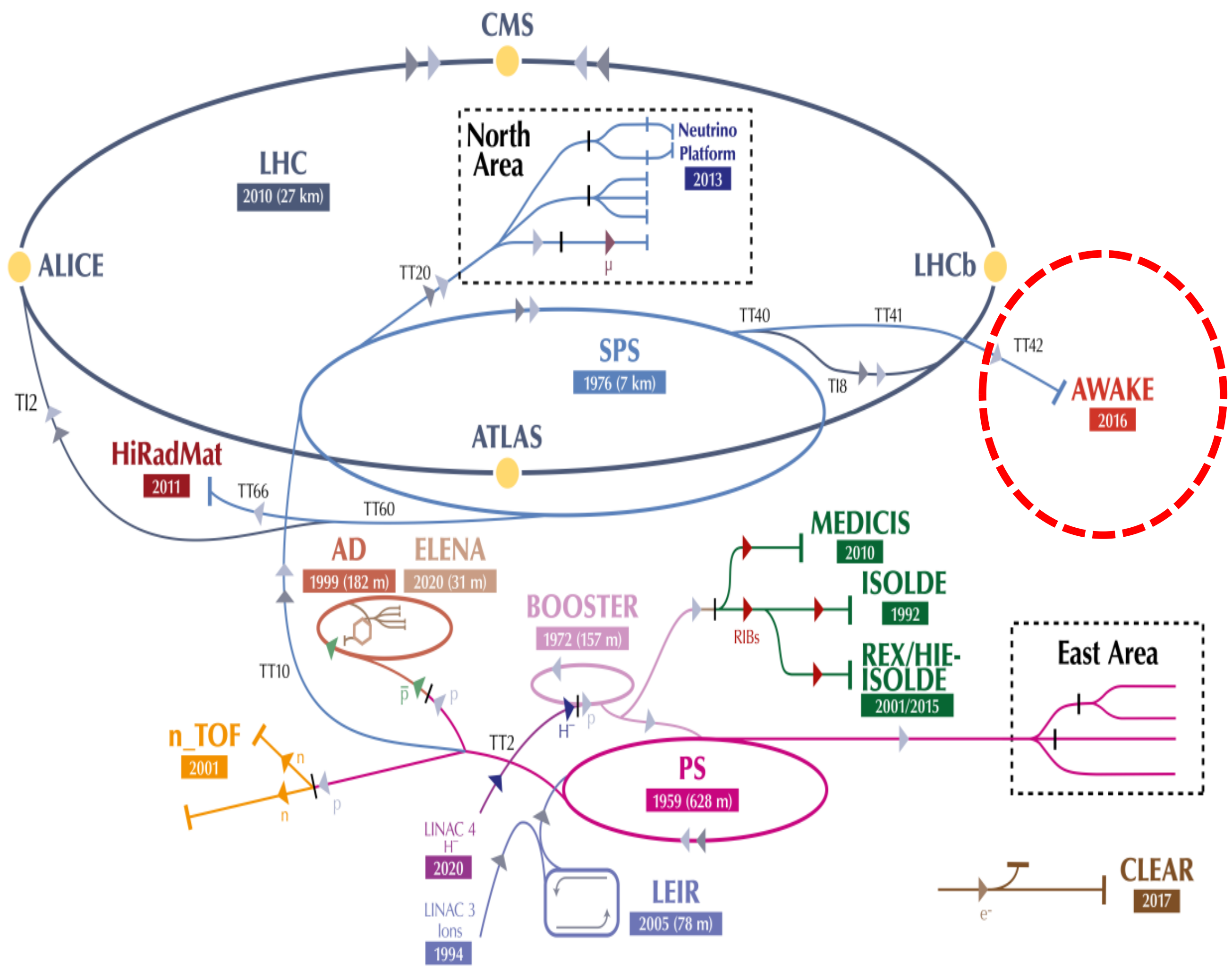
ask symmetry

A new wave of particle physics

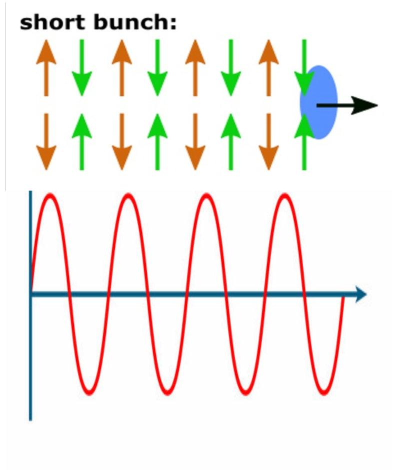
AWAKE at CERN

Advanced WAKEfield Experiment

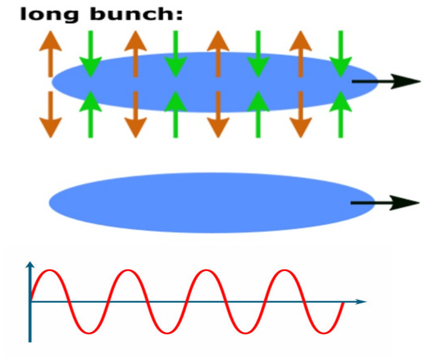
- ➔Accelerator R&D experiment at CERN.
- ➔Unique facility driving wakefields in plasma with a proton bunch.
  - ➔ At CERN highly relativistic protons with high energy (> kJ) available
- ➔Accelerating externally injected electrons to GeV scale.



Proton Bunch as a Drive Beam



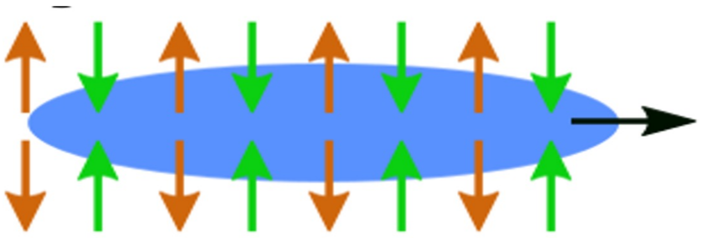
In order to create high wakefield amplitudes, the drive bunch length must be in the order of the plasma wavelength.



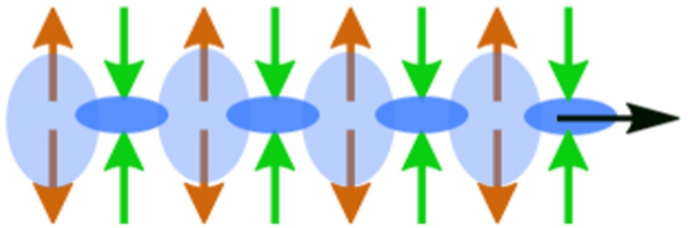
CERN SPS proton bunch: very long! (σ_z **= 6 - 10 cm**) → much longer than plasma wavelength (λ **= 1mm**)
→ Would create only small wakefield amplitudes

Self-Modulation of the Proton Bunch

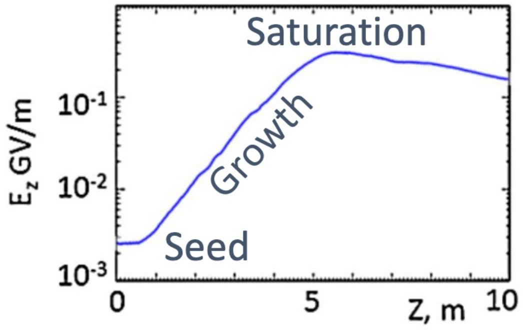
Self-Modulation Instability:



p$^+$ bunch

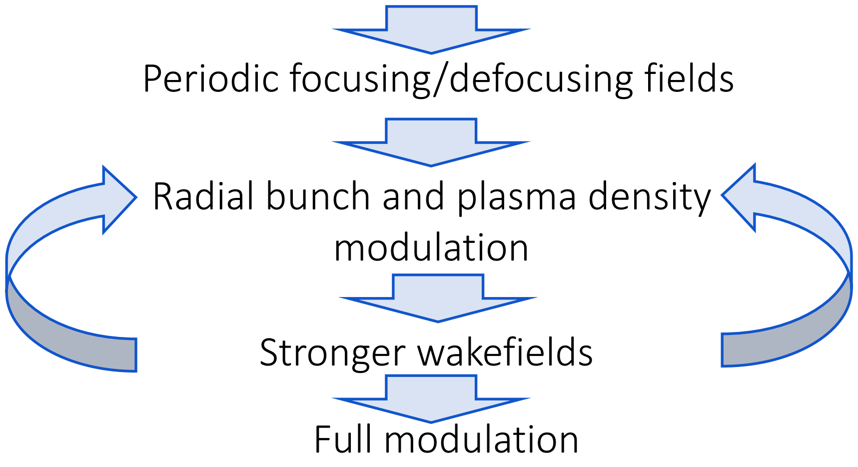


Density modulation on-axis → **micro-bunches**.



Pukhov, PRL107 145003 (2011)

