Laser-plasma particle acceleration

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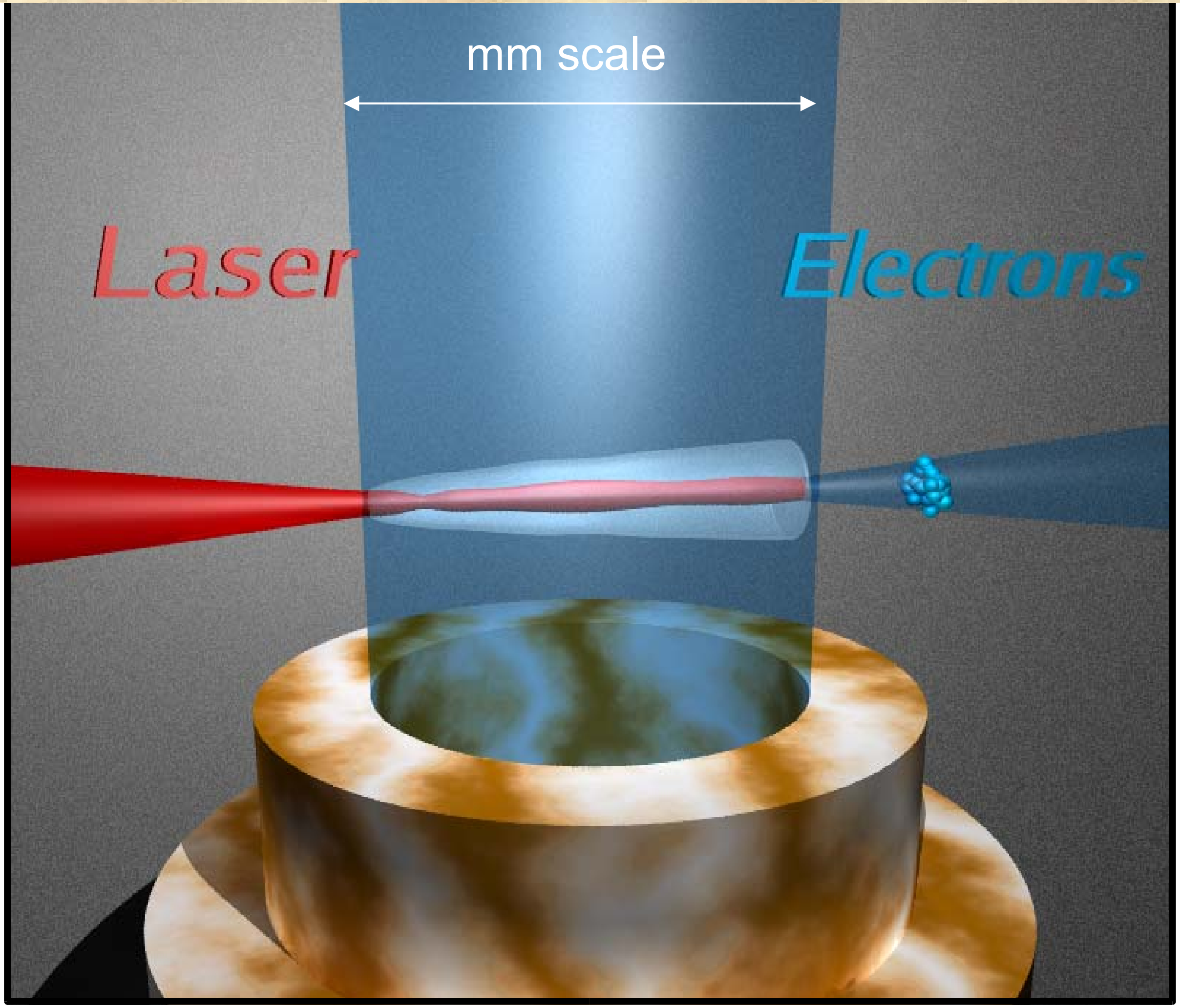
Laser plasma-based accelerators



Goals:
- GeV accelerator
- Table-top synchrotron

- E fields > 100 GeV/m → compact accelerators
- ultrashort electron bunches < 50 fs


Political Map of the World
Arctic Ocean
Greenland (DEN.)
U.S.
CANADA
RUSSIA
KAZAKHSTAN
MONGOLIA
CHINA
JAPAN
North Pacific Ocean
North Atlantic Ocean
UNITED STATES
MEXICO
Gulf of Mexico
TURKEY
IRAN
INDIA
ALGERIA
LIBYA
EGYPT
SAUDI ARABIA
SUDAN
CHAD
ETHIOPIA
ZAIRE
ANGOLA
SOUTH AFRICA
MADAGASCAR
BRAZIL
PERU
BOLIVIA
CHILE
ARGENTINA
COLOMBIA
VENEZUELA
INDONESIA
MALAYSIA
PHILIPPINES
AUSTRALIA
NEW ZEALAND
Indian Ocean
South Atlantic Ocean
South Pacific Ocean
Antarctica
Equator
Tropic of Cancer
Tropic of Capricorn
Antarctic Circle
Arctic Circle
Scale 1:75,000,000
Robinson Projection
standard parallels 38° N and 38° S
Boundary representation is not necessarily authoritative.

Particle Accelerators
Why Plasmas?

Tajima & Dawson, PRL ***43****, 267 (1979)*

Conventional Accelerators

- Limited by peak power and breakdown
- 20-100 MeV/m
- Large Hadron Collider (LHC) -- 27km, 2010
- Plans for “Next” Linear Collider (NLC) -- 100km ?

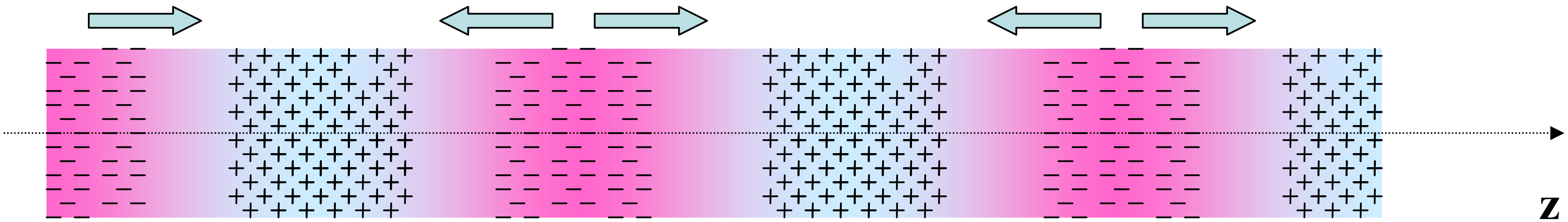
Plasma

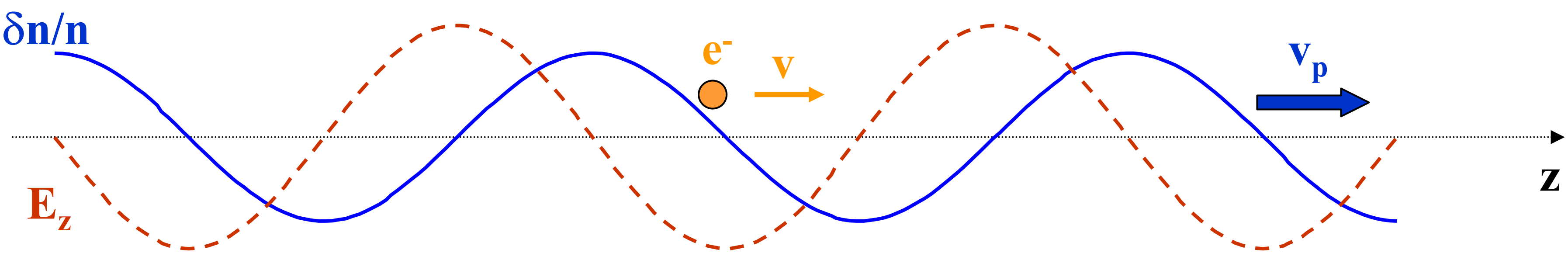
- No breakdown limit
- 10-100 GeV/m

High electric fields in plasmas: plasma waves

$$E_z = \frac{m_e c \omega_p}{e} \approx 300\ \mathrm{GV/m} \quad (\text{for } n_e = 10^{19}\ \mathrm{cm}^{-3})$$

$$\omega_p \propto n_e^{1/2}$$





For accelerating relativistic particles: $v_p \sim c$

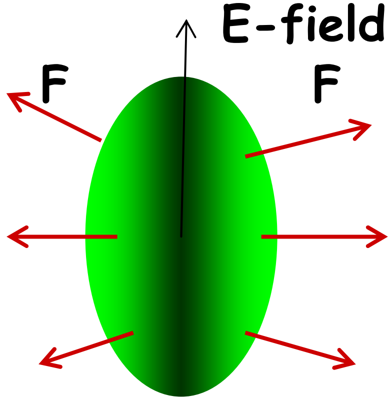
$$T_p \propto n_e^{-1/2}$$

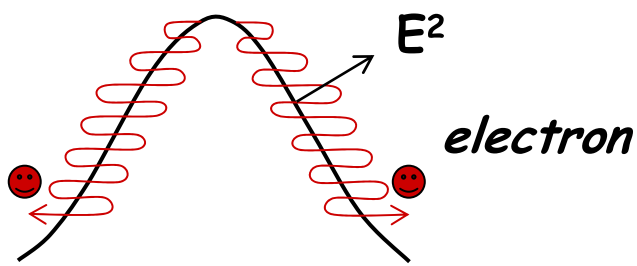
Bucket size is $T_p/2$=15 fs for n_e=10^{19} cm^{-3}

Plasma waves are excited by the ponderomotive force

The ponderomotive force of the laser field can transform the transverse laser field into a charge separation and a propagating plasma wave

- An electromagnetic field acts as a pressure on charged particles :
  it expels the electrons from high-intensity zones

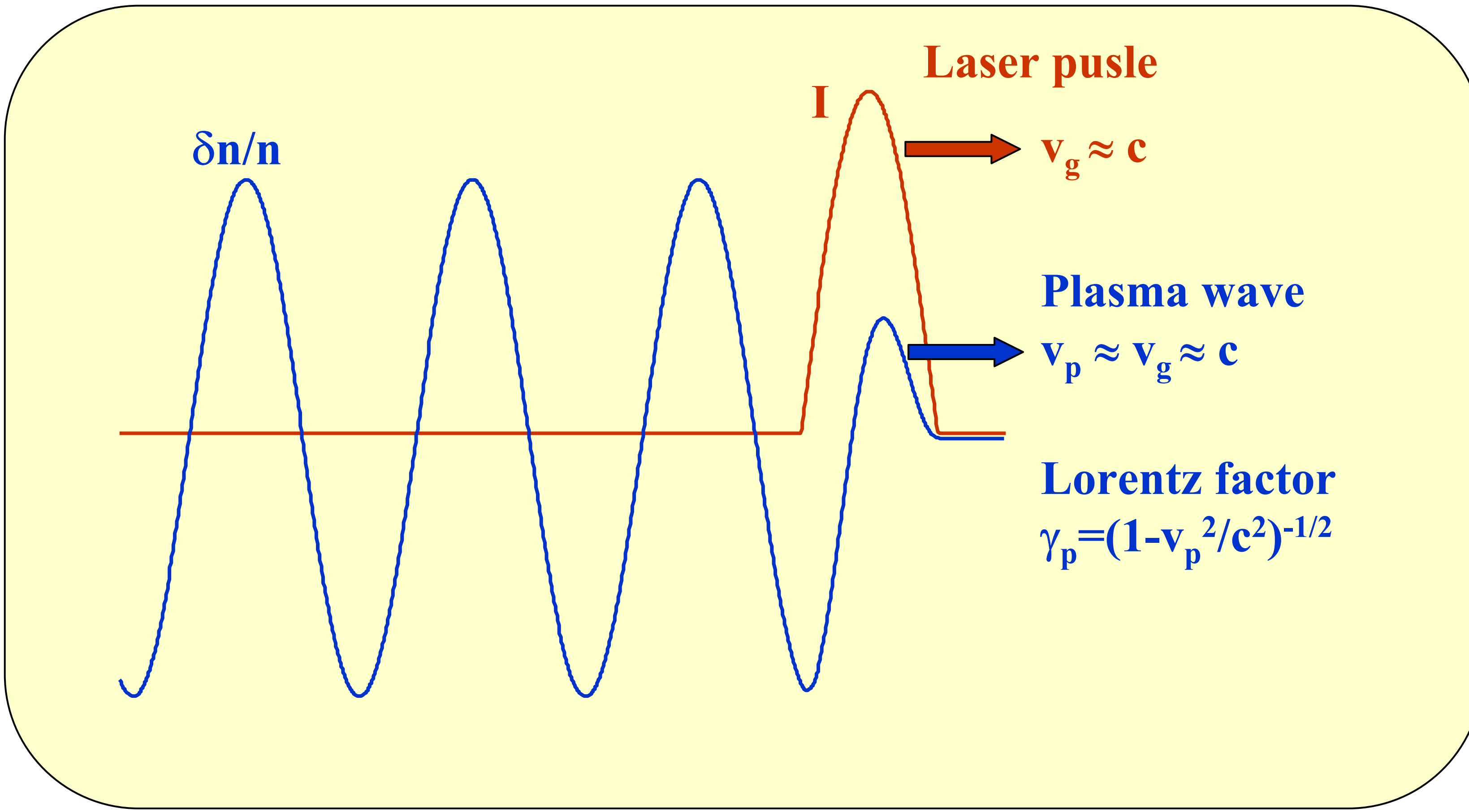




- Ions do not move because they are heavier

Laser wakefield (like the wake of a boat)

