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Plasma wakefield acceleration and high energy physics

Matthew Wing (UCL/DESY)

- Introduction and motivation
- Plasma wakefield acceleration
- Laser-driven plasma wakefield acceleration
- Electron-driven plasma wakefield acceleration
- Proton-driven plasma wakefield experiment at CERN
- Summary and outlook

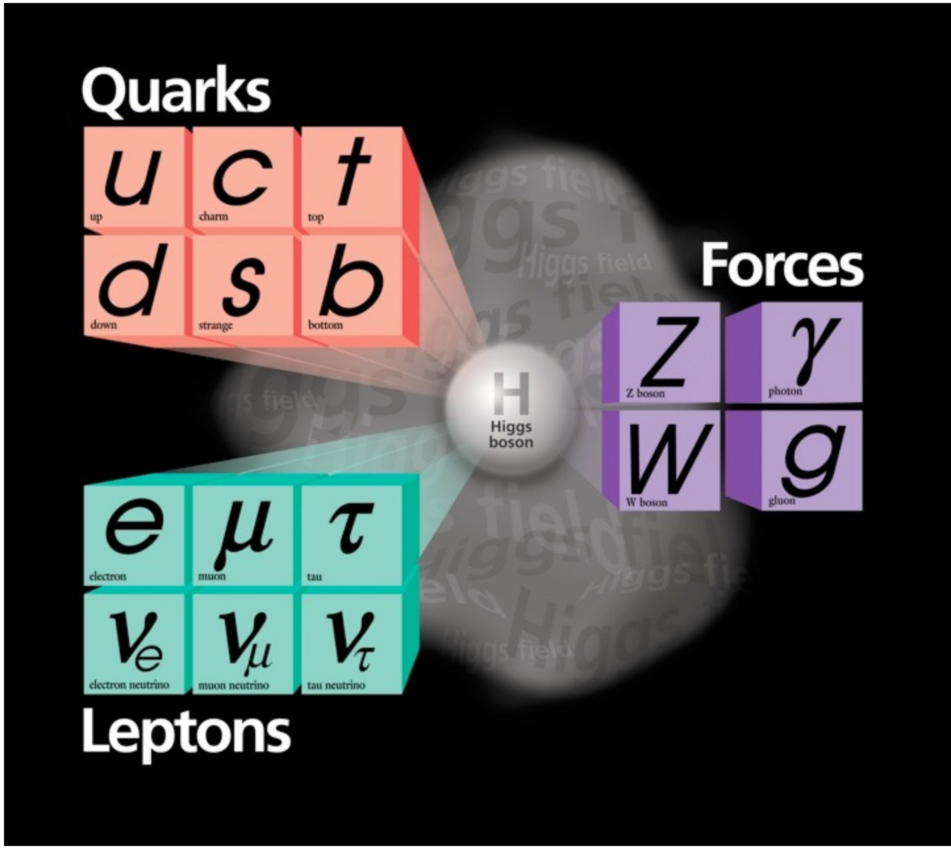
Physics at the Terascale meeting — 17 November 2015

Introduction and motivation

Motivation: big questions in particle physics

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

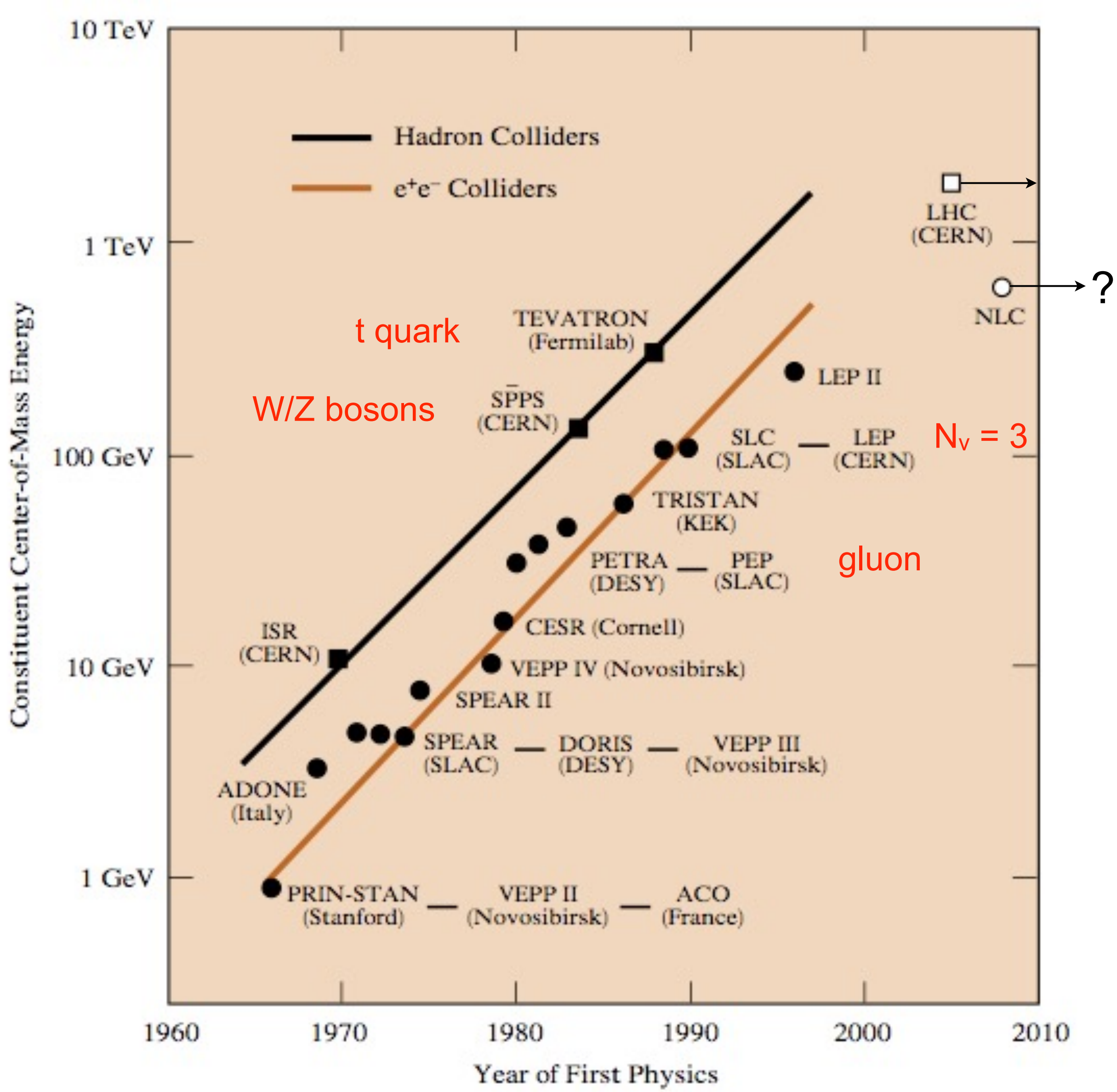
- a detailed understanding of the Higgs Boson/mechanism
- neutrinos and their masses
- why is there so much matter (vs anti-matter) ?
- why is there so little matter (*5%* of Universe) ?
- what is dark matter and dark energy ? Does supersymmetry occur at the *TeV* scale
- why are there three families ?
- hierarchy problem; can we unify the forces ?
- …



Colliders at the high energy frontier will be key to solving some of these questions

Motivation: colliders

- The use of (large) accelerators has been central to advances in particle physics.
- Culmination in *27-km* long LHC (*pp*); e.g. a future e^+e^- collider planned to be *30–50-km* long.
- The high energy frontier is (very) expensive; can we reduce costs ? Can we develop and use new technologies ?
- The Livingston plot shows a saturation …



Motivation: plasma wakefield acceleration as a solution

• Accelerating gradients achieved in the wakefield of a plasma are very high (3 orders of magnitude more than RF acceleration and up to ***100 GV/m***), but :

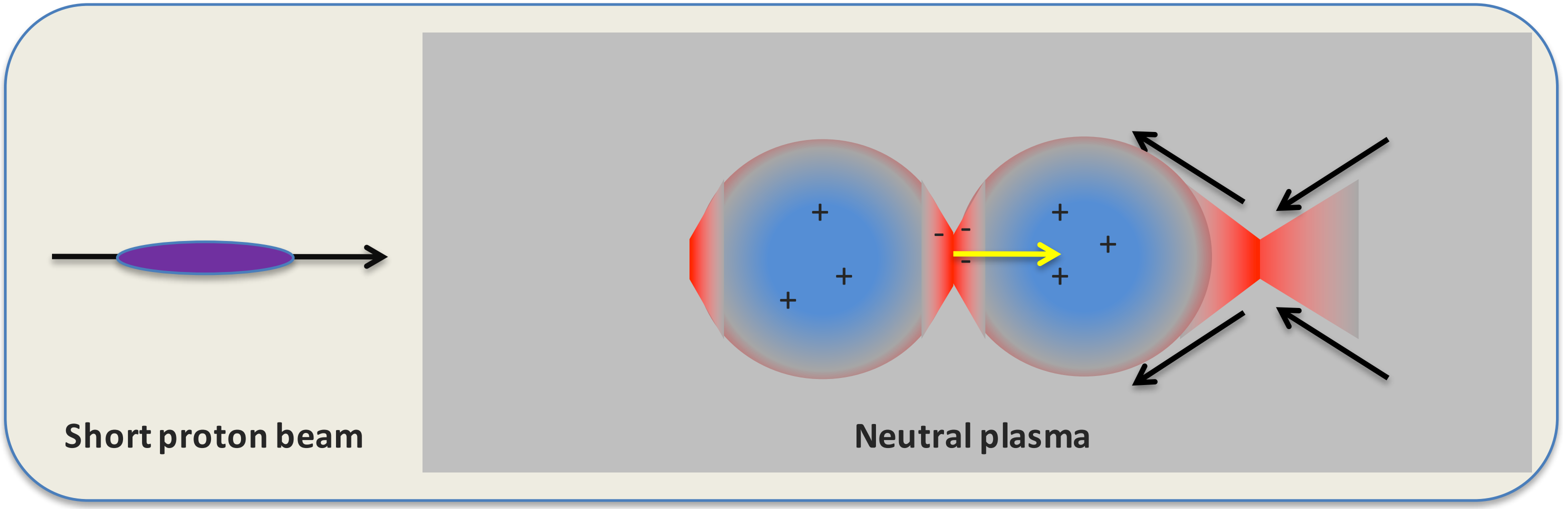
- we need high-energy beams (~ *TeV*);
- high repetition rate and high number of particles per bunch;
- efficient and highly reproducible beam production;
- small beams sizes (down to *nm* scale);
- large-scale accelerator complex.

• Ultimate goal : can we have *TeV* beams produced in a accelerator structure of a few *km* in length ?

• A challenge for accelerator, plasma and particle physics.

Plasma wakefield acceleration

Plasma wakefield acceleration



- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Oscillation of plasma electrons creates strong electric fields
- Longitudinal electric fields can accelerate particles in direction of proton bunch
- Transverse electric fields can focus particles
- A ‘witness’ bunch of e.g. electrons placed at the appropriate place can be accelerated by these strong fields

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 acceleration first proposed by T. Tajima and J.W. Dawson, Phys. Rev. Lett. **43** (1979) 267; use of particle beams proposed by P. Chen et al., Phys. Rev. Lett. **54** (1985) 693.

Plasma wakefield acceleration applications

Plasma wakefield acceleration could have applications in many areas of science and industry where accelerators are needed.

- Miniaturisation and 'table-top' accelerators
- E.g. medical applications, XFELs, etc.

Will here focus on general principles and successes of plasma wakefield acceleration but with definite focus on its application to high energy physics.

