AWAKE : A proton-driven plasma wakefield acceleration experiment

Matthew Wing (UCL/DESY)

- Motivation : particle physics; large accelerators
- General concept : proton-driven plasma wakefield acceleration
- AWAKE experiment at CERN
- Outlook

See, AWAKE Design Report, CERN-SPSC-2013-013, http://cds.cern.ch/record/1537318/files/SPSC-TDR-003.pdf

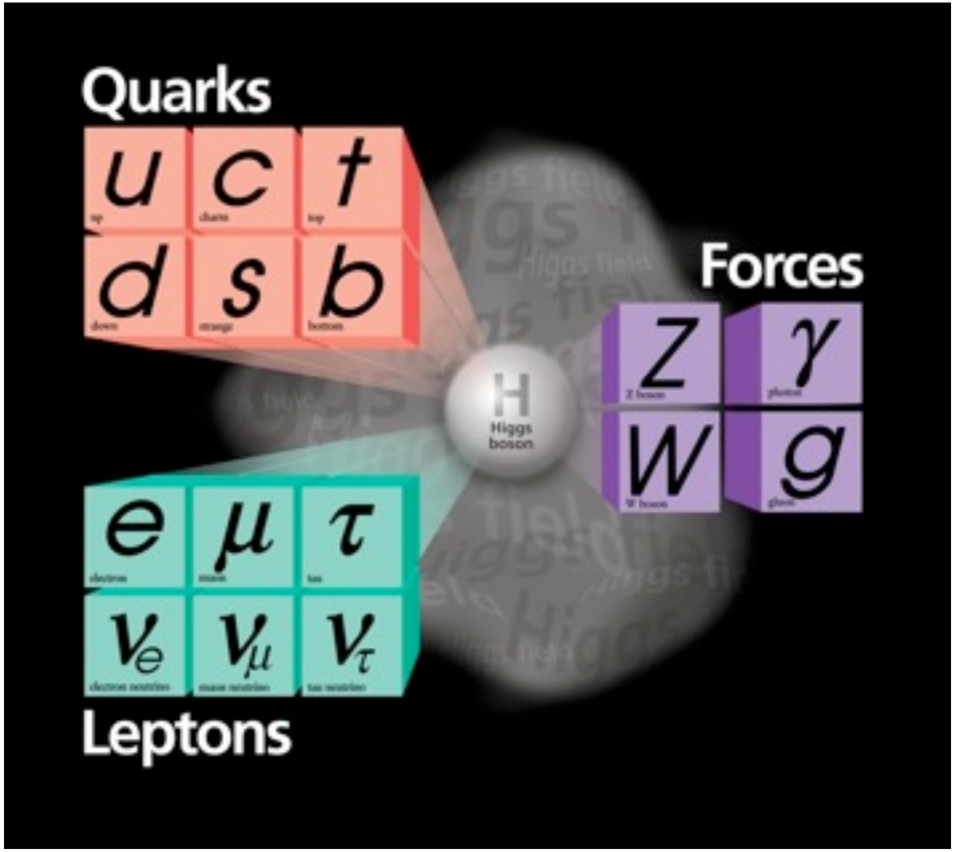
DESY Accelerator Seminar — 13 September 2013

Motivation

Motivation

- The use of (large) accelerators has been central to advances in particle physics.
- Culmination in *27-km* long LHC (*pp*); a future e^+e^- collider is planned to be *30–50-km* long.
- Such projects are (very) expensive; can we reduce costs ? are there new technologies which can be used or developed ?
- Accelerating gradients achieved in the wakefield of a plasma look promising, but :
  - we need high-energy beams (~ *TeV*);
  - high repetition rate and high number of particles per bunch;
  - large-scale accelerator complex.
- Ultimate goal : can we have a multi-*TeV* lepton collider of a few *km* in length ?
- A challenge for accelerator, plasma and particle physics.

Big questions in particle physics



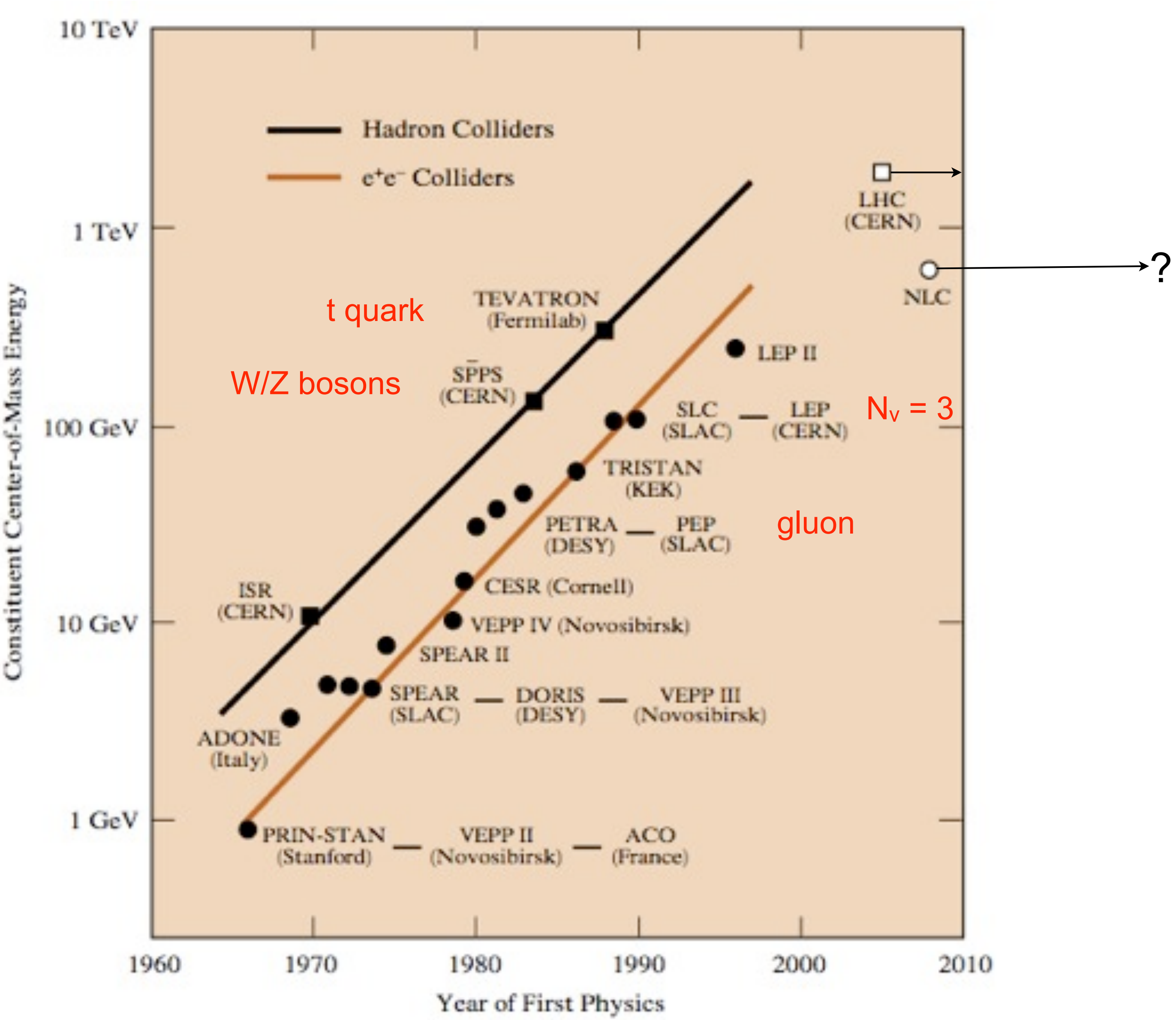
A TeV-scale e^+e^- linear collider is many people's choice for a next large-scale facility.

- An e^+e^- linear collider which can span to multi-TeV is clearly preferable.
- Precision environment of a lepton collider essential.
- Will strongly constrain alternative theories or phenomena proposed or yet to be discovered.
- May also discover new resonances otherwise unseen in a large-background environment.

The Standard Model is amazingly successful, but some things remain unexplained :

- what are the consequences of the "Higgs" particle discovery ?
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- can we unify the forces ?

Collider history



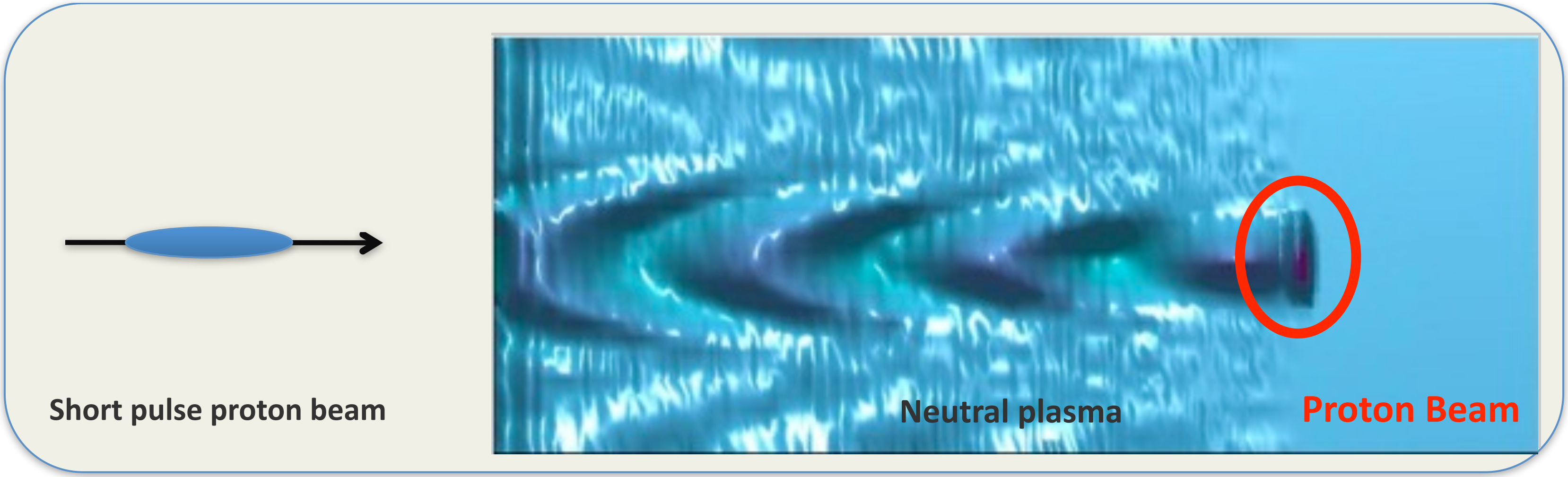
Collider parameters e⁻ beam

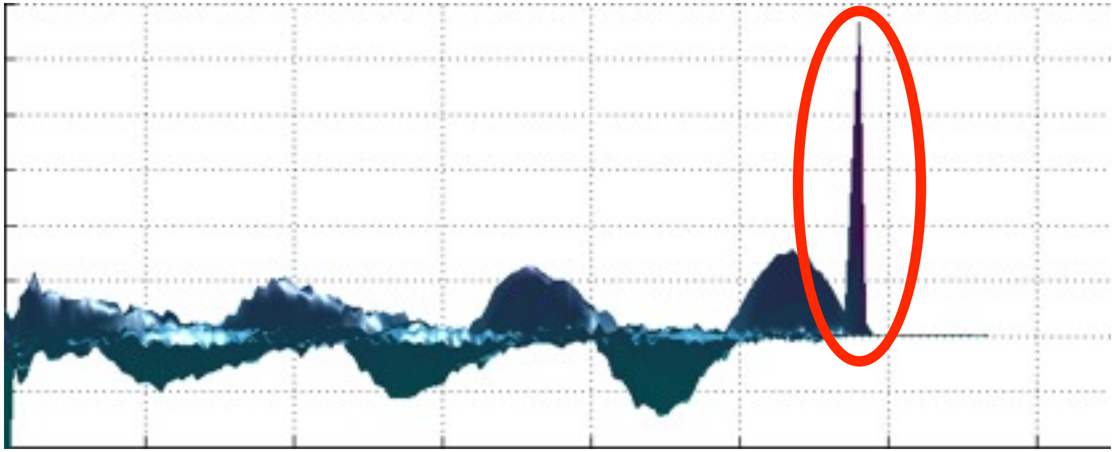
	ILC	LHeC
Energy (GeV)	125	60
Bunch population	2×10^{10}	2×10^{9}
Number of bunches	1312	–
Bunch separation (ns)	554	25 or 50
Collision rate (Hz)	5	–
Energy spread	0.19%	0.03%
Horizontal emittance	10 μm	50 μm
Vertical emittance	35 nm	50 μm
Beam size	729×7.7 nm^2	7×7 μm^2
Luminosity $\times 10^{34}$ cm^{-2}s^{-1}	0.75	0.1 (~1)

ILC TDR, June 2013
LHeC CDR, June 2012

Proton-driven plasma wakefield acceleration

Plasma wakefield acceleration explained





Thanks to J. Holloway (UCL)

Plasma considerations

Based on linear fluid dynamics :

$$\omega_p = \sqrt{\frac{n_p\, e^2}{\epsilon_0\, m_e}}$$

$$\lambda_p \approx 1\,[\mathrm{mm}]\sqrt{\frac{10^{15}\,[\mathrm{cm}^{-3}]}{n_p}} \quad \text{or} \quad \approx \sqrt{2}\,\pi\,\sigma_z$$

$$E \approx 2\,[\mathrm{GV\,m^{-1}}]\left(\frac{N}{10^{10}}\right)\left(\frac{100\,[\mu\mathrm{m}]}{\sigma_z}\right)^2$$

Relevant physical quantities :

- Oscillation frequency, ω_p
- Plasma wavelength, λ_p
- Accelerating gradient, E

where :

- n_p is the plasma density
- e is the electron charge
- ε_0 is the permittivity of free space
- m_e is the mass of electron
- N is the number of drive-beam particles
- σ_z is the drive-beam length

High gradients with :

