PHY 554
Fundamentals of Accelerator Physics
Lecture 24

Advanced Acceleration Methods

Navid Vafaei-Najafabadi

Vladimir N. Litvinenko

Center for Accelerator Science and Education

Department of Physics & Astronomy, Stony Brook University

Many Slides are taken from W.B. Mori PAC 2011 Tutorial presentation

Outline

- The Need for Advanced Accelerators
- The Physics of Plasma Accelerators
- A Brief History of Advanced Accelerators
- Future Outlook and Challenges

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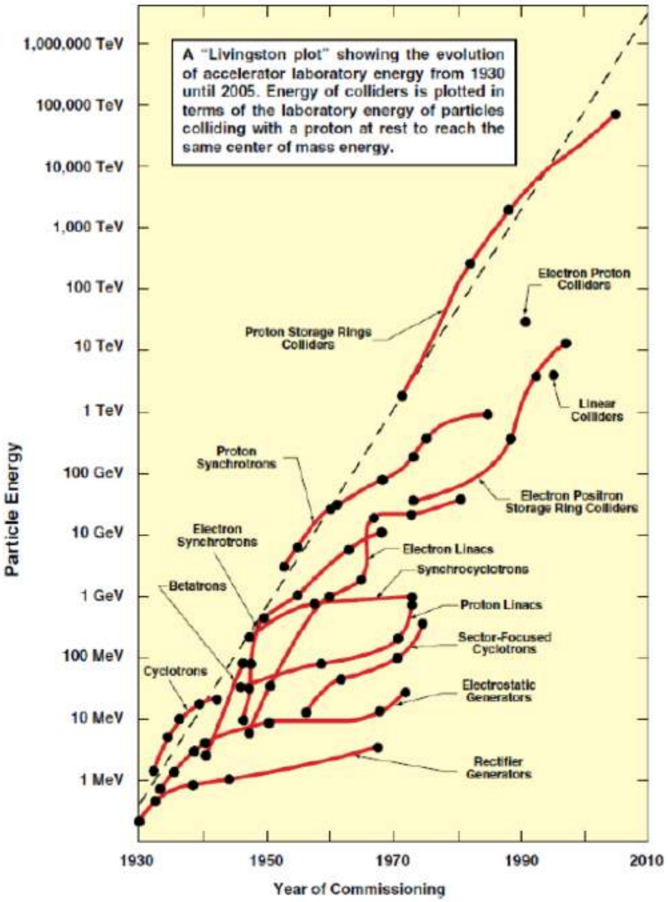
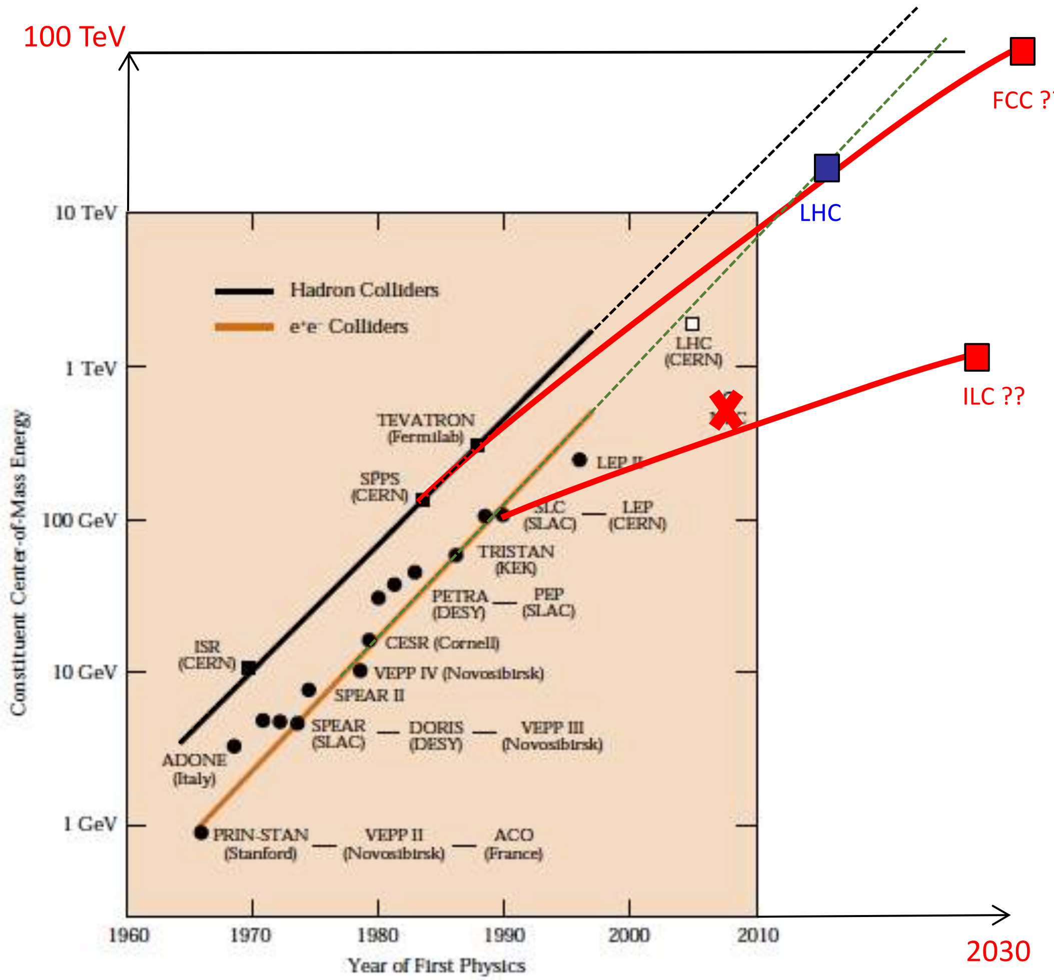
Livingston plot and the end of Moors laws for accelerators: Exponential progress in 20th century of accelerator energies stopped at about 1990



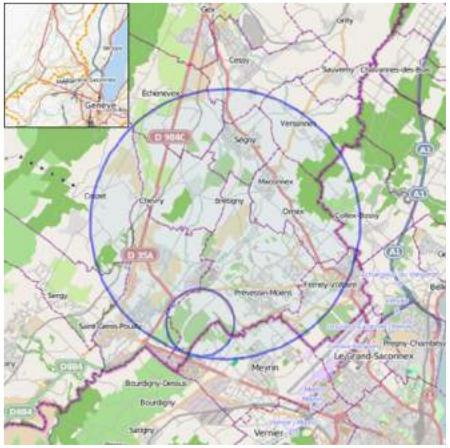
Courtesy: Stanley Livingston

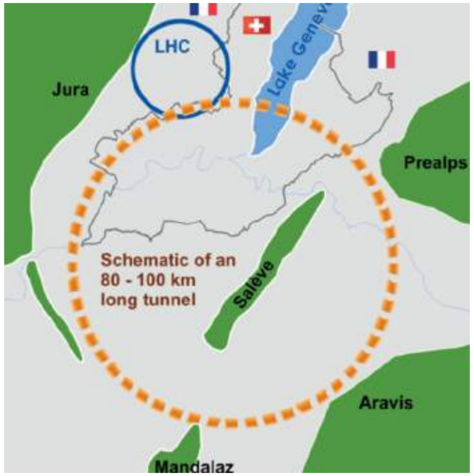


by WOLFGANG K. H. PANOFSKY

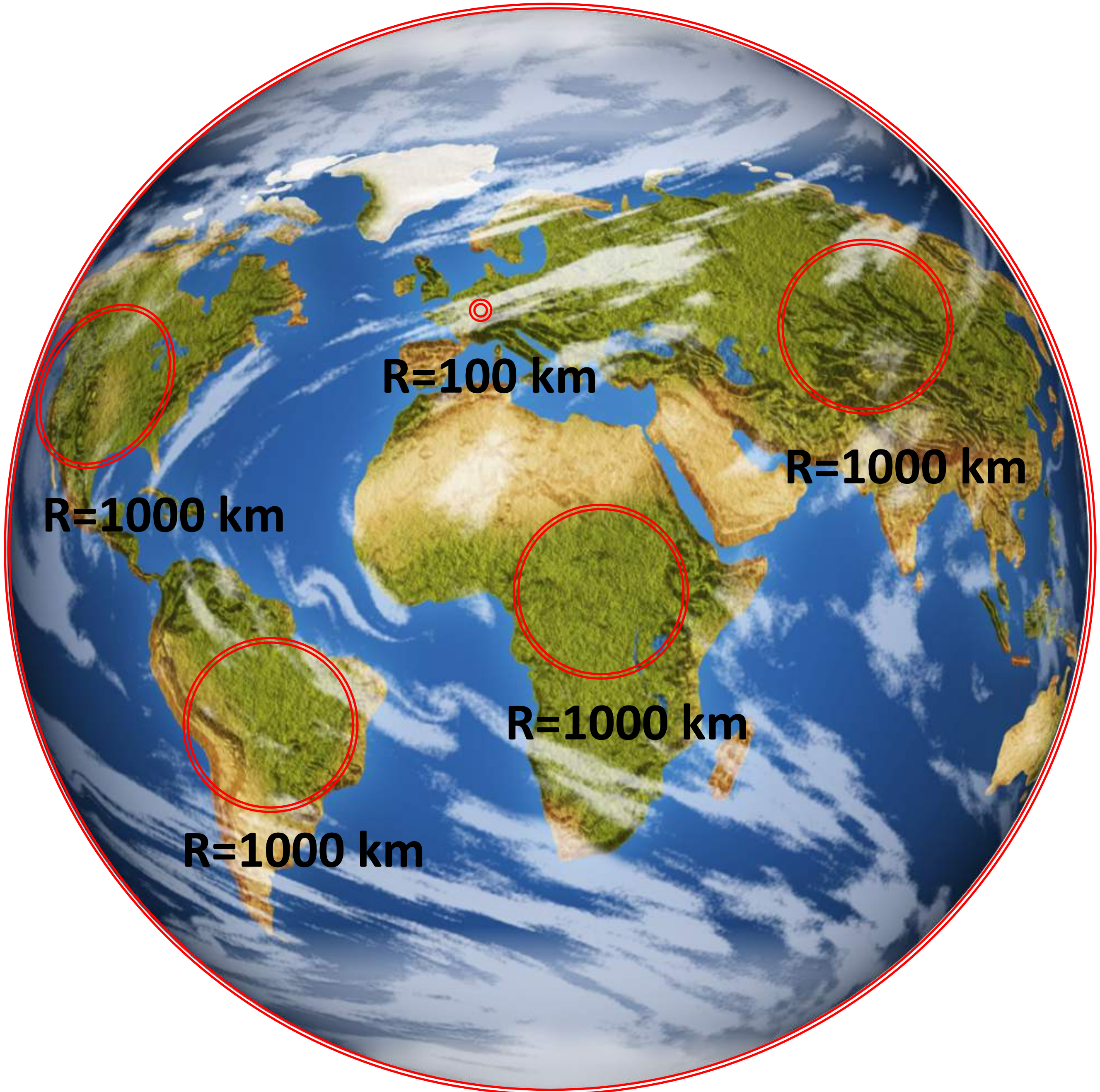
Circular colliders:

- Electron-position (e^+e^-) colliders stopped at c.m. energy of 209 GeV (104.5 GeV per beam, LEP, CERN, C = 27 km) because losses for synchrotron radiation became comparable with energy of the beam
- Large hadron collider (LHC, p on p at 2 x 6.5 TeV) occupies LEP tunnel with two 27 km rings powered superconducting 7.7 T magnets. Cost of such facility is in 10s on \$B and can be afforded only as large international collaboration
  - Physics community is discussing building future circular collider with circumference of 100 km to extend c.m. energy
    - to 350 GeV (!) for e^-e^+ collision: would need 100 MW of RF power to compensate for synchrotron radiation losses
    - To 100 TeV (!) for p-p collisions: would require superconducting magnets with field of 16 T





Ultimate proton circular collider

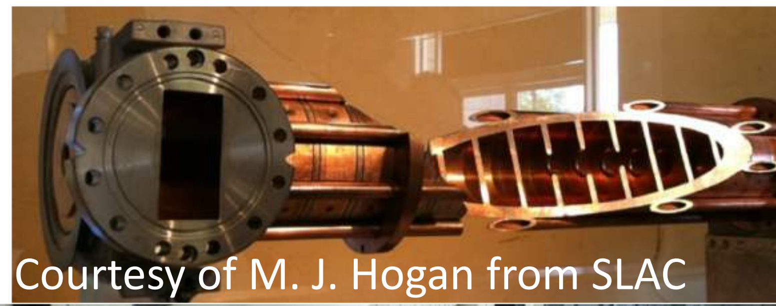


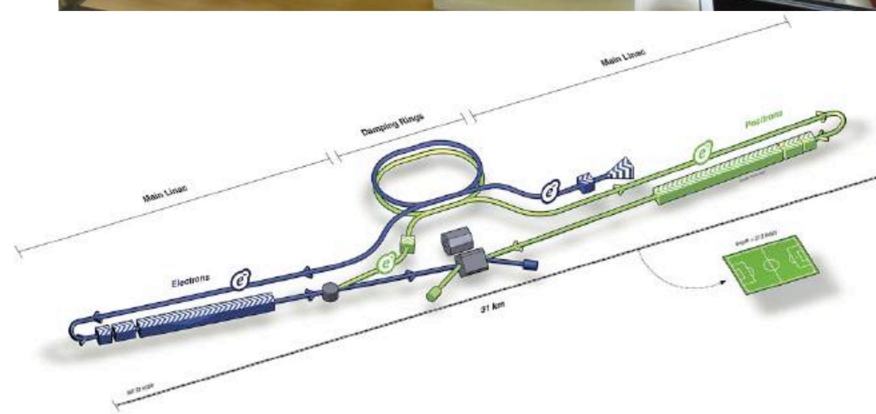
Linear colliders

- Synchrotron radiation is no longer a problem:
  - SR losses do not scale so aggressively with beam energy and are are very low
- Standard RF accelerators are limited in accelerating gradients
  - Room temperature RF:
    - 5 MV/m CW, ~100 MV/m pulsed*
  - Superconducting RF:
    - 20 MV/m CW, 35 MV/m pulsed
  - Main challenge is the size and the cost
    - International Linear Collider, ILC: 2 x 250 GeV, 31 km long, Estimated cost ~ $20B

$$\Delta E_{SR} = \frac{2e^4}{3m^2c^3}\int \frac{\left(\vec{\mathbf{E}} + \left[\vec{\beta}\times\vec{\mathbf{B}}\right]\right)^2 - \left(\vec{\beta}\cdot\vec{\mathbf{E}}\right)^2}{1-\vec{\beta}^2}dt; \;\; \vec{\beta} = \frac{\vec{\mathrm{v}}}{c};$$

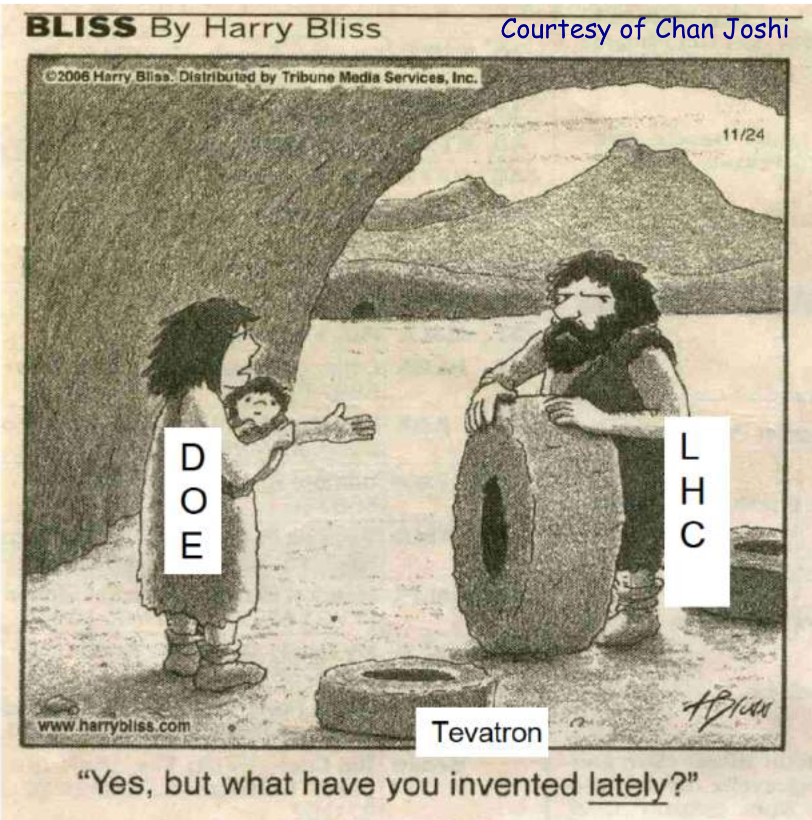
$$\vec{\mathbf{B}} = 0;\; \vec{\mathbf{E}} \parallel \vec{\beta} \Rightarrow \Delta E_{SR} = \frac{2e^4}{3m^2c^3}\int \vec{\mathbf{E}}^2 dt \approx \frac{2}{3}\frac{e^2}{L_{acc}}\gamma^2$$



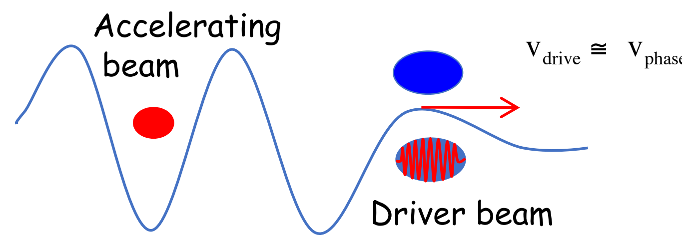


- * Pulsed room temperature Cu structures have a fatigue problem from stress caused by pulsed RF and are developing cracks…. This was one of the reasons to pick SRF as a technology for ILC

What is new?



- T. Tajima and J.M. Dawson PRL (1979)
- P. Chen, J.M. Dawson, et.al. PRL (1983)



- Conditions for large wake
  - a_o ~1 or n_b/n_o~1
  - τ_{dr} ~ a half of plasma period
  - Transverse size ~ $r_\perp \sim c/\omega_p$
- Typical requirements
  Laser power $P_L \sim a_o^2 r_\perp^2 \omega_0^2$ ~ 1 PW τ^2_{dr}[psec]/λ^2[μm]
  I_{peak} ~ 10 kA

$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} \equiv \frac{eE_o}{mc\omega_o} \equiv \frac{eA_o}{mc^2}$$

dimensionless vector potential of the laser wave, direct analog of the wiggler parameter K
i.e. is the measure of how relativistic are electrons are in the laser field

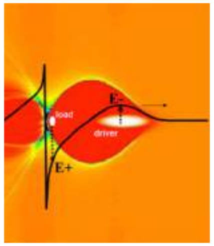
$$\omega_p = \sqrt{\frac{4\pi n_o e^2}{m}} \equiv c\sqrt{4\pi n_o r_e} \cong 5.6\,10^4 Hz\sqrt{n_o[sm^{-3}]}$$

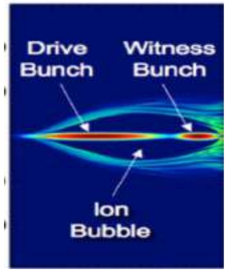
plasma frequency

Advanced accelerator methods

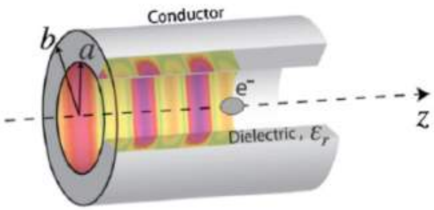
For today

- Plasma accelerators:
  https://en.wikipedia.org/wiki/Plasma_acceleration
  - Laser driven plasma accelerators
  - Beam driven plasma accelerators



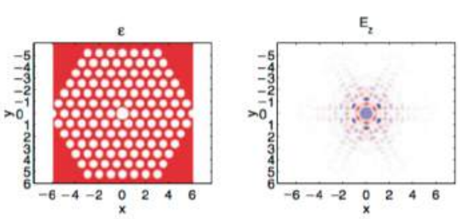


- Dielectric wakefield accelerators



- Photonic gap accelerators

(also called direct laser accelerators)



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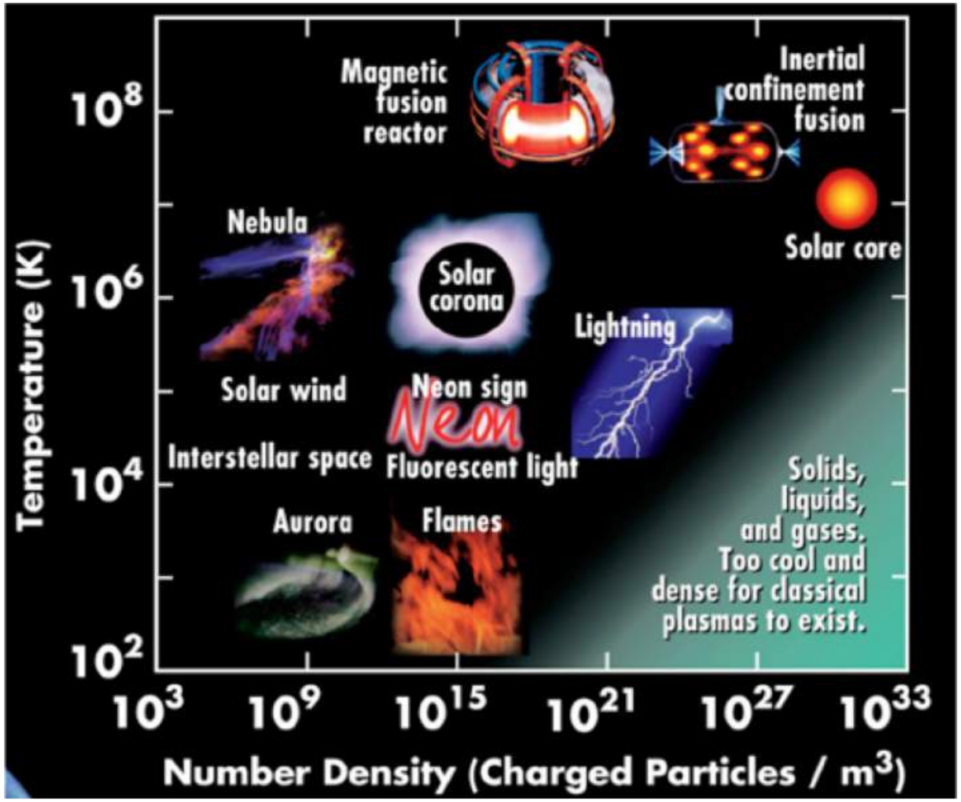
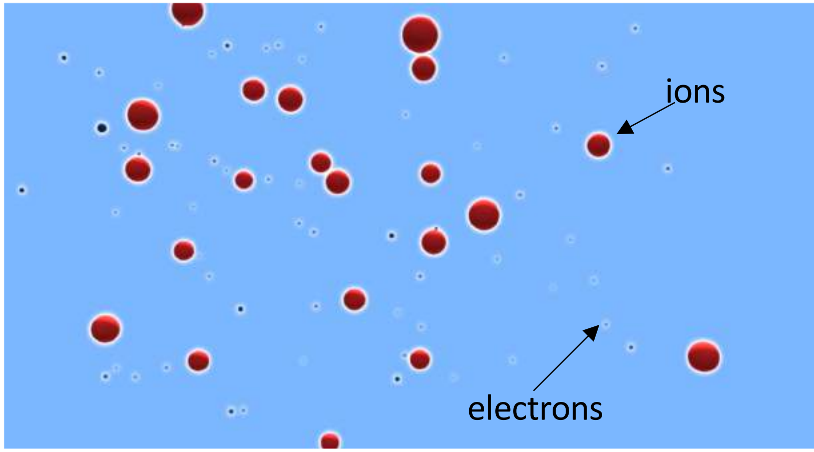
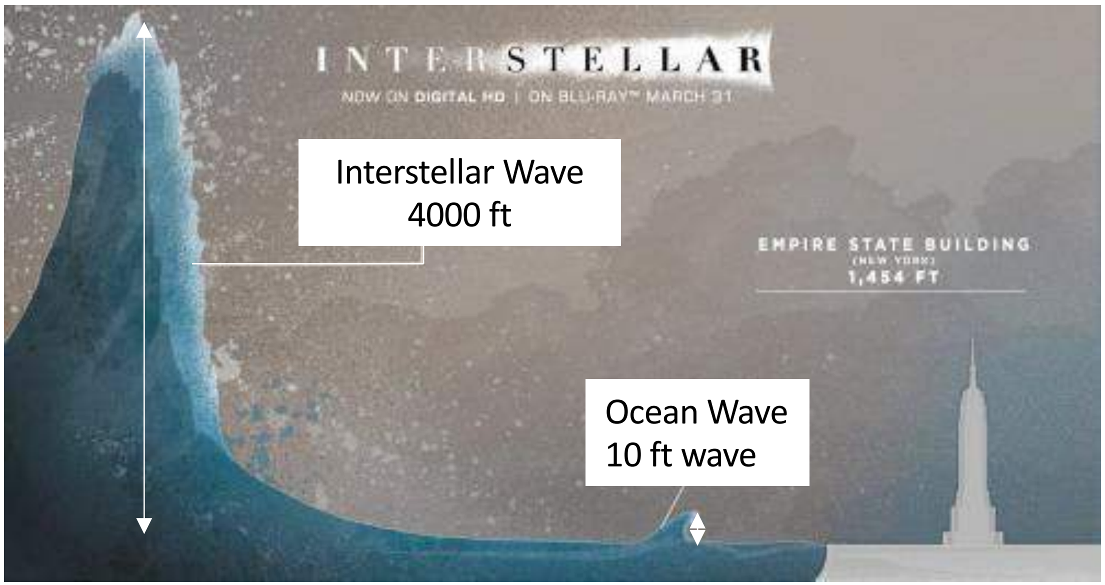
Plasma, More Common Than You Would Think



- Most of the universe exist in the state of plasma
- A plasma is a collection of electrons and ions that are not bound to each other
- The mass of the ions are several thousand times greater than the mass of the electrons.



