AWAKE Design Report

A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

AWAKE Collaboration

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MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

1. Brief Motivation
2. Proton-driven plasma wakefield acceleration
3. Self-modulation approach
4. Outline of proposed experiment
5. What we will measure
6. Proposed location
7. Required resources from CERN
8. Responsibilities & resources of other participating institutes
9. Timeline & outlook

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Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

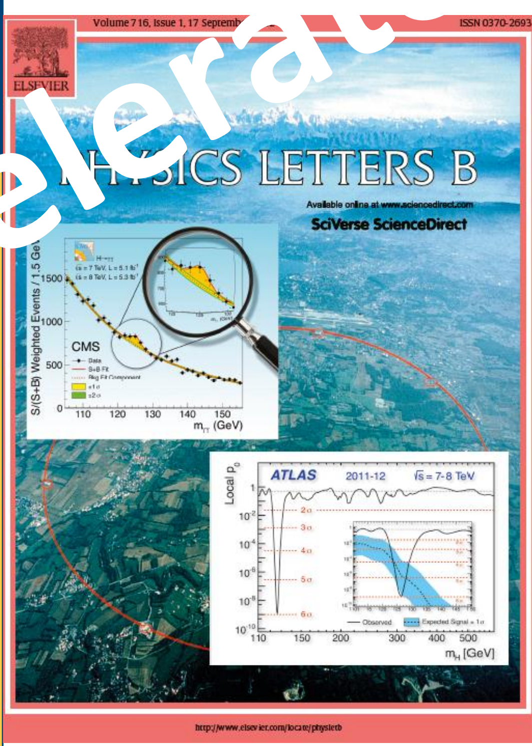
Leptons spin =1/2

Flavor		Mass GeV/c^2	Electric charge
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	tau	1.777	–1

Quarks spin =1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.002	2/3
d	down	0.005	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	173	2/3
b	bottom	4.2	–1/3

The most important tool for this development was the particle accelerator


Volume 716, Issue 1, 17 Septemb

ISSN 0370-2693

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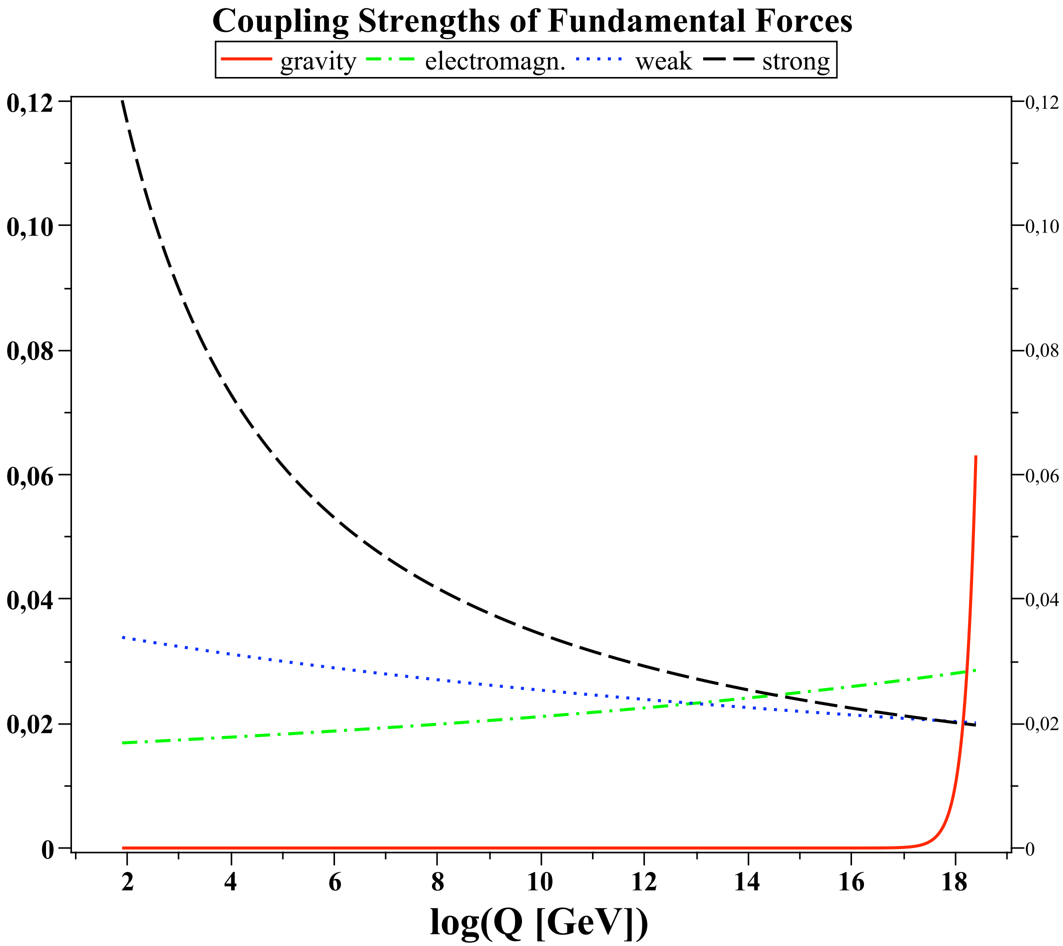
Particle physicists are convinced there are more discoveries to come:

Many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …



Need to find ways to explore physics at higher energy scales in a laboratory environment.

New acceleration technology !

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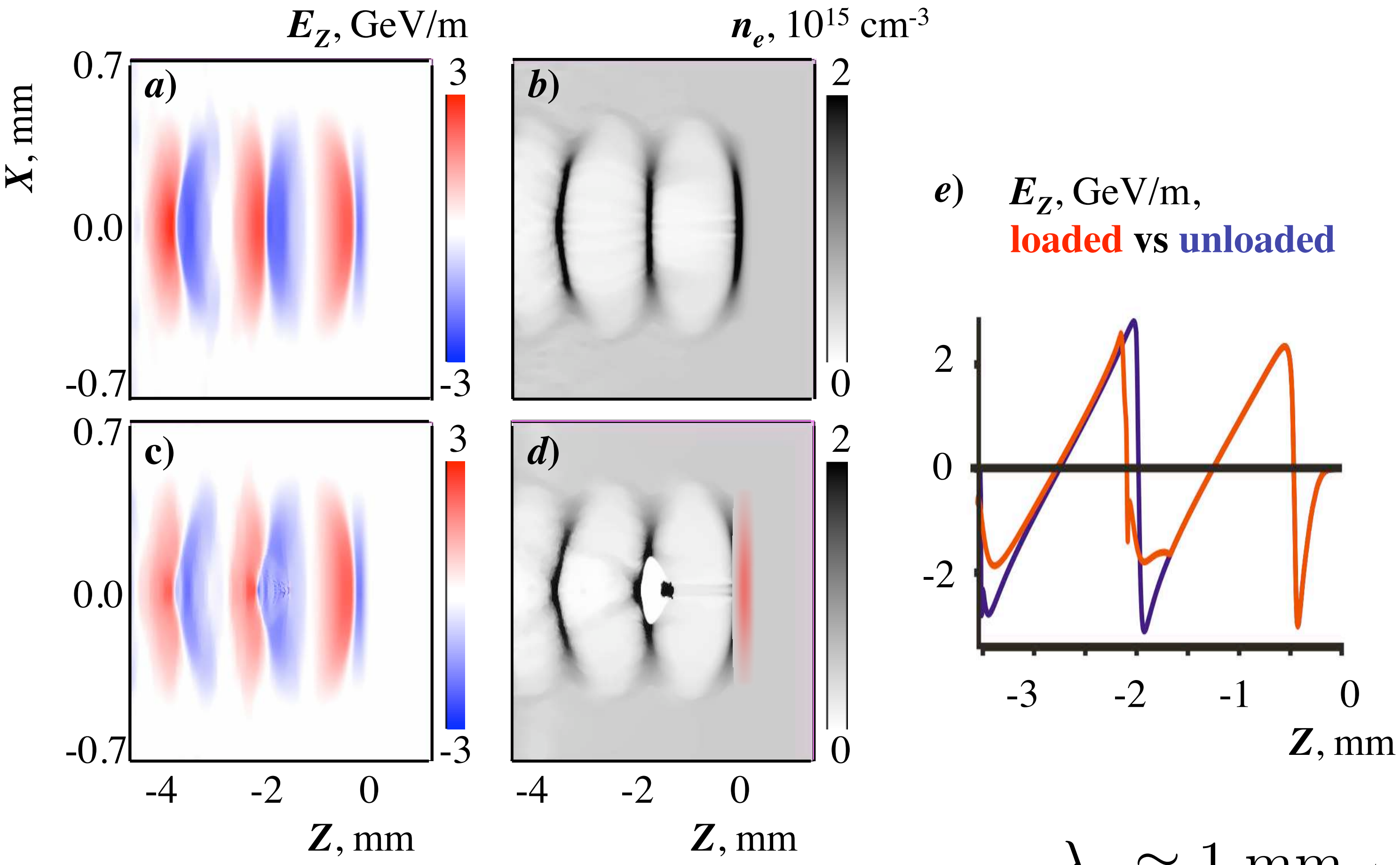
Plasma Wakefield Acceleration

Original proposal (T. Tajima, J. W. Dawson Phys. Rev. Lett. **43** (1979) 267) considered laser acceleration (LWFA). Impressive steps taken in recent years as lasers have become more and more powerful. Gradients ca 100 GV/m demonstrated.

Series of experiments at SLAC using electron beams (PWFA) demonstrated that beam driven wakefield acceleration (P. Chen et al., Phys. Rev. Lett. **54** (1985) 693) is also a very attractive option. Gradients 50 GV/m demonstrated.

Our plan – use protons bunches to drive the wakefields.

Plasma Wakefield Acceleration



$$\lambda_p \approx 1\ \mathrm{mm}\sqrt{\frac{1\cdot 10^{15}\mathrm{cm}^{-3}}{n_p}}$$

Size of accelerator structure set by plasma density

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

Why Proton-Driven Wakefield Acceleration

Both laser-driven and electron-bunch driven acceleration will require many stages to reach the TeV scale.

We know how to produce high energy protons (many TeV) in bunches with population > 10^{11}/bunch today, so if we can use protons to drive a wakefield we can have a simpler arrangement - single stage acceleration.