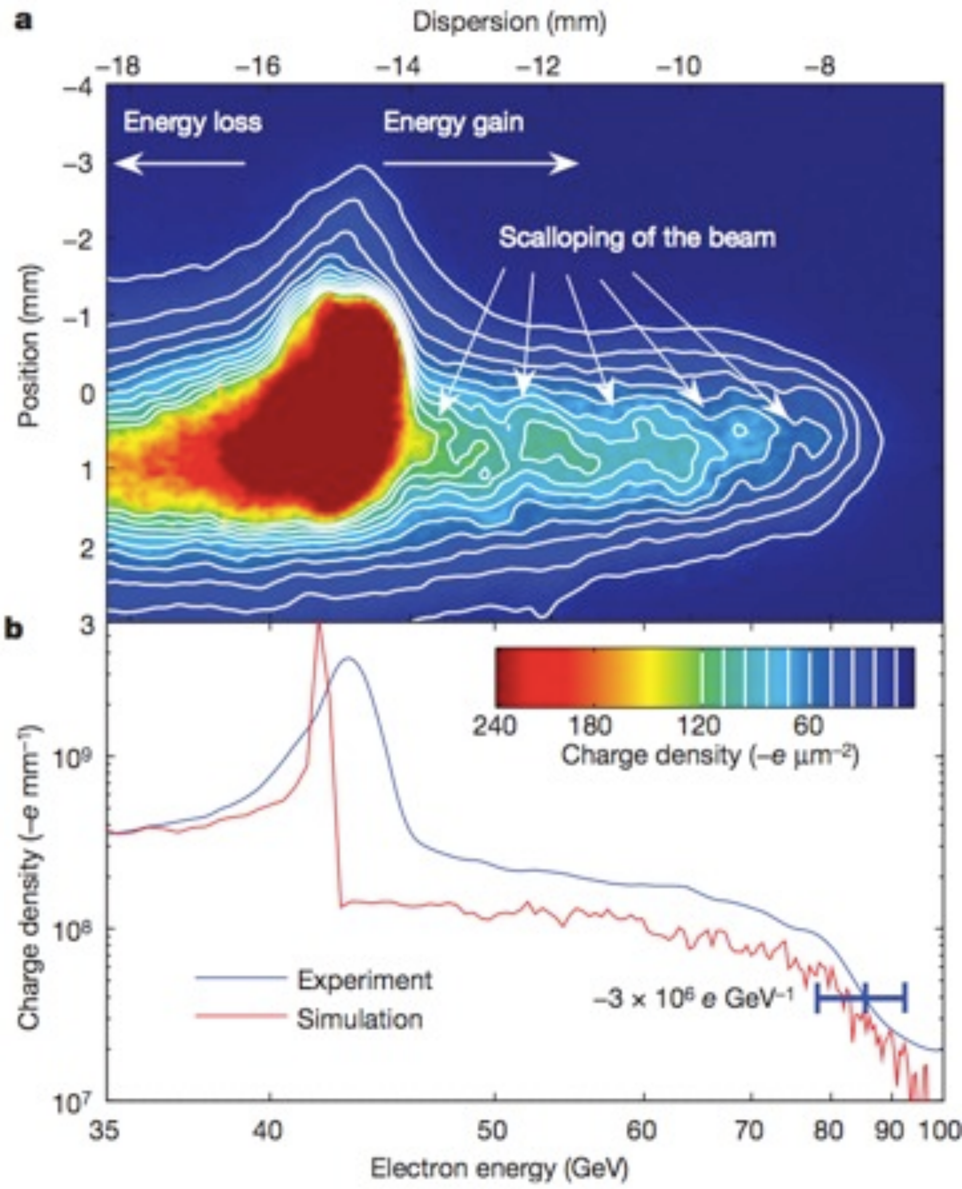
- Short drive beams (and short plasma wavelength)
- Pulses with large number of particles (and high plasma density)

Original idea: laser wakefield acceleration (T. Tajima & J.W. Dawson, Phys. Rev. Lett. **43** (1979) 267)

Can also use particle beams (P. Chen et al., Phys. Rev. Lett. 54 (1985) 693)

Plasma wakefield experiments

- Pioneering work using a LASER to induce wakefields up to *100 GV/m*.
- Experiments at SLAC[§] have used a particle (electron) beam :
    - Initial energy *E_e = 42 GeV*
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
    - Next stage, FACET project (http://facet.slac.stanford.edu)
- Have proton beams of much higher energy :
    - HERA (DESY) : *1 TeV*
    - Tevatron (FNAL) : *1 TeV*
    - CERN : *24 / 450 GeV* and *3.5 (7) TeV*



[§] I. Blumenfeld et al., Nature **445** (2007) 741.

Why protons ?

Lasers do not have enough energy :

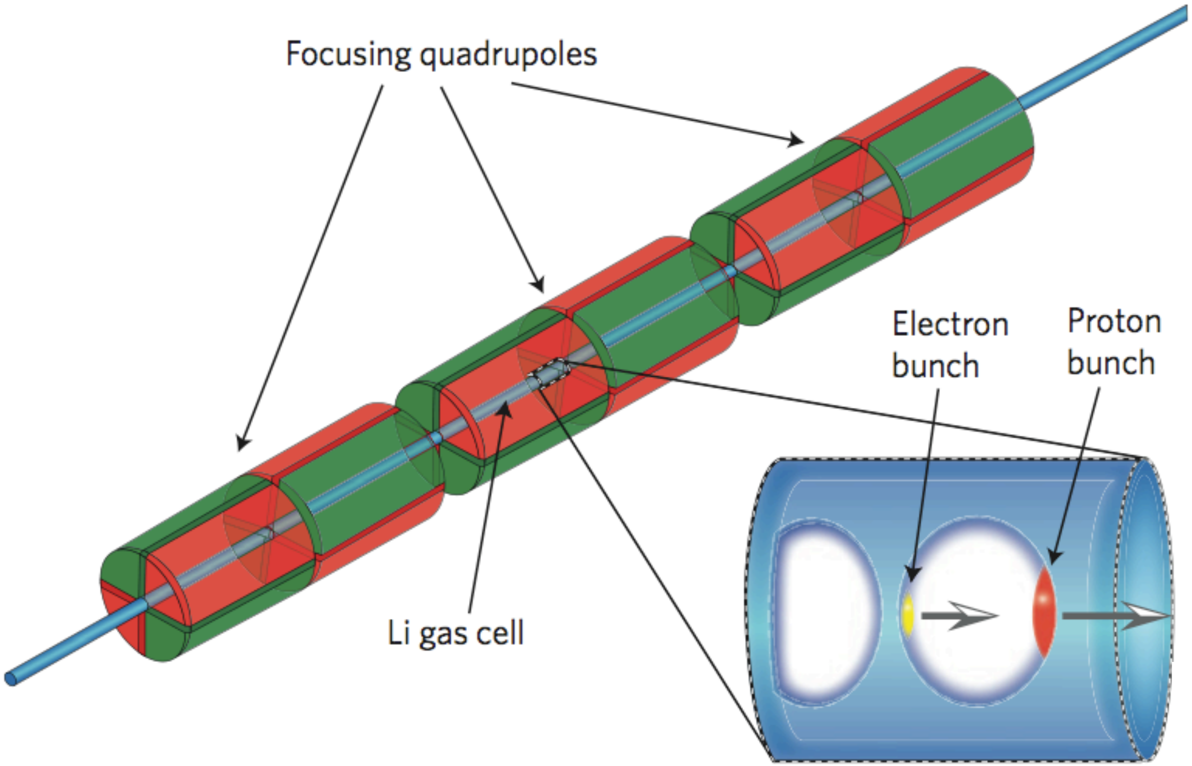
- Can not propagate long distances in plasma
- Can not accelerate electrons to high energy
- For high energy, need multiple stages.

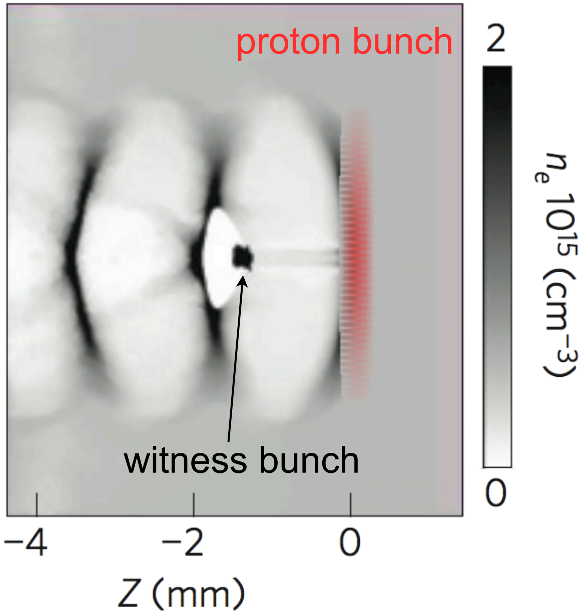
Electrons limited by transformer ratio $(E^{witness}/E^{drive}) < 2$ *:*

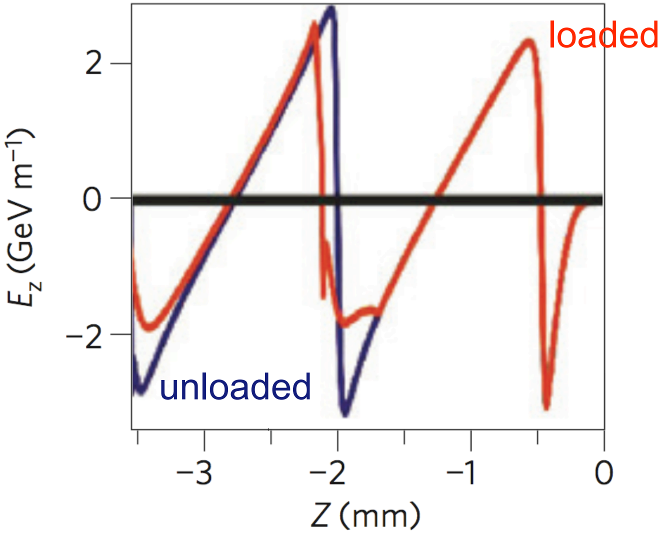
- So many stages needed to accelerate to the TeV scale using known electron beams

Proton beams at TeV scale are around today : what about using protons ?

PDPWA concept*





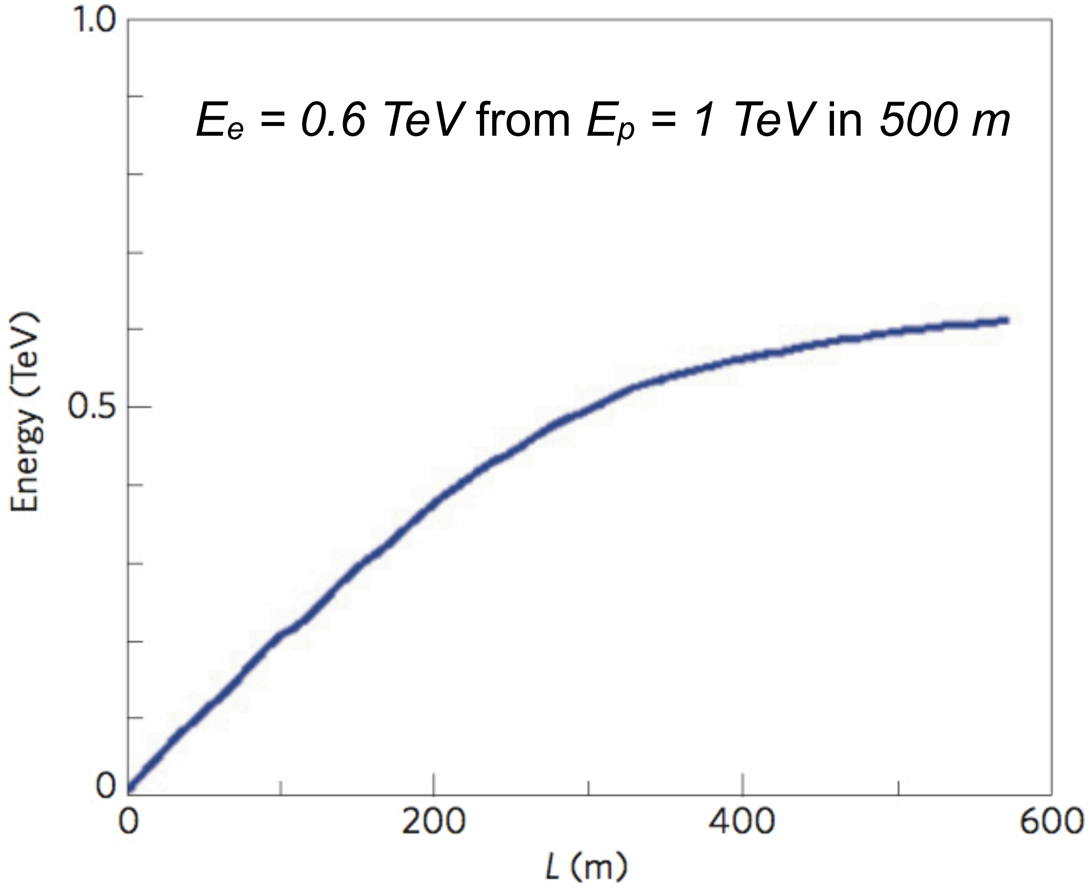


- Electrons ‘sucked in’ by proton bunch.
- Continue across axis creating a depletion region.
- Transverse electric fields focus witness bunch.
- Maximum accelerating gradient of *3 GV/m*.

