Review of Plasma Accelerators

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STFC Rutherford Appleton Laboratory,
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ICFA Mini-Workshop on Future Gamma-Gamma Collider, Beijing 2017

Brief Overview of Plasma Accelerators

1) Laser Plasma Accelerators
2) Electron/Positron beam-induced Plasma Wakefield Accelerator PWFA.
3) Ion beam-induced Plasma Wakefield Accelerators PWFA.

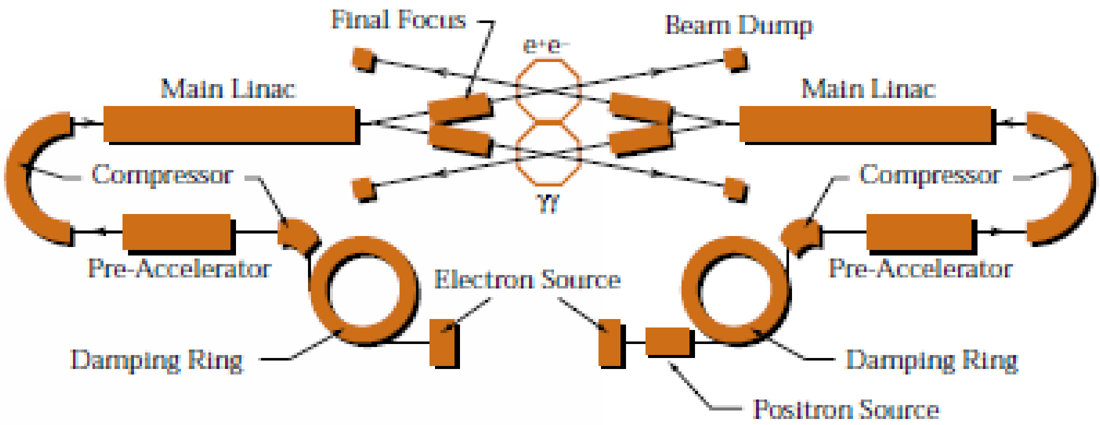
Extremely high accelerating gradients:1-100GeV/m

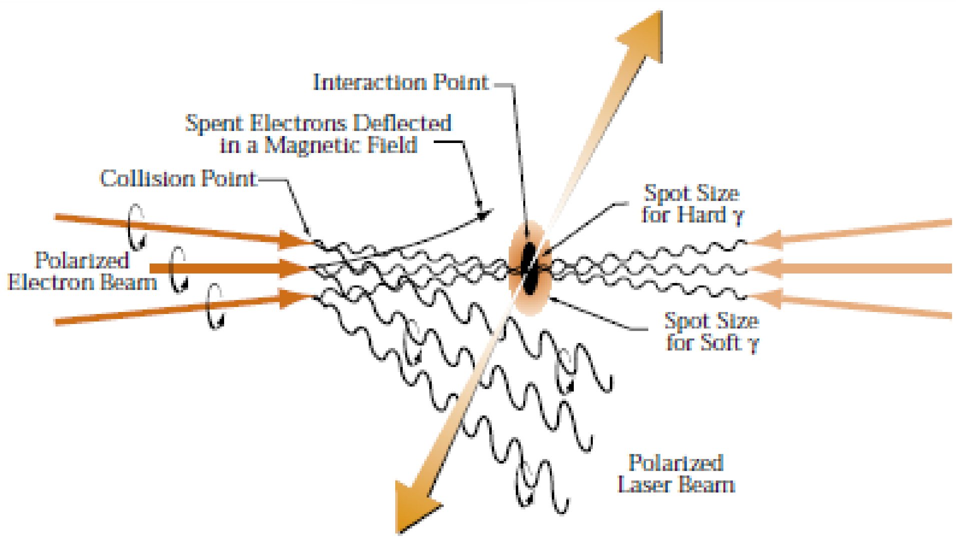
Transient Structures: few ps

Microscopic: 10-100 micron wavelengths

Gamma-Gamma Colliders

In the early 90's D Miller asked if plasma accelerators could replace the Linac in a gamma-gamma Collider.





Kim, Sessler 1996

Gamma-Gamma Collider parameters

Electron beam parameters:

Electron energy	250 GeV
Repetition rate	90 bunches separated by 1.4 ns, 180 Hz
Particles per bunch	$N_e = 0.65\times10^{10}$
Normalized rms emittance	$\gamma\varepsilon_x = 5\times10^{-6}$m - r, $\gamma\varepsilon_y = 8\times10^{-8}$m - r
Beta function at the IP	$\beta_x^* = \beta_y^* = 0.5$ mm
Rms bunch length	$\sigma_z = 0.1$ mm
Polarization	Fully polarized with helicity switching capabiity
CP-IP distance	b = 5 mm

Laser beam parameters:

Wave length	$\lambda = 1.053\mu$m
Micropulse energy	A = 1 J
Rayleigh length	$Z_R = 0.1$ mm
Rms micropulse length	$\sigma_{Lz} = 0.23$ mm
Peak power	0.5 TW
Average power	16.2 kW
Polarization	Fully polarized with helicity switching capability

Laser wakefield accelerators (LWFAs)

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

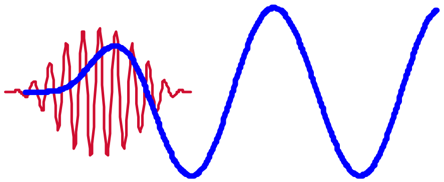
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Tajima *et al*, PRL, 1979

Laser Wakefield Acceleration

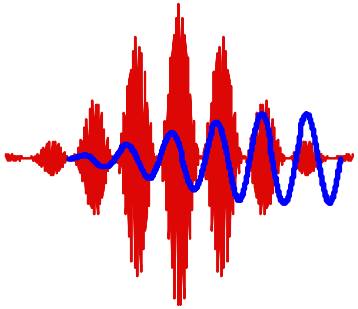
- Laser Wake Field Accelerator(LWFA)

  A single short-pulse of photons



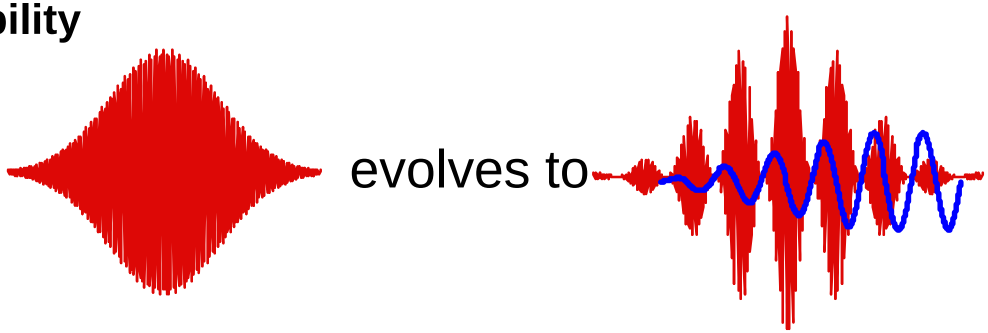
- Plasma Beat Wave Accelerator(PBWA)

  Two-frequencies, i.e., a train of pulses



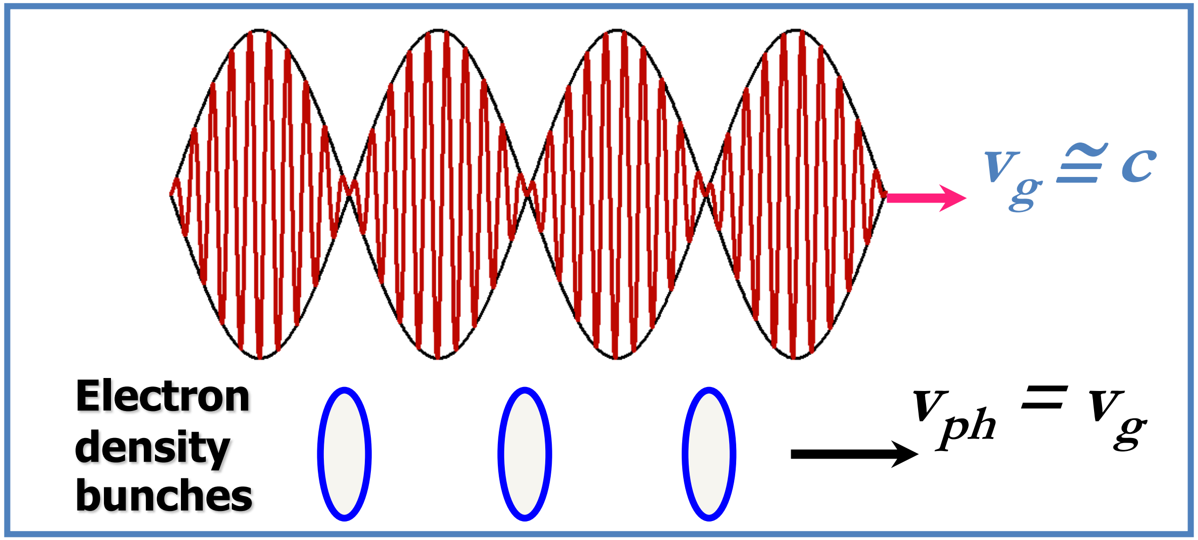
- Self Modulated Laser Wake Field Accelerator(SMLWFA)

  Raman forward scattering instability



Plasma Beat Wave Accelerator (PBWA)

- In the Plasma Beat Wave Accelerator (PBWA) a relativistic plasma wave is resonantly excited by the “ponderomotive” force of two lasers separated by the plasma frequency ω_p.
- The two laser beams beat together forming a modulated beat pattern in the plasma.



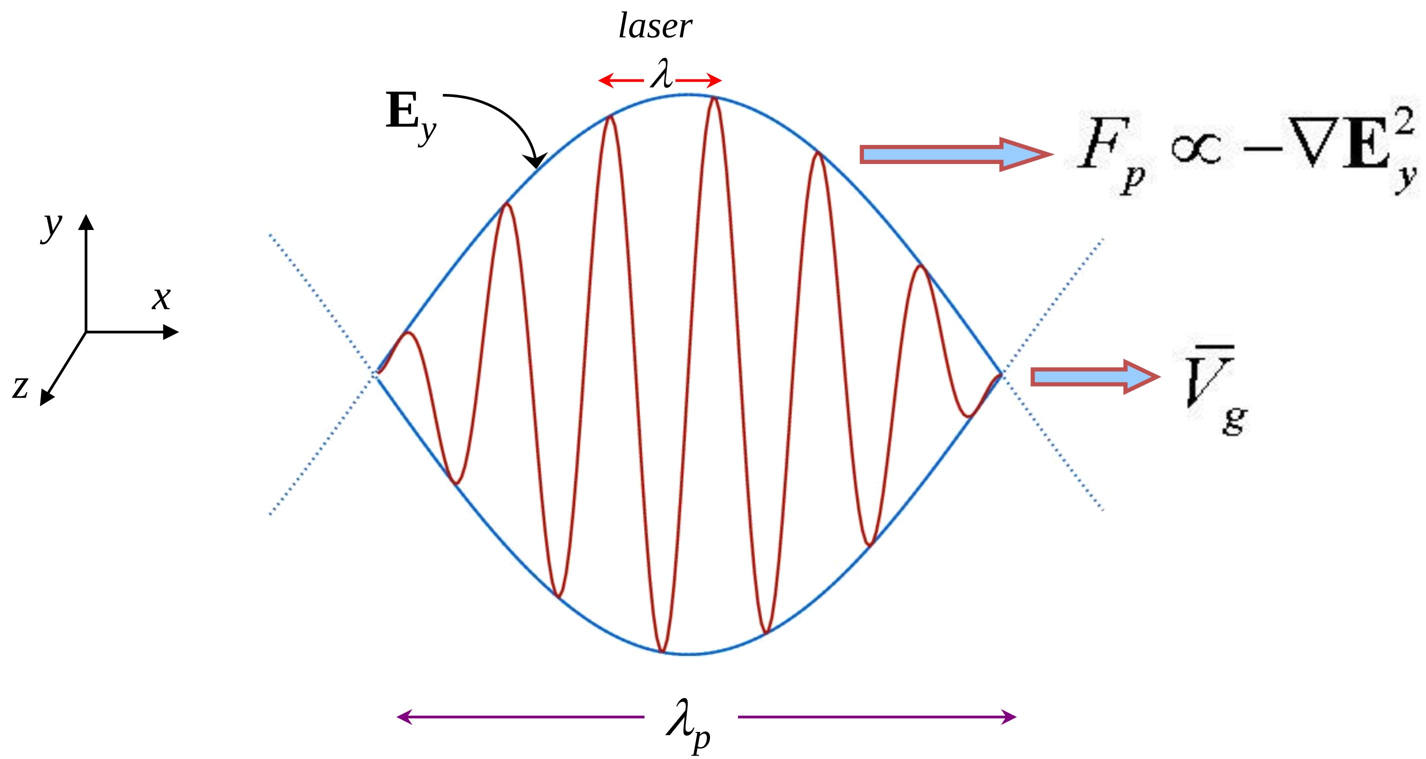
- For relativistic plasma wave the accelerating field $E_{||}$ is given by

$$E_{\|} = \varepsilon\sqrt{n_0} \quad \text{V/cm}$$

ε is the fractional electron density bunching, n_0 is the plasma density. For n_0 = 10^{18} cm^{-3}, ε = 10% $\Rightarrow$

$$E_{\|} = 10^8 \text{ V/cm}$$

Plasma Beat Wave



- Envelope of high frequency field moving at group speed $\underline{v}_g$

$$\underline{v}_g = c\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2} \quad \left.\right\} \quad \begin{aligned} &\omega^2 = \omega_{pe}^2 + c^2k^2 \\ &v_g = \frac{d\omega}{dk} = \frac{c^2k^2}{\omega} = c\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{1/2} \end{aligned}$$

- Ponderomotive force $F_p \propto -\nabla \mathbf{E}_y^2$ Laser field $\mathbf{E}_y$

Laser Plasma Accelerators

- The electric field of a laser in vacuum is given by

$$E_\perp = 30\sqrt{I} \ \ \text{V/cm}$$

- For short pulse intense lasers,

$$P = 10 \text{ TW}, \ \ \lambda_0 = 1 \ \mu\text{m}, \ \ I = 1.6\text{x}10^{18} \ \ \text{W/cm}^2$$

$$E_\perp = 40 \ \ \text{GV/cm}$$

- Unfortunately, this field is perpendicular to the direction of propagation and no significant acceleration takes place.
- The longitudinal electric field associated with electron plasma waves can be extremely large and can accelerate charged particles.