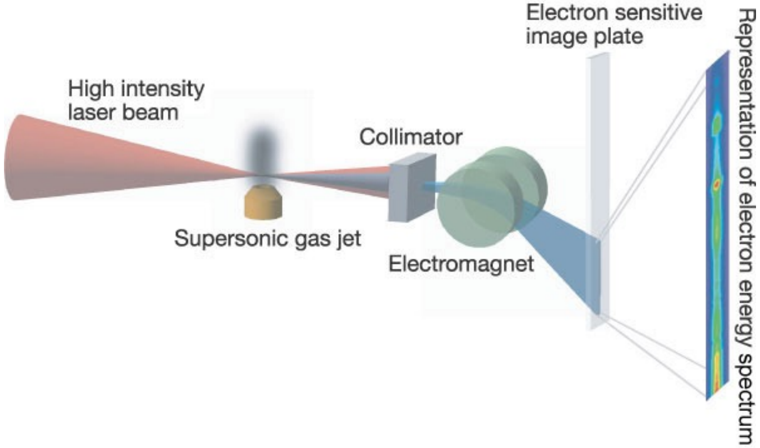
See talks at 2nd European Advanced Accelerator Concepts "EAAC 2015" workshop, September 2015, Elba
https://agenda.infn.it/conferenceTimeTable.py?confId=8146#20150913

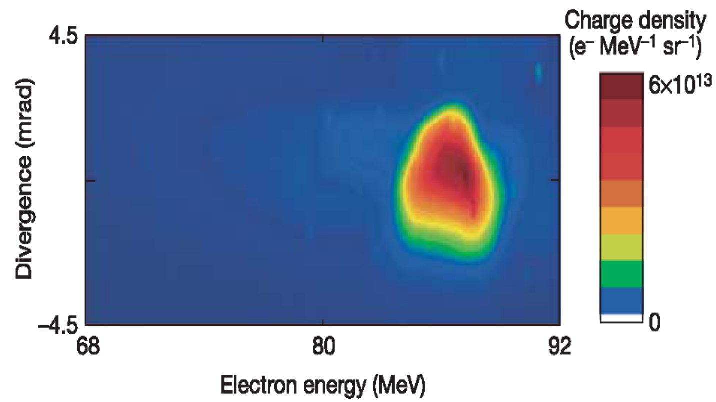
And talks at LCWS 2015, November 2015 Whistler, from E. Esarey (Laser wakefield acceleration), E. Adli (Beam-driven wakefield acceleration) and D. Schulte (Future LC requirements).
http://agenda.linearcollider.org/event/6662/other-view?view=standard

Laser-driven plasma wakefield acceleration

First laser-driven plasma wakefield experiments

2004 result: *10 TW* laser, *mm* scale plasma



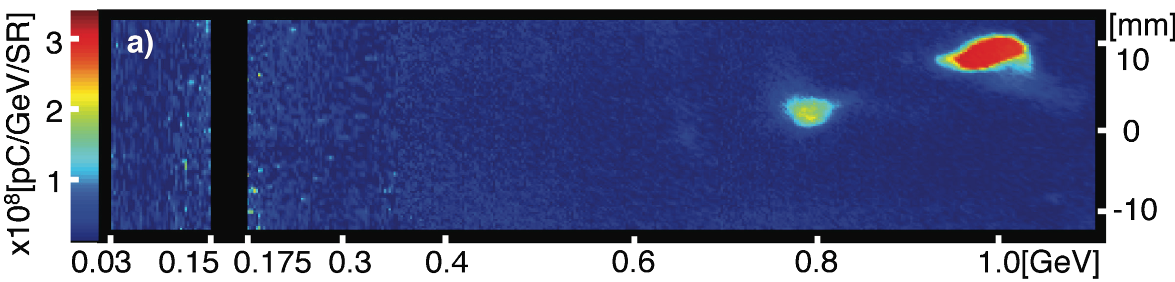


~ *100 MeV* beams.

S. Mangles et al., Nature **431** (2004) 535
C.G.R. Geddes et al., Nature **431** (2004) 538
J. Faure et al., Nature **431** (2004) 541

2006 result: *40 TW* laser, *cm* scale plasma

First *GeV* beams.



W.P. Leemans et al., Nature Phys. **2** (2006) 696
K. Nakamura et al., Phys. Plasmas **14** (2007) 056708

Accelerator based on laser plasma wakefield acceleration

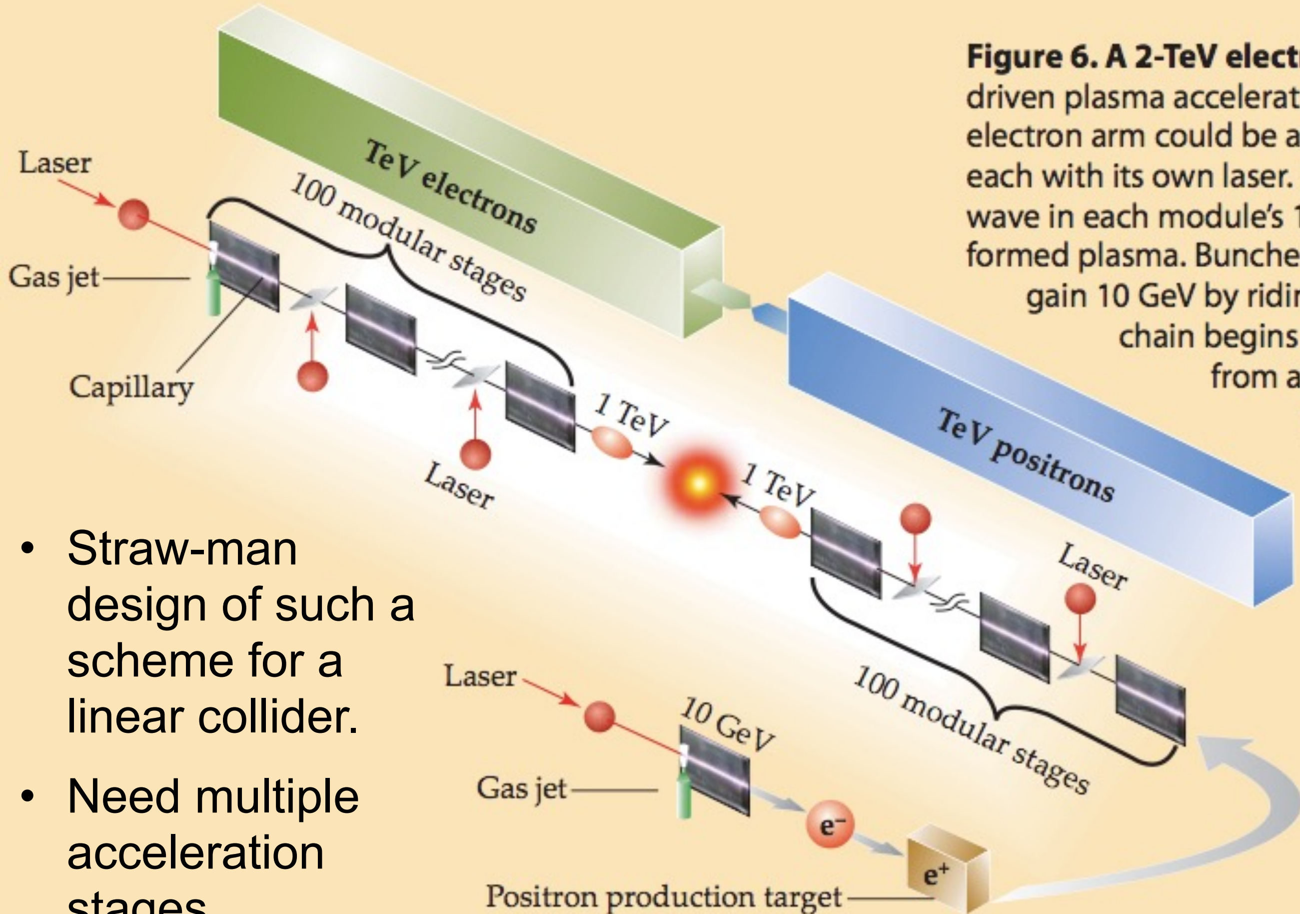


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

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

- Straw-man design of such a scheme for a linear collider.
- Need multiple acceleration stages.
- Acceleration using 100 stages of *10 GeV* each.
- Assume laser with high repetition rate, *O(10) kHz.*

Scaling in laser-driven plasma experiments

Energy gain limited by laser energy depletion

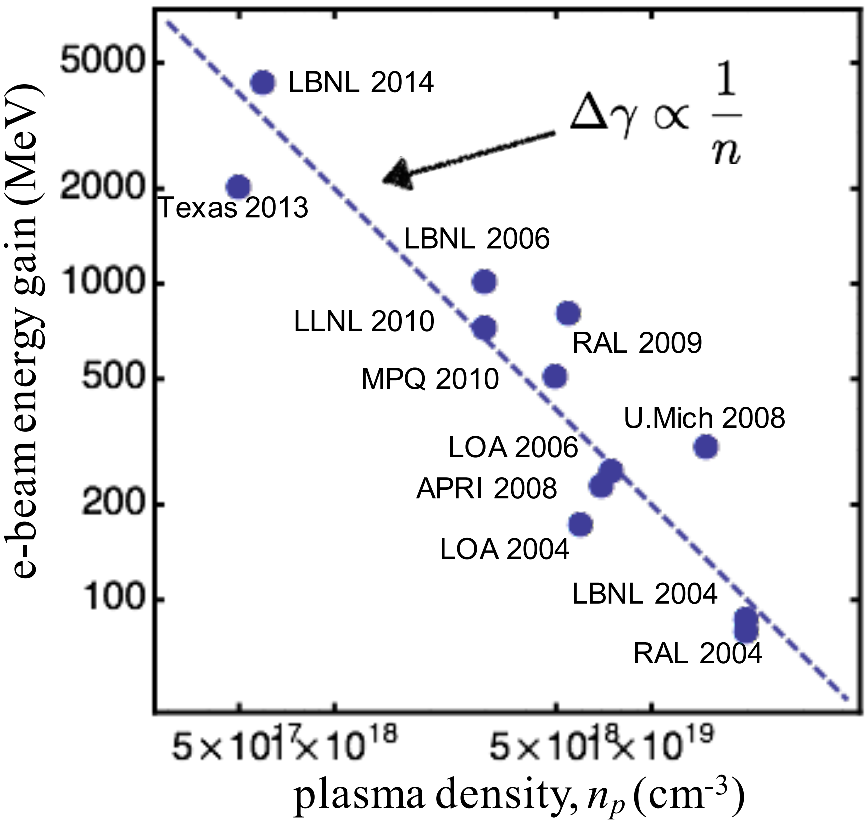
- Depletion length: $L_D \propto n^{-3/2}$
- Accelerating gradient: $E \propto n^{1/2}$
- Energy gain: $W \propto n^{-1}$

Staging is necessary to reach high energies

Example for a single stage

$W \sim 1$ GeV		$W \sim 10$ GeV
$n \sim 10^{18}$ cm^{-3}		$n \sim 10^{17}$ cm^{-3}
$L_D \sim 3$ cm	→	$L_D \sim 1$ m
$U_{laser} \sim 1$ J		$U_{laser} \sim 40$ J
$P_{laser} \sim 100$ TW		$P_{laser} \sim 1$ PW

LPA Experiments (single stage)



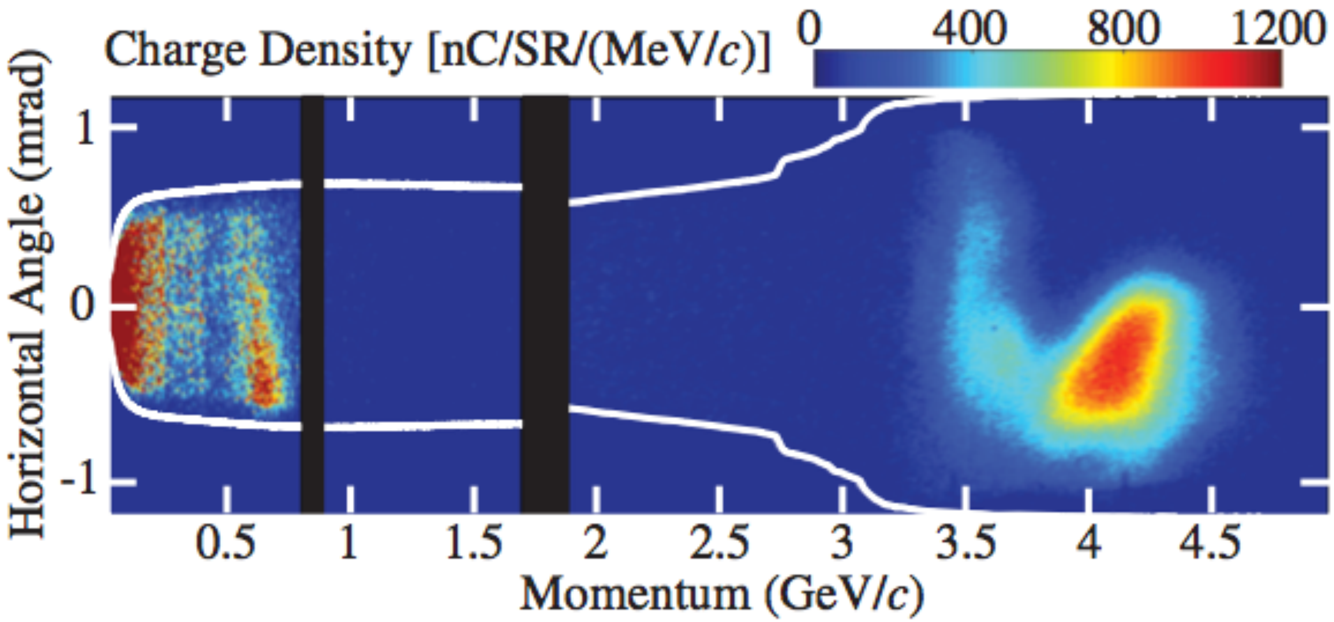
E. Esarey, LCWS2015

Latest results from BELLA laser, LBNL

Using a *310 TW* laser pulse (*15 J*) and *9 cm* plasma:

- *E = 4.2 GeV*
- *6%* rms energy spread
- *Q = 6 pC*

Reasonable agreement with simulation.



W.P. Leemans et al., Phys. Rev. Lett. **113** (2014) 245002

Simulations indicate *10 GeV* bunches can be achieved and that is the BELLA goal.