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

PDPWA concept

Proton beam impacting on a plasma to accelerate and electron witness beam



PDPWA concept

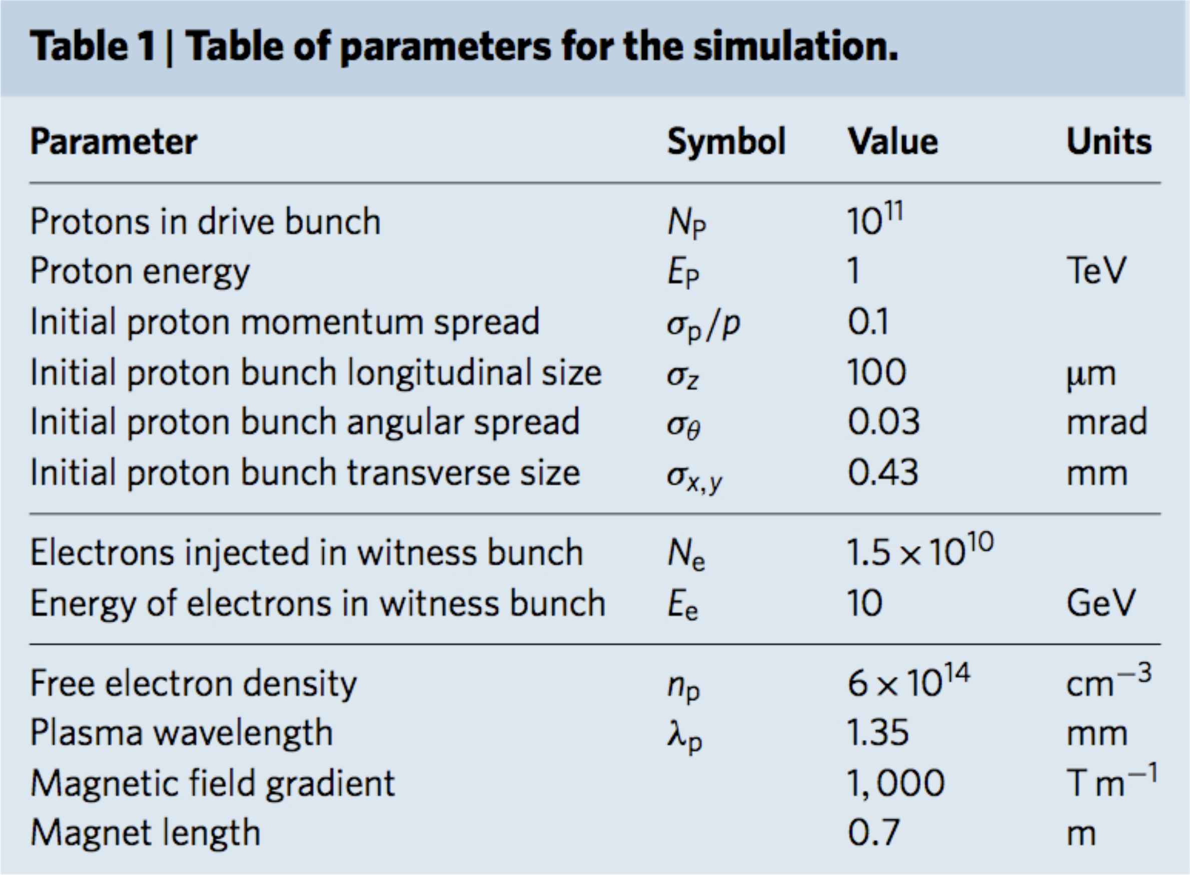


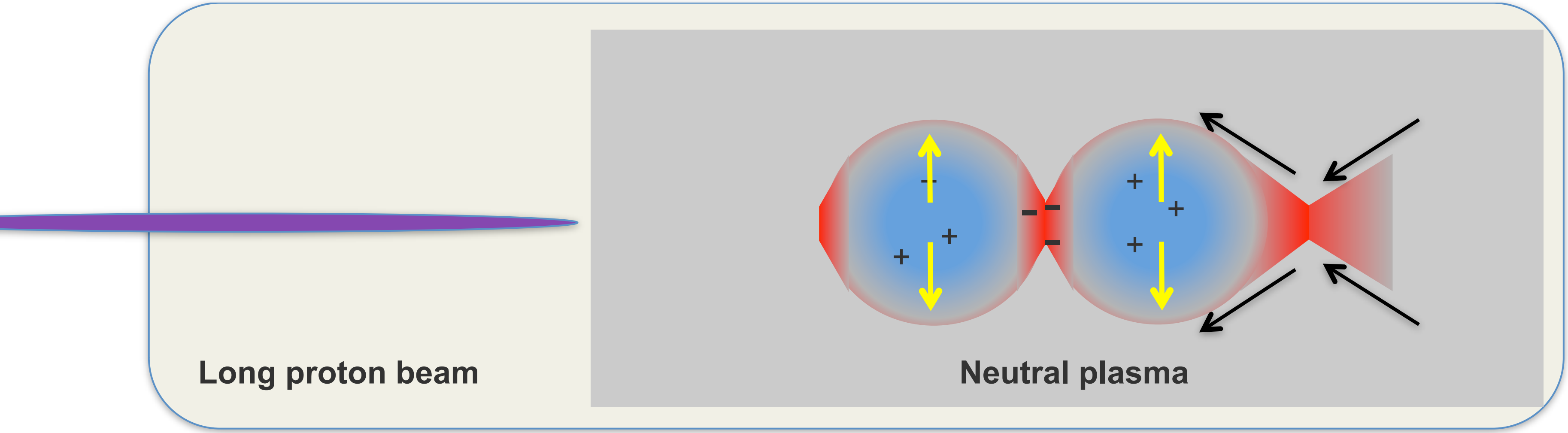
Table 1 | Table of parameters for the simulation.

Parameter	Symbol	Value	Units
Protons in drive bunch	N_P	10^{11}	
Proton energy	E_P	1	TeV
Initial proton momentum spread	σ_p/p	0.1	
Initial proton bunch longitudinal size	σ_z	100	µm
Initial proton bunch angular spread	σ_θ	0.03	mrad
Initial proton bunch transverse size	$\sigma_{x,y}$	0.43	mm
Electrons injected in witness bunch	N_e	1.5×10^{10}	
Energy of electrons in witness bunch	E_e	10	GeV
Free electron density	n_p	6×10^{14}	cm^{-3}
Plasma wavelength	λ_p	1.35	mm
Magnetic field gradient		1,000	$\mathrm{T\,m}^{-1}$
Magnet length		0.7	m

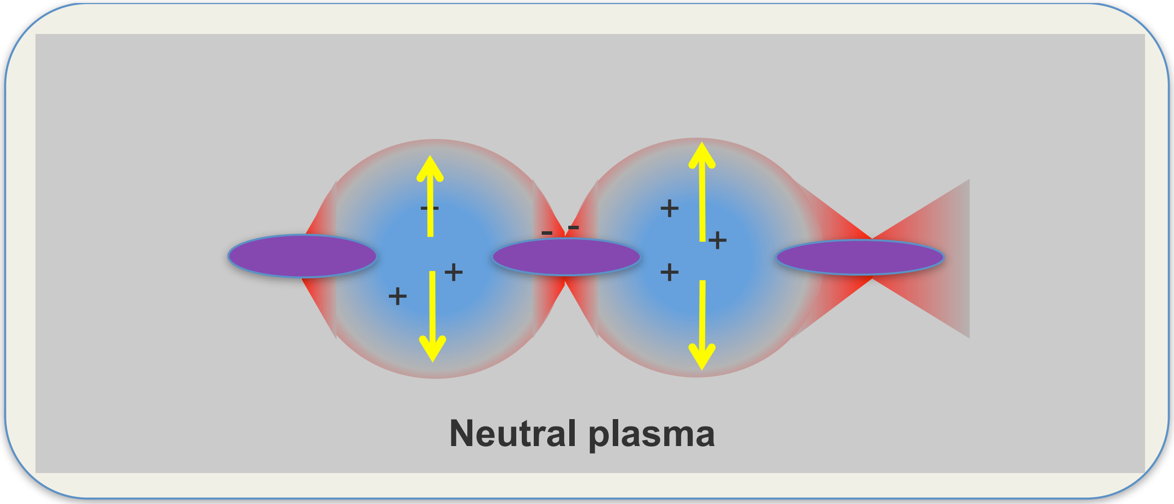
- Needs significant bunch compression < *100 µm* (or new proton source).
- Challenges include : sufficient luminosities for an e^+e^- machine, repetition rate, focusing, accelerating positrons, etc..

The AWAKE experiment at CERN

Long beam : self-modulation



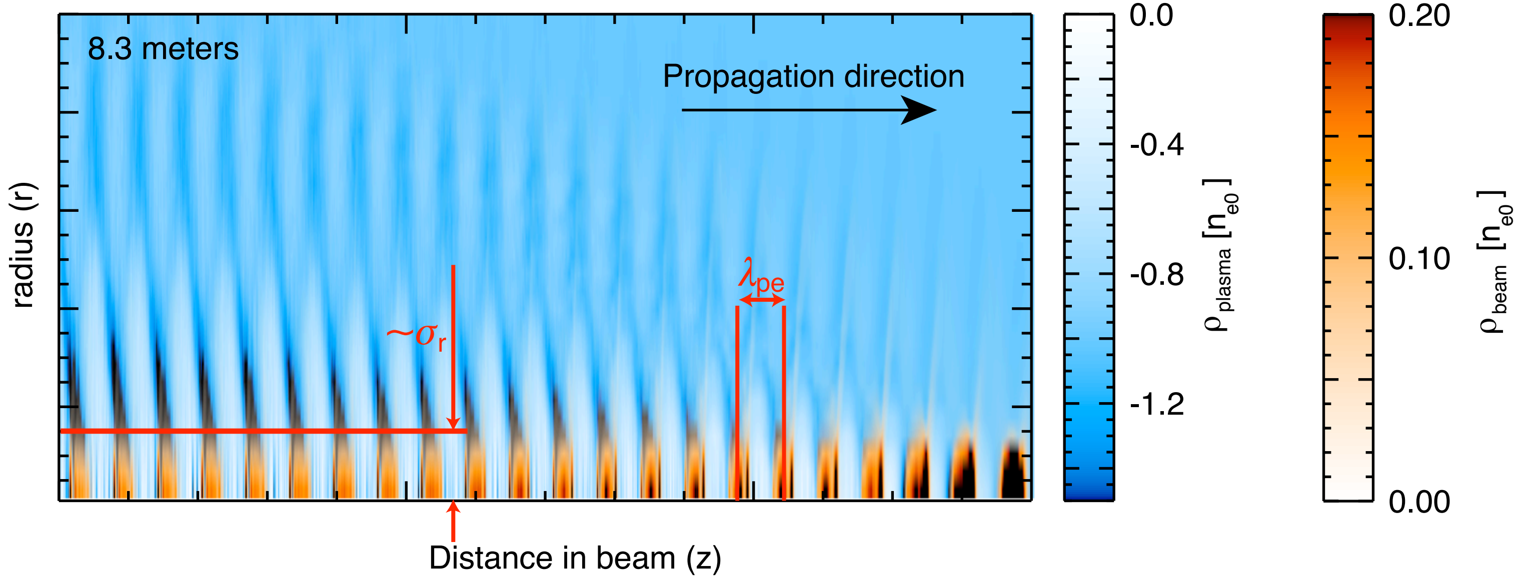
- Microbunches are spaced at the plasma wavelength and act constructively to generate a strong plasma wake.
- Seeding the modulation is critical. Use laser pulse (or short electron beam).



Self-modulated driver beam

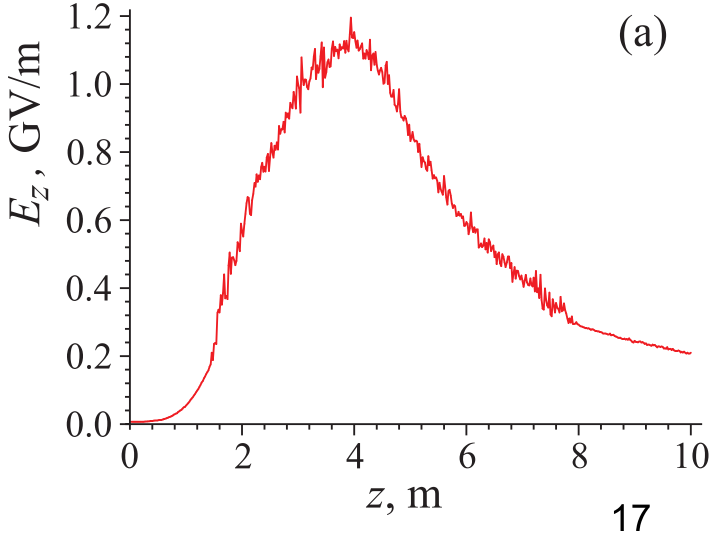
Thanks to J. Holloway (UCL)

Self-modulation of the proton beam



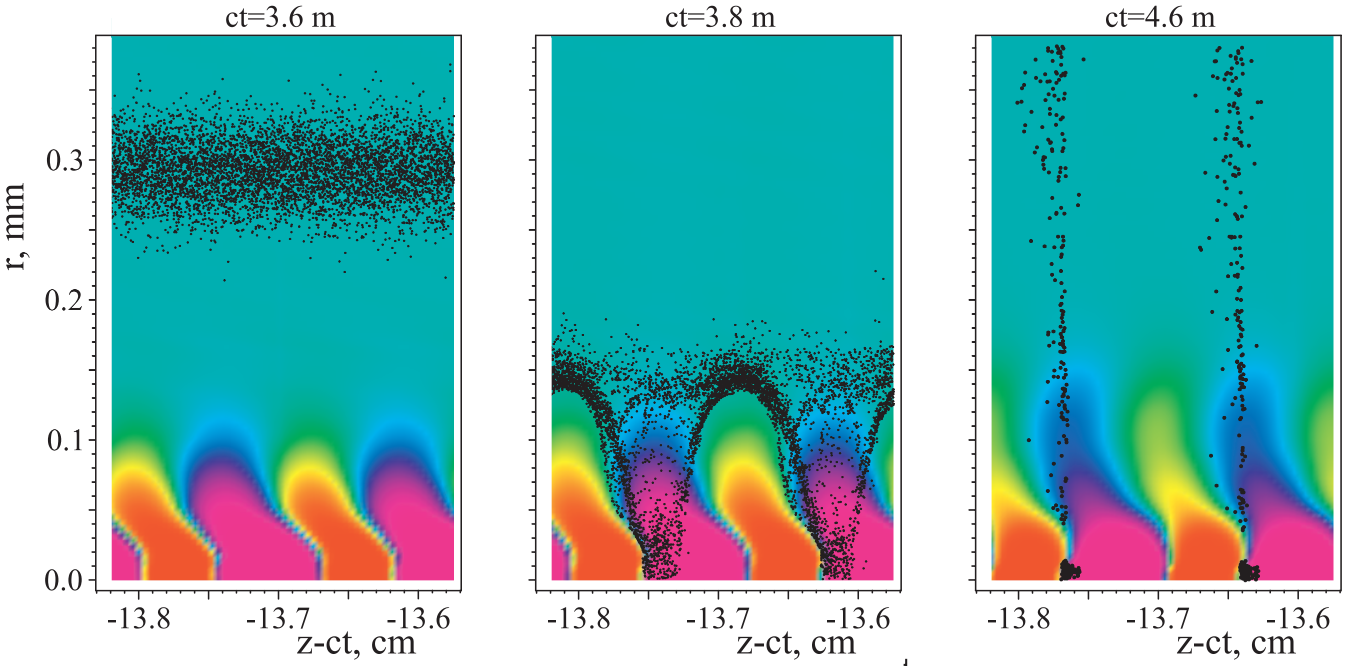
CERN SPS proton beam

Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b/W_b$	0.35%
Proton bunch normalized emittance, ϵ_{bn}	3.5 mm mrad



