Cockcroft Institute
Lectures on Accelerator Physics

Plasma Accelerators (III)---
Proton-driven plasma wakefield acceleration

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Outline

- Why proton-driven PWFA
- Short proton bunch production
- AWAKE experiment at CERN
- Colliders based on PD-PWFA
- Summary

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Motivation

- With an increase of beam energy, the size and cost of modern high energy particle accelerators reach the limit (break down + power)
- Plasma can sustain very large electric fields, a few orders of magnitude higher than the fields in metallic structures
- The plasma accelerators (laser driven-LWFA or beam driven-PWFA) have been developed rapidly in last 20 years, 50-100GV/m accelerating gradients have been demonstrated in labs
- The novel plasma accelerators can potentially minimize the size and cost of future machines
- Very high energy proton beams are available nowadays, why not use these proton beam to excite wakefield for the electron acceleration?

Energy gain

$$E = 240(\text{MeV/m})\left(\frac{N}{4\times10^{10}}\right)\left(\frac{0.6}{\sigma_z(\text{mm})}\right)^2$$

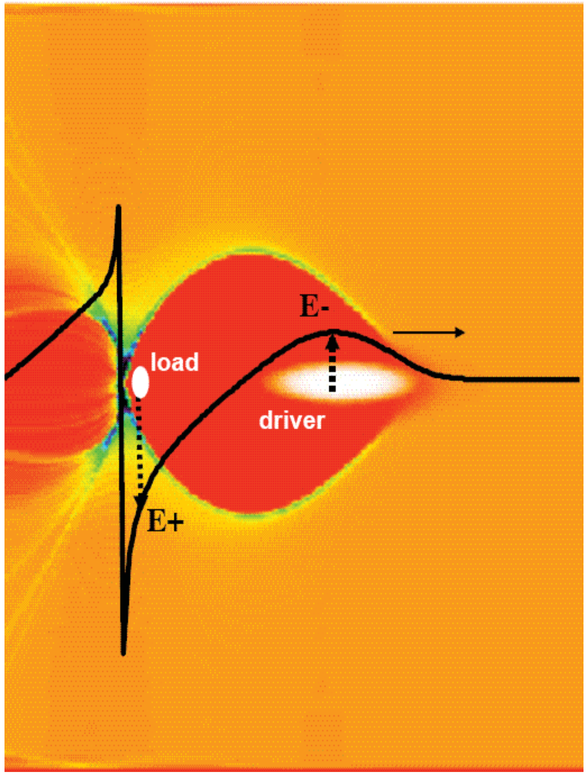
In the linear regime, the maximum achievable field scales as the bunch charge divided by bunch length squared, high intensity and short bunch length are required for high field production.

Transformer ratio limit *

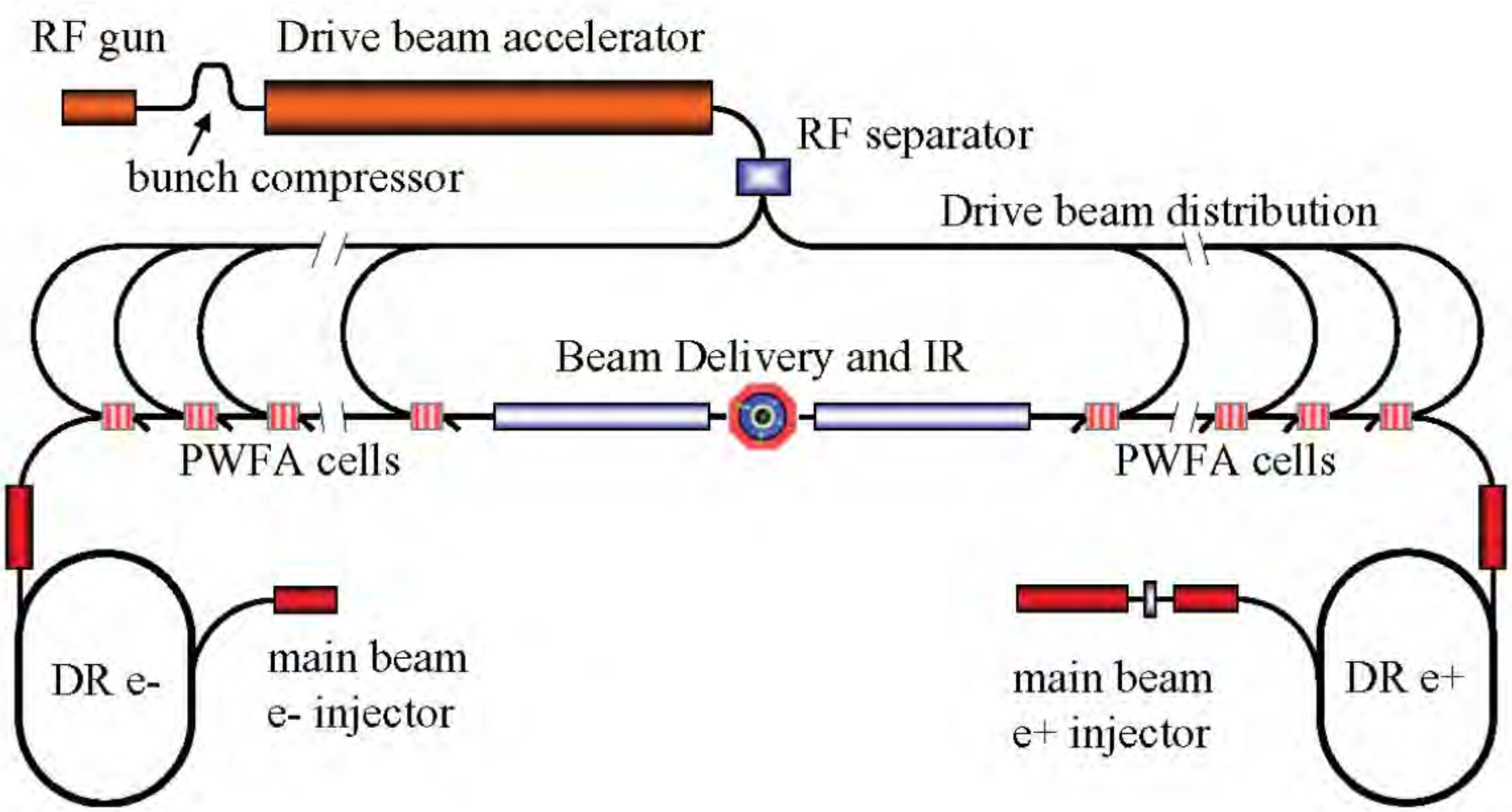
$$R = \frac{E_{\max}^{witness}}{E_{\max}^{drive}} \leq 2$$

for longitudinal symmetric bunch

*R.D. Ruth et al, SLAC-PUB-3374



PWFA-based linear collider*



*M. Hogan et al., Proceedings of PAC09 (TU1GRI01)
*A. Seryi et al., Proceedings of PAC09 (WE6PFP081)

Existing 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

high energy proton beam as driver

- Hugh energy stored in current 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) ~ 0.1 kJ
- However, the current proton bunches are quite longer to use as driver directly. Need much effort to compress the beam
- How to couple the energy of driver to the plasma and the witness beam efficiently?

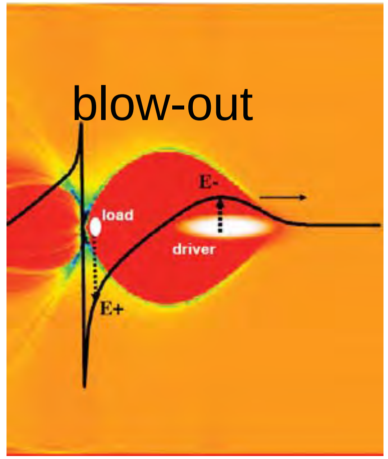
PWFA and PDPWA

Pros. of PWFA

Plasma electrons are expelled by space charge of beam, a nice bubble will be formed for beam acceleration and focusing.

The short electron beam is relatively easy to have (bunch compression).

Wakefield phase slippage is not a problem.



Cons. of PWFA

One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.

Easy to be subject to the head erosion due to small mass of electrons

Pros. of PDPWA

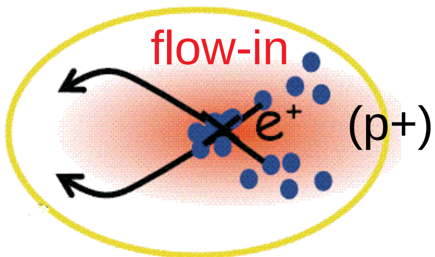
Very high energy proton beam are available today, the energy stored at SPS, LHC, Tevatron, HERA

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) ~ 0.1 kJ

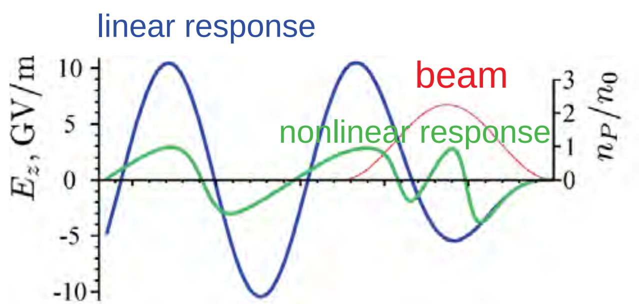


Cons. of PDPWA

Flow-in regime responds a relatively low field *vs*. blow-out regime.

Long proton bunches (tens centimeters), bunch compression is difficult.

Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel

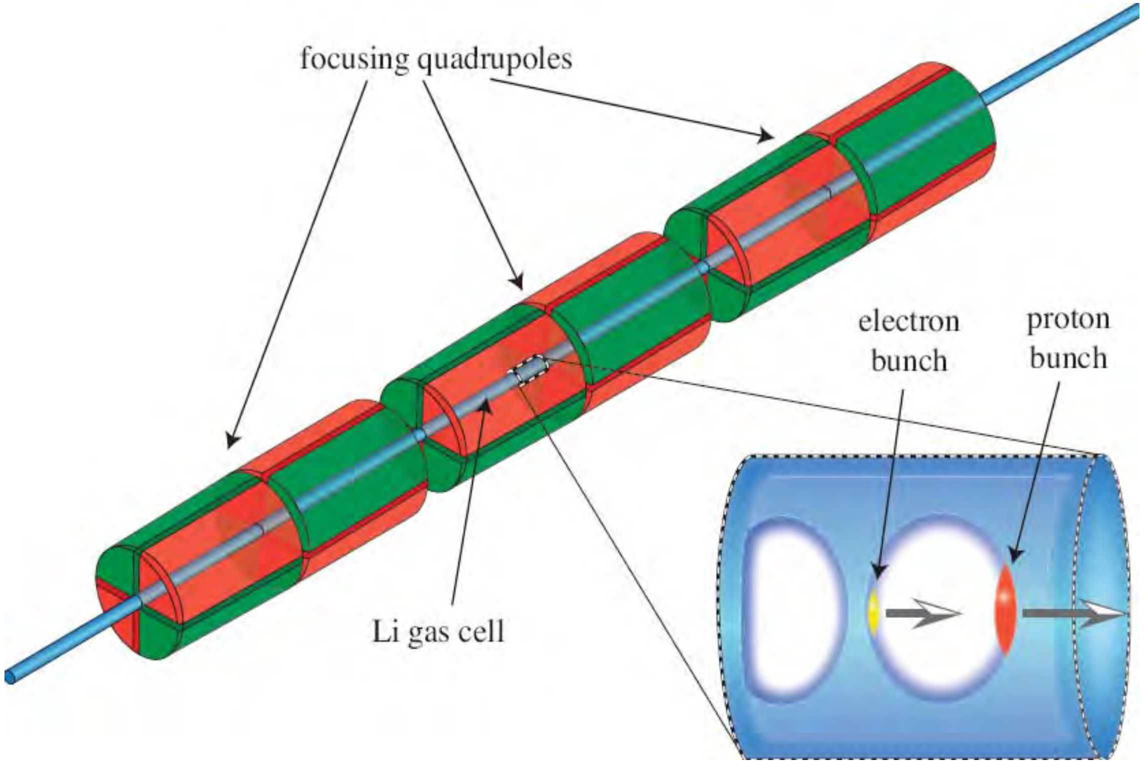


Proton-driven PWFA*

- The linear theory of PWFA holds for either negatively charged or positively charged beams
- The maximum achievable gradient scales as N/σ_z^2, therefore we need high current and short bunch for proton bunch driven PWFA
- Transformer ratio (the gained energy of witness beam / the energy of driver beam) is limited to 2 for longitudinal symmetric driven bunches
- 2D and 3D Particle-in-cell (PIC) simulations have given us very promising results for proton driven PWFA
- One of the biggest hurdles is to produce the short proton beam, in the scale of 100 micron.

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

Schematics of PD-PWFA



A thin tube containing Li plasma is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

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

Parameter settings

	Symbol	Value
Drive Beam		
Protons in drive bunch [10^{11}]	N_p	1
Proton energy [TeV]	E_p	1
Initial proton momentum spread	σ_p/p	0.1
Initial longitudinal spread [μm]	σ_z	100
Initial angular spread [mrad]	σ_θ	0.03
Initial bunch transverse size [mm]	$\sigma_{X,Y}$	0.4
Witness Beam		
Electrons in witness bunch [10^{10}]	N_e	1.5
Energy of electrons [GeV]	E_e	10
Plasma Parameters		
Free electron density [cm^{-3}]	n_p	6×10^{14}
Plasma wavelength [mm]	λ_p	1.35
External Field		
Magnetic field gradient [T/m]		1000
Magnetic length [m]		0.7

Simulations

- 2 D and 3 D Particle-In-Cell (PIC) codes are employed to simulate the interactions between plasma and beams.

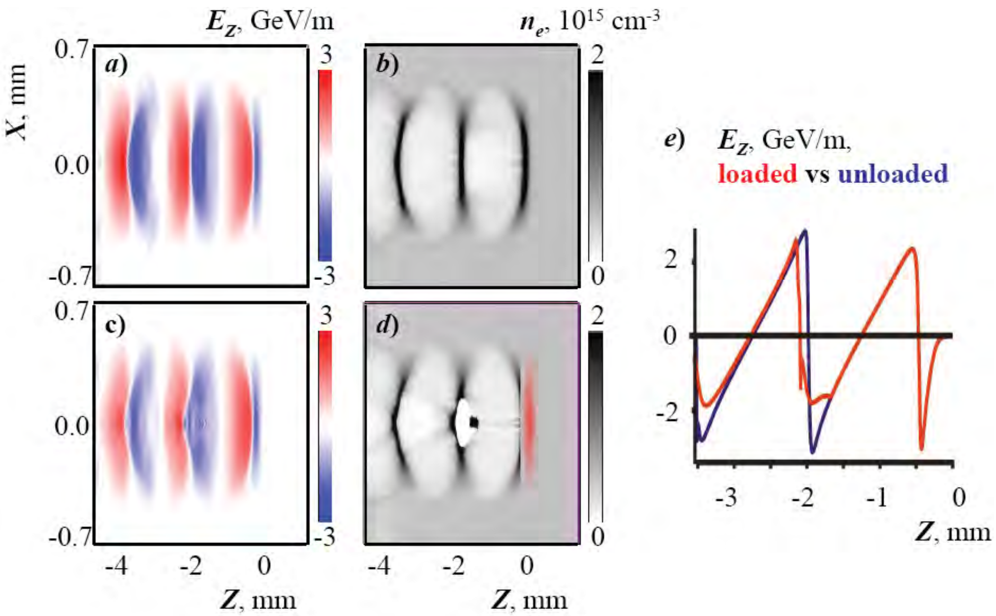
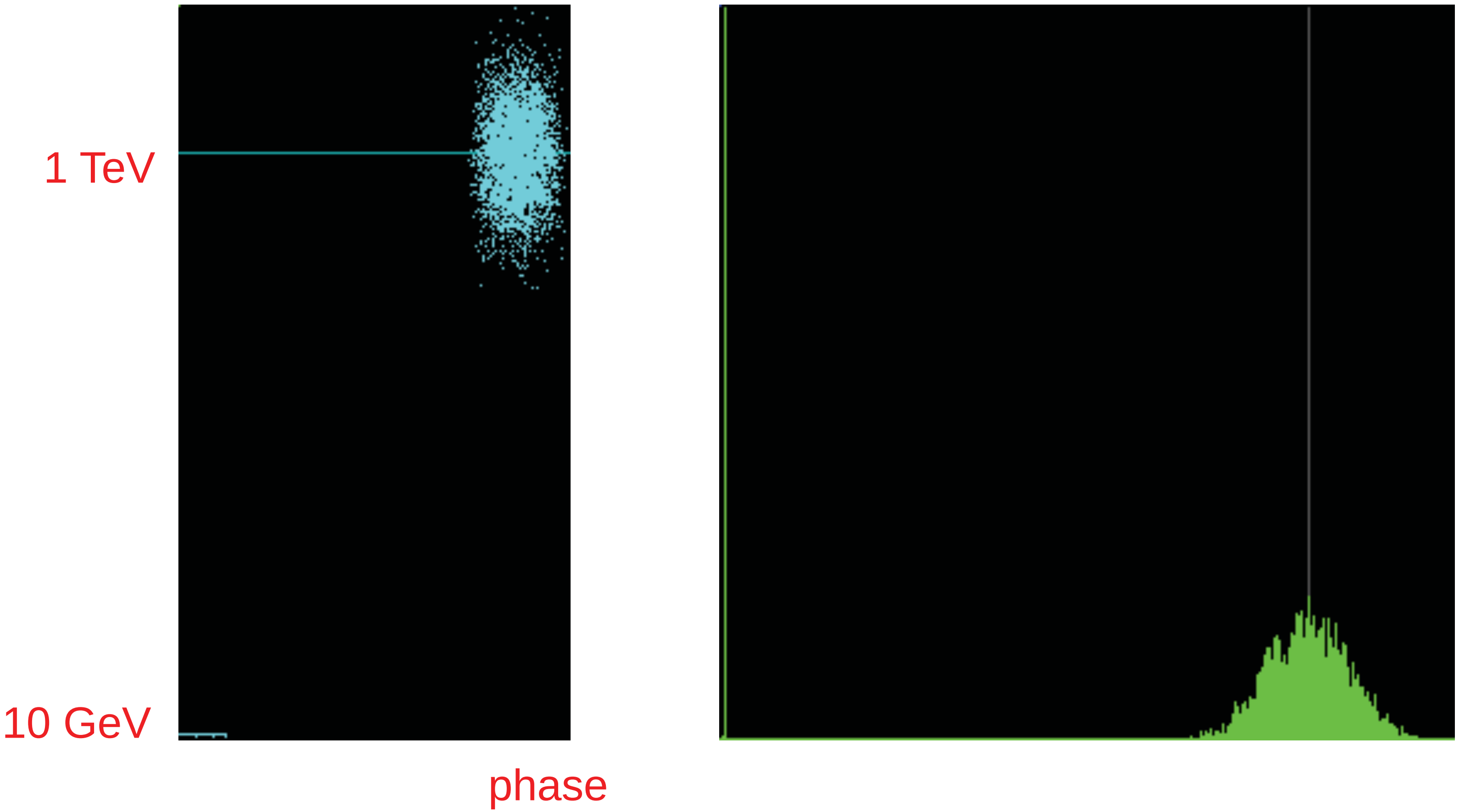


Fig.a-d), Simulation results for the unloaded (no witness bunch) case (a,b) and in the presence of a witness bunch (c,d). The witness bunch is seen as the black spot in the first wave bucket in d). d) also shows the driving proton bunch at the wavefront (red). e) The on-axis accelerating field of the plasma wave for the unloaded (blue curve) and loaded (red curve) cases.

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

Simulation results

- **Energy gain**



Phase space of driver & witness

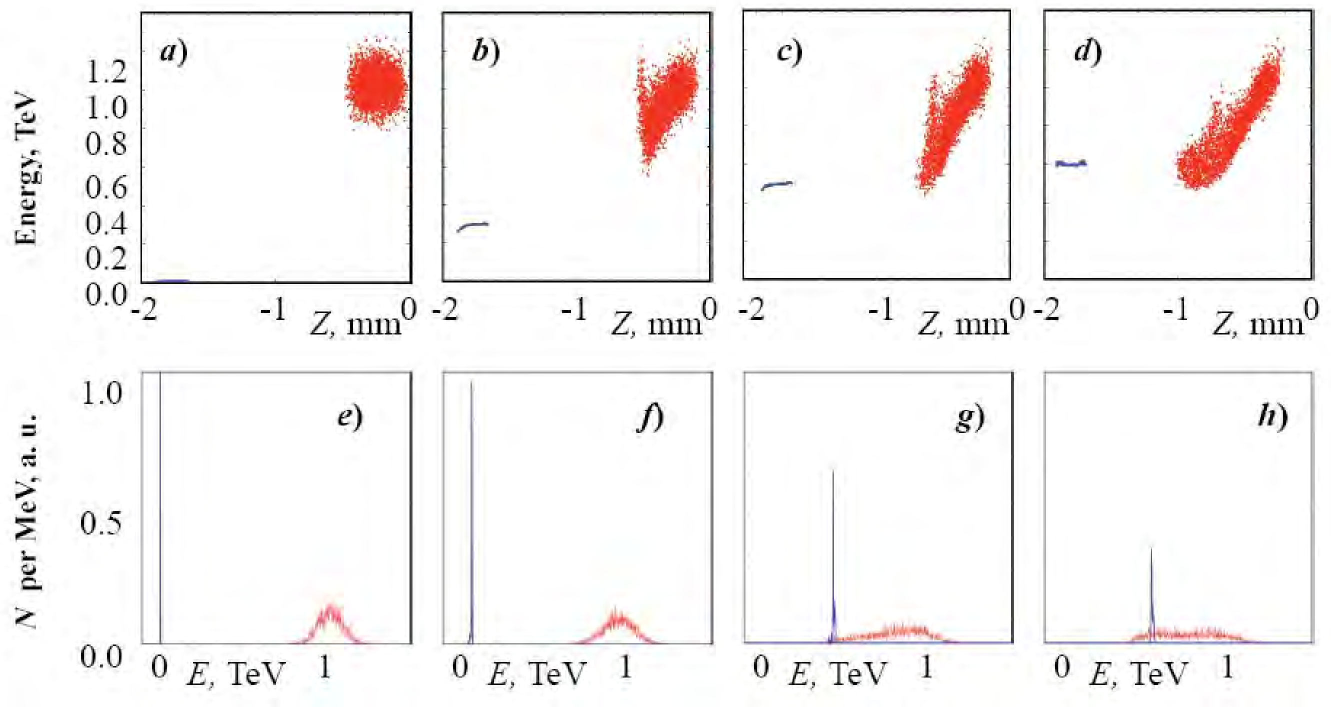


Fig. a-h), Snapshots of the combined longitudinal phase space of the driver and the witness bunches (energy versus coordinate) (a–d) and corresponding energy spectra (e–h). The snapshots are taken at acceleration distances *L*=0, 150, 300, 450 m. The electrons are shown as blue points and the protons are depicted as red points.

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

Energy gain & energy spread

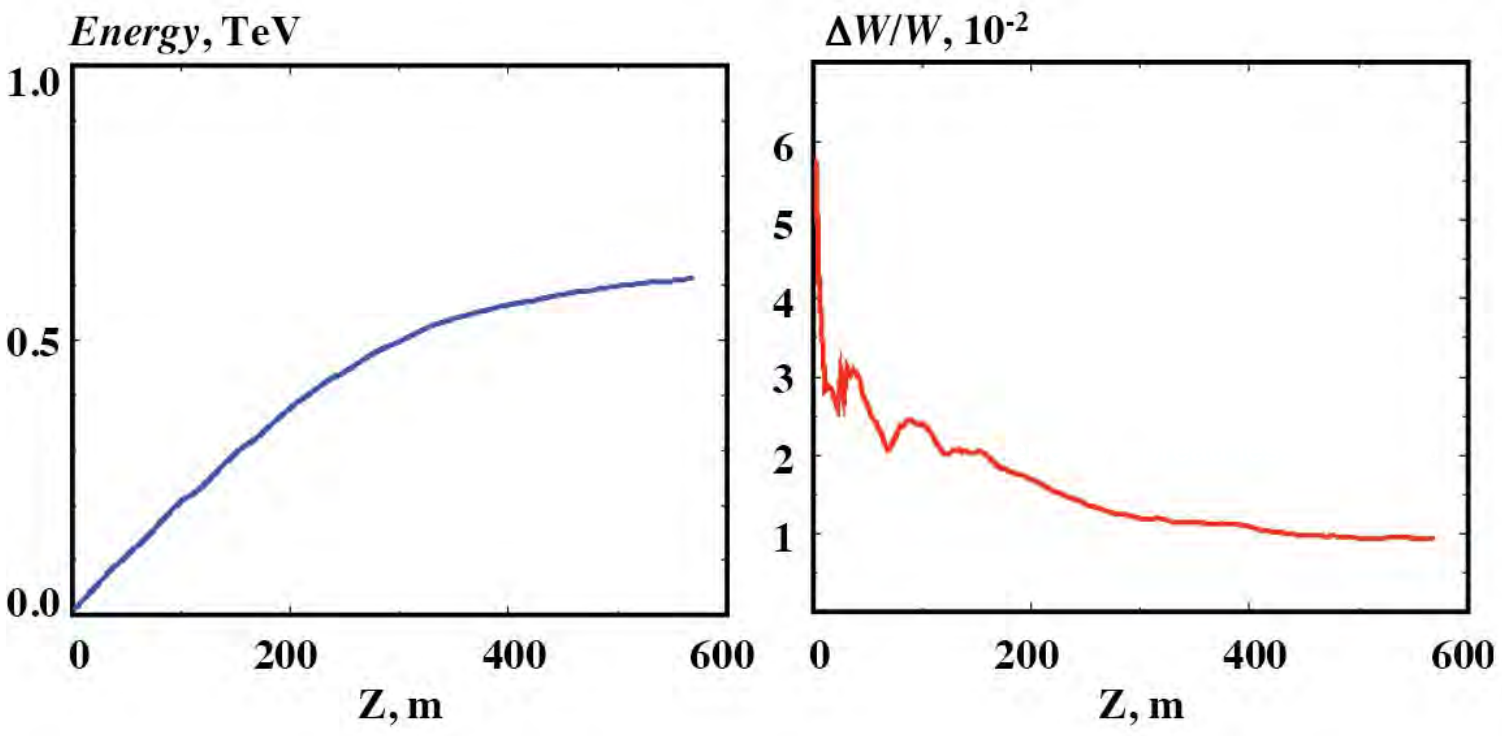


Fig. a,b), The mean electron energy in TeV (a) and the r.m.s. variation of the energy in the bunch as a percentage (b) as a function of the distance travelled in the plasma.

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

Simulation results

- Proton bunch can indeed to be used as the drive beam for exciting a large amplitude wakefield
- Proton-driven PWFA can bring a bunch of electrons to the energy frontier in only one stage.
- An unsolved questions, short beam!

Short proton bunch production

- 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
- Fast nanochoppers to get microbeam
- Conventional magnetic bunch compression*
- Plasma wakefield beam slicing via modulation

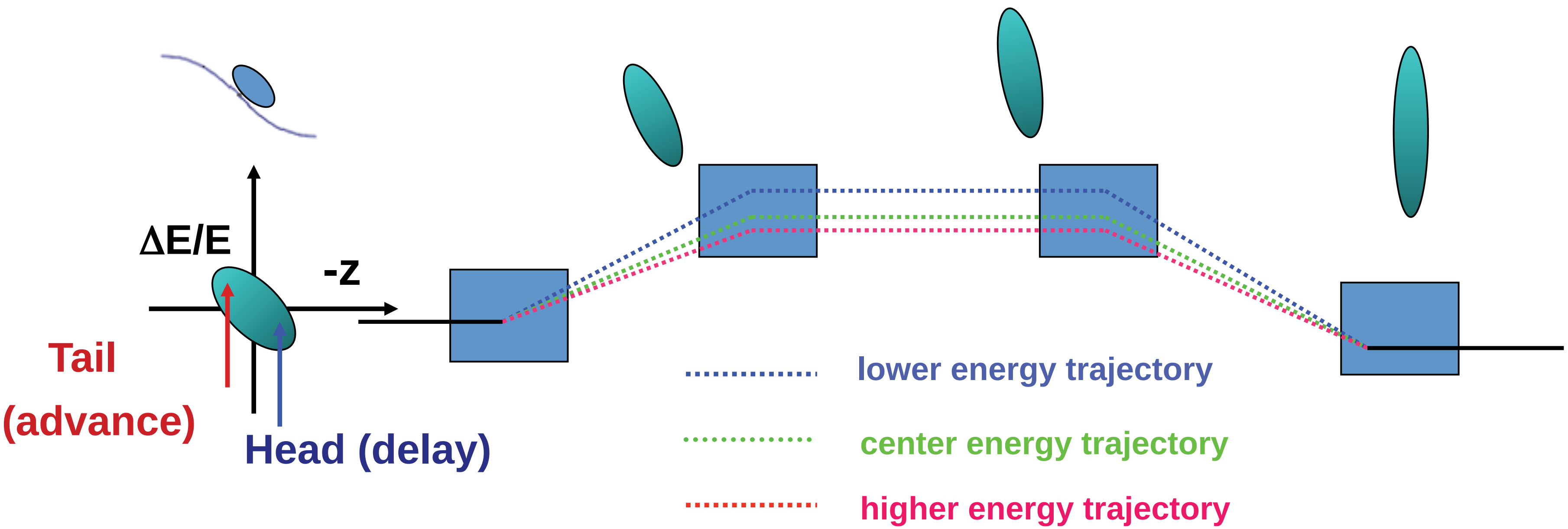
Magnetic bunch compression

- 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.



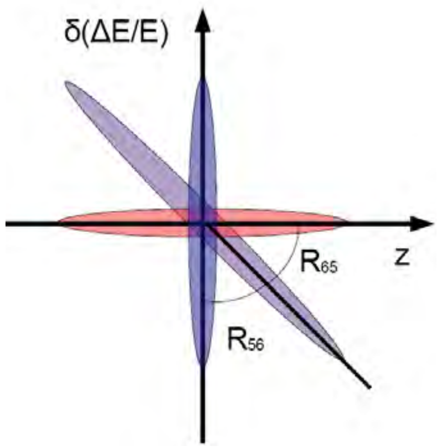
- To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.

