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

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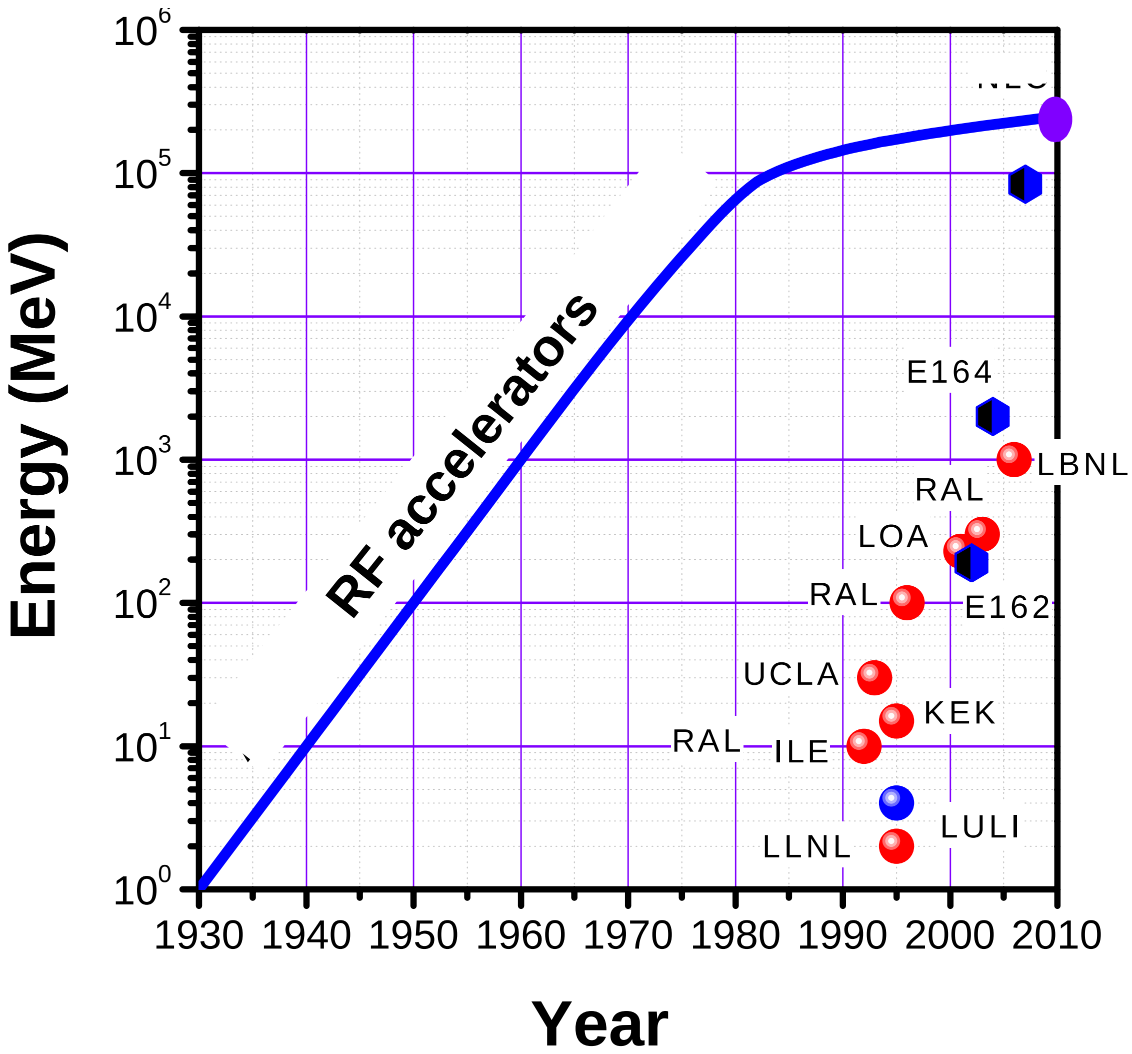
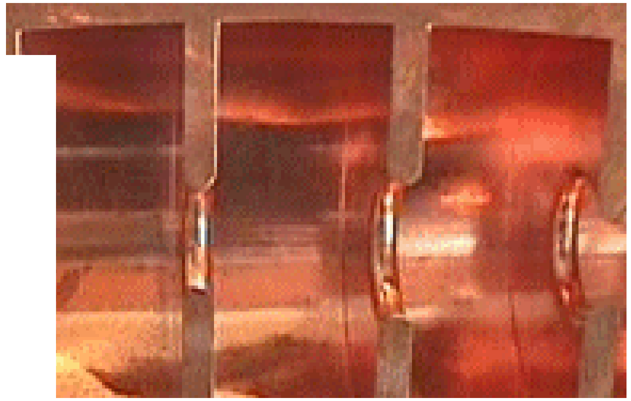
Interaction et Transport de Faisceaux Intenses dans les Plasmas

Outline

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

Limitation of linear accelerators





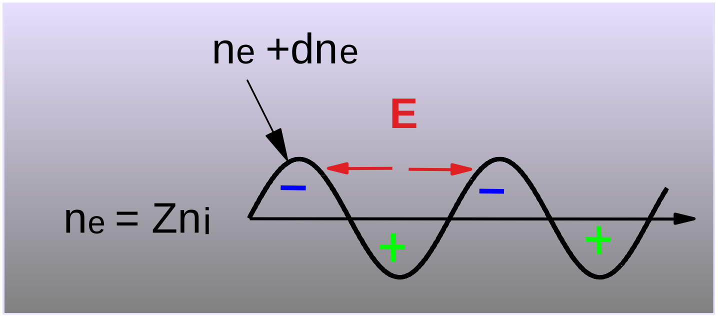
RF technology limitation

- E<50 MV/m
- B<10 Tesla
- Synchrotron radiation (e-)

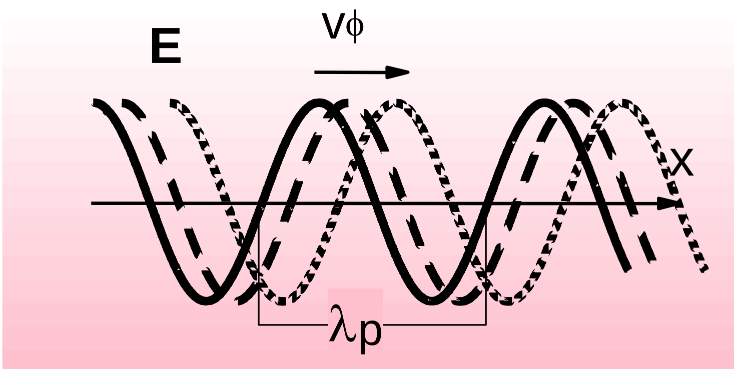
Test of new concepts: accelerators using plasmas

Interest of plasma for acceleration

Accelerating fields > 100 GV/m



- Charge space field and plasma wave

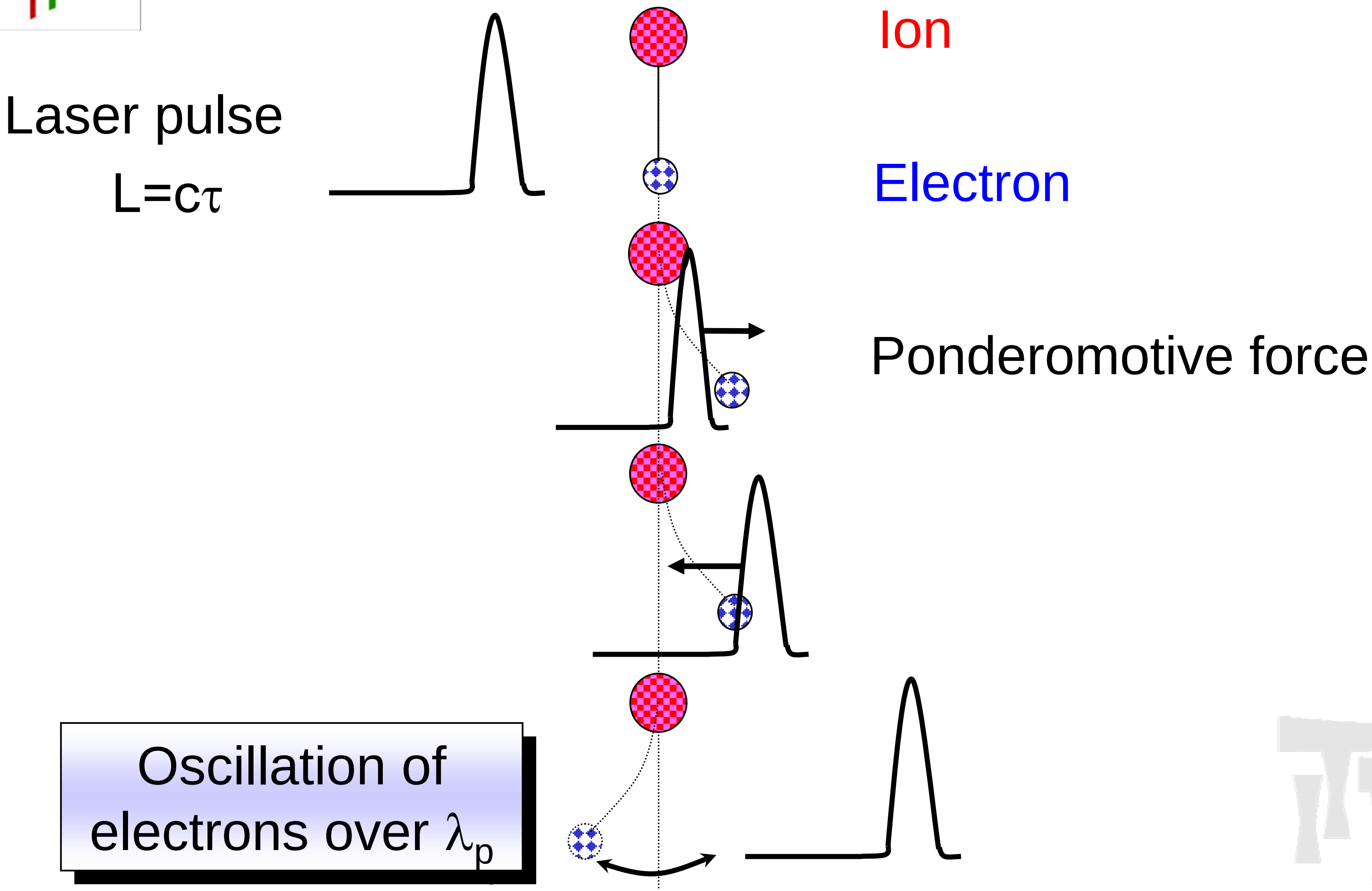


- Relativistic wave:

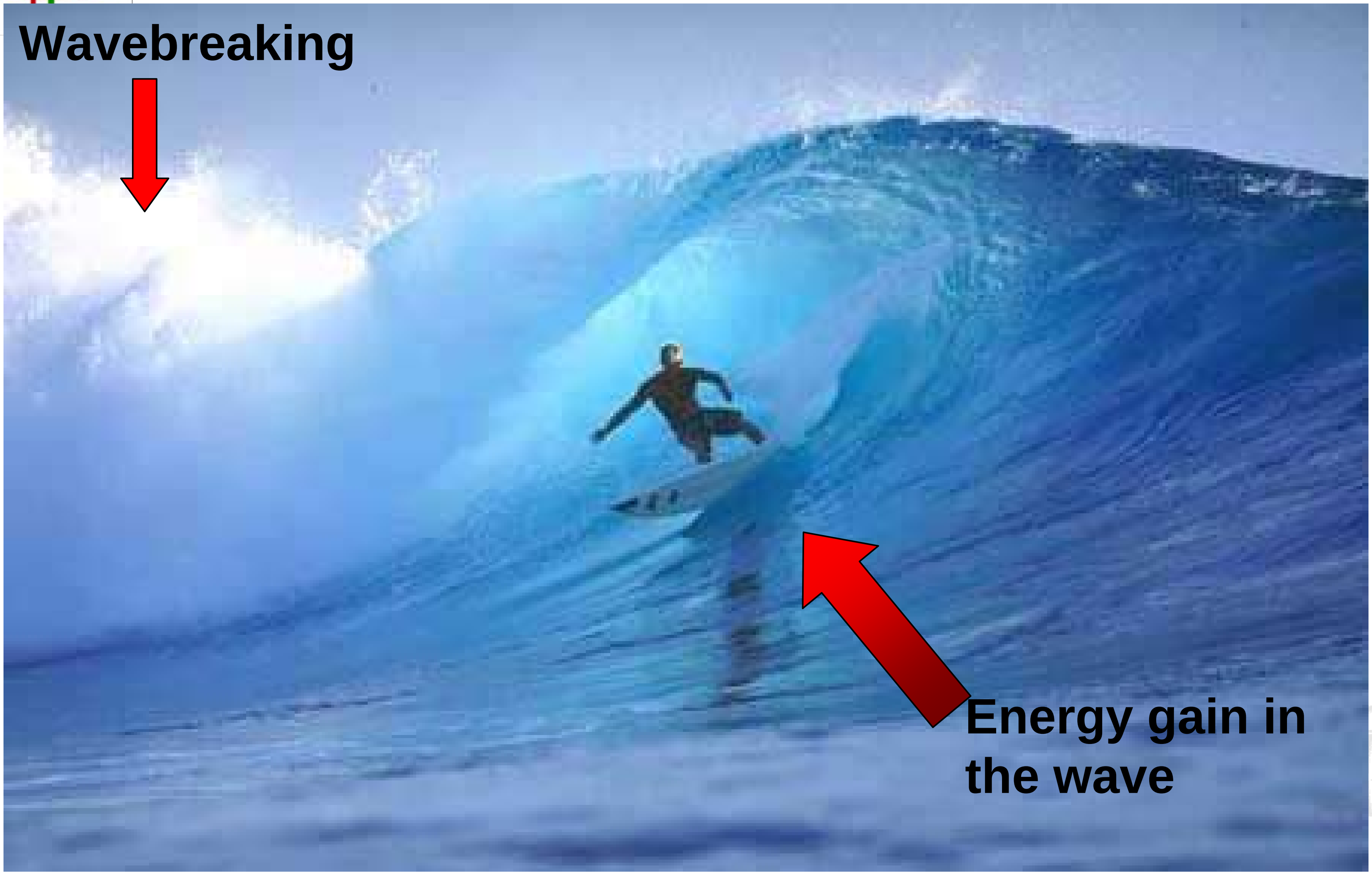
phase velocity of the order of c

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

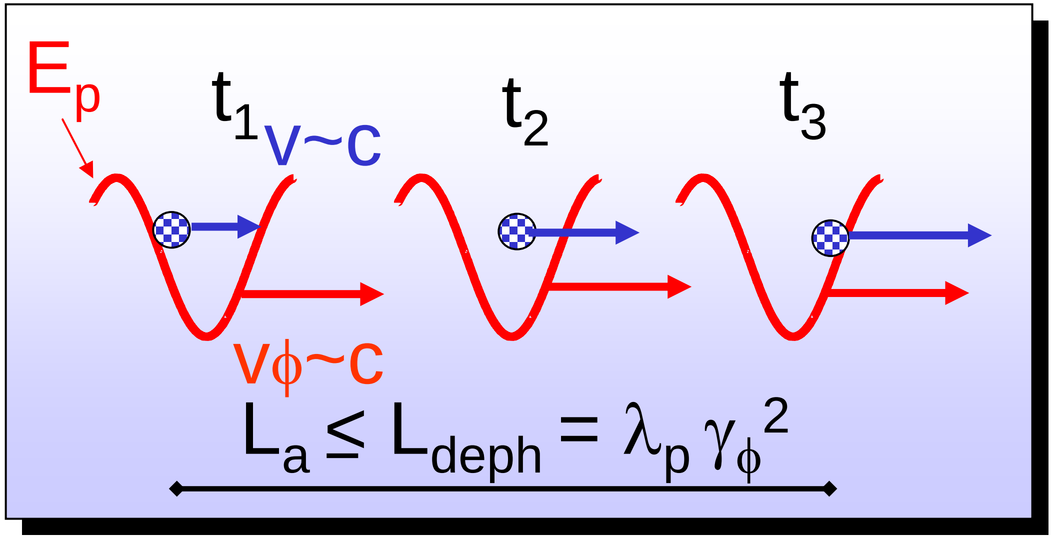
How to create a plasma wave



How to accelerate electrons



Energy gain of a relativistic electron in a plasma wave



- Energy gain

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

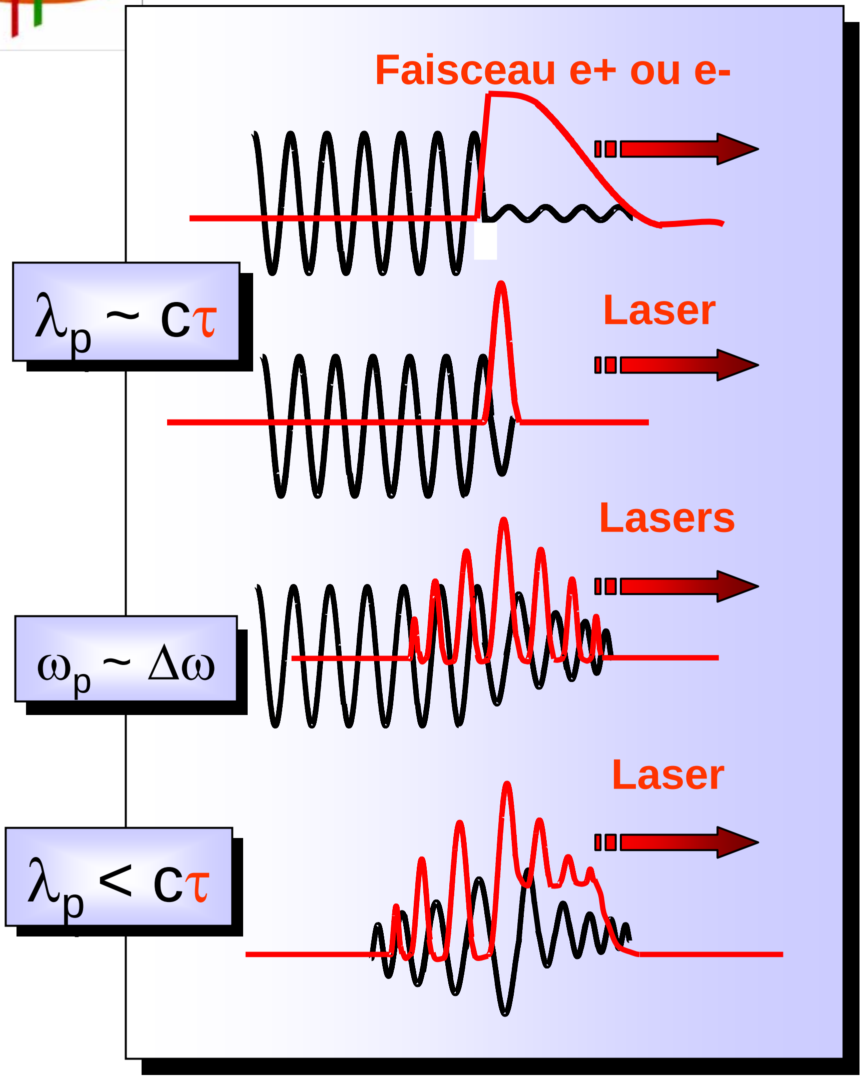
  $\sim 4mc^2 \gamma_\phi^2$

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

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

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

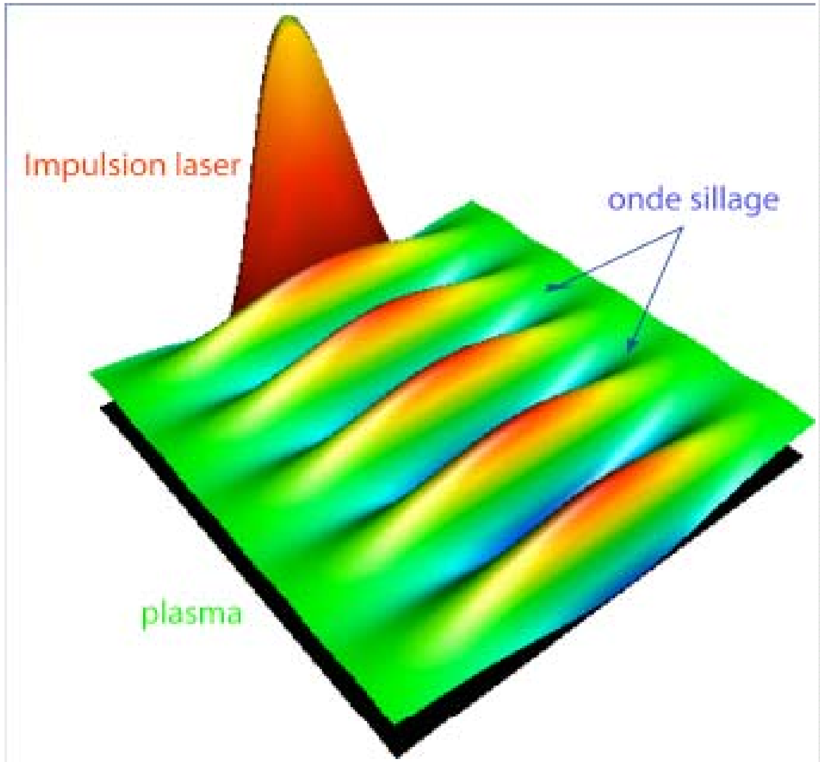
How to create a plasma wave



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

Example of wakefield

Characteristics of laser wakefield



- **•Ponderomotive force** :

$$F_p = -\mathrm{cste} \cdot \nabla I_L$$

- **•Ultra-short pulse duration**

$\tau_L < 100\,\mathrm{fs}$, ultra-intense

$I_L > 10^{17}\,\mathrm{W.cm}^{-2}$

- **•« Resonant » mechanism**

➡ $\lambda_p \simeq 2 \cdot c \cdot \tau$

➡ $n_e^r[\mathrm{cm}^{-3}] = \frac{1.7\times10^{21}}{\tau^2_{FWHM}[\mathrm{fs}]}$

- •Phase velocity : $\omega_L \gg \omega_p$

$$v_\phi = c(1 - \omega_p^2/\omega_L^2) \simeq c$$

- **•Depends on laser intensity** I_L

Laser wakefield is a simple and efficient mechanism

- Linear or non linear plasma waves can be created
- Plasma wave creation and electron acceleration can be controlled
  - Large « resonance »
  - Longitudinal and transverse fields amplitude can be tuned independantly
  - Accelerating and focusing length of the order of $\lambda_p/4$
- Injection of electrons : external source or from the plasma itself

Pioneering work and first advances

- Original proposal for plasma accelerators

  PRL Tajima et Dawson 1979

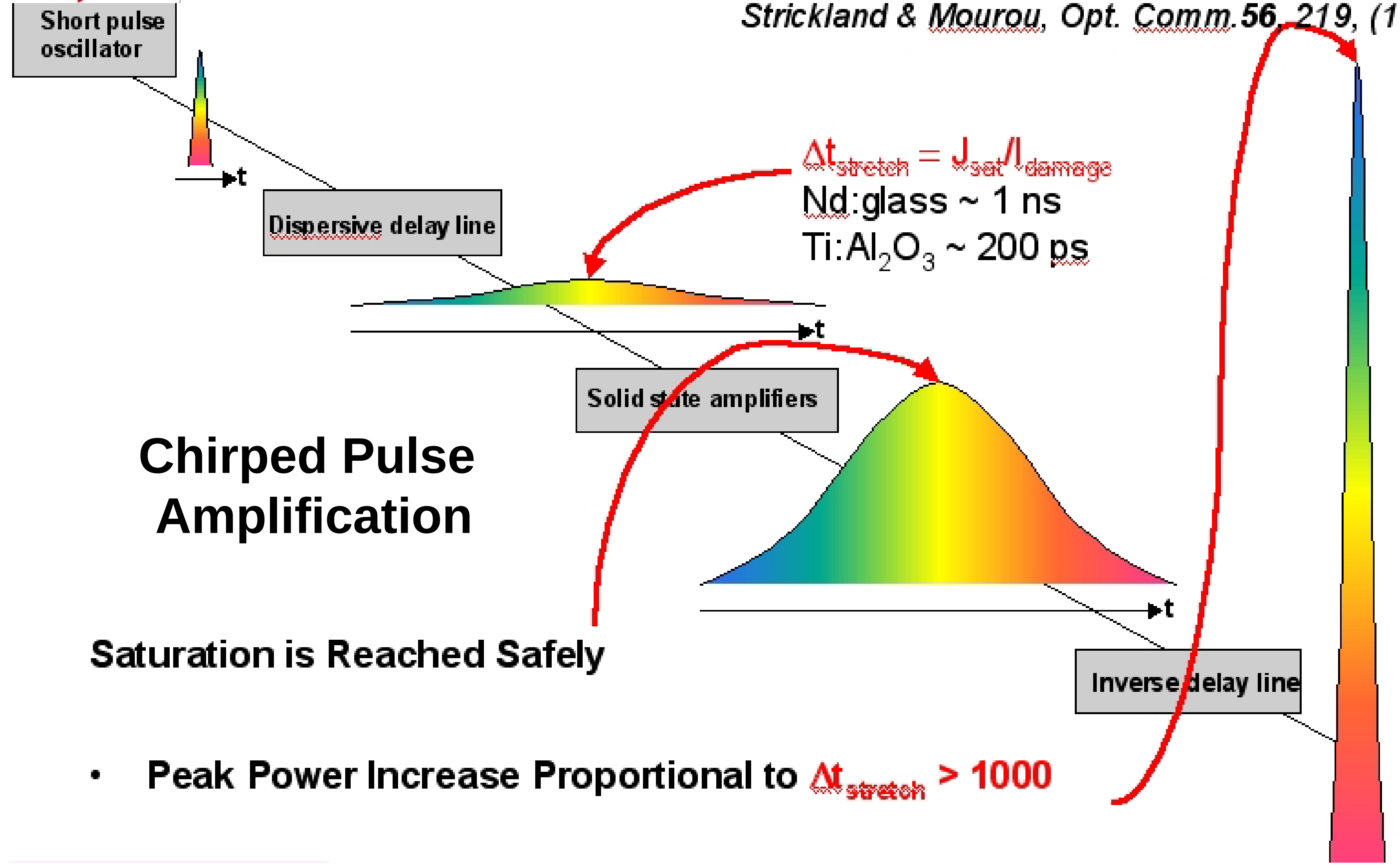
- Proof of principal as soon as 1993: UCLA et LULI

