Status of Laser Plasma Accelerators Activities in France*

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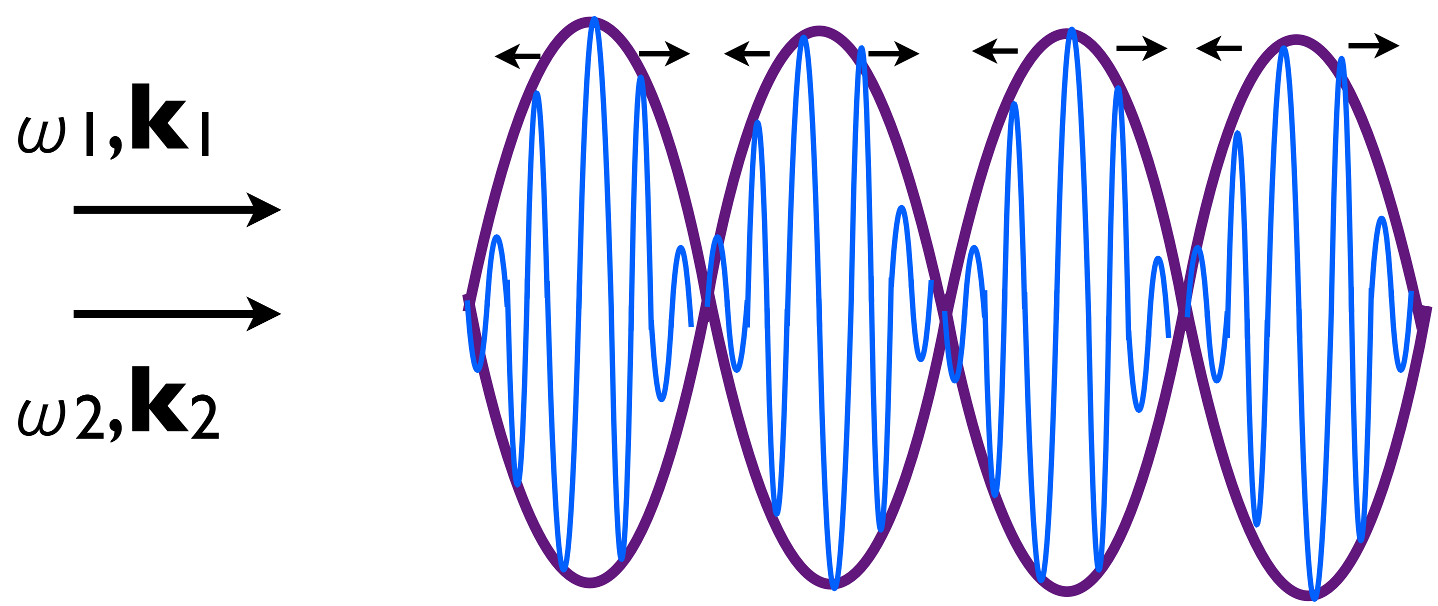
*Limited to electrons only

EuroNNAC workshop, CERN, May 6-9 (2011)

1) The laser beat waves : $\tau_L >> T_p$

$\mathbf{F} \approx -\nabla I$



Train of short resonant pulses

$\omega_1 - \omega_2 = \omega_p$

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

=> homogenous plasmas

saturation : relativistic, ion motion

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, 2nd Edition, Vol.1, (1984)

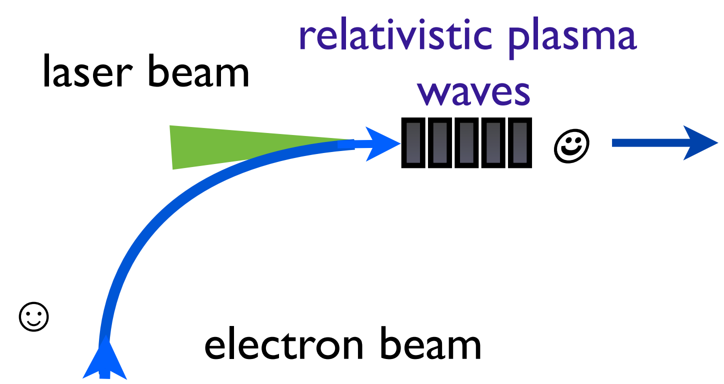
Electron gain demonstration Few MeV's:

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

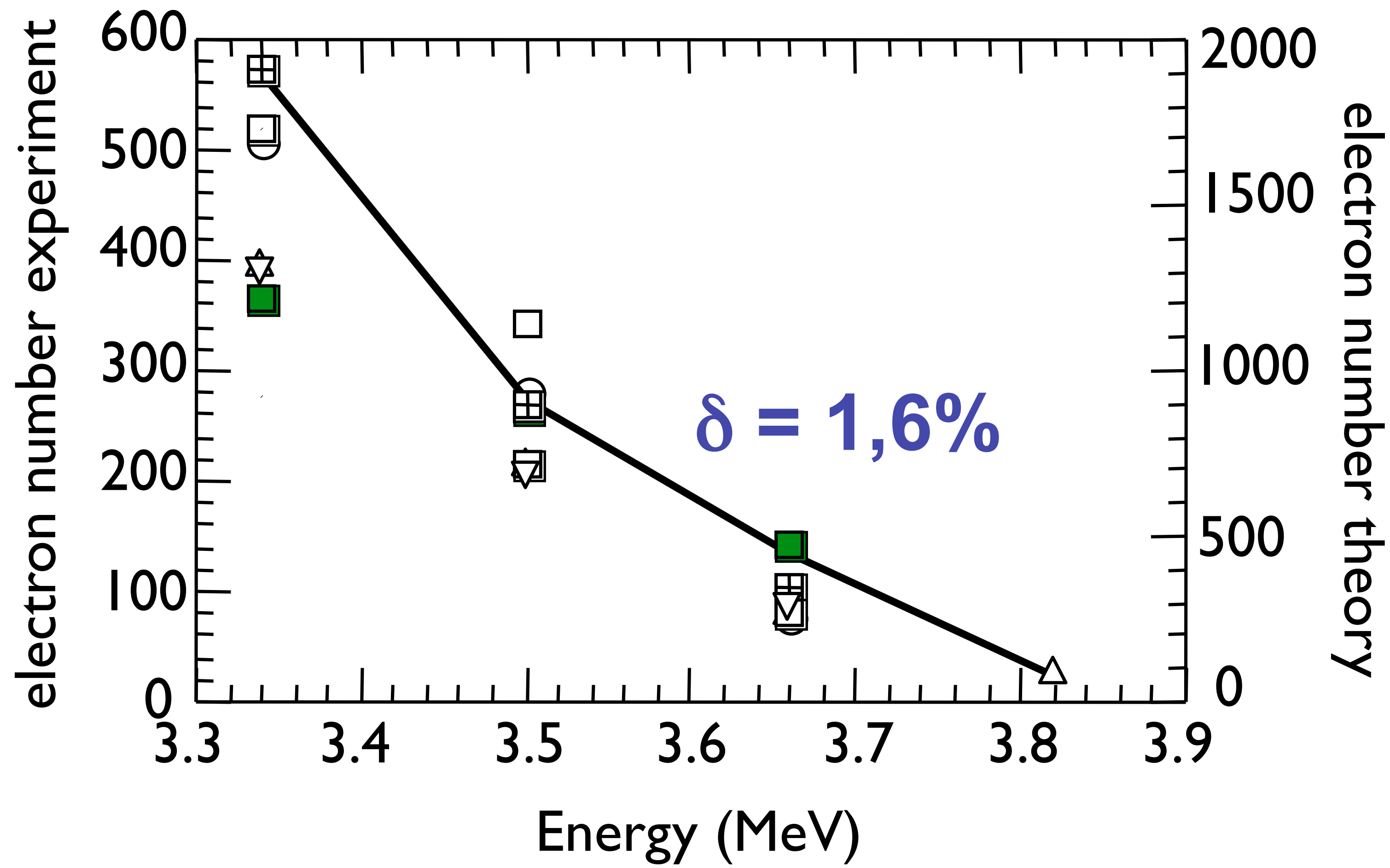
1995 : LBWF electrons acceleration from 3 to 3.8 MeV

LULI/LPNHE/LSI/LPGP/IC

Scheme of principle of the first experiments :



σ_w=100, γ_e=6, σ_{laser}=40µm, σ_e=40µm, divergence=10 mrad



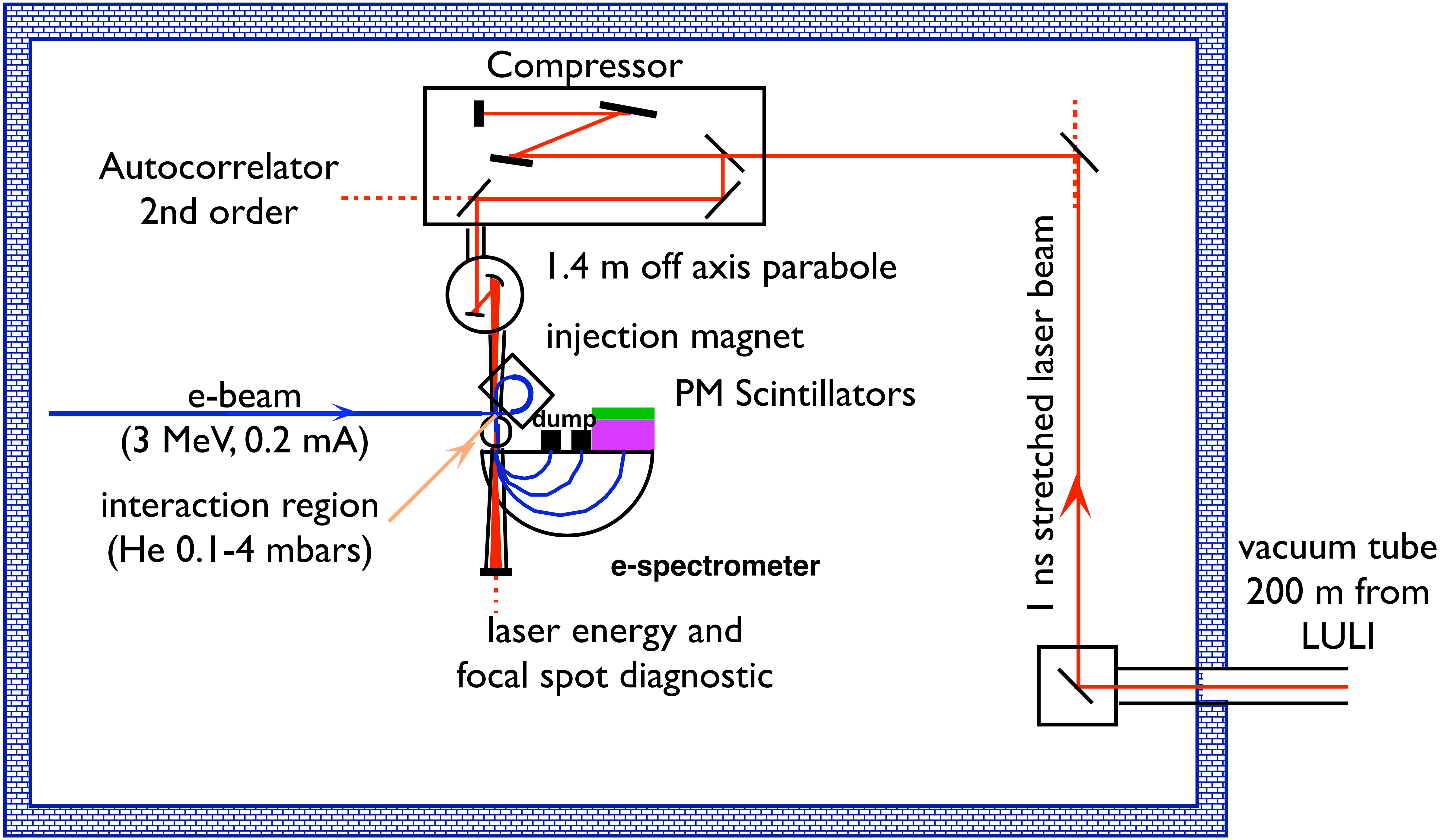
The 3-MeV electrons are accelerated up to ≈ 3.8 MeV

