PHY 554
Fundamentals of Accelerator Physics

Lecture 24
Advanced Acceleration Methods

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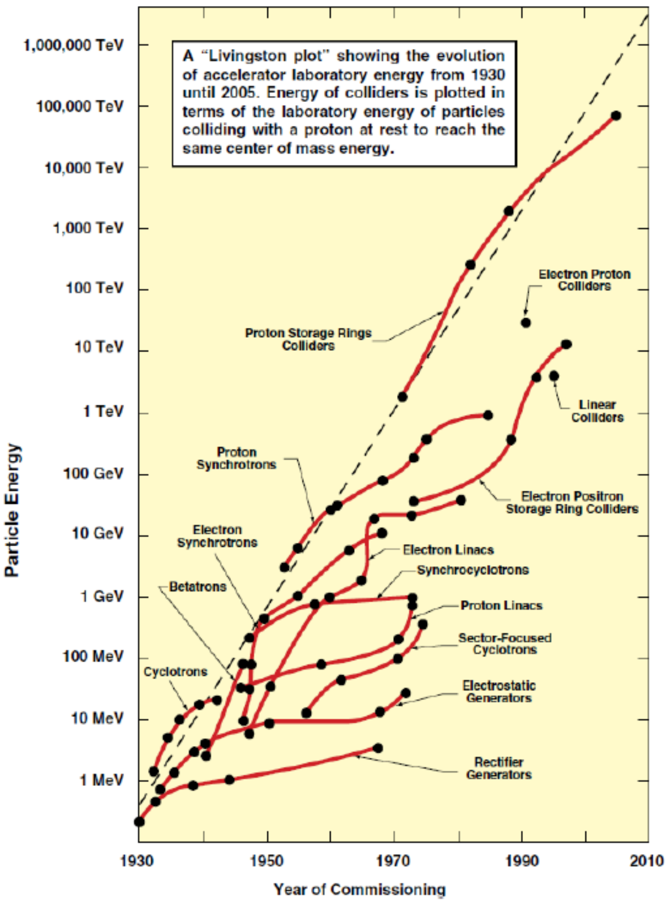
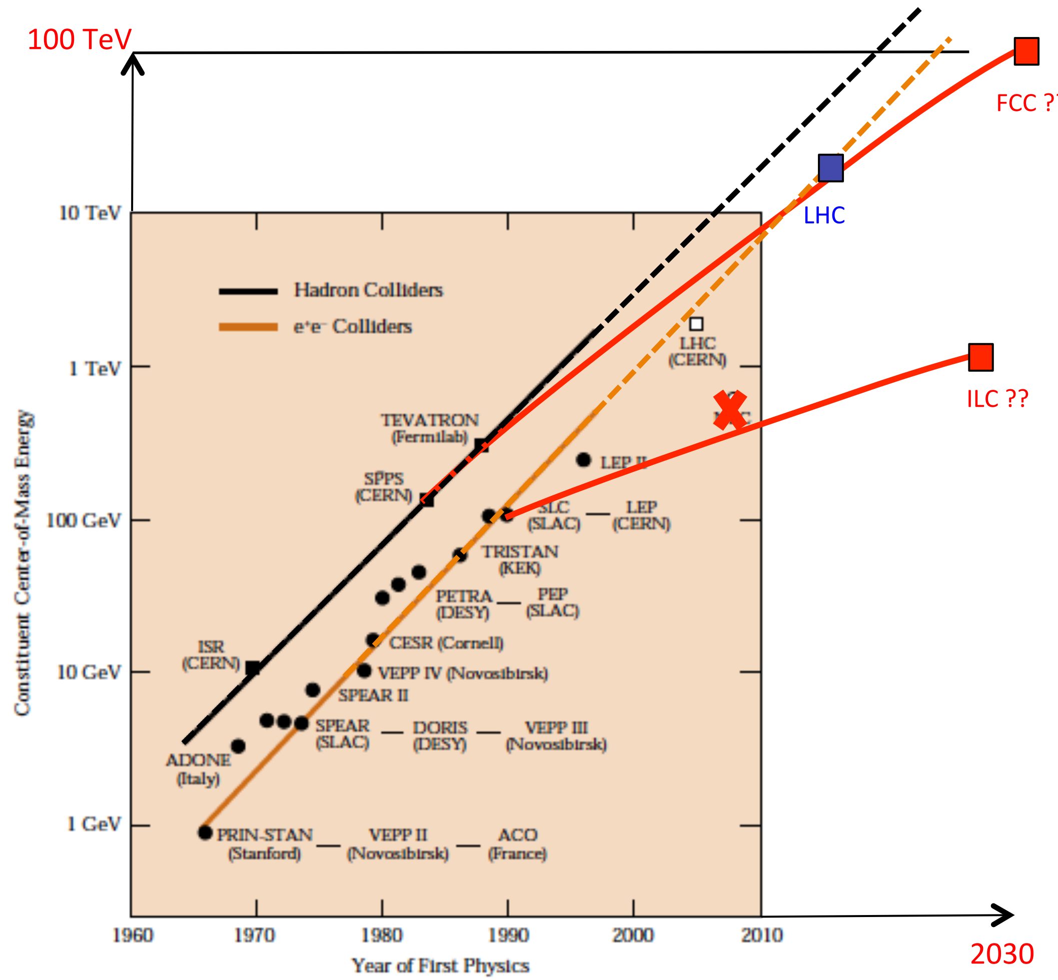
http://case.physics.stonybrook.edu/index.php/PHY554_fall_2016

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



Courtesy: Stanley Livingston



by WOLFGANG K. H. PANOFSKY

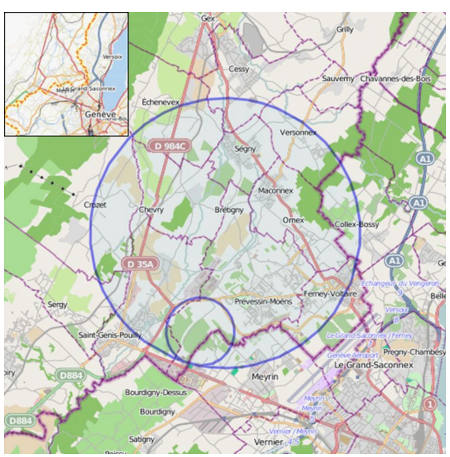
Why? Circular colliders:

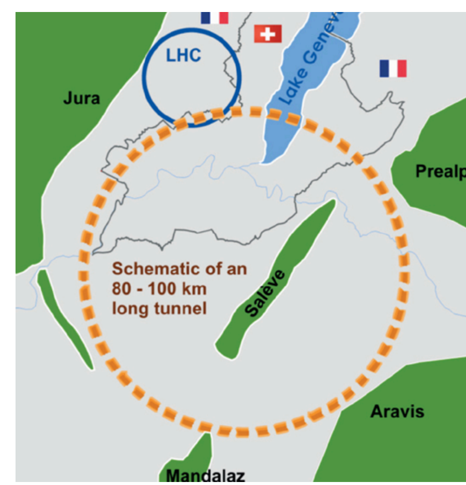
- Electron-position (e^+e^-) colliders stopped at c.m. energy of 209 GeV (104.5 GeV per beam, LEP, CERN, C = 27 km) because losses for synchrotron radiation became comparable with energy of the beam
- Large hadron collider (LHC, p on p at 2 x 6.5 TeV) occupies LEP tunnel with two 27 km rings powered 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

$$\Delta E_{SR}[keV] = 88.5\frac{E_e^4[GeV]}{\rho[m]}$$

$$\Delta E_{SR}[TeV] \approx 88.5\frac{E_e^4[TeV]}{\rho[km]}$$

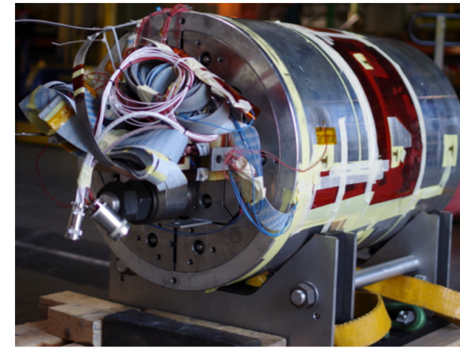
$$1 TeV\ e^{+/-} \rightarrow \rho >> 88.5 km$$



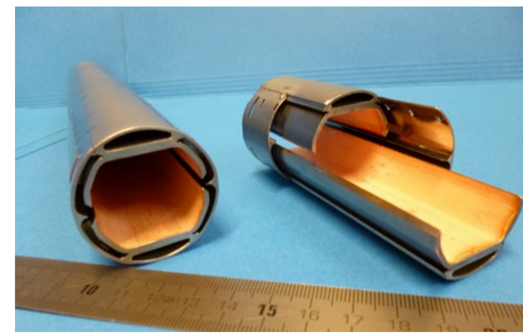


Identified FCC Challenges

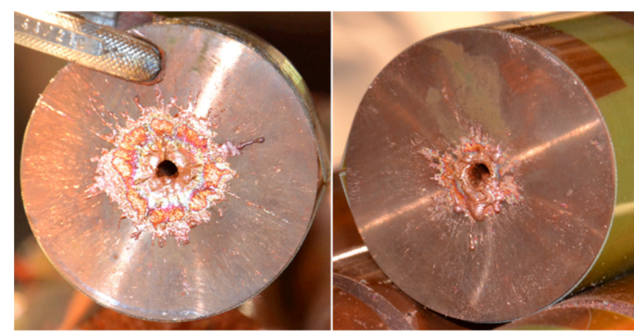
- Operational 16T (edge for Nb_3Sn) SM magnets (means reaching 20 T in tests)



- Synchrotron radiation
  - blessing: damping, higher luminosity
  - and curse: 30 W/m power to absorb at cryogenic t° 300 kW x Carnot
  - compare with room t° : 10 kW/m
  - SR caused desorption and vacuum



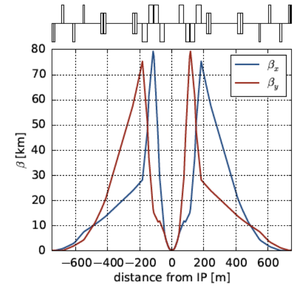
- Energy stored in the beam ~8.4 GJ
  - protection from accidental beam loss
  - the special beam abort dumps
  - sophisticated collimation system
  - …..



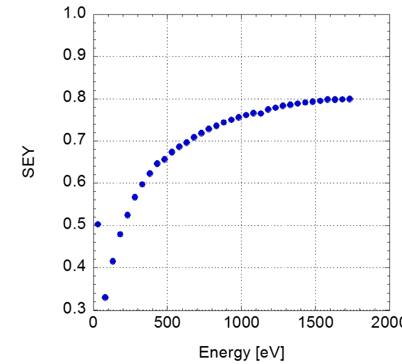
FCC CHALLENGES ARE LHC CHALLENGES ON STEROIDS

Identified FCC Challenges

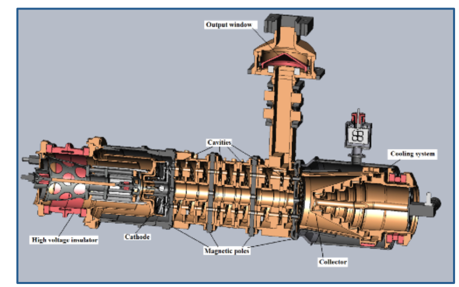
- Small β* at L*=45m
  - Dynamic aperture, energy acceptance for 100 hrs beam lifetime



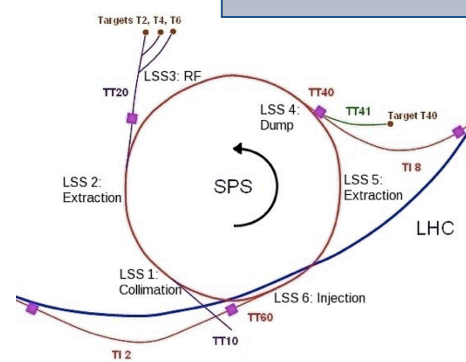
Optics for $\beta^* = 0.3\,\text{m}$



- Electron cloud at 25 nsec bunch pattern (SEY)
- 9 GW power consumption and related energy efficiency problems (SRF, Cryo, vacuum SR absorbers, RF transmitters..)



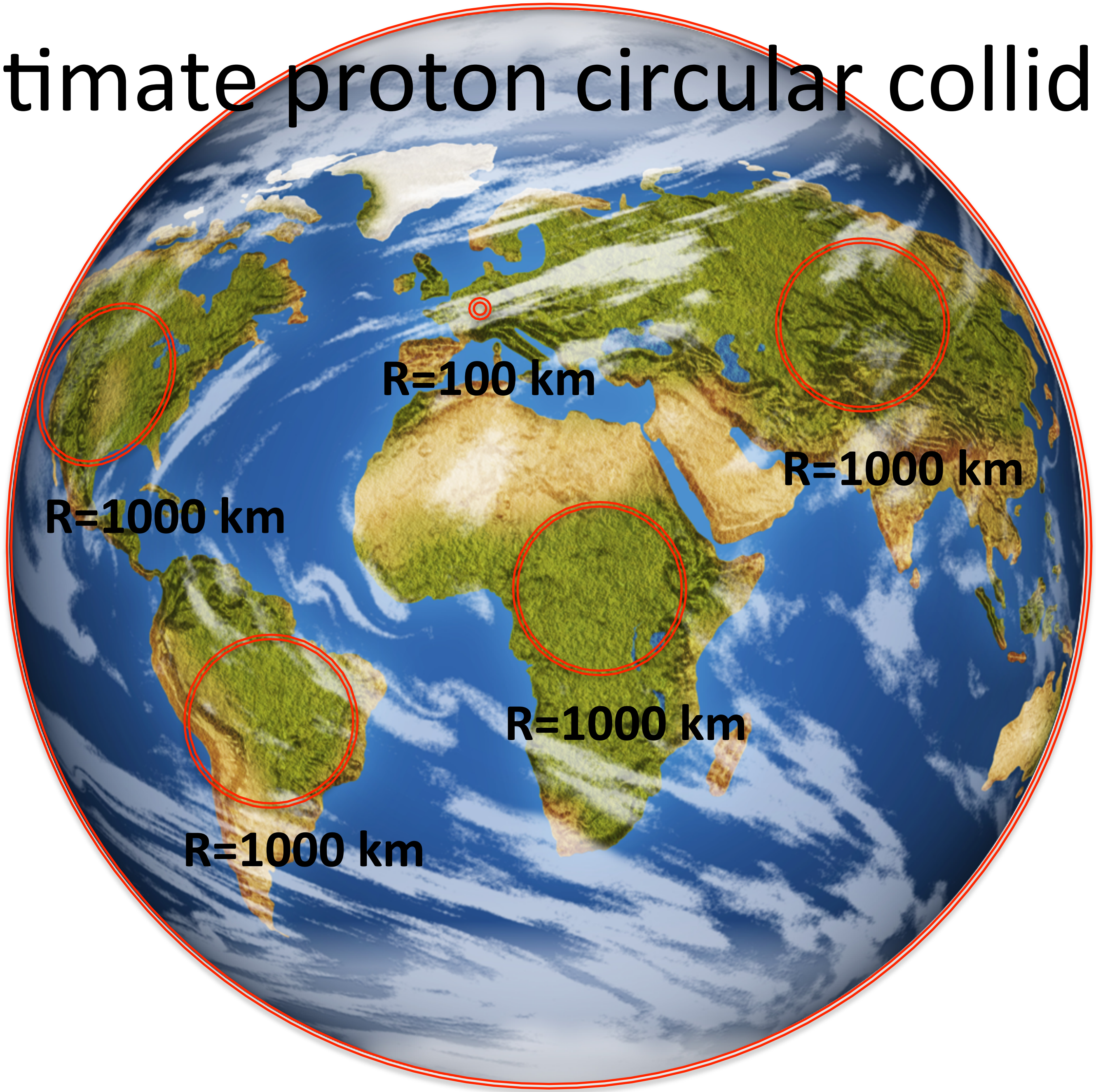
- Complicated and expensive injection chain, turn-around time and beam-beam burn off…



FCC CHALLENGES ARE LHC CHALLENGES ON STEROIDS

FCC, what next?

