Bringing Light into Research
Laser Plasma Accelerators : The Revolution

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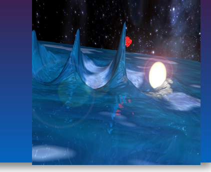
Laser Plasma Accelerators : Outline



- Introduction : context and motivations
- Laser wakefield principle
- Laser Plasma Accelerators
- 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...)

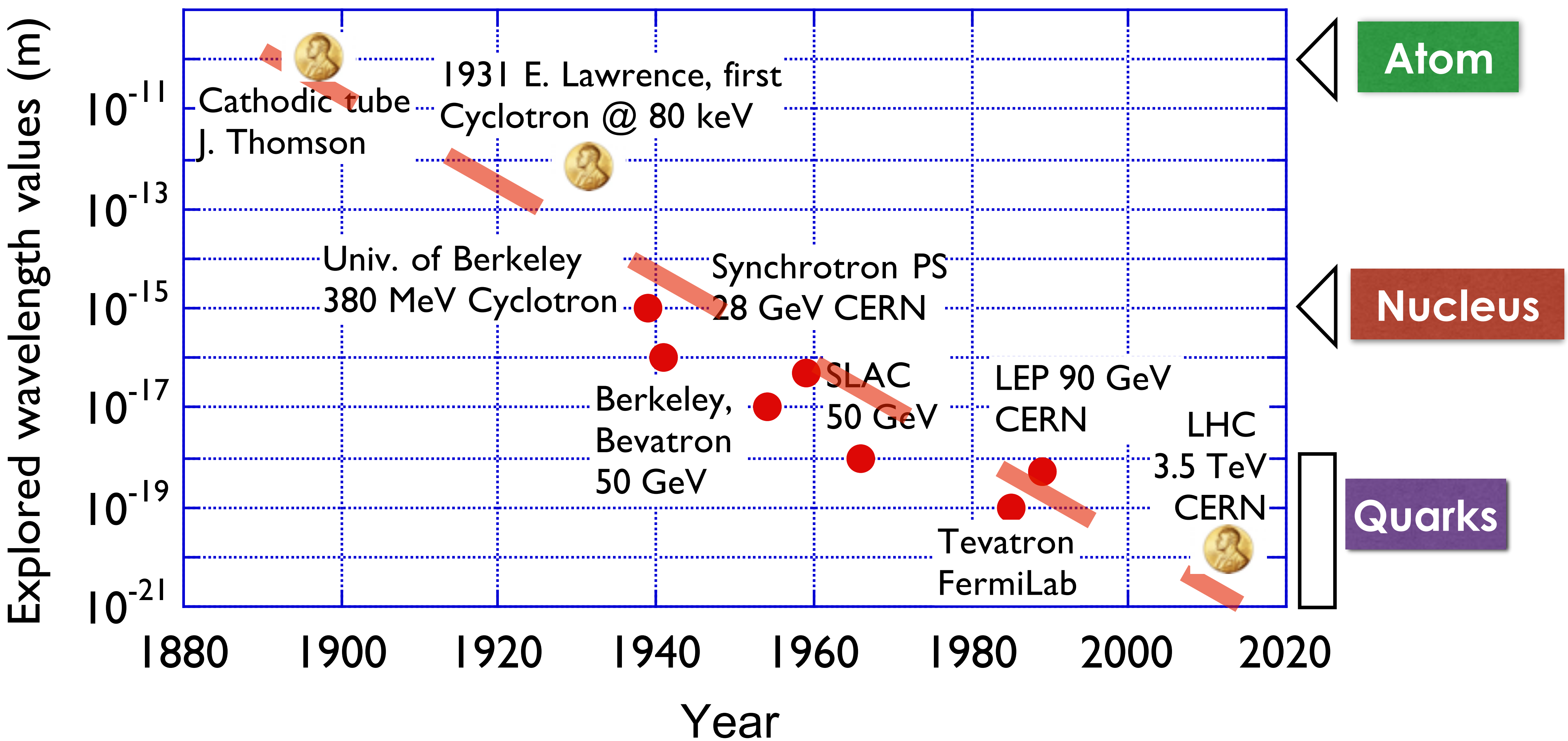
Application	Total syst. (2007) approx.	System sold/yr	Sales/yr (M$)	System price (M$)
Cancer Therapy	9100	500	1800	2.0 - 5.0
Ion Implantation	9500	500	1400	1.5 - 2.5
Electron cutting and welding	4500	100	150	0.5 - 2.5
Electron beam and X rays irradiators	2000	75	130	0.2 - 8.0
Radio-isotope production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