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

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



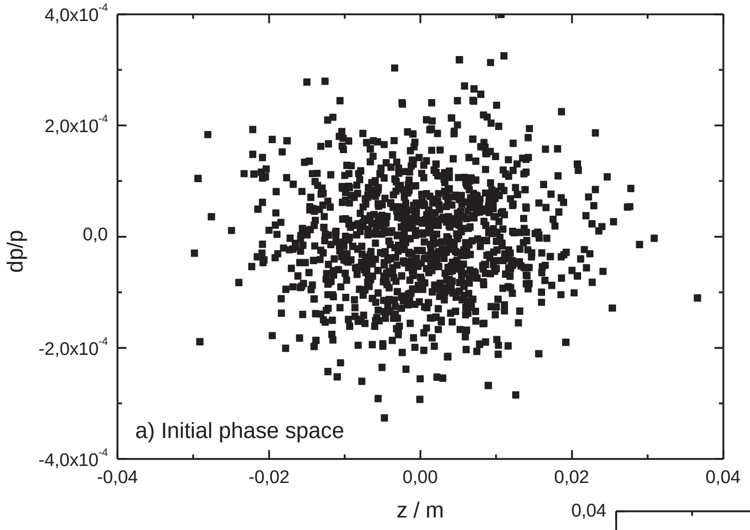
$$1+R_{56}R_{65}=0$$

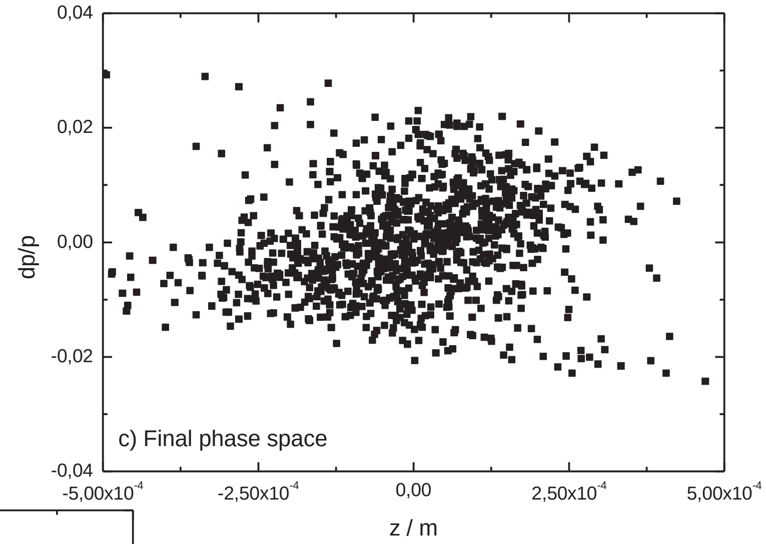
$$R_{65}=\frac{\delta}{z}=\frac{1}{z}\frac{\Delta E}{E}=\frac{eV_0}{E}\frac{\omega}{\beta c}$$

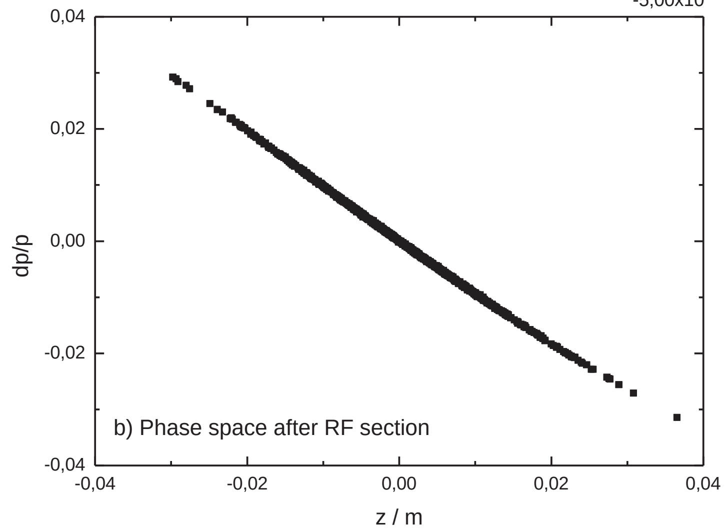
$$R_{56}=-2\theta_B\left(\frac{2}{3}L_B+\Delta L\right)$$

	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

Phase space of beam

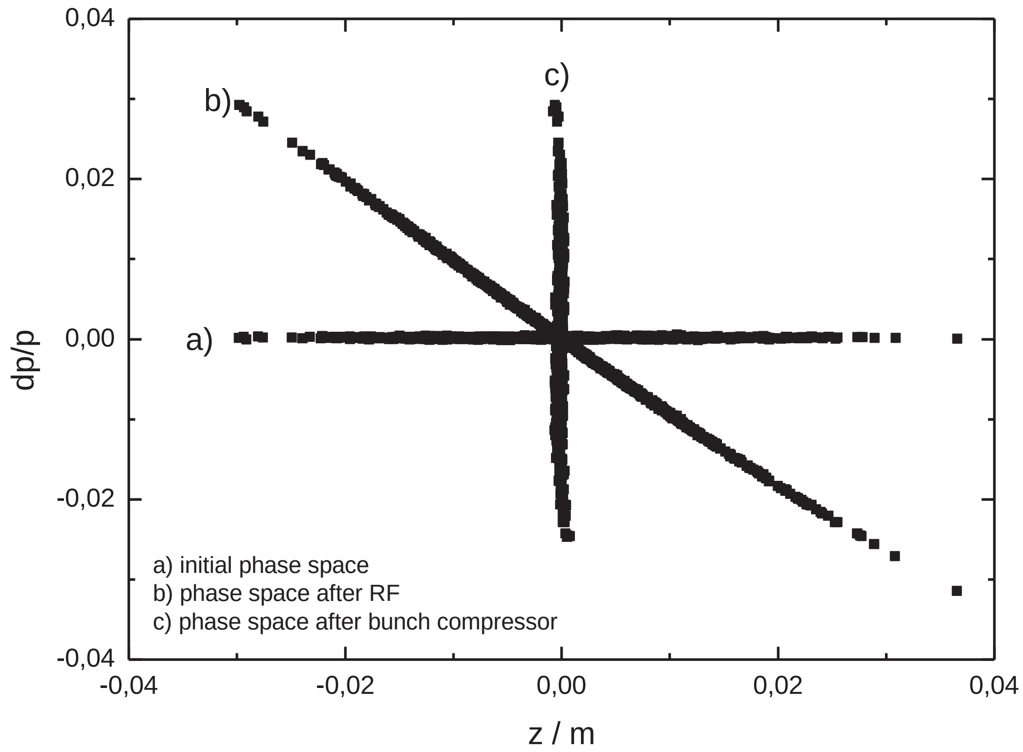






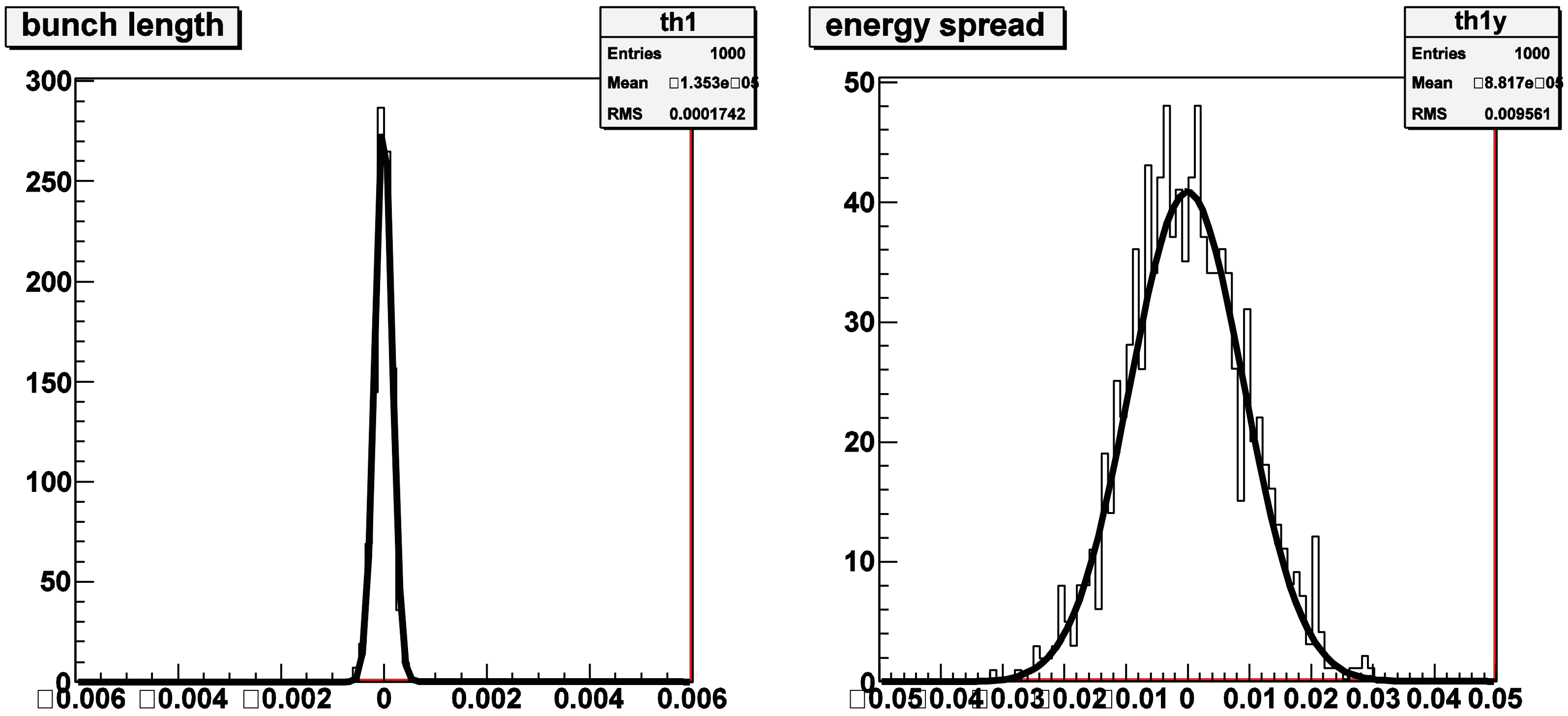
G. Xia, A. Caldwell et al.,
Proceedings of PAC09 (FR5RFP011)

Phase space of beam



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

Bunch length & energy spread

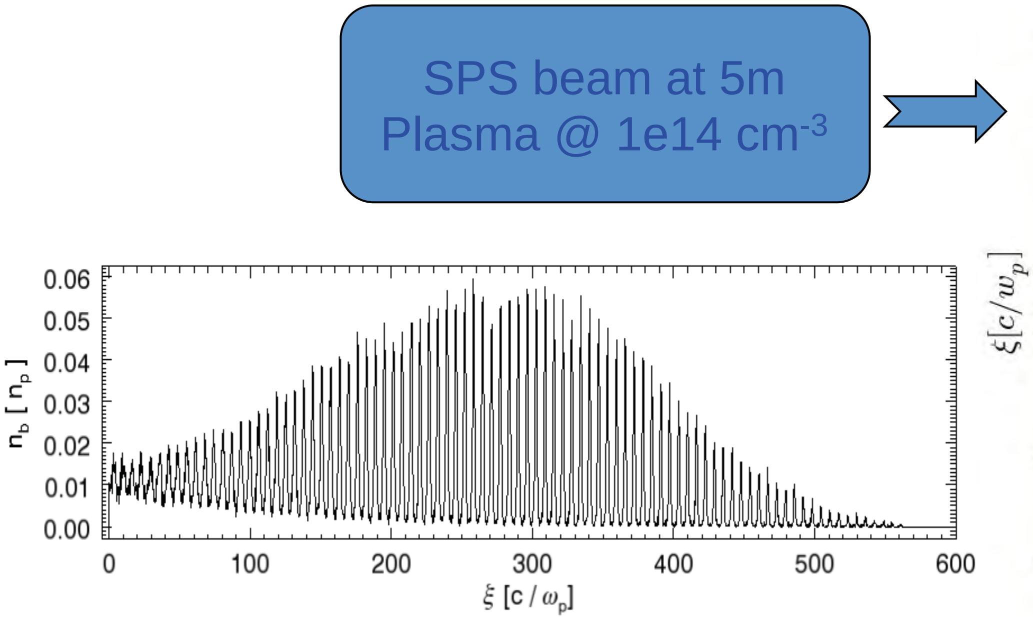


Fitting data show that the bunch length of 170 micron and the relative energy spread of 9e-3 can be achieved.

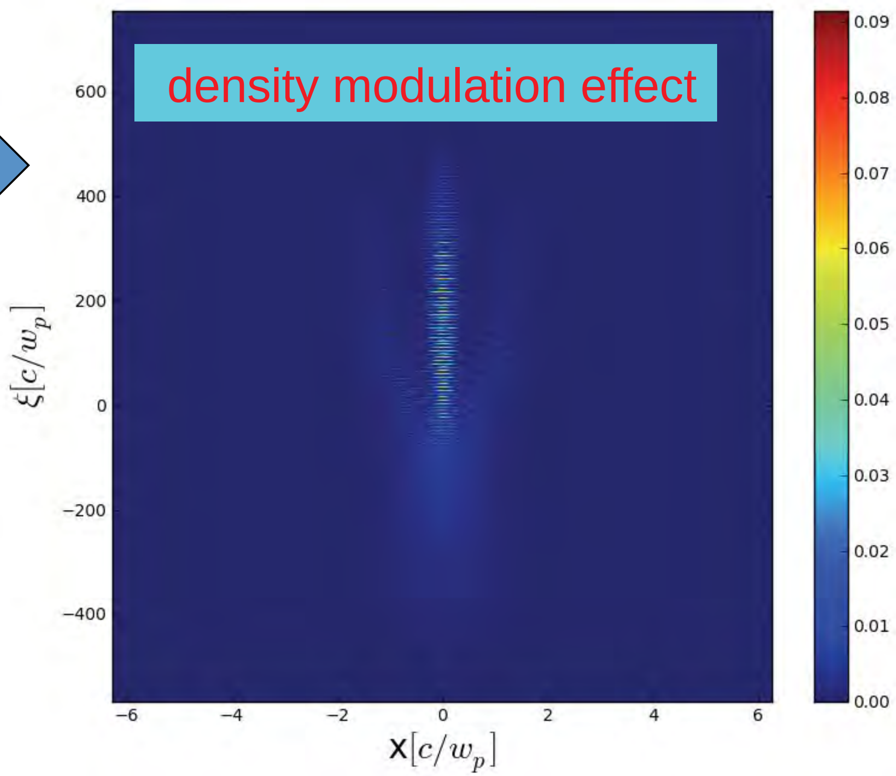
A. Caldwell, K. Lotov, A. Pukhov, G. Xia, Plasma Phys. Control. Fusion **53** (2011) 014003.

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.



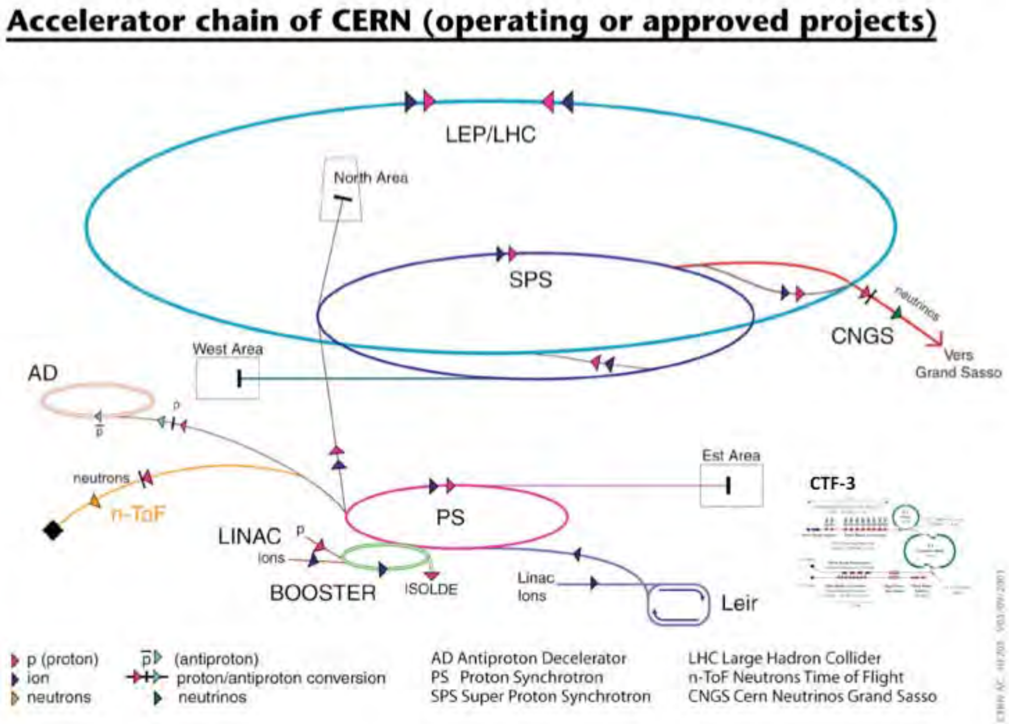
on-axis (X = 0) beam density profile after 5 m propagation in plasma



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

G. Xia, F.Zimmermann, et al., Proceedings of PAC09, (FR5RFP004)

Demonstration experiment at CERN



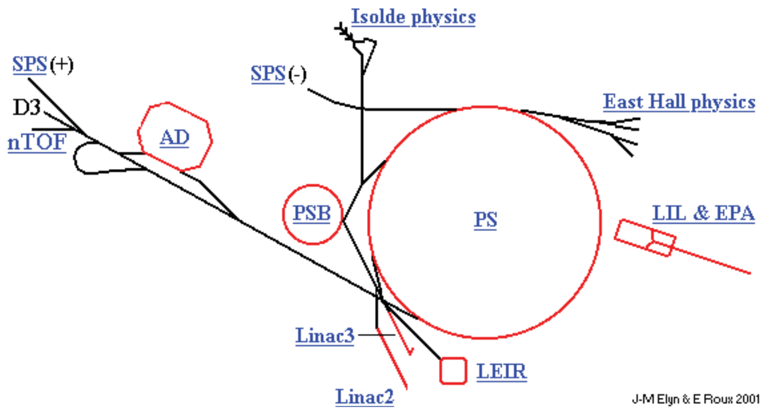
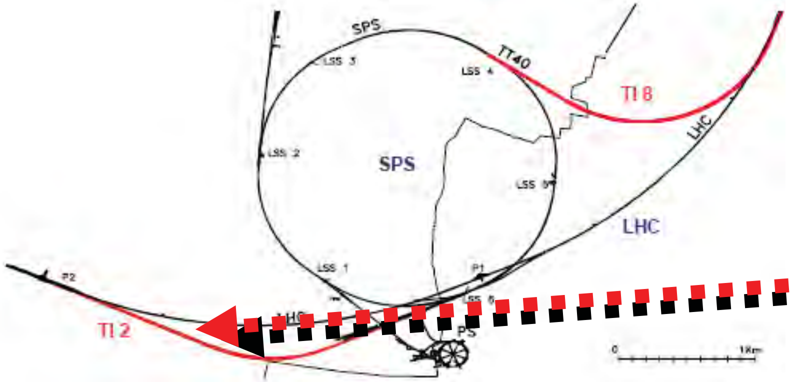


Figure: Beam lines … the PS East … T7 and T8 are near the bottom. The maximum length is below 100 m.



PS (East Hall Area) and **SPS** (West Area) could be used for our demonstration experiment

Long bunch modulation by wakefield

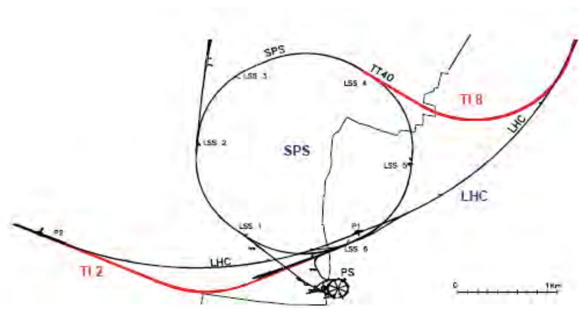
VLPL3D simulation

PS-beam:

10cm,10e11 p

Plasma: 10e13 1/cc

SPS beam for a test experiment



Super Proton Synchrotron-SPS	
Momentum [GeV/c]	450
Maximum protons/bunch [10^{11}]	1.15
rms bunch length [cm]	12
rms energy spread [10^{-4}]	2.8
rms transverse emittance [μm]	3.5
Bunch spacing [ns]	25

SPS beam for a test experiment

- large space available for SPS tunnel
- The SPS/LHC proton bunch has **excellent properties**:
  - Very stiff beam: can drive plasma without too much beam deterioration.
  - Well controlled and maintained (for LHC, CNGS, HiRadMat, …).
  - Variable in intensity (2e9-3.0e11) and emittance.
  - Carries significant stored energy for driving plasma waves:

- The issue is **how to couple** the proton energy to the plasma (via **modulation**):
  - CERN proton bunches are very long (120 mm), compared to the electron bunches used at SLAC (< 0.1 mm).
  - Plasma wavelength is at the 1 mm scale.
  - **How do we couple the proton beam energy into the plasma and then to the witness electron beam?**

Codes benchmarking

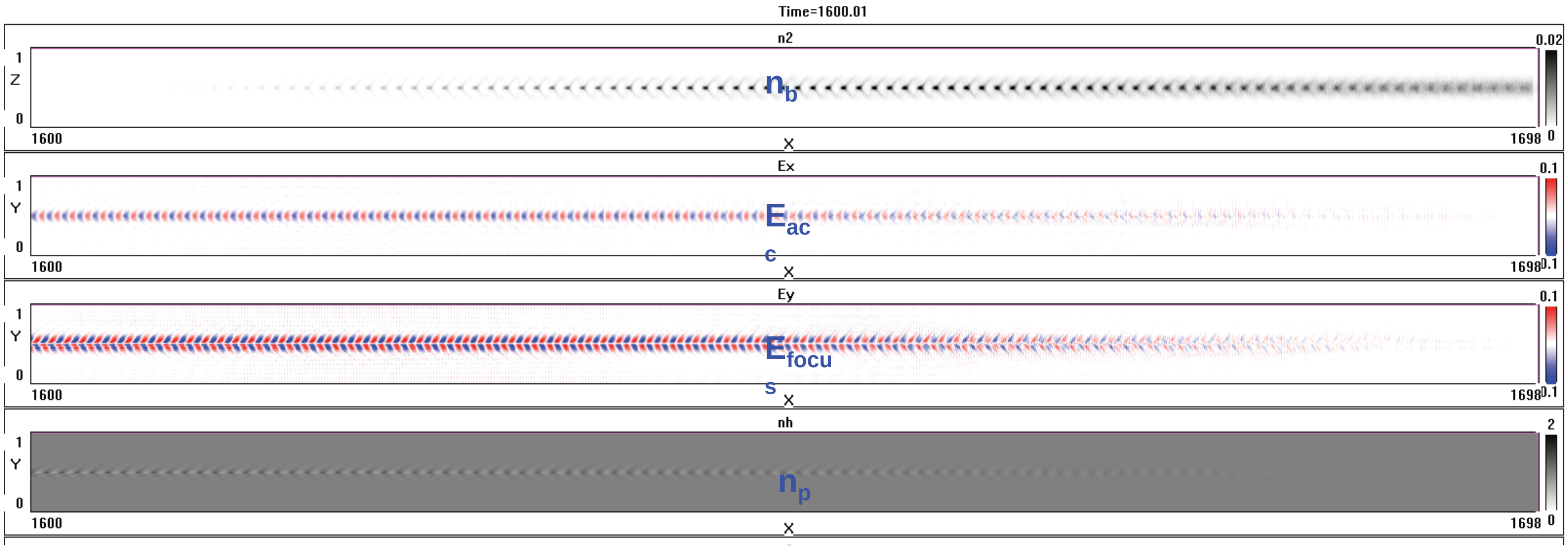
TABLE 1. PS, SPS and LHC parameter sets. The different symbols are defined in the text. SPS-LHC means the standard parameters of bunches in the SPS for injection into the LHC. SPS-Totem means the special parameters for bunches for use by the Totem experiment.

Parameter	PS	SPS-LHC	SPS-Totem	LHC
E_P (GeV)	24	450	450	7000
N_P (10^{10})	13	11.5	3.0	11.5
σ_{E_P} (MeV)	12	135	80	700
$\sigma_{z,0}$ (cm)	20	12	8	7.6
σ_r (μm)	400	200	100	100
c/ω_b (m)	2.3	4.0	3.2	6.3
σ_θ (mrad)	0.25	0.04	0.02	0.005
L_θ (m)	1.6	5	5	20
ϵ (mm-mrad)	0.1	0.008	0.002	$5 \cdot 10^{-4}$

Various particle-in-cell (PIC) codes are used to benchmark the results based on the same parameter set. Presently they show very good agreement

Seeding the instability

- Seed the instability via laser or electron beam prior to the proton beam (the instability will not start from random noise, rather from a well-defined seeded field
- The instability is seeded via half-cut beam (beam density abruptly increases)

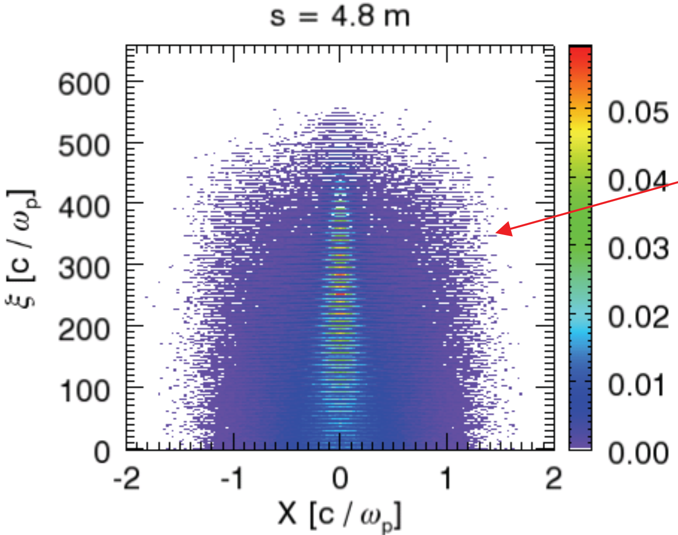


For SPS half-cut beam, at plasma density $n_p=10^{14}$ cm^{-3} ($\lambda_p \approx 3.33$ mm)
A strong beam density modulation is observed,
A nice wakefield structure is excited and
the wakefield amplitude is around 100 MV/m at 5 m plasma.