Electron spectra indicate an E_{field} of ≈ 0.7 GV/m

F. Amiranoff *et al.*, PRL 1995

1998 : LWF experiments

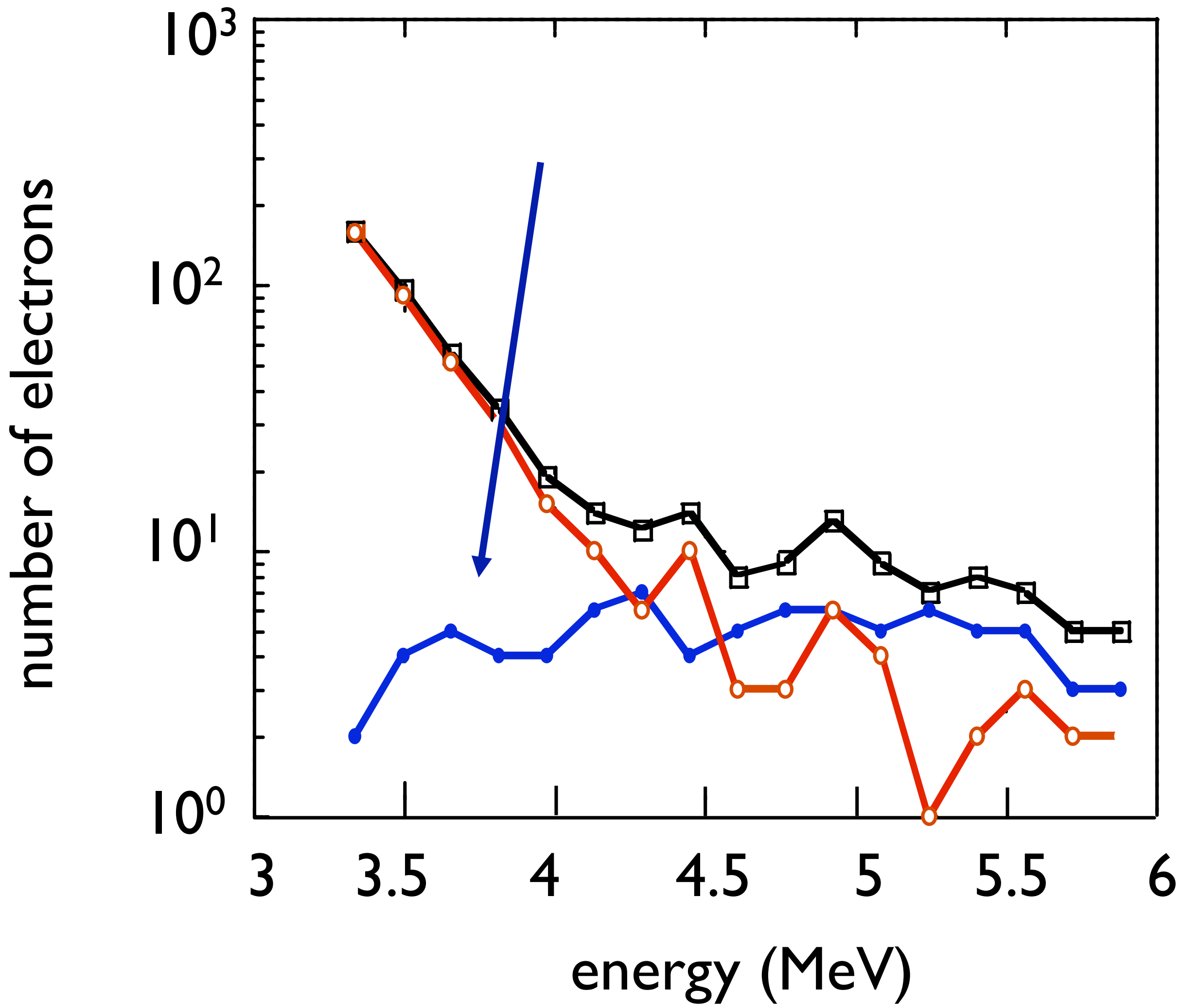
LULI/LPNHE/LSI/LPGP/IC



1998 : LWF acceleration from 3 to 4.5 MeV

LULI/LPNHE/LSI/LPGP/IC

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

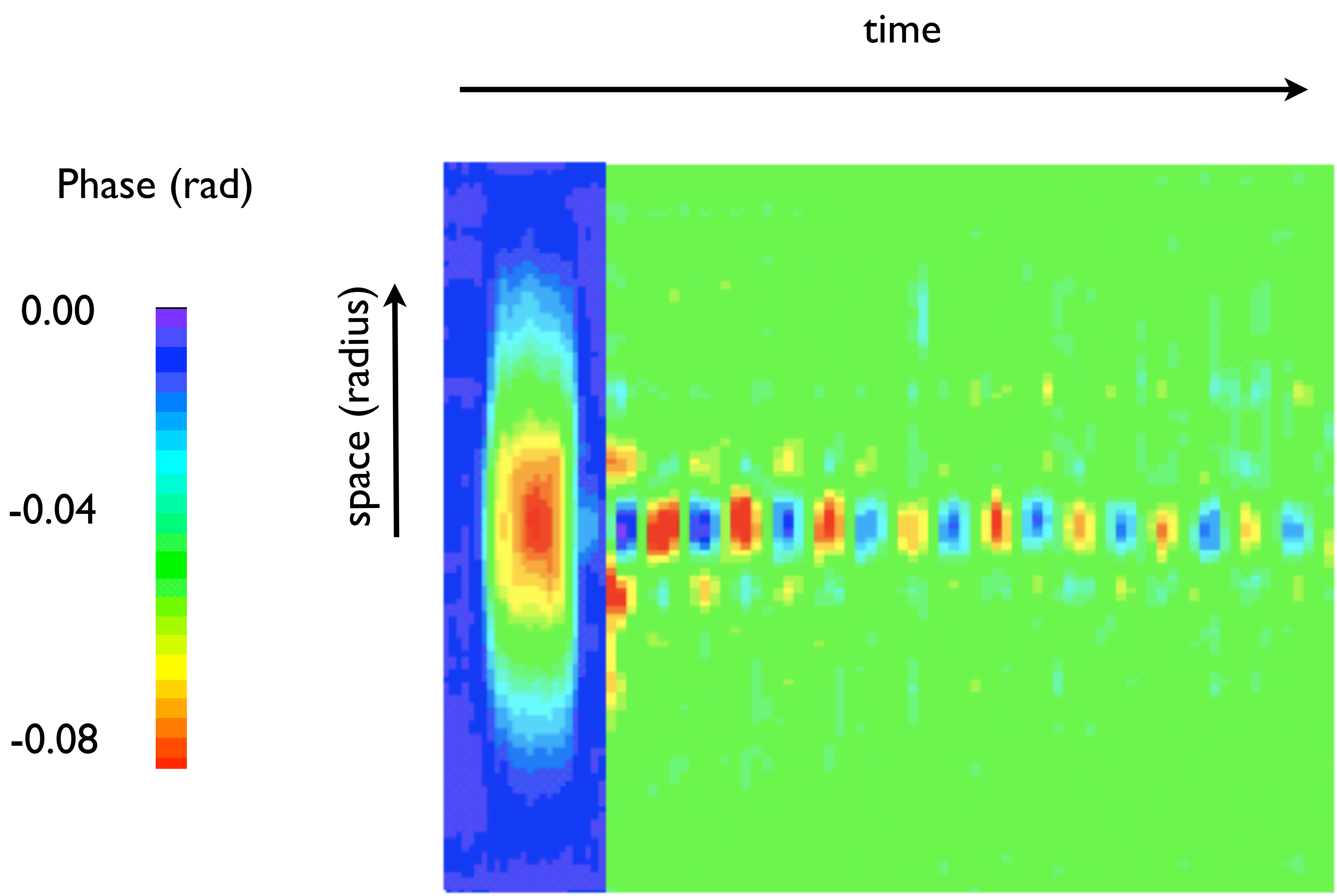


2.5 J, 350 fs, 10^{17} W/cm^2, 0.5 mbar of He

F. Amiranoff *et al.*, PRL 1998

1997 : Freq. domain interferometry : electron density pert.

LULI/LOA



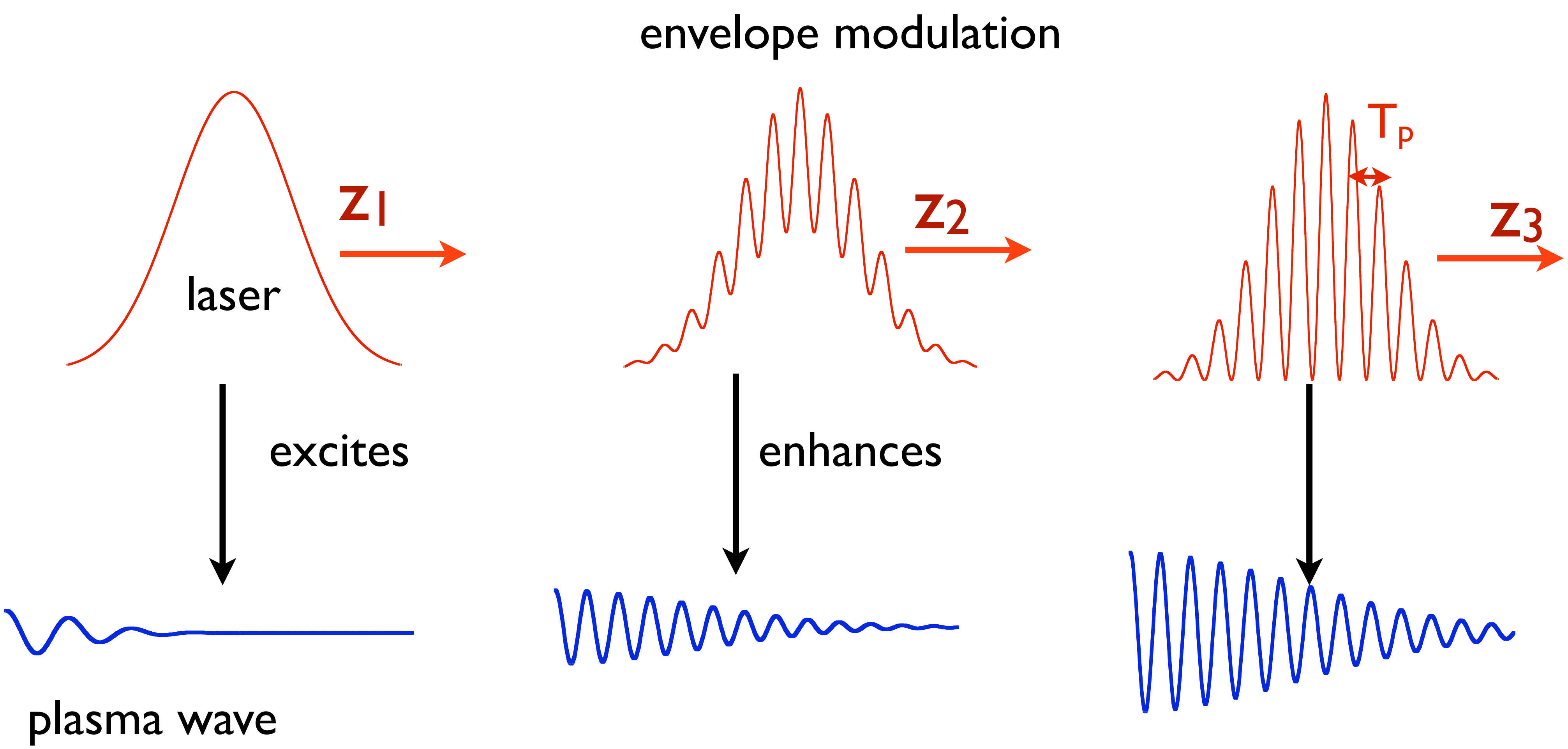
J.-R. Marquès *et al.*, Phys. Rev. Lett. **76**(19), 3566 (1996);
Phys. Rev. Lett. **78** (18), 3463 (1997); Phys. of Plasmas **5**(4), 1162 (1998)

SMLWF : theory (1992) and experiments (1995)

IC/ RAL/ UCLA/LULI

$cT_{laser} >> T_p$

(T. Antonsen and P. Mora, Ph. Sprangle et al., Andreev et al.,)



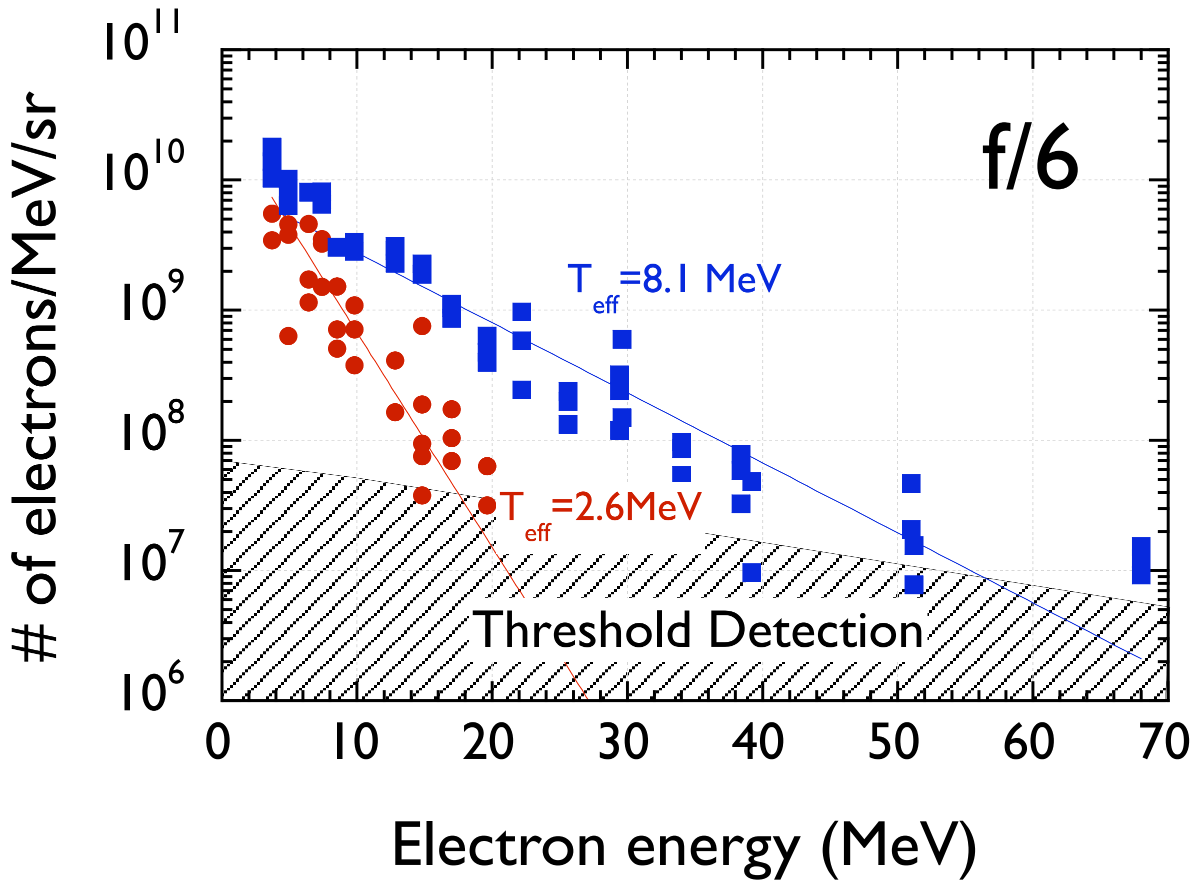
$P_L > P_c(GW) = 17\ n_c/n_e$ then wavebreaking can occured

