# A Story of Plasma Wake Acceleration

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## Outline

- •Motivation and principle
- •Laser Beat wave and Laser Wakefield
- •Self Modulated Laser Wakefield
- •Towards high quality electron beams in LPA
- • Particle Wakefield Accelerator
- •Applications
- •Conclusion and perspectives

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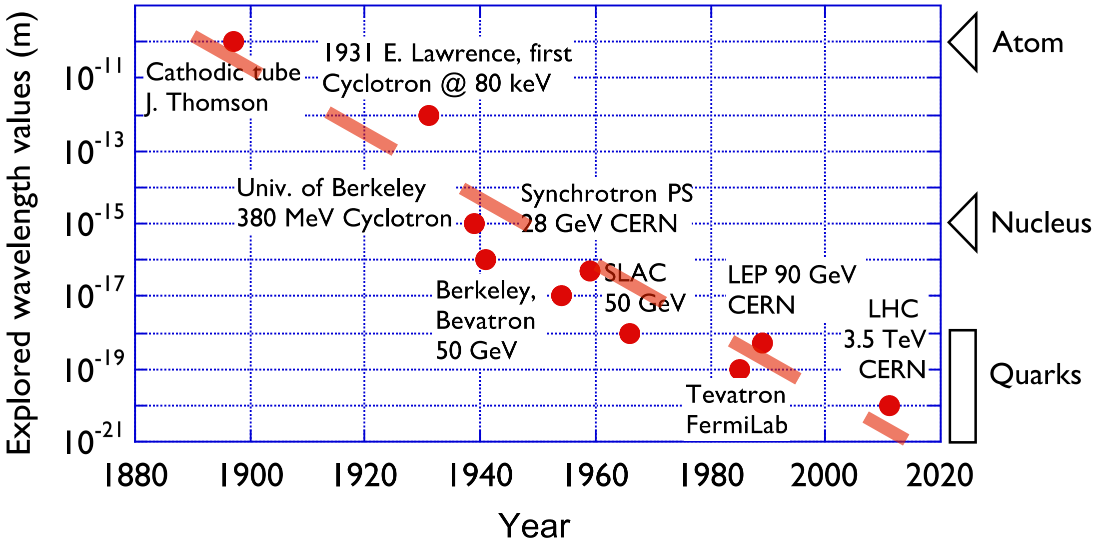
# Industrial Market for Accelerators

The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

| Application | Total systems (2007) approx. | System sold/yr | Sales/yr (M$) | System price (M$) |
|---|---|---|---|---|
| Cancer Therapy | 9100 | 500 | 1800 | 2.0 - 5.0 |
| Ion Implantation | 9500 | 500 | 1400 | 1.5 - 2.5 |
| Electron cutting and welding | 4500 | 100 | 150 | 0.5 - 2.5 |
| Electron beam and X rays irradiators | 2000 | 75 | 130 | 0.2 - 8.0 |
| Radio-isotope production (incl. PET) | 550 | 50 | 70 | 1.0 - 30 |
| Non destructive testing (incl. Security) | 650 | 100 | 70 | 0.3 - 2.0 |
| Ion beam analysis (incl. AMS) | 200 | 25 | 30 | 0.4 - 1.5 |
| Neutron generators (incl. sealed tubes) | 1000 | 50 | 30 | 0.1 - 3.0 |
| Total | **27500** | **1400** | **3680** | |

Total accelerators sales increasing more than 10% per year

## Accelerators : One century of exploration of the infinitively small



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## Compact and Cheaper High Energy Colliders a Grand Challenge for Science and Engineering in the 21st Century

**Particle Physics Project Prioritization Panel (P5) Report 2014: Building for Discovery**

**« A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost…For e+e- colliders, the primary goals are improving the accelerating gradient and lowering the power consumption »**

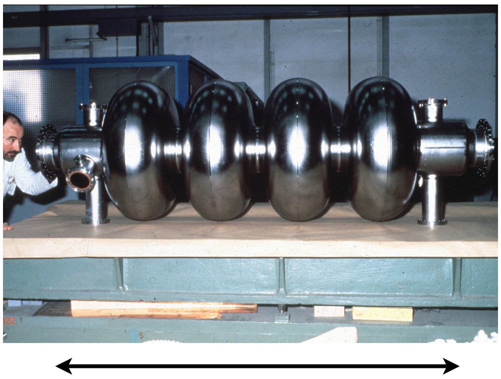
**NAE Grand Challenges for Engineering Tools of Scientific Discovery**

« **Engineers will be able to devise smaller, cheaper but more powerful atom smashers,** enabling physicists to explore realms beyond the reach of current technology »

Courtesy of C. Joshi

# Compactness of Laser Plasma Accelerators

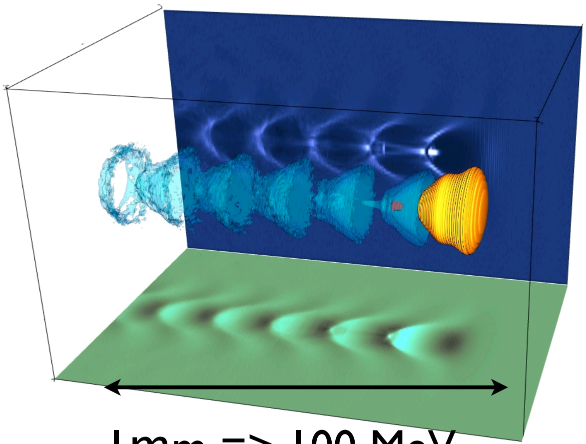
**RF Cavity**



1 m => 50 MeV Gain

Electric field < 100 MV/m

**Plasma Cavity**



1mm => 100 MeV

Electric field > 100 GV/m

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

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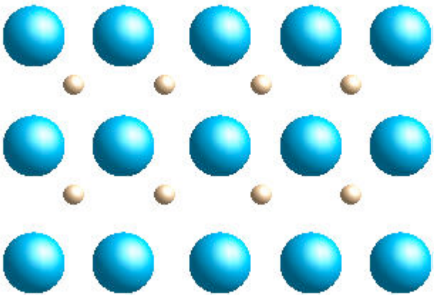
# 1956: Coherent Principle of Acceleration in Plasmas

Superconducting RF-Cavities : $E_z$ = 55 MVm

Plasma is an Ionized Medium => High Electric Fields



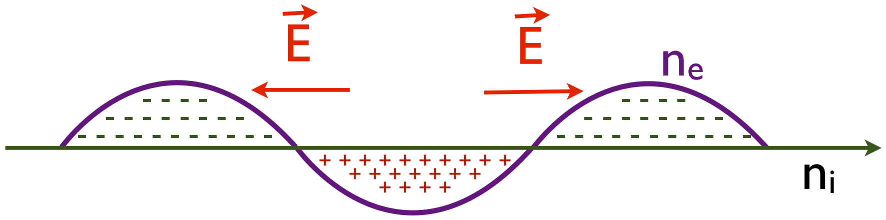
$$E_z\ (\mathrm{GV/m}) \approx \delta n/n \times \sqrt{n}$$

V. I. Veksler, "Coherent Principle of Acceleration of Charged Particles." *Proceedings of the CERN Symposium on High Energy Accelerators and Pion Physics*, vol. 1. Geneva, 1956. Pages 80–83.

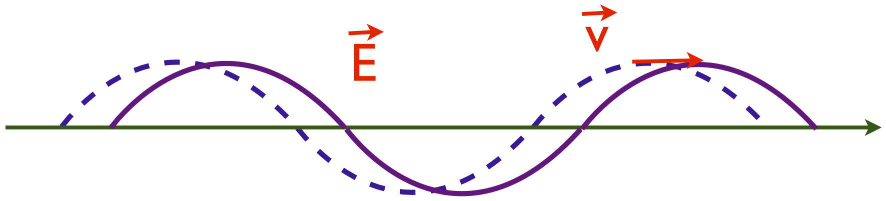
# Plasmas can support longitudinal electric fields

In a plasma, due to space charge electric field, electrons oscillate naturally at the plasma frequency

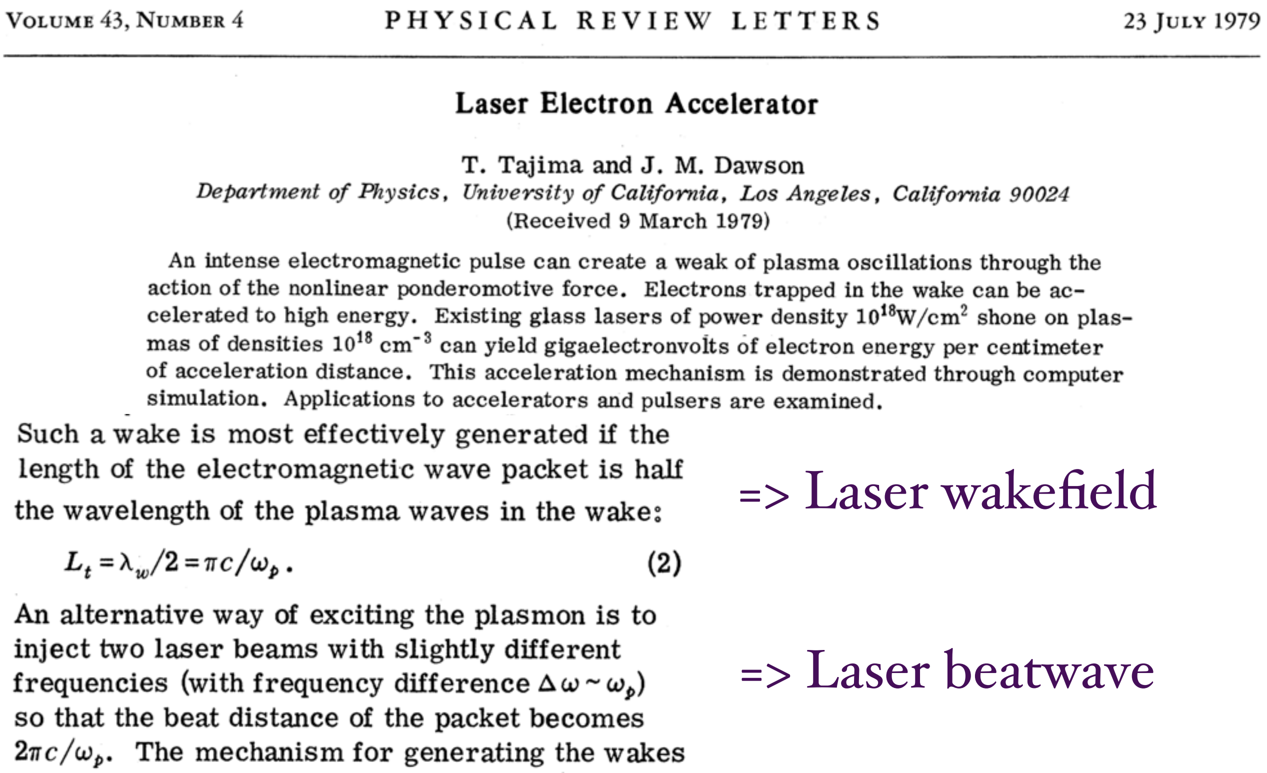
The space charge E-field can be very large : $E(GV/m) = 30\ [n_e/10^{17}cm^{-3}]^{1/2}\delta$



The phase velocity of these plasma waves can be close to **c**



# 1979 Relativistic plasma waves with Laser pulse



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

**Laser Electron Accelerator**

T. Tajima and J. M. Dawson
*Department of Physics, University of California, Los Angeles, California 90024*
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

Such a wake is most effectively generated if the length of the electromagnetic wave packet is half the wavelength of the plasma waves in the wake:

$$L_t = \lambda_w/2 = \pi c/\omega_p. \qquad (2)$$

An alternative way of exciting the plasmon is to inject two laser beams with slightly different frequencies (with frequency difference $\Delta\omega \sim \omega_p$) so that the beat distance of the packet becomes $2\pi c/\omega_p$. The mechanism for generating the wakes

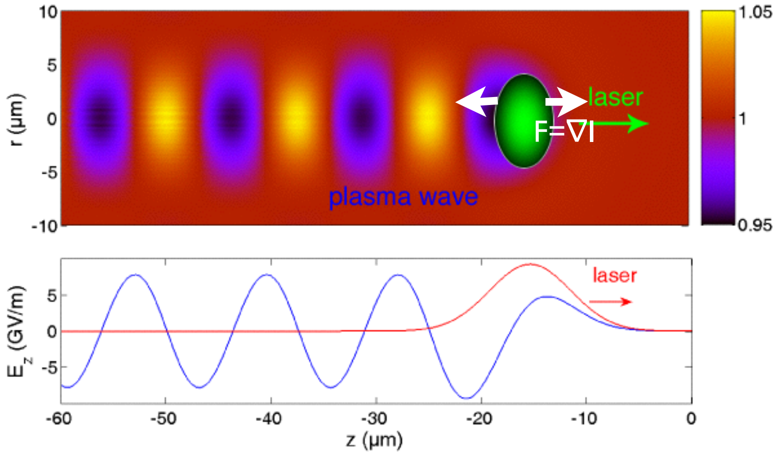
=> Laser wakefield

=> Laser beatwave

# 1979 How to excite a plasma wave ? the Laser Wakefield

## 1) The laser wake field : broad resonance condition $\tau_{laser} \sim T_p/2$ => short laser pulse

electron density perturbation and longitudinal wakefield



wave in the wake of a boat

$v_{phase}^{epw} = v_g^{laser} \sim c$

$E_z$ = 0.3 GV/m for 1 % Density Perturbation at $10^{17}$ cc$^{-1}$
$E_z$ = 300 GV/m for 100 % Density Perturbation at $10^{19}$ cc$^{-1}$

T. Tajima and J. Dawson, PRL **43**, 267 (1979)

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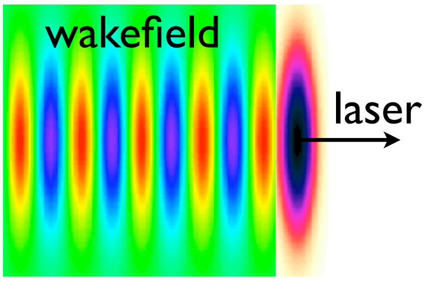
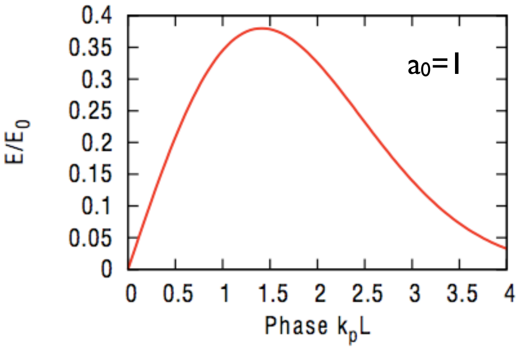
# Resonance condition for Laser Wakefield (twist movie)





$$\text{Optimum potential: } \frac{\partial\phi}{\partial L_0} = 0 \text{ which gives } k_p L_0 = \sqrt{2}$$

$$(\delta n_z/n_0)_{max} \approx 0.4 a_0^2$$

In the laser wakefield the resonance is very broad

$$n_e(cm^{-3}) = \frac{1.7 \times 10^{21}}{\tau_{FWHM}^2(fs)}$$

=> 30 fs @ 1.9x$10^{18}$cm$^{-3}$

Gorbunov et al. Sov. Phys. JETP 66 (87)

# Accelerated electrons in LWF

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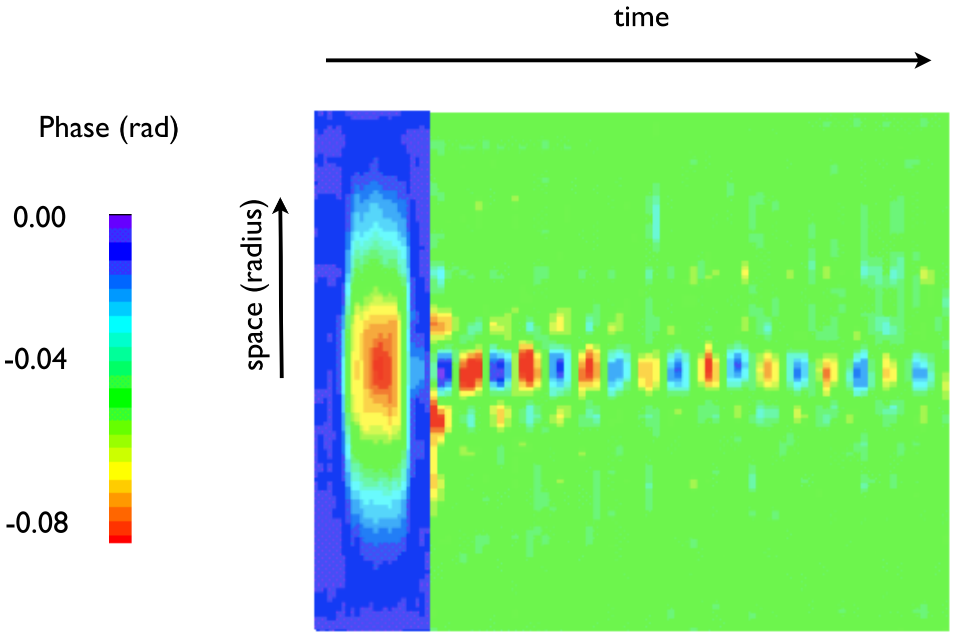
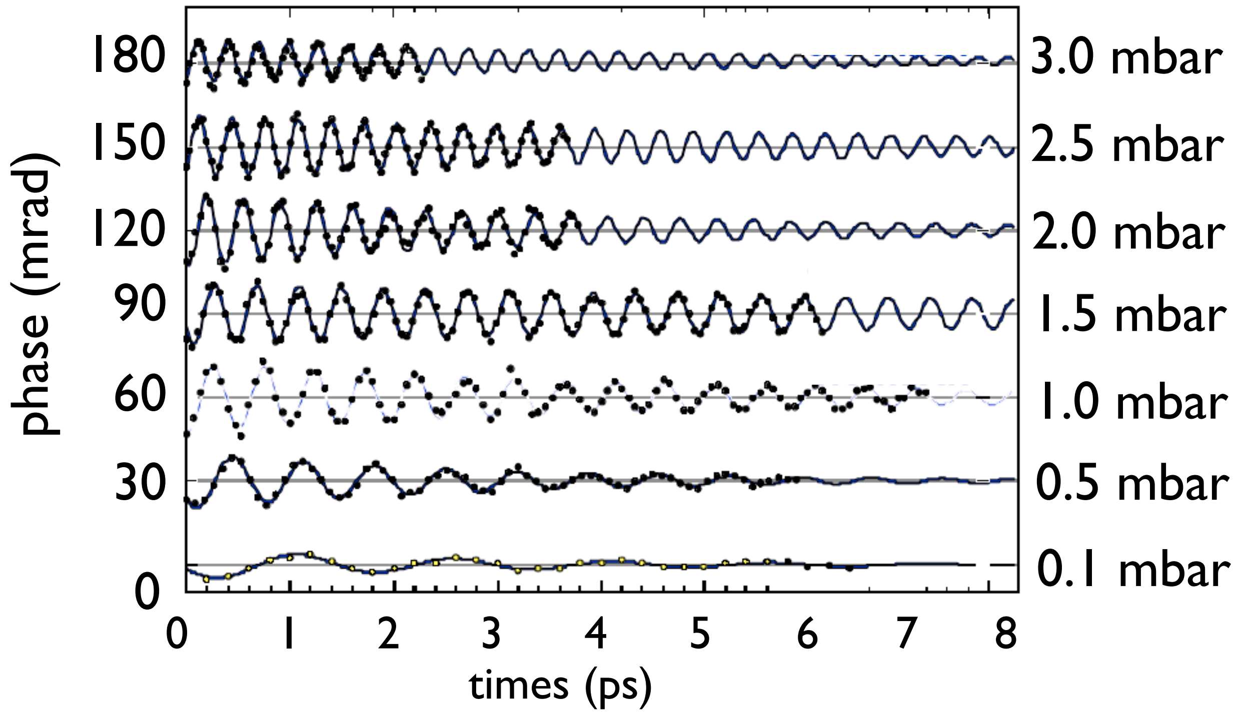
# Frequency domain interferometry : electron density pert.



