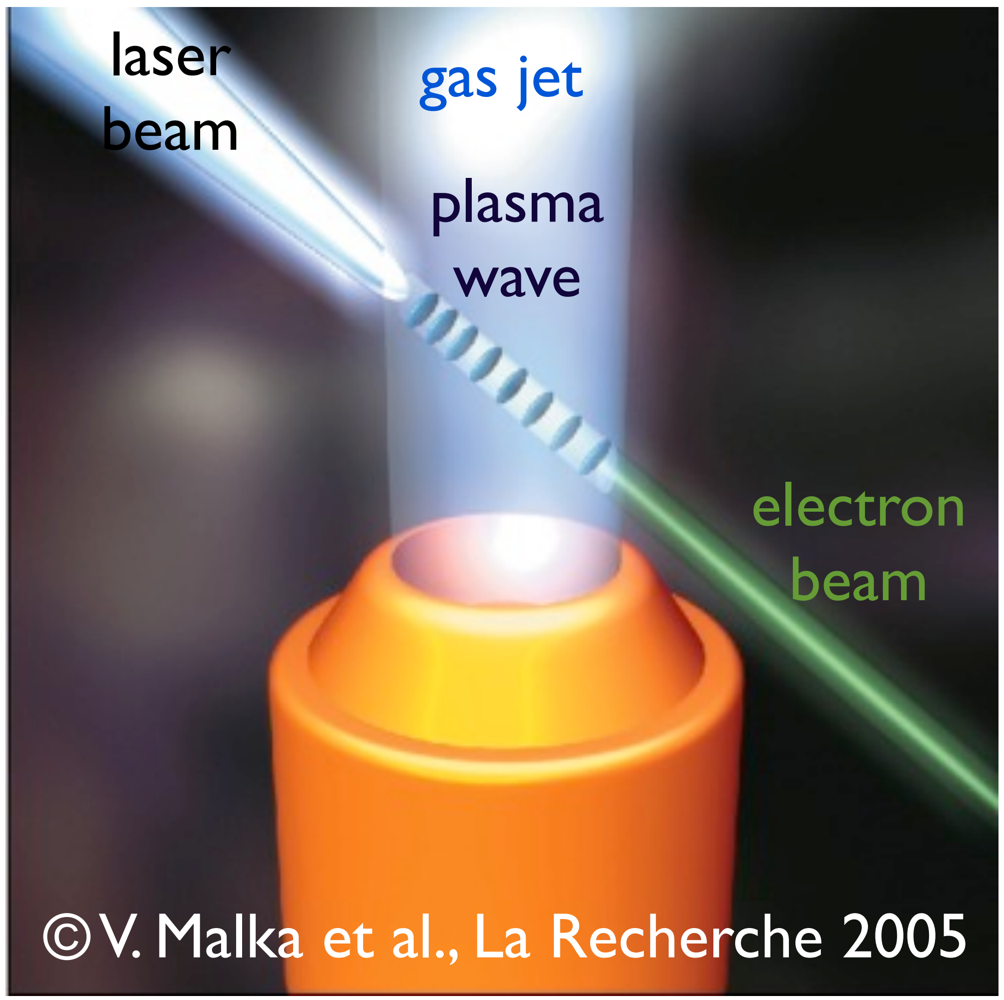
Laser Plasma Accelerators



Victor Malka

Laboratoire d'Optique Appliquée

ENSTA ParisTech – Ecole Polytechnique – CNRS
PALAISEAU, France

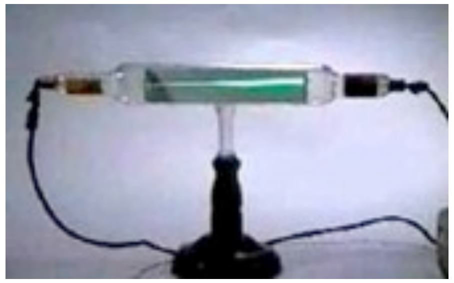
victor.malka@ensta.fr

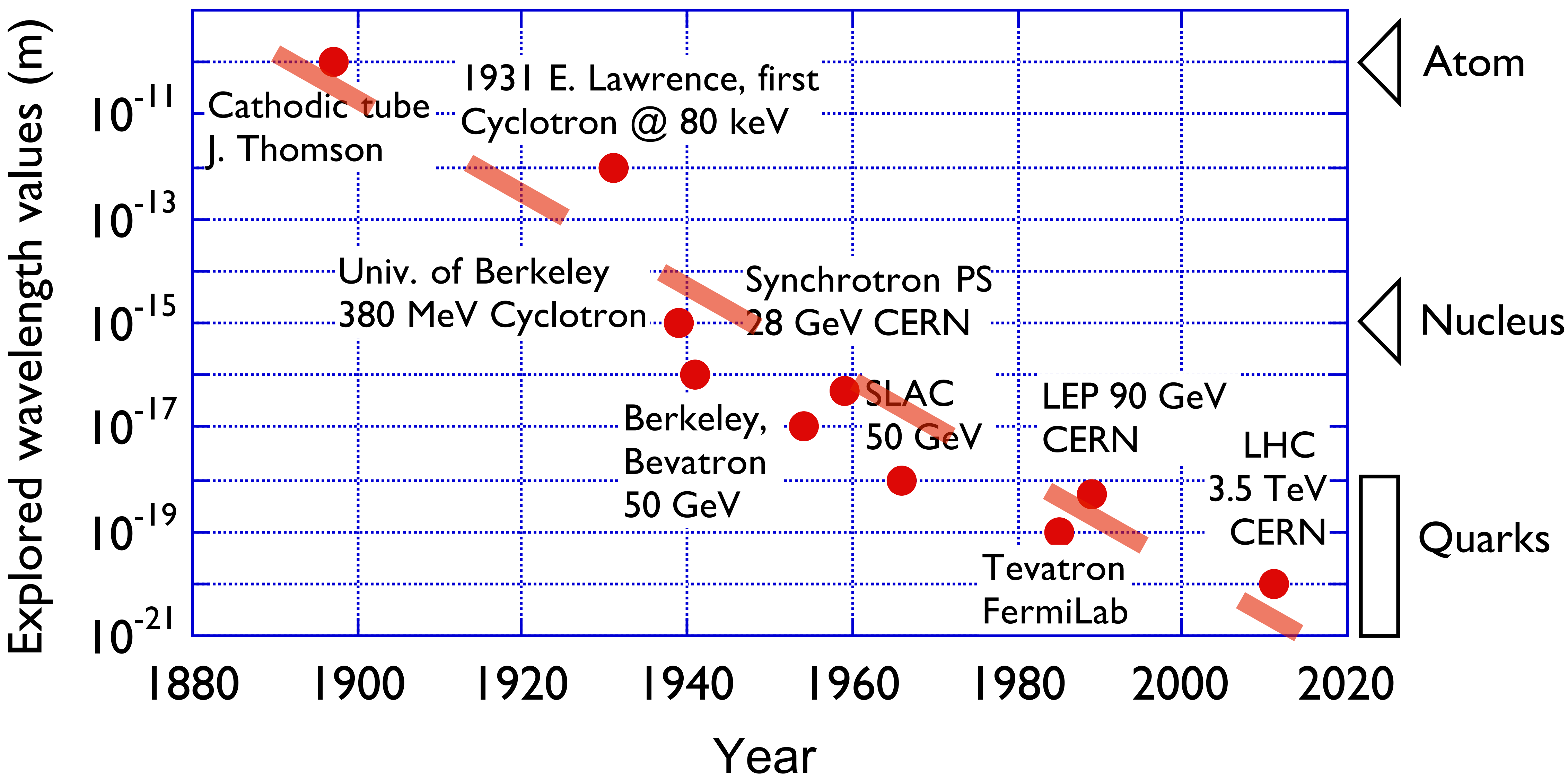
Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Colliding laser pulses regime
- Compton scattering X ray beam
- Conclusion and perspectives

- Introduction : context and motivations
- Colliding laser pulses regime
- Compton scattering X ray beam
- Conclusion and perspectives

Accelerators : One century of exploration of the infinitively small





Industrial Market for Accelerators

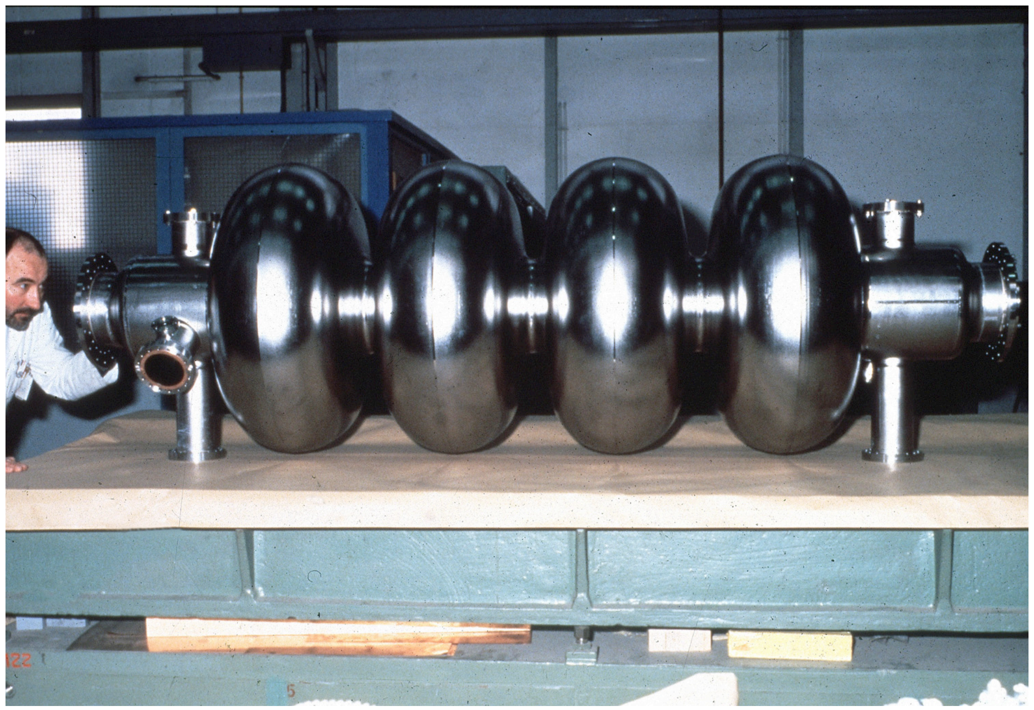
The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

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

Compactness of Laser Plasma Accelerators

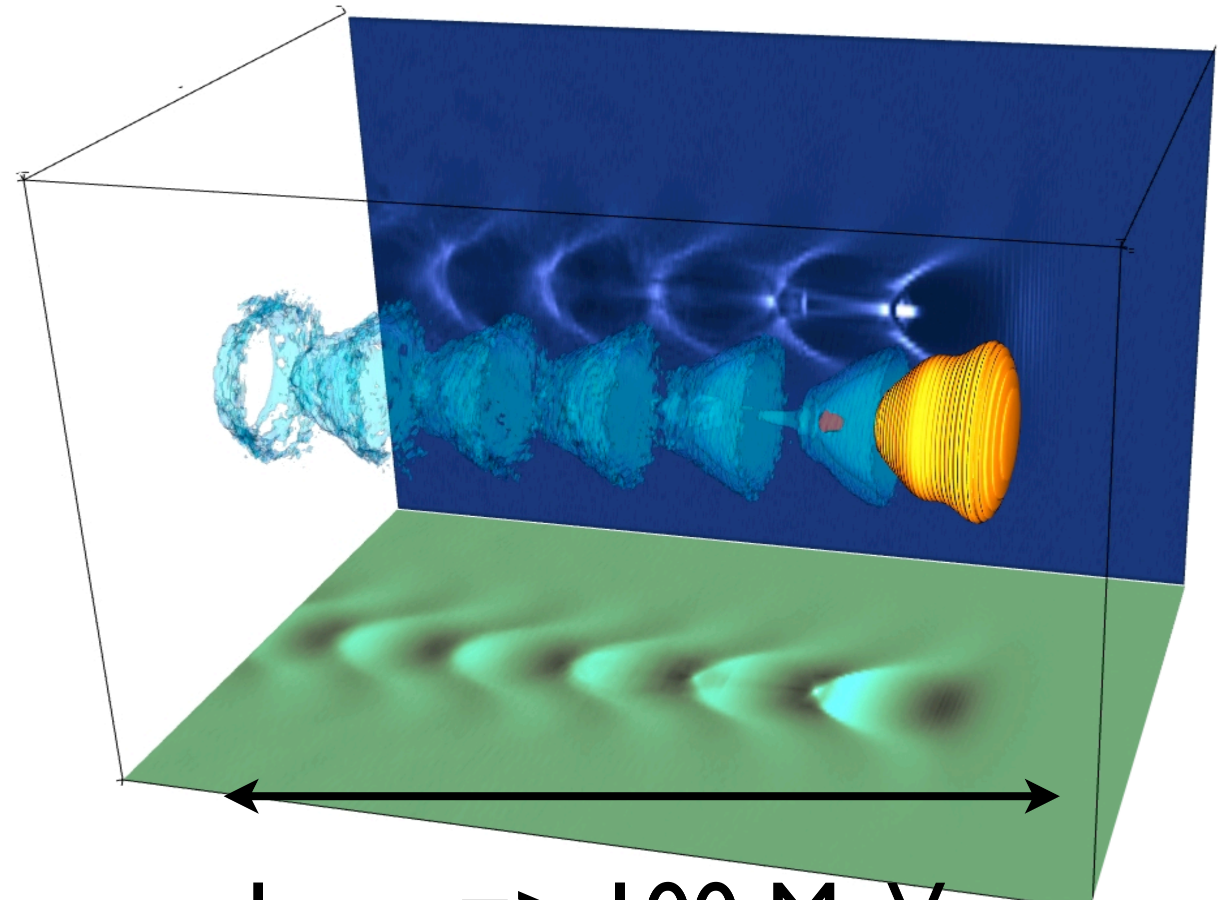
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

