Plasma Wakefield Acceleration and the AWAKE Experiment

CAS@ ESI: Basics of Accelerator Physics and Technology
7 – 11 October 2019, Archamps, France

Edda Gschwendtner, CERN

Outline

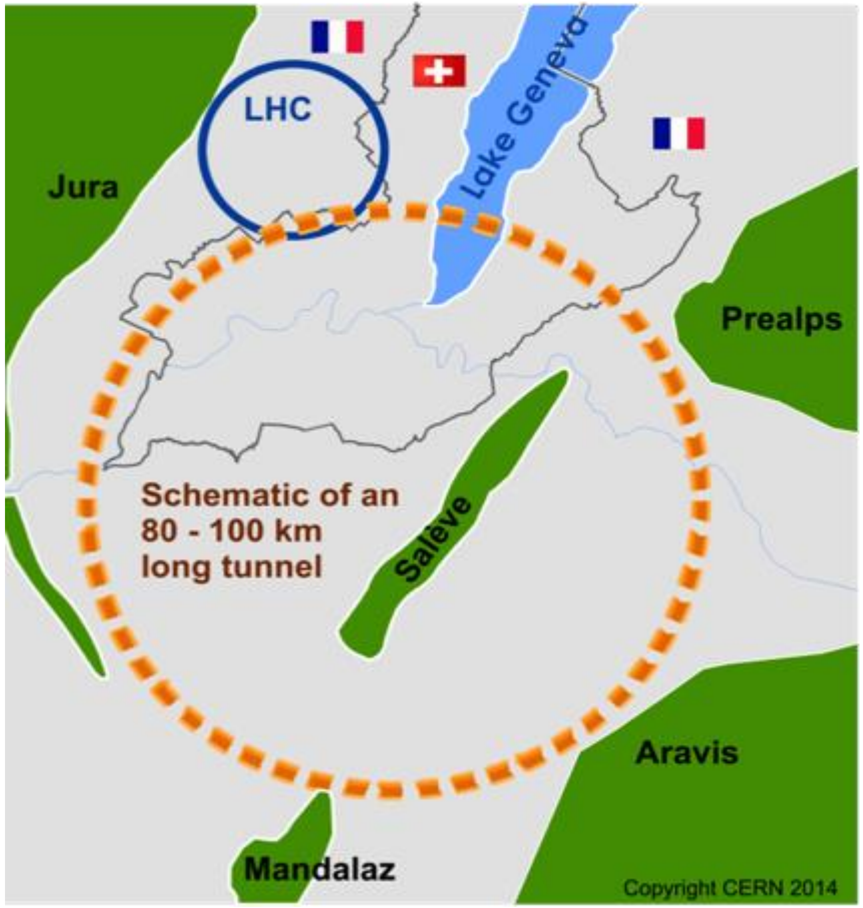
- Motivation
- Introduction to Plasma Wakefield Acceleration
- State of the Art
- The AWAKE Experiment

Discover New Physics

Accelerate particles to even higher energies

→ **Bigger accelerators: circular colliders**

Future Circular Collider: FCC



Limitations of conventional circular accelerators:

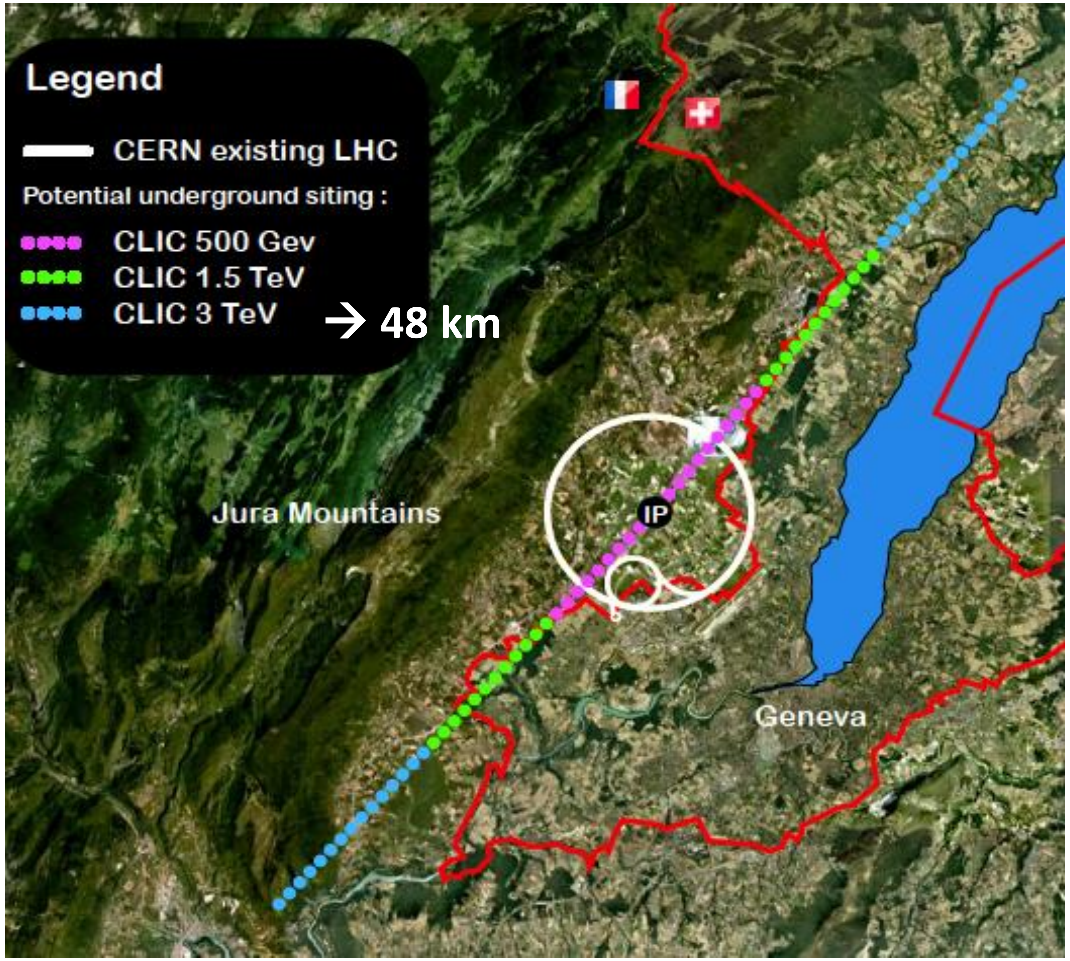
- For **hadron colliders**, the limitation is **magnet strength**. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach **100 TeV** proton-proton collision energy.
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

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

Discover New Physics

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

CLIC, electron-positron collider with 3 TeV energy

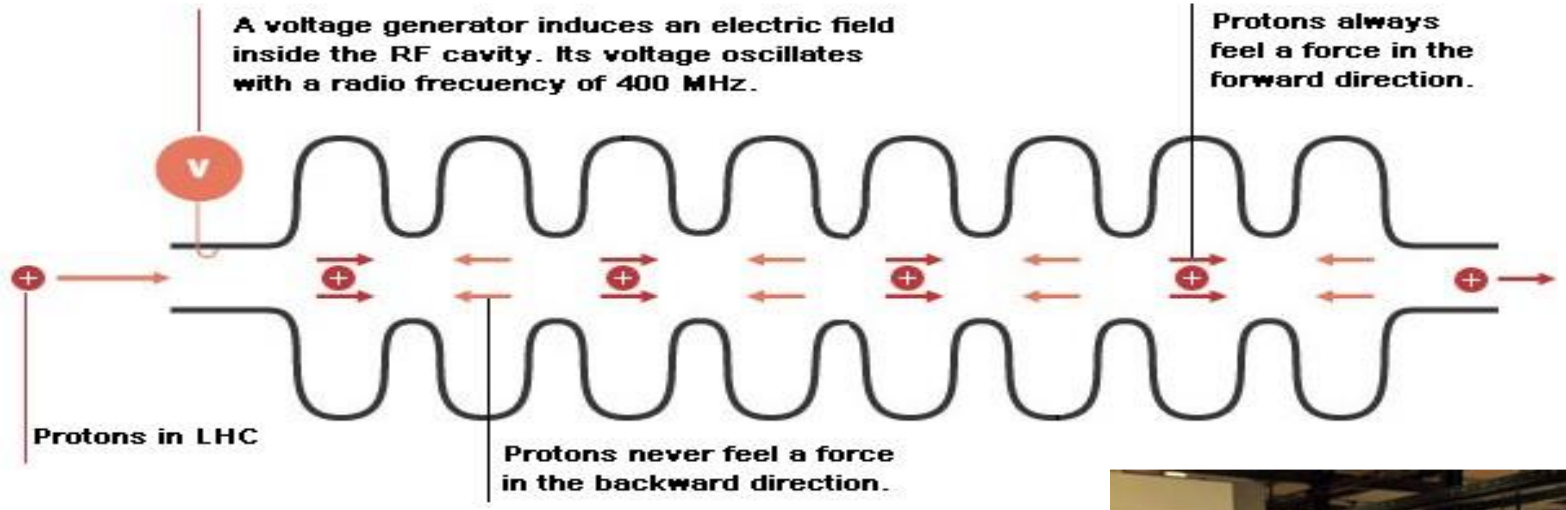


Limitations of linear colliders:

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

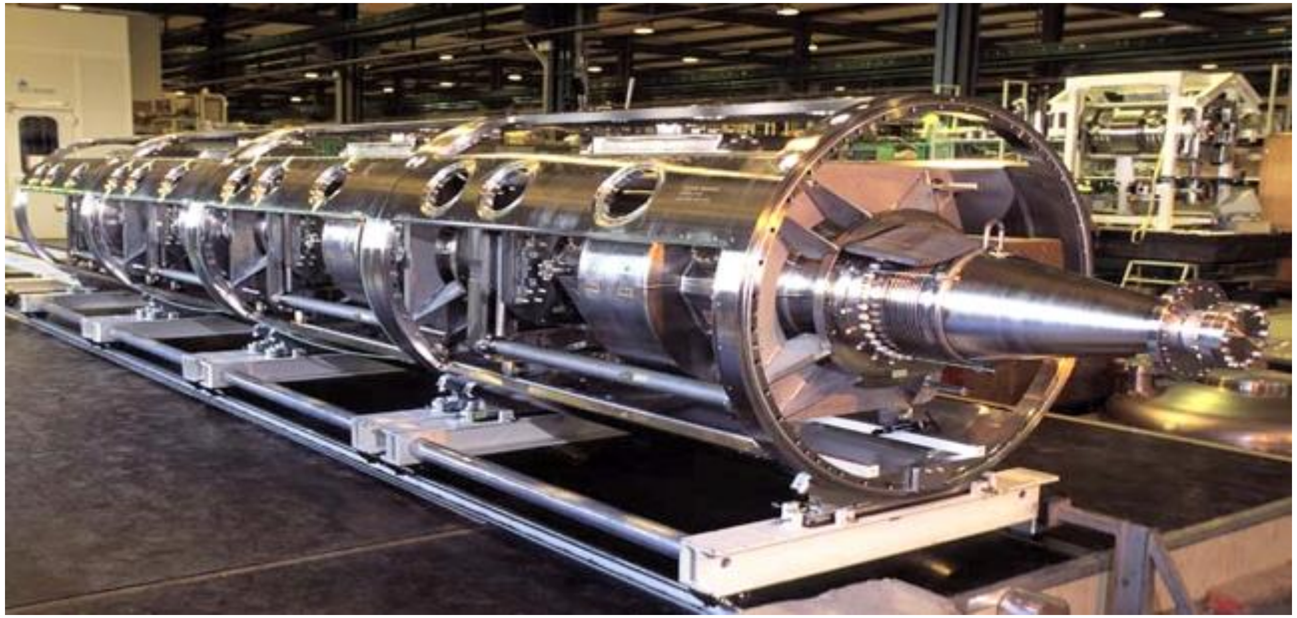
Conventional Acceleration Technology

Radiofrequency Cavities



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity

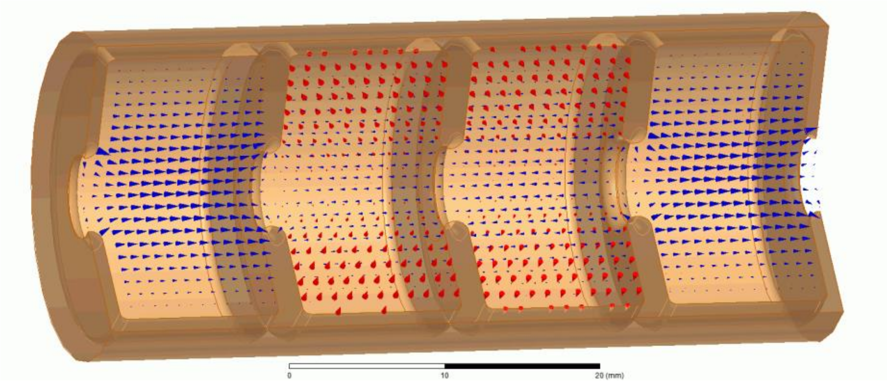


Conventional Accelerating Technology

Today's RF cavities or microwave technology:

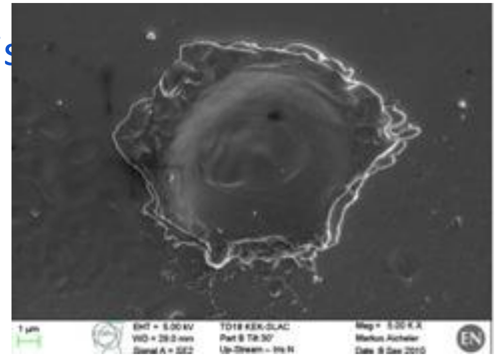
- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

- Typical gradients:
  - LHC: 5 MV/m
  - ILC: 35 MV/m
  - CLIC: 100 MV/m



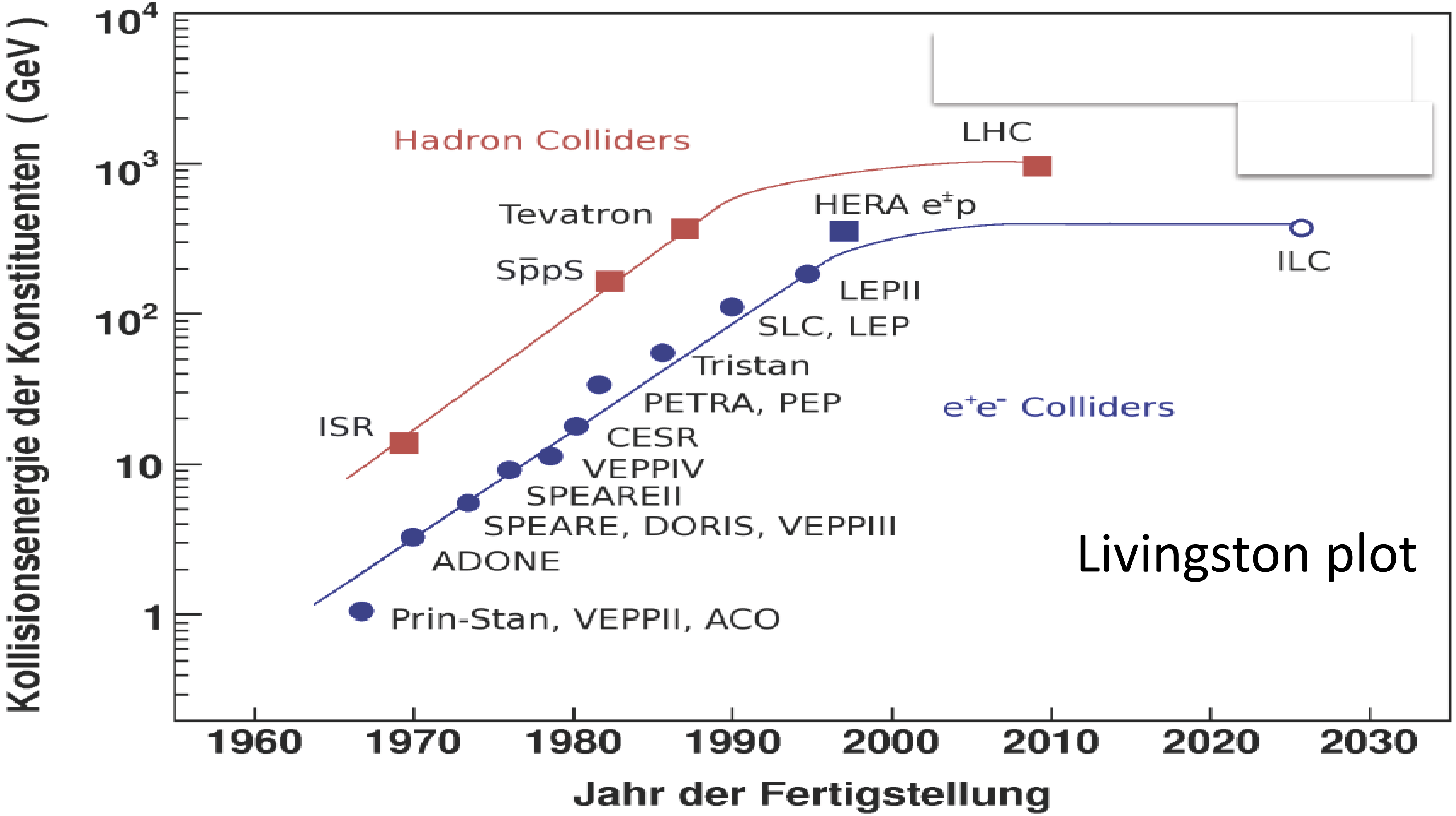
However:

- accelerating fields are limited to <100 MV/m
  - In metallic structures, a too high field level leads to break down of surfaces, creating electric dis
  - Fields cannot be sustained, structures might be damaged.



