Laser Plasma Accelerators
Status & Applications

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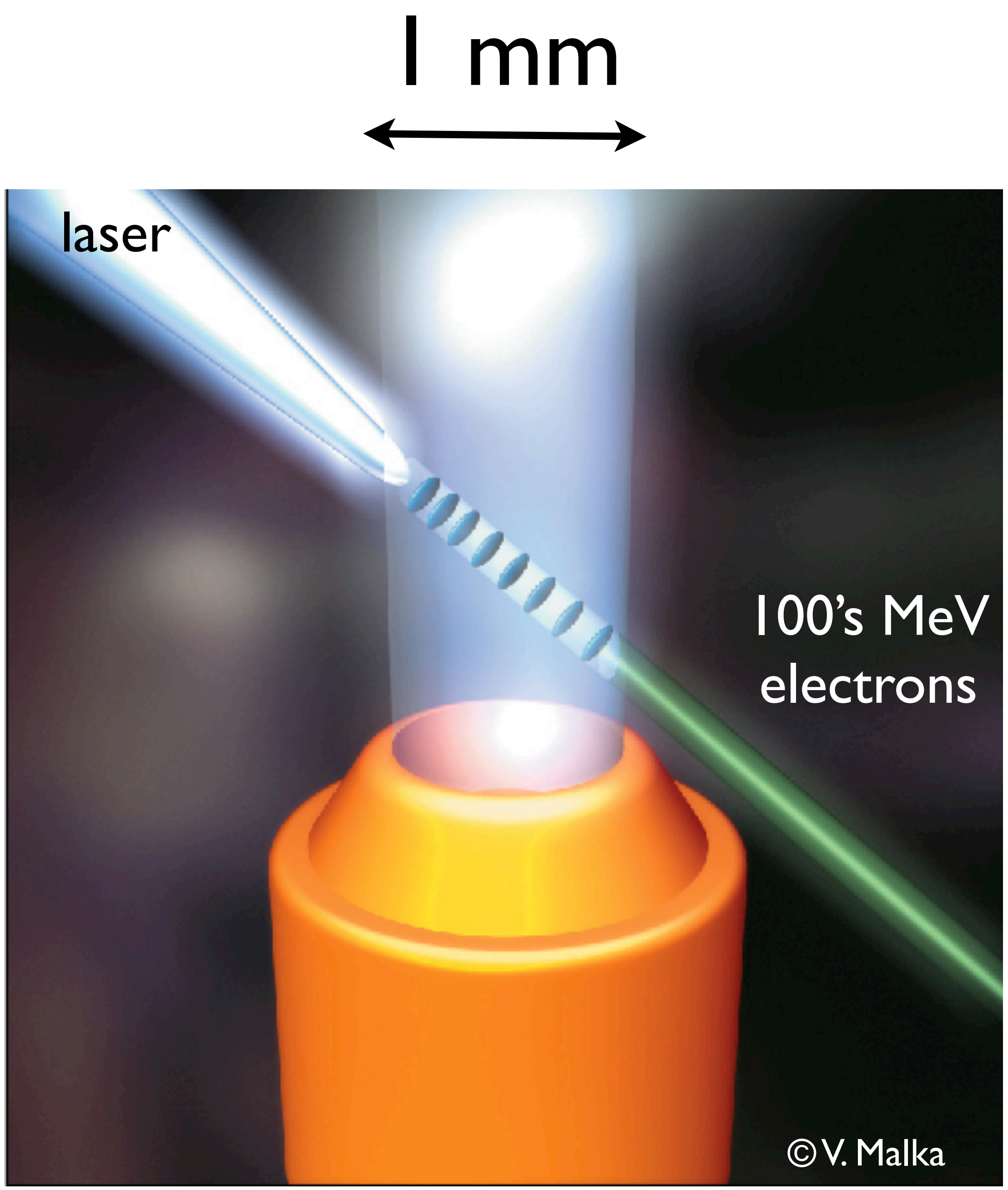
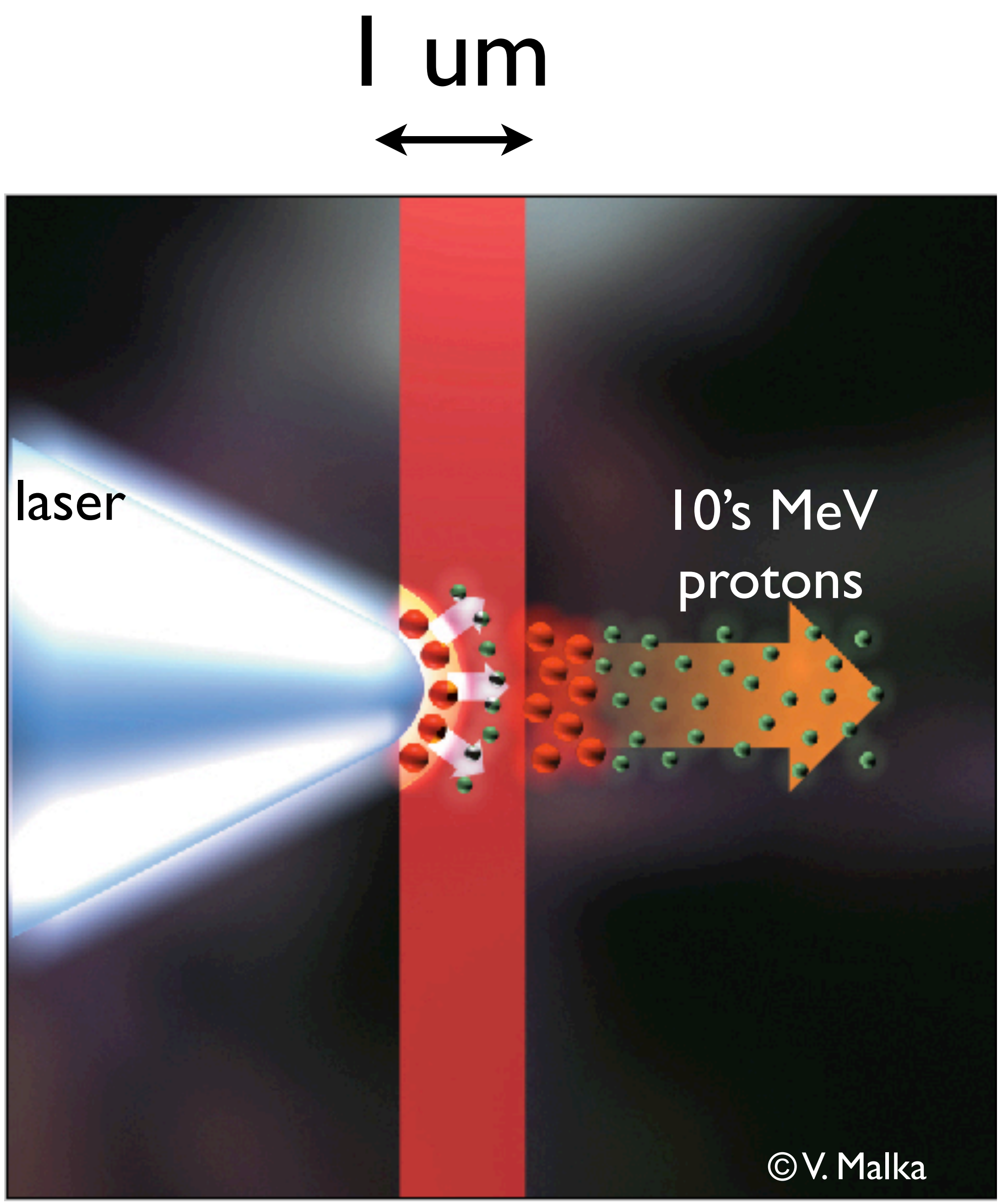
INFN Laboratori Nazionali di Legnaro (Italy) February 17 (2015)

Laser Based Accelerators : Principle





Laser Plasma Accelerators : Outline

- Introduction : context and motivations
- Electron beams produced with LPA
- Application to radiotherapy
- Proton beam produced with LPA
- Application to protontherapy
- Other Applications of LPA
- Conclusion and perspectives

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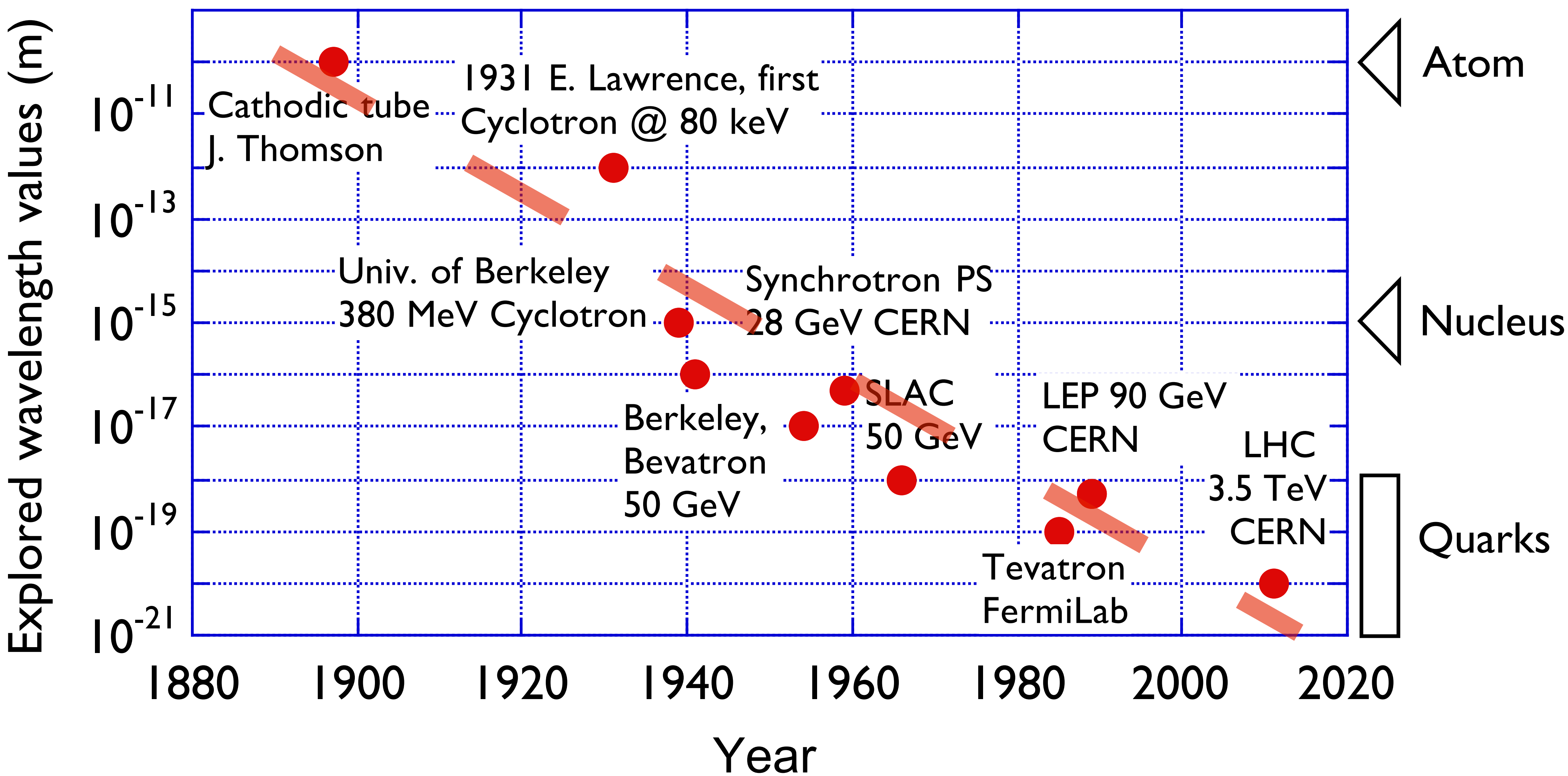
Accelerators : One century of exploration of the infinitively small



Industrial Market for Accelerators

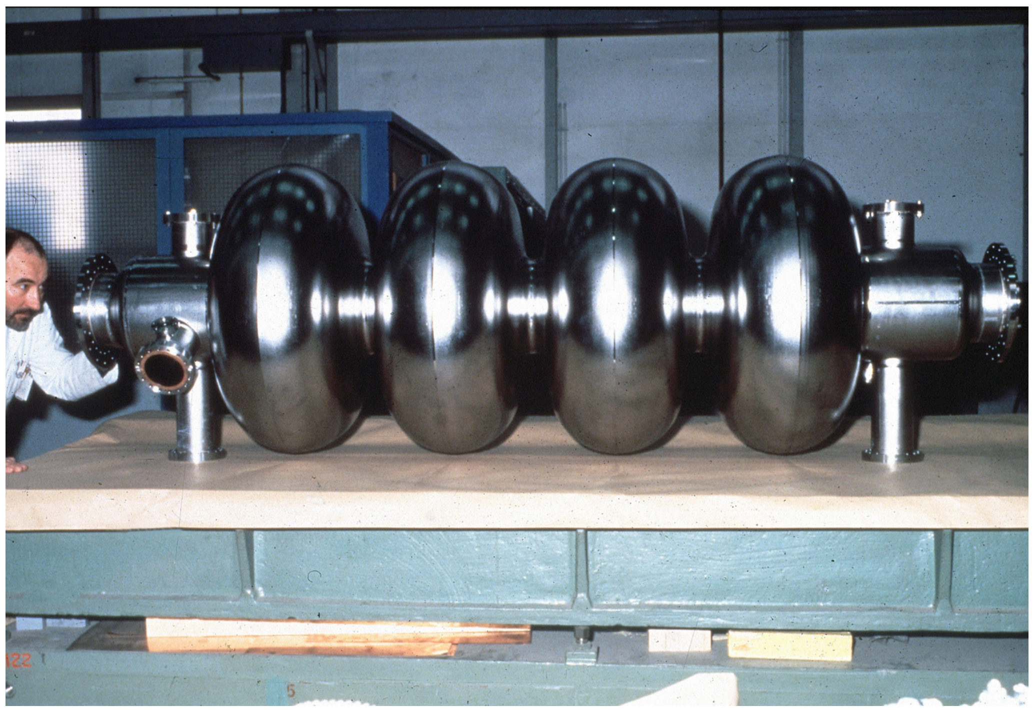
The development of state of the art accelerators for HEP has lead to :
research in other field of science (light source, spallation neutron sources…)
industrial accelerators (cancer therapy, ion implant., electron cutting&welding...)