J.-R. Marquès *et al.*, Phys. Rev. Lett. **76**(19), 3566 (1996); Phys. Rev. Lett. **78** (18), 3463 (1997); Phys. of Plasmas **5**(4), 1162 (1998)

# Electron density oscillation along the laser axis



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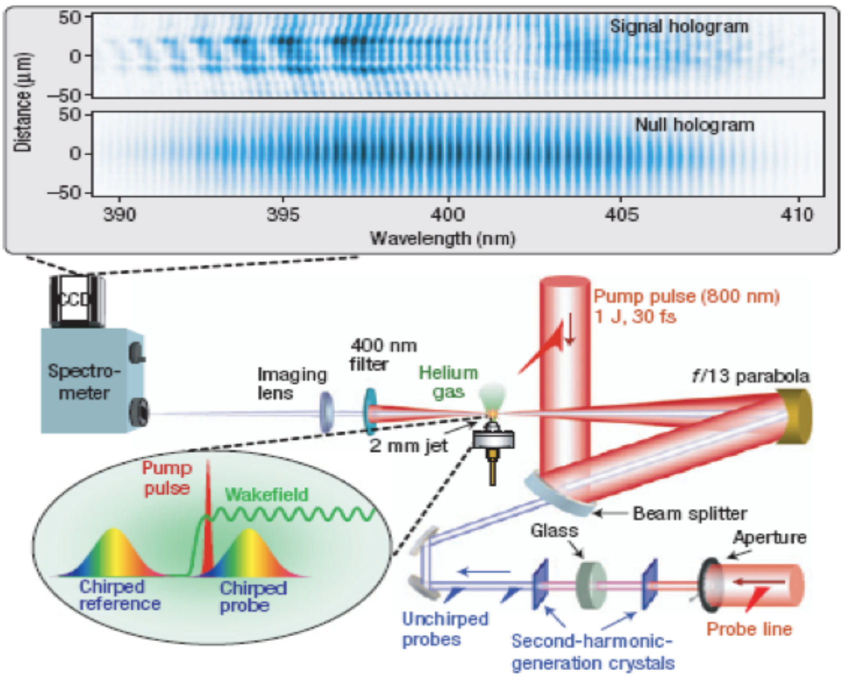
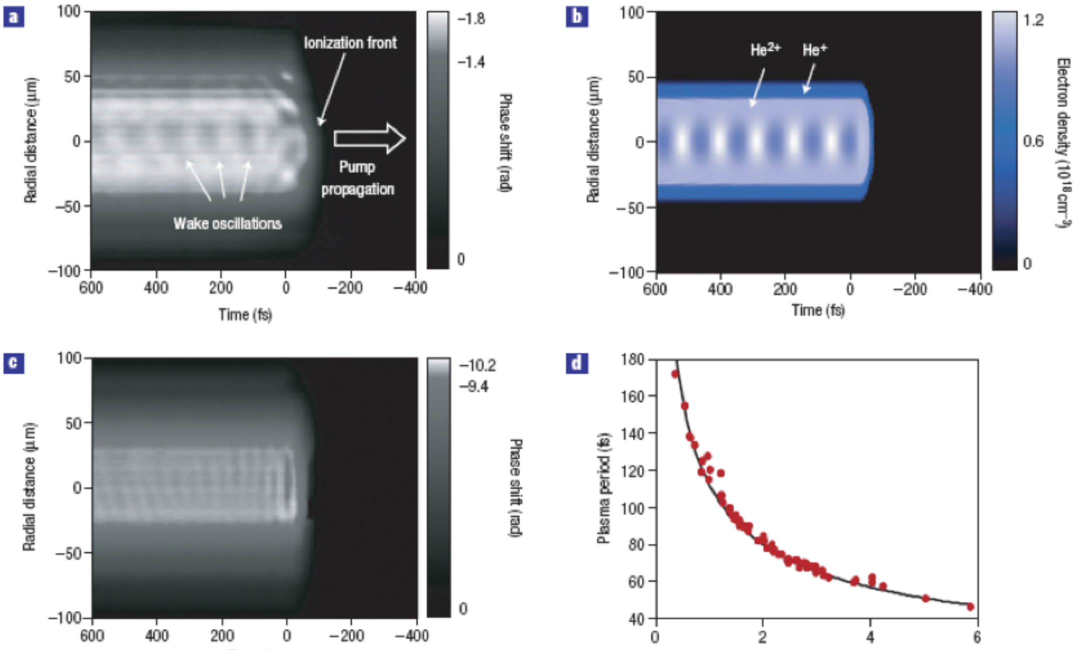
# Snapshots of laser wakefield



N. H. Matlis *et al.* , Nature Physics 2006

# Snapshots of laser wakefield



Small amplitude wakes with flats wavefronts. a) probe phase shift 10TW, 30 fs at $0.95\times10^{19}\text{cm}^{-3}$. b) Simulated wake density profile. c) same than a) at $5.9\times10^{19}\text{cm}^{-3}$. d) wake period versus $n_e$.

N. H. Matlis *et al.* , Nature Physics 2006

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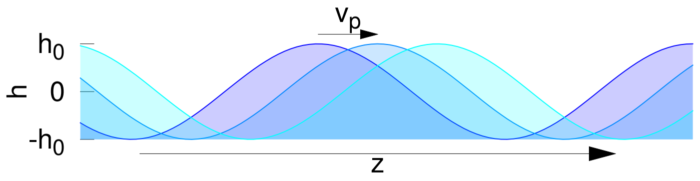
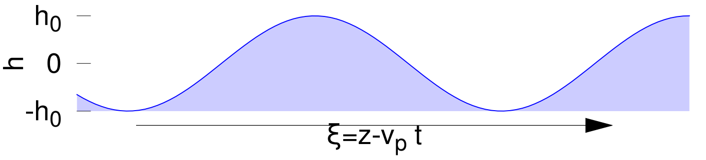
# Injection criteria : the surfer experiences

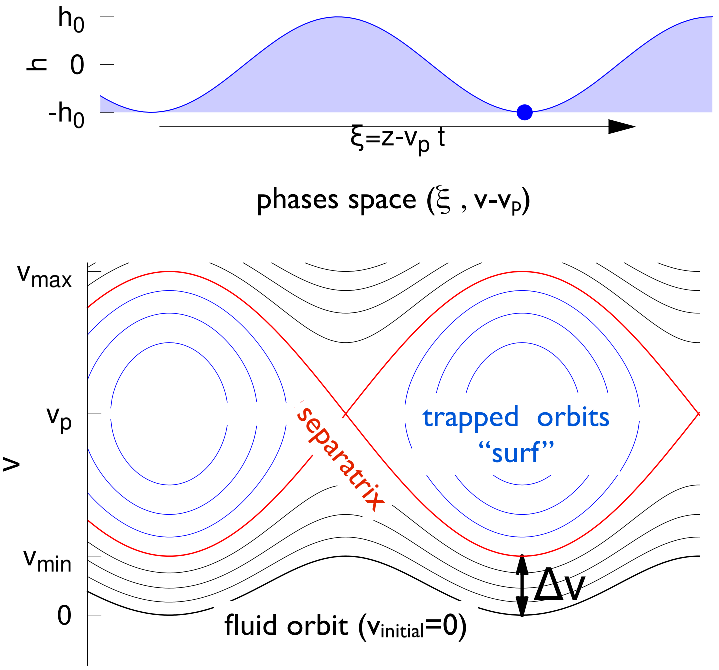


in the terrestrial reference frame
$h = h_0\cos(z-v_pt)$



in the wawe reference frame
$h = h_0\cos(\xi)$

# Injection criteria : the surfer experiences



## conclusions :

- trapped orbits allow higher energy gain
- One needs to transmit enough velocity ΔV

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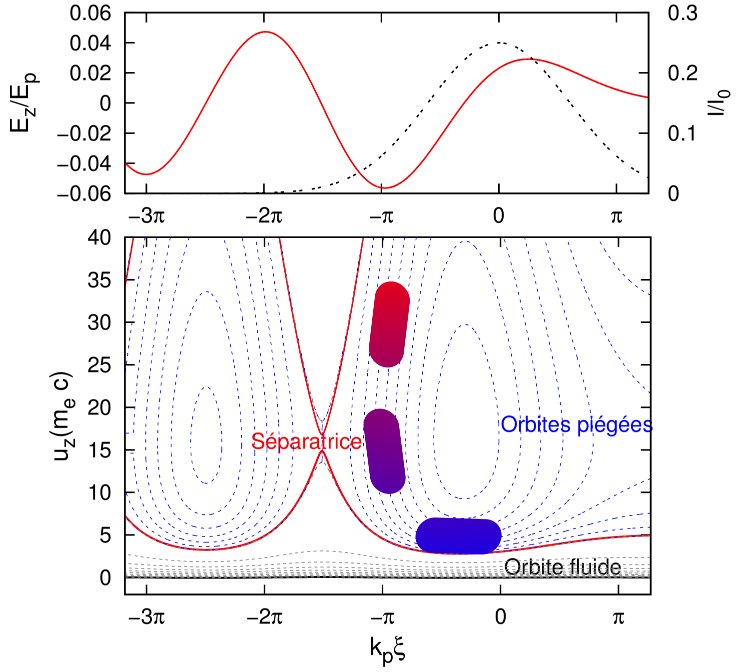
# 1 D maximum energy gain : $W_{max}$: $eE_pL_{deph}$



## In plasma wave :

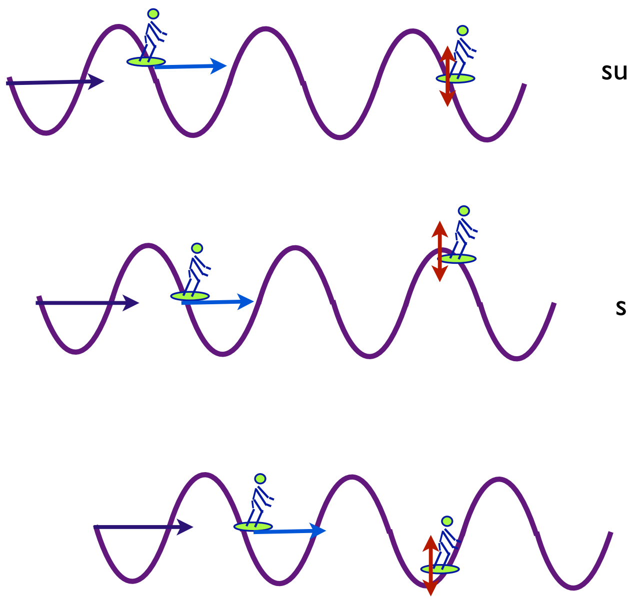
- E field is not homogenous
- Volume is phase space is conserved
- very small initial volume

## external injection :

- Size≈ µm
- Length≈ µm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging with conventional accelerator

# Trapping energy : analogy electron/surfer



surfer with enough initial velocity

surfer initially at rest

surfer with enough initial velocity

surfer initially at rest

surfer with enough initial velocity

surfer initially at rest

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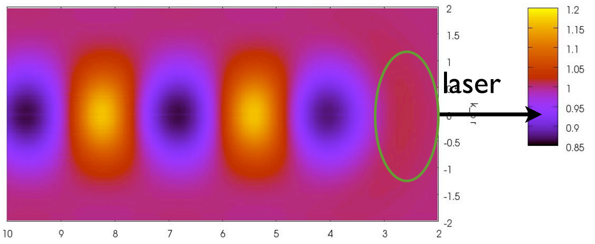
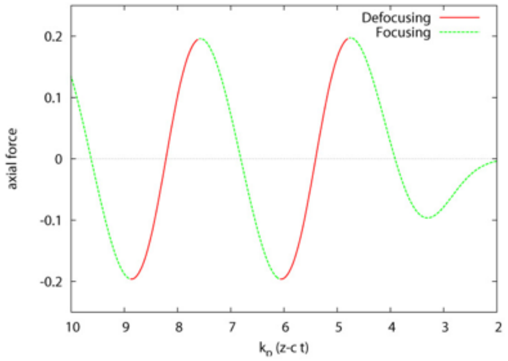
# Trapping energy : analogy electron/surfer

# Accelerating/decelerating and focusing/defocusing fields

$a_0=0.5$



electron density



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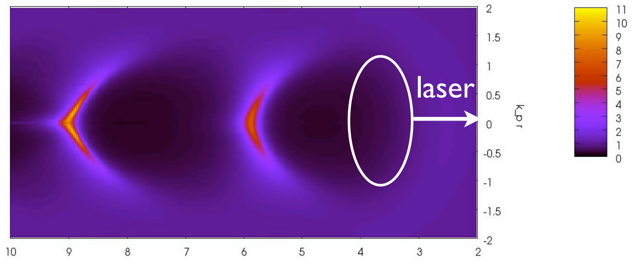
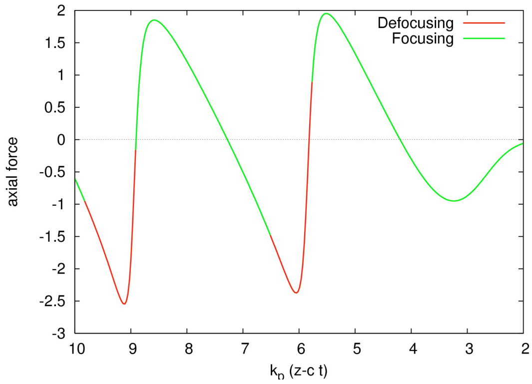
# Non Linear Plasma waves 3D : $a_0=2$ (30fs)





# Outline

- Motivation and principle
- **Laser Beat wave and Laser Wakefield**
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- Particle Wakefield Accelerator
- Applications
- Conclusion and perspectives

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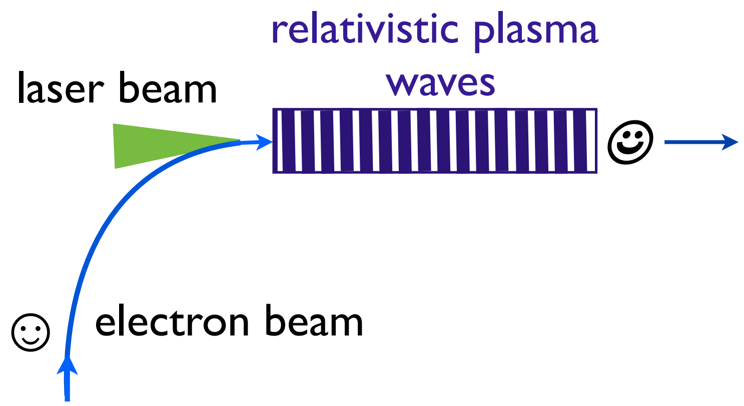
# External injection of electrons in laser driven wakefield

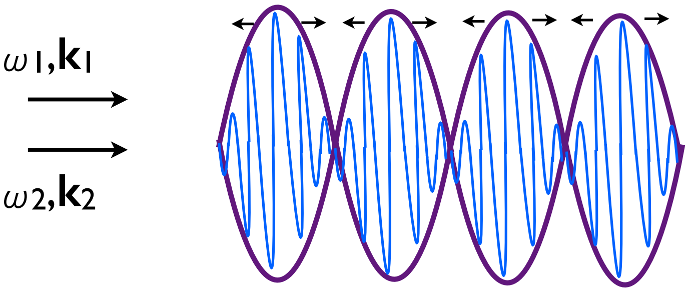
Scheme of principle of the first experiments :



# 1985-1995 How to excite a plasma wave ? the Beat Wave

## 11) The laser beat waves : $\tau_L >> T_p$

**F≈- ∇I**



$$$$!

$\omega_1 - \omega_2 = \omega_p$

linear growth rate $\delta(t) = 1/4\ a_1 a_2 \omega_p t$

=> homogenous plasmas

saturation : relativistic, ion motion

*Train of short resonant pulses*

**Optical demonstration by Thomson scattering :**

Clayton *et al.* PRL 1985, Amiranoff *et al.* PRL 1992, Dangor *et al.* Phys. Scrypta 1990

Chen, Introduction to plasma physics and controlled fusion, 2$^{nd}$ Edition, Vol.1, (1984)

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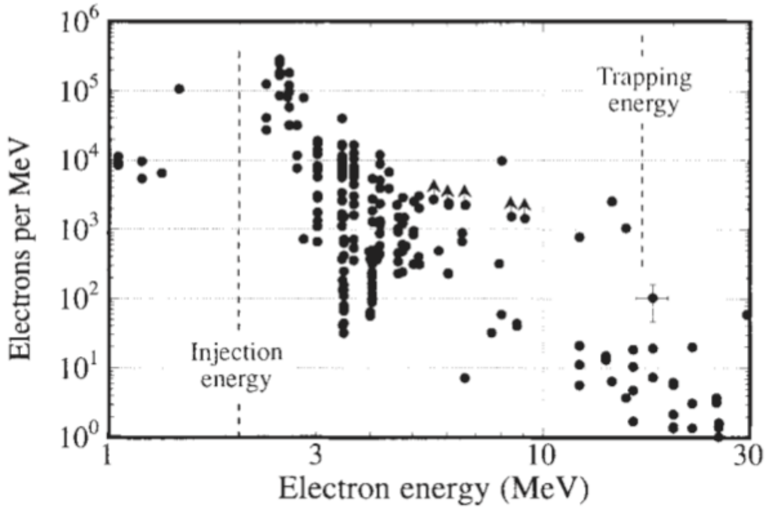
# 1992-1994 Accelerated electrons in LBWF

The 2-MeV electrons are accelerated up to ≈ 28 MeV

Electron spectra indicate an $E_{field}$ of ≈ 2.8 GV/m



M. Everett *et al.*, Nature 1994

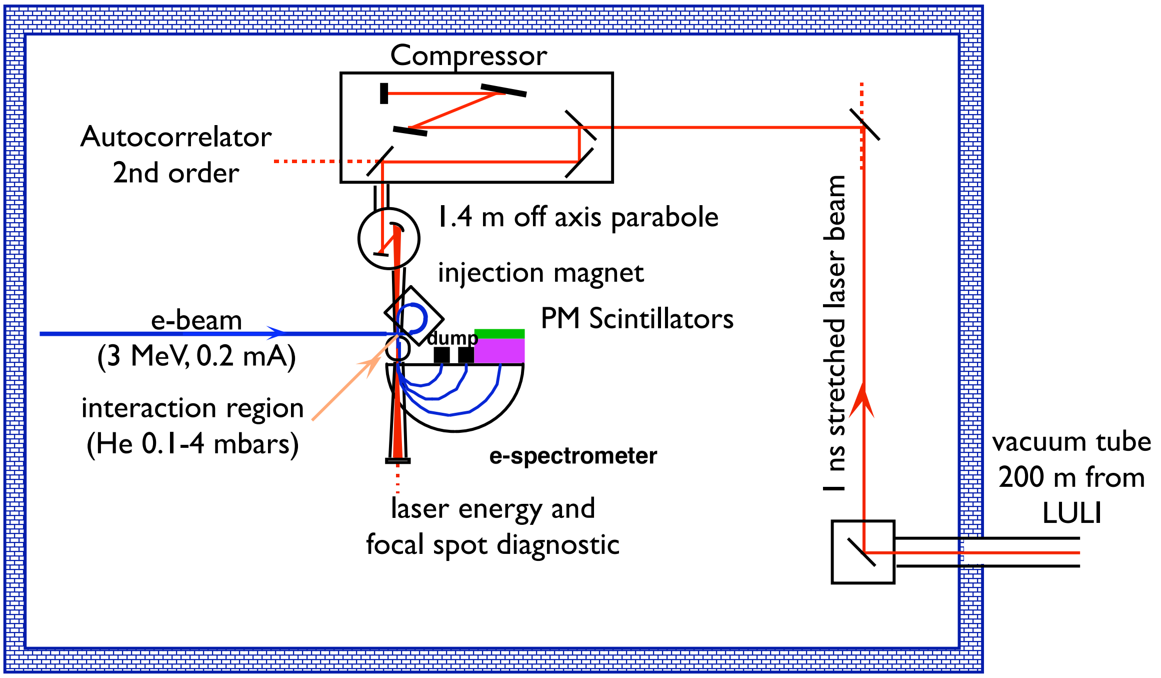
**Electron gain demonstration Few MeV's:**

Kitagawa *et al.* PRL 1992, Clayton *et al.* PRL 1993, N. A. Ebrahim *et al.*, J. Appl. Phys.1994, Amiranoff *et al.* PRL 1995

# 1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

## Electron spectra indicate an $E_{field}$ of ≈ 1 GV/m



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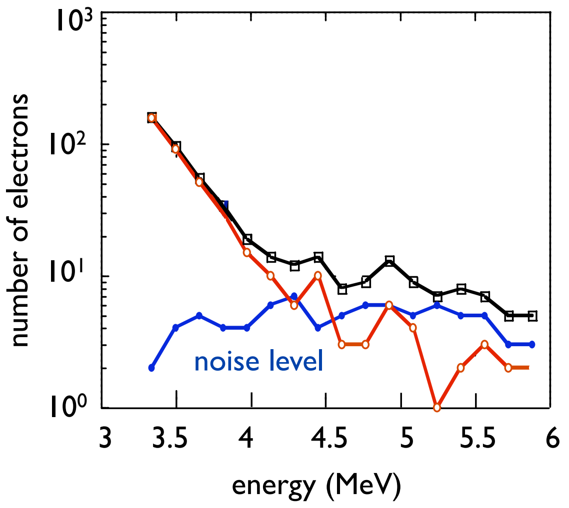
# 1998 Accelerated electrons in LWF