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



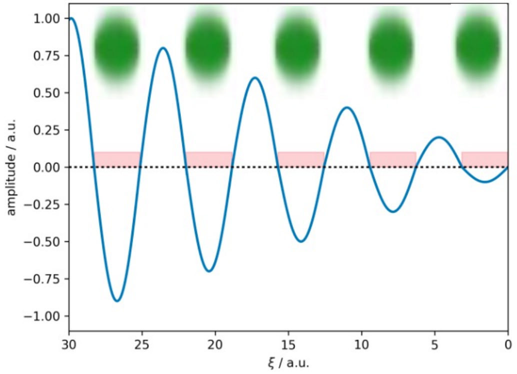
Initial transverse wakefields

Periodic focusing/defocusing fields

Radial bunch and plasma density modulation

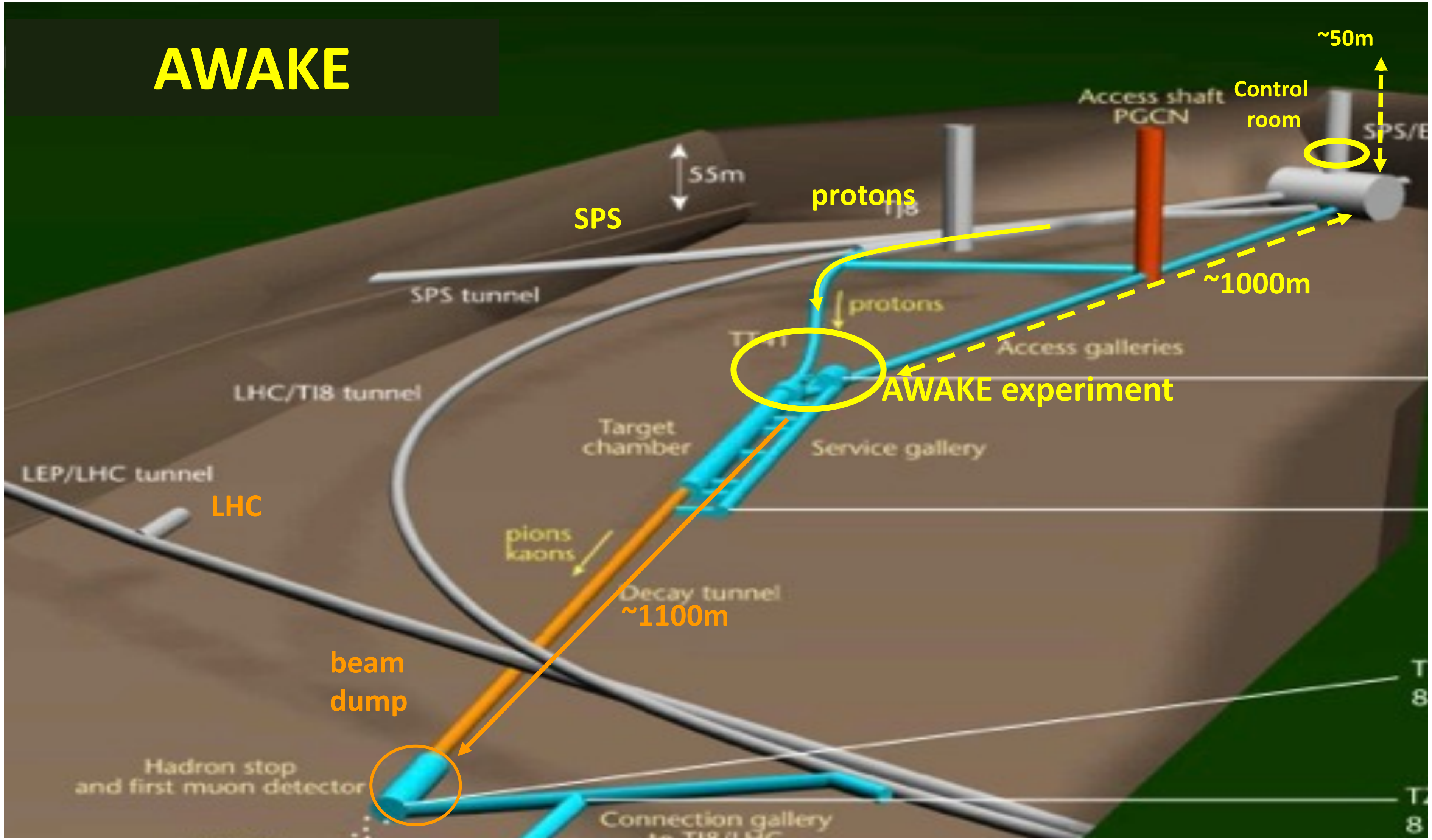
Stronger wakefields

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

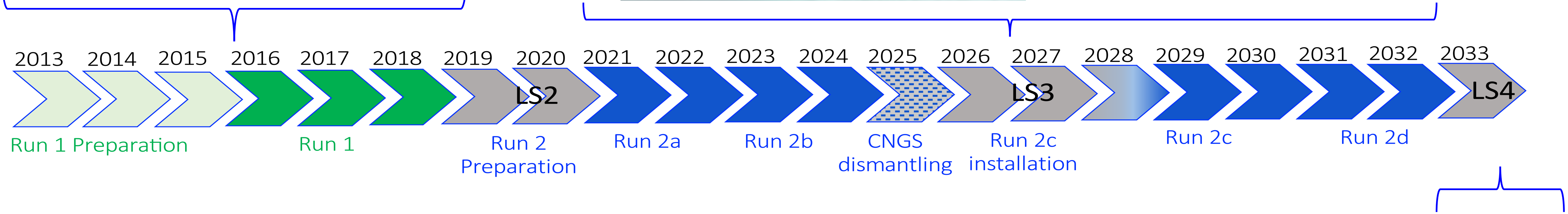
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2032)

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



Run 1 Preparation

Run 1

Run 2 Preparation

Run 2a

Run 2b

CNGS dismantling

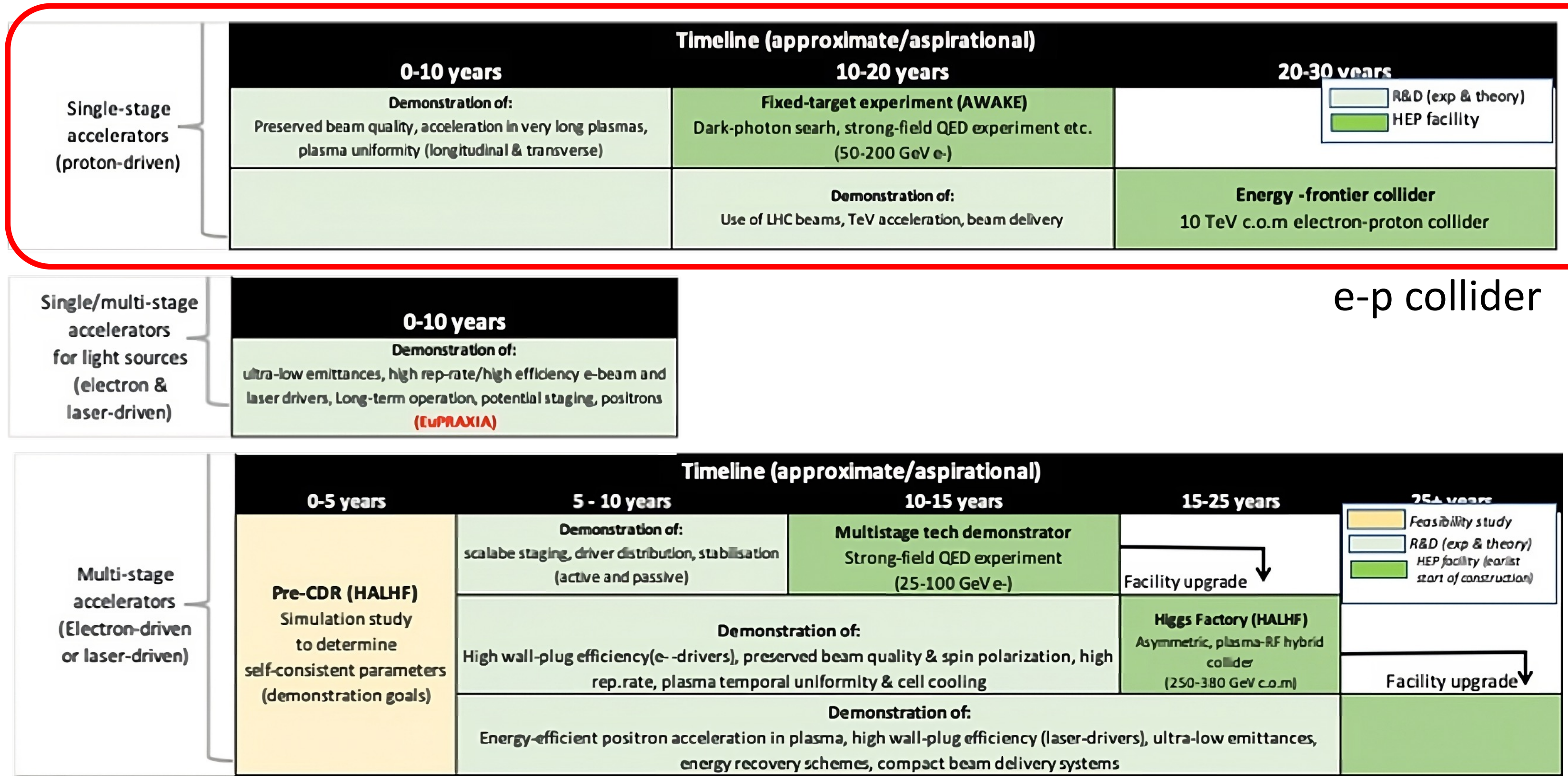
Run 2c installation

Run 2c

Run 2d

➔First applications >2033

AWAKE is Part of the European Strategy Roadmap



Single-stage accelerators (proton-driven)	Timeline (approximate/aspirational)		
	0-10 years	**10-20 years**	**20-30 years**
	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-)	
		Demonstration of: Use of LHC beams, TeV acceleration, beam delivery	**Energy -frontier collider** 10 TeV c.o.m electron-proton collider

⬜ R&D (exp & theory)
🟩 HEP facility

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

e-p collider

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

Multi-stage accelerators (Electron-driven or laser-driven)	Timeline (approximate/aspirational)				
	0-5 years	**5 - 10 years**	**10-15 years**	**15-25 years**	**25+ years**
	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	
		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			

🟨 Feasibility study
⬜ R&D (exp & theory)
🟩 HEP facility (earlist start of construction)

R. Pattathil, presented at EAAC 2023

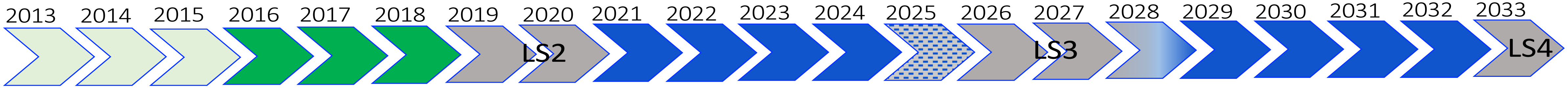
→ AWAKE allows to bridge the gap between the PWFA development in general and a e+/e- collider.

