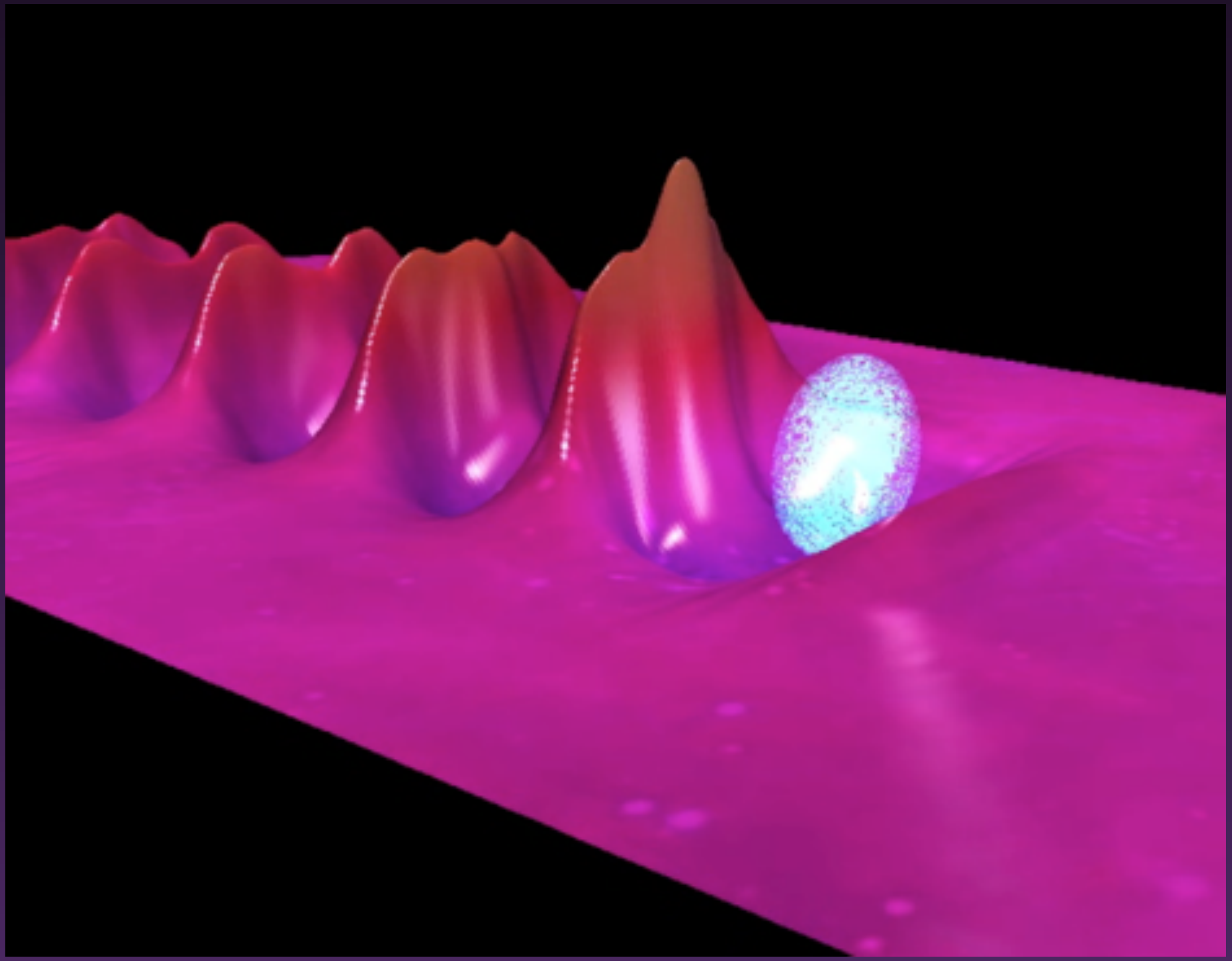
Laser Plasma Accelerators



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loa

Seminary at ALBA, Barcelona, Spain, October 20 (2014)

Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Laser wakefield principle
- Injection processes :
    - Bubble
    - Colliding
- Beam Loading
- Applications
- Conclusion and perspectives

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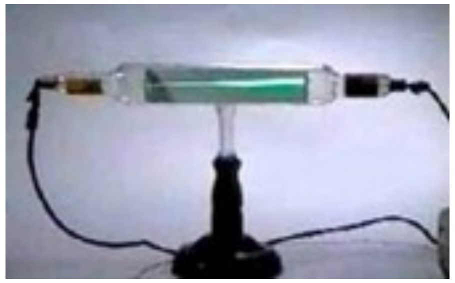
Industrial Market for Accelerators

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...)

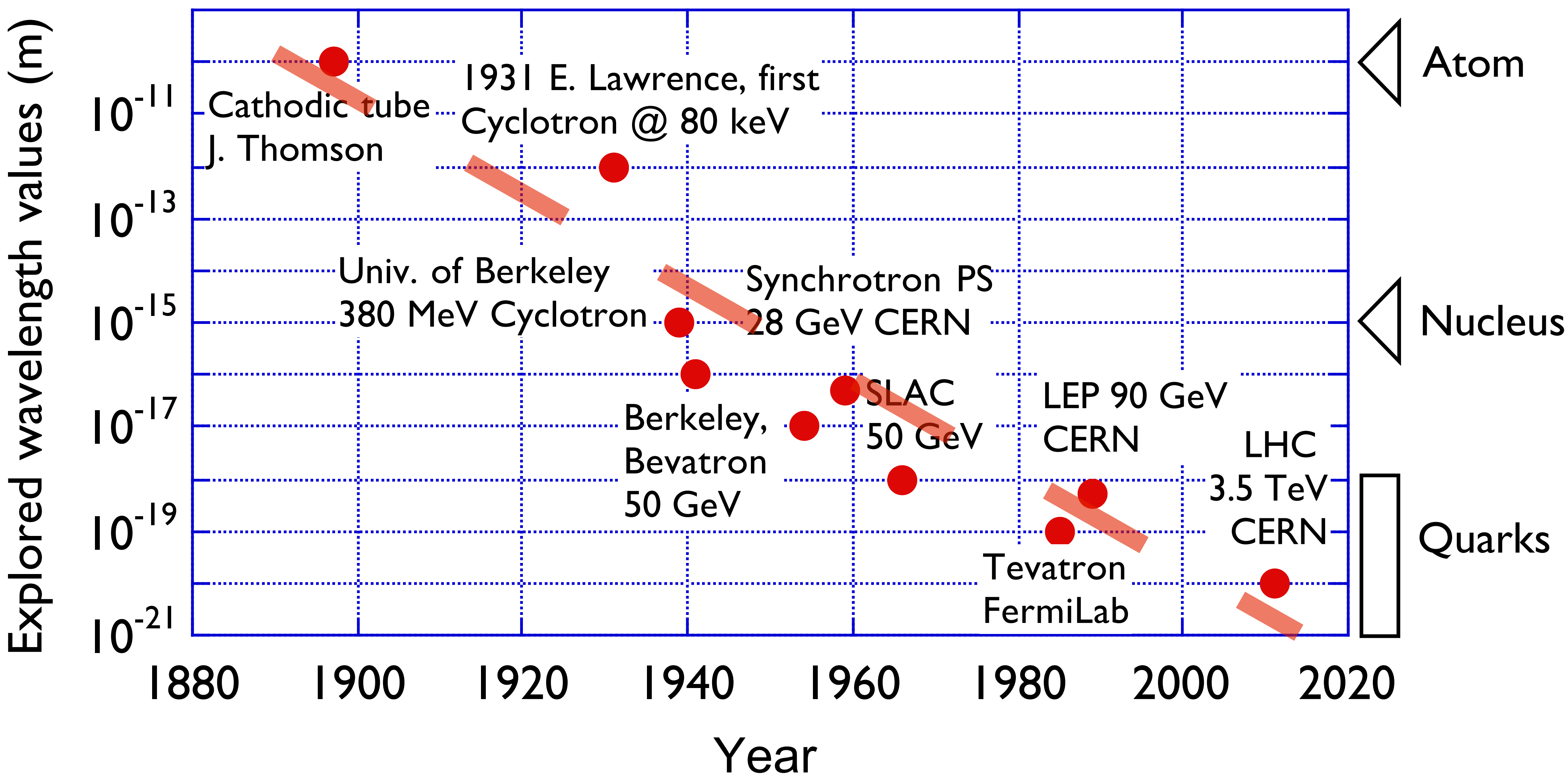
Application	Total systems (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production (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







Plasma Accelerators : motivations

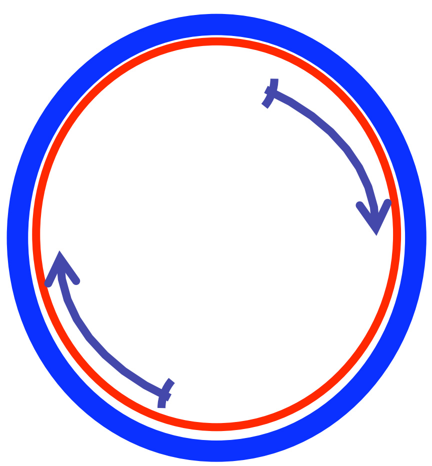
E-field $_{max}$ ≈ few 10 MeV /meter (Breakdown)

$R>R_{min}$ Synchrotron radiation

→ Energy ↗ → Length ↗ → Cost ↗

LEP at CERN

27 km



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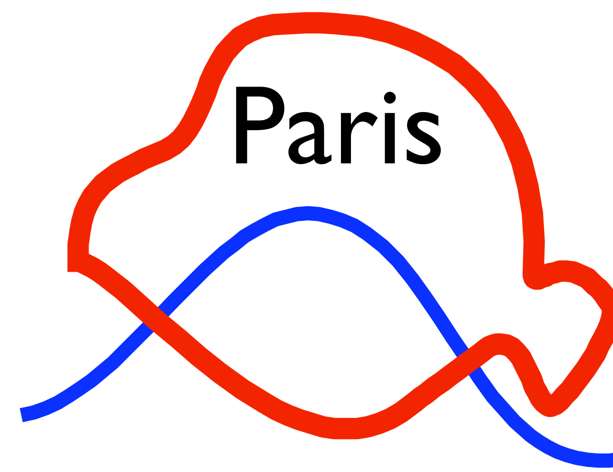


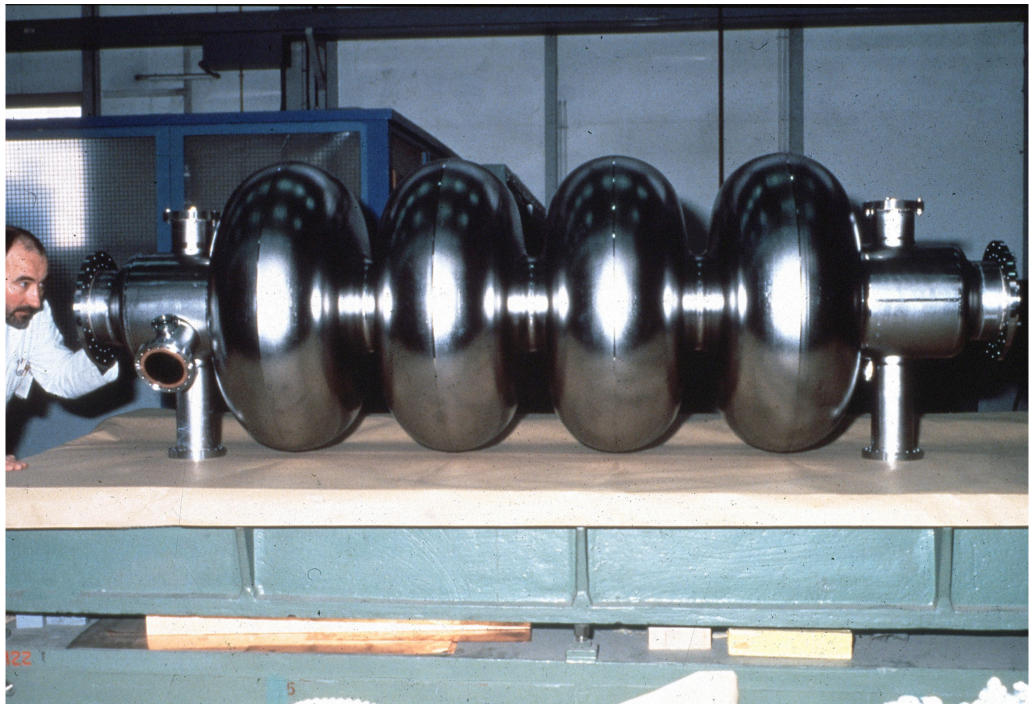
Circle road

31 km

➡ New medium : the plasma

Compactness of Laser Plasma Accelerators

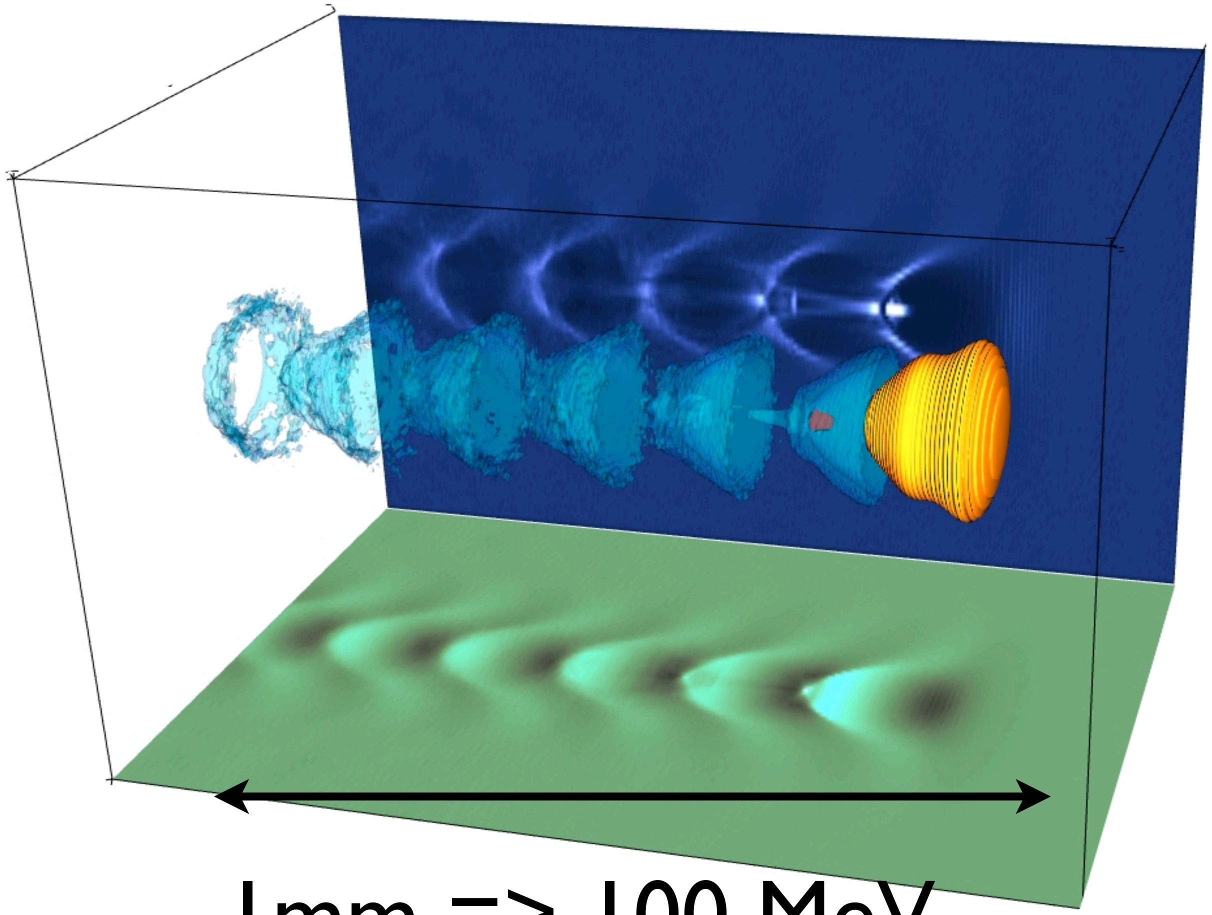
RF Cavity



1 m => 100 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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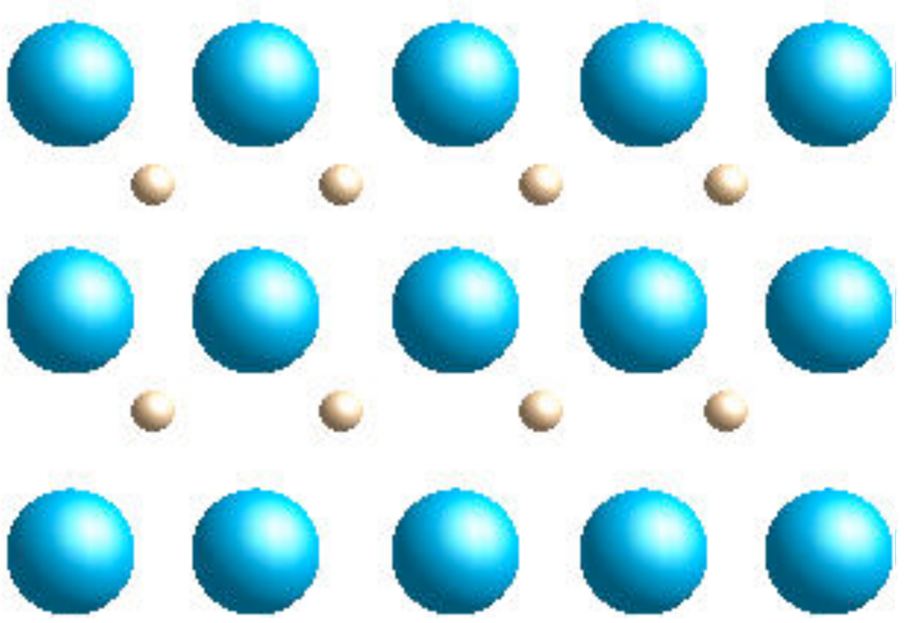
Why is a plasma useful ?

Superconducting RF-Cavities : E_z = 55 MVm

Plasma is an Ionized Medium => High Electric Fields

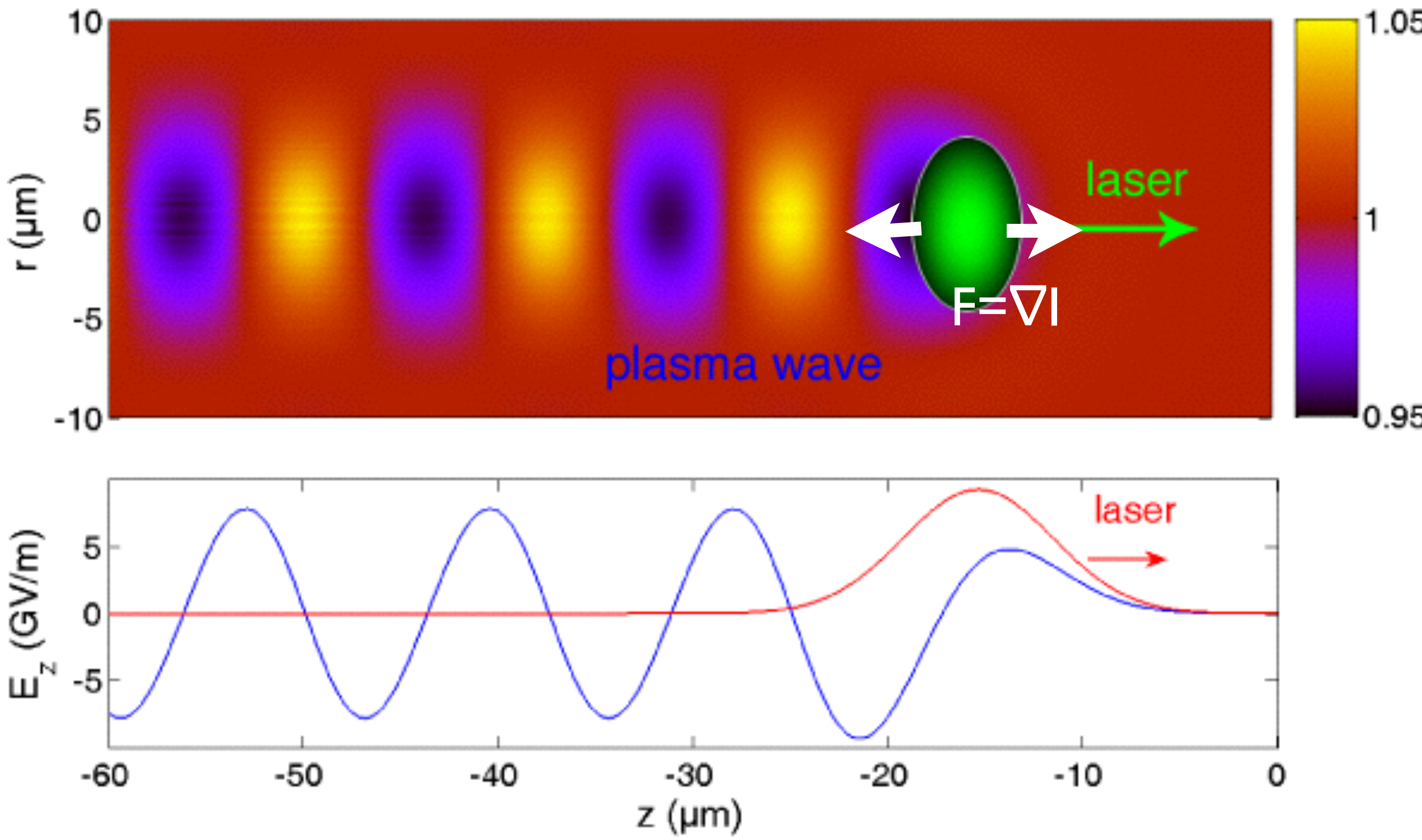


$$E_z\ (GV/m) \approx \delta n/n \times \sqrt{n}$$

How to excite relativistic plasma waves ?

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

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

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

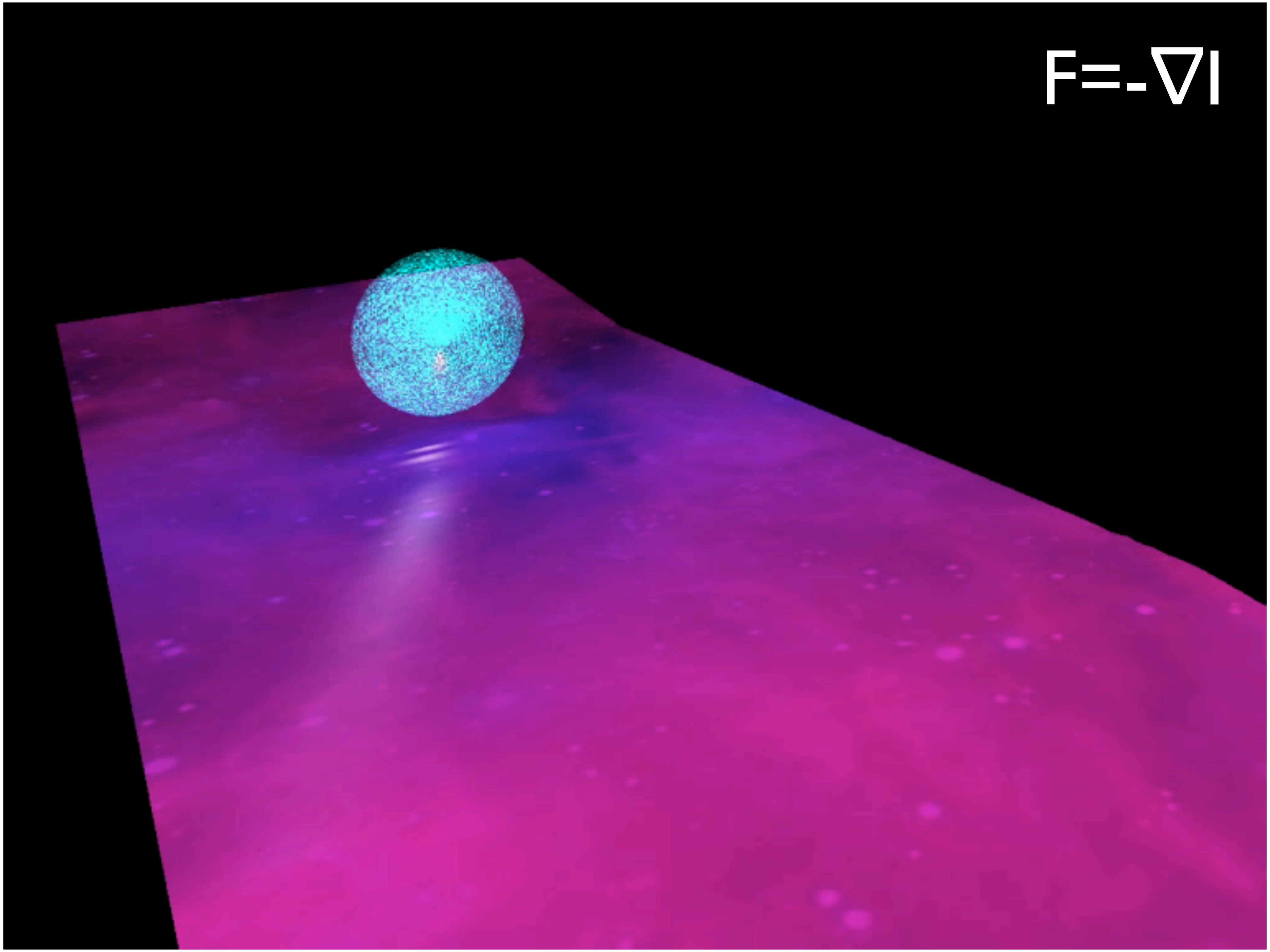
T. Tajima and J. Dawson, PRL **43**, 267 (1979)

Resonance : children are well aware....

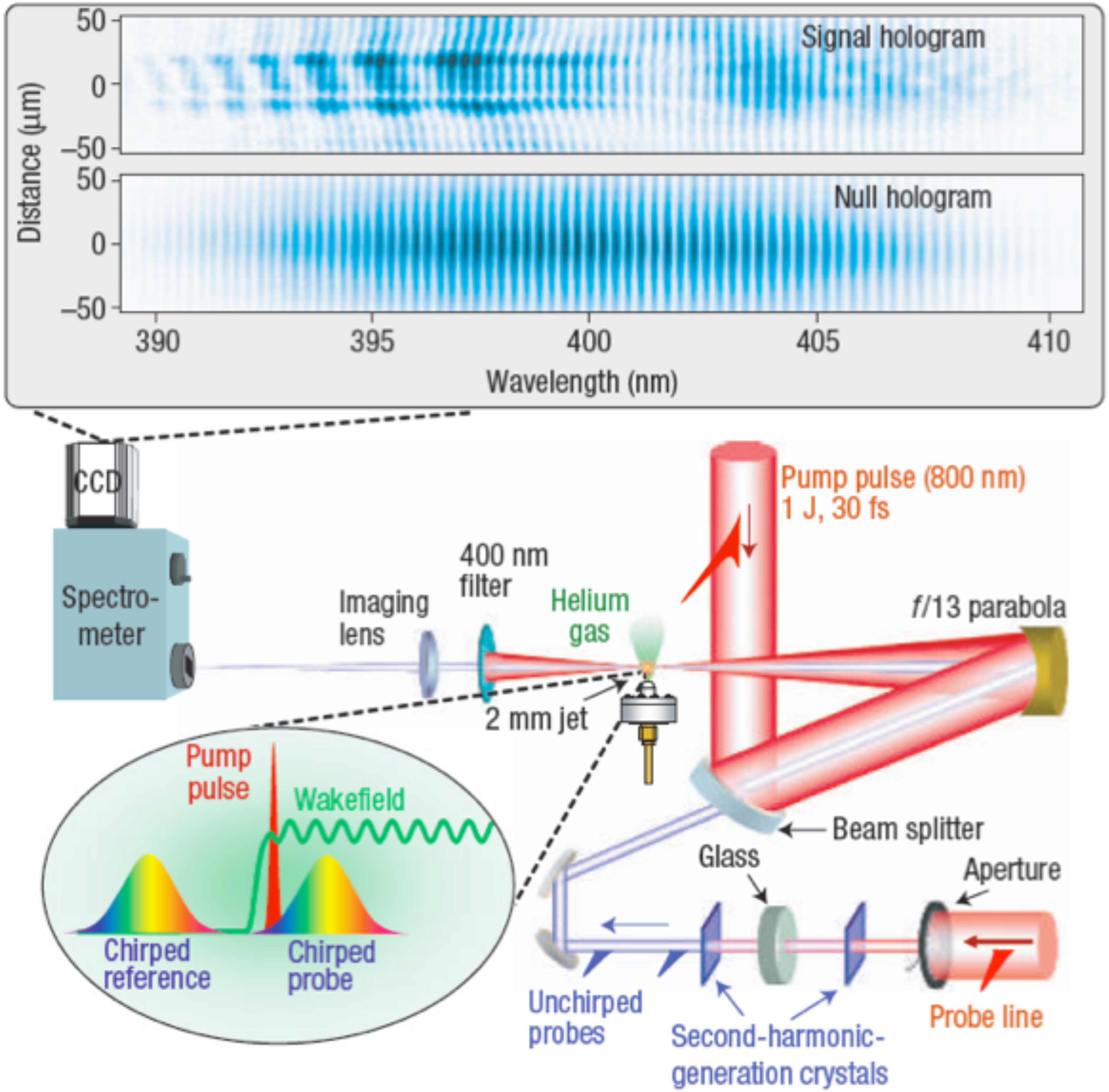
The laser wake field : broad resonance condition $\tau_{laser} \sim T_p/2$

my first swing experiments...