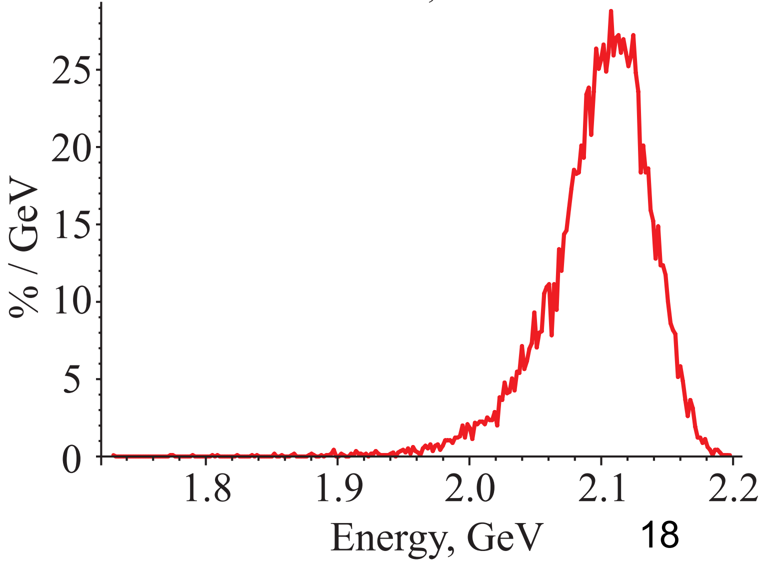
K.V. Lotov Phys. Plasmas **18** (2011) 024501

Injection of witness electrons

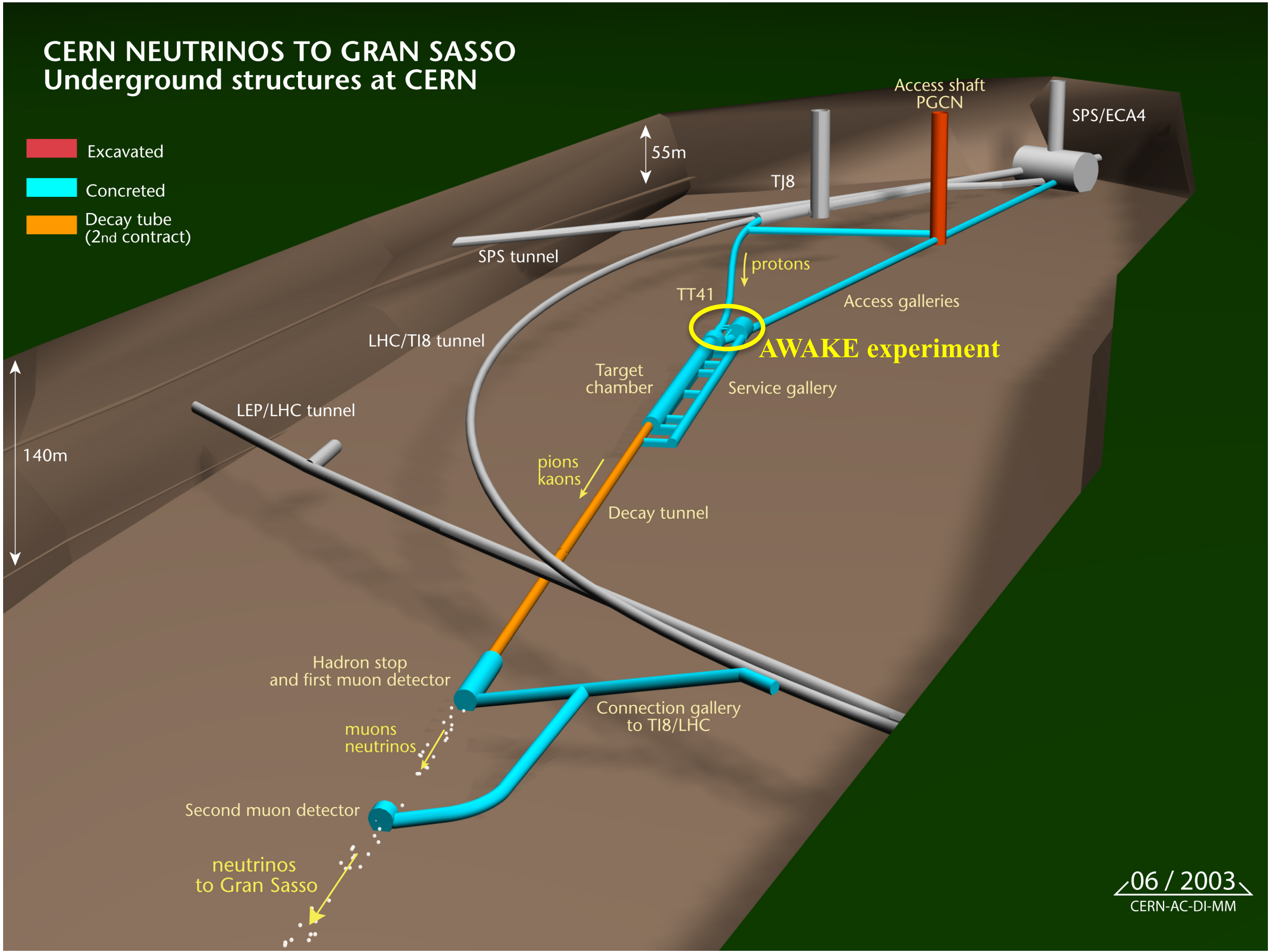


K.V. Lotov, J. Plasma Phys. **78** (2012) 455

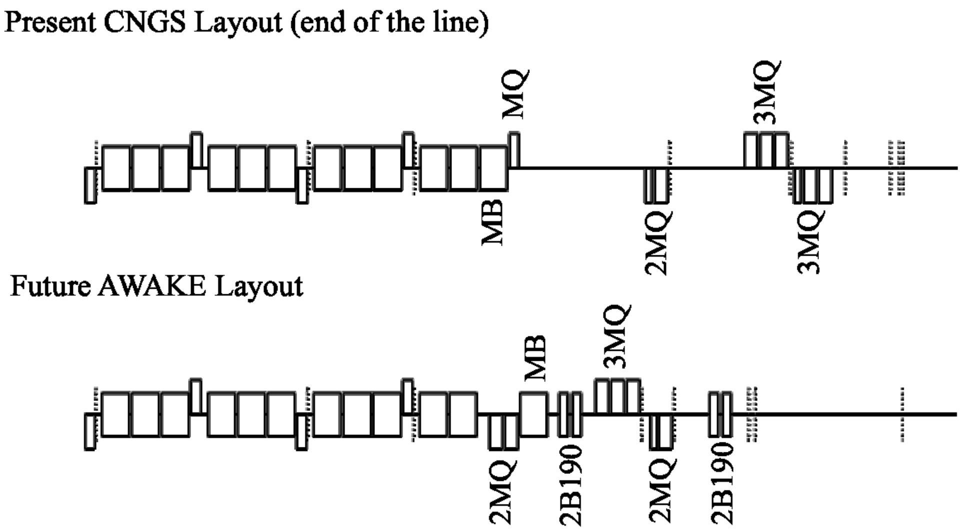
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ϵ_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m



CNGS facility at CERN



CNGS beamline

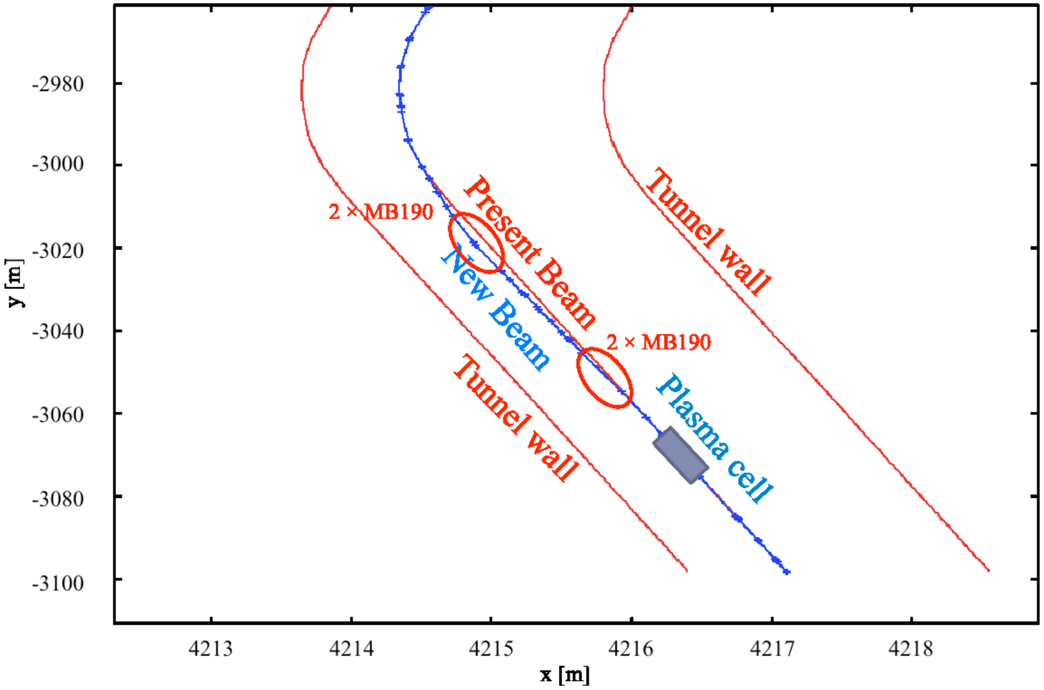


Relatively small modifications needed

- Rearrange some magnets
- More space for experiment
- Ease merging of laser and proton beam

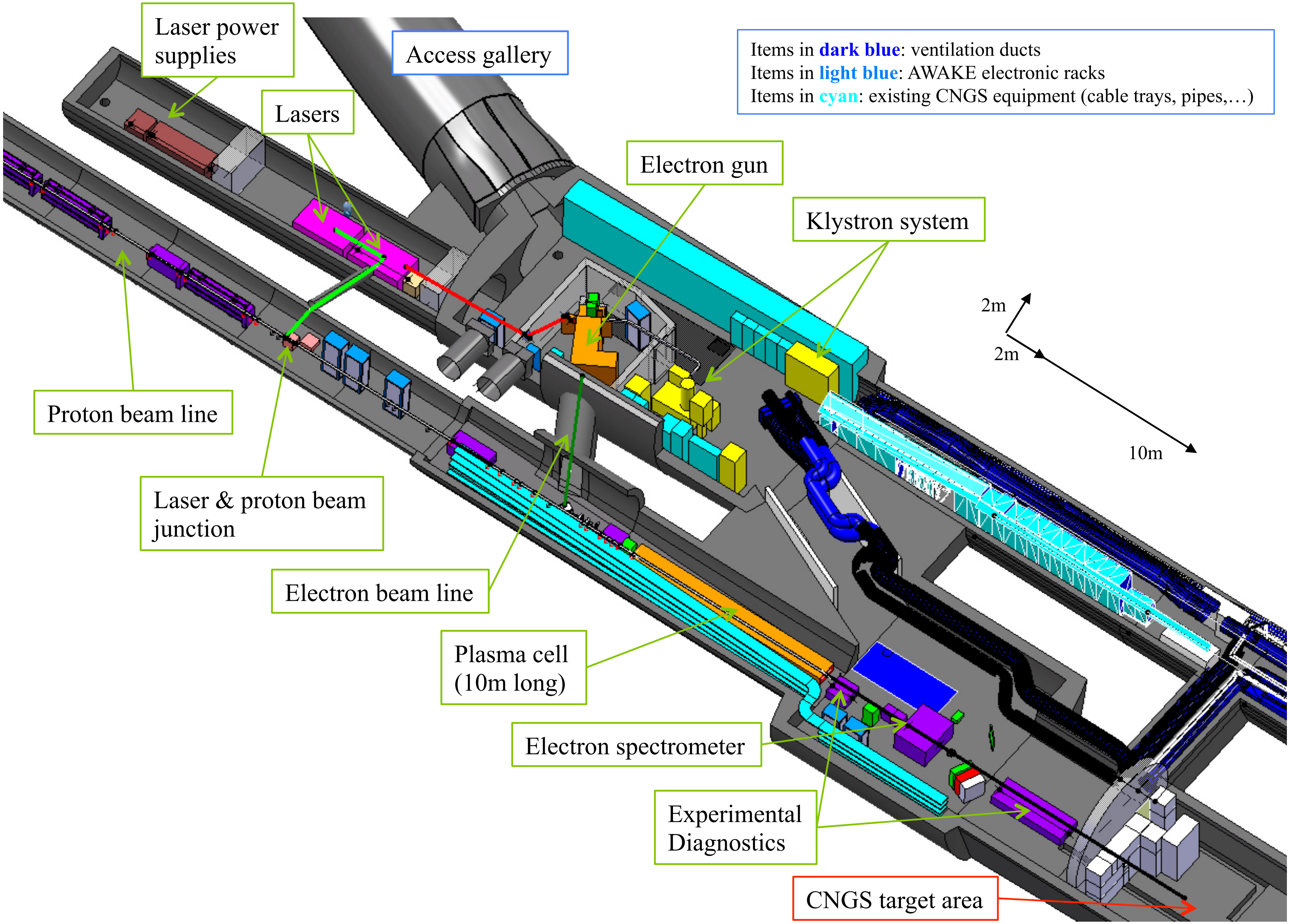
Some civil engineering needed ...