- First peaked spectra in 2004:

  RAL et LOA

The progress of laser plasma accelerators follows the evolution of laser systems

Strickland & Mourou, Opt. Comm. **56**, *219, (1985)*

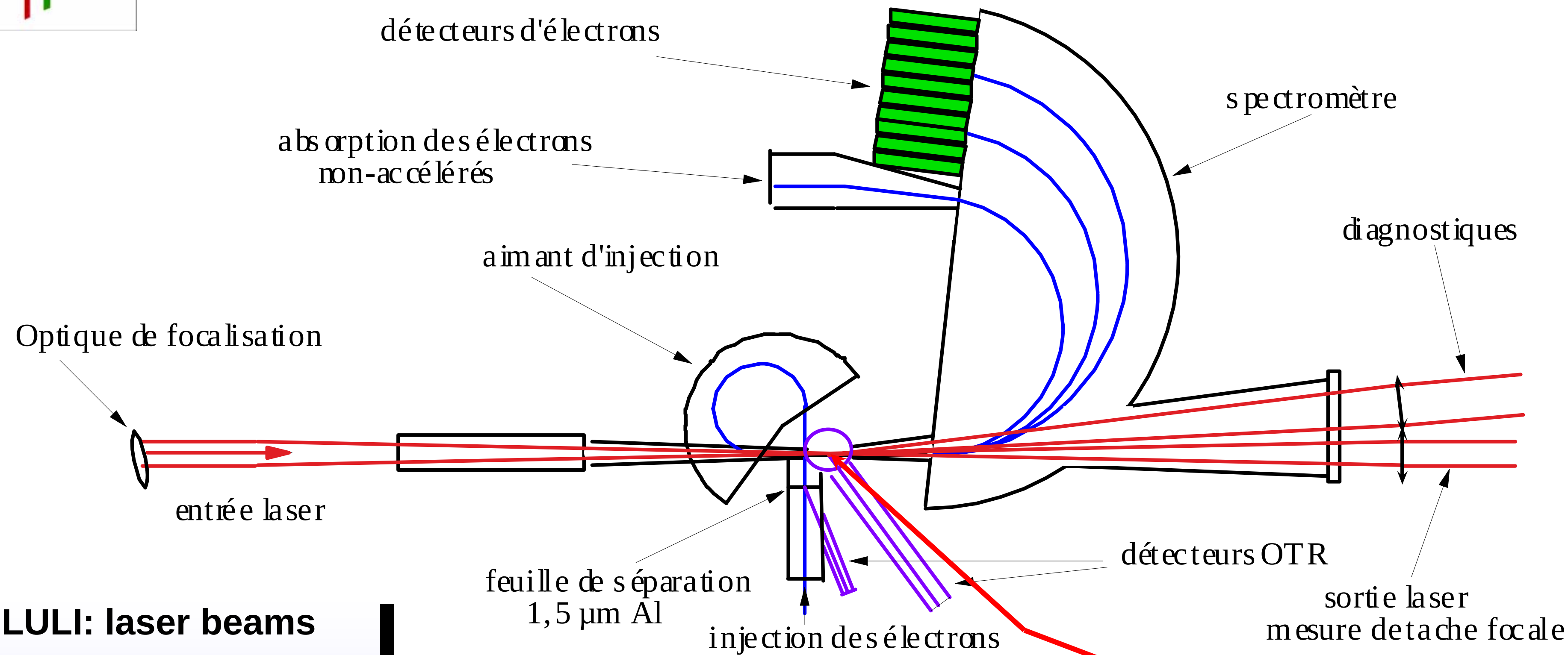


Chirped Pulse Amplification

Saturation is Reached Safely

- **Peak Power Increase Proportional to $\Delta t_{stretch}$ > 1000**

First demonstration of wakefield and beatwave at LULI



Plasma
λ_p ~ 300 µm

LULI: laser beams

Beatwave:
4J, 200ps + 12 J, 90ps
wakefield:
2.5 J, 400fs

LSI: electron beam
(Van de Graaf)

W = 3 MeV, I = 300 A, 0.4ms
~1000 e-/ps

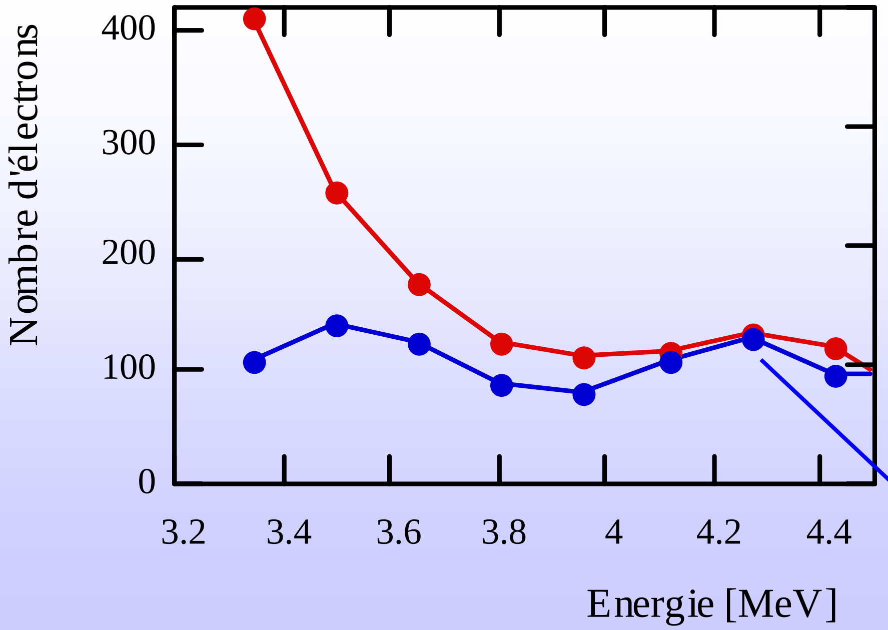
Collaboration LULI, LPGP, LLR, SESI

Acceleration in linear wakefield: Proof of principle

- 1998, 400fs, 2J
- $n_e = 5\ 10^{16}\ cm^{-3}$

$L_{laser} = \lambda_p$

Electrons injected at 3 MeV
Accelerated to 4.5 MeV
in a field of 1 GV/m



- Few electrons
- No trapping

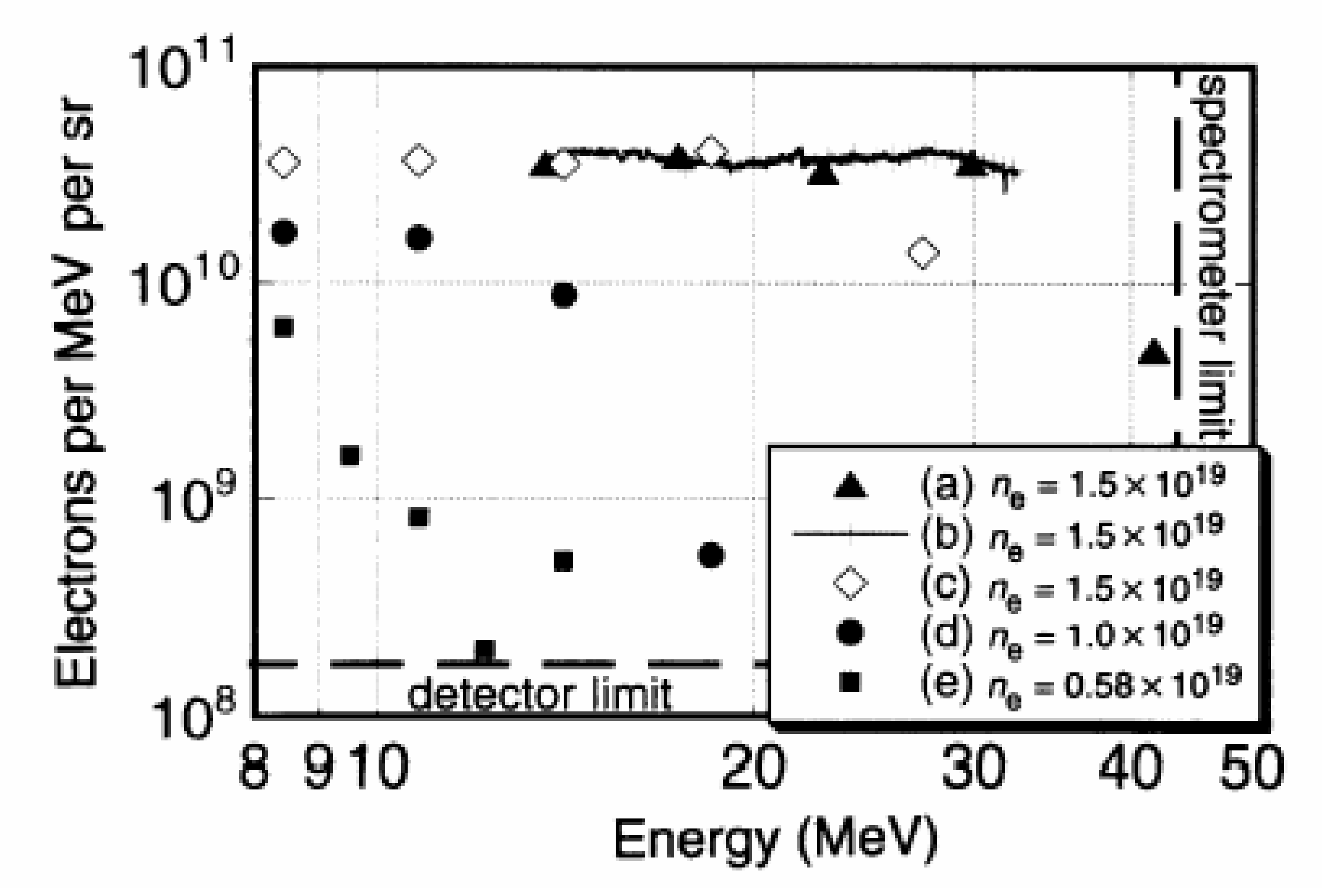
$\gamma_{e-} << \gamma_{onde} \sim 100$

Noise produced by scattered electrons in the plasma or the spectrometre

F.Amiranoff *et al.*, *Phys.Rev.Lett.* **81** , 9950 (1998)

Self-modulated wakefield (1995)