LULI/LPNHE/LSI/IC

## The 3-MeV electrons are accelerated up to ≈ 4.5 MeV
## Electron spectra indicate an $E_{field}$ of ≈ 1.4 GV/m

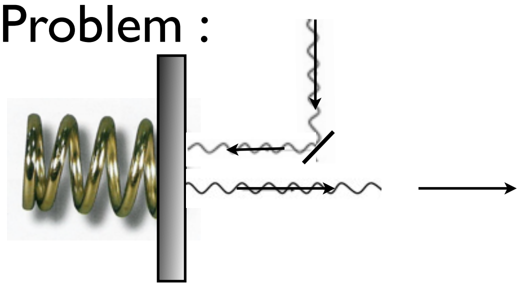


2.5 J, 350 fs, $10^{17}$W/cm$^2$, 0.5 mbar of He

F. Amiranoff *et al.*, PRL 1998

# Analogy : oscillating mirror’s problem

Problem :



spectrometer

$$E = E_0 sin[\omega_0 t + \delta\Phi(t)] \text{ with } \delta\Phi(t) = \pi \frac{\delta n}{n_0} \frac{\omega_p}{\omega_0} \frac{L}{\lambda_p} sin(\omega_p t) = A sin(\omega_p t)$$

$$E = E_0 sin[\omega_0 t + A sin(\omega_p t)]$$

$$E = Re[E_0 e^{i\omega_0 t} e^{iA sin(\omega_p t)}]$$

Expanding the second term in Bessel functions : $e^{iAsin(\omega_p t)} = \sum J_n(A) e^{in\omega_p t}$

$$\frac{E_{\omega_0+\omega_p}}{E_{\omega_0}} = \frac{J_1(A)}{J_0(A)} \approx A/2 \longrightarrow \qquad P_0 = (\frac{A_s}{A_0})^2 (\frac{\delta n}{n_0} \frac{\omega_p}{\omega_0} \frac{L}{\lambda_p})^2$$

which is the Bragg formula

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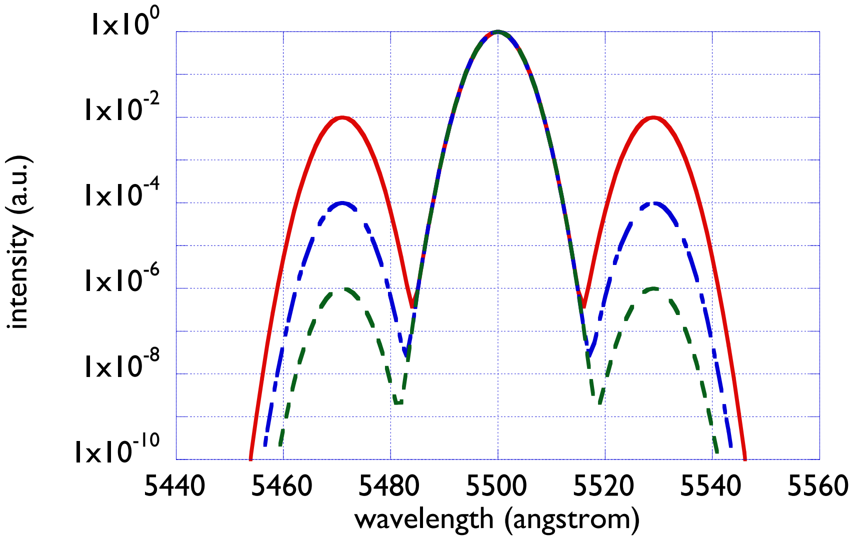
# Thomson scattering spectra

$n_e$=$10^{17}$cm$^{-3}$, δn/n=1%, $\lambda_0$=0.5μm,
L=$10^2$,$10^3$,$10^4$ μm



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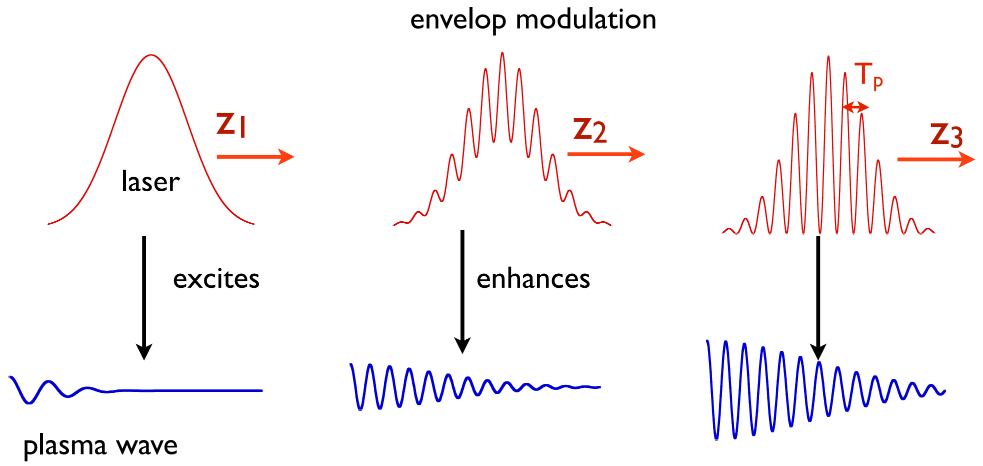
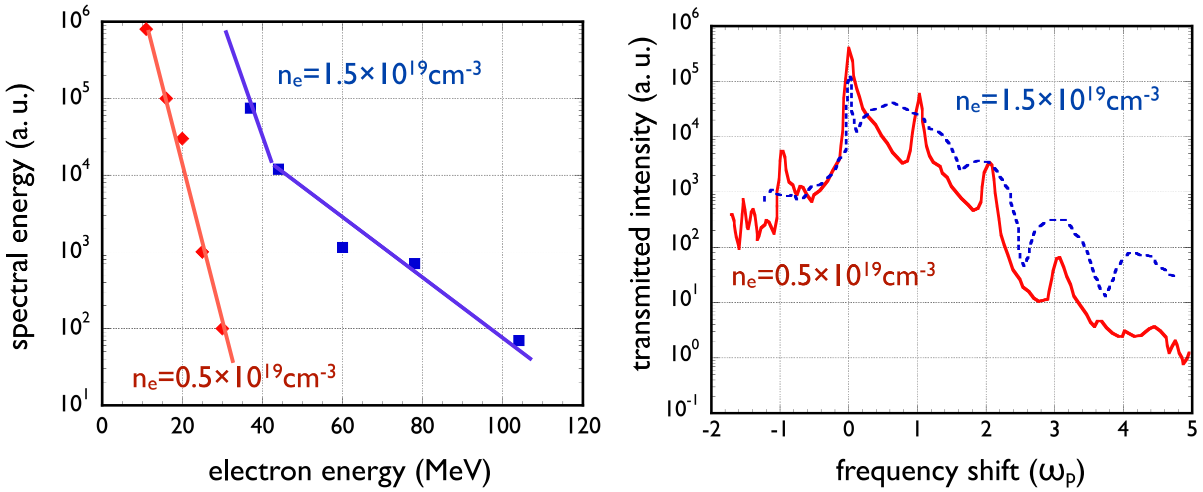
# 1992 How to excite a plasma wave: The SMLWF

Self modulated laser wakefield scheme : $c\tau_{laser} >> T_P$
(Andreev *et al.*, Antonsen *et al.*, Sprangle *et al.* 1992)



$P_L > P_c(GW) = 17\, n_c/n_e$ then wavebreaking can occur

# 1995 Relativistic wave breaking (RAL/IC/UCLA/LULI)



Multiple satellites : high amplitude plasma waves
Broadening at higher densities
Loss of coherence of the relativistic plasma waves

A. Modena *et al.*, Nature (1995)

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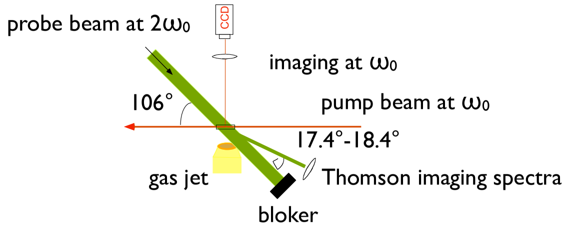
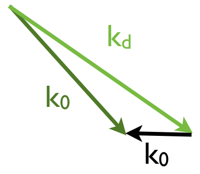
# 1998 Thomson scattering diagnostic

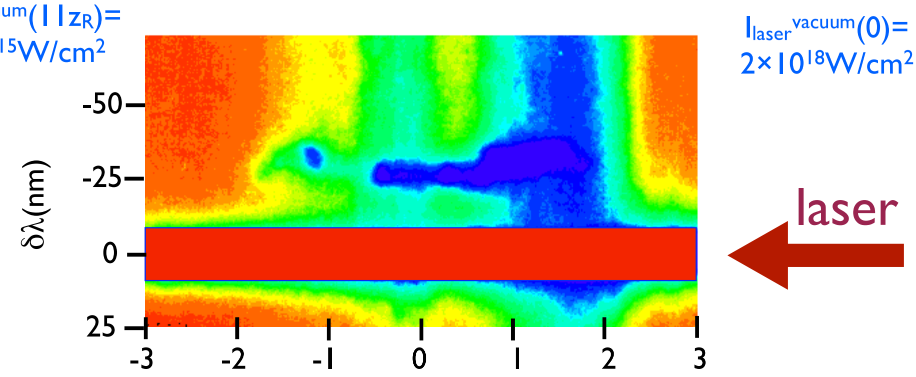
experimental set-up



waves geometry



$I_{laser}^{vacuum}(11z_R)=$
$2\times10^{15}$W/cm$^2$



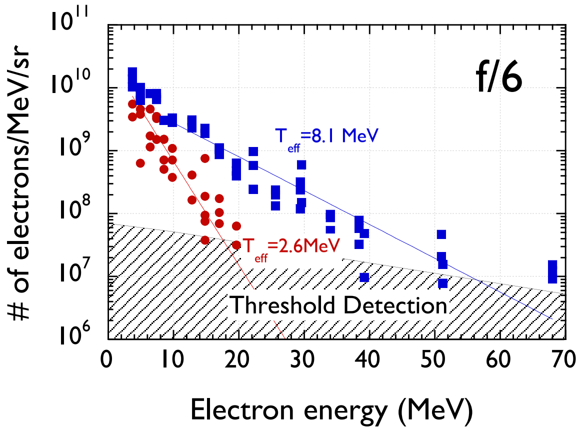
$I_{laser}^{vacuum}(0)=$
$2\times10^{18}$W/cm$^2$

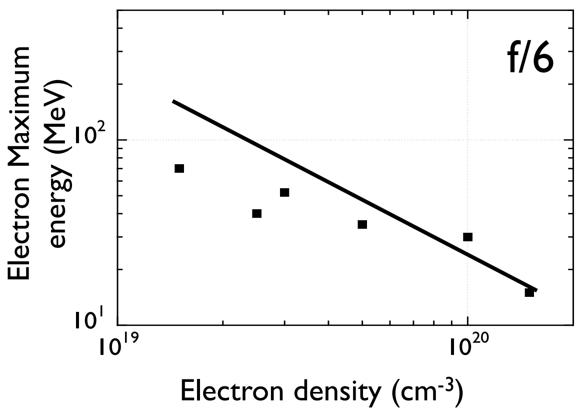
Clayton *et al.*, PRL **81**, 1 (1998)

# 2001 SMLWF with 10 Hz laser

## Spectra : $E_{max}$ increases when $n_e$ decreases

Parameters: $n_e=5\times10^{19}\text{cm}^{-3}$ & $1.5\times10^{20}\text{cm}^{-3}$, $\tau_L$=35fs, E=0.6J, $I_L= 2\times10^{19}\text{W/cm}^2$





V. Malka et al., Phys. of Plasmas **8**, 6 (2001)

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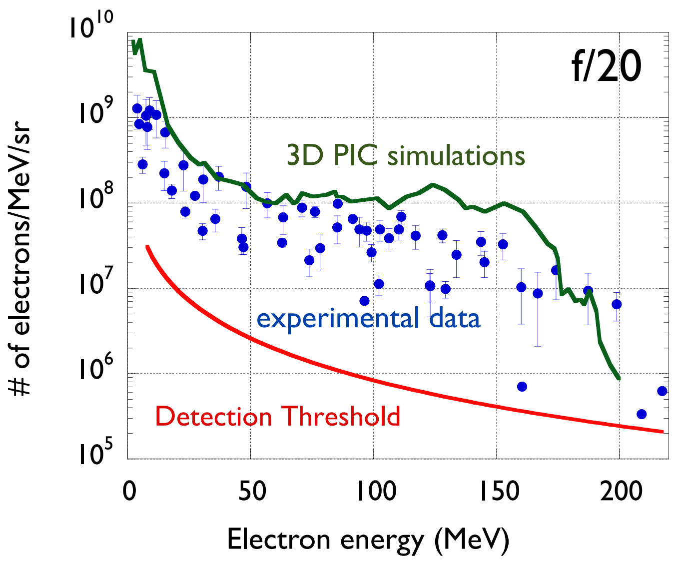
# 2002 The Forced Laser Wakefield: the NL regime

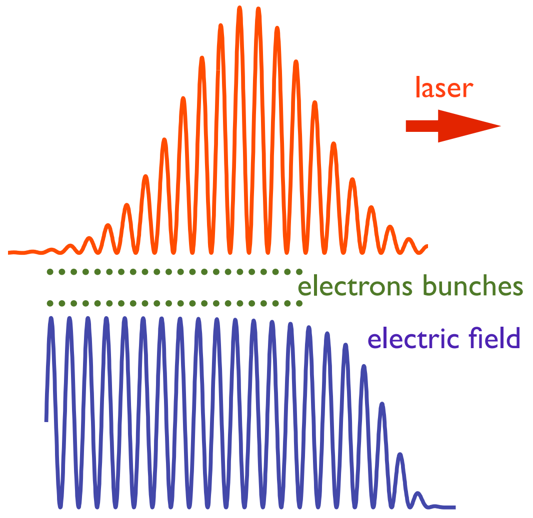
Parameters: $n_e=1.5\times10^{19}\text{cm}^{-3}$, $\tau_L$=35fs, E=0.6J, $I_L= 1\times10^{18}\text{W/cm}^2$ with $k_pw_0>1$



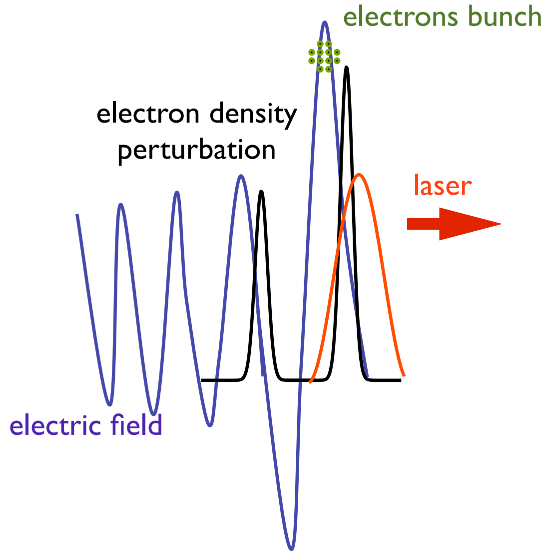
V. Malka *et al.*, Science **298**, 1596 (2002)

# SMLWF / FLWF (ps/fs) :multiple/single bunch

SMLWF: $\omega_p\tau >> 1$



FLWF: $\omega_p\tau \approx 1$



V. Malka, Europhysics News, April (2004)

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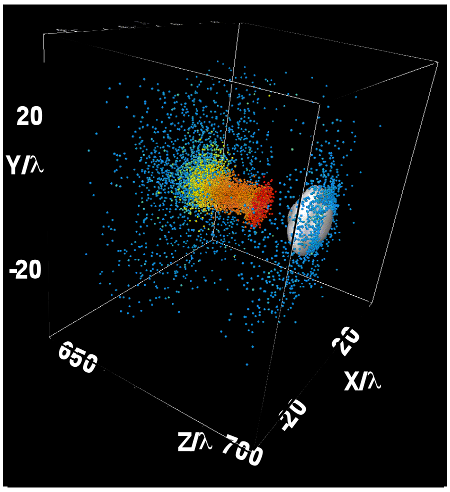
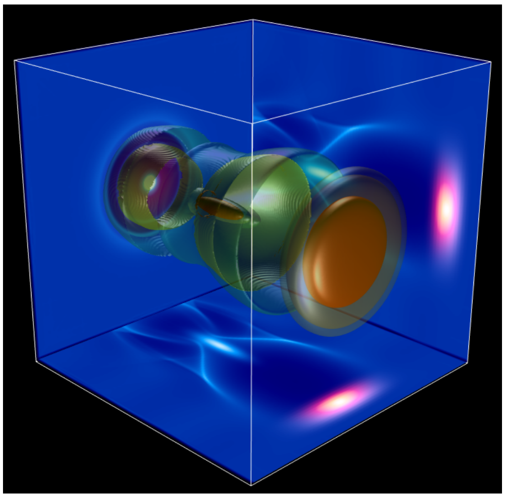
- Conclusion and perspectives

# 2002 The Bubble regime : QM energetic electron beam



VLPL, courtesy of A. Pukhov



Golp, courtesy of L. Silva

A.Pukhov & J.Meyer-ter-Vehn, Appl. Phys. B, **74** (2002)

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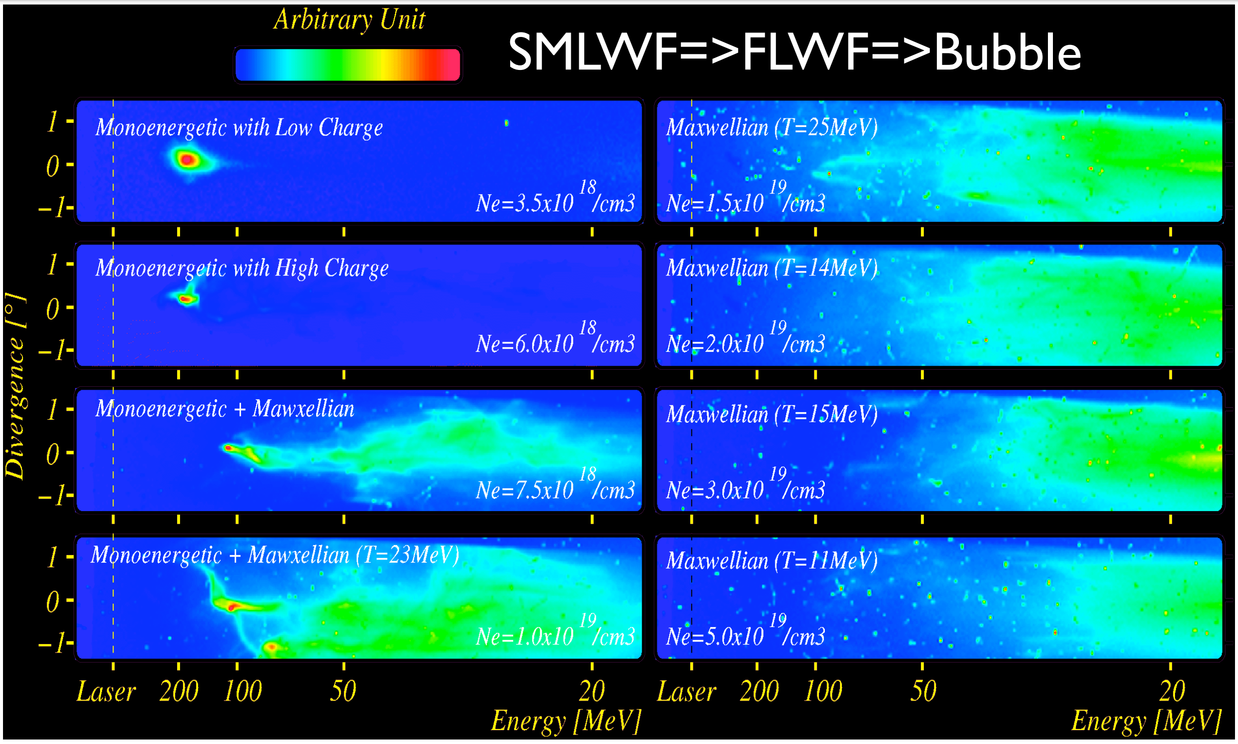
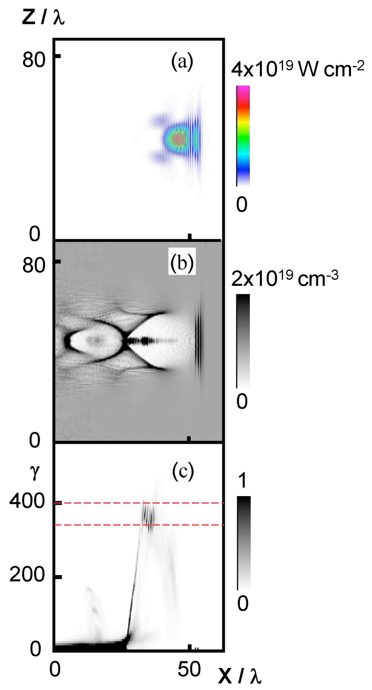
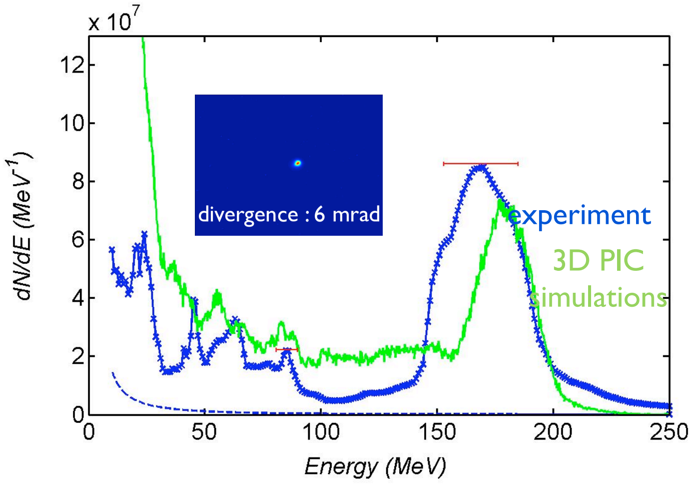
# 2005 The Bubble regime : distribution quality improvements



V. Malka *et al.*, Phys. of Plasmas **12**, 5 (2005)

# 2005 The Bubble regime : theory/experiments





Experimental parameters : E=1J, $\tau_L$=30fs,
$\lambda_L$=0.8µm, $I_L$=3.2×$10^{19}$W/cm$^2$, $n_e$=6×$10^{18}$cm$^{-3}$