Radiotherapy

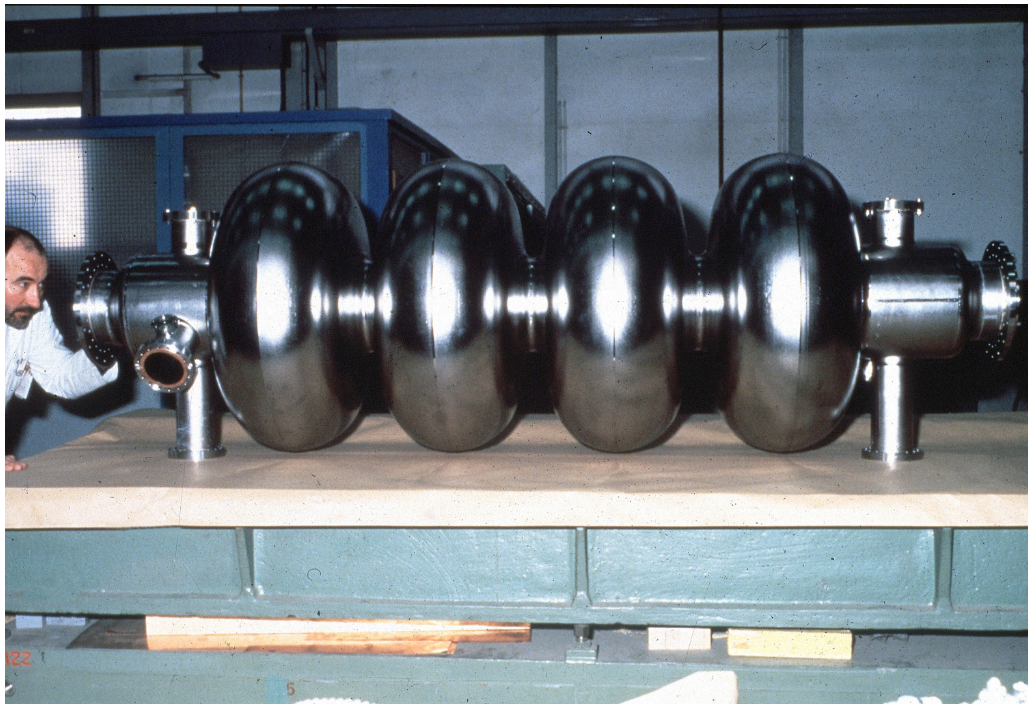
Imaging PET

Accelerators: One century of exploration of the infinitively small



Accelerators: One century of exploration of the infinitively small

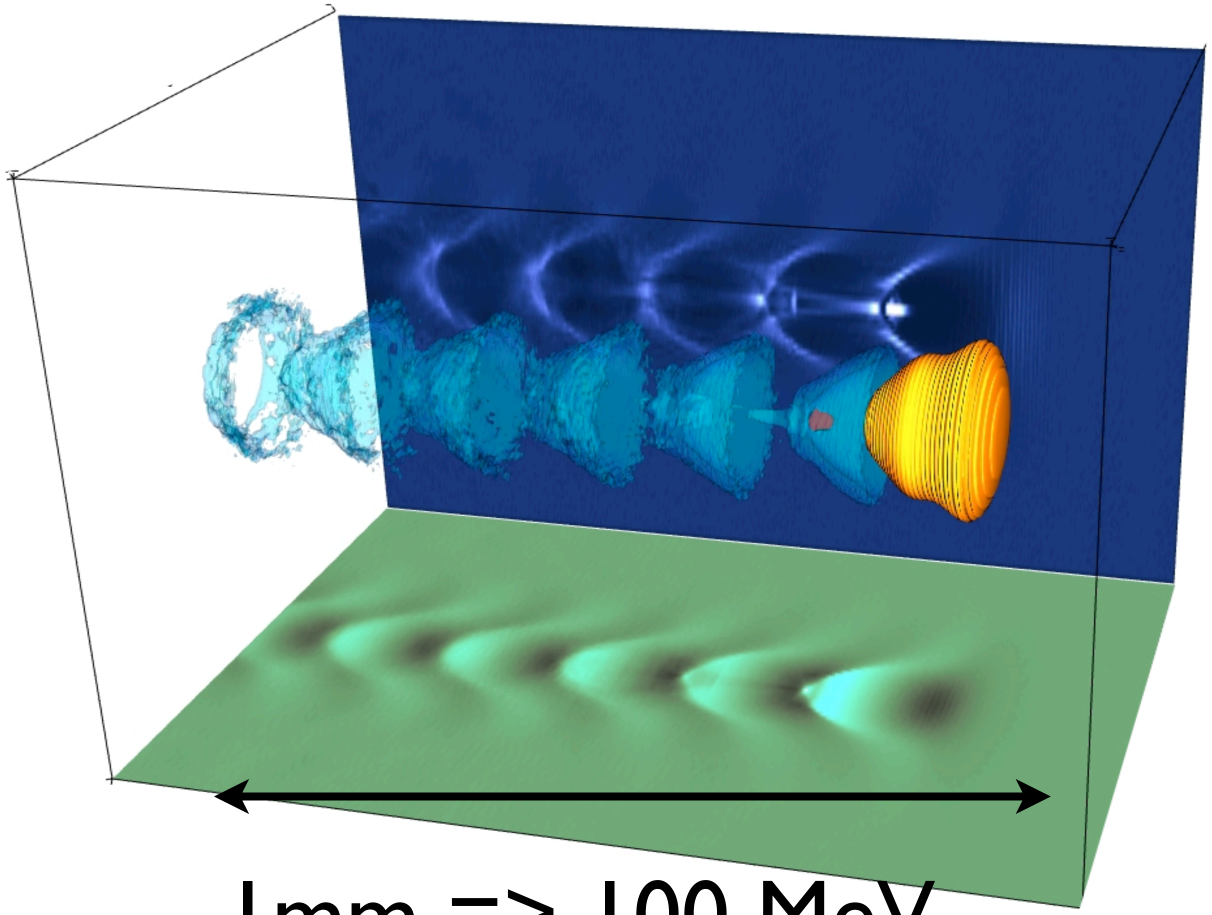
RF Cavity



1 m => 100 MeV Gain

Electric field < 100 MV/m

Plasma Cavity



1mm => 100 MeV

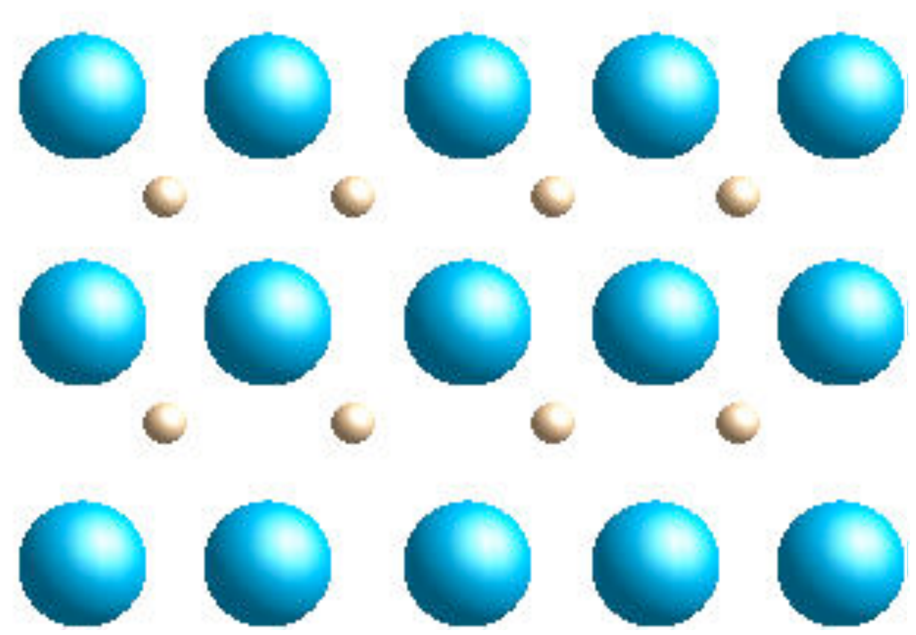
Electric field > 100 GV/m

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

Why is a plasma useful ?

Superconducting RF-Cavities : E_z = 55 MVm

Plasma is an Ionized Medium => High Electric Fields



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

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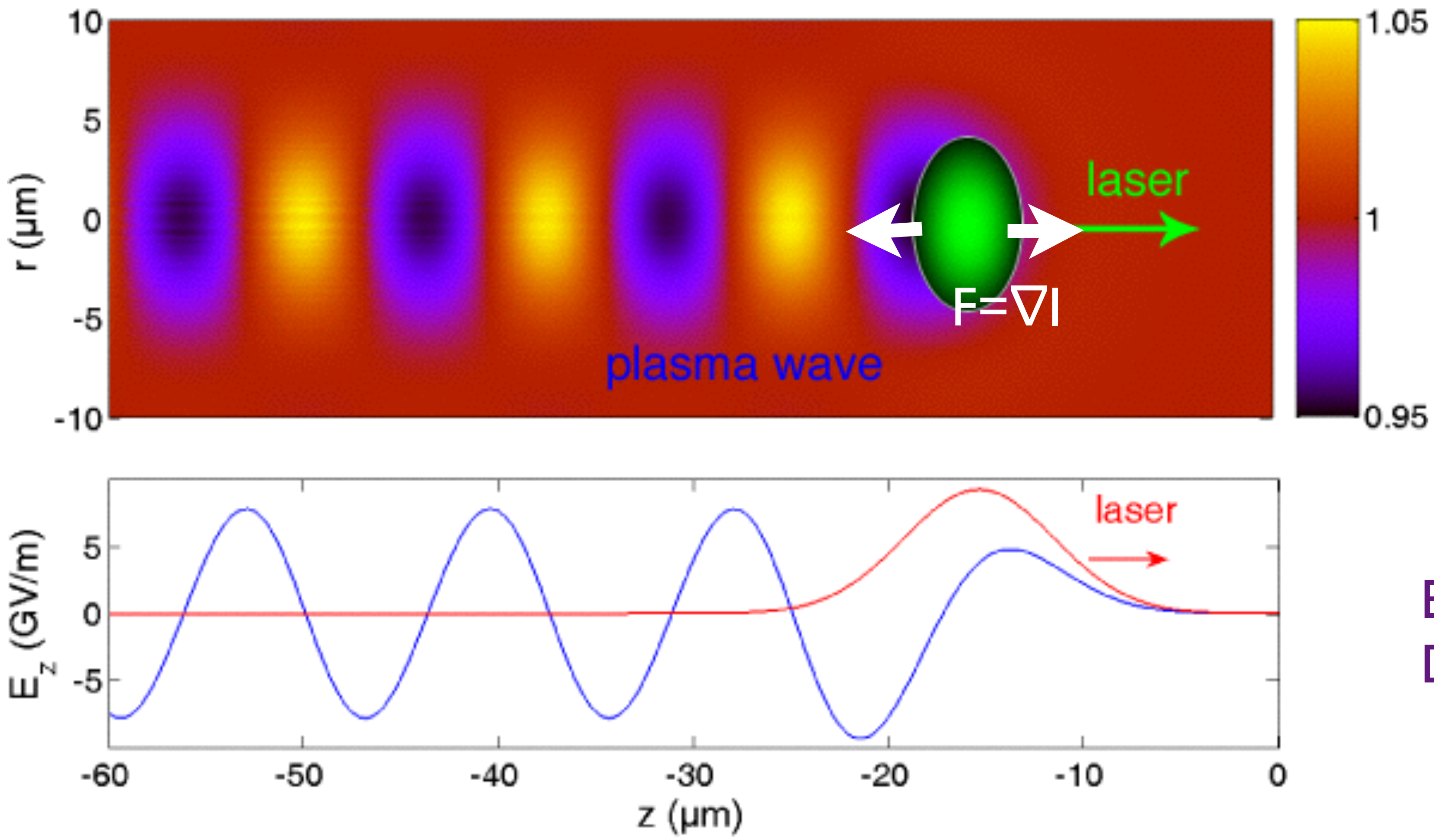
How to excite relativistic plasma waves ?