Ultimate proton circular collider



HW18, Fall 2015: Problem 1. 15 points. Turning the beam around – ultimate storage rings

Let's consider that we build a storage ring (magnets only), where ultra-relativistic charged particles traveling in circle of constant radius ***R*** while radiating synchrotron radiation. It means that the magnetic field is adjusted to the loss of its energy. Find the energy of the particle as function of the traveled distance ***s*** or angle ***s/R***; Find the distance when the particle's energy is reduced by a factor 2.
Loosing half of the energy is considered to be "dead-end" for recirculating the beams – than linear accelerators have to do the job. For R being 6,371 kilometers – that of the Earth, find critical energy of electrons, muons and protons when particles are loosing ½ of the energy in a single turn.

$$e^{+/-} : \Delta E_{eSR}[TeV] \simeq 88.5 \frac{E_e^4[TeV]}{\rho[km]}$$

$$p: \quad \Delta E_{pSR}[eV] \simeq 7.79 \frac{E_p^4[TeV]}{\rho[km]}$$

$$E_e = E_p \quad \Rightarrow \quad \frac{\Delta E_{eSR}}{\Delta E_{pSR}} = 1.15 \cdot 10^{13}$$

Problem 1: since we are considering ultra-relativistic particles, we can assume that $s=ct$, e.g. neglect $(1-\beta) <<< 1$. (a)Losses for radiation with fixed radius are

$$\frac{d\mathsf{E}_{SR}}{ds} = -mc^2 \frac{d\gamma}{ds} \cong \frac{2}{3}\gamma^4 \frac{e^2}{R^2}; \qquad (22\text{-}12)$$

where we used obvious: $E = \gamma mc^2; dE = -d\mathsf{E}_{SR}$. Solution is straightforward:

$$-\frac{d\gamma}{\gamma^4} = \frac{2}{3}\frac{r_c}{R^2}ds; \; r_c = \frac{e^2}{mc^2}; \; \frac{\gamma^{-3} - \gamma_o^{-3}}{3} = \frac{2}{3}\frac{r_c}{R^2}s = \frac{2}{3}\frac{r_c}{R}\theta; \theta = \frac{s}{R};$$

$$\gamma = \frac{\gamma_o}{\sqrt[3]{1 + 2\gamma_o^3 \frac{r_c}{R^2} s}} = \frac{\gamma_o}{\sqrt[3]{1 + 2\gamma_o^3 \frac{r_c}{R}\theta}};$$

(b) $\gamma = \gamma_o / 2$ means

$$\sqrt[3]{1 + 2\gamma_o^3 \frac{r_c}{R^2} s} = 2 \rightarrow s_{1/2} = \frac{7}{2}\frac{R^2}{\gamma_o^3 r_c}.$$

(a) with R= 6.371x10^6 m one turn is s=2πR and we have the relativistic factor of a particle loosing ½ of its energy in one turn around the Earth:

$$\text{(b)} \quad s_{1/2} = 2\pi R = \frac{7}{2}\frac{R^2}{\gamma_{cr}^3 r_c} \rightarrow \gamma_{cr} = \sqrt[3]{\frac{7}{4\pi}\frac{R}{r_c}}$$

Classical radius of the electron is 2.82E-15 m we get critical γ_{cr} = 1.08x10^7. The rest energy of electron is $m_e c^2$=0.511x10^6 eV (0.511 MeV), it means that the dead-end energy of electron storage ring at Earth is

$$E_{cr\,e} = 2\gamma_{cr} m_e c^2 = 5.52 \cdot 10^{12} eV = 5.52 TeV$$

Rest energy of a muon is $m_\mu c^2$=1.057 x10^8 eV (106 MeV), classical radius of 1.36E-17 m, γ_{cr} = 6.39x10^7 and

$$E_{cr\,\mu} = 2\gamma_{cr} m_\mu c^2 = 6.75 \cdot 10^{15} eV = 6{,}747 \; TeV$$

For proton with $m_p c^2$ =1.057 x10^8 eV (106 MeV), classical radius of 1.53E-18 m, γ_{cr} = 1.32x10^8 and

$$E_{cr\,p} = 2\gamma_{cr} m_p c^2 = 1.24 \cdot 10^{17} eV = 1.24 \cdot 10^5 \; TeV$$

Note, that the later will require average bending magnetic field of 65 T, which is not within reach of current technology.

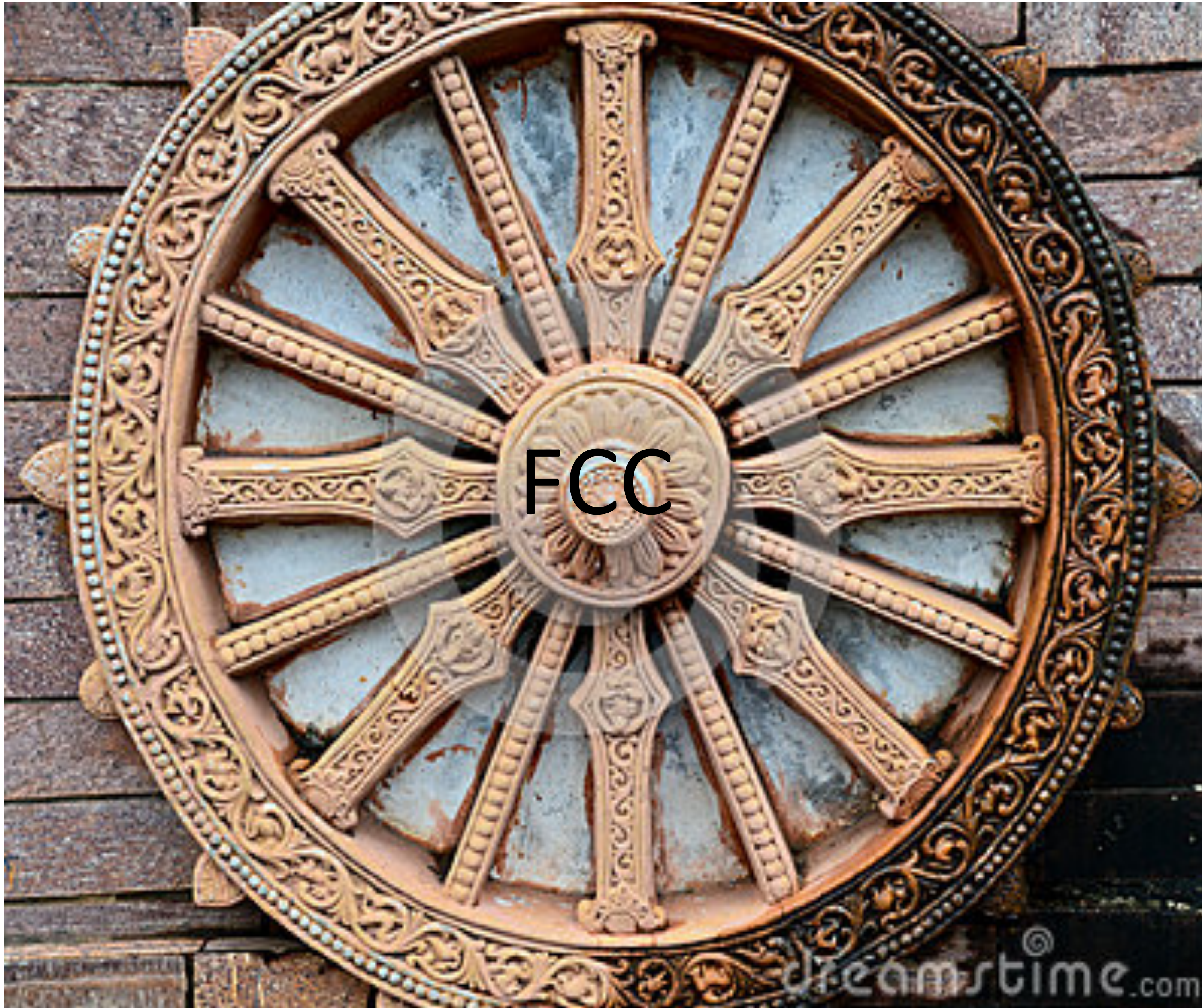
Reality hurts…

R	6371	6371	1000	500	km
Energy	124,075	28,670	4,500	2,250	TeV
<B>	64.92	15	15	15	T
Photon energy	675.031	8.328	0.205	0.051	GeV
SR @ 1 A	6.20E+07	1.77E+05	684	85.5	GW
	1.55E+06	4,420	106	27.2	kW/m

R	250	100	50	16	km
Energy	1125.00	500.00	225.00	50	TeV
<B>	15	16.67	15	10.5 (16)	T
Photon energy	13	3	0.5	0.02	MeV
SR @ 1 A	10.69	1.04	0.09	.003	GW
	6.80	1.66	0.272	0.030	kW/m

Next step in energy will require developing in-cryo-vacuum absorbers at kW/m level

What is new?
One more circular collider?
Ode more wheel?



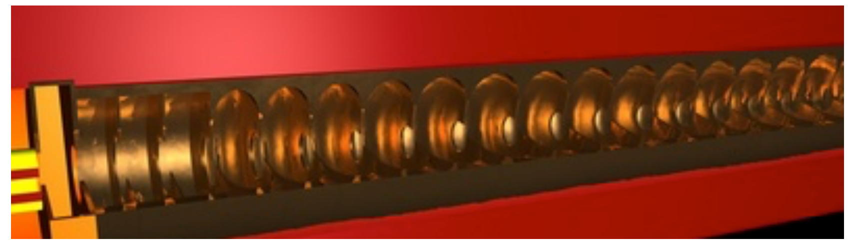
"Yes, but what have you invented lately?"

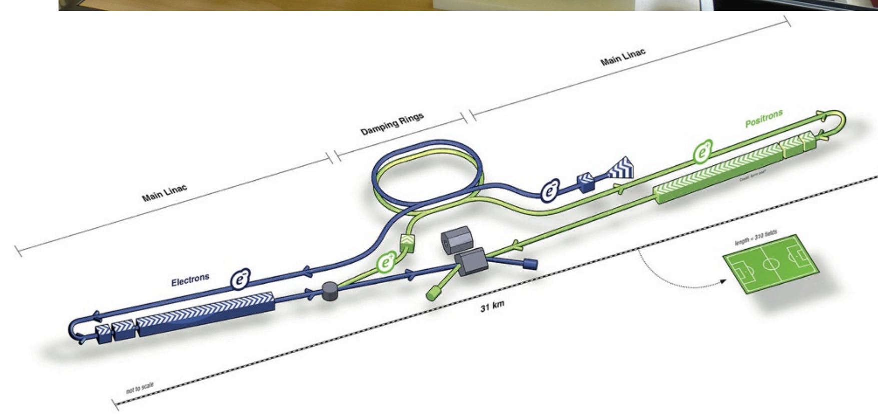
Why? Linear colliders

- 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

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

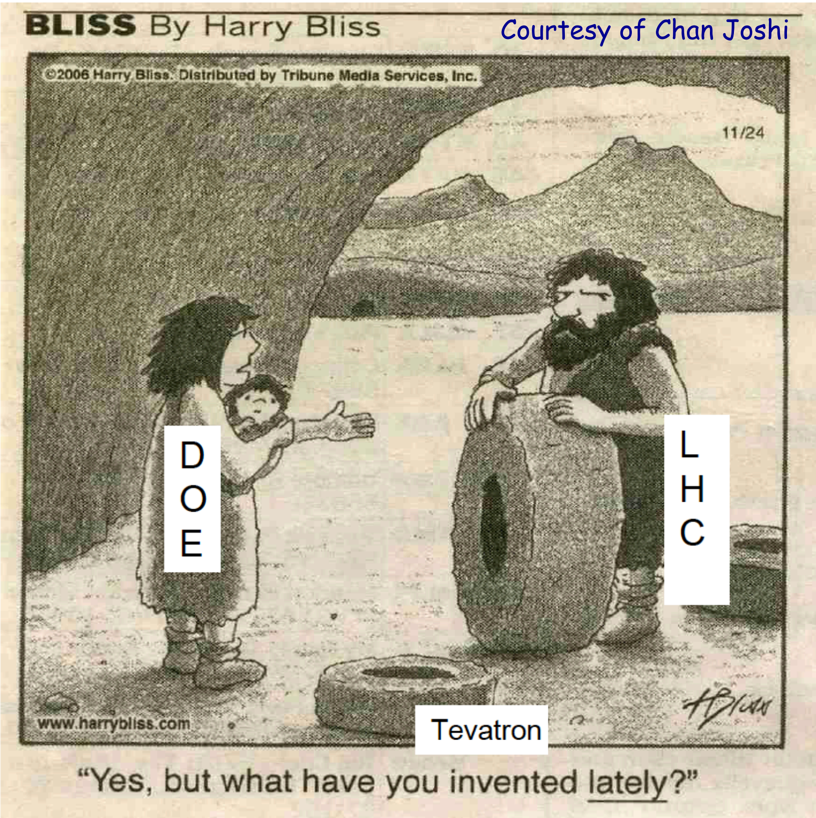
$$\vec{\mathbf{B}} = 0; \; \vec{\mathbf{E}} \parallel \vec{\beta} \Rightarrow \Delta E_{SR} = \frac{2e^4}{3m^2c^3}\int \vec{\mathbf{E}}^2 dt \approx \frac{2}{3}\frac{e^2}{L_{acc}}\gamma^2$$



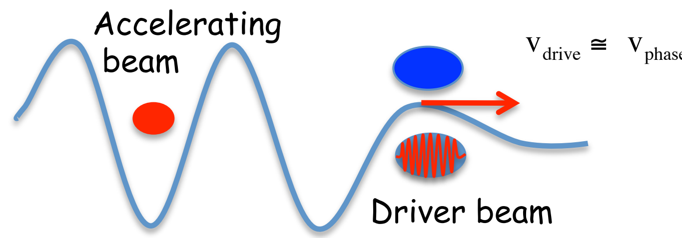


- * Pulsed room temperature Cu structures have a fatigue problem from stress caused by pulsed RF and are developing cracks…. This was one of the reasons to pick SRF as a technology for ILC

What is new?



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



- <u>Conditions for large wake</u>
  - $a_o \sim 1$ or $n_b/n_o \sim 1$
  - 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

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

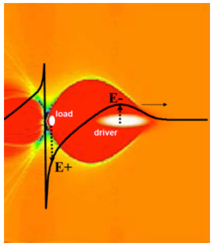
dimensionless vector potential of the laser wave, direct analog of the wiggler parameter K i.e. is the measure of how relativistic are electrons are in plasma

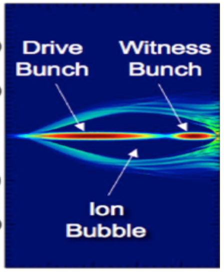
$$\omega_p = \sqrt{\frac{4\pi n_o e^2}{m}} \equiv c\sqrt{4\pi n_o r_e} \cong 5.6\,10^4 Hz\sqrt{n_o[sm^{-3}]}$$

plasma frequency

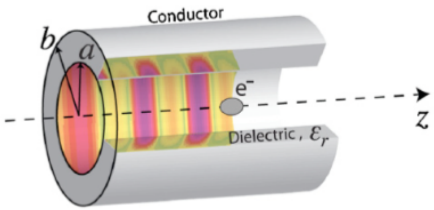
Advanced accelerator methods

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

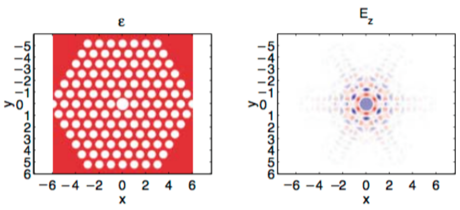




- Dielectric wakefield accelerators



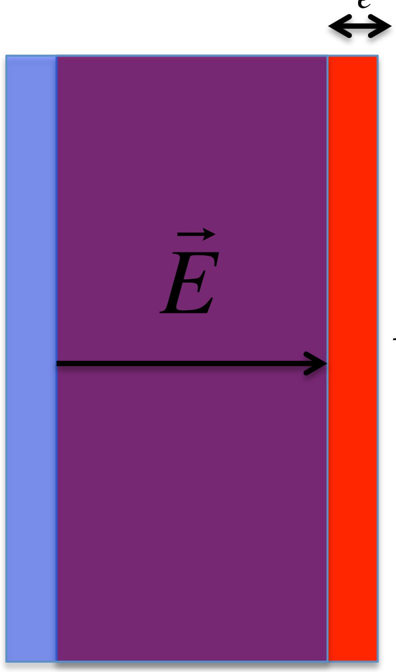
- Photonic gap accelerators



Neutral Plasma basics

$$x = x_e - x_i$$

$$\vec{E} = 0$$



$$\vec{E} = 0$$

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

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 $\omega_p^2 = 0 \rightarrow x_e = x_i$

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

TEM waves in Plasma

$$E_x = E_o \cos(kz - \omega t); m_e \ddot{x}_e = -eE_x \rightarrow x = -\frac{eE_o}{m_e \omega^2} \cos(kz - \omega t);$$

$$\dot{x} = \frac{eE_o}{m_e \omega} \sin(kz - \omega t); \vec{j} = \hat{x} e n_o \dot{x} = \hat{x} \frac{e^2 E_o}{m_e \omega} n_o \sin(kz - \omega t);$$

$$\frac{\partial \rho}{\partial t} + div\vec{j} = 0 \rightarrow \frac{\partial \rho}{\partial t} = 0; \qquad \frac{4\pi e^2}{m_e \omega^2} n_o \equiv \frac{\omega_p^2}{\omega^2}$$

$$curl\vec{B} = -\hat{x}\frac{\partial B_y}{\partial z} = \hat{x}\frac{1}{c}\frac{\partial E_x}{\partial t} + \frac{4\pi}{c}\vec{j} = \frac{\omega}{c}\left(1 - \frac{4\pi e_o^2}{m_e \omega^2} n_o\right) E_o \sin(kz - \omega t) =$$

$$\frac{\partial B_y}{\partial z} = -\frac{\omega}{c}\left(1 - \frac{\omega_p^2}{\omega^2}\right) E_o \sin(kz - \omega t); \quad curl\vec{E} = \hat{y}\frac{\partial E_x}{\partial z} = -\hat{y}\frac{1}{c}\frac{\partial B_y}{\partial t};$$

$$\frac{\partial^2 E_x}{\partial z^2} = -k^2 E_o \cos(kz - \omega t) = -\frac{\omega^2}{c^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right) E_o \cos(kz - \omega t); \quad k = \pm\frac{\omega}{c}\sqrt{1 - \frac{\omega_p^2}{\omega^2}}$$

It means that wave with $\omega < \omega_p$ decay in plasma and can not propagate.
Thus, for a laser pulse with wavelength $\lambda = \frac{2\pi c}{\omega}$ can propagate through a plasma with density limited by

$$n_o < \frac{\pi}{r_e \lambda^2}; r_e = \frac{e^2}{m_e c^2}$$

TEM waves that decay in Plasma

$$\omega < \omega_p$$

$$k = i\frac{\sqrt{\omega_p^2 - \omega^2}}{c} \rightarrow E = E_o e^{-\frac{\sqrt{\omega_p^2-\omega^2}}{c}z} \cos\omega t$$