J. Faure *et al.*, Nature **431**, 7008 (2004)

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# 2004 The Dream Beam


30 September 2004

International weekly journal of science

nature

www.nature.com/nature

**Dream beam**

The dawn of compact particle accelerators

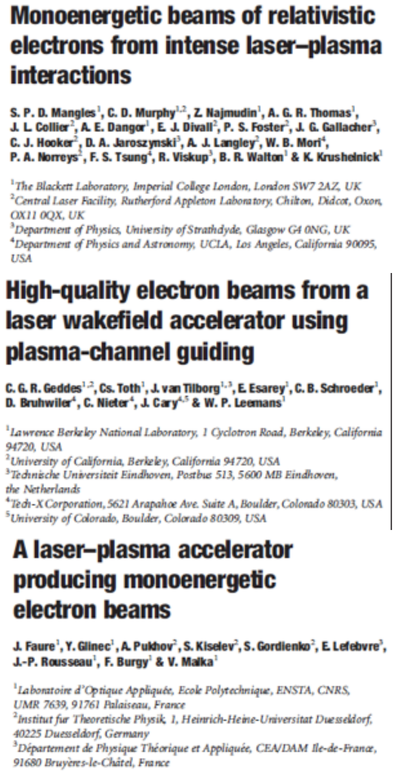
**Disease control** Europe plays catch-up

**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


**Monoenergetic beams of relativistic electrons from intense laser–plasma interactions**

**S. P. D. Mangles[1], C. D. Murphy[1,2], Z. Najmudin[1], A. G. R. Thomas[1], J. L. Collier[2], A. E. Dangor[1], E. J. Divall[2], P. S. Foster[2], J. G. Gallacher[3], C. J. Hooker[2], D. A. Jaroszynski[3], A. J. Langley[2], W. B. Mori[4], P. A. Norreys[2], F. S. Tsung[4], R. Viskup[3], B. R. Walton[1] & K. Krushelnick[1]**

*[1] The Blackett Laboratory, Imperial College London, London SW7 2AZ, UK*
*[2] Central Laser Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK*
*[3] Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK*
*[4] Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*

**High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding**

**C. G. R. Geddes[1,2], Cs. Toth[1], J. van Tilborg[1,3], E. Esarey[1], C. B. Schroeder[1], D. Bruhwiler[4], C. Nieter[4], J. Cary[4,5] & W. P. Leemans[1]**

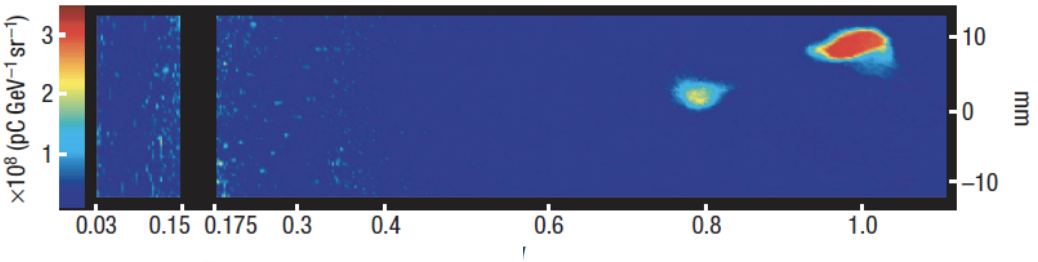
*[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA*
*[2] University of California, Berkeley, California 94720, USA*
*[3] Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, the Netherlands*
*[4] Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, Colorado 80303, USA*
*[5] University of Colorado, Boulder, Colorado 80309, USA*

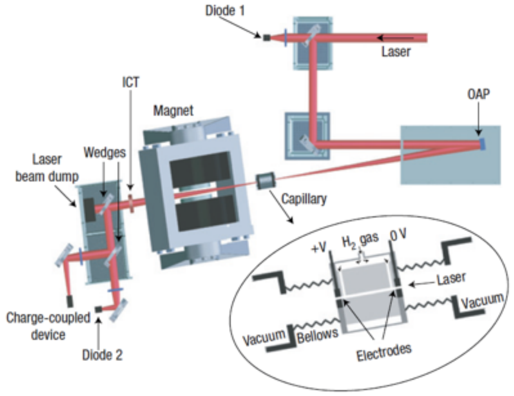
**A laser–plasma accelerator producing monoenergetic electron beams**

**J. Faure[1], Y. Glinec[1], A. Pukhov[2], S. Kiselev[2], S. Gordienko[2], E. Lefebvre[3], J.-P. Rousseau[1], F. Burgy[1] & V. Malka[1]**

*[1] Laboratoire d'Optique Appliquée, Ecole Polytechnique, ENSTA, CNRS, UMR 7639, 91761 Palaiseau, France*
*[2] Institut fur Theoretische Physik, 1, Heinrich-Heine-Universitat Duesseldorf, 40225 Duesseldorf, Germany*
*[3] Département de Physique Théorique et Appliquée, CEA/DAM Ile-de-France, 91680 Bruyères-le-Châtel, France*

# 2006 GeV electron beams from "cm scale" accelerator





310-μm-diameter
channel capillary

P = 40 TW

density $4.3\times10^{18}$ cm$^{-3}$

W. Leemans *et al.*, Nature Physics, september 2006

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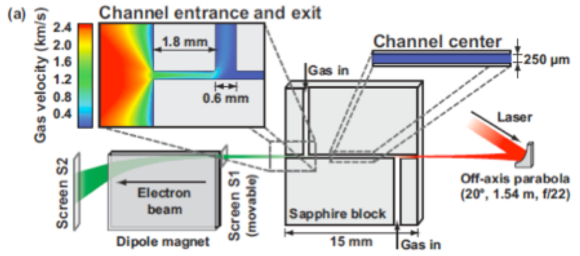
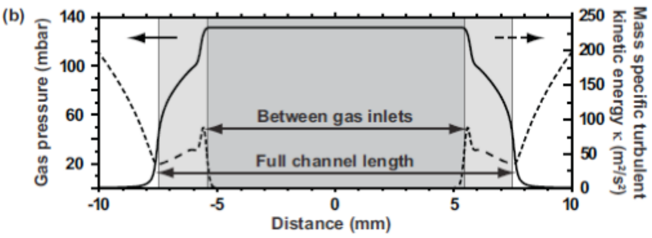
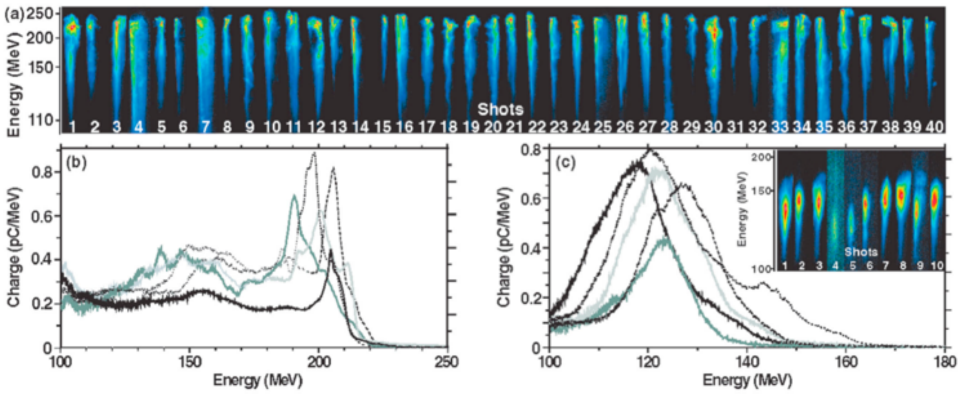
# 2009 Gas cell experiments at MPQ







Laser : 20 TW

1cm gas cell target

0.8J, 40 fs, $a_0$=0.9

$n_e$=7x10$^{18}$cm$^{-3}$

Stable e-beam :

10 pC

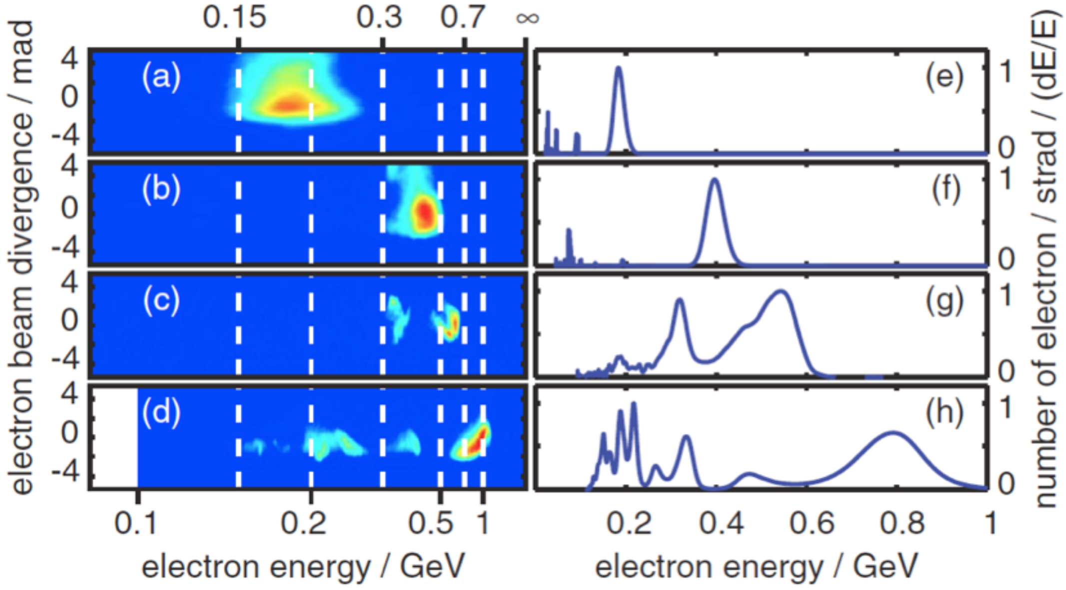
220 MeV

Div = 2 mrad

DE/E = 8%

J. Osterhoff et al., PRL 101, 085002 (2008)

# 2009 GeV electron beams from “cm scale” accelerator



Astra Gemini laser RAL :
11J, 55fs, a=3.9, 1cm gas jet target, density 5.7×10$^{18}$ cm$^{-3}$
0.8 GeV, >ten % relative energy spread, 300 pC

S. Kneip *et al.*, Phys. Rev. Lett. 103, 035002 (2009)

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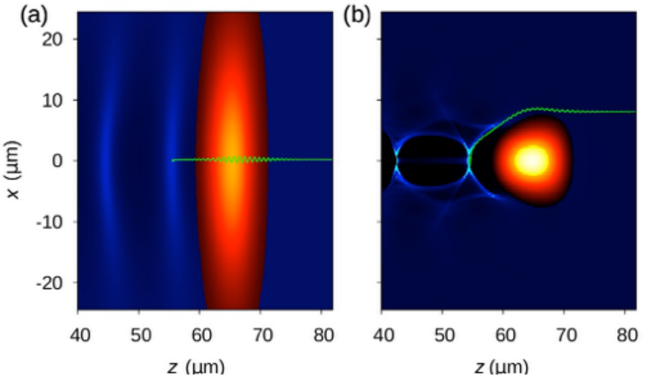
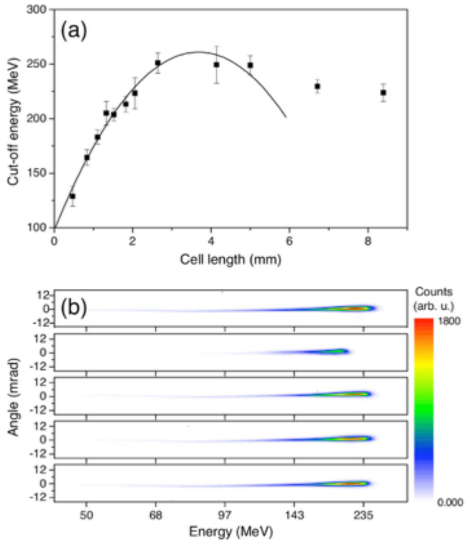
# 2013 Longitudinal injection

Two different self-injection mechanisms take place :

- At lower plasma density transverse injection is prevented

- Only one bunch is injected (longitudinal injection)

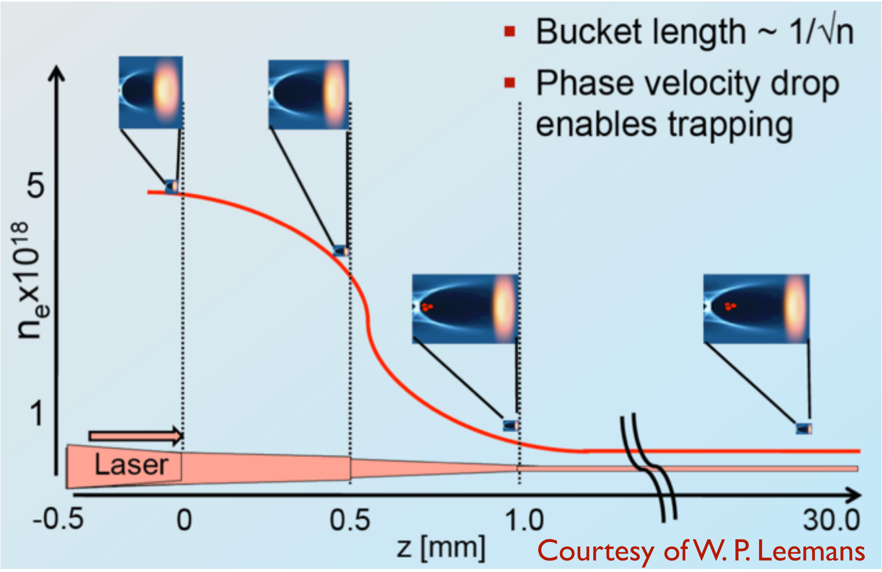




longitudinal injection improves
- the stability of the electron beam
and
- reduces the divergence of the electron beam

S. Corde *et al.*, Nature Communications (2013)

# 2005-2008 Density ramp injection



- Bucket length ~ 1/√n
- Phase velocity drop enables trapping

Courtesy of W. P. Leemans

$$v_p/c = (1 + \frac{\zeta}{k_p}\frac{dk_p}{dz})^{-1}$$

where, $\zeta = z - ct$ and $k_p(z)$

which depends on z through on density

$$\frac{k_p}{dz} = \frac{k_p}{2n_e}\frac{dn_e}{dz}$$

For a downward density, the wake phase velocity slow down facilitating electrons trapping

S. Bulanov *et al.*, PRE **58**, R5257 (1998), H. Suk *et al.*, PRL **86**, 1011 (2001), T.-Y Chien *et al.*, PRL **94**, 115003 (2005), T. Hosokai *et al.*, PRL **97**, 075004 (2006), C. G. R. Geddes *et al.* PRL **100**, 215004 (2008), J. Faure *et al.*, Phys. of Plasma **17**, 083107 (2011)

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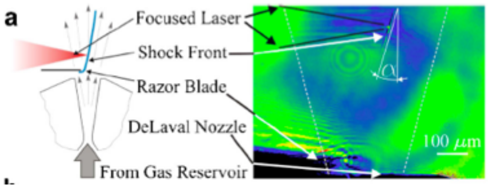
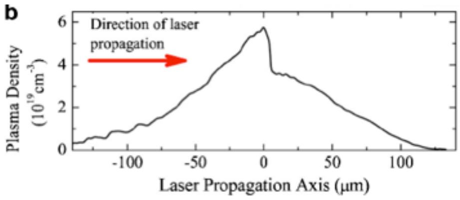
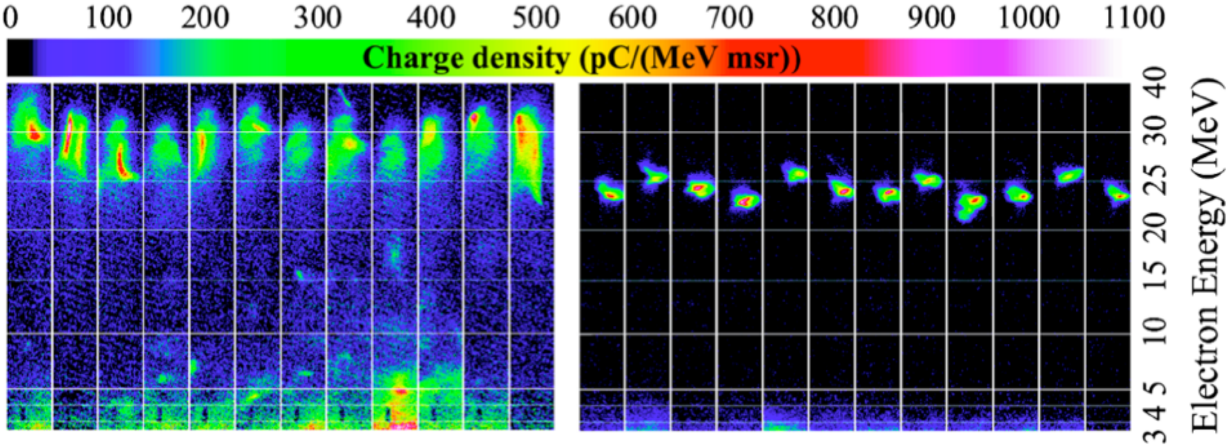
# 2010 Sharp density ramp injection : shock in gas jet



=>



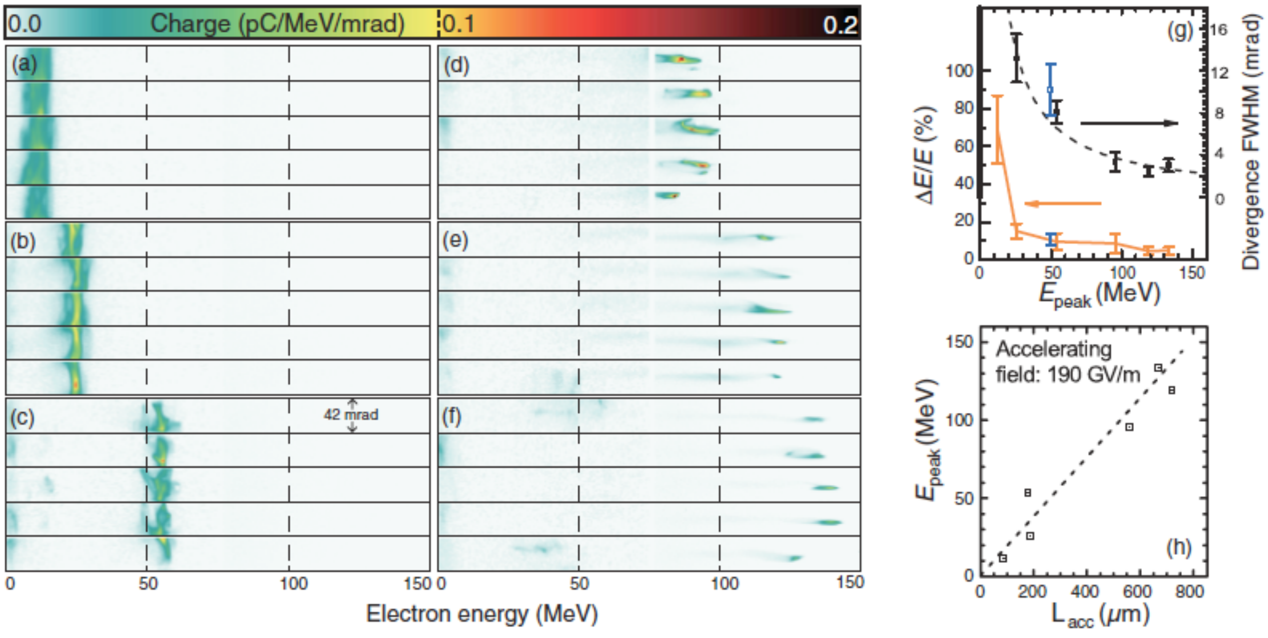


(a) Self injection

(b) Injection at density transition

K. Schmid et al., PRSTAB 13, 091301 (2010)

# 2013 Shock front injection



A. Buck *et al.*, PRSTAB 13, 091301 (2010)

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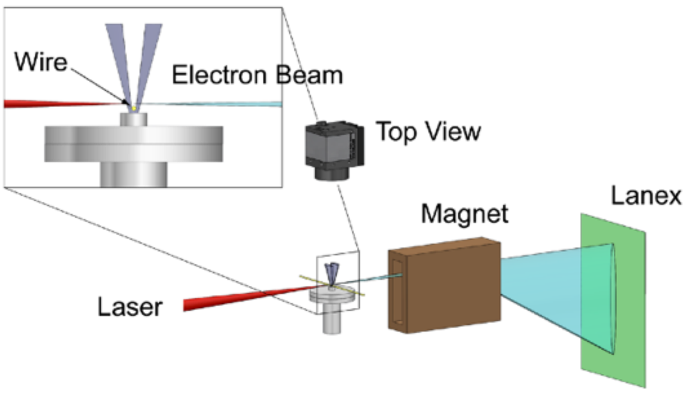
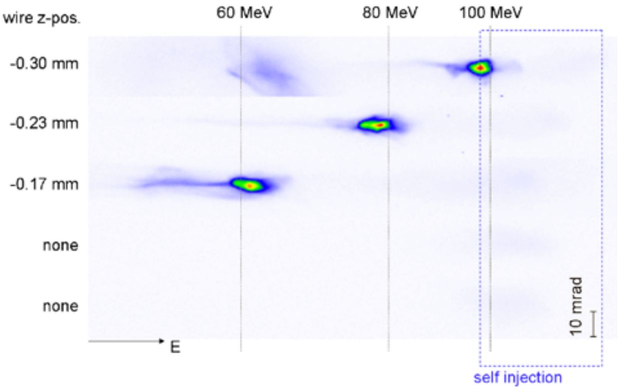
# 2013 Shock front injection : LLC