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

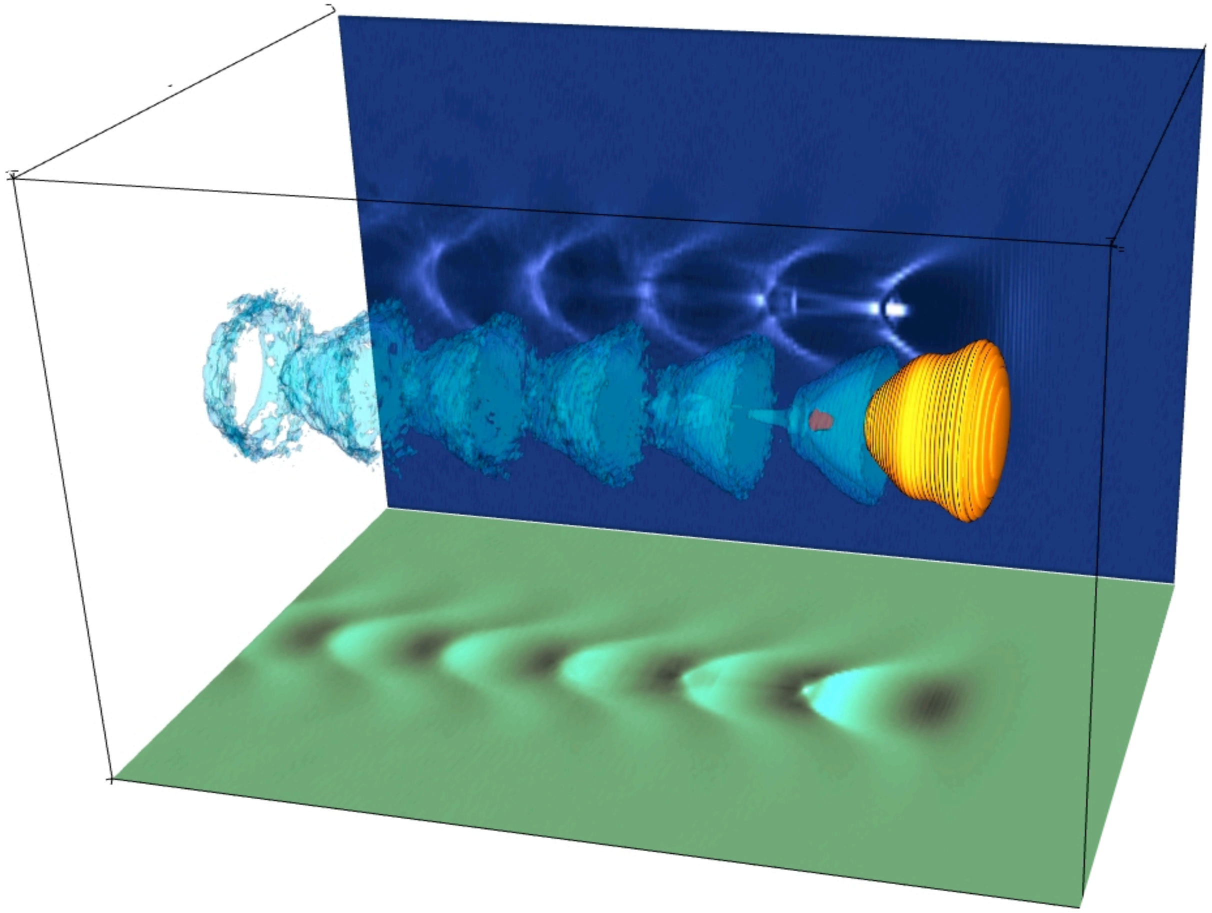
Compactness of Laser Plasma Accelerators

RF Cavity



Electric field < 100 MV/m

Plasma Cavity



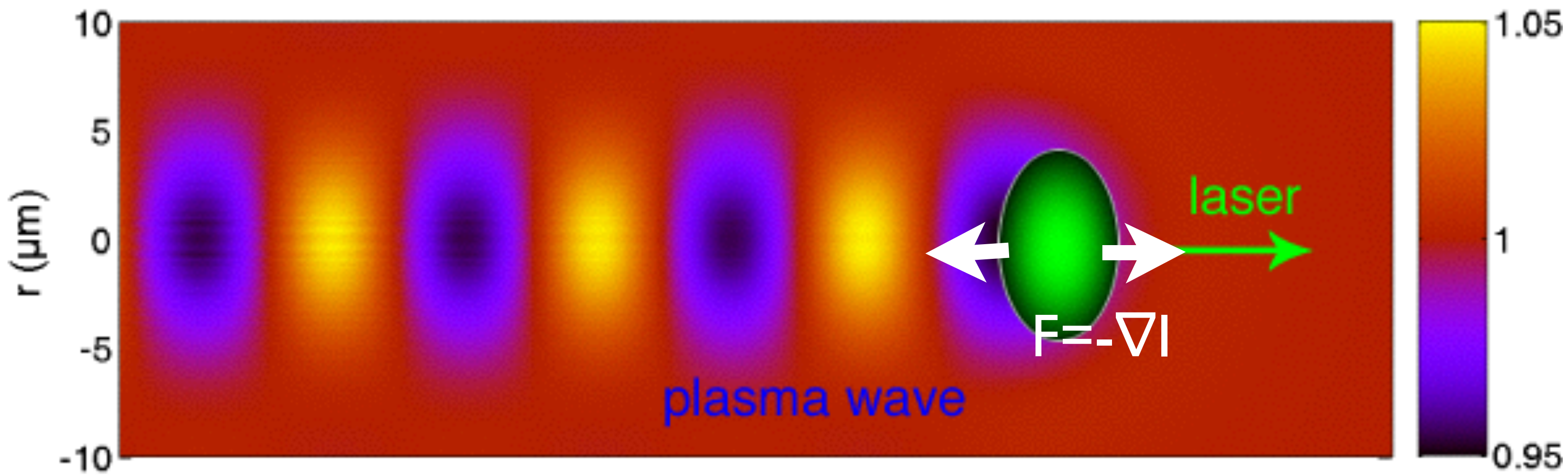
Electric field > 100 GV/m

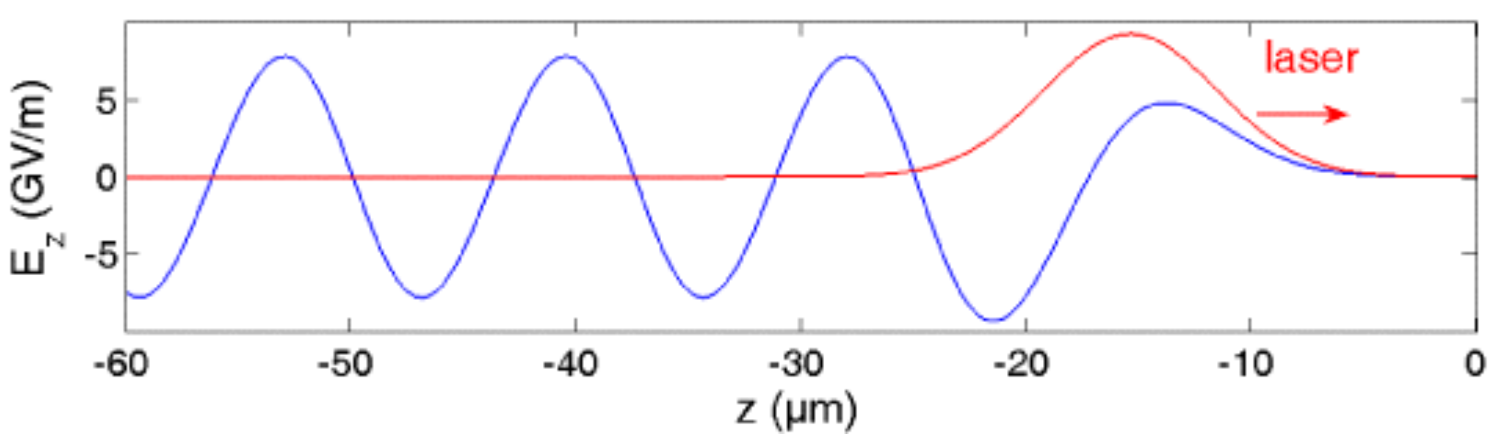
V. Malka et al., Science **298**, 1596 (2002)

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





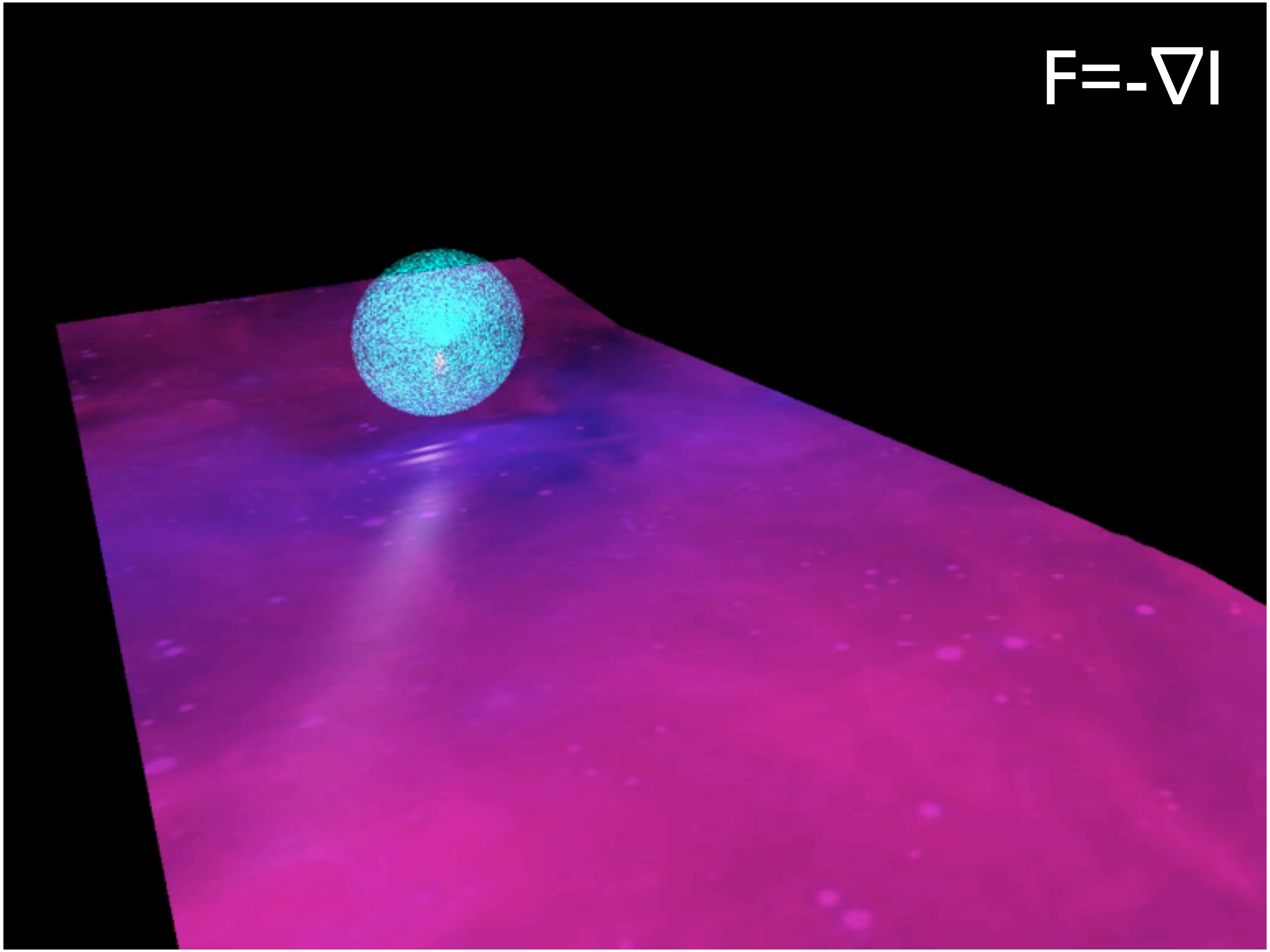
$v_{phase}^{epw} = v_g^{laser} \sim c$

wave in the wake of a boat

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

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

The laser wakefield



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

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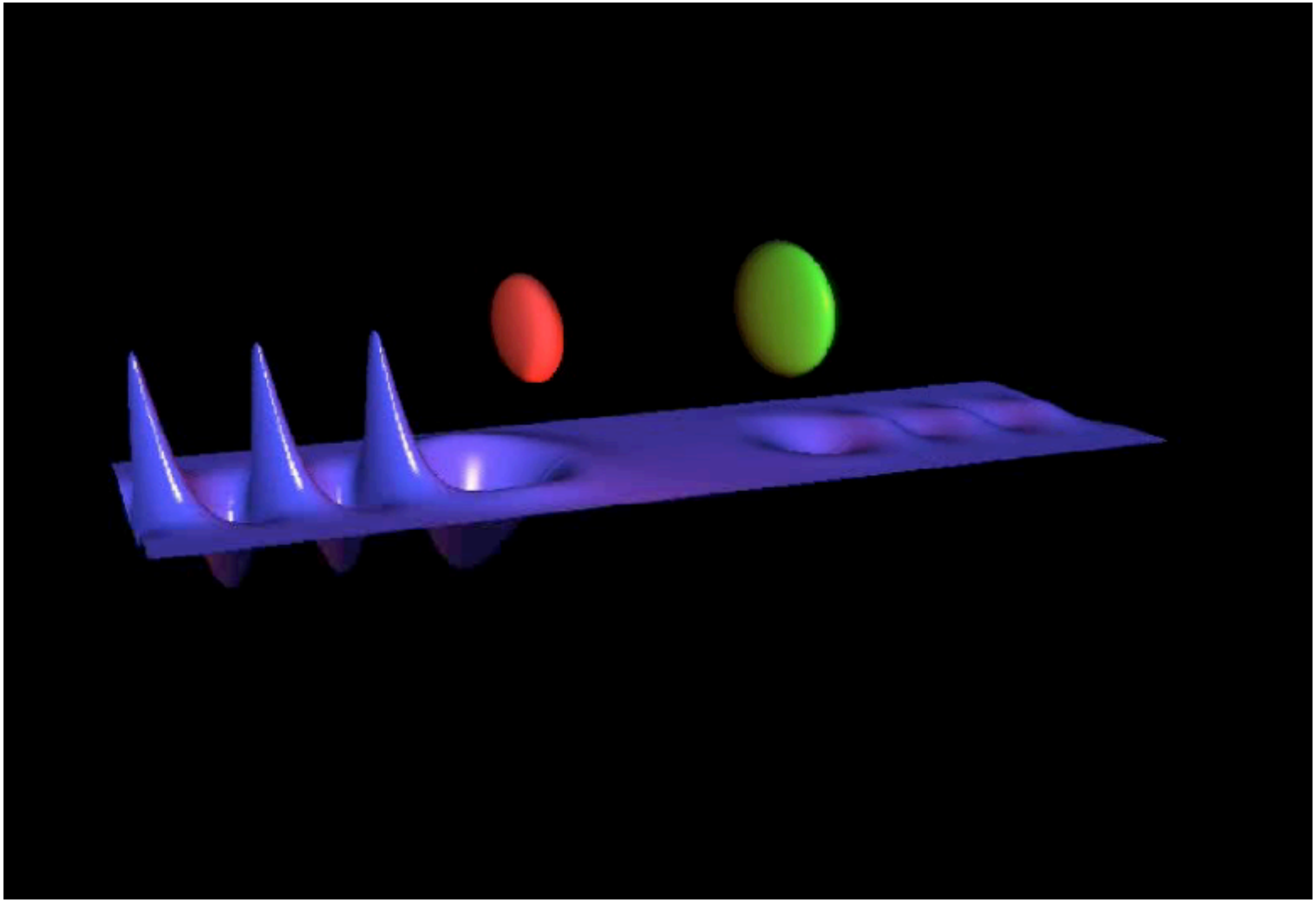
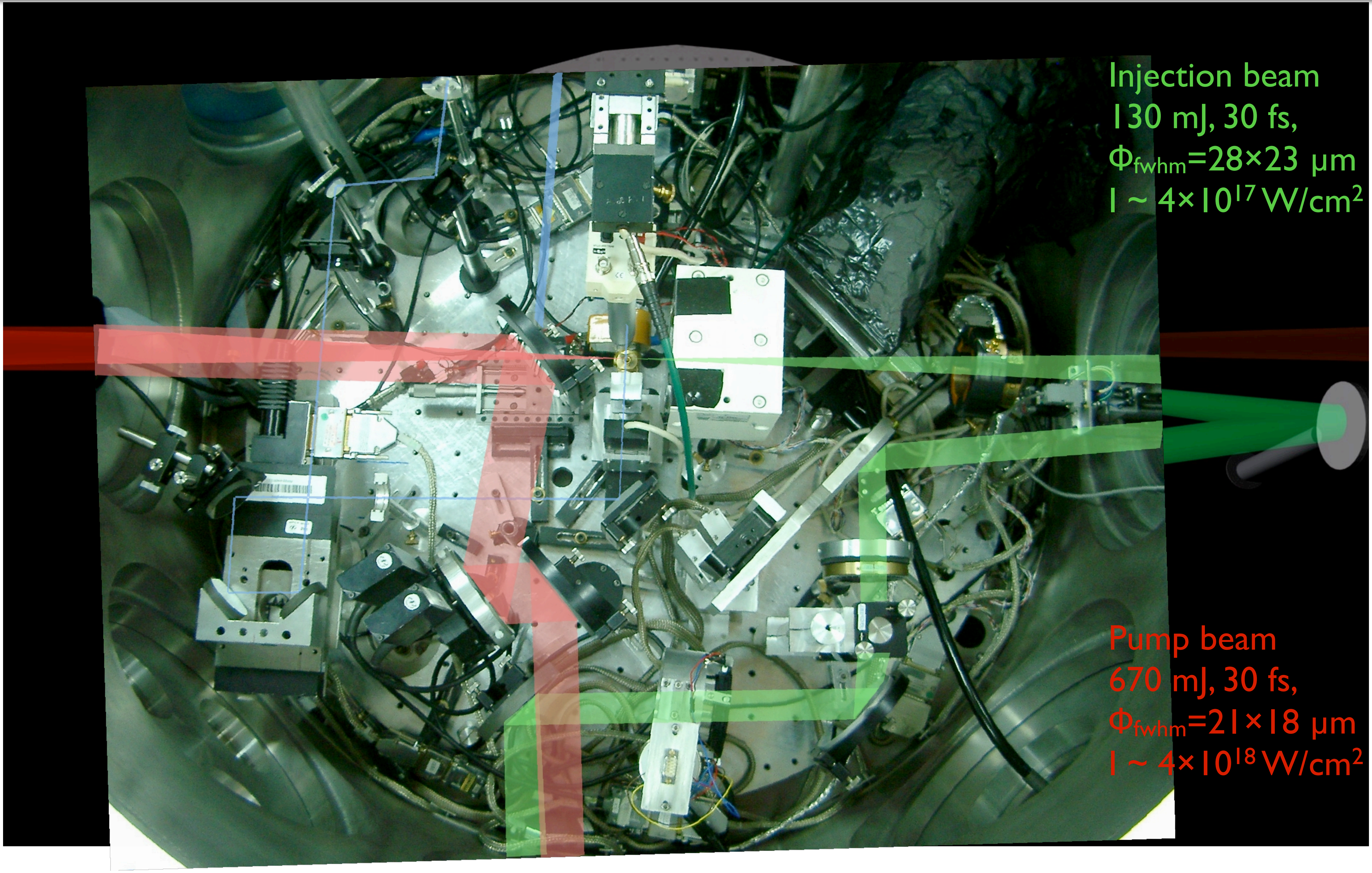
Colliding Laser Pulses Scheme