AWAKE Program

RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration



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

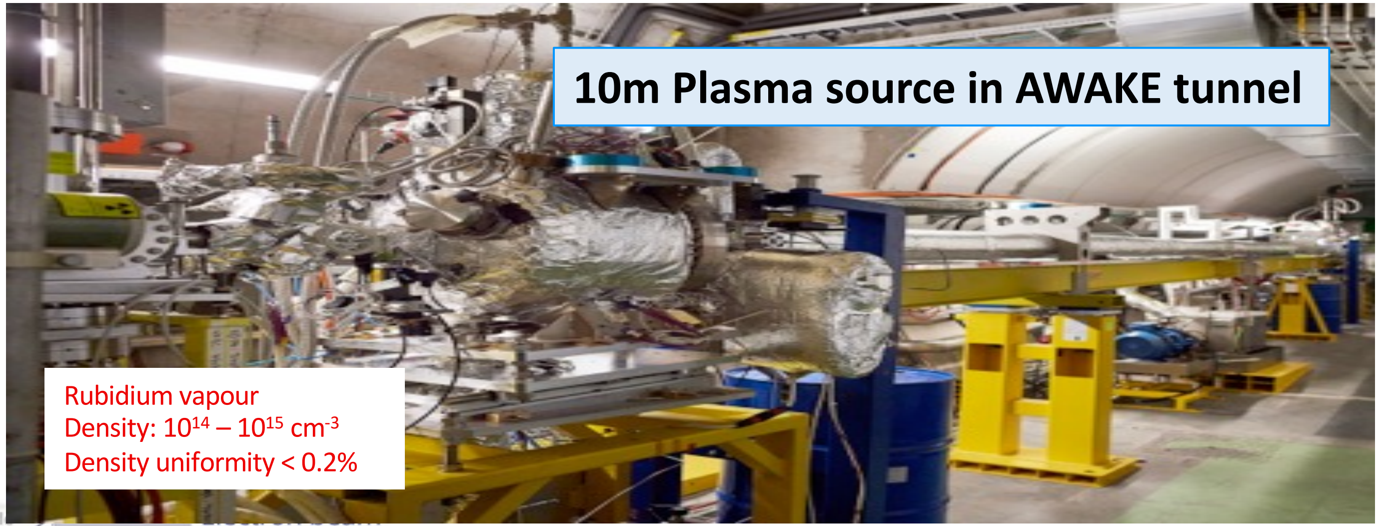
Run 2c

Run 2d

AWAKE Experiment and Run 1 Results

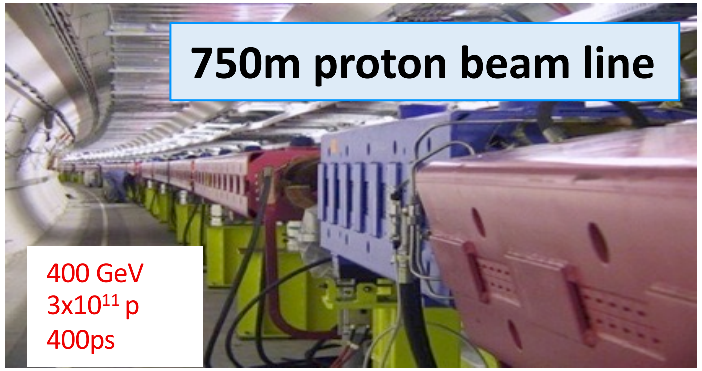
Ti: Sapphire Laser

Ti:Sapphire
500mJ
120 fs



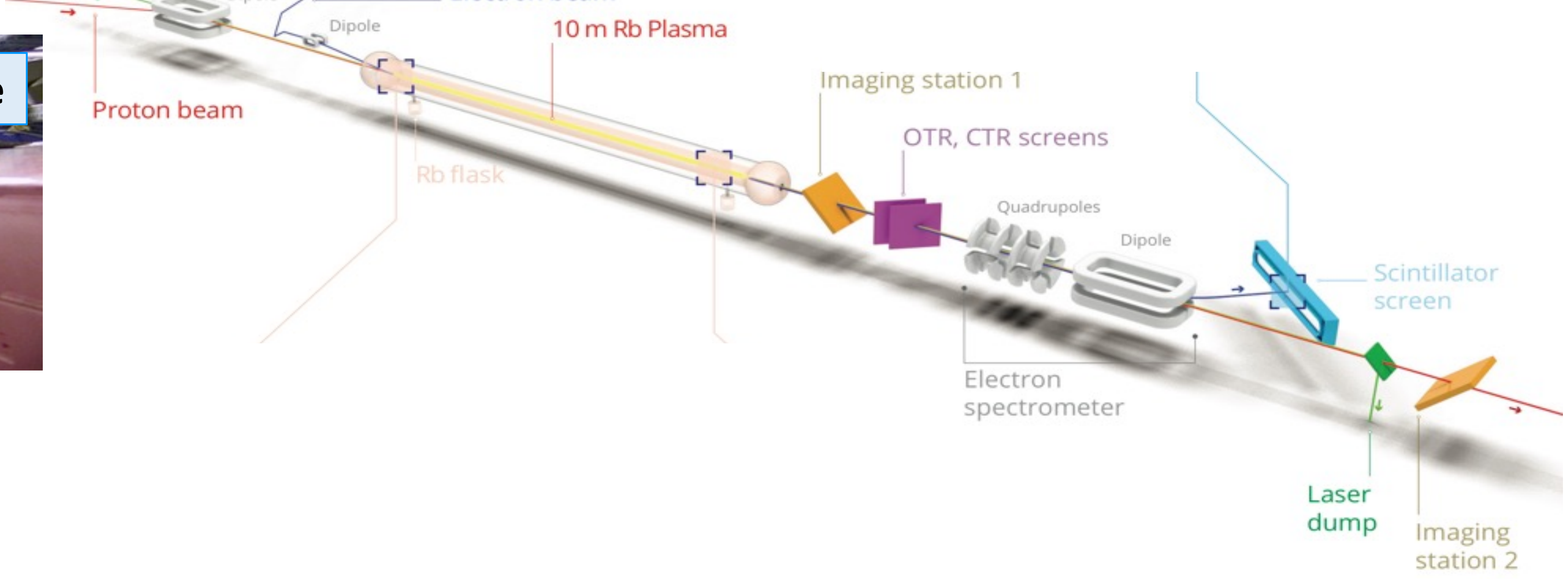
10m Plasma source in AWAKE tunnel

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



750m proton beam line

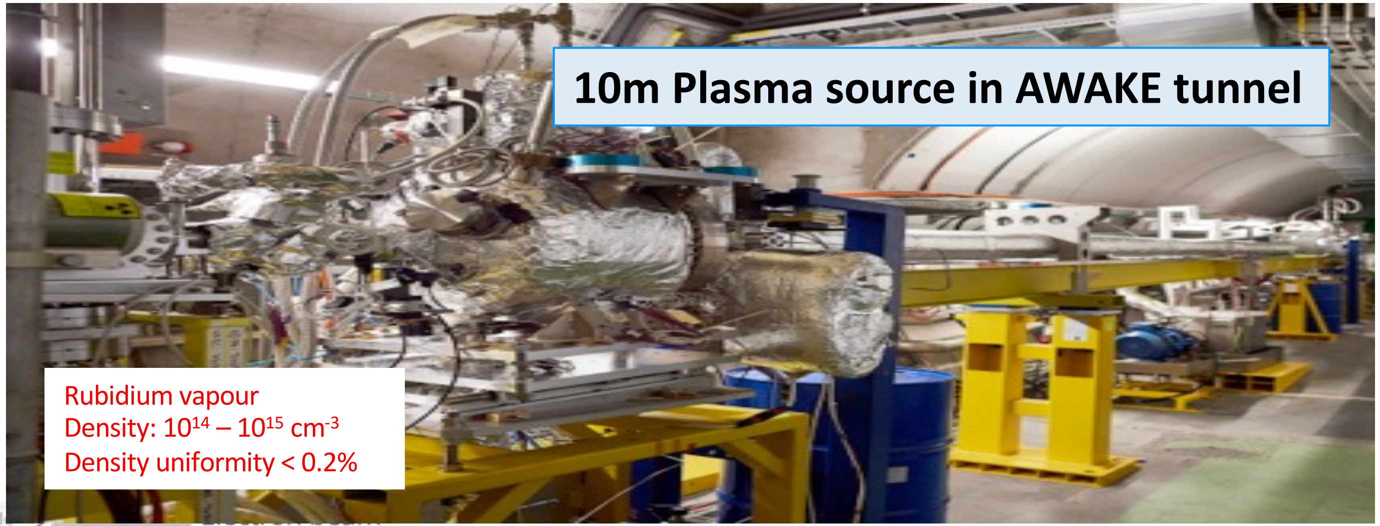
400 GeV
$3x10^{11}$ p
400ps



AWAKE Experiment and Run 1 Results

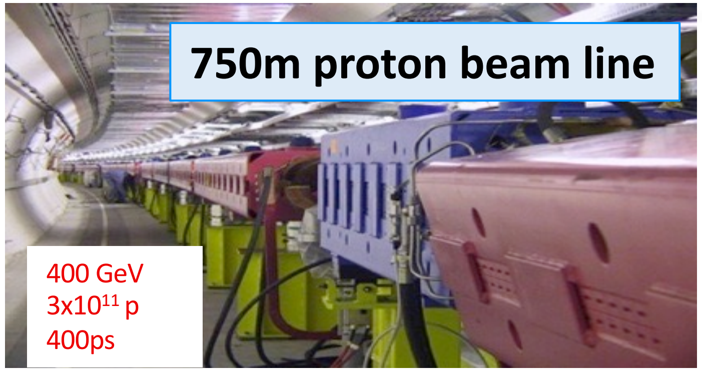
Ti: Sapphire Laser

Ti:Sapphire
500mJ
120 fs



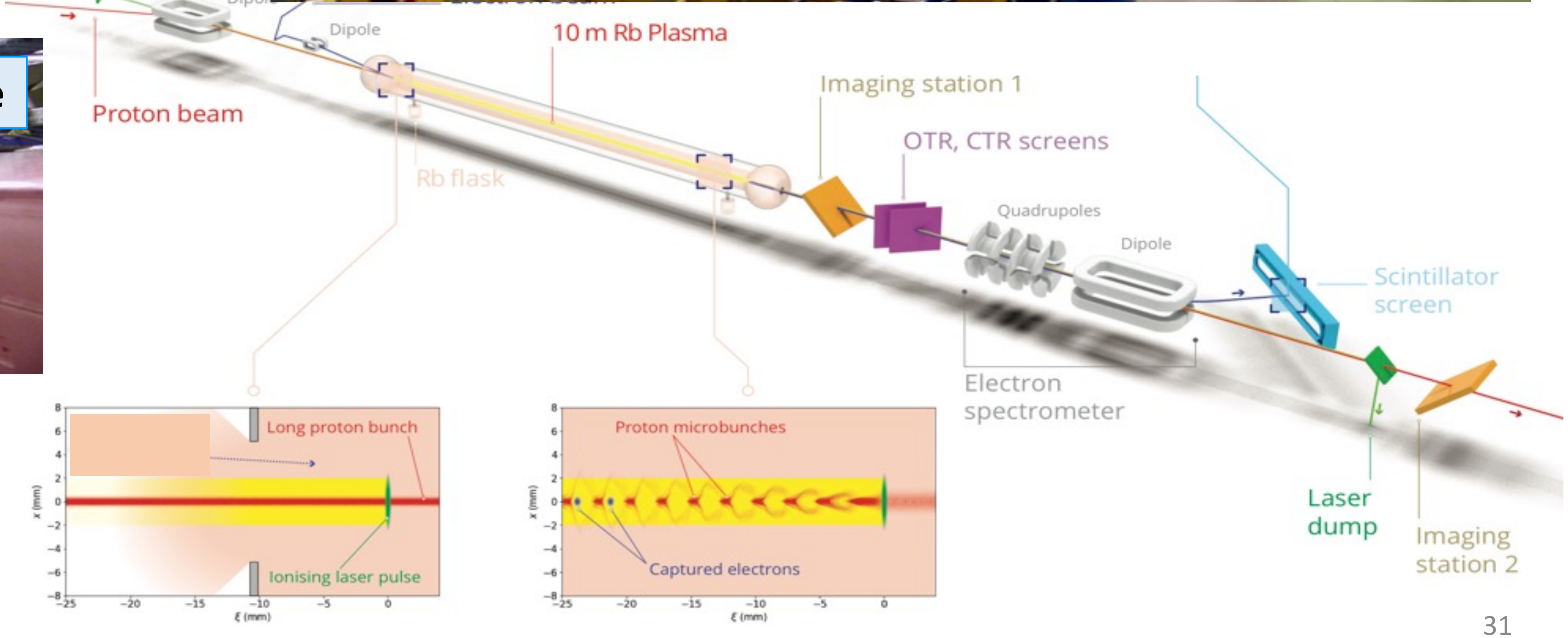
10m Plasma source in AWAKE tunnel

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



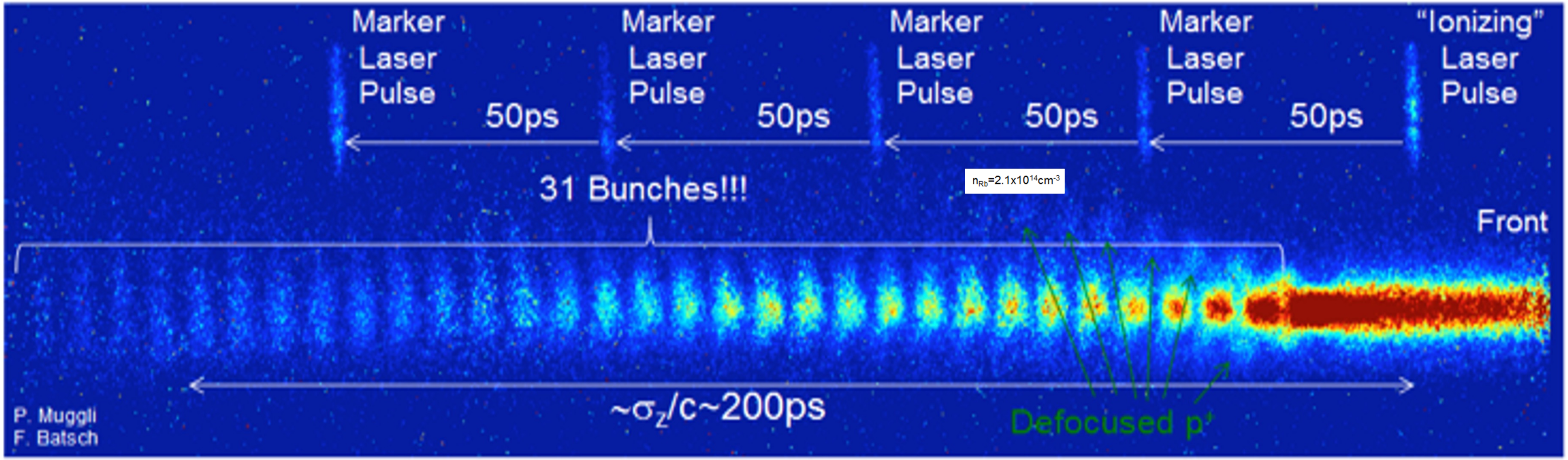
750m proton beam line

400 GeV
3×10^{11} p
400ps



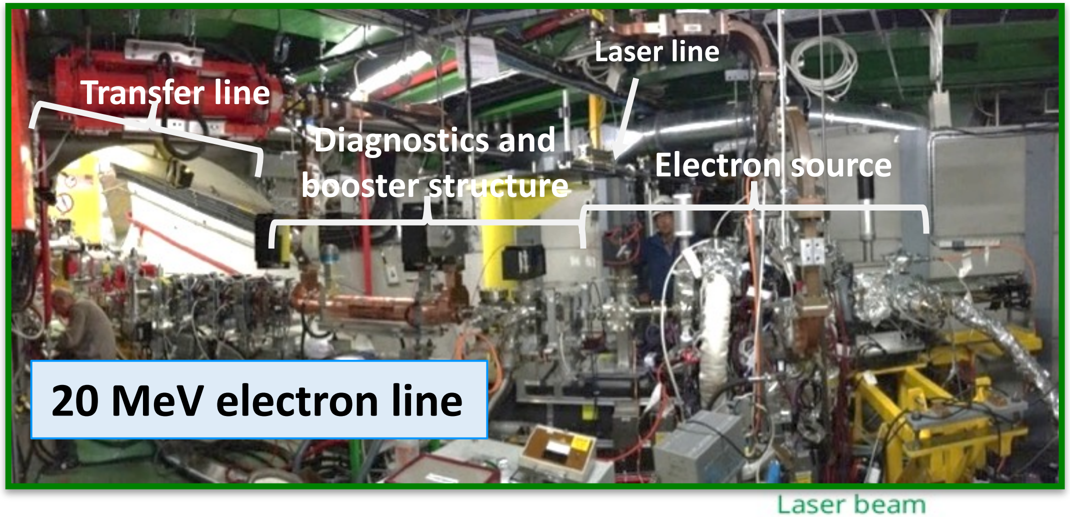
AWAKE Experiment and Run 1 Results

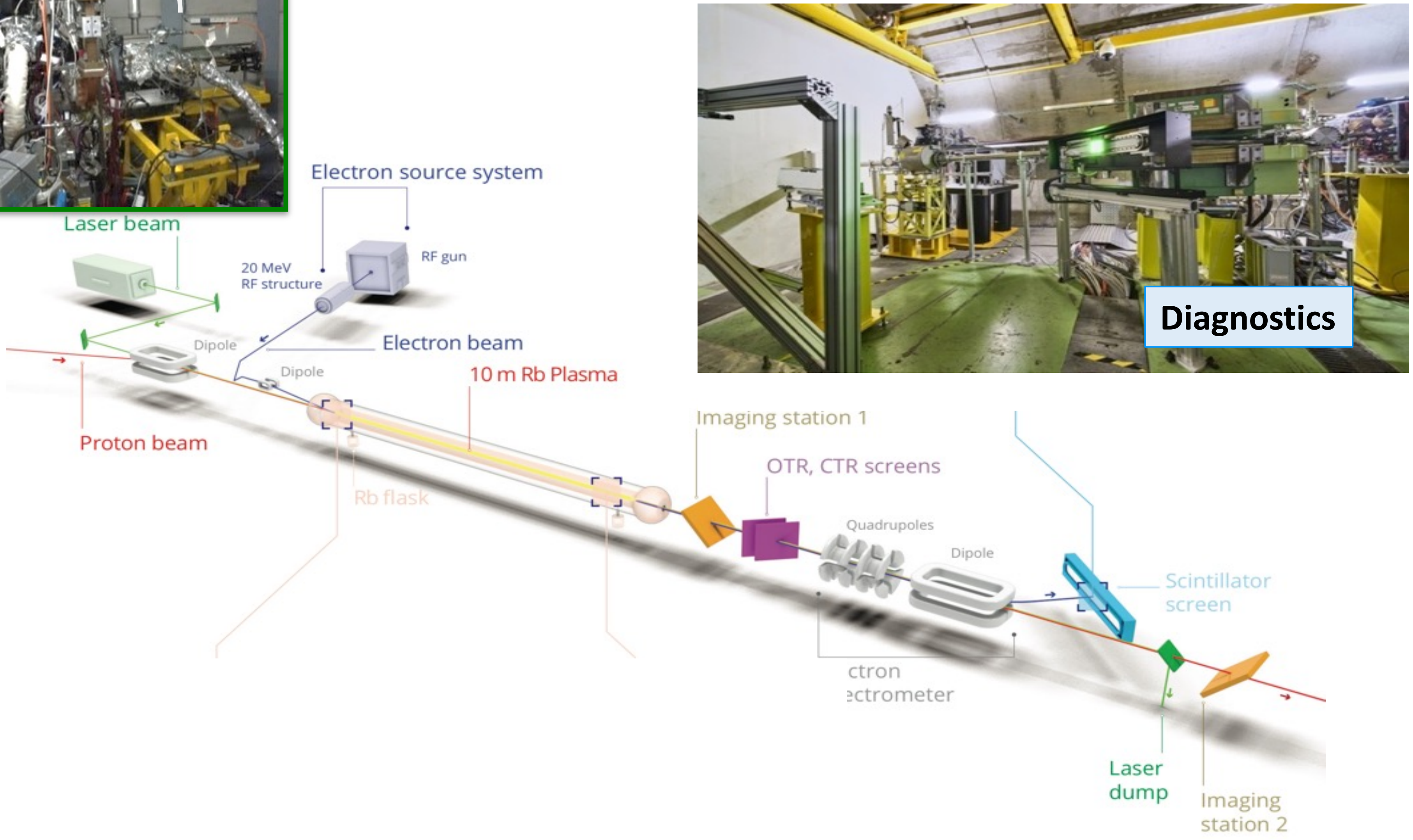
#1: Demonstration of Seeded Self-Modulation of the Proton bunch