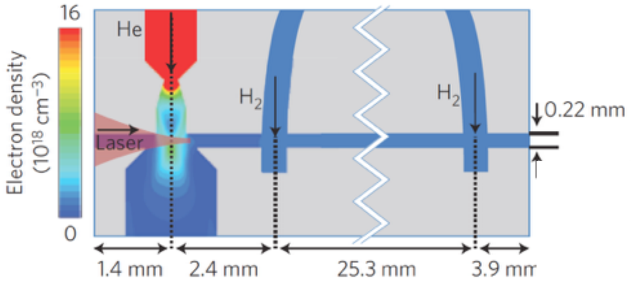
## Laser wakefield acceleration using wire produced double density ramps

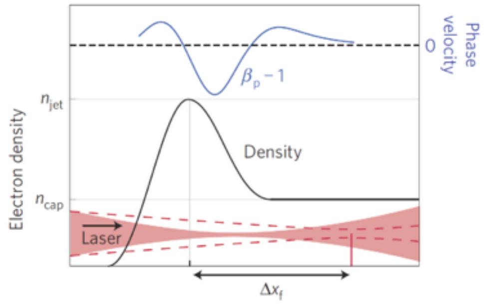


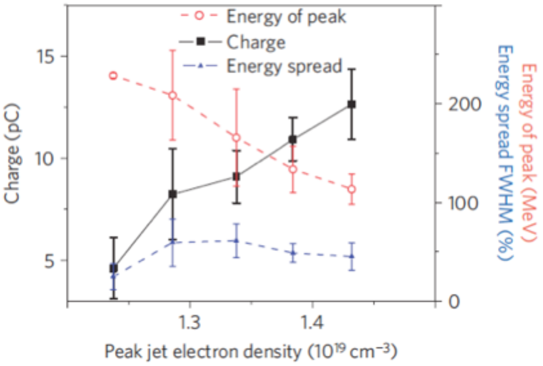


M. Burza *et al.*, PRSTAB 16, 011301 (2013)

# 2011 Density ramp + phase velocity control







Laser : 20 TW
0.8J, 40 fs, $a_0$=0.9
$n_e$=7x10$^{18}$cm$^{-3}$

Stable e-beam :
1-10 pC
100-400 MeV
Div = 2 mrad
DE/E> a few %

A. J. Gonslaves *et al.*, Nature Physics, August 2011

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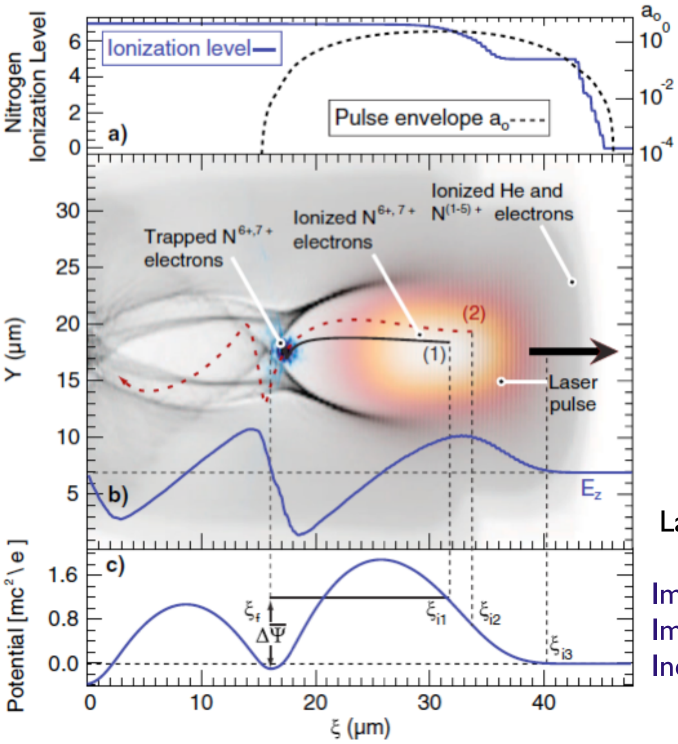
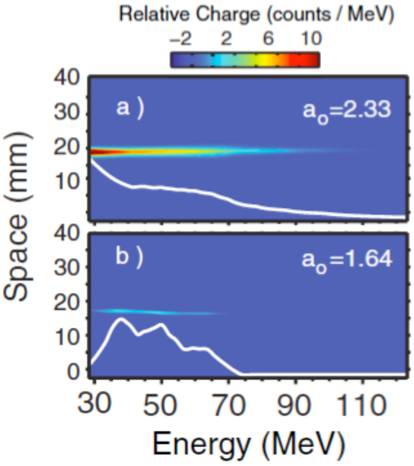


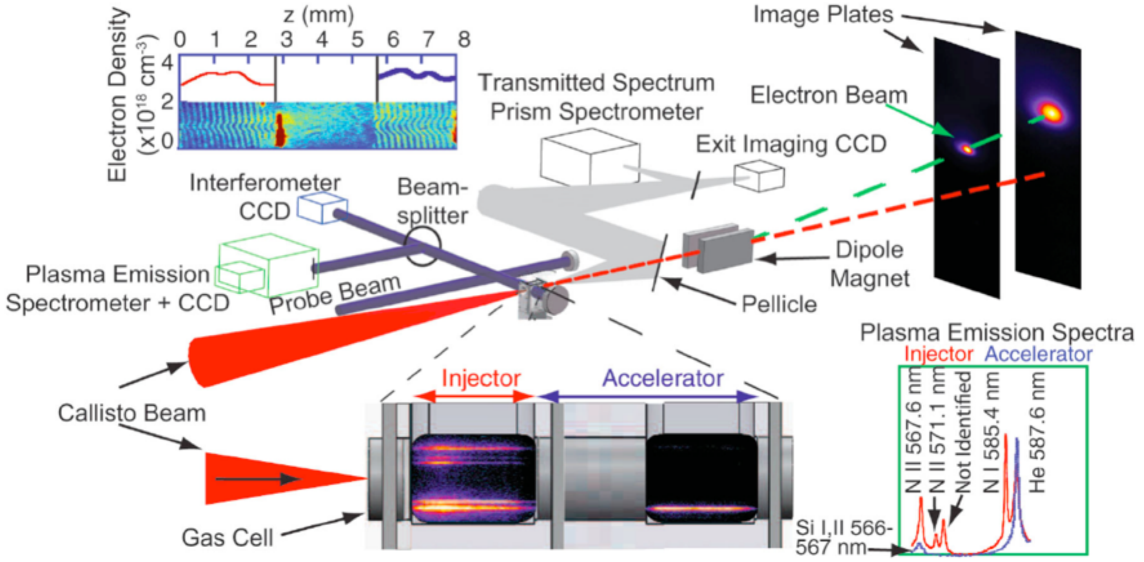


Laser: 10 TW, 0.8J, 45 fs, $a_0$≈2, $n_e$=1.4x10$^{19}$cm$^{-3}$

Improve the energy spread at low laser intensity
Improve the stability
Increase the charge

A. Pak et al., PRL 104, 025003 (2010), C. McGuffey et al., PRL 104, 025004 (2010)

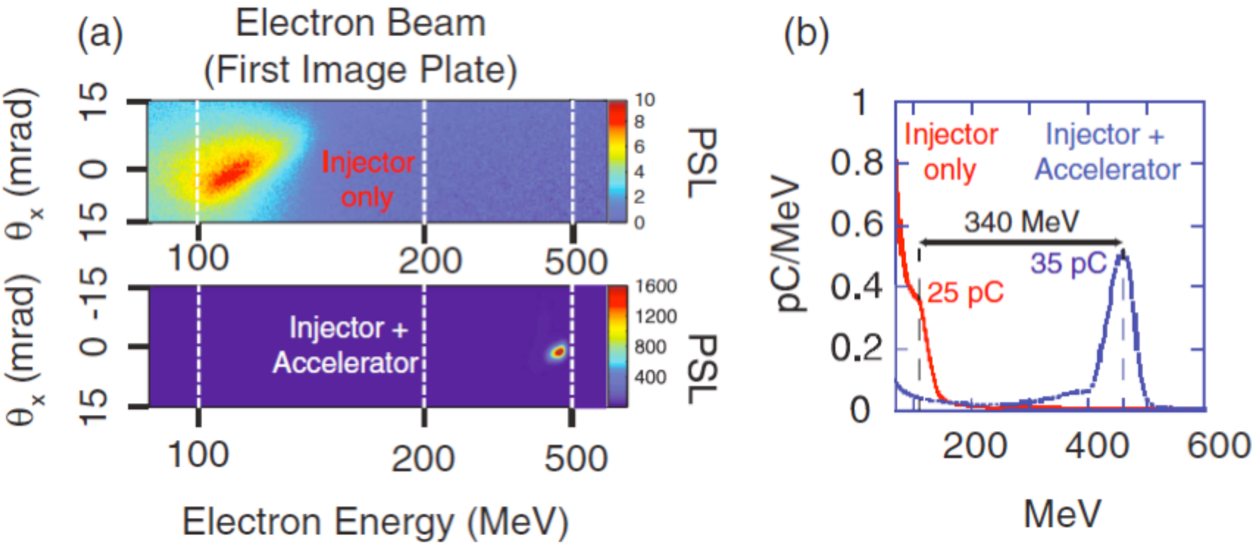
# 2010 Ionization Induced Trapping : 2 stage plasma acc.



Laser : 30-60 TW, 60 fs, $a_0$=2-2.8, $n_e$=3x10$^{18}$cm$^{-3}$ 35 pC, 460 MeV, div = 2 mrad, DE/E>5%

B. B. Pollock et al., PRL 107, 045001 (2011)

# Ionization Induced Trapping : two stage plasma accelerators

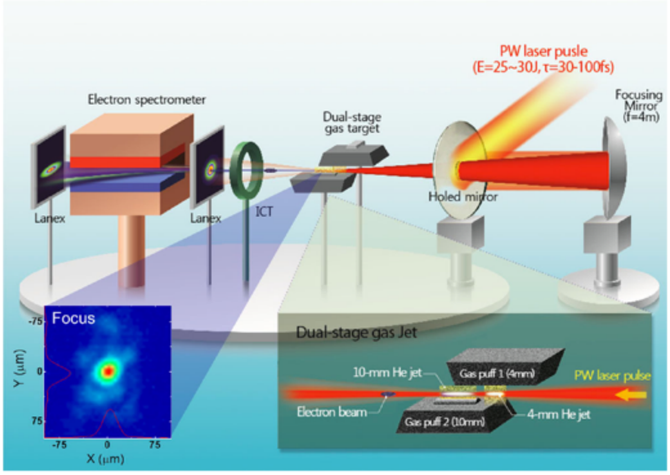


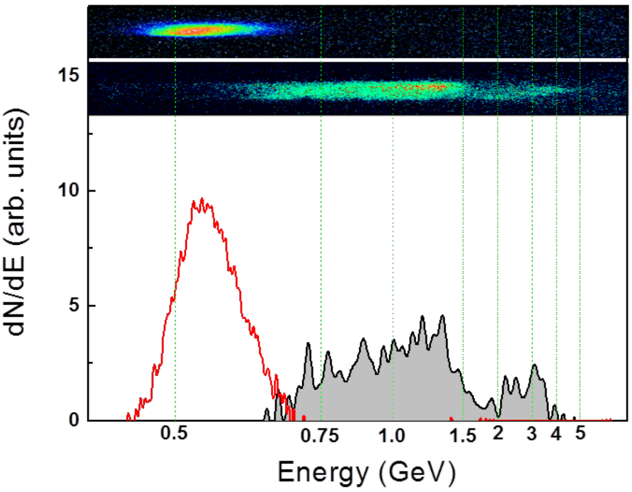
Laser : 30-60 TW, 60 fs, $a_0$=2-2.8, $n_e$=3x10$^{18}$cm$^{-3}$ 35 pC, 460 MeV, div = 2 mrad, DE/E>5%

B. B. Pollock et al., PRL 107, 045001 (2011)

# Double gas jet with PW laser : 3 GeV @ GIST-APRI

Double He gas jet : $d_e = 2.1\times10^{18}$ cm$^{-3}$ (4 mm) $d_e = 0.7\times10^{18}$ cm$^{-3}$ (10 mm)

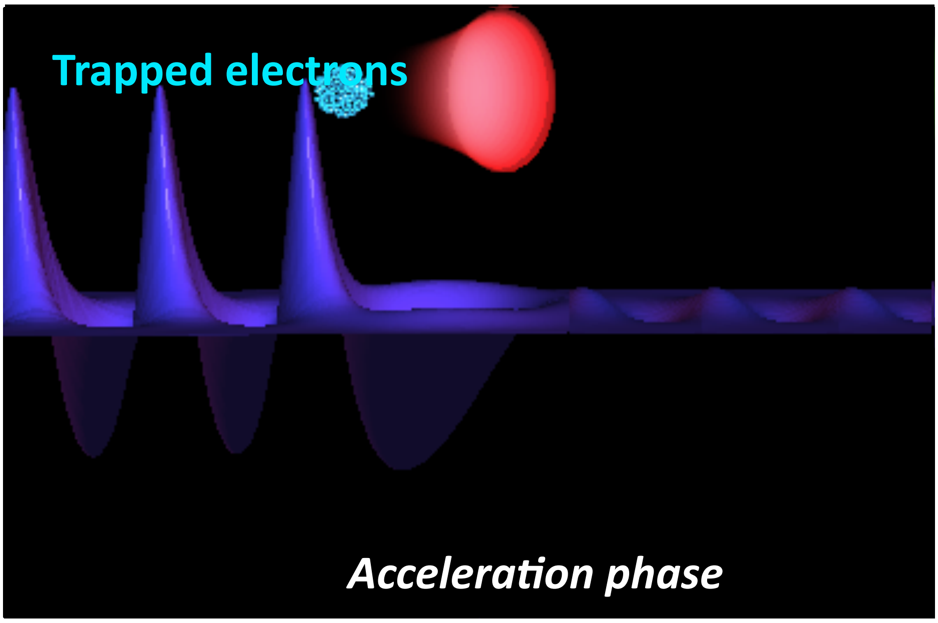




Hyung Taek Kim et al., PRL 111, 165002 (2013)

# Colliding Laser Pulses Scheme

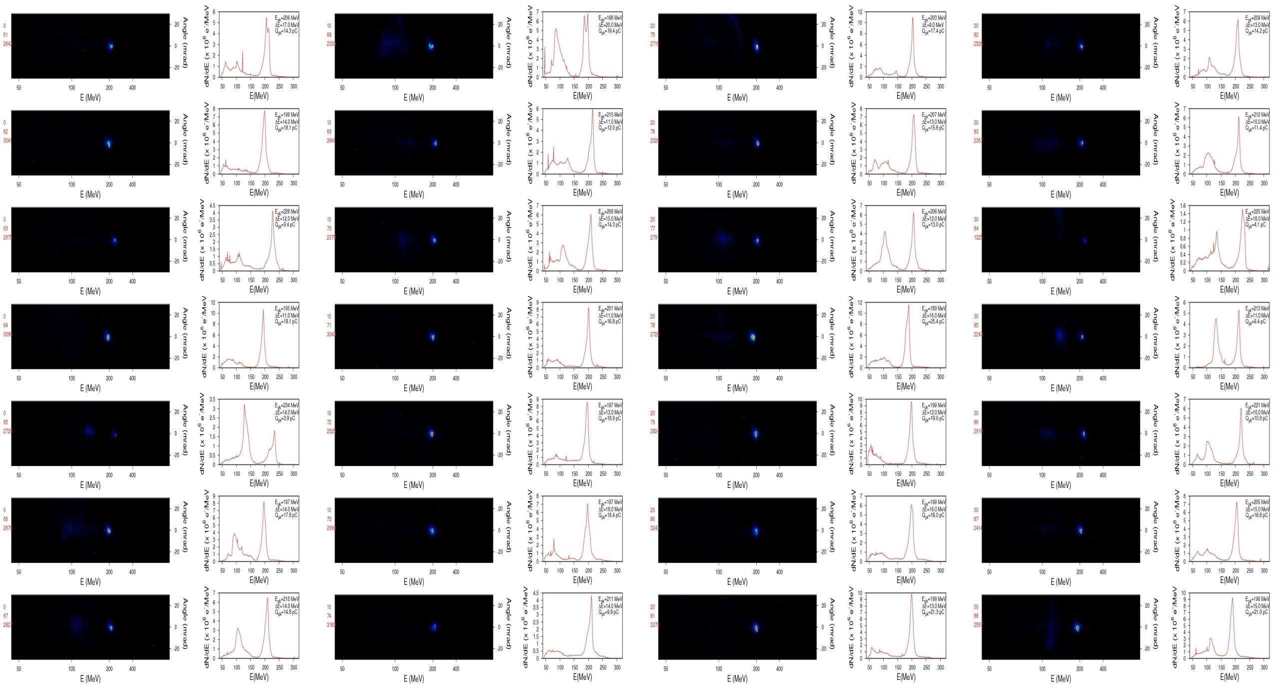
The first laser creates the accelerating structure, a second laser beam is used to heat electrons



Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

# Stable Laser Plasma Accelerators

Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}\mathrm{cm}^{-3}$



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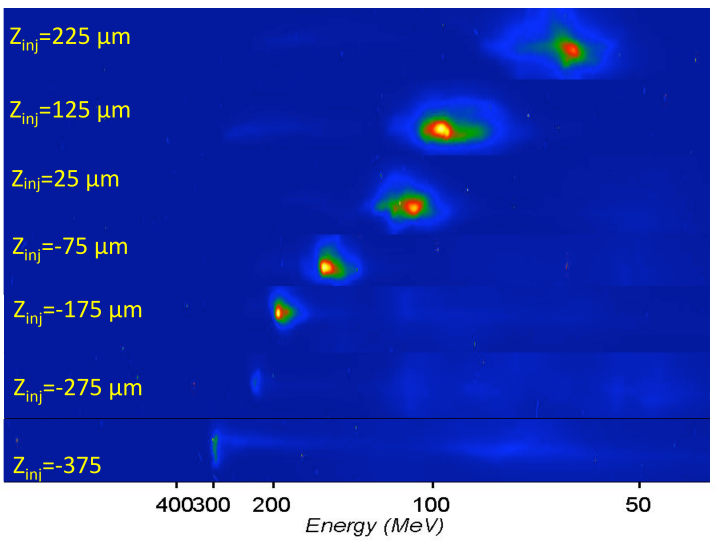
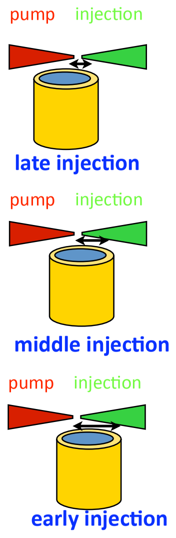
# Tunability of Laser Plasma Accelerators : electrons energy

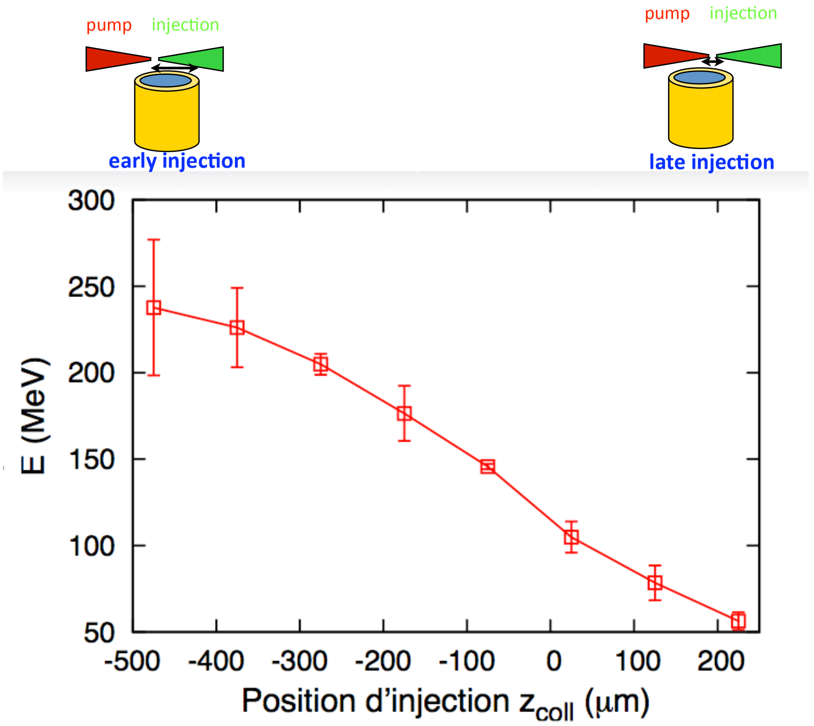




accelerating distance ⟷

J. Faure *et al.*, Nature **444**, 737 (2006)

# Tunability of Laser Plasma Accelerators : electrons energy



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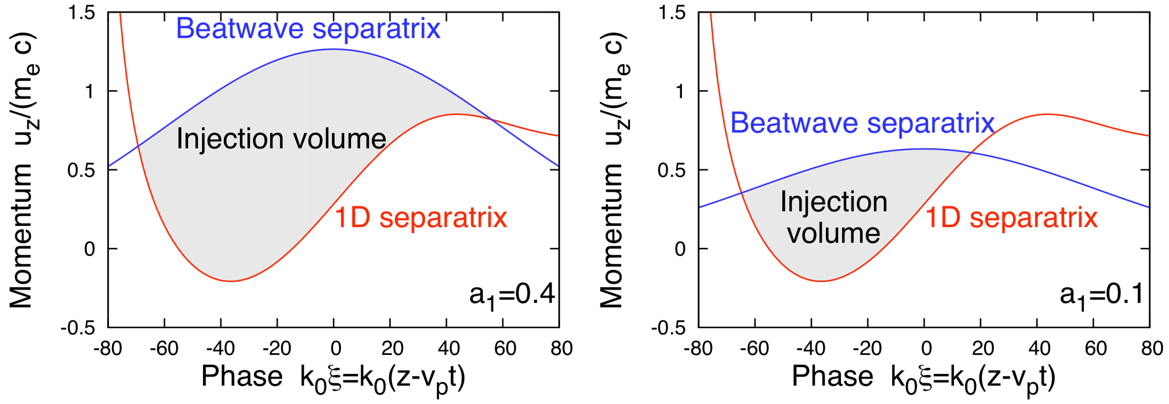
# Tunability of Plasma Accelerators: charge & energy spread

