A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

AWAKE Collaboration

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Outline

1. Brief Motivation
2. Proton-driven plasma wakefield acceleration
3. Self-modulation approach
4. Outline of AWAKE 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	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	[illegible]	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	[illegible]	60

FERMIONS

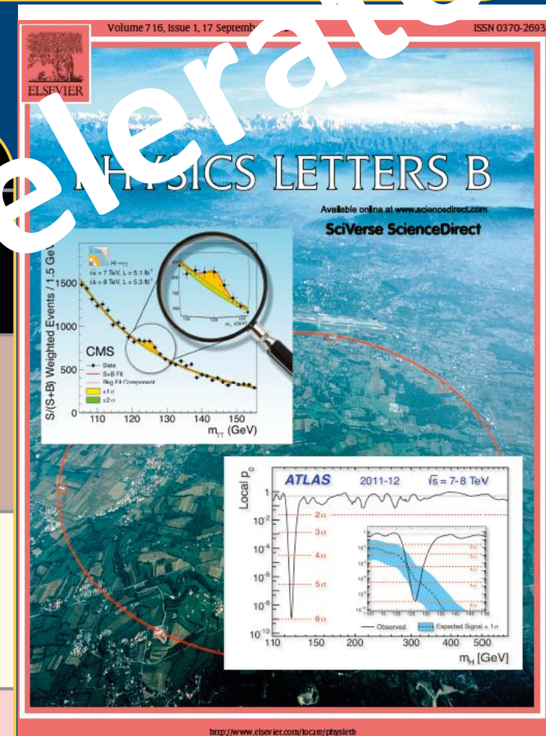
matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	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/c²	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

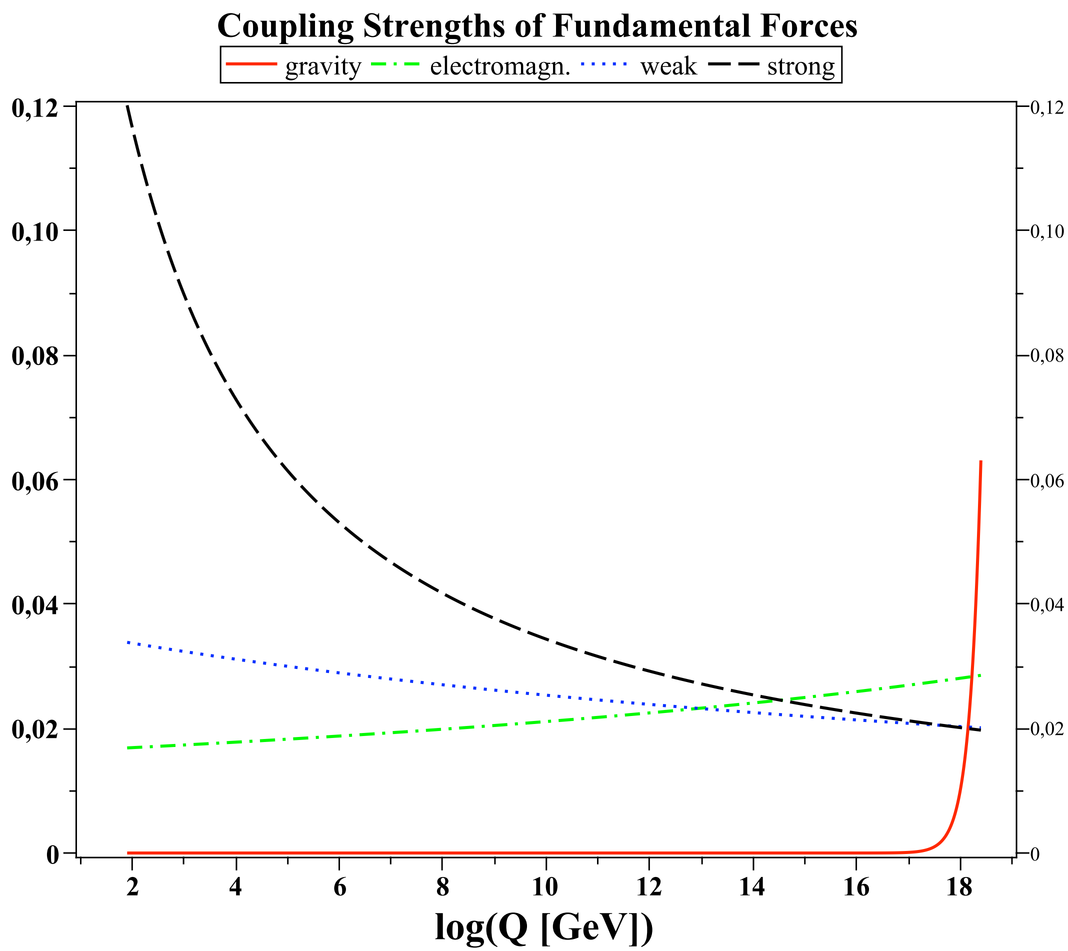


The most important development was for this particle accelerator

Particle physicists are convinced there are more discoveries to come:

Many things not explained in the standard model:

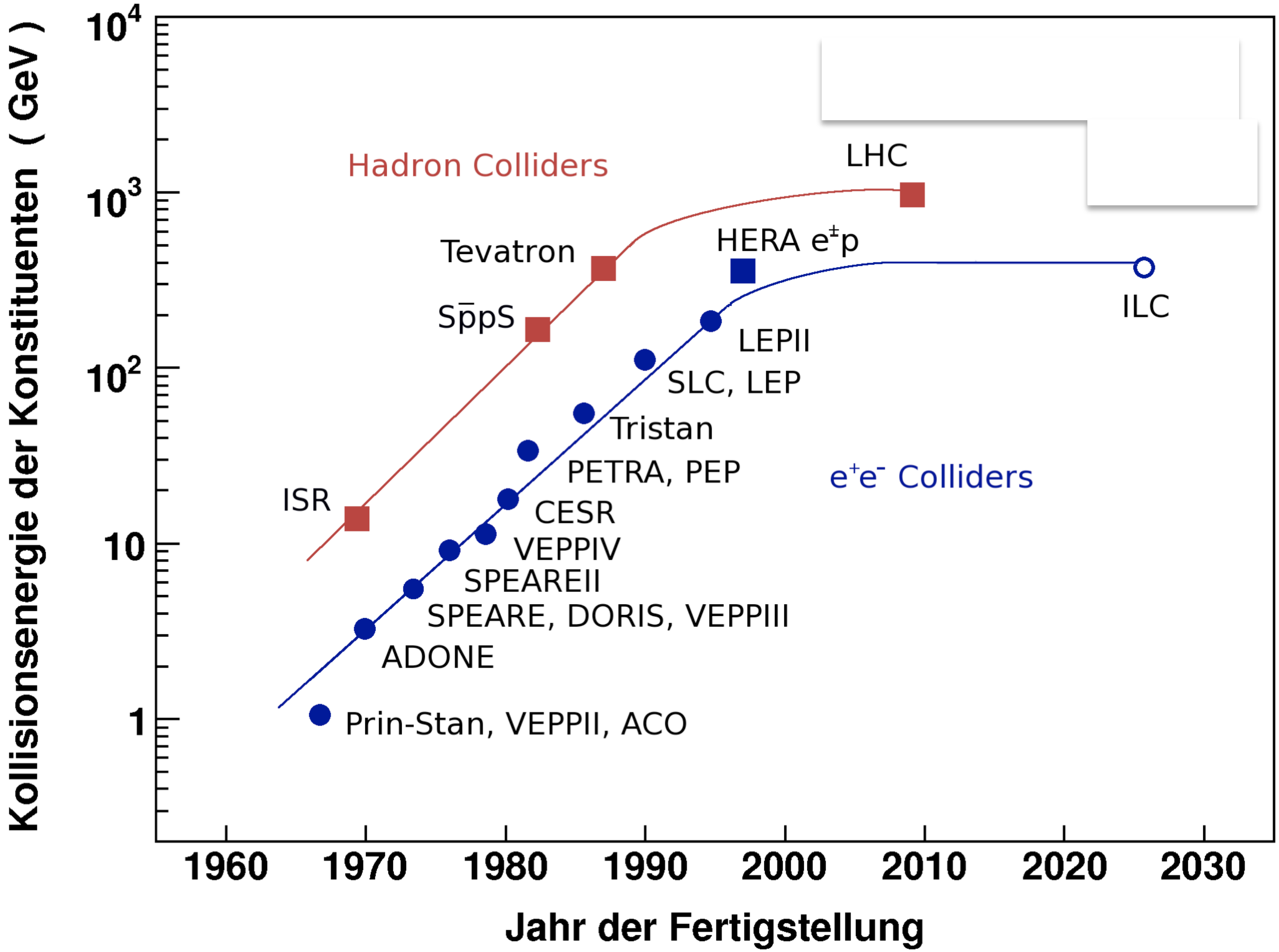
- why three families
- matter/antimatter imbalance
- neutrinos and neutrino mass
- hierarchy problem/unification
- dark matter
- dark energy
- …



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

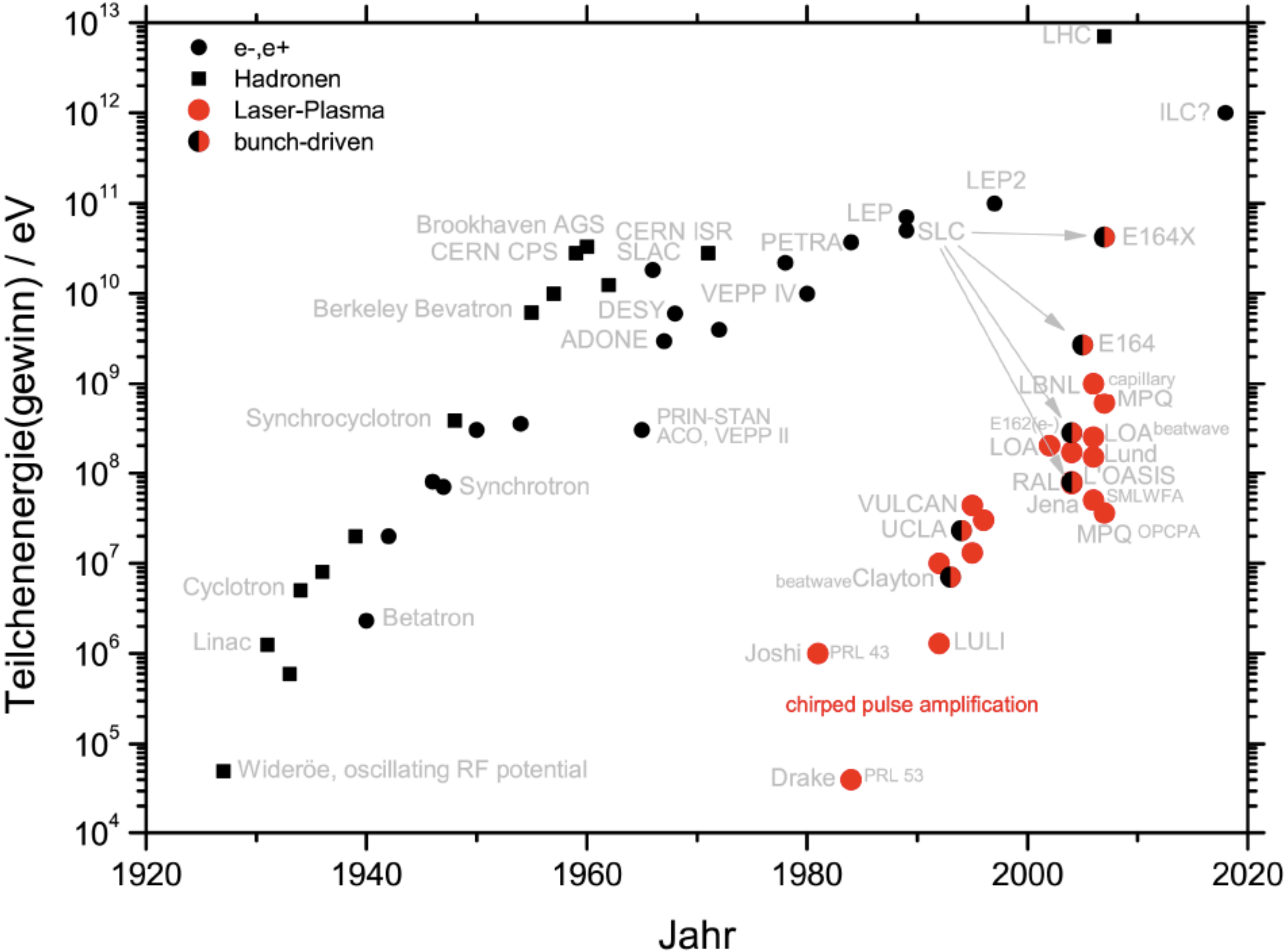
New acceleration technology !

The Livingston plot shows a saturation …



Practical limit for accelerators at the energy frontier: Project size and cost increasing with the energy ! New technology needed…

New Livingston Plot – Plasma Wakefield Acceleration



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Plasma Wakefield Acceleration

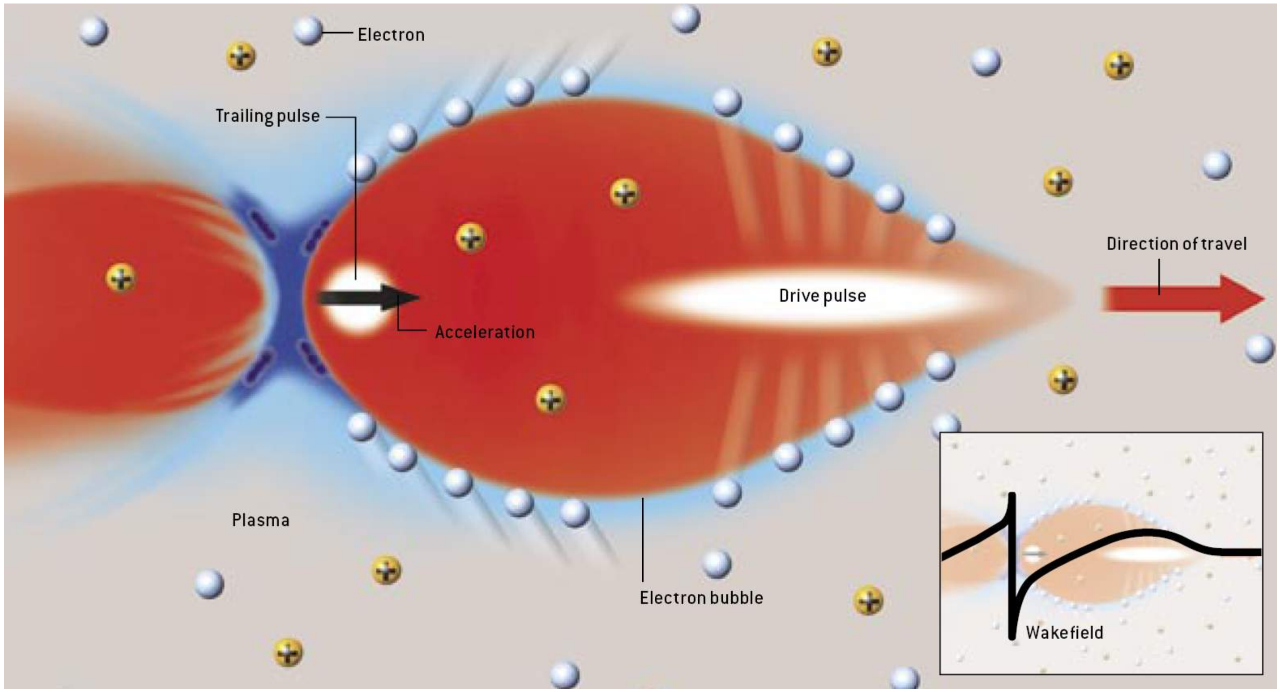
Original proposal (T. Tajima, J. W. Dawson Phys. Rev. Lett. **43** (1979) 267) considered laser acceleration (LWFA). Impressive steps taken in recent years as lasers have become more and more powerful. Gradients ca 100 GV/m demonstrated.

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

Original Proposal: T. Tajima and J. W. Dawson, *Phys. Rev. Lett.* **43** (1979) 267.