•Laser power **P = 25 TW (VULCAN), 0.8 ps, 20 J**



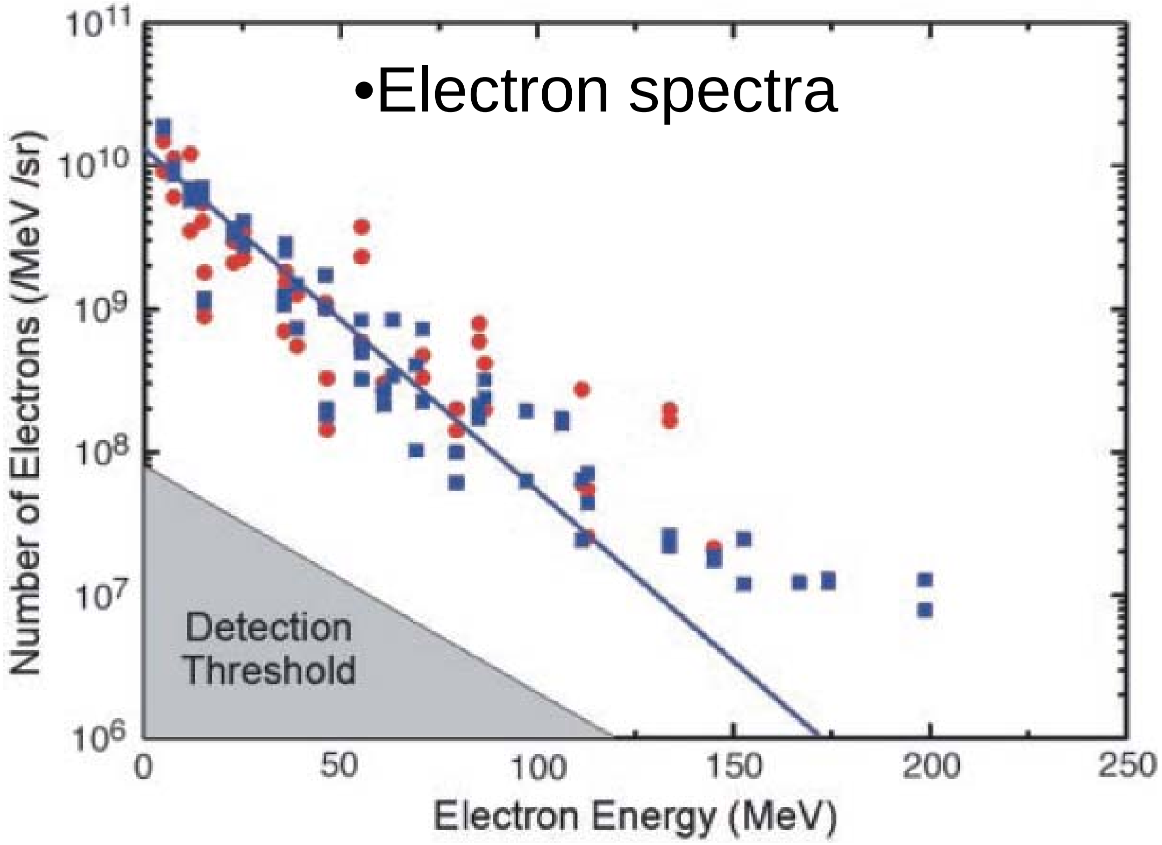
$L_{laser} >> \lambda_p$

A. Modena et al., Nature 377, 606 (1995)

Maxwellian spectrum in 2002

Gas jet, I = $3x10^{18}$W/cm^2, LOA salle Jaune 1J, 30fs

$L_{laser} > \lambda_p$



- n_e = 2.5 10^{19} cm^{-3} (squares)
- n_e = 6 10^{19} cm^{-3} (dots).
- Effective electron temperature 18 MeV exponential fit

V. Malka et al., Science 298, 1596 (2002)

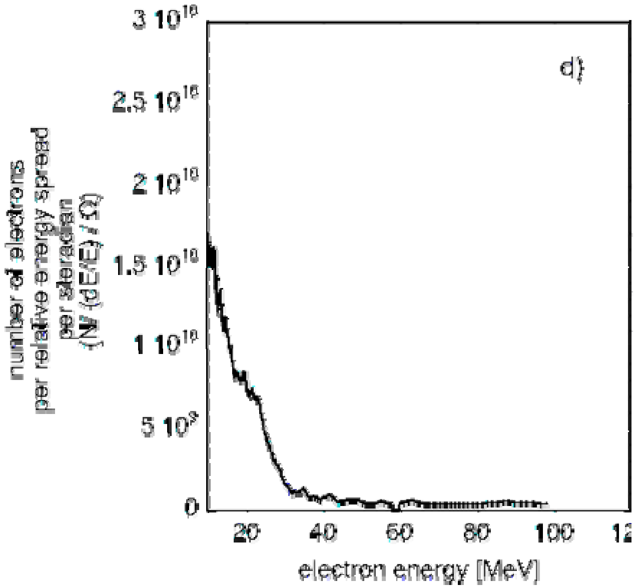
Breakthrough in 2004: Better quality spectra

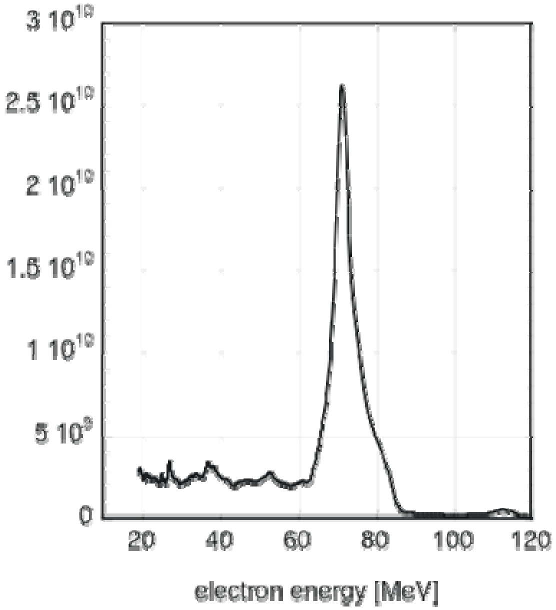
- Obtained by 3 groups
  - RAL/IC/UK: Mangles et al.
  - LOA/France: Faure et al.
  - LBNL/USA: C.G.R. Geddes et al.

$L_{laser} \sim \lambda_p$

High intensity

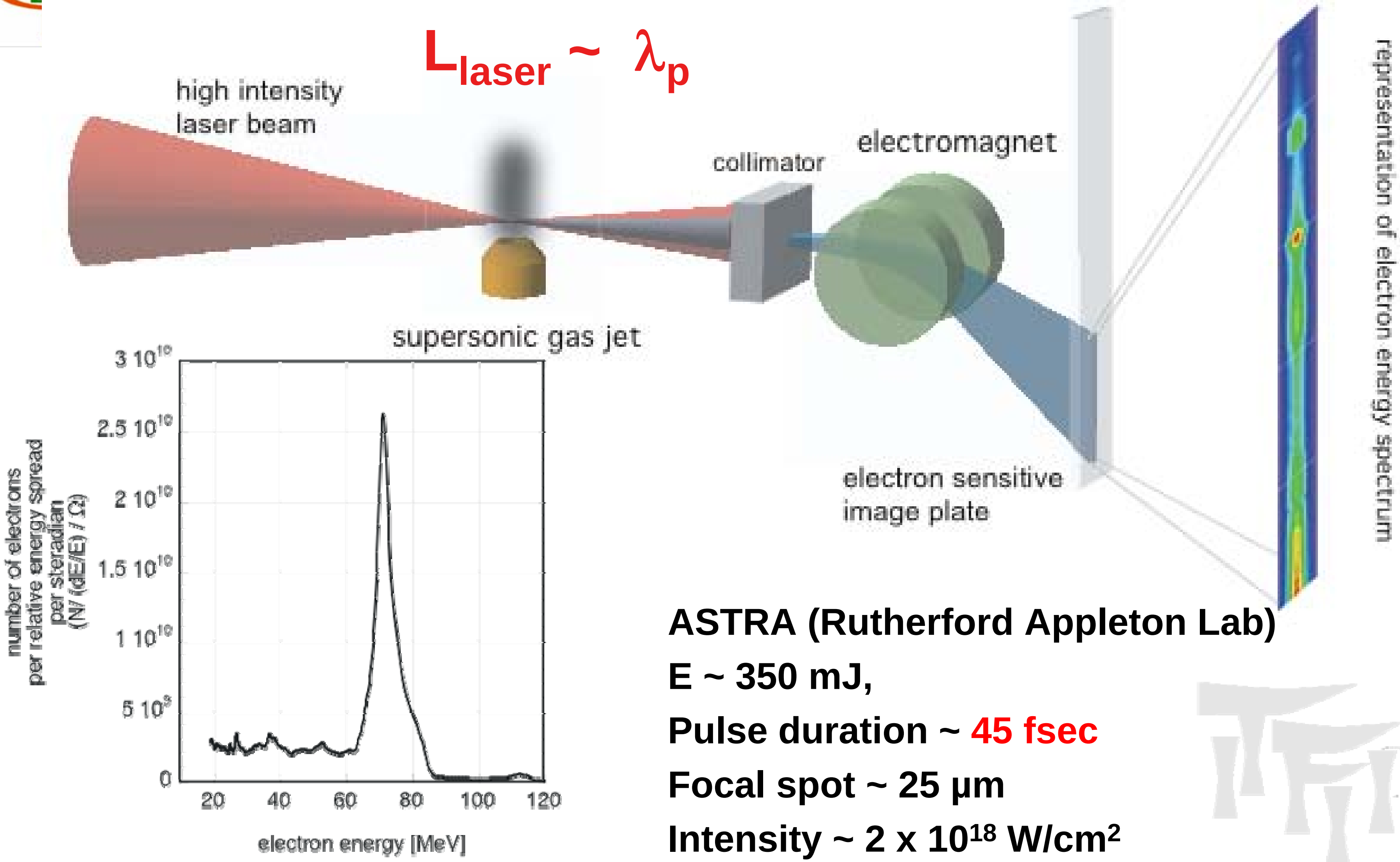
$L_{laser} > \lambda_p$ ⟹ $L_{laser} \sim \lambda_p$





Typical experimental set-up using gas jet target

$L_{laser} \sim \lambda_p$



ASTRA (Rutherford Appleton Lab)

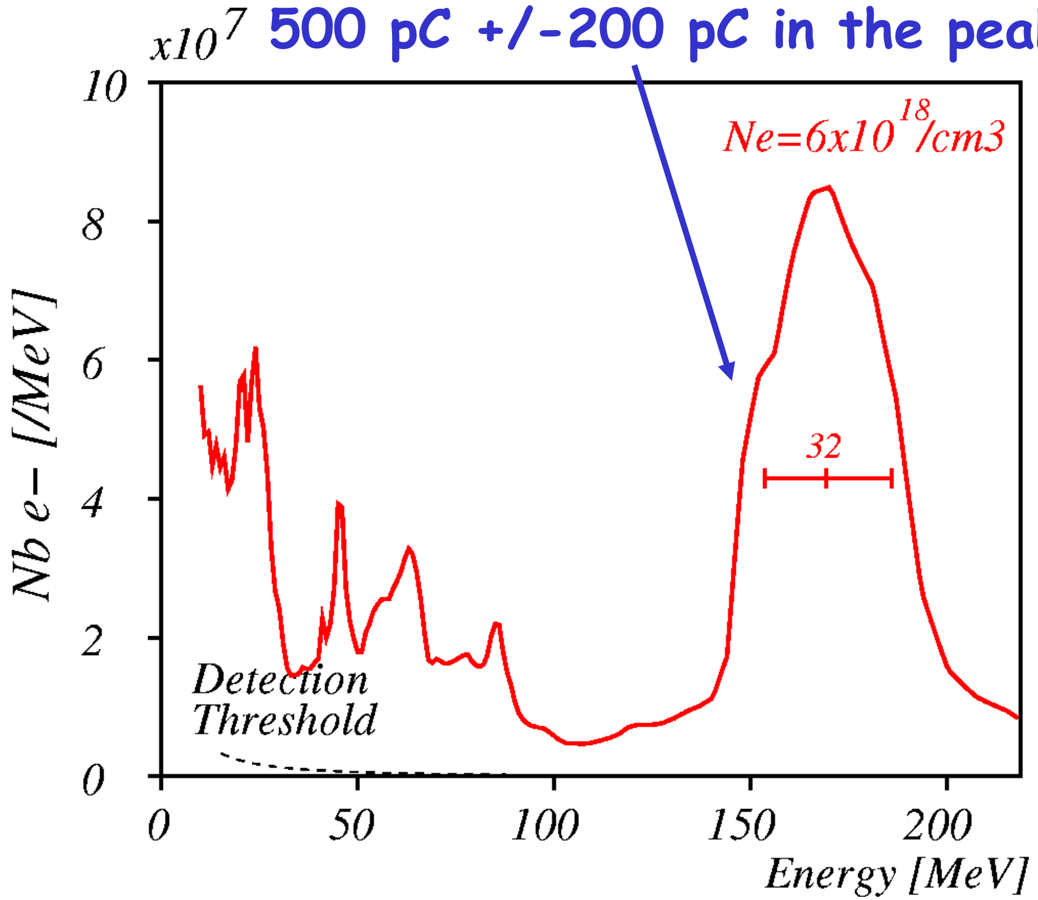
E ~ 350 mJ,

Pulse duration ~ 45 fsec

Focal spot ~ 25 μm

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

Non linear wakefield (Nature 2004)

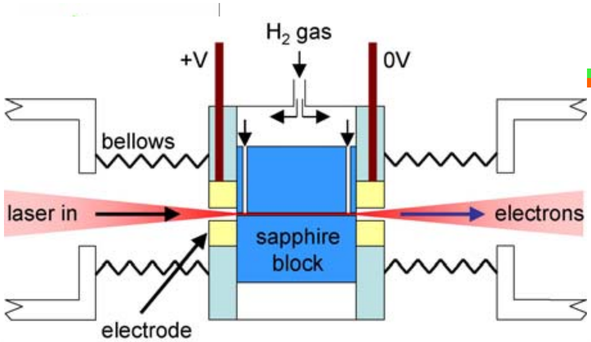


- Wavebreaking
- Trapping of plasma electrons
  - Lot of e-
  - Peaked spectra
  - Short pulse
  - Small emittance
- But difficult to control

