Novel Acceleration Techniques
Plasma Wakefield Acceleration

CERN-Fermilab HCP Summer School
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Edda Gschwendtner, CERN

Outline

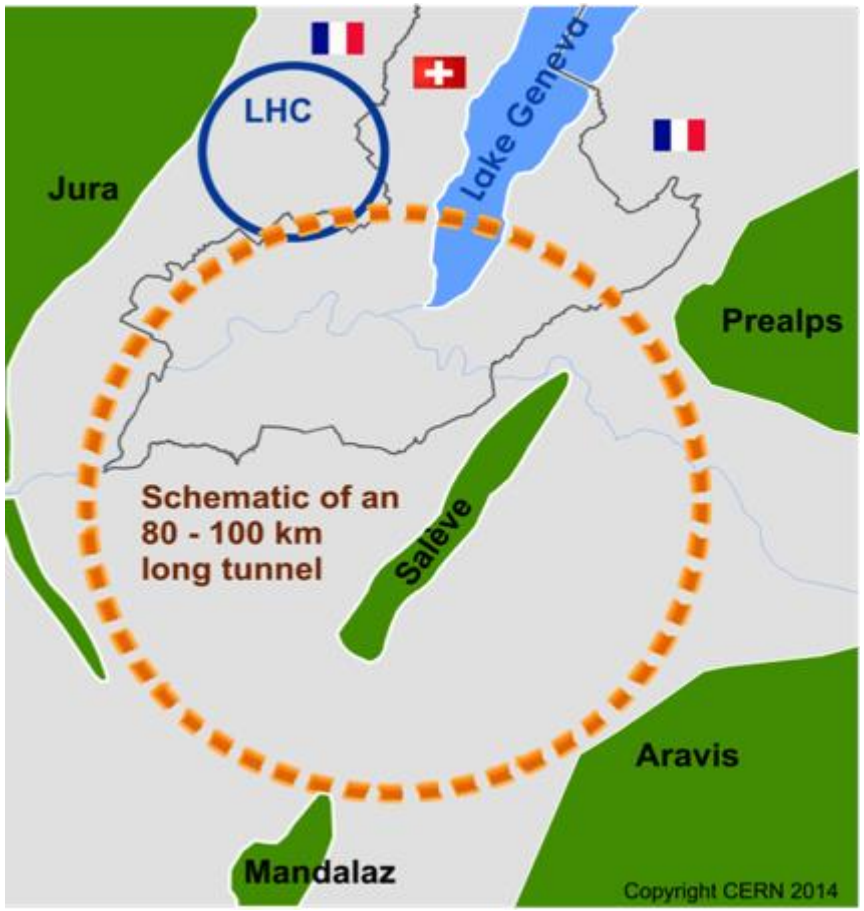
- Motivation
- Introduction to Plasma Wakefield Acceleration
- Key Challenges of Plasma Wakefield Acceleration and Experimental Results

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.

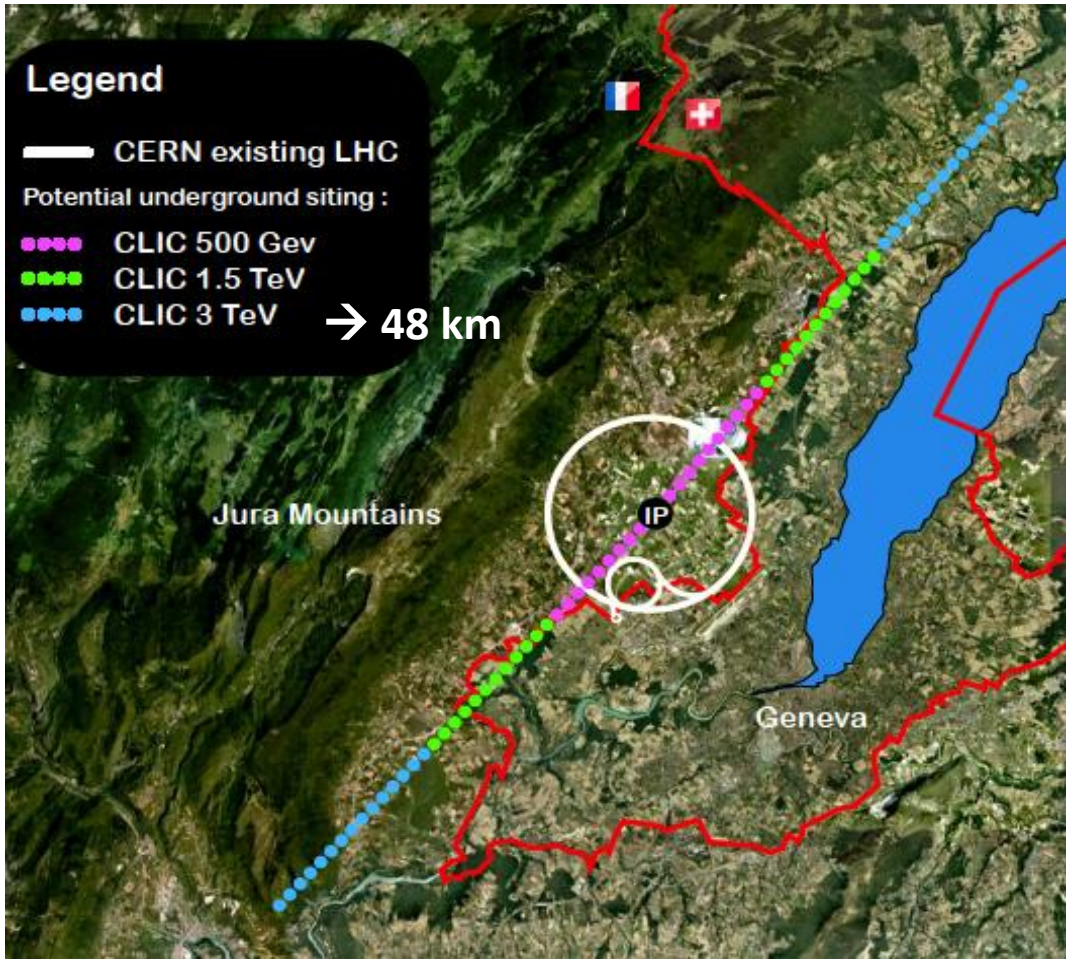
- For **electron-positron colliders**: Circular machines are limited by **synchrotron radiation** in the case of positron colliders. These machines are unfeasible for collision energies beyond **~350 GeV**.

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

Discover New Physics

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

CLIC, electron-positron collider with 3 TeV energy

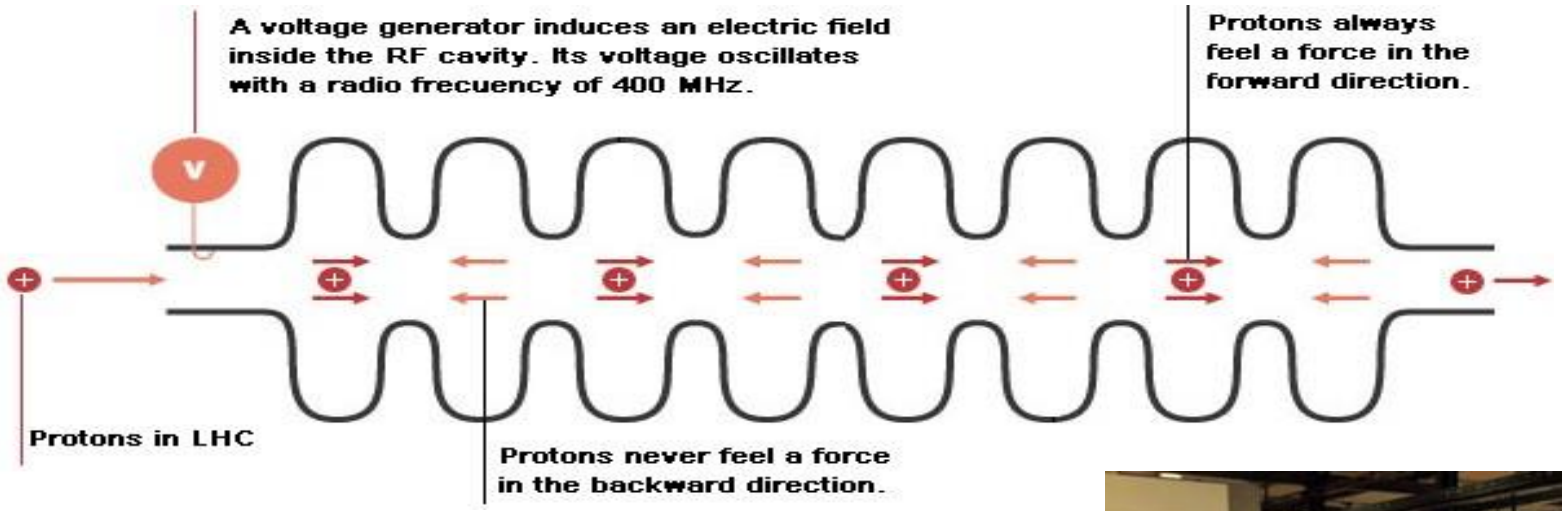


Limitations of linear colliders:

- 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.

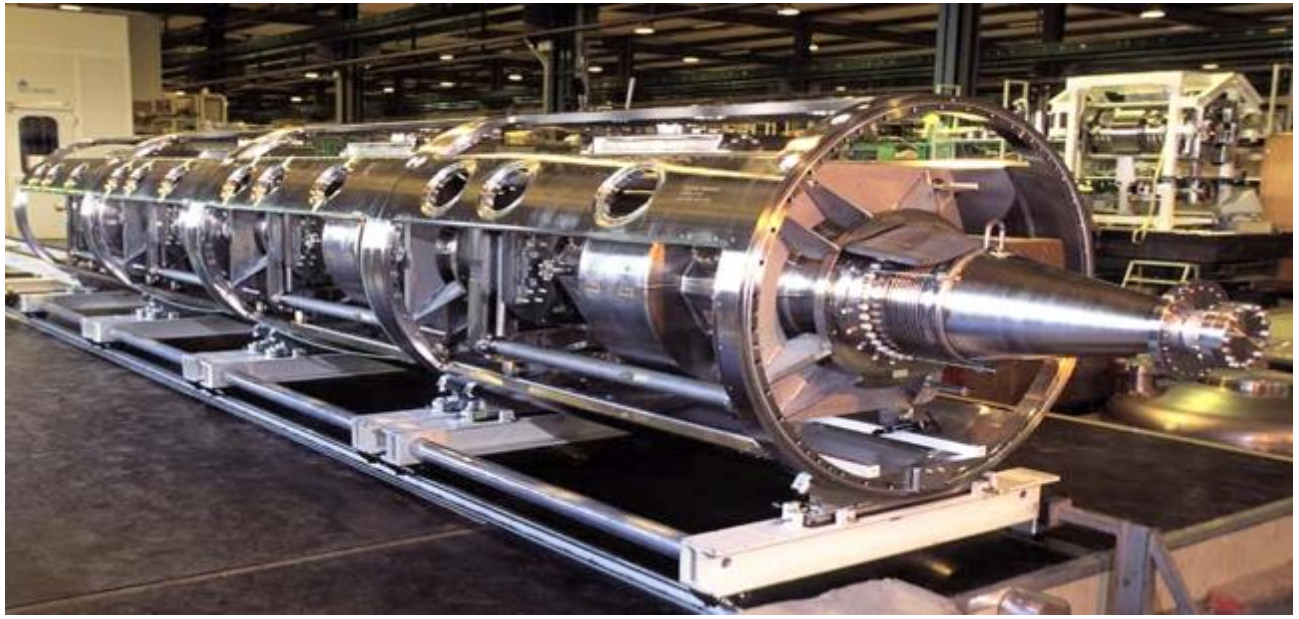
Conventional Acceleration Technology

Radiofrequency Cavities



(invention of Gustav Ising 1924 and Rolf Wideroe 1927)

LHC Cavity

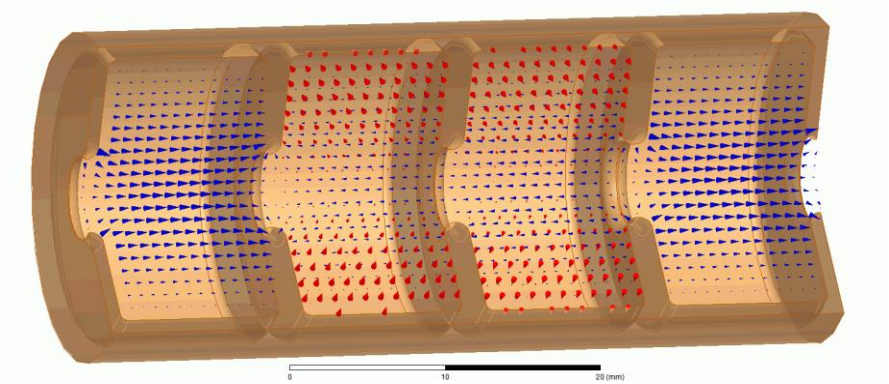


Conventional Accelerating Technology

Today's RF cavities or microwave technology:

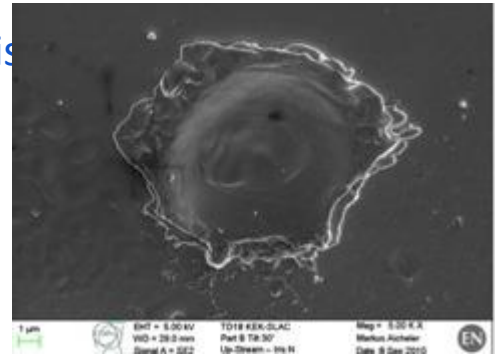
- Very successfully used in all accelerators (hospitals, scientific labs,…) in the last 100 years.

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



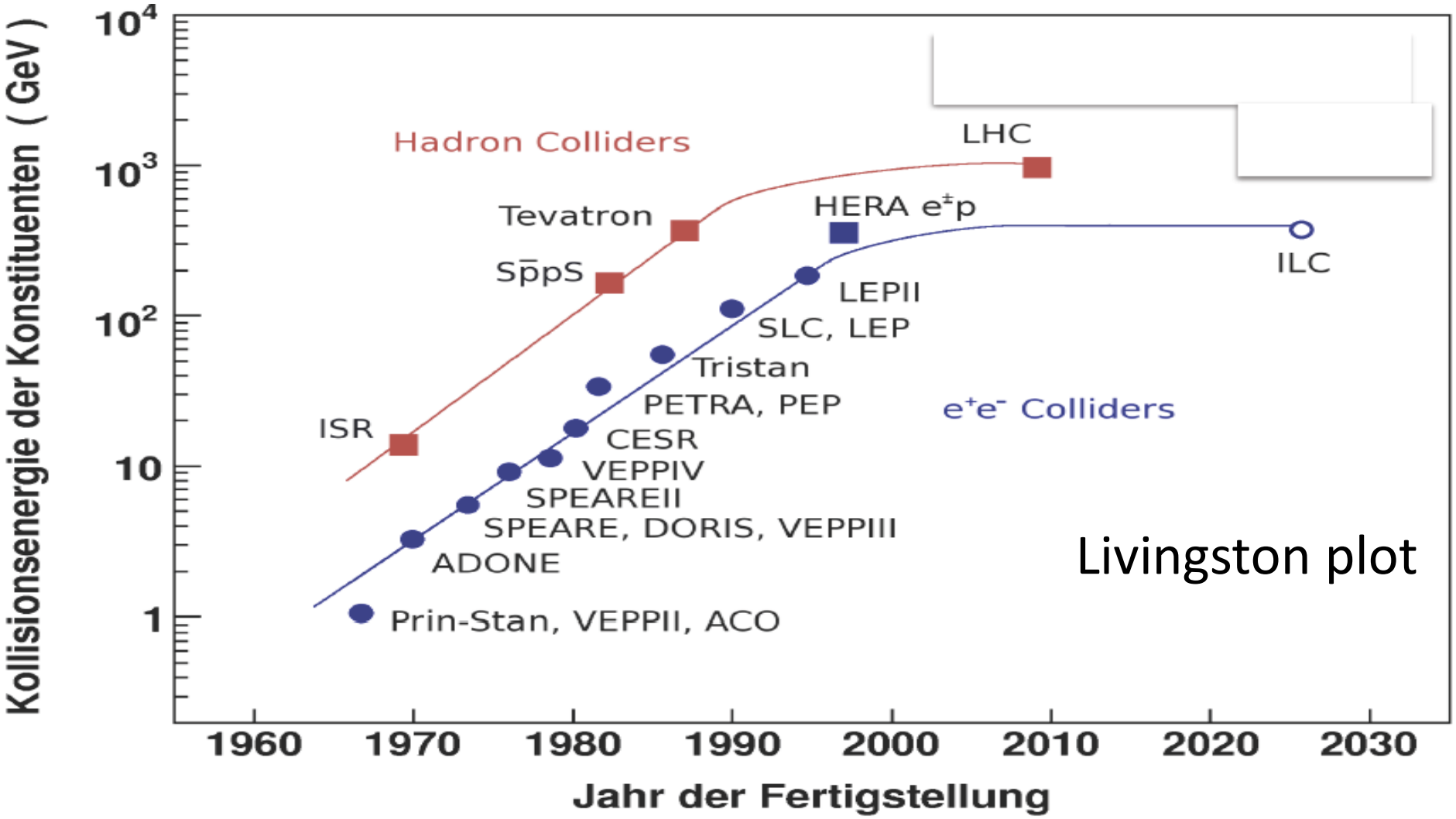
However:

- 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

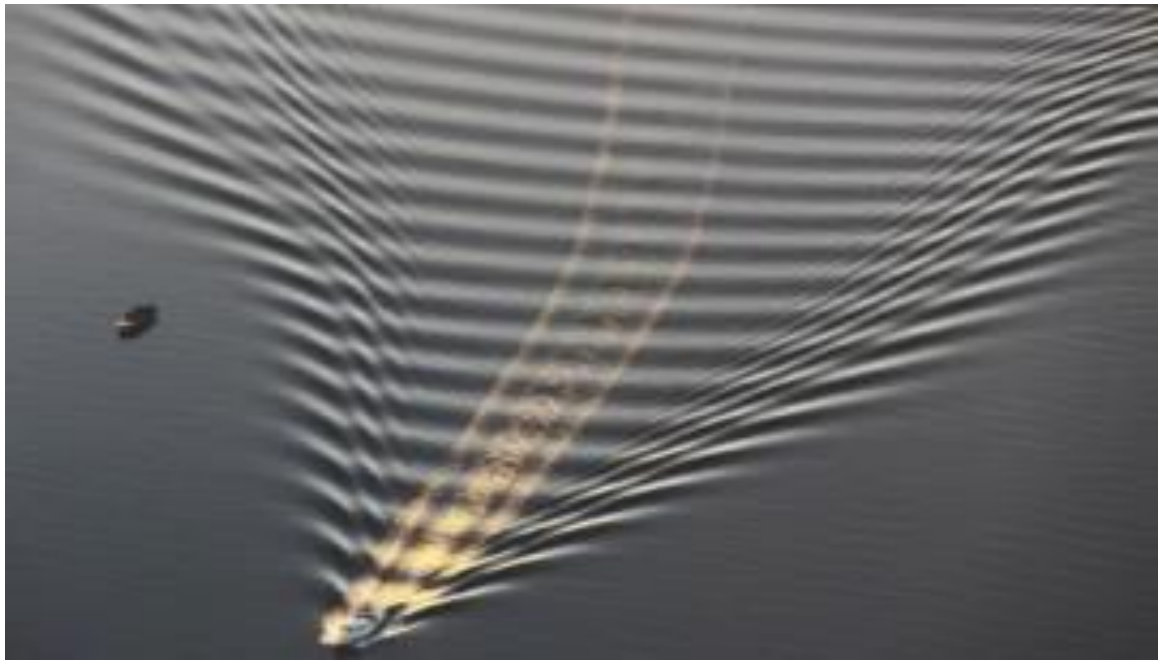


Livingston plot

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

Plasma Wakefield Acceleration

Wakefield excitation



Particle acceleration

Outline

- Motivation
- Introduction to Plasma Wakefield Acceleration
- Key Challenges of Plasma Wakefield Acceleration and Experimental Results

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.