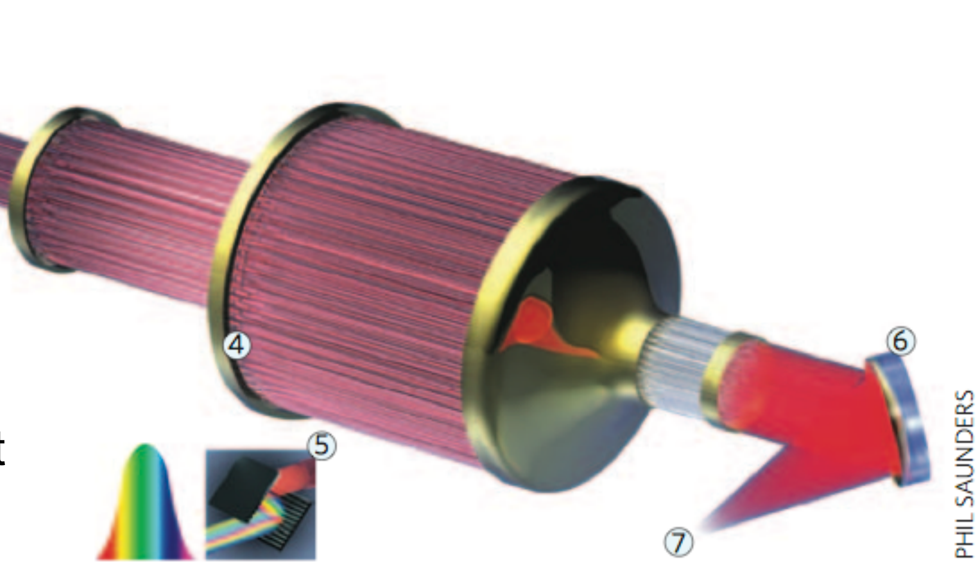
Measurements made using two stages (publications expected soon).

Combining laser fibres

Coherent combination of diode-pumped fibre lasers could lead to high-power, high-efficiency lasers.

Repetition rates of *O(10) kHz*

Challenge: need to combine ~ 10^4 fibre lasers



ICAN: International Coherent Amplification Network

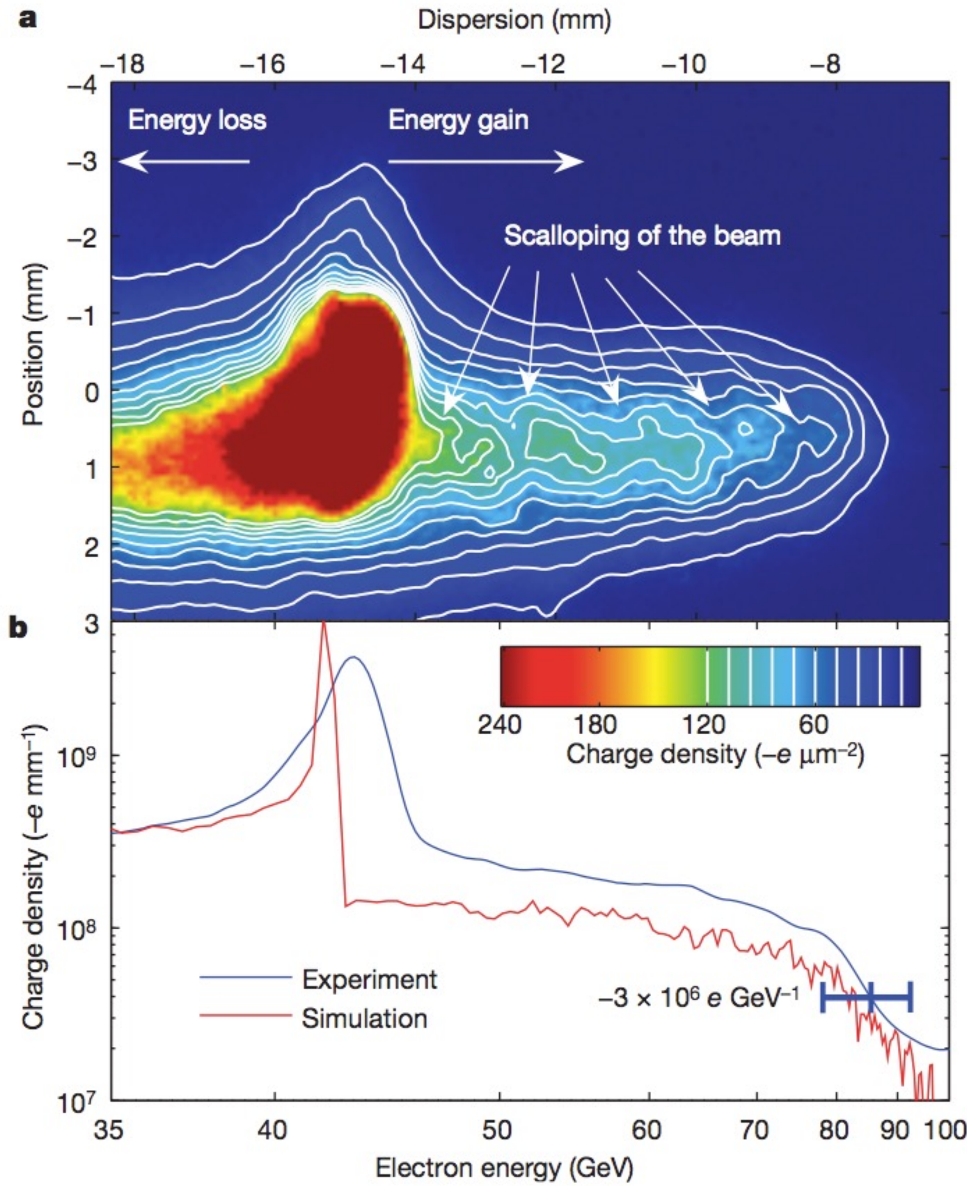
Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

G. Mourou et al., Nature Photonics **7** (2013) 258

Electron-driven plasma wakefield acceleration

First beam-driven plasma wakefield experiments

- Experiments at SLAC§ used a particle (electron) beam :
  - Initial energy E_e = *42 GeV*
  - Gradients up to ~ *52 GV/m*
  - Energy doubled over ~ *1 m*
  - Particles in head of beam 'transferred' energy to particles in tail
- Next stage, FACET project (http://facet.slac.stanford.edu)
- But also have proton beams of much higher energy.

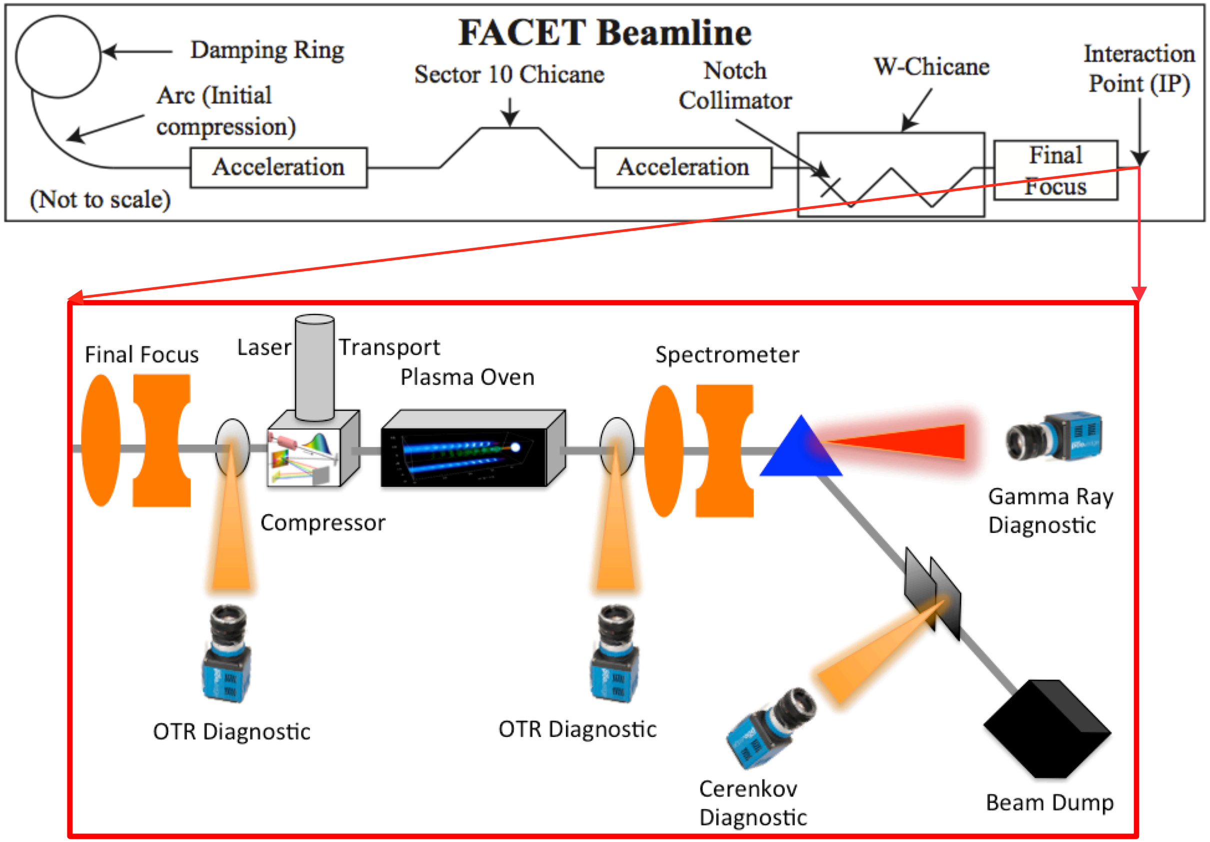


§ I. Blumenfeld et al., Nature **445** (2007) 741.

FACET project at SLAC

Facility for Advanced Accelerator Experimental Tests at SLAC is five-year programme by SLAC, UCLA, University of Oslo and Ecole Polytechnique to investigate:

- Two-bunch experiments: acceleration of a witness bunch.
- Metre-scale plasmas
- High gradients
- Low energy spread
- High efficiency
- Acceleration with e^{+}
- Emittance preservation

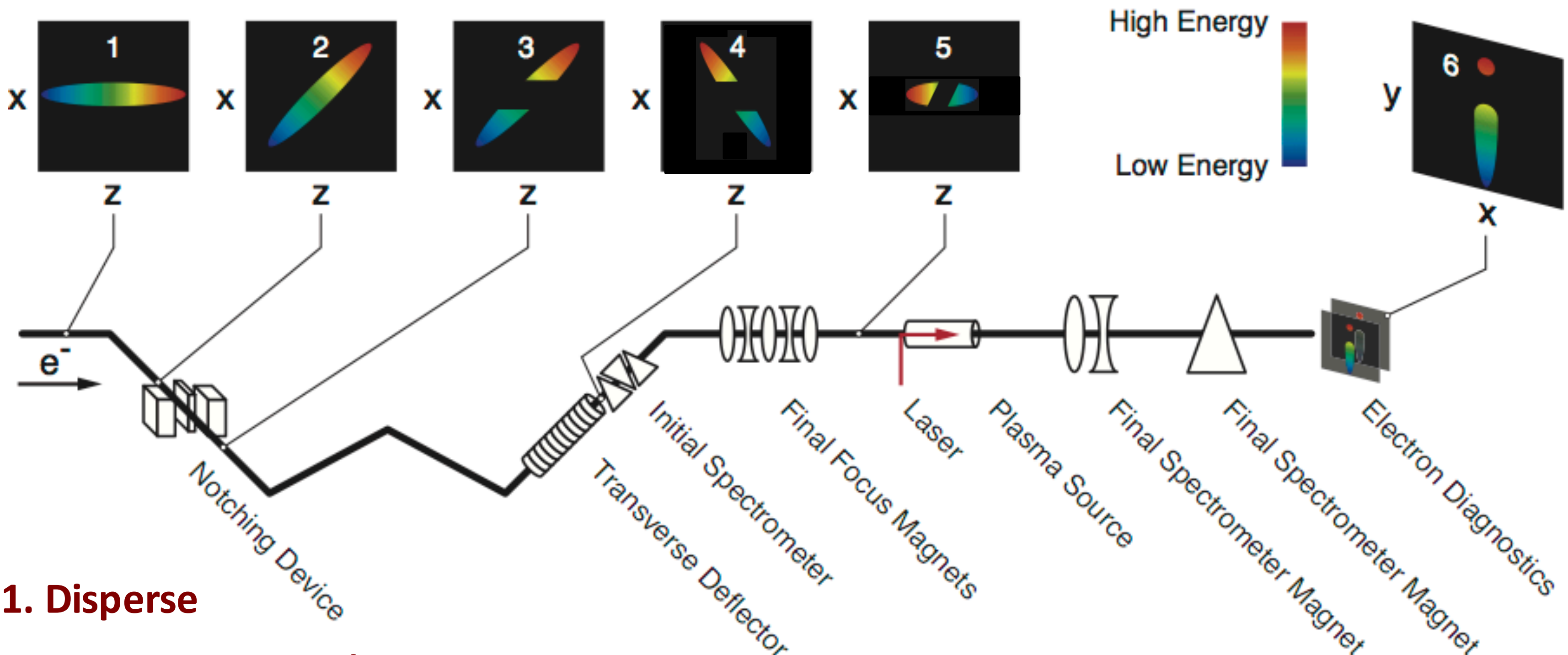


Electron or positron bunch:

- $E = 20\ GeV$
- $Q = 3\ nC$
- $\sigma_{z,r} = 20\ \mu m$
- $\varepsilon \sim 100\ \mu m$

FACET two-bunch generation

Single bunches generated so need to chop bunch in two.