- laser pulse: **1 J**, **35 fs**, **0.8 µm** (30 TW) LOA
- helium gas jet

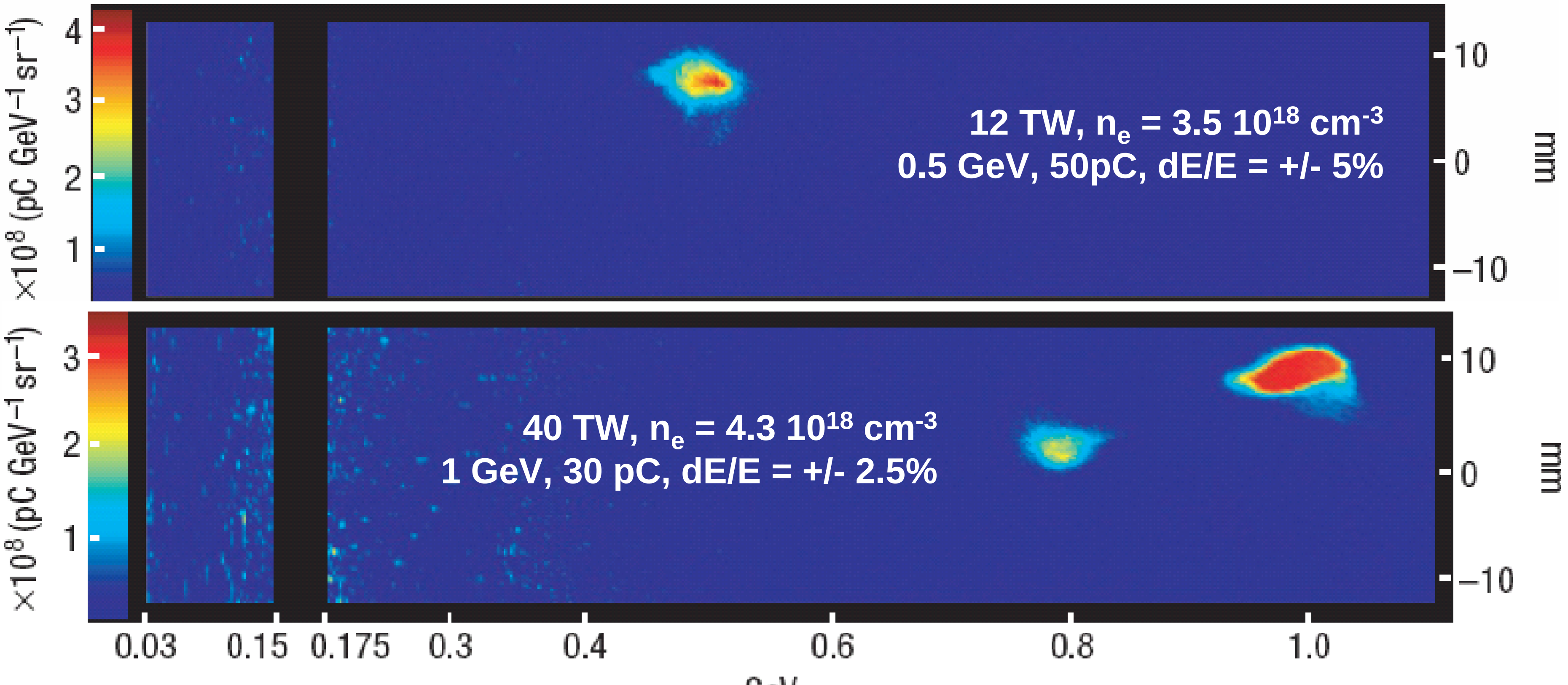
J. Faure et al., Nature 431, 541 (2004)

Wakefield in a plasma channel (2006)



Plasma channel U. Oxford
L = 33 mm, diamètre 190µm
r spot (1/e²) = 25 µm
Laser LBNL 40fs, 1.6J

Self-focusing, wavebreaking or bubble, trapping and guiding



Leemans et al. Nature **Physics 2, 696 (*2006*)**

Summary of experimental results

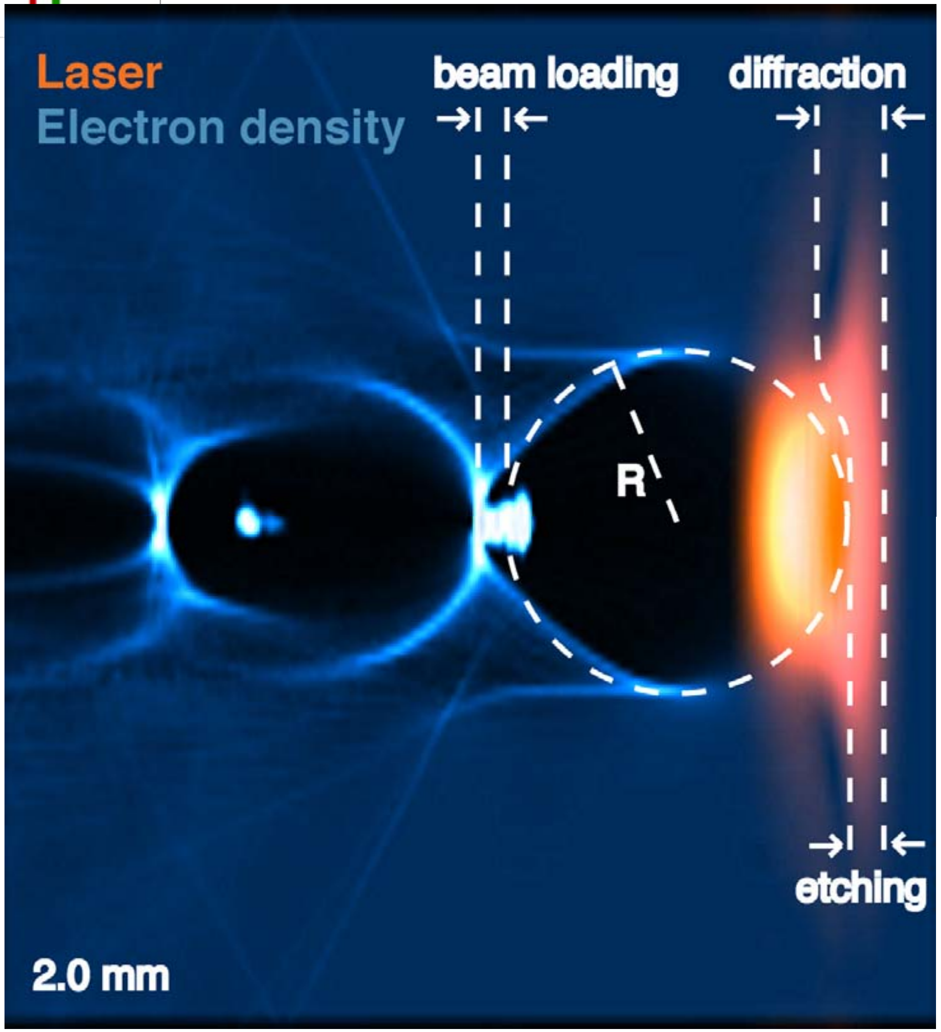
Mechanism	Labs	Energy Gain	Acc field	Acc length
Beatwave	UCLA, LULI, Canada, ILE	1 à 30 MeV	1 GV/m	1 à 10 mm
Linear laser wakefield	LULI	1.5 MeV	1 GV/m	2 mm
Non Linear laser wakefield	RAL, LULI, LOA, LBNL	60 à 1000 MeV	100 à 400 GV/m	1 à 30 mm

- High accelerating gradients
- Agreement with theory
- Broad spectra due to inadequate injectors
- **Guiding and controlled injection to improve the properties of the accelerated beam**

Towards a controllable laser plasma accelerator at high energy

- Strongly non linear regime: the bubble
  - Laser compression, ultra-high intensity >10^{18} W.cm^{-2}
  - Seld-injection of electrons
  - High electron density
  - Energy of accelerated e- can be increased by increasing laser energy
- Linear regime
  - Intermediate intensity < 10^{18} W.cm^{-2}
  - External injection of electrons
  - Low electron density
  - Energy of accelerated e- can be increased by guiding and staging

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)

Wei Lu talk, HEEAUP05 – UCLA & IST

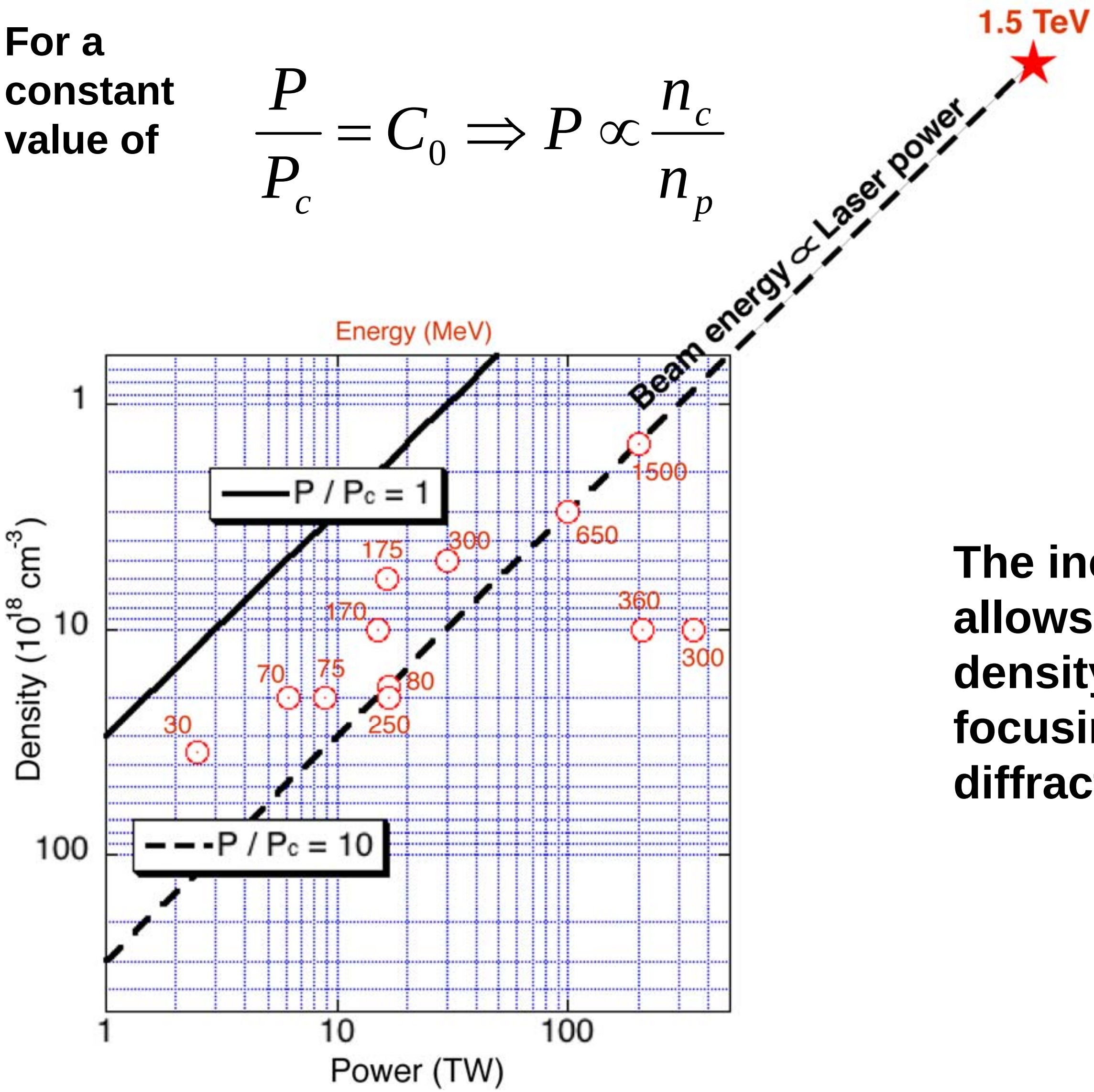
Scaling in non-linear regime

For a constant value of

$$\frac{P}{P_c} = C_0 \Rightarrow P \propto \frac{n_c}{n_p}$$

(200 PW laser)

$$\Delta E \propto P$$



The increase of laser power allows to decrease electron density and maintain self-focusing (to compensate diffraction)

- ***IST, UCLA***

Evaluation of non-linear regime

- Single stage, single laser beam….more simple to set-up
- Progress is linked to the evolution of laser systems:
  - Current power up to 1PW (100 TW)
  - Efficiency and repetition rate tend to decrease when the power is increased

