Cockcroft Institute Lectures – Register Attendance

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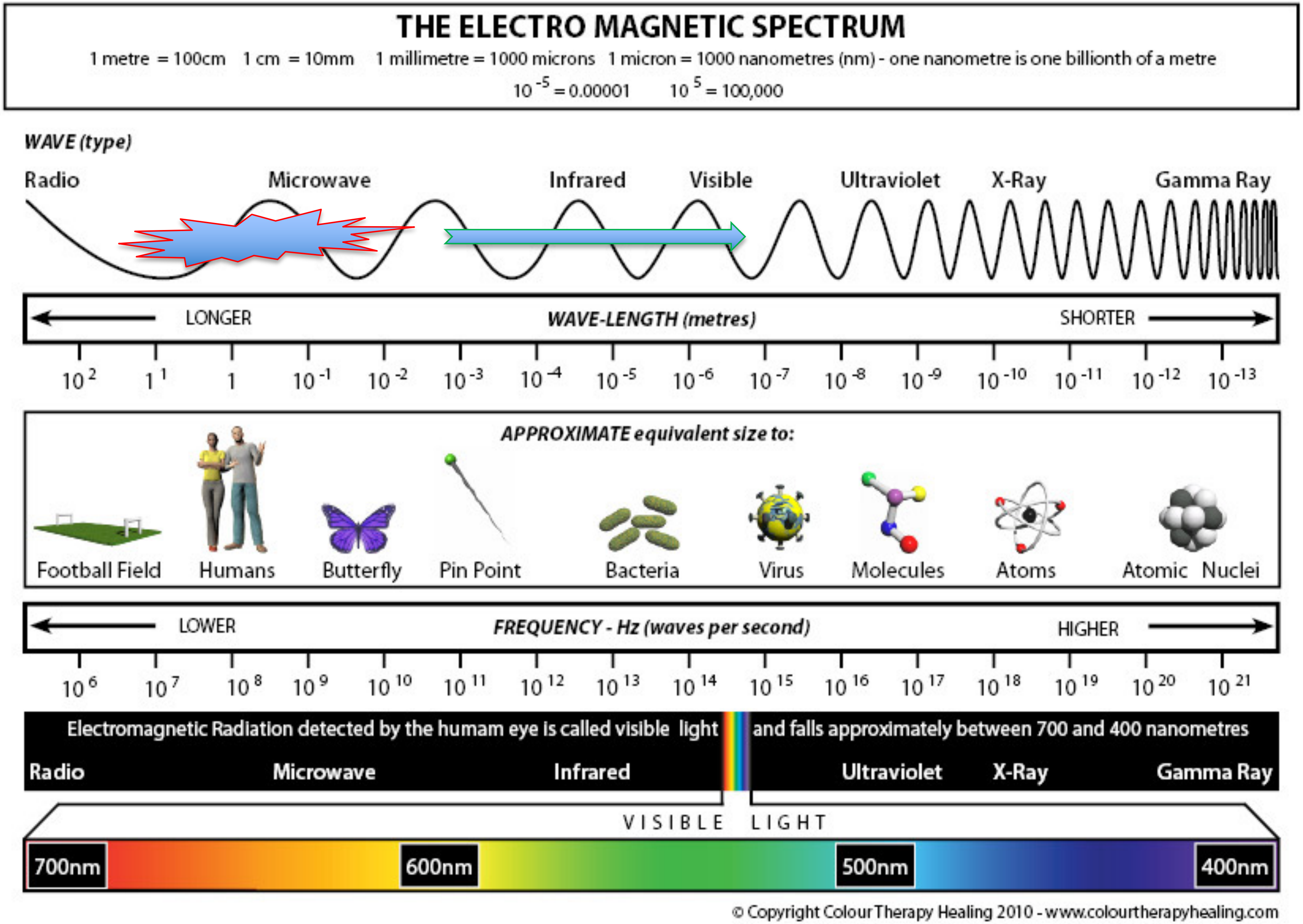
Record attendance for each day of lectures.

Short Wavelength Accelerators (II)

Guoxing Xia
Cockcroft Institute and the University of Manchester


THE ELECTRO MAGNETIC SPECTRUM
1 metre = 100cm 1 cm = 10mm 1 millimetre = 1000 microns 1 micron = 1000 nanometres (nm) - one nanometre is one billionth of a metre
10 -5 = 0.00001 10 5 = 100,000
WAVE (type)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-Ray
Gamma Ray
LONGER
WAVE-LENGTH (metres)
SHORTER
10 2
1 1
1
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
10 -7
10 -8
10 -9
10 -10
10 -11
10 -12
10 -13
APPROXIMATE equivalent size to:
Football Field
Humans
Butterfly
Pin Point
Bacteria
Virus
Molecules
Atoms
Atomic Nuclei
LOWER
FREQUENCY - Hz (waves per second)
HIGHER
10 6
10 7
10 8
10 9
10 10
10 11
10 12
10 13
10 14
10 15
10 16
10 17
10 18
10 19
10 20
10 21
Electromagnetic Radiation detected by the humam eye is called visible light and falls approximately between 700 and 400 nanometres
Radio
Microwave
Infrared
Ultraviolet
X-Ray
Gamma Ray
VISIBLE LIGHT
700nm
600nm
500nm
400nm
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Lecture I

- Particle accelerators
- Why short wavelength accelerators?
- Why plasmas?
- Why lasers?
- Laser wakefield accelerators (LWFA)
  - Electron acceleration from LWFA
  - Radiation sources
  - Proton/ion acceleration
- Conclusions

Learning objectives-Lecture I

? Motivations for short wavelength accelerators

? How laser-plasma acceleration works

? Limitations of laser-plasma accelerators

? Applications of laser-plasma accelerators

Lectures II

- Why beam driven plasma wakefield accelerators?
- Plasma wakefield accelerators (PWFA)
  - Electron driven PWFA
  - Positron driven PWFA
  - Proton driven PWFA
- Dielectrics in accelerators
  - Dielectric laser accelerators (DLA)
  - Beam driven dielectric accelerators (DWA)
  - THz driven dielectric structures
- Conclusions and future perspectives

Learning objectives-Lectures II

- ? Why beam driven PWFA and how it works
- ? Electron driven PWFA experiment
- ? Positron driven PWFA experiment
- ? Why proton driven PWFA and how it works
- ? Why dielectric accelerator and how it works
- ? Future perspectives

Why beam driven PWFA?

- Owing to the limited research facilities, PWFAs trailed much behind LWFAs in their development
- However, PWFAs possess a few advantages over LWFAs
- PWFA drivers propagate through plasma at close to the speed of light, *c*, leading to a plasma wave phase velocity much higher than that in LWFA, where laser pulses propagate at their group velocity, v_g, which is less than *c.* Limiting effect such as overtaking and dephasing of accelerated particles are mitigated.

Why beam driven PWFA?

- In PWFAs, strong transverse focusing fields in the plasma prevent the driver beam expansion, allowing much longer acceleration lengths than that in LWFAs. Meters long plasma was demonstrated
- The increased wake phase velocity reduces unwanted self injection of plasma electrons into the wakefield, mitigating the dark current
- Beam drivers have much greater parameter stability than the high intensity laser drivers
- Particle beams for PWFAs can be generated with megawatt power with efficiencies of ~10%. In contrast, state of the art high intensity laser systems deliver output power of ~100W with ~0.1% level wall-plug efficiency.

Beam driven facilities: status

Facility	Where	Drive (D) beam	Witness (W) beam	Start	End	Goal
AWAKE	CERN, Geneva, Switzerland	400 GeV **protons**	Externally injected electron beam (PHIN 15 MeV)	2016	2020+ 2030+	**Use for future high energy e-/e+ collider.** - Study Self-Modulation Instability (SMI). - Accelerate externally injected electrons. - Demonstrate scalability of acceleration scheme.
SLAC-FACET	SLAC, Stanford, USA	20 GeV **electrons** and **positrons**	Two-bunch formed with mask (e^-/e^+ and e^--e^+ bunches)	2012	Sept 2016	- Acceleration of witness bunch with high **quality and efficiency** - Acceleration of positrons - FACET II preparation, starting 2018
DESY-Zeuthen	PITZ, DESY, Zeuthen, Germany	20 MeV **electron** beam	No witness (W) beam, only D beam from RF-gun.	2015	~2017	- Study Self-Modulation Instability **(SMI)**
DESY-FLASH Forward	DESY, Hamburg, Germany	X-ray FEL type **electron** beam 1 GeV	D + W in FEL bunch. Or independent W-bunch (LWFA).	2016	2020+	- **Application (mostly) for x-ray FEL** - Energy-doubling of Flash-beam energy - Upgrade-stage: use 2 GeV FEL D beam
Brookhaven ATF	BNL, Brookhaven, USA	60 MeV **electrons**	Several bunches, D+W formed with mask.	On going		- **Study quasi-nonlinear PWFA regime.** - Study PWFA driven by multiple bunches - Visualisation with optical techniques
SPARC Lab	Frascati, Italy	150 MeV	Several bunches	On going		- Multi-purpose user facility: includes laser- and beam-driven plasma wakefield experiments
CLARA	Daresbury Lab	35-250 MeV	D+W bunches	on going		- LWFA with external injection energy boost, ICS, plasma energy recovery

FACET-II (10 GeV e+e-), LUND, BEPCII…

Courtesy to Edda Gschwendtner (CERN)

Brief history

- Concept on laser plasma-based accelerator was proposed by Tajima & Dawson in 1979.
- The idea was to excite large amplitude plasma electron waves by using short pulse laser (LWFA) in high density plasma.
- P. Chen et al. proposed to use electron bunch to excite the plasma electron wave (PWFA) in 1985 and this idea was confirmed experimentally by Rosenzweig et al (1988).
- The PWFA experiments conducted by UCLA/USC/SLAC collaboration achieved many highlights (FFTB/FACET at SLAC).
- Several other labs, such as ANL, BNL, DESY, INFN, CERN, Daresbury Lab joined in this exciting research field

Seminal papers on PWFA

VOLUME 54, NUMBER 7 PHYSICAL REVIEW LETTERS 18 FEBRUARY 1985

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

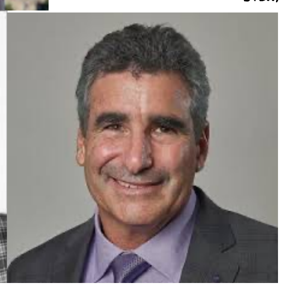
Pisin Chen[a]
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas
Department of Physics, University of California, Los Angeles, California 90024
(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 mc^2$ to $3\gamma_0 mc^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0^2 mc^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.

PACS numbers: 52.75.Di, 29.15.−n



Particle Accelerators, 1985, Vol. 17, pp. 171–189
0031-2460/85/1704–0171/$20.00/0

A PLASMA WAKE FIELD ACCELERATOR†

R. D. RUTH, A. W. CHAO, P. L. MORTON and P. B. WILSON

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

(Received December 14, 1984)

1. INTRODUCTION

One of the main parameters that determines the next generation of high energy accelerators is the acceleration gradient. Recently there has been interest in the use of plasma density waves for obtaining high acceleration gradients. The Plasma Beat-Wave scheme of Tajima and Dawson uses two beating lasers to excite the plasma at its resonant frequency.[1] The driven plasma provides an accelerating field that in principle can be of the order of several GeV/m.[2–5] This scheme has also been modified in the Surfatron,[6–8] although the basic principle is similar.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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CLIC Note No. 3

IMPROVING THE POWER EFFICIENCY

OF THE

PLASMA WAKEFIELD ACCELERATOR

S. van der Meer

ABSTRACT

Some methods are proposed to improve the efficiency of energy transfer from the primary beam to the secondary one. The first suggestion is to use beam diameters small compared to the plasma wavelength; in this regime the longitudinal wakefield depends little on the diameter. The second possibility is to use a continuous sequence of primary and secondary bunches without letting the plasma oscillations decay in between. It is shown how a steady-state solution providing equal deceleration or acceleration for all particles exists in first approximation.

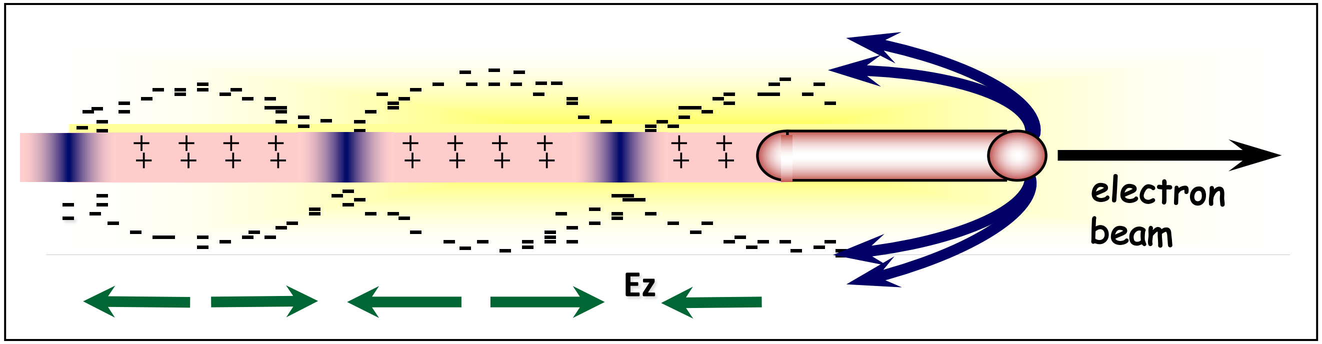
Basic principle of PWFAs

Electron motion solved with ...

driving force: Space charge of drive beam displaces plasma electrons.

restoring force: Plasma ions exert restoring force

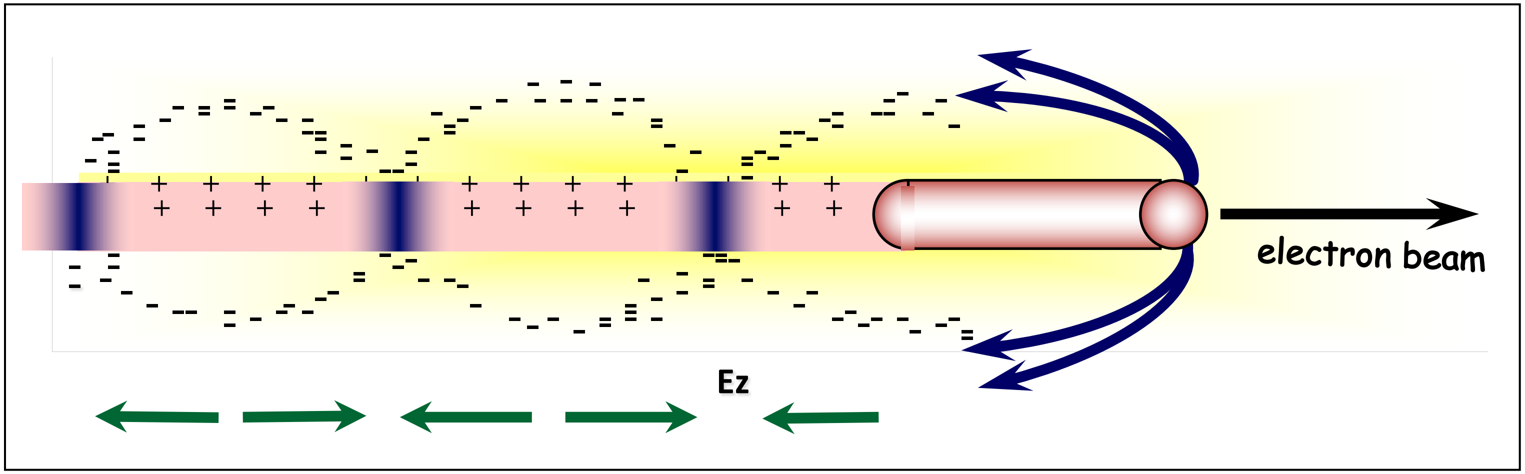
→ **Space charge oscillations (Harmonic oscillator)**



Longitudinal fields can accelerate and decelerate!

Basic principle

- Space charge of drive beam displaces plasma electrons



- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake behind a boat)
- Wake amplitude $\propto N_b / \sigma_z^2$ $\quad (for\ 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_p}})$
- Transformer ratio $E_{z\,acc.} / E_{dec.beam}$

Some useful tips

Relativistic plasma wavelength

$$\lambda_p = 2\pi c / \omega_p$$

Plasma frequency

$$\omega_p = \left[n_p e^2 / (\varepsilon_0 m) \right]^{1/2}$$

The field of a linear plasma wave

$$E_0 = \frac{m\omega_p c}{e} \approx 0.96 n_p^{1/2} \left[\mathrm{V/cm} \right]$$

The field is thus proportional to the square-root of the plasma density n_p. This means that a plasma density of 10^{18} cm^{-3} gives an accelerating gradient of 1 GeV/cm. In the nonlinear plasma wave, the field is even larger.

Some useful tips

- The plasma wave is linear as long as the density perturbation is small, i.e., $\delta n_p/n_p << 1$. A nonlinear wave can be excited in the case of $\delta n_p/n_p >> 1$.
- In the PWFA case, if the drive beam density $n_\mathrm{b} > n_\mathrm{p}$, and in LWFA case, if the normalized vector potential exceeds unity, $a_0 > 1$. The nonlinear wave can be excited.
- Beam density is given by $$n_b = \frac{N_b}{(2\pi)^{3/2}\sigma_r^2\sigma_z}$$

Key facts in PWFA

Relativistic, short, dense bunch: $E_{acc}\left[\mathrm{MV/m}\right]=244\frac{N_b}{2\times10^{10}}\left(\frac{600um}{\sigma_z}\right)^2$

with $\frac{\sigma_z}{\lambda_p}\cong\frac{1}{\sqrt{2\pi}}$ and $\frac{\sigma_r}{\lambda_p}<<2\pi$

Typically for 1GV/m: $N=2\times10^{10}$ $\sigma_z\cong200\mu m$ $\sigma_r<<137\mu m$ in $n_p=1.4\times10^{15}cm^{-3}$

Blowout, nonlinear regime: $\frac{n_b}{n_p}>1$

Pure ion column focusing: $\frac{B_\theta}{r}=\frac{1}{2}\frac{n_p e}{\varepsilon_0 c}\cong42kT/m$ free of geometric aberrations

Wave-breaking field: $E_{WB}=3.6GV/m$

Combination of large transverse focusing gradient and large accelerating field leads to large energy gain

All the beam particles and the wake are ultra-relativistic $\rightarrow$ no dephasing!

High energy (per particle) drive bunch

First experiment in 1988

VOLUME 61, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1988

Experimental Observation of Plasma Wake-Field Acceleration

J. B. Rosenzweig, D. B. Cline,[a] B. Cole,[b] H. Figueroa,[c] W. Gai, R. Konecny, J. Norem, P. Schoessow, and J. Simpson

High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 21 March 1988)

21 MeV drive beam,
15 MeV Witness beam,
Delay distance is variable.
Plasma density 10^{12}-10^{13} cm^{-3}

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipicosecond bunch of electrons in a plasma of density $n_e \simeq 10^{13}$ cm^{-3}, and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

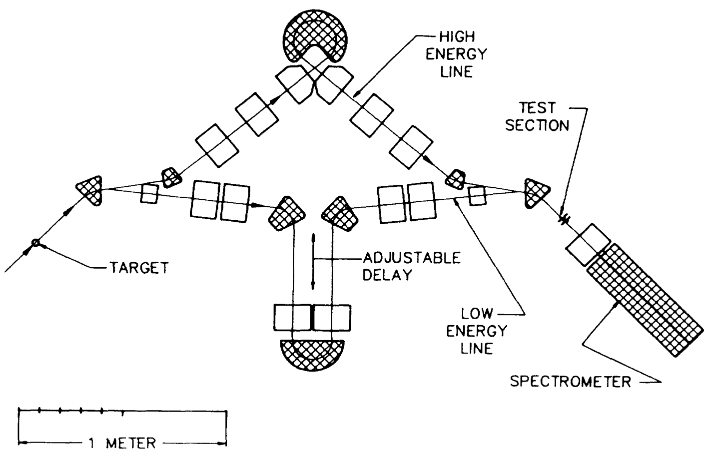


FIG. 1. Schematic of Argonne National Laboratory AATF layout.

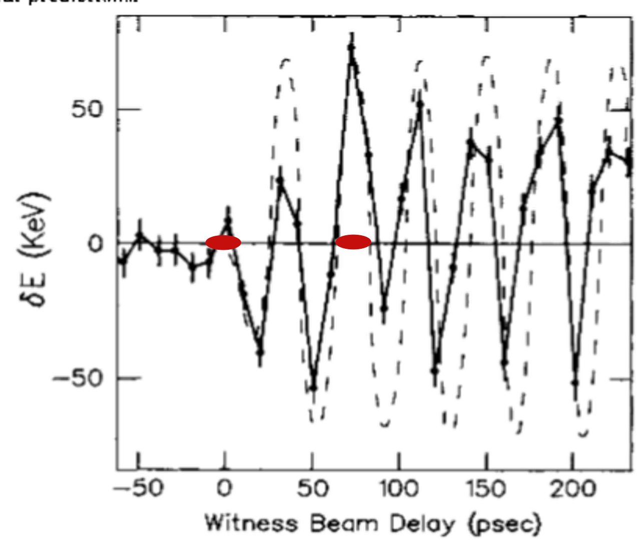
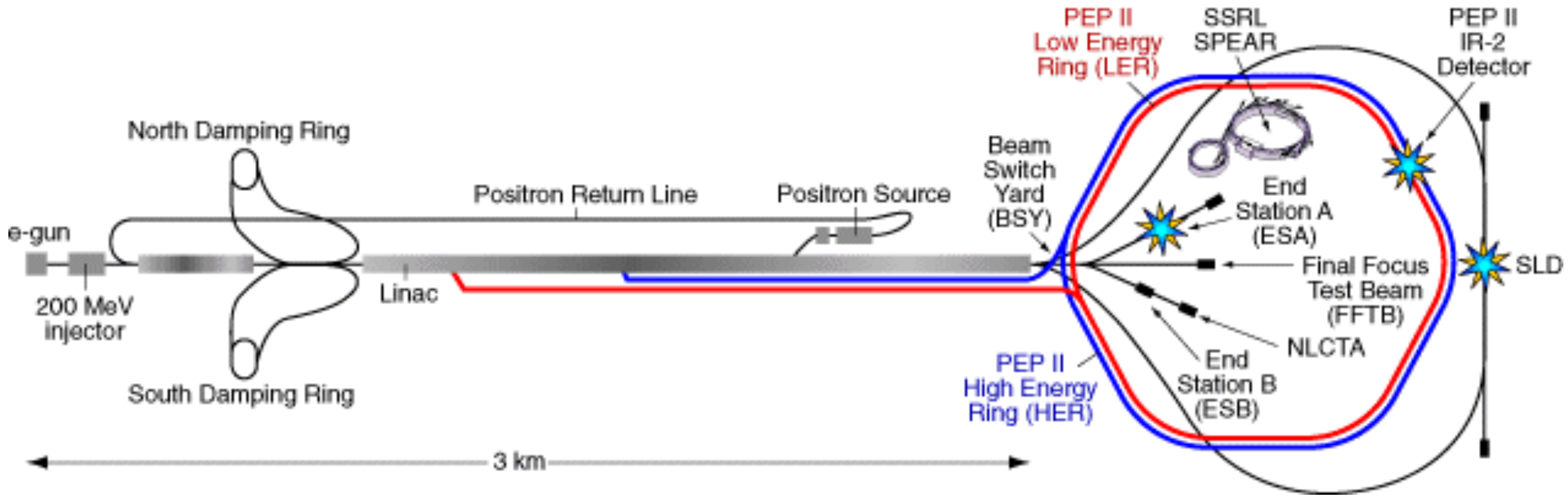
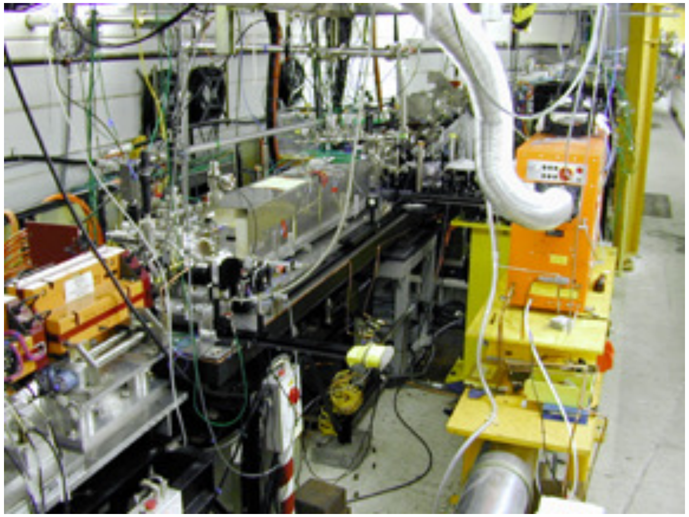


FIG. 2. Scan 1: Witness-beam energy-centroid change δE vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6 \times 10^{12}$ cm^{-3}. Theoretical predictions are given by the dashed line.

Experiments at FFTB@SLAC





Experiments by UCLA/USC/SLAC collaboration

Long beam *vs.* short beam

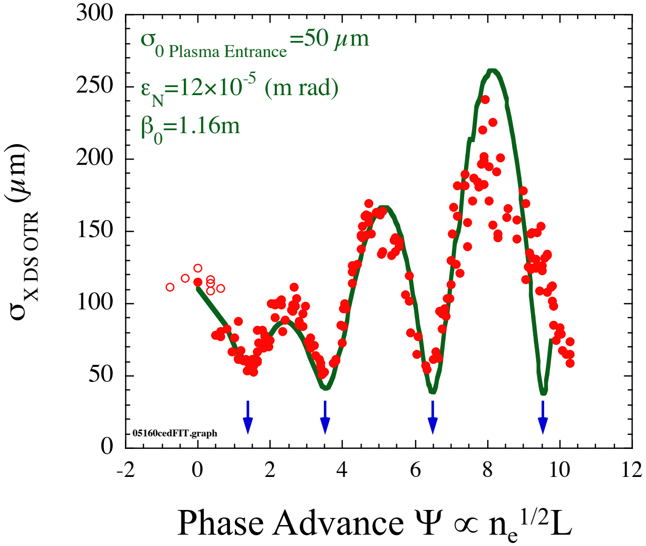
Table 1
Typical parameters for the long and short bunch experiments.

Parameter/symbol/unit	Long bunch	Short bunch
Beam	e^- and e^+	e^-
Energy E_0 (GeV)	28.5	28.5, 42
Beam relativistic factor γ_0	55,773	55,773, 82,192
Bunch length σ_z (μm)	730	50 to 15
Bunch radius $\sigma_{x,y}$ (μm)	30, 30	10, 10
Bunch population N_b	$1.8 \times 10^{10} e^-$, $1.2 \times 10^{10} e^+$	1.8×10^{10}
Beam density n_b (cm^{-3})	1.8×10^{15}, 1.2×10^{15}	2.3×10^{17} to 7.6×10^{17}
Normalized emittance[a] $\epsilon_{Nx,y}$ (m-rad)	50, 5×10^{-6}	50, 5×10^{-6}
Lithium plasma	Photo-ionized	Field-ionized
Density range n_e (cm^{-3})	10^{12}–5×10^{14}	10^{16}–3×10^{17}
Length L_p (cm)	140	10, 20, 30, 60, 90, 120

P. Muggli, M. Hogan, C.R. Physique 10, 116 (2009)

E-157/162 Results with 600 micron electron bunches

Focusing e⁻

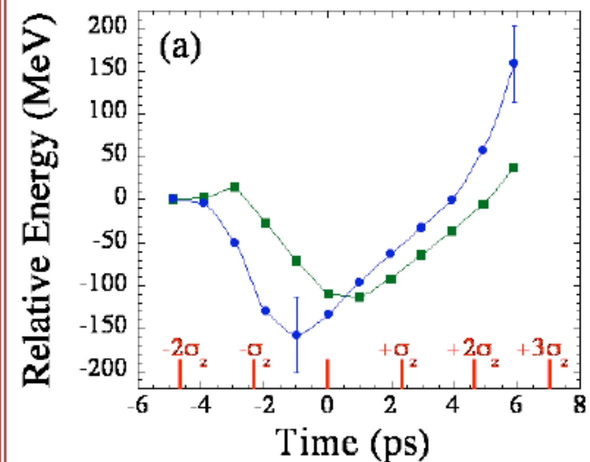


Phys. Rev. Lett. **88**, 154801 (2002)

X-ray Generation

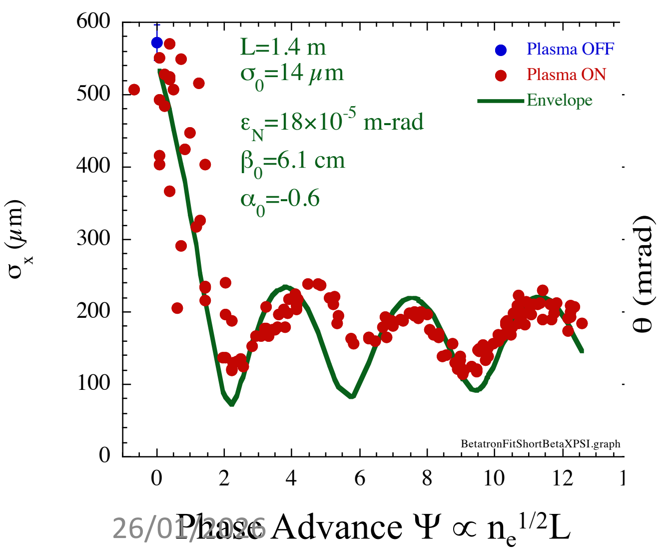
Phys. Rev. Lett. **88**, 135004 (2002)

Wakefield Acceleration e⁻



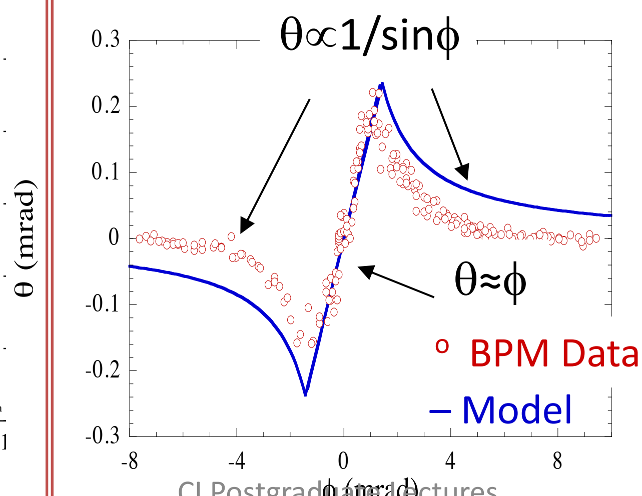
Phys. Rev. Lett. **93**, 014802 (2004)

Matching e⁻



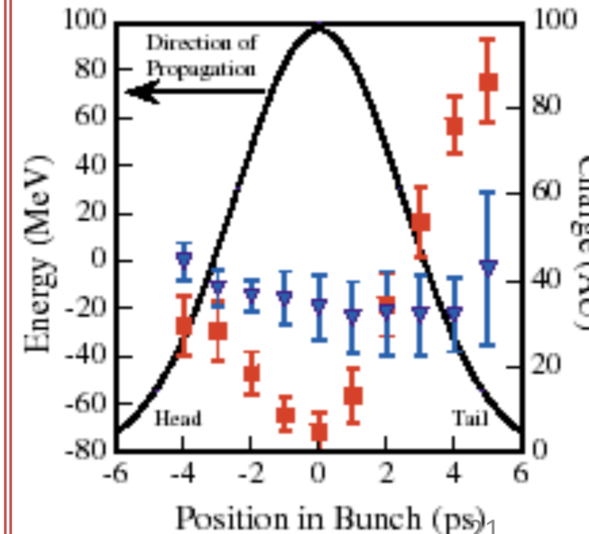
Phys. Rev. Lett. **93**, 014802 (2004)

Electron Beam Refraction at the Gas Plasma Boundary



Nature **411**, 43 (3 May 2001)

Wakefield Acceleration e⁺



Phys. Rev. Lett. **90**, 214801 (2003)

Energy gain scaling law

***14 GeV** Energy Gain in less than 30 cm !*

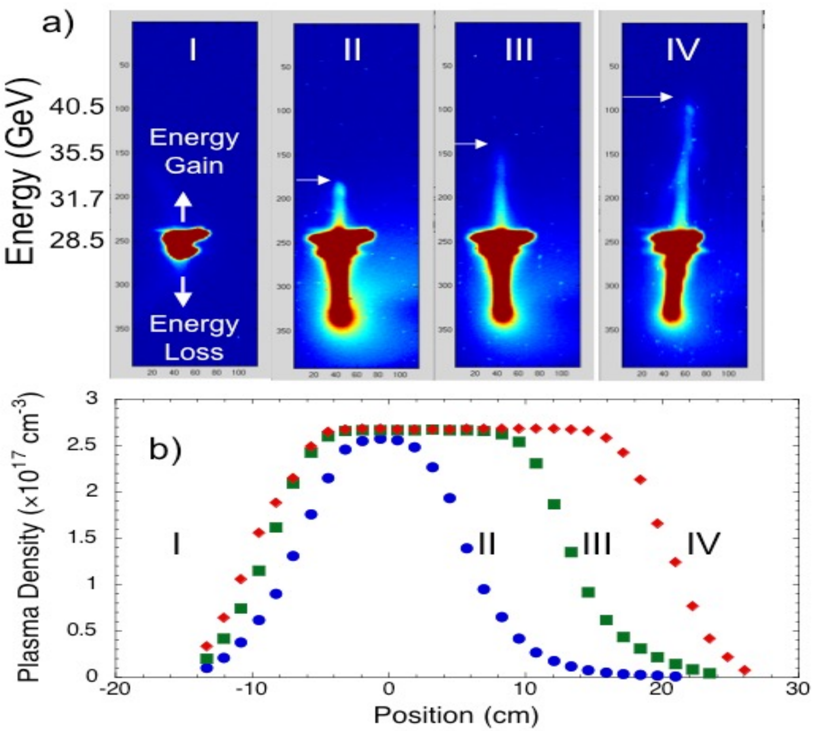
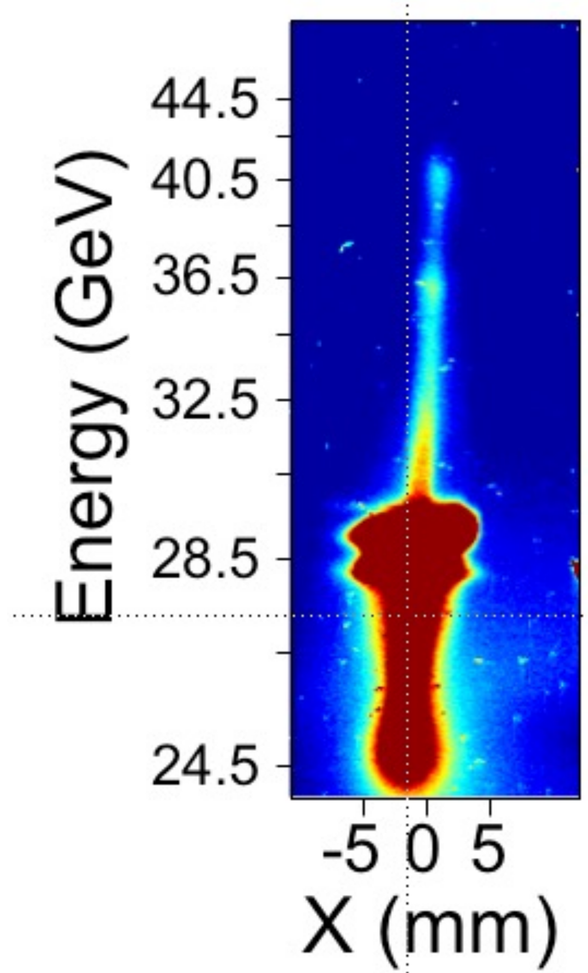
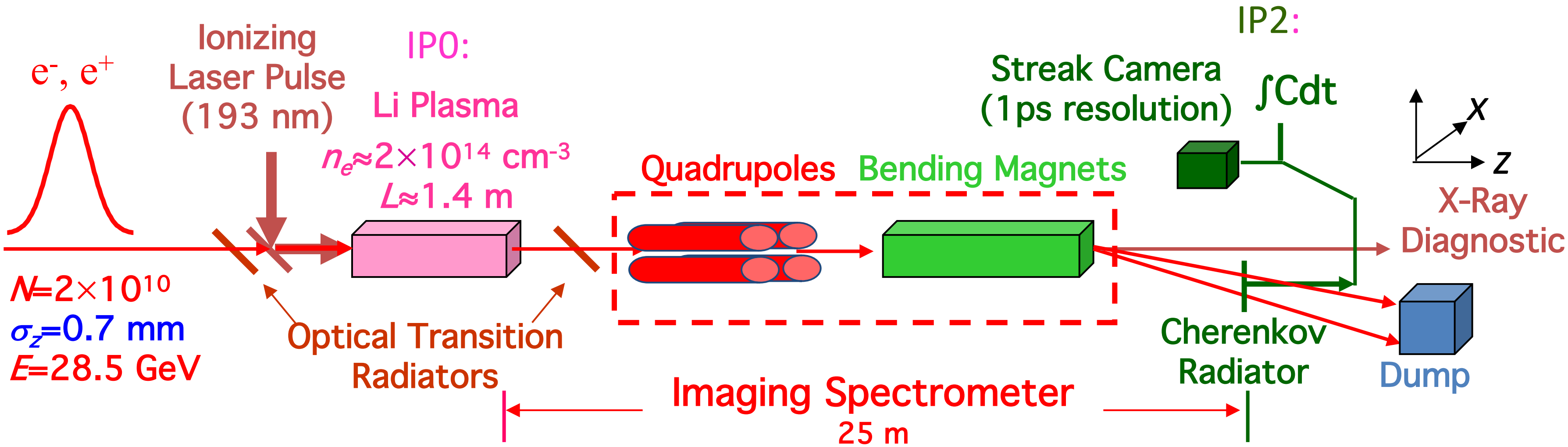


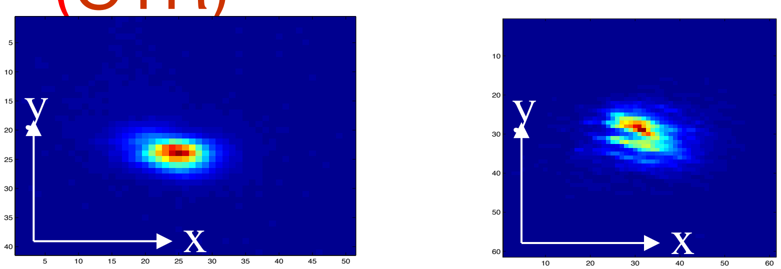
Figure 1: a) energy spectra before (I) and after propagation through the three longitudinal density profiles (II to IV) shown in Fig. b).



Long electron beam



- Optical Transition Radiation (OTR)

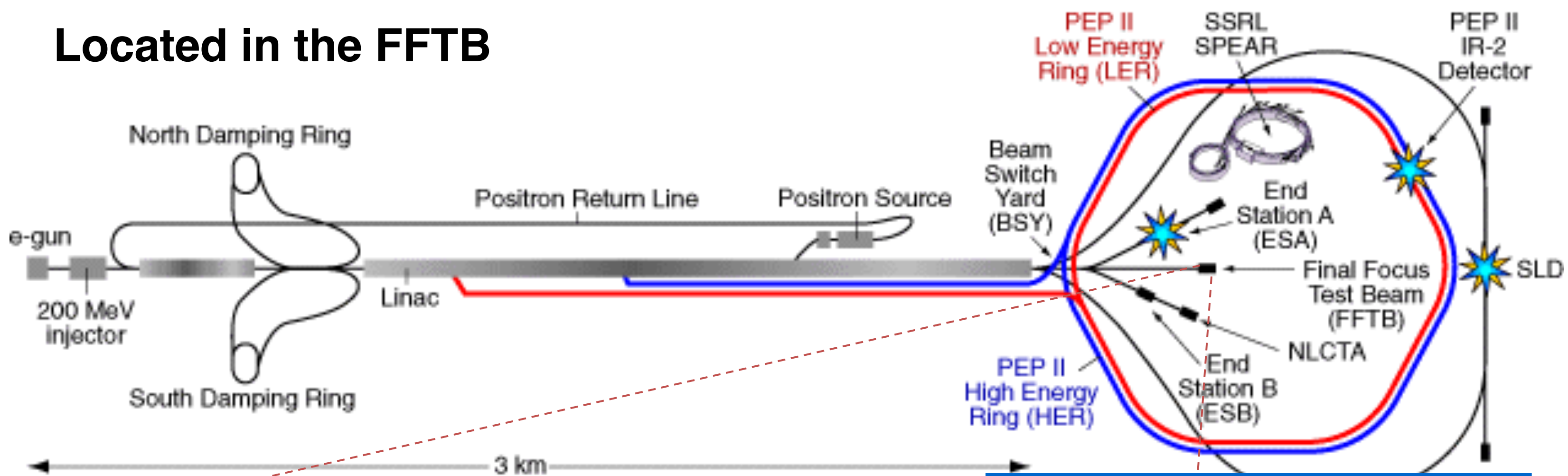


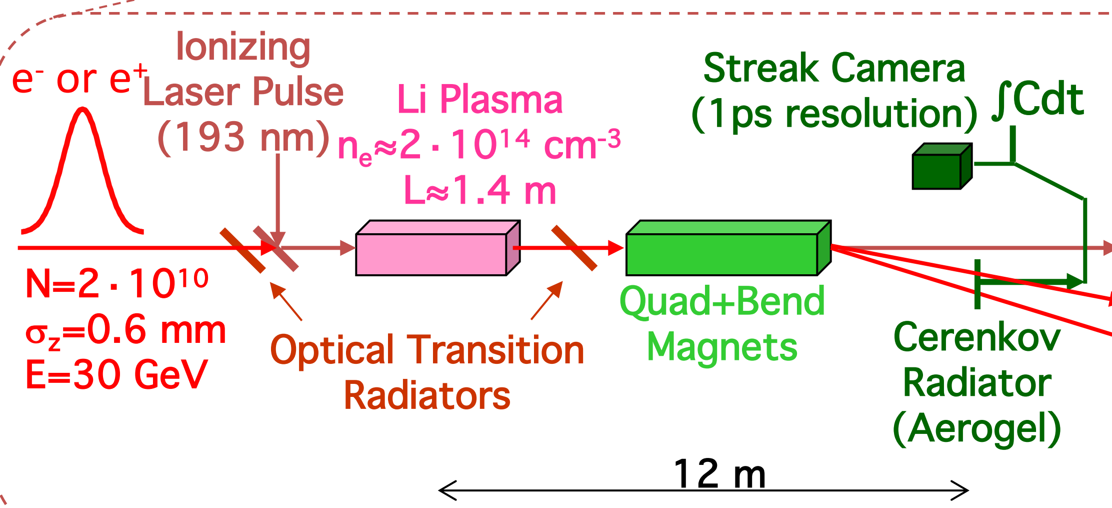
Lithium vapor plasma cell
Laser ionized!