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

electron density perturbation and longitudinal wakefield



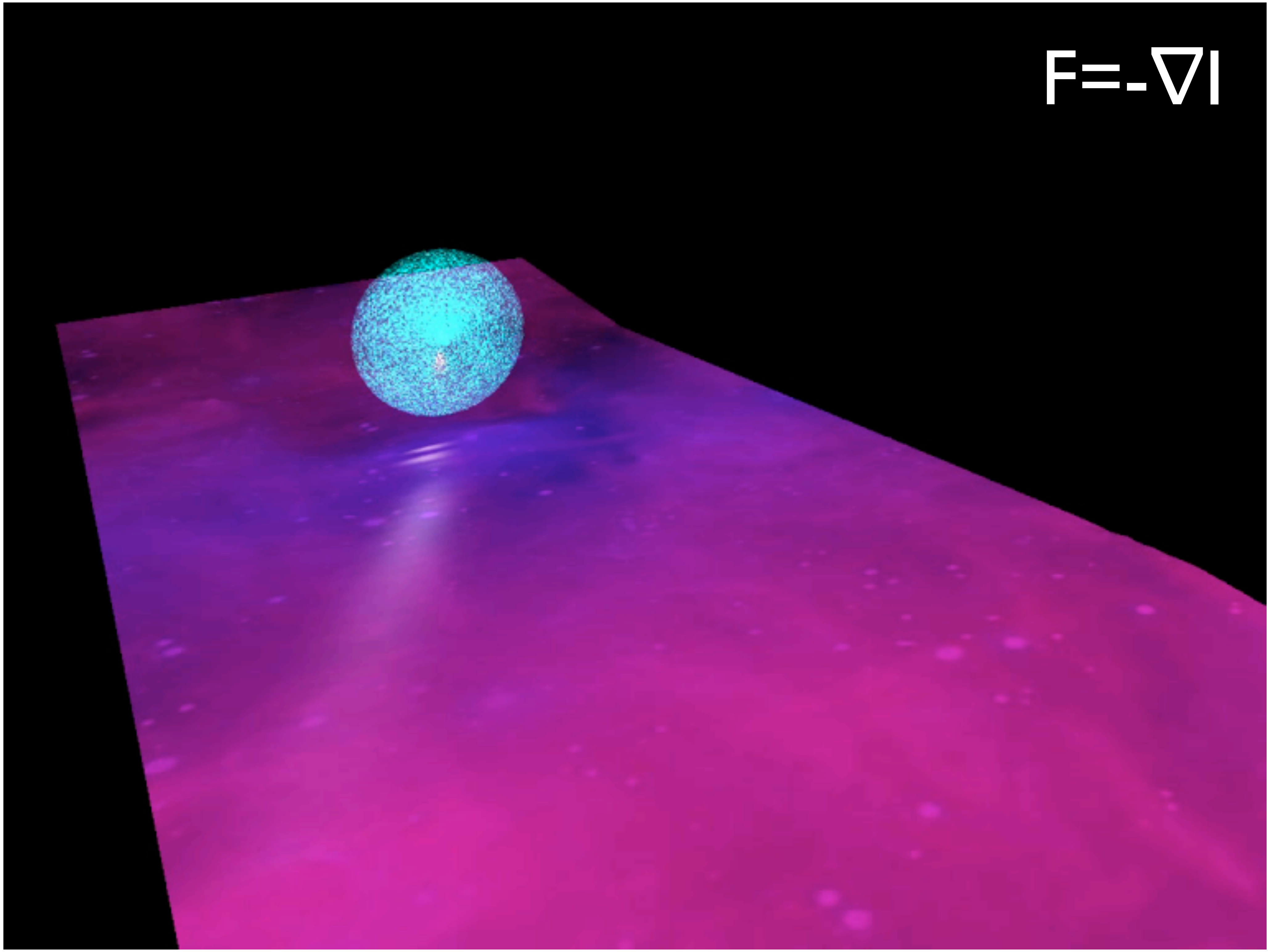
wave in the wake of a boat

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)

