Acceleration of particles in plasmas

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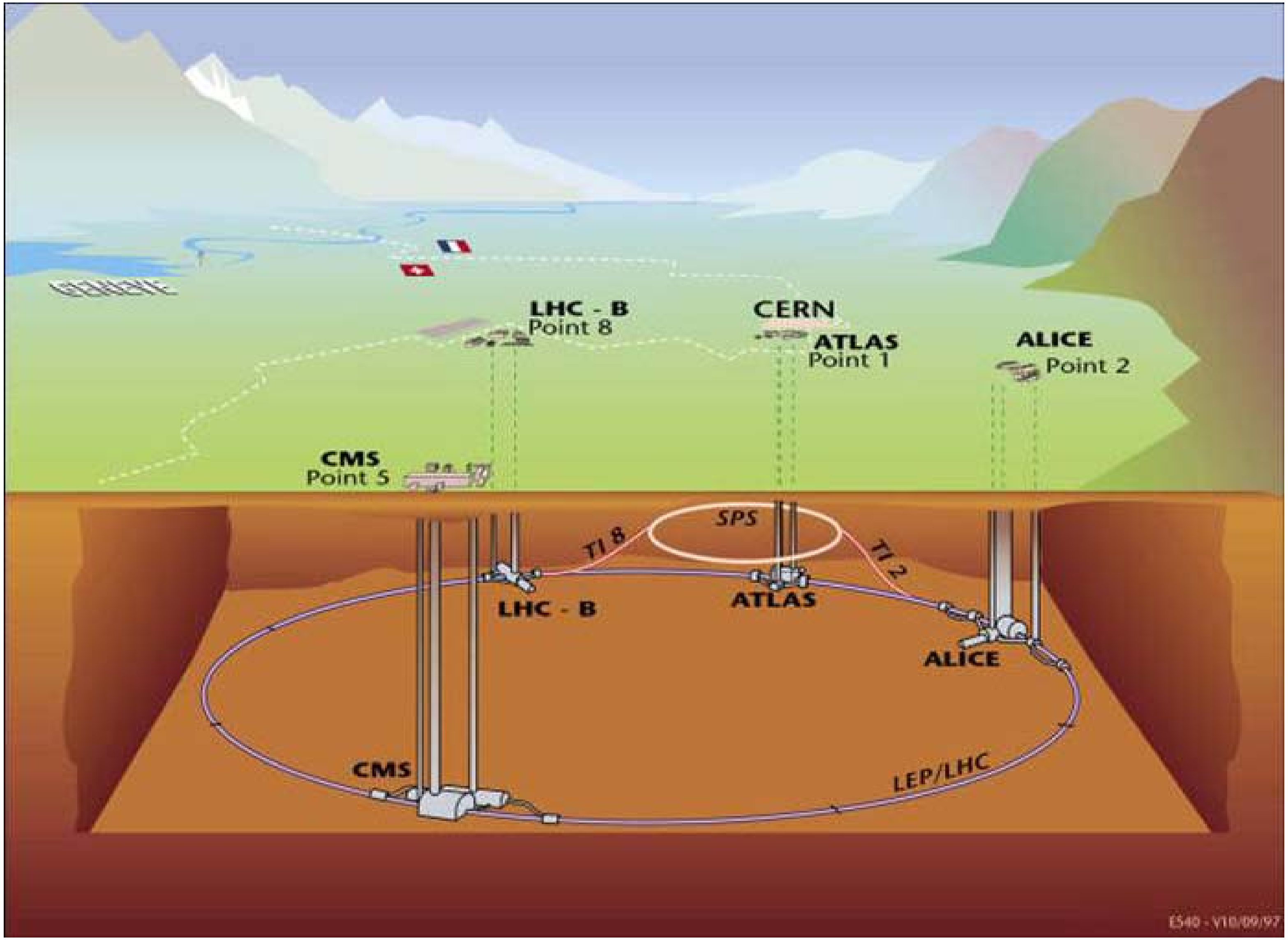
LOA

Outline of class

- Introduction to the subject (1st class)
- Excitation of plasma wakefields: a fluid model (1st and 2nd)
- Acceleration of particles in plasma waves (2nd)
- Injection of particles in plasma waves (3 rd)
- Nonlinear effects: the action of the plasma on the driver (3rd and 4th)
- Numerical methods (4th)
- State of the art of experiments and perspectives (5th)

Why alternative techniques ?



Why alternative techniques ?

- RF technology: it works, high performance, very robust…

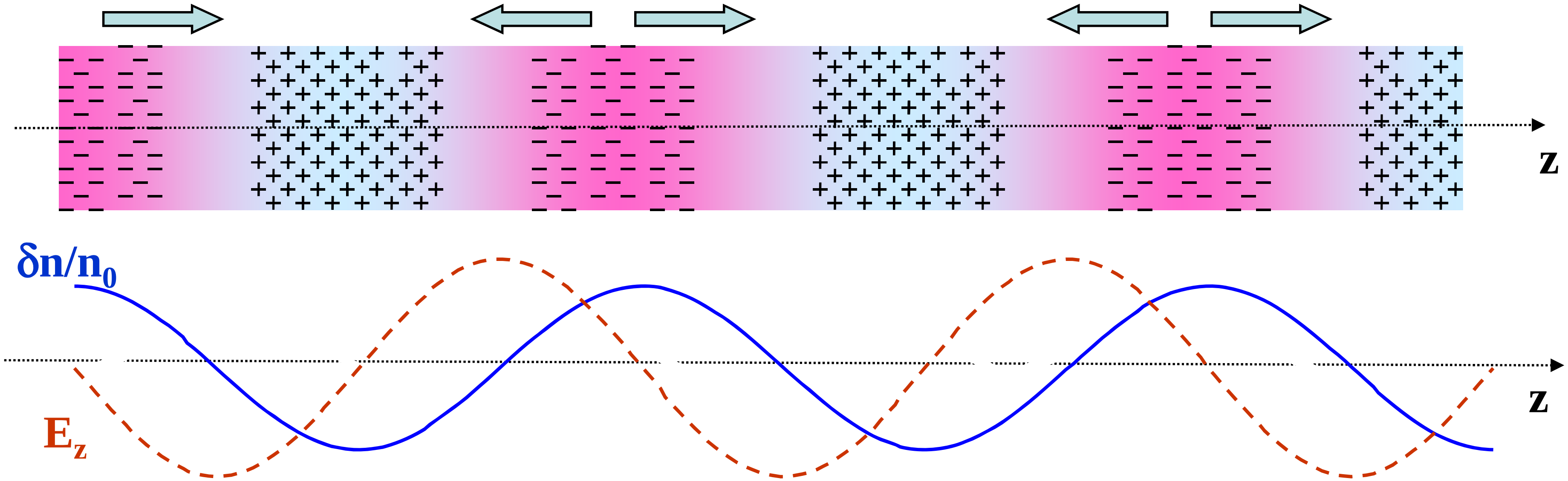
BUT

- Large size and cost of accelerators for High Energy Physics:
  - Limited accelerating gradients due to damage of RF structures at E_z<100 MV/m
  - Synchrotron radiation for electrons and positrons (LEP)
  - Example: ILC: 250 GeV electrons and positrons (2*11 km)

→ Initial motivation of plasma acceleration: find a technology that can produce *compact accelerators*

Plasmas as accelerating media

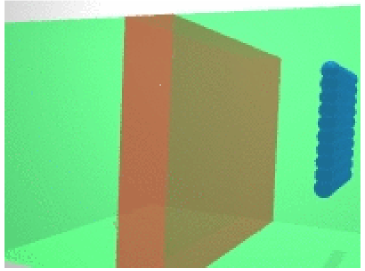
A plasma: collection of free electrons and ions: already ionized



$$E_z \approx 300 \ \ GV/m \qquad \text{(for } n_e = 10^{19}\ cm^{-3}\text{)}$$

E_Z is 10^4 greater. Can we make an accelerator 10^4 smaller (10 km → 1 m) ?

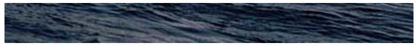
(Very) Basic plasma physics



- Natural plasma oscillation: plasma frequency : $\omega_p = (n_e e^2 / m \varepsilon_0)^{1/2}$

- Plasma wavelength: $\lambda_p = 2\pi c/\omega_p$. $\lambda_p = 10$ µm for $n_e = 5\times10^{18}$ cm^{-3} (compare with RF wavelength)

- Maximum electric field supported by a plasma: the wavebreaking field $E_z = m_e c\omega_p / e \sim n_e^{1/2}$ (for example $E_z = 300$ GV/m for $n_e = 10^{19}$ cm^{-3})



- Dispersion relation for a transverse EM wave (ω, k) :

$\omega^2 = \omega_p^2 + k c^2$

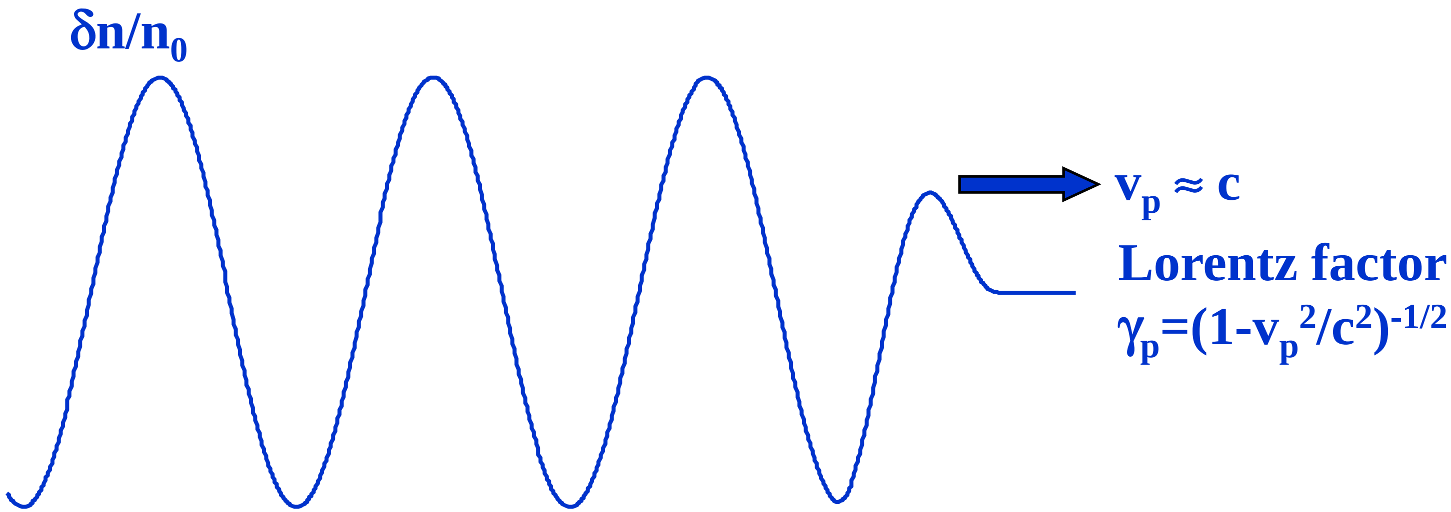
➡ Propagation possible only si $\omega > \omega_p$: the plasma is underdense ($n < 10^{21}$ cm^{-3} for $\lambda = 1$ µm). In most experiments, $n_e = 10^{18}$-10^{19} cm^{-3}