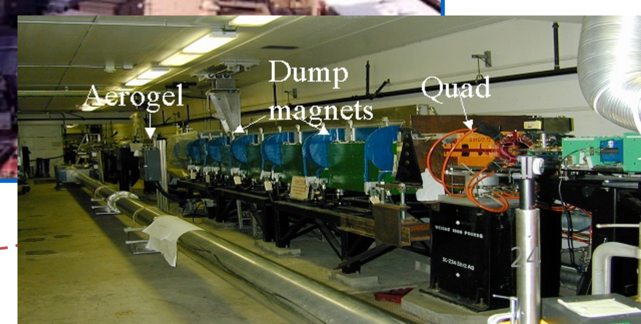
spatial resolution <9 μm

E-162 plasma wakefield experiment

Located in the FFTB







PWFA experiment E162

Typical parameters:

Long e^-- beam:

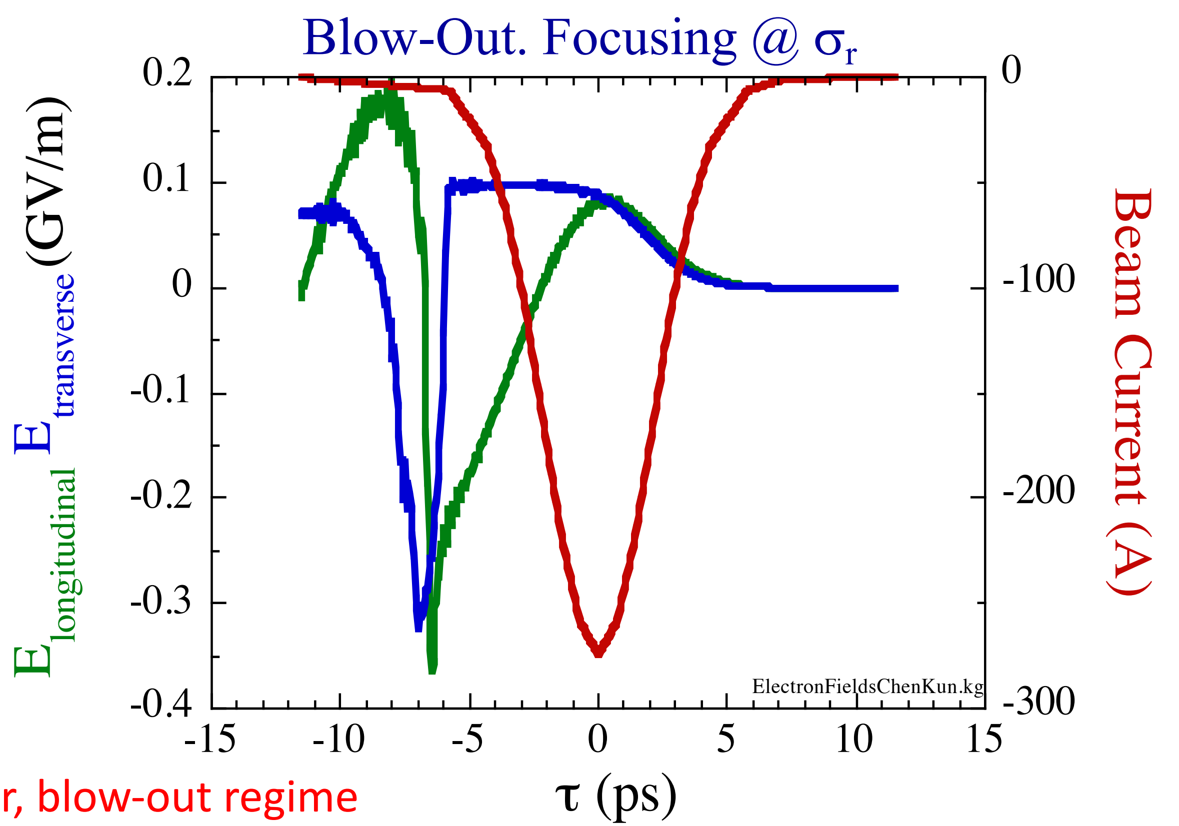
E	28.5 GeV
N	$<2\times10^{10}$ e^-
σ_z	0.63 mm (2.1 ps)
$\sigma_x=\sigma_y$	$\leq$70 μm
n_b	$\geq4\times10^{14}$ cm^{-3}
ε_{xN}	5×10^{-5} m-rad
ε_{yN}	0.5×10^{-5} m-rad

Plasma:

n_e	0-2×10^{14} cm^{-3}
L	1.4 m, laser ionized

2-D PIC Simulation OSIRIS

$n_e=1.5\times10^{14}$ cm^{-3}



Experiment: $n_b>n_e$ => nonlinear, blow-out regime

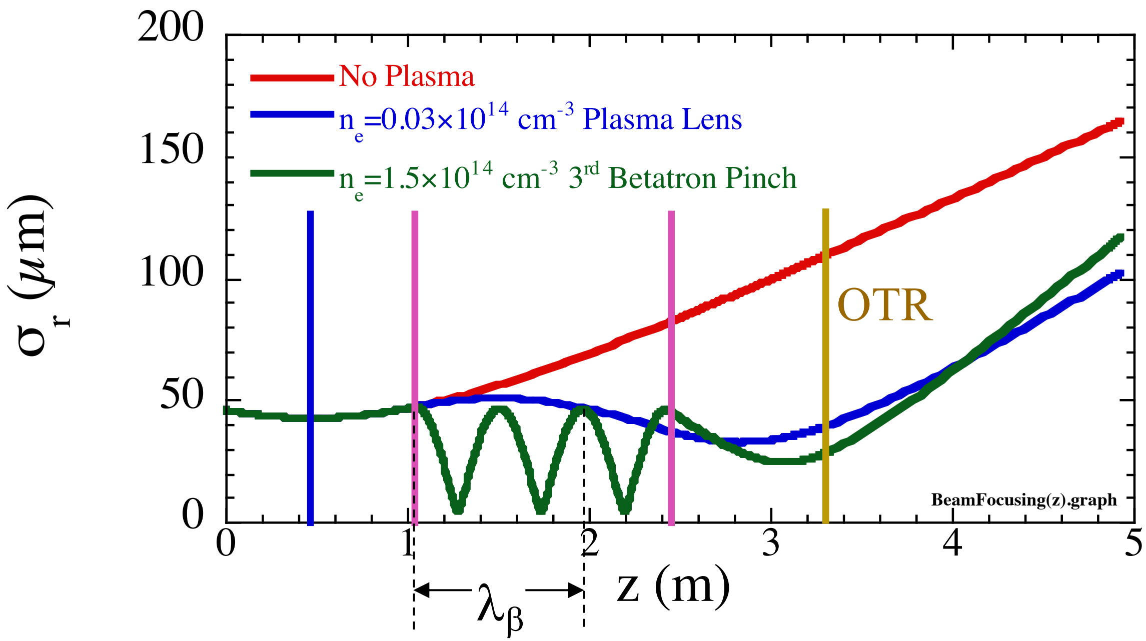
- Uniform focusing field (r,z)

Plasma focusing

Beam Envelope Model for Plasma Focusing

Plasma Focusing Force > Beam "Emittance Force"

$(\beta_{beam}=1/K> \beta_{plasma})$



Envelope equation:

$$\frac{\partial^2\sigma}{\partial z^2} + K^2\sigma = \frac{\varepsilon^2}{\sigma^3}$$

In an ion channel:

$$K = \frac{\omega_{pe}}{\sqrt{2\gamma c}} \propto \left(n_p\right)^{1/2}$$

with a focusing strength:

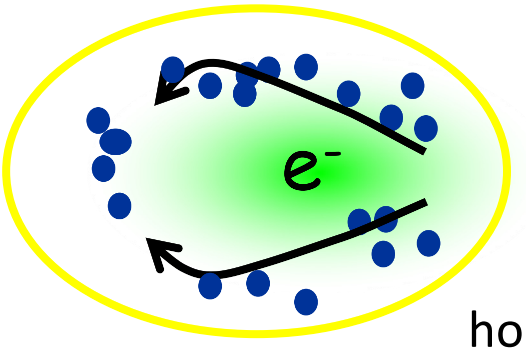
$$W = \frac{E_r}{rc} = \frac{B_\theta}{r} = \frac{1}{2}\frac{n_p e}{\varepsilon_0 c}$$

=6 kT/m

@ $n_p=2\times10^{14}$ cm^{-3}

Multiple foci (betatron oscillation) within the plasma

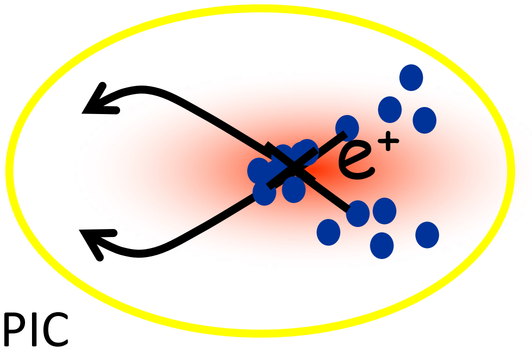
e^+ and e^- as drive beams

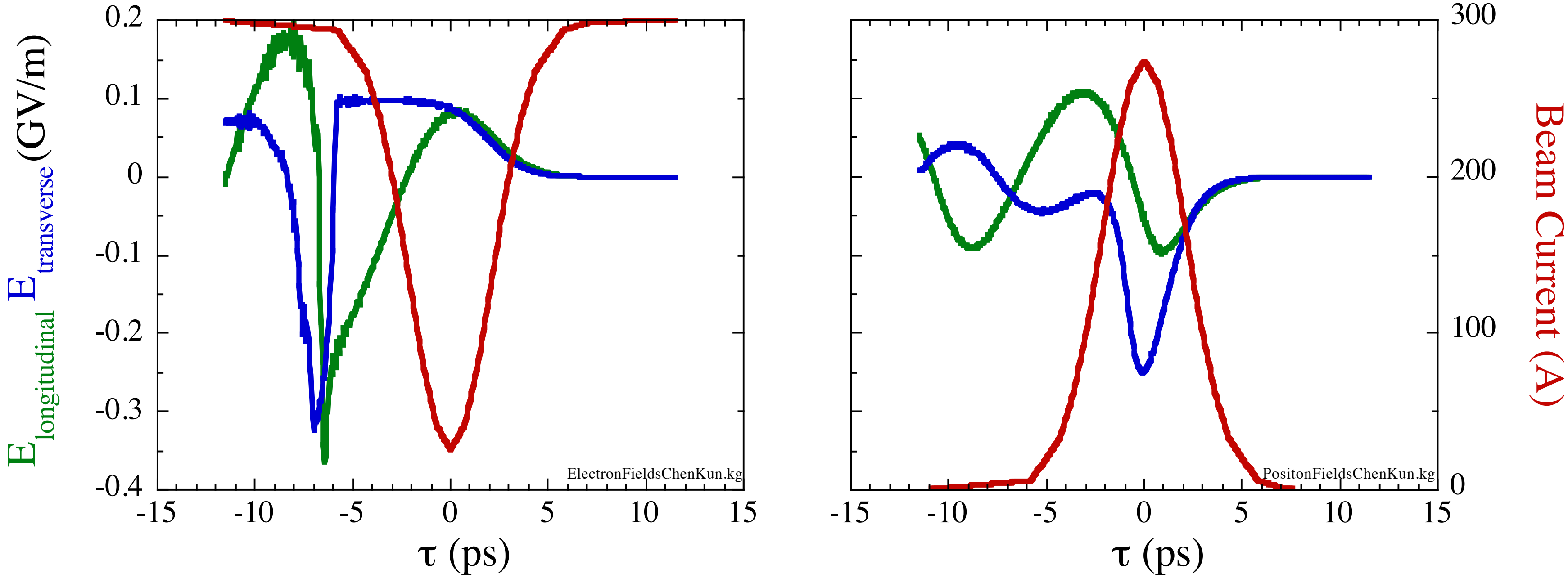


$\sigma_r = 35\ \mu m$

$N = 1.8\times10^{10}$

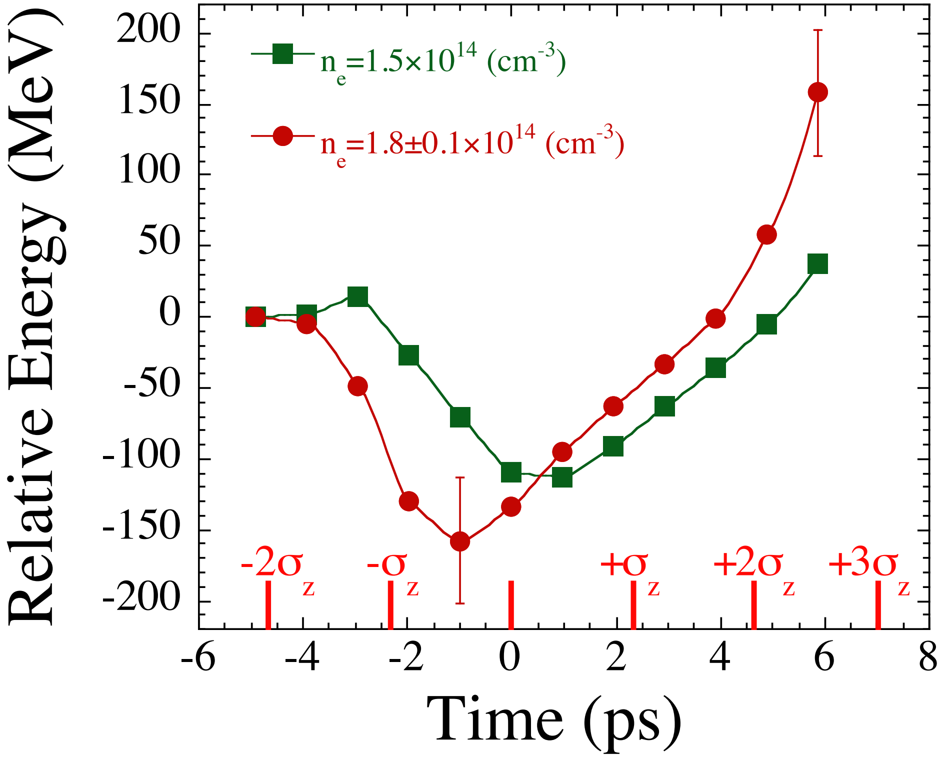
n_p=1.5×10^{14} cm^{-3}
homogeneous, QUICKPIC





- Blow-Out
- Accelerating "Spike"
- Fields vary along r, stronger
- Less Acceleration, "linear-like"

e^+ acceleration



PRE-IONIZED plasma

LONG bunch operation

$\sigma_z \approx 730$ µm

$N = 1.2\times10^{10}$ e^+

$k_p\sigma_z \approx \sqrt{2}$

PRL 93, 014802 (2004)

Energy gain smaller than, hidden by, incoming energy spread

Time resolution needed, but shows the physics

Peak energy gain: 279 MeV, L=1.4 m, ≈200 MeV/m

Acceleration gradient vs. bunch length

E-164X:

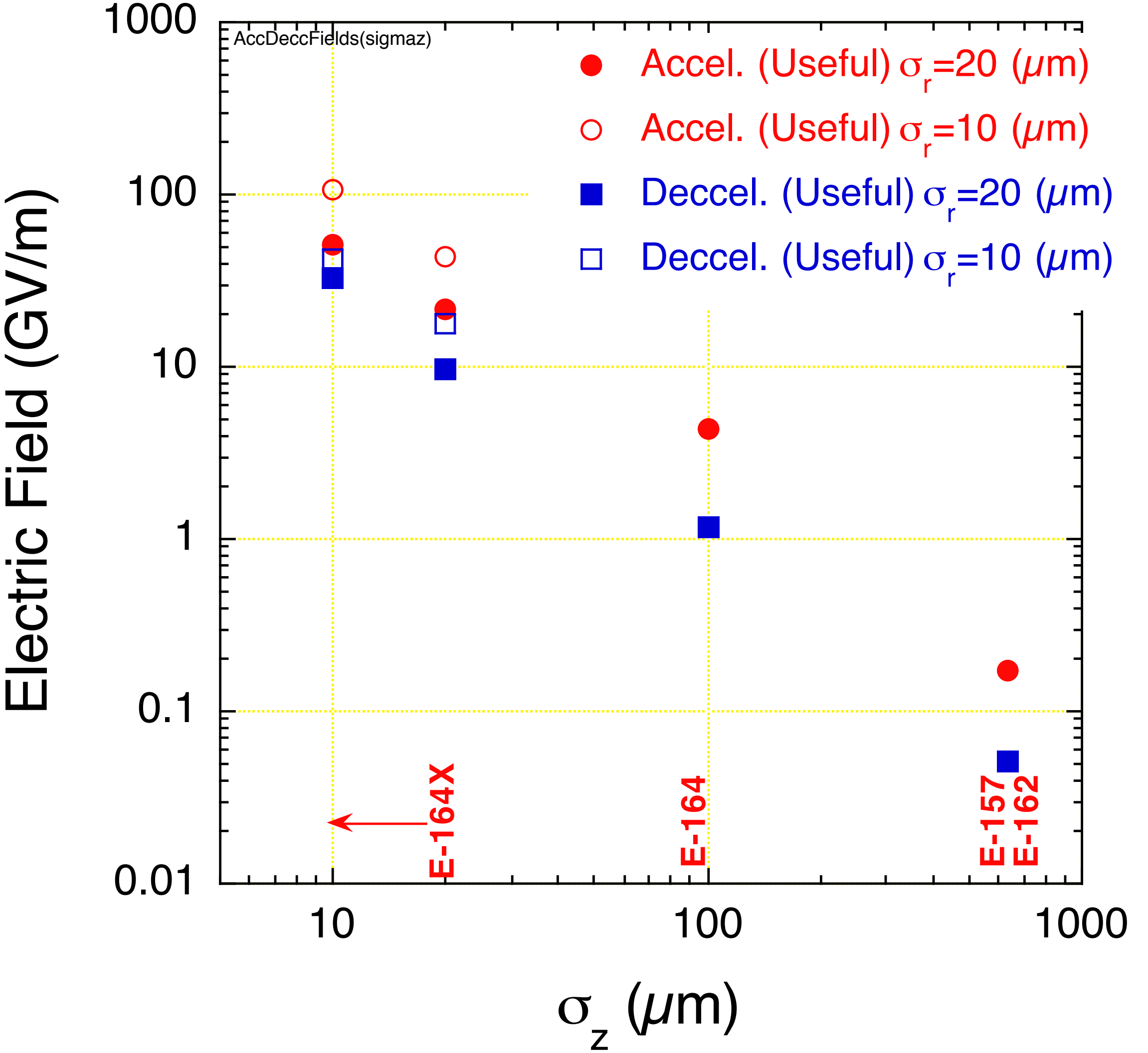
σ_z = 20 - 10 μm

> 10 GeV/m

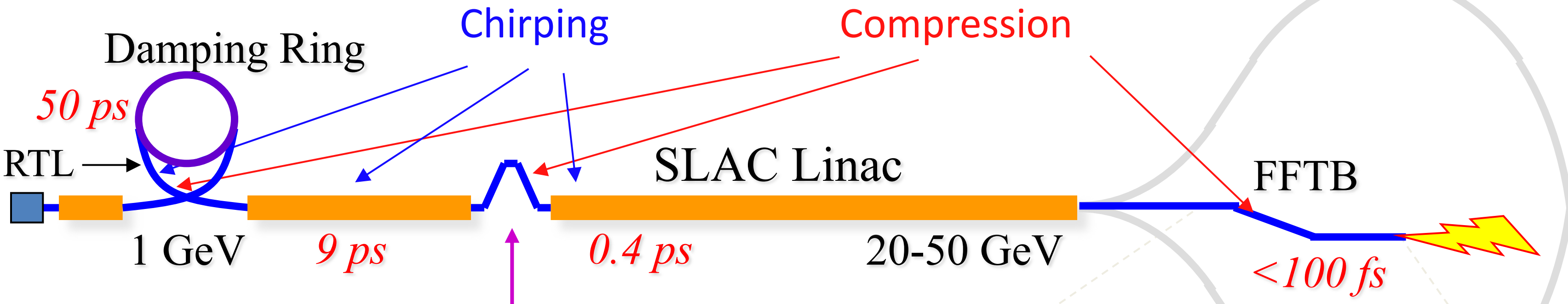
gradient!

(σ_r dependent! $k_p\sigma_r \approx 1$)

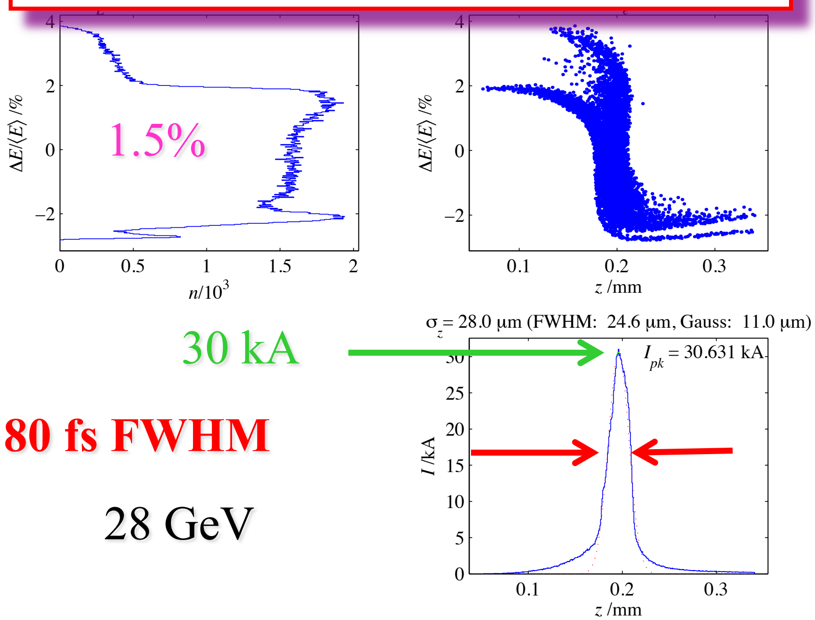
f_p = 2.8 THz, W = 3MT/m
@ $n_e = 10^{17}$ cm^{-3}



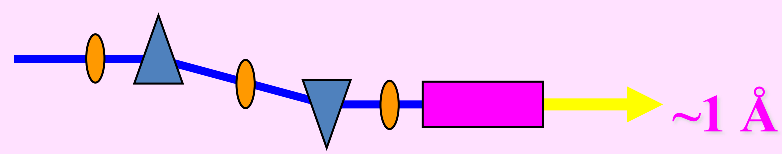
Short bunch experiment@ FFTB



Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

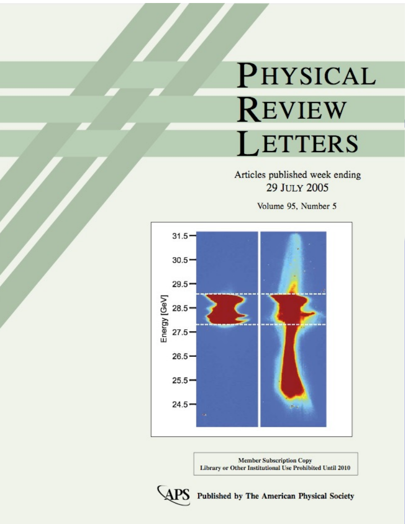


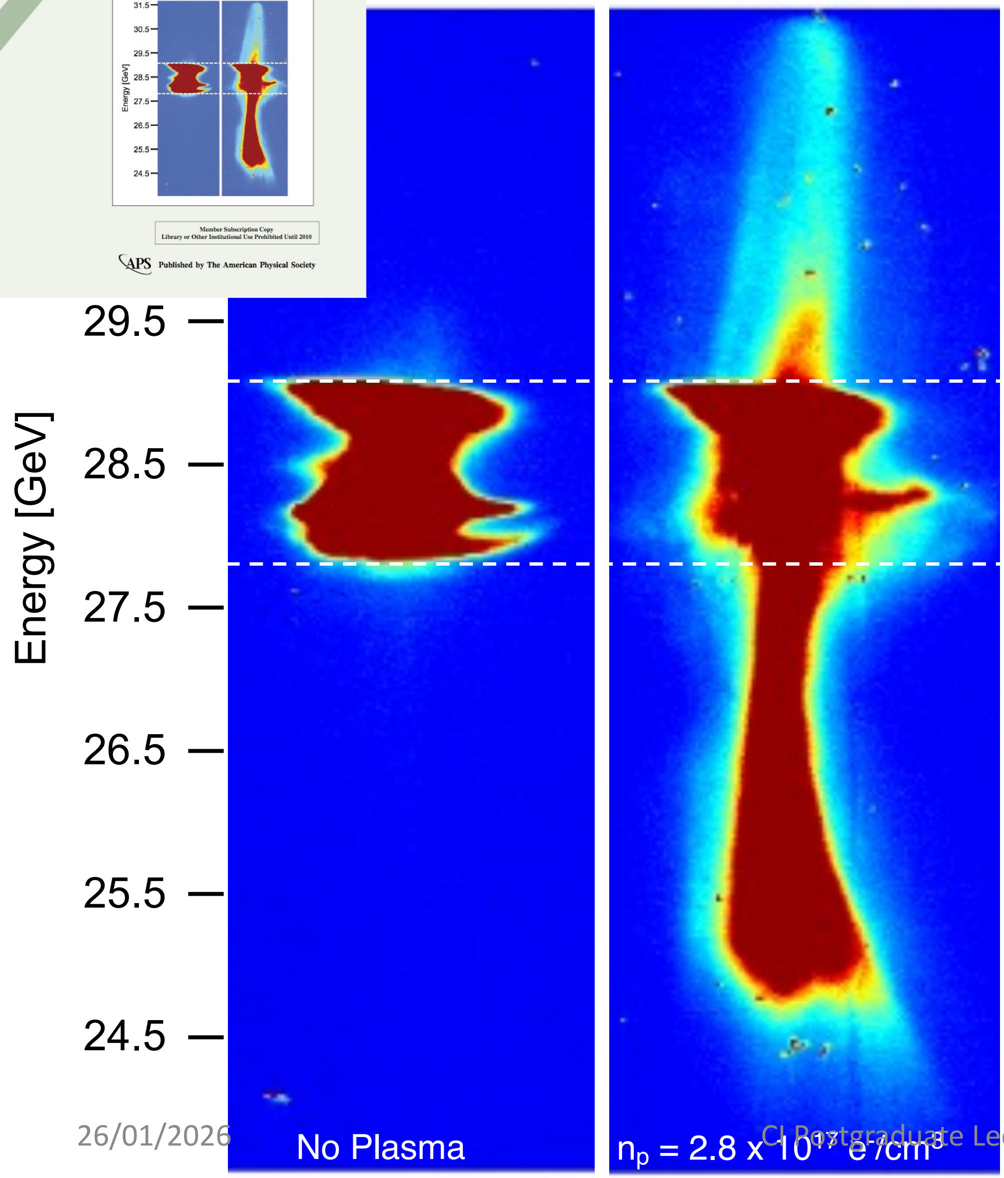
Existing bends compress to **< 100 fsec**



- Bunch length/current profile is the convolution of an incoming energy spectrum and the magnetic compression

GeV energy gain





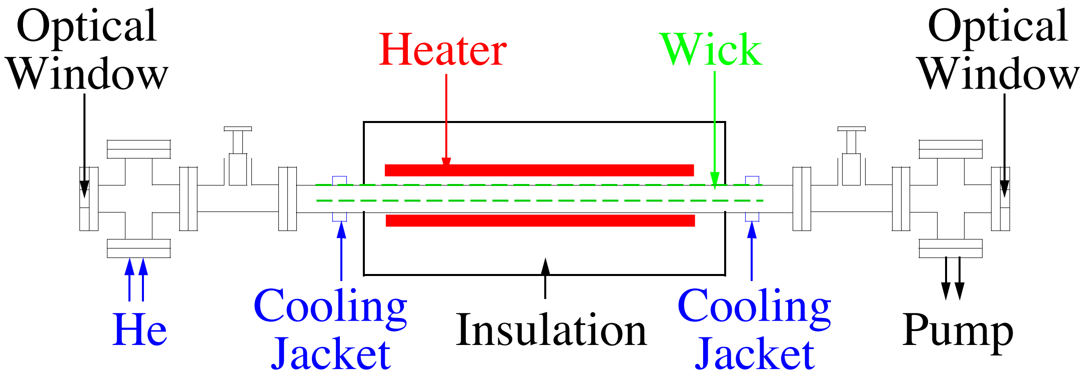
Accelerating Gradient > 27 GeV/m!
(Sustained Over 10cm)

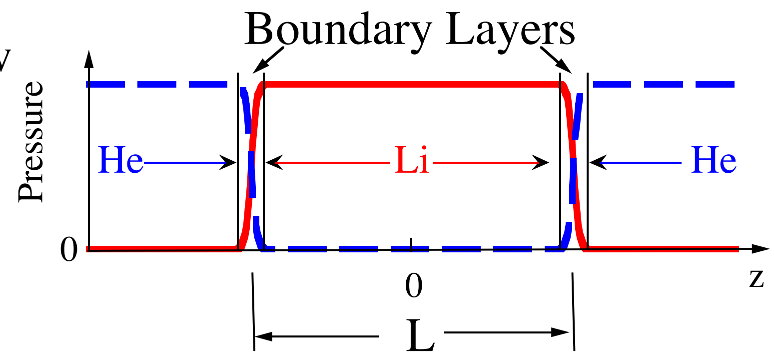
- Large energy spread after the plasma is an artifact of doing single bunch experiments
- Electrons have gained > 2.7 GeV over maximum incoming energy in 10cm
- Confirmation of predicted dramatic increase in gradient with move to short bunches
- First time a PWFA has gained more than 1 GeV
- Two orders of magnitude larger than previous beam-driven results
- Future experiments will accelerate a second "witness" bunch

M.J. Hogan et al. Phys. Rev. Lett. 95, 054802 (2005)

Plasma source

Plasma source starts with
metal vapor in a heat-pipe oven





Peak Field For A Gaussian Bunch:

$$E = 6GV/m \frac{N}{2x10^{10}} \frac{20\mu}{\sigma_r} \frac{100\mu}{\sigma_z}$$

Ionization Rate for Li:

$$W_{Li}\left[s^{-1}\right] \approx \frac{3.60x10^{21}}{E^{2.18}\left[GV/m\right]} \exp\left(\frac{-85.5.}{E\left[GV/m\right]}\right)$$

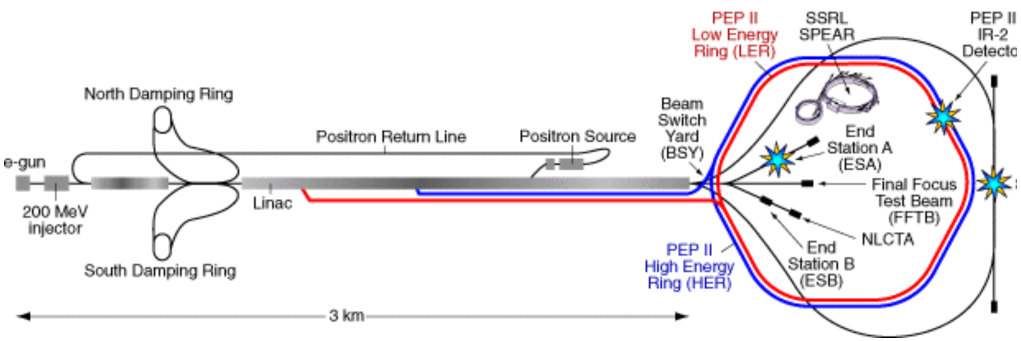
See D. Bruhwiler et al, Physics of Plasmas 2003

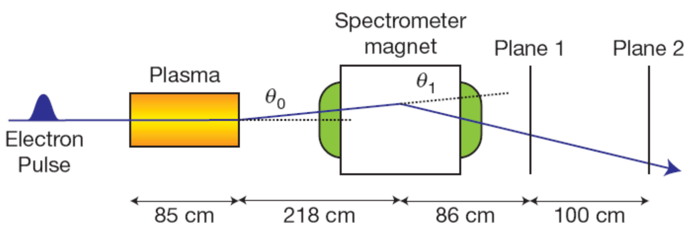
Space charge fields are high enough to field (tunnel) ionize - no laser!

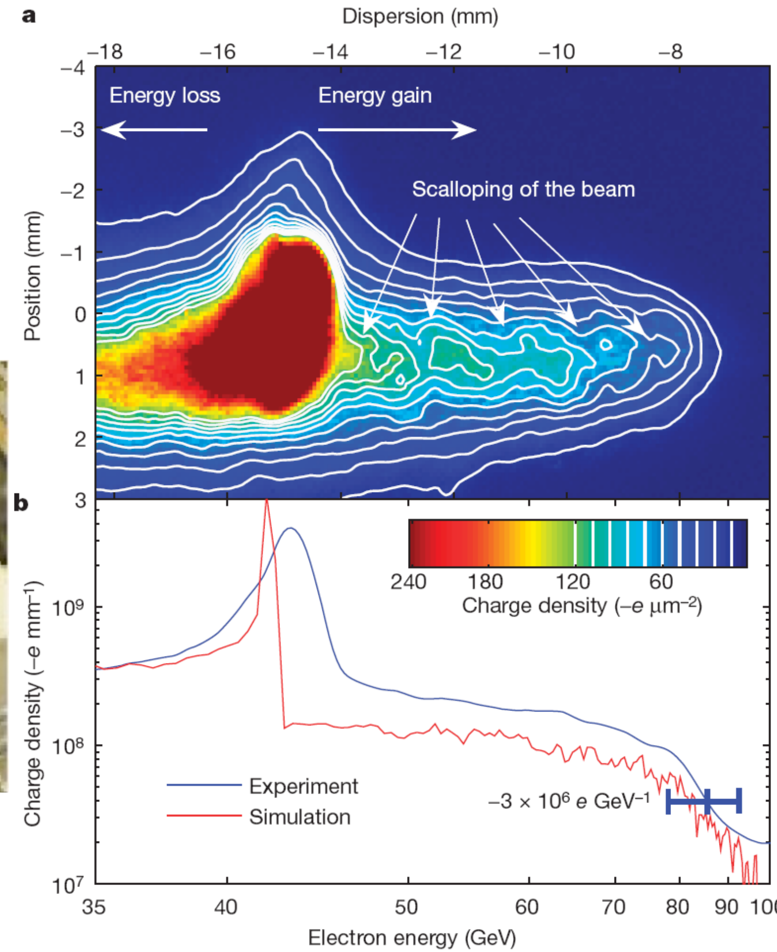
- No timing or alignment issues
- Plasma recombination not an issue

- However, can't just turn it off!
- Ablation of the head

Energy doubling experiment







Electron beam (beam energy 42 GeV, bunch length 50 fs, bunch charge 2.9 nC)

Plasma (heat Li oven, length 85 cm, density 2.7e17 cm-3)

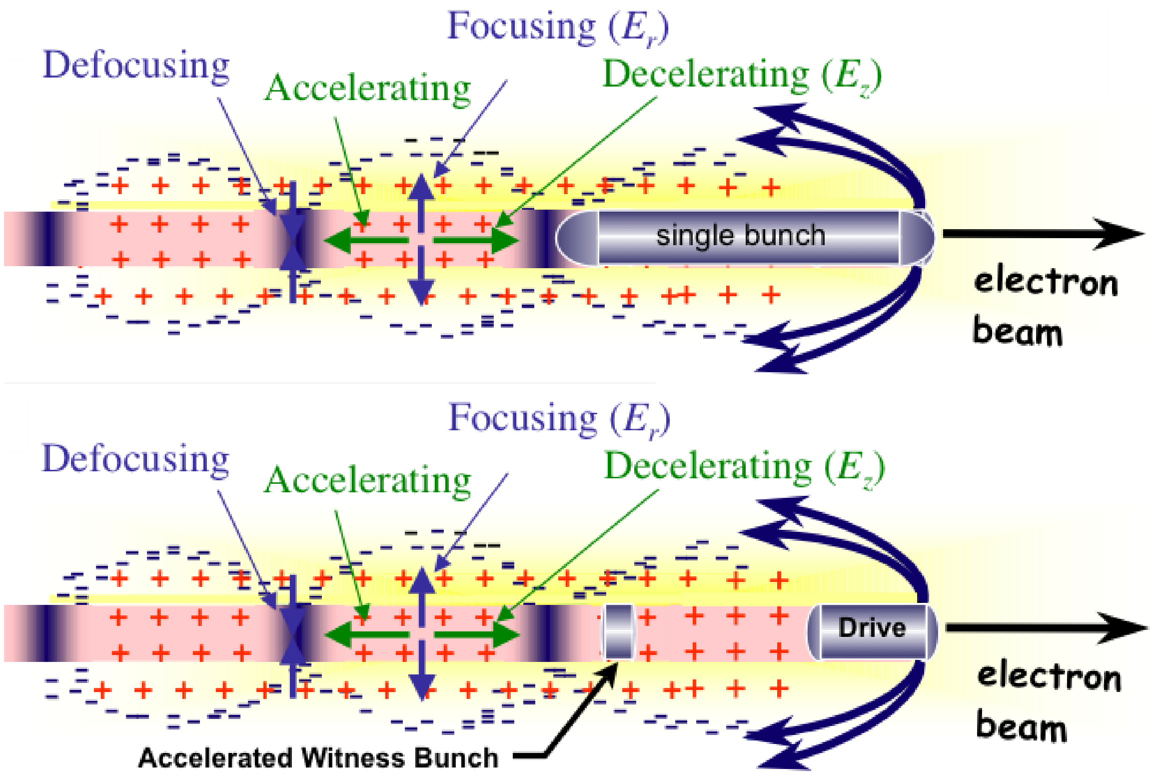
Max. energy gain

43 GeV (85 cm column) = 52 GeV/m !

Energy spectrum of the electrons in the 35-100 GeV range as observed in plane 2

Blumenfeld et al., Nature 445 (2007) 741

2nd generation PWFA experiment---FACET



The Facility for Advanced Accelerator Experimental Tests (FACET)

Physical mechanism of the Plasma Wakefield Accelerator for previous single bunch experiments in the FFTB (top) and the two bunch case proposed for FACET (bottom)

Layout of FACET

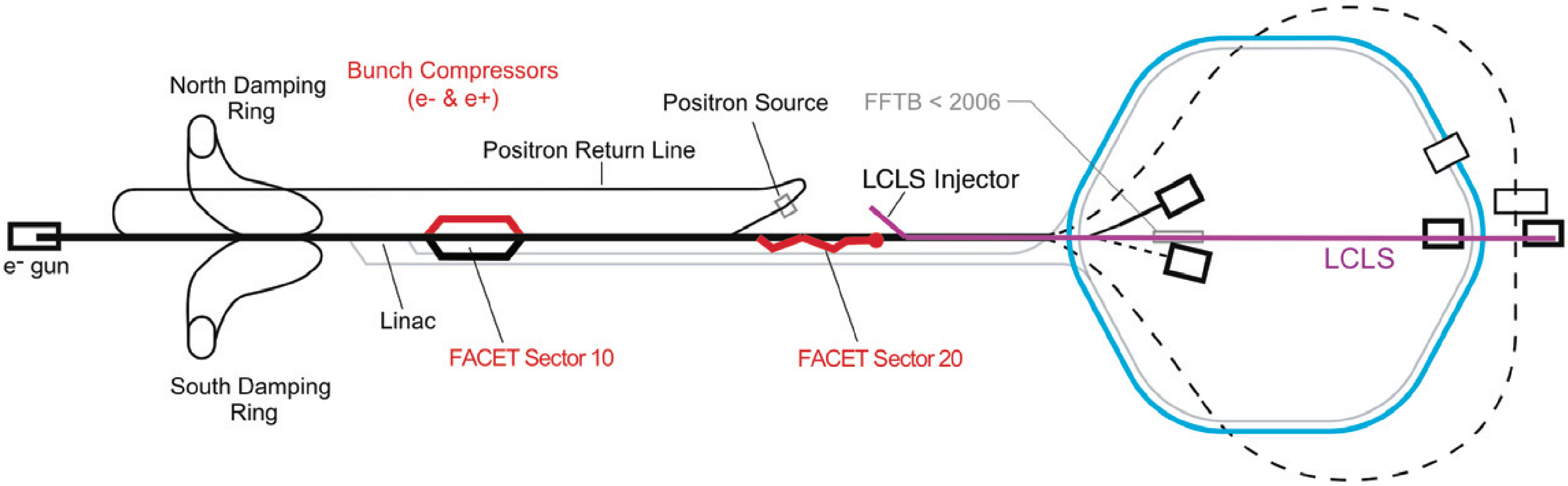


Figure 4. Schematic of the SLAC site with proposed FACET modifications to the linac systems marked in red. The positron bunch compressor is at Sector 10 and the experimental area is at Sector 20 along the linac. A shielding wall at the end of Sector 20 will allow access to the upstream portion of the linac during LCLS operations.