The Forced laser wakefield



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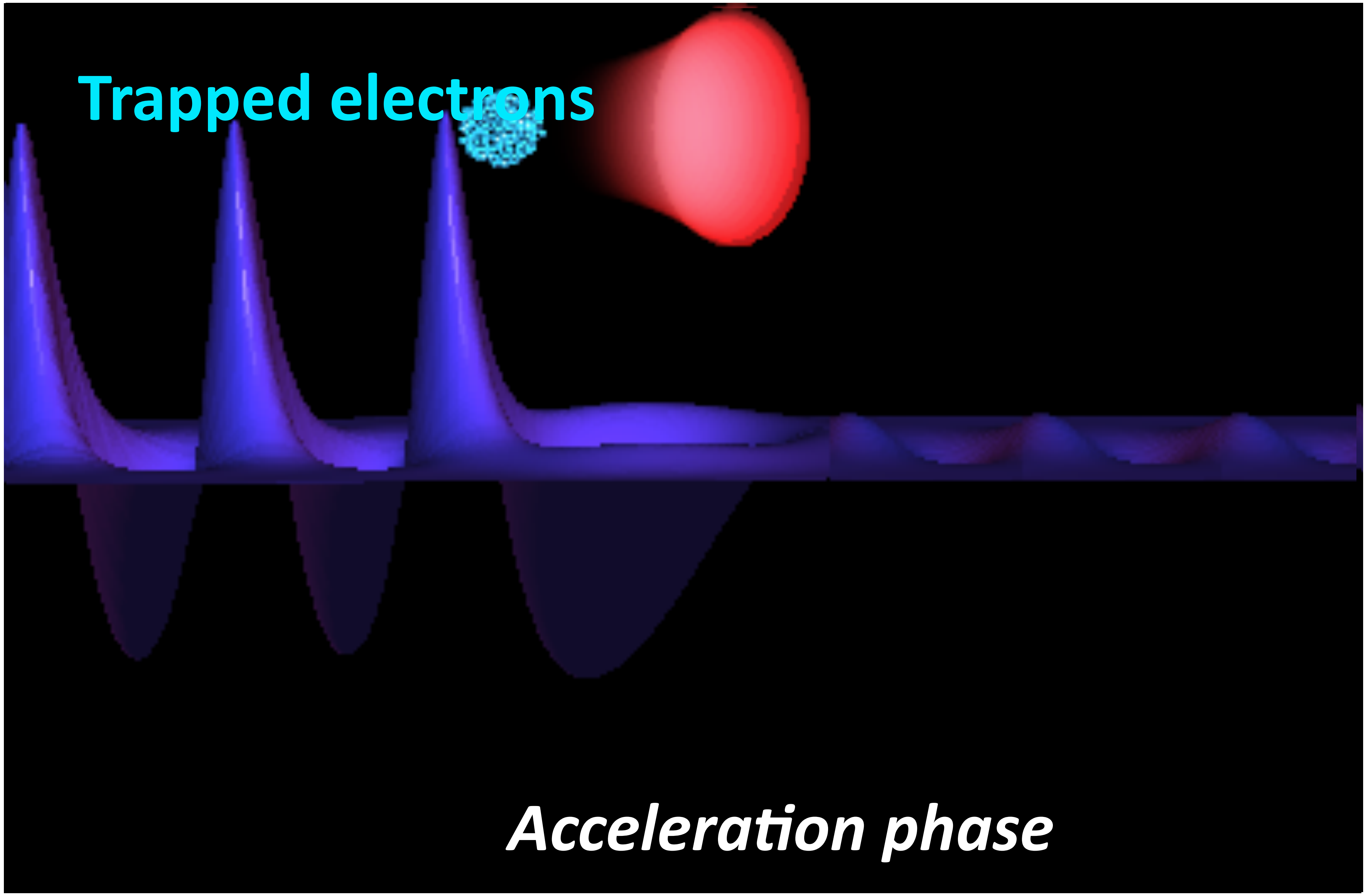
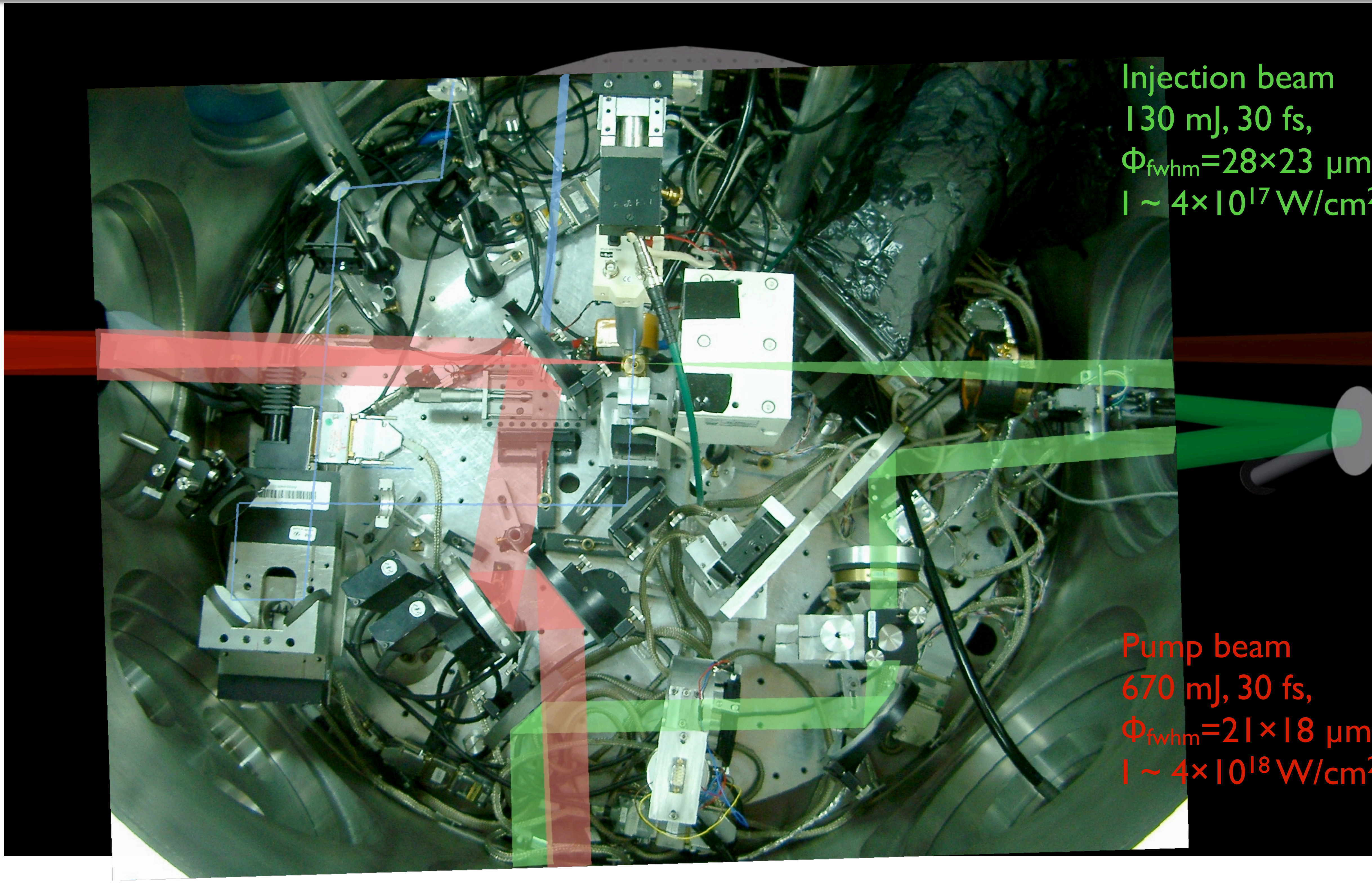
Colliding Laser Pulses Scheme

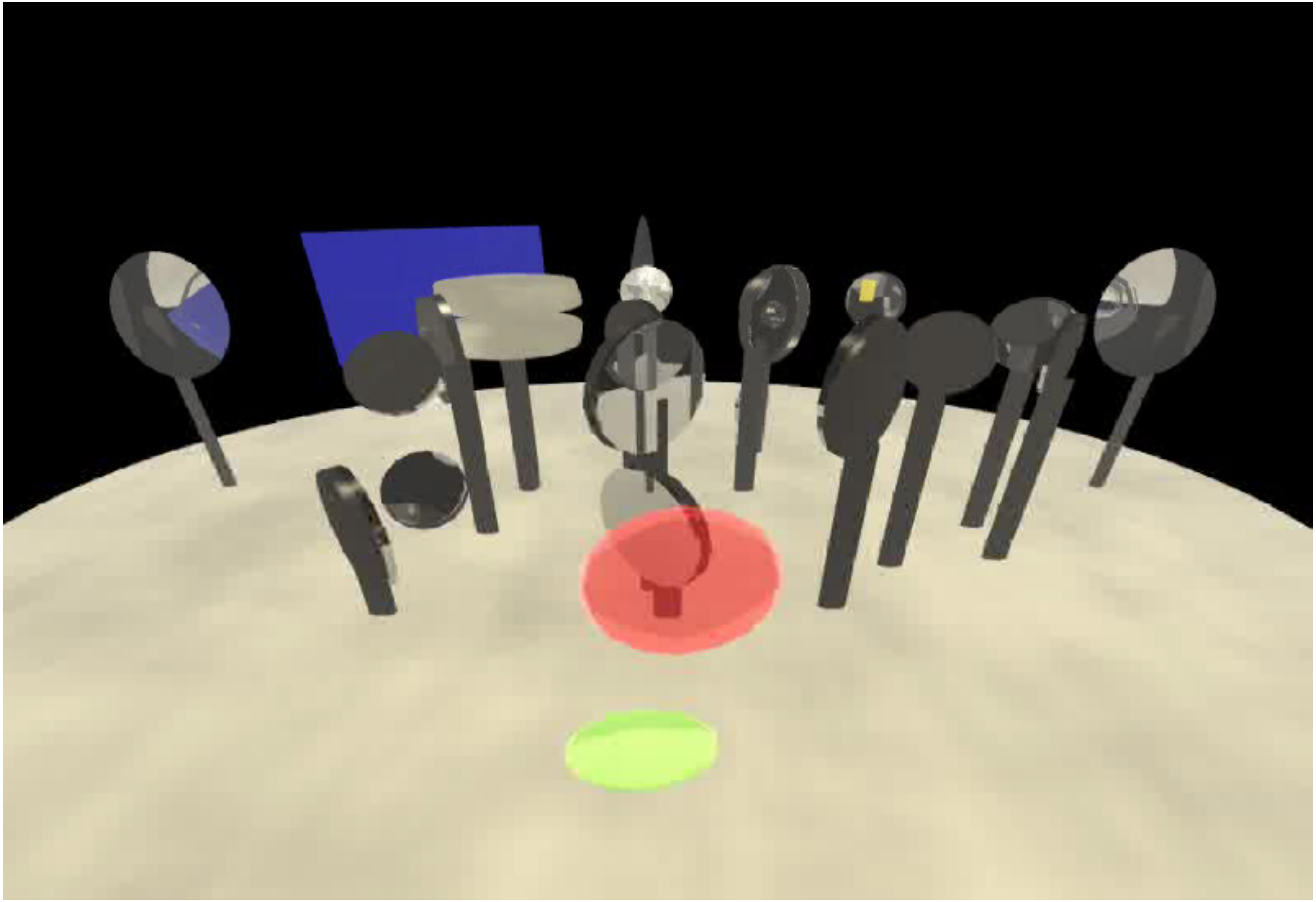


The first laser creates the accelerating structure
A second laser beam is used to heat electrons