Relativistic plasma waves

- Dispersion relation for a longitudinal wave, also called Langmuir waves or plasma waves: $\omega_{pe}^2 = \omega_p^2 + 3k_p^2 v_{th}^2$
- Consider a cold plasma: v_{th}=0 and the dispersion relation for a plasma wave in a cold plasma is $\mathbf{k_p = \omega_p / v_p}$
- A plasma wave: a travelling electrostatic field

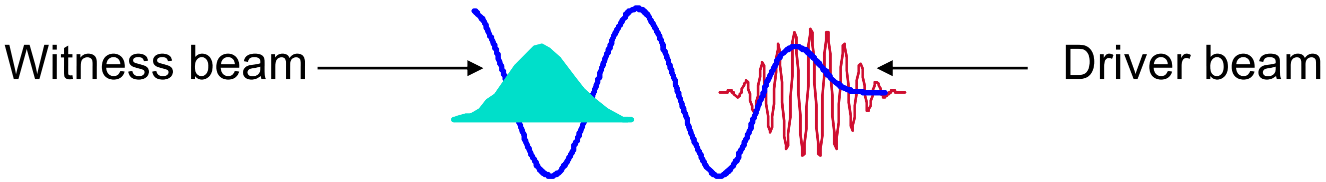
$$\delta n = \delta n_0 \exp\left[-i(\mathbf{k_p} \cdot \mathbf{r} - \omega_{pe} t)\right]$$

- Relativistic plasma wave: a wave with v_p close to c

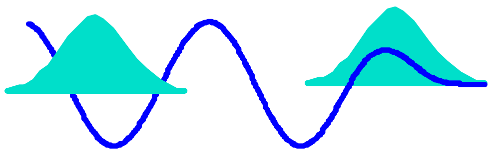


WAKEFIELDS

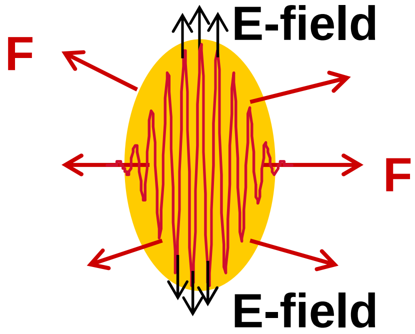
- Laser driver: an ultra-intense and ultra-short laser pulse

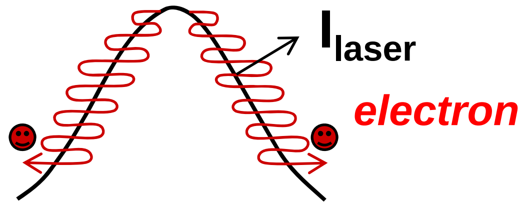


- Beam driver: an ultra-intense and ultrashort beam of particles

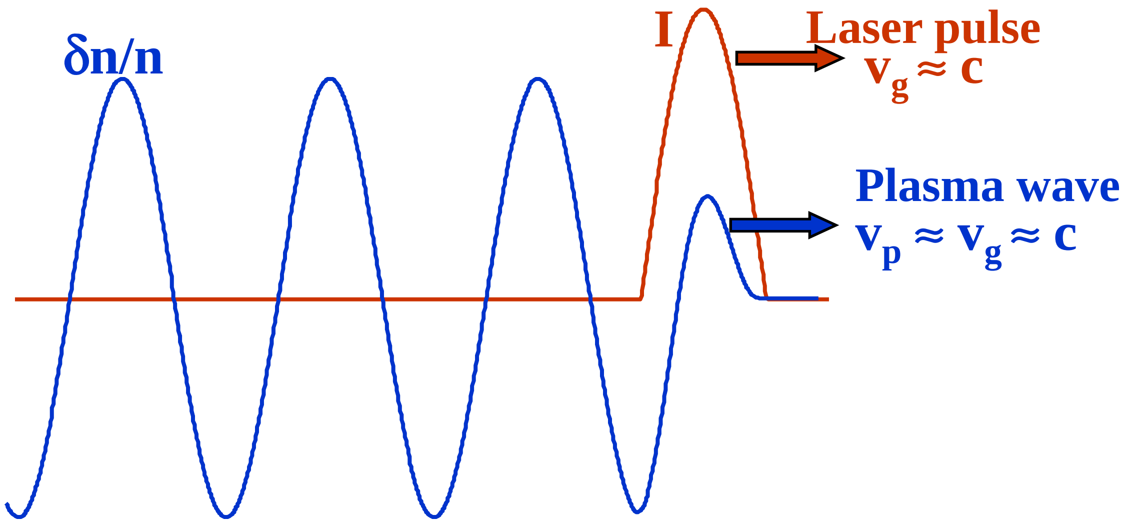


Laser driver (LFWA): ponderomotive force





- Ponderomotive force: pushes electrons outward at high laser intensities ($I > 10^{18}$ W/cm^2) $F_p \sim -\mathrm{d}\, I_{laser}$



1D picture

- Wakefield excitation is effective at resonance: $\tau_0 c \sim \lambda_p$

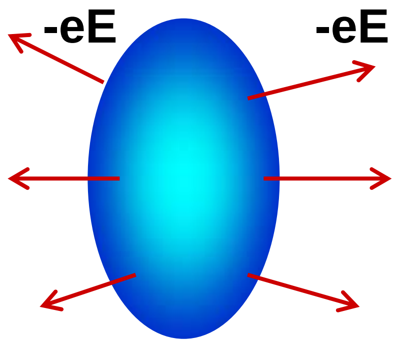
→ Short pulses are required ($\tau_0 < 100$ fs)

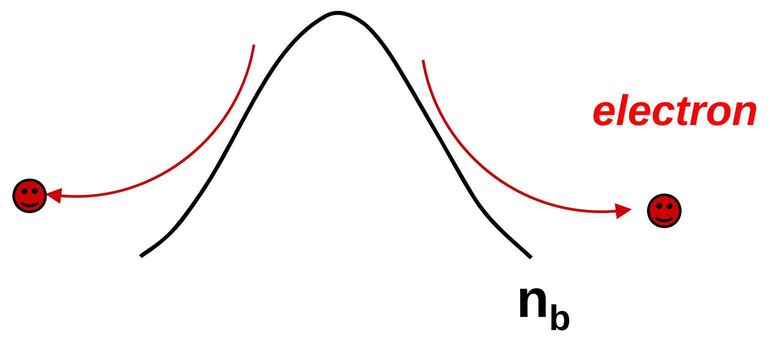
Beam driver (PWFA): Coulomb force

- The coulomb force pushes electrons outward

$$\frac{dp}{dt} = -eE$$

$$\nabla E = -\frac{en_b}{\varepsilon_0}$$

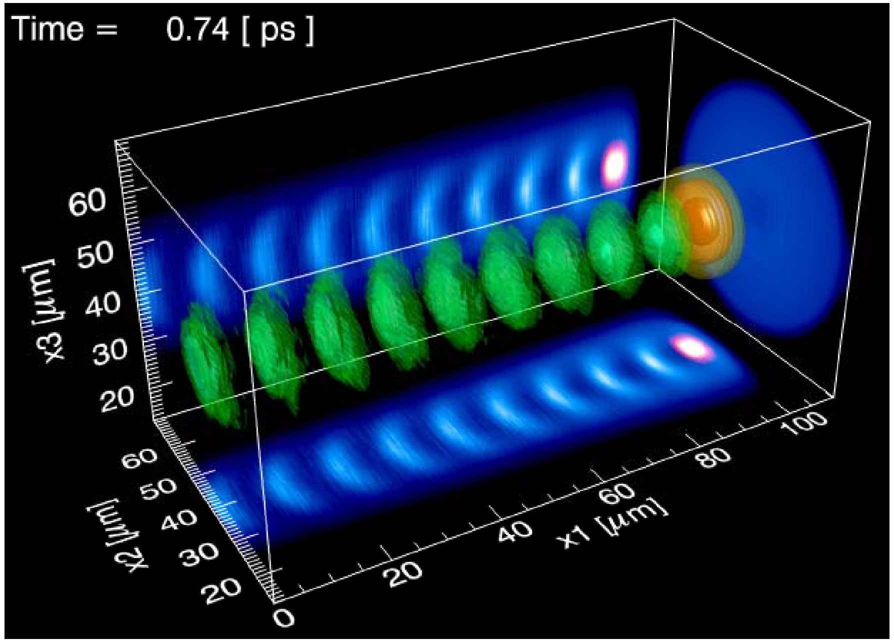


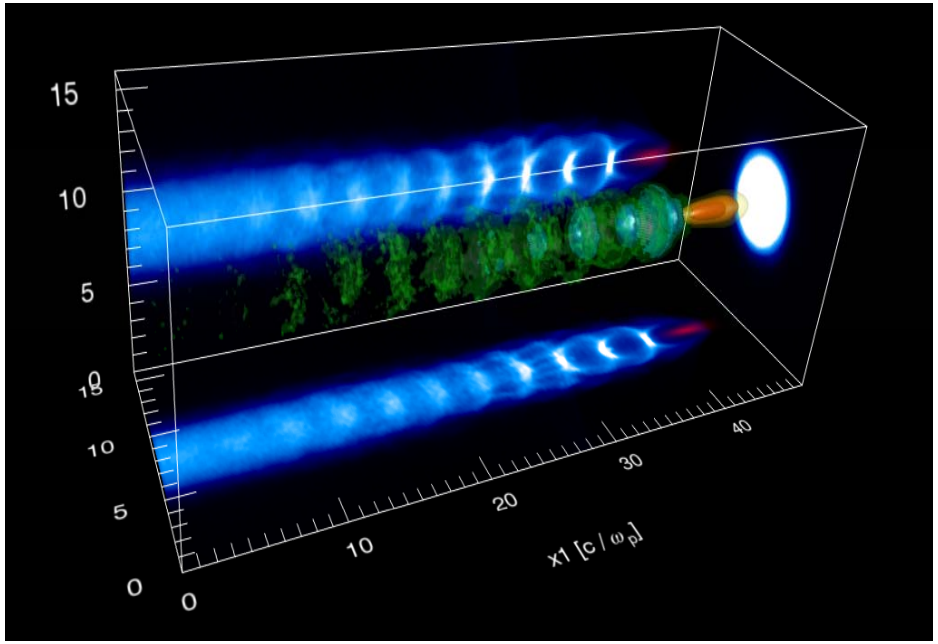


- Similar conclusion: needs an intense beam , $n_b > n_0$
- Ultrashort beam for resonance of wakefield excitation: $\tau_0 c \sim \lambda_p$

