Proton-driven plasma wakefield acceleration—a new route to a TeV lepton collider

Matthew Wing (UCL)

- Motivation : particle physics; large accelerators
- General concept : proton-driven plasma wakefield acceleration
- Towards a first test experiment at CERN
- Outlook

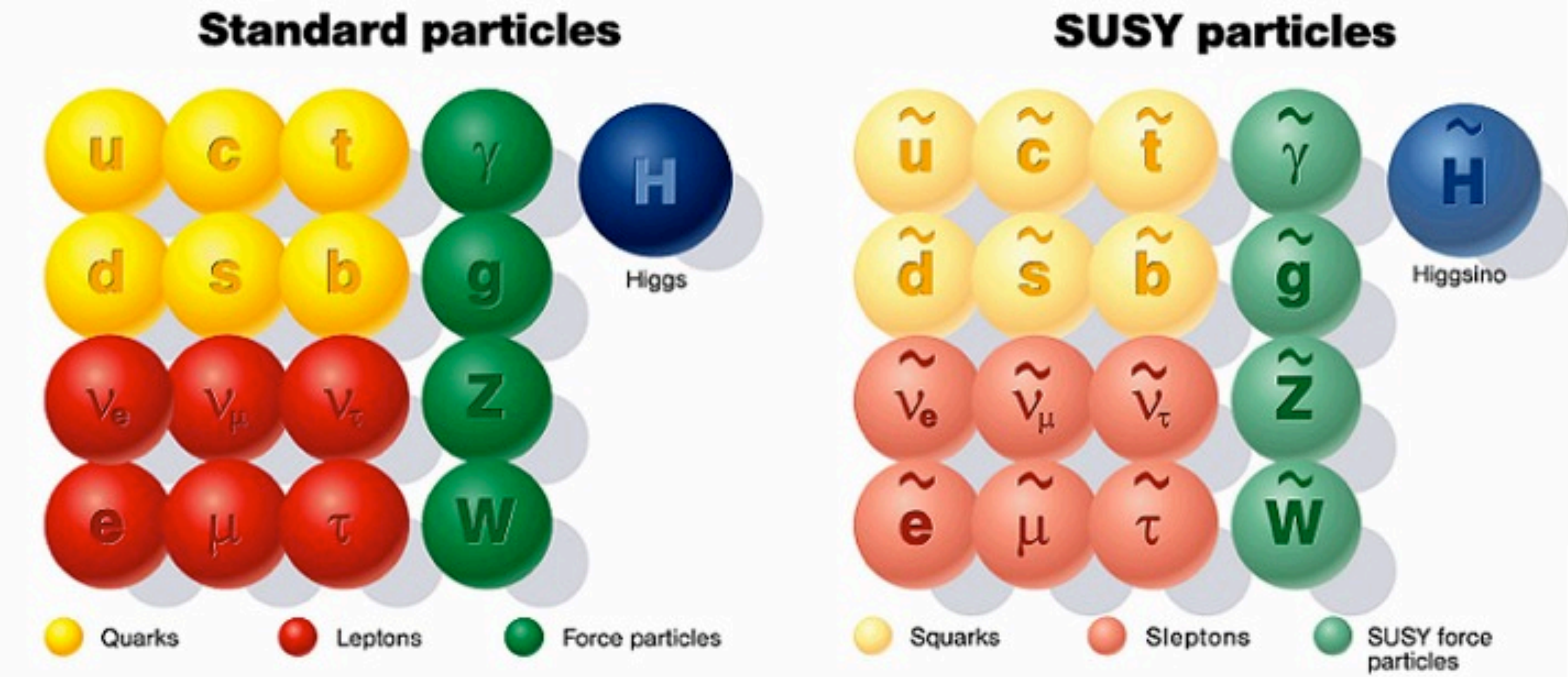
Seminar — Birmingham — 28 September 2011

Motivation

Motivation

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

Big questions in particle physics



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

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

Future energy-frontier colliders

The LHC is running and should for many years [future *pp* collider ?]

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

• An e^+e^- linear collider which can span to multi-TeV is clearly preferable.

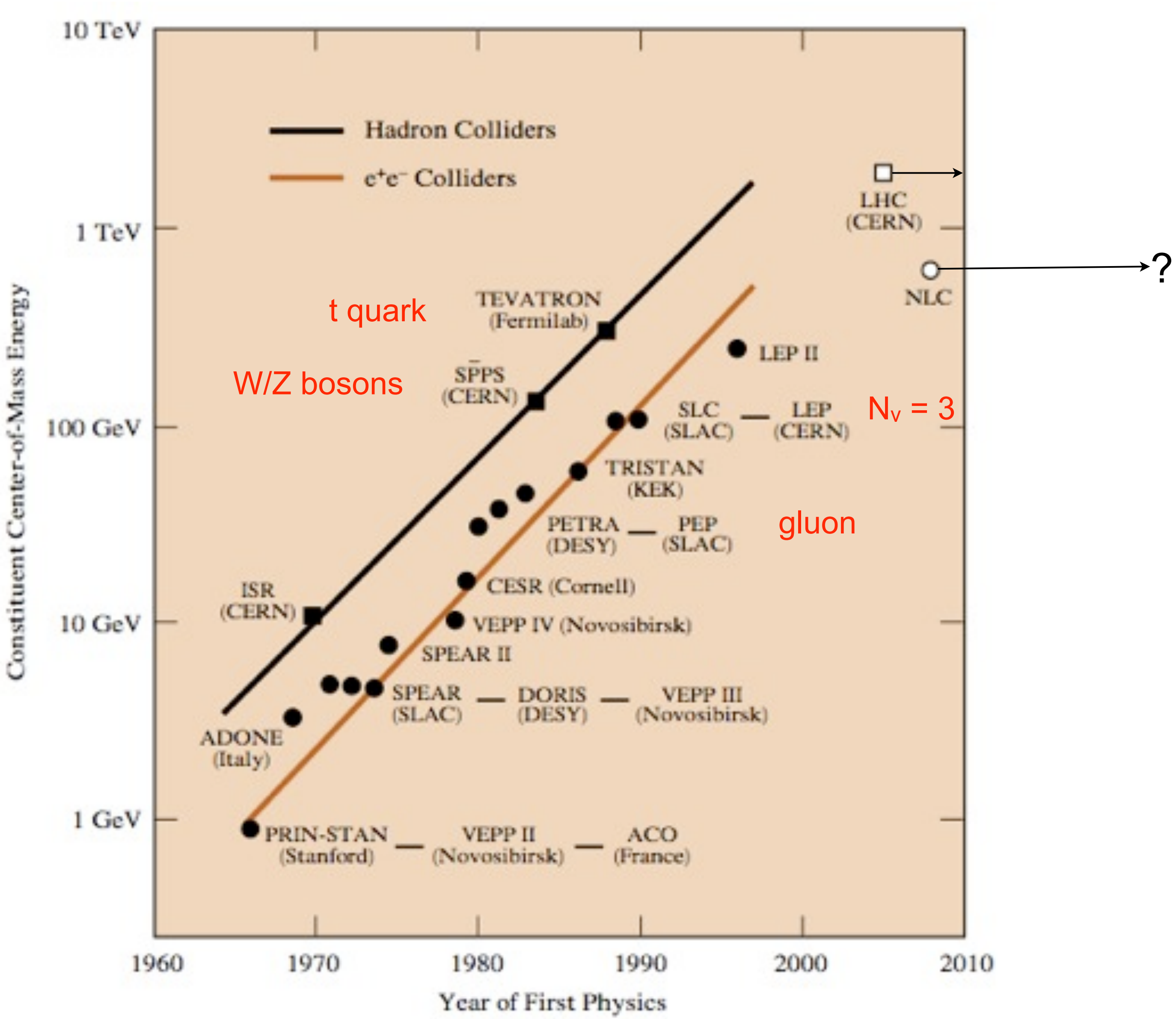
• Hope to discover Higgs particle and e.g. Supersymmetry at the LHC and future colliders.

• Precision environment of a lepton collider essential for measuring properties of newly-discovered particles or phenomena.

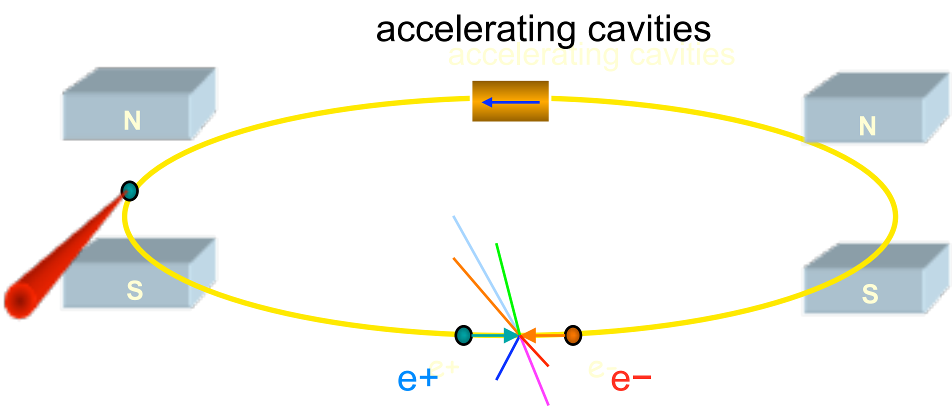
• Will strongly constrain alternative theories or phenomena proposed or yet to be discovered.

• May also discover new resonances otherwise unseen in a large-background environment.

Collider history



Conventional accelerators

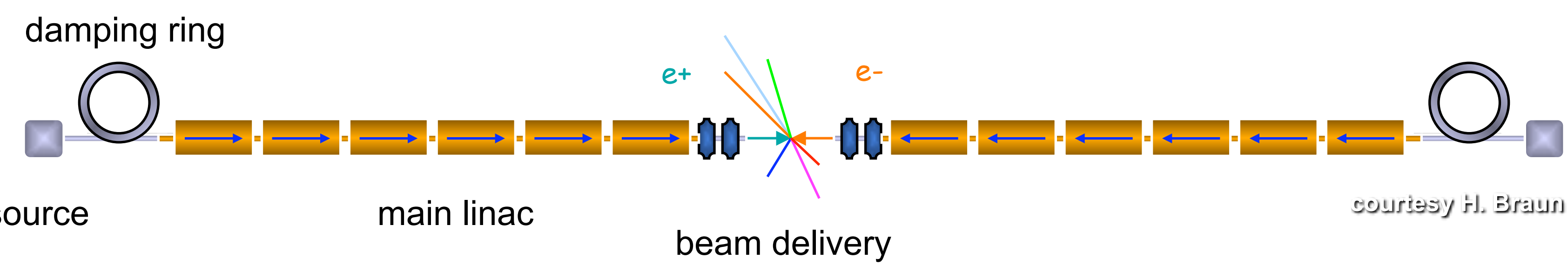


Circular colliders :

• Many magnets, few cavities so strong field needed;

• High synchrotron radiation;

• High repetition rate leads to high luminosity.