Getting a Larger Wave for Electrons to Ride



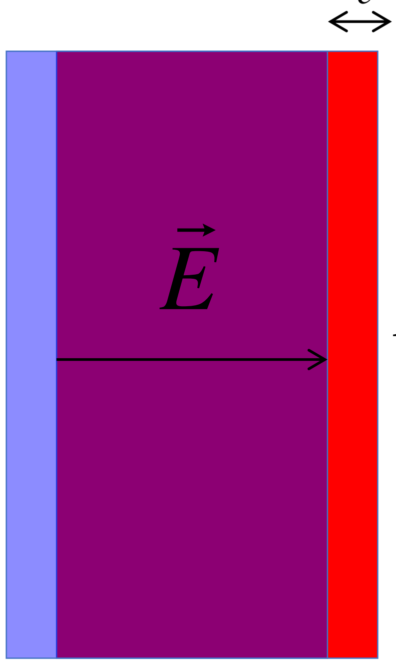
Plasma Wave
(40 GeV/m)

EM Wave in Copper Structure
(100 MeV/m)

- By getting the electrons a large potential wave to ride, colliders of the future could get hundreds of times smaller
- LHC: 27 km circumference -> ~70 m in length

Neutral Plasma Basics

$x = x_e - x_i$



$\vec{E} = 0$ $\qquad$ $\vec{E}$ $\qquad$ $\vec{E} = 0$

$\sigma = e \cdot n_o x$ $\qquad$ $\sigma = -e \cdot n_o x$

Gauss law

$$\oint \vec{E}\, d\vec{A} = 4\pi Q = 4\pi \oint \sigma\, dA \rightarrow E = 4\pi\sigma = 4\pi e \cdot n_o x$$

Equations of motion

$$m_e \ddot{x}_e = -eE \rightarrow \ddot{x}_e + \omega_{pe}^2 x_e = \omega_{pe}^2 x_i$$

$$M_i \ddot{x}_i = eZ_i E \rightarrow \ddot{x}_i + \omega_{pi}^2 x_i = \omega_{pi}^2 x_e$$

$$\omega_{pe}^2 = \frac{4\pi e^2 \cdot n_o}{m_e}; \omega_{pi}^2 = \frac{4\pi Z_i e^2 \cdot n_o}{M_i}$$

Oscillating solution

$$x_e = a_e \cos\omega_p t; x_i = a_i \cos\omega_p t \rightarrow \omega_p^4 = \omega_p^2 \left(\omega_{pe}^2 + \omega_{pi}^2\right)$$

$$\omega_p^2 = \omega_{pe}^2 + \omega_{pi}^2 \rightarrow \frac{a_i}{a_e} = -\frac{\omega_{pi}^2}{\omega_{pe}^2} = -\frac{Z_i m_e}{M_i} = \frac{Z_i}{A_i}\frac{m_e}{M_p} < \frac{1}{1{,}835} << 1$$

Plasma frequency

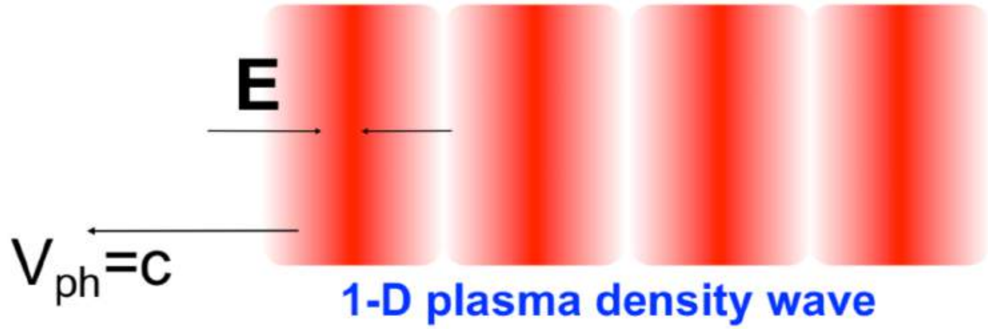
$$\omega_p = \sqrt{\frac{4\pi n_o e^2}{m_e^*}}; m_e^* = \frac{m_e \cdot M_i}{Z_i m_e + M_i}$$

$$\omega_p \cong \sqrt{\frac{4\pi n_o e^2}{m_e}} \equiv c\sqrt{4\pi n_o r_e} \cong 5.6\,10^4 Hz \sqrt{n_o[cm^{-3}]}$$

Trivial solution $\quad \omega_p^2 = 0 \rightarrow x_e = x_i$

For SI folks $\quad \omega_p \cong \sqrt{\dfrac{n_o e^2}{\varepsilon_o m_e}}$

Simple Wave Amplitude Estimate



$$\nabla \bullet E \sim ik_p E = -4\pi e n_1$$ **Gauss' Law**

$$k_p = \omega_p / V_{ph} \approx \omega_p / c$$

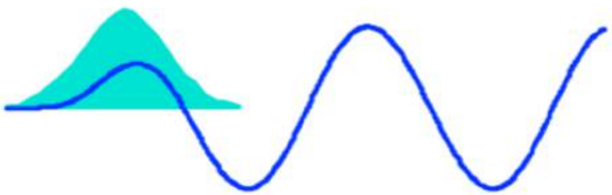
$$n_1 \sim n_o$$

$$\Rightarrow eE \sim 4\pi e n_o e^2 c / \omega_p = mc\omega_p$$

$$or \quad eE \sim \sqrt{\frac{n_o}{10^{16} cm^{-3}}} \, 10\, GeV/m$$

Slide from W.B. Mori PAC Tutorial presentation

Quasi-static Approximation
Sprangle, Esarey, Ting 1990



For a fixed driver shape the wake can be calculated. The wake only changes if the driver shape changes. The driver's shape changes very slowly.

Use appropriate variables

- Transform from:

$$(z, x, y; t)$$

- Transform to:

$$(\xi = z - v_\phi t, x, y; s = z)$$

Meaning of new variables

- $\xi = z - v_\phi t$ is the distance from front of the driver
- $s = z$ is the distance the driver has propagated into the plasma

Mathematical meaning of quasi-static approximation

$$\partial_s << \partial_\xi$$

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Important potential and forces inside a wake with $c \approx v_\phi$

Let the wake move at c and make the quasi-static approximation

$$E_z = -\partial_z \phi - 1/c\, \partial_t A_z$$

$$F_z \approx -q\partial_\xi(\phi - A_z)$$

$$\vec{F}_\perp = q\left(\vec{E}_\perp + (\vec{v}_b \times \vec{B})_\perp\right)$$

$$\vec{v_b} = \hat{z}c$$

$$F_\perp \approx q(-\nabla_\perp(\phi - A_z))$$

Psuedo-potenial

$$\psi = (\phi - A_z)$$

Don't choose a gauge where

$$\phi = A_z$$

Forces on relativistic particle

$$F_z = -\partial_\xi \psi$$

$$F_\perp = -\nabla_\perp \psi$$

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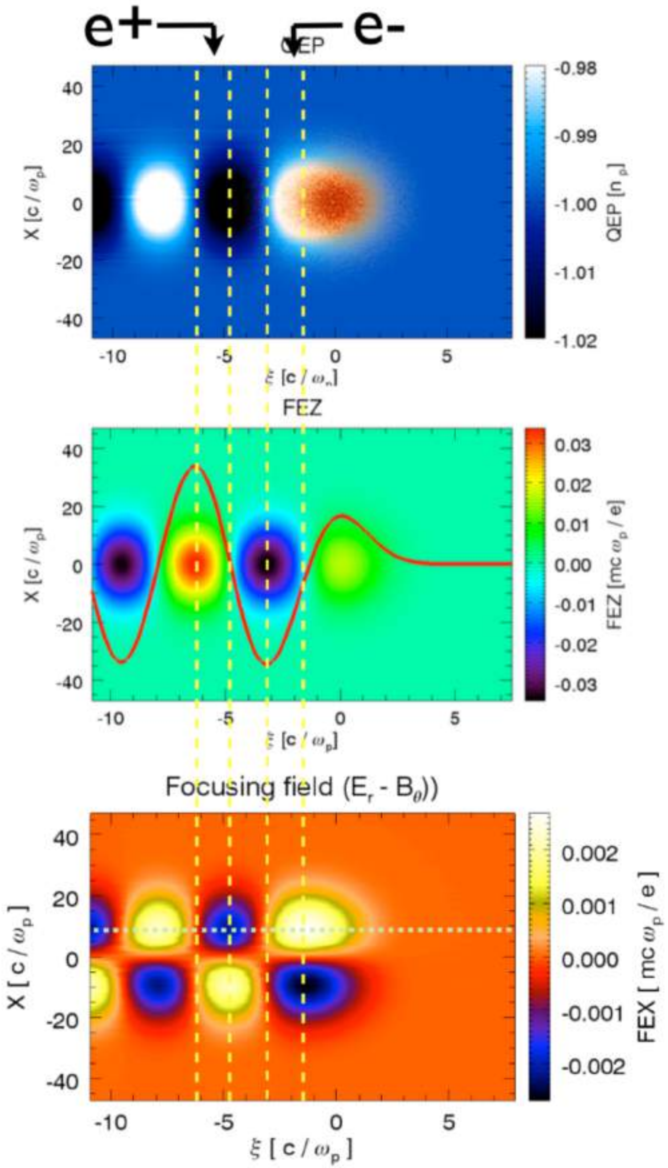
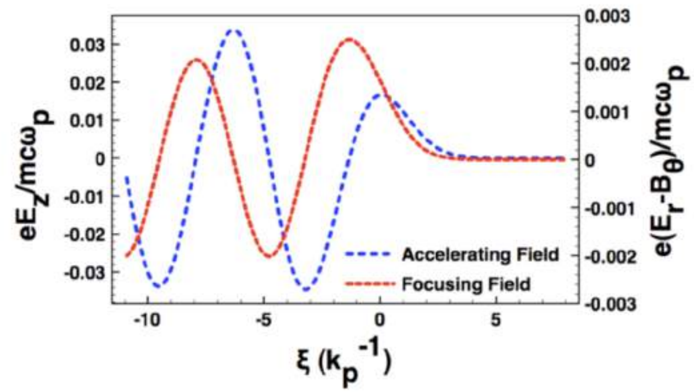
Linear Waves of Wide Particle Beams and Laser Drivers





- Fields can be calculated exactly using Greens functions
- The accelerating and focusing fields are $\pi/2$ out of phase
- Only half of accelerating phase can be used
- Formalism for electrons and positrons is the same, just move to their respective accelerating and focusing phase

Breakdown of Linear Theory

When the driver gets strong enough, the linear wave structure is no longer sustained

For a laser, this means $a_0 \sim 1$

a_0 is the normalized vector potential

$$a_0 = \frac{eA_0}{mc^2} = 0.85\times10^{-9}\sqrt{I[W/cm^2]\lambda^2[\mu m]}$$

Linear theory works when $a_0 \ll 1$

For a particle beam, it means Λ>1

Λ is the normalized charge per unit length

$$\Lambda = \frac{n_b}{n_p} k_p^2 \sigma_r^2 \approx \frac{I}{24\ kA}$$

Linear theory works when
$\Lambda < 1$ and $\frac{\mathrm{n_b}}{\mathrm{n_p}} < 10$ for e- beams
$\Lambda < 1$ and $\frac{\mathrm{n_b}}{\mathrm{n_p}} < 1$ for e+ beams

What Happens When $\Lambda \sim 1$

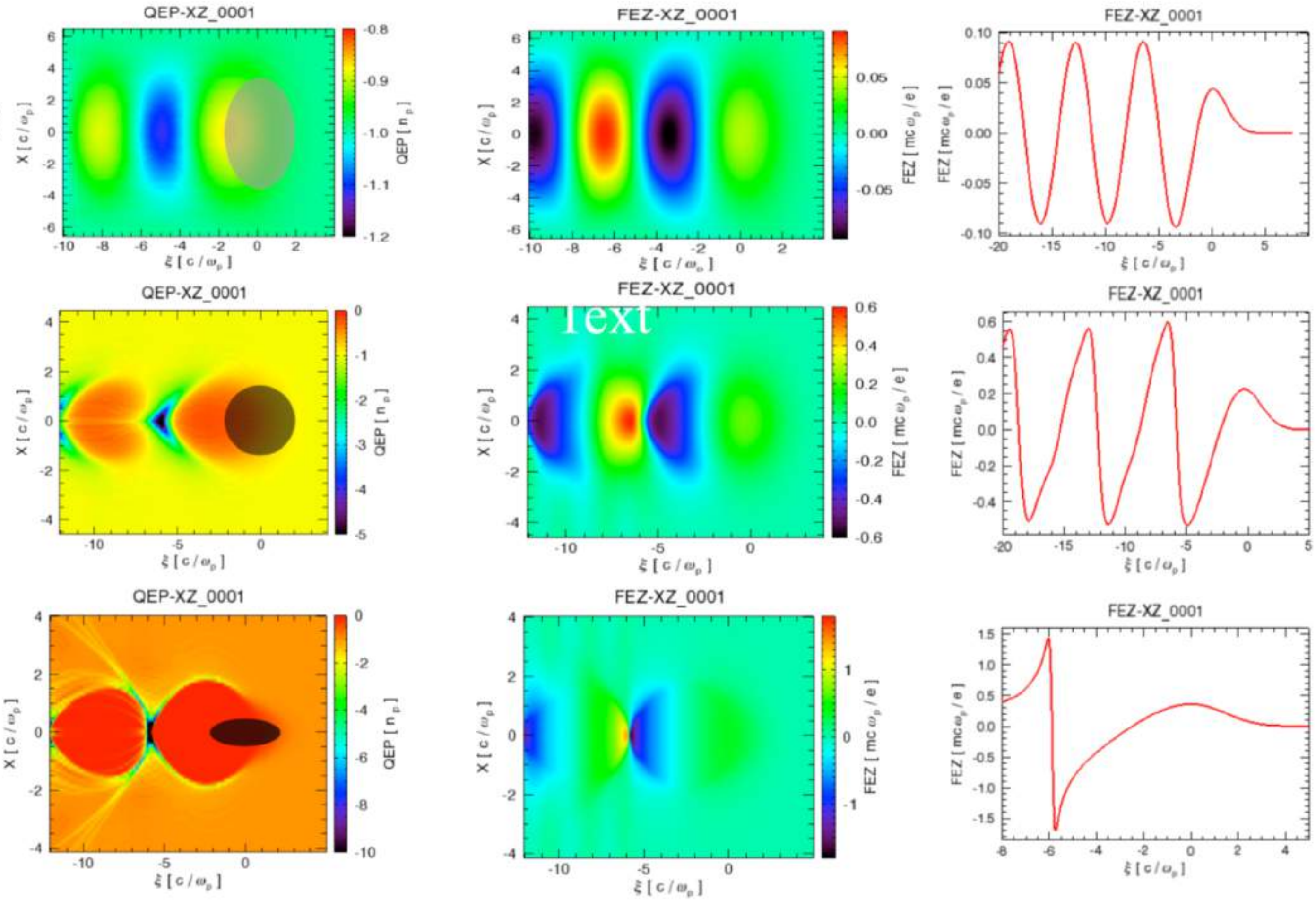
$k_p R_b \approx 2\sqrt{\Lambda}$ for $k_p \sigma_z \approx 1$

ne psi Ez

$k_p \sigma_r = 2.8$

$k_p \sigma_r = 1.0$

$k_p \sigma_r = 0.38$



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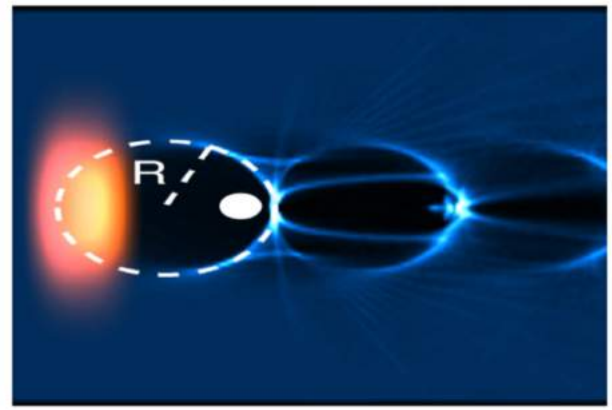
Very intense lasers also create a similar structure

Driven by an electron beam

Driven by a laser pulse



Called blowout or bubble

Need a nonlinear description of these wakes

Very stable wakes!

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Field Structure is Described by the Wake Potential

Field equations in Lorentz gauge

$$(\frac{1}{c^2}\partial_t^2 - \nabla^2)\vec{A} = \frac{4\pi}{c}\vec{J}$$

$$(\frac{1}{c^2}\partial_t^2 - \nabla^2)\phi = 4\pi\rho$$

Make quasi-static approximation

$$-\nabla_\perp^2\vec{A} = \frac{4\pi}{c}\vec{J}$$

$$-\nabla_\perp^2\phi = 4\pi\rho$$

Wake potential follow "2D electrostatic" equation

$$-\nabla_\perp^2\psi = 4\pi(\rho - \frac{J_z}{c})$$

Acceleration and focusing fields:

$$F_z = -\partial_\xi\psi$$

$$F_\perp = -\nabla_\perp\psi$$

Inside bubble there only ions so use Gauss's Law for cylinders

$$F_\perp = -2\pi e^2 n_0 x_\perp$$

Slide from W.B. Mori PAC Tutorial presentation

All Comes Down to Bubble Radius

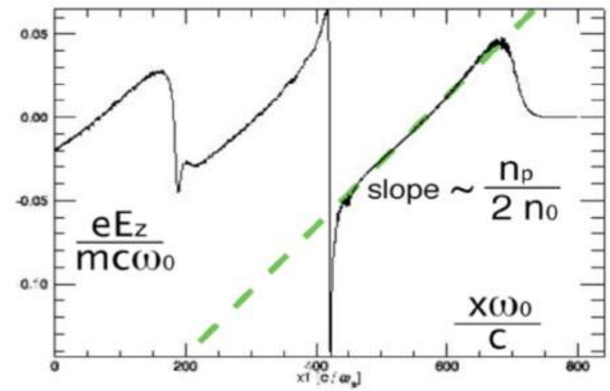
$$\overline{\psi} \approx k_p^2 \frac{r_b^2(\xi) - r^2}{4}$$

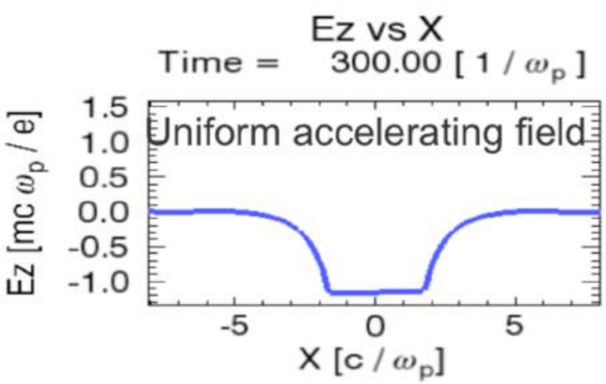
$$\frac{eE_z}{mc\omega_p} = \frac{r_b}{2}\frac{dr_b}{d\xi} \approx \frac{1}{2}\xi$$

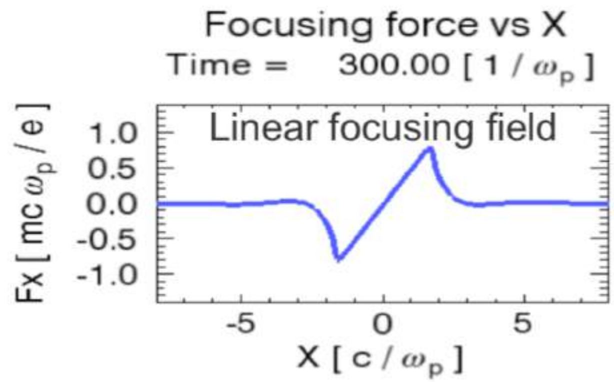
$$\frac{eE_M}{mc\omega_p} \approx \frac{1}{2}k_p R_b \approx \sqrt{\Lambda}$$

Bubble radius :

$$k_p R_b \approx 2\sqrt{\Lambda} \text{ or } k_p R_b \approx 2\sqrt{a_0}$$







The shape of the plasma structure in the relativistic blowout regime for large bubble is a circle: Lu, et al. *PRL*, **96**, 165002 (2006), *PoP*, **13**, 056709 (2006).

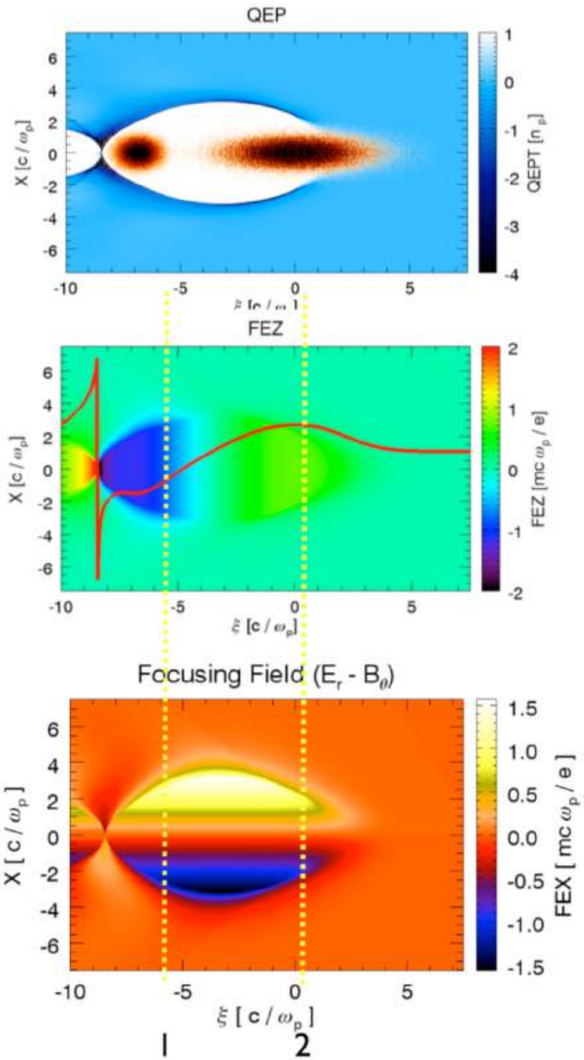
Beam Loading

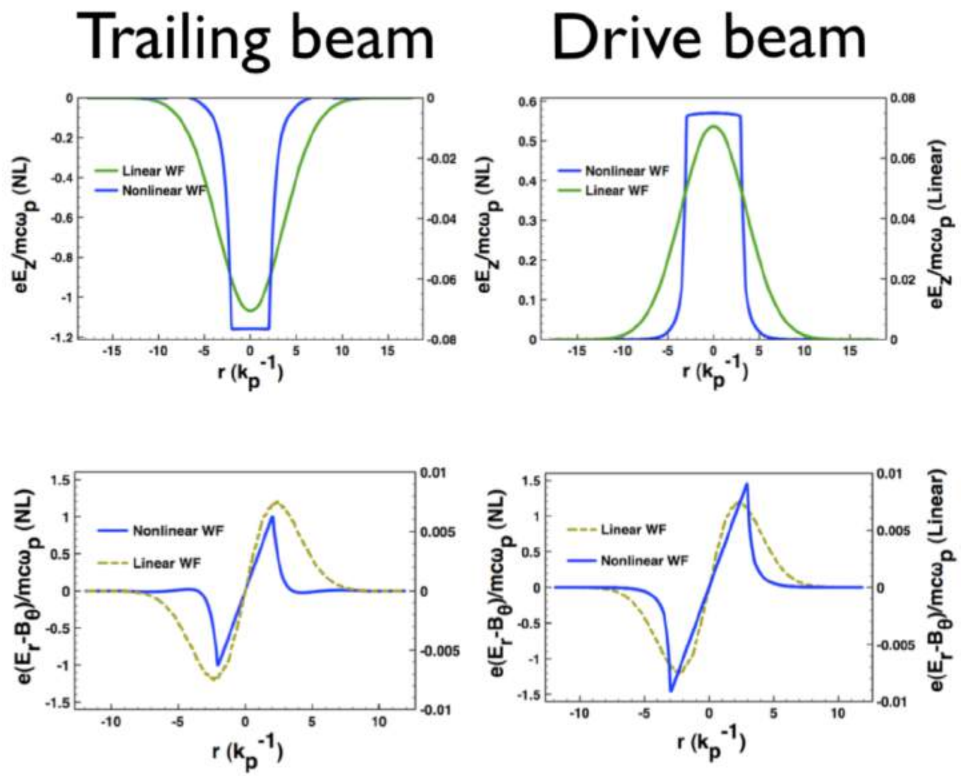
- Placing a bunch charge to get accelerated and extract energy at high efficiency, small energy spread, and emittance preservation
- The best properties of the loaded wake are:

$$\partial_\xi F_z = 0 \qquad \partial_\xi F_\perp = 0$$

$$\nabla_\perp F_\perp = C_{onstant} \qquad \nabla_\perp F_z = 0$$

Nonlinear wakefield is ideal for accelerating/focusing electrons





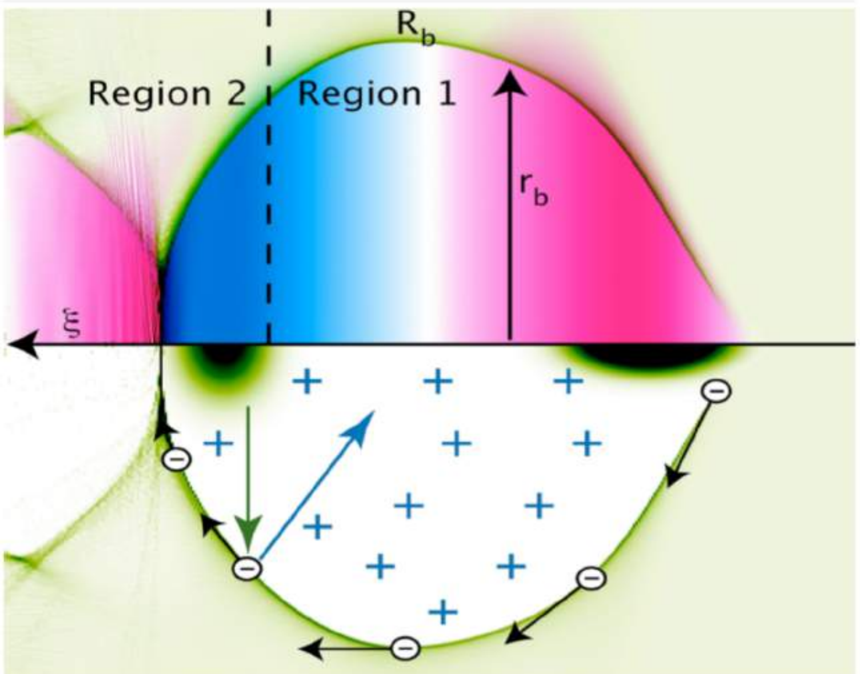
$$\partial_\xi F_z = 0 \qquad \partial_\xi F_\perp = 0$$