Linear regime ($n_b<n_0$):

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

Need very short proton bunches for strong gradients. Today's proton beams have

$$\sigma_z \approx 10 - 30\ \mathrm{cm}$$

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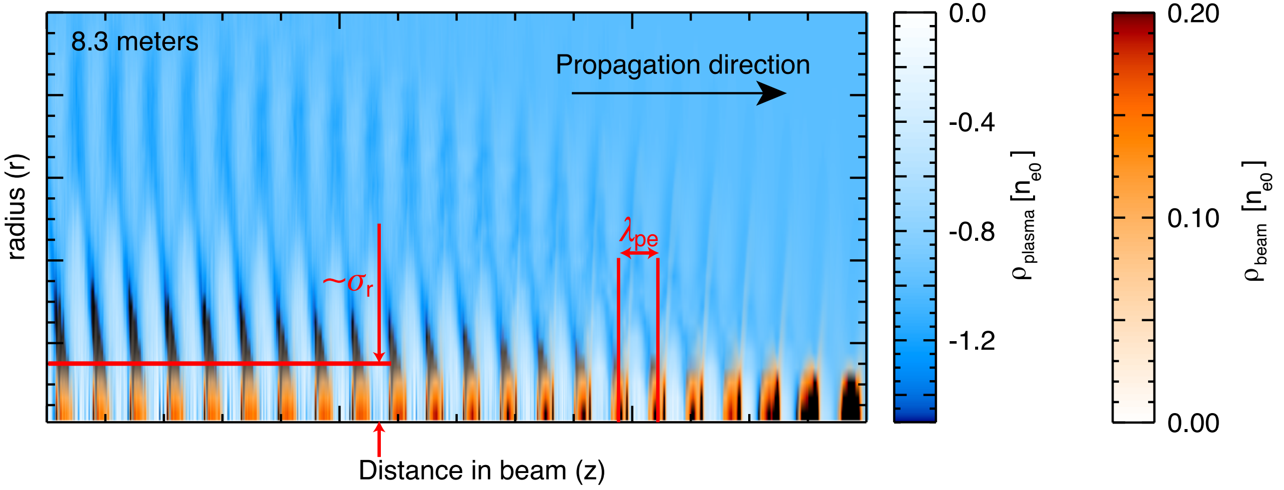
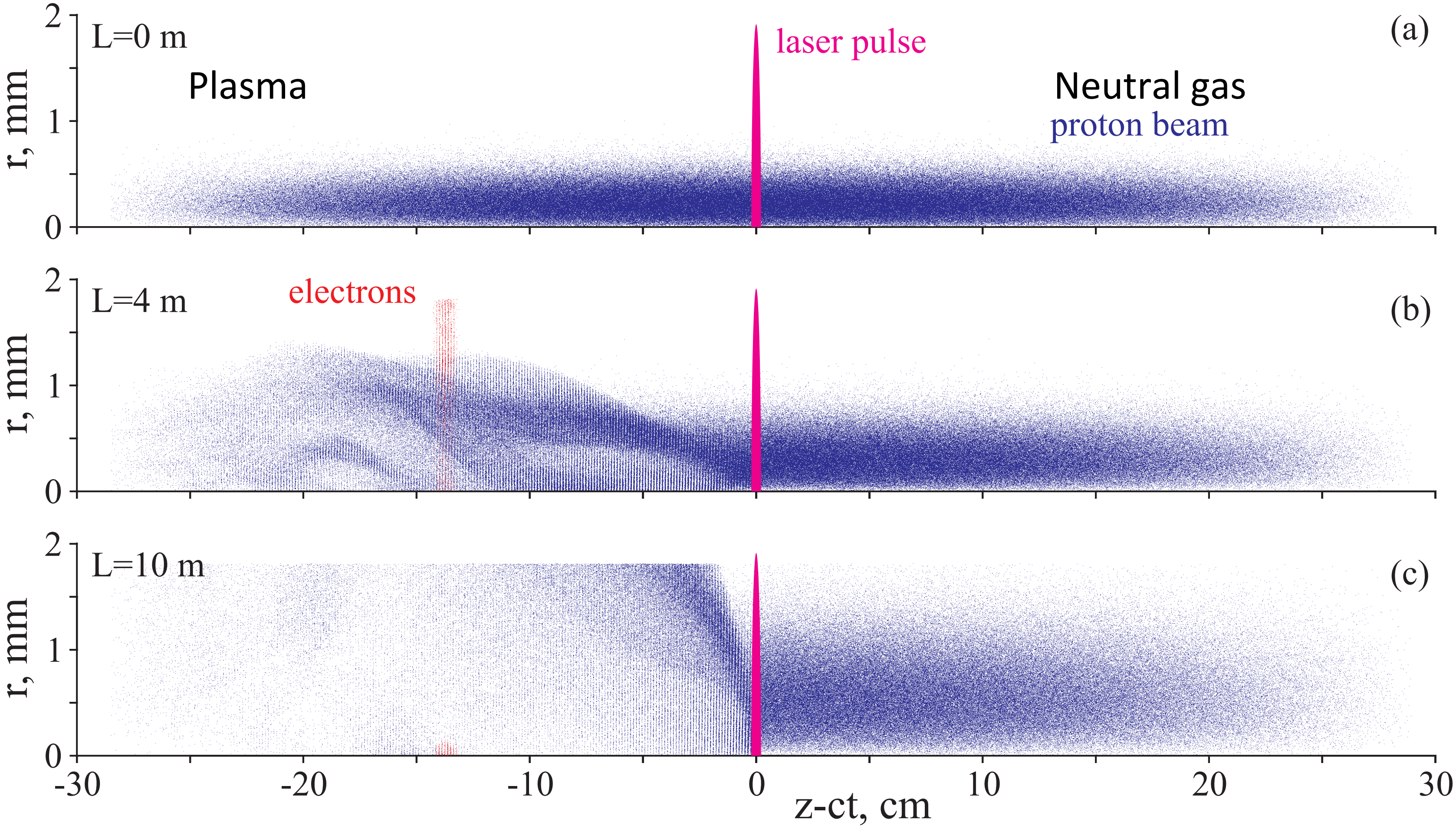
PWA via Modulated Proton Beam

Producing short proton bunches not possible today w/o major investment. Instead, modulate a long (SPS) bunch



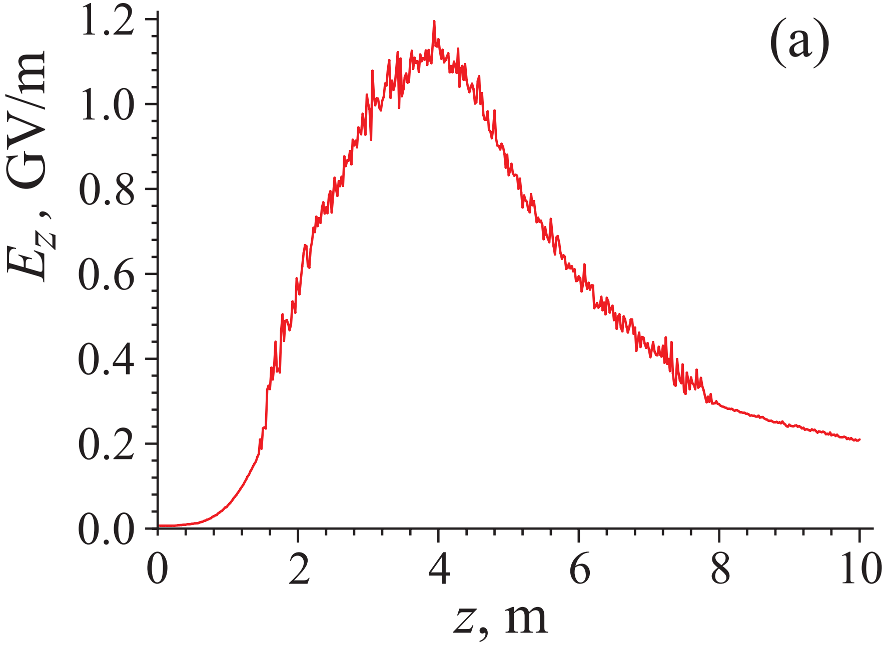
Microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). Naturally spaced at the plasma wavelength, and resonantly drive wakefields to large amplitudes. (N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)).

The modulation process develops over a distance of several meters. The wake phase velocity and strength of field vary

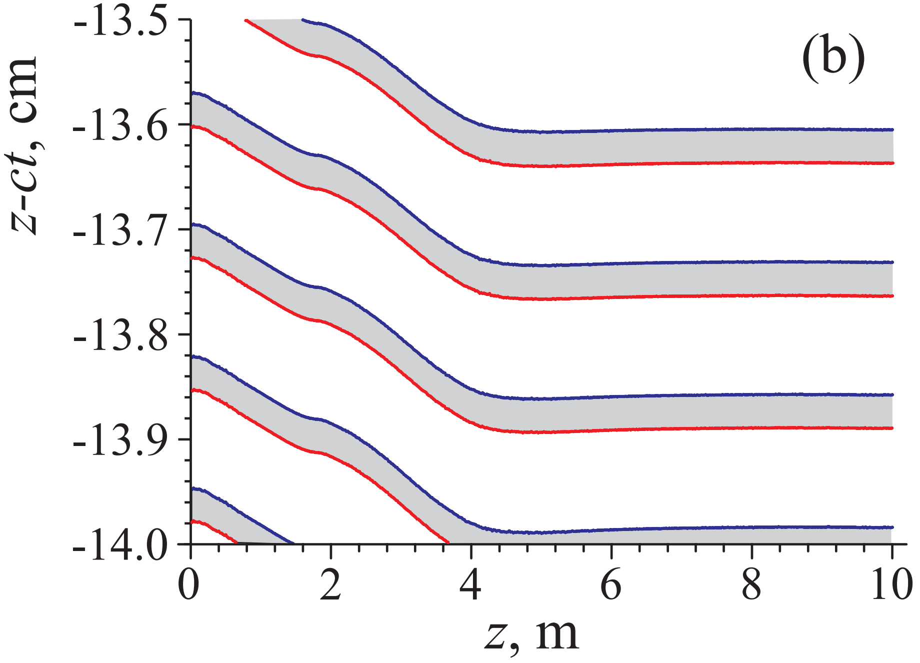


Using the same laser pulse for the electron photoinjector allows for precise phasing of the electron bunch and proton microbunches.

Strength of E-field versus propagation distance for nominal SPS parameters



Location of maximum acceleration phase versus propagation distance

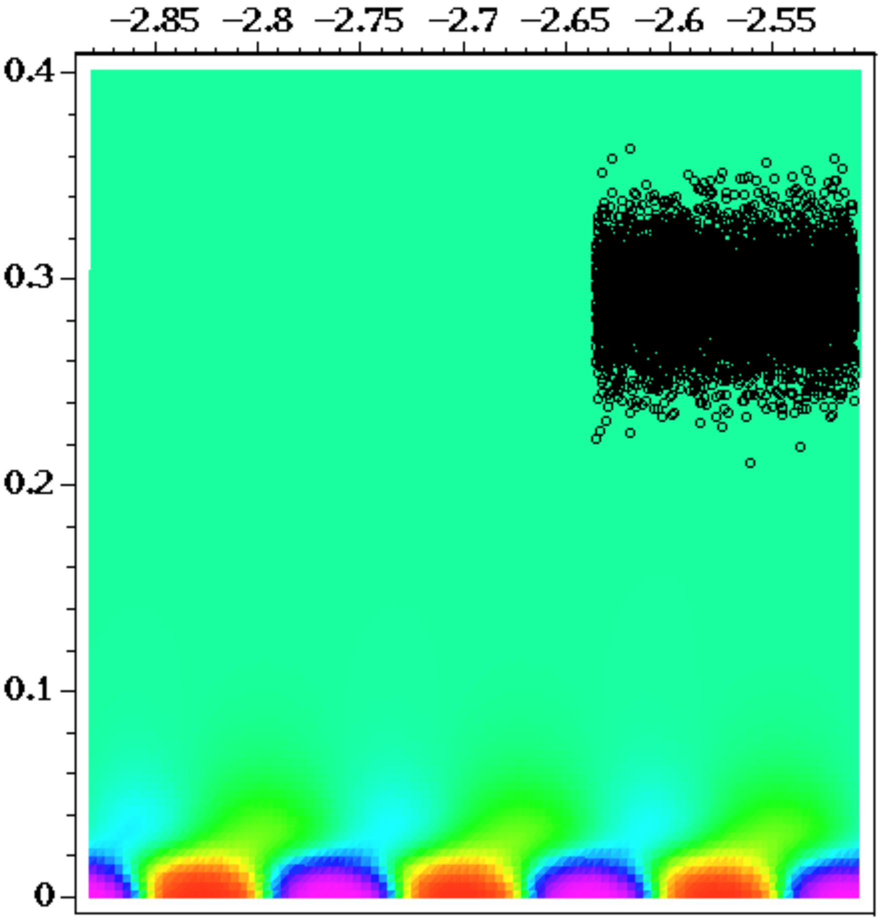


Need to inject electrons in region of constant phase velocity (=c)

Can freeze high-field with plasma density step … (see later)

Electron injection needs to occur after modulation has completed. For single plasma cell experiment, we achieve this using side-injection.