VLPL results from A. Pukhov

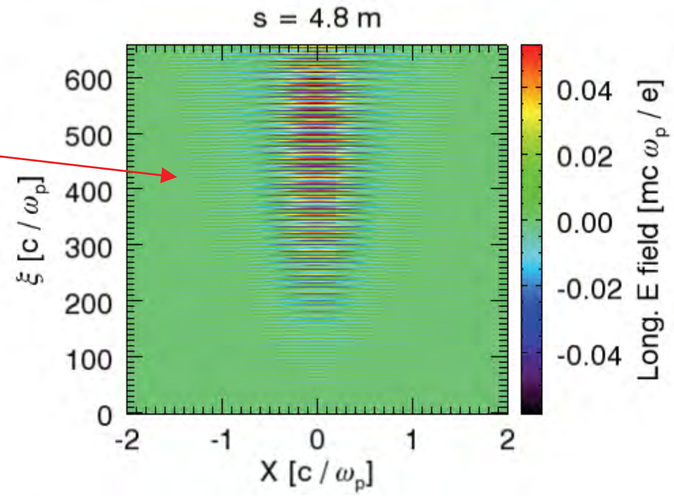
Simulations of SPS beam-driven PWFA

QuickPIC results

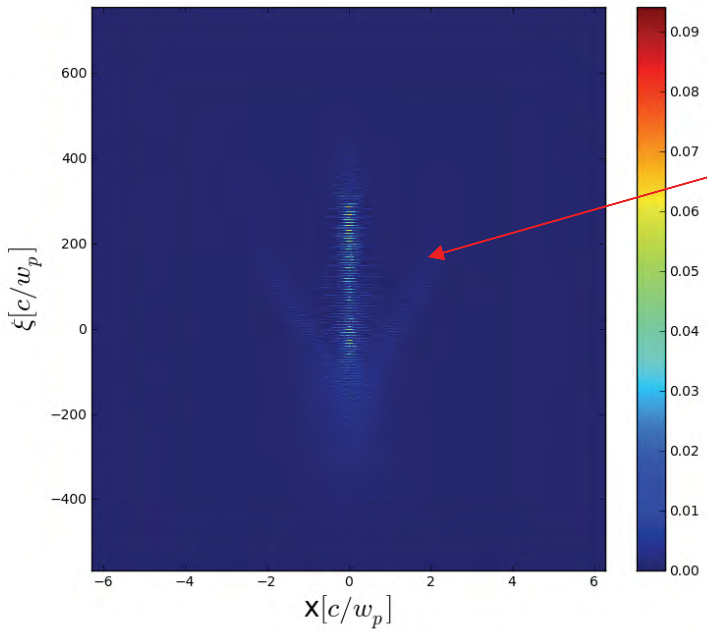


Beam density modulation

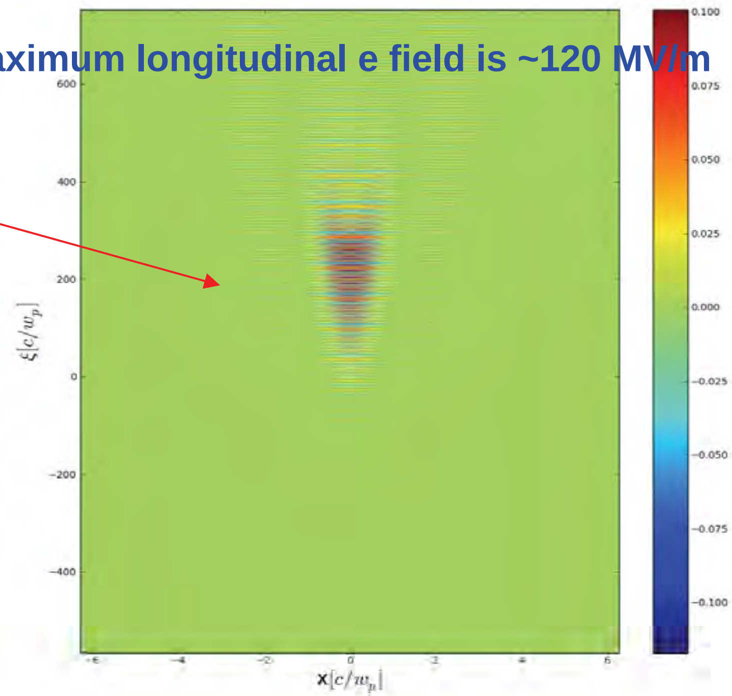
Half-cut
SPS beam
@4.8m plasma
(n_p=10^{14} cm^{-3})



Maximum longitudinal e field is ~120 MV/m



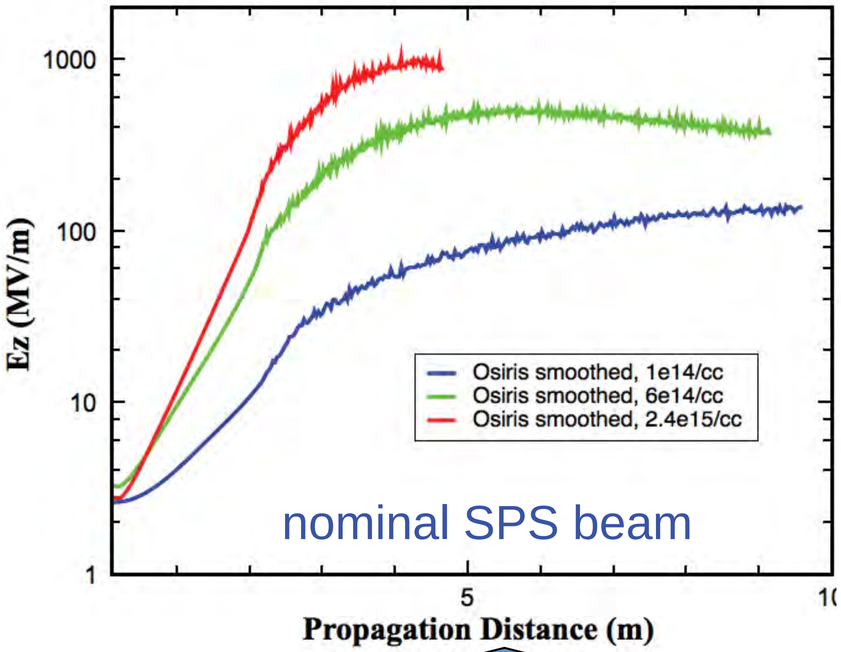
Full SPS beam
@ 10m plasma
(n_p=10^{14} cm^{-3})

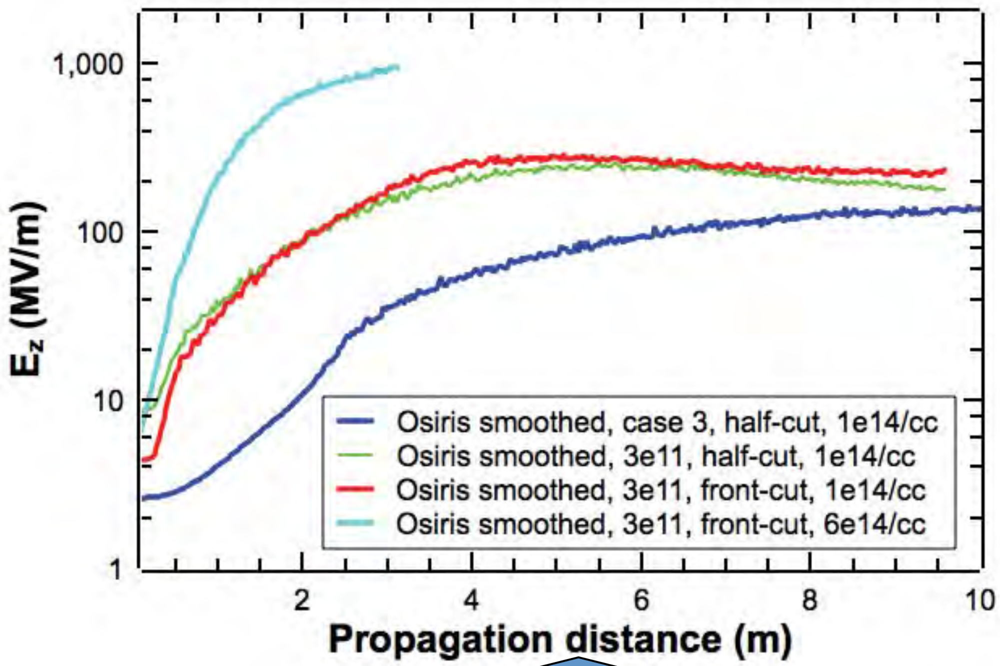


G. Xia, et al.,AIP Proceedings of Advanced Accelerators Concepts 2010, 510-515.

Simulations of SPS beam-driven PWFA

Simulation from 2D OSIRIS



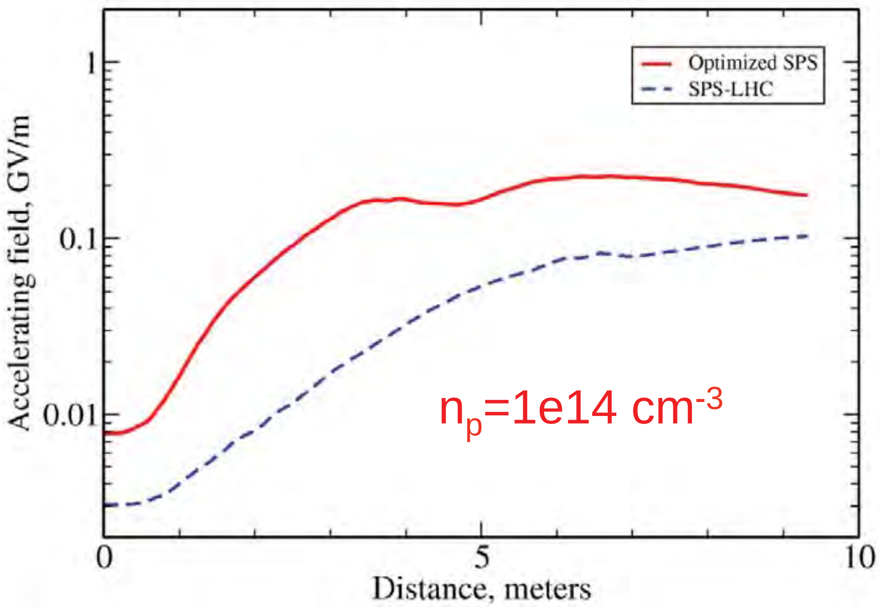


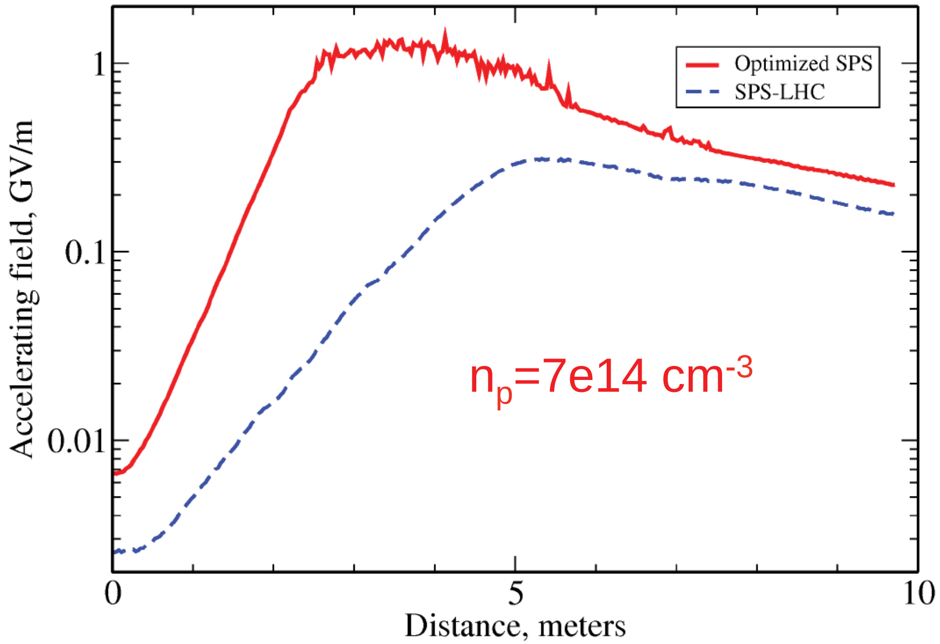
Bunch population, N_p	1.15×10^{11}
Bunch length, σ_z	12 cm
Beam radius, $\sigma_{x,y}$	200 µm
Beam energy, E	450 GeV
Energy spread, dE/E	0.03%
Normalized emittance, $\varepsilon_{x,y}$	3 µm
Angular spread, σ_θ	0.02 mrad

Bunch population, N_p	3×10^{11}
Bunch length, σ_z	8.5 cm
Beam radius, $\sigma_{x,y}$	200 µm
Beam energy, E	450 GeV
Energy spread, dE/E	0.04%
Normalized emittance, $\varepsilon_{x,y}$	2 µm
Angular spread, σ_θ	0.02 mrad

G. Xia, et al, Proceedings of PAC11 (MOP108), New York, 2011

Electron acceleration

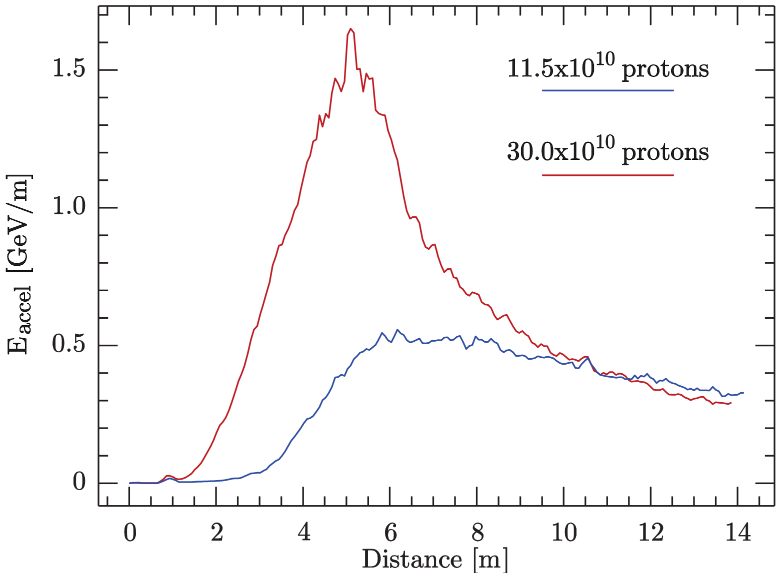


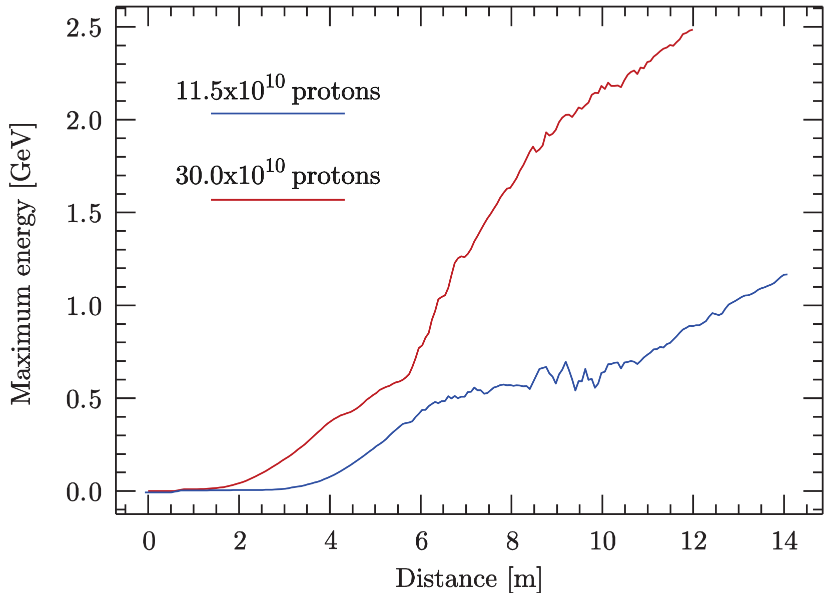


VLPL3D hydro-dynamic code (A. Pukhov)

10 MeV continuous e- beam to sample the wakefield

Electron acceleration





Plasma density in use: 7×10^{14} cm^{-3}

	SPS-LHC	SPS-Opt.
Beam energy [GeV]	450	450
Bunch population [10^{11}]	1.15	3.0
Beam radius [μm]	200	200
Angular spread [mrad]	0.04	0.04
Normalized emittance [μm]	3.5	3.5
Bunch length [cm]	12	12.4
Energy spread [%]	0.03	0.03

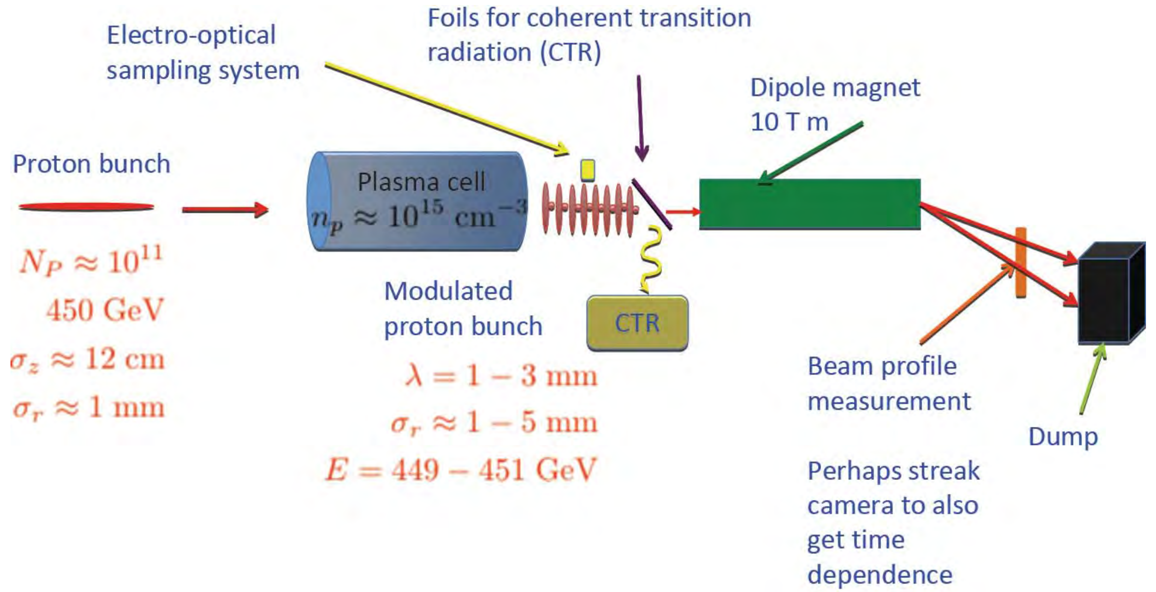
G. Xia, et al, Proceedings of PAC11 (TUOBN5), New York, 2011

Demonstration experiment at CERN

Scientific Goal of Experiments:

- Initial goal is to observe the energy gain of 1 GeV in 10 m plasma.
- A plan for reaching 100 GeV within 100 m plasma will be developed based on the initial round of experiments
- The very high energy electron beam achieved by using the LHC-like high energy beam

Experimental Setup:

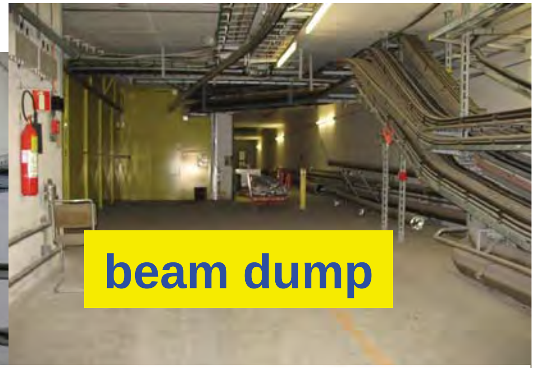


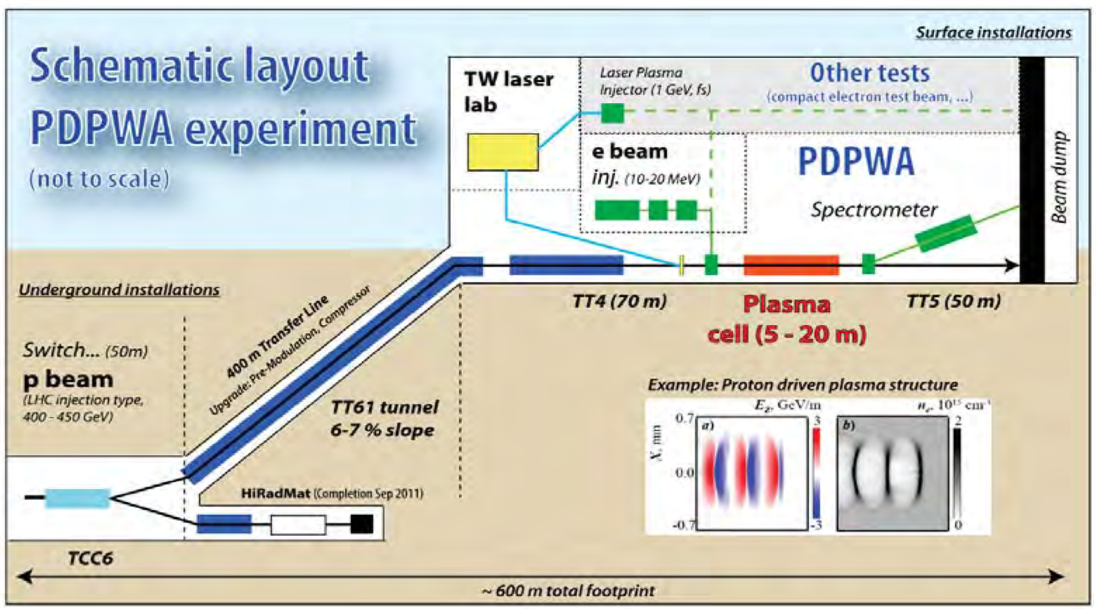
Expected Results:

- A long SPS drive beam (without compression) will be used in the first experiment. a self-modulation of the beam due to two-stream instability which produces many ultrashort beam slices at plasam.
- The modulation resonantly drives wakefield in the 200-500 MV/m with CERN SPS beam.
- Simulation shows with the optimum beam and plasma parameters, ≥ 1 GV/m field can be achieved in the experiment.

Demonstration experiment at CERN

- PD-PWFA has the potential to accelerate electron beam to the TeV scale in a single stage. As a first step, we would like to demonstrate the scaling laws of PD-PWFA in an experiment with an existing beam
- kick-off meeting-PPA09 held at CERN in December 2009
- A spare SPS tunnel is available for demonstration experiment
- With no bunch compression in the beginning





http://indico.cern.ch/conferenceDisplay.py?confId=745

http://cerncourier.com/cws/article/cern/41714

G. Xia et al, Proceedings of PAC11 (TUOBN5), New York, 2011

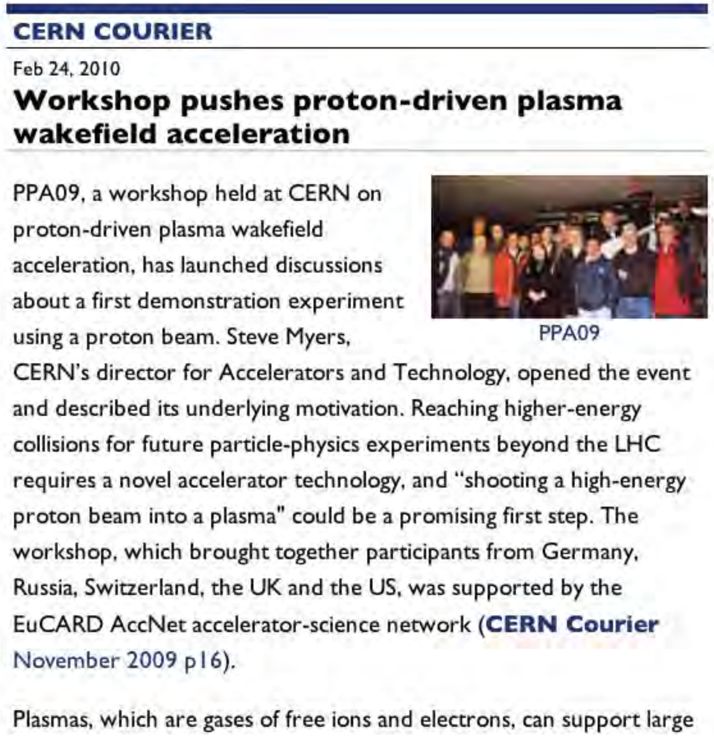
CERN's interest

PDPWFA collaboration:

•Several workshops, biweekly phone meeting, and site visit at CERN, strong collaboration team.

•Sumbitted the LoI in June to CERN

•Proposal defense at 102 SPSC meeting on June 28, 2011



CERN COURIER

Feb 24, 2010

Workshop pushes proton-driven plasma wakefield acceleration

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).

PPA09

Plasmas, which are gases of free ions and electrons, can support large

Steve Myers

CERN Director of Accelerators & Technology

"CERN is very interested in following and participating in novel acceleration techniques, and has as a first step agreed to make protons available for the study of proton-driven plasma wakefield acceleration."

AWAKE

- **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  - Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

- Proof-of-Principle Accelerator R&D experiment at CERN
  - First proton driven wakefield experiment worldwide
  - **Study the Self-Modulation Instability**
  - **Demonstration of high-gradient acceleration of electrons**
  - Approved in 2013
  - First beam expected in **2016**

- AWAKE Collaboration: 16 Institutes world-wide
  - Spokesperson: Allen Caldwell, MPI Munich
  - Deputy Spokesperson: Matthew Wing, UCL
  - Physics and Experiment Coordinator: Patric Muggli, MPI Munich
  - Simulation Coordinator: Konstantin Lotov, BINP
  - Technical Coordinator and CERN AWAKE Project Leader: Edda Gschwendtner, CERN
  - Deputy: Chiara Bracco, CERN

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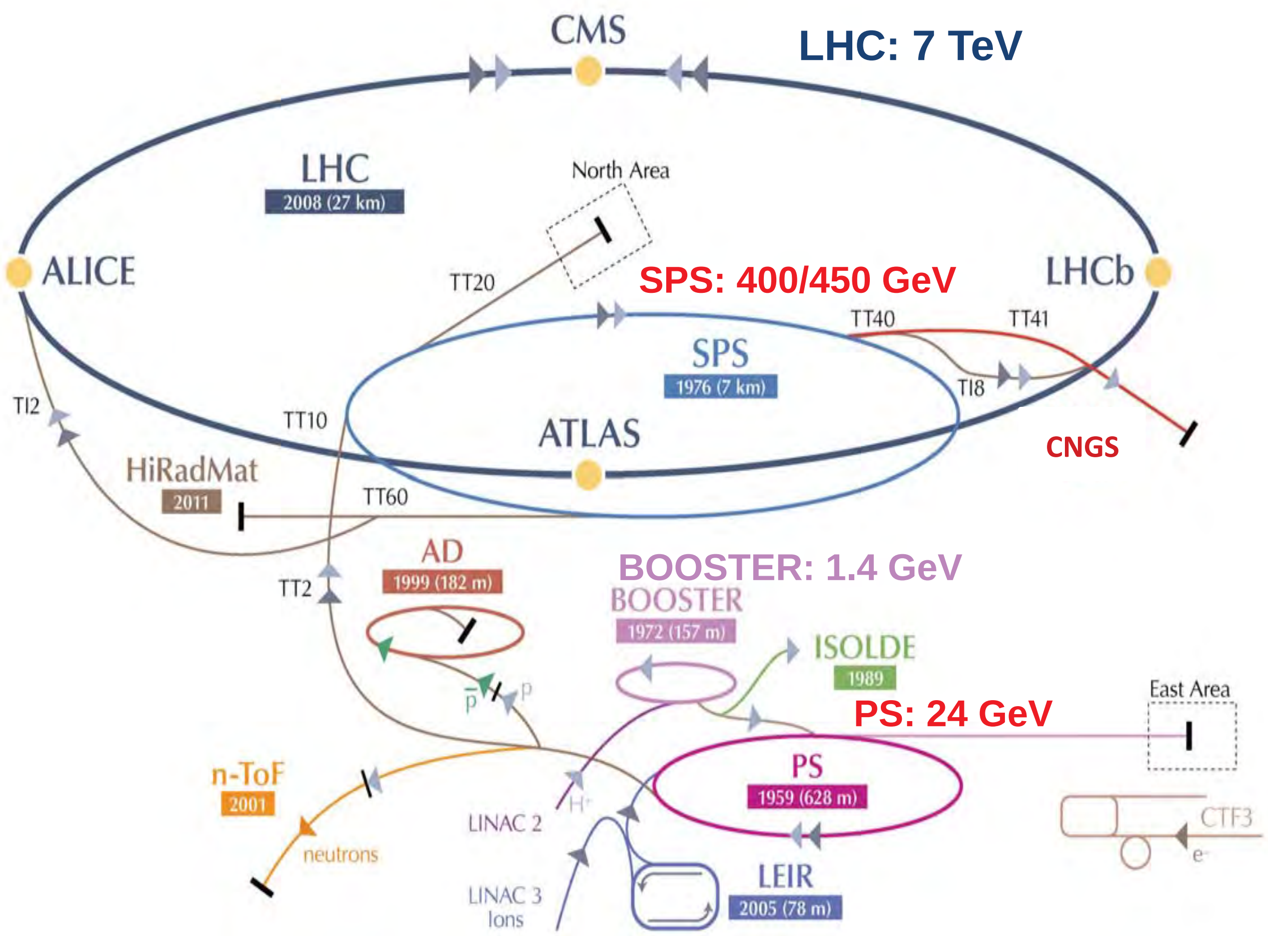
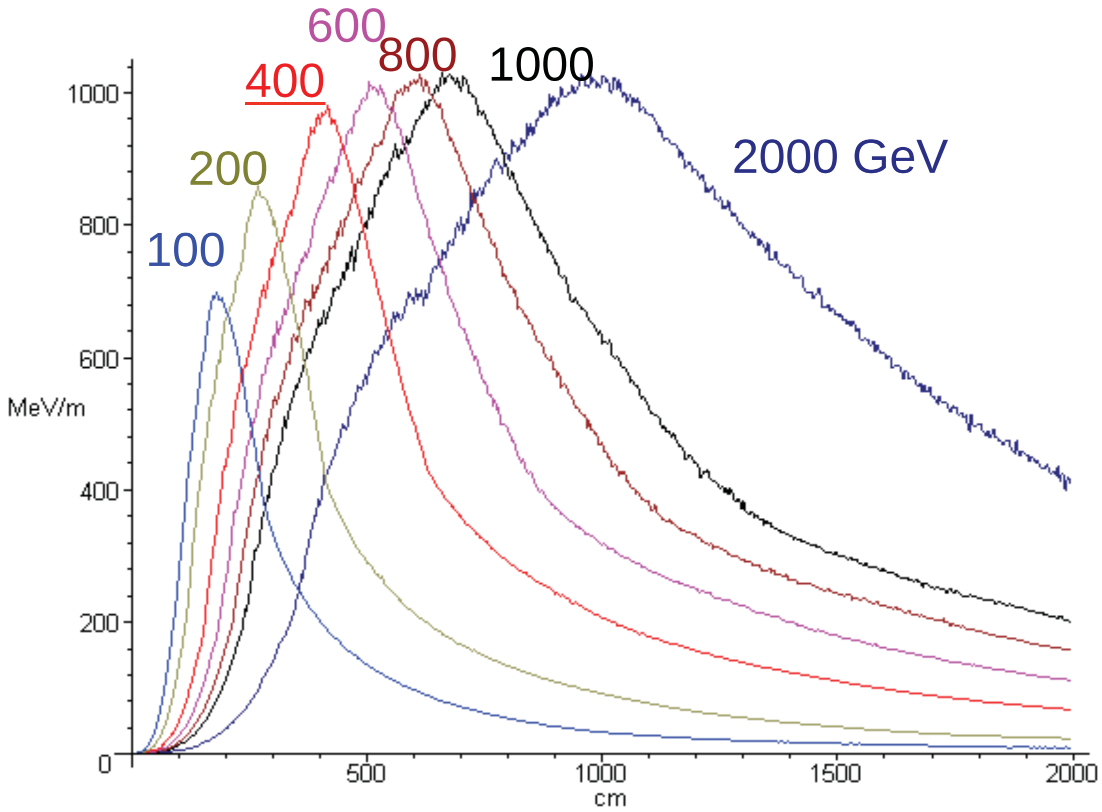
Drive Beam

In 2011:
5.3 10^{16} protons to LHC

1.37 10^{20} protons to CERN's Non-LHC Experiments and Test Facilities



Drive Beam: which proton energy?