Charge : controlling electrons heating processes => smaller $a_{inj.}$ means less heating and less trapping
Energy spread : Decreasing the phase space volume $V_{trap}$ of trapped electrons by reducing $a_{inj.}$ or by reducing $c\tau/\lambda_p$ by changing $n_e$ (i.e $\lambda_p$)

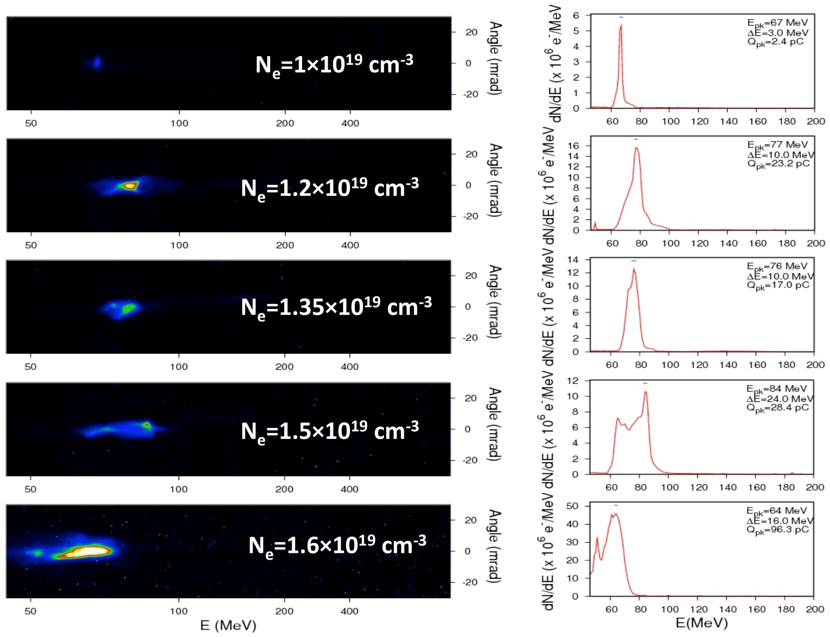


Evolution of injection volume with $a_1$ for $a_0 = 2$, $n_e = 7\times10^{18}\text{cm}^{-3}$.
Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

In practice, energy spread and charge are correlated:
Decreasing $a_1$ decreases the charge but also $V_{trap}$, and in consequence the energy spread

# Tuning charge & energy spread with the plasma density

increasing the plasma density



E=67 MeV
ΔE=3 MeV
Q$_{pk}$=2.4pC

E=77 MeV
ΔE=10 MeV
Q$_{pk}$=23.2pC

E=76 MeV
ΔE=10.0 MeV
Q$_{pk}$=17pC

E=84 MeV
ΔE=24 MeV
Q$_{pk}$=25.4pC

E=64 MeV
ΔE=16 MeV
Q$_{pk}$=96pC

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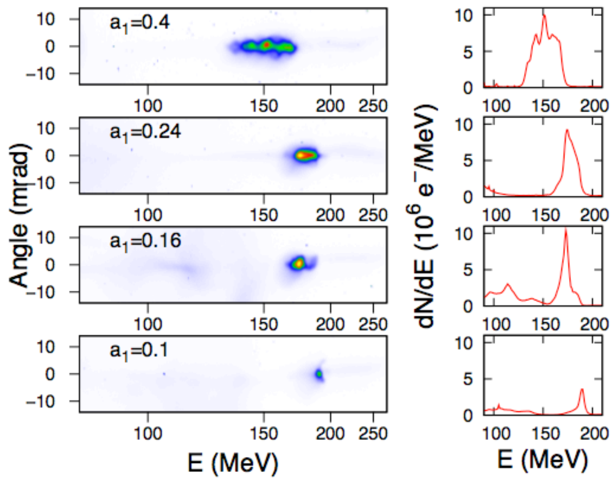
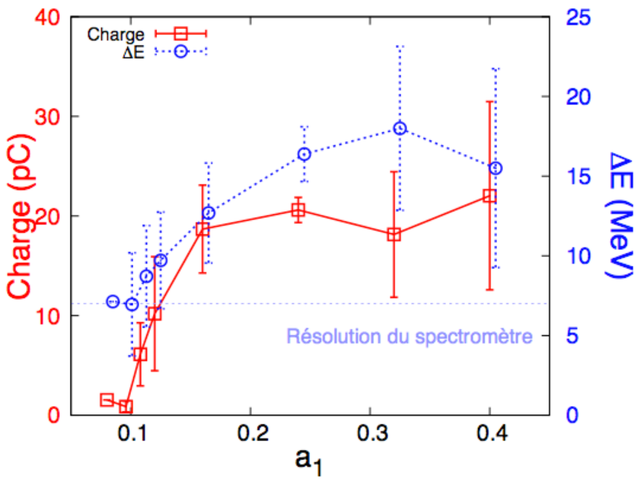
# Tuning charge & energy spread with the inj. laser intensity

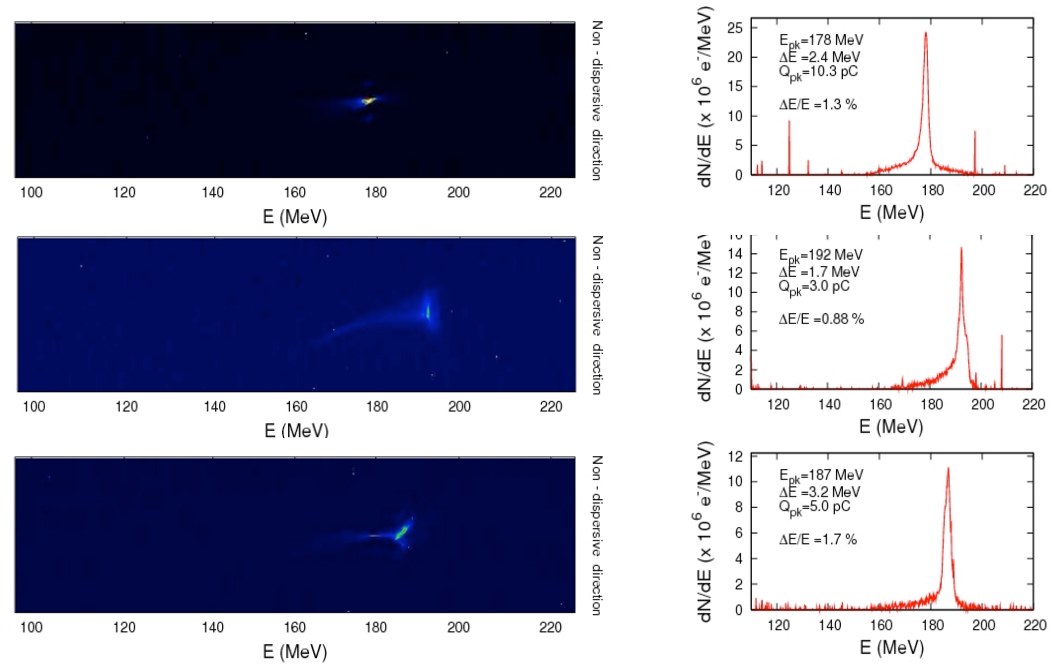




Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

# 1% relative energy spread



C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 194804 (2009)

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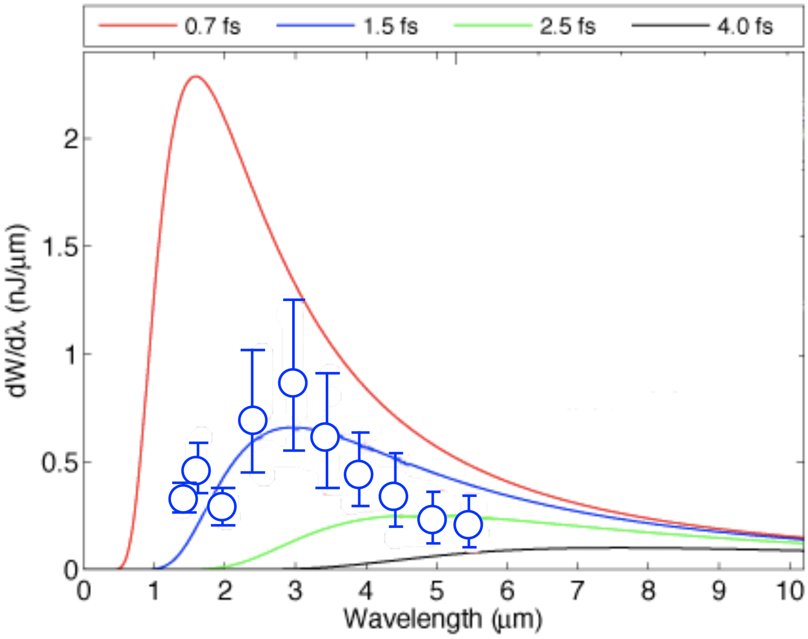
# 1.5 fs RMS duration : Peak current of 4 kA



Analytic CTR model

Gaussian pulse shape

Measured e-beam :

- Charge
- Energy
- Divergence

Bunch duration

Peak wavelength

Peak intensity

Spectral features

Peak at 3 μm

Coherent

## 1.5 fs RMS duration : Peak current of 4 kA

O. Lundh et al., Nature Physics, **7** (2011)

A. Buck *et al.*, Nature Physics **8**, (2011)

# Concept of Laser-Driven Plasma Linac: «Artistic view»

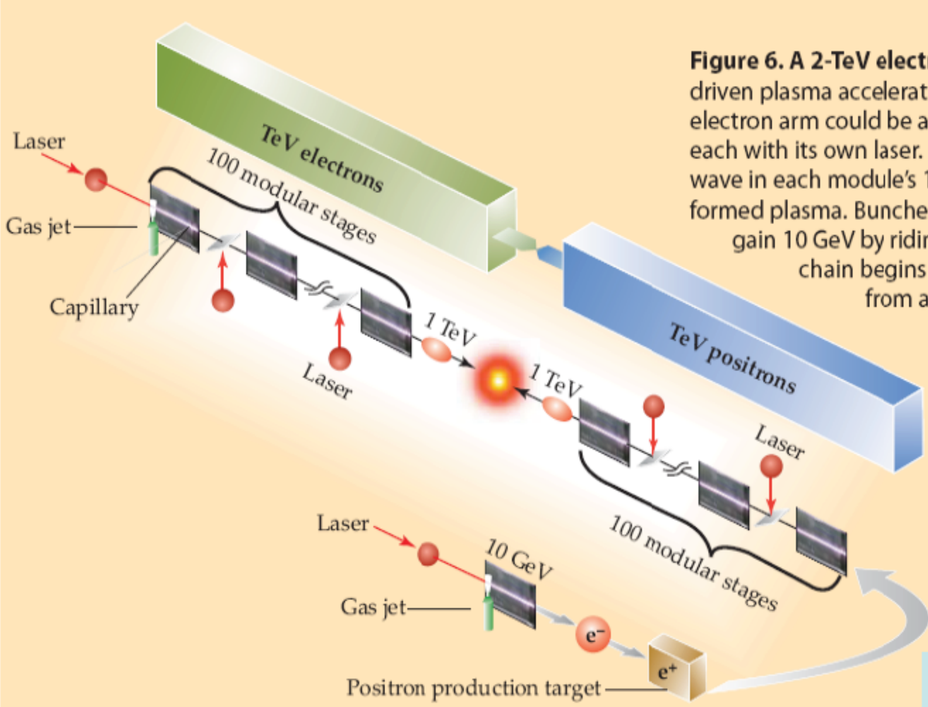


**Figure 6. A 2-TeV electron–positron collider** based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

W. Leemans, et al.,

W. Leemans et al., Phys. Today, March 2009

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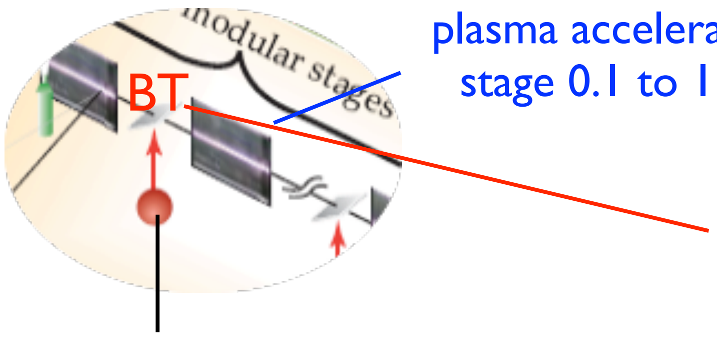
# Concept of Laser-Driven Plasma Linac : Challenges



plasma accelerator
stage 0.1 to 1m, $\eta$ = 1%

Beam transport :
1, 10 m to up to few
km in the last stages

$\eta$ = ? %

laser :10x50 m + focal of 5-10 m, $\eta$ = few %

overall wall-plug efficiency: $10^{-3}$, $10^{-4}$,
i.e. for a 1 MW e, $e^+$ beam,
required power of 1-10 GW

100 of kHz-PW Laser reliability,
plasma discharge reliability,
etc..

V. Malka Phys. of Plasma 19, 055501 (2012)

## Concept of Laser-Driven Plasma Linac : Challenges

1 PW laser at high rep rate (>100Hz): today in the best 1 Hz

Plasma and vacuum chambers

Transport between stages

Thermal effects on the guiding structure wall

External guiding/self-guiding

Collimation and beam filtering

Accelerating plasma structure: linear (<1GV/m) or non-linear (>few GV/m to 100s GV/m)

High efficiency laser driver : today in the best 1%

Courtesy of R. Assmann

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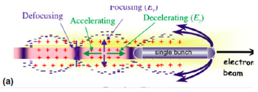
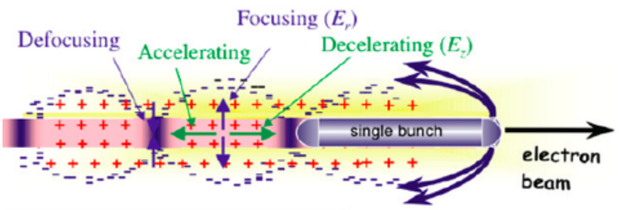
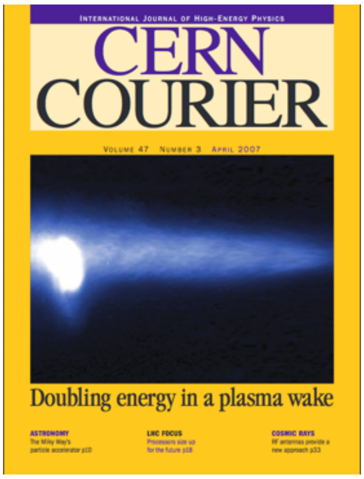
## Outline

- Motivation and principle
- Laser Beat wave and Laser Wakefield
- Self Modulated Laser Wakefield
- Towards high quality electron beams in LPA
- Particle Wakefield Accelerator
- Applications
- Conclusion and perspectives

# Single bunch PWFA at SLAC/FACET







INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 47 NUMBER 3 APRIL 2007

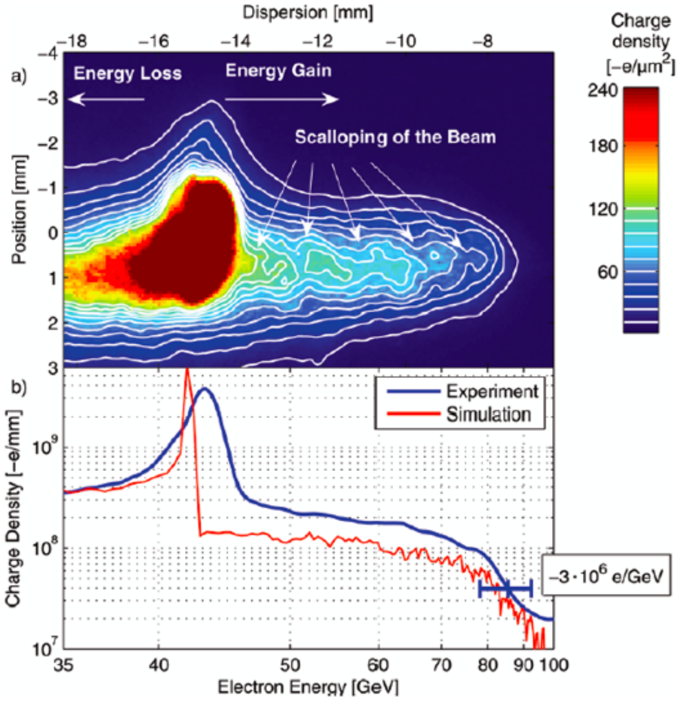
Doubling energy in a plasma wake

ASTRONOMY

LHC FOCUS

COSMIC RAYS

in 85 cm !



Courtesy of P. Muggli

Blumenfeld *et al.*, Nature 445 (2007), P. Muggli et al., Comptes Rendus de Physique 10 (2009)

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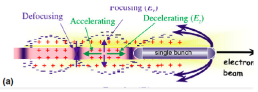
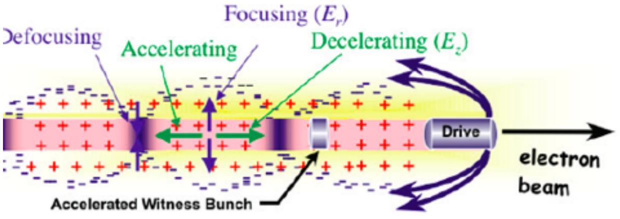
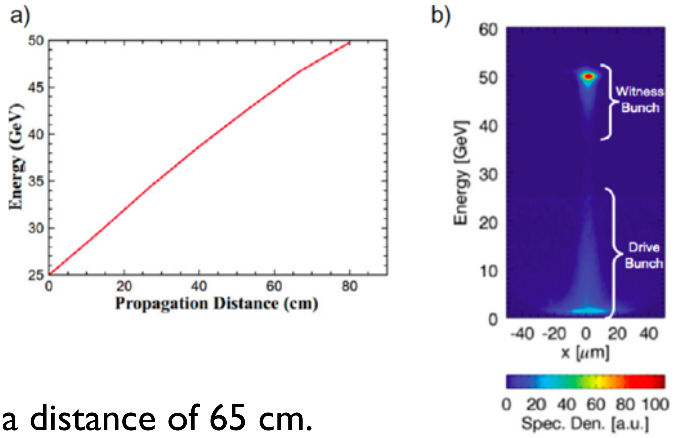
# Double bunches PWFA at SLAC/FACET



*work in progress*





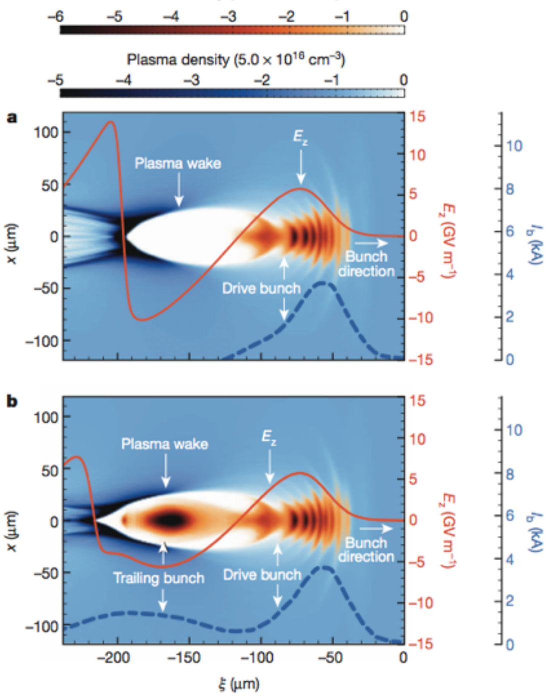
The energy gain is almost linear up to a distance of 65 cm.
At 80 cm, the 25 GeV witness bunch has doubled in energy with an 3% energy spread.
The energy transfer efficiency from the wake to the witness bunch is almost 56%.
The efficiency from the drive to the witness bunch is greater than 30%.

