# Particle Accelerators for High Energy Physics Based on Proton-Driven Plasma Wakefields

Colloquium
Brookhaven National Laboratory
September 25, 2025

Allen Caldwell
Max Planck Institute for Physics

# Outline

1. Conventional accelerators - motivation for new approaches

2. Plasma-based accelerators

3. The AWAKE solution - modulated proton bunches

4. Beyond AWAKE $\rightarrow$ ALiVE

# LHC

## Largest Collider built by Mankind

**Circumference: 26.7 km**

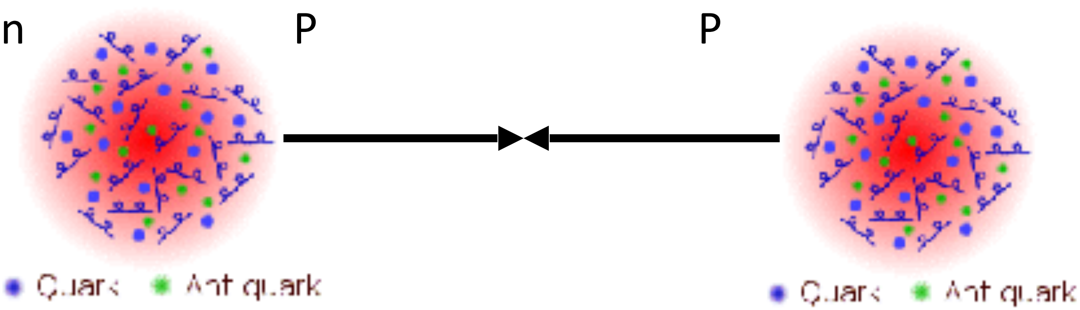
**Particle energy: 7 TeV**

**Luminosity:** $\mathscr{L} \sim 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

**Rate:** $R = \mathscr{L} \cdot \sigma$

# LHC Collides protons

proton P P

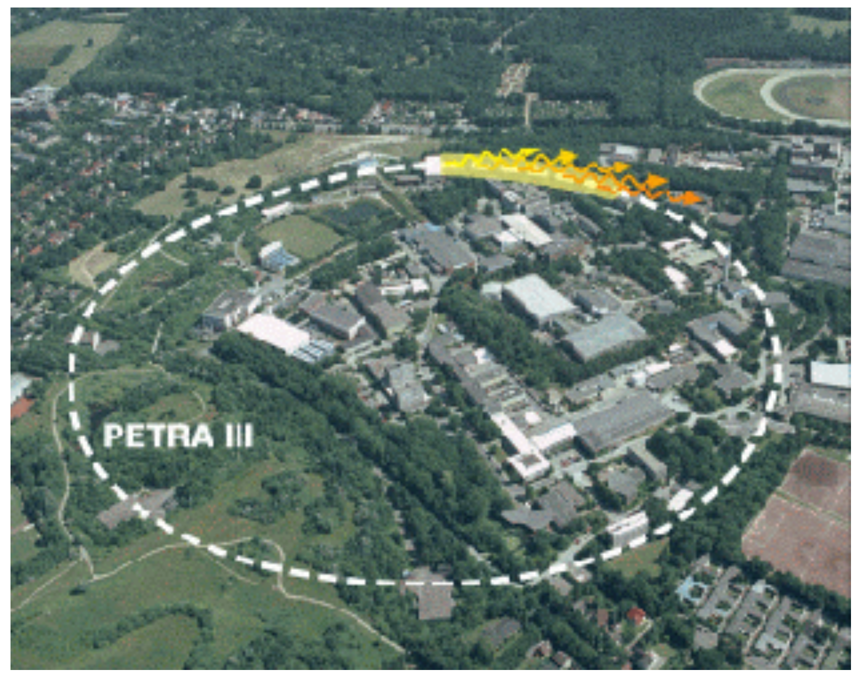


Leptons preferred: Collide point particles rather than complex objects

But, charged particles radiate energy when accelerated.

Power α $(E/m)^4$

Accelerating electrons and positrons in a circular accelerator hits energy limit.
Muons 200 times heavier! But, lifetime is 2 microseconds



# Larger Circular Accelerators ?

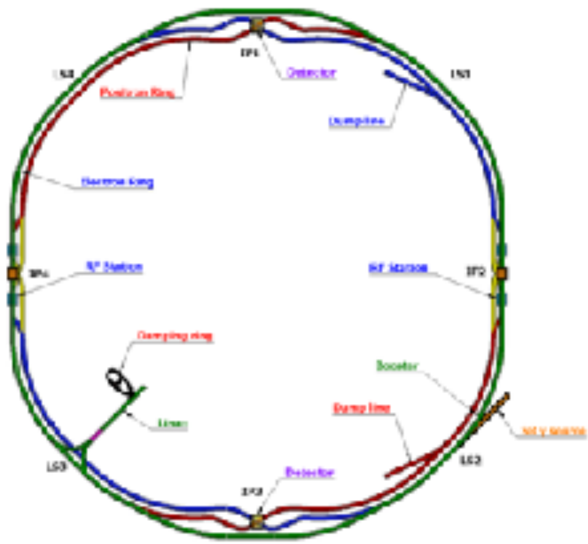


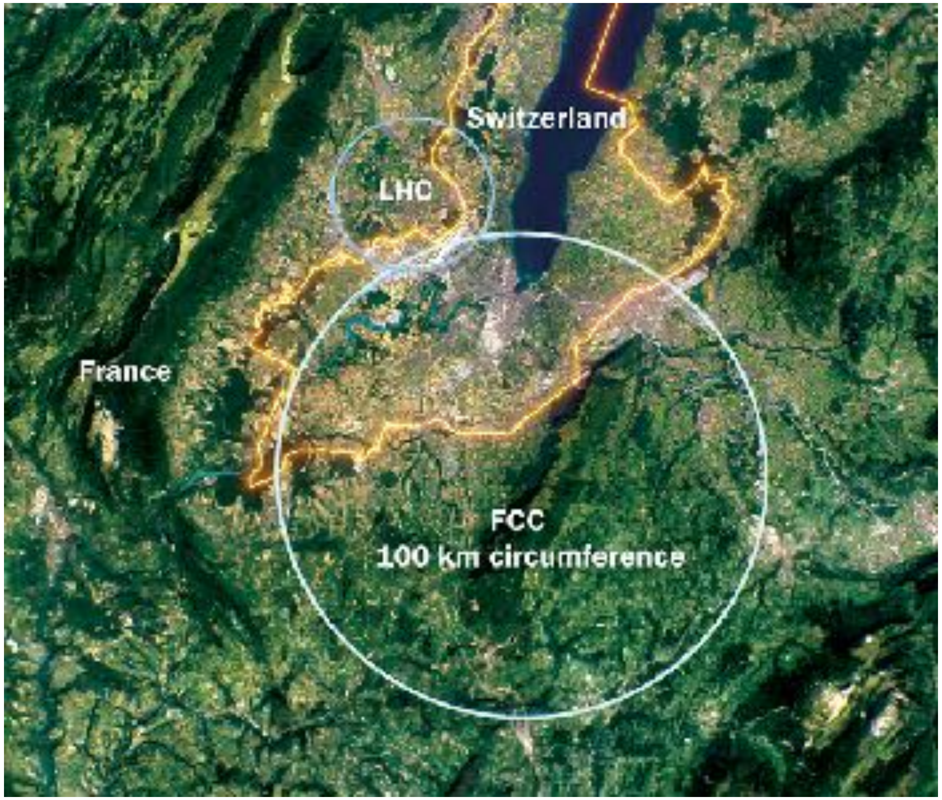
**Table 4.1.2:** CEPC main parameters with 50 MW upgrade

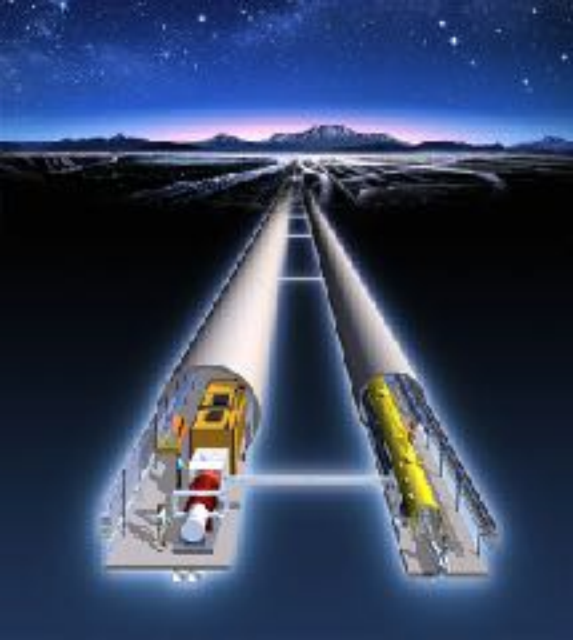
| | Higgs | Z | W |
|---|---|---|---|
| Number of IPs | 2 | | |
| Circumference (km) | 100.0 | | |
| SR power per beam (MW) | 50 | | |
| Half crossing angle at IP (mrad) | 16.5 | | |
| Bending radius (km) | 10.7 | | |
| Energy (GeV) | 120 | 45.5 | 80 |

For protons: energy limit of circular proton collider given by magnetic field strength ($E \propto B \cdot R$)

Energy gain relies in large part on magnet development.  Goal is to reach 50 TeV proton energy. Need 16T magnets in ~100 km tunnel.

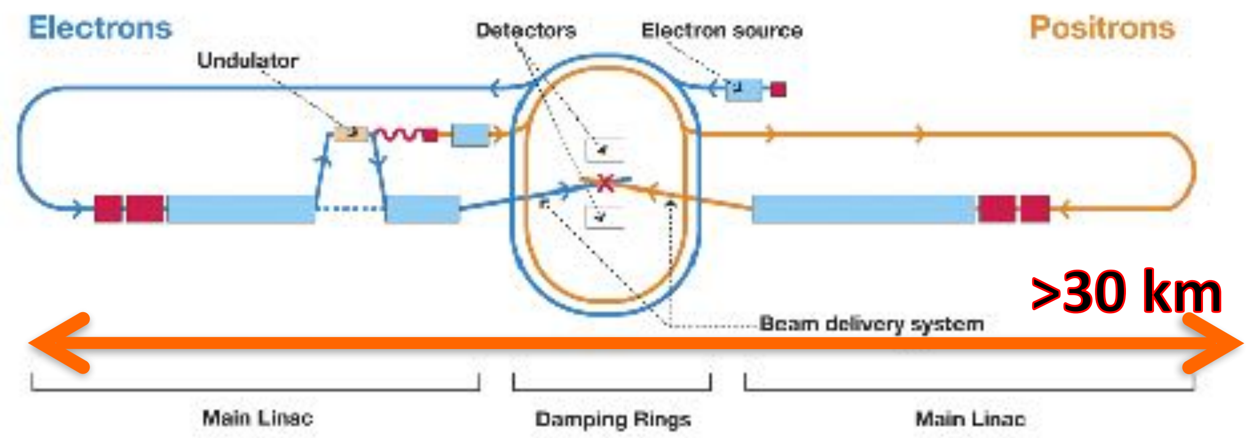
Note: not the most up-to-date layout





# International Linear Collider

**$e^+e^-$ collisions at 250-3000 GeV**




Length determined primarily by maximum acceleration gradient in RF cavities (30 → 100 (?) MV/m). Breakdown limited.

Electron and positron bunches only available one time for collisions:
- to get desired interaction rates, need tiny (nm scale) bunches

To reduce cost, maximize acceleration gradient
- this is where the plasma helps

# Plasma-based acceleration

**A plasma:** collection of free positive and negative charges (ions and electrons). Material is already broken down. A plasma can therefore **sustain very high fields.**

An intense **particle beam**, or intense **laser beam**, can be used to drive the plasma electrons.

Plasma frequency depends only on density:

$$\omega_p^2 = \frac{4\pi n_p e^2}{m} \qquad \lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1\cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

Ideas of **~100 GV/m** electric fields in plasma, using $10^{18}$ W/cm$^2$ lasers: 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979).
Using partice beams as drivers: P. **Chen et al**. Phys. Rev. Lett. 54, 693–696 (1985)

# Laser Wakefield Acceleration

Many important applications at few GeV level.

But, acceleration is ***DEPLETION-LIMITED***
i.e., the lasers do not have enough energy to accelerate a bunch of particles to very high energies

$$10^{10}\ \text{electrons} \cdot 10^{12}\ \text{eV} \cdot 1.6 \cdot 10^{-19}\ \text{J/eV} = kJ$$

This is orders of magnitude larger than laser energy today[1].

