Laser-plasma accelerators: state-of-the-art and perspectives

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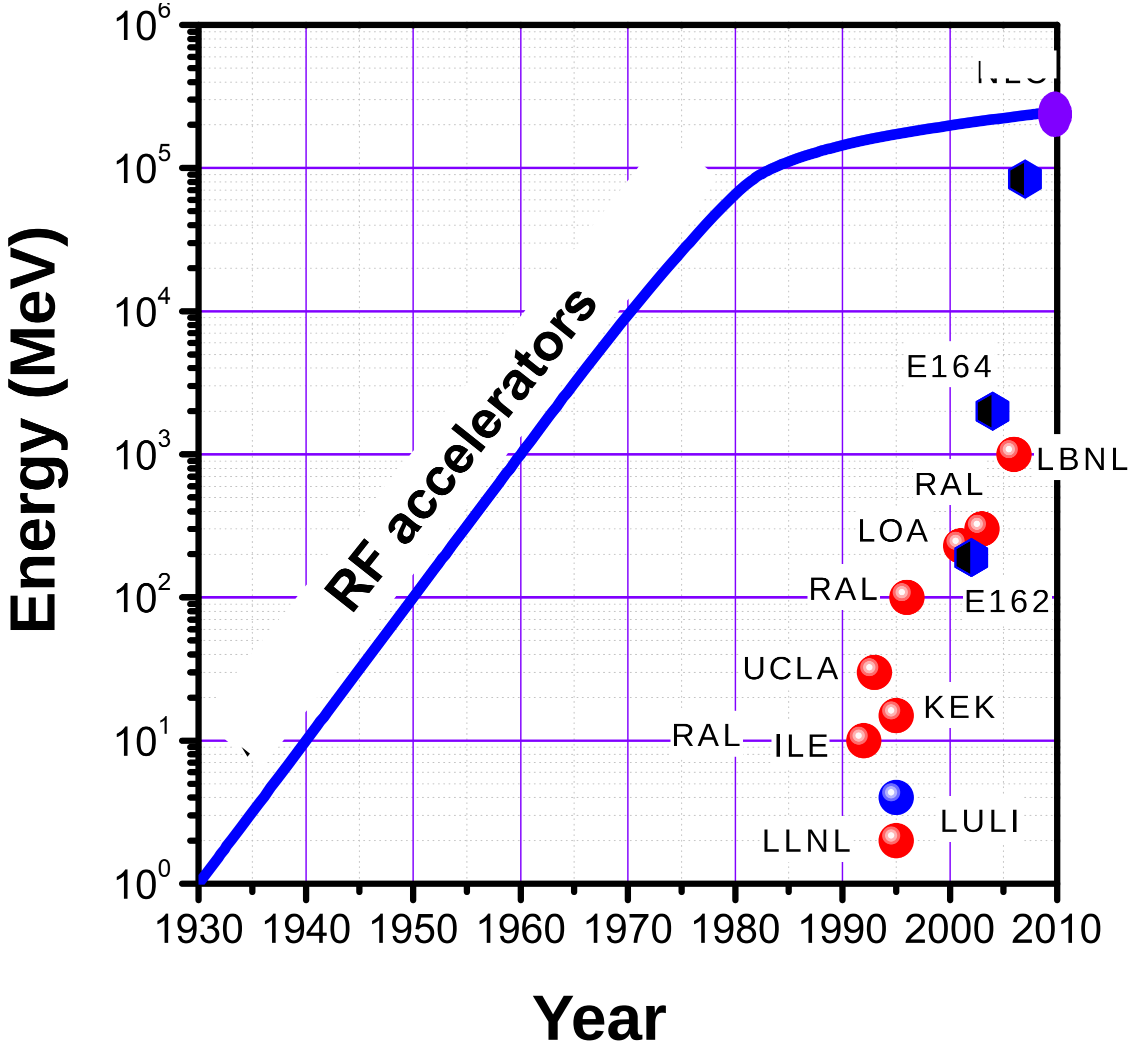
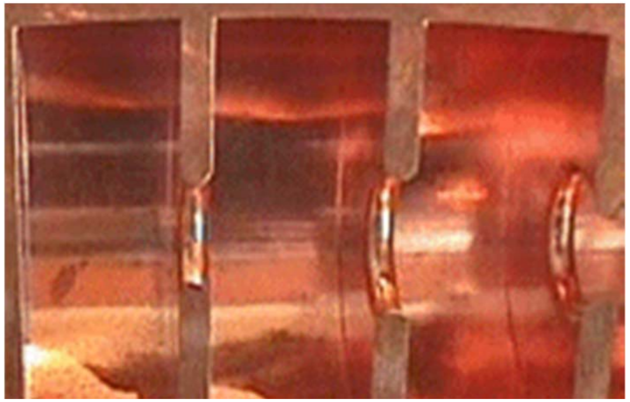
Outline

- Motivation
- Physics of acceleration in a plasma
  - Plasma wave
  - How to create it
  - Properties for acceleration
- Highlights of laser-plasma acceleration
  - Milestones
  - On-going studies
- Conclusion

Limitation of linear accelerators



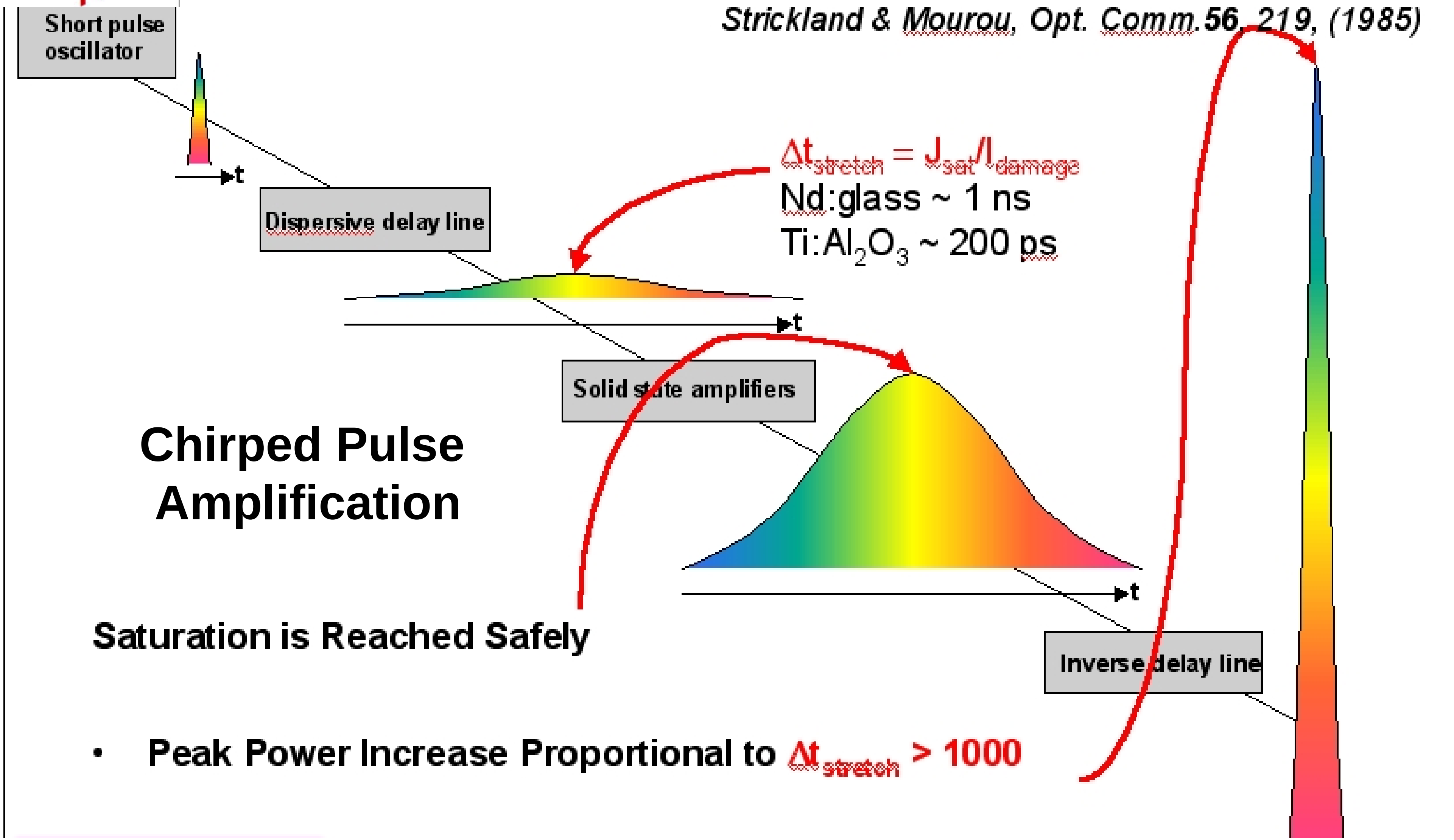


- **RF technology limitation**
  - **E<50 MV/m**
  - **B<10 Tesla**
  - **Synchrotron radiation (e-)**
- **Test of new concepts: accelerators using plasmas**