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

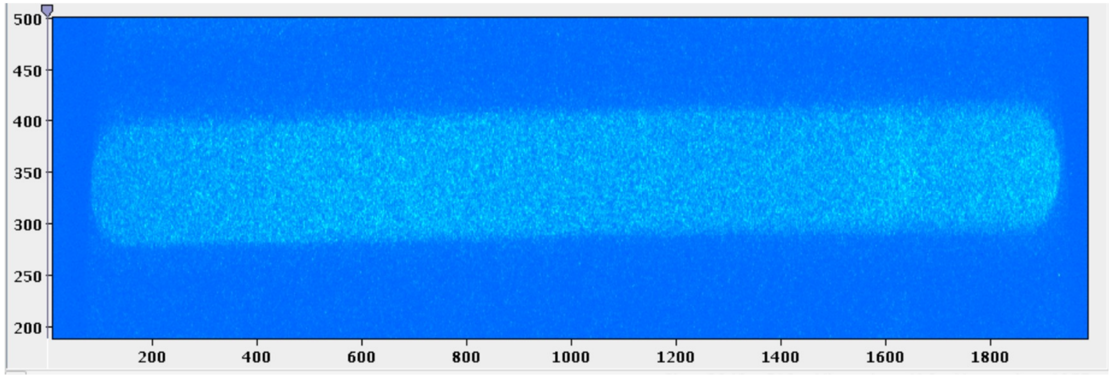




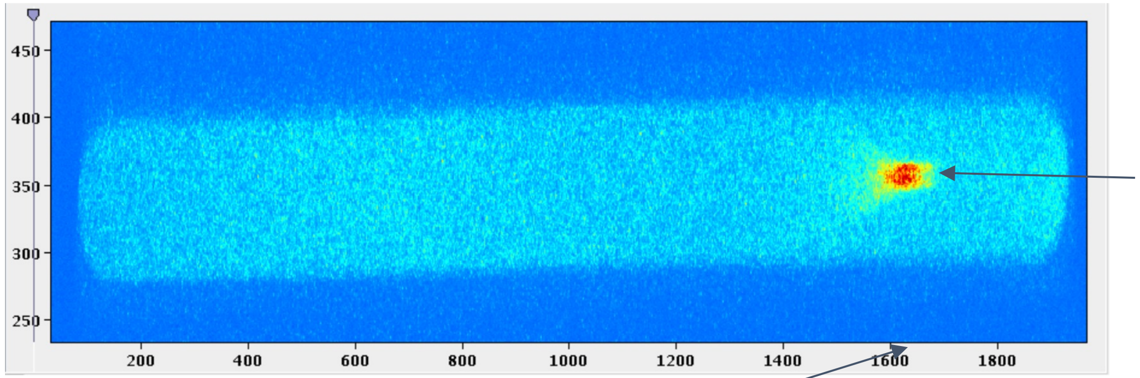
Run 1 Results: Electron Acceleration

#2: Demonstration of Electron Acceleration in Plasma Wakefield

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

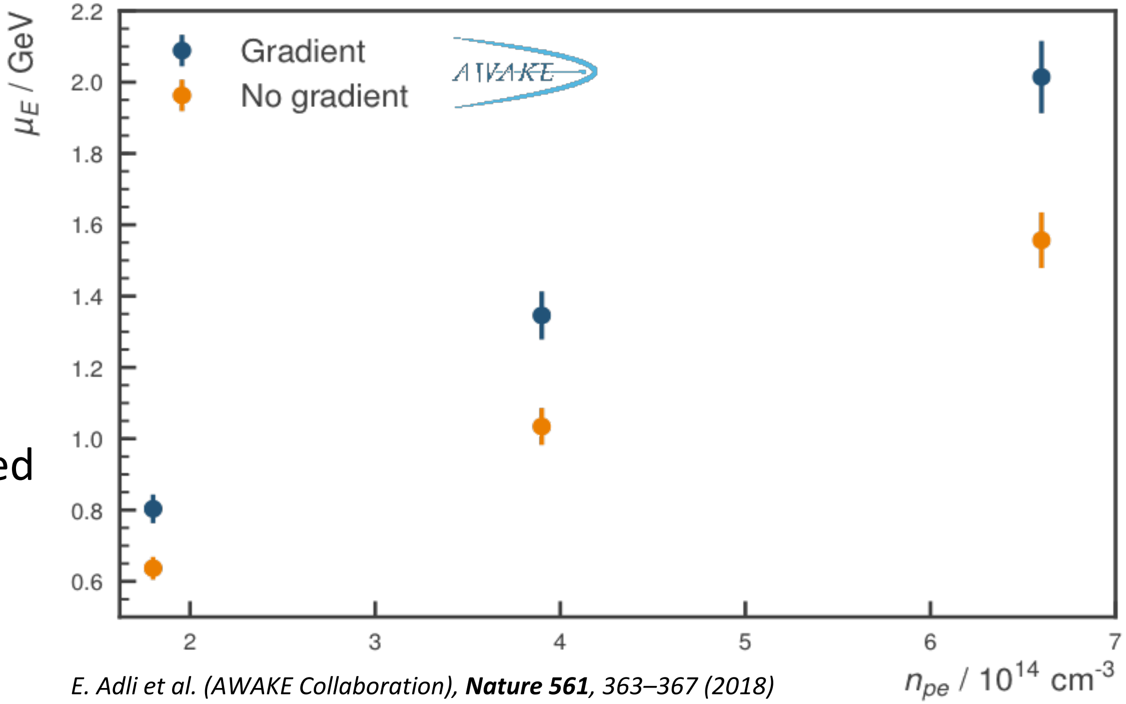


No accelerated electrons



Accelerated electrons

Convert pixel-size and dipole setting to energy



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

E. Gschwendtner, CERN

AWAKE Run 2

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

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

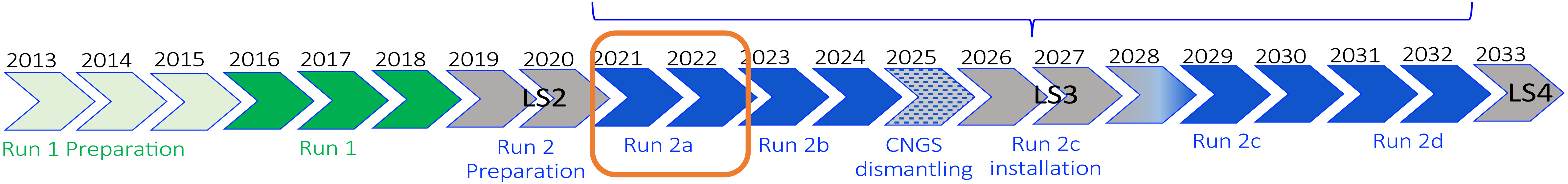
Paradigm change:

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

AWAKE 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

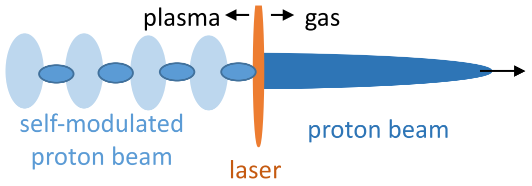
Run 2c

Run 2d

Run 2a Results – Seeding the Self-Modulation

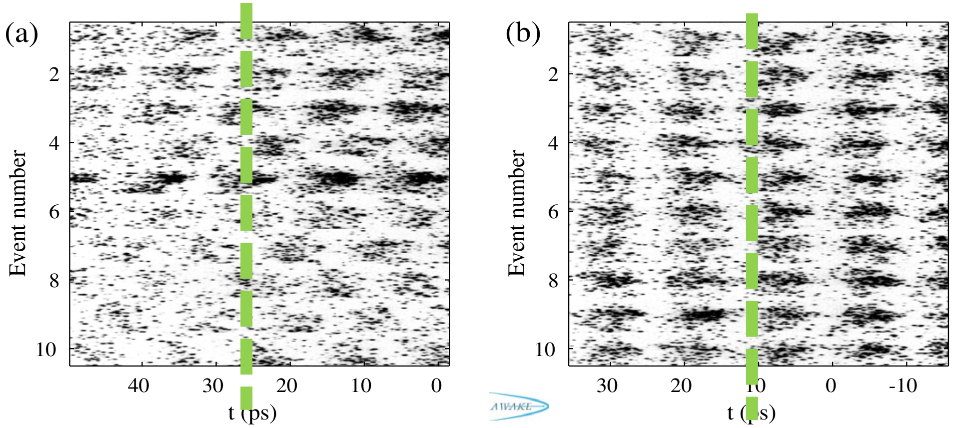
➔ Proton-bunch self-modulation process must be reproducible, reliable and stable.