Nonlinear regime

Ch. Joshi, UCLA

Plasma frequency depends only on density:

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

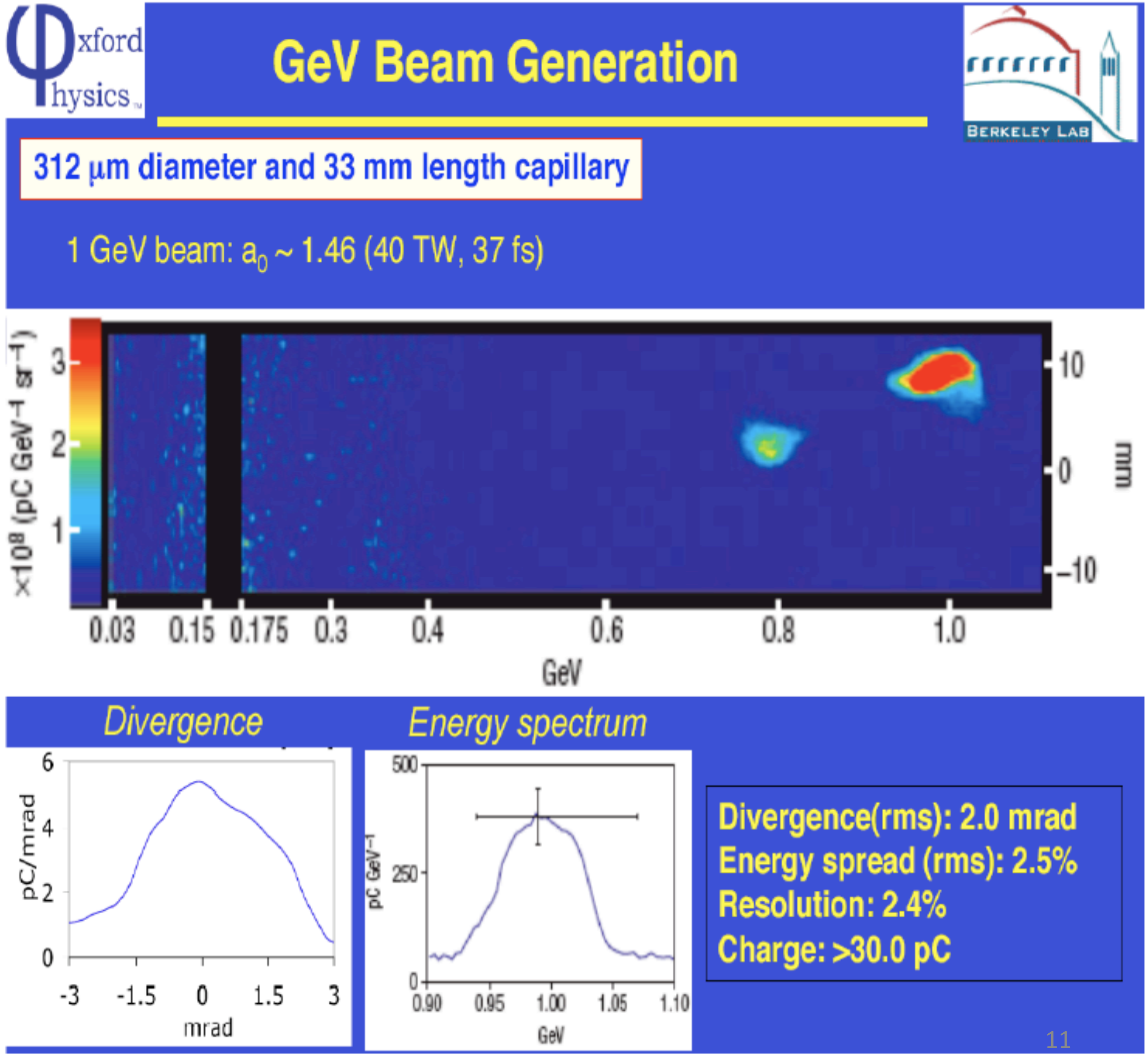
Produce an accelerator with mm (or less) scale 'cavities'

Laser Wakefield Acceleration

Just as predicted …

Gradients >50 GV/m achieved !

3 orders of magnitude higher than RF cavities.



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

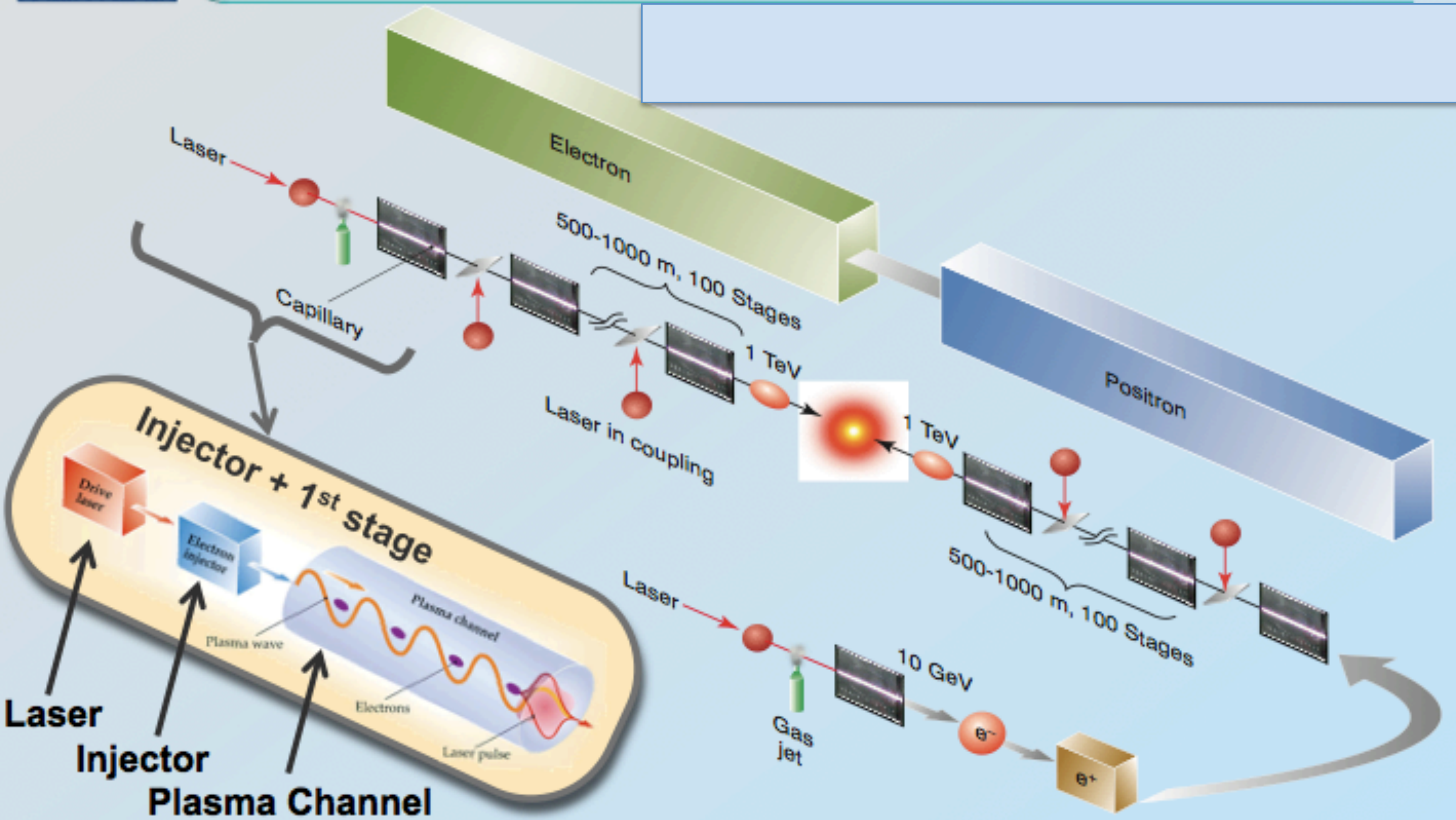
e.g.,

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

This is orders of magnitude larger than what is available today.

If use several lasers – need to have relative timing in the 10's of fs range
Many stages, effective gradient reduced because of long sections between accelerating elements …

Strawman design of a TeV LPA Collider

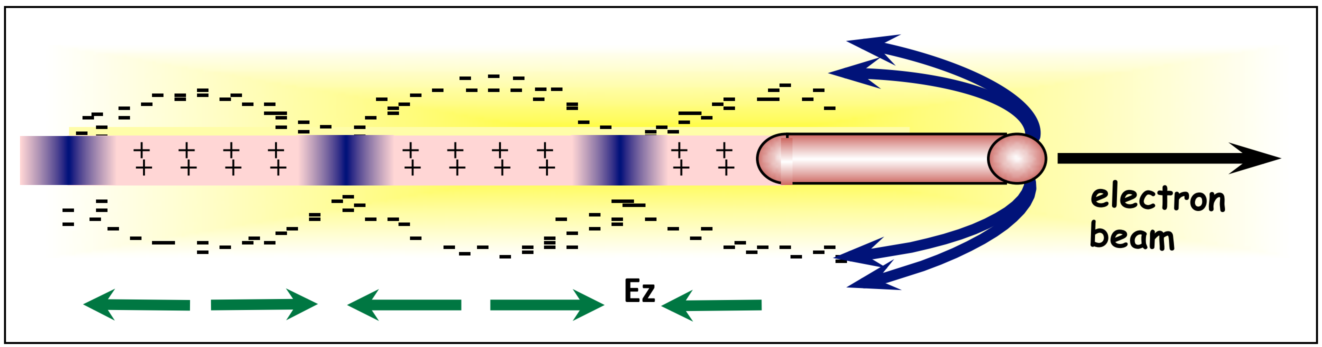


Leemans & Esarey, Physics Today, March 2009

Beam driven PWA

driving force: Space charge of drive beam displaces plasma electrons. → **Space charge oscillations (Harmonic oscillator)**

restoring force: Plasma ions exert restoring force



Electric fields can accelerate, decelerate, focus, defocus

Plasma also provides super-strong focusing force !
(many thousand T/m in frame of accelerated particles)

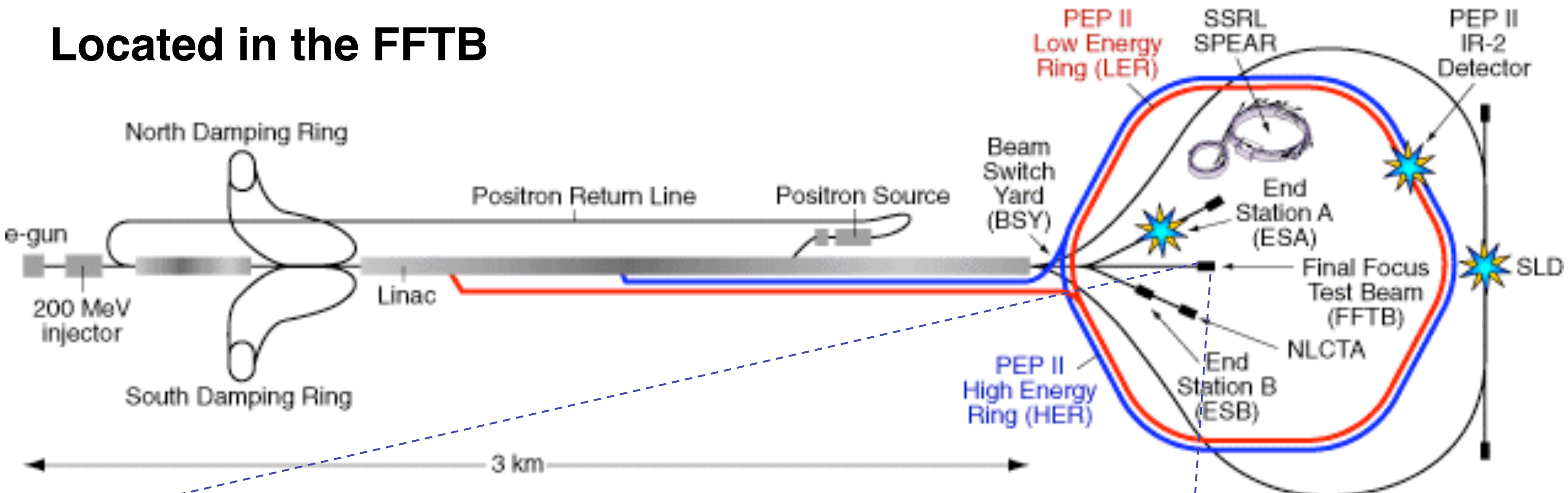
Experimental Layout (E-157)

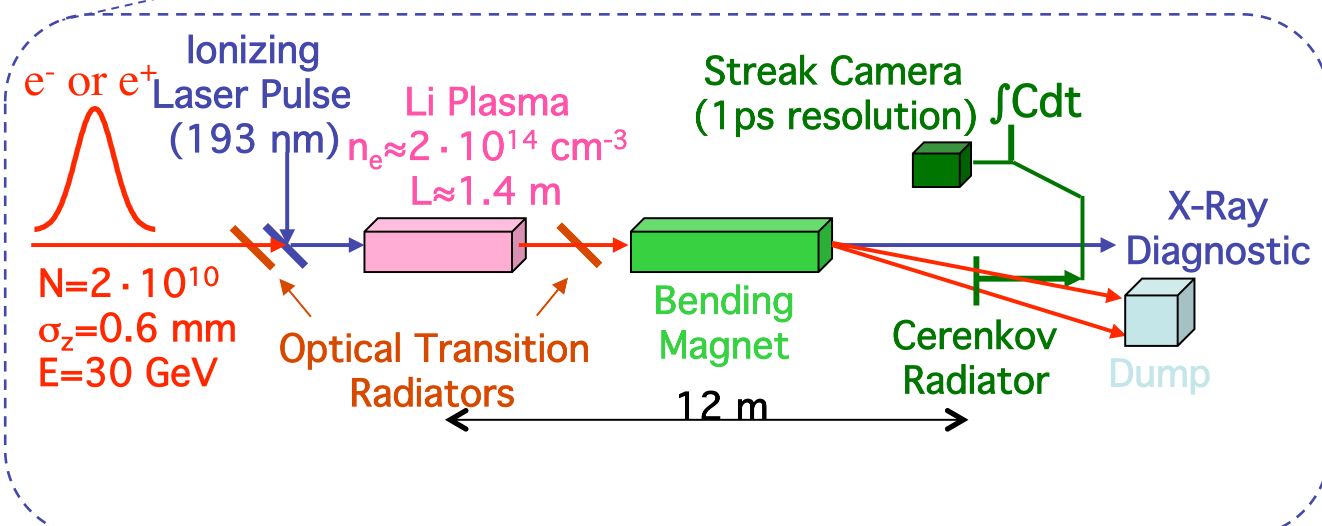
Stanford Linear Accelerator Center

UCLA

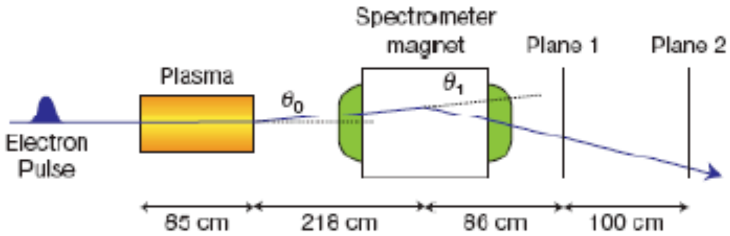
USC

Located in the FFTB



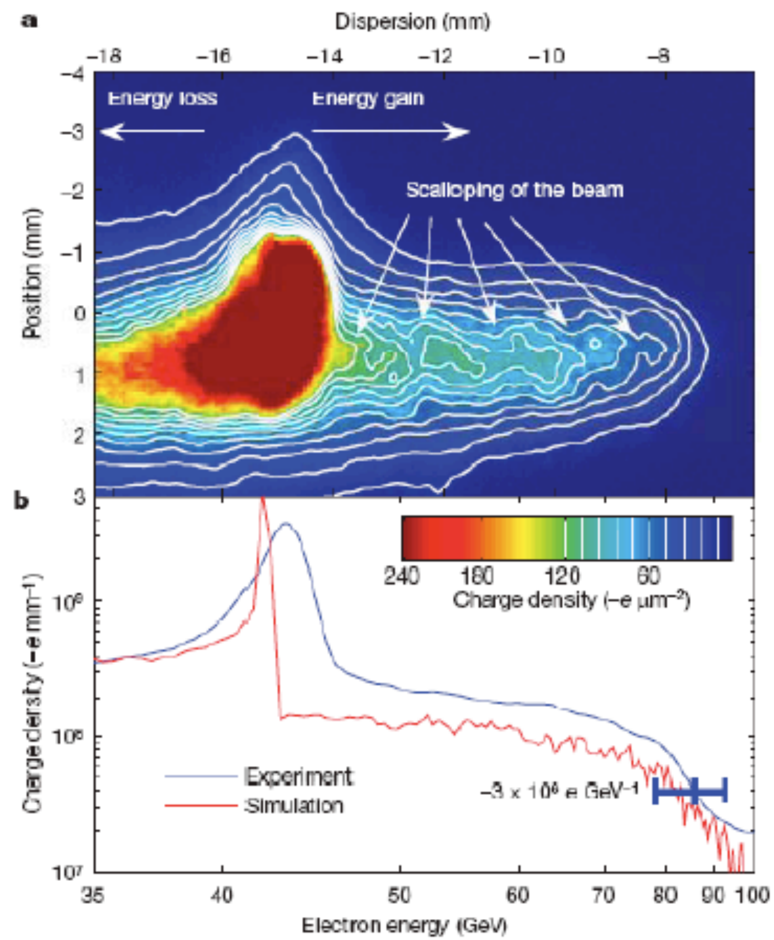


Highlight: latest SLAC/UCLA/USC results
(Nature 2007)



SLAC beam
- 42 GeV
- 3 nC @ 10 Hz
- focused to 10 μm spot size
- compressed to 50 fs

- Some electrons double their energy: from 42 to > 80 GeV
- E=50 GV/m over 0.8 meters



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

Why not continue with electrons ???