- several tens of kilometers for future linear colliders

Saturation at Energy Frontier for Accelerators



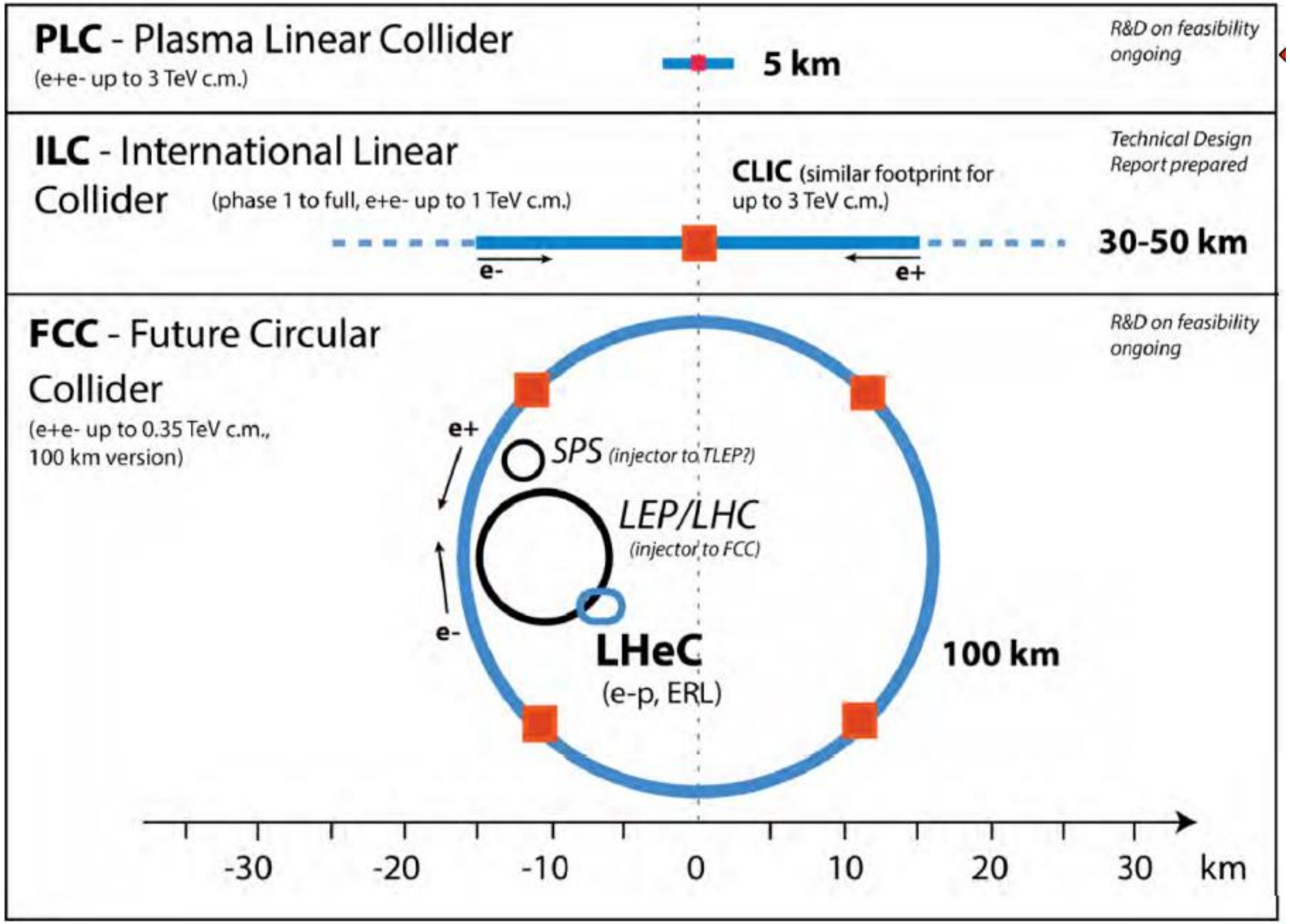
Livingston plot

➔ **Project size and cost increase with energy**

Plasma Wakefield Acceleration

➔Acceleration technology, which obtains ~1000 factor stronger acceleration than conventional technology.

Conventional vs. Plasma



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Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Collective plasma accelerators have recently received considerable theoretical and experimental investigation. Earlier Fermi[1] and McMillan[2] considered cosmic-ray particle acceleration by moving magnetic fields[1] or electromagnetic waves.[2] In terms of the realizable laboratory technology for collective accelerators, present-day electron beams[3] yield electric fields of ~10^7 V/cm and power densities of 10^{13} W/cm^2.

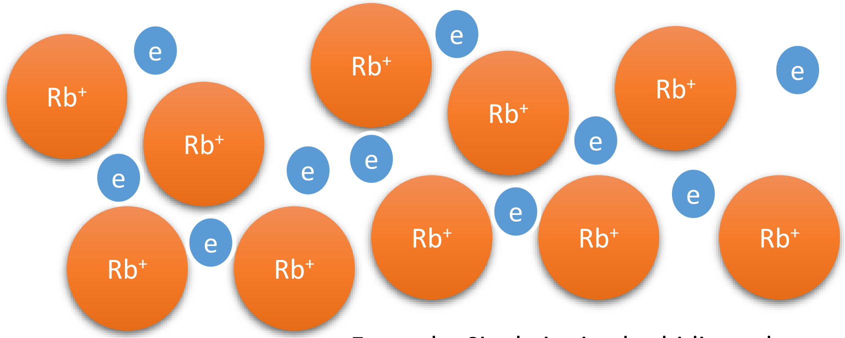
the wavelength of the plasma waves in the wake:

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

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

Plasma Wakefield

What is a plasma?



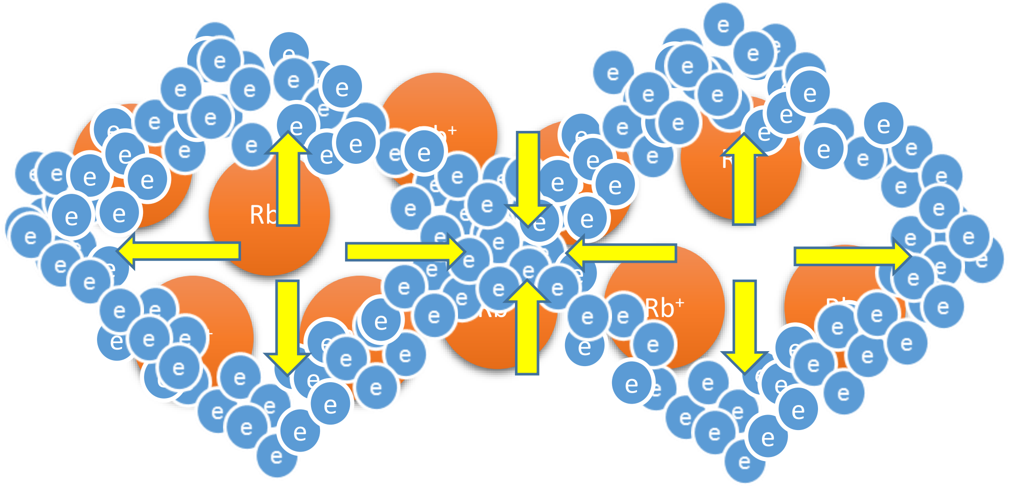
Example: Single ionized rubidium plasma

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

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?



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

Plasma Baseline Parameters

- A plasma of density n_{pe} is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \quad \rightarrow \quad \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \qquad k_{pe} = \frac{\omega_{pe}}{c}$$

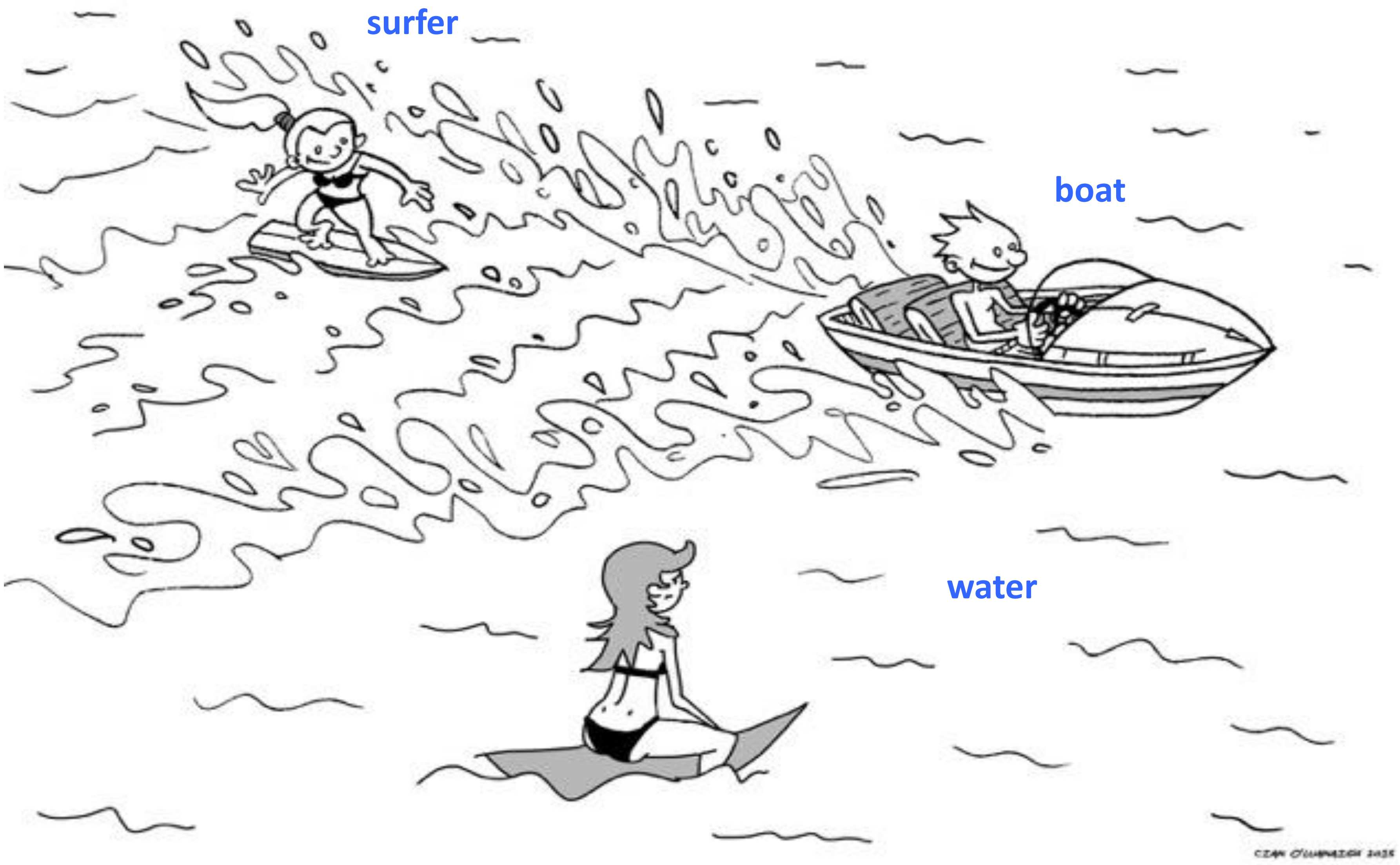
Example: n_{pe} = 7×10^{14} cm^{-3} (AWAKE) → $\omega_{pe} = 1.25 \times 10^{12}$ rad/s → $\frac{c}{\omega_{pe}}$ **= 0.2mm** → $k_{pe} = 5$ mm^{-1}

- This translates into a wavelength of the plasma oscillation

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \quad \rightarrow \quad \lambda_{pe} \approx 1\text{ mm} \sqrt{\frac{10^{15}\text{ cm}^{-3}}{n_{pe}}}$$

λ_{pe} = 1.2 mm → **Produce cavities with mm size!**

How to Create a Plasma Wakefield?



Analogy:
water → plasma

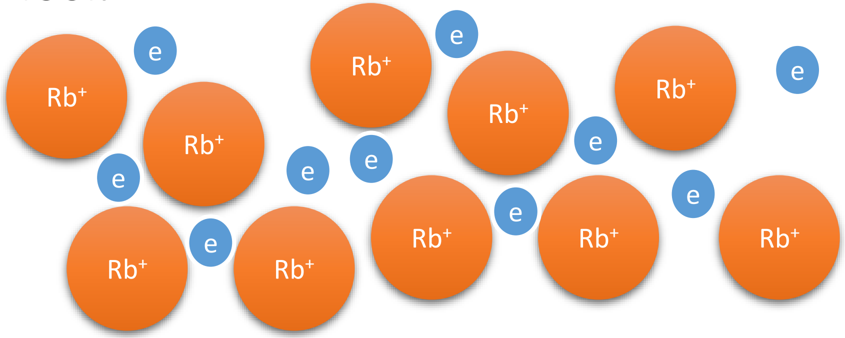
Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

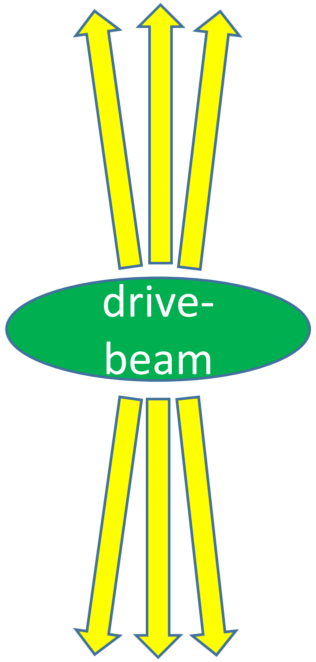
How to Create a Plasma Wakefield?

What we want:
Longitudinal electric field to accelerate charged particles.

Our Tool:



Single ionized rubidium **plasma**

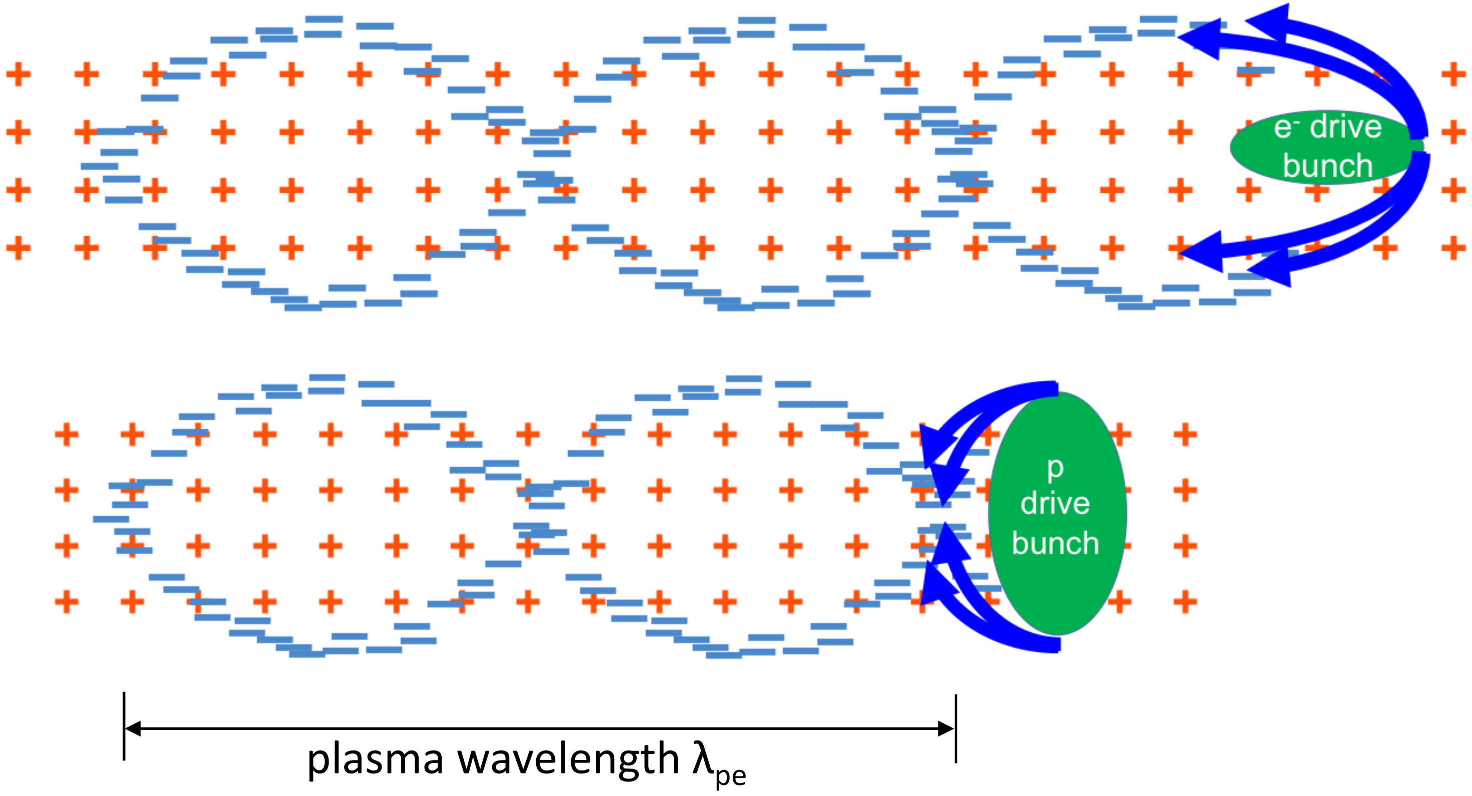


Charged particle bunches carry almost purely transverse Electric Fields.