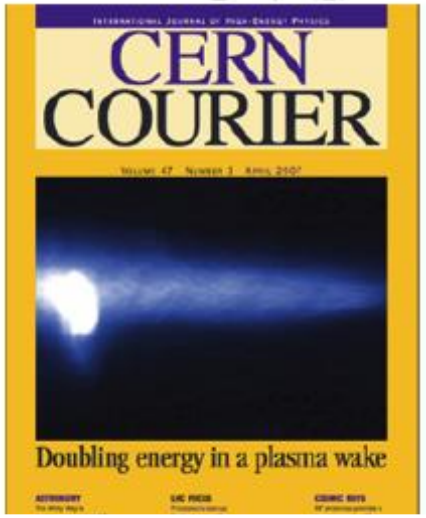
the wavelength of the plasma waves in the wake:

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

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

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

Now first Proton Driven Plasma Wakefield Experiment



Motivation for PWFA

- 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

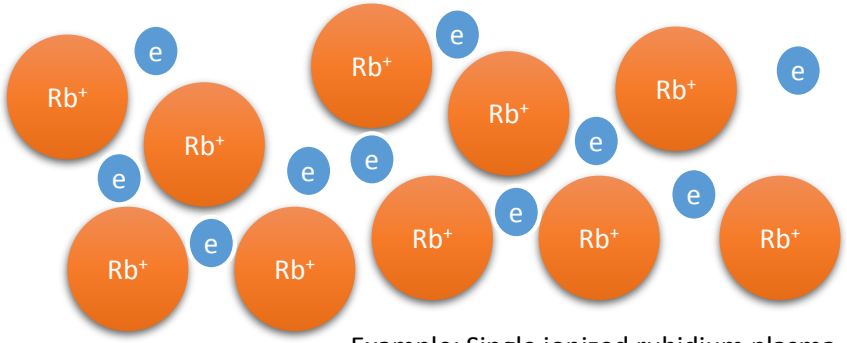
- Long term perspective of PWFA (>20 years):
  - High energy physics applications: Plasma-based high energy linear collider

  ➔ 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**.

Plasma Wakefield

What is a plasma?



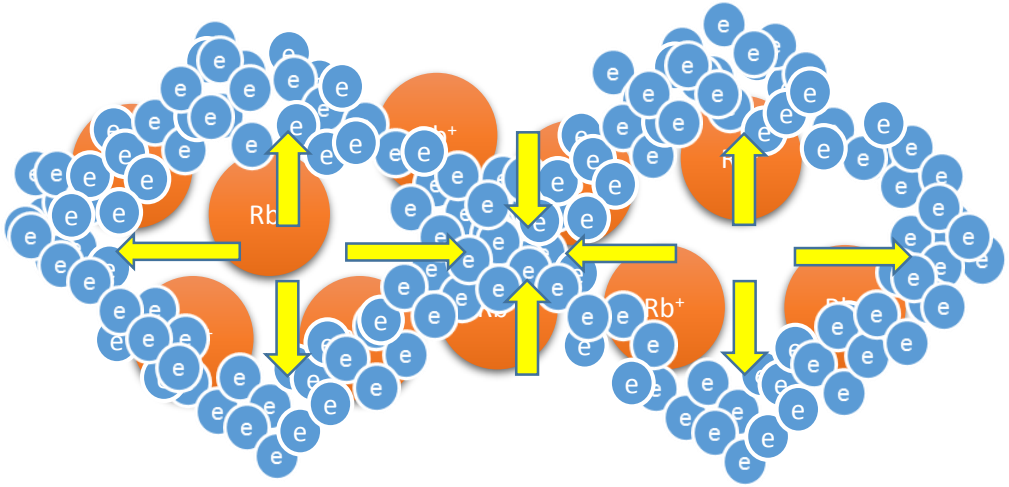
Example: Single ionized rubidium plasma

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

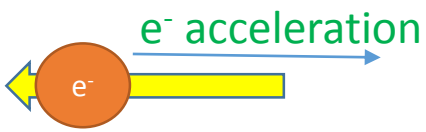
- This translates into a wavelength of the plasma oscillation

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

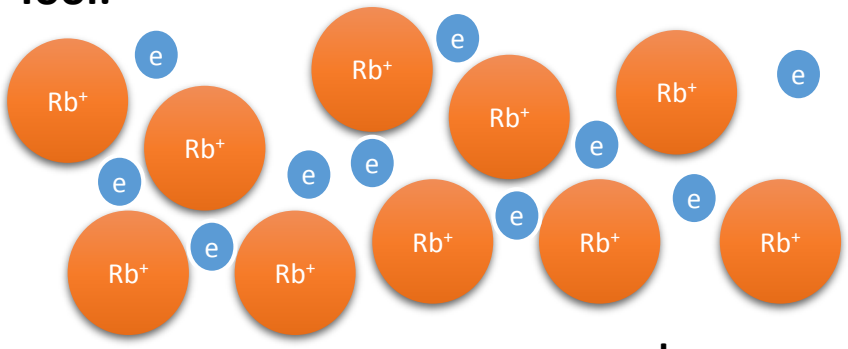
λ_{pe} = 1.2 mm → **Produce cavities with mm size!**

How to Create a Plasma Wakefield?

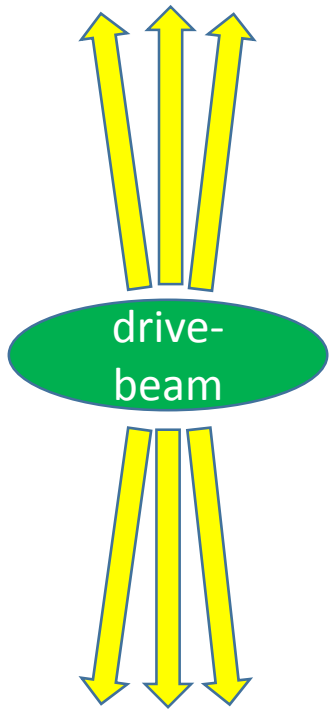
What we want:
Longitudinal electric field to accelerate charged particles.



Our Tool:



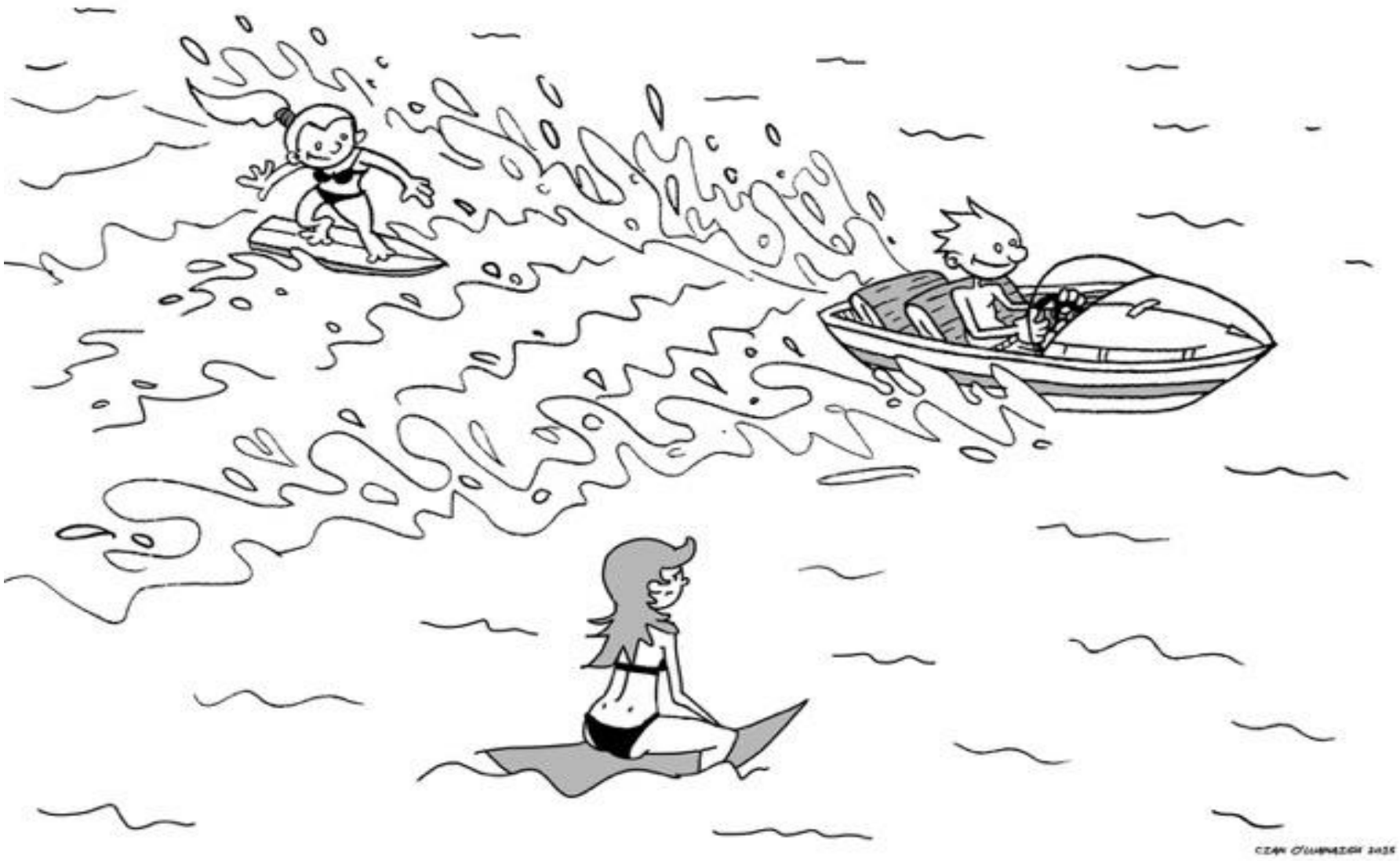
Single ionized rubidium **plasma**



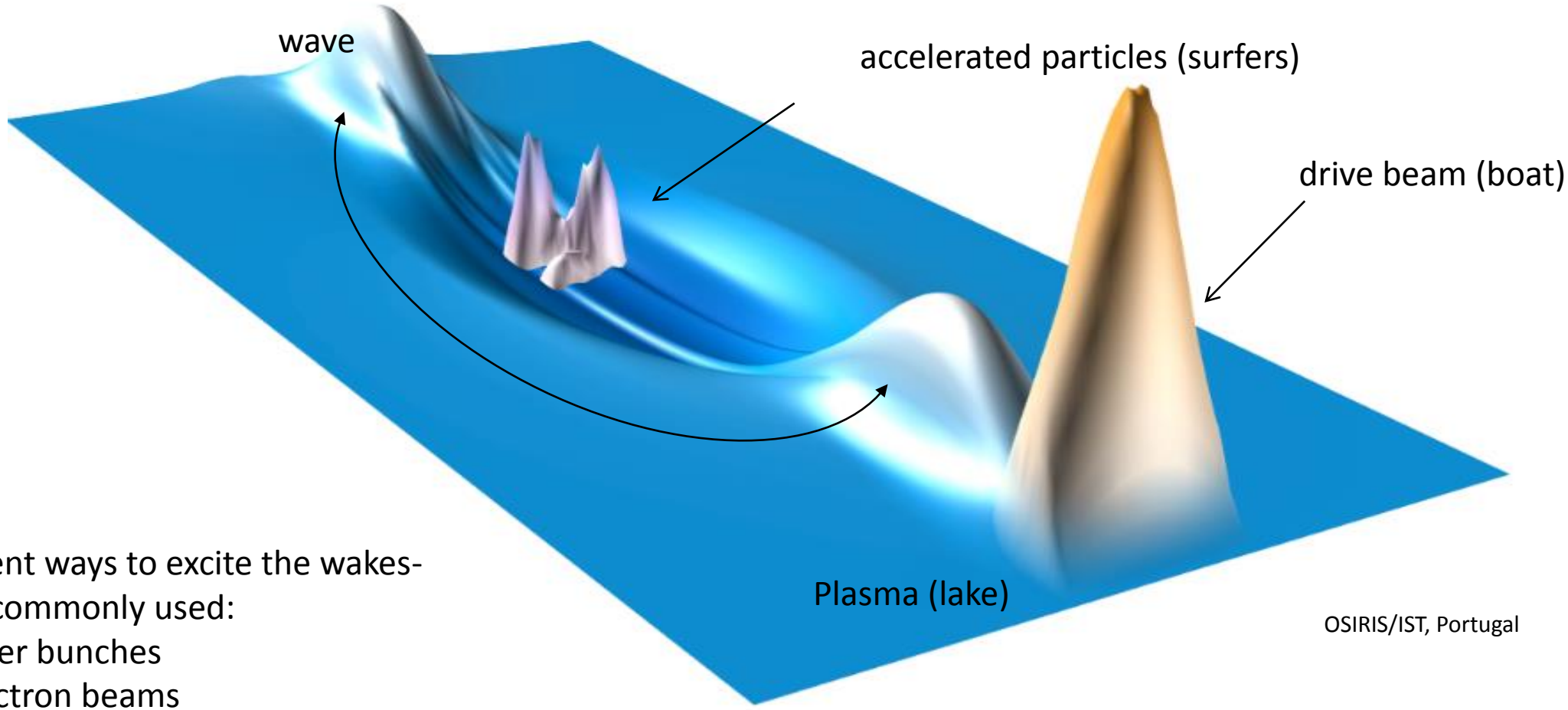
Charged particle bunches carry almost purely transverse Electric Fields.

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.

How to Create a Plasma Wakefield?



How to Create a Plasma Wakefield?



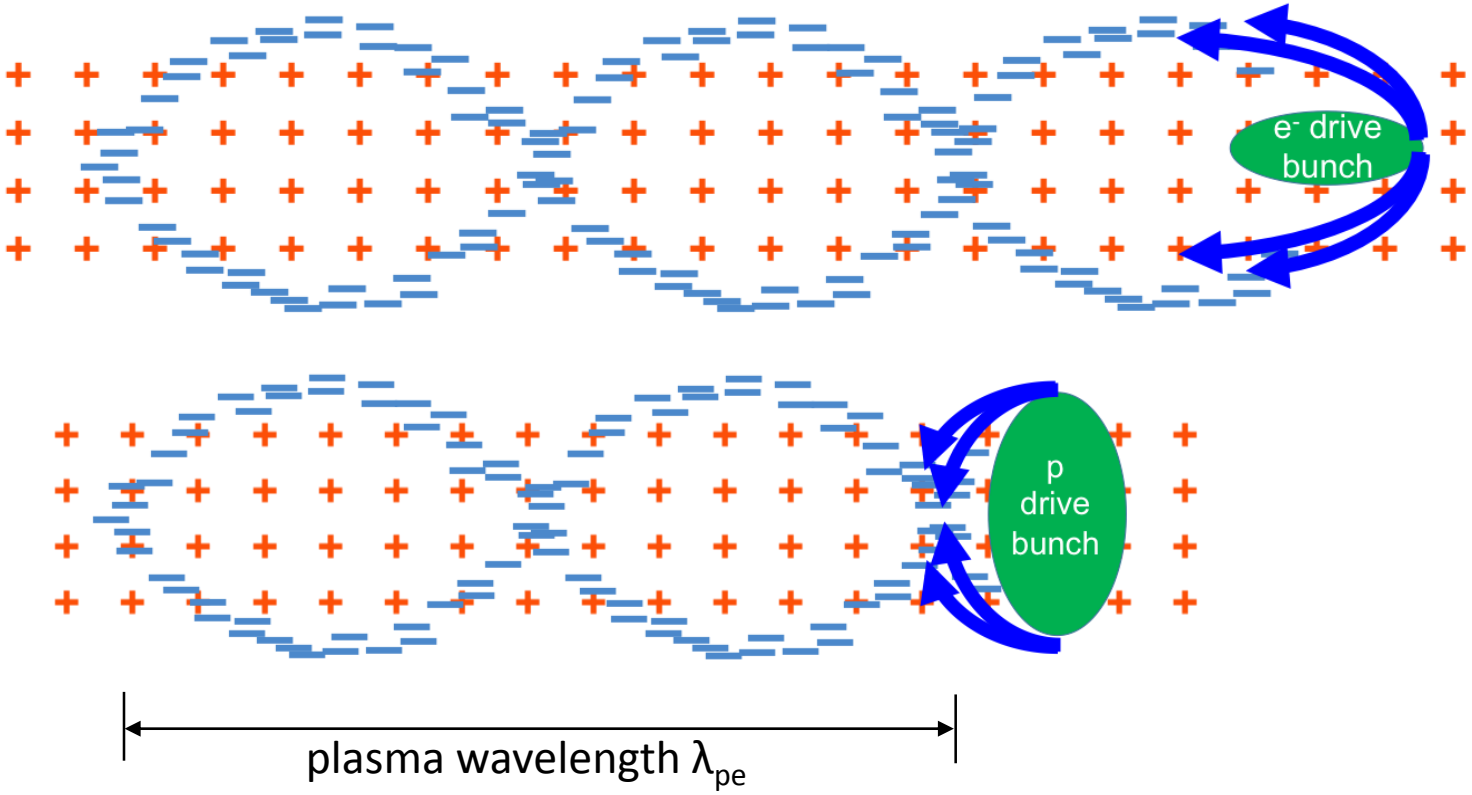
OSIRIS/IST, Portugal

Different ways to excite the wakes-
Most commonly used:

- Laser bunches
- Electron beams
- Protons bunches (first time to be done at CERN)

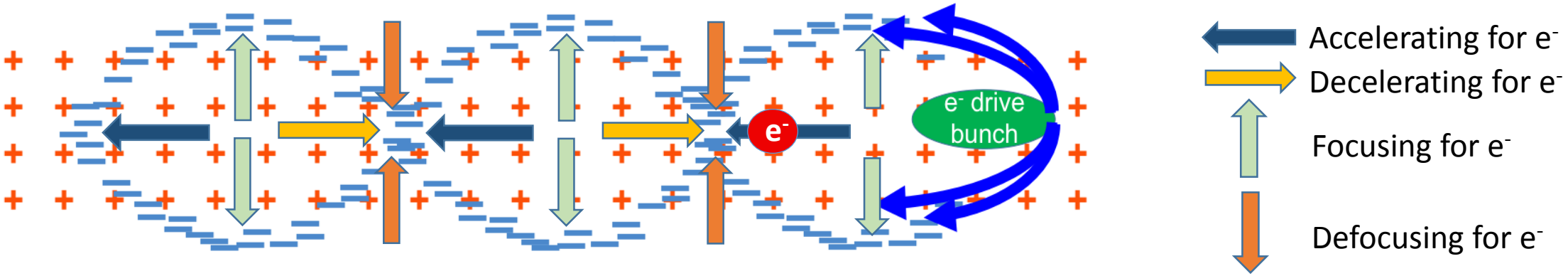
Principle of Plasma Wakefield Acceleration

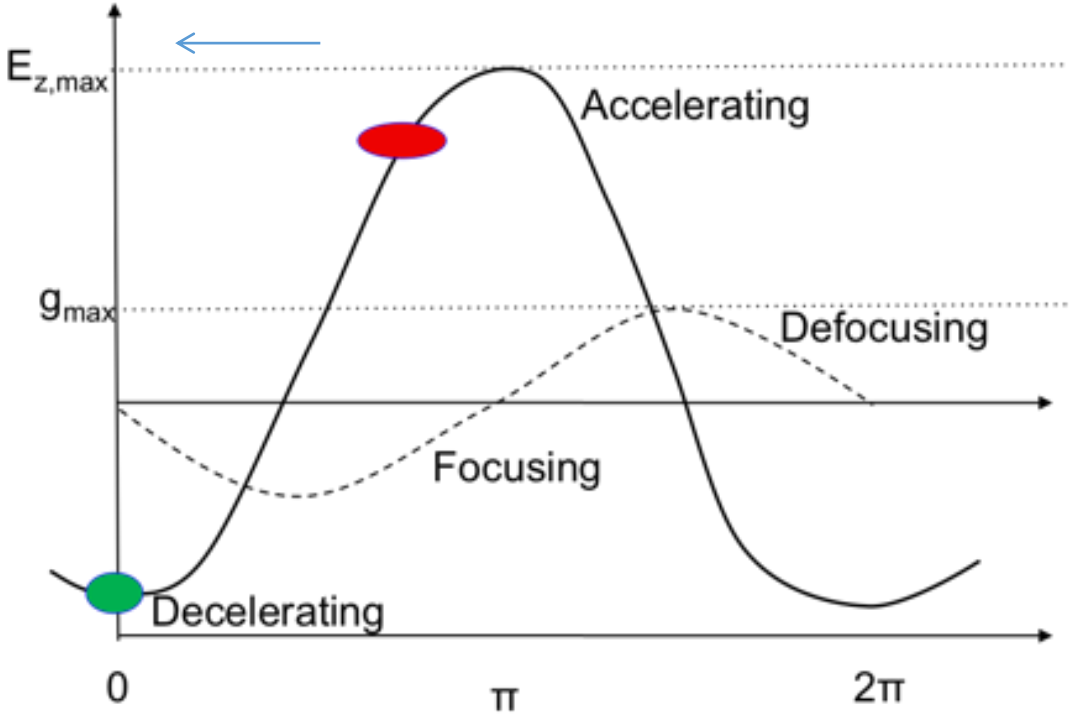
- Laser drive beam
  - ➔ Ponderomotive force
- Charged particle drive beam
  - ➔ Transverse space charge field
  - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam



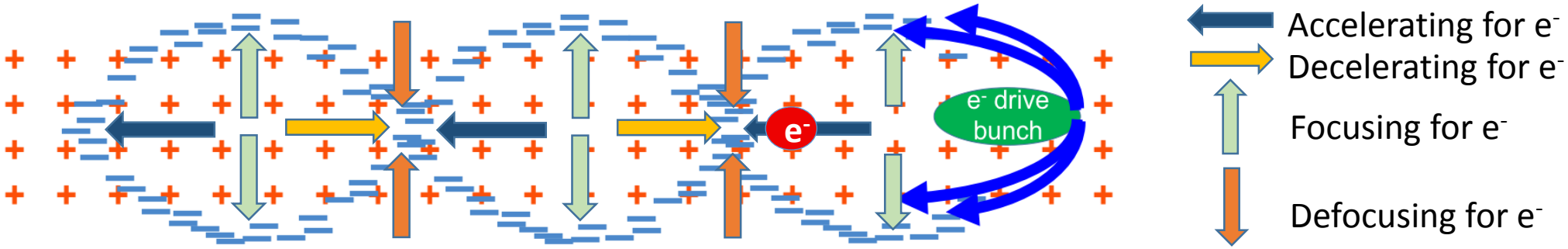
- Plasma wave/wake excited by relativistic particle bunch
- Plasma e^- are expelled by space charge force
- Plasma e^- rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake → no dephasing
- Acceleration physics identical for LWFA, PWFA

Where to Place the Witness Beam (Surfer)?