New concepts and innovative technology

- **Tajima et Dawson, Phys. Rev. Lett. 1979**
  - A plasma wave can be associated to very high accelerating gradients
  - Concept of laser wakefield to excite a relativistic plasma wave
- **Strickland et Mourou, Opt. Comm. 1985**
  - Concept of laser system using laser chirped pulse amplification
  - Short and intense laser pulse facilities have become available at the beginning of the 1990s
- Laser wakefield studies are now in full growth

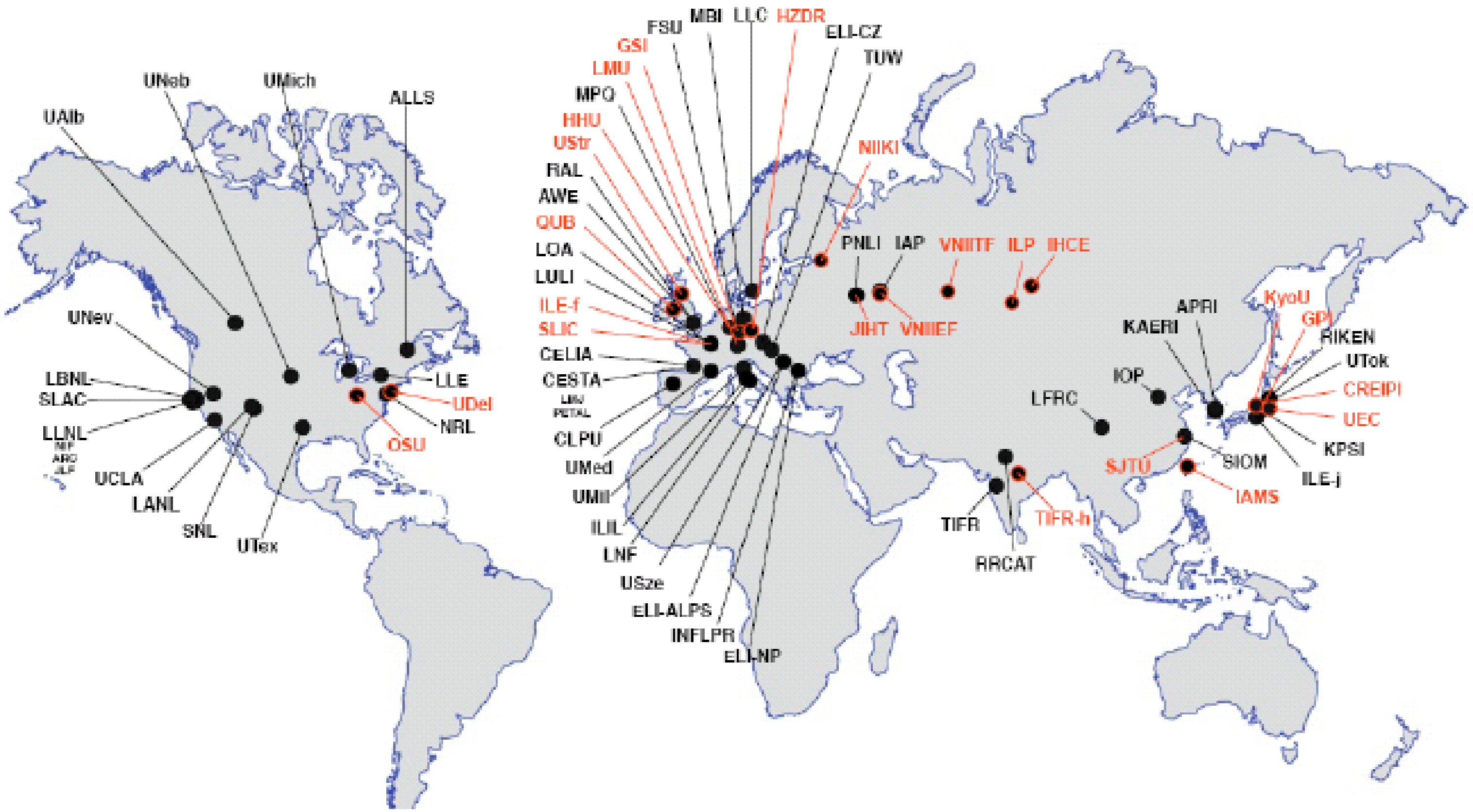
Principle of chirped pulse amplification



100 TW class Laser systems

2010 ICUIL World Map of Ultrahigh Intensity Laser Capabilities

2009
2010



More than half of the groups have research programs related to Laser Plasma Accelerators

Chris Barty, 2011
http://www.icuil.org

Current motivation

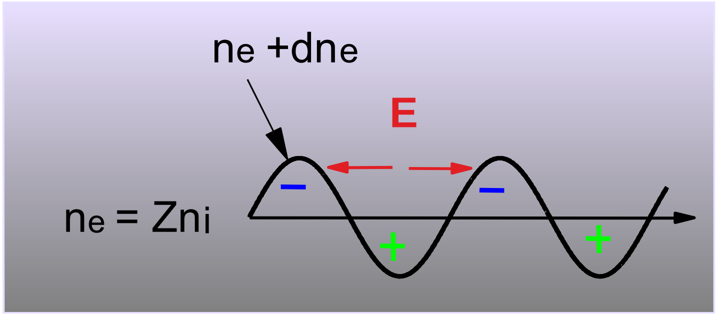
Go beyond the proof-of-principle demonstrations

- Laser plasma accelerators (LPA) constitute electrons and radiation sources (THz, X, gamma)
  - Compact (1GeV, 3cm, 100m²)
  - Very short duration (10 fs)
- Strong potential for evolution
  - Optimisation of the beam properties in the range 100MeV -1GeV
  - Control of the emitted radiation
  - Feasability studies for a high energy accelerator (multi-stages)