If use several lasers – need to have relative timing in the 10's of fs range

[1] with useful repetition rate; i.e., not the NIF laser

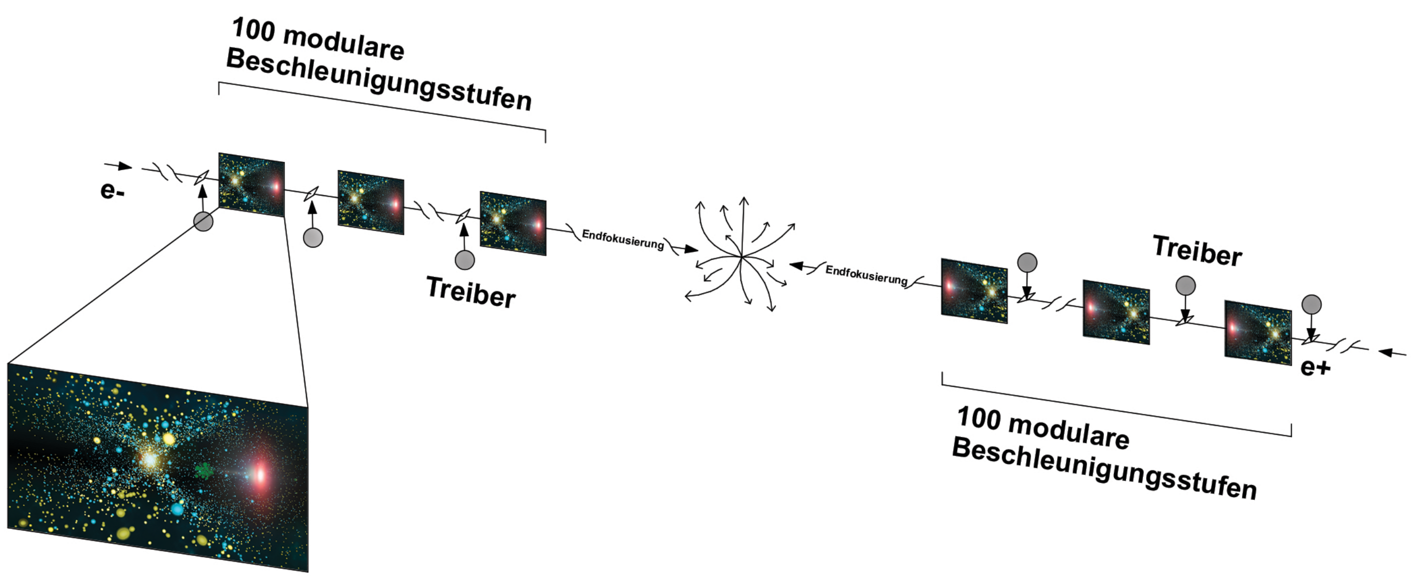
# Beam driven PWA

**driving force:** Space charge of drive beam displaces plasma electrons.
Electrons very effective drivers of plasma wakefields.

But there is a transformer limit theorem (symmetric bunches):

$$R = \frac{\Delta T^{\text{witness}}}{\Delta T^{\text{drive}}} \leq 2 \quad \text{T is the kinetic energy}$$

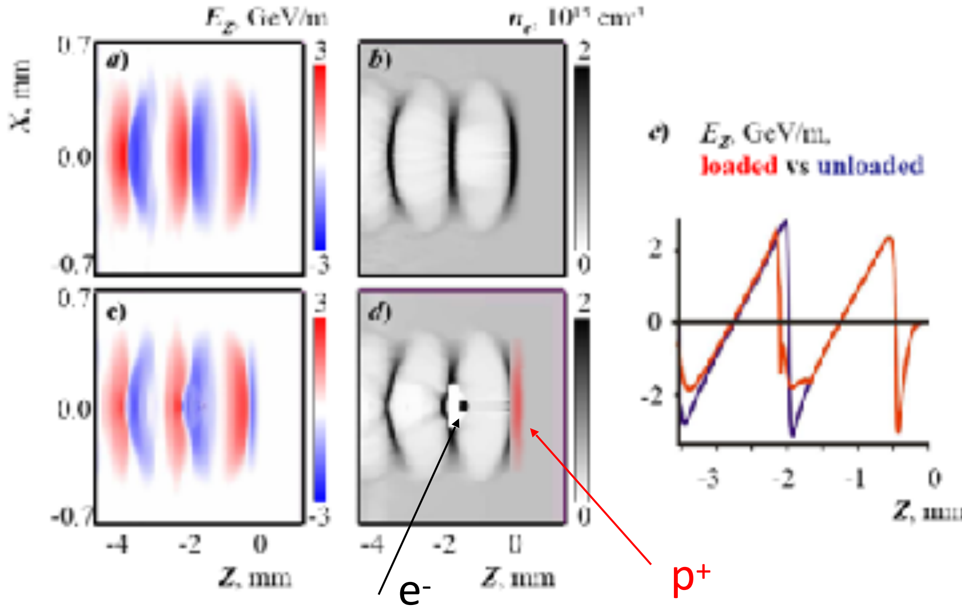
This means many stages required to produce a 1TeV electron beam from known electron beams (E.g., SLAC had 45 GeV)

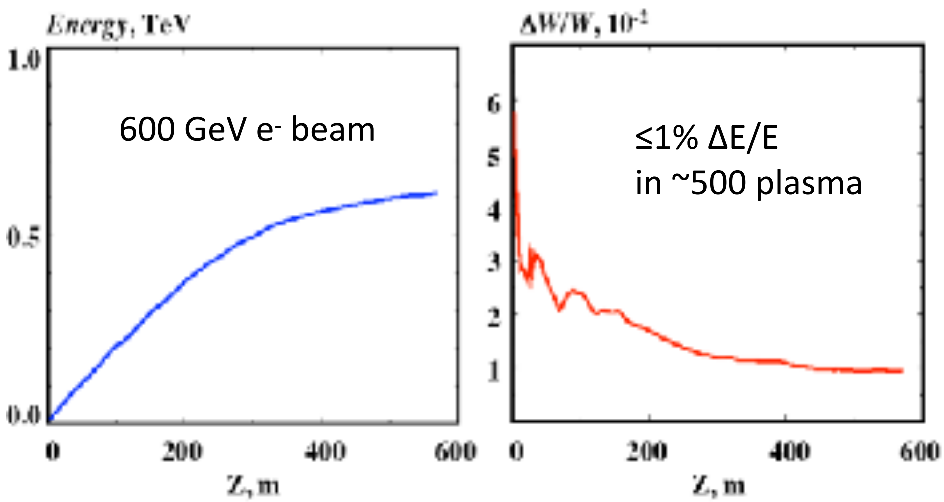


So why not use protons?
High energy proton beams available today

Basic idea:
- Accelerate protons in conventional circular accelerator
- Transfer energy to electrons/positrons in a plasma section

# Proton-driven plasma wakefield acceleration (PDPWA)




**Drive beam: $p^+$**

$E=1$ TeV, $N_p=10^{11}$

$\sigma_z=100\ \mu m$, $\sigma_r=0.43$ mm

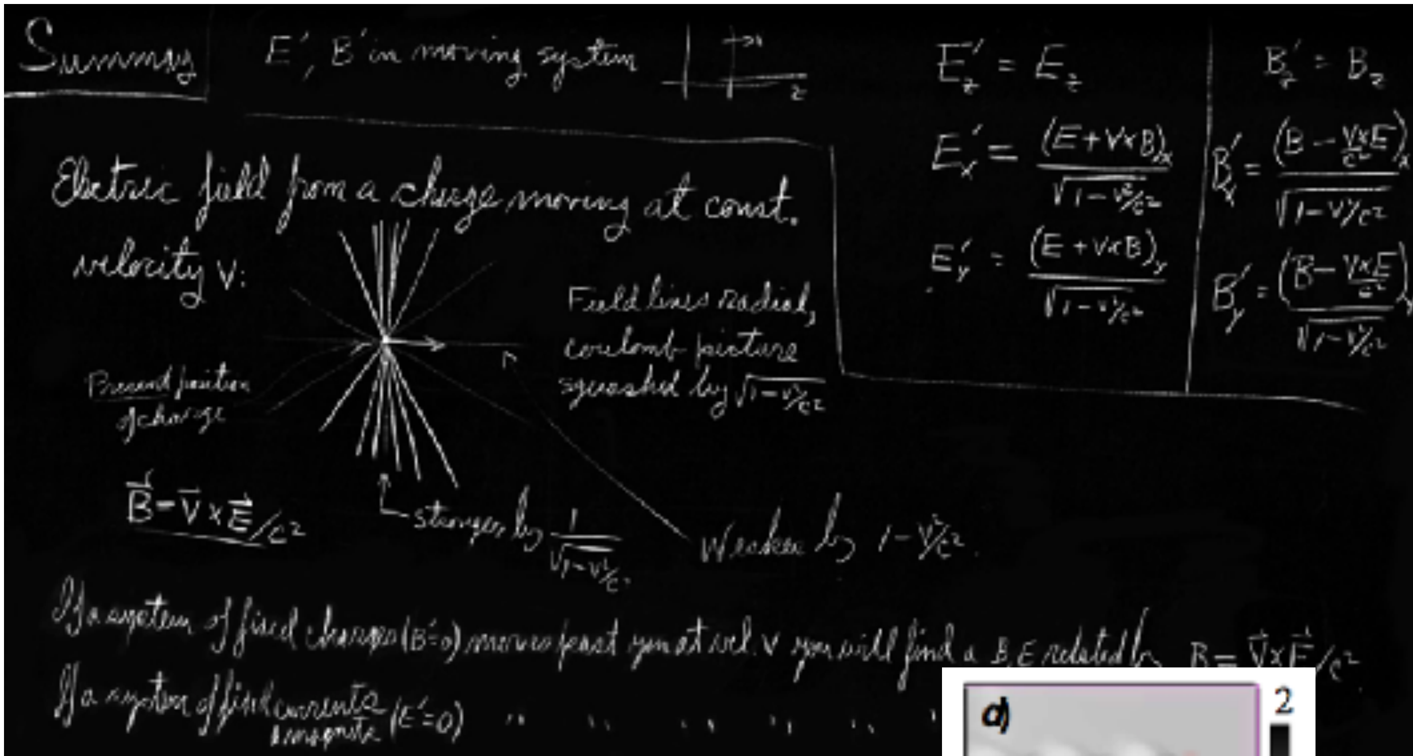
$\sigma_\theta=0.03$ mrad, $\Delta E/E=10\%$

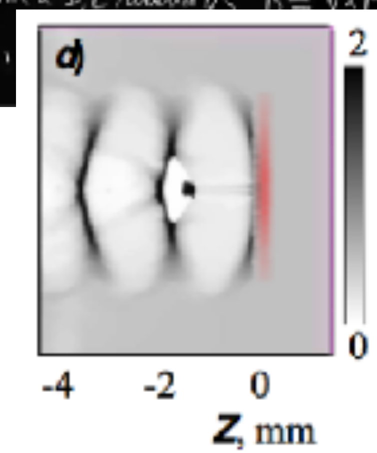
A. Caldwell, K. Lotov, A. Pukhov, F. Simon, *Nature Physics* ***5, 363 - 367 (2009)***

# Basic Aspects

Small beam dimensions required !

Feynman Lectures, CalTech




$$E_{z,\max} \approx 2\ \mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100\ \mu\mathrm{m}}{\sigma_z}\right)^2$$

Today's proton beams have $\sigma_z \approx 10 - 30\ \mathrm{cm}$

# Basic Aspects

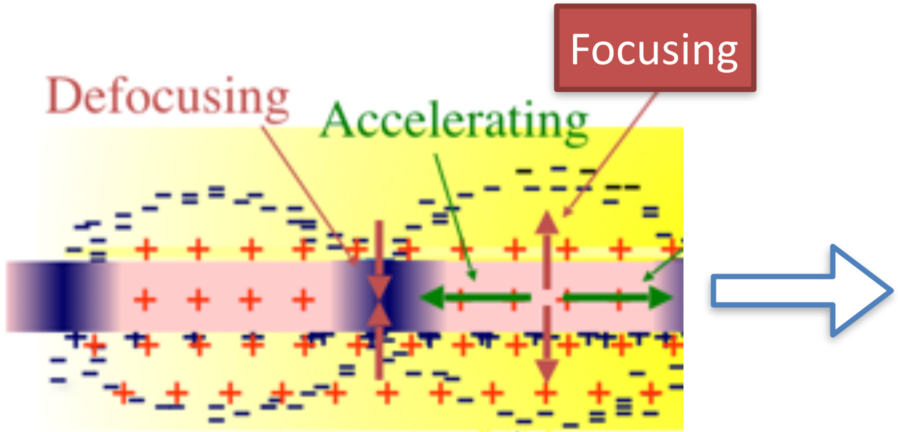



Figure: Patric Muggli

Proton

Electron

Do the electrons outrun the protons ?

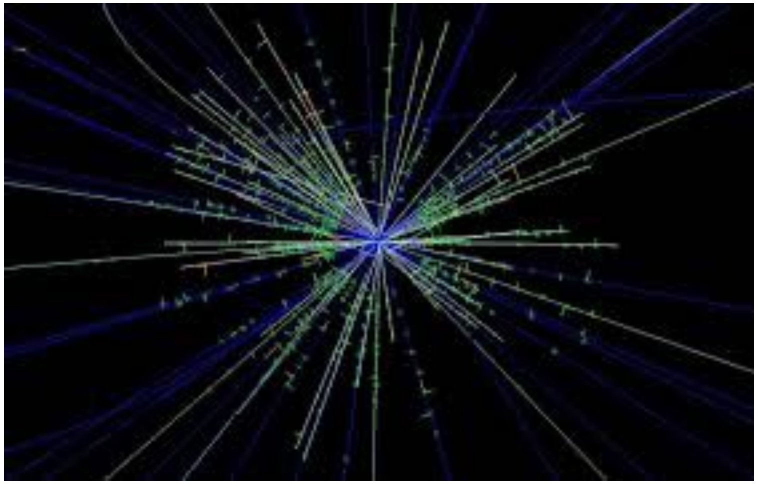
$$\delta \approx \frac{\pi L}{\lambda_p} \frac{1}{\gamma^2}$$

Phase slippage (protons 2000 times heavier than electrons) ?

# Basic Aspects

Proton (QCD) interactions ?

