Physics basis for AWAKE experiment

Konstantin Lotov

Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia

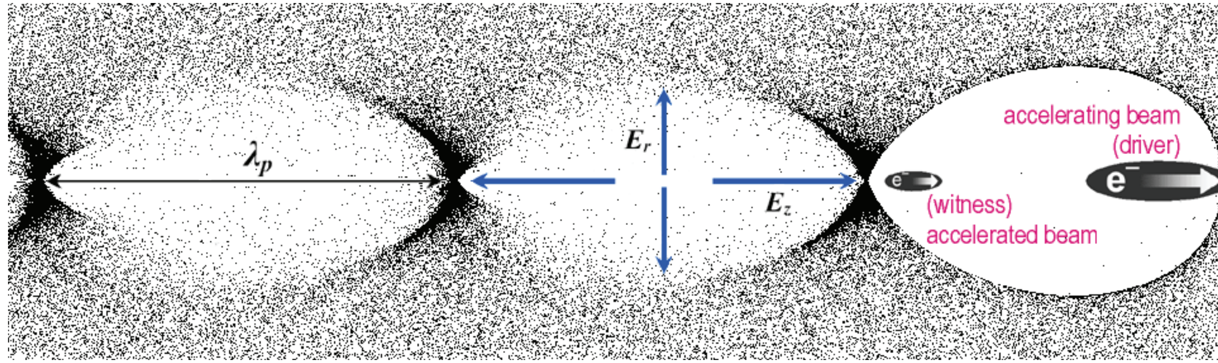
Novosibirsk State University, Novosibirsk, Russia

AWAKE Collaboration

AWAKE (Advanced proton driven plasma WAKEfield acceleration experiment) is the first experiment on plasma wakefield acceleration driven by a proton beam

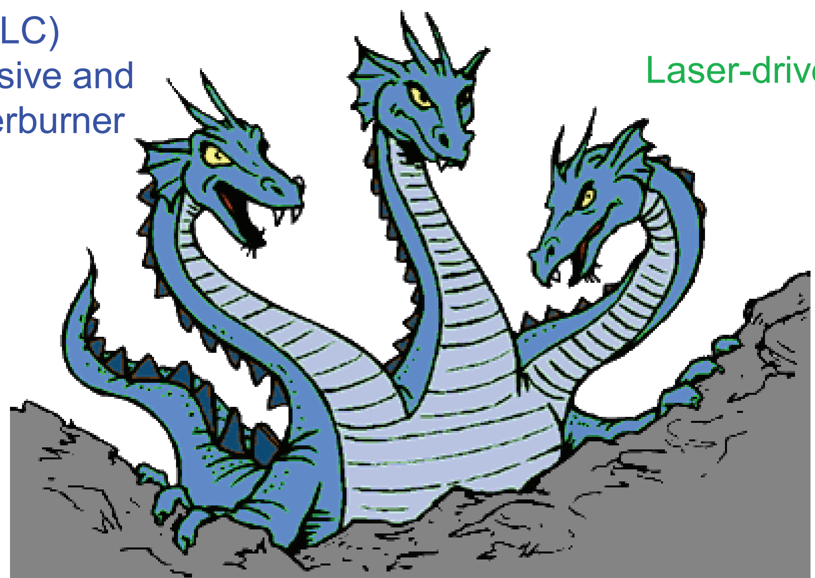
PWFA promises x100 higher acceleration rate, but has a great number of problems to solve on the way to real high-energy collider

One problem is related to the energy content of the accelerated bunch: ILC-like electron bunch has ~1 kJ at 250 GeV



Proton drivers: 20 kJ (SPS), >150kJ (LHC) drivers have enough energy in a single bunch to accelerate electrons to TeVs in a single plasma stage

Electron-driven: < 120 J (SLC) either many stages (expensive and complicated design) or afterburner (energy doubling after a conventional linac),

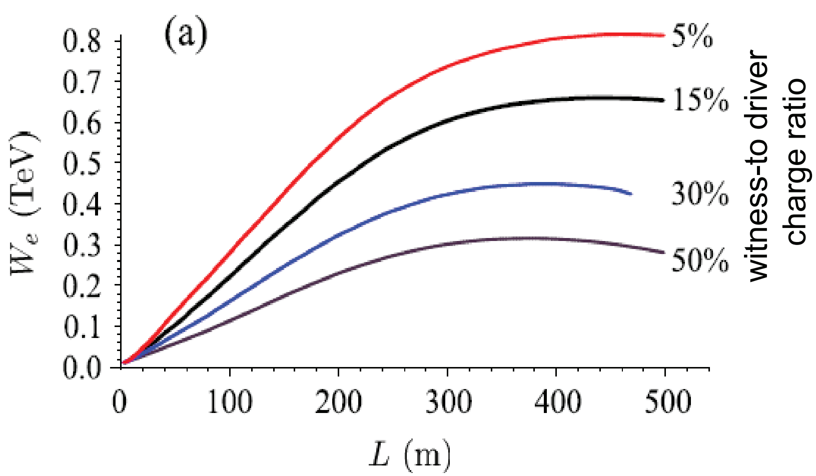


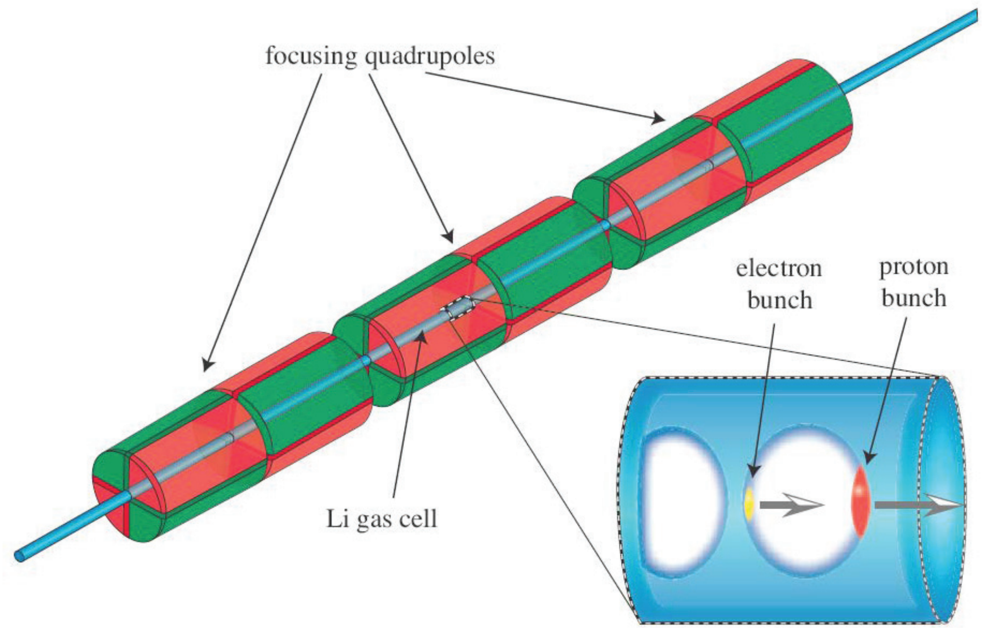
Laser-driven: < 50 J in the drive laser pulse,
< 10 GeV/stage,
many stages are needed for TeVs,

Compact radiation sources and electron injectors become the mainstream applications

Problem of the bunch length: must be much shorter than the plasma wavelength

If the proton driver is 100 μm short (σ_z), it nicely excites the wave and accelerates electrons:





Drive beam: p^+
E=1 TeV, $N_p=10^{11}$
σ_z=100 μm, σ_r=0.42 mm
σ_θ=0.024 mrad, ΔE/E=10%

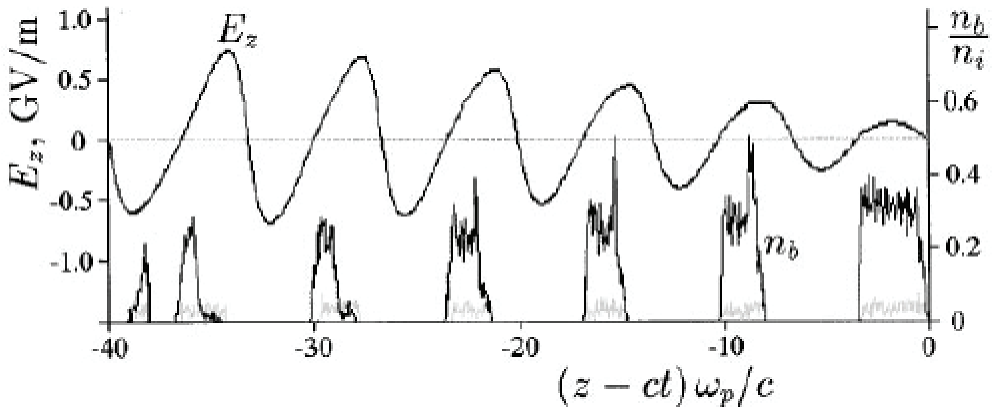
Witness beam: e^-
E_0=10 GeV

Plasma: $n_p=10^{15}$ cm^{-3}

A. Caldwell, K. Lotov, A. Pukhov, F. Simon, Nature Physics 5, 363 (2009).
K. Lotov, Phys. Rev. ST – Accel. Beams 13, 041301 (2010).