Simulations indicate can capture up to 40% of electron bunch this way.



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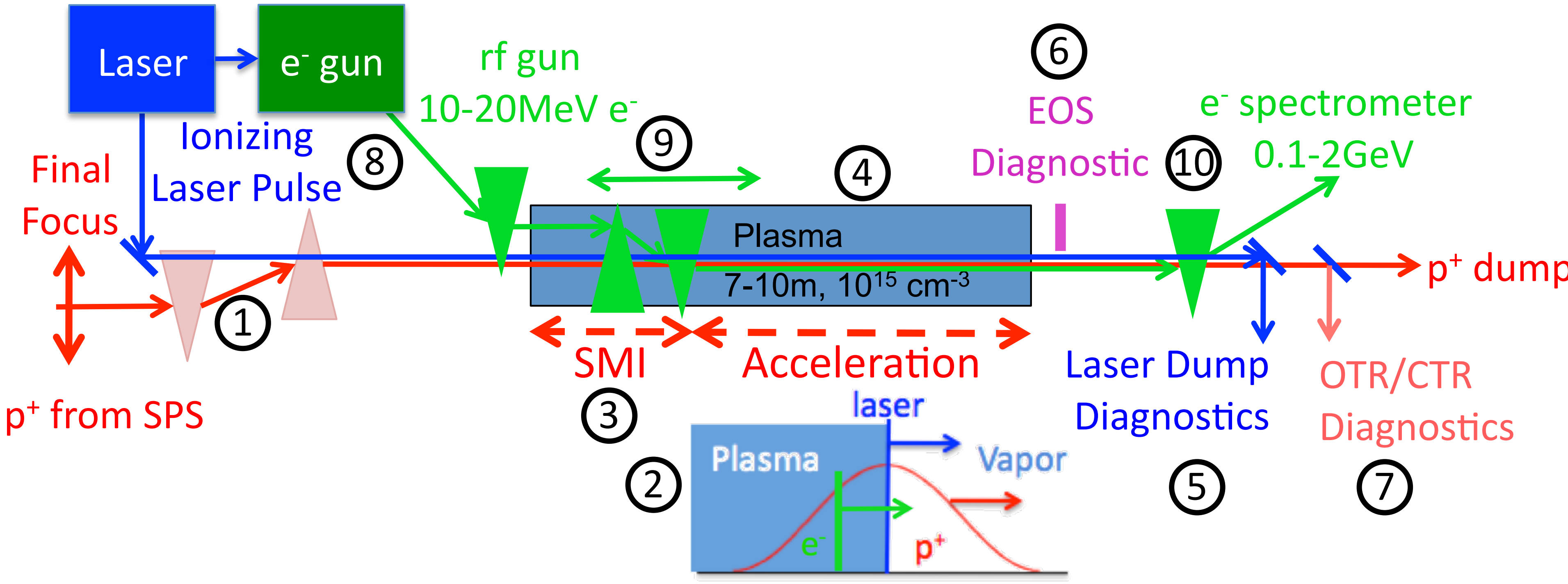


1. Merging of SPS proton beam & ionizing/seeding laser pulse
2. Schematic relative timing
3. SMI developing, electron bunch parallel to proton bunch
4. Acceleration sections
5. Laser pulse dumped & diagnosed
6. Electro-optical sampling diagnostic
7. Transition radiation diagnostics
8. RF electron gun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

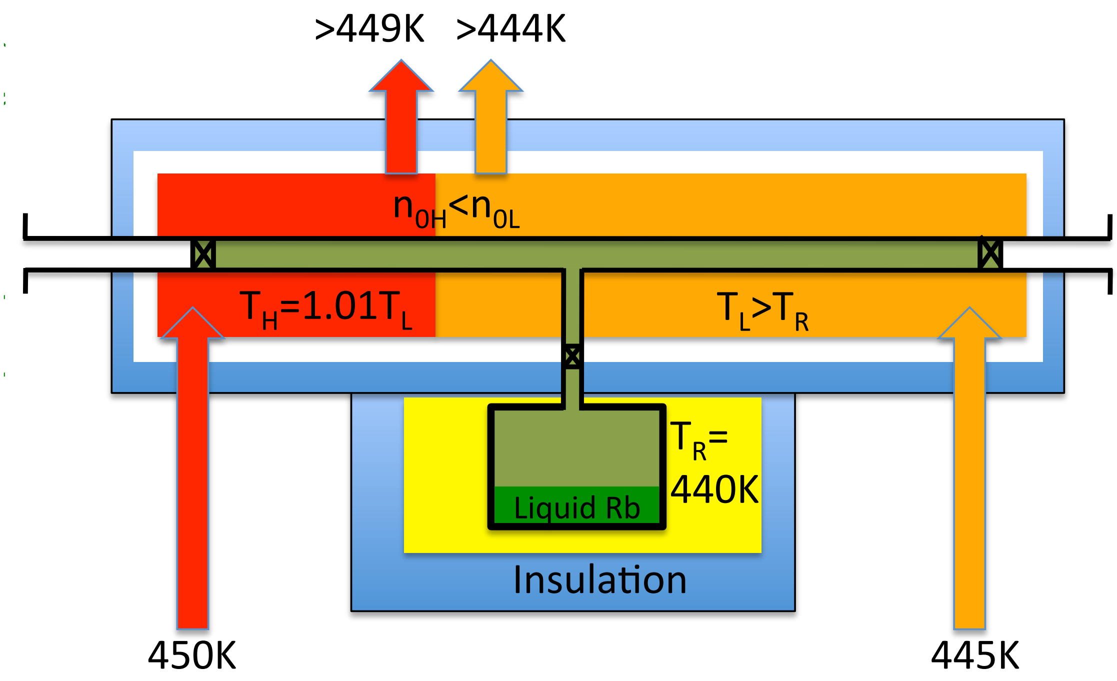
Table 1: Baseline parameters of the AWAKE experiment.

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

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 [25].

Choice for first experiments: Rubidium vapor cell



Delevoped at MPP

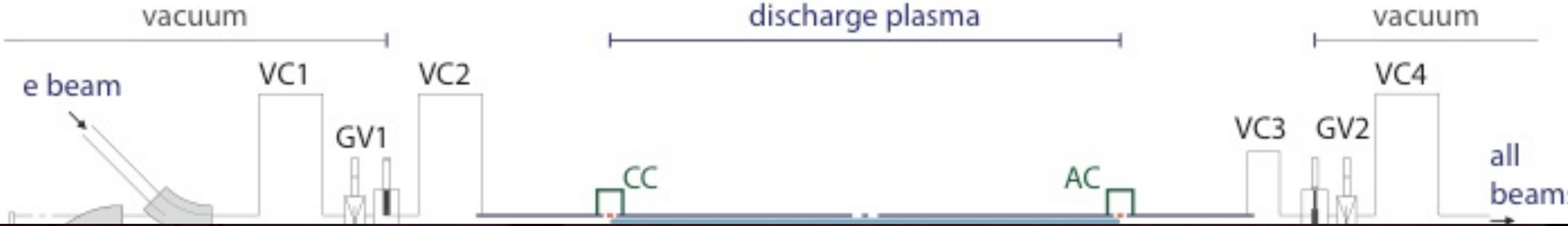
- Density uniformity set by temperature uniformity of neutral vapor. Fraction of a degree achievable using oil bath

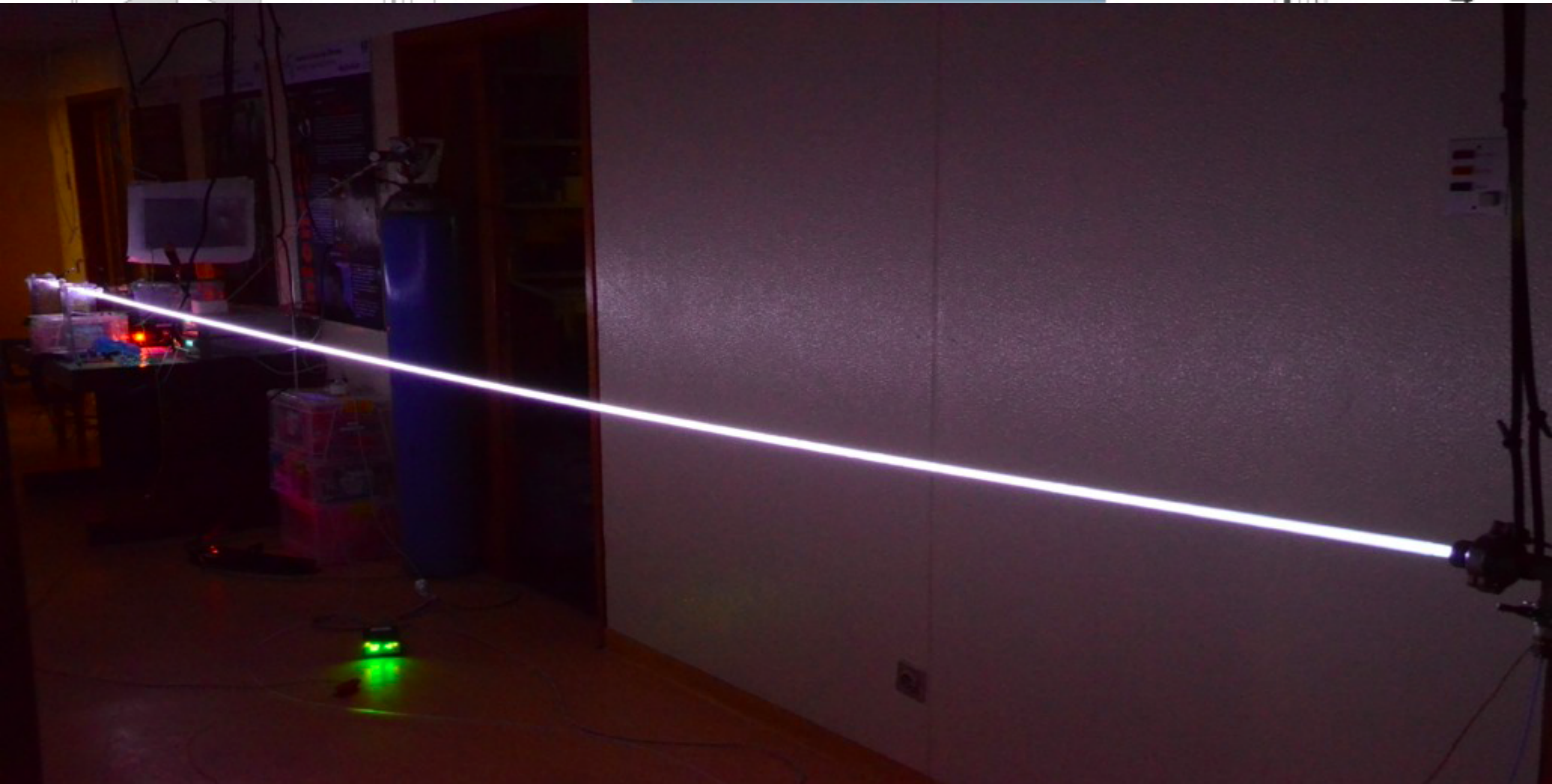
- Rubidium vapor sources available commercially