Laser pulse pressure

Particles motion in fast-oscillating field

$$m\ddot{\vec r} = \vec f(r,t);\ \vec f(r,t)=\vec f_o(r)\cos(\omega t);\ \vec r = \vec r_{slow}+\vec r_{fast};\ \vec r_{slow}=\langle \vec r\rangle_t;\ \langle \vec r_{fast}\rangle_t \to 0$$

$$m\ddot{\vec r}_{fast} \cong \vec f_o(\vec r_{slow})\cos(\omega t) \to \vec r_{fast} = -\frac{\vec f_o(\vec r_{slow})}{m\omega^2}\cos(\omega t)$$

$$m\langle\ddot{\vec r}\rangle = \left\langle \vec f_o(\langle\vec r\rangle+\vec r_{fast})\cos(\omega t)\right\rangle_t \cong \left\langle \vec f_o(\langle \vec r\rangle)\cos(\omega t)\right\rangle\downarrow_o + \left\langle \frac{\partial \vec f_o(\langle\vec r\rangle)}{\partial\langle\vec r\rangle}\vec r_{fast}\cos(\omega t)\right\rangle_t + O(\vec r_{fast}^2)$$

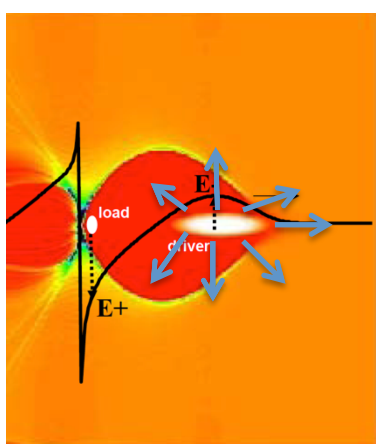
$$m\langle\ddot{\vec r}\rangle = -\frac{\vec f_o(\langle\vec r\rangle)}{m\omega^2}\cdot\frac{\partial \vec f_o(\langle \vec r\rangle)}{\partial\langle\vec r\rangle}\langle\cos^2(\omega t)\rangle_t \Rightarrow \frac{d\langle\vec p\rangle}{dt} \cong -\frac{\partial U}{\partial\vec r};\quad U=\frac{1}{2m\omega^2}\cdot\langle \vec f^2(\vec r,t)\rangle_t$$

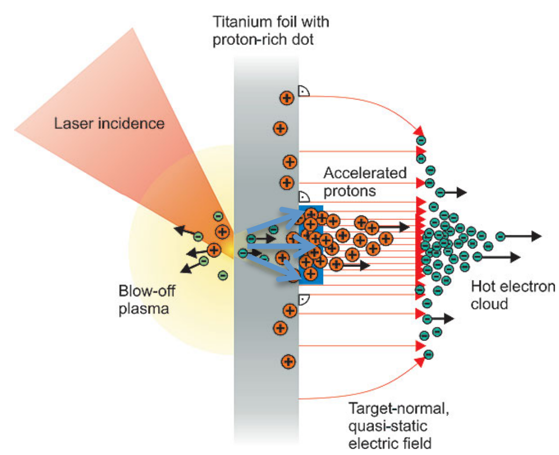
$$\vec f = \frac{e\vec A(\vec r)\omega}{c}\cos(\omega t);\quad \vec E = \vec E_o(\vec r)\cos(\omega t) = \frac{1}{c}\frac{\partial\vec A}{\partial t};\quad \vec A=\vec A_o(\vec r)\sin(\omega t);\quad \vec A_o = \frac{c\vec E_o}{\omega}=\frac{\lambda\vec E_o}{2\pi}$$

$$U=\frac{e^2\vec A^2(\vec r)}{4mc^2} \Rightarrow \frac{1}{mc^2}\frac{d\langle\vec p\rangle}{dt} = -\frac{\partial U_{eff}}{\partial\vec r};U_{eff}=\frac{\vec a_o^2(\vec r)}{4};\ \vec a_o=\frac{e\vec A}{mc^2}.$$

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

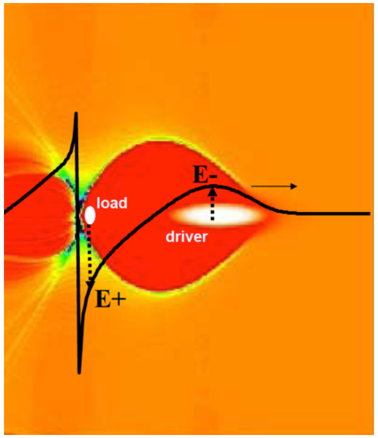
Pressure





$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} \equiv \frac{eE_o}{mc\omega_o} \equiv \frac{eA_o}{mc^2} << 1$$

Electrons motion is nonrelativistic, linear plasma



$$a_0 = \frac{eE_o\lambda_o}{2\pi mc^2} >> 1$$

Relativistic motion of electrons, nonlinear plasma, bubble or blow-out regime (e.g. an empty bubble from electrons)

Scaling

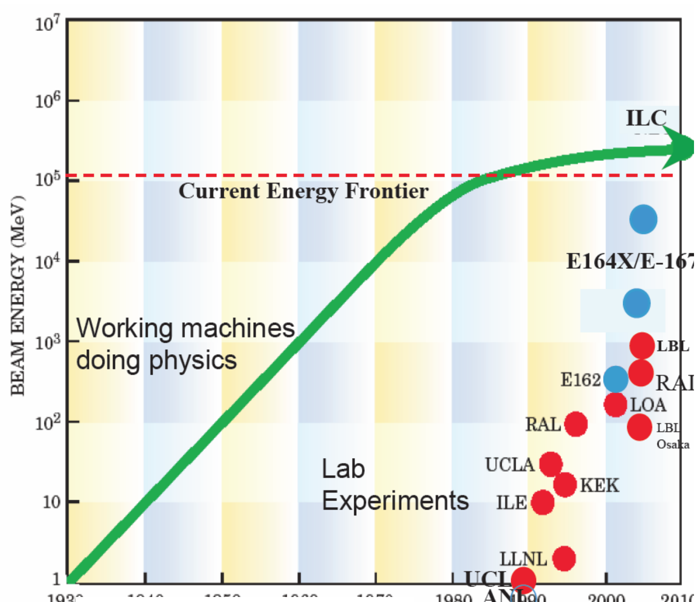
$$l_{buble} \sim \frac{c}{\omega_p}; \;\; r_{buble} \sim l_{buble}/2; \;\; E \sim \frac{4\pi q}{\pi r_{buble}^2} \cong 4\pi e n_o \frac{l_{buble}\pi r_{buble}^2}{\pi r_{buble}^2} \cong \frac{4\pi e c n_o}{\omega_p} = e\sqrt{\frac{4\pi n_o}{r_e}}$$

$$r_e = 2.8\cdot 10^{-13}\, cm; \;\; n_o = 10^{19}\, cm^{-3}; e = 4.8\cdot 10^{-10}\ \text{esu}; \;\; E \sim 10^7\ Gs = 3GV/cm$$

Compare this 300 GeV/m with 150 MeV/m in RF linacs

Breakthroughs

- Pre-Dawn.....
- 1994 Jet age' begins
  - 100 MeV in laser-driven gas jet at RAL
- ....
- **2004 'Dawn of Compact Accelerators'**
  - **Nearly mono-energetic beams at LBNL, LOA, RAL**
- **2007 Energy Doubling at SLAC**

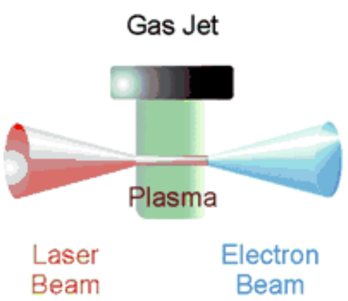


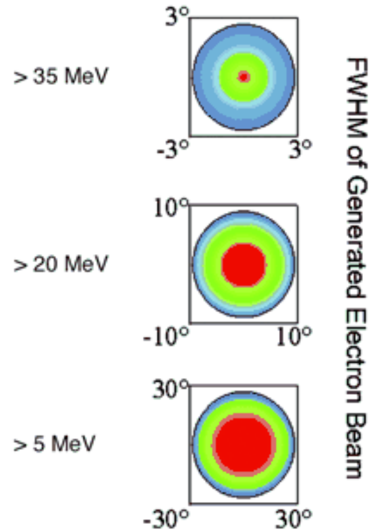
Courtesy of Chan Joshi

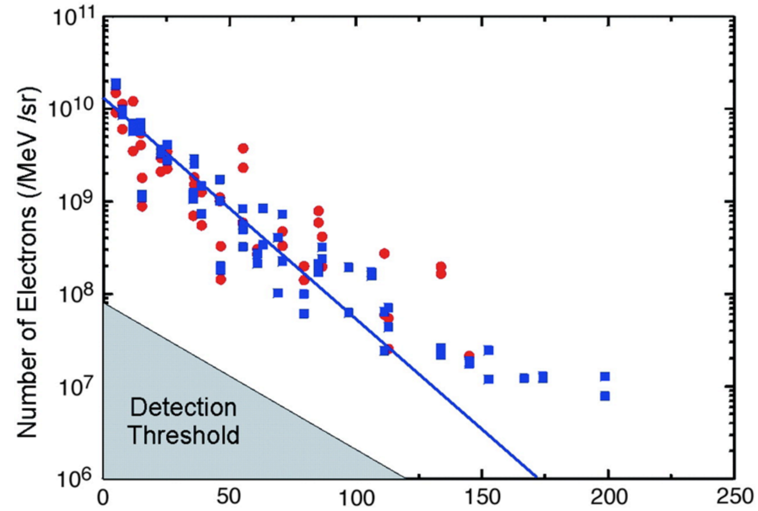
- FACET, SLAC, Palo Alto, California, USA
- Lawrence Berkeley National Laboratory, Berkeley, CA,USA
- University of California, Berkeley, California,USA
- UCLA, Los Angeles, California, USA
- Tech-X Corporation, Boulder, Colorado, USA
- University of Colorado, Boulder, Colorado, USA
- Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, UK
- Laboratoire d'Optique Applique´e, Ecole Polytechnique, Palaiseau, France
- Institut fur Theoretische Physik, Duesseldorf, Germany
- De´partement de Physique The´orique et Applique´e, Bruye`res-le-Cha^tel, France
- The Blackett Laboratory, Imperial College, London UK
- University of Strathclyde, Glasgow, UK
- Technische Universiteit Eindhoven, the Netherlands
- ....

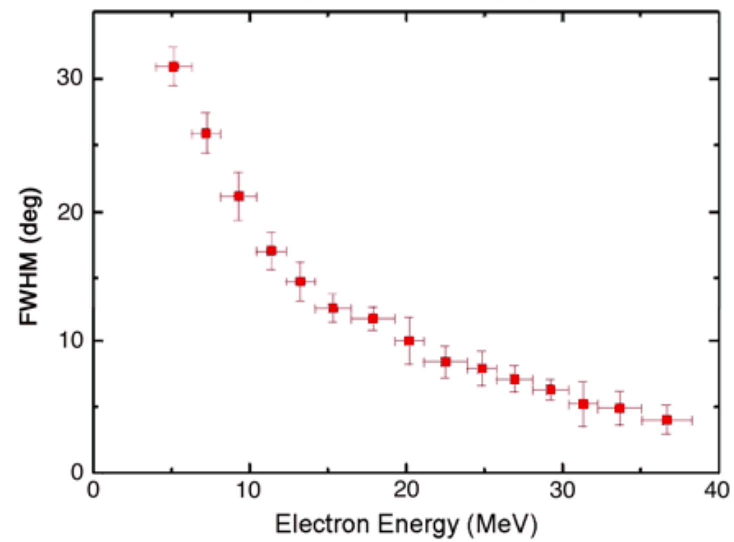
PRE-DAWN

Schematic of the experiment.





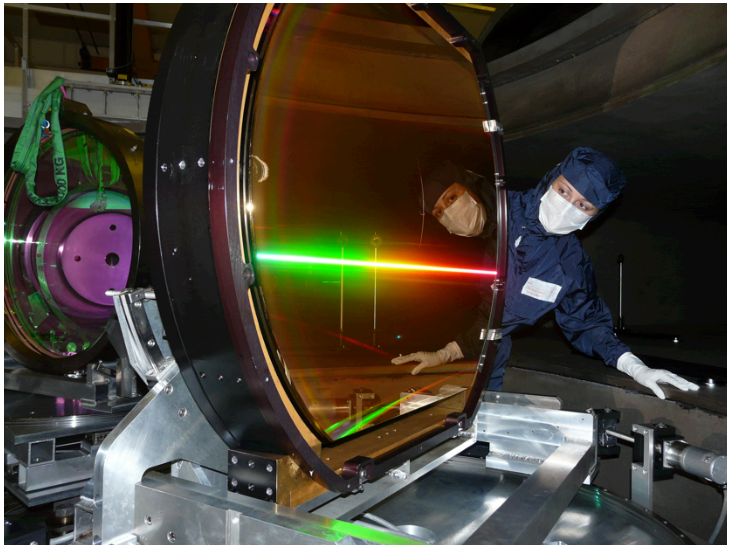


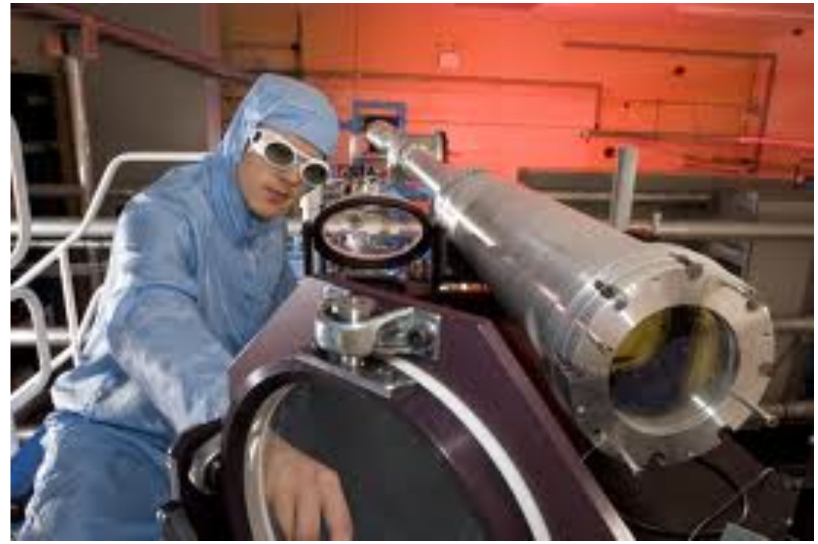


A high- intensity laser is focused onto the sharp edge of a gas jet with a uniform density profile. In this regime, the generated plasma wave breaks and accelerates electrons. It is observed that the high-energy electrons are well collimated in the direction of propagation of the laser beam

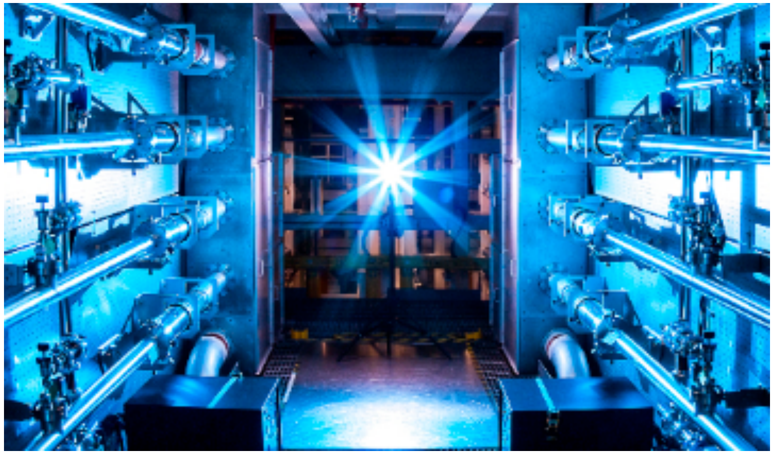
Science 22 , 2002, Vol. 298 no. 5598,
Electron Acceleration by a Wake Field Forced by an Intense Ultrashort Laser Pulse
V. Malka et all., LOA (Laboratoire d'Optique Appliquée,École Nationale Supérieure des Techniques Avancées,École Polytechnique) & others