… but compressing a proton bunch to a sub-millimeter scale is extremely difficult and complicated task

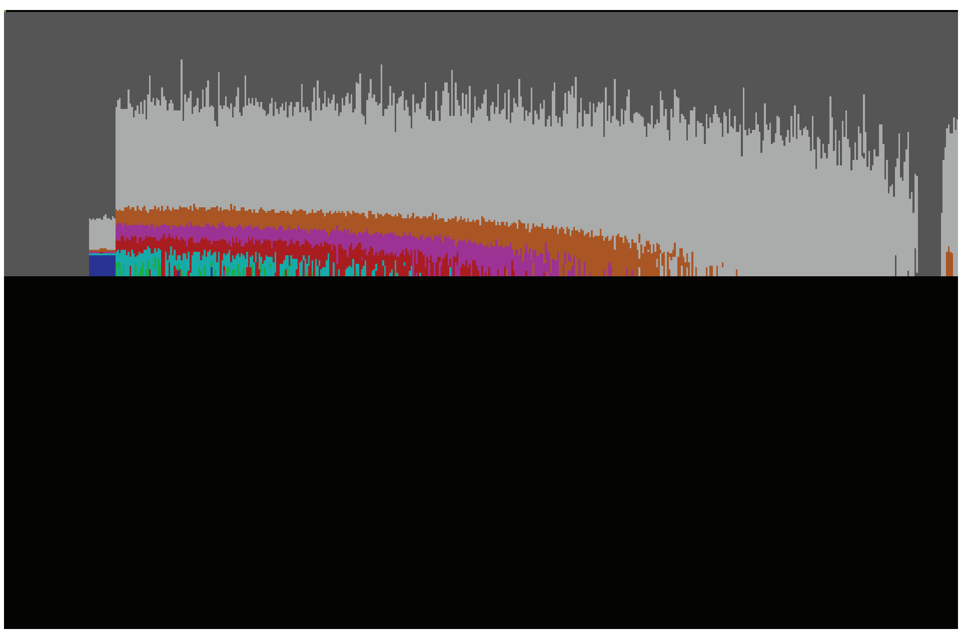
Extreme compression of proton bunches is unpractical, but multi-bunch wave excitation saves the concept



A train of short bunches can resonantly drive the plasma wave

It is easier to transform a long (>10 cm) proton bunch into a micro-bunch train than into a single short bunch

Even this scenario is too expensive for the first experiment



Cheap and easy solution:

Self-modulating beam

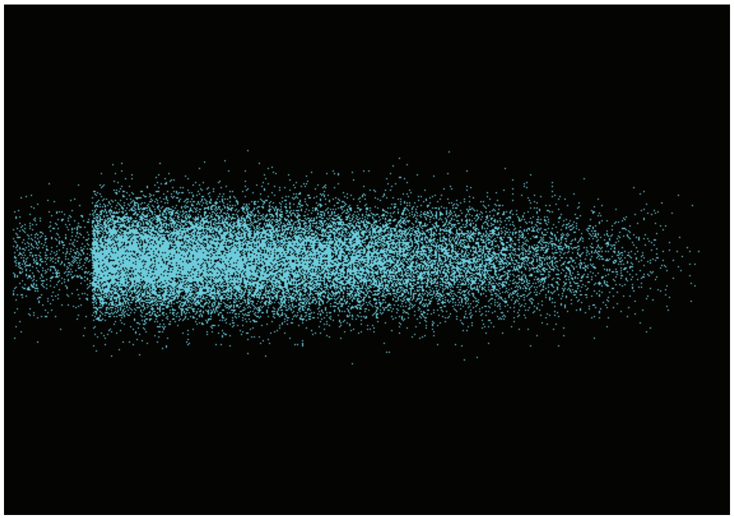
No compressor, no chopper, just let the plasma to modulate the beam via the transverse two-stream instability:

modulation of the beam radius produces modulation of the (de)focusing force, which further changes beam radius etc.

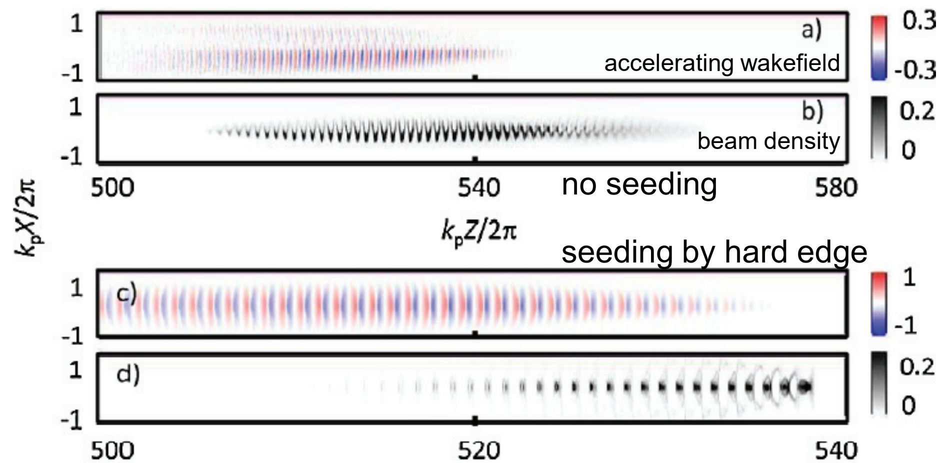
K. Lotov, Instability of long driving beams in plasma wakefield accelerators, Proc. EPAC-1998, p.806-808.

The seed perturbation is a necessary part of the concept

If developing from a noise, the transverse two-stream instability just breaks the beam, and there is no strong wakefield

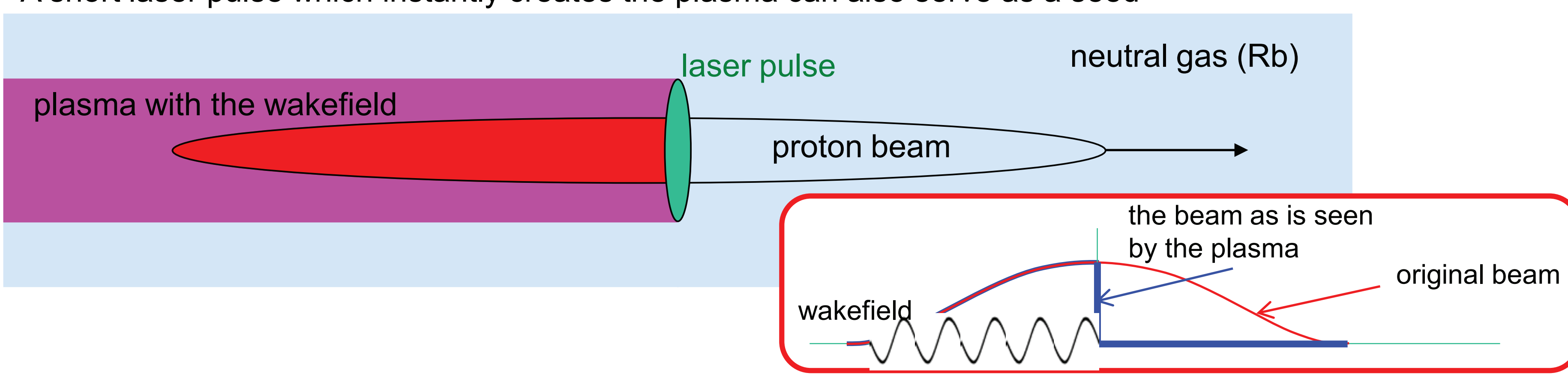


If the axisymmetric mode is externally seeded, then the beam is bunched, and strong wakefield is excited which is phase locked to the seed.