There is a limit to the energy gain of a trailing bunch in the plasma:

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

(for longitudinally symmetric bunches).

See e.g. SLAC-PUB-3374, R.D. Ruth et al.

This means many stages required to produce a 1TeV electron beam from known electron beams (SLAC has 45 GeV)

Proton beams of 1TeV exist today - so, why not drive plasma with a proton beam ?

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 an electron bunch we could potentially have a simpler arrangement - single stage acceleration.

Linear regime ($n_b < n_0$):

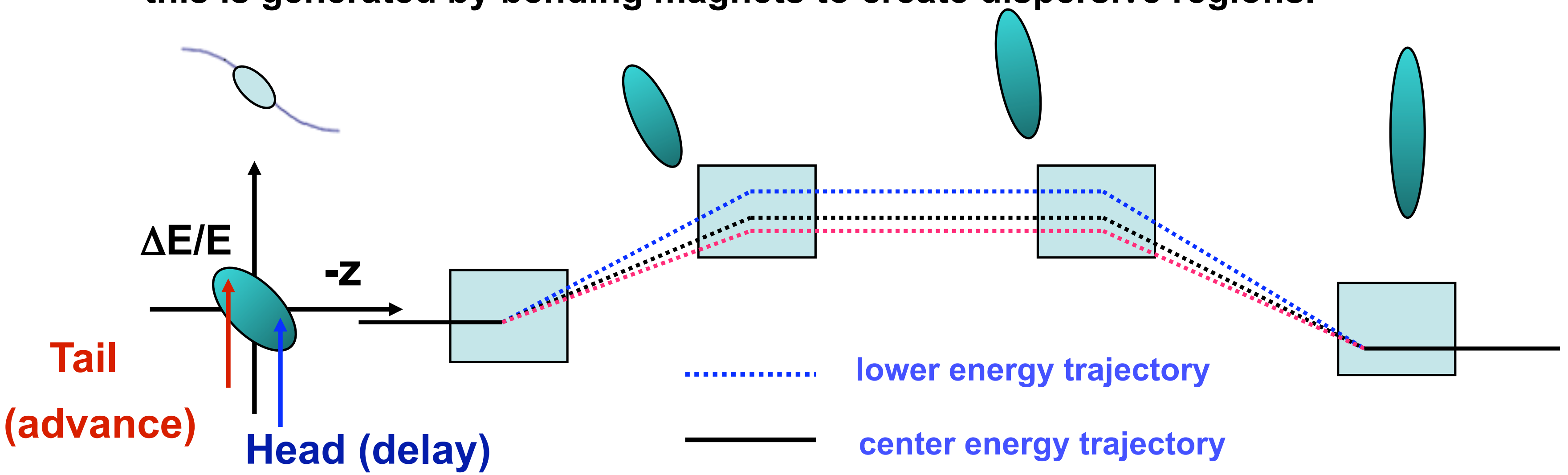
$$E_{z,\max} \approx 2 \text{ GeV/m} \cdot \left(\frac{N_b}{10^{10}} \right) \cdot \left(\frac{100\ \mu\text{m}}{\sigma_z} \right)^2$$

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

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

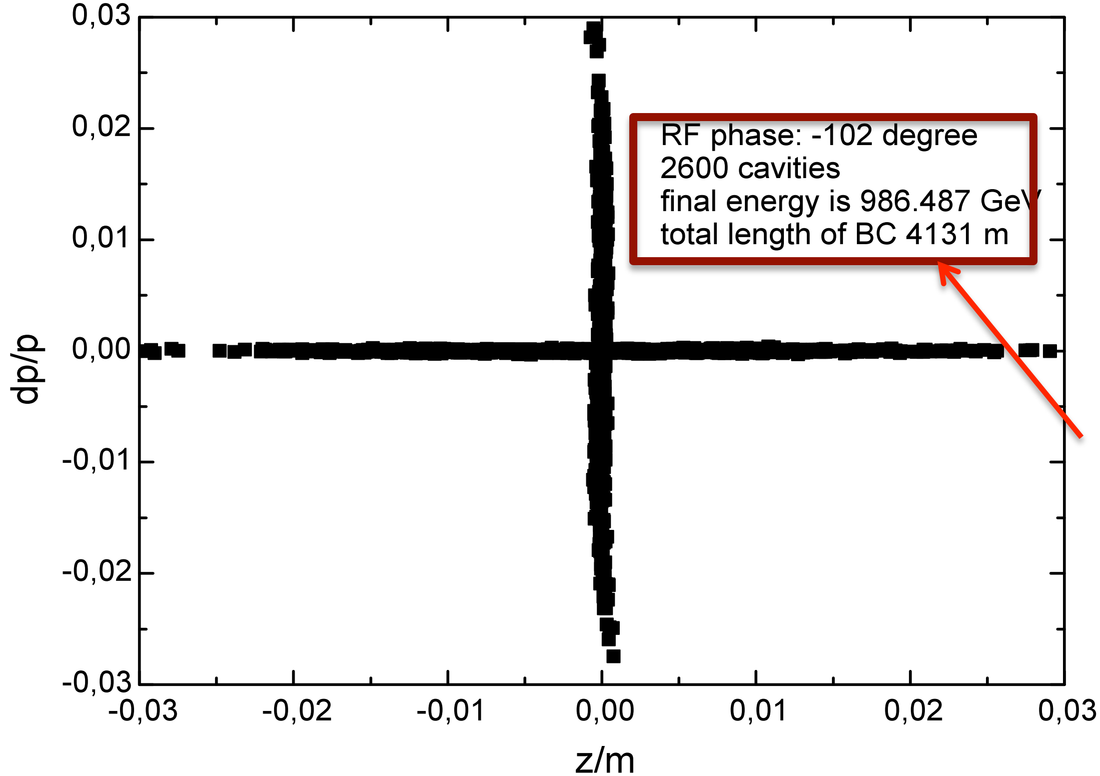
Magnetic bunch compression (BC)

- **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



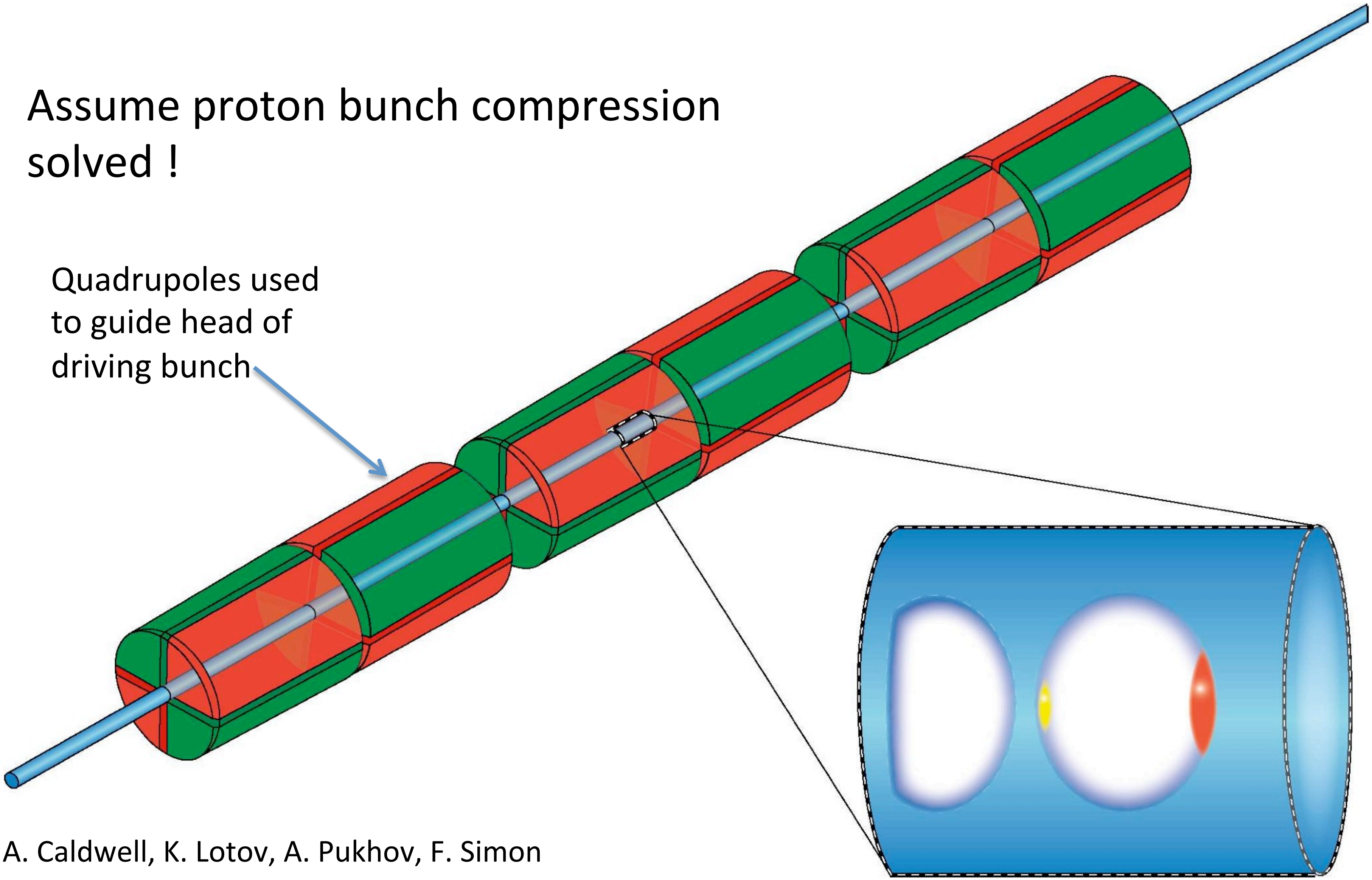
Too long – use in combination with other compression schemes

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

Simulation study

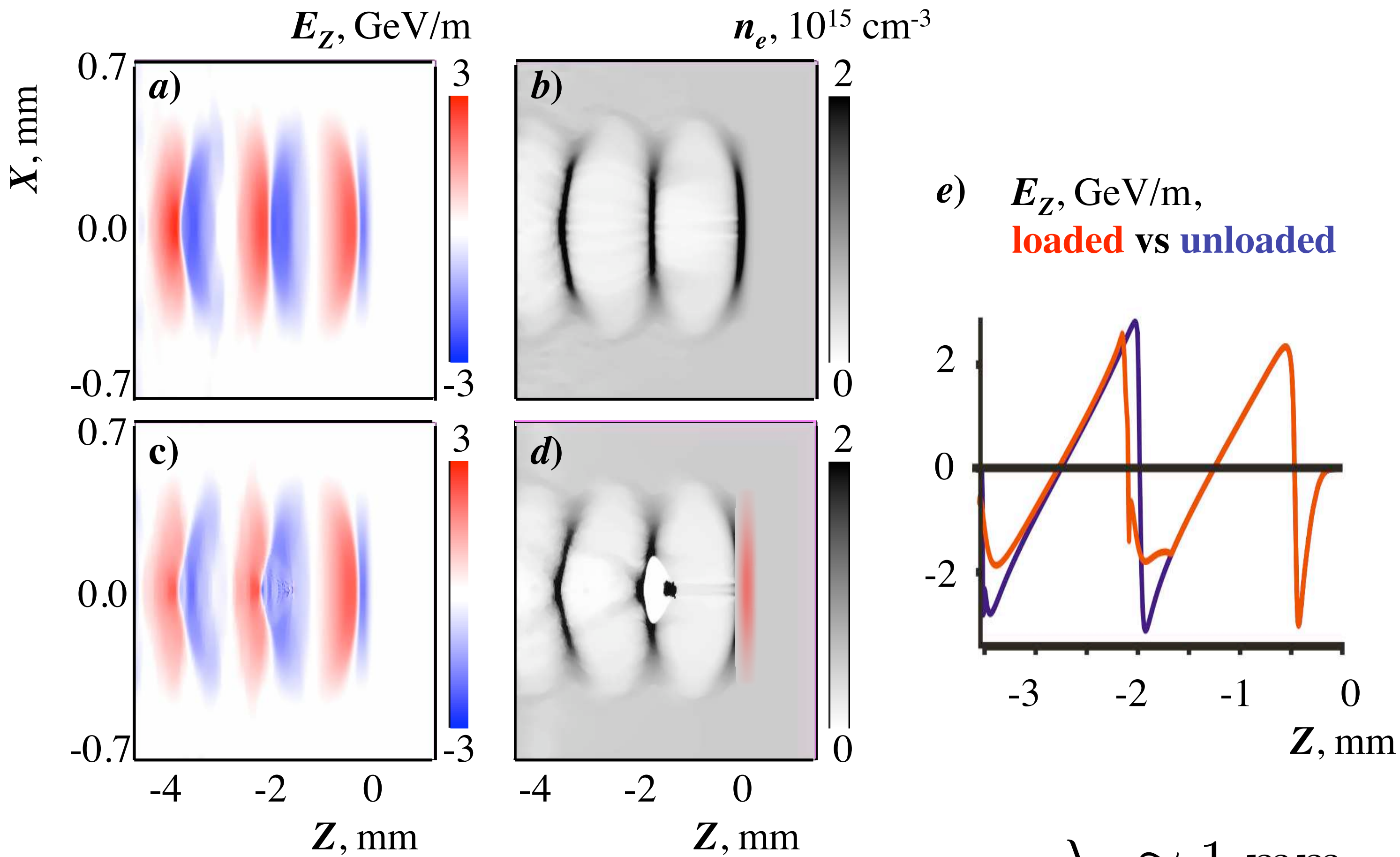
Assume proton bunch compression solved !