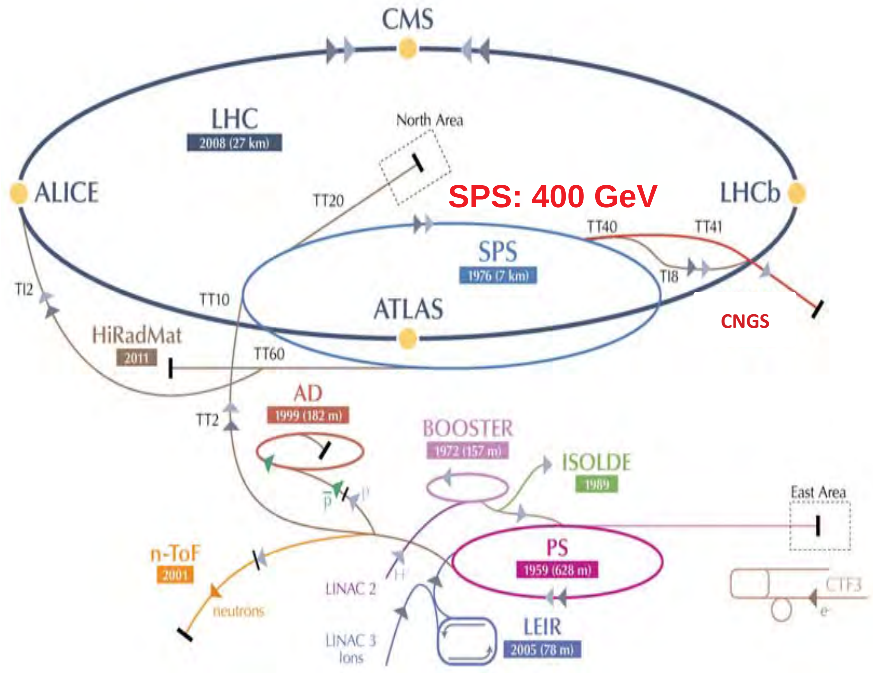
Variation of driver energy at constant normalized emittance

SPS-AWAKE parameters

K. Lotov et al., Physics of Plasma, 21, 083107 (20:

Drive Beam: SPS Proton Beam

➔ SPS Beam at 400 GeV/c



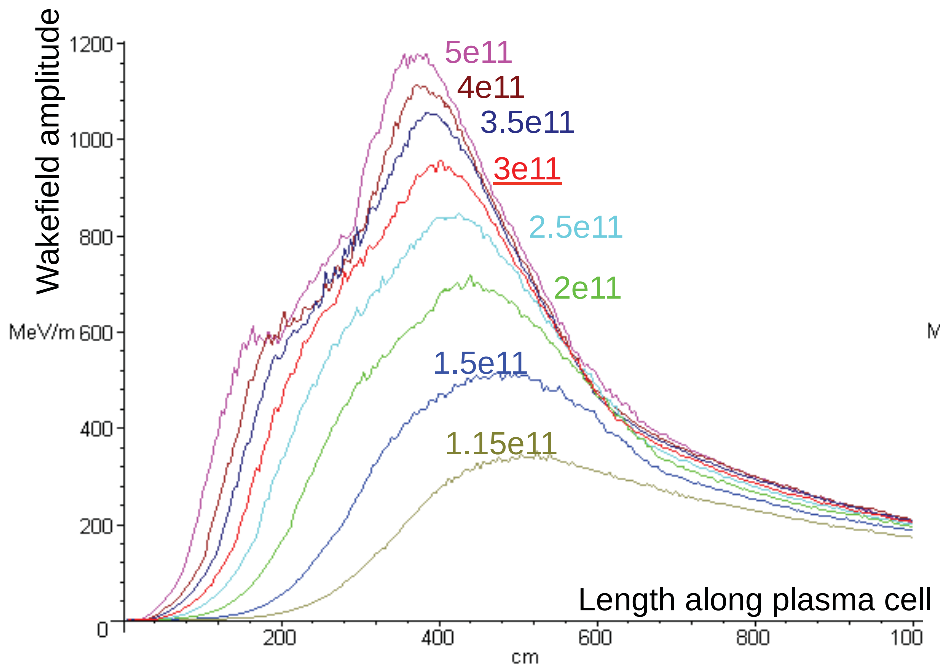
AWAKE will be installed in the CNGS, CERN Neutrinos to Gran Sasso, experimental facility.
CNGS physics program finished in 2012.

→ Proton beam for AWAKE requires:

– High charge
– Short bunch length
– Small emittance

Drive Beam: proton beam sensitivity

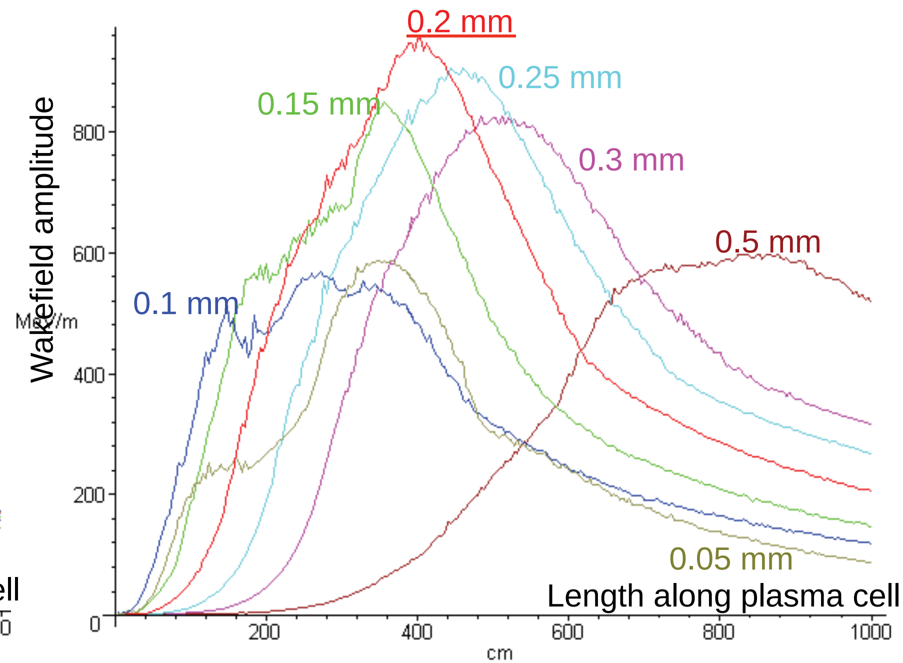
Proton beam population



The baseline regime is close to the limit (~40% of wave-breaking field)

Further increase of population does not result in proportional field growth.

Proton beam radius



Wide beams are not dense enough to drive the wave to the limiting field.
Narrow beams are quickly diverging due to the transverse emittance.

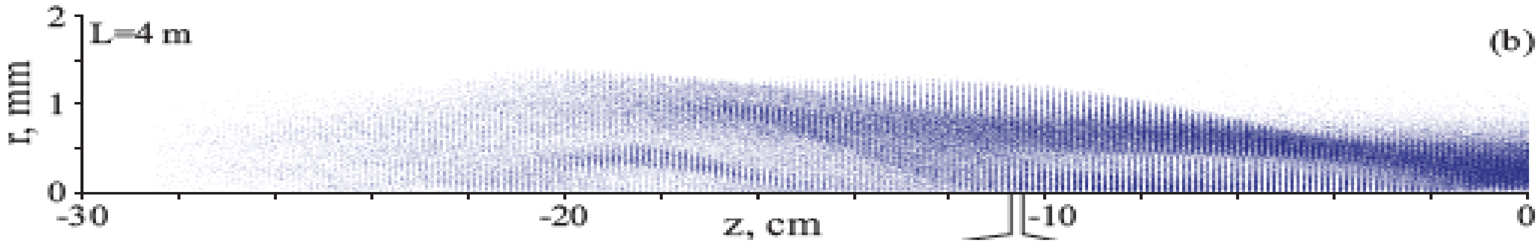
➔ Baseline radius is the optimum one for this emittance.

K. Lotov et al., Physics of Plasma, 21, 083107 (2014)

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%

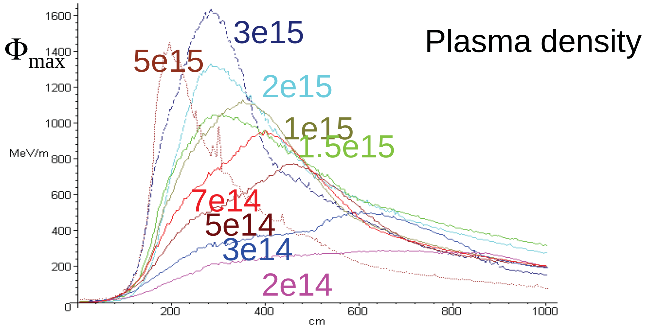
Long proton beam σ_z = 12cm! ←→ Compare with plasma wavelength of λ = 1mm.
→ Experiment based on Self-Modulation Instability!



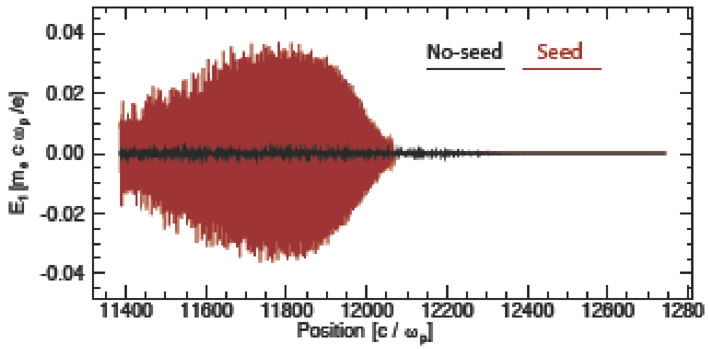
Self-modulation instability of the proton beam: modulation of a long (SPS) beam in a series of 'micro-bunches' with a spacing of the plasma wavelength.

Plasma Source: Requirements

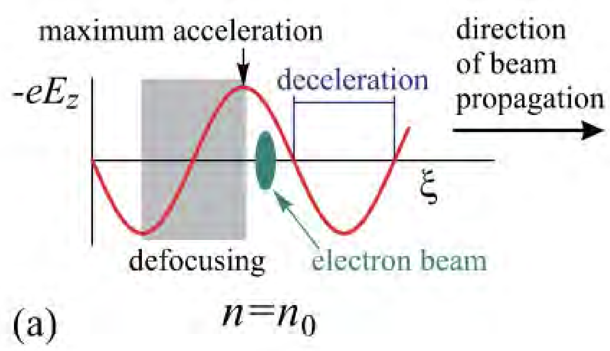
- Reach a strong wakefield
  - $E_z \ \alpha \ (n_e)^{-1/2}$



- Seeding of the SMI is necessary
  - Seeding shortens the length in the plasma
    - → until the SMI reaches saturation.
  - Fixes the phase of the wakefields
    - → deterministically inject the witness electron beam.
  - ➔ **Seeding**

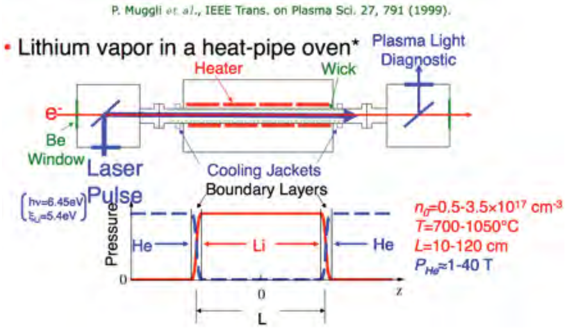


- Witness beam: very sensitive to the wakefield phase.
  - If λ_p changes locally, the witness electrons will be defocussed
  - → Wakefield phase is determined by the plasma density:
  - → Density must be constant with an accuracy of $\lambda_{pe}/4\sigma_z$
  - ➔ **$\Delta n/n \leq 0.002$**

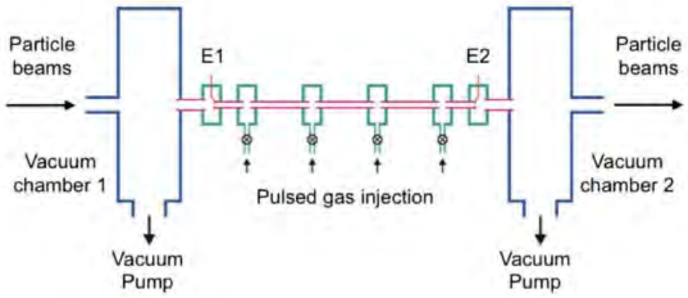


Plasma Sources: different types

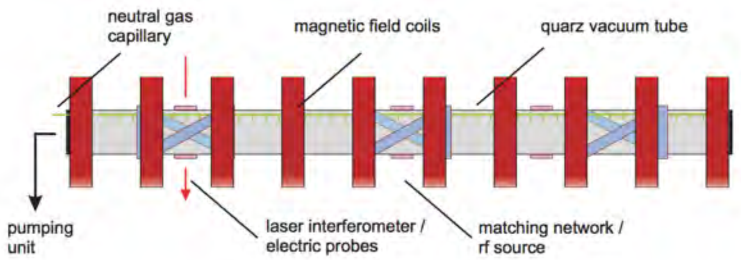
- Metal Vapor Source (Li, Cs, Rb) → SLAC experiments
  - Very uniform, very well known
  - Ionization with laser. Scaling to long lengths?



- Discharge plasma source
  - Simple, scalable
  - Uniformity? Density?

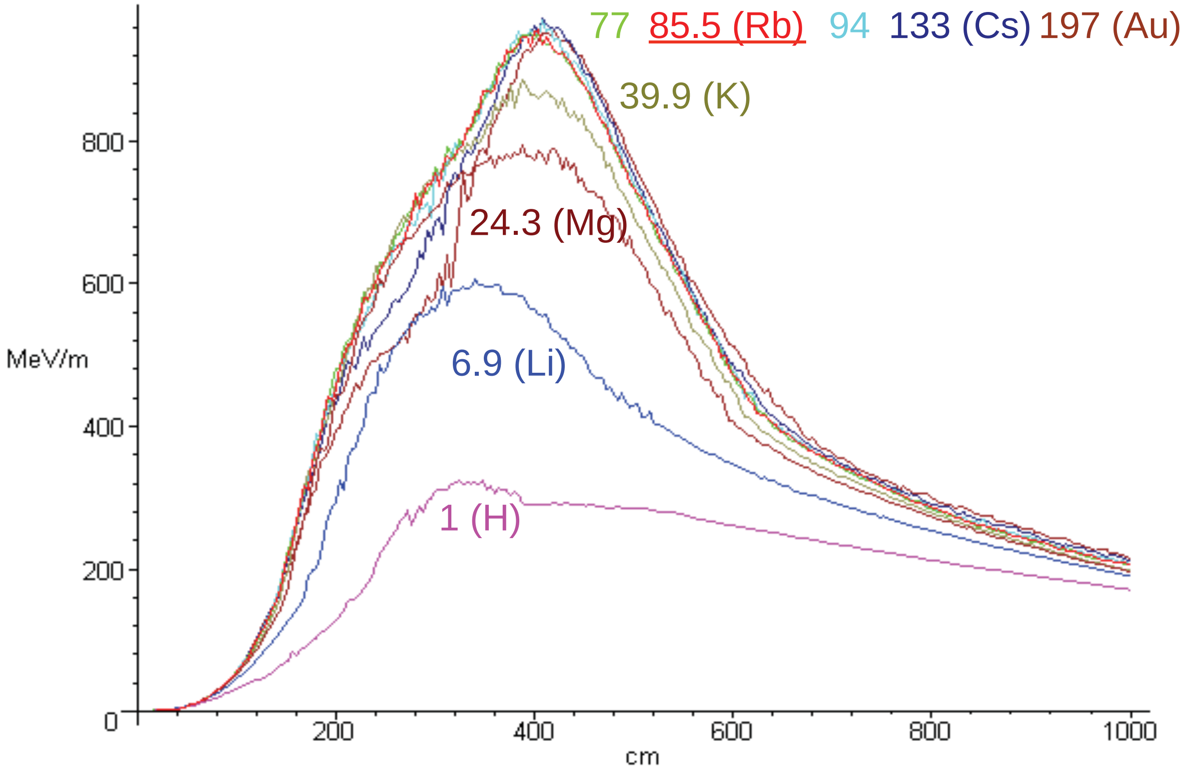


- Helicon source
  - Scalable, density recently achieved.
  - Uniformity?



Various sources

Maximum wakefield amplitude vs ion mass



Rubidium is heavy enough to have no problems with ion motion

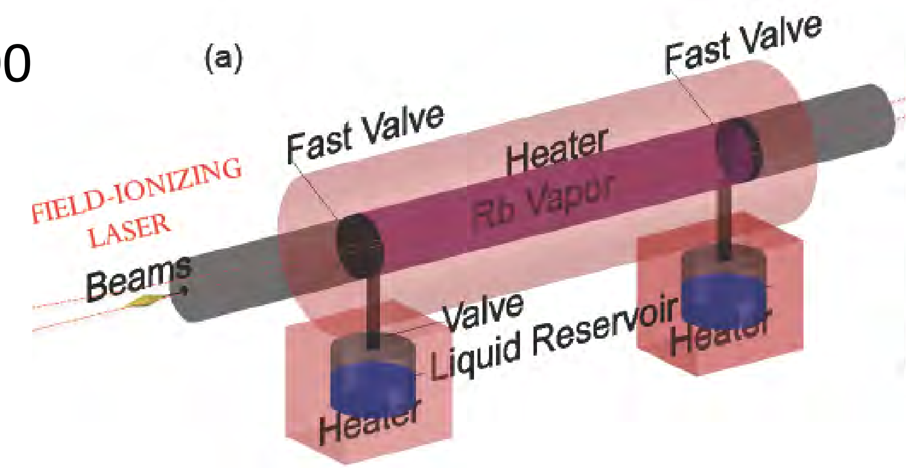
Rubidium Vapor Source

- Density adjustable from $\mathbf{10^{14} – 10^{15}\ cm^{-3}}$
- 10 m long, 4 cm diameter

- Plasma formed by field ionization of Rb
  - Ionization potential Φ_{Rb} = 4.177eV
  - above intensity threshold (I_{ioniz} = 1.7 x 10^{12}W/cm^2) 100% is ionized.

- Plasma density = vapor density

- System is oil-heated: 150˚ to 200
  → keep temperature uniformity
  → Keep density uniformity



Required:
$\Delta n/n = \Delta T/T \leq$ 0.002

Plasma Source: Rubidium Vapor

- Fast valves at both ends
  → separation of plasma from SPS beam vacuum.
  → Must be opened when laser/electron/proton passes through.

Plasma Source

- Rubidium Vapor Source is used
  - Ionization with laser beam

- Density uniformity of 0.2% required

- Seeding of SMI is needed in the plasma cell
  - Use laser beam for seeding

Laser Beam

- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of r > 3σ = 600 μm.

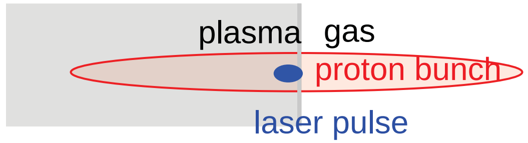
Laser Beam	
Laser type	Fiber Ti:Sapphire
Pulse wavelength	λ_0 = 780 nm
Pulse length	100-120 fs
Pulse energy (after compr.)	**450 mJ**
Laser power	4.5 TW
Focused laser size	$\sigma_{x,y}$ **= 1 mm**
Rayleigh length Z_R	5 m
Energy stability	±1.5% r.m.s.
Repetition rate	10 Hz

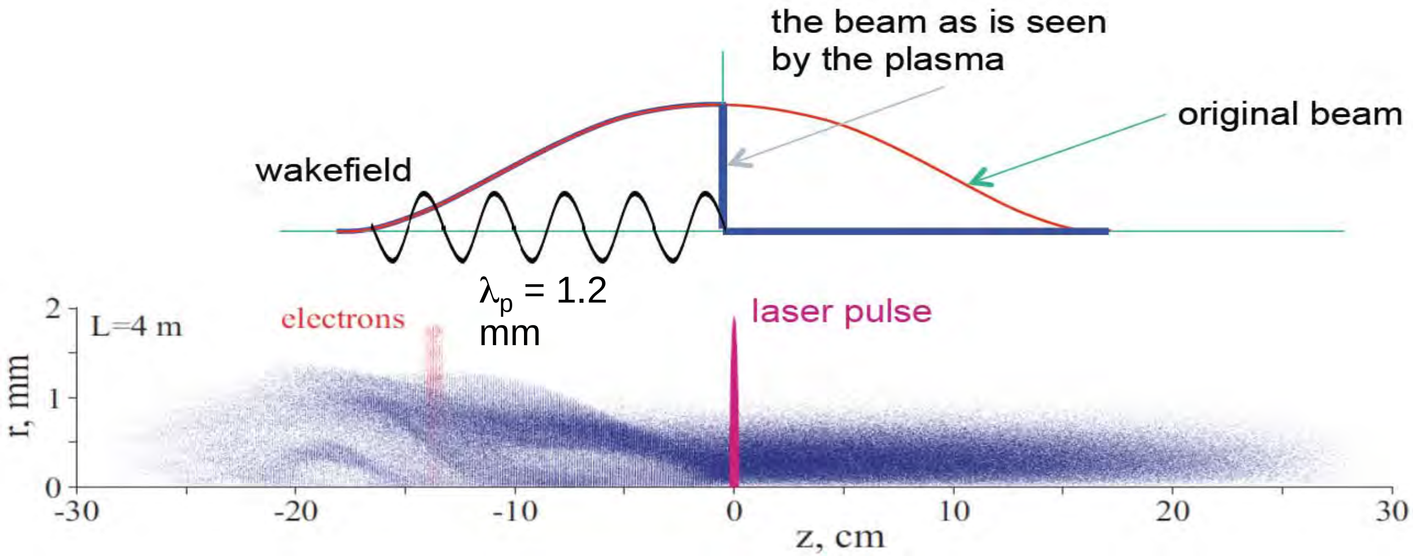
- Summary: ➔ 4.5 TW Laser for ionization and seeding

Proton Bunch Modulation

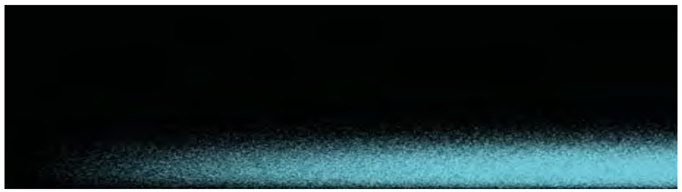
Self-Modulation Instability (SMI):

- Laser beam co-moving within the proton bunch effectively seeds the SMI
  - Laser pulse creates the ionization front
  - Ionization front acts as if long proton bunch is sharply cut
  - Laser pulse excites wakes to directly seed the self-modulation instability
  - grows exponentially until fully modulated and saturated.





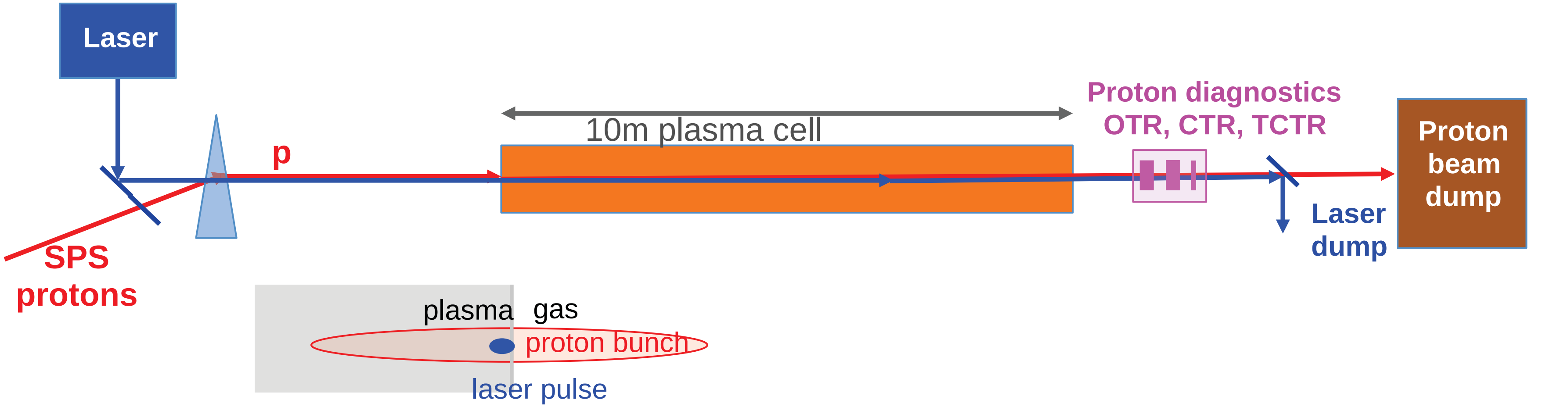
N. Kumar, A. Pukhov, K. Lotov, Phys. Rev. Letters (2010):



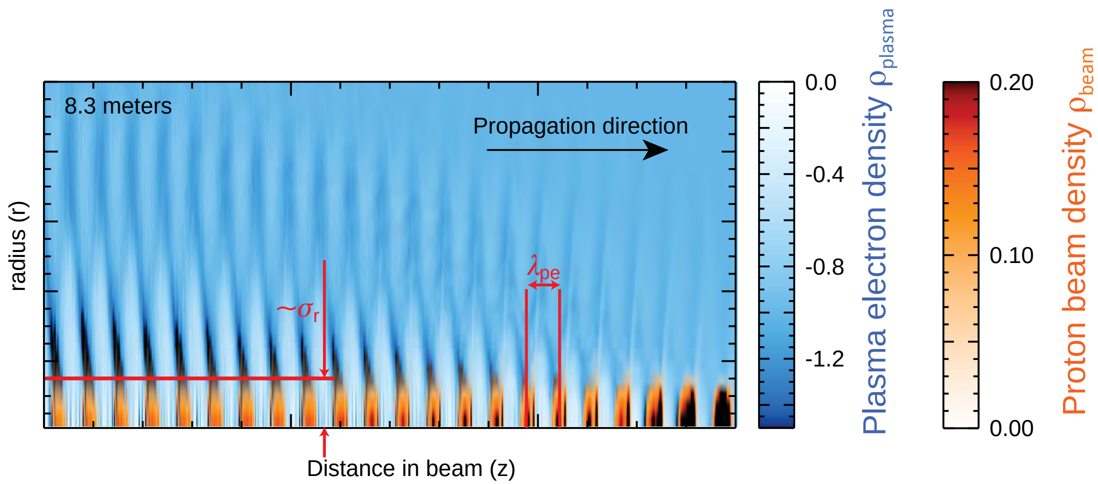
Self-modulated proton bunch resonantly driving plasma wakefields.

AWAKE: 1st Experimental Phase

- 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.



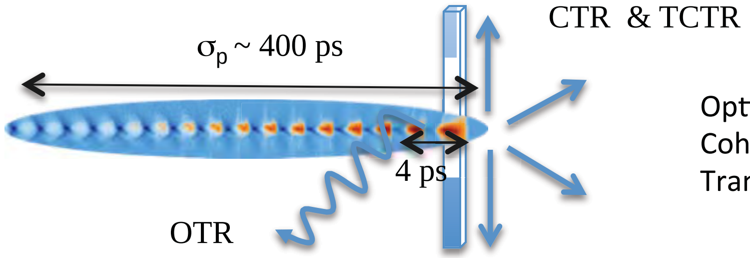
J. Vieira et al PoP 19063105 (2012)

Drive Beam Diagnostics

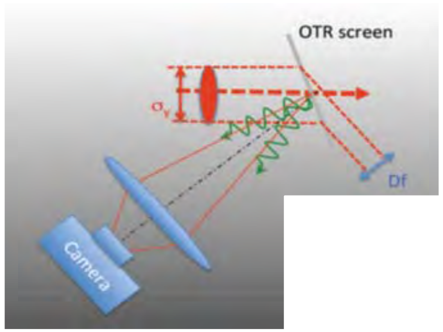
Direct Measurement of self-modulation instability of the proton beam

→ 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.

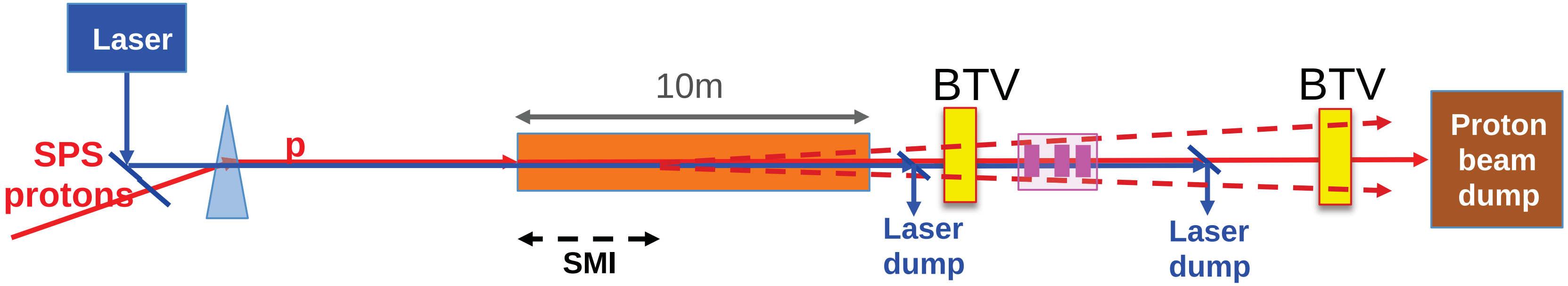


Optical Transition Radiation (OTR)
Coherent Transition Radiation (CTR)
Transverse Coherent Transition Radiation (TCTR)



Indirect Measurement by observing the proton bunch defocusing downstream the plasma

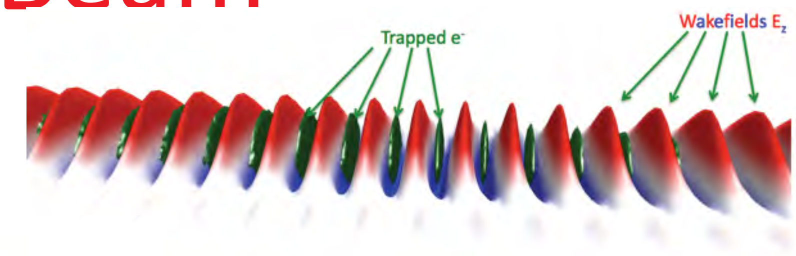
→ Proton bunch: 1mrad divergence

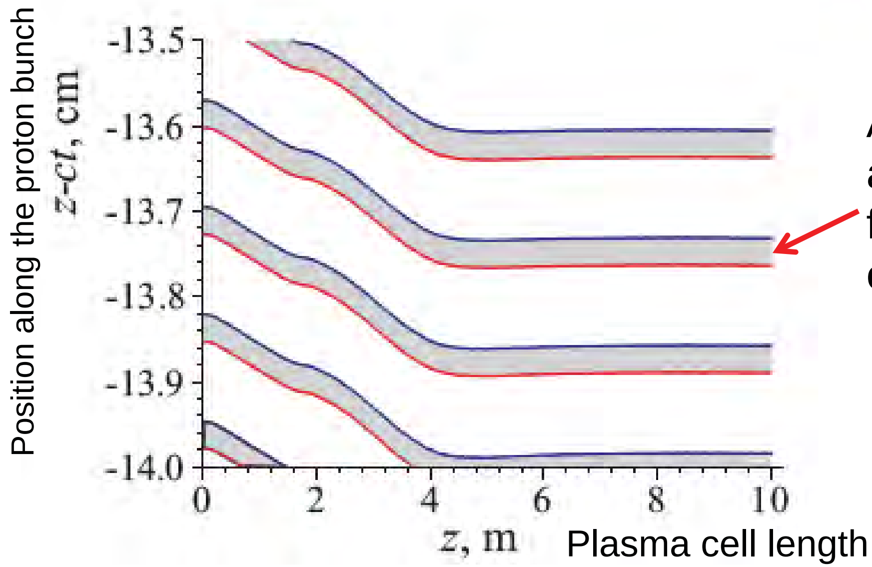


Witness Beam

Externally injected electron beam

→ **Which energy?**





→ Electrons must be trapped in the accelerating/focusing wakefield

SMI: grows in the first ~4 m and is then fully developed.