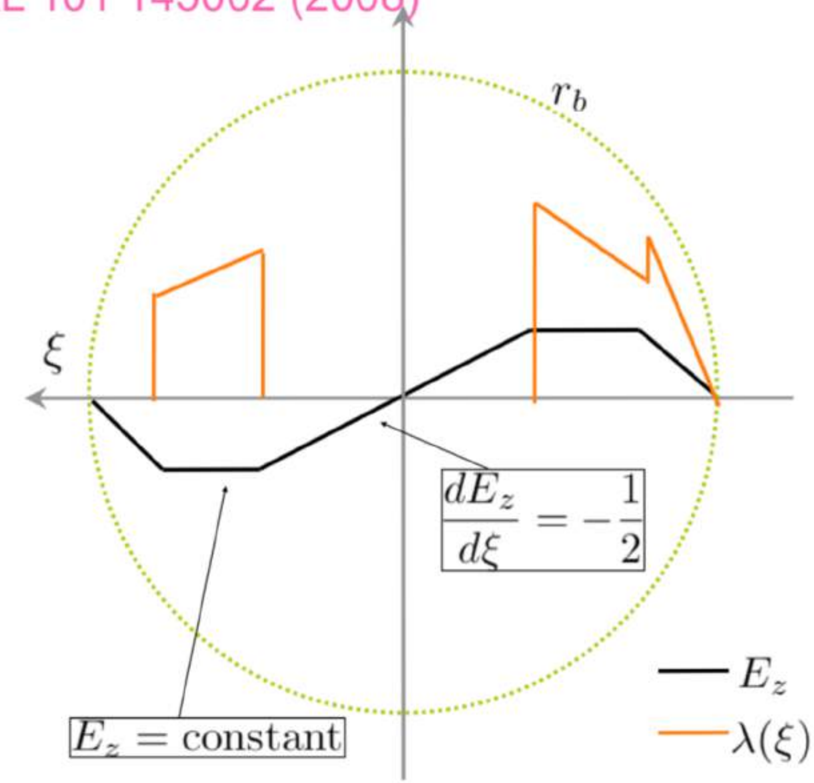
$$\nabla_\perp F_\perp = C_{onstant} \qquad \nabla_\perp F_z = 0$$

Note: A relativistic trailing beam does not modify the focusing fields

Nonlinear beam loading: Solve equation for $R_b(\xi)$

M. Tzoufras et al., PRL 101 145002 (2008)





$$\text{For } \frac{r_b}{R_b} \ll 1 \rightarrow \begin{cases} r_b \frac{d^2 r_b}{d\xi^2} + 2\left[\frac{dr_b}{d\xi}\right]^2 + 1 = \frac{4\lambda(\xi)}{r_b^2} \\ E_z = \frac{1}{2} r_b \frac{dr_b}{d\xi} \end{cases}$$

These equations are integrated for a trapezoidal $\lambda(\xi)$ to obtain $E_z(\xi)$ and $r_b(\xi)$. This allows us to design accelerators with 100% beam-loading efficiency that conserve the energy spread.

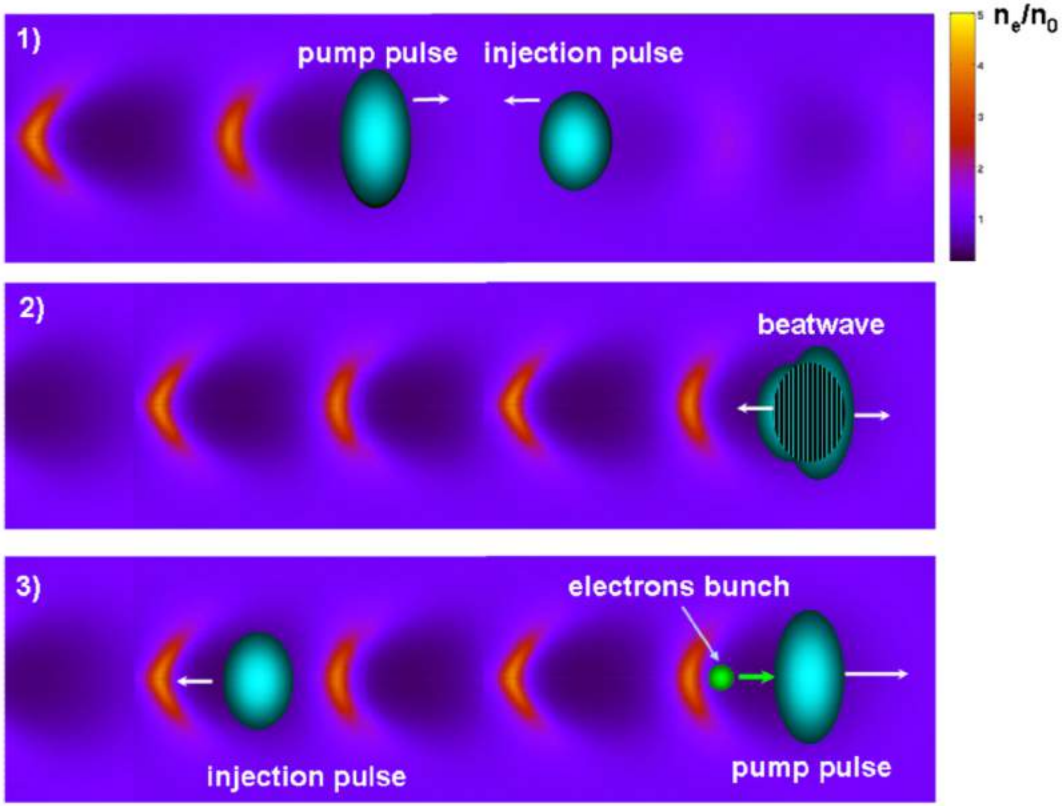
Slide from W.B. Mori PAC Tutorial presentation

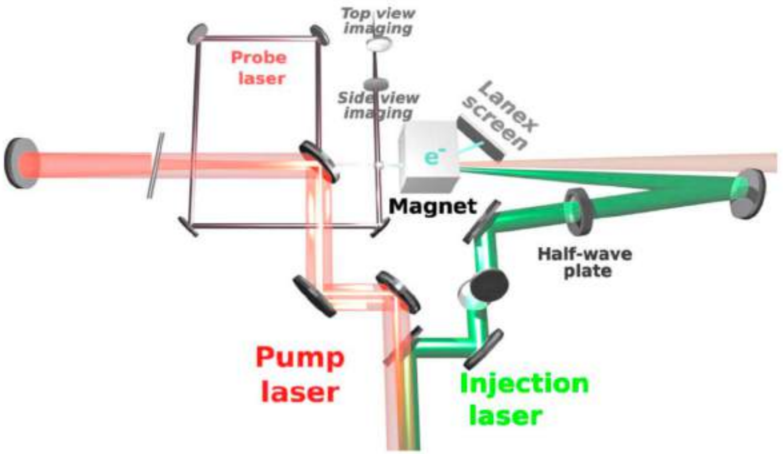
Injection Methods

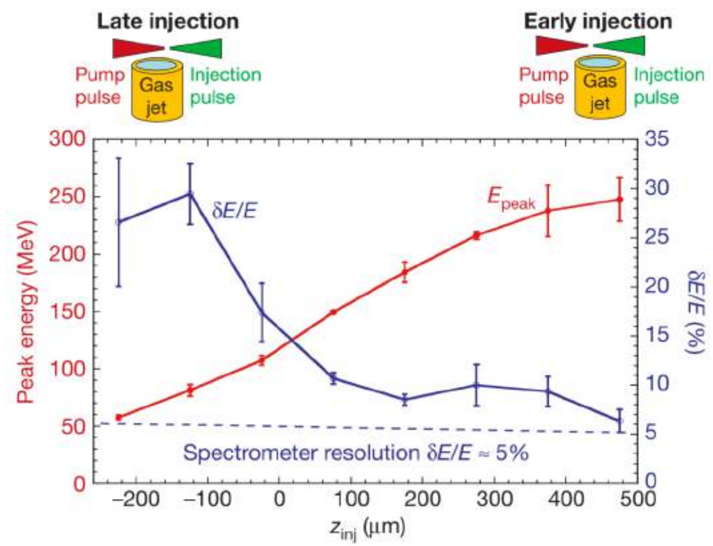
- Getting Charge into this relativistic structure is a significant challenge. Several methods:
  - Self injection
    - Charge is injected due to fluctuations of the bubble sheath
  - Colliding pulse injection
    - Two pulses colliding head on. The “driver” creates the wakefield, and the “injector” injects electrons
  - Ionization injection
    - Mixture of high-ionization-threshold (HIT) and low-ionization threshold(LIT) gases. Electrons from HIT are ionized and injected within the bubble driver in the LIT gas
  - Down ramp Injection

Colliding Pulse Injection

“Beatwave” between the two pulses results in electron injection





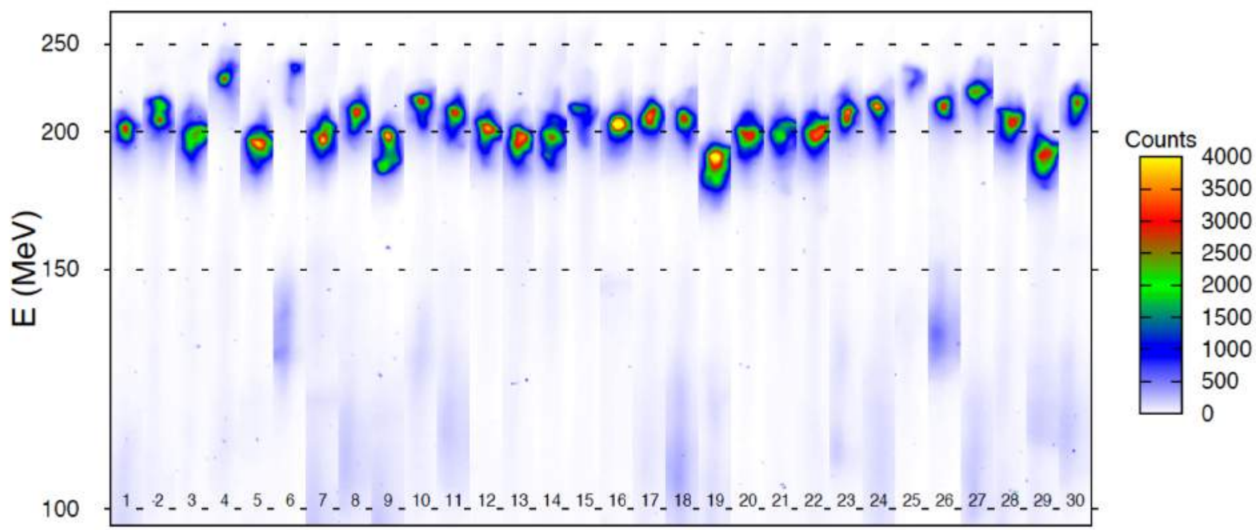


Src: V. Malka, et al., Phys. Plasmas 16, 056703 (2009)

Optimization

- Best optically injected beam measured: $E = 200$ MeV, $\Delta E/E = 1\%$, $Q = 10$ pC

Results: Stability



30 consecutive shots with $a_0 = 1.5$, $a_1 = 0.4$, $n_e = 5.7 \times 10^{18}$ cm^{-3}

- $E = 206$ MeV(5% rms fluct.)
- $\Delta E = 14$ MeV (21% rms fluct.)
- $\theta = 4.5$ mrad (36% rms fluct.)
- $Q_{peak} = 13$ pC (38% rms fluct.)

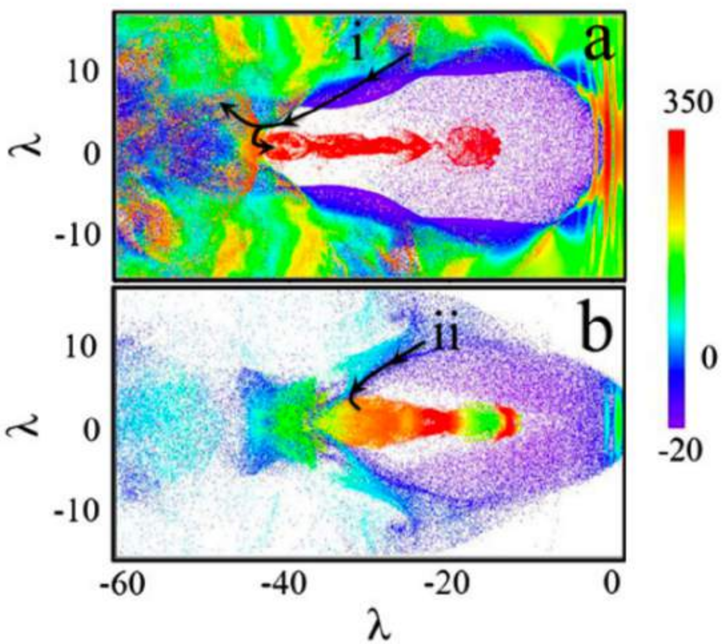
Laser fluctuations:

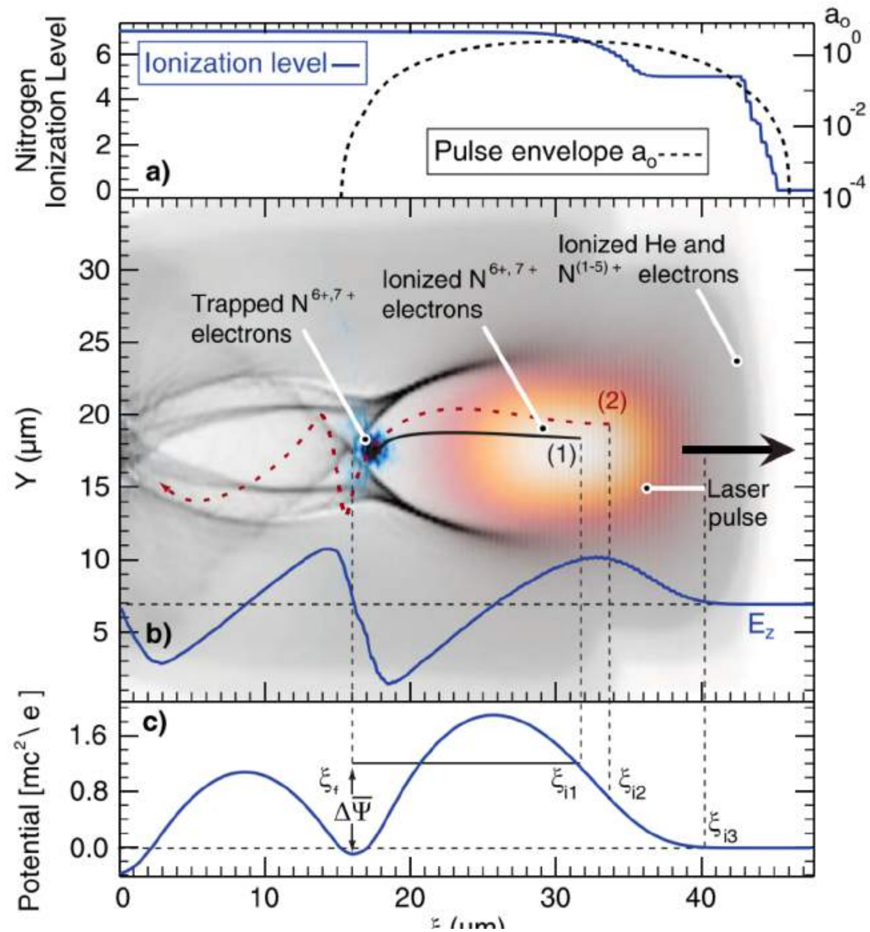
- Intensity: 17% rms (60 pktopk)
- Pointing: 8 μm rms (17 μm max.)

Ionization Injection

- Initially demonstrated at SLAC in Beam Driven Plasma wakefield (E. Oz. PRL (2006))
- Reported simultaneously in laser experiment by UCLA and Michigan (A. Pak and C. McGuffy, PRL (2010)
- Continuous ionization usually results in large energy spread

Trapping Condition: $\Delta \bar{\Psi} \lesssim -1.$



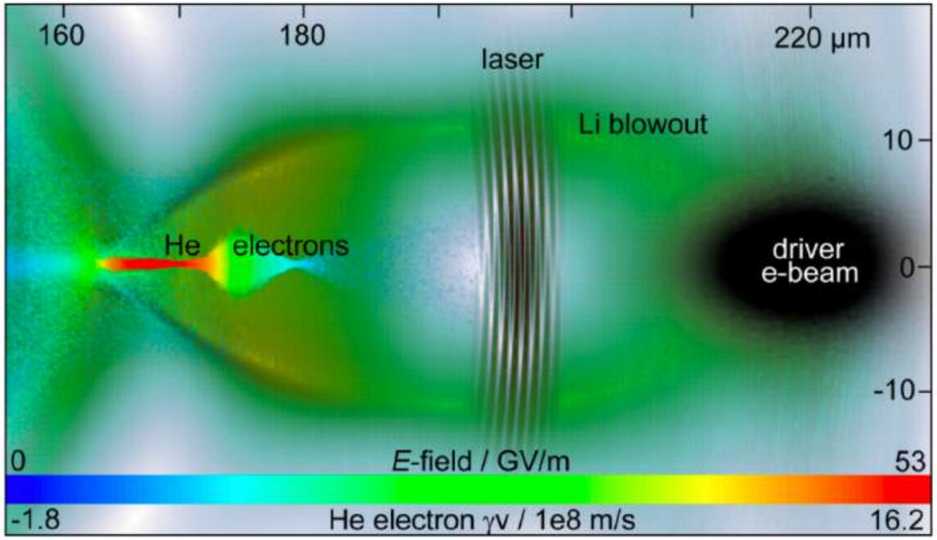


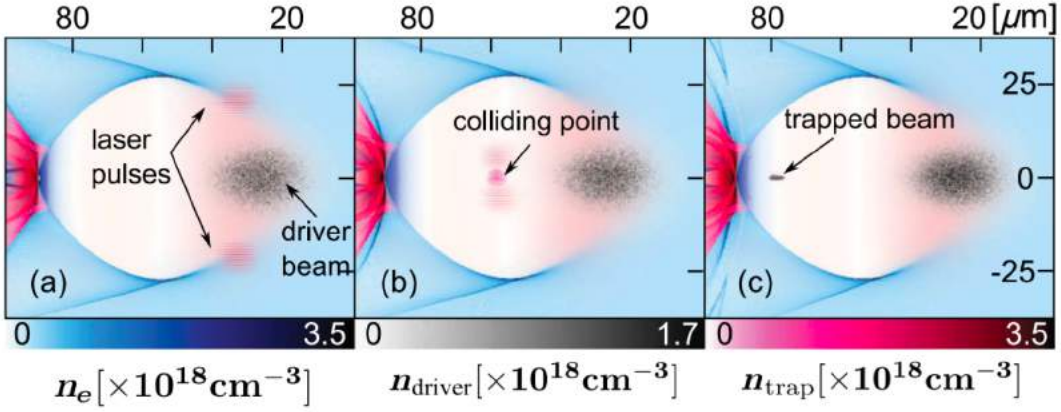
Trojan Horse

Confined ionization injection is expected to produce very small, high quality beam

For this to work, you need two “colors”:

- e-beam driver and laser as injector (most common)
- Lower intensity (but higher energy) driver (e.g. CO_2 laser) and high intensity injector (Ti:Sapphire laser)



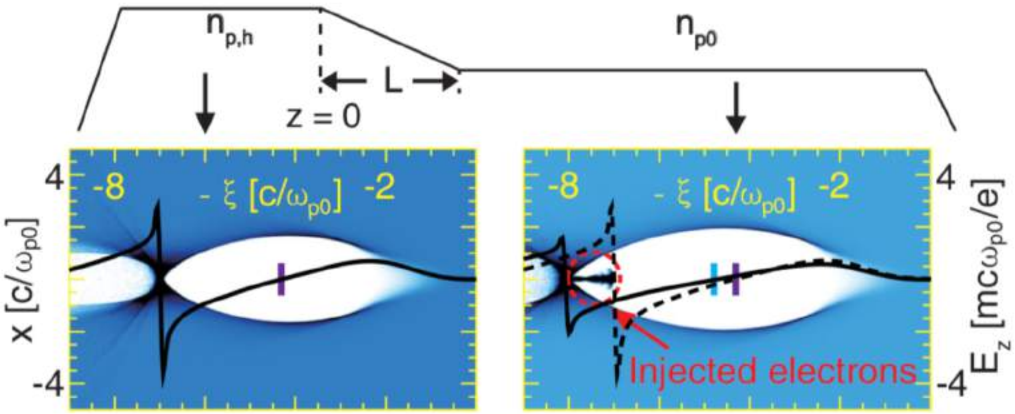


B. Hidding, PRL, 2012
F. Li, PRL, 2017

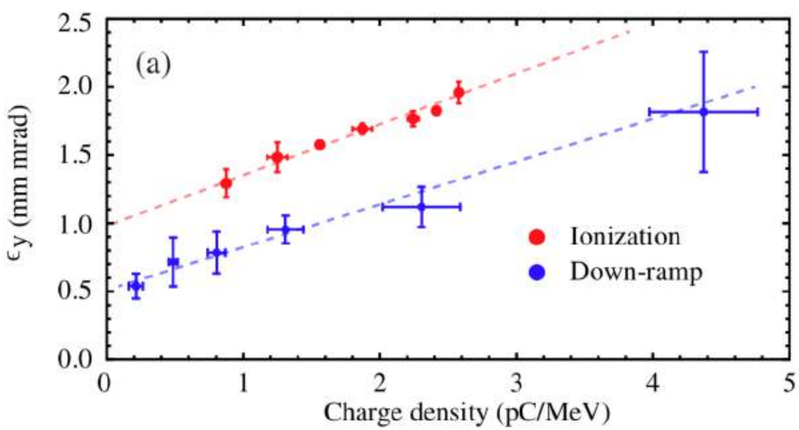
Down ramp Injection

Currently most promising technique for low emittance (high transverse quality) beam
Takes advantage of the dependence of $K_p R_b$ on plasma density

$$k_p R_b \approx 2\sqrt{\Lambda}$$



x. Xu, PRAB 20, 111303 (2017)