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



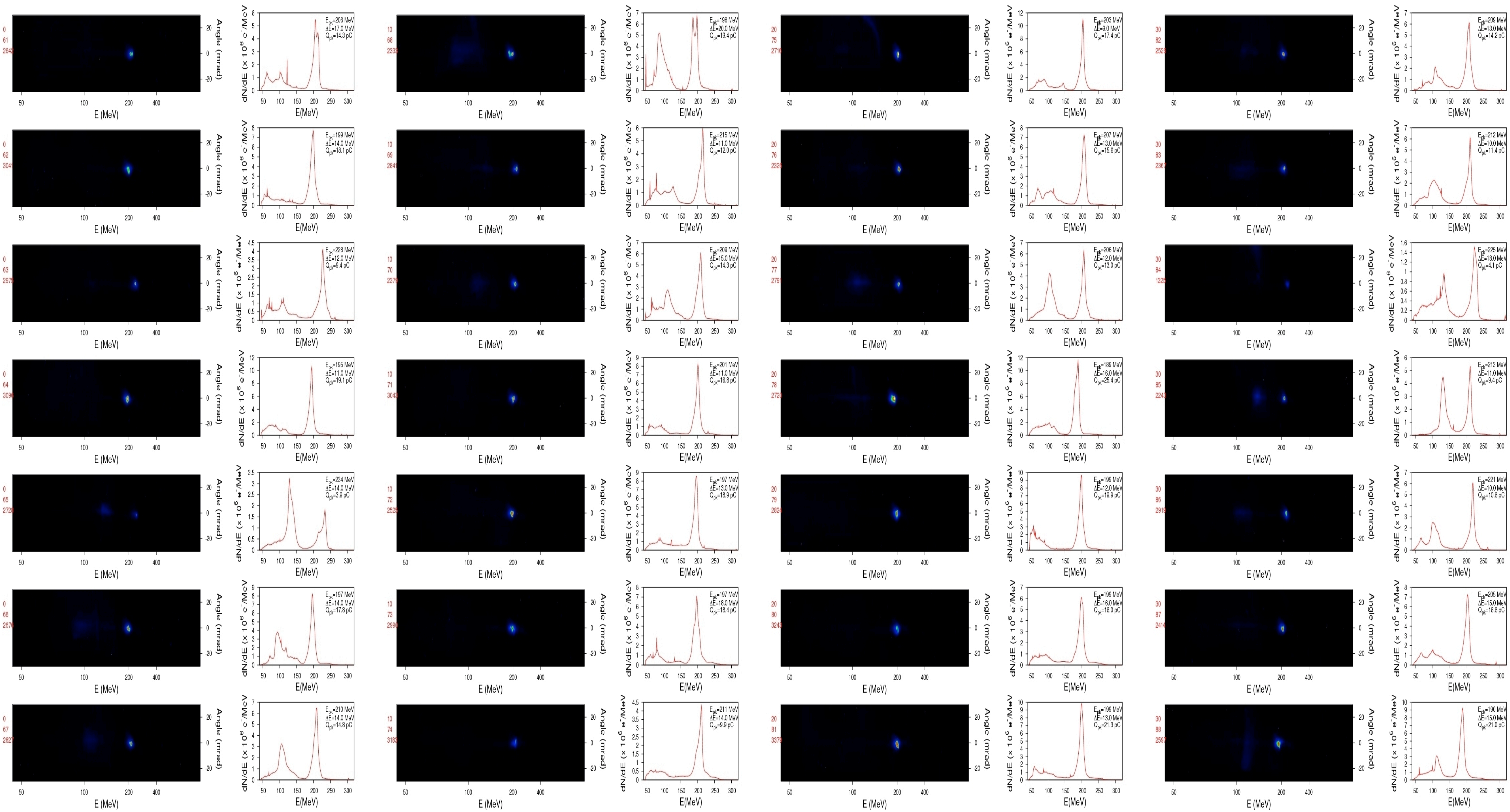
Experiments : J. Faure *et al.*, Nature **444**, 737 (2006)

Set-up for colliding pulses experiment

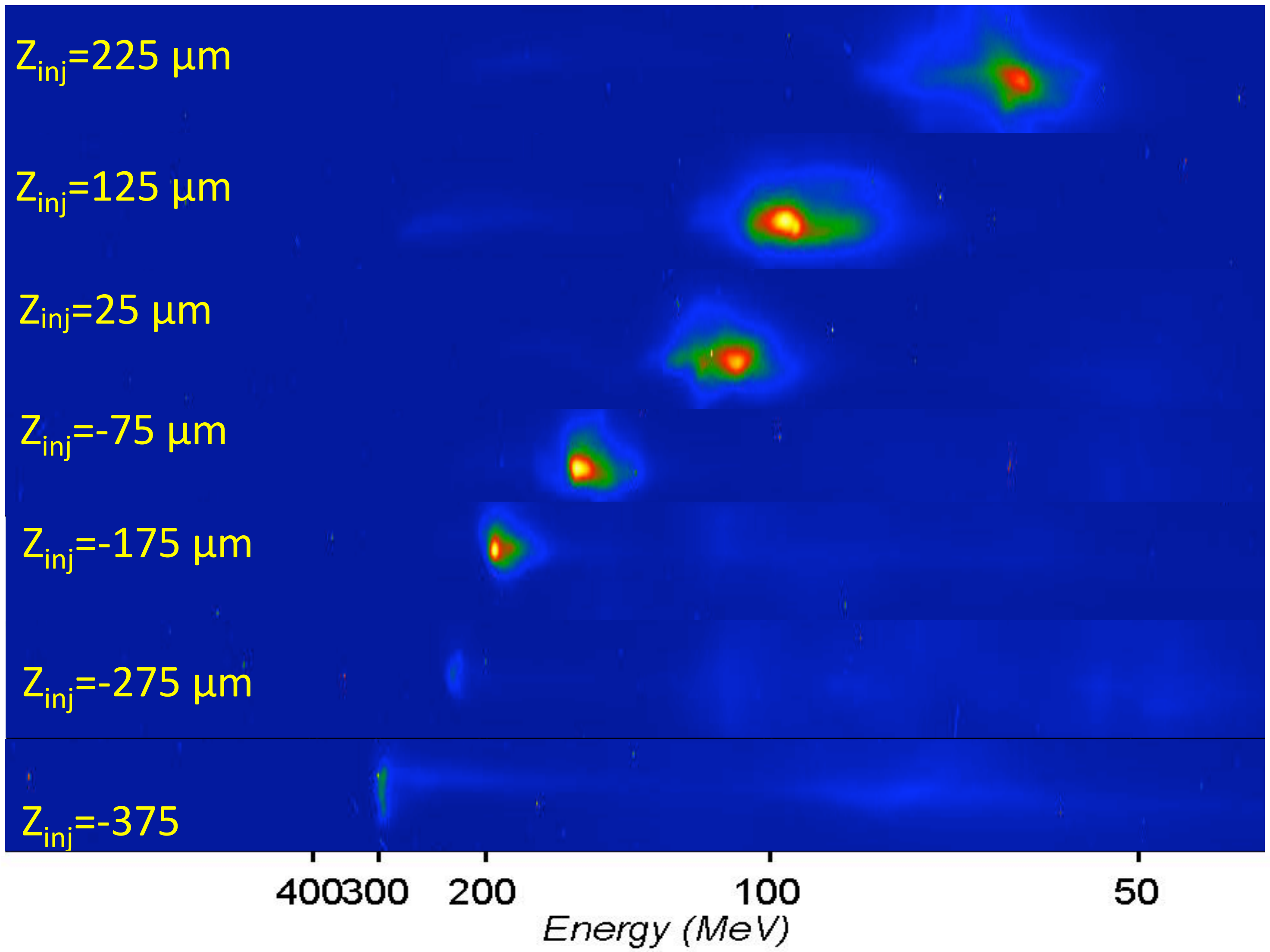


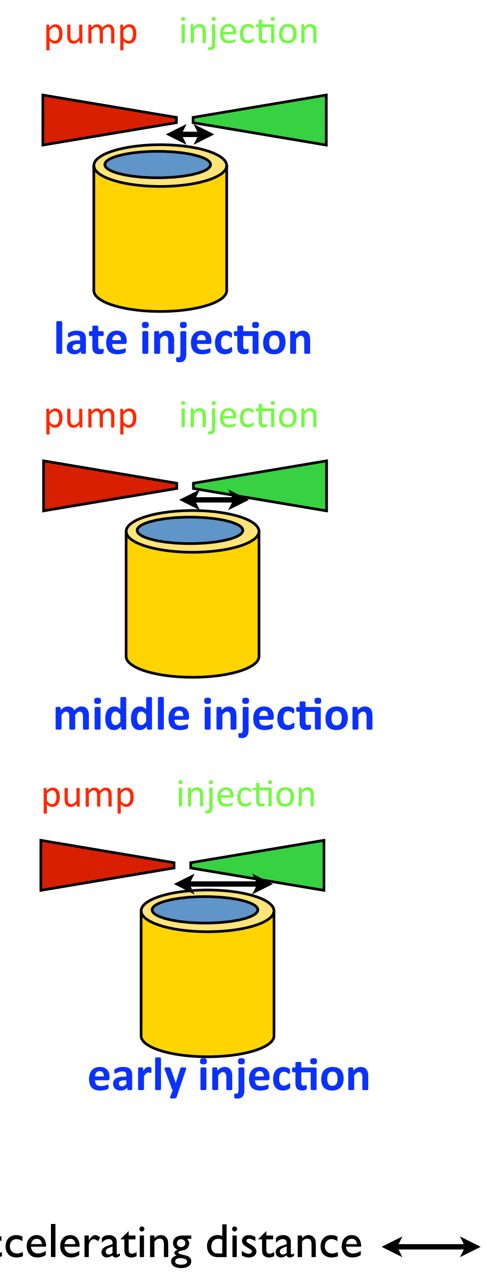
Towards a Stable Laser Plasma Accelerators

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



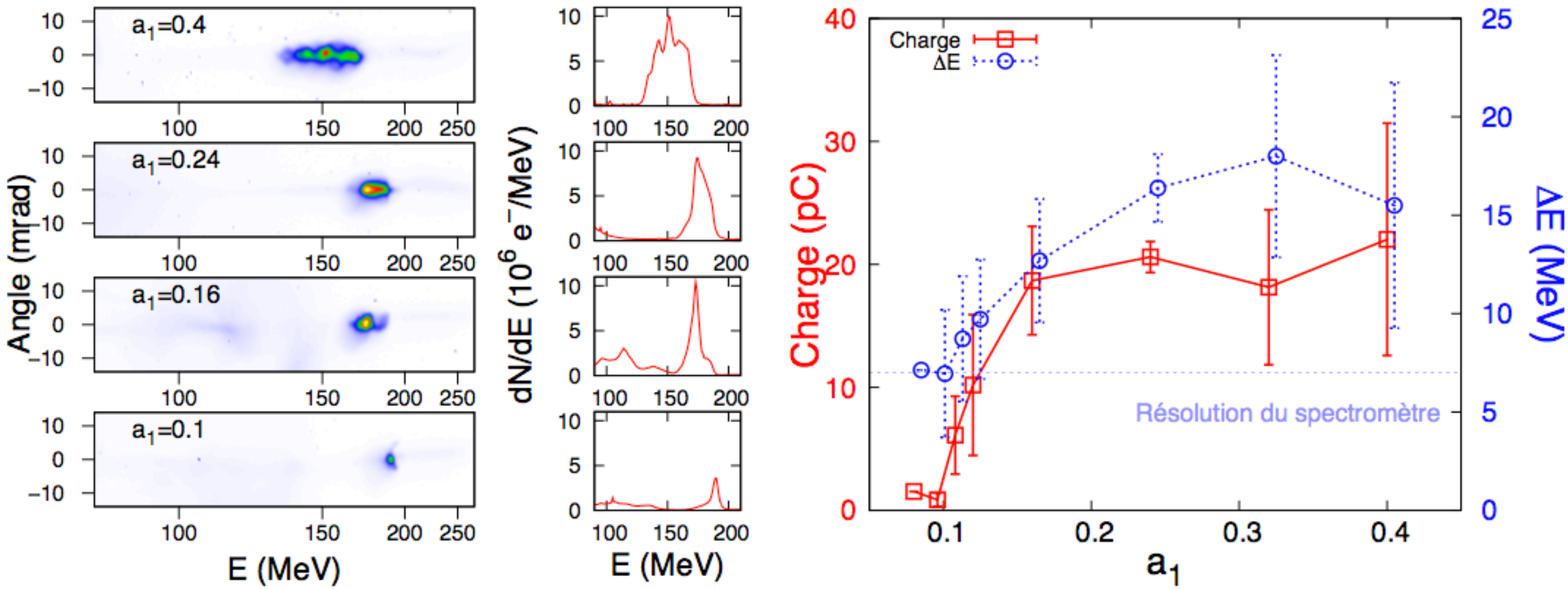
Tunability of Laser Plasma Accelerators : electrons energy





