Proton-Driven Plasma Wakefield Acceleration, AWAKE and Beyond

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on behalf of AWAKE Collaboration

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Motivations

- Due to limited research facilities, PWFAs research is much behind LWFAs
- PWFA drivers propagate through plasma at close to the speed of light, *c*, leading to a plasma wave phase velocity much higher than in LWFA, where laser pulses propagate at their group velocity, v_g, which is less than *c.* Limiting effect such as overtaking and dephasing of accelerated particles are mitigated.
- In PWFAs, strong transverse focusing fields in the plasma prevent the driver beam expansion, allowing much longer acceleration lengths than that in LWFAs. Meters long plasma was demonstrated
- The increased wake phase velocity reduces unwanted self injection of plasma electrons into the wakefield, mitigating the dark current generation
- Beam drivers have much greater parameter stability than the high intensity laser drivers
- Particle beams for PWFAs can be generated with MW powers with efficiencies of ~10%. In contrast, state-of-the-art high intensity laser systems deliver output power of ~100W with 0.1% level wall-plug efficiency.

Why protons?

- **Large energy stored in proton machines like Tevatron, HERA, SPS and LHC**
- **For example, the SPS/LHC beam carries significant stored energy for driving plasma waves**

  - **SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ**
  - **LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ**
  - **LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ**

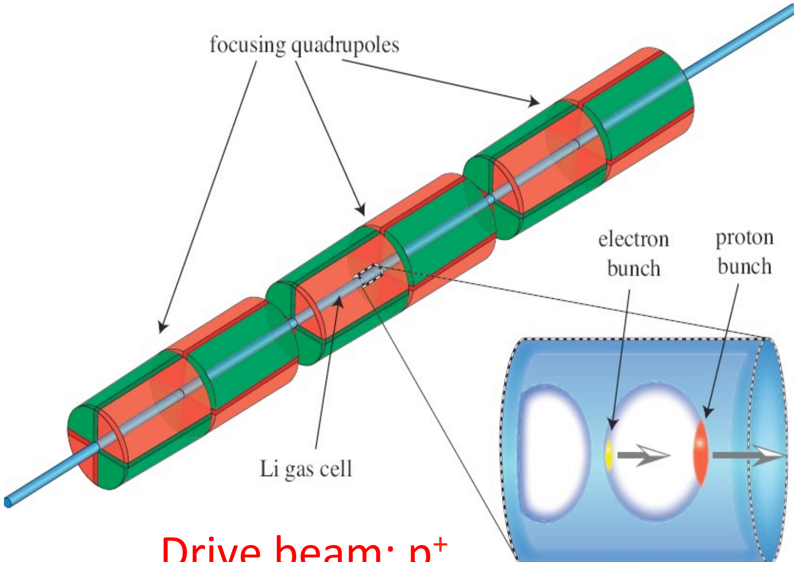
  - **SLAC (50 GeV, 2e10 e/bunch) ~ 0.16 kJ**
  - **ILC (250 GeV, 2e10 e/bunch) ~ 0.8kJ**

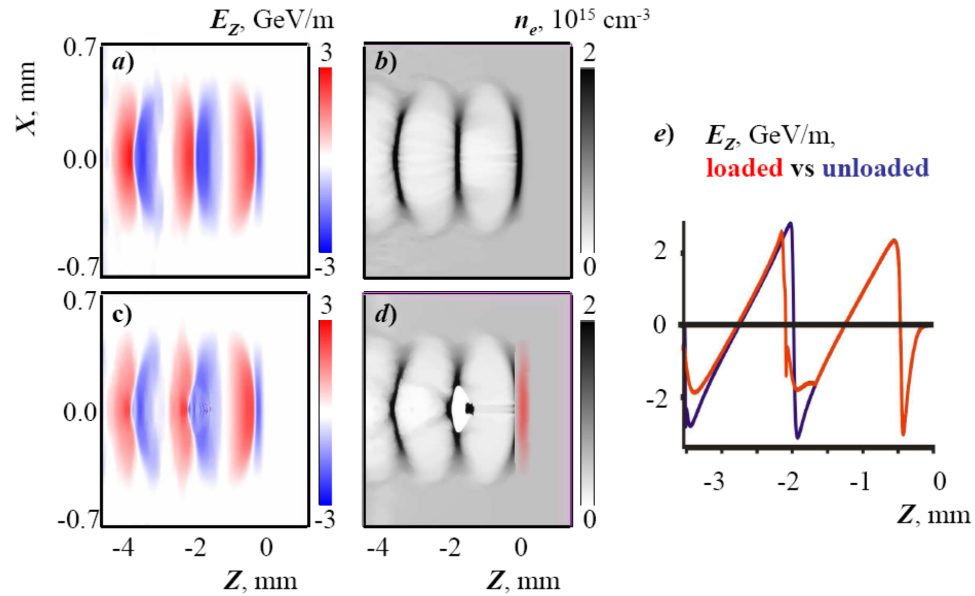
One stage plasma accelerator can bring electron bunch to the energy frontier!

High-energy proton machines

	HERA	TEVATRON	LHC
Circumference [km]	6.336	6.28	26.659
Maximum energy [TeV]	0.92	0.98	7.0
Energy spread [10^{-3}]	0.2	0.14	0.113
Bunch length [cm]	8.5	50	7.55
Transverse emit. [10^{-9} π m rad]	5	3	0.5
Particles per bunch [10^{10}]	7	26	11.5

Proton-driven PWFA





Drive beam: p^+

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

$\sigma_r=0.43$ mm, $\sigma_\theta=0.03$ mrad,

$\sigma_z=100$ μm, $\Delta E/E=10$ %

Witness beam: e^-

$E_0=10$ GeV, $N_e=1.5\times10^{10}$

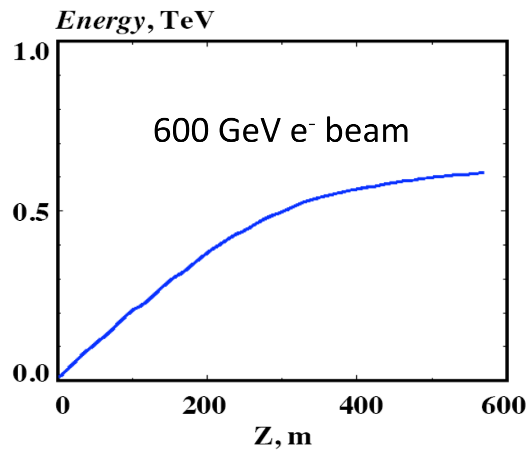
Plasma: Li^+

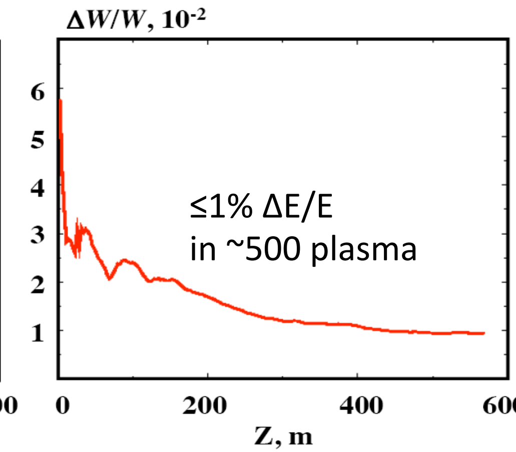
$n_p=6\times10^{14}$cm^{-3}

External magnetic field:

Field gradient: 1000 T/m

Magnet length: 0.7 m





* A. Caldwell et al., Nature Physics 5, 363 (2009)

Short proton bunch generation

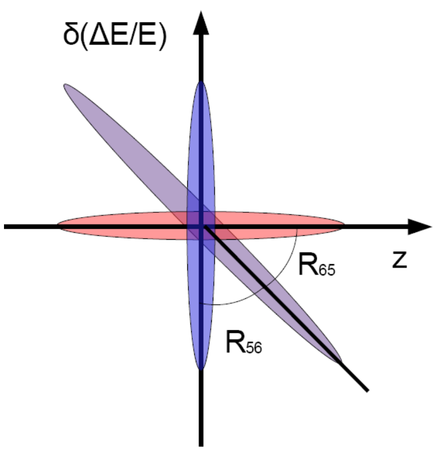
- Laser striking thin foil can produce short and low energy proton beam
- Emittance exchange technique, exchanges the longitudinal emittance to horizontal emittance
- Fast quads tunning for low momentum compaction factor before extraction in the ring
- Conventional magnetic bunch compression
- Plasma wakefield beam slicing via modulation

Bunch compressor design

For a thousand-fold compression, one stage compression looks infeasible

We expect that the ring could compress the bunch by a factor of 10 and the rest will be realized via magnetic chicane

$$\begin{pmatrix} z(s_2) \\ \delta(s_2) \end{pmatrix} = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ R_{65} & 1 \end{pmatrix} \begin{pmatrix} z(s_0) \\ \delta(s_0) \end{pmatrix} = \begin{pmatrix} 1 + R_{56}R_{65} & R_{56} \\ R_{65} & 1 \end{pmatrix} \begin{pmatrix} z(s_0) \\ \delta(s_0) \end{pmatrix}$$



$$1 + R_{56}R_{65} = 0$$

$$R_{65} = \frac{\delta}{z} = \frac{1}{z}\frac{\Delta E}{E} = \frac{eV_0}{E}\frac{\omega}{\beta c}$$

$$R_{56} = -2\theta_B\left(\frac{2}{3}L_B + \Delta L\right)$$

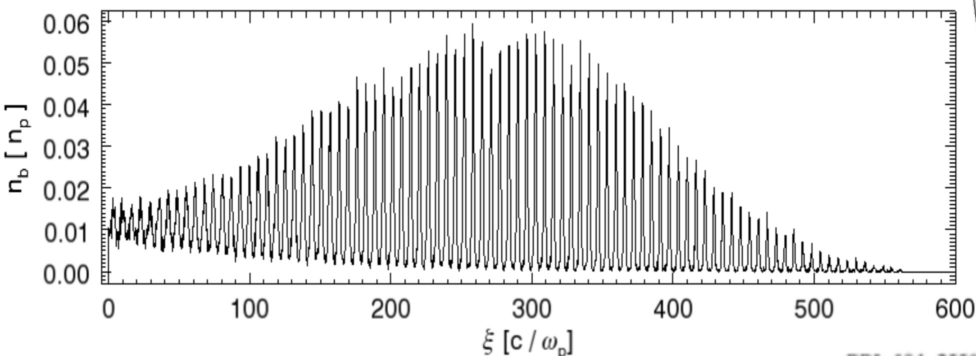
	Value
Bunch charge	**10^{11}**
Proton energy [TeV]	**1**
Initial energy spread [%]	**0.01**
Initial bunch length [cm]	**1.0**
Final bunch length [μm]	**165**
RF frequency [MHz]	**704.4**
Average gradient of RF [MV/m]	**25**
Required RF voltage [MV]	**65,000**
RF phase [degree]	**-102**
Compression ratio	**~60**
Momentum compaction (MC) [m]	**-1.0**
Second order of MC [m]	**1.5**
Bending angle of dipole [rad.]	**0.05**
Length of dipole [m]	**14.3**
Drift space between dipoles [m]	**190.6**
Total BC length [m]	***4131***
Final beam energy [GeV]	**986.5**
Final energy spread [%]	**0.93**