Beat wave generation

For the plasma beat wave the equation for the plasma wave can easily be derived by introducing slowly varying amplitudes describing the laser field,

$$\mathbf{E}_{1,2} = Re\mathbf{E}'_{1,2}(x,t)\exp\{i(k_{1,2}x - \omega_{1,2}t)\}$$

and the electron density perturbation as,

$$\delta n_e = n_e - n_o = Re\delta n'_e(x,t)\exp\{ik_p x\}$$

Note we have not separated the timescales in the density perturbation since this mode can be strongly nonlinear.

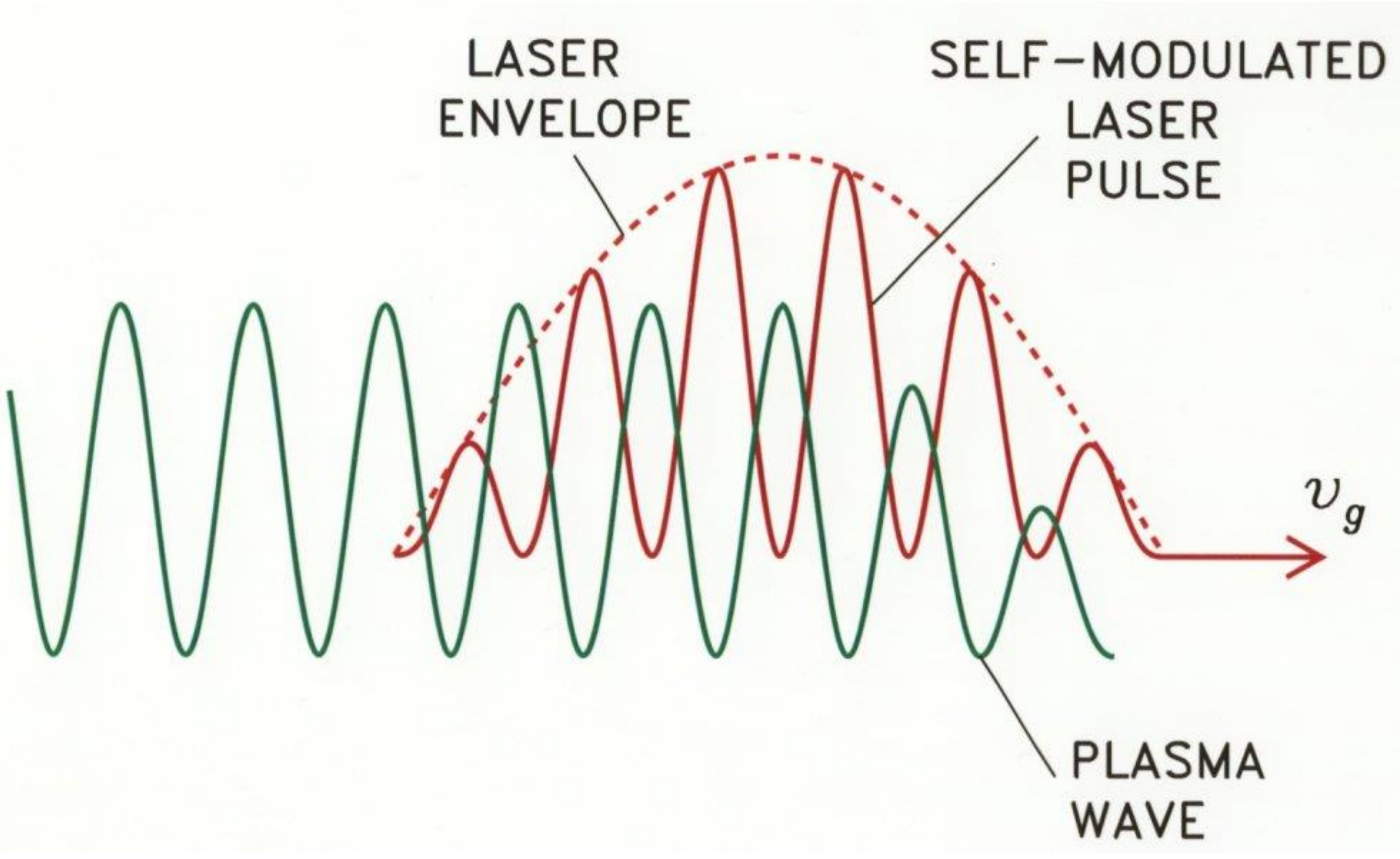
The equation for the electron density perturbation is found to be,

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\delta n_e = \frac{3}{8}\omega_p^2\frac{\delta n_e^2}{n_o^2}\delta n_e - \frac{n_o}{2}\omega_{pe}^2\alpha_1\alpha_2 e^{-i\delta t}$$

where $\alpha_j = \frac{eE_j}{m_e\omega_j c}, j = 1,2$ is the normalised quiver velocity in the field of each laser $\delta = \omega_1 - \omega_2$.

The 1st term on the RHS is the relativistic mass shift in the electron plasma wave and the 2nd term is the laser beat drive term.

Self-Modulated Laser Pulse



Short pulse wakefield generation

In the envelope approximation assume a pulse of the form,

$$\boldsymbol{a}(z,\, t) = \tfrac{1}{2}\boldsymbol{a}_0(\xi,\, \tau)\,\mathrm{e}^{-i\theta} + c.c.,$$

Where the amplitude is cast in the frame of the moving laser pulse, with

$$\theta = \omega_0 t - k_0 z \qquad \xi = z - v_g t$$

The final equations for $\boldsymbol{a}_o$ and Φ are obtained on

$$\frac{\partial^2 \Phi}{\partial \xi^2} = \frac{\omega_{p0}^2}{c^2}\, G,$$

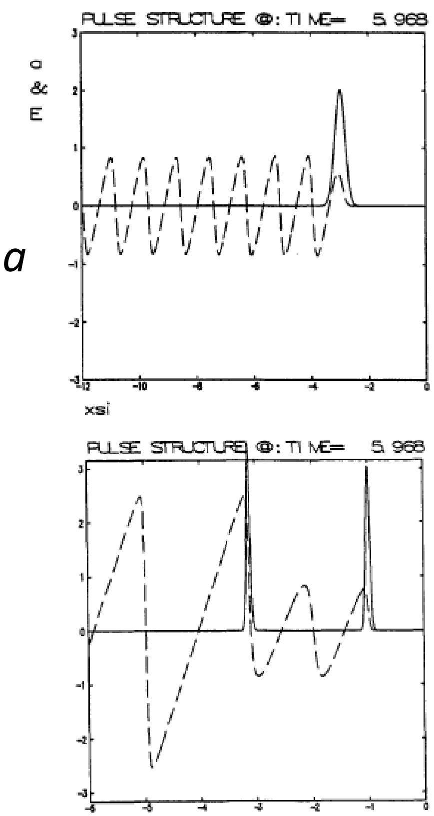
$$2i\omega_0 \frac{\partial a_0}{\partial \tau} + 2c\beta_0 \frac{\partial^2 a_0}{\partial \tau\, \partial \xi} + \frac{c^2 \omega_{p0}^2}{\omega_0^2} \frac{\partial^2 a_0}{\partial \xi^2} = -\omega_{p0}^2 H a_0$$

where

$$G = \frac{\sqrt{\gamma_{\|}^2 - 1}}{\beta_0 \gamma_{\|} - \sqrt{\gamma_{\|}^2 - 1}}, \quad H = 1 - \frac{\beta_0}{\gamma_a(\beta_0 \gamma_{\|} - \sqrt{\gamma_{\|}^2 - 1})}.$$

Valid for arbitrary laser pulses and laser intensities

E,a



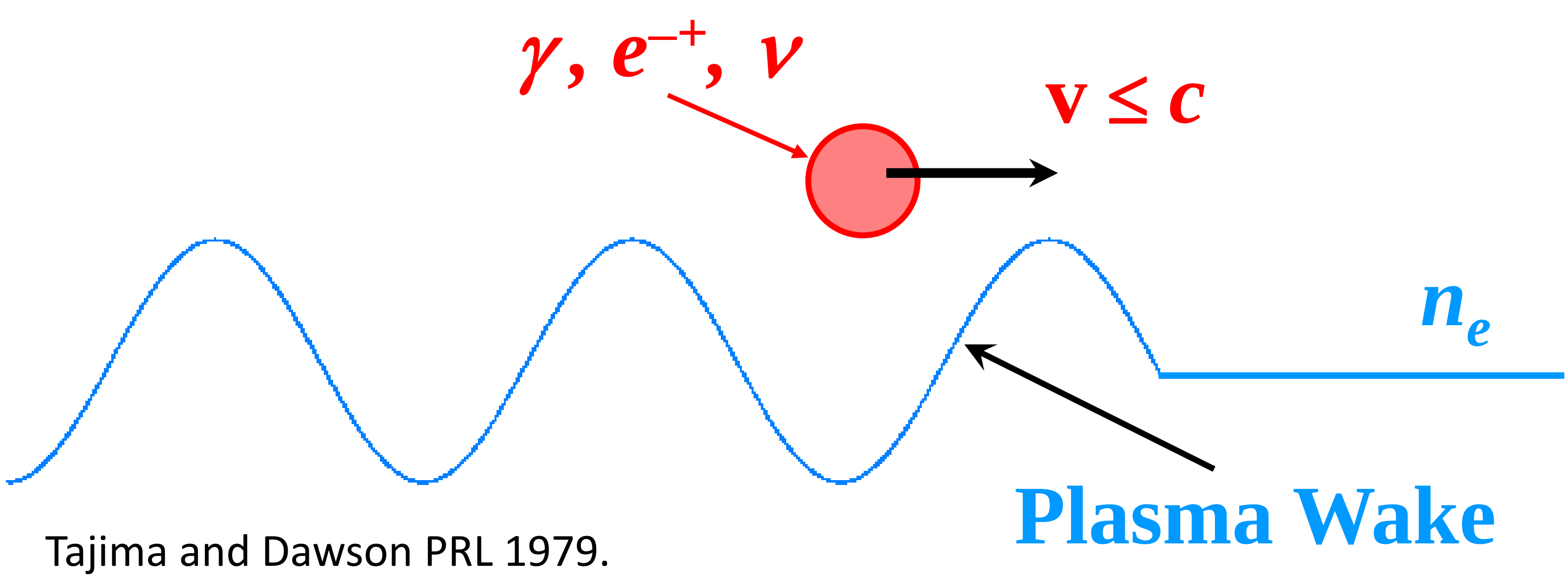
ξ

Short Pulse-Plasma Wakes

photon beam
electron beam
neutrino beam
ion beams

All very similar

*** Drive Plasma Wakes**



Tajima and Dawson PRL 1979.