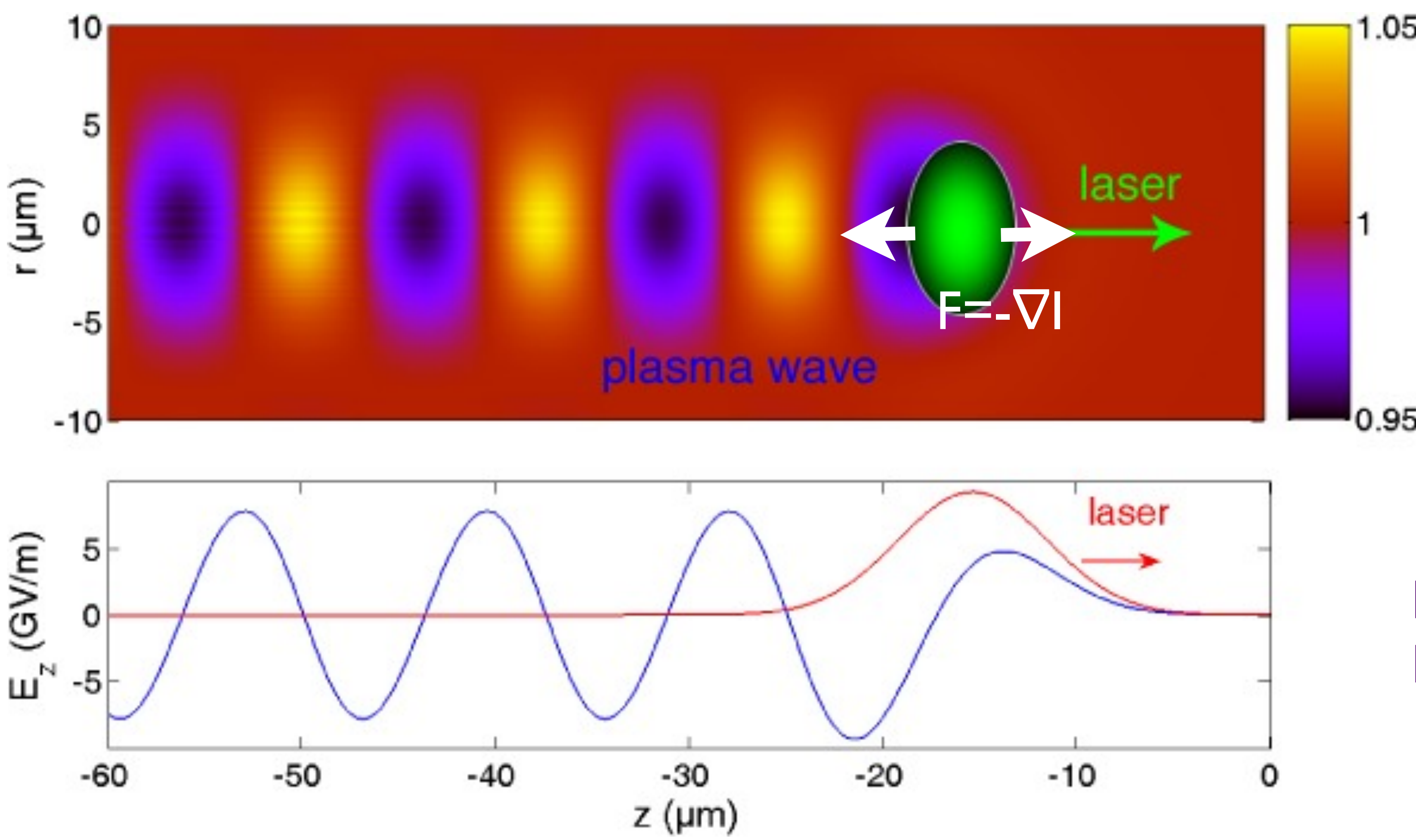
Electric field > 100 GV/m

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

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



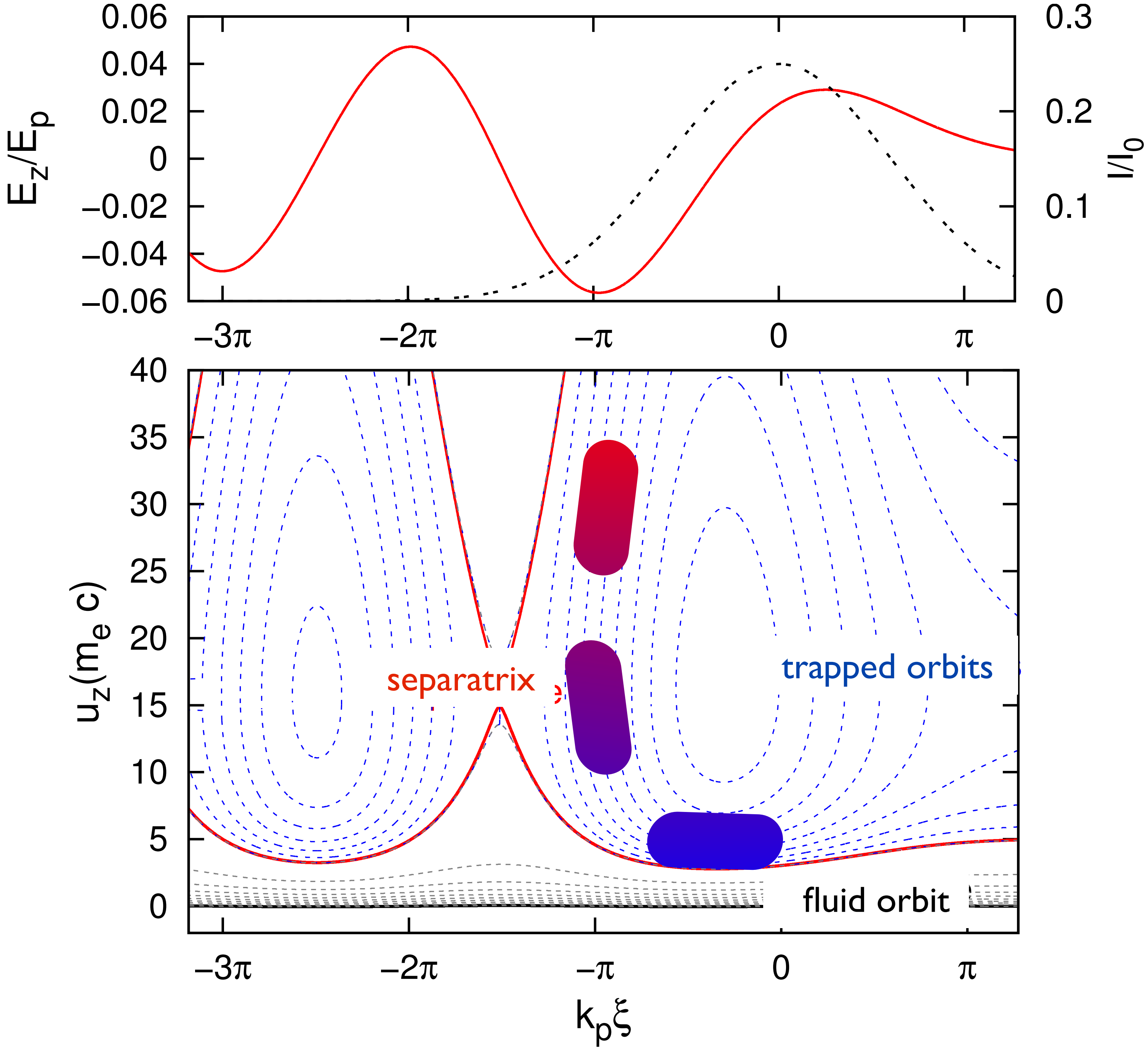
wave in the wake of a boat

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)

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 :

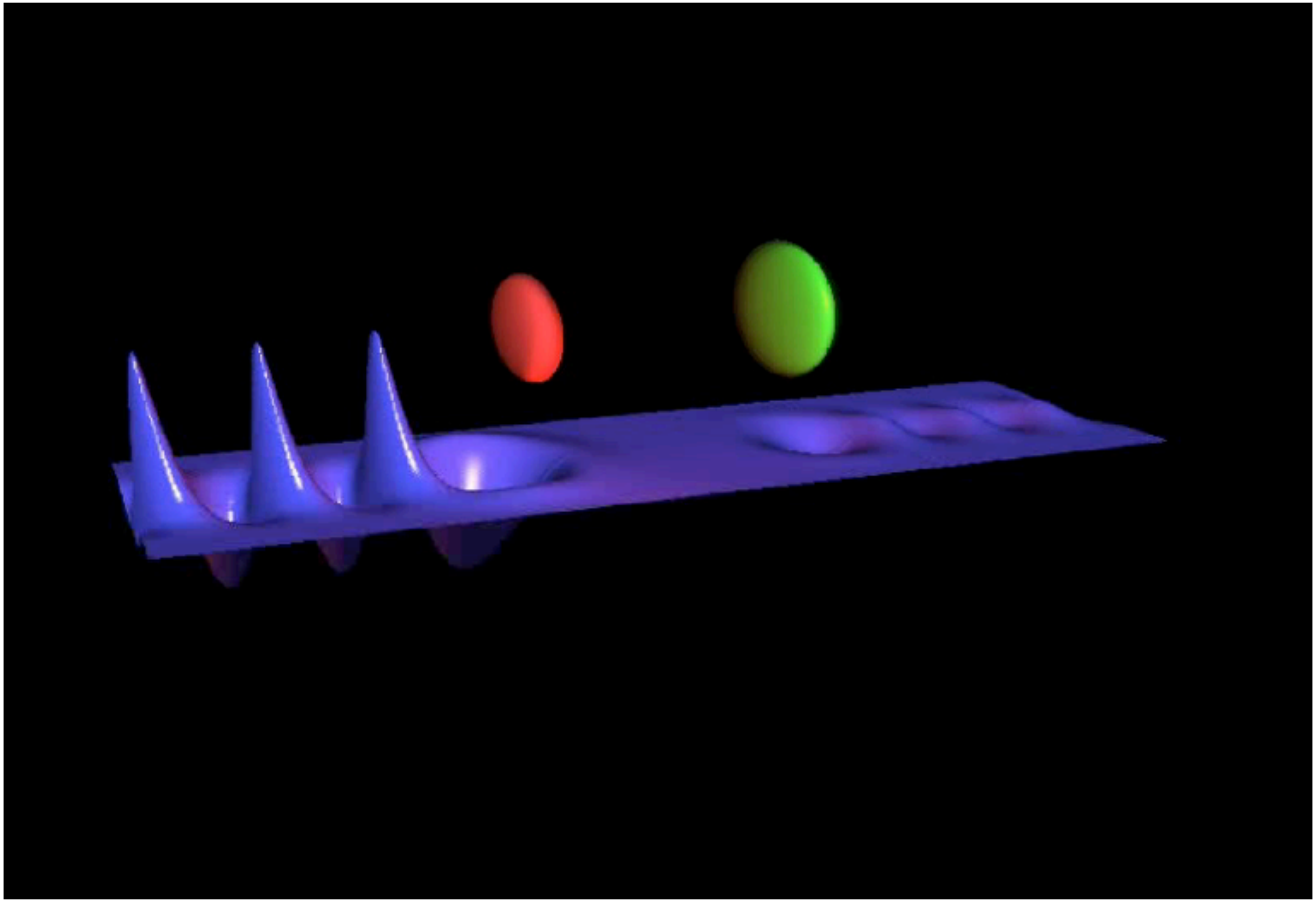
- Size≈ µm
- Length≈ µm (fs)
- Synchronization ≈ fs
- Controle ?

=> very challenging with conventional accelerator

- Introduction : context and motivations
- **Colliding laser pulses regime**
- Compton scattering X ray beam
- Conclusion and perspectives

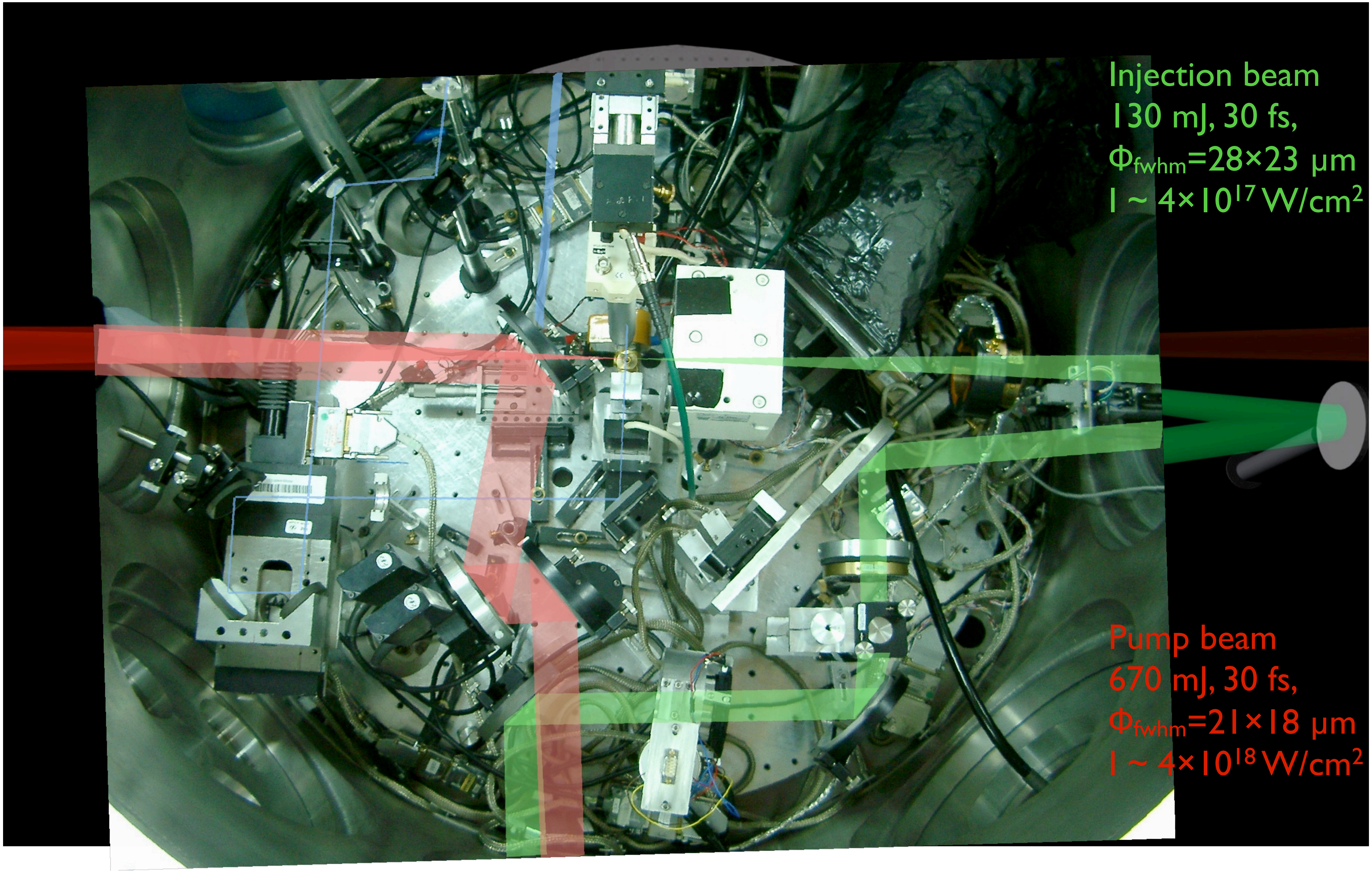
Colliding Laser Pulses Scheme

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

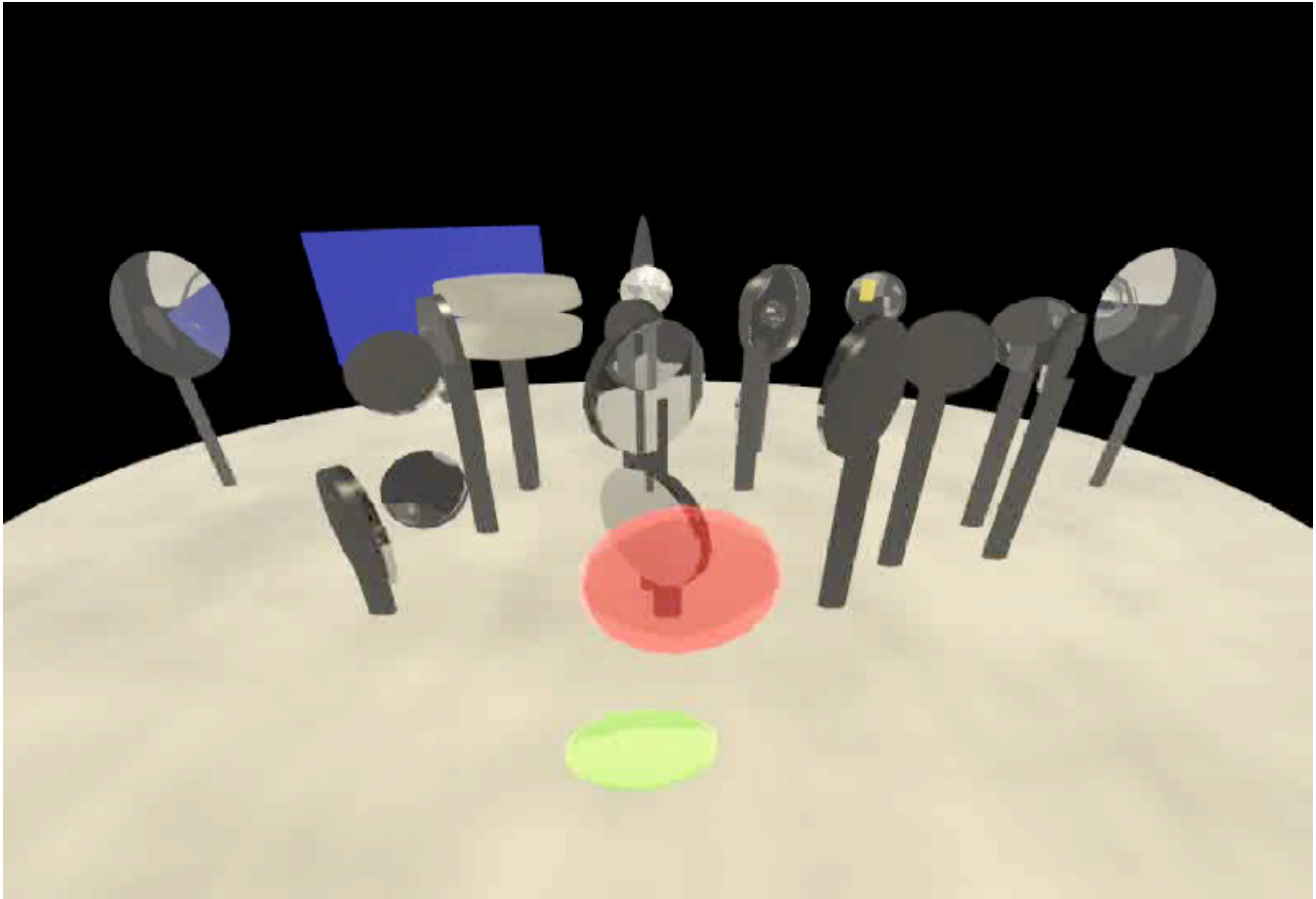


Theory : E. Esarey *et al.*, PRL **79**, 2682 (1997), H. Kotaki *et al.*, PoP **11** (2004)
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

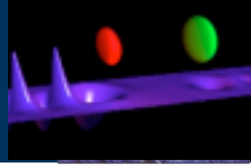
Set-up for colliding pulses experiment



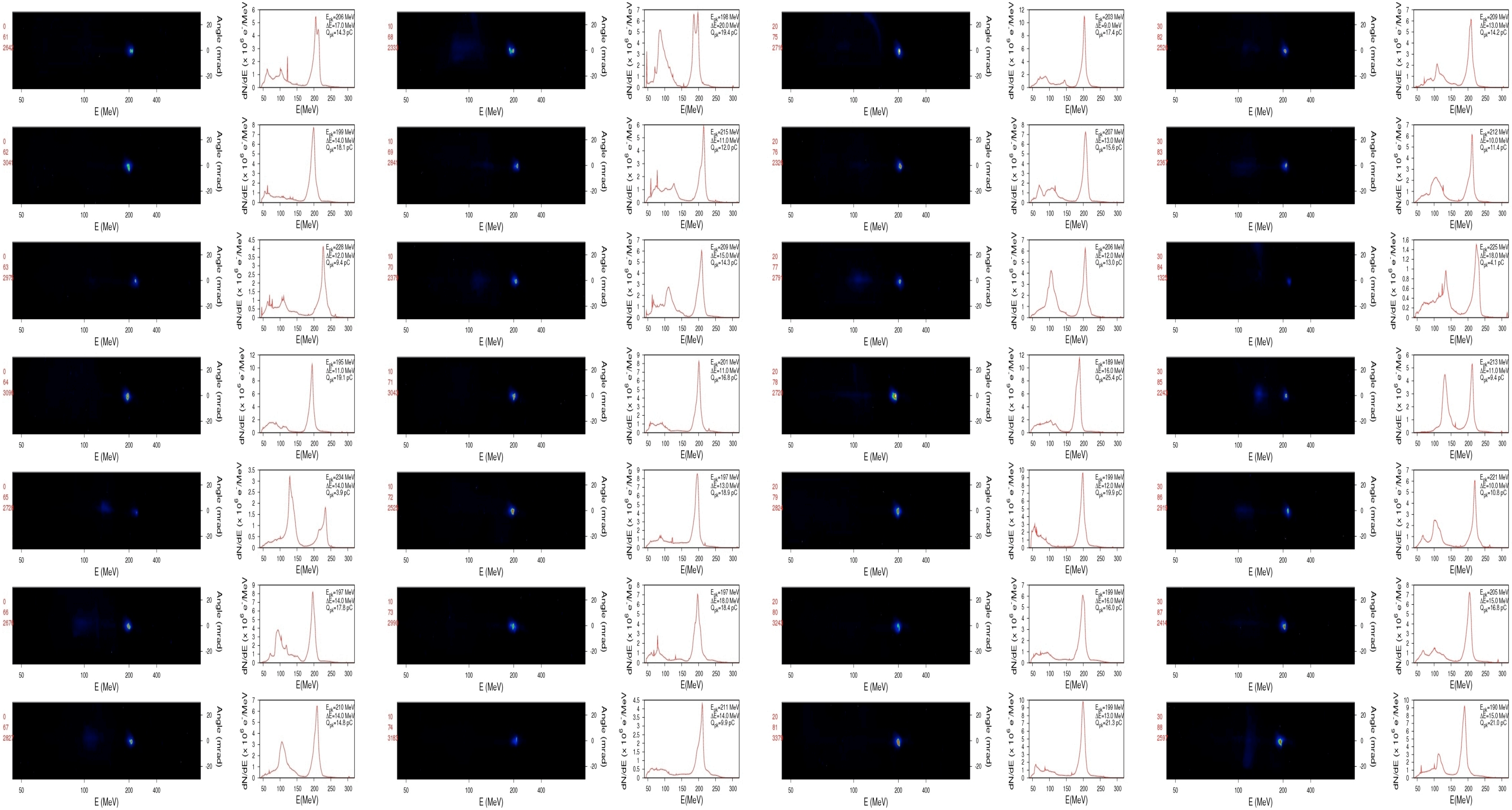
The colliding of two laser pulses scheme