LHCb event display

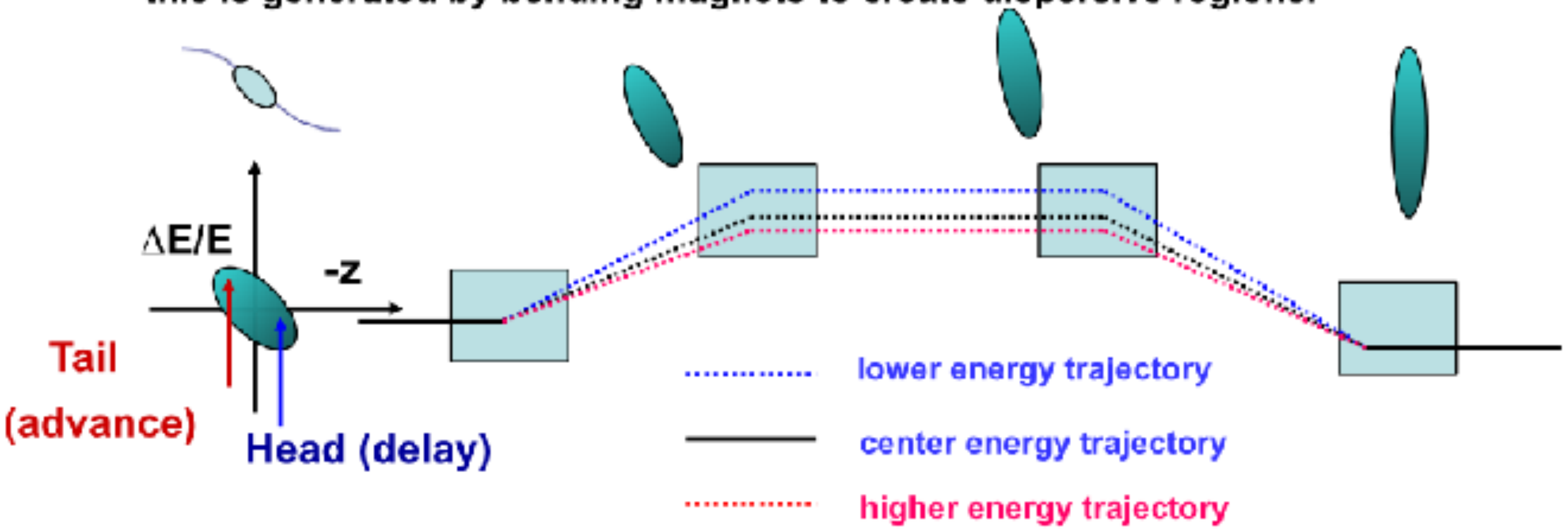


$$\lambda = \frac{1}{n\sigma} \quad n = 1 \cdot 10^{15}\ \mathrm{cm}^{-3} \quad \Rightarrow \lambda > 1000\ \mathrm{km}$$

Fundamental issue: **proton bunch length**. Can we squeeze the protons together to increase the electric field strength & plasma Wakefield ?

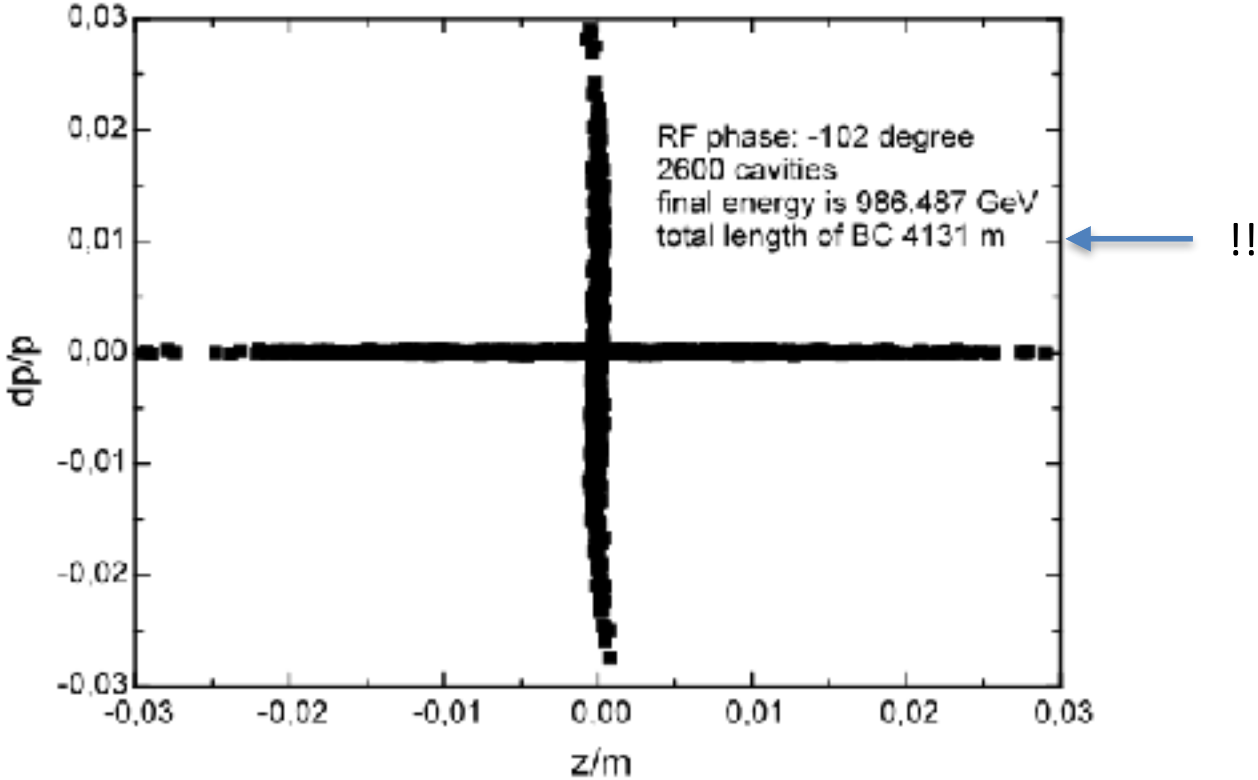
# Magnetic bunch compression (BC)

- Beam compression can be achieved:
  (1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  (2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.




- To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.

# Phase space of beam




!!

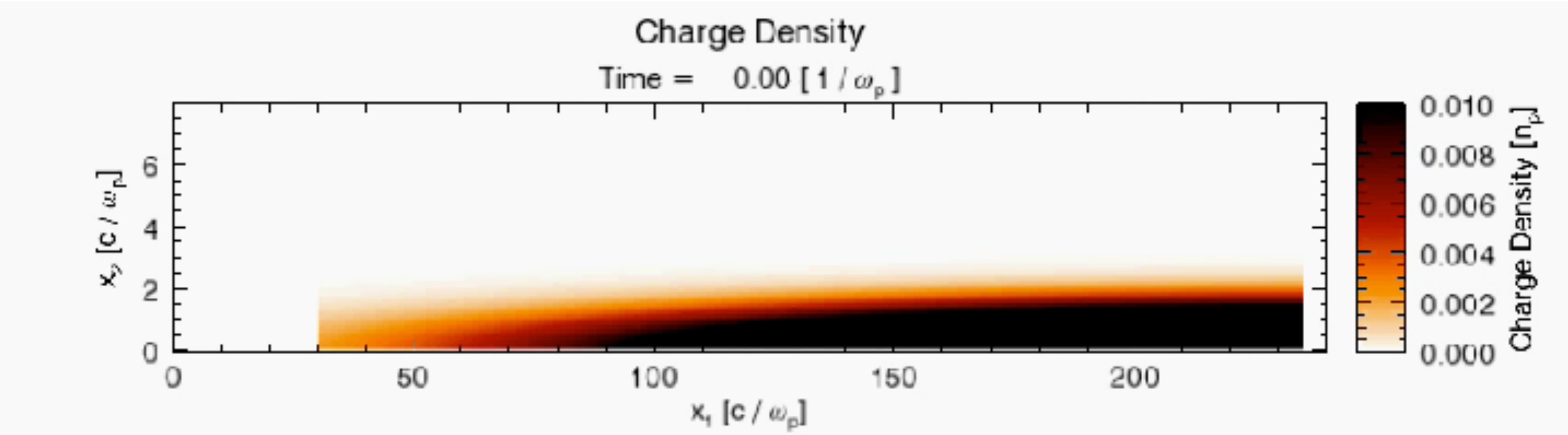
See A. Caldwell, G. Xia et al., Preliminary study of proton driven plasma wakefield acceleration, Proceedings of PAC09, May 3-8, 2009, Vancouver, Canada

# The AWAKE solution

# Modulated Proton Beam

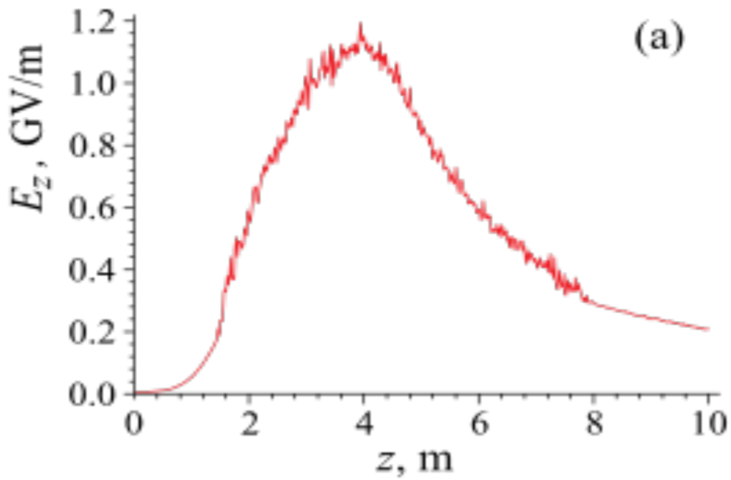
AWAKE Solution ! microbunches are generated by the interaction between the bunch and the plasma. The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.

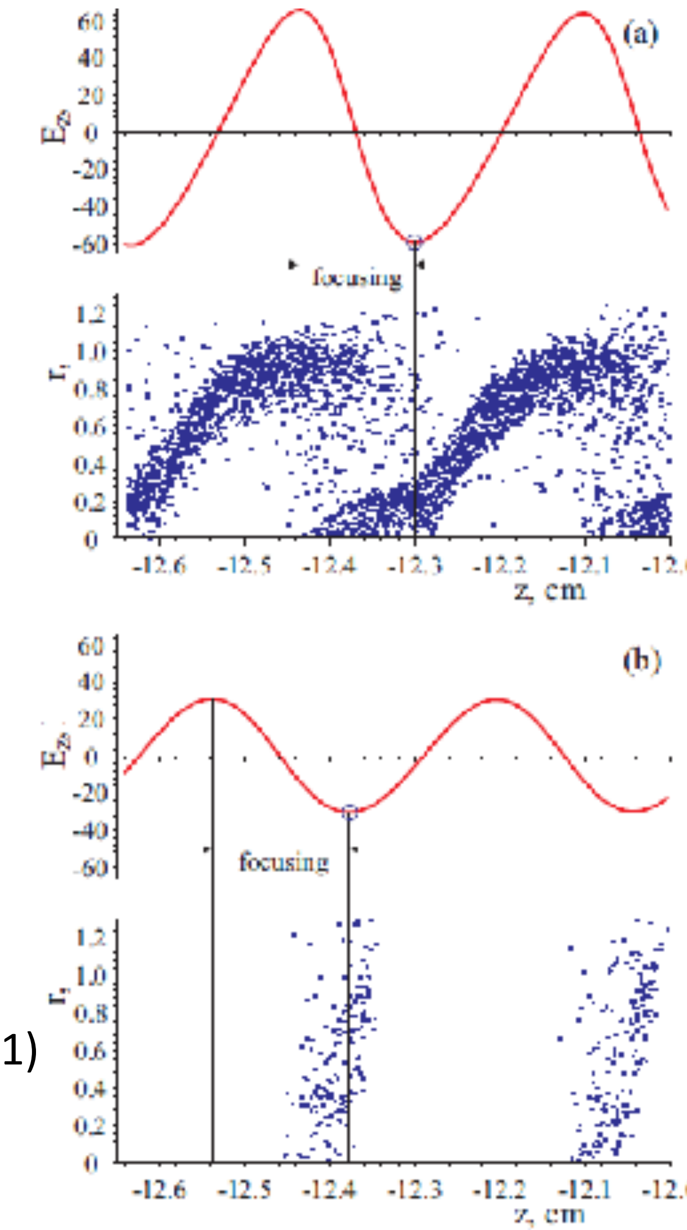
N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)




Propagation of a ‘cut’ proton bunch in a plasma. From Wei Lu, Tsinghua University

# Freezing the Modulation



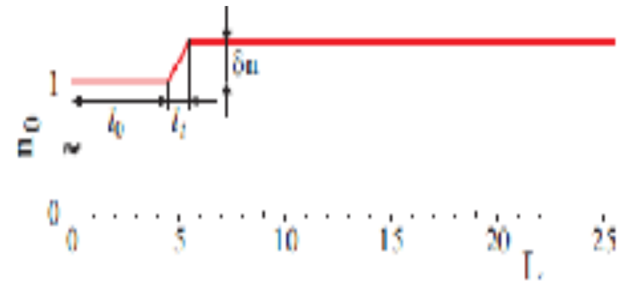

... wakefield amplitude quickly drops after the beam gets modulated.

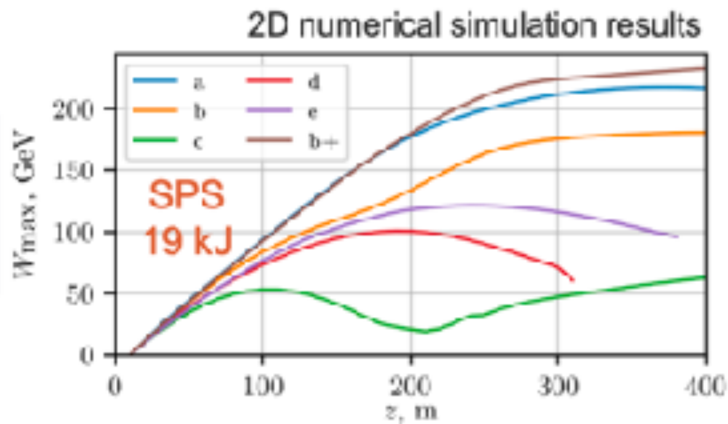
Reason: defocusing regions keep on moving along the beam and destroys the bunches.