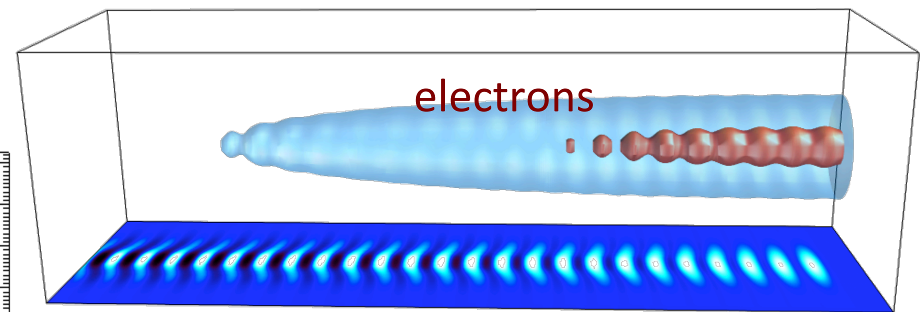
G. Xia, A. Caldwell et al., Proceedings of PAC09 (FR5RFP011)

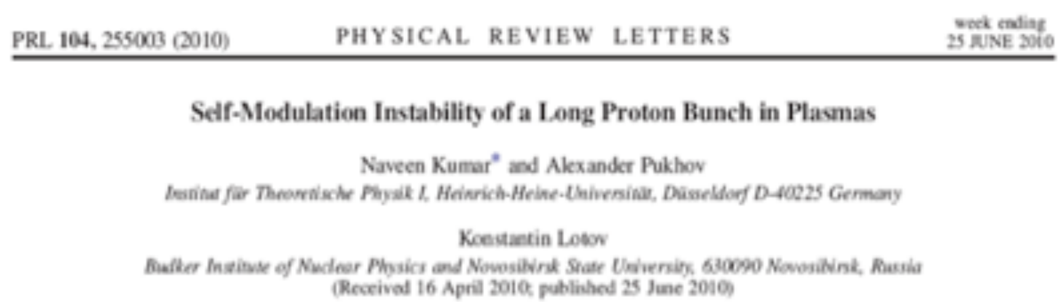
Plasma wakefield slicing via modulation

- Magnetic bunch compression: formidable RF power for energy chirp!
- Self-modulation via plasma wakefield (the transverse instability modulates the long bunch into many ultra short beamlets at plasma wakelength.

SPS beam at 5m
Plasma @ 1e14 cm^{-3}






PRL 104, 255003 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Self-Modulation Instability of a Long Proton Bunch in Plasmas

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(Received 16 April 2010; published 25 June 2010)

on-axis (X = 0) beam density profile after 5 m propagation in plasma

G. Xia, et al., AIP Proceedings of Advanced Accelerators Concepts 2010, 510-515.

From concept to experiment

CERN COURIER

Feb 24, 2010

Workshop pushes proton-driven plasma wakefield acceleration

PPA09

PPA09, a workshop held at CERN on proton-driven plasma wakefield acceleration, has launched discussions about a first demonstration experiment using a proton beam. Steve Myers, CERN's director for Accelerators and Technology, opened the event and described its underlying motivation. Reaching higher-energy collisions for future particle-physics experiments beyond the LHC requires a novel accelerator technology, and "shooting a high-energy proton beam into a plasma" could be a promising first step. The workshop, which brought together participants from Germany, Russia, Switzerland, the UK and the US, was supported by the EuCARD AccNet accelerator-science network (**CERN Courier November 2009 p16**).

CERN Courier November 2013

Plasma acceleration

AWAKE: to high energies in a single leap

Proton-driven plasma wakefield acceleration could accelerate electrons to the terascale in a single plasma stage. The AWAKE project is set to verify this novel technique using proton beams at CERN.

To complement the results that will come from the LHC at CERN, the particle-physics community is looking for options for future lepton colliders at the tera-electron-volt energy scale. These will need to be huge circular or linear colliders. With the accelerating gradients of today's RF cavities or microwave technology limited to about 100 MV/m, the length of the linear machines would be tens of kilometres. However, plasma can sustain much higher gradients and the idea of harnessing them in plasma wakefield acceleration is gathering momentum. One attractive idea is to use a high-energy proton beam as the driver of a wakefield in a single plasma section.

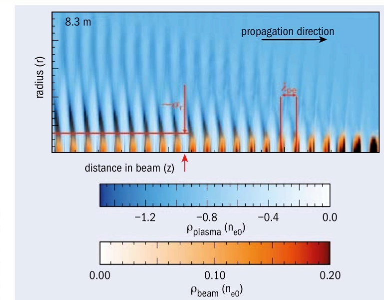

Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing from yellow to dark red.

J. Plasma Physics: page 1 of 7. © Cambridge University Press 2012
doi:10.1017/S0022377812000086

A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

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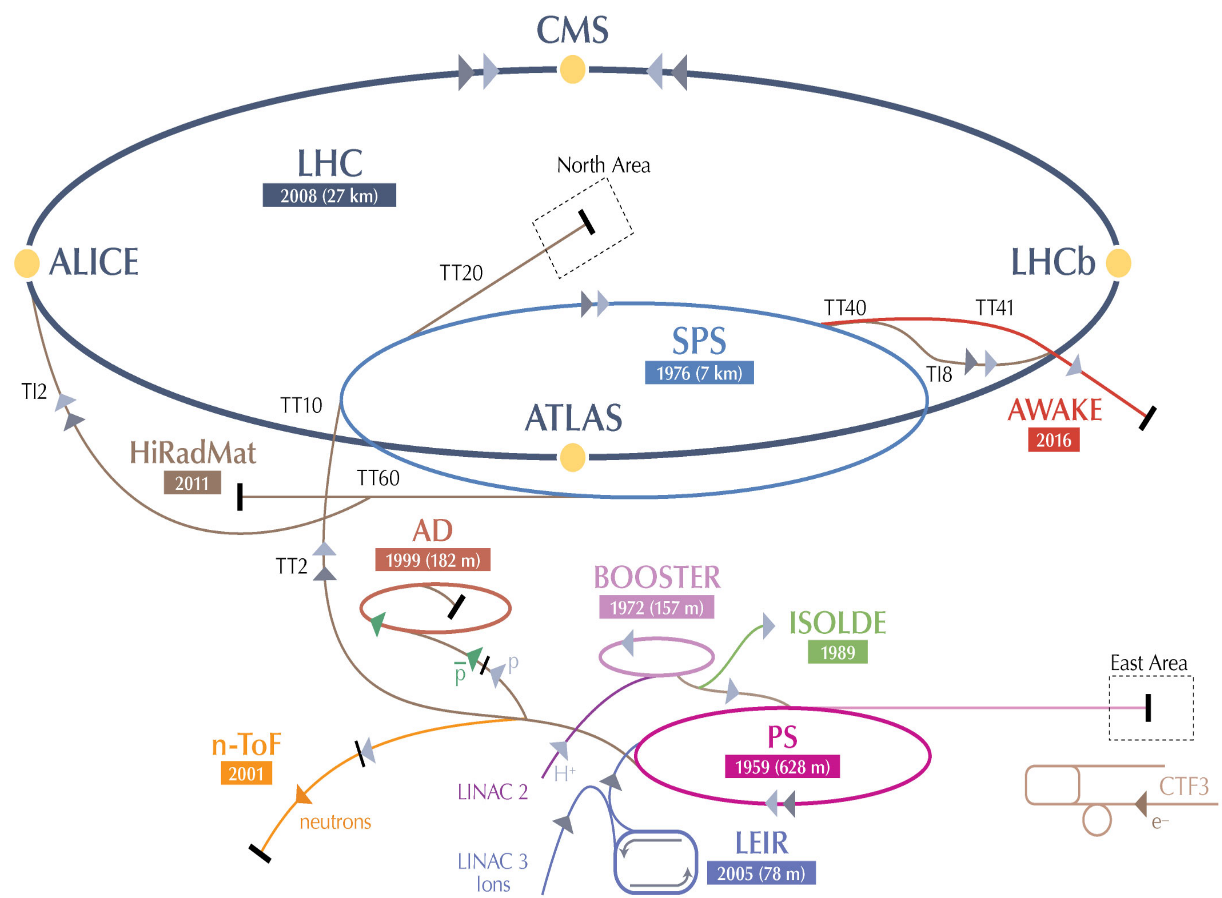
(Received 20 September 2011; accepted 2 January 2012)

AWAKE: Advanced Wakefield Experiment

The primary goal of AWAKE is to demonstrate acceleration of a 10-20 MeV single bunch electron beam up to 1 GeV in a 10 m of plasma.



AWAKE time line

- 2013

  Approval of project at CERN including funding profile.
- 2014-2015

  Design, procurement and installation of the equipment, development of **plasma cells**.