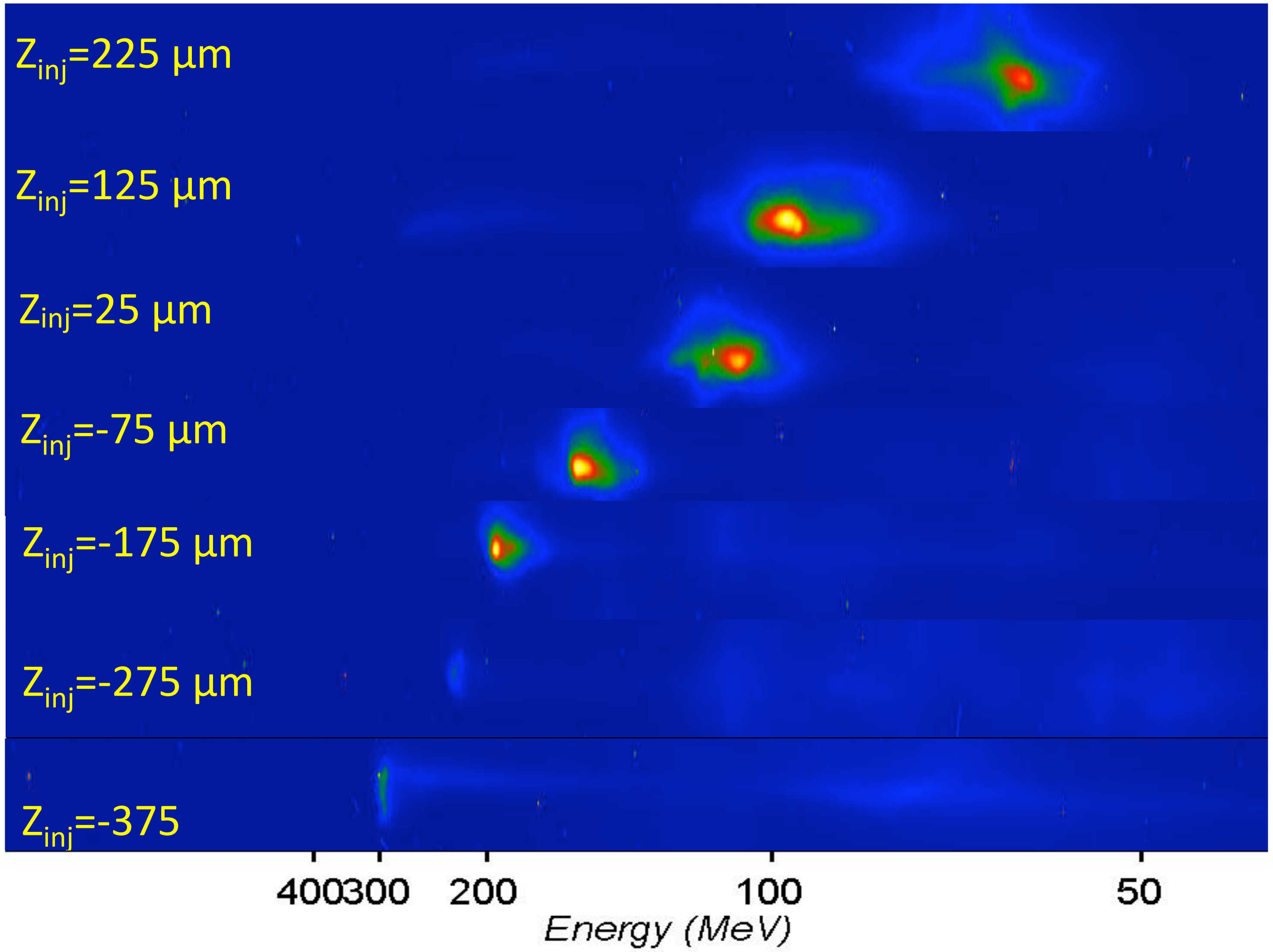
Towards a Stable Laser Plasma Accelerators

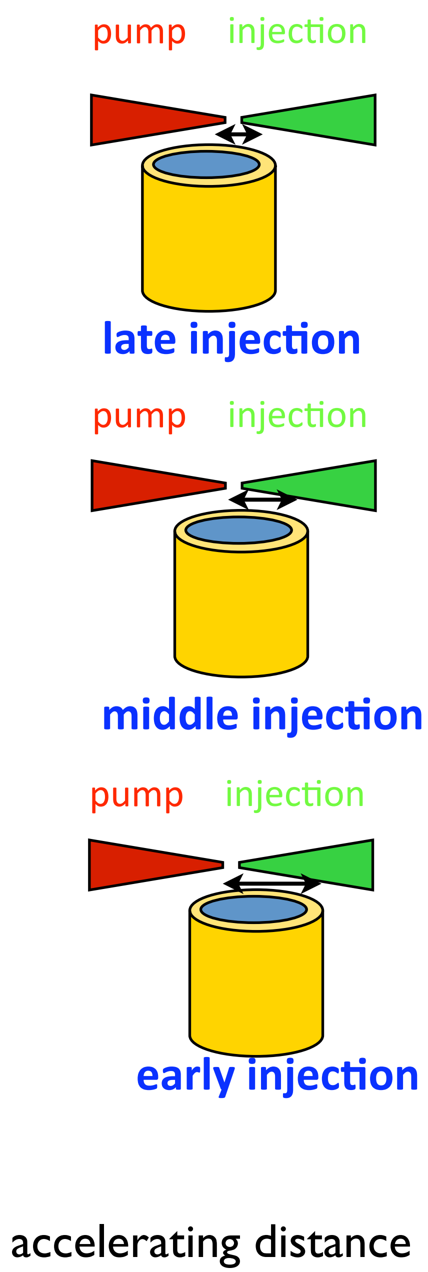


Series of 28 consecutive shots with : a_0=1.5, a_1=0.4, $n_e=5.7\times10^{18}cm^{-3}$



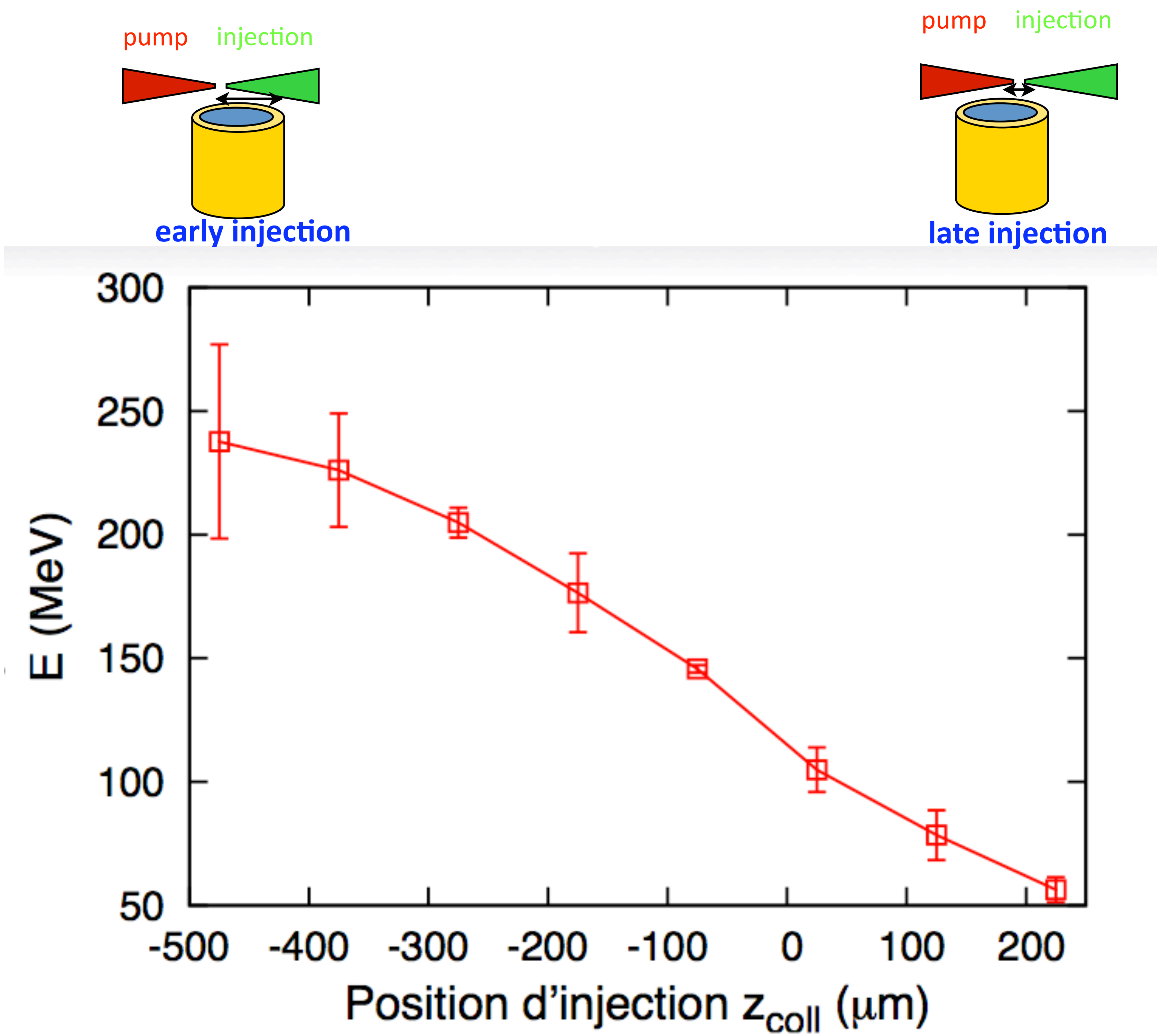
Tunability of Laser Plasma Accelerators : electrons energy





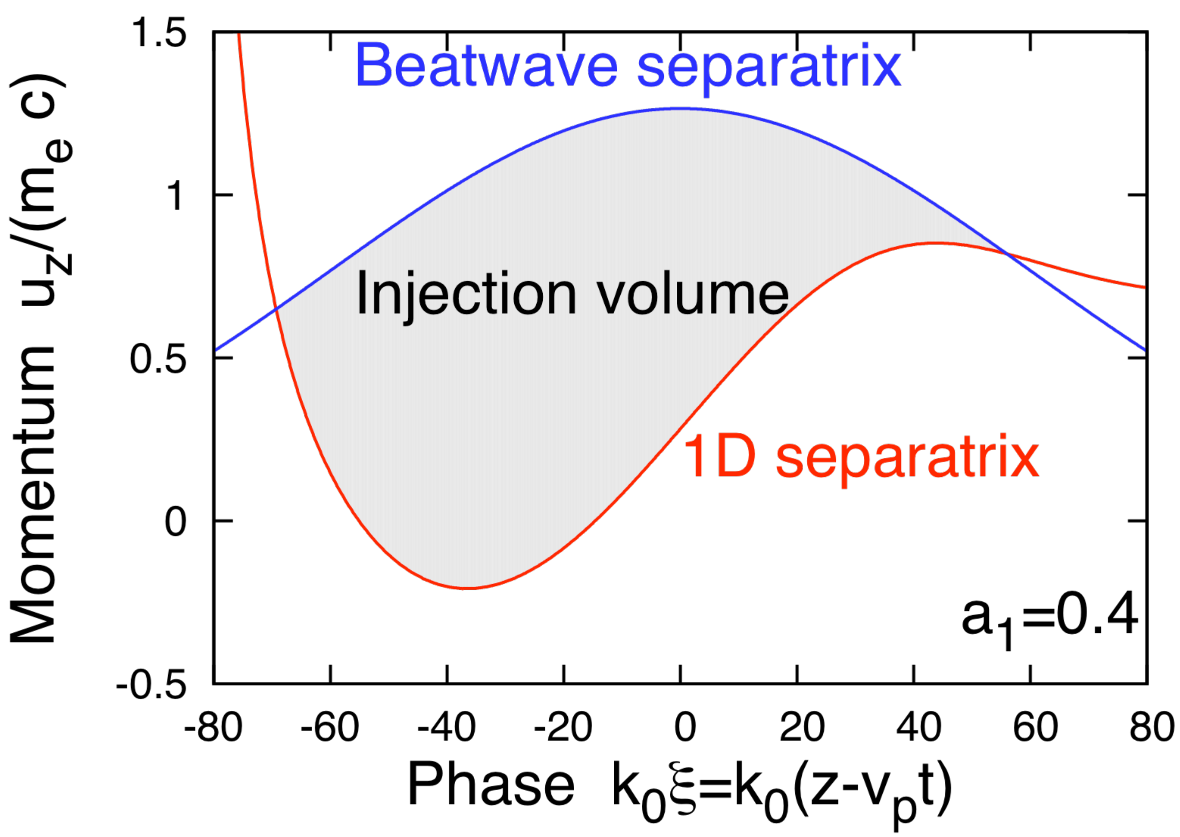
J. Faure *et al.*, Nature **444**, 737 (2006)

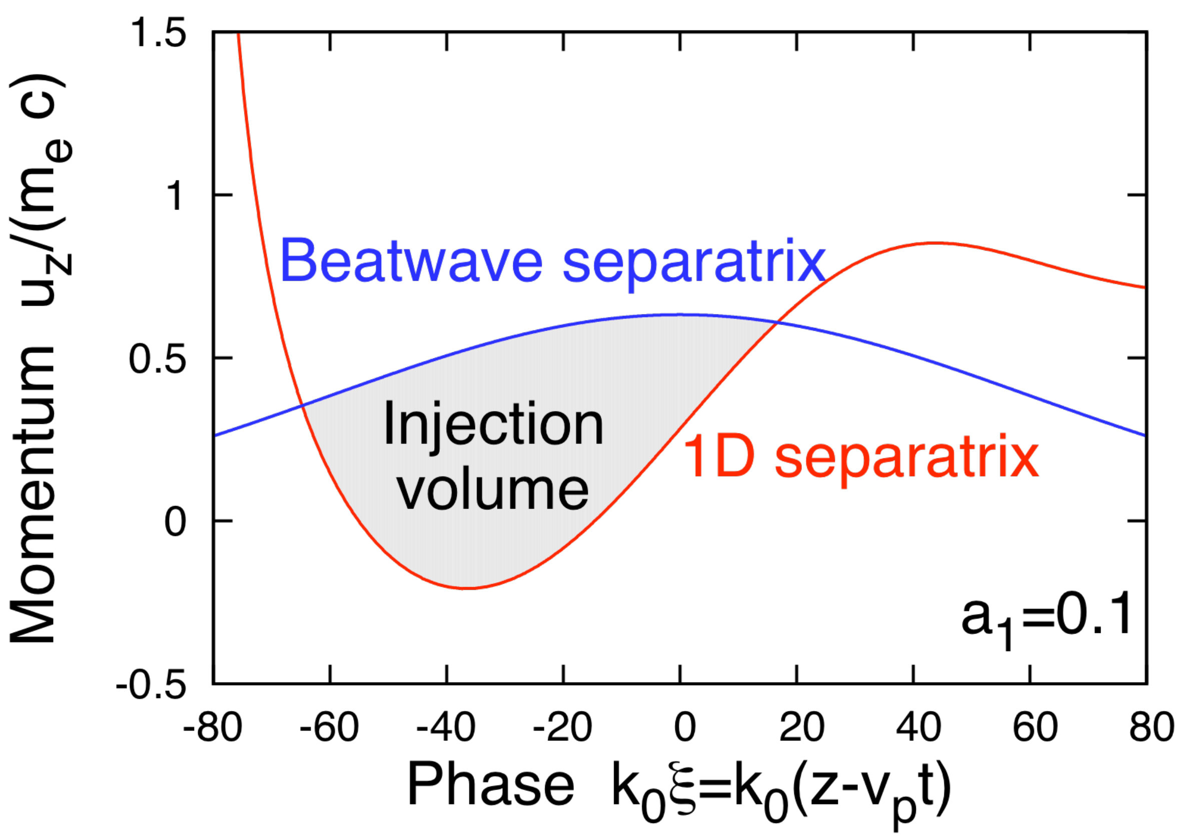
Tunability of Laser Plasma Accelerators : electrons energy