The laser wakefield

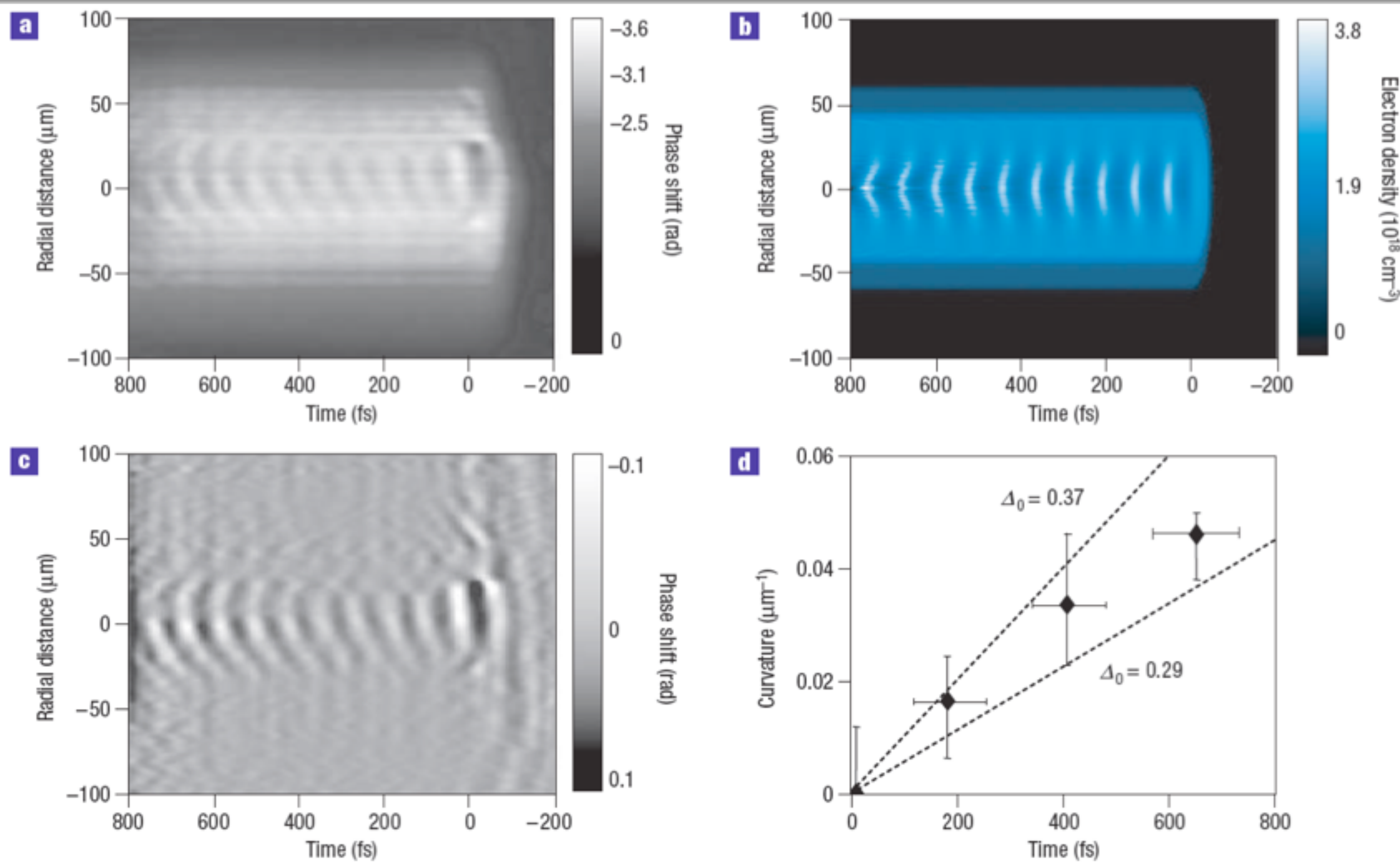


Snapshots of laser wakefield



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

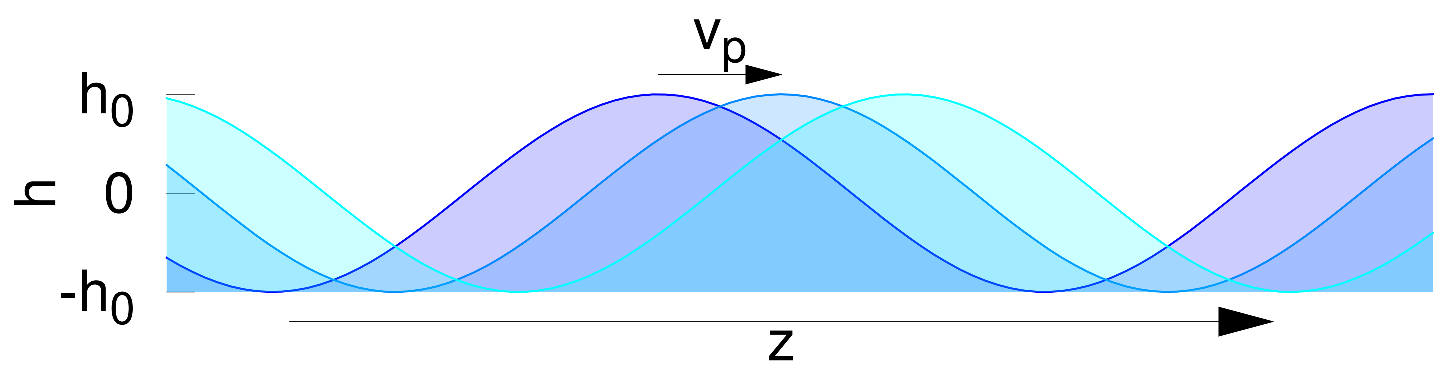
Snapshots of laser wakefield



Strongly driven wake with curve wavefronts. a) probe phase profile for 30 TW at 2.2×10^{19} cm^{-3}. b) simulated density profile. d) same than a) without n_e background.

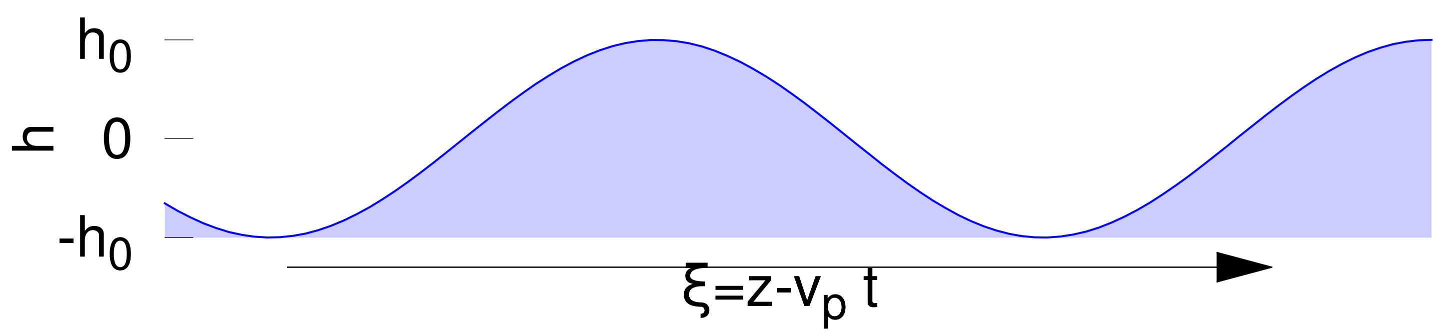
N. H. Matlis *et al.* , Nature Physics 2006

Trapping condition



in the terrestrial reference frame

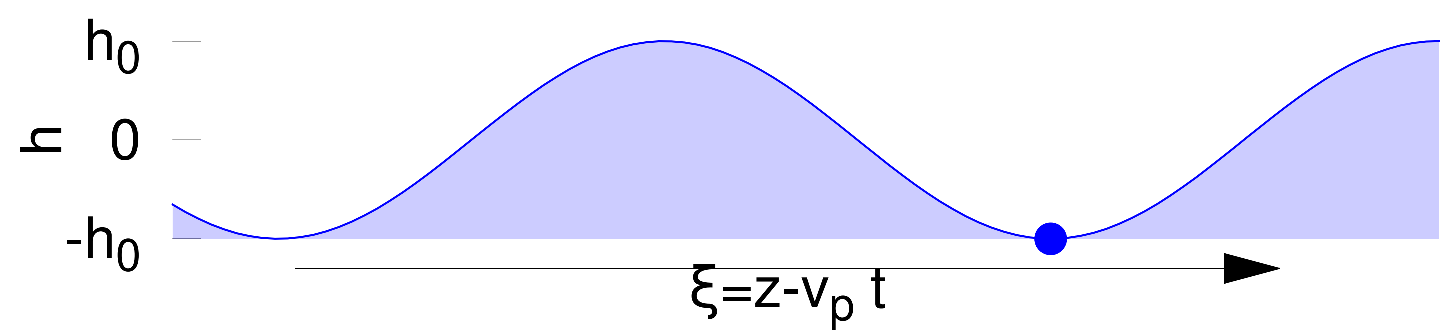
$h = h_0\cos(z - v_p t)$



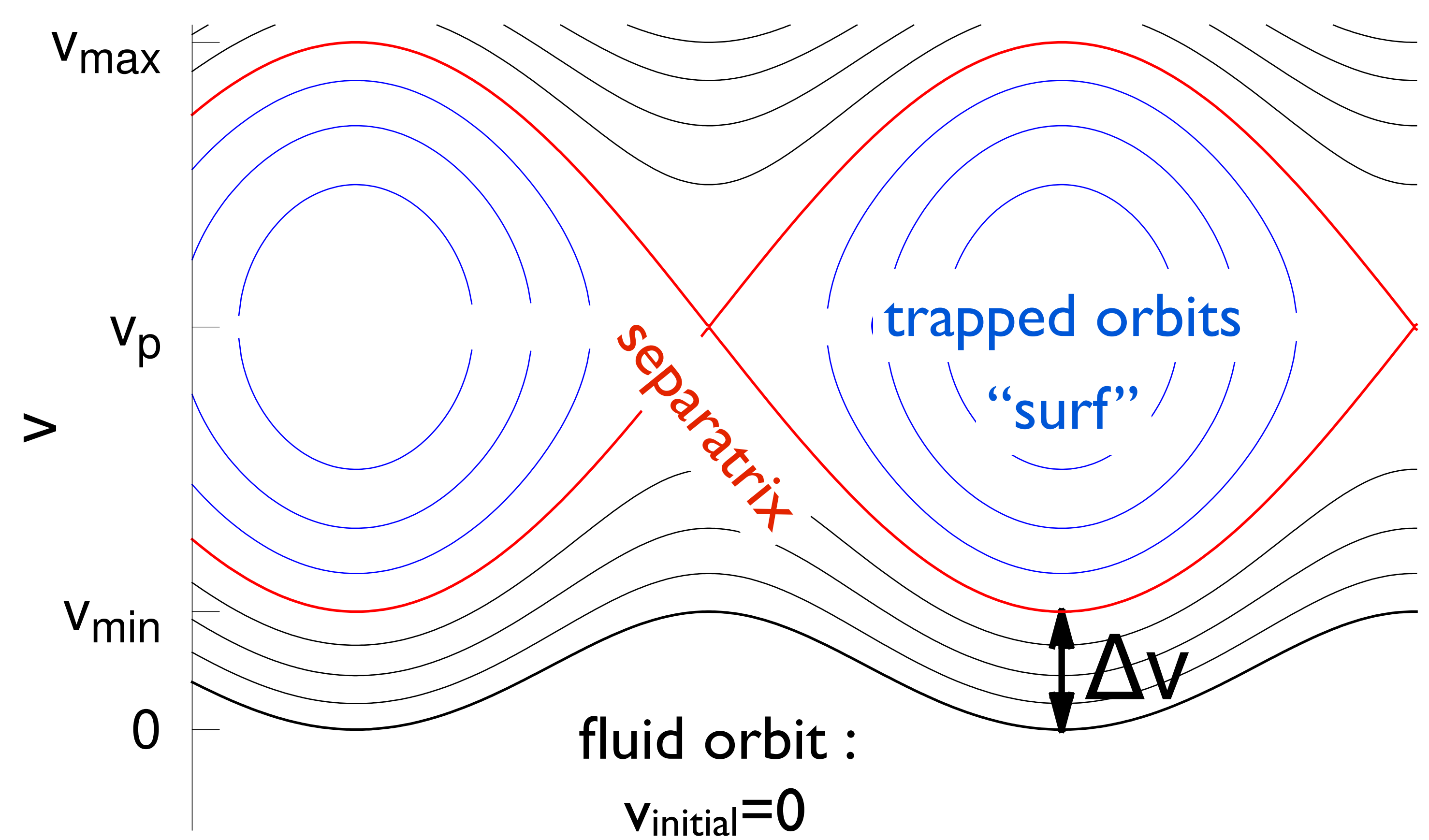
in the wawe reference frame

$h = h_0\cos(\xi)$

Trapping condition



phases space (ξ , $z-v_pt$)

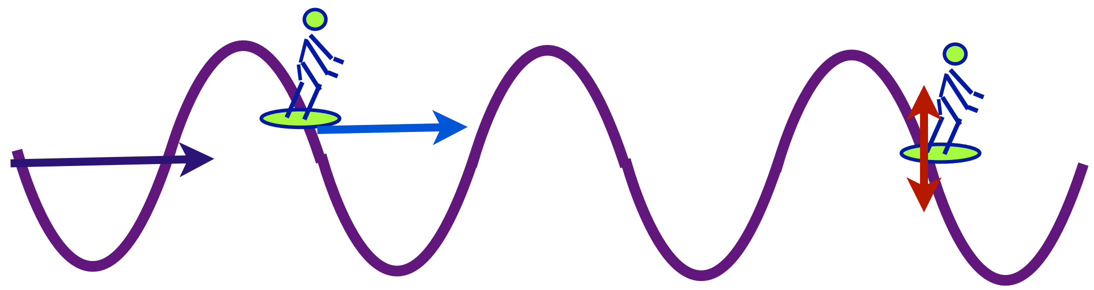


conclusions :

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

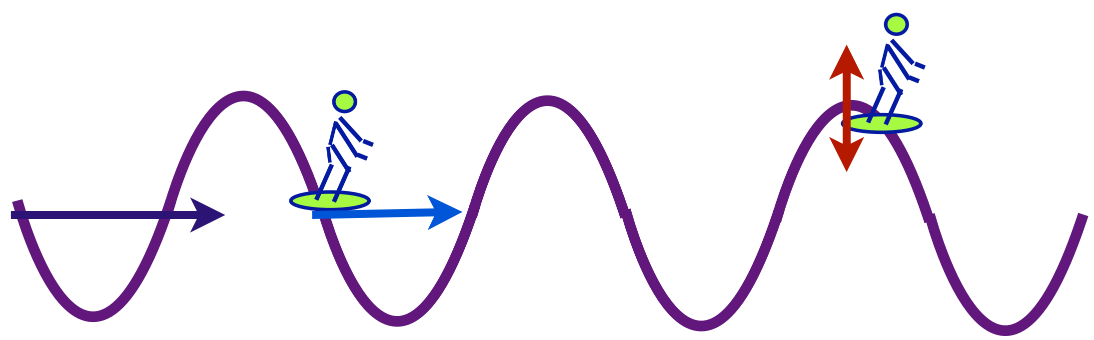
Trapping energy : analogy electron/surfer

surfer with enough initial velocity



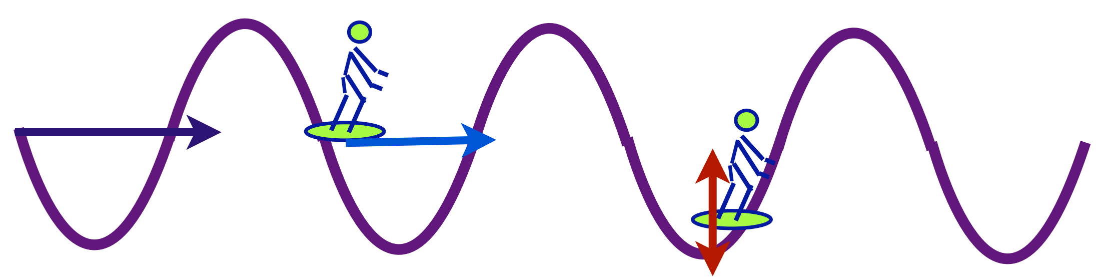
surfer initially at rest

surfer with enough initial velocity



surfer initially at rest

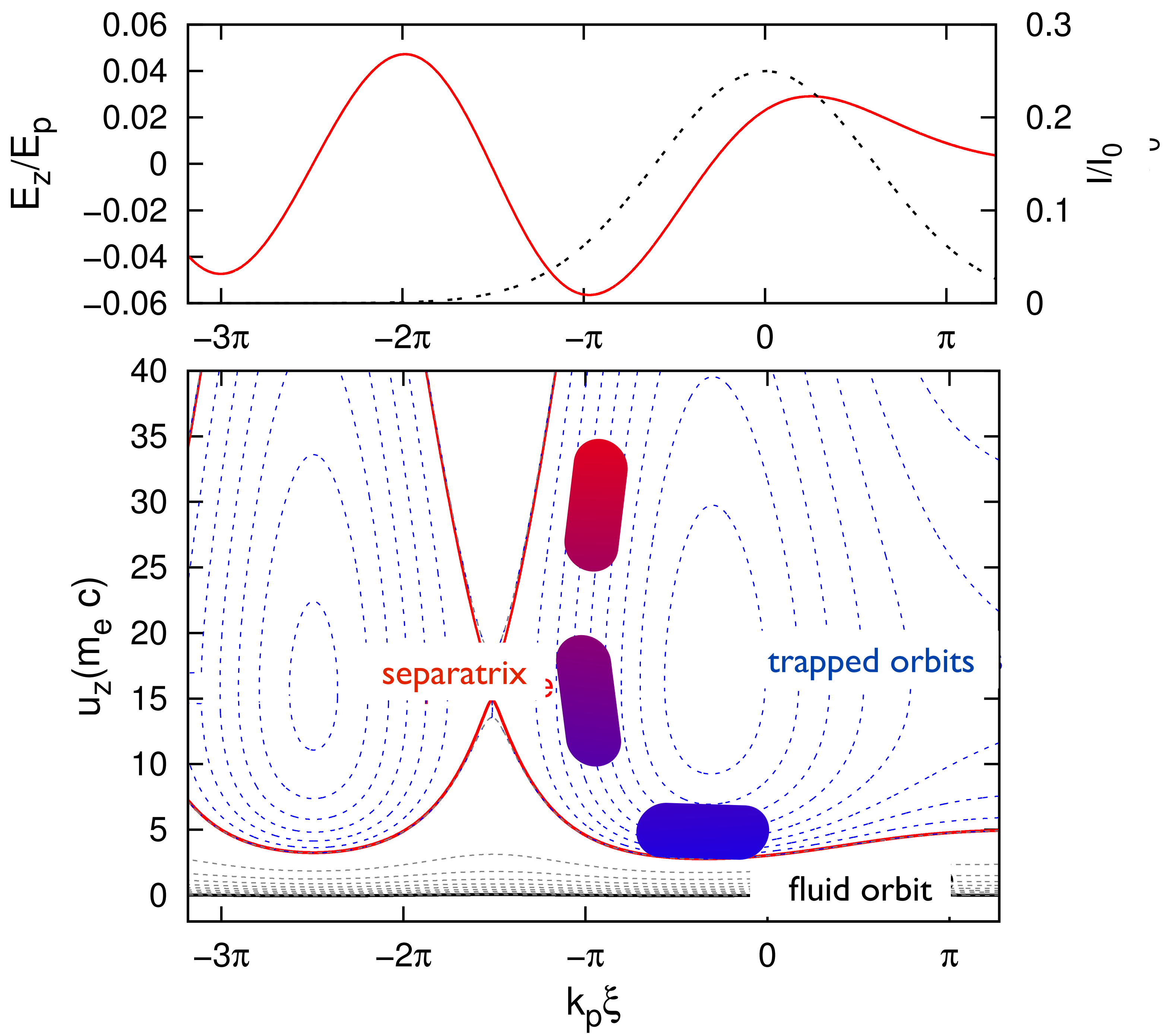
surfer with enough initial velocity



surfer initially at rest

Trapping energy : analogy electron/surfer

Trapping condition in relativistic plasma wave



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

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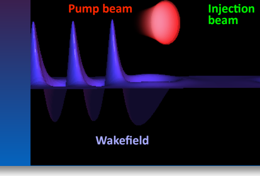

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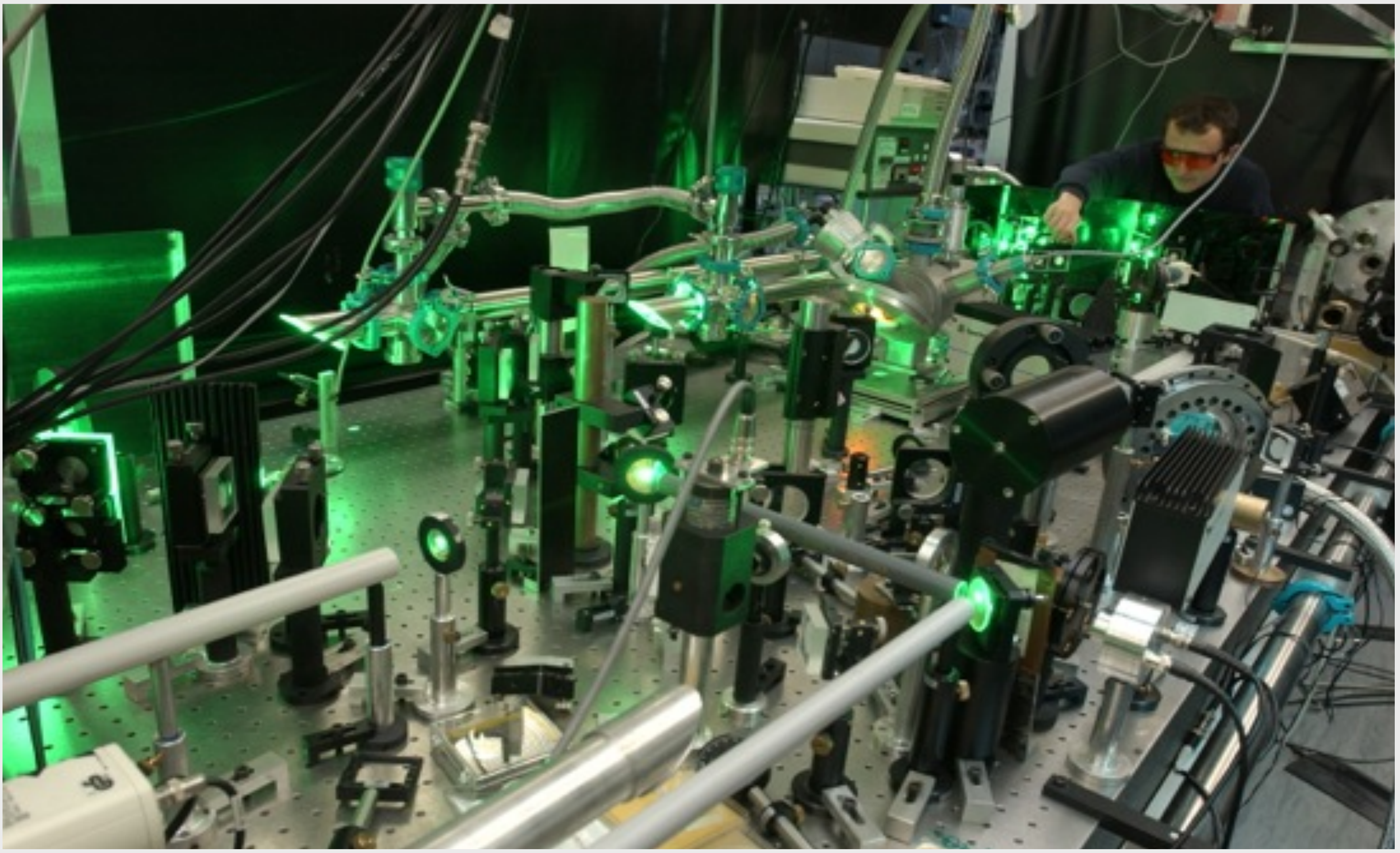
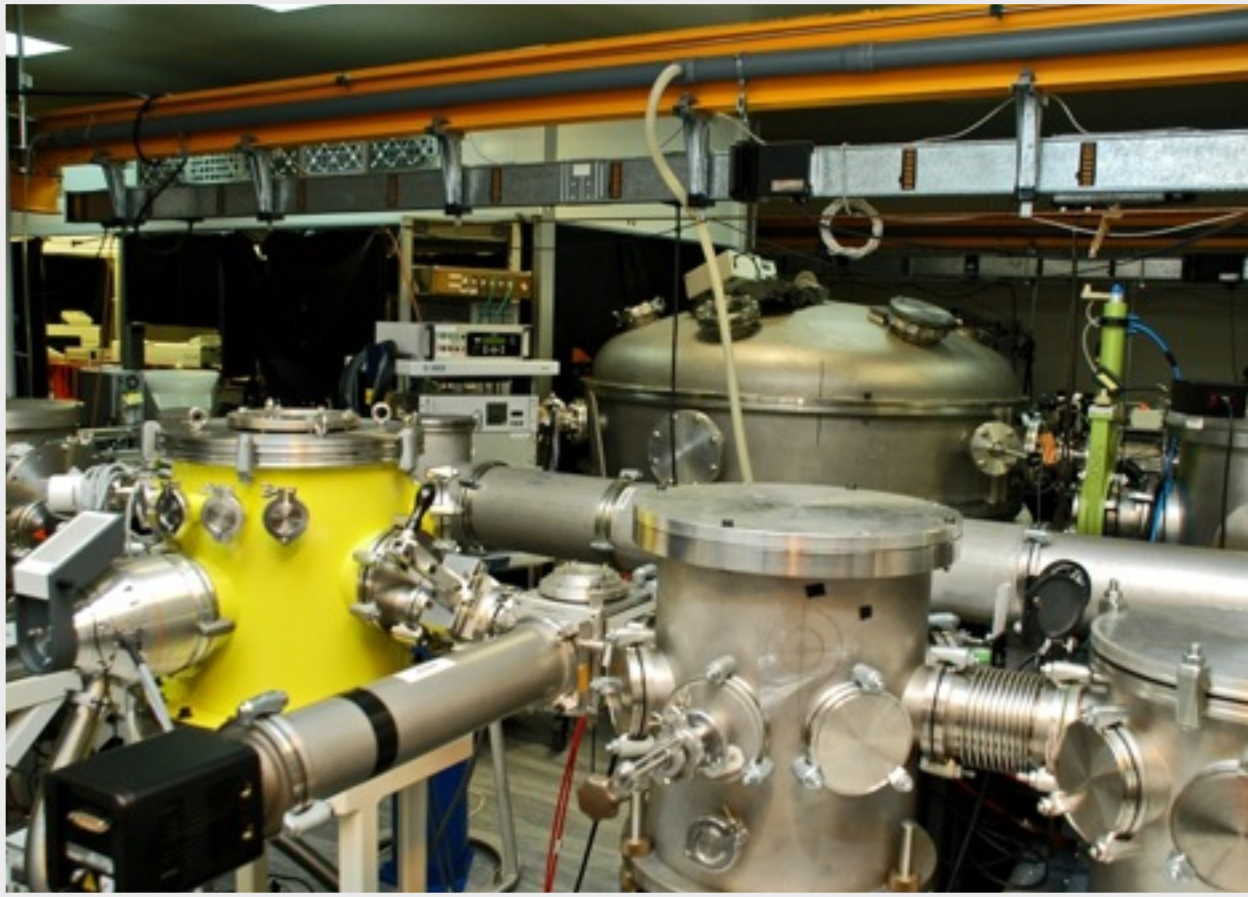
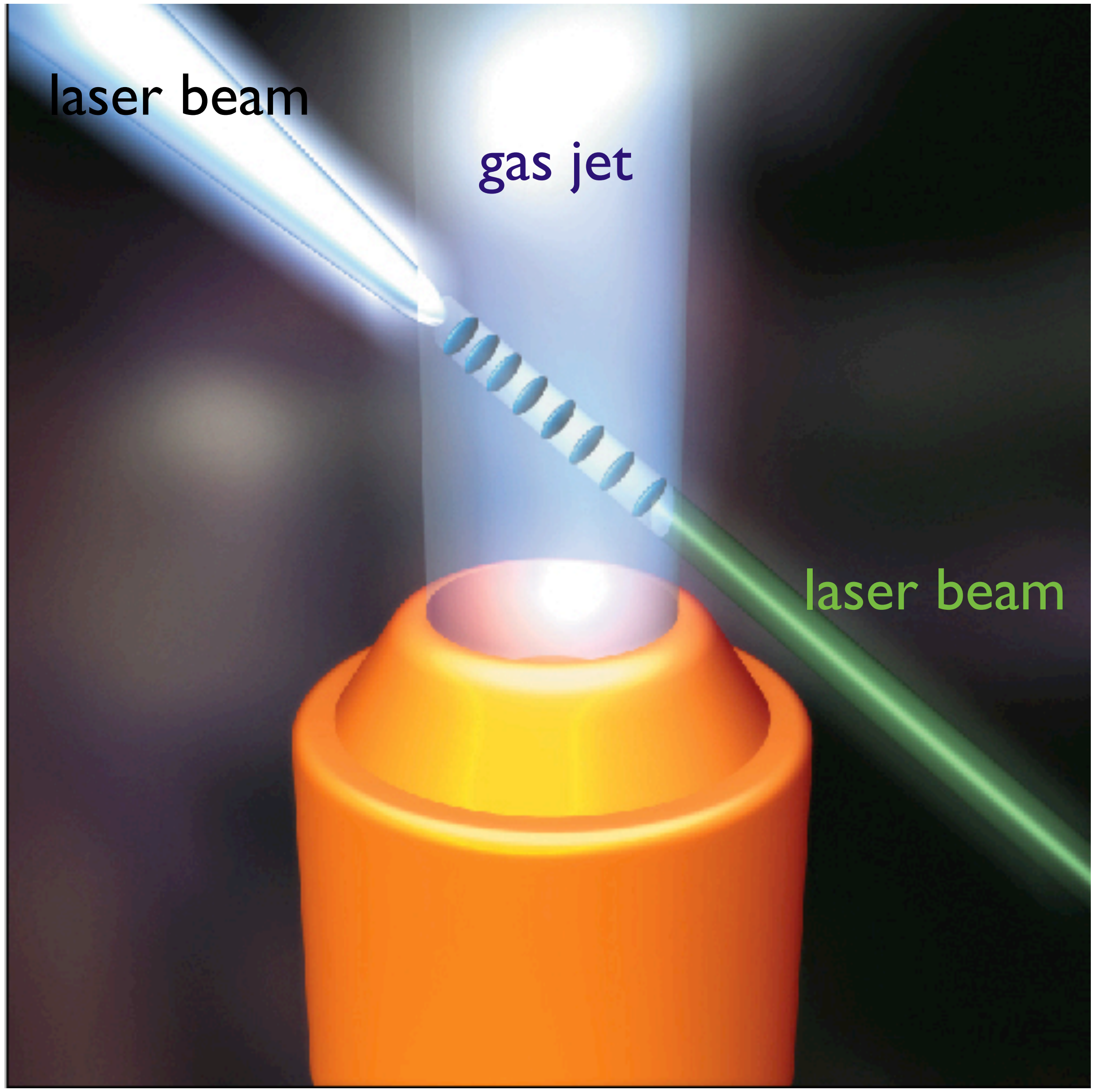
Laser "Salle Jaune"