  Modification and installation of the **beam line and the experimental facility.**
- 2016

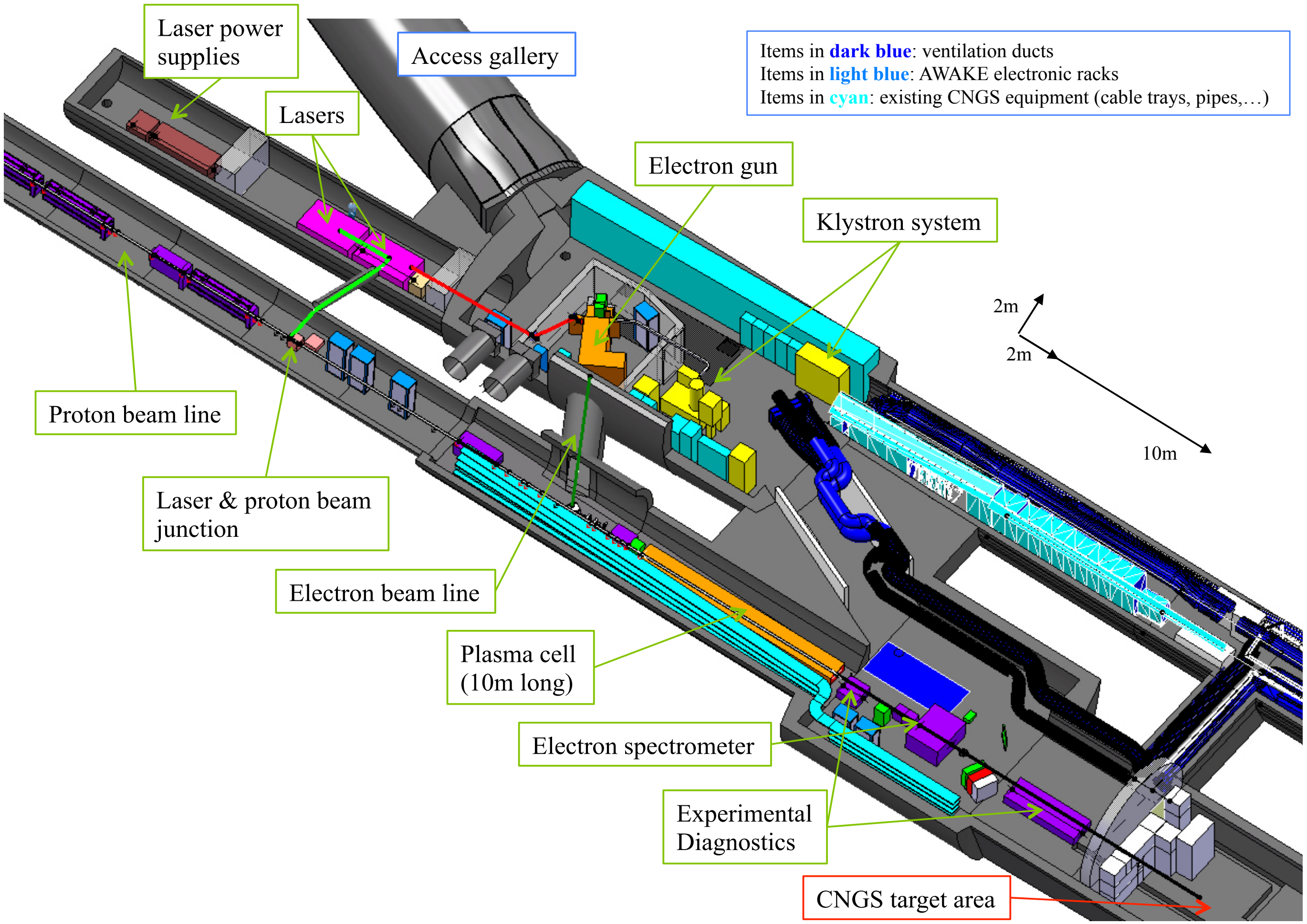
  First proton beam to the AWAKE experiment, beam–plasma commissioning.

  Beginning of taking data
- 2017

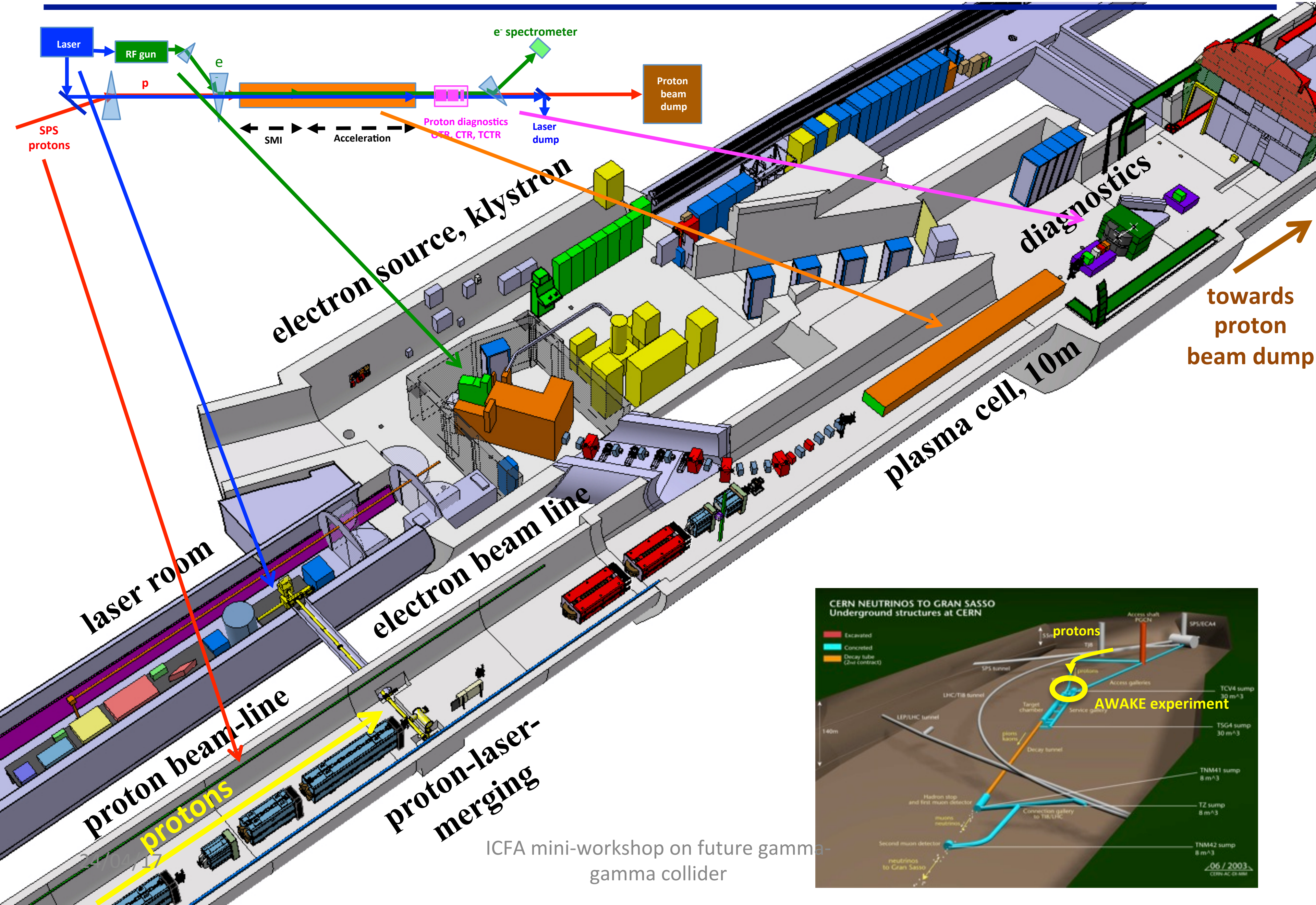
  Installation of the electron source and beam line and diagnostics.

  Delivery and installation of the electron photo-injector, commissioning of the magnetic spectrometer.
- **More data taking!**
- International Effort
- 16 institutions in 9 countries across Europe and Asia.

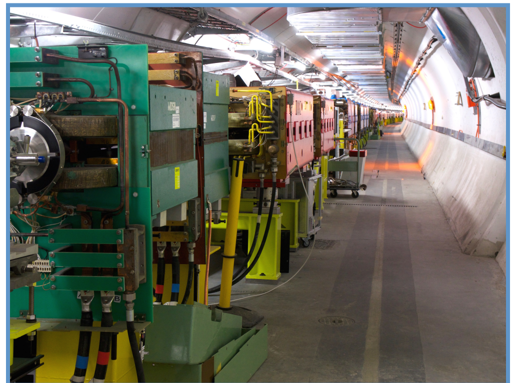
AWAKE experiment layout

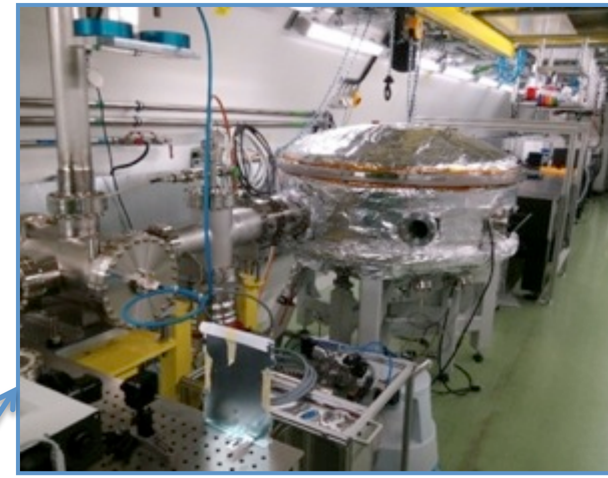


AWAKE at CERN

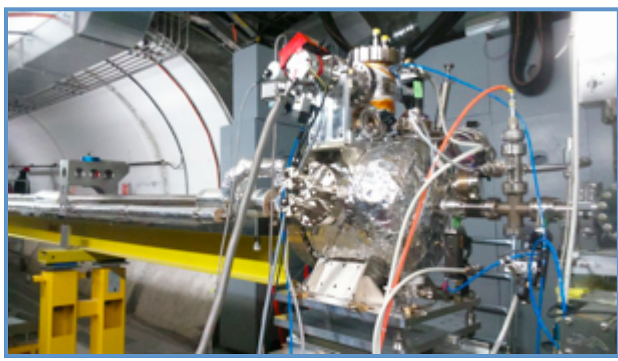


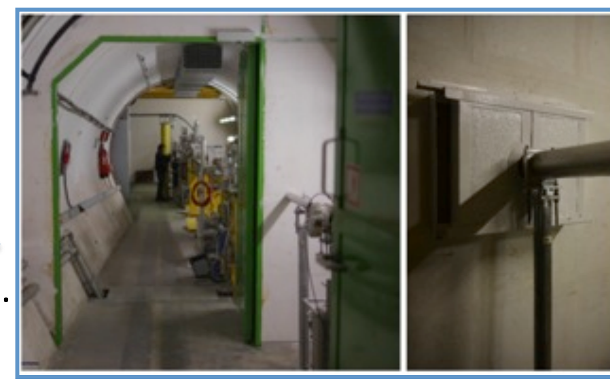
AWAKE installation





Proton beam line installed.
Detectors installed.
Laser and laser line installed.
Plasma cell installed.
Plasma wakefield simulations.
Fire safety compartments.
Safety clearance HW/beam permits.