A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

# Freezing the Modulation

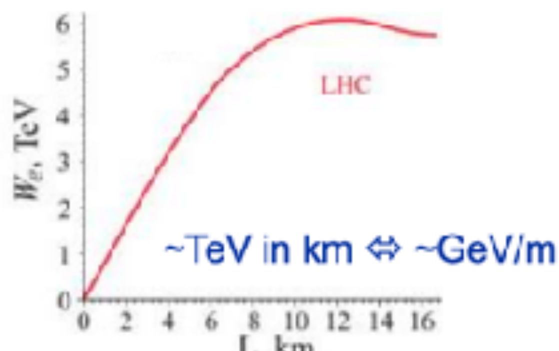
Remedy: control of the wave phase by the plasma density profile




P. Tuev, K. V. Lotov, PPFC 63, 125027 (2021)

**SPS Driver (19 kJ):**
~ 200 GeV in ~200 m
~ $10^9$ $e^-$

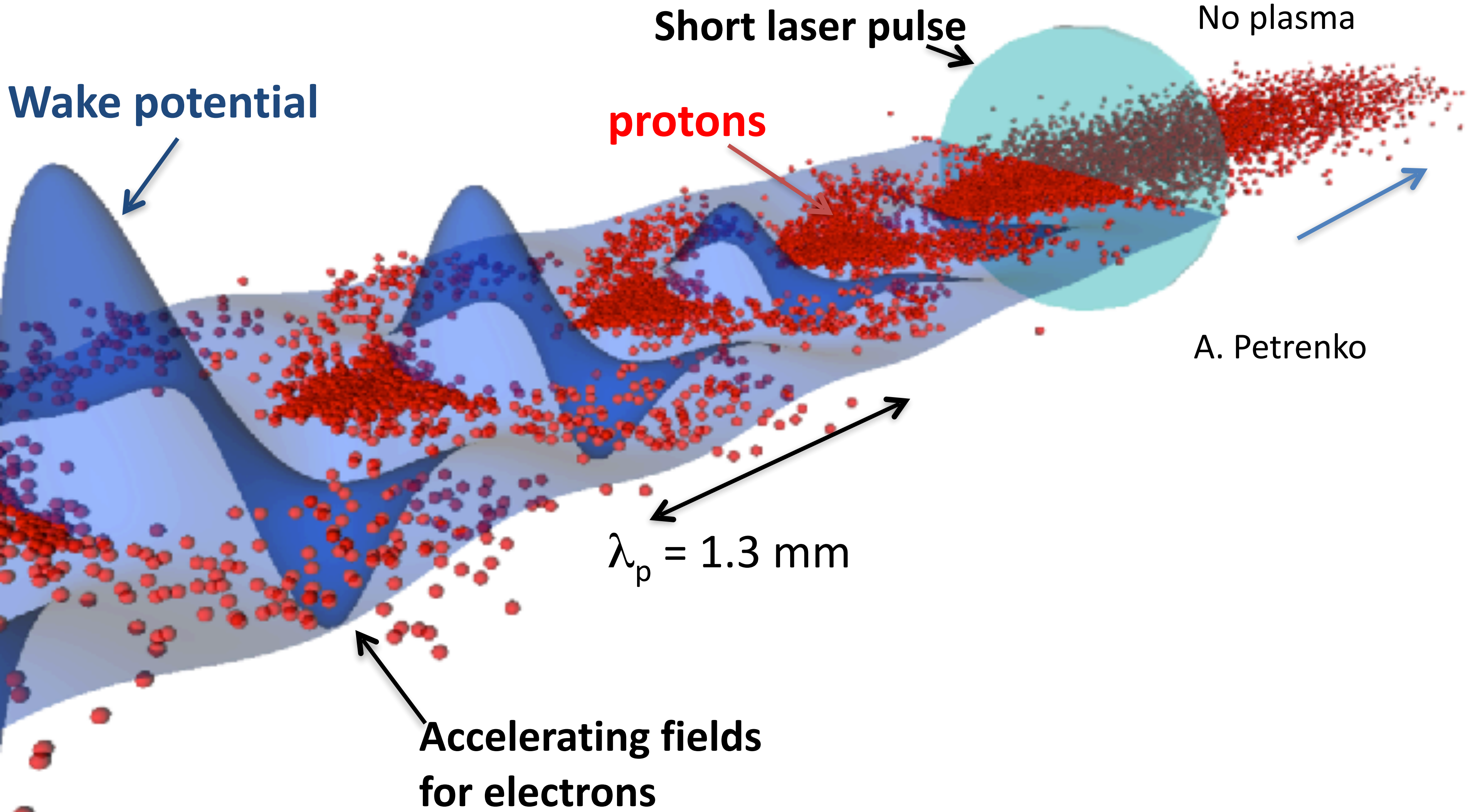



**LHC Driver (112 kJ):**
~ 5 TeV in ~7 km
~ $10^9$ $e^-$

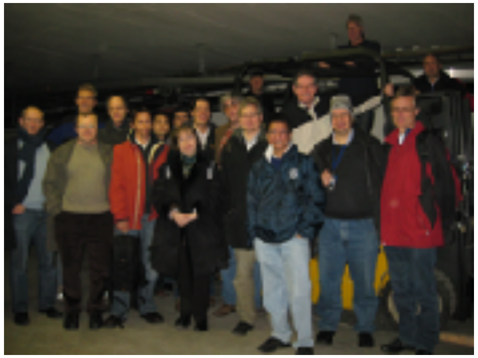
A. Caldwell, K. V. Lotov, Phys. Plasmas 18, 13101 (2011)

# Seeded self-modulation

The self-modulation can be seeded by a sharp start of the beam (or beam-plasma interaction).



# History

2009  Kickoff workshop at CERN

2011 June meeting of the SPSC – Letter of Intent to perform experiment (TT4/5 area).

2012 June meeting in Lisbon – AWAKE Collaboration officially formed

2013 April meeting of the SPSC – Design Report. Use CNGS area

Significant reduction in cost from re-using existing facility !
Positive recommendation from SPSC.
Approval from Research Board August 2013.

Experimental program started end 2016.

# AWAKE

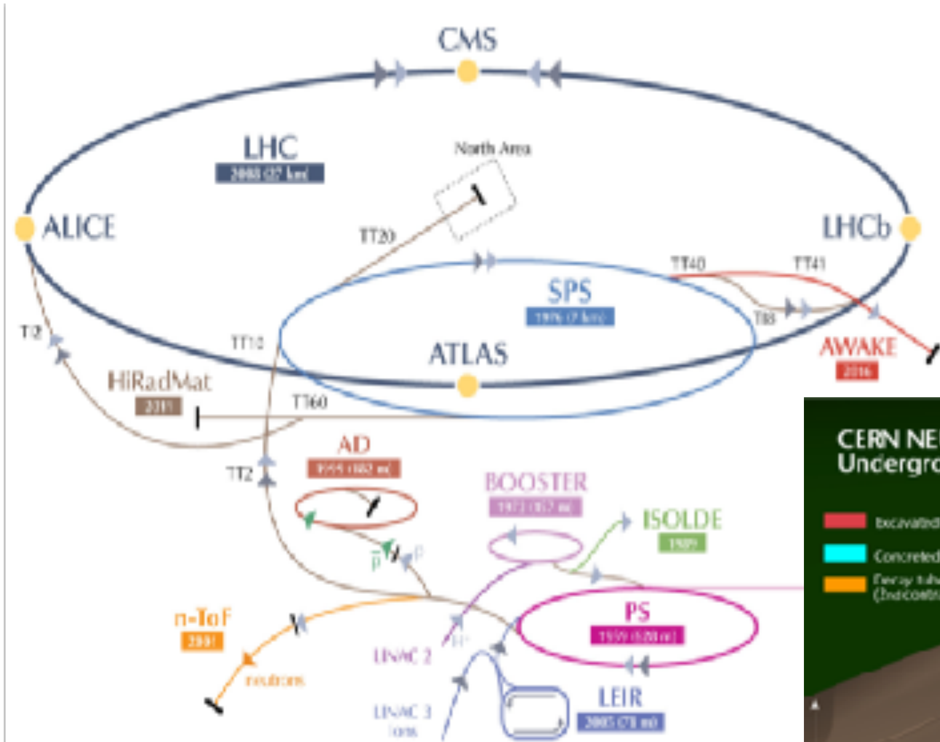
- AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven plasma wakefield experiment worldwide

## AWAKE Collaboration: 23 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-Universität of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE – Instituto Universitéario de Lisboa, Lisbon, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk Russia
- GoLP/Institutode Plasmas e Fusao Nuclear, Instituto Superior Téchnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Uppsala University, Uppsala, Sweden
- Wigner Institute, Budapest, Hungary
- Swiss Plasma Center group of EPFL, Lausanne Switzerland

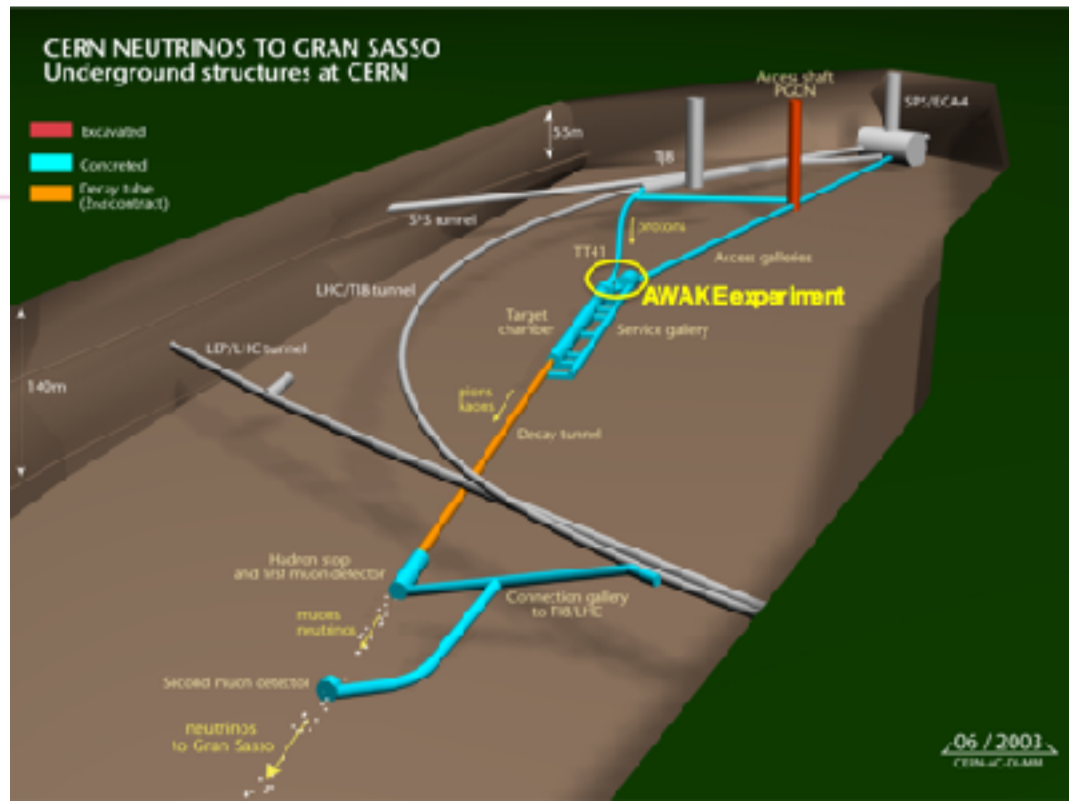
# AWAKE at CERN




**AWAKE is installed in**

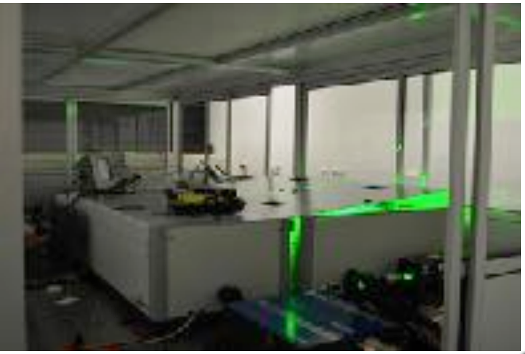
**CNGS Facility** (CERN Neutrinos to Gran Sasso)