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

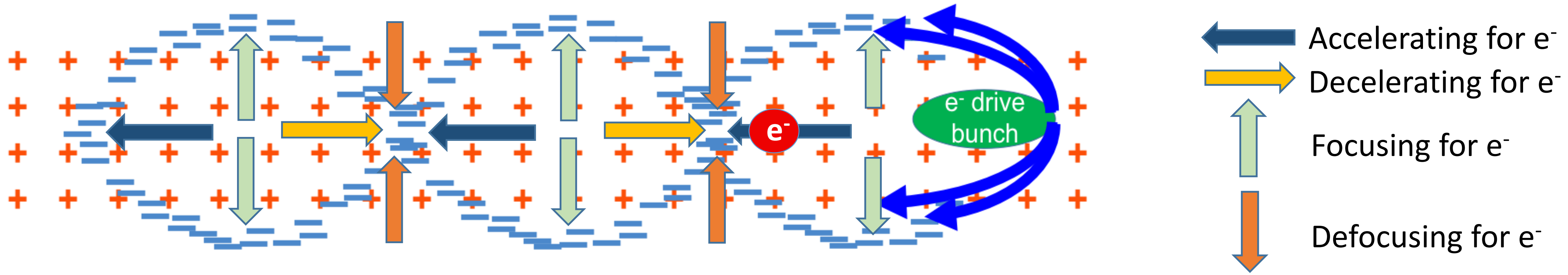
Principle of Plasma Wakefield Acceleration

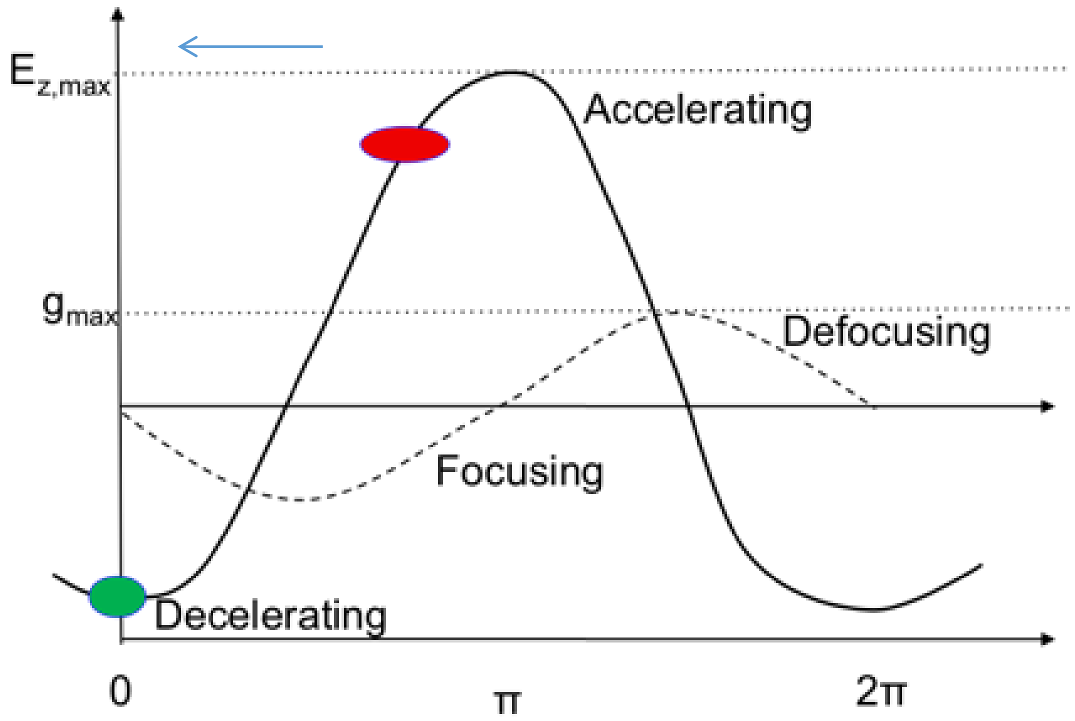
- Laser drive beam
  - ➔ Ponderomotive force
- Charged particle drive beam
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



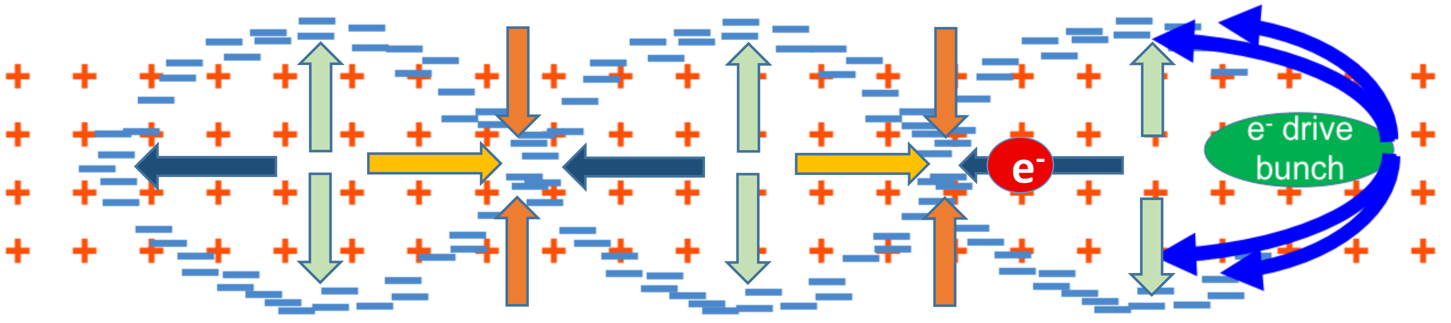
- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Wakefields



Accelerating for e^-
Decelerating for e^-
Focusing for e^-
Defocusing for e^-

How strong can the fields be?

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

$$e\,E_{WB} = 96\,\frac{V}{m}\sqrt{\frac{n_{pe}}{cm^{-3}}}$$

- The ion channel left on-axis, where the beam passes, induces an **ultra-strong focusing field:**

$$g = 960\,\pi\,\frac{n_{pe}}{10^{14}\,cm^{-3}}\,\frac{T}{m}$$

Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE) ➔ eE_{WB} = 2.5 GV/m ➔ g = 21kT/m
Example: n_{pe} = 7x10^{17} cm^{-3} ➔ eE_{WB} = 80 GV/m ➔ g = 21MT/m

Plasma Wakefield, Linear Theory

(R. D. Ruth, P. Chen, SLAC-PUB-3906, 1986)

When drive beam density is smaller than plasma density ($n_b << n_p$) → **linear theory.**

- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

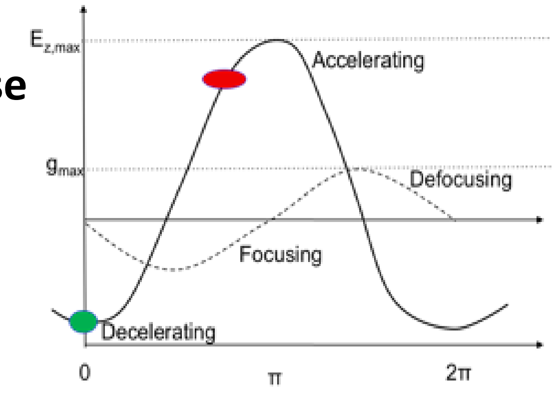
$$eE_z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

B.E. Blue 2003

➔ $eE_z \approx N/\sigma_z^2$

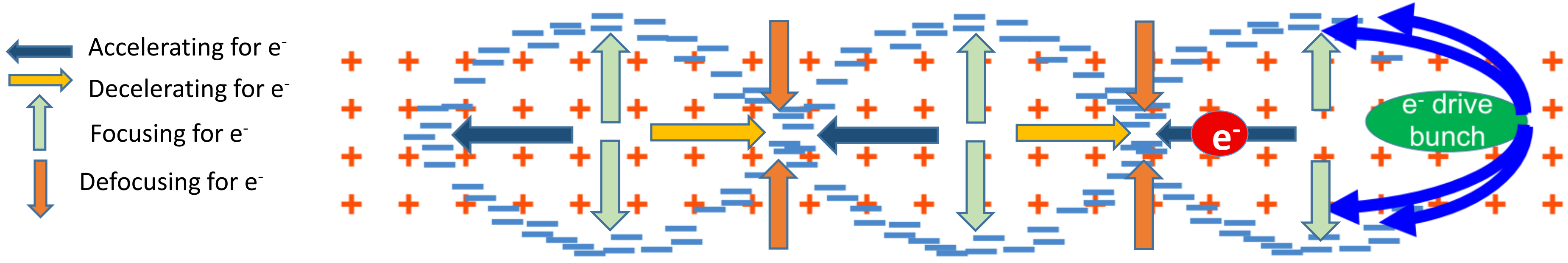
- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- **Accelerating gradient** increases linearly with N/σ_z
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**
- The **accelerating field is maximized** for a value of

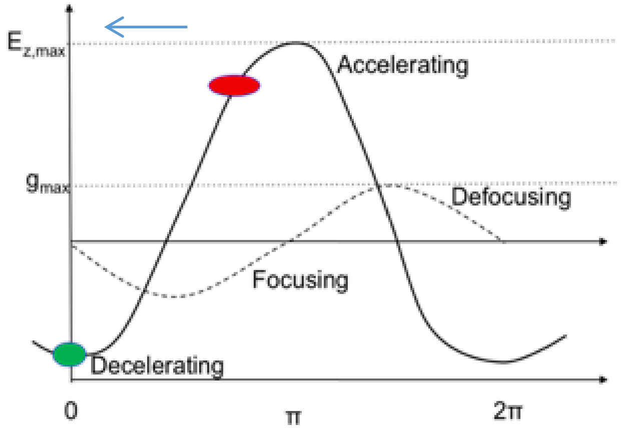
$k_{pe}\,\sigma_z \approx \sqrt{2}$
$k_{pe}\,\sigma_r \leq 1$



Example: $n_{pe} = 7\times10^{14}$ cm^{-3} (AWAKE), $k_{pe} = 5$ mm^{-1} ➔ **drive beam: $\sigma_z = 300\mu m$, $\sigma_r = 200\mu m$**

Plasma Wakefield, Linear Theory





Linear Theory: Maximum accelerating electric field reached with drive beam of N and σ_z:

$$E_{acc} = 110 \frac{MV}{m} \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6mm)^2}$$

← Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

Examples of accelerating fields for different beam parameters and plasma parameters fields:

$N = 3x10^{10}$, σ_z = 300µm, n_{pe}= $7x10^{14}$ cm^{-3} ➔ **E_{acc} = 600 MV/m**
$N = 3x10^{10}$, σ_z = 20µm, n_{pe}= $2x10^{17}$ cm^{-3} ➔ **E_{acc} = 15 GV/m**

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

Now first Proton Driven Plasma Wakefield Experiment

Laser-Driven Plasma Acceleration Facilities

ALEGRO
Advanced LinEar collider study GROup

Table 2.2: Laser facilities (≳100 TW) performing LWFA R&D in Europe.

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
ELBE [16]	HZDR	Dresden, Ge	30	1	1
GEMINI [17]	STFC, RAL	Didcot, UK	15	0.5	0.05
LLC [18]	Lund Univ	Lund, Se	3	0.1	1
Salle Jaune [19]	LOA	Palaiseau, Fr	2	0.07	1
UHI100 [20]	CEA Saclay	Saclay, Fr	2	0.08	1
CALA* [21]	MPQ	Munchen, Ge	90	3	1
CILEX* [22]	CNRS-CEA	St Aubin, Fr	10-150	1-10	0.01
ELIbeamlines* [23]	ELI	Prague, TR	30	1	10
ILIL* [24]	CNR-INO	Pisa, It	3	0.1	1
SCAPA* [25]	U Strathclyde	Glasgow, UK	8	0.3	5
ANGUS	DESY	Hamburg, Ge	5	0.2	5

Table 2.3: Laser facilities (≳ 100 TW) performing LWFA R&D in Asia

Facility	Institute	Location	Energy (J)	Peak power (PW)	Rep. rate (Hz)
CLAPA	PKU	Beijing, PRC	5	0.2	5
CoReLS [28]	IBS	Gwangju, Kr	20-100	1-4	0.1
J-Karen-P* [29]	KPSI	Kizugawa, Jn	30	1	0.1
LLP [30]	Jiao Tong Univ	Shanghai, PRC	5	0.2	10
SILEX*	LFRC	Myanyang, PRC	150	5	1
SULF* [31]	SIOM	Shanghai, PRC	300	10	1
UPHILL [32]	TIFR	Mumbai, In	2.5	0.1	
XG-III	LFRC	Myanyang, PRC	20	0.7	

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

Facility	Institute	Location	Gain media	Energy (J)	Peak power (PW)	Rep. rate (Hz)
BELLA [7]	LBNL	Berkeley, CA	Ti:sapphire	42	1.4	1
Texas PW [8]	U. Texas	Austin, TX	Nd:glass	182	1.1	single-shot
Diocles [9]	U. Nebraska	Lincoln, NE	Ti:sapphire	30	1	0.1
Hercules [10]	U. Michigan	Ann Arbor, MI	Ti:sapphire	9	0.3	0.1
Jupiter [11]	LLNL	Livermore, CA	Nd:glass	150	0.2	single-shot

Beam-Driven Plasma Acceleration Facilities

ALEGRO
Advanced LinEar collider study GROup

Table 3.1: Overview of PWFA facilities

	AWAKE	CLEAR	FACET-II	FF>>	SparcLAB	EuPR@Sparc	CLARA	MAX IV
operation start	2016	2017	2019	2018	2017	2022	2020	tbd
current status	running	running	construction	commissioning	PWFA, LWFA commissioning	CDR ready??	construction	design
unique contribution	protons	rapid access and operation cycle	high energy peak-current electrons, positrons	MHz rep rate 100kW average power 1 fs resolution bunch diagn. FEL gain tests	PWFA with COMB beam, LWFA external injection, test FEL	PWFA with COMB beam, X-band Linac LWFA ext. inj. test FEL	ultrashort e^- bunches	low emittance, short pulse, high-density e^- beam
research topic	HEP	instrumentation irradiation AA technology	high intensity e^-, e^+ beam driven exp.	high average power e^- beam driven exp.	PWFA LWFA FEL	PWFA, LWFA, FEL, other applications	FEL	PWFA, Soft X-FELs
user facility	no	yes	yes	no	no	yes	partially	no
drive beam	p^+	e^-	e^-	e^-	e^-	e^-	e^-	e^-
driver energy	400 GeV	200 MeV	10 GeV	0.4−1.5 GeV	150 MeV	600 MeV	240 MeV	3 GeV
ext. inject.	yes	no	no/yes	yes??	no	no	no	no
witness energy	20 MeV	na	tb ugraded	0.4−1.5 GeV	150 MeV	600 MeV	na	3 GeV
plasma	Rb vapour	Ar, He capillary	Li oven	H, N, noble gases	H, capillary	H, capillary	He, capillary	H, gases
density [cm^{-3}]	1-10E14	1E16-1E18	1E15-1E18	1E15-1E18	1E16-1E18	1E16-1E18	1E16-1E18	1E15-1E18
length	10 m	5-20 cm	10-100 cm	1-30 cm	3 cm	> 30 cm	10-30 cm	10-50cm
plasma tapering	yes	na	yes	yes	yes	yes		yes
acc. gradient	1 GeV/m average	na	10+ GeV/m peak	10+ GeV/m peak	>1 GeV/m??	>1 GeV/m??	na	10+ GeV/m peak
exp. E gain	1+ GeV	na	≈10 GeV	≈1.5 GeV	40 MeV ??	> 500 MeV	na	3 GeV

FACET, SLAC, US – Electrons as Driver

Premier R&D facility for PWFA: Only facility capable of e^+ acceleration

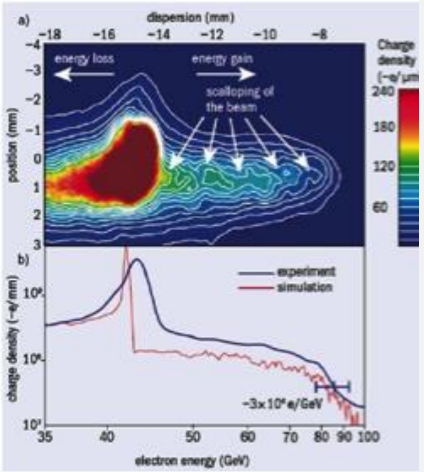
- **Timeline:**
  - Commissioning (2011)
  - Experimental program (2012-2016)
- **Key PWFA Milestones:**
  - ✓ Mono-energetic e^- acceleration
  - ✓ High efficiency e^- acceleration
  - ✓ First high-gradient e^+ PWFA
  - ✓ Demonstrate required emittance, energy spread

- Facility hosted more than 200 users, 25 experiments
- One high profile result a year
- Priorities balanced between focused plasma wakefield acceleration research and diverse user programs with ultra-high fields
- Unique opportunity to develop future leaders

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

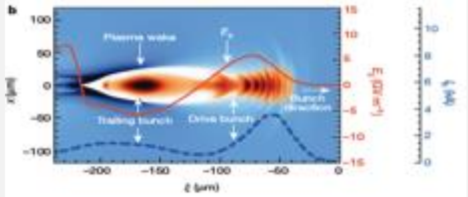
*I. Blumenfeld et al, Nature 455, p 741 (**2007**)*

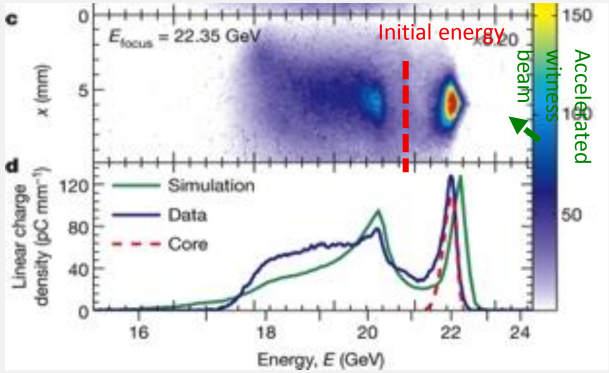
→ **gradient of 52 GV/m**



High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

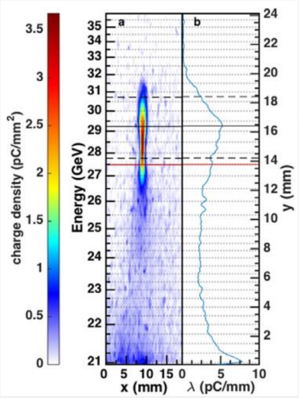
*M. Litos et al., doi, Nature, 6 Nov **2014**, 10.1038/nature 13882*





70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient ➔ **Up to 30% transfer efficiency, ~2% energy spread**

9 GeV energy gain in a beam-driven plasma wakefield accelerator
*M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017*



Positron Acceleration, FACET

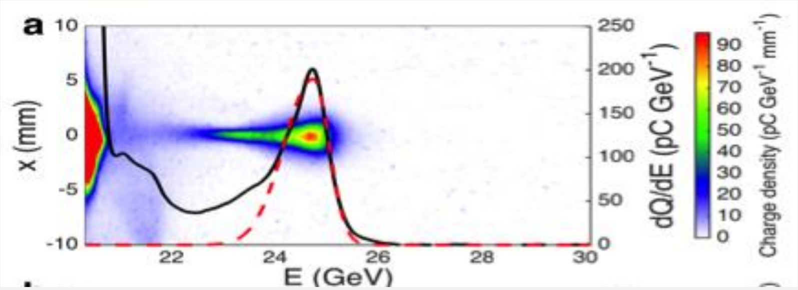
Positrons for high energy linear colliders: **high energy, high charge, low emittance**.