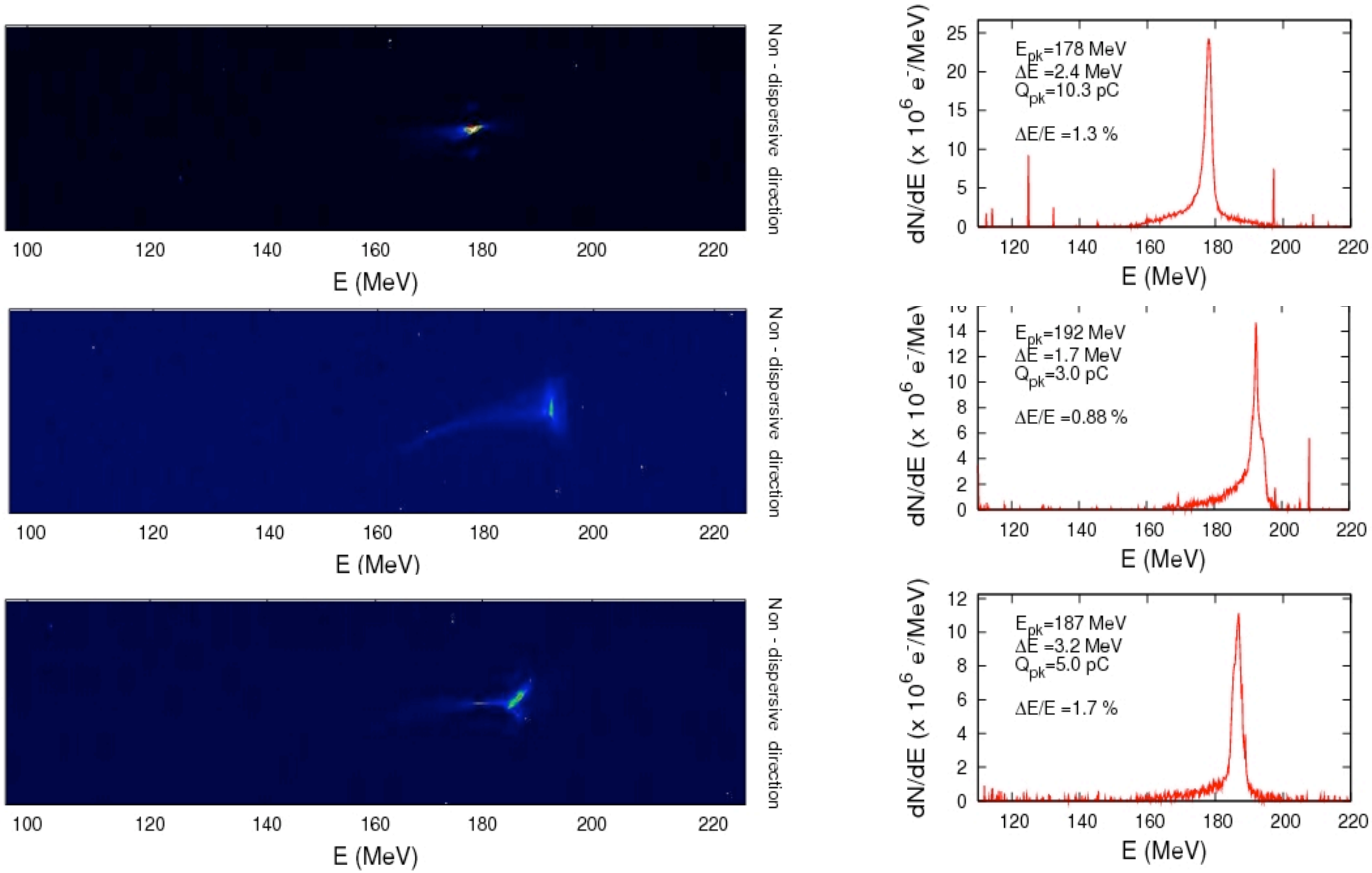
J. Faure *et al.*, Nature **444**, 737 (2006)

Tunability of Laser Plasma Accelerators : electrons charge



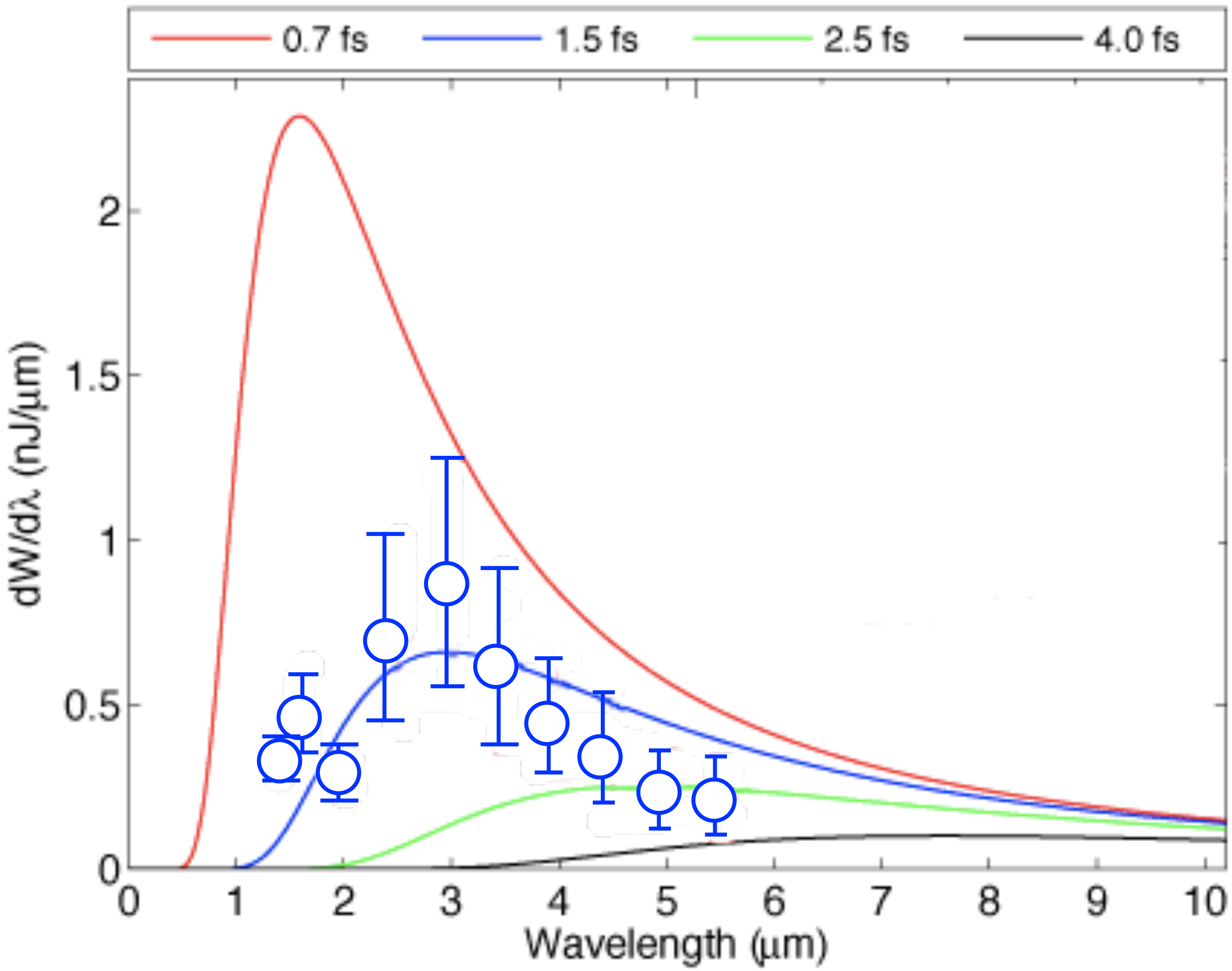
C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

1% relative energy spread with LPA



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

1.5 fs & few kA electron beam with LPA



1.5 fs RMS duration : Peak current of 4 kA

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

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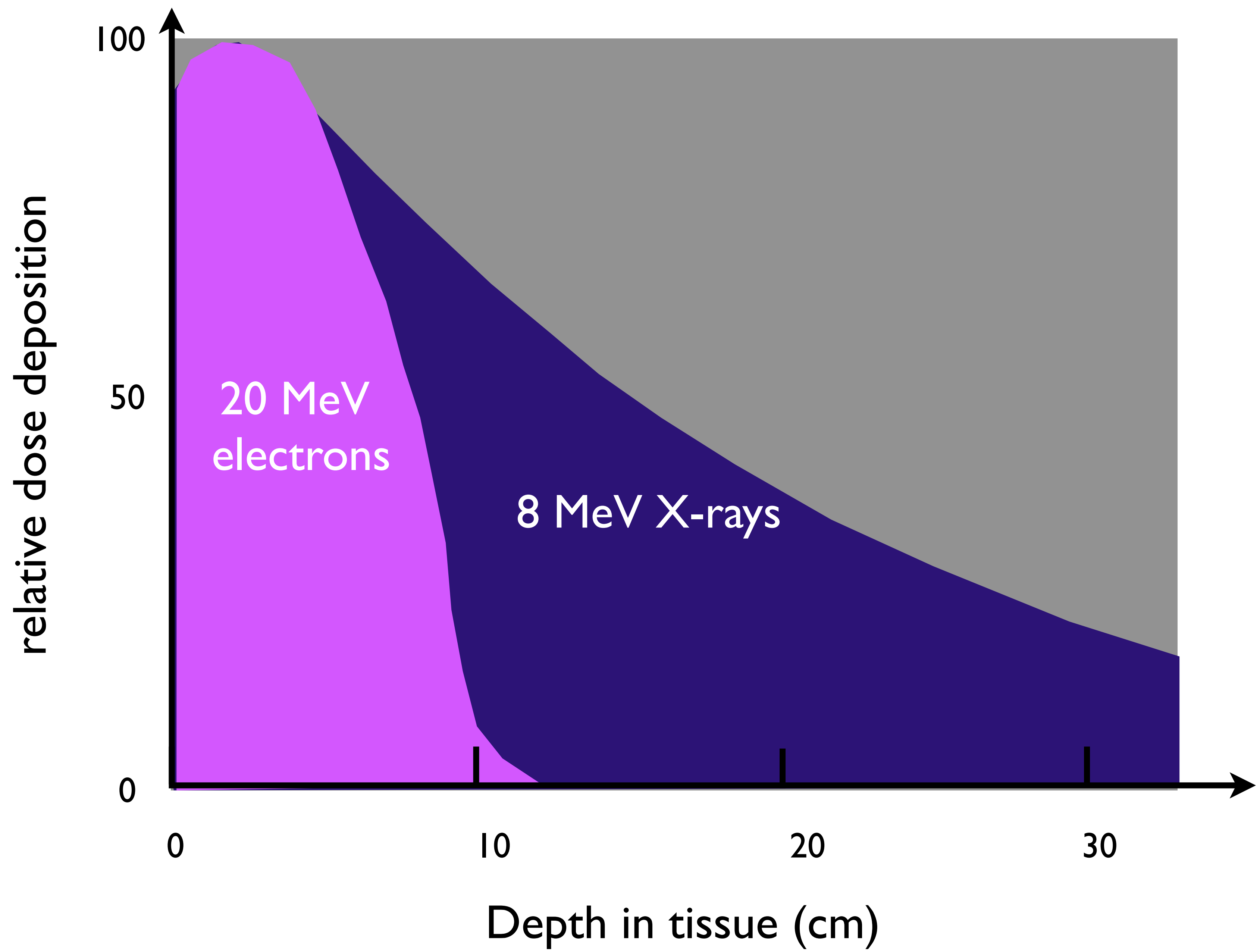
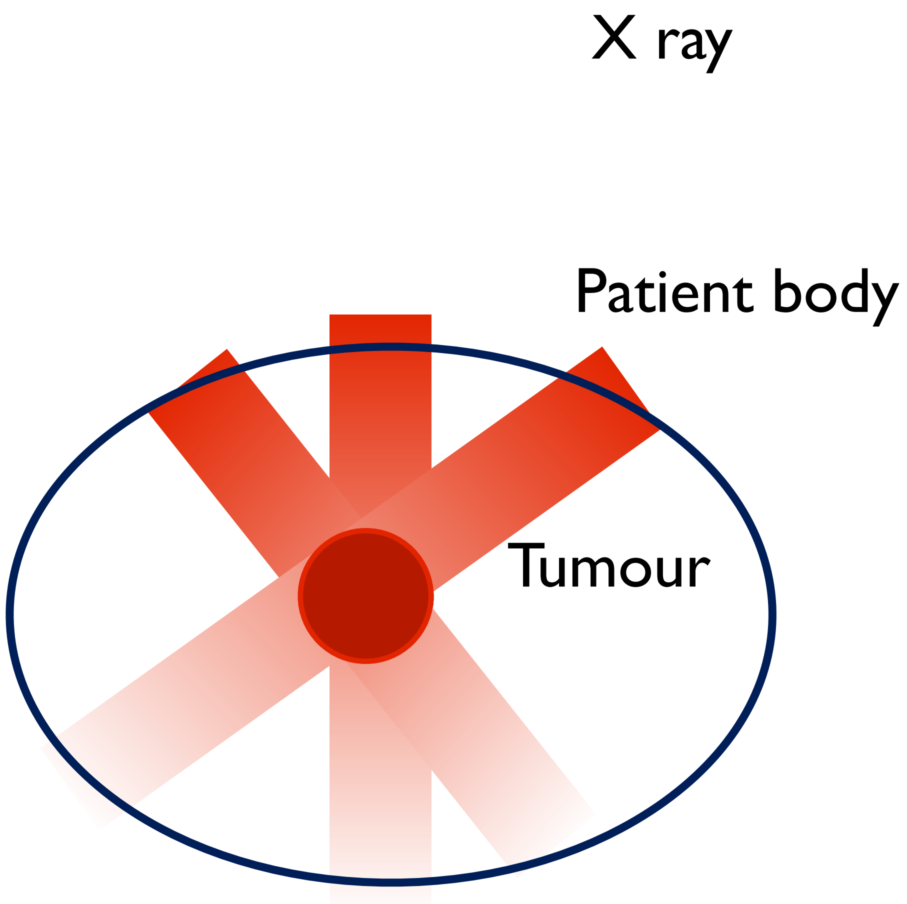
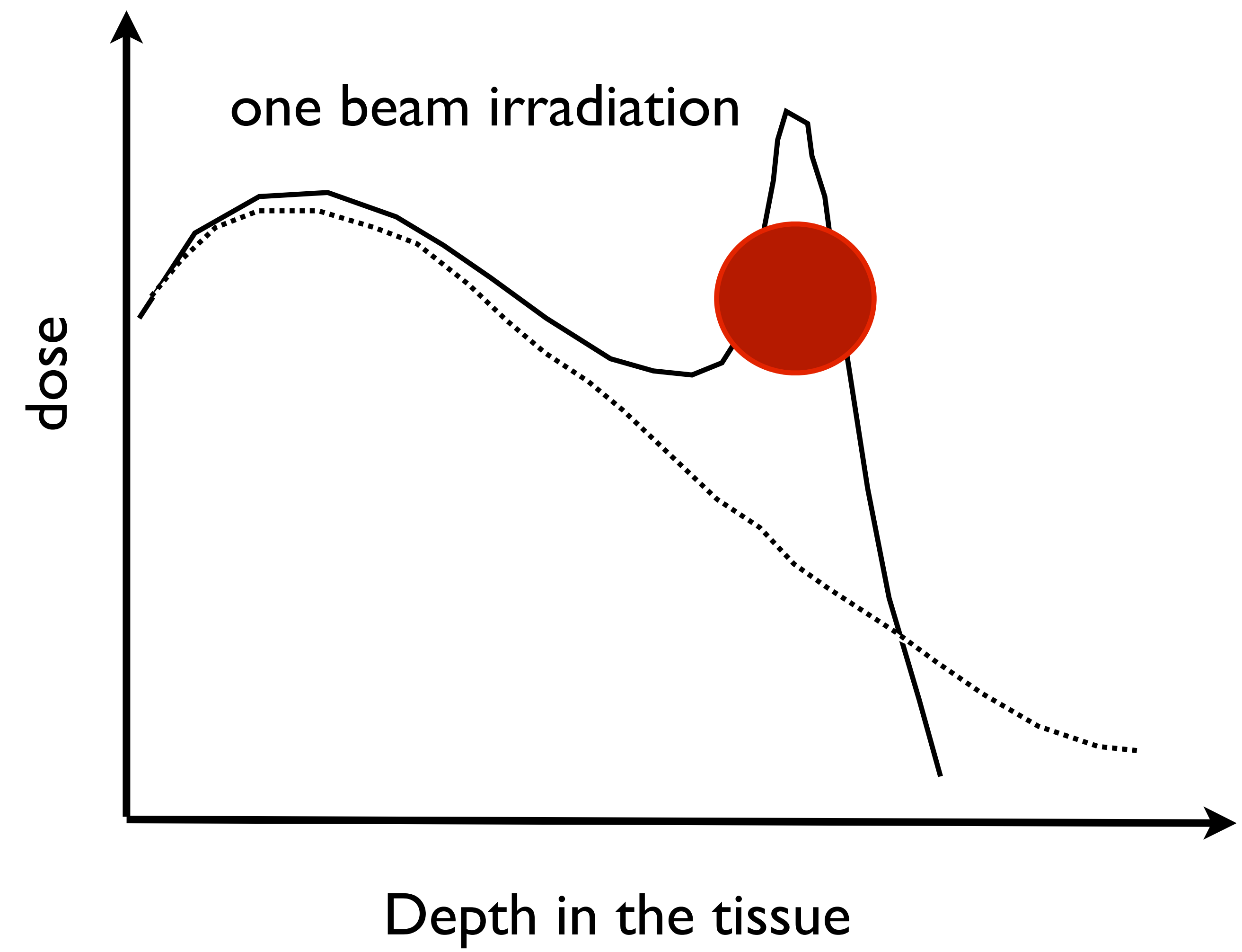
Medical applications : cancer treatment