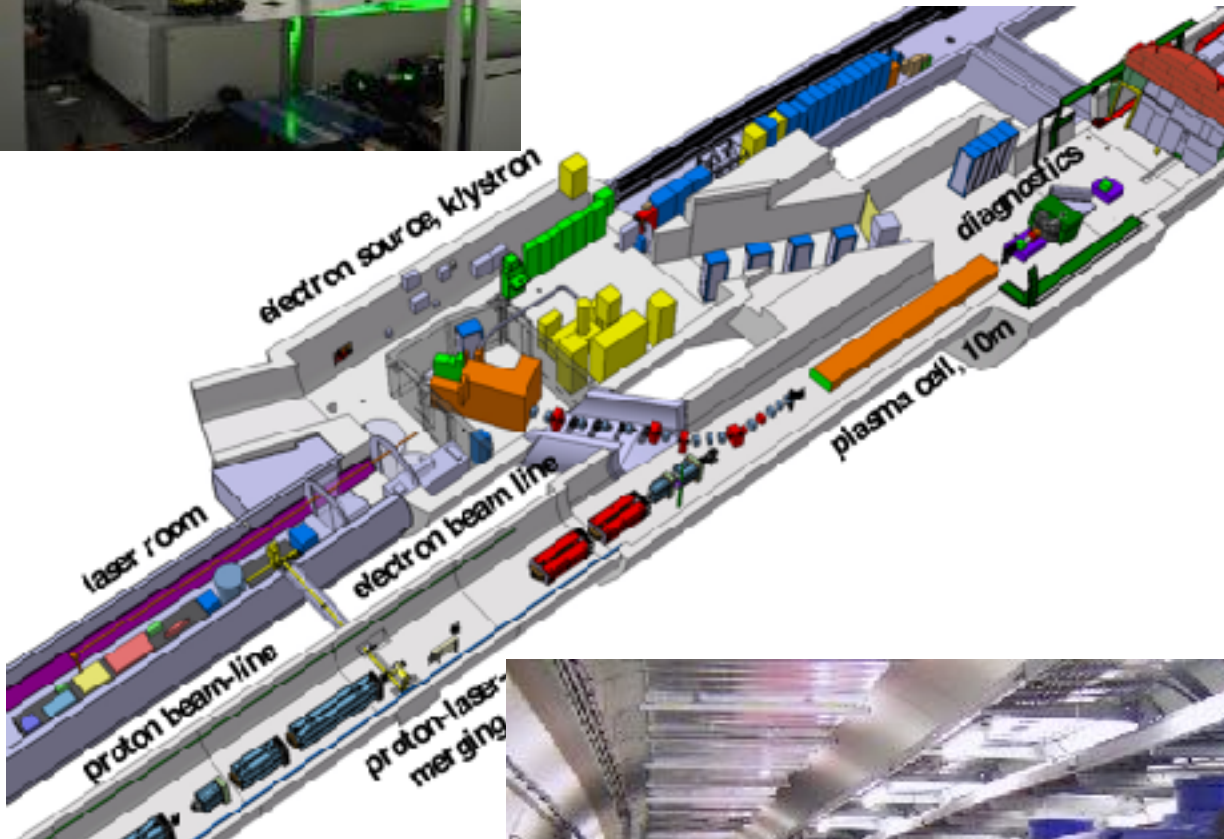
→ CNGS physics program finished in 2012



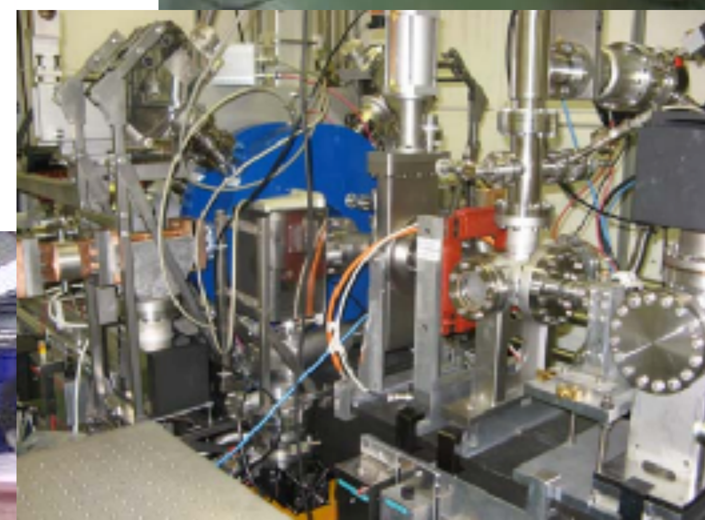

A. Caldwell et al., "Path to AWAKE: Evolution of the concept", Nucl. Instrum. Meth. A829 (2016) 3-16; E. Gschwendtner et al. [AWAKE Collaboration], "AWAKE, The Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN," Nucl. Instrum. Meth. A829, 76 (2016).