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

3-D PIC OSIRIS Simulation





Laser Wake

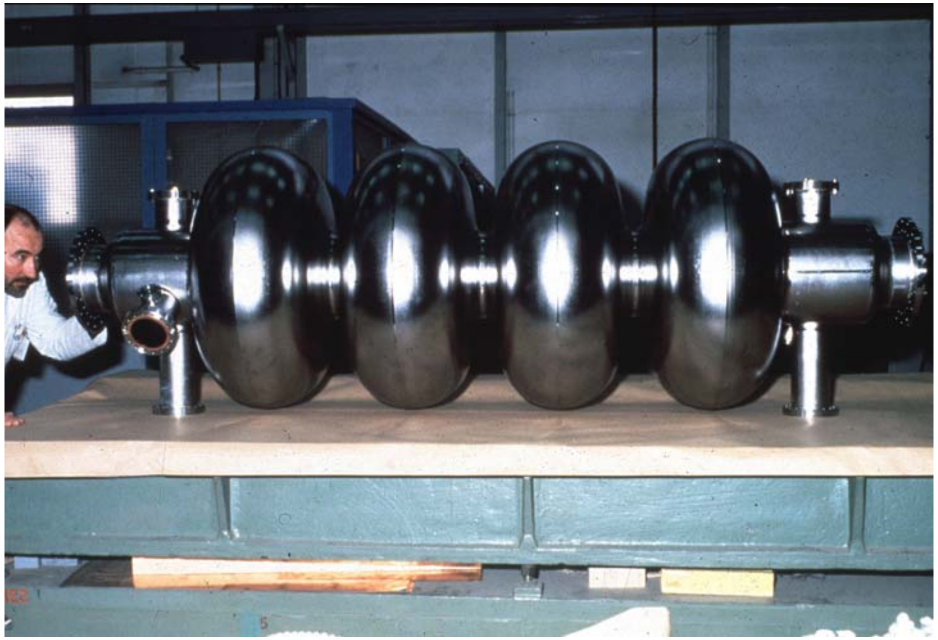
Electron beam Wake

UNIVERSITY OF SOUTHERN CALIFORNIA

UCLA

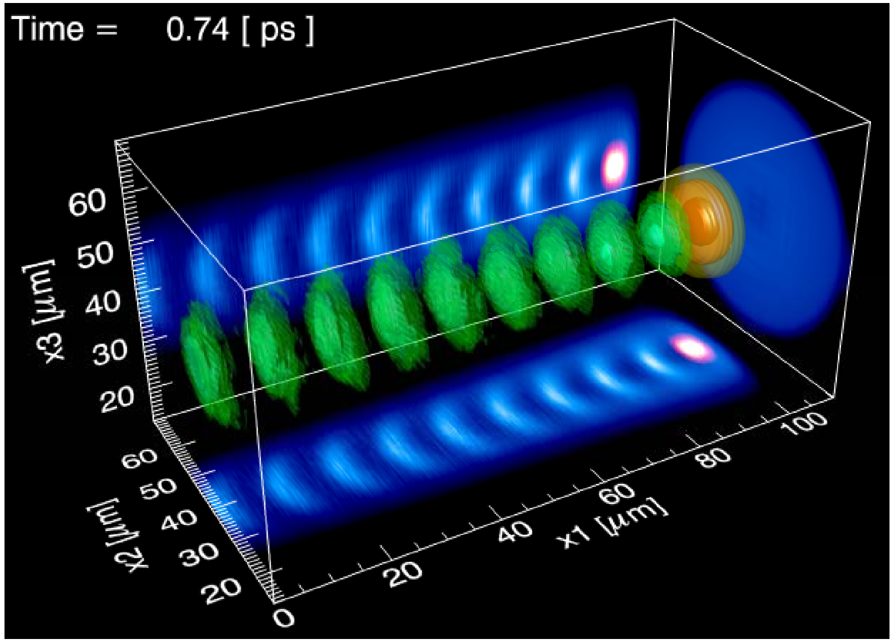
Wakefields as plasma cavities

RF cavity: 1 m



E_z = 10-100 MV/m

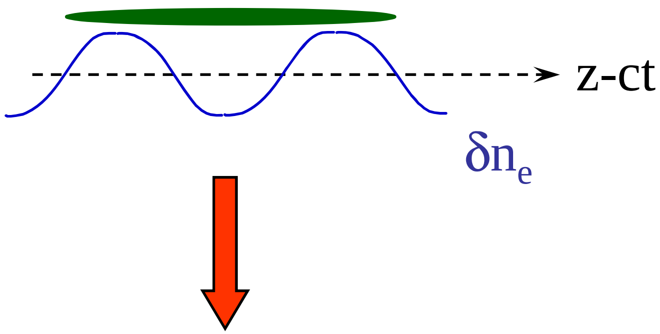
Plasma wave: 100 µm



E_z = 10-100 GV/m

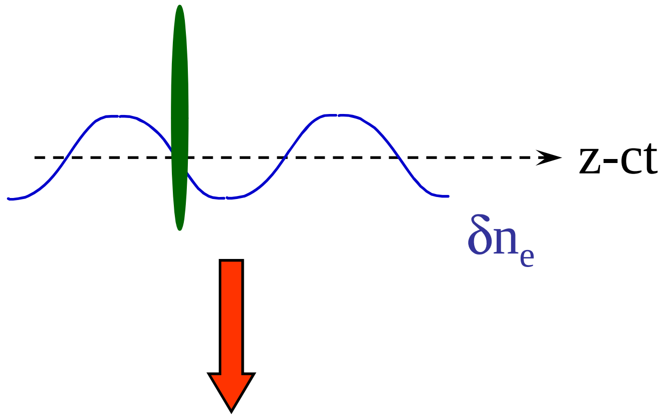
Injecting electrons in plasma wakefields

$L_{bunch} > \lambda_p$



Different phases
Different electric fields
100 % energy spread

$L_{bunch} < \lambda_p$



Electrons « in phase »
Monoenergetic acceleration

Requires L_{bunch} < 100 fs
Challenge for RF technology

→ Need to find ways to inject sub-100 fs electron bunches

Brief History of the field

- 1979: T. Tajima & J. Dawson; « Laser Electron Accelerator », PRL
- 1980's: generation and measurement of relativistic plasma waves (UCLA) using long laser pulses.
- 1980-90: External Injection of particles into plasma waves (USA, UCLA. France, LULI, Japan). Gain of a few MeV's. Broad energy distribution.
- Mid 1990's: advent of short pulse lasers (500 fs – 1 ps)
- 1995: first e-beam (England: RAL, IC. USA: University of Michigan). Broad energy distribution

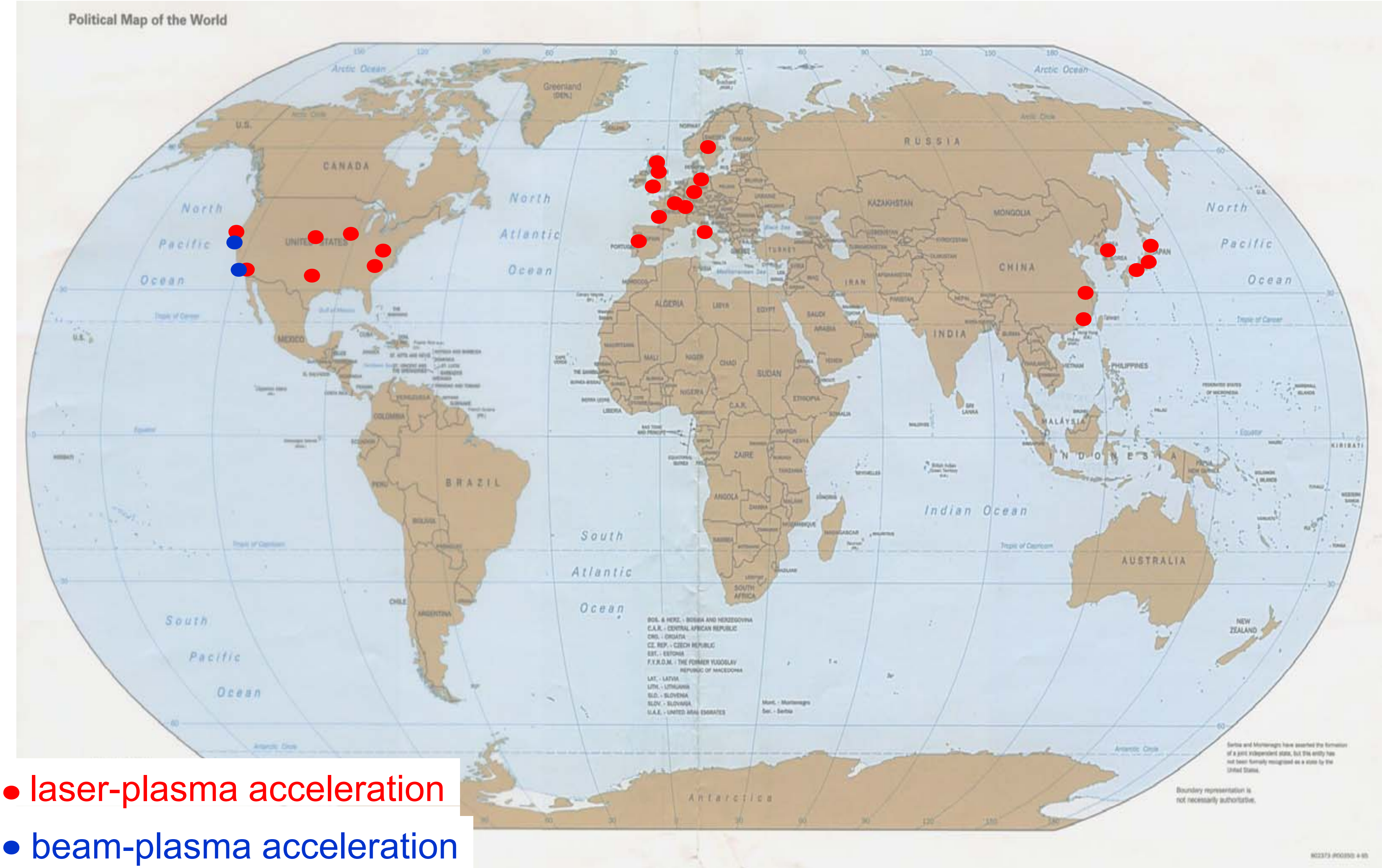
Laser driver (ultrashort: 30-50 fs)