First demonstration of positron acceleration in plasma (FFTB)

*B.E. Blue et al., Phys. Rev. Lett. 90, 214801 (**2003**)*
M. J. Hogan et. al. Phys. Rev. Lett. 90 205002 (2003).

Energy gain of 5 GeV. Energy spread can be as low as 1.8% (r.m.s.).

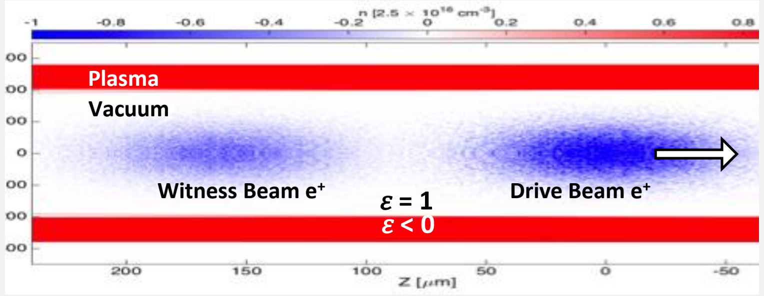
*S. Corde et al., Nature **524**, 442 (2015)*



High-density, compressed positron beam for non-linear PWFA experiments. Energy transfer from the front to the back part of the bunch.

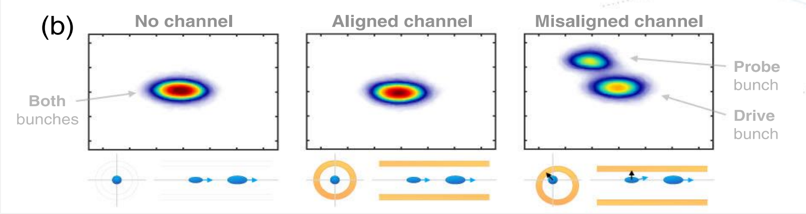
Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.
S. Gessner et. al. Nat. Comm. 7, 11785 (2016)



Measurement of **transverse wakefields in a hollow plasma** channel due to off-axis drive bunch propagation.

*C. A. Lindstrøm et. al. Phys. Rev. Lett. 120 124802 (**2018**).*



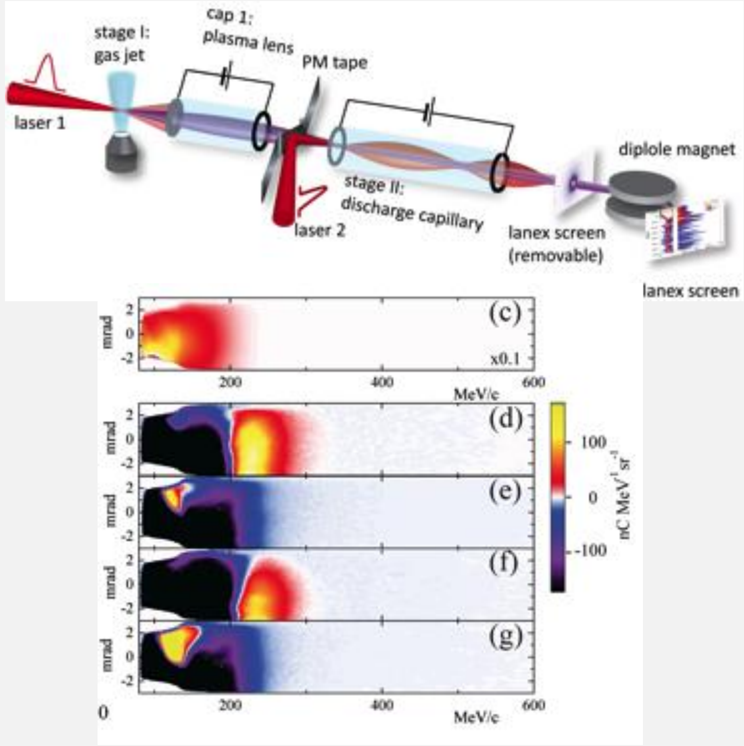
➔ **Emittance blow-up is an issue!** → Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma → but then strong transverse wakefields when beams are misaligned.

BELLA, Berkeley Lab, US– Laser as Driver

Laser Driven Plasma Wakefield Acceleration Facility: Today: PW laser!

Multistage coupling of independent laser-plasma accelerators

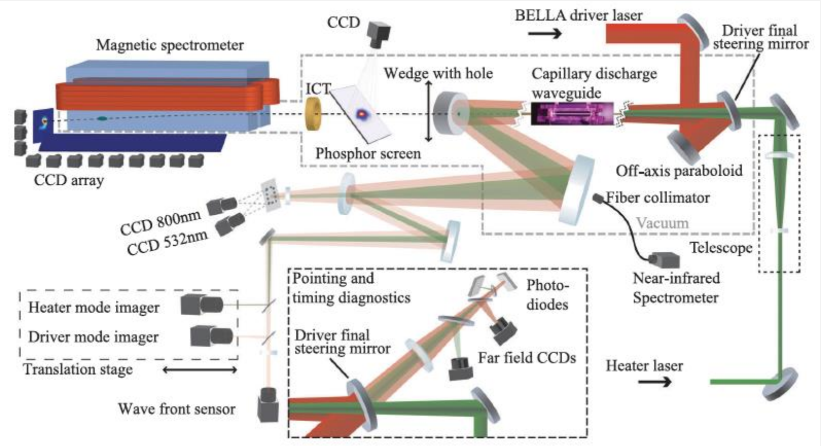
*S. Steinke, Nature **530**, 190 (2016)*



Staging demonstrated at 100MeVs level.

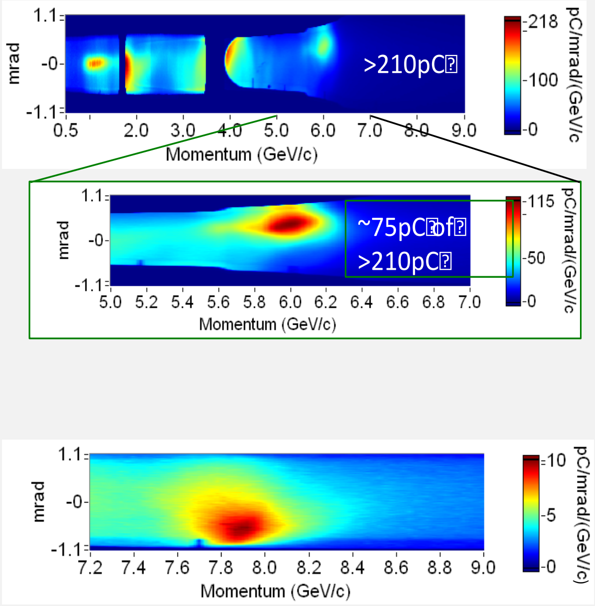
Petawatt laser guiding and electron beam **acceleration to 8 GeV** in a laser-heated capillary discharge waveguide

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



Laser heater added to capillary

Electron spectra, up to 6-8 GeV



→ path to 10 GeV with continued improvement of guiding in progress

What about a proton beam as a driver?

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

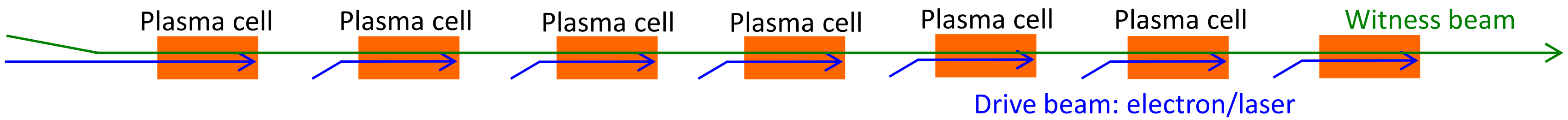
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

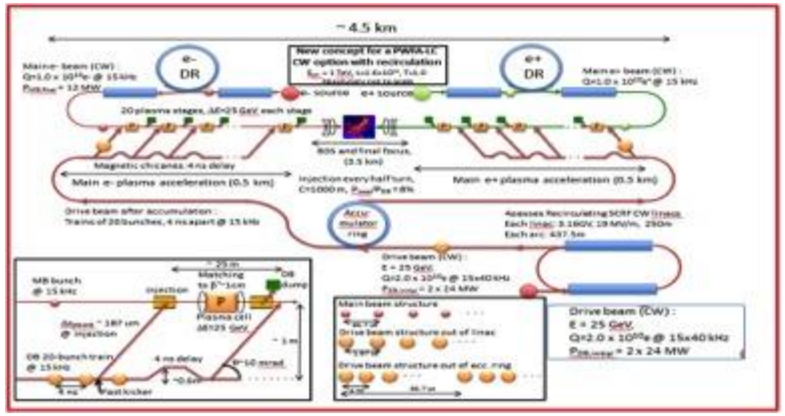
Witness beams:

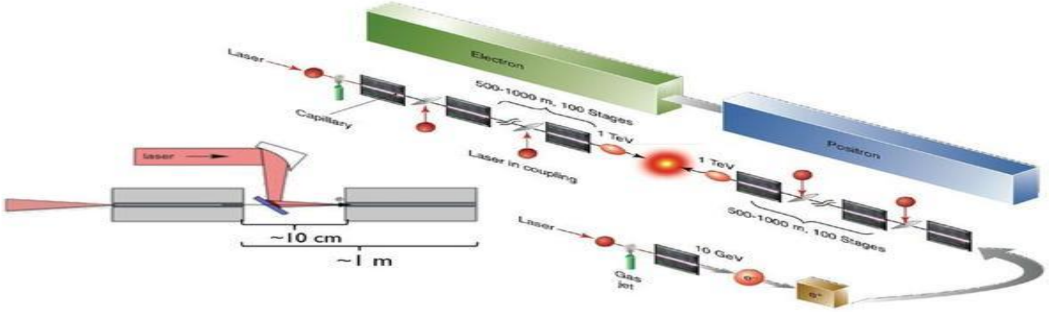
Electrons: 10^{10} particles @ 1 TeV ~few kJ

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….







E. Adli *et. al.*,arXiv:1308.1145 [physics.acc-ph]

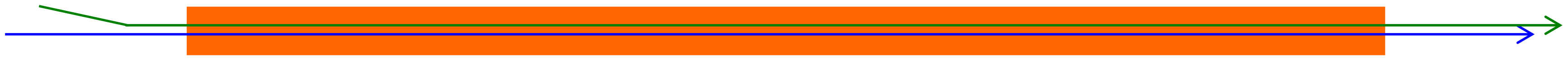
C. B. Schroeder *et. al*. Phys. Rev. ST Accel. Beams **13**, 101301

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

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

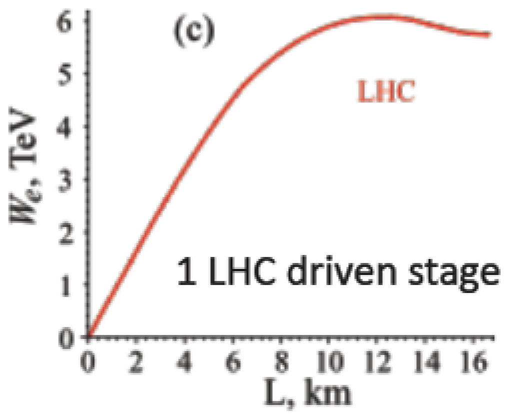
- **Proton drivers**: large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.



Dephasing:

SPS: ~70 m
LHC: ~few km

FCC: ~ ∞

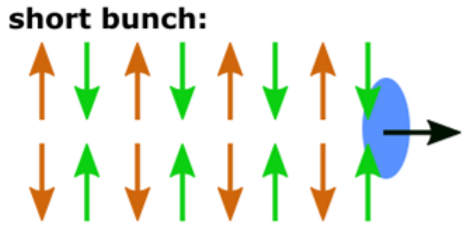


Seeded Self-Modulation of the Proton Beam

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

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

N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)



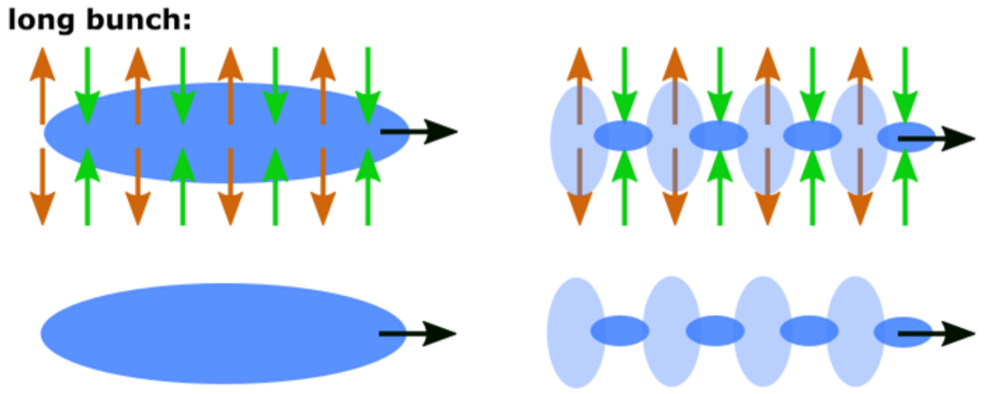
Self-Modulation:

a) Bunch drives wakefields at the initial seed value when entering plasma.

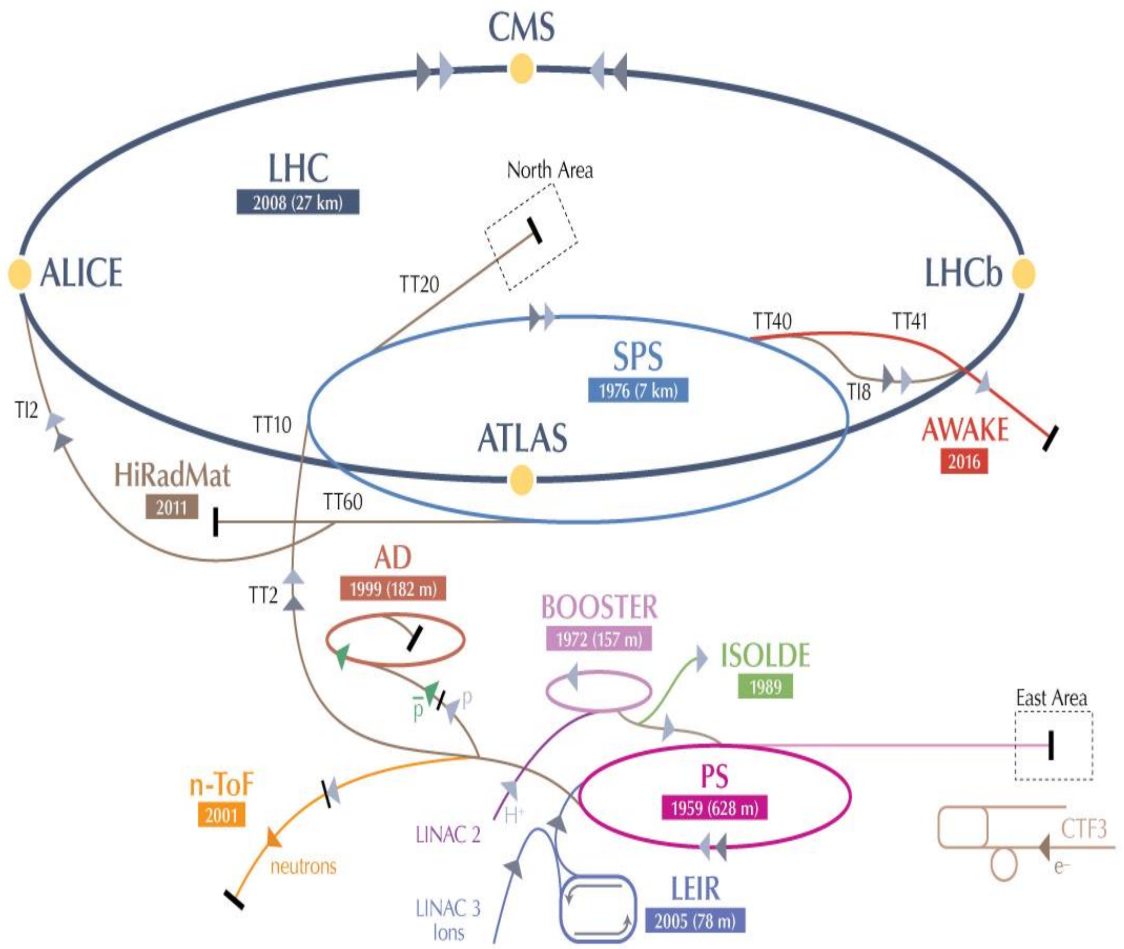
- **Initial wakefields act back** on the proton bunch itself. → On-axis density is modulated. → Contribution to the wakefields is $\propto n_b$.