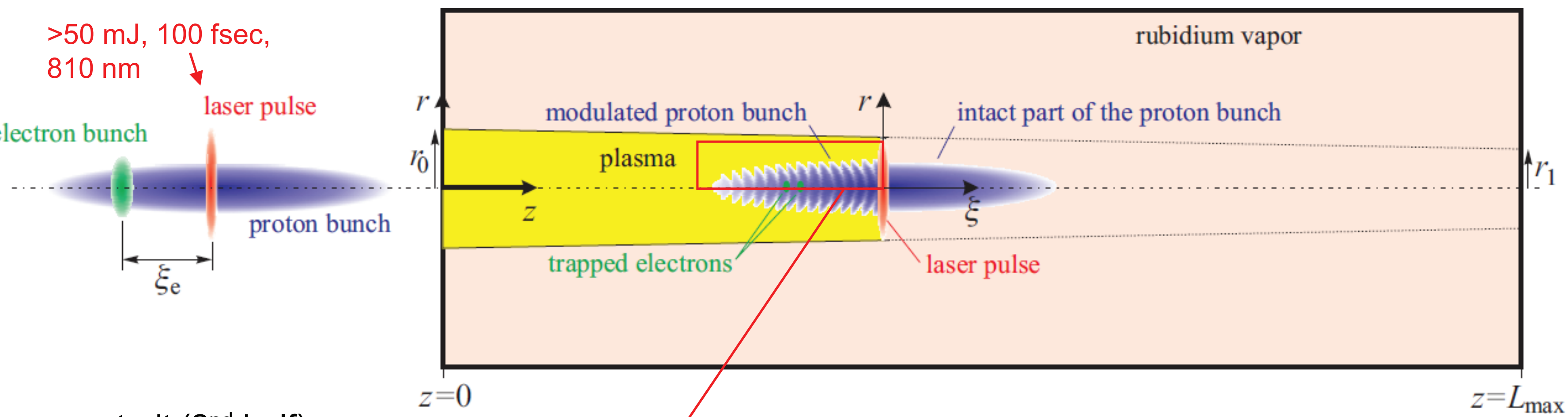


N.Kumar, A.Pukhov, and K.Lotov, Phys. Rev. Lett. 104, 255003 (2010).

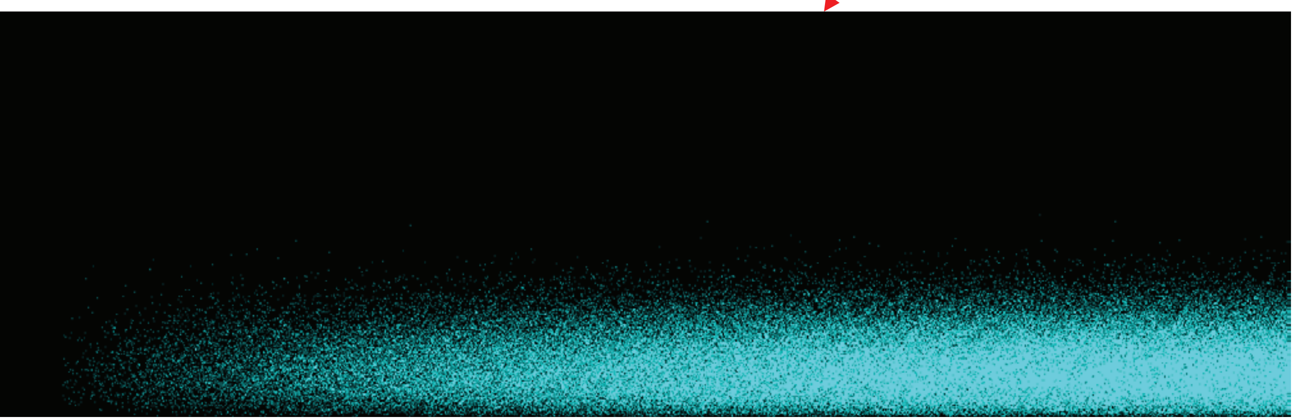
A short laser pulse which instantly creates the plasma can also serve as a seed

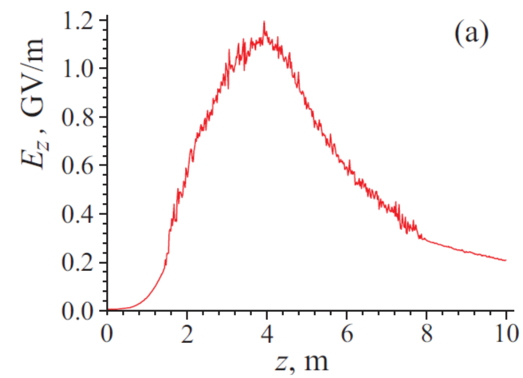


AWAKE experiment:

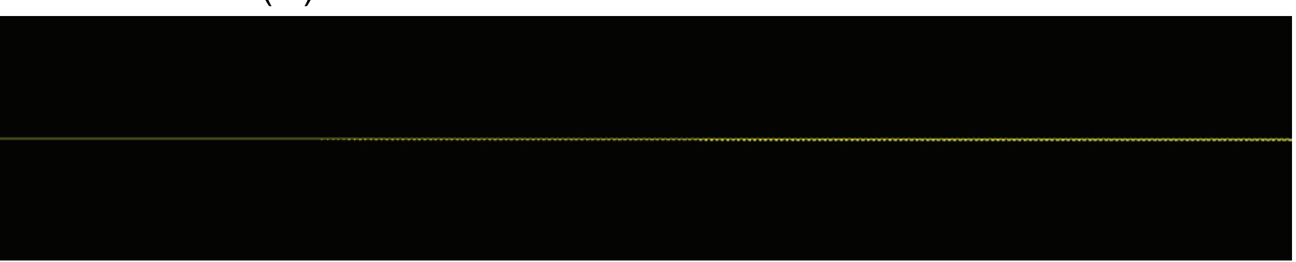


Beam portrait (2nd half)