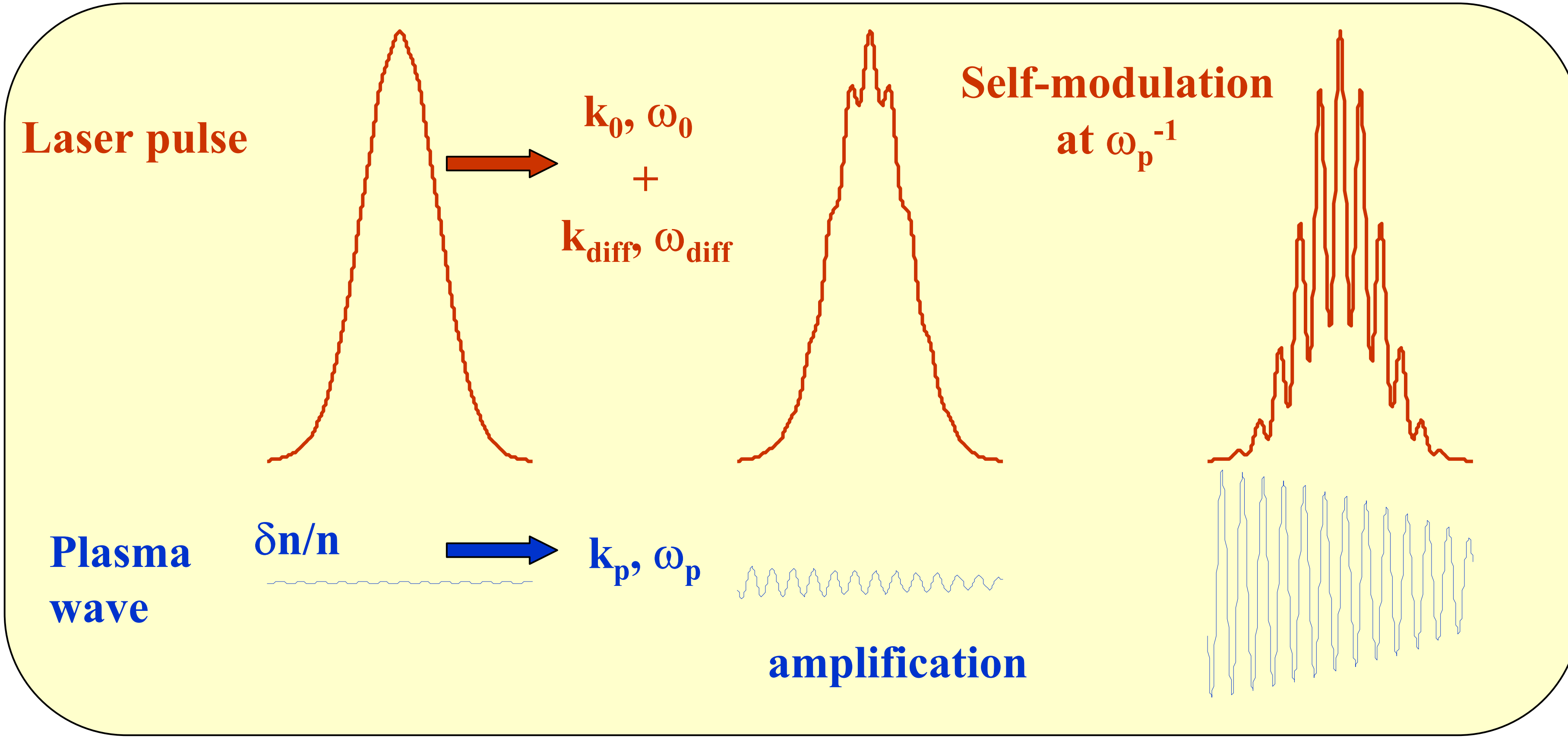
$c\tau \sim \lambda_p$ → Short pulses are better



Self-modulated laser wakefield

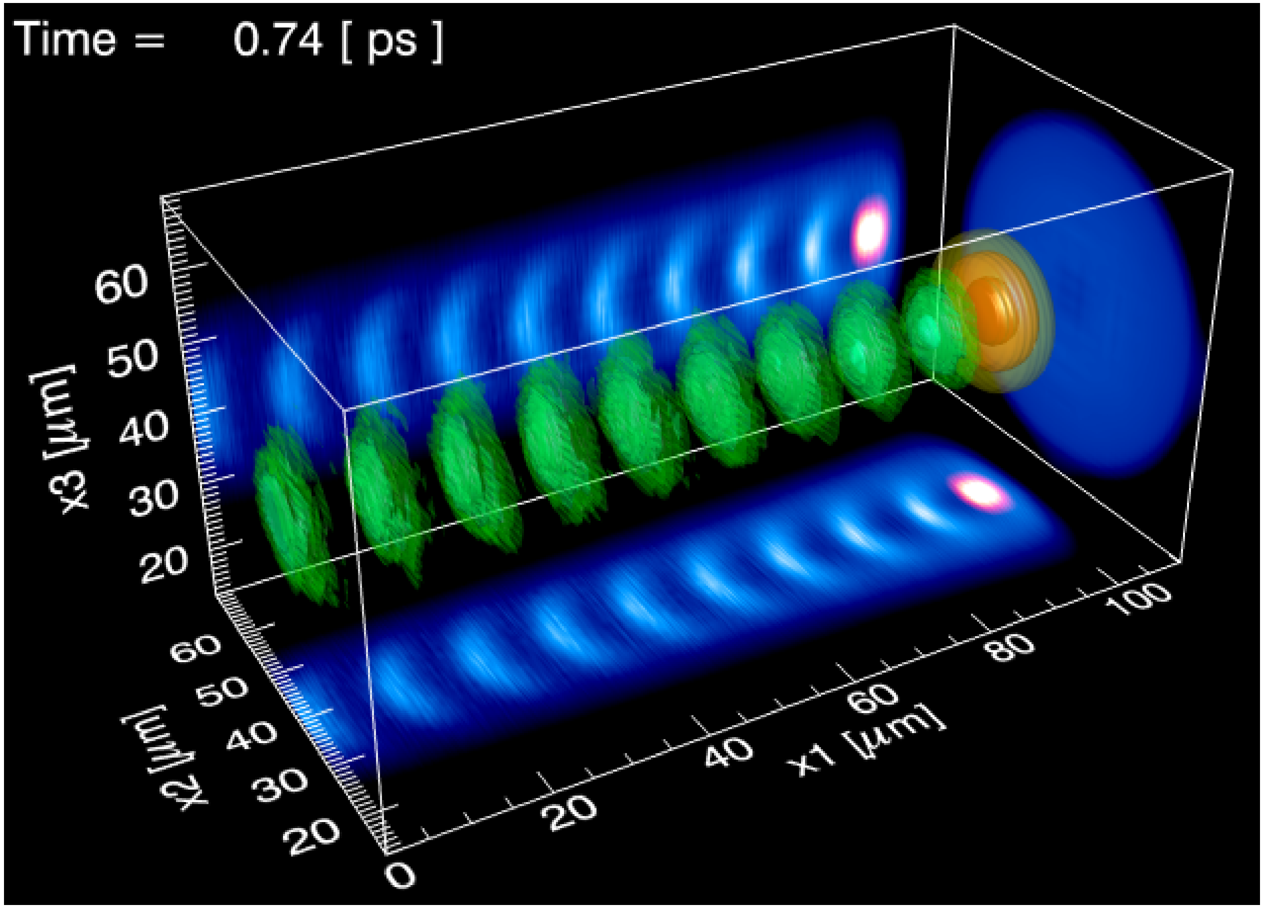
Raman forward instability

$c\tau \gg \lambda_p$ → **longer pulses**



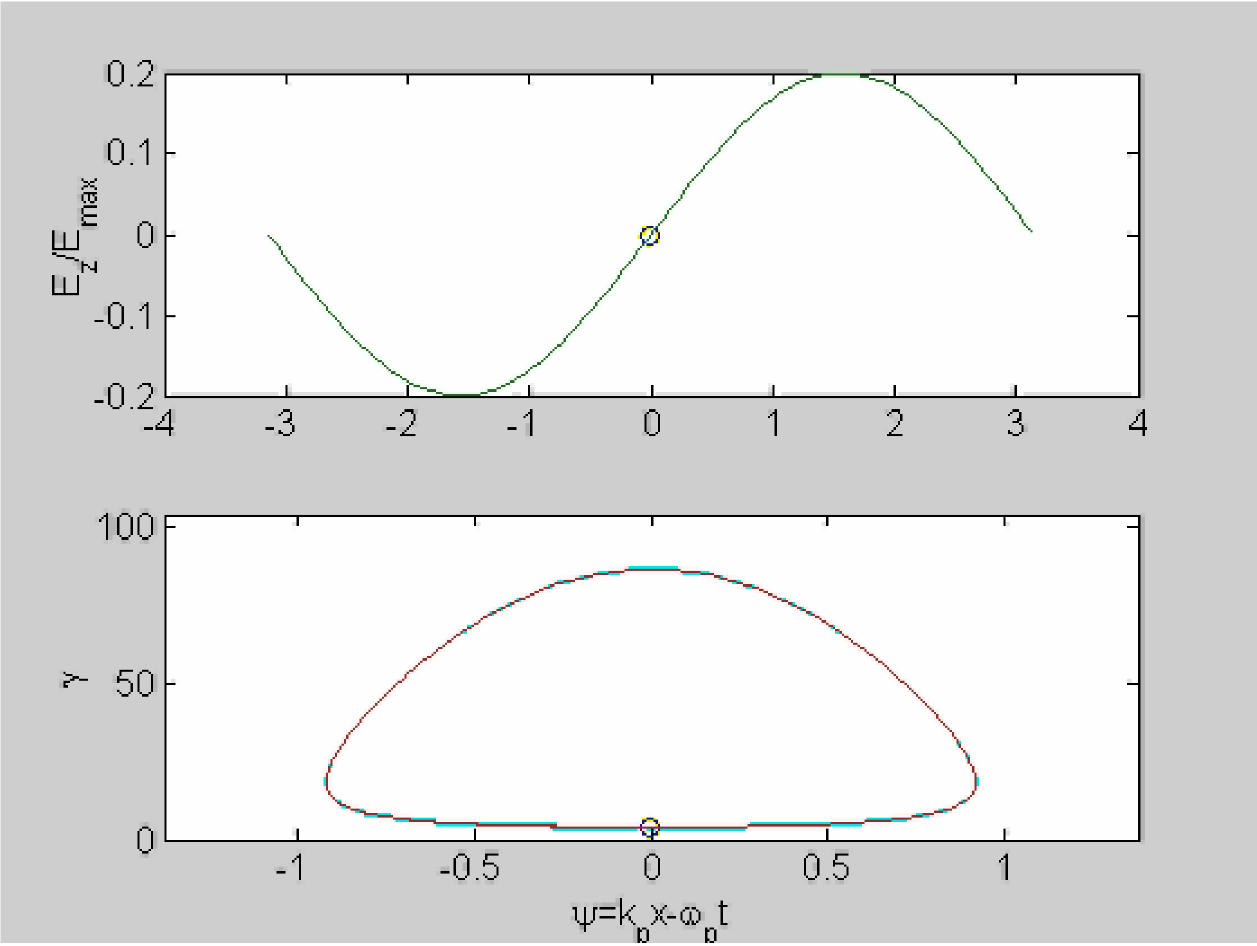
Nonlinear wakes

3-D PIC OSIRIS Simulation



Laser Wake

Electron trajectory in plasma wave



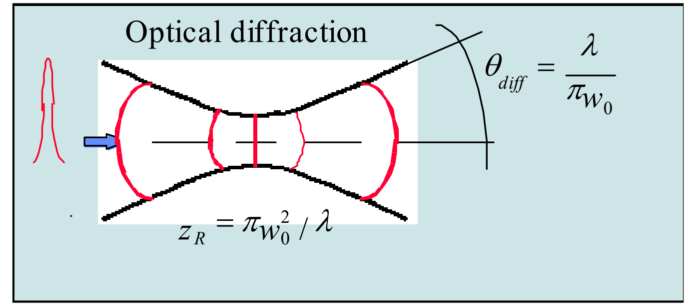
Acceleration limit: Dephasing length

$$W = 4 m_e c^2 \gamma_p^2 \frac{\delta n}{n}$$ **=1 GeV for a dn/n=1 plasma wave on a 1 cm length in a n_e=10^{18} cm^{-3} plasma**

3 Limits to Energy gain $\Delta W = eE_z L_{acc}$

- **Diffraction:**

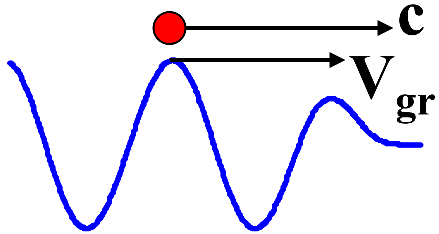
$$L_{dif} \cong \pi L_R = \pi^2 w_0^2 / \lambda$$



order mm!

(but overcome w/ channels or relativistic self-

- **Dephasing:**



$$L_{dph} = \frac{\lambda_p / 2}{1 - V_{gr}/c}$$

order 1 cm x $10^{18}/n_o$

- **Depletion:**

For small a_0 >> L_{dph}

For a_0 >~ 1 L_{dph} ~ L_{depl}

$$\Delta W_{ch}[MeV] \sim 60 \left(\lambda_p / w_0\right)^2 P[TW]$$

What kind of lasers ?