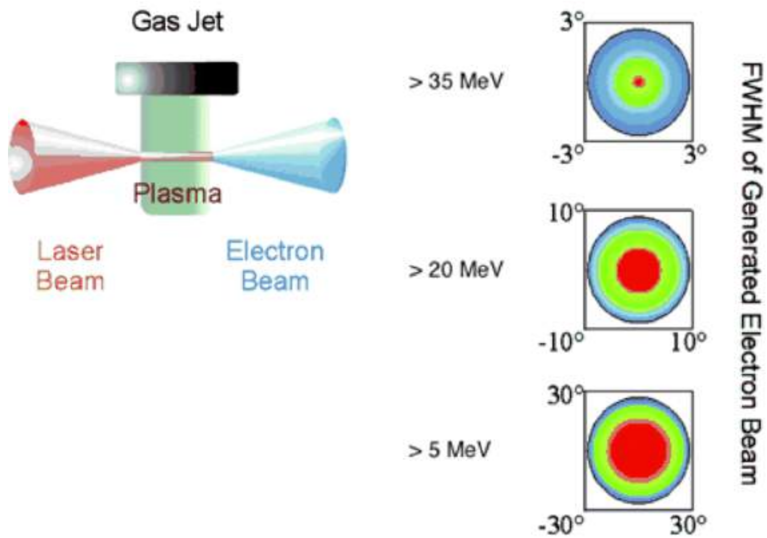
Barber, PRL 119, 104801 (2017)

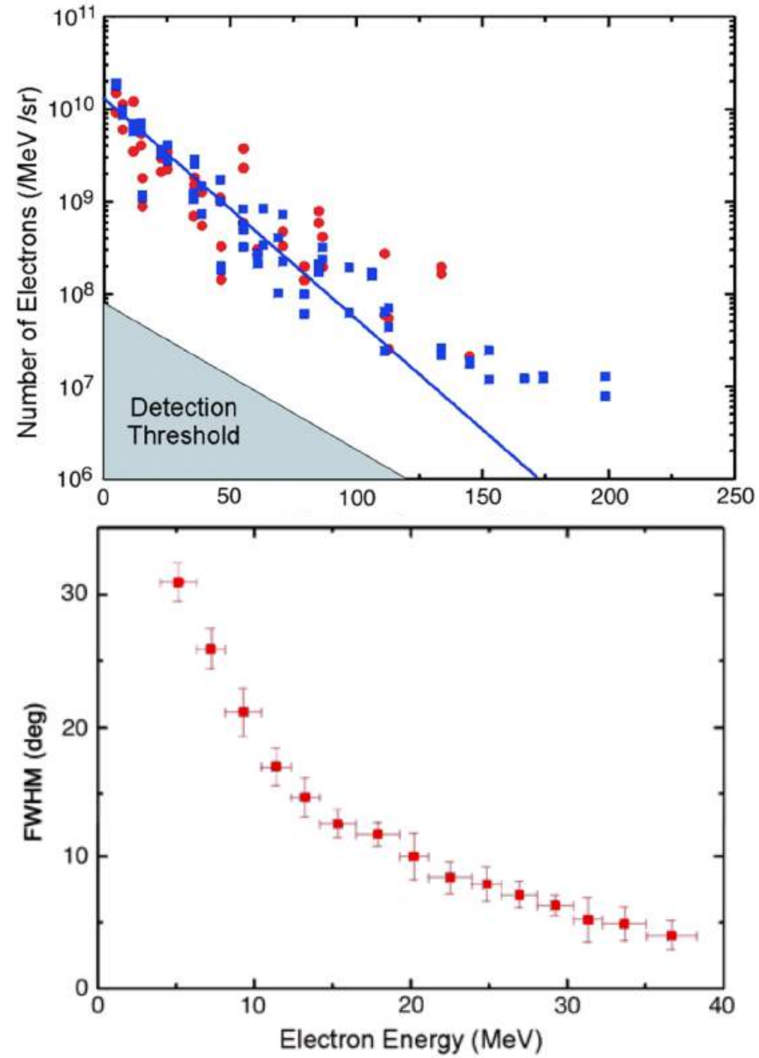
Outline

- The Need for Advanced Accelerators
- The Physics of Plasma Accelerators
- A Brief History of Advanced Accelerators
- Future and Challenges

PRE-DAWN

Schematic of the experiment.

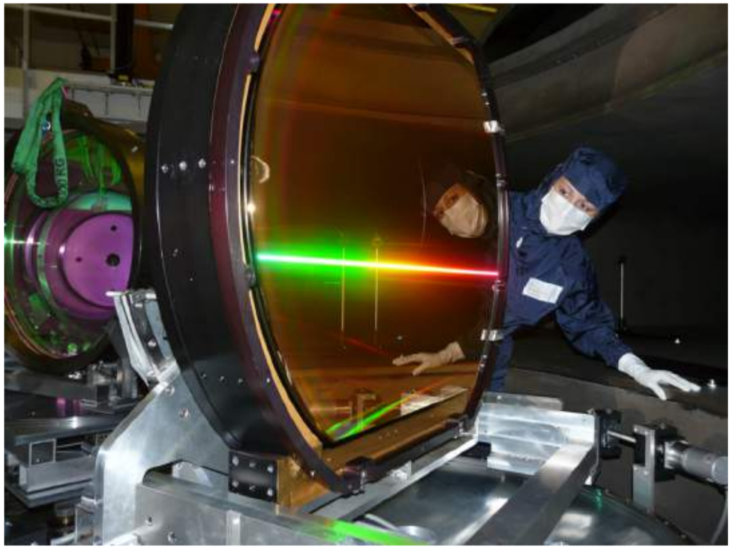


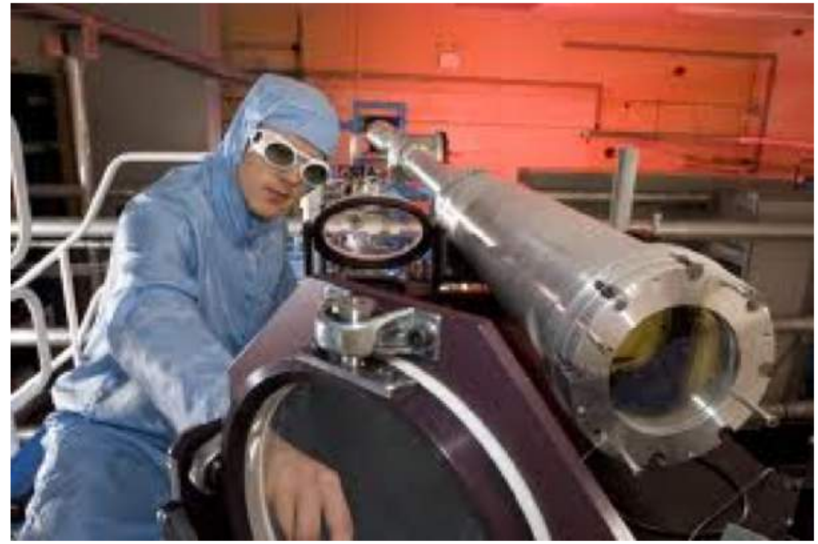


A high- intensity laser is focused onto the sharp edge of a gas jet with a uniform density profile. In this regime, the generated plasma wave breaks and accelerates electrons. It is observed that the high-energy electrons are well collimated in the direction of propagation of the laser beam

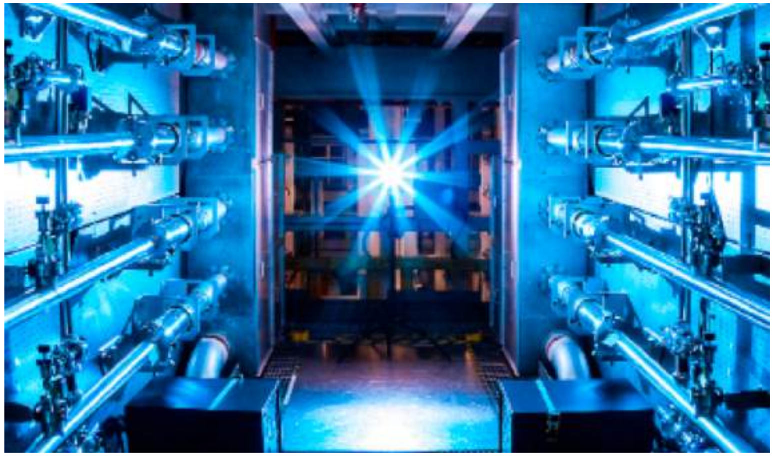
Science 22 , 2002, Vol. 298 no. 5598,
Electron Acceleration by a Wake Field Forced by an Intense Ultrashort Laser Pulse
V. Malka et all., LOA (Laboratoire d'Optique Appliquée,École Nationale Supérieure des Techniques Avancées,École Polytechnique) & others

Vulcan Petawatt Laser Facility

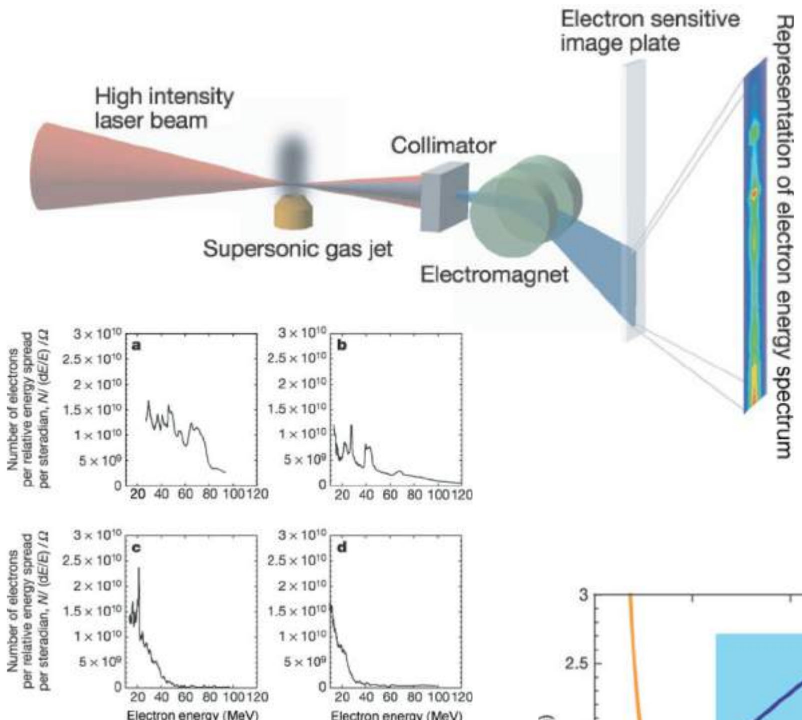


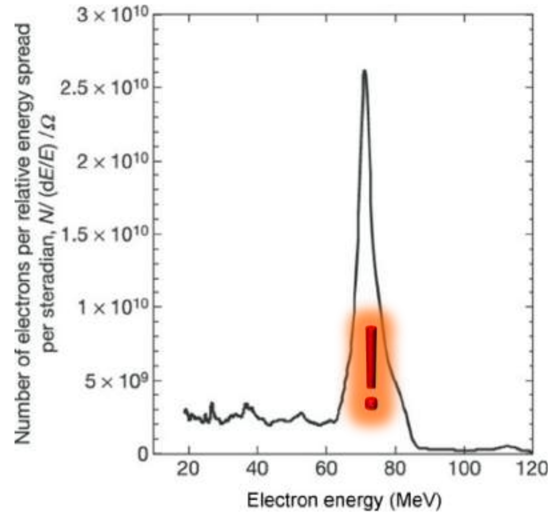


Livermore Laser Facility

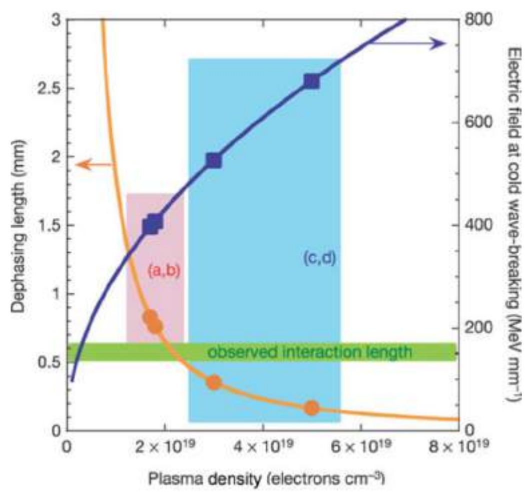


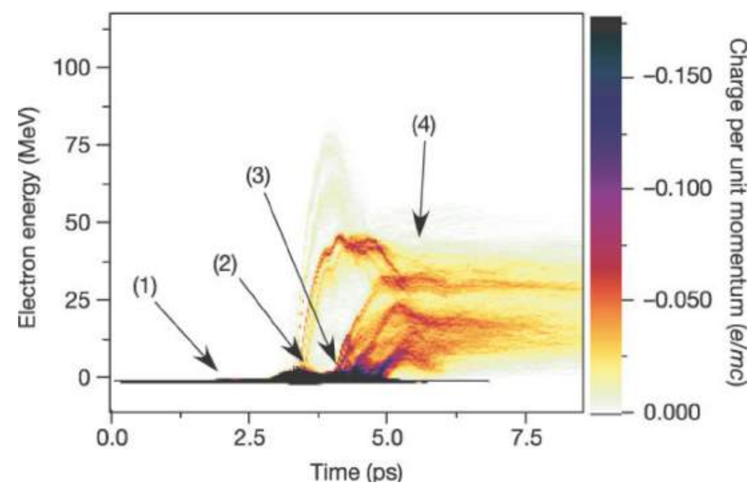
2004 Triple Nature Papers





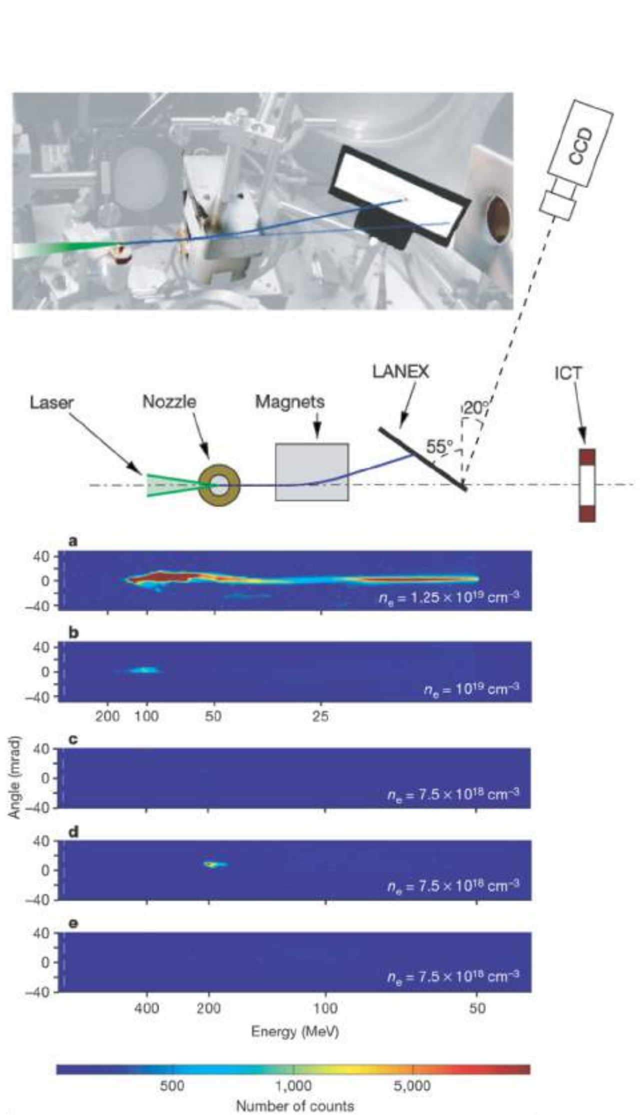
73 MeV
spread 3%?

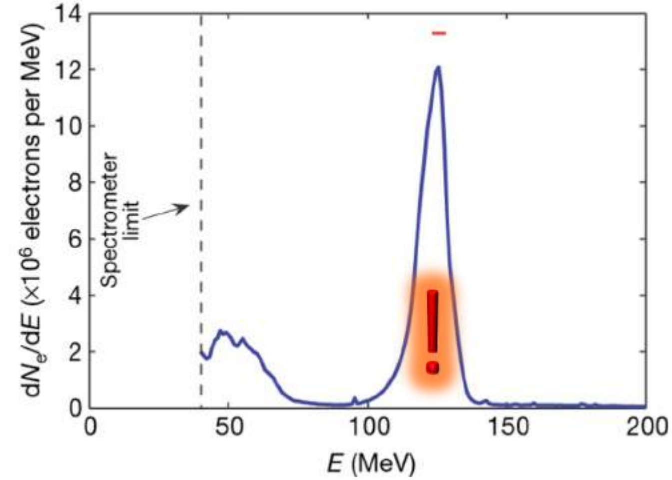




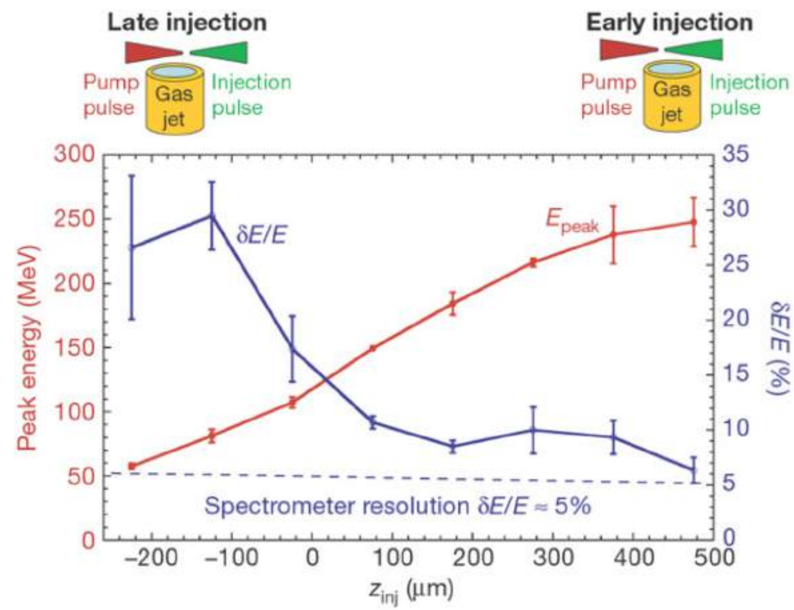
Nature 431, 2004, Monoenergetic beams of relativistic electrons from intense laser-plasma interactions, S. P. D. Mangles et .all, RAL & others

2004 Triple Nature Papers





125 MeV
spread 9%



Nature 431/444, 2006, A laser-plasma accelerator producing monoenergetic electron beams/Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses, J. Faure et al.,LOA

2006- 1 GeV Beams Have Arrived!

1.0 GeV Beam Generation

Courtesy of E. Esarey (LBL)

312 μm diameter and 33 mm length capillary

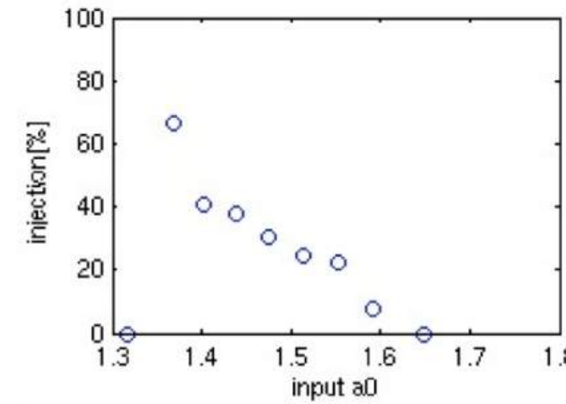
Laser: 1500(±15%) mJ/pulse

Density: $4x10^{18}/cm^3$

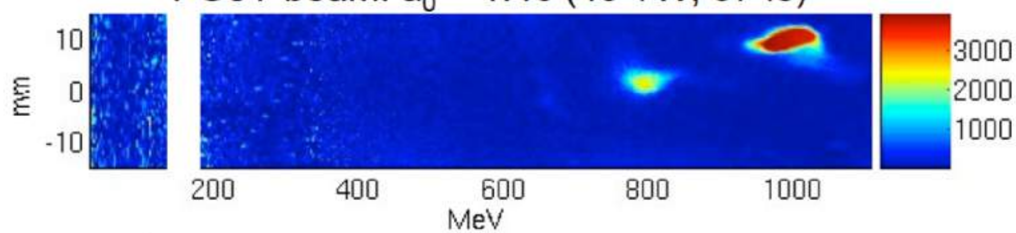
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

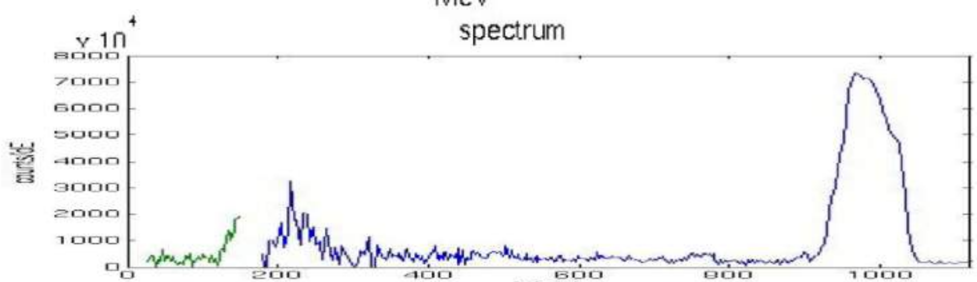
Less injection at higher power

Relativistic effect, self-modulation



1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)





Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: > 30.0 pC

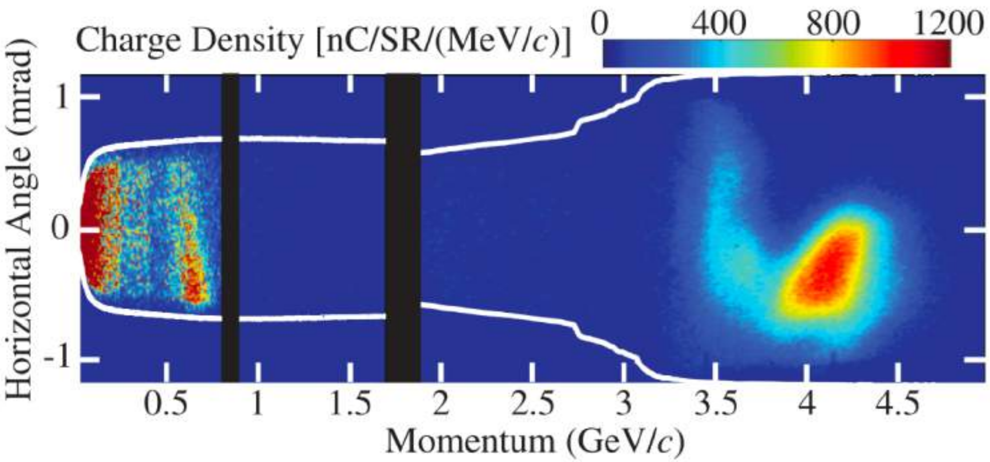
Less stable operation

Laser power fluctuation, discharge timing, pointing stability

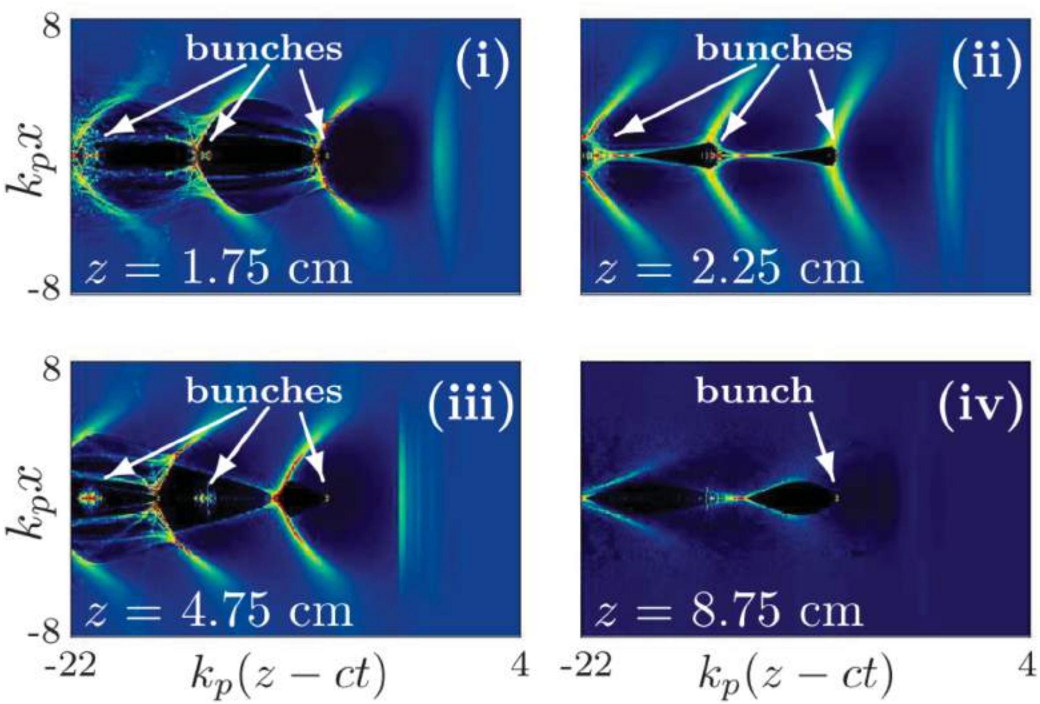
High-

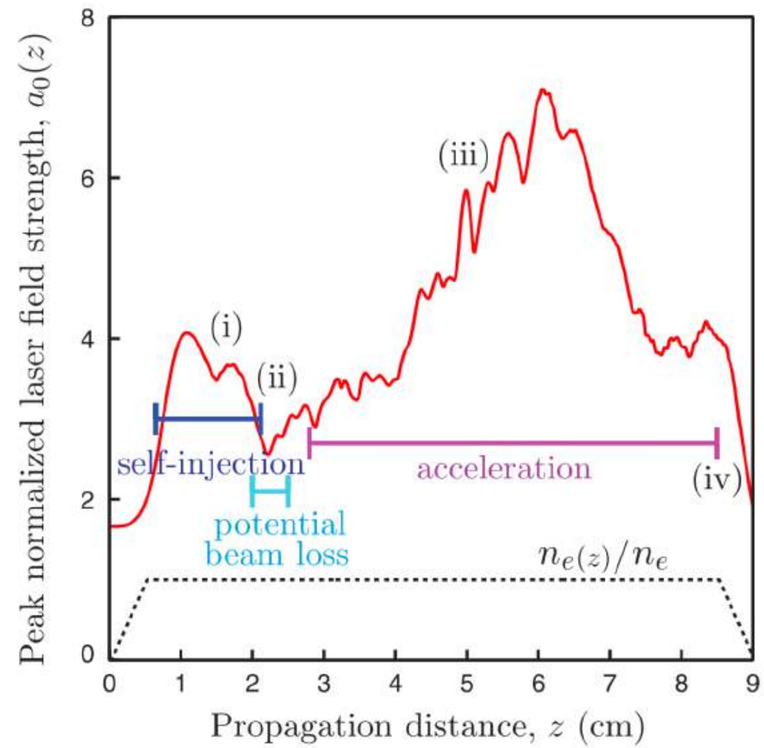
C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary & W. P. Leemans