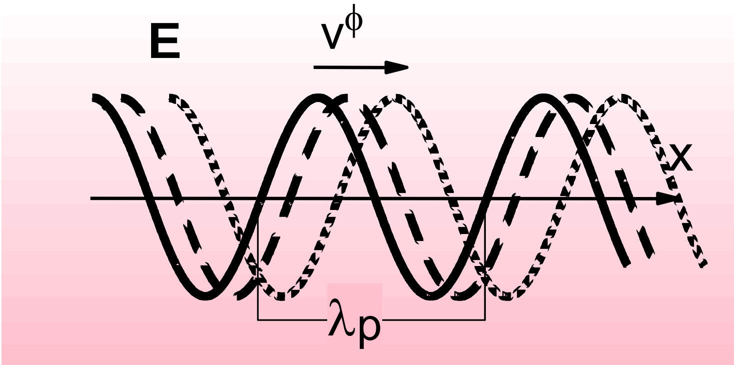
Physics of acceleration in a plasma

Electric field associated to a plasma wave

Accelerating fields > 100 GV/m



- Charge space field and plasma wave

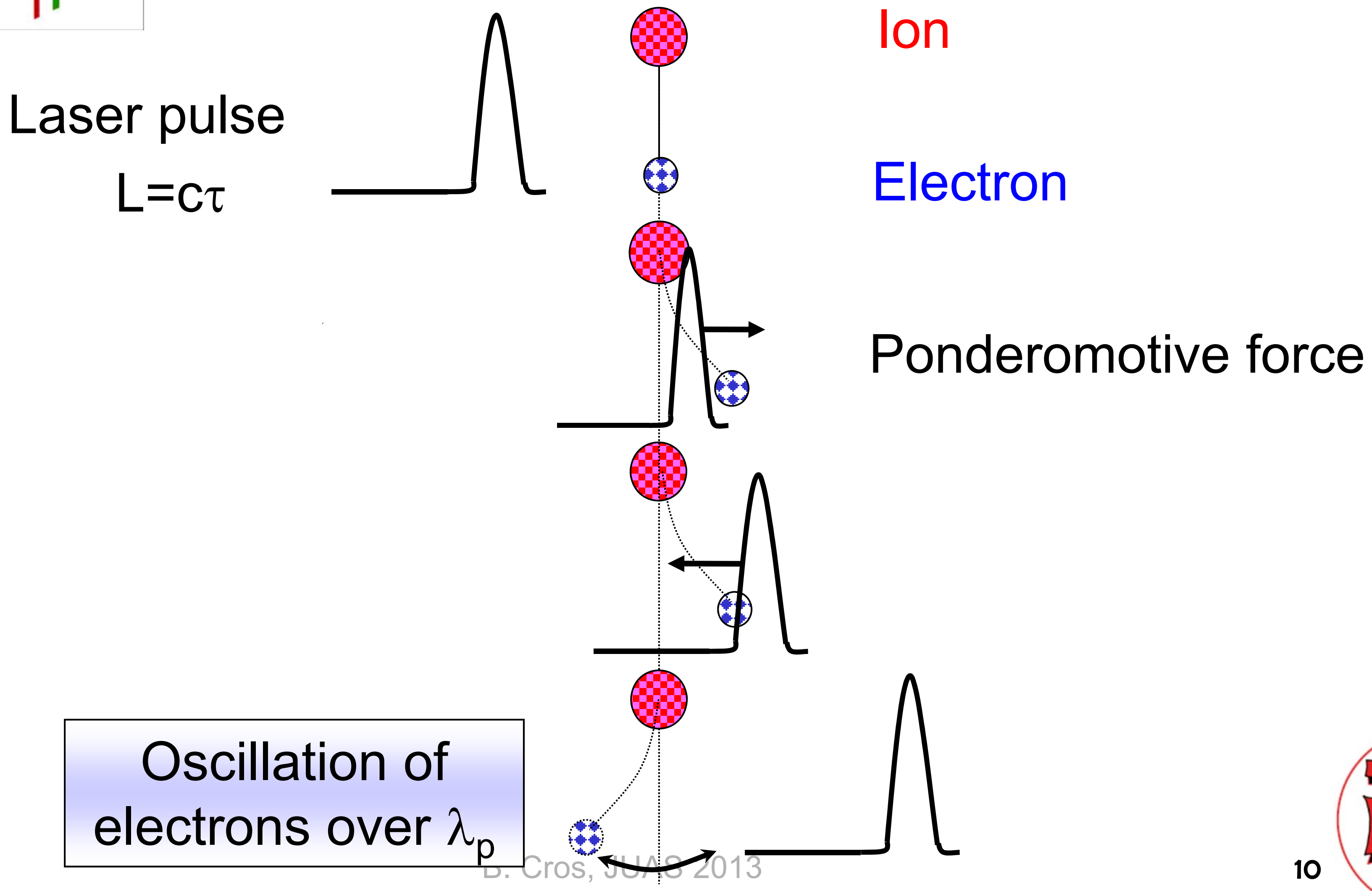


- Relativistic wave:

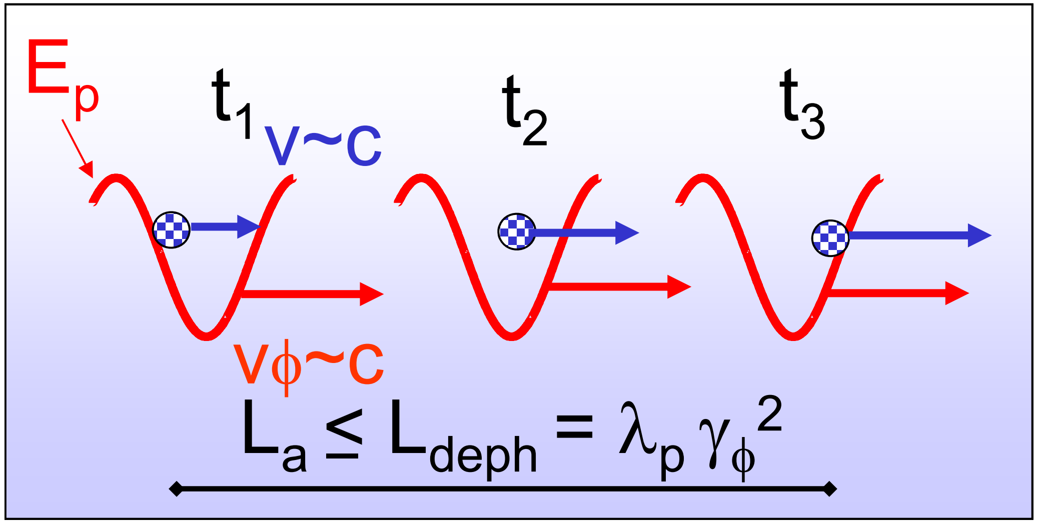
phase velocity of the order of c

$$E(GV/m) = 30\left[\frac{n_e(cm^{-3})}{10^{17}}\right]^{1/2}\frac{dn_e}{n_e}$$

How to create a plasma wave



Dephasing length for accelerated electrons



- Energy gain

$$\Delta W = e\, E_p\, L_a$$

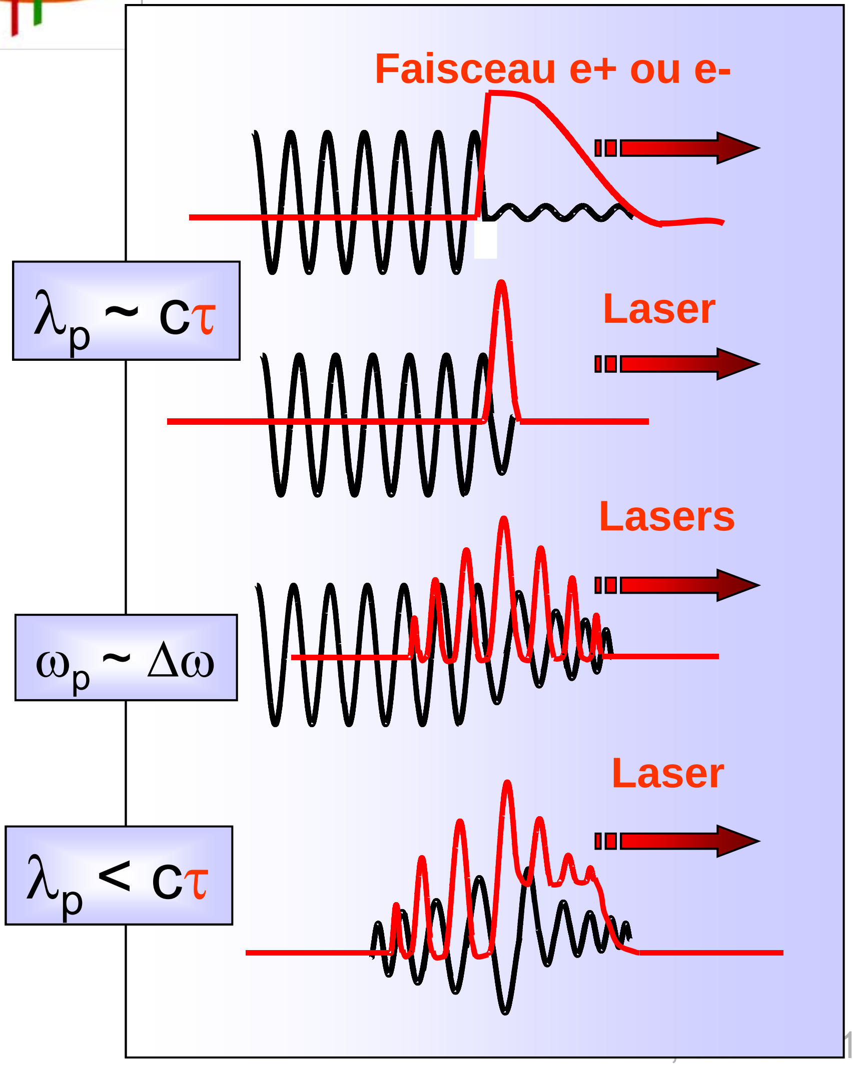
$$\sim 4mc^2\gamma_\phi^{\,2}$$

$$\gamma_\phi = \lambda_p / \lambda_0$$

- $\Delta W \sim n_e^{-1}$
  - $\mathbf{E_p \sim n_e^{1/2}}$
  - $\mathbf{L_a \sim n_e^{-3/2}}$