- Valve development started with industry

Discharge Cell

(Instituto Superior Tecnico, Lisboa and Imperial College, London)

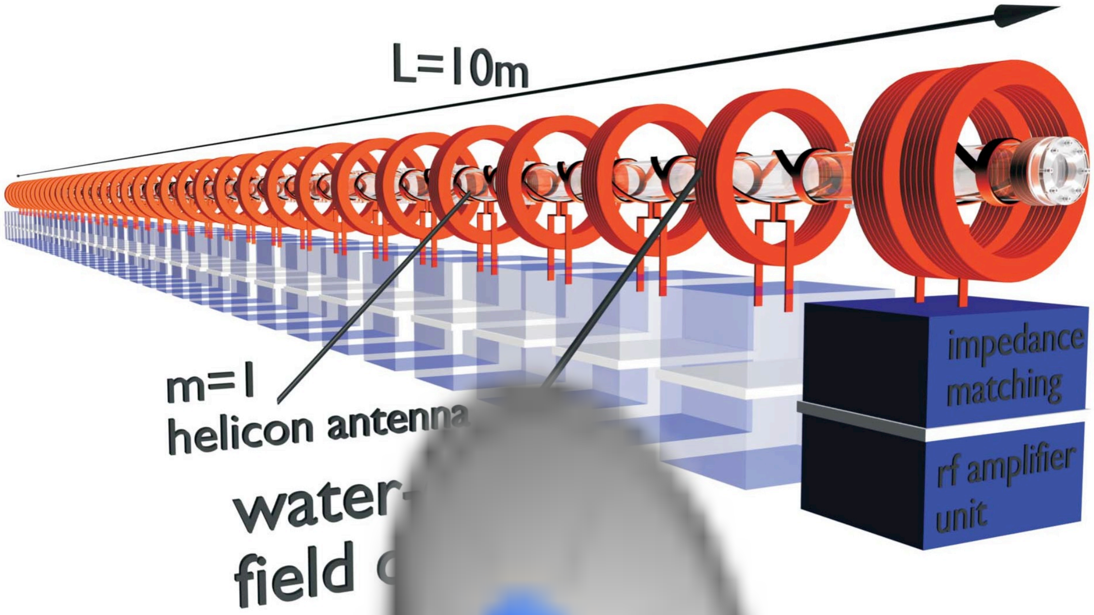




R&D for long, uniform cells

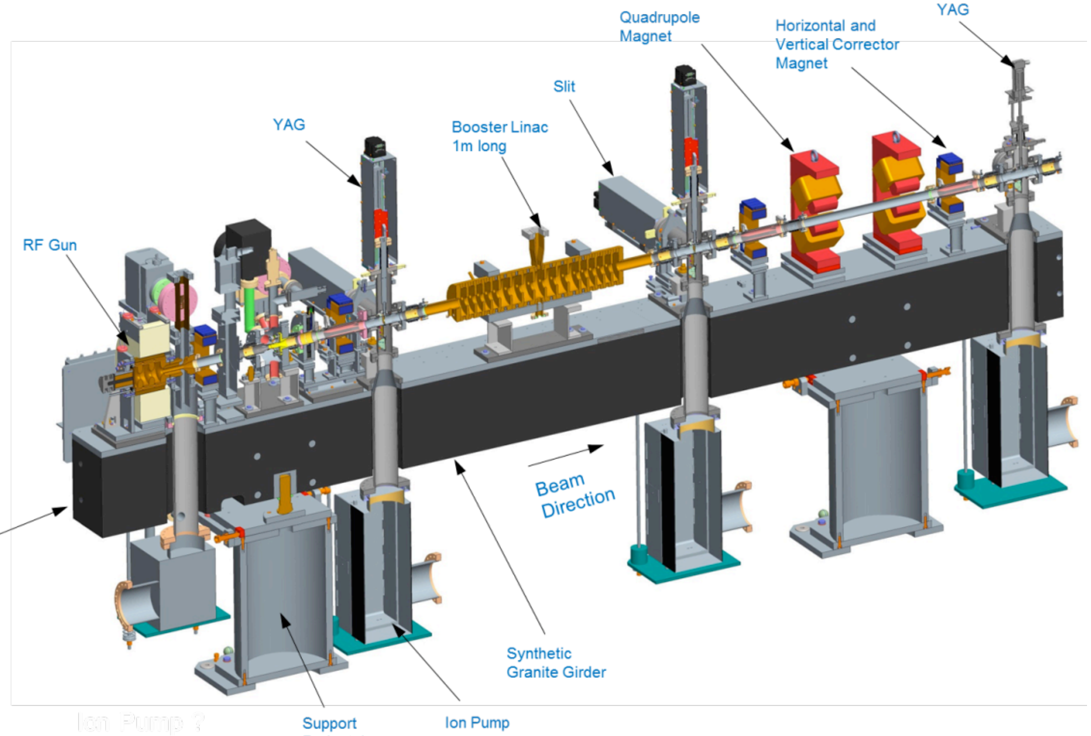
Helicon Cell

(Max Planck Institute for Plasma Physics)



1 meter prototype at the IPP in Greifswald.

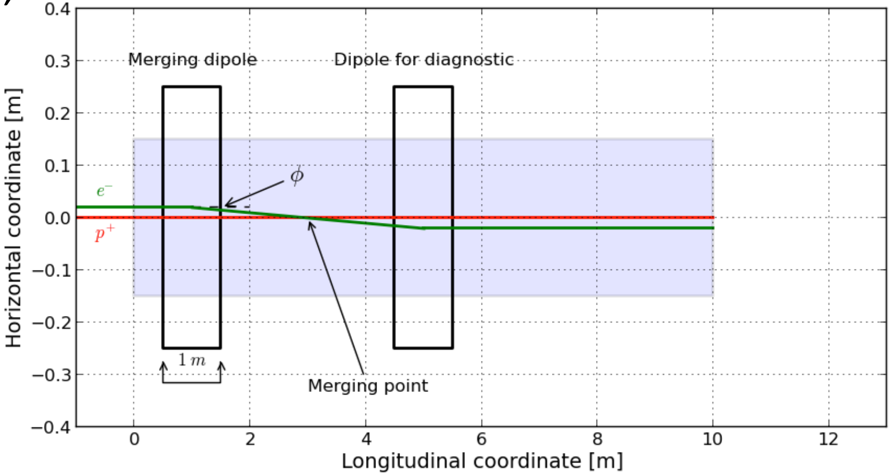
Electron Source



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

ASTeC, STFC Daresbury Laboratory, Warrington, UK

Merging of electron bunch with proton bunch achieved with dipoles around plasma cell.



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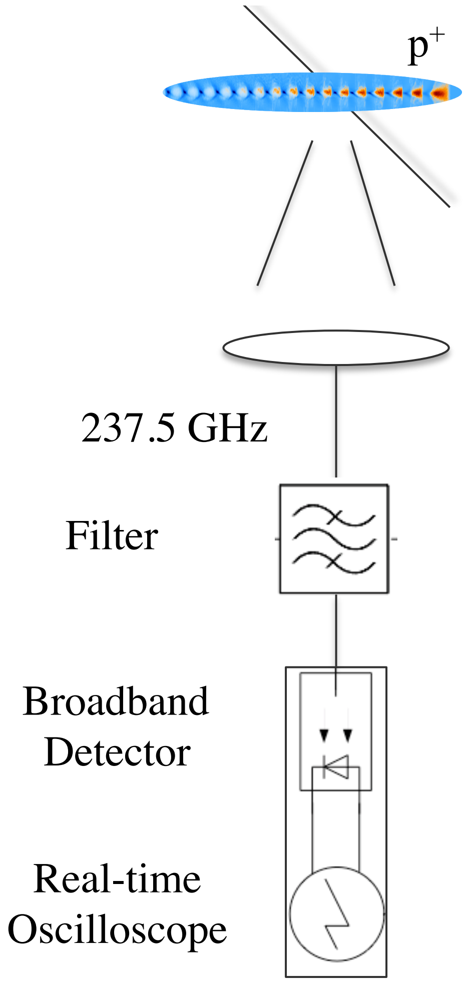
Measurement Plan

1. After commissioning the proton beam and plasma cell, start with demonstration of modulation of proton bunch.
    a. OTR to demonstrate increase in transverse bunch size
    b. Resolve radius modulation along bunch with streak camera
    c. Coherent transition radiation at modulation frequency
    d. Electro-optical sampling for direct field measurement
    e. Transverse CTR – distinguish SMI from hosing

Schematic for incoherent TR



(Developed at MPP)

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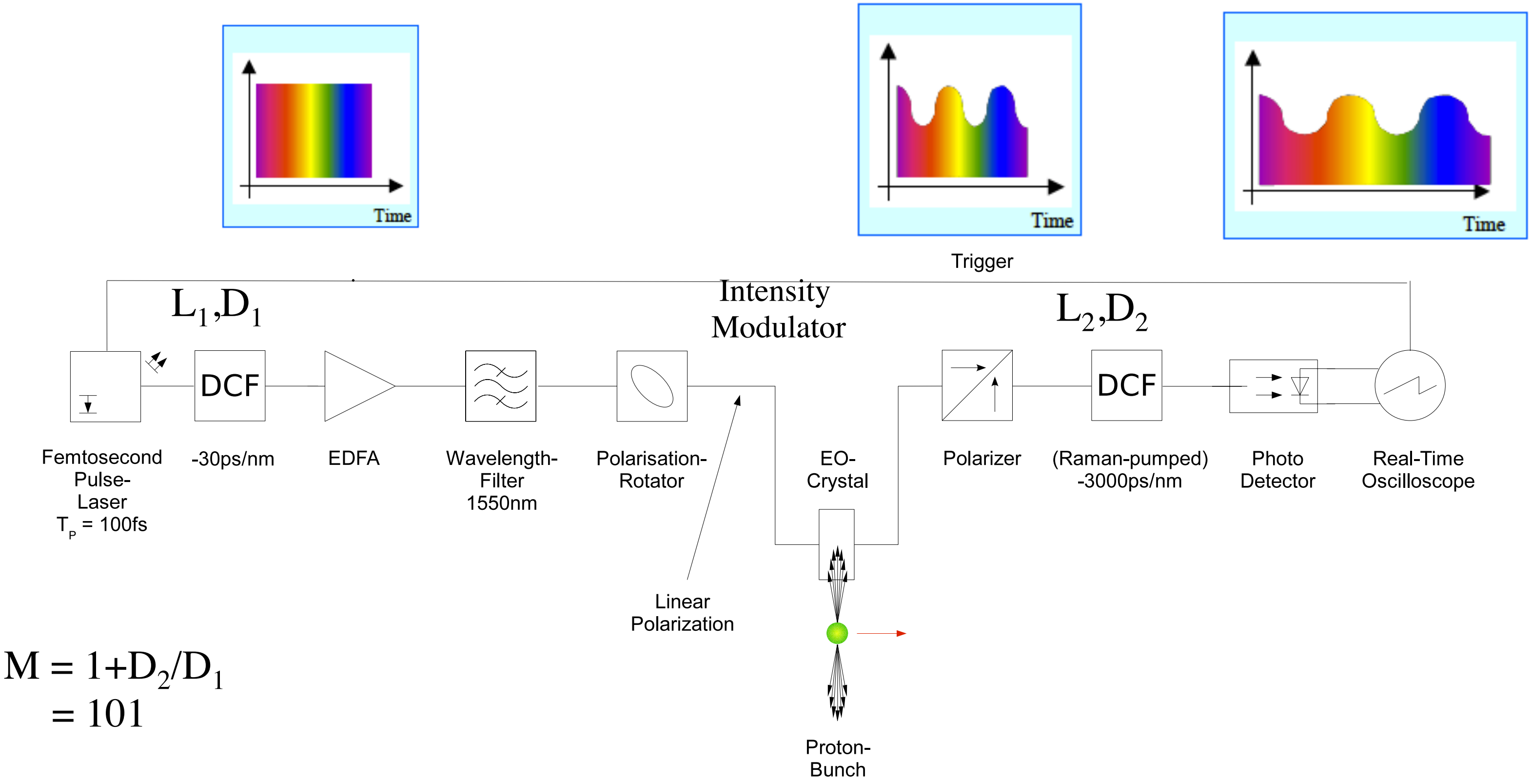