- Laser Intensity: $$I = \frac{E}{S} \times \frac{1}{\tau}$$
- Normalized potential vector $$a = (I\lambda^2)^{1/2}$$
- Ponderomotive force $$F \propto -\nabla a^2$$

↓

- ultra-short lasers: t < 1 ps
- powerful: P=10-100 TW
- ultra-intense: $I > 10^{18}$ W/cm^2

Shorter pulses

↓

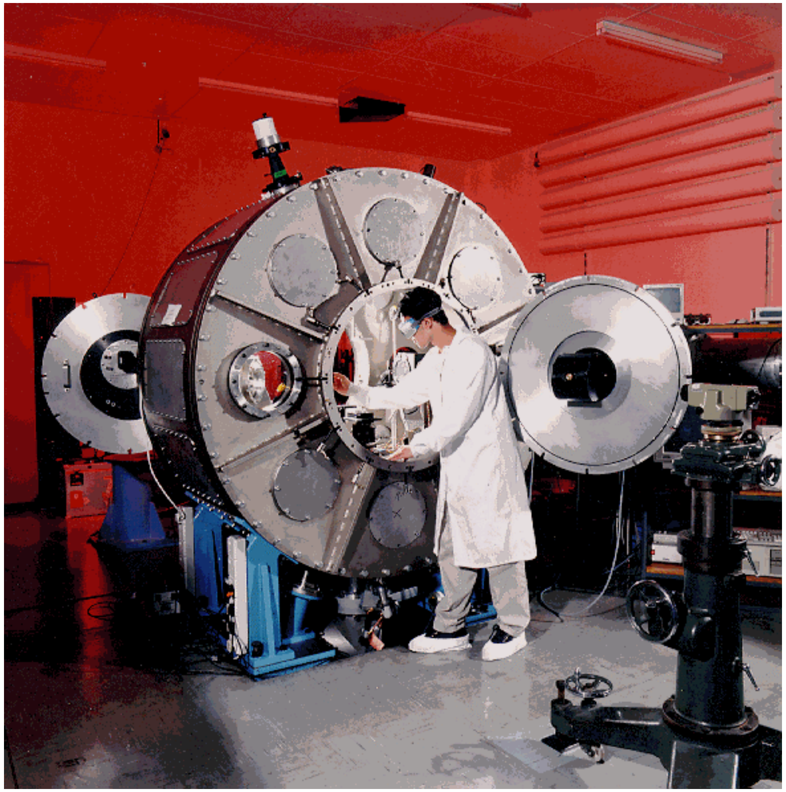
Less energy

↓

More compact lasers

First experiments: large facilities

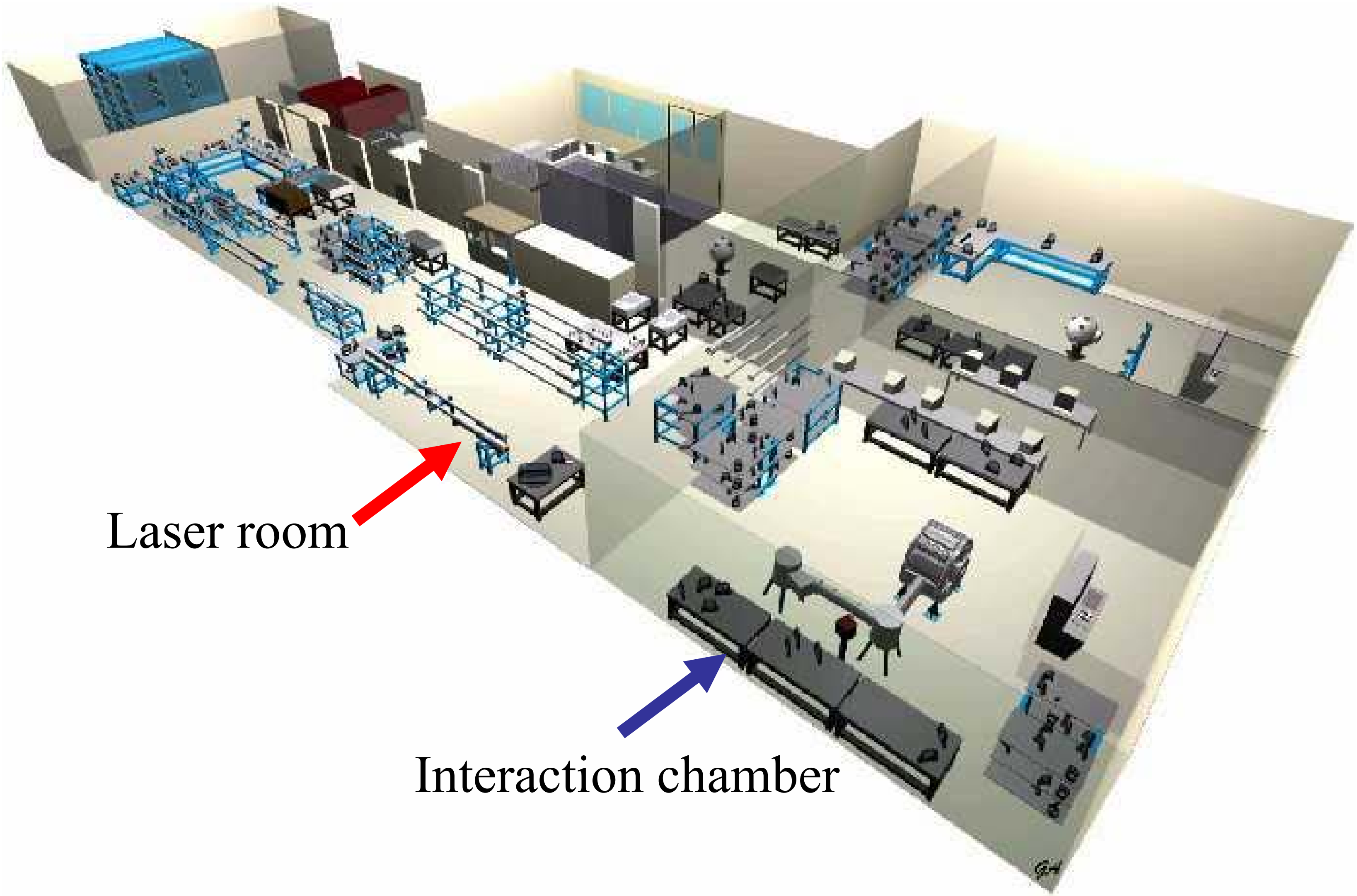
Rutherfold Lab (UK 1996): Nd:Glass laser
LULI (1994-1998): Nd:Glass laser



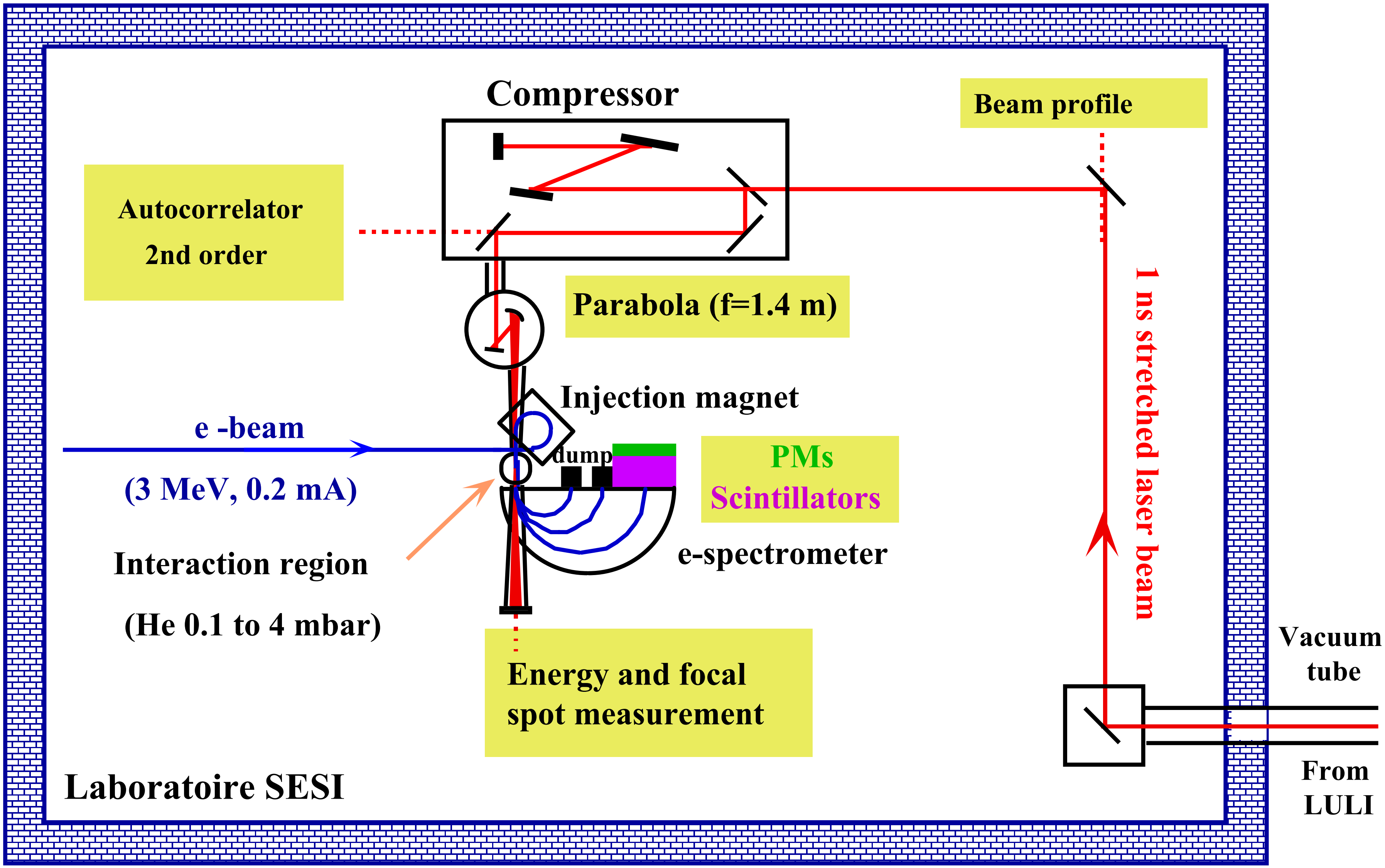
Big lasers: > 100 J per shot in 1 ps. One shot every 20-40 minutes

Proof of principle experiments

VULCAN Laser at Rutherford, UK



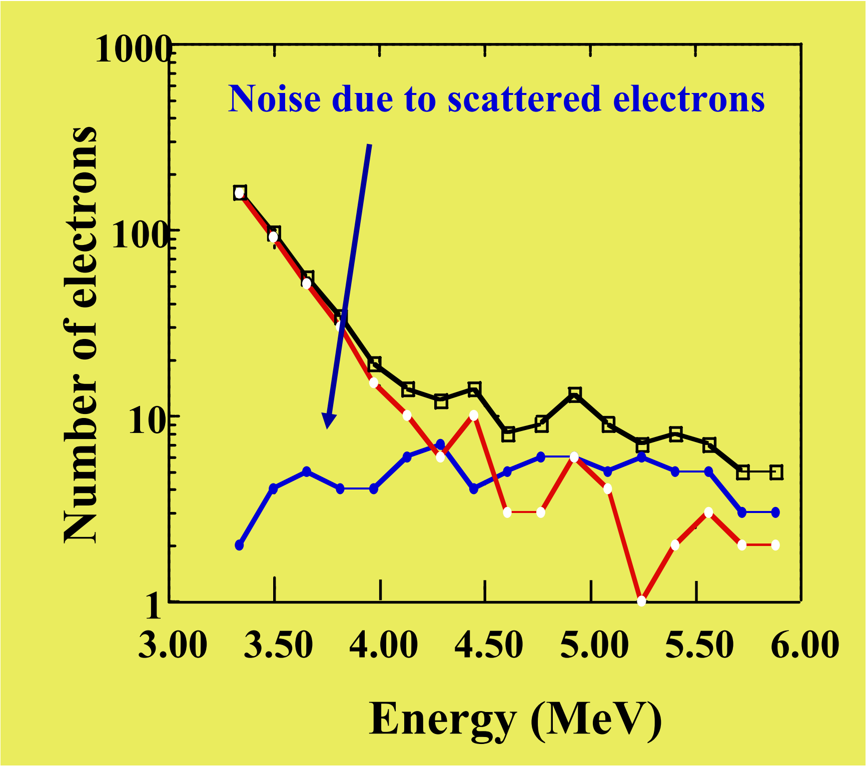
Laser wakefield proof-of-principle experiment at Ecole Polytechnique



Wakefield : Acceleration in 1.5 GV/m

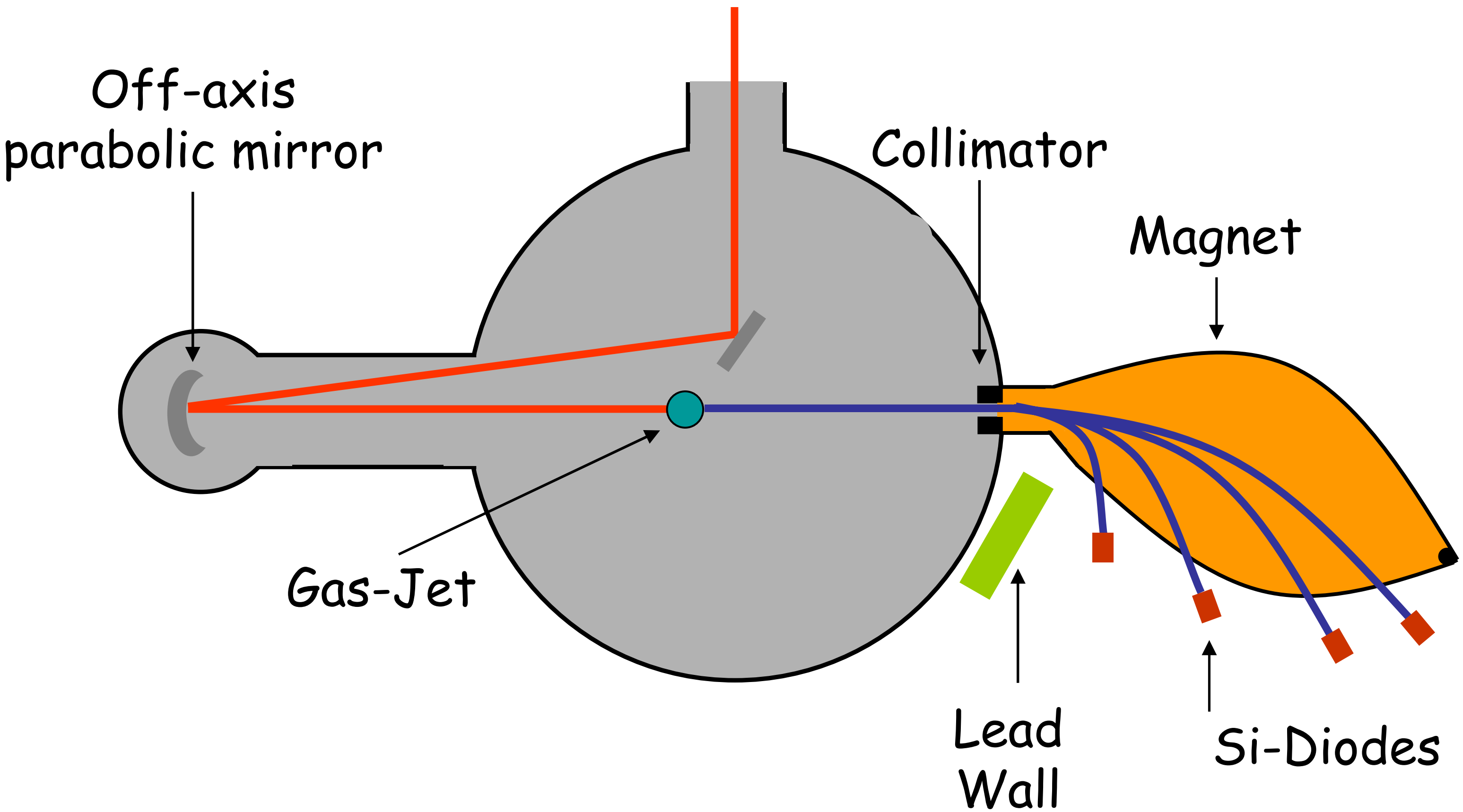
The 3-MeV electrons are accelerated up to ≈ 4.5 MeV