Vulcan Petawatt Laser Facility

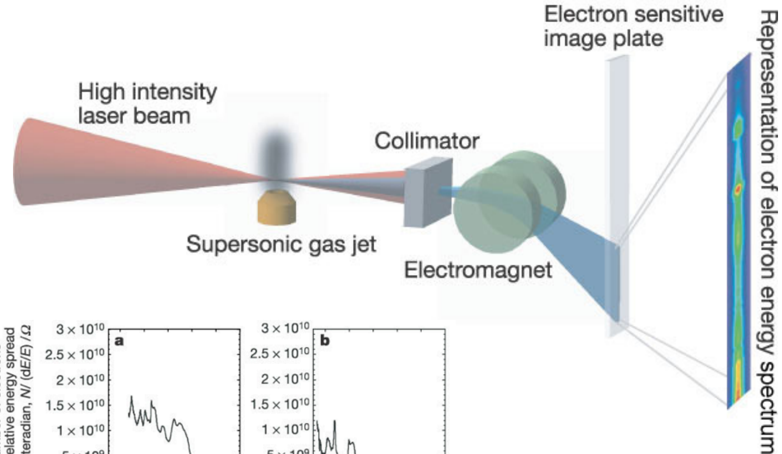


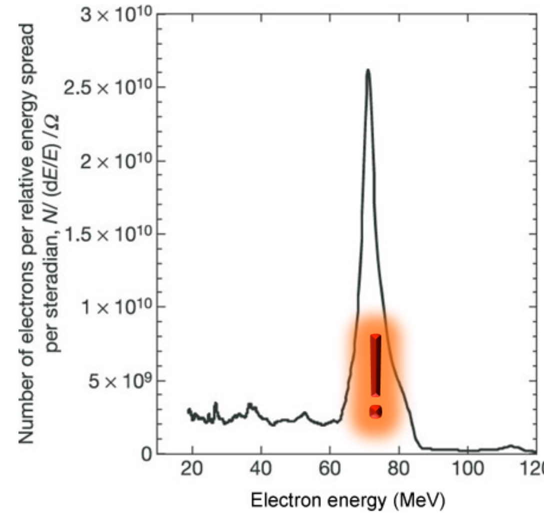


Livermore Laser Facility

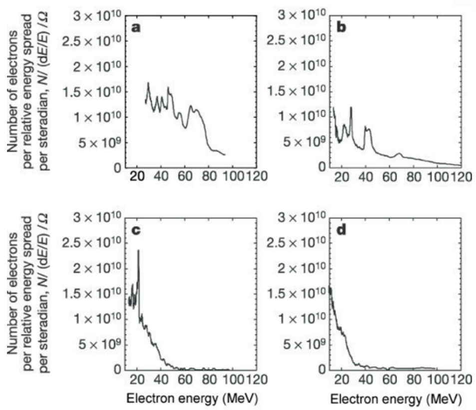


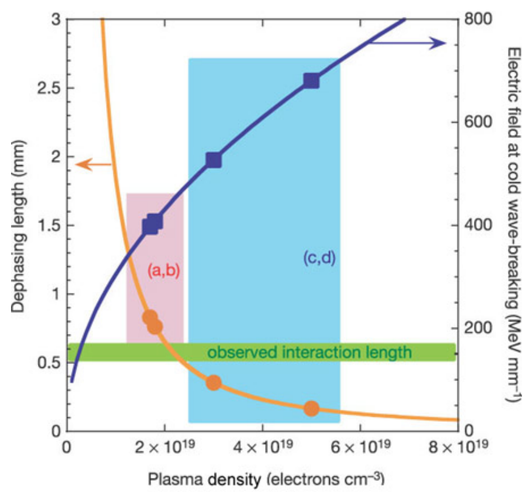
Dream beams 2004-2007

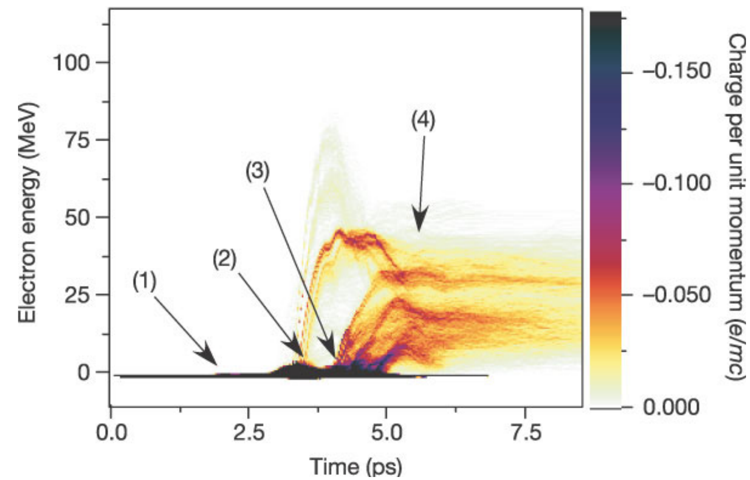




73 MeV
spread 3%?

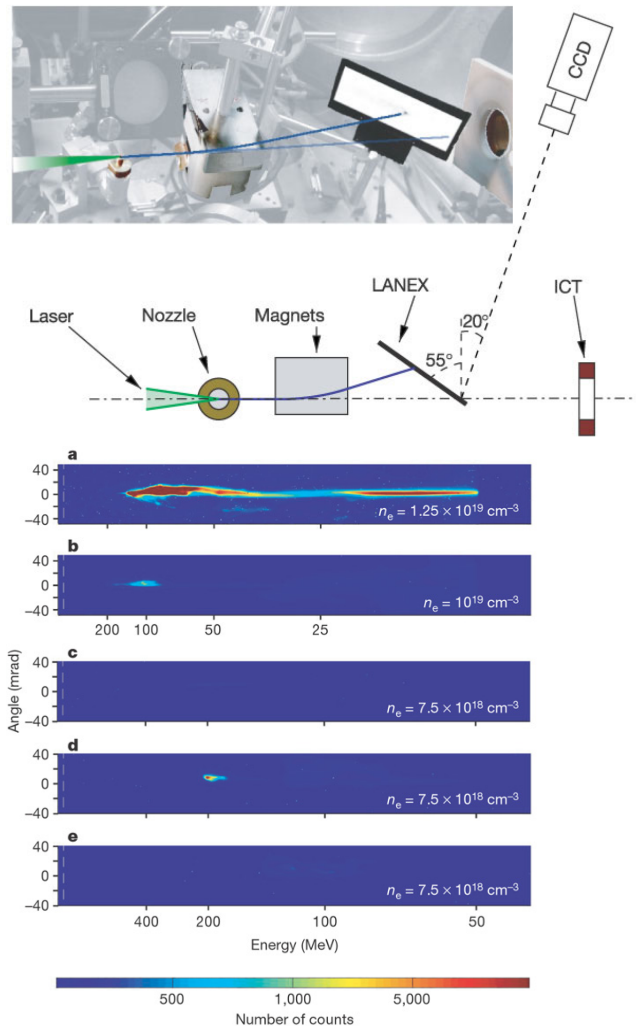


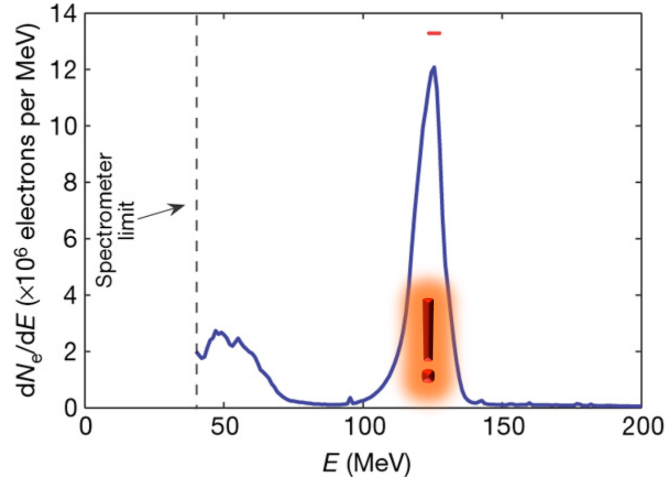




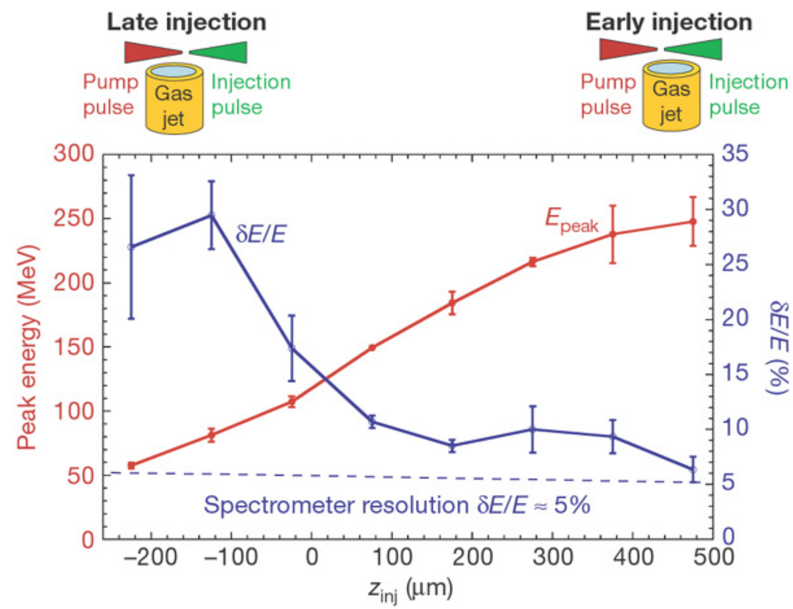
Nature 431, 2004, Monoenergetic beams of relativistic electrons from intense laser-plasma interactions, S. P. D. Mangles et .all, RAL & others

Dream beams 2004-2007





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

Dream beams 2004-2007

1.0 GeV Beam Generation

Courtesy of E. Esarey (LBL)

312 μm diameter and 33 mm length capillary

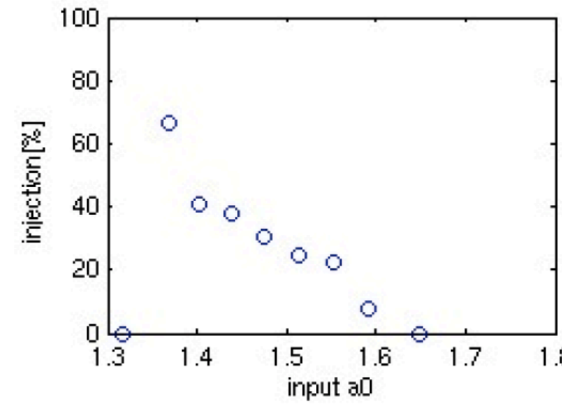
Laser: 1500(±15%) mJ/pulse

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

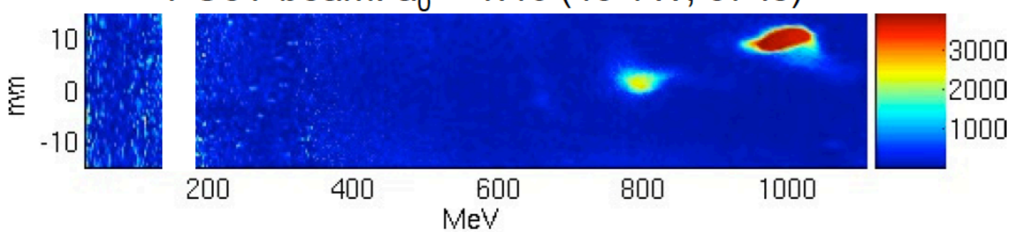
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

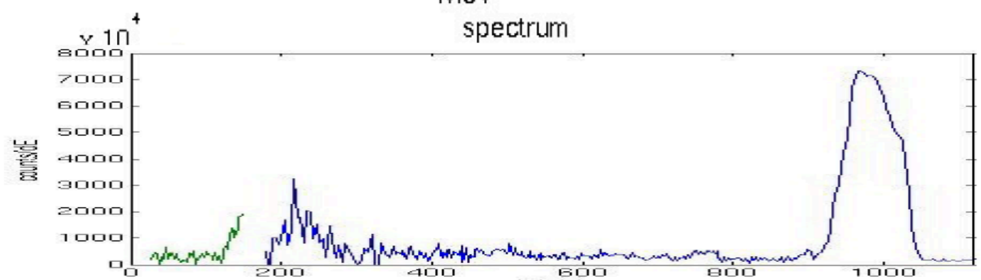
Less injection at higher power

Relativistic effect, self-modulation



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





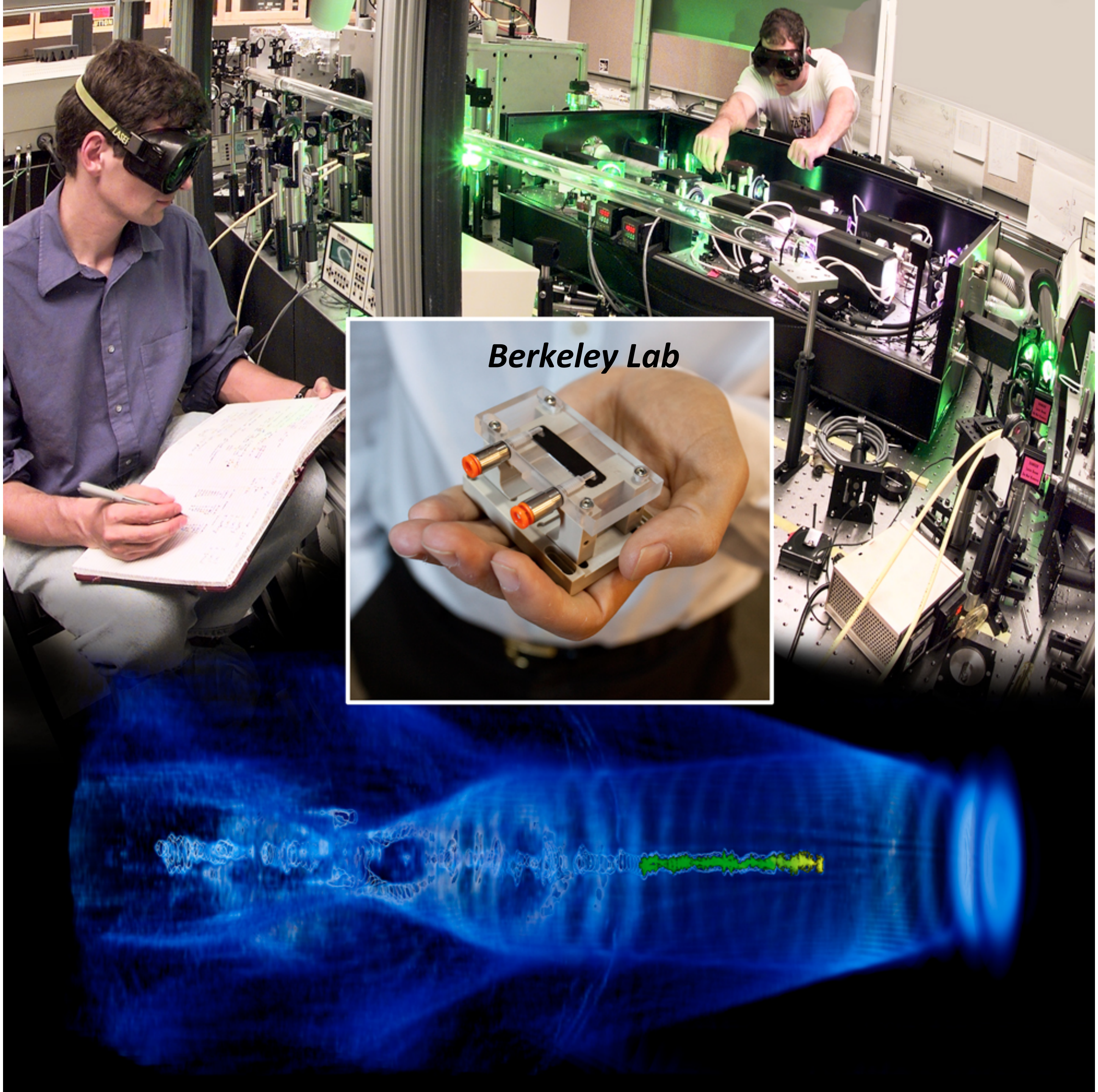
Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: > 30.0 pC

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


Berkeley Lab

The BELLA laser: LBNL

Dream beams 2004-2007

Top energy!

07 | 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 x 10^{10}

Energy 50 GeV

Rep Rate 60 HZ

Energy/pulse 320 J

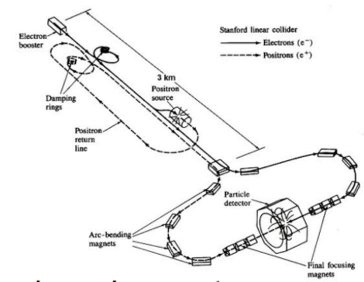
Focal Spot Size 10 microns

Pulse Width 50 fs

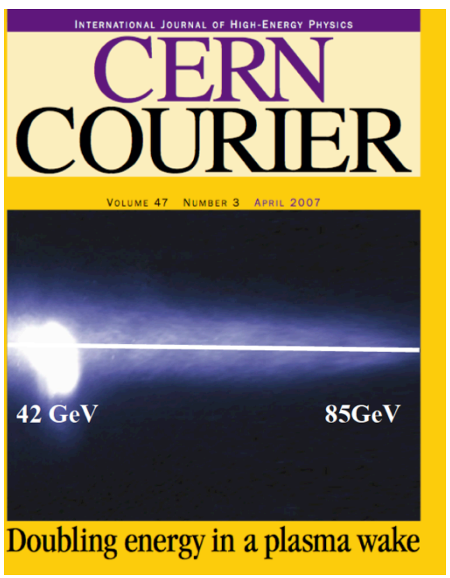
Focused Intensity 7 x 10^{21} W/cm^2

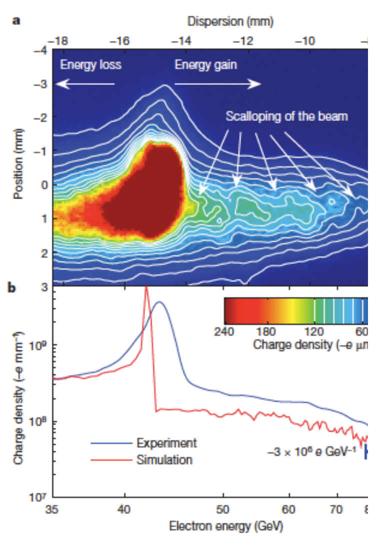
SLAC NATIONAL ACCELERATOR LABORATORY

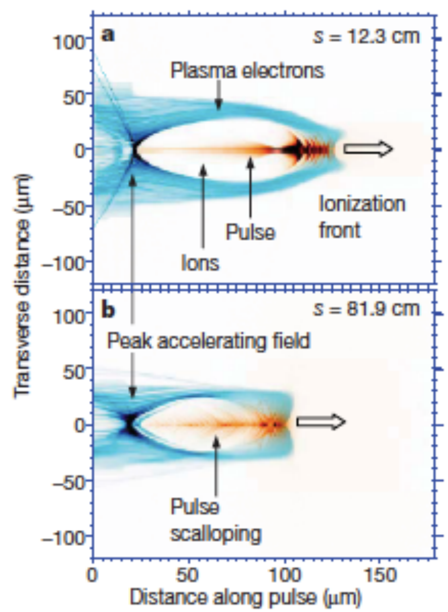
New SLAC National Accelerator Laboratory logo