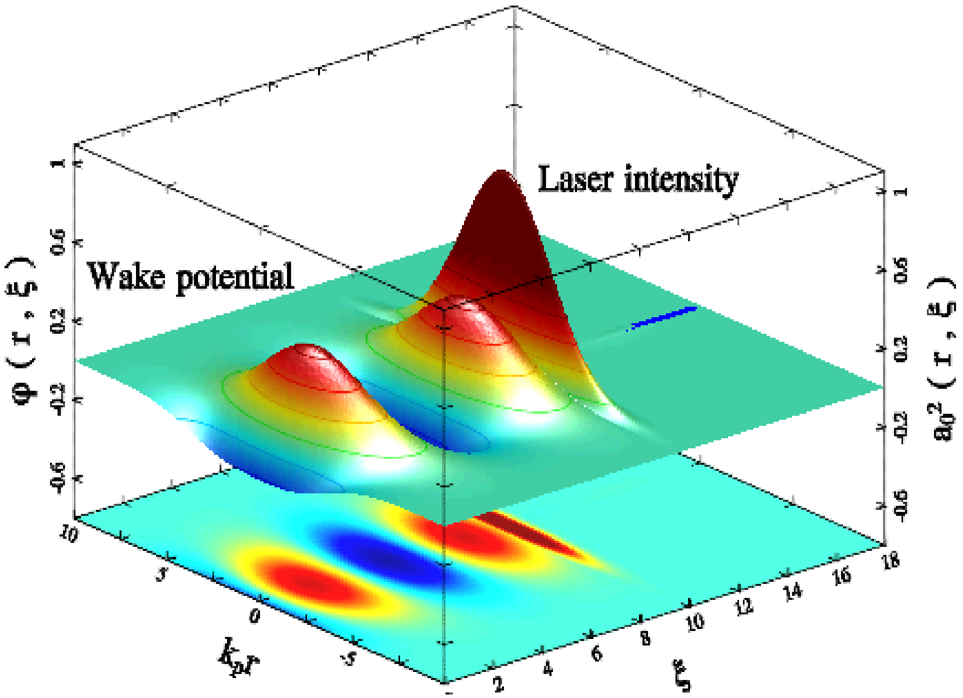
n_e	10^{17}cm^{-3}	10^{19}cm^{-3}
γ_ϕ	100	10
L_a	1 m	1 mm
ΔW_{max}	20 GeV	200 MeV

Mechanism of excitation of a plasma wave



- Plasma wakefield
  - Linear, resonant
- Laser wakefield
  - Linear, resonant
- Laser beatwave
  - Linear, resonant
- Non linear wakefield
  - Self-modulated
  - bubble
  - Instability leads to wavebreaking

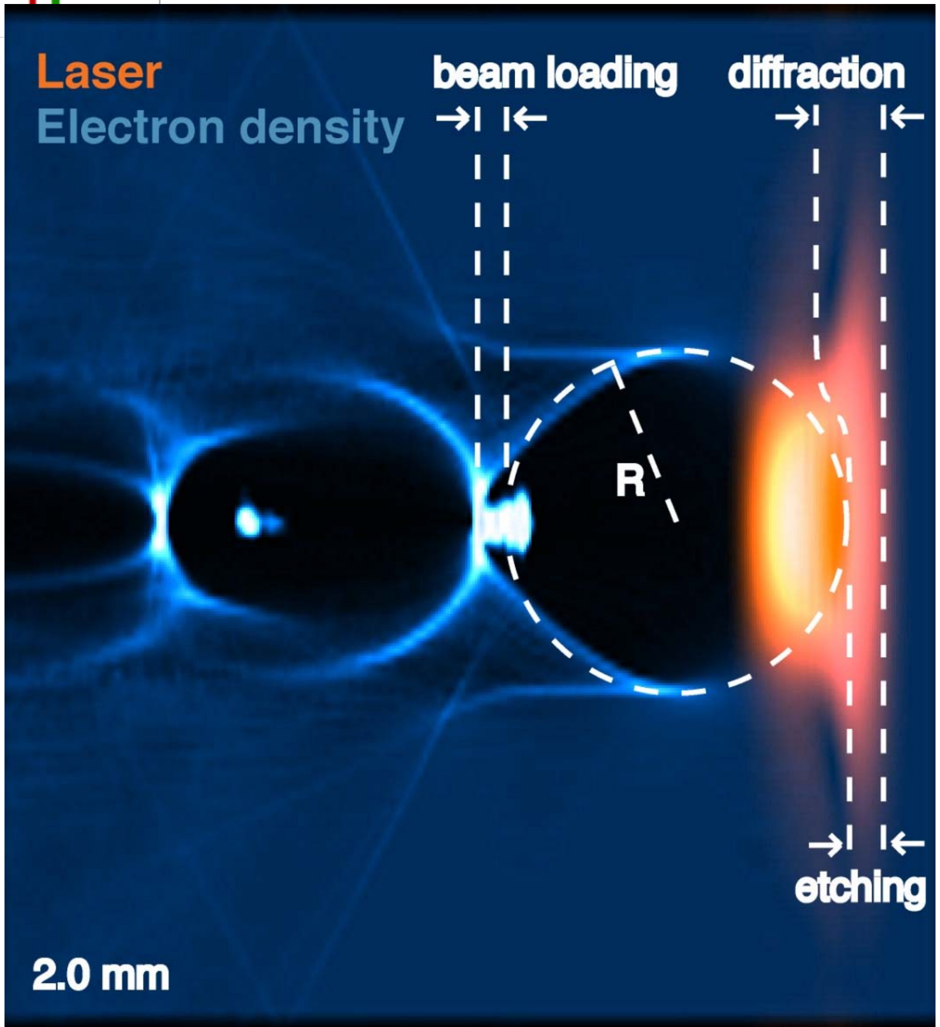
Laser wakefield: « linear » regime



- Ponderomotive force ~ gradient of laser energy
- Accelerating structure sine wave: λ_p~10-100µm
- Accelerating field: 1-100 GV/m
- It is necessary to inject electrons produced by an external source

$$E(GV/m) = 30\left[\frac{n_e(cm^{-3})}{10^{17}}\right]^{1/2}\frac{dn_e}{n_e}$$

Non linear wakefield with self-injection



- Compression and self-focusing of the pulse
- Expulsion of electrons: creation of a bubble (ions)
- Electrons self-injected at the back of the bubble by accelerating and focusing fields
- Injected electrons modify the back of the bubble (beam loading)
- Generation of betatron radiation

Wei Lu talk, HEEAUP05 – UCLA & IST

Energy gain in a laser plasma accelerator

$$\Delta W = e\, E_p\, L$$

- The length of acceleration is determined by
  - The dephasing of electrons entering a decelerating phase of the plasma : $L_{deph} \propto 1/\, n_e^{3/2}$
  - The damping of laser energy $L_{am} \propto 1/\,(a_0^2\, n_e^{3/2})$
- Optimum length: $L_{deph} \sim L_{am}$ and $a_0 \sim 1$

$$\Delta W \propto 1/n_e$$

- **To increase energy gain requires**
  - **To lower electron density**
  - **To increase interaction length**

Milestones of Laser plasma acceleration

Pioneering work and first advances

- Original proposal for plasma accelerators

  PRL Tajima et Dawson 1979
- Proof of principle as soon as 1993: UCLA et LULI
- First peaked spectra in 2004:

  RAL et LOA

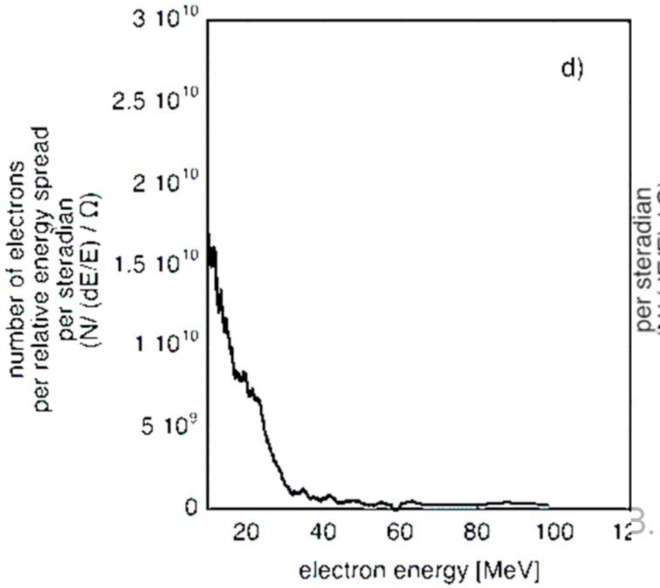
Breakthrough in 2004: Better quality spectra

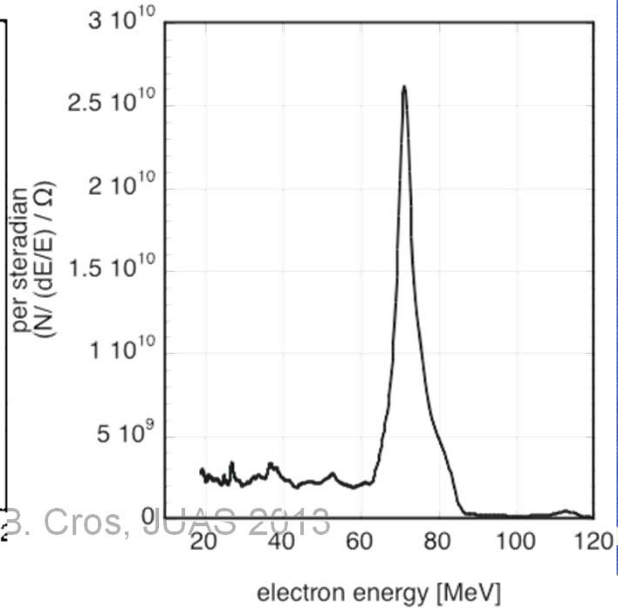
- Obtained by 3 groups
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