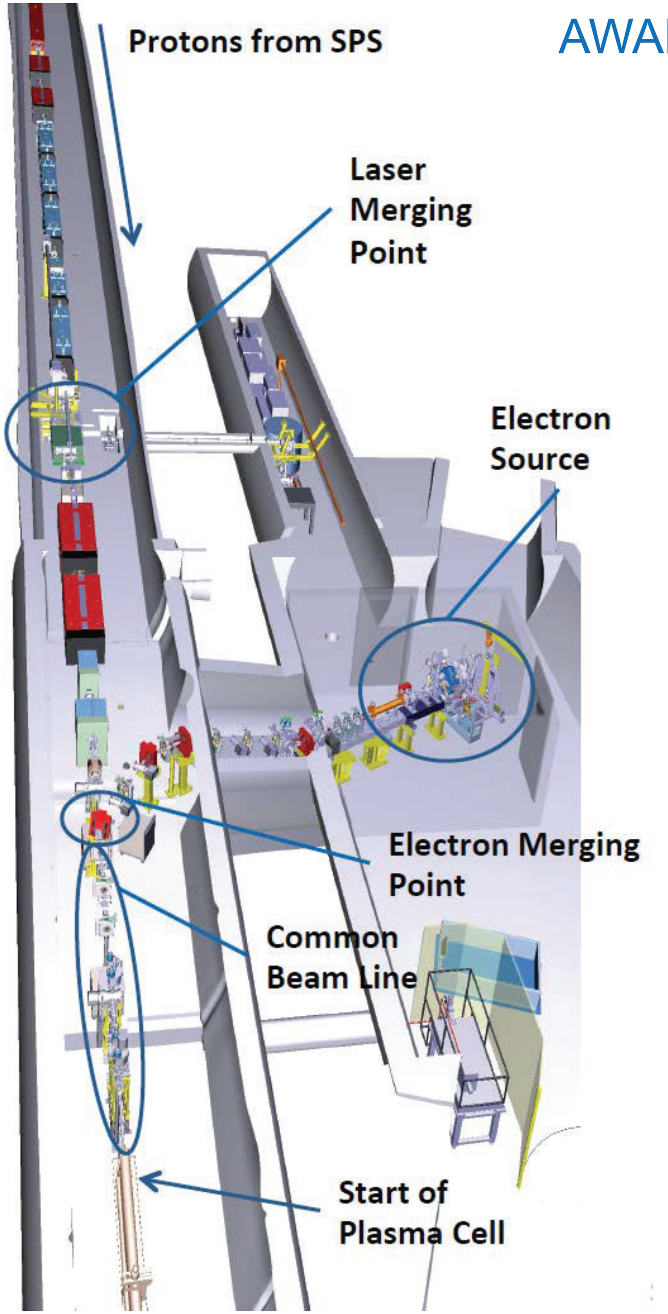


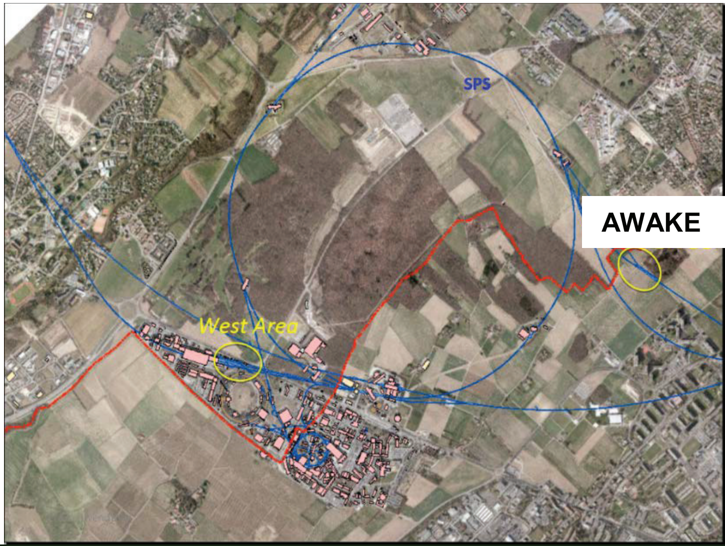


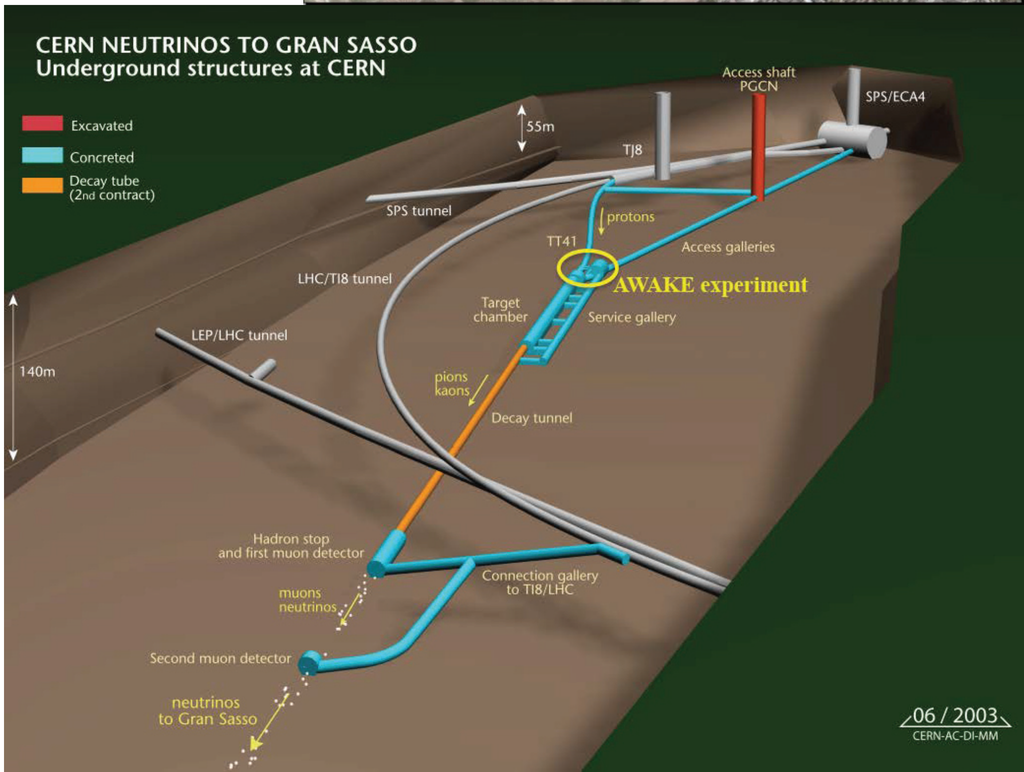
Excited field (Φ)



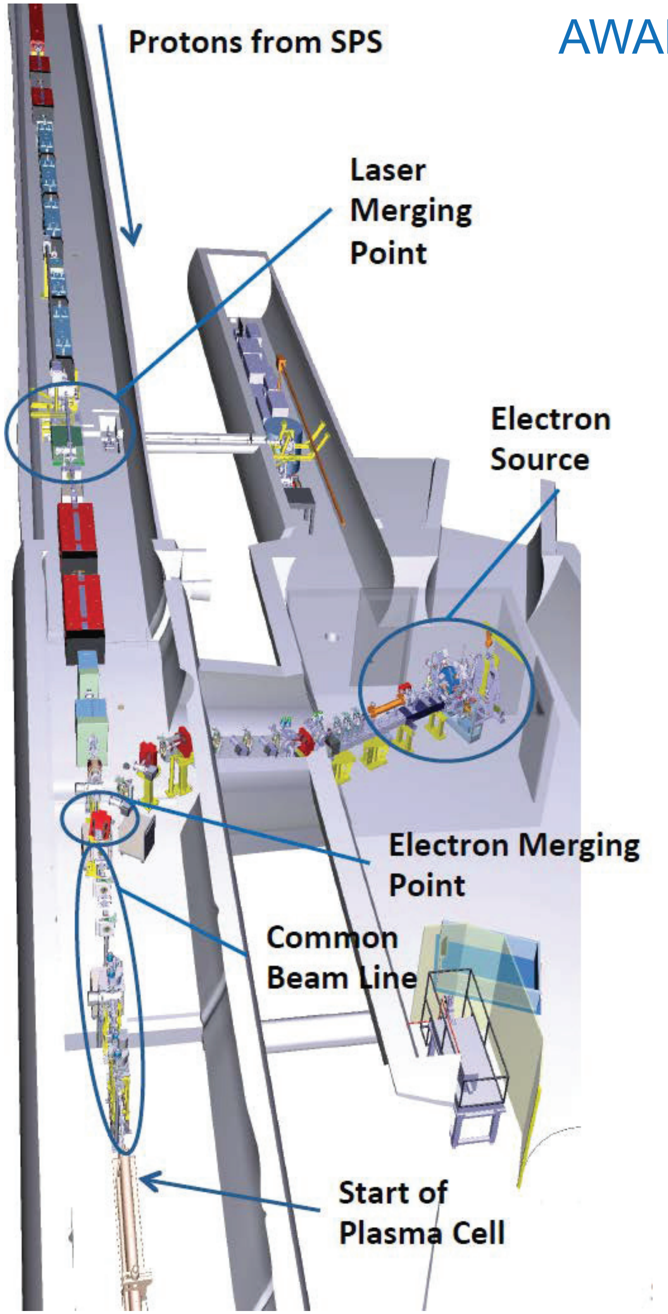
AWAKE experiment





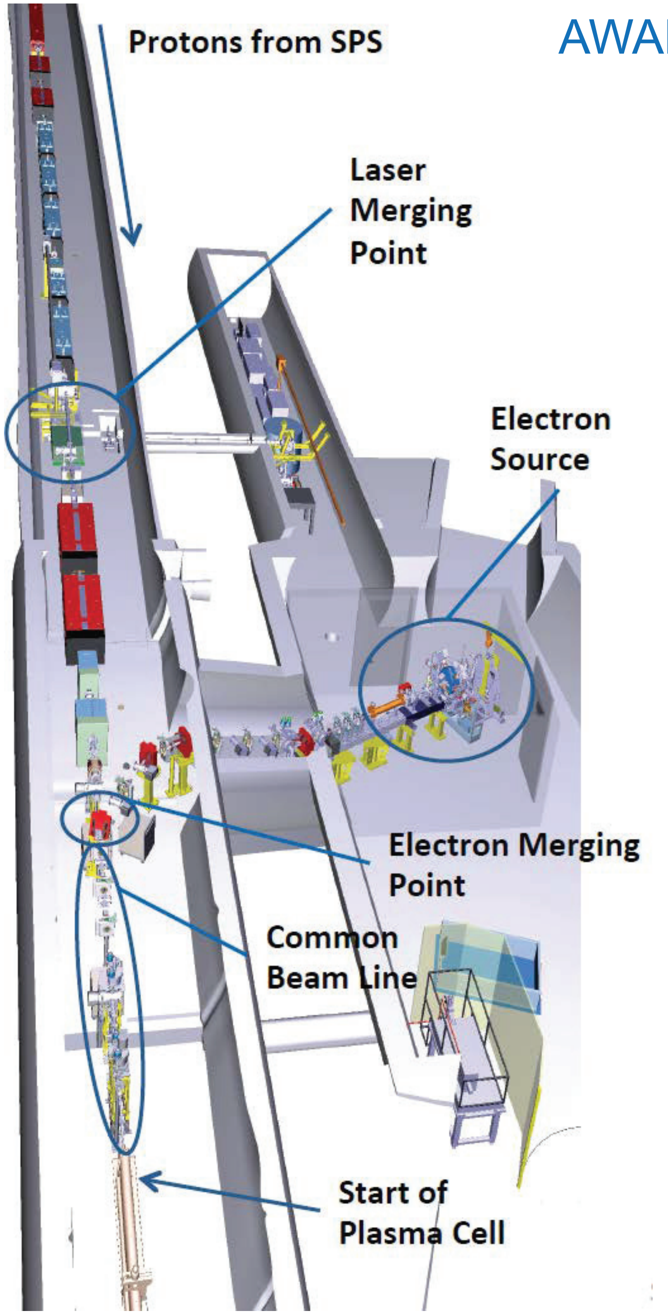


AWAKE experiment



Proton beam	
Beam momentum	400 GeV/c
Protons/bunch	3×10^{11}
Bunch extraction frequency	0.03 Hz (ultimate: 0.14 Hz)
Bunch length (σ)	0.4 ns
Bunch size at plasma entrance ($\sigma_{x,y}$)	200 μm
Normalized emittance (RMS)	3.5 mm mrad
Relative energy spread ($\Delta p/p$)	0.035%
Beta function ($\beta^*_{x,y}$)	4.9 m
Dispersion ($D^*_{x,y}$)	0
Laser beam to plasma	
Laser type	Fibre titanium: sapphire
Pulse wavelength (L_0)	780 nm
Pulse length	100–120 fs
Laser power	4.5 TW
Focused laser size ($\sigma_{x,y}$)	1 mm
Energy stability (RMS)	$\pm$ 1.5%
Repetition rate	10 Hz
Plasma source	
Plasma type	Laser ionized rubidium vapor
Plasma density	7×10^{14} cm^{-3}
Length	10 m
Plasma radius	$\geq$ 1 mm
Skin depth	0.2 mm
Wavebreaking field $E_0 = mc\omega_{cp}/e$	2.54 GV/m