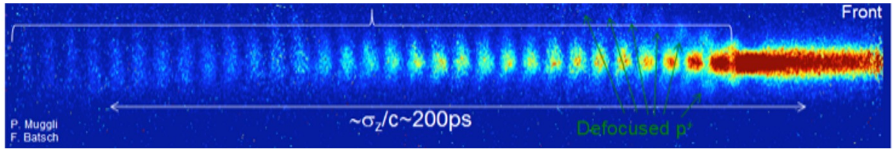
Seeding with the relativistic ionization front



Unseeded: phase not reproducible

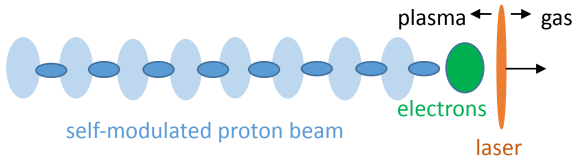
Seeded with laser ionization front





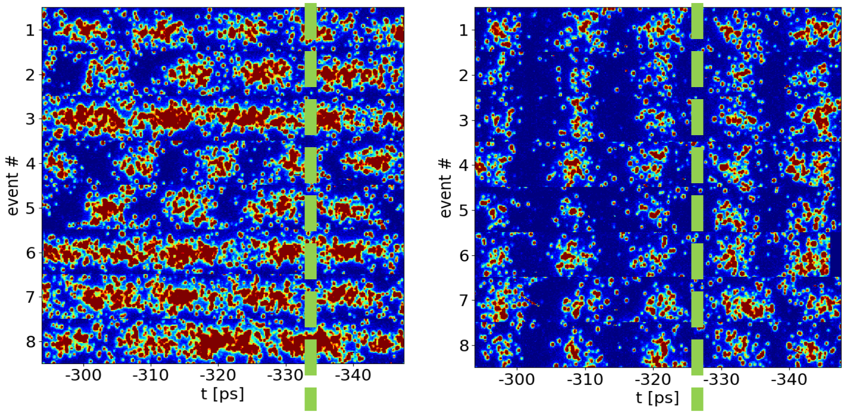
F. Batsch, P. Muggli et al. (AWAKE Collaboration), Phys. Rev. Lett. 126, 164802 (2021).

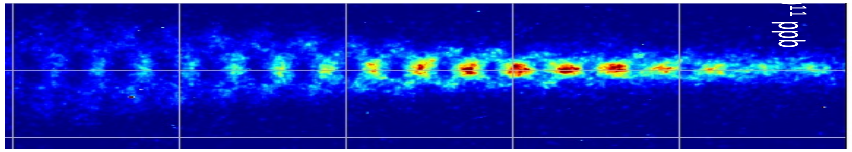
Seeding with the electron bunch



No e⁻ bunch → SMI

with e⁻ bunch → seeded SM



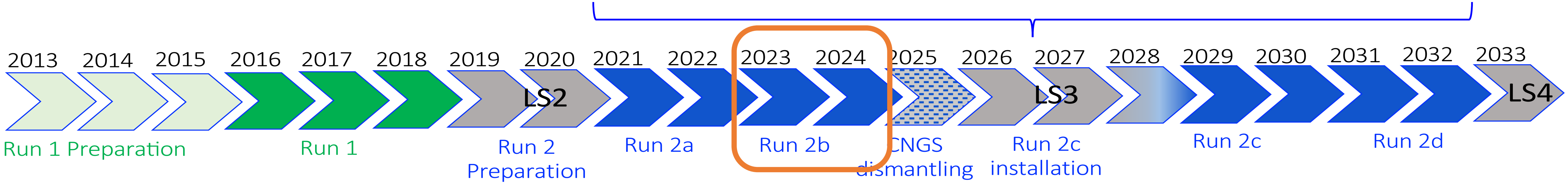


L. Verra et al. (AWAKE Collaboration), Phys. Rev. Lett. 129, 024802 (2022)

AWAKE Program

RUN 2 (2021-2032)

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



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

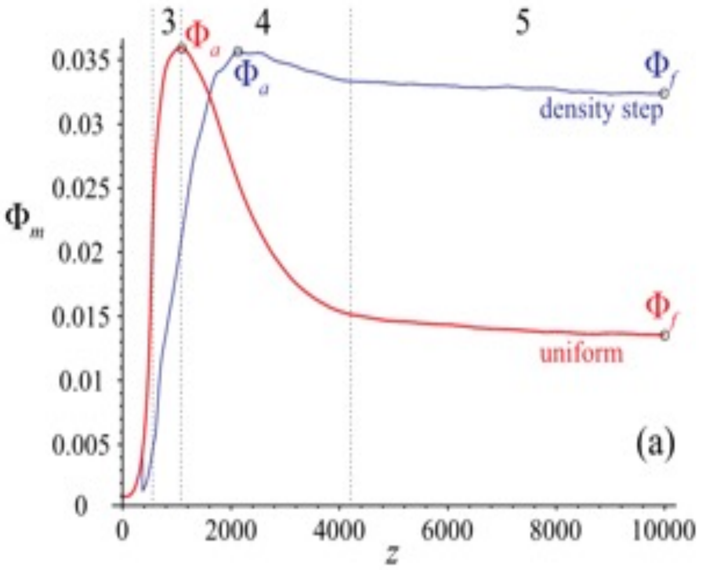
Run 2d

Run 2b Results – Stabilizing Large Wakefield Amplitudes

Introducing a density step in the plasma cell

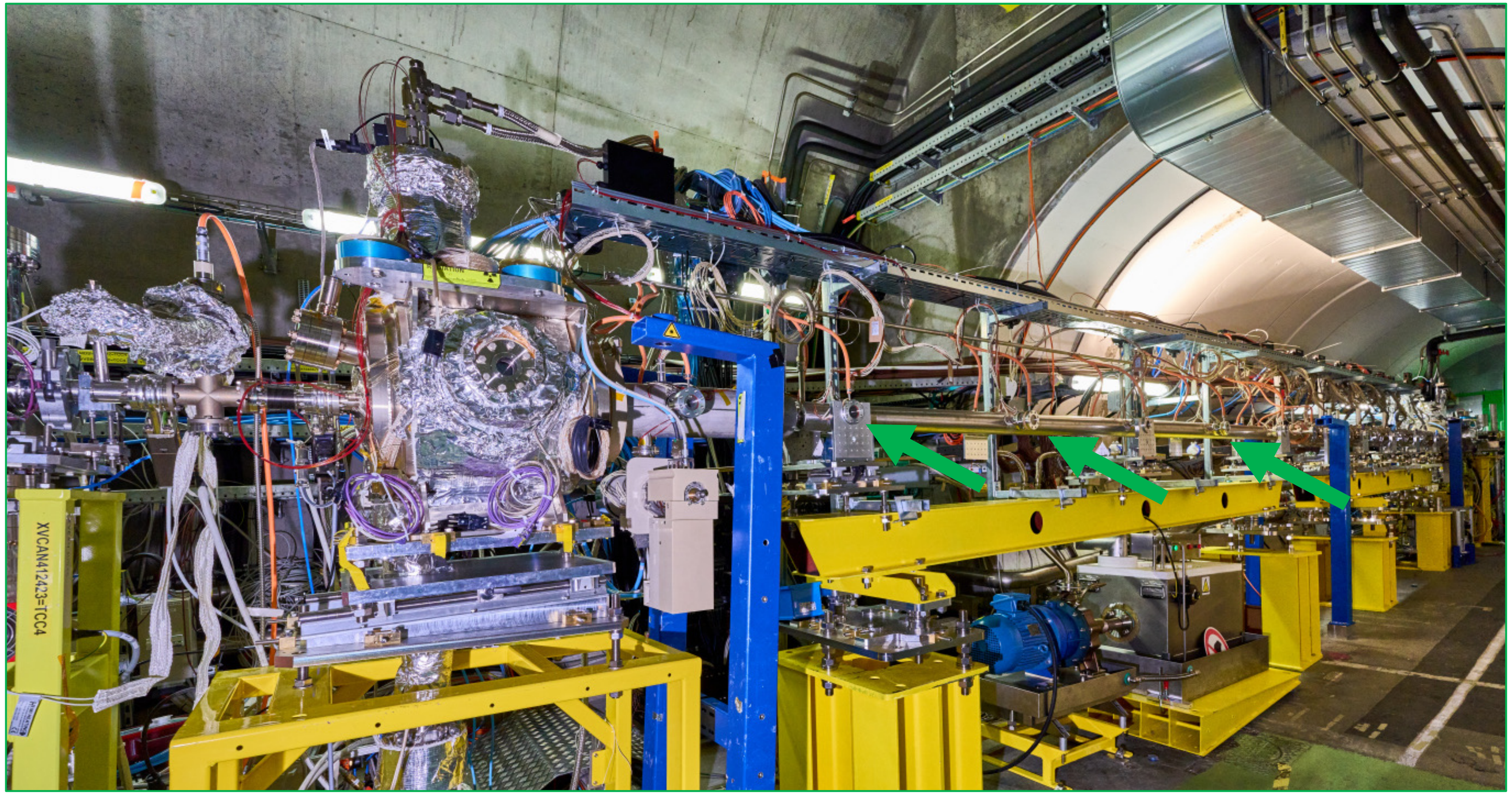
➔ stabilization of the micro-bunches

➔ Increased wakefield amplitudes after SSM saturation



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

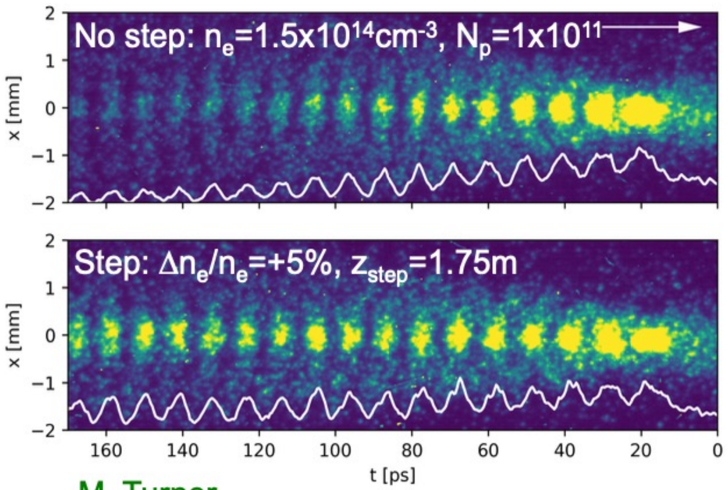


- Length: ~ 10 m, independent electrical heater of 50 cm from 0.25 to 4.75 m, Step height up to ±10%
- 10 diagnostic viewport ➔ to measure light emitted by wakefields dissipating after the passage of the proton bunch

Run 2b Results – Stabilizing Large Wakefield Amplitudes

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

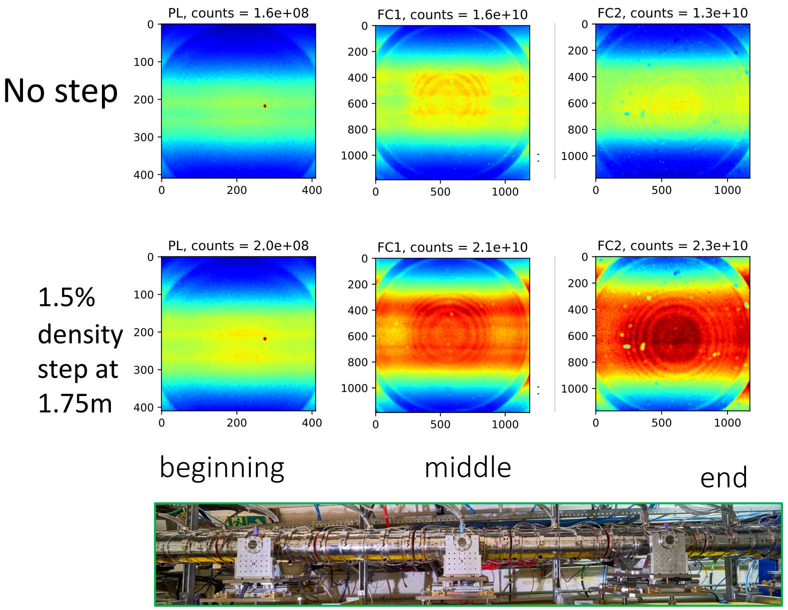
Proton Bunch Time-Resolved Images



M. Turner

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

Plasma Light

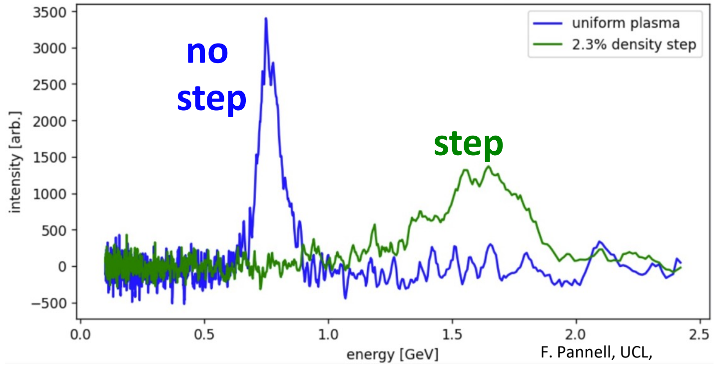


- ➔ plasma density step clearly influences plasma light from dissipating wakefields