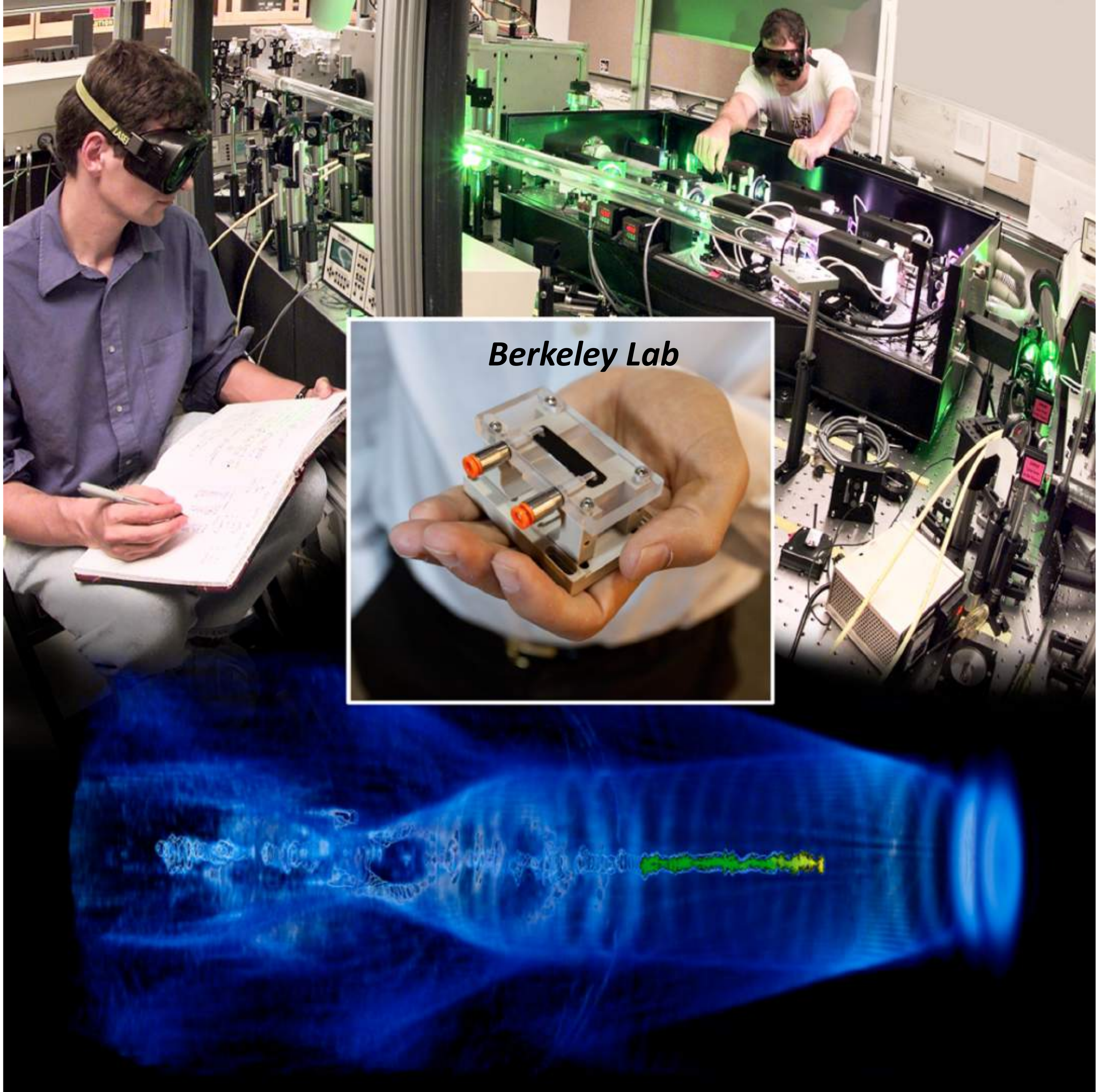
2014- 4 GeV in 10 cm- Close to 8 GeV now



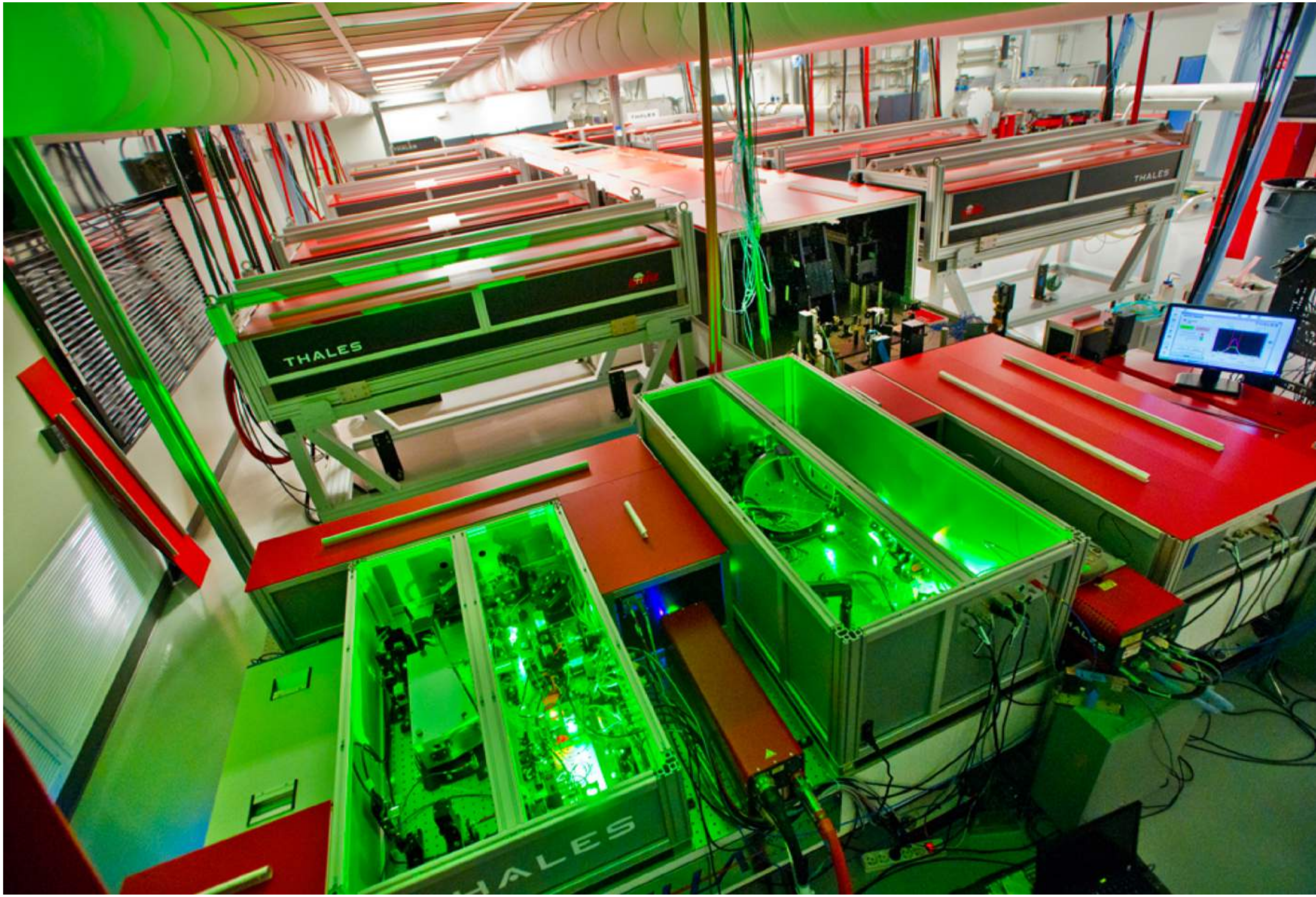
15 pC
4 GeV
300 TW Laser energy






Berkeley Lab

The BELLA (Petawatt) laser: LBNL



SLAC National Accelerator Laboratory

- At 3 km, it is the longest linear accelerator in the world
- Up to 42 GeV particle beams from the full 3 km
- From 2012- 2016, the first 2km of SLAC linac provide compressed, 3 nC, 20 GeV electron or positron beam to at 1-10 Hz
- Meter-scale pre-ionized lithium plasma source with typical density ~1x10^{17} cm^{-3}

2007- PWFA Doubling Energy

Vol 445 | 15 February 2007 | doi:10.1038/nature05538 nature

Nature v.445, p.741 (2007) LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

$N = 4 \times 10^{10}$

Energy 50 GeV

Rep Rate 60 HZ

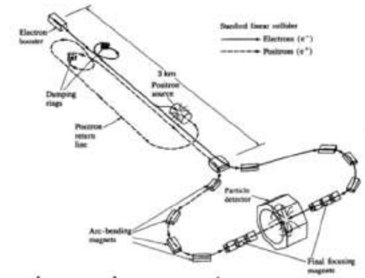
Energy/pulse 320 J

Focal Spot Size 10 microns

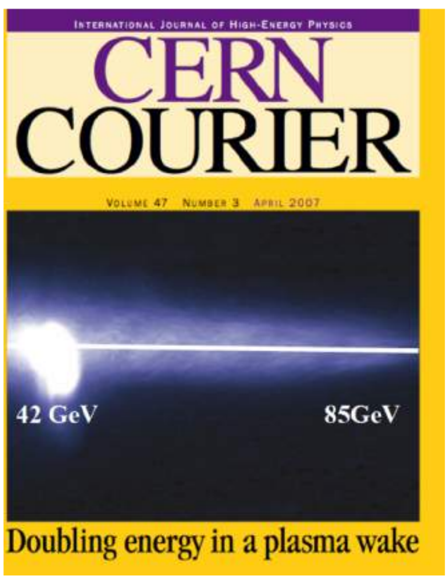
Pulse Width 50 fs

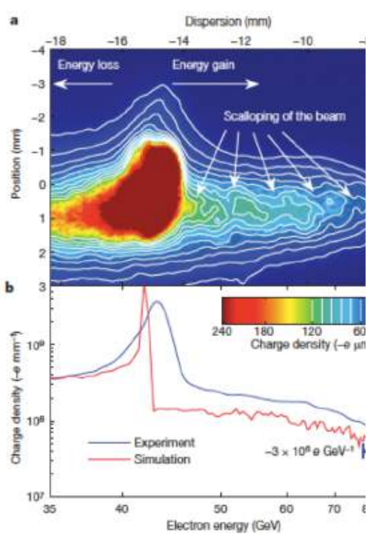
Focused Intensity 7×10^{21} W/cm^2

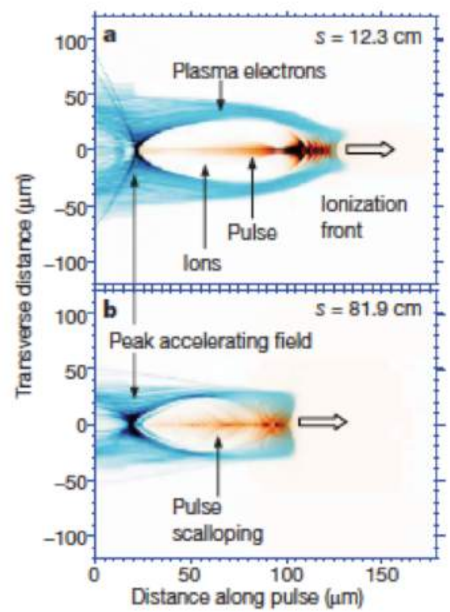
SLAC NATIONAL ACCELERATOR LABORATORY

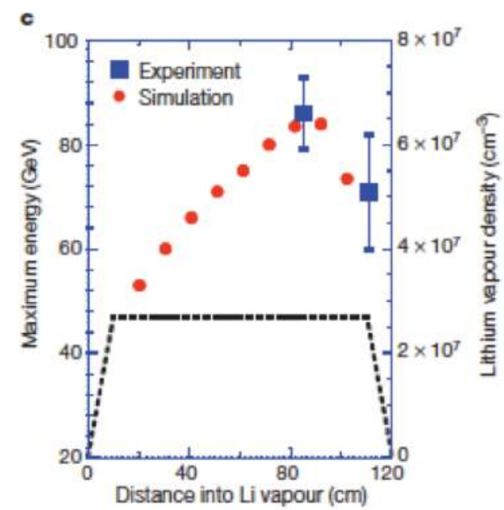


Comparable to the most intense laser beams to-date







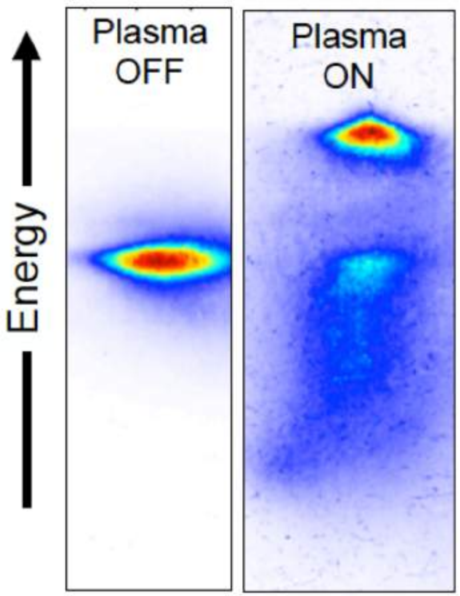


Beam Loaded PWFA

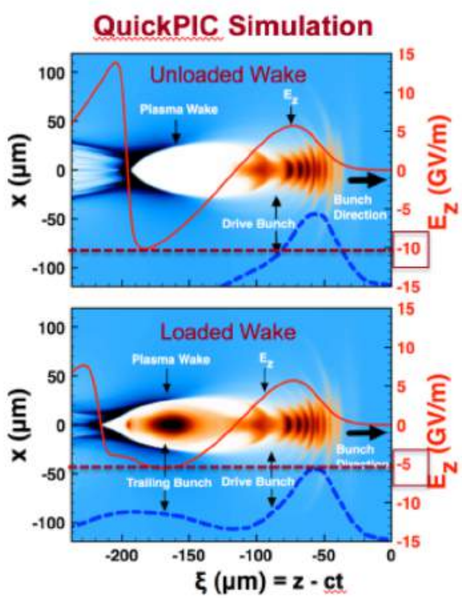
Litos et al., *Nature* November 2014

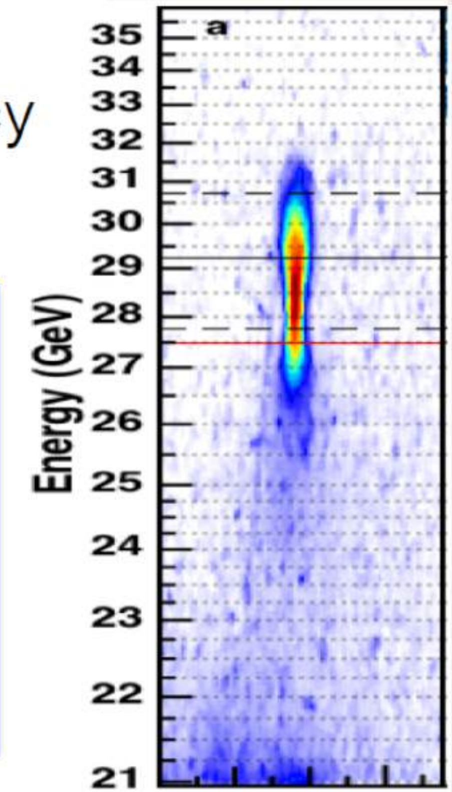
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

Beam loading is key for:
Narrow energy spread & high efficiency



2 GeV Energy Gain
~2% dE/E
~30% efficiency





9 GeV
Energy Gain

Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

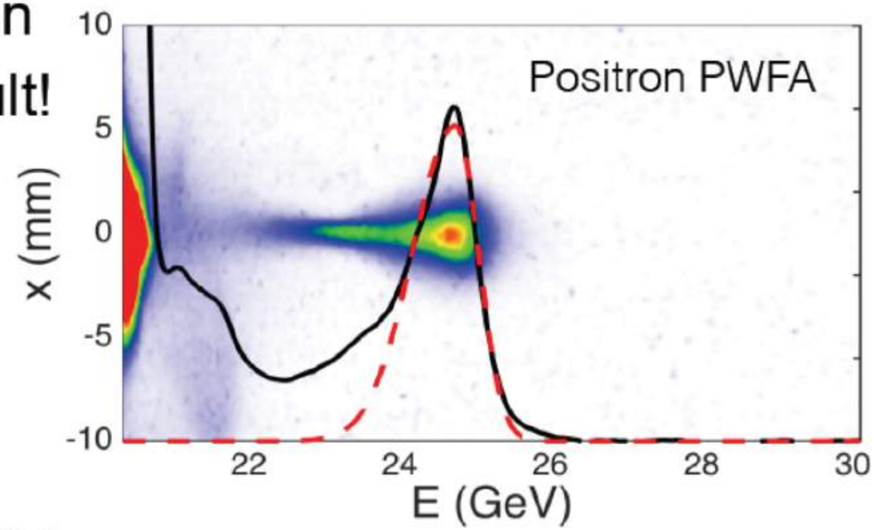
Corde et al., *Nature* August 2015

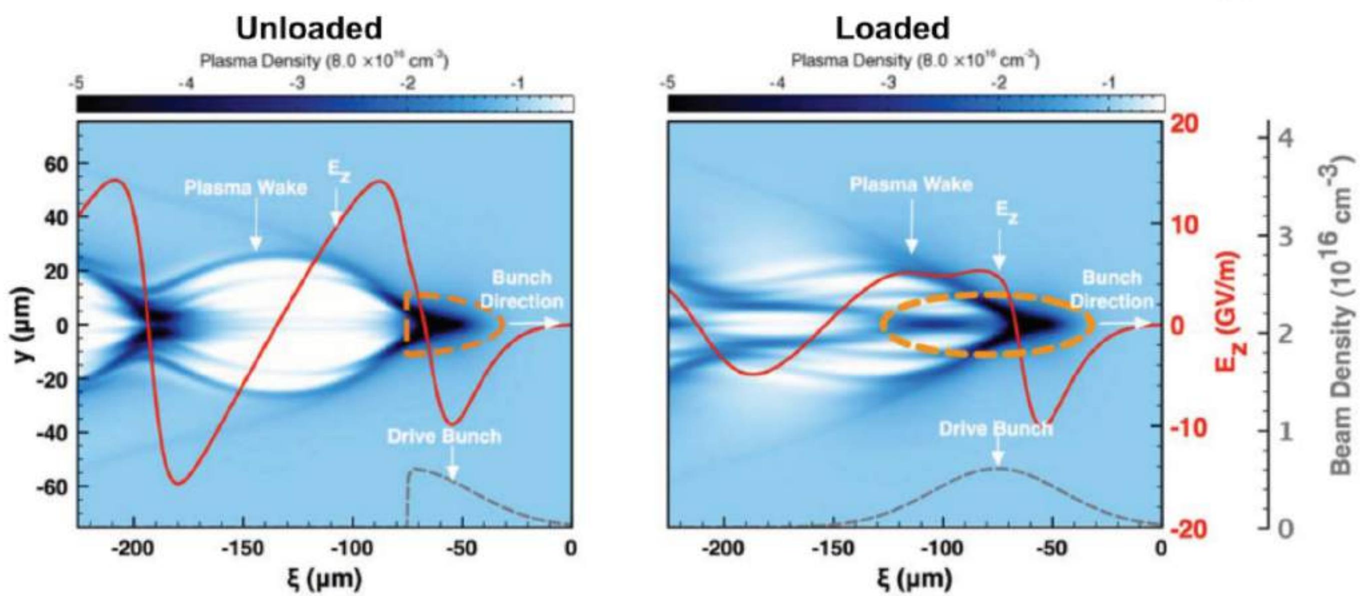
Multi-GeV Acceleration of Positrons

UCLA SLAC

Injecting a single high-intensity positron bunch produced a very surprising result!