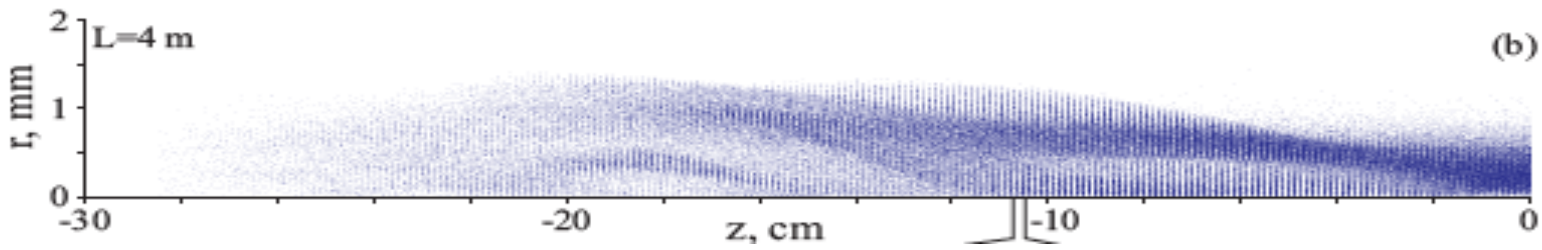




Proton beam specifications

Nominal SPS Proton Beam Parameters	
Momentum	400 GeV/c
Protons/bunch	$3\ 10^{11}$
Bunch length	σ_z = 0.4 ns (12 cm)
Bunch size at plasma entrance	$\sigma^*_{x,y}$ = 200 μm
Normalized emittance (r.m.s.)	3.5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.35%

Long proton beam σ_z = 12cm! ←→Compare with plasma wavelength of λ = 1mm.
→ Experiment based on Self-Modulation Instability!



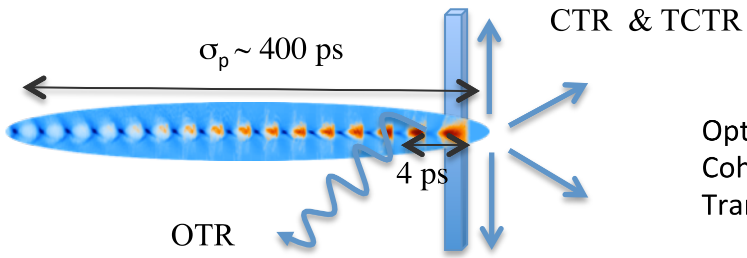
Self-modulation instability of the proton beam: modulation of a long (SPS) beam in a series of 'micro-bunches' with a spacing of the plasma wavelength.

Drive beam diagnostics

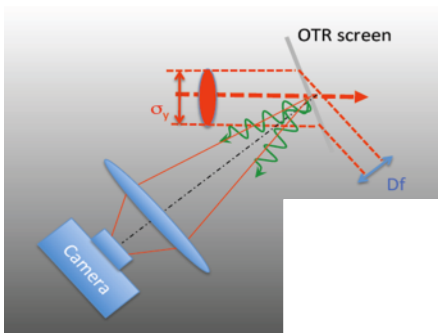
Direct Measurement of self-modulation instability of the proton beam

→ results in radial modulation of the proton beam (micro-bunches)

– Measured by using the radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field. → streak-camera.

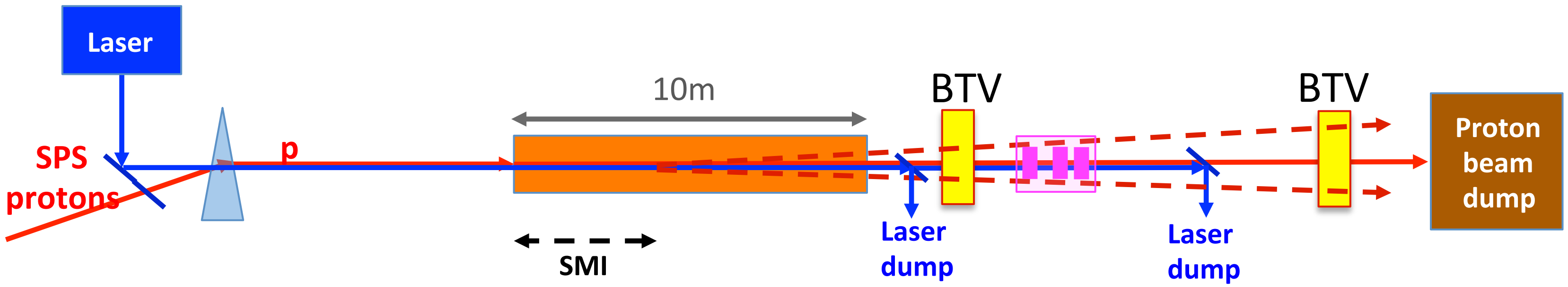


Optical Transition Radiation (OTR)
Coherent Transition Radiation (CTR)
Transverse Coherent Transition Radiation (TCTR)



Indirect Measurement by observing the proton bunch defocusing downstream the plasma

→ Proton bunch: 1mrad divergence



Witness beam

→ Optimal electron energy is 10-20 MeV

  – Electron energy = wakefield phase velocity at self-modulation stage.

→ Electron bunch length:

  – Should be small to be in phase with high field region.

→ Electron beam should have small enough size and angular divergence to fit into high capture efficiency region.

→ Electron beam intensity: get good signal in diagnostics!

Electron beam	Baseline	Range for upgrade phase
Momentum	16 MeV/c	10-20 MeV
Electrons/bunch (bunch charge)	1.25 E9	0.6 – 6.25 E9
Bunch charge	0.2 nC	0.1 – 1 nC
Bunch length	σ_z =4ps (1.2mm)	0.3 – 10 ps
Bunch size at focus	$\sigma^*_{x,y}$ = 250 μm	0.25 – 1mm
Normalized emittance (r.m.s.)	2 mm mrad	0.5 – 5 mm mrad
Relative energy spread	$\Delta p/p$ = 0.5%	<0.5%

Electron source

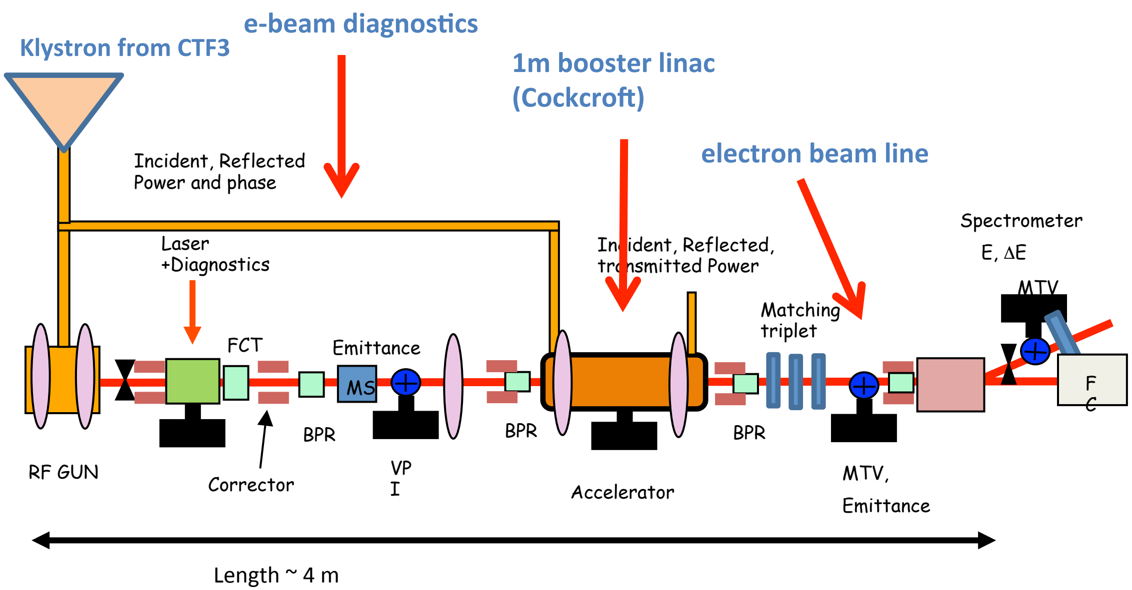
PHIN Photo-injector for CTF3/CLIC:

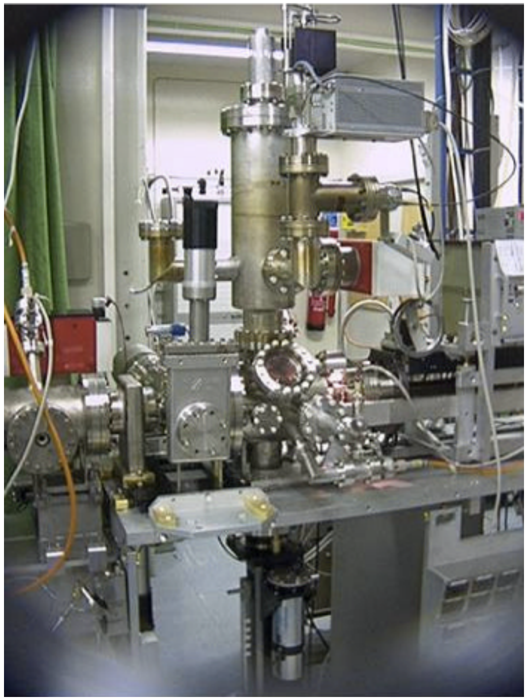
- Charge/bunch: 2.3 nC
- Bunch length: 10 ps
- 1800 bunches/train, 1.2μs train-length
- → Program will stop end 2015