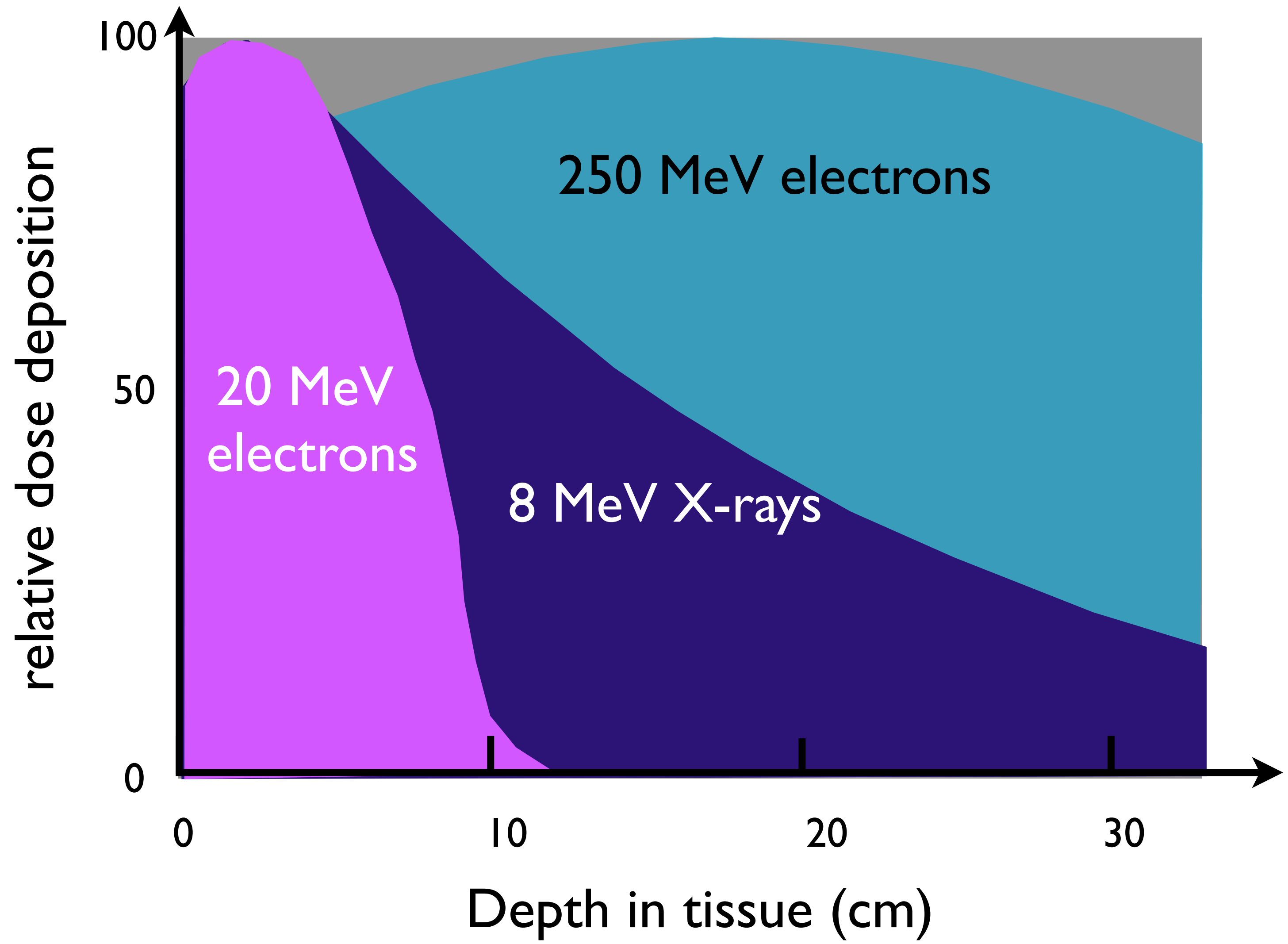
95% of radiotherapy is done with X ray

Radiotherapy : principle



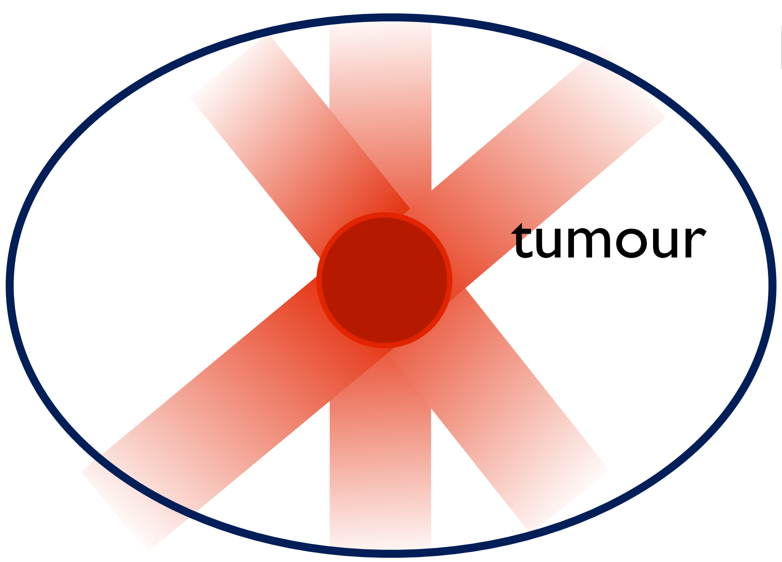


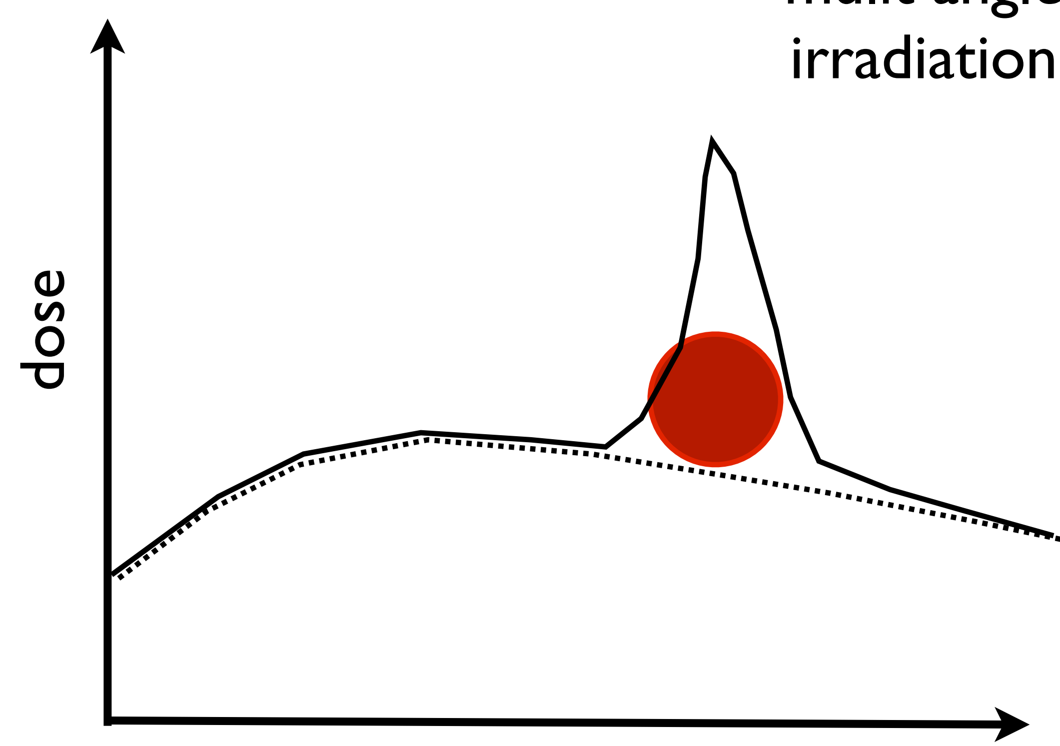
Medical applications : cancer treatment



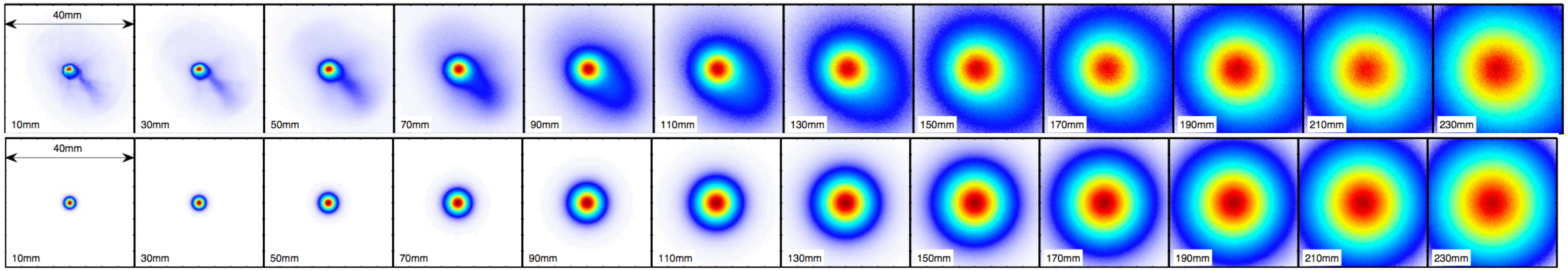
VHE electron depose the dose deep in the body

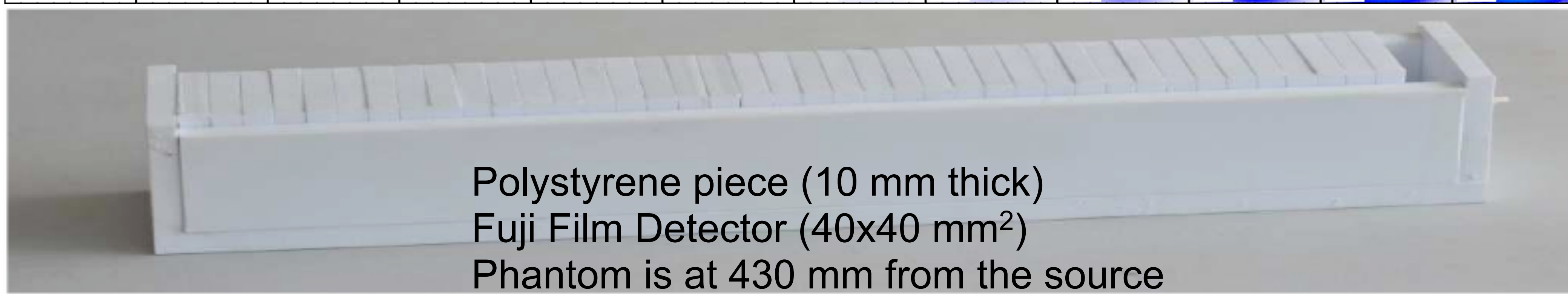
Medical applications : cancer treatment



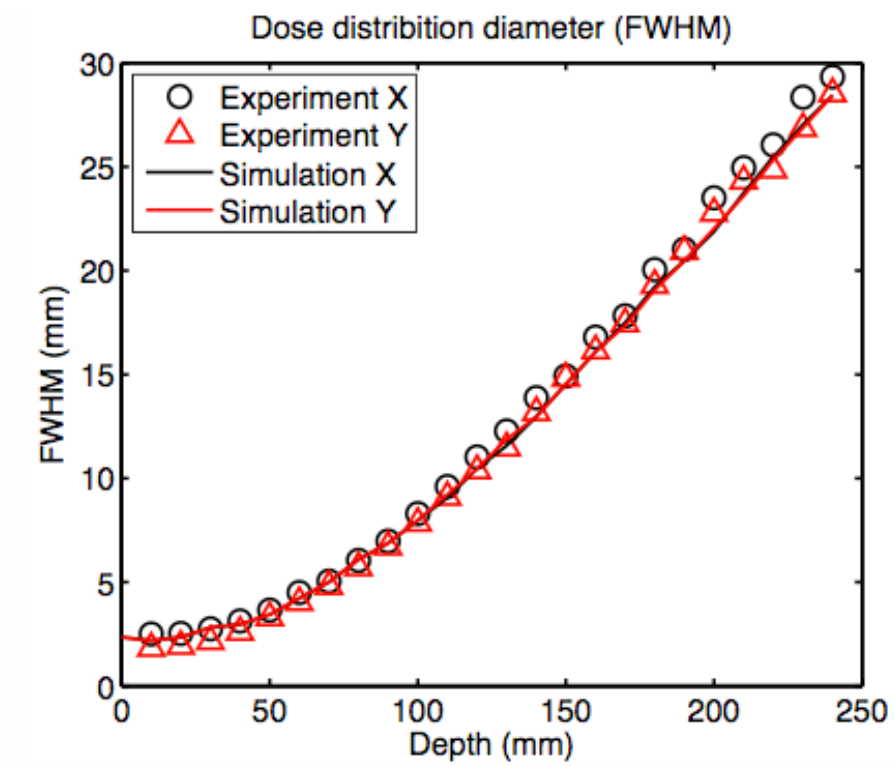


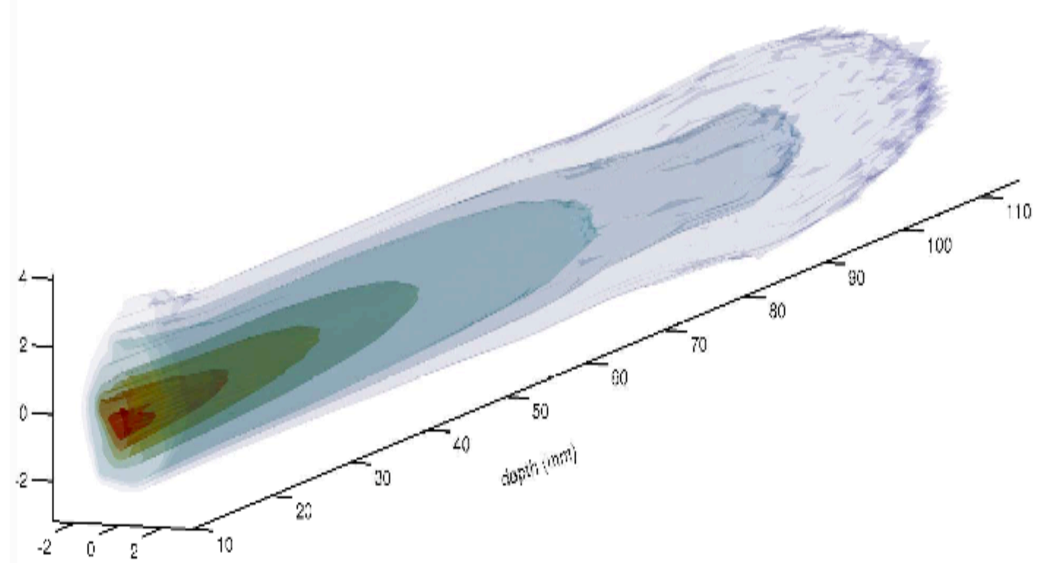
Some examples of applications : radiotherapy