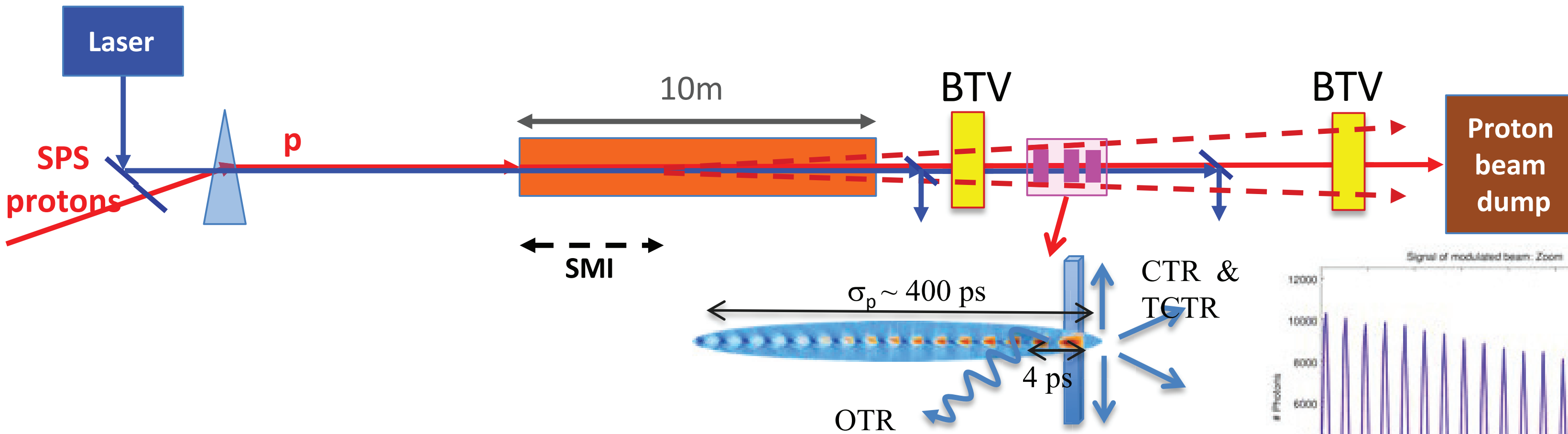
AWAKE experiment

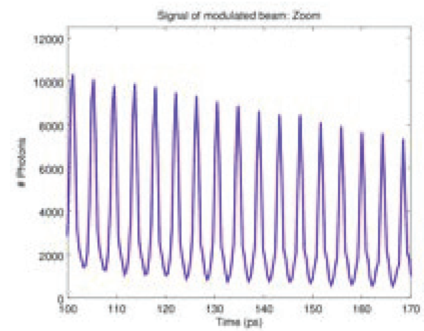


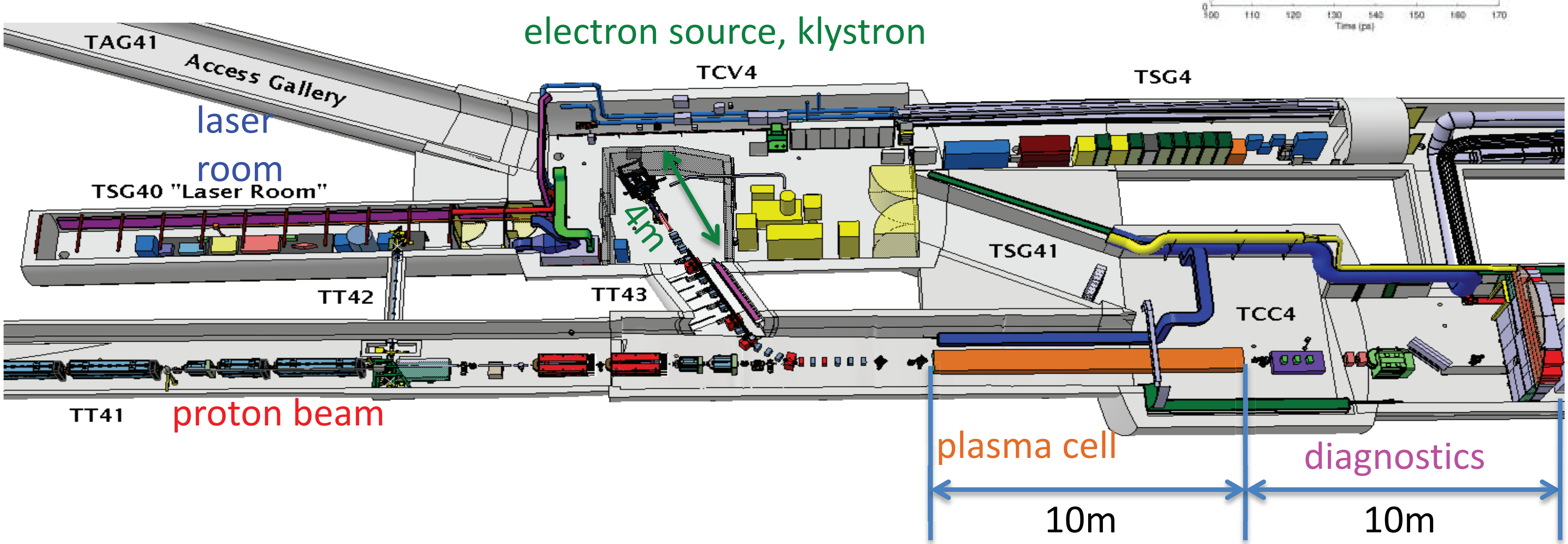
AWAKE electron beam parameters.

Parameter	Baseline	Possible range
Beam energy (MeV)	16	10–20
Energy spread (%)	0.5	0.5
Bunch length (σ) (ps)	4	0.3–10
Beam size at focus (σ) (μm)	250	0.25-1
Normalized emittance (RMS) (mm mrad)	2	0.5-5
Charge per bunch (nC)	0.2	0.1 – 1

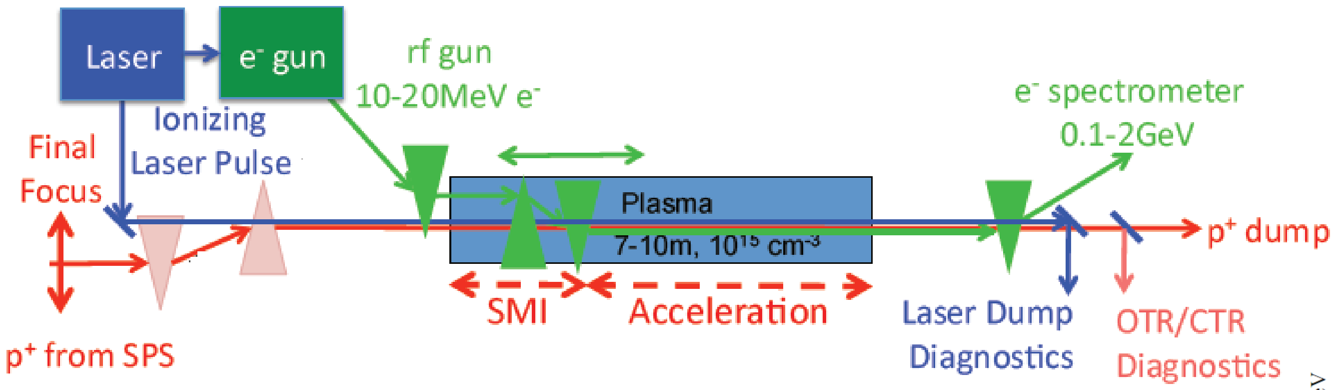
AWAKE experiment (Phase 1): Self-modulation diagnostics