1. Disperse

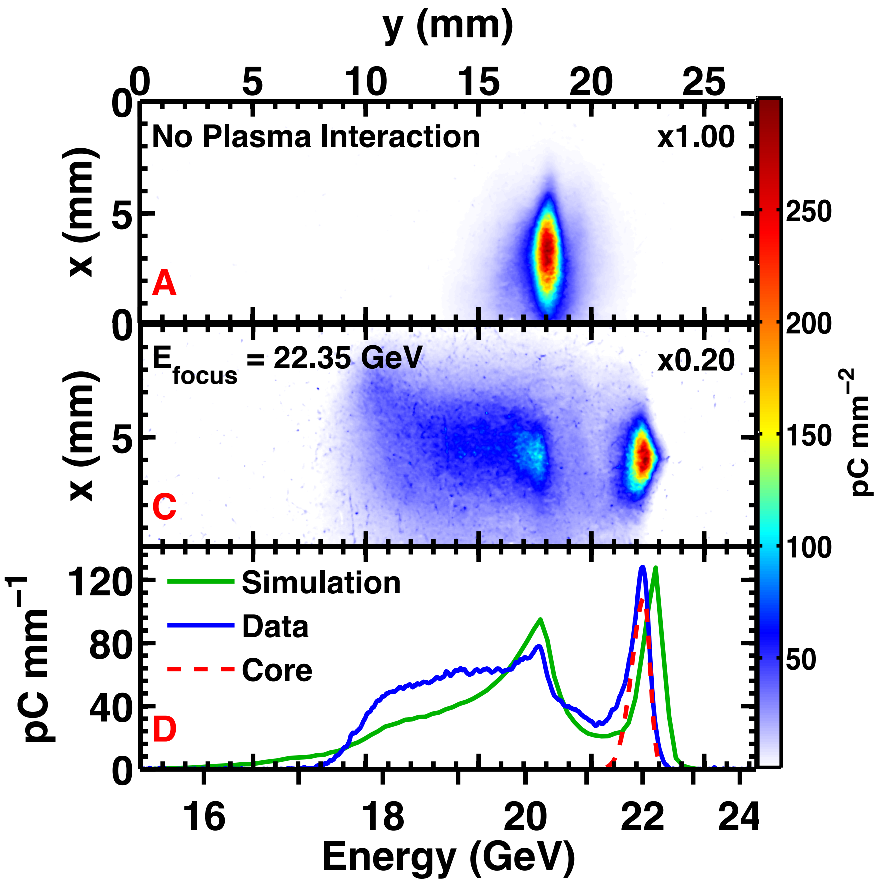
2. Chop

3. Compress

4. Accelerate

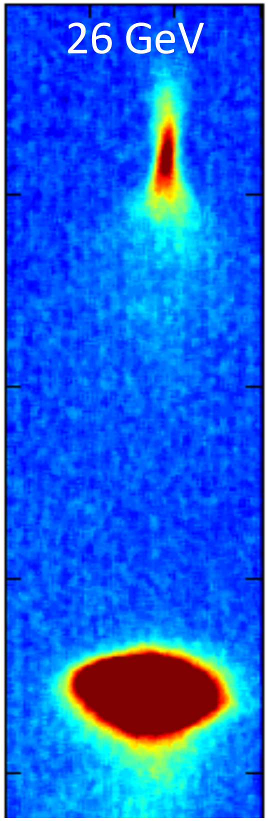
5. Diagnose

FACET two-bunch results



- *1.7 GeV* energy gain in *30 cm* of Li vapour plasma.
- 2% energy spread.
- Accelerated bunch has charge ~ *70 pC*
- Up to *30%* wake-to-bunch energy transfer efficiency (mean *18%*).
- *6 GeV* energy gain in *1.3 m* of plasma.

1.3 m plasma

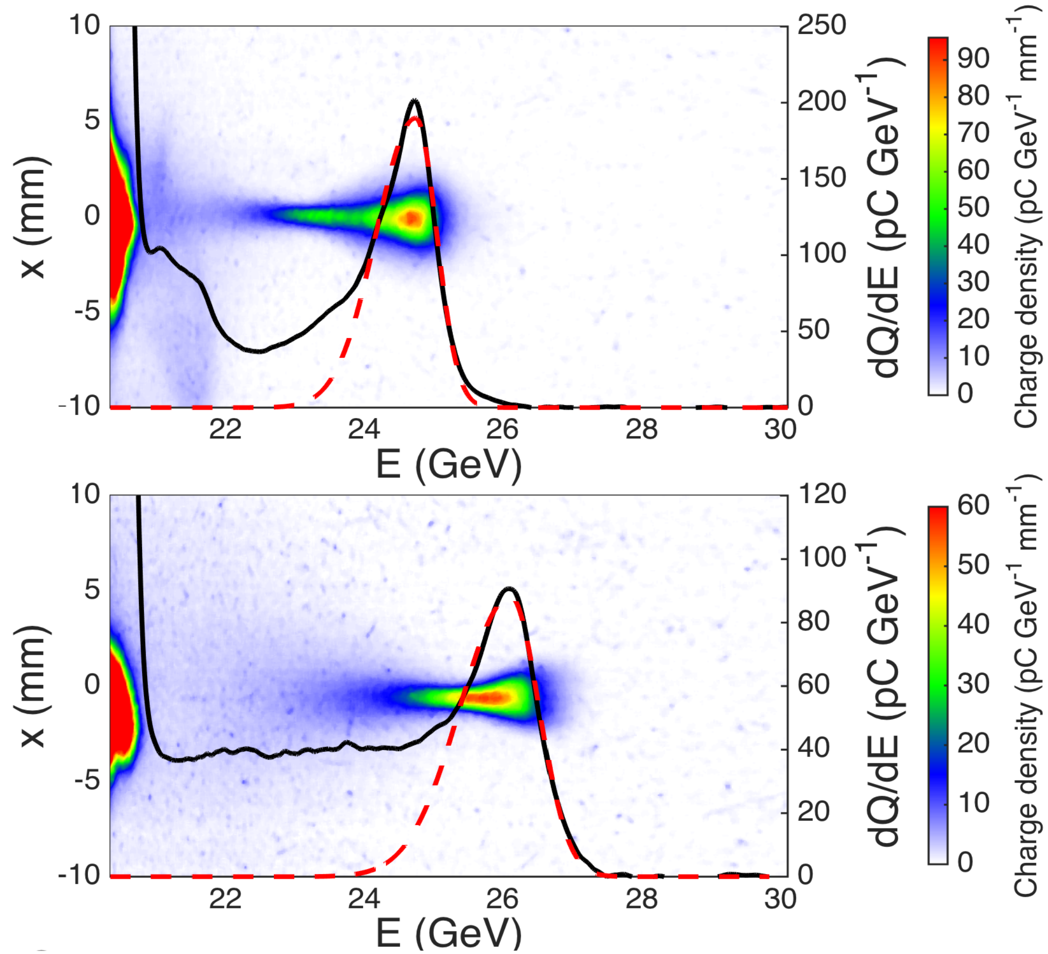


2014

M. Litos et al., Nature **515** (2014) 92

FACET positron acceleration

- Energy gains of about *5 GeV* over *1.3 m* of plasma.
- Energy spread about *2%*.
- *30%* energy efficiency from wake.
- Charge of up to *200 pC*.
- Note this is single-bunch running.
- Application to ‘afterburner’ for high energy positrons.



FACET programme to continue even with LCLS II

S. Corde et al., Nature **524** (2015) 442

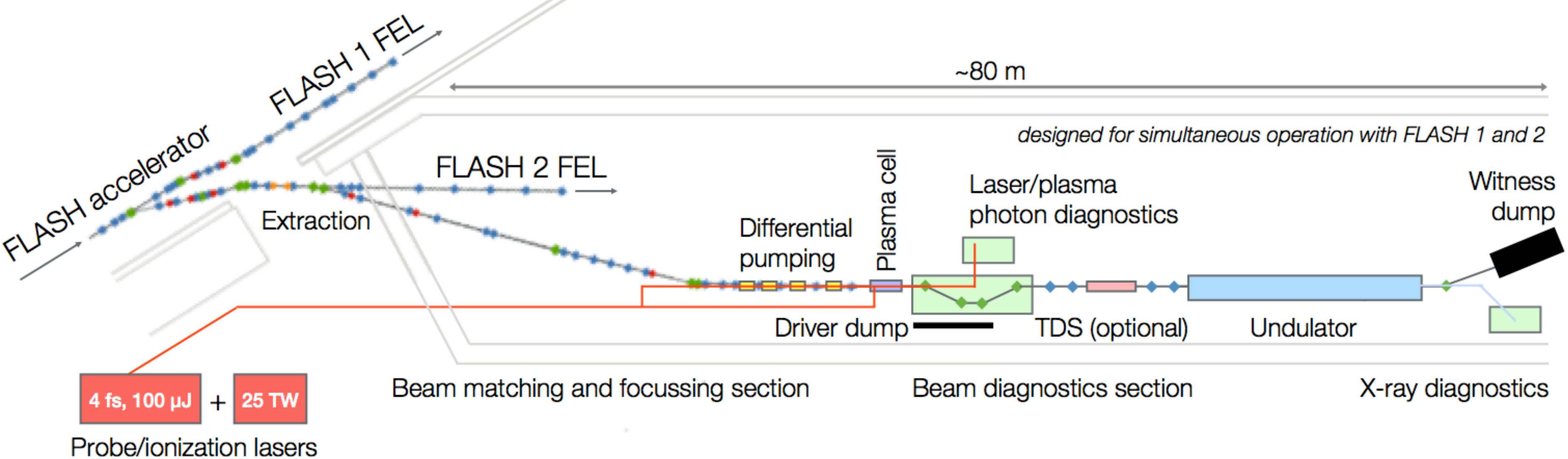
FLASHForward▸▸

Future-oriented wakefield-accelerator research and development at FLASH

Conceptual design concluded,
technical design in progress,
experiments to start in 2016, run for 4 years+

FLASH capabilities of particular interest for plasma-wakefield studies

- FEL-quality driver beam at 1.25 GeV, post-compression for ~10 kA level peak current
- variable longitudinal beam shape (e.g. triangular)
- 20 fs level laser-to-beam synchronization for diagnostics/laser-triggered injection schemes



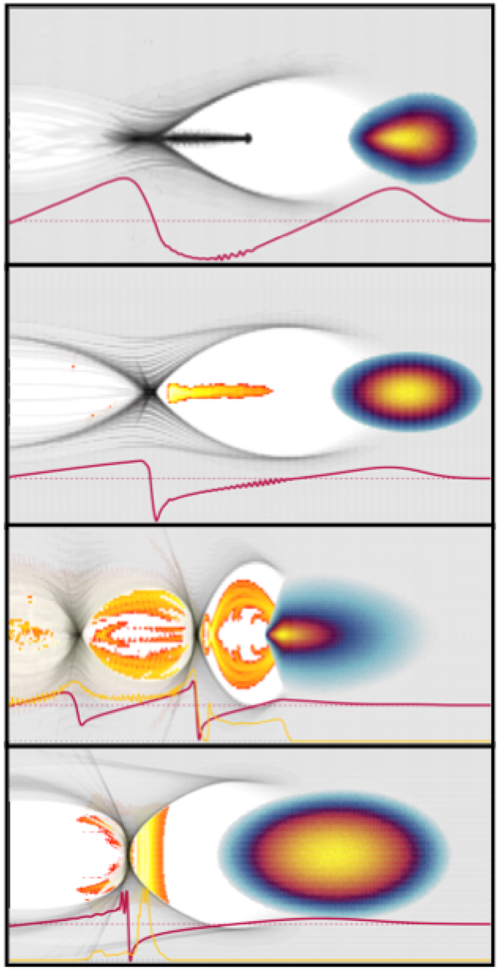
Main objectives:

- demonstration of novel beam injection schemes for unprecedented quality from a plasma with *> 2.5 GeV, ~fs duration, ~100 nm norm. emittance, > kA currents, ~‰ uncorrelated energy spread*
- the application of these beams in undulators to test feasibility of FEL gain
- investigation of stability of and control over plasma-accelerated beams

DESY

Contact Jens Osterhoff
jens.osterhoff@desy.de
for more details

In-plasma beam-generation techniques require current control, allow for sub-fs, sub-μm emittance electron bunches



- **Density down-ramp injection**
  J. Grebenyuk et al., NIM A 740, 246 (2014)

  $I_B \gtrsim 1\ \mathrm{kA}$

- **Laser-induced ionization injection**
  B. Hidding et al., Physical Review Letters 108, 035001 (2012)

  $I_B \gtrsim 5\ \mathrm{kA}$

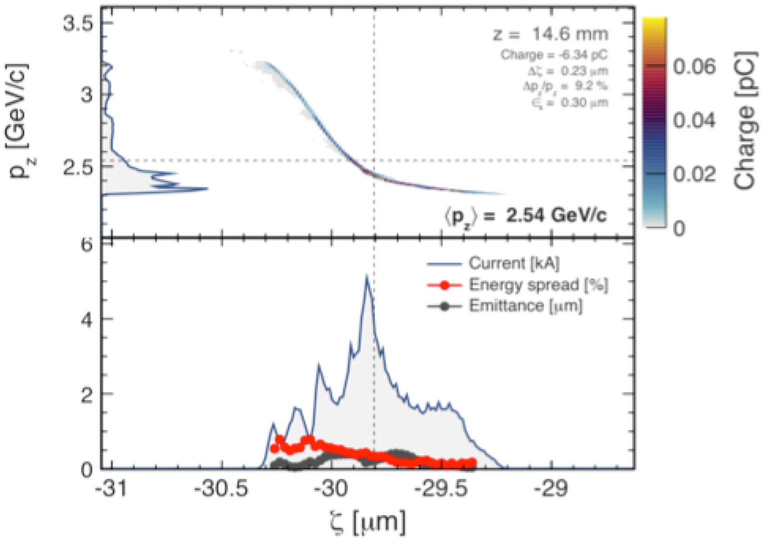
- **Beam-induced ionization injection**
  A. Martinez de la Ossa et al., NIM A 740, 231 (2014)