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

- Micro-bunches separated by plasma wavelength λ_{pe}.
- drive wakefields resonantly.



AWAKE at CERN



Advanced WAKEfield Experiment

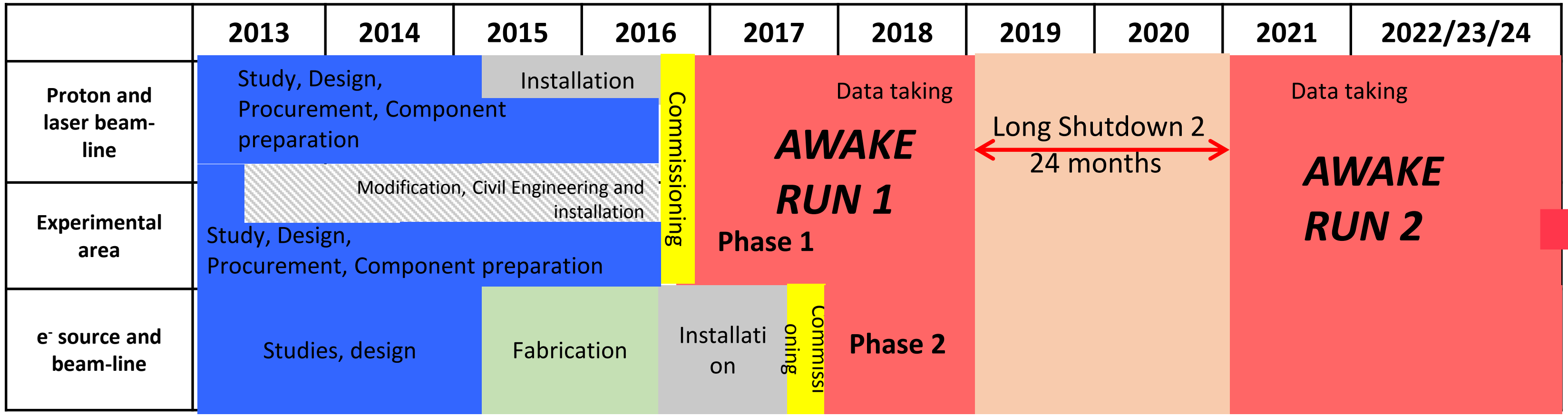
- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First proton beam sent to plasma end 2016
- First electron acceleration in 2018

AWAKE

AWAKE Collaboration: 22 institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitéario de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland

AWAKE Timeline

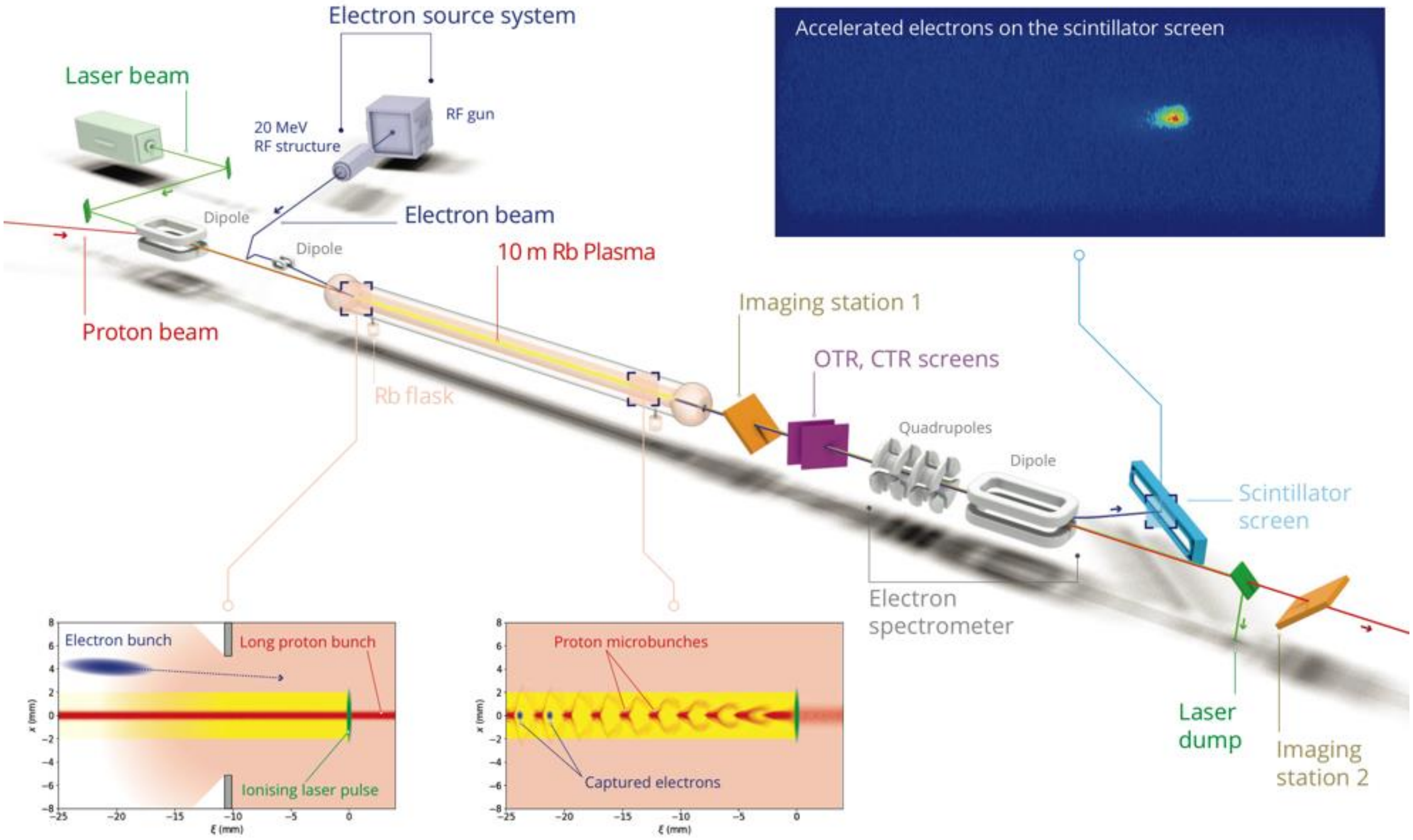


AWAKE++: After Run 2:
kick-off particle physics driven applications

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

AWAKE Run 2: proposed for after LS2:
achieve high-charge bunches of electrons accelerated to **high energy, about 10 GeV,** while maintaining **beam quality** through the plasma and showing that the process is **scalable**.

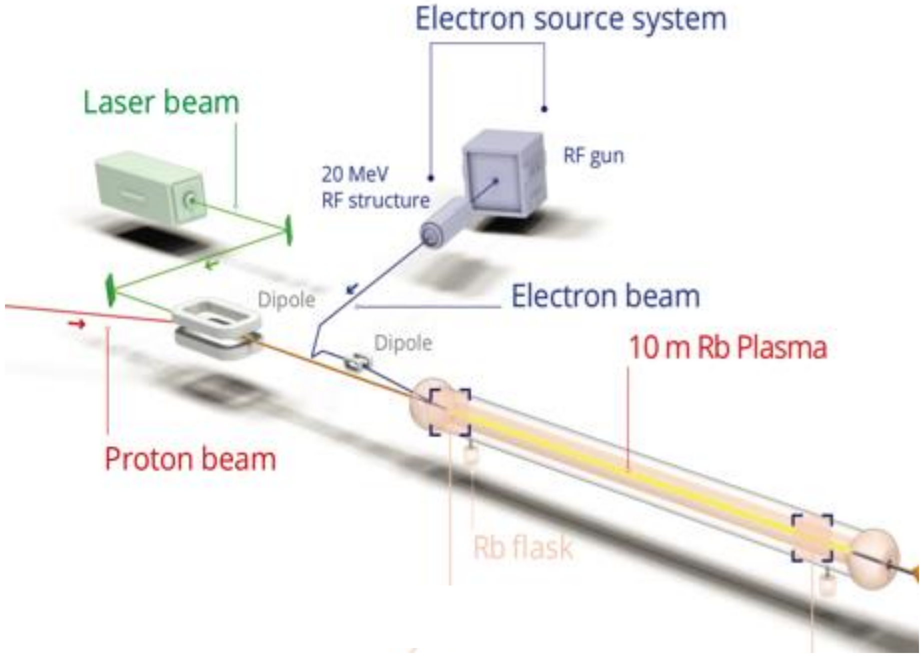
AWAKE Experiment

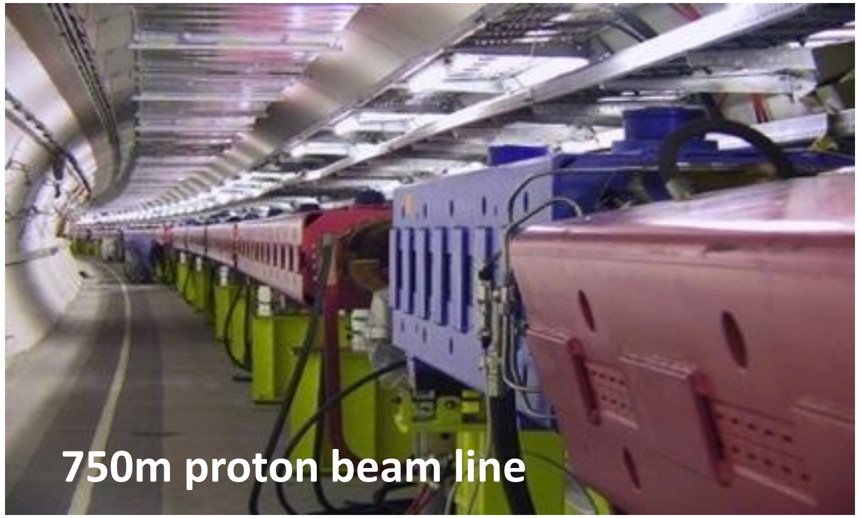


AWAKE Proton Beam Line

Parameter	Protons
Momentum [MeV/c]	400 000
Momentum spread [%]	±0.035
Particles per bunch	$3 \cdot 10^{11}$
Charge per bunch [nC]	48
Bunch length [mm]	120 (0.4 ns)
Norm. emittance [mm·mrad]	3.5
Repetition rate [Hz]	0.033
1σ spot size at focal point [μm]	200 ±20
β-function at focal point [m]	5
Dispersion at focal point [m]	0

Plasma linear theory: $k_{pe}\, \sigma_r \leq 1$
With $\boldsymbol{\sigma_r}$ **= 200 µm**
$k_{pe} = \omega_{pe}/c = 5\ mm^{-1}$
➔ **$n_{pe} = 7 \times 10^{14}\ cm^{-3}$**

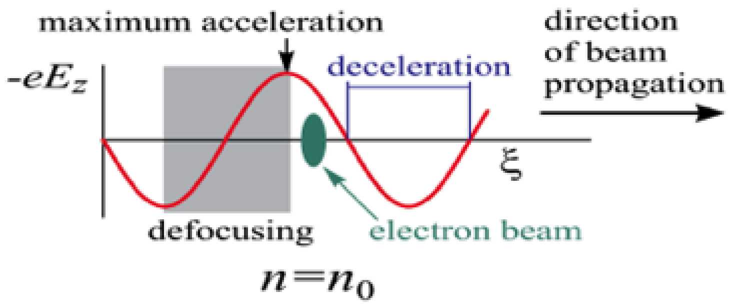


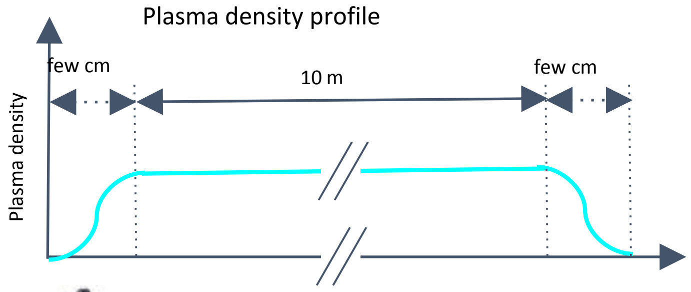


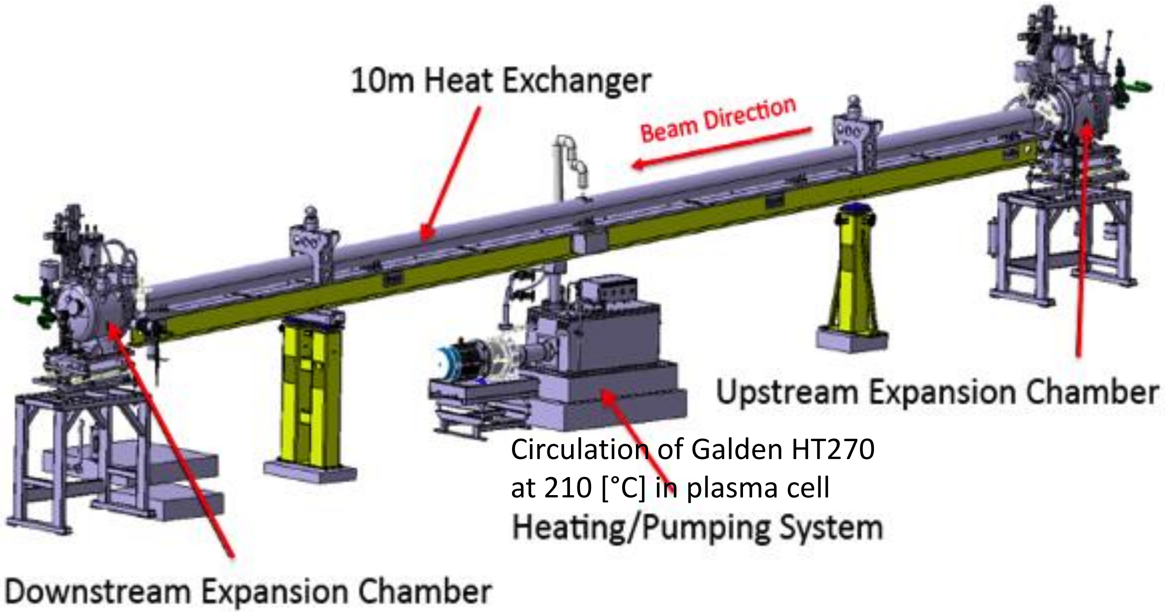
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment. The proton beam must be steered around a mirror which **couples a terawatt class laser** into the beamline.
Further downstream, the **witness electron beam** will injected into the same beamline.