Quadrupoles used to guide head of driving bunch



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

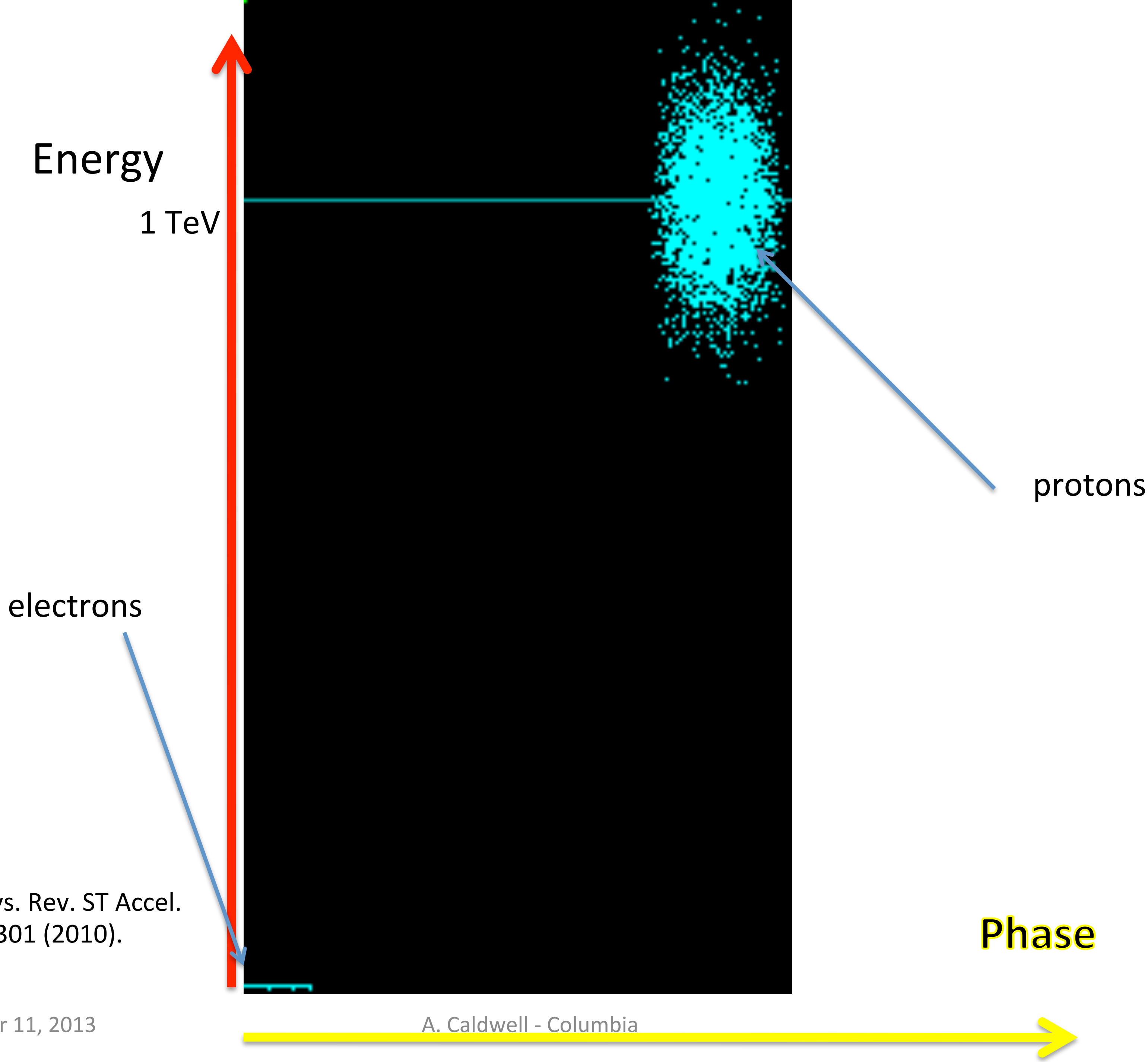
Plasma Wakefield Acceleration



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

Size of accelerator structure set by plasma density

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



K. V. Lotov, Phys. Rev. ST Accel. Beams **13**, 041301 (2010).

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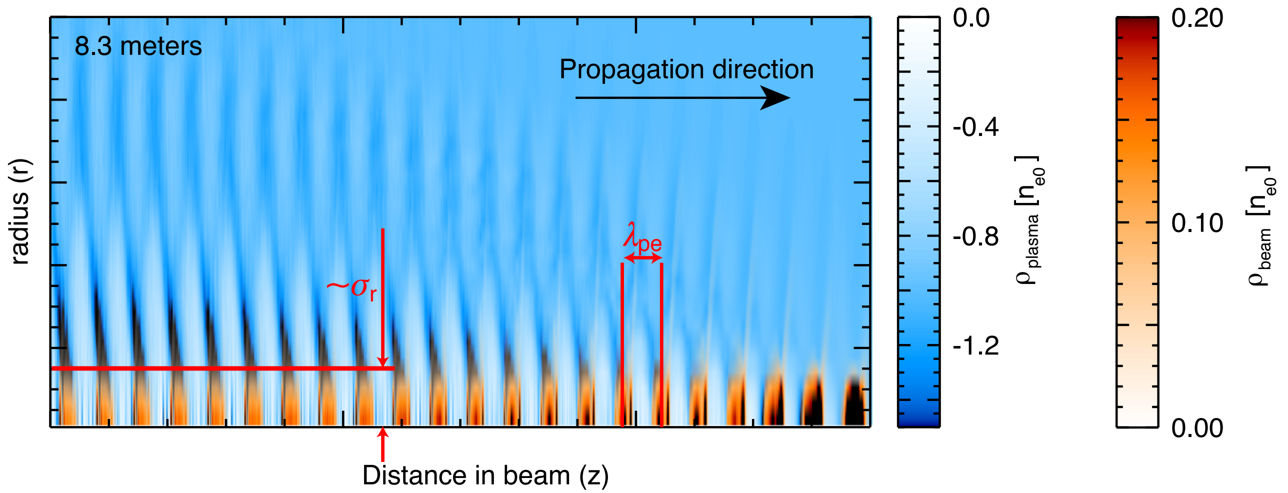
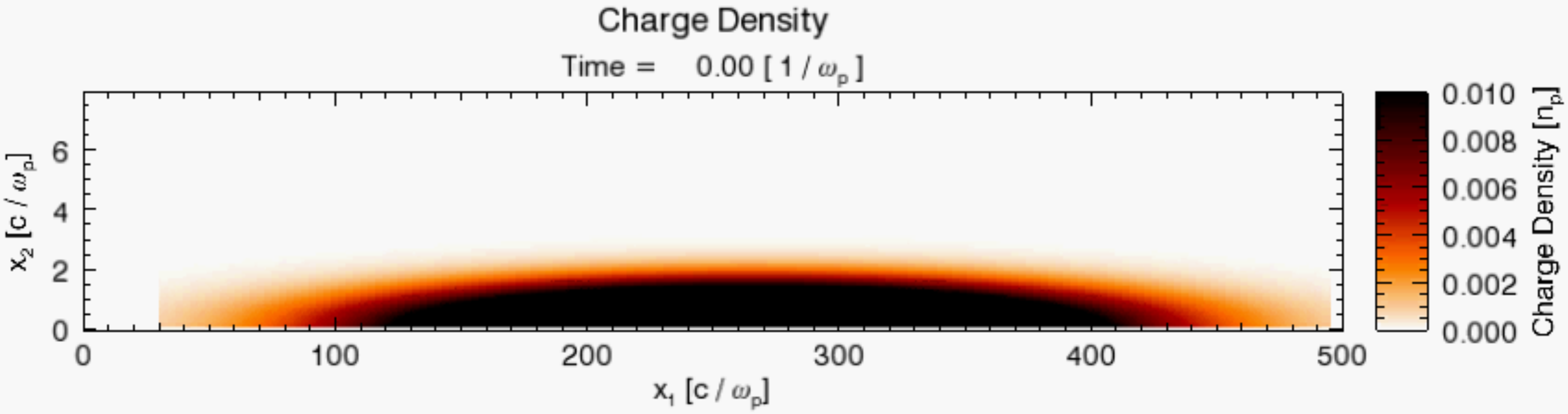
PWA via Modulated Proton Beam

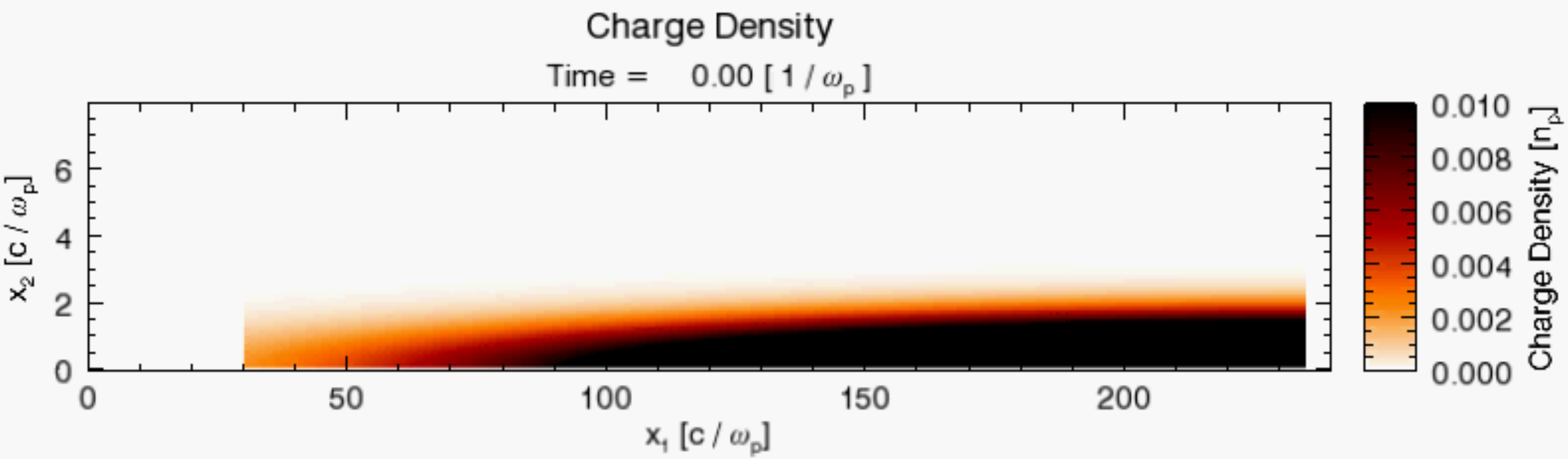
Producing short proton bunches not possible today w/o major investment. Instead, modulate a long (SPS) bunch



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)).

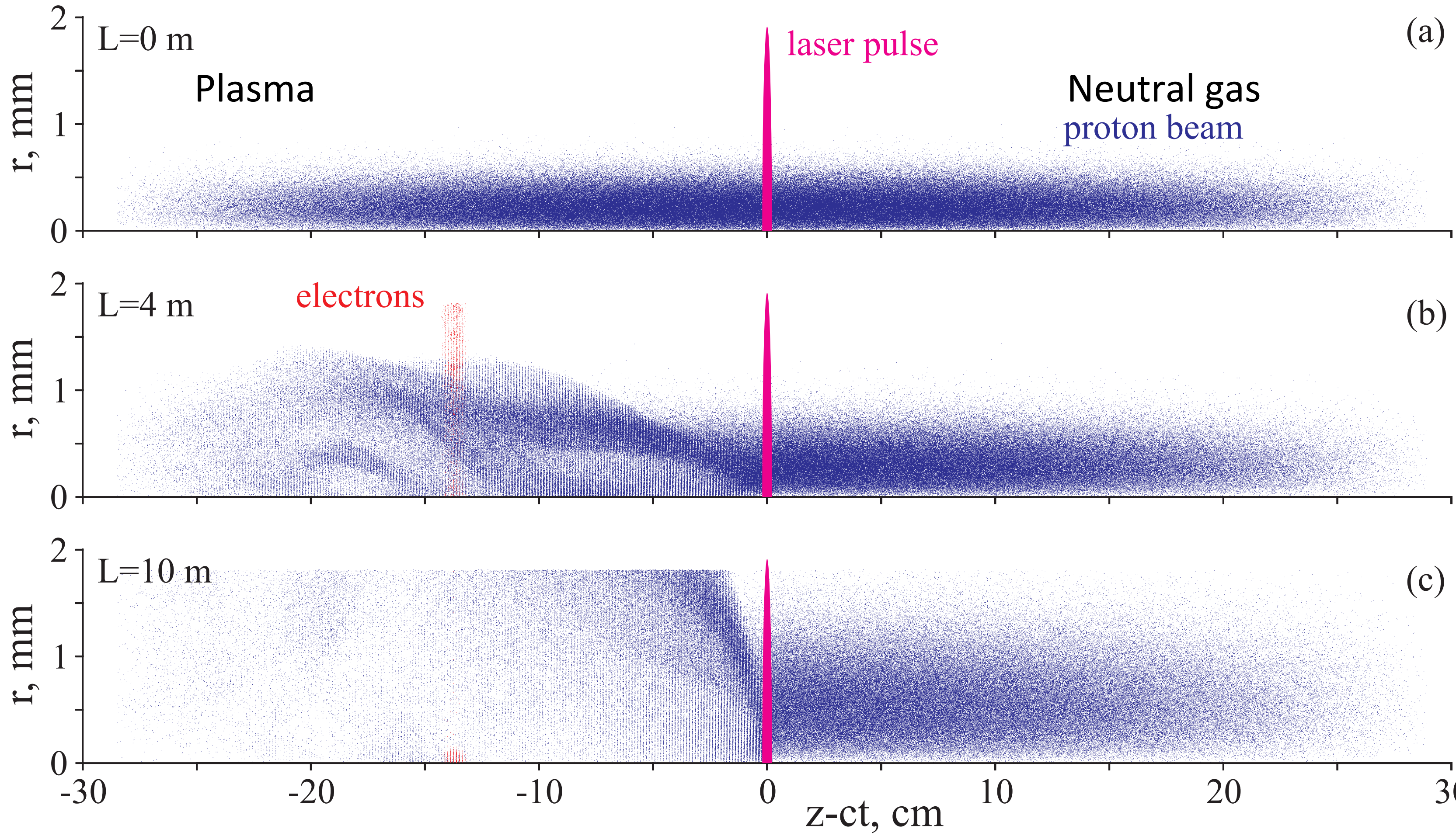


Charge Density
Time = 0.00 [1 / ωp]
x2 [c / ωp]
0
2
4
6
0
100
200
300
400
500
x1 [c / ωp]
0.010
0.008
0.006
0.004
0.002
0.000
Charge Density [np]



Charge Density
Time = 0.00 [1 / ωp]
x2 [c / ωp]
0
2
4
6
0
50
100
150
200
x1 [c / ωp]
0.010
0.008
0.006
0.004
0.002
0.000
Charge Density [np]

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.

Phase velocity of the wake

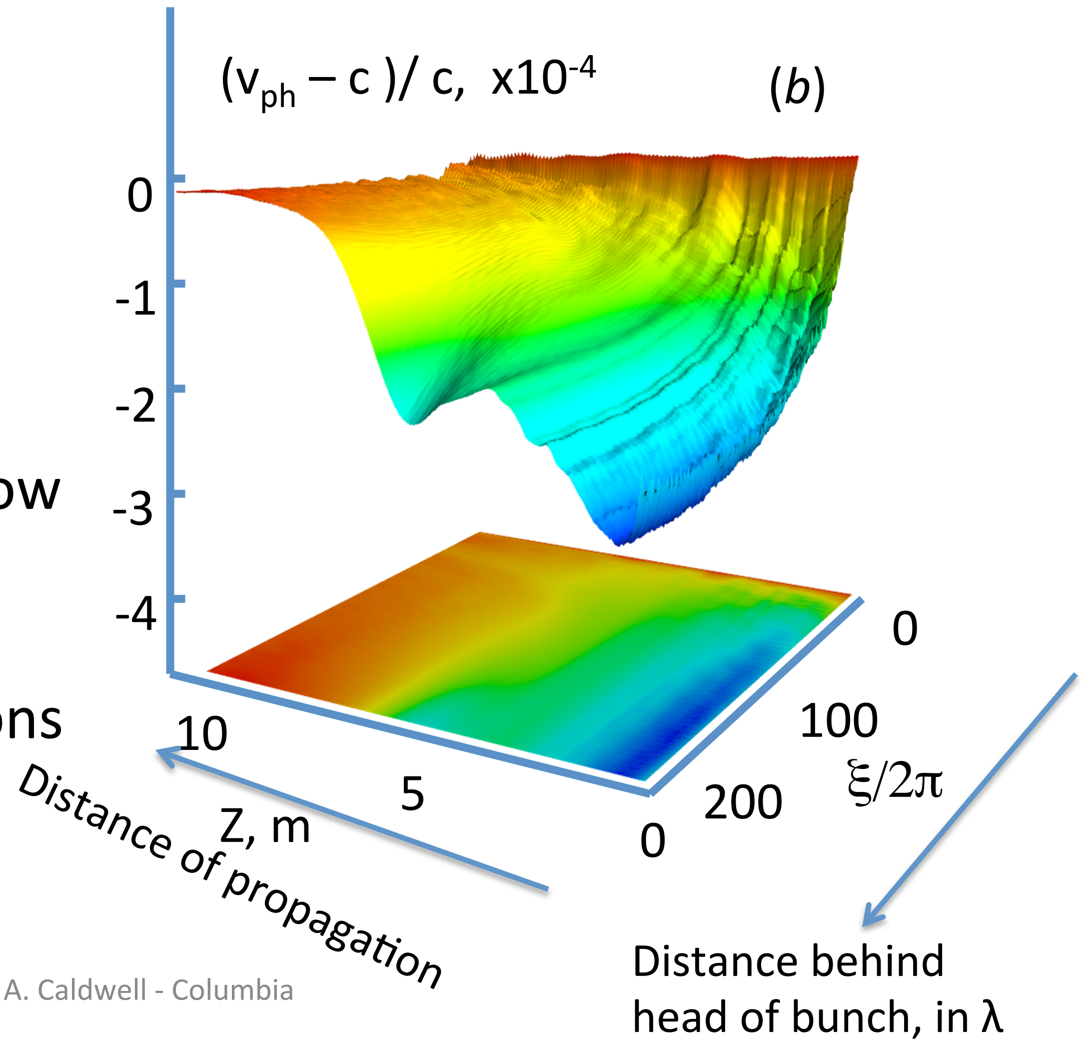
To trap & accelerate electrons in the wake of the protons, it is important that the wake phase velocity matches the electron velocity. Initially, the gamma-factor is