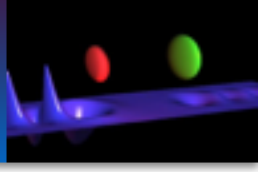
Set-up for colliding pulses experiment



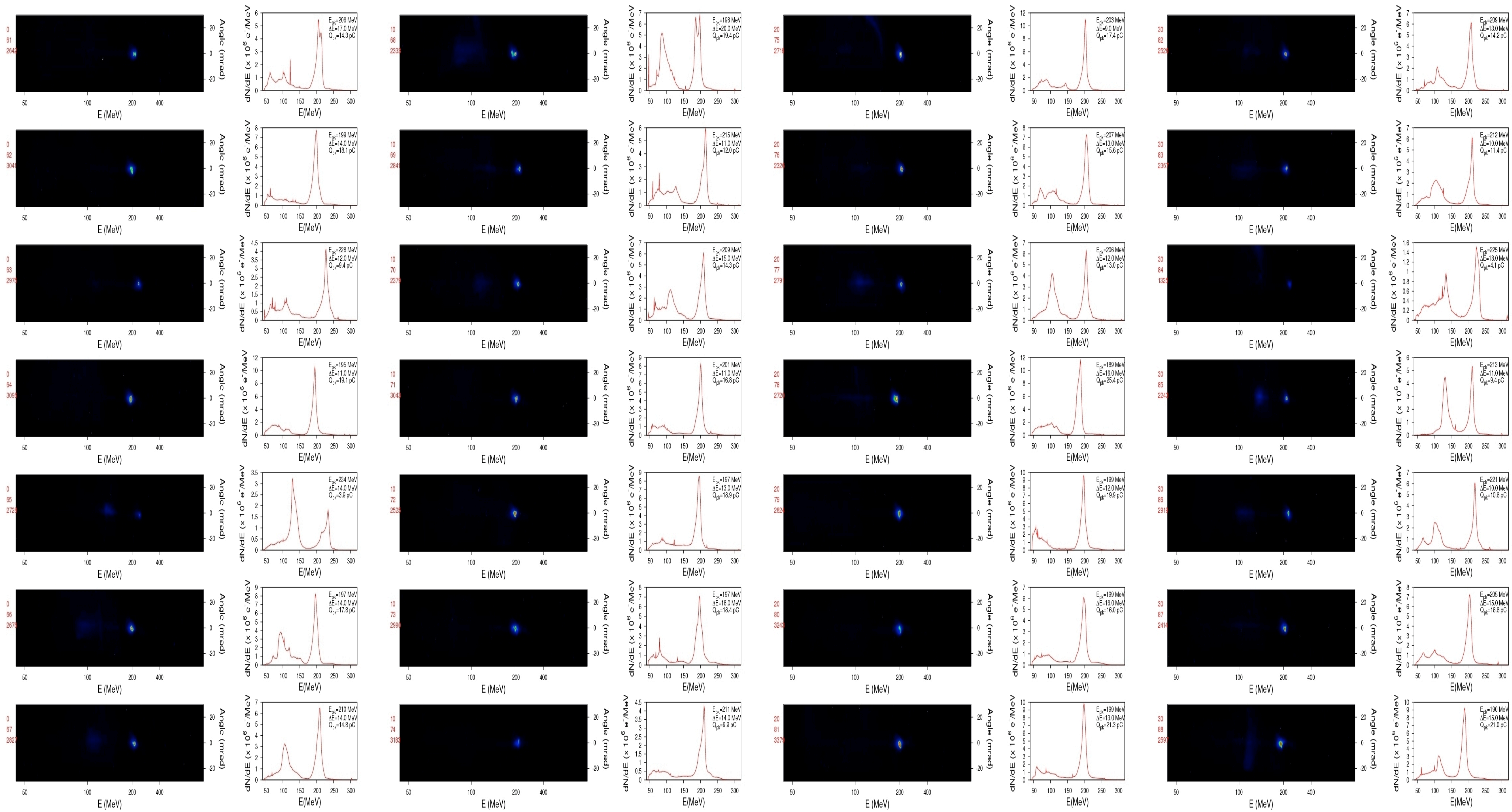
The colliding of two laser pulses scheme