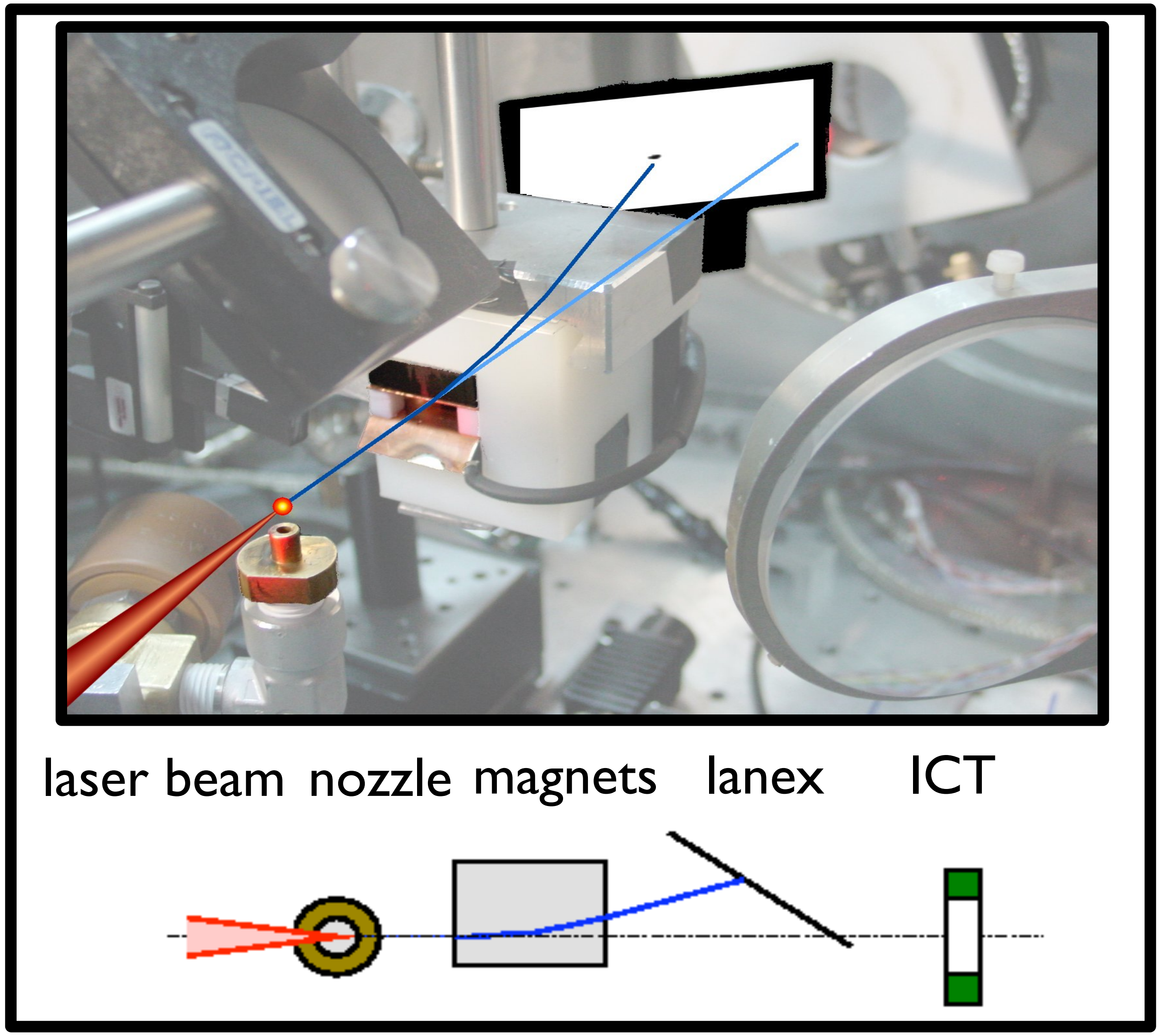


Ti:sapphire CPA laser
1.5 J / 30 fs - 10 Hz

The Bubble regime : experimental set-up

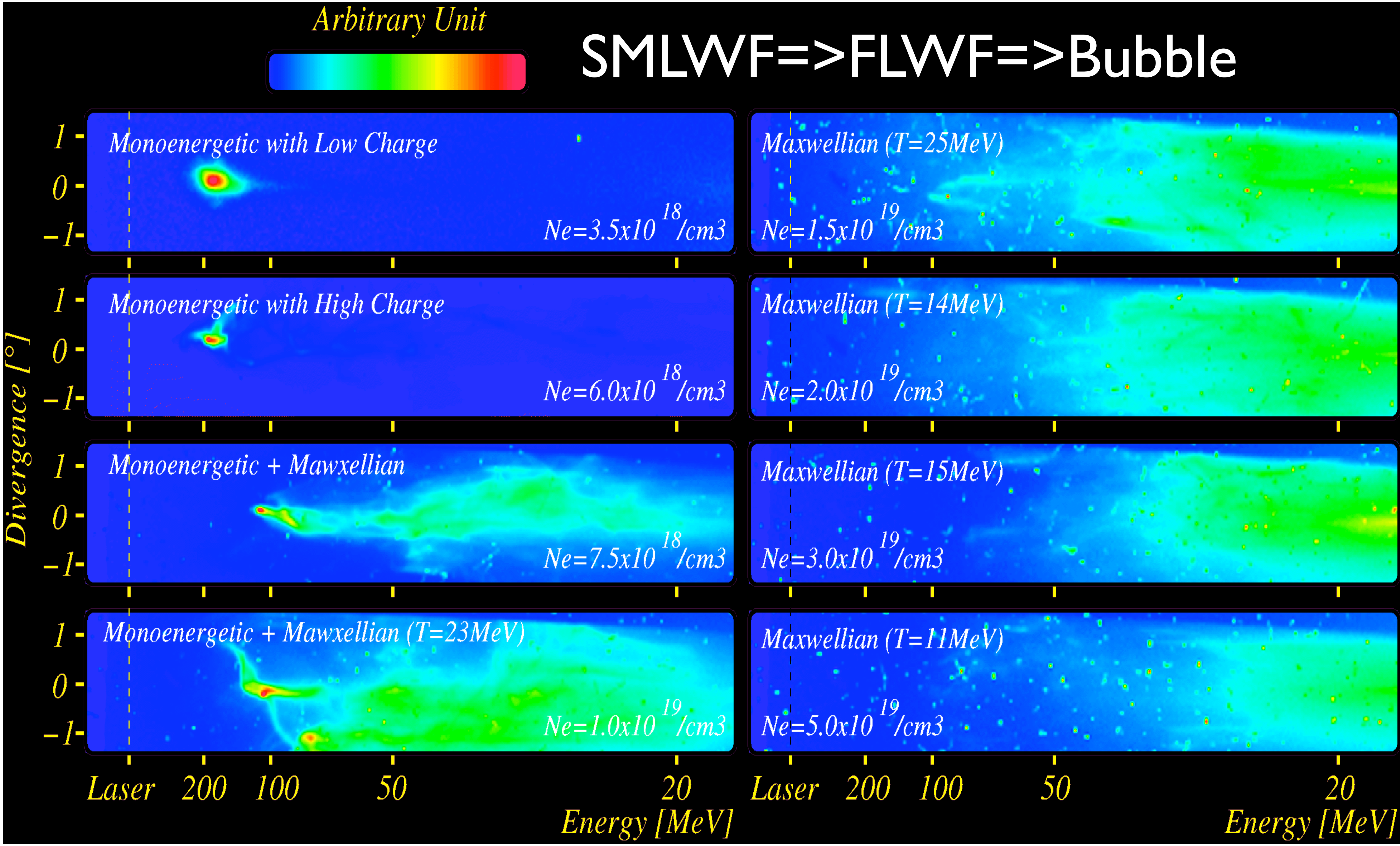


Scheme of principle



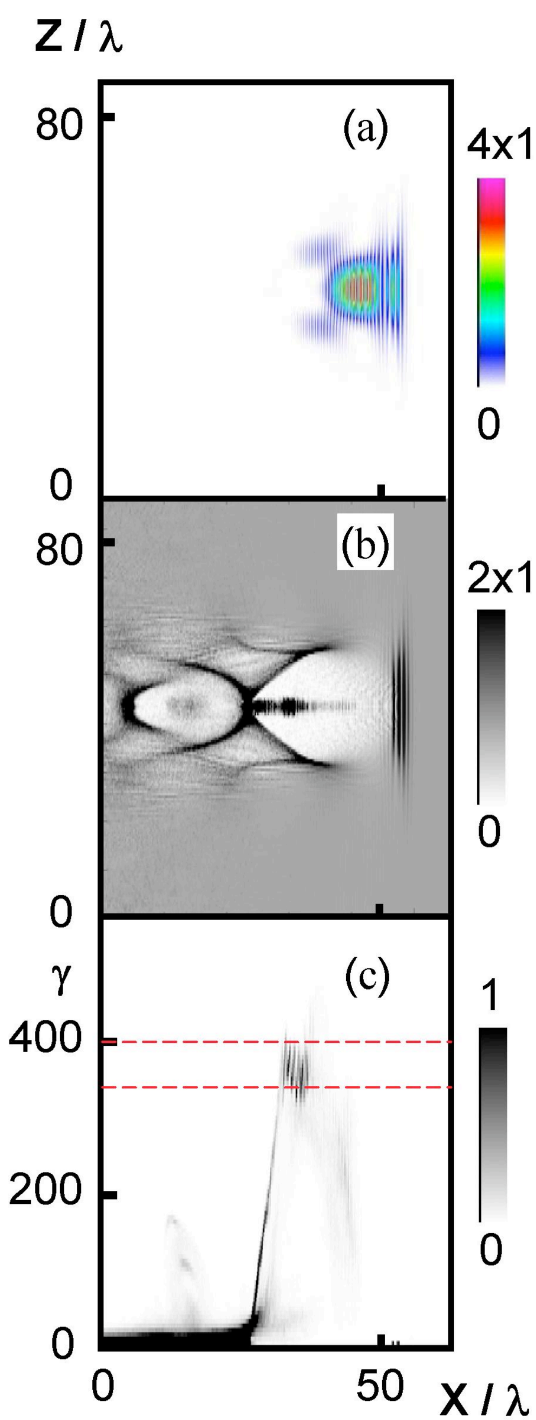
Experimental set up

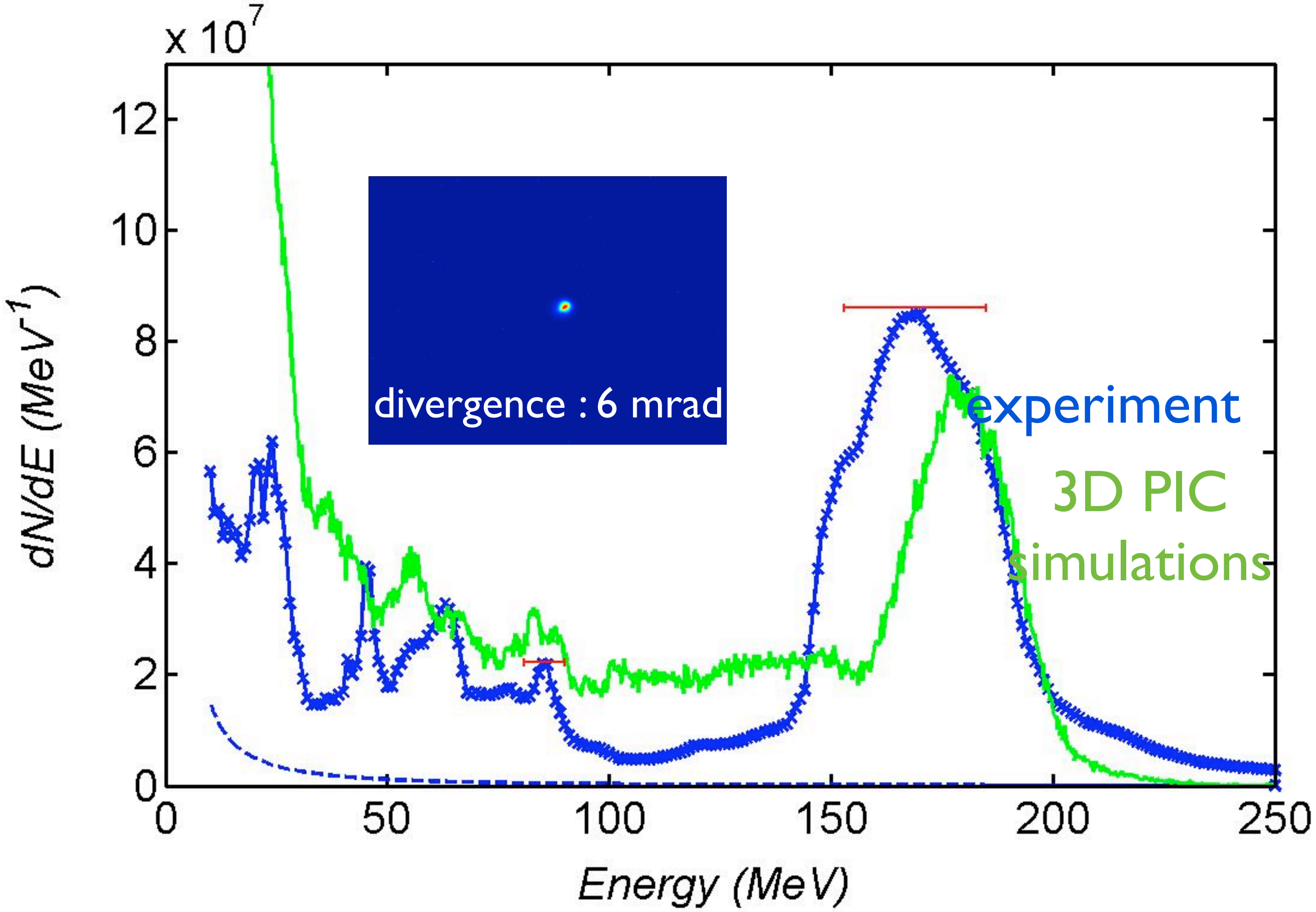
The Bubble regime : distribution quality improvements



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

The Bubble regime : theory/experiments

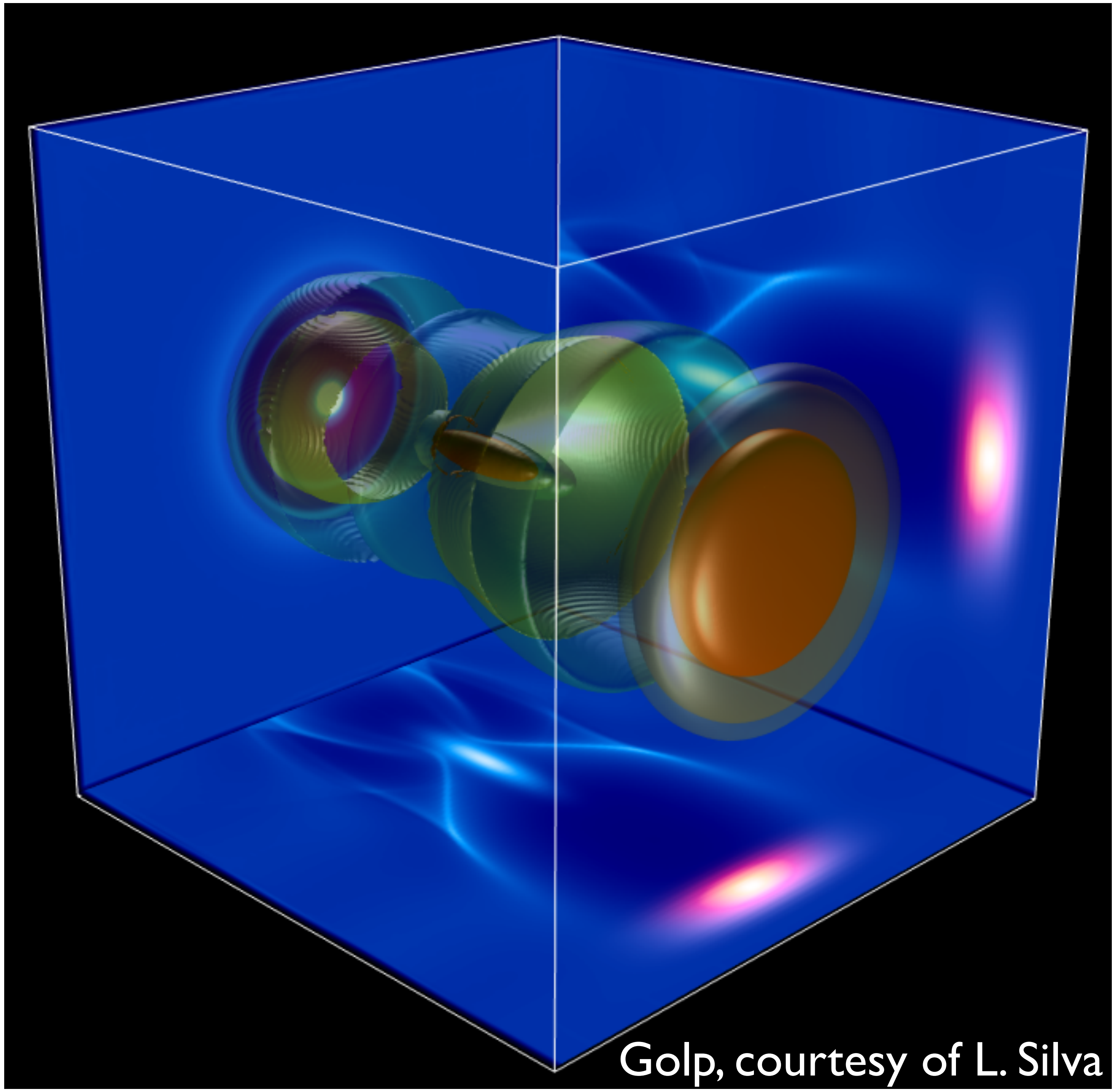




Experimental parameters : E=1J, τ_L=30fs,
λ_L=0.8µm, $I_L=3.2\times10^{19}$W/cm^2, $n_e=6\times10^{18}$cm^{-3}

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

The Bubble/Blow Out regime: Q.M.E. electron beam



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

The Dream Beam

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*

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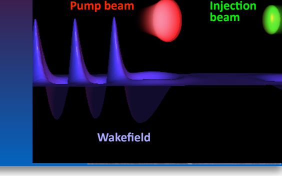
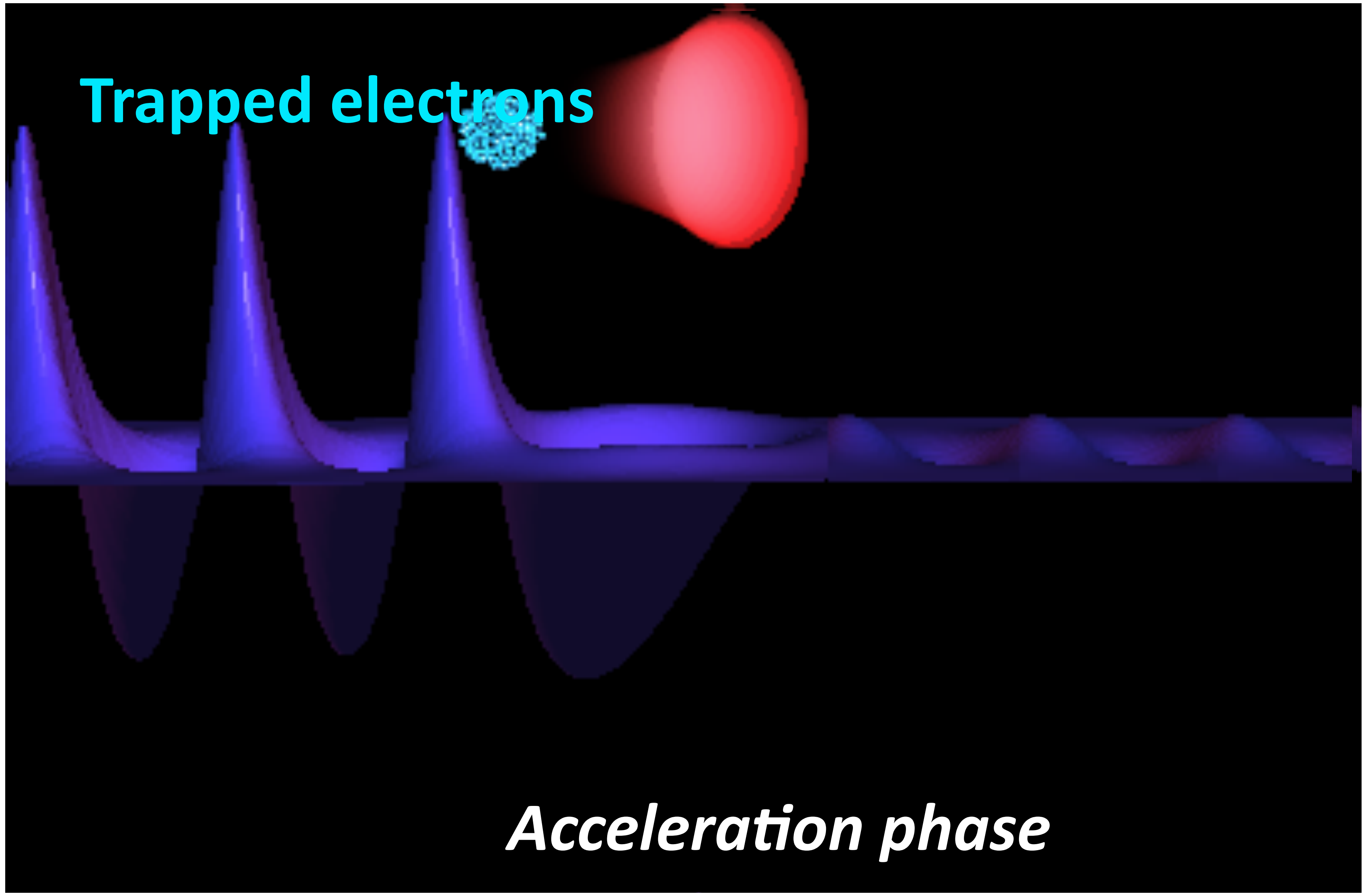
Colliding Laser Pulses Scheme



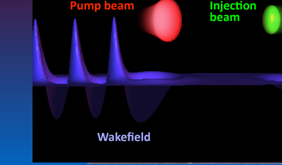
The first laser creates the accelerating structure
A second laser beam is used to heat electrons