$\gamma_{min} \sim 40$

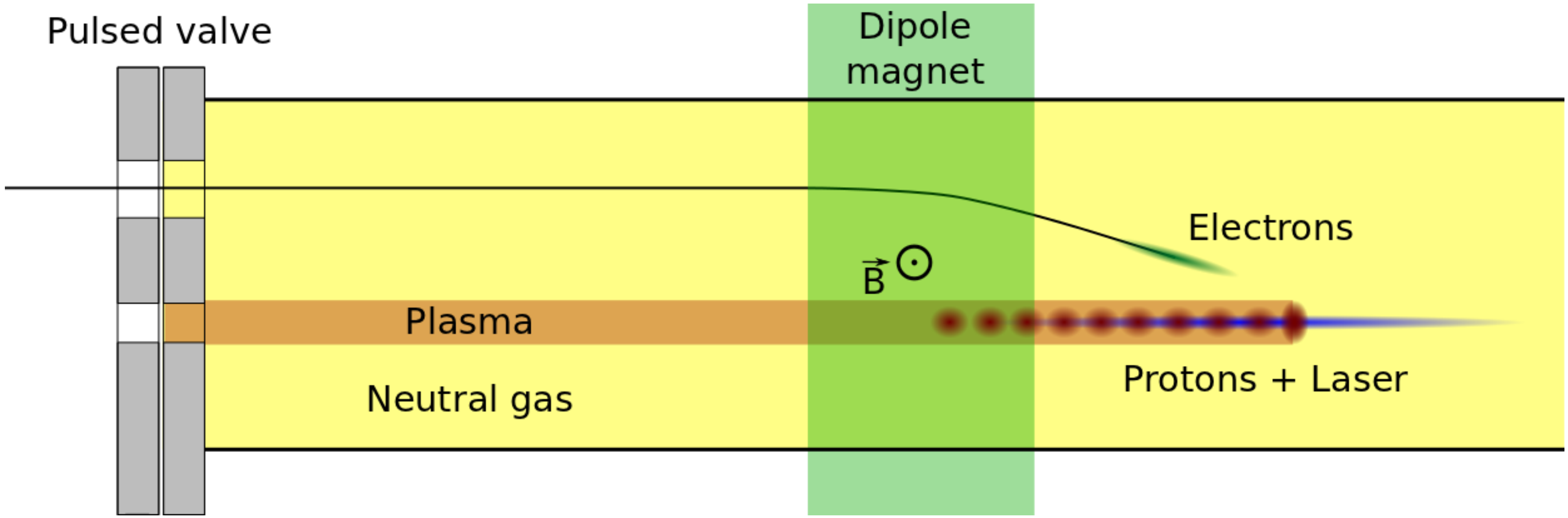
This is order of magnitude below that of the beam.

Requires that we inject electrons after the phase velocity has stabilized.

Pukhov et al., Phys Rev Lett (2011)



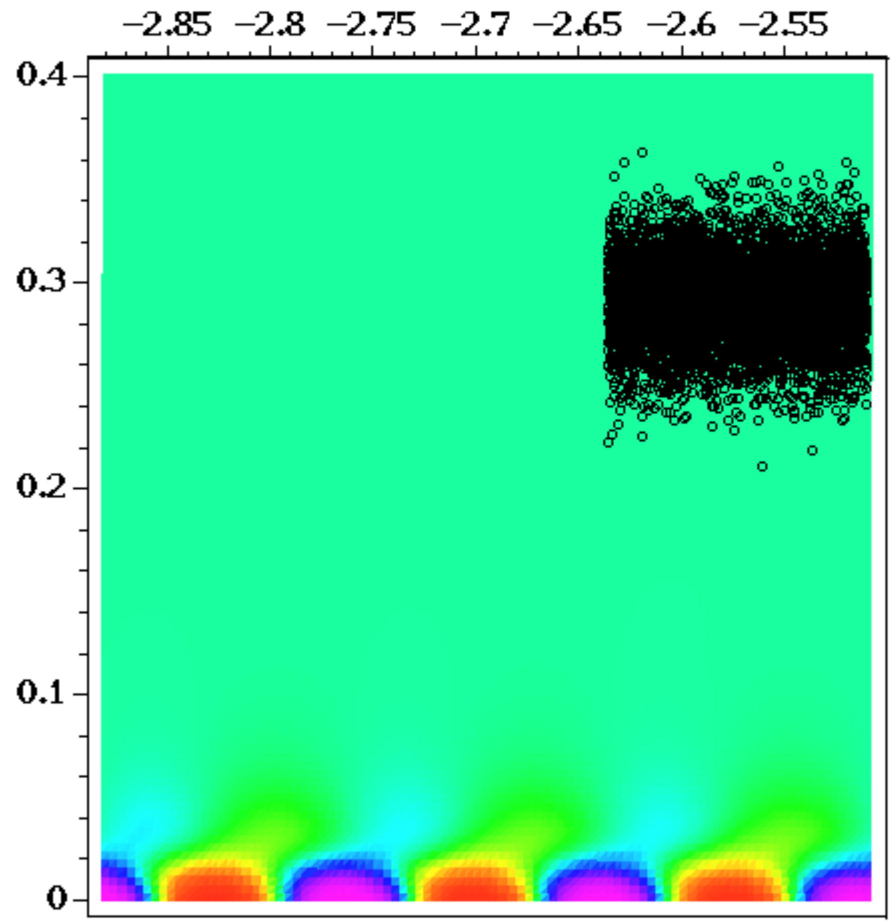
Solution: Delayed Electron Injection



Electron bunch injected off-axis at an angle, so that it merges with the proton bunch once the modulation is developed and the phase velocity is high.

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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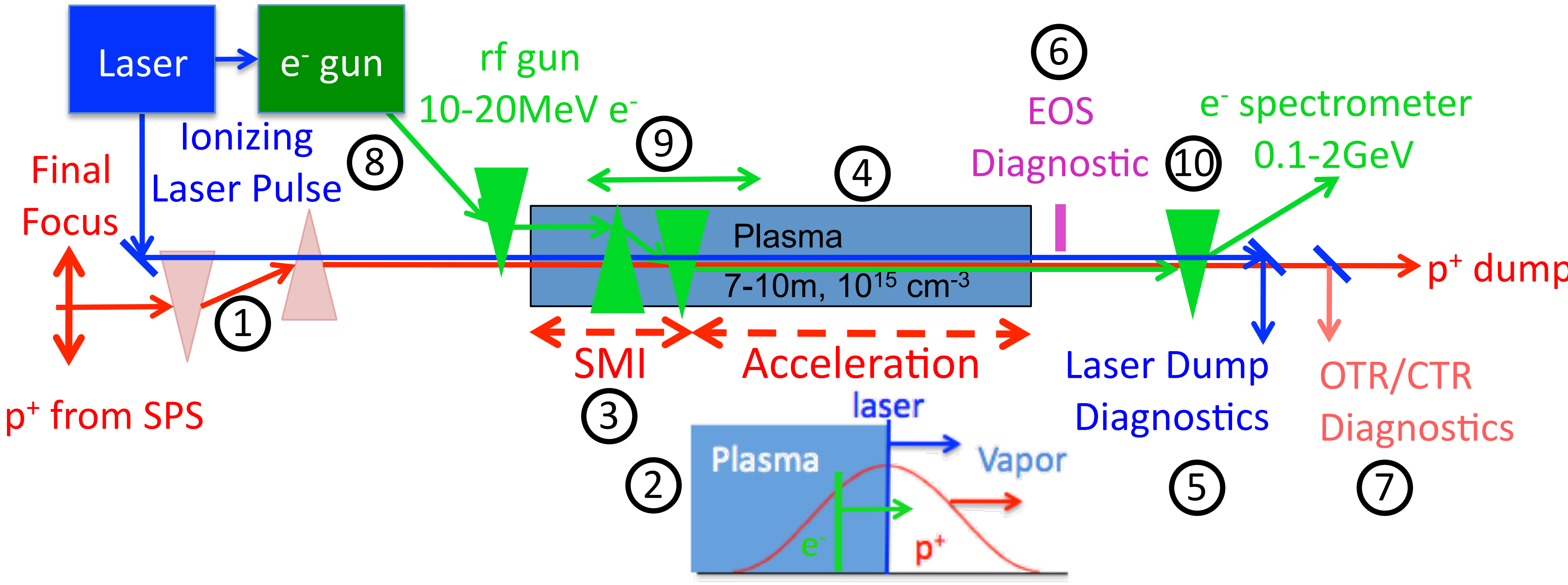


1. Merging of SPS proton beam & ionizing/seeding laser pulse
2. Schematic relative timing
3. SMI developing, electron bunch parallel to proton bunch
4. Acceleration sections
5. Laser pulse dumped & diagnosed
6. Electro-optical sampling diagnostic
7. Transition radiation diagnostics
8. RF electron gun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

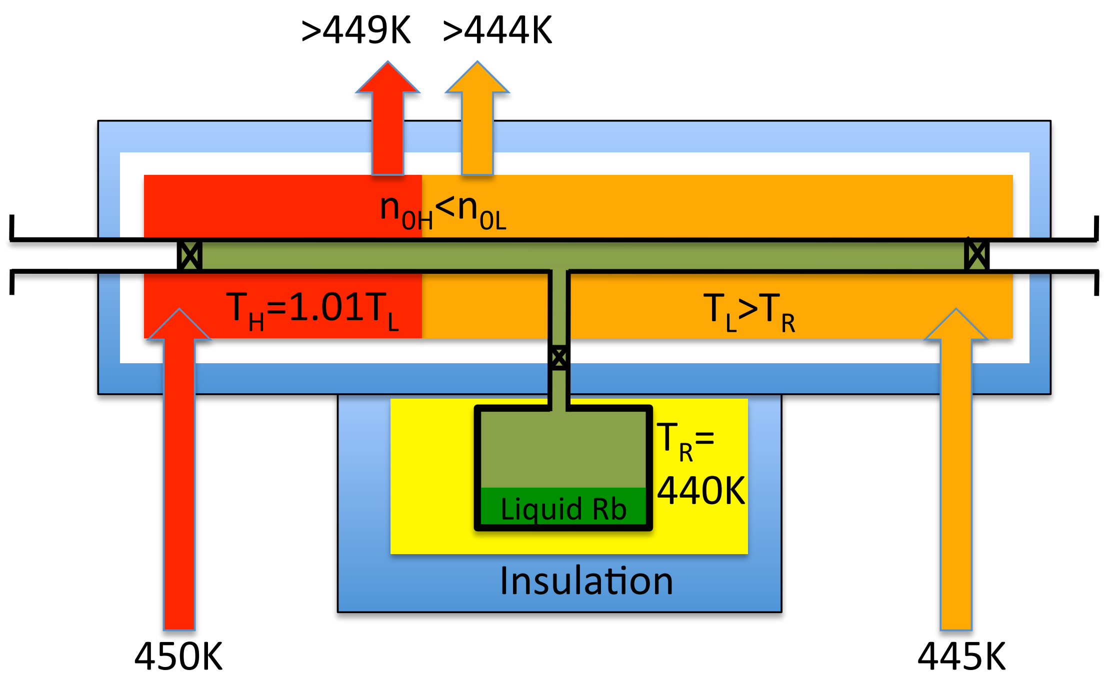
Table 1: Baseline parameters of the AWAKE experiment.

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



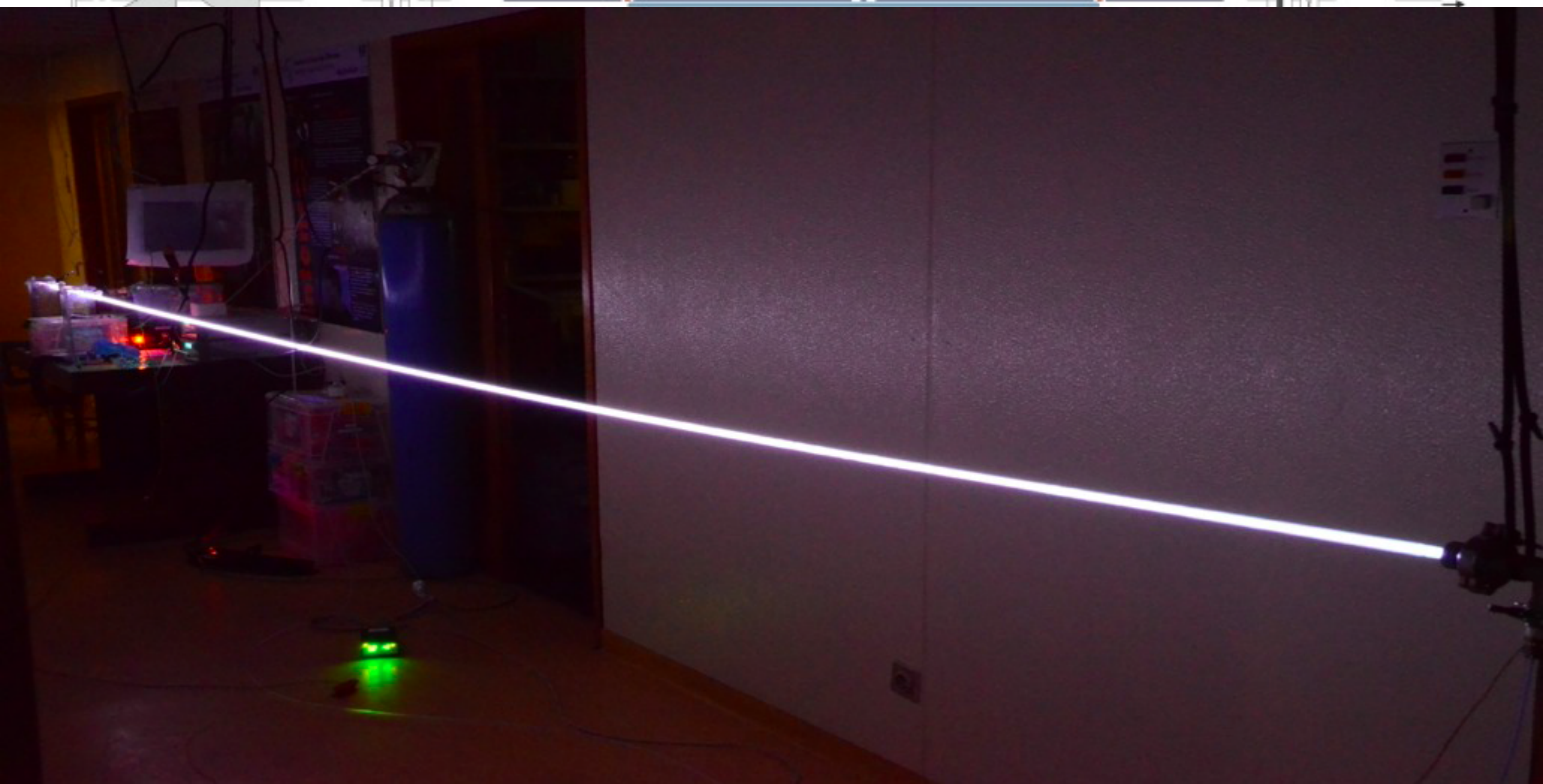
Delevoped at MPP

- 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

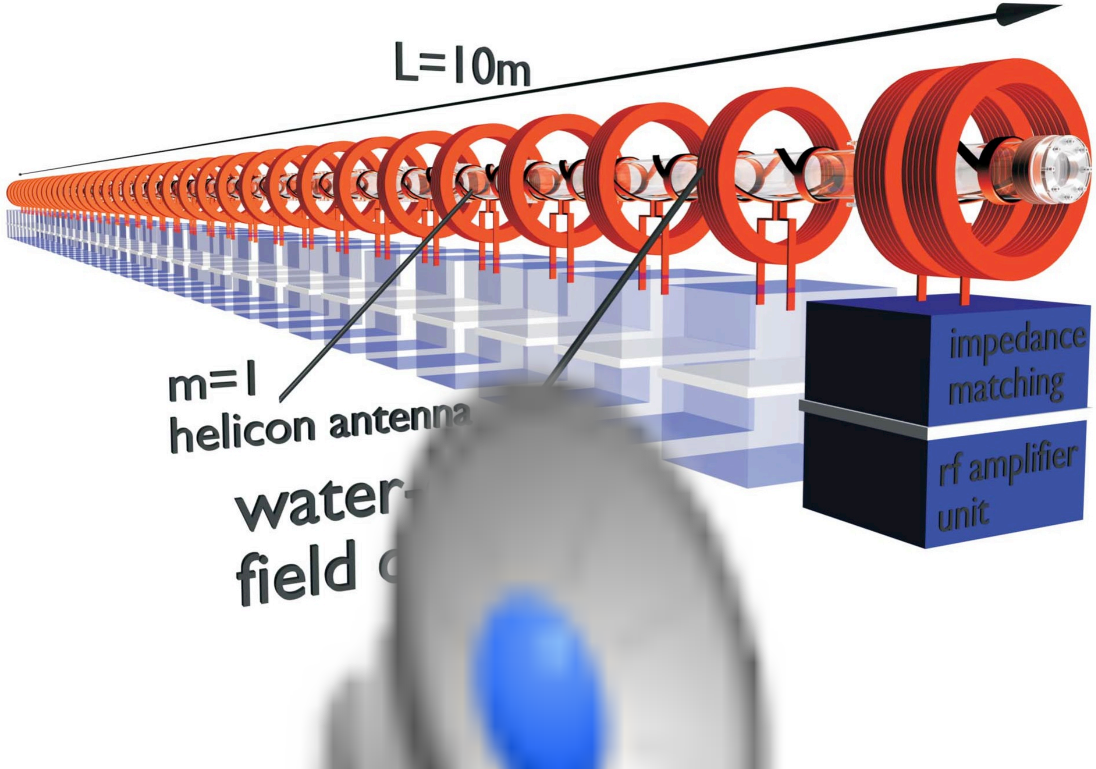
Discharge Cell
(Instituto Superior Tecnico, Lisboa and Imperial College, London)