Linear colliders :

• Few magnets, many cavities so efficient RF power production needed;

• Single pass so need small cross section for high luminosity and very high beam quality;

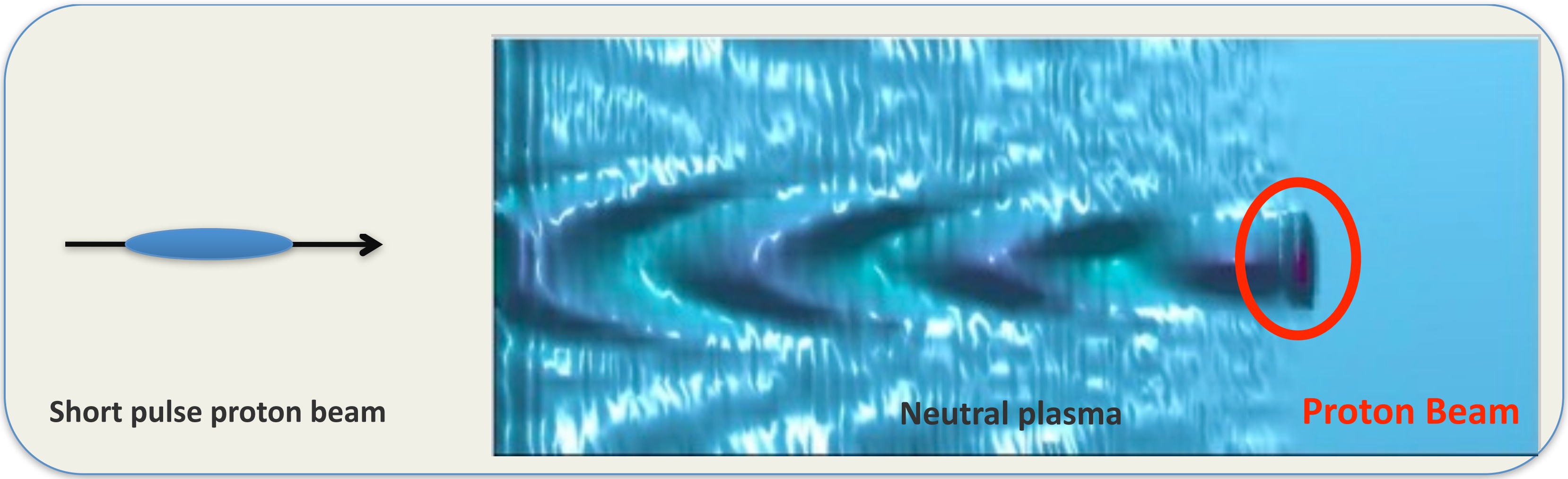
• The higher the gradient, the shorter the linac.

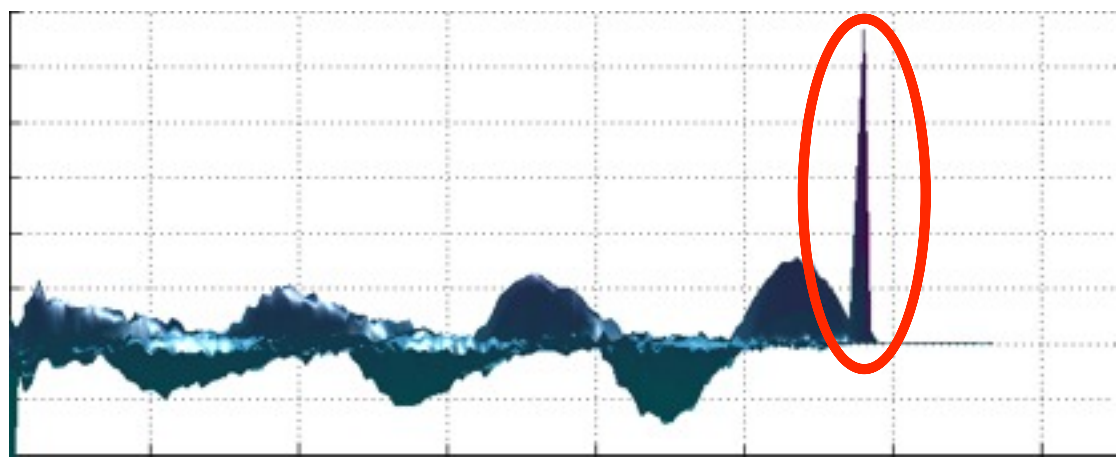
Current / proposed accelerators

Parameter	ILC	CLIC
E_{CM} (TeV)	0.5–1	3
Bunch separation (ns)	369	0.5
No. particles/bunch	2×10^{10}	4×10^{9}
No. bunches/train	2625	312
Repetition rate (Hz)	5	50
Accelerating gradient (MV/m)	35	100
Beam size (nm^2)	640×5.7	45×0.9

Proton-driven plasma wakefield acceleration

Plasma wakefield acceleration explained





Thanks to J. Holloway (UCL)

Plasma considerations

Based on linear fluid dynamics :

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

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

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

Relevant physical quantities :

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

where :

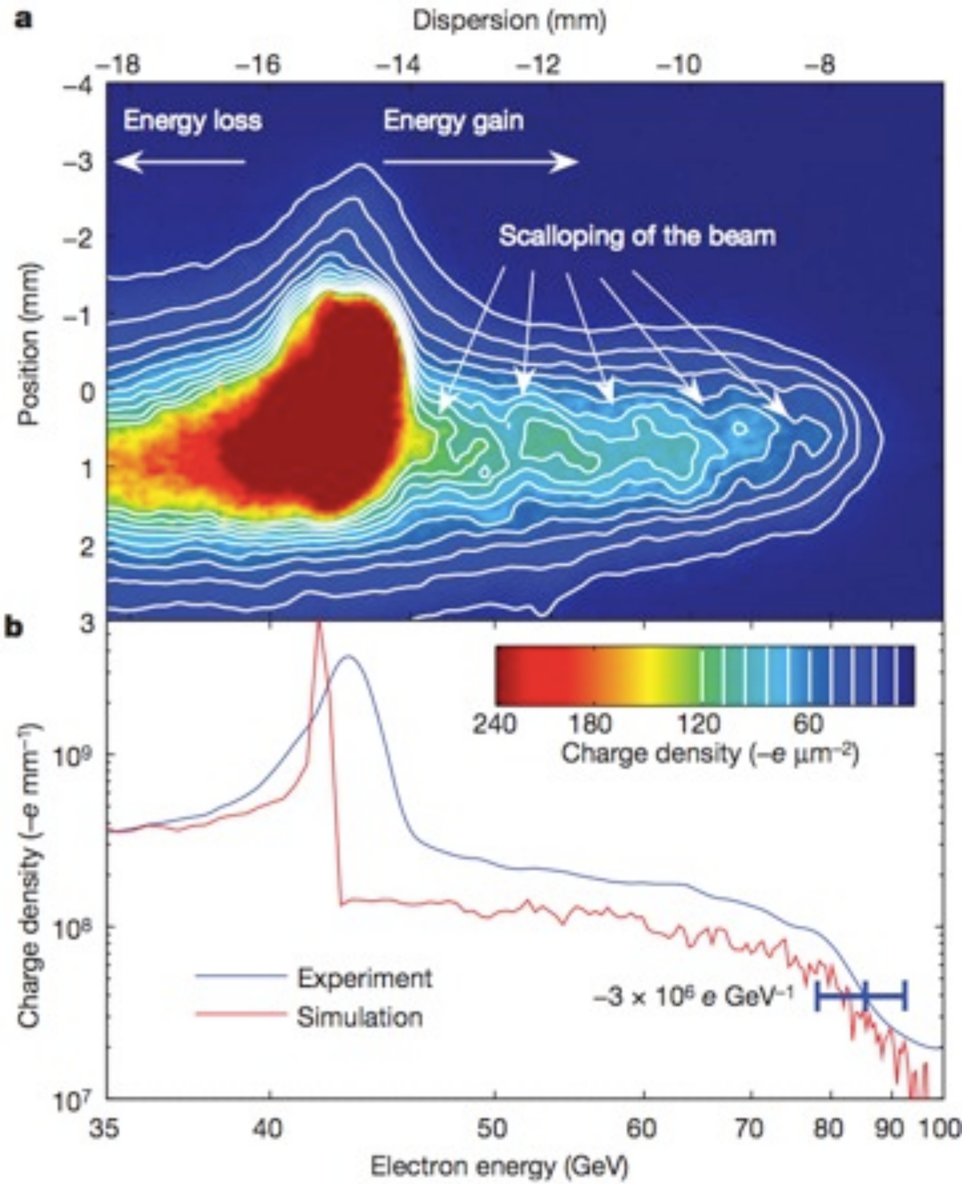
- n_p is the plasma density
- e is the electron charge
- ε_0 is the permittivity of free space
- m_e is the mass of electron
- N is the number of drive-beam particles
- σ_z is the drive-beam length

High gradients with :