- 2004: first monoenergetic beams
  100 MeV level in mm scale
- 2006: 1 GeV e-beam in cm scale
  (USA, Berkeley)
  controlled optical injection,
  stable, tuneable e-beams
  (France, LOA)

Electron beam driver

2000-2006
Experiments at SLAC (UCLA, USC)
2006: energy doubling of SLAC
Electron beam.
42 GeV → 80 GeV in 0.8 m

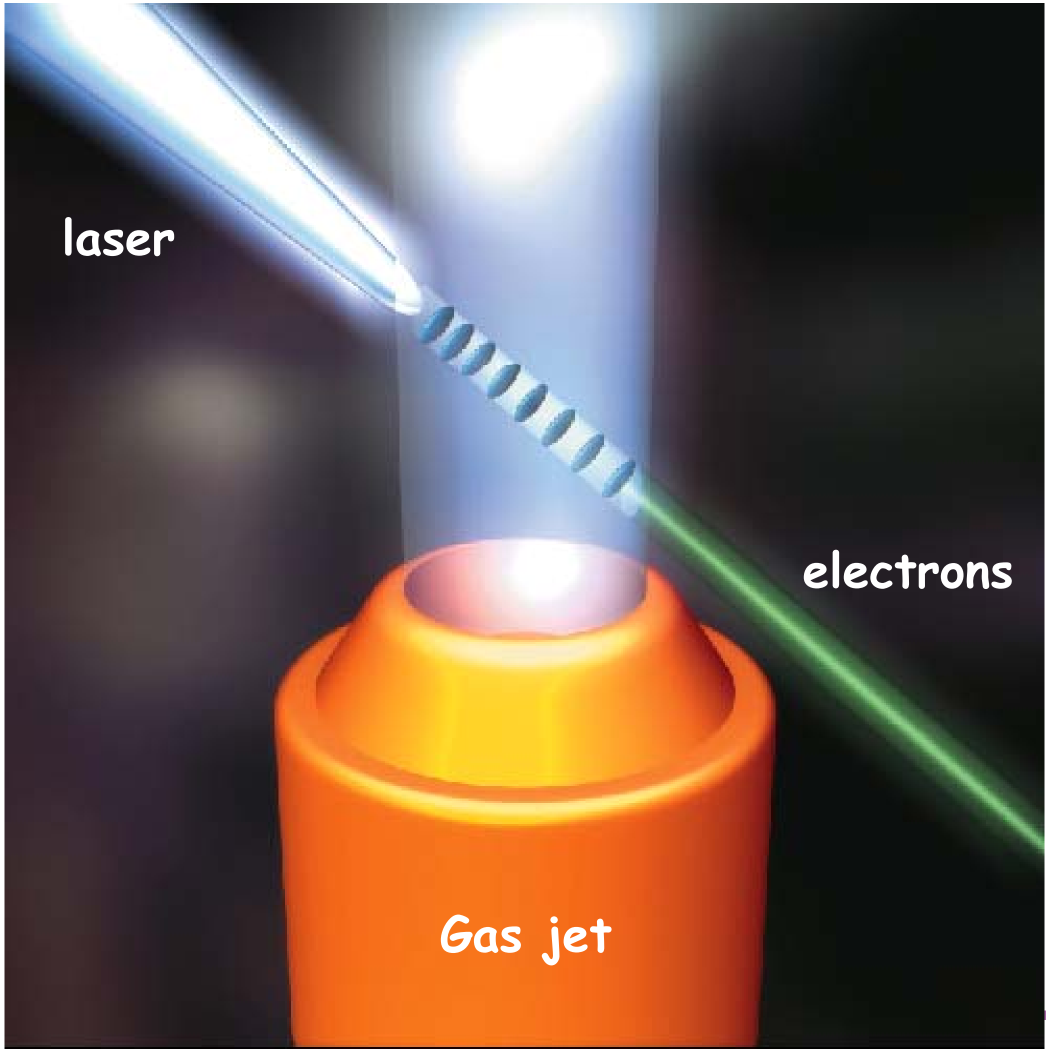
Laboratories in the world

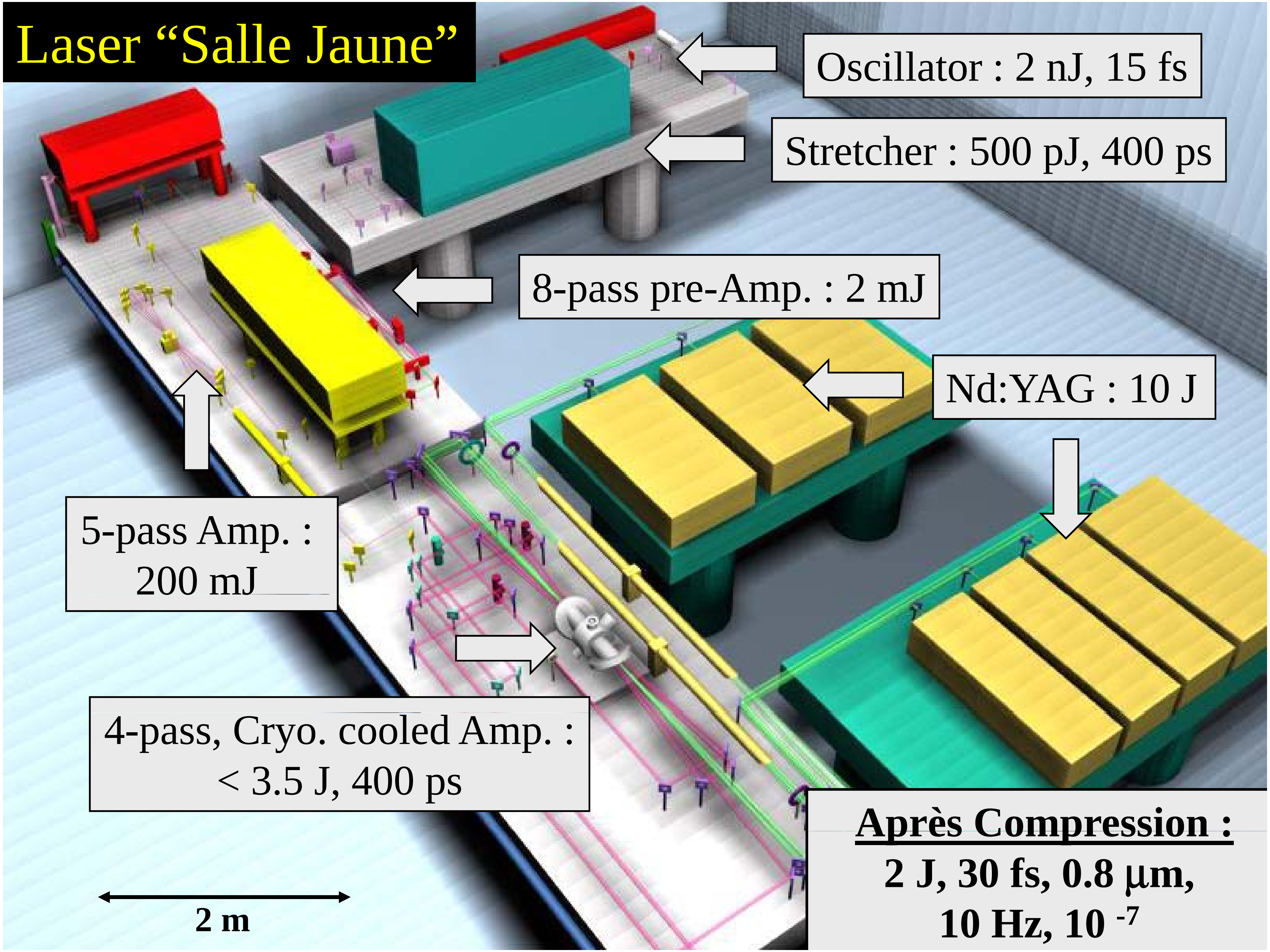


- laser-plasma acceleration
- beam-plasma acceleration

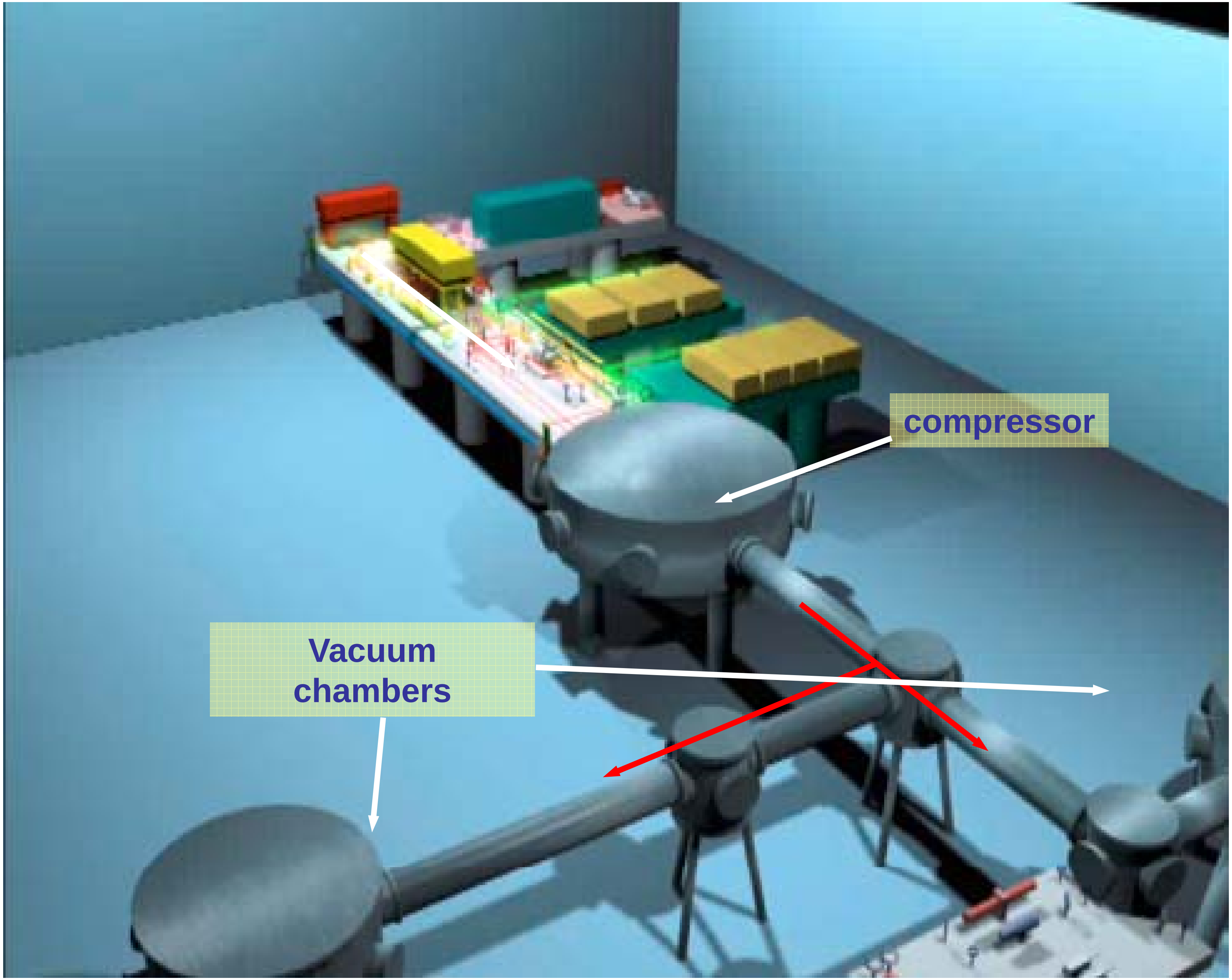
State of the art of LWFA

- Scale: 100 MeV in mm scale

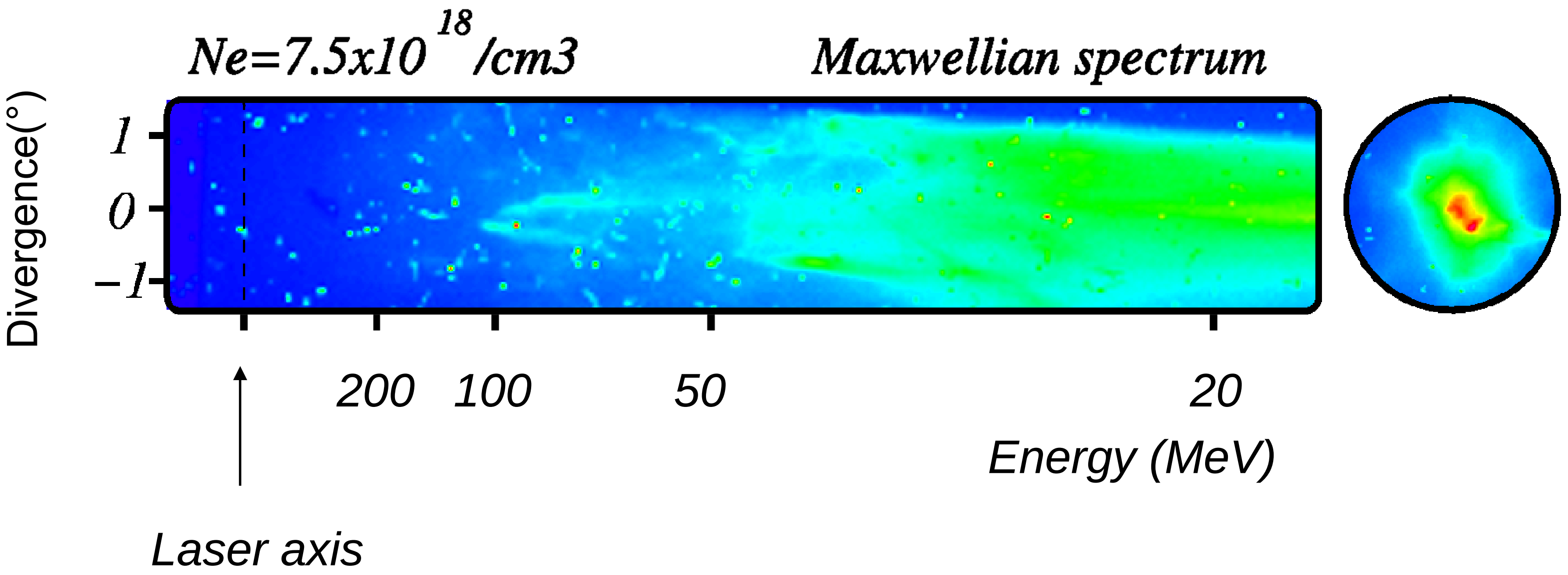




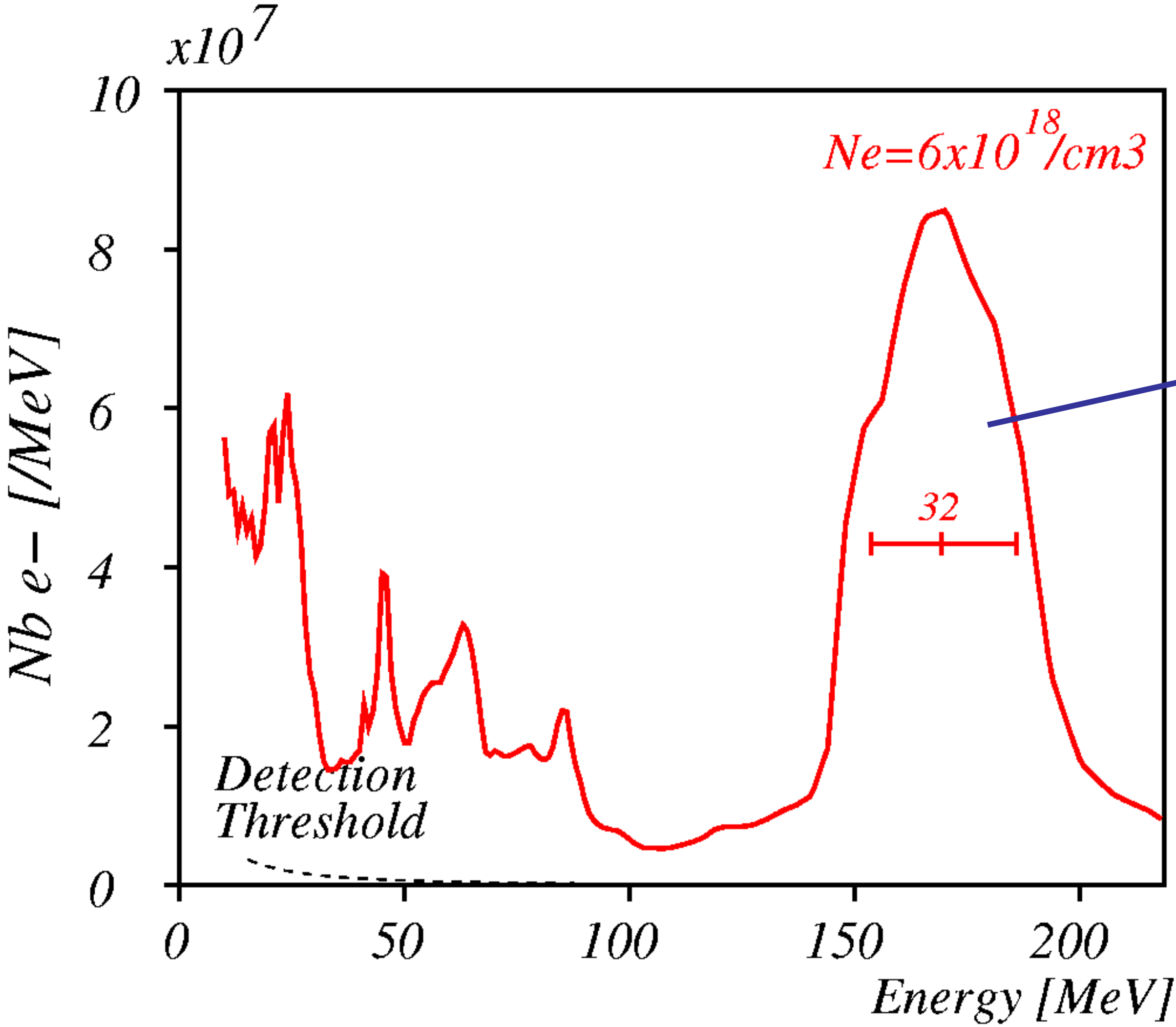