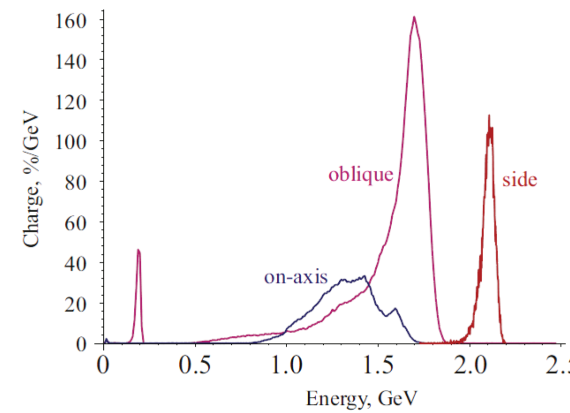


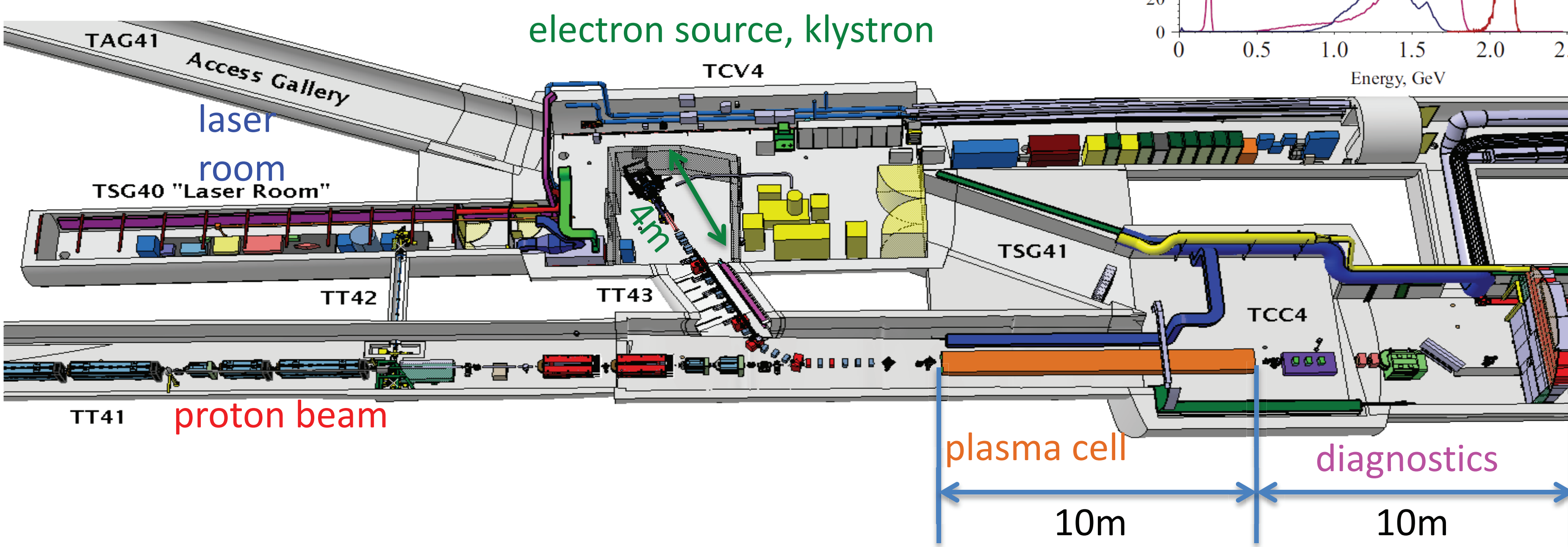




AWAKE experiment (Phase 2): Electron beam diagnostics







AWAKE

AWAKE Collaboration: 16+3 Institutes world-wide:

Collaboration members:

- John Adams Institute for Accelerator Science
- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

Associated members:

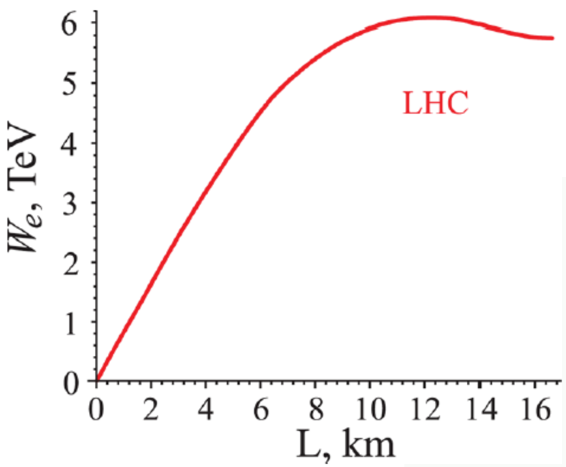
- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL

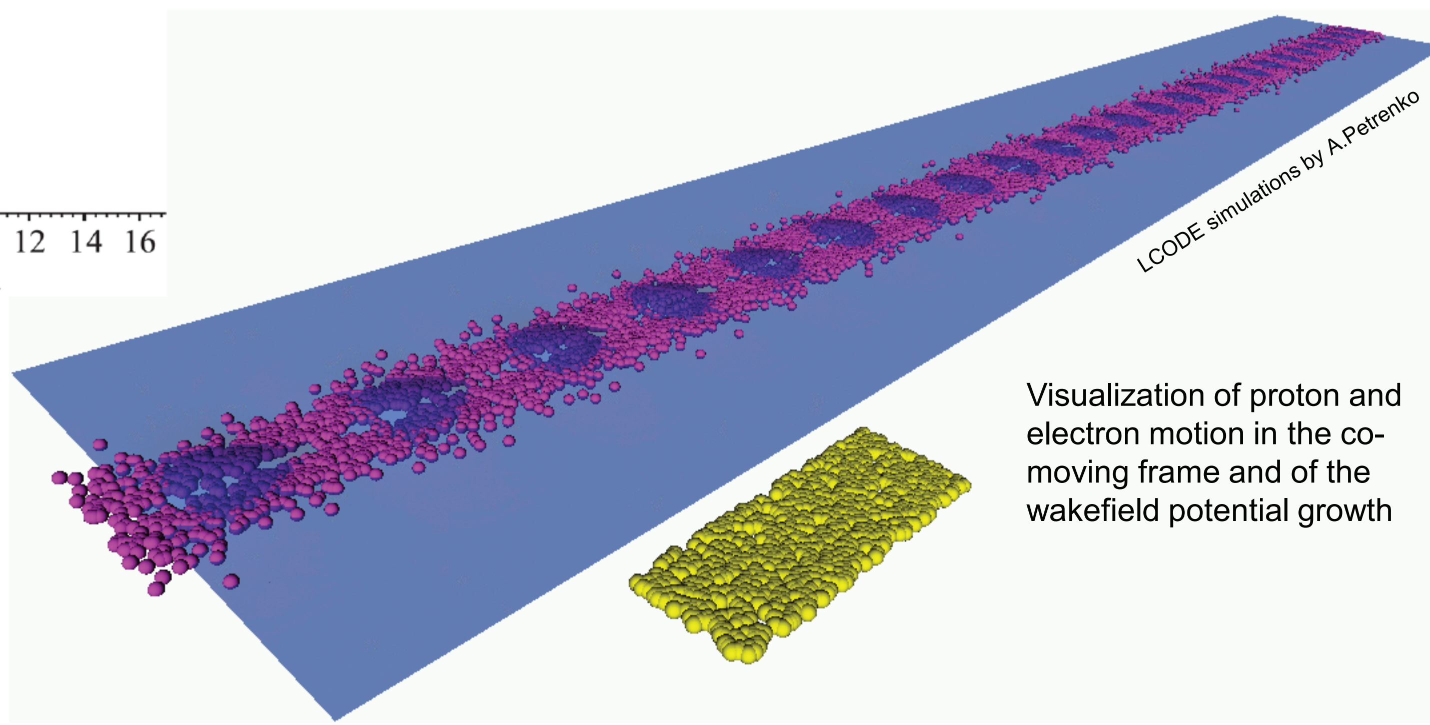
Further groups have also expressed their interest to join AWAKE.

Why AWAKE experiment is so important and interesting?

- First PWFA experiment with a proton driver. Yes, but not only.

- First experiment on controlled evolution of the drive beam. The mechanism of evolution was discovered in simulations and needs experimental verification. If successful, it will open the path to much higher energies with relatively inexpensive additions to existing facilities.