Wakefields



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: $n_{pe} = 7\times10^{14}\ cm^{-3}$ **(AWAKE)** ➔ $eE_{WB} = 2.5$ **GV/m** ➔ **g = 21kT/m**
Example: $n_{pe} = 7\times10^{17}\ cm^{-3}$ ➔ $eE_{WB} = 80$ **GV/m** ➔ **g = 21MT/m**

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:

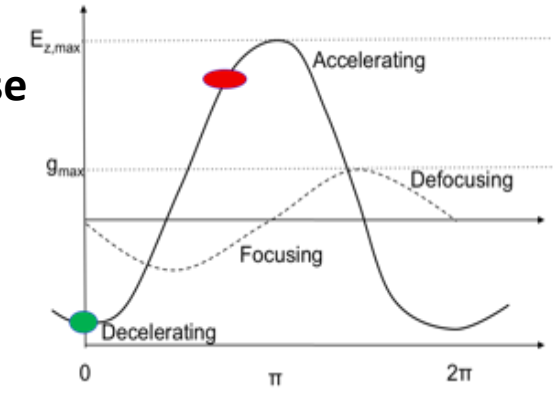
$$eE_Z = \sqrt{n_p}\,\frac{n_b}{n_p}\,\frac{\sqrt{2\pi}\,k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+\frac{1}{k_p^2\sigma_r^2}}\sin k_p(z-ct) \quad (eV/cm)$$

B.E. Blue 2003

→ $eE_z \approx N/\sigma_z^2$

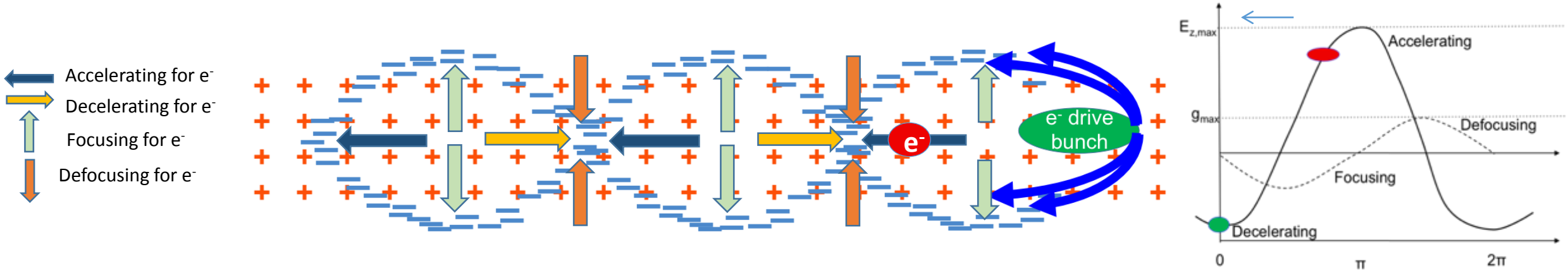
- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- **Accelerating gradient** increases linearly with **N/σ_z**
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**
- The **accelerating field is maximized**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

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



Example: n_{pe} = 7x10^{14} cm^{-3} (AWAKE), k_{pe} = 5 mm^{-1} → drive beam: σ_z = 300µm, σ_r = 200µm

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.

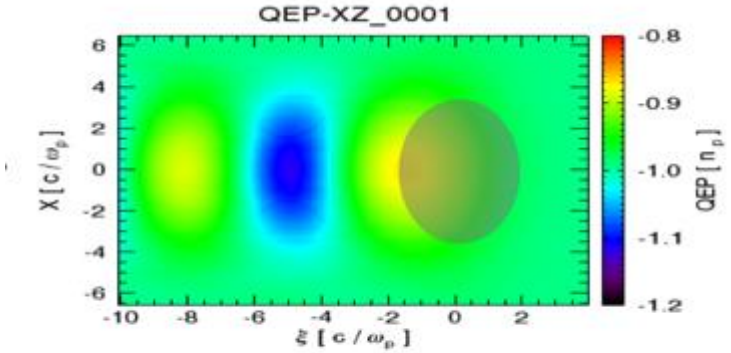
Examples of accelerating fields for different beam parameters and plasma parameters fields:

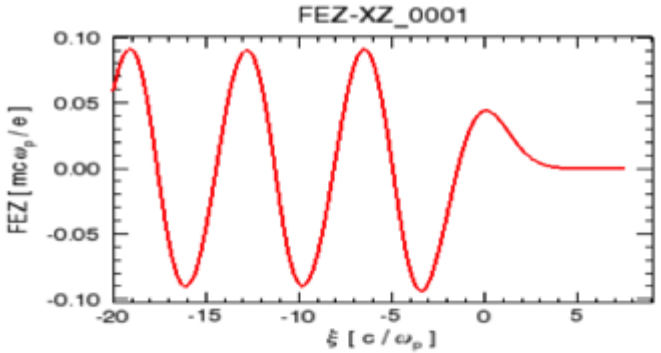
$N = 3\times10^{10}$, $\sigma_z = 300\mu m$, $n_{pe} = 7\times10^{14}\ cm^{-3}$ ➔ **E_{acc} = 600 MV/m**
$N = 3\times10^{10}$, $\sigma_z = 20\mu m$, $n_{pe} = 2\times10^{17}\ cm^{-3}$ ➔ **E_{acc} = 15 GV/m**

From Linear to Non-Linear

Electron density :

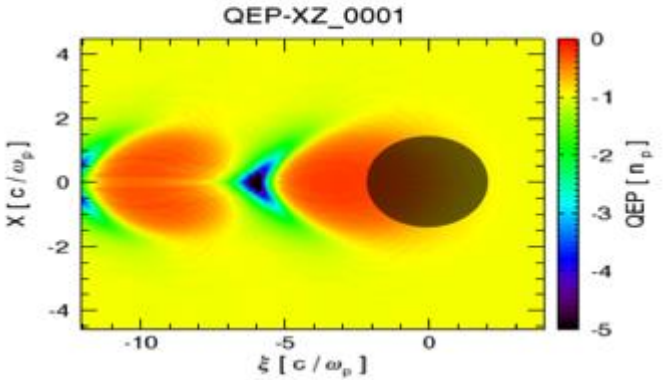
Longitudinal fields :

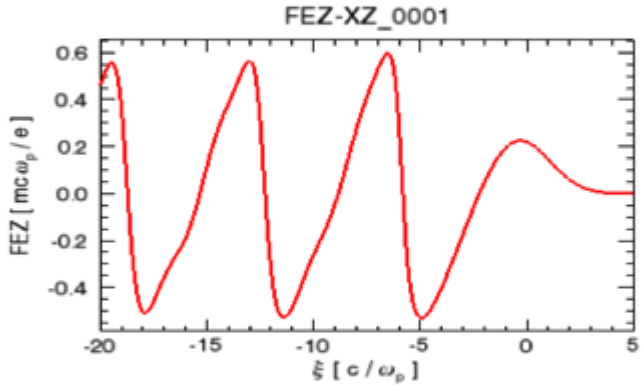




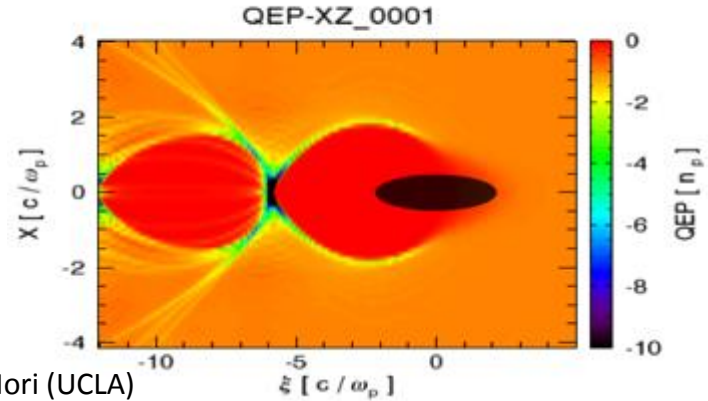
$n_b << n_{pe}$
– linear regime

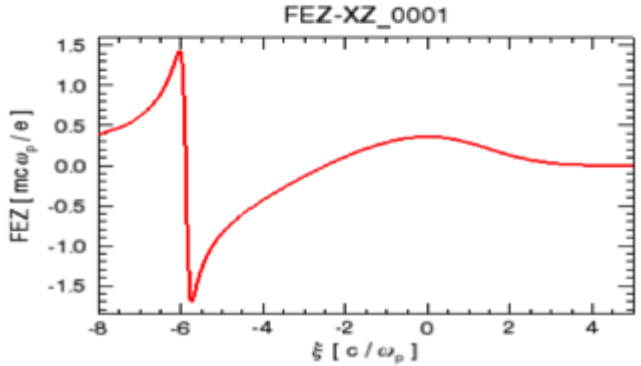
- *lower wakefields*
- *transverse forces not linear in r*
+ Symmetric for positive and negative witness bunches
+ Well described by theory





$n_b \sim n_{pe}$
– non-linear wakes



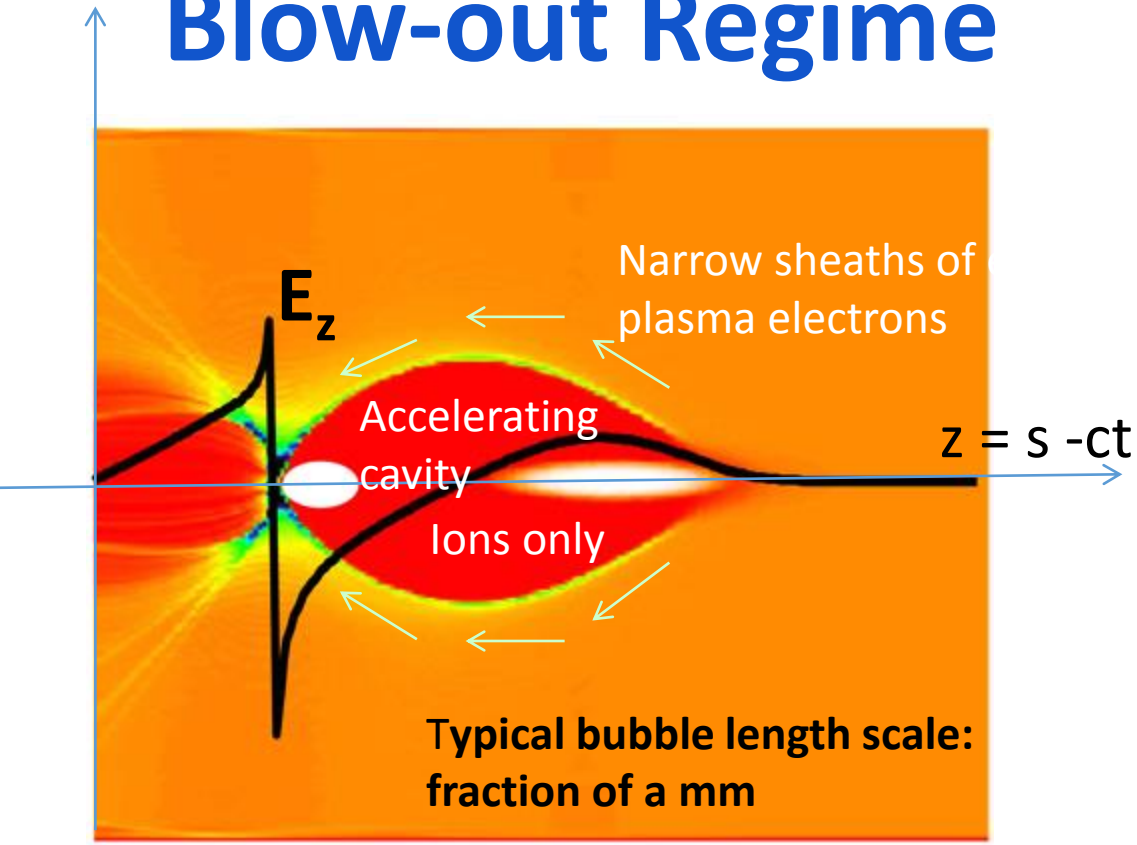


$n_b >> n_{pe}$
– **blow-out regime**

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

W. Mori (UCLA)

Blow-out Regime



- **Space-charge force** of the driver blows away **all the plasma electrons** in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a **narrow sheath** around the evacuated area, and are **pulled back by the ion-channel** after the drive beam has passed
- An **accelerating cavity** is formed in the plasma
- The back of the blown-out region: **ideal for electron acceleration**

→ **High charge witness** acceleration possible → charge ratio to witness of same order
→ **Linear focusing in r**, for electrons; very strong quadrupole (MT/m)
→ **High transformer ratios (>2)** can be achieved by shaping the drive bunch
→ **E_r independent of x**, can **preserve incoming emittance** of witness beam

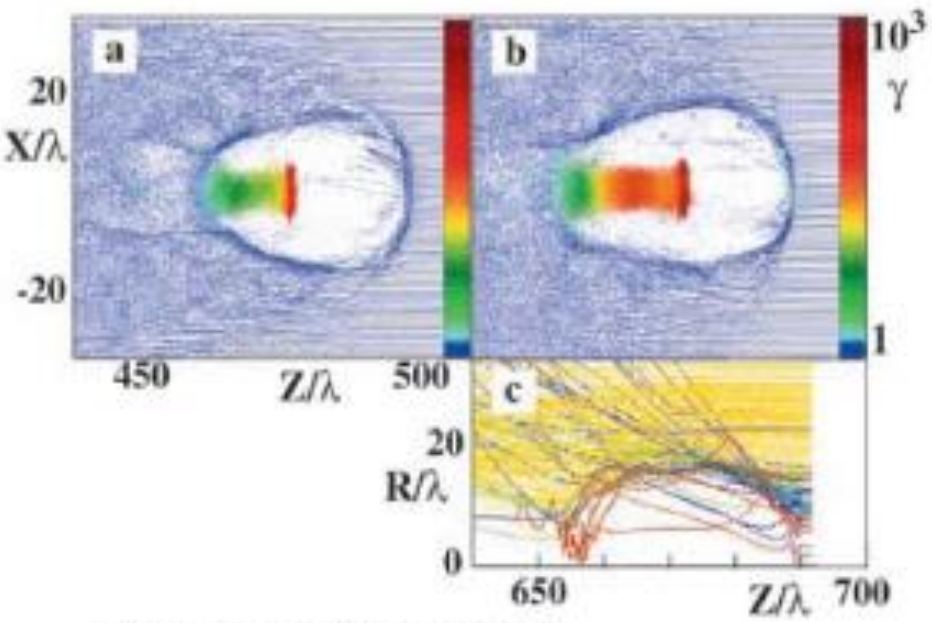
Self-Injection Scheme

Appl. Phys. B 74, 355–361 (2002)
DOI: 10.1007/s003400200795
Applied Physics B
Lasers and Optics

A. PUKHOV[1,✉]
J. MEYER-TER-VEHN[2]

Laser wake field acceleration: the highly non-linear broken-wave regime

[1] Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany

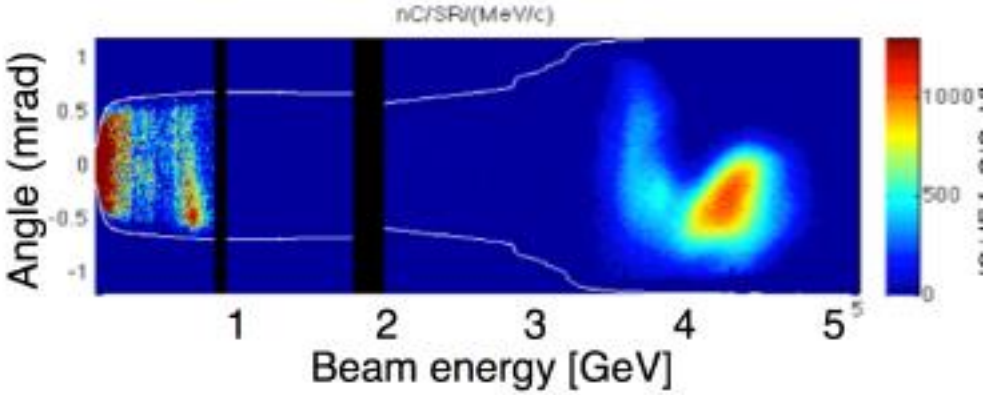


Pukhov, ter-Vehn 2002

4.25 GeV beams obtained from 9cm plasma channel powered by 310TW laser pulse (15 J)

W.P.Leemans et al., PRL 2014

Electron beam spectrum

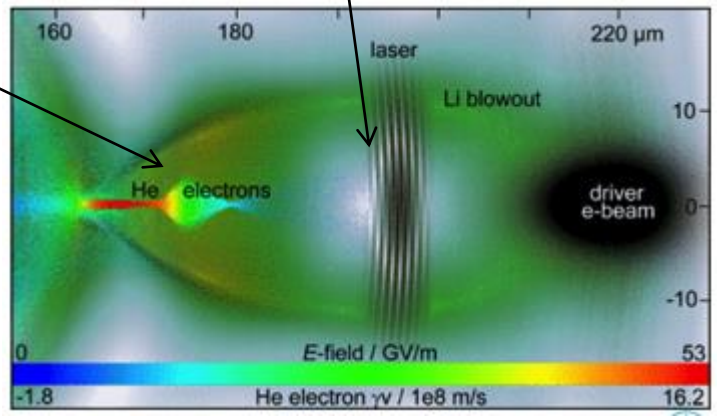


Example of FACET-II Experiment 'Trojan Horse': High Brightness Beam

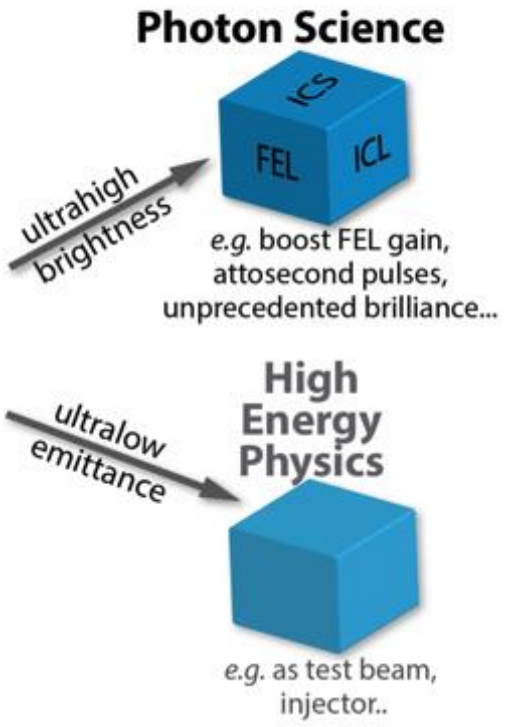
Plasma photocathode: Tunable production of electron bunches of ultrahigh quality by laser release from higher ionization threshold inside the electron-driven plasma wave

Released electrons are rapidly accelerated and form bunch with ultralow emittance

Synchronized laser pulse tunnel ionizes in focus and releases ultracold electron population



B. Hidding et al., PRL 108, 035001 (2012)



Two plasma components:

- Beam-driven plasma wakefield using low-ionization-threshold gas such as Li
- Laser-controlled electron injection via ionization of high-ionization threshold gas such as He

Ultra-high brightness beams:

- Sub-μm spot size
- fs pulses
- Small emittance (nm mrad)

$$B_{6D} = \frac{I}{\epsilon_n^2 \cdot 0.1\% \sigma_W}$$

current, emittance, energy spread

Laser-Driven Plasma Acceleration Facilities

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

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

Outline

- Motivation
- Introduction to Plasma Wakefield Acceleration
- Key Challenges of Plasma Wakefield Acceleration and Experimental Results

Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam

First Beam Driven Acceleration 1988

VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 21 March 1988)

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipiscosecond bunch of electrons in a plasma of density $n_e = 10^{13}$ cm^{-3}, and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