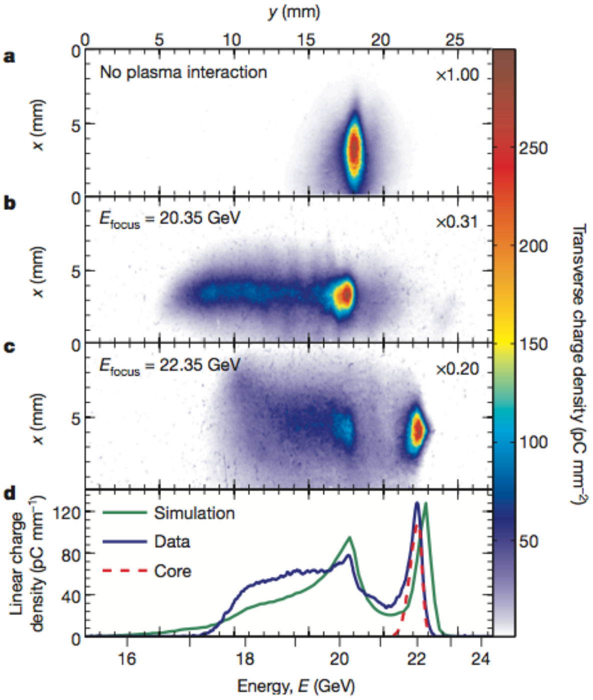
M. Hogan *et al.*, NJP, **12** (2010)

Courtesy of P. Muggli

# 2 bunches PWFA at SLAC/FACET : impressive milestone

## Gain:1.6 GeV, Energy spread: 0.7% AND > 30 % energy transfert





M. Litos *et al.*, Nature, 13882 (november 2014)

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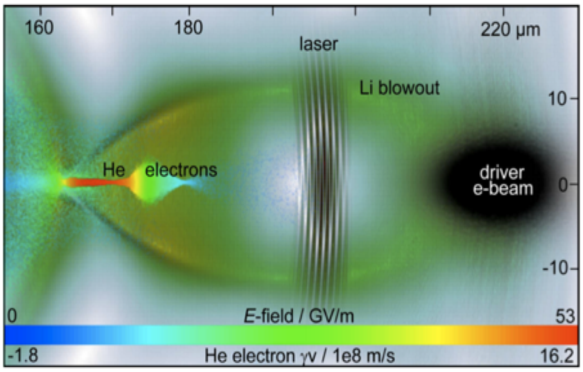
# Laser & Particle beams

## Ultra-Bright Electron Beams with PWFA and Laser

- Plasma bubble (wake) can act as a high-frequency, high-field, high-brightness electron source
- Ultra-high brightness beams for BES applications:
  - Unprecedented emittance (down to $10^{-9}$ m rad)
  - Sub-μm spot size
  - fs pulses

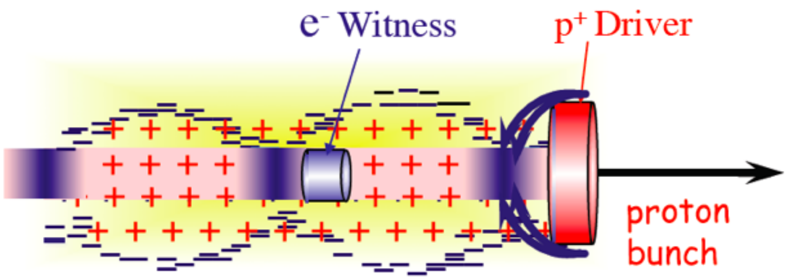
- Ingredients: electron & laser pulse (synchronized to fs level), plasma source with mixed ionization threshold
- Release laser pulse is strongly focused, needs 100 μJ, only, to ionize medium locally in focus at $10^{15}$ W/cm$^2$



Courtesy of M. Hogan

Leverages efficiency and rep rate of conventional accelerators to produce beams with very high brightness for XFEL applications

# Proton Driven PWFA at CERN : AWAKE project



=> SLAC, 20GeV bunch with $2x10^{10}e^-$ ~60J Driver

=> SLAC-like driver for staging (FACET= 1 stage, collider 10+ stages)

=> SPS, 450GeV bunch with $3x10^{11}p^+$ ~22kJ Driver
LHC, 7TeV bunch with $3x10^{11}p^+$ ~336kJ Driver

=> A single SPS or LHC $p^+$ bunch could produce an ILC bunch in a single PWFA stage!

**Large average gradient (~GeV/m, 100's m)**

Courtesy of P. Muggli

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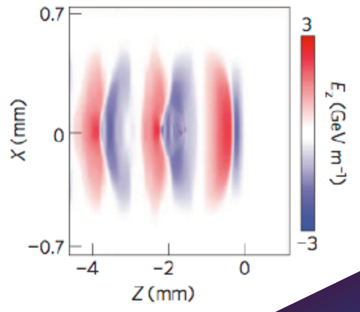
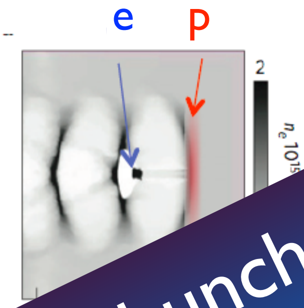
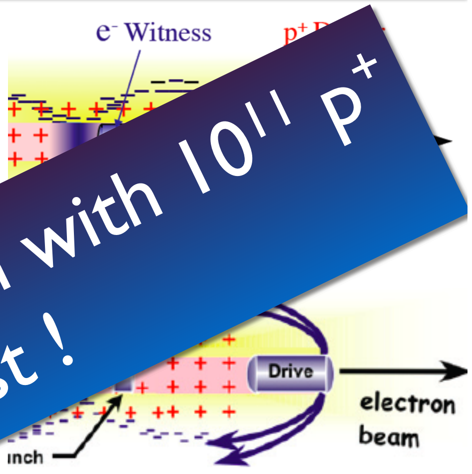
# Proton Driven PWFA at CERN : AWAKE project

$p^+$
$E_0$=1 TeV
$\sigma_z$=100$\mu$m
N=$10^{11}p^+$

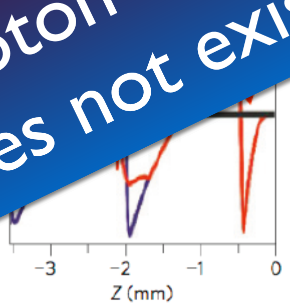
e-
$E_0$=1 GeV
N=$10^{11}e^-$







| Parameter | Symbol | Value | |
|---|---|---|---|
| Protons in drive bunch | $N_P$ | | |
| Proton energy | $E_P$ | | |
| Initial proton momentum spread | | | |
| Initial proton bunch longitudinal | | | |
| Initial proton bunch angul | | | |
| Initial proton bunch | | | |
| Electron | | | |
| E | | | |
| Pl | | | mm |
| Ma | | | T m$^{-1}$ |
| Magi | | .7 | m |



100 $\mu$m long proton bunch with $10^{11}$ $p^+$
does not exist !

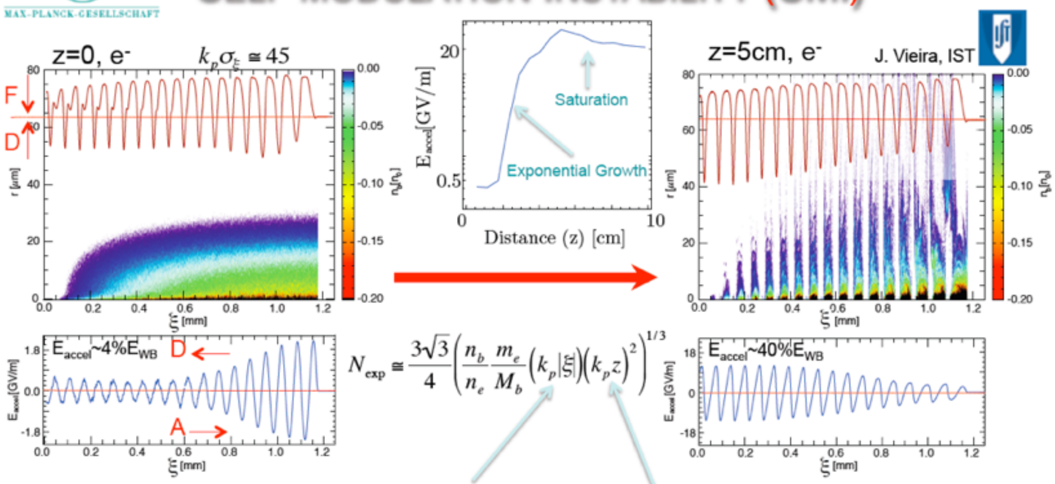
Caldwell *et al.*, Nature Physics, **5**, 363 (2009)

Courtesy of P. Muggli

Gradient ~1.5GV/m (av.): Gain of 0.6 TeV in 500 meter
Reasonable energy spread of less than 1%

# Proton Driven PWFA at CERN : SMI

## Self-Modulation Instability (SMI)



$$N_{exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$

Grows along the bunch & along the plasma
Convective instability

Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

- ❐ Initial small transverse wakefields modulate the bunch density
- ❐ Associated longitudinal wakefields reach large amplitude through resonant excitation: ~$E_{WB}$=mc$\omega_{pe}$/e~46GV/m @ $n_e$=2.3x10$^{17}$cm$^{-3}$

J. Vieira et al., Phys. Plasmas 19, 063105 (2012)

P. Muggli

© P. Muggli

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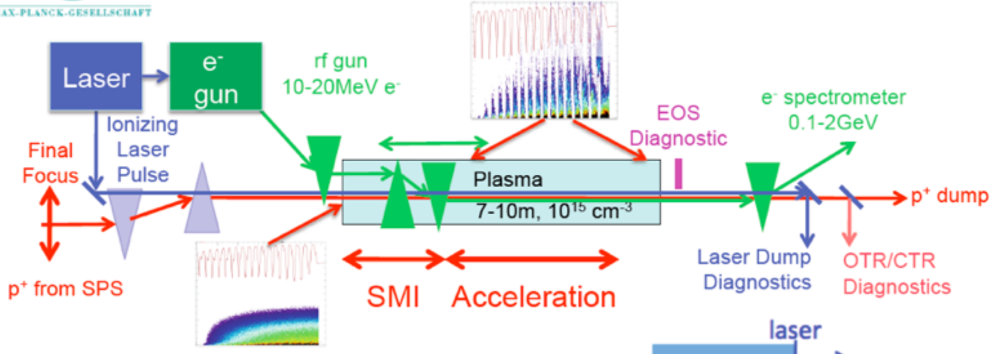
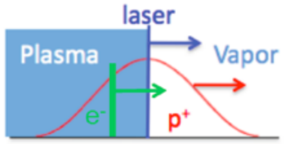
# Experimental Set-up at CERN : controlling the SMI

## Based-Line Experimental Set-up





- ❐ Laser ionization of a Rb metal vapor, 7-10m plasma, $n_e$=10$^{14}$-10$^{15}$cm$^{-3}$
- ❐ Injection of 10-20MeV test e- at the 3m point (SMI saturated, $v_\phi$=$v_{p+}$)
- ❐ SMI-acceleration "separated"
- ❐ 0.1-5GeV electron spectrometer
- ❐ OTR + streak camera, electro-optic sampling for p$^+$-bunch modulation diag.
- ❐ Additional optical diagnostics

P. Muggli

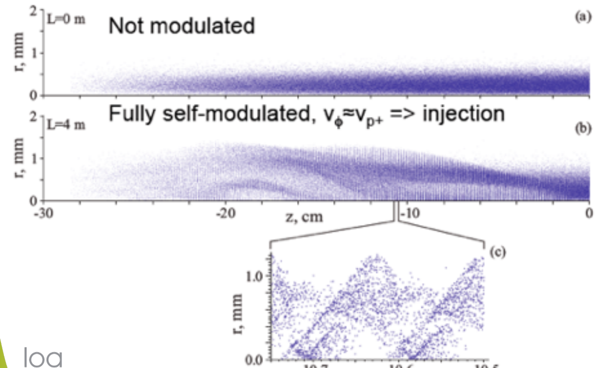
© P. Muggli

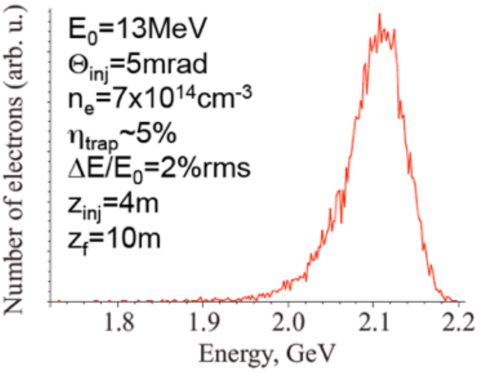
# Experimental Set-up at CERN

## Side Injection Simulation Results

*Table 1: Proton beam parameter at upstream entrance of the plasma cell.*

| Parameter | Nominal Value |
|---|---|
| Energy | 400GeV |
| Bunch Intensity | $3\times10^{11}$ p$^+$ |
| Energy per Bunch | 19.2kJ |
| Repetition Rate | 0.03Hz |
| Energy Spread | 0.34% (rms) |
| Transverse Normalized Emittance | $\varepsilon_N$= 3.5mm-mrad |
| Focused Transverse Size (at $\beta^*$=5m) | $\sigma_r^*$= 0.2mm |
| Bunch Length | $\sigma_z$= 12cm |
| Angle Accuracy | <0.05mrad |
| Pointing Accuracy | <0.5mm |
| Focal Position | Plasma Cell Entrance |
| Number of Run Periods/Year | 4 |
| Length of Run Period | 2 weeks |
| Total Number of Protons/Year | $4.86\times10^{15}$ |





❒ Results from LCODE, K. Lotov

R. Assmann *et al.*, PPCF, **084013** (2014)

© P. Muggli

P. Mug

# Outline

- Motivation and principle
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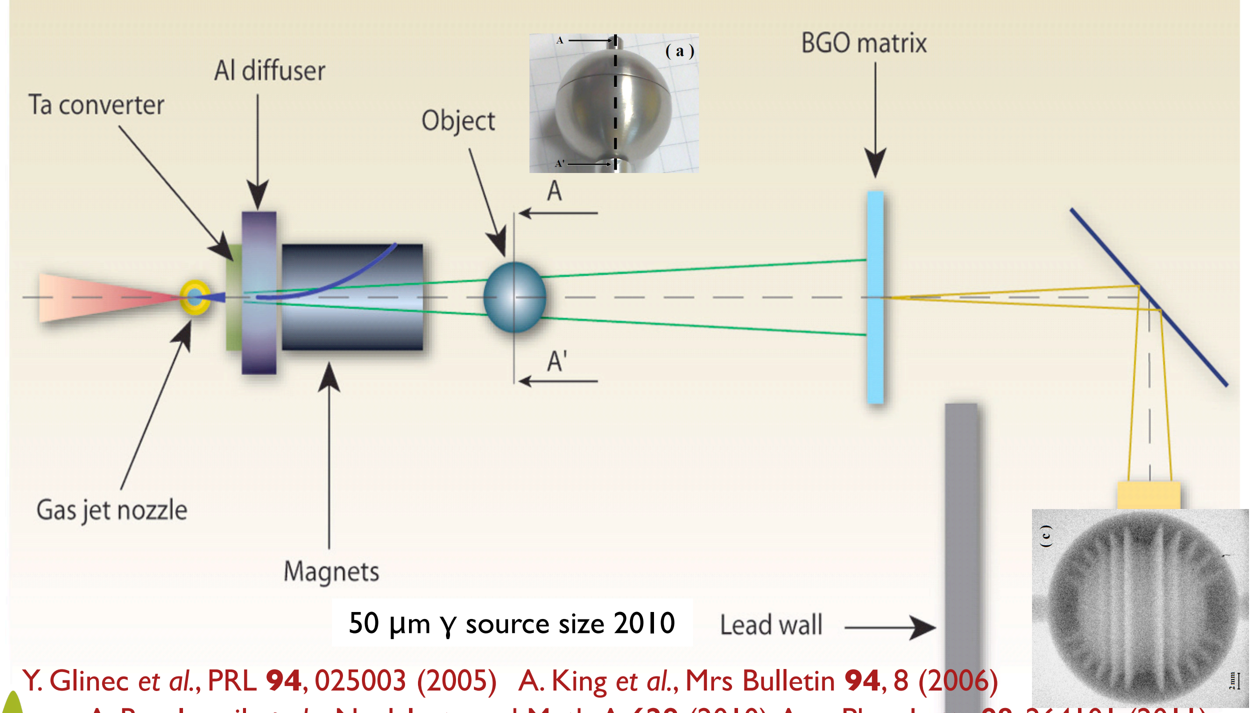
- Particle Wakefield Accelerator
- **Applications**
- Conclusion and perspectives

# Some examples of applications : radiography

Non destructive dense matter inspection

High resolution radiography of dense object with a low divergence, point-like electron source



50 µm γ source size 2010

Y. Glinec *et al.*, PRL **94**, 025003 (2005)   A. King *et al.*, Mrs Bulletin **94**, 8 (2006)
A. Ben-Ismail *et al.*, Nucl. Instr. and Meth. A **629** (2010), App. Phys. Lett. **98**, 264101 (2011)

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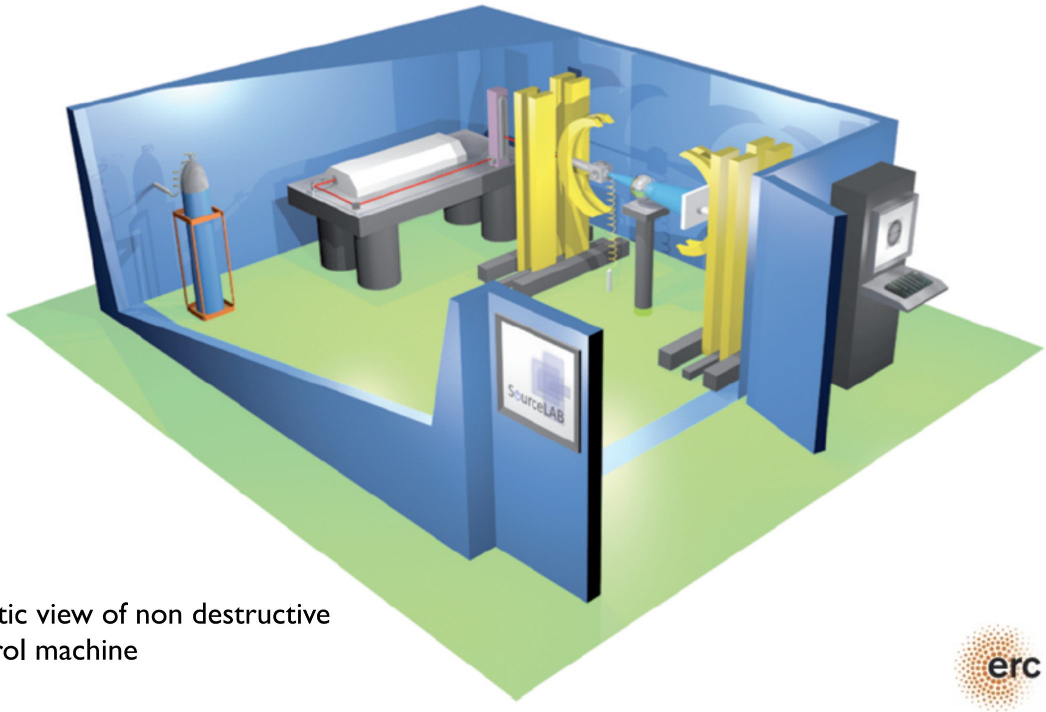
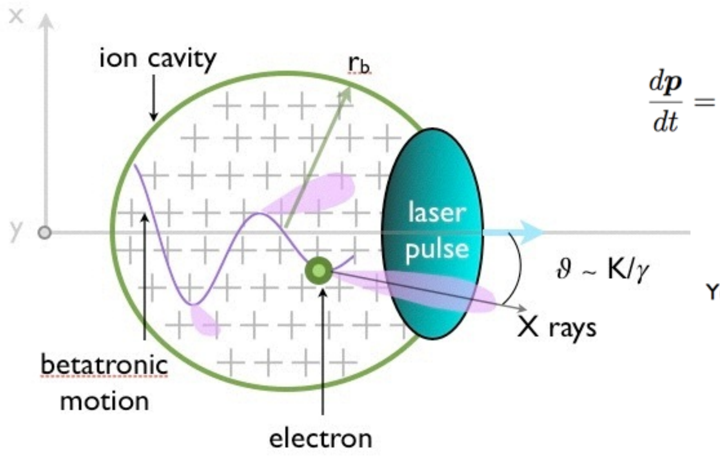
# Some examples of applications : Non Destructive Control



Artistic view of non destructive control machine

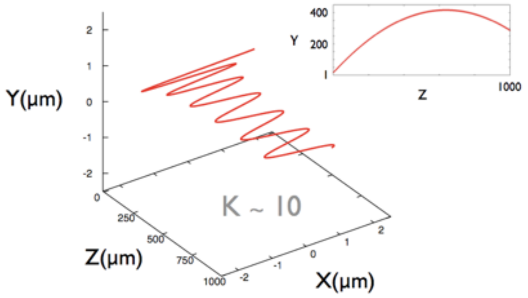
# Betatron radiation properties



*Transverse force*

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F}_{\parallel} + \boldsymbol{F}_{\perp} = -\frac{m\omega_p^2}{2}\zeta\hat{\boldsymbol{z}} - \frac{m\omega_p^2}{2}(x\hat{\boldsymbol{x}} + y\hat{\boldsymbol{y}})$$