Tunability of Plasma Accelerators: charge & energy spread

<u>Charge</u> : controlling electrons heating processes => smaller $a_{inj.}$ means less heating and less trapping
<u>Energy spread</u> : 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)

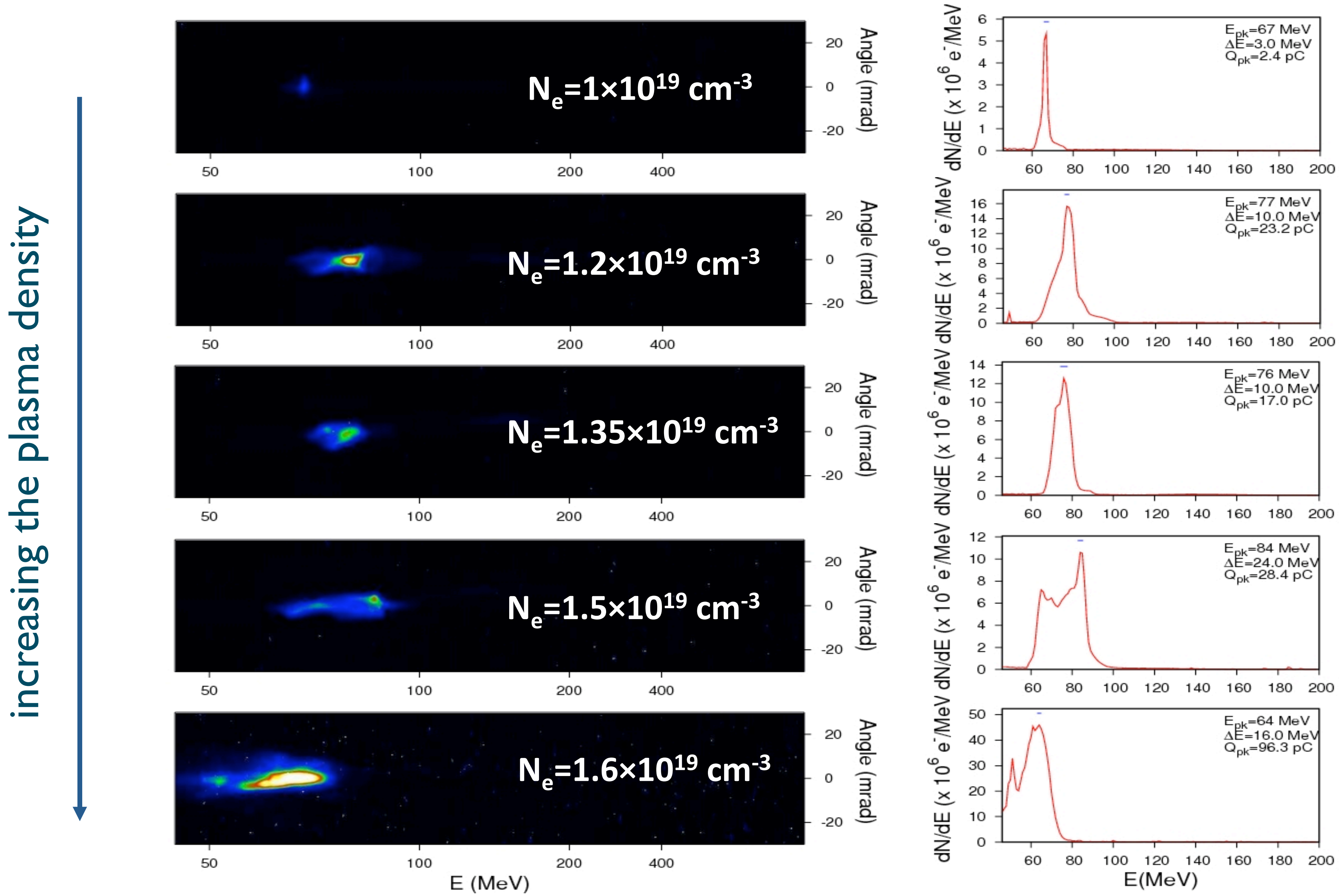




Evolution of injection volume with a_1 for $a_0 = 2$, $n_e = 7\times10^{18} cm^{-3}$.
Fields are computed for the 1D case and the beatwave separatrix corresponds to the circular polarization case.

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 densiy



E=67 MeV
ΔE=3 MeV
Q_{pk}=2.4pC

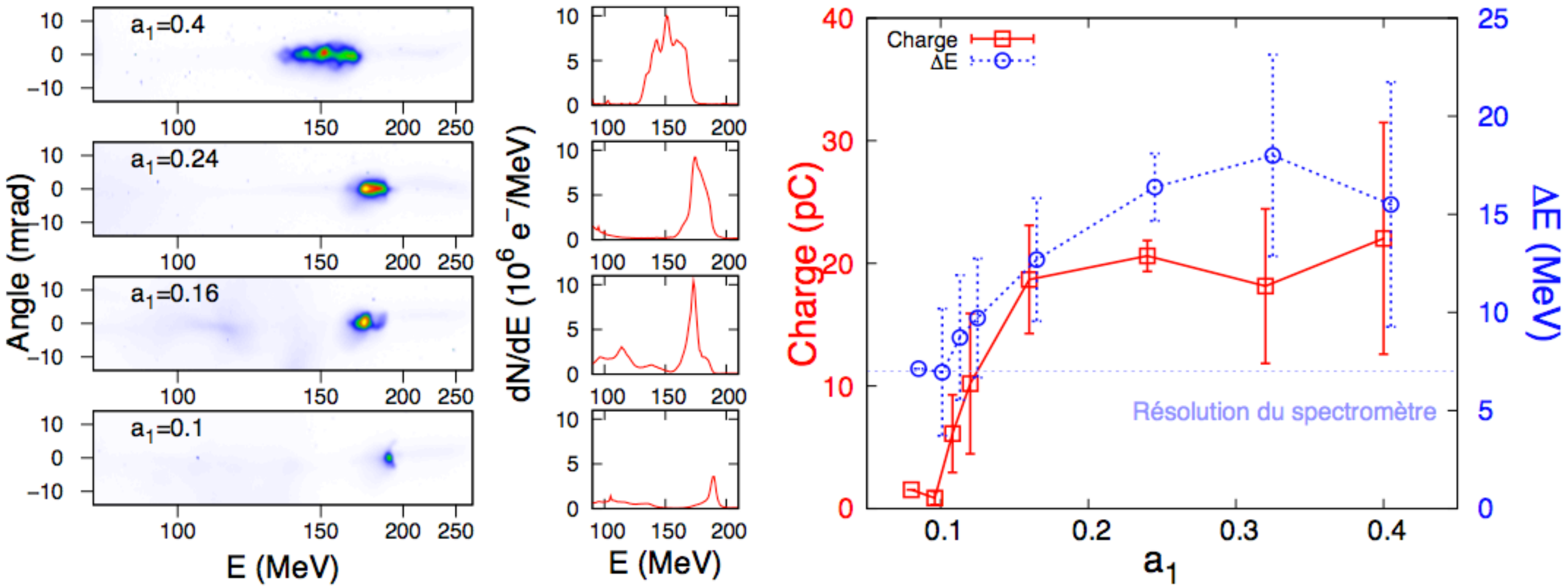
E=77 MeV
ΔE=10 MeV
Q_{pk}=23.2pC

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

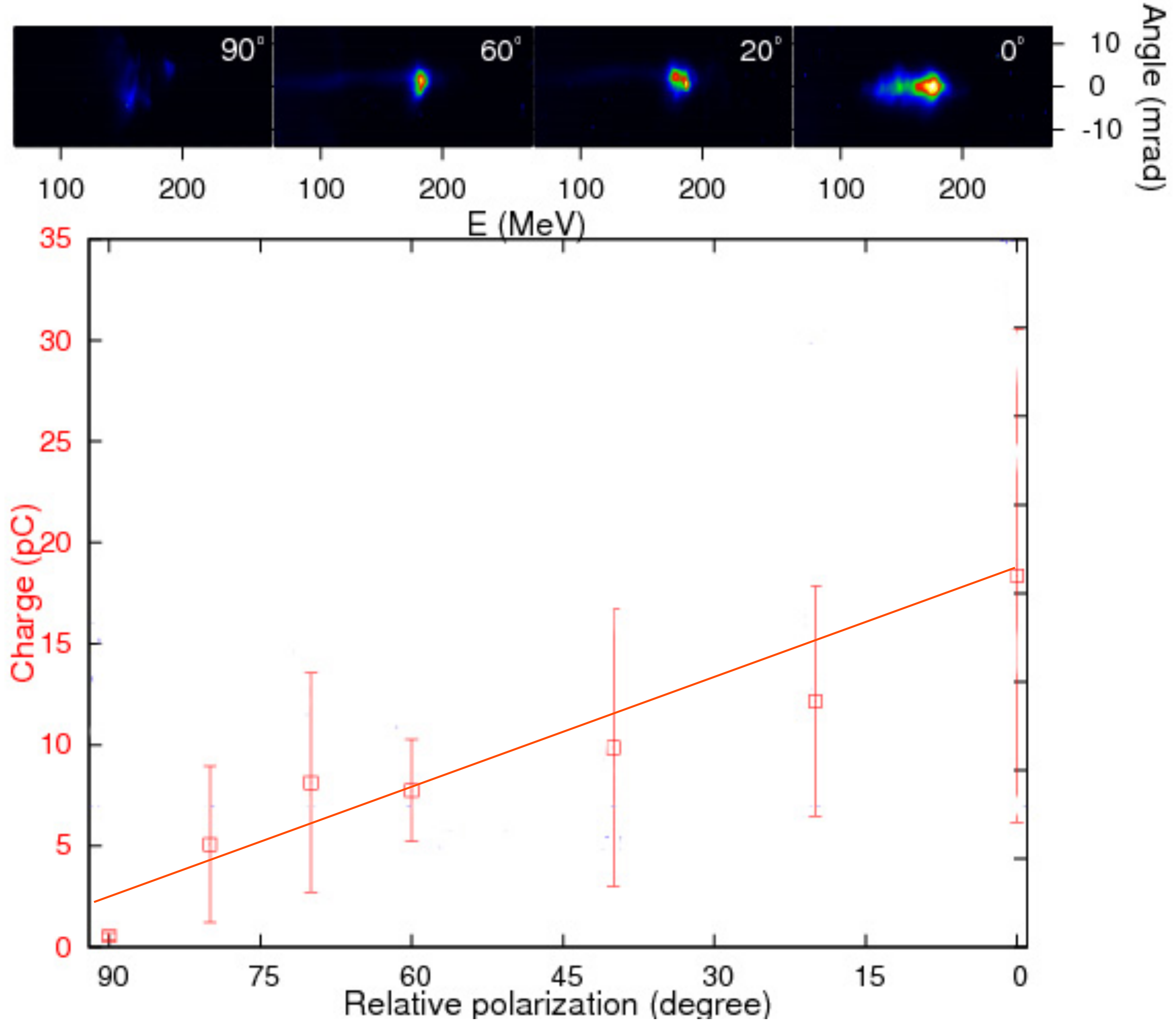
Tuning charge & energy spread with the inj. laser intensity



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

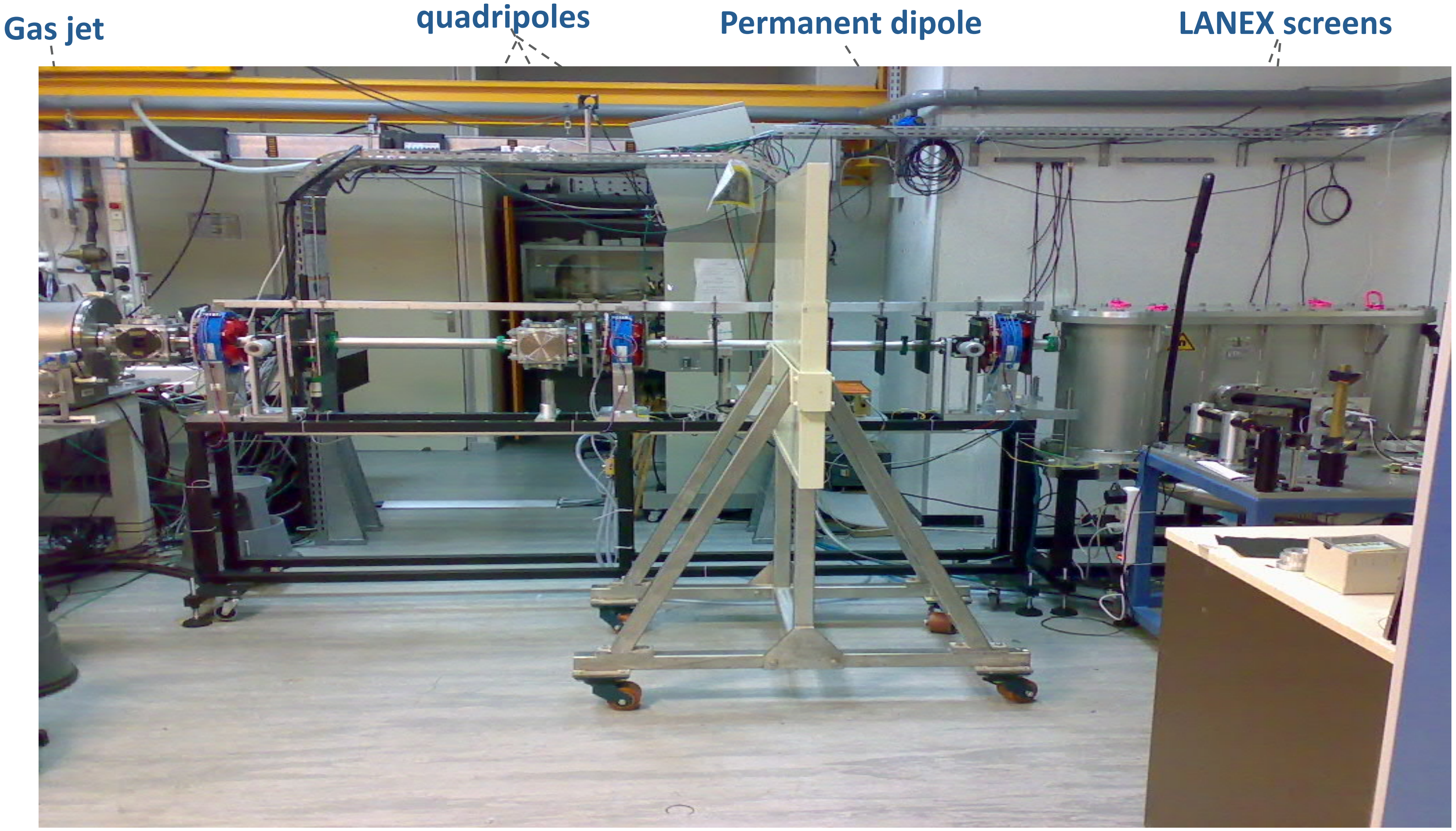
C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