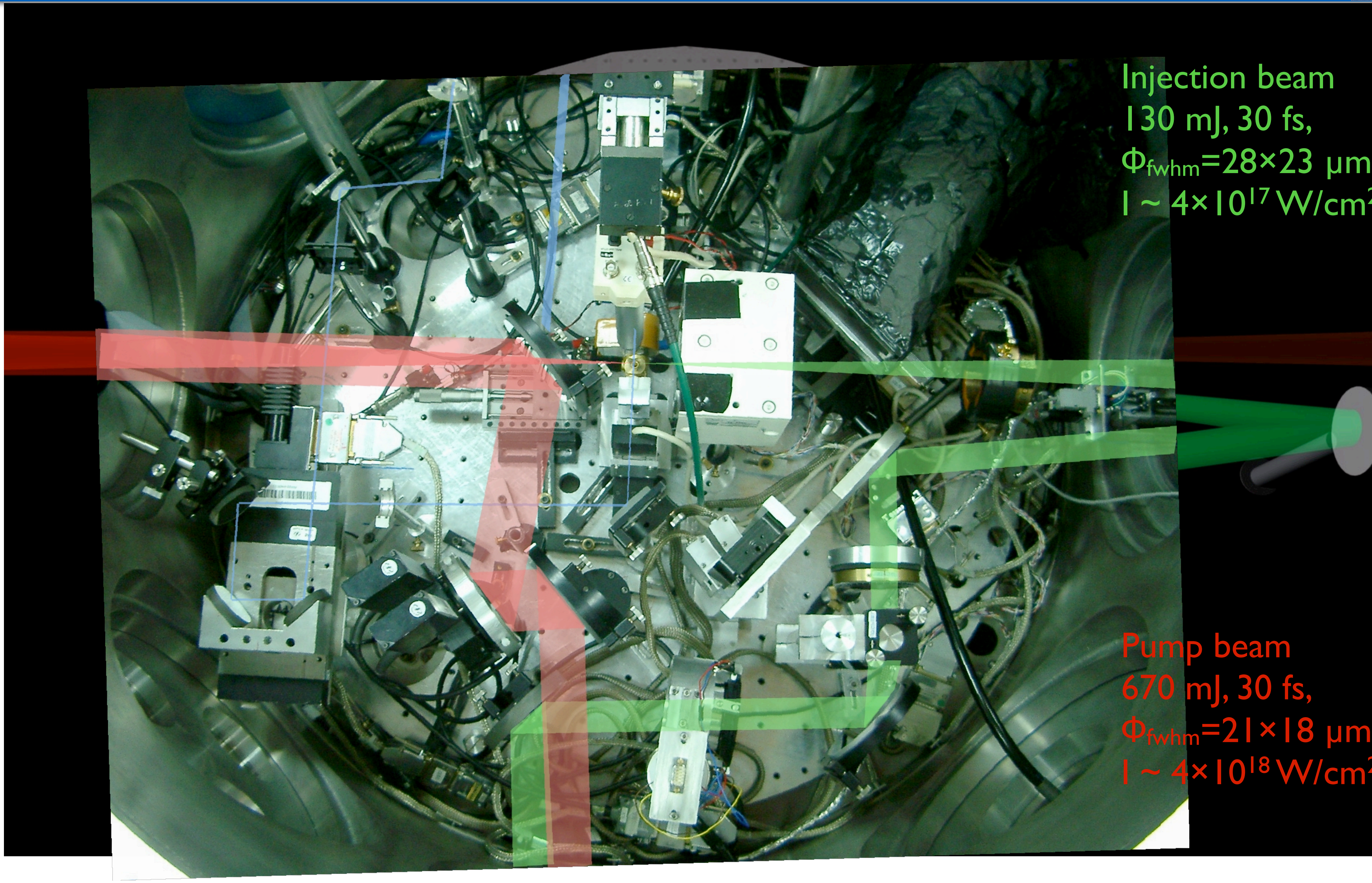


Ponderomotive force of beatwave: $F_p \sim 2a_0a_1/\lambda_0$ (a_0 et a_1 can be "weak")
Boost electrons locally and injects them INJECTION IS LOCAL and IN FIRST BUCKET

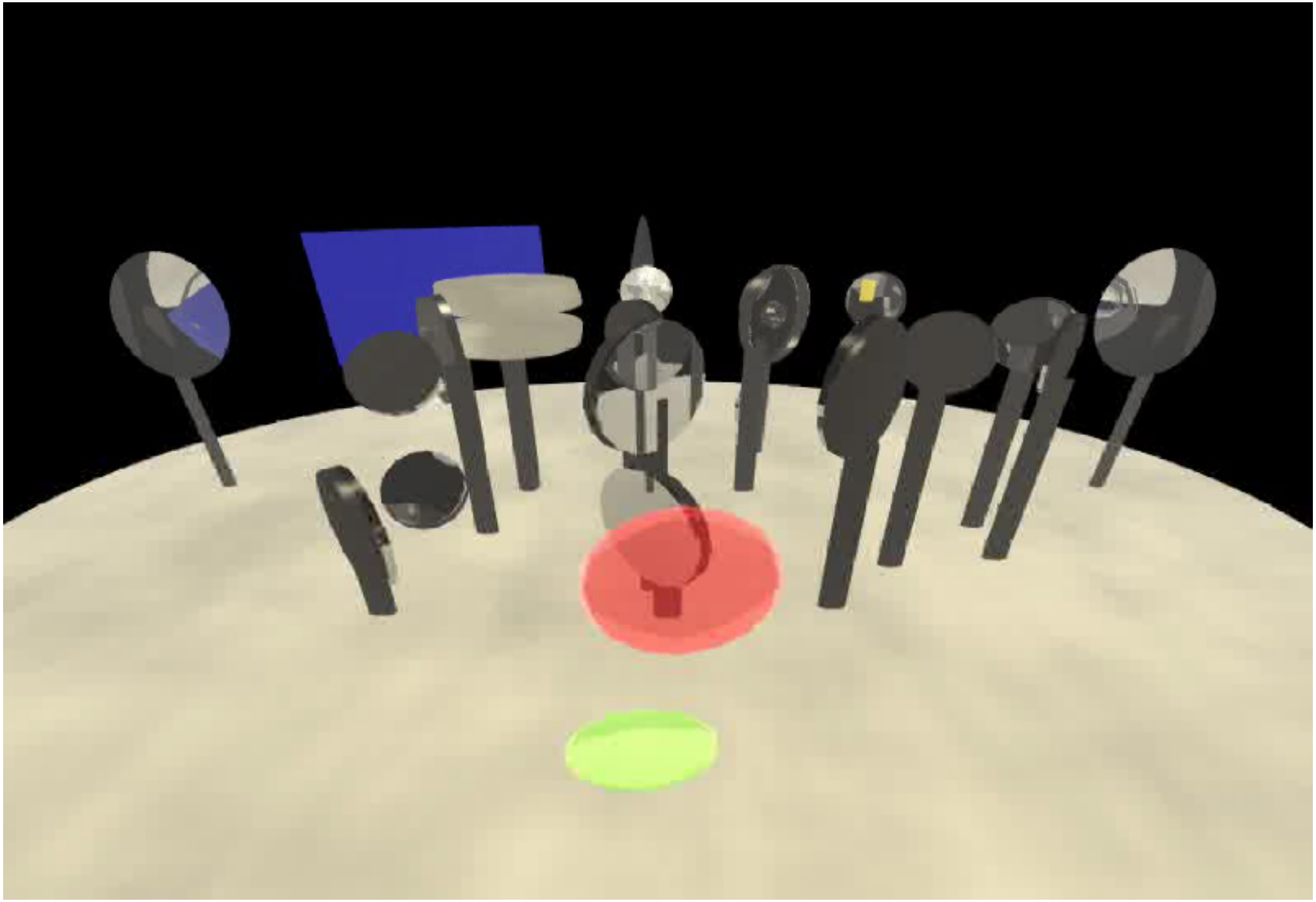
Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Set-up for colliding pulses experiment

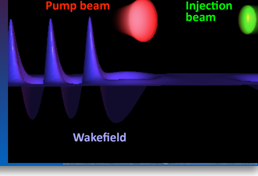




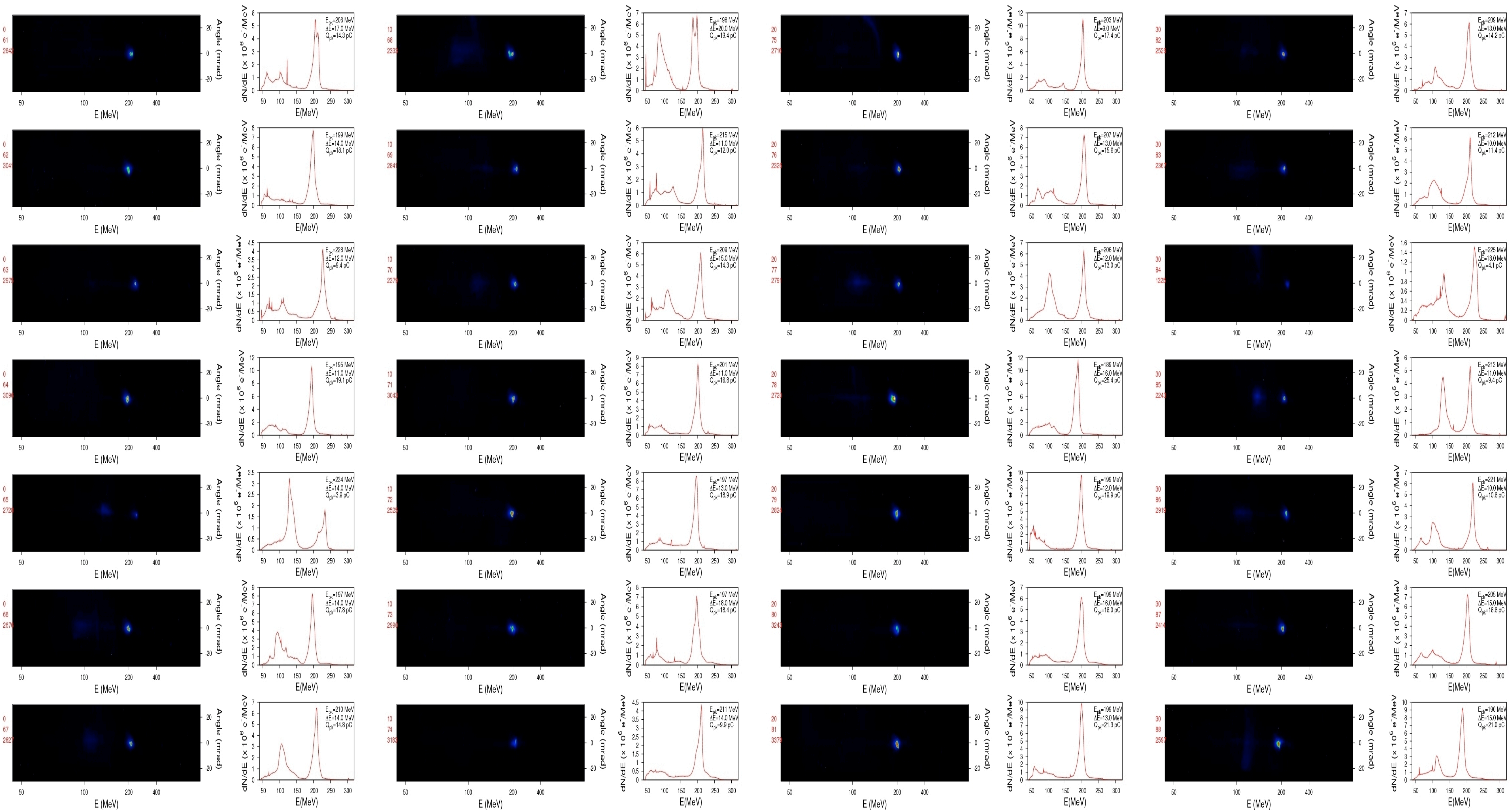
The colliding of two laser pulses scheme



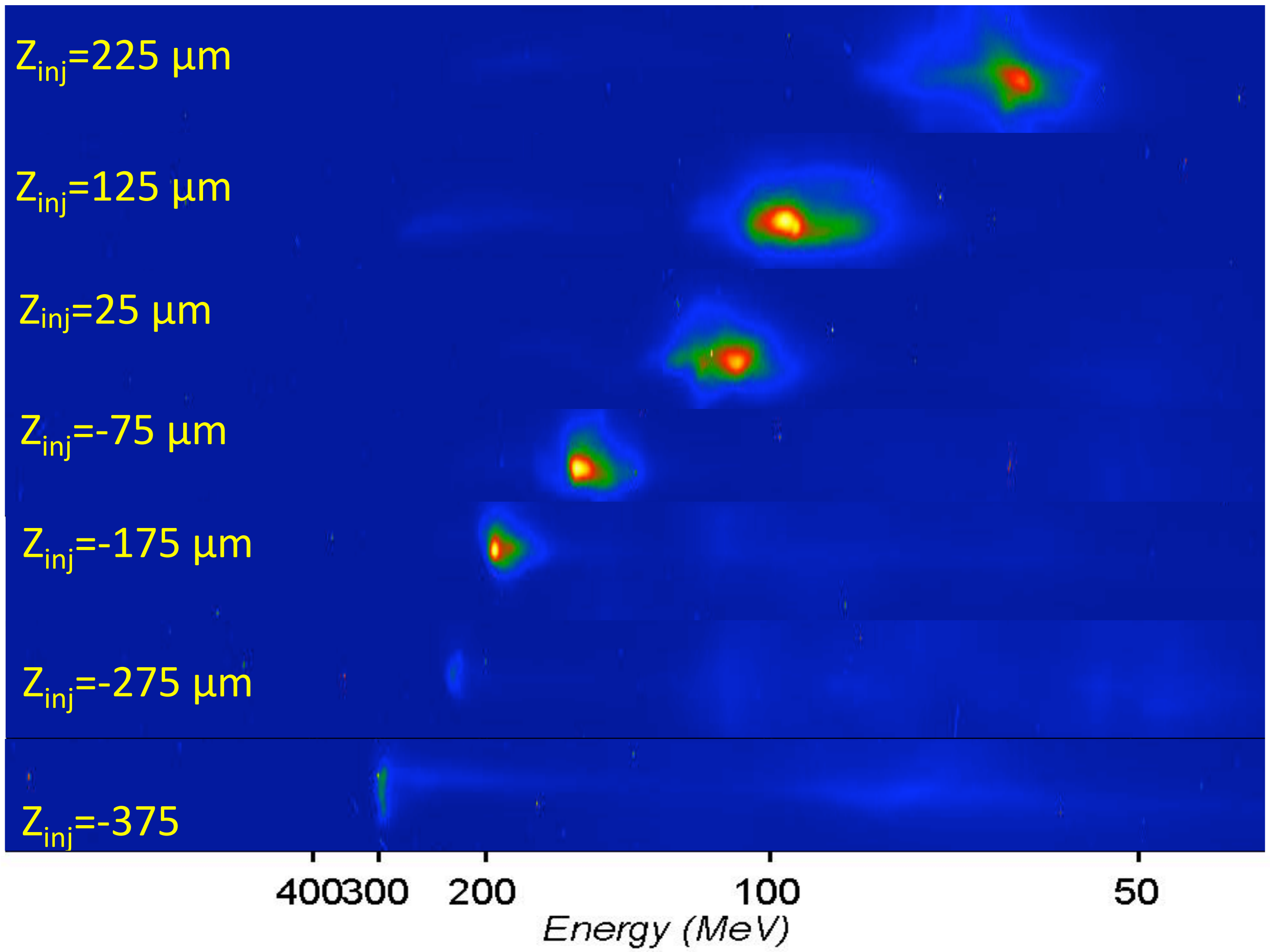
Towards a Stable Laser Plasma Accelerators

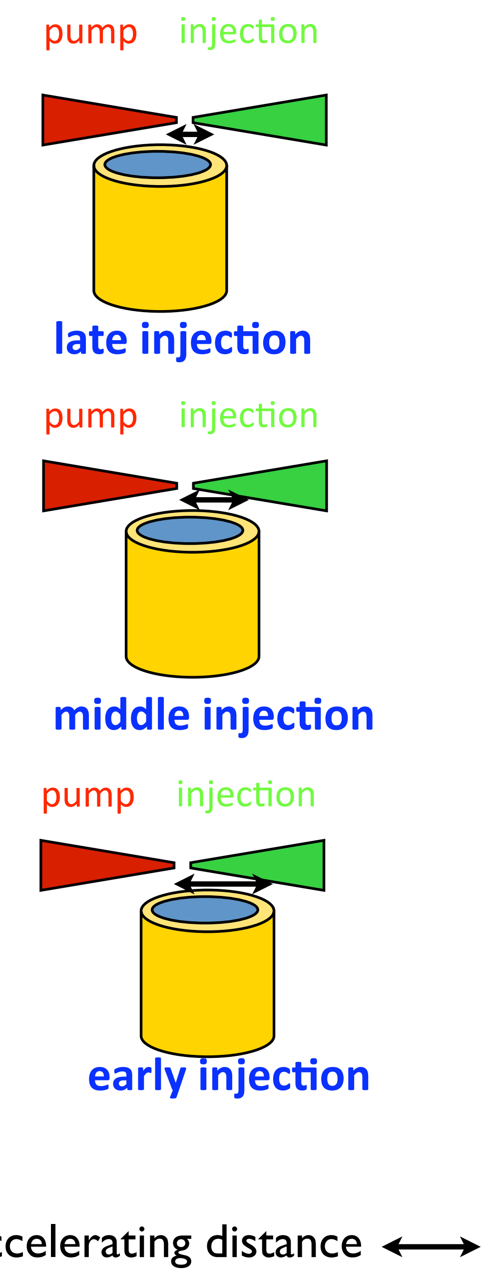


Series of 28 consecutive shots with : $a_0=1.5$, $a_1=0.4$, $n_e=5.7\times10^{18}cm^{-3}$



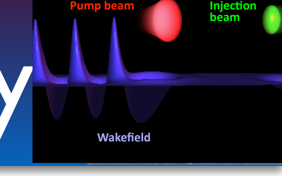
Tunability of Laser Plasma Accelerators : electrons energy

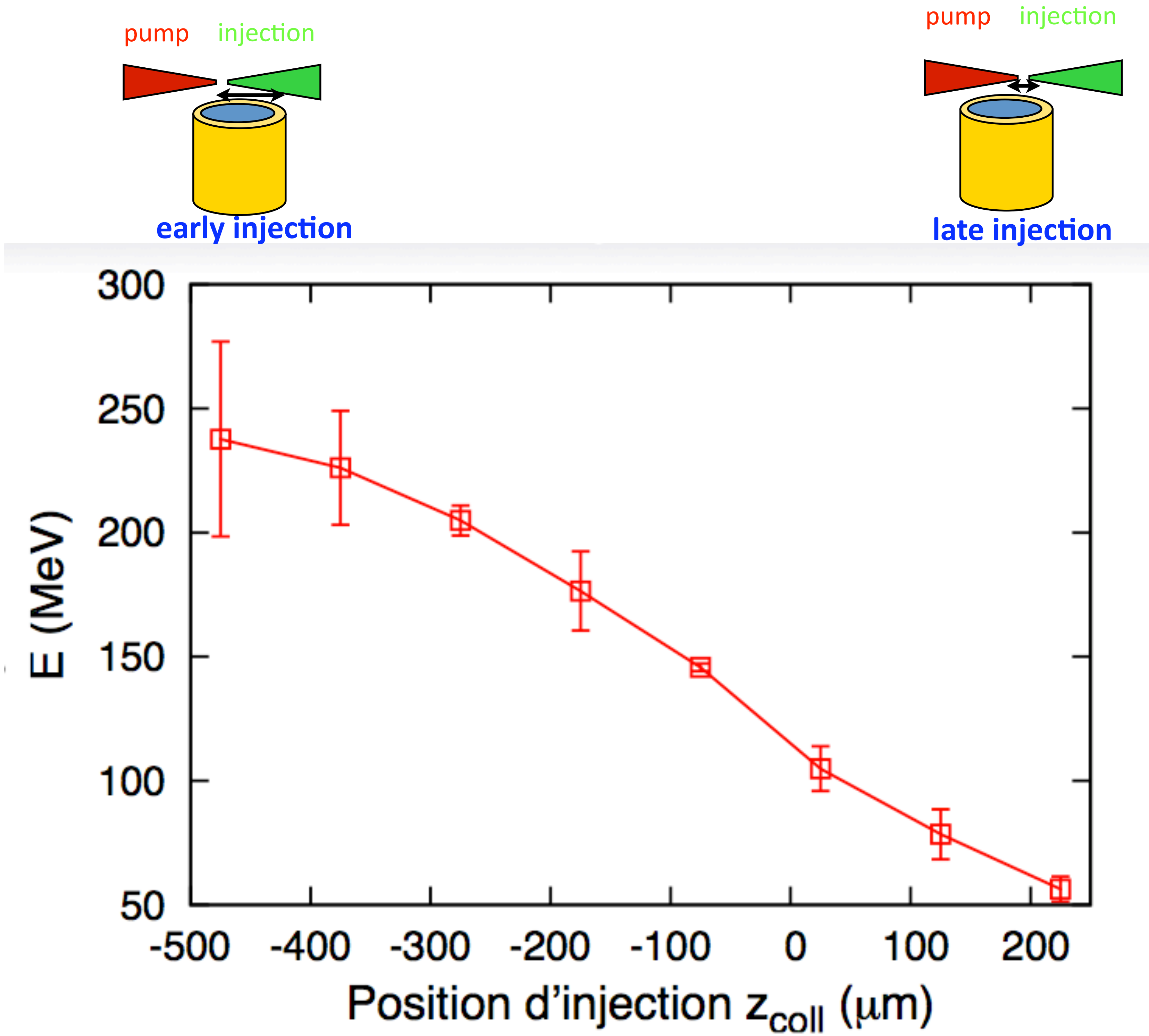




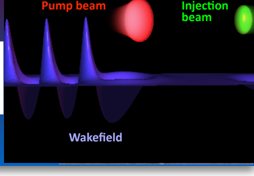
J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons energy

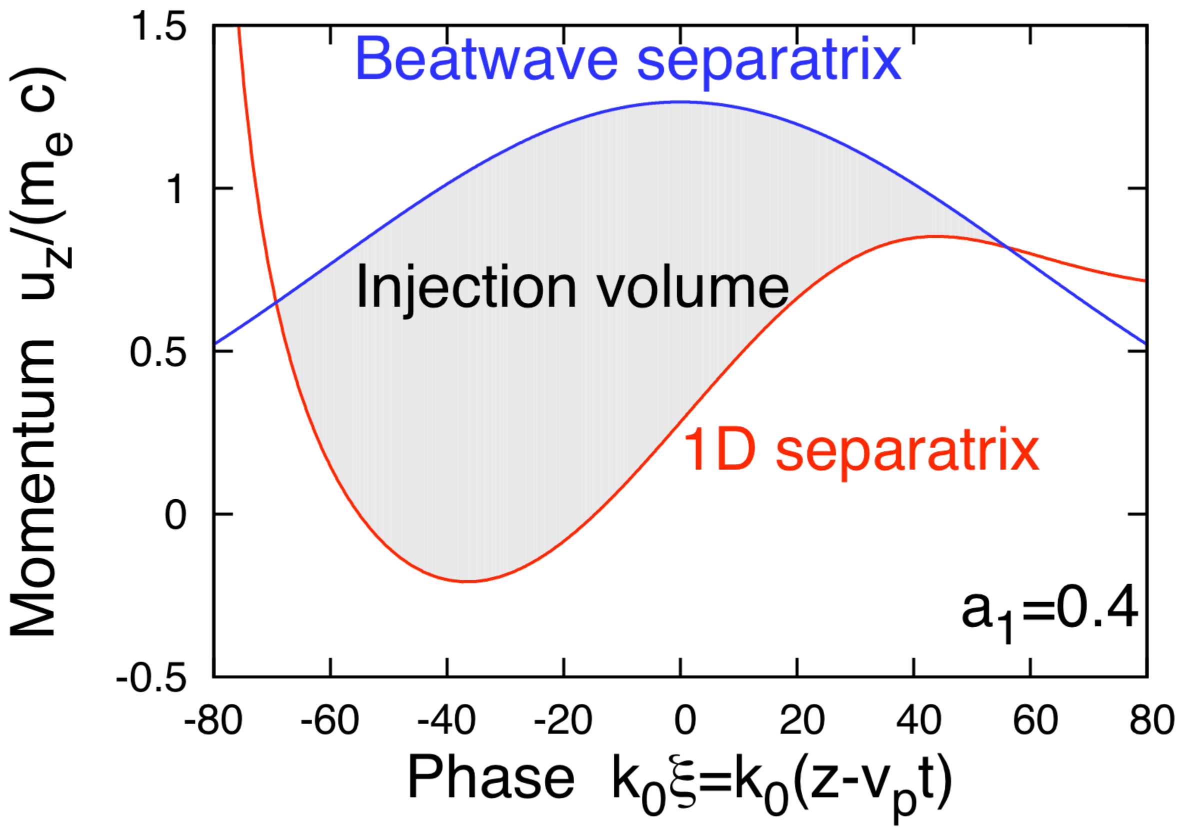


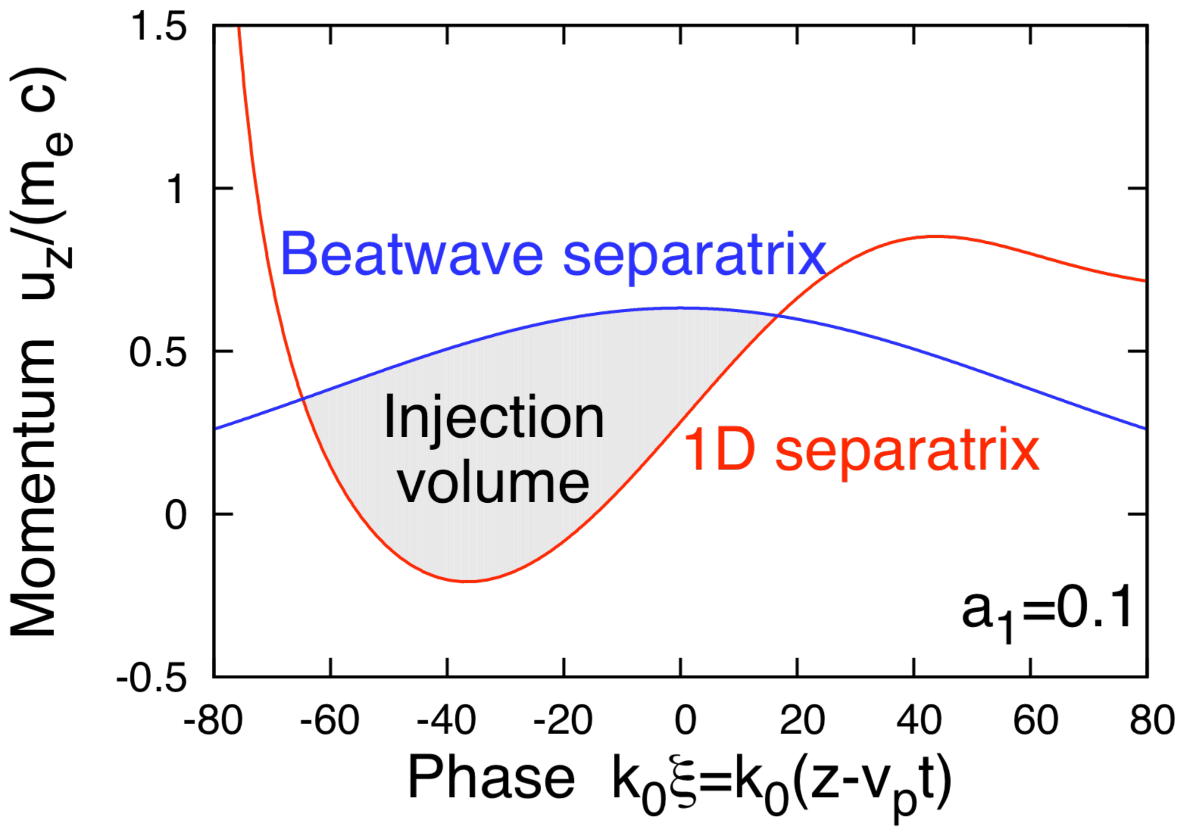


Tunability of Plasma Accelerators: charge & energy spread



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 λ_p)