Laser "Salle Jaune"
Oscillator : 2 nJ, 15 fs
Stretcher : 500 pJ, 400 ps
8-pass pre-Amp. : 2 mJ
Nd:YAG : 10 J
5-pass Amp. : 200 mJ
4-pass, Cryo. cooled Amp. : < 3.5 J, 400 ps
Après Compression :
2 J, 30 fs, 0.8 µm, 10 Hz, 10 -7
2 m


compressor
Vacuum chambers

LWA: quasi-monoenergetic beams



Quasi-monoenergetic spectrum



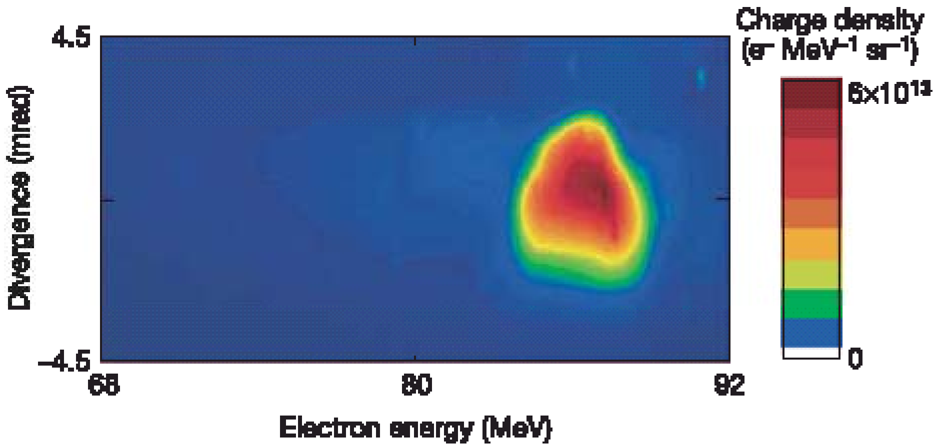
500 pC +/-200 pC in the peak at 170 MeV

δE/E=20 % limited by spectrometer resolution

Lack of stability

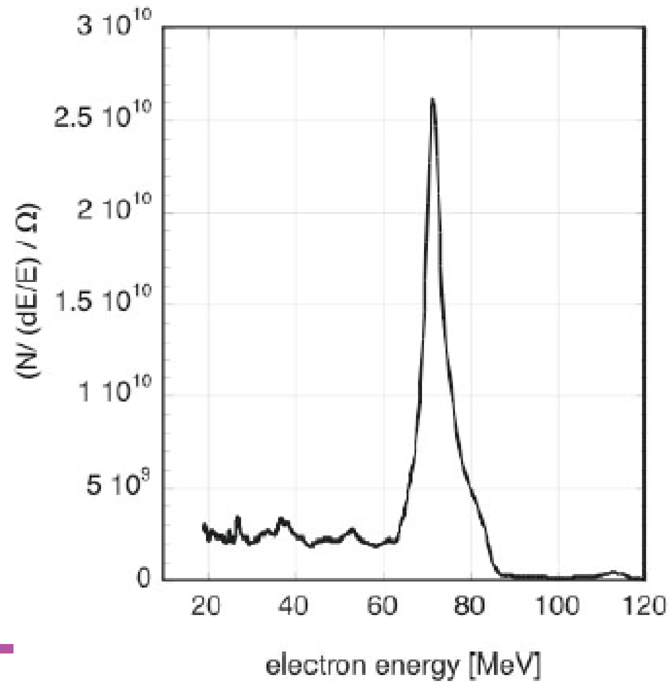
Other quasi-monoenergetic results

• Berkeley experiment:
Used plasma channel for guiding
$n_e = 2\times10^{19}$ cm^{-3}
$c\tau \sim 2.2\times\lambda_p$
85 MeV