Much smaller job than was needed in the West area



Layout of AWAKE experiment

Items in **dark blue**: ventilation ducts
Items in **light blue**: AWAKE electronic racks
Items in **cyan**: existing CNGS equipment (cable trays, pipes,…)



Laser power supplies

Access gallery

Lasers

Electron gun

Klystron system

Proton beam line

Laser & proton beam junction

Electron beam line

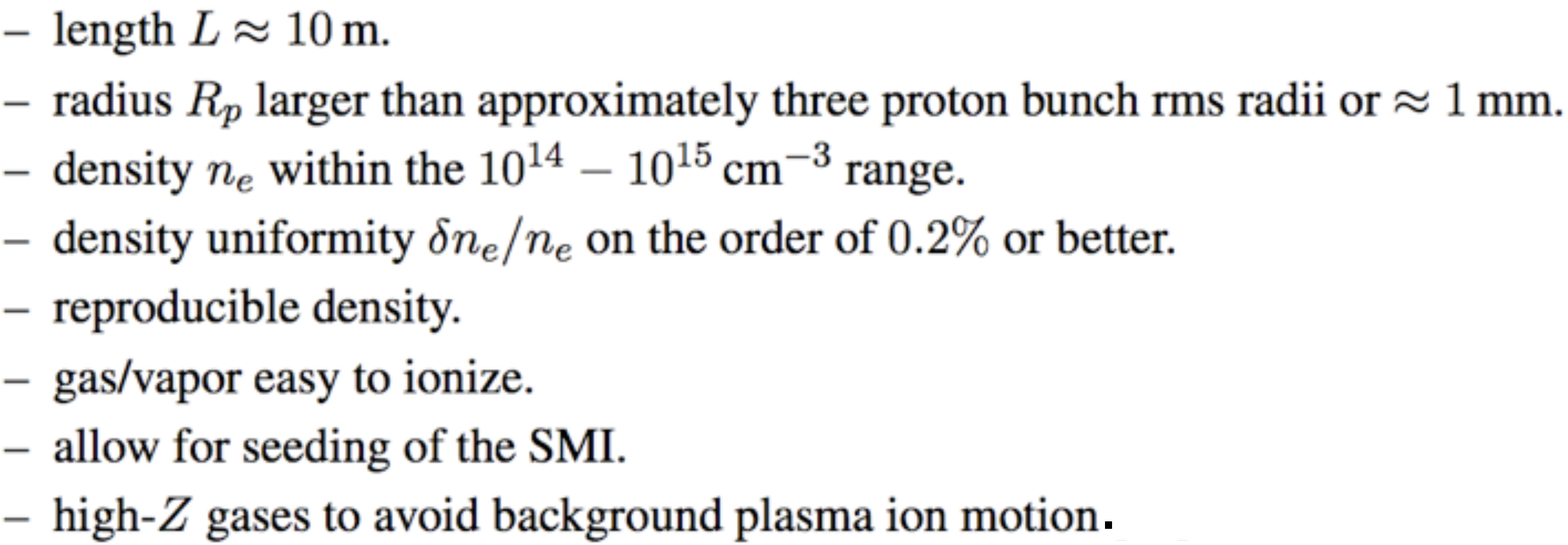
Plasma cell (10m long)

Electron spectrometer

Experimental Diagnostics

CNGS target area

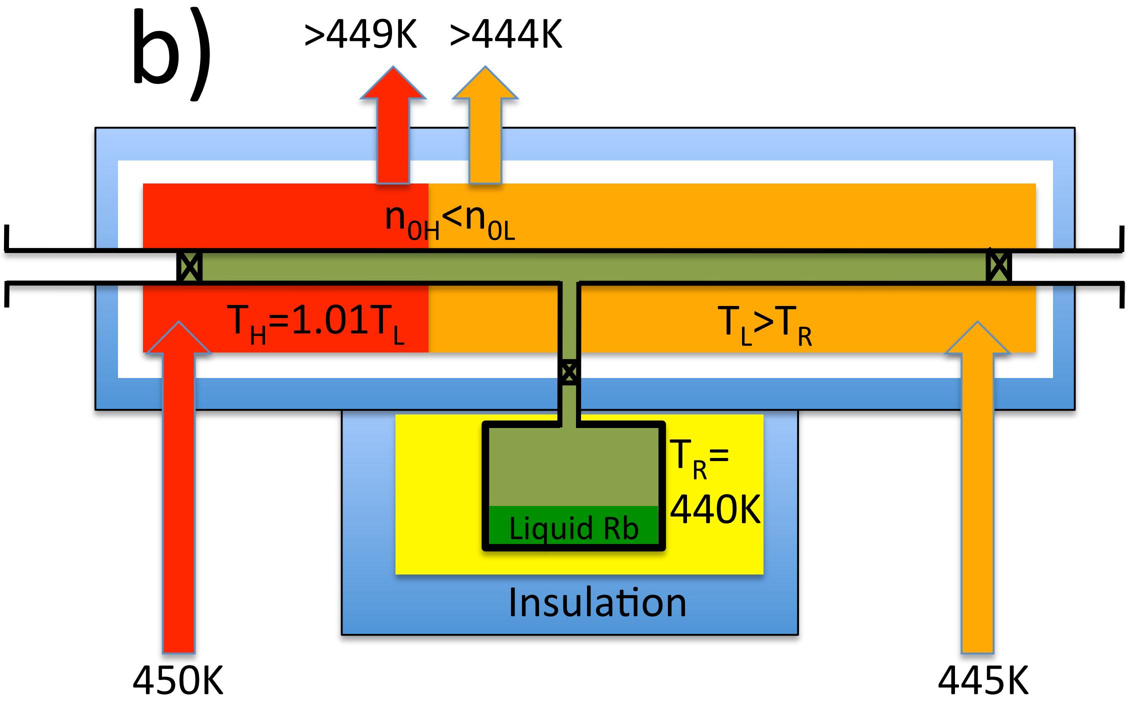
Plasma requirements



- length $L \approx 10\,\mathrm{m}$.
- radius R_p larger than approximately three proton bunch rms radii or $\approx 1\,\mathrm{mm}$.
- density n_e within the $10^{14} - 10^{15}\,\mathrm{cm}^{-3}$ range.
- density uniformity $\delta n_e / n_e$ on the order of 0.2% or better.
- reproducible density.
- gas/vapor easy to ionize.
- allow for seeding of the SMI.
- high-Z gases to avoid background plasma ion motion.

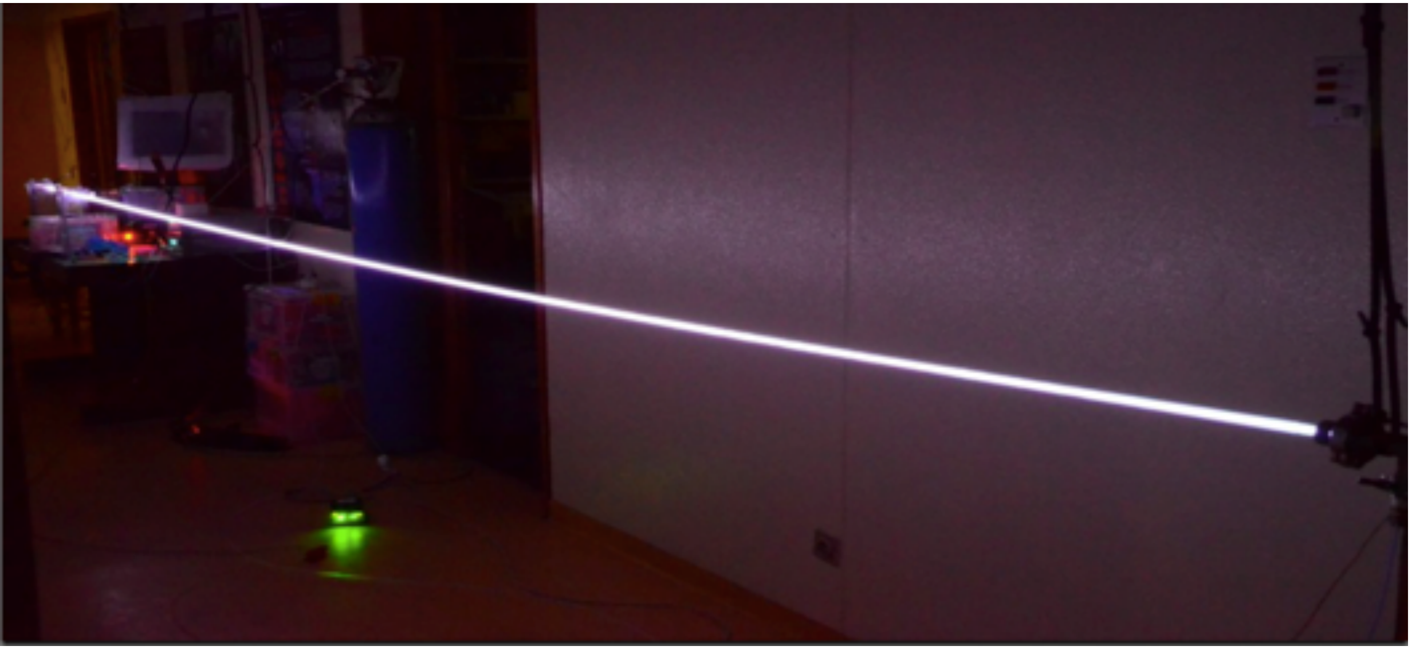
Three technologies being considered, with a Rubidium vapour cell as default

Rubidium plasma source



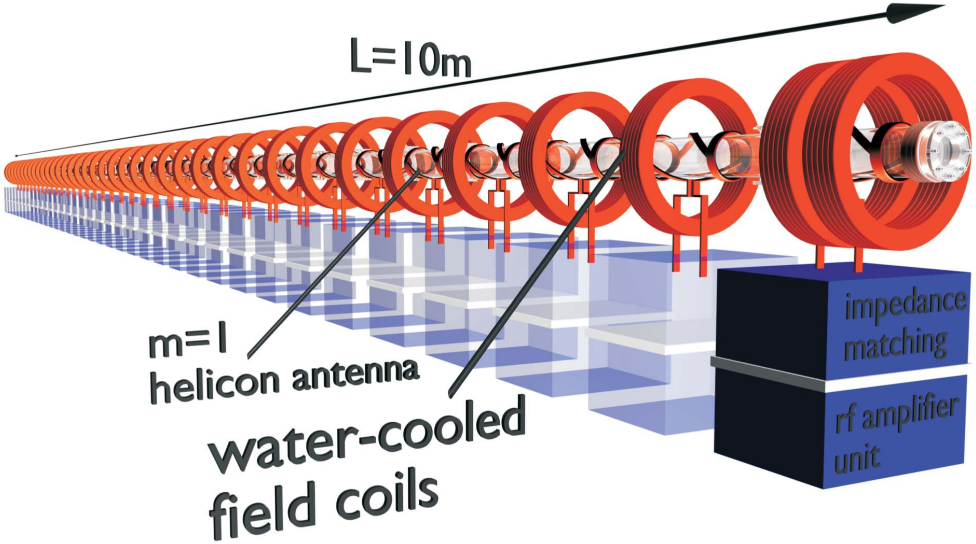
- Synthetic oil surrounding Rb for temperature stability and hence density uniformity
- Vacuum tube surrounding oil suppressing heat loss
- Rubidium vapour sources available commercially; development of fast valves started in collaboration with industry
- Need *1 − 2 TW* laser with *30 − 100 fs* pulse

Discharge and helicon cells



- High-voltage discharge in argon-filled dielectric tube.
- Plasma cells of up to 3 m developed

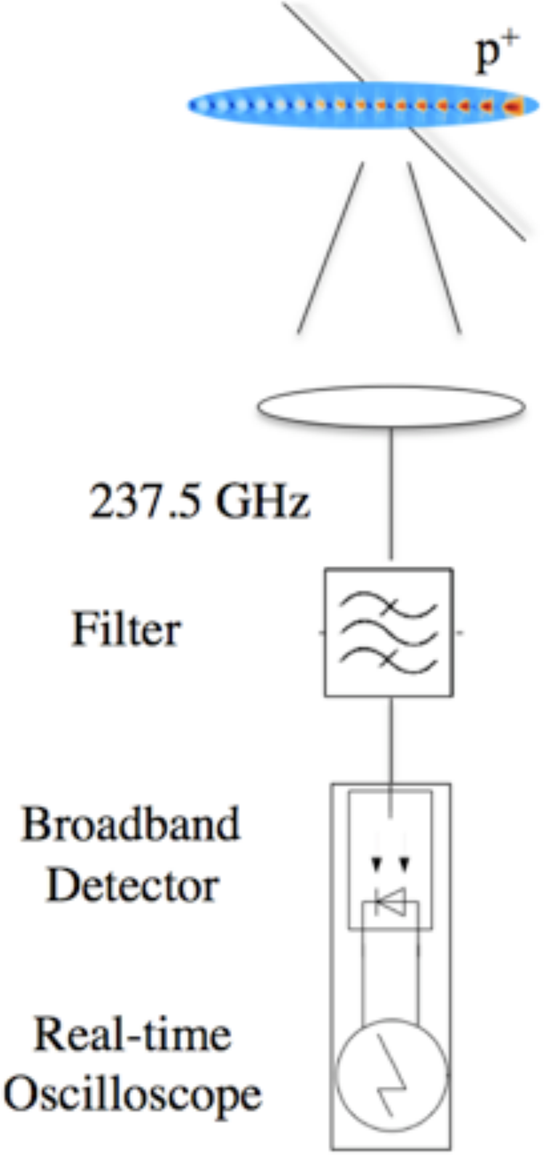
- Cells using helicon waves using RF power antenna systems
- Need to demonstrate such low densities
- 1 m prototype under test