$$M = 1+D_2/D_1$$
$$= 101$$

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   a. OTR to demonstrate increase in transverse bunch size
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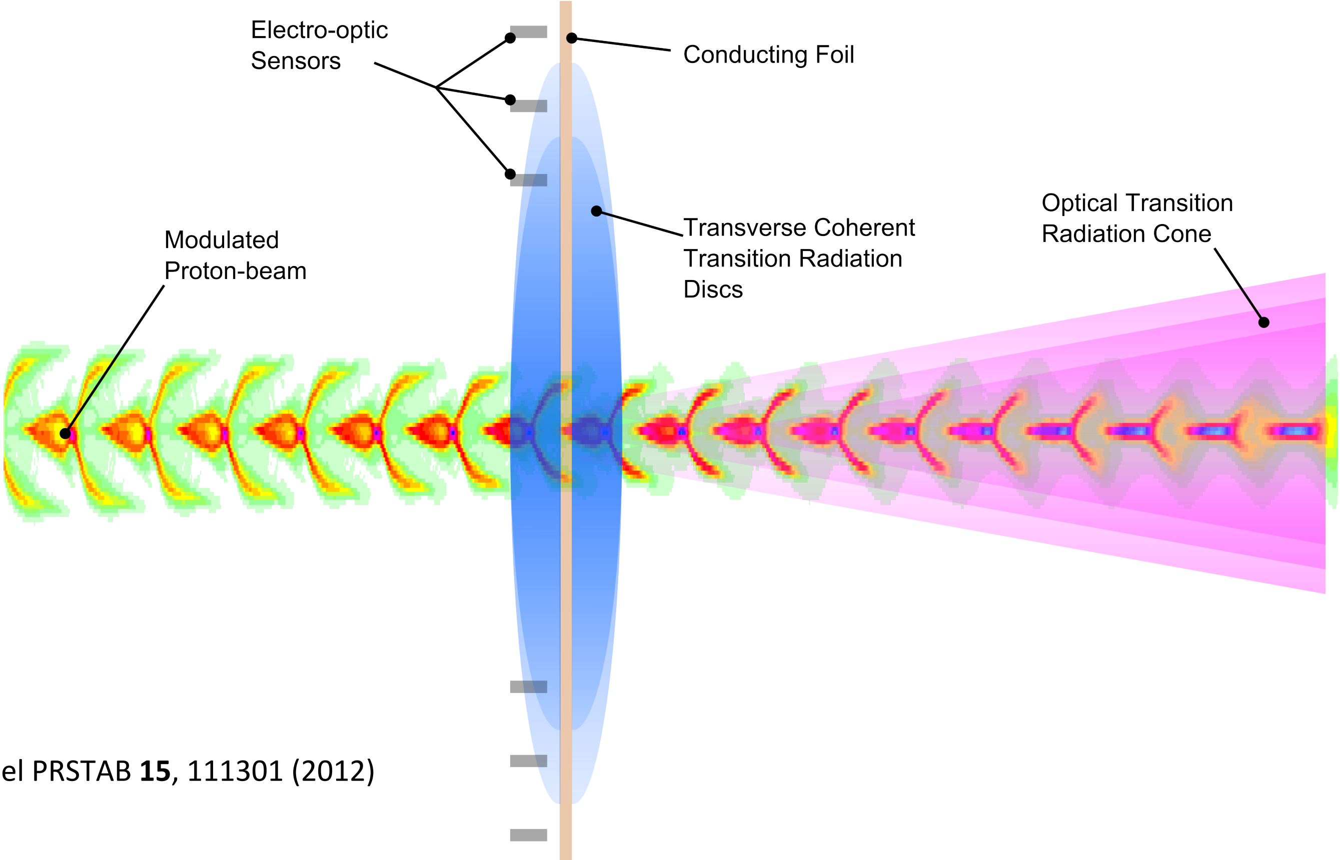
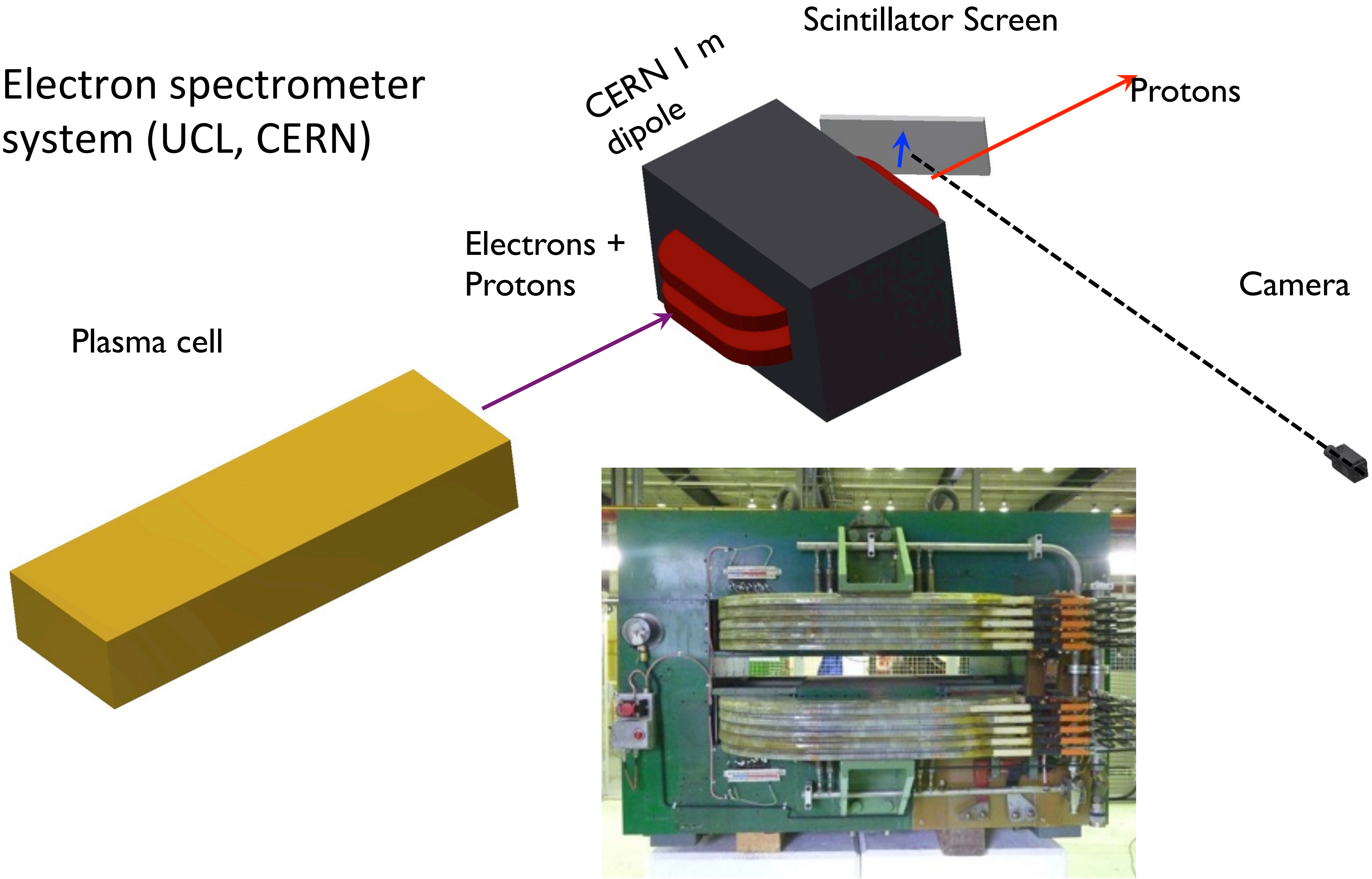


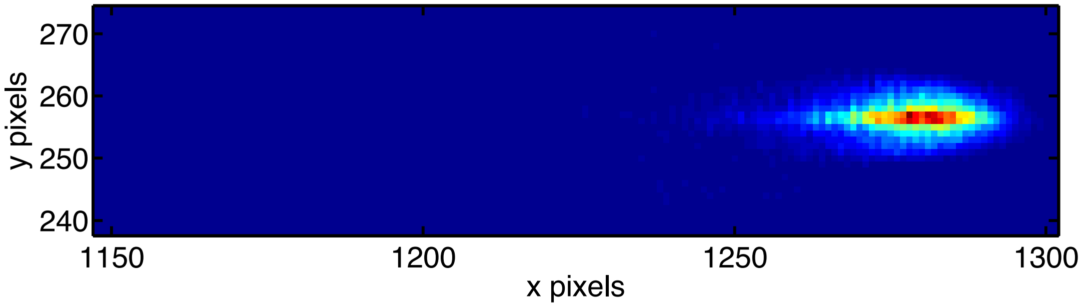
A. Pukhov, T. Tückmantel PRSTAB **15**, 111301 (2012)

2. After commissioning the electron beam and side-injection, demonstration of electron acceleration.

Electron spectrometer system (UCL, CERN)