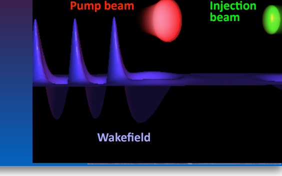


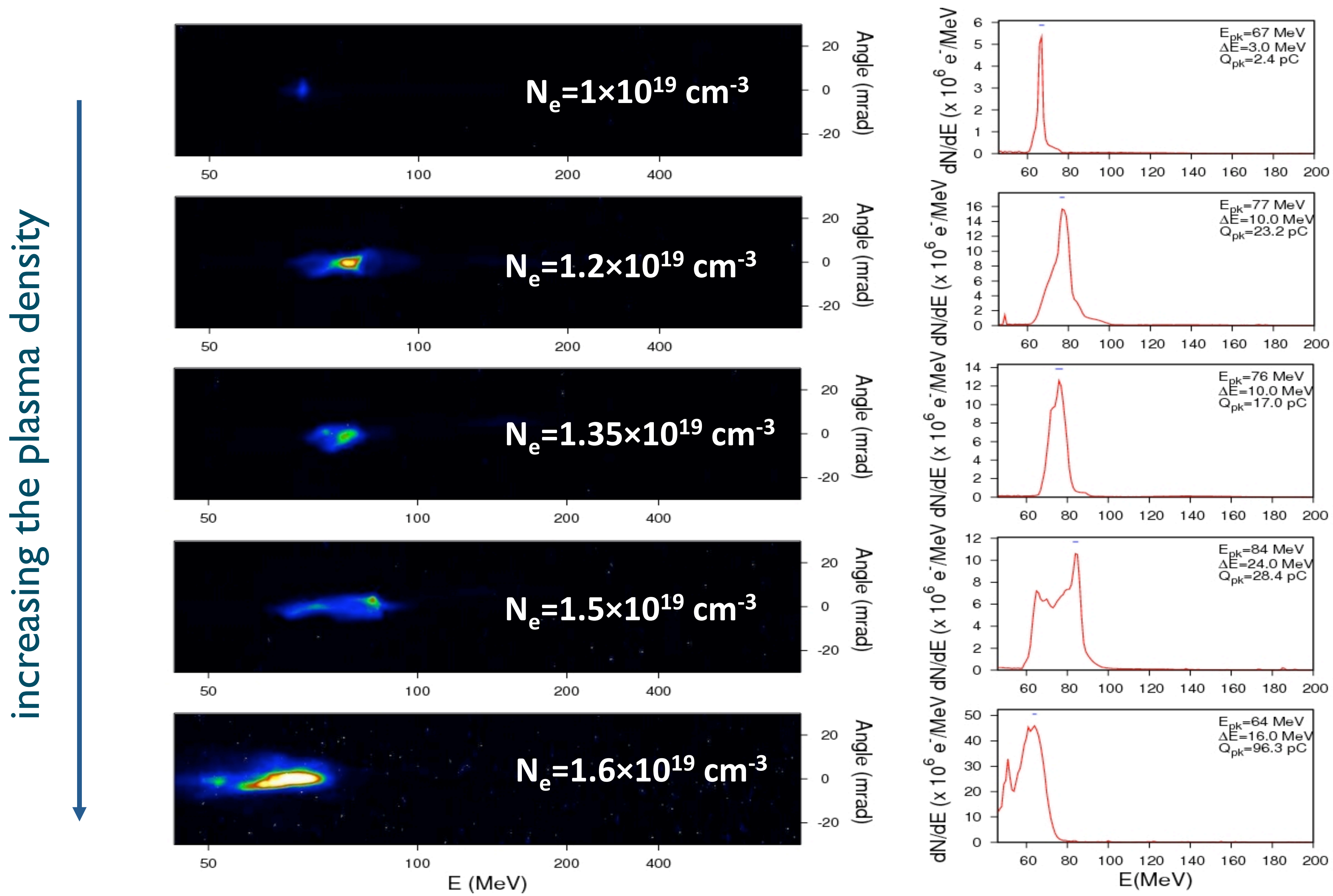


Evolution of injection volume with a_1 for $a_0 = 2$, $n_e = 7\times10^{18}cm^{-3}$.
Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

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





E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

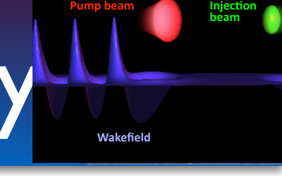
E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

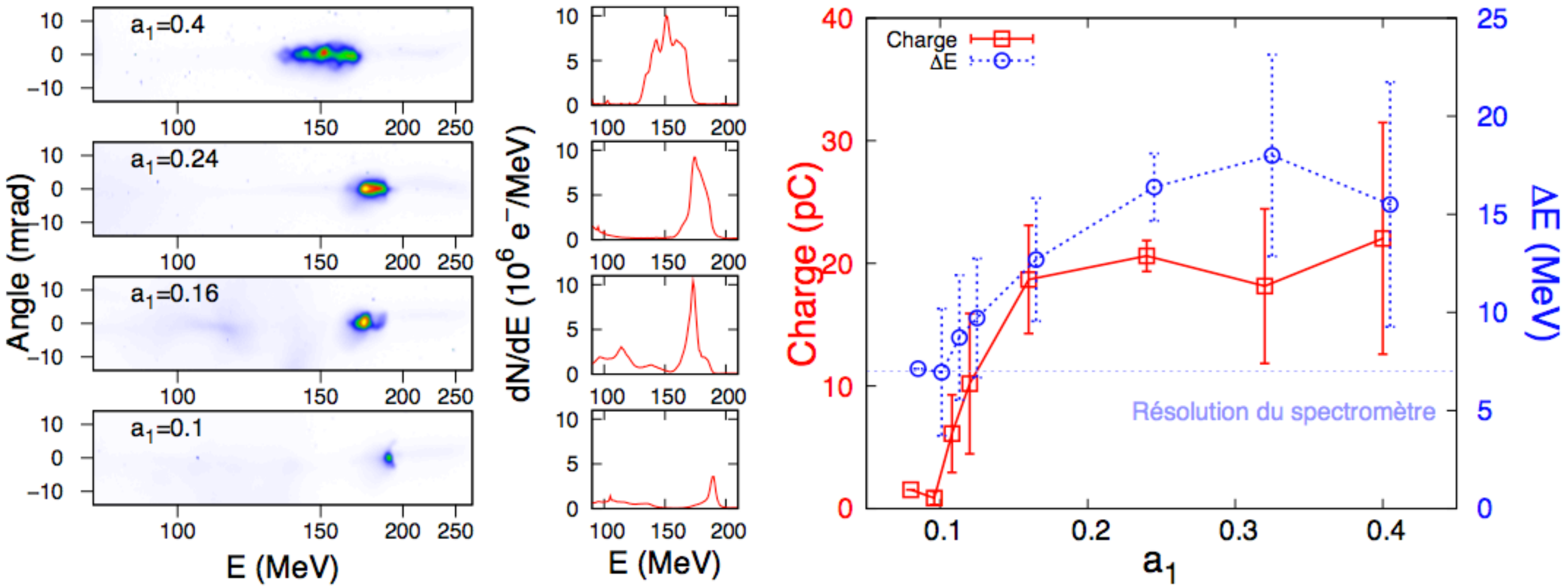
E=76 MeV
ΔE=10.0 MeV
Q_{pk}=17pC

E=84 MeV
ΔE=24 MeV
Q_{pk}=25.4pC

E=64 MeV
ΔE=16 MeV
Q_{pk}=96pC

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)

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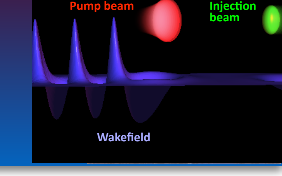

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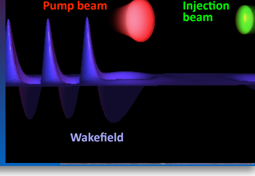
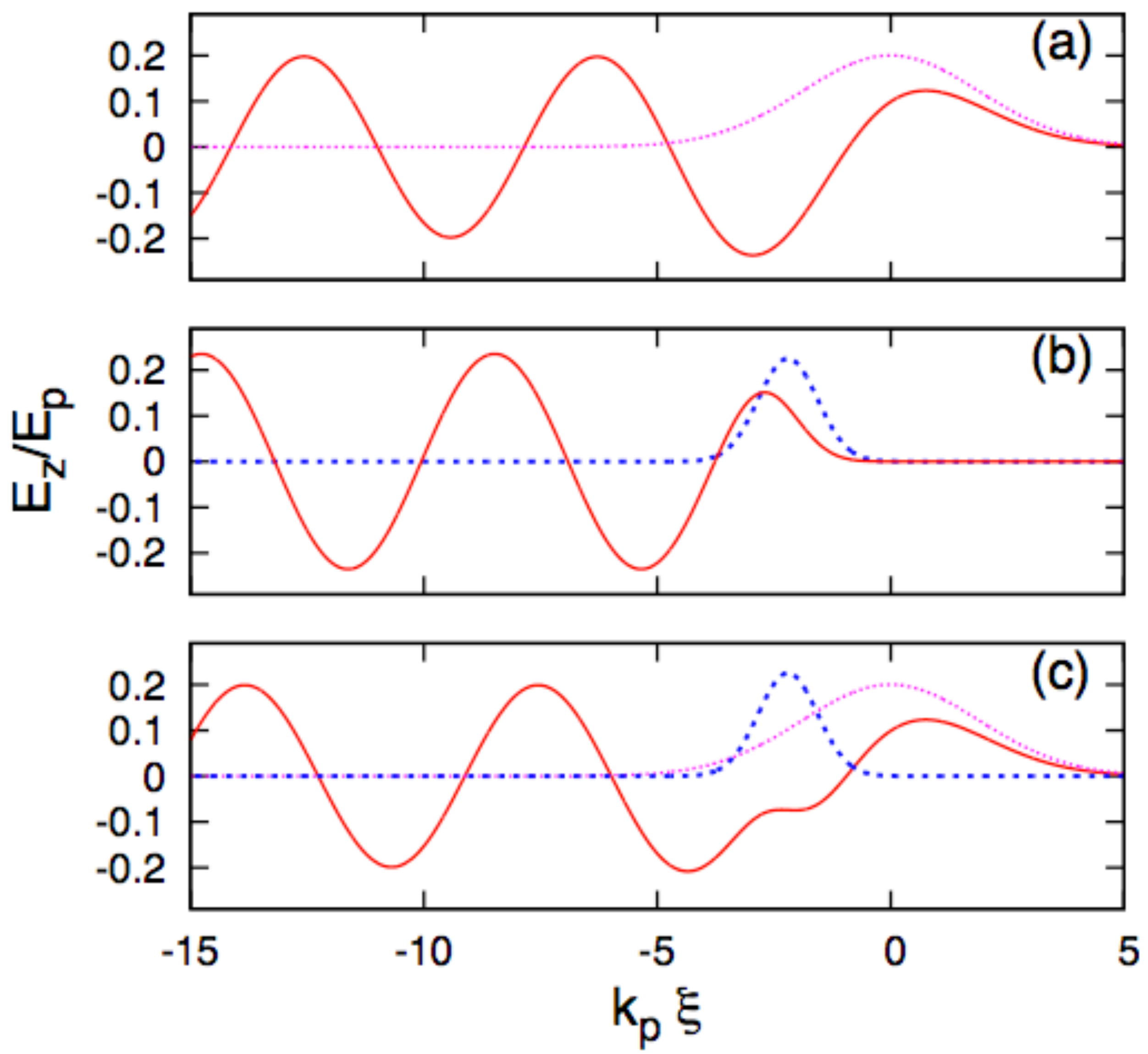
Electron beam dynamics in plasma waves : beam loading



Parameters: n_e=1.5 10^{19}cm^{-3},τ =35fs, E=0.6J, I=2 10^{18} W/cm^2



Laser wakefield
n_e=7 10^{18}cm^{-3},τ = 30fs, a_0 = 0.5

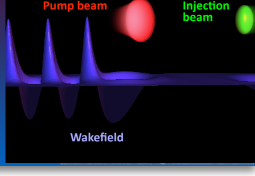
E-beam wakefield
n_b/n_e=0.11, τ = 10fs, d_{FWHM}=4μm (Q=7pC)
The end of the bunch experiments a modified wakefield

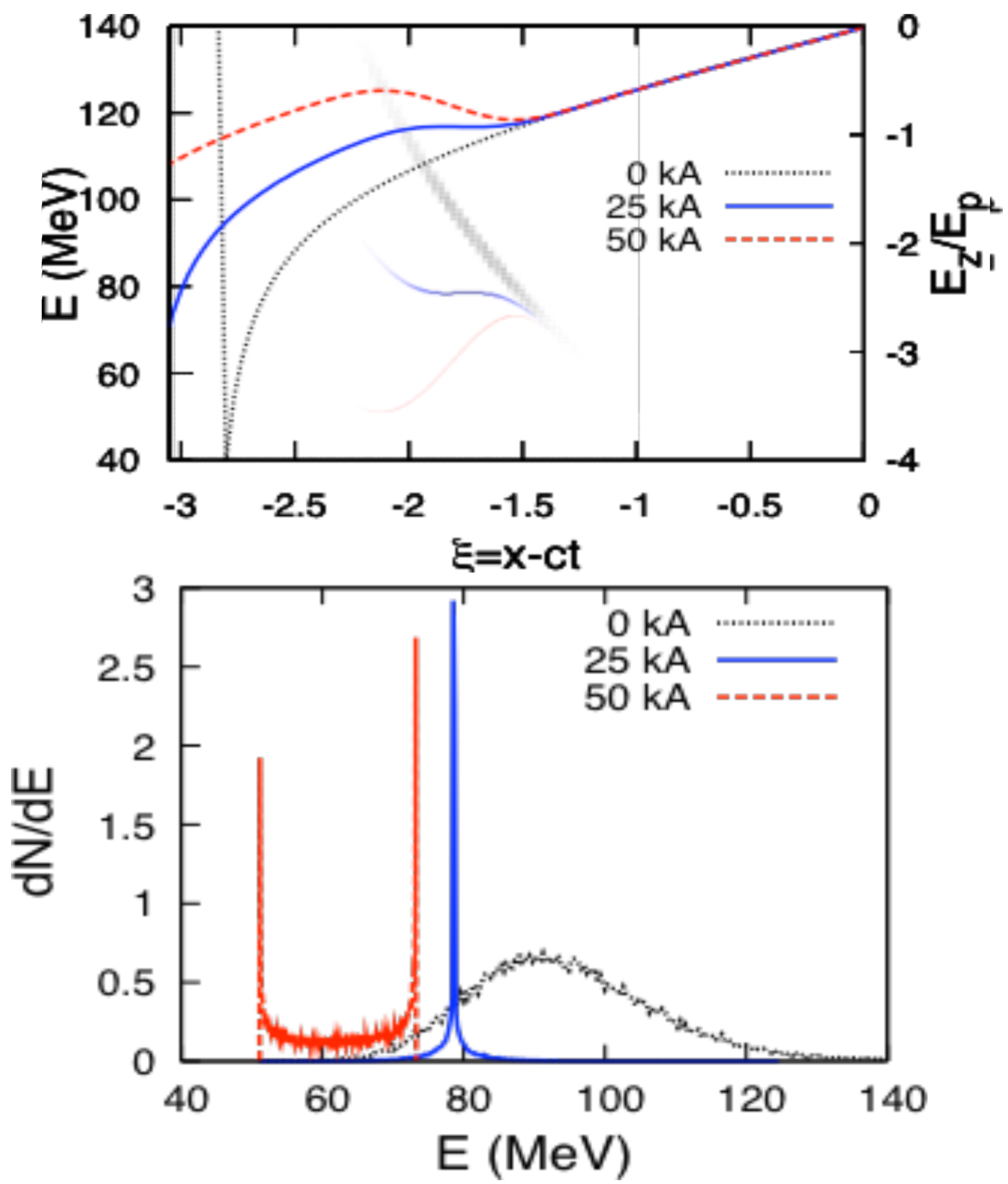
Limitation of the accelerated charge
Influence on energy and energy spread

Observables : correlation charge/energy spread/energy

T. Katsouleas *et al.*, (1987), M. Tzoufras *et al.*, Phys. Rev. Lett., **101** (2008)

Electron beam dynamics in plasma waves : beam loading





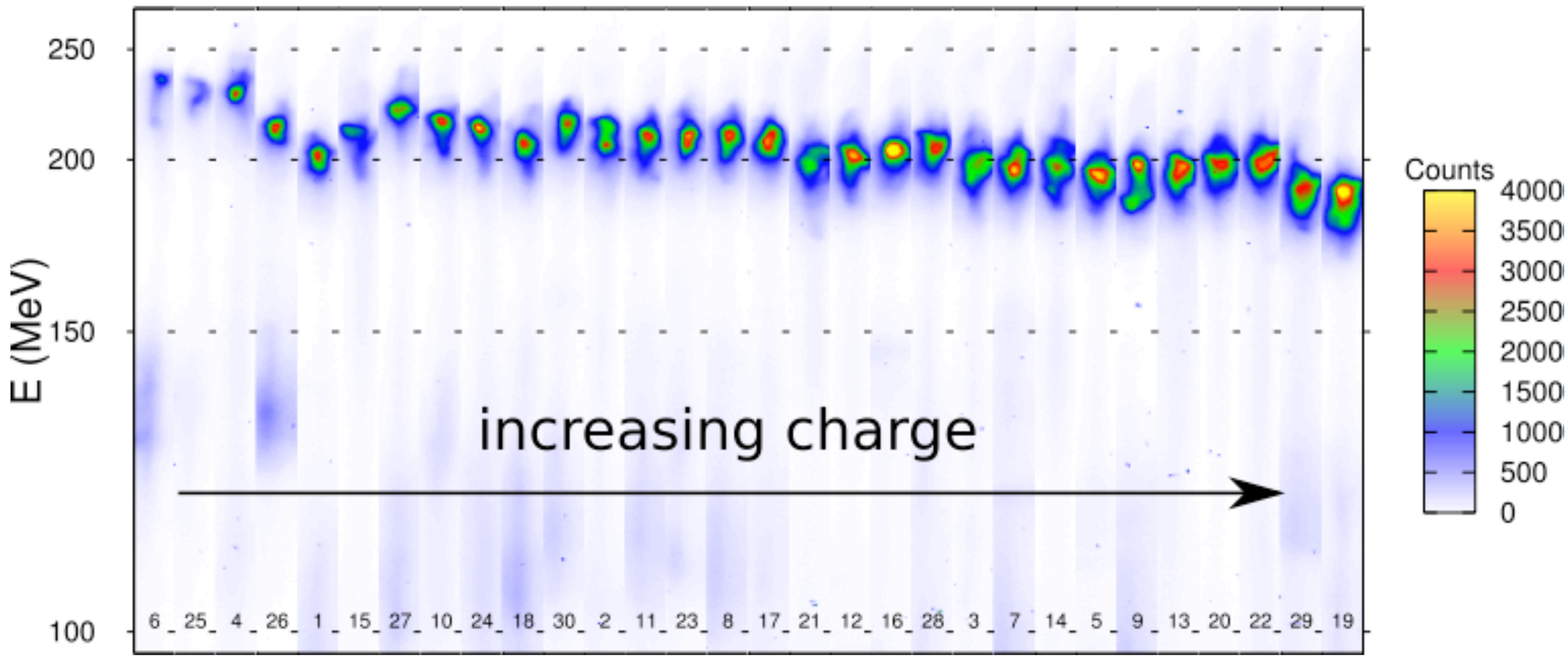
Low charge
=> large energy spread

Optimal charge
=> flat E field
=> low energy spread

High charge
=>End of the beam decelerated
=>high energy spread

Observables : correlation charge/energy spread/energy

Electron 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}

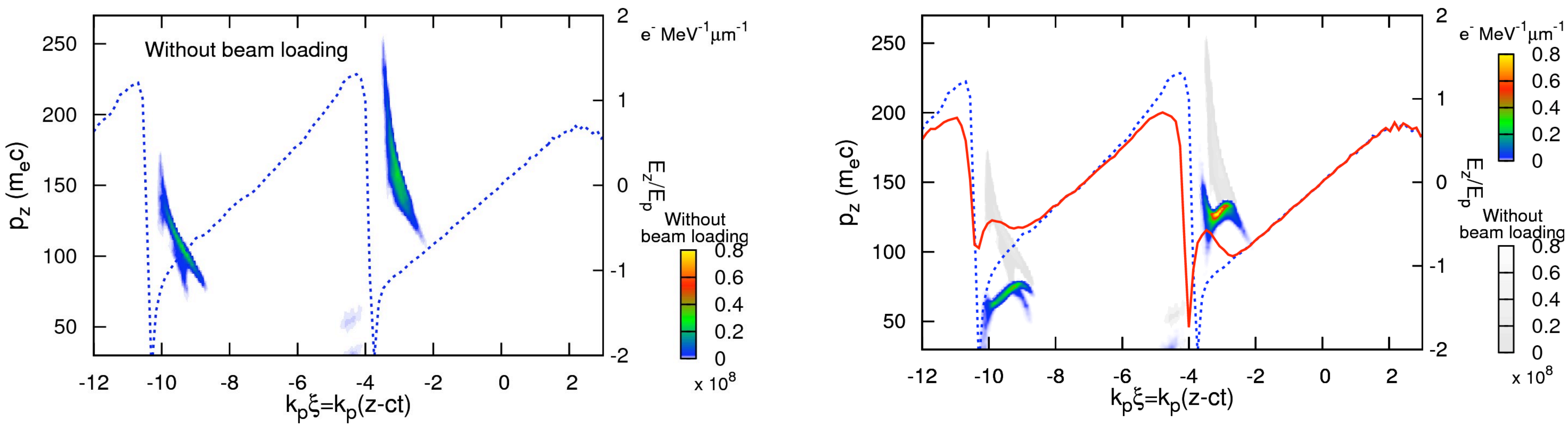
Clear correlation !

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

Simulations without and with beam loading effect

3D PIC simulations with experiment parameters (300 µm acceleration) with p_z>12mec are treated as test particle : no beam loading

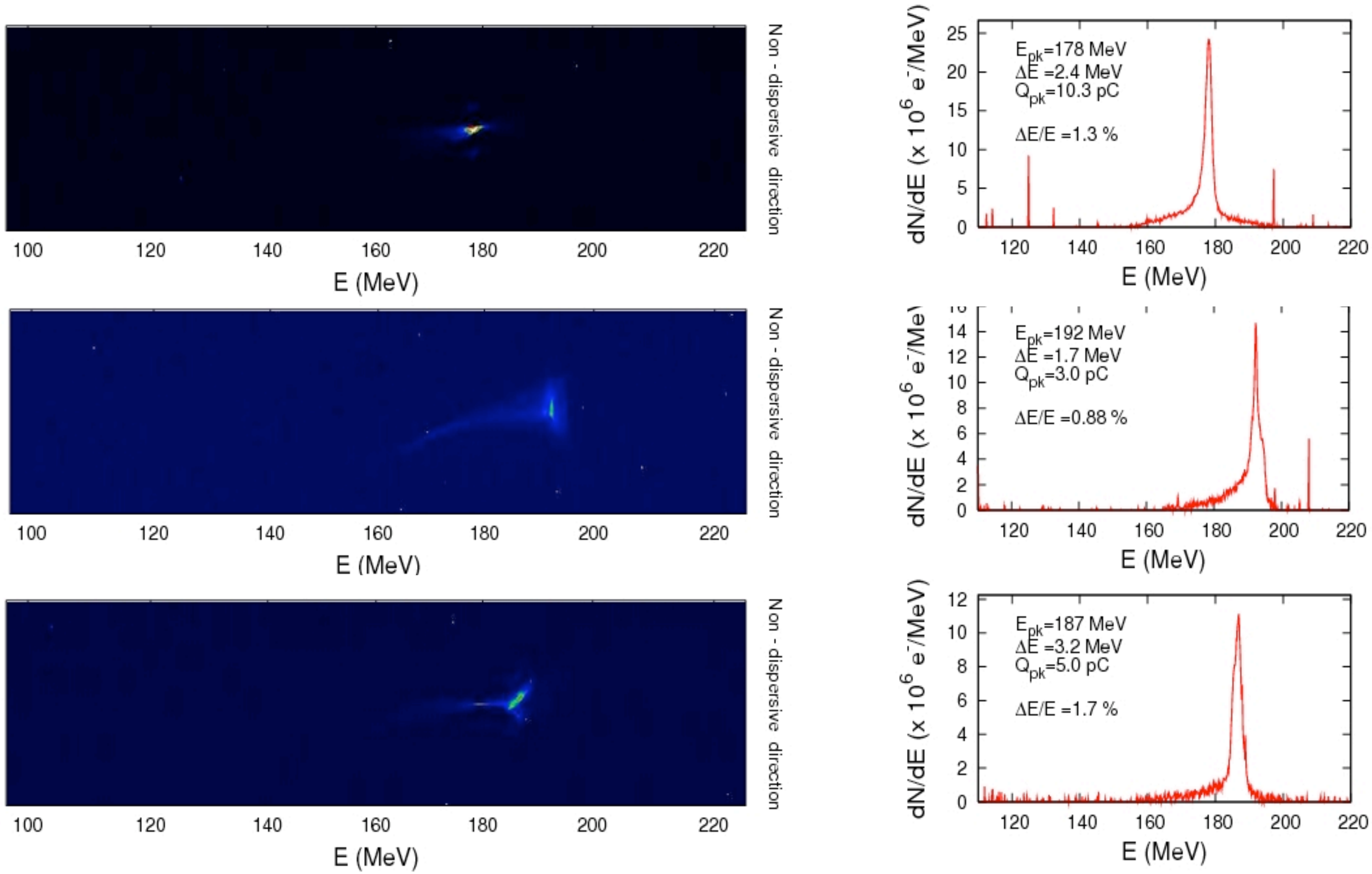
a_1=0.3, Q_{peak}= 48pC



Only changes the high energy cut-off => BL improves the energy spread
Experiment : 0.8 GV.m⁻¹.pC⁻¹, Simulations : 1 GV.m⁻¹.pC⁻¹

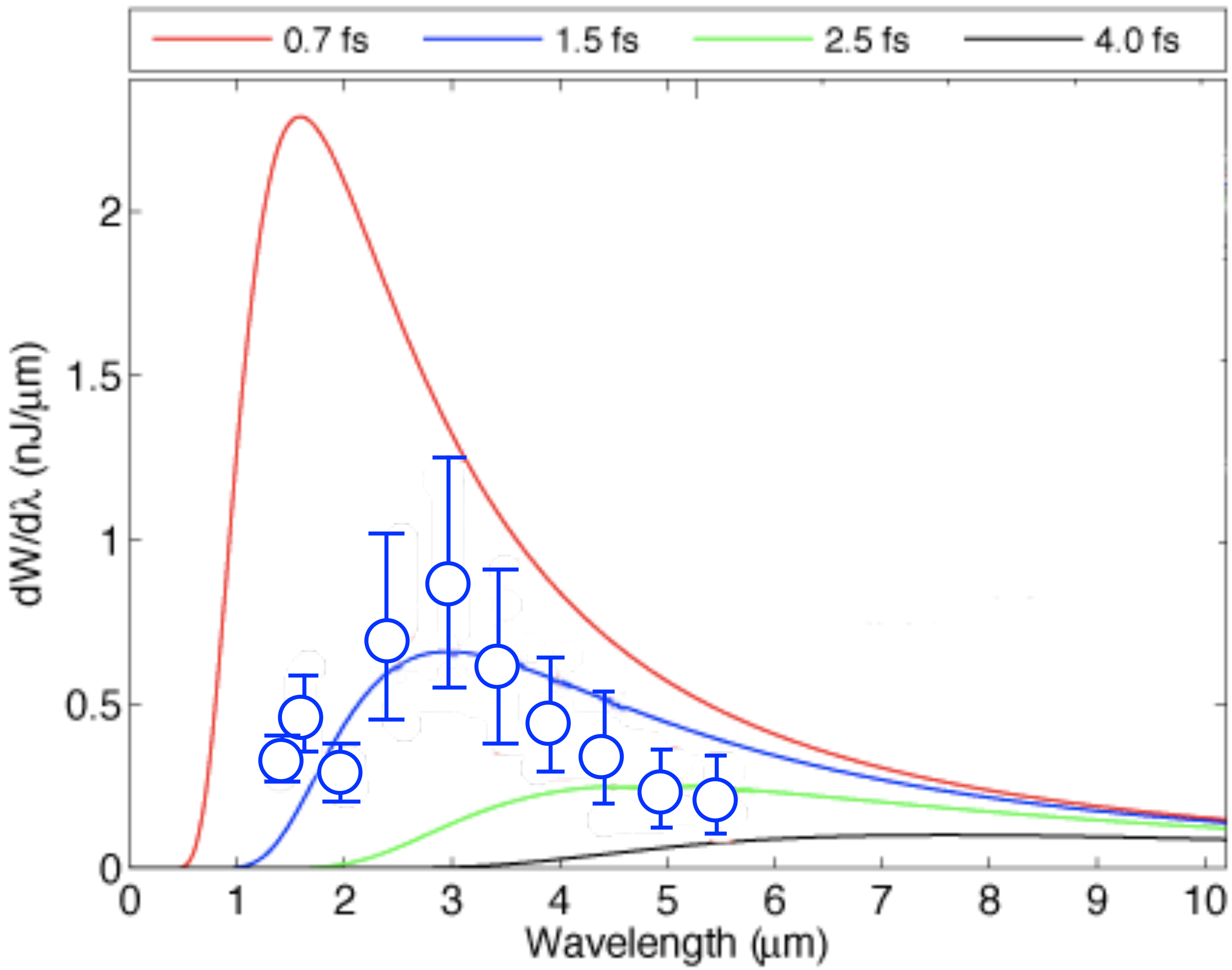
C. Rechatin et al., New Journal of Physics 12 (2010)