$L_{laser} \sim \lambda_p$

High intensity

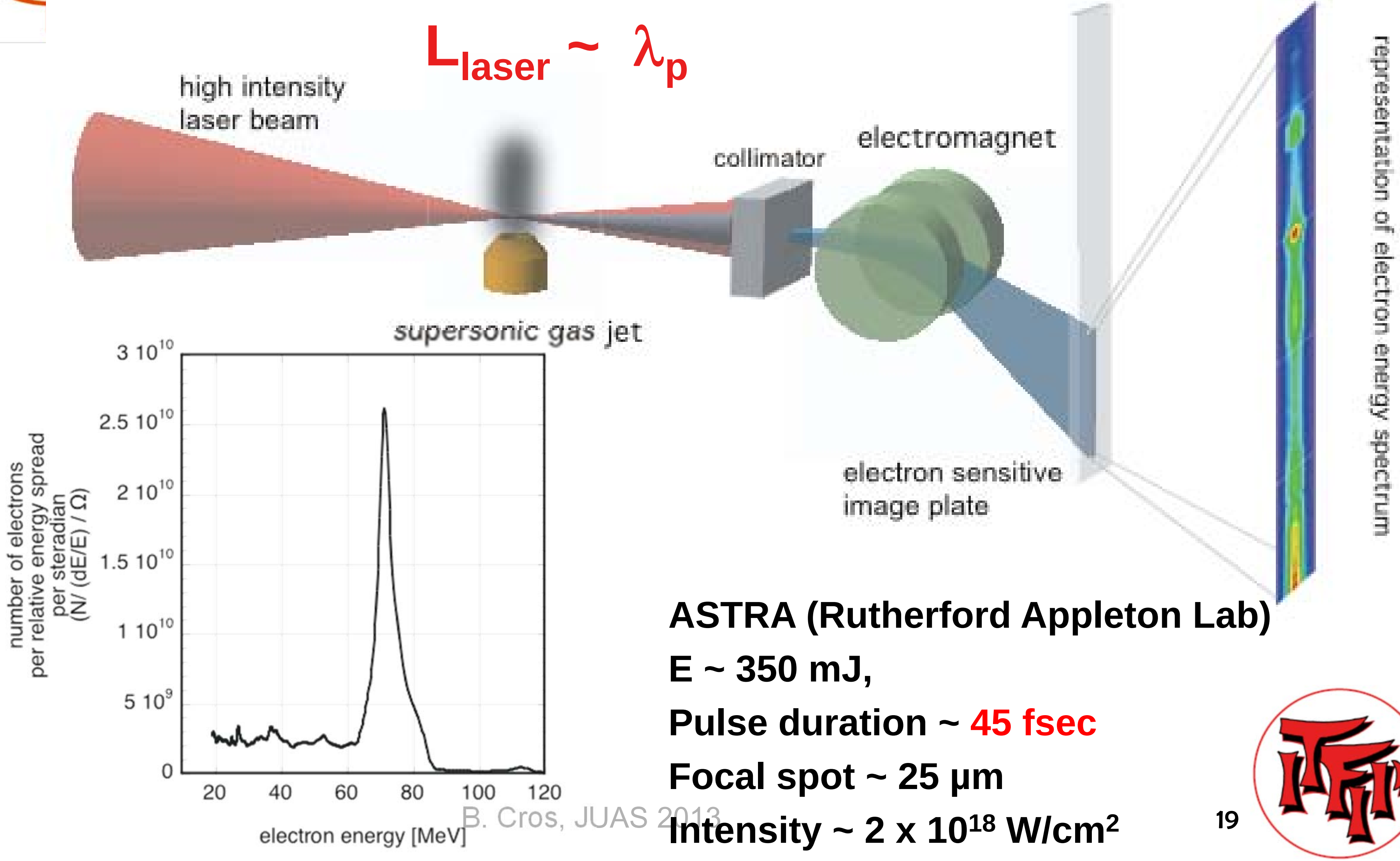
$L_{laser} > \lambda_p$ ⟹ $L_{laser} \sim \lambda_p$





Typical experimental set-up using gas jet target

$L_{laser} \sim \lambda_p$



ASTRA (Rutherford Appleton Lab)

E ~ 350 mJ,

Pulse duration ~ 45 fsec

Focal spot ~ 25 µm

Intensity ~ 2 x 10^{18} W/cm^2

Current trends of LPA

- **Status**
  - High accelerating gradients demonstrated
  - Agreement with theory
  - Broad spectra due to inadequate injectors

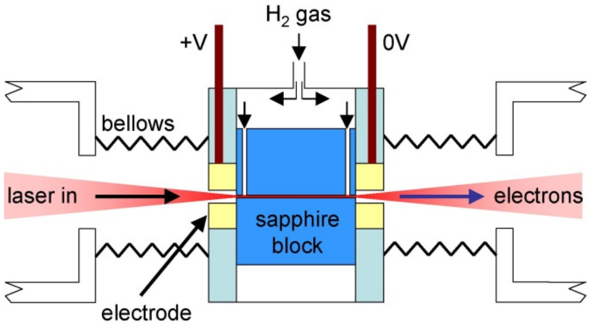
- **Objective:** control the properties of the accelerated beam

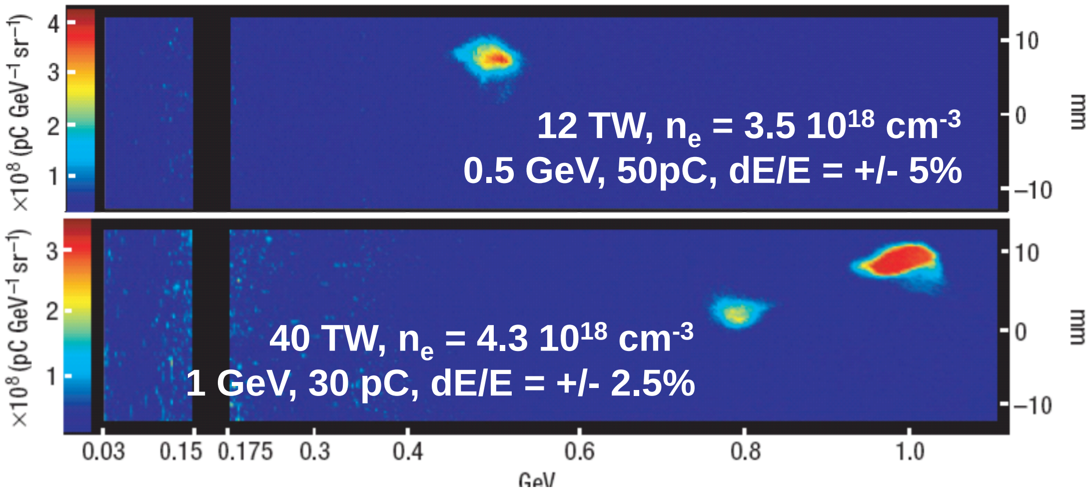
- **Main issues**
  - Increase acceleration length
  - Inject electrons in the accelerating structure in a precise and controlled way

- **The methods depend on the acceleration regime and on the required electron beam characteristics.**

Performance of LPA (energy)