- Wakefield phase velocity is slower than that of the drive beam.
- Approaches light velocity at z ~4m.

Witness Beam

→ Optimal electron energy is 10-20 MeV

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

→ Electron bunch length:

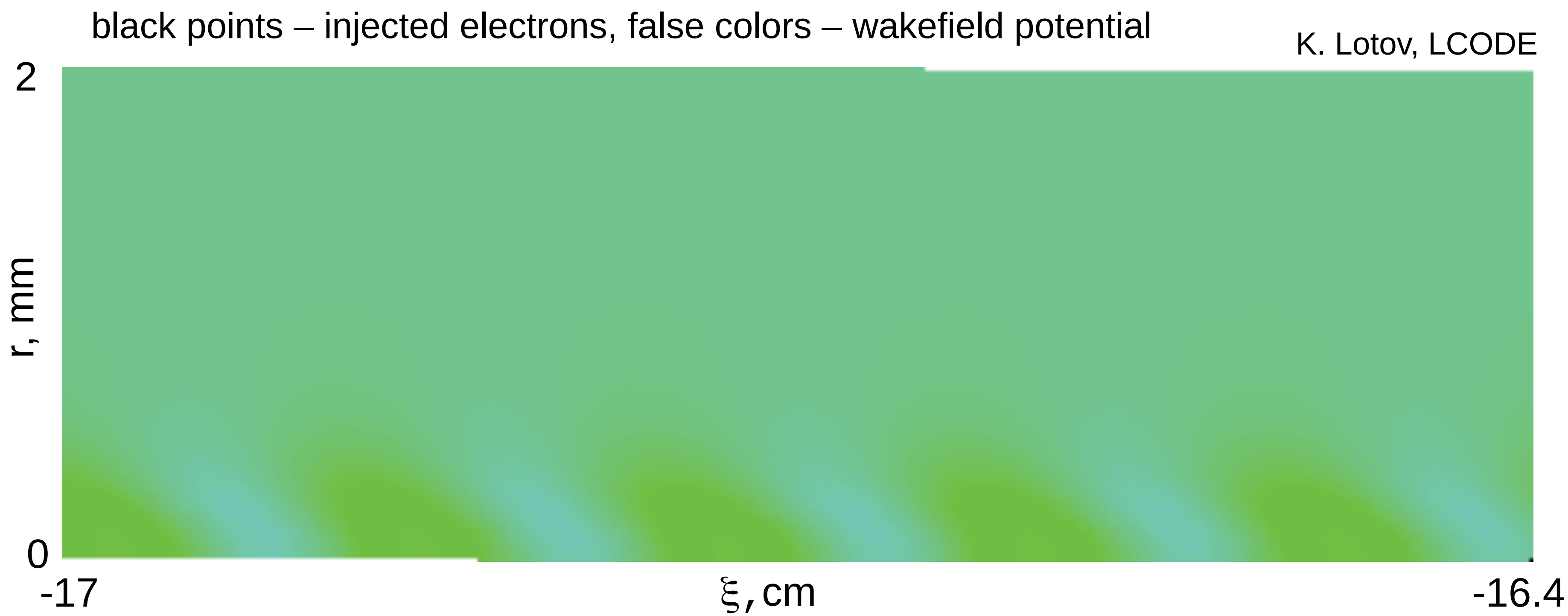
- Should be small to be in phase with high field region.

→ 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 Trapping and Acceleration



- Electrons are trapped from the very beginning by the wakefield
- Trapped electrons make several synchrotron oscillations in their potential wells
- After z=4 m the wakefield moves forward in the light velocity frame

Electron Source

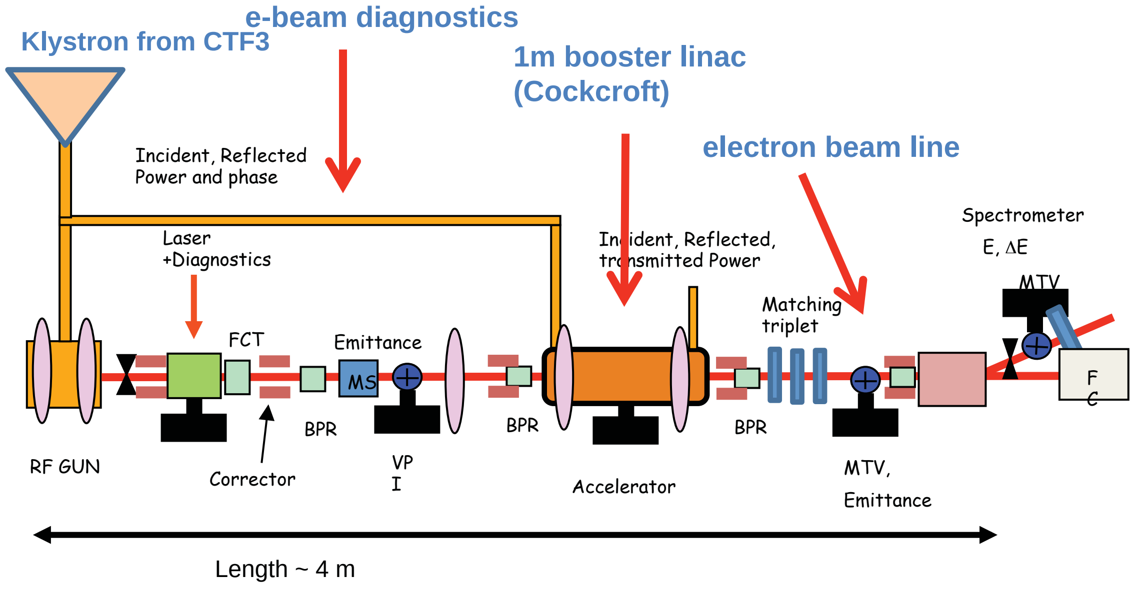
PHIN Photo-injector for CTF3/CLIC:

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

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.

→ Fits to requirements of AWAKE

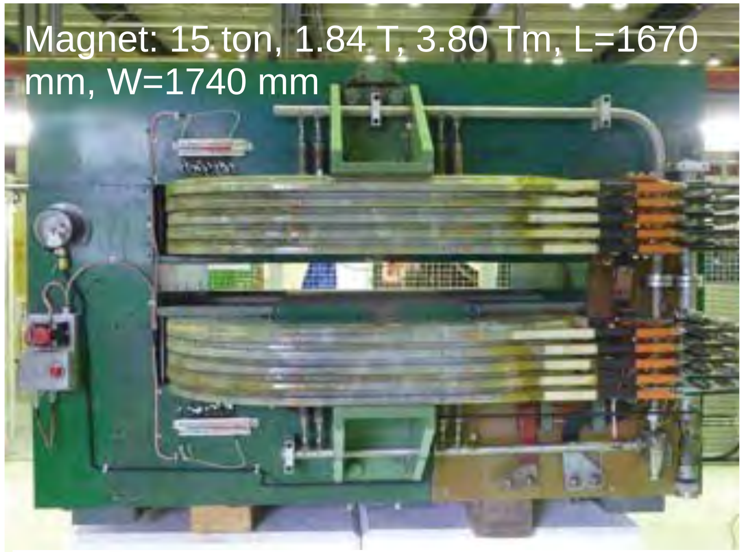
→ Photo-injector laser derived from low power level of plasma ionization laser system.

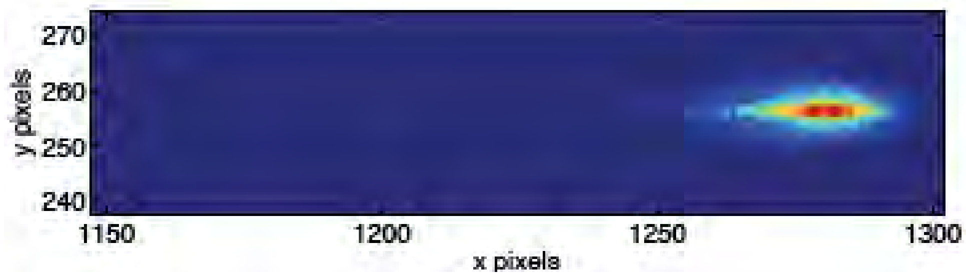


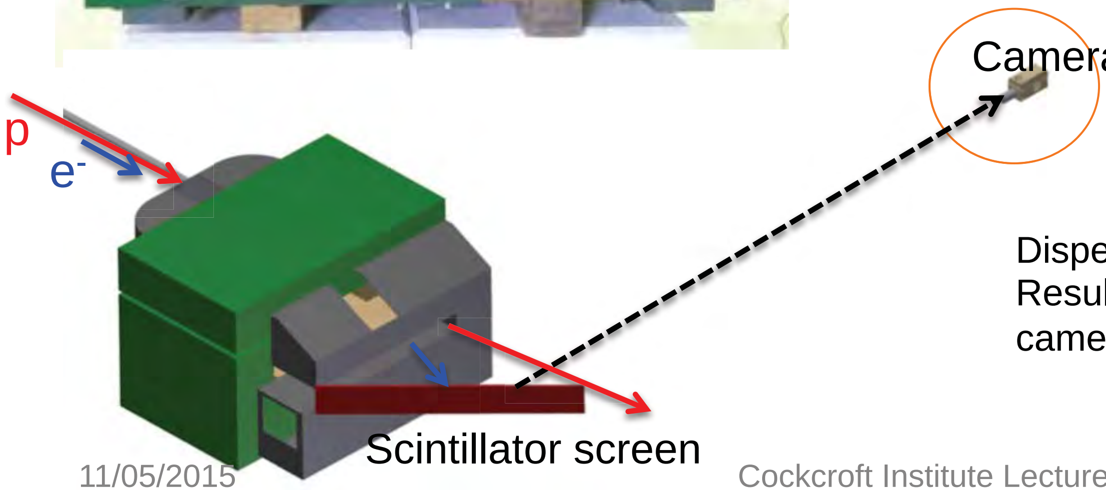
Witness Beam Acceleration

Probe the accelerating wakefields with externally injected electrons
→ Electron spectrometer

- Measure **peak energy and energy spread** of electrons.
- Spectrometer magnet separates electrons from proton beam-line.







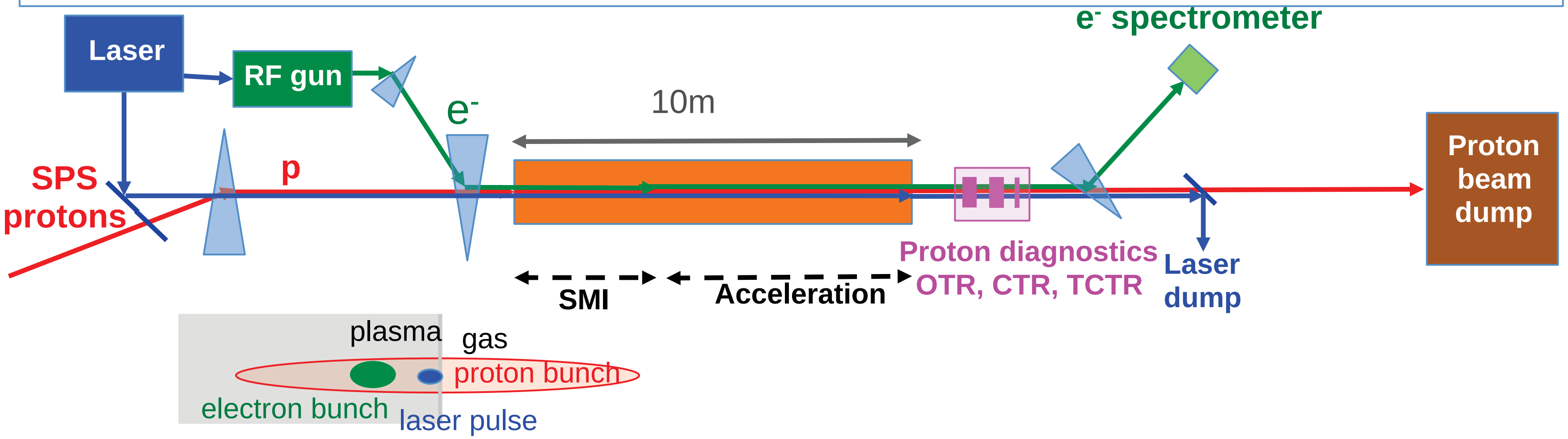
Dispersed electron impact on scintillator screen. Resulting light collected with intensified CCD camera.

Witness Beam and Diagnostics

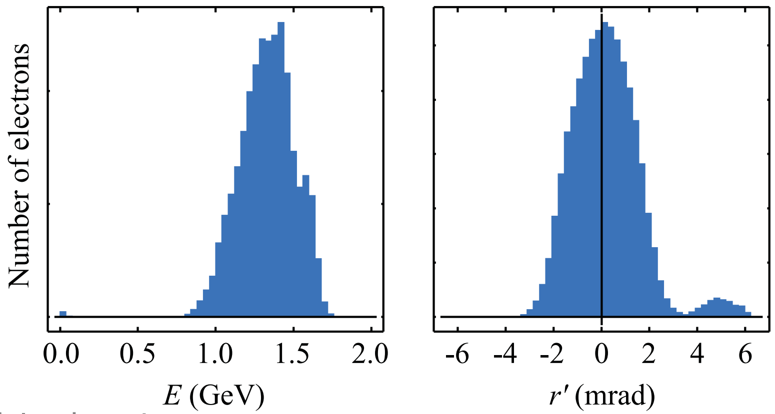
- Externally injected electrons
- Electron energy: 10 – 20 MeV
- Energy and number of accelerated electrons depend on injection delay into wakefield
- Use the Photo-injector PHIN from CLIC
- Photo injector laser derived from low power level of the plasma source ionizing system.
- Electron spectrometer is used to probe the accelerating wakefields.

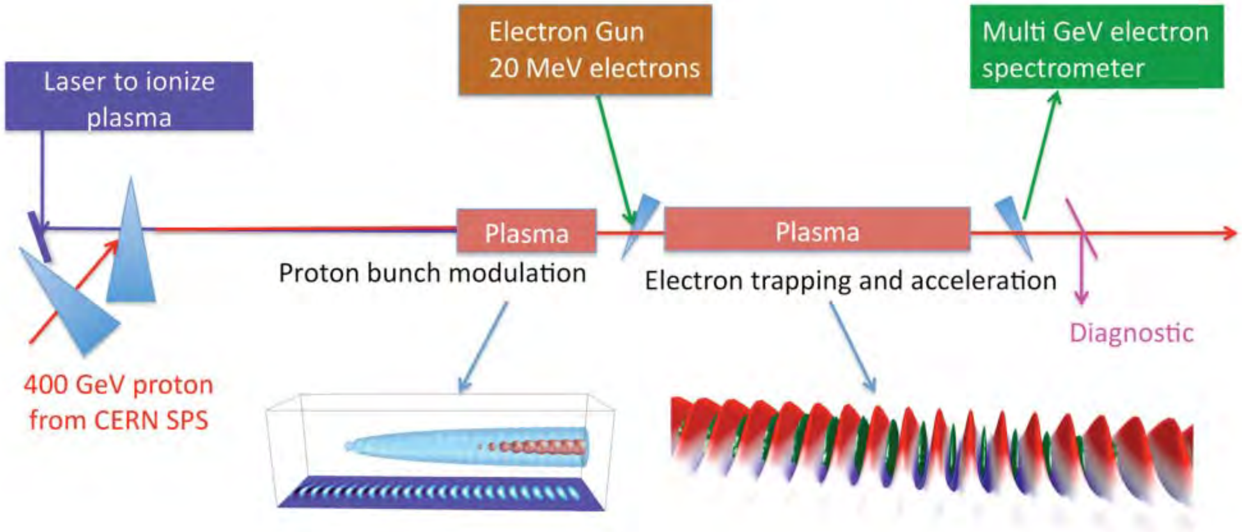
AWAKE: 2nd Experimental Phase

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

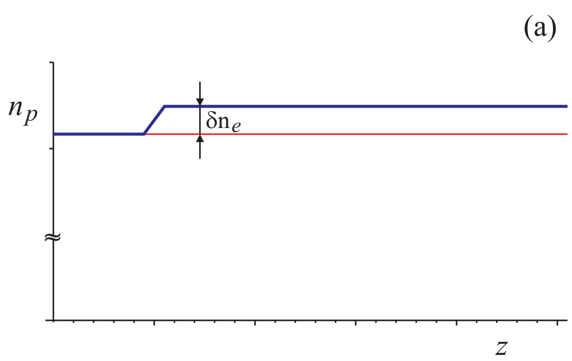


- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad

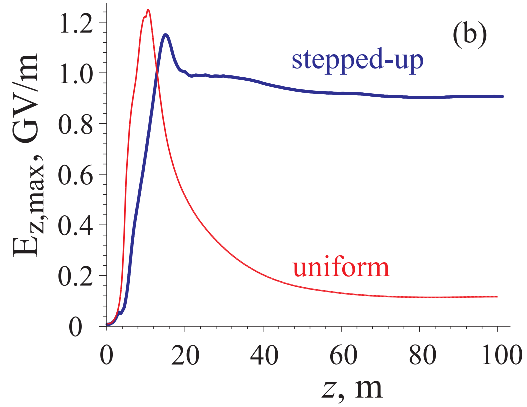




- **Split-cell mode**: SMI in 1st plasma cell, acceleration in 2nd one.
- New scalable uniform plasma cells (helicon or discharge plasma cell)
- Step in the plasma density → maintains the peak gradient
- Need ultra-short electron bunches (~ 300fs) → bunch compression → Almost 100% capture efficiency