• Imperial college \ RAL
Long Rayleigh length
$n_e = 2\times10^{19}$ cm^{-3}
$c\tau \sim 2\times\lambda_p$
75 MeV

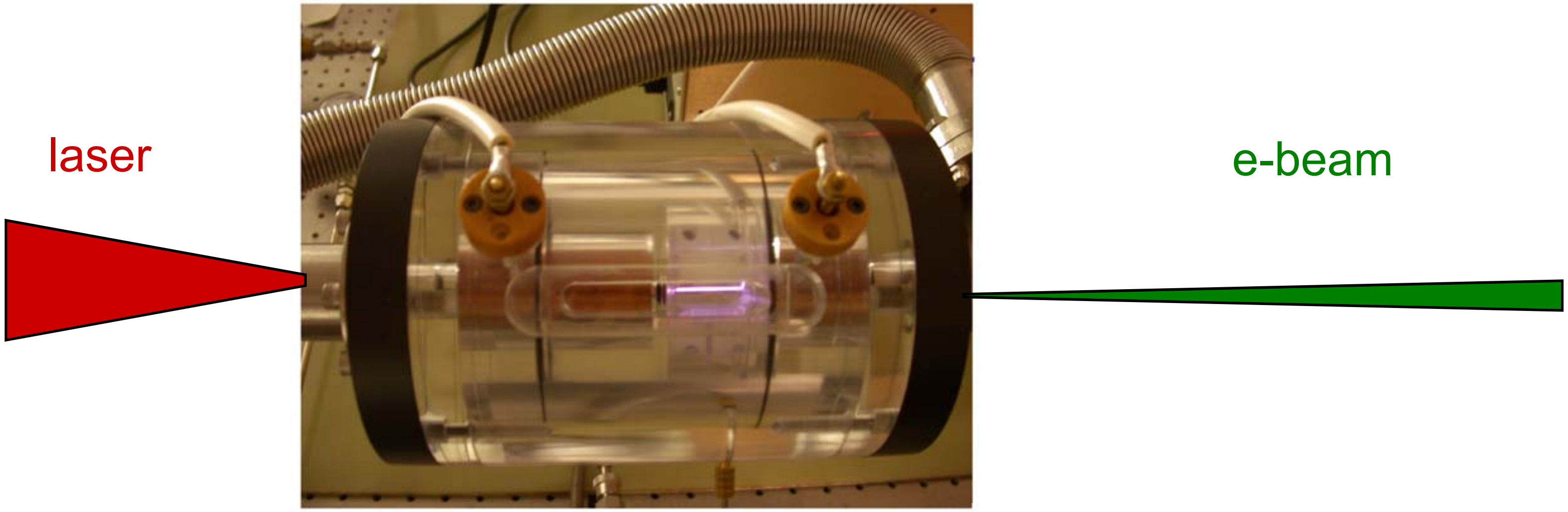
Demonstrated by ~20 groups around the world

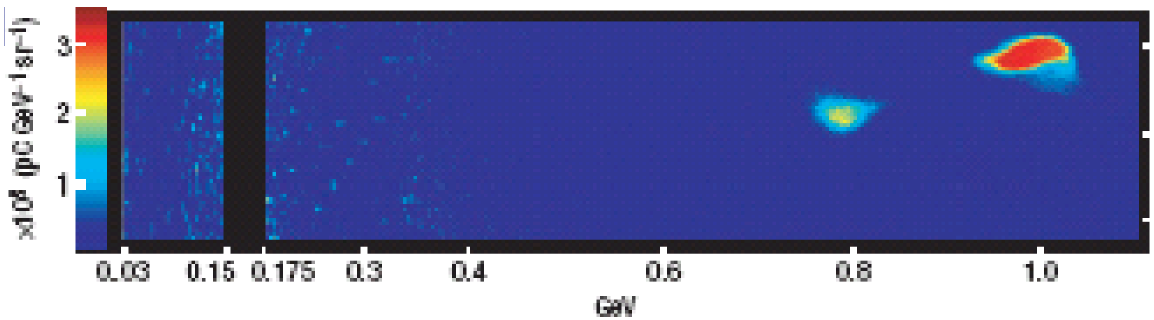


The path to higher energy

- Scale: 1 GeV in cm scale

- Berkeley experiment using plasma waveguide (Nat. Phys. 2006)



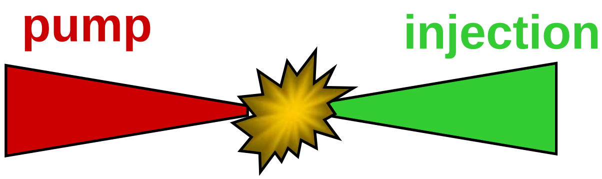


- Charge: ten's of pC
- δE/E=5 % (instrument limited)

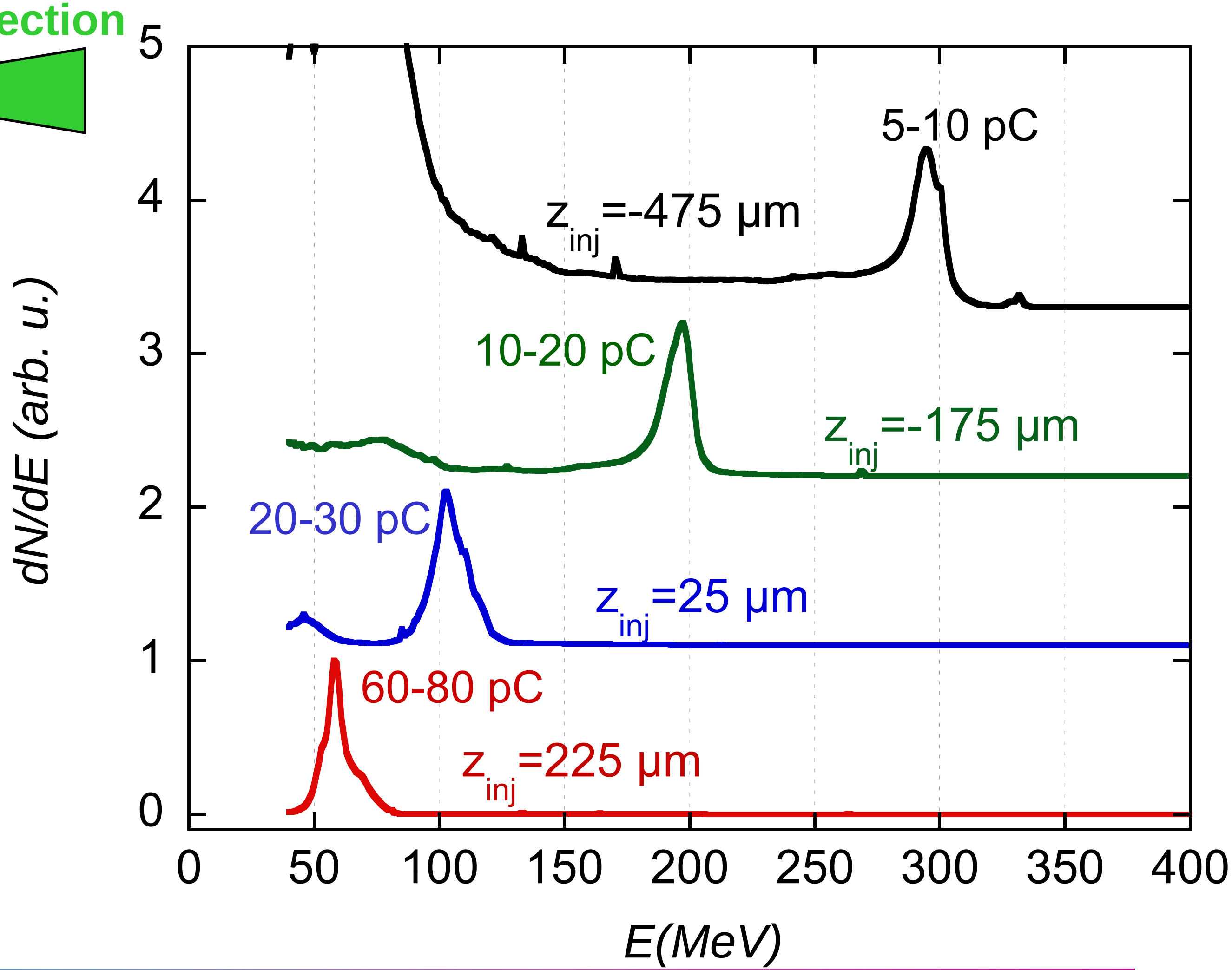
→ **Stable operation @ 450 MeV, unstable @ 1 GeV**

Increased control and stability

- Two laser pulses: 1 for *injecting* electrons, 1 for *accelerating* them



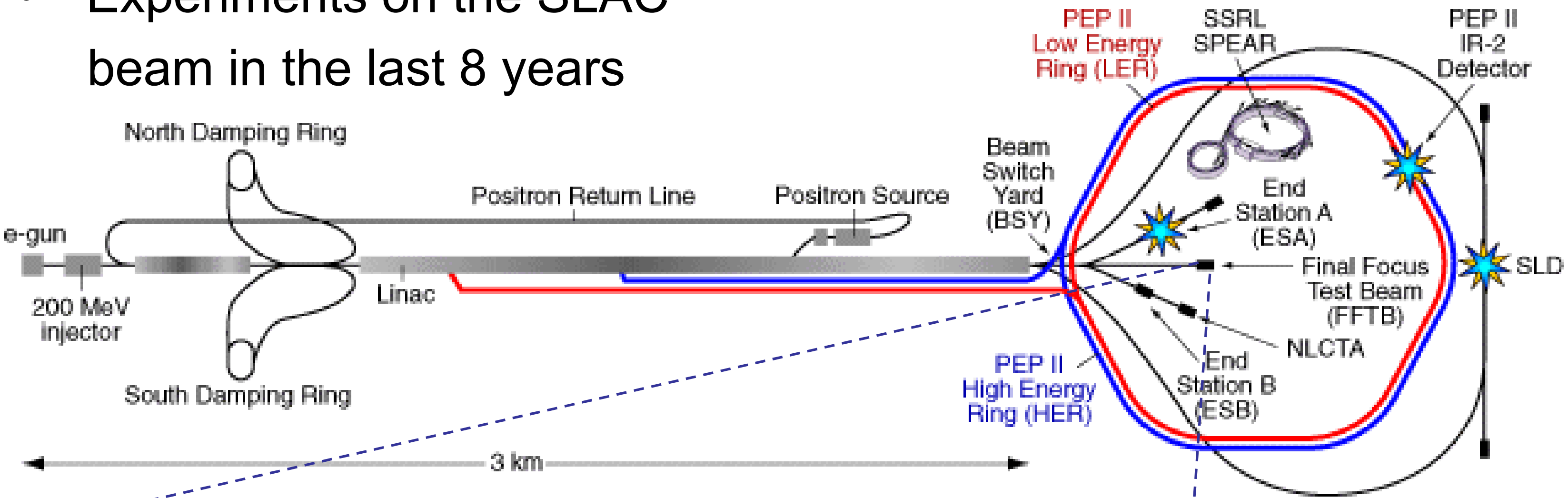
- Charge: ten's of pC
- δE/E=5 % (instrument limited)
- tuneable
- stability < 10 % rms