L = 33 mm, diam 190µm
r spot (1/e²) = 25 µm
Laser LBNL 40fs, 1.6J



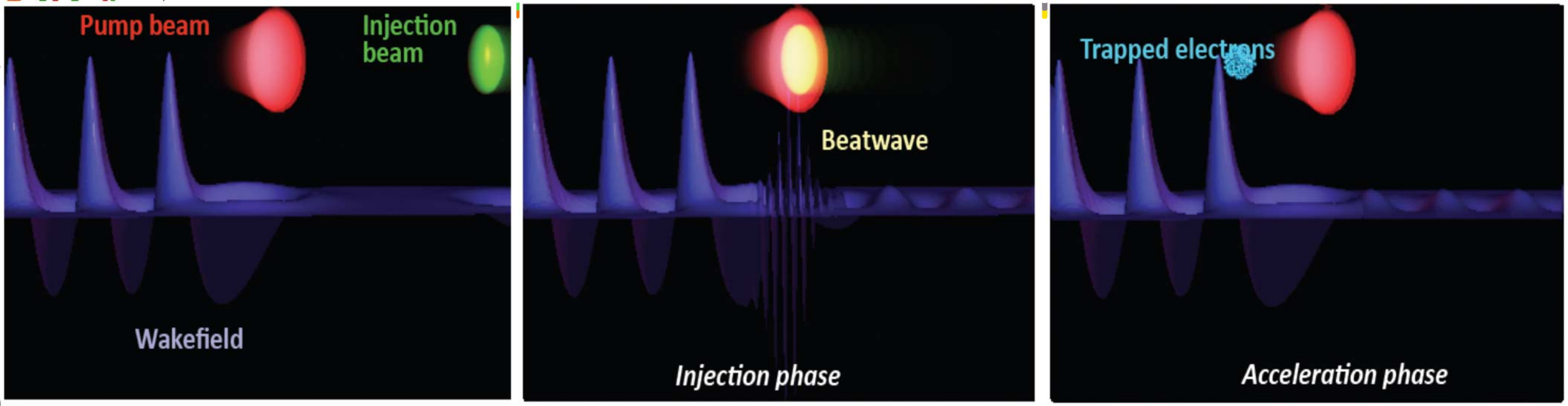


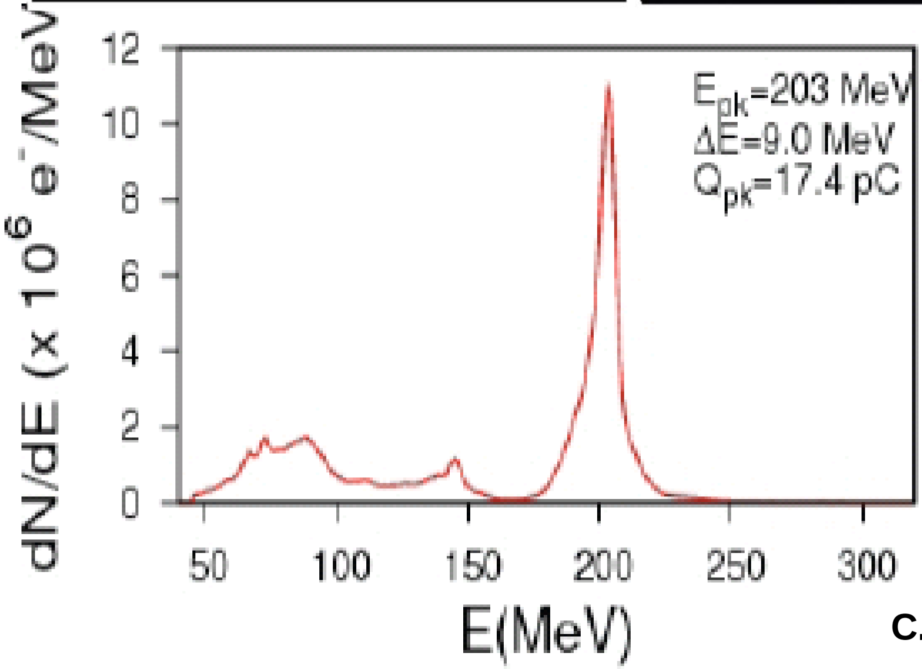
- Existing lasers with power <100TW produce an electron bunch with an energy of the order of 1 GeV over a length of 3 cm

  - 40TW
  - length 3 cm in a plasma channel
  - Divergence 1.6mrad (rms)

Leemans et al. Nature **Physics 2, 696 (*2006*) Berkeley+guiding Oxford**

Control of injection by colliding laser beams



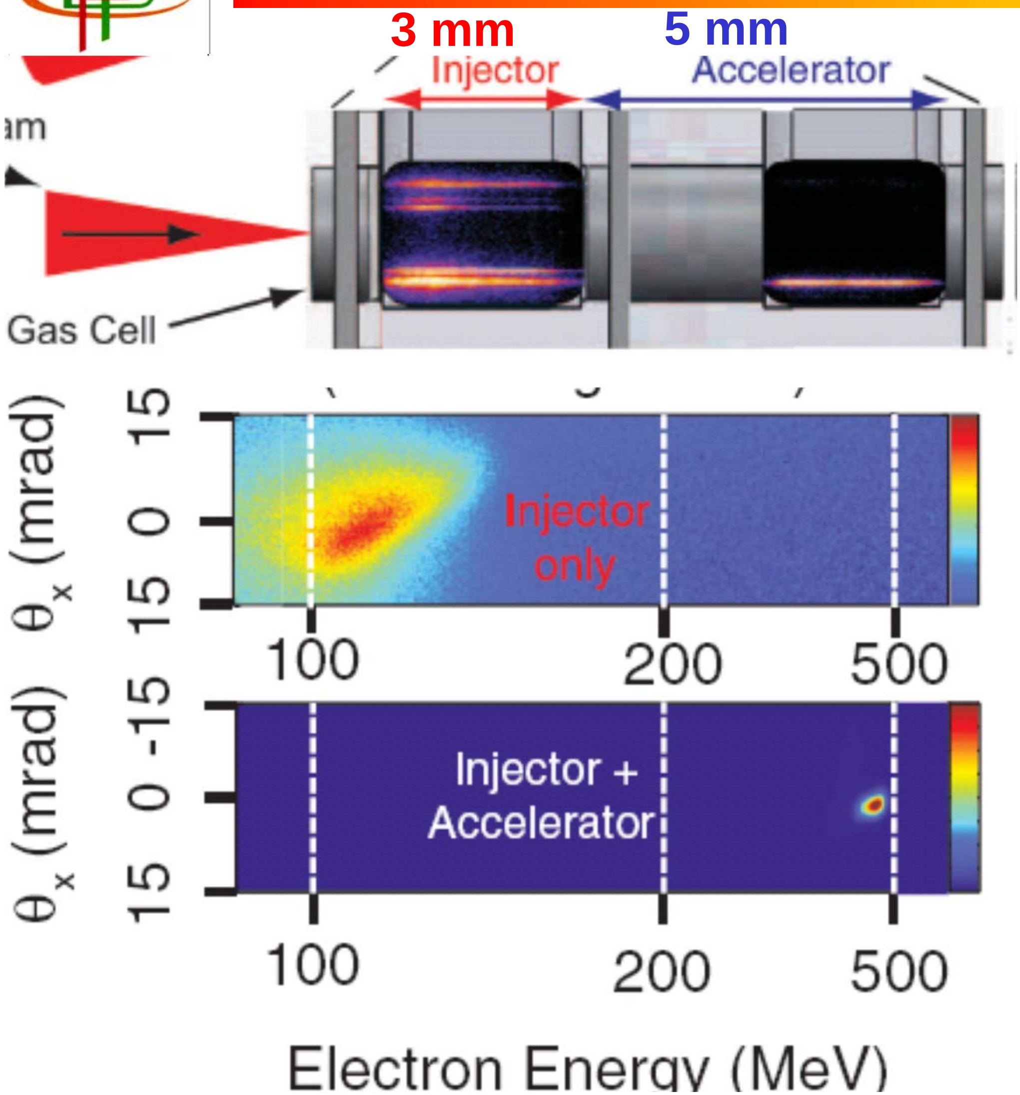


- Stabilisation of injection
- Control of electron energy

J. Faure *et al.*, Nature (2006)

C. Rechatin *et al.*, Phys. Rev. Lett. (2009)

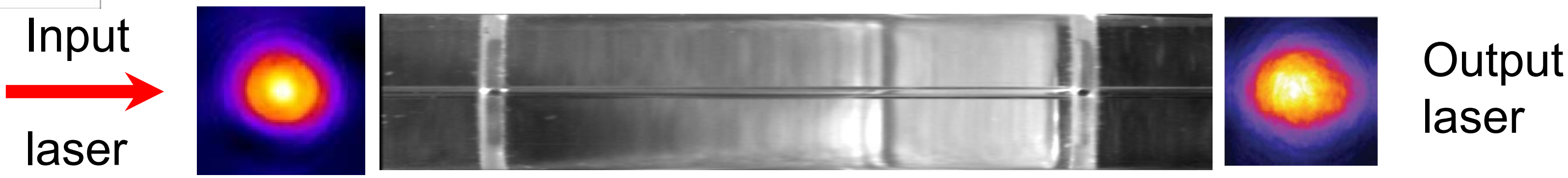
Test of electron injection controlled by ionisation