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

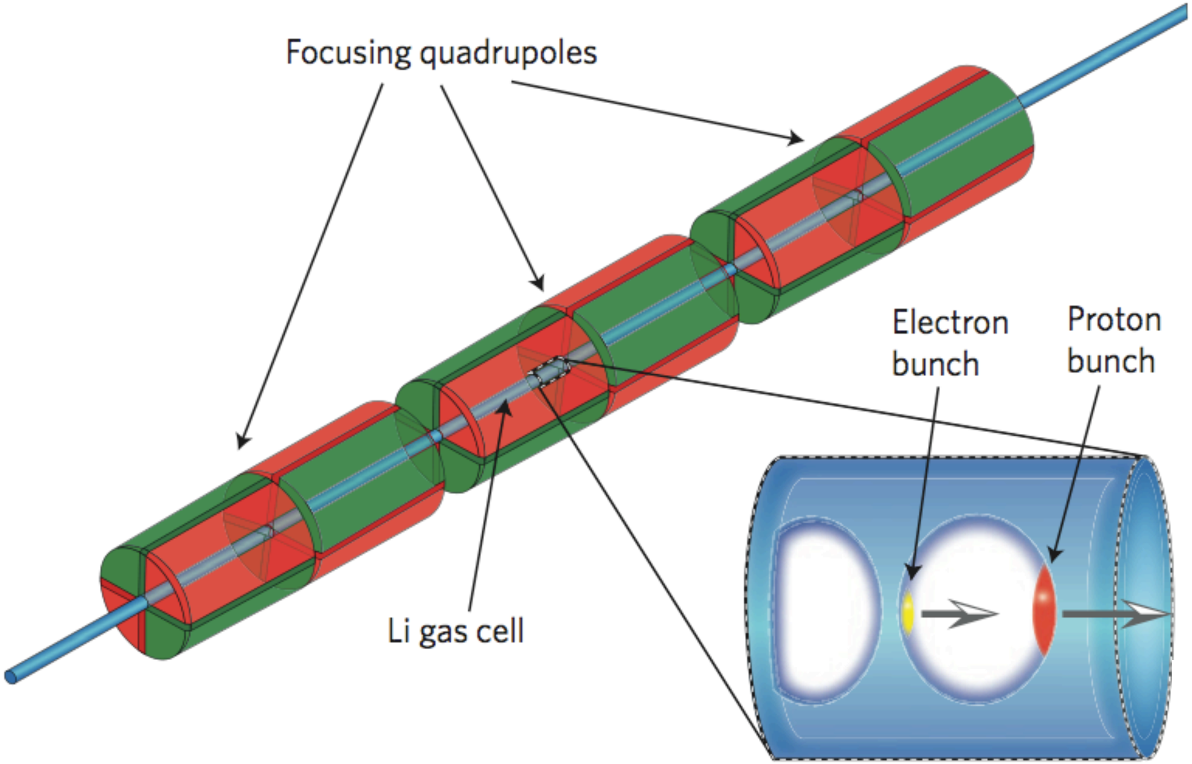
Plasma wakefield experiments

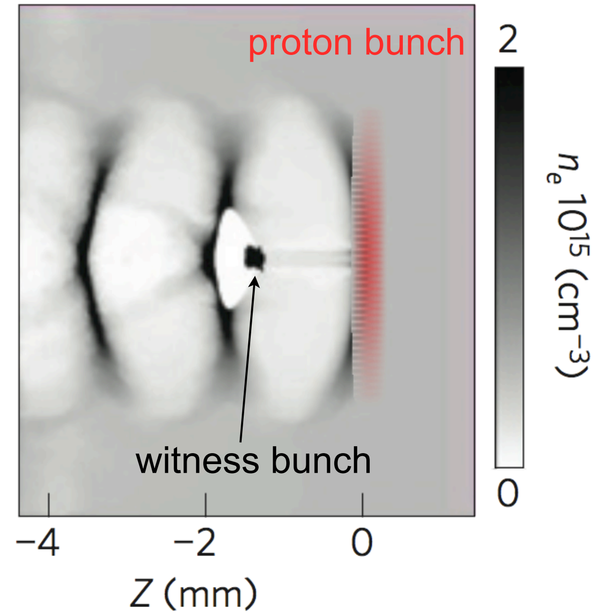
- Pioneering work using a LASER to induce wakefields.
- Experiments at SLAC[§] have used a particle (electron) beam :
    - Initial energy E_e = *42 GeV*
    - Gradients up to ~ *52 GV/m*
    - Energy doubled over ~ *1 m*
    - Next stage, FACET project (http://facet.slac.stanford.edu)
- Have proton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

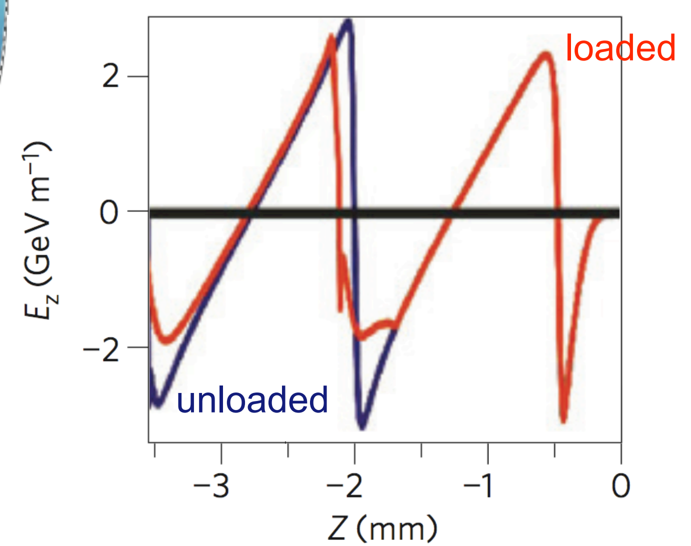


§ I. Blumenfeld et al., Nature **445** (2007) 741.

PDPWA concept*





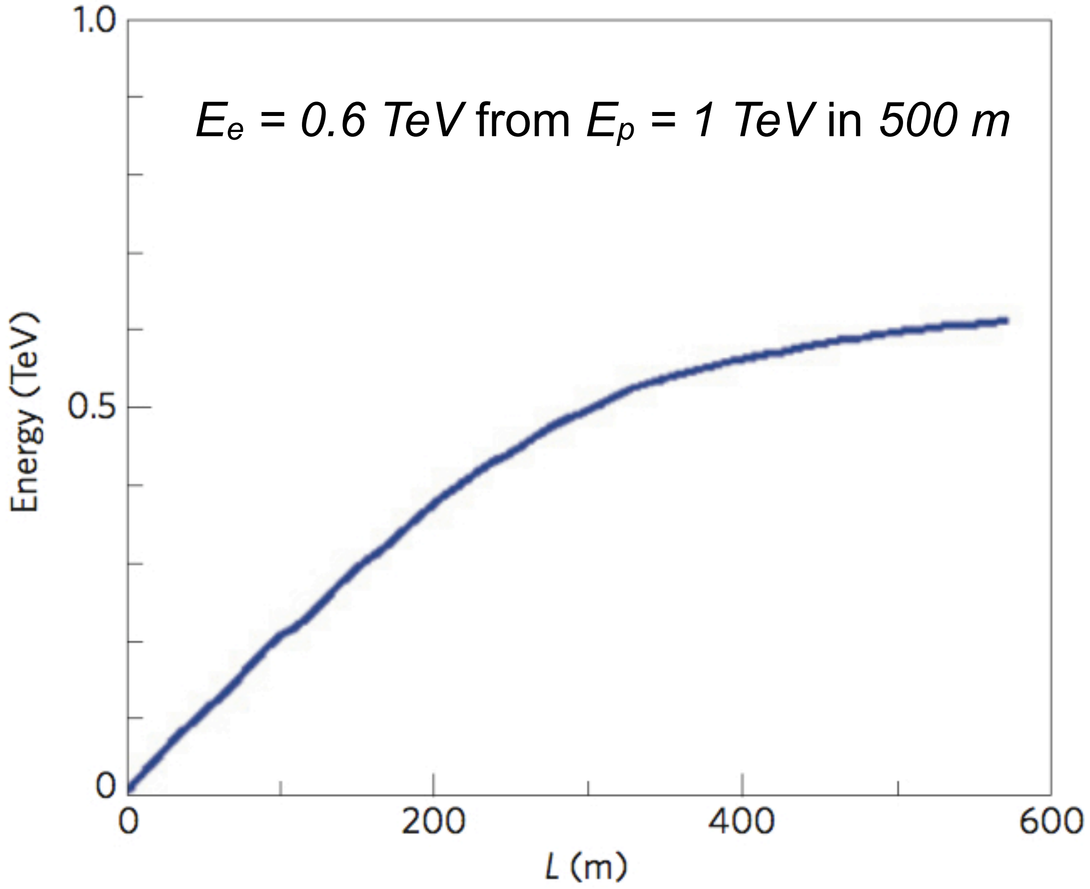


- Electrons ‘sucked in’ by proton bunch.
- Continue across axis creating a depletion region.
- Transverse electric fields focus witness bunch.
- Maximum accelerating gradient of *3 GV/m*.

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

PDPWA concept

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



PDPWA concept

Table 1 | Table of parameters for the simulation.

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

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

Towards a test experiment

PDPWA Collaboration and practicalities

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

Letter of Intent
for a Demonstration Experiment in
Proton-Driven Plasma Wakefield Acceleration

E. Adli[24], W. An[22], R. Assmann[3], R. Bingham[19], A. Caldwell[16], S. Chattopadhyay[4], N. Delerue[12],
F. M. Dias[8], I. Efthymiopoulos[3], E. Elsen[5], S. Fartoukh[3], C. M. Ferreira[8], R. A. Fonseca[8],
G. Geschonke[3], B. Goddard[3], O. Grülke[17], C. Hessler[3], S. Hillenbrand[11], J. Holloway[19,23], C. Huang[14],
D. Jarozinsky[25], S. Jolly[23], C. Joshi[22], N. Kumar[7], W. Lu[21,22], N. Lopes[8], M. Kaur[18], K. Lotov[2],
V. Malka[13], M. Meddahi[3], O. Mete[3], W.B. Mori[22], A. Mueller[11], P. Muggli[16], Z. Najmudin[9],
P. Norreys[19], J. Osterhoff[5], J. Pozimski[9], A. Pukhov[7], O. Reimann[16], S. Roesler[3], H. Ruhl[15],
H. Schlarb[5], B. Schmidt[5], H.V.D. Schmitt[16], A. Schöning[6], A. Seryi[10], F. Simon[16], L.O. Silva[8],
T. Tajima[15], R. Trines[19], T. Tückmantel[7], A. Upadhyay[7], J. Vieira[8], O. Willi[7], M. Wing[23], G. Xia[16],
V. Yakimenko[1], X. Yan[20], F. Zimmermann[3]

• HERA, Tevatron and LHC beams can not be used. Possibility of PS (*24 GeV*) or SPS (*450 GeV*) proton beam.

• Letter of intent submitted to CERN SPSC, 25 institutes (6 UK), reviewed June, decision October.

• Two years of experimentation with e.g. four lots of 2-week running periods.

• Collaborating institutes will need to provide (in-kind) resources of e.g. magnets, experimental equipment, e.g. plasma cell, and effort to run and analyse.

• Will have a beamline available for future experimentation of plasmas, accelerators, etc..

CERN interest / coordination

"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."
Steve Myers, CERN Director of Accelerators and Technology.

European Network on Novel Accelerators (EuroNNAc)

• Initiative by EuCARD, CERN, DESY and Ecole Polytechnique.

• Scope : Plasma wakefield acceleration and direct laser acceleration for electrons and positrons. Includes proton drivers.

• Build network and prepare significant FP8 bid for advanced accelerators in 2013.

http://www.cern.ch/euronnac

Simulation of PDPWA

• Various codes have been used : 2D fluid LCODE [Lotov], 3D PIC VLPL [Pukhov], 3D PIC OSIRIS [Hemker et al.], 3D quasi-static QuickPIC [Huang et al.], 3D PIC EPOCH [Arber et al.].

• Fixed and representative parameters for code benchmarking.