Plasma waves driven by electrons, photons, ions and neutrinos

Electron beam

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = -\omega_{pe0}^2 n_{e-beam}$$

$\delta n_e \equiv$ Perturbed electron plasma density

Photons

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \boxed{\frac{\omega_{pe0}^2}{2m_e}\nabla^2\int\frac{d\mathbf{k}}{(2\pi)^3}\hbar\frac{N_\gamma}{\omega_\mathbf{k}}}$$

Neutrinos

$$(\partial_t^2 + \omega_{pe0}^2)\delta n_e = \boxed{\frac{\sqrt{2}n_{e0}G_F}{m_e}\nabla^2 n_\nu}$$

Ponderomotive force

physics/9807049

physics/9807050

+

Kinetic/fluid equations for electron beam, photons, neutrinos coupled with electron density perturbations due to PW

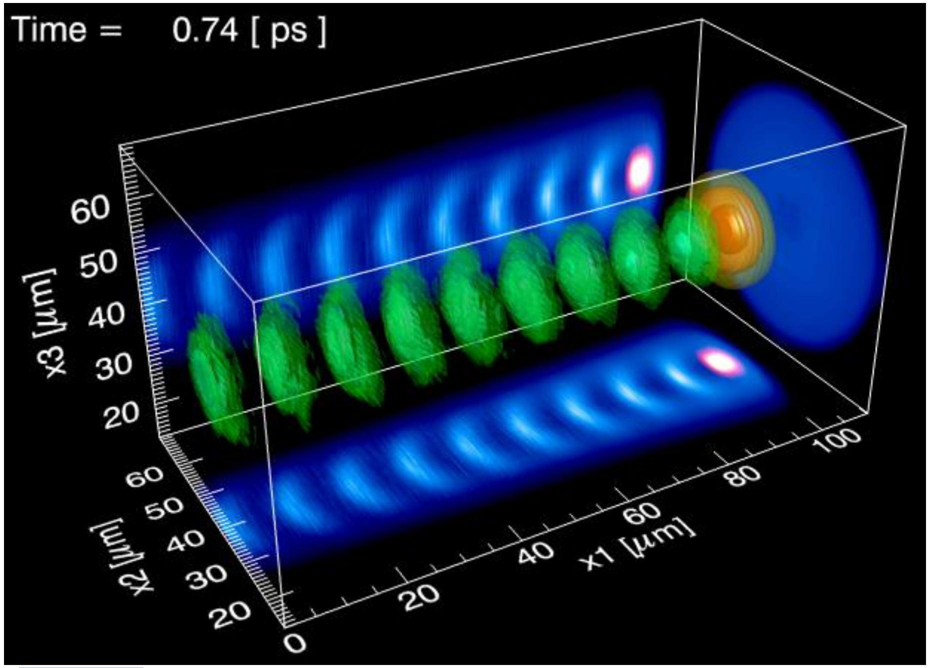
Self-consistent picture of collective e,γ,ν-plasma interactions

Laser & Electron Wakes

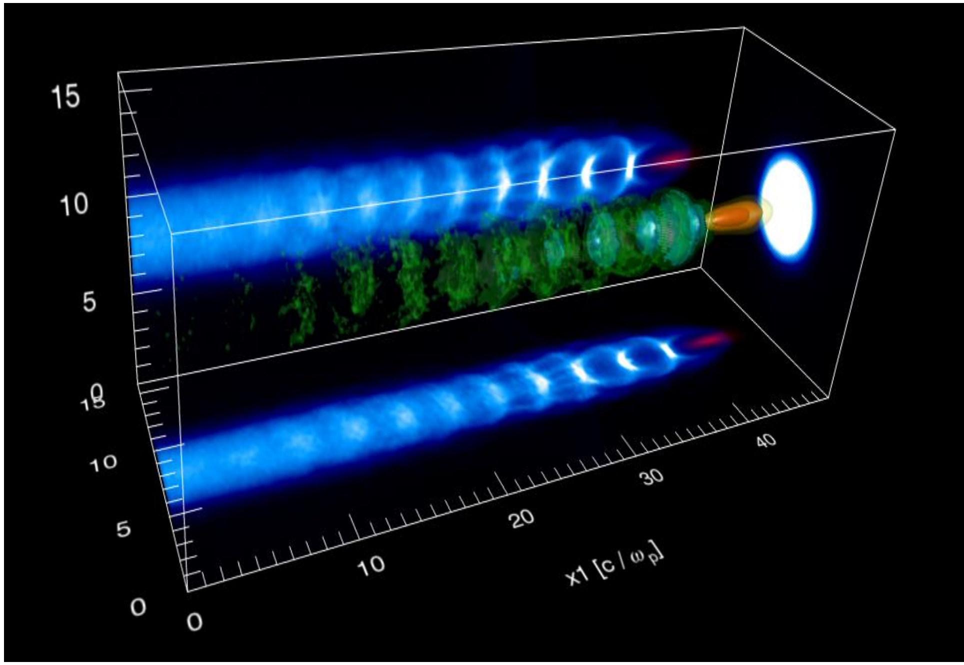
Nonlinear wakes are *similar* with laser or particle beam drivers:

3-D PIC OSIRIS Simulation

(self-ionized gas)



Laser Wake



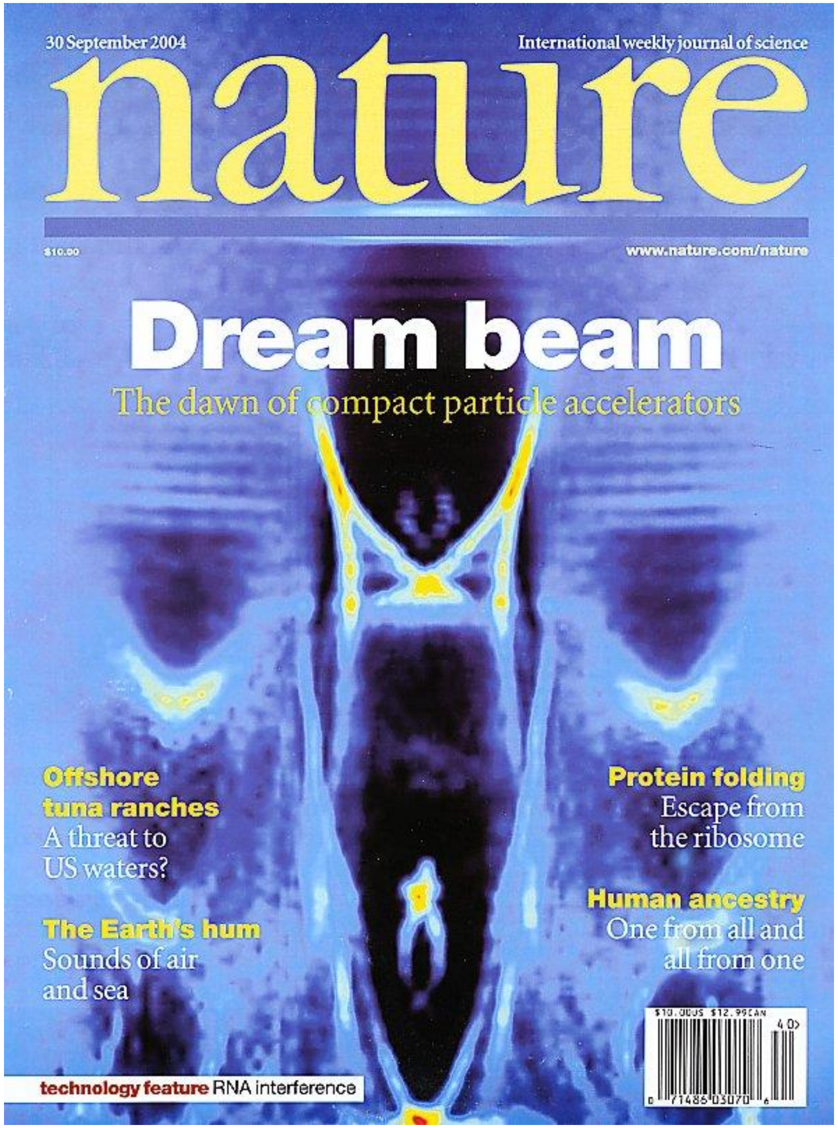
Electron beam Wake

INSTITUTO SUPERIOR TÉCNICO

USC UNIVERSITY OF SOUTHERN CALIFORNIA

UCLA

A Plasma Revolution



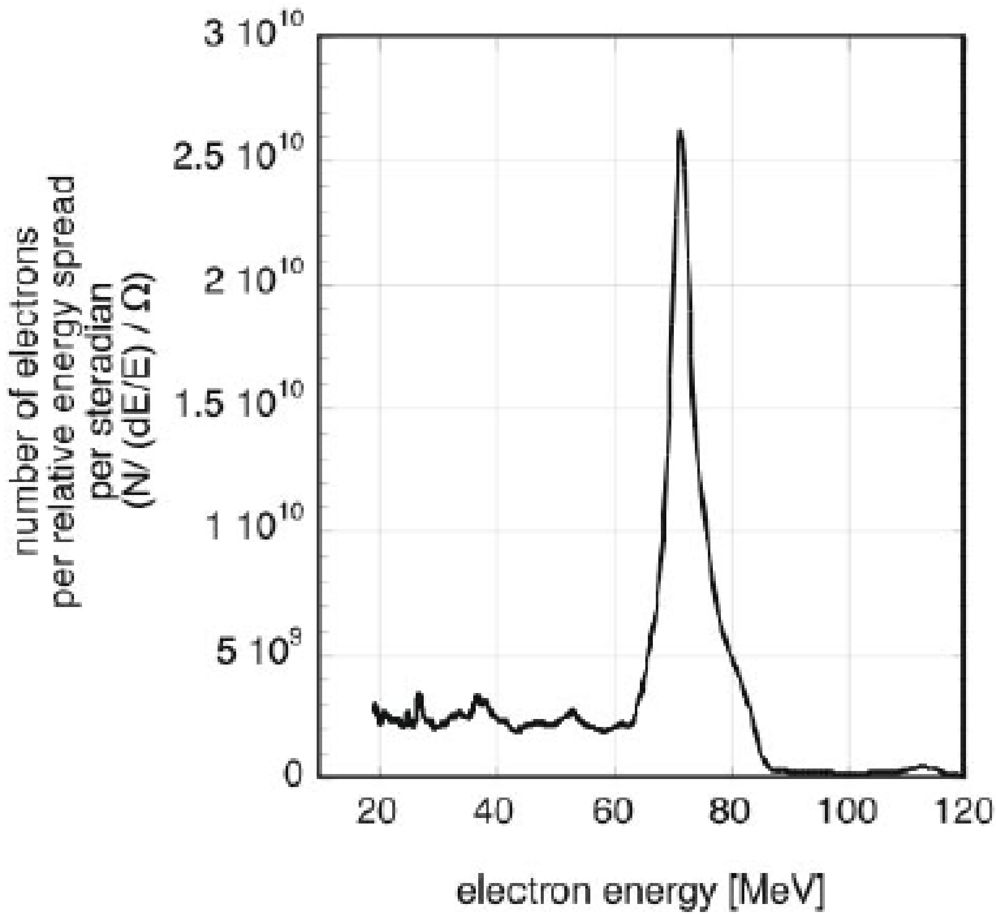
3 papers in Nature changed the landscape

S.P.D. Mangles *et al*, Nature, 2004
C.G.R. Geddes *et al*, Nature, 2004
J. Faure *et al*, Nature, 2004

Demonstrating laser wakefield acceleration of mono-energetic electron beams in the “Bubble regime”

Imperial College London

Mono-energetic spectra can be observed at higher power ($\Delta E/E$ = 6 %)