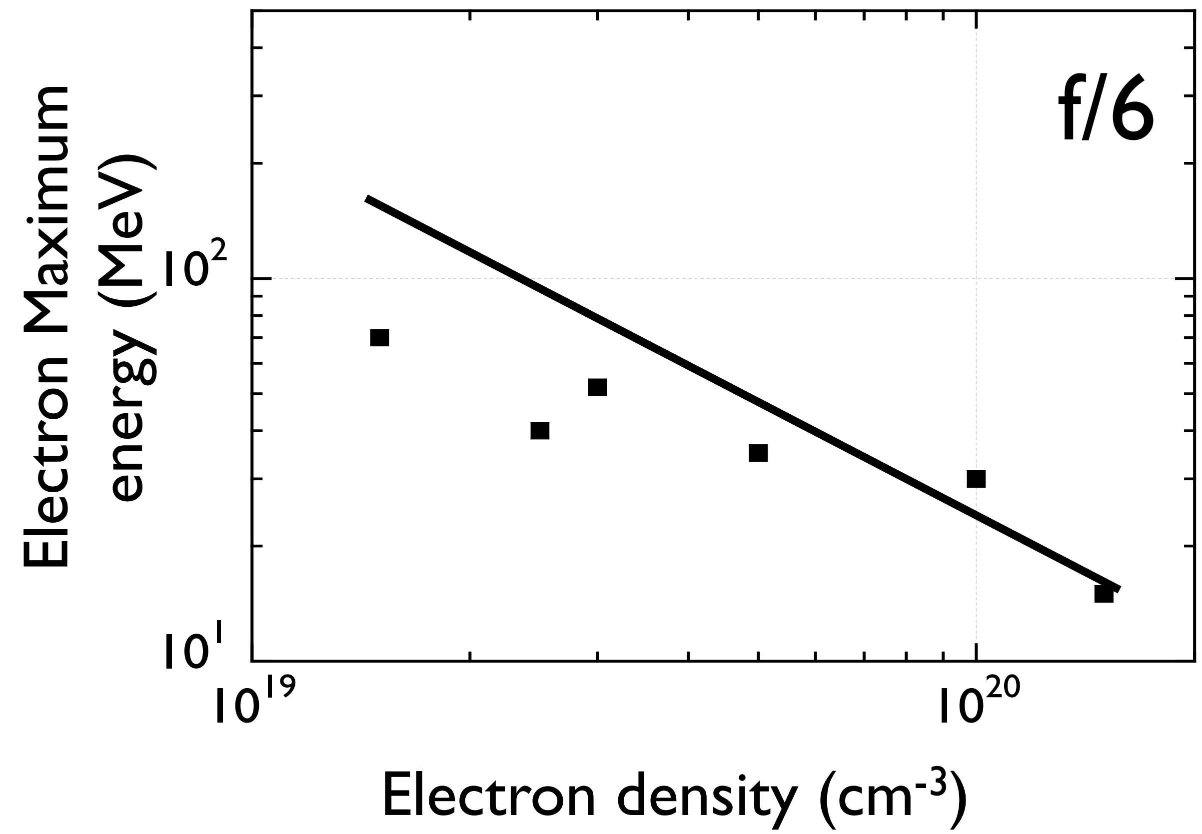
A. Modena *et al.*, Nature (1995)

LOA/LULI/IC

Spectra : E_{max} increases when n_e decreases

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



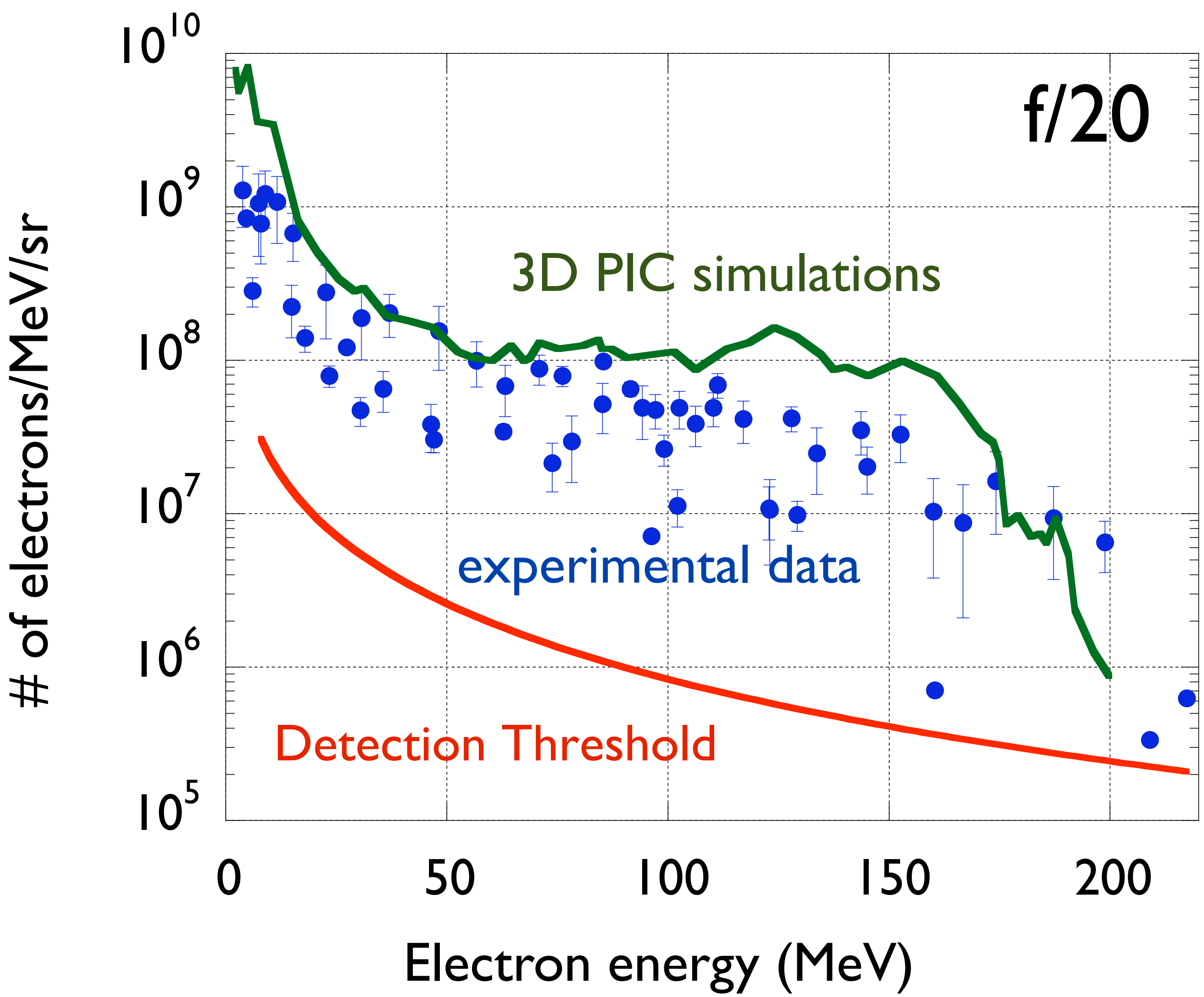


V. Malka et al., Phys. of Plasmas **8**, 6 (2001)

2002 : Forced Laser Wakefield, from 0 to 200 MeV in 1 mm

LOA/IC/CEA

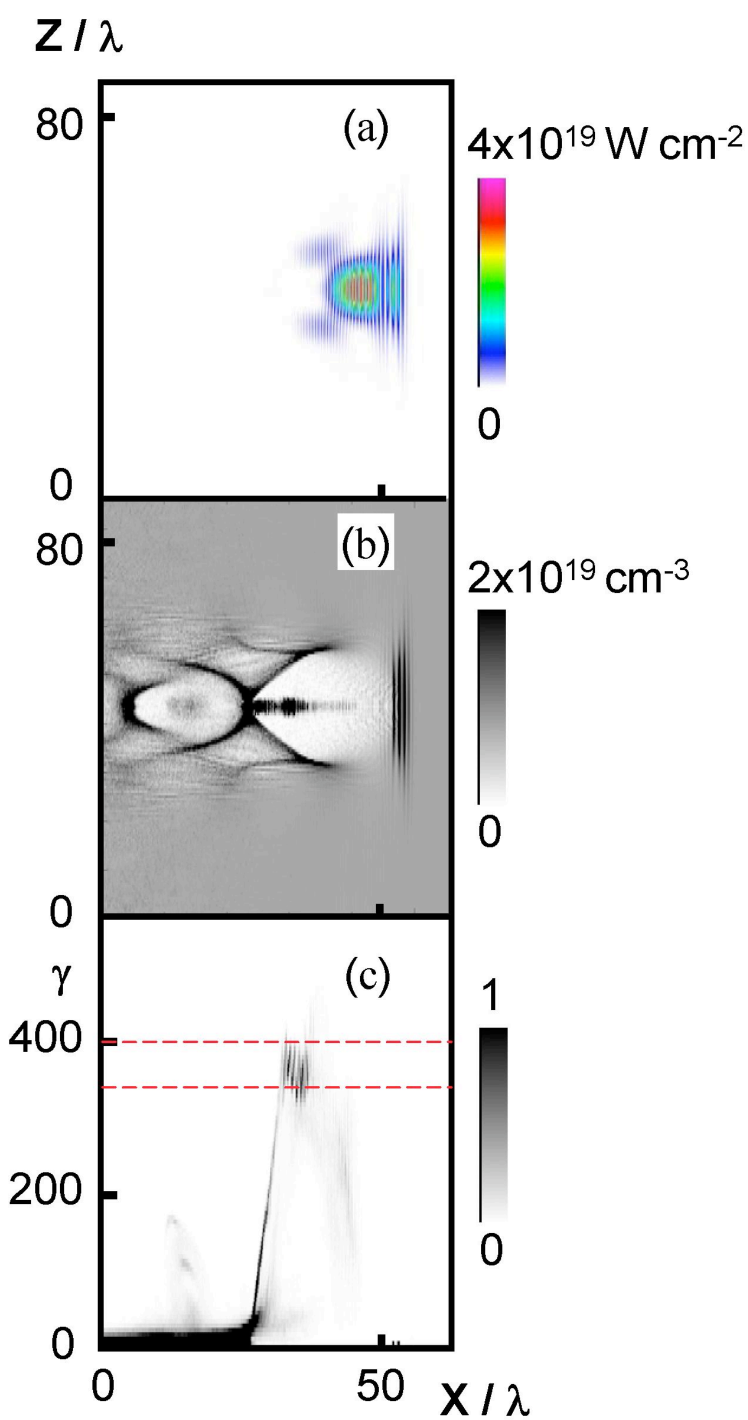
Parameters: n_e=1.5×10^{19}cm^{-3}, τ_L=35fs, E=0.6J, I_L= 1×10^{18}W/cm^2 with $k_p w_0$>1