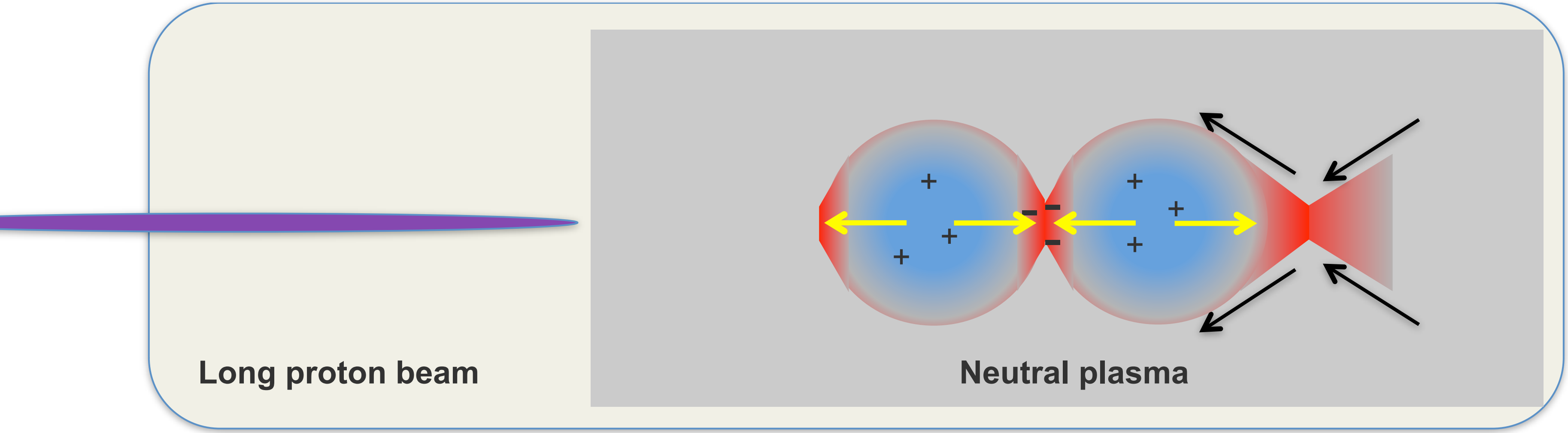
• Initial Gaussian and half-cut beam.

Table 1: Basic beam parameters of the SPS.

Parameter	Nominal	Optimized
Momentum [GeV/c]	450	450
Protons/bunch [10^{11}]	1.15	3.0
rms longitudinal emittance [eVs]	0.05	0.05
rms energy spread [MeV]	135	135
rms bunch length [cm]	12	12
rms transverse normalized emittance [μm]	3.5	3.5
beam size [μm]	200	200
beta function at plasma cell [m]	5	5

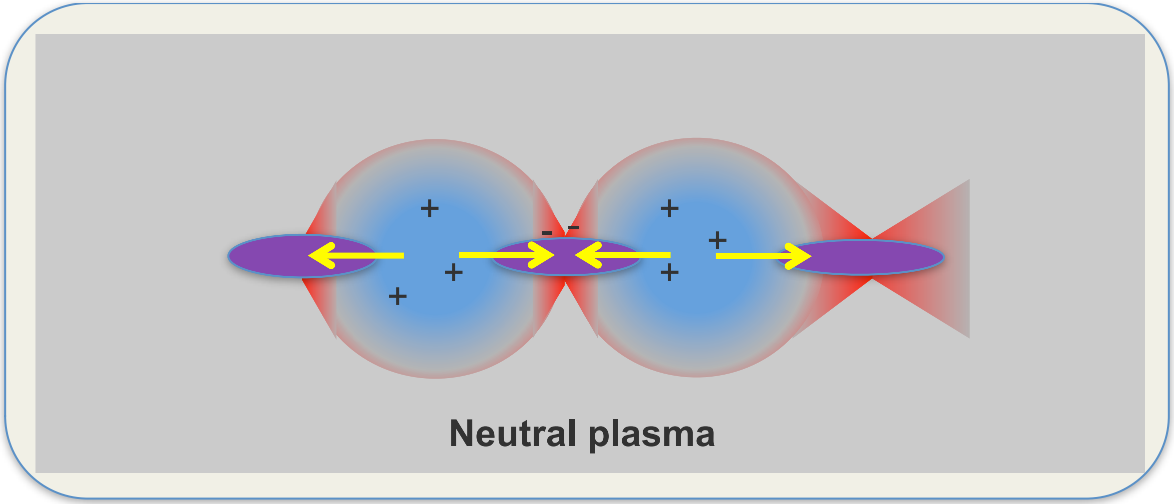
• Note proton bunch length compared to concept. Beam compression expensive.

Long beam : self-modulation



• Microbunches are spaced at the plasma wavelength and act constructively to generate a strong plasma wake.

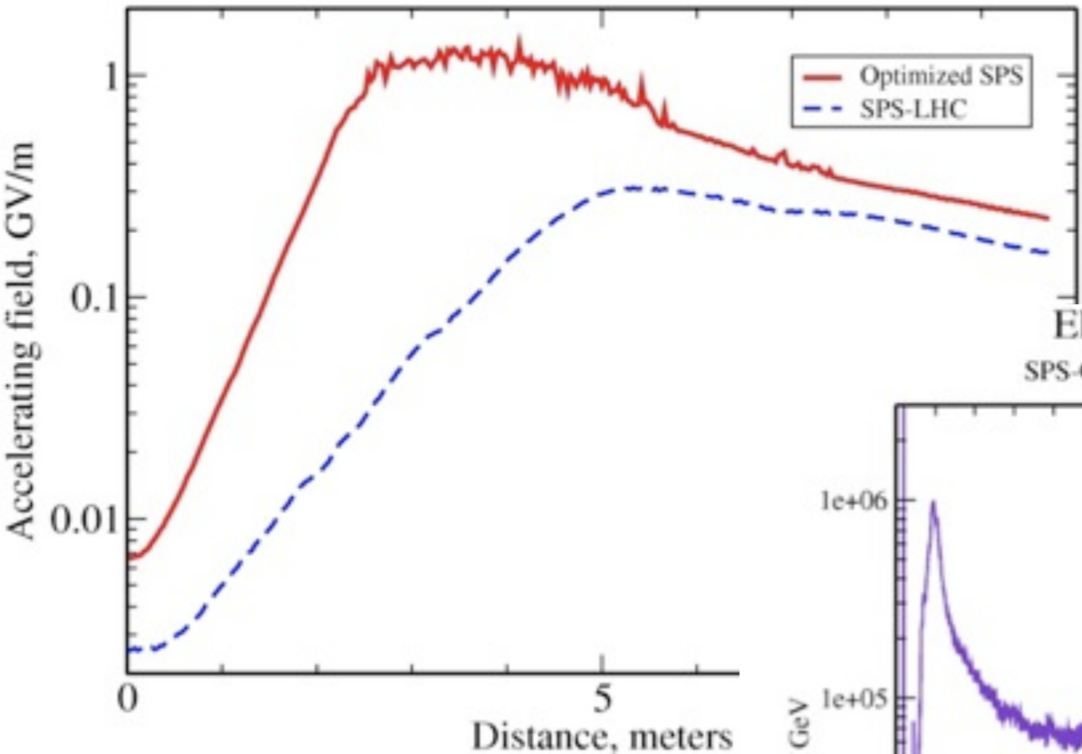
• Seeding the modulation is critical. Use laser pulse or short electron beam.



Self-modulated driver beam

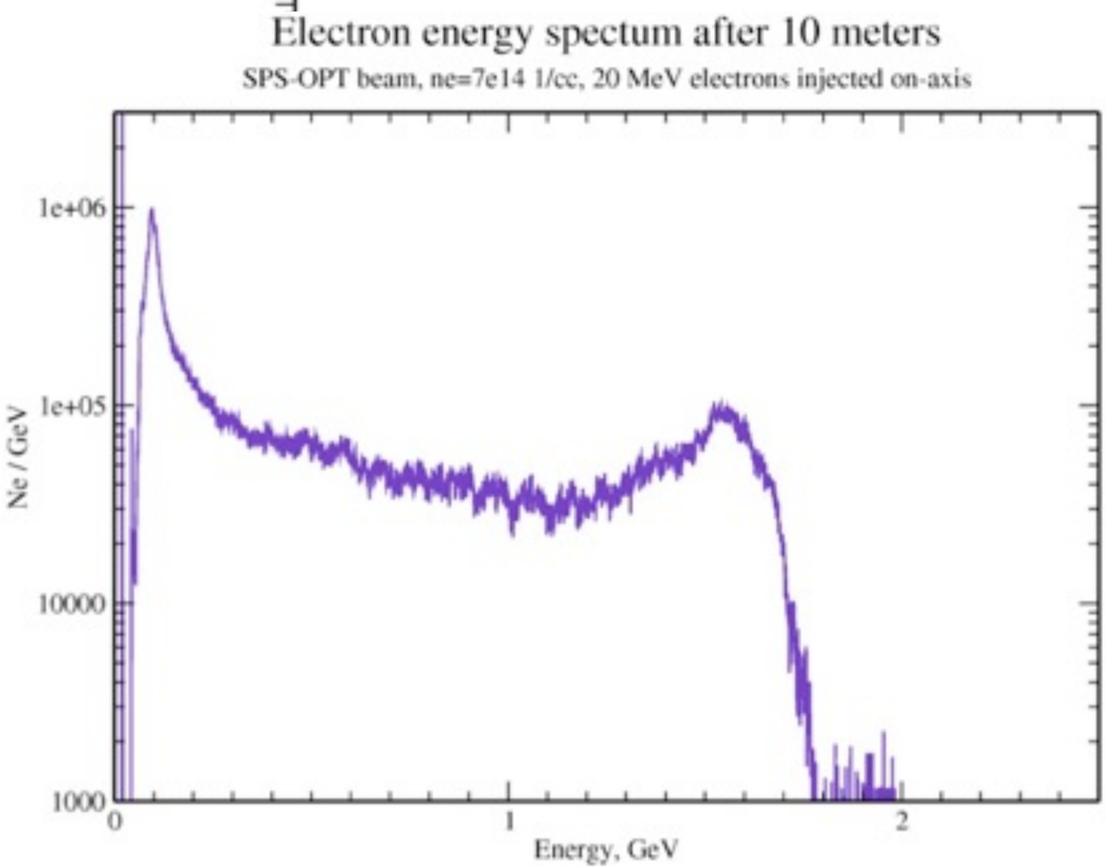
Thanks to J. Holloway (UCL)