R&D for long, uniform cells

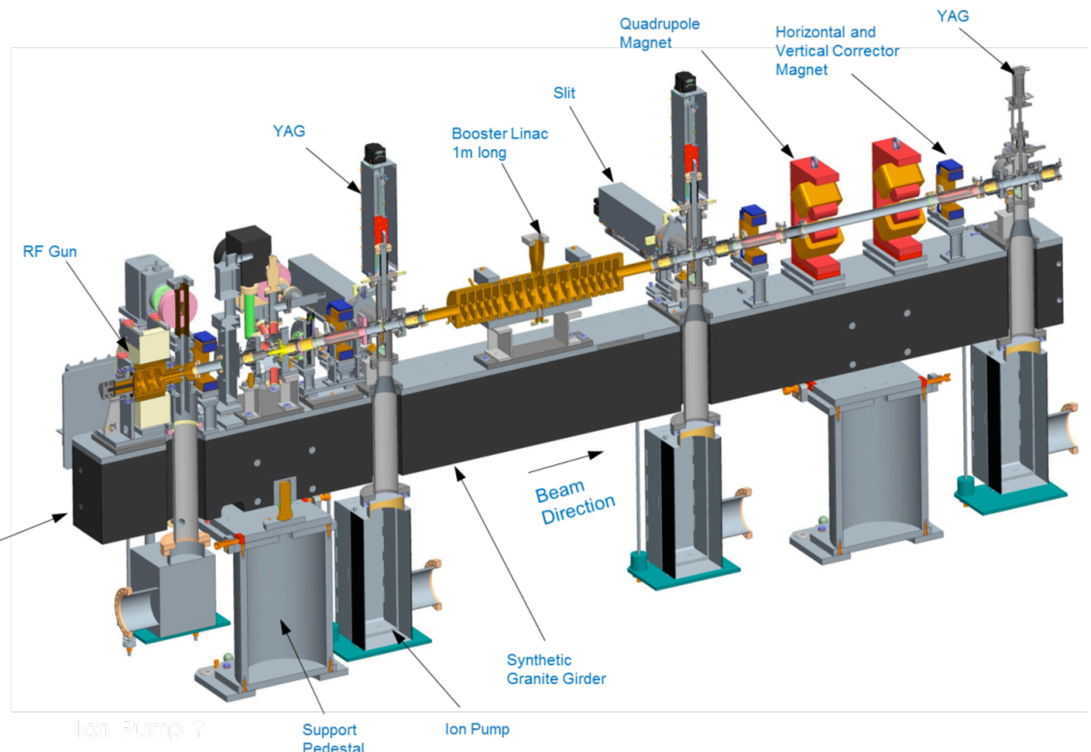
Helicon Cell

(Max Planck Institute for Plasma Physics)



1 meter prototype at the IPP in Greifswald.

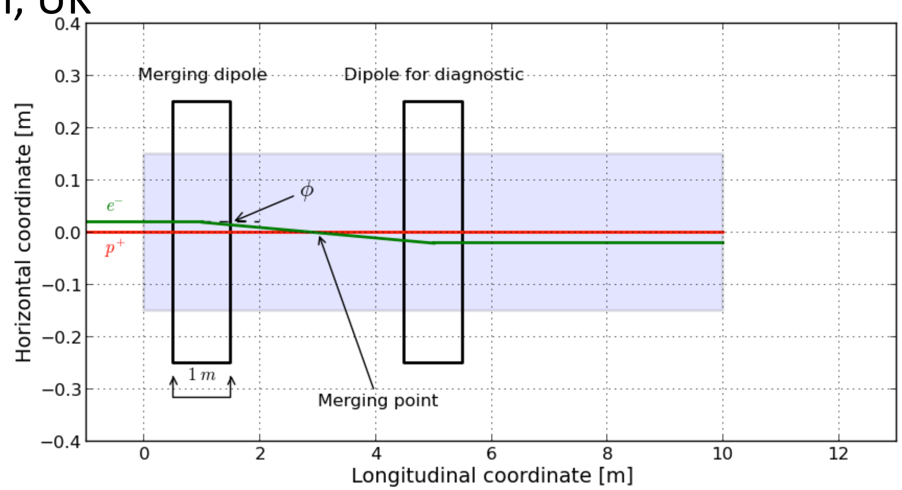
Electron Source



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.

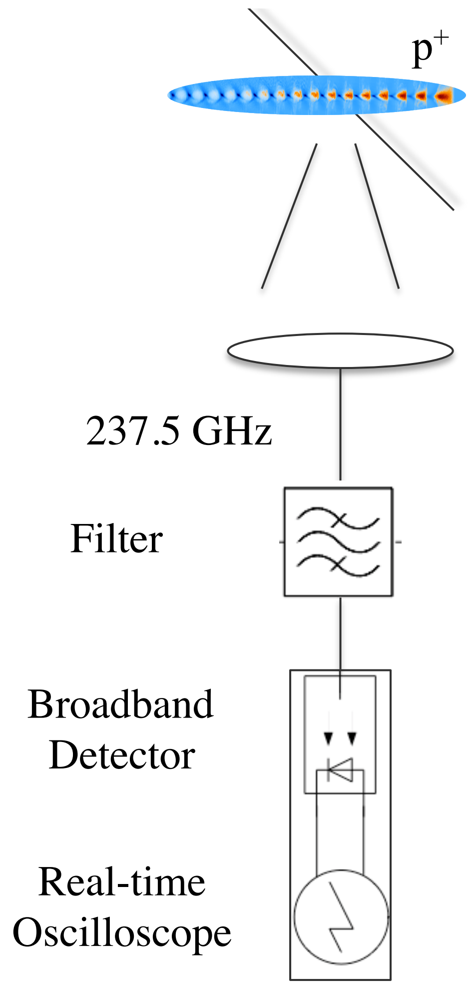


Outline

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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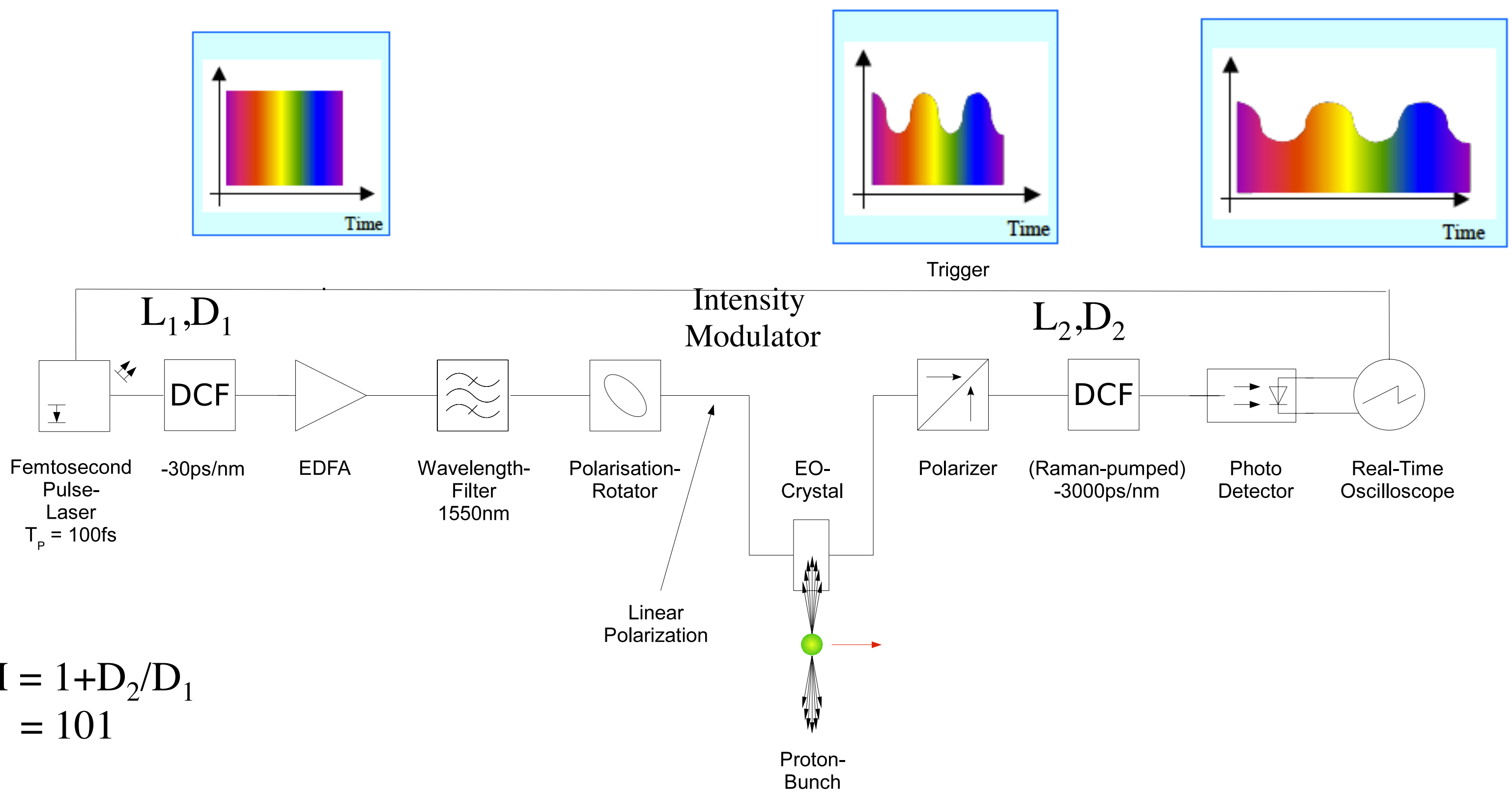

$$M = 1 + D_2/D_1 = 101$$

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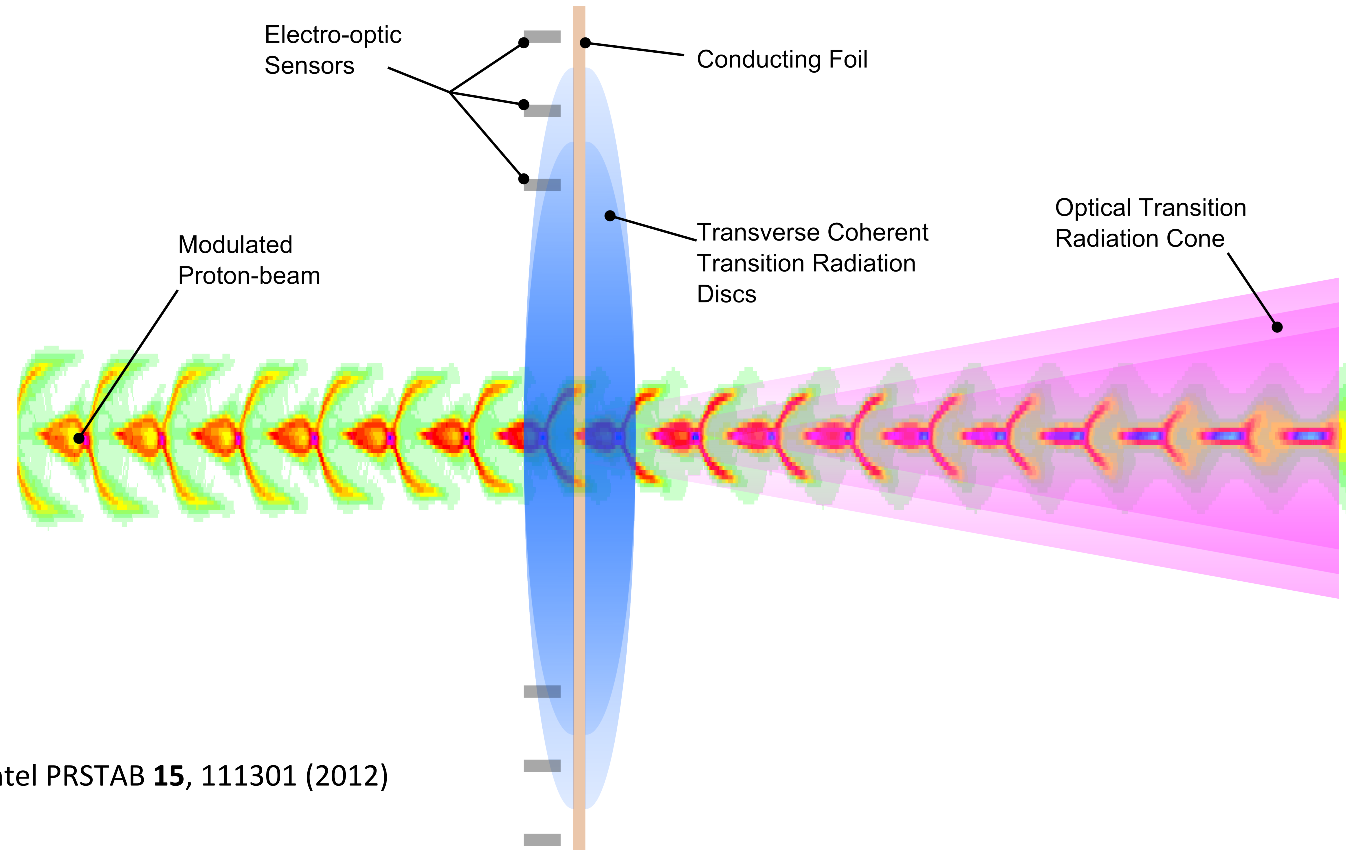
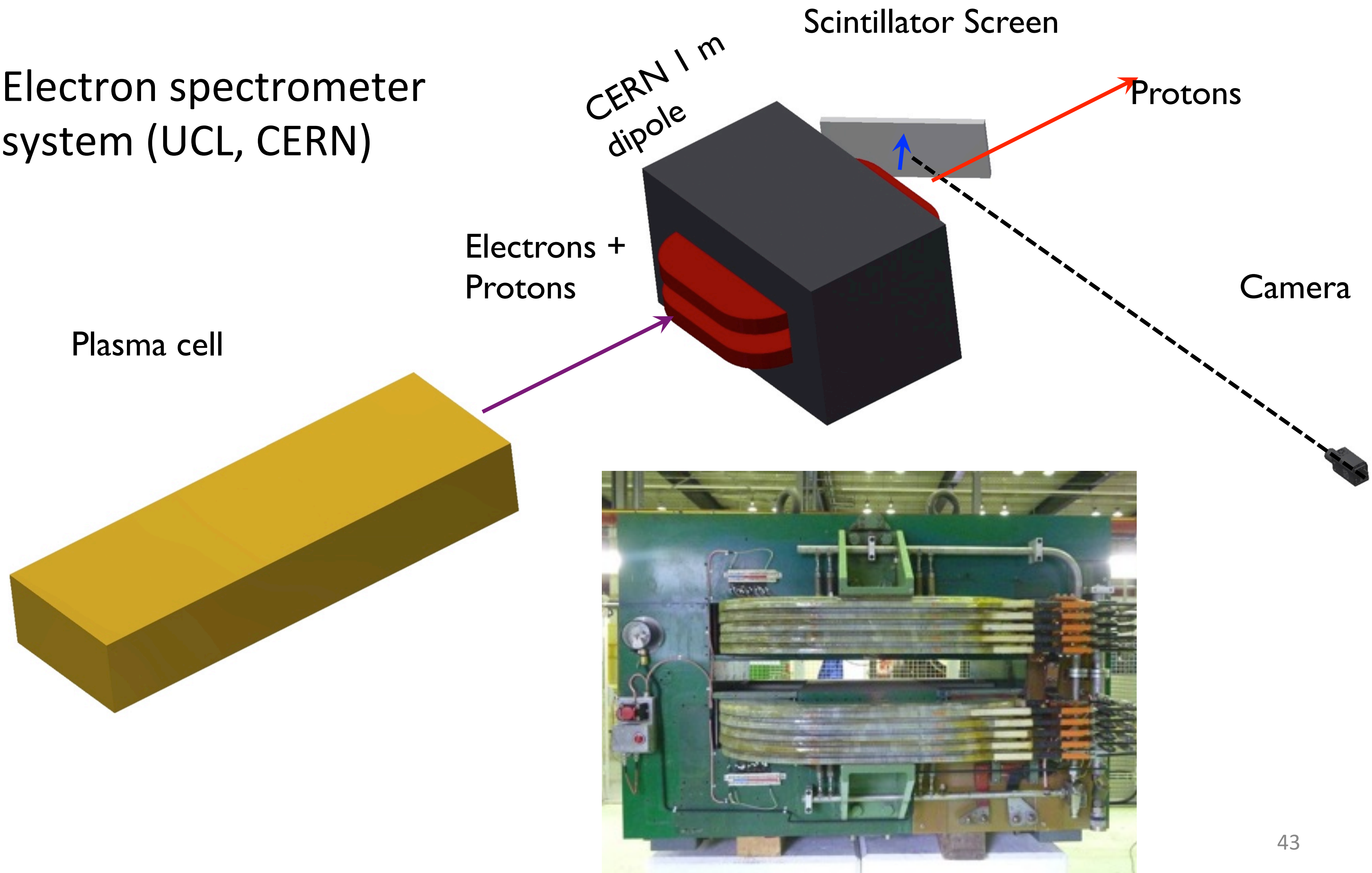