Tuning charge & energy spread with the inj. laser intensity



C. Rechatin *et al.*, New Journal of Physics **11** (2009)

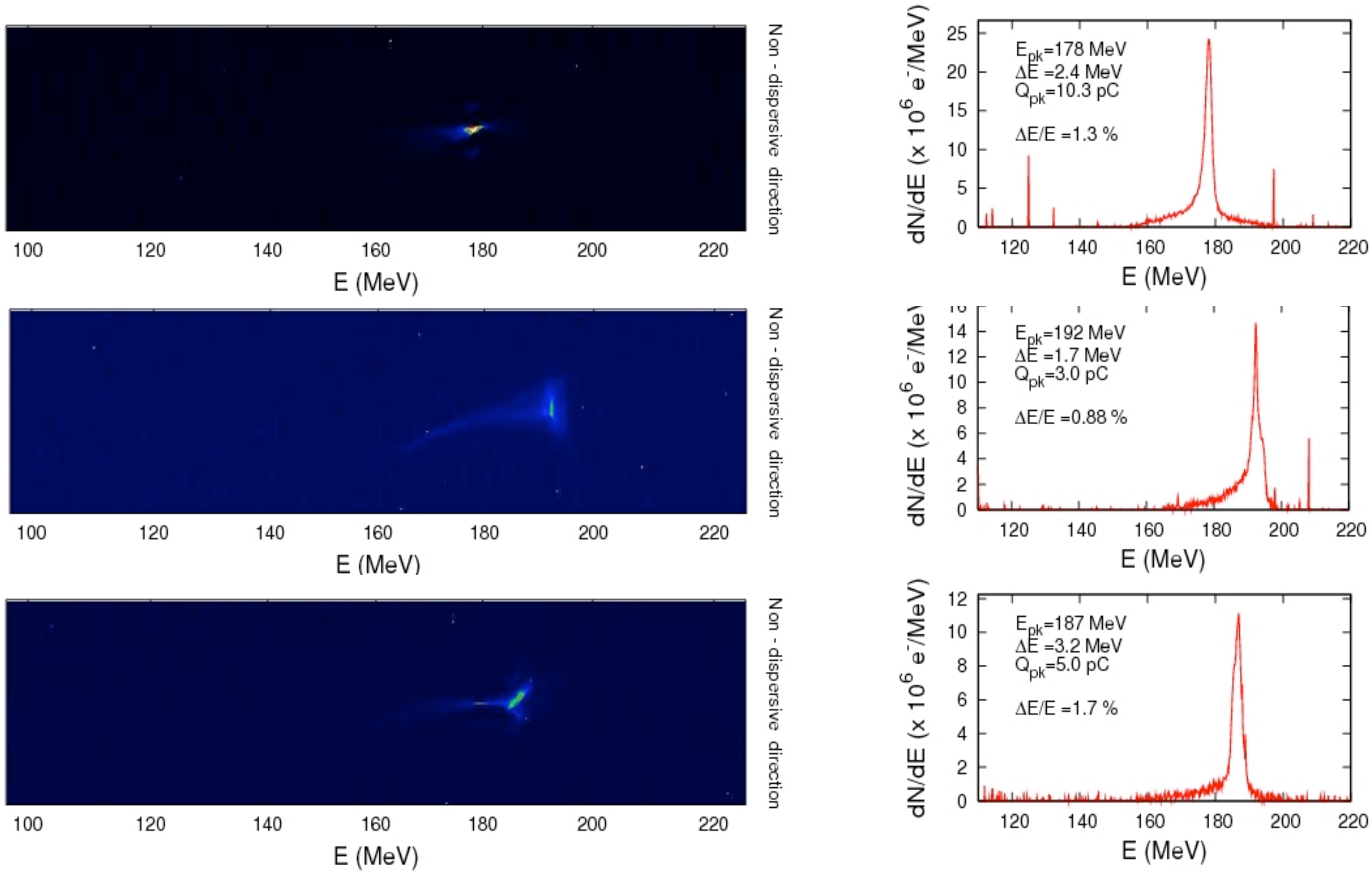
1 % energy spread has been measured



Resolution < 1 % expected

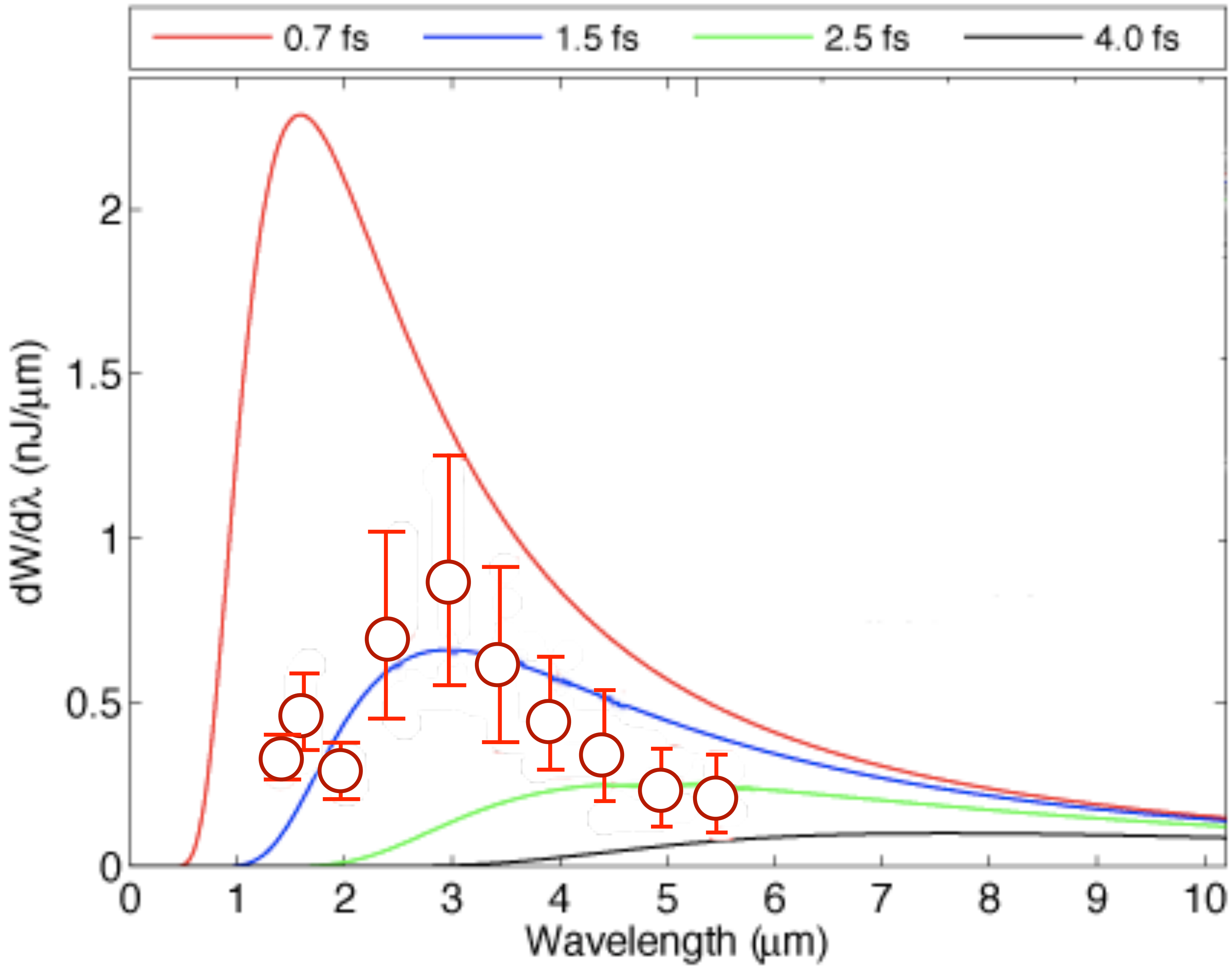
In collaboration with A. Specka, H. Videau
LLR, CNRS, Ecole Polytechnique

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

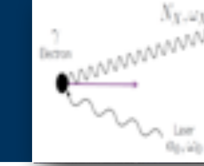
Peak at 3 µm

Coherent

1.5 fs RMS duration : Peak current of 4 kA

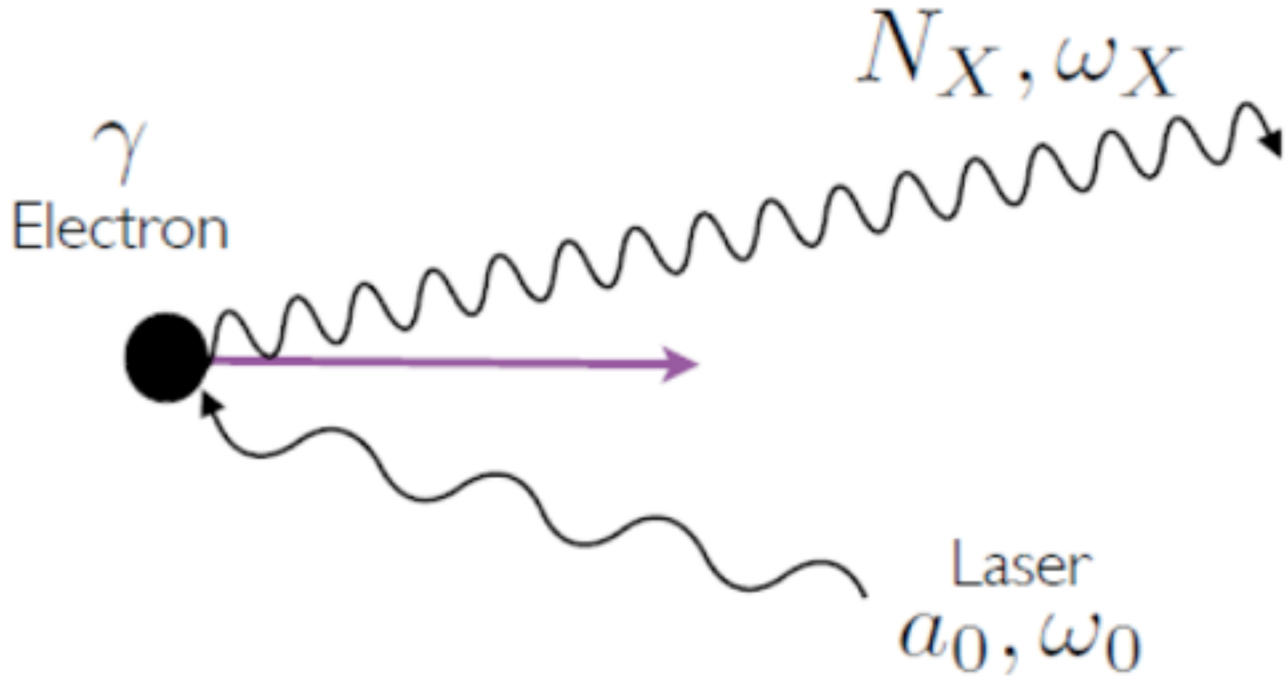
O. Lundh et al., Nature Physics, **7** (2011)

Laser Plasma Accelerators : Outline



- Introduction : context and motivations
- Colliding laser pulses regime
- **Compton scattering X ray beam**
- Conclusion and perspectives

Inverse Compton Scattering



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

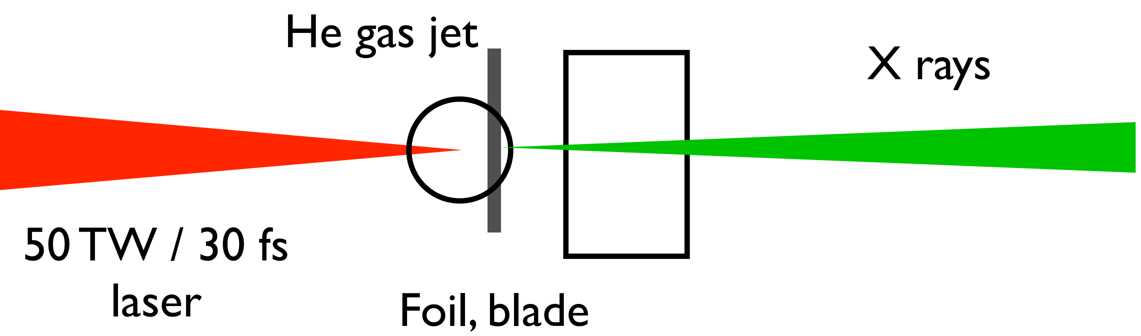
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

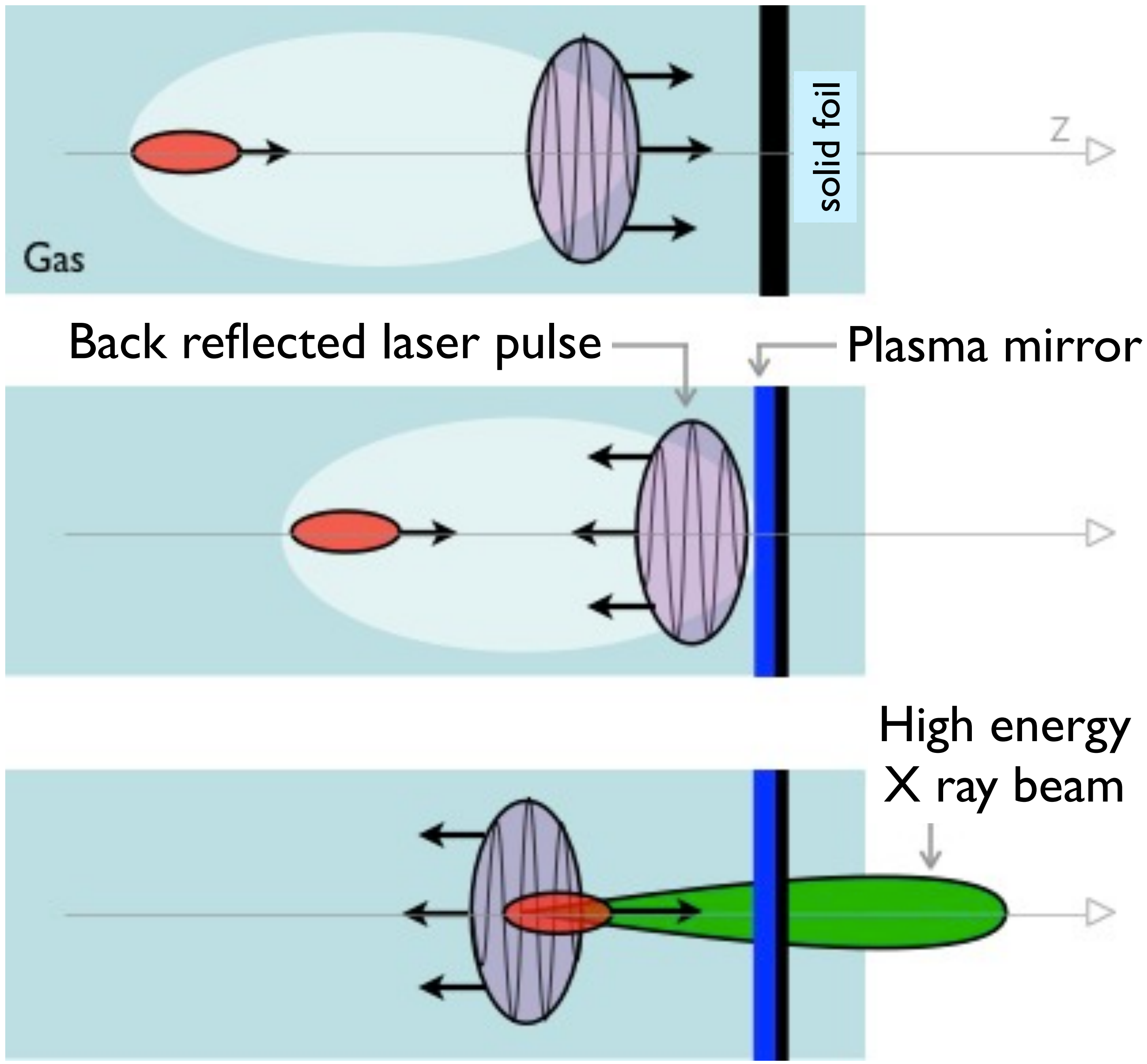
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

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

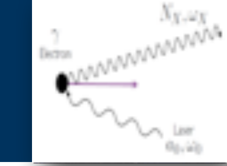
A plasma mirror reflects the laser beam

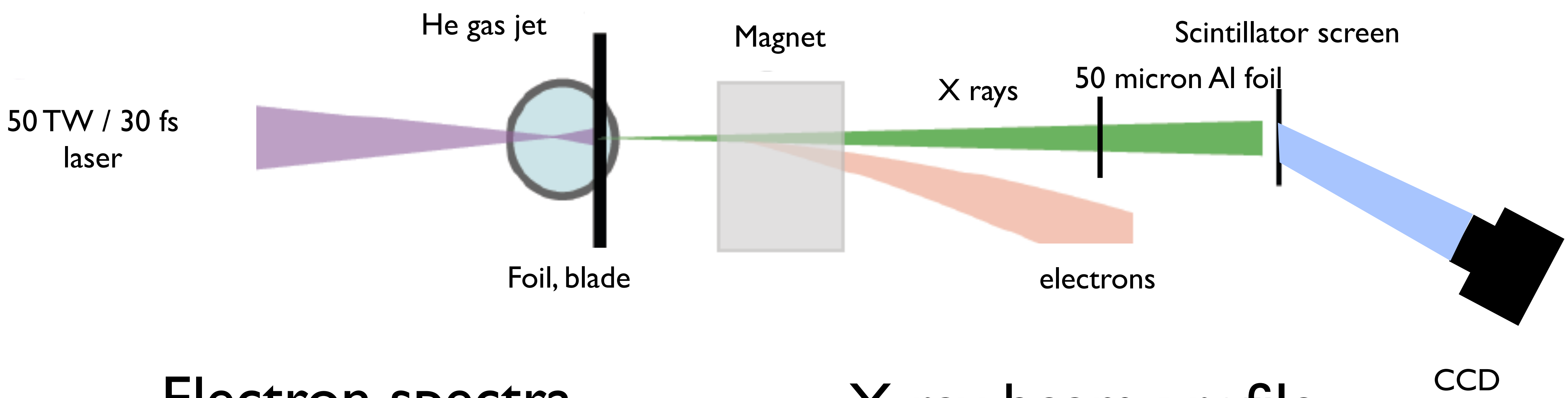
The back reflected laser collides with the accelerated electrons

No alignement : the laser and the electron beams naturally overlap

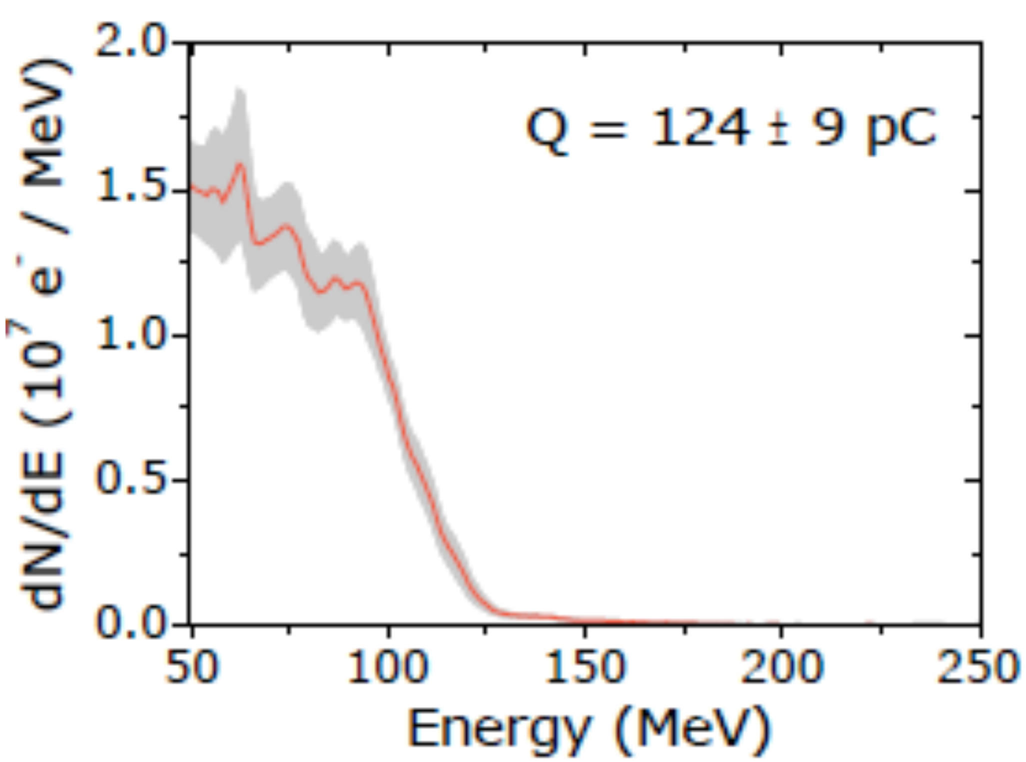
Save the laser energy !