AWAKE Plasma Cell

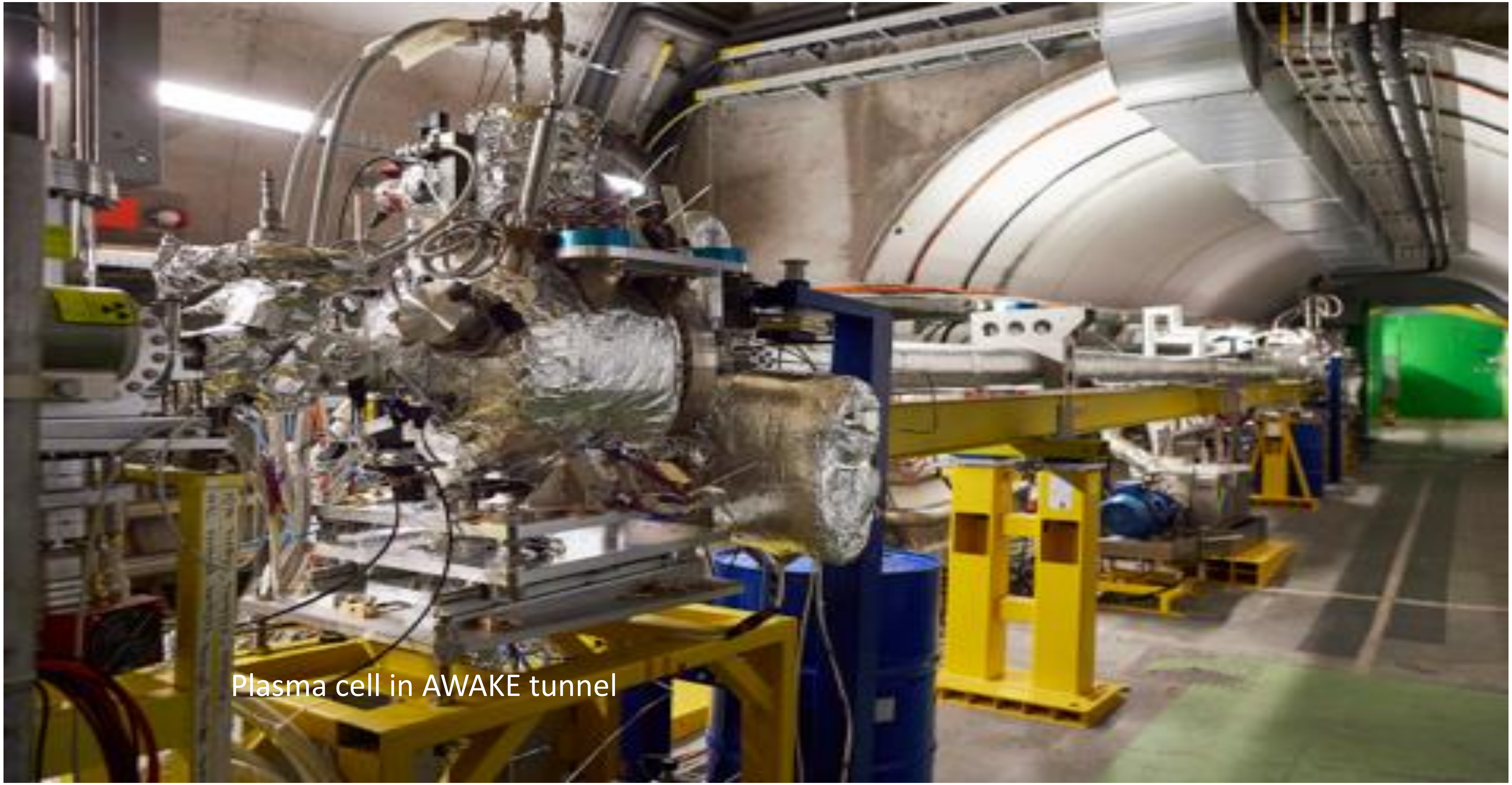
- **10 m long**, 4 cm diameter
- Rubidium vapor, field ionization threshold ~10^{12} W/cm^2
- Density adjustable from 10^{14} – 10^{15} cm^{-3} ➔ **7x 10^{14} cm^{-3}**
- Requirements:
  - **density uniformity better than 0.2%**
    - Fluid-heated system (~220 deg)
    - Complex control system: 79 Temperature probes, valves
  - **Transition between plasma and vacuum as sharp as possible**







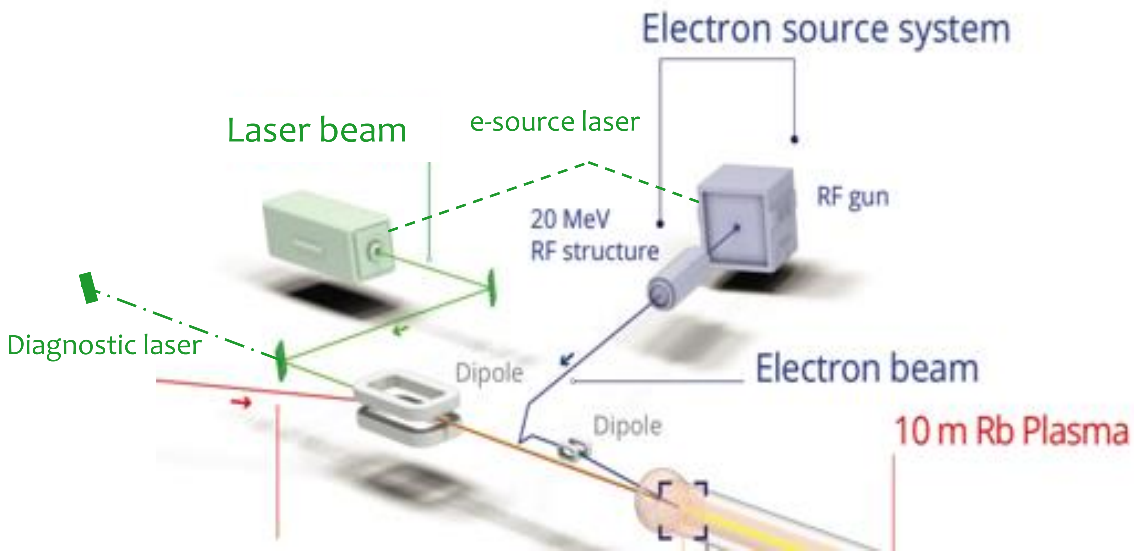
AWAKE Plasma Cell

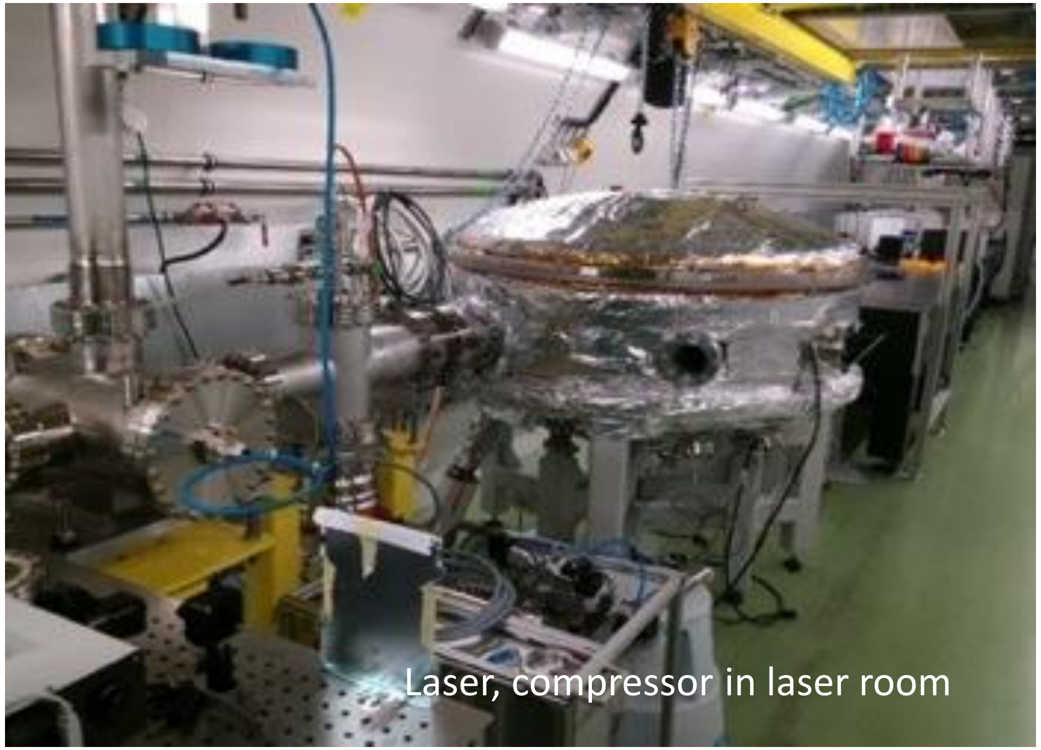


Plasma cell in AWAKE tunnel

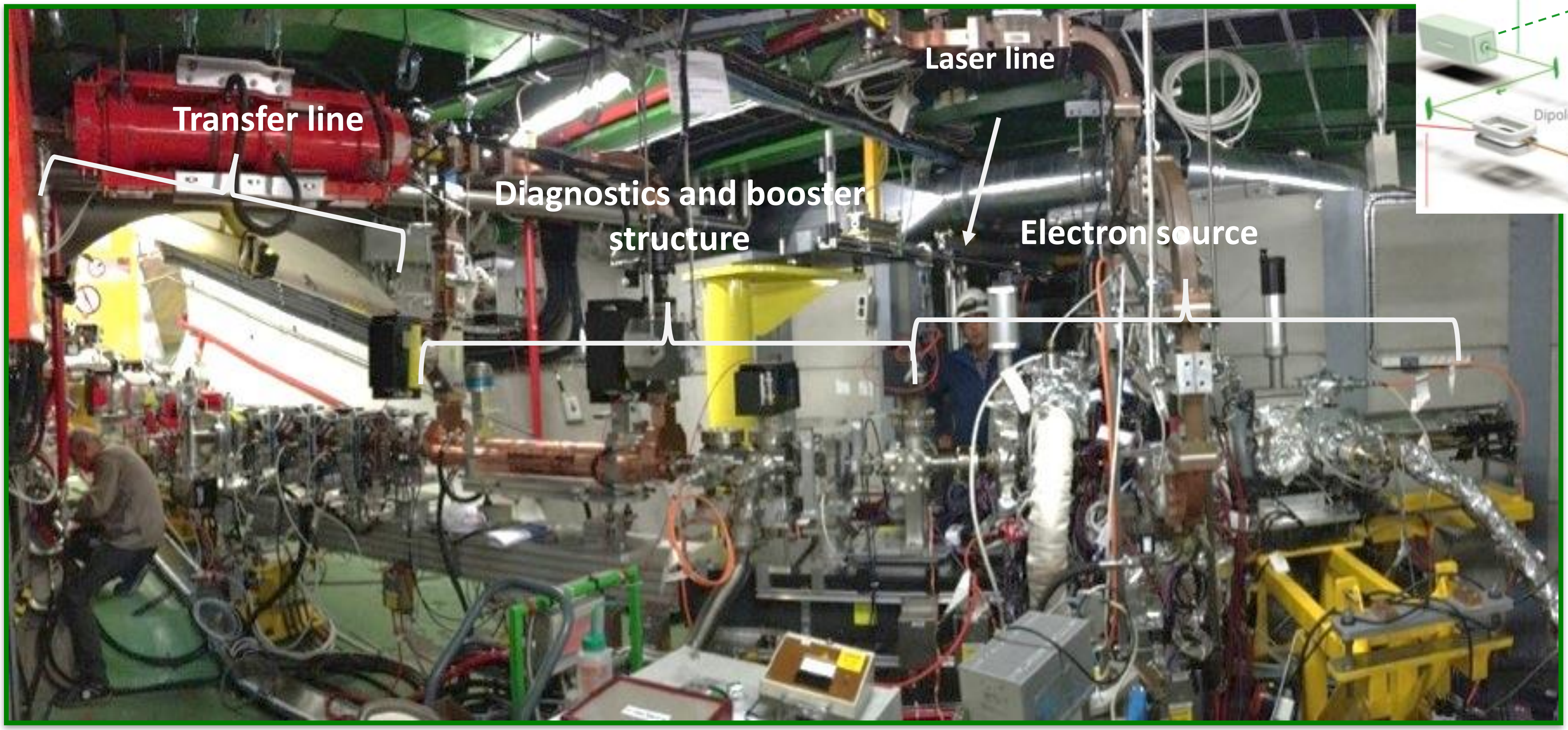
Laser and Laser Line

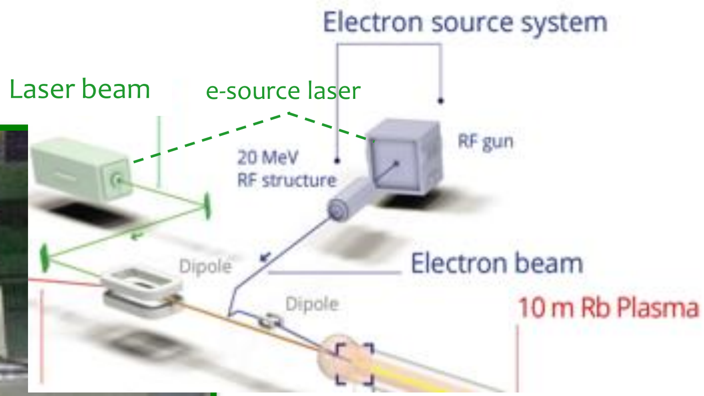
AWAKE uses a short-**pulse Titanium:Sapphire laser** to ionize the rubidium source.
→ Seeding of the self-modulation with the ionization front.
The laser can deliver up **to 500 mJ in a 120 fs pulse envelope**.





Electron Beam System





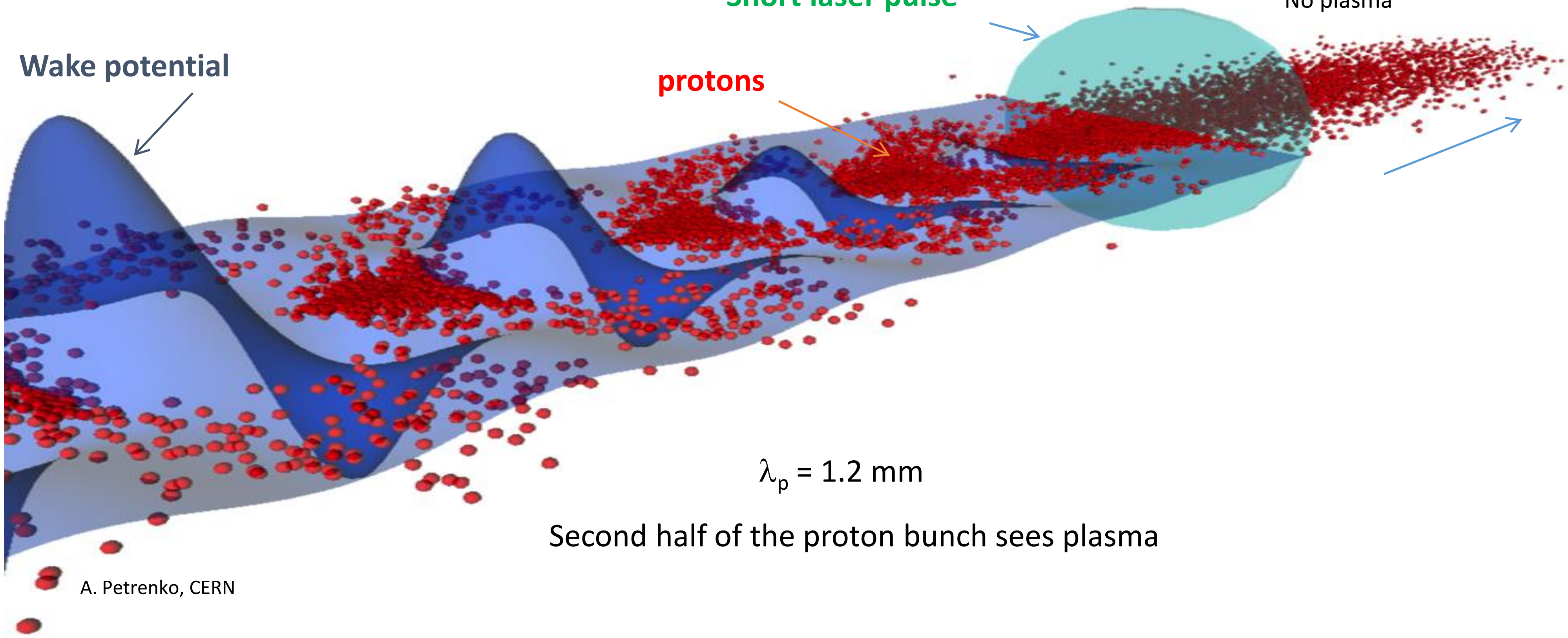
A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**
A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

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

Outline

- Introduction to Plasma Wakefield Acceleration
- AWAKE, The Advanced Wakefield Experiments
- AWAKE Results
- What's Next

Seeded Self-Modulation Results

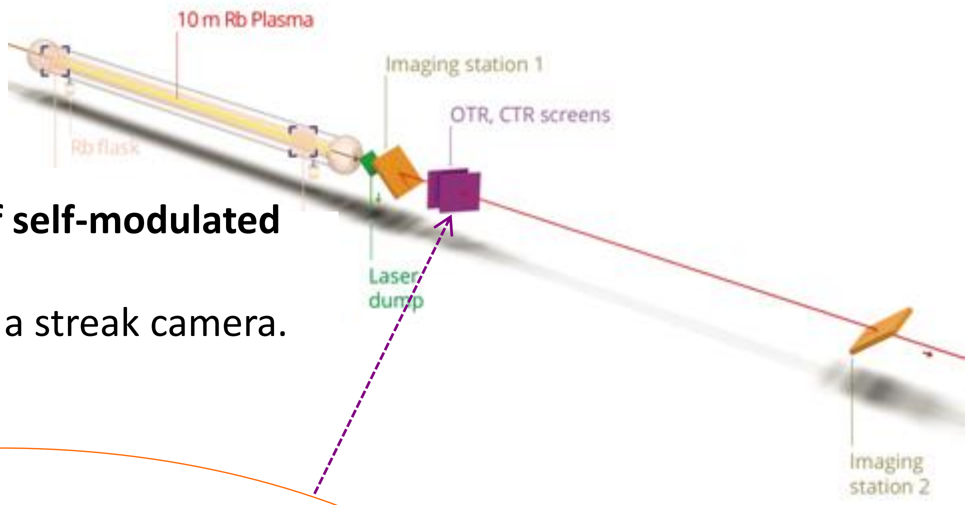


λ_p = 1.2 mm

Second half of the proton bunch sees plasma

A. Petrenko, CERN

Diagnostics for Seeded Self-Modulation



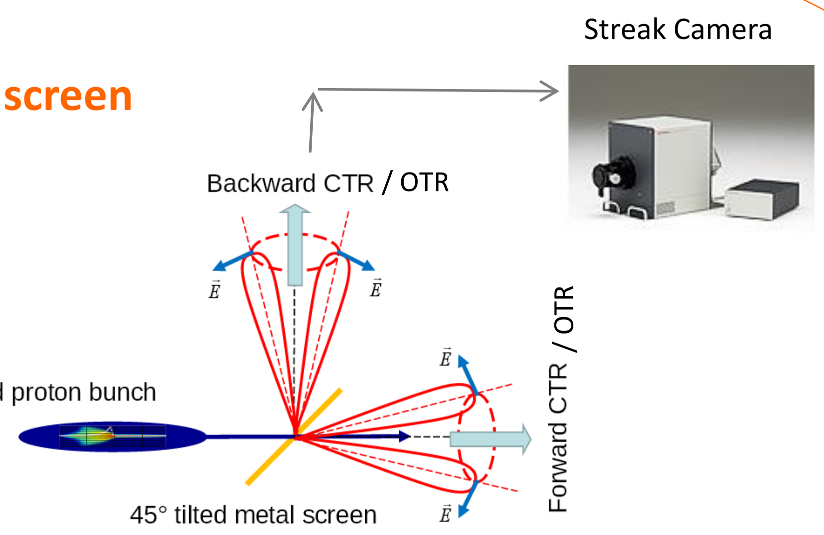
Direct SSM Measurement:

Measure longitudinal structure of self-modulated proton bunch.