1% relative energy spread



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

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

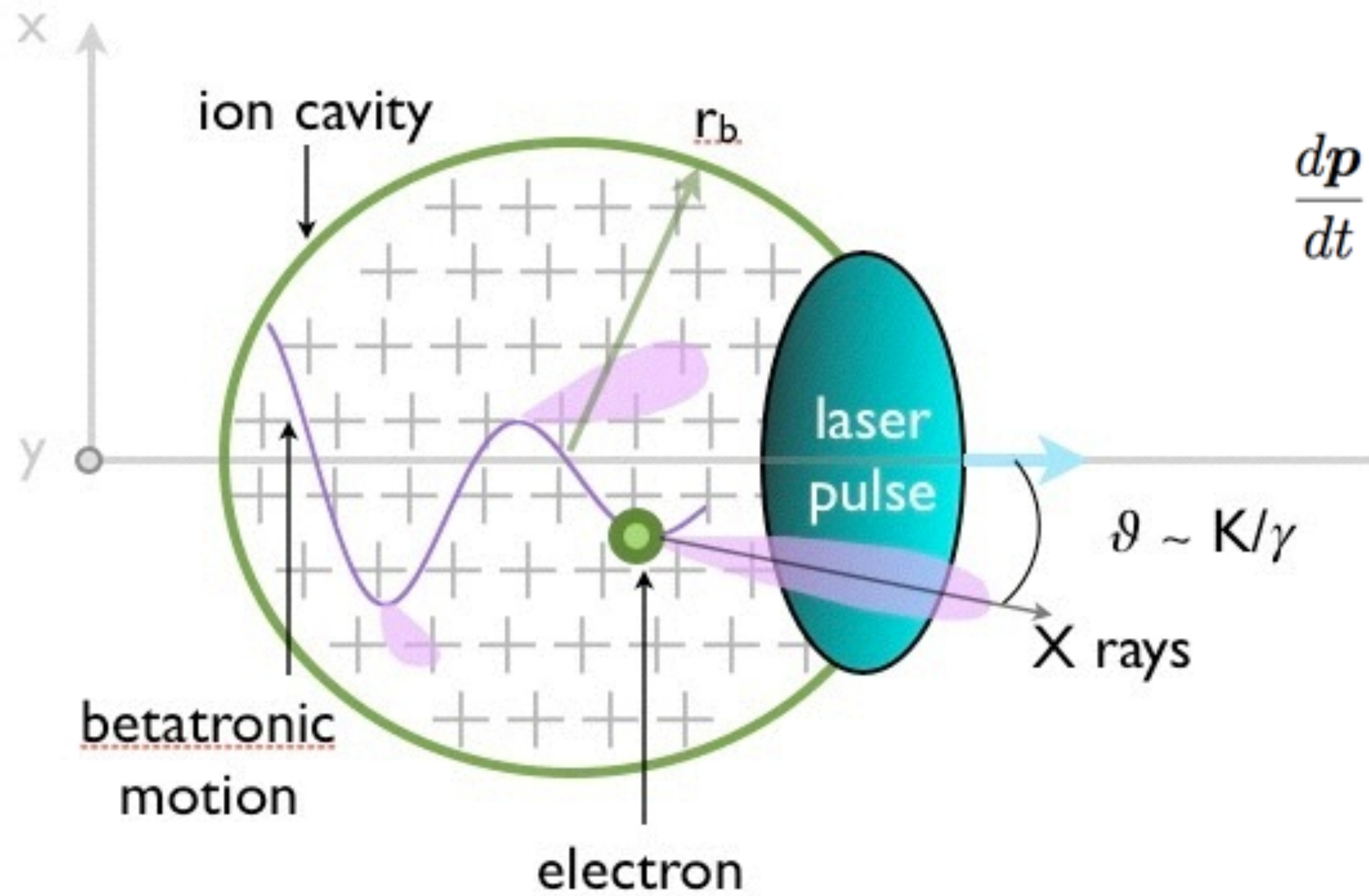
Coherent

1.5 fs RMS duration : Peak current of 4 kA

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

- Introduction : context and motivations
- Laser wakefield principle
- Injection processes :
  - Bubble
  - Colliding
- Beam Loading
- **Applications**
- Conclusion and perspectives

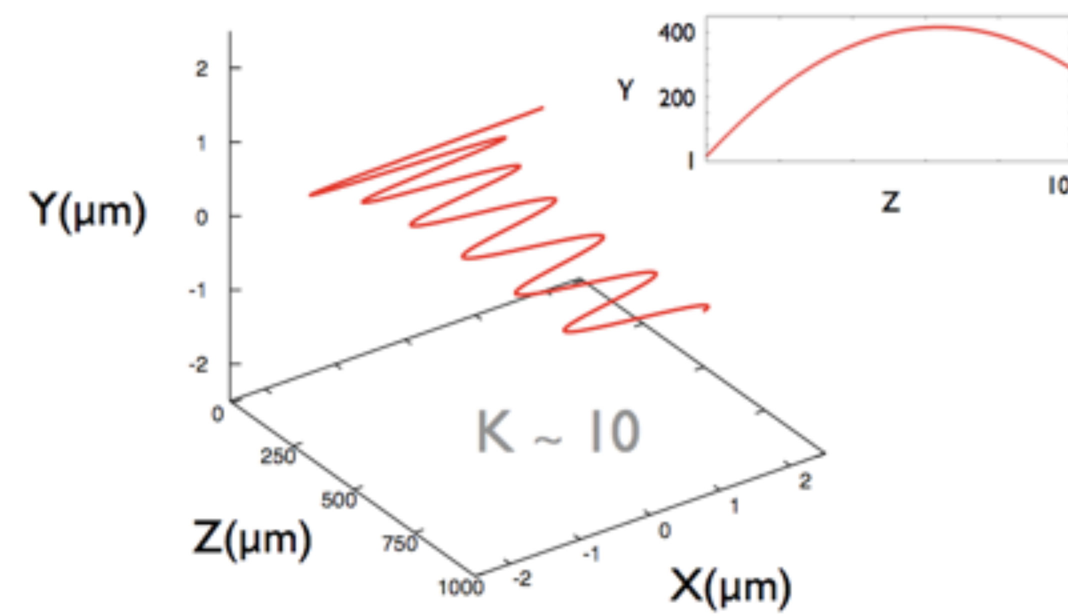
Betatron radiation properties



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:

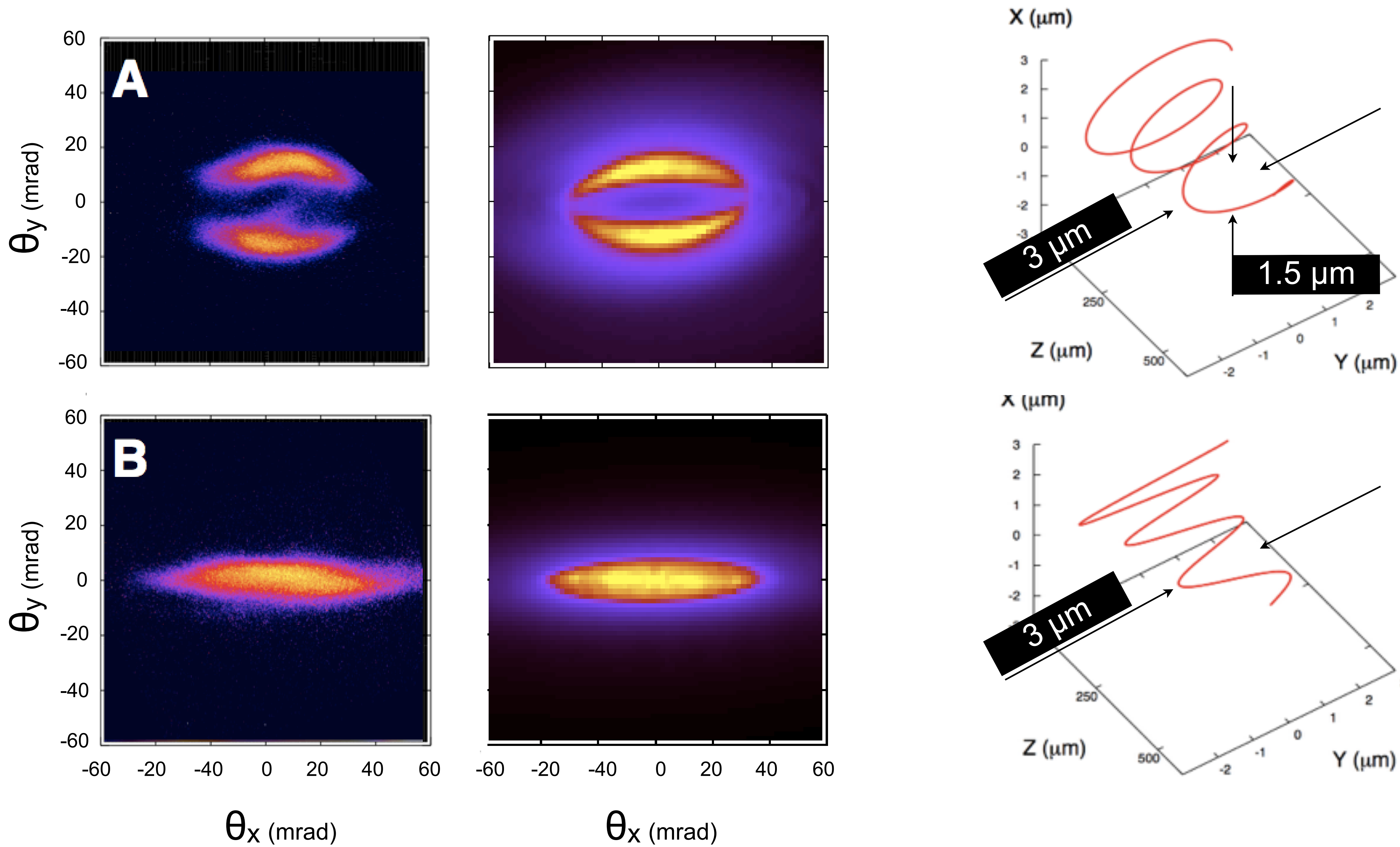
$$\lambda_u = \sqrt{2\gamma}\lambda_p \qquad K = r_\beta k_p \sqrt{\gamma/2}$$

$$\xrightarrow[r_\beta \sim 1\ \mu\text{m}]{\sim 100\ \text{MeV}} \qquad n_e \sim 10^{19}\ \text{cm}^{-3}$$

$$\lambda_u \sim 200\ \mu\text{m} \qquad K \sim 5$$

A more precise source size estimation

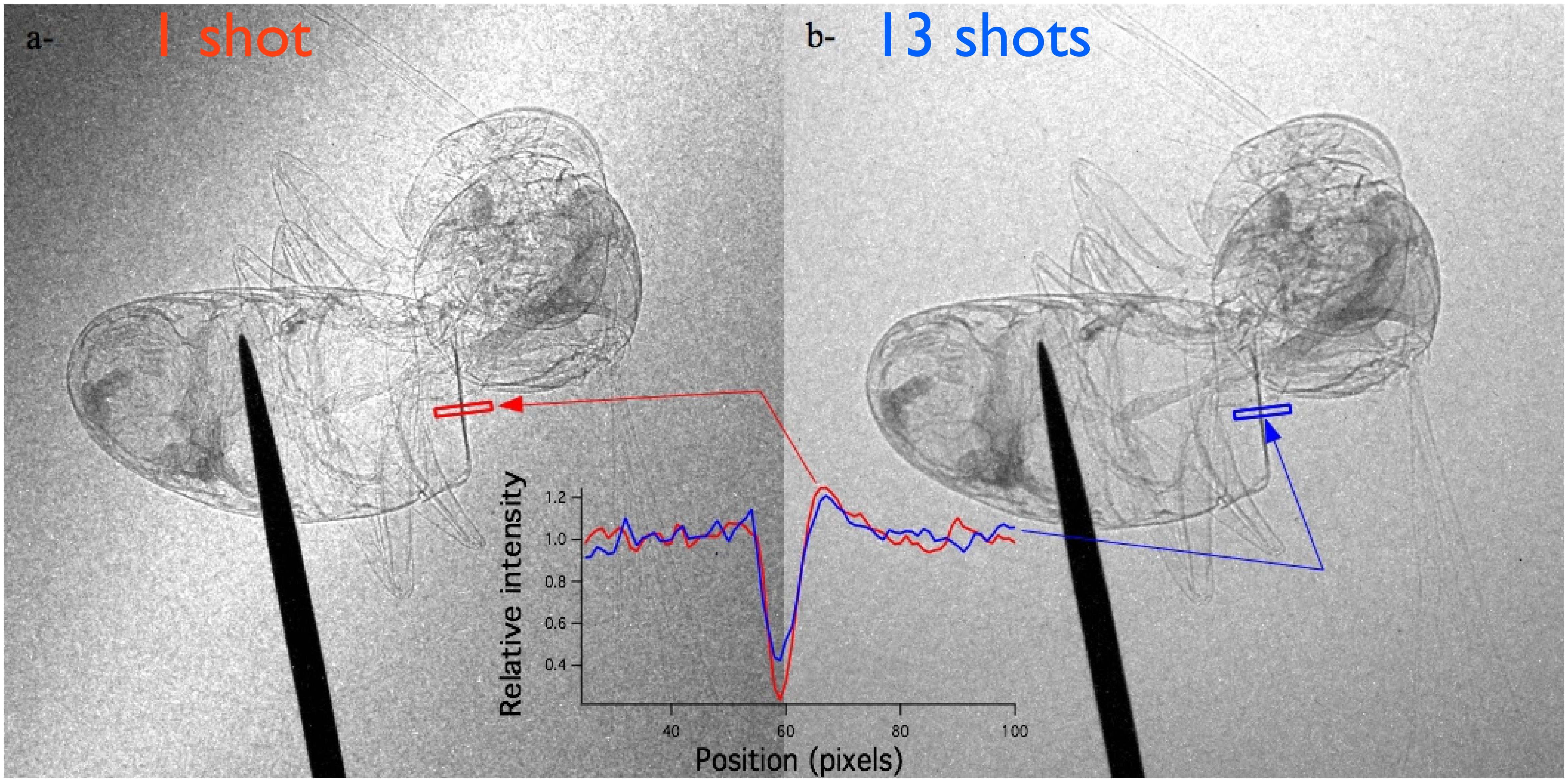
Experimental profiles | Calculated profiles | Electron orbits



Phase contrast imaging : results

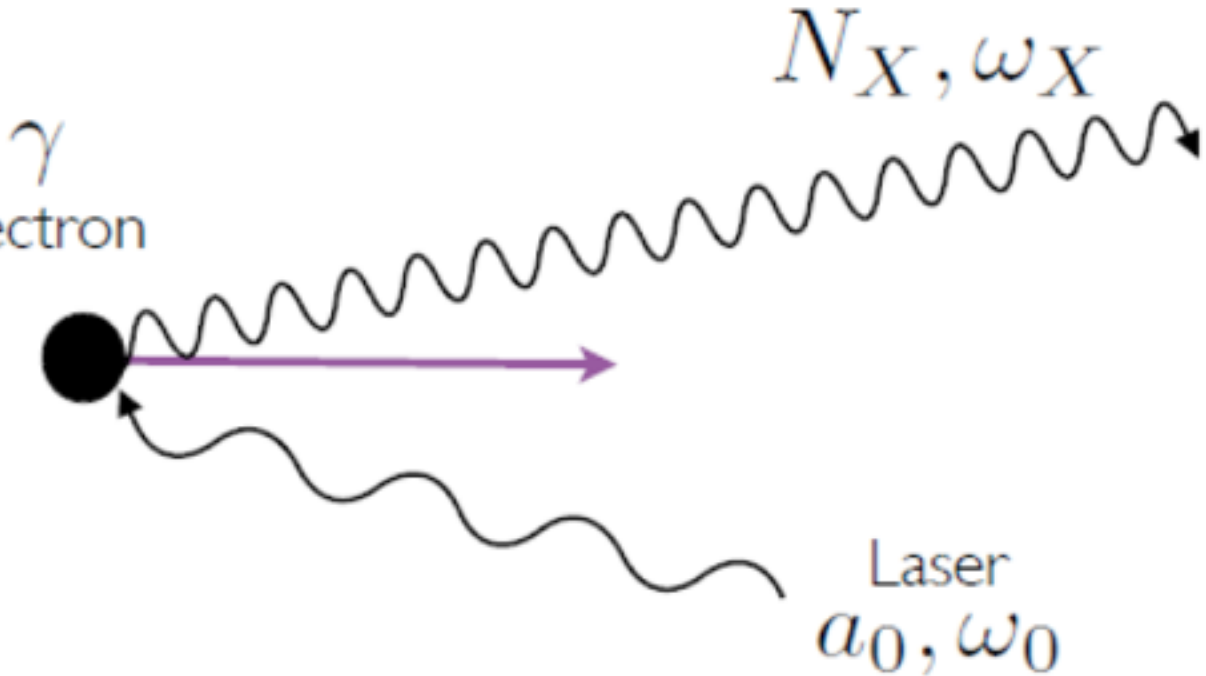
Bee contrast image :

- 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 : $\omega_x = 4\gamma^2\omega_0$

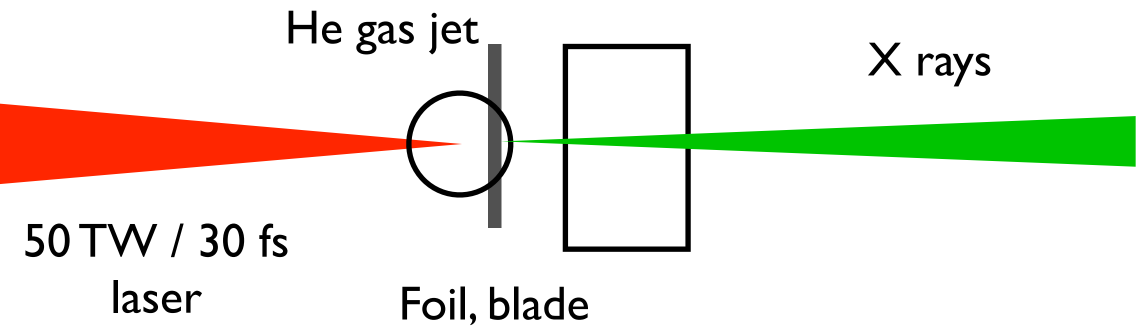
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

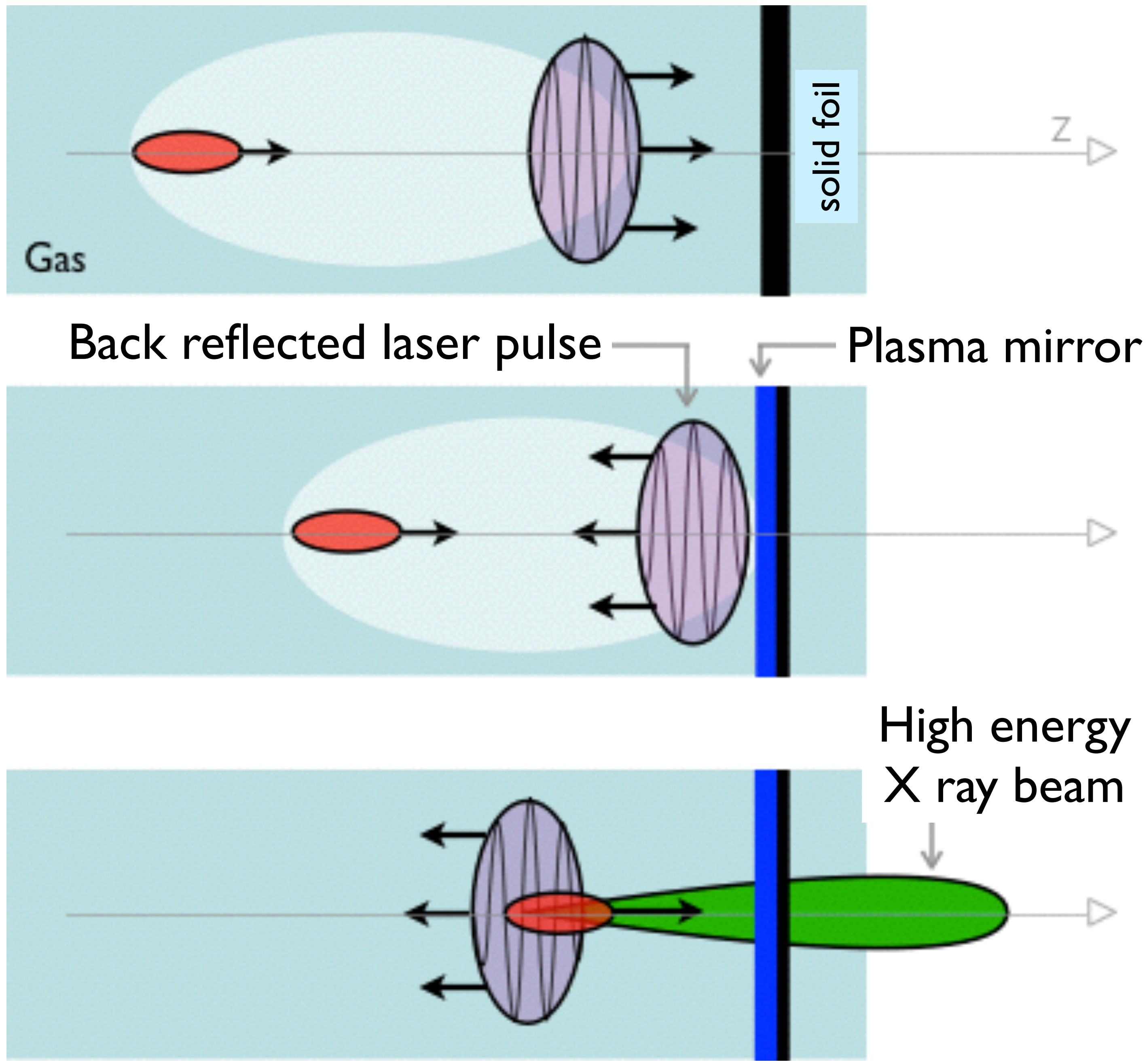
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

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

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

Inverse Compton Scattering : New scheme





A single laser pulse

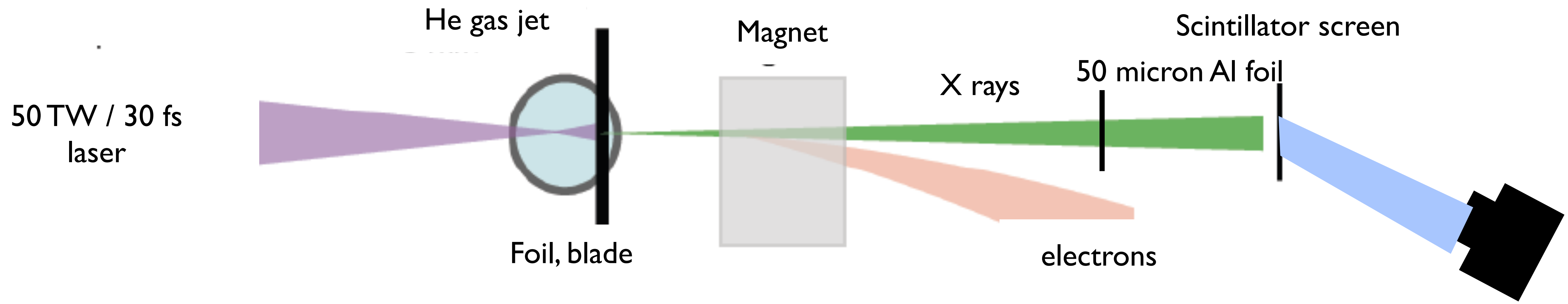
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

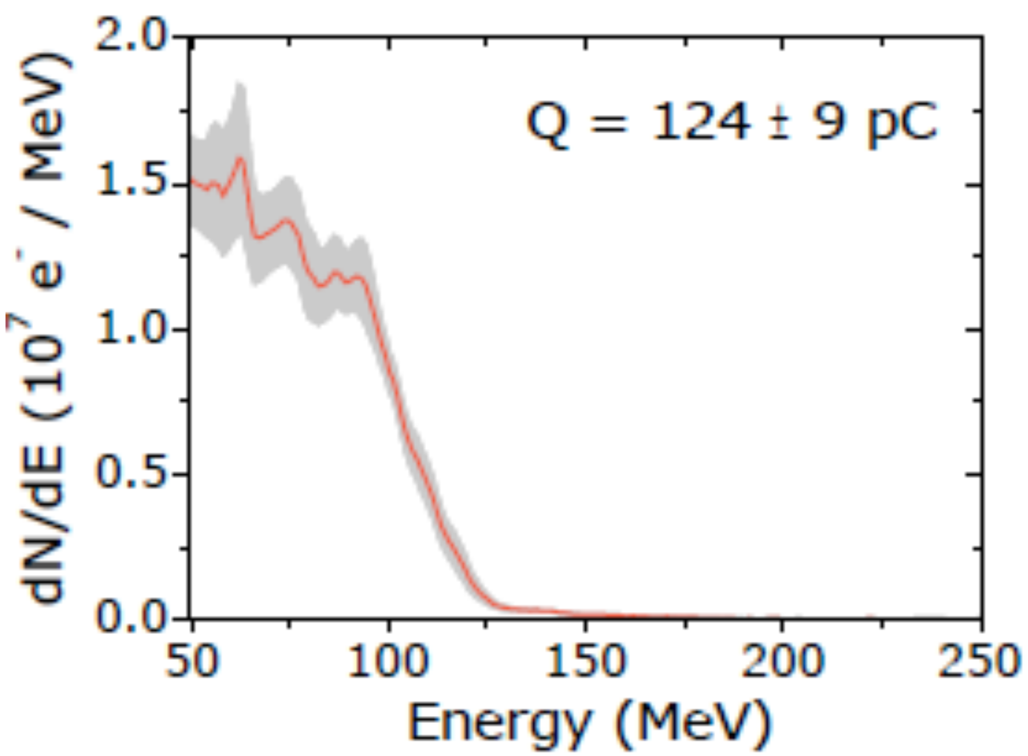
No alignement : the laser and the electron beams naturally overlap

Save the laser energy !