Inverse Compton Scattering : Experimental set-up

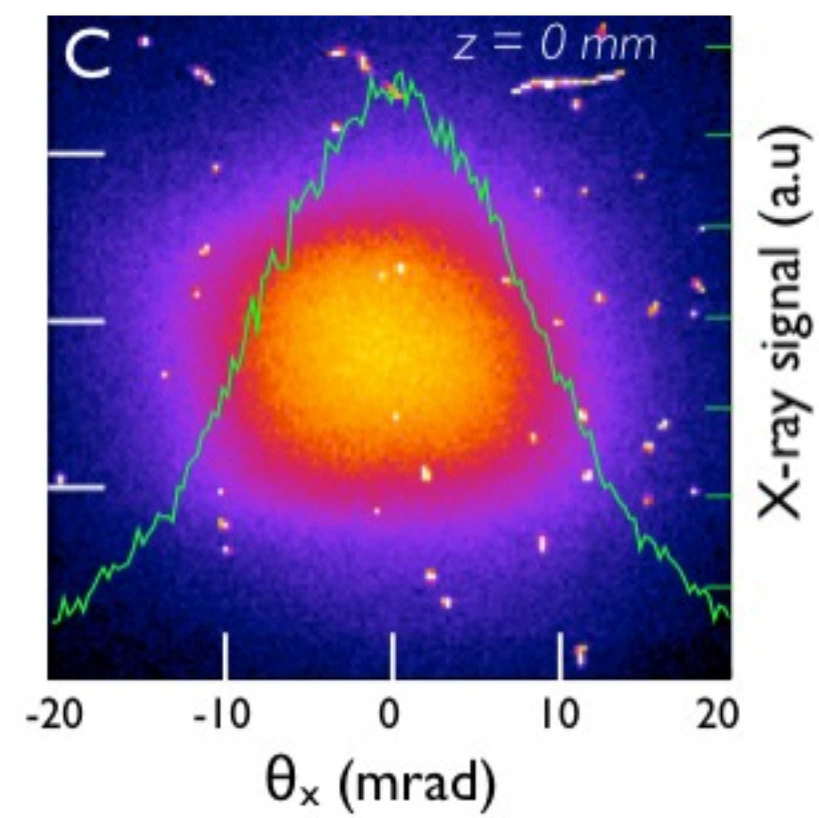




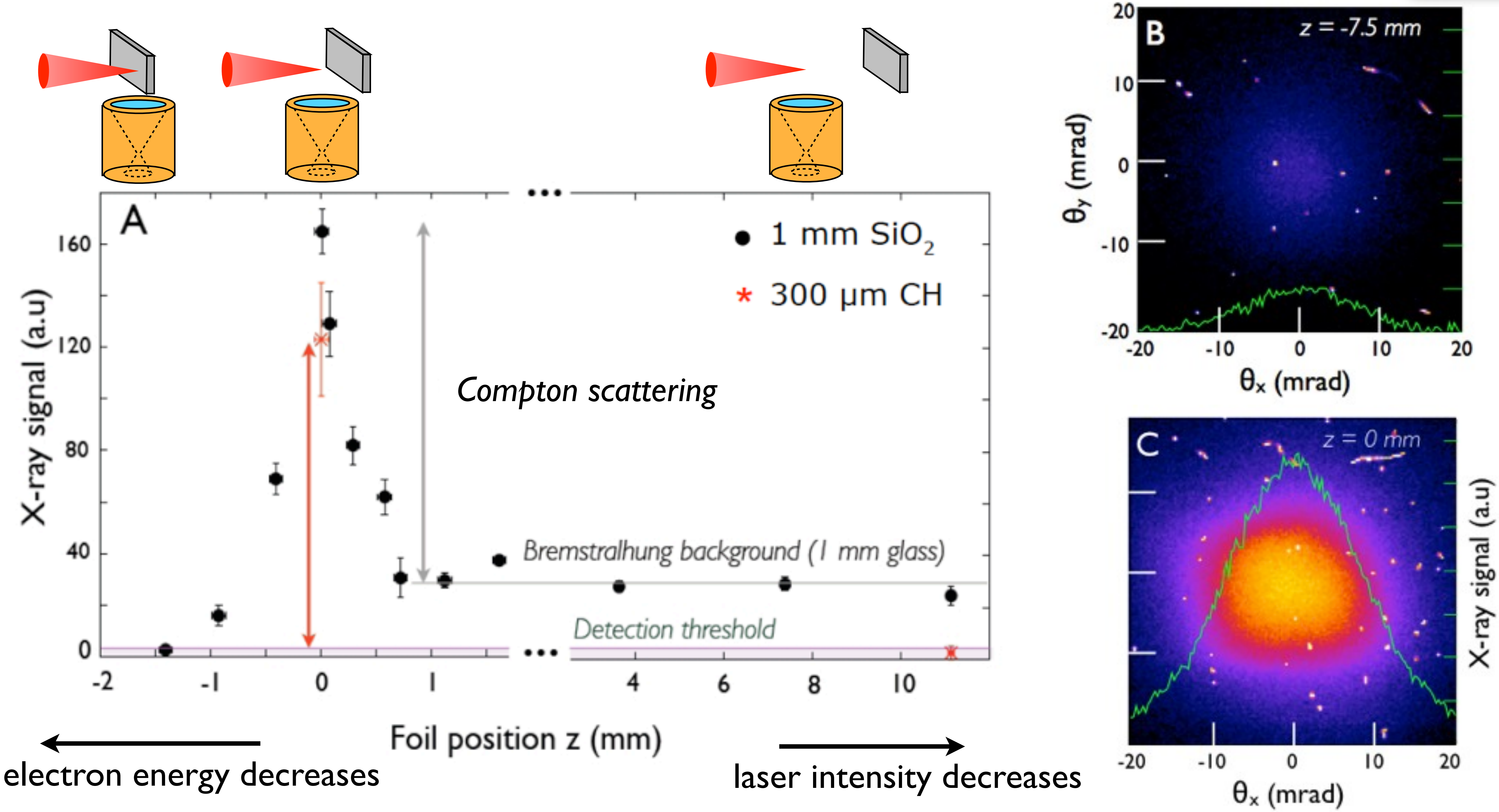
Electron spectra



X ray beam profile

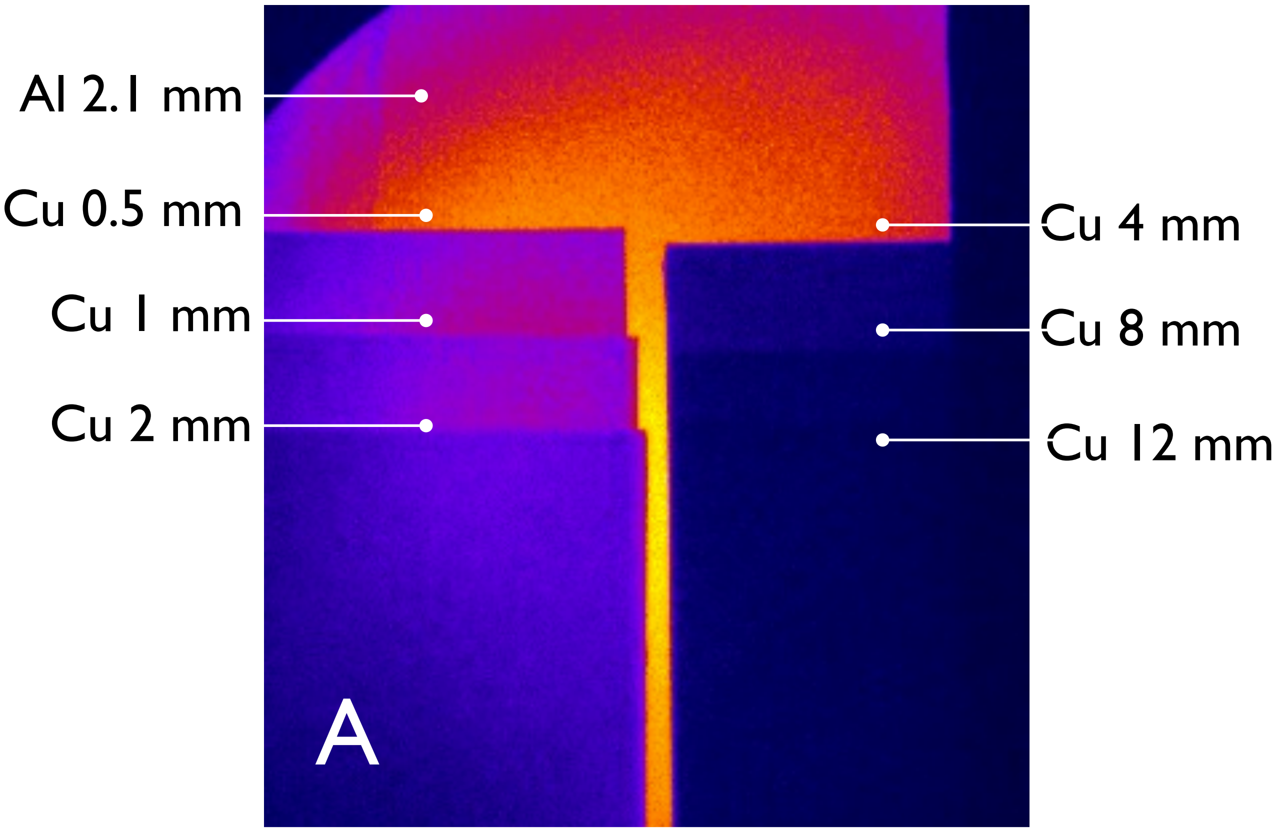


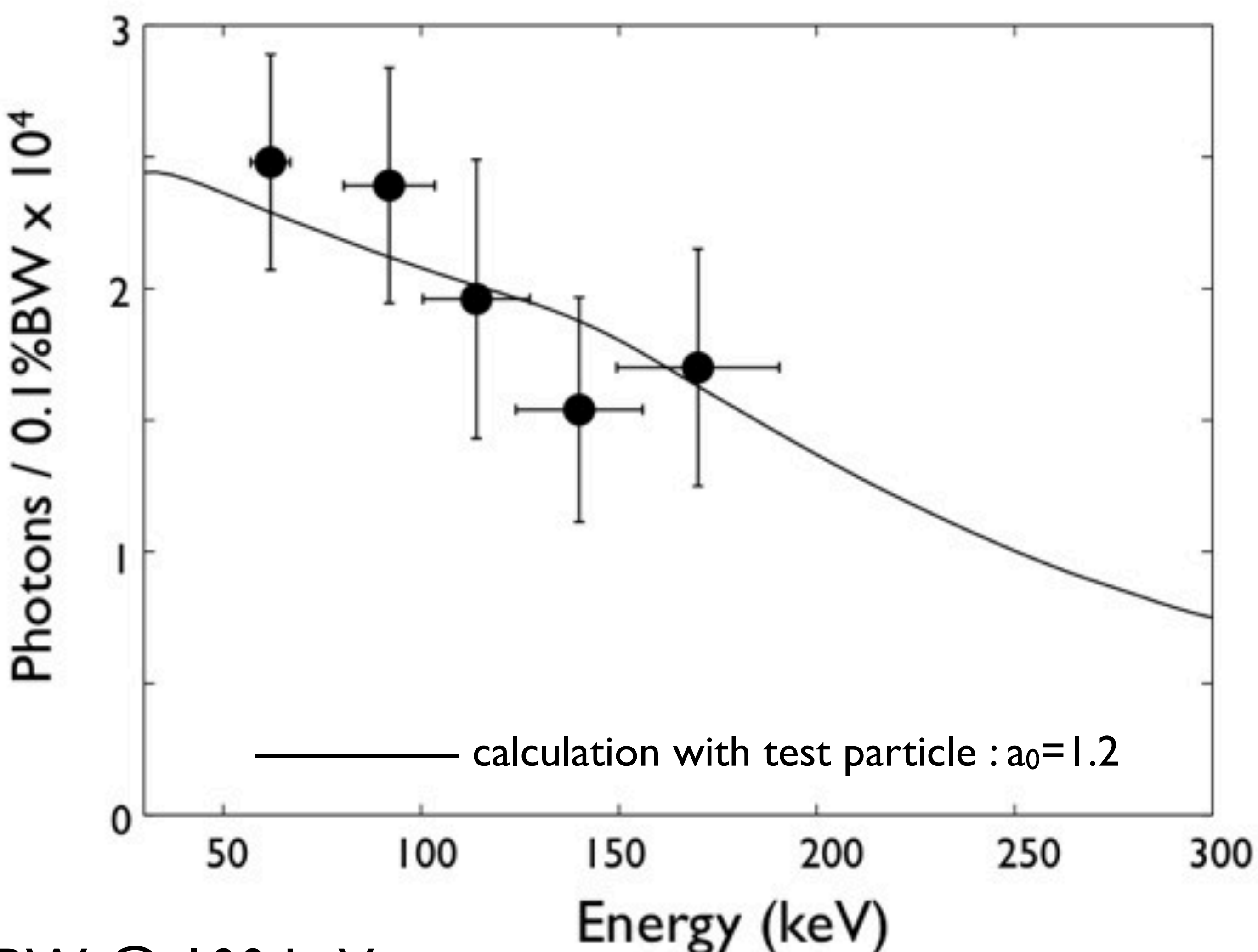
Inverse Compton Scattering : Experimental results



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

Inverse Compton Scattering : Compton Spectra



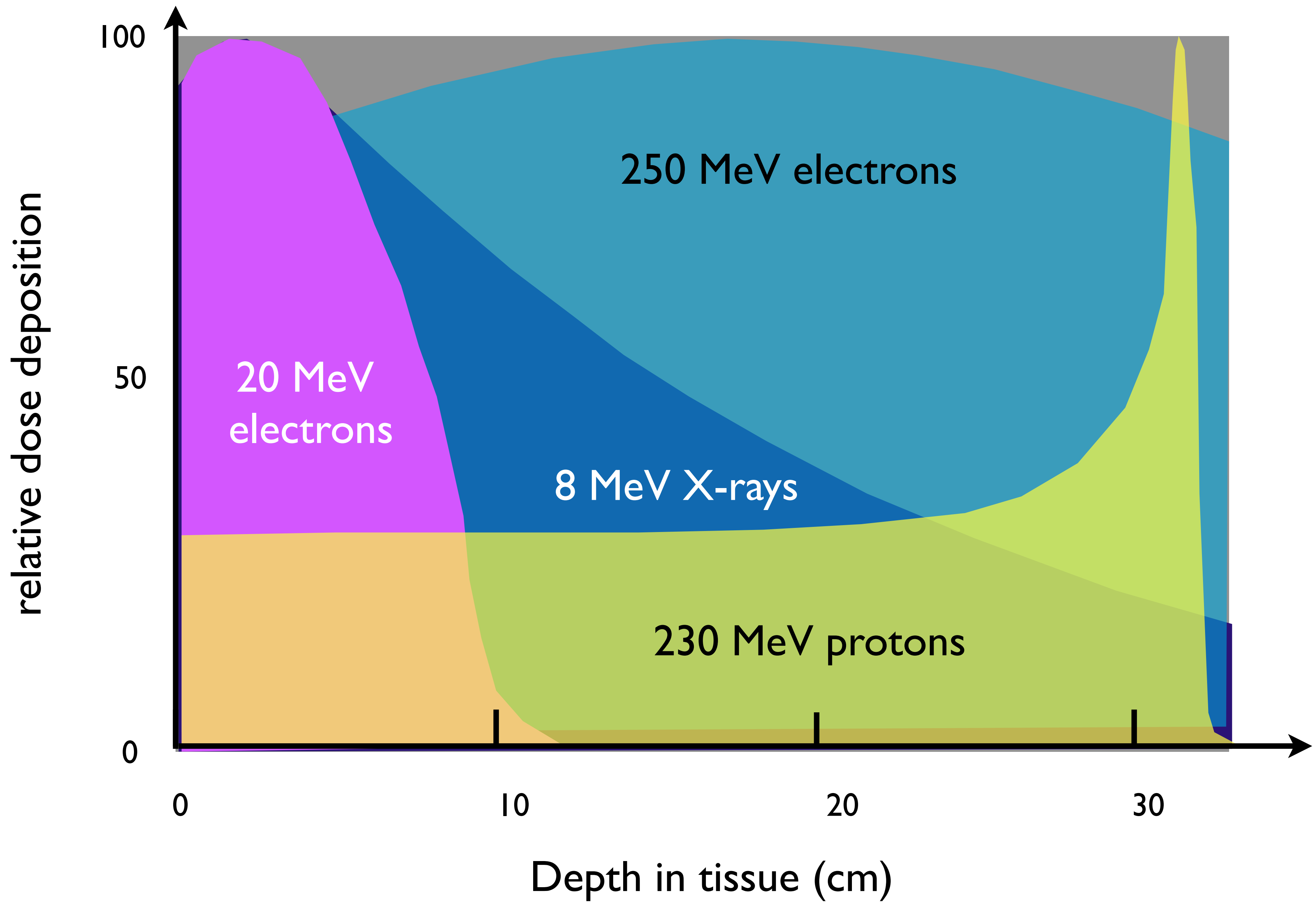


- About 10^8 ph/tir, a few 10^4 ph/shot/0.1%BW @ 100 keV
- Broad electron spectrum => broad X ray spectra
- Brigthness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