In a maximum field of 1.5 GV/m

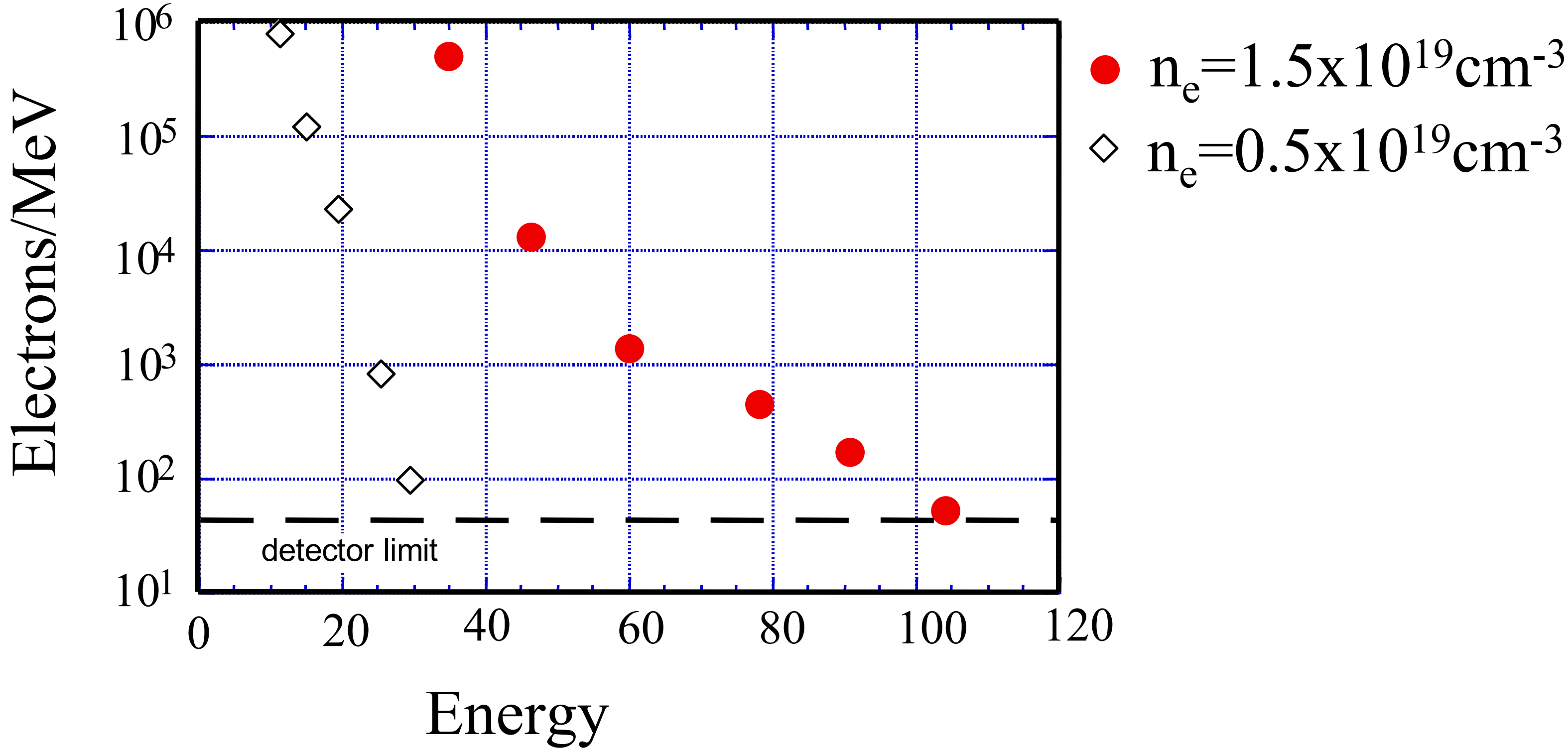


2.5 J, 350 fs, 10^{17}W/cm^2, 0.5 mbar He

Rutherford experiment (1995): $c\tau >> \lambda_p$
No external injection



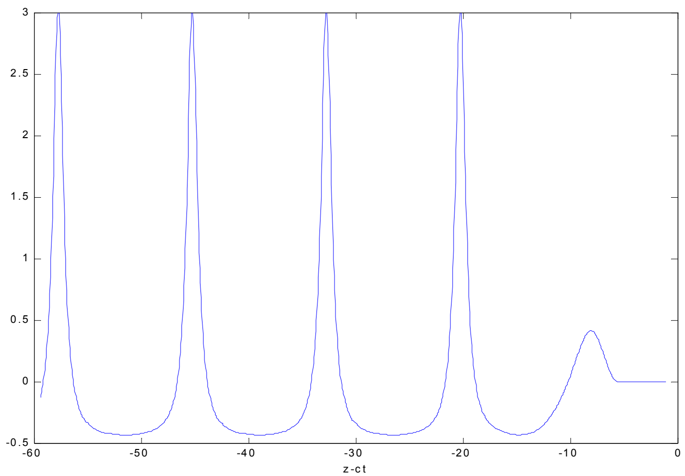
Self-modulated laser wakefield: $c\tau \gg \lambda_p$
Observation of an electron beam



Modena et al. Nature 377, (95)

Electrons come from “wavebreaking”