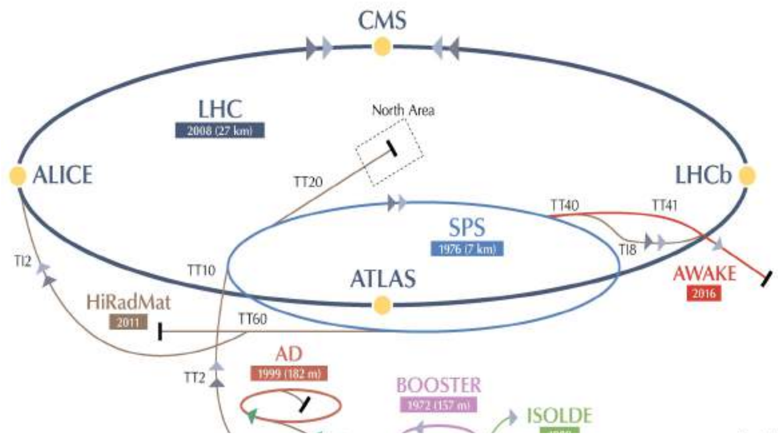
- Energy gain 4 GeV in 1.3 meters
- 1.8% energy spread
- Low beam divergence
- No halo



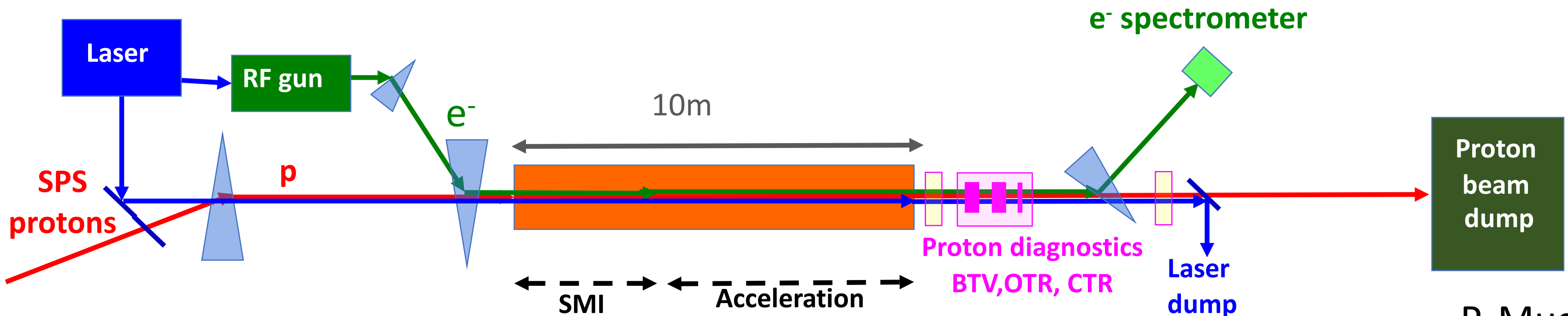


New PWFA regime warrants further exploration and development towards PWFA-LC application

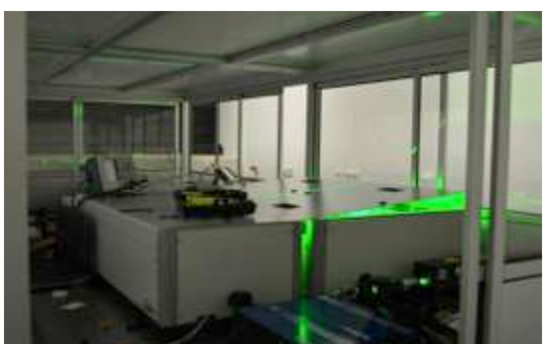
The AWAKE Facility at CERN using 400 GeV protons to drive PWA



- Phase 1: Understand **the physics of self-modulation instability** processes in plasma. → **Start Q4 2016**
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons. → **Start Q4 2017**
- Phase 3: **Reach higher gradients, develop long scalable and uniform plasma** cells, production of **shorter electron and proton bunches** → **2021 ++**

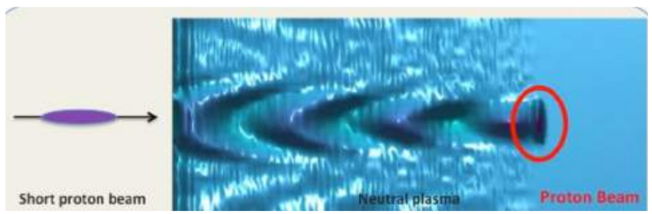


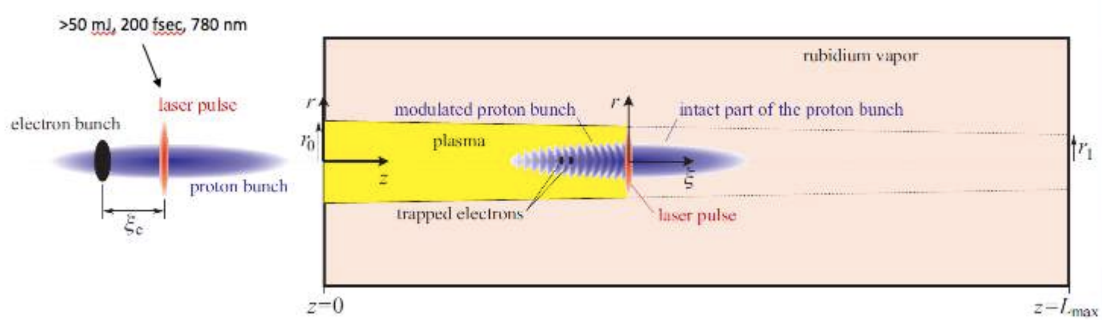
P. Muggli

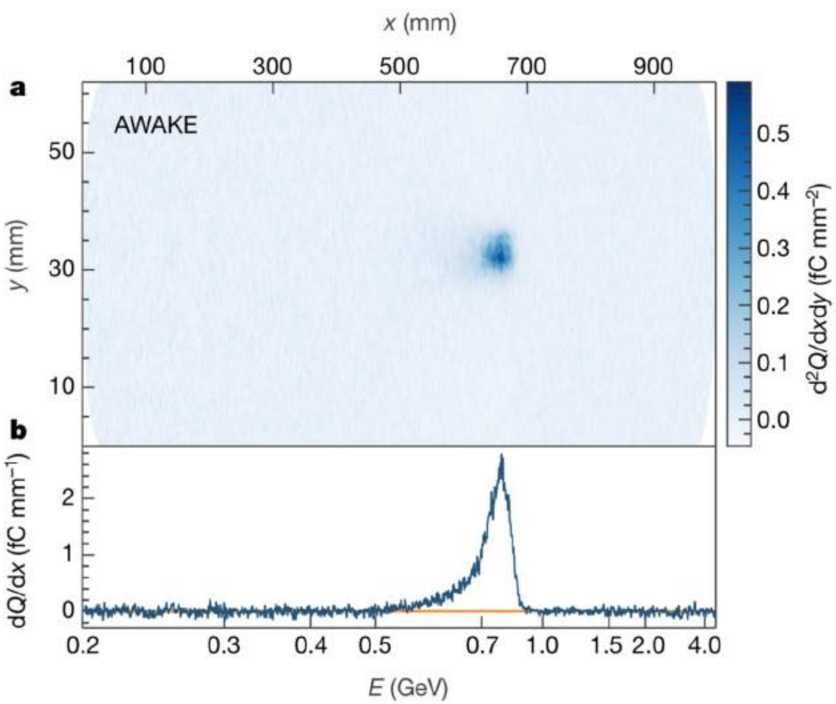


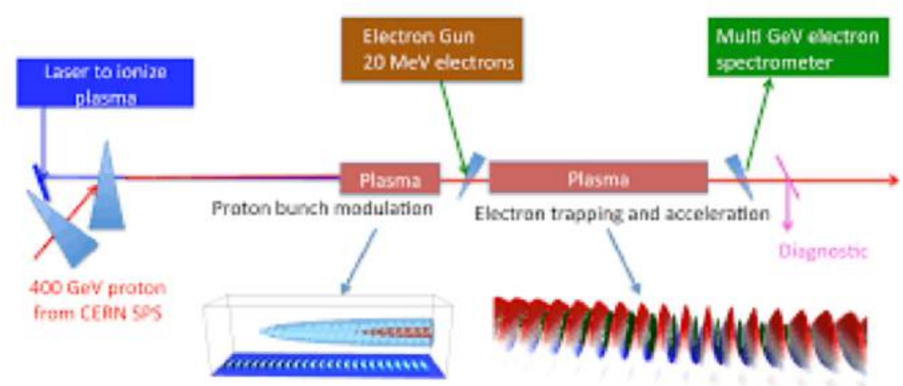
Proton drivers for PWA:
how to use TeV-scale proton beam to drive PWA?

Self-Modulating Instability of Proton Beam in Plasma







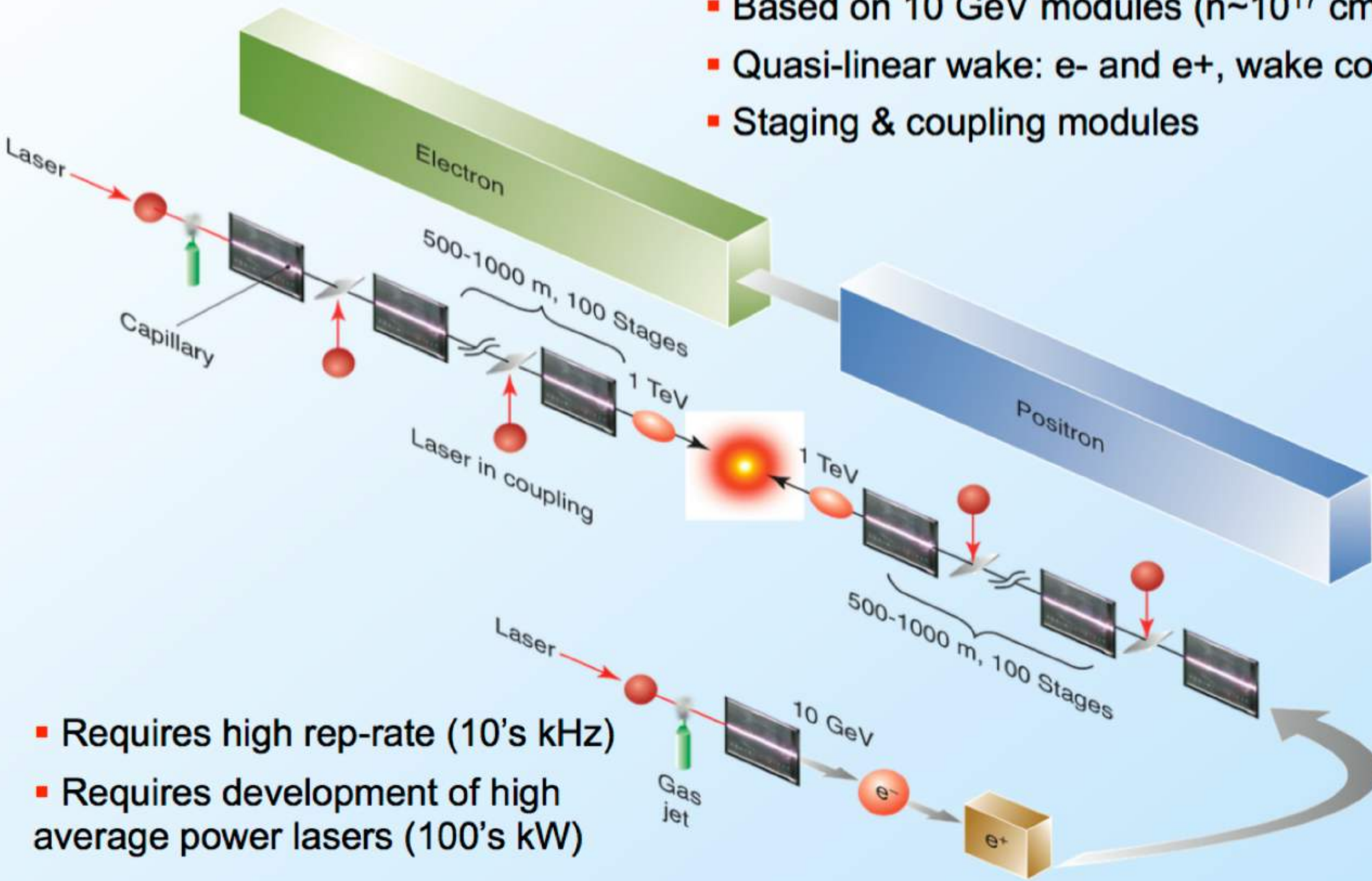


Outline

- The Need for Advanced Accelerators
- The Physics of Plasma Accelerators
- A Brief History of Advanced Accelerators
- Future and Challenges

Conceptual LPA Collider

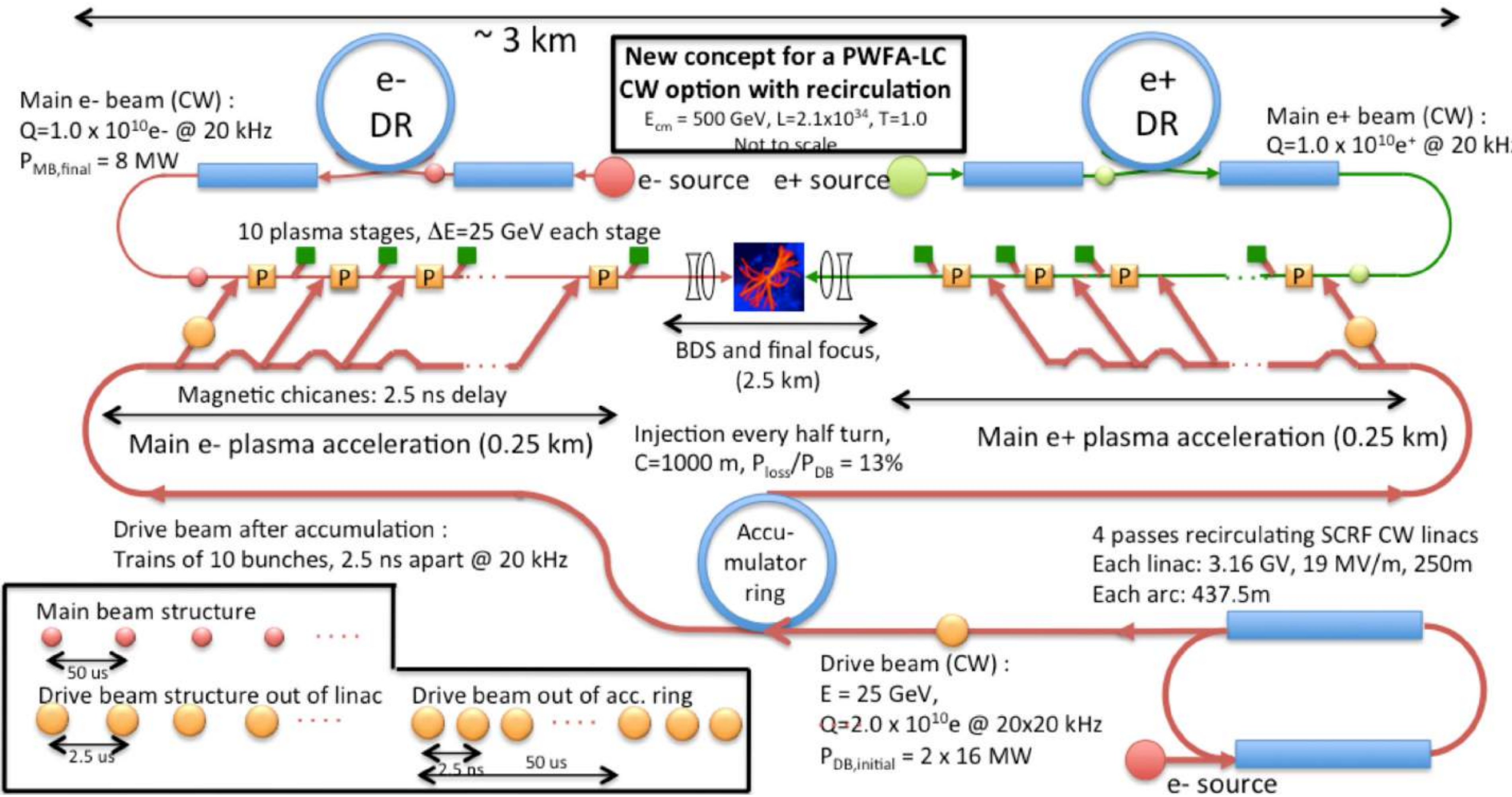
- Based on 10 GeV modules ($n \sim 10^{17}$ cm^{-3})
- Quasi-linear wake: e- and e+, wake control
- Staging & coupling modules



- Requires high rep-rate (10's kHz)
- Requires development of high average power lasers (100's kW)

Leemans & Esarey, Physics Today, March 2009

Beam driven linear collider



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

Future of LPWA

S. F. Martins, R. A. Fonseca,W. Lu,W. B. Mori and L. O. Silva, NATURE PHYSICS. V. 6, p.311, APRIL 2010

Table 1 | Laser/plasma parameters for the different LWFA regimes of a 250 J laser.

	Self-guiding		External-guiding
	Bubble-SI*	Blowout-SI	Blowout-EI†
Laser			
a_0	53.0	5.8	2.0
Spot (μm)	10	50	100
Duration (fs)	33	110	160
Power (PW)	9.4	2.8	1.4
Plasma			
Density (10^{16} cm^{-3})	1,500	27	2.2
Length (cm)	0.25	22	528
Electron beam (simulation)			
Energy (GeV)	3 (3.4)	13 (5-13)	53 (40)
Charge (nC)	14 (25)	2.0 (0.6-2.2)	1.5 (0.3)

Parameters are obtained from refs 9 and 10, for the bubble and blowout regimes, respectively. Ref. 9 uses a circularly polarized laser. Here, for consistency with the other cases, we use linearly polarized lasers and modify their formulae appropriately. The decrease in laser intensity from the strongly nonlinear regime ($a_0 = 53$) to the weakly nonlinear regime ($a_0 = 2$) is accompanied by a steep increase in the acceleration length, and thus on the computational modelling requirements, because the laser wavelength (0.8 μm) must always be resolved in a full PIC simulation.

*Self-injected (SI) electrons.

†Externally injected (EI) electrons.

Sample: 11 GeV had 0.3 nC of FWHM charge, energy spread of 3.7% and normalized emittances of 3.4 and 9.2mmmrad

$$a_0 = 0.853 \times 10^{-9} \lambda(\mu\mathrm{m}) \sqrt{I(\mathrm{W\,cm^{-2}})}$$

Blow-out regime $\quad 2 \le a_o \le 2\omega_O/\omega_p$

Bubble regime $\quad a_o \ge 2\omega_O/\omega_p$

Optimal accelerating structure $\quad a_o \ge 4$

The idea of the bubble regime is that the spot size is also roughly matched to the bubble radius

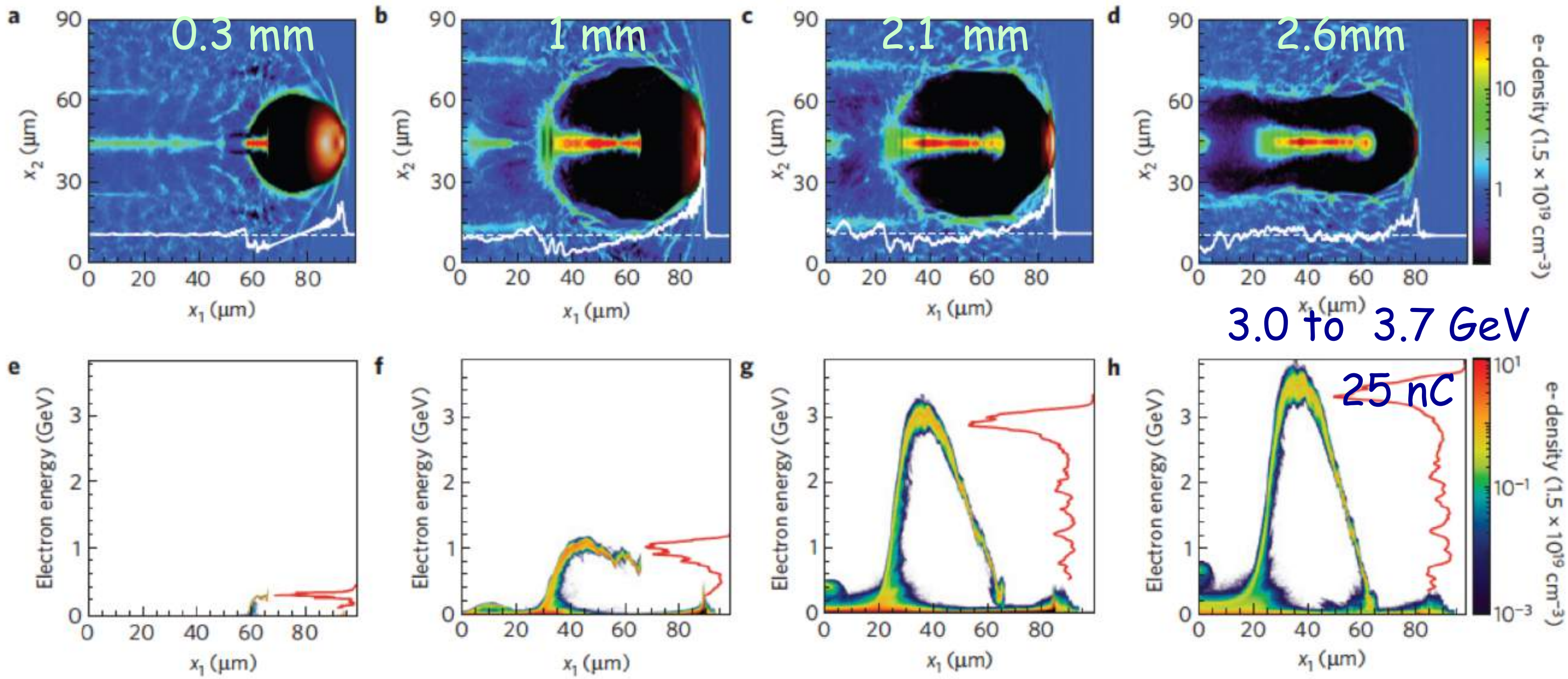
Future of LPWA

S. F. Martins, R. A. Fonseca,W. Lu,W. B. Mori and L. O. Silva, NATURE PHYSICS. V. 6, p.311, APRIL 2010

Bubble regime $a_o \geq 2\omega_o/\omega_p$

250 J laser

*FWHM 11% energy spread , 16.7 nC, ε = 500 mm mrad**



*Cause: the high transverse momentum acquired by the injected electrons

The simulations are done in the Lab frame

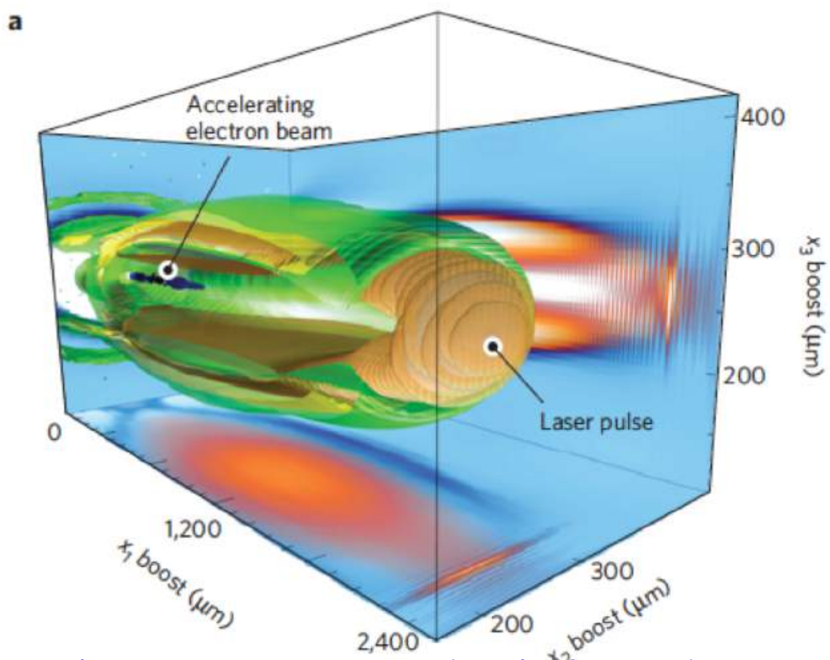
Future of LPWA

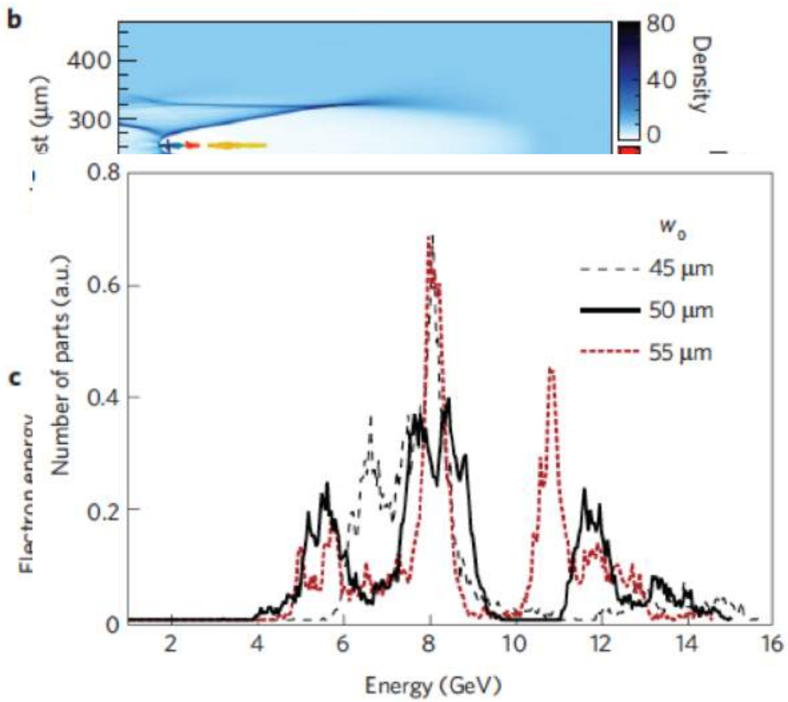
S. F. Martins, R. A. Fonseca,W. Lu,W. B. Mori and L. O. Silva, NATURE PHYSICS. V. 6, p.311, APRIL 2010