E ~ 500 mJ,

pulse duration ~ 40 fsec

Focal spot ~ 25 μm

Density ~ 2 x 10^{19} cm^{-3}

Significant shot-to-shot fluctuations in

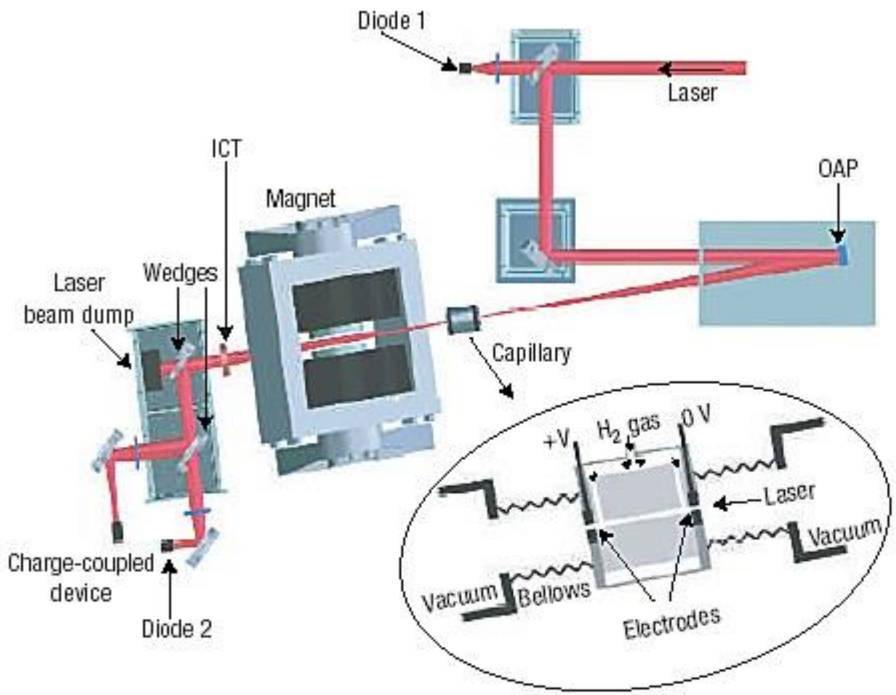
a) energy spread

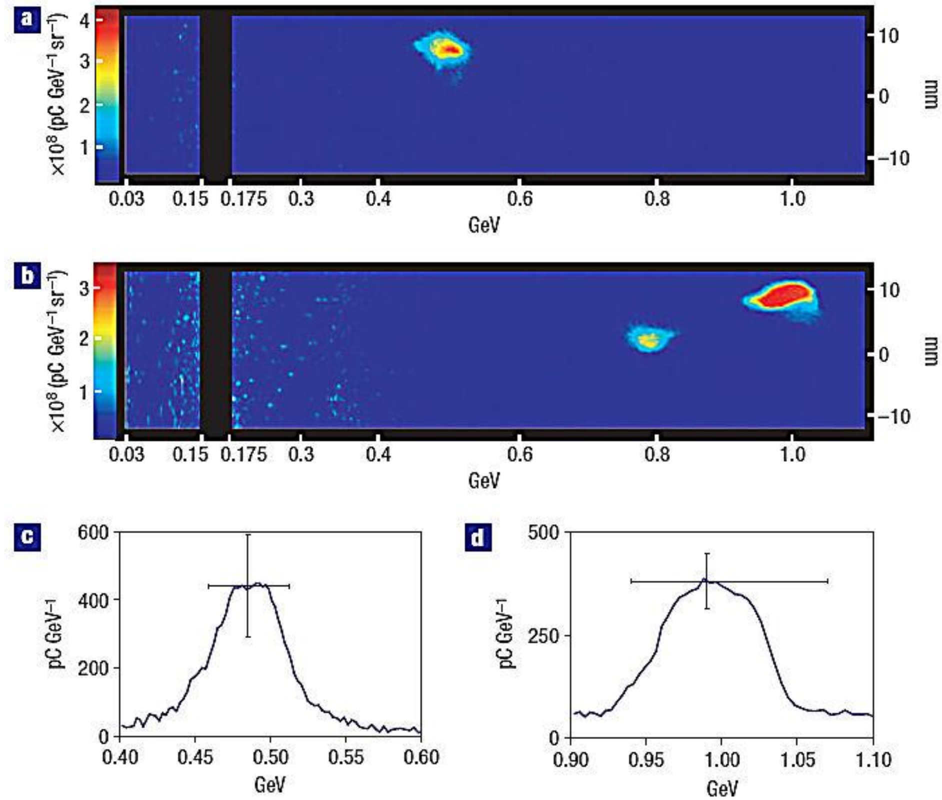
b) peak energy

Careful control of laser and plasma conditions is necessary

Courtesy: K. Krushelnick, IC

LBL/Oxford Capillary Guided GeV Laser Plasma Accelerator





- The plasma channel was formed in a hydrogen-filled capillary discharge waveguide (inset). The laser beam was deflected into the capillary using an f/25 off-axis parabola (OAP). Diode 1 and 2 were used to measure the guiding efficiency.

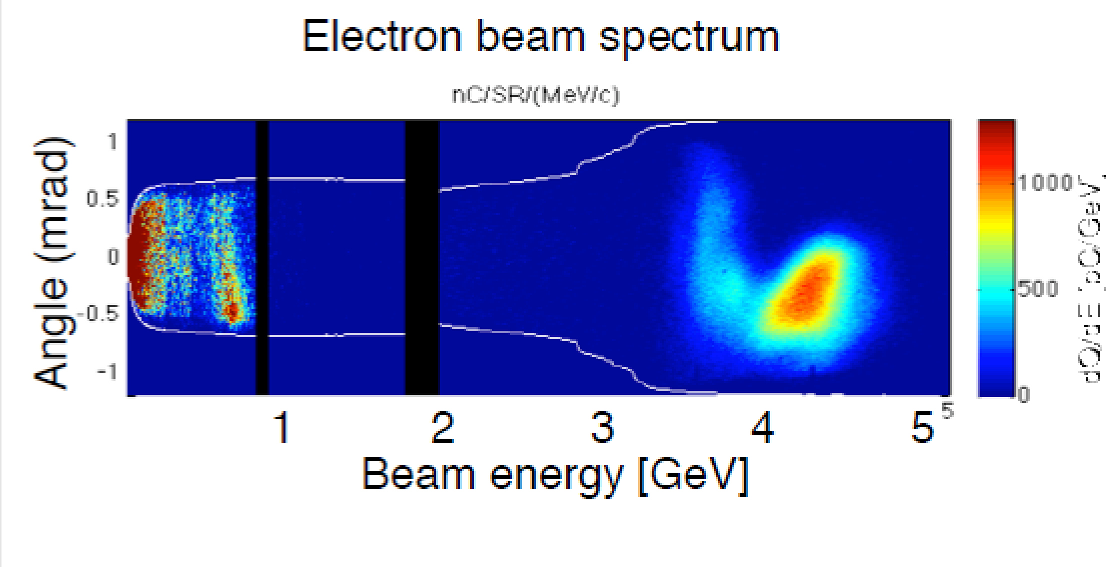
(a) Example of 0.5 GeV bunch. Horizontal axis is beam energy, vertical axis is the beam size in the undeflected plane.

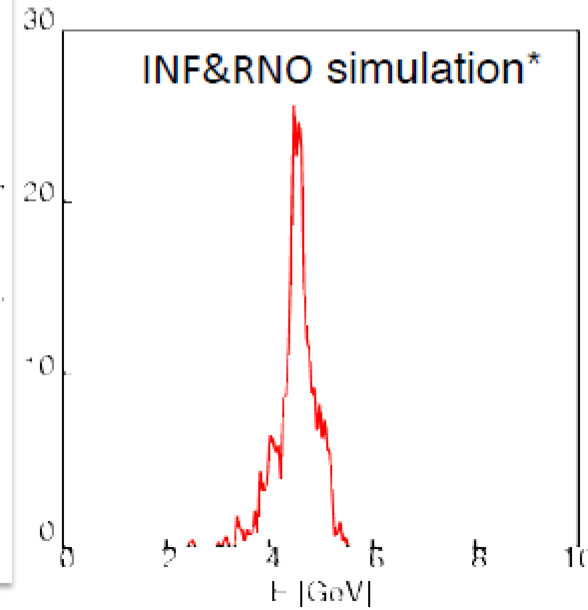
(b) The 0.5 (1.0) GeV beam was obtained in the 225 (310) μm capillary.

(c) and (d) Vertically integrated spectra for the 0.5 and 1.0 GeV beams.

4.25 GeV beams have been obtained from 9 cm plasma channel powered by 310 TW laser pulses (15 J): BELLA Group @LBNL

*C. Benedetti et al., proceedings of AAC2010, proceedings of ICAP2012





- **Laser** (E=15 J):
  - Measured) longitudinal profile (T_0= 40 fs)
  - Measured far field mode (w_0=53 µm)
- **Plasma:** parabolic plasma channel (length 9 cm, n_0~6-7x10^{17} cm^{-3})

W.P. Leemans et al.,PRL 2014; A.J. Gonsalves et al., PoP 2015

	Exp.	Sim.
Energy	4.25 GeV	4.5 GeV
ΔE/E	5%	3.2%
Charge	~20 pC	23 pC
Divergence	0.3 mrad	0.6 mrad

A road map of single stage LWFA

P(PW)	τ(fs)	n_p (cm^{-3})	w_0 (μm)	L(m)	a_0	$\Delta n_c/n_p$	Q(nC)	E(GeV)
0.020	30	1×10^{18}	14	0.016	1.76	60%	0.18	0.99
0.040	30	1.5×10^{18}	14	0.011	2.53	40%	0.25	0.95
0.100	**30**	$\mathbf{2.0\times10^{18}}$	**15**	**0.009**	**3.78**	**0%**	**0.40**	**1.06**
0.200	100	1.0×10^{17}	45	0.52	1.76	60%	0.57	9.9
2.0	**100**	$\mathbf{3.0\times10^{17}}$	**47**	**0.18**	**5.45**	**0%**	**1.8**	**10.2**
2.0	**310**	$\mathbf{1.0\times10^{16}}$	**140**	**16.3**	**1.76**	**60%**	**1.8**	**99**
40	330	4.0×10^{16}	146	4.2	7.6	0%	8	106
20	1000	1.0×10^{15}	450	500	1.76	60%	5.7	999
1000	1000	6.5×10^{15}	460	82	12.1	0%	40	1040

Courtesy Wei Lu

Beams from High-Energy Accelerators Used to do Experiments of interest to HEP

Only place in the world to study this topic !!

SLAC
NATIONAL ACCELERATOR LABORATORY
New SLAC National Accelerator Laboratory logo

N = 2-4 x 10^{10}

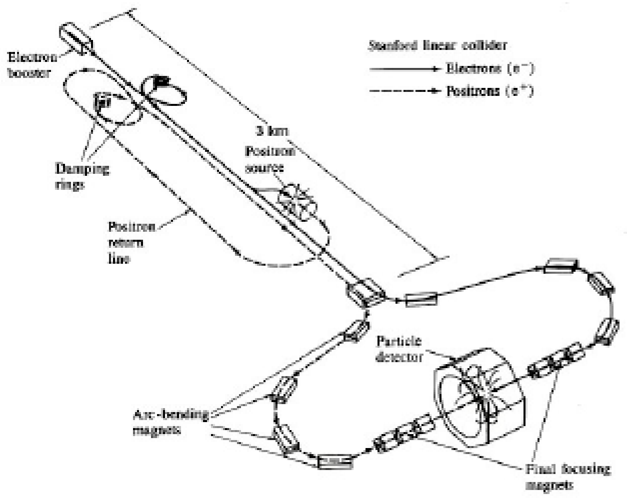
Energy 20-50 GeV

Rep Rate 10-60 HZ

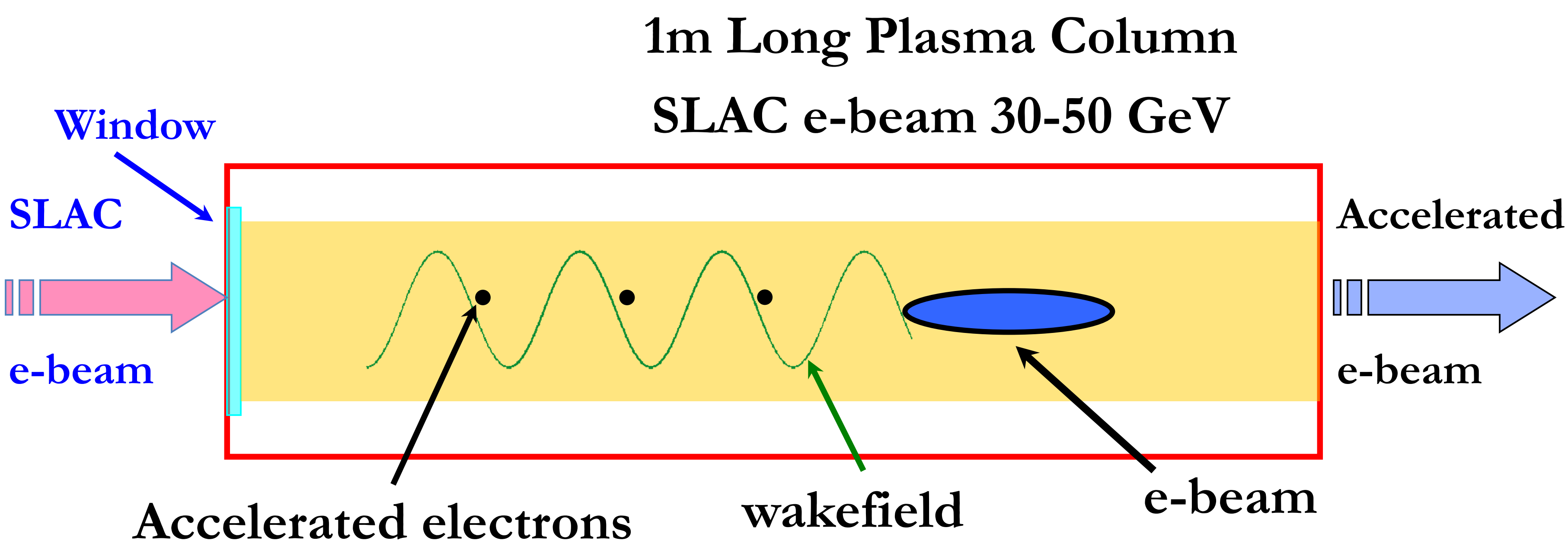
Energy/pulse 60-300 J
Focal Spot Size 30-1 micron