→ Fits to requirements of AWAKE

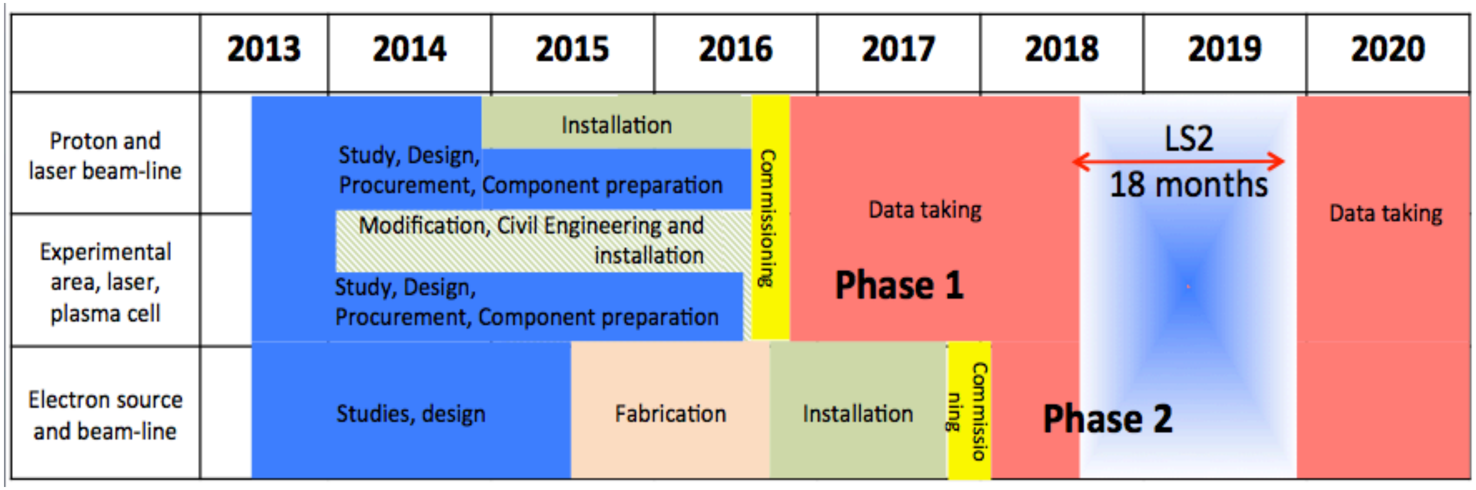
→ Photo-injector laser derived from low power level of plasma ionization laser system.

Laser beam for electron source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	500 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.





AWAKE timeline

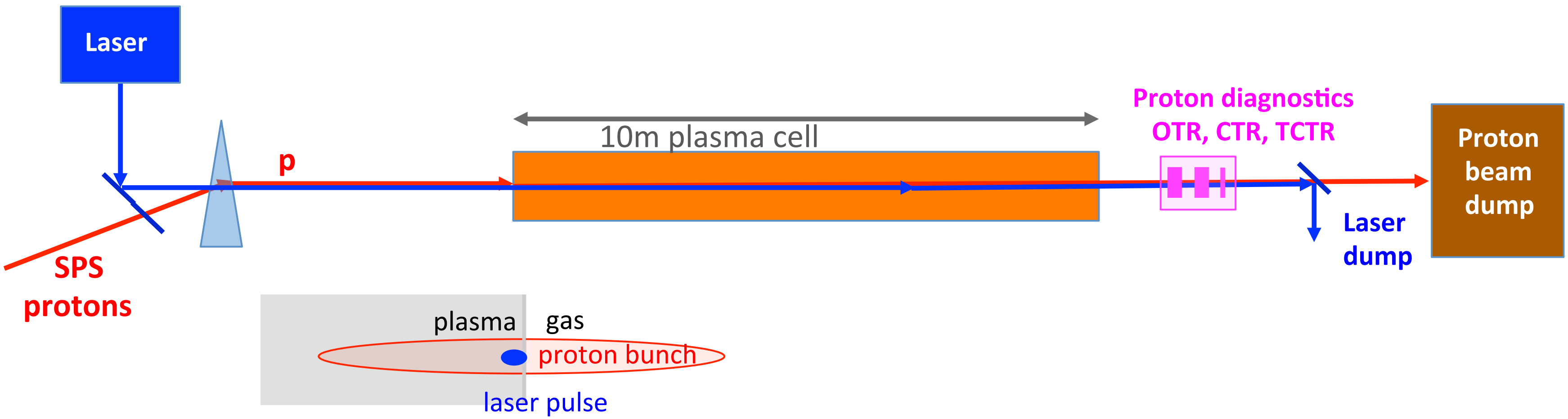


2016 Phase 1: Self-Modulation Instability physics
2017-18 Phase 2: Electron acceleration physics

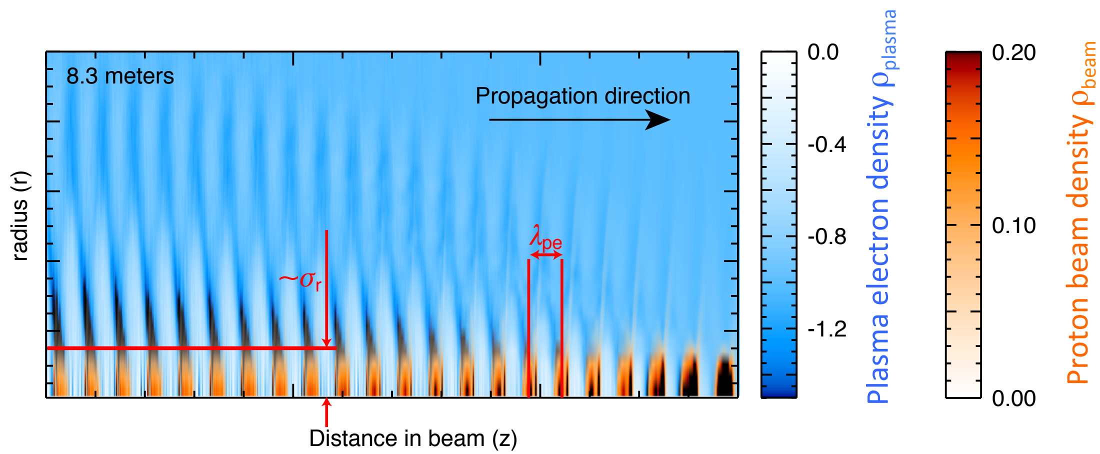
Run-scenario	Nominal
Number of run-periods/year	**4**
Length of run-period	**2 weeks**
Total number of beam shots/year (100% efficiency)	**162000**
Total number of protons/year	**$4.86{\times}10^{16}$ p**
Initial experimental program	**3 – 4 years**

AWAKE Run I: Phase I

- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability** processes in plasma.



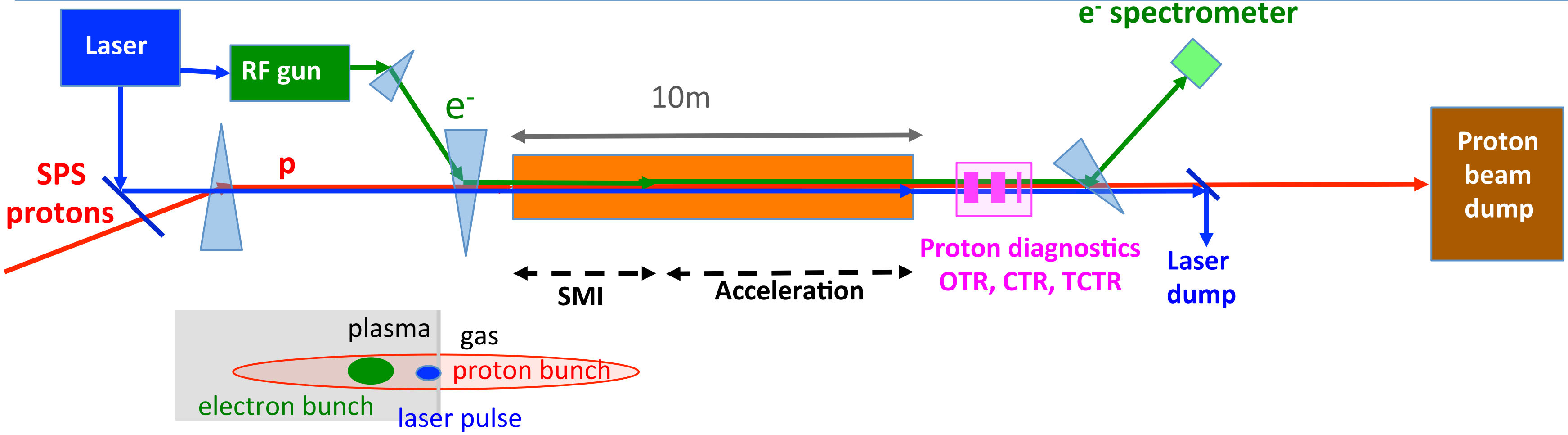
Self-modulated proton bunch resonantly driving plasma wakefields.