# AWAKE Overview



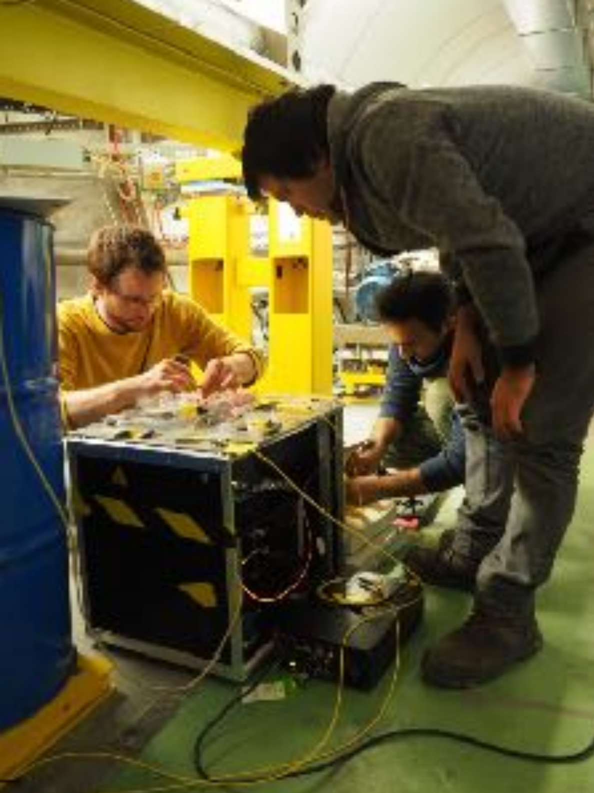






# AWAKE Overview

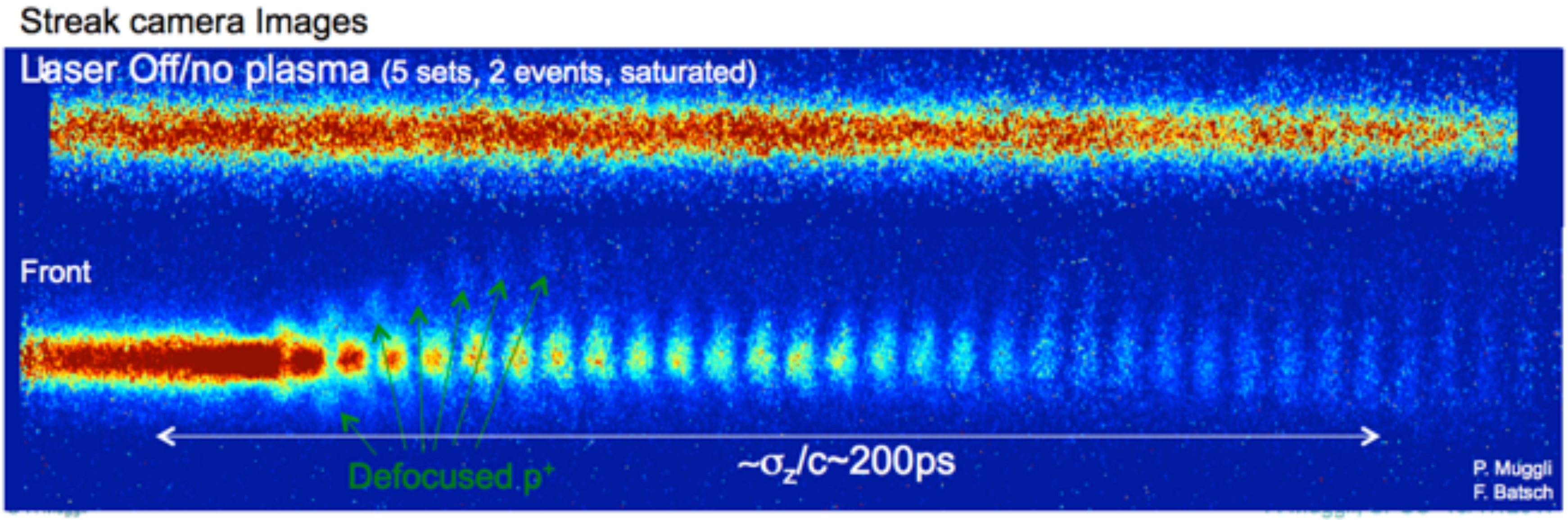
# First Run
December 9-12, 2016

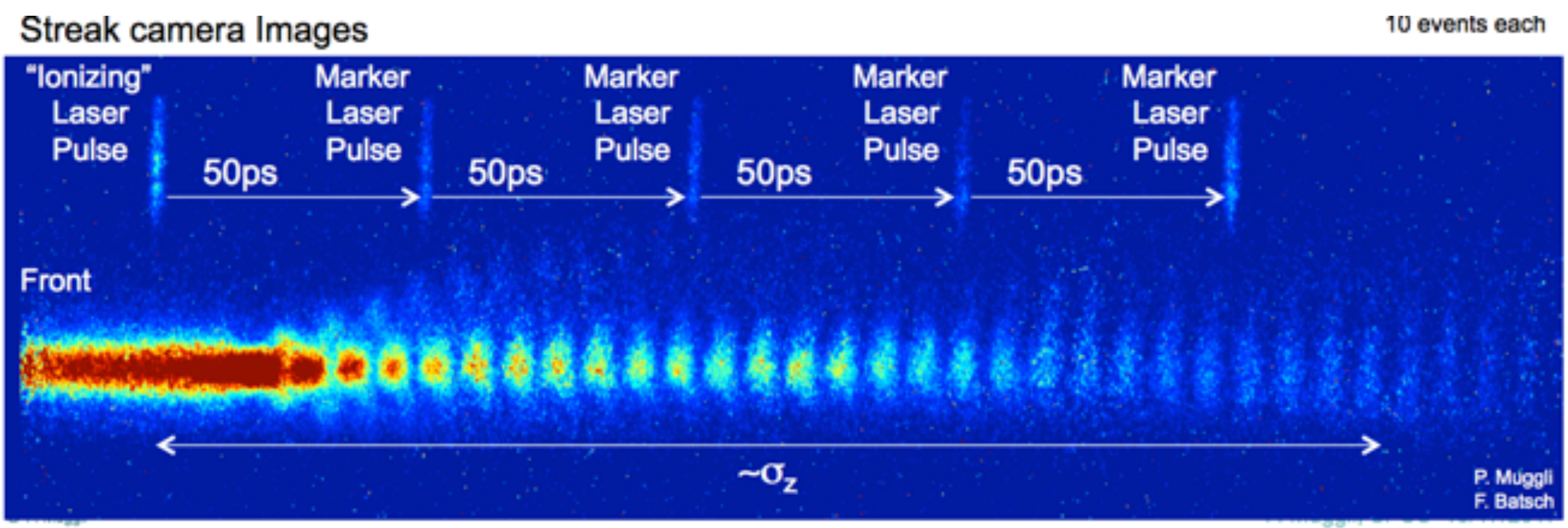






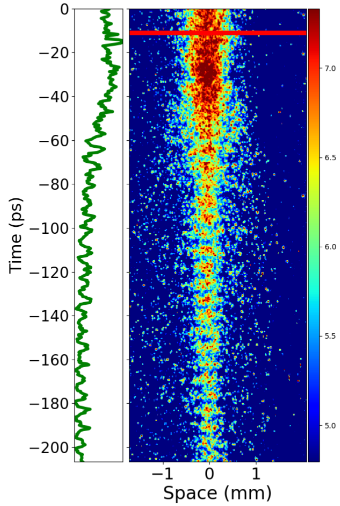
# Observation of Seeded SMI



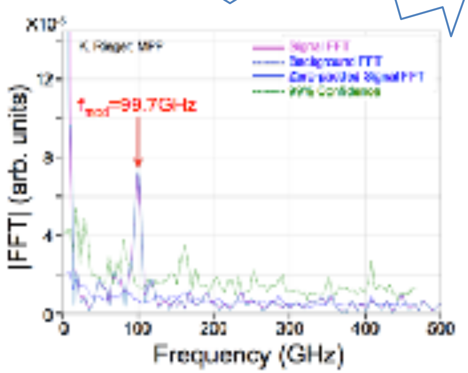



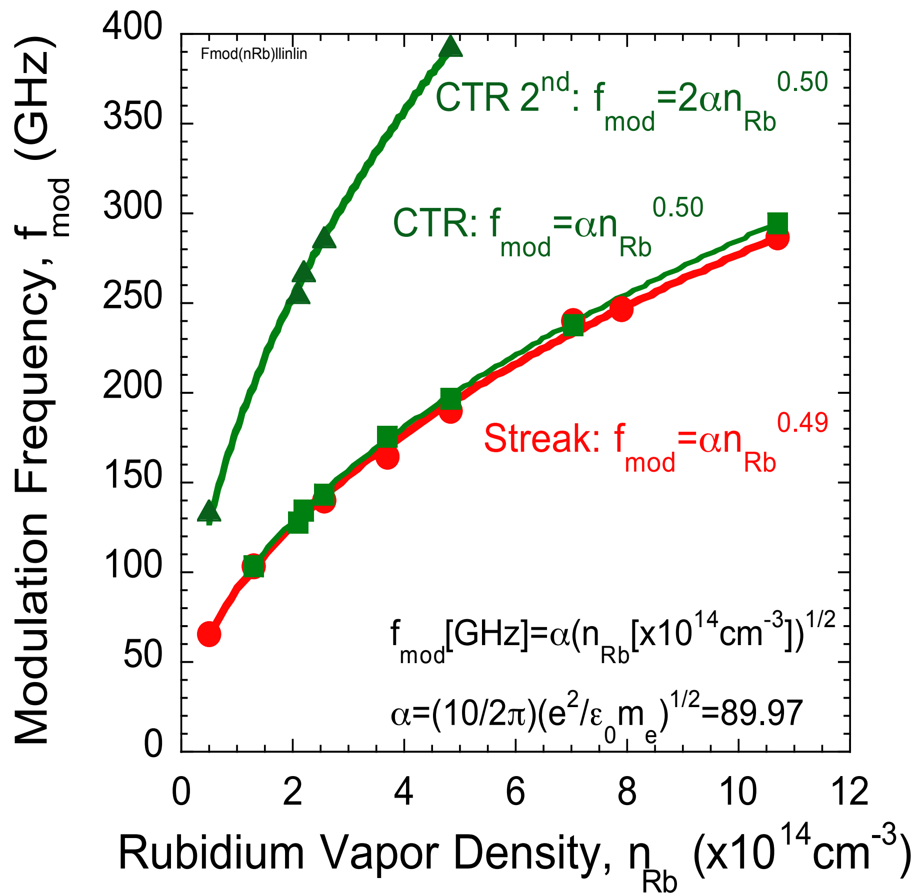
# AWAKE

## Modulation at the expected frequency




**FFT**

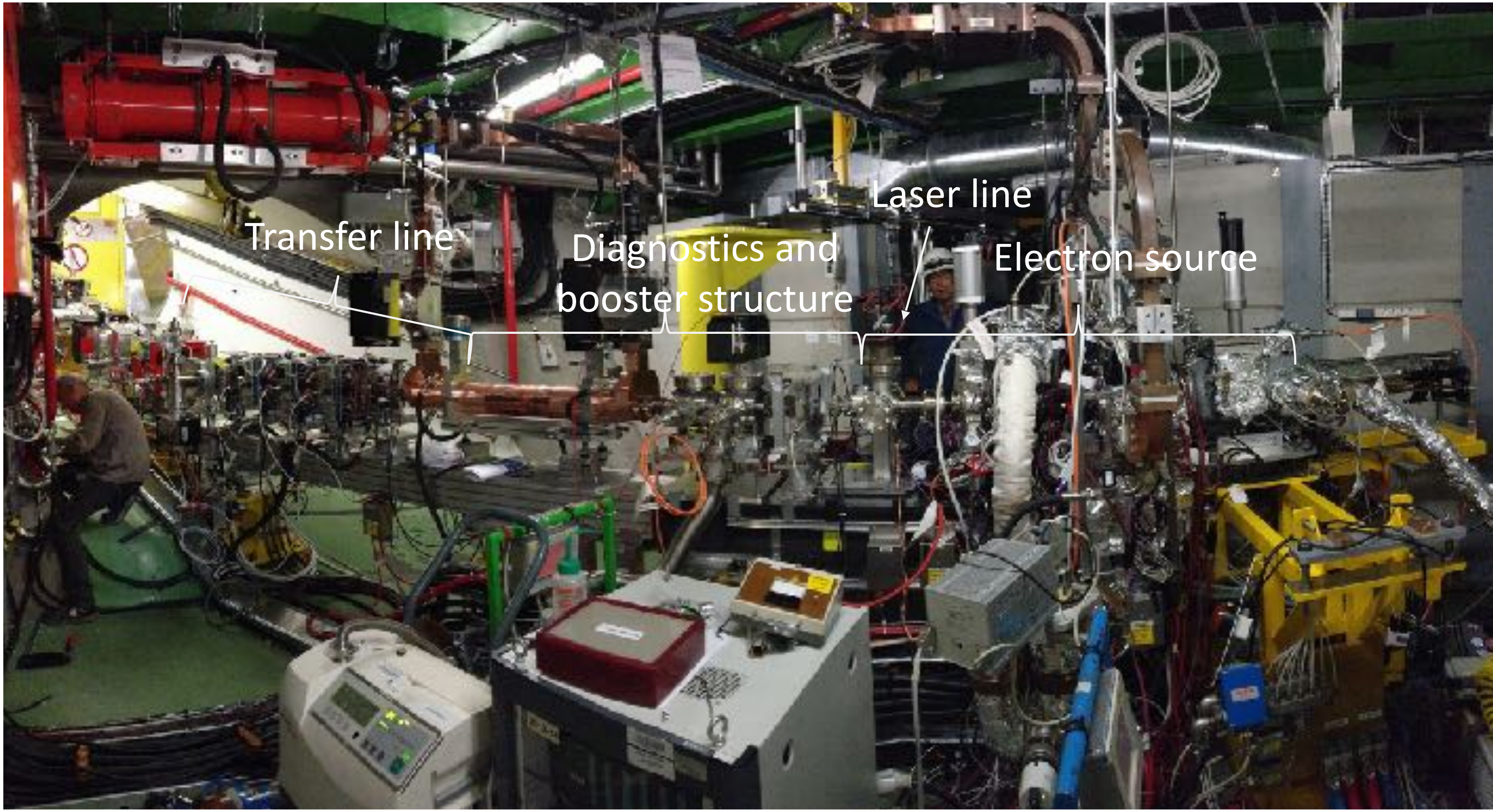



→ works exactly as predicted!

E. Adli et al.,(AWAKE Collaboration), PRL **122**, 054802 (2019)

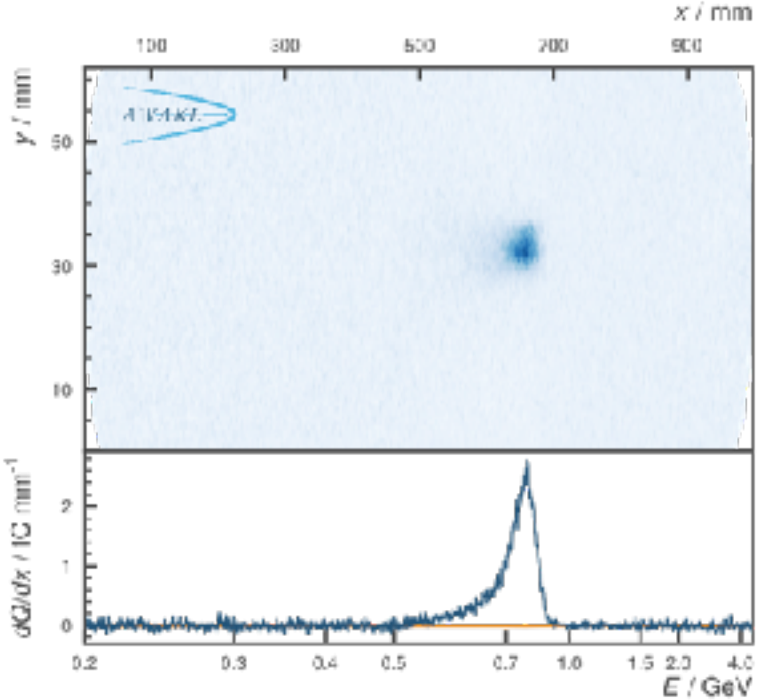
# Electron Line

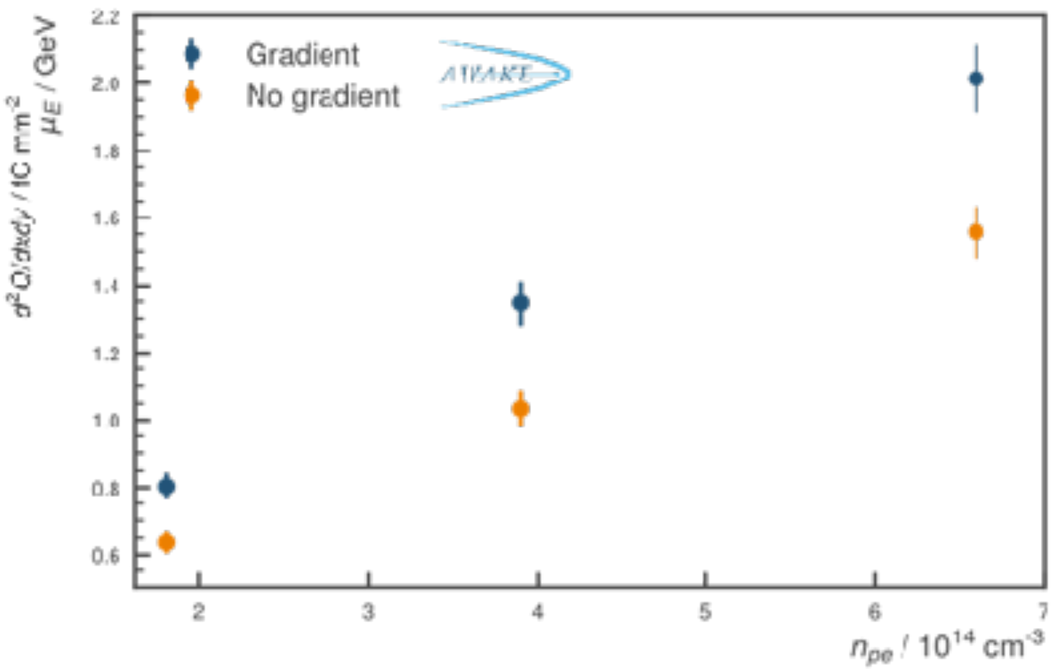


# AWAKE

## Electron Acceleration Results

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




**Electron acceleration in a proton-driven plasma wakefield works !**

**With todays existing proton bunches via seeded self-modulation!**



Maximum accelerated charge ~100 pC (~20% of injected)

2016-2018 Proof-of-Principle

**success!**

Demonstrated:

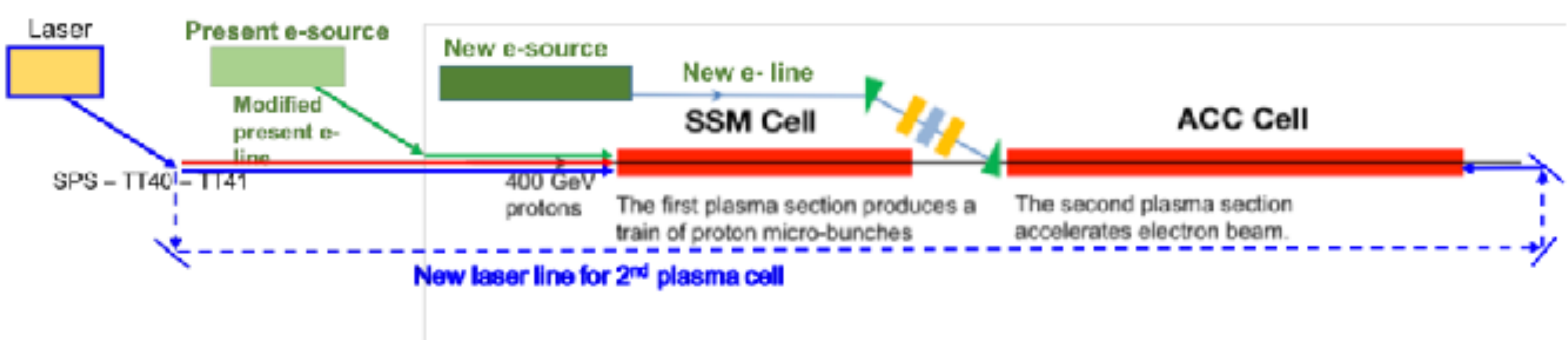
-phase stable proton modulation

-electron acceleration in wakefield

# Run 2 (2021-)

Goals:
stable acceleration of bunch of electrons with high gradients over long distances
'good' electron bunch emittance at plasma exit
Be prepared to start particle physics experiment after Run 2

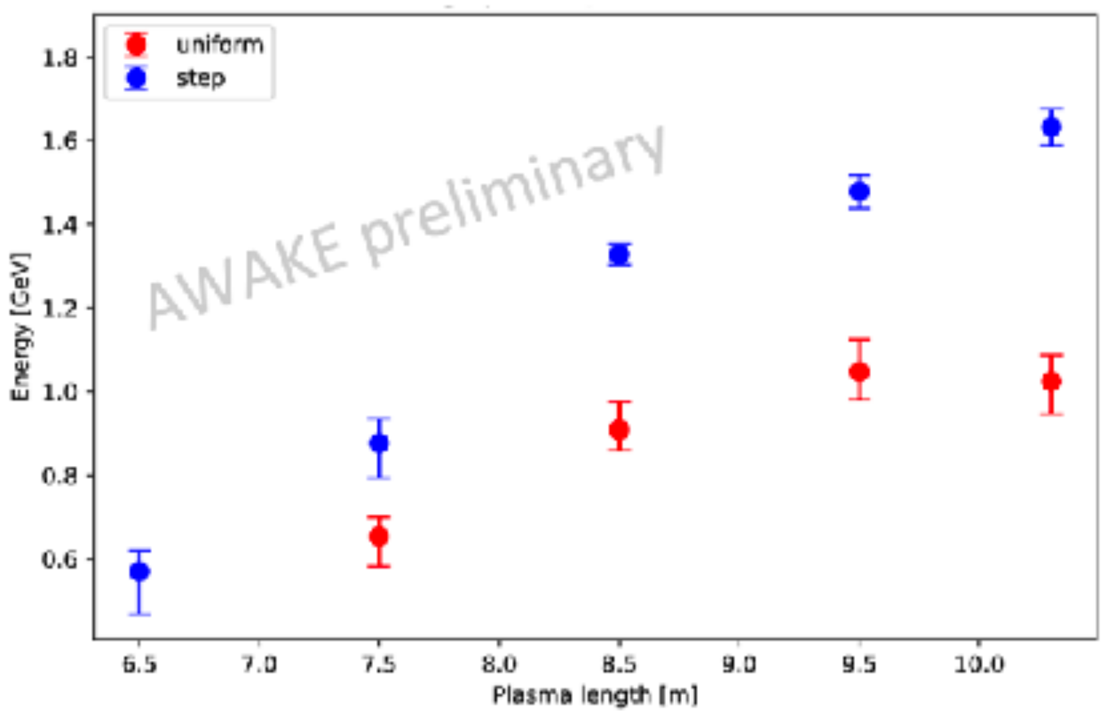
Baseline design




Four phases:
- seeding the SSM with an electron bunch (2021-2022)
- plasma cell with density step to freeze the modulation structure (2023-2024)
- inject electrons & accelerate without emittance blowup (2028-)
- implement scalable plasma cell technologies (2028-)

# New Plasma Cell

# First Results




F. Pannell *et al.* (AWAKE)
see AWAKE 2024 SPSC report

2024 dedicated to studying the effect of the density step:

- plasma light production
- higher energy electron acceleration
- stay tuned for results!