Simulation results

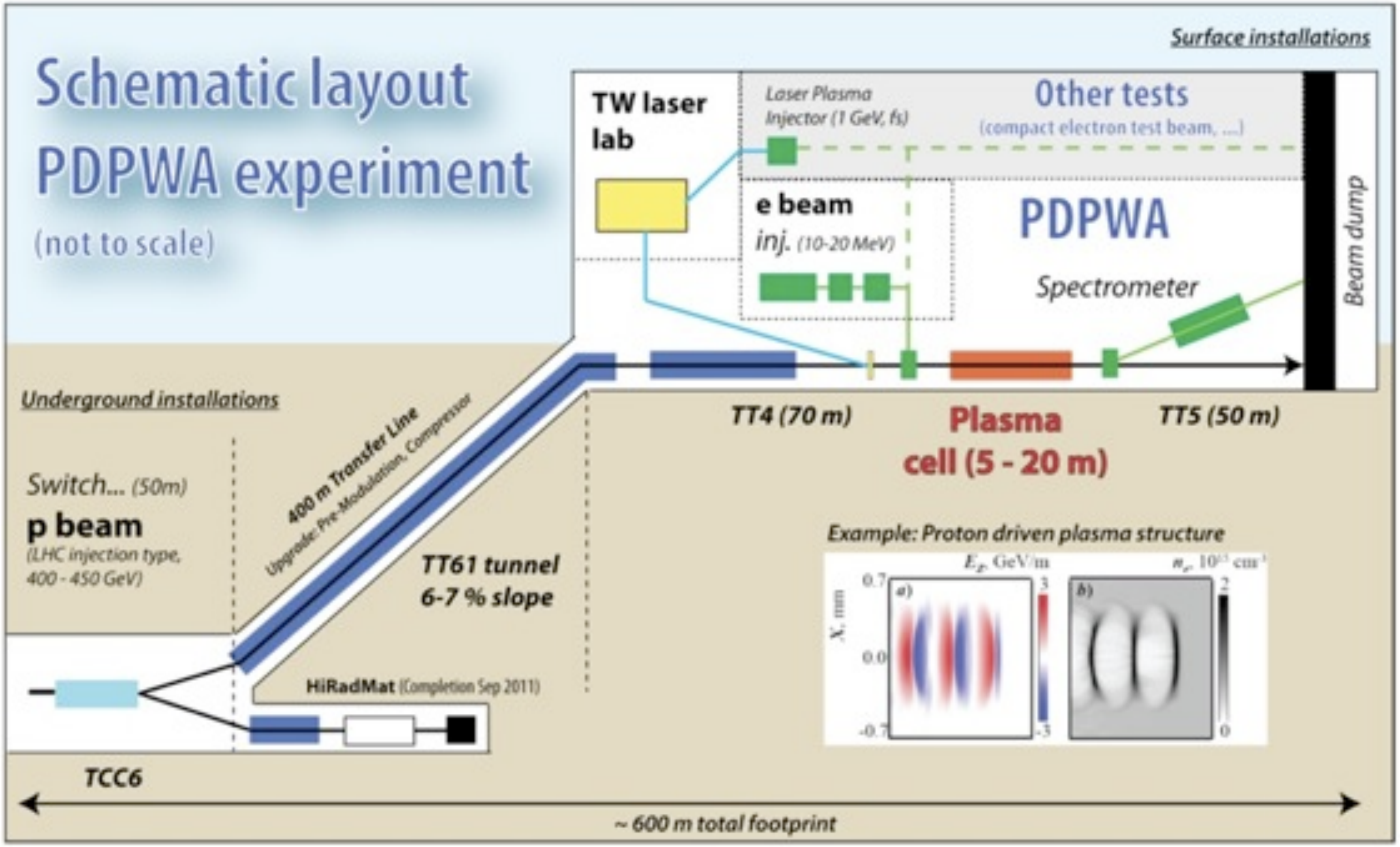


Wakefields of about *1 GV/m.*

Electrons accelerated to > *1 GeV*.



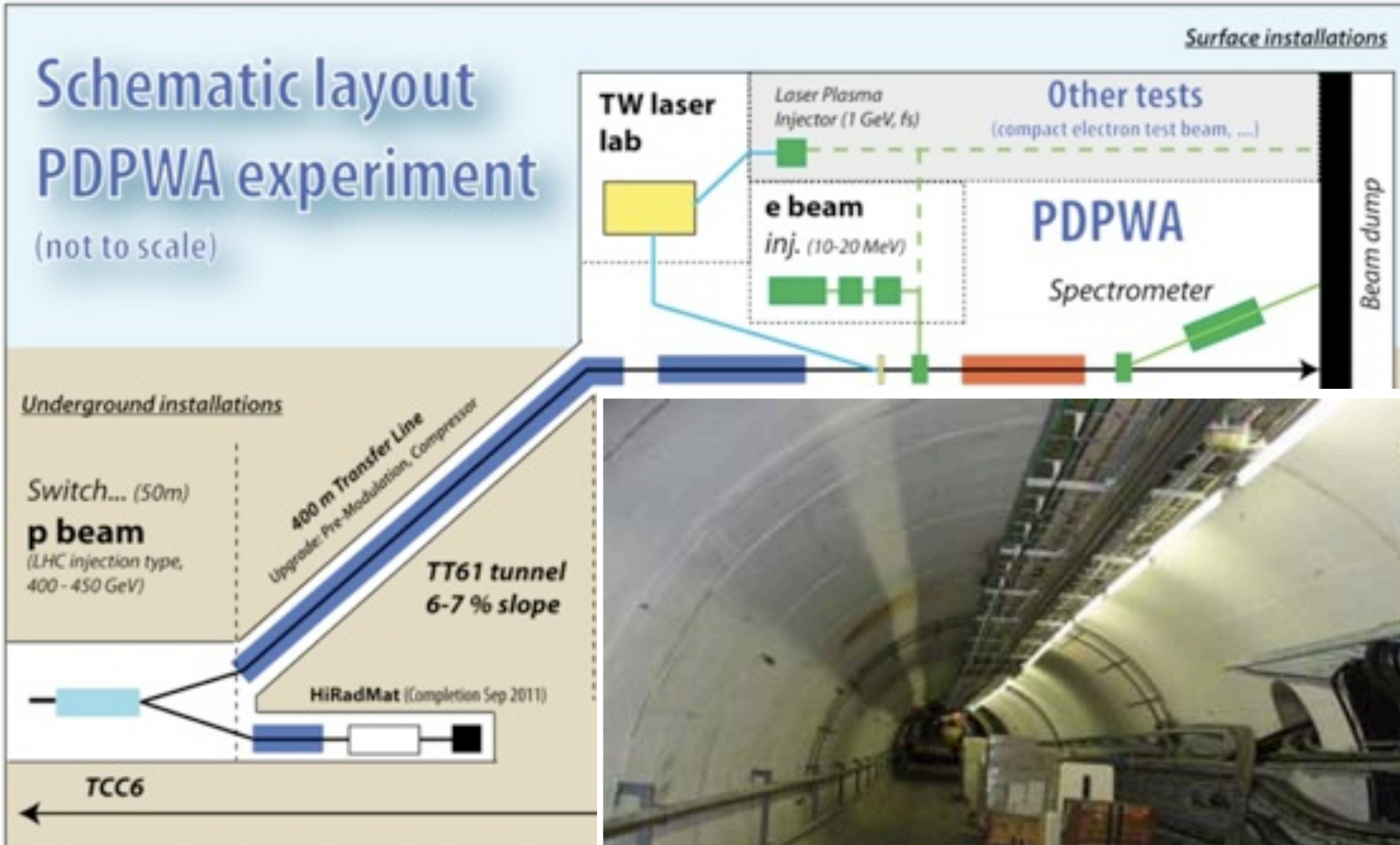
Proposed experiment at CERN



Near-term (5-year) plan :

- Achieve > *1 GeV* energy self-modulation of proton beam in ~ *5–10 m* plasma.
- Acceleration of *~10 MeV* witness electrons to > *1 GeV*.

Proposed experiment at CERN



Near-term (5-year) plan :

- Achieve > *1 GeV* energy self-modulat
- Acceleration of *~10 MeV* witness elec

Plasma cell design

• Plasma cells have typically been cm-long, up to *1 m* for SLAC experiment. Need to extend to *5–10 m* (short-term) and *O(100) m* (long-term).

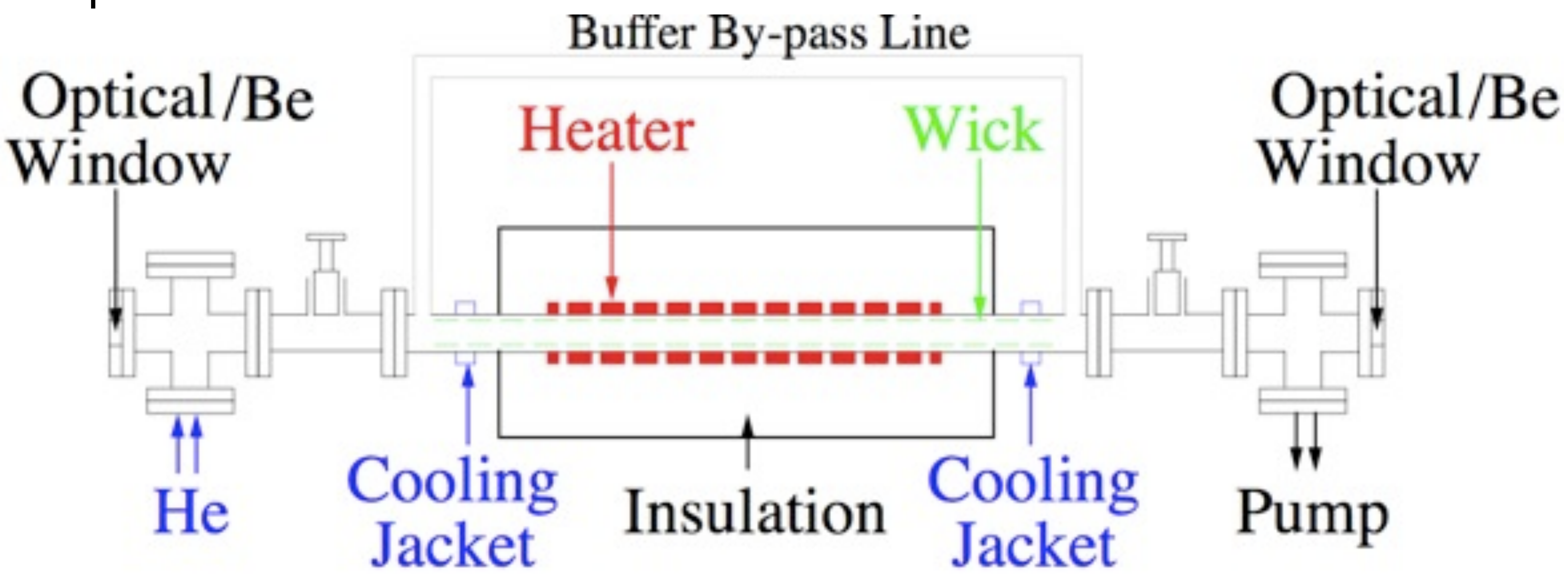
• Densities have typically been high whereas we need $n_e \sim 10^{14}–10^{15}\ cm^{-3}$.

• Density needs to be uniform and well-known.