  $I_B \gtrsim 7.5\ \mathrm{kA}$

- **Wakefield-induced ionization injection**
  A. Martinez de la Ossa et al., Physical Review Letters 111, 245003 (2013)

  $I_B \gtrsim 10\ \mathrm{kA}$

A. Martinez de la Ossa *et al.*, to be published

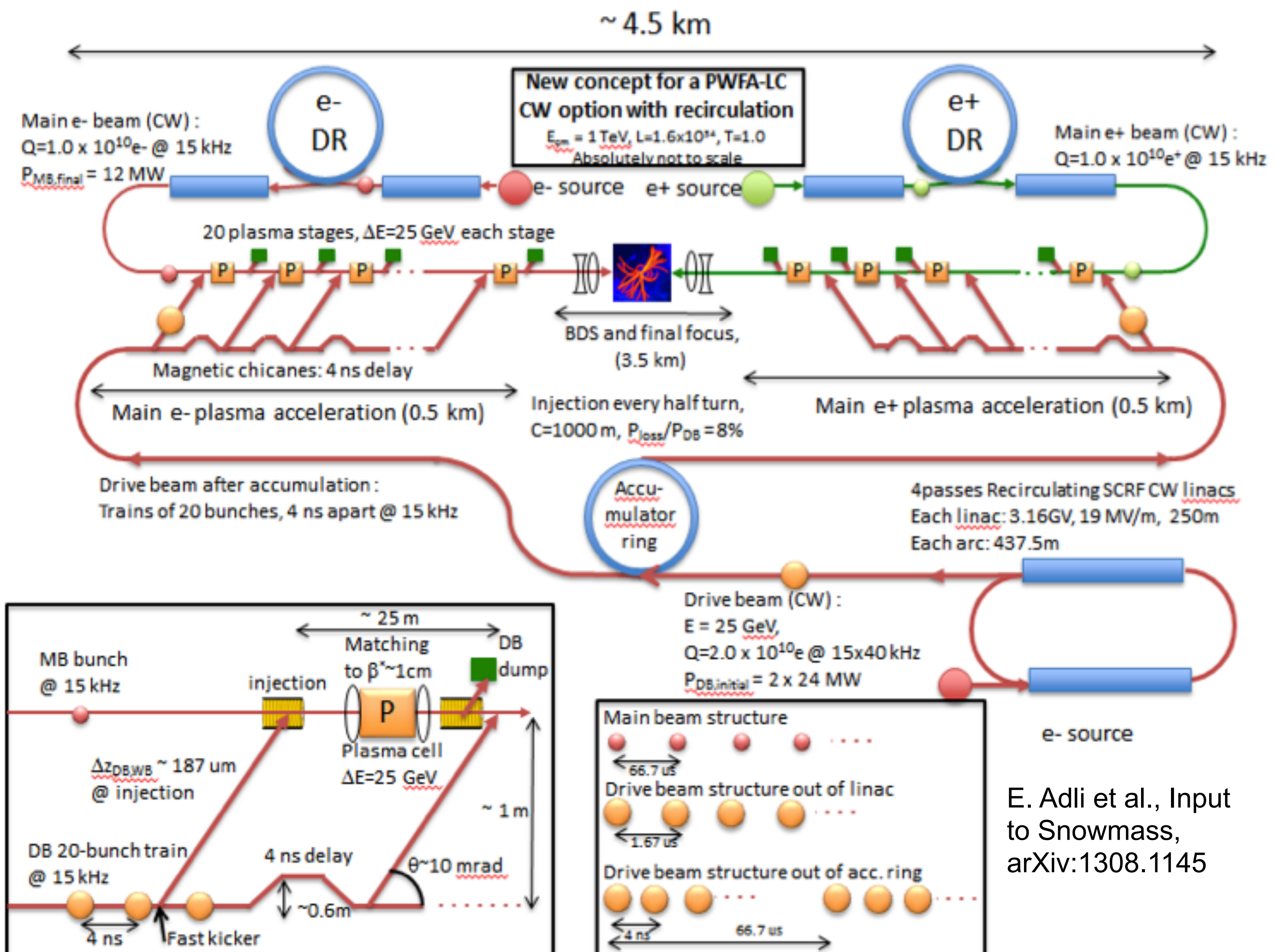


- Duration: 770 as rms
- Current: 5 kA (tunable)
- Normalized emittance: 300 nm
- Uncorrelated energy spread: < 1%

Contact Jens Osterhoff
jens.osterhoff@desy.de
for more details

e^+e^- collider based on beam-driven plasma wakefield acceleration

- Straw-man design of such a scheme for a linear collider.
- Need multiple acceleration stages.
- Acceleration to *500 GeV* over *0.5 km.*



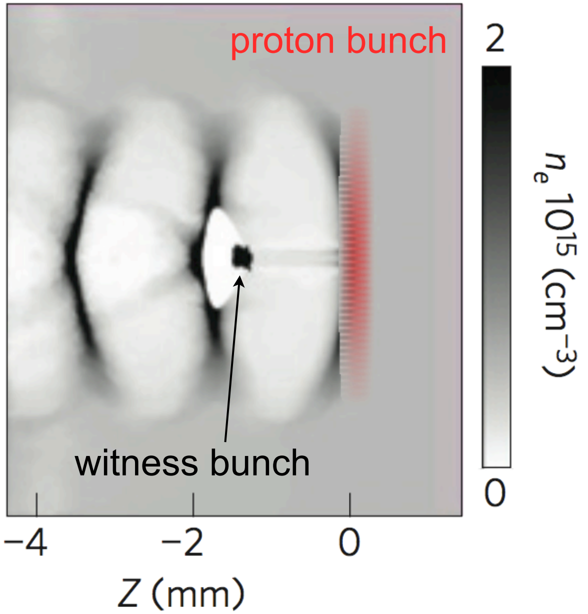
E. Adli et al., Input to Snowmass, arXiv:1308.1145

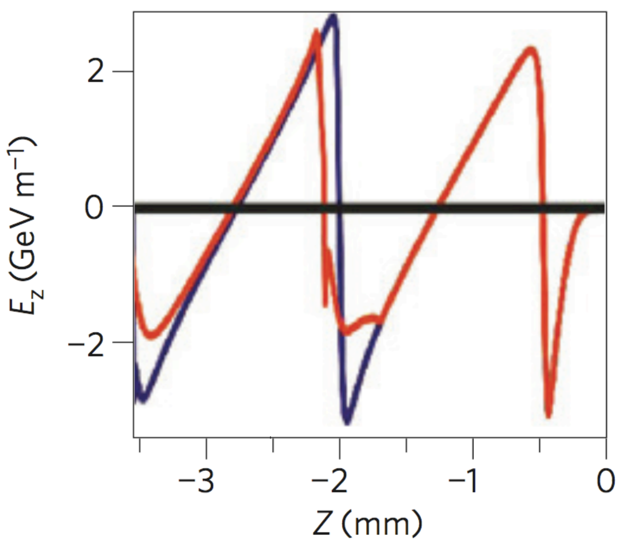
Proton-driven plasma wakefield acceleration

Proton-driven plasma wakefield acceleration 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





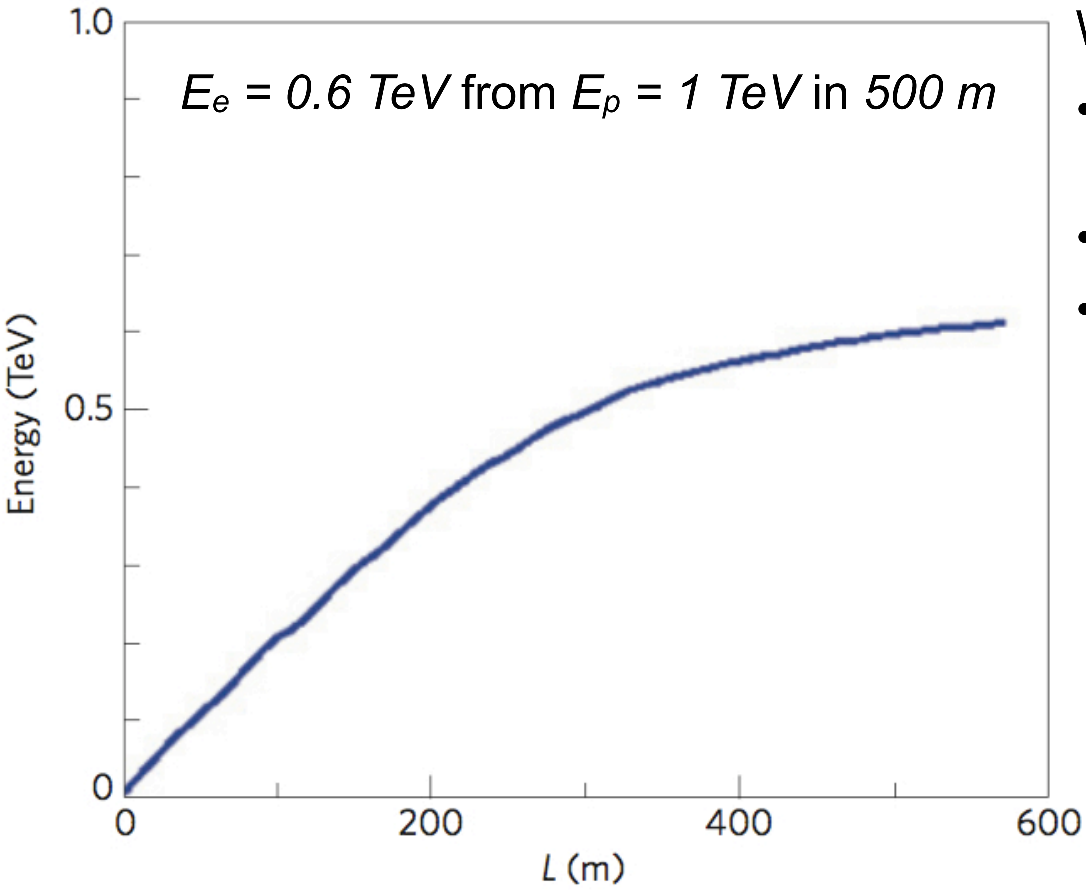
Note proton bunch length, *100 µm*; cf LHC, bunch length, *~10 cm*

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

Possibilities with proton drivers

From original paper: proton beam impacting on a plasma to accelerate and electron witness beam.

Can be tuned, but already shows spectacular acceleration.



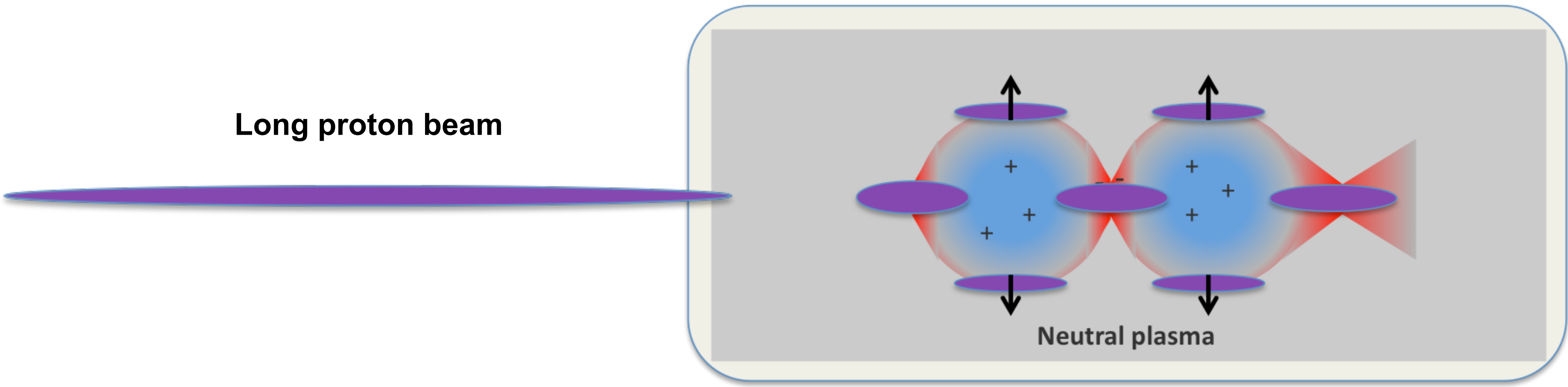
Why use protons ?

- Proton beams at the *TeV* scale and *kJ* of energy (LHC: *~120 kJ*)
- Use of existing infrastructure.
- Can have a one-stage acceleration process.

Long proton bunches ?

Use self-modulation instability where micro-bunches are generated by a transverse modulation of the bunch density.