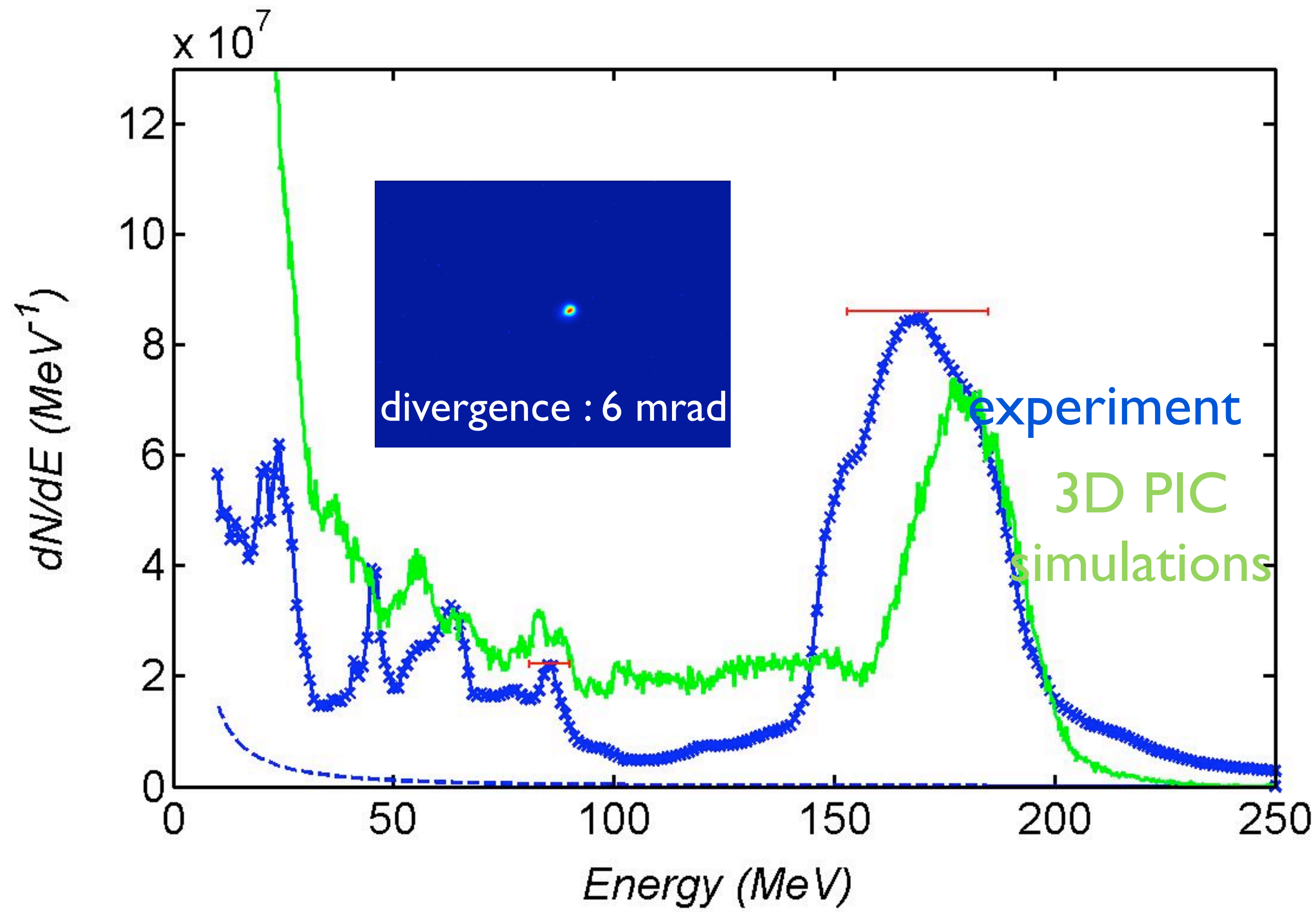


V. Malka *et al.*, Science **298**, 1596 (2002)

2004 : QM distribution in the bubble regime

LOA/UD





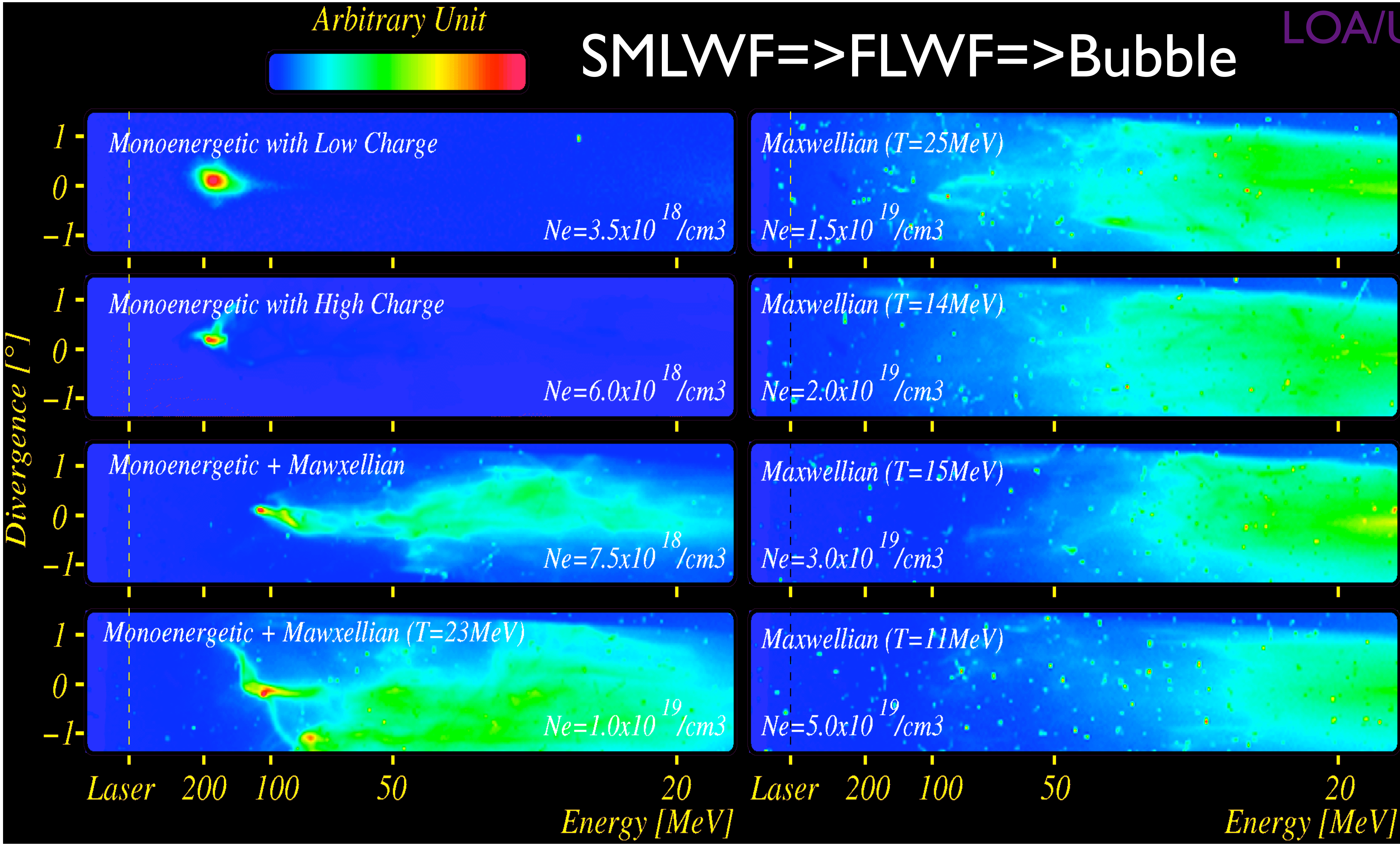
Experimental parameters : E=1J, τ_L=30fs,
λ_L=0.8μm, $I_L=3.2\times10^{19}$W/cm^2, $n_e=6\times10^{18}$cm^{-3}

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

2005 : Distribution quality improvements

SMLWF=>FLWF=>Bubble

LOA/UD

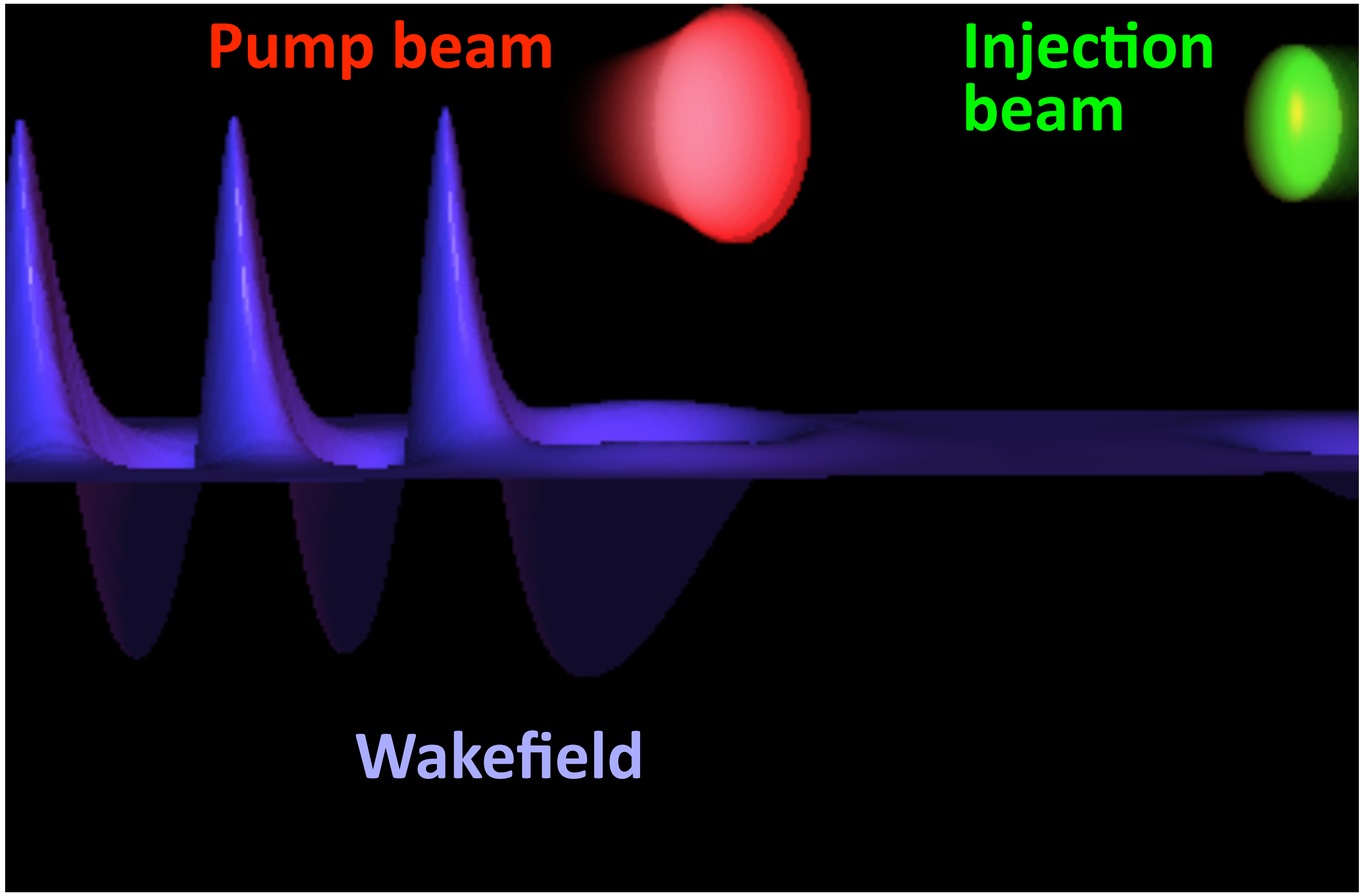


V. Malka *et al.*, Phys. of Plasmas **12**, 5 (2005)

2006 : Colliding Laser Pulses Scheme

LOA/CEA

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



Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$ (a_0 et a_1 can be "weak")
Boost electrons locally and injects them INJECTION IS LOCAL and IN FIRST BUCKET

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)

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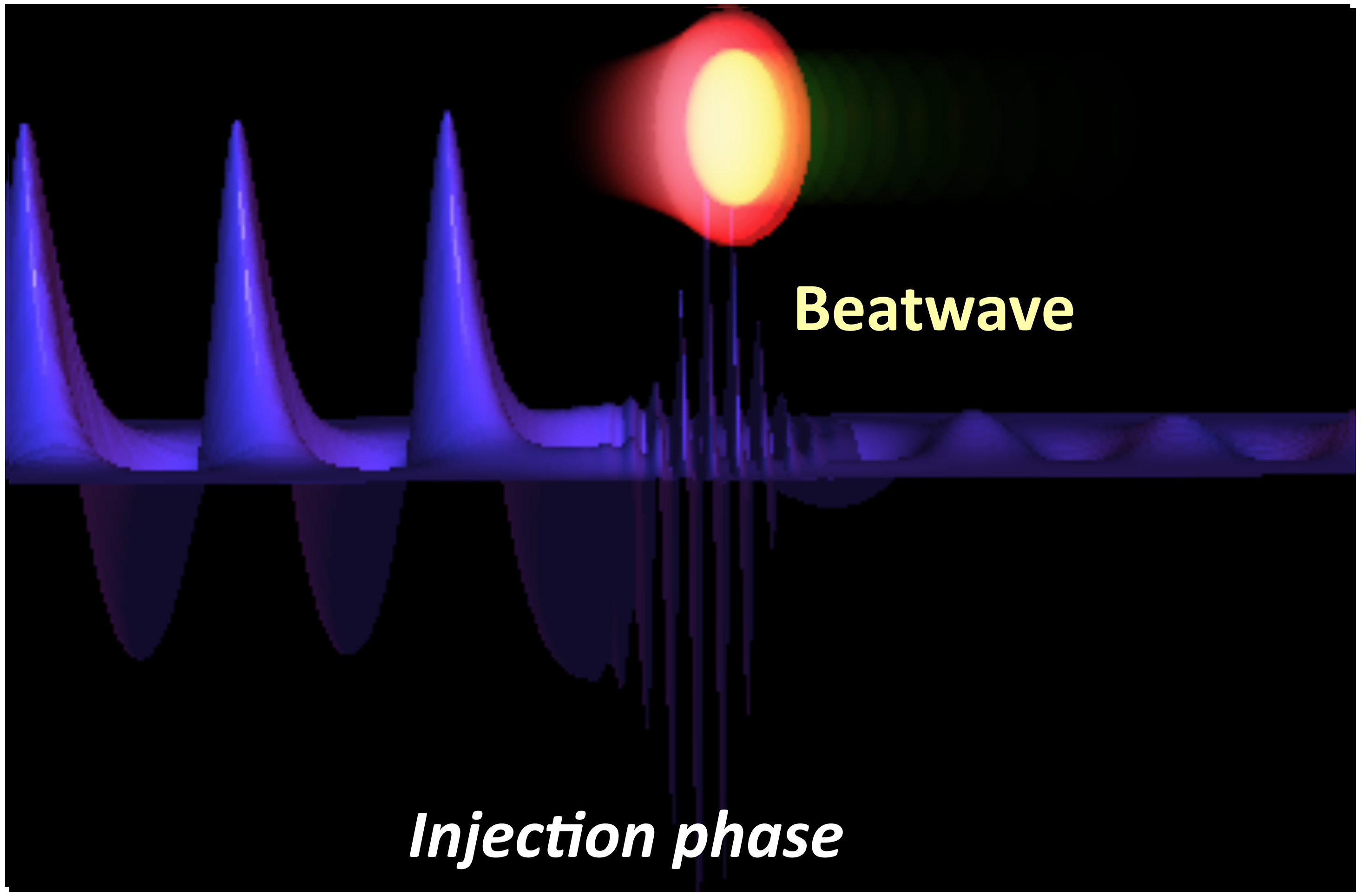

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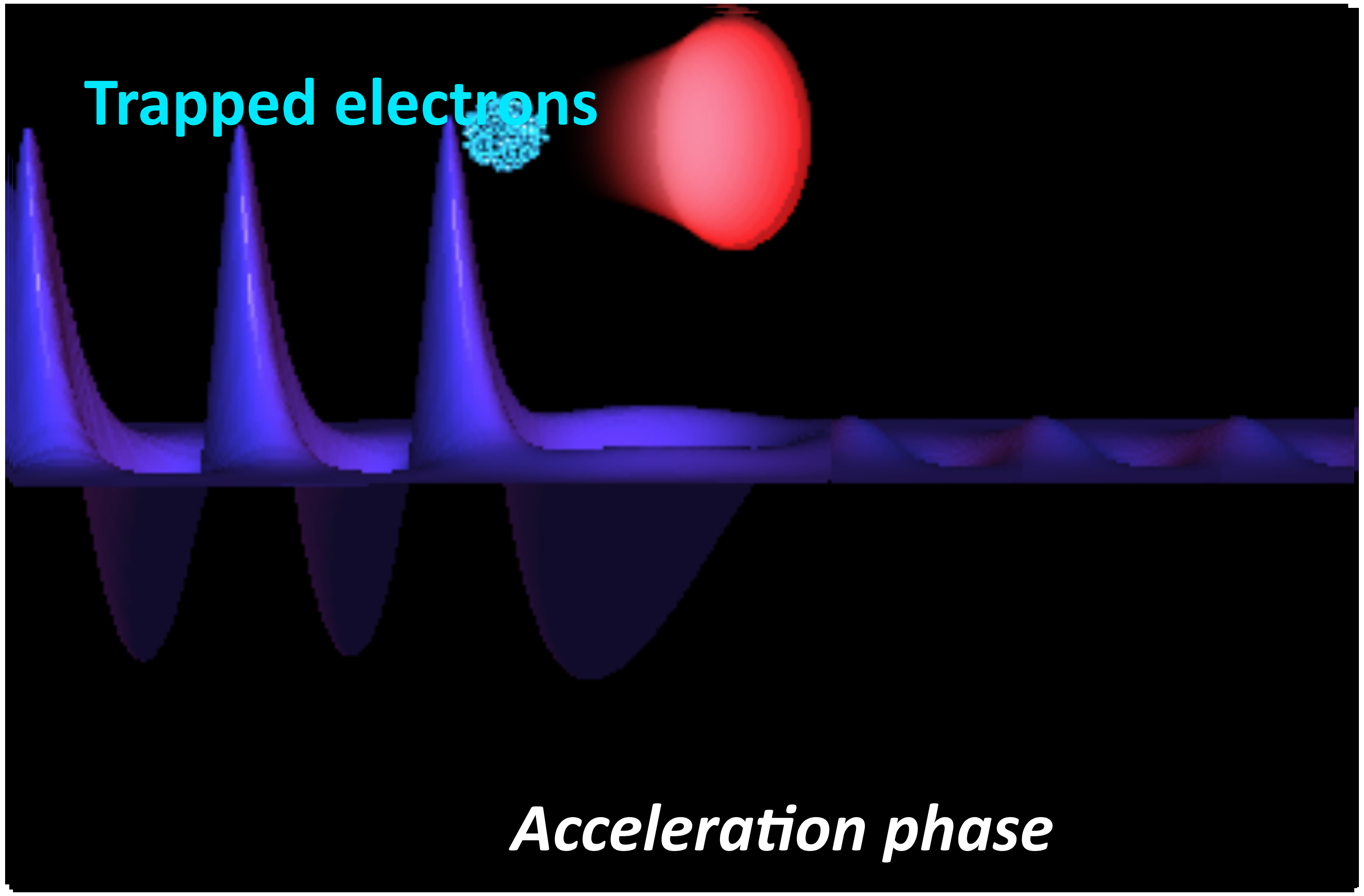