Towards a Stable Laser Plasma Accelerators



Series of 28 consecutive shots with : a_0=1.5, a_1=0.4, n_e=5.7×10^{18}cm^{-3}



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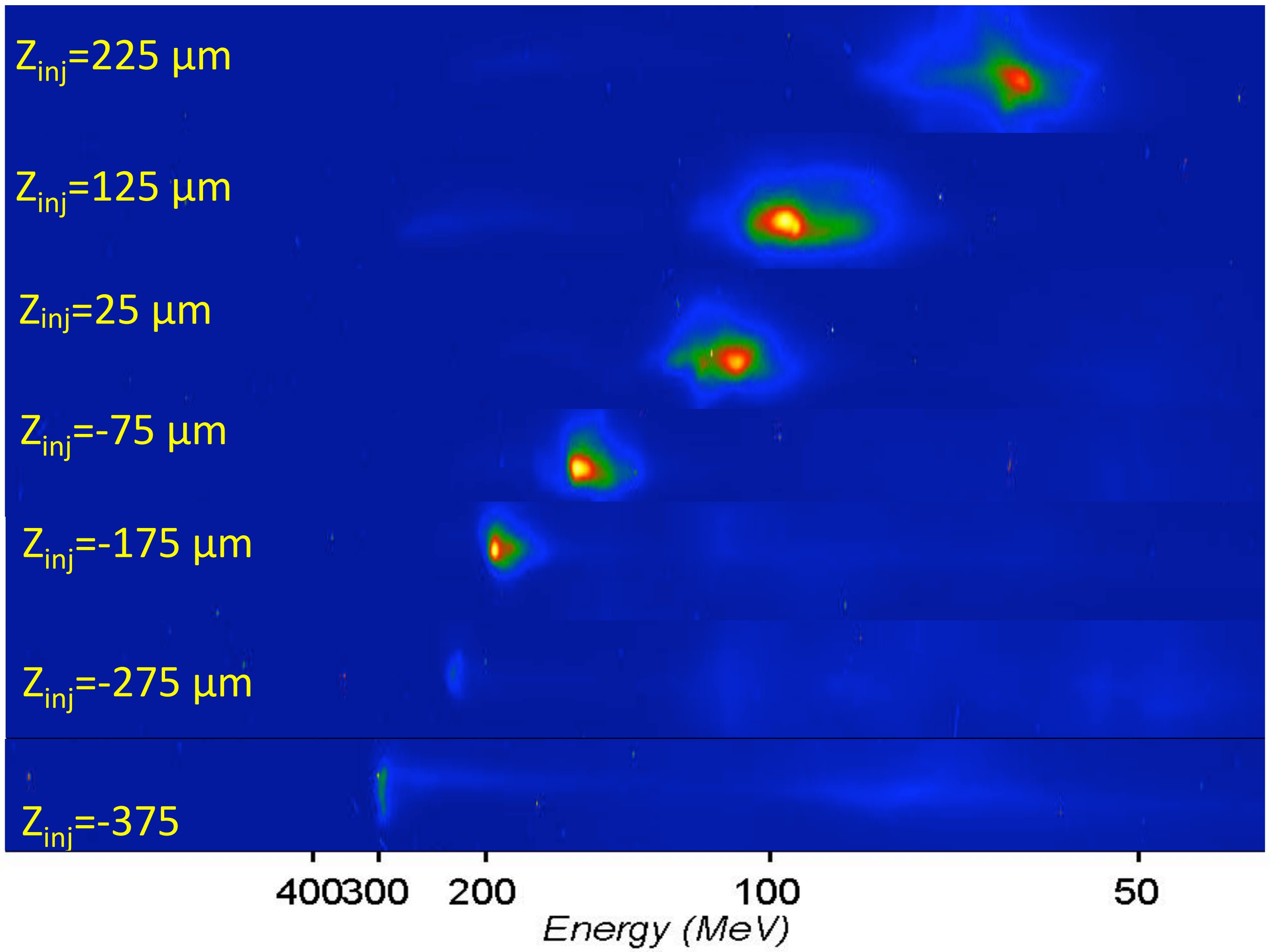
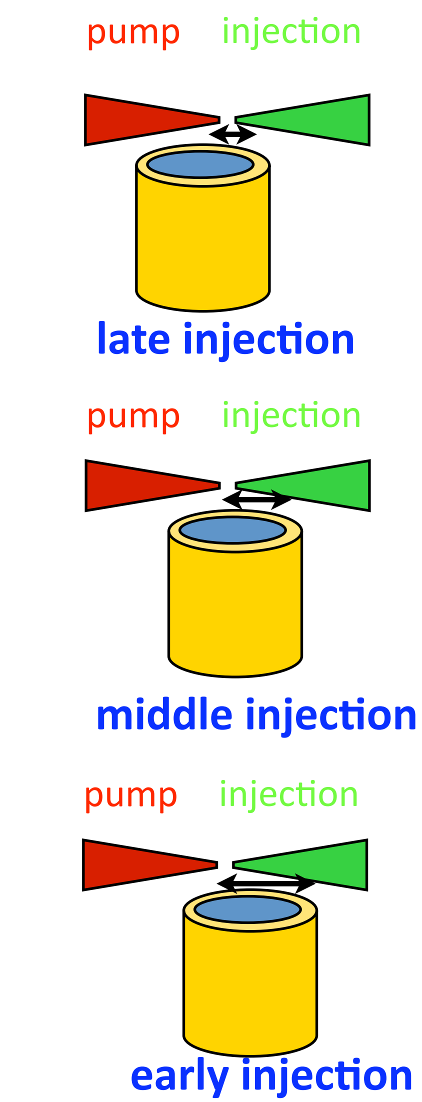
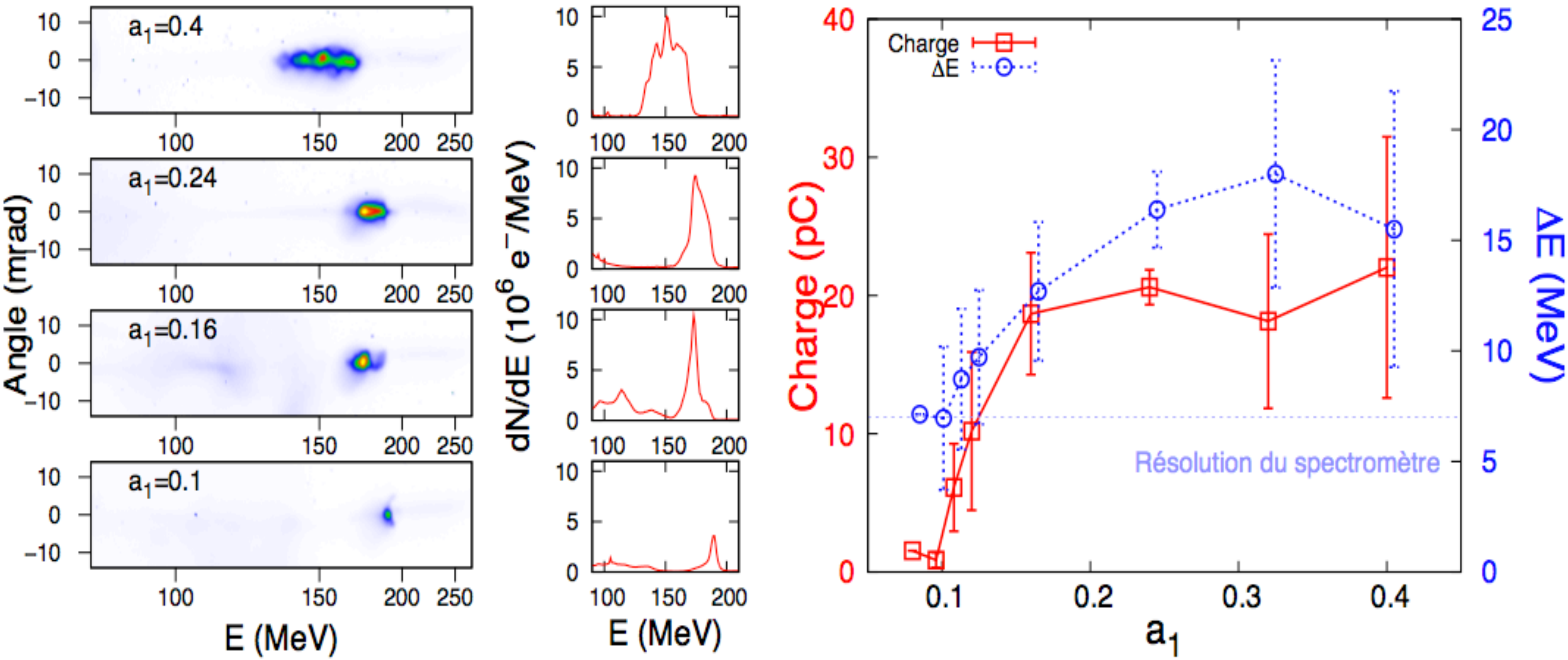
Tunability of Laser Plasma Accelerators : electrons energy