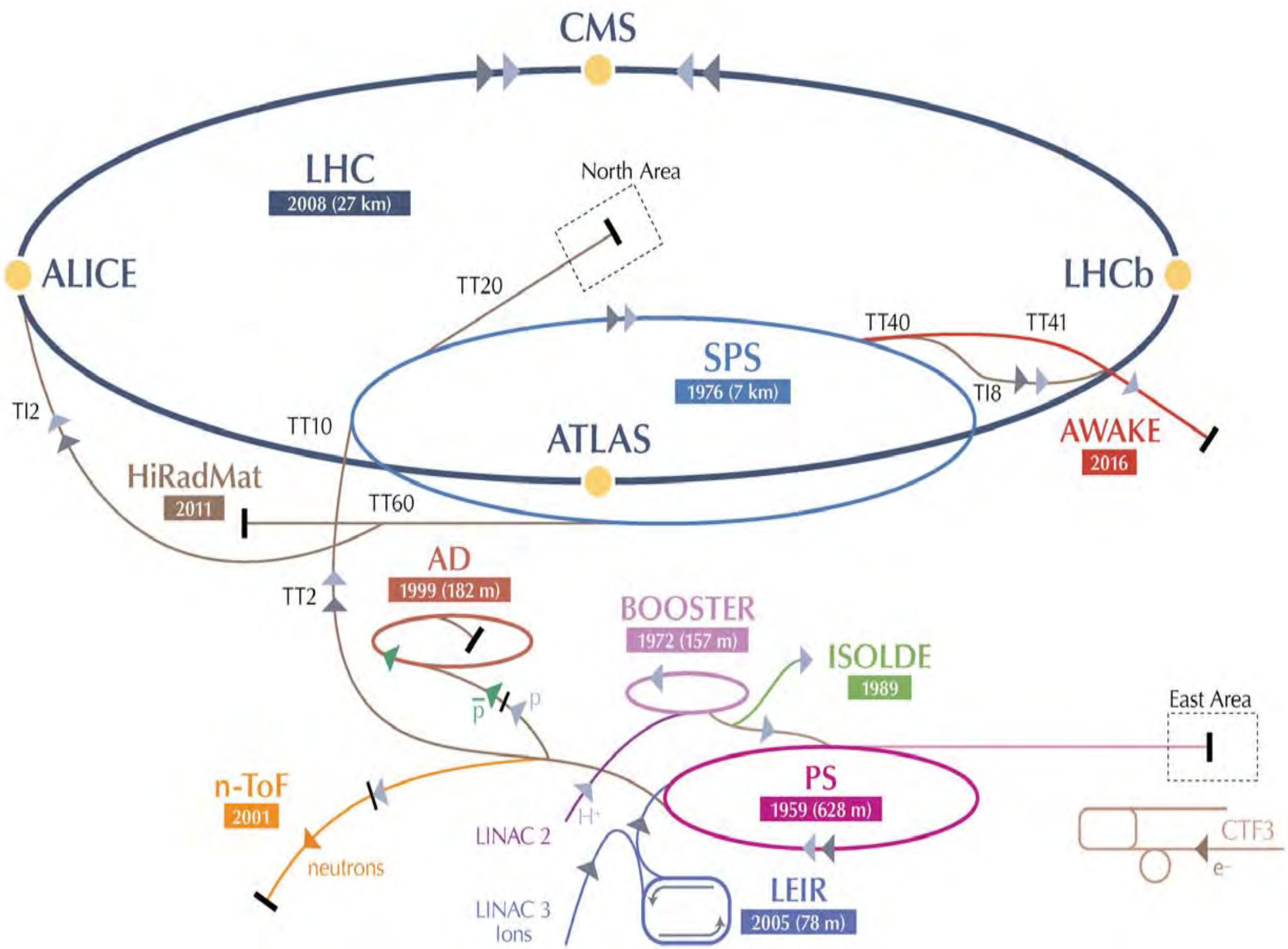


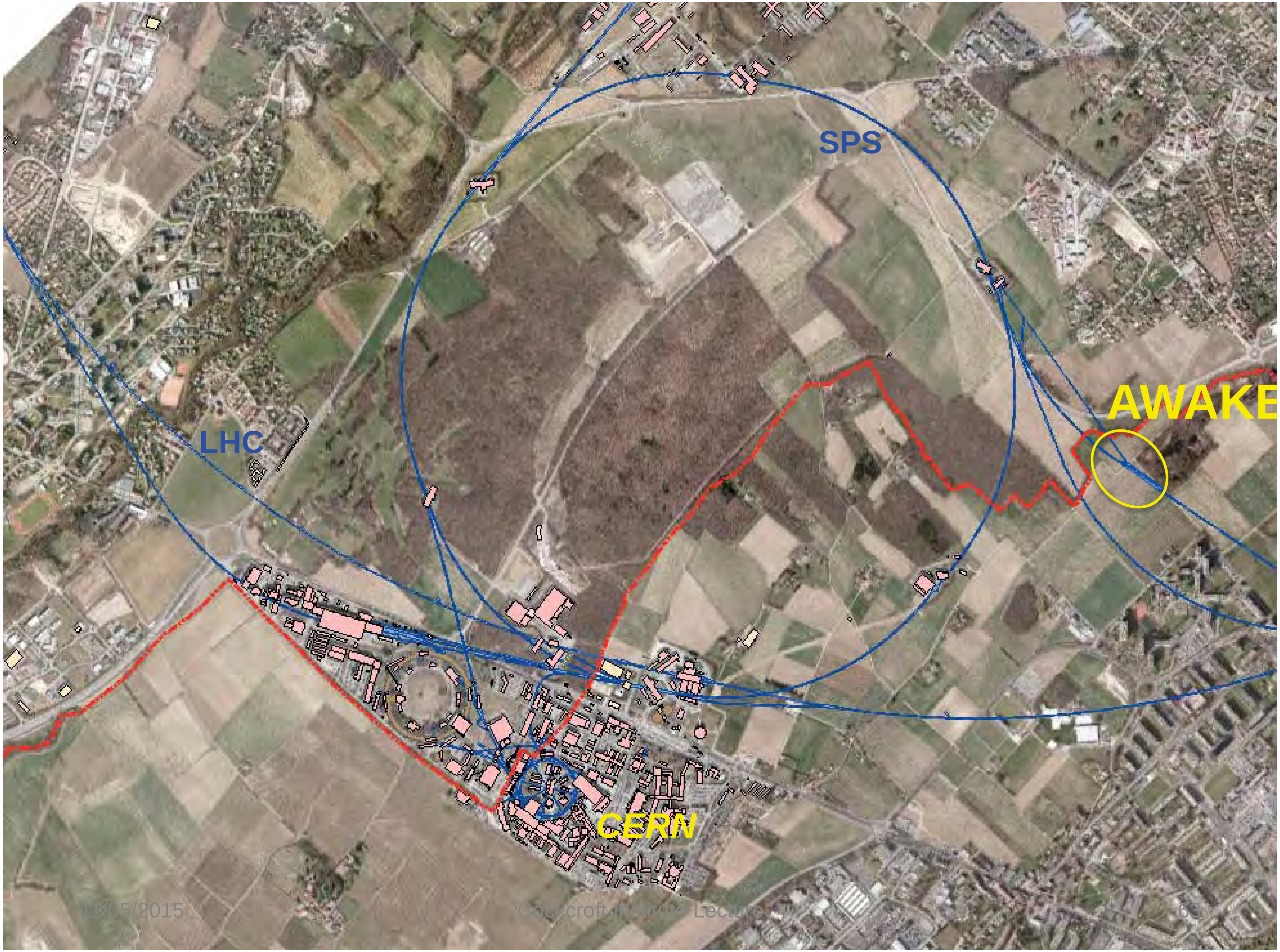
Plasma density profile



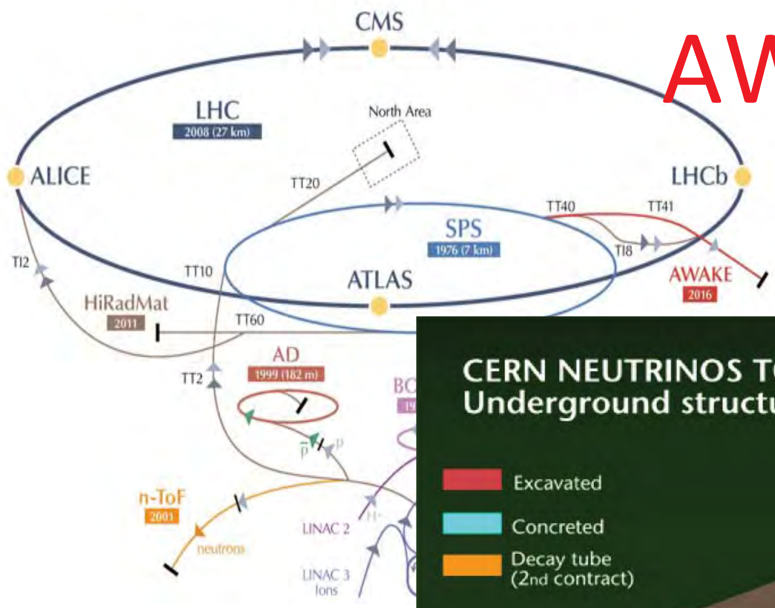
Maximum wakefield amplitude

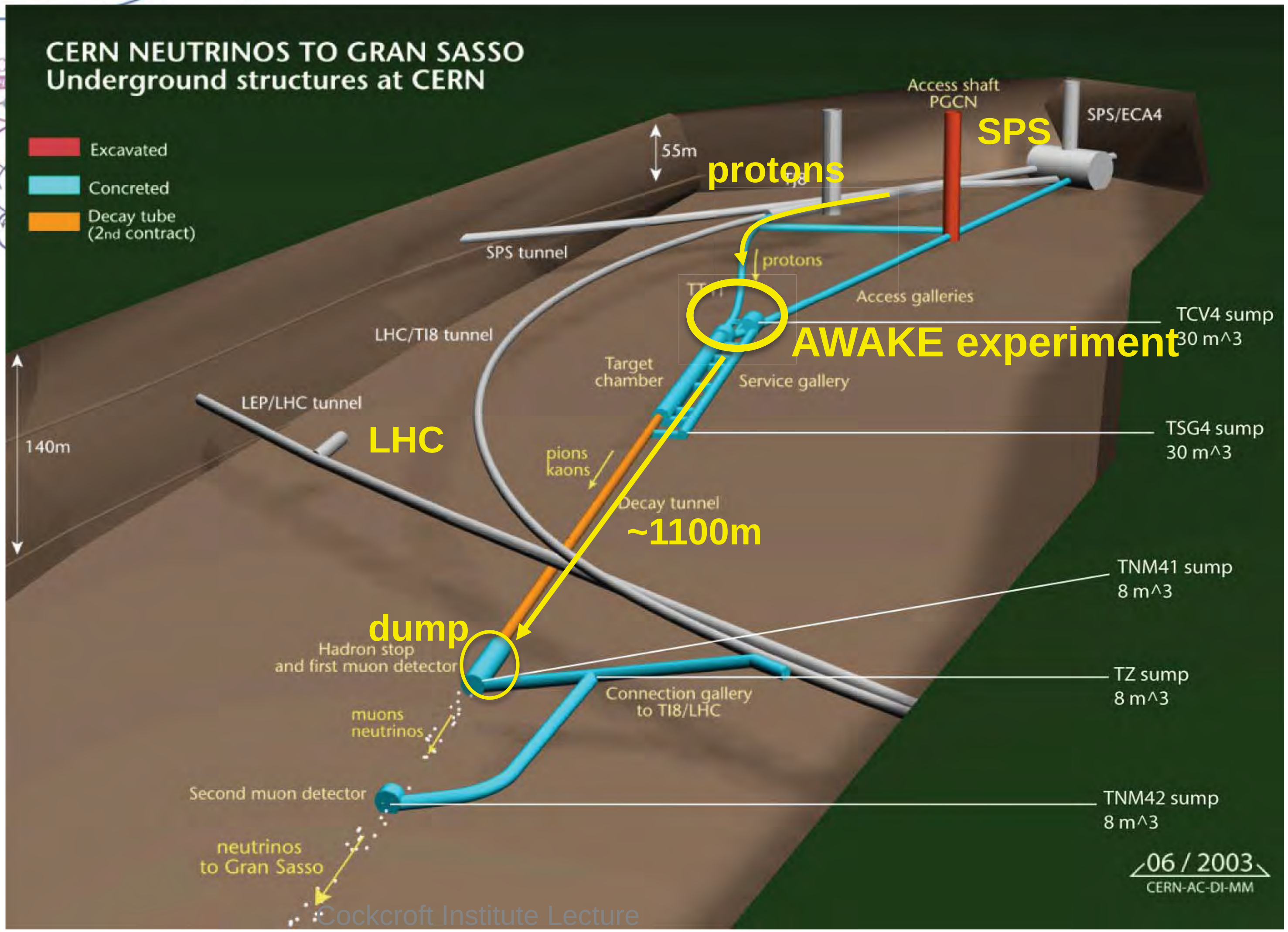
AWAKE at CERN



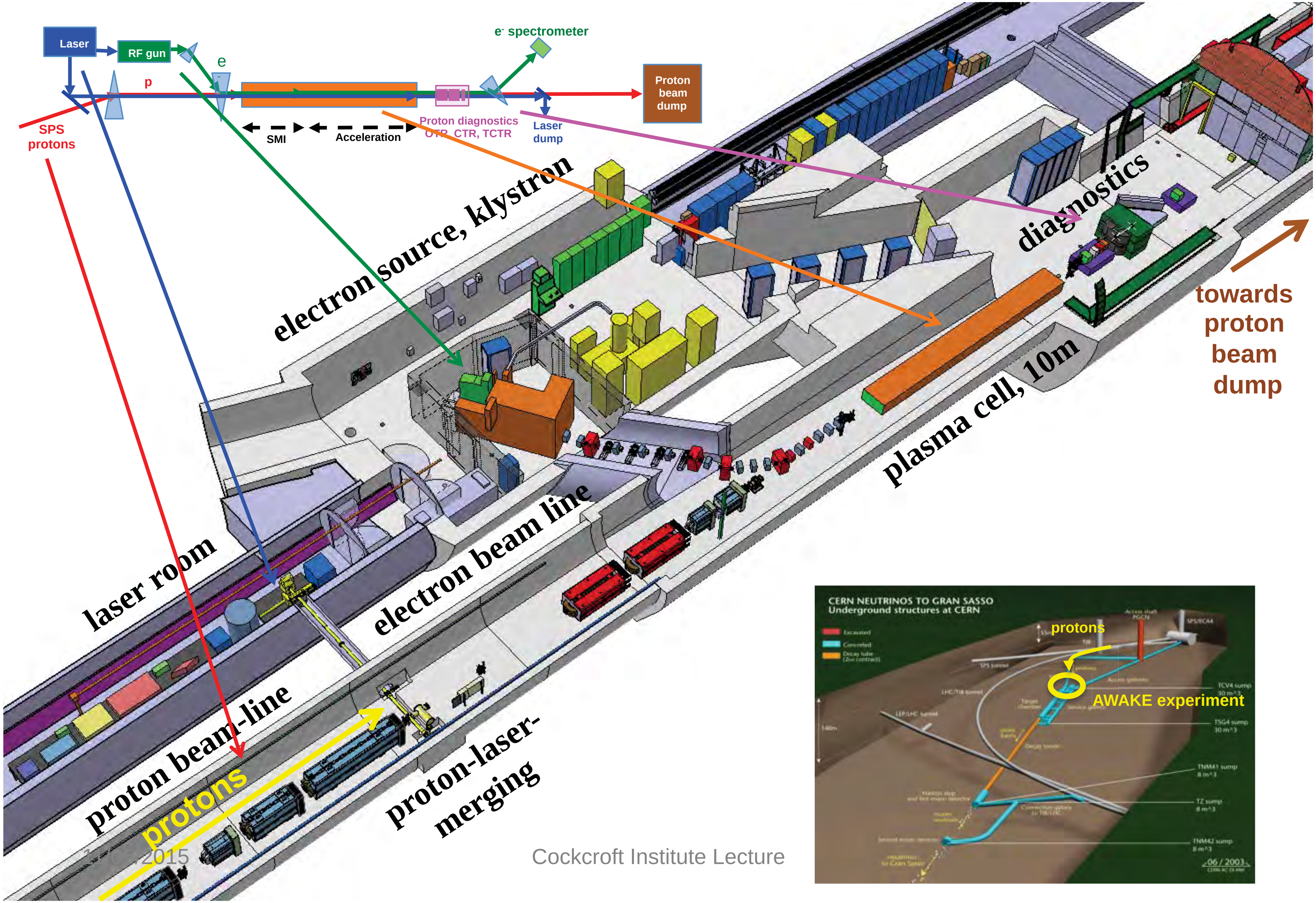

SPS
LHC
AWAKE
CERN

AWAKE at CERN



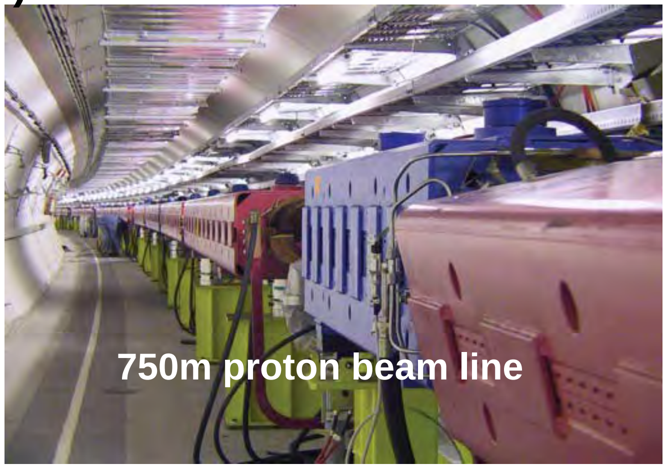


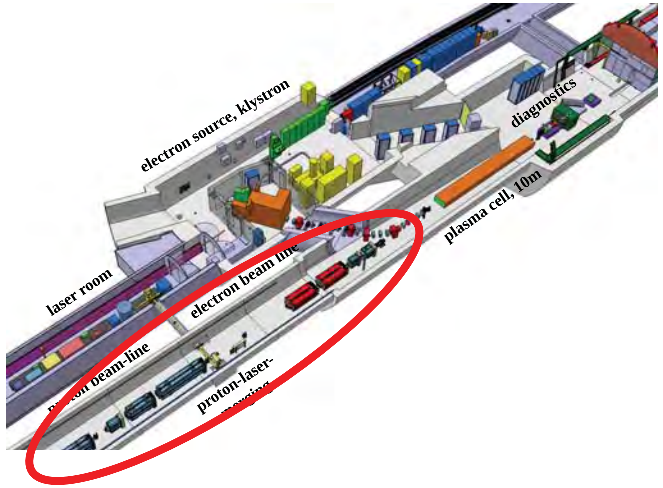
AWAKE Experimental Facility at CERN

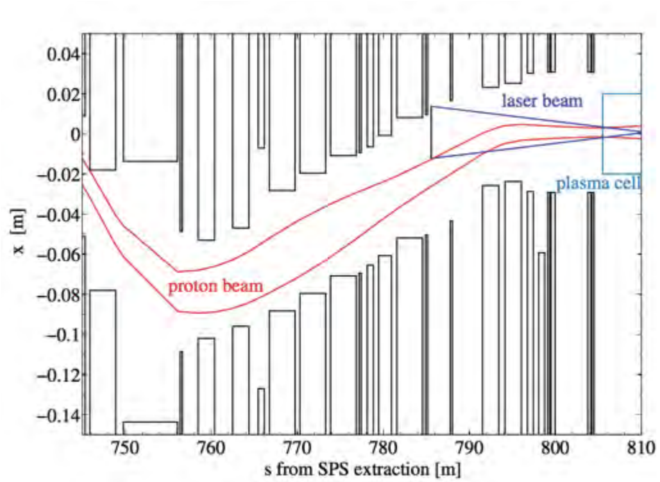


Proton Beam Line

Change of the proton beam line only in the **downstream part (~80m)**



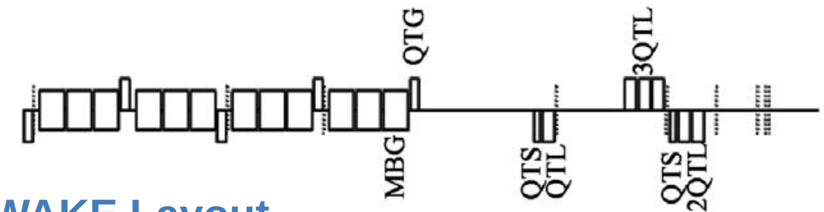




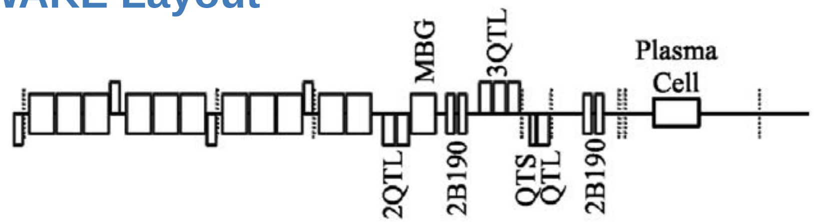
Laser-proton merging 20m upstream the plasma cell

→ **Displace existing magnets** of the final focusing to fulfill optics requirements at plasma cell

CNGS Layout

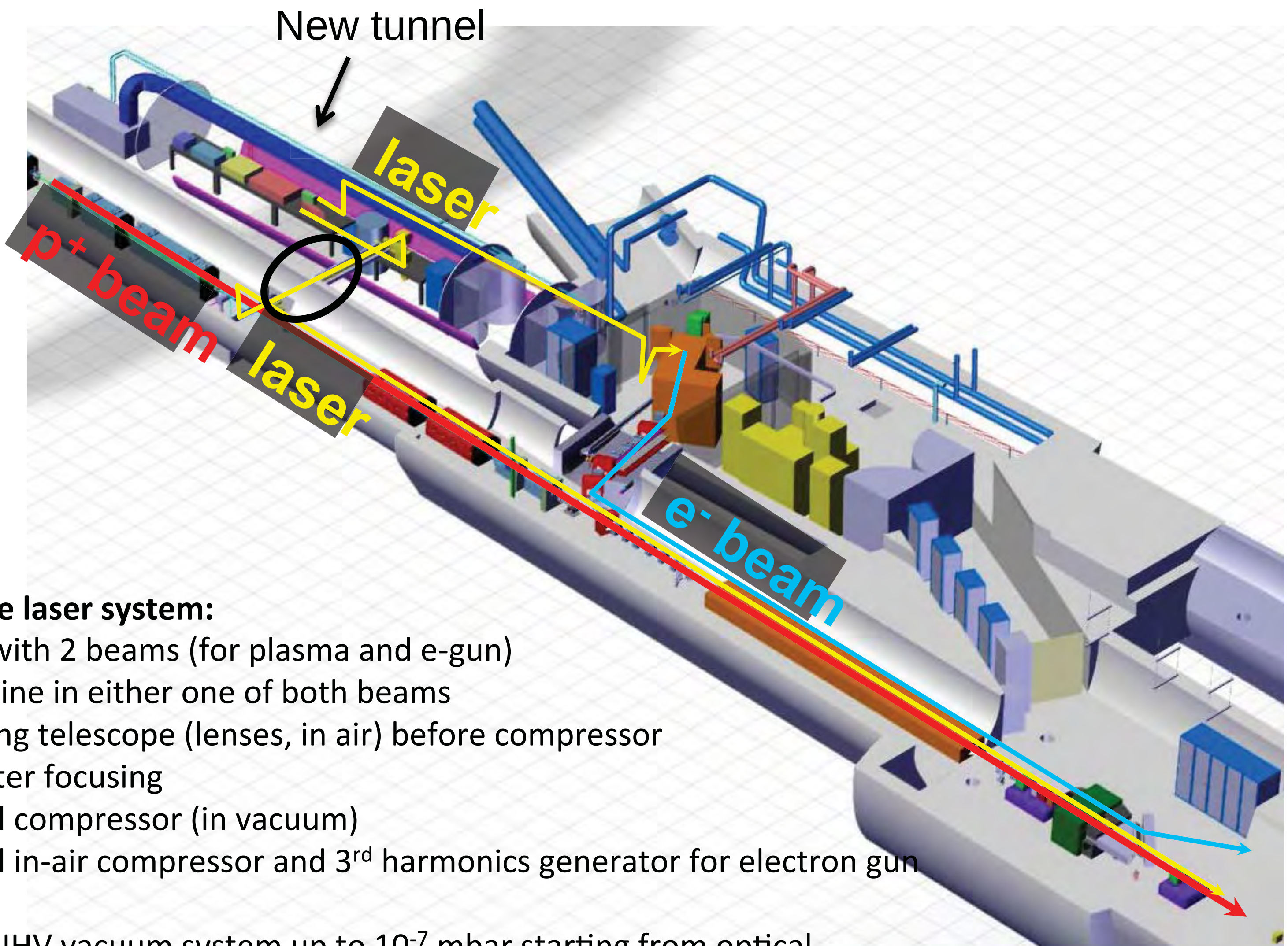


AWAKE Layout



→ Move existing dipole and **4 additional dipoles** to create a **chicane for the laser mirror** integration.

Laser System

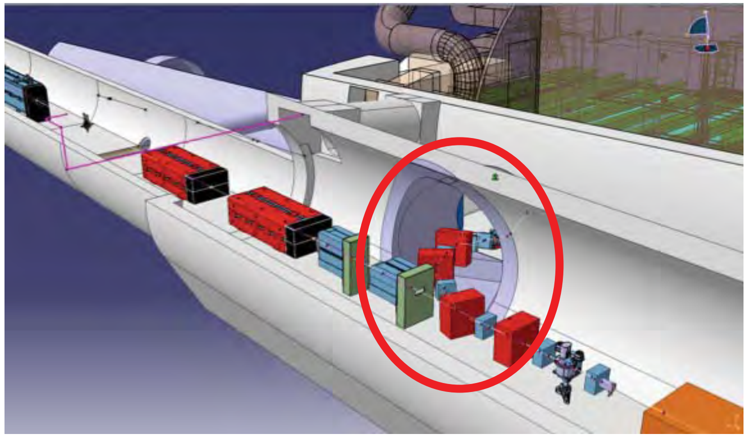


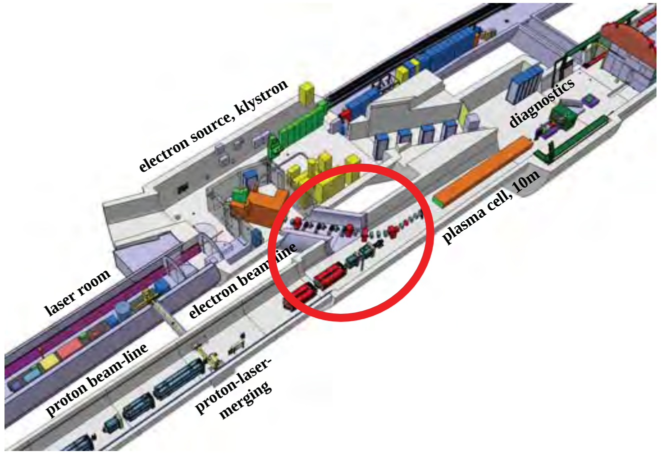
Ti: Sapphire laser system:

- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

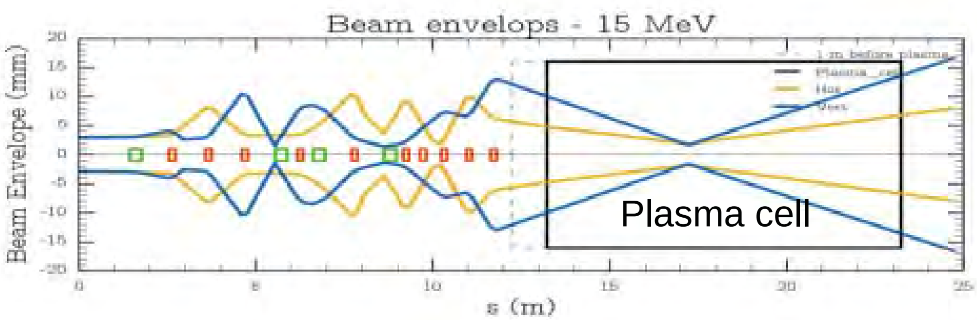
Complete UHV vacuum system up to 10^{-7} mbar starting from optical compressor

Electron Beam Line



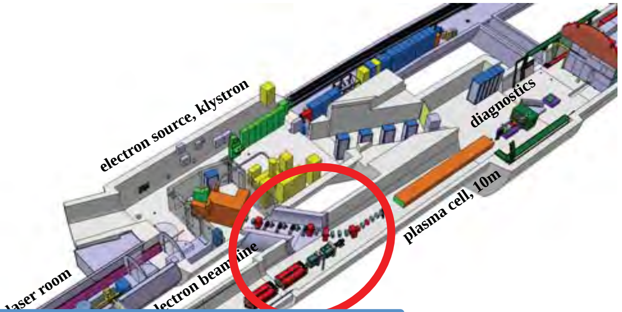


- Completely **new beam line and tunnel**:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel → 1m level difference
  - 7.2% slope of the plasma cell
  - ~5 m common beam line between electron and proton
- **Common diagnostics** for proton (high intensity, 3E11 p) and electron beam (low intensity, 1.2E9 e)
- **Flexible electron beam optics**: focal point can be varied by up to 6 m inside the plasma cell



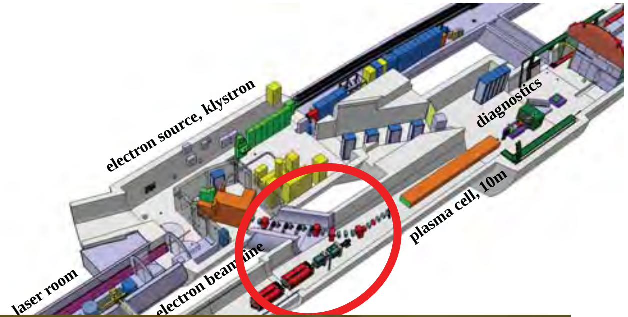
Electron beam envelope (H, V)

Electron Beam Line

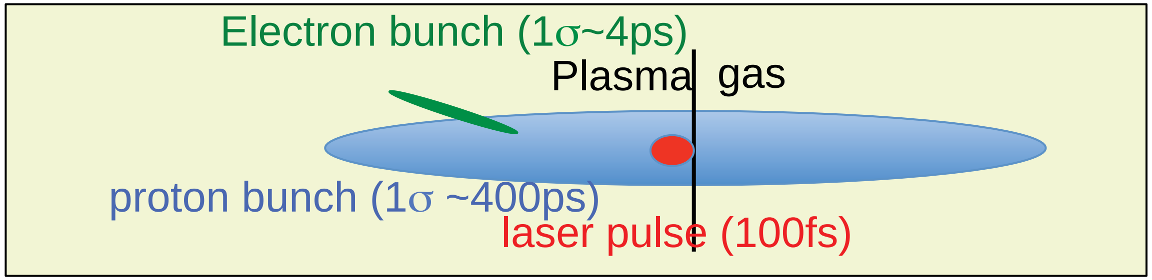


Excavation June – October 2014

Electron Beam Line



Proton/Electron/Laser Synchronization

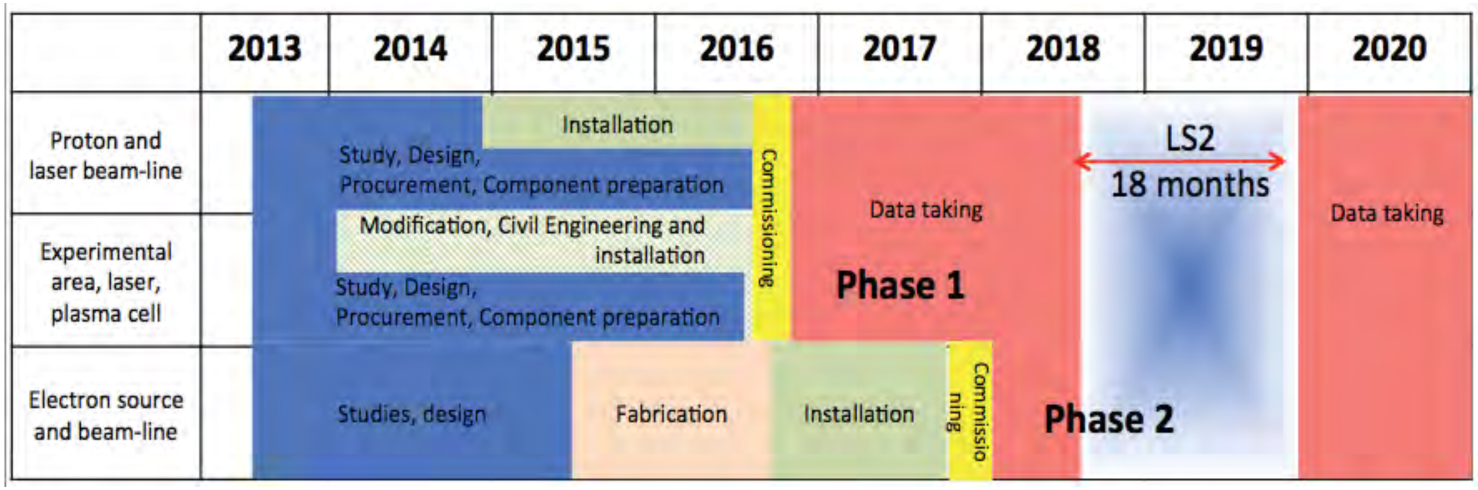


- Synchronization between proton beam and laser pulse: ~ 100 ps (cf. proton bunch length 1σ~400ps).
    - SPS beam must synchronize to the AWAKE reference just before extraction.

- Synchronization between electron beam and laser pulse: ~ 100 fs (cf. plasma period ~4ps)
    - For deterministic injection of e- bunch into plasma wakefields
    - Achieved by driving the RF-gun of the electron source with a laser pulse derived from same laser system as used for plasma ionization.

- Exchange of synchronization signals on ~3 km long fibres between the AWAKE facility and SPS RF Faraday Cage in the control room

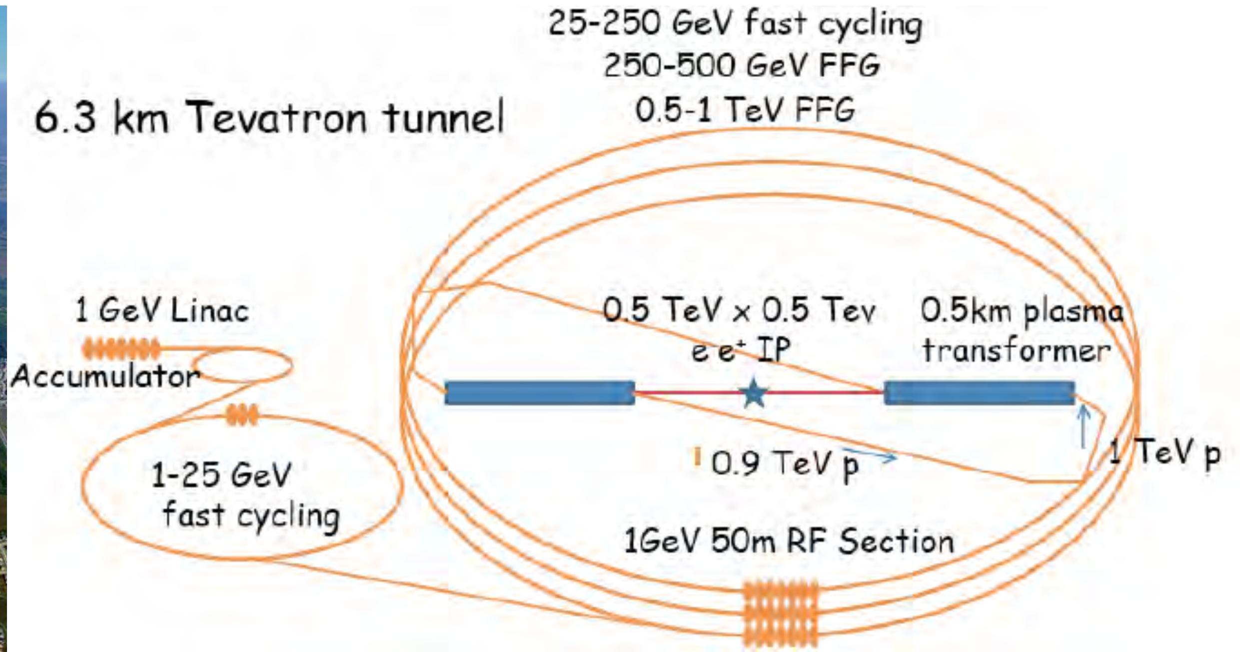
AWAKE Timeline



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	**4.86×10^{16} p**
Initial experimental program	**3 – 4 years**

Collider based on proton driven PWFA



Concept for high repetition rate of proton driven plasma wakefield acceleration

3 ring + injectors + recovery

V. Yakimenko, BNL, T. Katsouleas, Duke, LAPW09

Luminosity

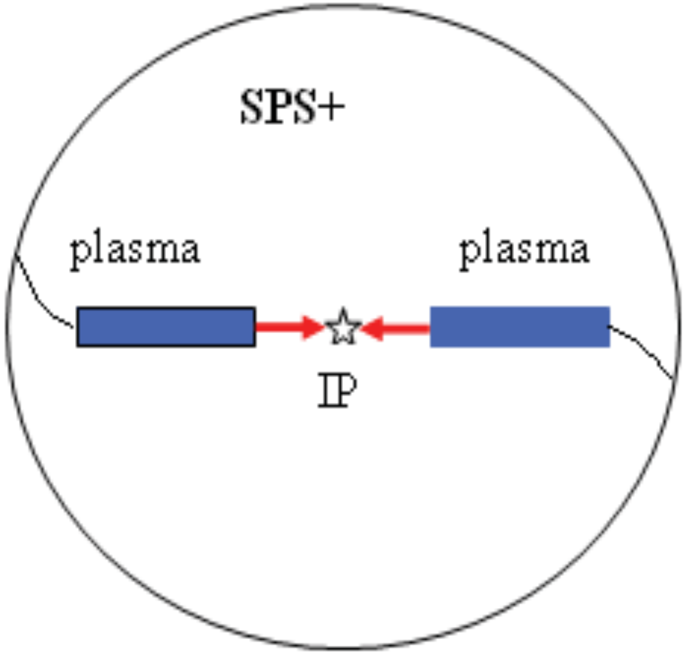
$$L = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$ Gaussian shaped beams

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: 60 nm (horizontal) and 0.7 nm (vertical)

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

Phase slippage

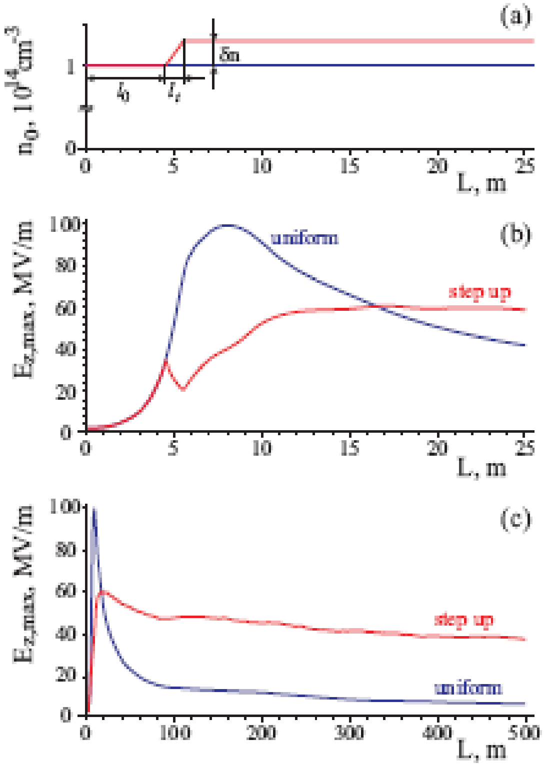
Phase slippage because protons heavy (move more slowly than electrons)