Pulse Width 15 micron compressed

Focused intensity 10^{19} W/cm^2 – 10^{23} W/cm^2



1 – 5 PW class, short pulse energy delivery systems, at a high rep rate

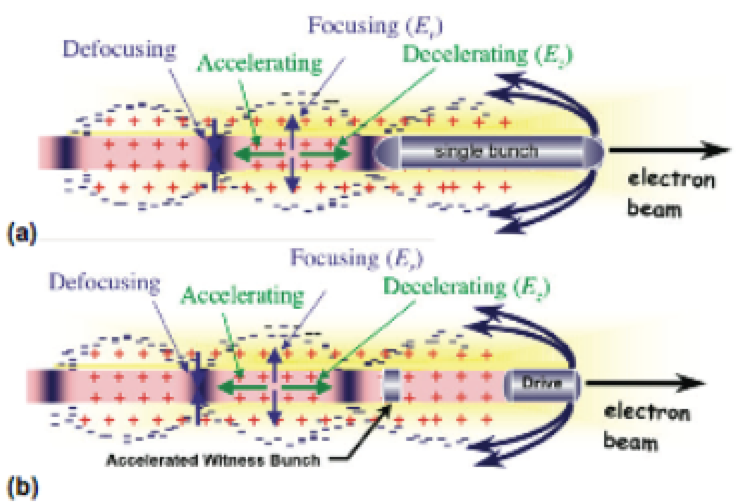


- Front of beam generates plasma wakefield
- Tail of beam particles interacts with wakefield

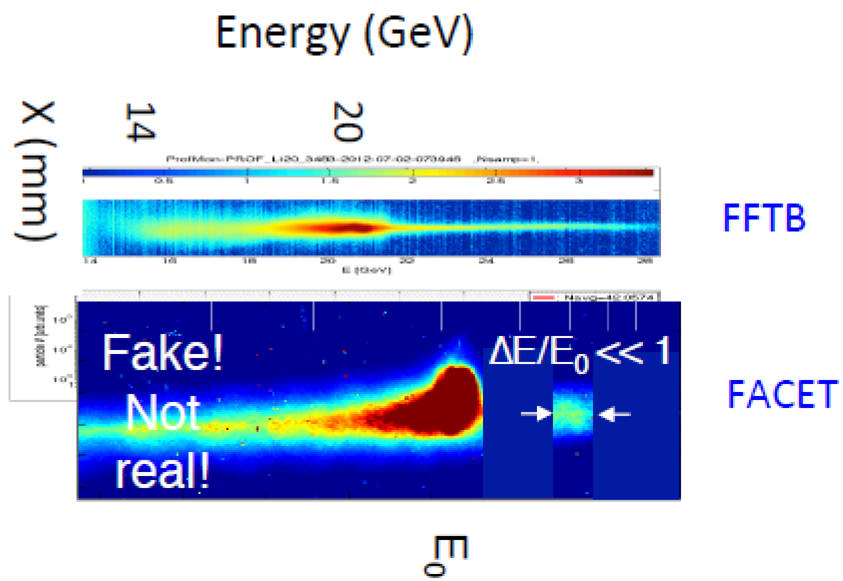
⇨ Accelerated and decelerated beam.

Goals of the E200 Electron Acceleration Expts

FFTB single bunch 2006



FACET Two bunch 2013/14



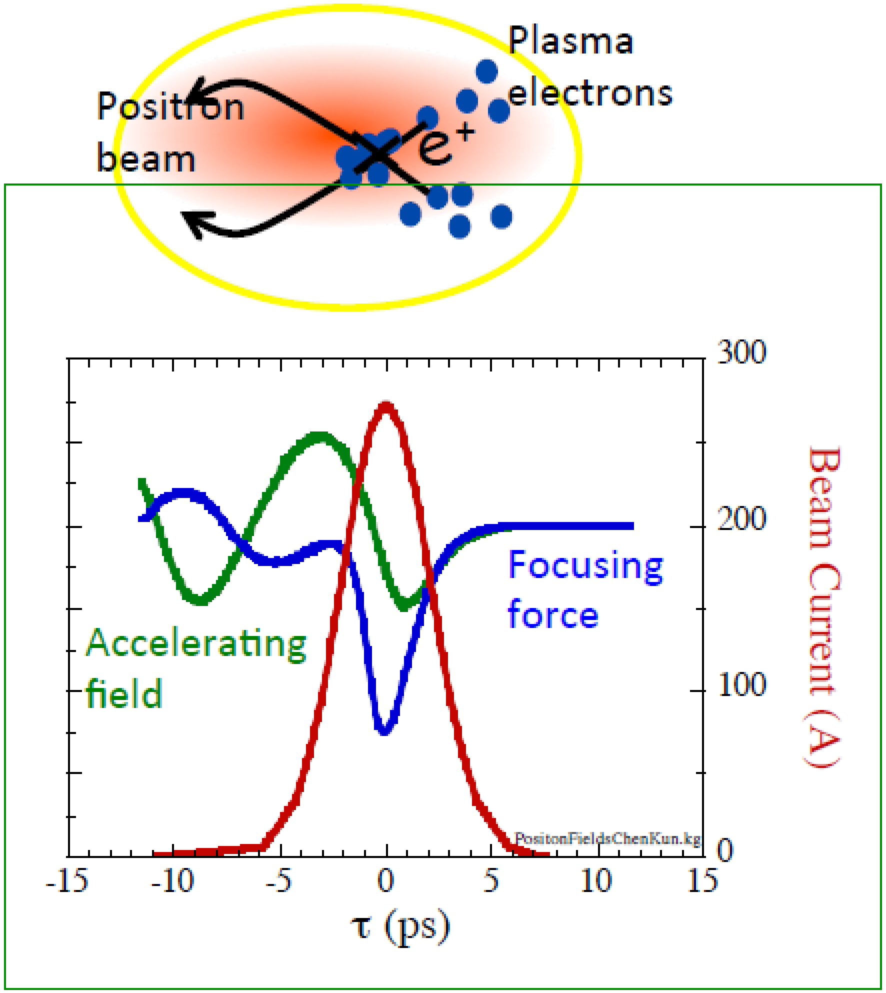
Synthetic Data

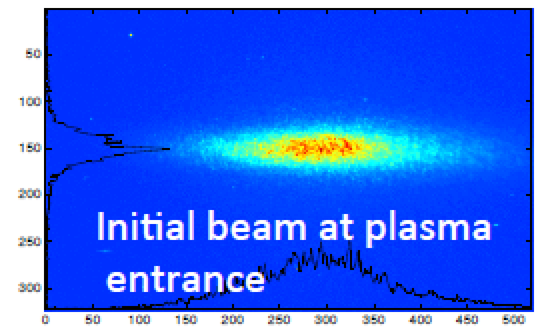
Reliable operation of the LINAC to give Drive Bunch- Witness Bunch configuration
Formation of 1.3 m long preformed plasma using laser preionization
Repeat PWFA experiment in the preformed plasma to show narrow energy spread $\Delta E/E_0$

Courtesy Chan Joshi

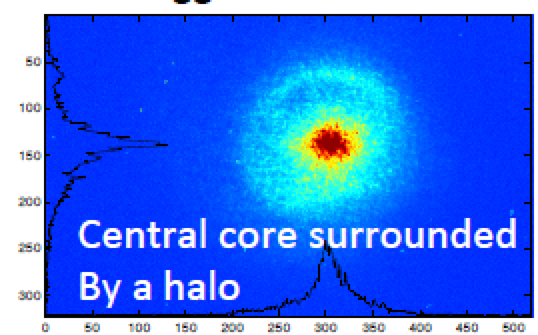
Positron driven wakefields

28 GeV Positron Beam at SLAC propagates through a dilute plasma





E 162 Collaboration
P. Muggli et al PRL 2008

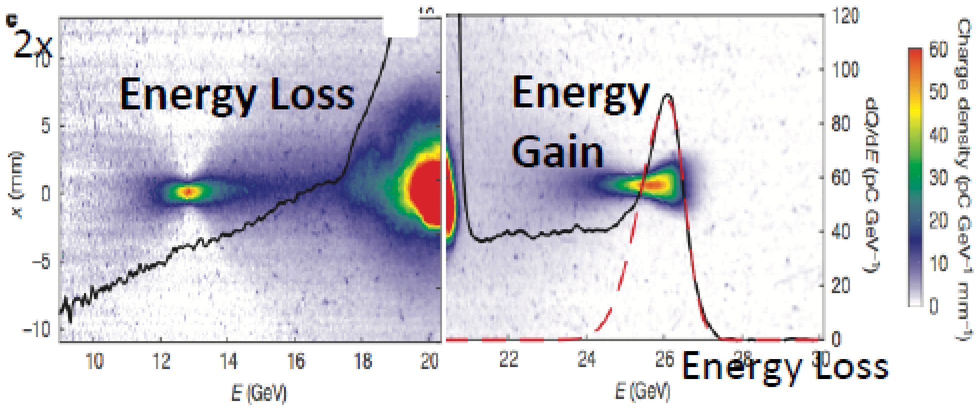


Beam exiting plasma

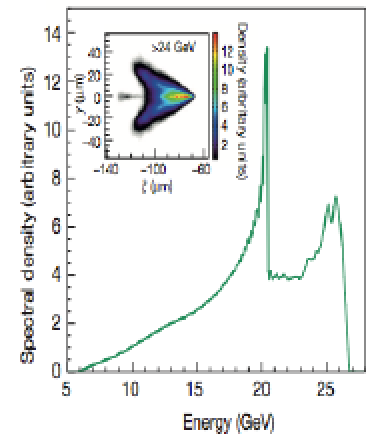
Courtesy Chan Joshi

Energy Spectra Comparison to Experiment

Experimental Results



Simulation



- ➢Plasma length 1.3 m
- ➢Energy gain ~ 3-10 GeV (5 GeV shown)
- ➢Gradient of ~ 4 GeV/m
- ➢Energy spread of fit (red curve) ~ 2.2% rms
- ➢Over 200 pC accelerated charge (220 pC shown)
- ➢Wake-to-bunch Efficiency ~ 30%

Courtesy Chan Joshi

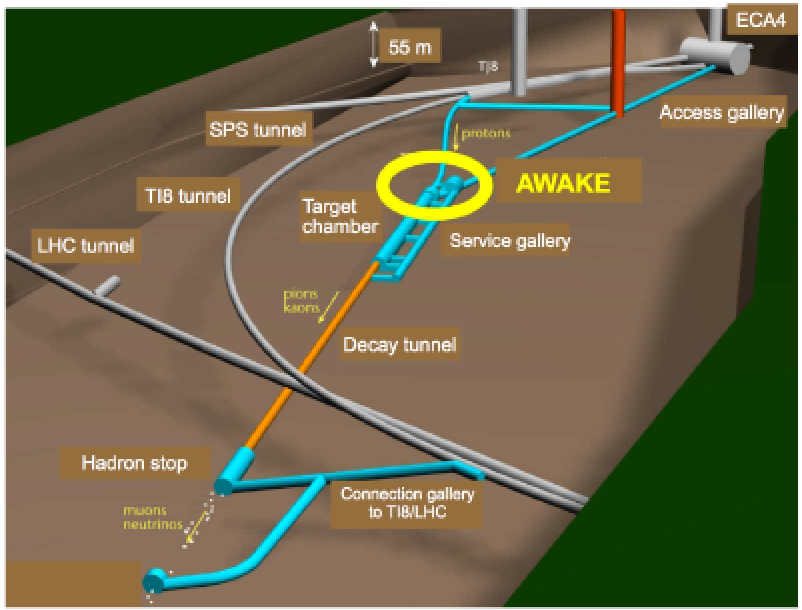
Short pulse Electron and Positron Drivers

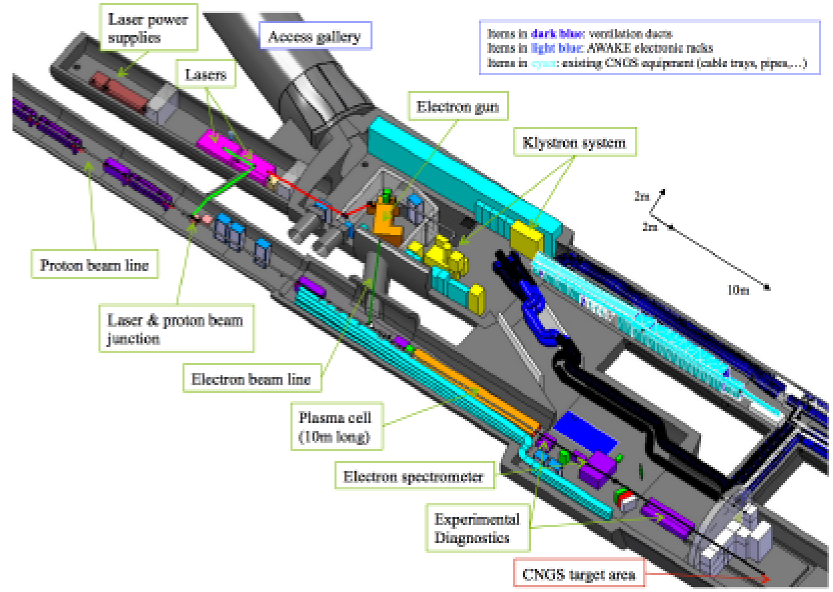
Progress in Beam-Driven Plasma Accelerators