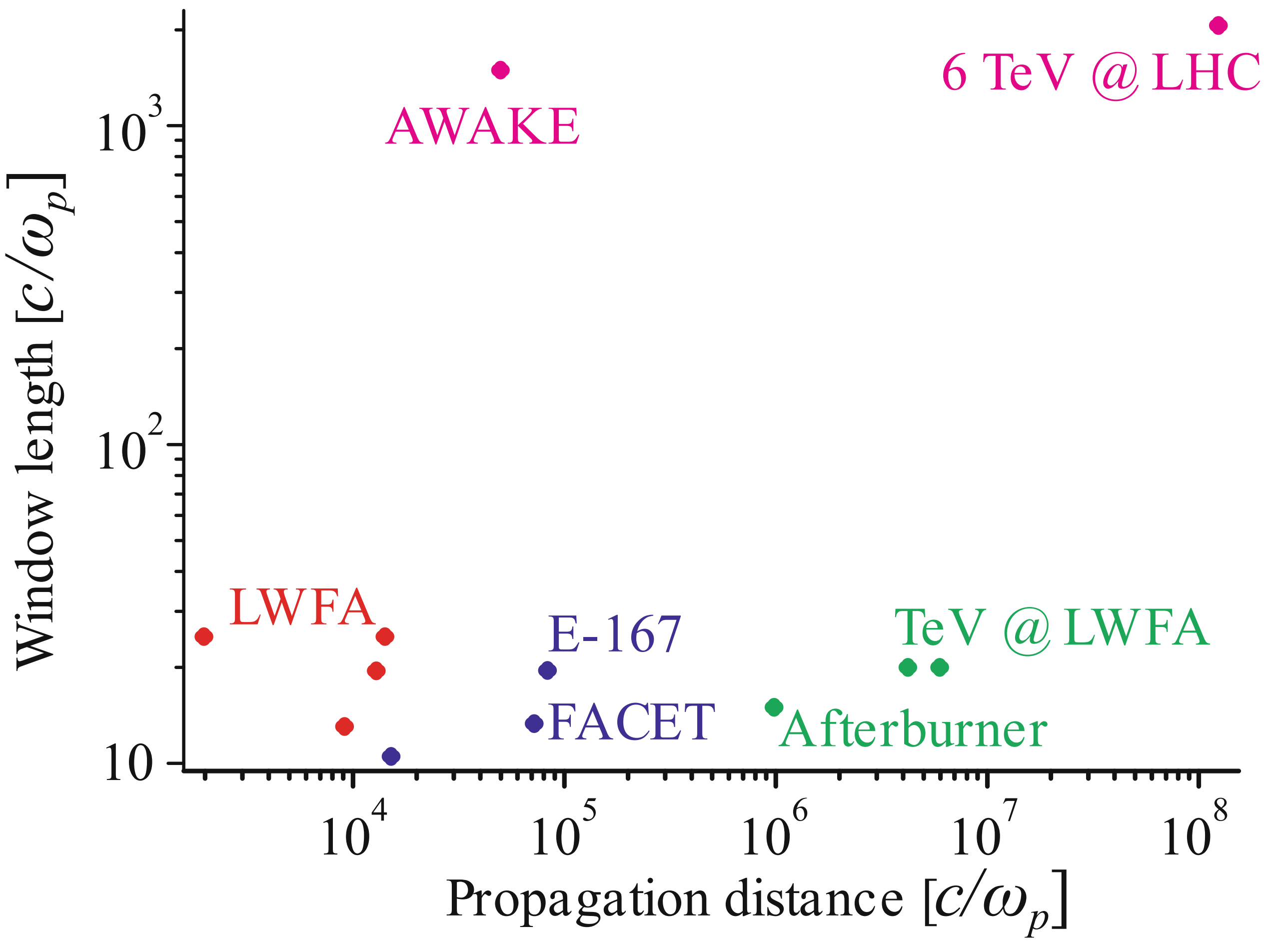




Visualization of proton and electron motion in the co-moving frame and of the wakefield potential growth

Why AWAKE experiment is so important and interesting?

- Experimental points at completely unexplored parameter area. This is important to benchmark simulation codes that are widely used in PWFA studies



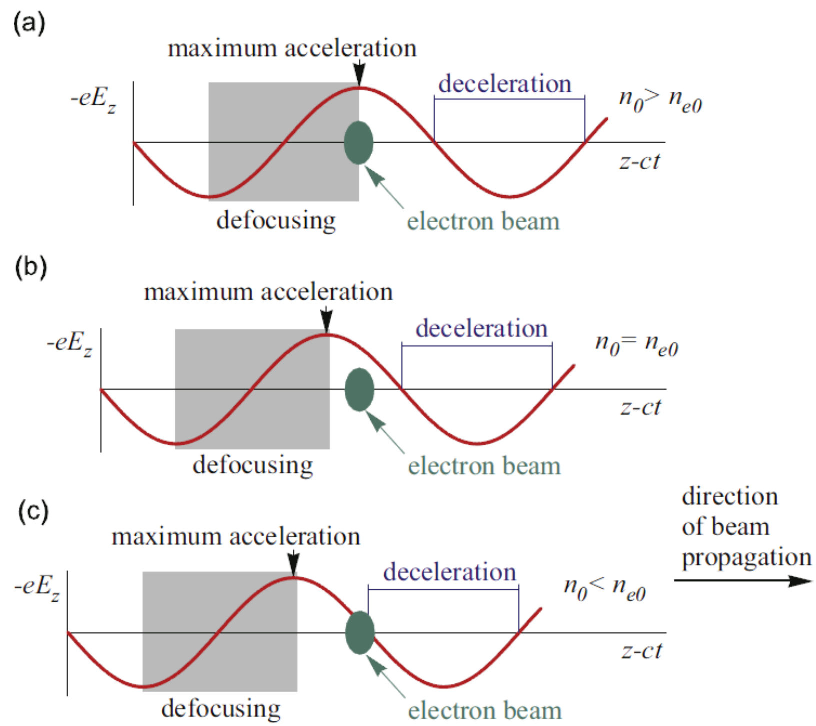
Challenges of AWAKE: plasma uniformity

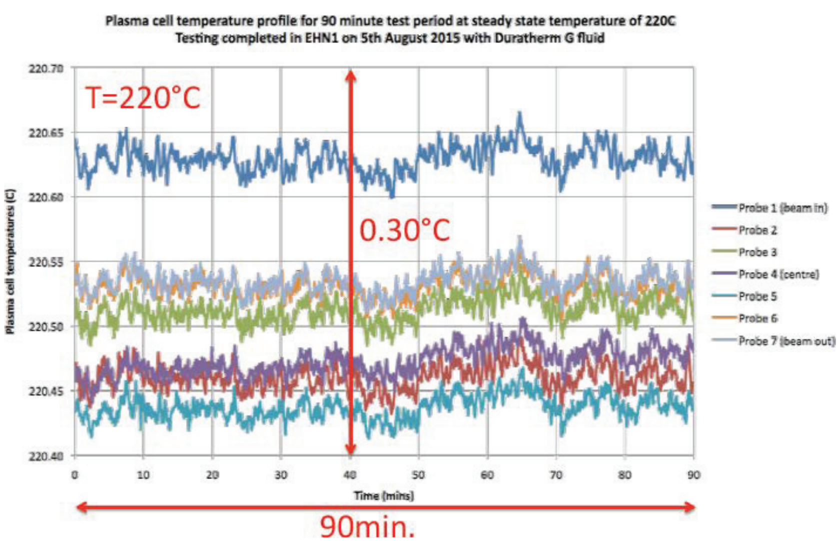
Resonant wave excitation by ~100 micro-bunches needs the most uniform plasma ever made:

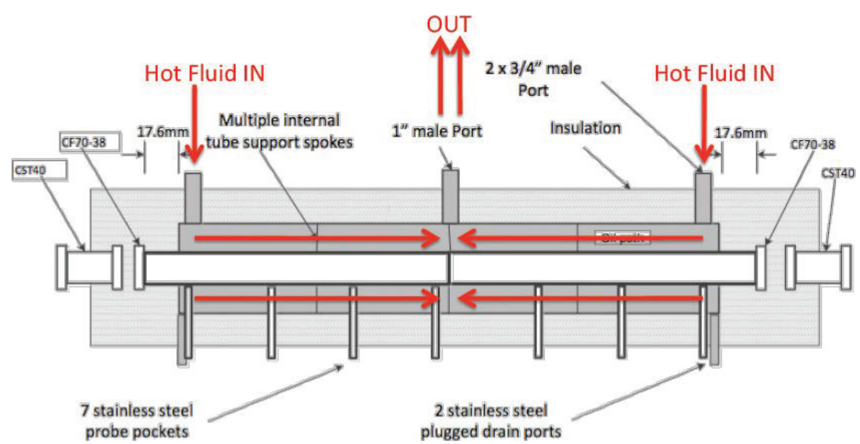
uniformity better than 0.2% over 10 meters.

Otherwise, accelerated electrons may fall into defocusing or decelerating phase of the wave.

Obtained by “instant” ionization (by a short laser pulse) of a highly-uniform temperature-stabilized Rb gas cell.