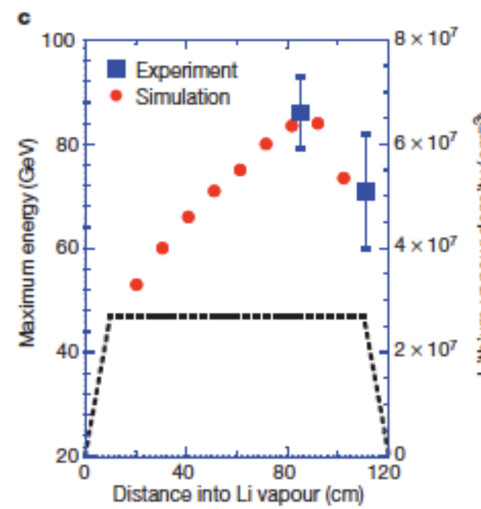


Comparable to the most intense laser beams to-date

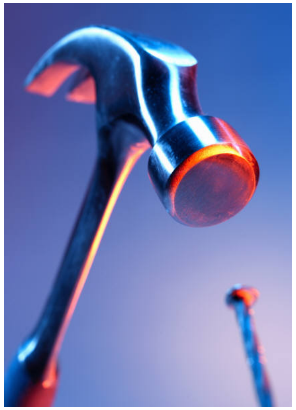








Understanding



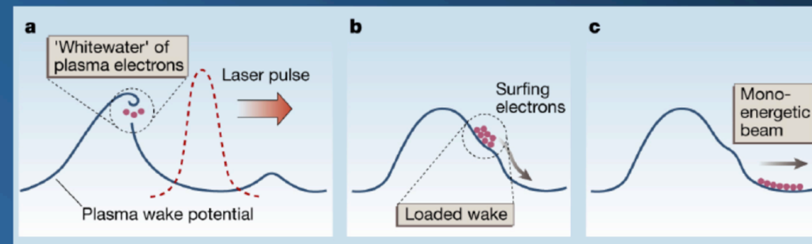
Recipe for a Monoenergetic Beam

Courtesy of
W. Leemans (LBL)

a. Excitation of wake (self-modulation of laser)
Onset of self-trapping (wavebreaking)

b. Termination of trapping (beam loading)
Acceleration

c. Dephasing
If L > or < dephasing length: large energy spread
If L ~ dephasing length: monoenergetic



T. Katsouleas, Nature 2004

2004 Results: High-Quality Bunches

- **Approach 1: bigger spot**
  - RAL/IC⁺ (12.5 TW -> ~20 pC, 80 MeV)
  - LOA^ (33 TW -> ~500 pC, 170 MeV)
  - **For GeV -> 1 PW class laser**
- **Approach 2: preformed channel guided**
  - LBNL* (9TW, 2mm channel -> ~300 pC, 86 MeV)
  - **For GeV -> ~10-50 TW class laser$, longer guiding structure**

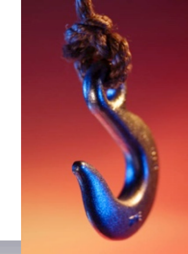
Courtesy of
W. Leemans (LBL)

⁺S. Mangles et al, *Nature* **431**(2004) 535; ^J. Faure et al, *Nature* **431**(2004) 541
*C.G.R. Geddes et al, *Nature* **431** (2004) 538; $W.P. Leemans et al, *IEEE Trans. Plasmas* Sci. **24** (1996) 331.

NATURE|Vol 444|7 December 2006

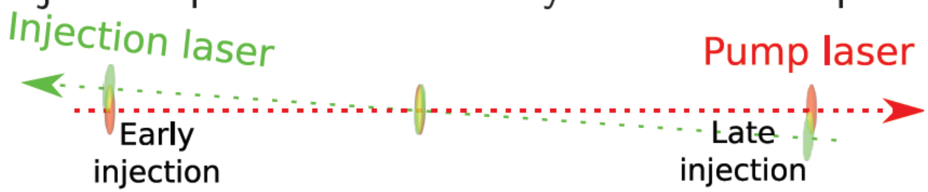
Figure 1 | Surfing, tow-in style. Pete Cabrinha takes a record-breaking ride on the 70-foot 'Jaws' wave off the north shore of Maui, Hawaii, on 10 January 2004, for which he won the coveted Billabong XXL.

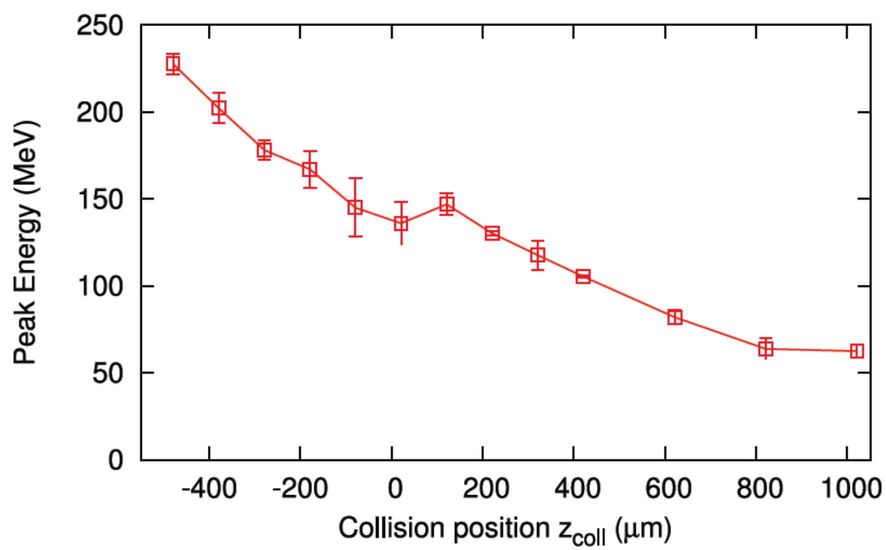
Knobs & Hooks



Results: Control of Beam Energy

The injection position is fixed by the collision position



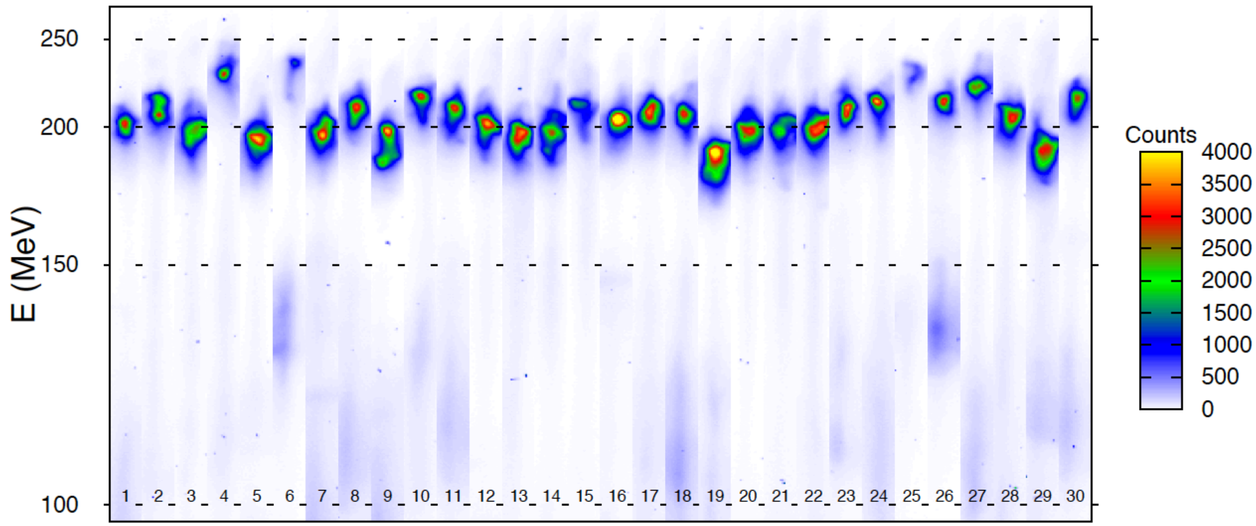


- Acceleration length, hence energy can be tuned

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.)

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 $2 \le a_o \le 2\omega_o/\omega_p$

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

Optimal accelerating structure $a_o \ge 4$

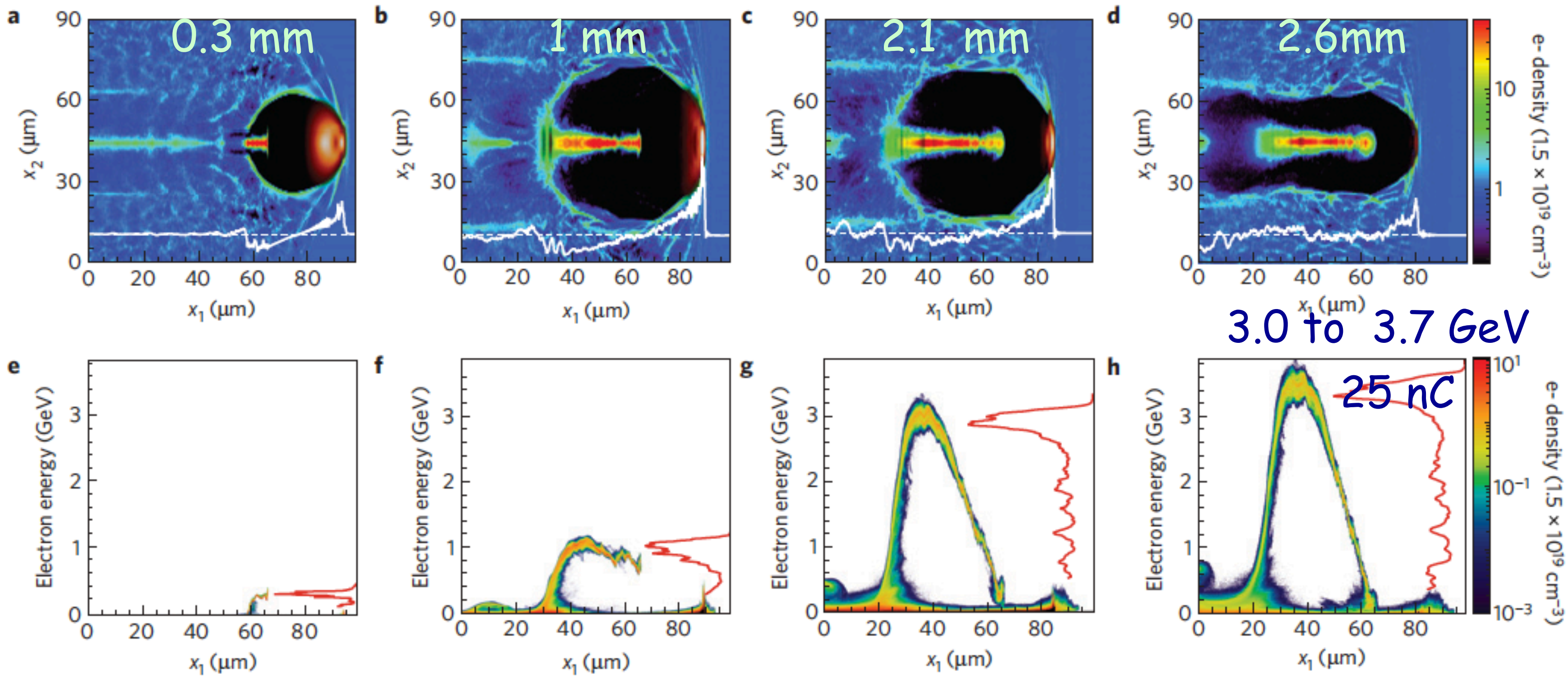
The idea of the bubble regime is that the spot size is also roughly matched to the bubble radius

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

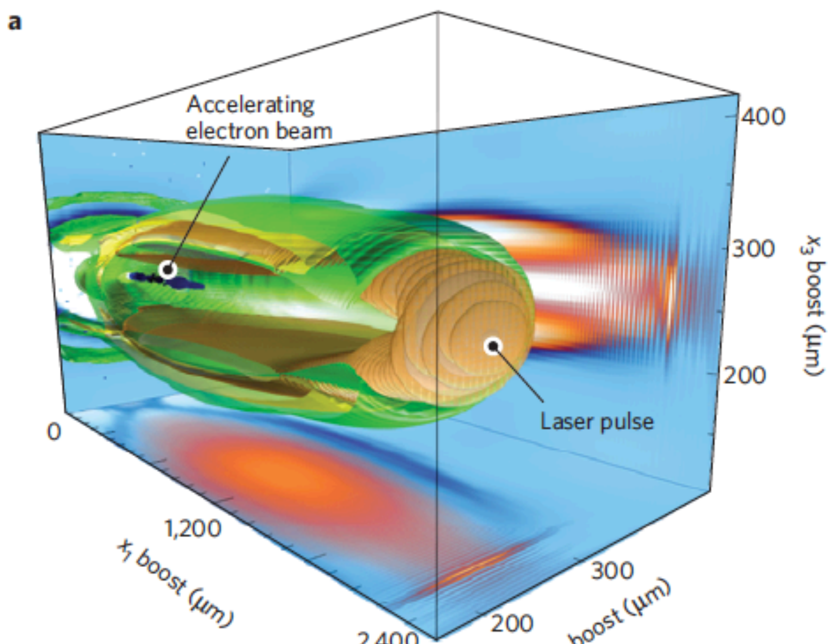
Future of LPWA

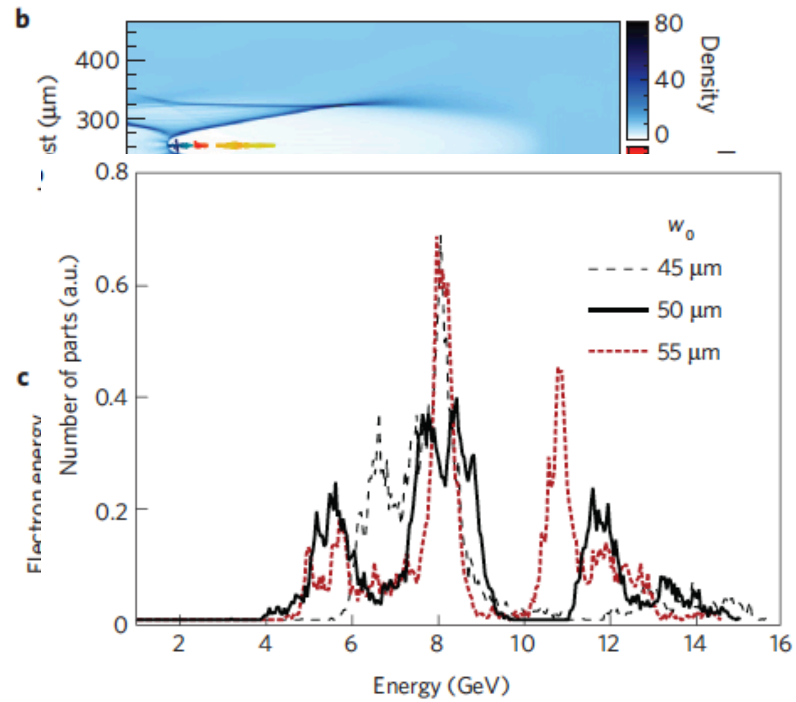
S. F. Martins, R. A. Fonseca, W. Lu, W. B. Mori and L. O. Silva, NATURE PHYSICS. V. 6, p.311, APRIL 2010