Self-modulation instability: causes exponential growth of plasma wave

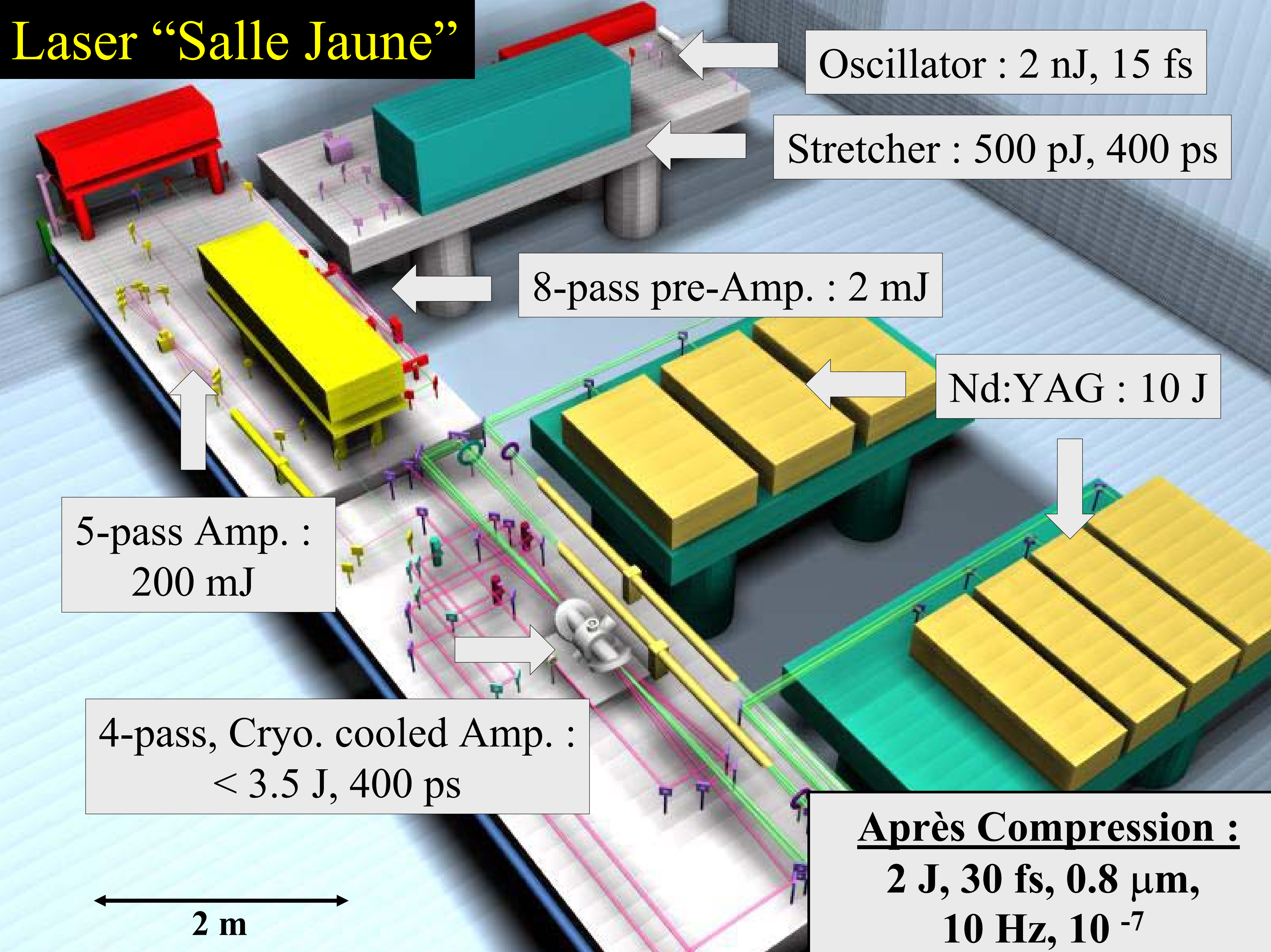


Massive trapping and acceleration: generation of an electron beam

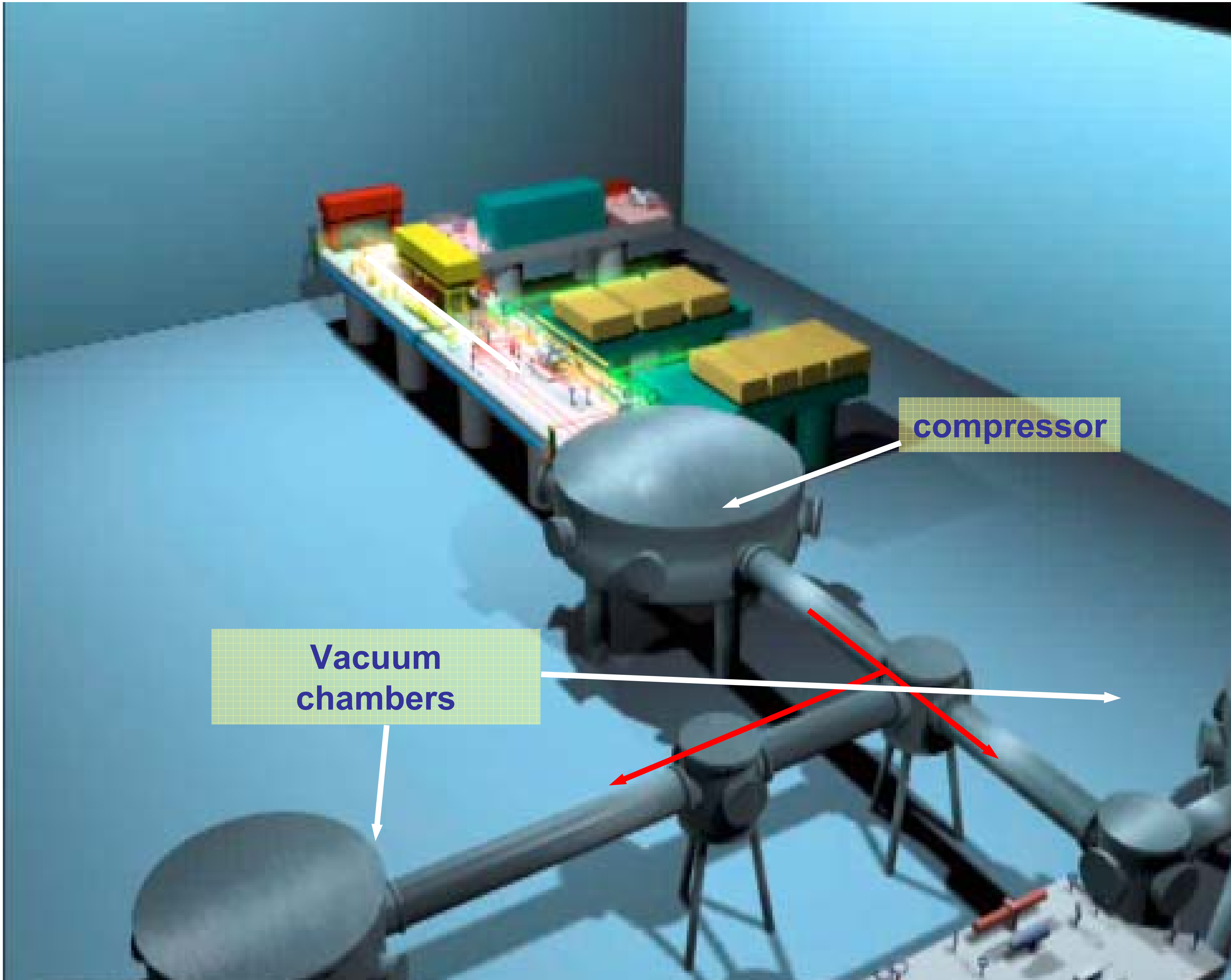
Recent experiments: small facilities

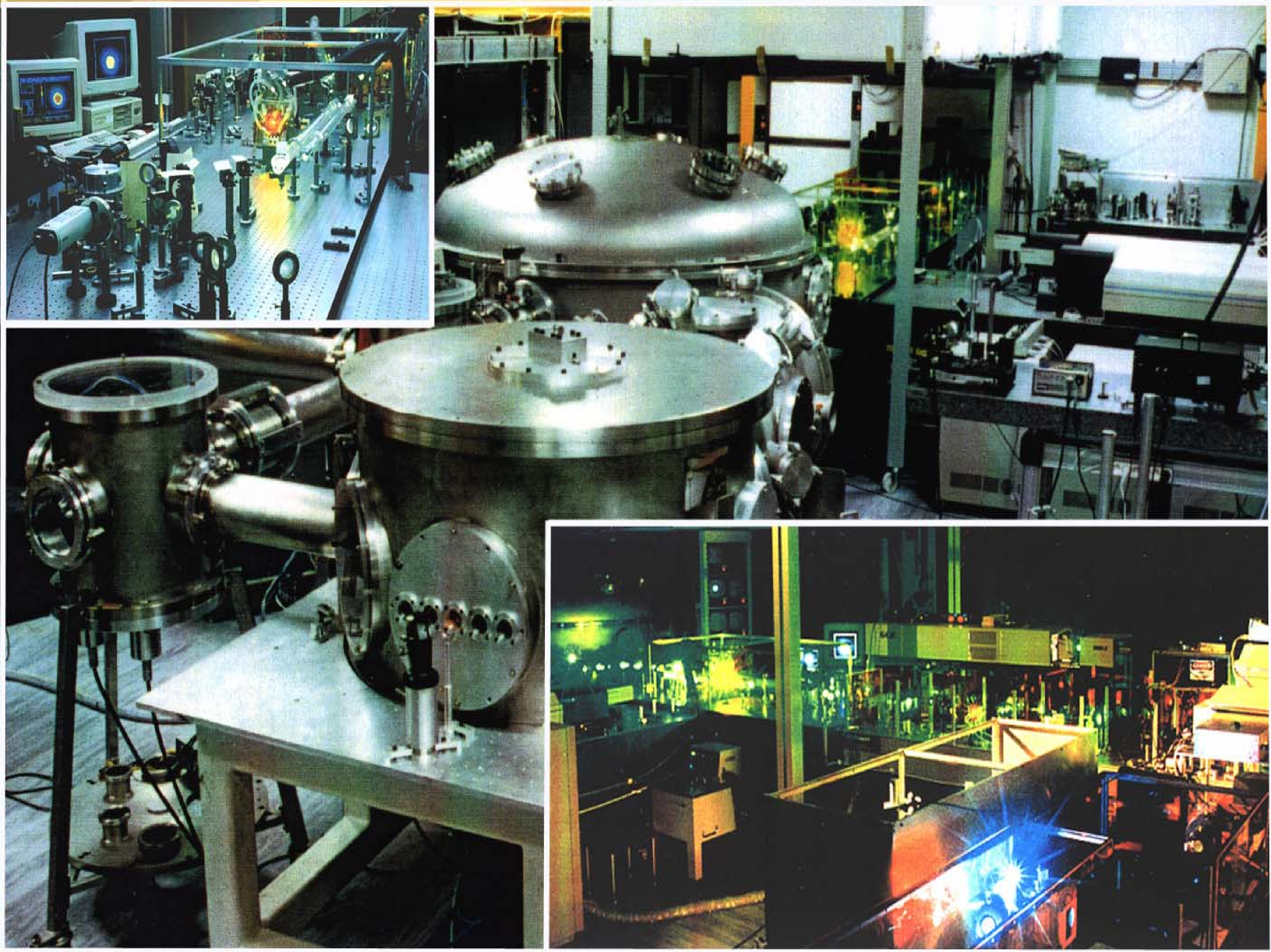
- Experimental exploration allows constant progress in this field

New experiments use
- ultrashort pulses (30 fs)
- low energy (1 J)
- Small scale lasers
- High repetition rate (10 Hz)

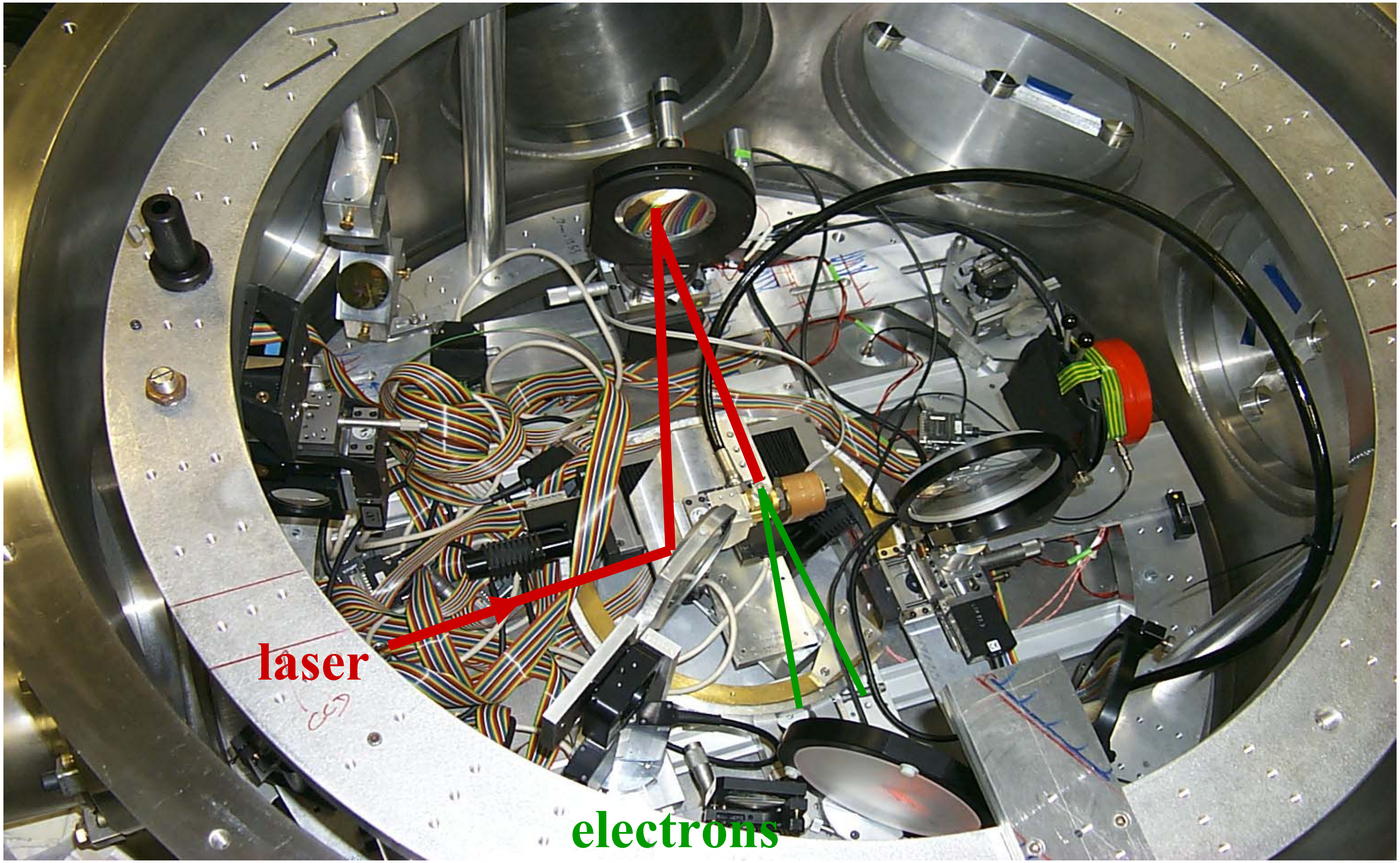


Laser "Salle Jaune"
Oscillator : 2 nJ, 15 fs
Stretcher : 500 pJ, 400 ps
8-pass pre-Amp. : 2 mJ
Nd:YAG : 10 J
5-pass Amp. : 200 mJ
4-pass, Cryo. cooled Amp. : < 3.5 J, 400 ps
Après Compression :
2 J, 30 fs, 0.8 μm, 10 Hz, 10 -7
2 m