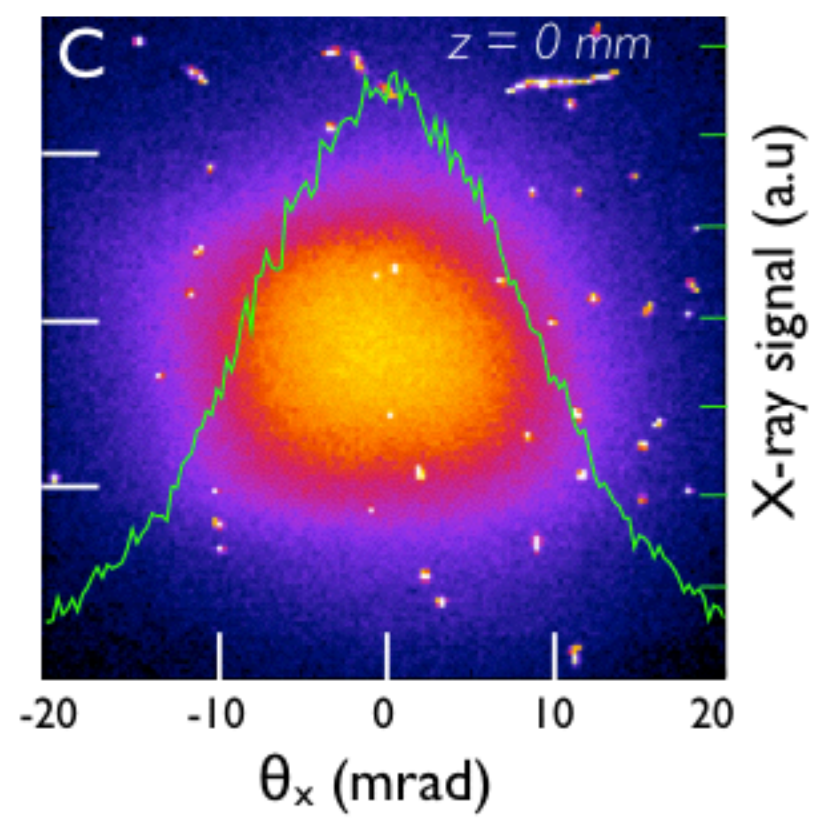
Inverse Compton Scattering : Experimental set-up



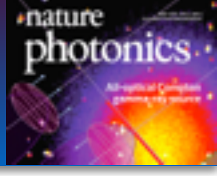
Electron spectra

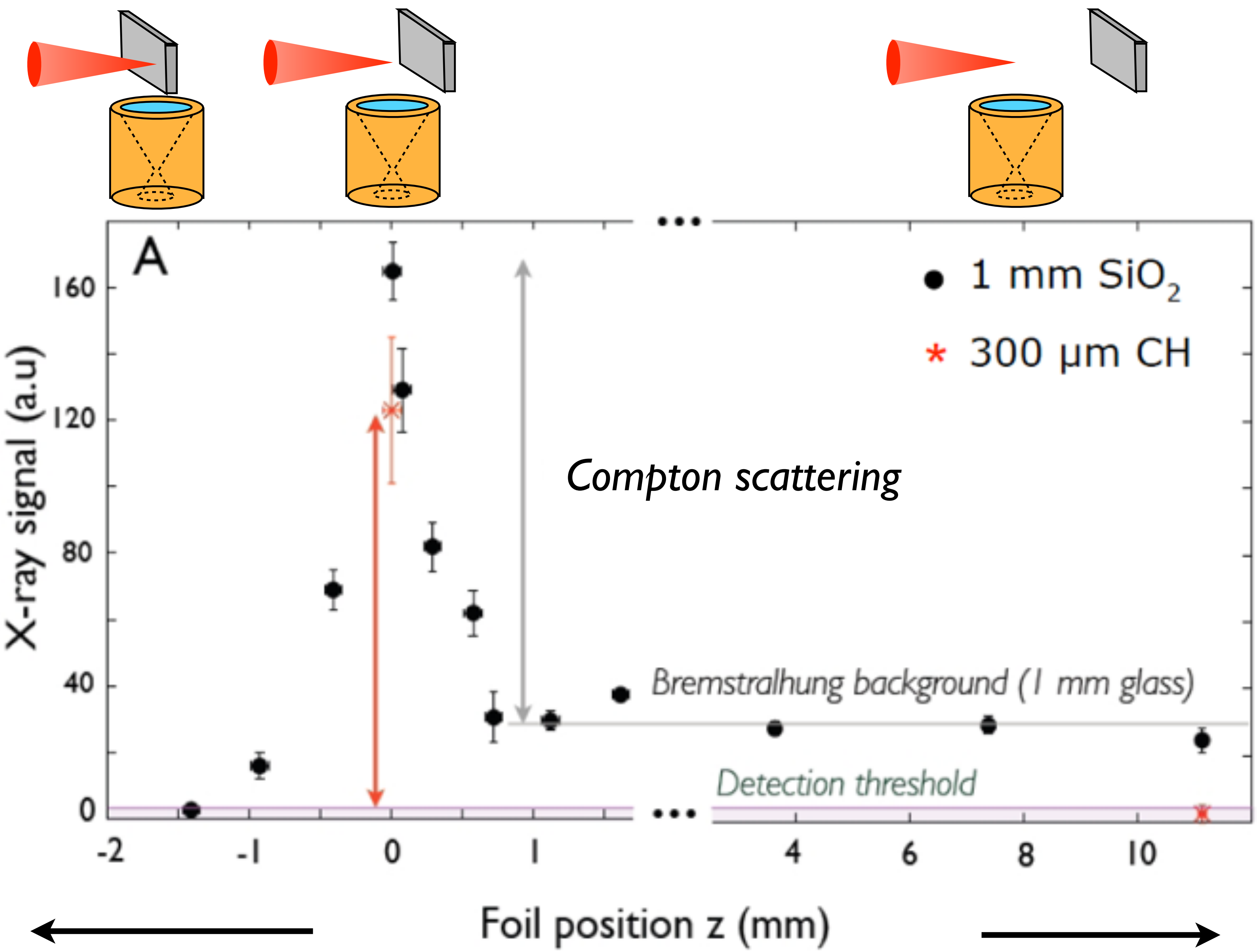


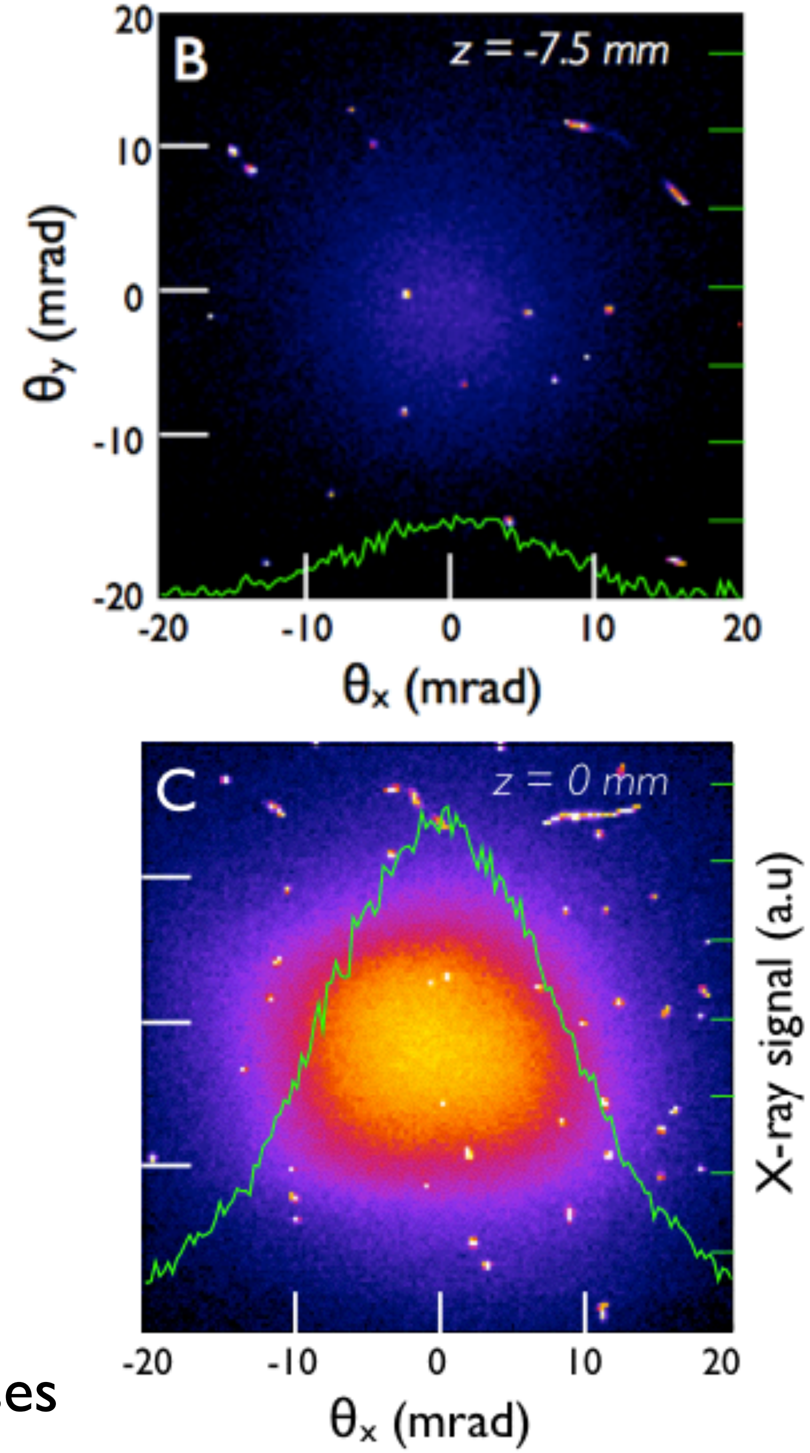
X ray beam profile



Inverse Compton Scattering : Experimental results





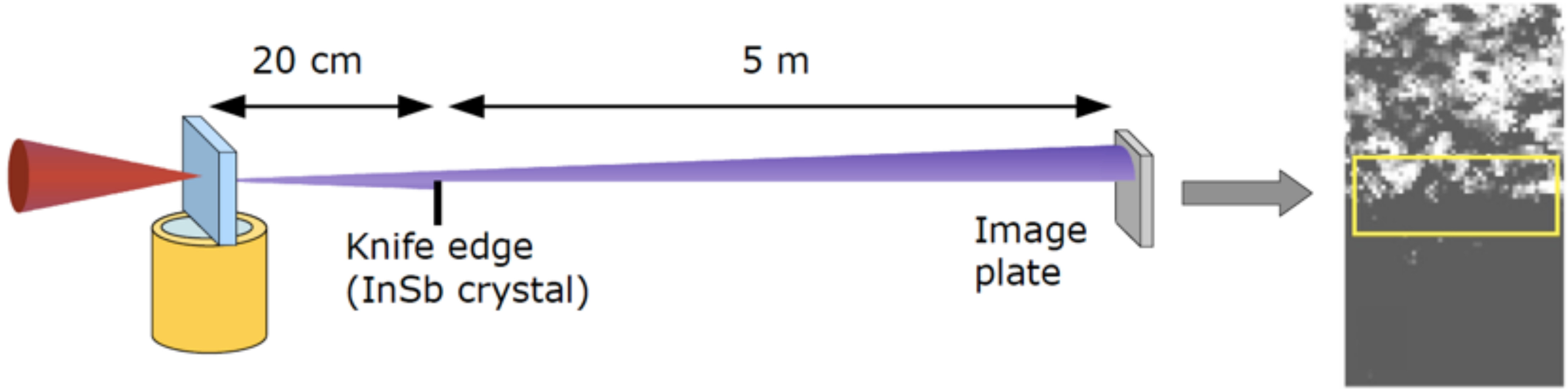


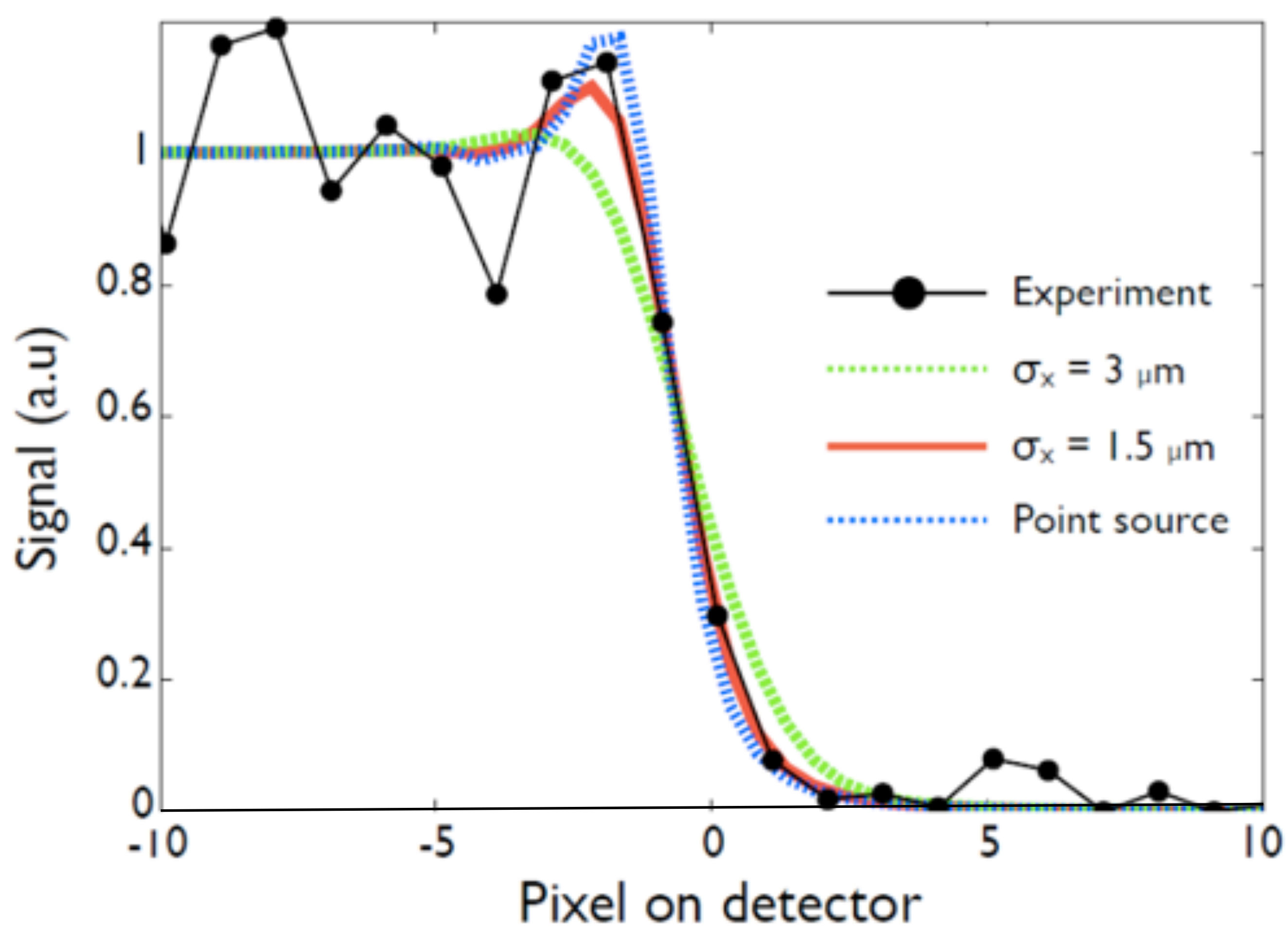
electron energy decreases

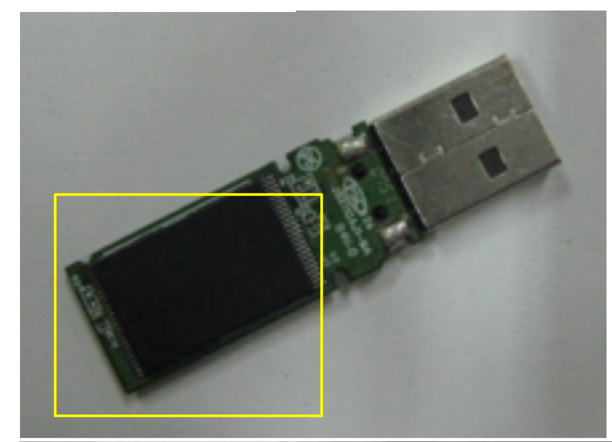
laser intensity decreases

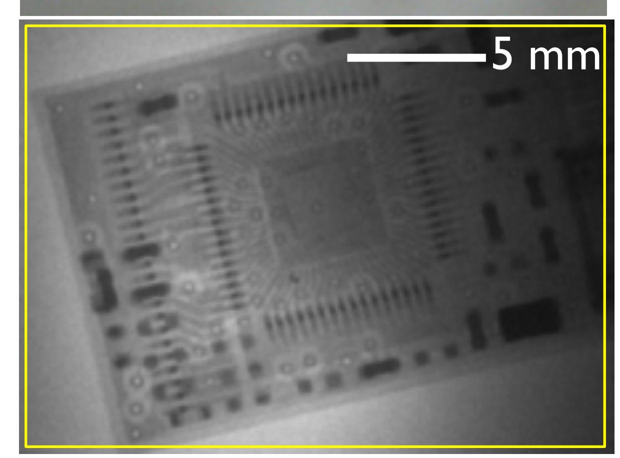
- The foil must be placed at the right to maximize a_0 and the electrons energy

Inverse Compton Scattering : Source size



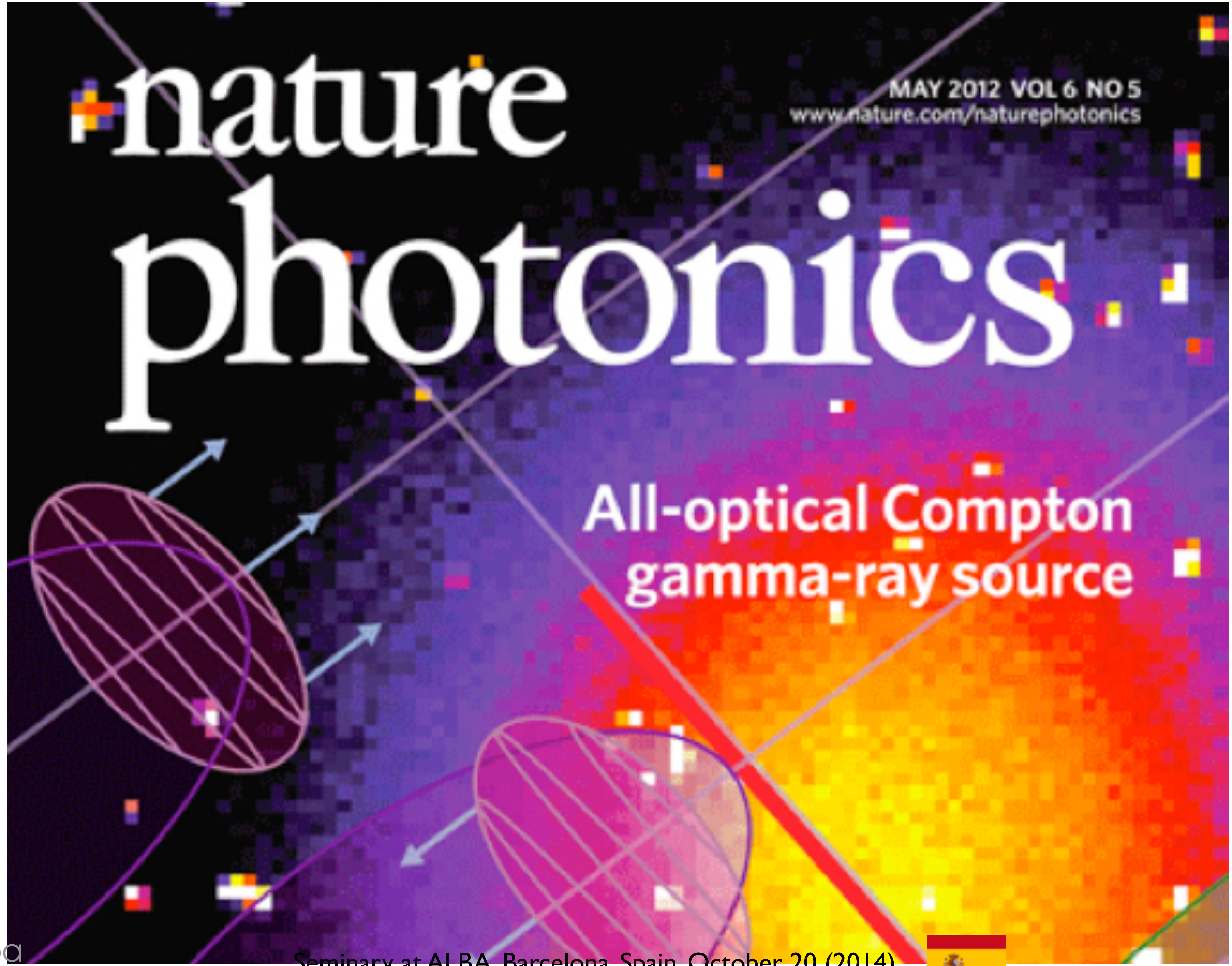






- In this image the resolution is limited by the detector and the small magnification

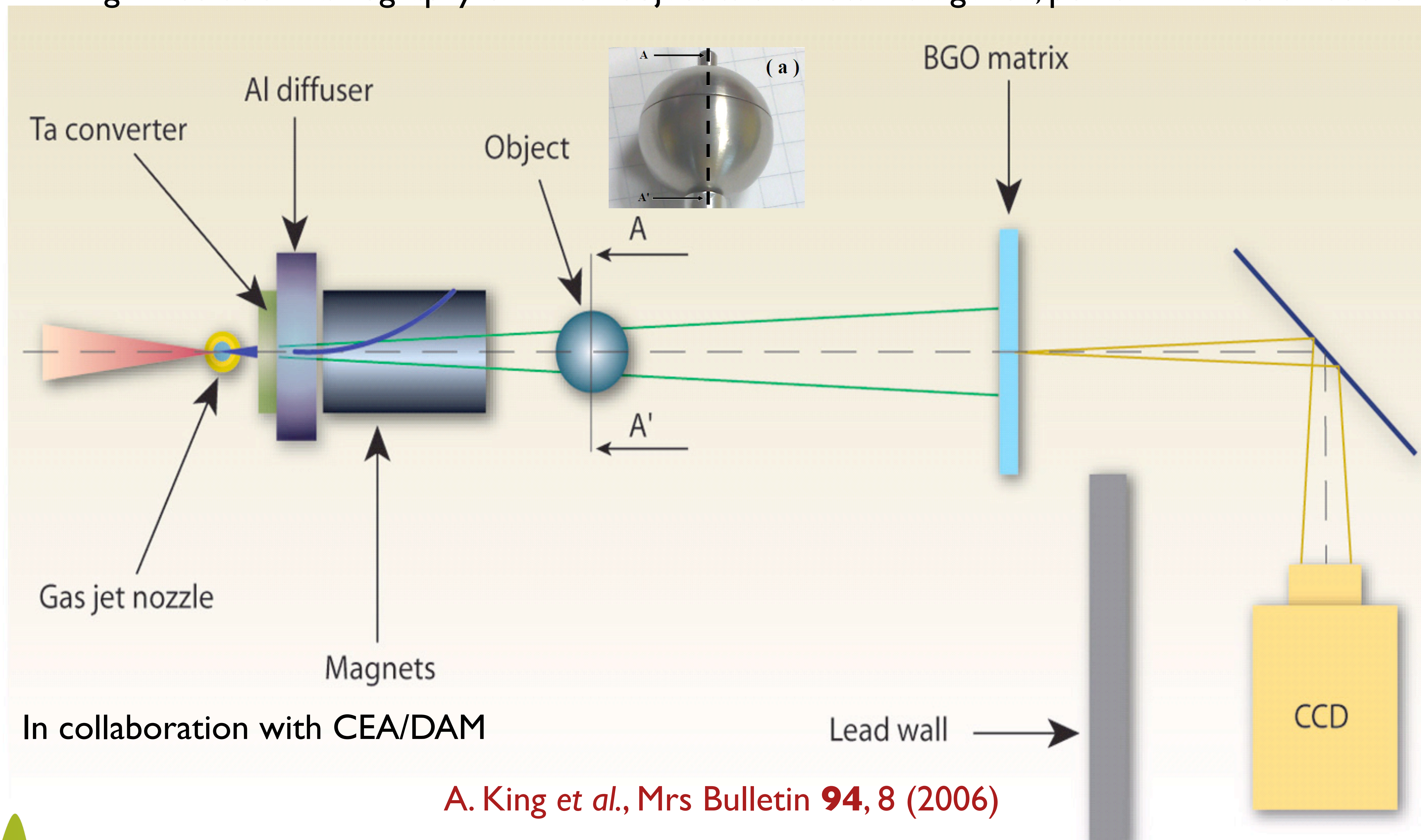
Inverse Compton Scattering : Compton Spectra



Some examples of applications : radiography

Non destructive dense matter inspection

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

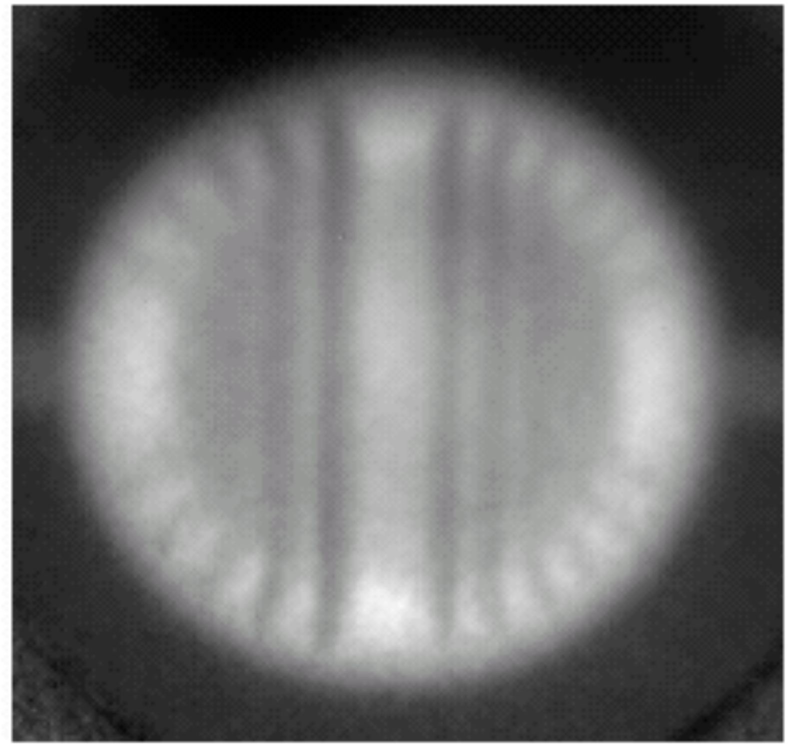


In collaboration with CEA/DAM

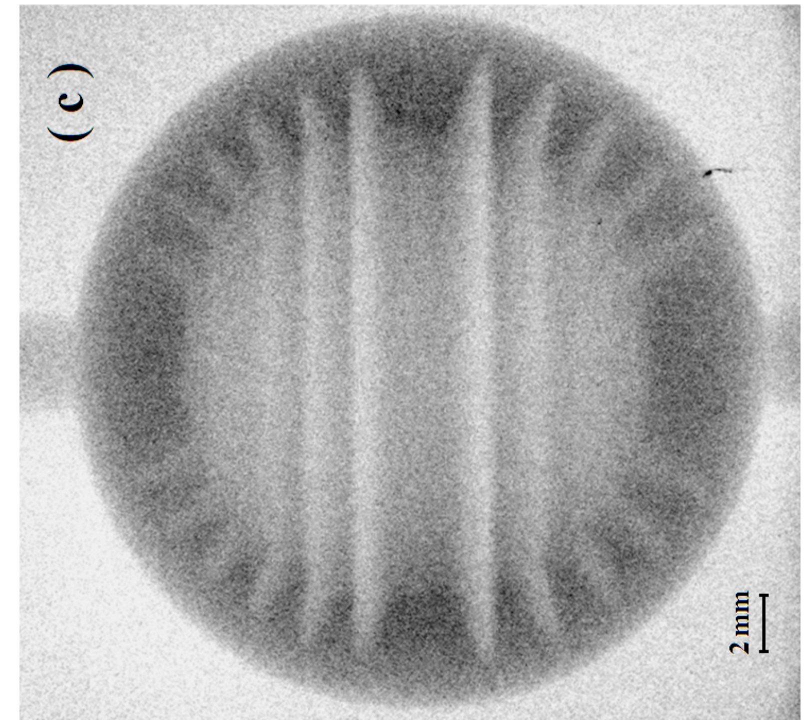
A. King *et al.*, Mrs Bulletin **94**, 8 (2006)

Some examples of applications : radiography results

Cut of the object in 3D
Spherical hollow object in tungsten with sinusoidal structures etched on the inner part.