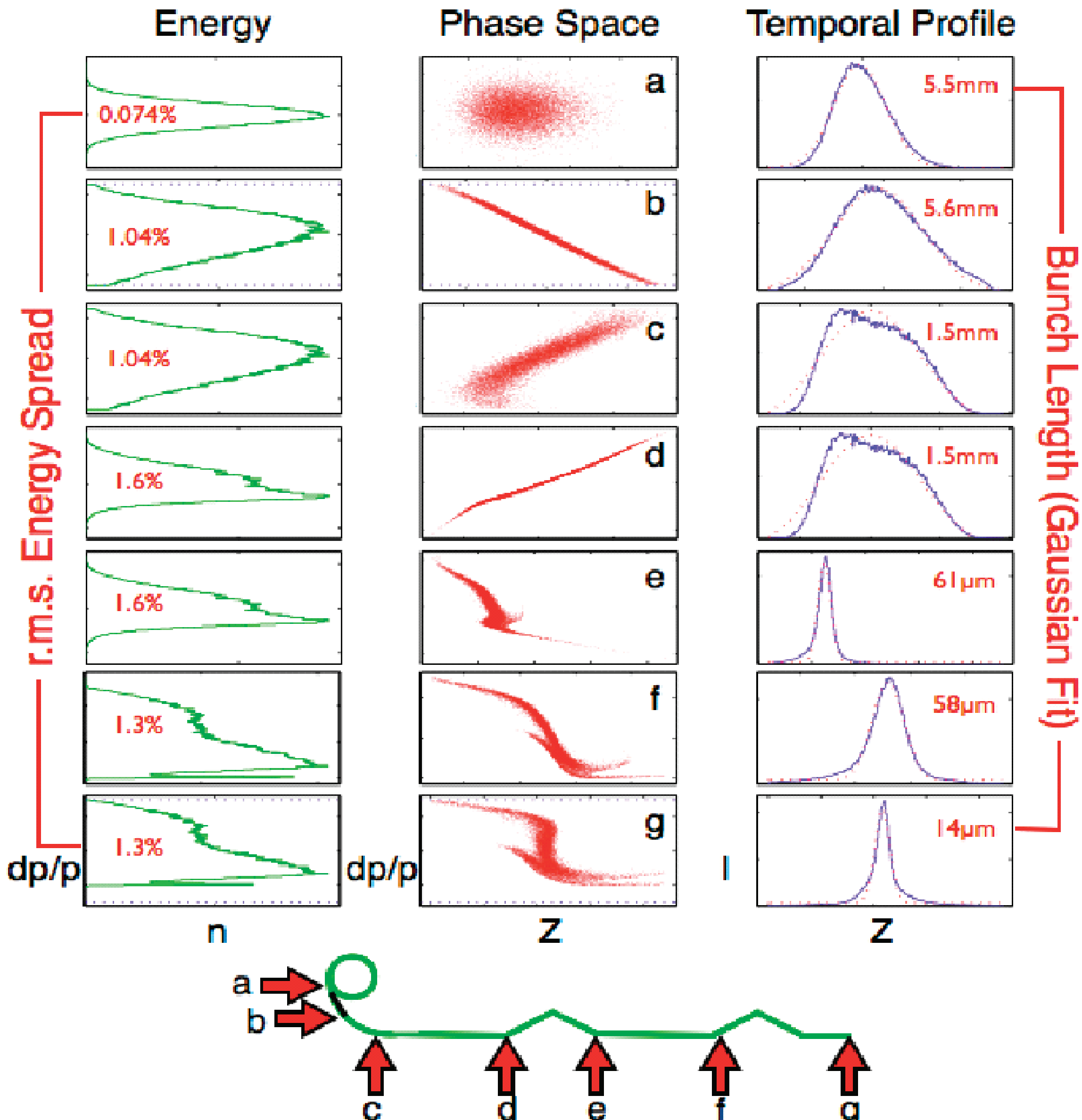
M. Hogan, et al., New Journal of Physics 12 (2010) 055030

FACET beam parameters

Energy	23 GeV with full compression and maximum peak current
Charge per pulse	3 nC per pulse with full compression
Pulse length at the focal point or interaction point IP (σ_z)	25 μm with 4% full-width (fw) momentum spread with full compression and 40 μm with 1.5% fw momentum spread with partial compression
Transverse spot size at IP ($\sigma_{x,y}$)	$<$10 μm nominal
Momentum spread	4% full-width with full compression (3% full-width at half-maximum (FWHM)) $<$0.5% full width without compression
Momentum dispersion at IP (η and η')	0
Drift space available for experimental apparatus	2 m from the last quadrupole to the focal point; approximately 23 m from the focal point to the beam dump
Transverse space available for experimental apparatus	3 m (width)$\times$3 m (height)

M. Hogan, et al., New Journal of Physics 12 (2010) 055030

FACET bunch compression



Simulation results

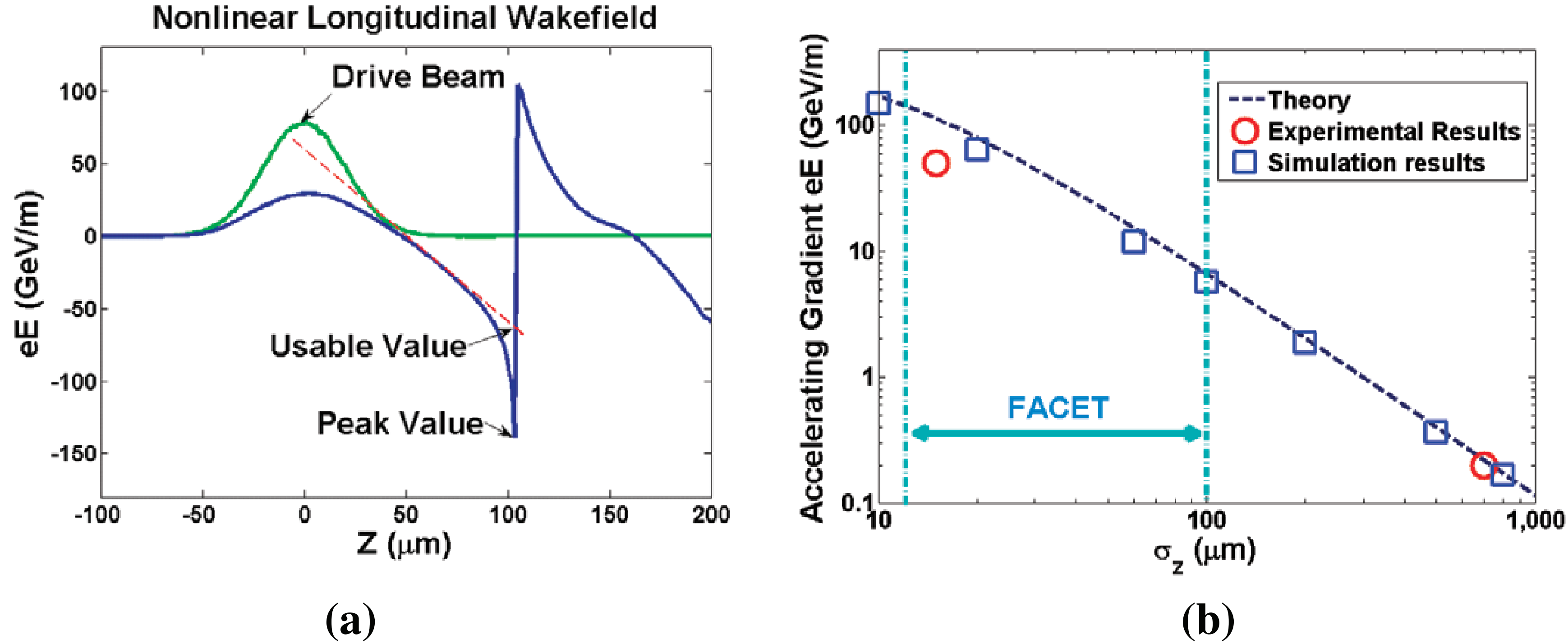
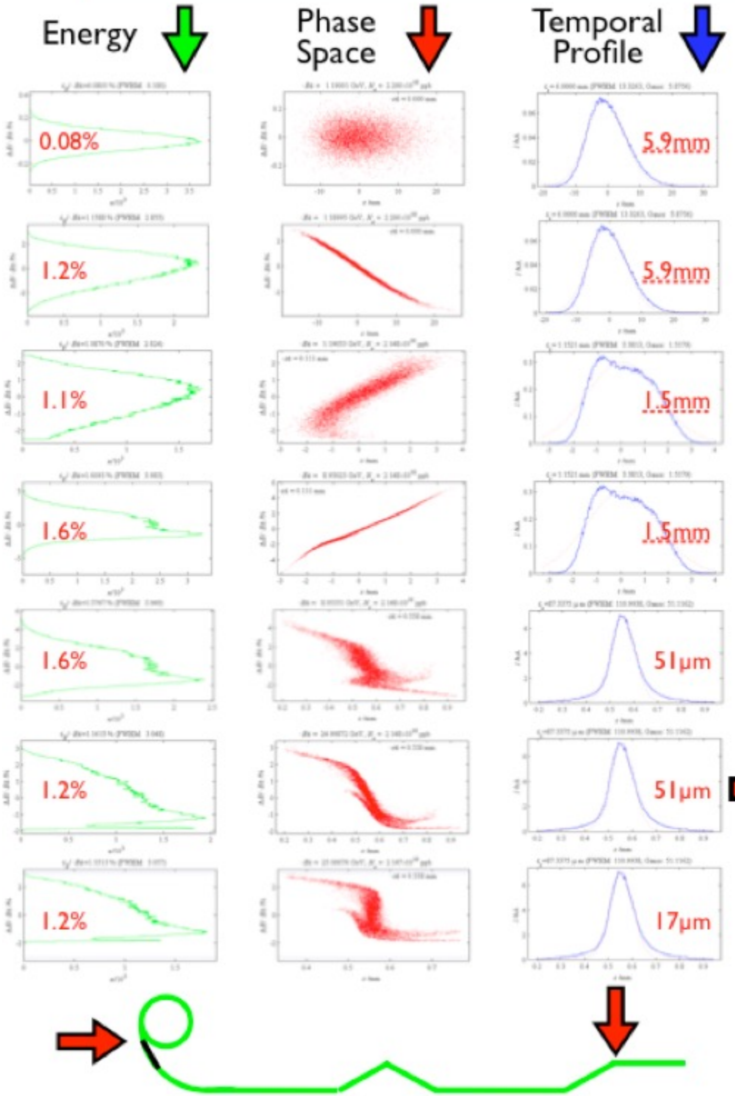


Figure 2. (a) Nonlinear longitudinal wakefield excited by the drive beam in a plasma. (b) Peak accelerating field versus drive electron bunch length for $N = 2 \times 10^{10}$ electrons for a fixed beam spot size of 5 μm. The density is varied such that the normalized bunch length is kept fixed at $k_p\sigma_z = \sqrt{2}$. As the bunch length is shortened, there is a transition from the linear to the nonlinear regime. The dashed line is the prediction from linear theory for narrow bunches (equation (1)). The squares are the results obtained from QuickPIC simulations. The circles are experimental data points. Note that in the experiments the bunch length is not exactly matched to $k_p\sigma_z = \sqrt{2}$. When the exact experimental parameters are simulated, the gradients are in agreement, e.g. see [8].

M. Hogan, et al., New Journal of Physics 12 (2010)055030

FACET

Generate Two Bunches by Selectively Collimating During Bunch Compression Process



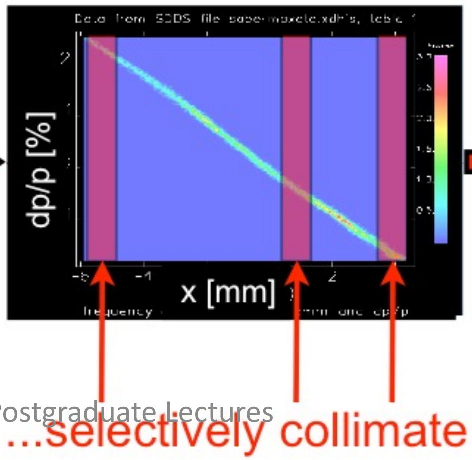
Exploit Position-Time Correlation on e- bunch to create separate drive and witness bunch

FR5RFP022 – Patric Muggli

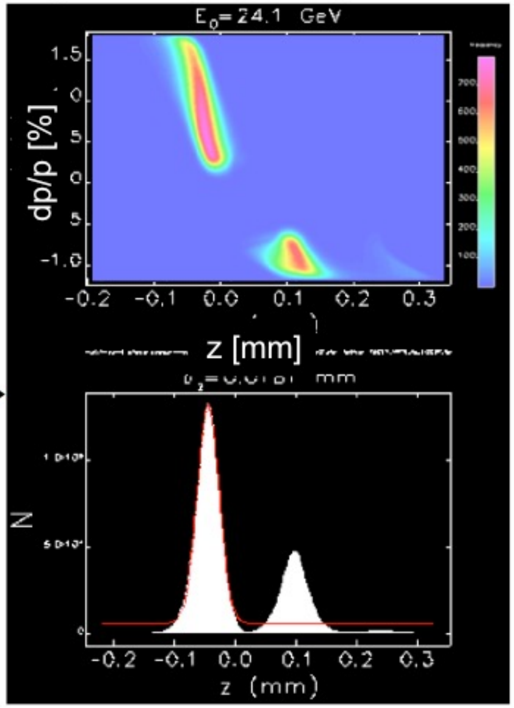
PAC09

Disperse the beam in energy

$$x \propto \Delta E/E \propto t$$



Adjust final compression

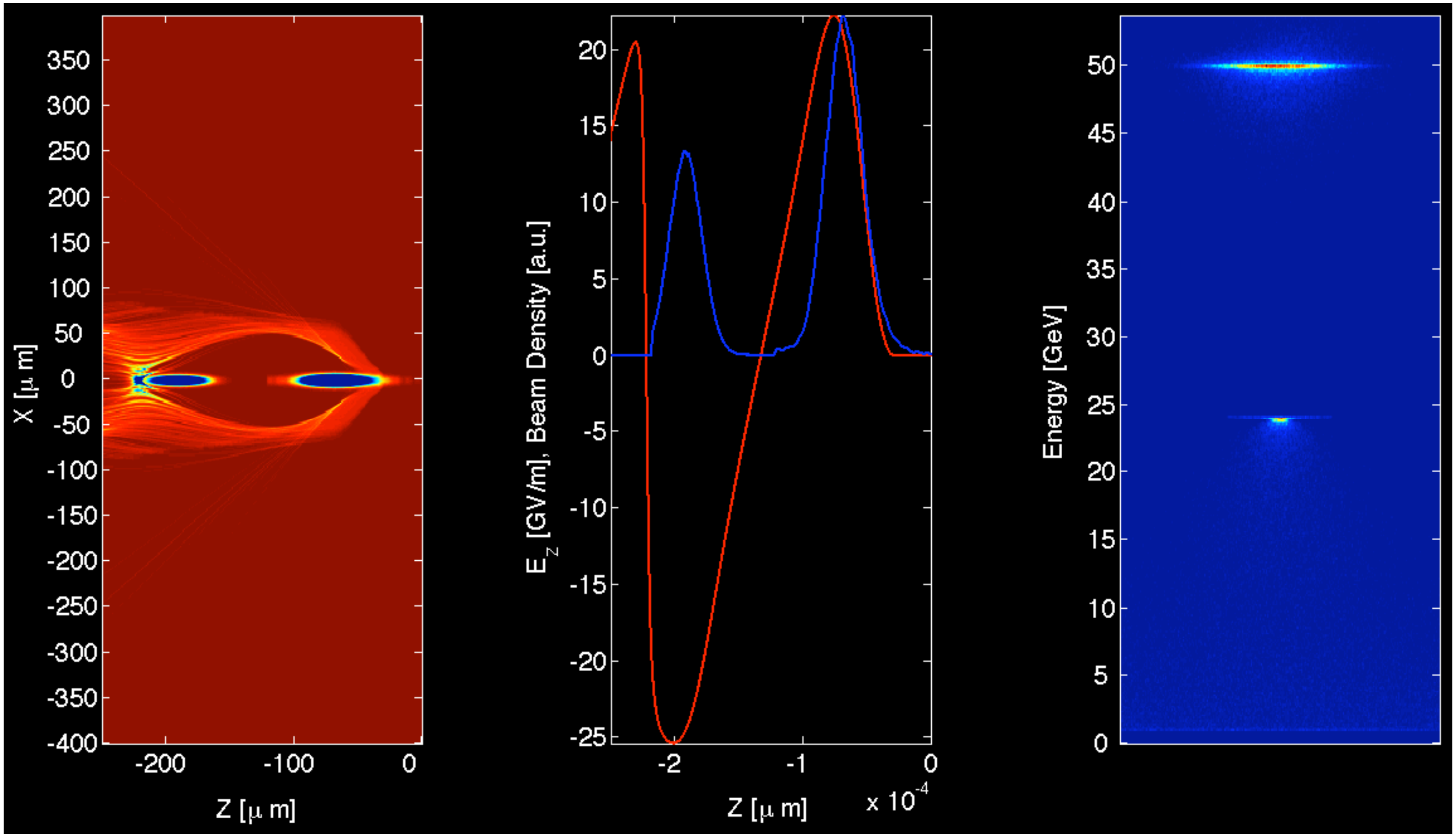


Two bunch acceleration at FACET

Double Energy of a 25GeV Beam in ~1m

WE6RFP097 – Chengkun Huang

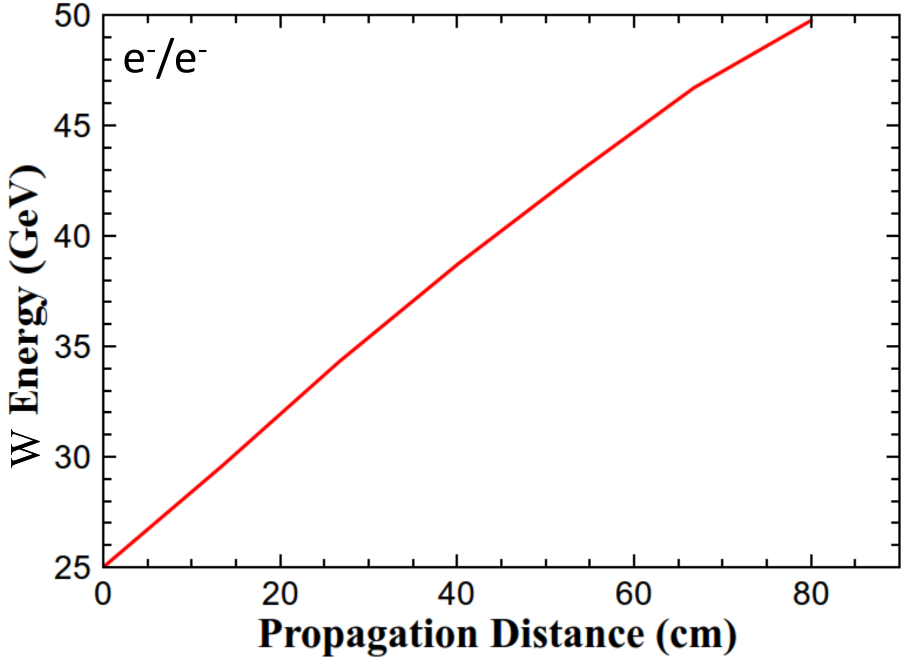
Drive beam to witness beam efficiency of ~30% with small dE/E

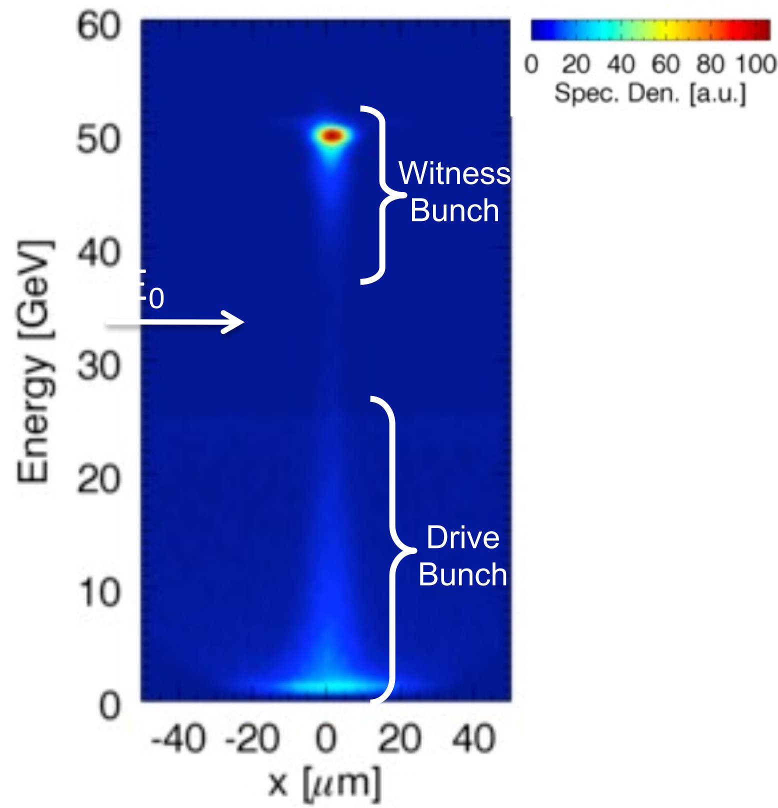


M. Hogan, PAC09

Bunch acceleration at FACET

QuickPIC simulation, D: σ_z=30μm, N=3x$10^{10}$$e^-$
W: σ_z=10μm, N=1x$10^{10}$$e^-$, σ_{r0}=3μm
Δz=115μm, n_p=$10^{17}$$cm^{-3}$, E_0=25GeV





Wake evolution "bends" energy gain

L_p=80cm, gain 25GeV, $\Delta E/E_0 \approx 3\%$,
BUNCH ACCELERATION!

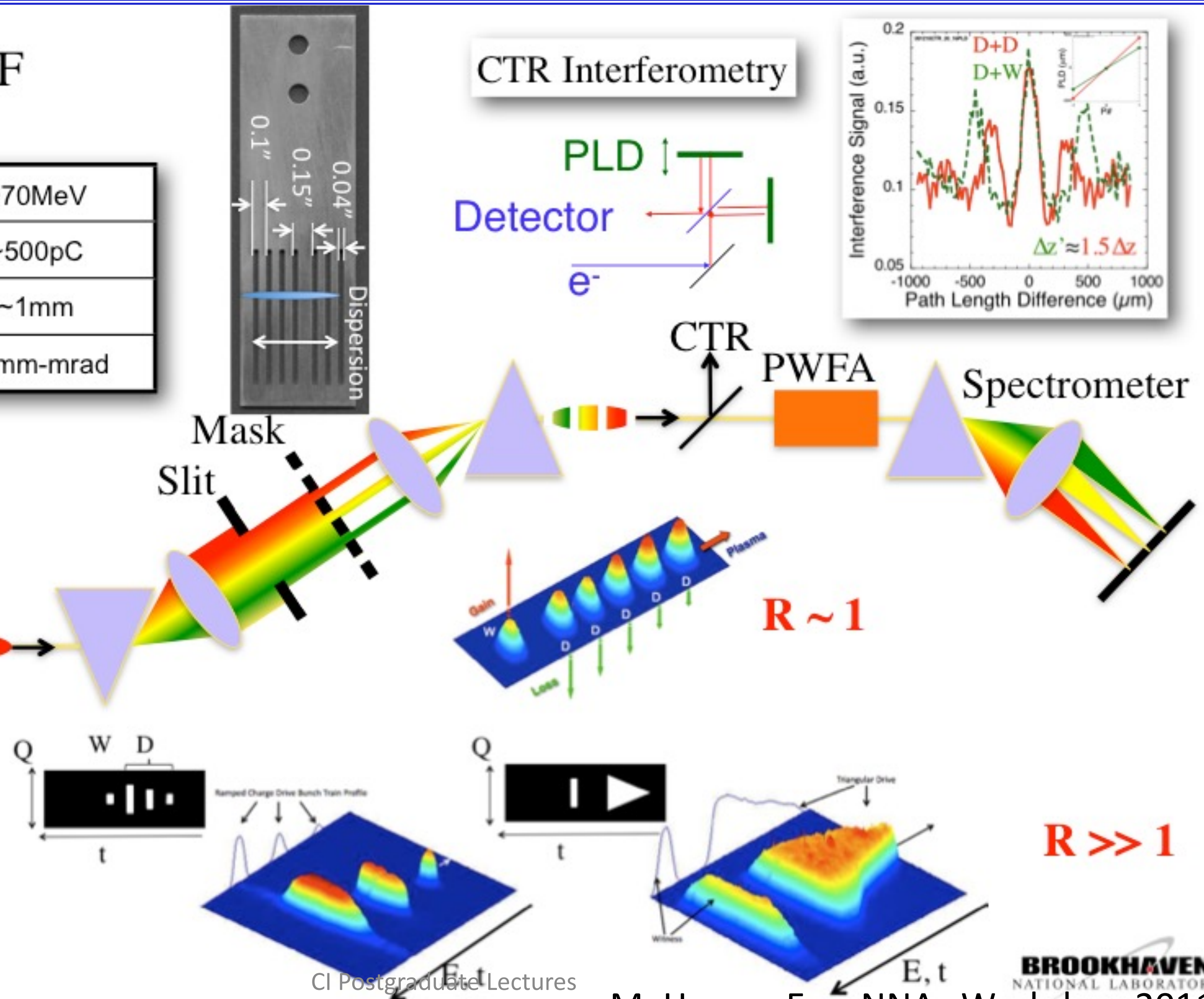
D to W energy transfer efficiency ≈30%
No bunch shaping, bunches carved out of a single SLAC bunch

Hogan, New J. Phys. 12, 055030 (2010)

Multibunch experiment @ BNL

BNL ATF

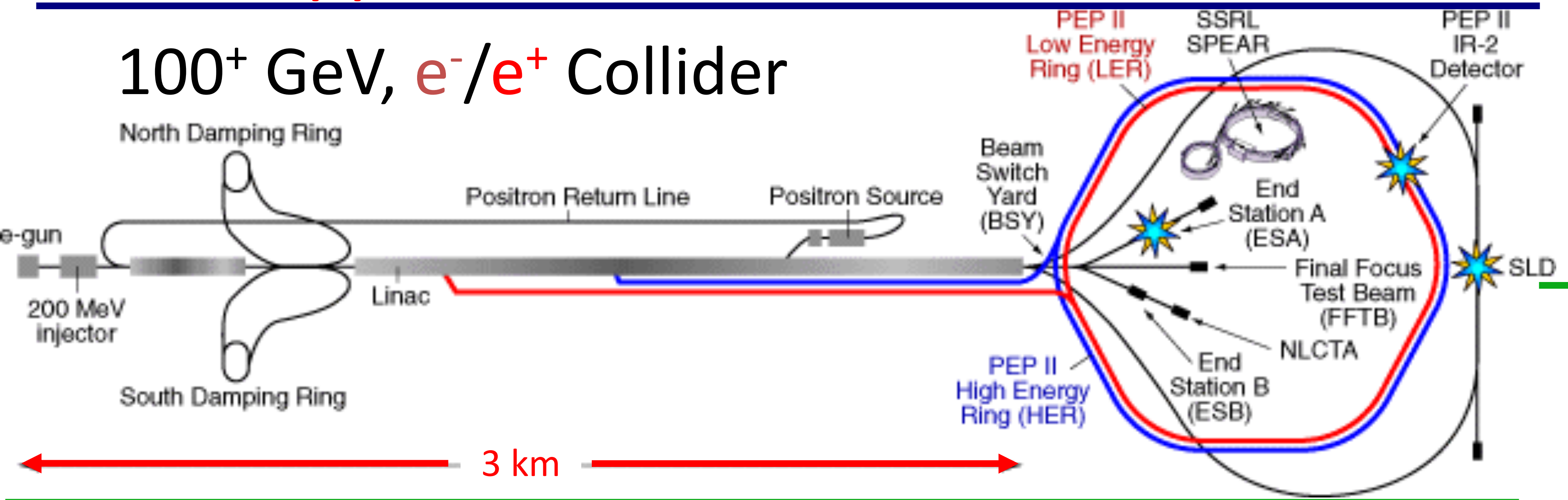
Energy	~70MeV
Charge/bunch	~500pC
Bunch Length	~1mm
Norm. Emittance	~1mm-mrad

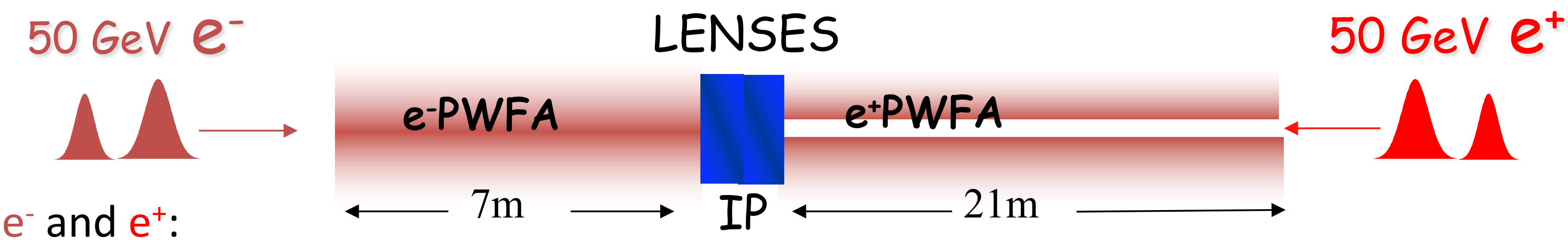


M. Hogan, EuroNNAc Workshop 2011

Applications---afterburner scheme

100^{+} GeV, e^{-}/e^{+} Collider





e^{-} and e^{+}:

Driver bunches: σ_z=63 μm, σ_r=5 μm, $N=3\times10^{10}$ e^{-}/e^{+}, 50 -> 0 GeV

Witness bunches: σ_z=32 μm, σ_r=5 μm, $N=1\times10^{10}$ e^{-}/e^{+}, 50 -> 100^{+} GeV

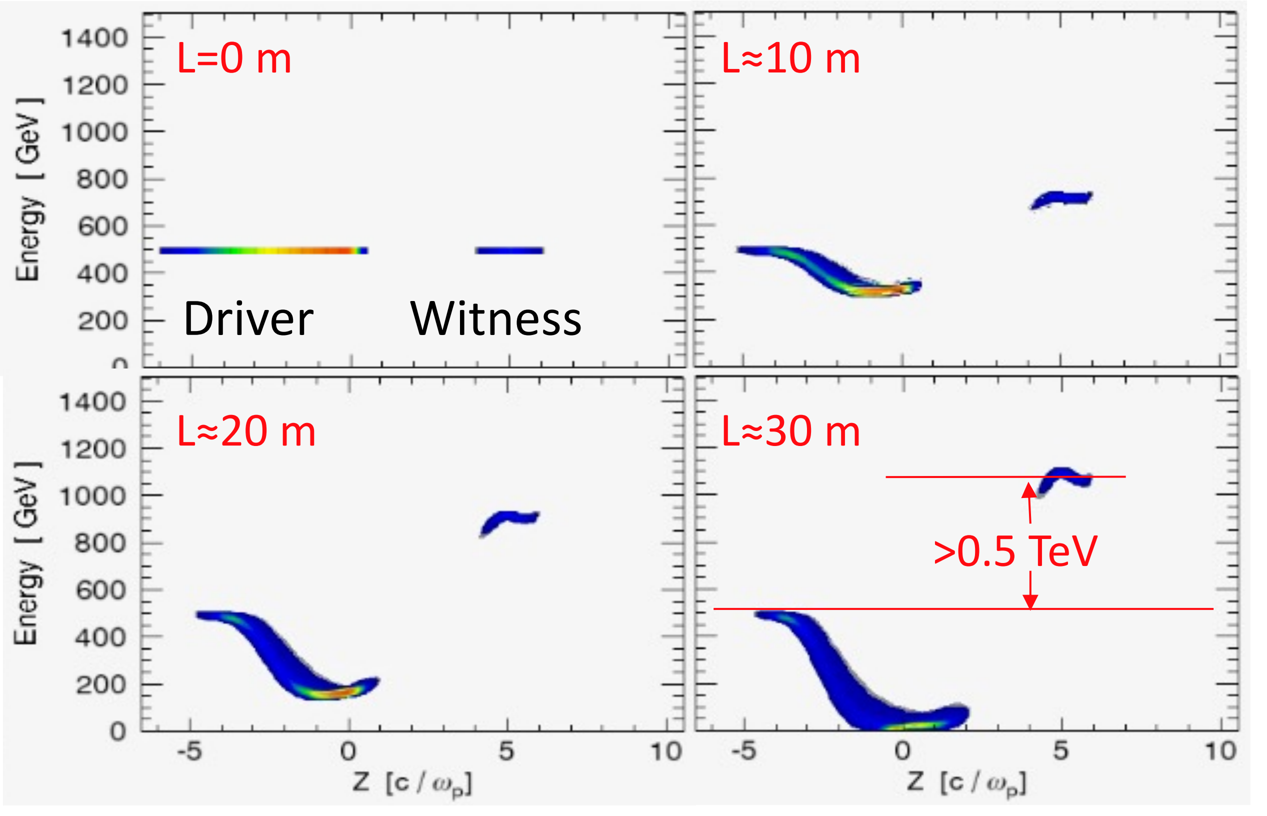
Delay: d=200 μm

Plasma: $n_e=1.8\times10^{16}$ cm^{-3}, L=7, 21 m

Accelerating gradient: 8, 3 GV/m, $\Delta E/E$ <10%

S. Lee *et al.*, PRST-AB (2001)

Simulation results



Simulations by C. Huang UCLA

$N_D=3\times10^{10}$, $N_w=10^{10}$,

$\varepsilon_{Nx}=\varepsilon_{Ny}=2230\times10^{-6}$ m-rad, $\sigma_x=\sigma_y=15$ µm , (beam matched to the plasma)

$\sigma_{zD}=145$ µm , $\sigma_{zW}=10$ µm, $\Delta z=100$ µm

$N_e=5.66\times10^{16}$ cm^{-3}, $L_p=30$ m, pre-ionized, Gradient>17 GeV/m

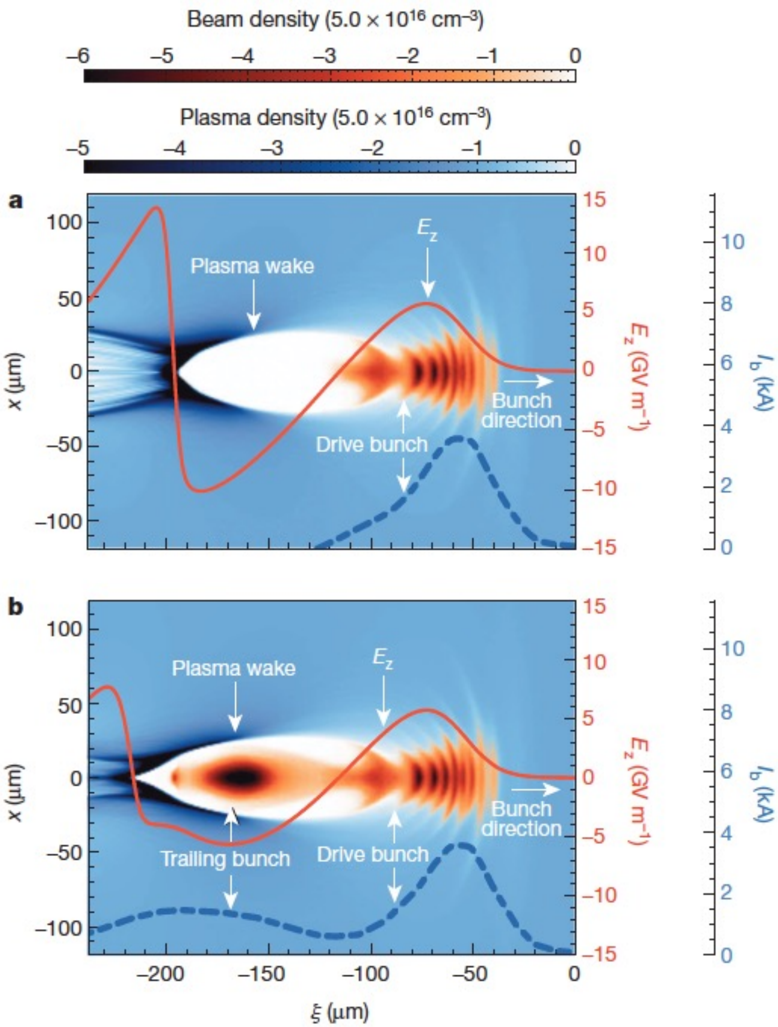
Doubling the energy of 500 GeV bunch possible! ,… in only ≈30 m! (simulation)

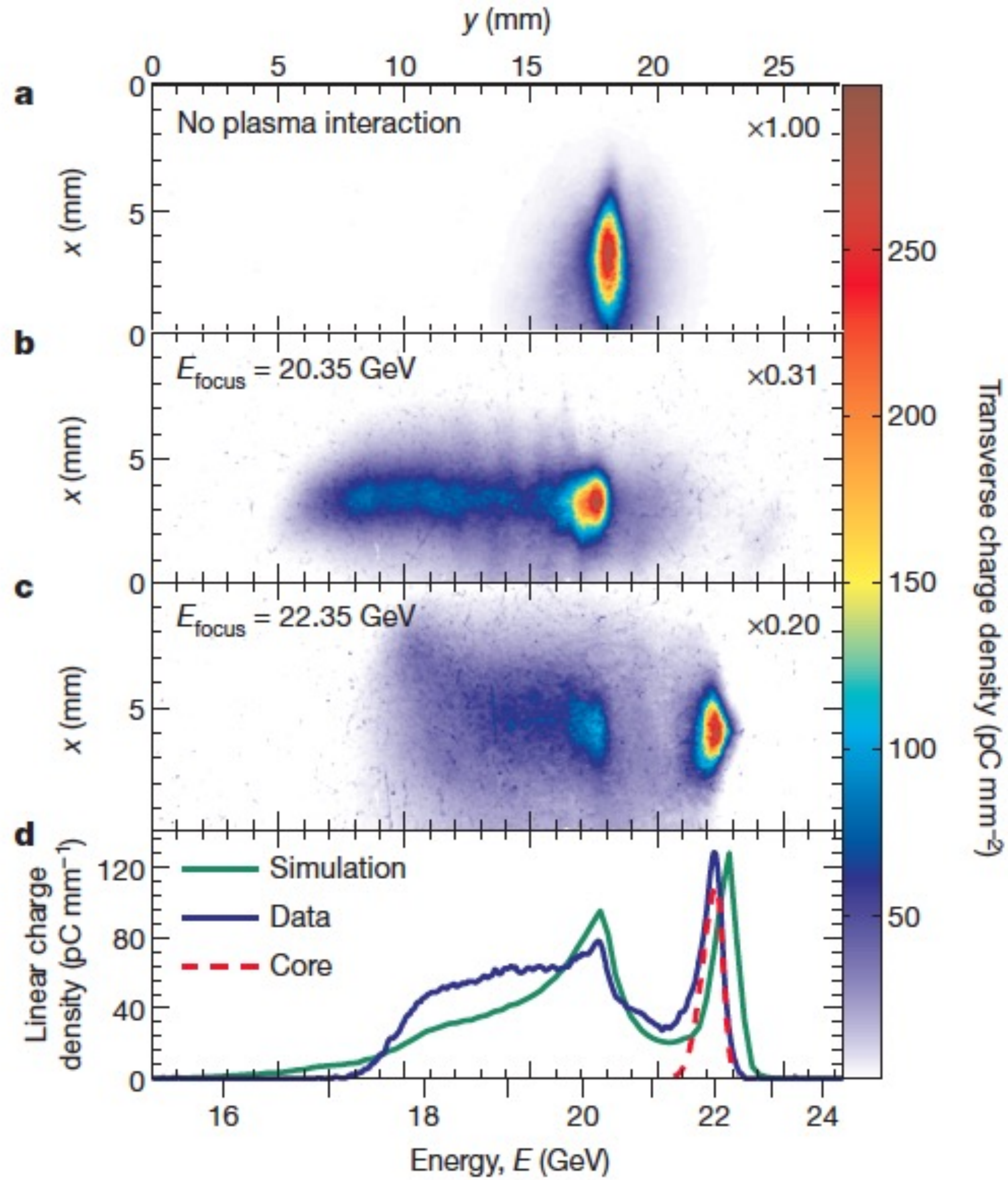
LETTER
doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