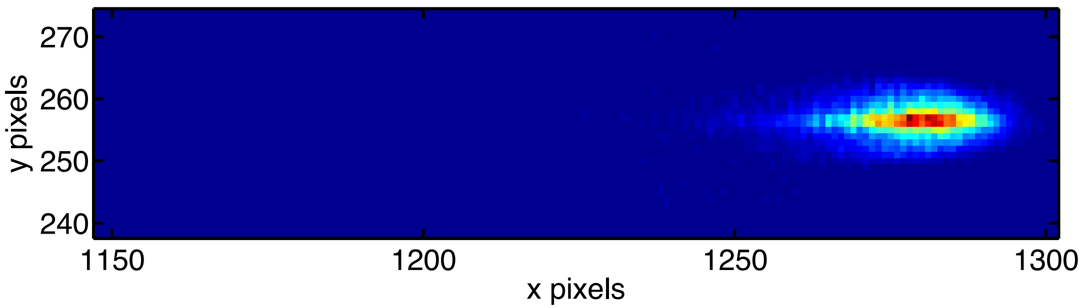
A. Pukhov, T. Tückmantel PRSTAB **15**, 111301 (2012)

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

Electron spectrometer system (UCL, CERN)

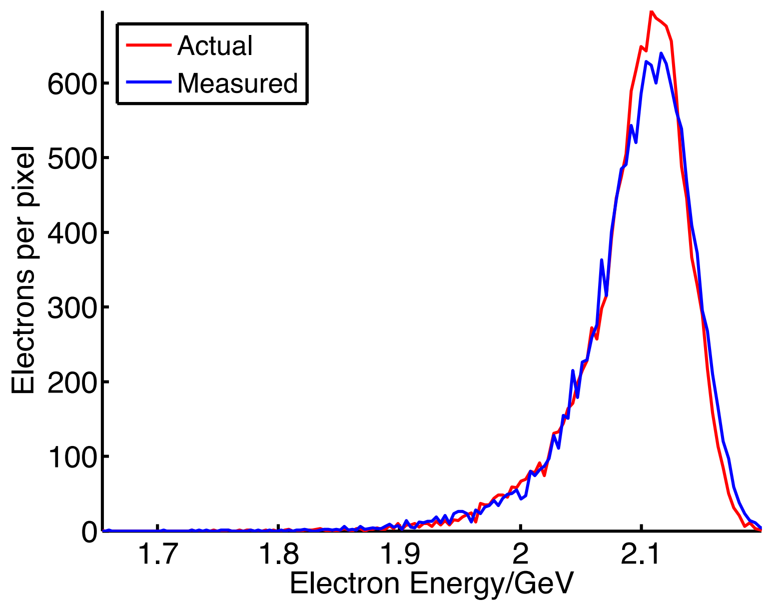


Electron Spectrometer



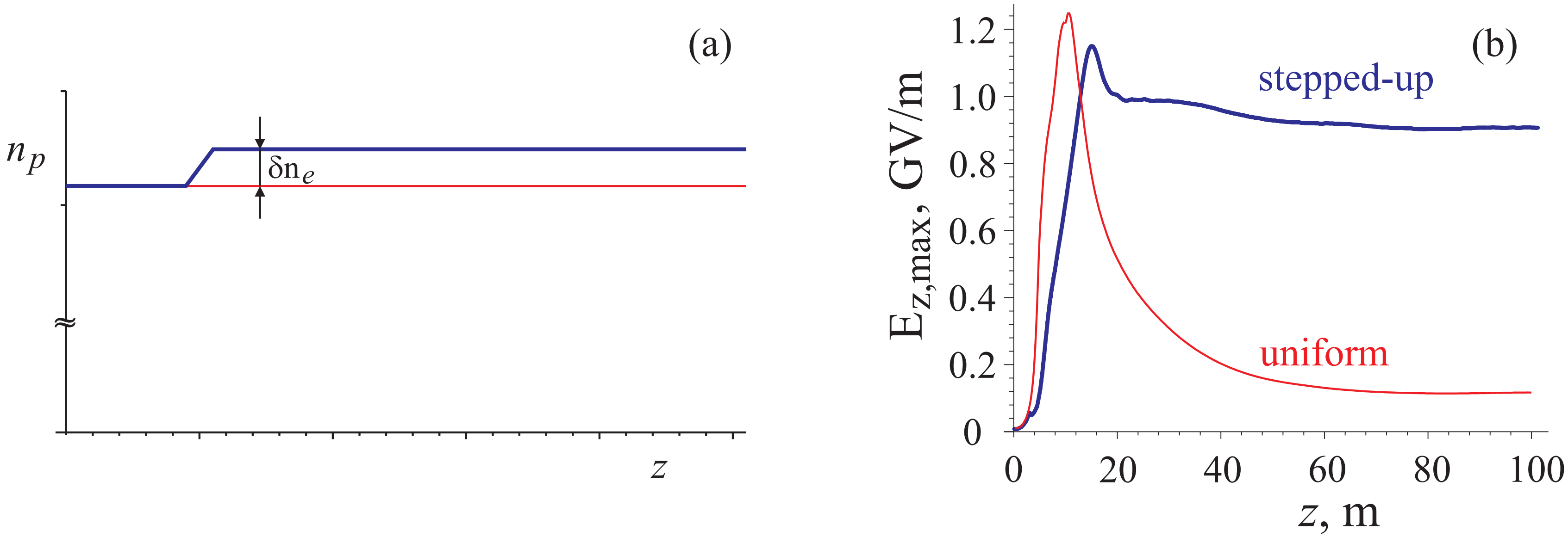
Simulation of scintillator screen shot from full simulation of electrons in plasma cell & tracking through spectrometer

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



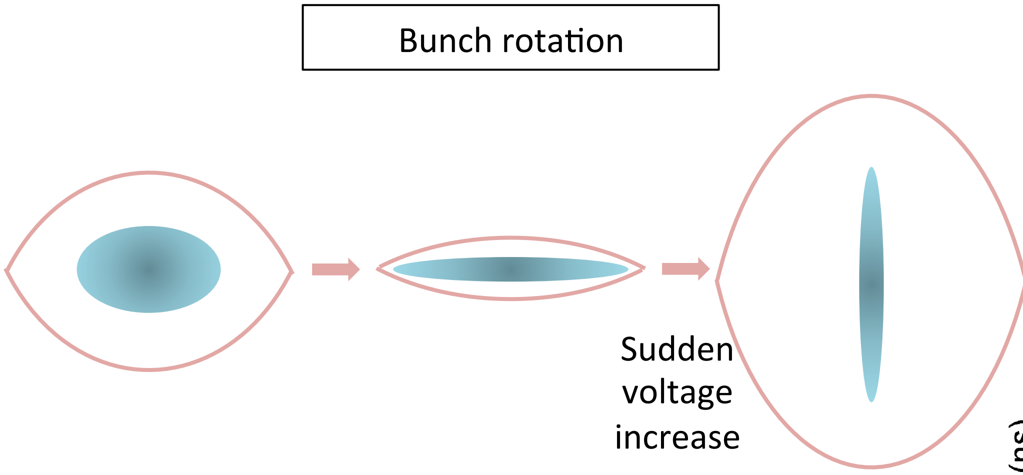
3. Experiments with density steps and 2 plasma cells. Separate the SMI phase from the acceleration phase. Achieve large energy gains for electron bunches.

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

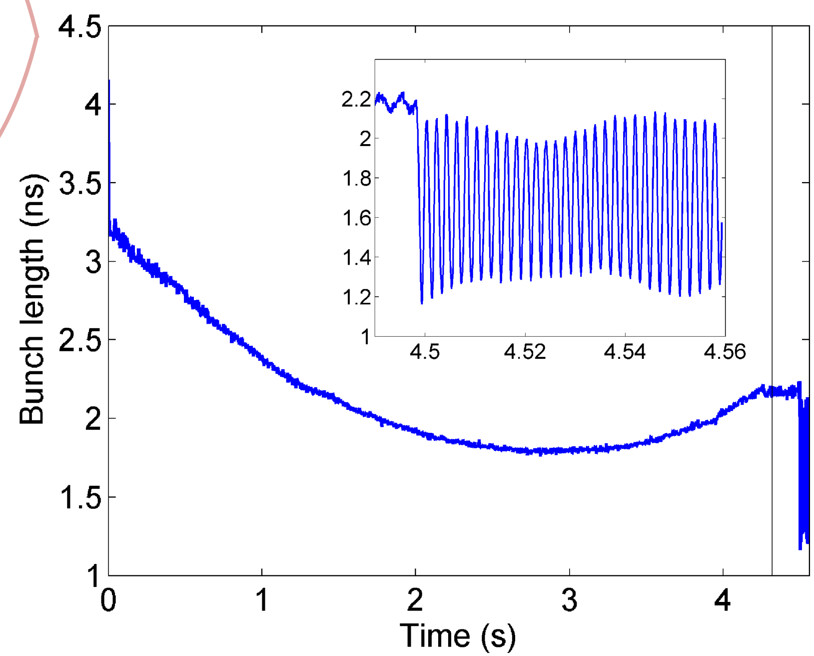


Possibility for density step, either in single plasma cell or in double cell will be tried out in AWAKE experiment. Potential for very significant energy gains 10's-100 GeV with SPS beam.