Argonne National Lab

Theoretical paper for beam driven PWFA 1985

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

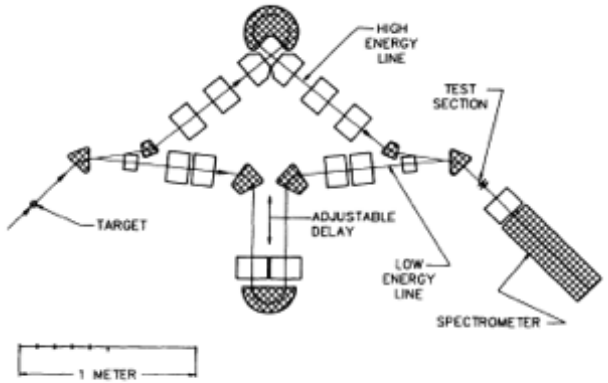


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

- Drive beam: 21 MeV, witness beam: 15 MeV
  $\sigma_z = \sigma_r = 2.4$mm, charge: 2-3nC
- DC plasma source, Argon, $n_e = 0.7\text{-}7\times10^{13}$cm^{-3}

Linear theory: $n_e = 8\times10^{12}$cm^{-3}

➔ Result: **Wakefields of order 1 MV/m**

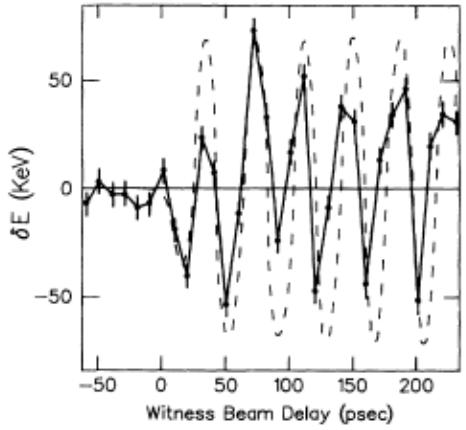


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6\times10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

Record Acceleration, at SLAC: 42 GeV

Final Focus Test Beam Facility, **FFTB** at SLAC

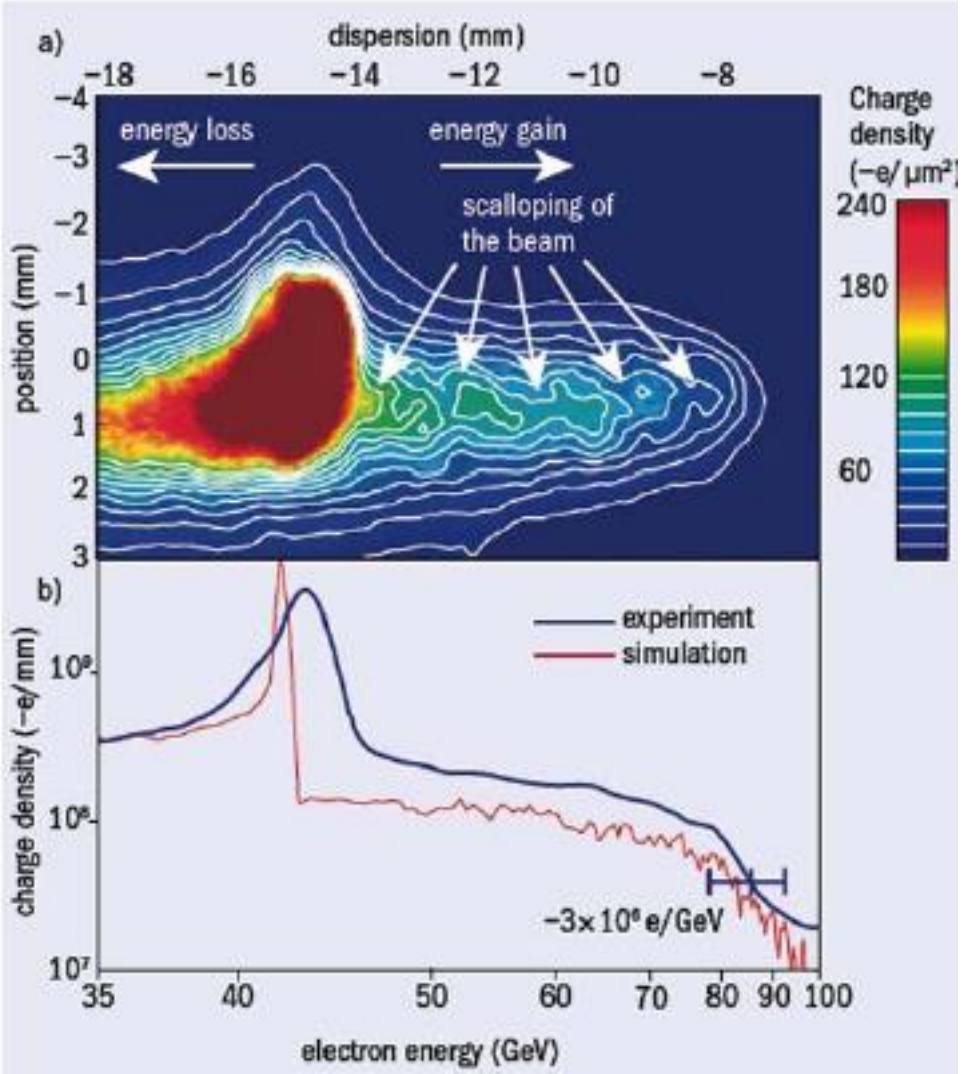
I. Blumenfeld et al, Nature 455, p 741 (**2007**)

Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, σ_x = 10µm, 50 fs

85cm Lithium vapour source, $2.7 \times 10^{17} cm^{-3}$

➔ Accelerated electrons from 42 GeV to 85 GeV in 85 cm.

➔ Reached accelerating gradient of **52 GeV/m**



Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam

Accelerating Field, Energy in PWA

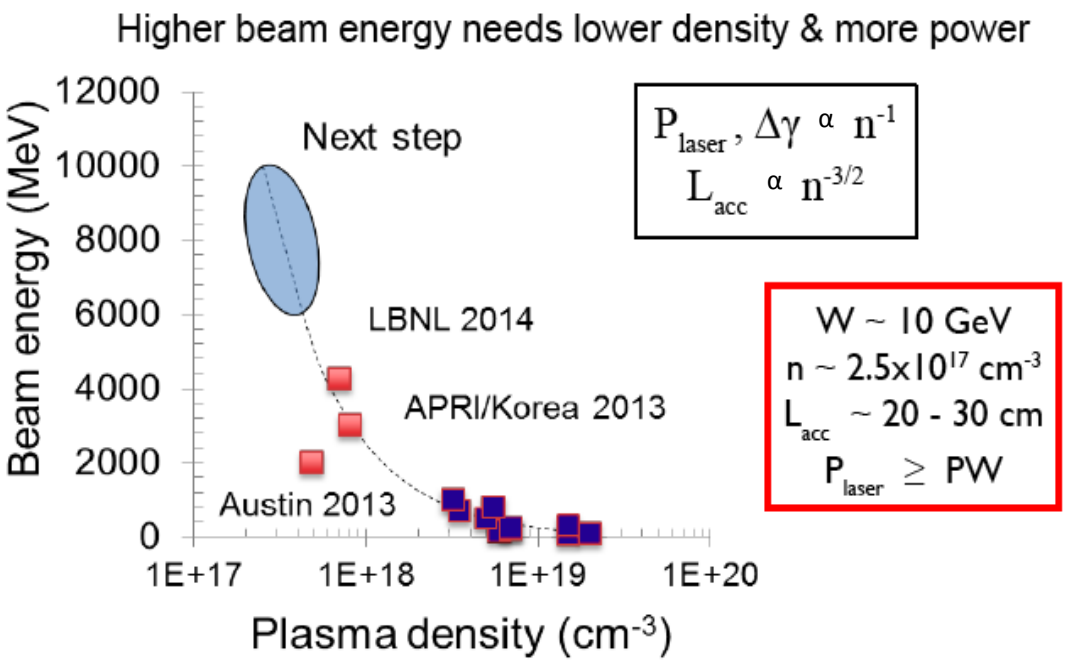
The maximum accelerating field (wave-breaking field) is:

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

Example: $n_{pe} = 10^{16}\ cm^{-3} \rightarrow E_{WB} = 10GV/m$

Increase gradient by increasing density.

➔ Advantage of beam-driven PWFA



➔For LWFA:

dephasing: laser group velocity depends on plasma density, is slower than c.

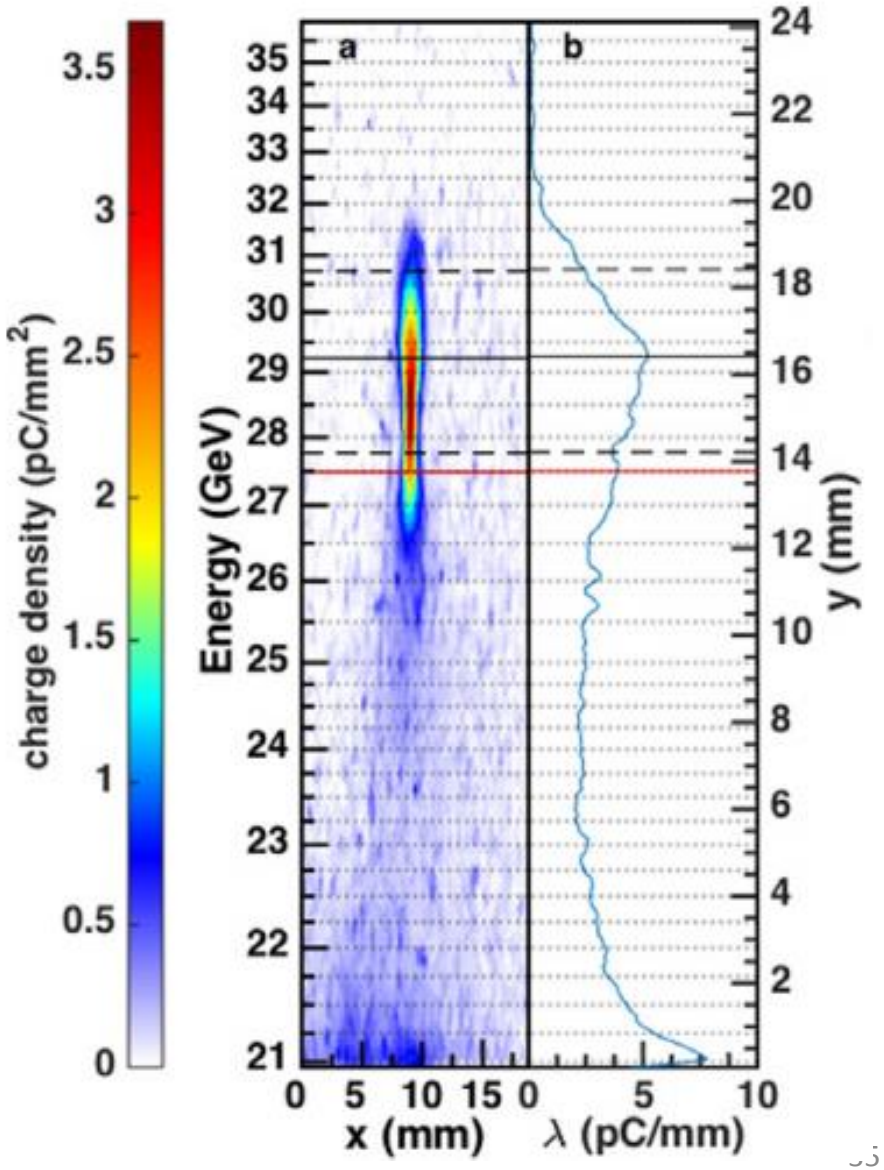
- Electron energy reach is limited by dephasing: → move to lower densities and longer accelerators.
- Lower density needs higher laser power (Significant progress since Chirped Pulse Amplification, CPA, Nobel Prize 2018 to D. Strickland & G. Mourou)

SLAC – FACET

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

- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: 5 10^{16} cm^{-3}, λ_π = 200 µm
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)



Later the plasma oven was extended from 0.3 to 1.3 meters long.

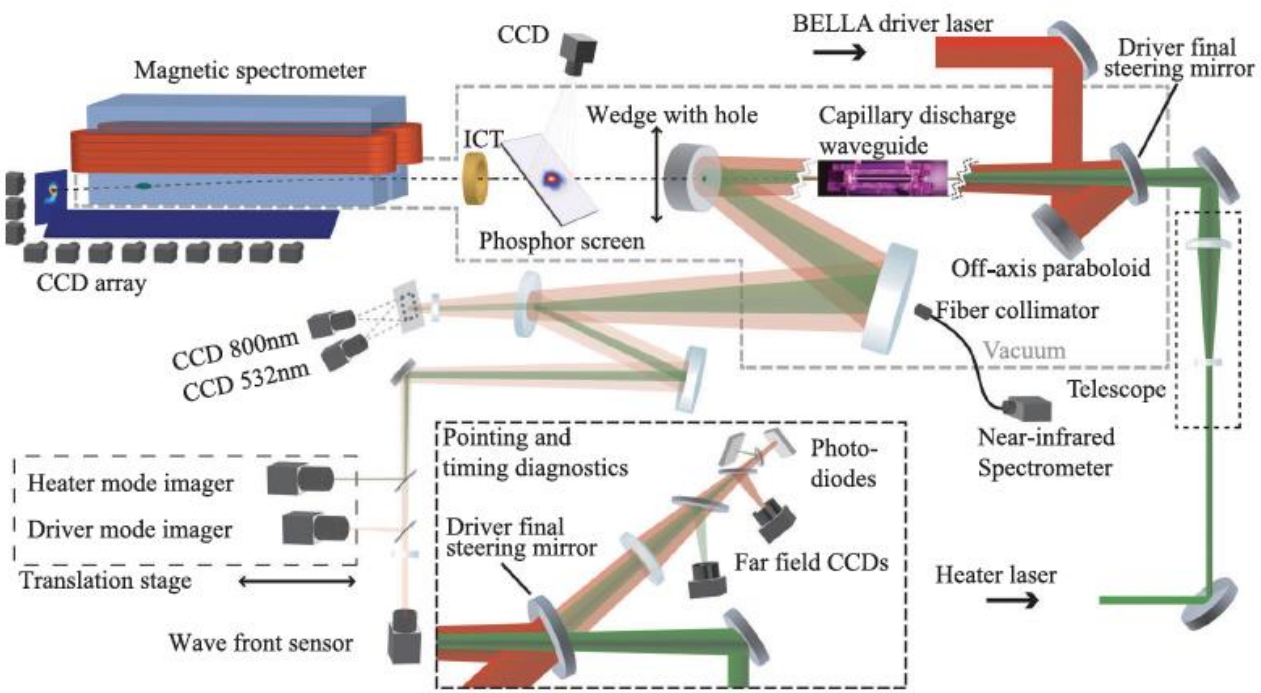
The accelerated beam had a spectral peak at **9 GeV energy gain.**

M Litos et al **2016** Plasma Phys. Control. Fusion 58 034017

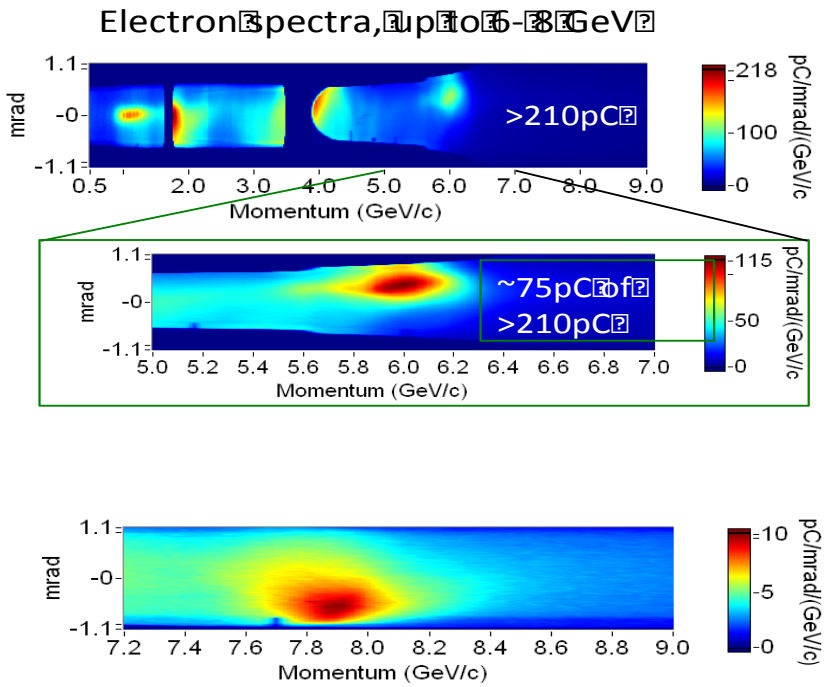
BELLA, Berkeley Lab

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

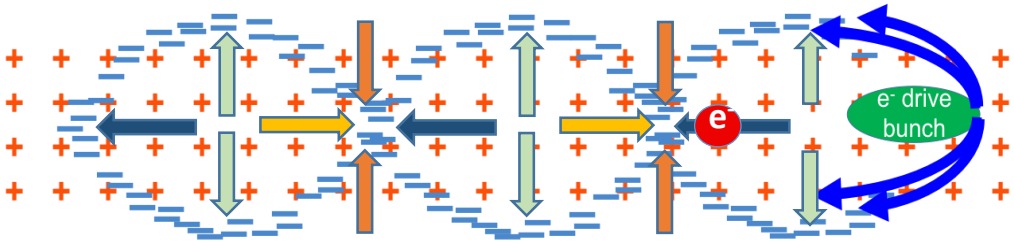


→ path to 10 GeV with continued improvement of guiding in progress

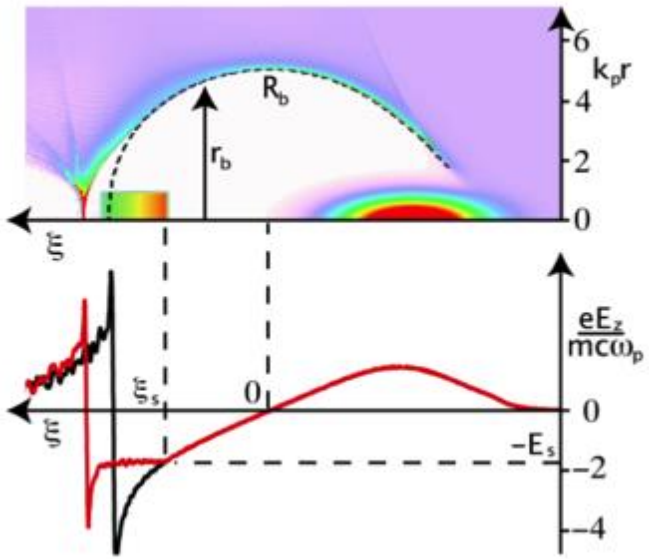
Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam

Optimization



- Reduce energy spread:
  - Beam loading (idea: Simon van der Meer, 1985)
    - Shape the witness beam to get optimized fields in the plasma, ie minimize energy spread
    - Extract energy from and flatten the E_z field, while extracting field energy.