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

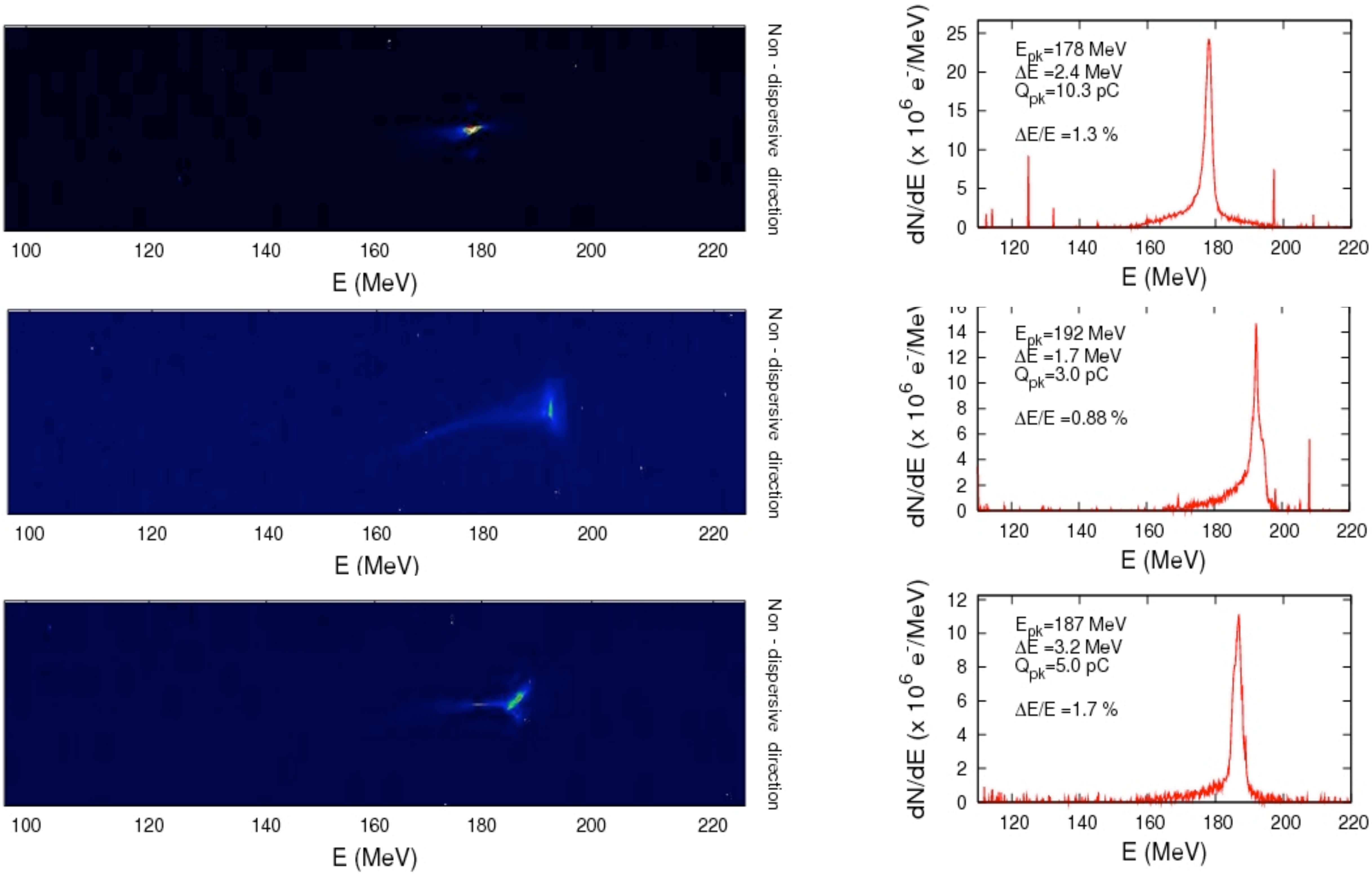
Tuning charge & energy spread with the inj. laser intensity



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

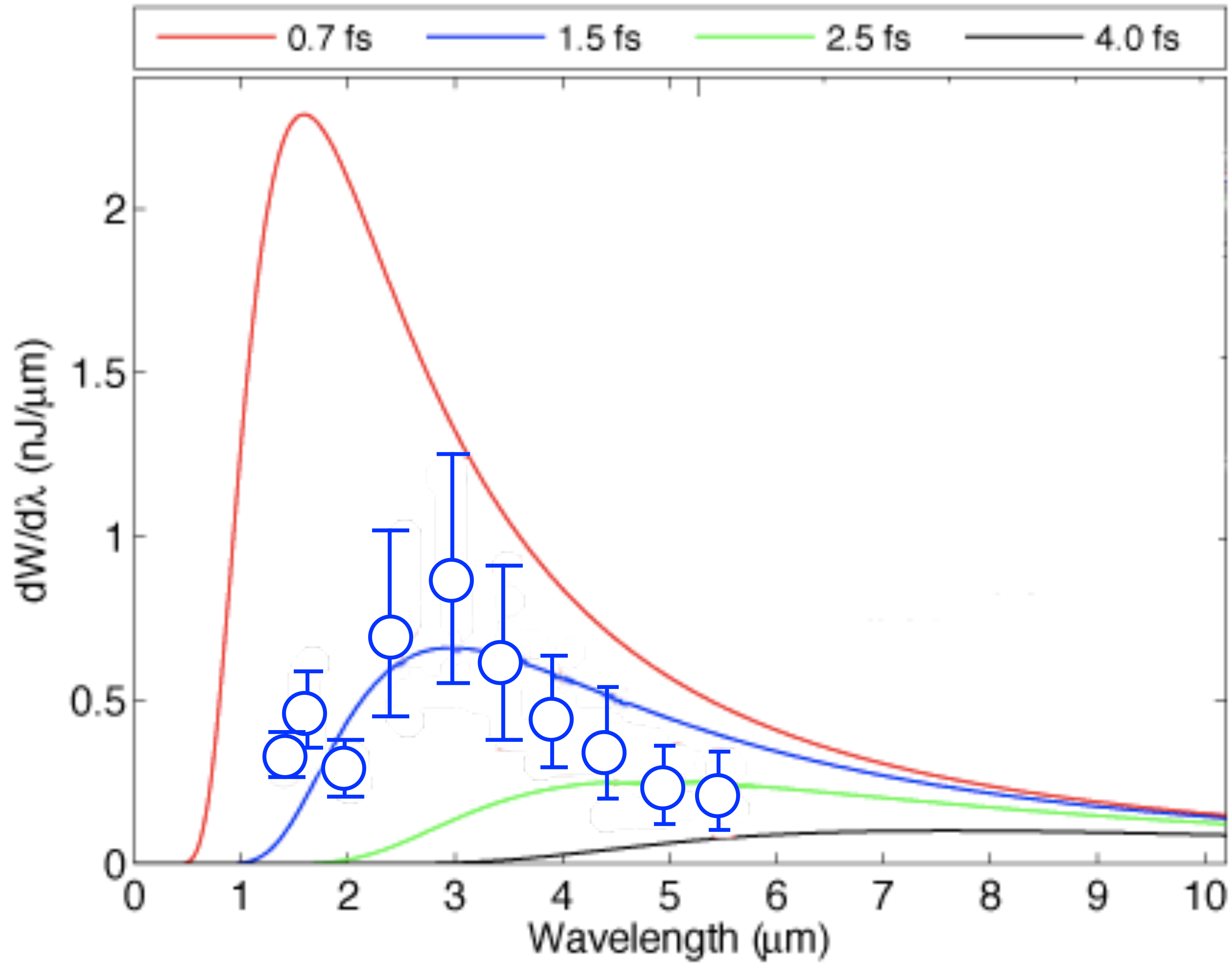
C. Rechatin *et al.*, Phys. Rev. Lett. **102**, 164801 (2009)