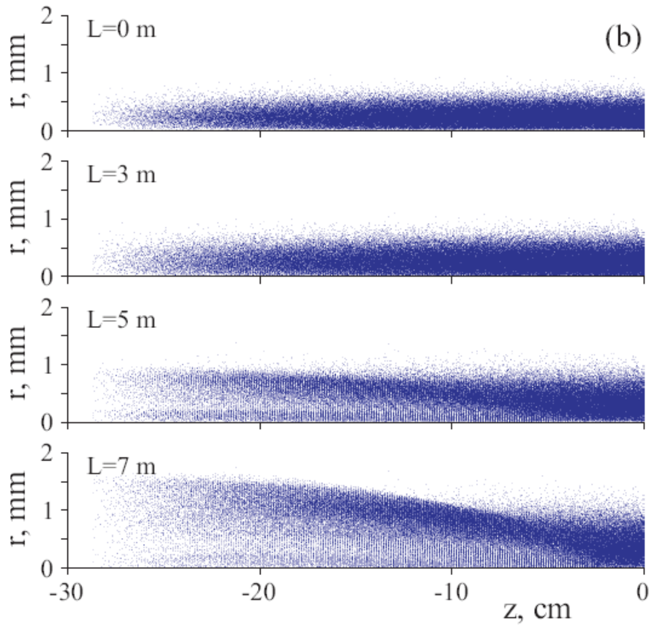
$$\delta = \frac{\pi L}{\lambda_p}\left[\frac{1}{\gamma_{1i}\gamma_{1f}} - \frac{1}{\gamma_{2i}\gamma_{2f}}\right] \approx \frac{\pi L}{\lambda_p}\left[\frac{M_P^2 c^4}{E_{driver,i}E_{driver,f}}\right]$$

$$L \leq \frac{1}{2}\left[\frac{E_{driver,i}E_{driver,f}}{M_P^2 c^4}\right]\lambda_p \approx 300 \text{ m for } E_{driver,i} = 1TeV, E_{driver,f} = 0.5TeV, \lambda = 1mm$$

Few hundred meters possible but depends on plasma wavelength

Plasma density variation





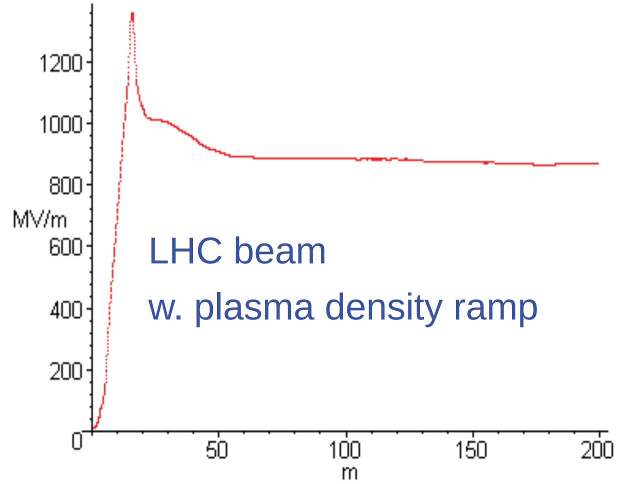


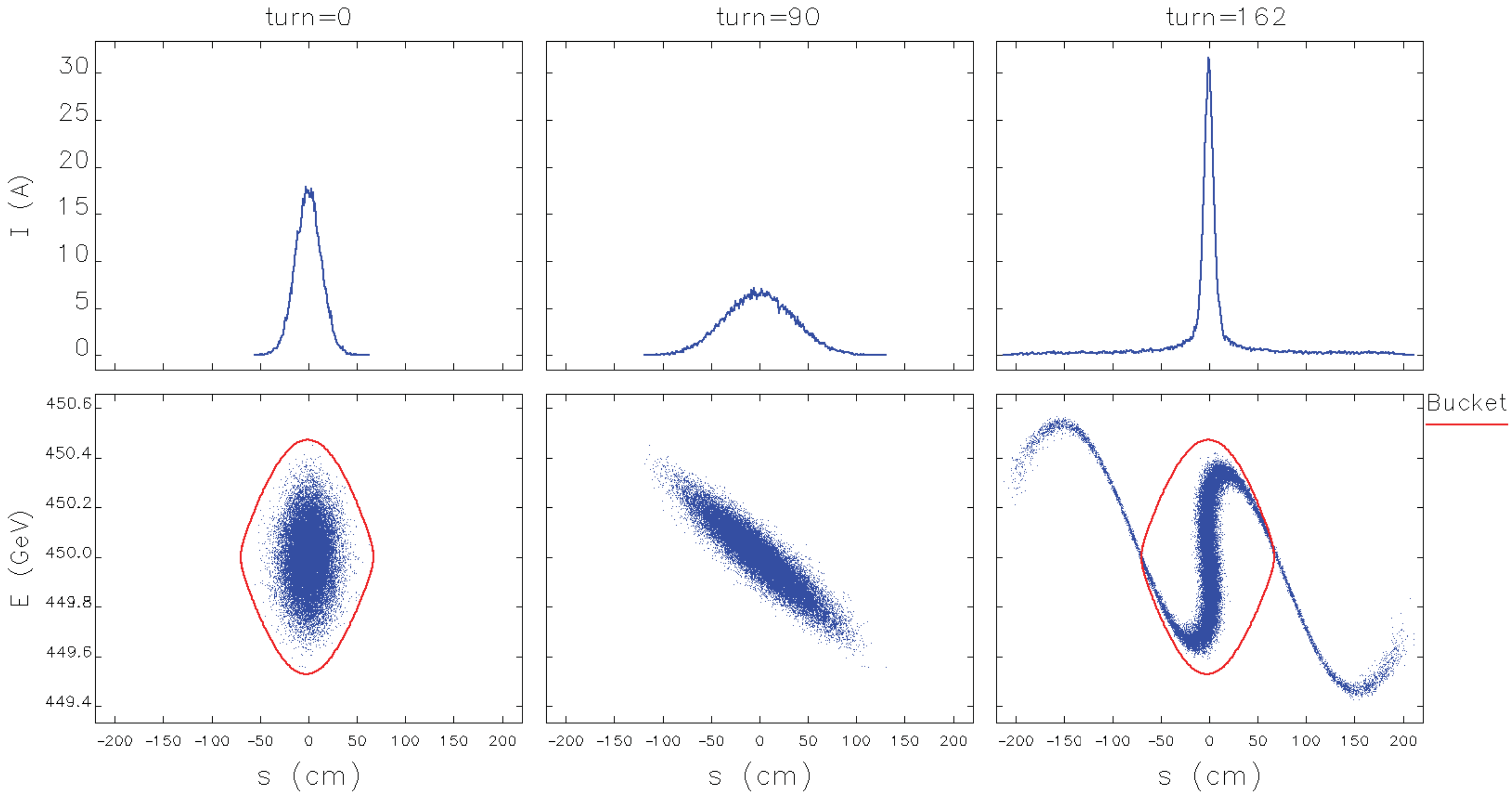
FIG. 4. Parametrization of the density profile (a); maximum wakefield amplitude behind the beam versus propagation distance on small (b) and large (c) scales for uniform and step-up plasma density profiles.

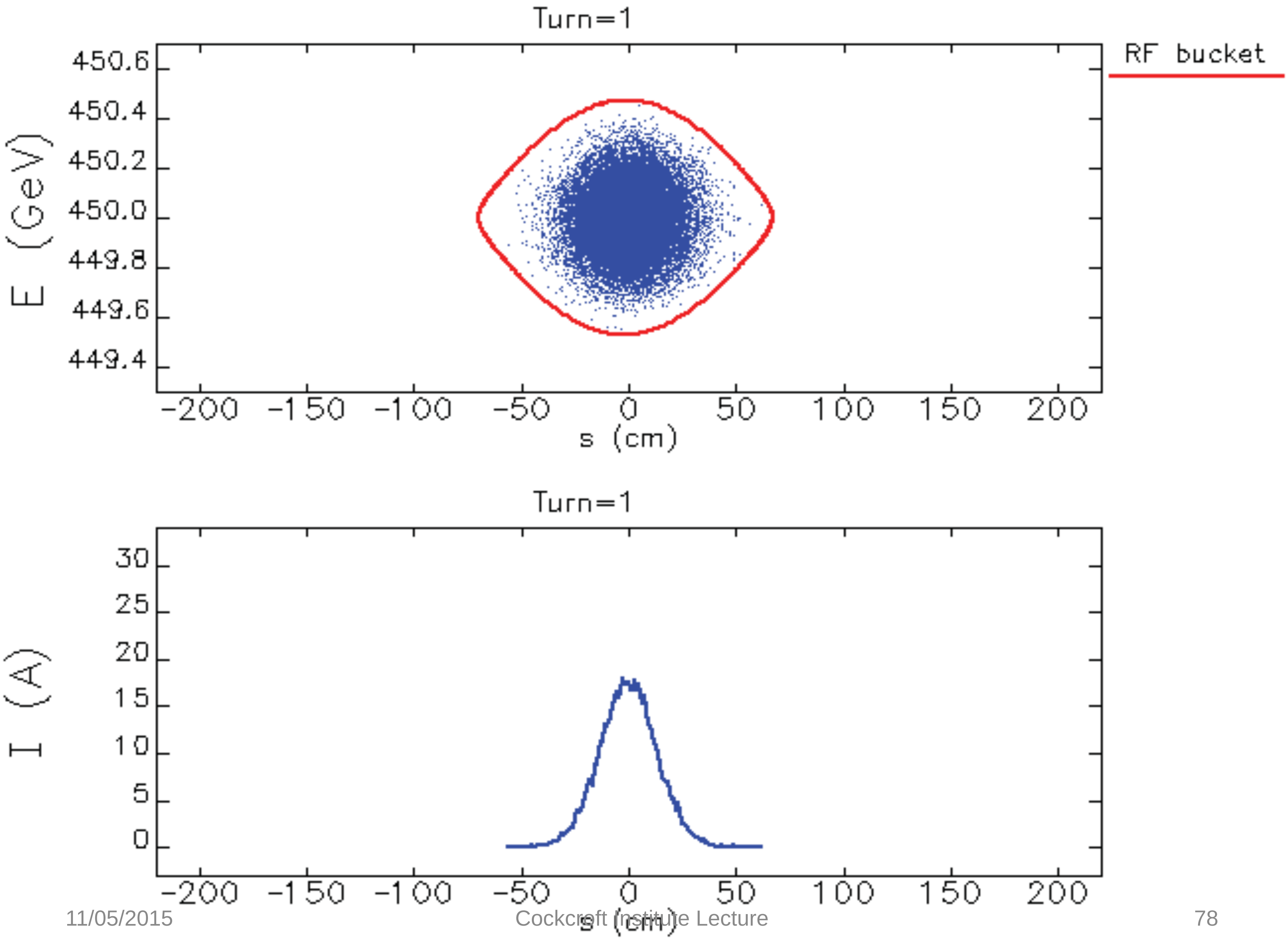
~ 900 MV/m field propagates stably for 200 m!

Increasing the plasma density properly at the moment of developed instability, the wave shift with respect to the main body of the beam will be stopped and one can obtain a stable bunch train that propagates in plasma for a long distance

(K. Lotov)

Bunch rotation in the SPS



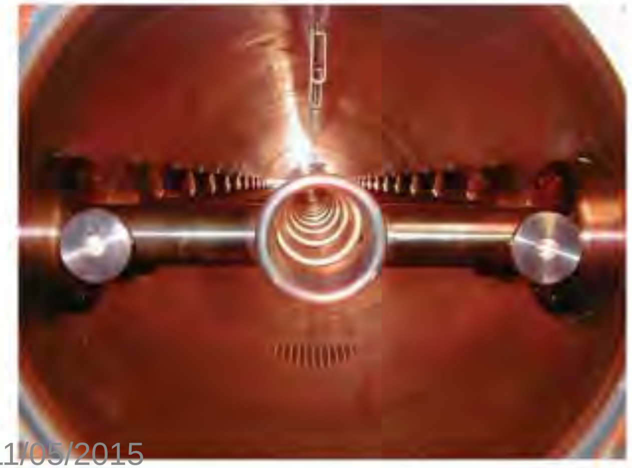

Turn=1
RF bucket
450.6
450.4
450.2
450.0
449.8
449.6
449.4
E (GeV)
-200
-150
-100
-50
0
50
100
150
200
s (cm)
Turn=1
30
25
20
15
10
5
0
I (A)
-200
-150
-100
-50
0
50
100
150
200
s (cm)

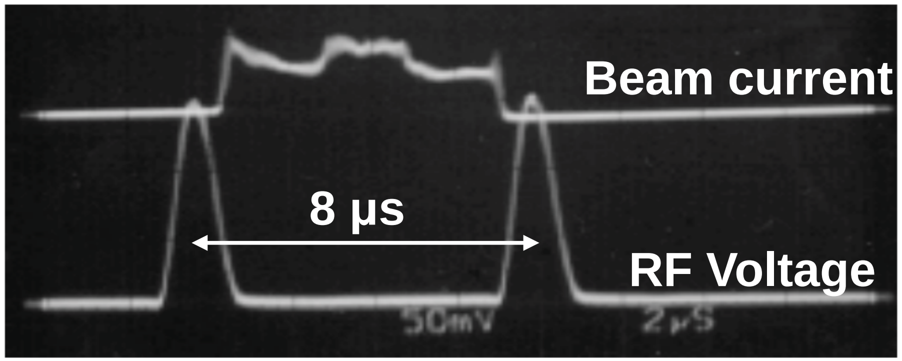
200 MHz RF system in the SPS:

- 4 Travelling Wave cavities:
  2 cavities of 5 sections
  2 cavities of 4 sections
  11 cells/section
  2(3) spare sections
- Power/cavity:
  - 700 kW for full ring (FT/CNGS beams) - continuous mode
  - 1.05 MW for half ring (LHC-type beams) - pulsed mode (after some upgrade)
- Voltage:
  maximum used 8.0 MV

RF-structure quality factor Q = 200,
filling time = 600 ns
(1 beam turn in SPS takes 23 μs)

Barrier bucket experiments in SPS:





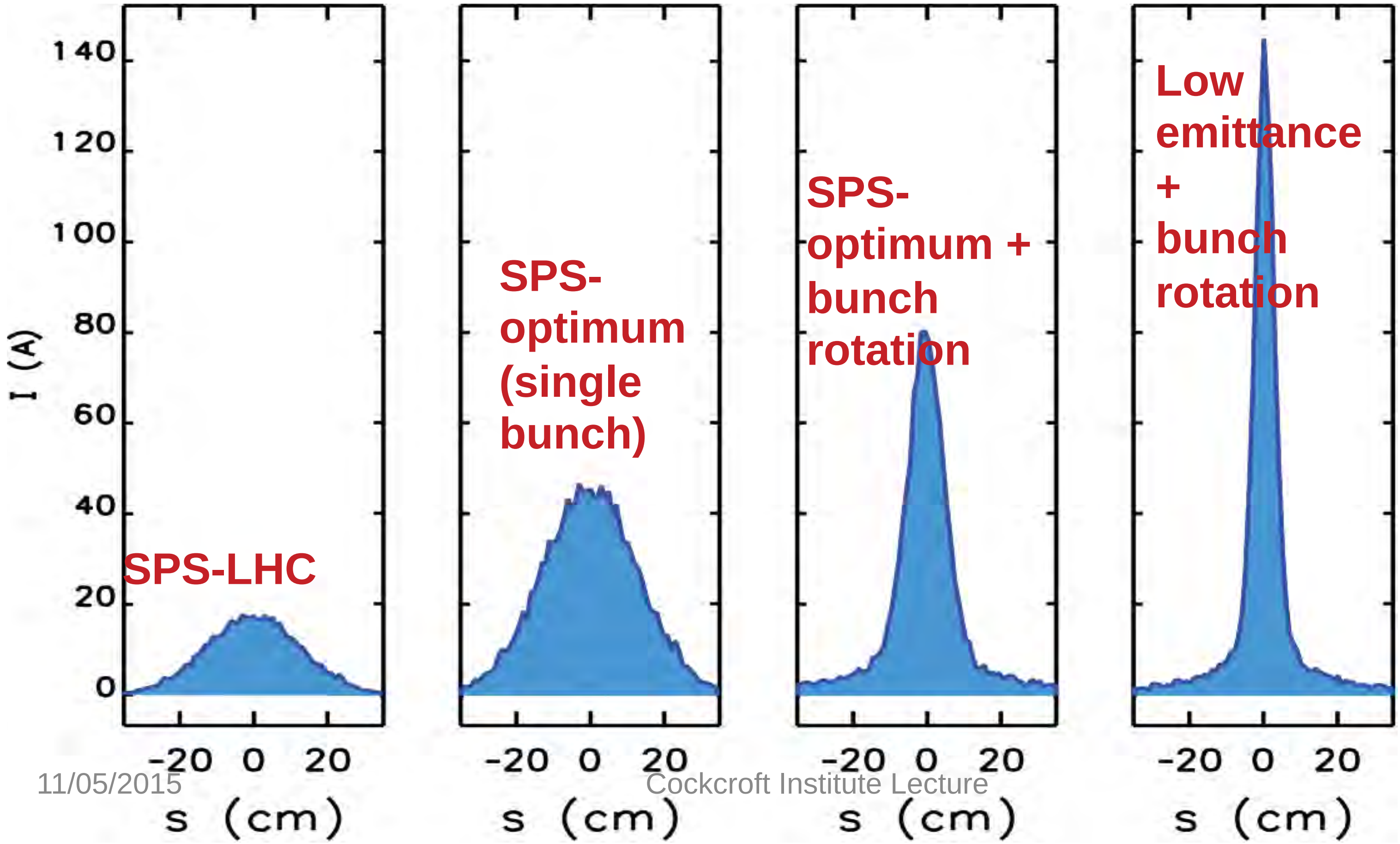
http://sl.web.cern.ch/SL/Publications/hrf2000-032.pdf

From presentation by E. Shaposhnikova et. al.: https://espace.cern.ch/be-dep/IPAC%20posters/MOPC058.pdf

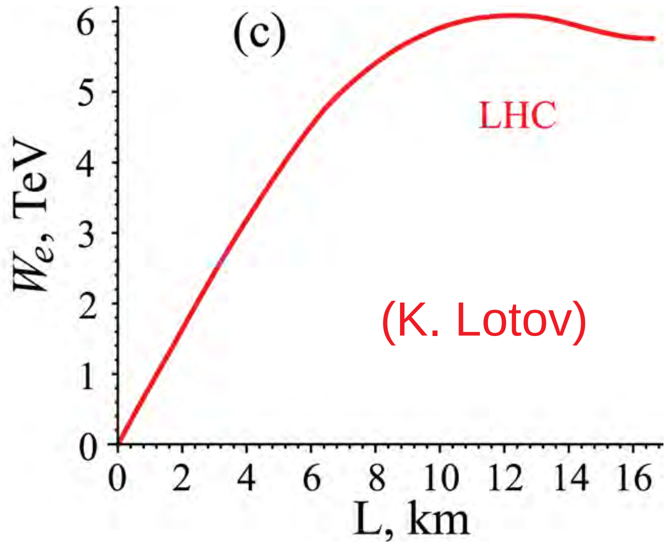
Table 1. Parameters for SPS–LHC and SPS–optimum beams.

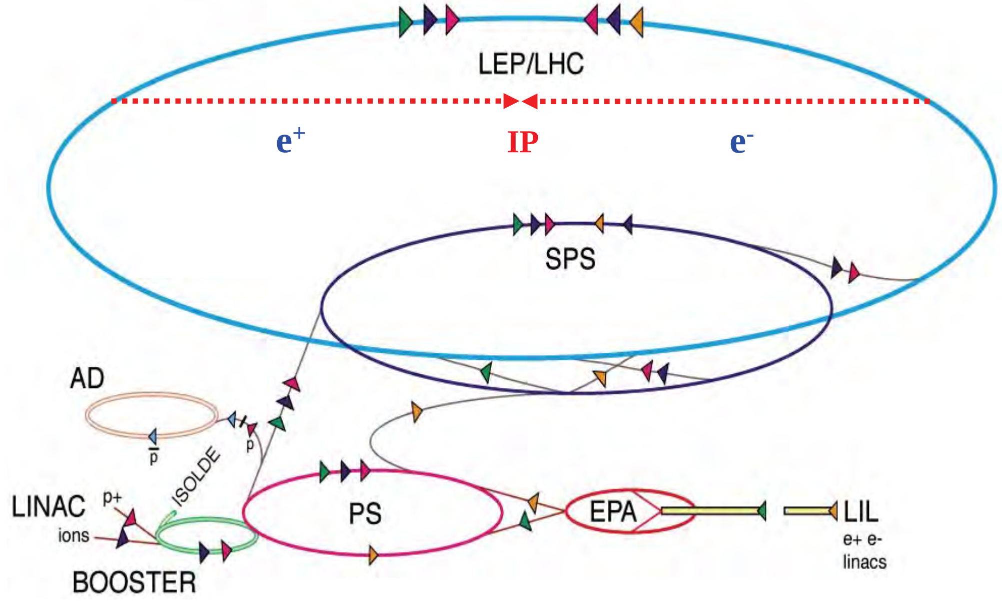
	SPS–LHC	SPS–optimum
Beam energy (GeV)	450	450
Bunch population (10^{11})	1.15	3.0
Beam radius (μm)	200	200
Angular spread (mrad)	0.04	0.04
Normalized emittance (μm)	3.5	3.5
Bunch length (cm)	12	12.4
Energy spread (%)	0.03	0.03

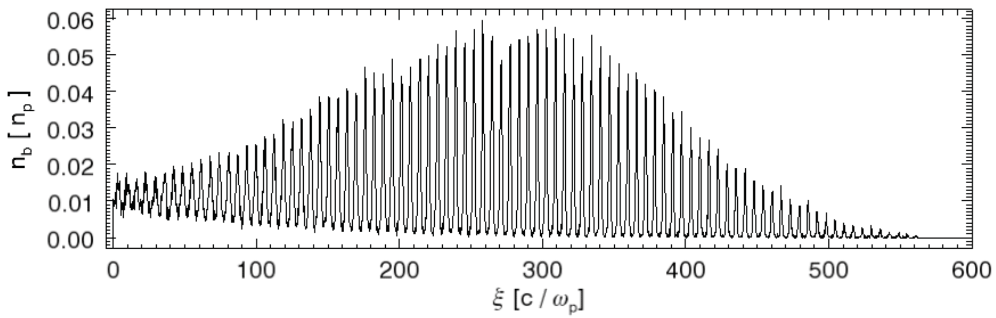
In order to suppress multibunch instabilities longitudinal emittance in the SPS is blown up by a factor of 2. In the single bunch mode the longitudinal emittance blow-up can be switched off.



Multi-TeV lepton collider at LHC







From idea to real 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.

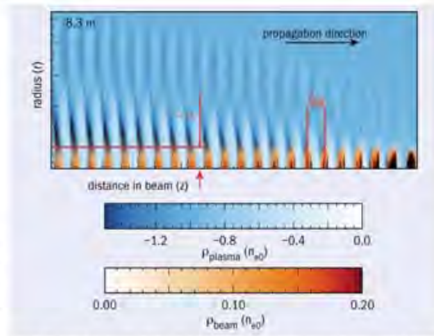


Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing from yellow to dark red.

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

G. XIA[1], R. ASSMANN[2], R. A. FONSECA[3], C. HUANG[4], W. MORI[5], L. O. SILVA[3], J. VIEIRA[3], F. ZIMMERMANN[2] and P. MUGGLI[1]
for the PPWFA Collaboration

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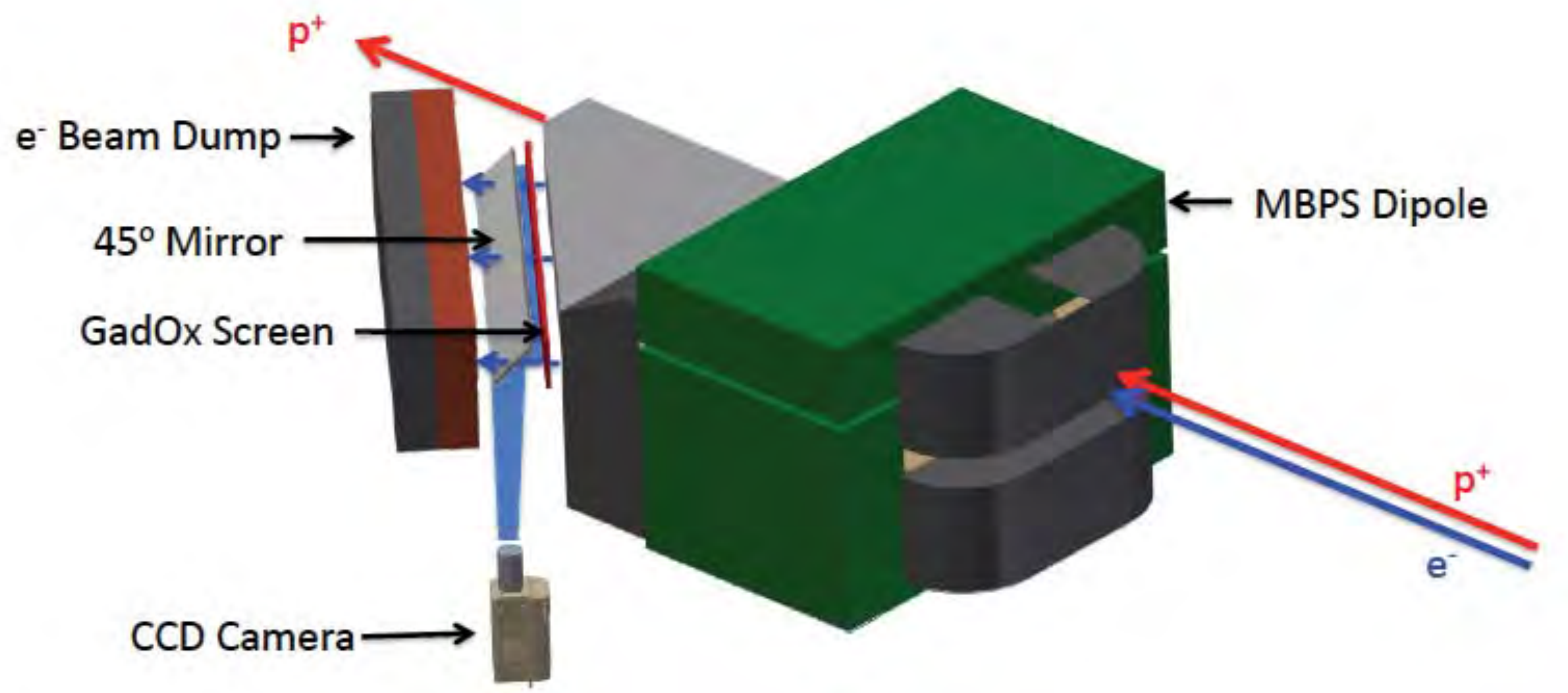
(xiaguo@mpp.mpg.de)
[2]CERN, Geneva, Switzerland
[3]GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
[4]Los Alamos National Laboratory, Los Alamos, NM, USA
[5]University of California, Los Angeles, CA, USA

(Received 20 September 2011; accepted 2 January 2012)

UK's contribution to AWAKE

- Energy spectrometer
- Electron injector
- Discharge plasma source
- Others,
  - plasma simulation, collider design based on proton driven PWFA, radiation calculation, diagnostics, etc.