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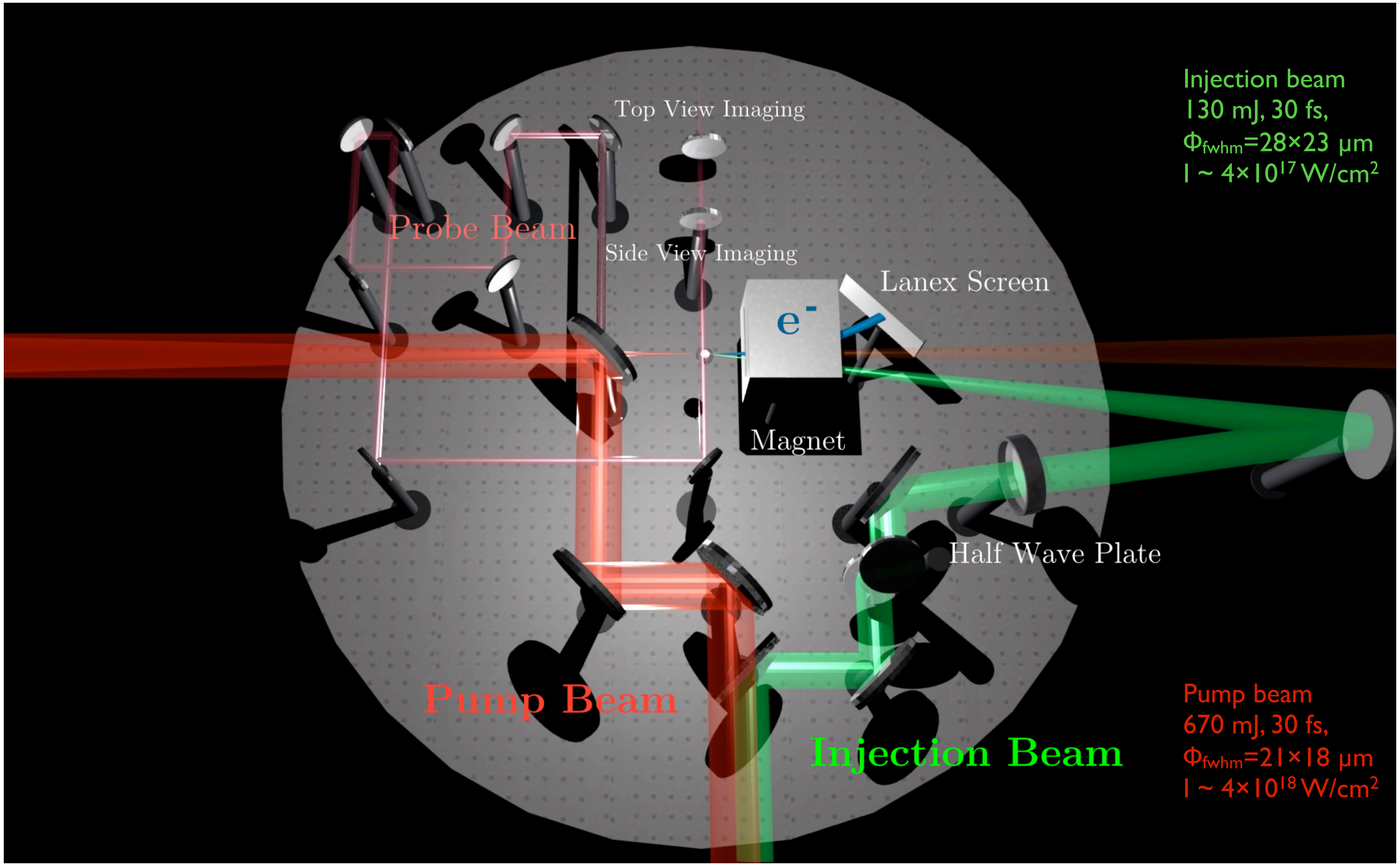
Compactness of Laser Plasma Accelerators

LOA/CEA



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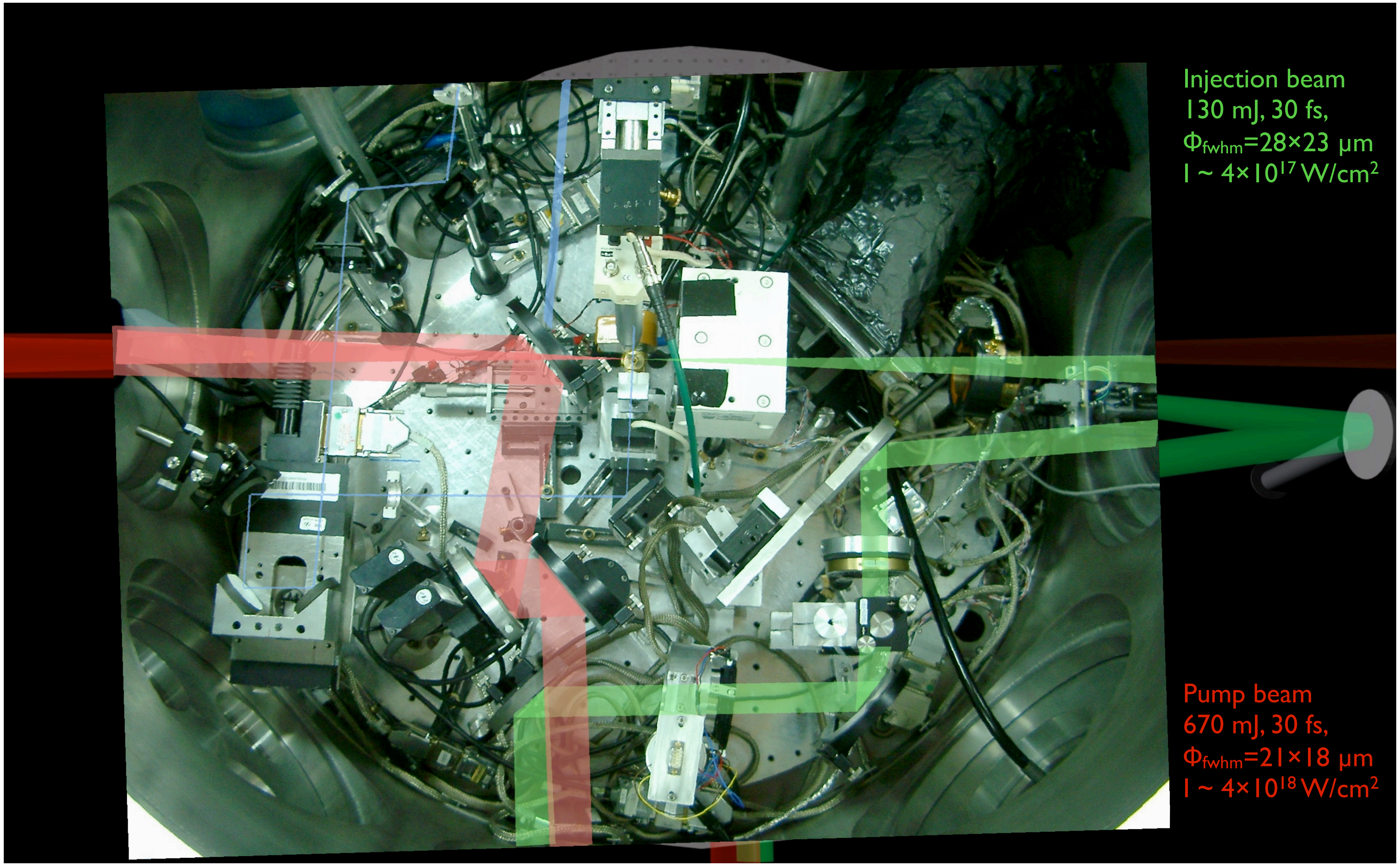
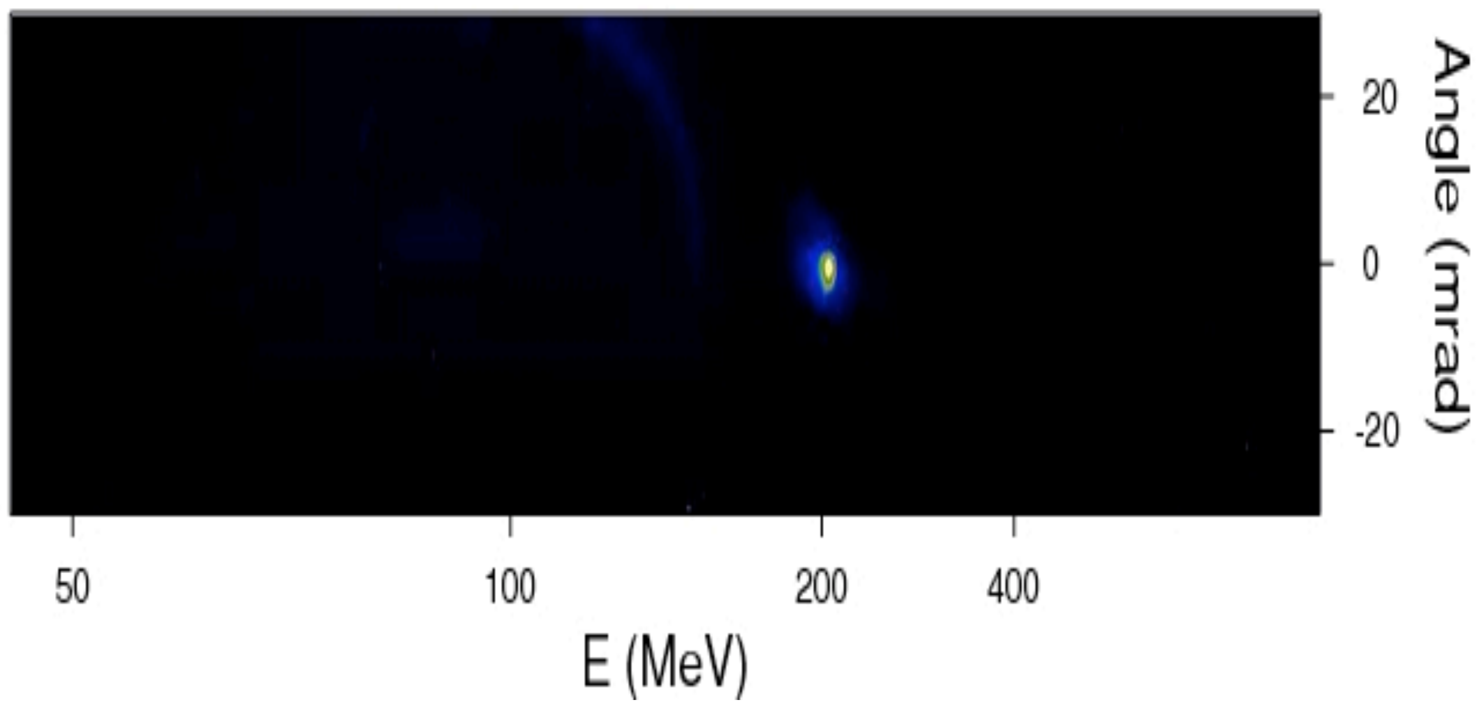
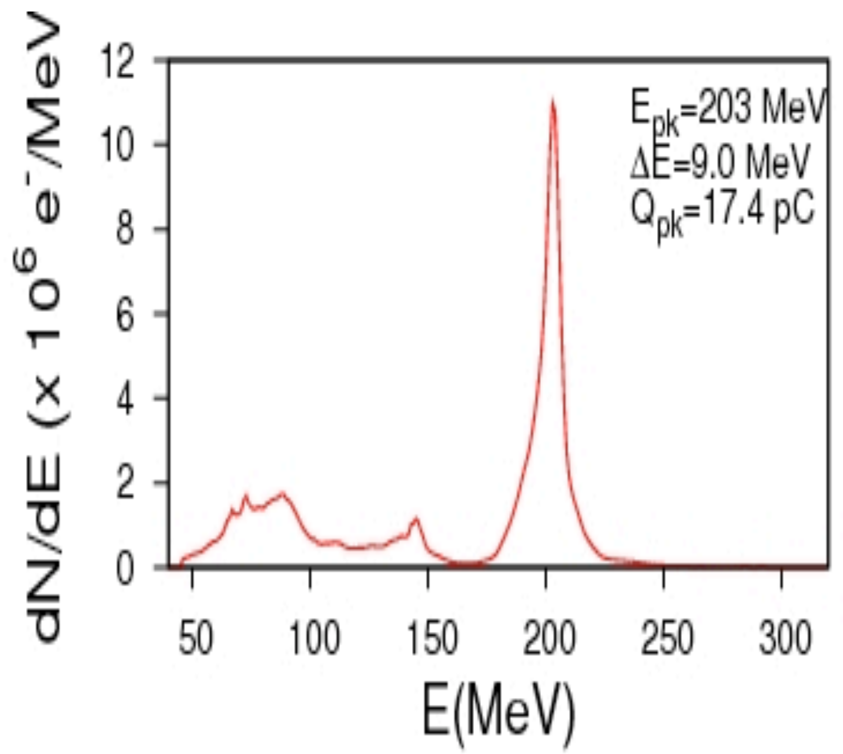