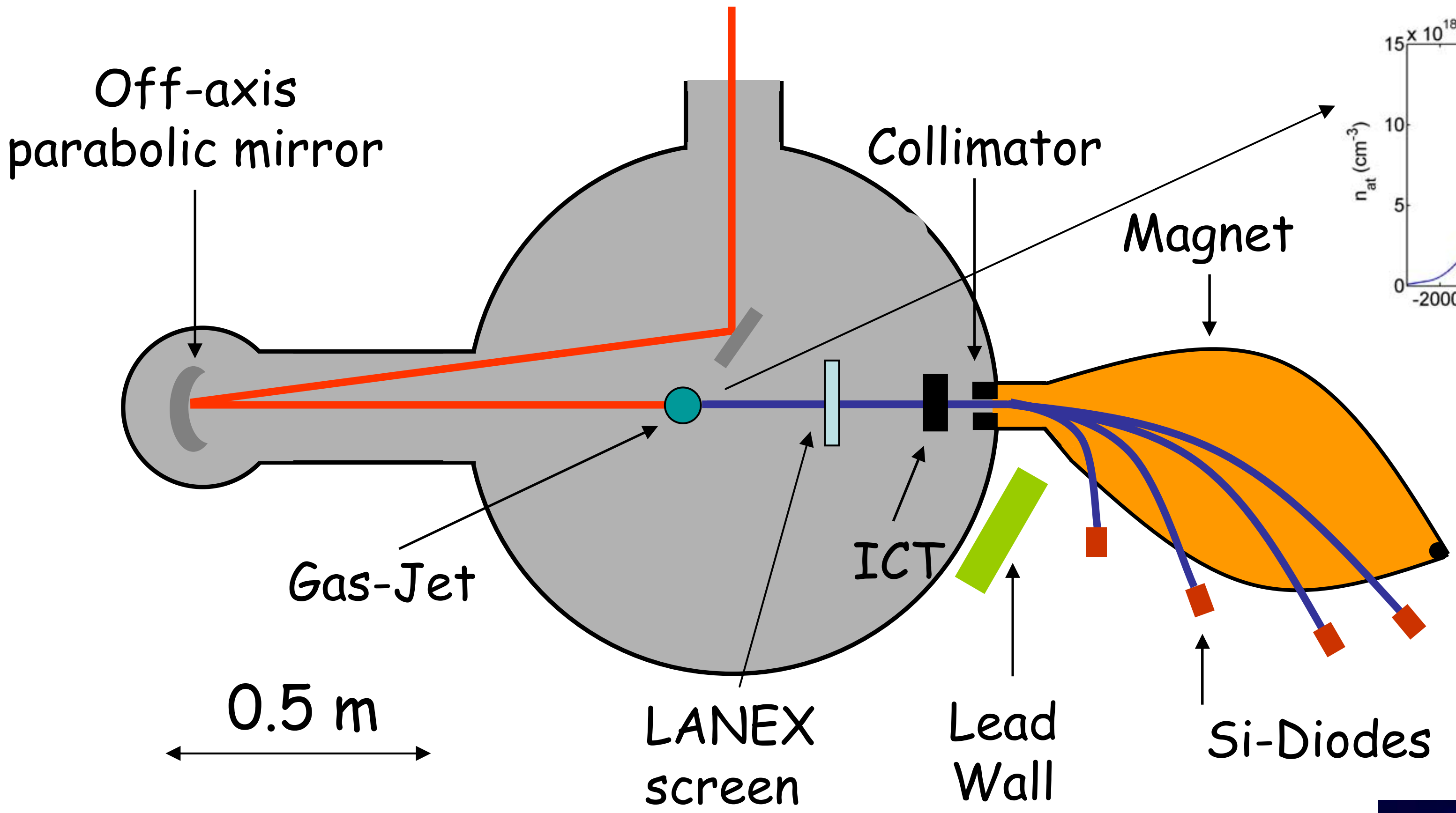

compressor
Vacuum chambers

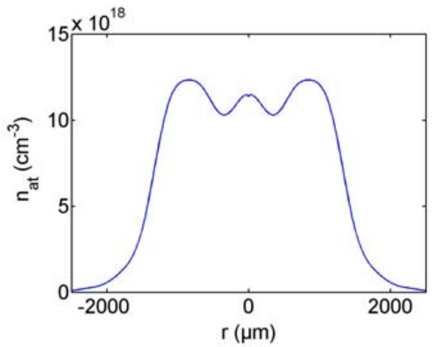


Interaction chamber



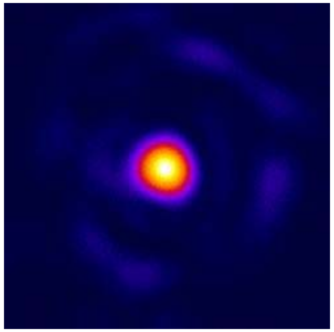
Experimental set-up





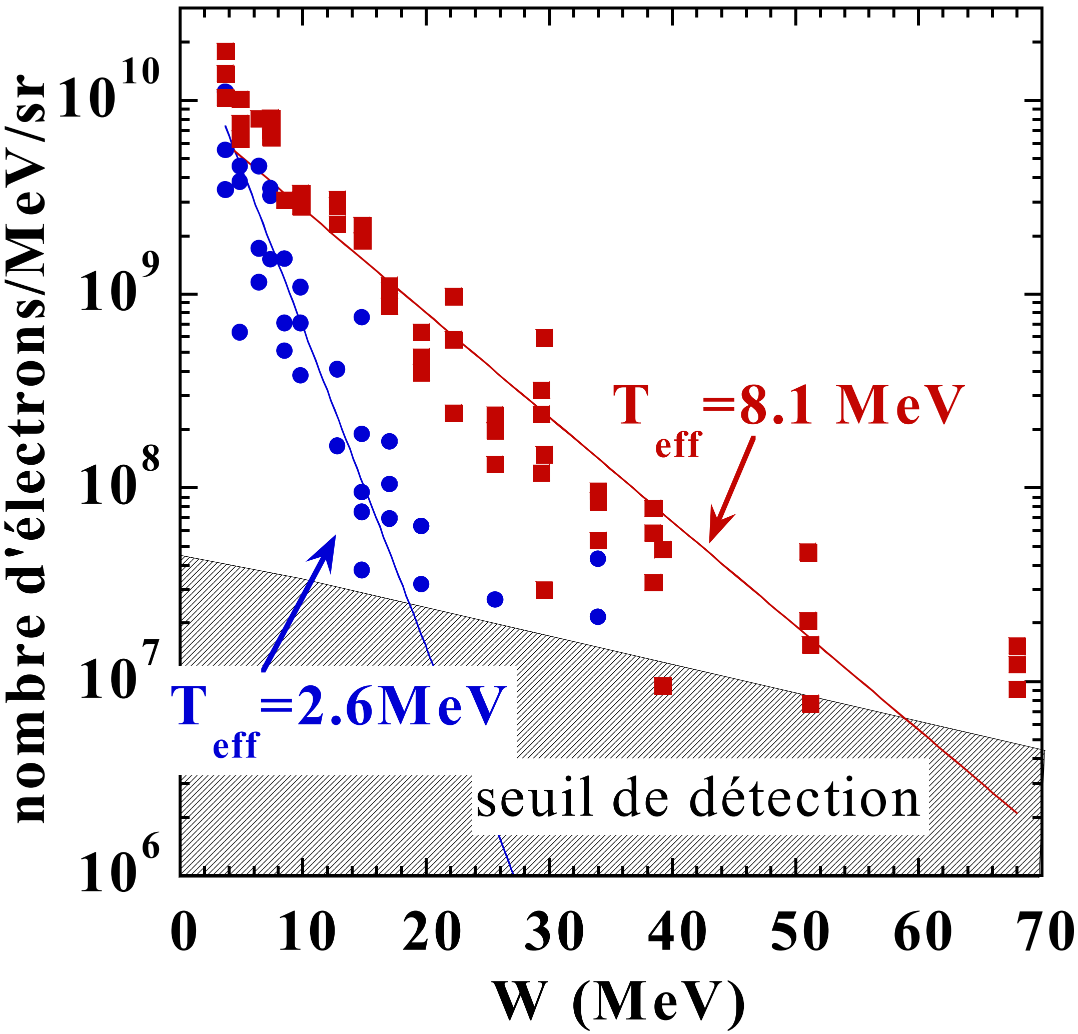
Laser parameter:
1 J, 30 fs
w_0=18 μm, z_R=1.25 mm
$I_0=3\times10^{18}$ W/cm^2

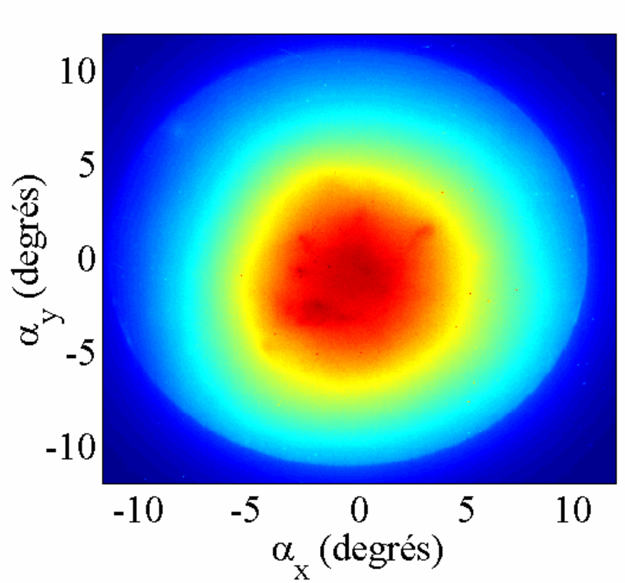
Focal spot (deformable mirror)



Electron spectrum: Maxwellian distribution

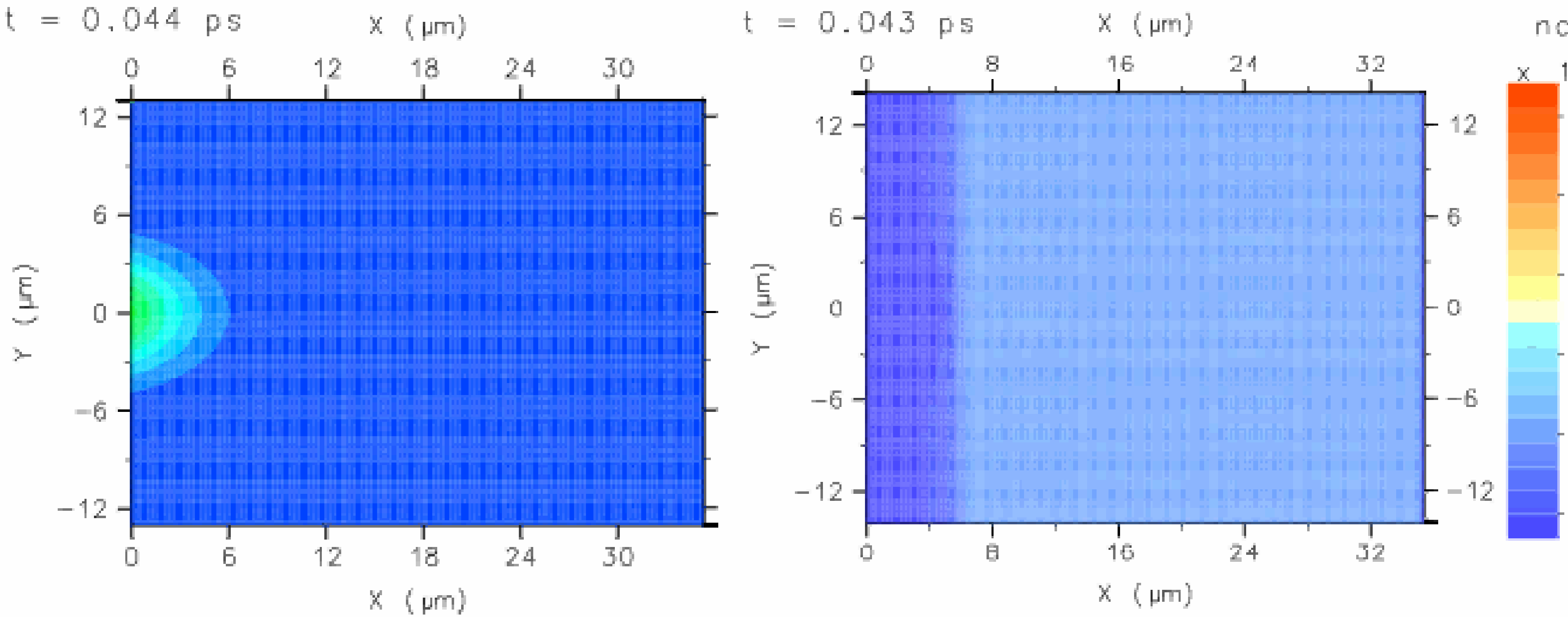
W_{max} at 70 MeV
Charge of 1-10 nC





Spectrum can be controlled

2D PIC simulations
(courtesy Erik Lefebvre)



Breakthrough in the field

In all previous experiments: maxwellian-like energy distribution, and 100 % energy spread

→ difficult to transport the beam and to refocus it
→ electron bunch stretches as it propagates (does not stay short)
→ few high energy electrons (1 pC at 100 MeV +/- 5 MeV)

New generation of experiments: monoenergetic beams

LOA: Faure et al., Nature 431, (2004)
LBNL: Geddes et al., Nature 431 (2004)
Imperial college: Mangles et al., Nature 431 (2004)

Recipe:
→ Longer interaction length (several mm instead of hundreds of μm)
→ Shorter pulses

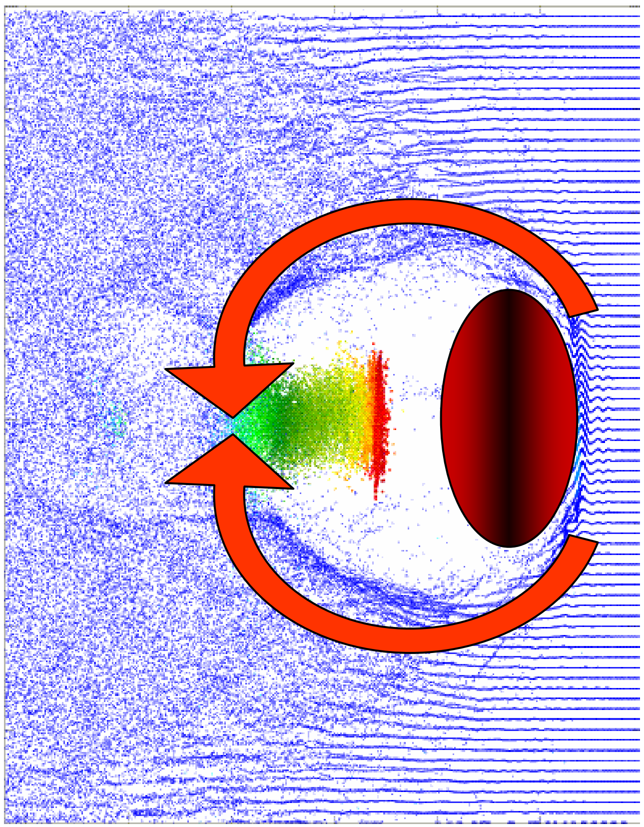

30 September 2004
International weekly journal of science
nature
£10.00
www.nature.com/nature
Dream beam
The dawn of compact particle accelerators
Disease control
Europe plays catch-up
The Earth's hum
Sounds of air and sea
Protein folding
Escape from the ribosome
Human ancestry
One from all and all from one
technology feature RNA interference

Quasi-monoenergetic electron beams in plasmas: virtual or real ?