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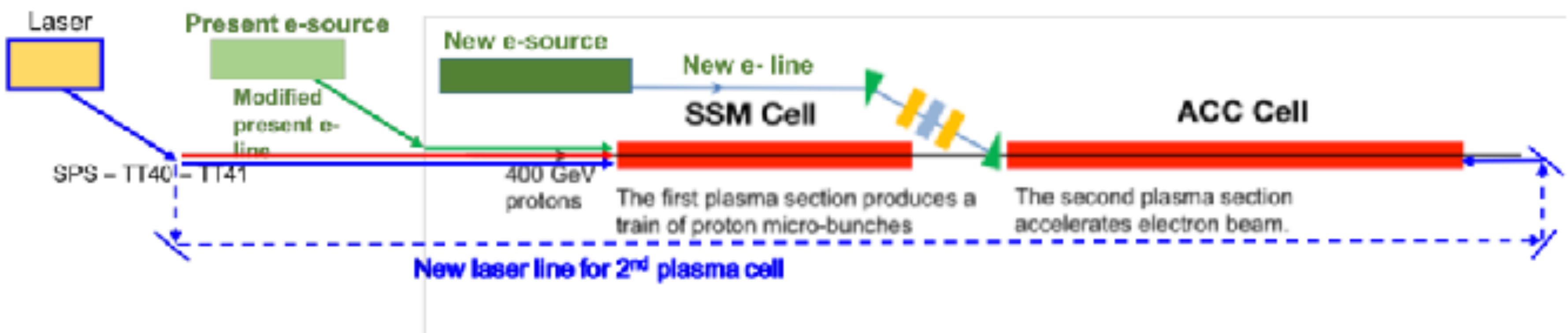
Be prepared to start particle physics experiment after Run 2

Baseline design




Four phases:
- seeding the SSM with an electron bunch (2021-2022) ✓
- plasma cell with density step to freeze the modulation structure (2023-2024) ✓
- inject electrons & accelerate without emittance blowup (2028-)
- implement scalable plasma cell technologies (2028-)

# Clear Time Line Towards an Accelerator


➢ **Milestones for AWAKE Run 2: → transition from proof-of-principle to applications**

M. Turner, SPSC Nov 2023

- **Physics with a high energy electron beam**
  - search for dark photons in beam dump experiments
  - Fixed target experiments in new energy regime

Energy & Flux important - luminosity determined by target properties. Much more relaxed parameters for plasma accelerator

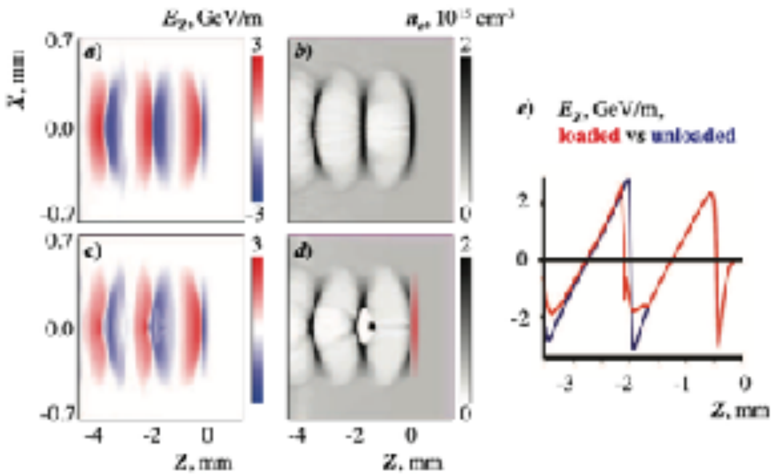
- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

New energy regime means new physics sensitivity even at low luminosities !

# Beyond AWAKE

Proton-driven PWFA

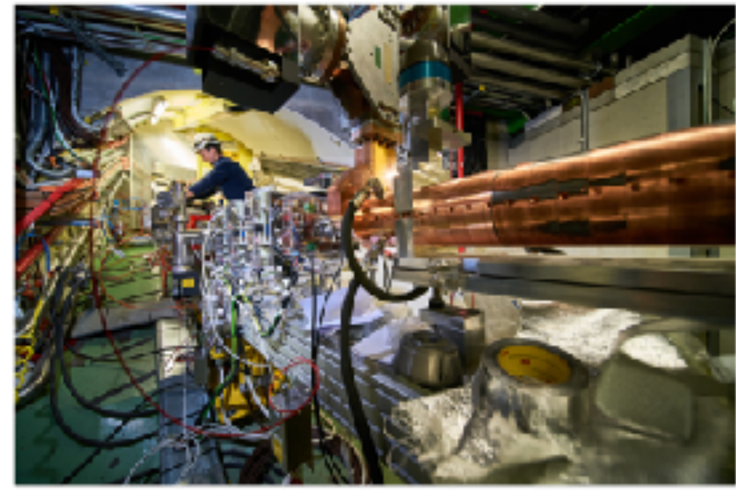
First studies imagined a short proton bunch



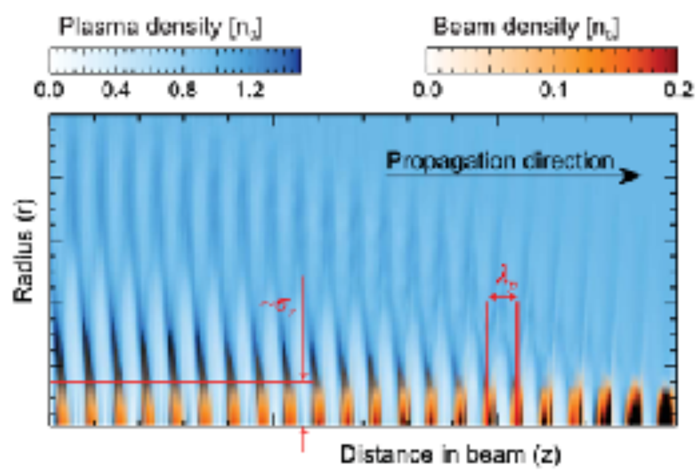

## AWAKE successfully accelerates electrons

Proton beams from the SPS at CERN were used to generate plasma waves upon which the electrons "surfed"

29 AUGUST, 2018 | By Achintya Rao



No short proton bunches - modulate bunch in plasma




Accelerate electrons

# ALiVE

AWAKE has allowed us to prove the concept, develop technology and will allow for a range of particle physics project.

However, not suitable for a high energy collider due to limited repetition rate (proton drive bunches only used once;  Low energy transfer efficiency).

**currently <0.1 Hz for AWAKE!**

$$\mathscr{L}_{\text{real}} = \frac{N_1 N_2 N_b f}{4\pi\sigma_x\sigma_y}\mathscr{H}$$

Go back to original scheme of driving plasma with short proton bunches.  Advantages:
- plasma uniformity requirement greatly reduced
- higher drive beam → witness beam energy transfer efficiency

Need to design a new proton driver that produces short bunches at a high rate

# First Investigations

- Higgs Factory: generate interest in the community

but **positron acceleration an unsolved challenge**

So consider initially only accelerating electron beams

- Electron beams for
    - asymmetric Higgs Factory (e.g., accelerate electrons to 375 GeV and collide with conventionally accelerated positrons - the HALHF scheme)
    - an electron injector for the EIC
    - LEP-3 (to reach t-tbar thresh hold, need 290 GeV electrons)
    - an electron injector for the LHeC

Studies are at a preliminary stage. Here a couple of examples …

# Preliminary Investigation of a Higgs Factory based on Proton-Driven Plasma Wakefield Acceleration

Assumed a fast cycling synchrotron …

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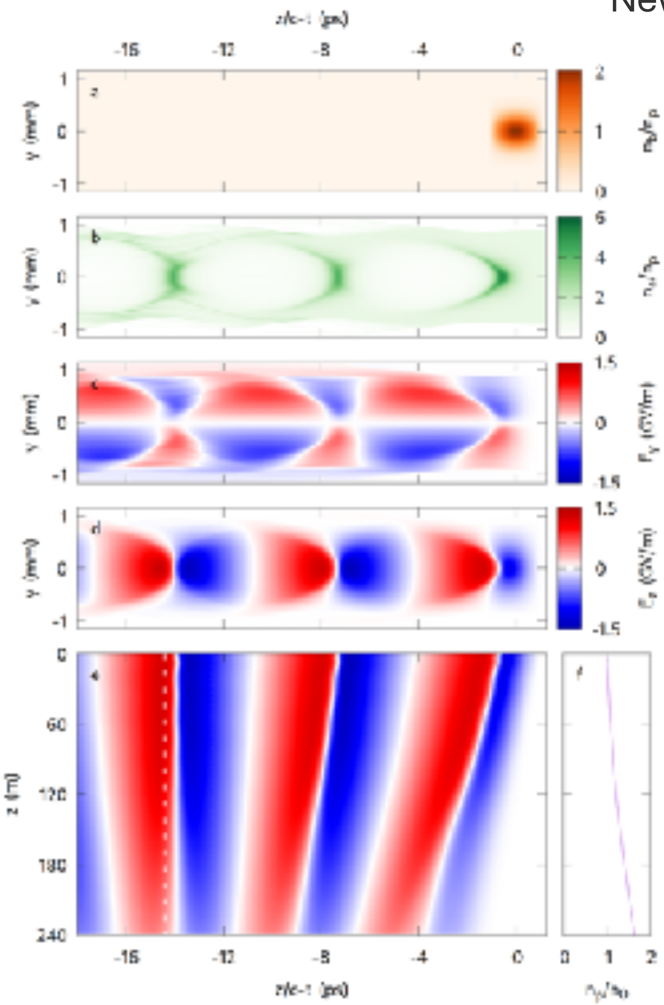
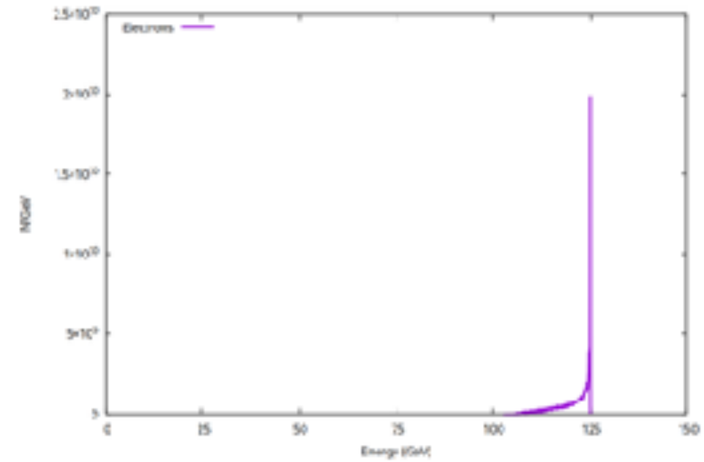


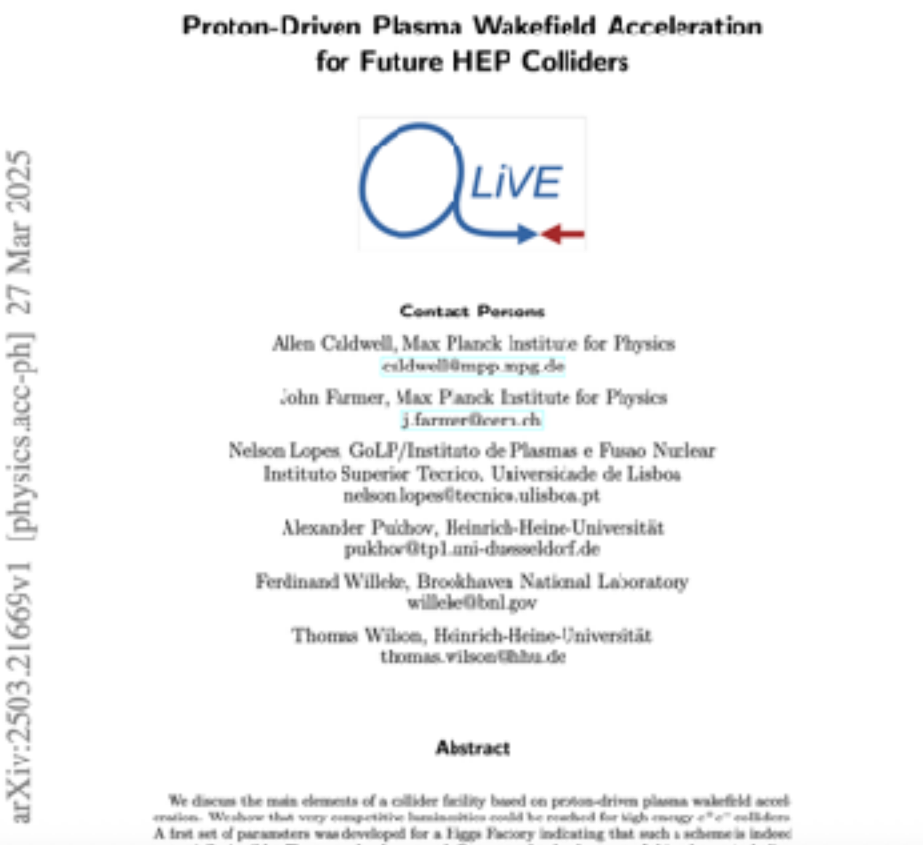

what we're looking for!