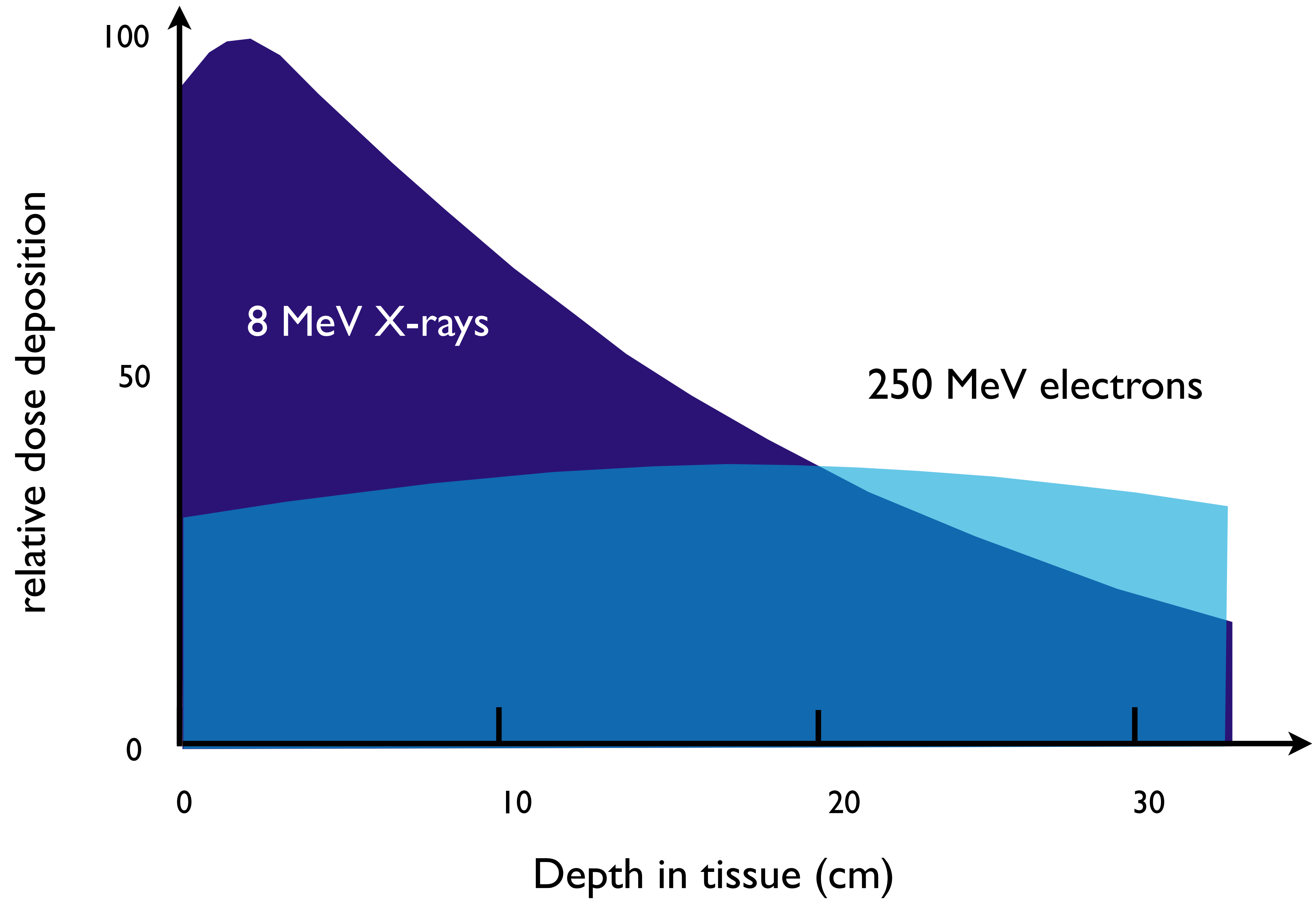
K. Ta Phuoc *et al.*, Nature Photonics **6** (2012)

- Introduction : context and motivations
- Colliding laser pulses regime
- Compton scattering X ray beam
- **Conclusion and perspectives**

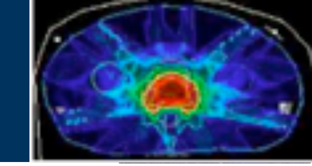
Some examples of applications : radiotherapy

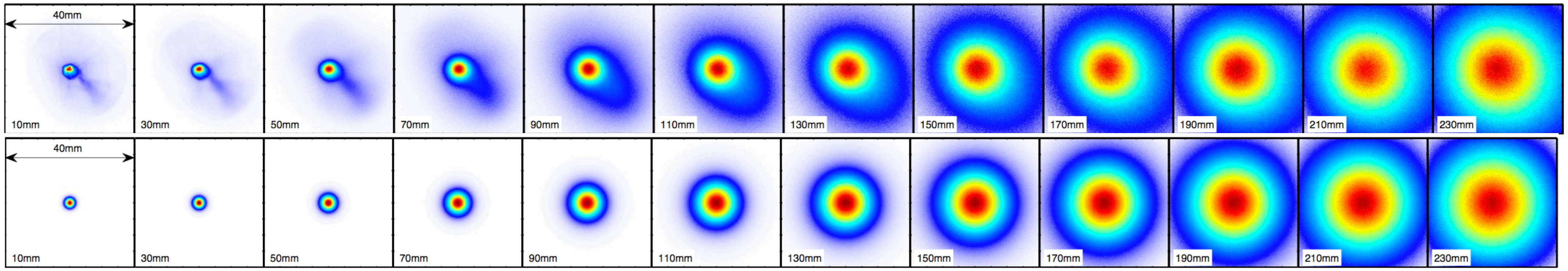


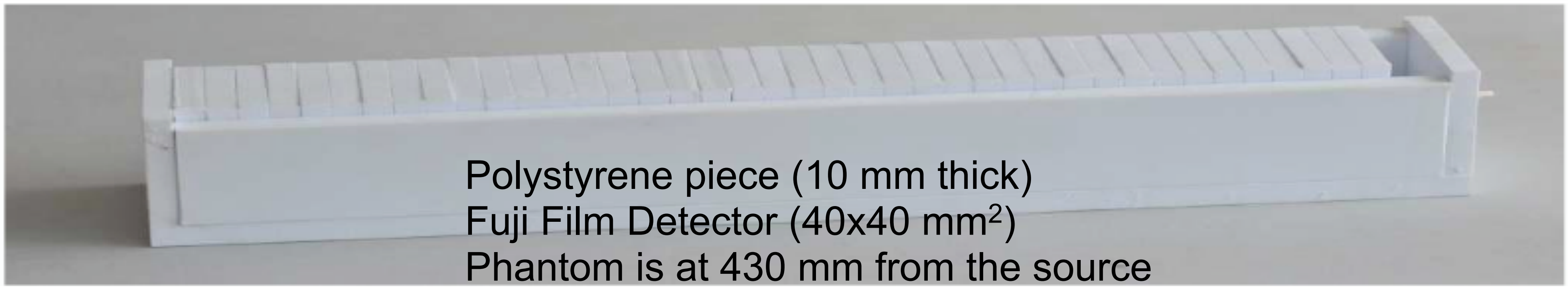
Some examples of applications : radiotherapy



Some examples of applications : radiotherapy

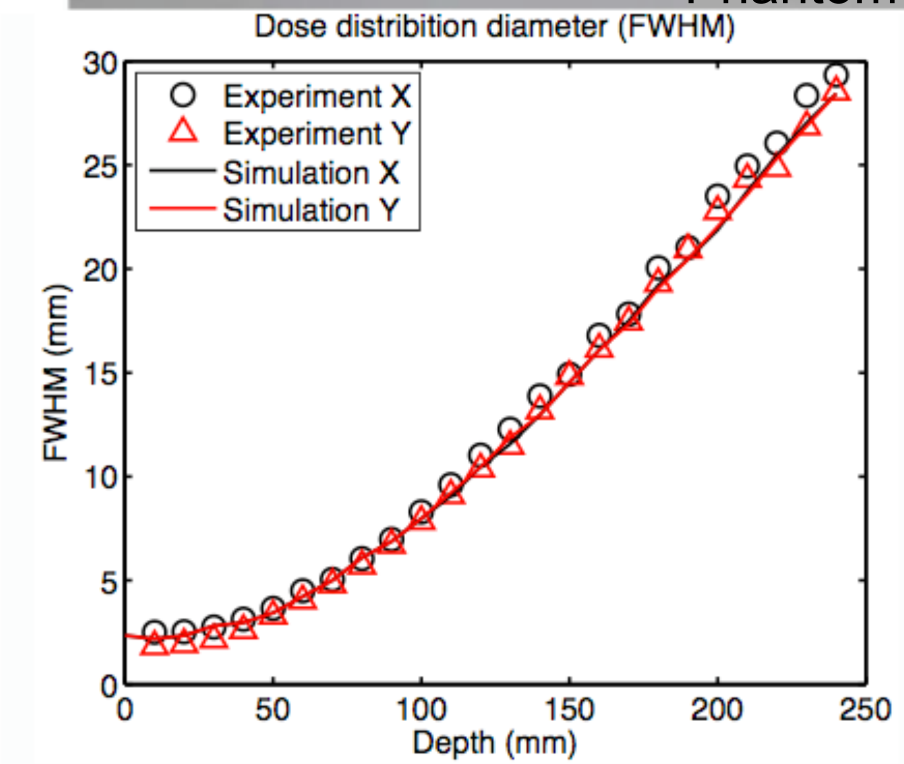


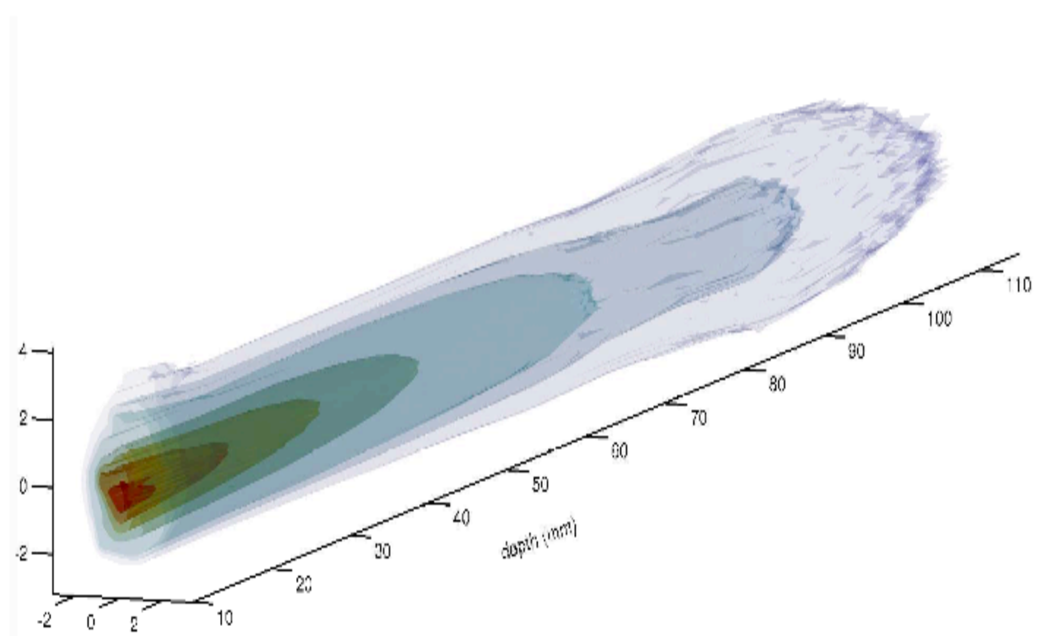




Polystyrene piece (10 mm thick)
Fuji Film Detector (40x40 mm^2)
Phantom is at 430 mm from the source

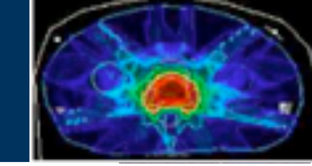
E_{pic}=120 MeV
ΔE=20 MeV
Q_{pic}=30pC
Θ=4.5mrad
D_{max}=1Gy/tir



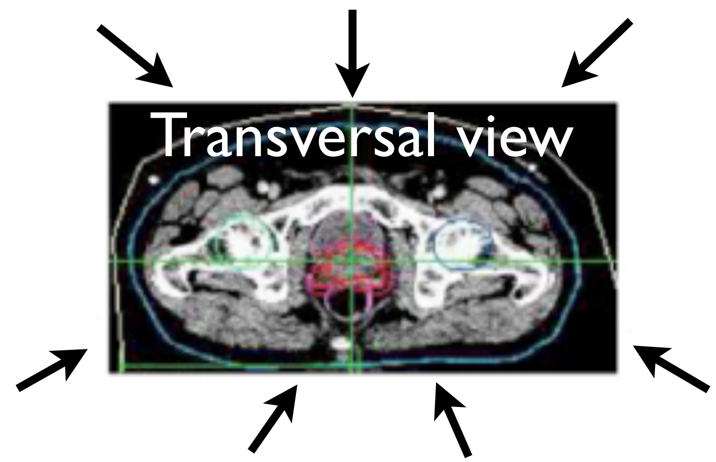


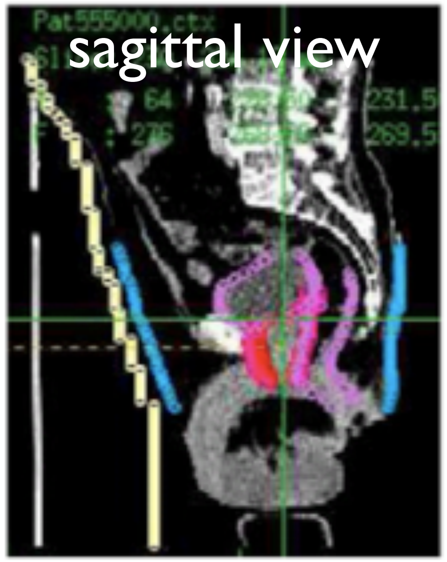
Y. Glinec *et al.* Med. Phys. **33**, 1, 155-162 (2006),
O. Lundh *et al.*, Med. Phys. 39, 3501 (2012)

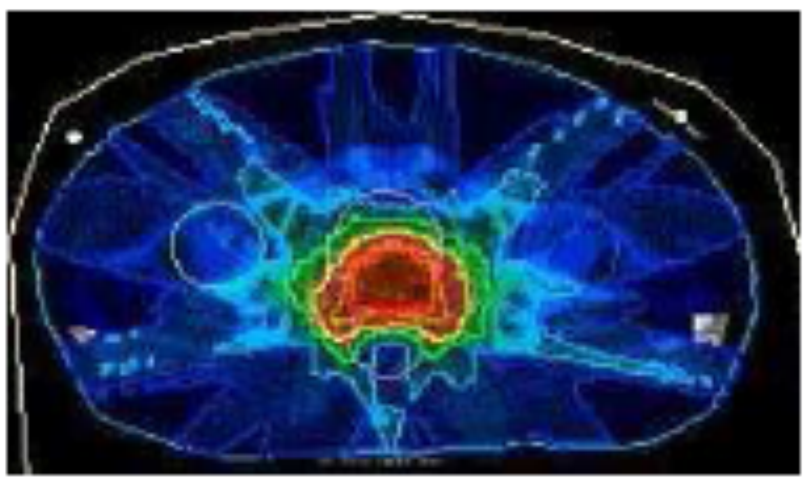
Some examples of applications : radiotherapy



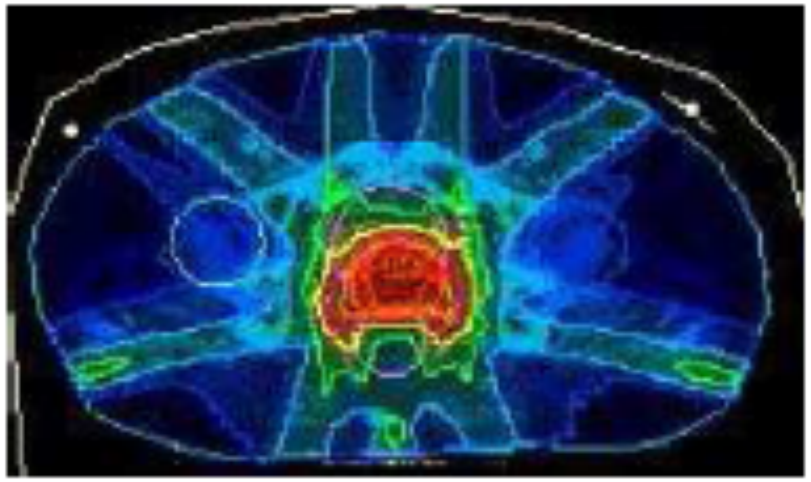
simulations of prostate cancer with 7 irradiation beams