Blow-out regime $2 \leq a_o \leq 2\omega_o/\omega_p$

250 J laser

*FWHM 8-20% energy spread , 2.2 nC , $\varepsilon_{x,y}$ = 5/25 mm mrad**





Plasma moves to the left with γ=10

Simulation results for a LWFA in the self-guiding/self-injection blowout regime

*Larger emittance in the laser polarization plane

The simulations are done in an optimal Lorentz frame

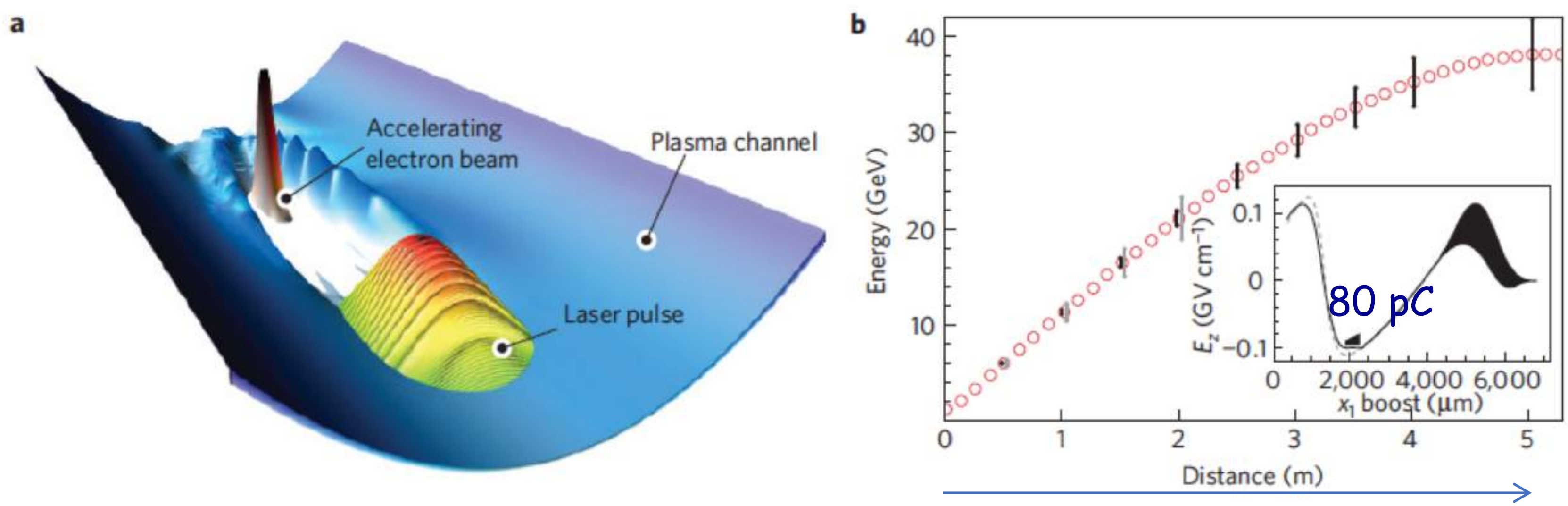
Future of LPWA

S. F. Martins, R. A. Fonseca, W. Lu, W. B. Mori and L. O. Silva, NATURE PHYSICS. V. 6, p.311, APRIL 2010

$a_o = 2$ QuickPIC

250 J laser

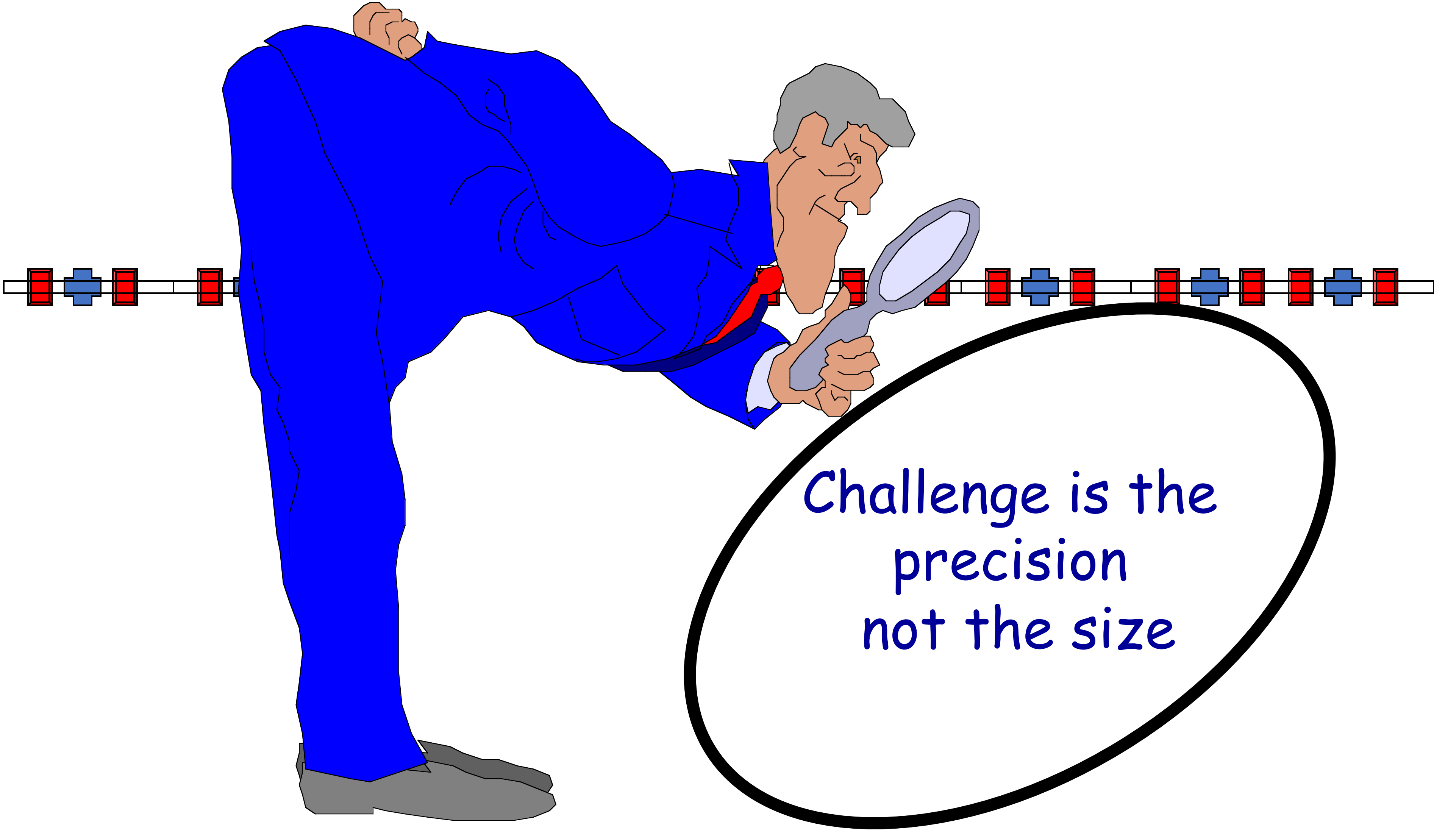
The FWHM energy spread is 10% at 30 GeV , 20% at the final 40 GeV



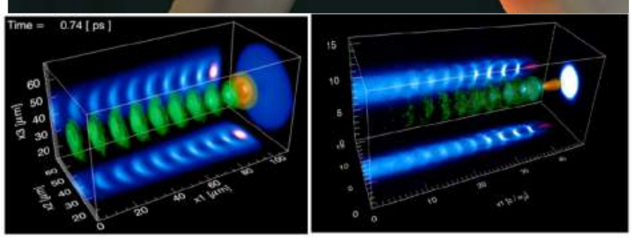
Plasma moves to the left with γ=10

Simulation results for a LWFA in the external-guiding/external-injection blowout regime

The simulations are done in an optimal Lorentz frame

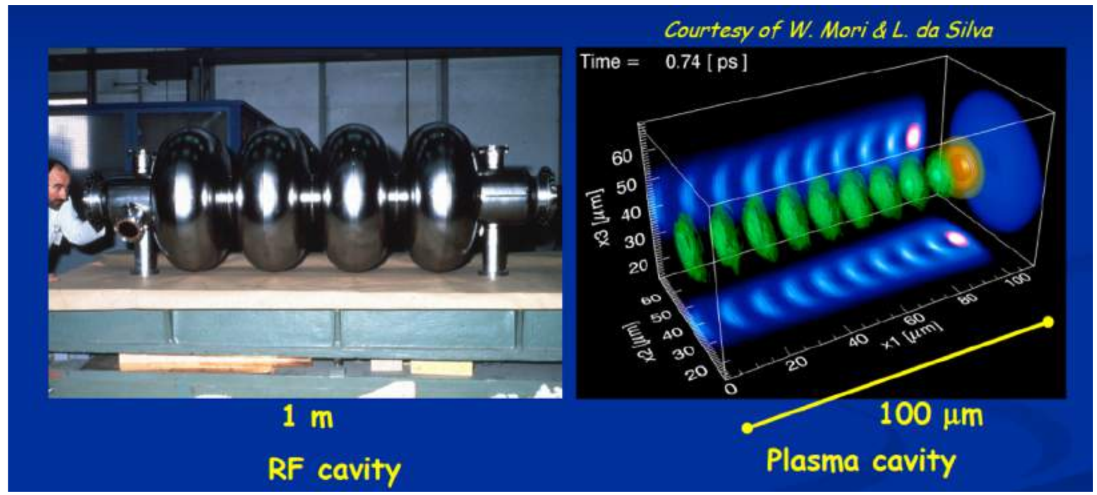

Challenge is the
precision
not the size

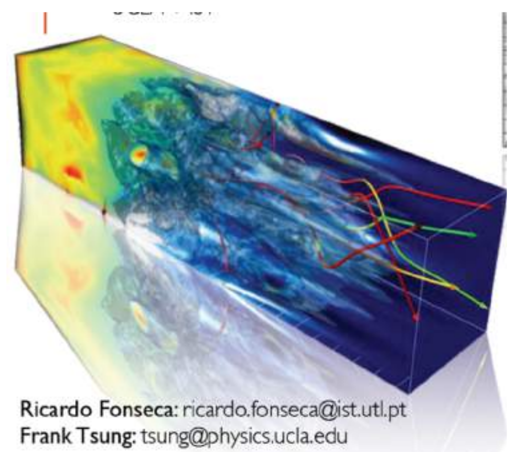
New scale *requires not only physicists but **engineers** with the skills and knowledge for handling the much more delicate, and likely virtual "nuts and bolts" of future accelerators*



Laser Wake

Electron beam Wake





Challenges of new acceleration methods

- High accelerating gradient – looks very good …
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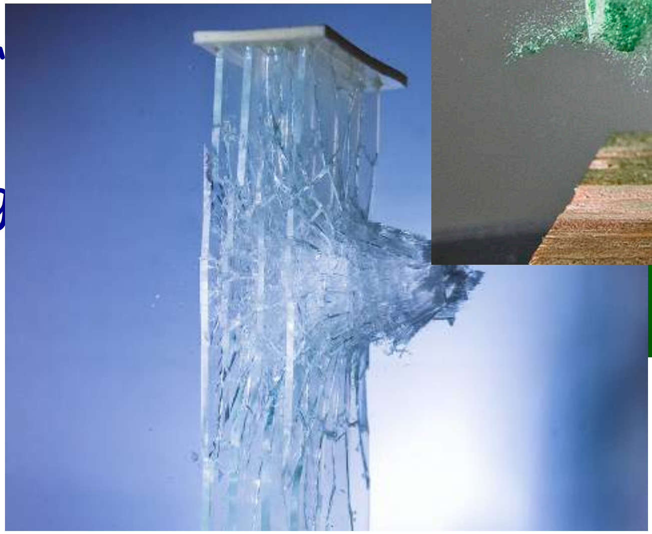
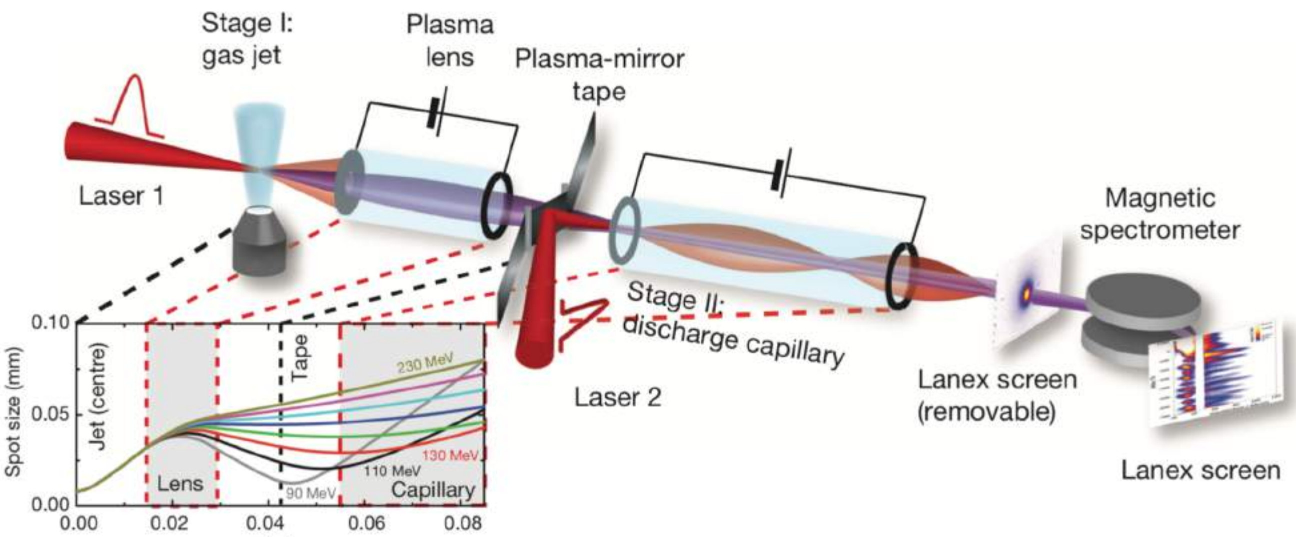
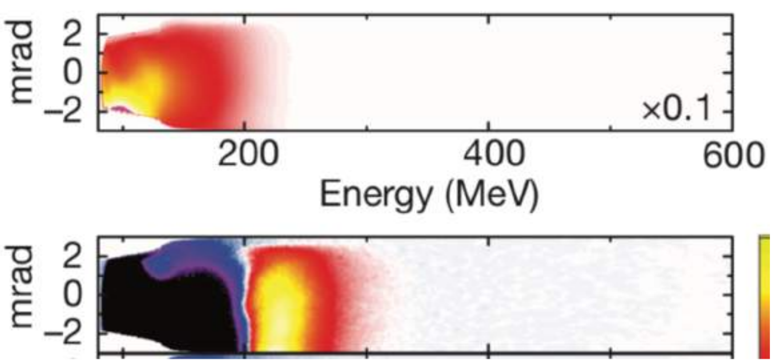
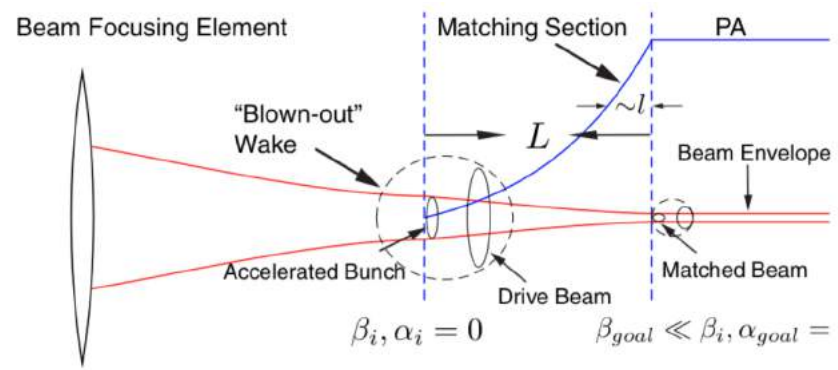


Staging Challenges





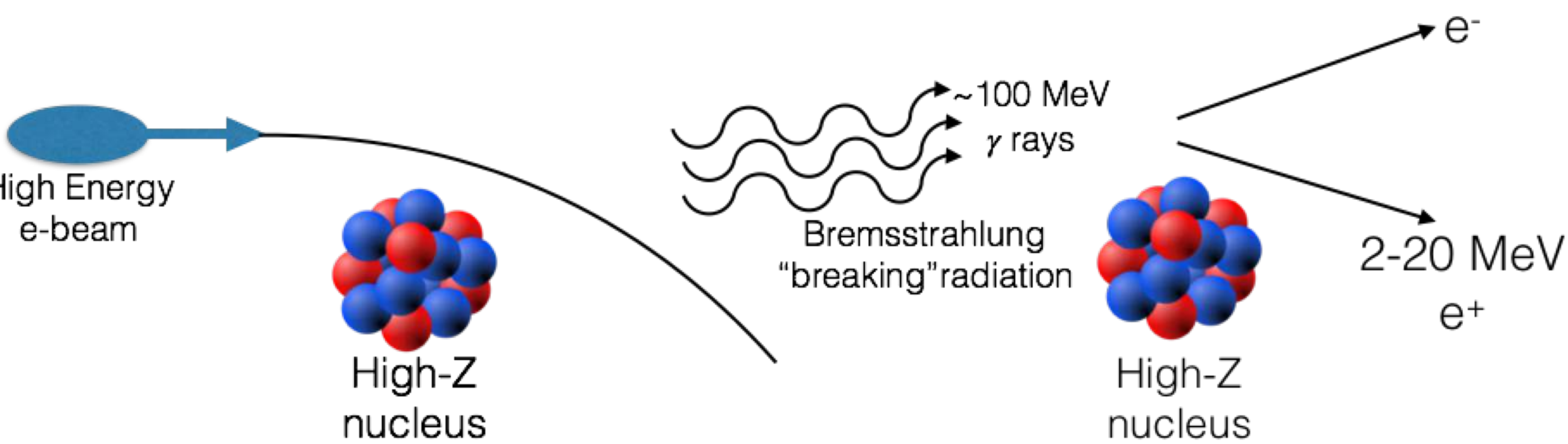


LBNL Multi-stage experiment:
S. Steinke Nature, 530, 190 (2016)

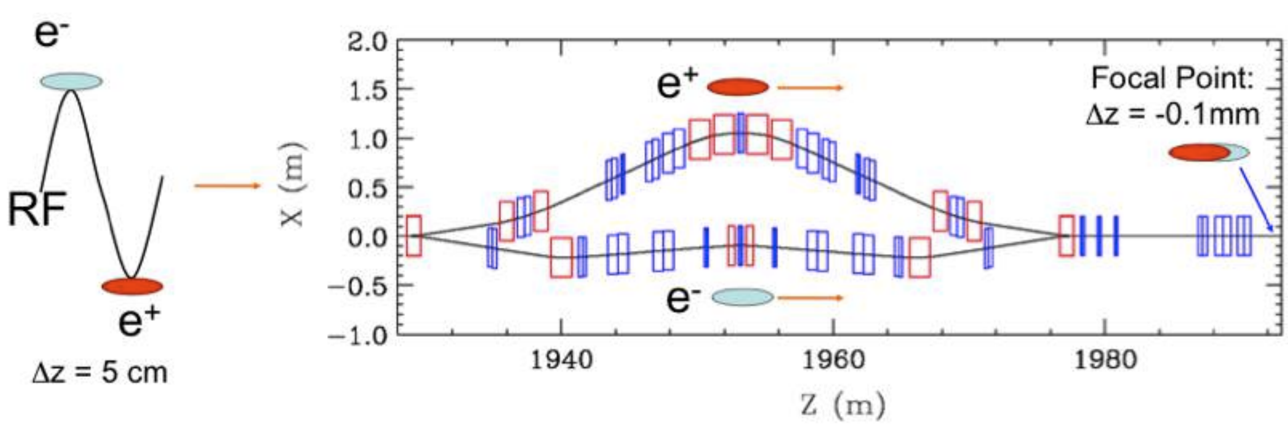
Longitudinally tailored plasma density profile for extraction:
PRL 116, 124801 (2016)

The End

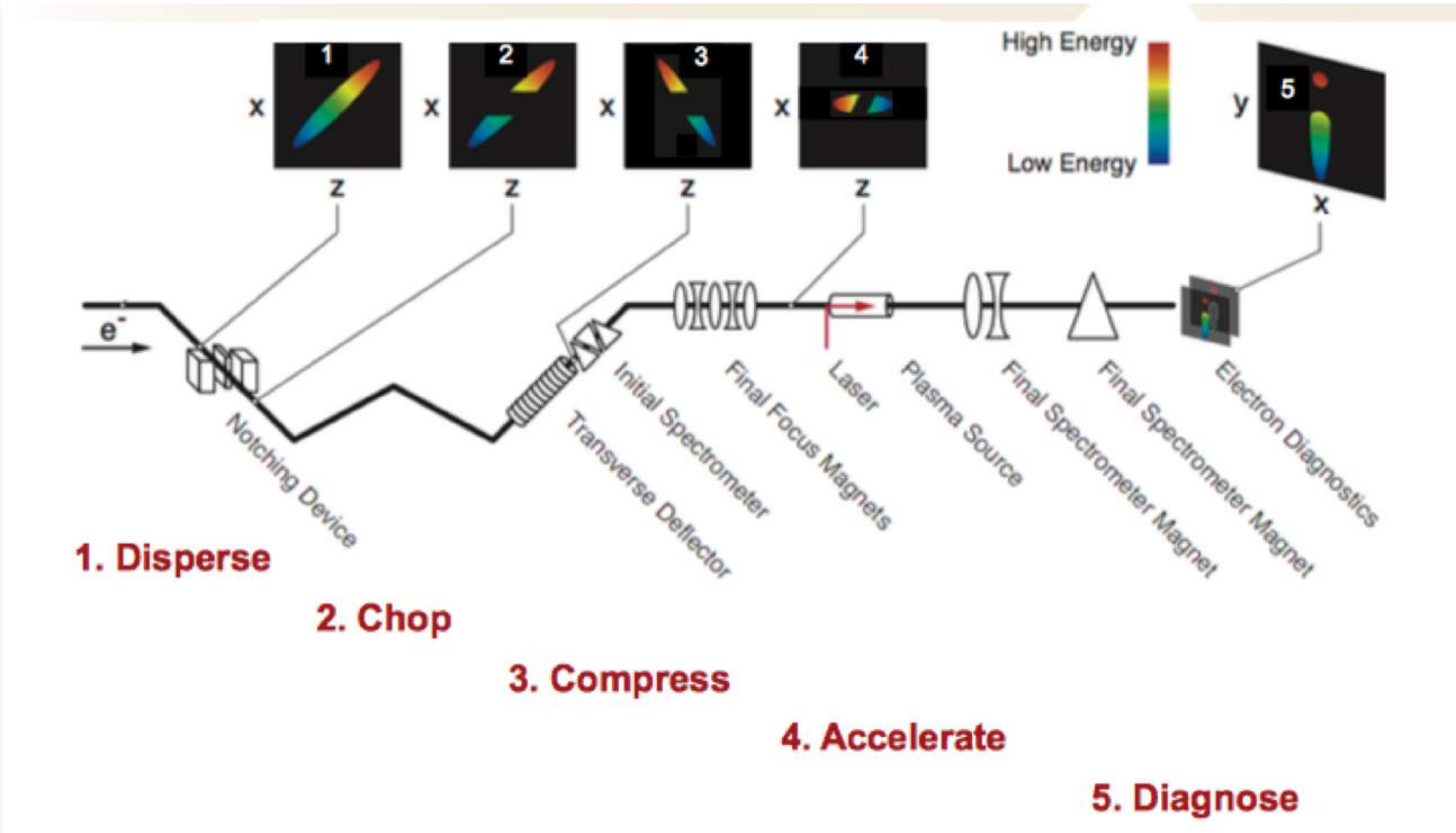
Positron Production and Acceleration



Positrons are captured and reinserted into the linear accelerator

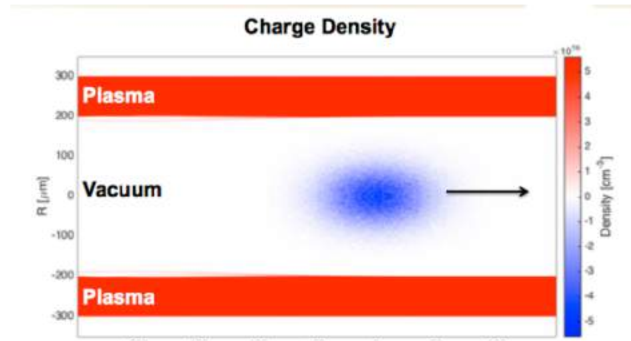


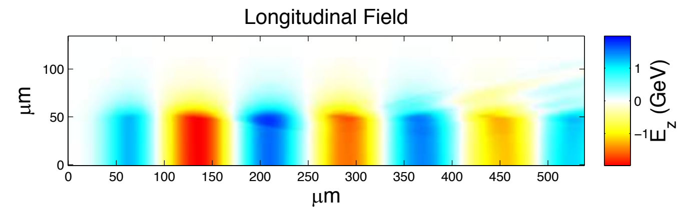
Two Bunch Generation

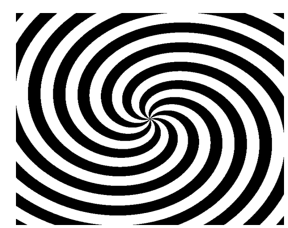


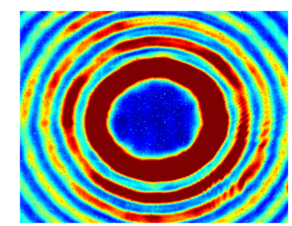
Hollow Channel

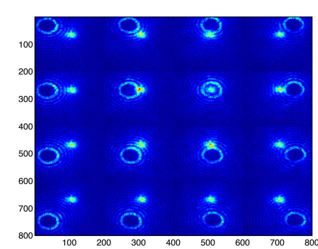
- Hollow channels provide a method to accelerate beams in a plasma without transverse forces from background ions.
- We use a special binary optic to create a hollow laser beam, which we use to ionize an annulus of plasma.
- The first hollow channel experiment studied the transverse effects of a hollow channel plasma on a positron beam.