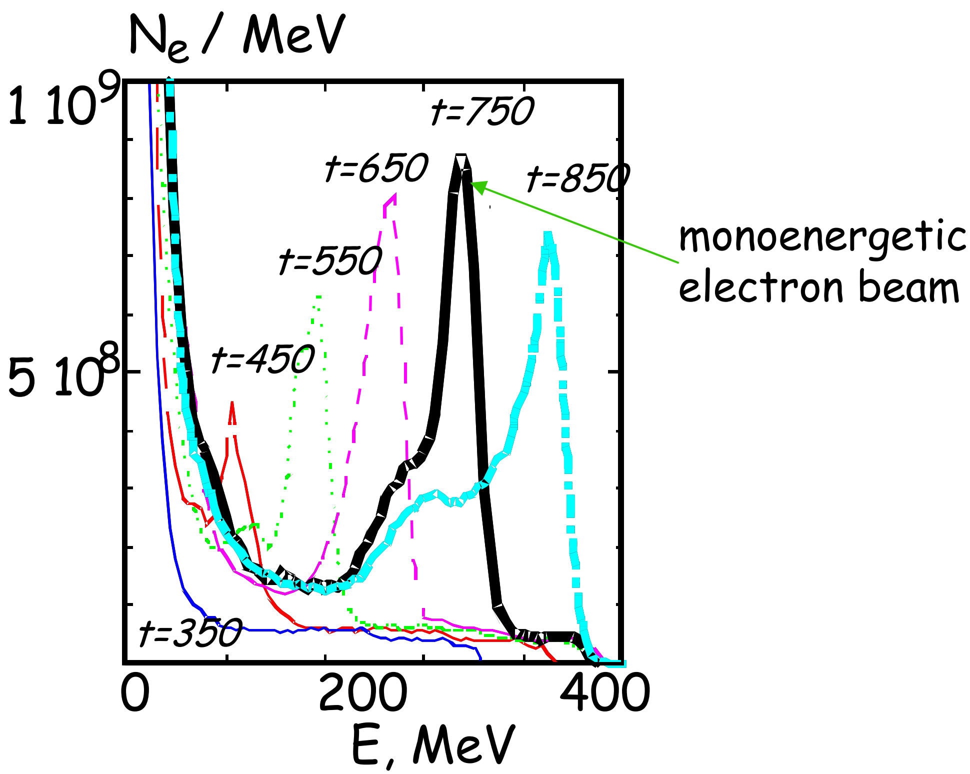
VLPL

$$c\tau \leq \lambda_p \; and \; w_0 \leq \lambda_p$$

Very nonlinear wakefield
Bubble formation



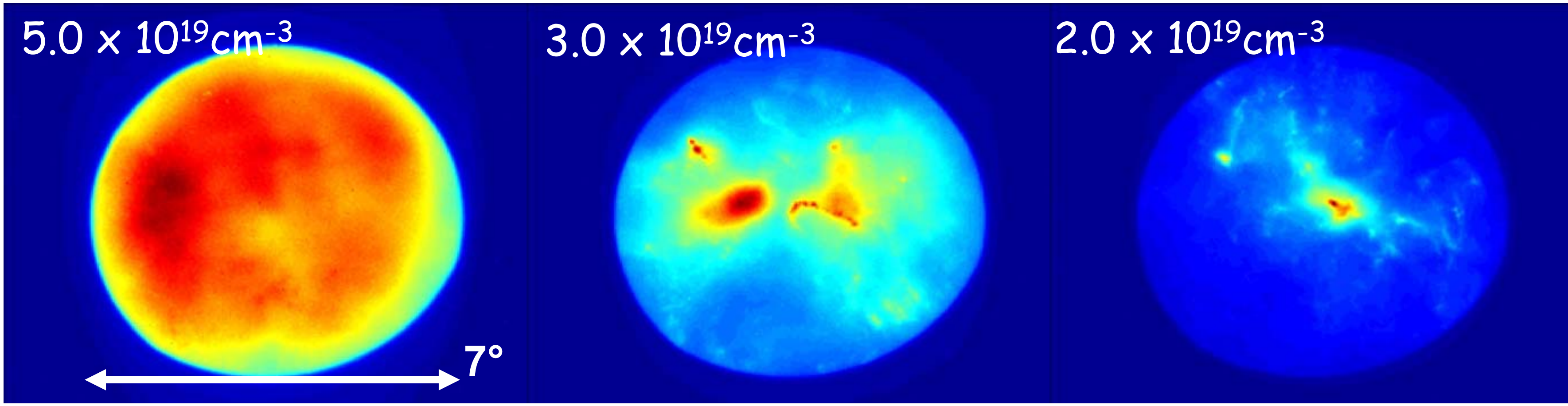
Time evolution of electron spectrum



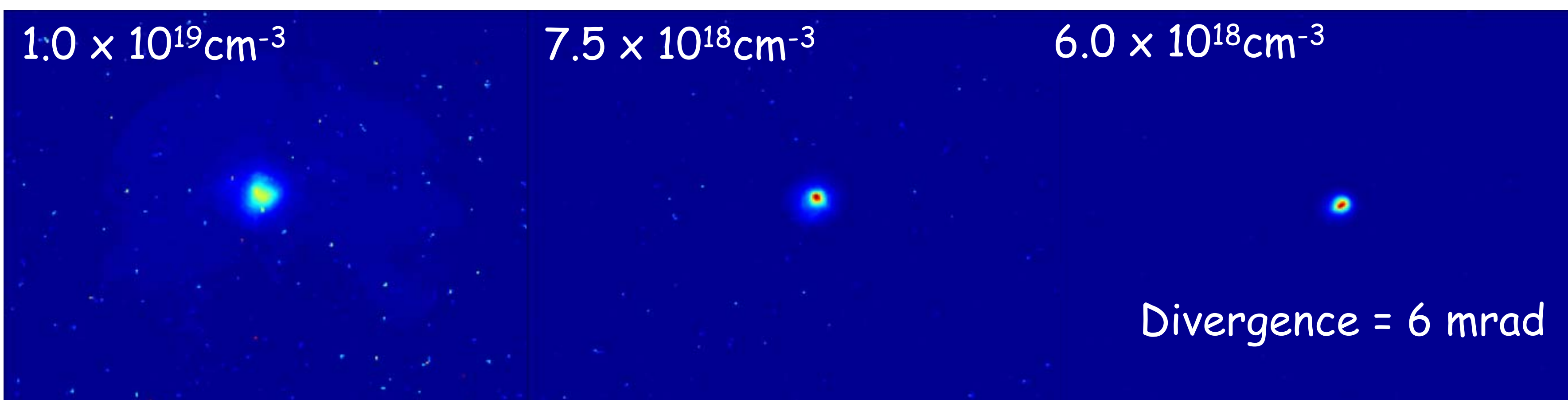
Pukhov & Meyer-ter-Vehn, Appl. Phys. B 2002

Improvement of spatial quality: density scan

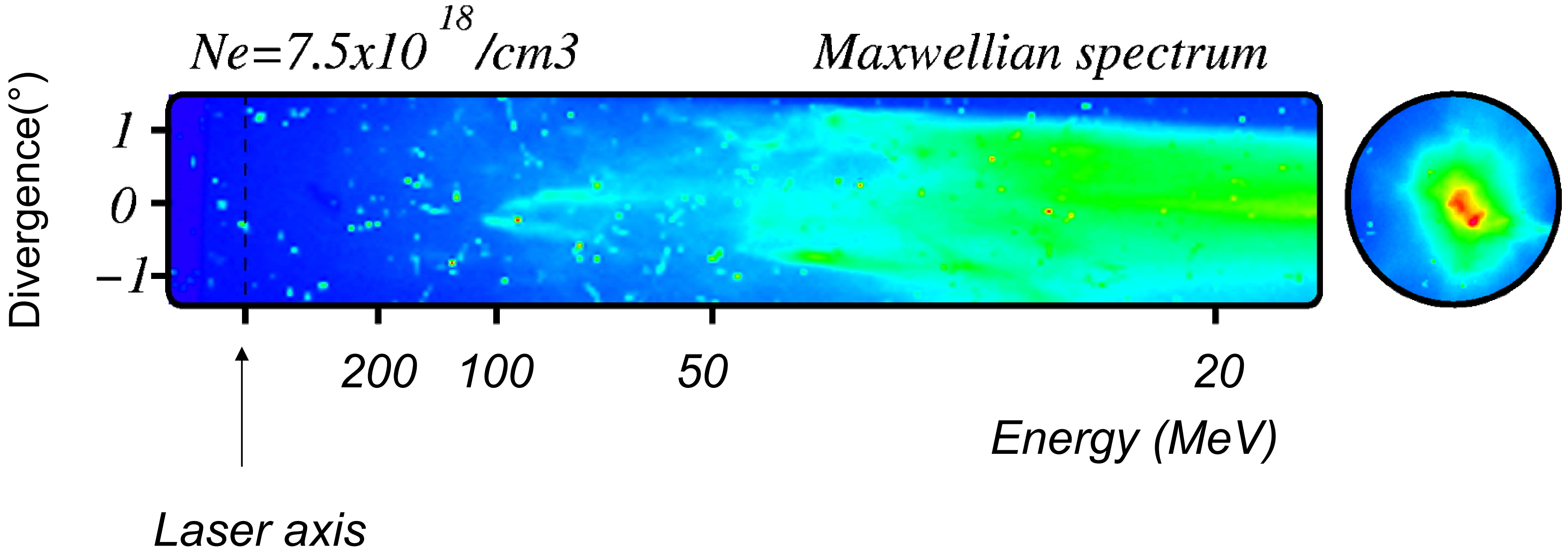
SMLWF → **Laser wakefield**



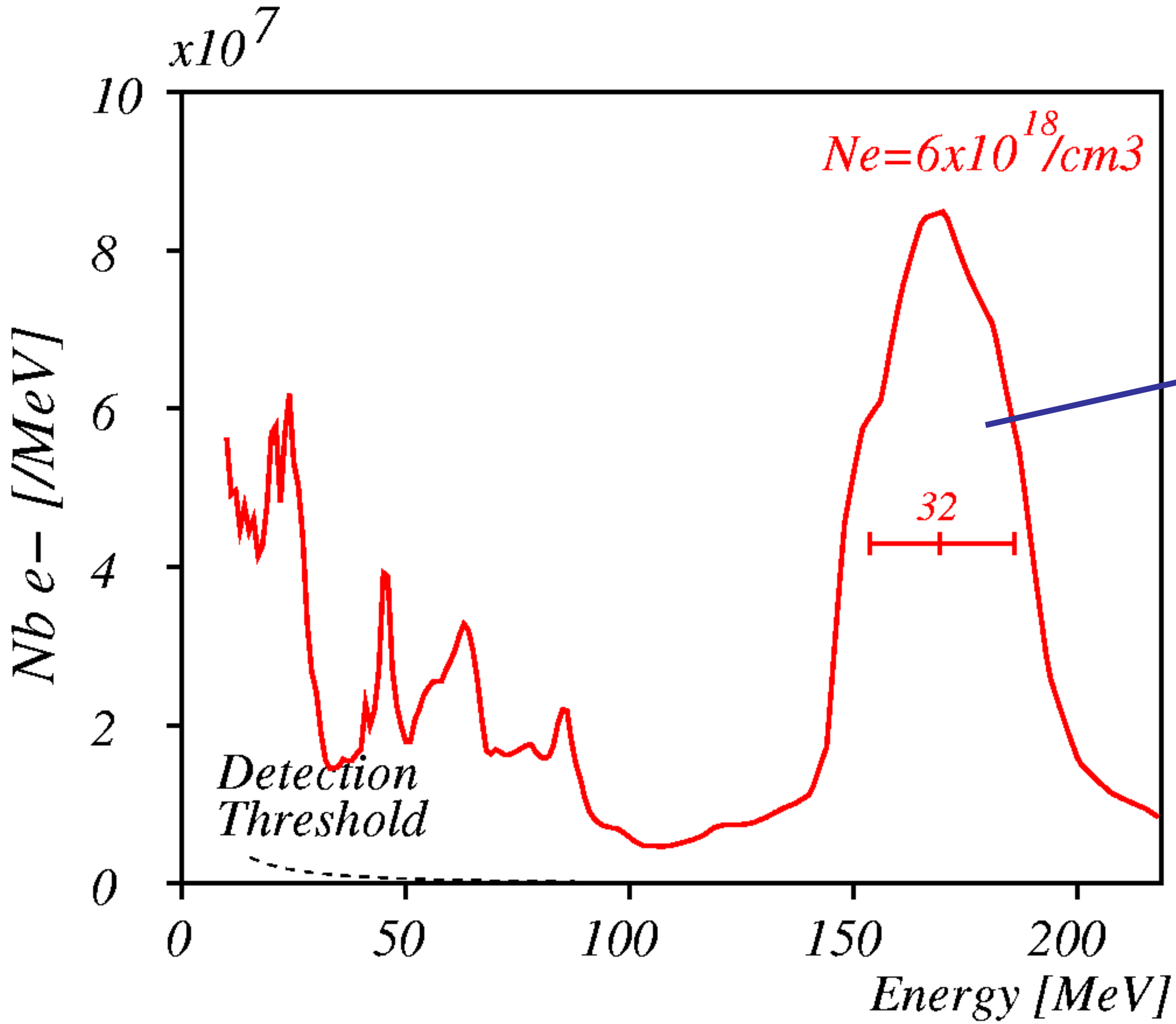
Laser wakefield → **Bubble regime ?**



Improvement of electron energy distribution

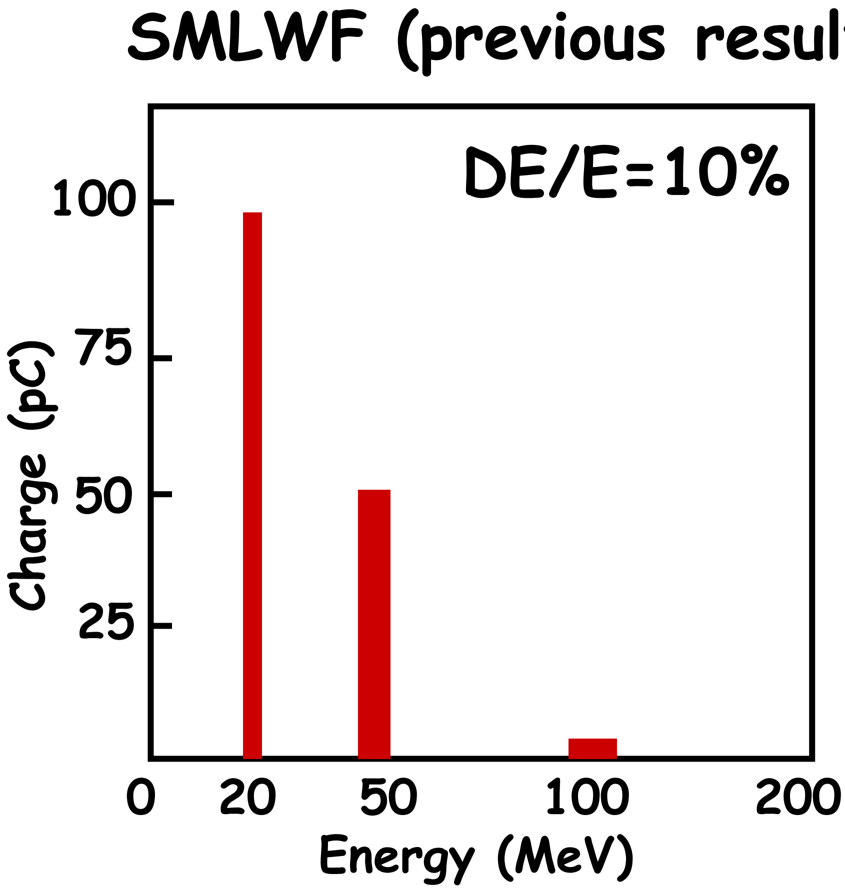


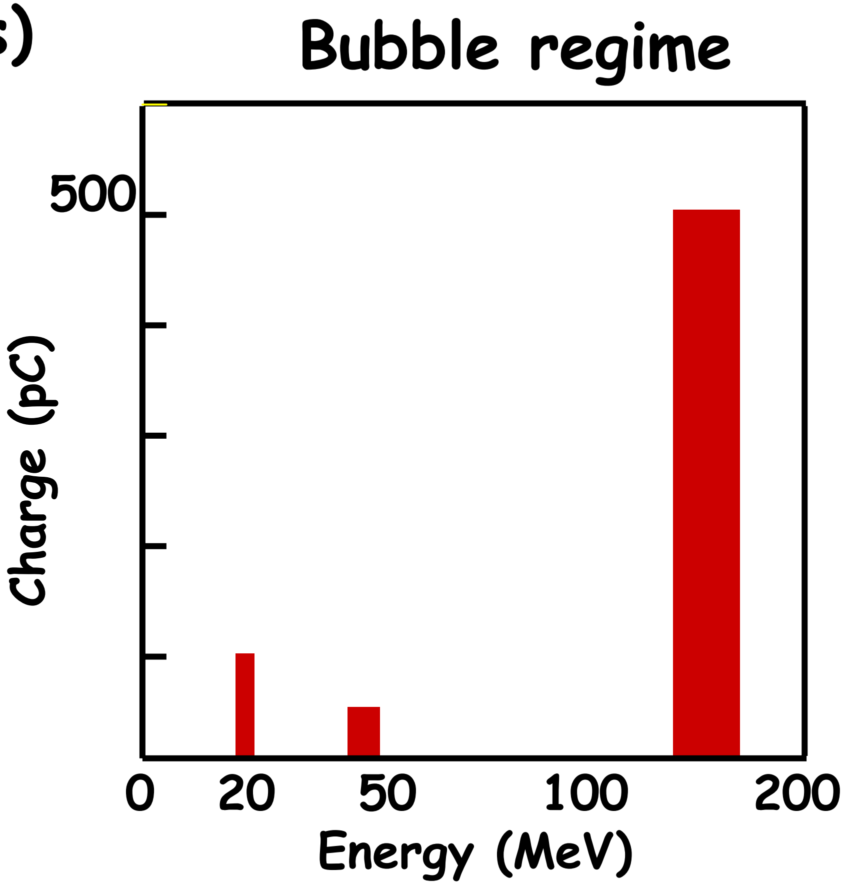
Quasi-monoenergetic electron spectrum at 170+/-20 MeV