1) Two beam experiments with electrons
2) Positron acceleration experiments
   i) single bunch ii) two bunches
3) Two bunch experiments with hollow plasma channels
4) Generation of low emittance beams

Chan Joshi et al

The AWAKE experiment at CERN





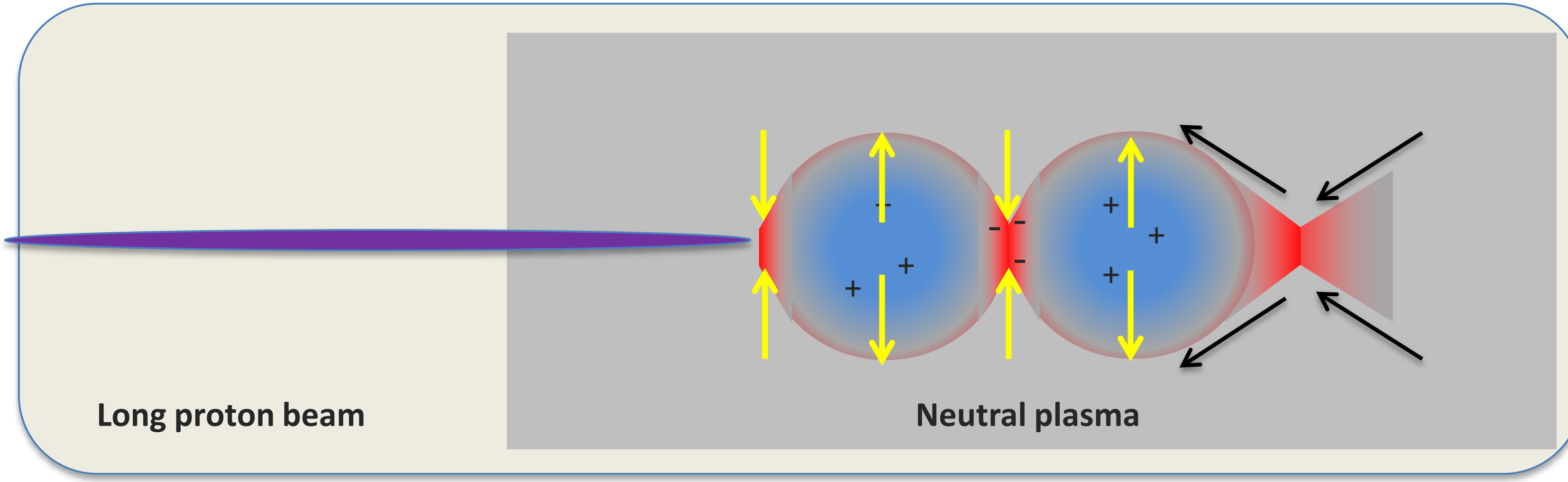
Gschwendtner et al., NIMA, 2016

Preferable to use heavier protons to accelerate electrons, for a given Lorentz factor they contain much more energy to drive a wake

AWAKE is a modification to the CNGS area which will use the SPS proton bunch to drive a wake in a 10m long plasma cell

The Self-Modulation Instability

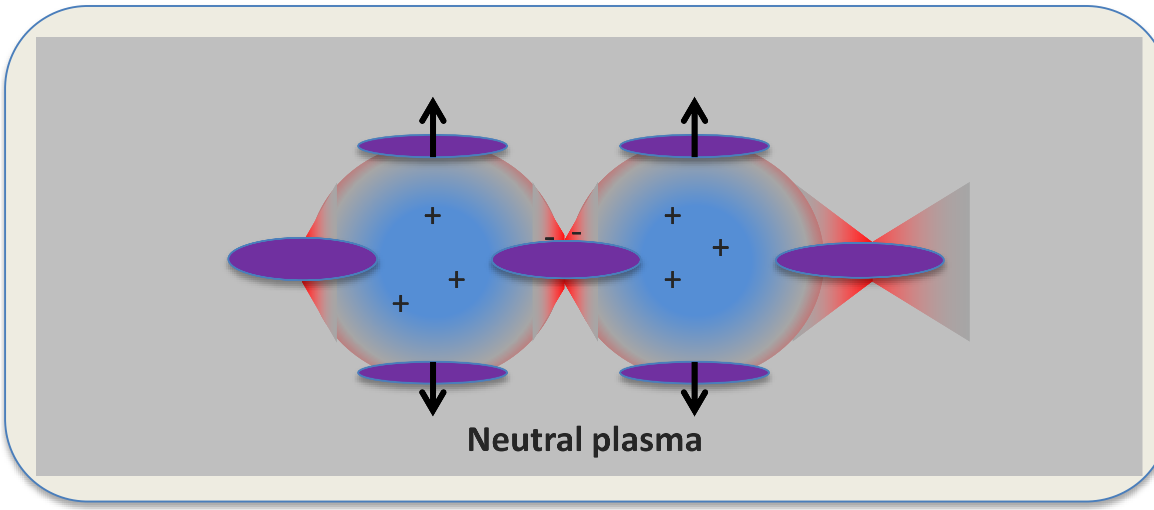
Affects long drive beams.



- Microbunches are spaced λ_p apart.
- Charge density increased.
- Micro bunch lengths are much closer to the ideal driver length of:

$$\sigma_{res} = \lambda_p / \pi\sqrt{2}$$

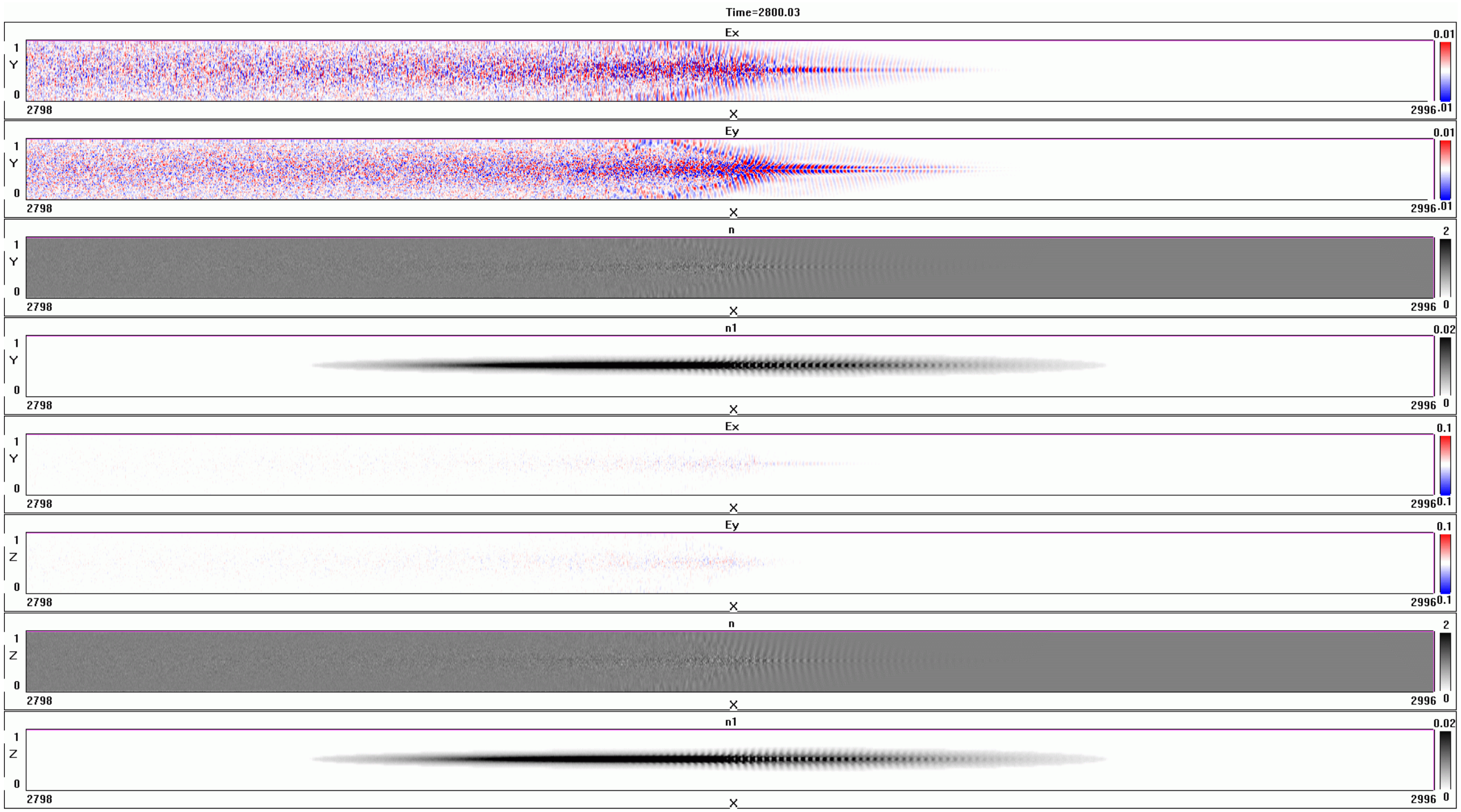
These properties then allow the modulated beam to drive a wakefield much more effectively.



Self-modulated driver beam

J Hollaway 2012

Modulation of a long ion beam



r_b=1 mm, n_p=1e11, σ_z=12 cm, E_p=450 GeV, n_0= 1e14cm-3 (λ_p=3mm)

Length of simulation=8.4 meters

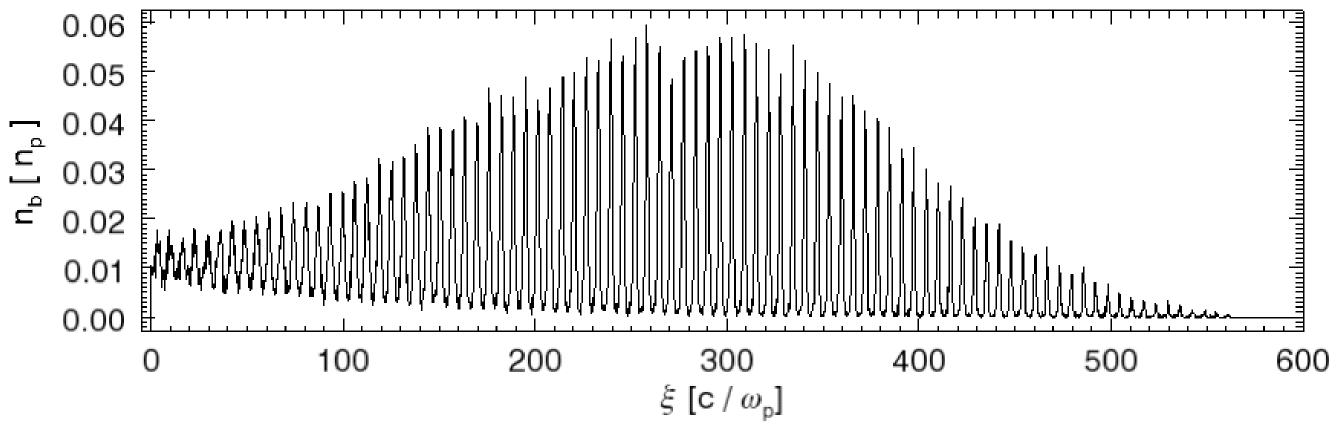
Proton Wakefield SPS Accelerator

Parameter	Proton beam	Electron beam
Energy (GeV)	450	0.01
Intensity (10^{10} particles)	11.5 / 30	10^{-4} / 10^{-1}
Energy deviation (MeV)	135	1
Bunch length (cm)	12	10 / 0.5
Beam transverse size (μm)	200	200 / 2000
Beam divergence (mrad)	0.04	0.1 / 1.7
Emittance (μm)	3.5	0.02 / 3.5
Plasma parameters		
Plasma density (cm^{-3})	7×10^{14}	
Plasma length (m)	5 / 10	

Table 1: Summary of plasma and proton- and electron-beam parameters used for current simulations. The proton beam with 11.5×10^{10} particles represents normal SPS running, whereas an increase in intensity would be provided for this experiment. The parameters of the electron beam are still being optimised with representative parameters given for a “long” and “short” beam configuration.