2006 : Stable electron beam

LOA/CEA



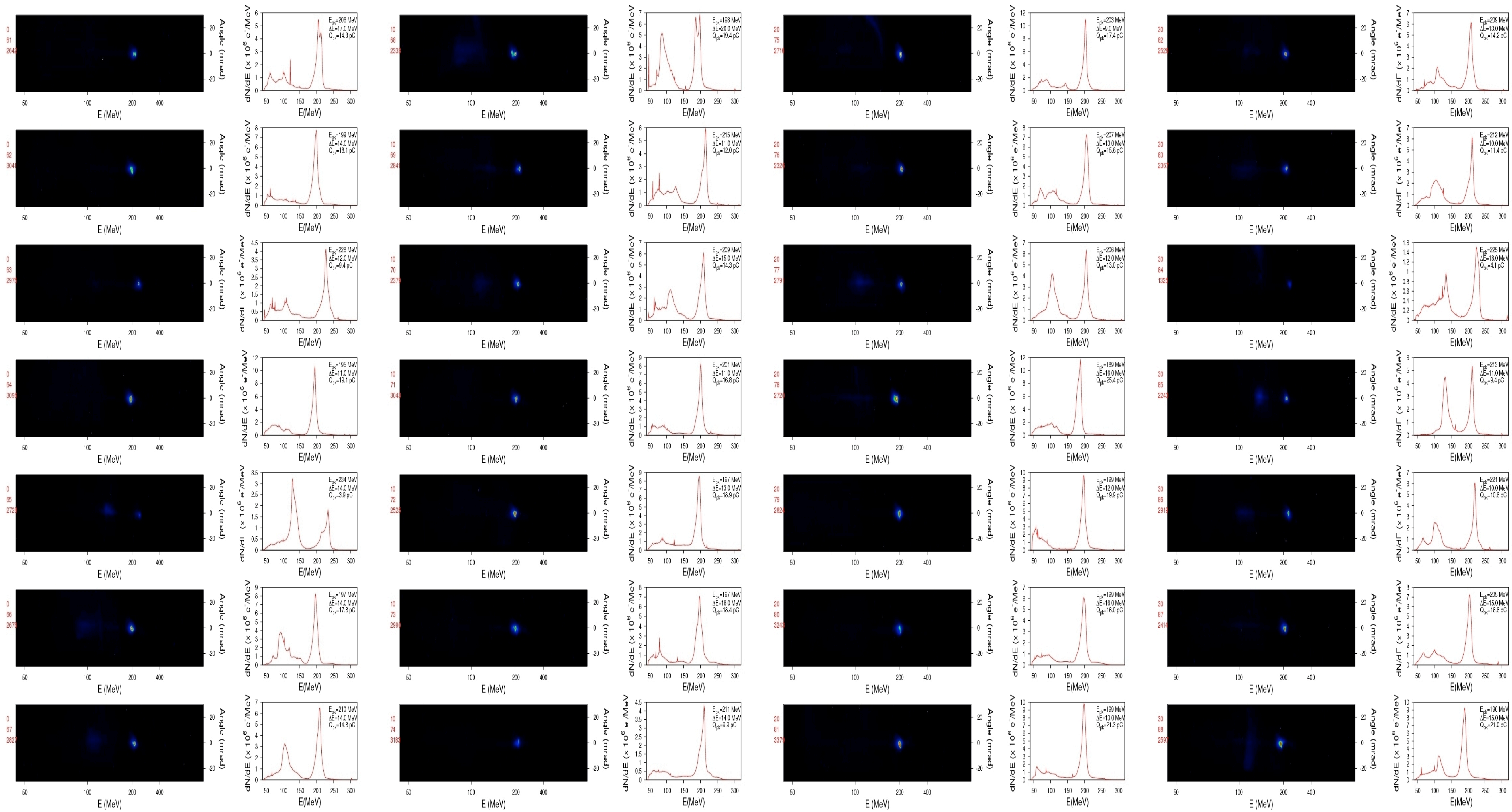


Nb: very few electrons at low energy, δE/E=5% limited by the spectrometer

2006 : Stable electron beam

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

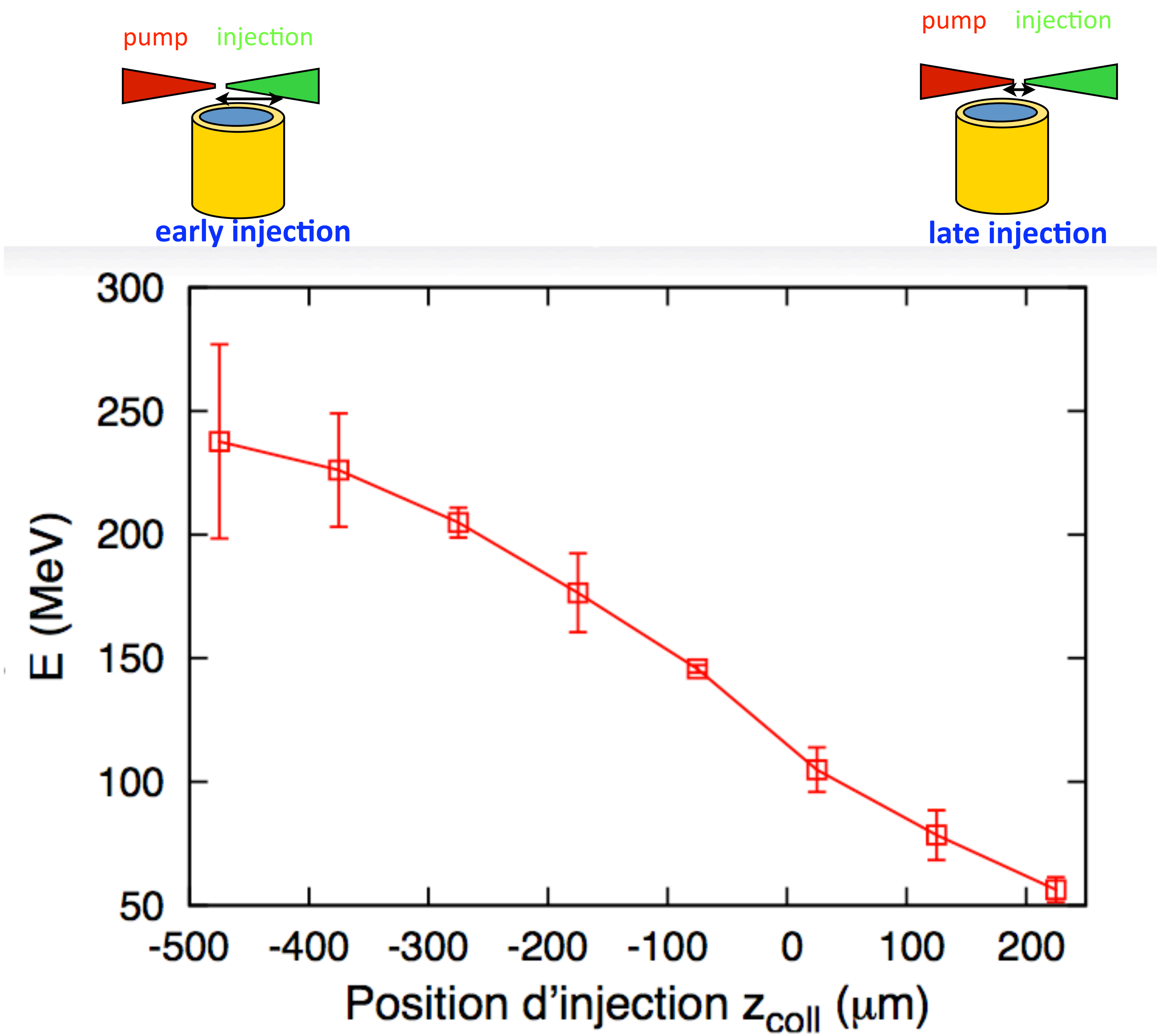
LOA/CEA



Nb: very few electrons at low energy, $\delta E/E=5\%$ limited by the spectrometer

2006 : electron beam energy tunability

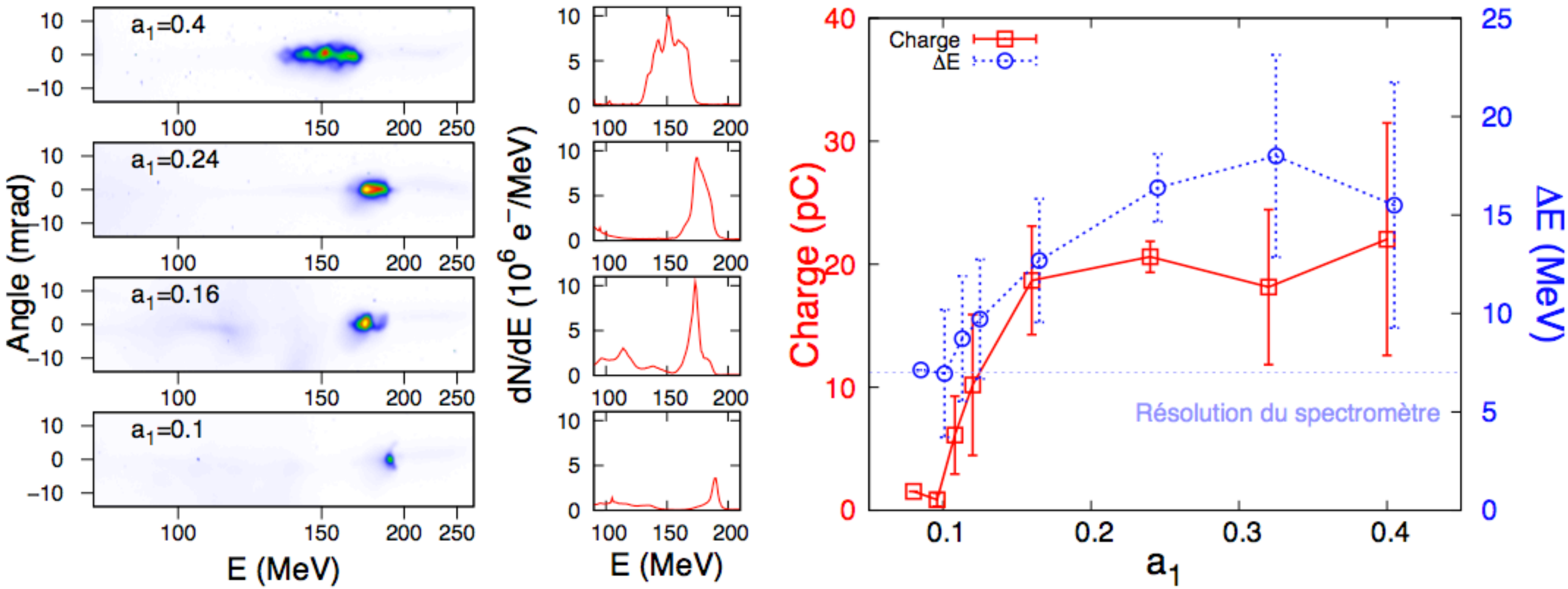
LOA/CEA



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

2009 Control of the charge and energy spread

LOA/CEA

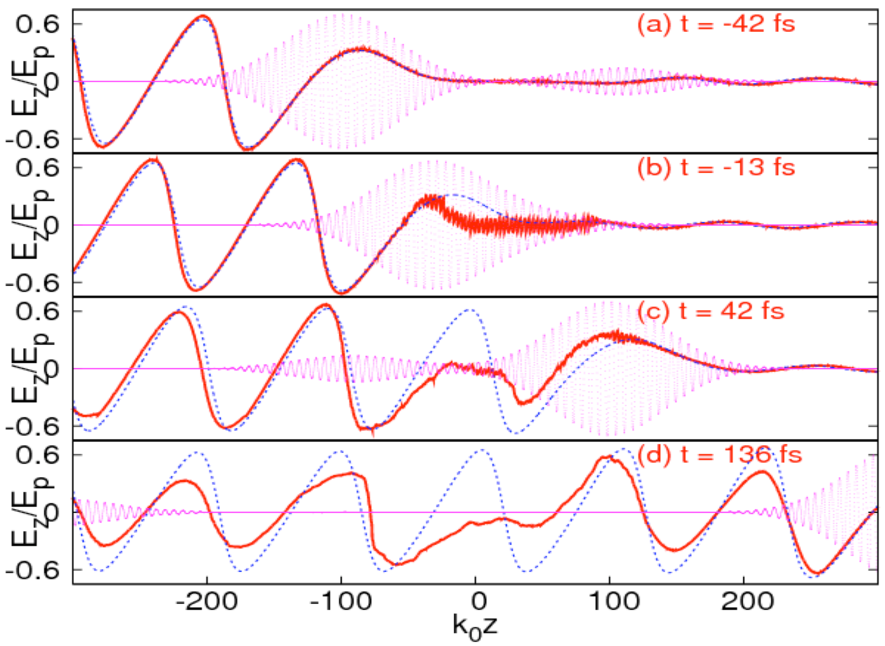


Charge from 60 pC to 5 pC, ΔE from 20 to 5 MeV

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

2007-2009 Theoretical work, PIC simulations (fluid model failed)

LOA/CEA

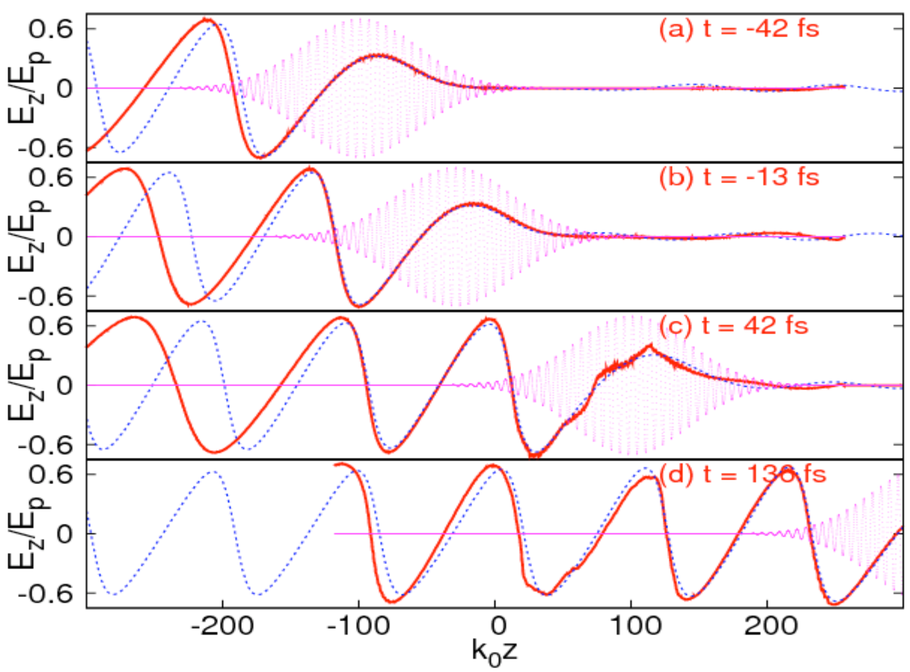


// polarisation:

The beatwave prevents a large scale collective oscillation and thus the plasma wave excitation :

=> The wakefield is inhibited at the collision position.