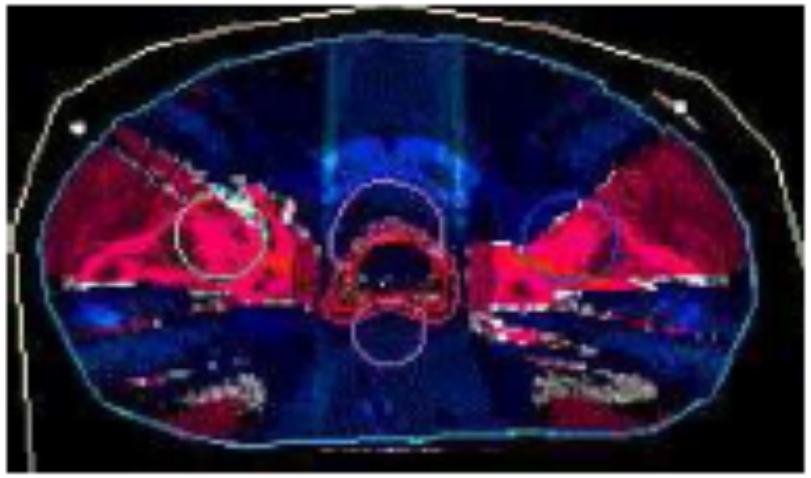




250 MeV electrons



X rays IMRT



Difference

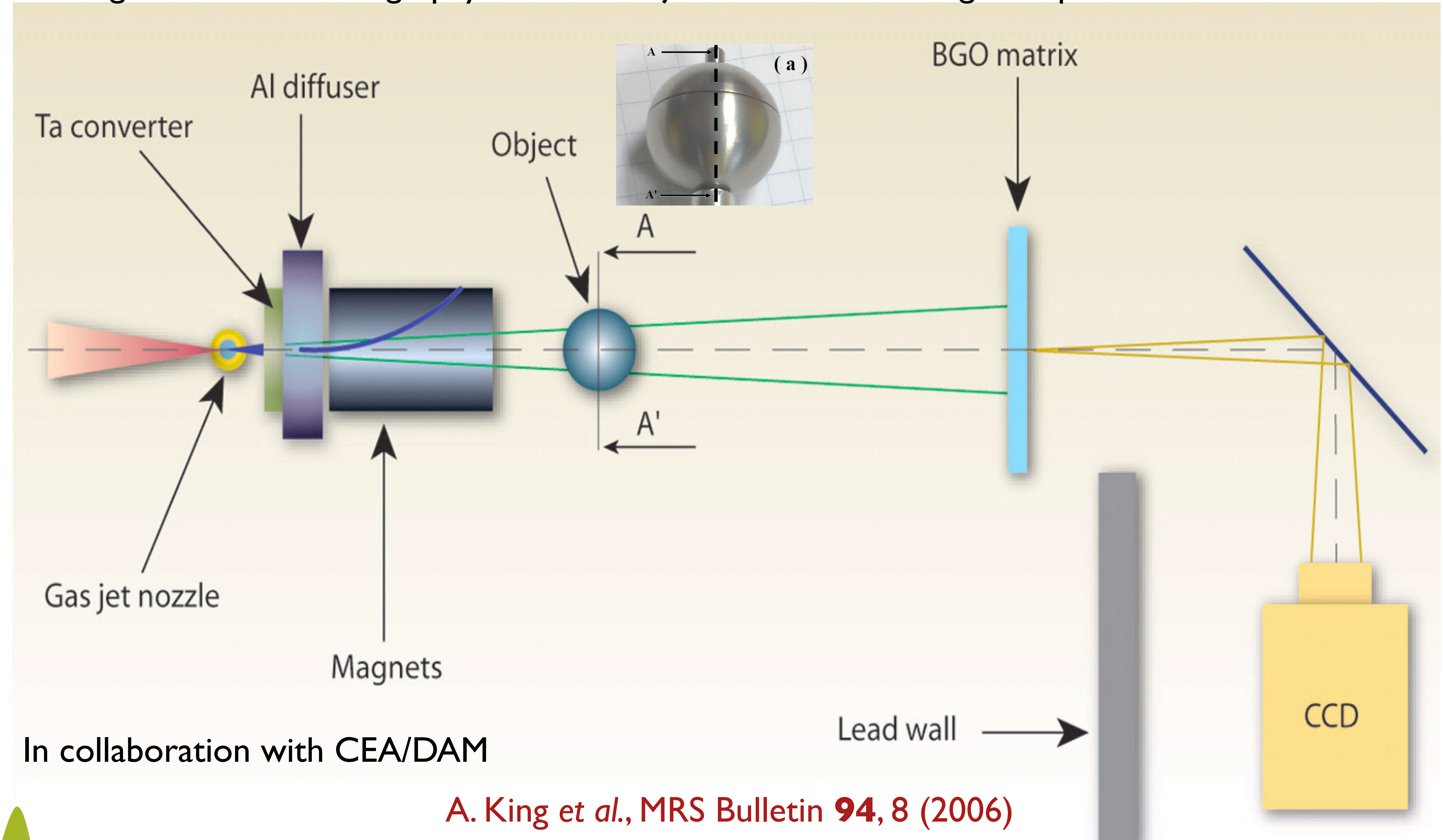
A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

T. Fuchs *et al.* Phys. Med. Biol. **54**, 3315-3328 (2009)

Some examples of applications : radiography

Non destructive dense matter inspection

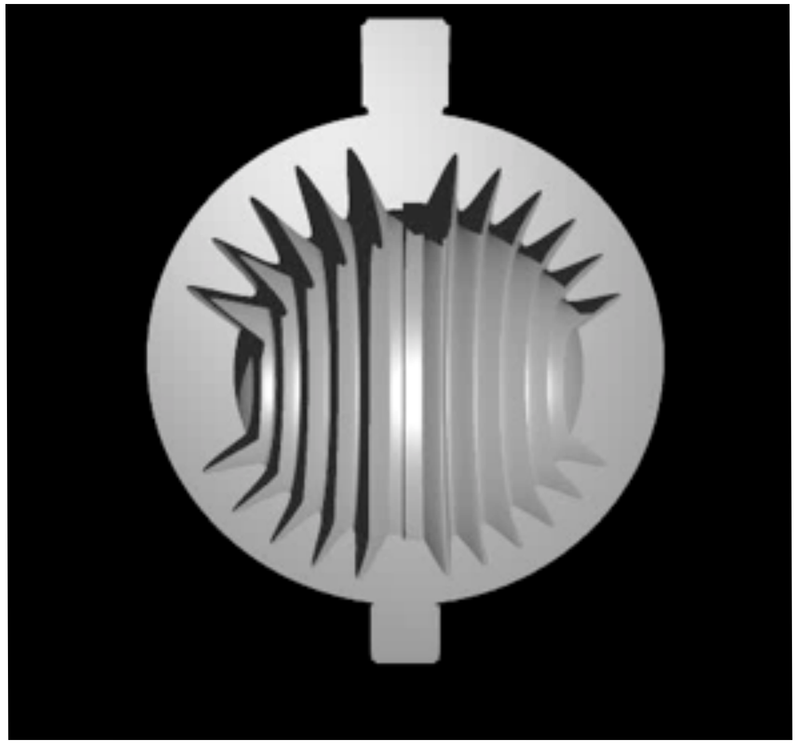
High resolution radiography of dense object with a low divergence, point-like electron source



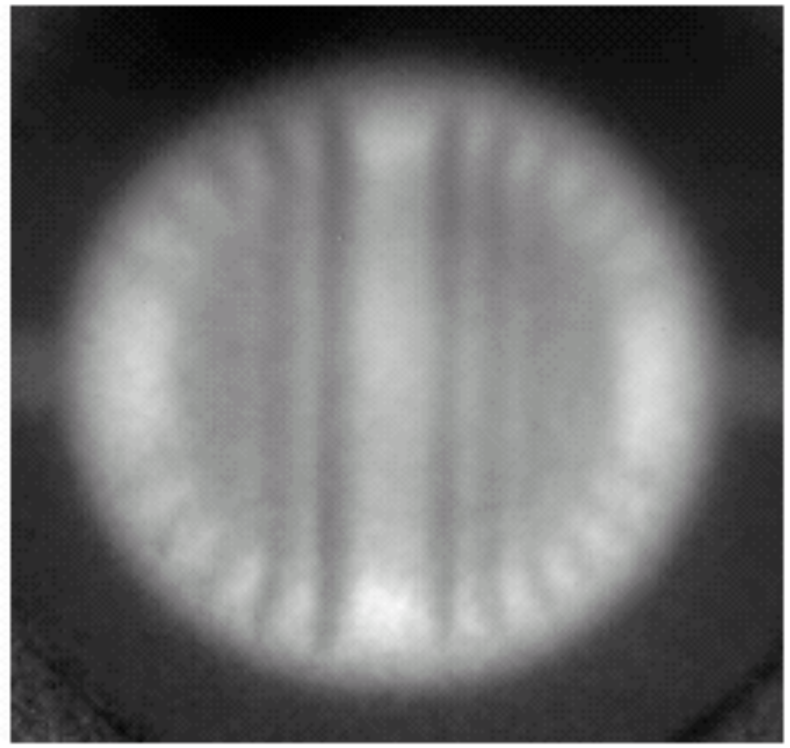
In collaboration with CEA/DAM

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

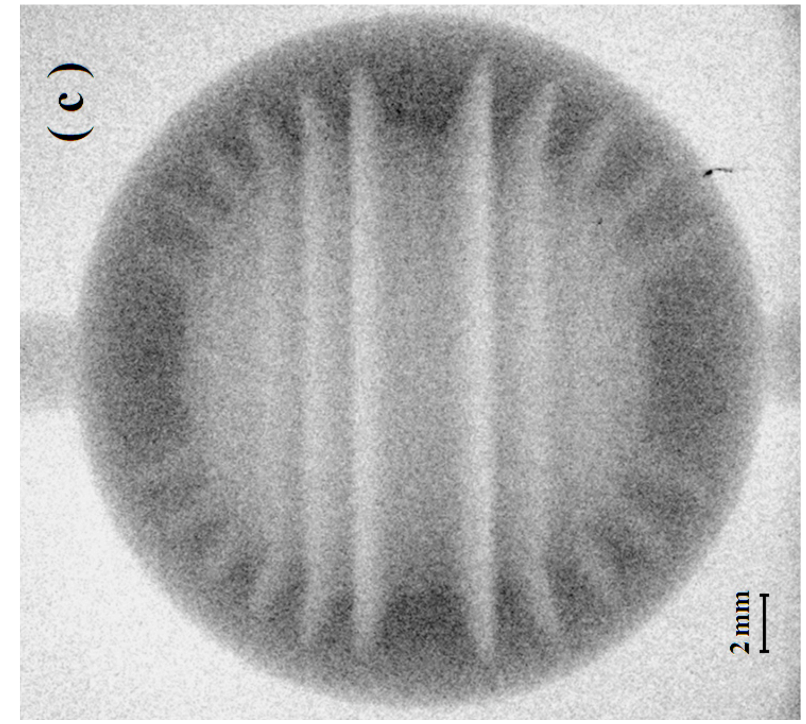
Some examples of applications : radiography results



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



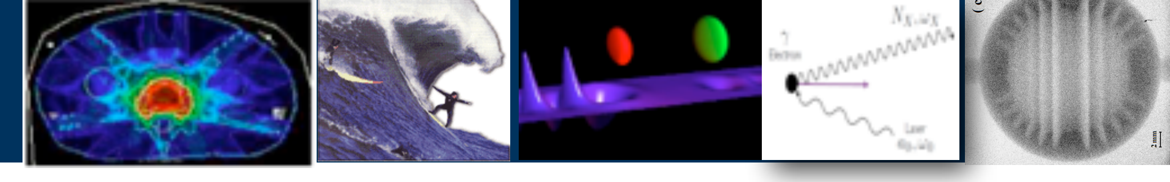
400 µm γ source size
2005



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)

Conclusions (1)



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 % √

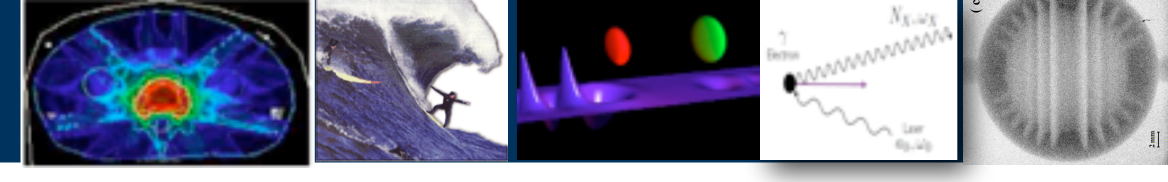
Ultra short e-bunch : 1,5 fs rms √

Low divergence : 2 mrad √

Low emittance[1-3] : 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 (2)



Physics point of view : many new aspects of the interaction have been revealed :

Colliding pulses injection √

Heating processes with crossed polarized lasers[1] √

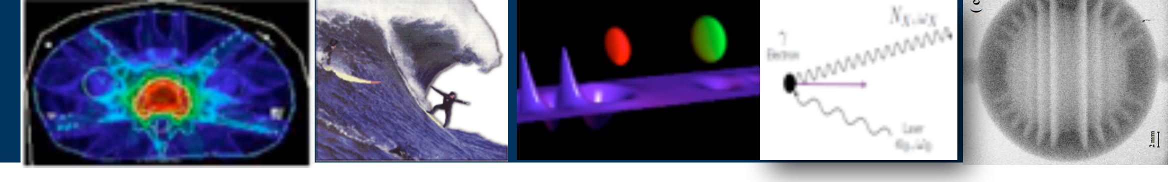
Inhibited plasma waves effect √

Beam loading effect : optimum current of a few kA √

Single injection[2,3] √

Double injection[3] √

[1]C. Rechatin *et al.*, NJP **11**, 013011 (2009), [2]S. P. D. Mangles *et al.*, Phys. Rev. Lett. **96**, 215001 (2006)
[3]Y. Glinec *et al.*, Phys. Rev. Lett. **98**, 194801 (2007)



Results extremely important for :

Designing future accelerators

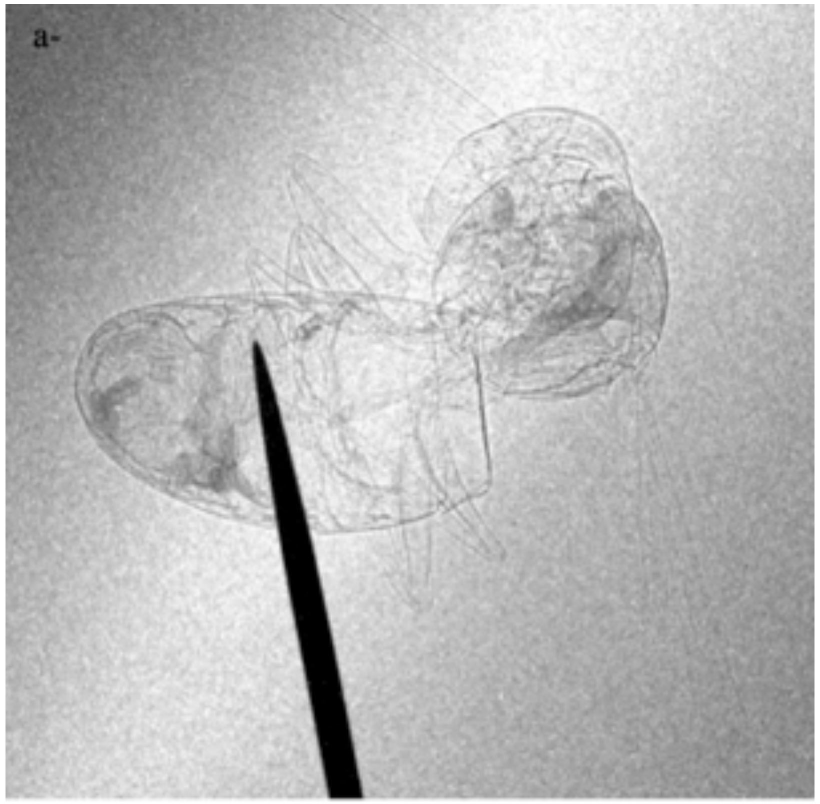
Compact X ray source (Thomson, Compton, Betatron, or FEL)

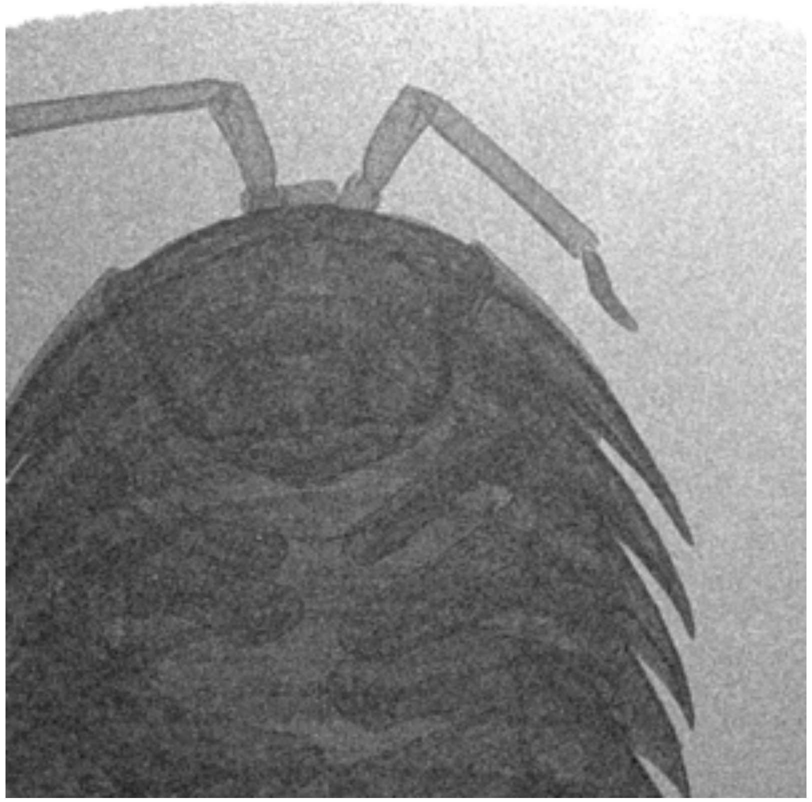
Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

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)

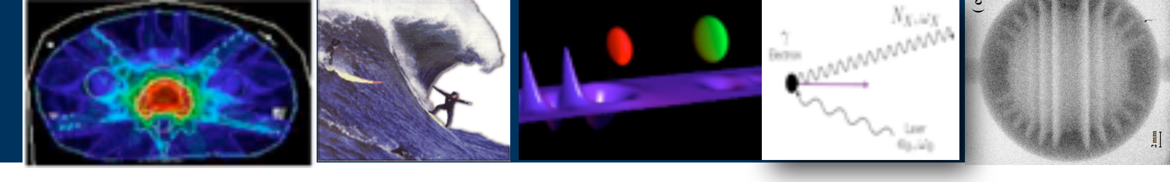




Courtesy of K. Krushelnick

V. Malka *et al.*, Nature Physics **4** (2008)

Acknowledgements



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

E. Lefebvre and X. Davoine from CEA/DAM

erc

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

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