*Longitudinal Force*



## Betatron oscillation properties:

$$\lambda_u = \sqrt{2\gamma}\lambda_p \qquad \xrightarrow[r_\beta \sim 1\ \mu\mathrm{m}]{\sim 100\ \mathrm{MeV}} \qquad \lambda_u \sim 200\ \mu m$$

$$K = r_\beta k_p \sqrt{\gamma/2} \qquad\qquad K \sim 5$$

$$n_e \sim 10^{19}\ \mathrm{cm}^{-3}$$

A. Rousse *et al.*, Phys. Rev. Lett. **93**, 135005 (2004)

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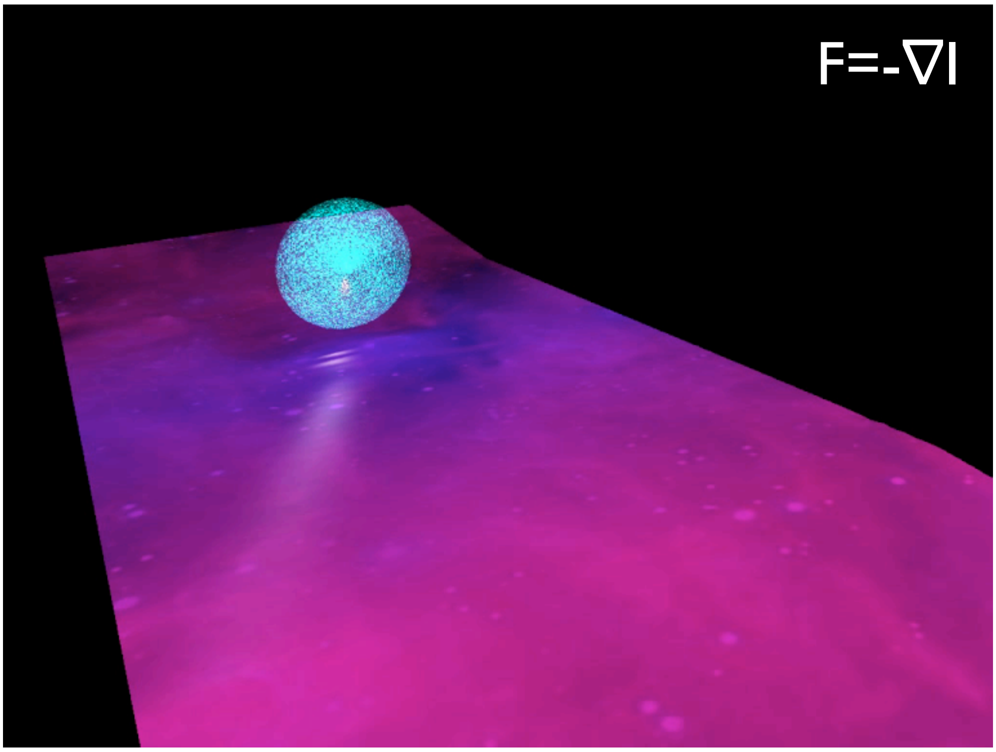
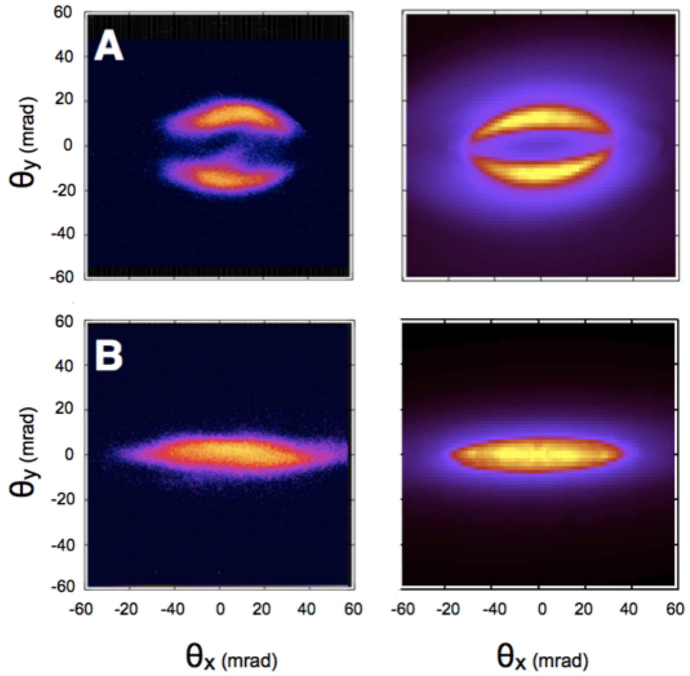
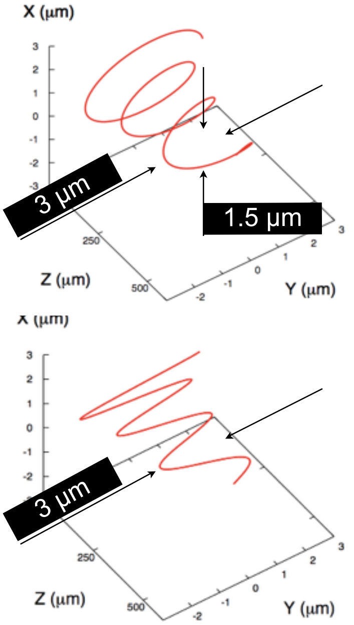
# The Forced laser wakefield



# A more precise source size estimation

Experimental profiles | Calculated profiles | Electron orbits





K. Ta Phuoc *et al.*, Phys. Rev. Lett. **97**, 225002 (2006)

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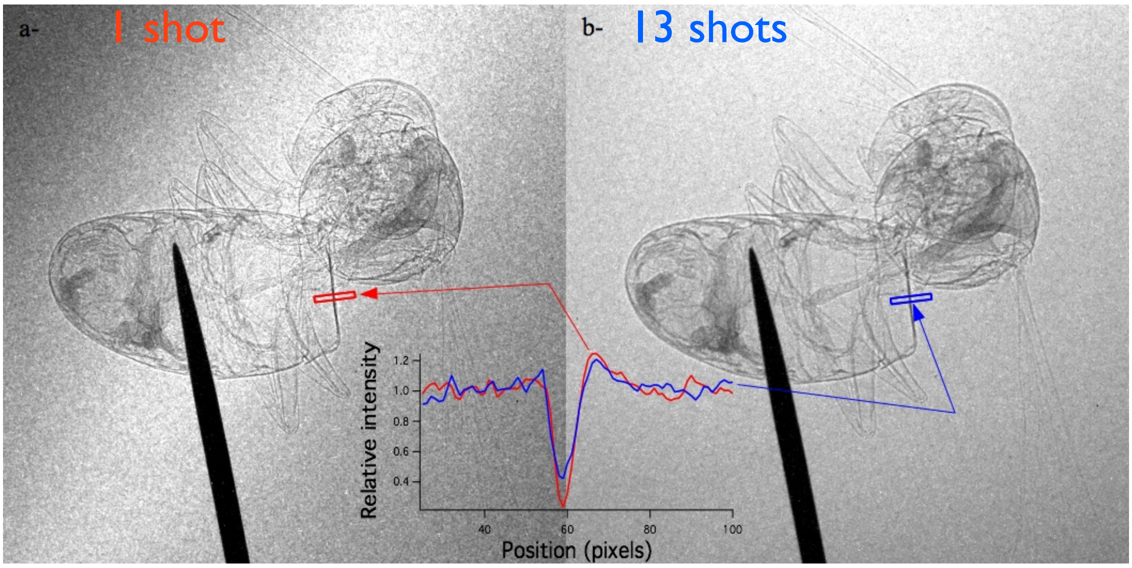
# Phase contrast imaging : results

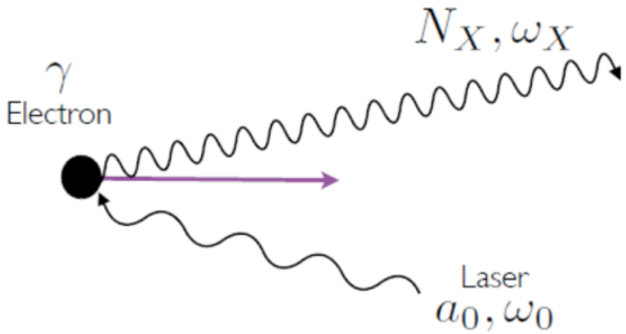
Bee contrast image :

- Contrast of 0.68 in single shot.
- Very tiny details can be observed in single shot that disappear in multi shots.



S. Fourmaux *et al.*, Opt. Lett. **36**, 2426 (2011)

# Inverse Compton Scattering



Doppler upshift : high energy photons with modest electrons energy : $\omega_x = 4\gamma^2\omega_0$

For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

The number of photons depends on the electron charge $N_e$ and $a_0^2$ : $N_x \propto a_0^2 \times N_e$

Duration (fs), source size (µm) = electron bunch length and electron beam size

Spectral bandwidth : $\Delta E/E \propto 2\Delta\gamma/\gamma, \gamma^2\Delta\theta^2$

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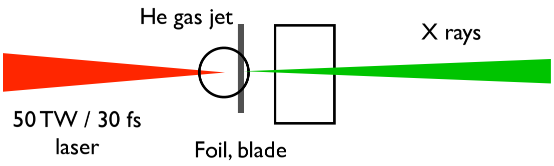
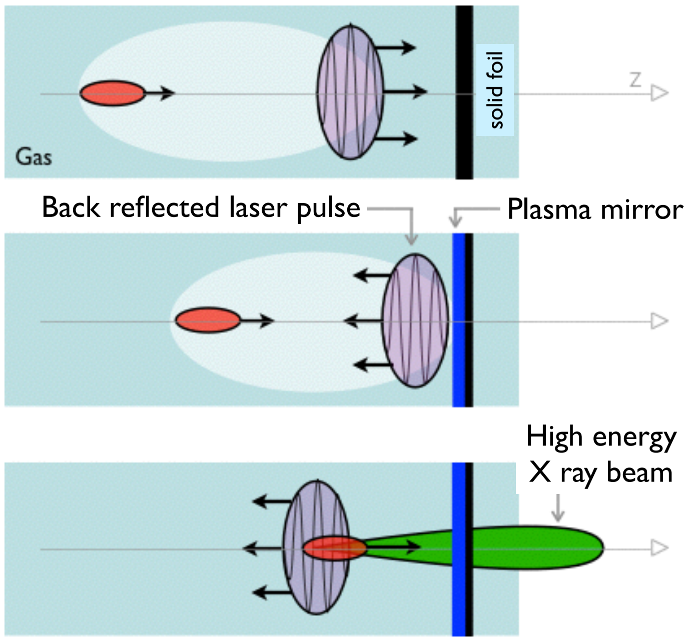
# Inverse Compton Scattering : New scheme





A single laser pulse

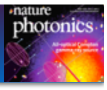
A plasma mirror reflects the laser beam

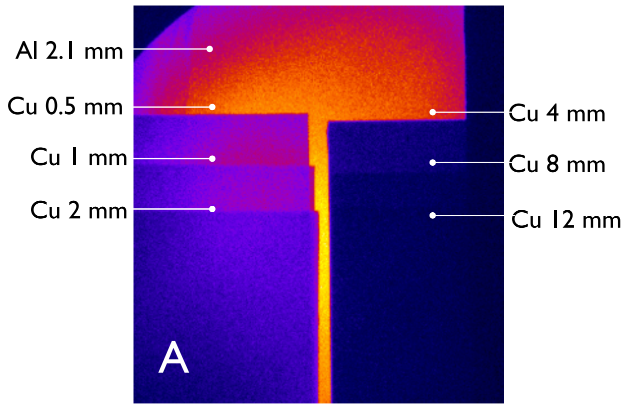
The back reflected laser collides with the accelerated electrons

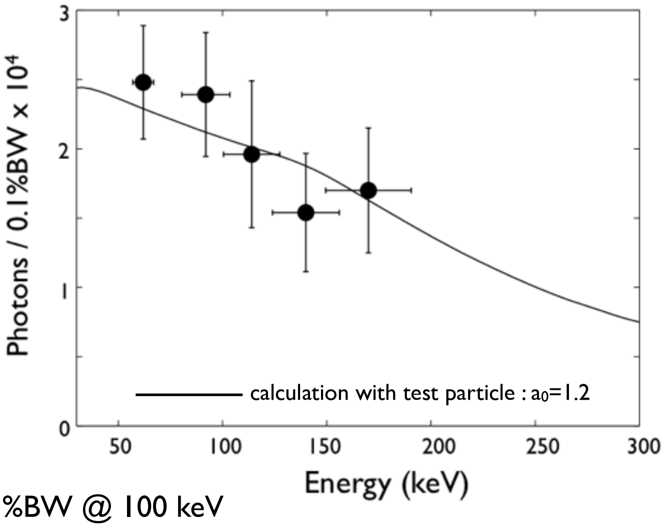
No alignment : the laser and the electron beams naturally overlap

Save the laser energy !

# Inverse Compton Scattering : Compton Spectra







- About $10^8$ ph/shot, a few $10^4$ ph/shot/0.1%BW @ 100 keV
- Broad electron spectrum => broad X ray spectra
- Brigthness: $10^{21}$ ph/s/mm$^2$/mrad$^2$/0.1%BW @100 keV

K. Ta Phuoc *et al.*, Nature Photonics **6** (2012)

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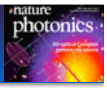
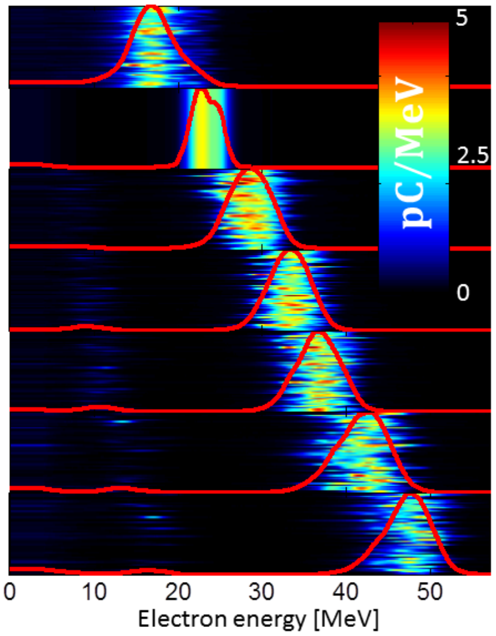
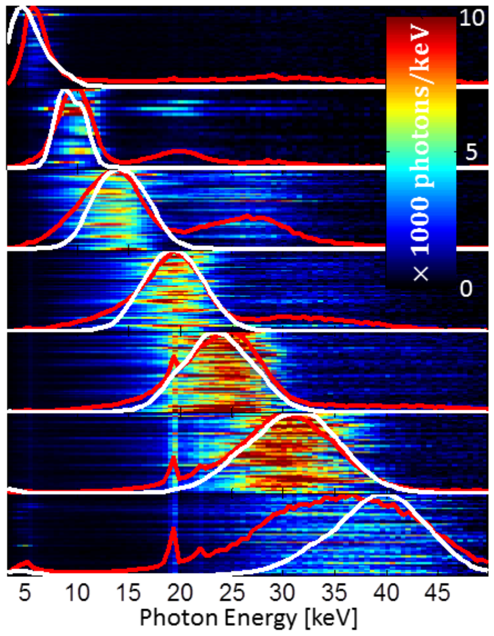
# Inverse Compton Scattering : Compton Spectra

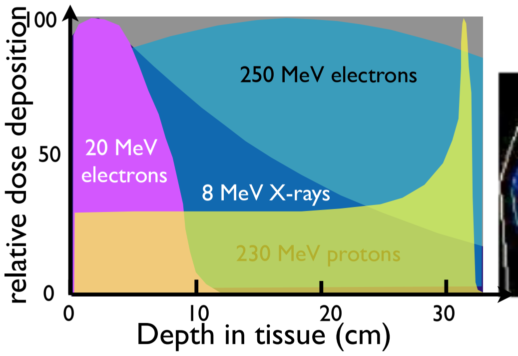




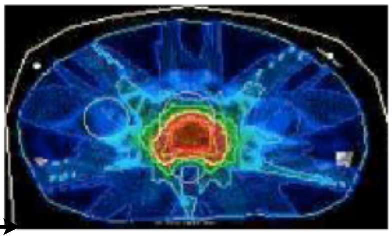


Courtesy of S. Karsh

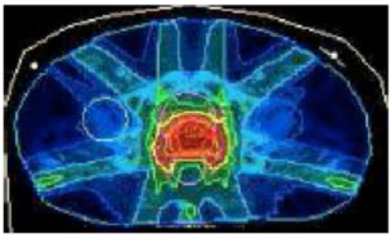
# Some examples of applications : radiotherapy



simulations of prostate cancer with 7 irradiation beams



250 MeV electrons



X rays IMRT

A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

T. Fuchs *et al.* Phys. Med. Biol. **54**, 3315-3328 (2009), in coll. with DKFZ
Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006),
O. Lundh *et al.,* Medical Physics **39**, 6 (2012)

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# Conclusions for Laser Driven Wakefield Acceleration

## Accelerators point of view :

Good beam quality & Monoenergetic dE/E down to 1 % √
Beam is very stable √
Energy is tunable: up to 400 MeV √
Charge is tunable: 1 to tens of pC √
Energy spread is tunable: 1 to 10 % √
Ultra short e-bunch : 1,5 fs rms √
Low divergence : 2 mrad √
Low emittance[1-3] : < $\pi$.mm.mrad √
With PW class laser : peak energy at 4.5 GeV √

[1] S. Fritzler *et al.*, Phys. Rev. Lett. **92**, 165006 (2004), [2] C. M. S. Sears *et al.*, PRSTAB **13**, 092803 (2010) [3] E. Brunetti *et al.*, Phys. Rev. Lett. **105**, 215007 (2010)

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# Perspectives 1 for Laser Driven Wakefield Acceleration

## New ideas for controlling the injection ?

Cold injection scheme[1], Two colors colliding pulses[2], Two pulses ionization injection[3], Trojean injection[4]

Magnetic control of injection[5], positron acceleration in NL LPAW[6]

Control phase of the electric field[7], Transverse injection scheme[8]…

## New numerical code/scheme for long accelerating distance runs ?

Boost Frame, Fourier decomposition codes, moving frames

New schemes to reduce artificial Cerenkhov effect and/or emittance growth, etc..

## New diagnostics ?

New diagnostics such as betatron[9], magnetic field[10], interferometry in the frequency-time[11], etc...

[1] X. Davoine *et al.*, Phys. Rev. Lett. **102**, 065001(2009), PRL, [2] X. L. Xu *et al.*, PRSTAB **17**, 061301 (2014), [2] L. L. Yu *et al.*, PRL **112**, 125001 (2014), [3] N. Bourgeaois *et al.*, PRL **111**, 155004 (2013), [4] B. Hidding et al, PRL **108**, 035001 (2012), [5] J. Vieira *et al.*, Phys. Rev. Lett. **106**, 225001(2011), [6] J. Vieira *et al.*, PRL **112**, 215001 (2014), [7] A. Lifshitz *et al.*, NJP **14**, 053045 (2012), [8] R. Lehe *et al.*, PRL **111**, 085005 (2013), [9] A. Rousse *et al.*, Phys. Rev. Lett. **93**, 13 (2004), [9] K. Ta Phuoc *et al.*, Phys. Rev. Lett. **97,** 225002 (2006), [10] M. C. Kaluza *et al.*, Phys. Rev. Lett. **105**, 115002 (2010), [10] A. Buck *et al.*, Nature Physics **8,** (2011), [11] N. H. Matlis *et al.* , Nature Physics 2006,

## Perspectives 2 for Laser Driven Wakefield Acceleration

### Short term perspective (< 10 years):

Relevant applications in medicine, radiobology, material science
Compact FEL with moderate average power (10 Hz system)
Compact X ray source (Thomson, Compton, Betatron, or FEL)

### Long term possible applications (>40-50 years):

High energy physics that will depend on the laser technology evolution, on laser to electron transfer efficiency, on progress of multistage design, acceleration of positron, etc...)

V. Malka *et al.*, Nature Physics **4** (2008), V. Malka Phys. of Plasma 19, 055501 (2012)
E. Esarey et al. , Rev. Mod. Phys. **81** (2009), S. Corde et al., Rev. Mod. Phys. **85** (2013)

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## Perspectives for Particle Driven Wake Field Acceleration

Proton beam seems today the best driver
Proton beam will be benefit of shortness driver
2 GeV high quality e- beam (4 m & GV/m)
Doubling 42 GeV electron energy in less than 1m
Positron acceleration is demonstrated
Increasing activities on beam driver (FACET, CLARA, INFN, DESY)

Many challenges/open questions :
Producing stable, reliable and long plasma devices
Synchronization/jitter issues
Beam loading effects

## From Plasma Acceleration to Plasma Accelerators

Laser-PWAs allow today to explore several applications with the hope of compactness and cost reduction. They allow to produce secondary sources for many applications (particularly for pump-probe experiments, bright X-rays beam, electron diffraction,

**It is a very exciting time for plasma accelerators !**

Proton beam driver exist and allow a single stage efficient accelerator

The involvement of accelerators community will be a key element of success of this wonderful and exciting research

## A wonderful tool for Science and Societies

LPAW 2015

Guadeloupe Carribean Island (France)

May 11-17

www.lpaw2015.com

We hope to see you !

***Organizing committee:***

- *-Guillaume Lambert (Laboratoire d'Optique Appliquée)*
- *-Alessandro Flacco (Laboratoire d'Optique Appliquée)*
- *-Alec Thomas (University of Michigan)*
- *-Victor Malka (Laboratoire d'Optique Appliquée)*

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