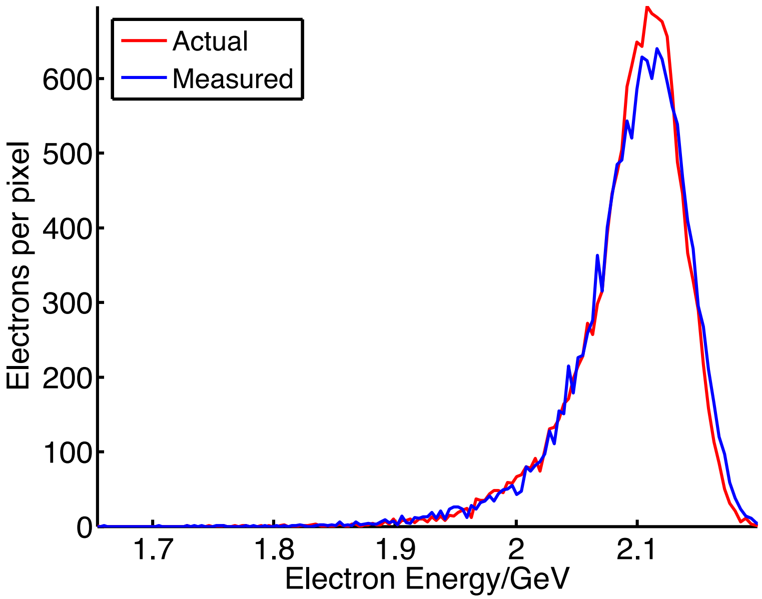


Electron Spectrometer



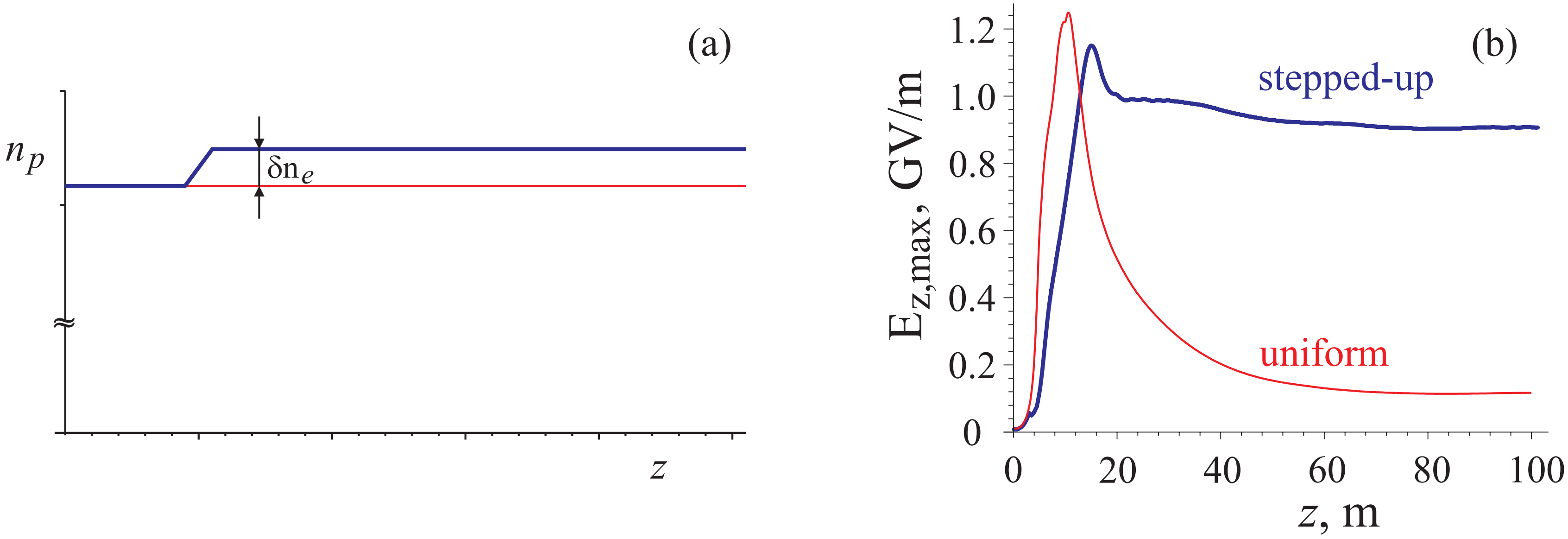
Simulation of scintillator screen shot from full simulation of electrons in plasma cell & tracking through spectrometer

Comparison of true electron energy spectrum with that reconstructed from captured screen image (simulation).



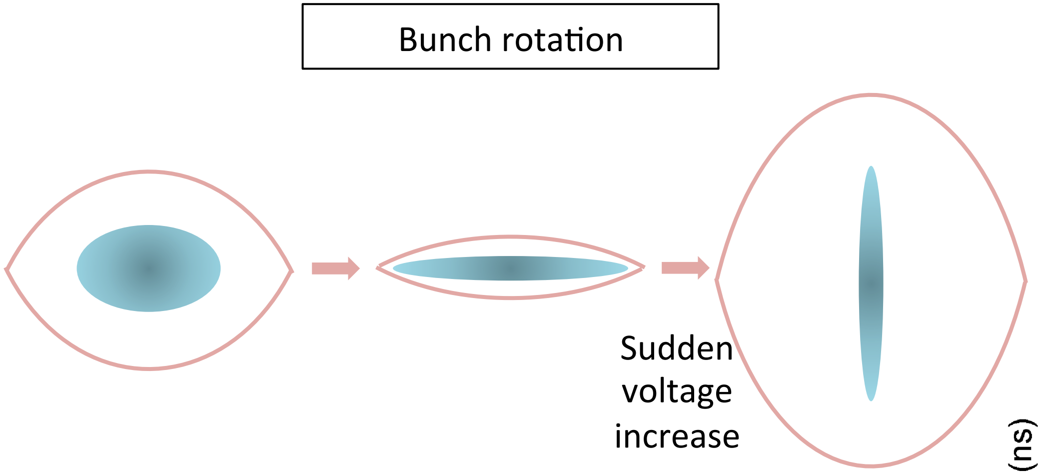
3. Experiments with density steps and 2 plasma cells. Separate the SMI phase from the acceleration phase. Achieve large energy gains for electron bunches.

Simulations for LHC beam parameters A. Caldwell and K. V. Lotov, Phys. Plasmas **18**, 103101 (2011).



Possibility for density step, either in single plasma cell or in double cell will be tried out in AWAKE experiment. Potential for very significant energy gains 10’s-100 GeV with SPS beam.

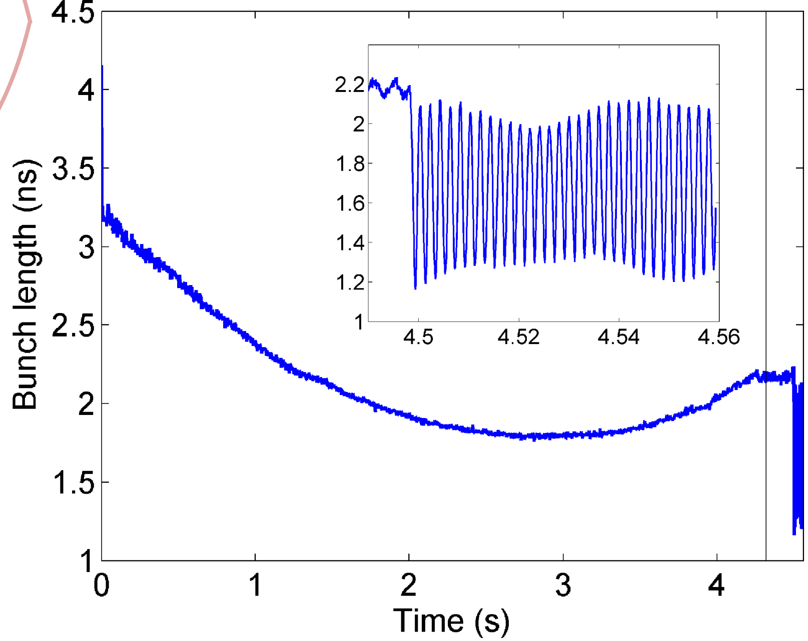
4. Experiments with compressed SPS bunches – demonstration of multi GeV/m gradients



Bunch rotation

Sudden voltage increase

Already tried out in SPS – it works !



Long-term: investigate ab-initio designs for short proton bunch accelerators.

Investigate what can be achieved by also tuning pre-SPS accelerator parameters.

Peak current increased to 59A from ca 48A. Not yet optimized.

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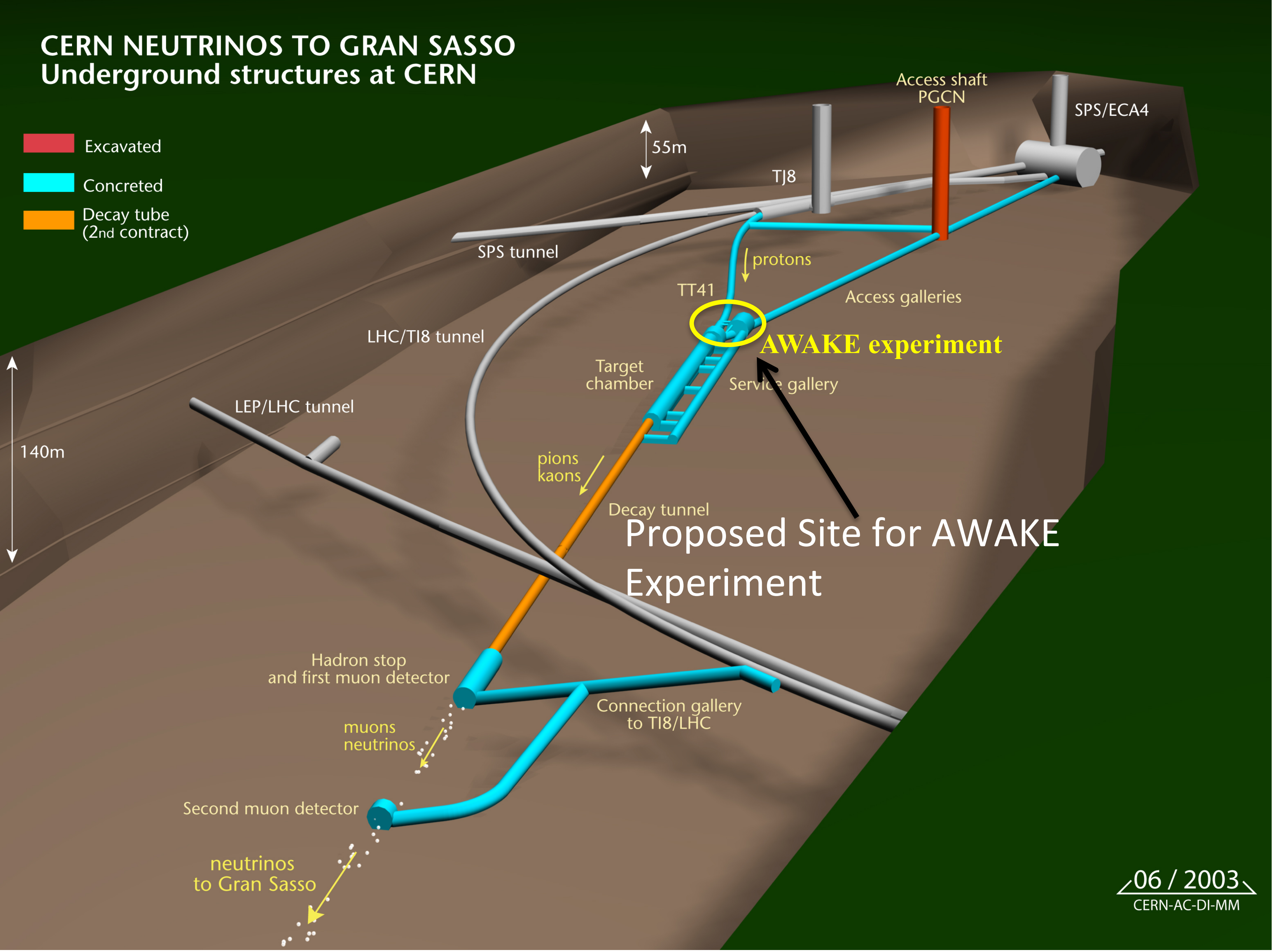
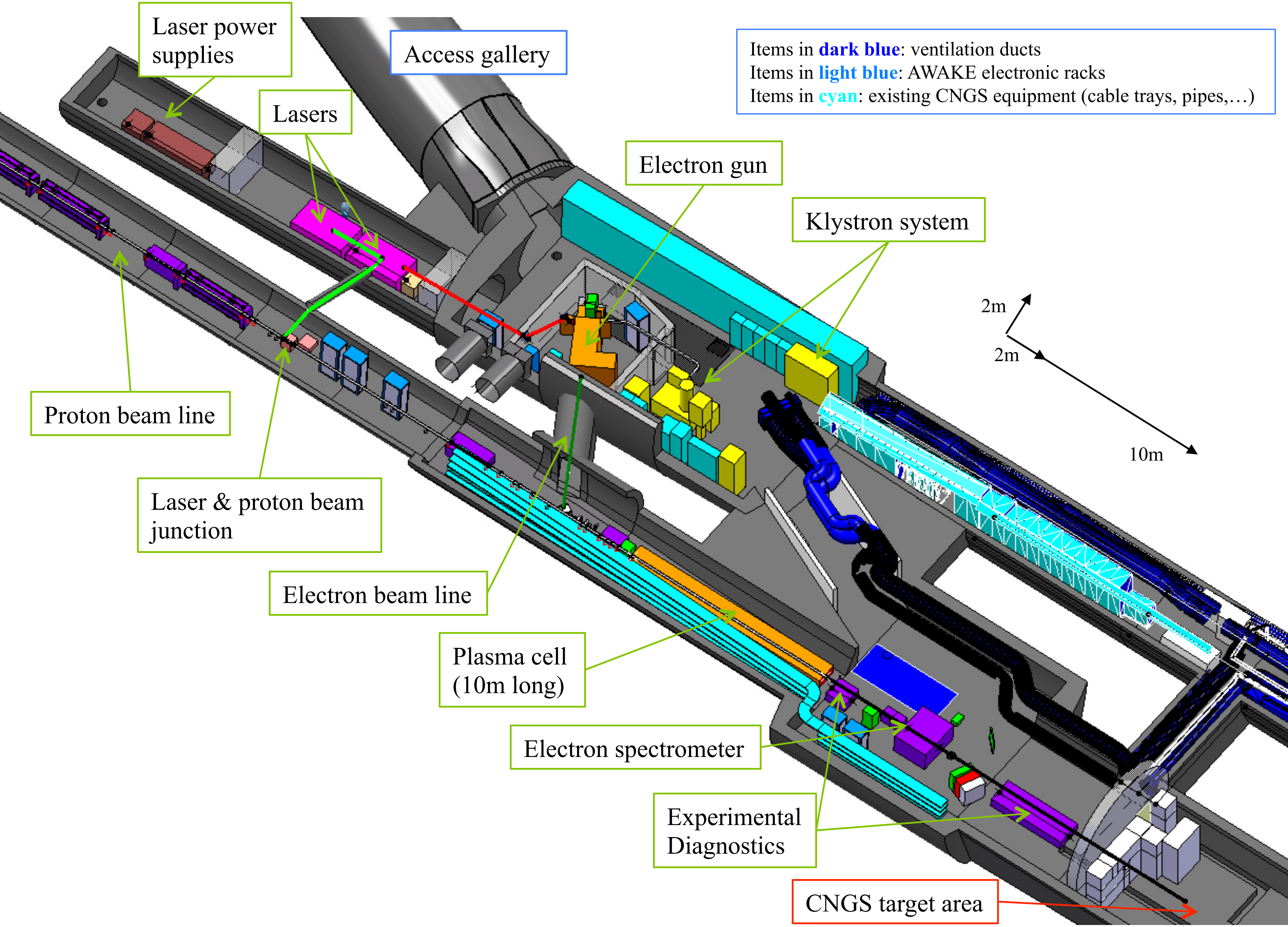
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN



Proposed Site for AWAKE Experiment

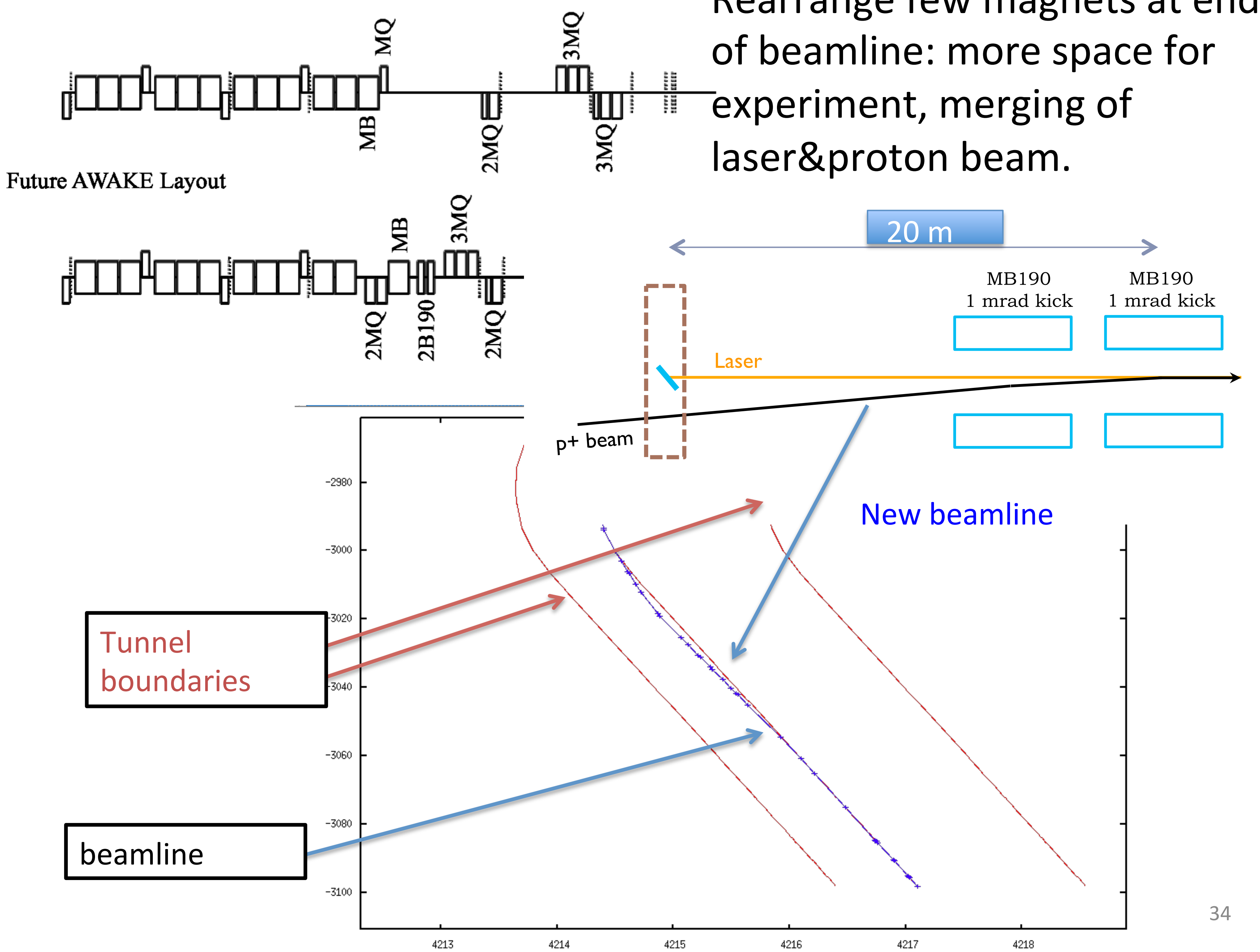


Items in **dark blue**: ventilation ducts
Items in **light blue**: AWAKE electronic racks
Items in **cyan**: existing CNGS equipment (cable trays, pipes,…)

Rearrange few magnets at end of beamline: more space for experiment, merging of laser&proton beam.

Present CNGS Layout (end of the line)

Future AWAKE Layout



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	Cost [kCHF]	Staff [PY]
SPS beam studies		
Subtotal SPS beam studies	*360*	*0.9*
Proton and electron beam line		
Magnet system (magnets, power converters, cabling, interlocking)	313	0.9
Control system (Interlock, operational software)	75	1.5
Beam instrumentation	650	2.3
Beam dynamics, commissioning, coordination	360	2.5
Electron beam line	600	0.6
Subtotal	*1998*	*7.8*
Experimental area		
Secondary e^- beam dynamics, safety files, commissioning, coordination	360	3.5
Layout, integration, installation	535	6.85
Magnet system (magnets, power converters, cabling)	193	0.55
Laser system (beam transport, safety)	139	0.7
Beam instrumentation	360	-
Operational software	-	1.0
Subtotal	*1587*	*12.6*
General services, infrastructure and safety		
Civil engineering	448	0.75
General services (cooling & ventilation, electricity, additional cabling, transport)	1470	2.35
Safety system (radiation protection, access, fire, evacuation)	680	2.35
Control system (RF synchronization, timing, high-level software, ethernet, GSM)	205	2.3
Survey	60	0.2
Drawings, mechanical design	280	3.45
Vacuum system	1400	1.5
Subtotal	*4543*	*12.9*
Total	**8488**	**34.2**

The CNGS beamline is fully operational. Much lower cost and effort than for West Area.

The experimental area is adequate for the first generations of experiments.

		2014	2015	2016	Total
SPS studies	FTE cost [kCHF]	0.3 120	0.3 120	0.3 120	0.9 360
Proton and electron beam line	FTE Cost [kCHF]	2.5 658	3.2 820	2.1 520	7.8 1998
Experimental area	FTE Cost [kCHF]	4.4 525	4.3 572	3.9 490	12.6 1587
General services, infrastructure and safety	FTE Cost [kCHF]	4.45 1643	6 2280	2.45 620	12.9 4543
Total	FTE Cost [kCHF]	11.65 2946	13.8 3792	8.65 1750	34.2 8488

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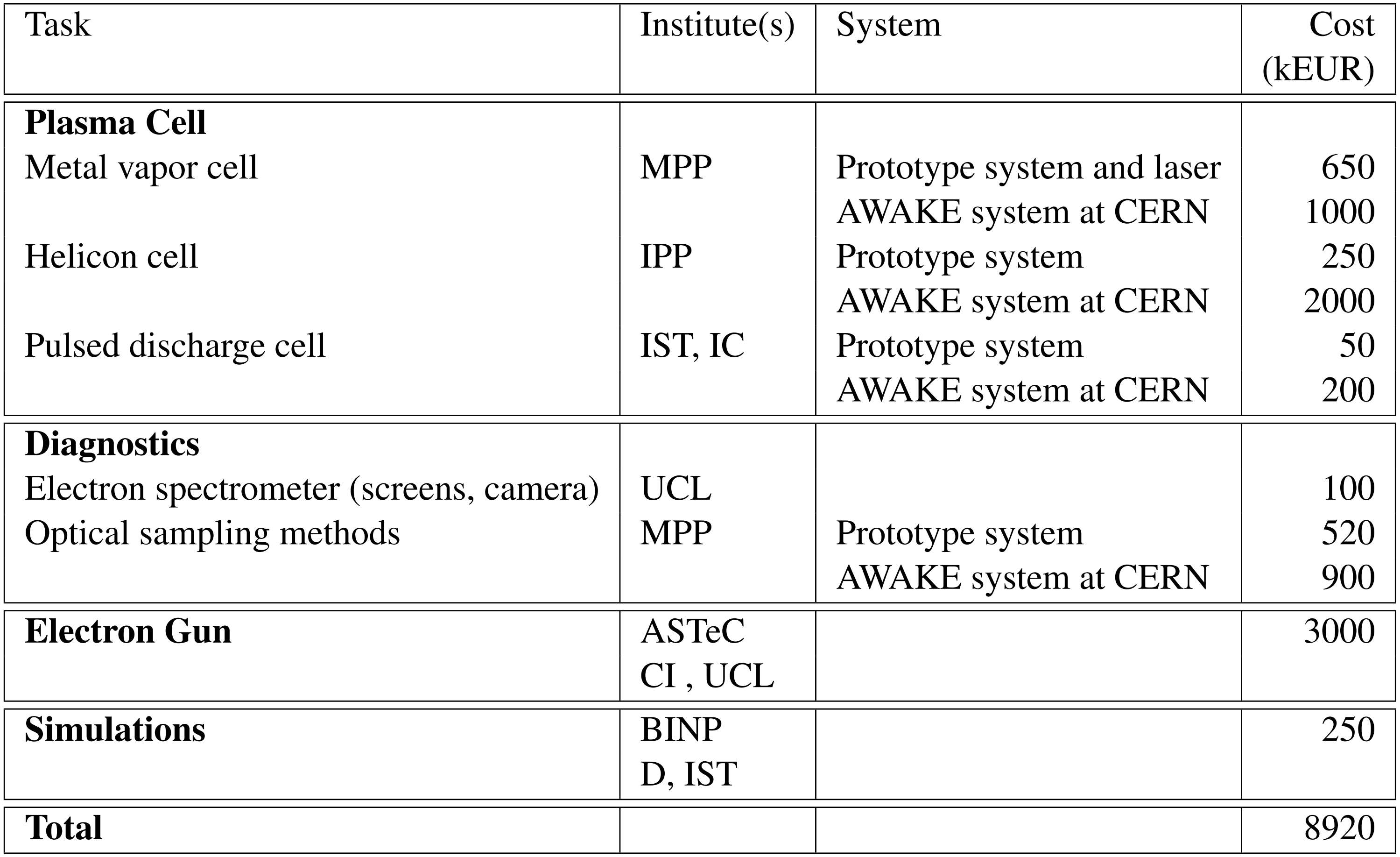