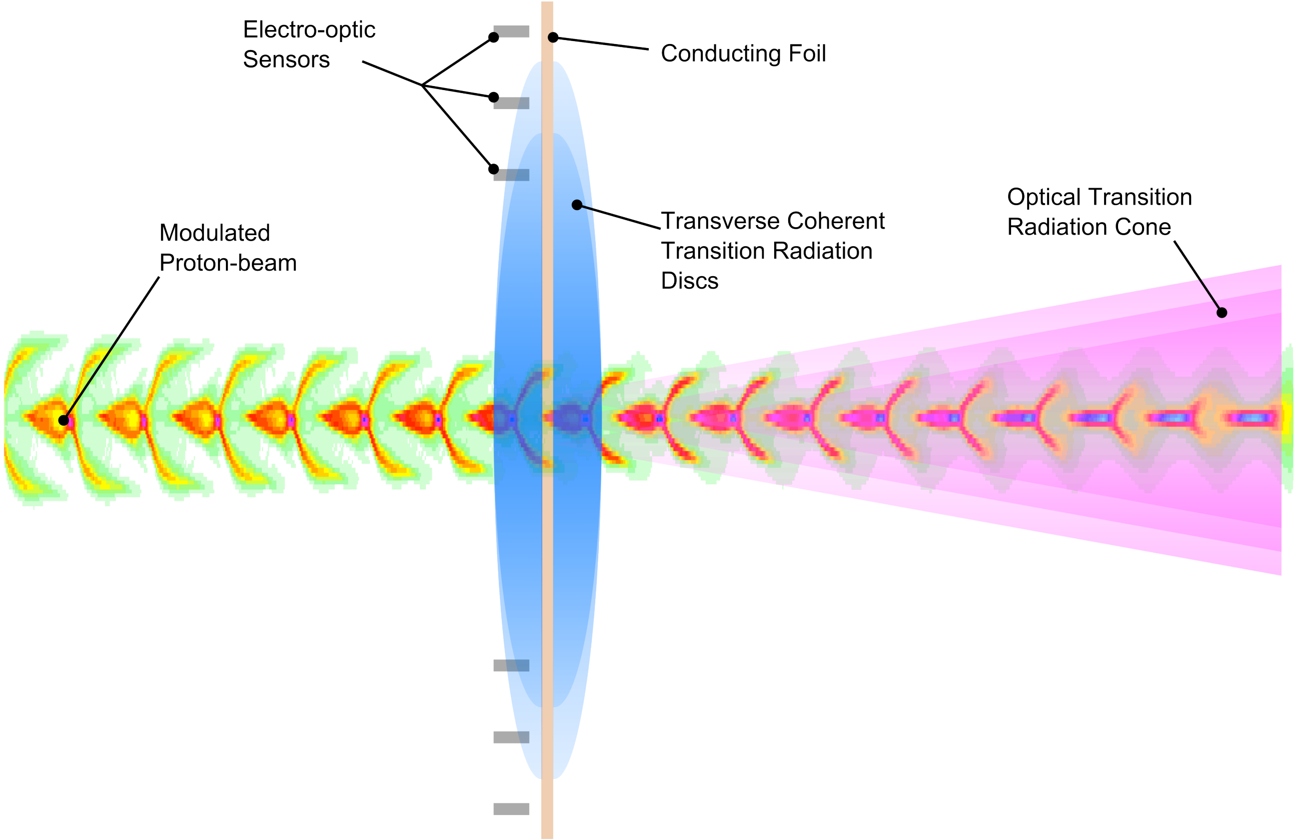
- Both of these technologies have the potential to be used over long distances

Measurement of self-modulation

- Initially commission proton beam and plasma cell
- Measure self-modulation of proton bunch
  - OTR to demonstrate increase in transverse bunch size
  - Resolve radius modulation along bunch with streak camera
  - Coherent transition radiation at modulation frequency



Transverse CTR



New idea, needs to be looked at experimentally

Distinguish SMI from hosing instability

A. Pukhov, T. Tueckmantel, Phys. Rev. STAB **15** (2012) 111301

Electron source

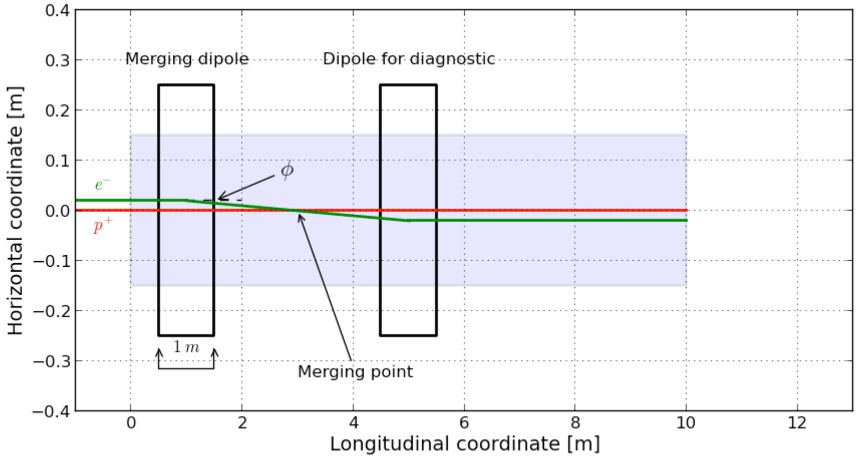
Side injection can utilise long bunches

For electron bunch acceleration, would like :

- High charge
- Short lengths
- Variation of energy

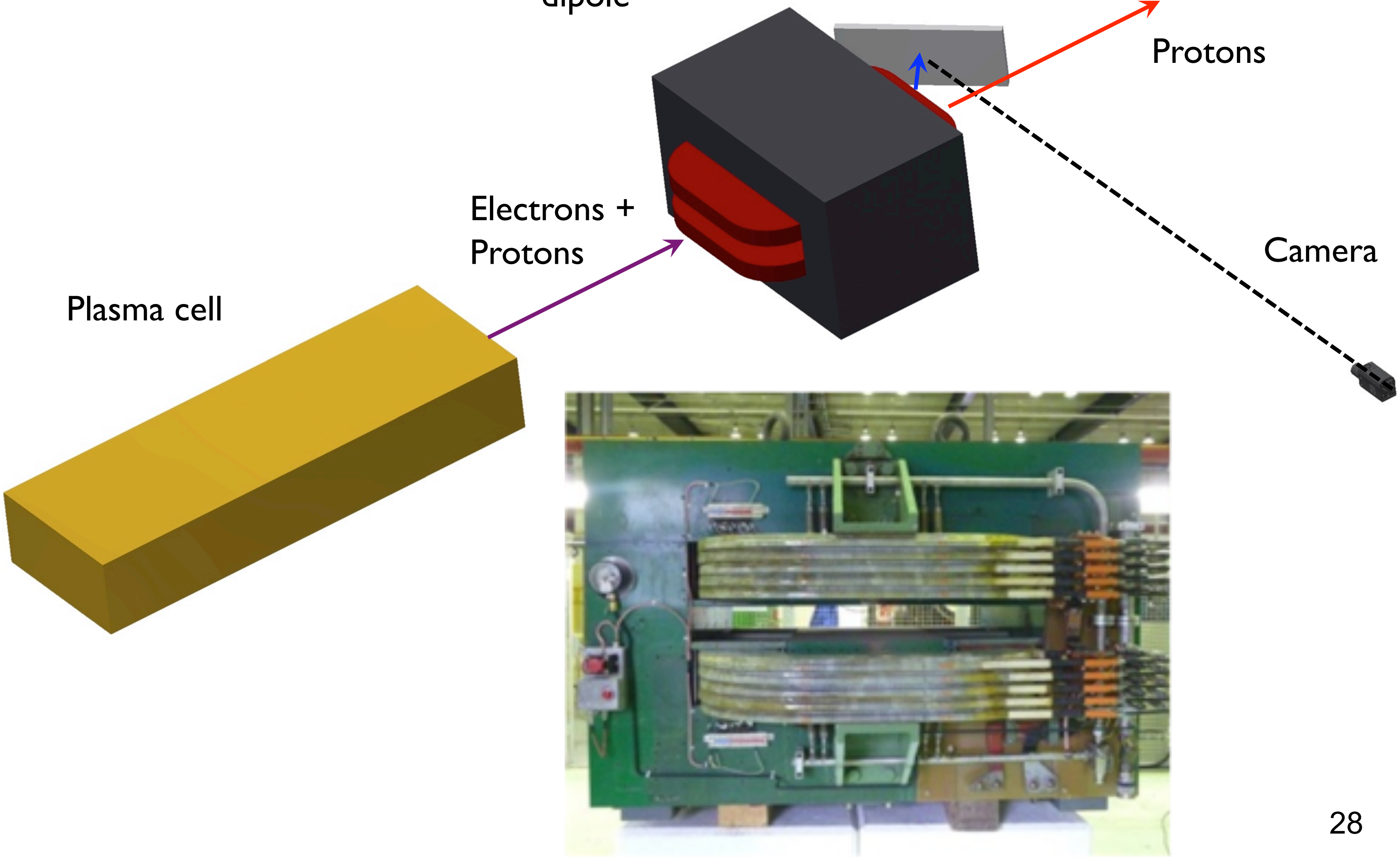
Ideally design electron source for specific needs of AWAKE

Parameter	Nominal value
Beam Energy	$10 - 20\,\mathrm{MeV}$
Energy Spread (rms)	$< 1\%$
Bunch Length	$0.3 - 10\,\mathrm{ps}$
Laser / RF Synchronization	$0.1\,\mathrm{ps}$
Synchronization to Experiment	$0.1\,\mathrm{ps}$
Free Repetition Rate	$10\,\mathrm{Hz}$
Synchronized Repetition Rate	$0.03\,\mathrm{Hz}$
Focused Transverse Size	$< 250\,\mu\mathrm{m}$
Angular Divergence	$< 3\,\mathrm{mrad}$
Normalized Emittance	$0.5\,\mathrm{mm\,mrad}$
Bunch Charge	$1 - 1000\,\mathrm{pC}$

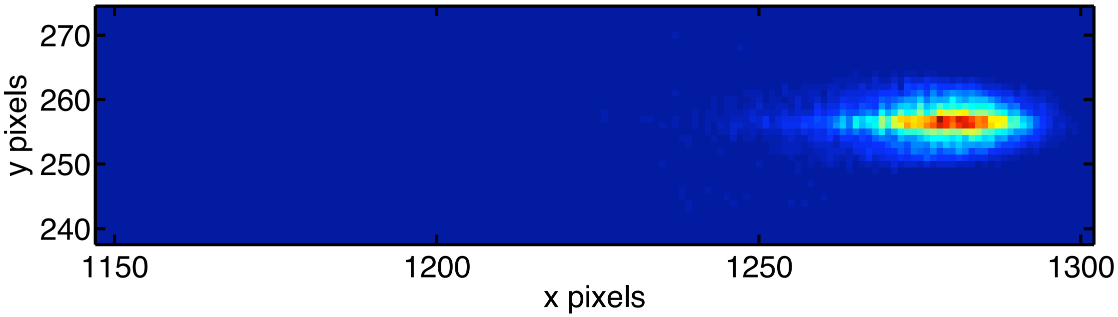


Electron and proton bunches merged with dipoles around plasma cell

Electron spectrometer



Electron energy spectrum

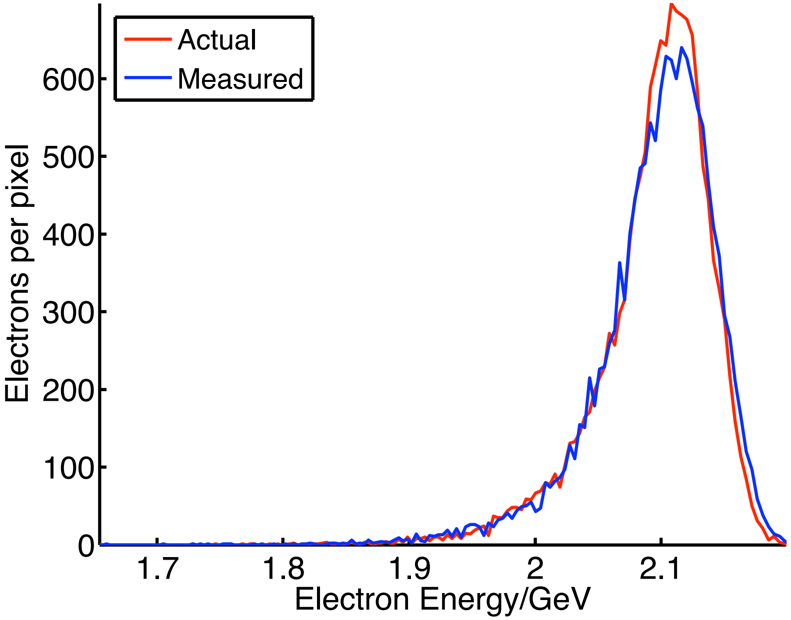


Simulation of scintillator screen shot of electrons exiting plasma and tracked through spectrometer

Comparison of true and reconstructed electron energy spectrum

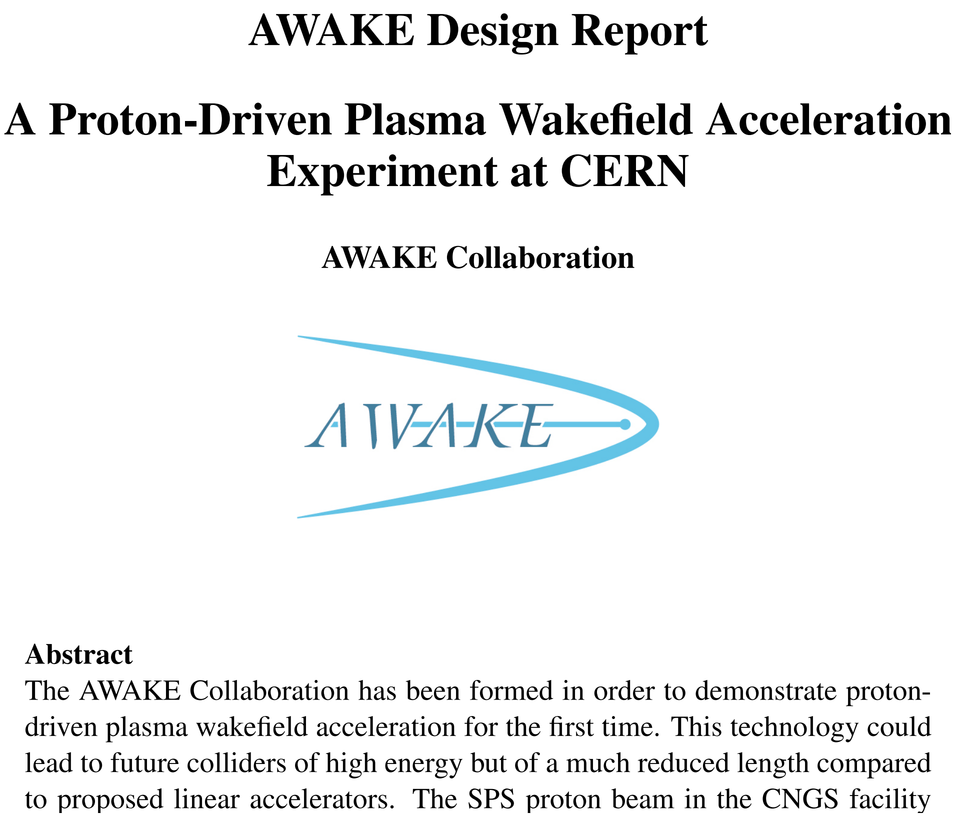
Magnet can measure large range in energies

System suited for experimental programme



AWAKE Collaboration and practicalities

Collaboration of accelerator, plasma and particle physicists and engineers formed.