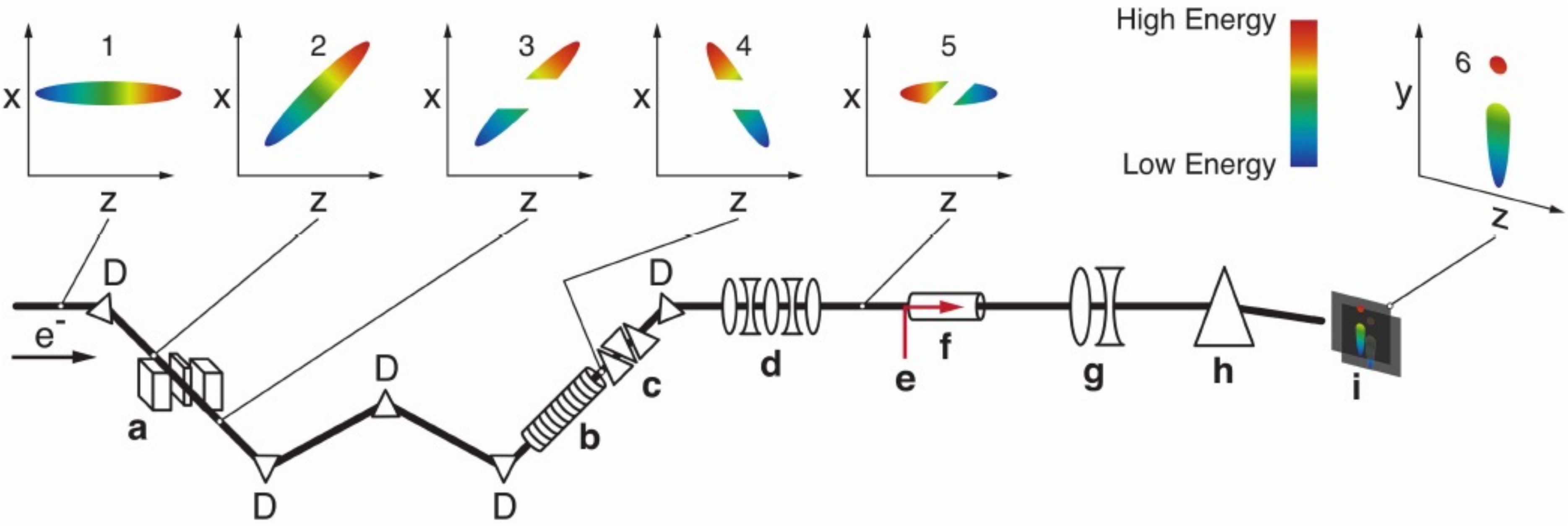
M. Litos[1], E. Adli[1,2], W. An[3], C. I. Clarke[1], C. E. Clayton[4], S. Corde[1], J. P. Delahaye[1], R. J. England[1], A. S. Fisher[1], J. Frederico[1], S. Gessner[1], S. Z. Green[1], M. J. Hogan[1], C. Joshi[4], W. Lu[5], K. A. Marsh[4], W. B. Mori[3], P. Muggli[6], N. Vafaei-Najafabadi[4], D. Walz[1], G. White[1], Z. Wu[1], V. Yakimenko[1] & G. Yocky[1]

Accelerating gradient 4.4 GeV/m
Final energy spread of training bunch:0.7%


Beam density (5.0 × 10^16 cm^-3)
Plasma density (5.0 × 10^16 cm^-3)
a
Plasma wake
E_z
Drive bunch
Bunch direction
b
Plasma wake
E_z
Trailing bunch
Drive bunch
Bunch direction
x (µm)
E_z (GV m^-1)
I_b (kA)
ξ (µm)

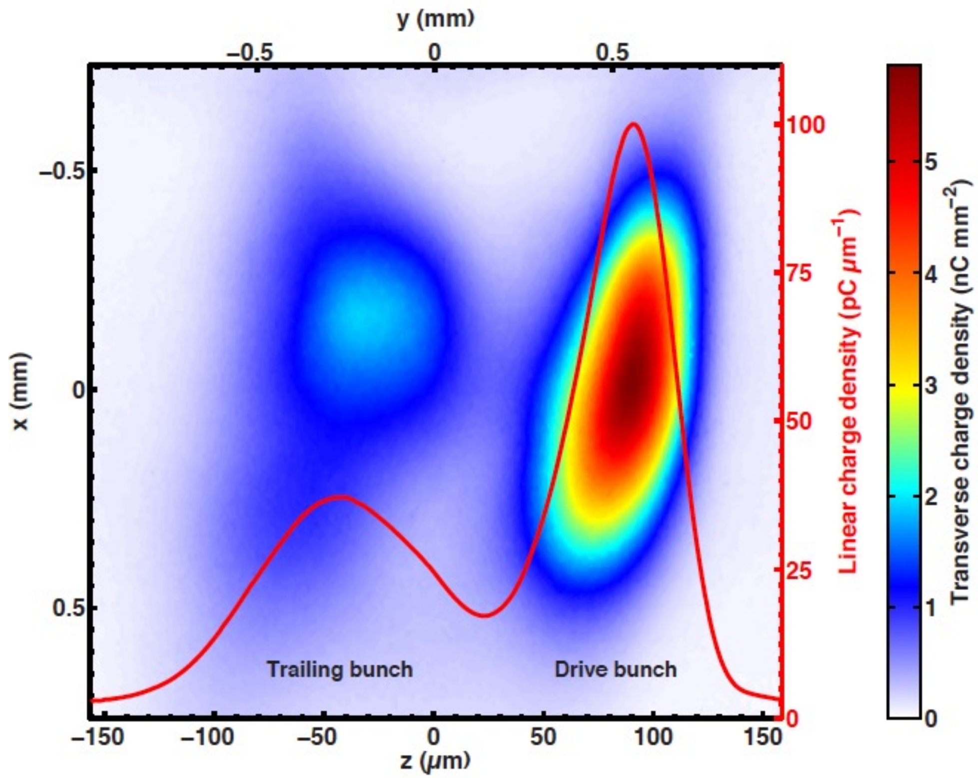

y (mm)
a
No plasma interaction
×1.00
b
E_focus = 20.35 GeV
×0.31
c
E_focus = 22.35 GeV
×0.20
d
Simulation
Data
Core
x (mm)
Linear charge density (pC mm^-1)
Energy, E (GeV)
Transverse charge density (pC mm^-2)

Two bunches at FACET



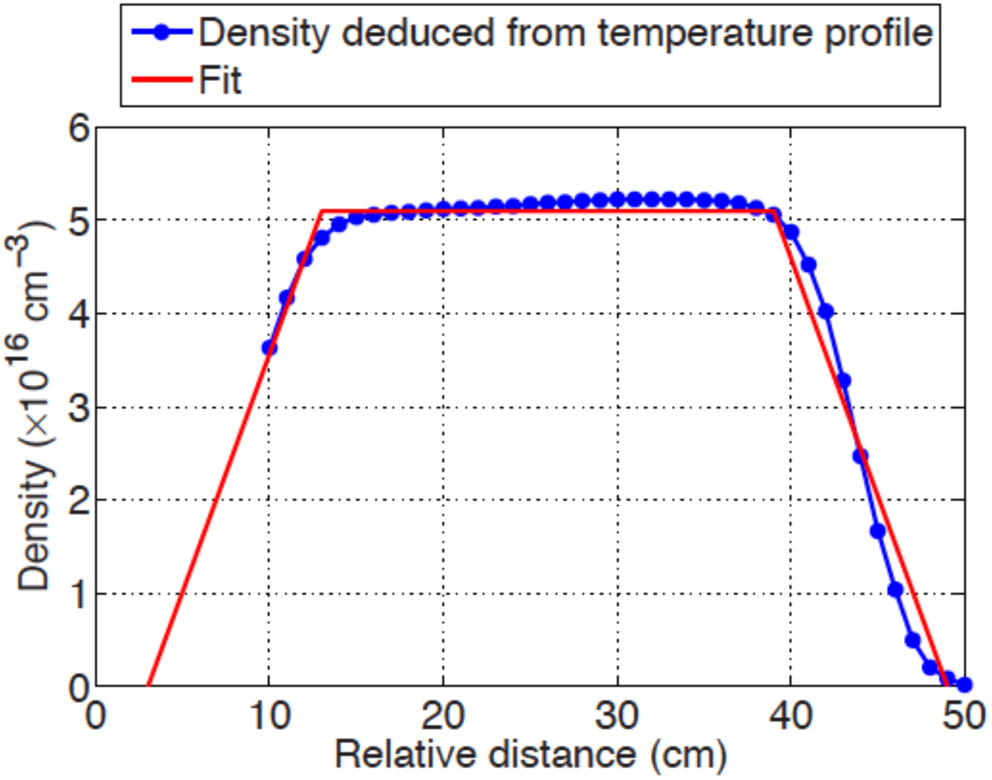
Extended Data Figure 1 | FACET experimental area schematic. Electron beam line features: a, beam notching device, b, transverse deflecting structure, c, initial spectrometer, d, final-focus quadrupole magnets, e, lithium plasma ionization laser, f, lithium vapour column, g, spectrometer imaging quadrupole magnets, h, spectrometer dipole magnet, and i, Cherenkov and phosphor screens. Bend dipole magnets in the 'W'-shaped chicane are each labelled 'D'. The arrow beneath the e^- symbol indicates the electron beam's direction of motion (left to right).

Longitudinal profile of two bunch



Extended Data Figure 2 | Measured longitudinal profile of two-bunch beam. Image of a typical two-bunch beam streaked onto a profile monitor screen by the transverse deflecting radio-frequency structure (Extended Data Fig. 1b). The drive bunch appears on the right-hand side. Overlaid on the image is the projected longitudinal profile (red line). The left (*x*) and top (*y*) axes show the transverse dimensions of the streaked beam on the profile monitor screen, while the colour axis indicates the charge density of the transverse profile. The bottom (*z*) axis shows the streaked dimension (*y*) with the appropriate scaling factor applied to give the corresponding longitudinal coordinate. The right axis shows the linear charge density corresponding to the projected longitudinal profile.

Plasma density profile



Extended Data Figure 3 | Lithium vapour column density profile. The profile of the neutral vapour pressure density of the lithium vapour column deduced from the measured temperature profile (temperature versus relative distance of insertion of a thermocouple probe) along the heat pipe oven is shown as the blue line. The simple fit used to describe the density profile in our model is shown as the red line.

Positrons in hollow plasma

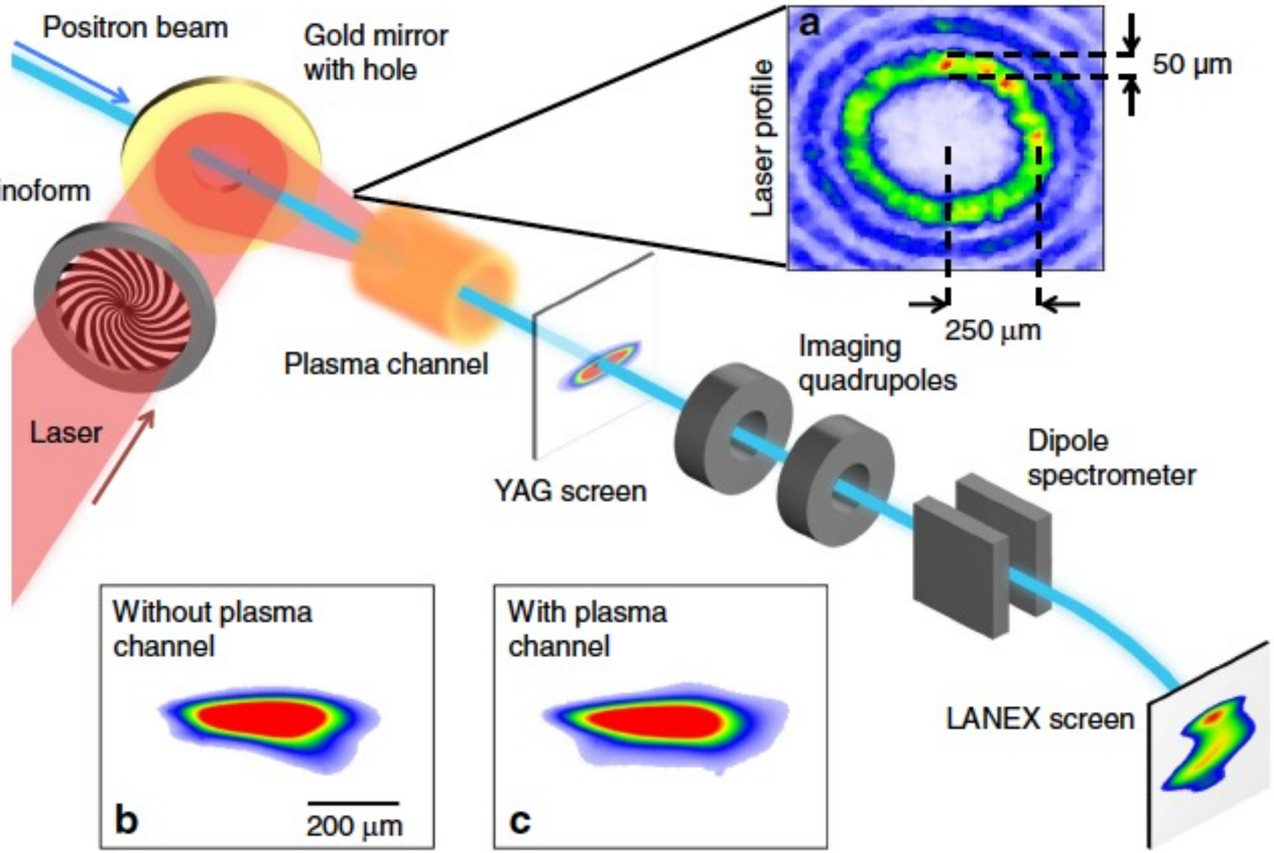


Figure 1 | Experimental layout. The laser passes through the kinoform and is coupled to the beam axis by a gold mirror with a small central hole. Inset (**a**) shows the laser profile upstream of the lithium oven. A scintillating YAG screen 1.95 m downstream of plasma is used to measure the positron beam profile. Inset (**b**) shows the positron beam spatial profile as imaged on the YAG screen with the laser off and no plasma present. Inset (**c**) shows the beam profile with the laser on when the positron beam propagates through the plasma channel. The two profiles are similar, indicating that there are no net focusing forces because of the plasma channel. A scintillating Lanex screen downstream of the dipole measures the beam energy spectrum.

Gessner et al., Nat. Commun. 7: 11785 (2016)

Positrons in hollow plasma

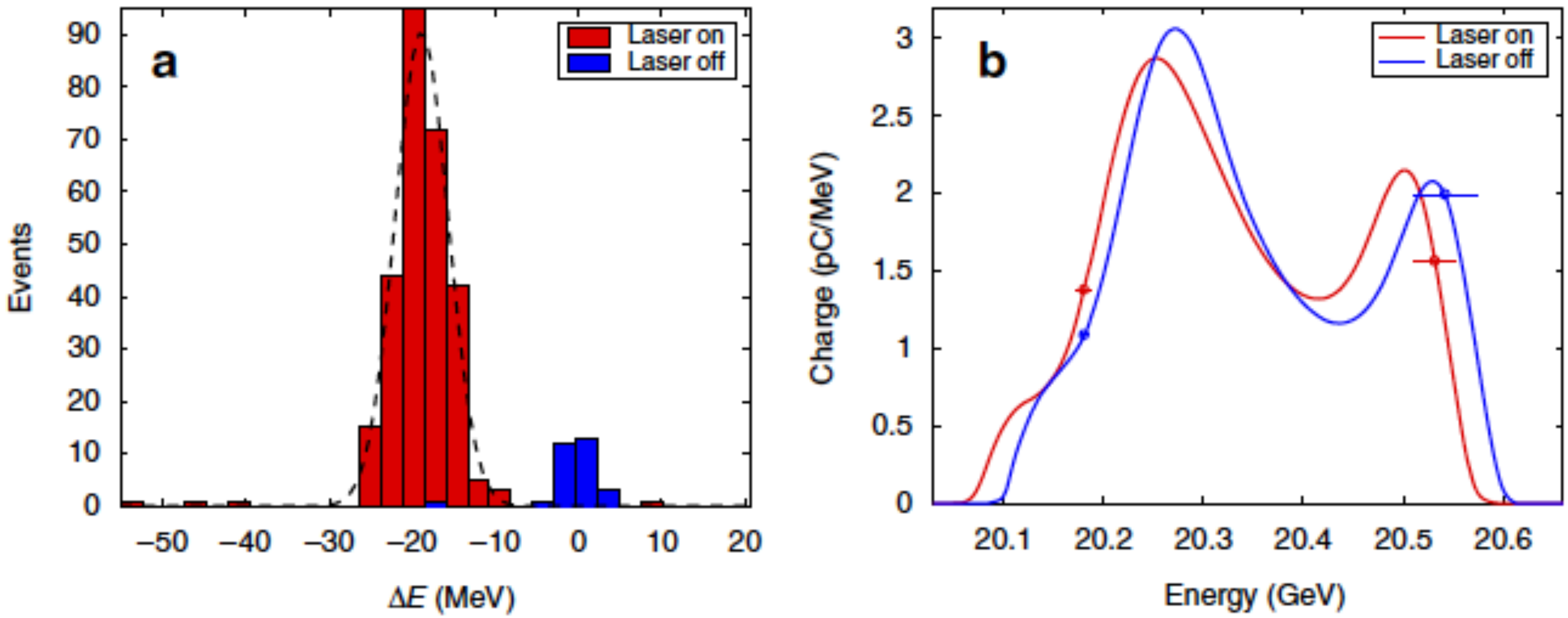
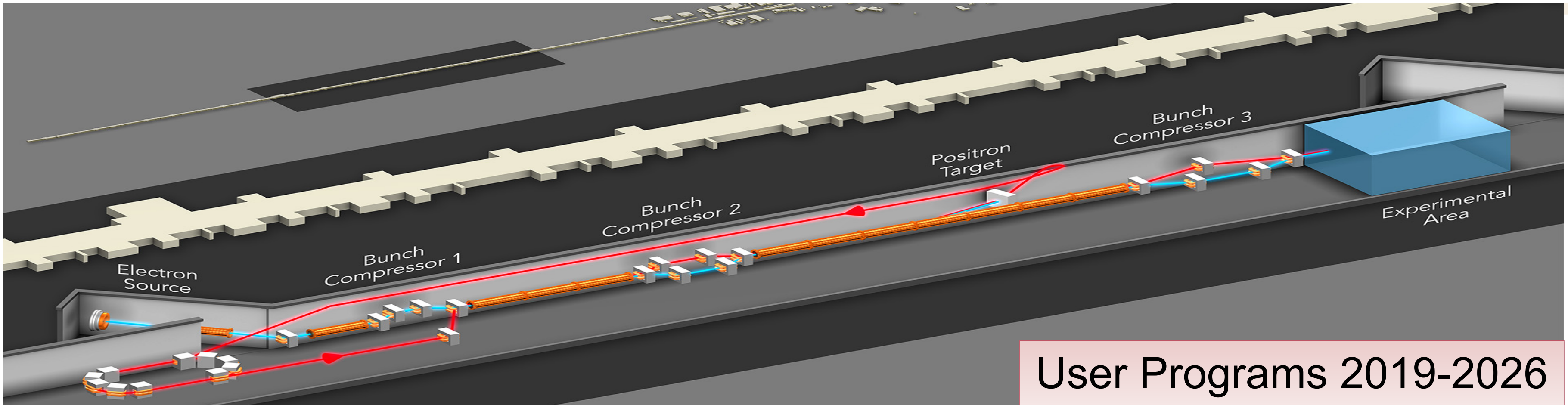


Figure 4 | Energy loss measurements. (**a**) A histogram of the beam energy loss for all 315 shots corrected for incoming energy jitter (see the Methods for details). The plasma channel is present when the laser is on (red). When the laser is off (blue) the beam is propagating through neutral lithium vapour. We fit the laser-on data to a gaussian (black dashed curve) with mean energy loss 18.9 MeV and width 3.2 MeV. (**b**) A comparison of the average beam energy spectra for laser on and laser off shots. The s.d. error bars represent the statistical uncertainty in the upper and lower regions of the spectrum due to averaging (see Supplementary Fig. 4 for details). The error has been multiplied by a factor of five so that it is visible in the plot.

Deceleration field: 220 MV/m!

Gessner et al., Nat. Commun. 7: 11785 (2016)

FACET II



User Programs 2019-2026

Timeline:

- Nov. 2013, FACET-II proposal, Comparative review
- CD-0 Aug. 2015
- CD-1 Oct. 2015
- CD-2/3A Sep. 2016
- CD-2/3 Apr. 2018
- CD-4 2021
- Experimental program (2019-2026)

Key R&D Goals:

- High brightness beam generation, preservation, characterization
- e^+ acceleration in e^- driven wakes
- Staging challenges with witness injector
- Generation of high flux gamma radiation

Three stages:

- Photoinjector (e- beam only)
- e+ damping ring (e+ or e- beams)
- “sailboat” chicane (e+ and e- beams)

On schedule to start commissioning in 2019

V. Yakimenko, Workshop on Beam Acceleration in Crystals, June 24-25, 2019

FACET II parameters

TABLE II. Common machine parameters for all following FACET-II configurations.

Parameter	e^-	e^+
Injected energy @ sector 11, E_i, MeV	335	
Pulse rep. rate f_{rep}, Hz	1–30	1–5
Emittance into sector 20, $\gamma\epsilon_{x,y}$, μm-rad	3–4	13

TABLE III. Two-bunch mode parameters. β^* refers to the optical beta function magnitude at the interaction waist in sector 20.

Parameter (units)	Drive pulse	Witness pulse
Final beam energy E_f (GeV)	10.0	
Bunch charge Q_b (nC)	1.3	0.6
Peak current I_{pk} (kA)	30	15
β^* (cm)	5–50	
Bunch spacing (μm)	150	
Final rms energy spread, dE/E (%)	0.8	0.3

TABLE IV. Single-bunch, high Q mode parameters.

Parameter (units)	Value
Final beam energy E_f (GeV)	10.0
Bunch charge Q_b (nC)	2.0
Peak current I_{pk} (kA)	50–200
β^* (cm)	5–100
Final rms energy spread, dE/E (%)	1.2

TABLE V. Single-bunch, high-quality mode parameters.

Parameter (units)	Value
Final beam energy E_f (GeV)	13.0
Bunch charge Q_b (nC)	2.0
rms bunch length σ_z (mm)	0.1
β^* (m)	10
Final rms energy spread, dE/E (%)	0.05

V. Yakimenko et al., Phys. Rev. Accel. Beams 22, 101301 (2019)

Latest FACET-II results

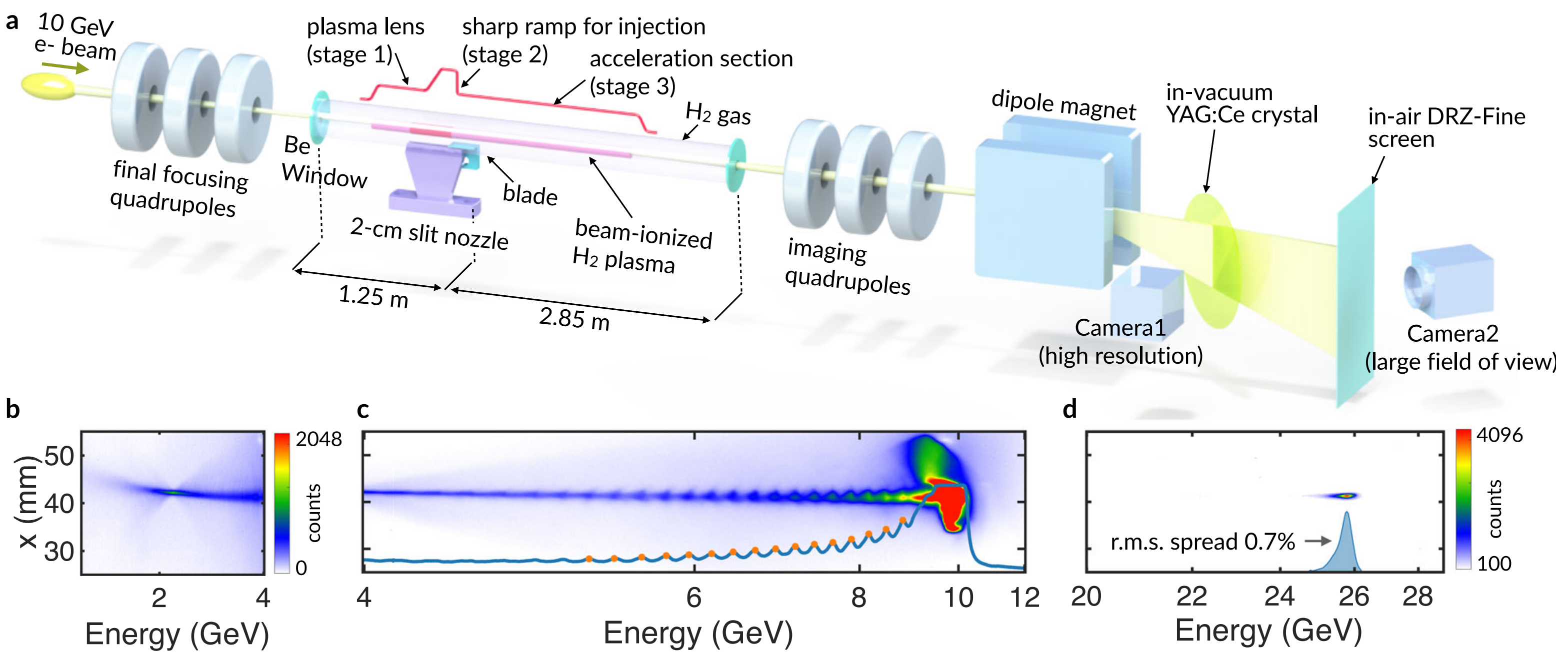
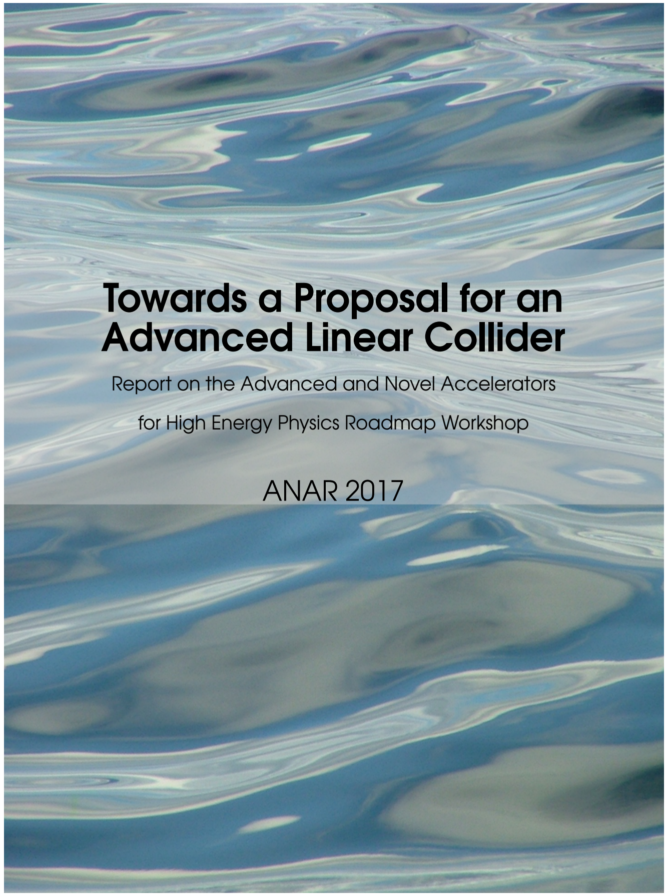


Fig. 1 | Experimental setup, drive-beam depletion, and self-injection in a meter-scale plasma wakefield. a A 10 GeV electron drive bunch is focused by quadrupole magnets into a four-meter-long hydrogen-filled region confined by beryllium windows with sub-mm apertures. A two-centimeter-long supersonic gas jet with a movable blade creates a sharp density downramp. As the drive bunch approaches its vacuum waist, its electric field ionizes the hydrogen to form a plasma column (magenta cylinder) and excite a wake. The plasma prior to the gas jet acts as a plasma lens to further focus the drive bunch. Plasma electrons injected at the downramp are accelerated in the wake formed in the subsequent acceleration section. **b** Energy spectrum showing drive beam depletion to ~1 GeV (at 5.3 Torr, 1.7×10^{17} cm^{-3}, gas jet off), indicating significant energy transfer to the wake. The spectrometer is focused at 2 GeV. **c** Energy-dependent betatron oscillations of the drive bunch envelope (at 2.4 Torr, 7.8×10^{16} cm^{-3}, gas jet off) enable determination of the effective plasma length[12]. **d** A distinct injected bunch accelerated to 26 GeV with 0.7% r.m.s. energy spread appears only when the gas jet is activated (at 4 Torr, 1.3×10^{17} cm^{-3}, gas jet on). For this shot, the spectrometer quadrupoles focus at 15 GeV.

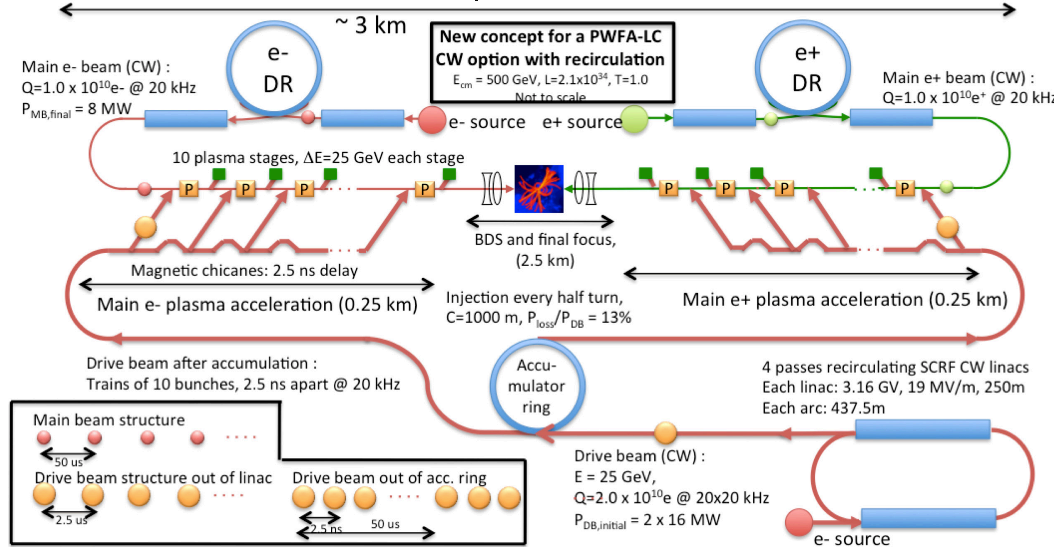
C. Zhang et al., Nat. Commun. 16: 10719 (2025).

Applications---PWFA based $e^{+} e^{-}$ collider



http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Advanced_Accelerator_Development_Strategy_Report.pdf

A Conceptual PWFA-LC



E_{cm} = 500 GeV, L=2.1x10^{34}, T=1.0

C=1000 m, P_{loss}/P_{DB} = 13%

Q=2.0 x 10^{10}e @ 20x20 kHz

$P_{DB,initial}$ = 2 x 16 MW

E. Adli et al., ArXiv 1308.1145

J. P. Delahaye et al., Proceedings of IPAC2014

Key elements for the next decade:

- Beam quality – focus on emittance preservation at progressively smaller values
- Positrons – use FACET-II positron beam identify optimum regime for positron PWFA
- Injection – ultra-high brightness sources, staging studies with external injectors

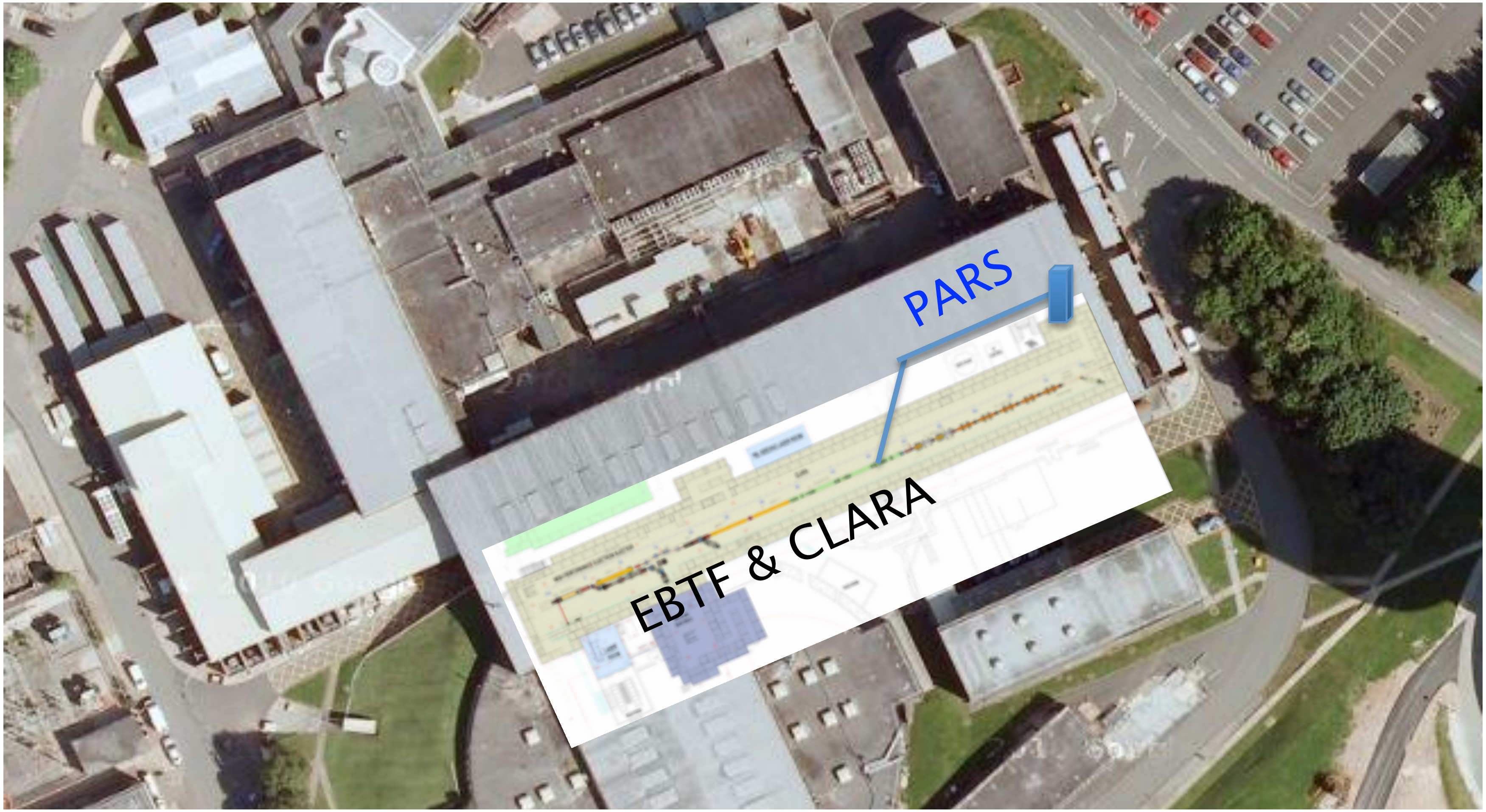
(M. J. Hogan)

PWFA at CLARA/FEBE

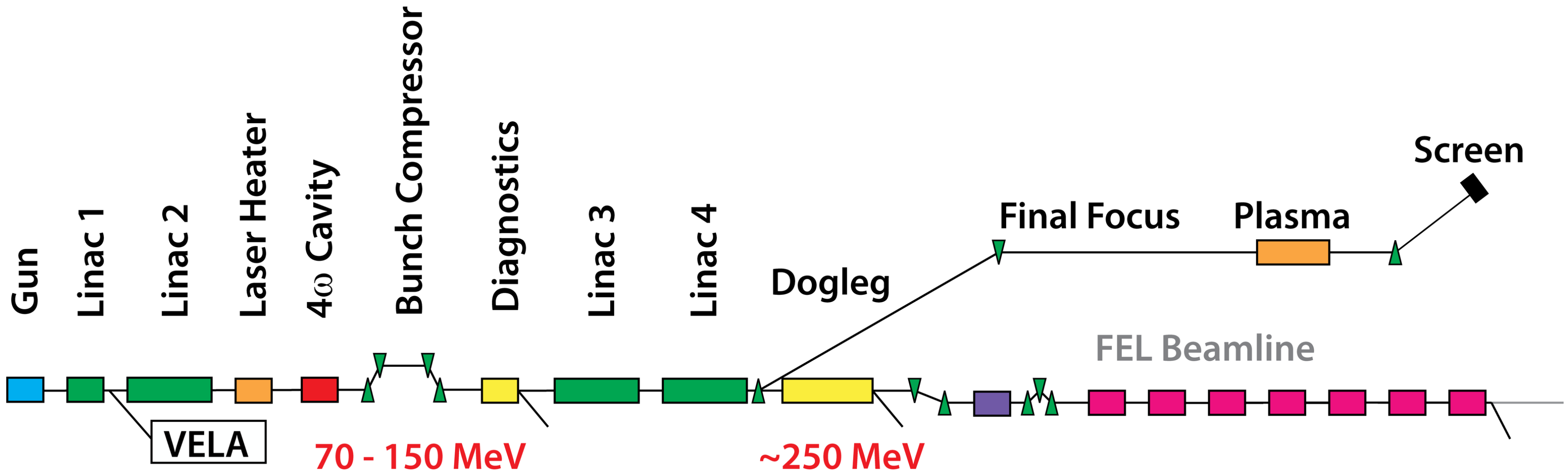
- **Why it makes sense**
  - Free space available close to CLARA beam line
  - Unique beam properties (low emittance, high charge, relativistic, ultrashort)
  - Diverse beam operation modes
  - Well developed beam diagnostic equipment for VELA and CLARA (deflecting cavities, longitudinal bunch length measurement, etc.)
  - FEBE 100 TW laser will be available in 2025/26

- **Possible contributions to advanced accelerator community**
  - Two-bunch experiment for energy doubling of CLARA beam
  - High transformer ratio (laser shaping of the bunch density profile, hard-edge bunch for an efficient wakefield excitation)
  - Ultrashort pulse x-rays production from betatron radiation
  - Plasma lens focusing effect
  - Hybrid wakefield acceleration
  - External injection in LWFA
  - Inverse Compton scattering based radiation source
  - Many others…

Plasma acceleration research station (PARS->FEBE)



FEBE beam line at CLARA



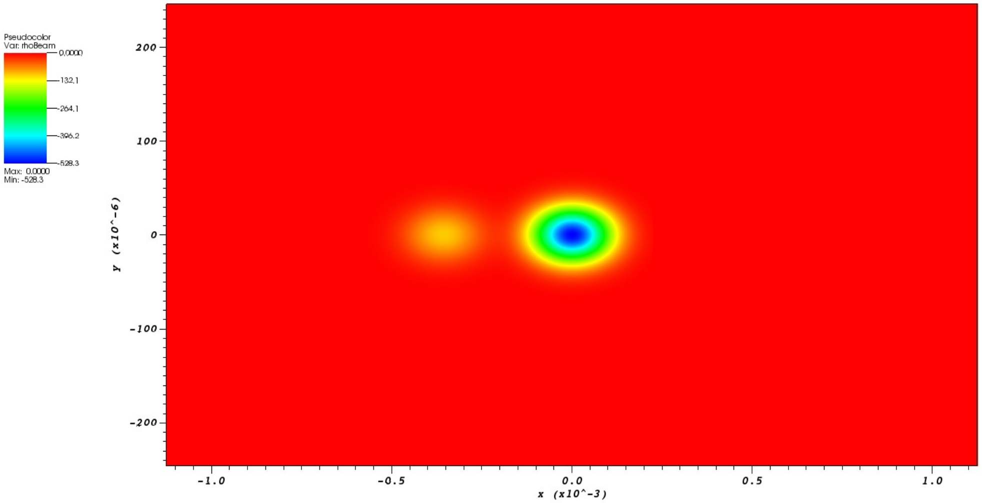
CLARA beam parameters

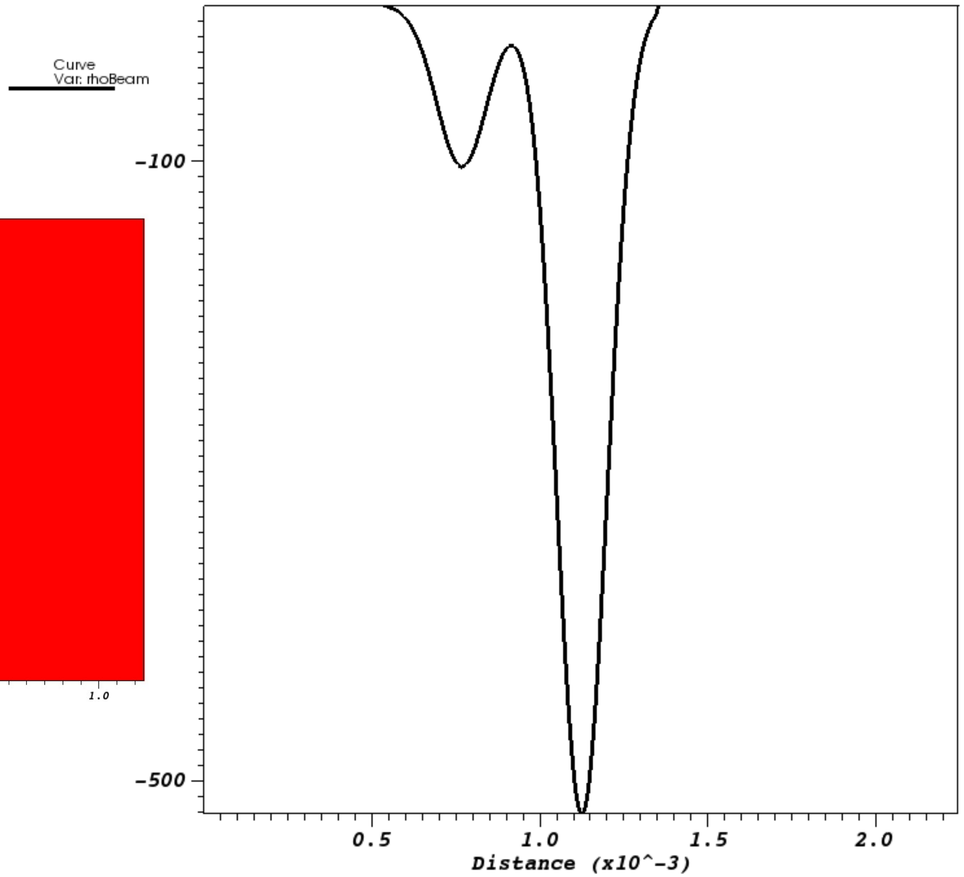
	Operating Modes			
Parameter	**Seeding**	**SASE**	**Ultra-short**	**Multibunch**
Max Energy (MeV)	250	250	250	250
Macropulse Rep Rate (Hz)	1–100	1–100	1–100	1–100
Bunches/macropulse	1	1	1	16
Bunch Charge (pC)	250	250	20–100	25
Peak Current (A)	125–400	400	$\sim$1000	25
Bunch length (fs)	850–250 (flat-top)	250 (rms)	<25 (rms)	300 (rms)
Norm. Emittance (mm-mrad)	≤ 1	≤ 1	≤ 1	≤ 1
rms Energy Spread (keV)	25	100	150	100
Radiator Period (mm)	27	27	27	27

Table 3.1: Main parameters for CLARA operating modes.