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

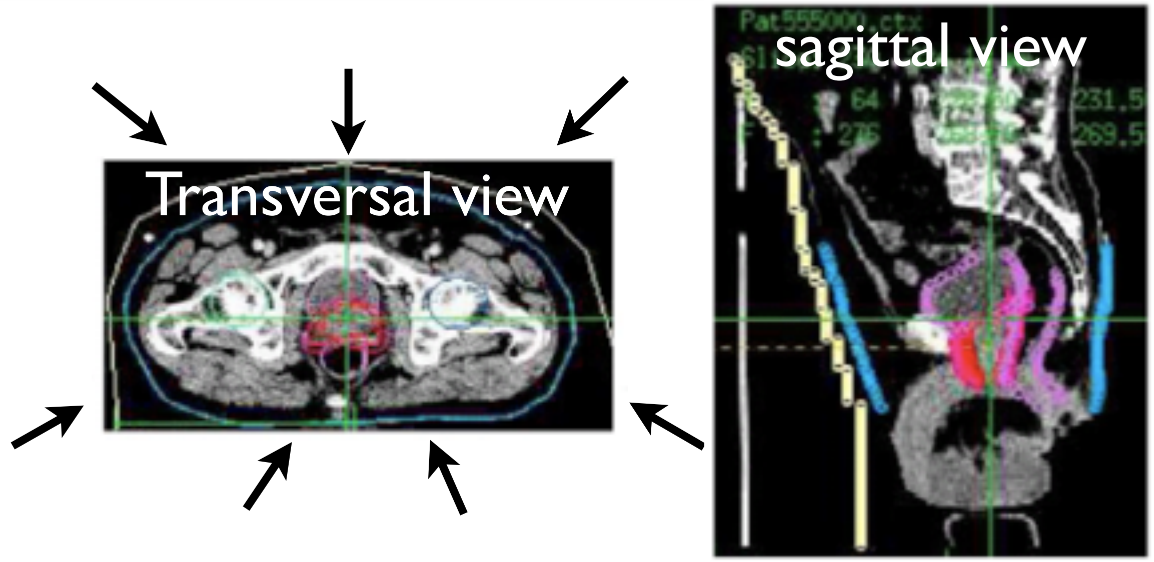




O. Lundh *et al.*, Medical Physics **39**, 6 (2012)

Cancer treatment improvements : real case of prostate

irradiation at 7 angles



(a) 250 MeV electrons

(b) X rays IMRT

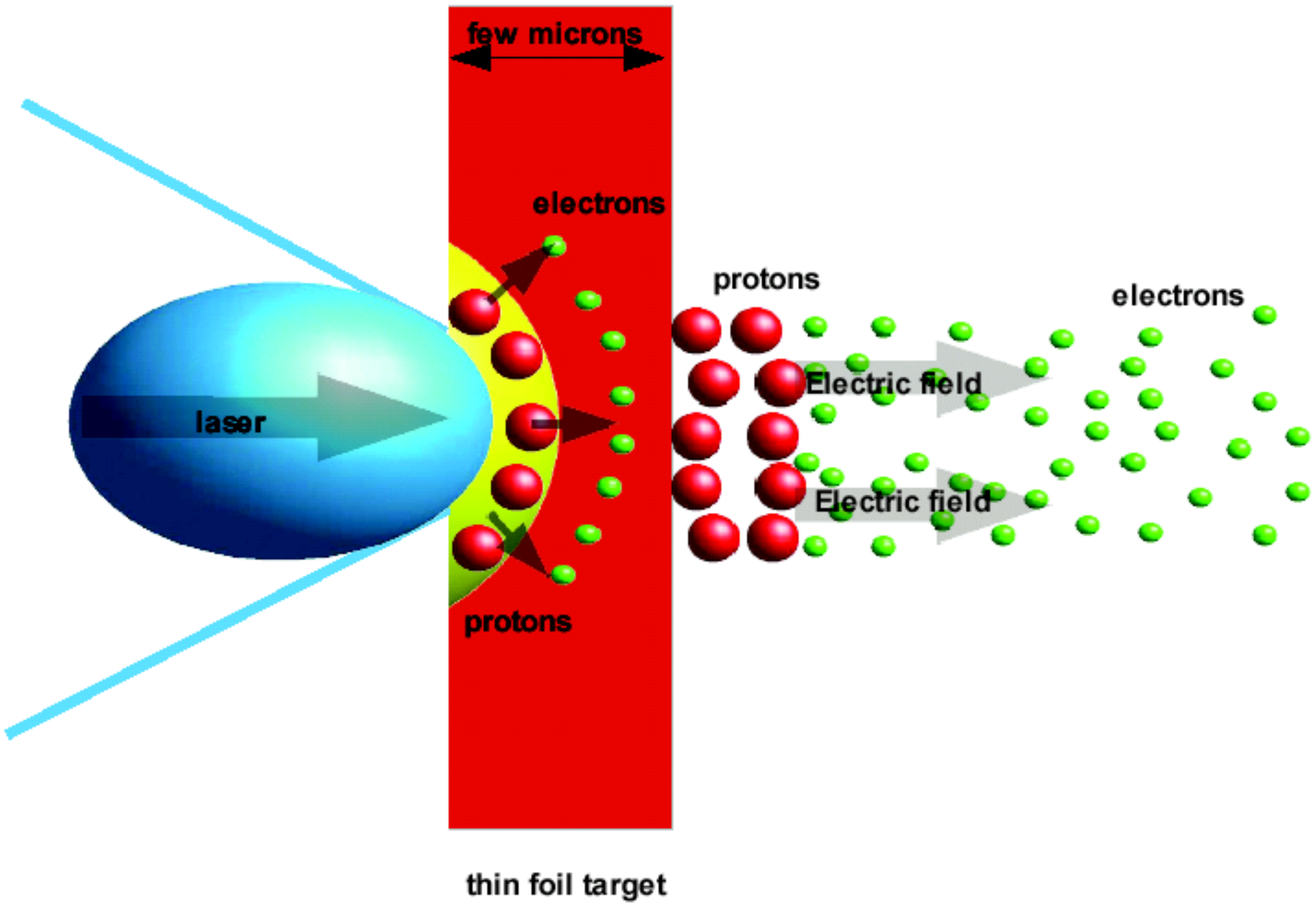
(c) Difference

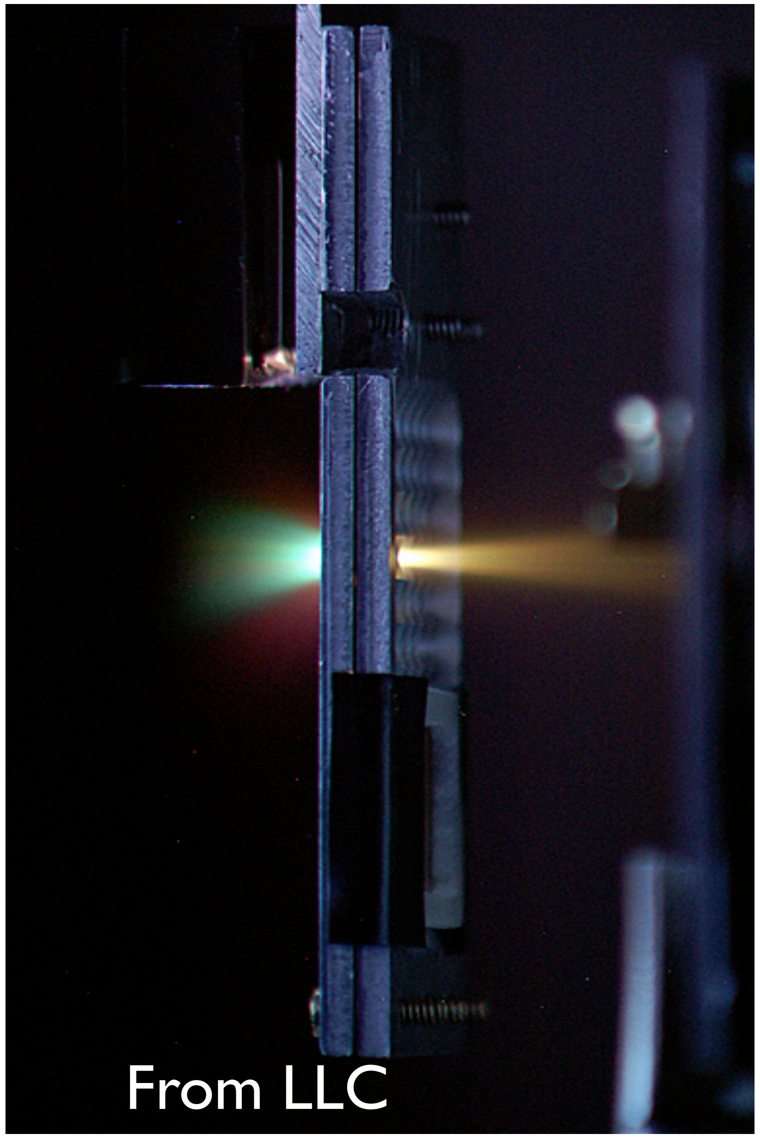
Laser-accelerated electrons can provide a better dose sparing of critical structures (up to 19%) at a similar target coverage compared to photons.