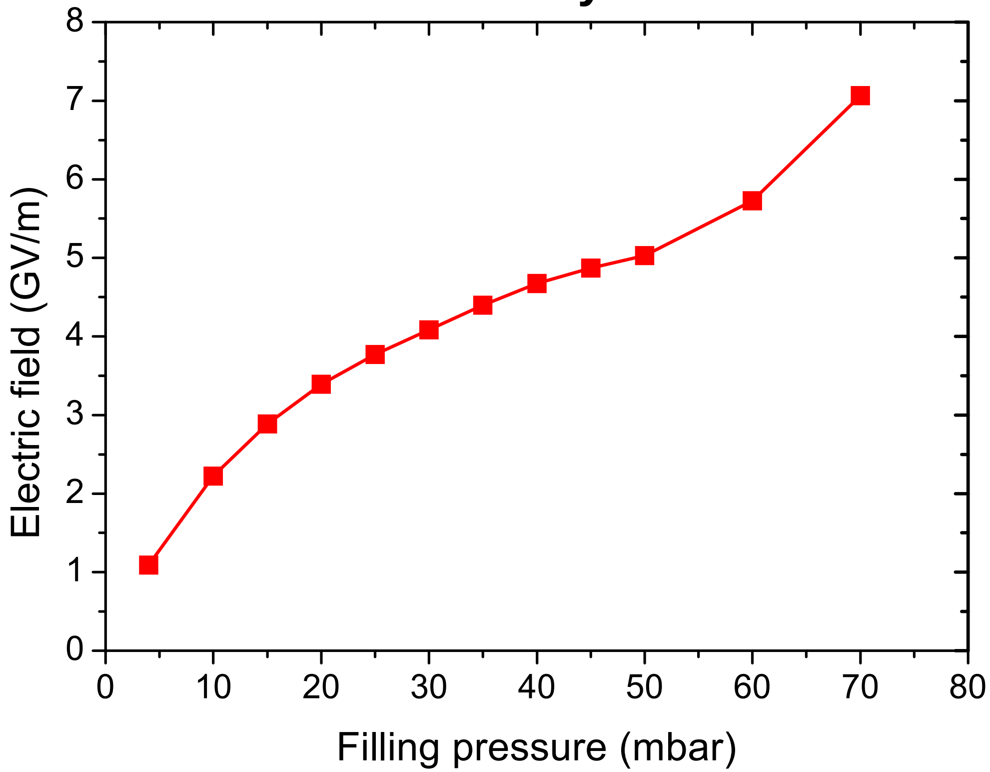
- Laser 40TW, n_e=3x10^{18}cm^{-3}
- Impurities (0.5% Nitrogen) in the injector:
  - Ionisation at the peak of the laser pulse controls the time when electrons are created
- Lower density accelerator (Helium):
  - Means longer dephasing length ie longer acceleration length

Pollock et al., Phys Rev. Lett 2011 (LLNL)

LPA in the linear regime



Capillary tube D~100 µm, L = 8 cm, filled with hydrogen
Laser intensity ~ 10^{17} W/cm^2 - 4 TW



- Laser guiding by capillary tubes
- Accelerating field in the range (1-10 GV/m) over a long distance (8 cm)
- Measured by optical diagnostic

Wojda et al. Phys. Rev. E 80, 066403 (2009)

Andreev et al. New J. Phys. 12 (2010) 045024.

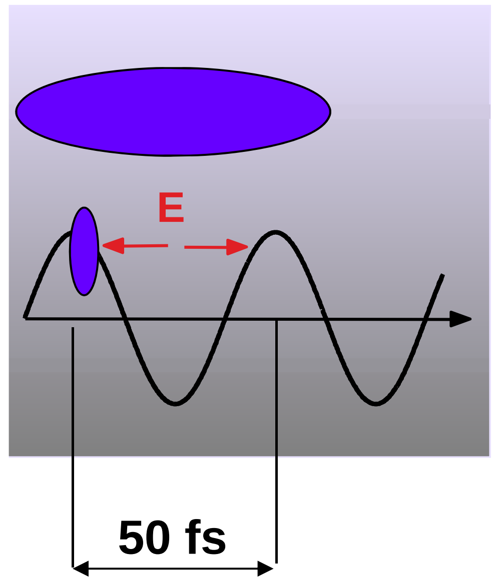
Linear regime requires external injection of electrons

- Accelerating field in the range (1-10) GV/m, controllable process, lower laser intensity
- No wavebreaking implies an external electron source is required
- The process is scalable by using multiple stage

- Next challenge: inject and accelerate electrons

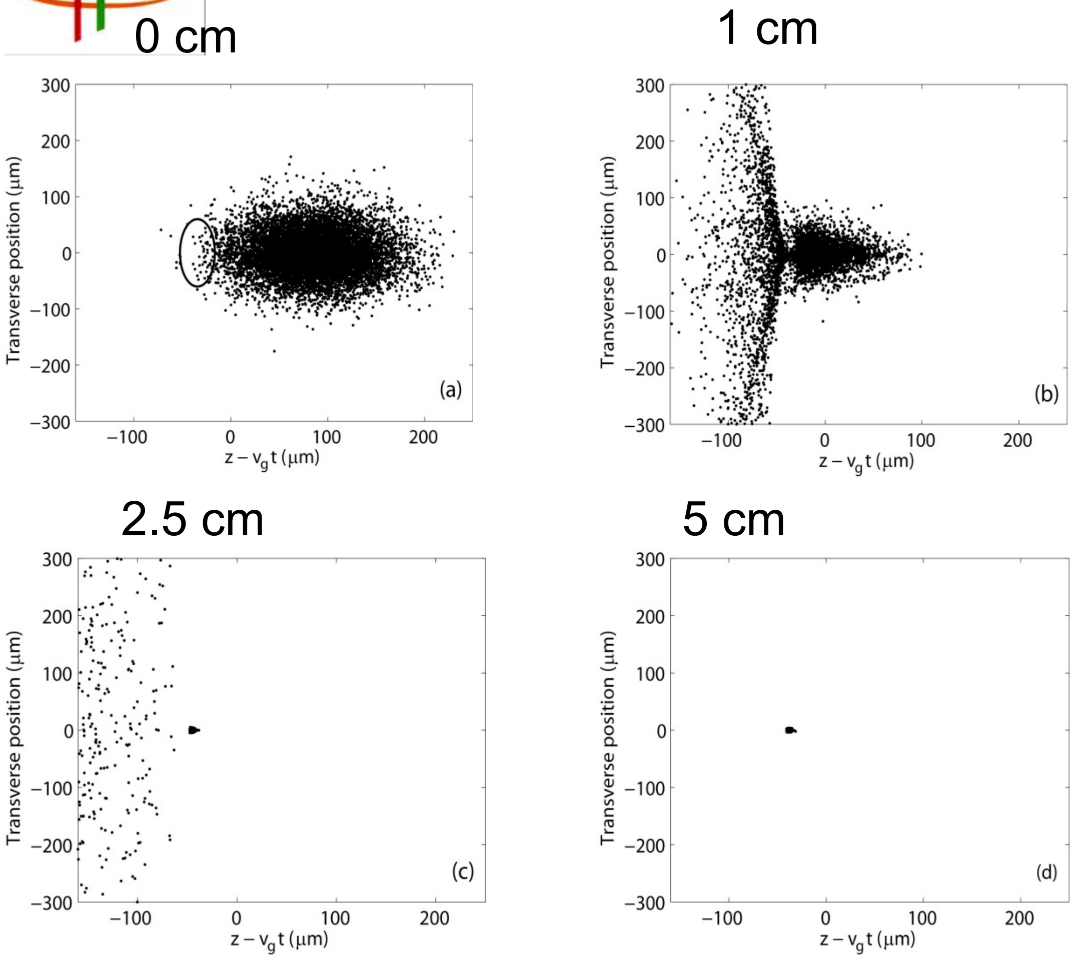
How to synchronise?

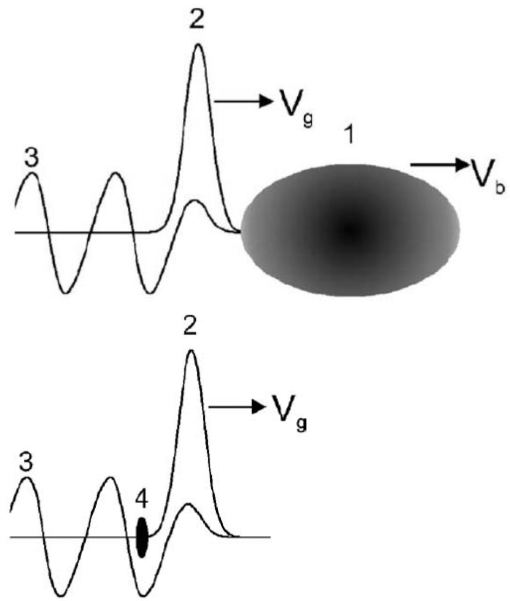
- It is necessary to synchronise the electron bunch and put it in the accelerating phase of the plasma wave
  - Electrons source: PI duration ~ 200 fs
  - Plasma wave period ~ 50fs, ~12 fs useful for acceleration (accelerating and focusing)



- It is necessary to compress the electron bunch and to find an alternative to electronic systems which cannot achieve this time range

Injection of electrons in front of the laser pulse





Trapping, compression and acceleration of an electron bunch in a plasma wave at different positions in the plasma. (U. Twente)