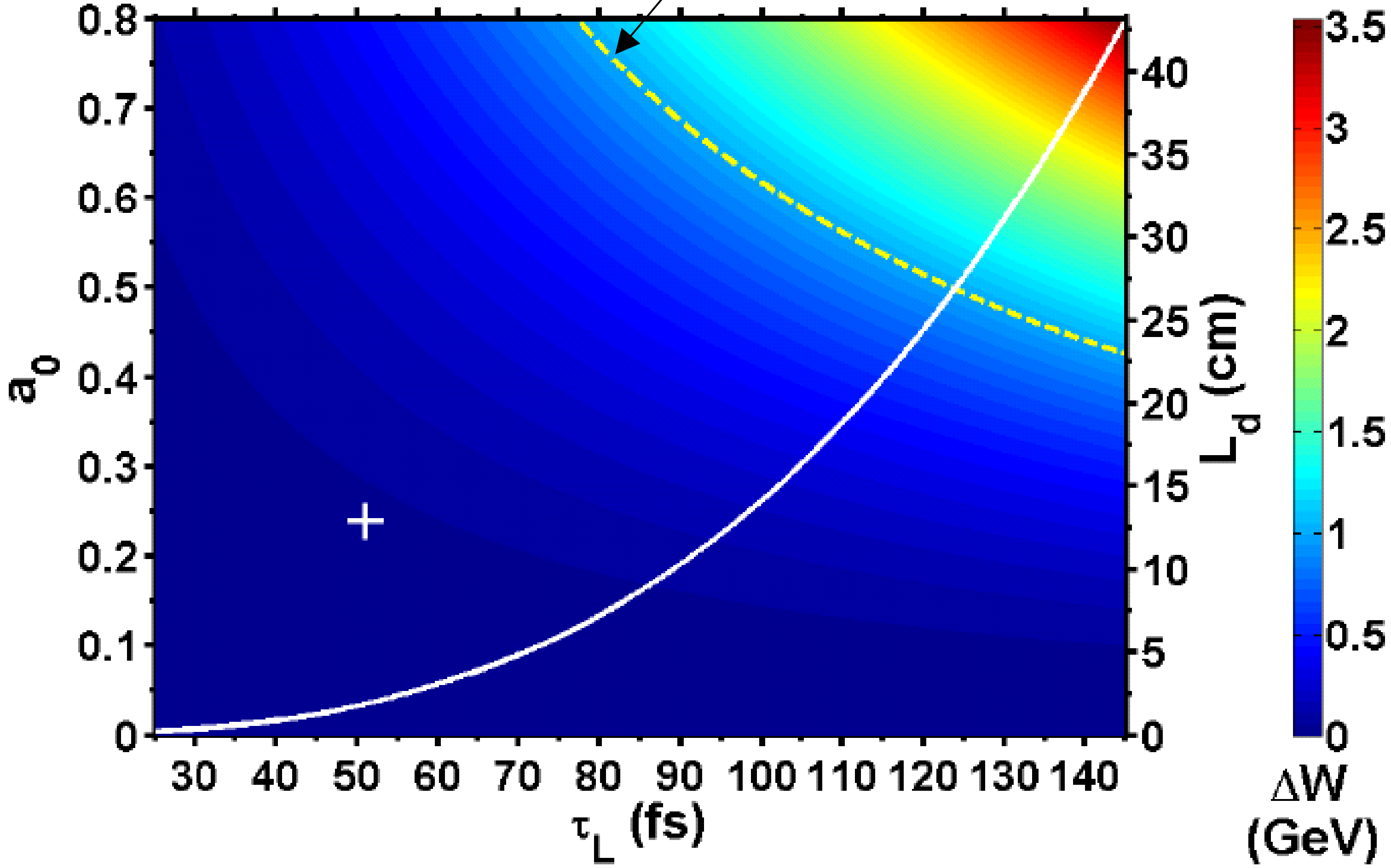
Evaluation of linear regime

- Moderate accelerating field (1-10 GV/m) but the process can be controlled and the laser energy is lower
- Successive stages can be used to increase electron energy
- It is necessary to:
  - Guide the laser beam to create a long plasma
  - Control the length of the plasma to achieve a good quality of acceleration
  - Inject electrons from an external source

On-going efforts in the linear regime

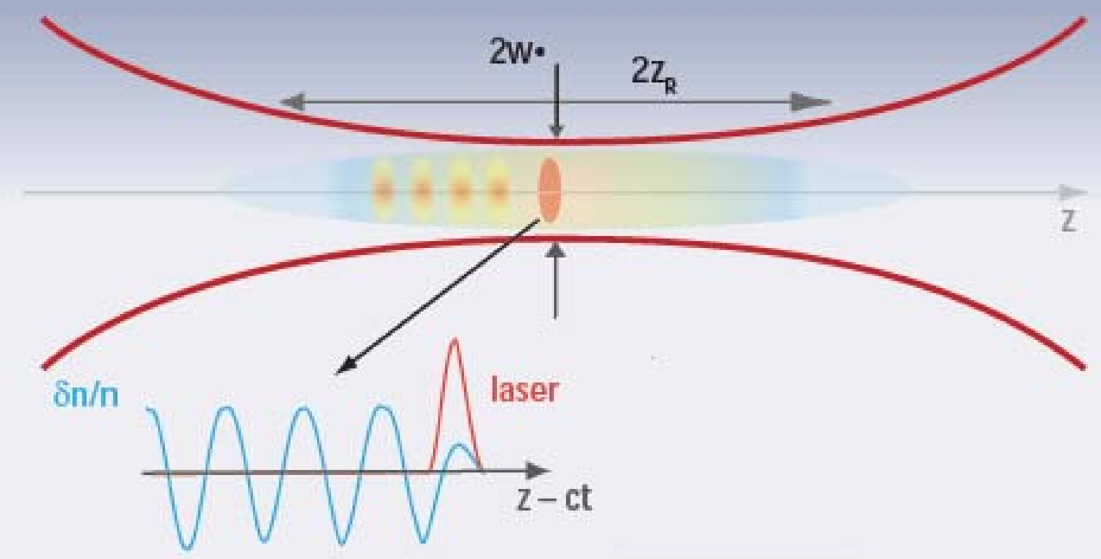
Dephasing length for linear resonant wakefield increases with pulse duration

I GeV energy gain



- Density decreases →

Guiding is necessary to create a plasma over the dephasing length

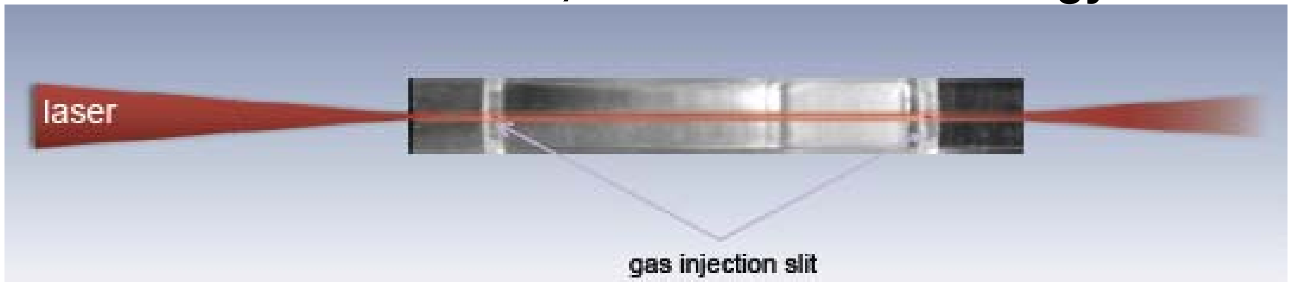


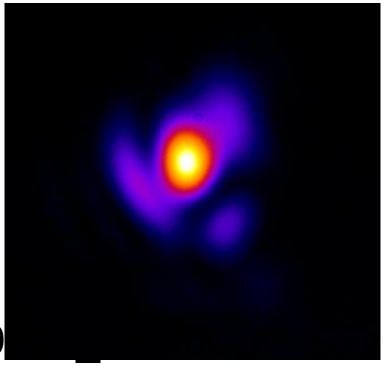
$$w_0 = \frac{\pi \lambda_L \cdot f}{D} \qquad Z_R = \frac{\pi \lambda}{w_0^2}$$

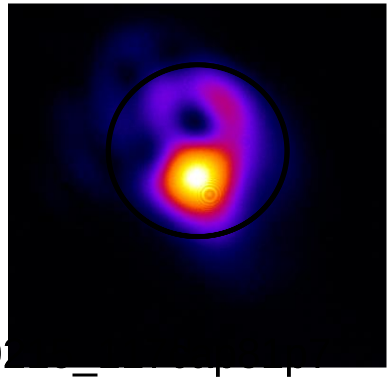
- Diffraction limits the interaction length to 0.1 to 5 mm
- Guiding using plasma channel, capillary tubes

Guiding in capillary tubes

Multimode w/a =0.52, transmission in energy 93%





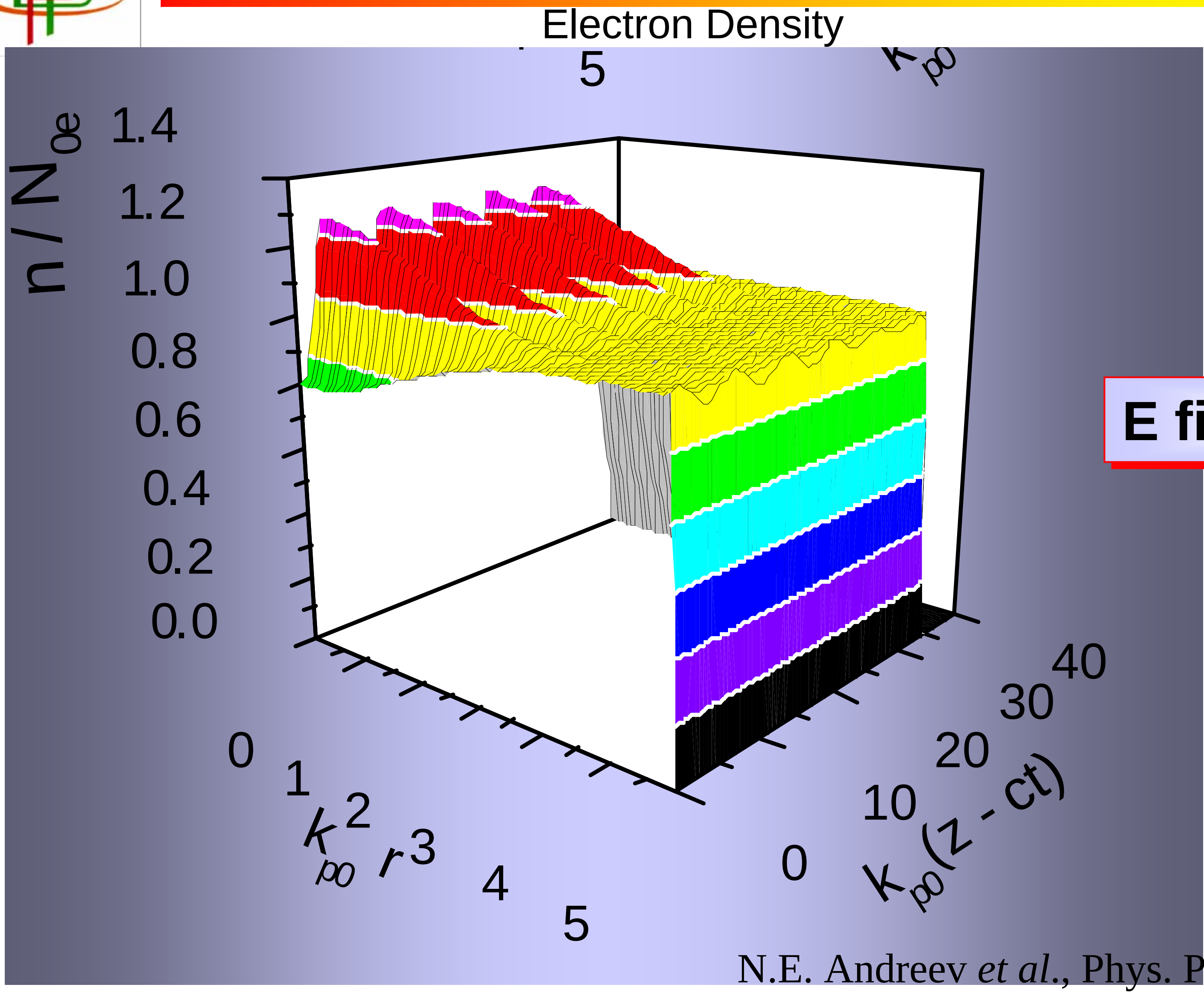


Incident power 24TW,
(37 fs, 0.9J)
Intensity 9 10^{17}W cm^{-2}
vaccuum

Capillary output
L = 81.7mm, 2r = 150µm
Intensity 1.6 10^{18}W cm^{-2}
30 mbar H2