AWAKE Design Report

A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

AWAKE Collaboration

Abstract

The AWAKE Collaboration has been formed in order to demonstrate proton-driven plasma wakefield acceleration for the first time. This technology could lead to future colliders of high energy but of a much reduced length compared to proposed linear accelerators. The SPS proton beam in the CNGS facility

9.2.1 Institutes Committed to AWAKE

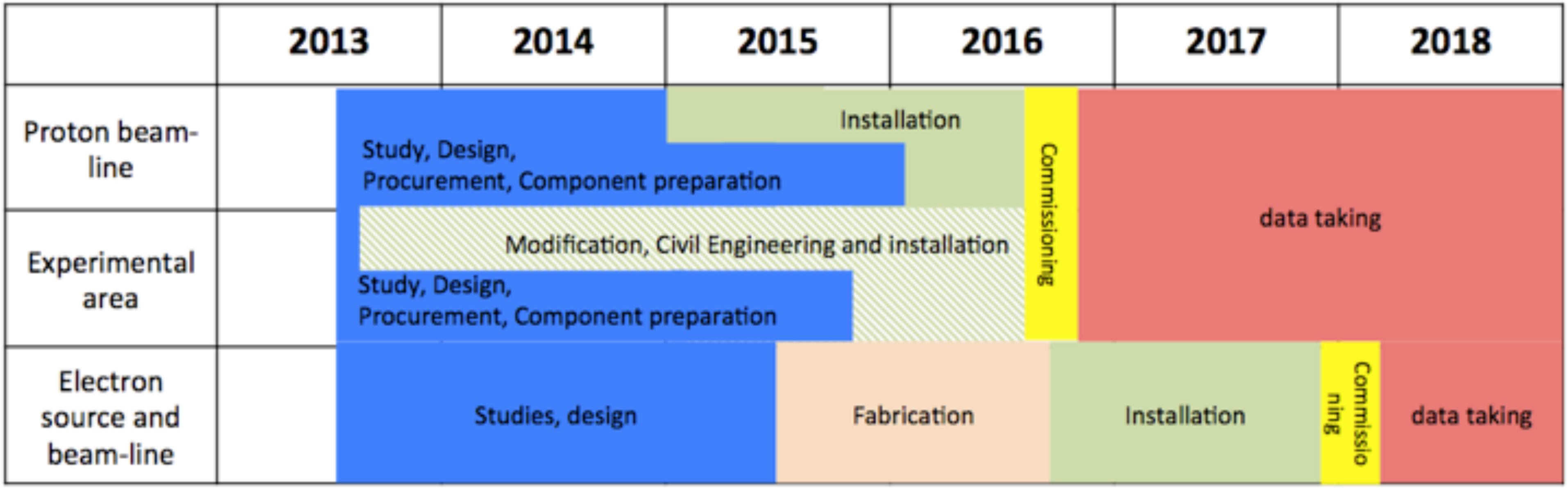
ASTeC, STFC Daresbury Laboratory, Warrington, UK
Budker Institute of Nuclear Physics (BINP), Novosibirk, Russia
CERN, Geneva, Switzerland
Cockroft Institute (CI), Daresbury, UK
Heinrich Heine University, Düsseldorf (D), Germany
Instituto Superior Técnico, Lisboa (IST), Portugal
Imperial College (IC), London, UK
Ludwig Maximilian University (LMU), Munich, Germany
Max Planck Institute for Physics (MPP), Munich, Germany
Max Planck Institute for Plasma Physics (IPP), Greifswald, Germany
Rutherford Appleton Laboratory (RAL), Chilton, UK
University College London (UCL), London, UK
University of Strathclyde (S), Glasgow, Scotland, UK

More institutes committing (DESY, ...).

Now a (fully) approved CERN project; on their Medium-Term Plan and significant funding.

- Expect first protons to plasma cell end of 2016
- Expect electron injection end of 2017
- Periods of running for 3 − 4 years

Science programme



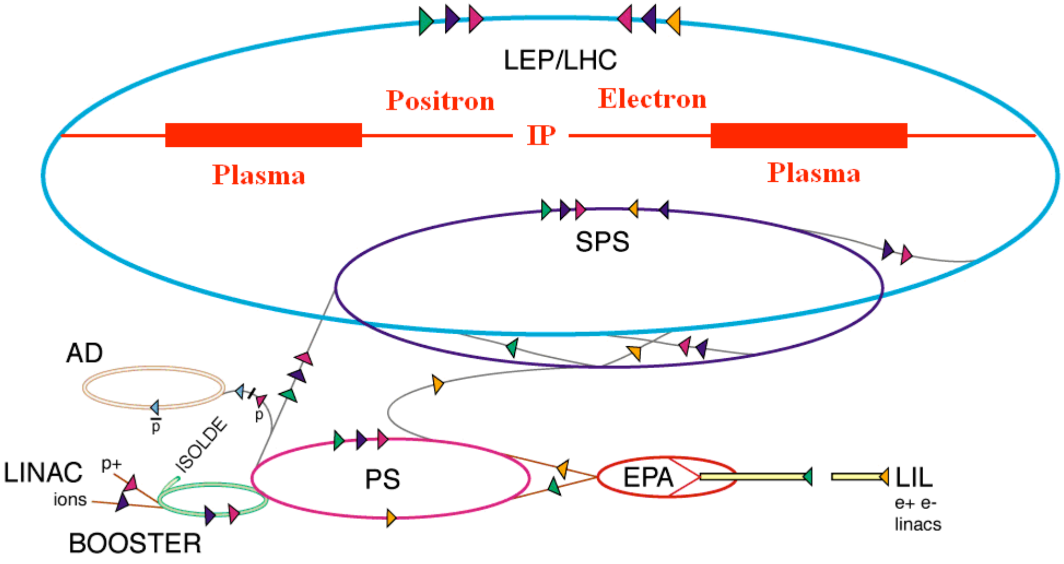
	2013	2014	2015	2016	2017	2018
Proton beam-line	Study, Design, Procurement, Component preparation		Installation	Commissioning data taking		
Experimental area	Modification, Civil Engineering and installation Study, Design, Procurement, Component preparation					
Electron source and beam-line	Studies, design		Fabrication	Installation	Commissioning	data taking

1. Benchmark experiments – first experiment demonstrating proton-driven plasma wakefield acceleration
2. Detailed understanding of the self-modulation process
3. Demonstration of high-gradient accelerations of electrons
4. Develop long, scalable and uniform plasma cells; test in AWAKE experiment
5. Develop scheme for production and acceleration of short proton bunches

Outlook

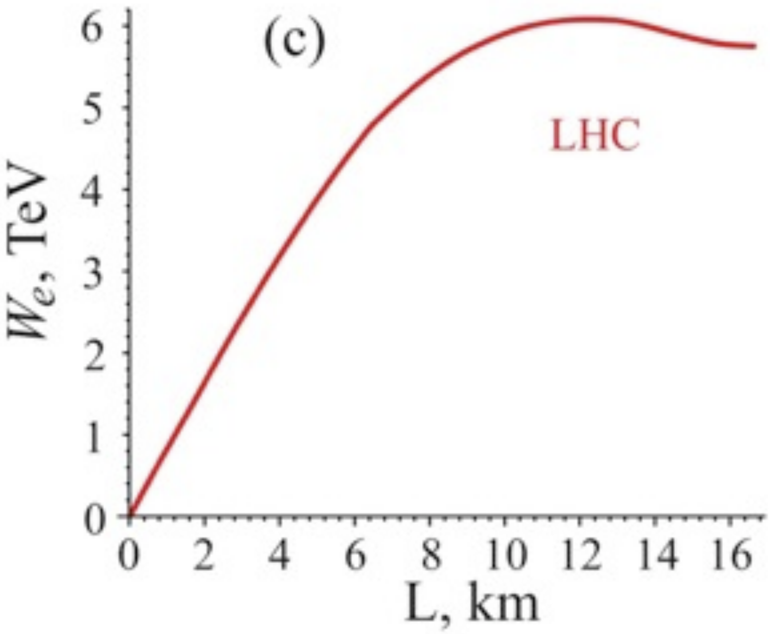
The future

- Consider intermediate stage to possible “full” experiment.
- Consider compressing proton beam —magnetic compression, cutting the beam into slices, etc..
- Ultimate goal of application to future collider.



G. Xia et al.
EAAC proc.

Electron energy gain



Could be used for :

- *ep* (*60×7000 GeV*) LHeC collider
- TeV-scale e^+e^- collider

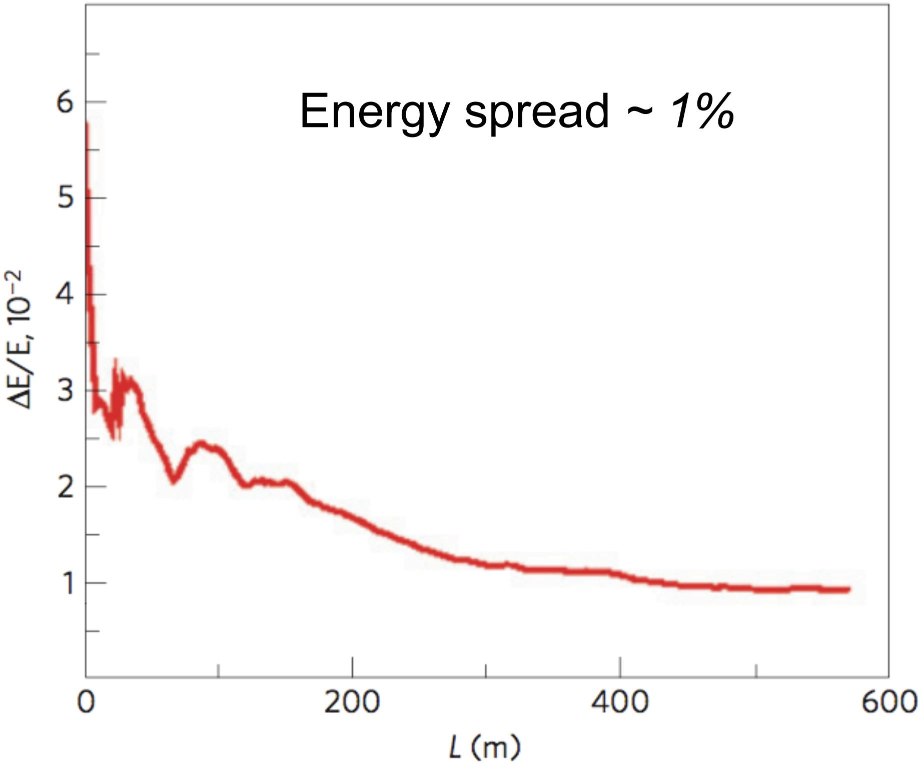
A. Caldwell & K. Lotov, Phys. Plasmas **18** (2011) 103101

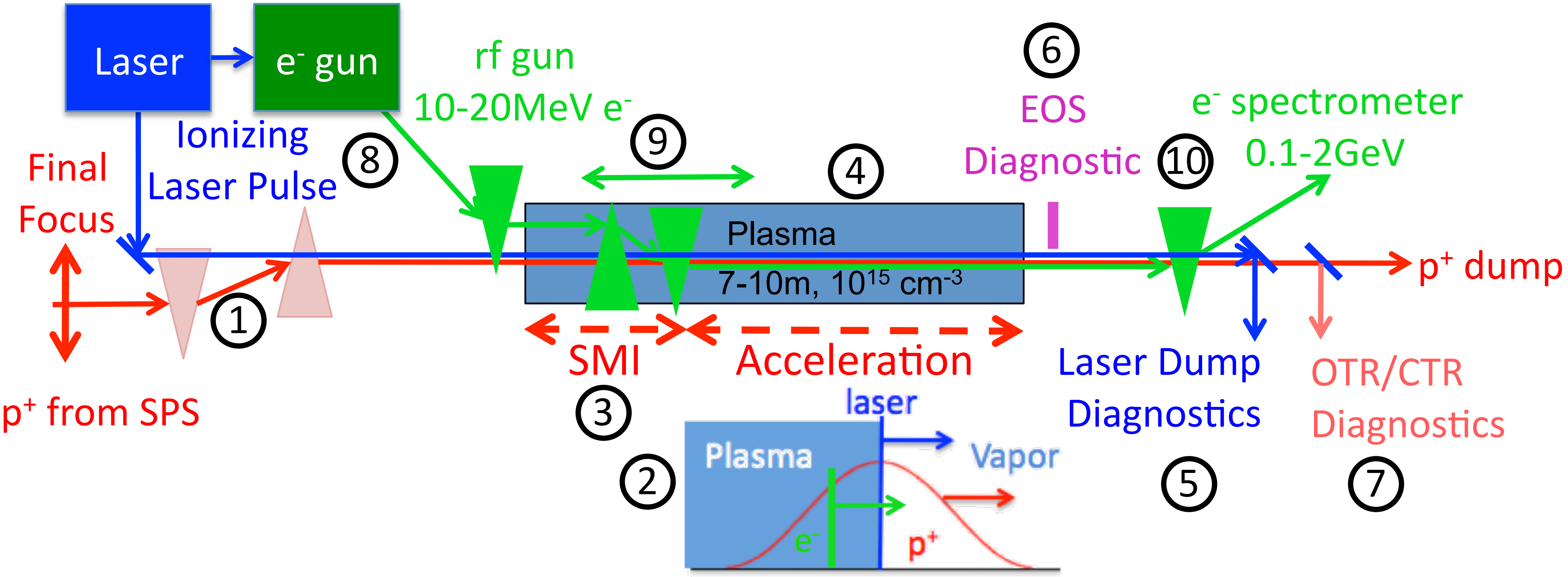
Summary

- Plasma wakefield acceleration could have a huge impact on many areas of science and industry using particle accelerators.
- Presented an idea to have a high energy lepton collider based on proton-driven plasma wakefield acceleration.
- The self-modulation instability allows immediate experimentation.
- Proof-of-principle AWAKE experiment at CERN.
- To realise a TeV-scale lepton collider a factor of ~ *10* shorter than current designs.