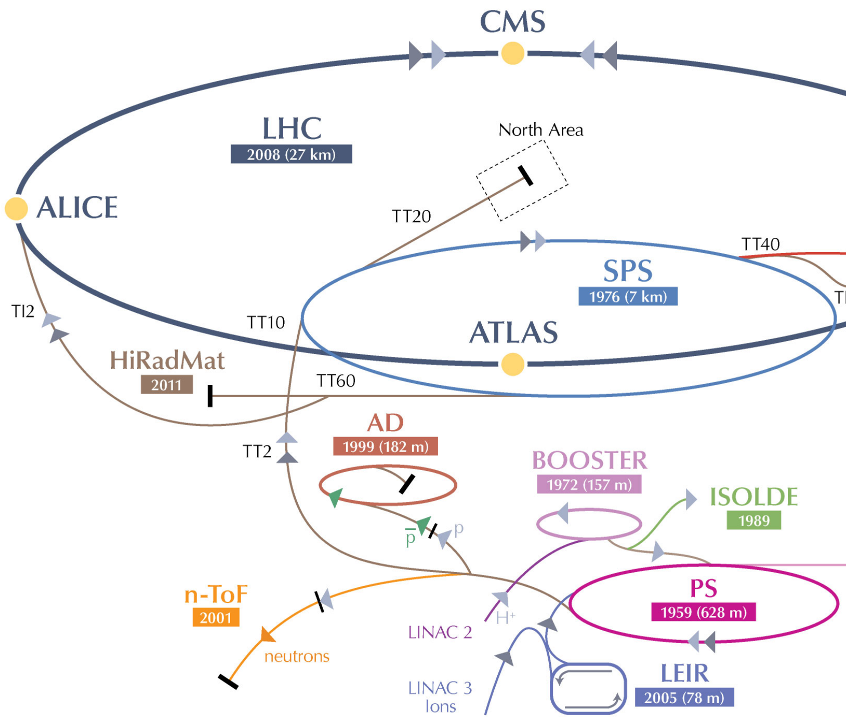
N. Kumar, A. Pukhov, K.V. Lotov, Phys. Rev. Lett. 104 (2010) 255003



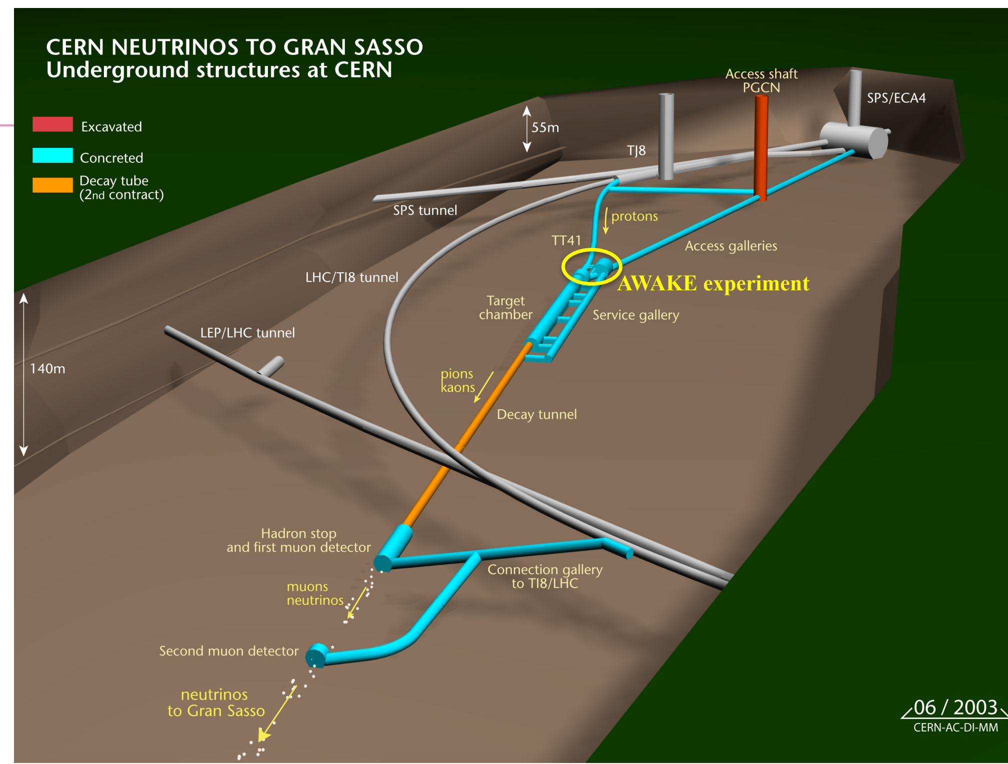
Self-modulated driver beam

- Micro-bunches are spaced λ_p apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, GV/m.
- Self-modulation instability allows **current beams to be used.**

AWAKE experiment at CERN



AWAKE is a collaboration of 16 institutes world-wide



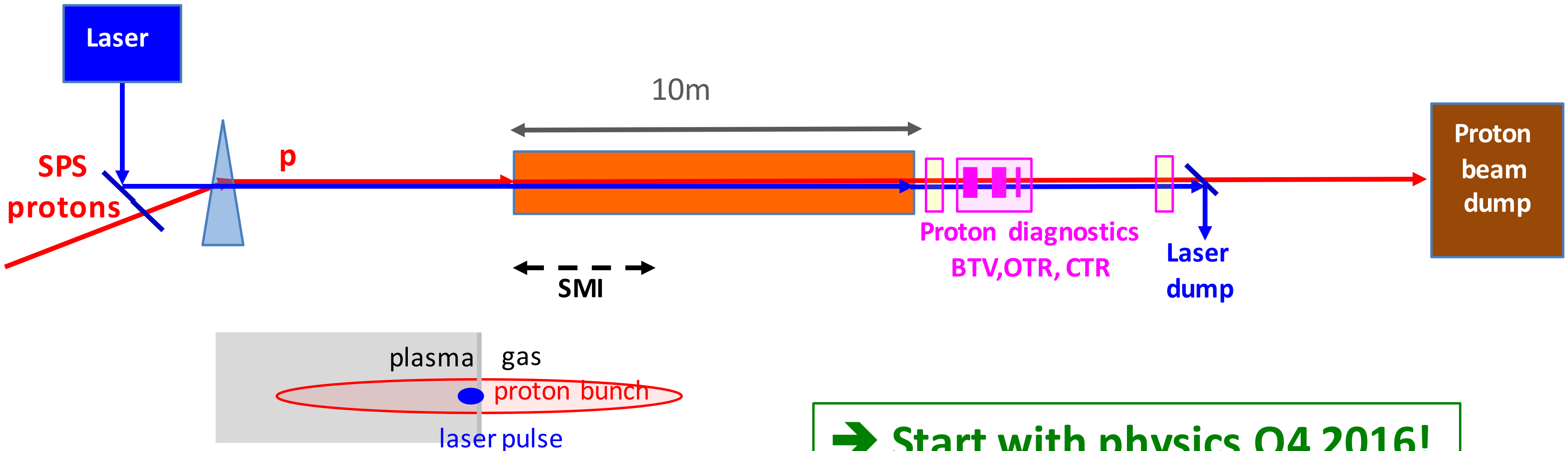
Advanced proton-driven plasma wakefield experiment.

To use *400 GeV* SPS beam in CNGS target area.

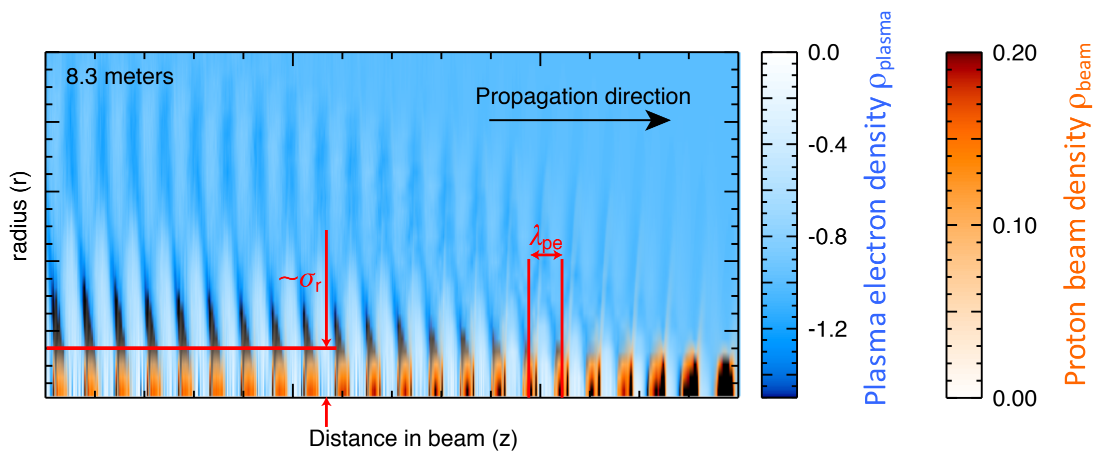
AWAKE Coll., R. Assmann et al., Plasma Phys. Control. Fusion **56** (2014) 084013

AWAKE experimental programme

Phase 1: understand the physics of self-modulation instability process in plasma



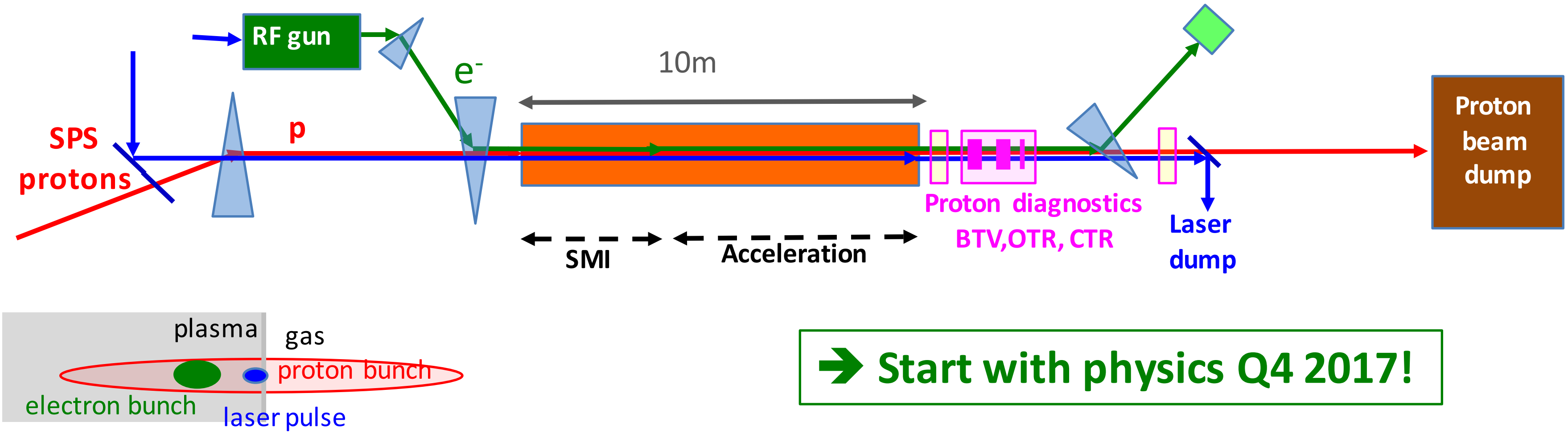
➔ Start with physics Q4 2016!



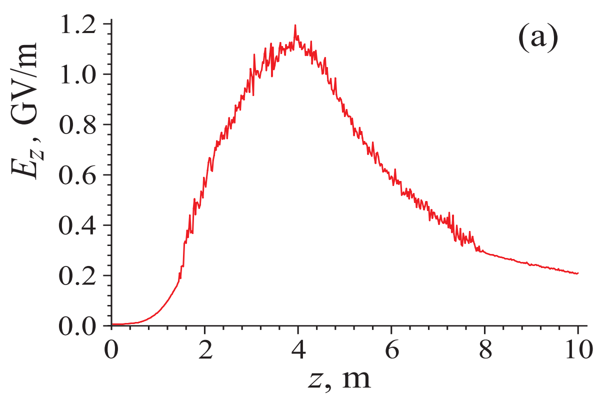
J. Vieira et al., Phys. Plasmas **19** (2012) 063105

AWAKE experimental programme

Phase 2: probe the accelerating wakefields with externally injected electrons.