• Various designs :

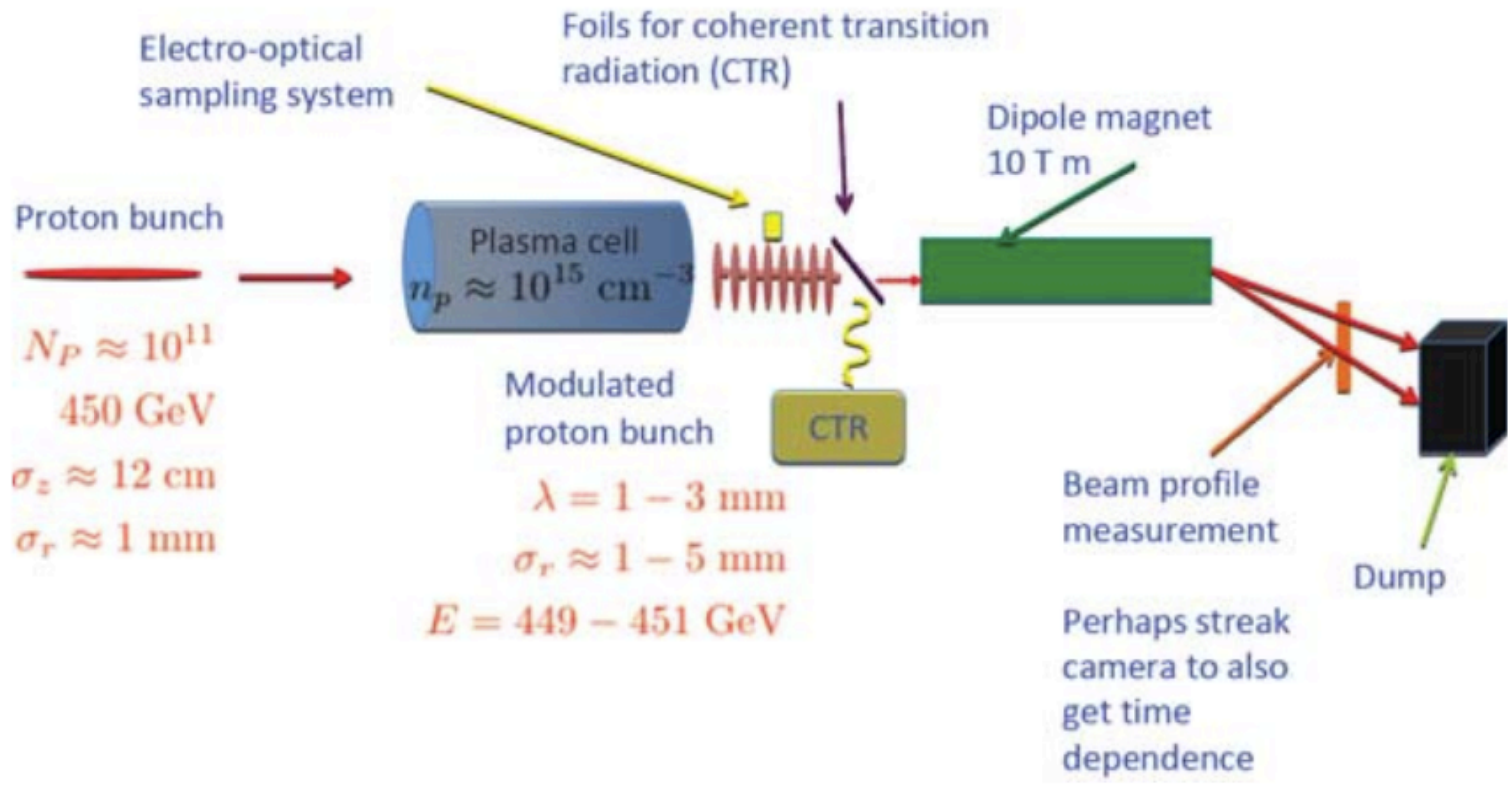
- Li (or e.g. Cs) vapour created in oven as used in SLAC experiment.
- Gas discharge cell.
- Helicon plasma cell.

E.g.



• Will pursue all three designs

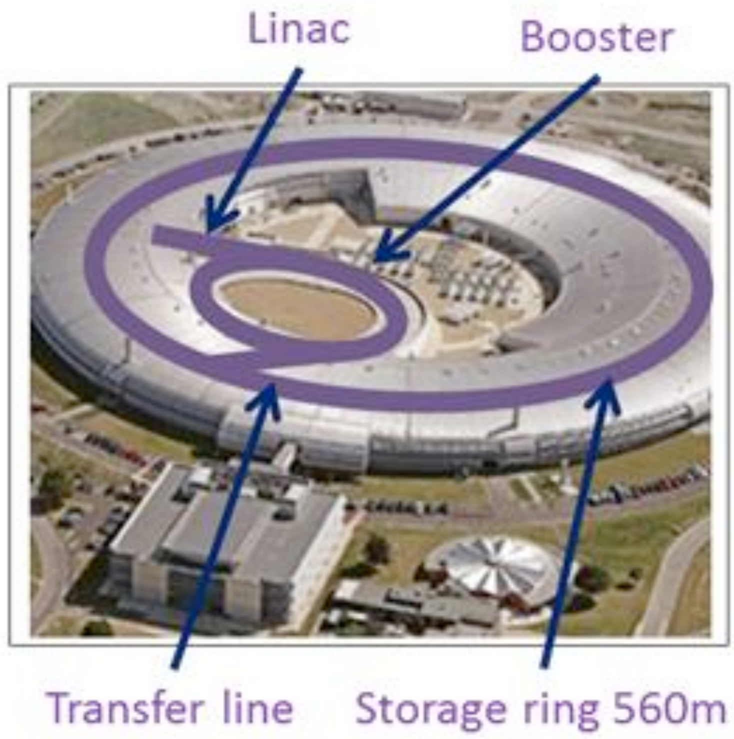
Beamline design and diagnostics



- Study in detail interaction of electron and proton beams and plasma.
- Benchmarking of PIC simulation against experimental data.
- Beam and plasma diagnostic tools to be developed.

Testing self-modulation at Diamond (?)

- The Diamond light source has a *3 GeV* electron beam with $\sigma_z = 2.6\ cm$.
- Idea* to test self-modulation effect on this beam.
- Have performed simulations of :
  - Default Diamond beam
  - Cooled beam (from the storage ring)
  - Radially compressed beam
  - Cut beam
  - Seeded beam, using an ideal short pulse.



* P. Norreys

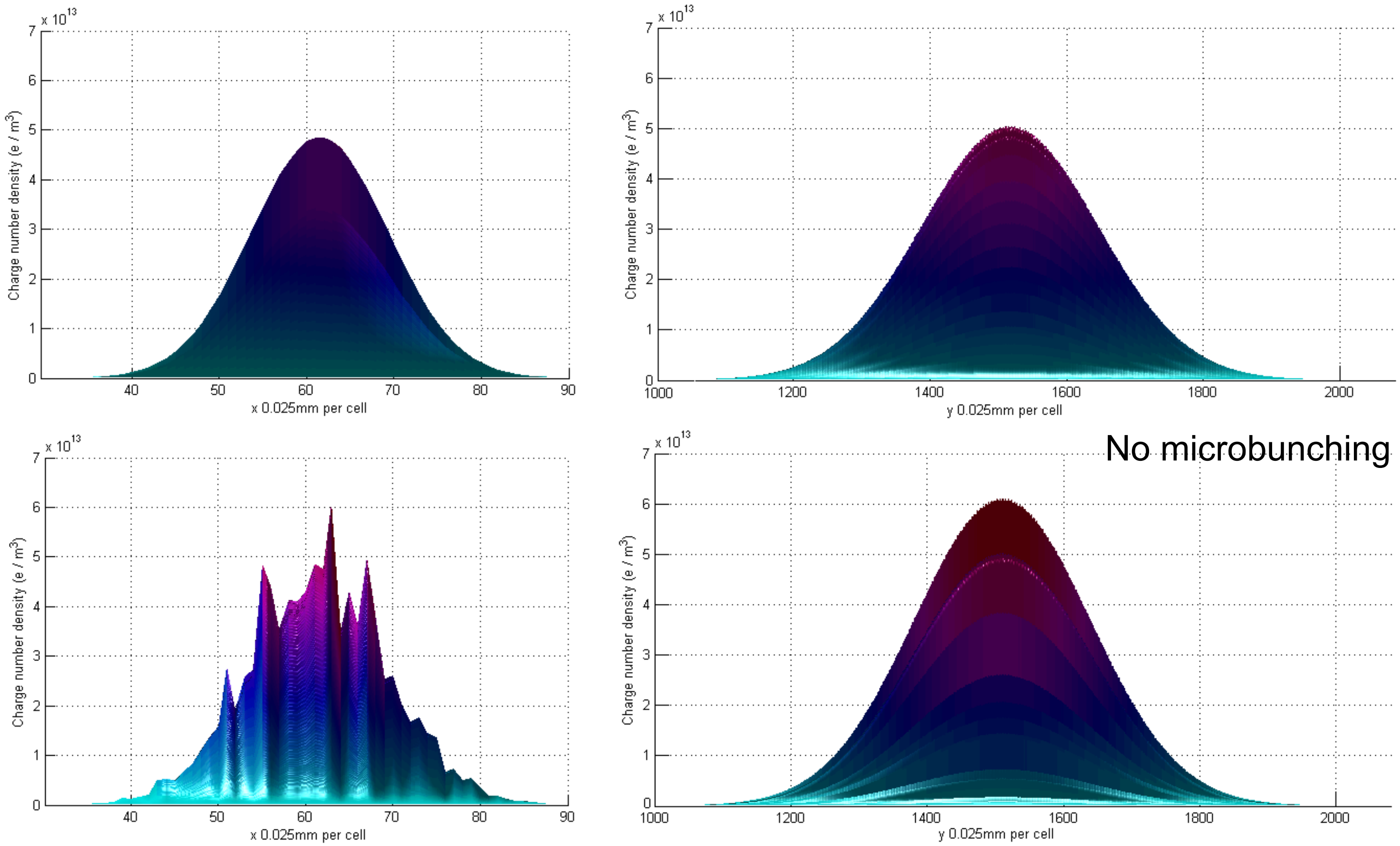
Default Diamond beam

- Energy, *3 GeV*.
- Emittance, *140 nm*.
- Charge, *2 nC*.
- Bunch length, *2.6 cm.*
- Energy spread, *0.0007.*

Rear view | Side View

Before:

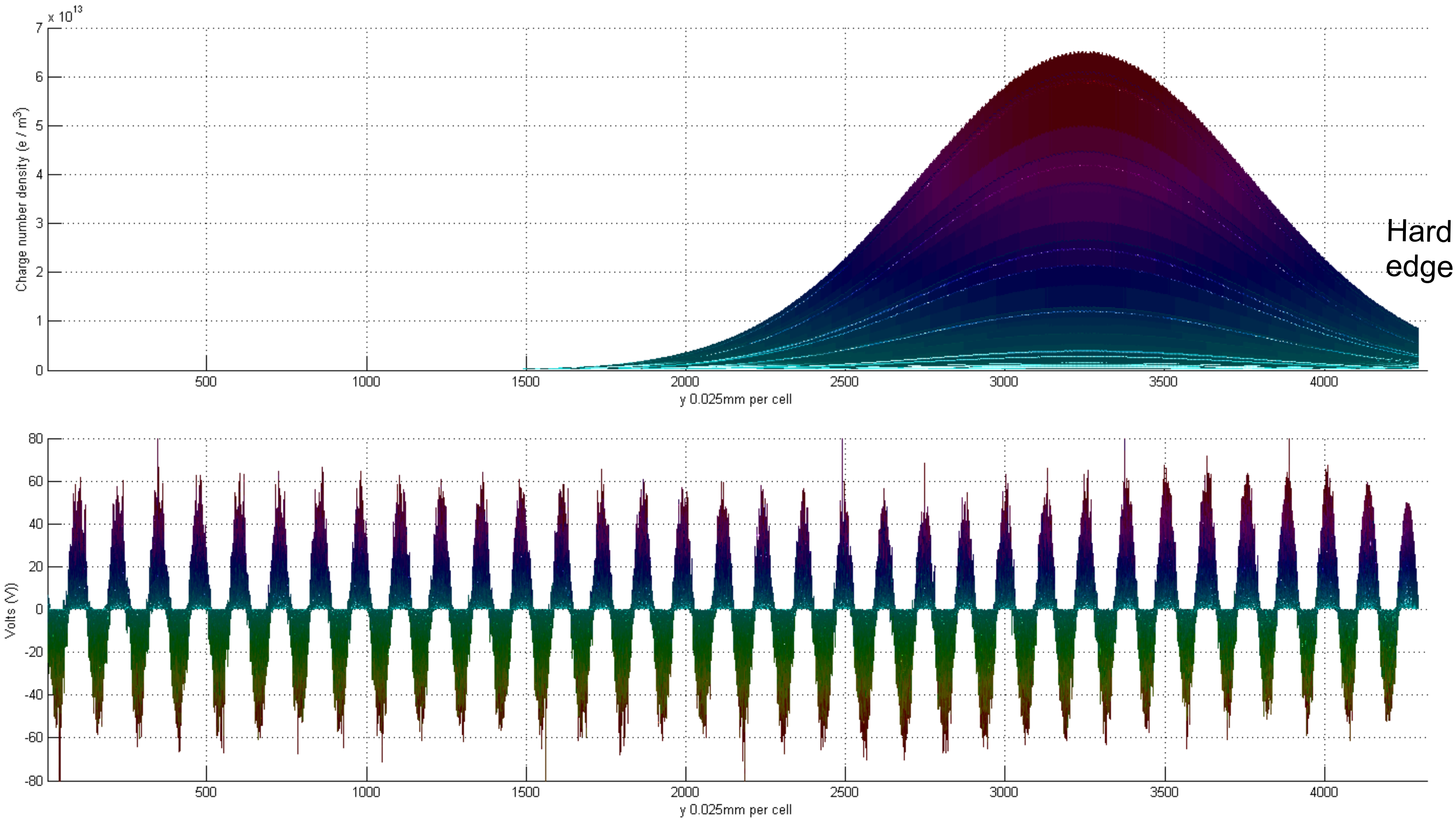
After:



Simulation of the untreated Diamond beam.

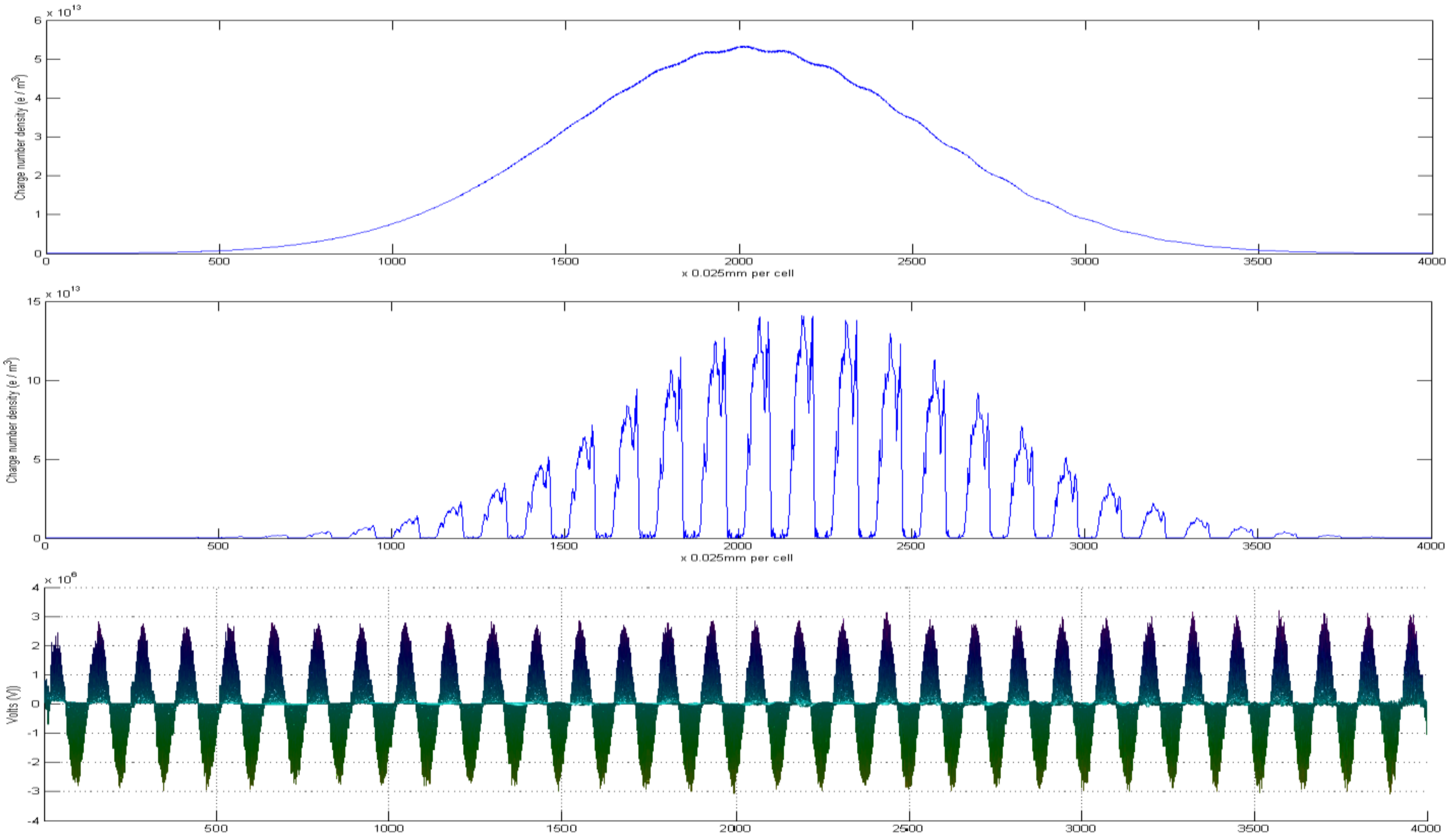
A cut beam

A cut beam has more of a kick and leads to a wakefield but only of *70 kV/m*.



An idealised initiator

Short pulse seeds a wakefield which modulates the electron beam and reinforces a wakefield of *2 GV/m*. Need to optimise the requirements for a laser.



Photon acceleration as a diagnostic tool

• Want to measure large-amplitude wakefields, e.g. the “plasma bubble”.

• Want to study the photon acceleration of a “witness” laser pulse co-propagating with the wakefield to determine its shape, the plasma density, etc..

• Use very short, sub-10 fs probes.

• Light moving through a media whose density is a function of time suffers a frequency shift and whose density is a function of space changes direction.

• Photon acceleration is a combination of these effects.

• Real opportunity to image in detail the plasma and wakefield development :

  - Only been “seen” in simulations;
  - Hence opportunity to improve simulations to make more reliable for the future.

• To do (IC, RAL & UCL) test experiments at ASTRA TA2 facility of CLF.

• Then port experimental experience and set-up to CERN SPS along with all the associated benefits in simulation.

UK involvement in proton-driven PWA

- UK interest from Cockcroft, Imperial, JAI/Oxford, RAL, Strathclyde, UCL :
  - design and build of a plasma cell;
  - design and build electron gun;
  - optimise seeding needed for self-modulation;
  - photon acceleration for diagnostics;
  - diagnostics for electron or proton beam.
  - general setting-up, running of experiment and analysis of results.
- Trying to get project on Roadmap and funded from STFC. Applied for a PRD grant and have been passed on to Accelerator Strategy Board.
- During next year, all groups will be working on technical design report, ramping up R&D and getting funding.
- Potential for UK to be significant group in the collaboration.

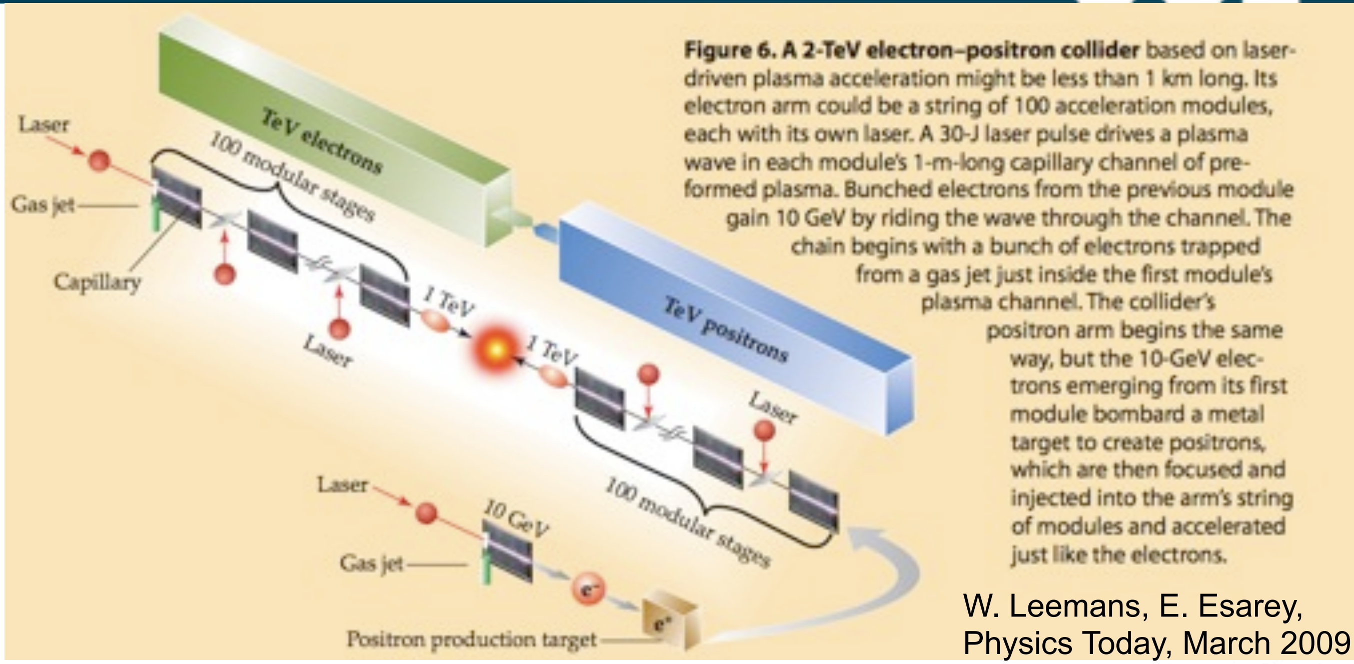
Outlook

Future experimentation

- The idea of proton-driven wakefield acceleration will follow a staged approach.
- If first experiment successful, then move on to :
    - Reach an energy gain of *100 GeV* over *100 m*;
    - Intermediate stage to possible "full" experiment;
    - Consider compressing proton beam—magnetic compression, cutting the beam into slices, etc..
- Ultimate goal of application to a TeV-scale lepton collider.

The future

- A TeV e^+e^- linear collider *O(km)* long
- But hopefully not too "far" !