LPGP-LLC

Laser wakefield in linear regime



Propagation length

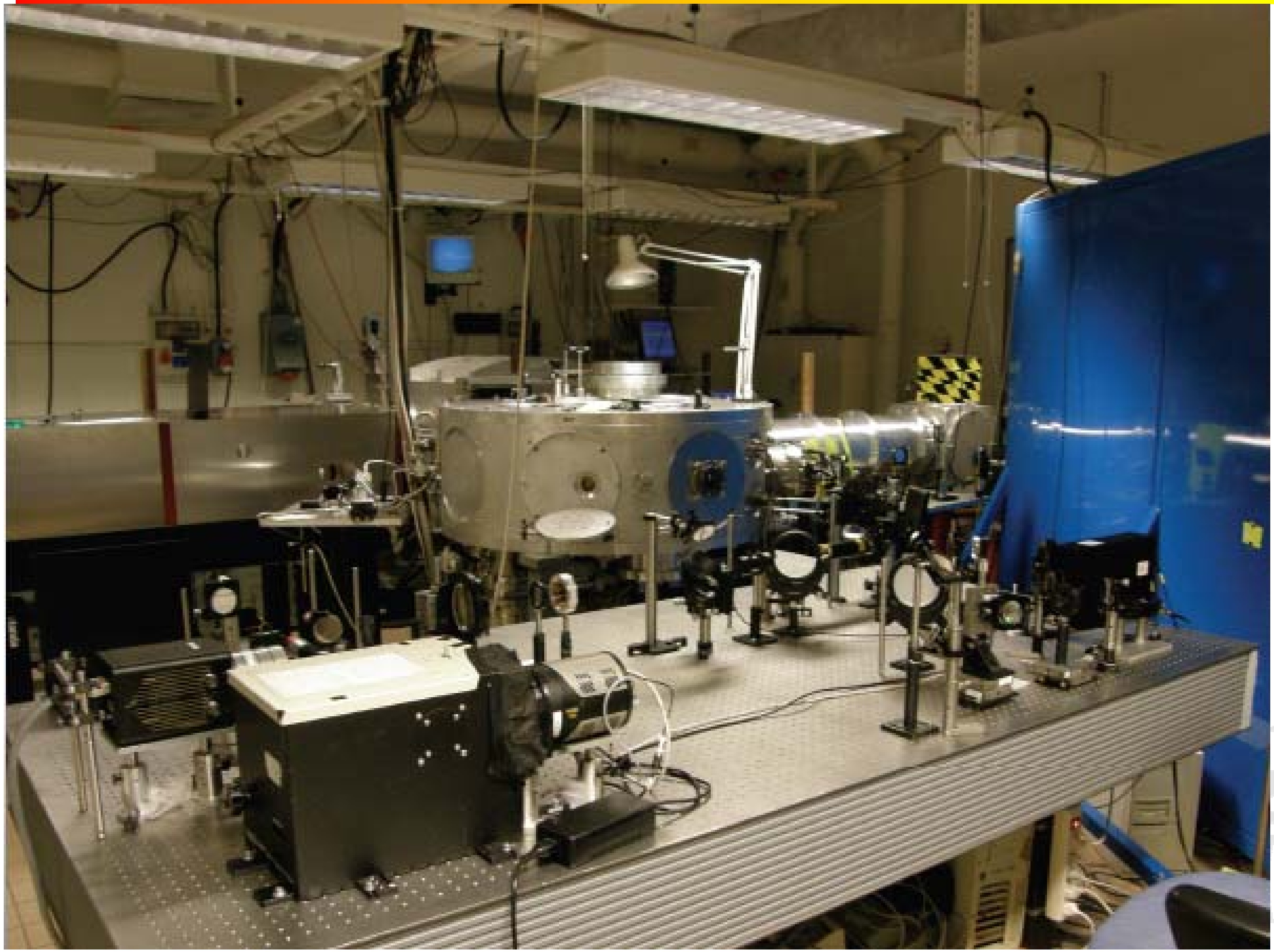
4.6 cm

E field: 16 GV/m

N.E. Andreev *et al.*, Phys. Plasmas 9, 3999 (2002)

Laser system at LLC (40 TW)

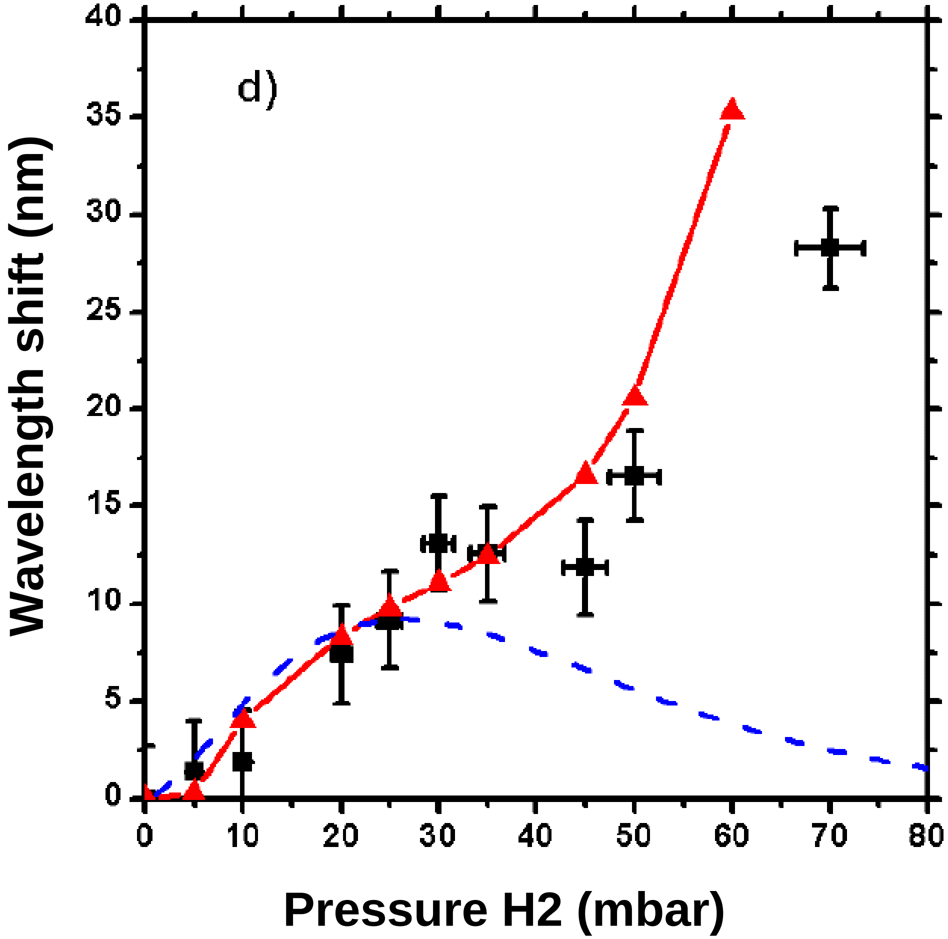
Experimental area



Measurement of the amplitude of the plasma wave over 8 cm

Capillary Tube D = 100 µm, **L = 8 cm**, filled with hydrogen

Laser $\lambda = 0.8$ µm, τ_{FWHM}= 51 fs, $I_L = 10^{17}$ W/cm^2



Optical diagnostic:

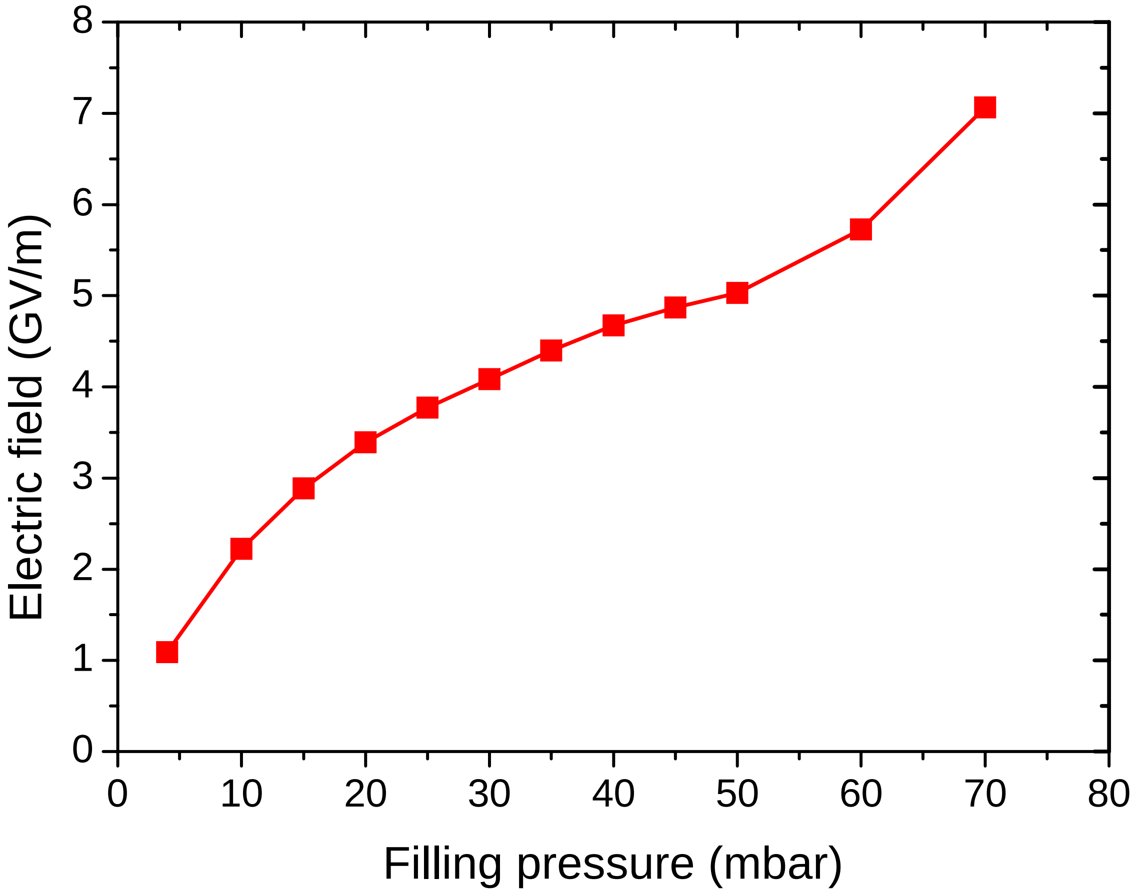
Changes of the laser spectrum due to the density modulation

Excellent agreement with simulation

F. Wojda, et al. PRE **80,** 066403 (2009)

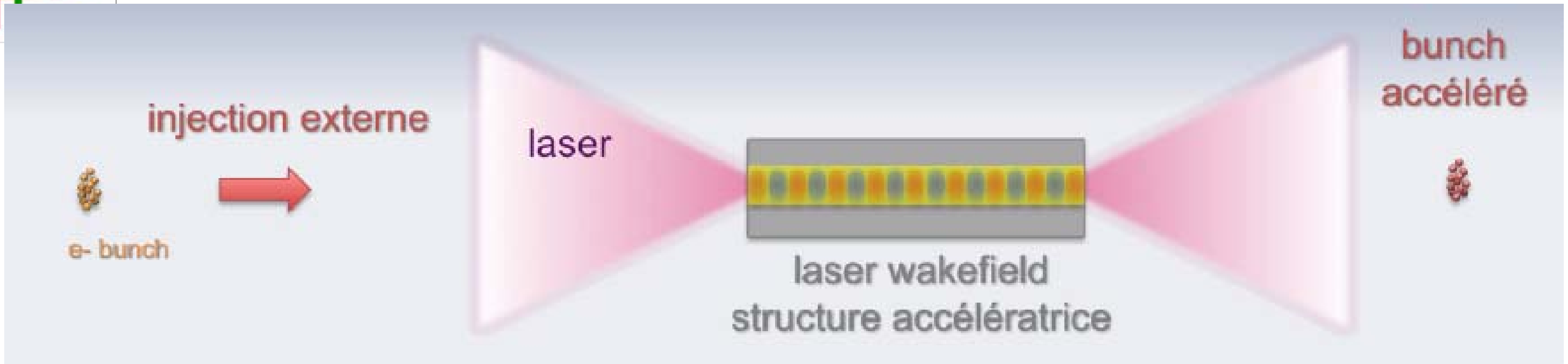
Accelerating field in the linear regime

Capillary Tube D = 100 µm, **L = 8 cm**, filled with hydrogen
Laser $\lambda = 0.8$ µm, $\tau_{FWHM} = 51$ fs, $I_L = 10^{17}$ W/cm^2