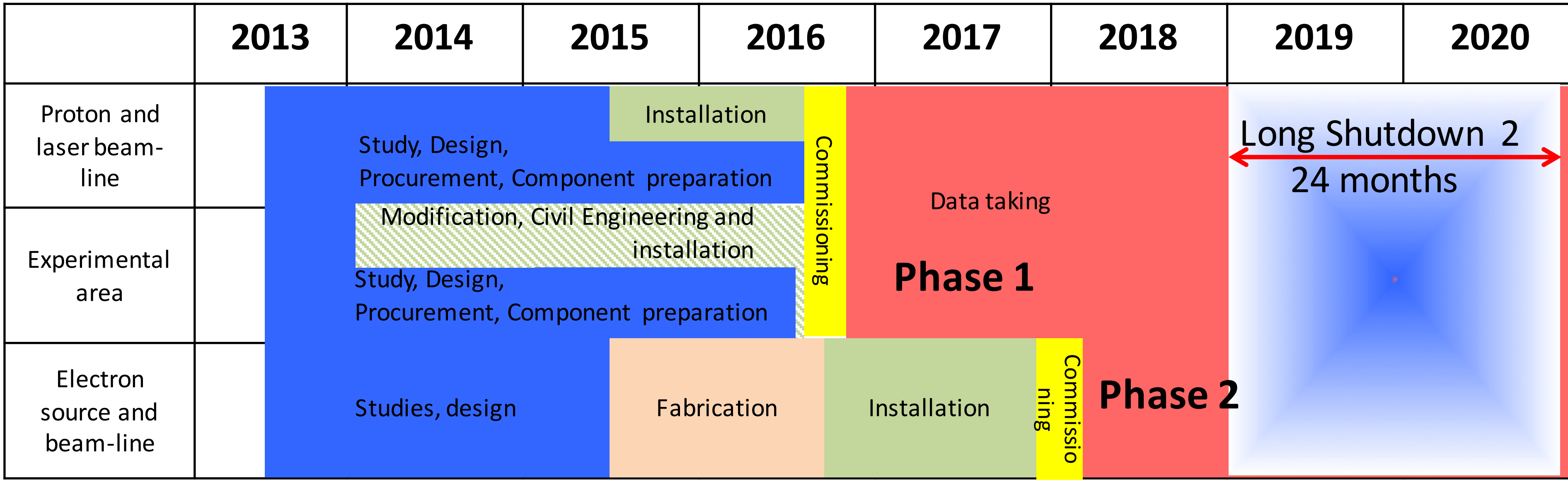


➔ Start with physics Q4 2017!



Demonstrate GeV acceleration of electrons with proton-driven wakefields

AWAKE physics and timeline



After initial running, developing a programme for after LS2:

- Demonstrate that gradients can be maintained over long distances
- Demonstrate a scalable plasma technology
- Inject short electron and proton bunches
- Develop design for a plasma based collider

Proton-driven plasma wakefield accelerator

A. Seryi, ILC-Note-2010-052

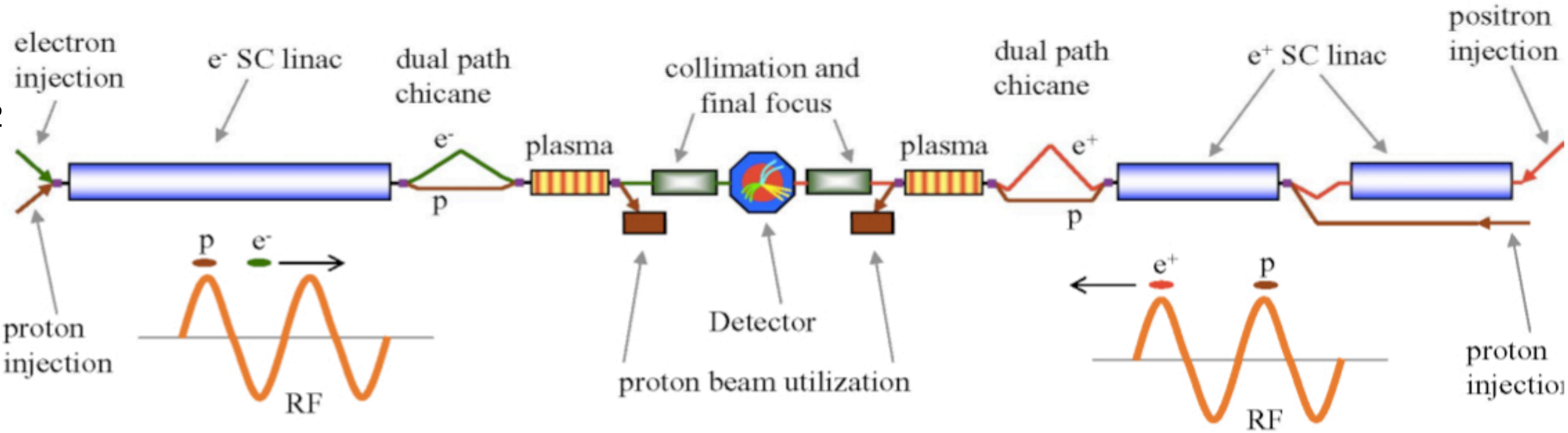


Figure 1: Concept for a multi-TeV upgrade of the International Linear Collider based on proton-driven plasma acceleration. The phase slippage controlling chicanes within the linacs are not shown. Not to scale.

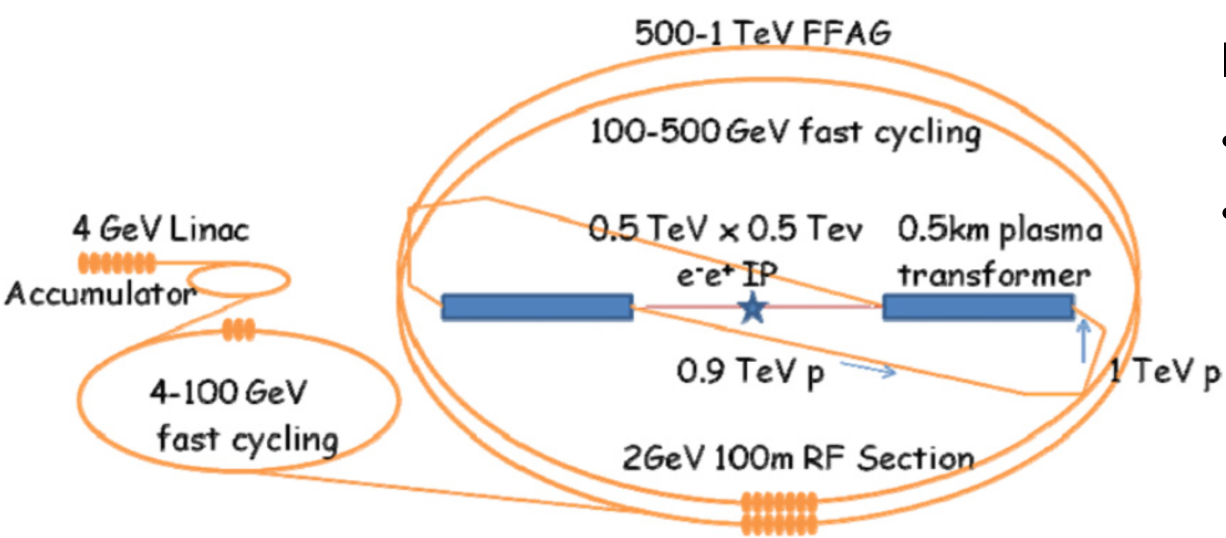


Figure 1. Layout of the high-average beam power proton driver for the PWFA that will fit into the 6.3 km Tevatron tunnel.

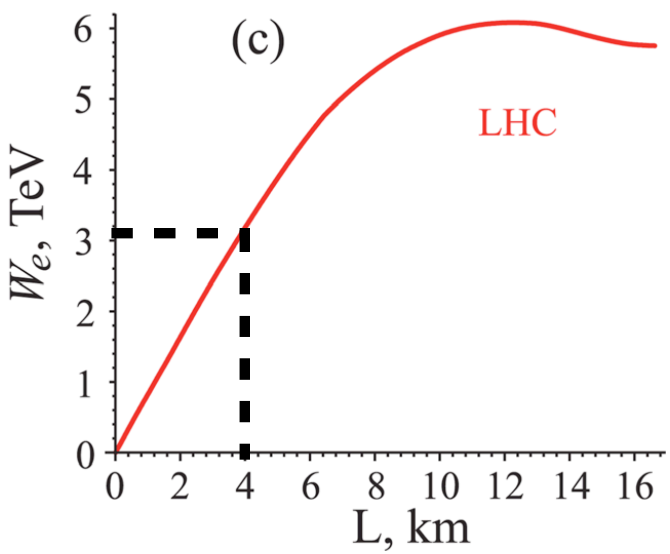
Initial designs:

- Use as an afterburner.
- Or as a new facility to achieve a linear collider.

V. Yakimenko and T. Katsouleas, Plasma Phys. Control. Fusion **53** (2011) 085010

Particle physics application

- Application based on existing infrastructure.
- Very high energy, but more modest luminosities.
- Consider *e(3 TeV)—P(7 TeV)* collisions, $\sqrt{s} \sim 9$ *TeV*.



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

VHEeP: A very high energy electron–proton collider based on proton-driven plasma wakefield acceleration

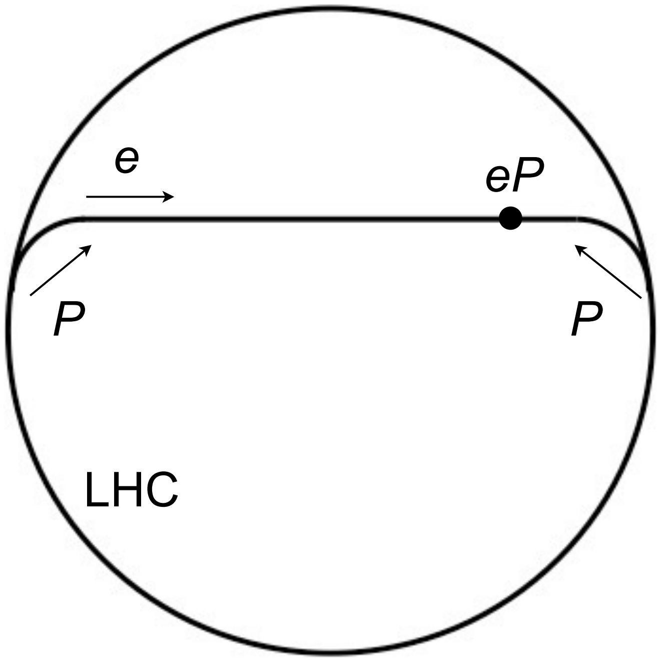
Allen Caldwell (MPI)
Matthew Wing (UCL/DESY/Univ. Hamburg)

- Introduction
- Accelerator based on plasma wakefield acceleration
- Physics in very high energy *eP* collisions
- Summary and outlook