Electron Acceleration

External injection downstream of the density step

n_{pe} ~ 6.2×10^{14} cm^{-3}, 2.3% step at 1.75 m



F. Pannell, UCL, AWAKE Collaboration

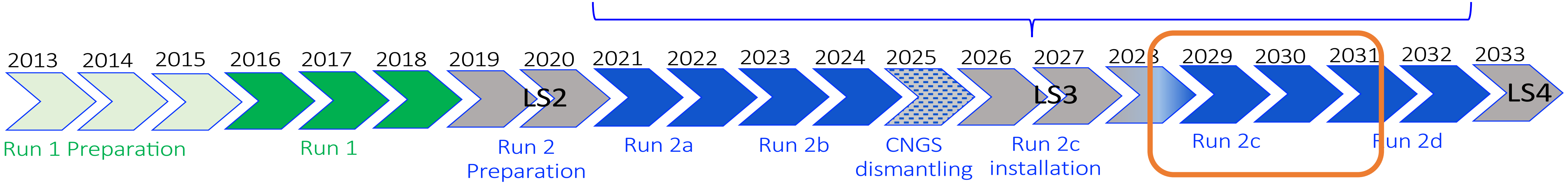
- ➔ Plasma density step clearly influences energy of the accelerated electrons: electron energy much higher

➔ 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***.

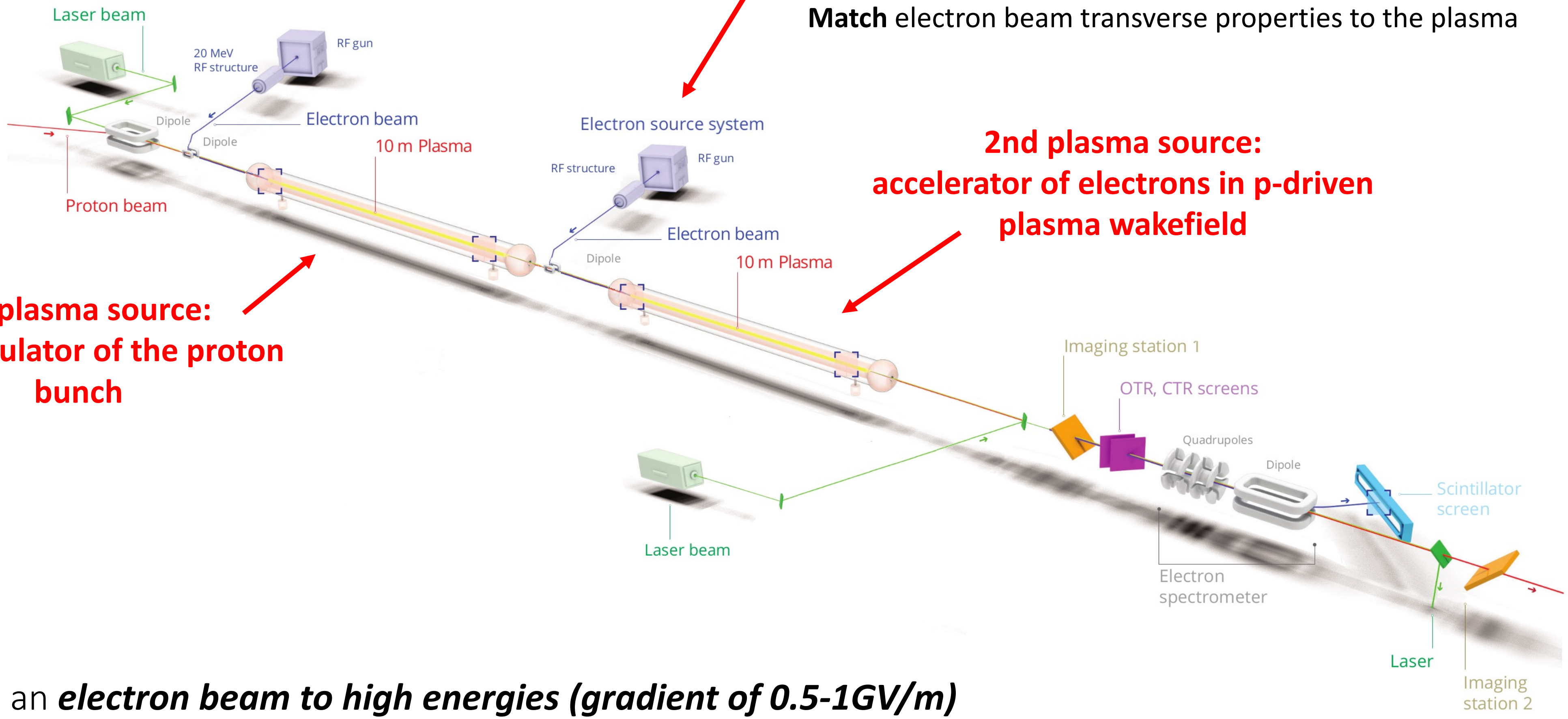
AWAKE Run 2c – Start after LS3

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

Blow-out regime

Beam loading: reach small ∂E/E

Match electron beam transverse properties to the plasma

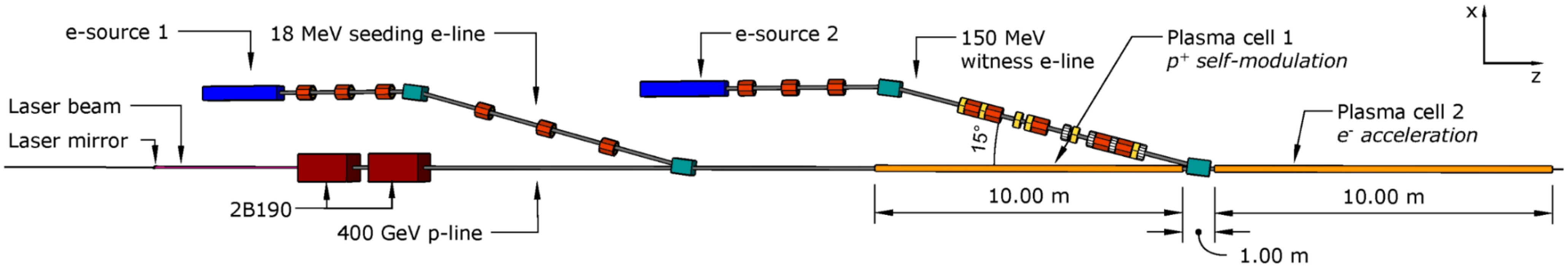


2nd plasma source: accelerator of electrons in p-driven plasma wakefield

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

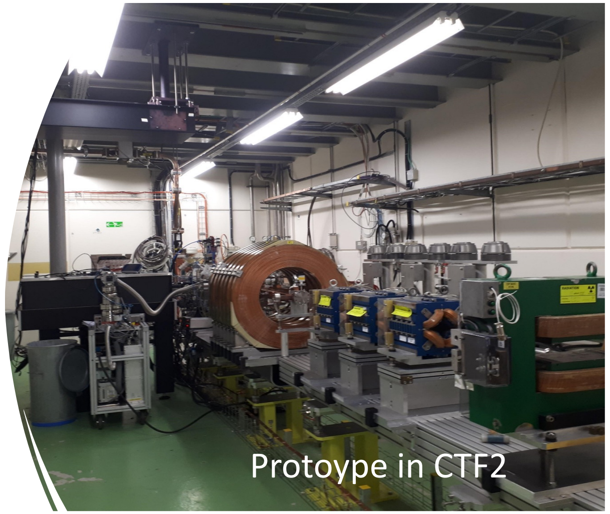
- ➔Accelerate an ***electron beam to high energies (gradient of 0.5-1GV/m)***
- ➔while controlling the ***electron beam quality (~10 mm-mrad emittance, 10% energy spread)***

AWAKE Run 2c – Ongoing Studies



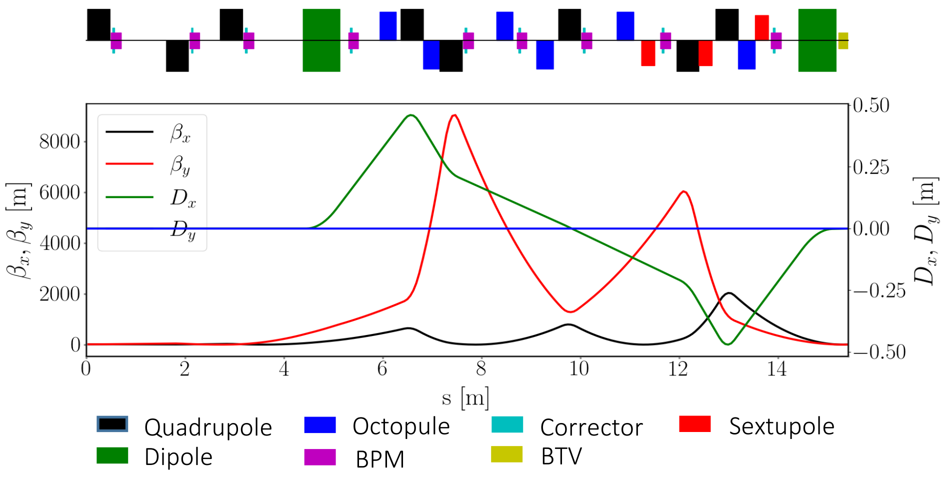
➔ Studies, design and prototyping already advancing well for several experimental elements of Run 2c

Run 2c electron source prototype

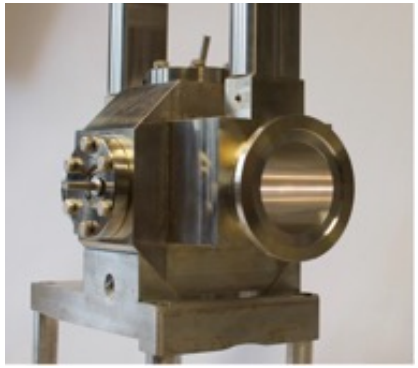


S-band e-gun (INFN) with
X-band accelerator (CLIC/CLEAR)

150 MeV beamline



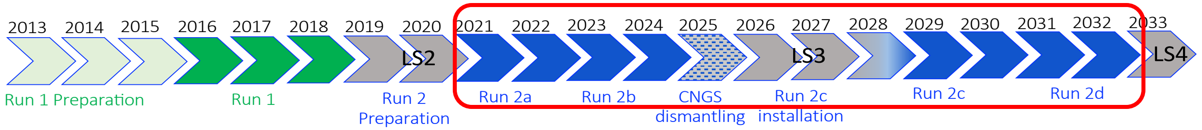
Beam instrumentation



BPMs 10 µm resolution

Run 2 – Broader Impact

Examples of technological advancements



Machine Learning

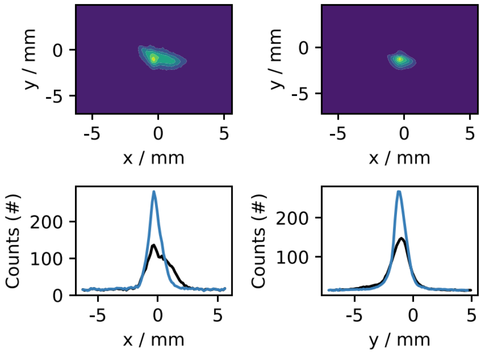
→ Running test-bed for operation efficiency studies and Machine Learning

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



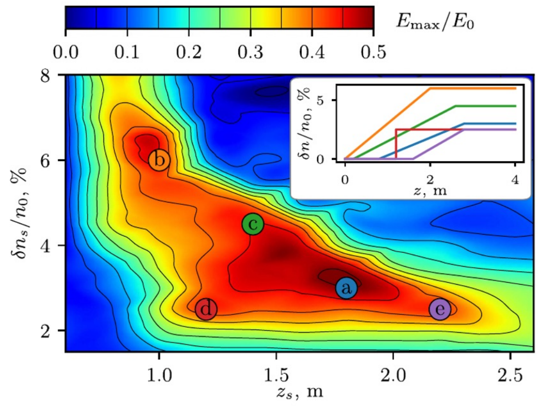
Velotti, F. M., et al. *Machine Learning: Science and Technology* 4.2 (2023): 025016.