Energy spectrometer



Wide range of energy acceptance from tens of MeV to more than 2 GeV

Electron injector

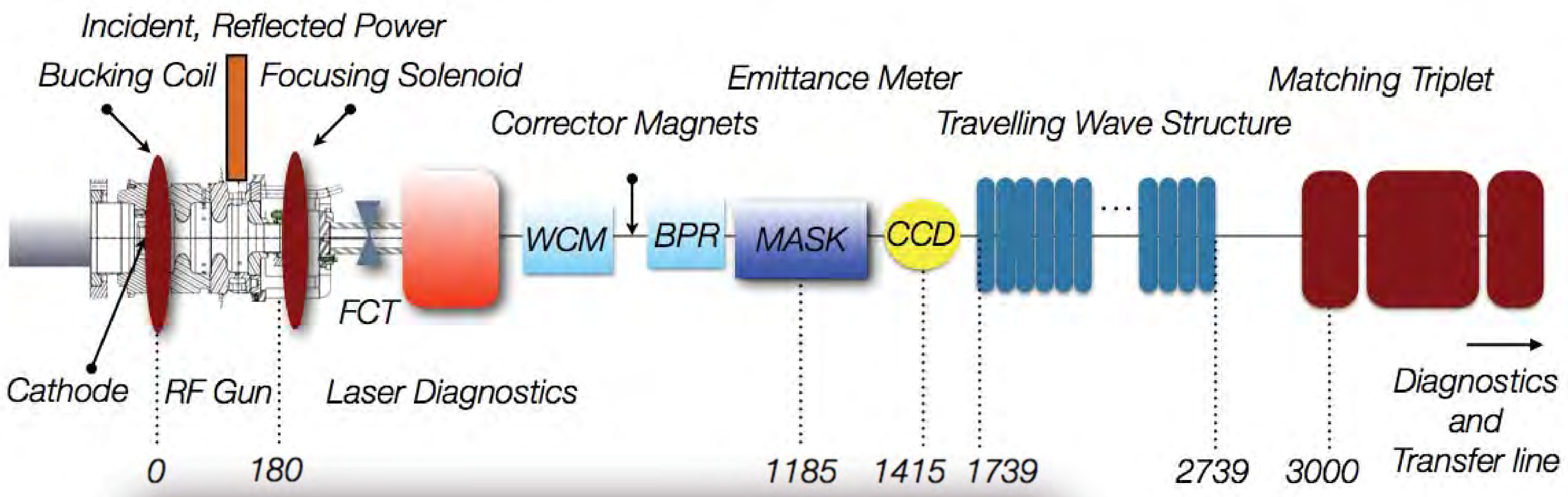
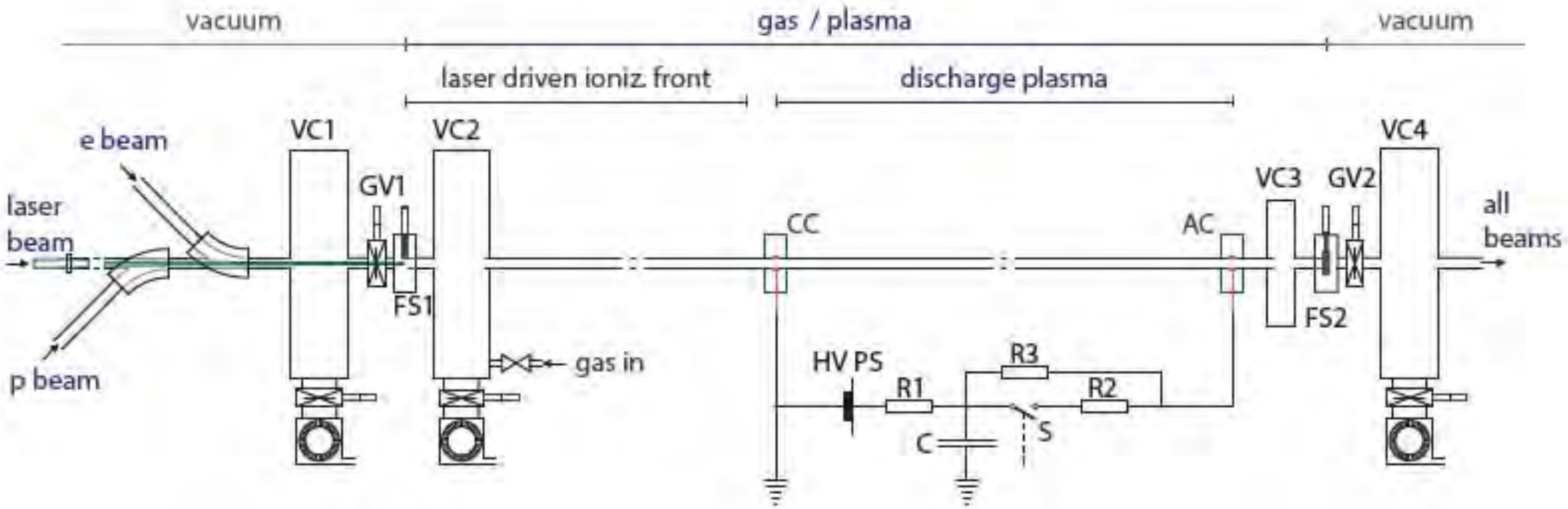


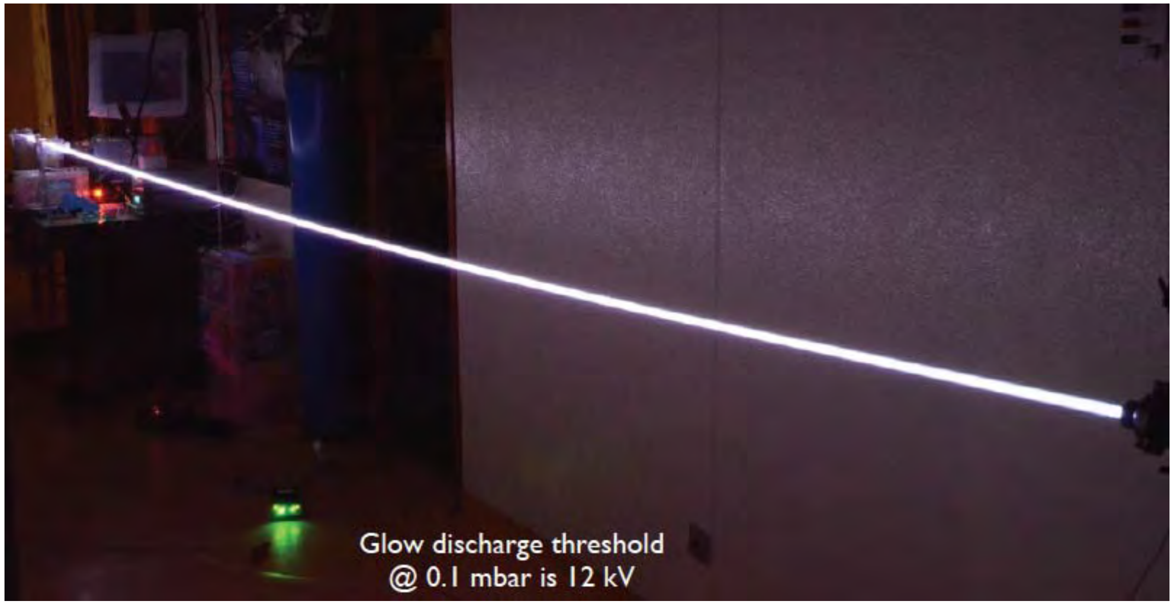
Table 1: Specifications for the simulation studies.

Parameter	Baseline	Range of interest
Beam energy (MeV)	16	10-20
Energy spread (σ, %)	0.5	-
Bunch length, (σ, ps)	4	0.3-10
Beam focus size, (σ, μm)	250	250-1000
Norm. emittance (rms, mm-mrad)	2	0.5-5
Bunch charge, (nC)	0.2	0.1-1

Specifications for AWAKE e[-] beam.

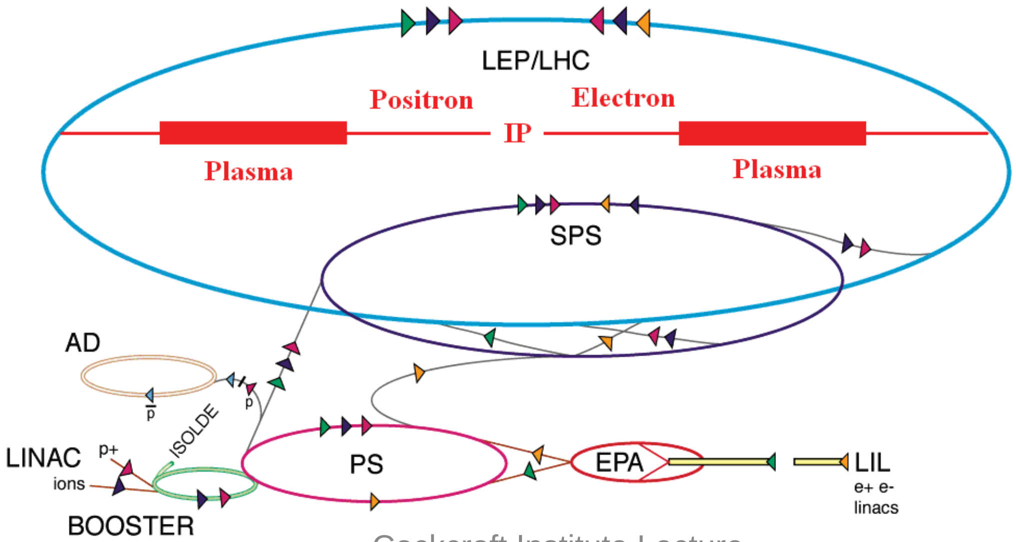
Discharge plasma source



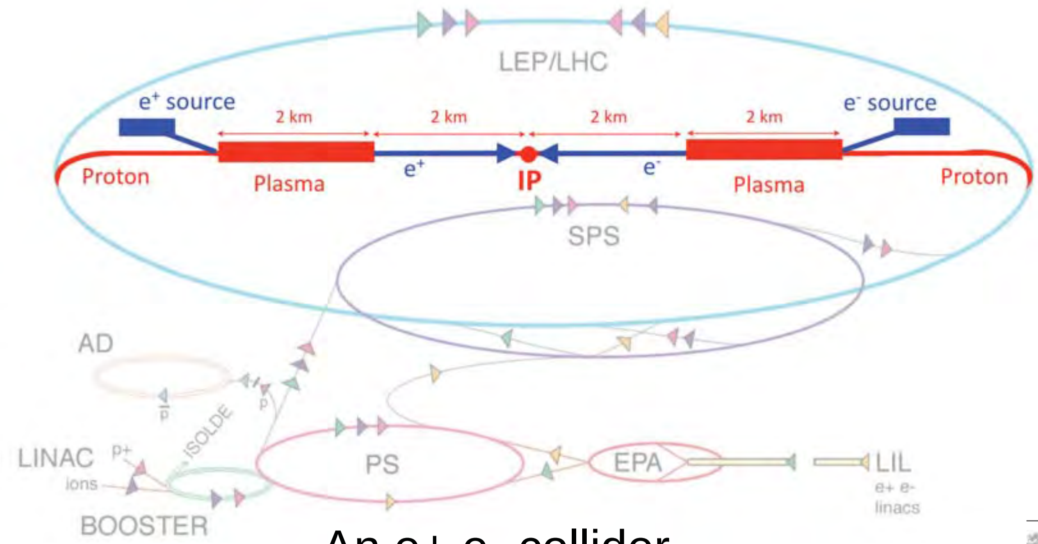


Future collider based on PDPWA

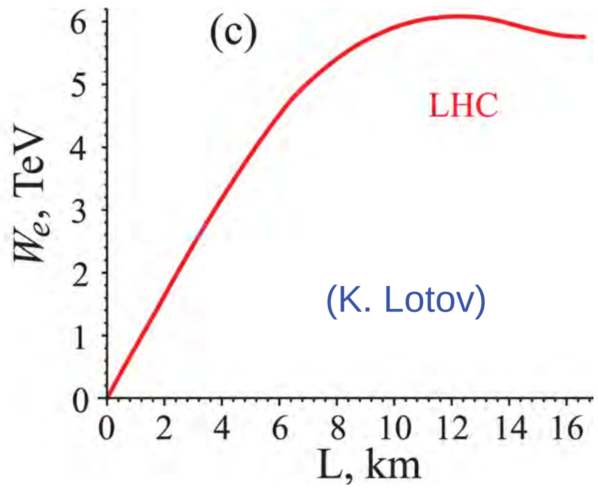
- A self-consistent e^-- e^+ collider (multi-TeV CoM energy) or an e^-- p^+ collider (> 2 TeV CoM) have been designed based on existing CERN infrastructure;
- The key issues for collider design have been studied (e.g. positron acceleration, efficiency, CoM energy, luminosity, dephasing, plasma channel, efficiency, etc.).



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



An e+ e- collider



Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Collider design issues based on proton-driven plasma wakefield acceleration

G. Xia [a,b,*], O. Mete [a,b], A. Aimidula [b,c], C.P. Welsch [b,c], S. Chattopadhyay [a,b,c], S. Mandry [d], M. Wing [d,e]

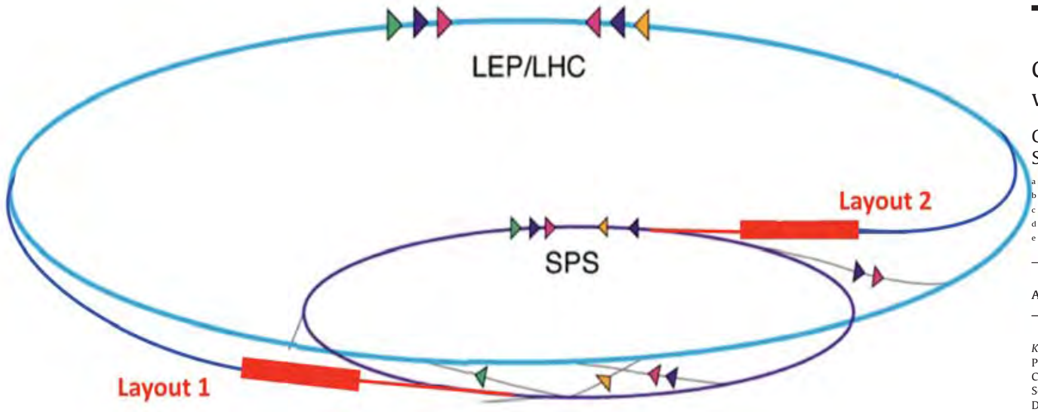
[a] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
[c] The University of Liverpool, Liverpool, United Kingdom
[d] Department of Physics and Astronomy, University College London, London, United Kingdom
[e] Deutsche Elektronen-Synchrotron DESY, Hamburg, Germany

ARTICLE INFO

Keywords:
PDPWA
Colliders
Self-modulation instability
Dephasing

ABSTRACT

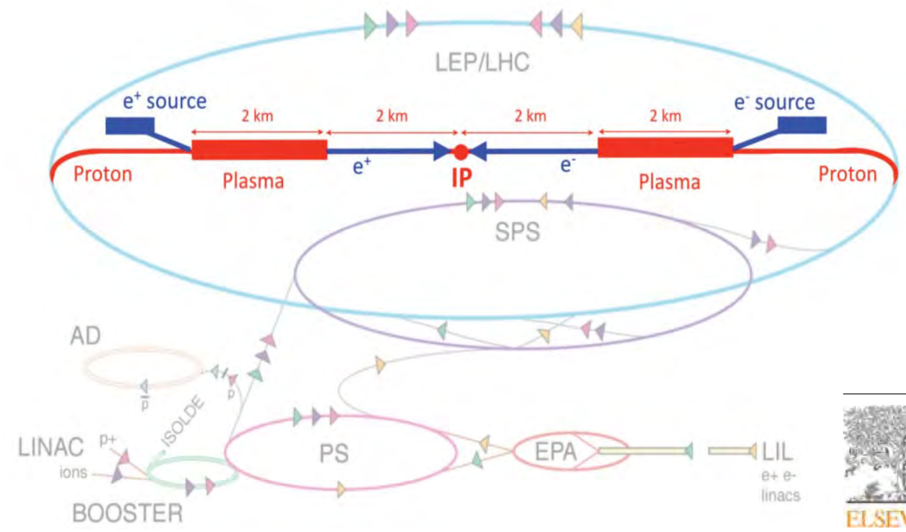
Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy 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.



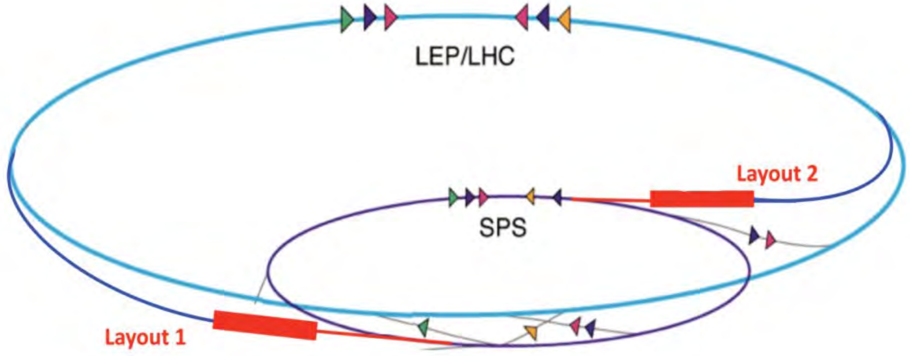
An e-p collider

Future collider based on PD-PWFA

An e+ e- collider



An e-p collider



accelerating gradient >1 GV/m

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Collider design issues based on proton-driven plasma wakefield acceleration

G. Xia [a,b,*], O. Mete [a,b], A. Aimidula [b,c], C.P. Welsch [b,c], S. Chattopadhyay [a,b,c], S. Mandry [d], M. Wing [d,e]

[a] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
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[d] Department of Physics and Astronomy, University College London, London, United Kingdom
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Summary

- AWAKE is the first proton-driven plasma wakefield acceleration in the world. It is also the first beam driven plasma wakefield acceleration experiment in Europe.
- AWAKE experiment will study the self modulated proton driven plasma wakefield acceleration; Proton beam from CNGS beam line will be used for the first experiment in the end of 2016.
- The first experiment goal is to demonstrate 1 GeV electron energy gain @ 10 m plasma, 100 GeV @ 100 m plasma as the second step;
- The AWAKE experiment at CERN will shed light on a future compact Higgs factory or next generation energy frontier collider design.

- UK is the strong partner to the AWAKE project and give key contributions to the experiment, e.g. the discharge plasma source, diagnostics, simulations, electron injector, energy spectrometer, etc.
- The collaborated institutes include: CI, UCL, IC, RAL, JAI, Strathclyde University, etc.

Phase slippage

- Due to the heavy mass of proton, the relativistic factor γ of a TeV proton beam is smaller than that of an electron beam with energy of 1 GeV. Therefore the electrons may overrun the wakefield (the group velocity of the wakefield is the same as the velocity of the driver) and the acceleration process will cease.

$$\frac{d(\gamma_i m_i c^2)}{dt} = -qE_{dec} v_i$$

$$\frac{d(\gamma_e m_e c^2)}{dt} = eE_{acc} v_e$$

$$\Delta d = \int_0^T (v_e - v_i) dt = \frac{m_e c^2}{e}\left[\frac{\gamma_e - \gamma_{e0}}{E_{acc}} + \frac{m_i e}{m_e q}\frac{\gamma_i - \gamma_{i0}}{E_{dec}}\right]$$

$$\frac{d(\gamma_i m_i v_i)}{dt} = -qE_{dec} \qquad m_i c\left(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right) = -qE_{dec} T$$

$$\frac{d(\gamma_e m_e v_e)}{dt} = qE_{acc} \qquad m_e c\left(\sqrt{\gamma_e^2 - 1} - \sqrt{\gamma_{e0}^2 - 1}\right) = eE_{acc} T$$

$$\Delta d = \frac{m_e c^2}{eE_{acc}}(\gamma_e - \gamma_{e0})\left[1 - \frac{\left(\sqrt{\gamma_e^2 - 1} - \sqrt{\gamma_{e0}^2 - 1}\right)(\gamma_i - \gamma_{i0})}{\left(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)(\gamma_e - \gamma_{e0})}\right]$$

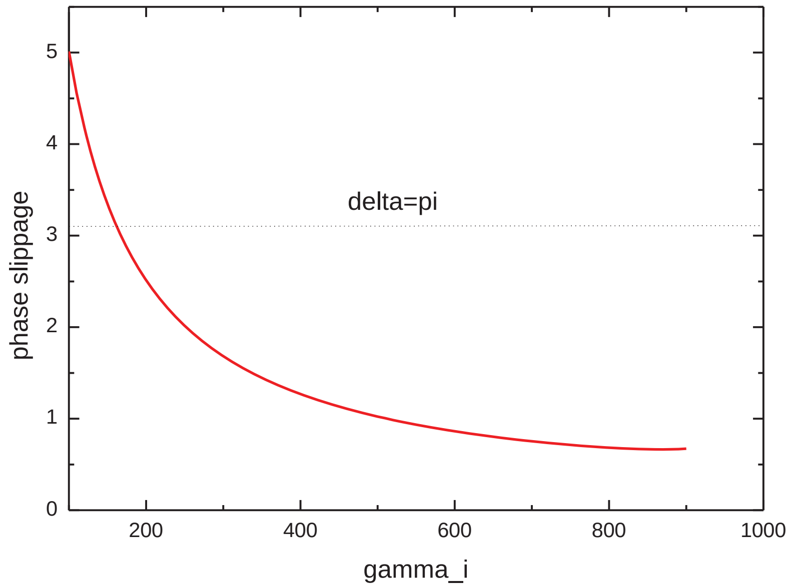
For $\gamma_e >> \gamma_i$ $$\Delta d \approx \frac{m_e c^2}{eE_{acc}}(\gamma_e - \gamma_{e0})\left[1 - \frac{(\gamma_i - \gamma_{i0})}{\left(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)}\right]$$

G. Xia et al., IPAC11 (WEPZ024)

Phase slippage

$$\delta = k_p \Delta d \approx \frac{1}{eE_{acc}/m_e c\omega_p}(\gamma_e - \gamma_{e0})\left[1 - \frac{(\gamma_i - \gamma_{i0})}{\left(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i0}^2 - 1}\right)}\right]$$

For a single stage PDPWA with a 1 TeV proton drive beam that accelerates electrons to 500 GeV energy (assuming electron injection energy far less than 500 GeV), $\gamma_{i0} = 1000$, $\gamma_e - \gamma_{e0} \approx 10^6$. If we assume that the wakefield amplitude is $eE_{acc}/m_e c\omega_p \sim 1$, then the phase slippage is $k_p \Delta d = 10^6 \left[1 - (\gamma_i - 1000)/\left(\sqrt{\gamma_i^2 - 1} - \sqrt{1000^2 - 1}\right)\right]$ which has to be smaller than π. Fig.1 shows the phase slippage as a function of the final energy of the proton for a 1 TeV drive beam. It can be seen that the final energy of a 1 TeV proton beam has to be larger that 160 GeV in order to satisfy the phase slippage requirement. Using the average accelerating (decelerating) field of ~ 1.4 GV/m, the maximum dephasing length is about 600 m. And the transformer ratio of such a single stage PDPWA is about 0.6. This provides the basic parameter to design such an acceleration stage.

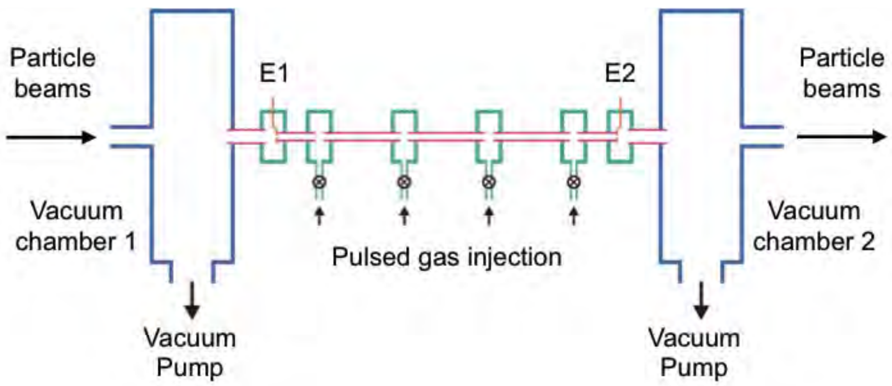


Phase slippage of a 1 TeV proton beam *vs*. *gamma_i* of the proton beam.

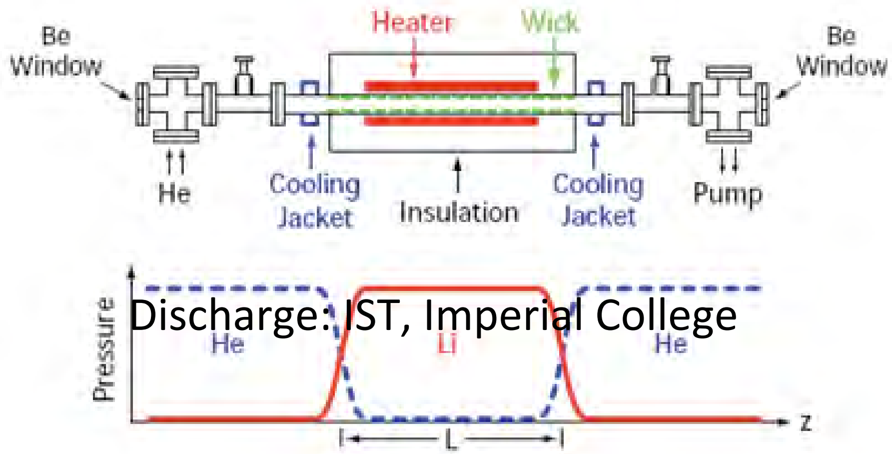
G. Xia et al., IPAC11 (WEPZ024)

Plasma cells

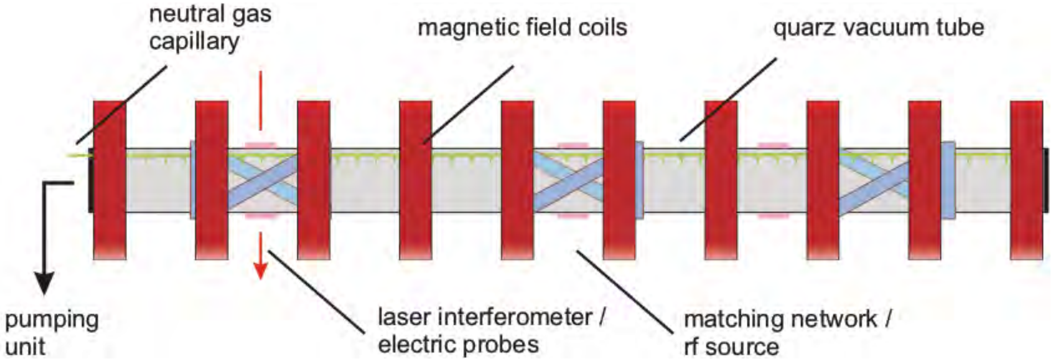
Discharge: IST, Imperial College



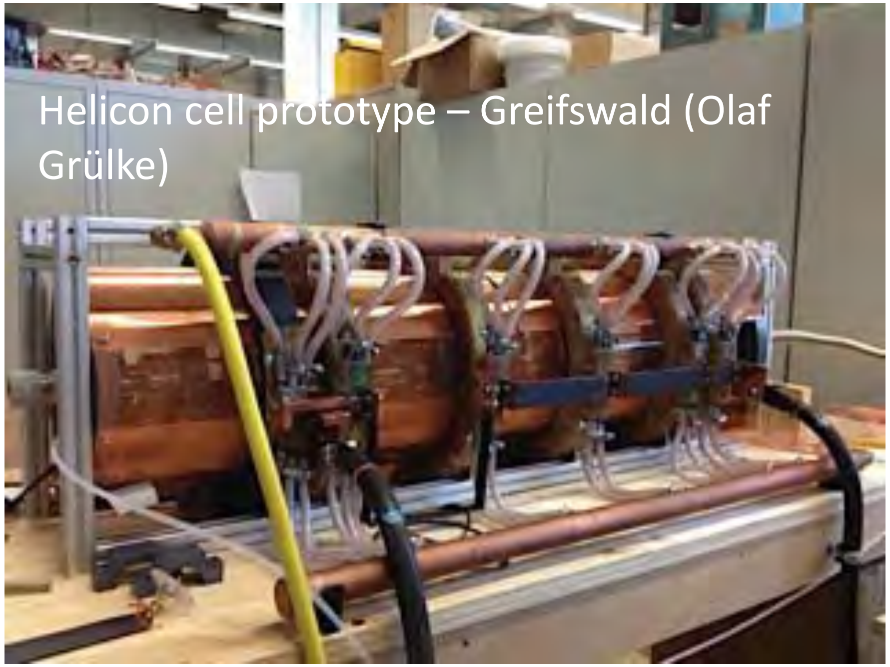
Metal vapor, a la SLAC experiment:
UCLA, Max Planck Institute for Physics



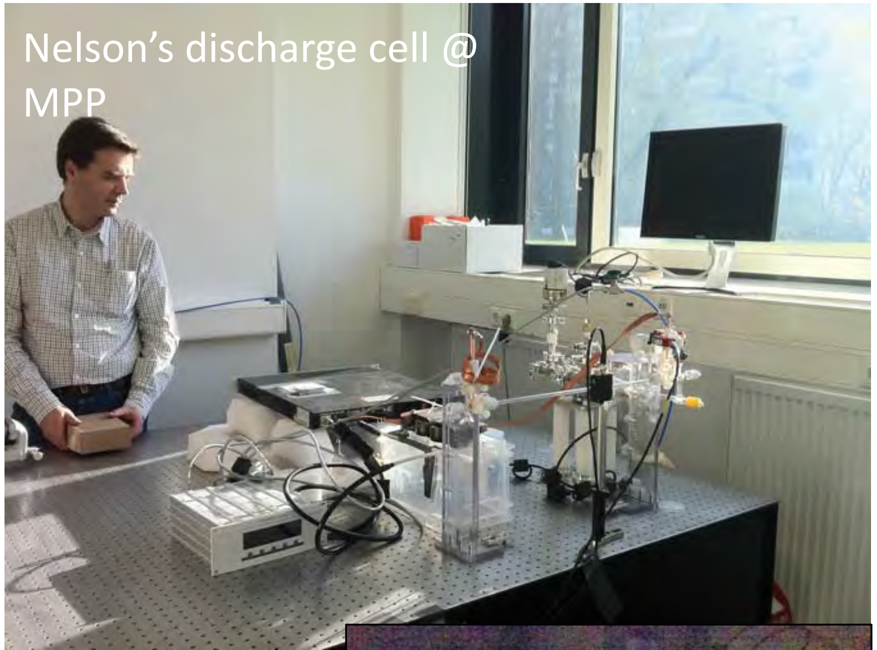
Helicon – Max Planck Institute for Plasma Physics



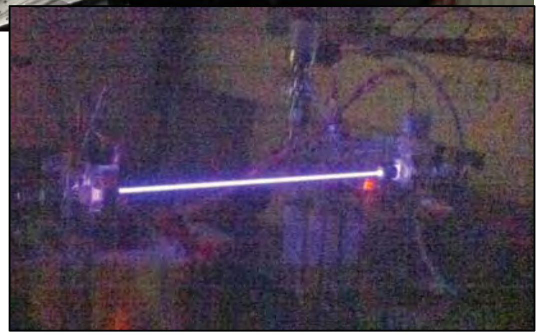
Plasma cells

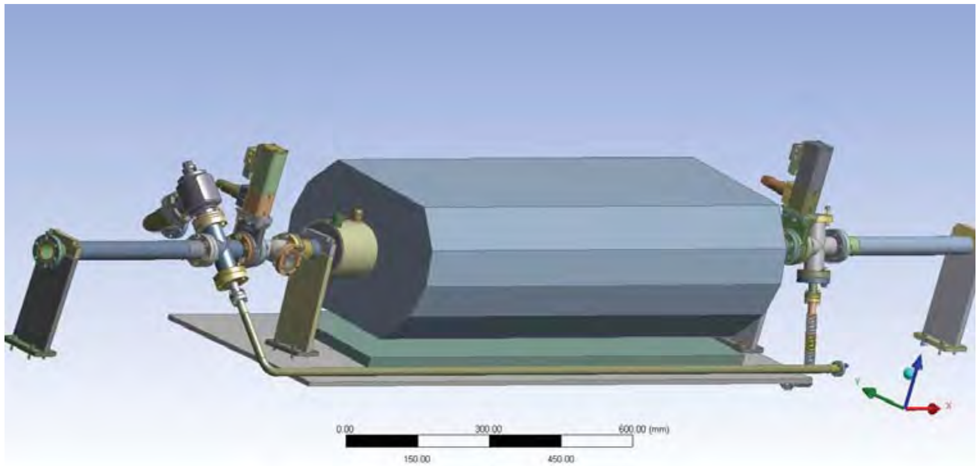


Helicon cell prototype – Greifswald (Olaf Grülke)



Nelson's discharge cell @ MPP





Heat pipe oven concept + vapor cell
E. Öz, P. Muggli

Status and outlook

- AWAKE experiment will be the first proton-driven plasma wakefield accelerator worldwide
- Simulation shows that working in self-modulation regime, SPS beam can excite the field around ~ 1 GV/m with a high density plasma.
- Future experiment will be carried out based upon the first round experiments for even higher energy electron beam acceleration
- AWAKE experiment will give input to the future design for a compact, more affordable, multi-TeV lepton collider.

Thanks to Edda for many nice pictures!

Thanks for your attention!