Blow-out regime $2 \leq a_o \leq 2\omega_0/\omega_p$

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

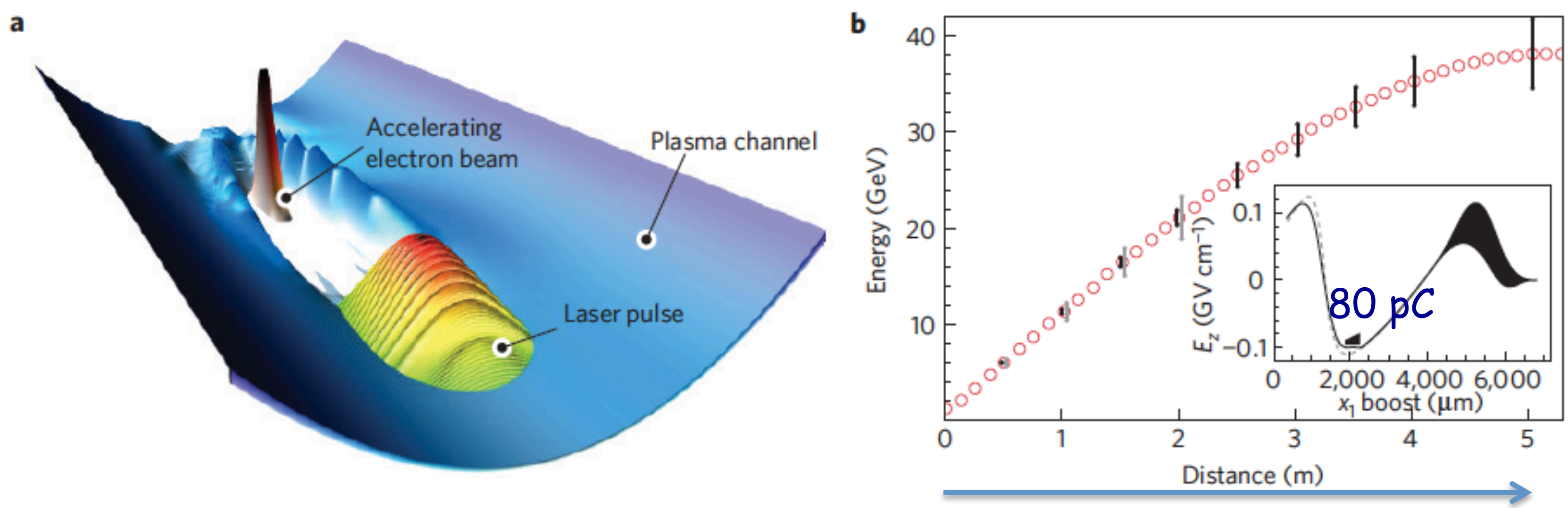
Future of LPWA

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



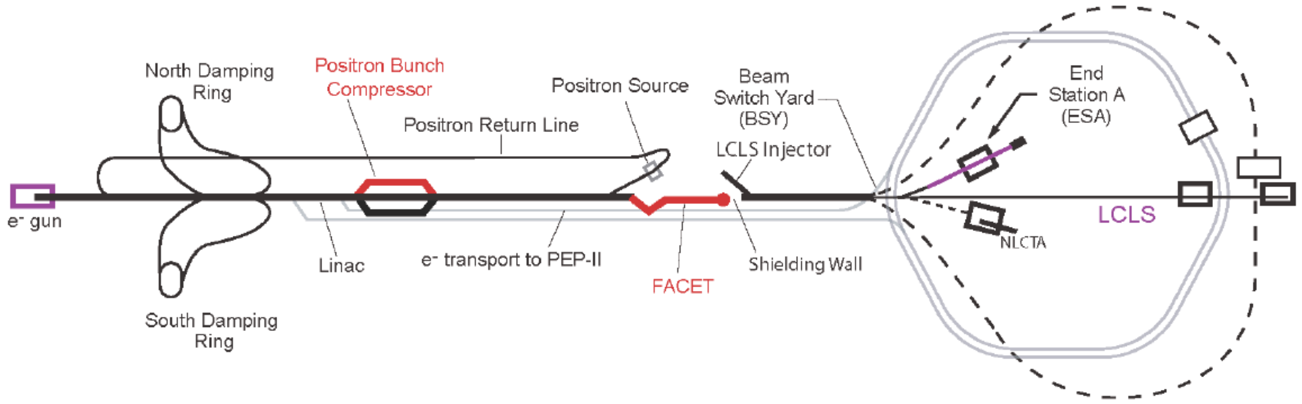
Plasma moves to the left with γ=10

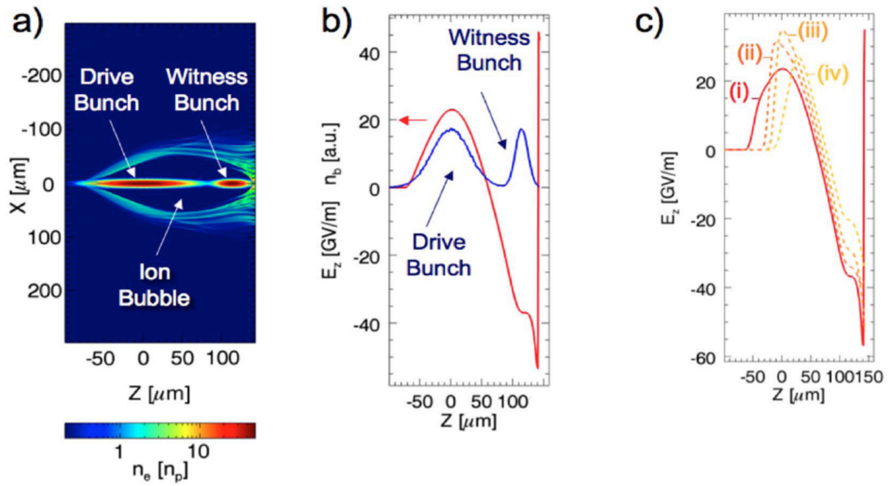
Simulation results for a LWFA in the external-guiding/external-injection blowout regime

The simulations are done in an optimal Lorentz frame

FACET: beam-driven PWA

- Use the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons
  - Compressed 25 GeV beams → ~20 kA peak current
  - Small spots necessary for plasma acceleration studies
- Two separate installations
  - Final bunch compression and focusing system in Sector 20
  - Expanded Sector 10 bunch compressor for positrons

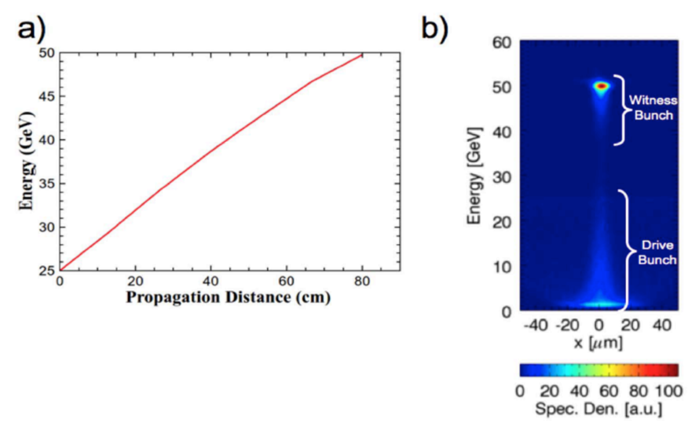




Transformer ratio of 2
Good beam loading efficiency

Drive Bunch
30 micron
3e10

Witness Bunch
10 microns
1e10



5% energy spread
Energy doubling in less than 1 meter

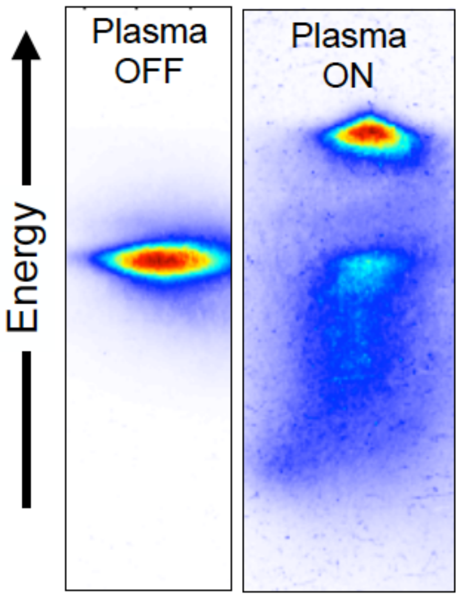
Beam driven PWA

Litos et al., *Nature* November 2014

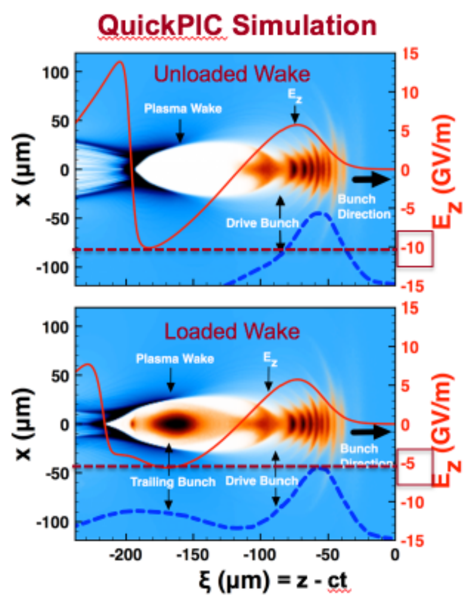
High-Efficiency Acceleration of an Electron Bunch in a Plasma Wakefield Accelerator

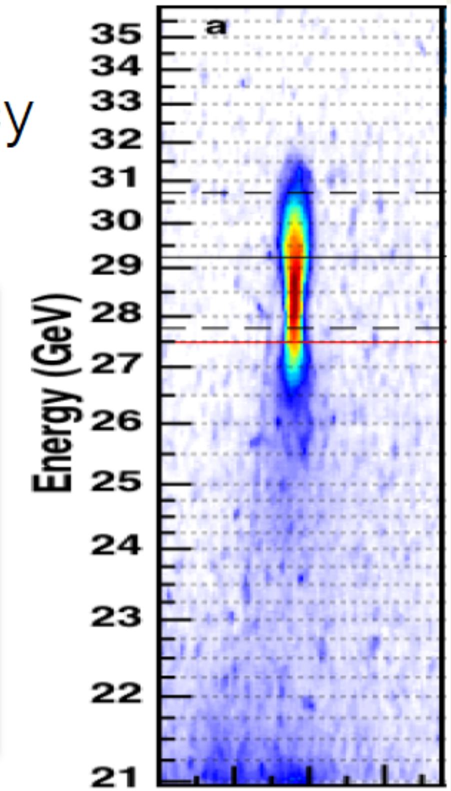
SLAC

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



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





9 GeV
Energy Gain

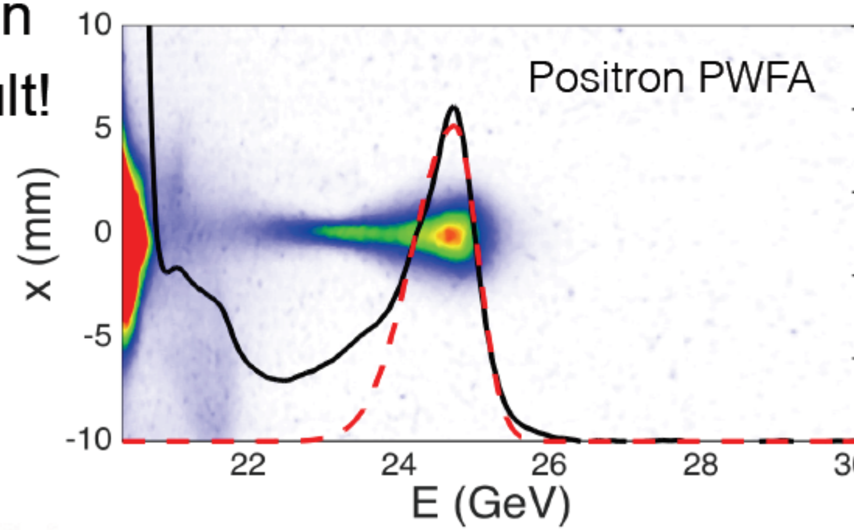
Narrow energy spread acceleration with high-efficiency has been demonstrated
Next decade will focus on simultaneously preserving beam emittance

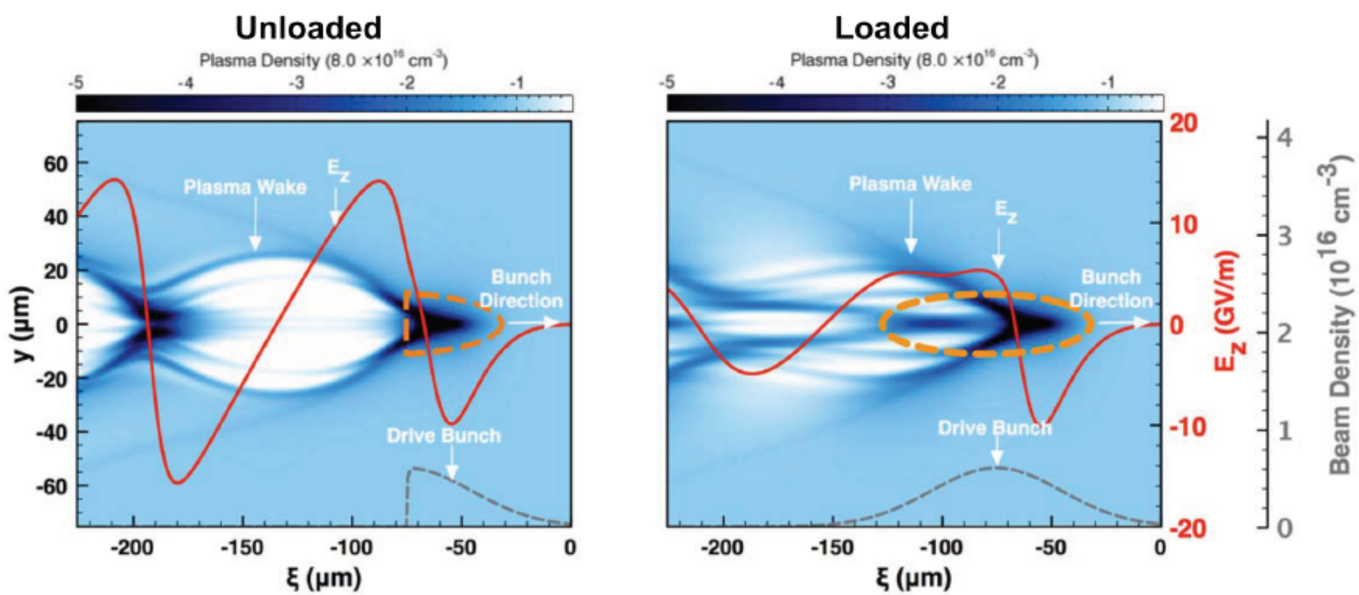
Corde et al., *Nature* August 2015

Multi-GeV Acceleration of Positrons

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

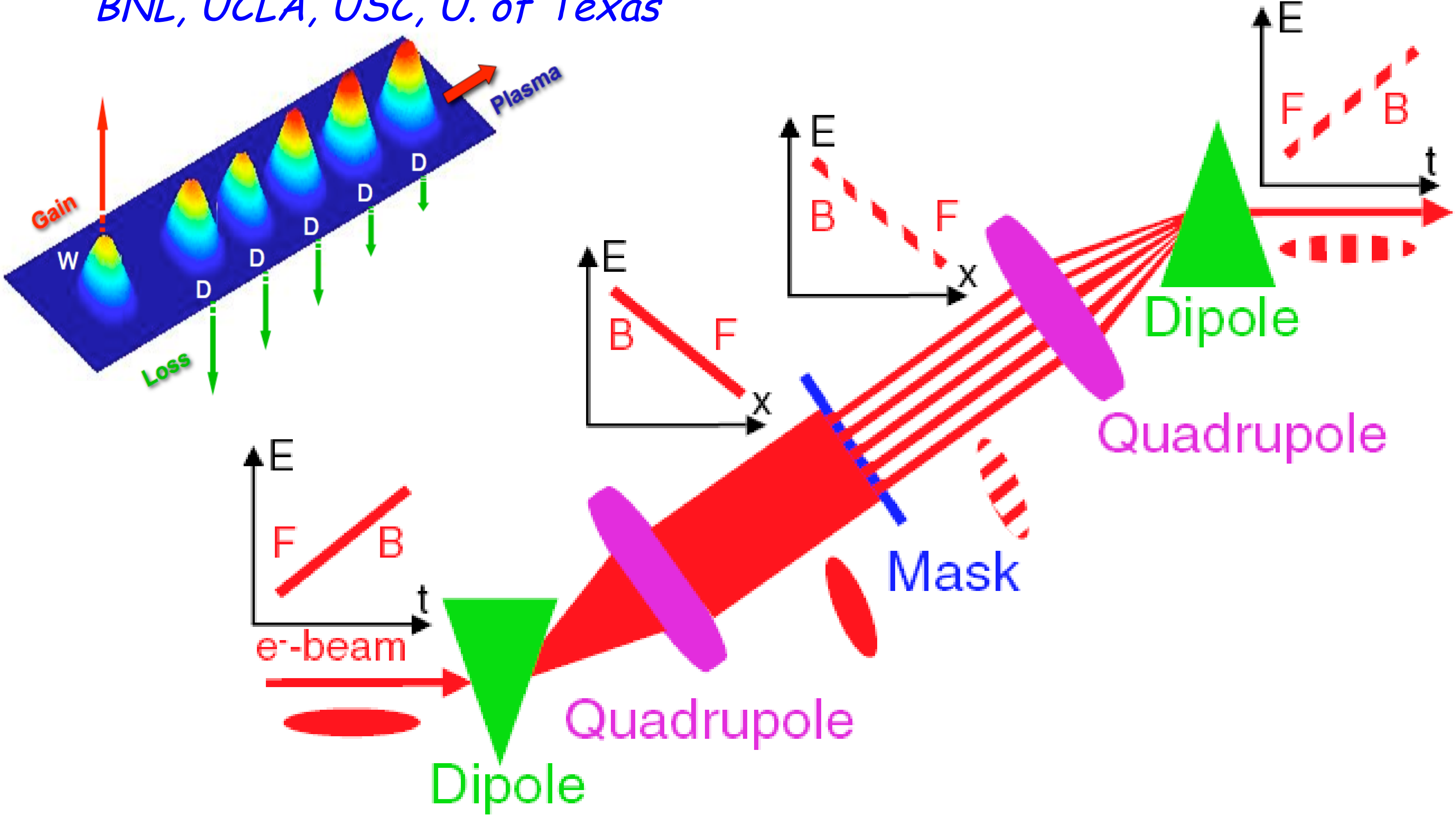




New PWFA regime warrants further exploration and development towards PWFA-LC application

Multibunch Plasma Wakefield

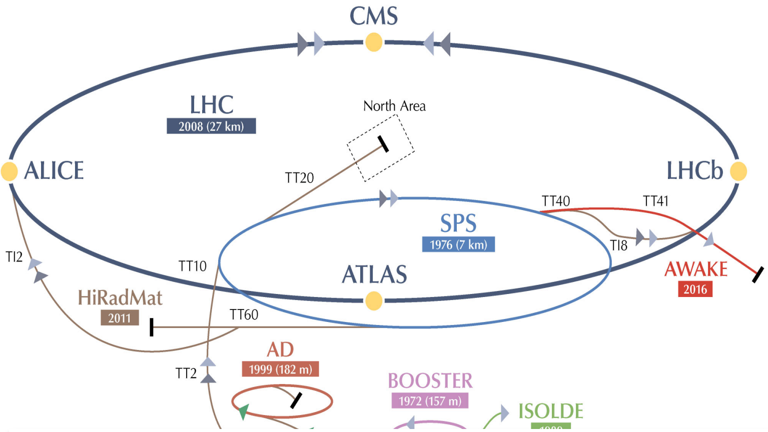
BNL, UCLA, USC, U. of Texas



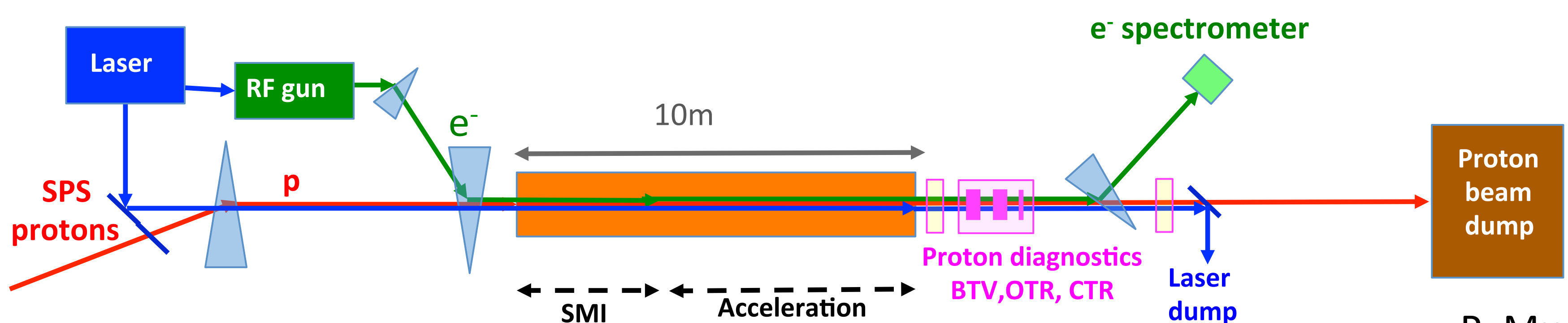
Simplified schematic of the mask principle. Only the dogleg section of the beam line is depicted (not to scale), and three quadrupole magnets are omitted. The side graphs represent the beam energy correlation with the beam front labelled by "F" and the back by "B."