See, AWAKE Design Report, CERN-SPSC-2013-013, http://cds.cern.ch/record/1537318/files/SPSC-TDR-003.pdf

Back-up


Energy spread ~ *1%*
ΔE/E, 10⁻²
6
5
4
3
2
1
0
200
400
600
L (m)



1. Merging of SPS proton beam & ionizing/seeding laser pulse
2. Schematic relative timing
3. SMI developing, electron bunch parallel to proton bunch
4. Acceleration sections
5. Laser pulse dumped & diagnosed
6. Electro-optical sampling diagnostic
7. Transition radiation diagnostics
8. RF electron gun
9. e/p bunch merging section
10. Electron spectrometer system

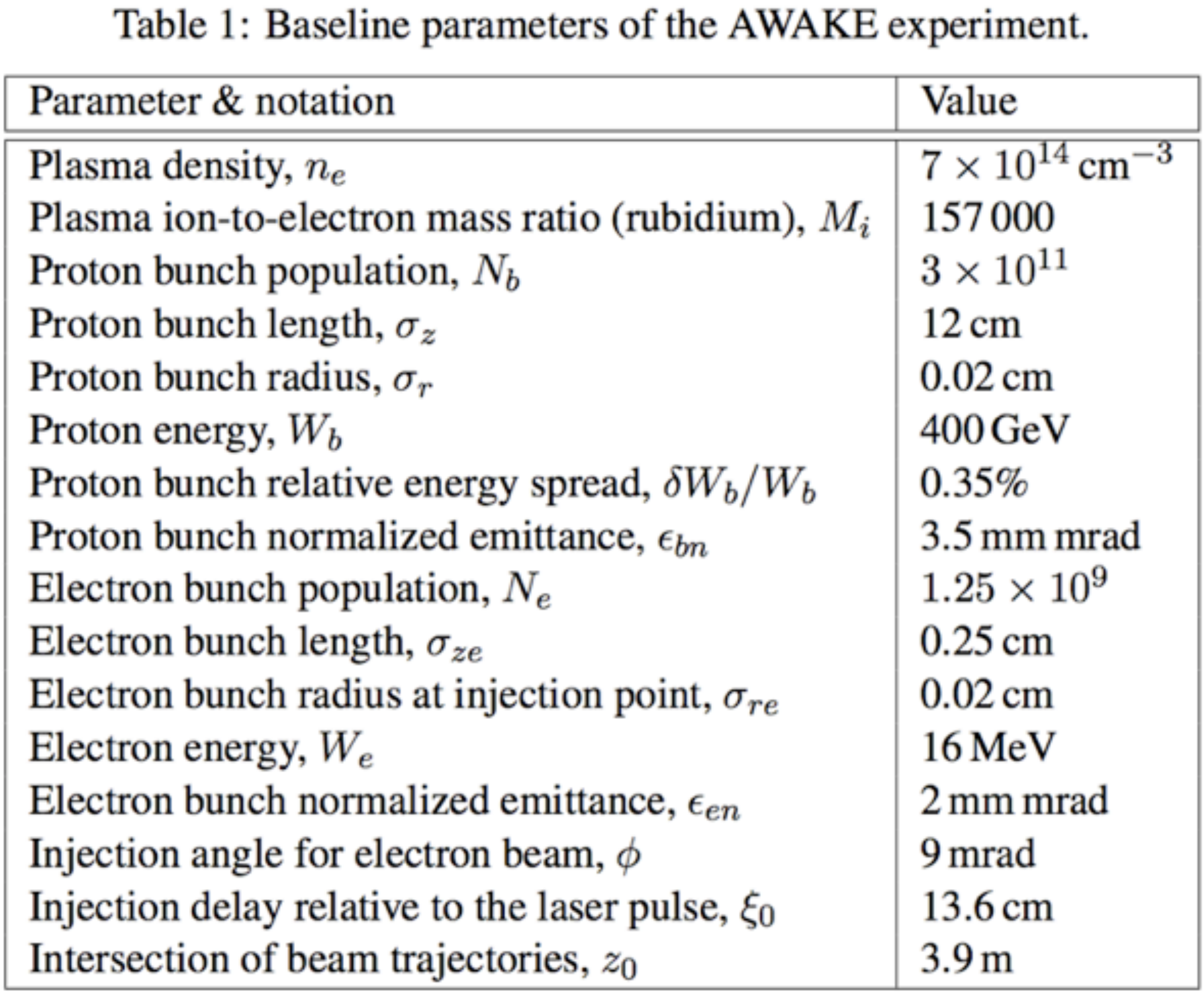
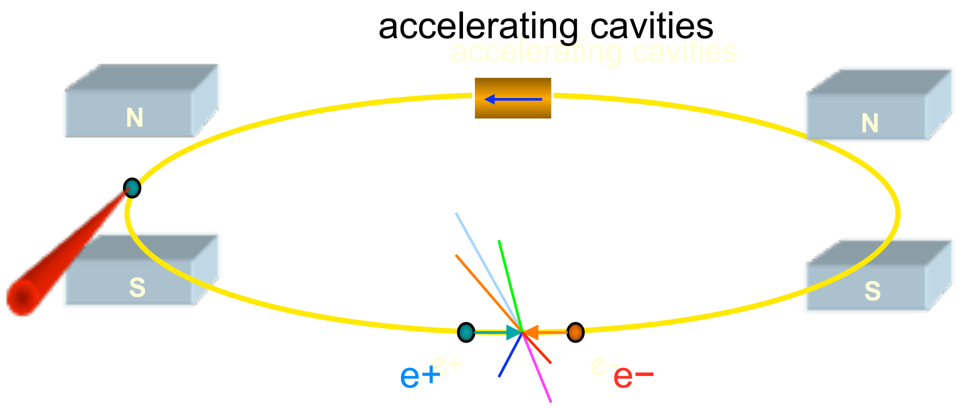


Table 1: Baseline parameters of the AWAKE experiment.

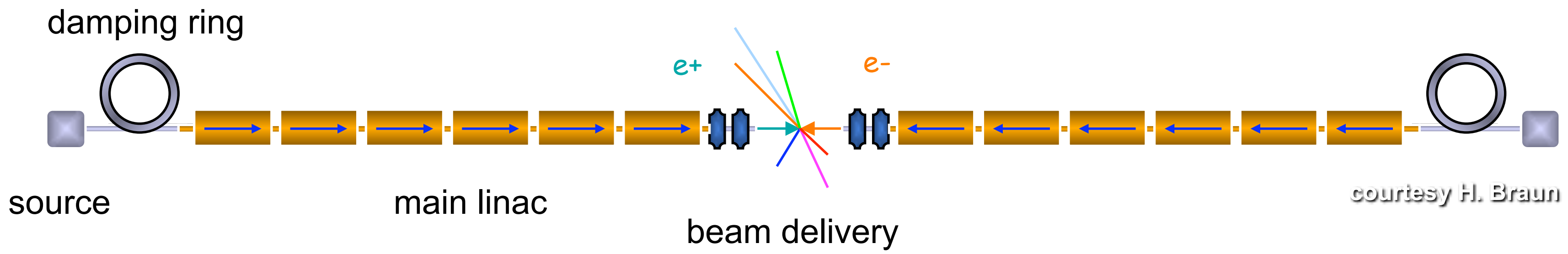
Parameter & notation	Value
Plasma density, n_e	$7 \times 10^{14}\,\mathrm{cm}^{-3}$
Plasma ion-to-electron mass ratio (rubidium), M_i	157 000
Proton bunch population, N_b	3×10^{11}
Proton bunch length, σ_z	12 cm
Proton bunch radius, σ_r	0.02 cm
Proton energy, W_b	400 GeV
Proton bunch relative energy spread, $\delta W_b/W_b$	0.35%
Proton bunch normalized emittance, ϵ_{bn}	3.5 mm mrad
Electron bunch population, N_e	1.25×10^9
Electron bunch length, σ_{ze}	0.25 cm
Electron bunch radius at injection point, σ_{re}	0.02 cm
Electron energy, W_e	16 MeV
Electron bunch normalized emittance, ϵ_{en}	2 mm mrad
Injection angle for electron beam, ϕ	9 mrad
Injection delay relative to the laser pulse, ξ_0	13.6 cm
Intersection of beam trajectories, z_0	3.9 m

Conventional accelerators



Circular colliders :

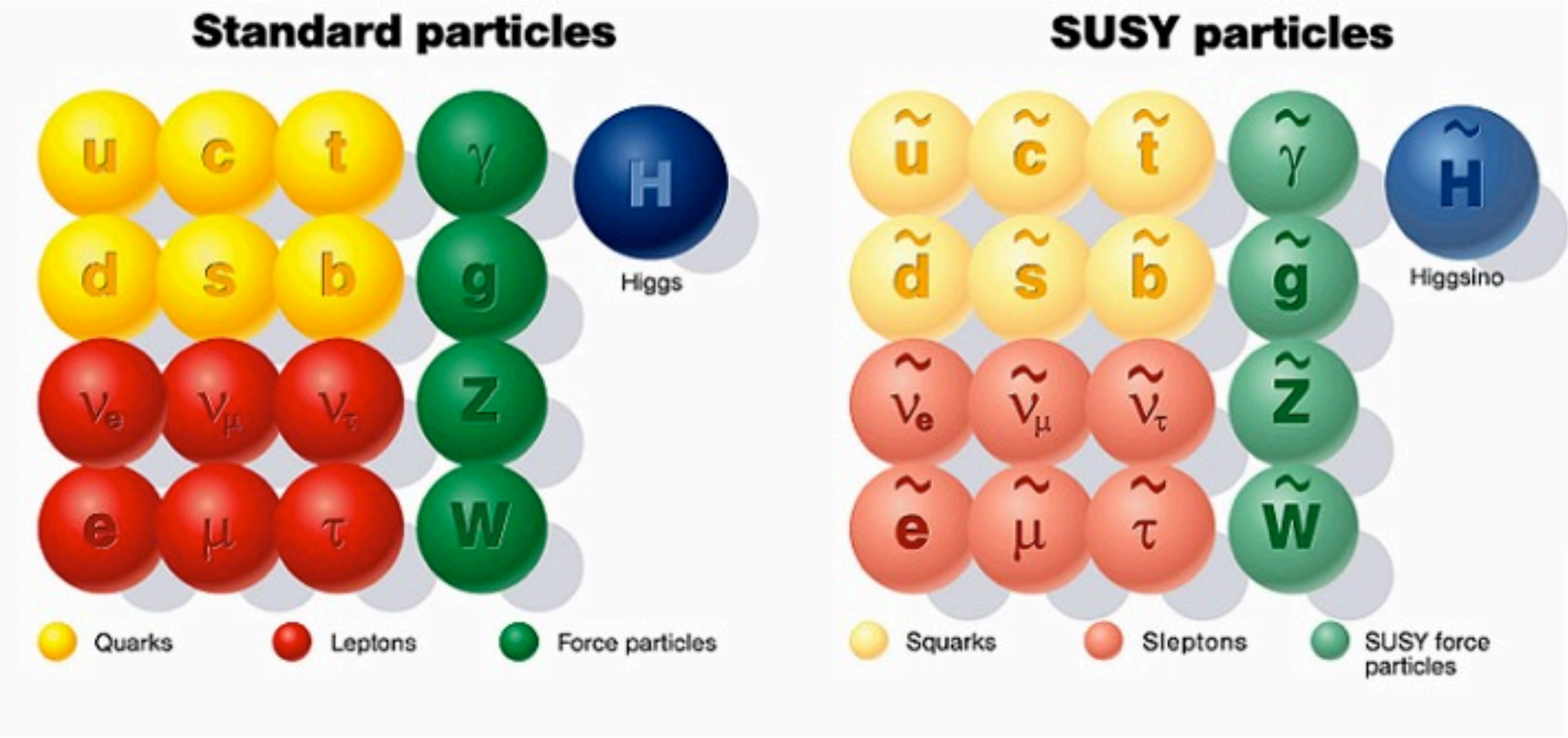
- Many magnets, few cavities so strong field needed;
- High synchrotron radiation;
- High repetition rate leads to high luminosity.



courtesy H. Braun

Linear colliders :

- Few magnets, many cavities so efficient RF power production needed;
- Single pass so need small cross section for high luminosity and very high beam quality;
- The higher the gradient, the shorter the linac.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