Sufficient charge in the witness bunch to flatten the accelerating field
→ **reduce energy spread**

SLAC – FACET

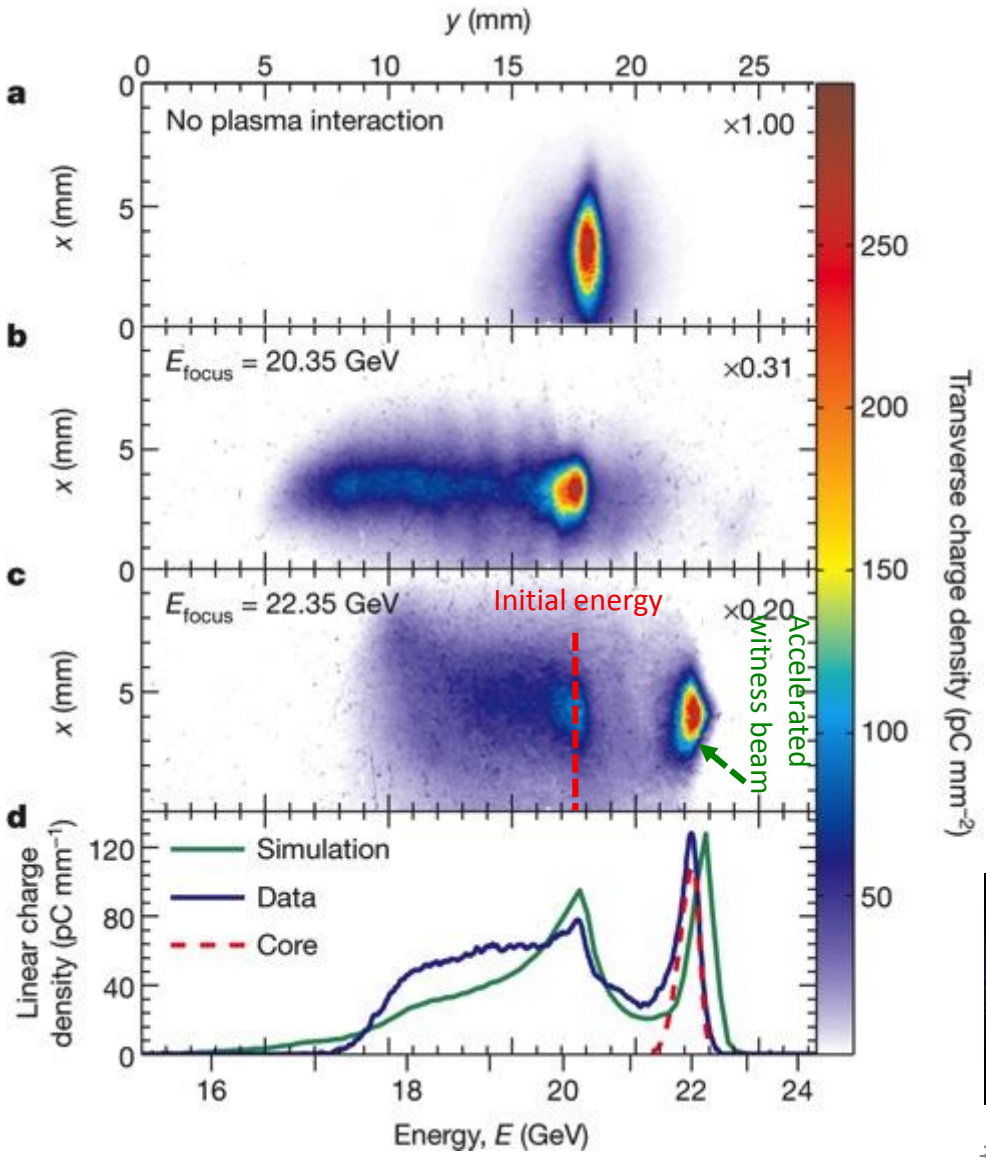
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

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

- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: 5 10^{16} cm^{-3}, λ_π = 200 µm
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)

First demonstration of a high-efficiency, low energy-spread plasma wakefield acceleration experiment:

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



SLAC – FACET

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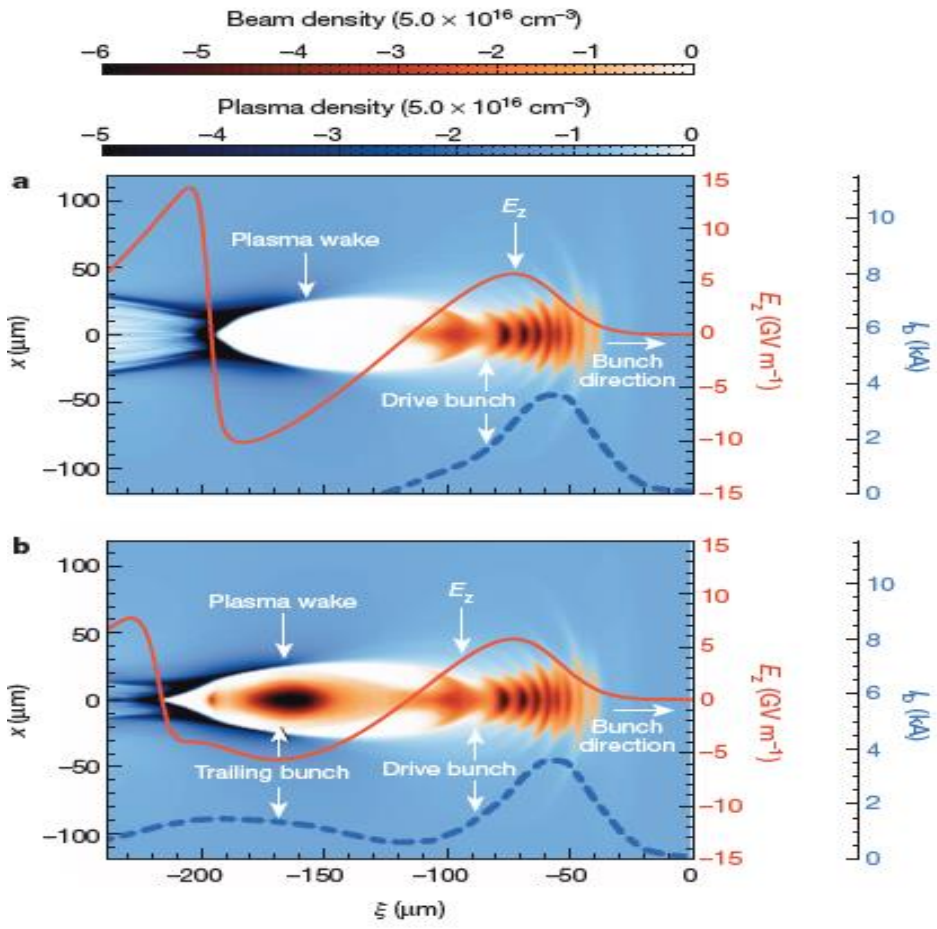


→ Electric field in plasma wake is **loaded** by presence of trailing bunch

→ Allows efficient energy extraction from the plasma wake

Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam

Transformer Ratio

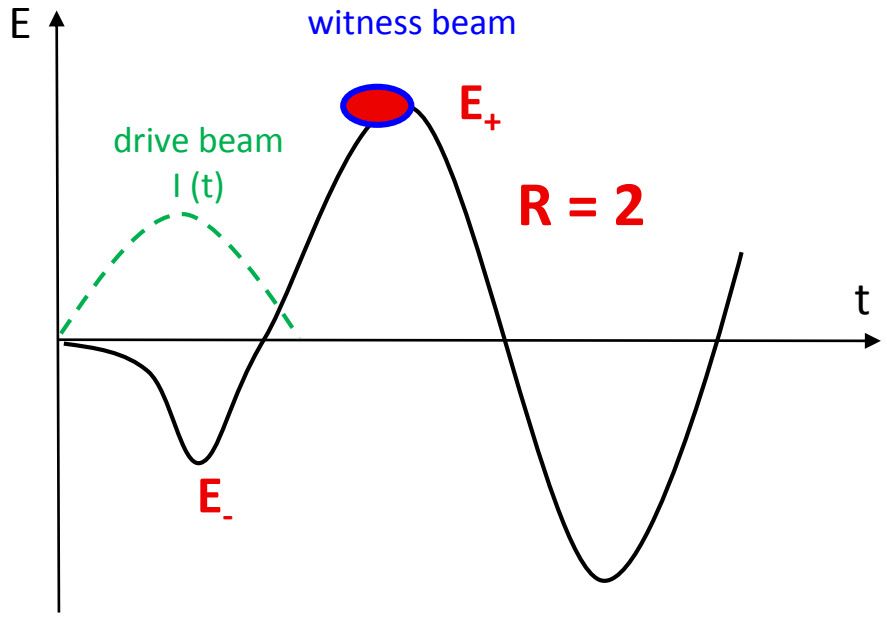
Would be fantastic to take a 1 GeV electron drive beam with 10^{11} electrons to accelerate 10^{9} electrons by 100 GeV. Energy conservation is fulfilled.

BUT: not possible in reality

Limited by the **Transformer Ratio R ≤ 2**:

$$R = \frac{E_+}{E_-} = \frac{\text{Peak accelerating field behind the drive bunch}}{\text{Peak decelerating field within the drive bunch}}$$

(Short symmetric bunches)



Example:
Assume that E_- = 10 GV/m
With R = 2 ➔ E_+ = 20 GV/m

Drive beam (e^-) with **30 GeV** → decelerates 10GeV/m ➔ 3m total
Witness beam: gains 20 GeV/m ➔ gets **60 GeV** in 3m
Of course energy conservation must be fulfilled: $N_D = 3N_W$.

Increasing the Transformer Ratio

$$R = \frac{E_+}{E_-}$$

- Adjust the drive beam profile

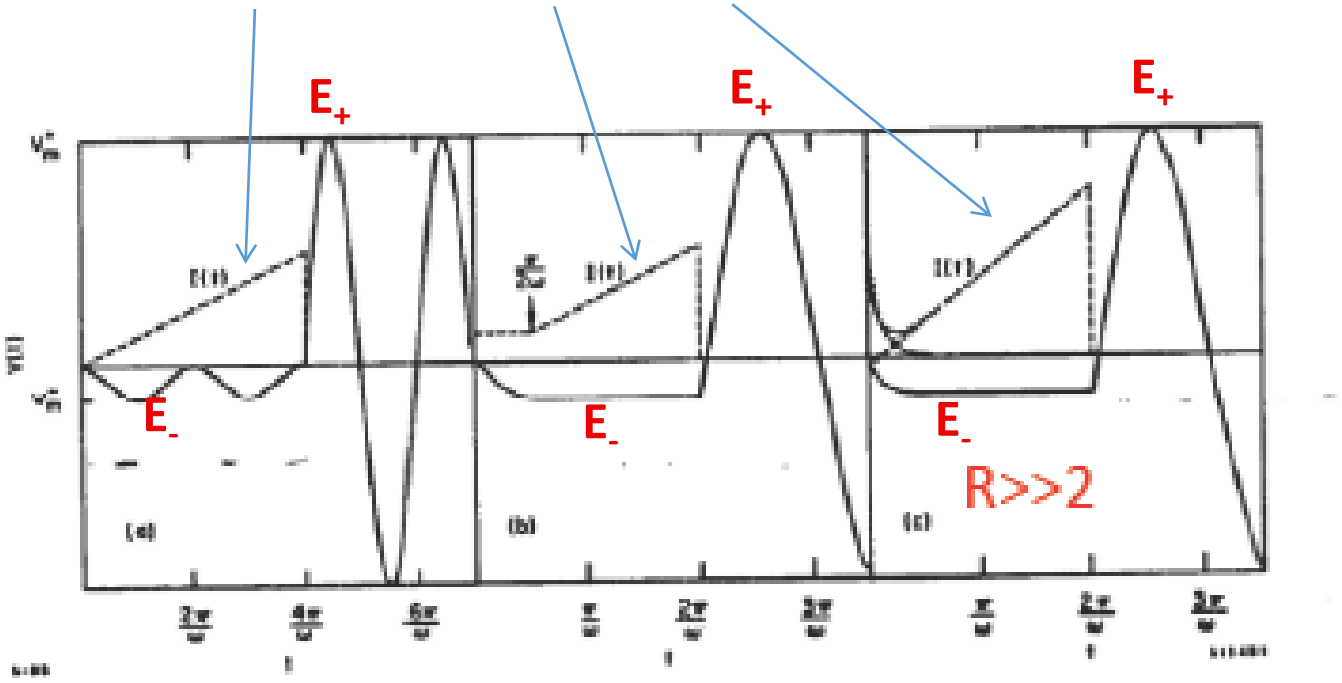
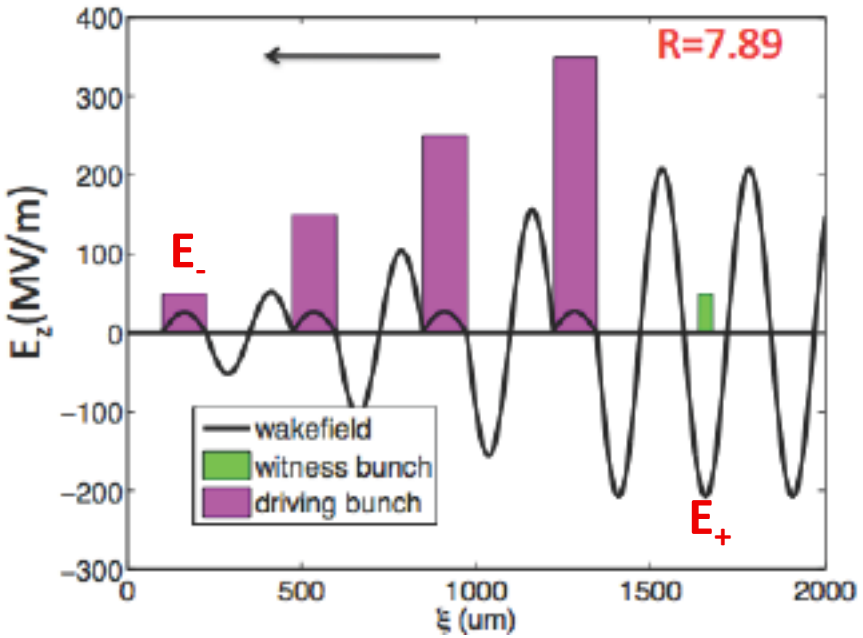


Figure 9. The voltage induced by three different asymmetric current distributions interacting with a single mode.

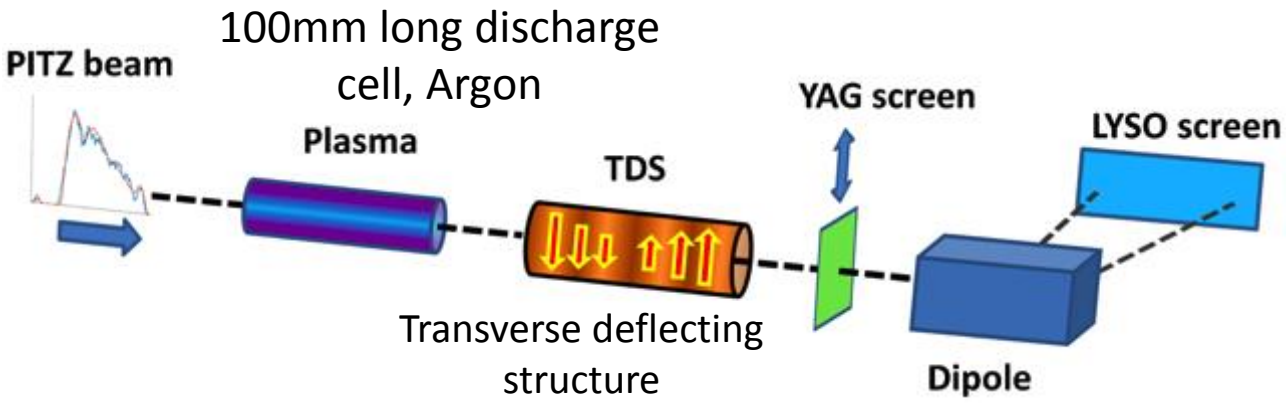
- Multiple drive beam bunches

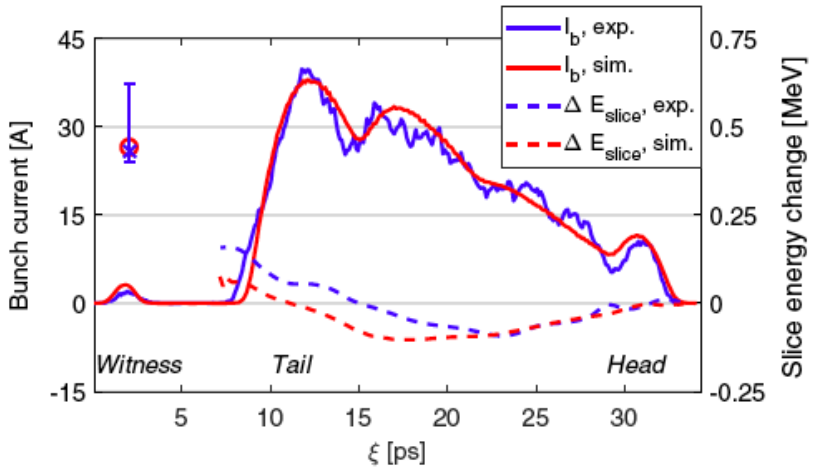


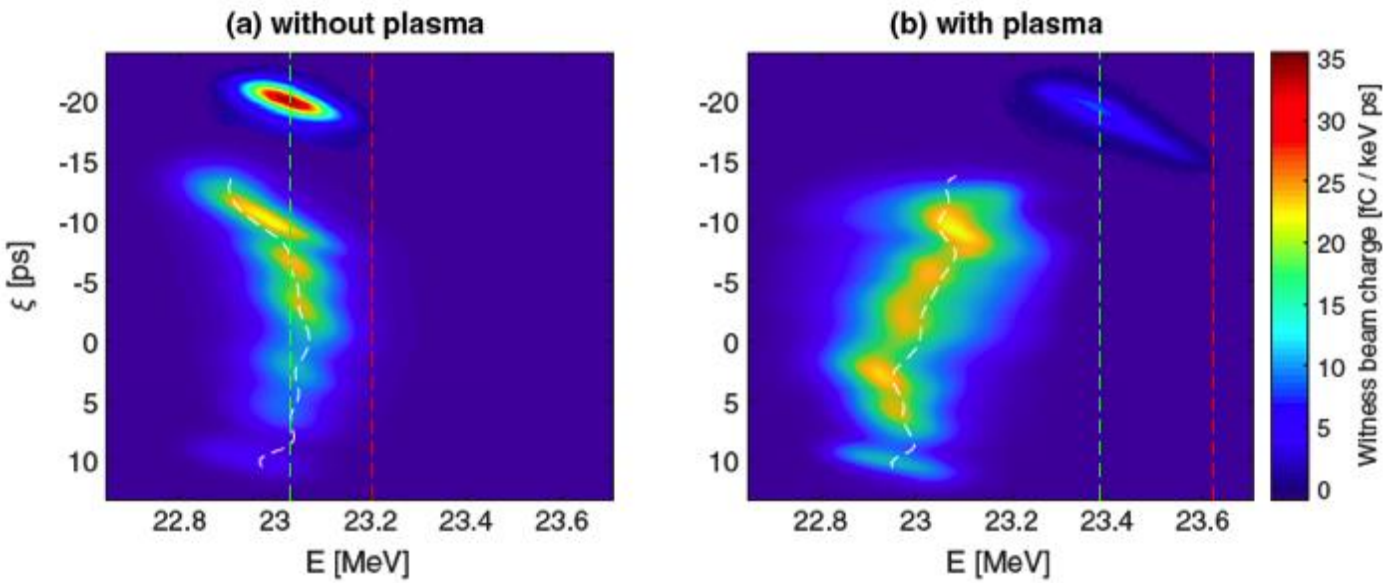
Tzoufras, PRL 101, 145002 (2008)

DESY PITZ, 2018

- Photoinjector Test facility at DESY, Zeuthen (PITZ)
- 1.3GHz, 0.01-5nC, up to 25 MeV, ε_{norm} = 0.1 mmm rad
- Drive beam: 508 pC, 20ps
- Witness beam: 10 pC, 0.7ps, delay 10ps.







G. Loisch et al., Observation of High Transformer Ratio Plasma Wakefield Acceleration, PRL **121,** 064801 (2018).

➔ Transformer Ratio:4.6 + 2.2/– 0.7

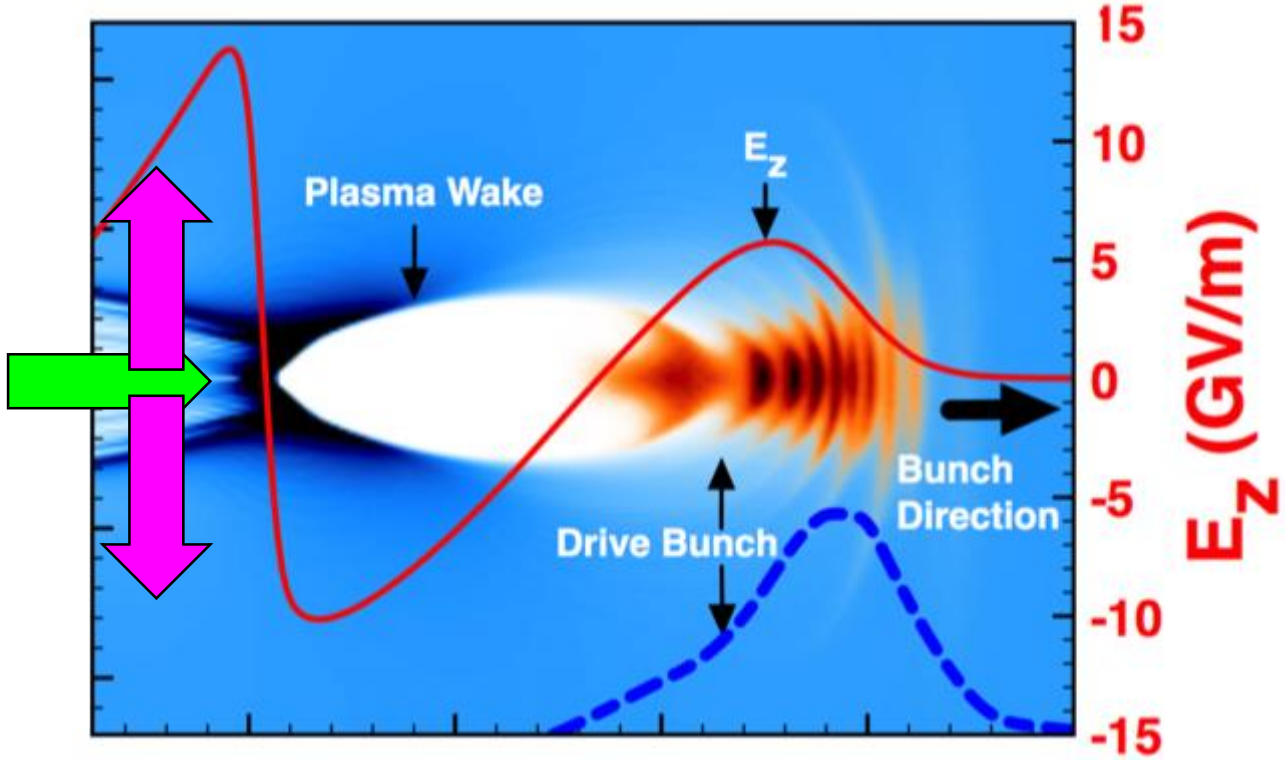
Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated Energy
- Beam quality
- Transformer Ratio
- Positron acceleration
- Protons as drive beam

Positron Acceleration

- Interested in using positrons for high energy linear colliders:
  - Parameters for positrons: **high energy, high charge, low emittance**.