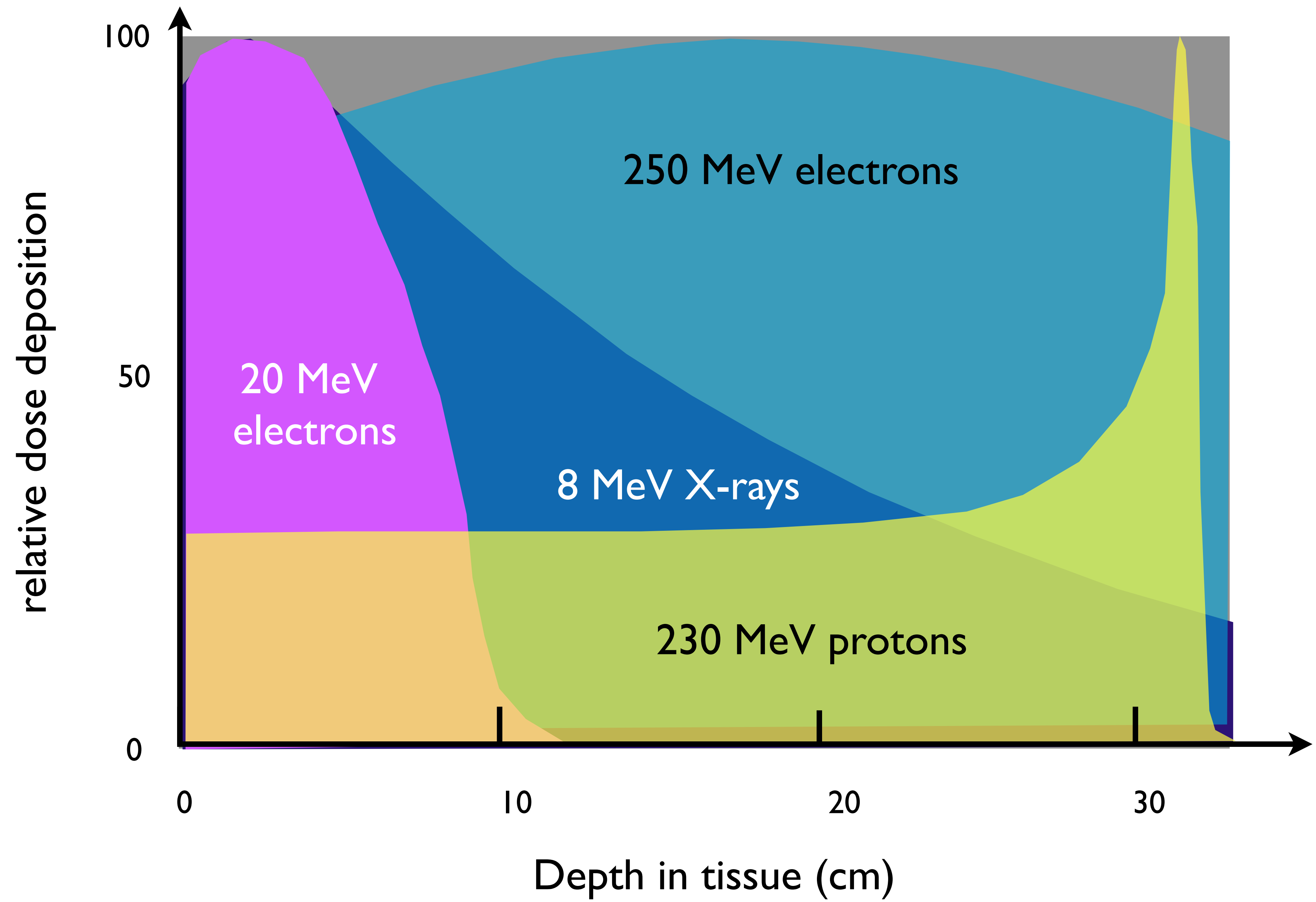
400 μm γ source size
2005



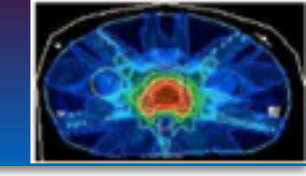
50 μm γ source size
2010

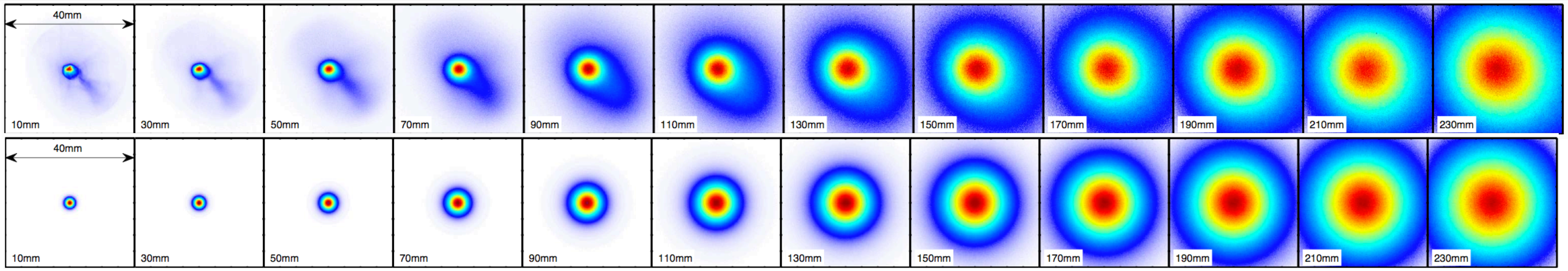
Y. Glinec *et al.*, PRL **94**, 025003 (2005)
A. Ben-Ismail *et al.*, Nucl. Instr. and Meth. A **629** (2010)
A. Ben-Ismail *et al.*, App. Phys. Lett. **98**, 264101 (2011)

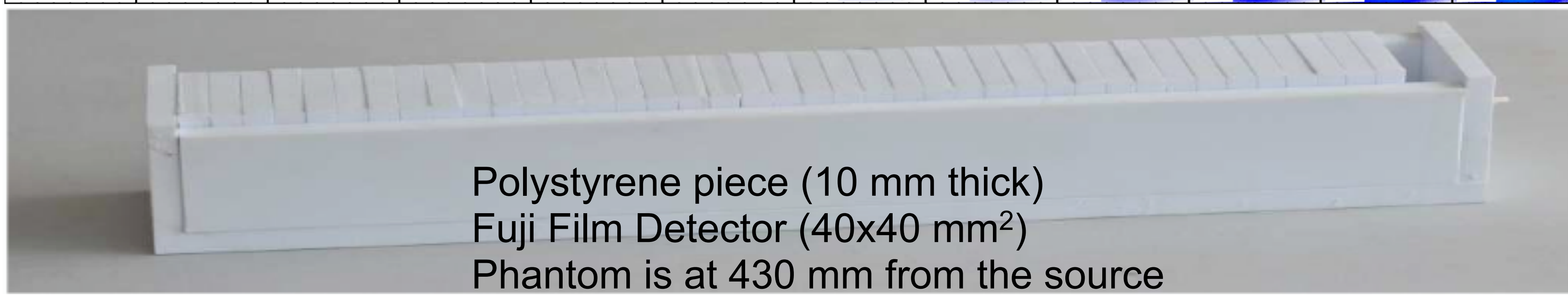
Some examples of applications : radiotherapy



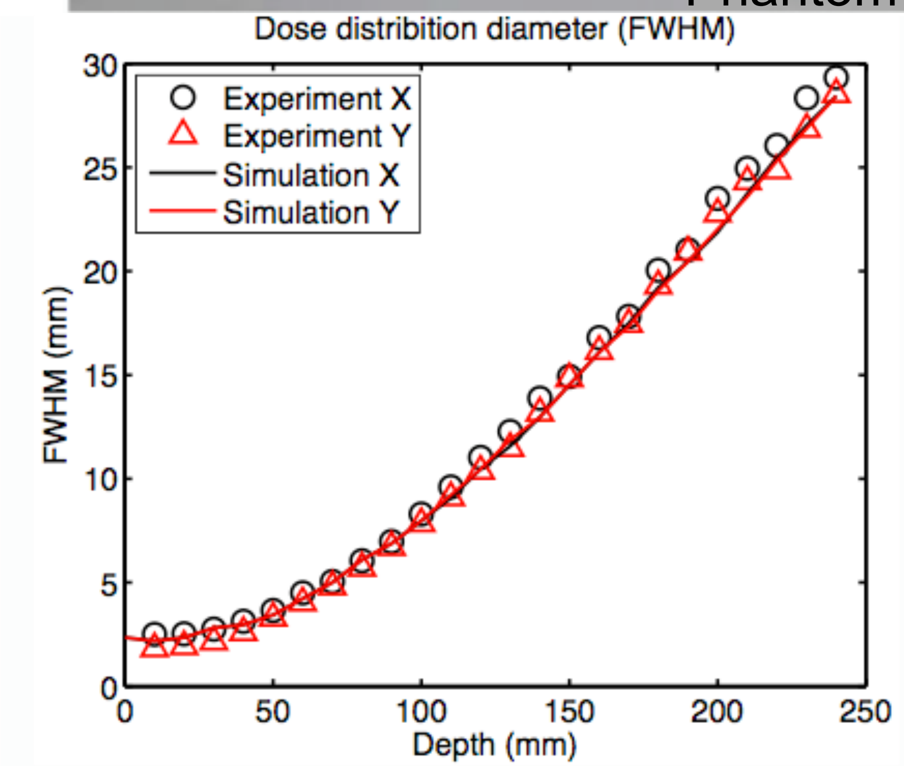
Some examples of applications : radiotherapy

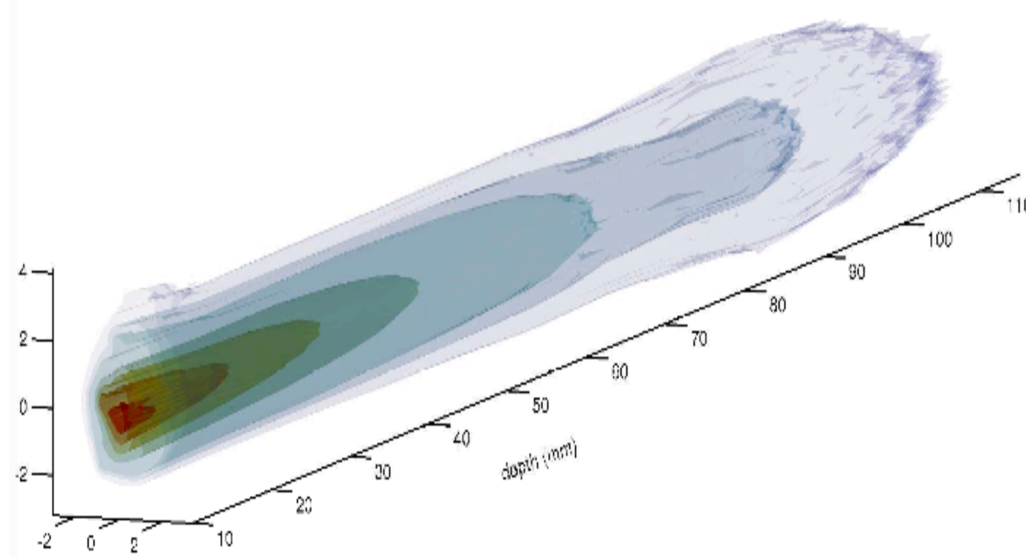






E_{pic}=120 MeV
ΔE=20 MeV
Q_{pic}=30pC
Θ=4.5mrad
D_{max}=1Gy/tir

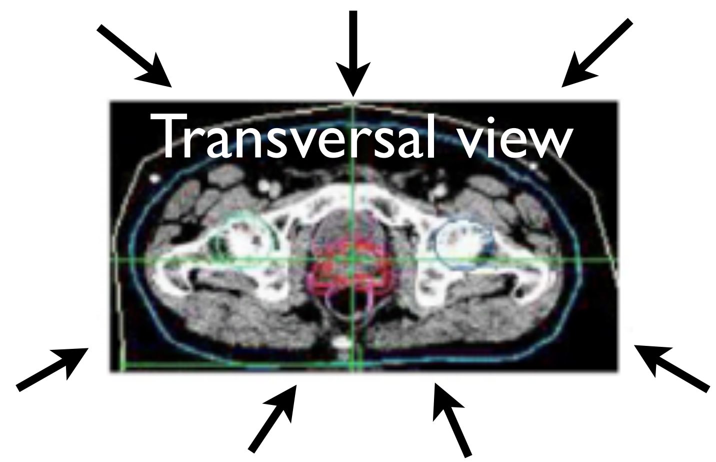


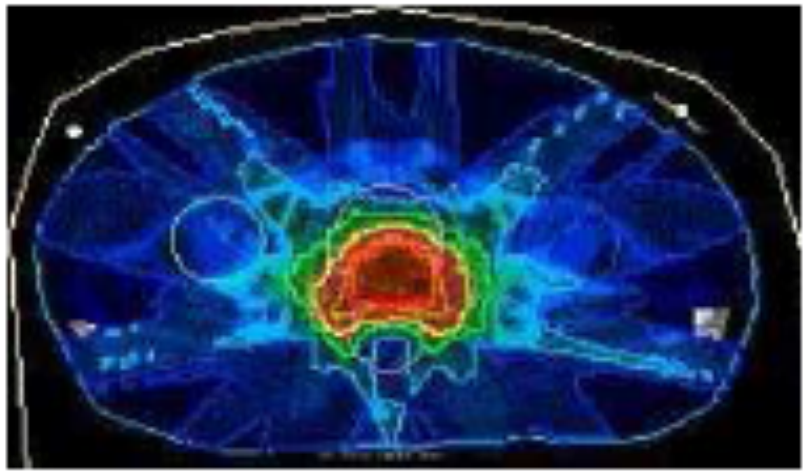


Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006),
O. Lundh *et al.*, to be submitted

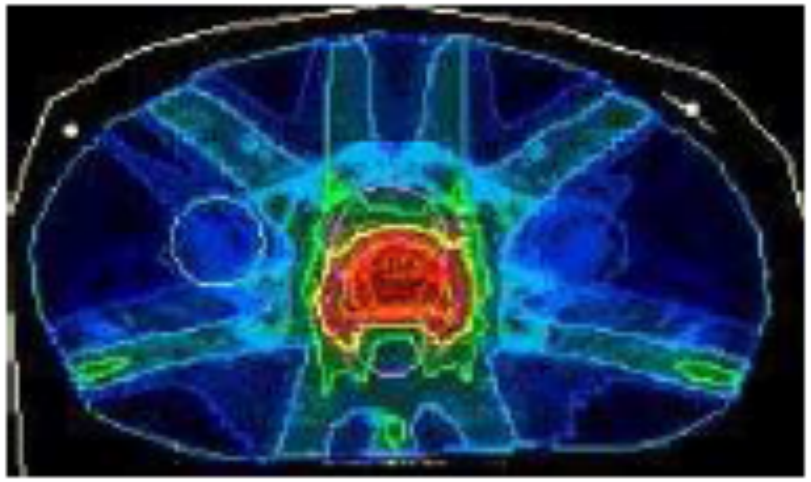
Some examples of applications : radiotherapy

simulations of prostate cancer with 7 irradiation beams

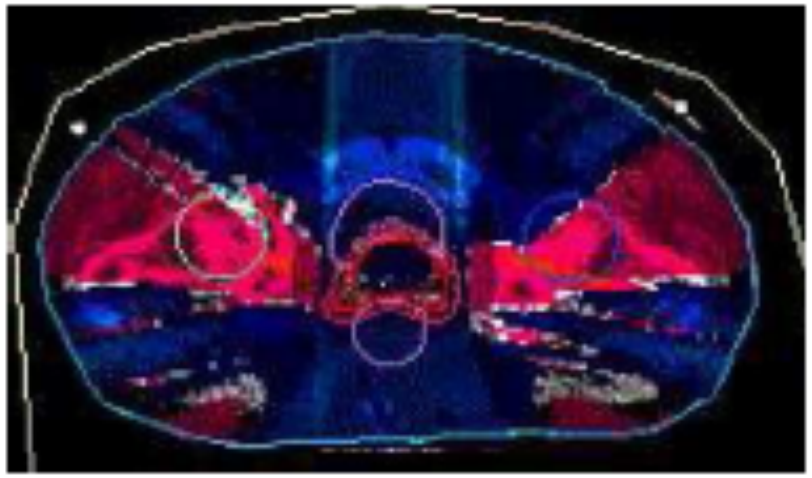




250 MeV electrons



X rays IMRT

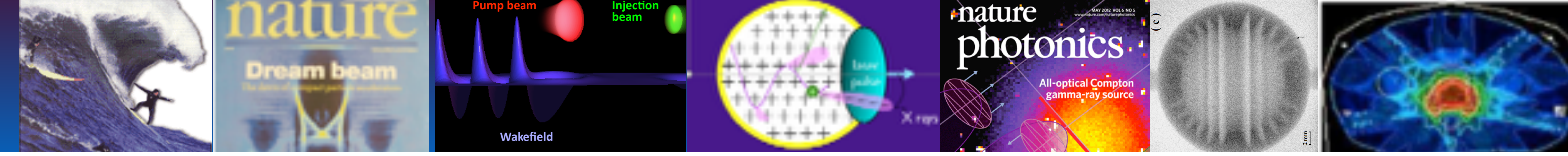


Difference

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

Outline



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    - Colliding
- Beam Loading
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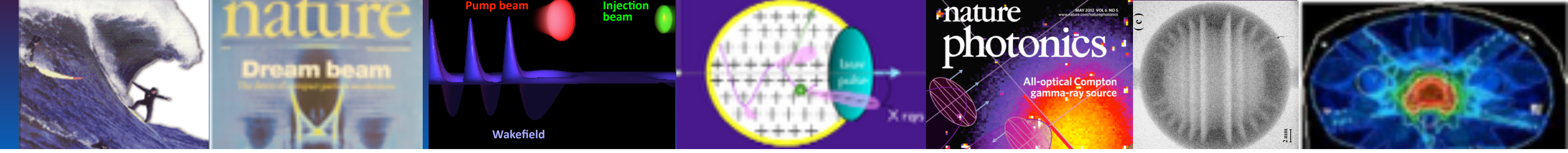
Conclusions

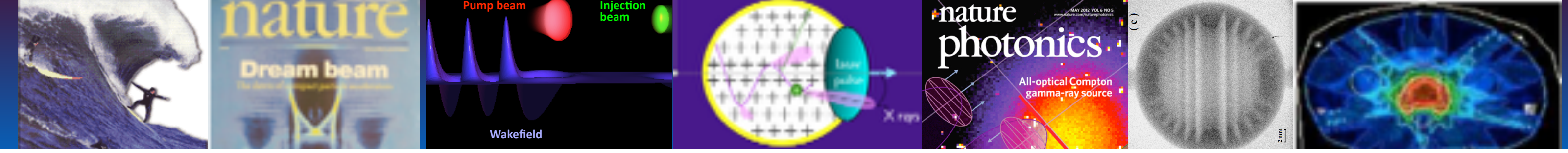


Accelerators point of view :

- 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 % √
- Peak energy at 1.4 GeV √
- Ultra short e-bunch : 1,5 fs rms √
- Low divergence : 2 mrad √
- Low emittance[1-3] : π.mm.mrad √

[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)

Conclusions



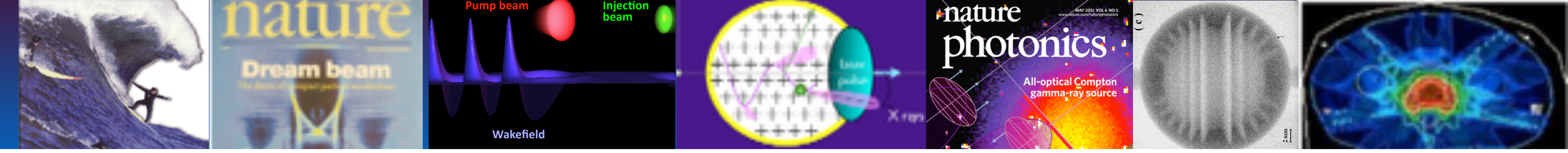
Laser plasma accelerators can deliver high quality X ray beams

(i) Betatron : 10^8-10^9 ph/shot - fs - micron - 10's keV

(ii) Compton : 10^8-10^9 ph/shot - fs - micron - 100's keV

(iii) Bremstralhung: 10^5-10^6 ph/shot - ps - 10's micron - 10's MeV

They allow to make high resolution absorption/contrast images
They will allow ultra fast time resolved studies



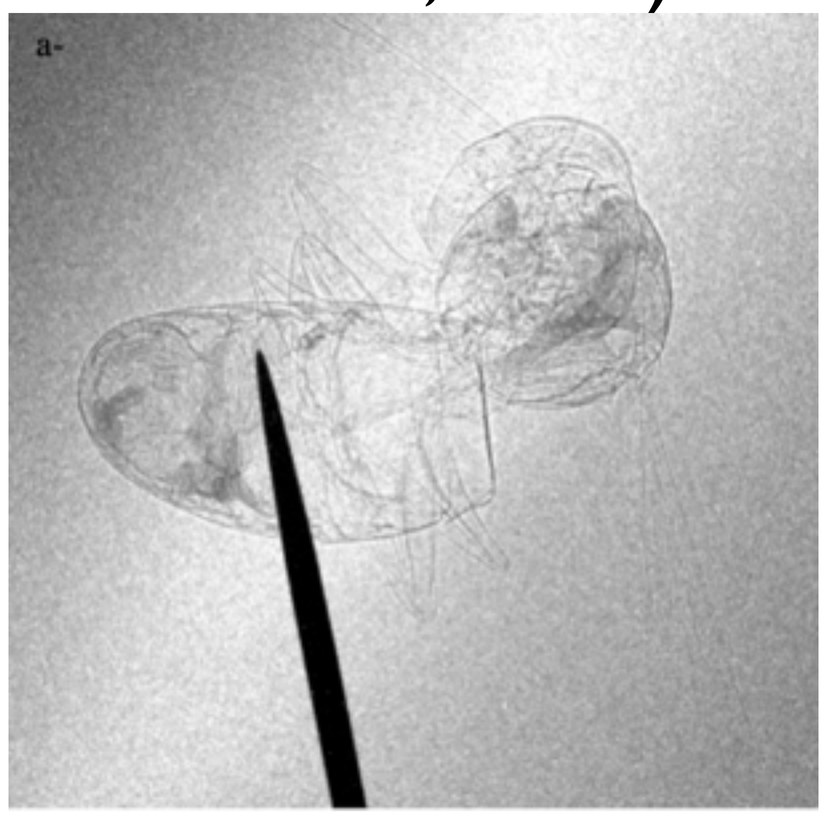
Results extremely important for :

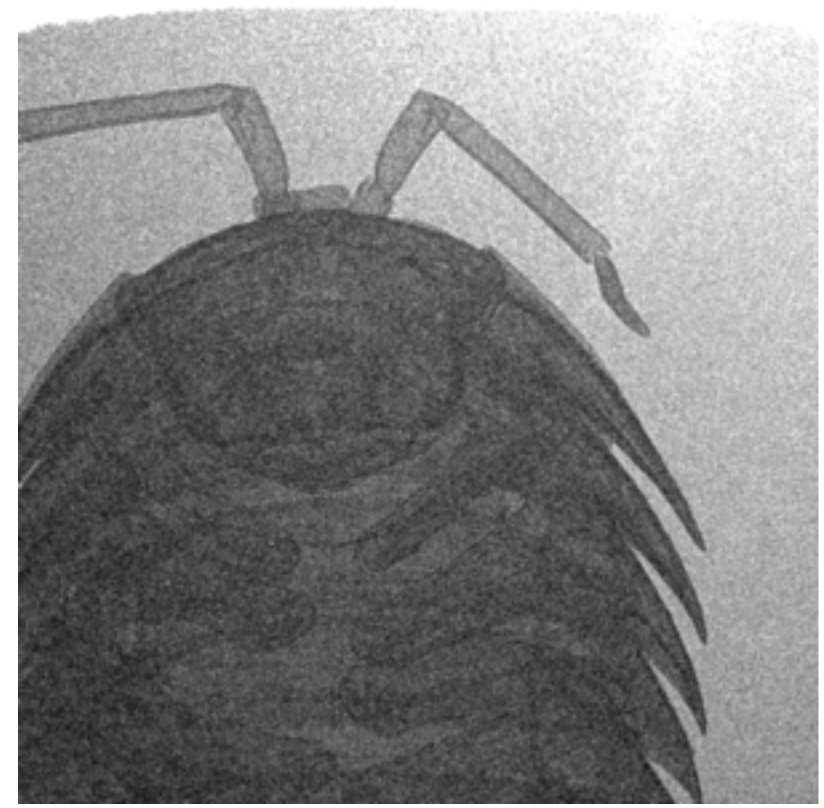
Designing future accelerators
Compact X ray source (Thomson, Compton, Betatron, or FEL)
Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

First X rays betatron contrast images

S. Fourmaux *et al.*, Opt. Lett. **36**, 13 (2011)

S. Kneip *et al.*, Appl. Phys. Lett. **99**, 093701 (2011)

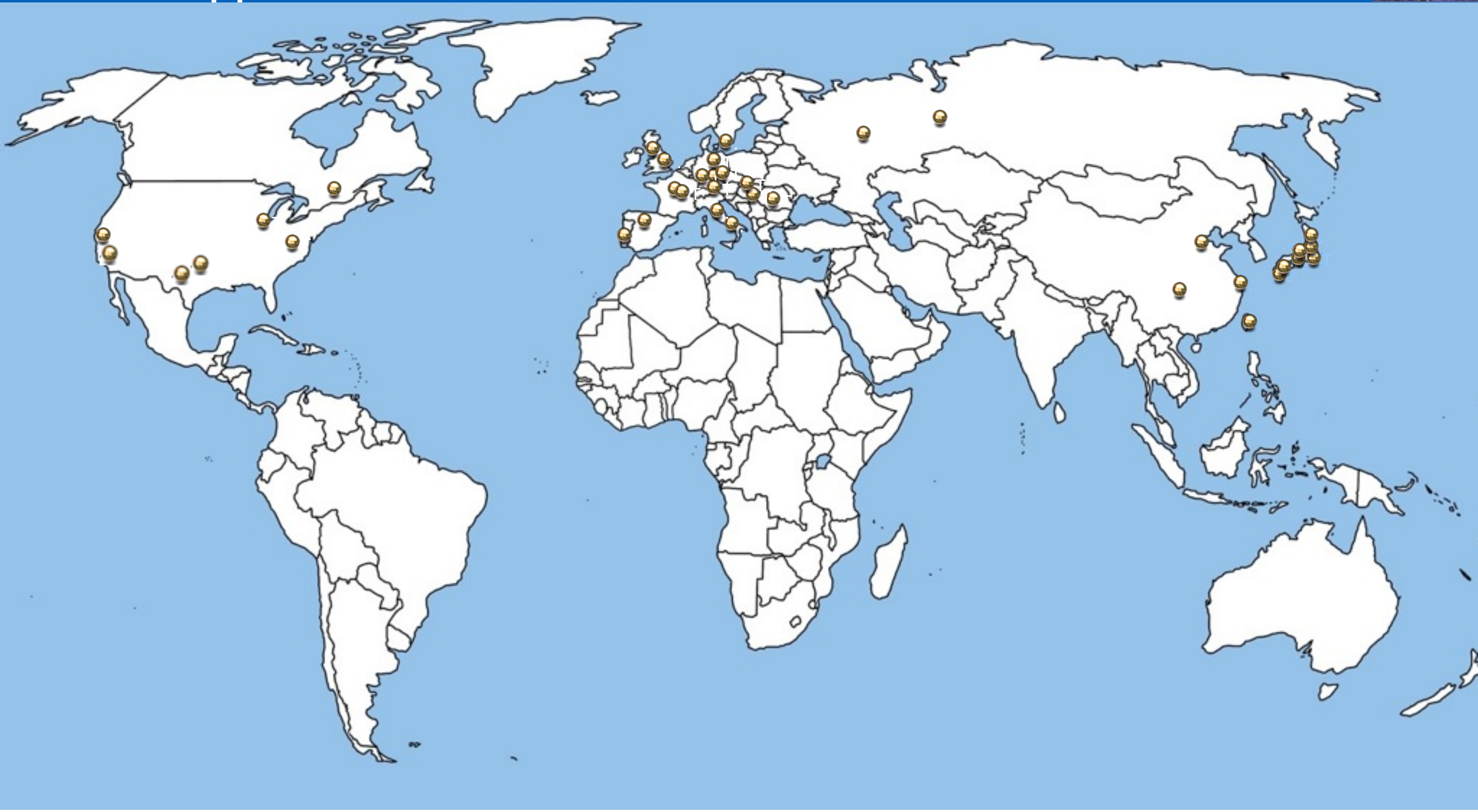




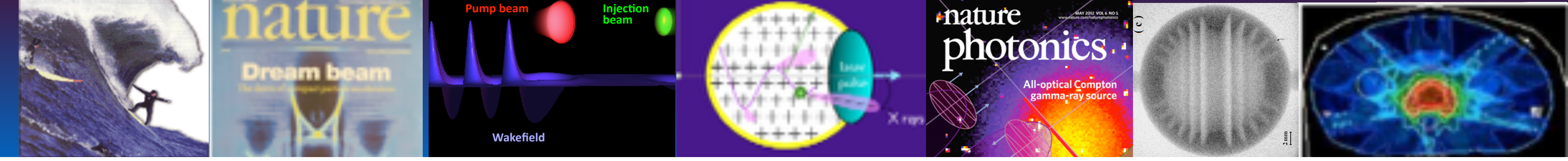
Courtesy of K. Krushelnick

V. Malka *et al.*, Nature Physics **4** (2008)
E. Esarey et al. , Rev. Mod. Phys. **81**, 1229 (2009)
S. Corde et al., Rev. of Modern Physics **85**, 1 (2013)

Laser plasma accelerator is a wonderful tool for Science, for Societal applications and for Academic Activities



Acknowledgements



A. Ben Ismail, S. Corde, J. Faure, S. Fritzler, Y. Glinec, A. Lifshitz, R. Lehe, O. Lundh, C. Rechatin, Kim Ta Phuoc, A. Rousse, and C. Thaury from LOA

E. Lefebvre and X. Davoine from CEA/DAM

CARE/FP6-Euroleap/FP6-Accel1/ANR-PARIS/ERC contracts