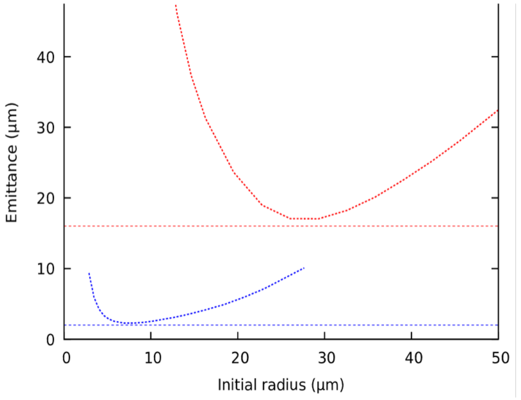
Simulations

→ 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.

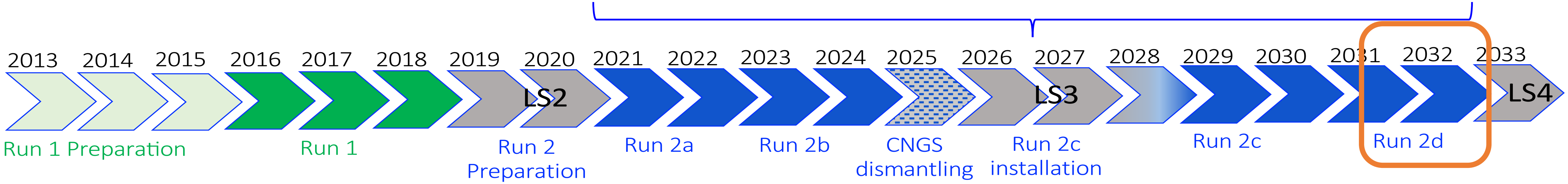




AWAKE Program

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*

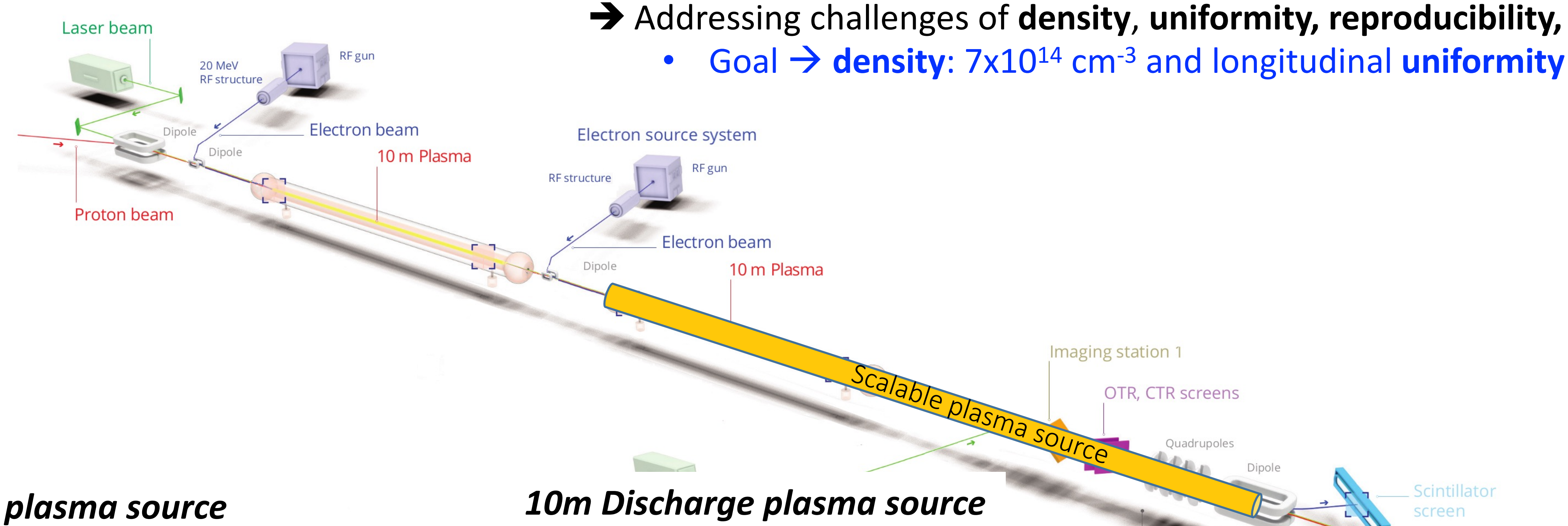
➔ **Run 2c (2028-2031): QUALITY**: demonstrate ***electron acceleration and emittance control of externally injected electrons***.

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

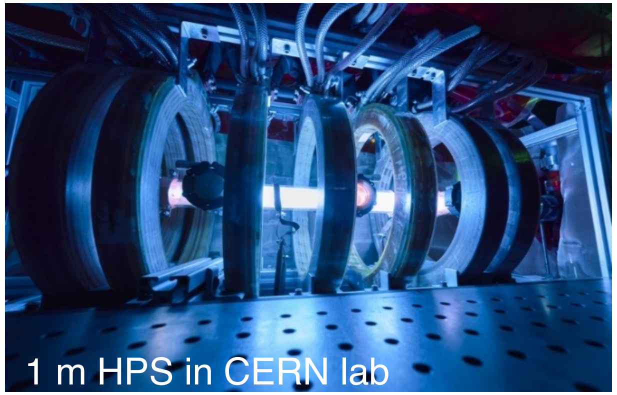
AWAKE Run 2d: Demonstrate Scalable Plasma Sources

Scalable plasma source R&D program:

- ➔ Dedicated plasma source labs at CERN
- ➔ 5 collaborating institutes
- ➔ Addressing challenges of **density**, **uniformity, reproducibility, scalability**
  - Goal → **density**: 7x10^{14} cm^{-3} and longitudinal **uniformity**: 0.25%



1m Helicon plasma source



1 m HPS in CERN lab

10m Discharge plasma source

10 m DPS run May 2023

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

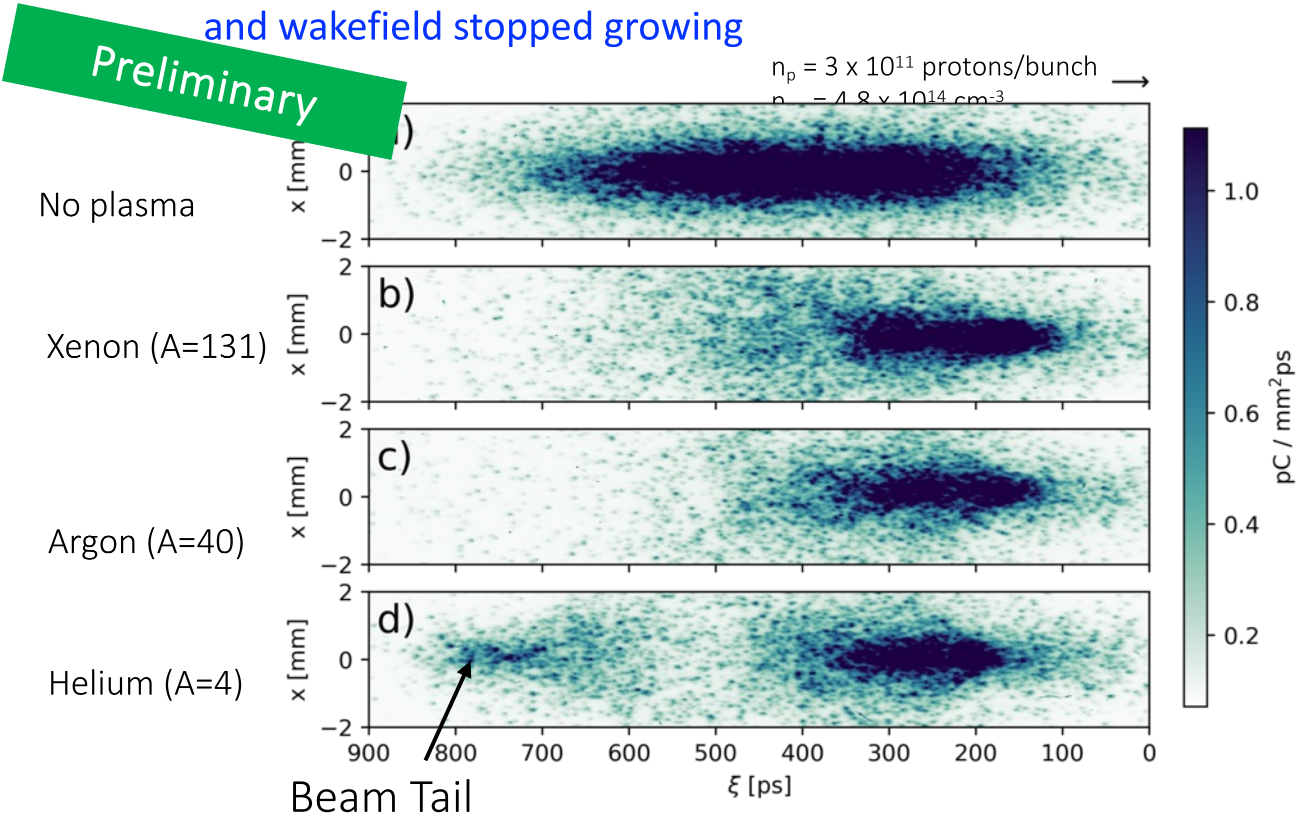
➔ Demonstrated self-modulation of the proton bunch

➔ Flexible operation allowed to study various physics effects.

DPS Ion Motion Studies

Ions move due to the ponderomotive force of the radial wakefields

- ➔ Change in plasma wavelength and therefore resonance condition
- ➔ Appearance of beam tail when ion motion becomes significant and wakefield stopped growing



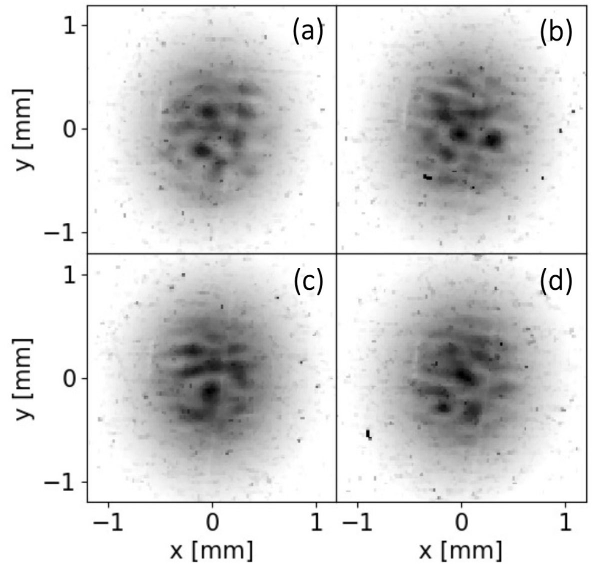
M. Turner, CERN

DPS Current Filamentation Studies

If proton bunch is wider than plasma skin depth ➔ CFI.

High plasma density of $n_{pe,\ discharge} = 9\times10^{14}\ \text{cm}^{-3}$.