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

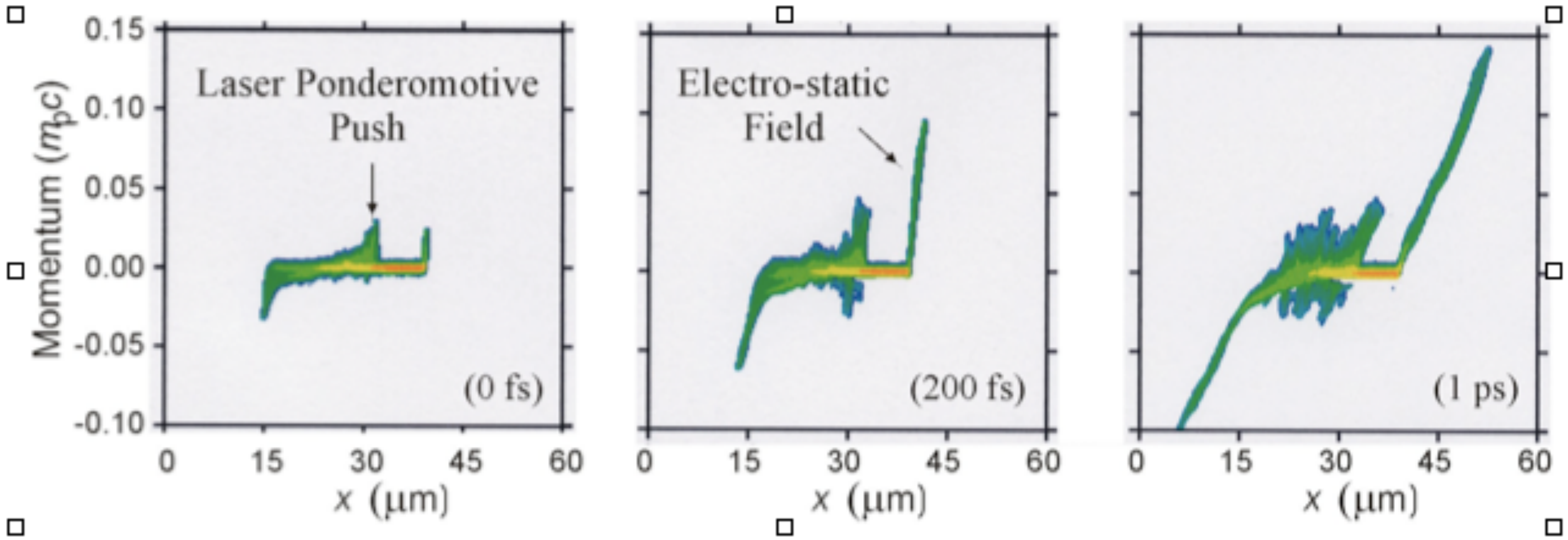
Laser Plasma Accelerators : Outline

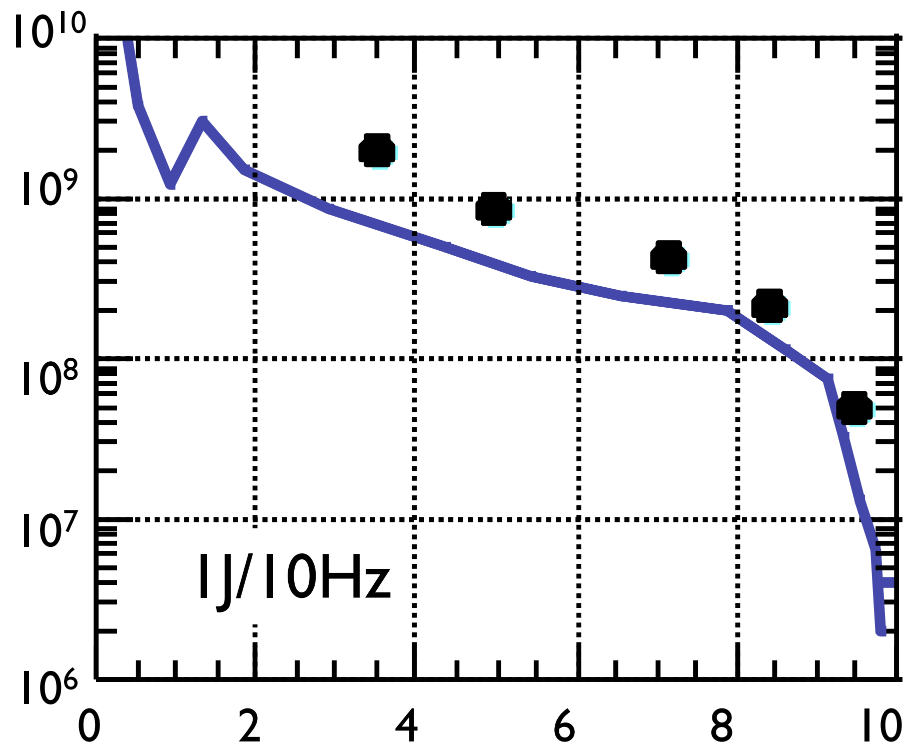
Protons acceleration : principe

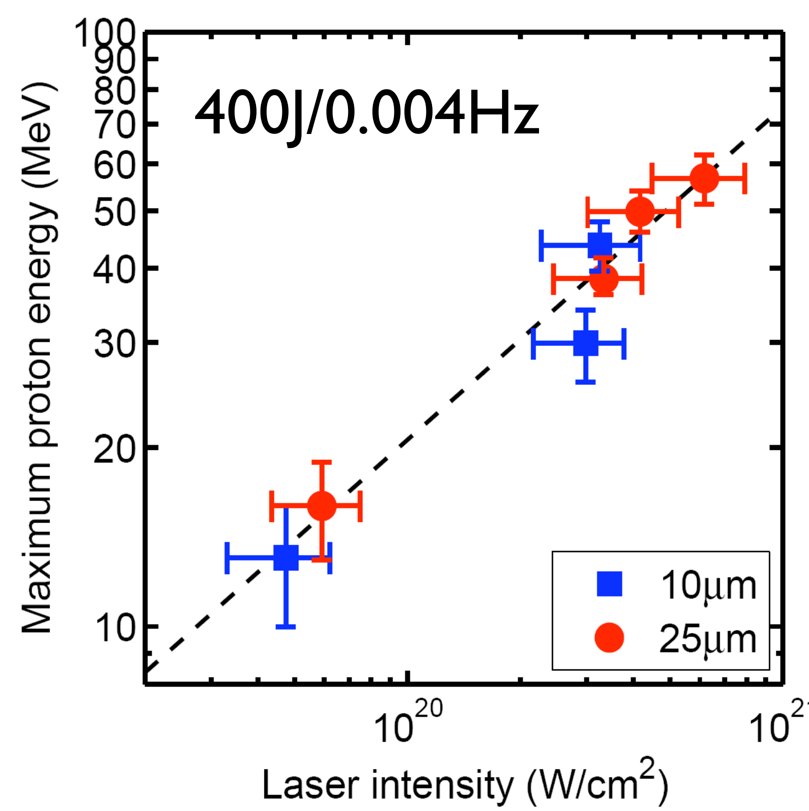




Three proton beams are produced



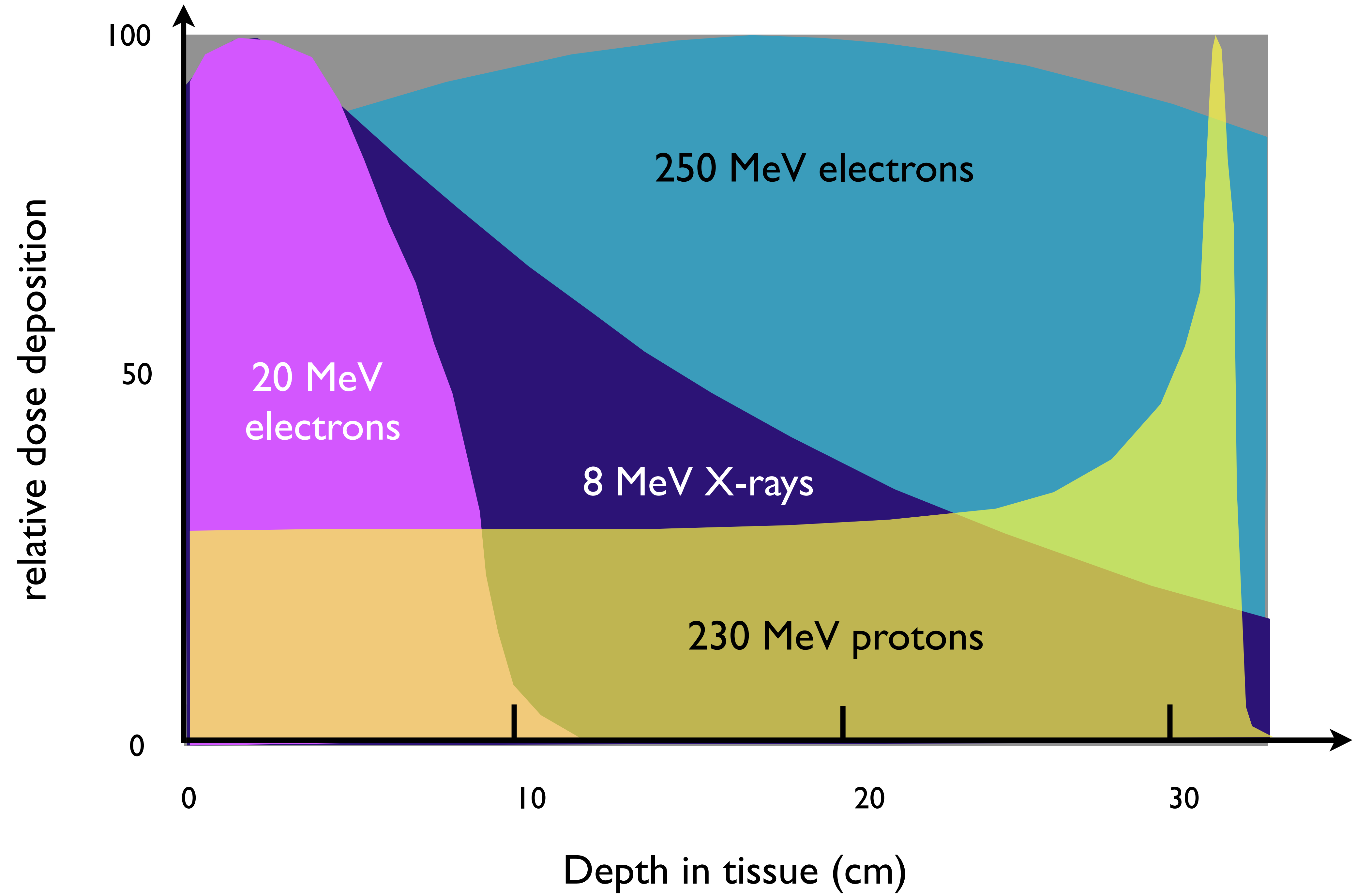




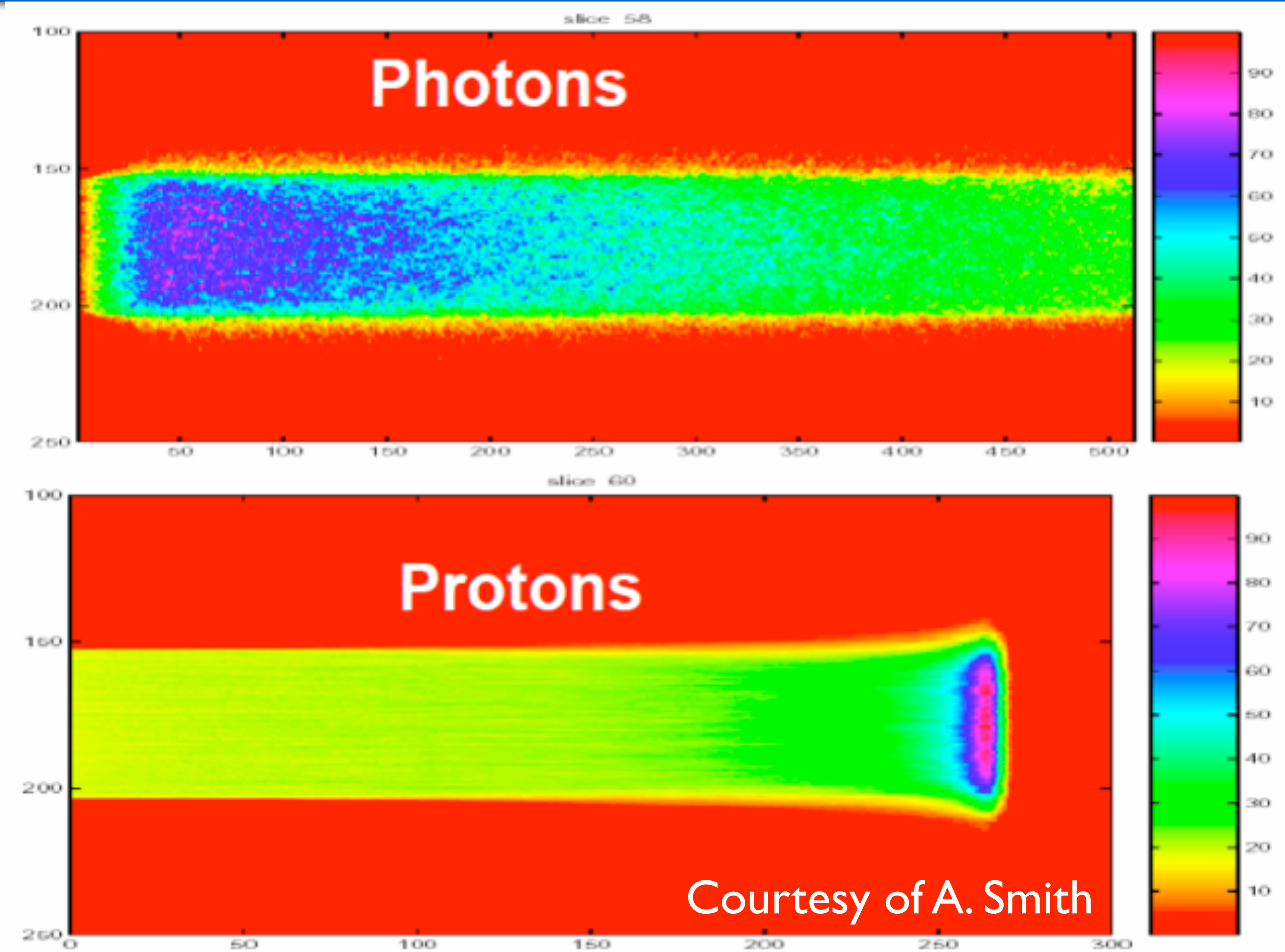
V. Malka et al., Appl. Phys. Lett. 83, 15(2003), Med. Phys. 31, 6(2004)

Robson et al., Nature Physics 3 (2007)

Protons provide superior dose distributions



Protons stop, electron and X rays do not stop



-The « optimum » dose distribution delivers 100% dose to the tumour target and not to critical normal tissues.
-Proton beams deliver dose distribution that are more optimum than those from photon beams

Protontherapy : potentiel patient benefit in France

Very selective prescription because of the cost and of the weight of the infrastructure.
Determined by the need of having an high balistic precision.

Medical impact	Tumour localisation	Nb of patient per year	Total
Major prescriptions	Eyes tumours	400 / 450	
	Neuro-oncology and Rachis	2.000 / 2.500	
	Childs and adolescent	300 / 500	
	Sarcomes retro-peritony	80 / 100	**2.800 / 3.550**
other possible prescriptions	ORL	500 / 1.000	
	Lungs (poumons)	3.000 / 4.000	
	other cancers	1.000 / 1.500	**4.500 / 6.500**
Potential prescriptions	Some prostate cancers	2.500 / 3.000	
	Re-irradiations	500 / 1.000	**3.000 / 4.000**

recent publication: protontherapy should be beneficial for 15% of patients wich requires radiotherapy treatment (i.e. 27.000 patients per year in France)
Capacity of protontherapy in France : 600 patients per year (800 en 2011).

Protontherapy : numbers

- 10 millions more people affected each year
- 6 millions are treated by conventional radiotherapy
- 9% of them could be treated by proton therapy: only 0.1% actually are
- About 500 more proton therapy centers required to satisfy the need

Laser Based Approach : potential advantages

The SAPHIR consortium

SAPHIR: Source Accélérée de Protons par laser de Haute Intensité pour la Radiothérapie
(Accelerated Proton Source by Ultra Intense Laser for Protontherapy)

Economical Challenges

Reduction of the investment and operating costs
Reduction of the overall size of the equipments
Reduction of radioprotection constraints
Optimization of dose deposition

Technical challenges

Getting more than 65 MeV pour eye treatment and 150-200 MeV for others.
Proton energy spectrum fully controlled
Stability and reproducibility of applied dose

Total budget (consolidated) : 20 M€

Financial support
OSEO: 6.25 M€
Region Ile de France: 1 M€

7 Partners

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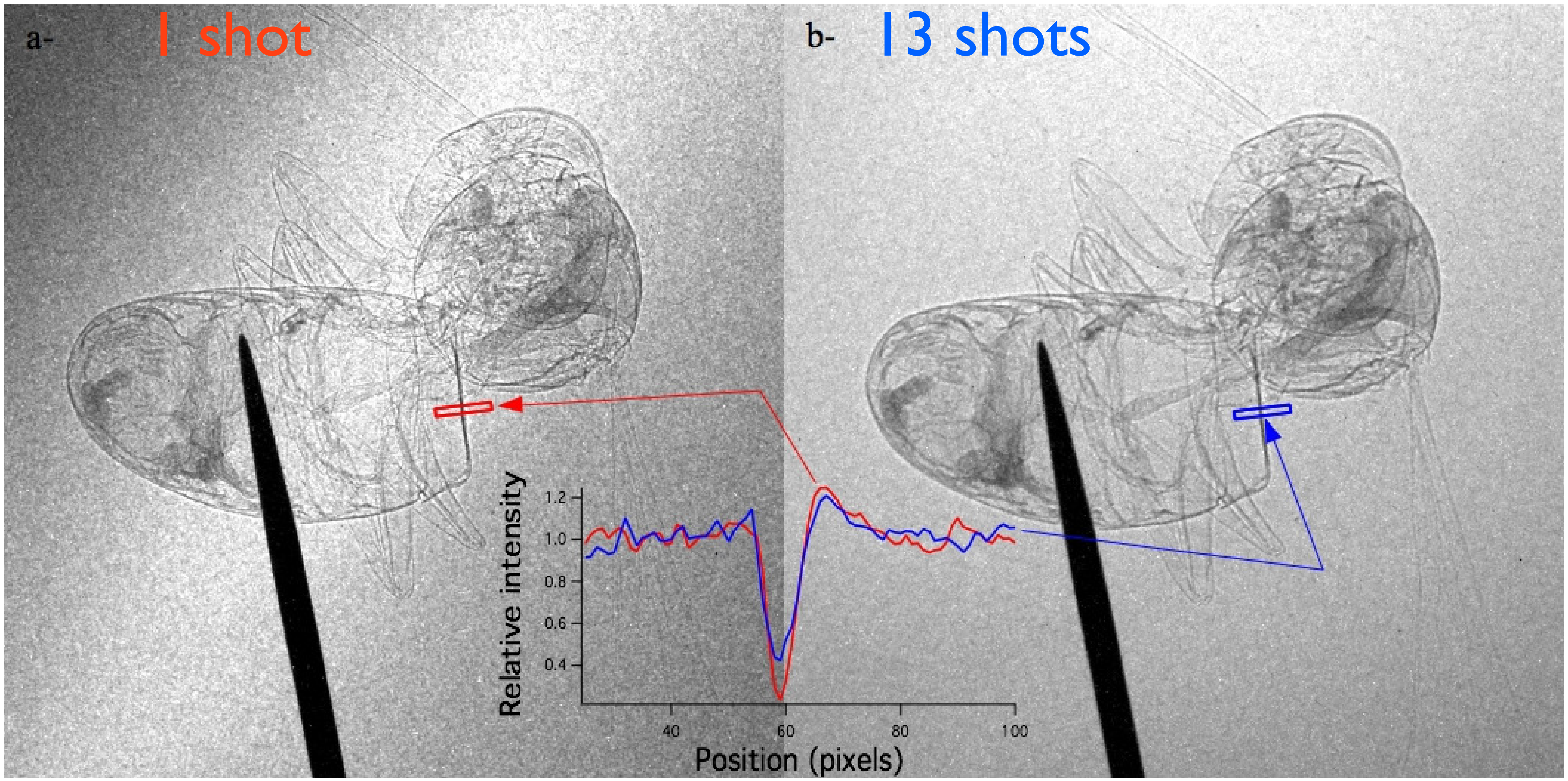
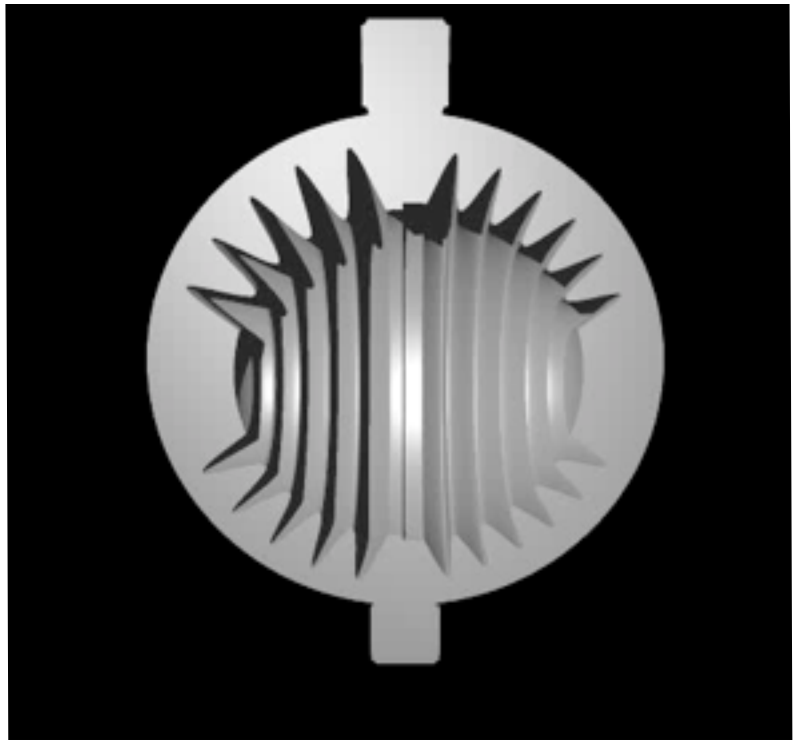
X ray Phase Contrast Radiography: Results

Bee contrast image :

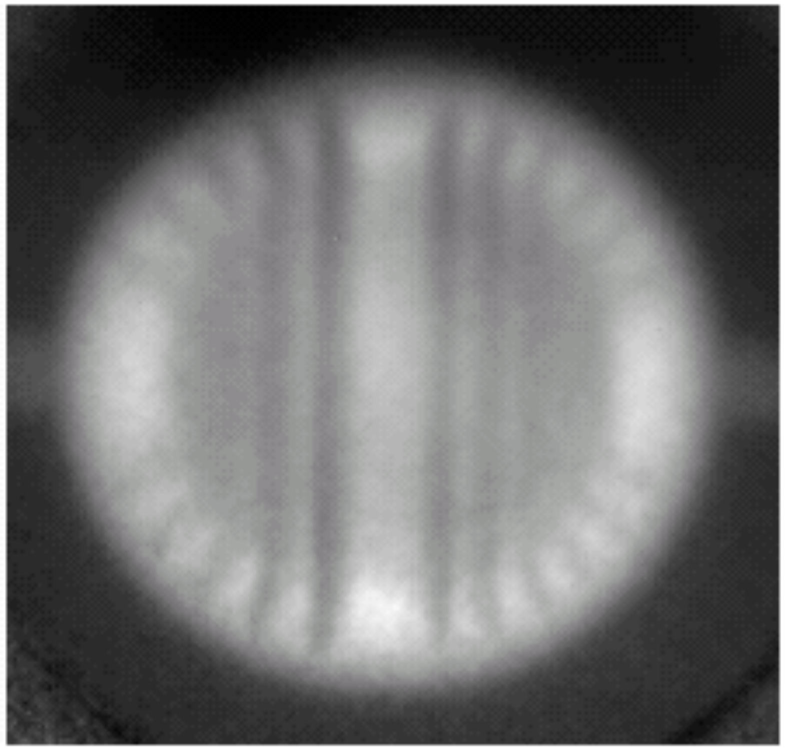
- Contrast of 0.68 in single shot.
- Very tiny details can be observed in single shot that disappear in multi shots.