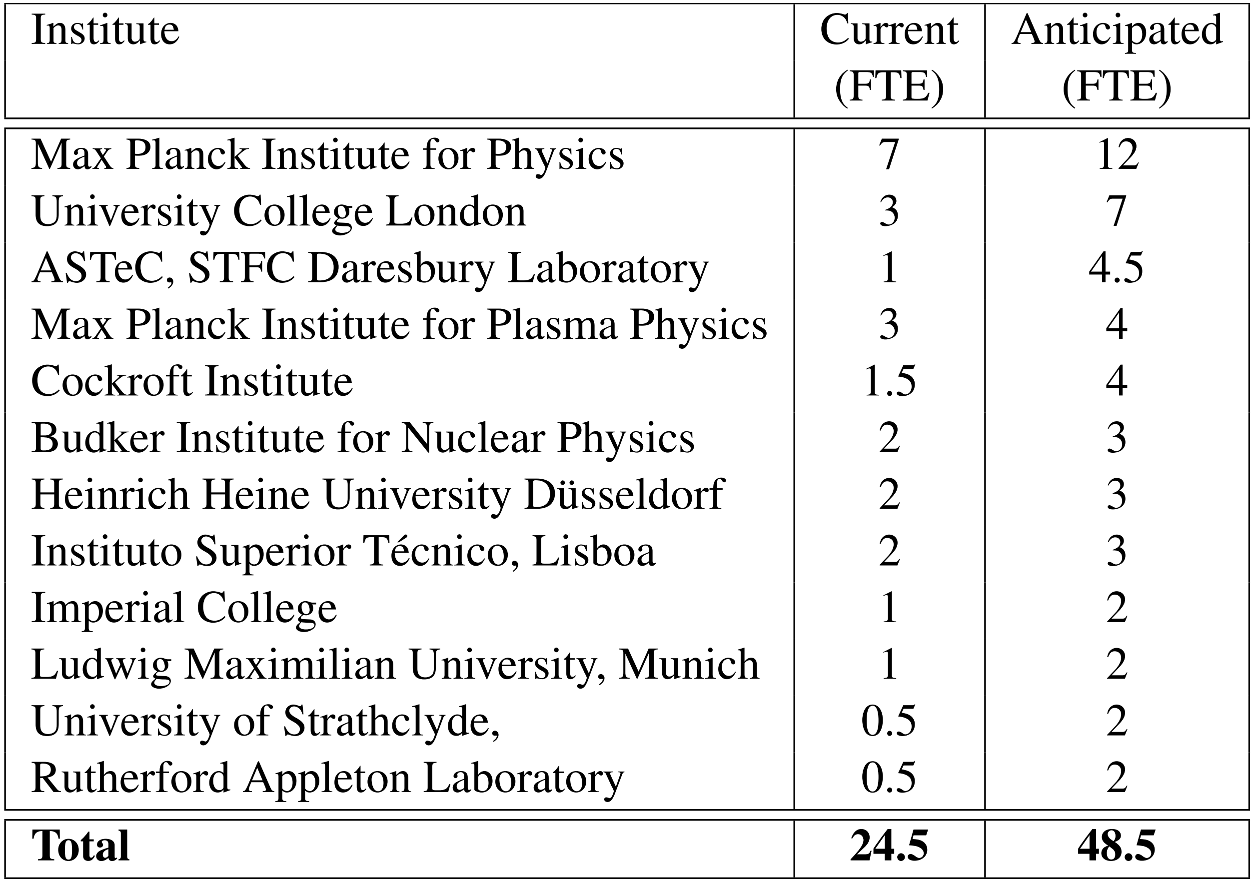
Task	Institute(s)	System	Cost (kEUR)
Plasma Cell			
Metal vapor cell	MPP	Prototype system and laser	650
		AWAKE system at CERN	1000
Helicon cell	IPP	Prototype system	250
		AWAKE system at CERN	2000
Pulsed discharge cell	IST, IC	Prototype system	50
		AWAKE system at CERN	200
Diagnostics			
Electron spectrometer (screens, camera)	UCL		100
Optical sampling methods	MPP	Prototype system	520
		AWAKE system at CERN	900
Electron Gun	ASTeC CI , UCL		3000
Simulations	BINP D, IST		250
Total			8920

Metal vapor cell & discharge cell funding available

Helicon system for CERN requires success of funding application

Electron gun funding applied for; if not successful will develop a collaborative solution.

Manpower from participating institutes (current and anticipated)



Institute	Current (FTE)	Anticipated (FTE)
Max Planck Institute for Physics	7	12
University College London	3	7
ASTeC, STFC Daresbury Laboratory	1	4.5
Max Planck Institute for Plasma Physics	3	4
Cockroft Institute	1.5	4
Budker Institute for Nuclear Physics	2	3
Heinrich Heine University Düsseldorf	2	3
Instituto Superior Técnico, Lisboa	2	3
Imperial College	1	2
Ludwig Maximilian University, Munich	1	2
University of Strathclyde,	0.5	2
Rutherford Appleton Laboratory	0.5	2
Total	**24.5**	**48.5**

Will be sufficient to carry out research program.

Participating Institutes:

ASTeC, STFC Daresbury Laboratory
Budker Institute of Nuclear Physics
CERN
Cockroft Institute
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
University College London
University of Strathclyde

Interested Institutes:

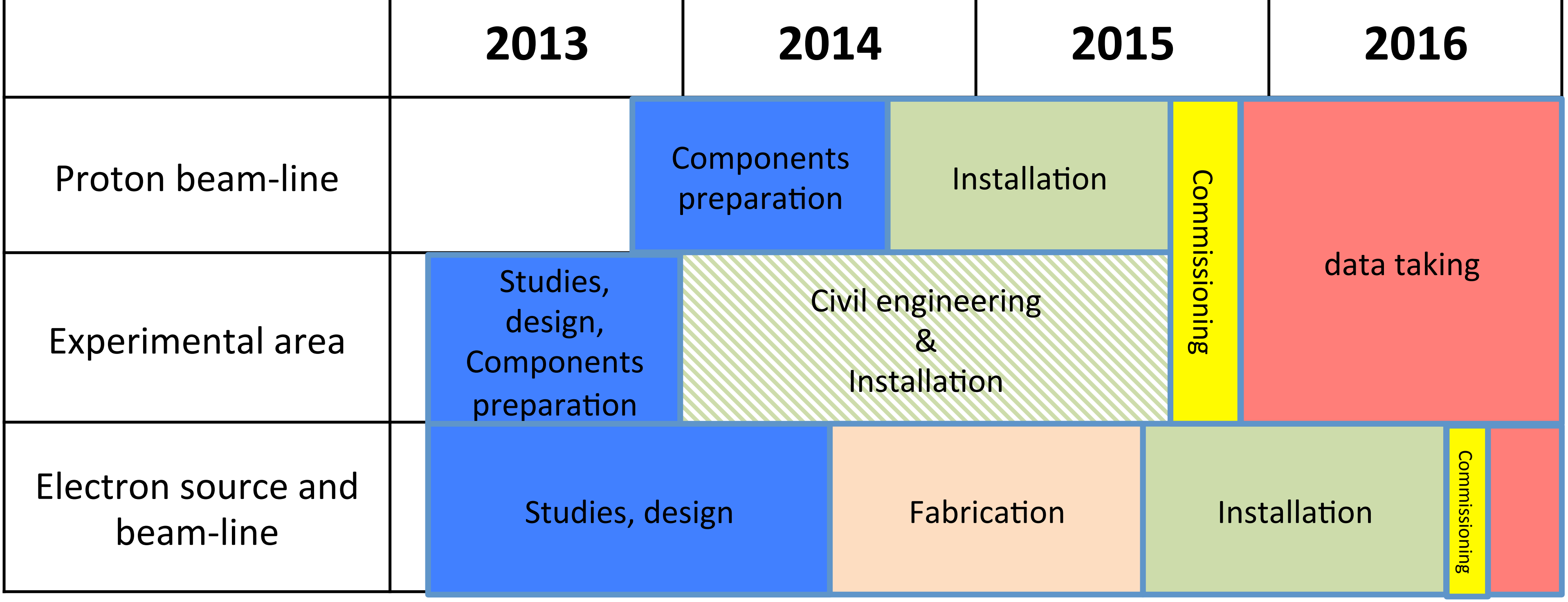
DESY
John Adams Instutyte fir Accellerator Science
Panjab University
State Key Laboratory of Nuclear Physics and Technology
Tsinghua University
Wigner Research Center for Physics

	Management Positions	Person	Institute
	Spokesperson	Allen Caldwell	MPP
	Deputy spokesperson	Matthew Wing	UCL
	Beam lines, experimental areas and infrastructure	Edda Gschwendtner	CERN
	Experimental aspects	Patric Muggli	MPP
	Theory & simulations	Konstantin Lotov	BINP

	Task Groups	Person	Institute
1	Metal vapor plasma cell	Erdem Öz	MPP
2	Helicon plasma cell	Olaf Grulke	IPP
3	Pulsed discharge plasma cell	Nelson Lopes	IC/IST
4	Proton and electron beam lines	Chiara Bracco	CERN
5	Experimental area	Edda Gschwendtner	CERN
6	Radiation protection	Helmut Vincke	CERN
7	Electron source	Tim Noakes	ASTeC/CI
8	Electron spectrometer	Simon Jolly	UCL
9	Optical sampling diagnostics	Patric Muggli	MPP
10	Simulations	Konstantin Lotov	BINP

Outline

1. Brief Motivation
2. Proton-driven plasma wakefield acceleration
3. Self-modulation approach
4. Outline of proposed experiment
5. What we will measure
6. Proposed location
7. Required resources from CERN
8. Responsibilities & resources of participating institutes
9. Timeline & outlook



Science Program (first three years after start of data taking):

1. Benchmark experiments – first ever proton-driven plasma wakefields
2. Detailed comparison of experimental measurements with simulations
3. Demonstration of high-gradient acceleration of electrons
4. Develop long, scalable & uniform plasma cells; test in AWAKE experiment
5. Develop scheme for production and acceleration of short proton bunches

Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

Summary

- Beam- and laser-driven wakefield experiments have shown the potential of plasmas for producing high gradients
- Protons are ideal drivers because of the large energy carried in a bunch
- Exploiting the self-modulation instability allows for immediate experimentation
- CERN SPS beam ideal tool to perform this accelerator R&D
- The AWAKE collaboration has the required expertise in both experimentation&simulation
- AWAKE will allow us to learn what is required to make a real accelerator based on proton-driven wakefield acceleration