DIS 2015 Workshop — 28 April 2015

As well as considering designs for a linear collider

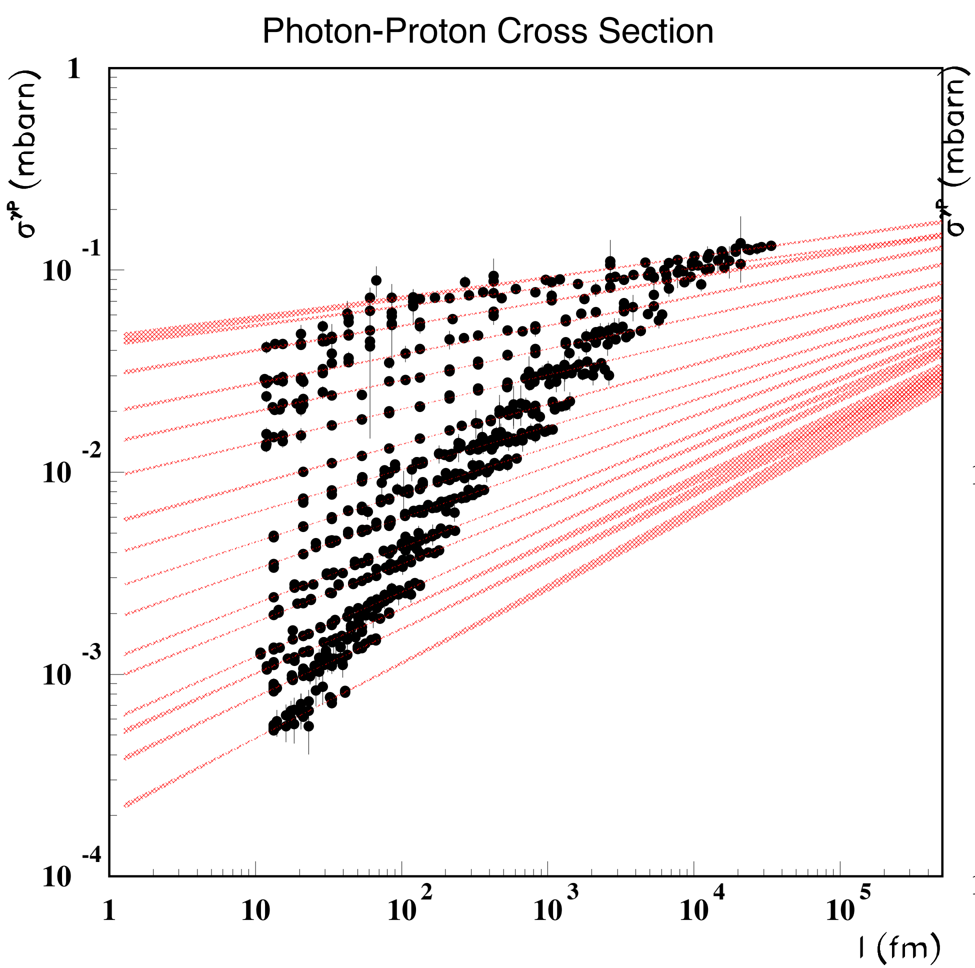
Plasma wakefield accelerator

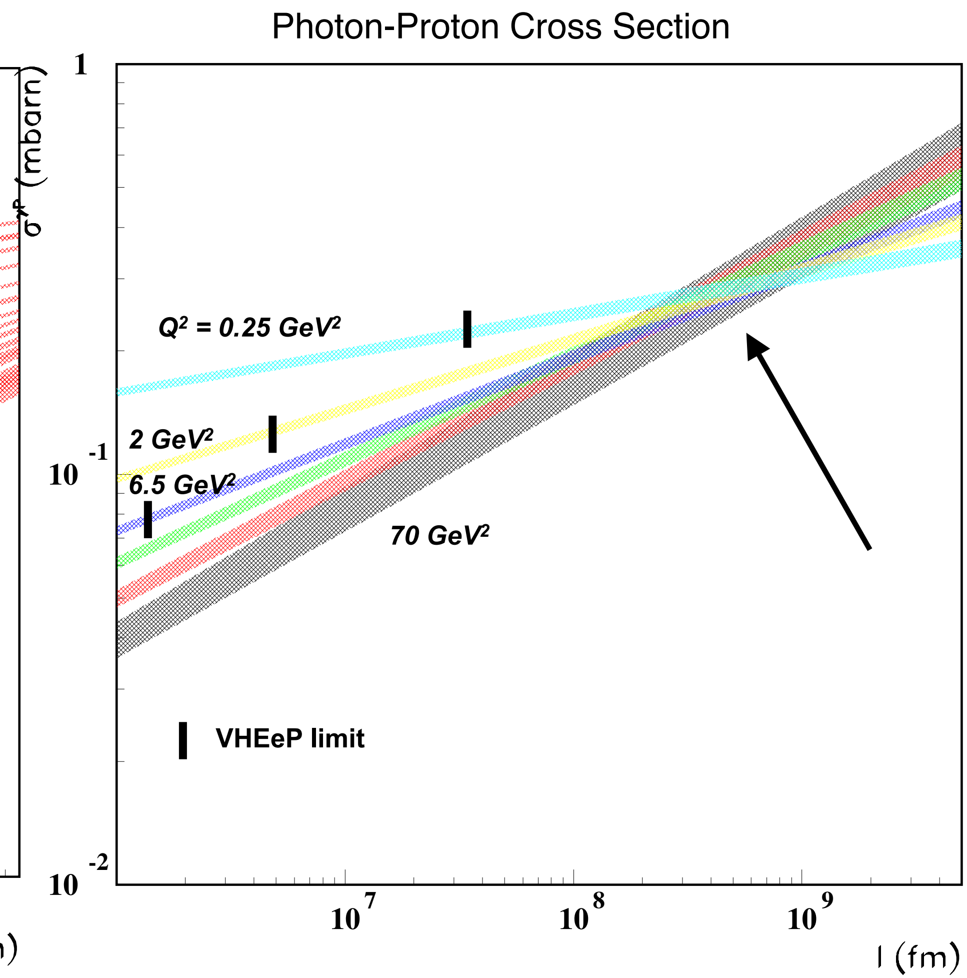


- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- Luminosity ~ $5 \times 10^{28}\ cm^{-2}\ s^{-1}$, but looking to increase.

- Physics at very low parton momentum fraction, *x*, does not need high luminosities.
- Variation of beam energy: γP total cross section, F_L, etc.
- Leptoquarks beyond the reach of LHC given the high $\sqrt{s}$ and other contact interactions.

Search for proton saturation at plasma accelerator





Onset of saturation—completely different proton structure at low *x*.

Summary and outlook

Summary

- Plasma wakefield acceleration could be the technology to reach the high energy frontier with more compact facilities.
- Energy gains of ~ *5 GeV* have been measured in laser- and electron-driven plasma wakefield acceleration.
- Accelerating gradients up to ~ *100 GeV/m* have been observed.
- Bunches with reasonable properties are produced: %-level energy spread, *O(100) pC* of charge.
- Positrons and electrons have both undergone significant acceleration.
- Several new experiments will be happening over the coming years investigating:
  - Staging and maximum energy through laser-driven acceleration
  - Two bunch running for electron beams and high-quality production
  - Use of protons as a driver of plasma wakefield acceleration.

European demonstration plasma wakefield accelerator

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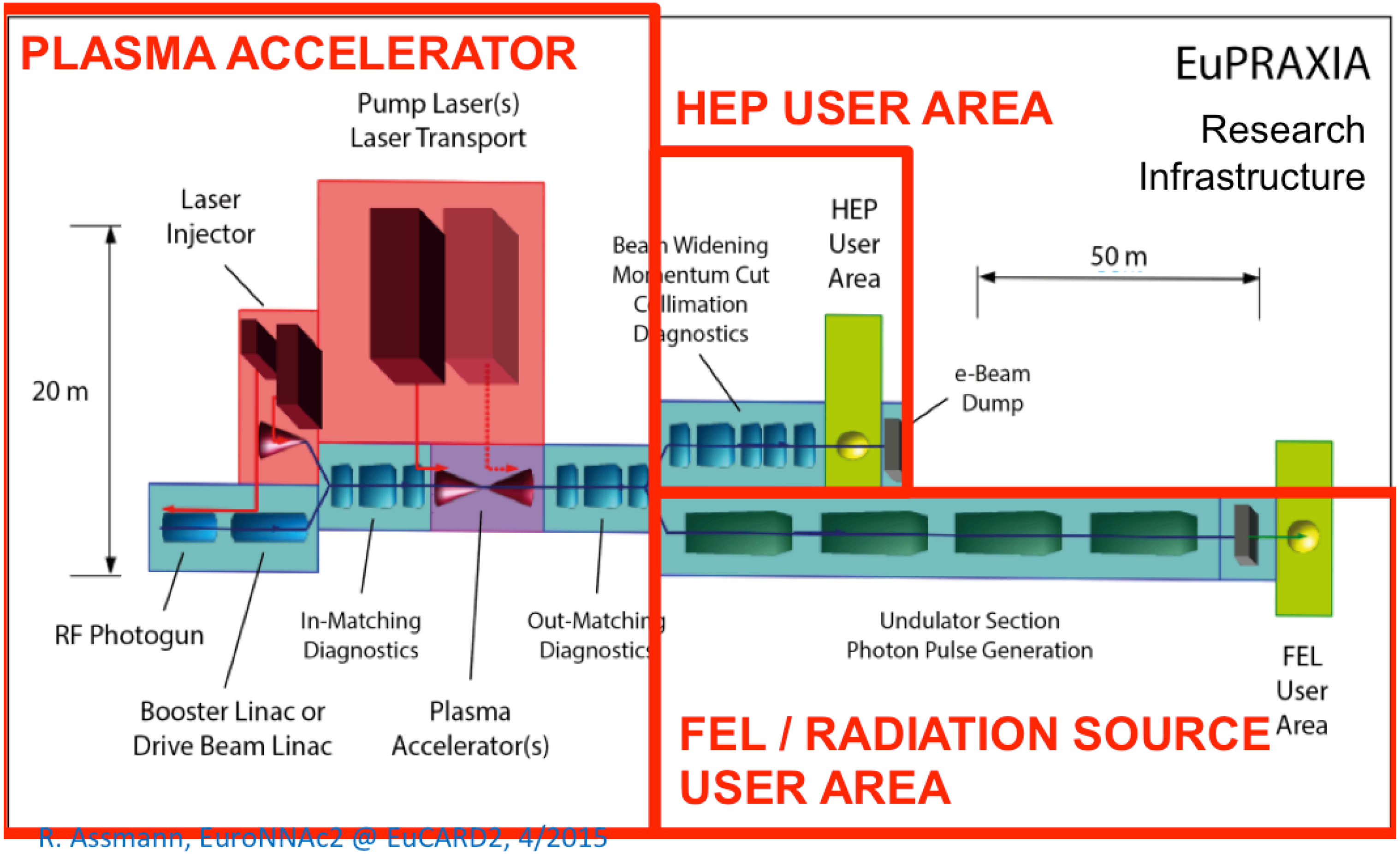


EuPRAXIA: European design study for an "**Eu**ropean **P**lasma **R**esearch **A**ccelerator with e**X**cellence **I**n **A**pplications". Funded as 3 MEUR "Design Study"

Outlook

Plasma wakefield acceleration is very promising but has a number of issues to be addressed in order to come up with a realistic collider design.

Plasma and accelerator physicists need to work together to develop a sound design and high energy physicists need to consider the possible physics cases.

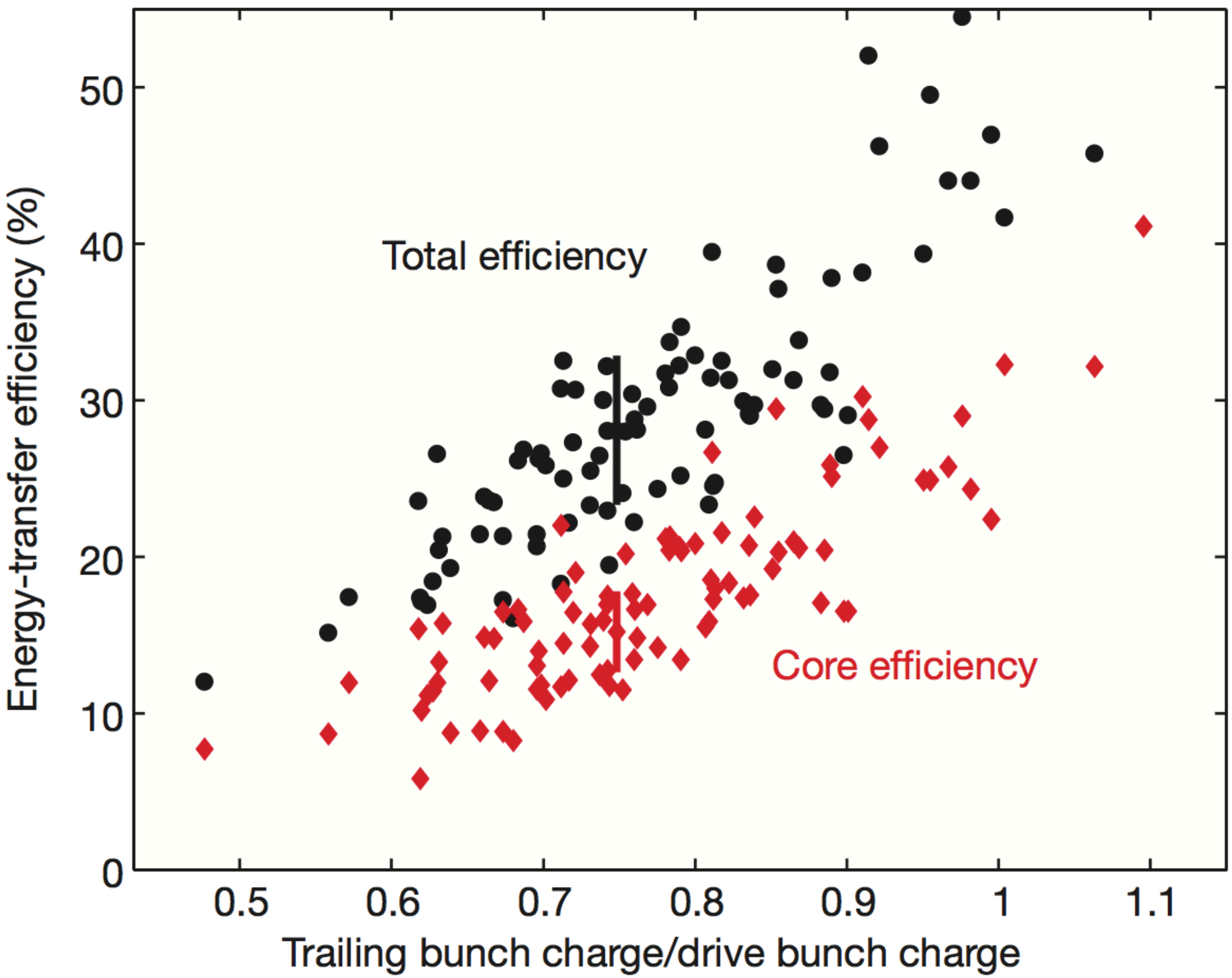
The involvement of large labs, SLAC, DESY and CERN, is significant and should enable many questions to be answered.

The coming experiments, AWAKE, BELLA, FACET, FLASHForward, etc., will tell us a lot about beam quality, ultimate plasma stage lengths, reproducibility, and hence energy and luminosity of a possible collider.

Extras

FACET efficiency

Efficiency: energy gain by trailing bunch / energy loss by drive bunch

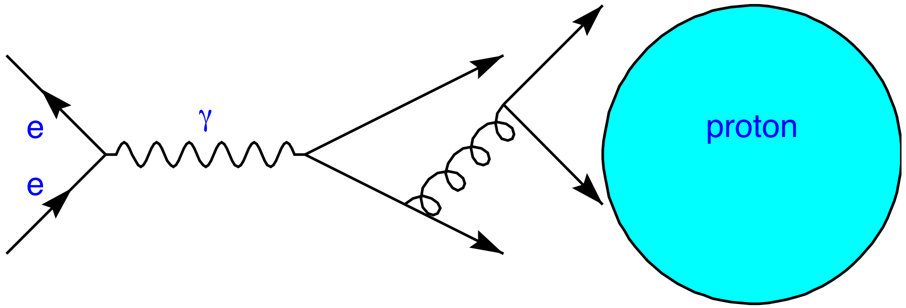


$\sigma_{\gamma P}$ at large coherence lengths

Look at behaviour of $\sigma_{\gamma P}$ in the proton rest frame in terms of Q^2 and coherence length, *l.*

Electron is a source of photons which is a source of partons.

Coherence length is distance over which quark−antiquark pair can survive.



If cross sections become same as a function of Q2, the photon states have had enough time to evolve into a universal size.

Look at what HERA data has shown and what the potential of VHEeP is.