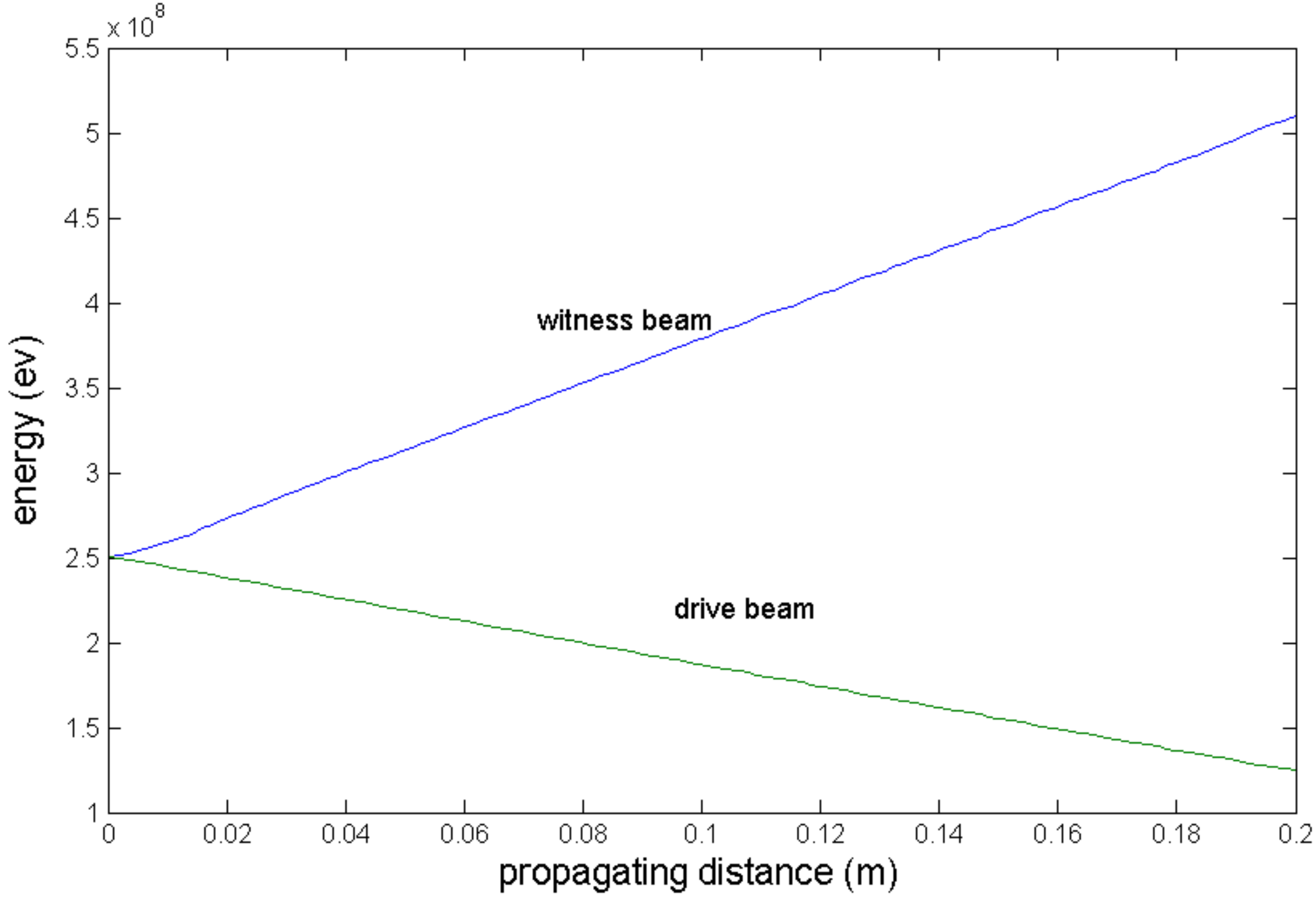
CLARA CDR, July 2013

Two-bunch acceleration

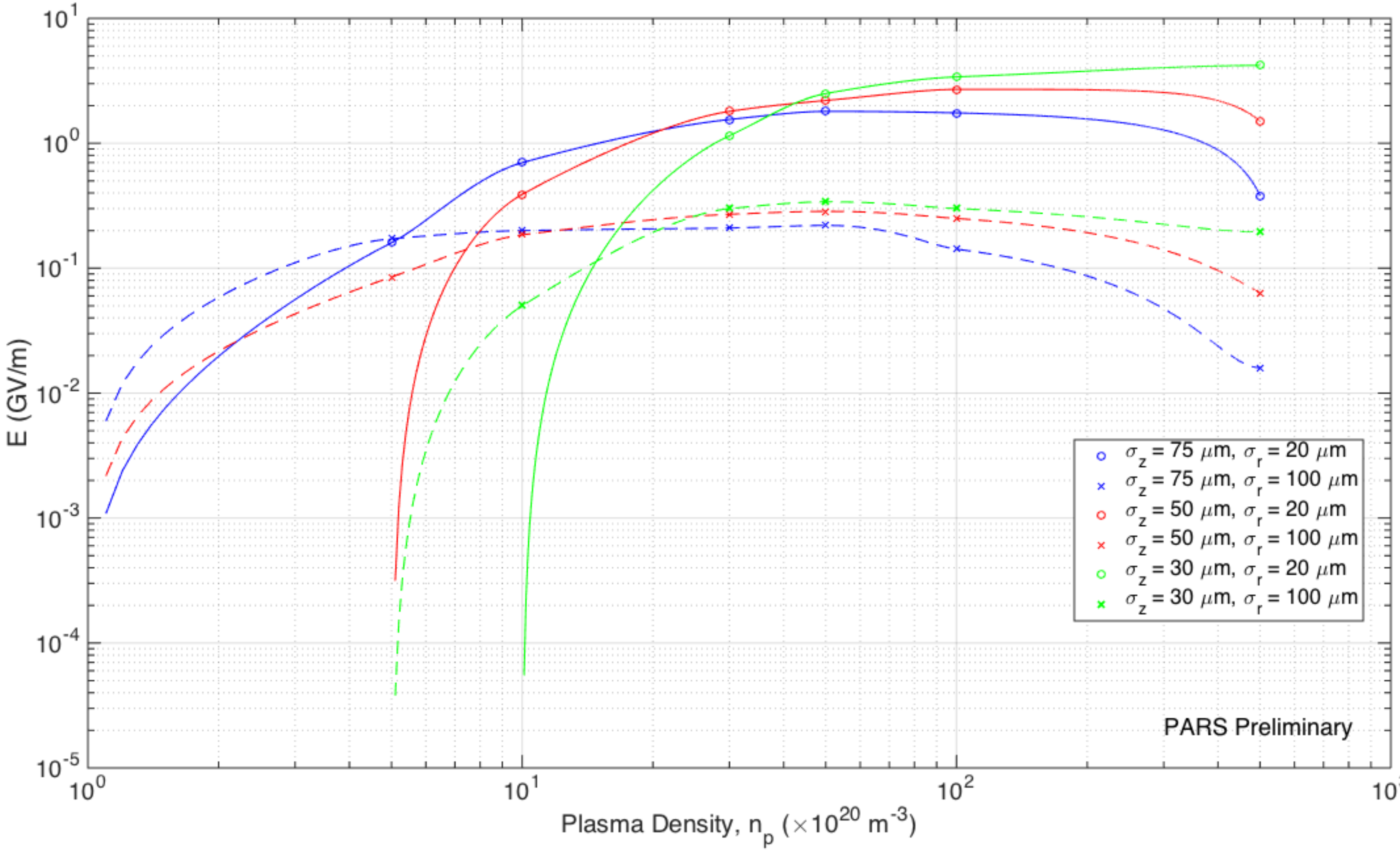




Two-bunch acceleration



Plasma density scan



O. Mete

Proton driven plasma wakefield acceleration (PDPWA)

	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

- **Huge 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?**

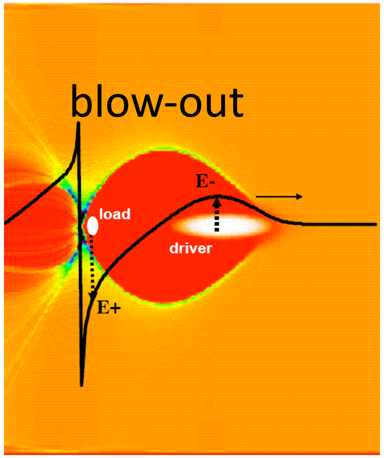
PWFA and PDPWA

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

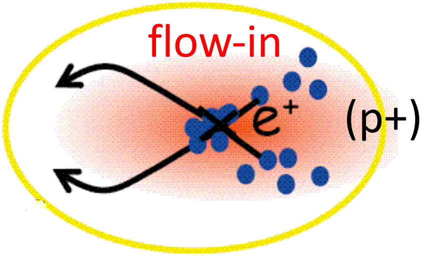
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.

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

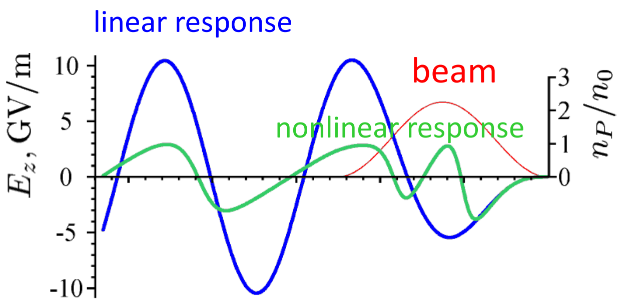


Cons. of PDPWA

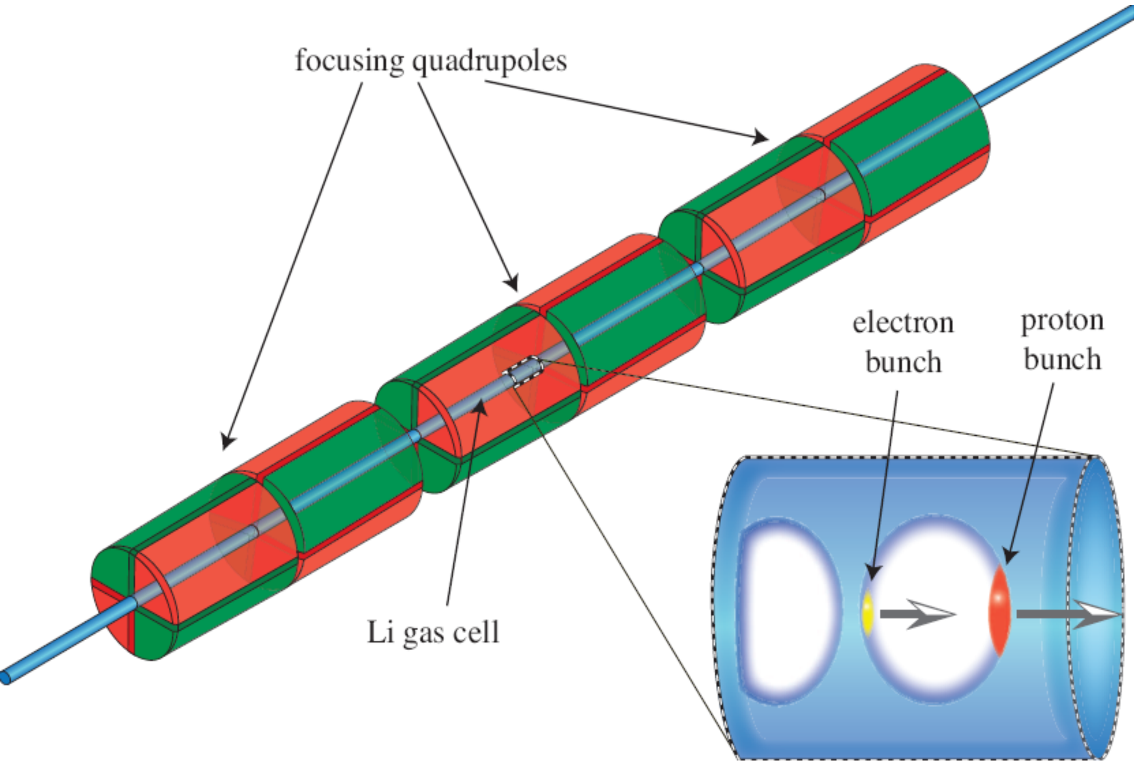
Flow-in regime responds a relatively low field *vs*. blow-out regime.

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



Schematics of PDPWA



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 setting

	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

Simulation

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

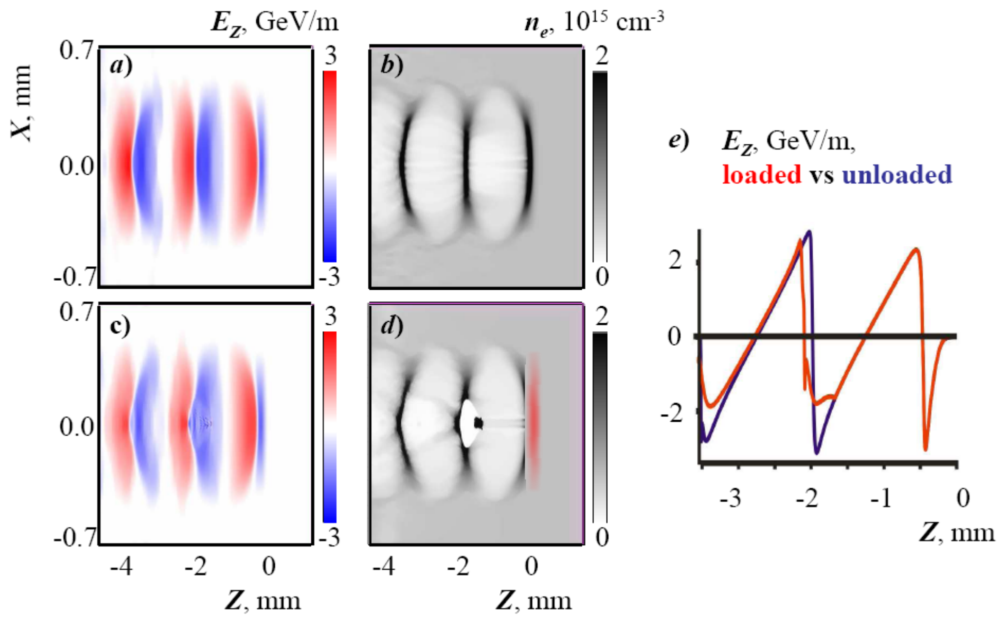


Fig.a-d), Simulation results for the unloaded (no witness bunch) case (a,b) and in the presence of a witness bunch (c,d). The witness bunch is seen as the black spot in the first wave bucket in d). d) also shows the driving proton bunch at the wavefront (red). e) The on-axis accelerating field of the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

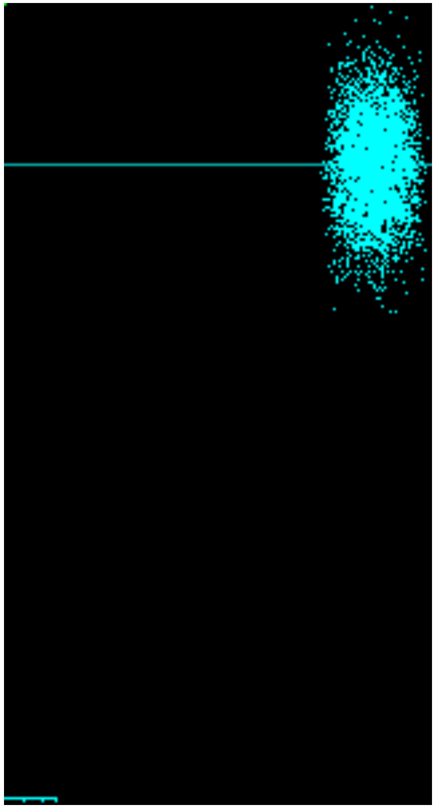
* A. Caldwell et al., Nature Physics 5, 363 (2009)

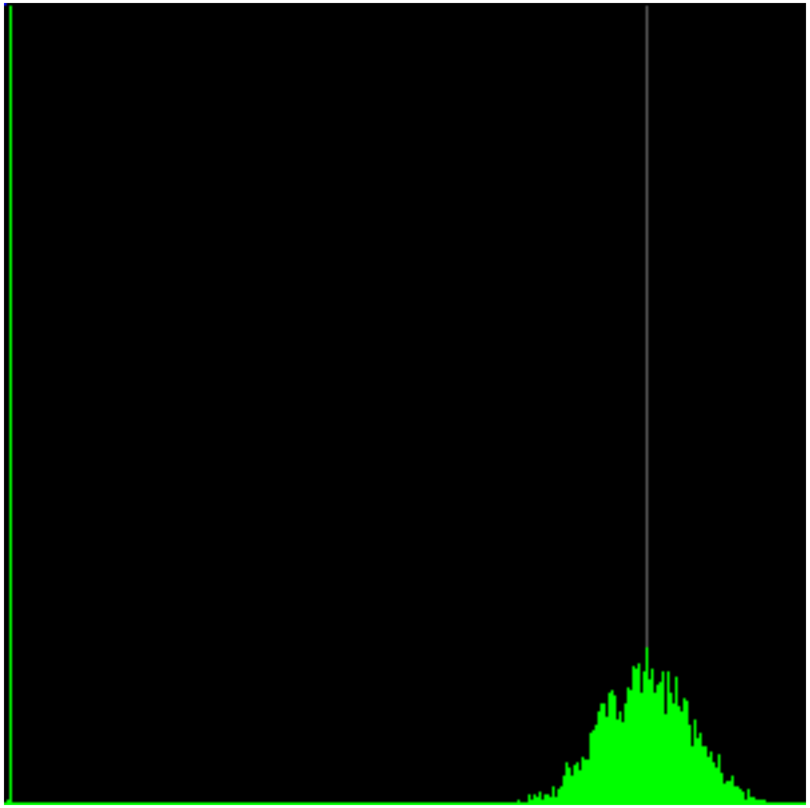
Simulation results

- **Energy gain**

1 TeV

10 GeV





phase

Phase space of driver & witness

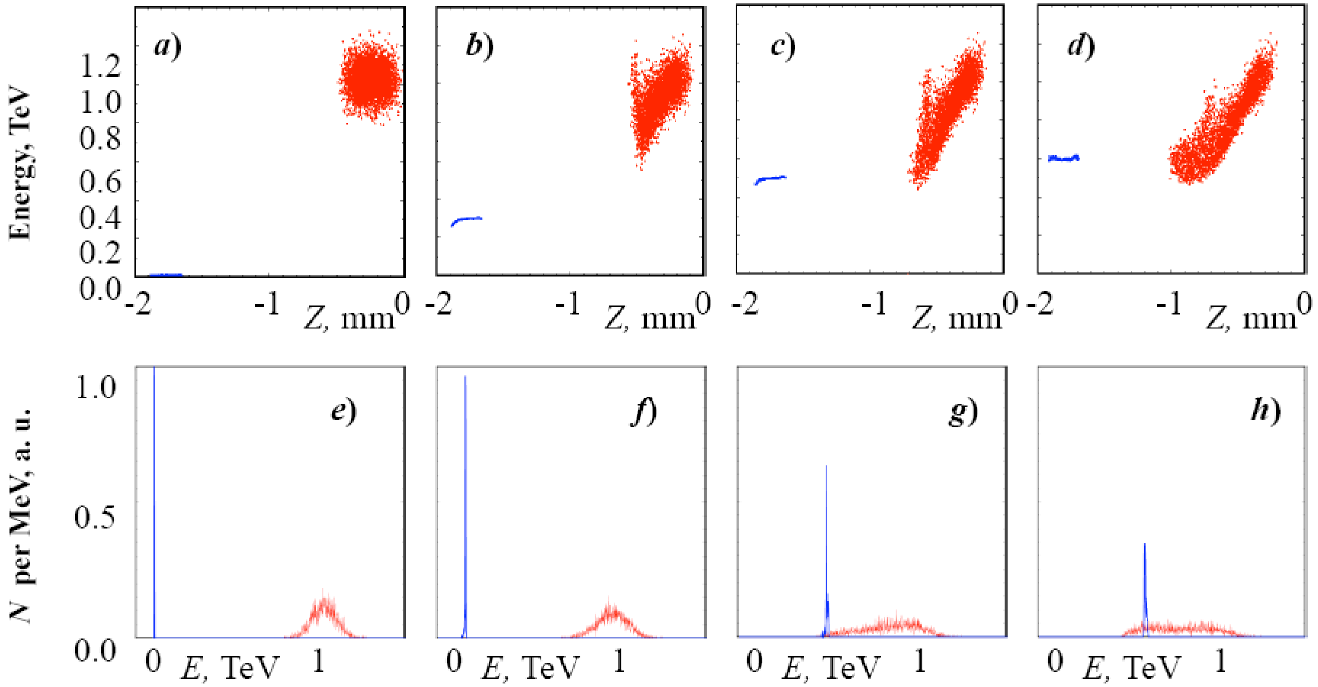


Fig. a-h), Snapshots of the combined longitudinal phase space of the driver and the witness bunches (energy versus coordinate) (a–d) and corresponding energy spectra (e–h). The snapshots are taken at acceleration distances *L*=0, 150, 300, 450 m. The electrons are shown as blue points and the protons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

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

Energy gain & energy spread

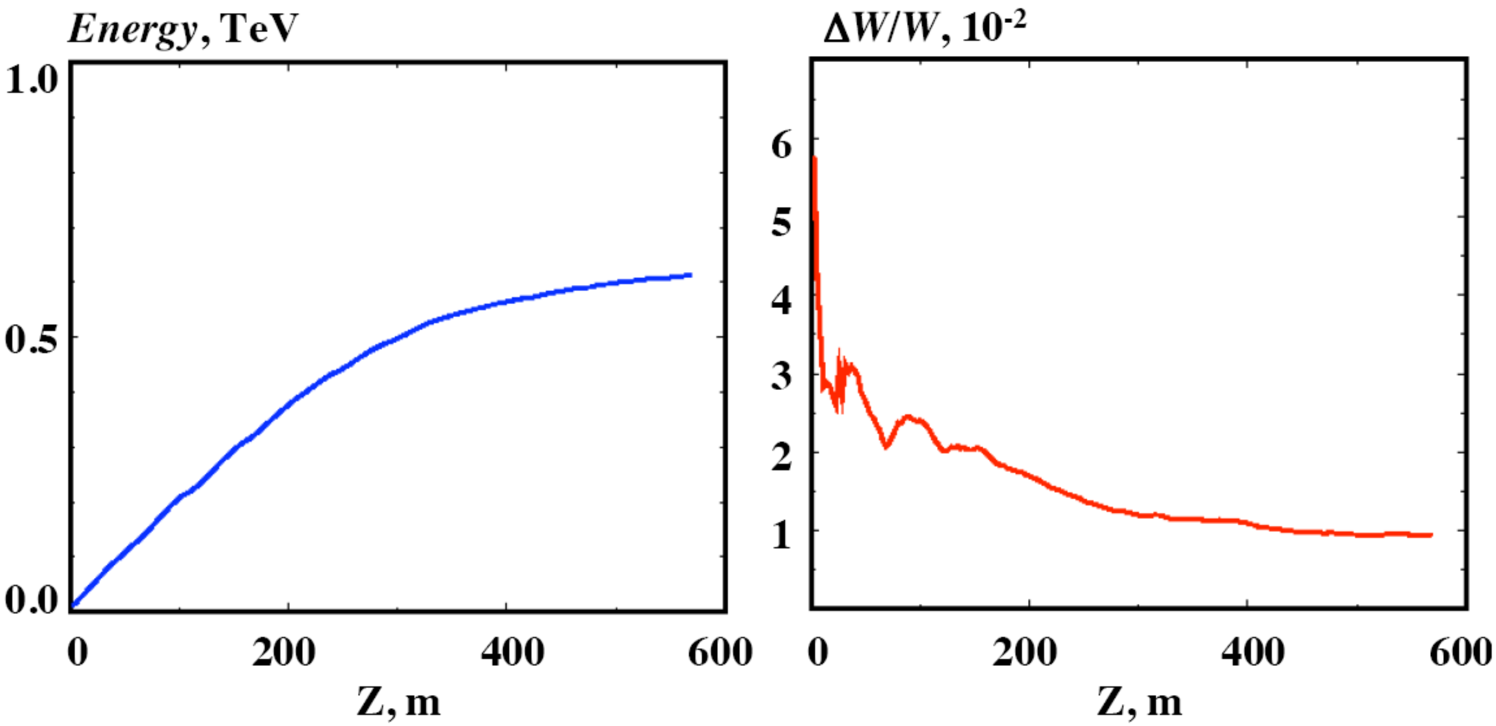


Fig. a,b), The mean electron energy in TeV (a) and the r.m.s. variation of the energy in the bunch as a percentage (b) as a function of the distance travelled in the plasma.

* 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!**

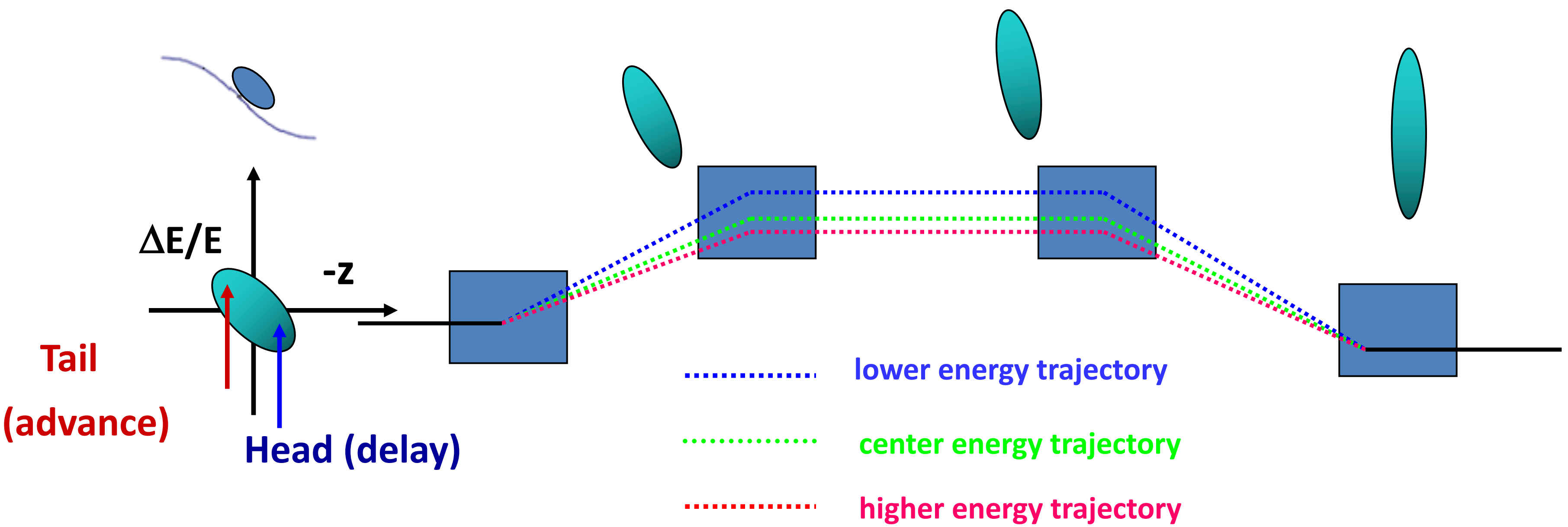
Magnetic bunch compression

- 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.



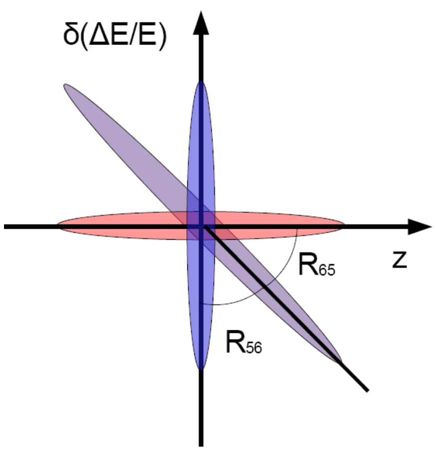
- **To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.**

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

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



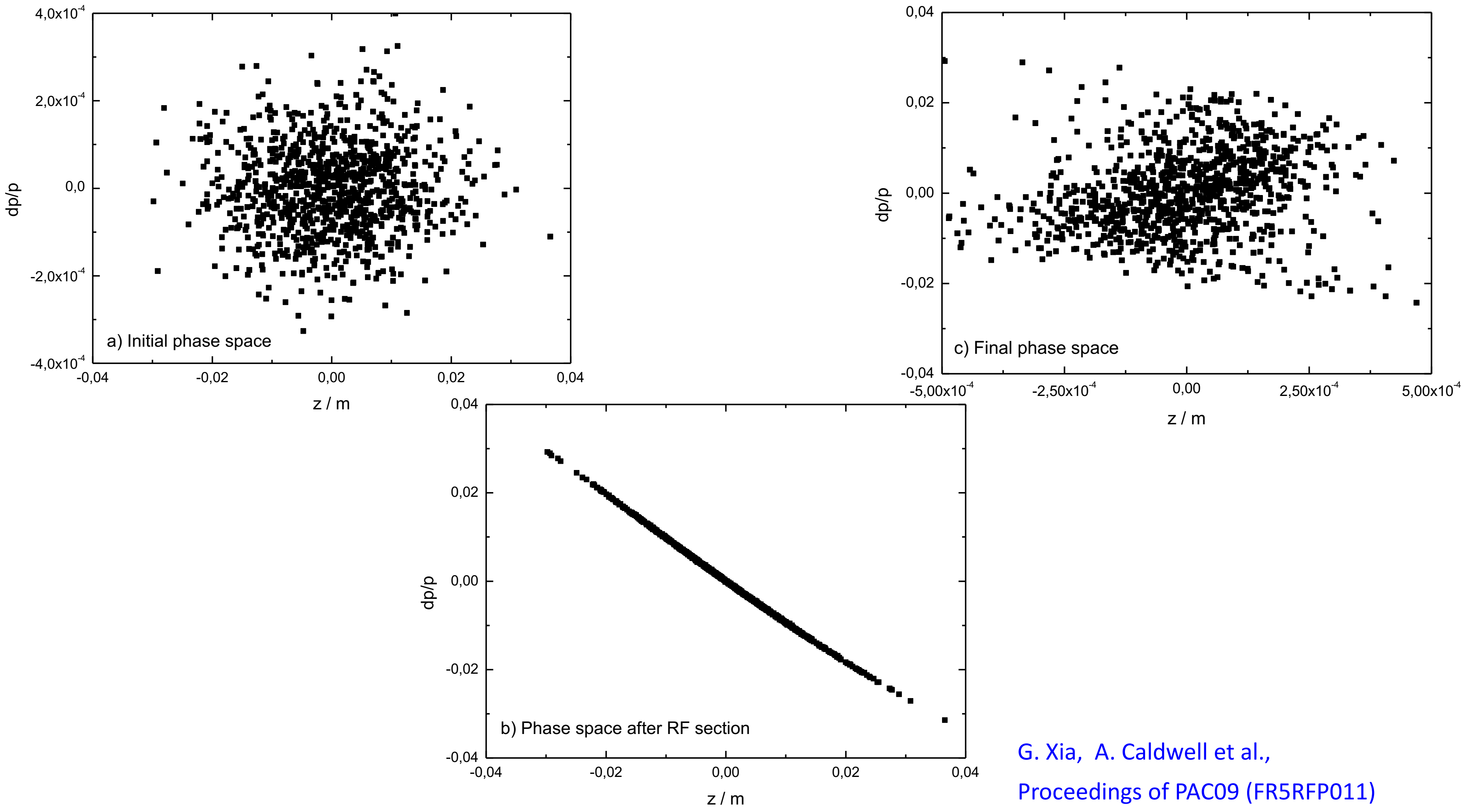
$$1 + R_{56}R_{65} = 0$$

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

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

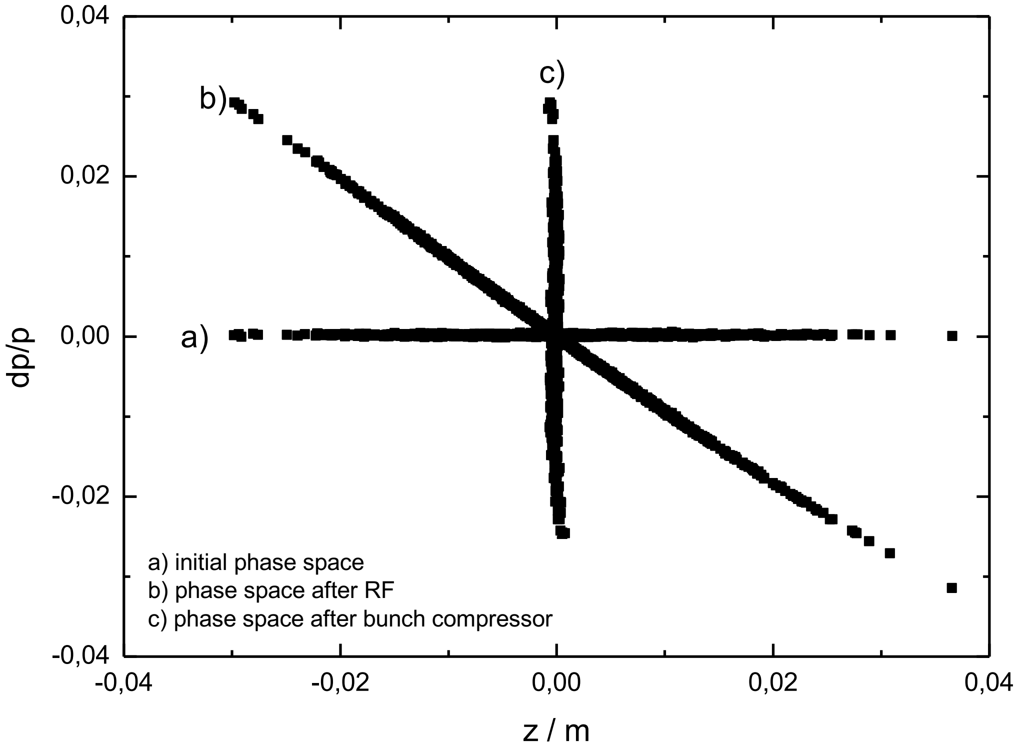
	Value
Bunch charge	**10^{11}**
Proton energy [TeV]	**1**
Initial energy spread [%]	**0.01**
Initial bunch length [cm]	**1.0**
Final bunch length [μm]	**165**
RF frequency [MHz]	**704.4**
Average gradient of RF [MV/m]	**25**
Required RF voltage [MV]	**65,000**
RF phase [degree]	**-102**
Compression ratio	**~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)

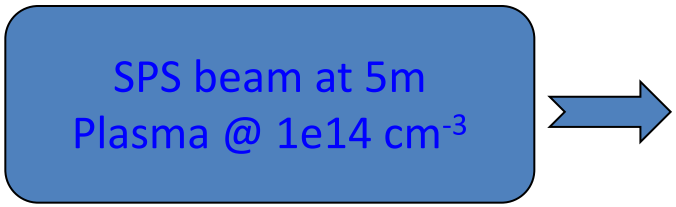
Phase space of beam

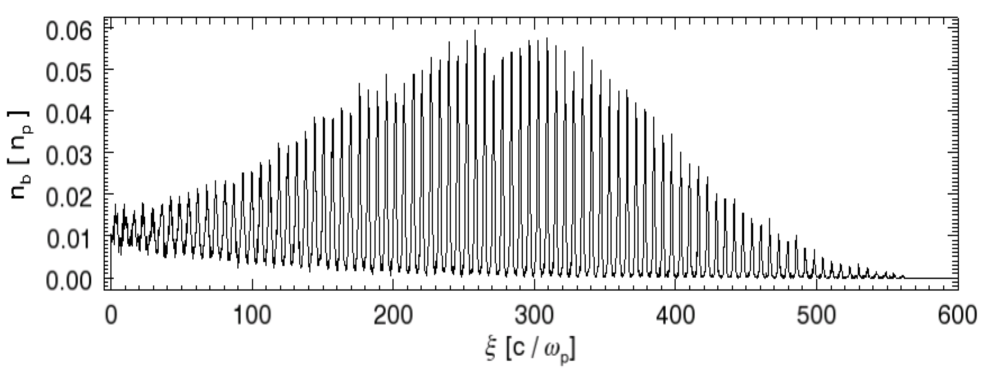


G. Xia, A. Caldwell et al., Proceedings of PAC09 (FR5RFP011)

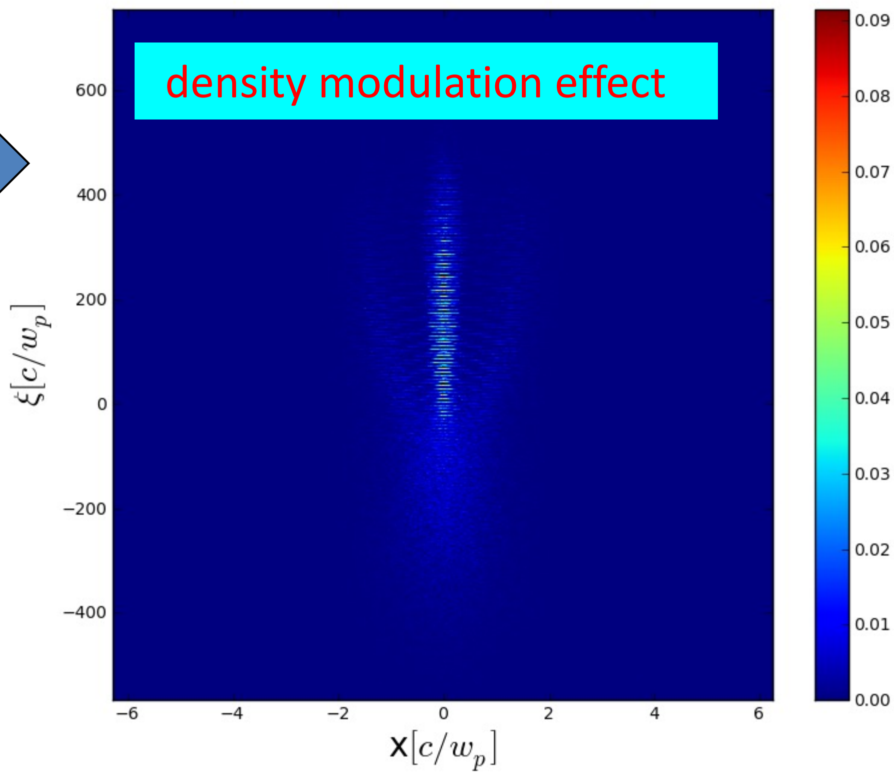
Plasma wakefield slicing via modulation

- 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)

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.

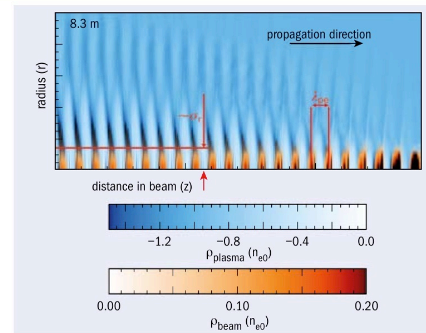


Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing from yellow to dark red.