© V.Yakimenko

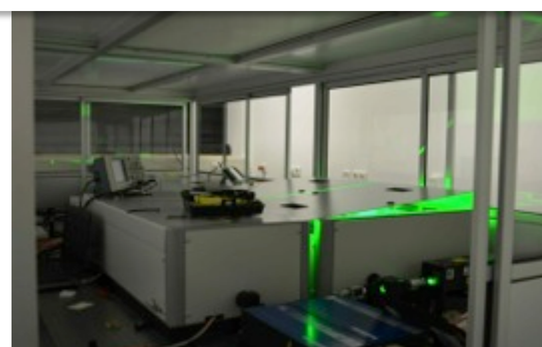
The AWAKE Facility at CERN
using 400 GeV protons to drive PWA



- 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 ++**

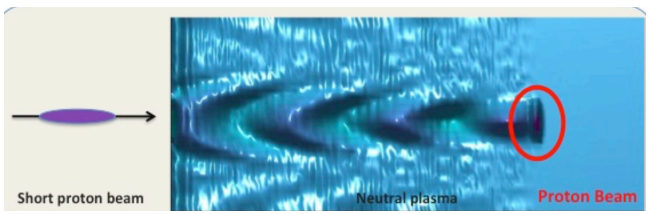


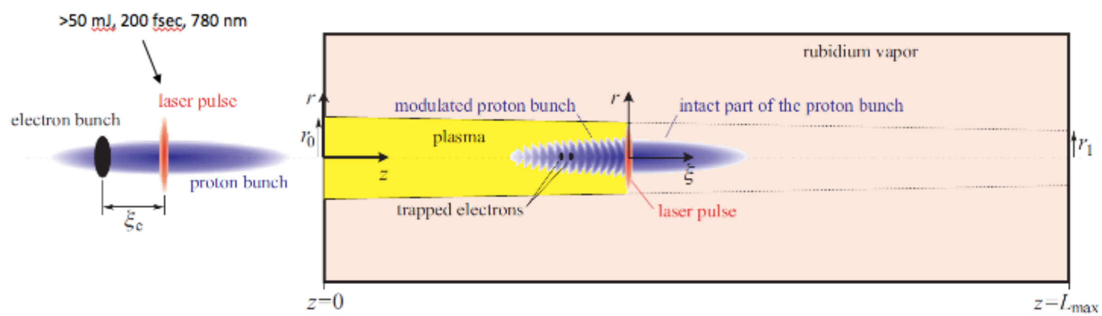
P. Muggli

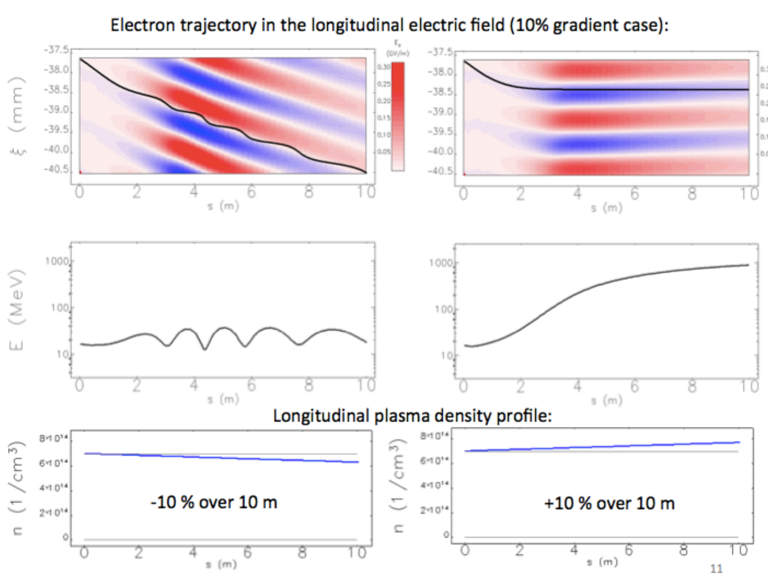


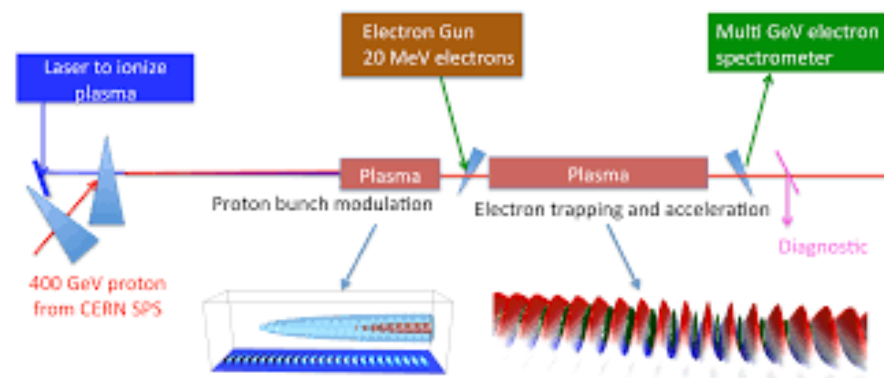
Proton drivers for PWA:
how to use TeV-scale proton beam to drive PWA?

Self-Modulating Instability of Proton Beam in Plasma







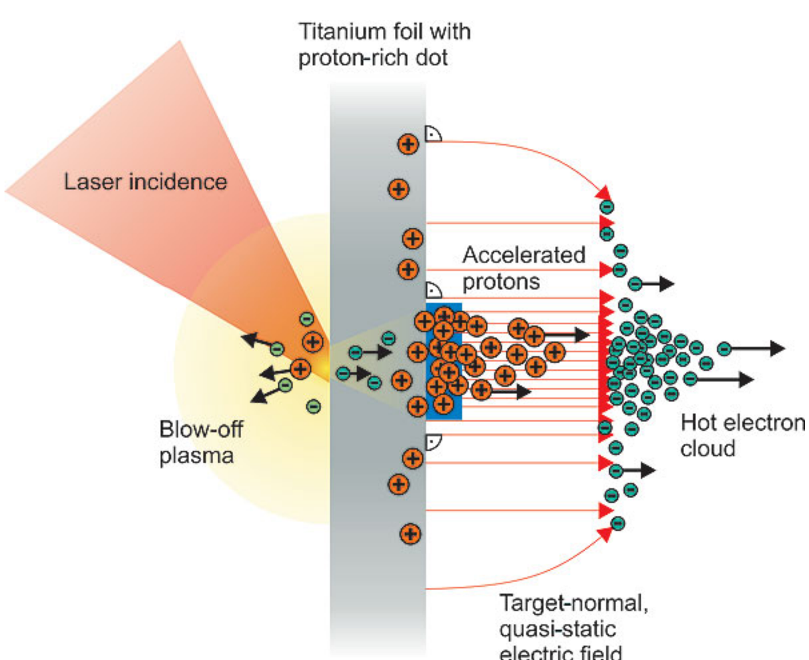


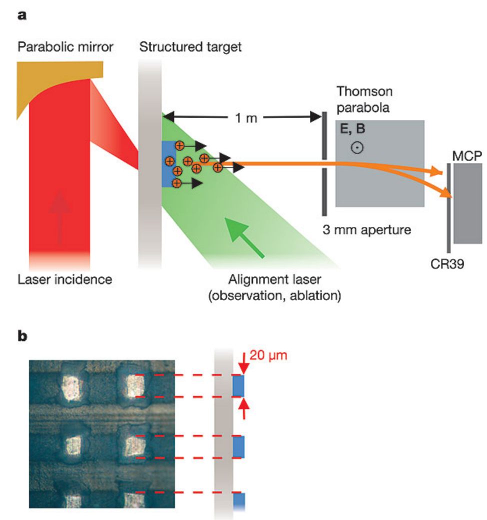
Many other methods are in the play for advanced accelerator methods:

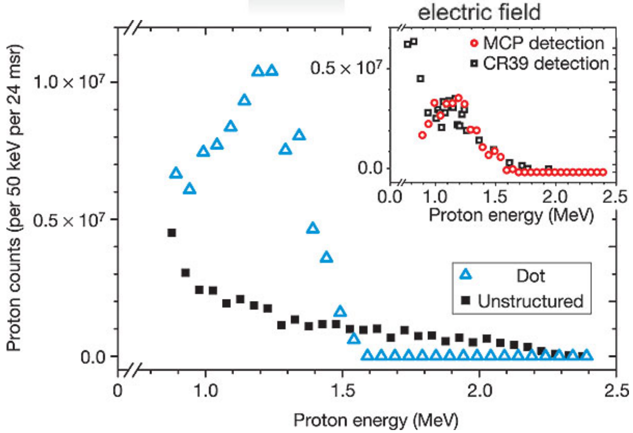
dialectic slabs/waveguides
photonic band-gap accelerator structures

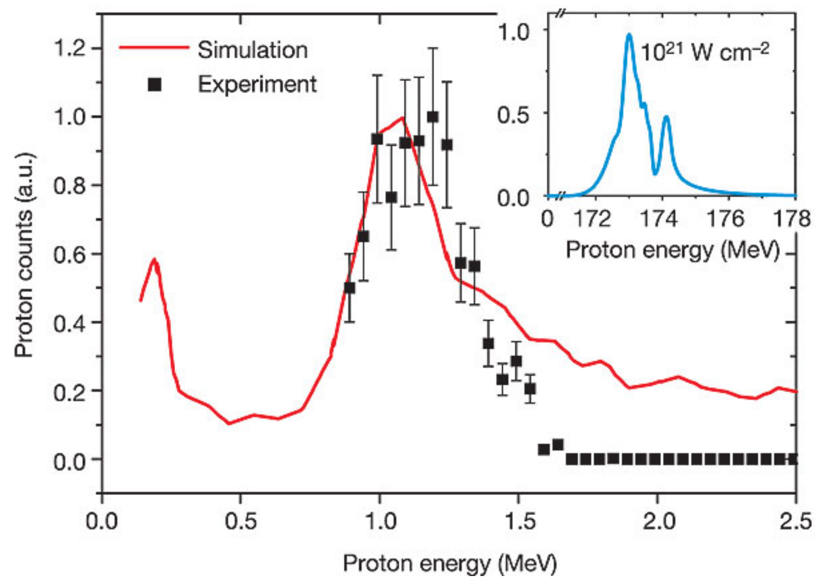
<u>including accelerating hadrons</u>

Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets





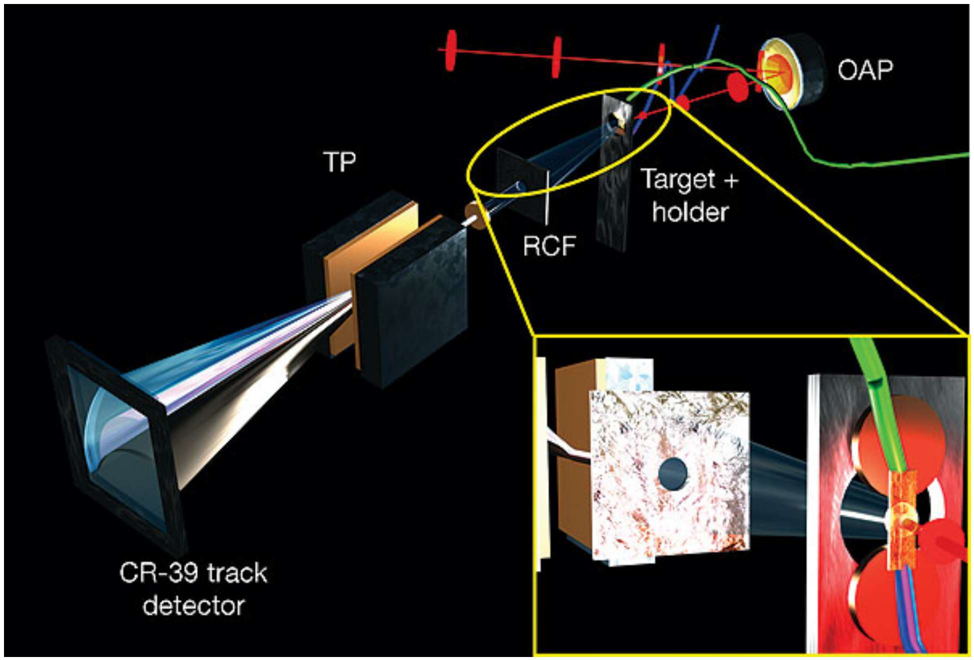


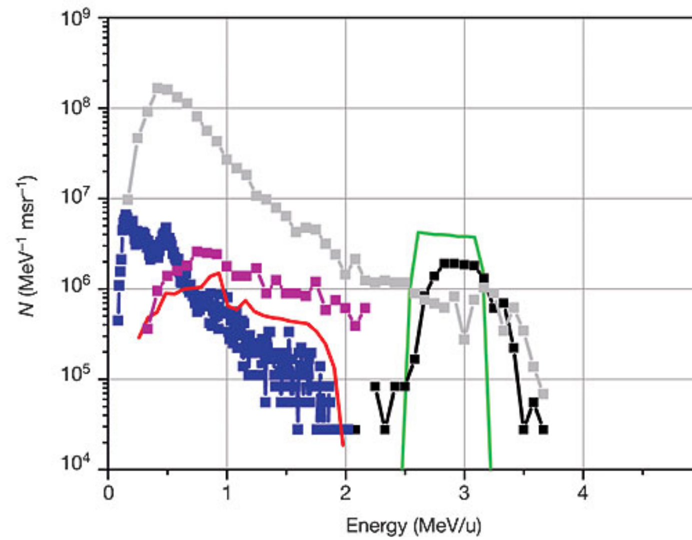


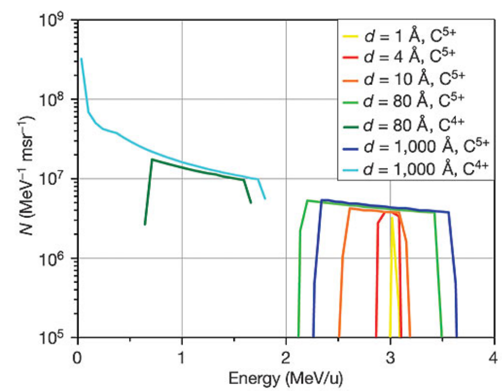
target normal sheath acceleration—TNSA

Nature 439, 2006, H. Schwoerer et al. Institut für Optik … Jena, Germany…

Laser acceleration of quasi-monoenergetic MeV ion beams



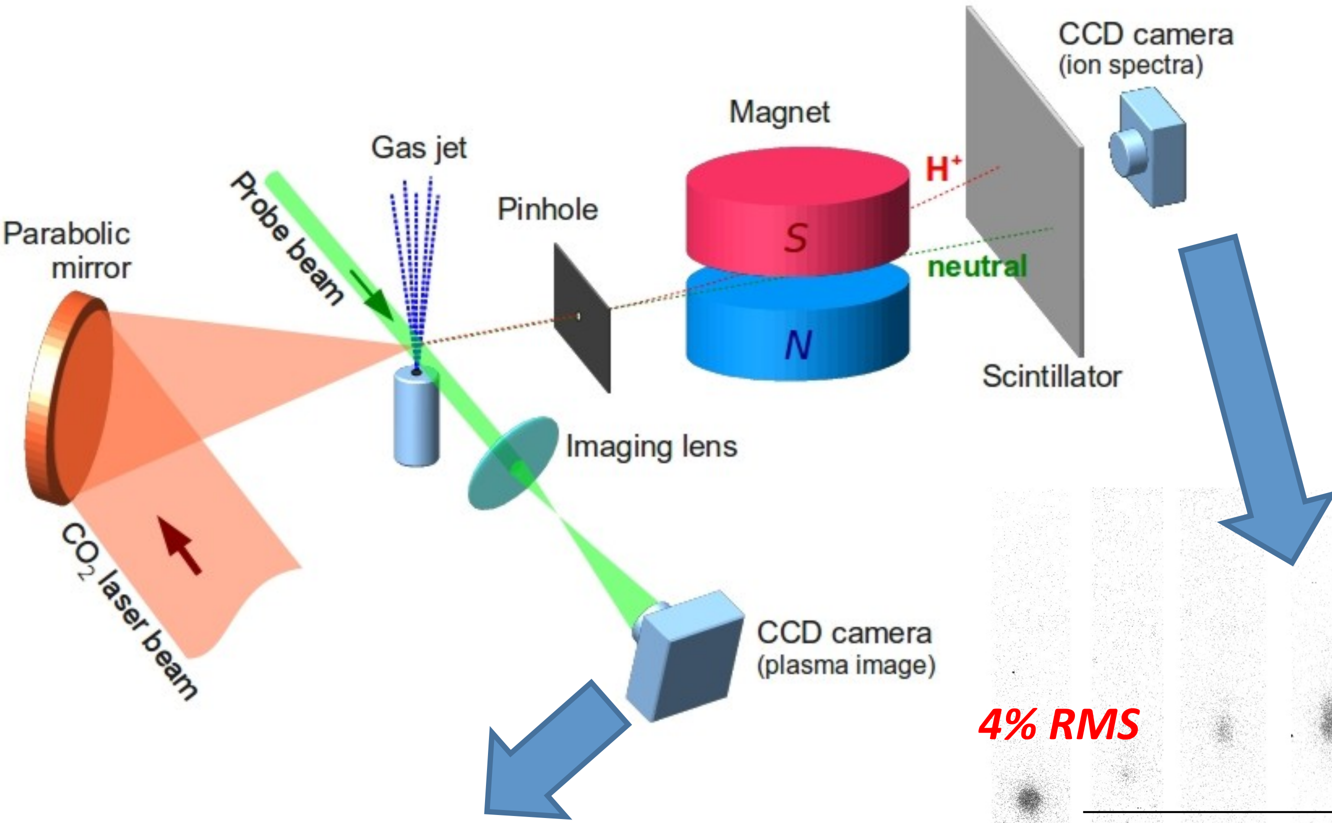


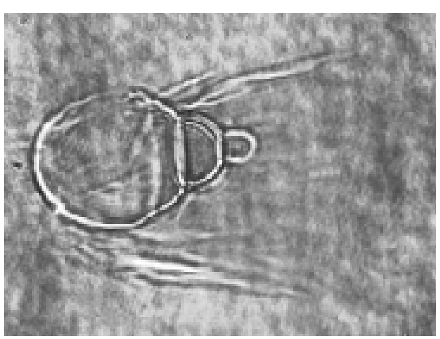


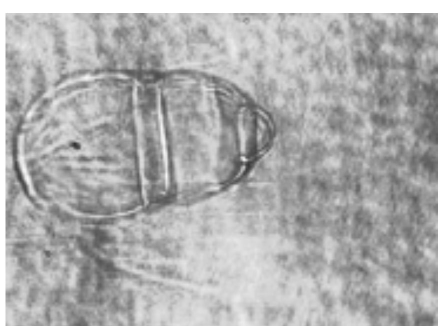
Nature 439, 2006, B. M. Hegelich et al., Los Alamos National Laboratory & Others