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



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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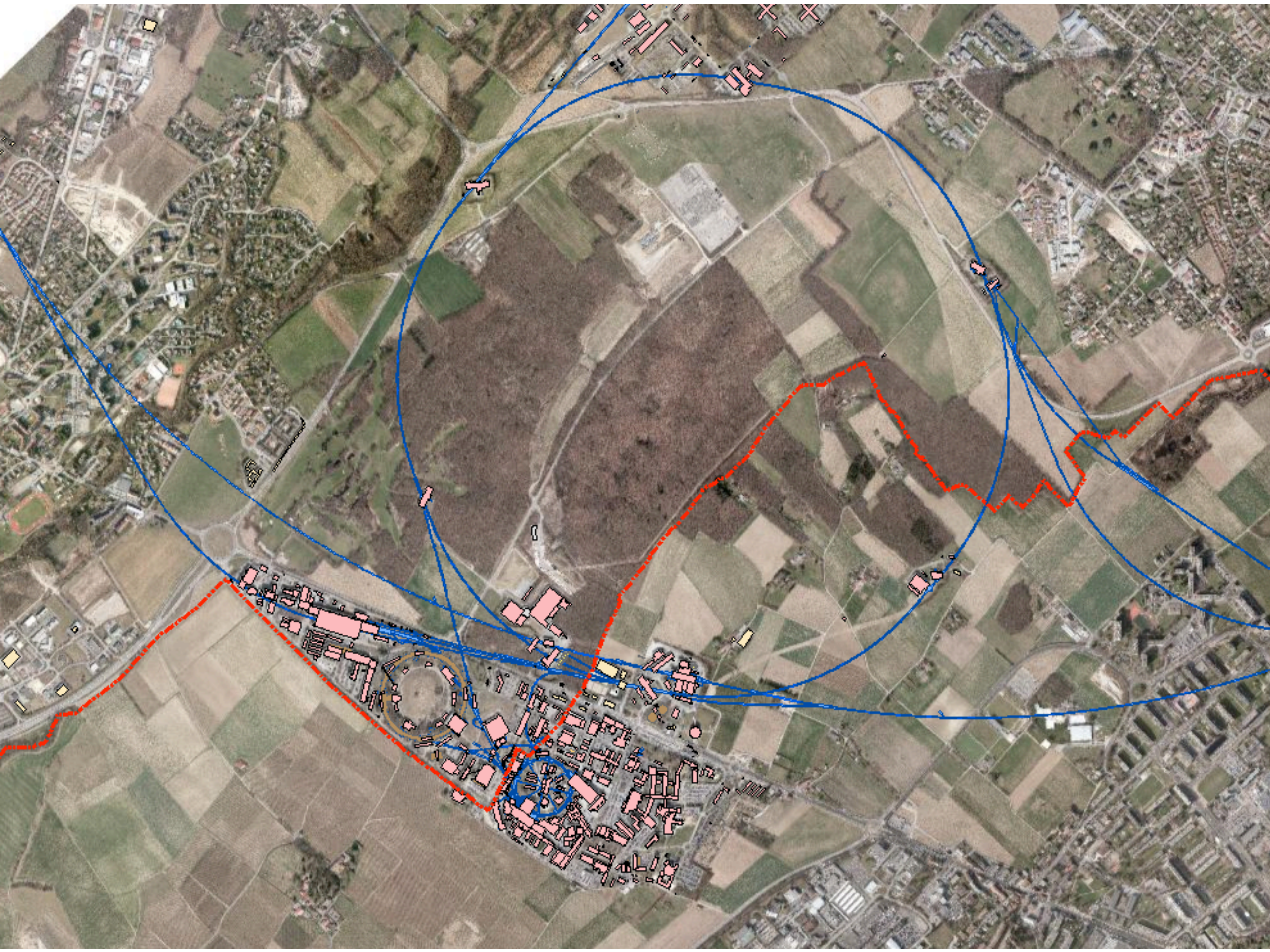
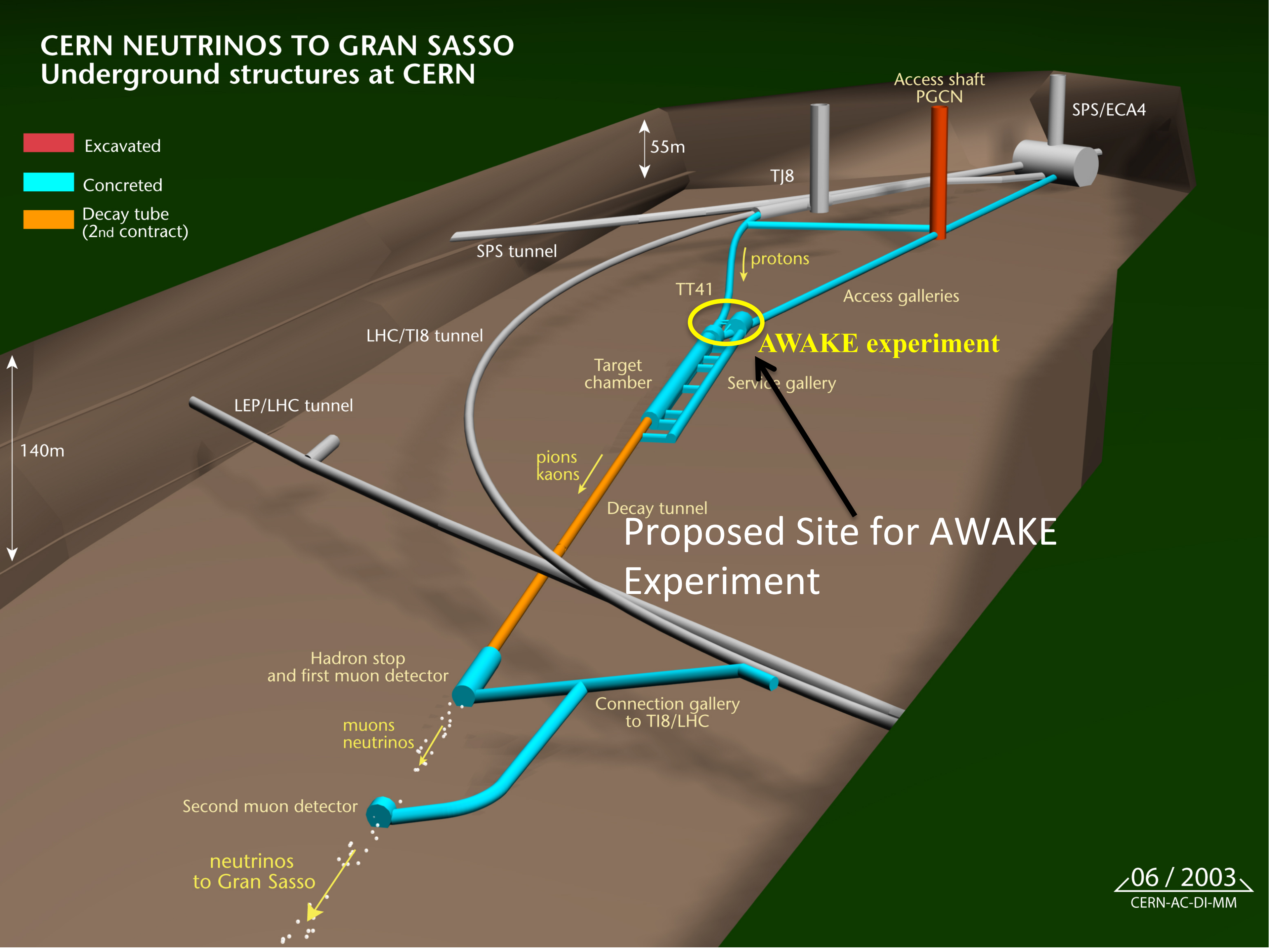
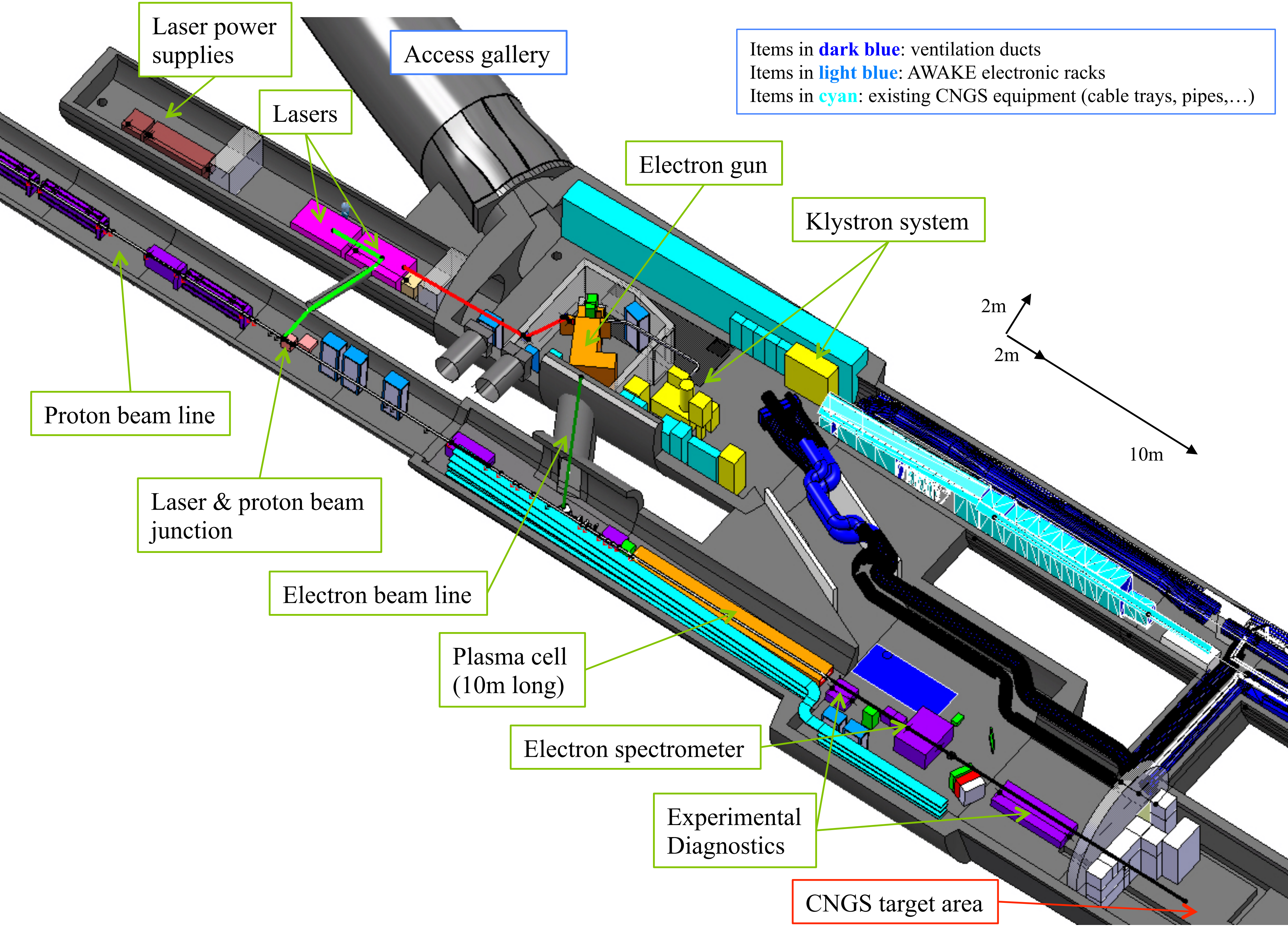
8. Responsibilities & resources of other participating institutes
9. Timeline & outlook

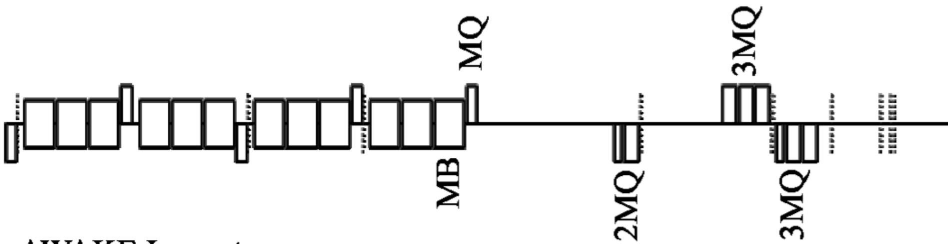



CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
TJ8
Access shaft
PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
AWAKE experiment
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Proposed Site for AWAKE
Experiment
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM



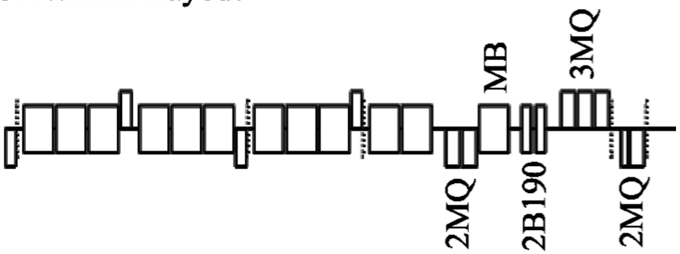
Laser power supplies
Access gallery
Lasers
Items in dark blue: ventilation ducts
Items in light blue: AWAKE electronic racks
Items in cyan: existing CNGS equipment (cable trays, pipes,…)
Electron gun
Klystron system
2m
2m
10m
Proton beam line
Laser & proton beam junction
Electron beam line
Plasma cell (10m long)
Electron spectrometer
Experimental Diagnostics
CNGS target area

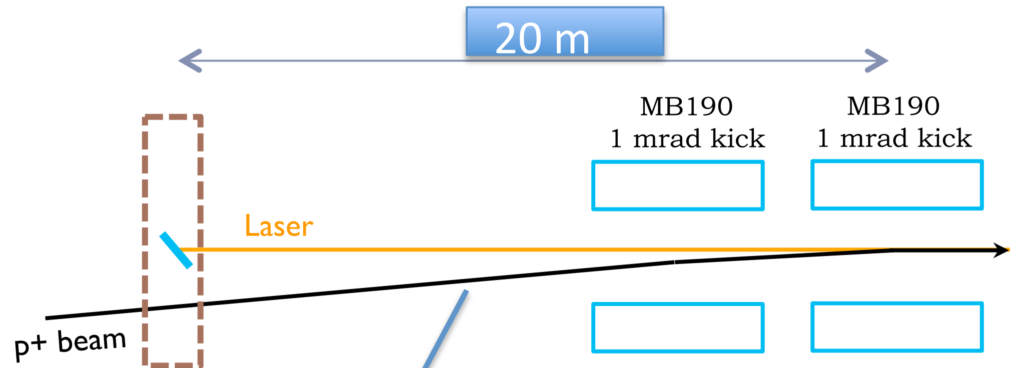
Present CNGS Layout (end of the line)

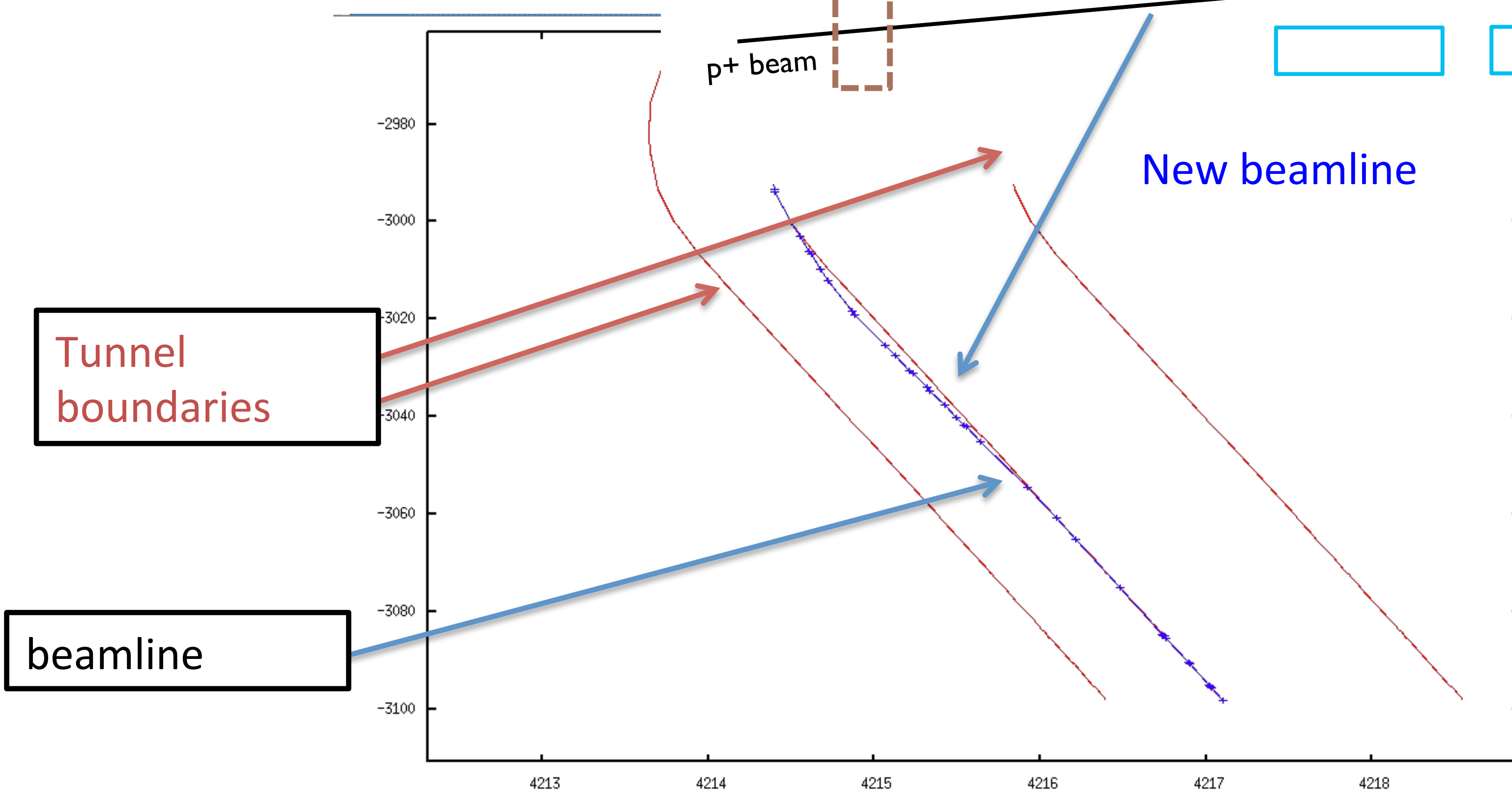


Rearrange few magnets at end of beamline: more space for experiment, merging of laser&proton beam.

Future AWAKE Layout







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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
DESY

Interested Institutes:

John Adams Institute for Accelerator Science
Wigner Research Center for Physics

AWAKE

	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

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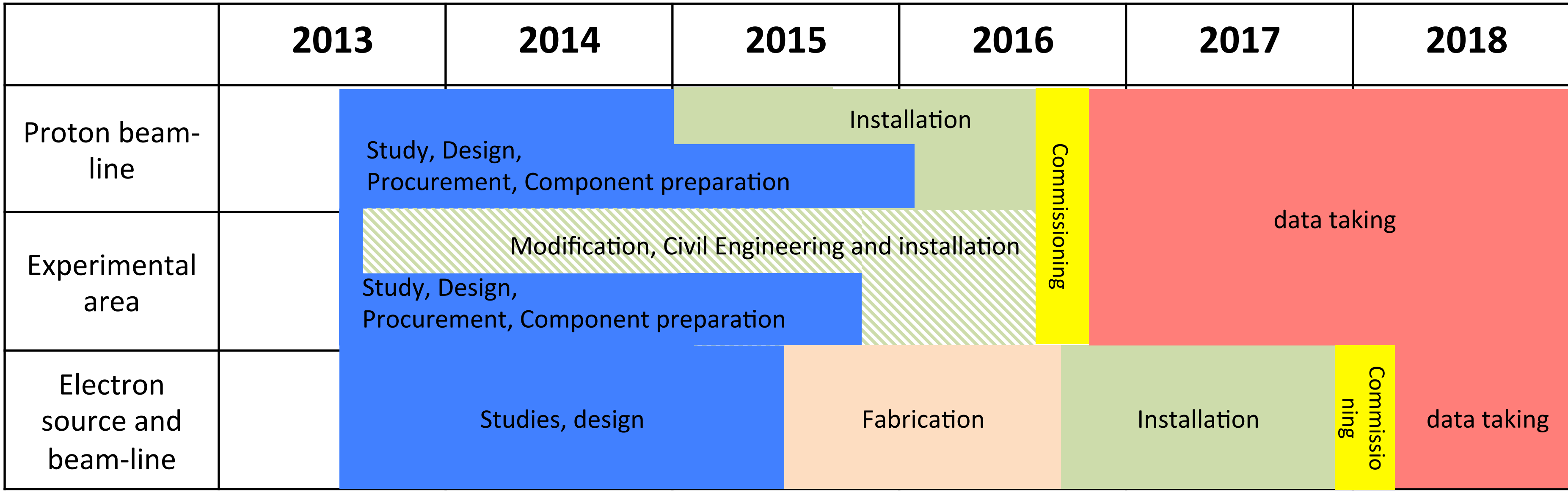
- June 2012: Official CERN Study Project
  - Mandate to identify best site for the AWAKE facility and write a design report.
- 25 March 2013: Submit AWAKE Design Report to CERN management and SPS Committee
  - Use the CNGS facility for AWAKE (not West Area).
- 9-10 April 2013: SPSC Meeting
  - Very positive feedback; List of questions – Answers sent back to referees
- Mid May 2013: several discussion with CERN management and finance group
  - Needed resources for AWAKE@CERN are fully included in the CERN Medium-Term Plan
  - AWAKE program has been stretched from 3 years to 5 years.
- 17-21 June 2013: Council week
  - MTP with AWAKE fully funded inside is approved.
- 25-26 June 2013: SPSC meeting
  - **SPSC recommends AWAKE proposal** for approval.
- 31 July 2013: IEFC meeting
  - Present detailed planning and manpower needs as agreed with various groups
- 28 August 2013: Research Board
  - **Approval of the AWAKE experiment.**

Time-scale for AWAKE as in the MTP



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