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]
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[3]GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
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[5]University of California, Los Angeles, CA, USA

(Received 20 September 2011; accepted 2 January 2012)

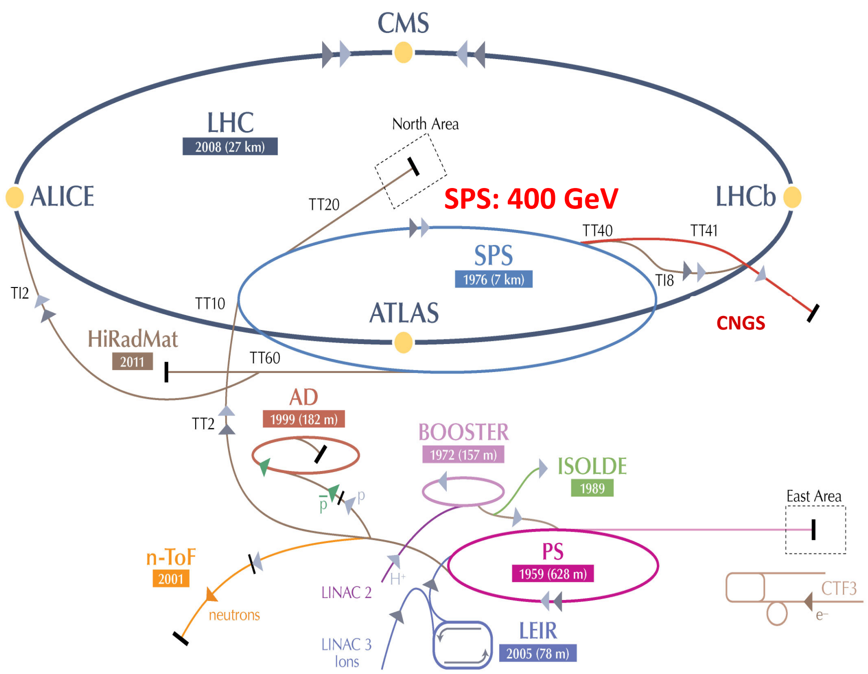
AWAKE

- **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 in late **2016**

- AWAKE Collaboration: 23 Institutes world-wide
  - Spokesperson: Allen Caldwell->Patric Muggli, MPI Munich
  - Deputy Spokesperson: Matthew Wing, UCL
  - Physics and Experiment Coordinator: Patric Muggli, MPI Munich
  - Simulation Coordinator: Alexander Pukhov, BINP
  - Technical Coordinator and CERN AWAKE Project Leader: Edda Gschwendtner, CERN
  - Deputy: Chiara Bracco, CERN

Drive beam: SPS proton beam



➔ SPS Beam at 400 GeV/c

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

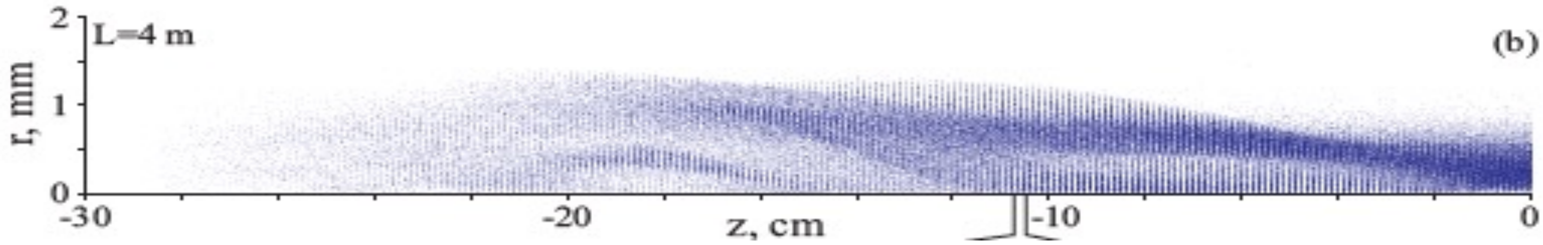
→ Proton beam for AWAKE requires:

- High charge
- Short bunch length
- Small emittance

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)-0.2ns (6 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%

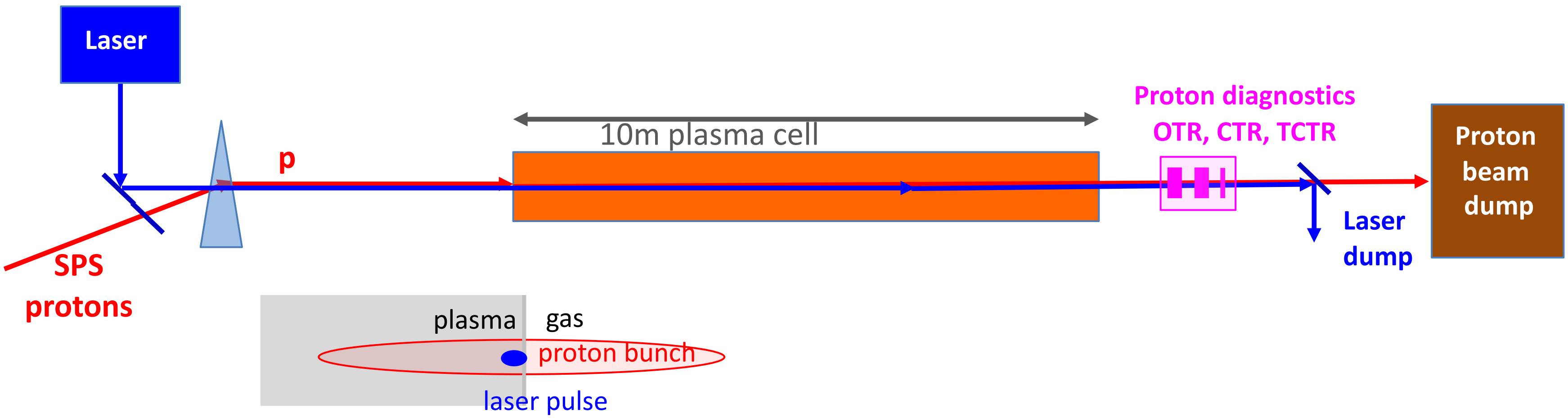
Long proton beam σ_z = 12cm! ←→Compare with plasma wavelength of λ = 1mm.
→ Experiment based on Self-Modulation Instability!



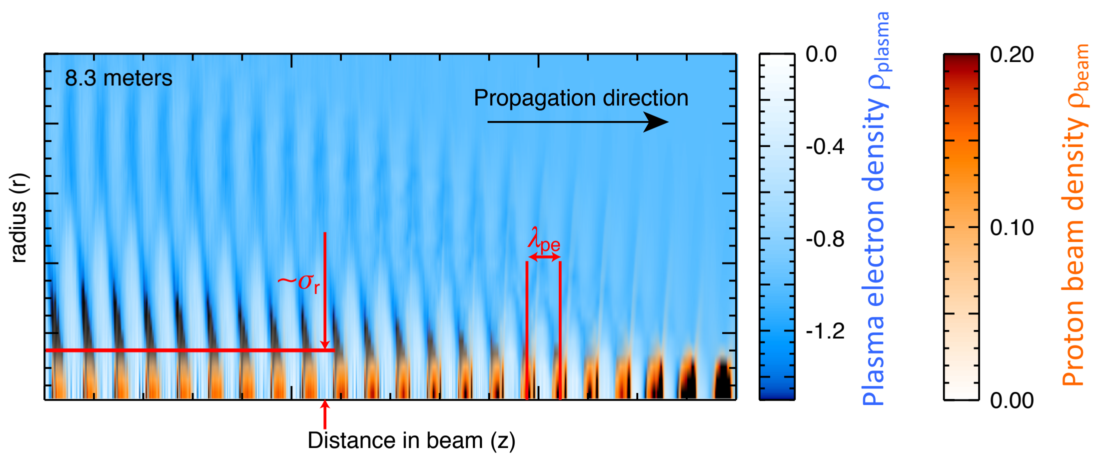
Self-modulation instability of the proton beam: modulation of a long (SPS) beam in a series of 'micro-bunches' with a spacing of the plasma wavelength.

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.



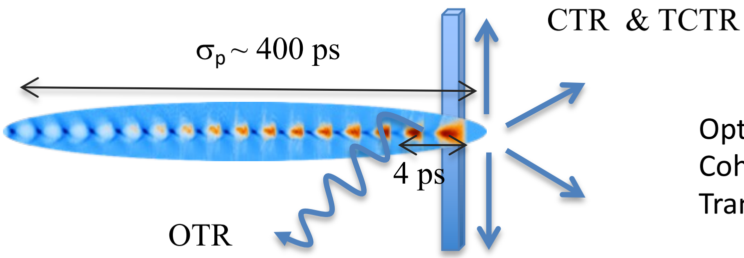
J. Vieira et al PoP 19063105 (2012)

Drive beam diagnostics

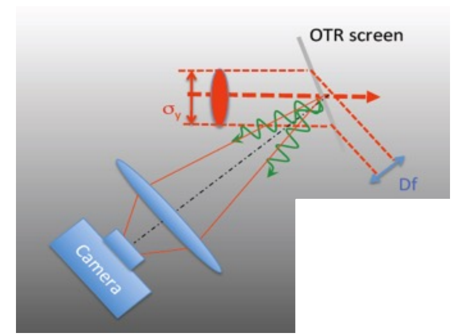
Direct Measurement of self-modulation instability of the proton beam

→ 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.

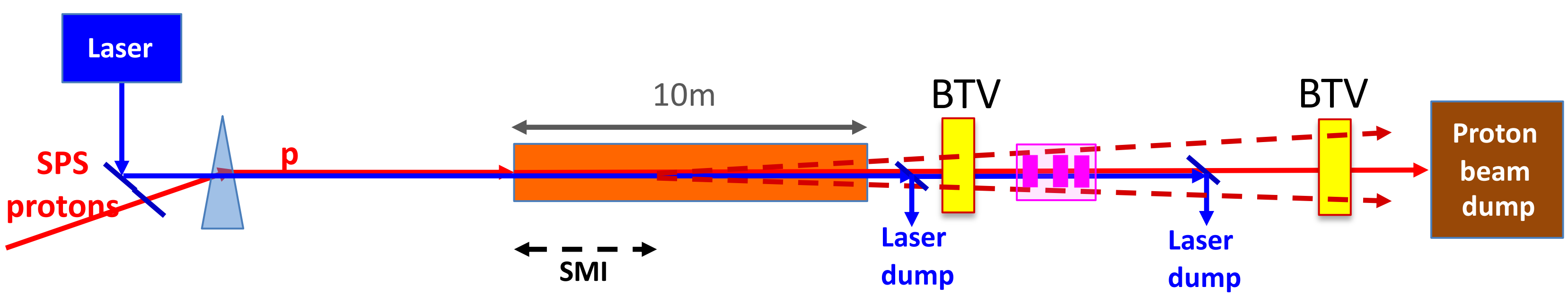


Optical Transition Radiation (OTR)
Coherent Transition Radiation (CTR)
Transverse Coherent Transition Radiation (TCTR)



Indirect Measurement by observing the proton bunch defocusing downstream the plasma

→ Proton bunch: 1mrad divergence



Witness beam

→ Optimal electron energy is 10-20 MeV
  – Electron velocity = 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 source

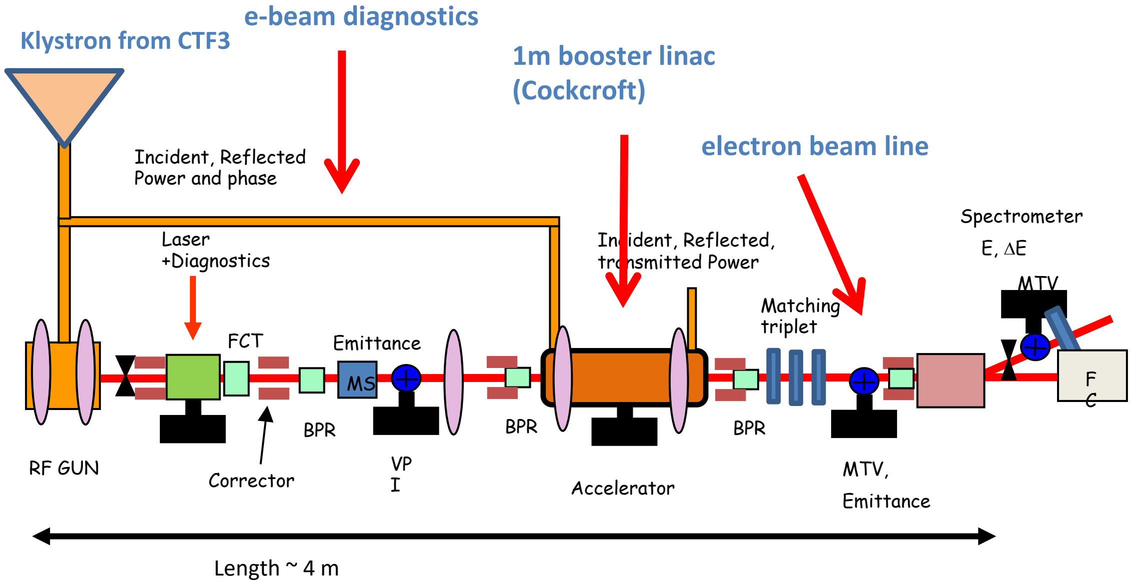
PHIN Photo-injector for CTF3/CLIC:

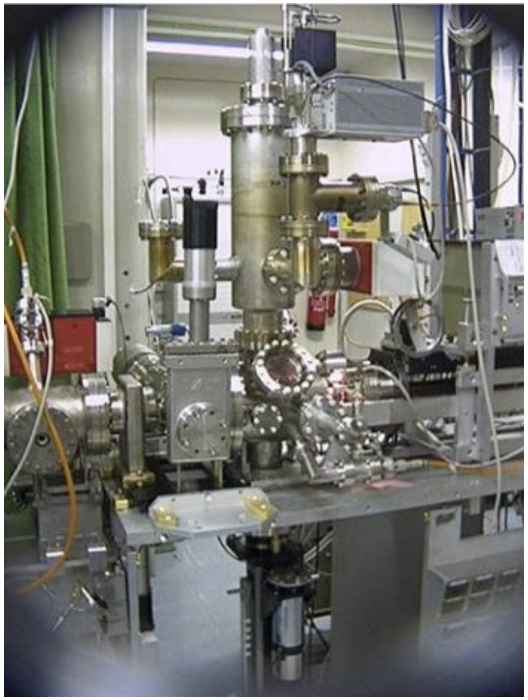
- Charge/bunch: 2.3 nC
- Bunch length: 10 ps
- 1800 bunches/train, 1.2μs train-length
- → Program will stop end 2015

→ Fits to requirements of AWAKE

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

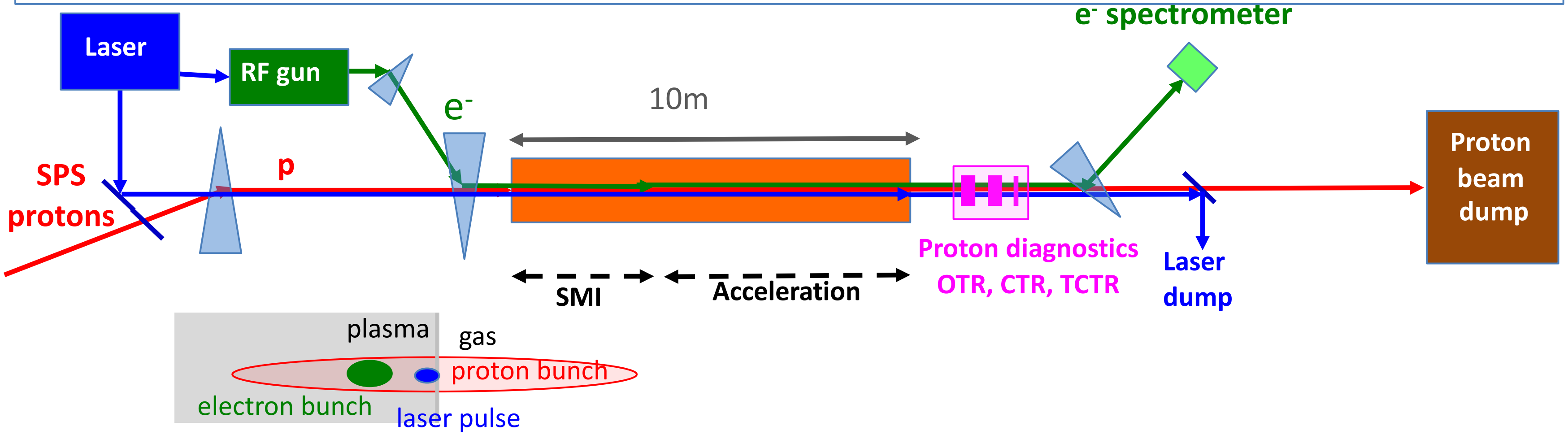
Laser beam for electron source	
Laser type	Ti:Sapphire Centaurus
Pulse wavelength	λ_0 = 260 nm
Pulse length	10 ps
Pulse energy (after compr.)	500 μJ
Electron source cathode	Copper
Quantum efficiency	3.00 E-5
Energy stability	±2.5% r.m.s.



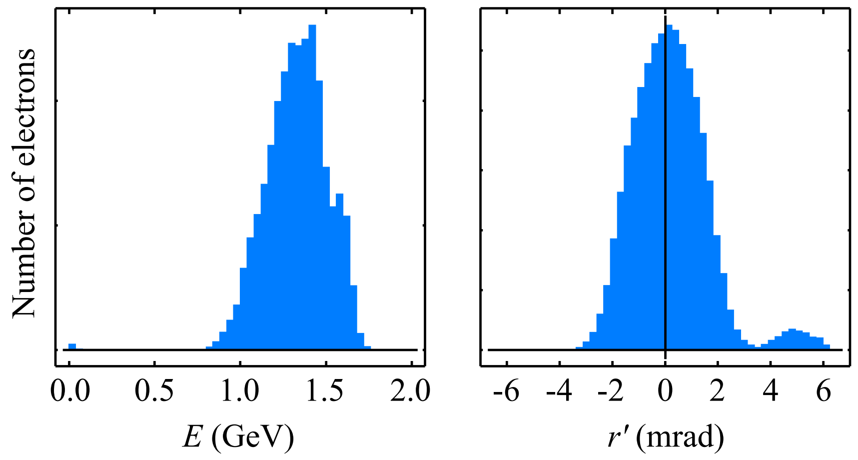


AWAKE: 2nd experimental phase

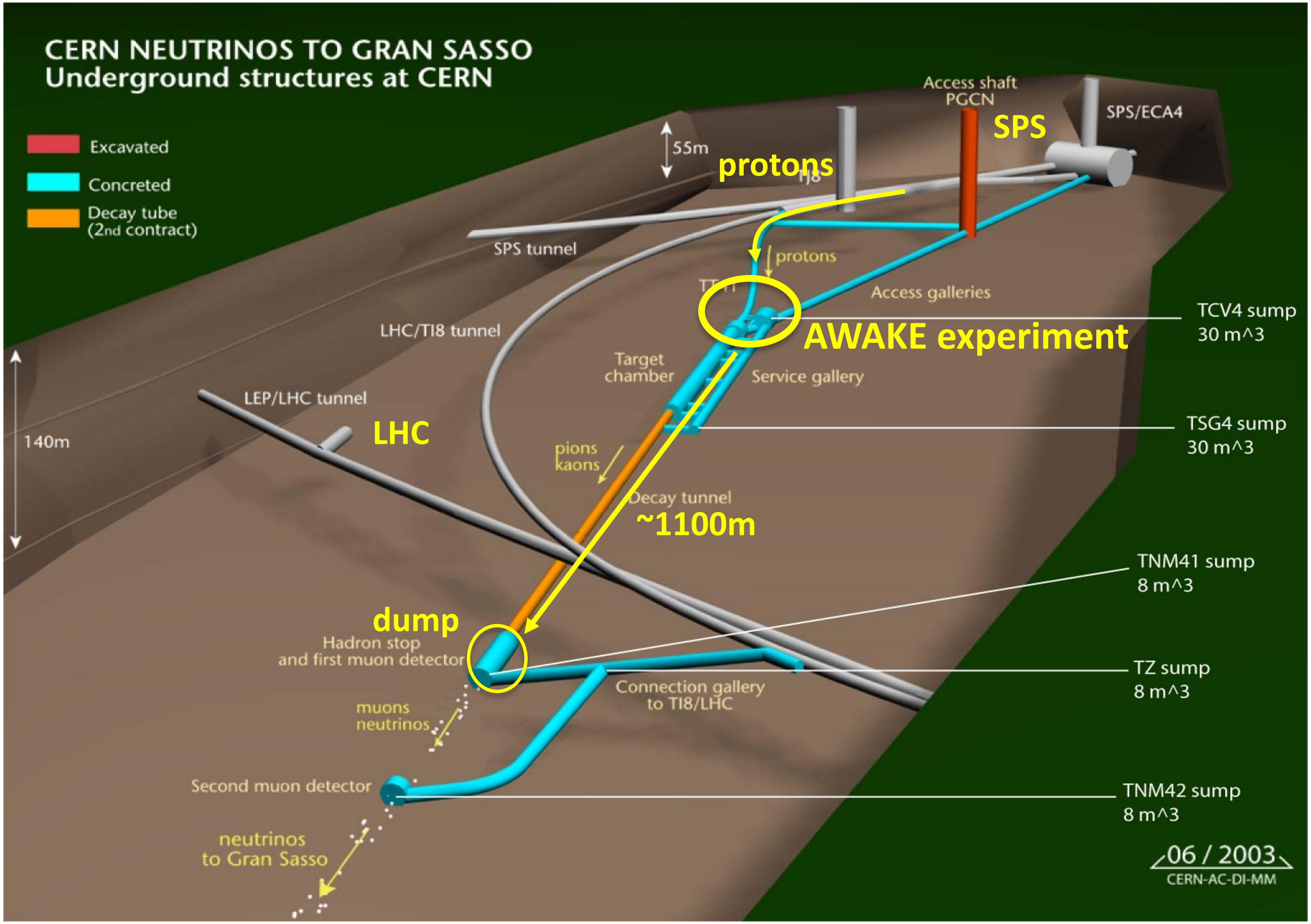
Probe the accelerating wakefields with externally injected electrons, including energy spectrum measurements for different injection and plasma parameters.



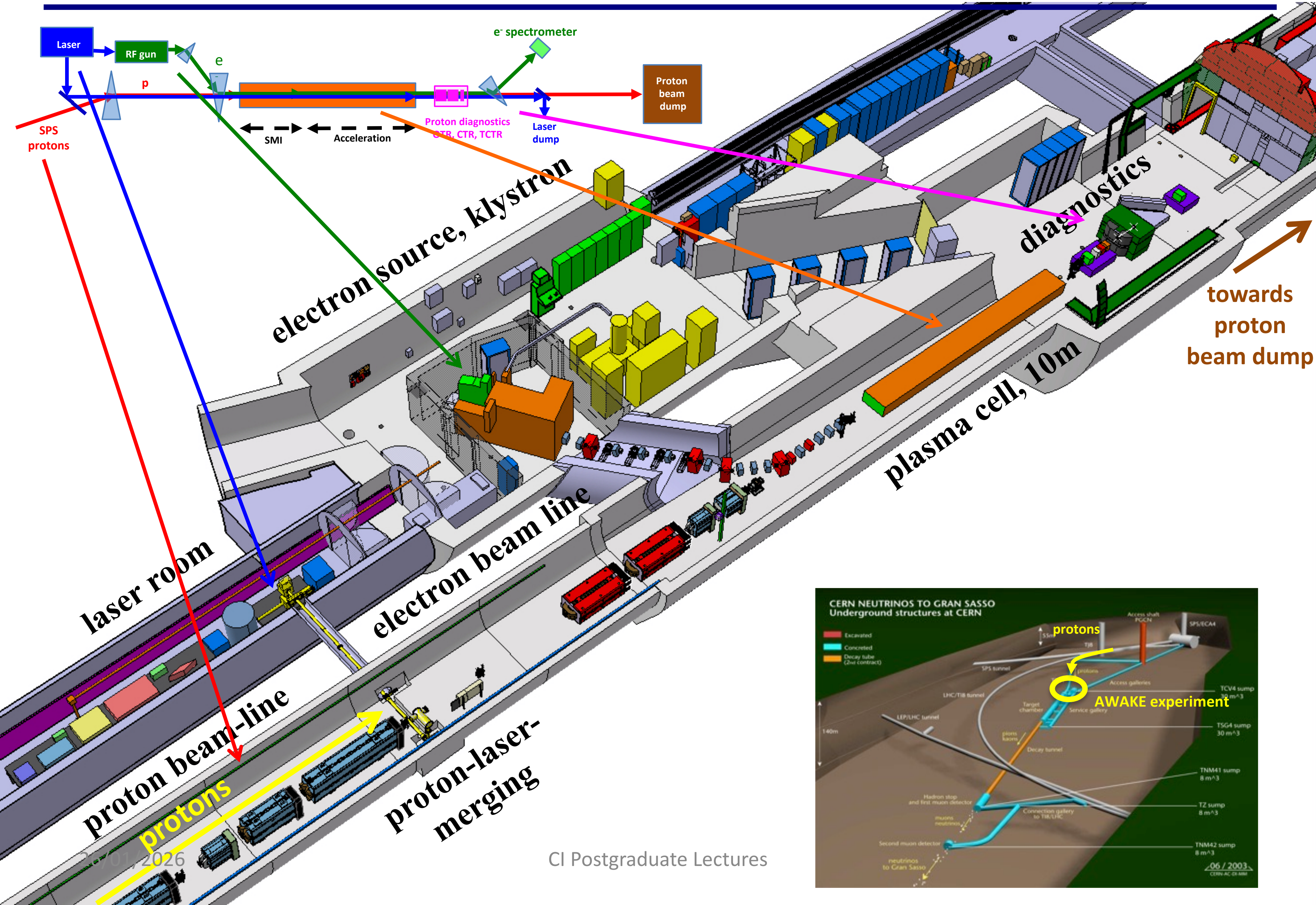
- Trapping efficiency: **10 – 15 %**
- Average energy gain: **1.3 GeV**
- Energy spread: $\pm$ 0.4 GeV
- Angular spread up to $\pm$ 4 mrad



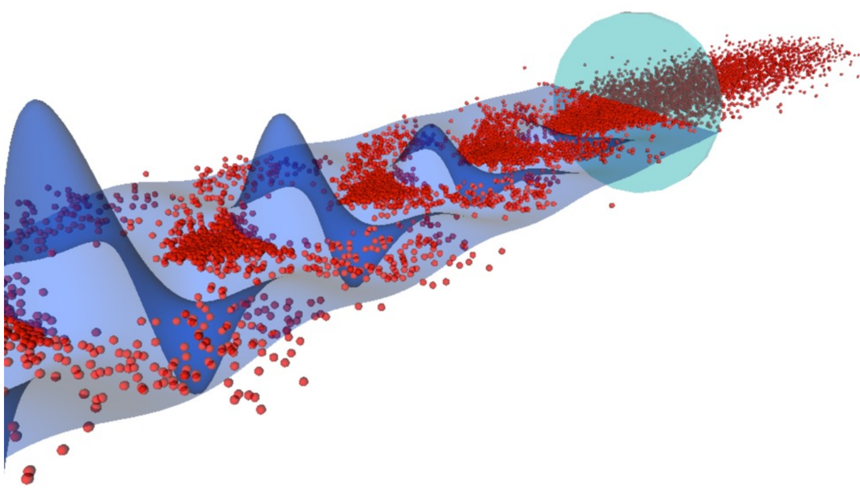
AWAKE at CERN

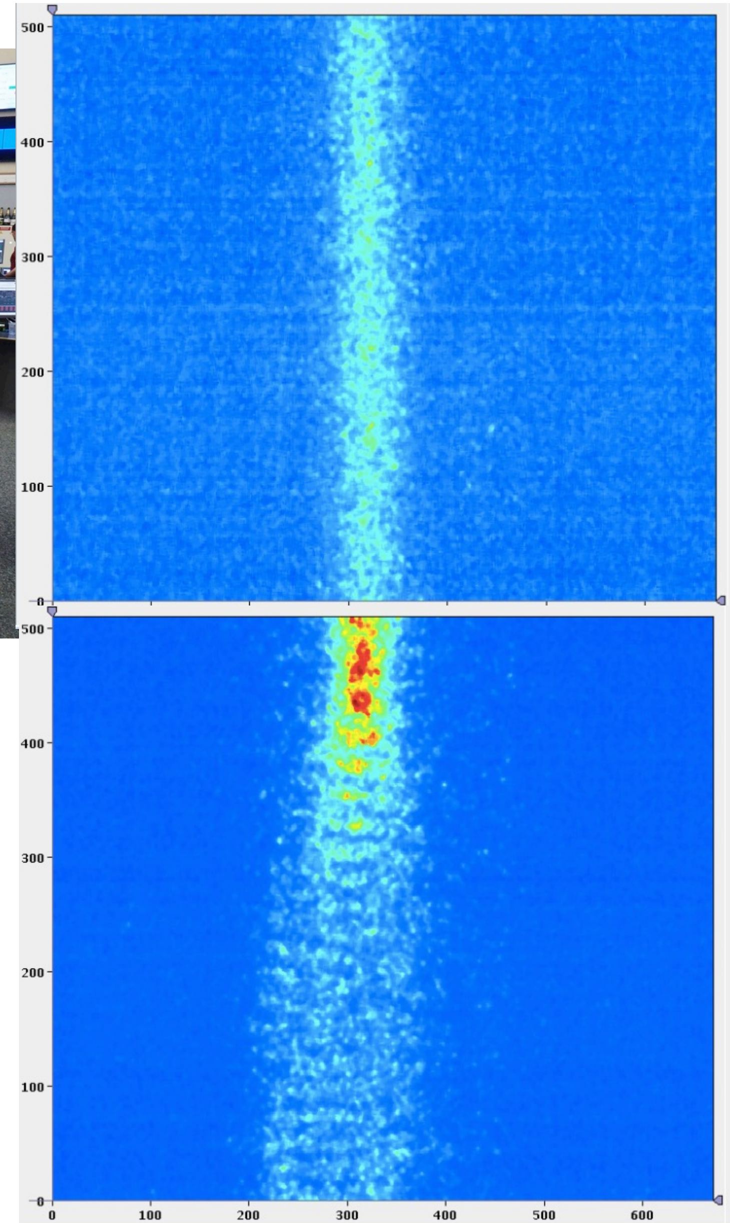


AWAKE at CERN

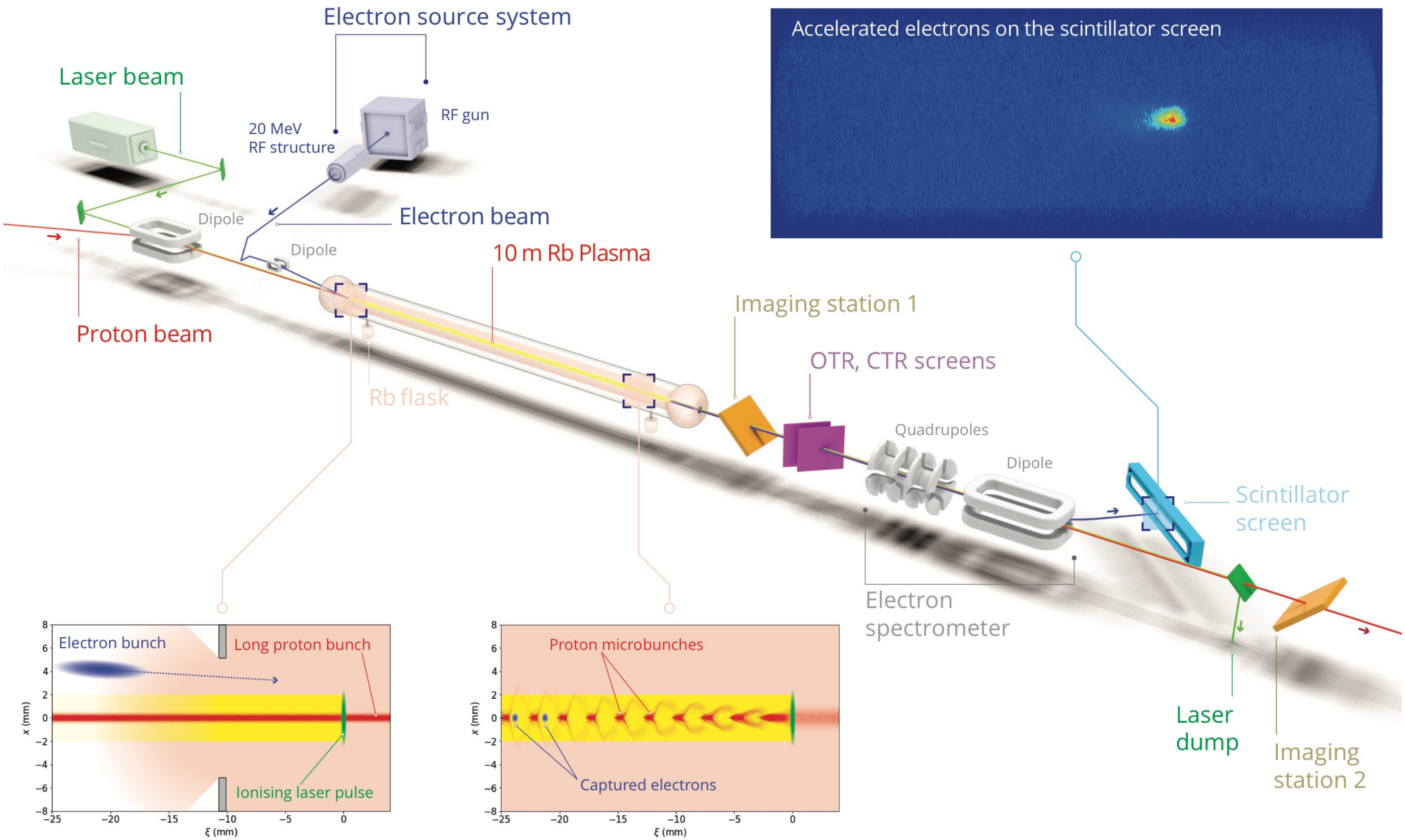


AWAKE milestone in 2016

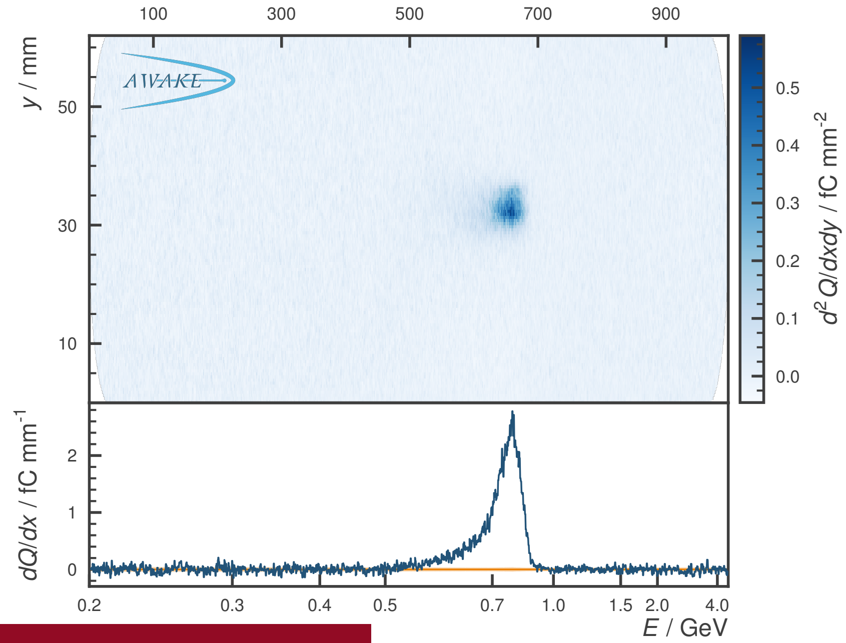




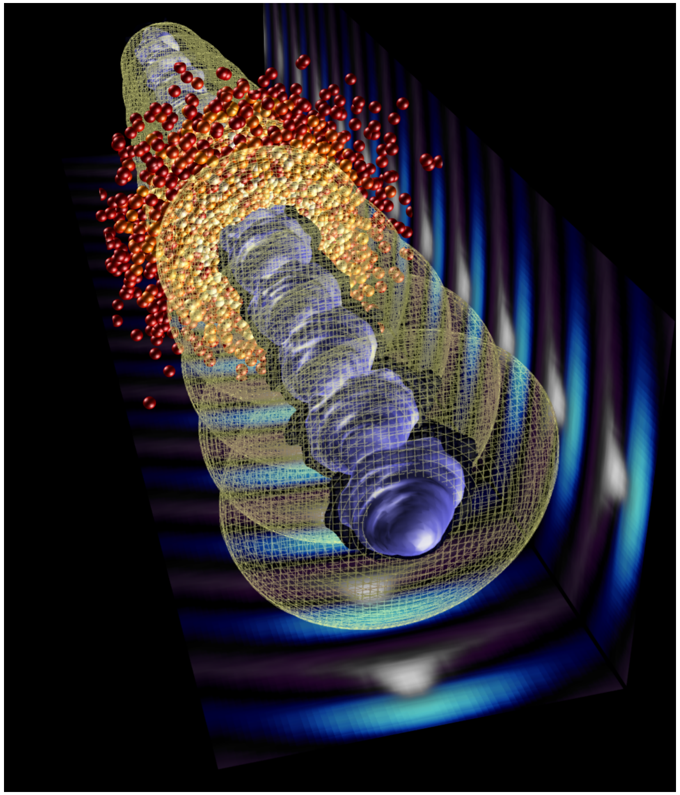
AWAKE highlight 2018



AWAKE highlights in 2018



nature
International journal of science



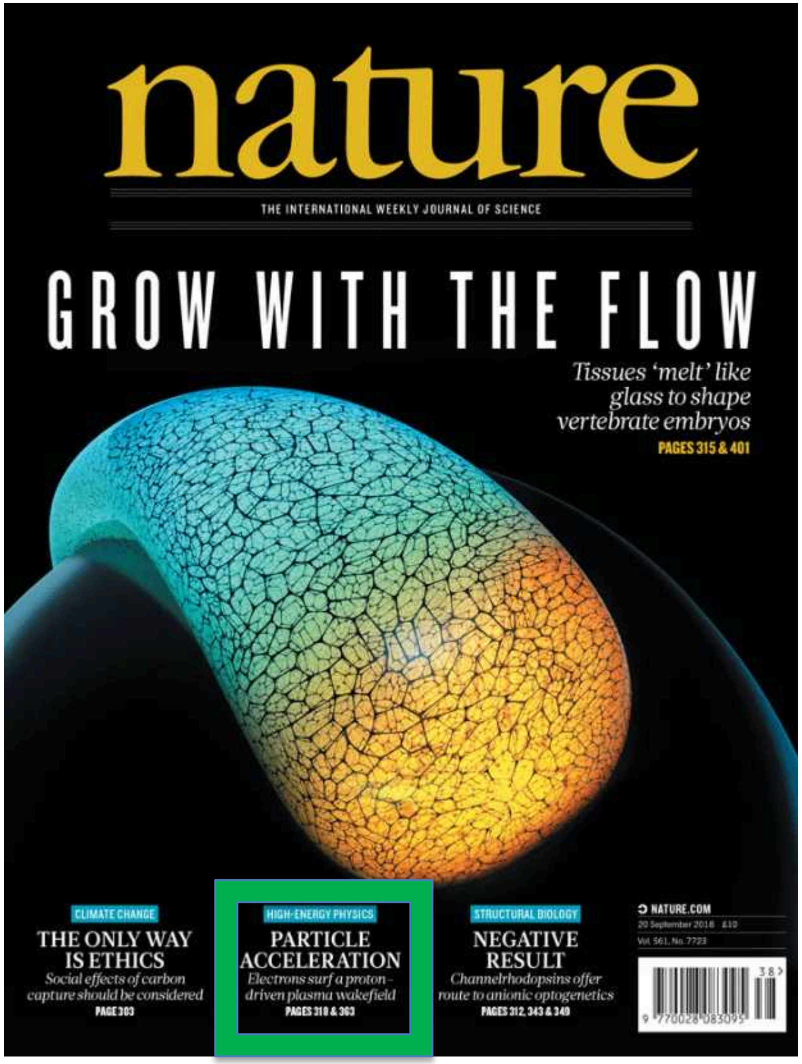
J. Viera, IST

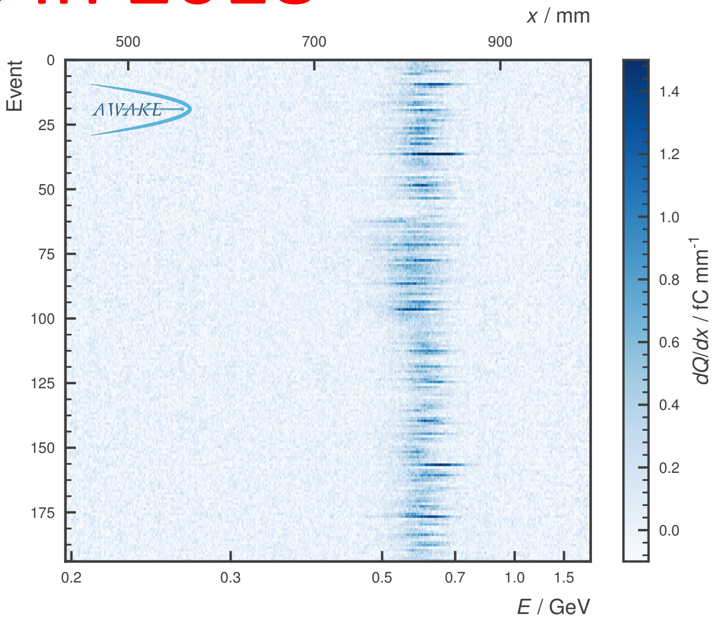
CERN's pioneering mini-accelerator passes first test

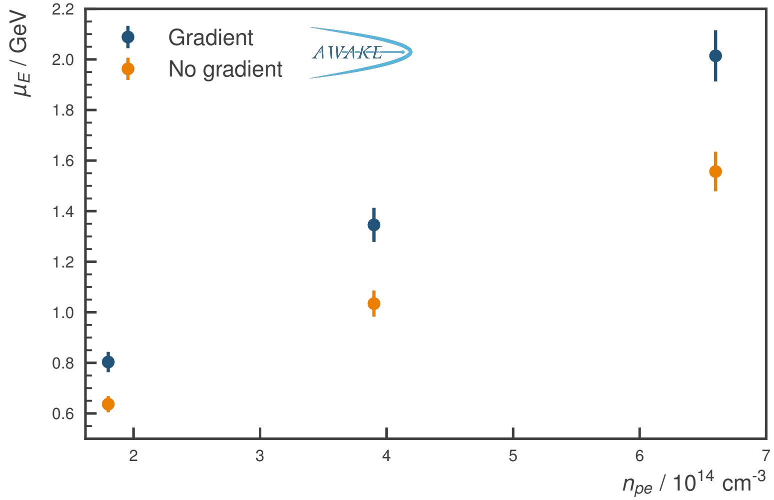
Physicists achieve powerful acceleration by 'surfing' electrons on proton waves over short distances.