The Proton SPS Experiment

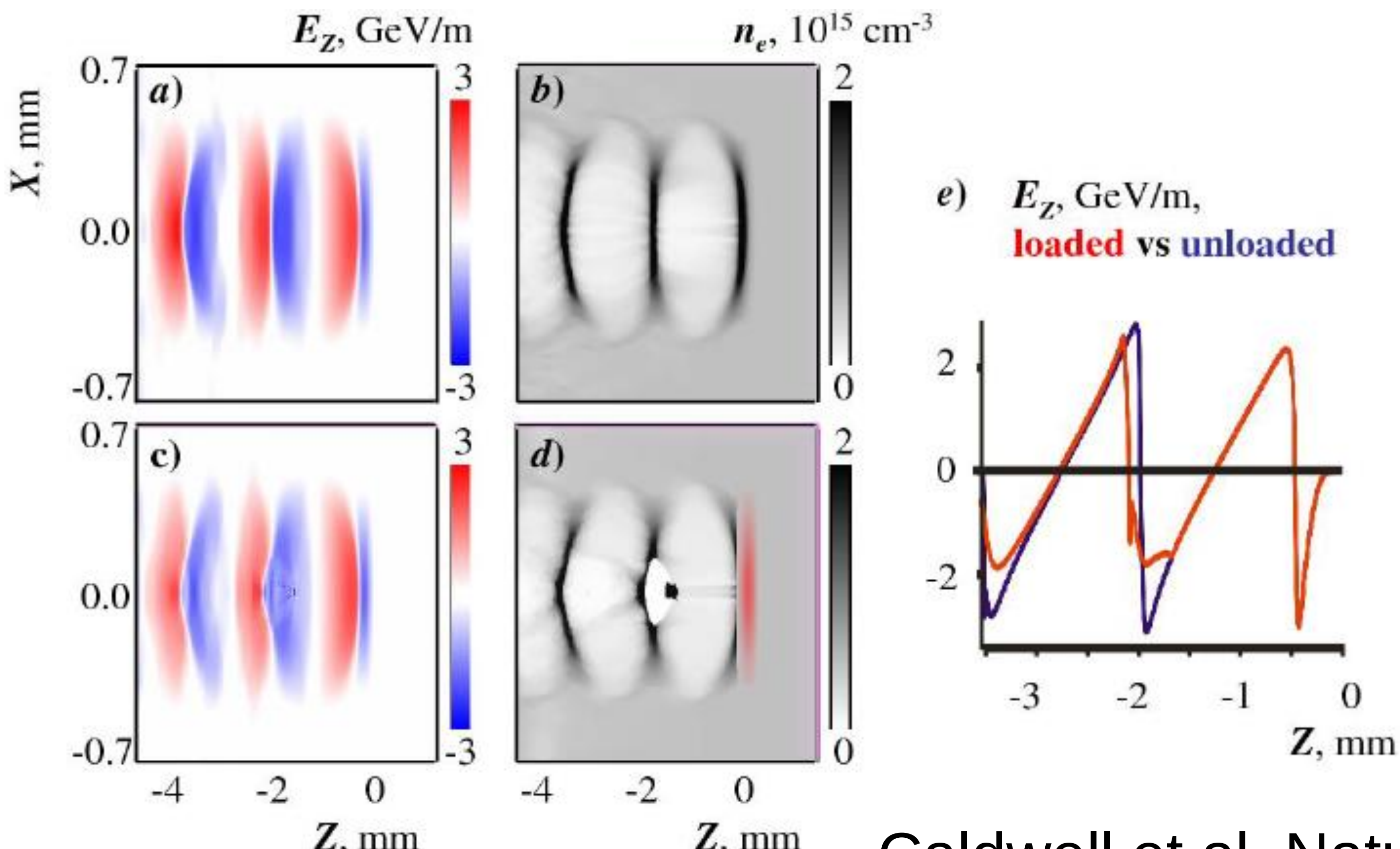
The Super Proton Synchrotron beam at CERN Feeds the LHC.
Collaboration led by Allen Caldwell aims to use the SPS beam to drive PWA.
Initial goal is to observe the energy gain of 1 GeV in 5-10m plasma.A plan for reaching 100 GeV within 100 m plasma will be developed based on the proof of principle experiment.



The uncompressed SPS beam will be used in the first experiment.
It has a beam length of σ_z = 12 cm. Far longer than the λ_p.
Solution: Increase wakefield driving ability using transverse modulation.

Short Proton Driver

Goal to accelerate electrons to TeV in 600m



Caldwell et al Nature Physics 2009

Raman Amplification

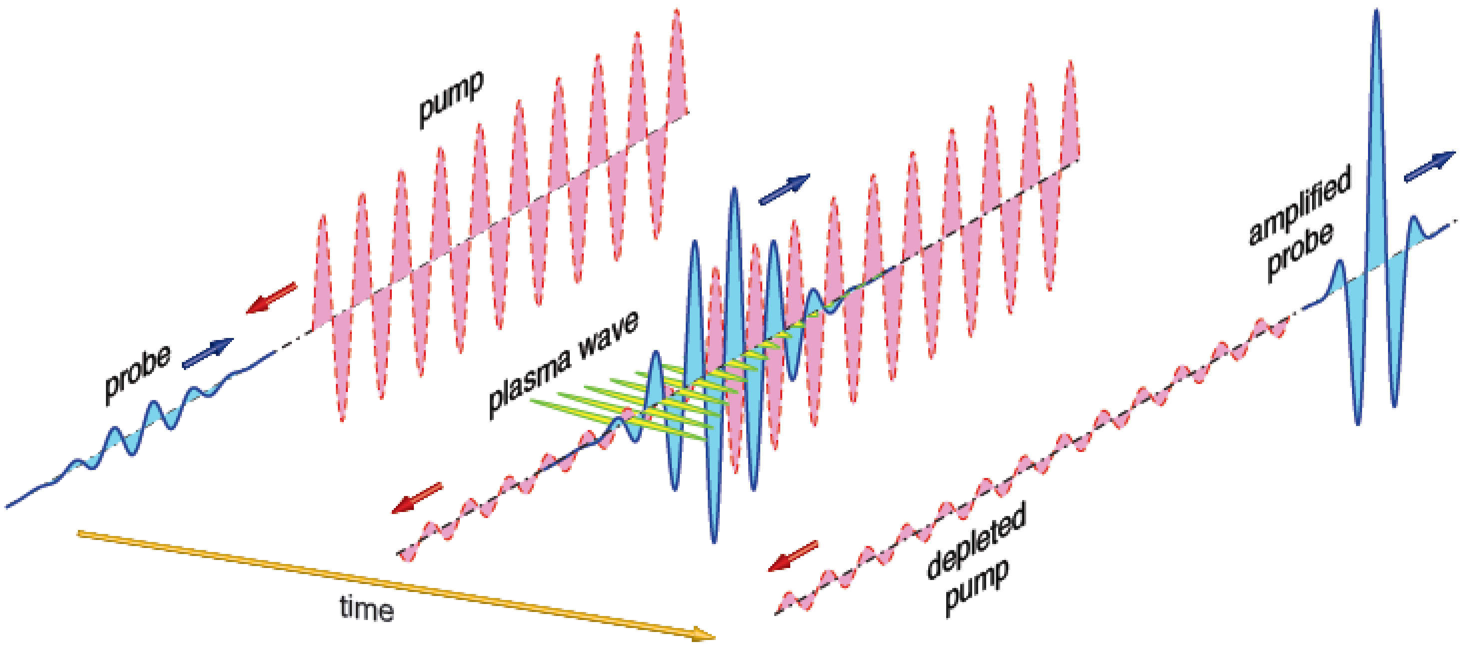
- Pulse compression in plasma, or: making an instability work for you

- Why pulse compression in plasma?
  - Solid optics: max. intensity 10^{12} W/cm^2
  - Plasma: max. intensity 10^{17} W/cm^2 [1,2]

- Results:
  - Experiments: Princeton [3,4], Livermore [5]
  - Simulations: RAL/IST/St. Andrews [6]
  - Being studied by many: Princeton, LLNL, UCB, LANL, U. Strathclyde, LULI/U. Bordeaux, South Korea, Taiwan...

[1] G. Shvets *et al.,* Phys. Rev. Lett. **81**, 4879 (1998).
[2] V.M. Malkin *et al.,* Phys. Rev. Lett. **82**, 4448 (1999).
[3] Y. Ping *et al.,* Phys. Rev. Lett. **92,** 175007 (2004).
[4] J. Ren *et al.,* Nature Physics **3**, 732 (2007).
[5] Y. Ping, R Kirkwood *et al.,* Phys. Plasmas **16**, 123113 (2009).
[6] R. Trines, F. Fiúza *et al.*, Nature Physics **7**, 87 (2011).

How it works



•A long laser pulse (pump) in plasma will spontaneously scatter off Langmuir waves: Raman scattering

Stimulate this scattering by sending in a short, counter propagating pulse at the frequency of the scattered light (probe pulse)

Because scattering happens mainly at the location of the probe, most of the energy of the long pump will go into the short probe: efficient pulse compression

Boosting the pulse energy

- High power = (high intensity)*(large spot)
- High energy = (high power)*(long duration)

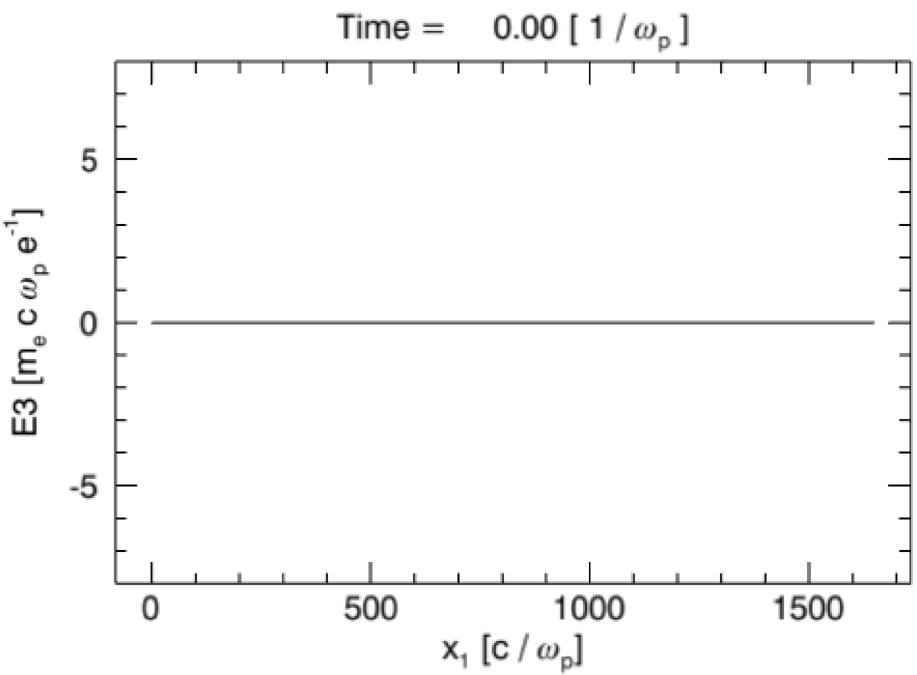
- High intensity: studied by "almost everyone" (theory, simulations, experiments)
- Large spot: few results (theory mostly1-D; some quasi-2D fluid simulations; LLNL experiments); see [6] for details
- Long duration: only Clark & Fisch, and not even for the probe pulse [7]

[6] R. Trines, F. Fiúza *et al.*, Nature Physics **7**, 87 (2011).