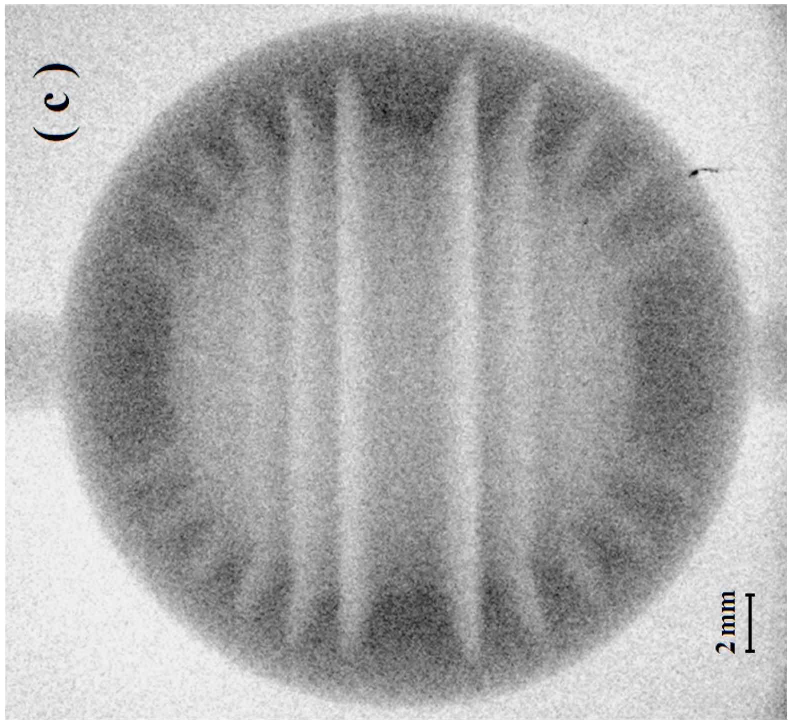
Some examples of applications : radiography results



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



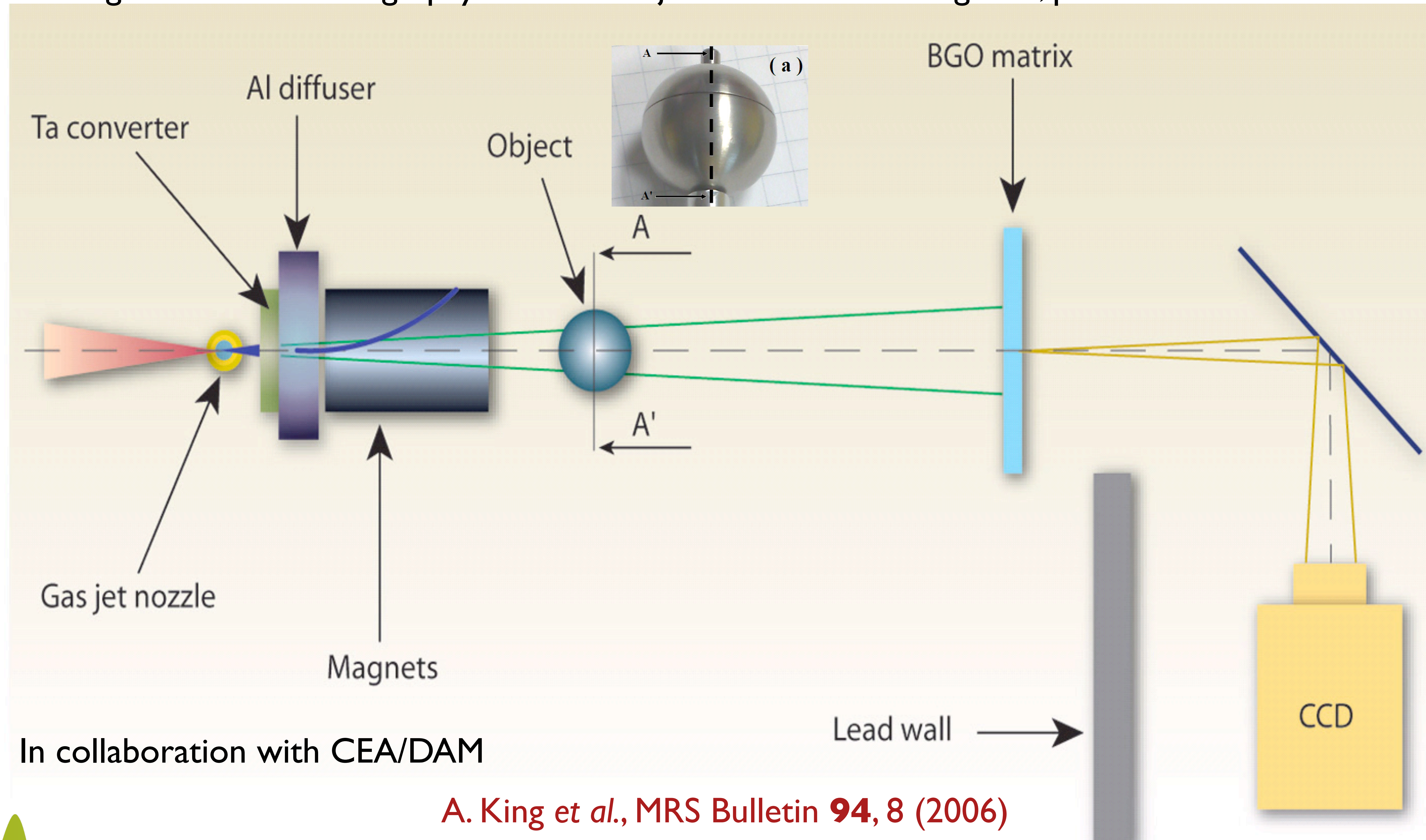
50 µm γ source size
2010

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 : radiography

Non destructive dense matter inspection

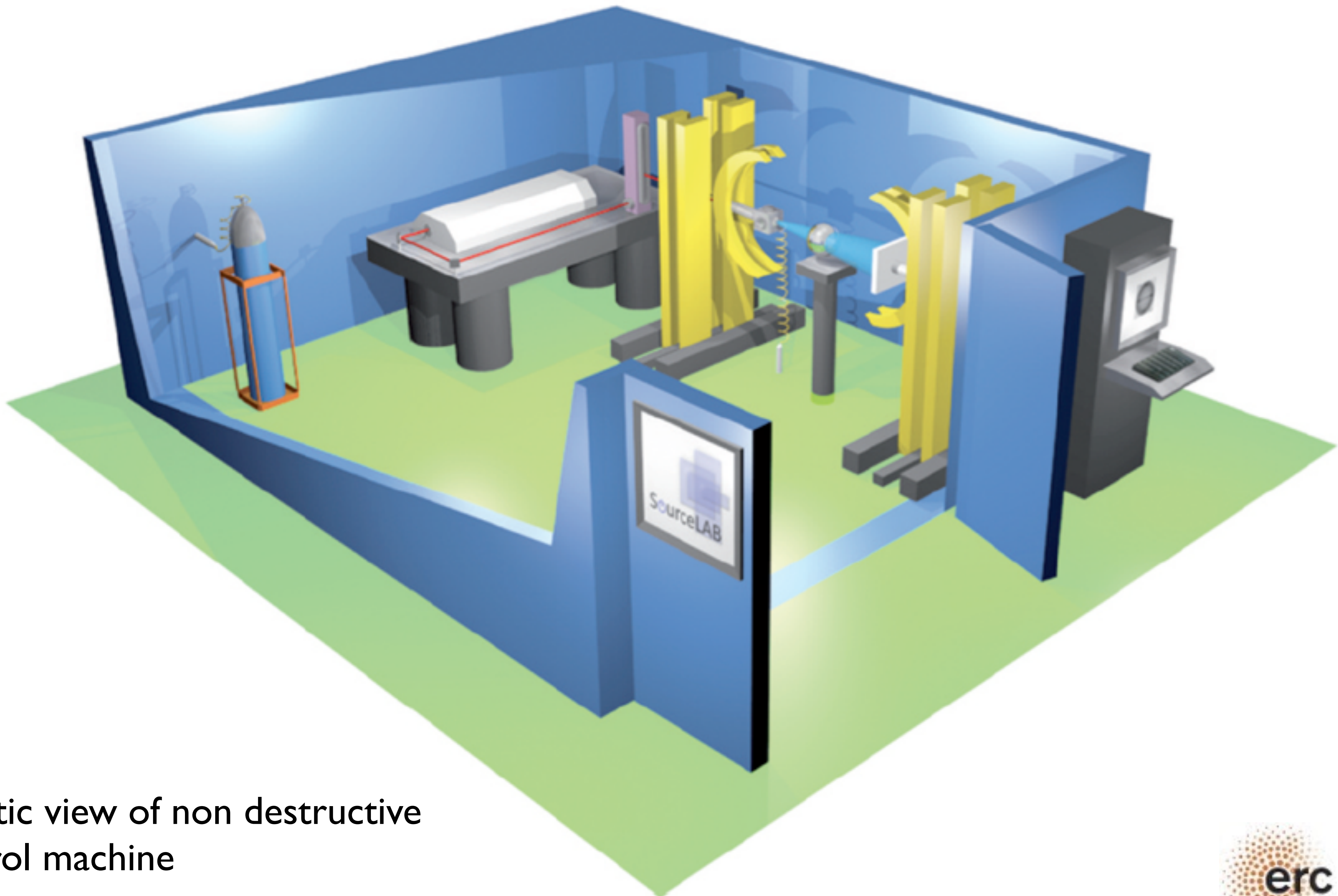
High resolution radiography of dense object with a low divergence, point-like electron source



In collaboration with CEA/DAM

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

Some examples of applications : Non Destructive Control



Artistic view of non destructive control machine

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Properties of e-beam produced by LPA

Good beam quality & Monoenergetic dE/E down to 1 %	√
Beam is very stable	√
Energy is tunable: 20-300 MeV	√
Charge is tunable: 1 to tens of pC	√
Energy spread is tunable: 1 to 10 %	√
Ultra short e-bunch : 1,5 fs rms	√
Few GeV with PW laser	√

Conclusion and Perspectives

- Stability has been improved by improving the laser contrast
- They produce quasi monoenergetic beam (structured target or RPA)
- Peak energy still moderated : 19MeV with 10 Hz laser-5HFZD, about100 MeV with PW large scale laser Los Alamos, 25 MeV with 30 J-ps CO2 laser UCLA, 60 MeV with PW-30fs in Corels.
- Number of proton per second can be a problem ?
- Target fabrication and alignment at high repetition rate ? In progress (LIBRA)
- Biological response with high current dose?
- Electron LPA satisfies mostly all the requirements *at moderate cost*
- Proton LPA is still very challenging

V. Malka et al., Nature Physics **4**, June 2008

Perspectives

Results extremely important for :

Designing future accelerators

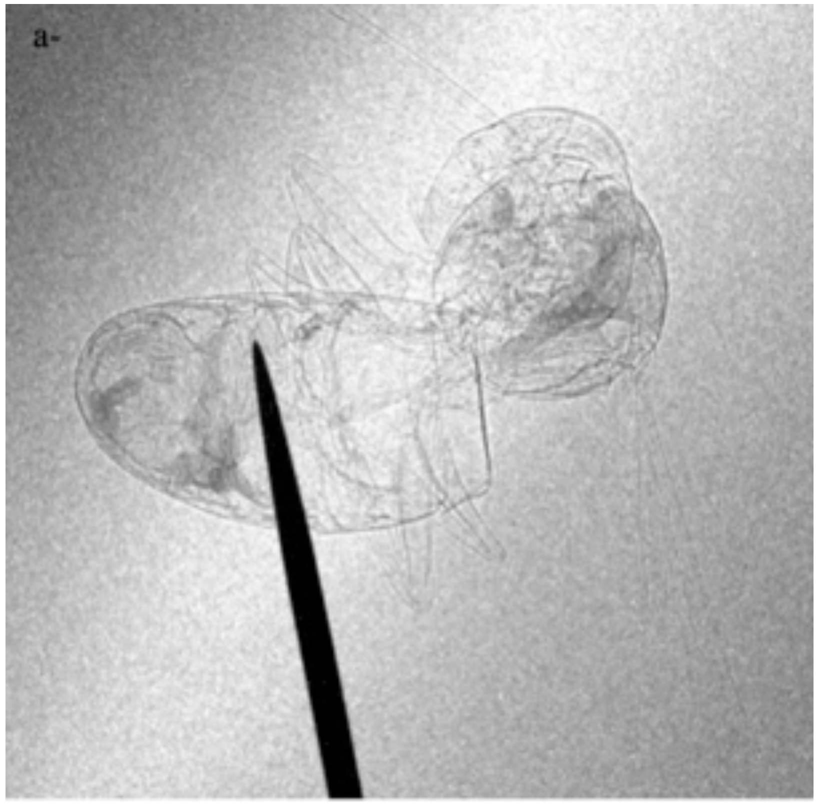
Compact X ray source (Thomson, Compton, Betatron, or FEL)

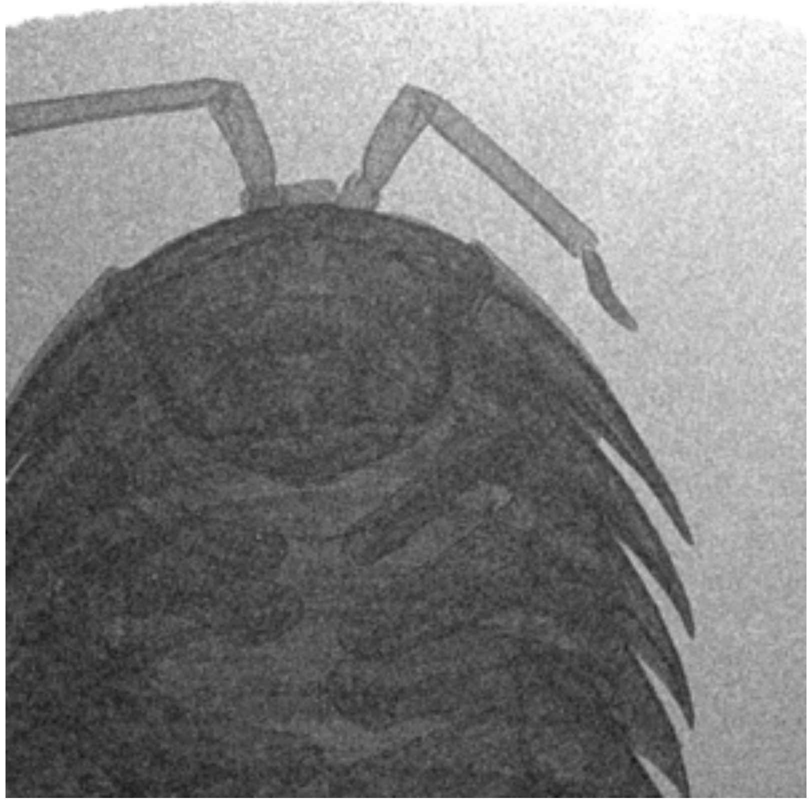
Applications (chemistry, radiotherapy, medicine, material science, ultrafast phenomena studies, etc...)

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)

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J. Faure, C. Rechatin, S. Corde, K. Ta Phuoc, O. Lundh, A. Ben Ismail, A. Lifshitz, A. Flacco, S. Fritzler, Y. Glinec, A. Guemnie-Tafo, M. Manclossi, F. Sylla ,Y. Gauduel, A. Rousse

Laboratoire d'Optique Appliquée – LOA

E. Lefebvre, X. Davoine

CEA/DAM Ile de France, France

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