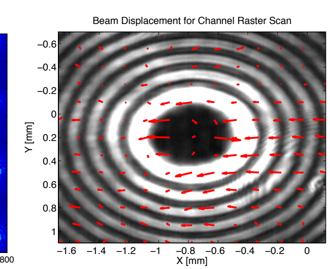






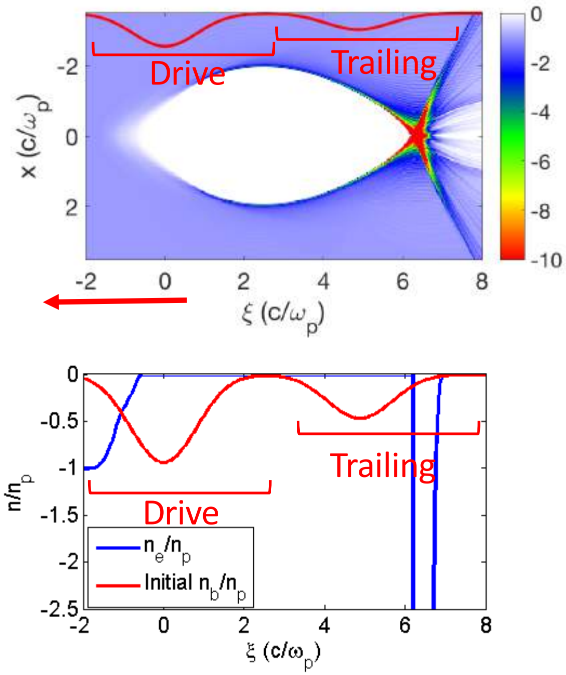




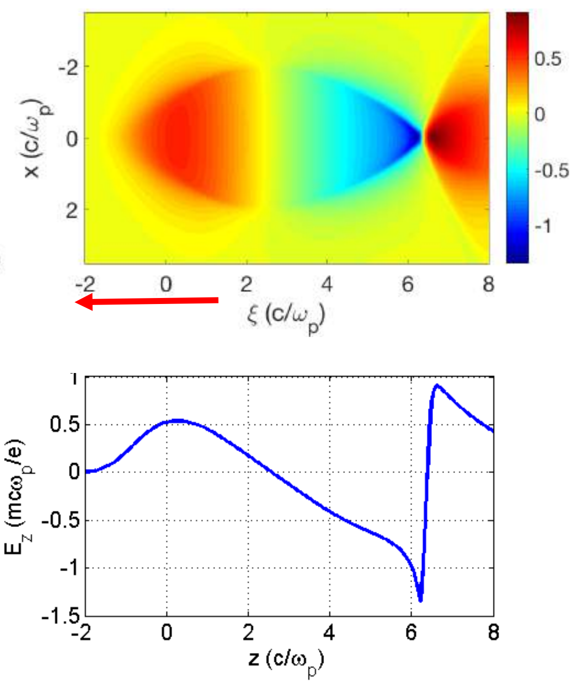


Fields Within the Wakefield

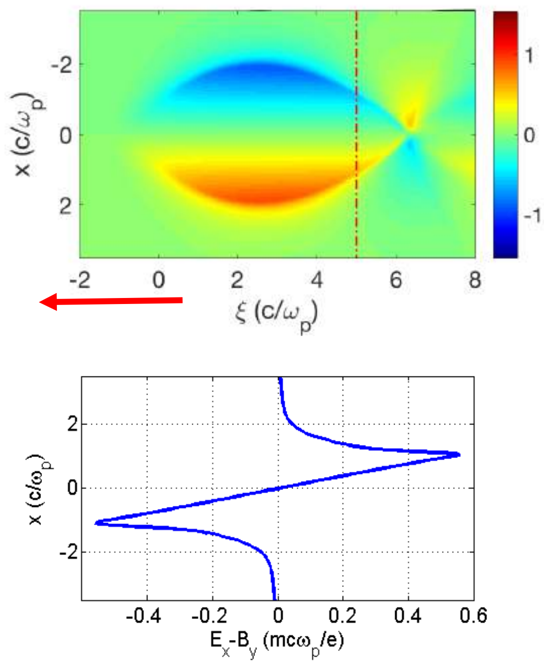
On-axis Density



Longitudinal Force



Transverse Force

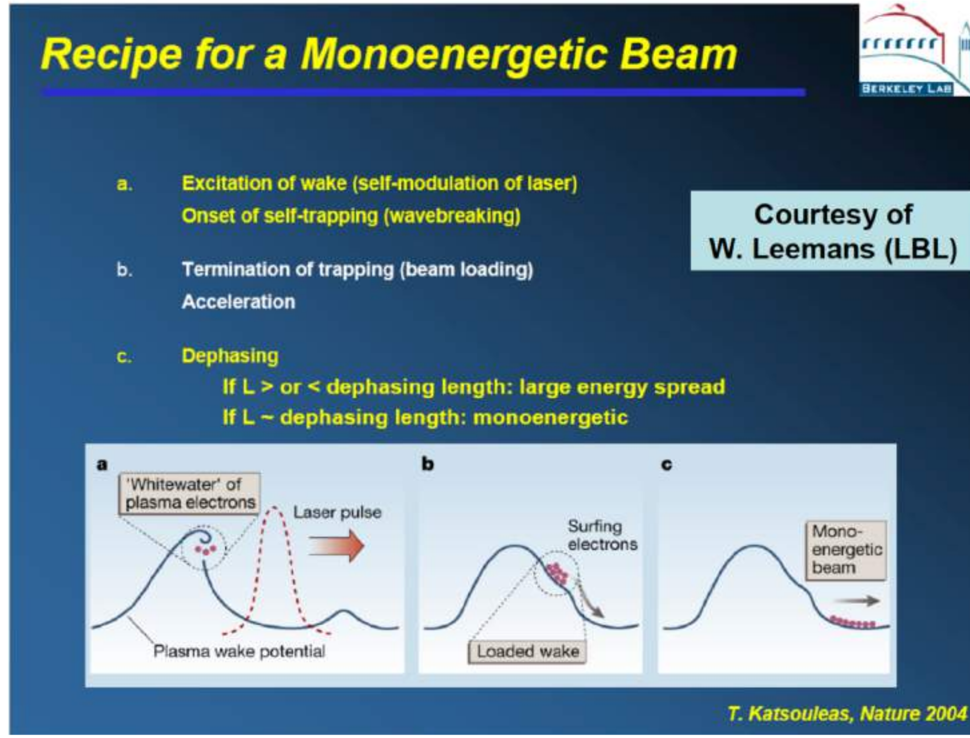


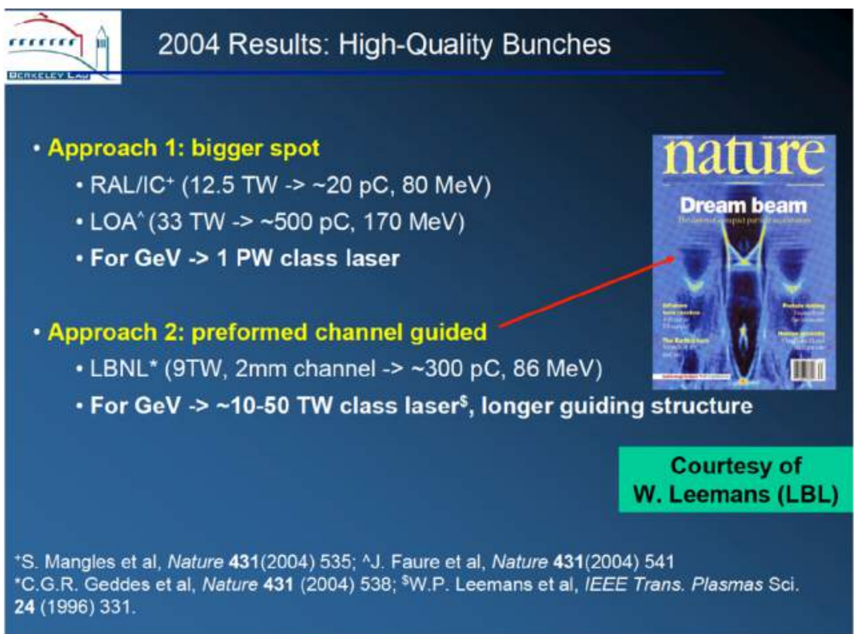
"Blowout regime" occurs as $n_e \rightarrow 0$

Nonlinear accelerating force
E normalized to 50 GeV/m

Linear Focusing Force, similar to quadrupole magnets in a conventional accelerator

Understanding





On the node of a wave

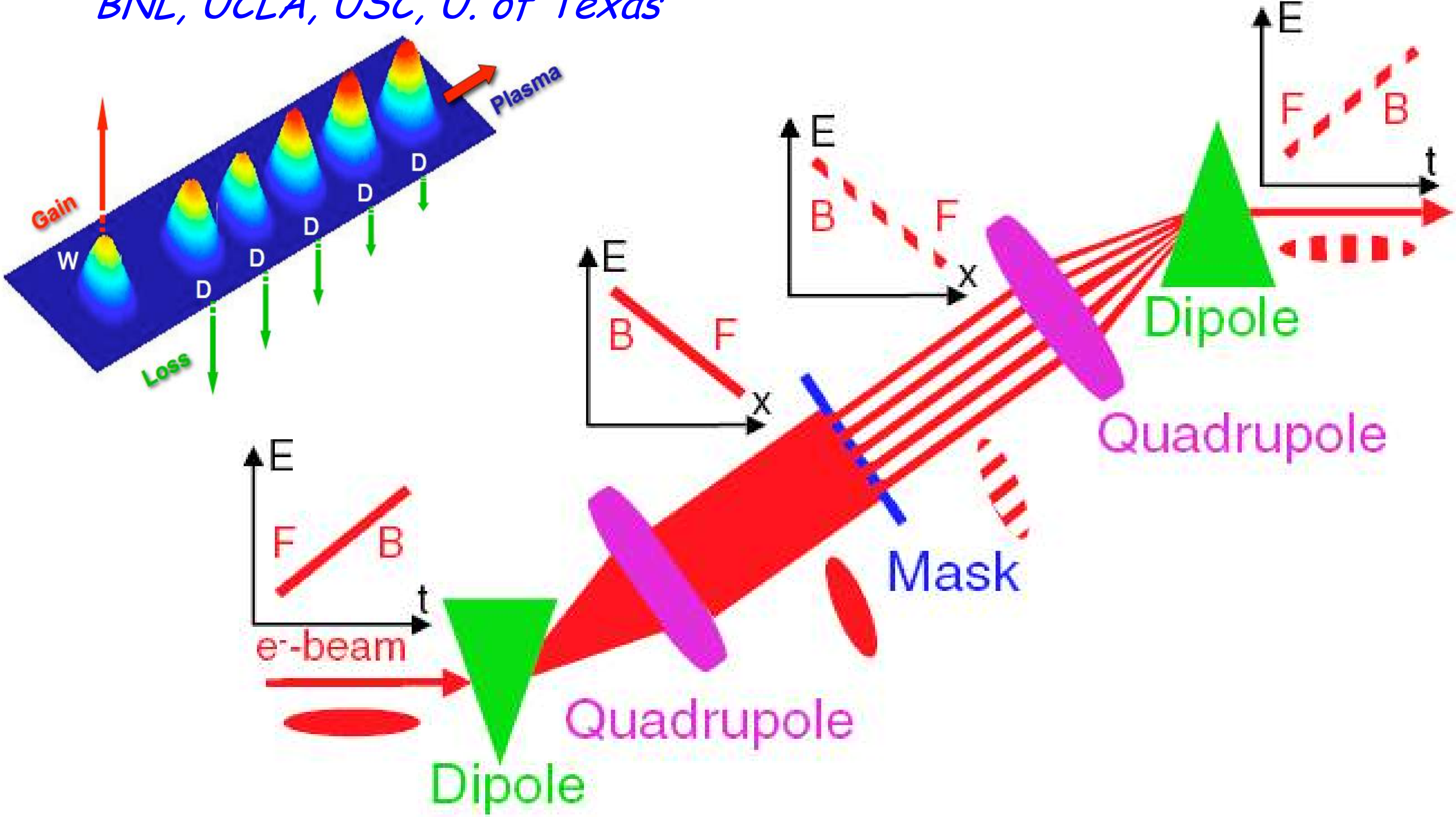
Tom Katsouleas

NATURE|Vol 444|7 December 2006

Figure 1 | Surfing, tow-in style. Pete Cabrinha takes a record-breaking ride on the 70-foot 'Jaws' wave off the north shore of Maui, Hawaii, on 10 January 2004, for which he won the coveted Billabong XXL.

Multibunch Plasma Wakefield

BNL, UCLA, USC, U. of Texas



Simplified schematic of the mask principle. Only the dogleg section of the beam line is depicted (not to scale), and three quadrupole magnets are omitted. The side graphs represent the beam energy correlation with the beam front labelled by "F" and the back by "B."

Many other methods are in the play for advanced accelerator methods:

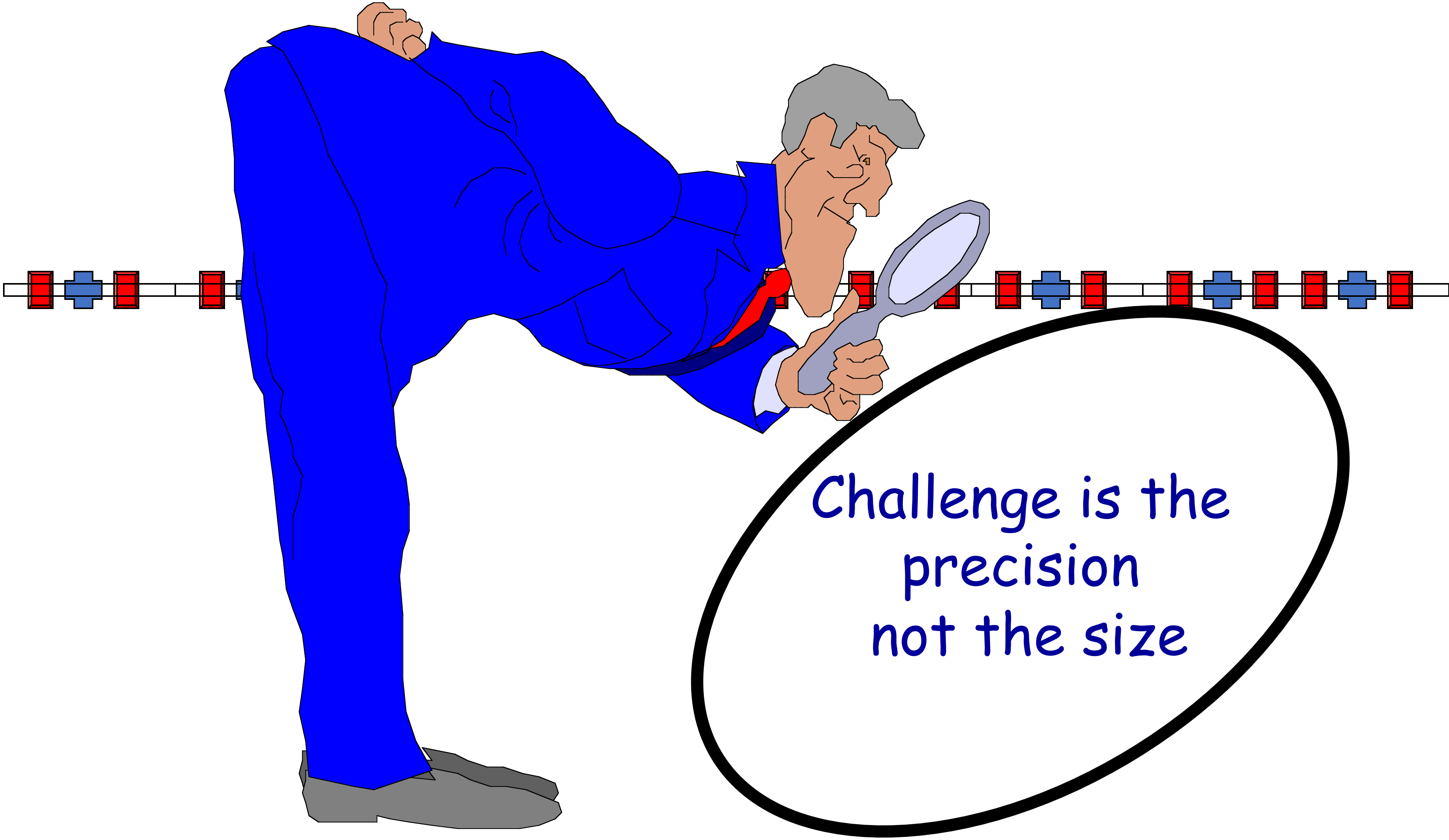
dialectic slabs/waveguides
photonic band-gap accelerator structures

including accelerating hadrons

Almost any presentation is out-of-date:
field is developing very fast!

There is a lot of promise…

What are the challenges?


Challenge is the
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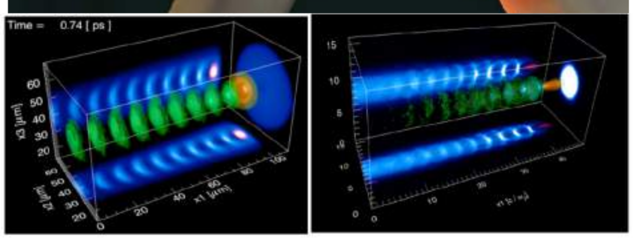

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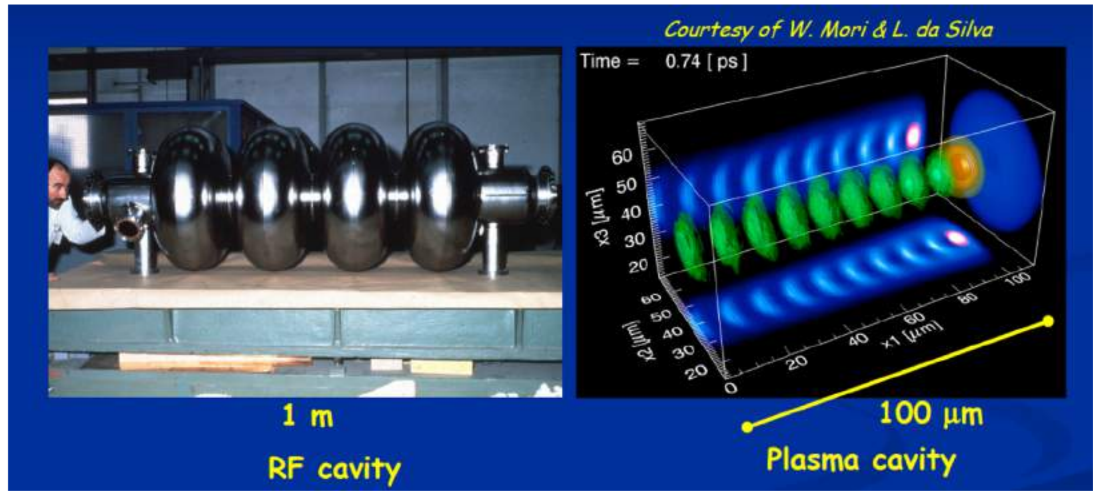

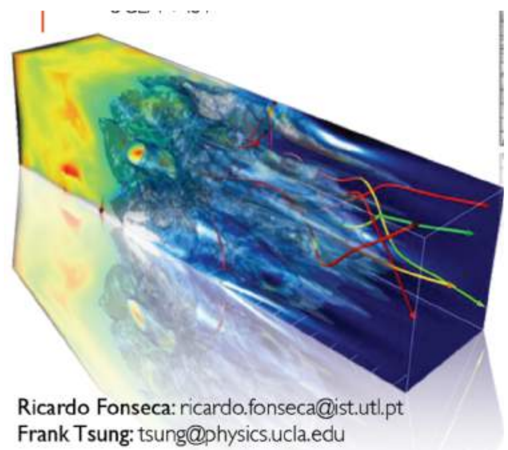

Challenges of new acceleration methods .. contunued

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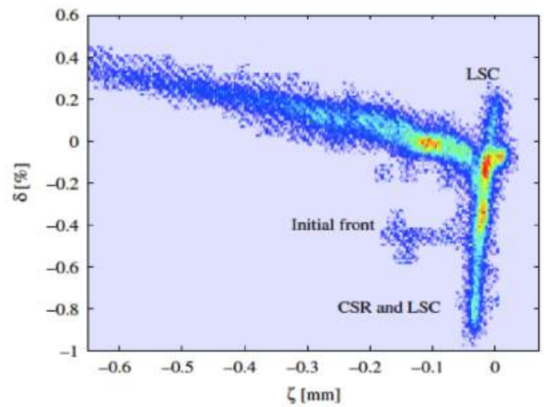
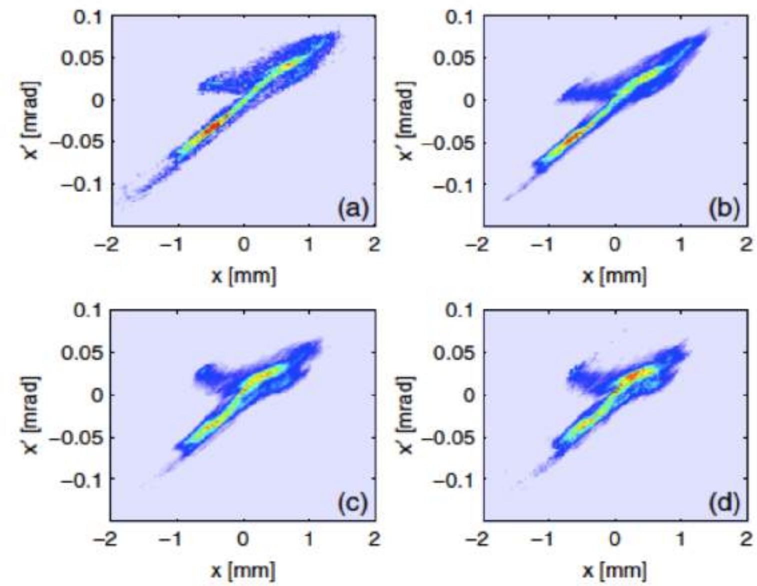
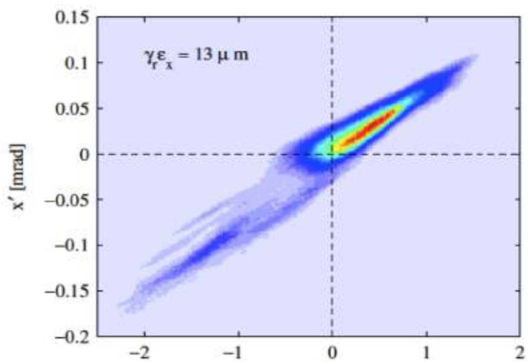
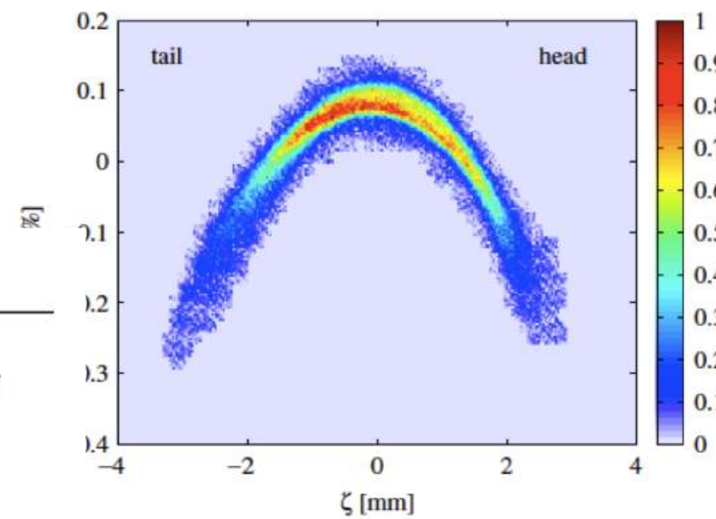
Most Importantly: we need to quantify these beams

Measure the beam phase space distribution as it is done in all accelerators









PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 050704 (2009)

Time-resolved electron beam phase space tomography at a soft x-ray free-electron laser

Michael Röhrs, Christopher Gerth, Holger Schlarb, Bernhard Schmidt, and Peter Schmüser

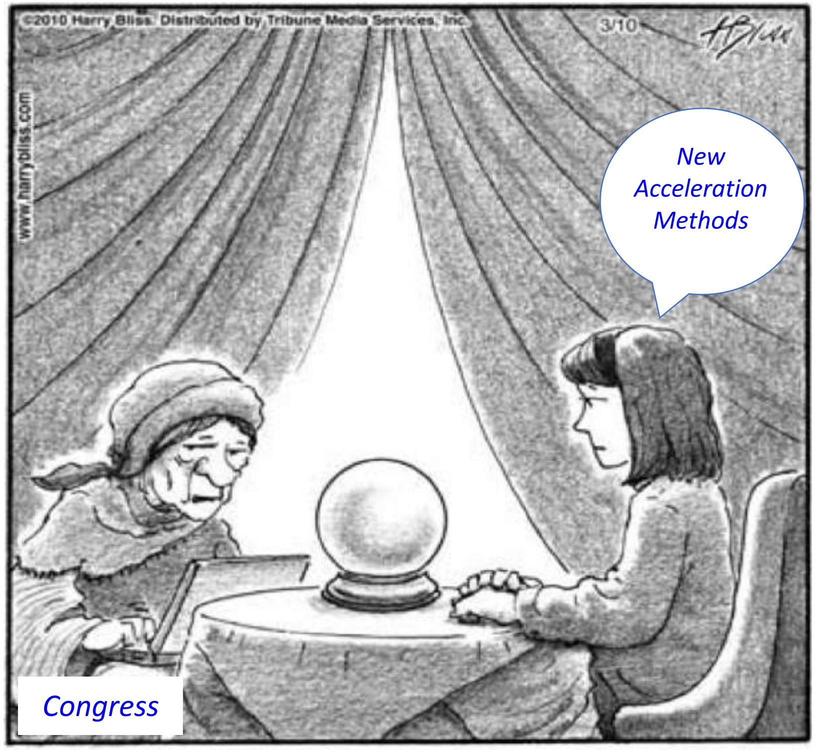
Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany

(Received 12 December 2008; published 19 May 2009)

Accelerators for 21st century? May be…

Many things will depend on

- Ability to produce really good quality mono-energetic beams
- Using existing accelerator technology (i.e. injectors of fsec bunches, FELs..) in combination with new acceleration methods
- New generation of brave accelerator physicists



"Stay with me. I just want to cross-check your fortune with a quick Google search."