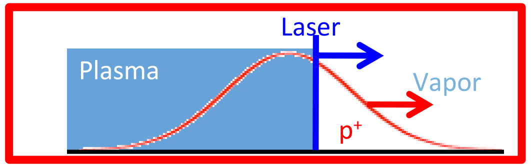
→ Image OTR light onto the slit of a streak camera.

→ Time resolved measurement.

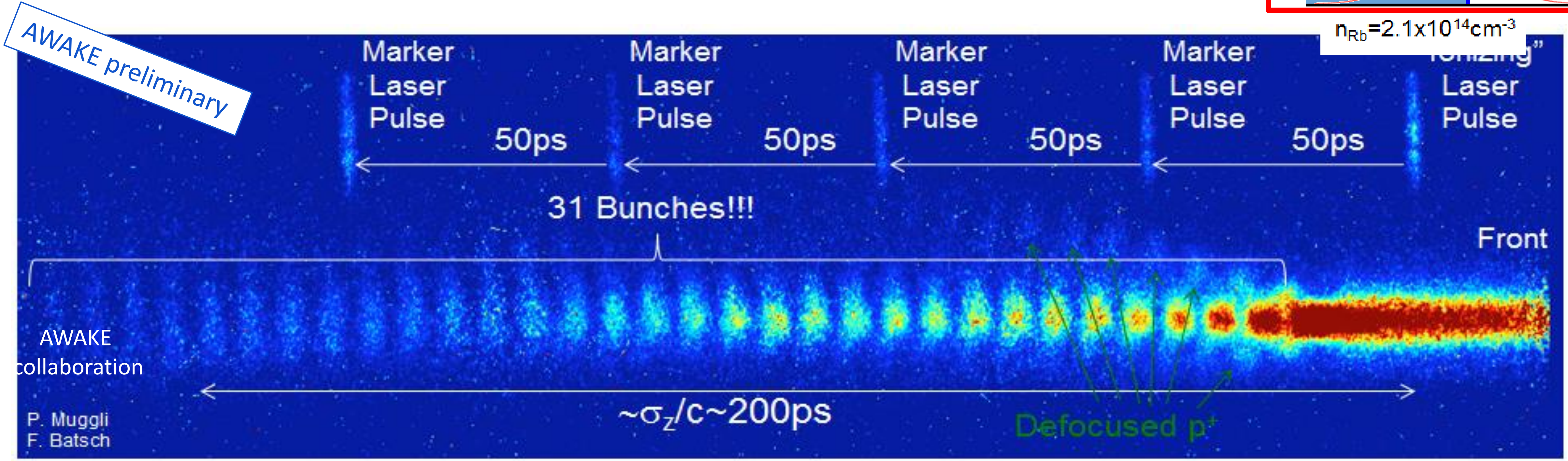
OTR screen



Results: Direct Seeded Self-Modulation Measurement



n_{Rb}=2.1x10^{14}cm^{-3}



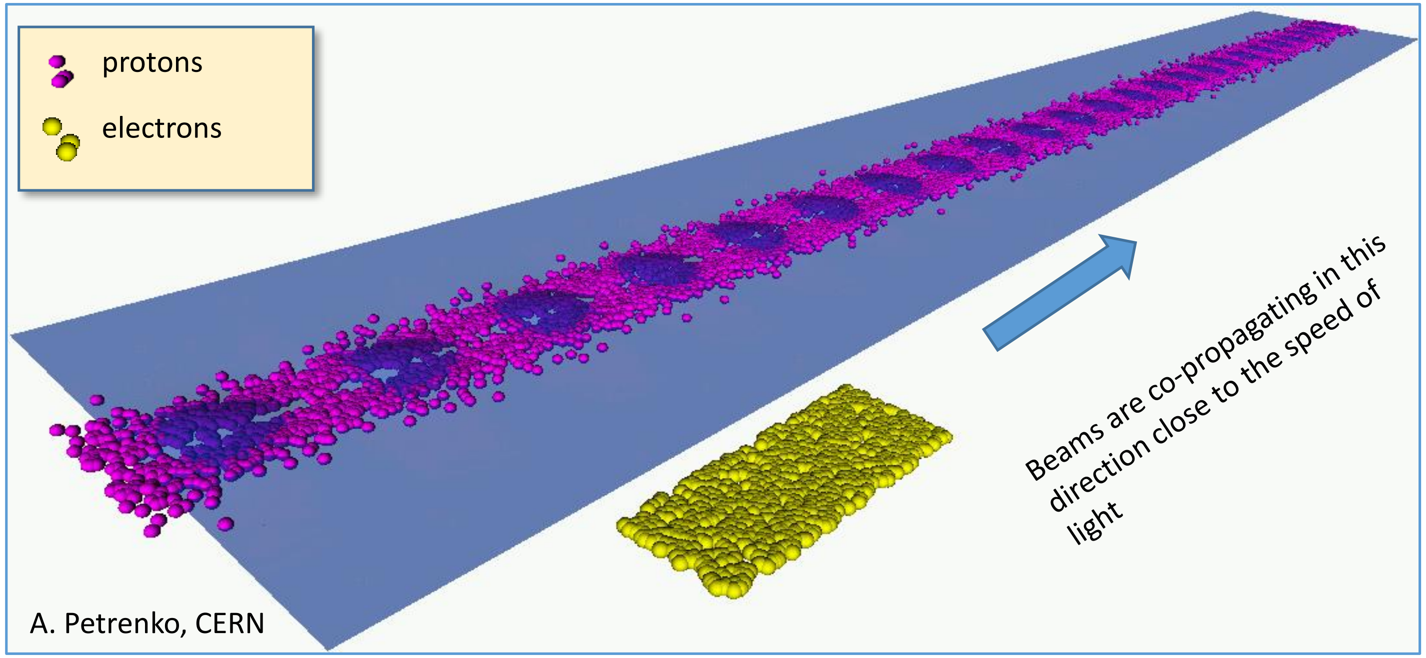
- Effect starts at laser timing → **SM seeding**
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e$^-$ external injection.

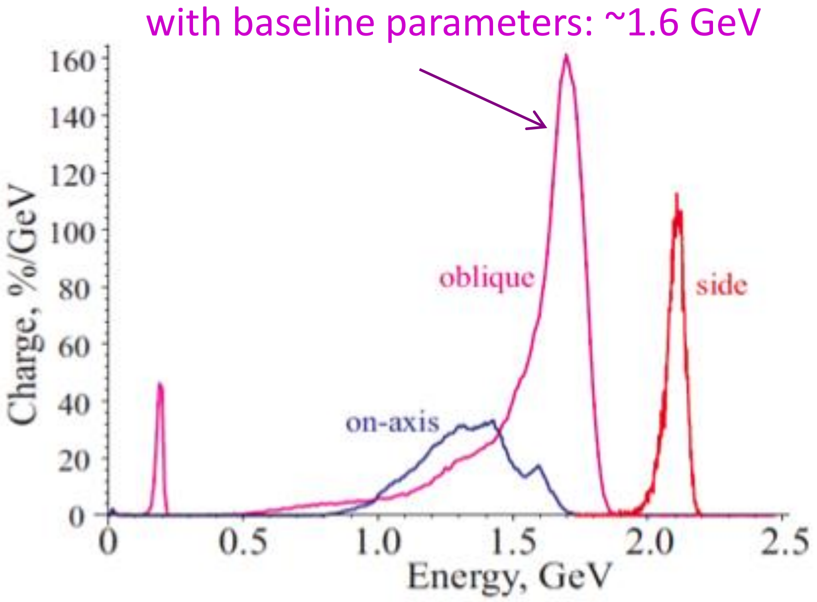
→ **1st AWAKE Milestone reached**

AWAKE Collaboration, 'Experimental observation of proton bunch modulation in a plasma, at varying plasma densities'. **Phys. Rev. Lett. 122, 054802 (2019).**

Electron Acceleration Results 2018

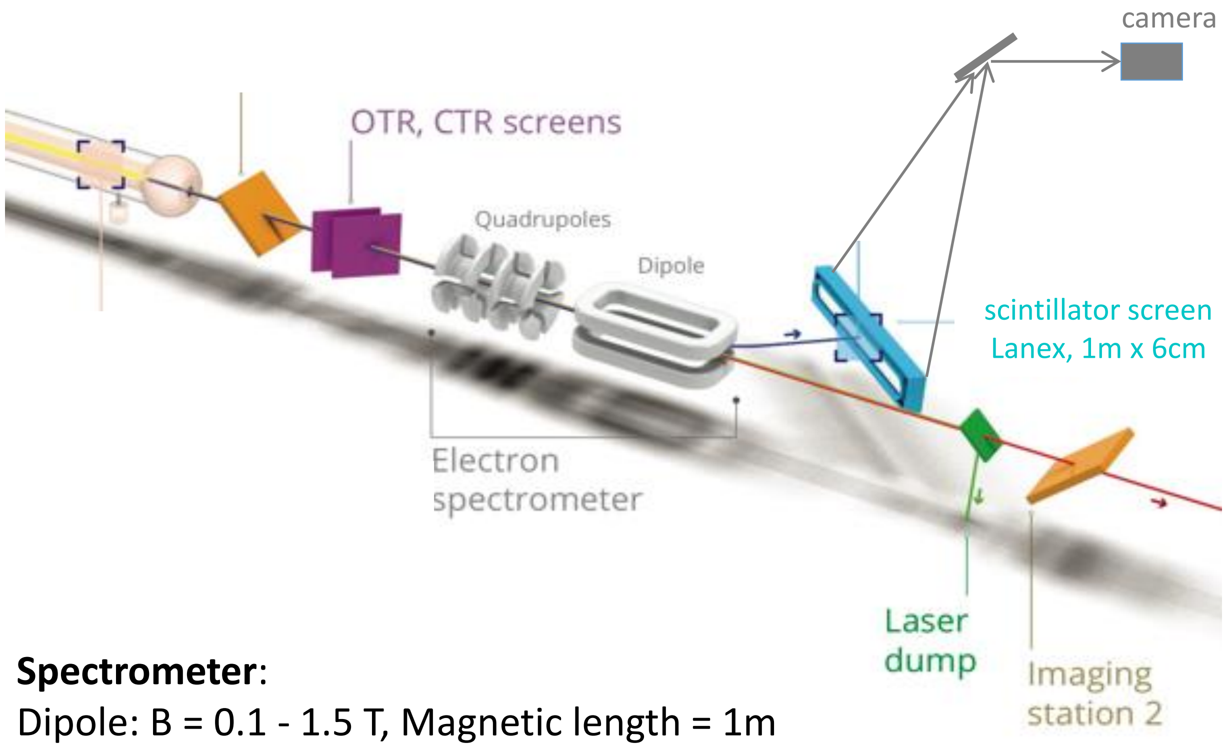
Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:





A. Caldwell et al., AWAKE Coll., Nucl. Instrum. A 829 (2016) 3

Electron Acceleration Diagnostics



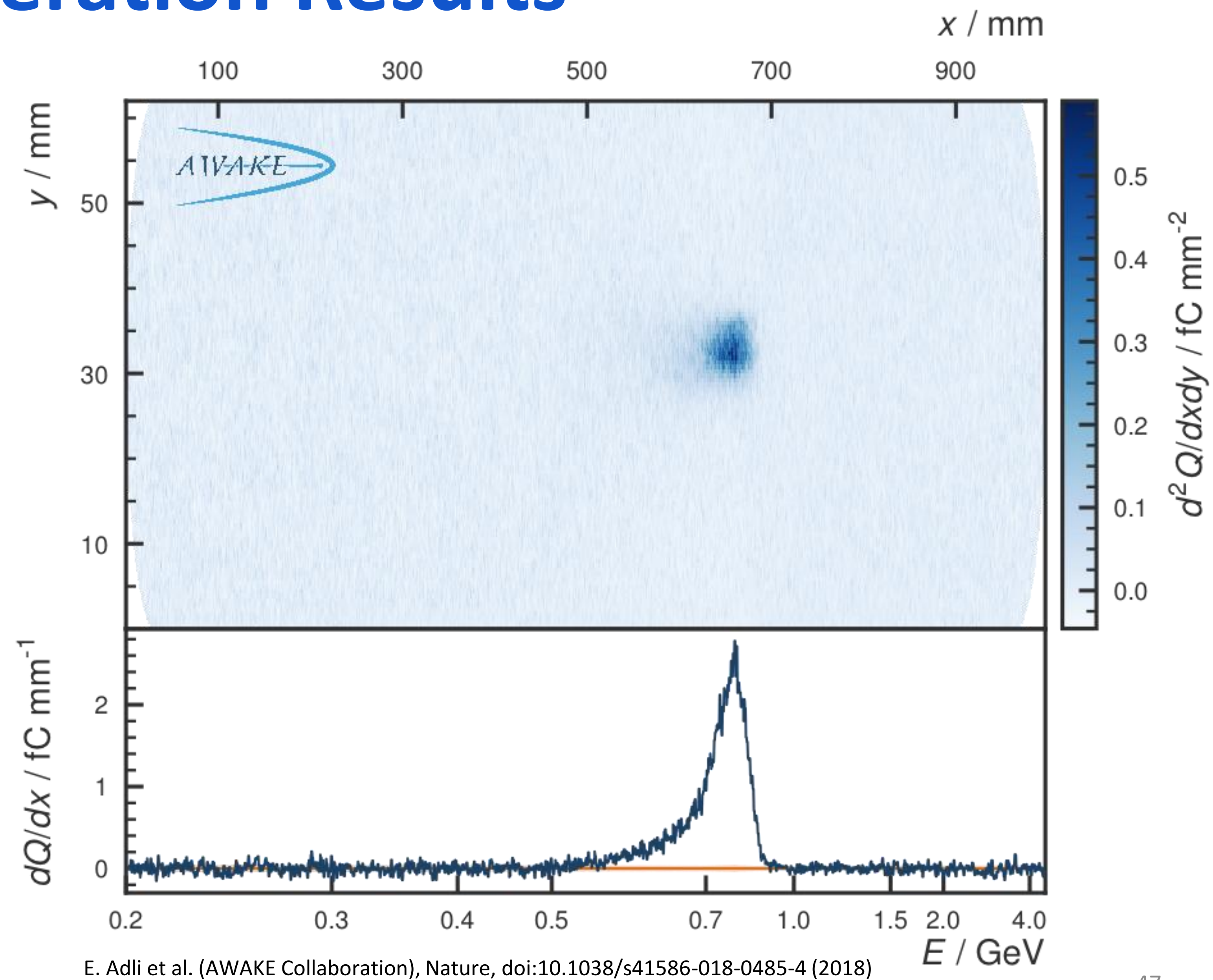
Spectrometer:
Dipole: B = 0.1 - 1.5 T, Magnetic length = 1m
→ detect electrons with energies ranging from 30MeV - 8.5 GeV

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.