Electron-driven blowout wakes:



But the field is defocusing in this region.

Positron Beam at FACET, 2015

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).

High-density, compressed positron beam for non-linear PWFA experiments.
1.3m plasma cell, 20 MeV beam.
New observations:

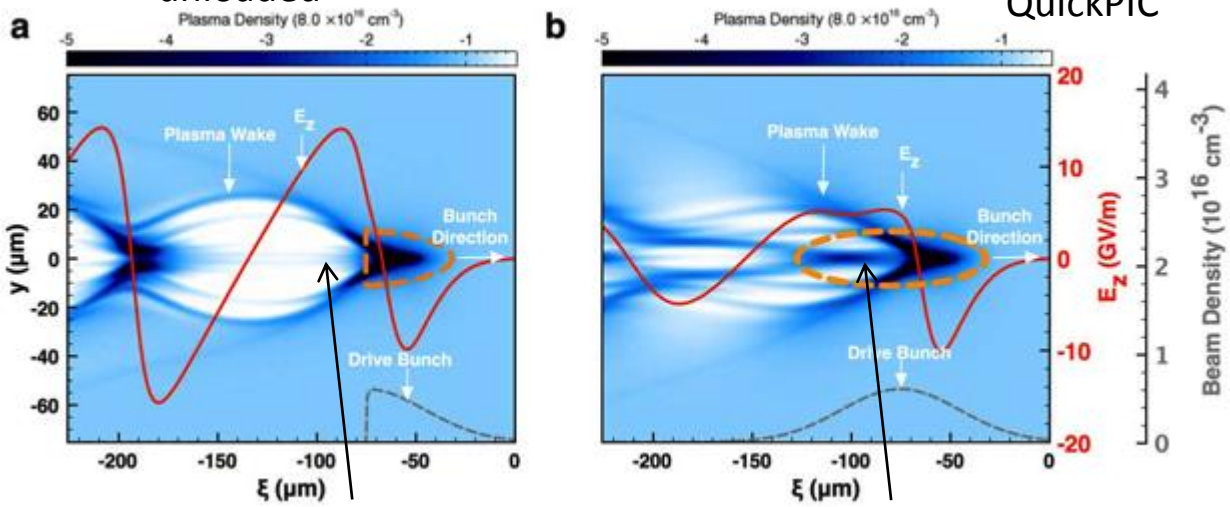
- Accelerated positrons form a spectrally-distinct peak with an **energy gain of 5 GeV**.
- Energy **spread can be as low as 1.8%** (r.m.s.).

But emittance blow-up!

unloaded

loaded

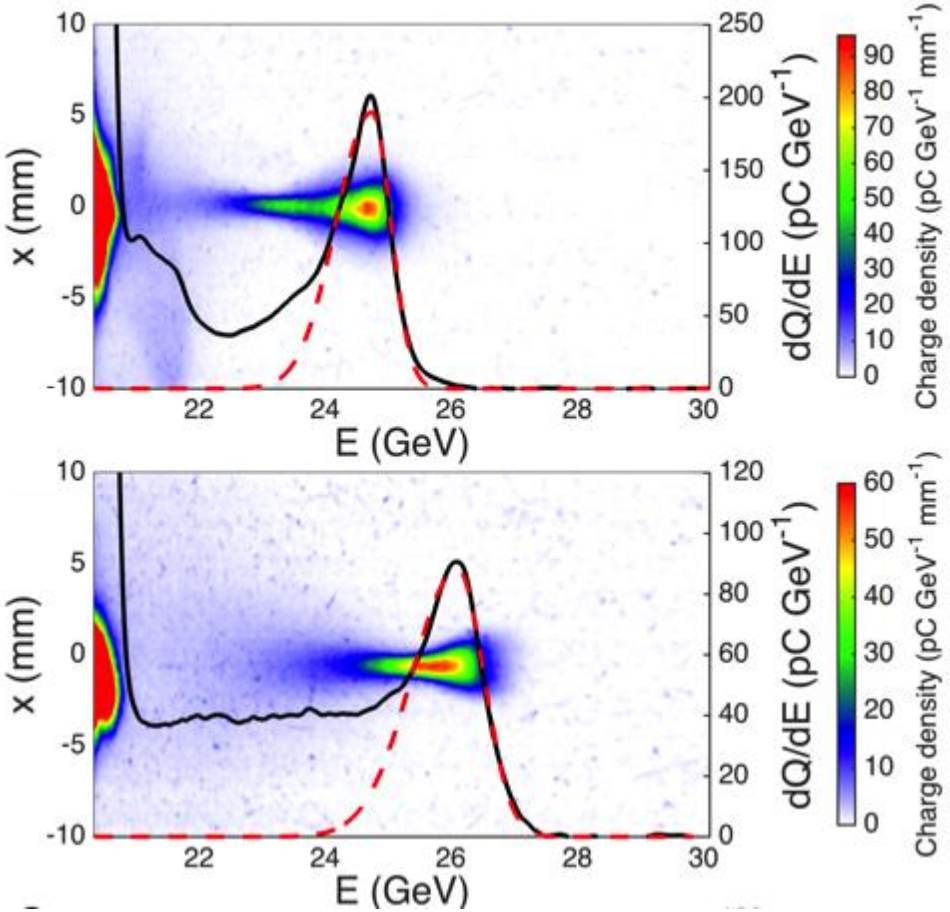
QuickPIC



defocusing

focusing

➔ Beam loading affects transverse fields for positron driven wakes!

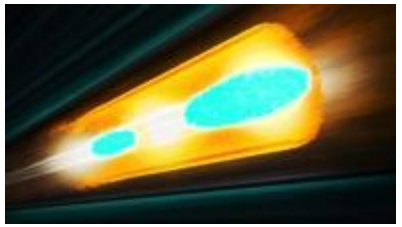


S. Corde *et al.*, Nature **524**, 442 (2015)

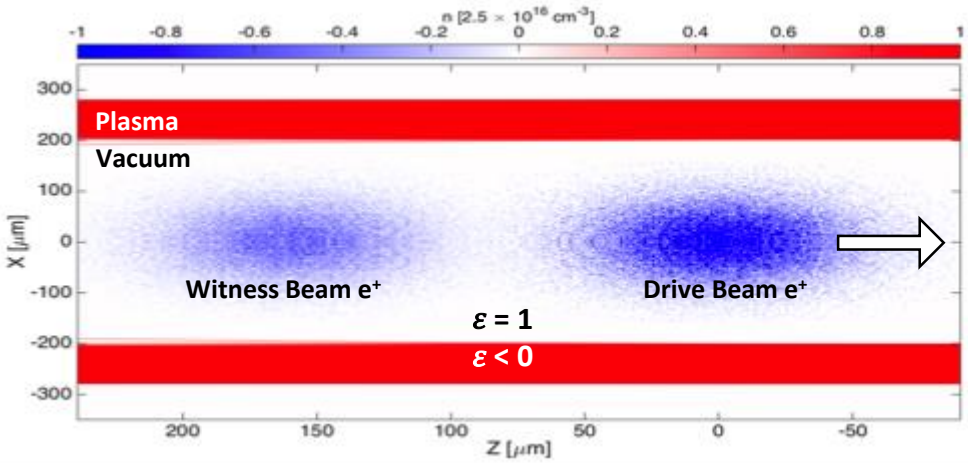
S. Doche *et al.*, Nat. Sci. Rep. 7, 14180 (2017)

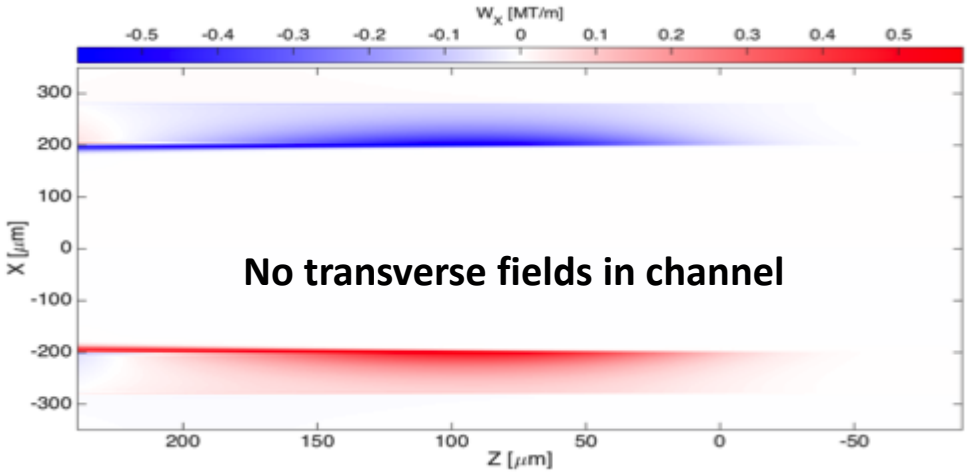
Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake

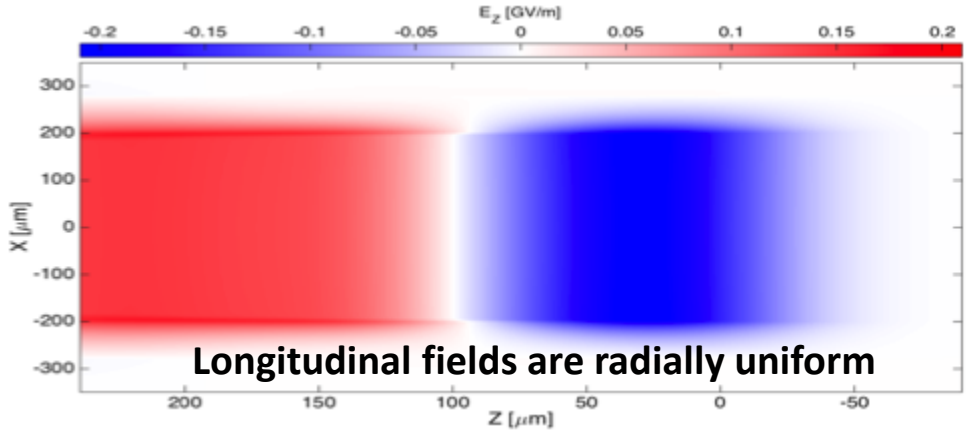
Positron Acceleration in Hollow Channel at FACET



- There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.
- Treat the plasma as dielectric



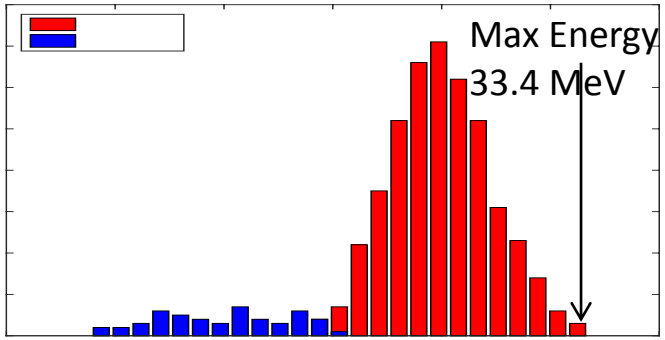




Positron Acceleration in Hollow Channel at FACET, 2016, 2018

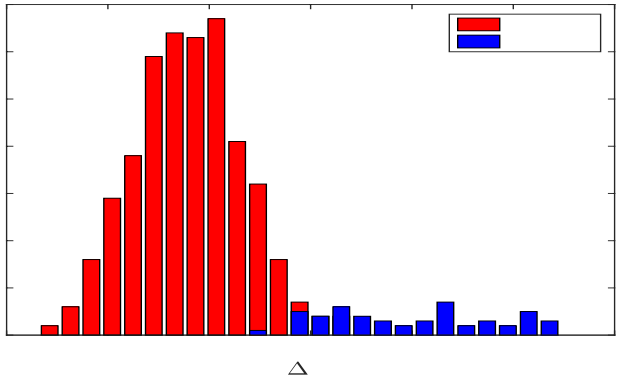
First Demonstration of Acceleration in Hollow channel

Mean <ΔE> = 19.9 MeV



Witness beam gains energy from the wake.

Mean <ΔE> = -11.0 MeV



Drive beam transfers energy to witness beam.

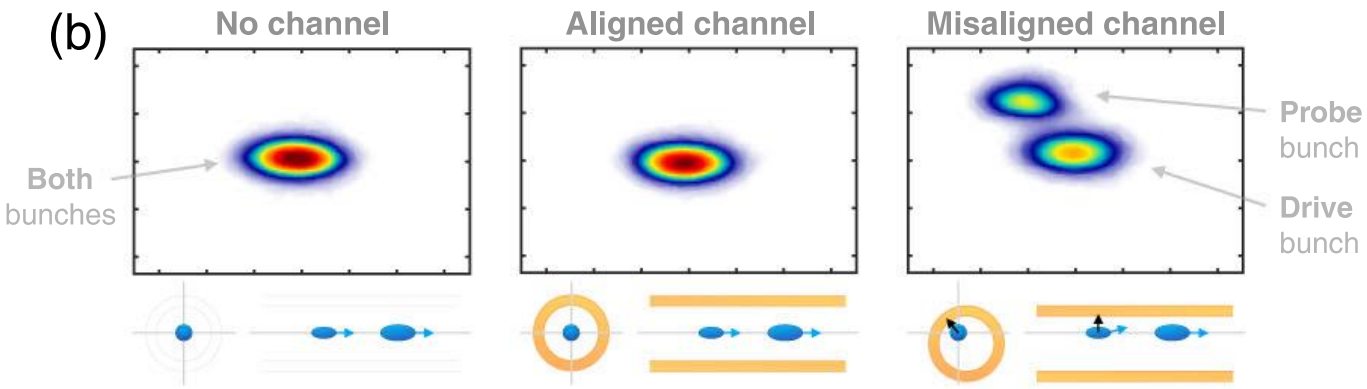
S. Gessner et. al. *Nat. Comm.* 7, 11785 **(2016)**

Measurement of transverse wakefields in hollow channel

→ the result agrees with theoretical calculation:

10^6 V/(pC m mm)

Or about **10,000 times stronger than the wakefields in CLIC!**



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

Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
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- Protons as drive beam

Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:

Lasers: ~40 J/pulse

Electron drive beam: 30 J/bunch

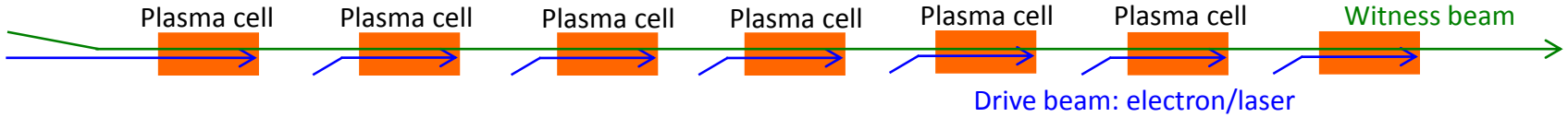
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

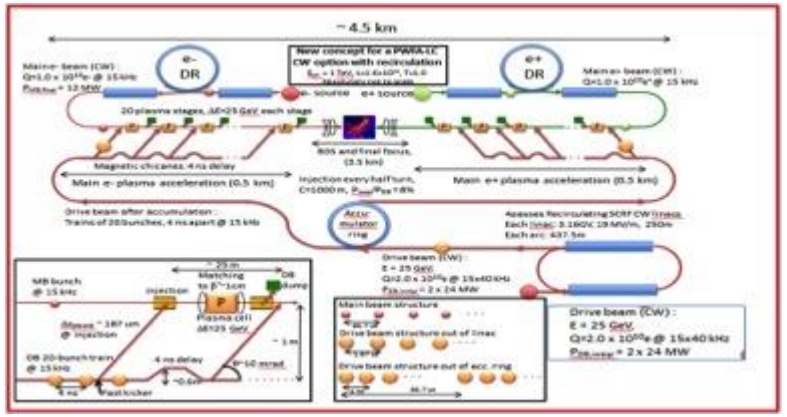
Witness beams:

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

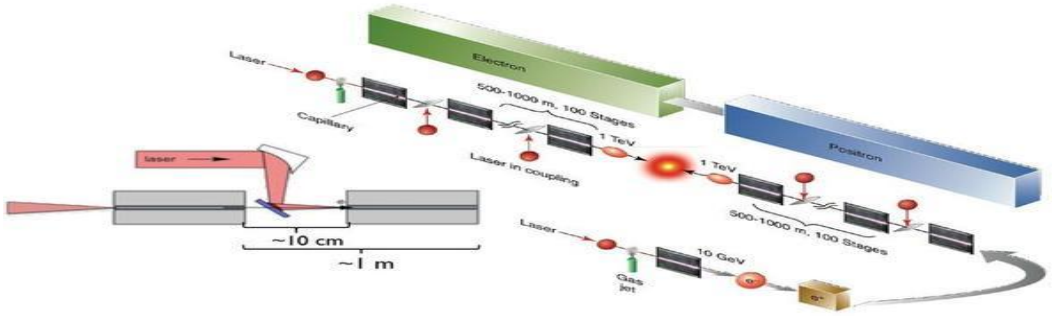
To reach TeV scale:

- **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

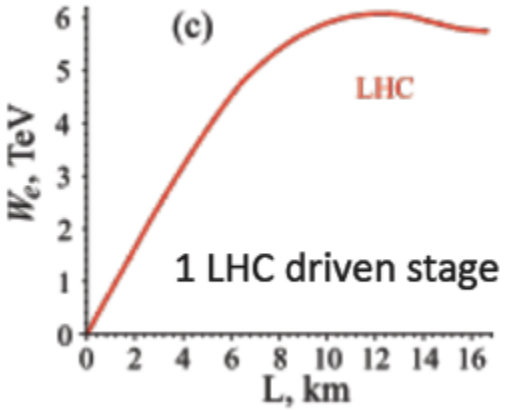
Witness beams:
Electrons: 10^{10} particles @ 1 TeV ~few kJ

- **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)

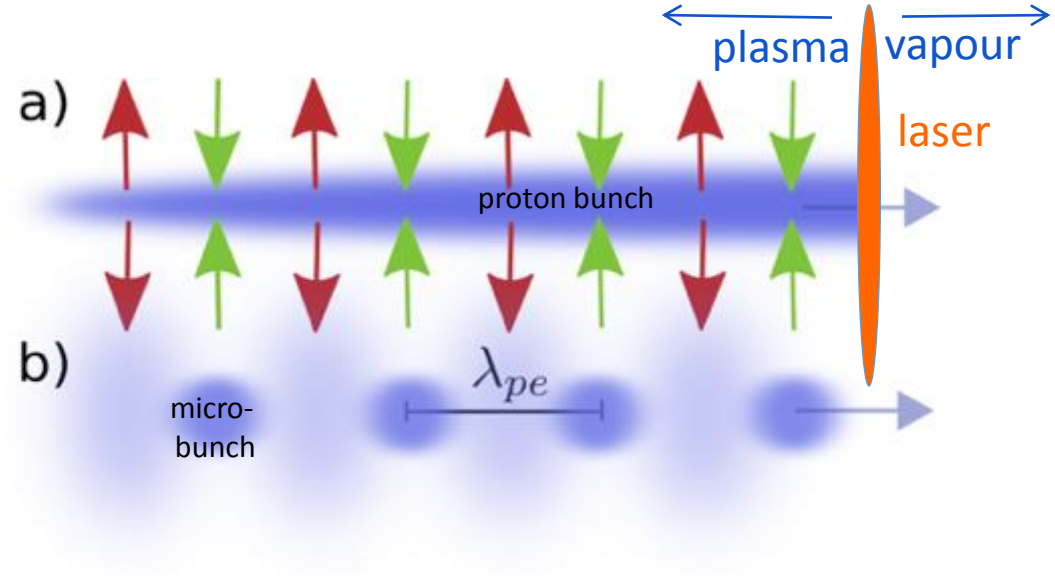
Self-Modulation:

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

- **Initial wakefields act back** on the proton bunch itself. → On-axis dens 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.