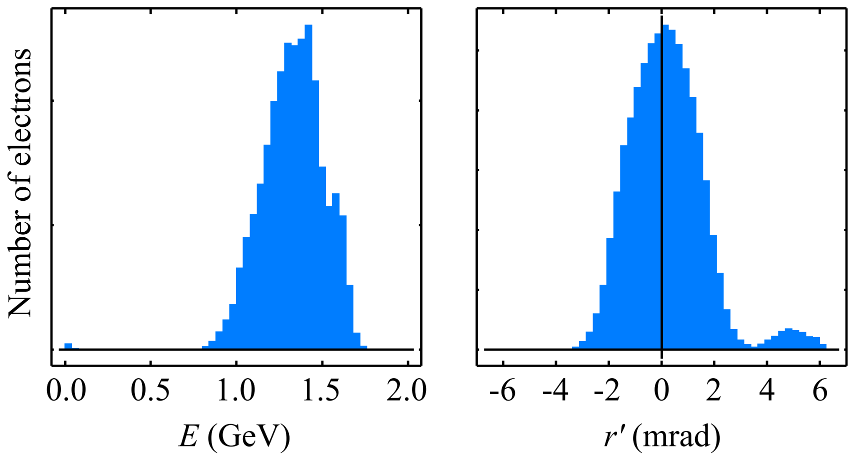
J. Vieira et al PoP 19063105 (2012)

AWAKE Run I: Phase II

Probe the accelerating wakefields with externally injected electrons, including energy spectrum measurements for different injection and plasma parameters.

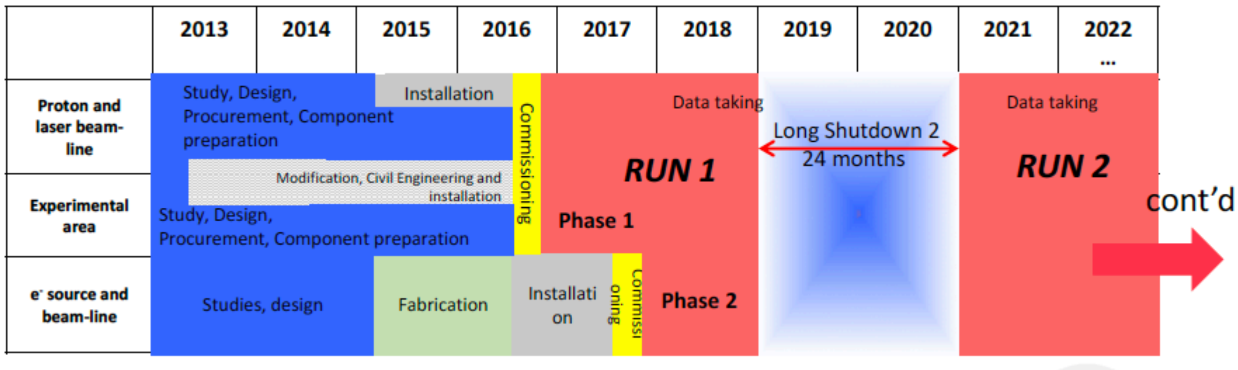


- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad



AWAKE Run II

AWAKE Timeline



Run 1 – until LS2 of the LHC.

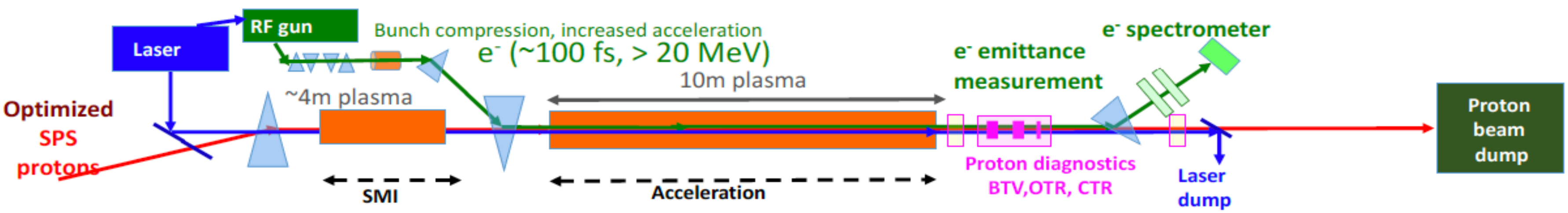
After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

After Run 2 – particle physics driven applications

E. Gschwendtner (CERN)

Goals:

- Accelerate an electron beam, while **preserving beam quality** as well as possible
- **Demonstrate scalability** of the AWAKE concept



Requirement:

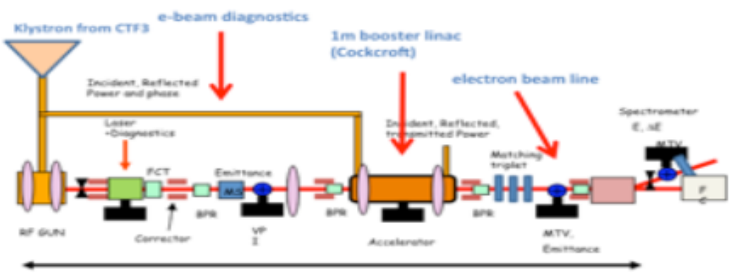
- Sustain gradient in SMI wake over long distance → density step for freezing modulation
- Short electron bunch with higher energy for loading wakefield
- Compressed proton beam in SPS
- Alternative plasma cell developments (scalable)

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

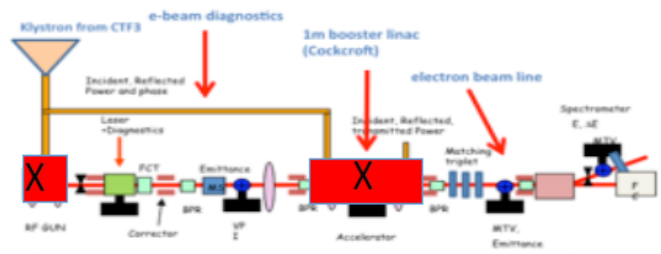
AWAKE Run II: electron injector

Modify phase 2 injector (S-band)



Cannot provide parameters in available space (bunch length, 50 MeV and 400 A).

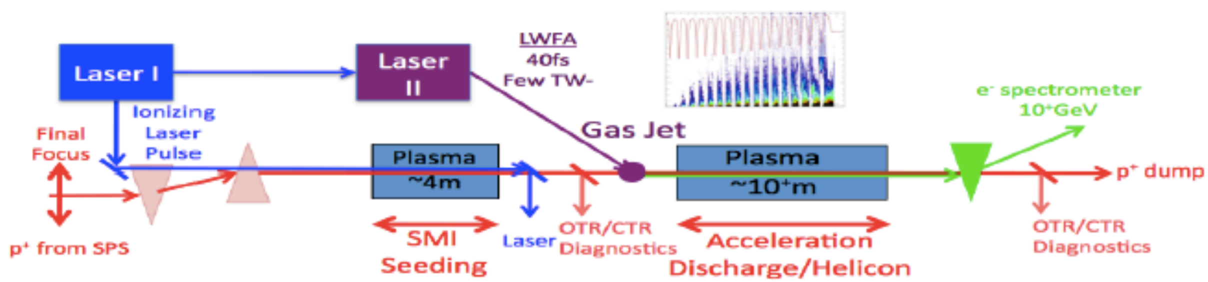
Modify phase 2 injector, upgrade with X-band, interesting technology



X-band structure: ~60 MV/m gives required boost

X-band gun: Based on best SLAC results could provide required energy and current in available space. Requires development work.

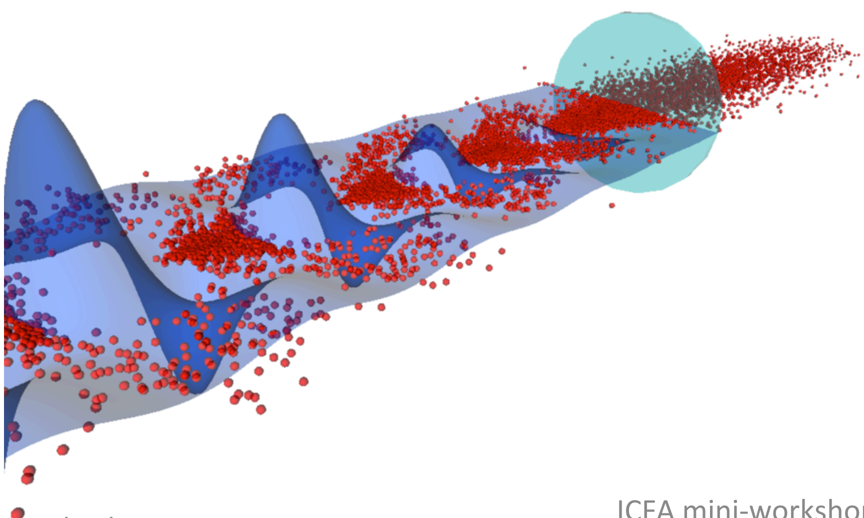
Laser wakefield acceleration injector

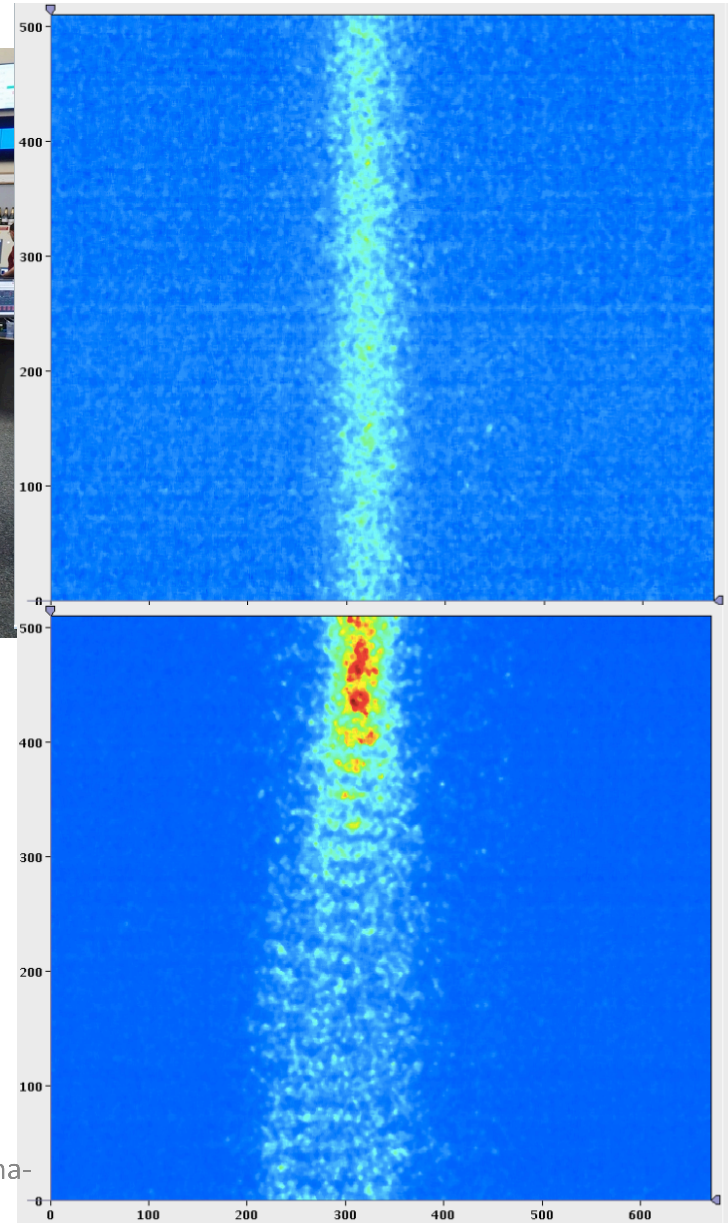


- 100+ MeV routinely reached with few MW Ti:Sa laser
- very short bunches possible (few um)
- compact
- AWAKE energy requirement (< 100 MeV) relaxed with respect to state-of-the-art (4 GeV)