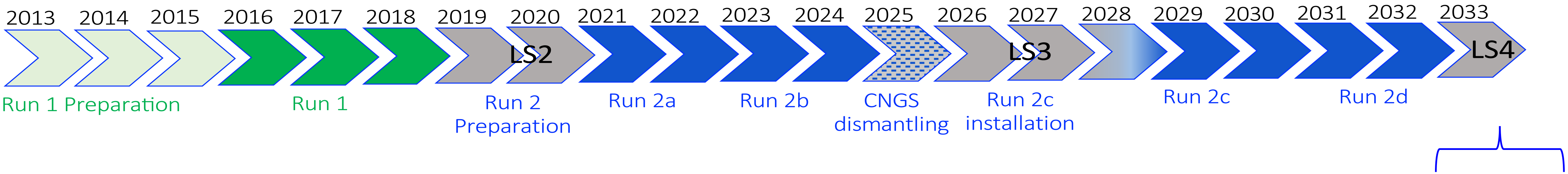
Wide proton bunch optics: $\frac{\sigma}{\delta}$ ~3



Clear evidence of filamentation→ Important for PWFA design

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

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

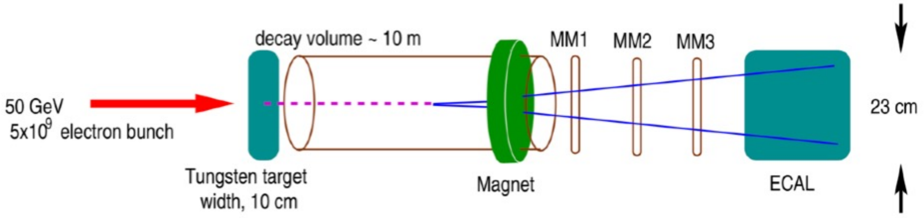
First Applications with AWAKE-Like Technology

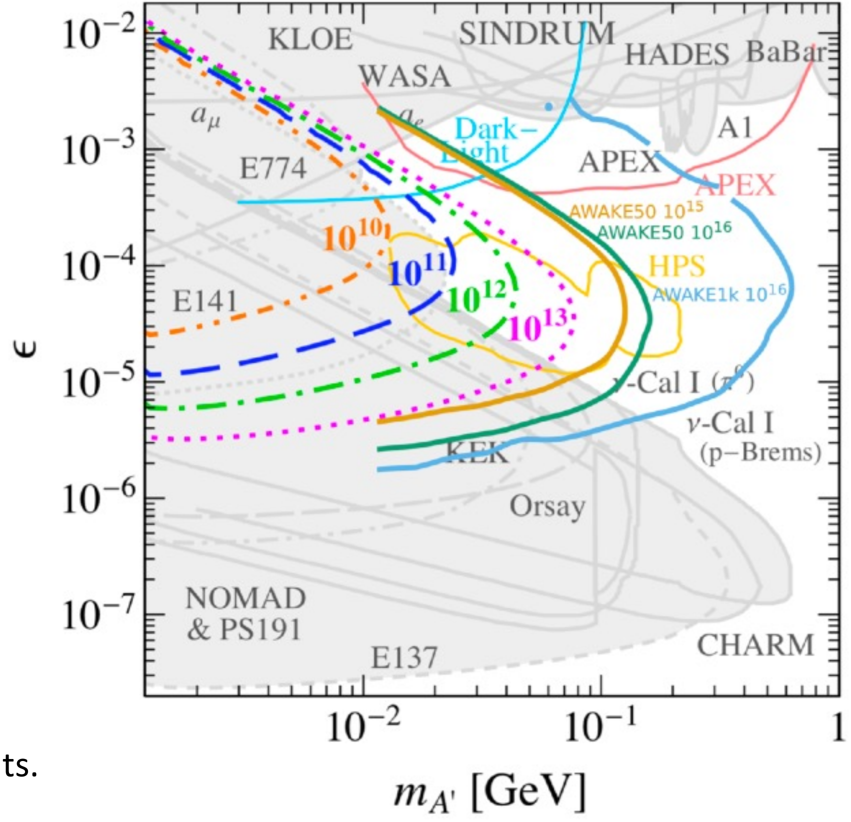
➔ Within the context of the **Physics Beyond Colliders Project (PBC),** AWAKE performed preliminary studies on possible first particle physics applications in the nearer future.

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.

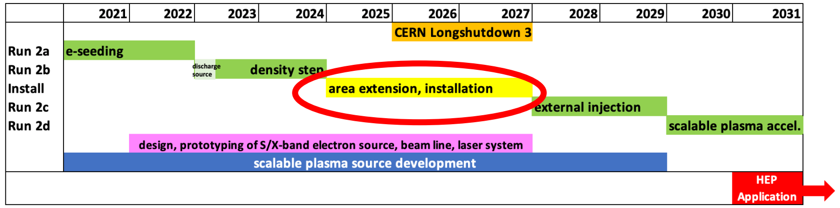
- AWAKE is a unique proton-driven plasma wakefield acceleration experiment at CERN
  - Proton-driven plasma wakefield acceleration interesting because of large energy content of driver.
  - Modulation process means existing proton machines can be used.
  - AWAKE uses protons from CERN's SPS.
  - Complex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

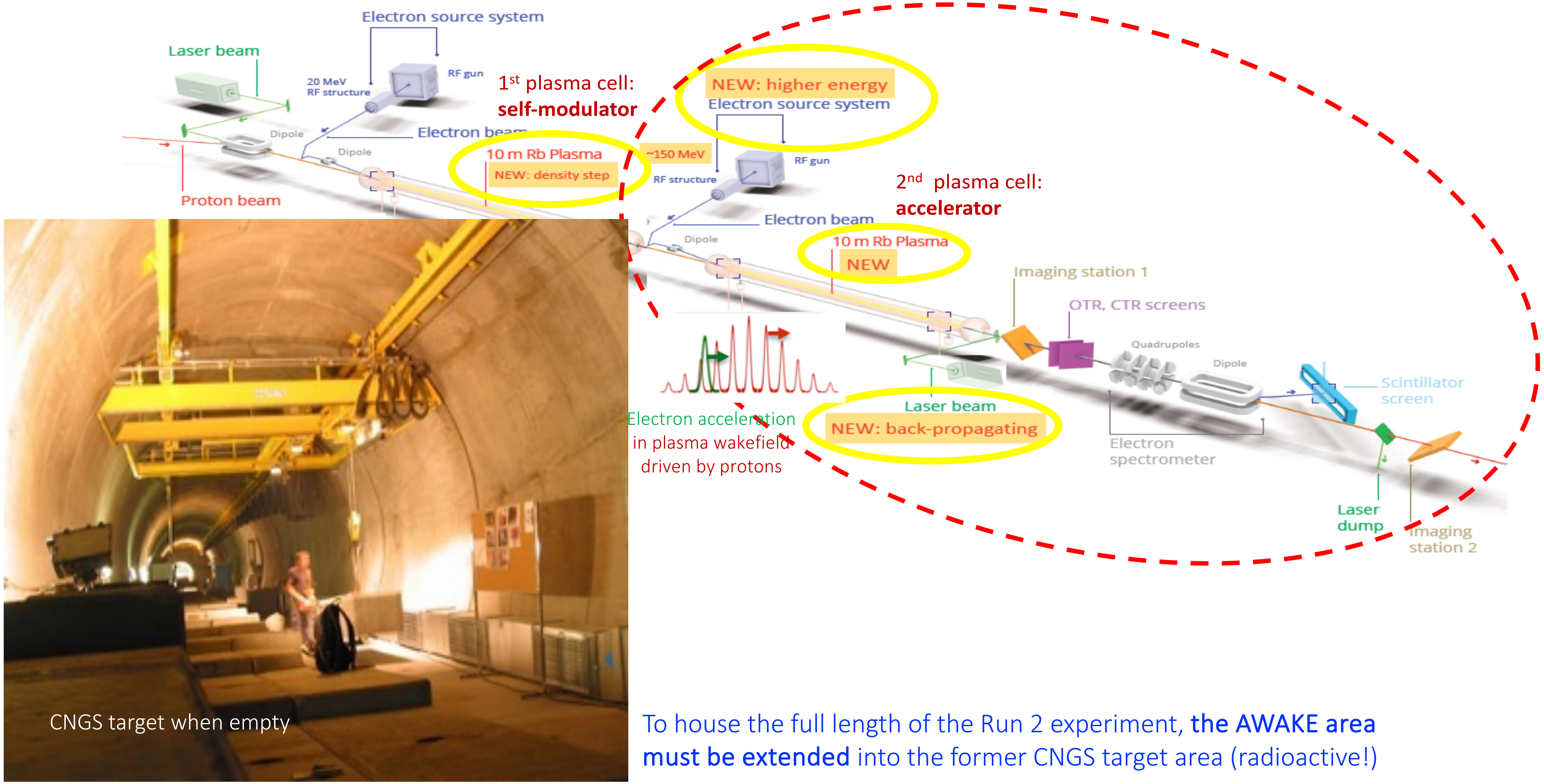
- AWAKE developed a well-defined plan towards first applications of particle physics experiments
  - AWAKE Run 2 is ongoing.
  - AWAKE met all milestones to date.

Back-Up

AWAKE Run 2c - Preparation

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



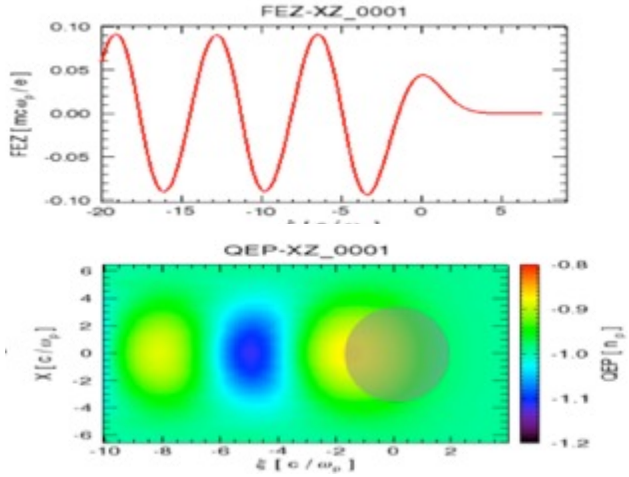


To house the full length of the Run 2 experiment, **the AWAKE area must be extended** into the former CNGS target area (radioactive!)

Introduction – Beam Quality in PWA

Different regimes:

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

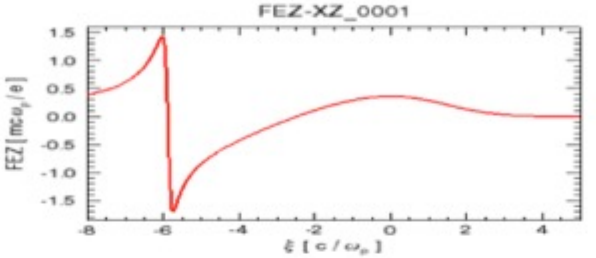


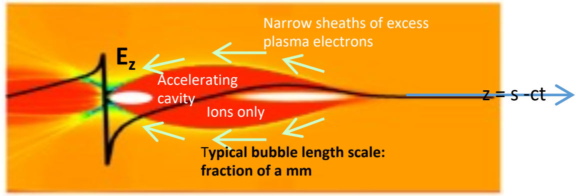
- – *lower wakefields*
- – *transverse forces not linear in r*
- + Symmetric for positive and negative witness bunches
- + Well described by theory

Accelerating field is maximised for a value of

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

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

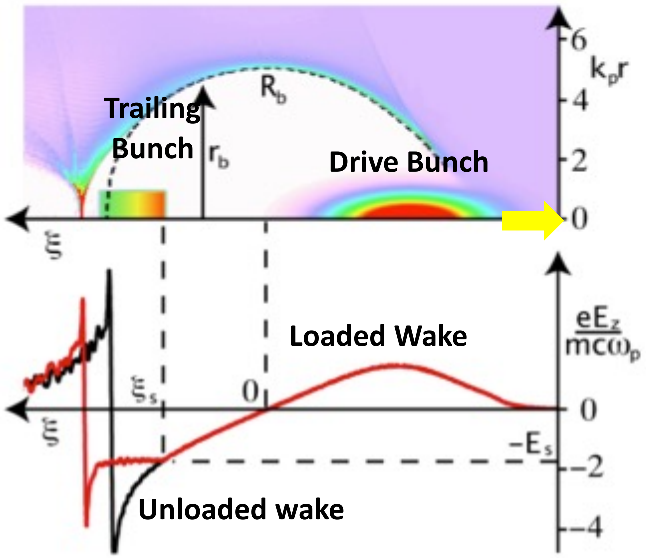




- + Higher wakefields
- + transverse forces linear in r (emittance preservation)
- + High charge witness acceleration possible
- – *Requires more intense drivers*
- – *Not ideal for positron acceleration*

Beam loading

Blown Out Wake



Sufficient charge in the witness bunch to flatten the accelerating field

→ **reduce energy spread**