From ICT:
500 pC +/-200 pC in the bump at 170 MeV

SMLWF / Bubble regime: Improvement of the charge





Charge at high energy (170 MeV) improved by more than 1000

Conclusions

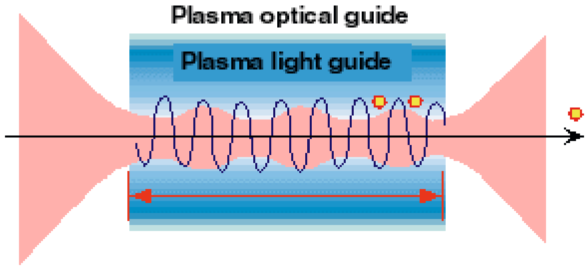
- Recent results : improvement of beam quality
  - spatial beam quality (5-10 mrad)
  - charge at high energy
  - control of electron spectrum: MONOENERGETIC
- Work in progress
  - measurement of bunch duration : evidence of sub-30 fs
- Future:
  - electron sources up to ≈ 1 GeV (nC, <1 ps)

Perspectives

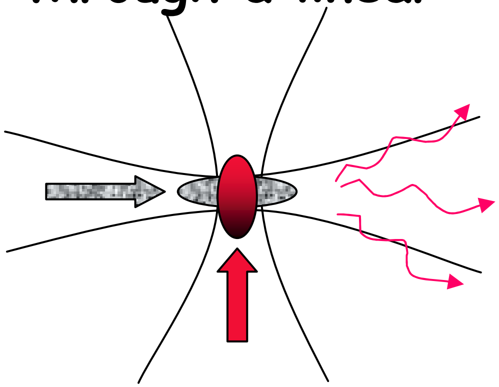
- Main problem with current result: beam is unstable
  energy spectrum fluctuates

- Cause:
  - Propagation relies on self-focusing which is an unstable mechanism
  - Injection mechanism is highly nonlinear

- Solution to propagation:
  - use a guiding device



- Solution to injection
  - use external injector. But needs to develop ultrashort injectors
  - trigger injection using another laser beam through a linear mechanism (such as interferences)



Possible impact of laser generated particles

X-rays:diffraction
γ-rays:radiography

Medicine
Radiotherapy
Proton-therapy
PET

Electrons and Protons generated by Laser-Plasma Interactions

Accelerator Physics
Injector

Chemistry
Radiolysis

Particle Accelerators
Requirements for High Energy Physics

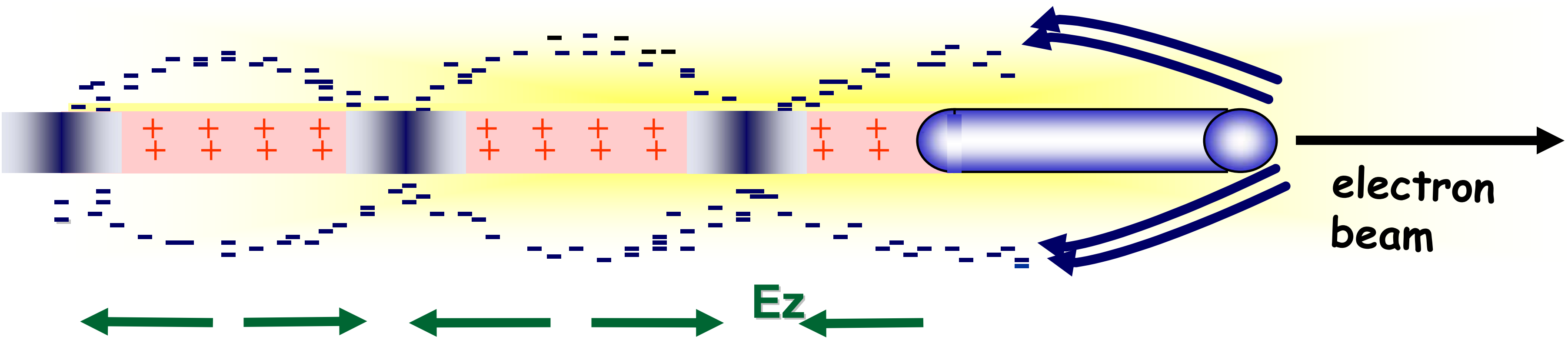
- High Energy
- High Luminosity (event rate)
  - $L = fN^2/4\pi\sigma_x\sigma_y$
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma \sim .1 - 10\%$
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y < 1$ mm-mrad
- Low Cost (one-tenth of $6B/TeV)
  - Gradients > 100 MeV/m
  - Efficiency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

⇨ Requires a feasibility study:

- Think tank ALPAGE at Ecole Polytechnique (LULI, LOA, LLR, LAL…)
- Workshop will be organized in June on this subject (jerome.faure@ensta.fr)

Beam-driven Wakefield Accelerators

- Space charge of beam displaces plasma electrons



- Plasma ions exert restoring force =>
  - •Net Focusing force on beam ($F/r=2\pi ne^2/m$)
  - •Space charge oscillations (short beam)

No diffraction

- Wake Phase Velocity = Beam Velocity (like wake

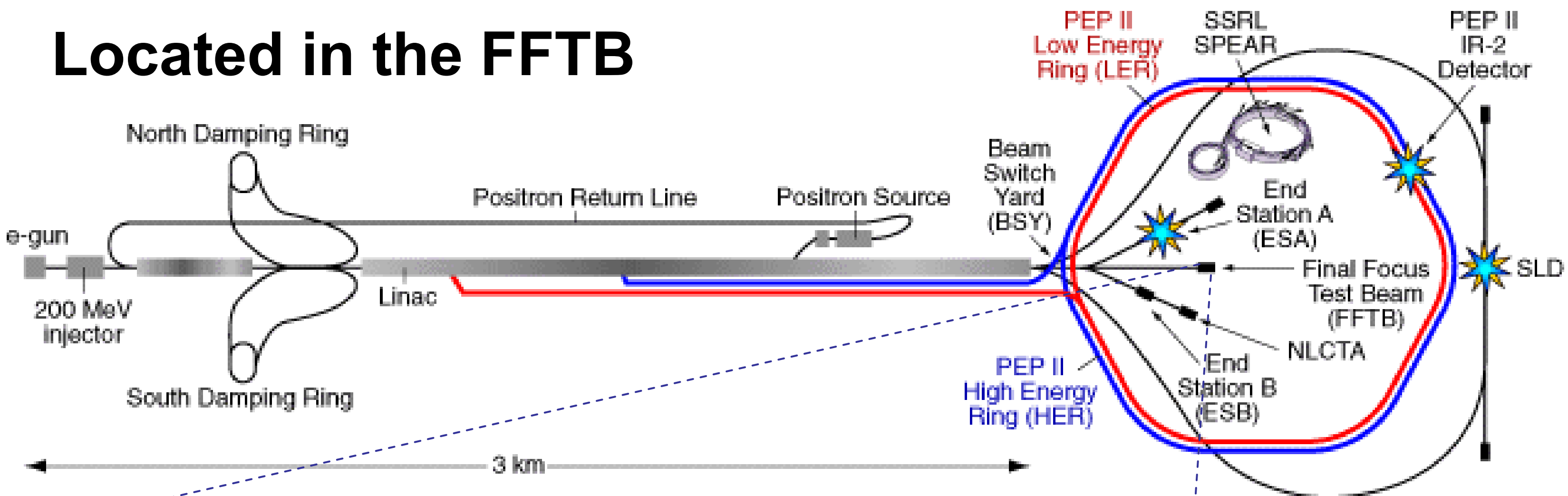
No dephasing

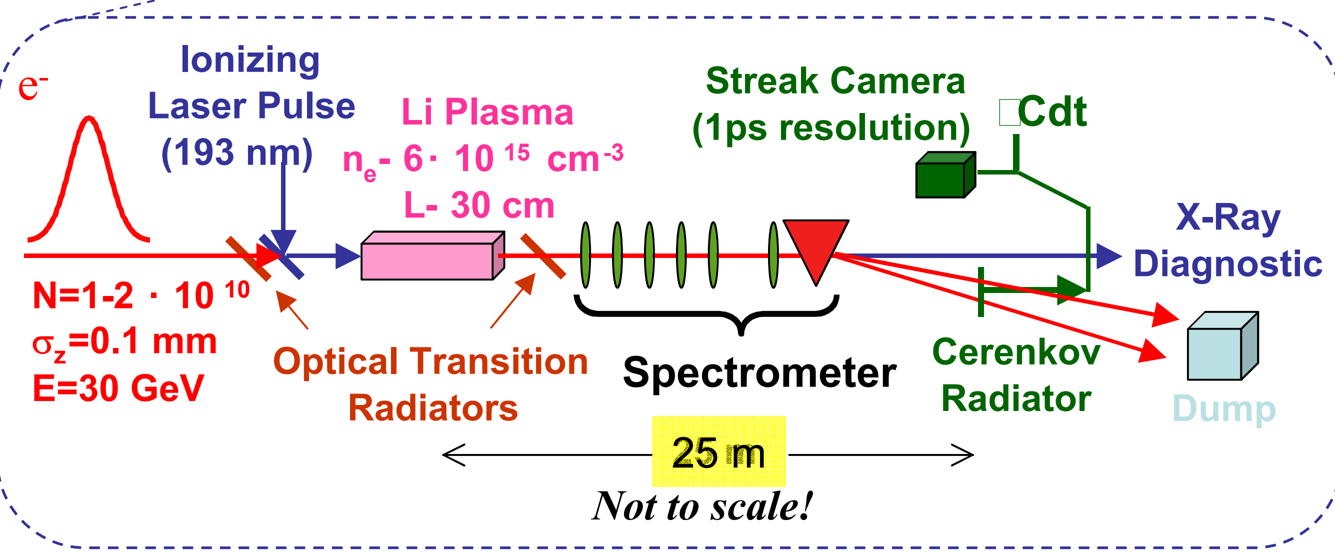
- Wake amplitude $\propto N_b / \sigma_z^2$

PWFA Experiments @ SLAC Share Common Apparatus

Courtesy P. Muggli
USC / UCLA /SLAC

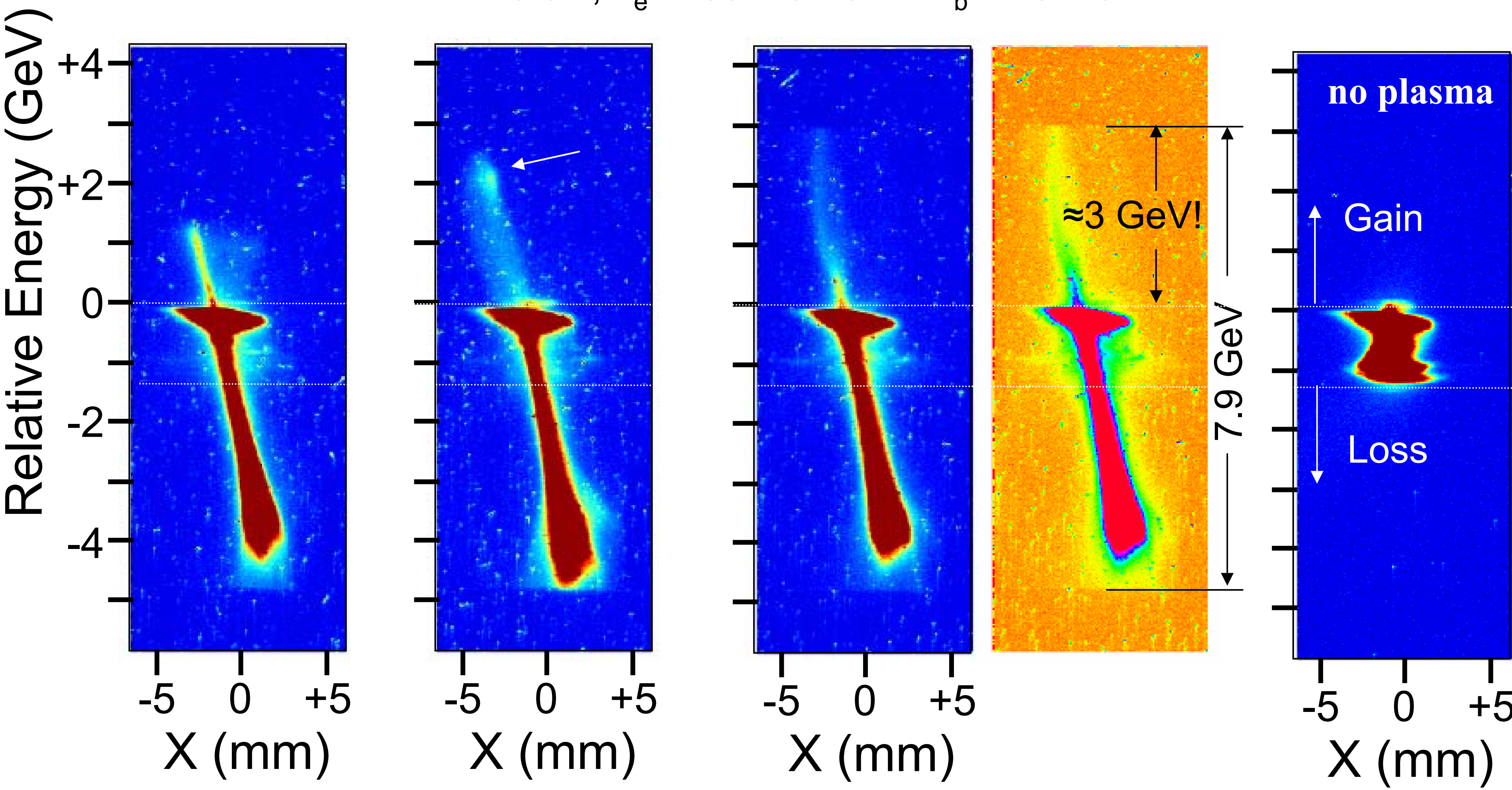
Located in the FFTB





E164X Breaks GeV Barrier

L≈10 cm, $n_e \approx 2.55\times10^{17}$ cm^{-3} $N_b \approx 1.8\times10^{10}$



➡ Energy gain exceeds ≈ 4 GeV in 10 cm

Courtesy P. Muggli
USC / UCLA /SLAC