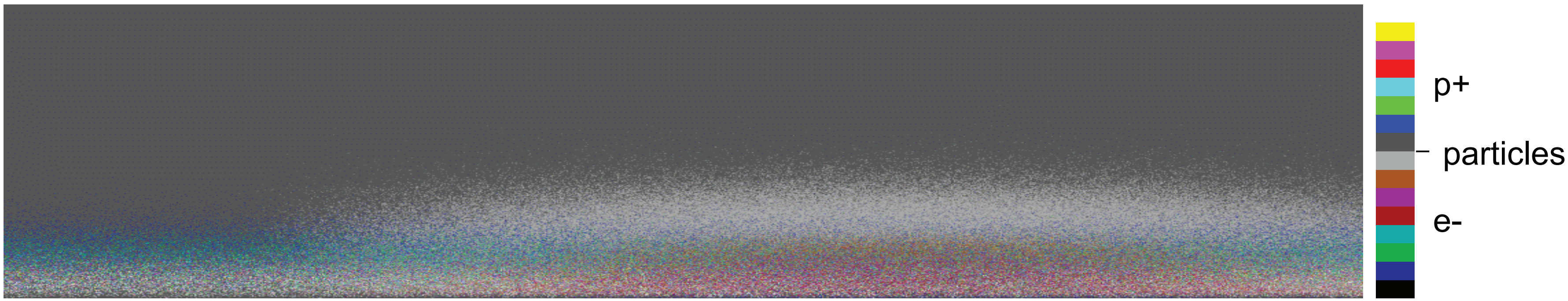






Challenges of AWAKE: Trapping of witness electrons by the plasma wave

Plasma lens effect: the electrons are repelled by the incompletely neutralized proton beam current:

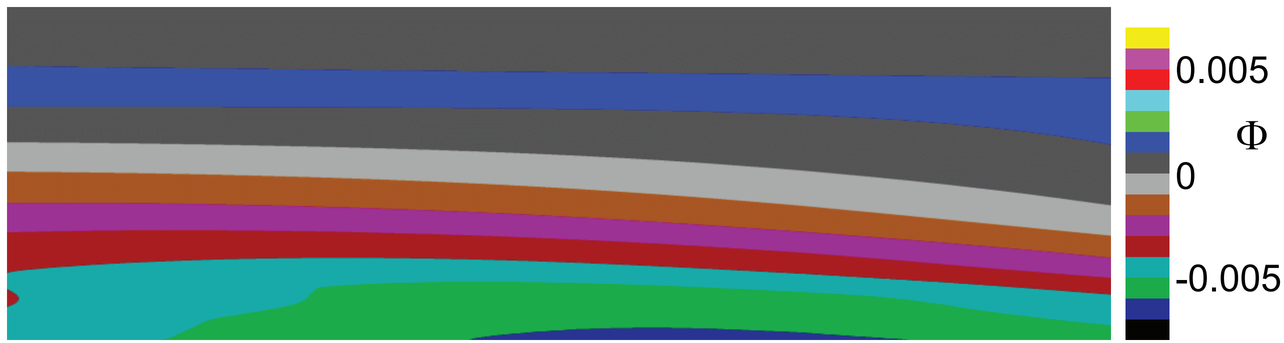


If the plasma density grows,

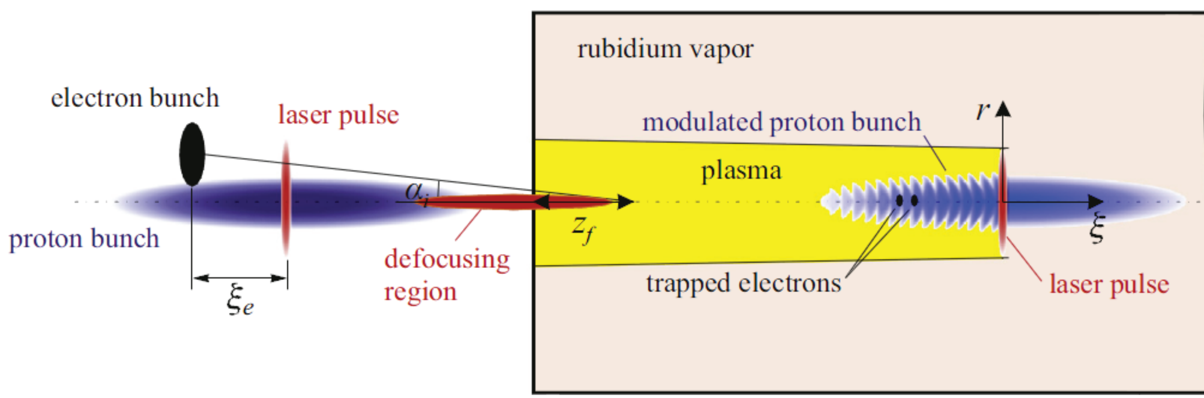
wave phase quickly changes,

effect of "fast" wakefield component (seeded by the laser pulse) averages out

"slow" component (from the proton beam current) defocuses the electrons

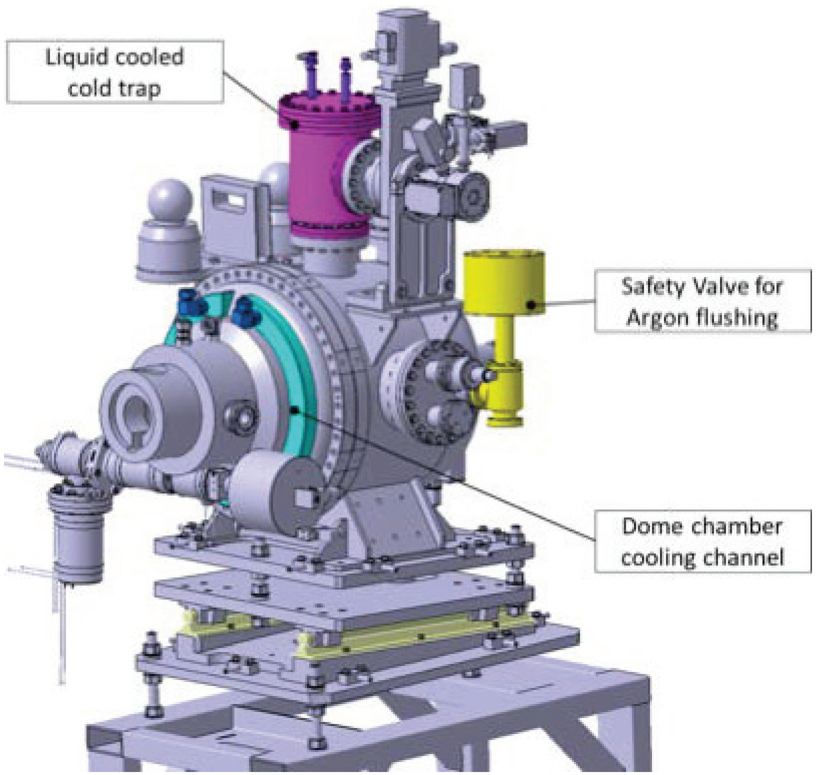


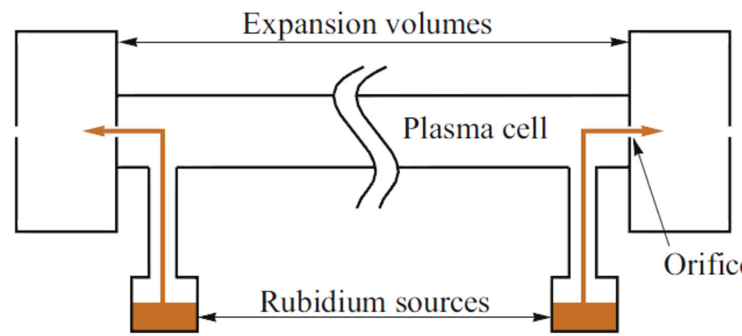
Solution: oblique injection

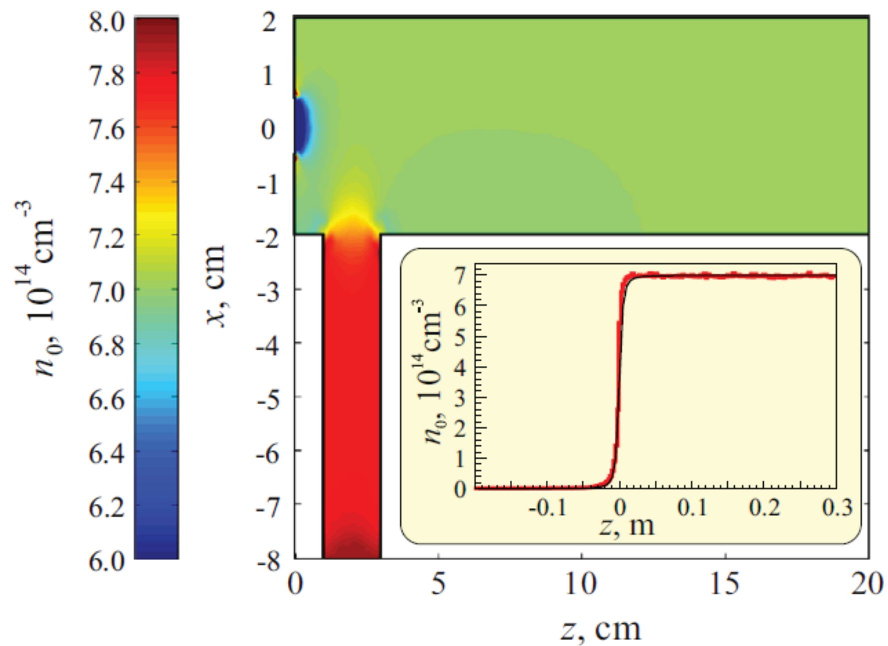


Challenges of AWAKE: Plasma-vacuum interface

We need sharp separation of high vacuum and hot rubidium without a foil.
Solution: continuous flow to large expansion volumes through small apertures.
The defocusing region (with increasing density) extends ~6 cm into the plasma cell.







To conclude:

AWAKE experiment at CERN is close to start running.

This will be the first experiment on plasma wakefield acceleration driven by a proton beam,

and also the first experiment on controlled self-organization of the driver.

It will be an important benchmark for computer codes

and will test a number of novel technical solutions.

Thank you