→ collaboration with LWFA-experts initiated

AWAKE milestone in 2016





Future perspectives

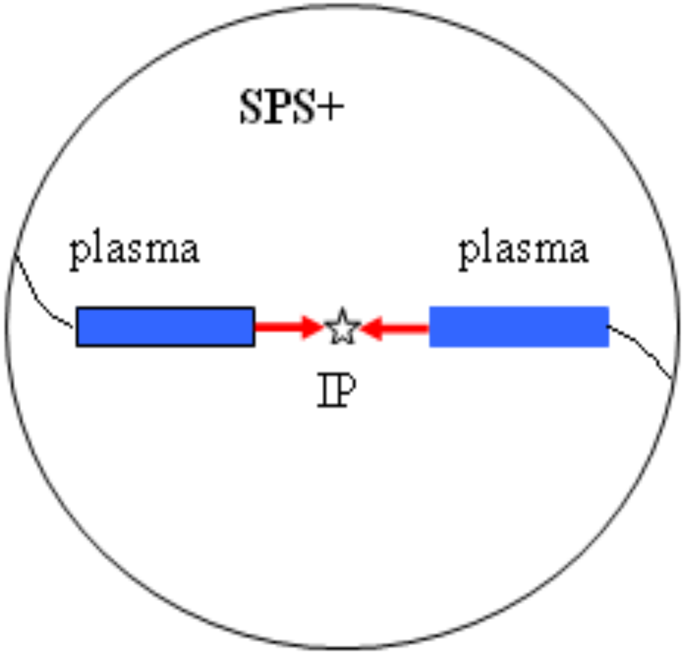
$$L = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$ Gaussian shaped beams

suppose $N_1 = N_2 = 10^{11}$

SPS cycle time $22s$ 288 bunches

so assume $f = 15$ Hz

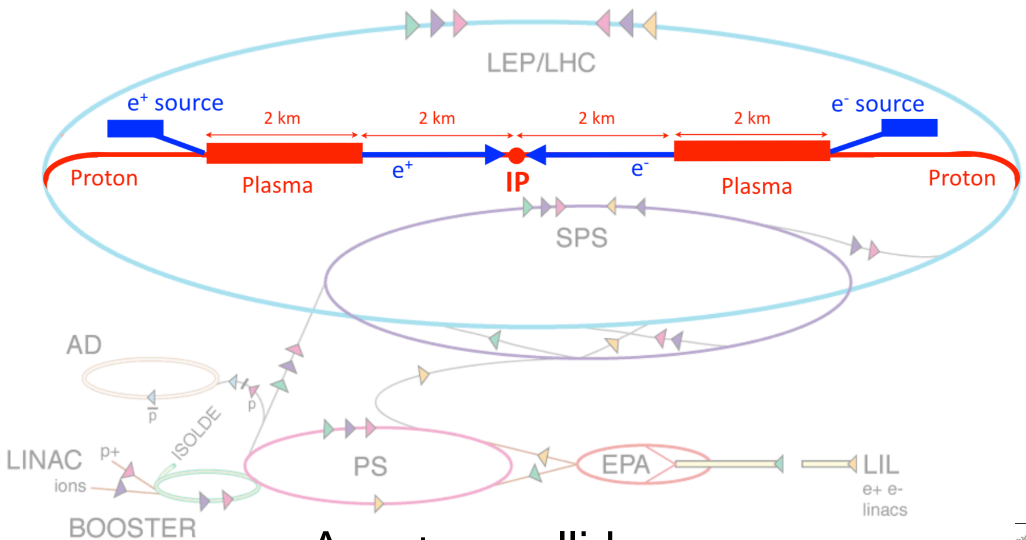
$$L \approx \left(\frac{1\ \mu\mathrm{m}^2}{\sigma_x\sigma_y}\right) 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$



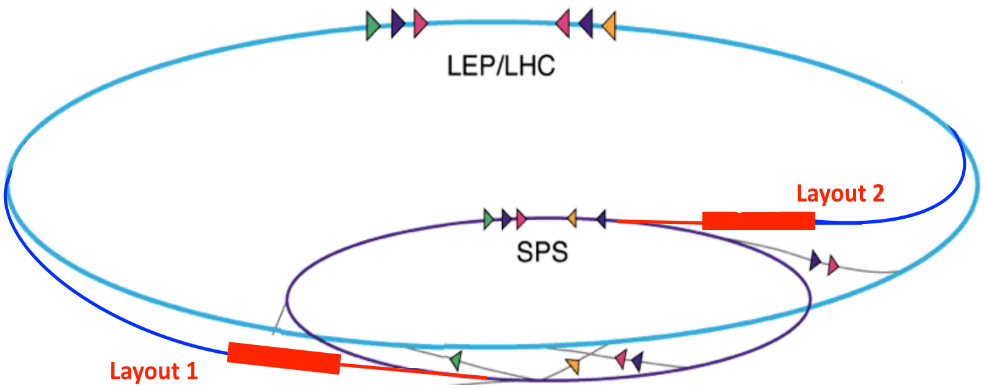
IP beam sizes: 42 nm (horizontal) and 1 nm (vertical)

$L = 5\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

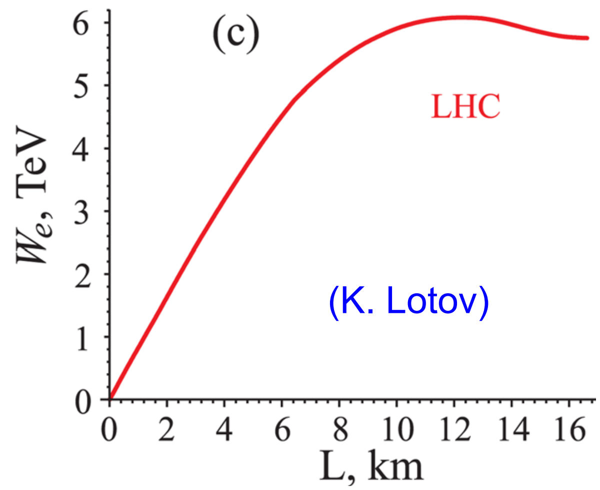
e^+e^- and *e-p* colliders

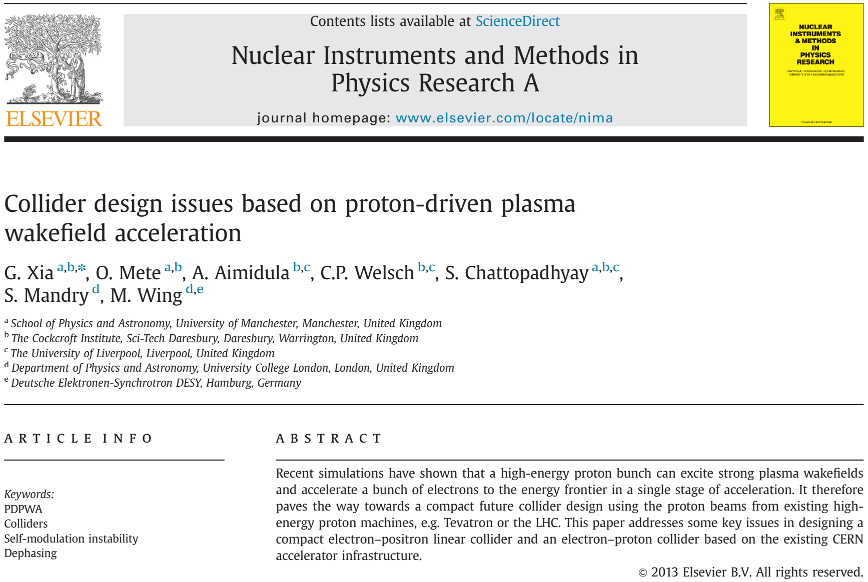


An e+ e- collider



An e-p collider





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Collider design issues based on proton-driven plasma wakefield acceleration