| Parameter | | Value | unit |
|---|---|---|---|
| Beam Energy | $E$ | 125 | GeV |
| Number of particles per bunch | N | $2 \times 10^{10}$ | |
| $e^-$ bunch length | $\sigma_{e^-,z}$ | 105 | μm |
| $e^+$ bunch length | $\sigma_{e^+,z}$ | 75 | μm |
| Horizontal $\beta$-function at IP | $\beta_x^*$ | 13 | mm |
| Vertical $\beta$-function at IP | $\beta_y^*$ | 0.41 | mm |
| Norm. horizontal $e^-$ emittance | $\gamma\varepsilon_{e^-,x}$ | 100 | nm |
| Norm. vertical $e^-$ emittance | $\gamma\varepsilon_{e^-,y}$ | 100 | nm |
| Norm. horizontal $e^+$ emittance | $\gamma\varepsilon_{e^+,x}$ | 400 | nm |
| Norm. vertical $e^+$ emittance | $\gamma\varepsilon_{e^+,y}$ | 400 | nm |
| Bunch frequency | $f$ | 7.2 | kHz |
| Centre-of-mass energy | $E_{cm}$ | 250 | GeV |
| Geometric luminosity | $\mathcal{L}_{geom}$ | 1 | $10^{34}$ cm$^{-2}$s$^{-1}$ |
| Simulated luminosity | $\mathcal{L}$ | 7 | $10^{34}$ cm$^{-2}$s$^{-1}$ |
| Luminosity in the top 1% | $\mathcal{L}_{1\%}$ | 0.25 | $10^{34}$ cm$^{-2}$s$^{-1}$ |

Using FFA scheme - see next slide

# ALiVE

**Submission to the EPPSU this spring**


arXiv:2503.21669v1 [physics.acc-ph] 27 Mar 2025

**Proton-Driven Plasma Wakefield Acceleration for Future HEP Colliders**

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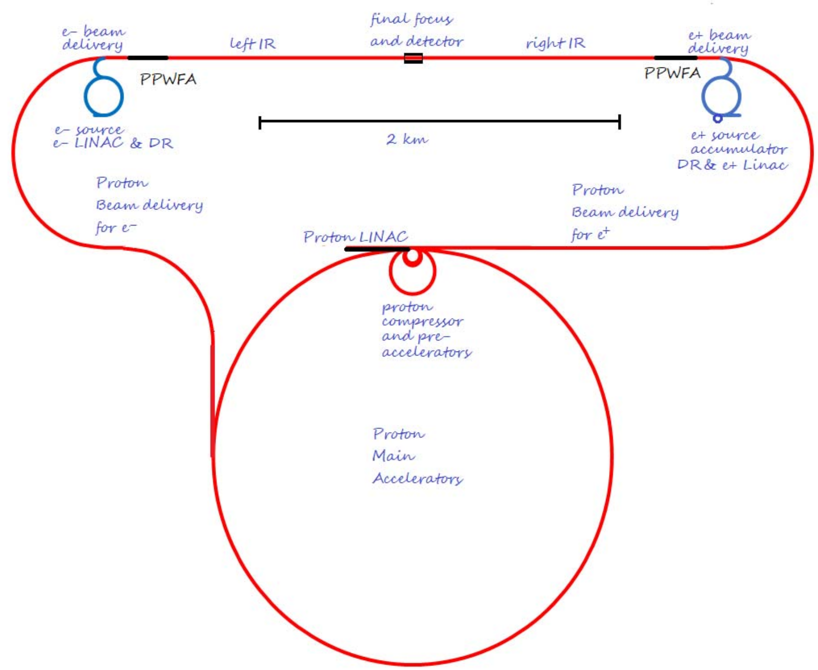
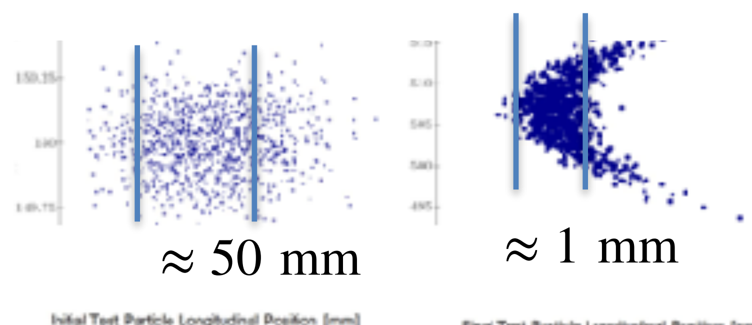
**Abstract**

We discuss the main elements of a collider facility based on proton-driven plasma wakefield acceleration. We show that very competitive luminosities could be reached for high energy $e^+e^-$ colliders. A first set of parameters was developed for a Higgs Factory indicating that such a scheme is indeed

Based on:

- FFA (Fixed-Field, alternating gradient) concept
- developed by F. Willeke (BNL).
- Can produce high rate of short proton bunches!



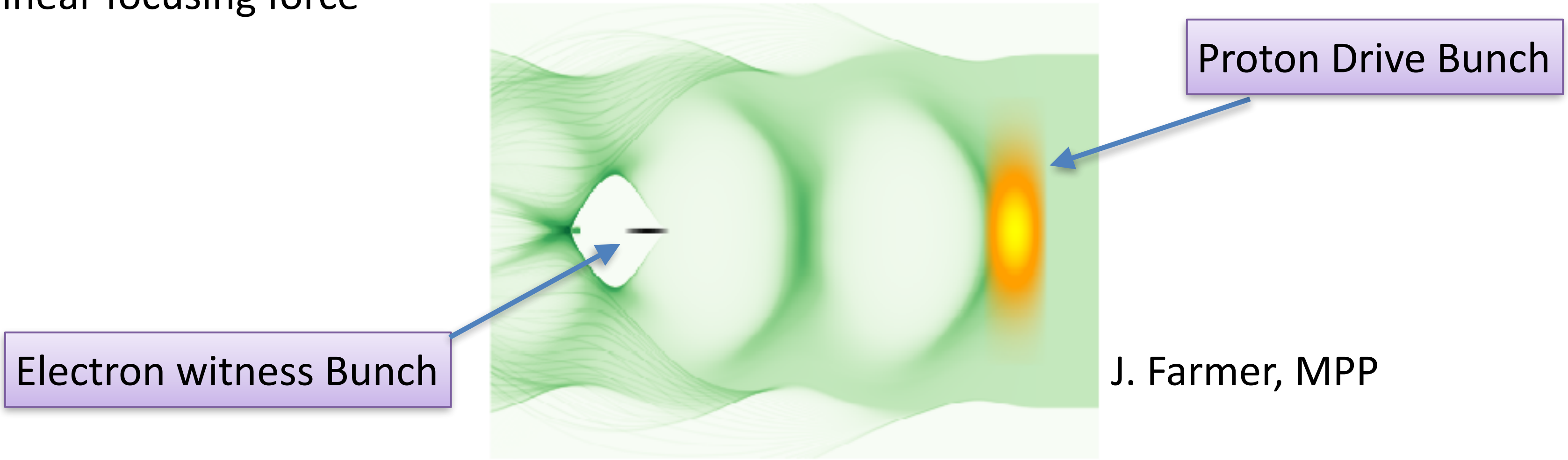




400 GeV Proton Bunches accelerating electron bunches to the energy needed for a Higgs Factory

# Positron Acceleration?

A big issue which we have not solved:

- for electrons, the compact electron bunch produces its own plasma blowout that results in a linear focusing force




J. Farmer, MPP

- positrons suck the plasma electrons in, causing emittance blowup. Good ideas needed (let me know if you're interested!)

# LEP3 positrons with ALiVE electrons?

- High-quality LEP3 positrons could be collided with plasma-accelerated electrons to reach the ~350 GeV $t\bar{t}$ threshold
- This would be an asymmetric scheme in both energy and bunch dimensions, with the key differences between the two bunches being the far **shorter** electron bunch length, it's **round** emittance profile, and it's **lower** charge

**LEP3 positrons [1]**

| Parameter | LEP2 | LEP3 (ZH) | LEP3 (WW) | LEP3 (Z) |
|---|---|---|---|---|
| beam energy [GeV] | 45.6 | 115 | 80 | 45.6 |
| number of experiments | 4 | 2 | 2 | 2 |
| Circumference [m] | 26659 | 26659 | 26659 | 26659 |
| crossing angle at the IP [mrad] | 0 | 30 | 30 | 30 |
| Bending radius [m] | 3026 | 2863 | 2863 | 2863 |
| SR power per beam [MW] | 0.33 | 50 | 50 | 50 |
| beam current [mA] | 3 | 9 | 39 | 371 |
| number bunches/beam | 8 | 20 | 220 | 500 |
| bunch intensity [10^11] | 1.5 | 2.5 | 1.0 | 2.5 |
| SR energy loss/turn [GeV] | 0.1 | 5.4 | 1.3 | 0.12 |
| total RF voltage [GV] | 0.3 | 6.0 | 1.6 | 0.60 |
| RF frequency [MHz] | 352 | 800 | 800 | 800 |
| longitudinal damping time [turns] | 360 | 21 | 63 | 339 |
| horizontal beta* [m] | 2.0 | 3.5 | 0.2 | 0.1 |
| vertical beta* [mm] | 50 | 1.0 | 1.0 | 1.3 |
| horizontal emittance [nm] | 45 | 3.8 | 1.0 | 0.3 |
| vertical emittance [pm] | 300 | 7.5 | 3.0 | 6.5 |
| horizontal rms IP spot size [µm] | 300 | 44 | 18 | 8 |
| vertical rms IP spot size [nm] | 3873 | 87 | 55 | 81 |
| horiz. beam-beam parameter | 0.07 | 0.37 | 0.33 | 0.01 |
| vert. beam-beam parameter | 0.06 | 0.10 | 0.11 | 0.11 |
| rms bunch length SR only [mm] | 2.5 | 2.4 | 2.5 | 1.4 |
| rms bunch length with SR + BS [mm] | 2.3 | 2.6 | 2.0 | 5.4 |
| beam lifetime rad Bhabha + BS [min] | 1390 | 17 | 19 | 38 |
| luminosity per IP [10^34 cm-2s-1] | 1.000 | 1.4 | 4.2 | 40 |
| integrated luminosity/year [fb-1] | 1.000 | 3.4 | 1.6 | 5.5 |
| years of operation | | 5 | 3 | 5 |
| total number of events [10^6] | | 0.35 | 112 | 9.4E+05 |

[1] "LEP3 Parameters" Slide 12, https://indico.cern.ch/event/1546804/

## ALiVE electrons

Energy $E$ = 290 GeV

**Bunch population $N_b$ = 2 x $10^{10}$ (3.2 nC)**

**Horizontal emittance $\gamma\varepsilon_x$ = 100 nm**

**Vertical emittance $\gamma\varepsilon_y$ = 100 nm**

Horizontal size $\sigma_x$ = 44 µm

Vertical size $\sigma_y$ = 87 nm

**Bunch length $\sigma_z$ = 70 µm**

Horizontal beta-star $\beta^*_x$ = 10 km (!)

Vertical beta-star $\beta^*_y$ = 42 mm

We here assume that the transverse bunch sizes can be matched! this will require focussing of the plasma-produced bunch

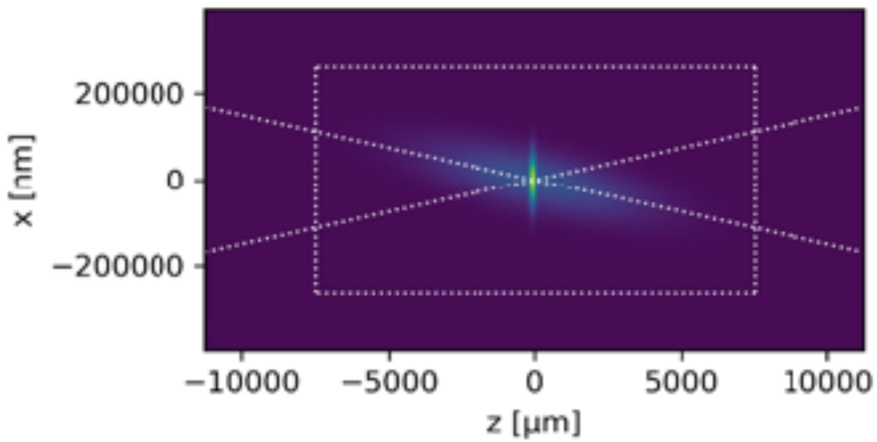
Slide from T. Wilson, HHU

# Simulation Results

A GuineaPig++ simulation was performed to assess the possible performance of this scheme, the results show:

- A luminosity of $L = 8 \times 10^{27}$ cm$^{-2}$ per crossing with **99.95% in the top 1%**
- Assuming 11.25 kHz operation with 20 bunches/beam, this results in a total luminosity of **0.2 x10$^{34}$ cm$^{-2}$ s$^{-1}$**
- The electron beam would not be reused, but the horizontal and vertical tune-shifts of the positron beam are $\boldsymbol{\xi_x = 0.01}$ and $\boldsymbol{\xi_y = 0.13}$, within cited tolerances for LEP3 [1]

[1] "LEP3 Parameters" Slide 10, https://indico.cern.ch/event/1546804/




Snapshot of the simulation at the midpoint of the interaction, the long high-population low-density positrons moving across the much shorter and comparatively high-density electron bunch. The bunches are colliding at a 30 mrad angle, which is modelled as a skew in GuineaPig++

Slide from T. Wilson, HHU

# Outlook

particle physics community wants a new big project defined soon
- CERN pushing for the FCC-ee
- FNAL/US aiming for a Muon Collider

We are not ready to compete with our plasma-based schemes, but making progress.

Final choices on collider projects will depend on:

- funding
- competition (China?)
- progress in technology

In the meantime, we push our approach … Maybe at the end we catch up

Your interest in joining this endeavor is welcome!