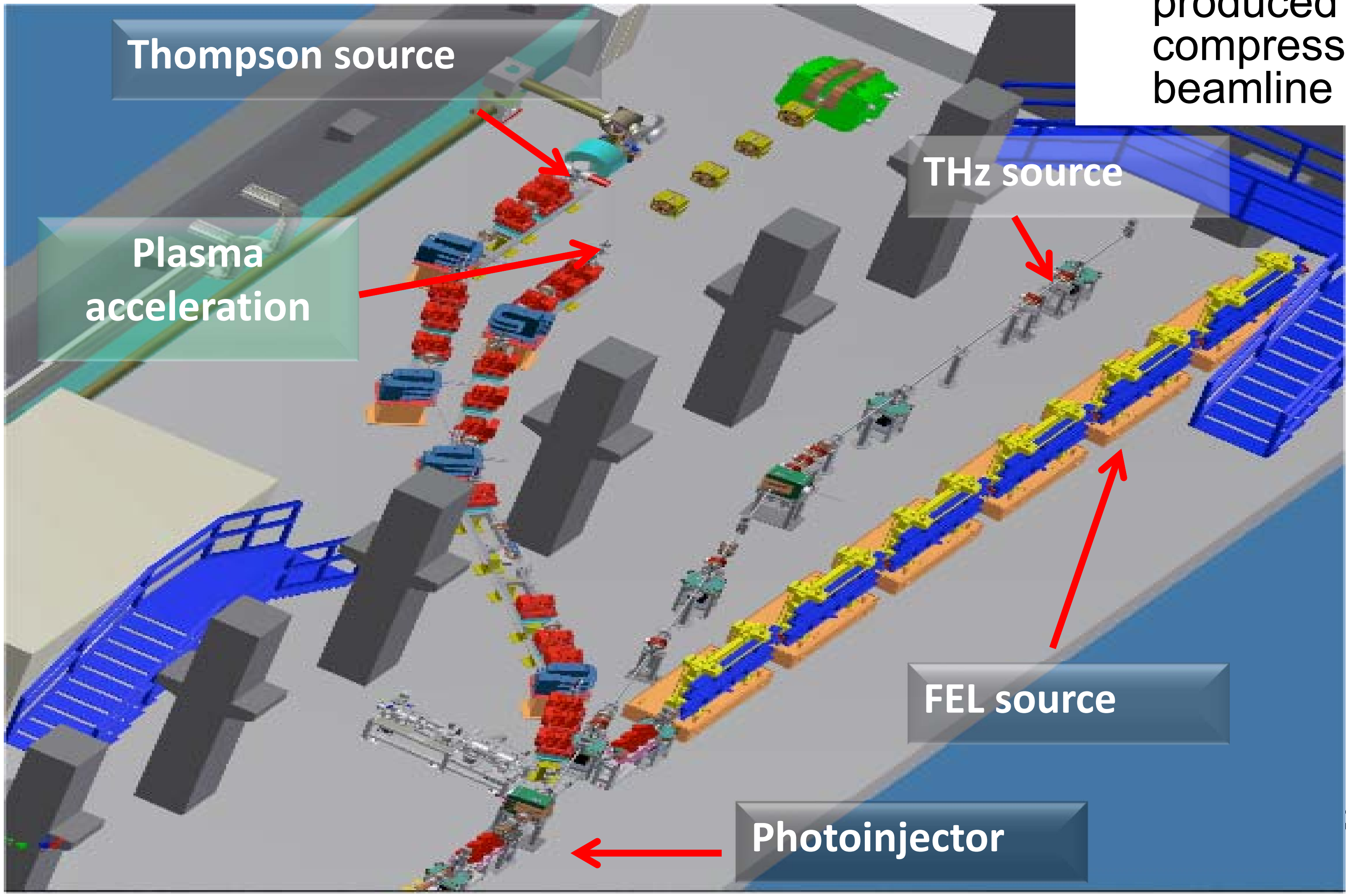
NIM A 566 p.244 (2006)

SPARC_LAB project

Sources for Plasma Accelerators and Radiation Compton

with Lasers And Beams (INFN, Frascati)

- Injection of bunches produced by a PI after compression in the beamline

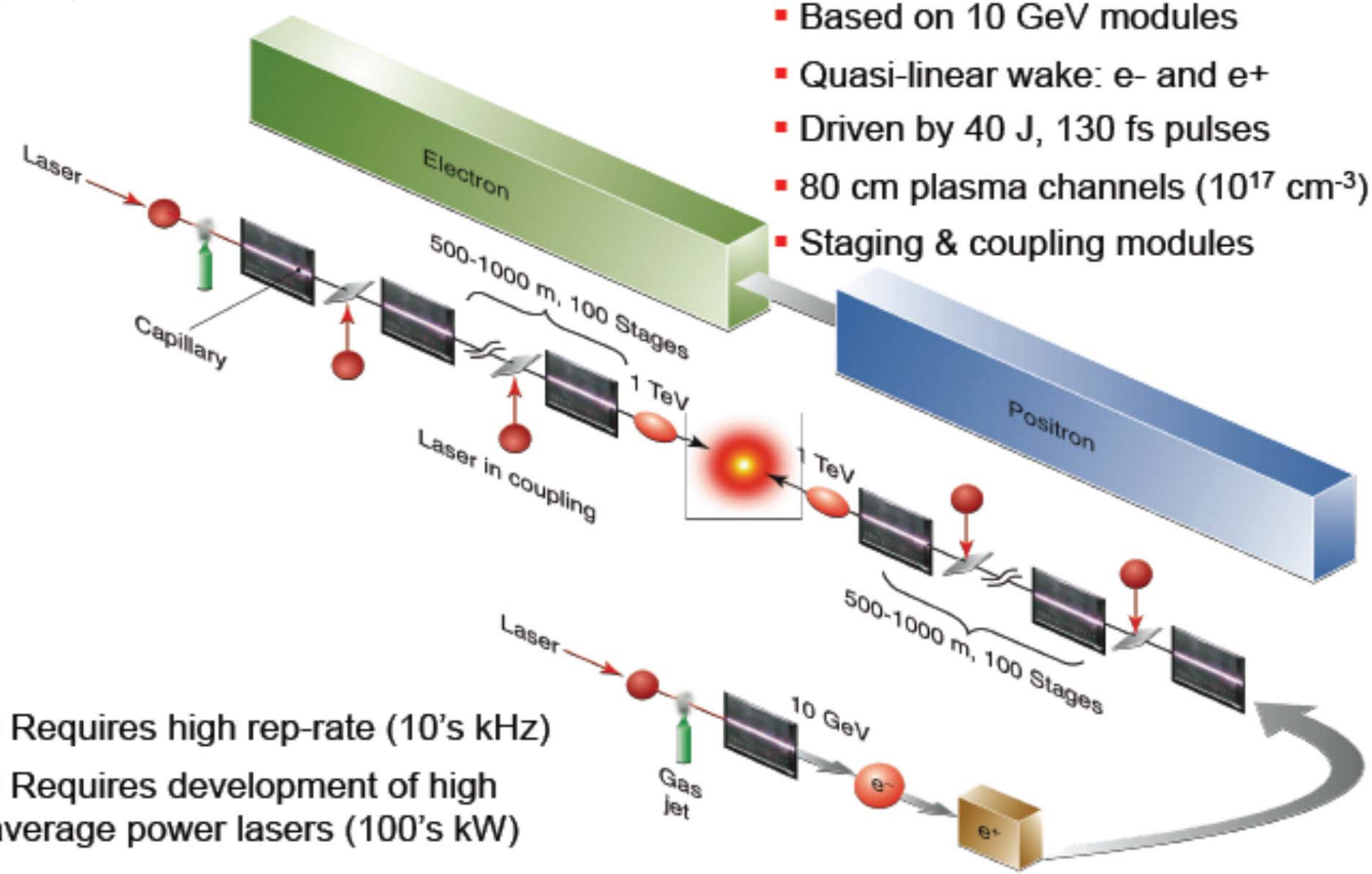


Challenges for LPA

- Improve the performance of **laser systems**:
  - Beam quality, reliability , stability
  - Average power (10Hz à 10kHz)
- Develop **external injection schemes** to increase the energy of electrons and quality of the beam in low density plasmas:
  - Optical injectors
  - RF injectors
- Test **multi-stages acceleration** to compensate for laser damping and electron dephasing in the plasma (10 GeV max per stage)

Laser plasma collider concept

- Based on 10 GeV modules
- Quasi-linear wake: e- and e+
- Driven by 40 J, 130 fs pulses
- 80 cm plasma channels (10^{17} cm^{-3})
- 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

Conclusion et perspectives

- LPA currently produce electron bunches of extremely short duration (<10fs), up to 1 GeV, dE/E~2.5% rms
- Laser guiding and increased laser energy should produce electron bunches in the ~10 GeV range in one stage (ex: BELLA project in the USA or APOLLON 10 PW in France)
- Very active and motivating field of research:
  - involving laser, plasma and accelerator physics,
  - several facilites under development,
  - need for students, researchers and engineers