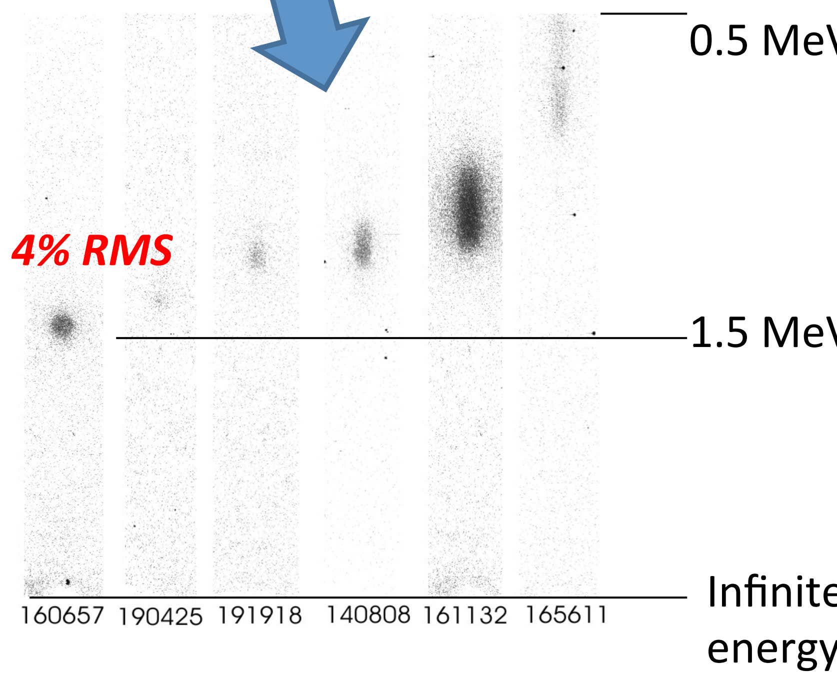
Ions Energy Scaling

Monoenrgetic ion beam by RPA





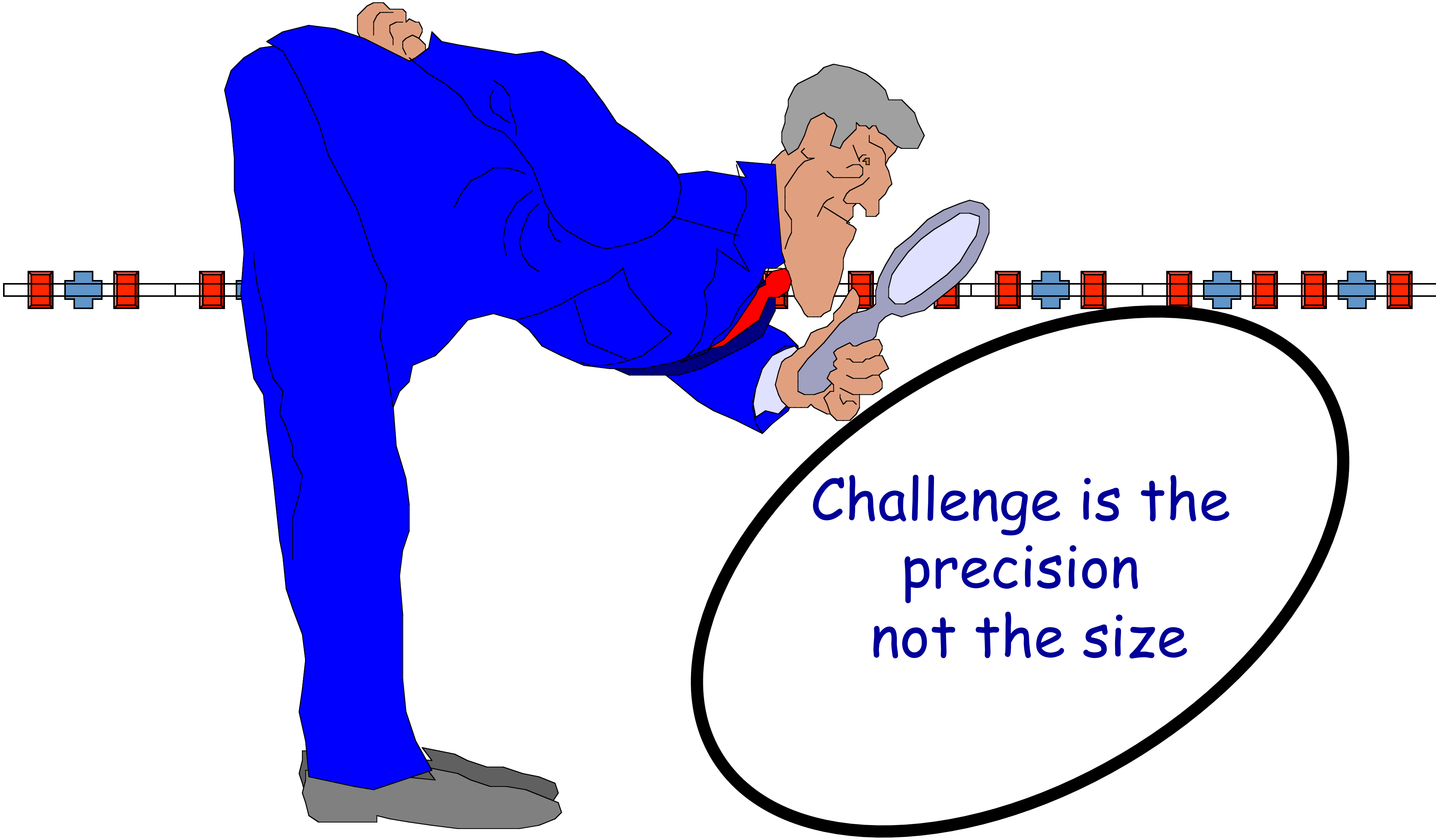




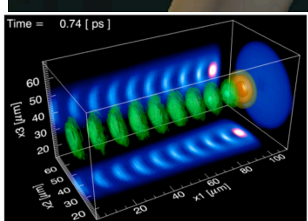
Almost any presentation is out-of-date: field is developing very fast!

There is a lot of promise…

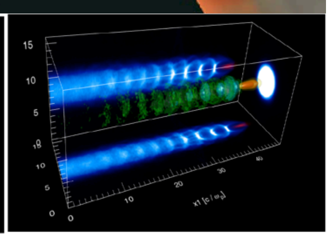
What are the challenges?


Challenge is the precision not the size

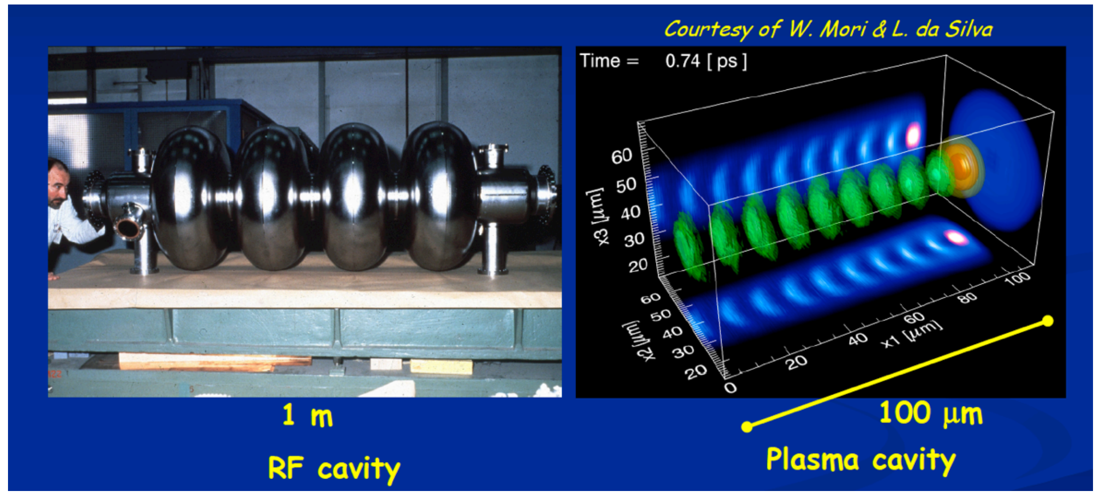
New scale *requires not only physicists but **engineers** with the skills and knowledge for handling the much more delicate, and likely virtual "nuts and bolts" of future accelerators*

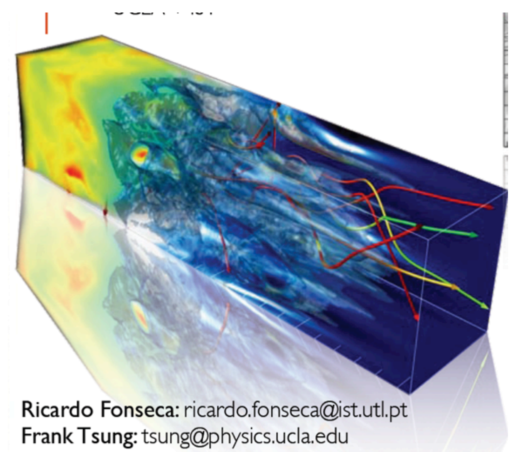


Laser Wake



Electron beam Wake



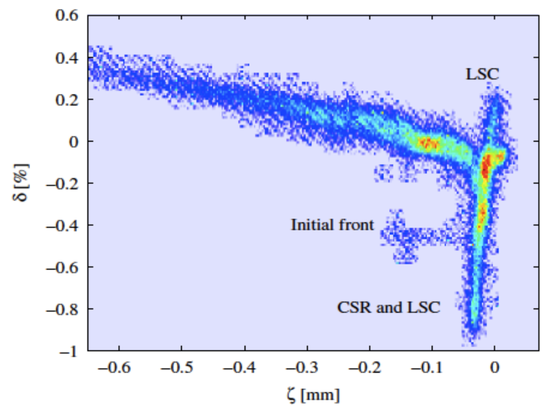


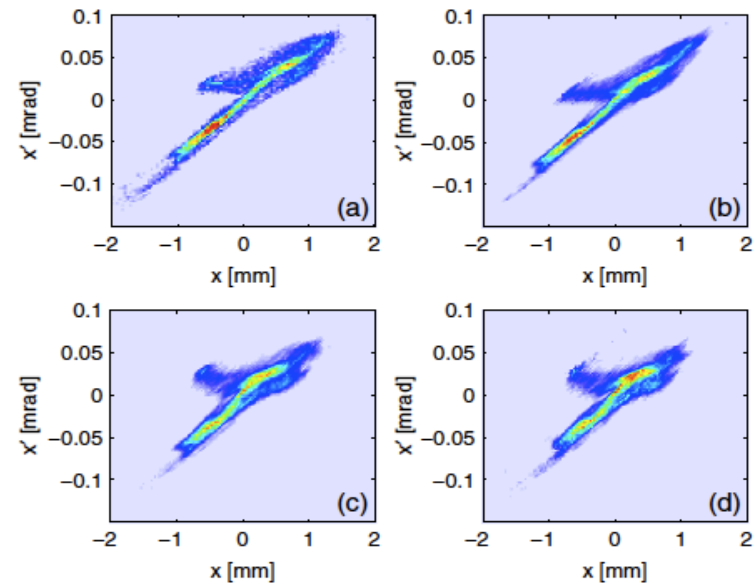
Challenges of new acceleration methods .. contunued

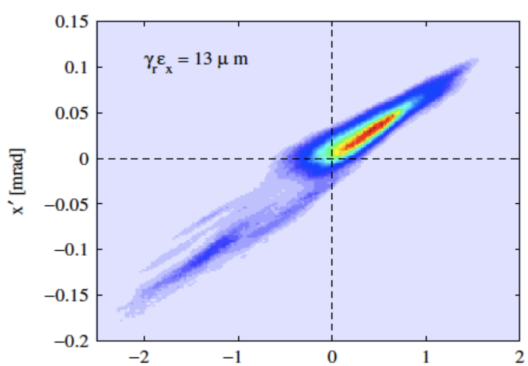
- High accelerating gradient – looks very good …
- Repeatability from shot to shot
  - Beam parameters…..
  - Direction…
  - Rebuilding the target…
- Good beam quality…
  - No '
- Staging

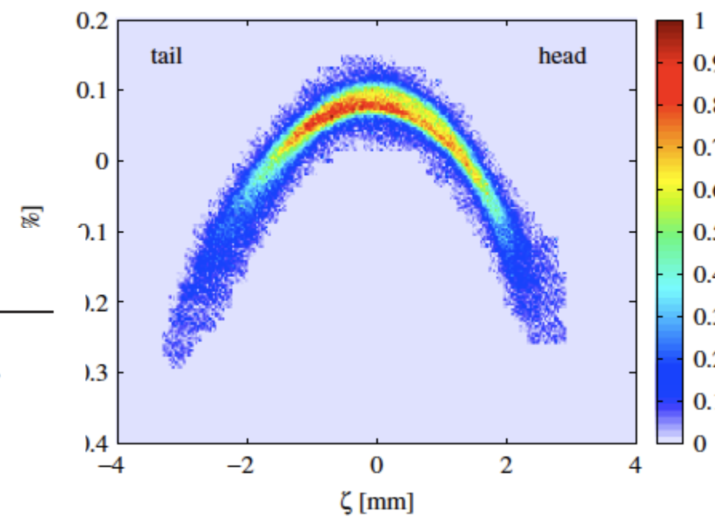
Most Importantly: we need to quantify these beams

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









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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

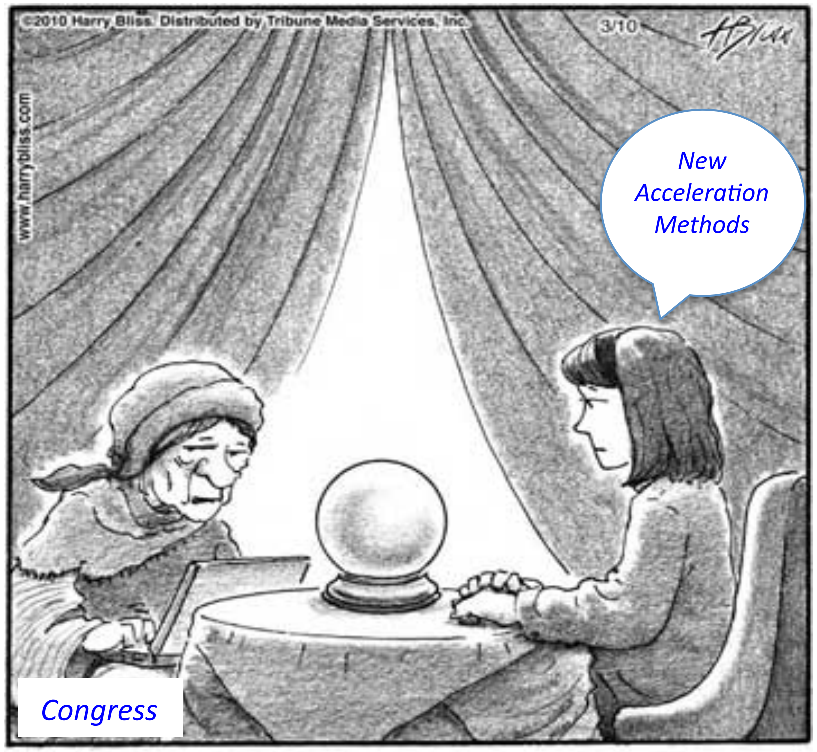
Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany

(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."