The Cockcroft Institute of Accelerator Science and Technology

AWAKE highlights in 2018

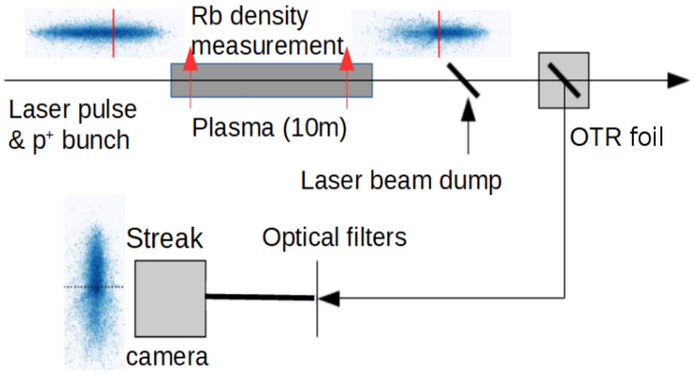


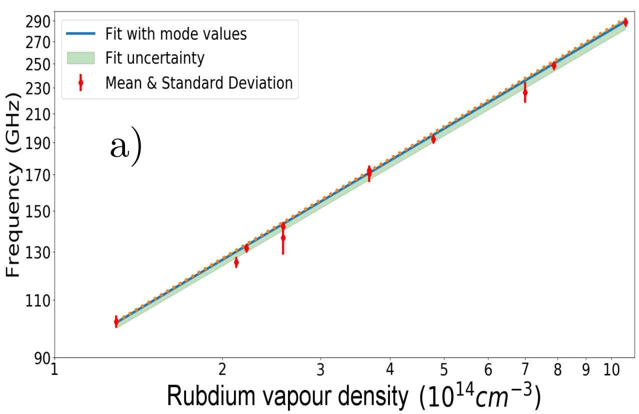


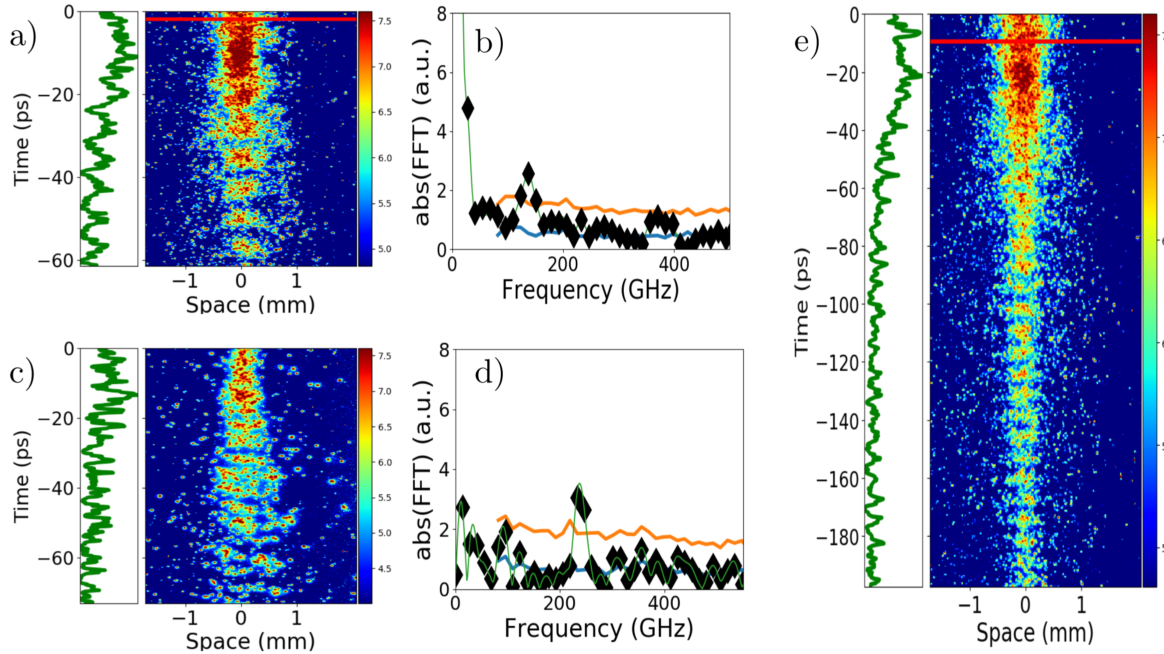


E. Adli, et al., Nature, **561**, 363-367 (2018).

AWAKE highlights

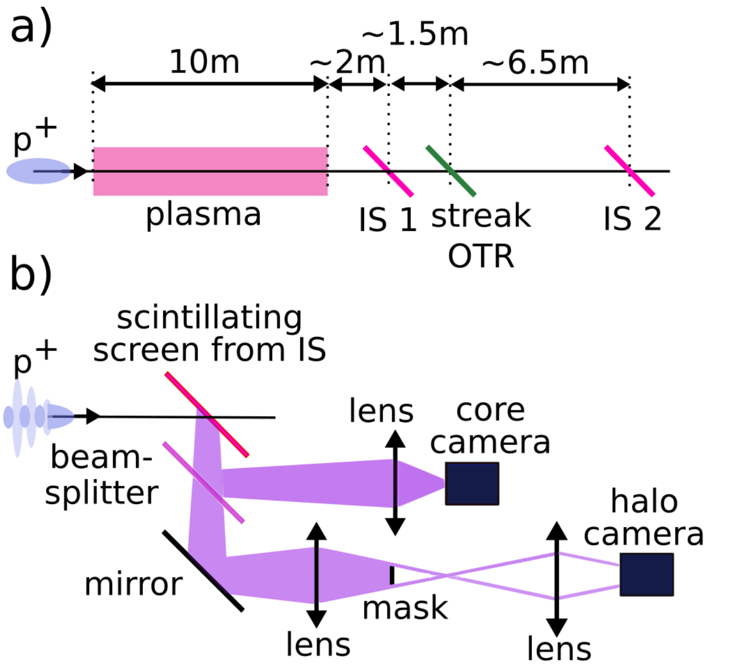


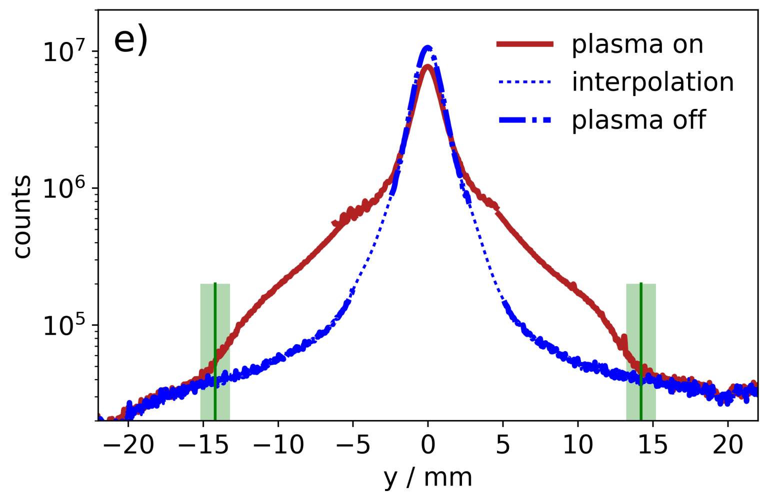


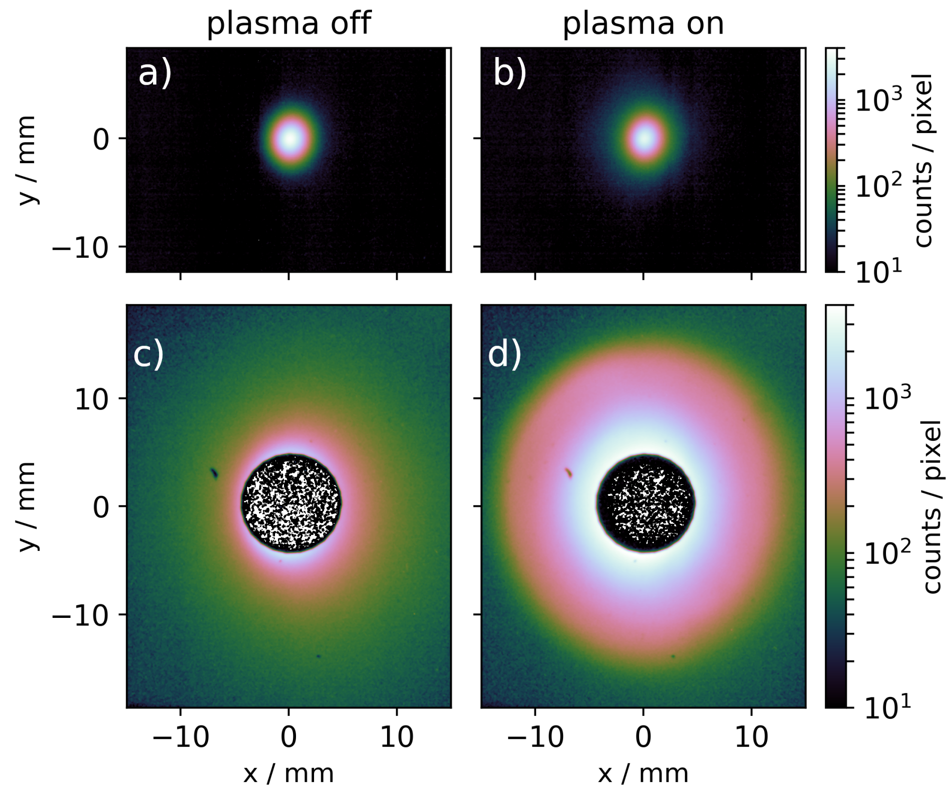


AWAKE Collaboration, PRL 122 (5) 054801 (2019)
AWAKE Collaboration, PRL 122 (5) 054802 (2019)
AWAKE Collaboration, PRL 125 (26) 264801(2020)
AWAKE Collaboration, PRL 126 (16) 164802(2021)
AWAKE Collaboration, PRL 129 (2) 024802 (2022)
AWAKE Collaboration, PRL 132 (7) 075001 (2024)
AWAKE Collaboration, PRL 134 (15) 155001 (2025)

AWAKE highlights





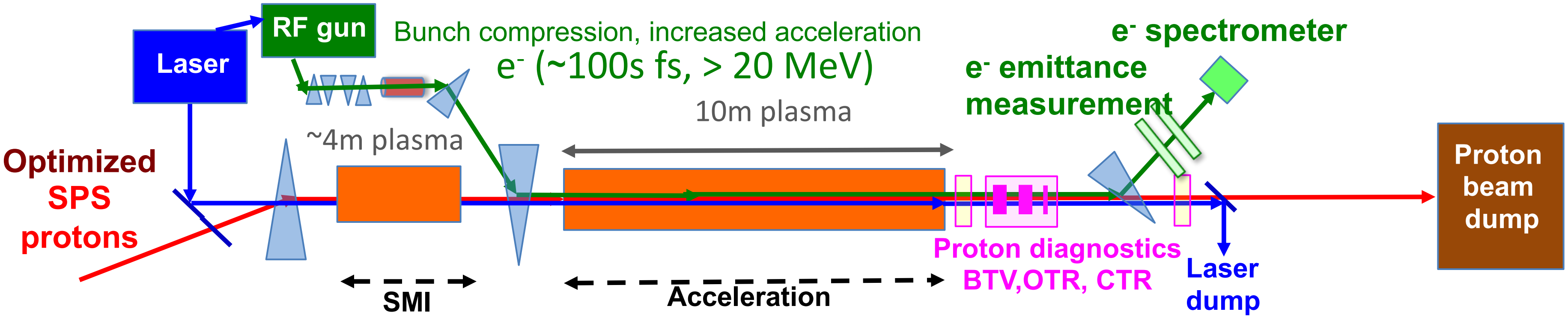


M. Turner et al. "Experimental observation of plasma wakefield growth driven by the seeded self-modulation of a proton bunch", arXiv:1809.01191 (2018)

AWAKE current activity - Run 2

Possible injectors?

Scalable sources?



AWAKE Run 2, 2021-202x (after LHC LS2) : main goals

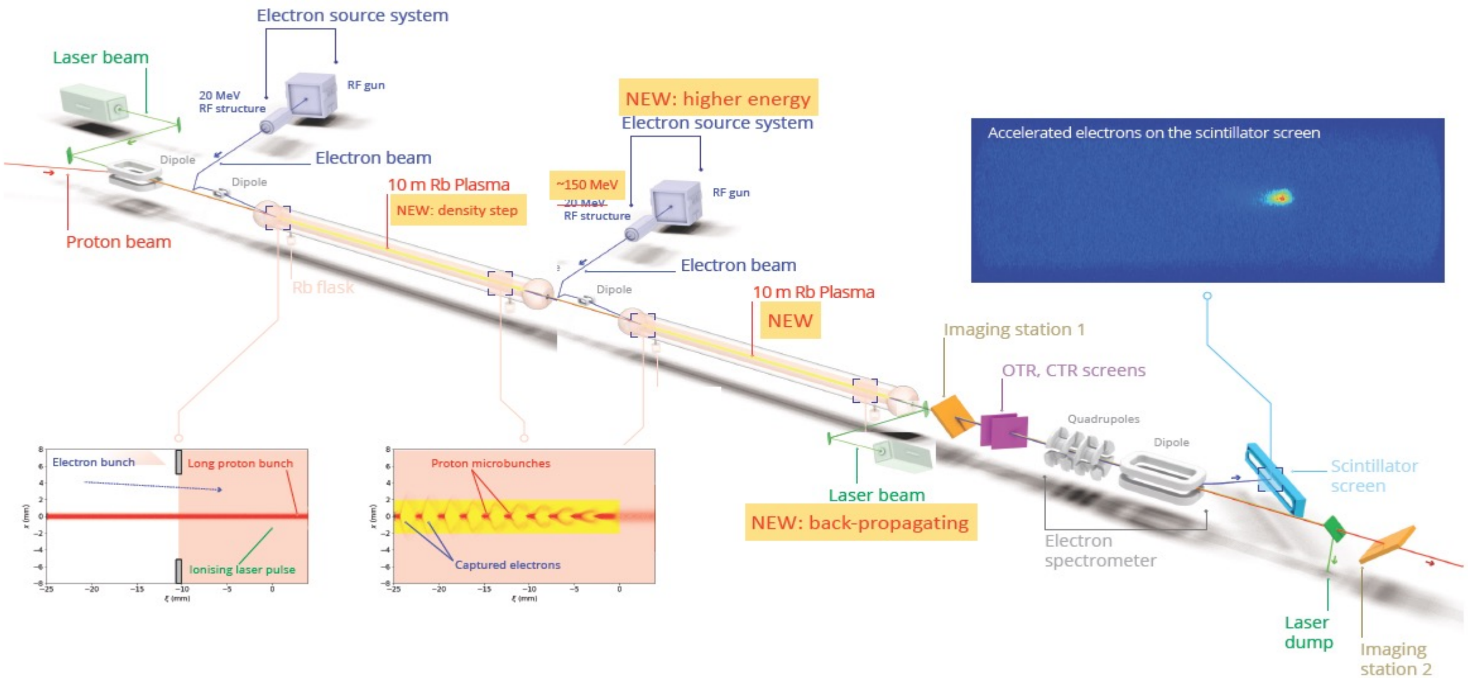
Accelerate an electron beam, while preserving beam quality as well as possible

- injection: into the wake of an already modulated proton beam
- generate optimum electron bunch to be accelerated

Demonstrate scalability of the AWAKE concept

- sustain gradient in SMI wake over long distance
- scalable length plasma sources

AWAKE Run 2a,2b (2021-2026)



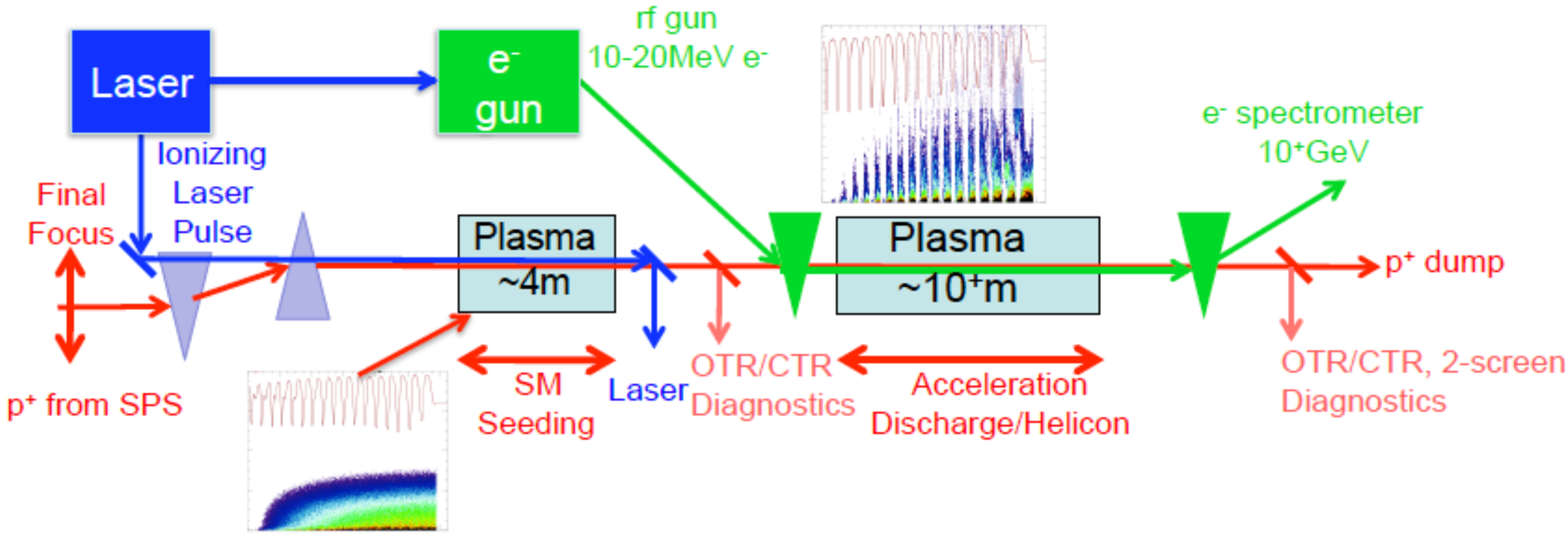
Goals:

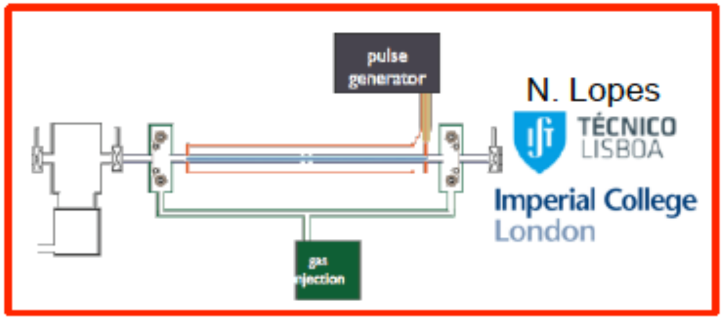
Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

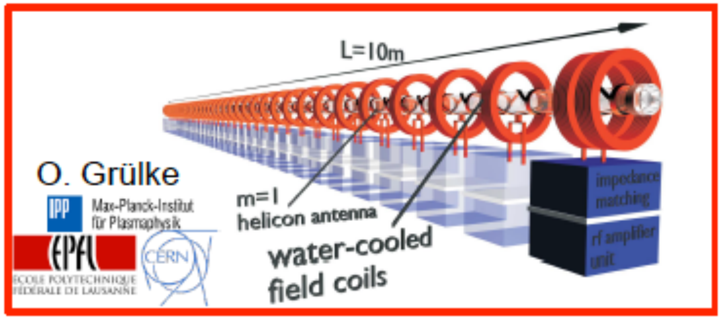
Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon plasma source or discharge plasma source)

Experimental setup for Run II (2021-LS3)



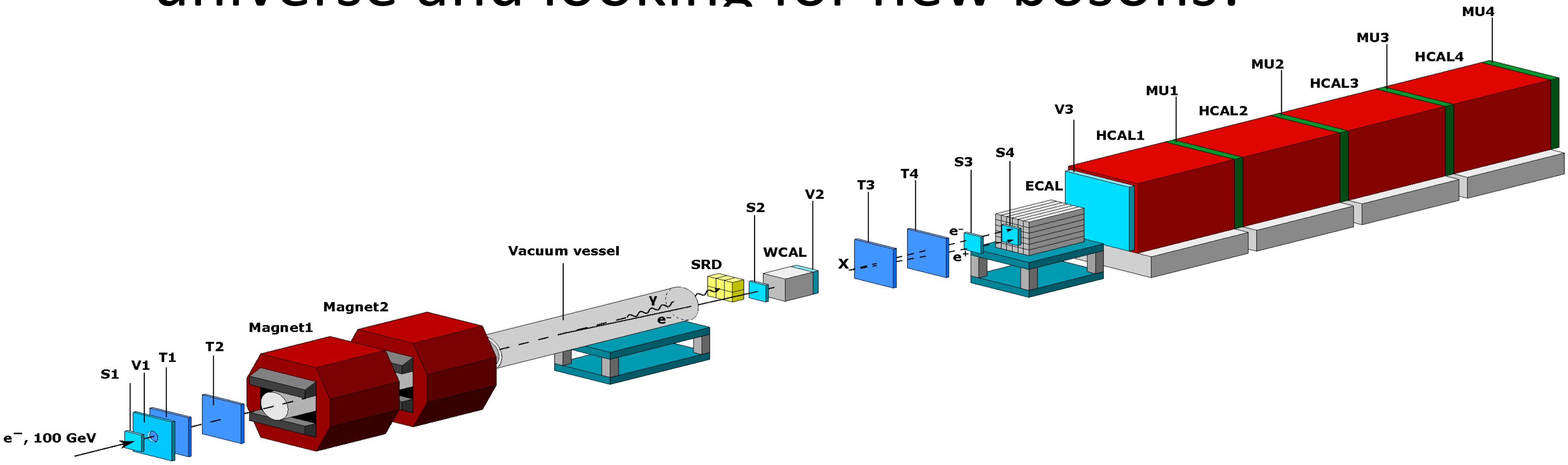




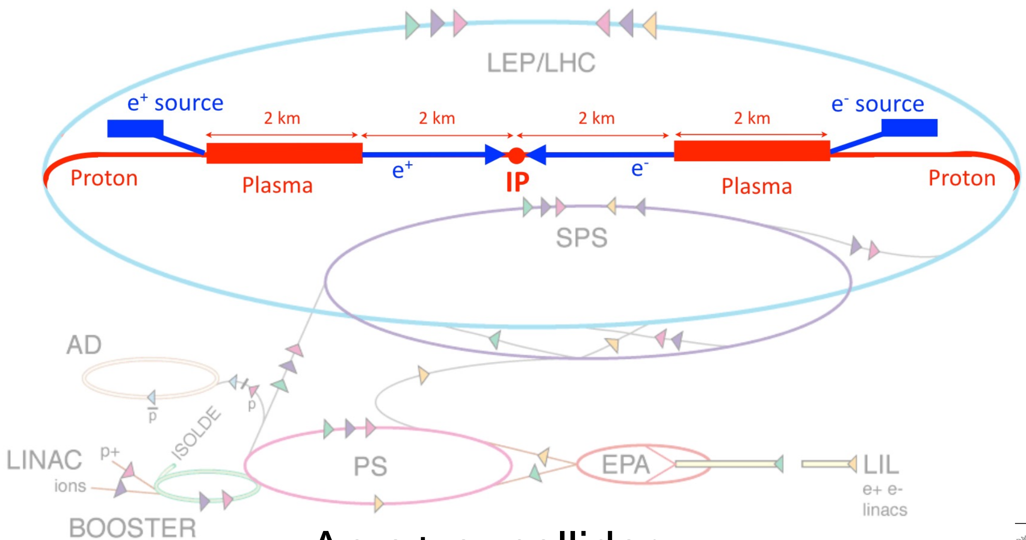
- ✧ Laser ionization of a metal vapor (Rb), 3-4m plasma for p+ SSM only, SEEDING NECESSARY!
- ✧~10m discharge or helicon source for acceleration only (scales to 100's m)
- ✧Inject short e- bunch ($\sigma_z << \lambda_{pe}$), quality of the bunch: ΔE/E, ε => beam loading and blow-out
- ✧Density step to maintain accelerating gradient

AWAKE Run 2c,2d (2028-203x)-> application

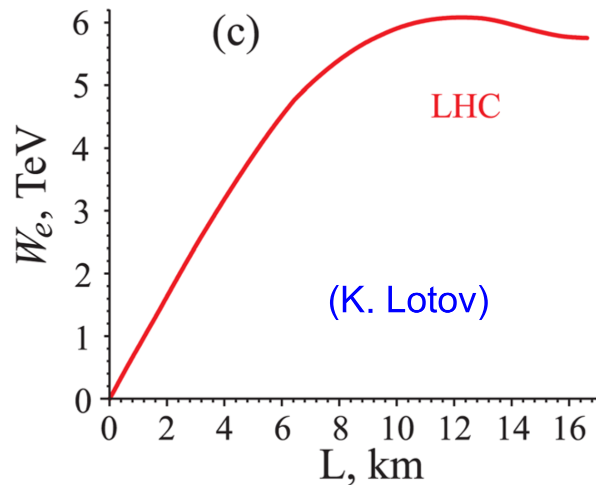
- A long and modular plasma cell to boost e- energy up to 100 GeV
- A fix target experiment at CERN (50-100 GeV electron), similar to NA64-dark side of the universe and looking for new bosons!



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



An e+ e- collider



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

ELSEVIER

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]

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[b] The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
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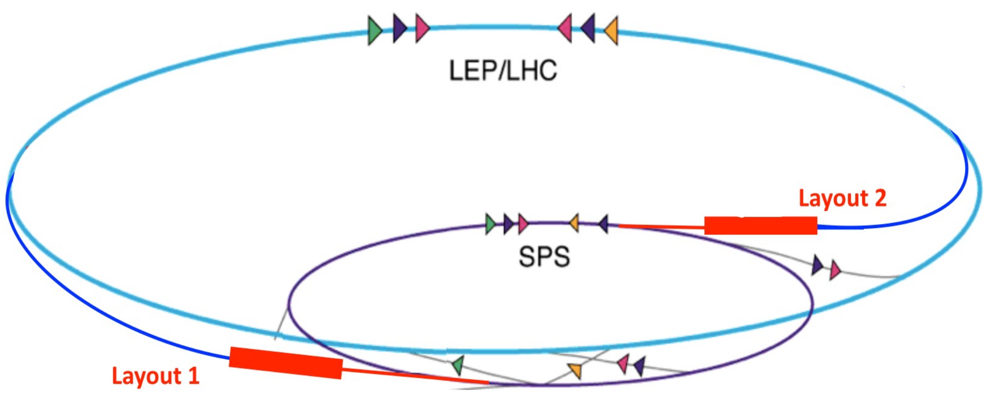
ARTICLE INFO

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

2022 fast plasma recovery time-60ns

Article

Recovery time of a plasma-wakefield accelerator

https://doi.org/10.1038/s41586-021-04348-8

Received: 30 June 2021

Accepted: 13 December 2021

Published online: 2 March 2022

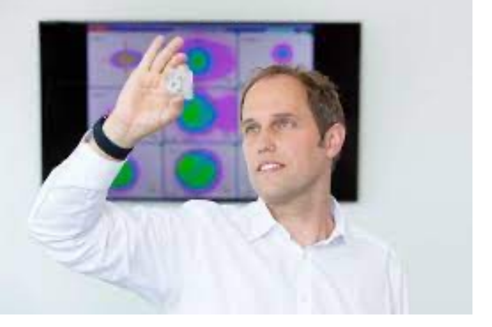
Open access

Check for updates

R. D'Arcy[1✉], J. Chappell[2], J. Beinortaite[1,2], S. Diederichs[1,3], G. Boyle[1], B. Foster[4], M. J. Garland[1], P. Gonzalez Caminal[1,3], C. A. Lindstrøm[1], G. Loisch[1], S. Schreiber[1], S. Schröder[1], R. J. Shalloo[1], M. Thévenet[1], S. Wesch[1], M. Wing[1,2] & J. Osterhoff[1]

The interaction of intense particle bunches with plasma can give rise to plasma wakes[1,2] capable of sustaining gigavolt-per-metre electric fields[3,4], which are orders of magnitude higher than provided by state-of-the-art radio-frequency technology[5].

Richard D'Arcy



Jens Osterhoff

Richard D'Arcy, et al., Nature 603, 58 (2022)

2022-PWFA driven FEL

Article

Free-electron lasing with compact beam-driven plasma wakefield accelerator

https://doi.org/10.1038/s41586-022-04589-1

Received: 11 June 2021

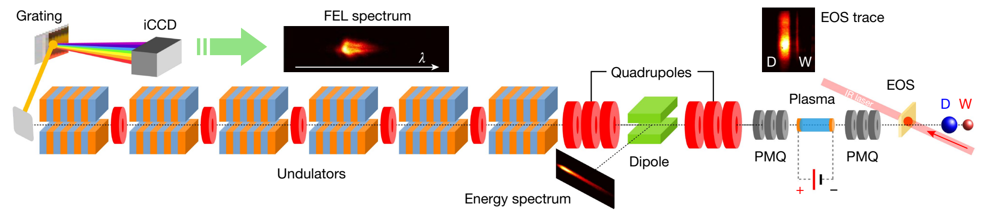
Accepted: 25 February 2022

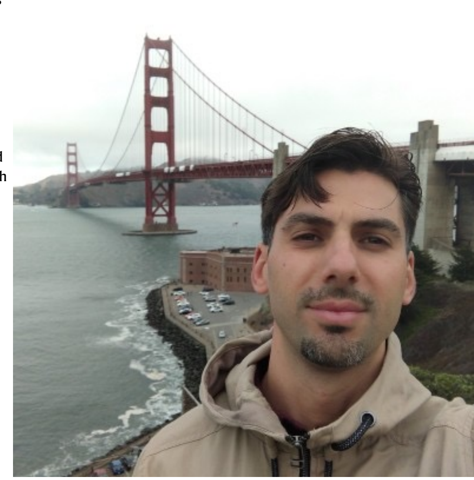
Published online: 25 May 2022

Check for updates

R. Pompili[1✉], D. Alesini[1], M. P. Anania[1], S. Arjmand[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], B. Buonomo[1], F. Cardelli[1], M. Carpanese[2], E. Chiadroni[1], A. Cianchi[3,4,5], G. Costa[1], A. Del Dotto[1], M. Del Giorno[1], F. Dipace[1], A. Doria[2], F. Filippi[2], M. Galletti[3,4,5], L. Giannessi[1], A. Giribono[1], P. Iovine[6], V. Lollo[1], A. Mostacci[7], F. Nguyen[2], M. Opromolla[8], E. Di Palma[2], L. Pellegrino[1], A. Petralia[2], V. Petrillo[8], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[8], J. Scifo[1], A. Selce[2], V. Shpakov[1], A. Stella[1], C. Vaccarezza[1], F. Villa[1], A. Zigler[1,9] & M. Ferrario[1]

The possibility to accelerate electron beams to ultra-relativistic velocities over short distances by using plasma-based technology holds the potential for a revolution in the field of particle accelerators[1–4]. The compact nature of plasma-based accelerators would allow the realization of table-top machines capable of driving a free-electron laser (FEL)[5], a formidable tool to investigate matter at the sub-atomic level by generating coherent light pulses with sub-ångström wavelengths and sub-femtosecond durations[6,7]. So far, however, the high-energy electron beams required to operate FELs had to be obtained through the use of conventional large-size radio-frequency (RF) accelerators, bound to a sizeable footprint as a result of their limited accelerating fields. Here we report the experimental evidence of FEL lasing by a compact (3-cm) particle-beam-driven plasma accelerator. The accelerated beams are completely characterized in the six-dimensional phase space and have high quality, comparable with state-of-the-art accelerators[8]. This allowed the observation of narrow-band amplified radiation in the infrared range with typical exponential growth of its intensity over six consecutive undulators. This proof-of-principle experiment represents a fundamental milestone in the use of plasma-based accelerators, contributing to the development of next-generation compact facilities for user-oriented applications[9].





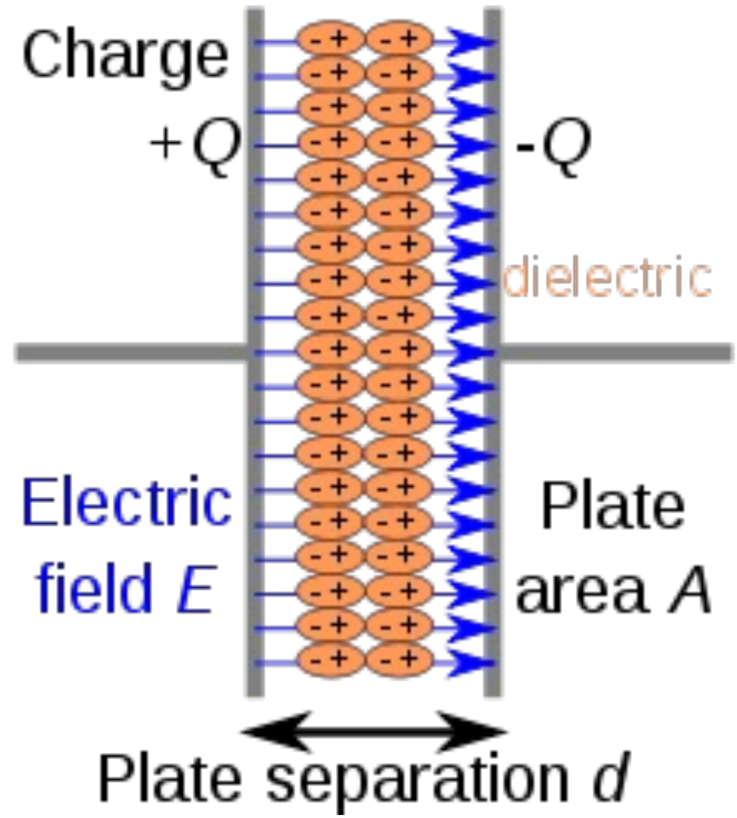
R. Pompili et al., Nature 605, 659 (2022)

Riccardo Pompili

Massimo Ferrario

Why dielectrics?

- A **dielectric material** is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in a conductor, but only slightly shift from their average equilibrium positions causing **dielectric polarization**



Why dielectrics?

- Dielectric strength of an insulating material is the maximum electric field that a pure material can withstand under ideal conditions without breaking down (i.e., without experiencing failure of its insulating properties).
- For example, dielectric strength for diamond is about 2000 MV/m. For the fused silica (SiO_2) is about 1500 MV/m

Dielectric Laser Accelerators (DLA)

S-Band RF

***f* = 2-4 GHz, λ= 10-20 cm**

metal

X-Band RF

***f* = 8-12 GHz, λ= 2.5-3.75 cm**

metal

Optical

***f* ≈10-100 THz, λ ≈1-10 μm**

dielectric materials

RF structures

- high gradient

- machining tolerance
- transverse wakefield
- breakdown ($E_z \leq 100$ MV/m)

Laser-driven photonic crystal

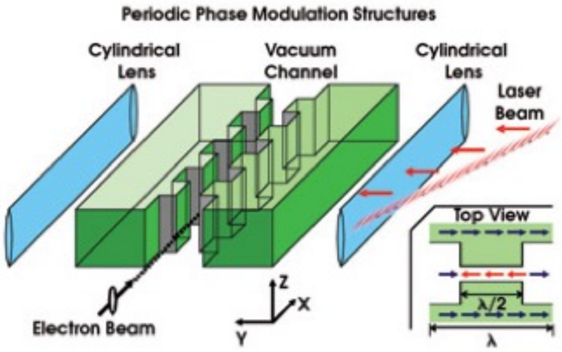
- higher field gradient (1 GV/m)
- Dielectric : high breakdown threshold (1-5 GV/m)

Typical structures of DLA

Phase Mask Structure

Silica, λ=800nm, Ez=830 MV/m

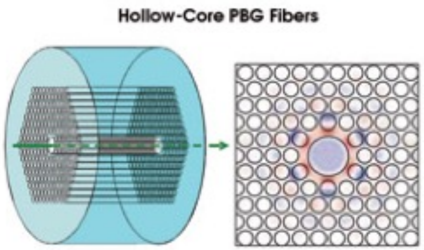
T. Plettner, *et al, PRST-AB,* **9**, 111301 *(2006).*



Wave Guiding Structures

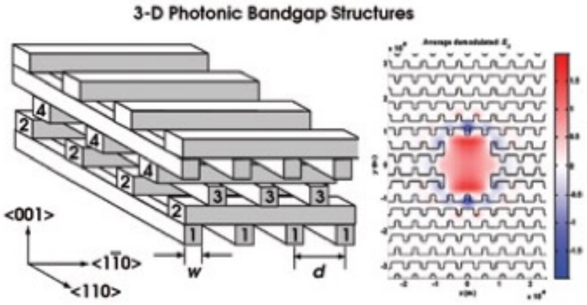
Silica, λ=1890 nm, E =400 MV/m

X. Lin, *PRST-AB,* **4**, 051301 (2001).

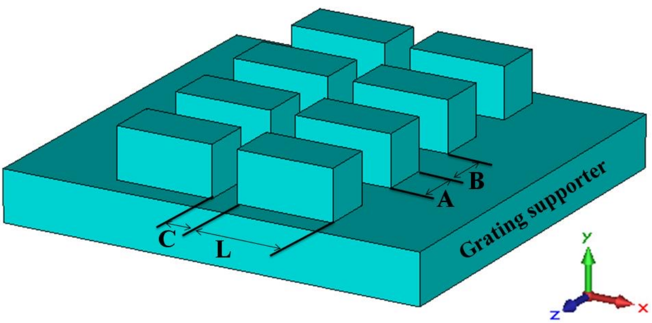


Silicon, λ=2200nm, Ez=400 MV/m

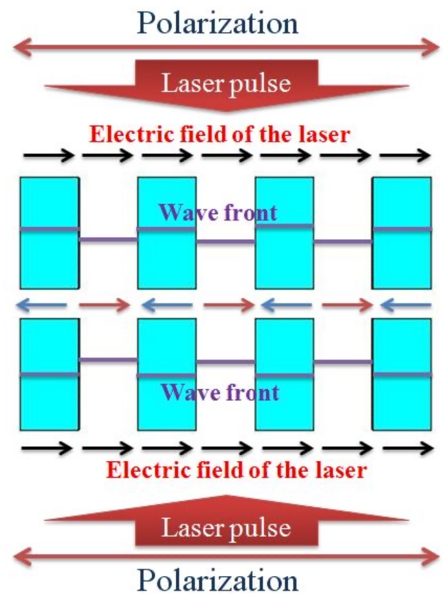
B. Cowan, *et al*, *PRST-AB,* **11**, 011301 (2008).