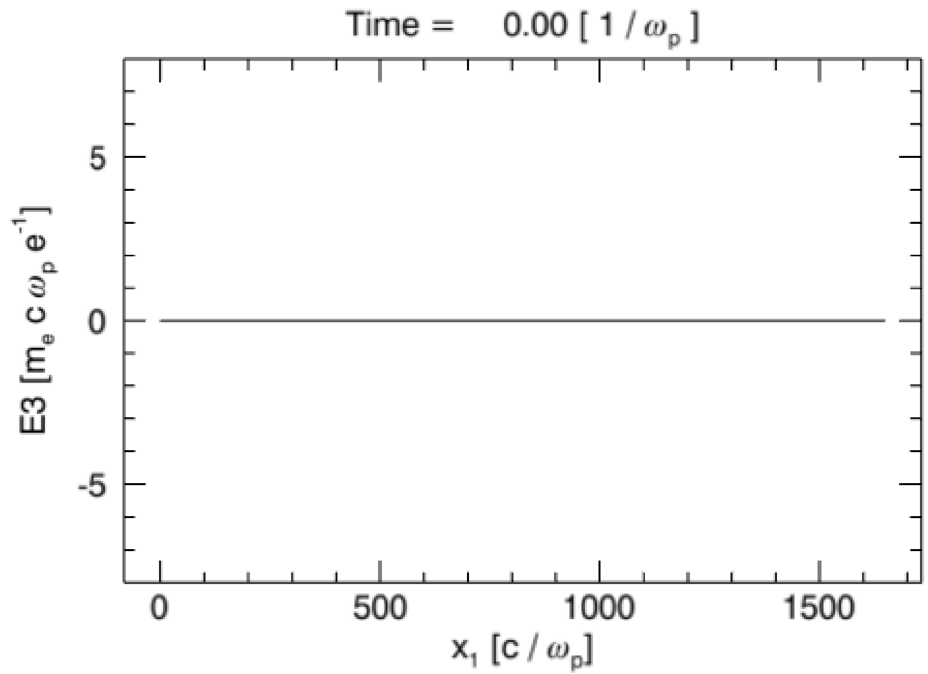
[7] D. Clark and N. Fisch, Phys. Plasmas **9**, 2772 (2002); *ibid*. **10**, 4837 (2003)

Pump (in)stability

10^{16} Wcm^{-2} pump



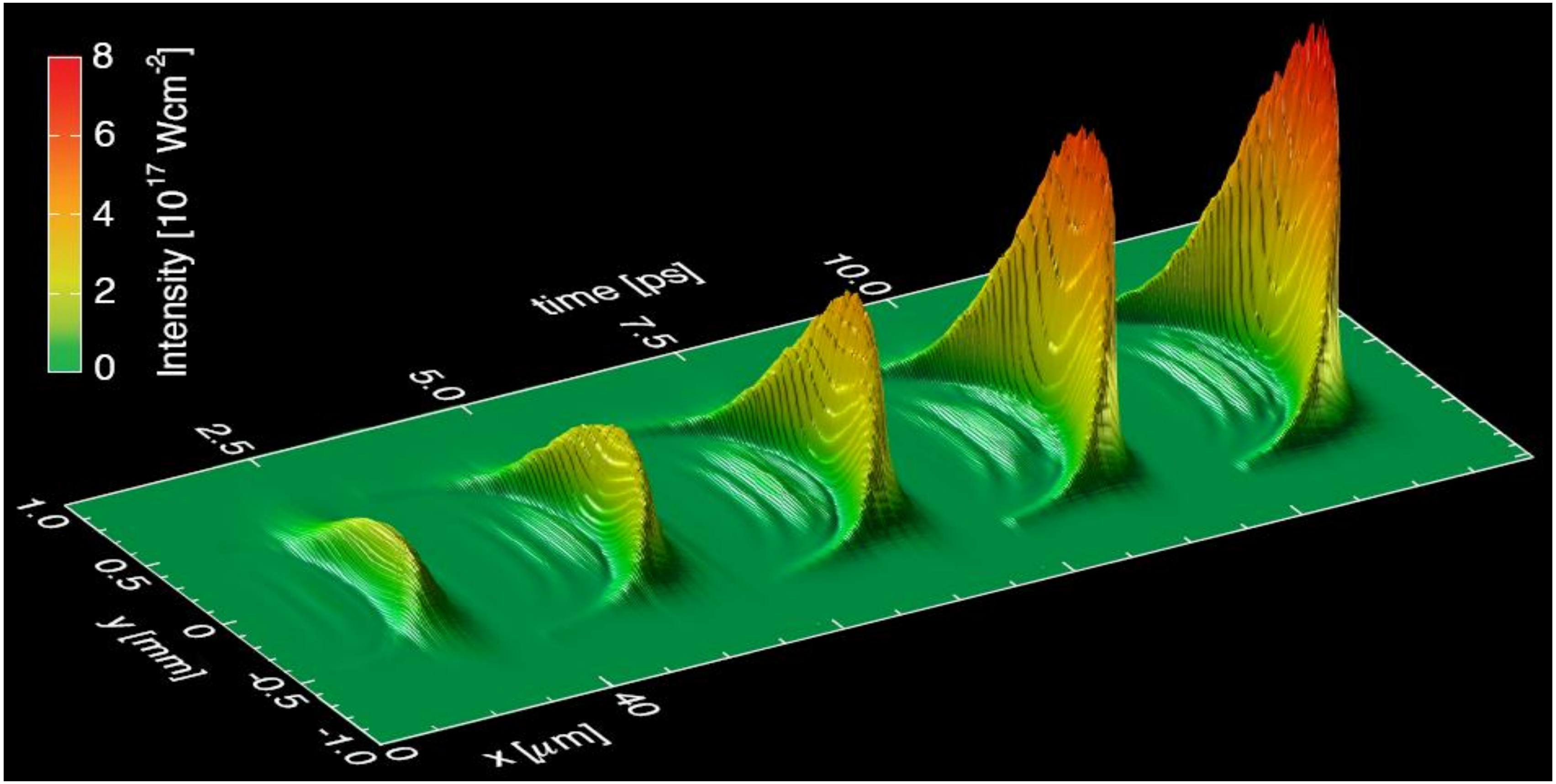
10^{15} Wcm^{-2} pump



- Pump is unstable, probe does not grow

Pump is stable, probe grows nicely

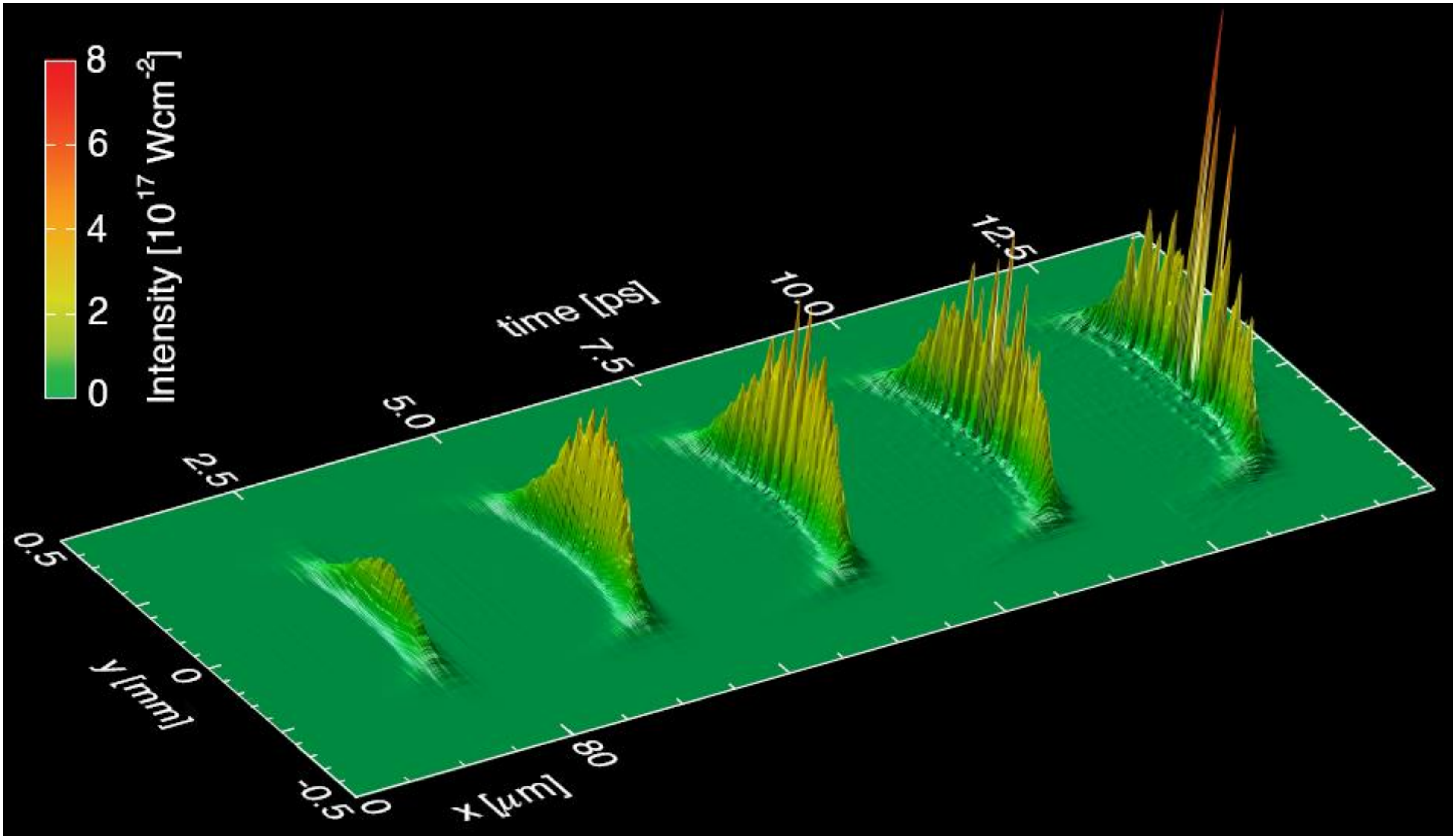
The good news



For a $2*10^{15}$ W/cm^2 pump and ω_0/ω_p = 20, the probe is amplified to $8*10^{17}$ W/cm^2 after 4 mm of propagation, with limited filamentation

10 TW → 2 PW and transversely extensible!

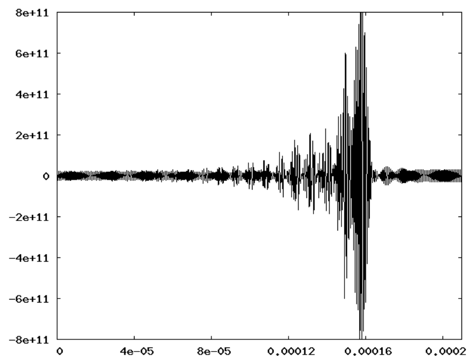
A ‘bad’ example



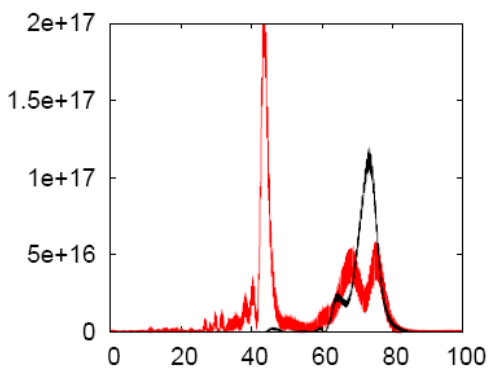
For a $2*10^{15}$ W/cm^2 pump and $\omega_0/\omega_p = 10$, the probe is strongly amplified, but also destroyed by filamentation

Limits to high intensity

- Modulational instability, RFS



For high density ($\omega_0/\omega_p = 10$)

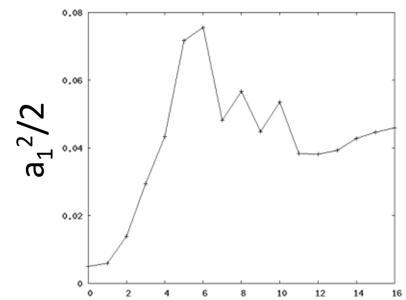


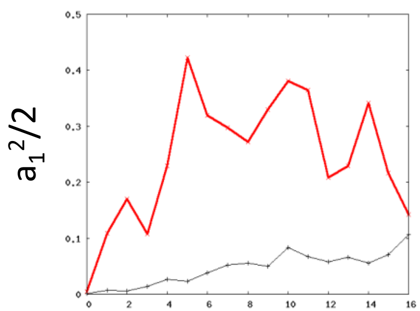
Ditto, for intense pump

Pump: $I=2*10^{15}$ W/cm^2 or

$I=2*10^{16}$ W/cm^2 ($\omega_0/\omega_p = 20$)

Saturation (wakefields)





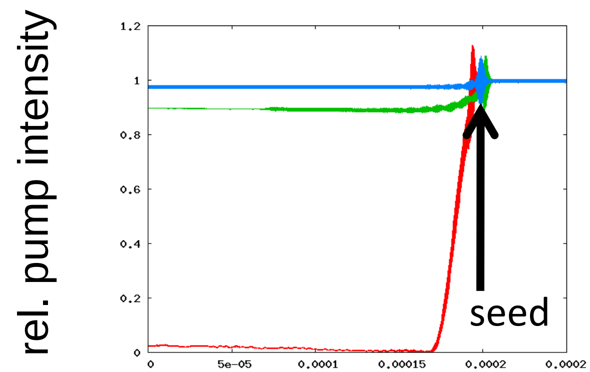
red: high density (10^{19} cm^{-3})

→ saturation

black: low density (10^{18} cm^{-3})

→ poor energy transfer

Langmuir wave breaking



Pump intensity before and after seed; ω_0/ω_p = **10**, **20**, **40**

Low plasma density triggers wave breaking, which halts amplification and reduces efficiency

The near future of LWFA

The energy frontier

ELI – Extreme Light Infrastructure

Centres in Czechia, Romania, Hungary.

10 – 200(?) PW lasers at up to 10Hz, compared to 1PW now

Goal of >10 GeV in a single stage

Vulcan 20PW

Conclusions

- **Plasma wakefield accelerators produce electron beams in the multi GeV range.**
- **Capable of reaching the 50GeV range in one stage.**
- **Future requirements need to demonstrate high rep rate with good beam quality with high luminosity.**

The future looks bright.

Thank you