Electric field of the plasma wave deduced from optical diagnostic

How to inject electrons in the linear regime



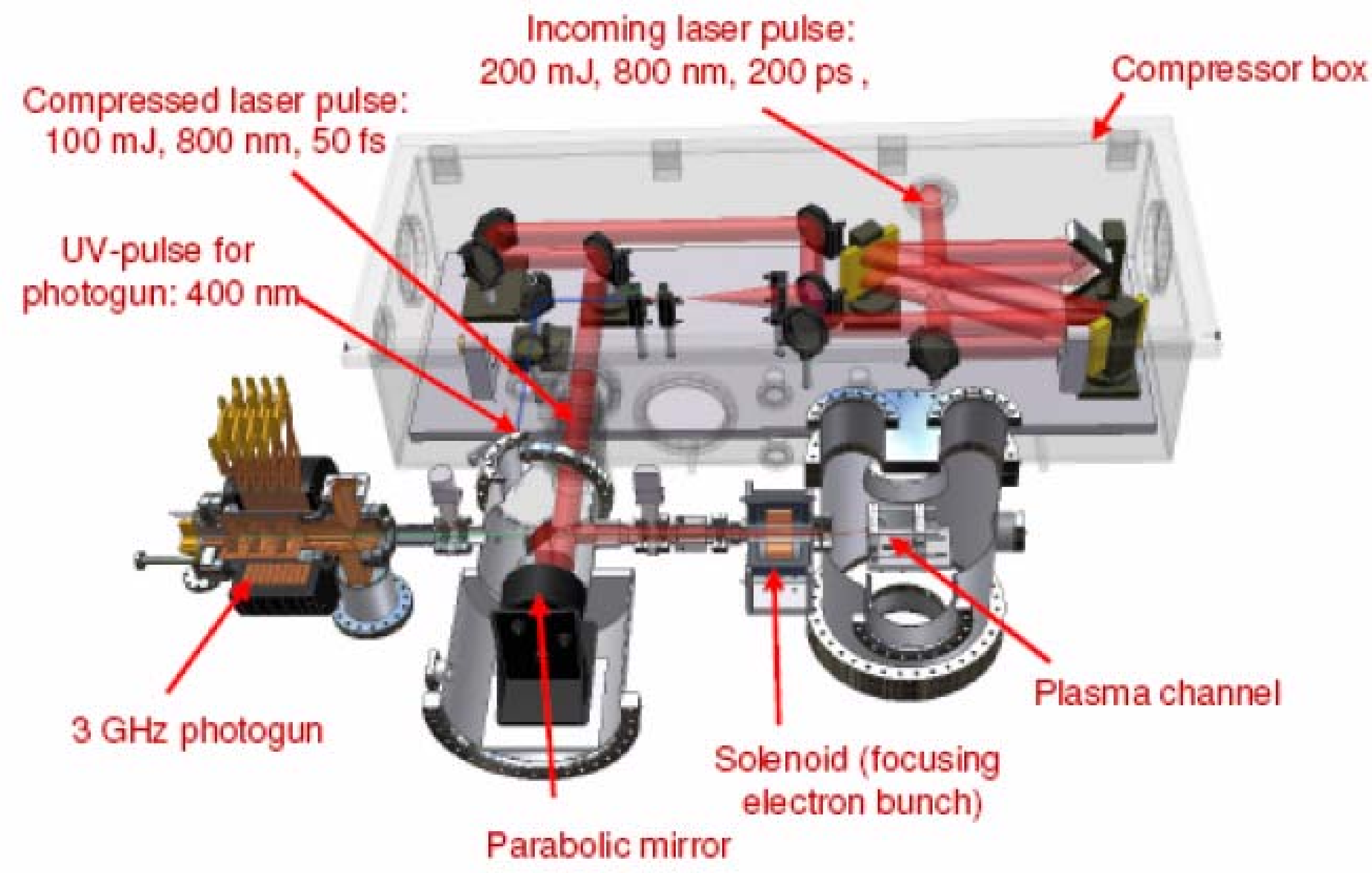
•Linear regime: electrons of the plasma are not trapped

•External electron sources:

laser-plasma OR

RF photo-injector

Project of RF injection at TUE



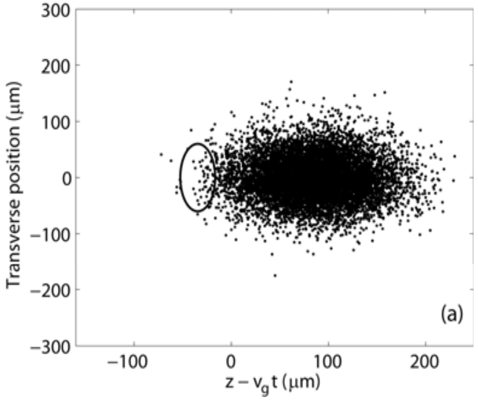
How to synchronise?

- It is necessary to synchronise the electron bunch and put it in the accelerating phase of the plasma wave
  - Electrons source: duration ~ 200 fs
  - Plasma wave: period 50fs and 10 fs useful for acceleration

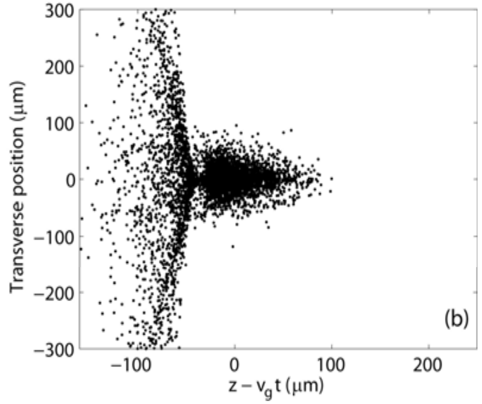
- It is necessary to compress the electron bunch and to find an alternative to electronic systems which cannot achieve this time range

Injection of electrons in front of the laser pulse

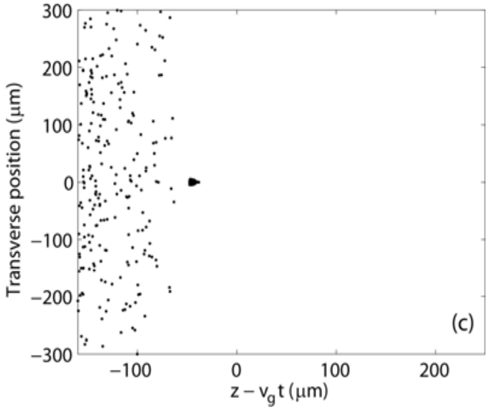
0 cm



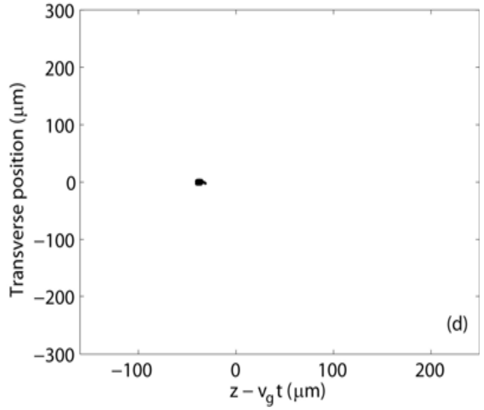
1 cm

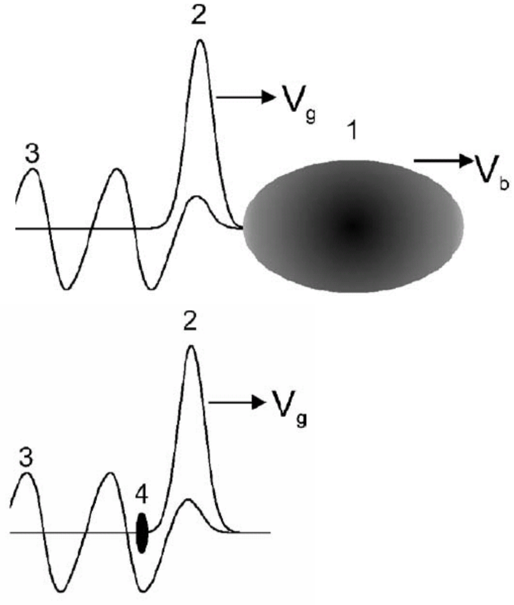


2.5 cm



5 cm





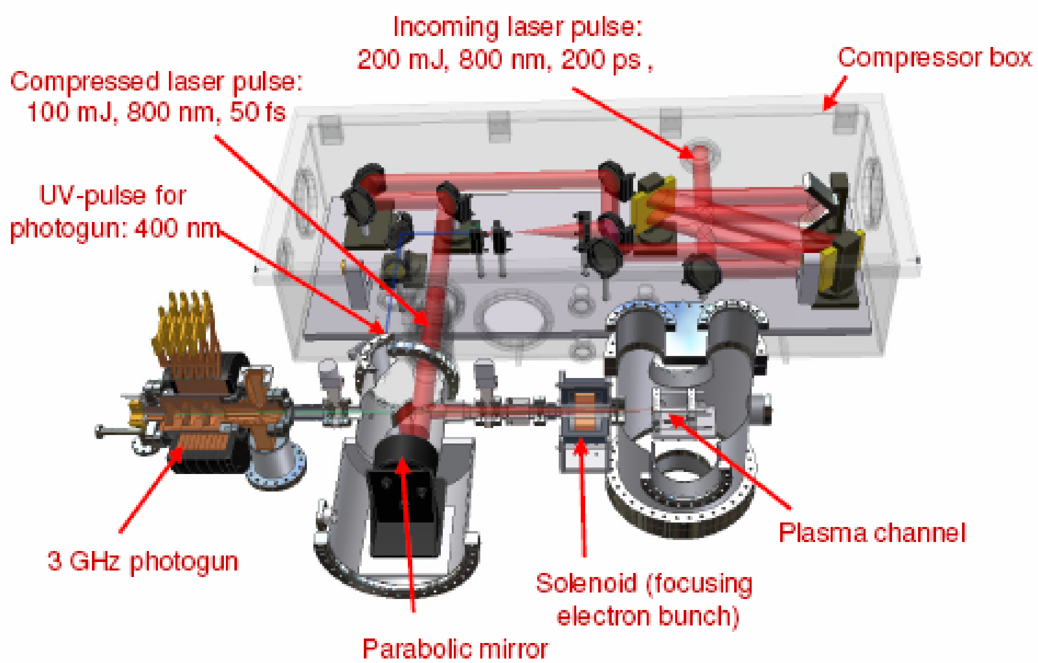
trapping, compression and acceleration of an electron bunch in a plasma wave at different positions in the plasma. (U. Twente)

NIM A 566 p.244 (2006)

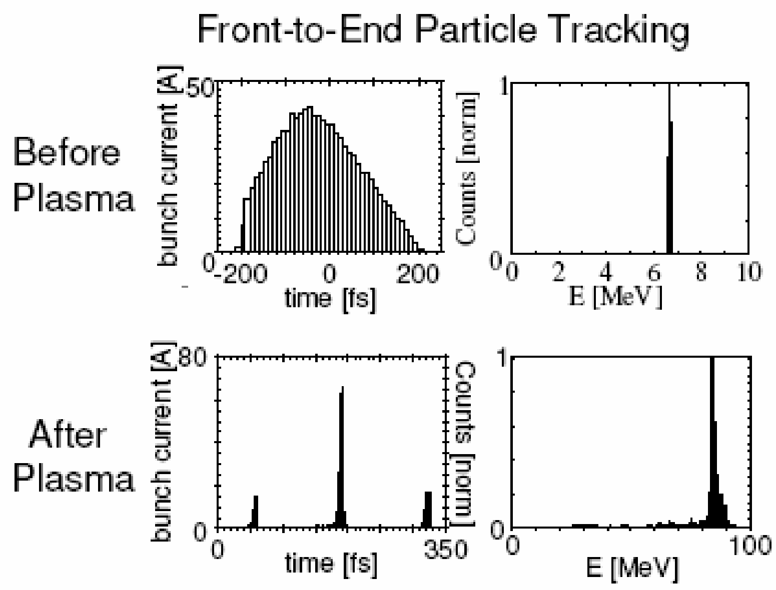
Laser Wakefield Acceleration with External Injection

Injection of 200 fs electron bunch
Into (linear) Laser Wakefield
Driven by 2 TW laser pulse

Setup



Expected Results



Status:
Testing (training) Photogun

Conclusion

- Non linear wakefiled
- Important advances have been made over the last few years
    - Spectrum: max energy (GeV), peak dE/E qq %
    - Beam quality: collimated, short pulse duration
- First applications underway
- Next steps: non linear wakefield will be tested with high power lasers under construction (P > 10 PW)
- Linear wakefield
    - PW created successfuly over a long distance
    - a dedicated facility to test external injection is necessary
        - Laser (1-10 J, 50-100 fs), multi- beams
        - Injector : electron bunches of short duration <100 fs, or compression (100) in the plasma, Relativistic, a few MeV
        - Coupling and transport between stages