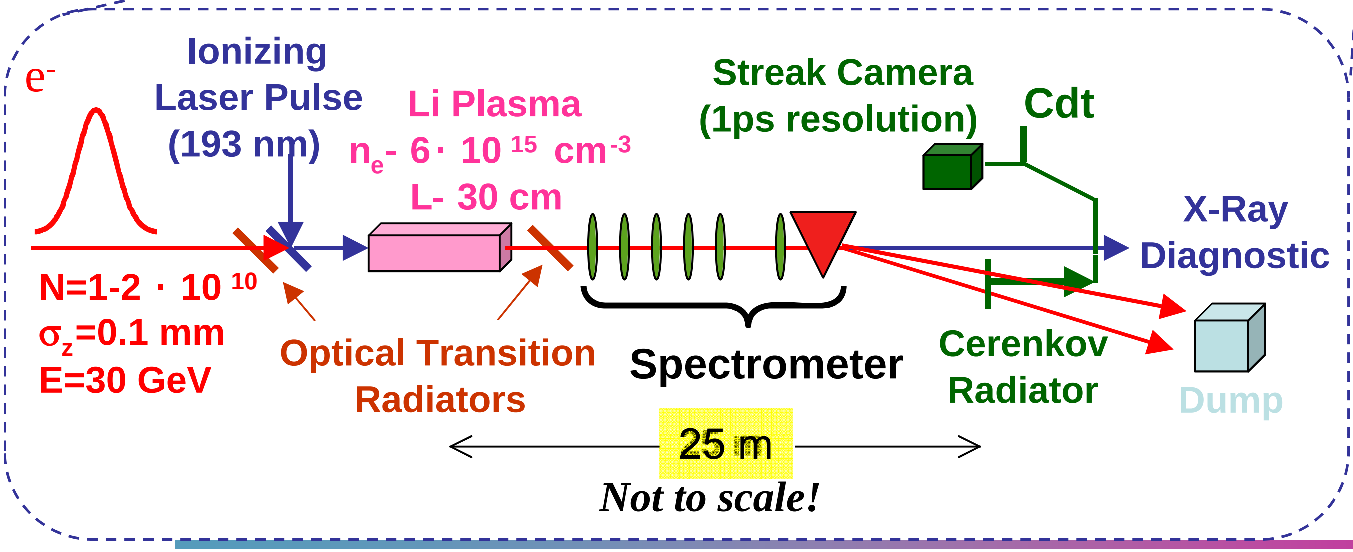


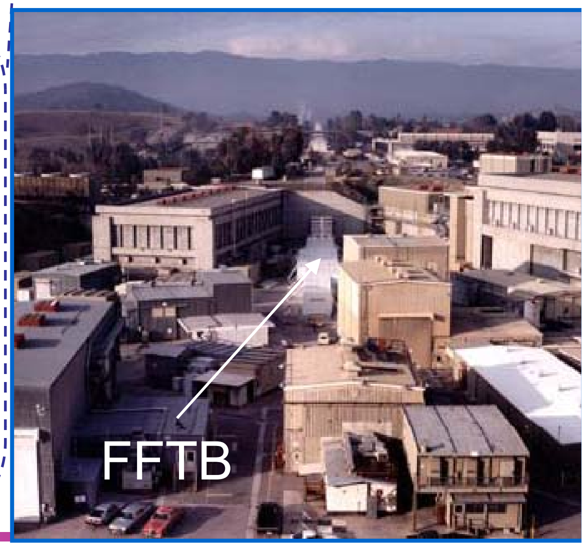
Published in Nature, December 2006

State of the art of PWFA

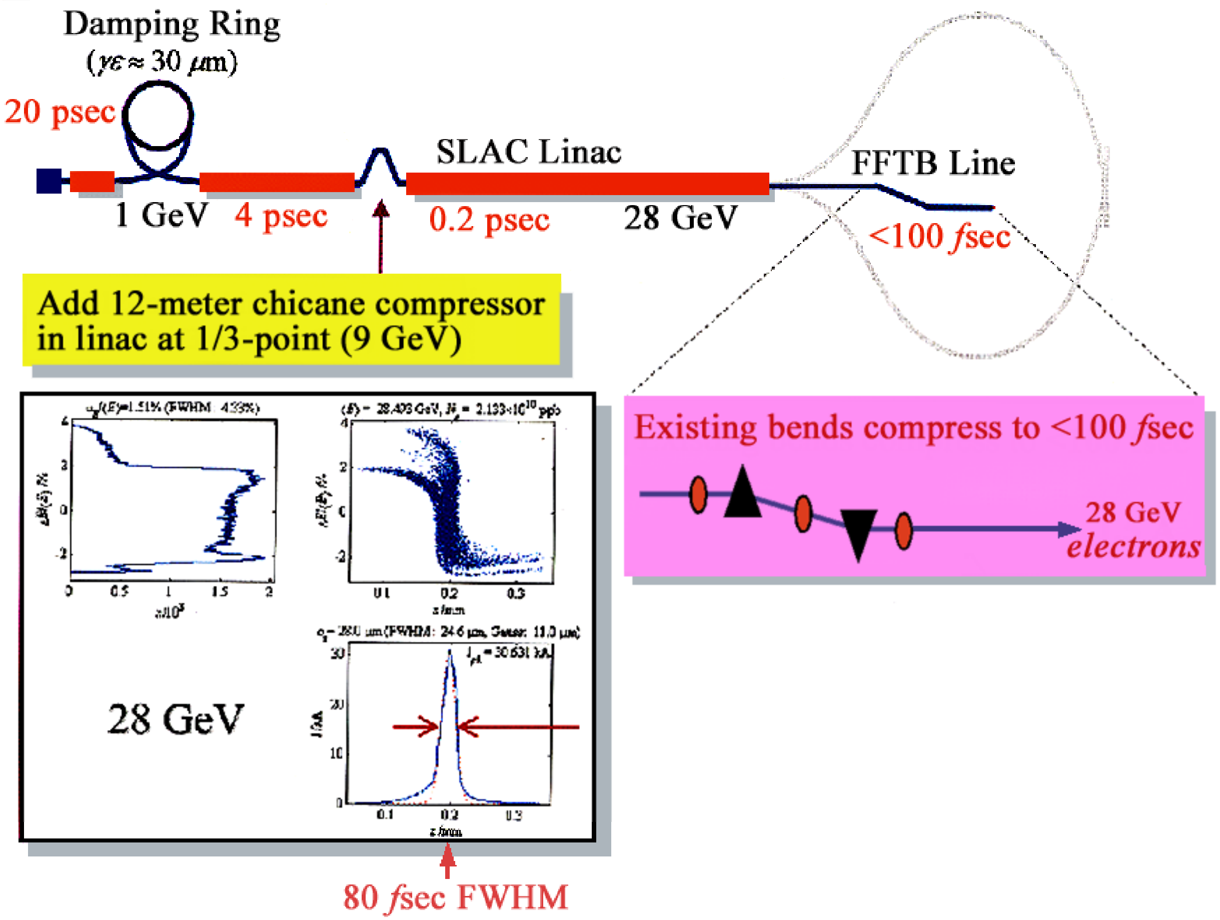
- Experiments on the SLAC beam in the last 8 years



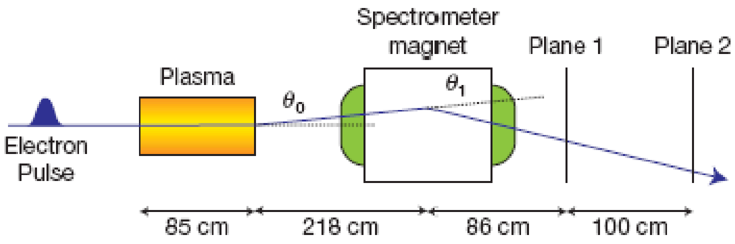




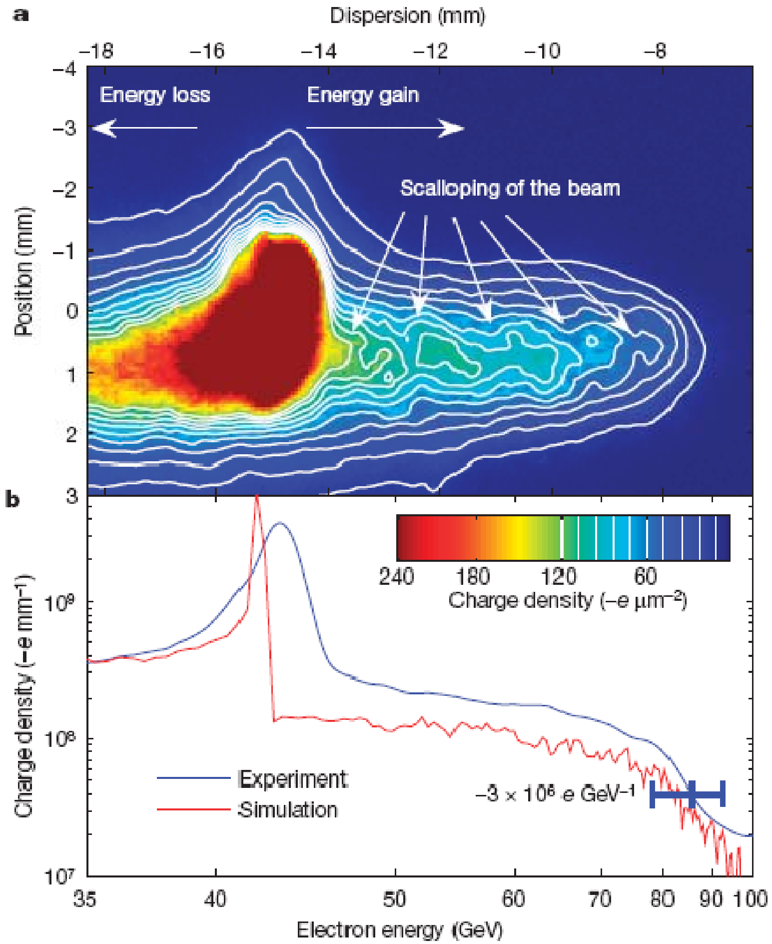
Sub-Picosecond Pulse Source



Highlight: latest SLAC/UCLA/USC results
(Nature 2007)