=> Trapping is more difficult



Crossed polarization:

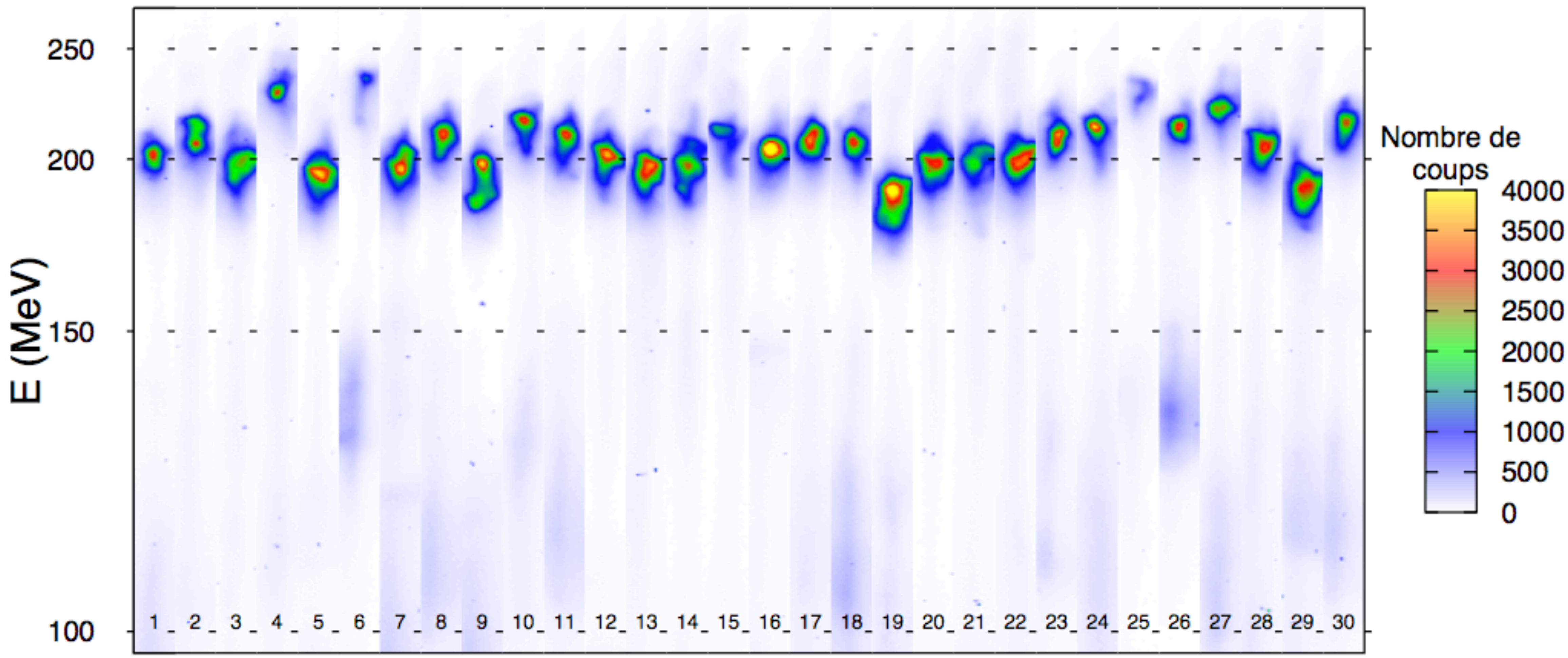
=> no beatwave

=> no wake inhibition

=> Trapping is easier

C. Rechatin *et al.*, Phys. of Plasmas **14**, 6 (2007), V. Malka *et al.*, Physics of Plasmas **16**, 5 (2009), C. Rechatin *et al.*, New Journal of Physics **11** (2009)

2009 e-beam dynamics in plasma waves : beam loading



30 tirs consécutifs avec $a_0 = 1.5$, $a_1 = 0.4$, $n_e = 5.7 \times 10^{18}$ cm^{-3}

Nb: very few electrons at low energy
δE/E=5% limited by the spectrometer

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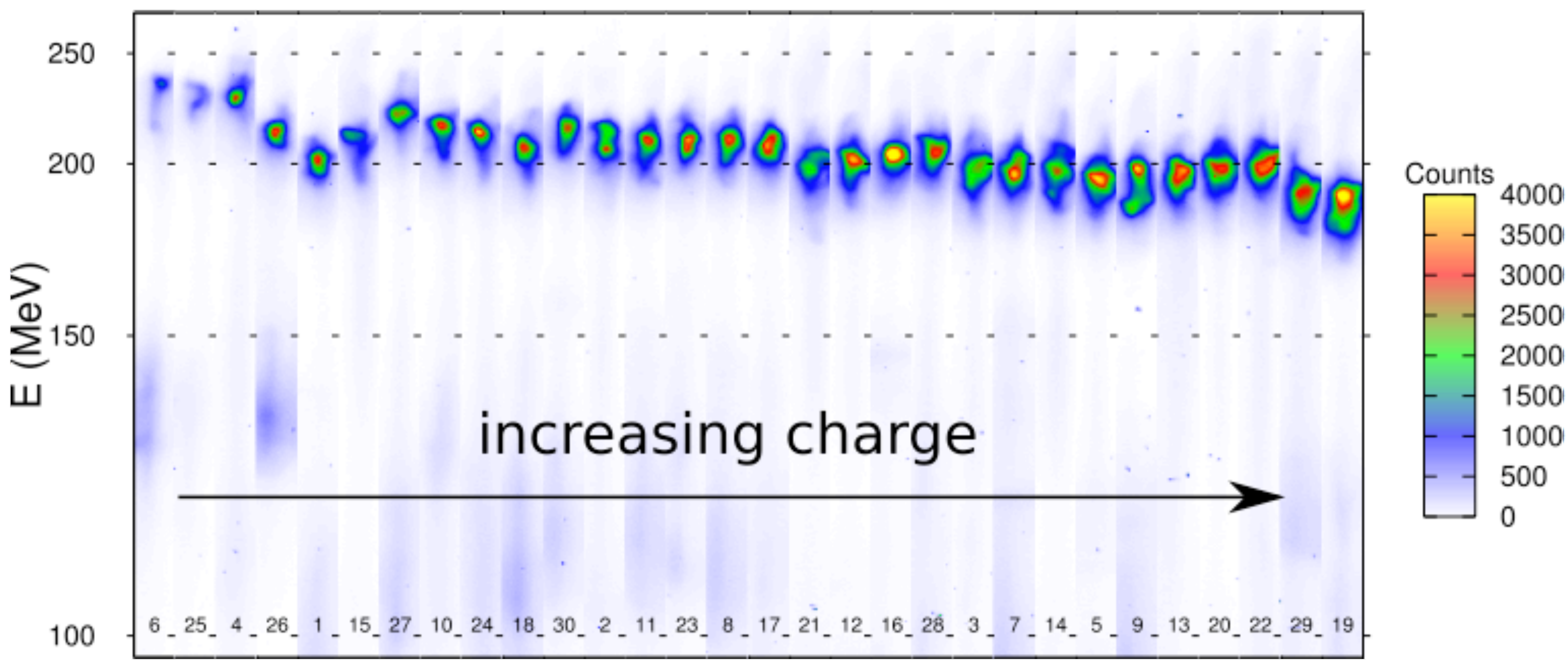
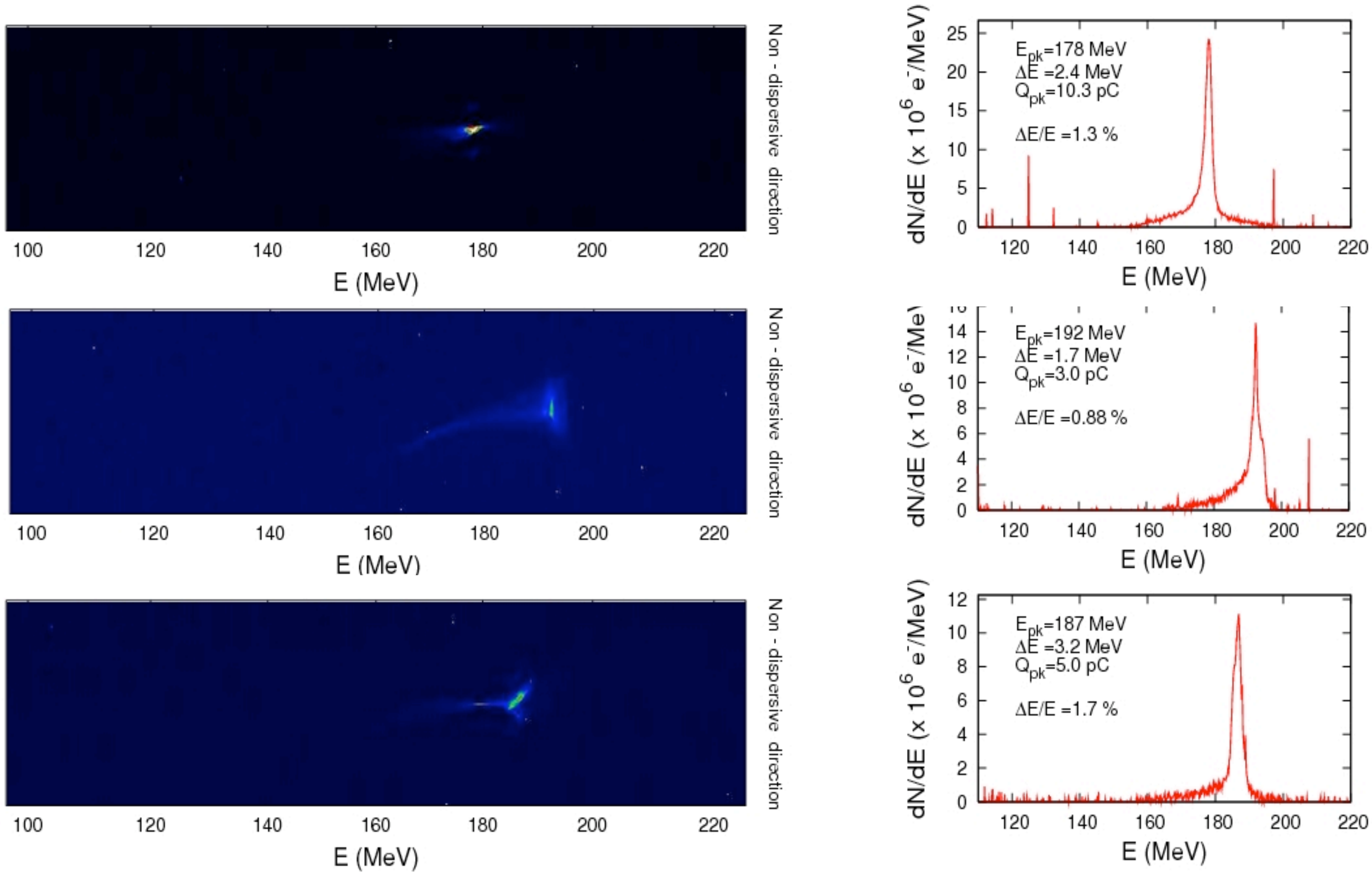


30 tirs consécutifs avec $a_0 = 1.5$, $a_1 = 0.4$, $n_e = 5.7 \times 10^{18}$ cm^{-3}

Clear correlation !