W. Leemans, E. Esarey, Physics Today, March 2009

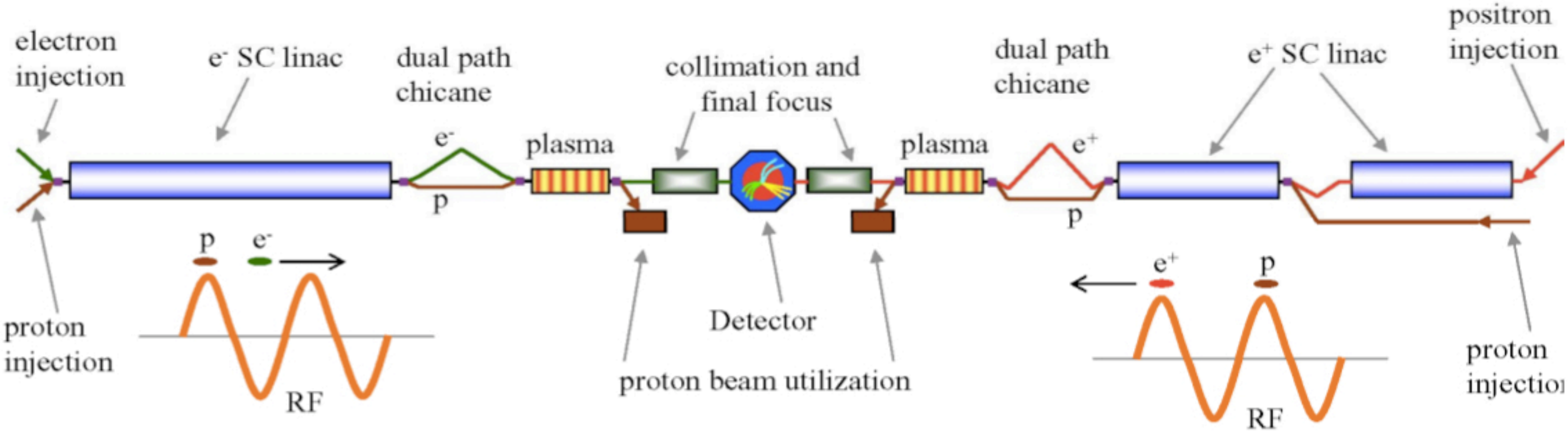


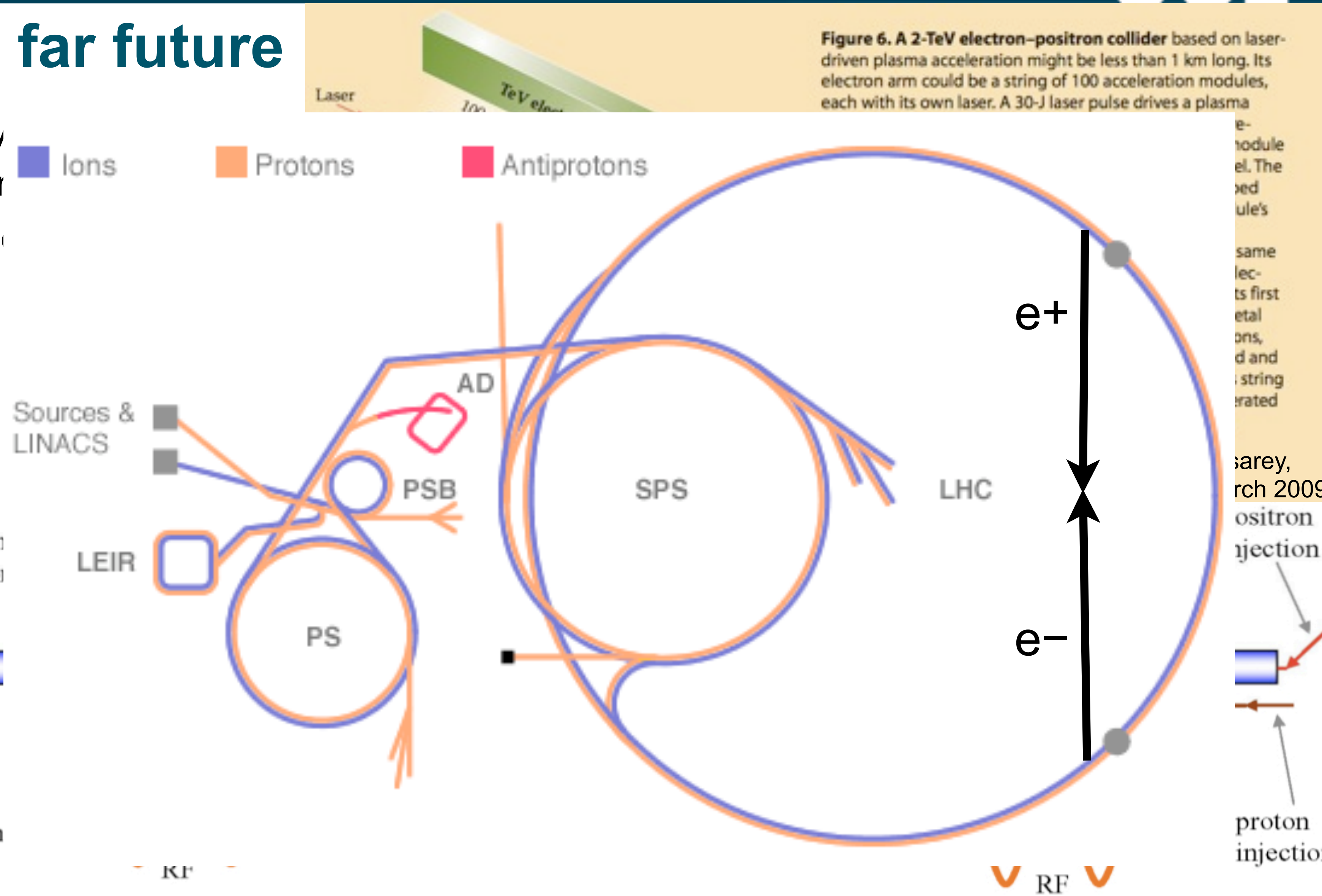
Figure 1: Concept for a multi-TeV upgrade of the International Linear Collider based on proton-driven plasma acceleration. The phase slippage controlling chicanes within the linacs are not shown. Not to scale.

A. Seryi, ILC-Note-2010-052

The far future

• A TeV
collider

• But h
“far” !



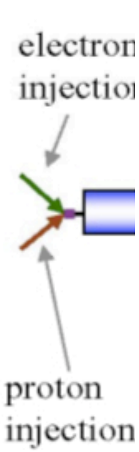
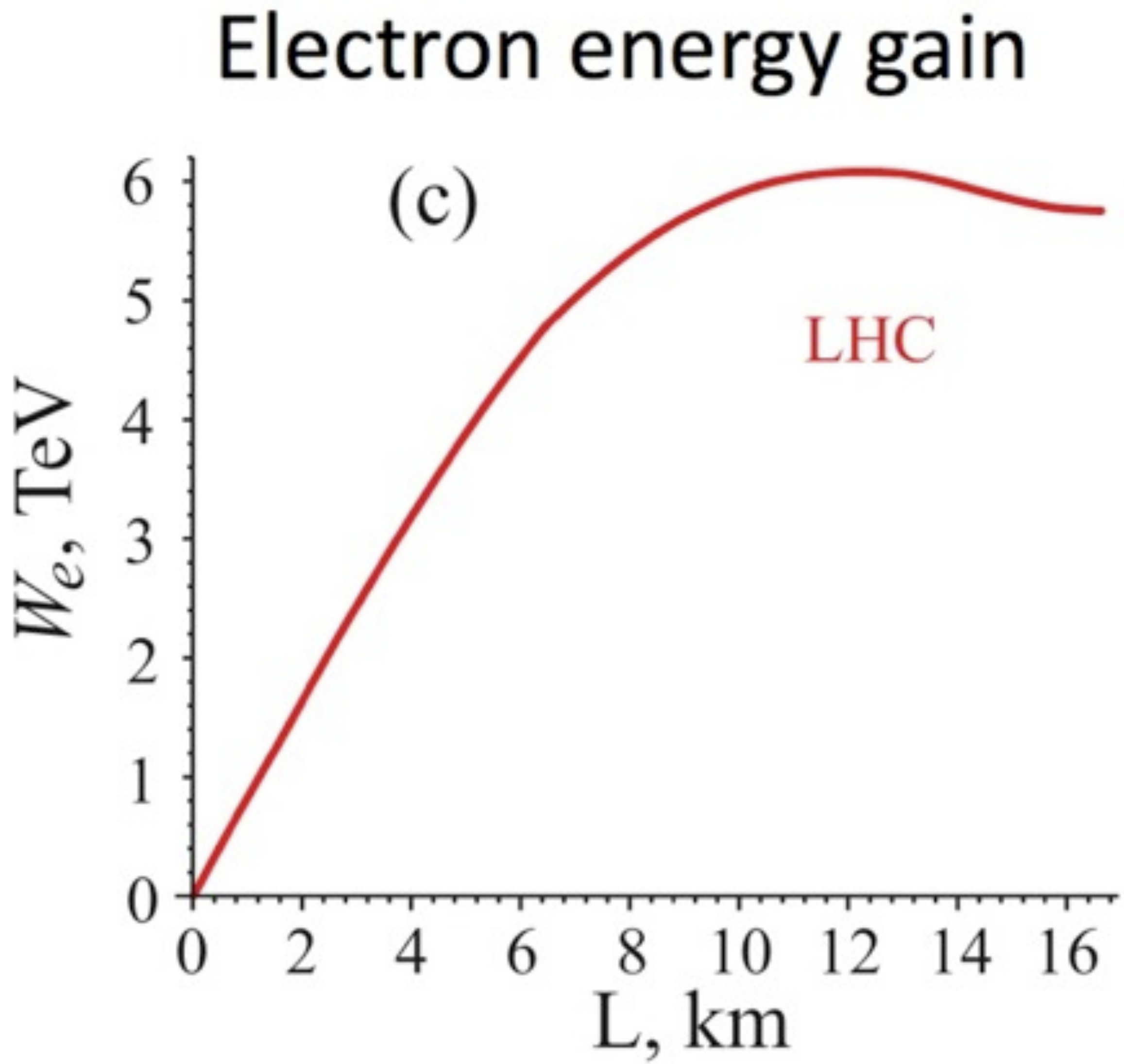


Figure 1: Concept for a multi-TeV upgrade of the International Linear Collider based on proton-driven plasma acceleration. The phase slippage controlling chicanes within the linacs are not shown. Not to scale.

A. Seryi, ILC-Note-2010-052

Using the LHC



K. Lotov

Summary

- Plasma wakefield acceleration could have a huge impact on many areas of science and industry using particle accelerators.
- Presented an idea to have a high energy lepton collider based on proton-driven plasma wakefield acceleration.
- Has interest and needs input from accelerator, plasma and particle physics.
- Proof-of-principle experiment proposed.
- Many challenges : beam sizes, long plasma cells, rates, etc..
- To realise a TeV-scale lepton collider a factor of ~ *10* shorter than current designs.

Back-up