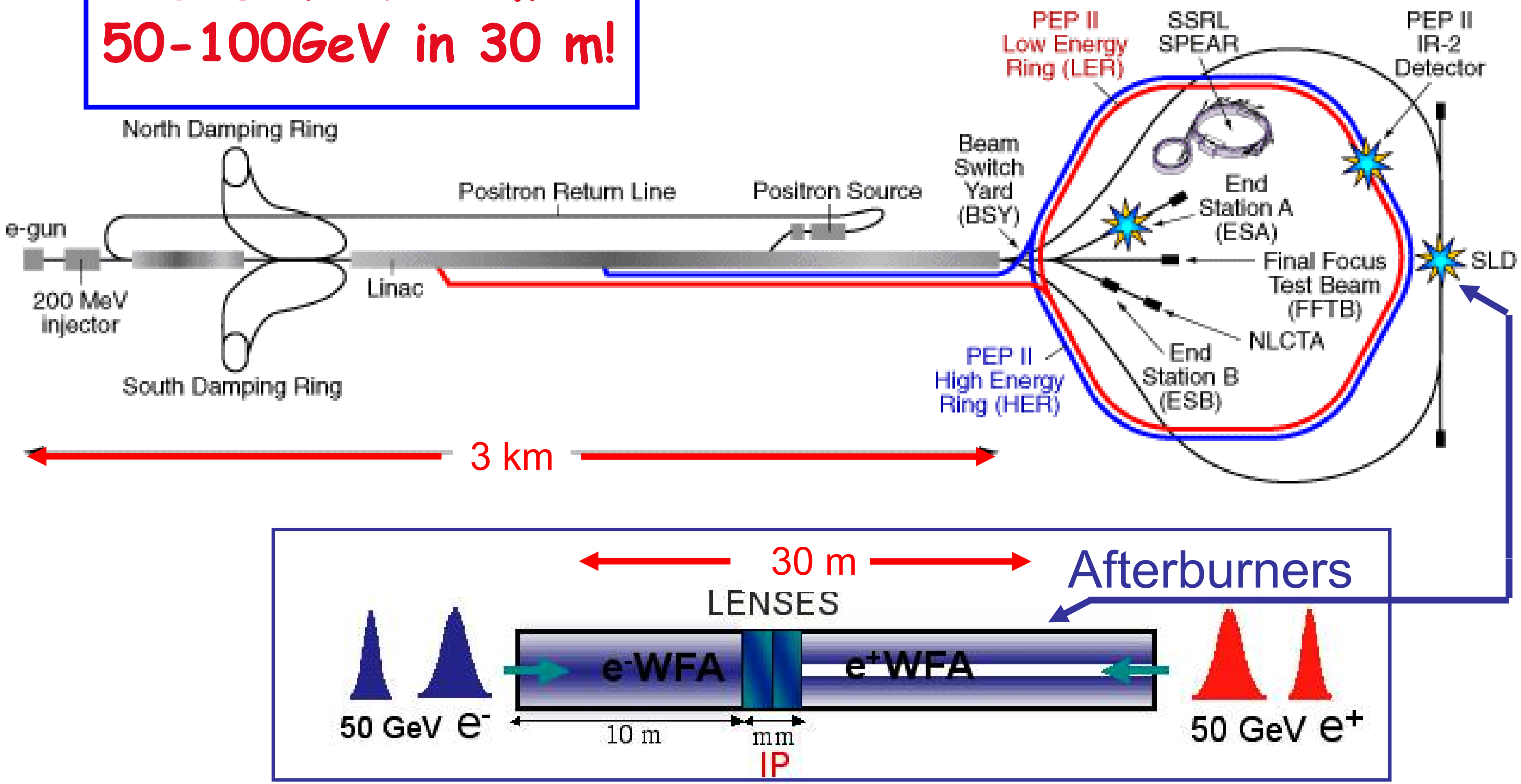
SLAC beam
- 42 GeV
- 3 nC @ 10 Hz
- focused to 10 μm spot size
- compressed to 50 fs



- Some electrons double their energy: from 42 to > 80 GeV
- E=50 GV/m over 0.8 meters

A Plasma Afterburner (Energy Doubler) of Relevance to Future Colliders Could be Demonstrated at SLAC

0-50GeV in 3 km
50-100GeV in 30 m!



S. Lee et al., Phys. Rev. STAB, 2001

Particle accelerators: requirements for High Energy Physics

- High Energy
- High Luminosity (event rate)
  - $L = fN^2/4\pi\sigma_x\sigma_y$
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma \sim .1 - 10\%$
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad
- Low Cost (one-tenth of $6B/TeV)
  - Gradients > 100 MeV/m
  - Efficiency > few %

Potential of laser-plasma accelerators for HEP

REQUIREMENTS	LWFA status
• High Energy	• In progress: 1 GeV staging necessary
• High Luminosity (event rate) – $L=fN^2/4\pi\sigma_x\sigma_y$	• Challenge low repetition rate (10 Hz) charge < 1nC
• High Beam Quality – $\delta\gamma/\gamma \sim .1$ - 10% – $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad	• $\delta\gamma/\gamma \sim 5\%$ demonstrated ε_n estimated at a few mm-mrad
• Low Cost (one-tenth of $6B/TeV) – Gradients > 100 MeV/m – Efficiency > few %	• E > 100 GV/m demonstrated lasers : 1 % laser → e-beam: 10 %

→ Laser technology needs to improve: repetition rate, efficiency of lasers

Laser-plasma accelerators as synchrotron source

- Near future experiments
  - will produce GeV e-beams, several 100 pC
  - with state of the art upcoming lasers (PW lasers)
- Laser-plasma accelerators produce
  - sub-50 fs electron bunches
- Possibility of producing
  - bright femtosecond X-ray sources
  - with compact accelerator
  - with perfect synchronization to the laser pulse
  - lower brillance than state of the art synchrotron source (repetition rate+ lower charge …)

→ Of interest to synchrotron users

→ **Promising as synchrotron source with current laser technology**

Potential of plasma-plasma accelerators for HEP

REQUIREMENTS	PWFA status
• High Energy	• 40 GeV gain demonstrated
• High Luminosity (event rate) – $L=fN^2/4\pi\sigma_x\sigma_y$	• OK: mimic main beam
• High Beam Quality – $\delta\gamma/\gamma \sim .1 - 10\%$ – $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad	• Challenge: beam quality need to improve: 2 beam experiment coming
• Low Cost (one-tenth of $6B/TeV) – Gradients > 100 MeV/m – Efficiency > few %	• E > 50 GV/m demonstrated efficiency ?

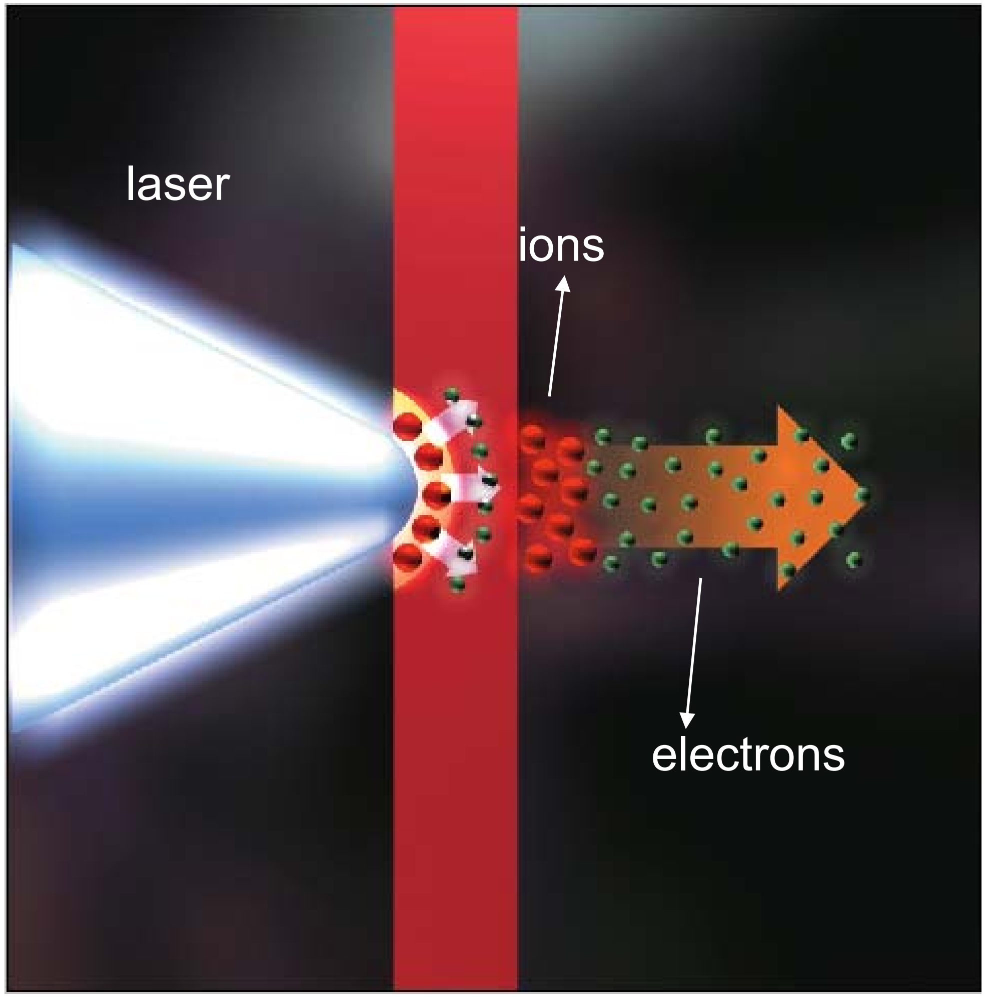
→ **Promising scheme for high energy physics**

Note: ion acceleration also possible

Ions are heavy →static plasma fields instead of travelling wave

State of the art:

- tens of MeV protons on thin foils (~10 μm)
- Heavier ions (C) also possible
- Very laminar flow
- Usually 100 % energy spread
- First quasi-monoenergetic results (Nature 2006)



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