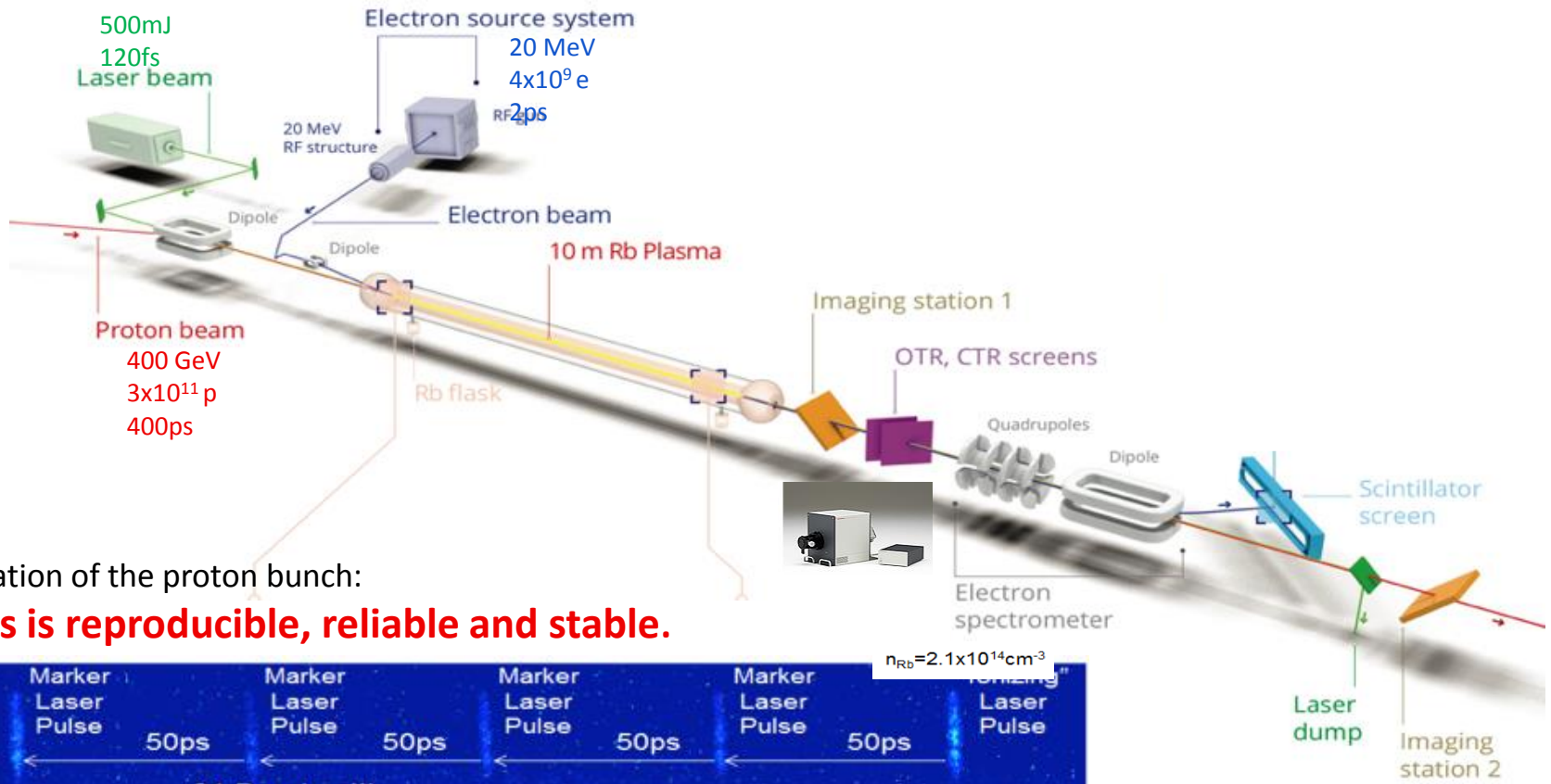
AWAKE: Seeding of the instability by

- Placing a **laser** close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front

➔ Seeded Self-Modulation

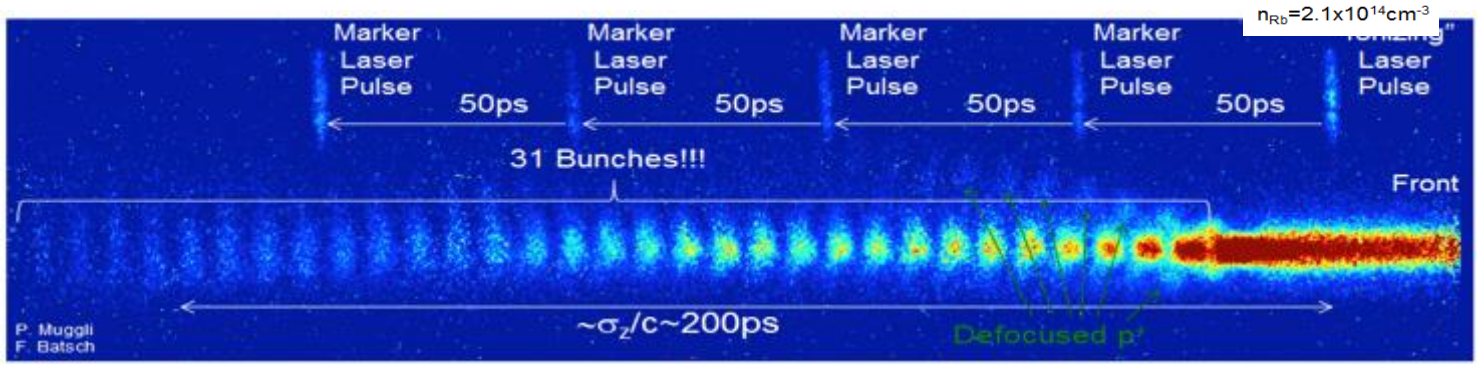
AWAKE, CERN

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.



Seeded self-modulation of the proton bunch:

➔ **SSM process is reproducible, reliable and stable.**



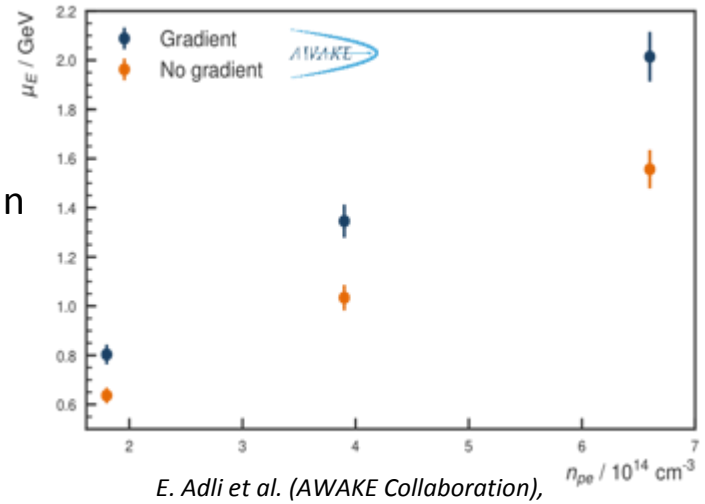
E. Adli et al. (AWAKE Collaboration), ***Phys. Rev. Lett. 122, 054802 (2019).***
M. Turner et al. (AWAKE Collaboration) ***PRL, 122, 054801 (2019).***

AWAKE, CERN

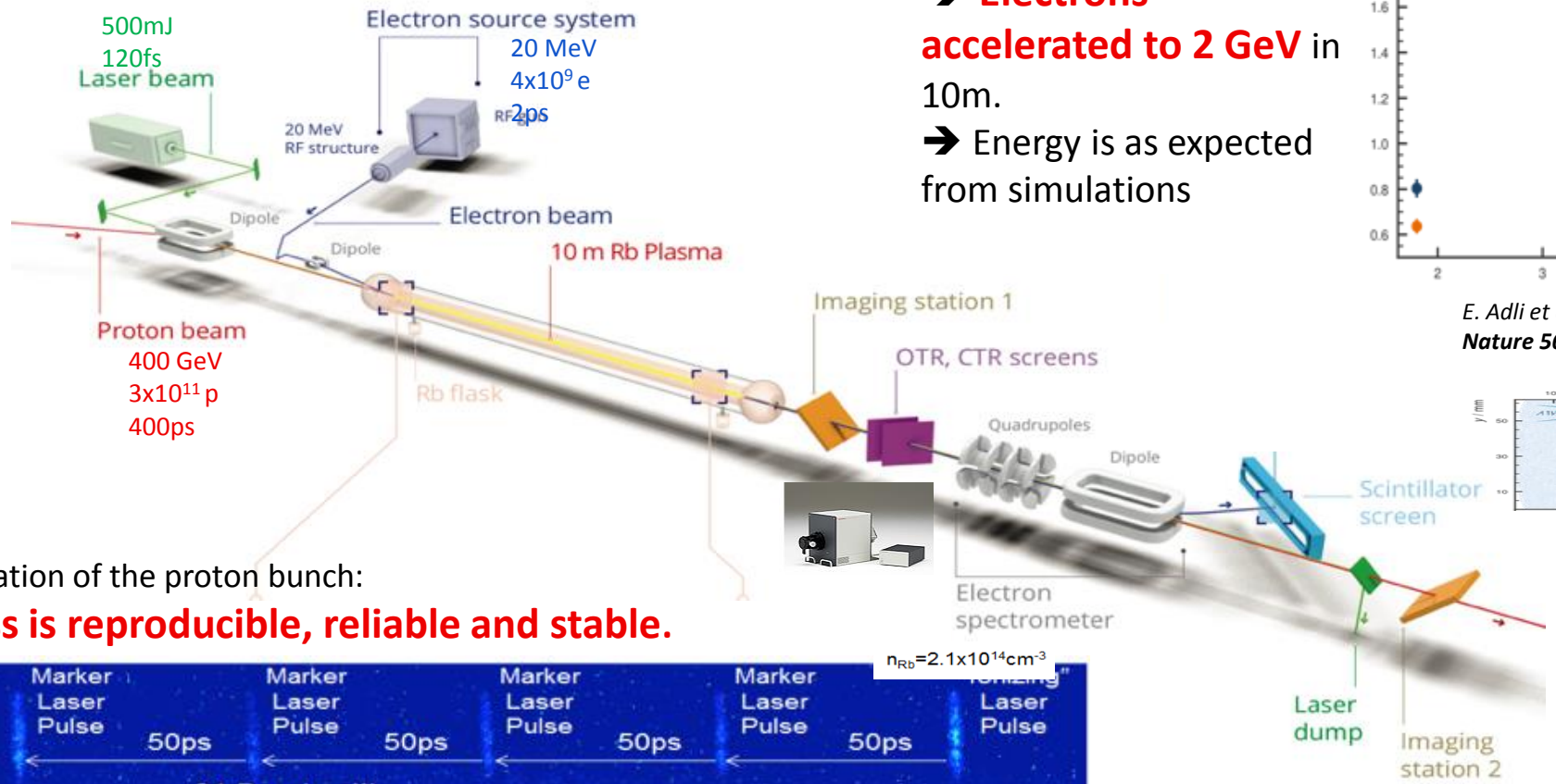
AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

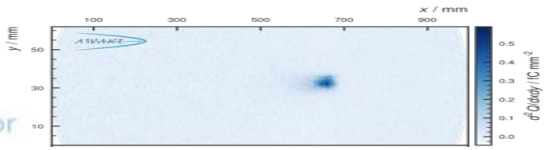
➔ **Electrons accelerated to 2 GeV** in 10m.

➔ Energy is as expected from simulations



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





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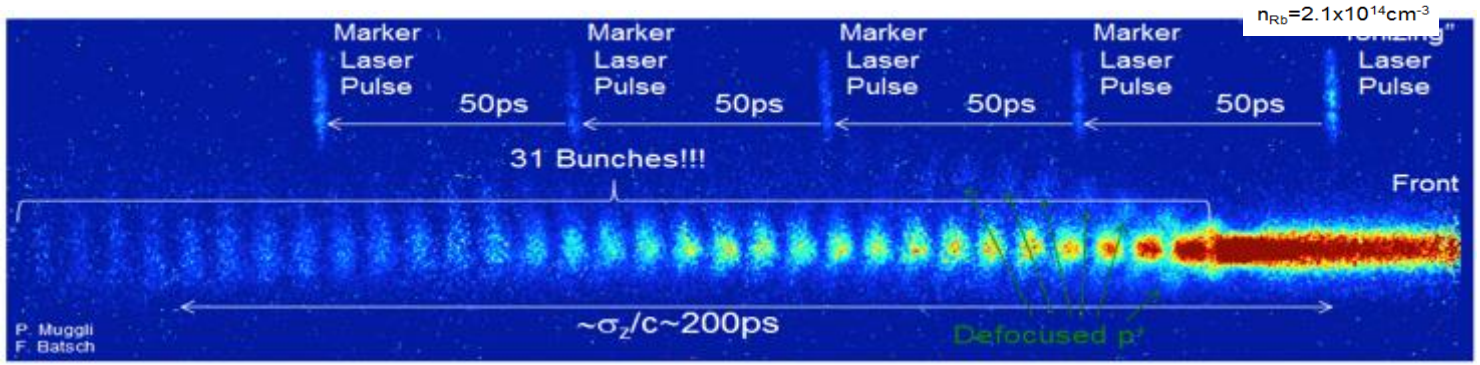


E. Adli et al. (AWAKE Collaboration), ***Phys. Rev. Lett. 122, 054802 (2019).***

M. Turner et al. (AWAKE Collaboration) ***PRL, 122, 054801 (2019).***

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

Summary

- Remarkable progress in the last decades in beam driven plasma wakefield acceleration.

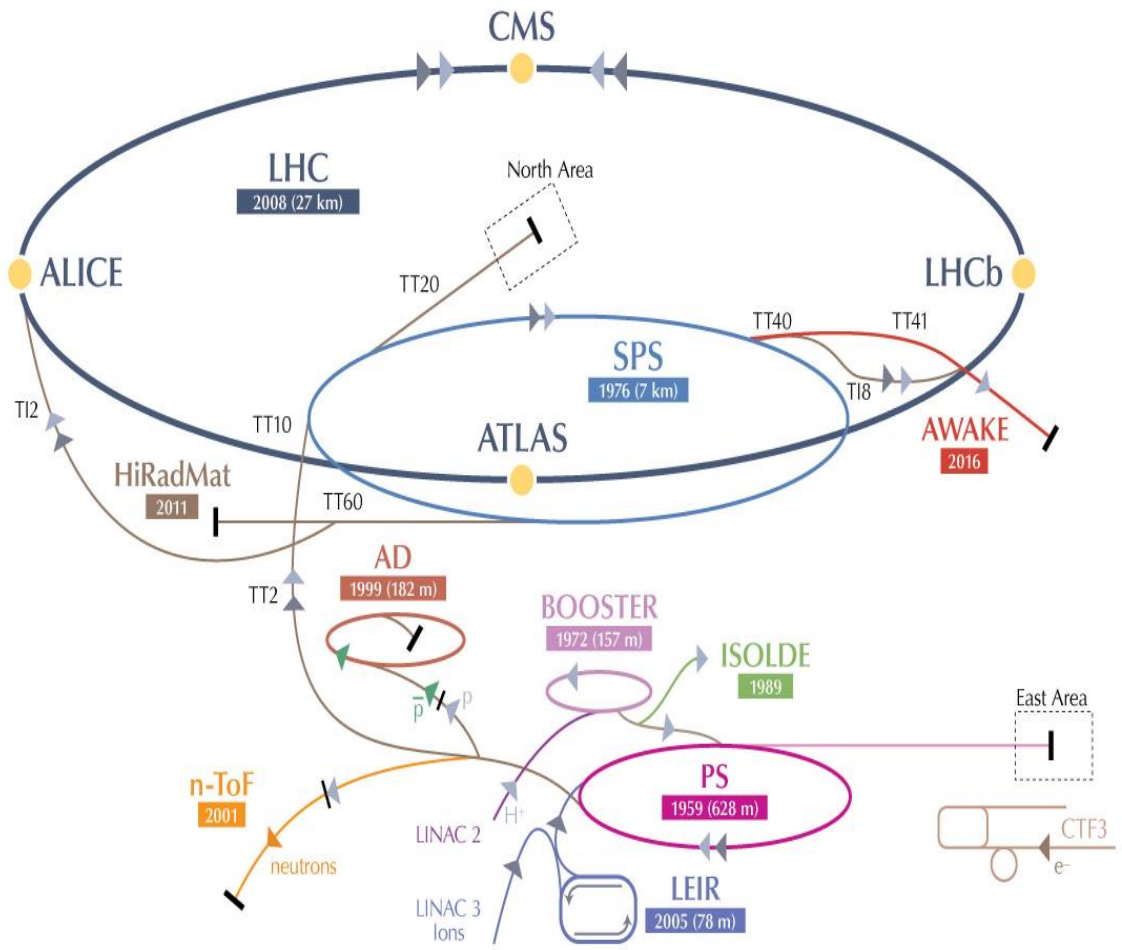
- Much progress needs to be made to reach realistic collider beam parameters.
  - Many facilities will offer new potential for meeting the challenges.

➔ **Lots of opportunities for young students and scientists!!**

Extra Slides

Facilities – AWAKE

AWAKE at CERN



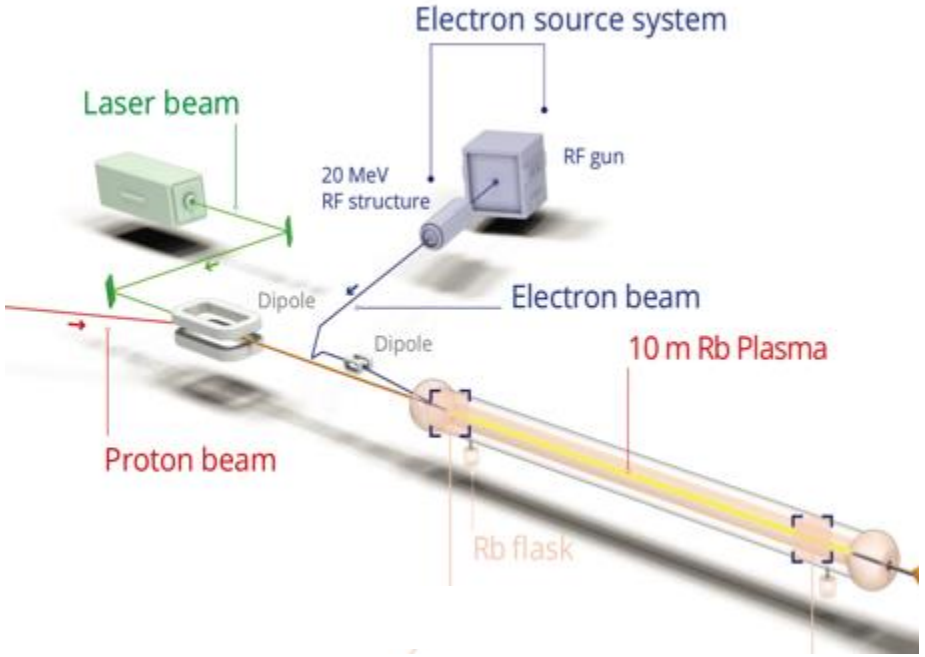
Advanced WAKEfield Experiment

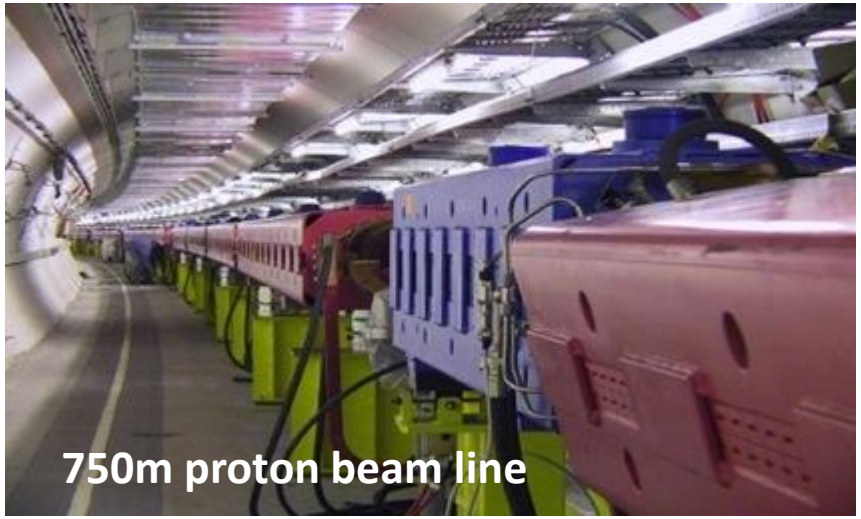
- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First beam end 2016

AWAKE Proton and Laser Beam Line

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

Plasma linear theory: $k_{pe}\,\sigma_r \leq 1$
With $\boldsymbol{\sigma_r = 200\ \mu m}$
$k_{pe} = \omega_{pe}/c = 5\ mm^{-1}$
➔ $\mathbf{n_{pe} = 7x10^{14}\ cm^{-3}}$





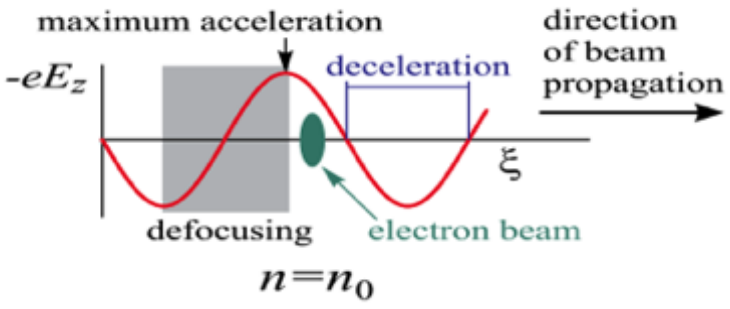
The AWAKE beamline is designed to deliver **a high-quality beam** to the experiment.