Electron Acceleration Results

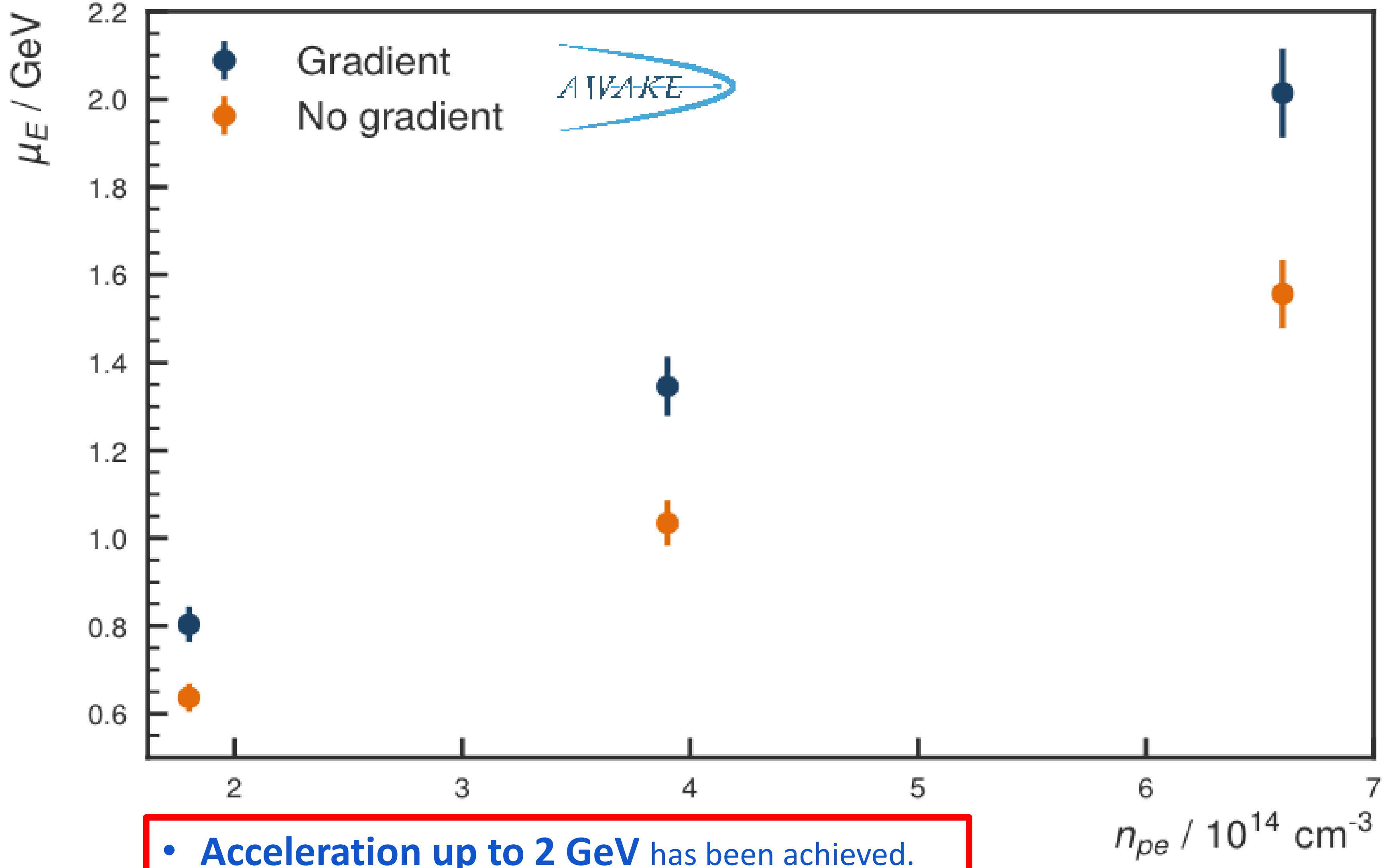
Event **at n_{pe} =1.8 x 10^{14} cm^{-3} with 5%/10m** density gradient.

- Acceleration to **800 MeV**.



E. Adli et al. (AWAKE Collaboration), Nature, doi:10.1038/s41586-018-0485-4 (2018)

Electron Acceleration Results



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

E. Adli et al. (AWAKE Collaboration), Nature, doi:10.1038/s41586-018-0485-4 (2018)

Outline

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AWAKE Run 2

Goal:

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

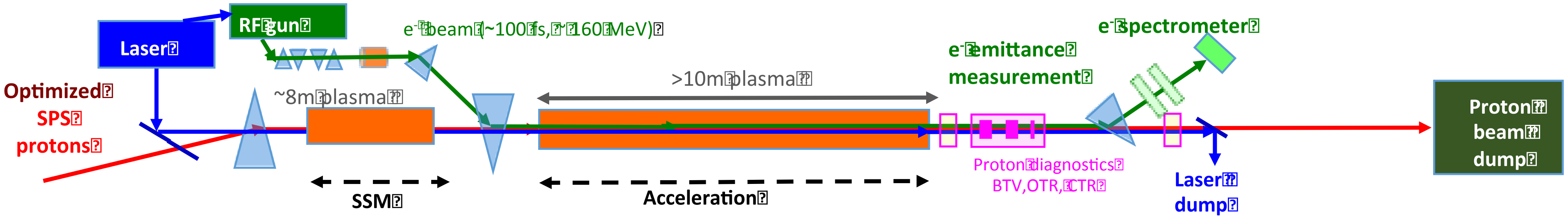
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

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

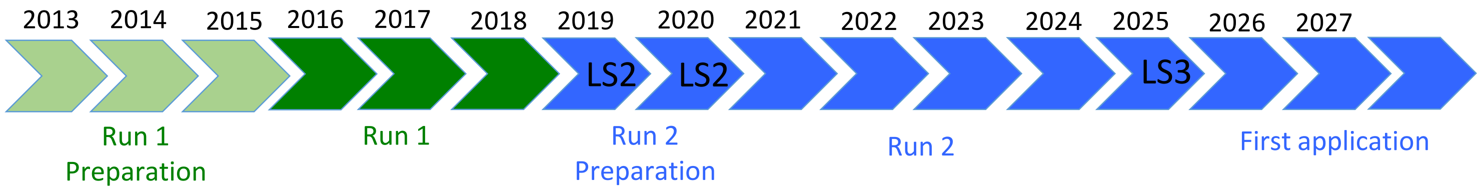
➔ Freeze the modulation with **density step** in first plasma cell

➔ For emittance control: need to work in **blow-out regime** and do **beam-loading**

➔ R&D on different **plasma source technologies**

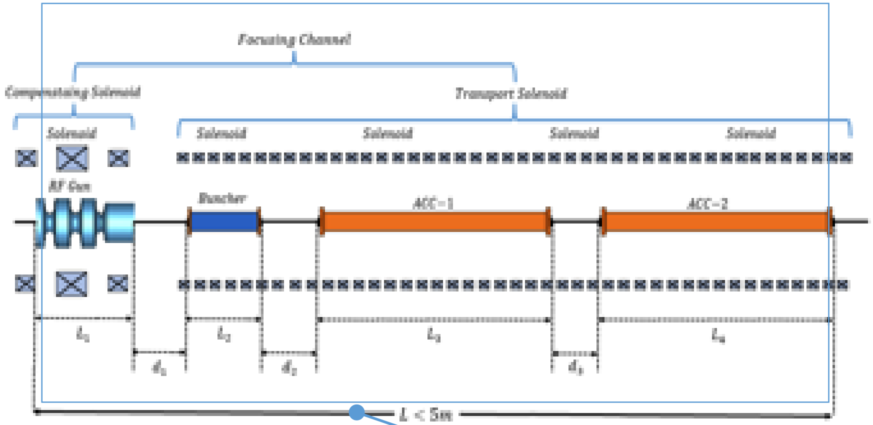


E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

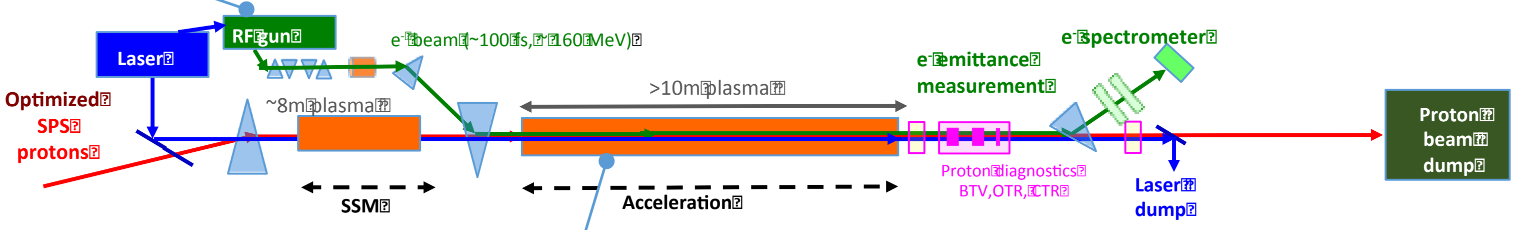


AWAKE Run 2

X-band electron source



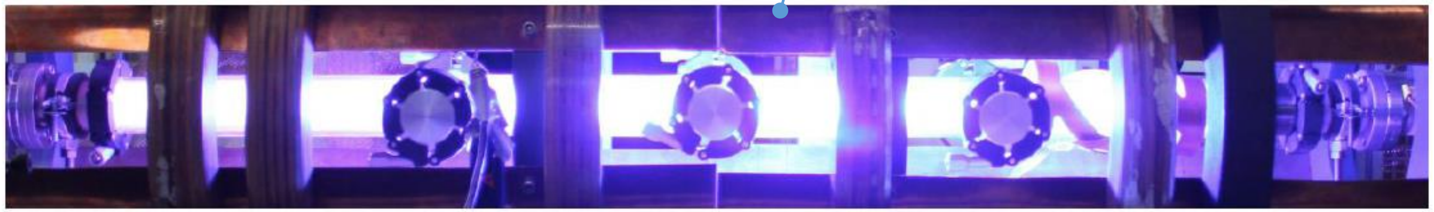
Preliminary Run 2 electron beam parameters	
Parameter	Value
Acc. gradient	>0.5 GV/m
Energy gain	10 GeV
Injection energy	$\gtrsim$ 50 MeV
Bunch length, rms	40–60 μm (120–180 fs)
Peak current	200–400 A
Bunch charge	67–200 pC
Final energy spread, rms	few %
Final emittance	$\lesssim$ 10 μm

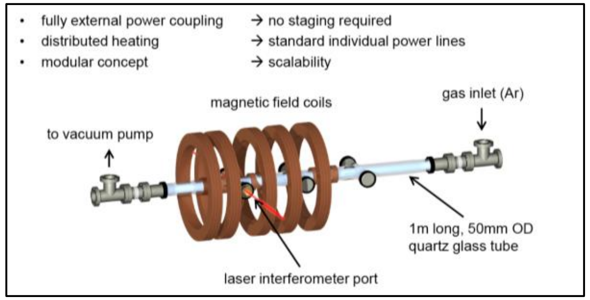


E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)

Accelerating plasma cell

Helicon plasma cell





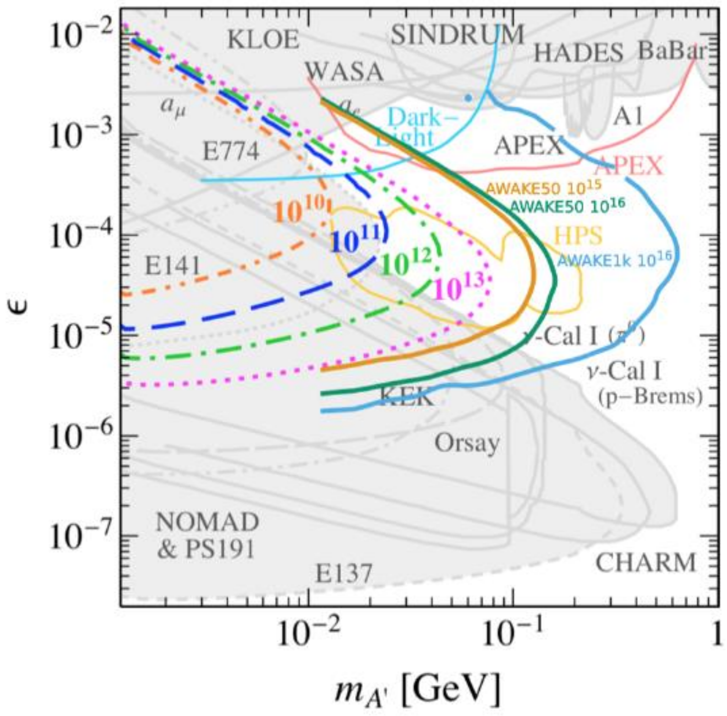
Applications with AWAKE-Like Scheme

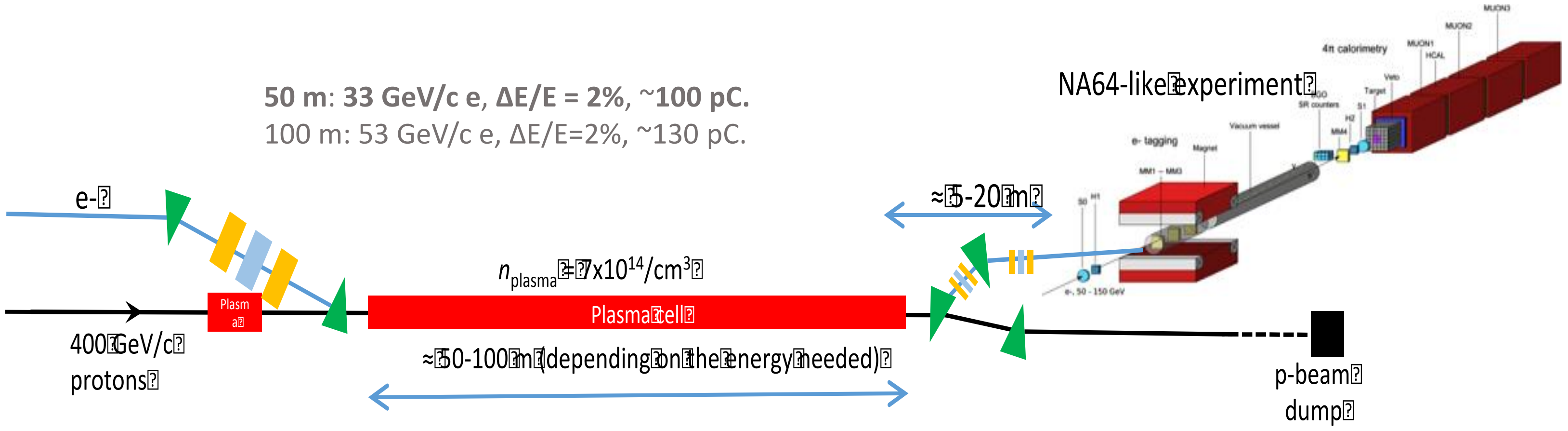
→ **Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!**

First Application:

→ **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV), **3 orders of magnitude increase in electrons** (compared to NA64)

→ deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**



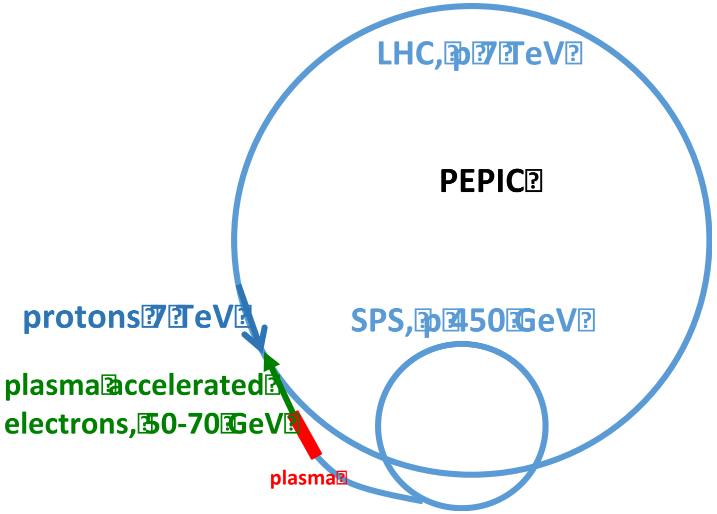


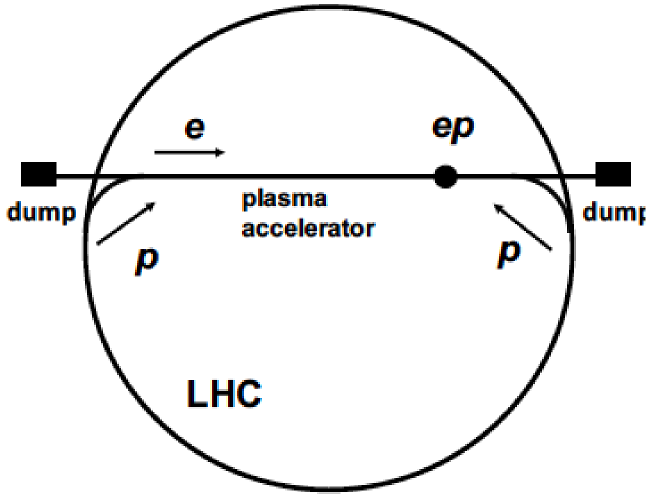
Applications with AWAKE-Like Scheme

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

Using **the SPS or the LHC beam as a driver**, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider

- **PEPIC:** LHeC like collider: E_e up to O (70 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy
- **VHEeP:** choose E_e = 3 TeV as a baseline and with E_P = 7 TeV yields $\sqrt{s}$ = 9 TeV. → CM ~30 higher than HERA. Luminosity ~ 10^{28} – 10^{29} cm^{-2} s^{-1} gives ~ 1 pb^{-1}/yr.





VHEeP: A. Caldwell and M. Wing, Eur. Phys. J. C 76 (2016) 463

Summary and Outlook

→Many encouraging results in the plasma wakefield acceleration technology. Plasma wakefield acceleration is an exciting and growing field with a huge potential.

→AWAKE: Proton-driven plasma wakefield acceleration interesting because of large energy content of driver. Modulation process means existing proton machines can be used.

→AWAKE has for the first time demonstrated proton driven plasma wakefield acceleration of externally injected electrons to GeV levels. Next step is to accelerate high quality, high energy electrons.

Outlook:

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

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

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

Extra Slides

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	$<10^{-1}$
Staging	single, two	multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	improvements by 10^{7}

Outlook

- Short term perspective of PWFA (< 10 years):
  - Compact FEL based: 5 – 10 GeV energy range
  - Compact X-ray sources: electron accelerated in strong transverse field of plasma emit betatron radiation

  ➔applications in medicine, radiobiology, material science

- Long term perspective of PWFA (>20 years):
  - High energy physics applications: Plasma-based high energy linear collider

  ➔ depends strongly on progress in many fields.

The most demanding application of plasma wakefield acceleration is to build a **compact, efficient, Plasma-Based Linear Collider**.