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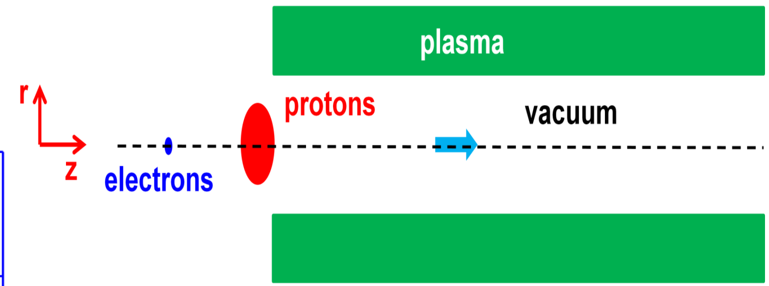
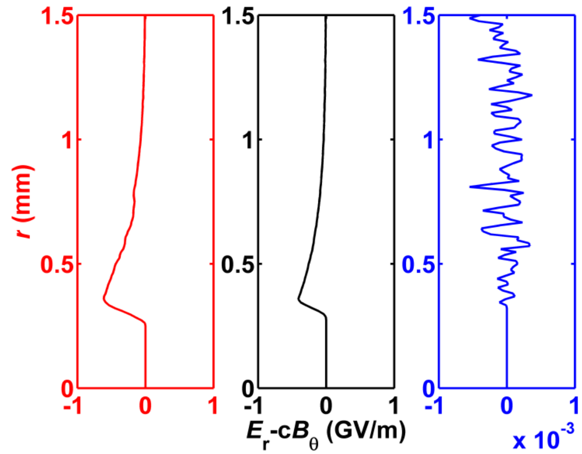
ABSTRACT

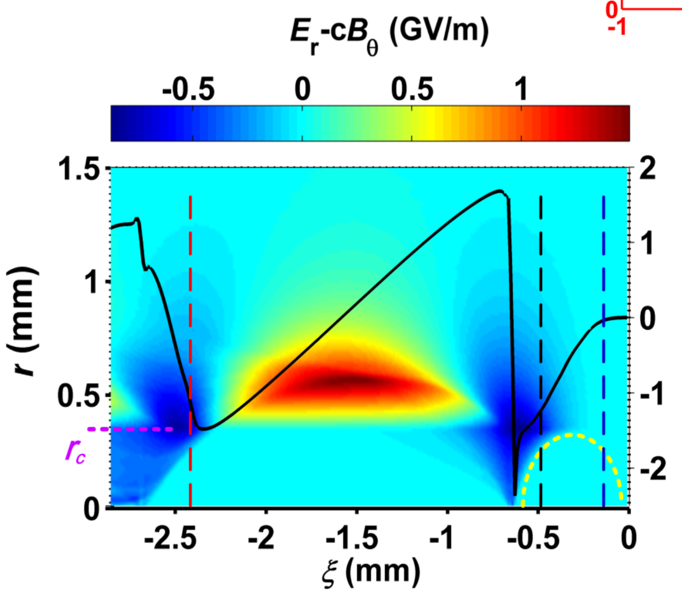
Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.

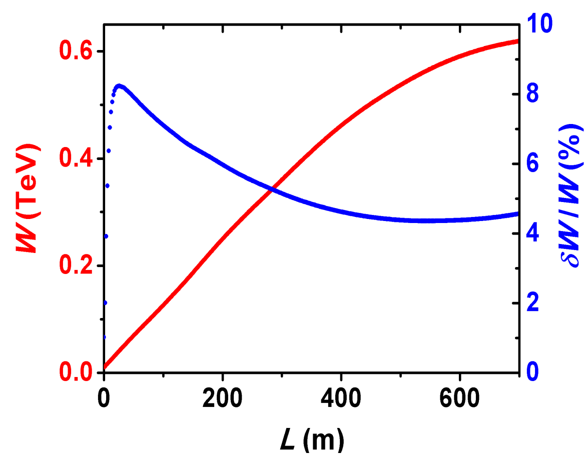
Hollow plasma for good beam quality

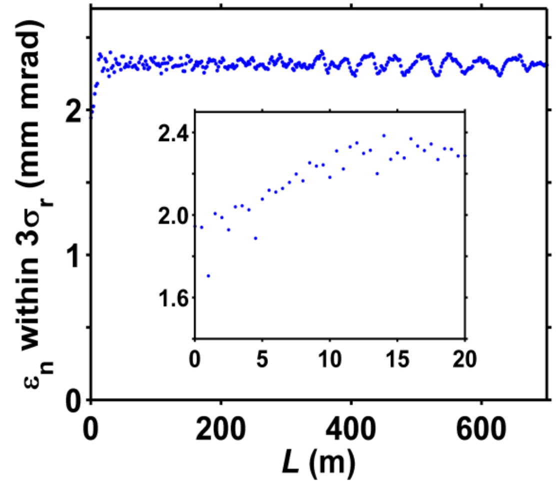
- **Hollow plasma channel for electron acceleration**
- **Create a regime completely without transverse plasma wakefields**
- **Conservation of the norm. emittance of the witness beam**







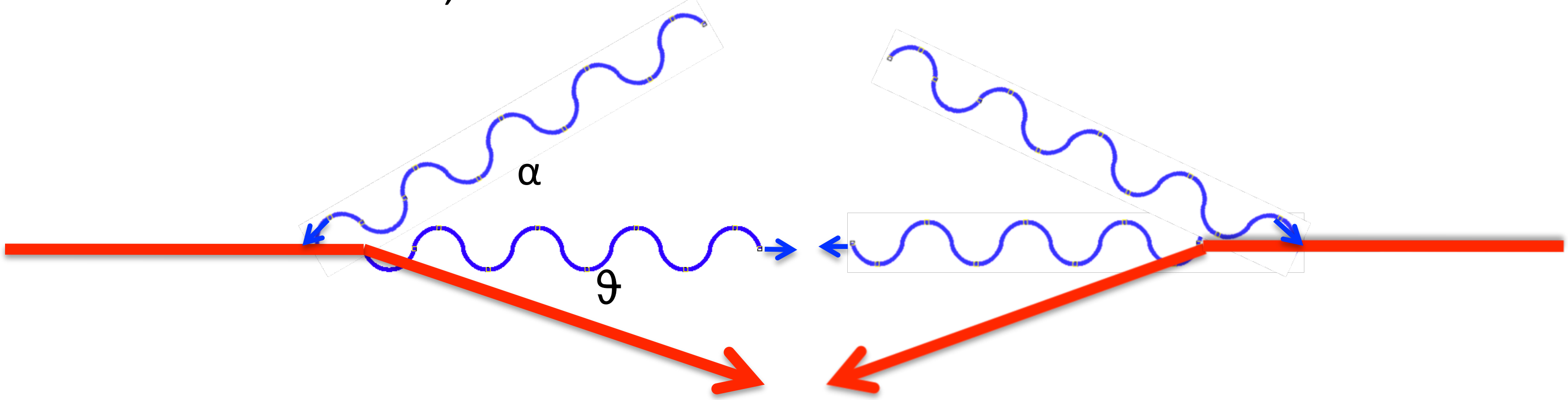




Y. Li et al, submitted to PoP in 2017.

Gamma-gamma collider

- Collide electron beam with laser beam just before the IP (at small angle α)
- Hard backscattered photons move almost in direction of initial electron (angle ~1/γ)
- Photons collide, electrons as well



Backscattered photons form a spectrum with maximum energy given by

$$x = \frac{4E_0\hbar\omega_0}{m^2c^4} \qquad \hbar\omega_m = \frac{x}{x+1}E_0$$

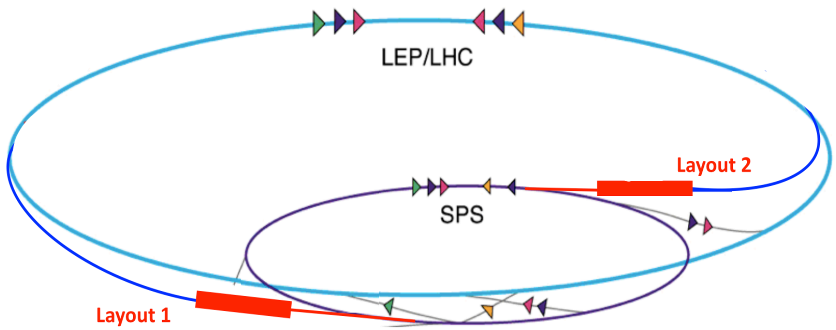
Practical maximum is 83% of electron energy

-> Typical laser wavelength O(μm), some J per pulse

Many photons are softer than maximum energy

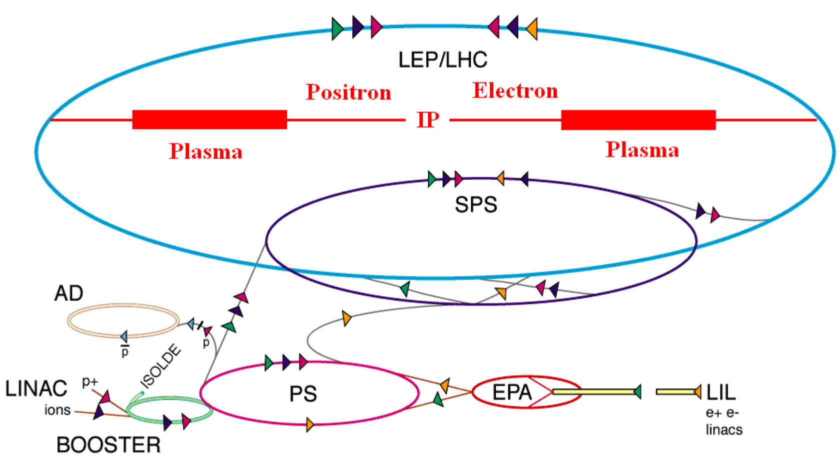
-> Typical luminosity O(10%) of geometric e^-e^- luminosity

Gamma-gamma collider



Using SPS as driver, it is possible to create 50-100 GeV electron beam in ~ 100 m long plasma.

Such electrons can interact with laser to produce photons for gamma-gamma collider



An e^-e^+ collider (multi-TeV CoM energy) or an e^-- p^+ collider (> 2 TeV CoM) could be achieved based on existing CERN infrastructure;

Multi-TeV electrons interact with laser for producing gamma photons to collider

The luminosity of the collider is low

Conclusions

- Proton-driven plasma wakefield acceleration is very promising to provide energy frontier beam in a single stage acceleration
- Self-modulation process can generate short proton bunches for driving large amplitude plasma wakefield
- AWAKE run 1 will demonstrate modulation process and proton-driven electron acceleration before LS2 of the LHC.
- First milestone has been achieved in 2016 to observe the self-modulation process
- AWAKE Run II will demonstrate stable and high quality electron beam generation
- Long term future of AWAKE scheme exciting due to many opportunities, such as *ee*, *ep* colliders, fixed target experiment and gamma-gamma collider, etc.