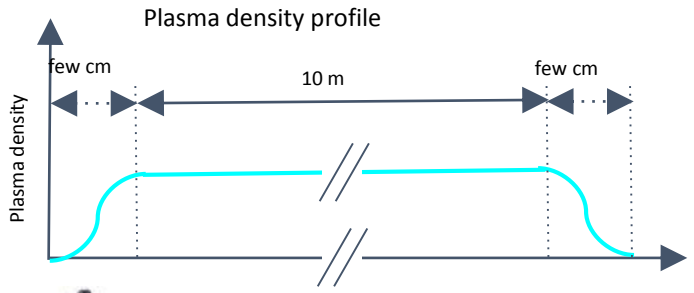
The proton beam must be steered around a mirror which **couples a terawatt class laser (Ti:Saph, 500mJ, 120fs)** into the beamline.

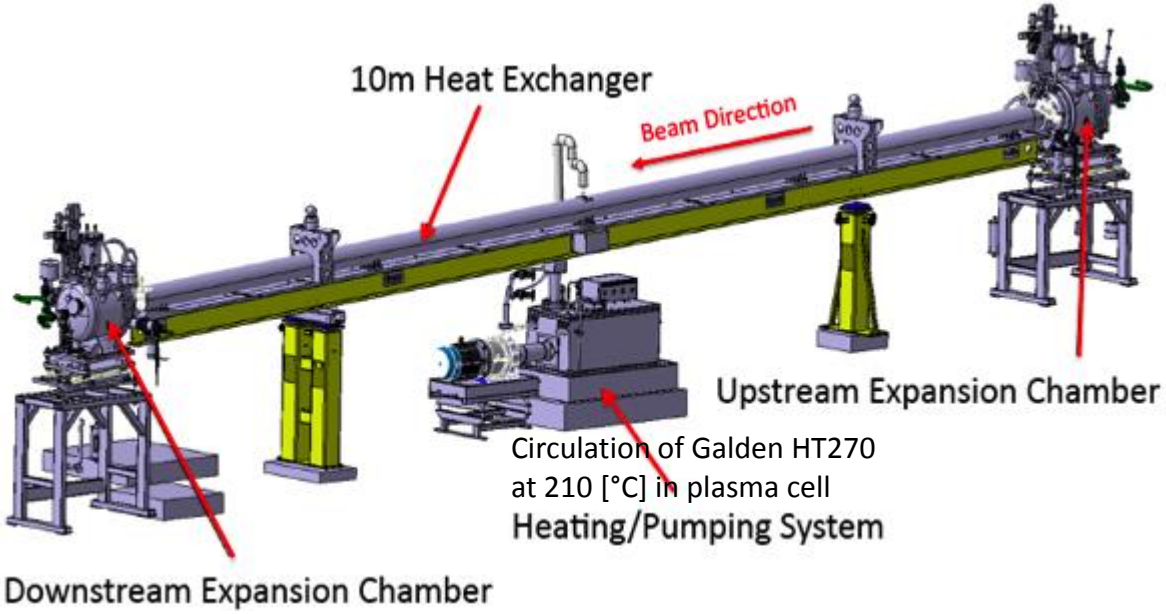
Further downstream, a **trailing electron beam** will injected into the same beamline.

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**

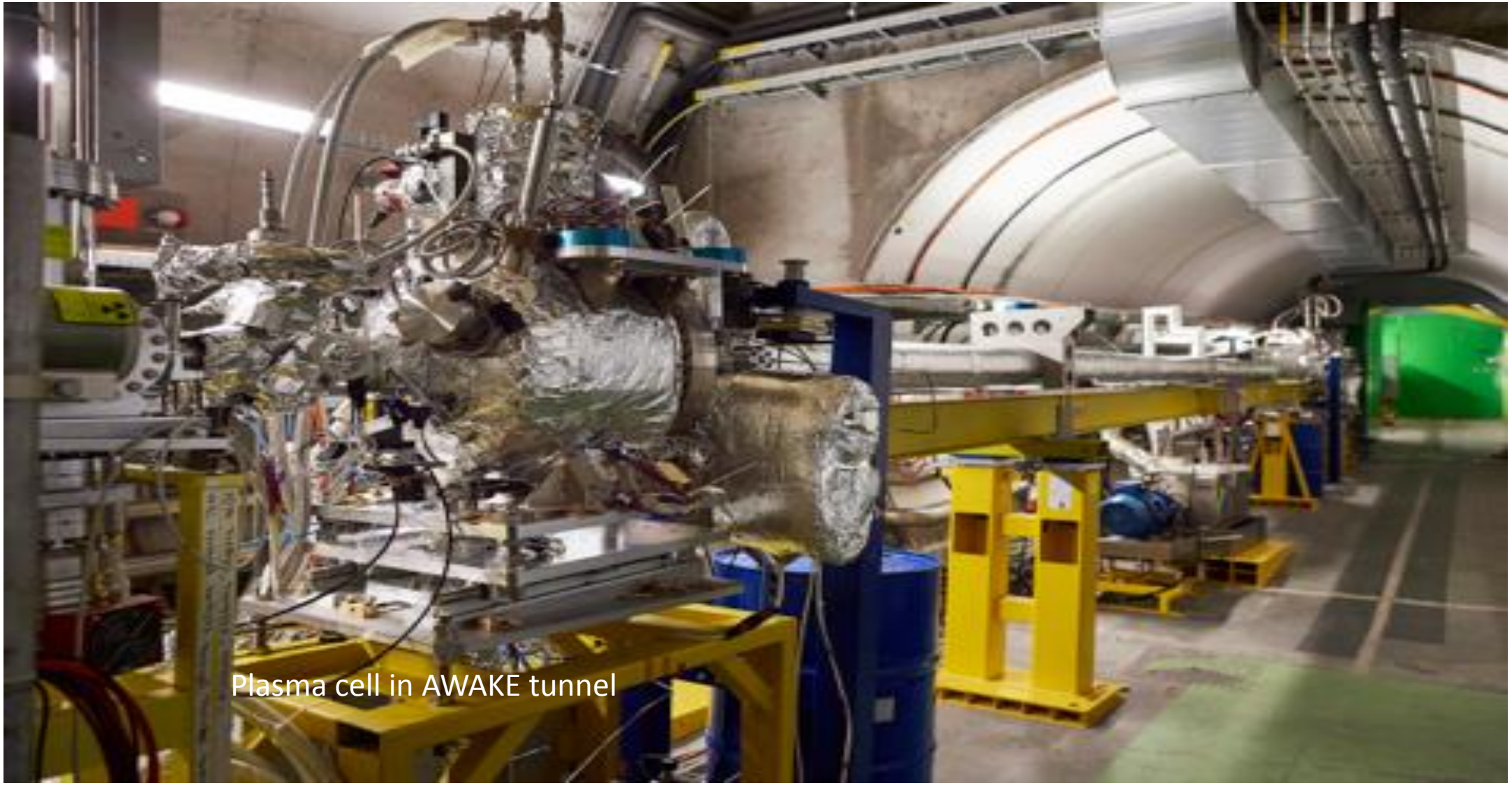




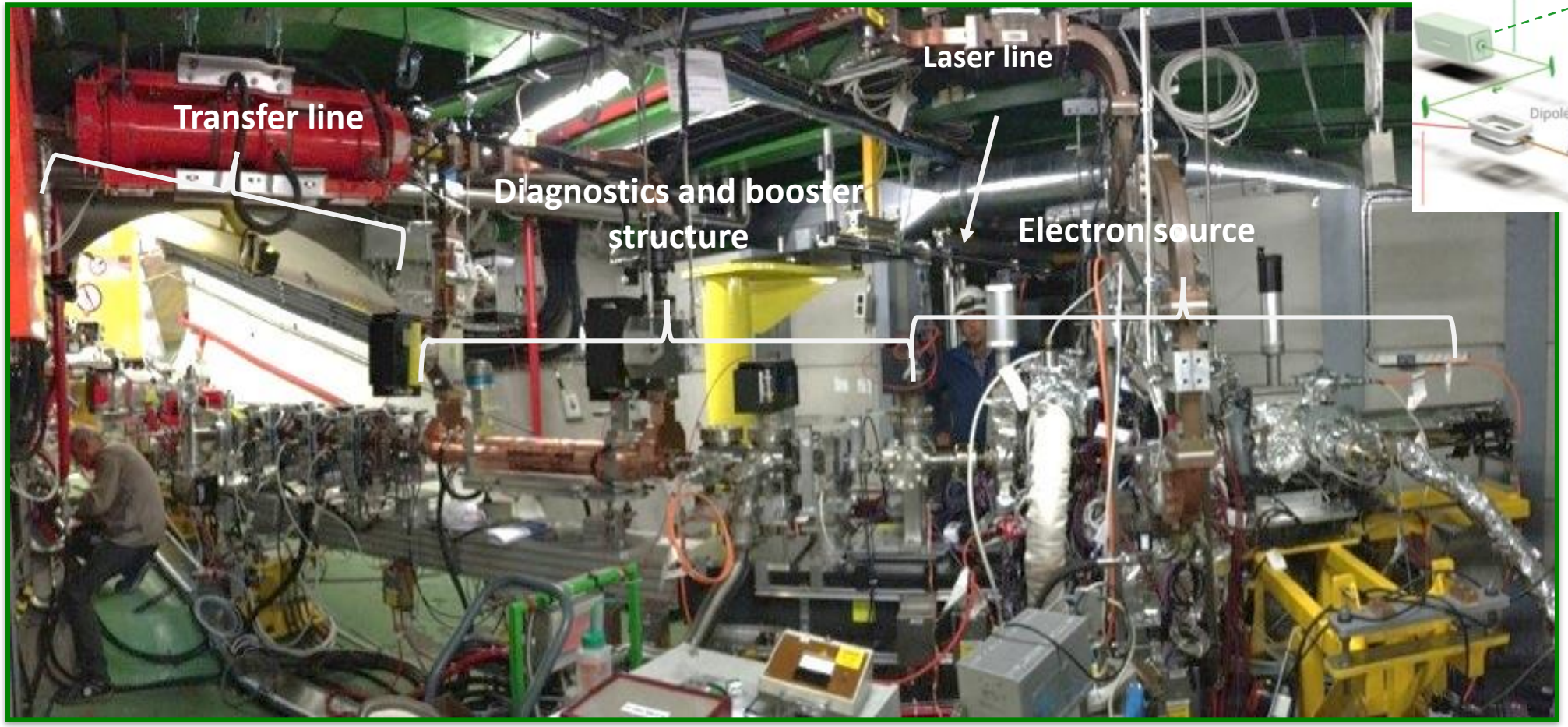


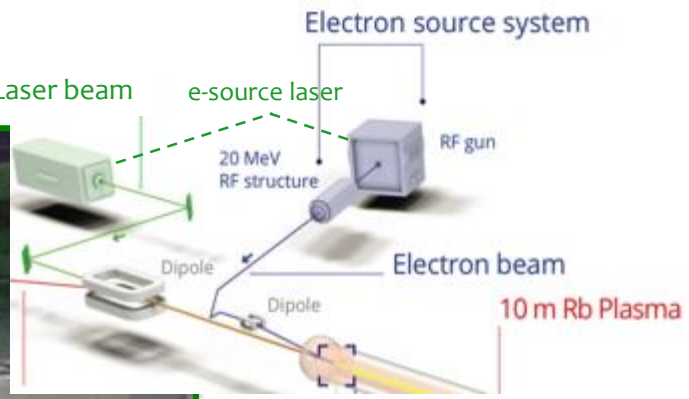
E. Öz et al., NIM A 740(11), 197 (2014)
E. Öz et al., NIM A829, 321 (2016)
F. Batsch et al., NIM A, 909, 359 (2018)

AWAKE Plasma Cell



Electron Beam System



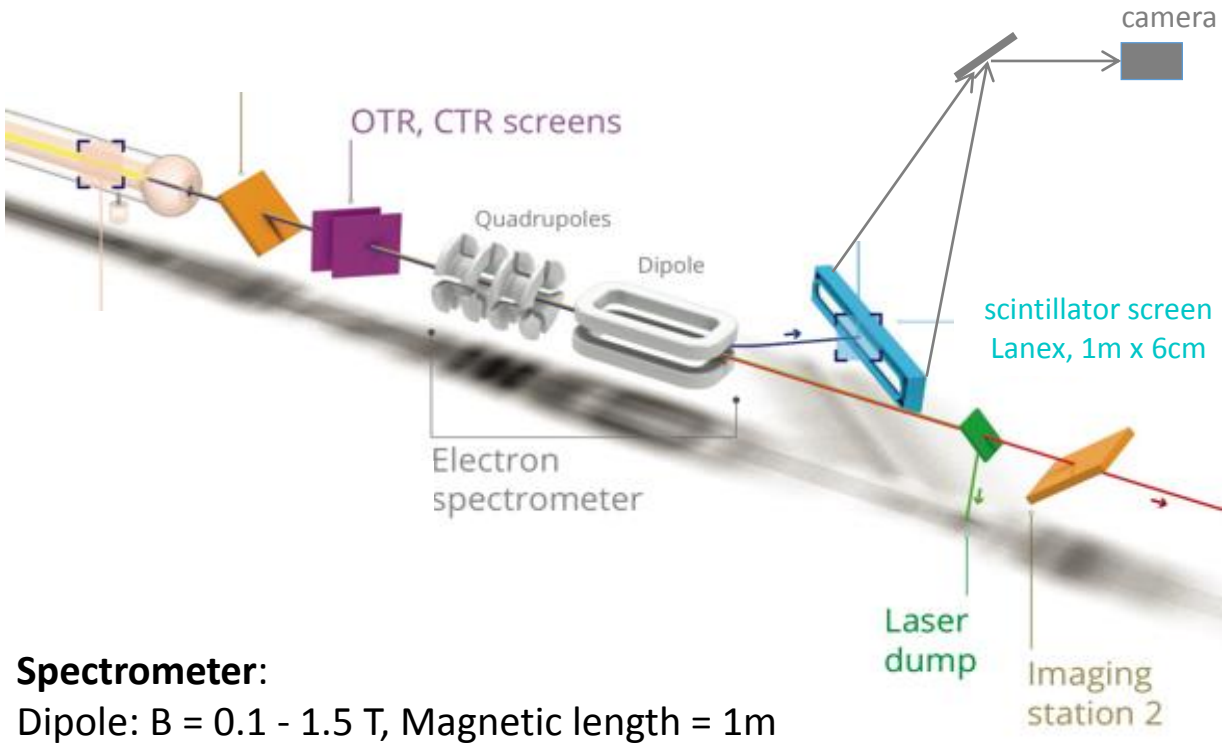


20MeV/c,
σ ~2ps,
~650pC.

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

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

Electron Acceleration Diagnostics



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

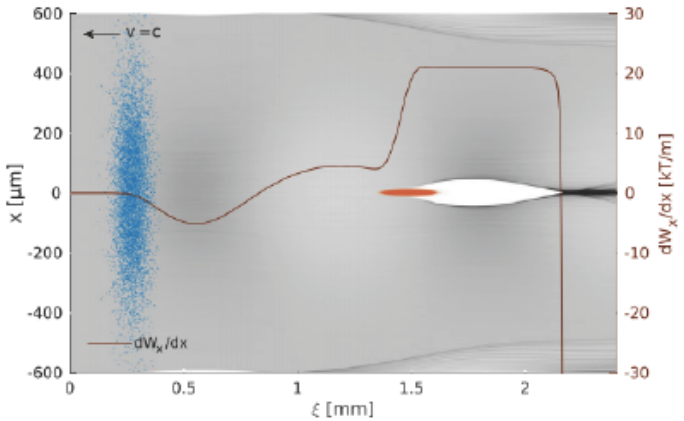
Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a **dipole spectrometer and the dispersed electron impact on the scintillator screen.**
The resulting light is collected with an intensified CCD camera.

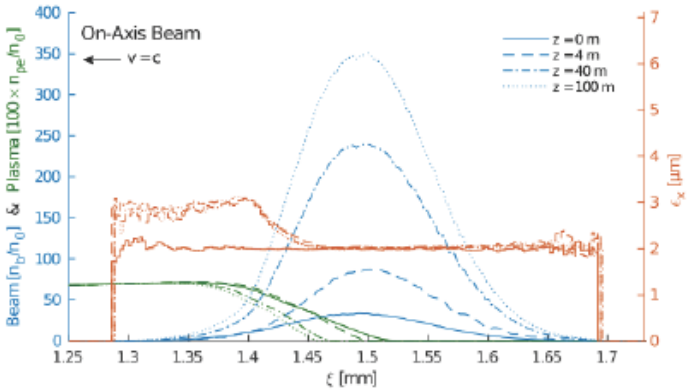
AWAKE Run 2

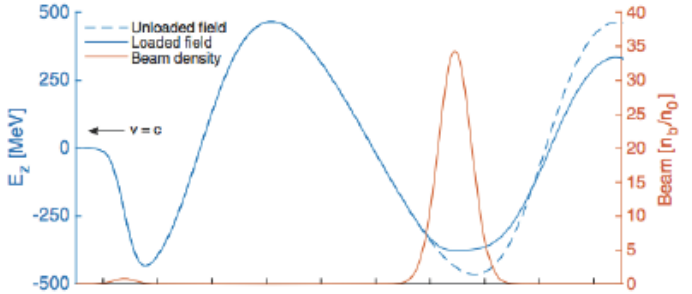
Proposing Run 2 for 2021 after CERN Long Shutdown 2

✧Acceleration of an externally injected e⁻ bunch with small final ε and ΔE/E @ GeV

OLSEN, ADLI, and MUGGLI PHYS. REV. ACCEL. BEAMS **21,** 011301 (2018)







Typical parameters:

σ_z=60μm

σ_r=5.25μm

(matched for ε_N=2mm-mrad, n_e=7x10^{14}cm^{-3}, ~$\varepsilon_N^{1/4}$)

Q=100pC

Blow-out and beam loading

~73% charge with $\Delta\varepsilon_N/\varepsilon_N$<5%, ΔE/E~%

- AWAKE Run 1: Proof-of-Concept
- AWAKE Run 2: Accelerate electron beam to high energy while preserving beam quality so that it can be used for first physics application.

✧Challenging parameters to produce with low energy particles (σ_r,σ_z)

✧Challenging to measure (σ_r)

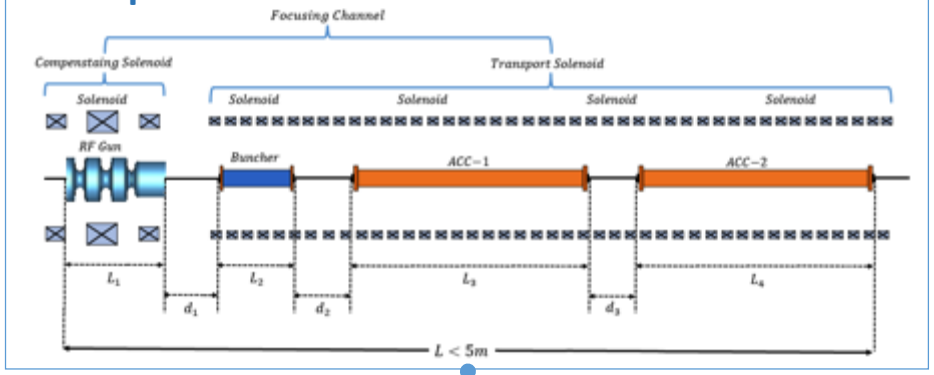
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

Goals:

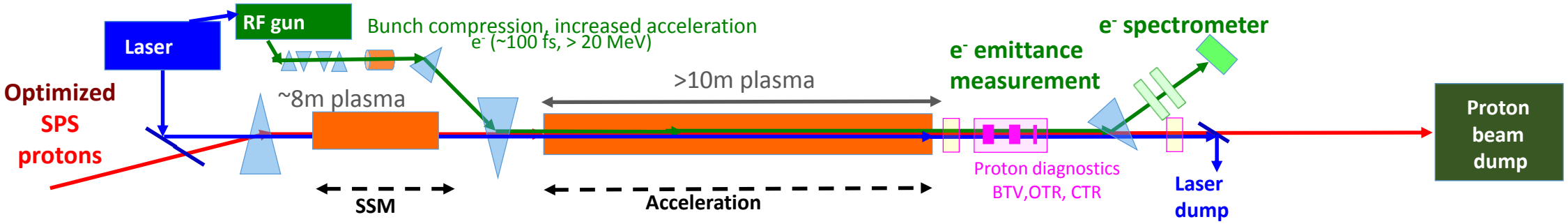
- **Accelerate an electron beam to high energy** (gradient of 0.5-1GV/m)
- **Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)
- **Demonstrate scalability** of the AWAKE concept (R&D plasma sources)

Proposal: 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)