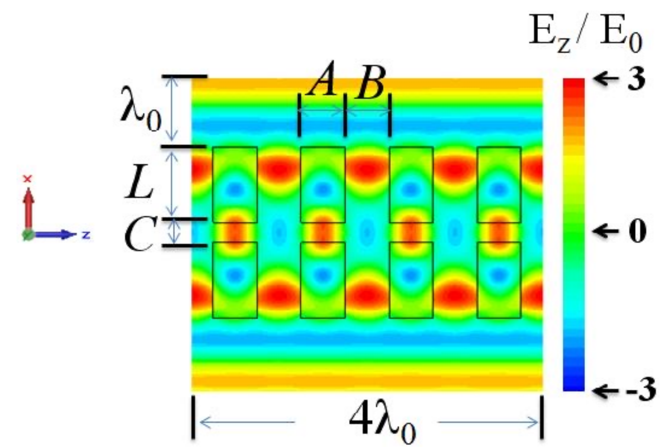
Dielectric dual-grating structure



Structure overview



Working principle



Simulation result

Laser driven dielectric accelerators

LETTER

doi:10.1038/nature12664

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

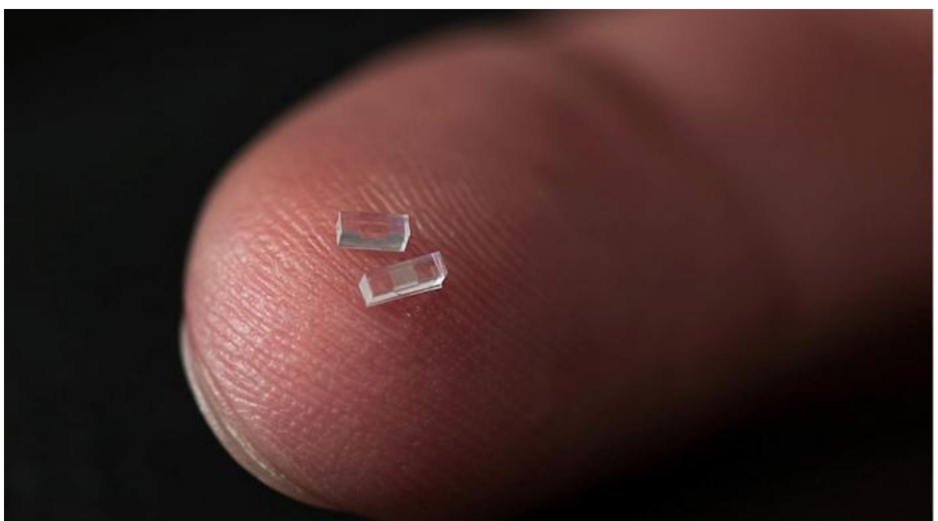
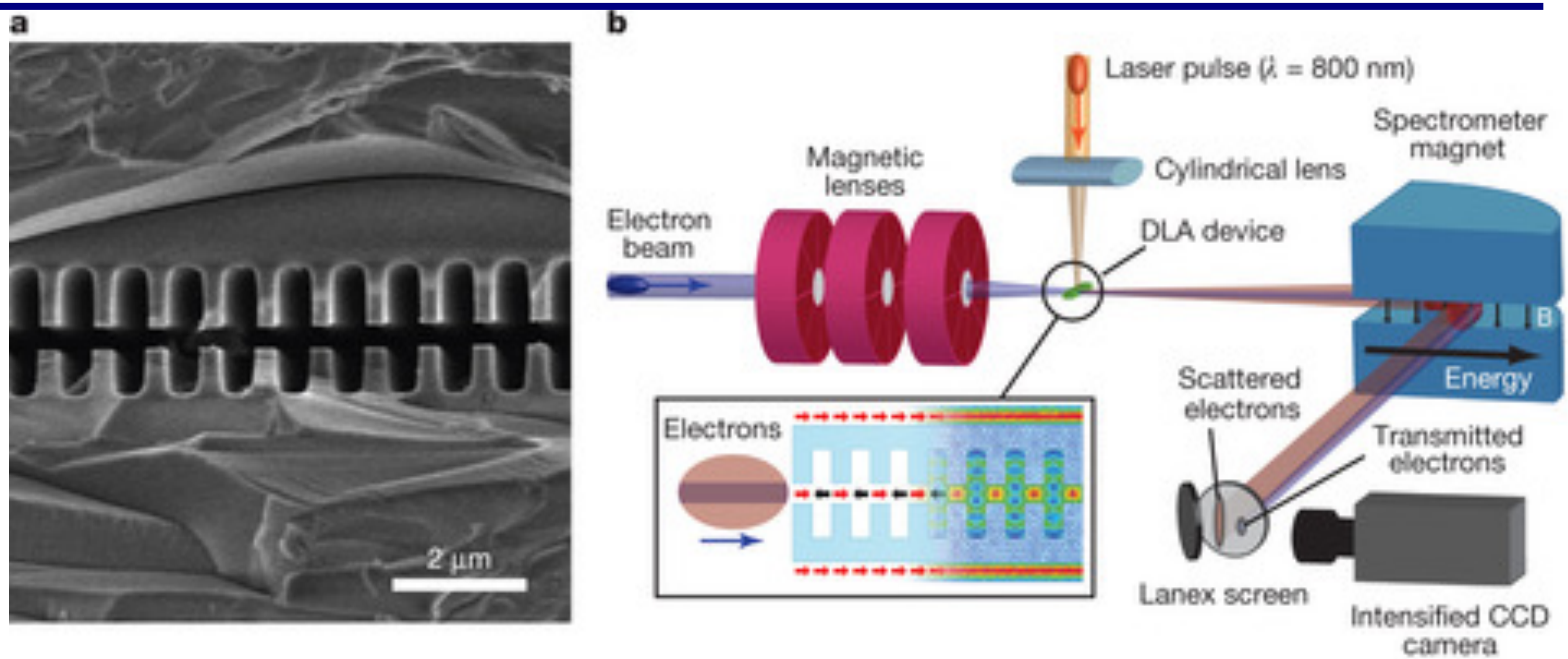


Photo by Brad Plummer, SLAC (2013)

Laser driven dielectric acceleration

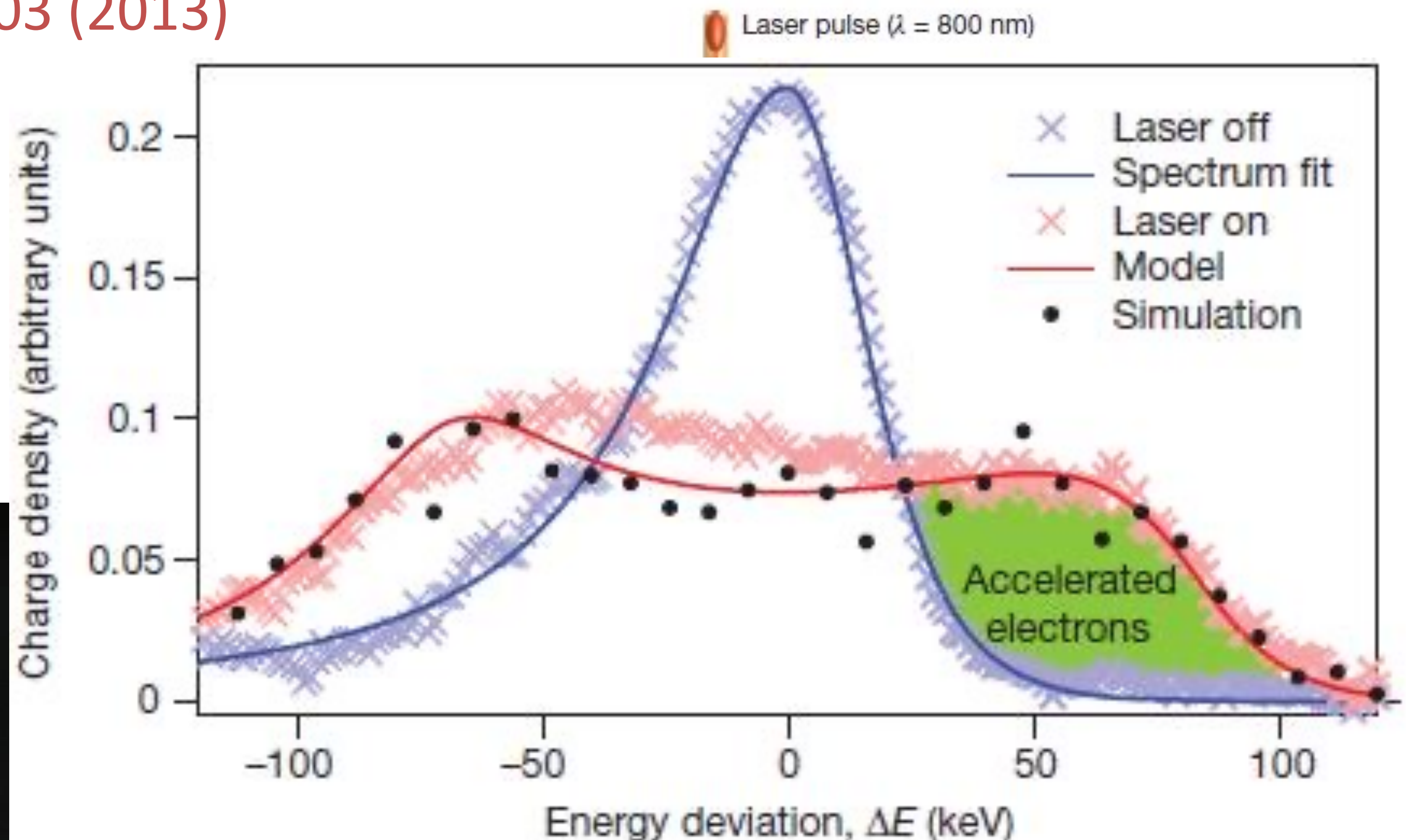


Scanning electron microscope image of the longitudinal cross-section of a DLA structure fabricated as depicted in Extended Data Fig. 1a. Scale bar, 2 µm. b, Experimental set-up.

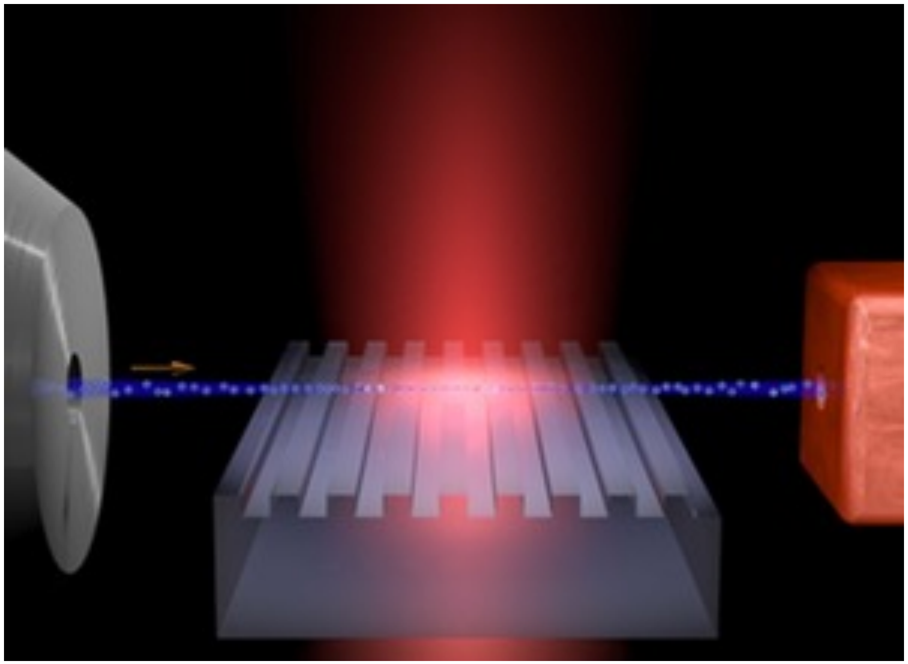
60 MeV injected electron beams;
250 MeV/m accelerating field;
~ 563 optical period in structures;
1e6 electrons

Milestone experiment

E. A. Peralta1 *et al*. NATURE
VOL 503 (2013)



One more step forward (nonrelativistic beam)



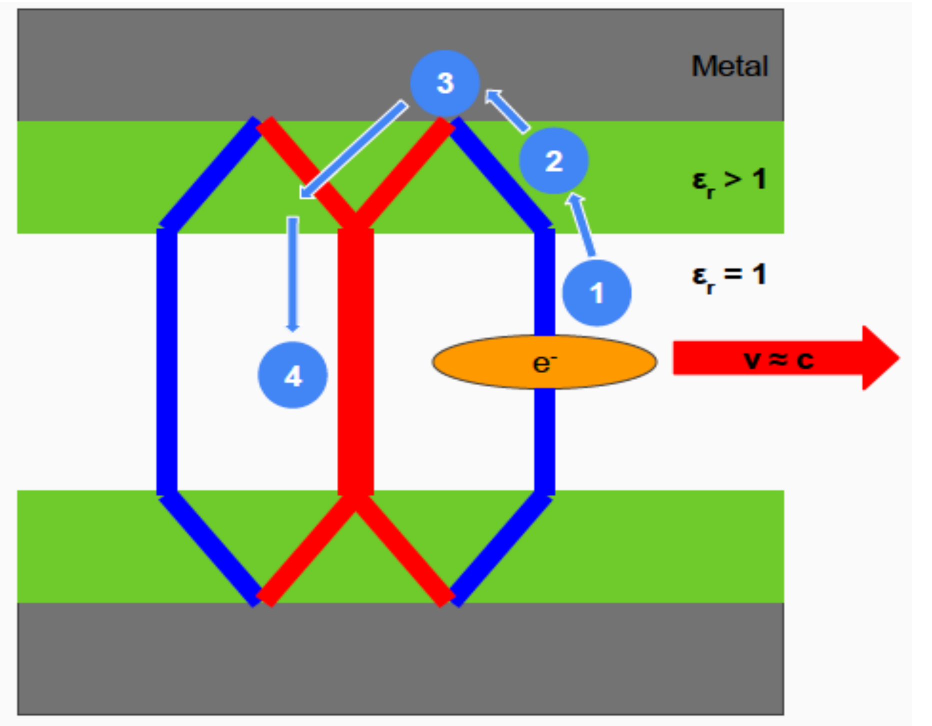
Electron source: 28 keV

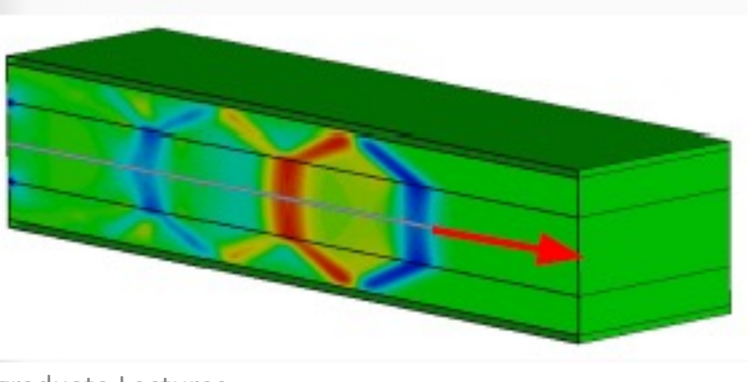
Observed maximum acceleration gradient: 25 MeV/m

John Breuer and Peter Hommelhoff
Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure
Phys. Rev. Lett. **111**, 134803 (2013)

Beam driven dielectric acceleration

1) Relativistic electron bunch with ‘pancake’ electric field
2) Image charge created in dielectric, cannot propagate at c due to $\varepsilon_r > 1$
3) The field is reflected at the metal layer
4) The field is coupled back to the vacuum behind the drive bunch, with a sign shift

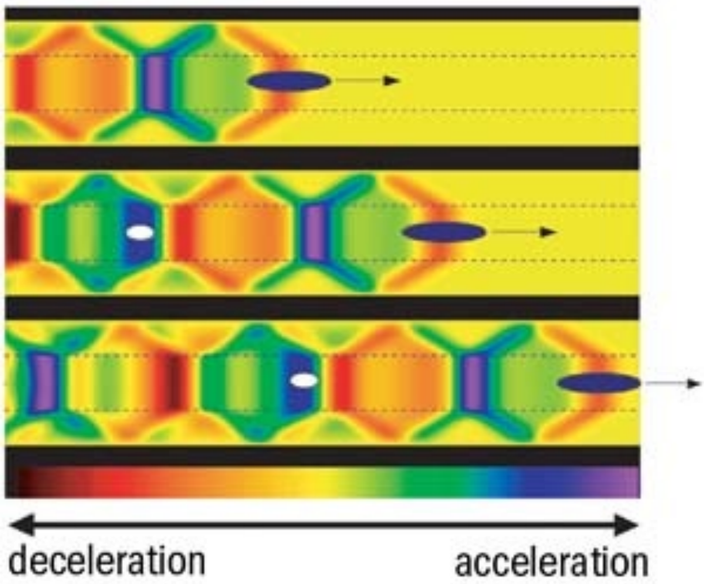




T. Pacey

Beam driven dielectric accelerators

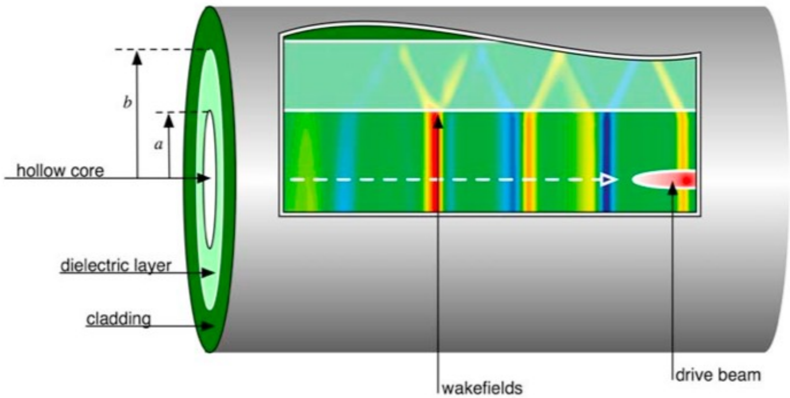
- High gradient DWA applications
  - HEP
  - Radiation Source
  - Advanced accelerator for future FEL
    - ~GV/m fields reduce size of machine
    - Larger scales (THz), relax emittance, higher charge beams
- Relevant Issues in DWA research
  - Determine achievable field gradients
  - High energy gain in acceleration
  - Transformer ratio enhancement
  - Resonant excitation of structure
  - Dielectric/metal heating issues
  - Cladding composition, dielectric material and thickness
  - Alternate geometries (planar)
  - Periodic structure development (1D, 3D)
  - Transverse modes and beam-breakup



$$E \sim \frac{N_b}{\sigma_z^2}$$

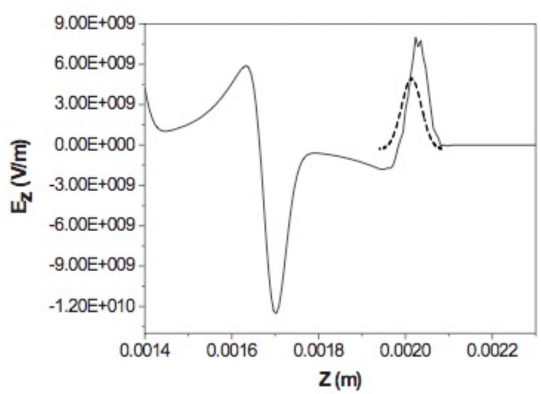
Accelerating gradient scales with high charge, short beams

Dielectric wakefield accelerators



- Electron bunch (β ≈ 1) drives wake in cylindrical dielectric structure
  - Dependent on structure properties
  - Generally multi-mode excitation
- Wakefields accelerate trailing bunch

- Design Parameters a,b σ_z ε



Ez on-axis, OOPIC

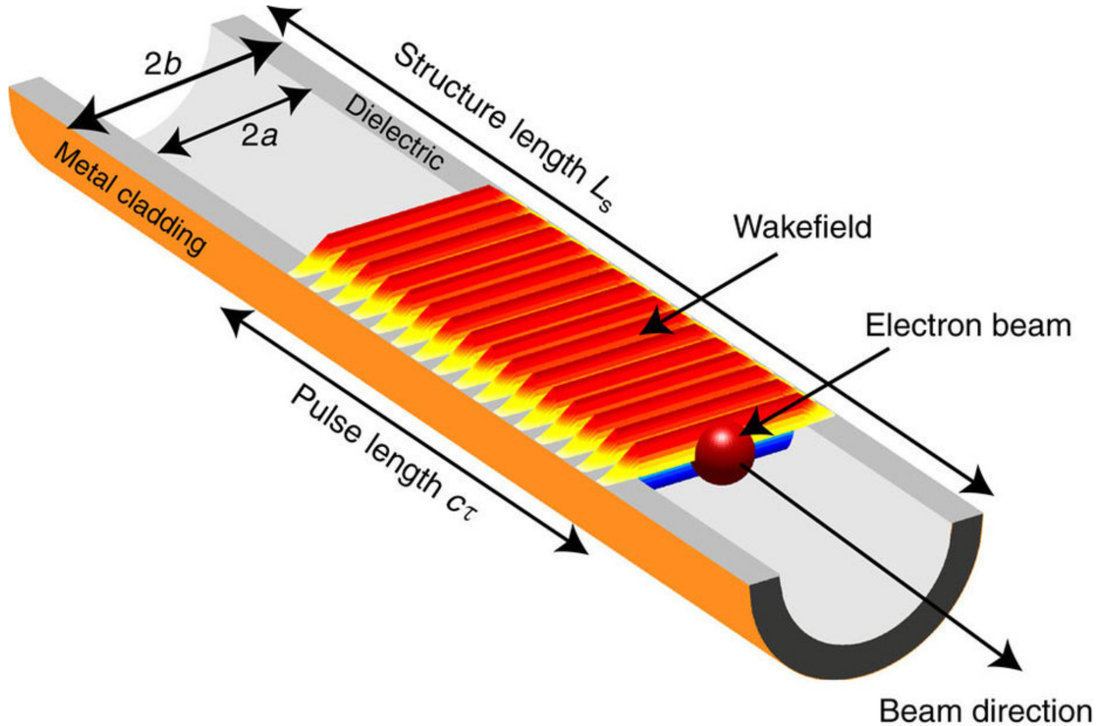
- Peak decelerating field

$$eE_{z,dec} \approx \frac{-4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}\varepsilon\sigma_z} + a\right]}$$

- Transformer ratio (unshaped beam)

$$R = \frac{E_{z,acc}}{E_{z,dec}} \leq 2$$

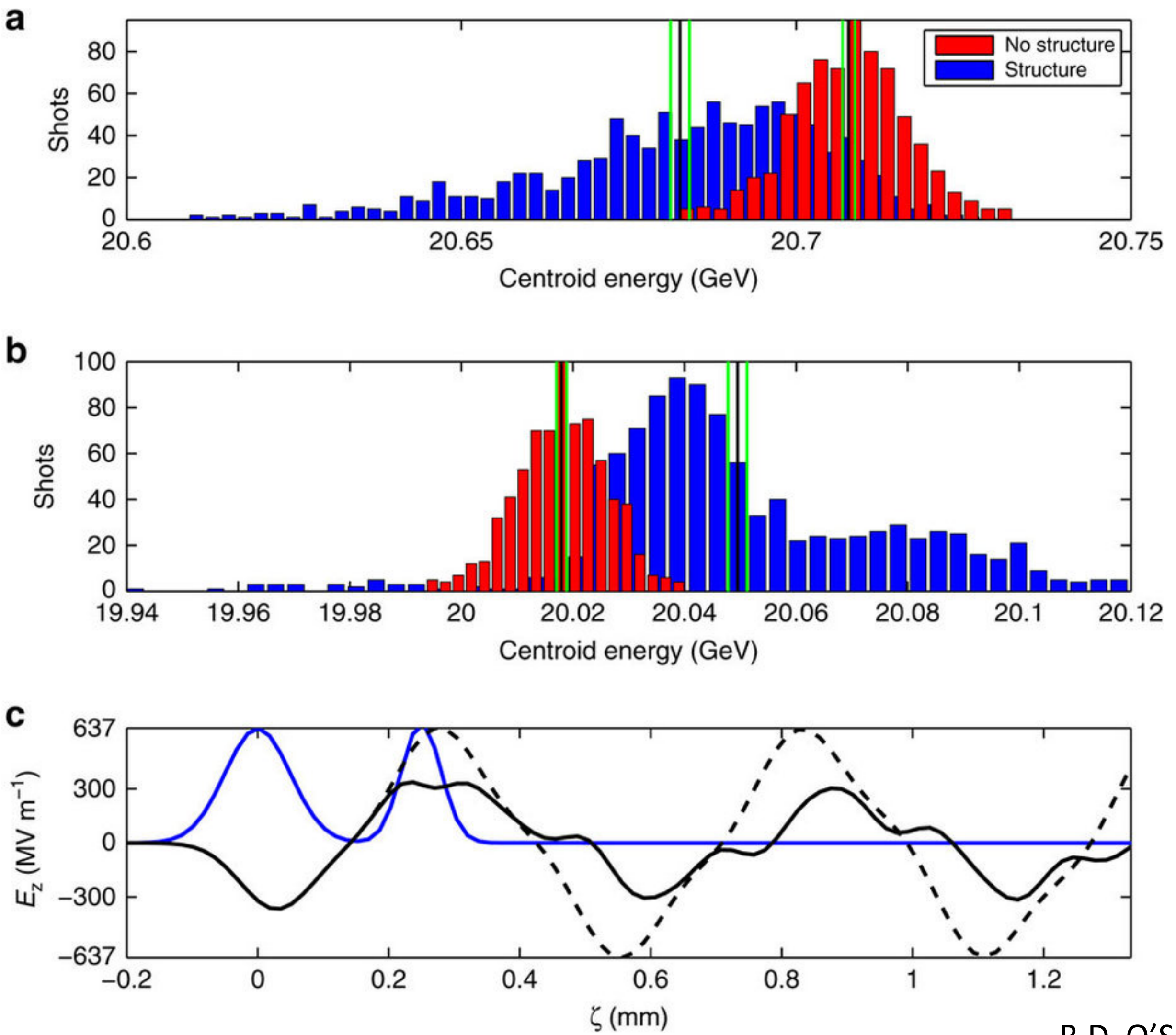
Recent results from FACET (2016)



A cutaway view with the dielectric shown in grey and metal cladding in copper. The beam (dark red) travels along the structure in the vacuum region, leaving an idealized accelerating wakefield Ez shown in a colour intensity map (red to blue). The wakefield inside of the excited wave-train is shown as constant in magnitude as a function of distance behind the beam, consistent with theory and simulation assuming lossless media.

B.D. O'Shea et al., Nat. Commun. 7: 12763 (2016).

Recent results from FACET (2016)



Histogram of centroid energy of (a) the driver and (b) witness bunch. Blue and red indicate measurements made with and without the structure, respectively. A mean decelerating gradient of 252±14 MeV m^{-1} is observed in the driver; a mean accelerating gradient of 320±17 MeV m^{-1} is seen by the witness. (c) Theoretical prediction of wake from beam current (blue), with (black) and without (dashed) witness beam.

B.D. O'Shea et al., Nat. Commun. 7: 12763 (2016).

DWA experiment at DL

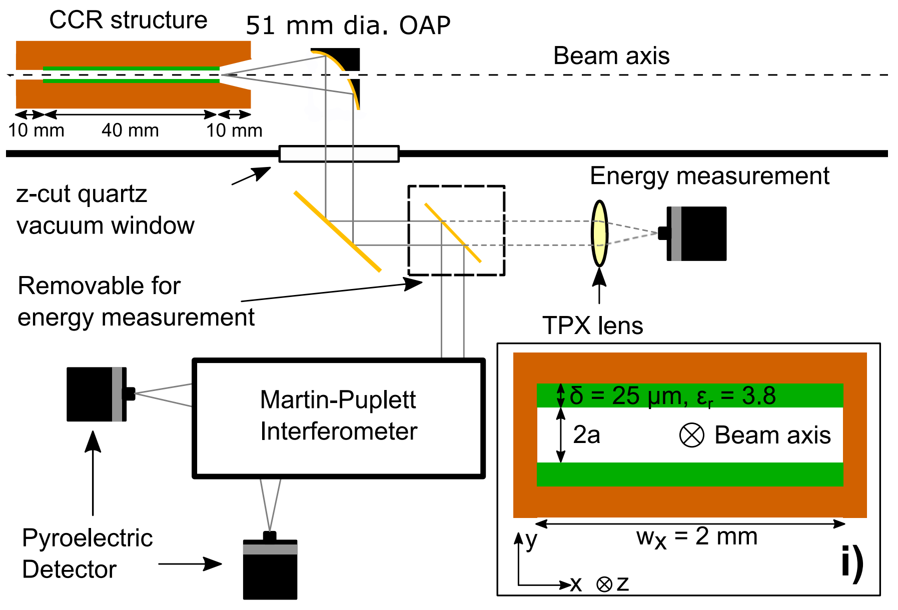
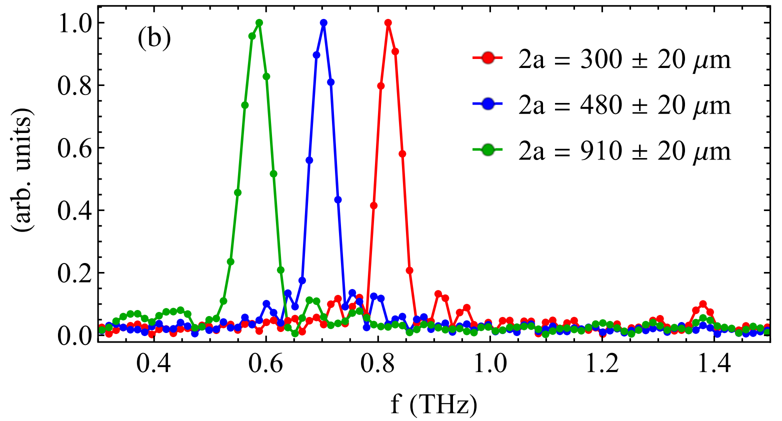
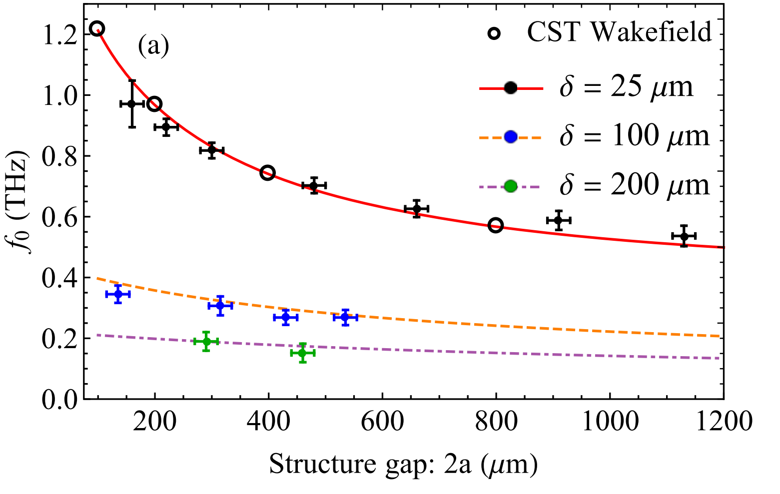


FIG. 1. Experimental setup. The CCR was collected by a 51 mm diameter off axis parabolic (OAP) mirror with a hole to pass the electron beam. TPX lenses were used for focusing of the CCR onto the detectors. All mirrors were gold coated and polished to optical finish. An additional pyroelectric detector (not shown) was used for shot-to-shot subtraction of environmental noise. Inset i), cross-section of the DLW with coordinate system and parameter notation.





T. Pacey et al., Phys. Rev. Accel. Beams 22 (9), 091302 (2019)

THz driven dielectric structures

- **Terahertz (THz) radiation** falls in between infrared radiation and microwave radiation in the electromagnetic spectrum
- **Terahertz radiation** – also known as **submillimeter radiation**, **terahertz waves**, **tremendously high frequency**, consists of electromagnetic waves within the frequency bands from 0.3 to 3 terahertz (THz; 1 THz = 10^{12} Hz). Wavelengths of radiation in the terahertz band correspondingly range from 1 mm to 0.1 mm

THz driven dielectric structures

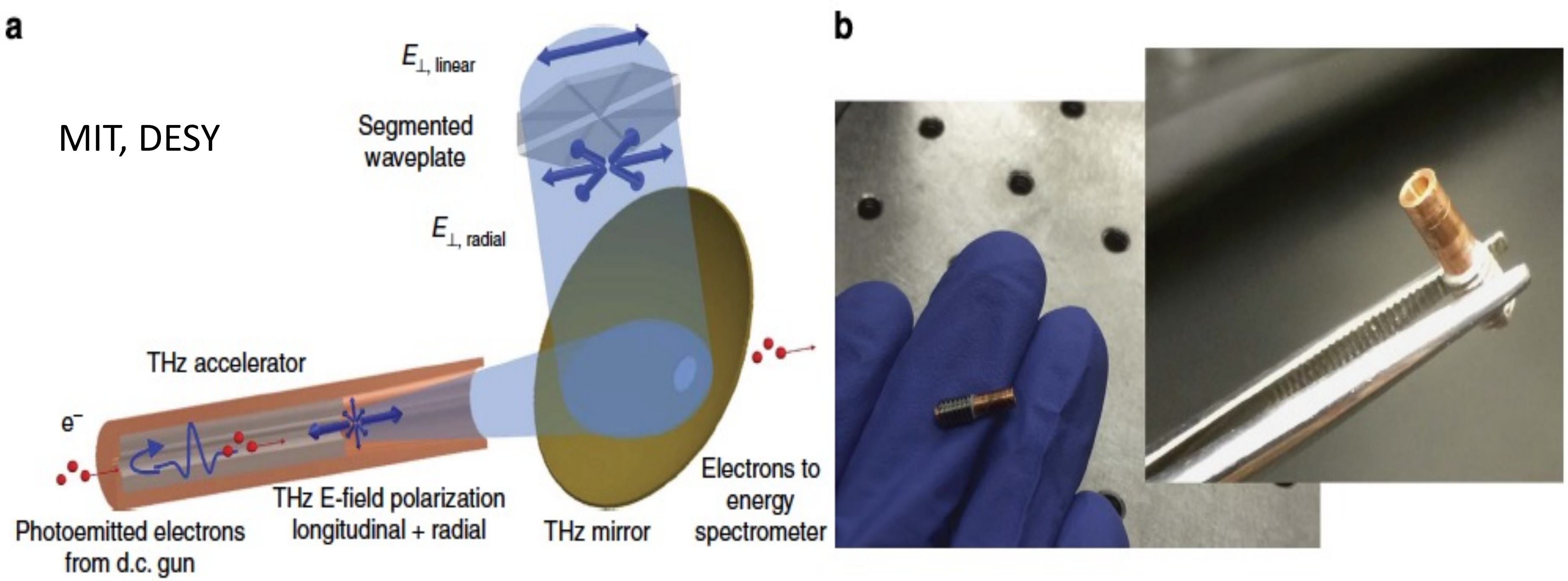


Figure 1 | Terahertz-driven linear accelerator. (**a**) Schematic of the THz LINAC. Top right: a linearly polarized THz pulse is converted into a radially polarized pulse by a segmented waveplate before being focused into the THz waveguide. The THz pulse is reflected at the end of the waveguide to co-propagate with the electron bunch, which enters the waveguide through a pinhole (lower left). The electron bunch is accelerated by the longitudinal electric field of the co-propagating THz pulse. The electron bunch exits the THz waveguide and passes through a hole in the focusing mirror (right) for the THz pulse. (**b**) Photograph of the compact millimetre scale THz LINAC. (**c**) The time-domain waveform of the THz pulse determined with electro-optic

E. A. Nanni et al., THz driven linear acceleration, Nat. Commun. 6, 8486 (2015)

THz driven dielectric structures

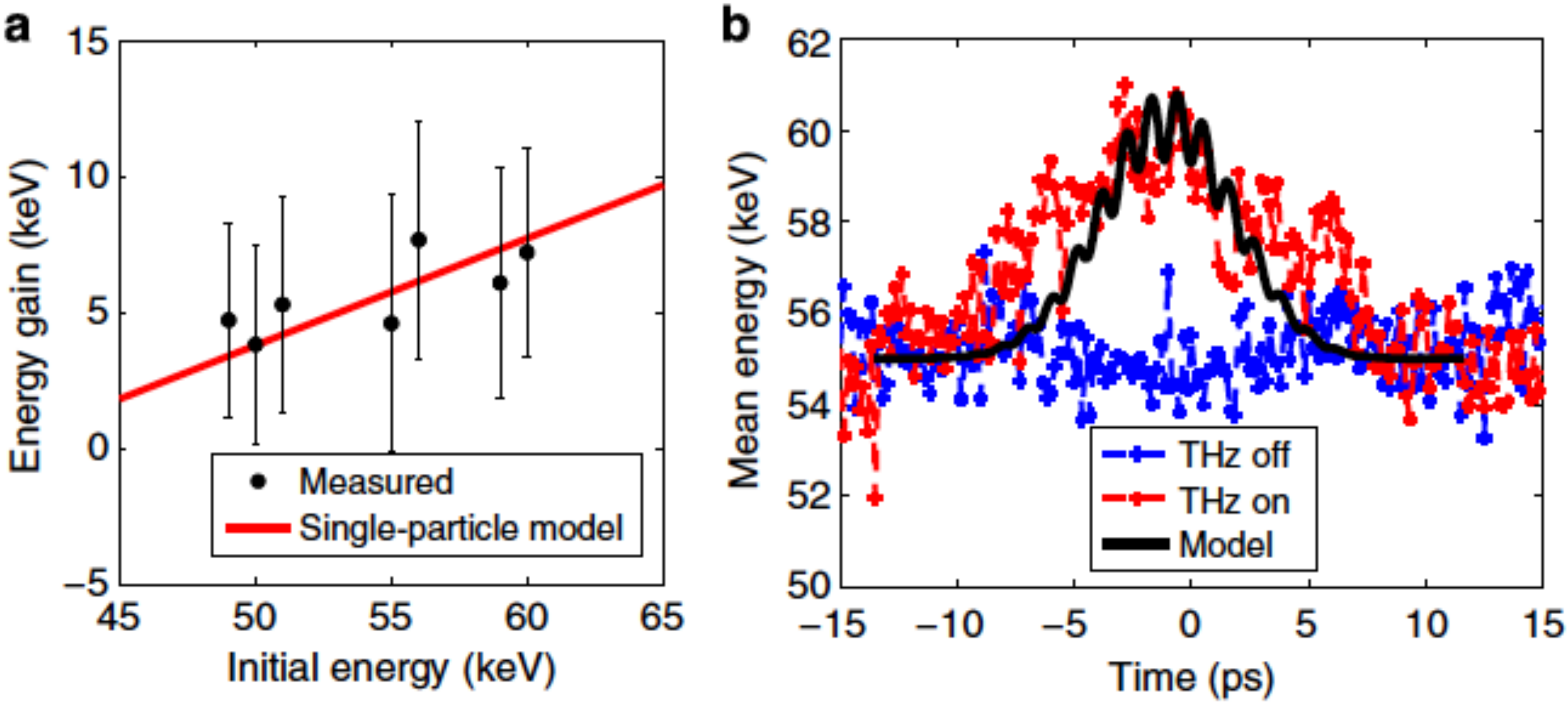


Figure 3 | Acceleration gradient and terahertz phasing. (**a**) Scaling of energy gain for accelerated electrons as a function of the initial electron energy at the entrance of the THz LINAC. Black dots with one s.d. error bars are measured values and the red line is a single-particle model. (**b**) The temporal profile for the mean energy gain of accelerated electrons comparing the THz on and THz off signal against the simulated electron bunch. The initial electron energy was set at 55 keV to ensure stable performance of the d.c. electron gun over the acquisition time of the data set.

Accelerating gradient: 2.5MV/m!

E. A. Nanni et al., THz driven linear acceleration, Nat. Commun. 6, 8486 (2015)

THz driven dielectric structures

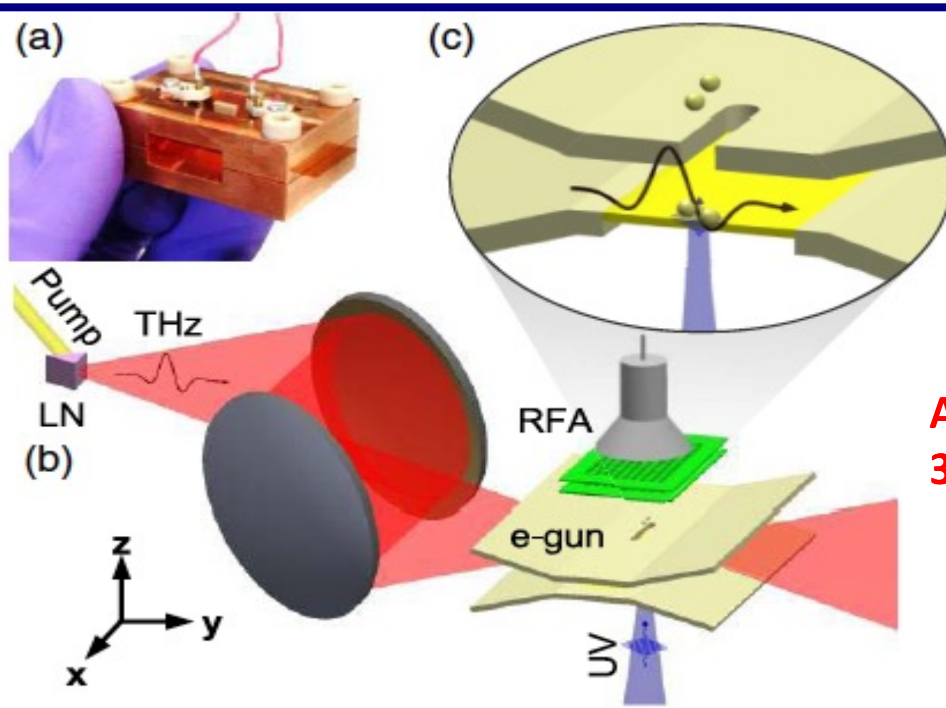


Fig. 1. THz gun concept. (a) Photograph of the THz gun; (b) a single-cycle THz pulse, generated via optical rectification in lithium niobate (LN), is coupled into the THz gun, which takes the form of a parallel-plate waveguide for field confinement. A UV-backilluminated photocathode emits an electron bunch, which is accelerated by the THz field. The bunch exits through a slit on the top plate, and a retarding field analyzer (RFA) measures its energy spectrum. (c) Cross section of the gun, showing the UV-photoemitted electrons accelerated by the THz field and exiting through the slit.

Accelerating field: 300 MV/m!

MIT, DESY

Huang et al., Terahertz driven all optical electron gun, Optica 3, 1209 (2016)

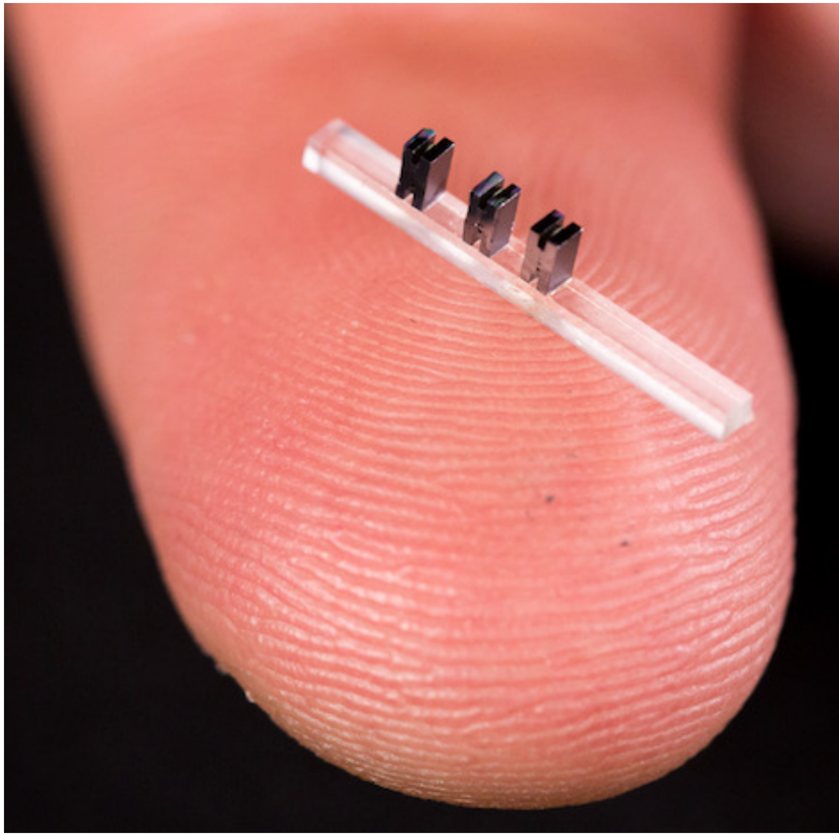
Conclusions and future perspectives

- PWFAs have several advantages over LWFAs due to their intrinsic properties
- The experiments at SLAC (FFTB, FACET/FACET-II) have achieved many milestones on electron and positron driven PWFAs
- AWAKE experiment has demonstrated electron acceleration for PDPWFA
- Proton driven PWFA will advance the future collider design in a single stage
- Dielectric laser accelerators have demonstrated several hundreds MV/m field
- THz driven structures have recently achieved 300 MV/m accelerating field
- Beam driven dielectric accelerators can produce THz radiation, accelerate a second witness beam efficiently and de-chirp the drive beam energy
- **The extensive short wavelength accelerator R&D will open the doors to many compact, cheap and advanced accelerators for research and applications (radiation sources, colliders, medical, biology, etc.).**

Learning objectives-Lecture II

- ✓ Why beam driven PWFA and how it works
- ✓ Electron driven PWFA experiments
- ✓ Positron driven PWFA experiments
- ✓ Why proton driven PWFA and how it works
- ✓ Why dielectrics and how it works
- ✓ Future perspectives

Small is good !



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THANKS FOR YOUR ATTENTION!