Nb: very few electrons at low energy
$\delta E/E$=5% limited by the spectrometer

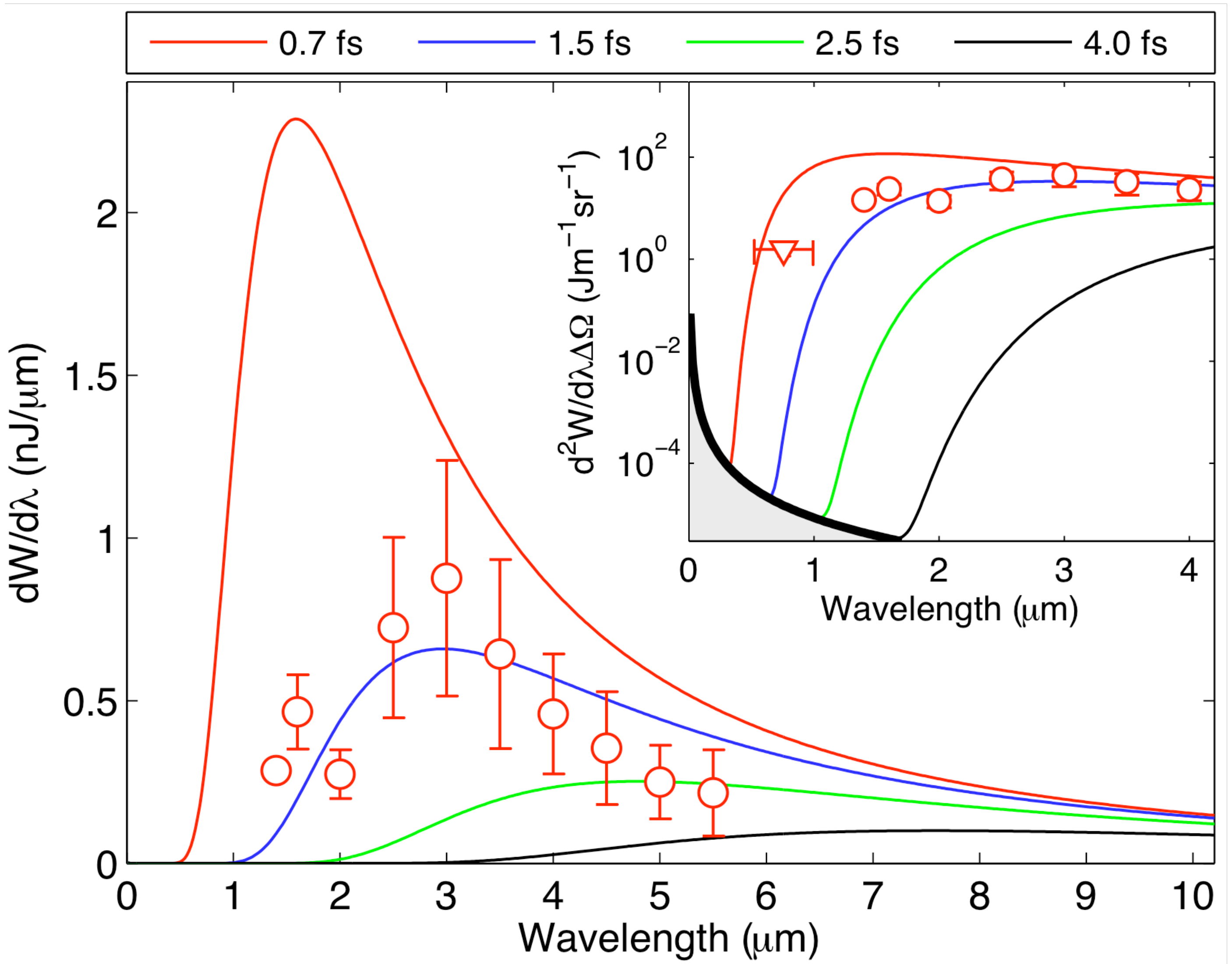
2009 : From Quasi-Mono to Mono energetic electron beam



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

In collaboration with A. Specka, H. Videau, LLR, CNRS, Ecole Polytechnique

2010 : 1.5 fs RMS duration - Peak current of 4 kA



Spectral features

Peak at 3 μm

Coherent

Analytic CTR model

Gaussian pulse shape

Measured e-beam :

- Charge
- Energy
- Divergence

Bunch duration

Peak wavelength

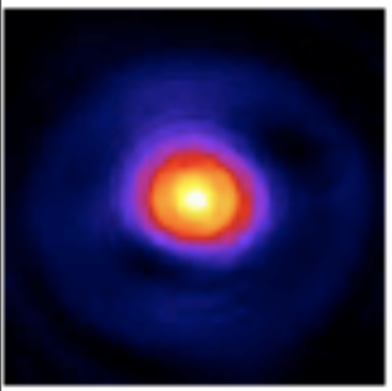
Peak intensity

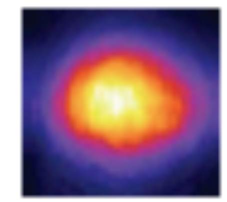
1.5 fs RMS duration : Peak current of 4 kA

O. Lundh *et al.*, Nature Physics, March 2011

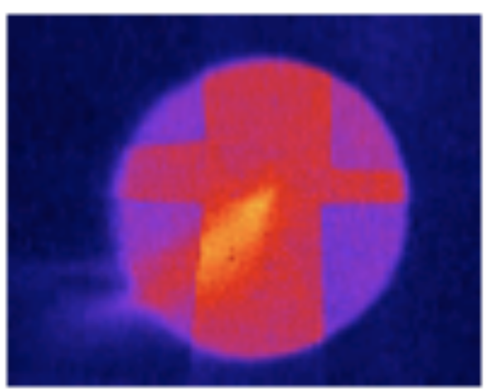
Recent achievements

- Optimisation of laser guiding using capillary tubes (10cm):
  - vacuum or under-dense plasmas
  - Relevant for moderate intensities in laser wakefield schemes
  - Active control of laser properties to improve coupling





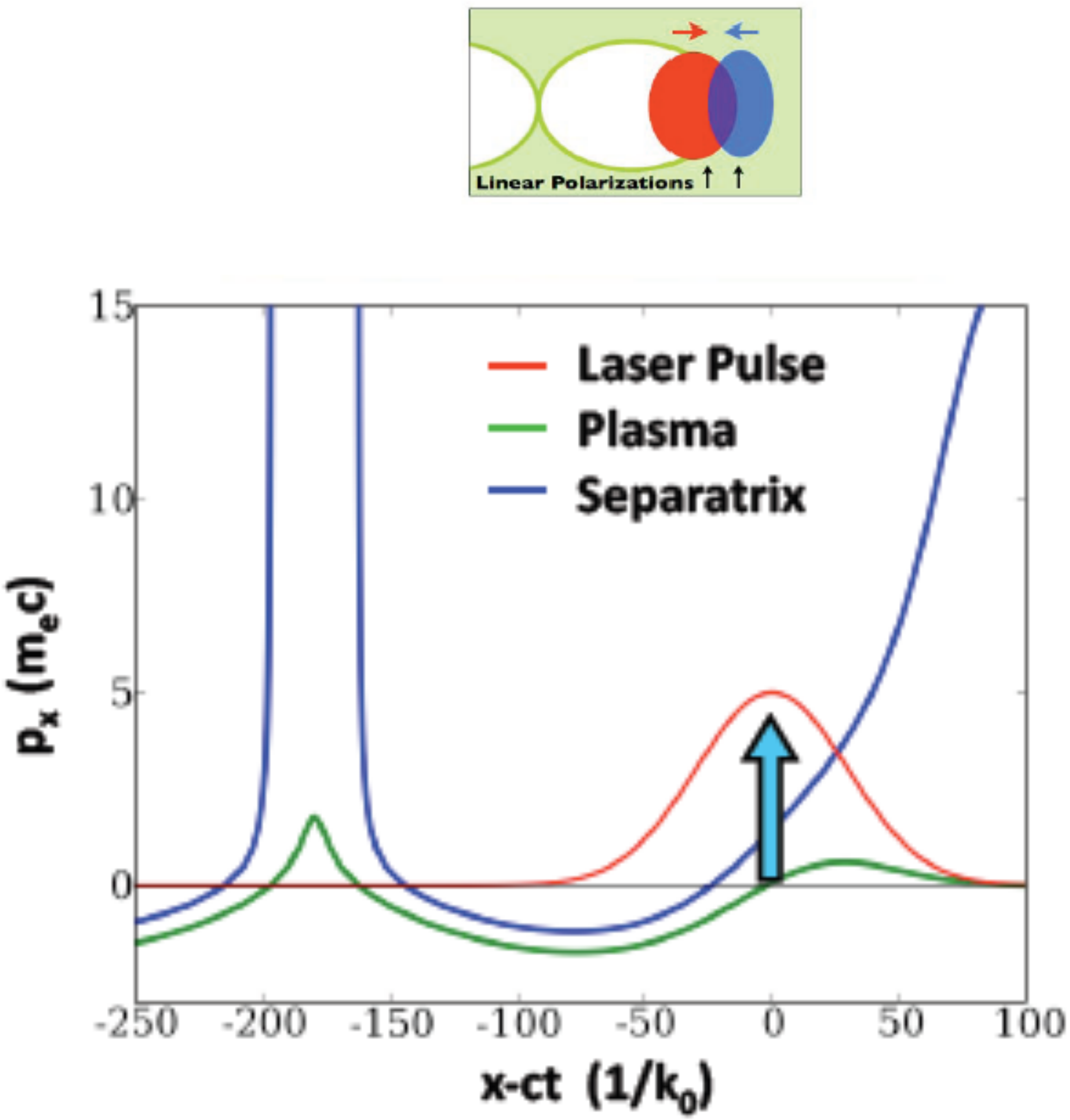
- Measurement of a plasma wave in the wake of an intense laser beam guided in a capillary tube over 8 cm, using optical diagnostics. **Measured field up to 7GV/m over 8 cm.**

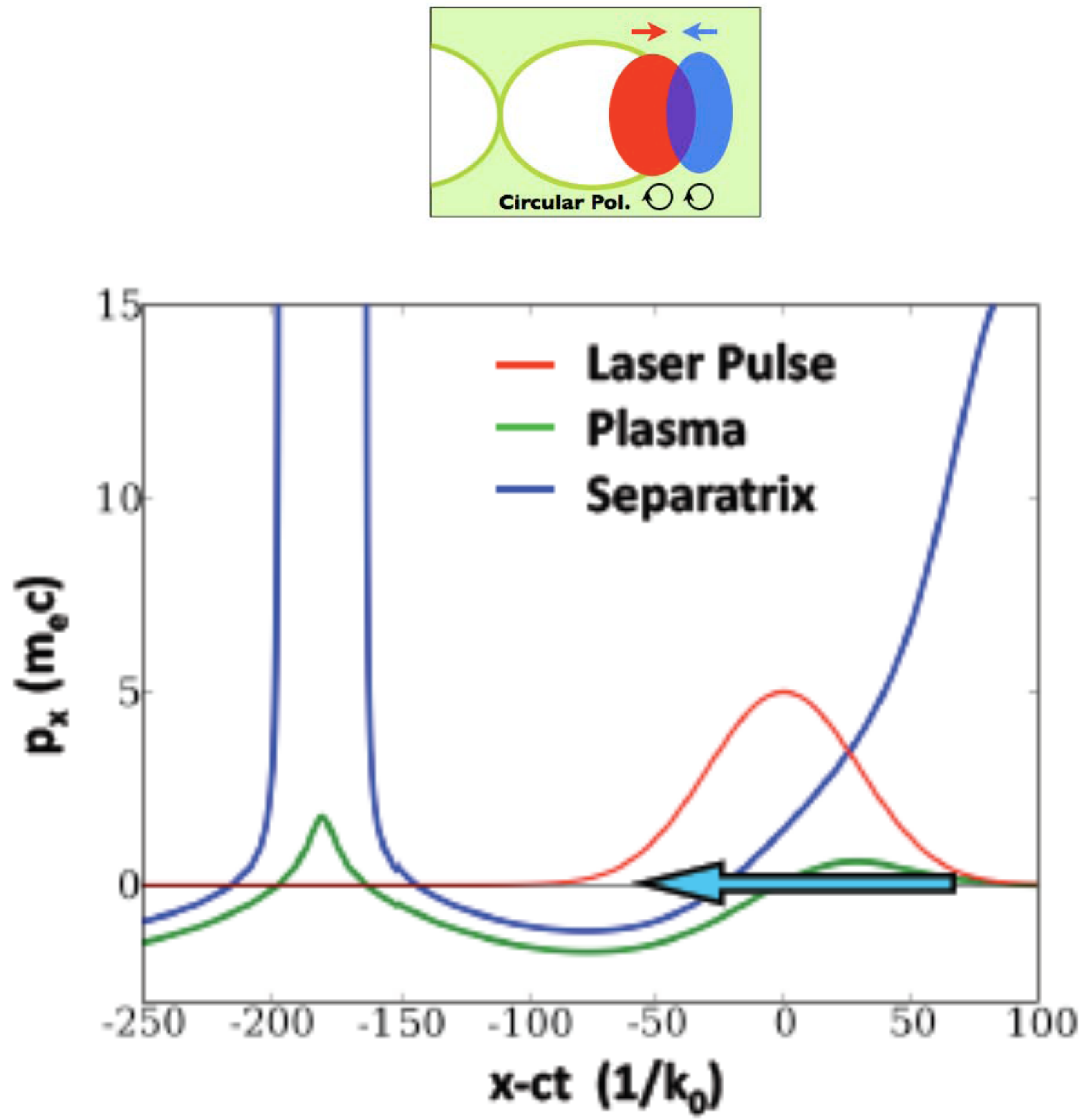


- Study of the influence of guiding on electron acceleration and X ray emission:
  - determination of the threshold for electron self-injection over a few centimeters,
  - use of the X-ray beam as a diagnostic of the acceleration process
  - Optimisation of the X-ray source (1-10keV)

Phys. Rev. E **80**, 066403 (2009), New J. Phys. **12**, 045024 (2010), JOSA B **27**, 1400 (2010), Plasma Phys. Control. Fusion **53**, 014005 (2011), Rev. Sc.Inst **82**, 033102 (2011)

Cold Injection Scheme : control of emittance





X. Davoine *et al.*, Phys. Rev. Lett. **102**, 6 (2009)

Applications :

X/γ rays for non destructive material inspection with 50 microns resolution

Radiobiological studies of high dose rate

Femtochemistry

Medical applications - Electrontherapy with low energy-10 MeV (IORT/CEA) and high energy-200 MeV (LOA)

Compact light X rays source :
- -betatron (as a source of as a diagnostic)
- -NL Thomson scattering

V. Malka *et al.*, Nature Physics **4**, June 2008, A. Rousse *et al.*, PRL 2004, K. Ta Phuoc *et al.*, PRL 2006, Y. Glinnec *et al.*, PRL 2005, A. Ben Ismail *et al.*, NIMA 2010, O. Rigaud *et al.* Cell Death and Disease 1e**73**, (2010)

Conclusions

France has contributed since the nineties to the development of laser plasma accelerators first at LULI/LPNHE, and then at LOA with researchers from more than 7 laboratories : CEA (DAM & Saclay), CPhT, LLR, LPGP, LOA and LULI.

European Collaborations : CERN, LLC, IC, RAL, GoLP, UD, INFN, etc...

Non European Collaborations : UCLA, USC, BNL, CUOS, UD, etc...

Around ten researchers in France work in this field (not at full time)

List of european contracts related to LPA developments :

- 2003 CARE/Phin
- 2006 Euroleap-FP6
- 2009 Laptech-FP7
- 2009 EUCARD/Annac
- 2009 ERC-Paris