1% relative energy spread



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

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

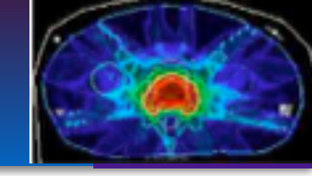
Peak at 3 µm

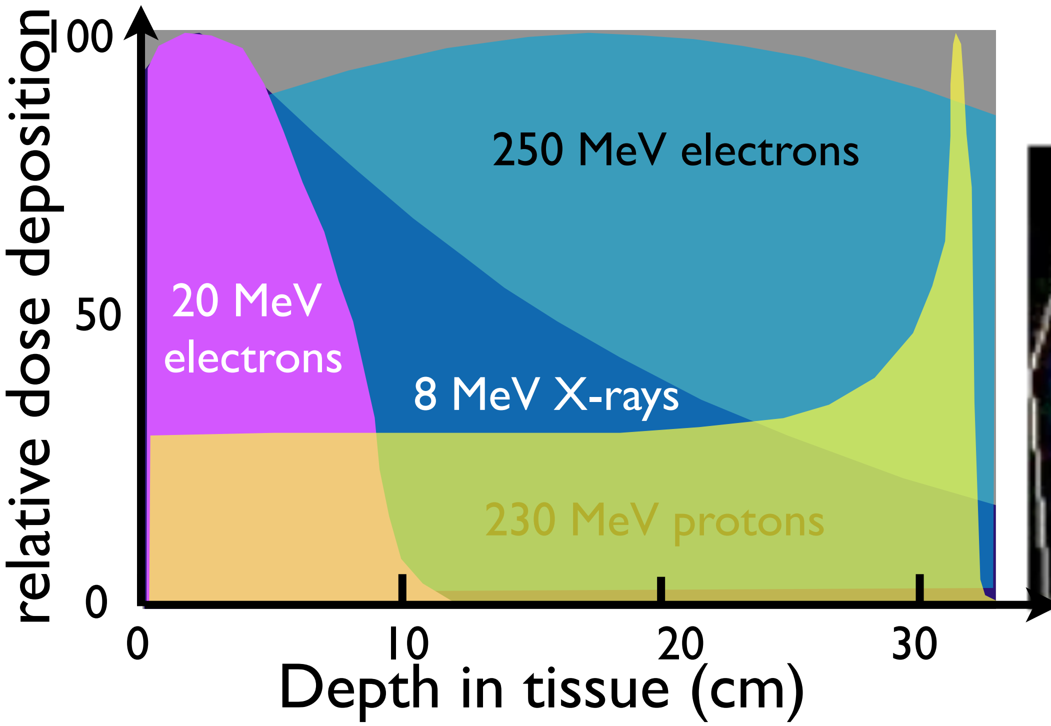
Coherent

1.5 fs RMS duration : Peak current of 4 kA

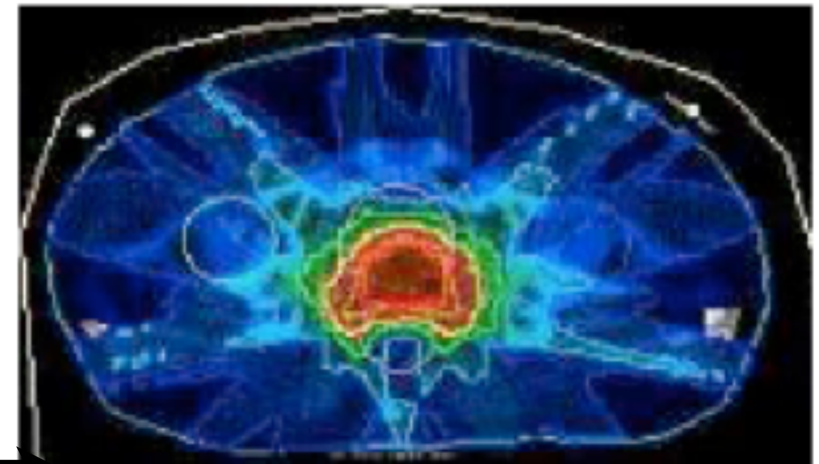
O. Lundh et al., Nature Physics, **7** (2011)

Some examples of applications : radiotherapy

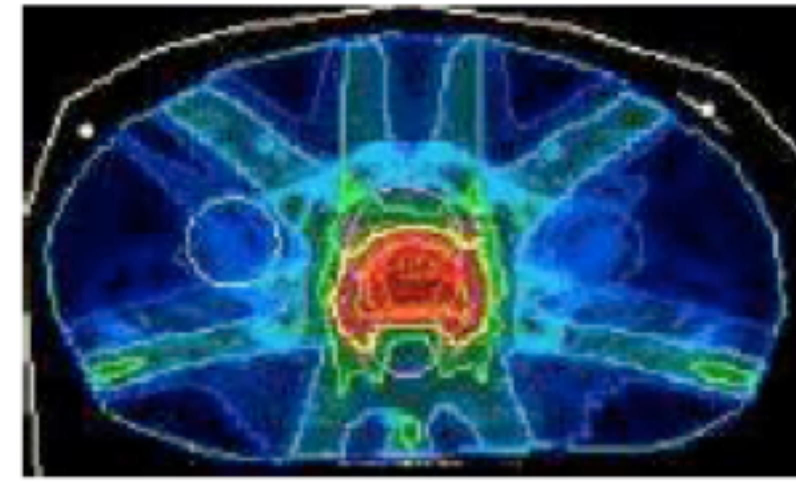




simulations of prostate cancer with 7 irradiation beams



250 MeV electrons



X rays IMRT

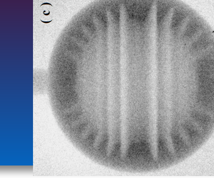
A comparison of dose deposition with 6 MeV X ray an improvement of the quality of a clinically approved prostate treatment plan. While the target coverage is the same or even slightly better for 250 MeV electrons compared to photons the dose sparing of sensitive structures is improved (up to 19%).

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),

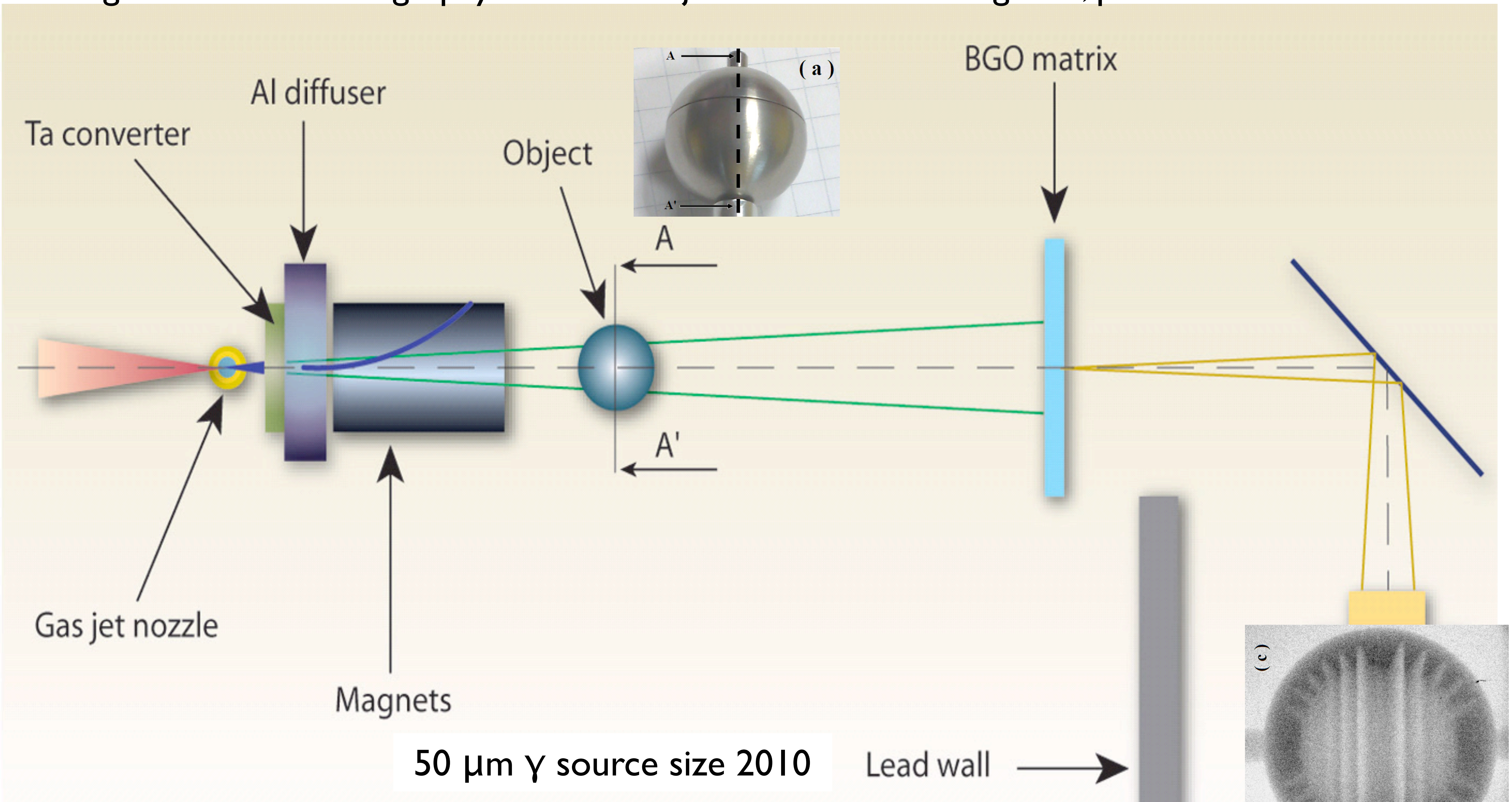
O. Lundh *et al.*, Medical Physics **39**, 6 (2012)

Some examples of applications : radiography



Non destructive dense matter inspection

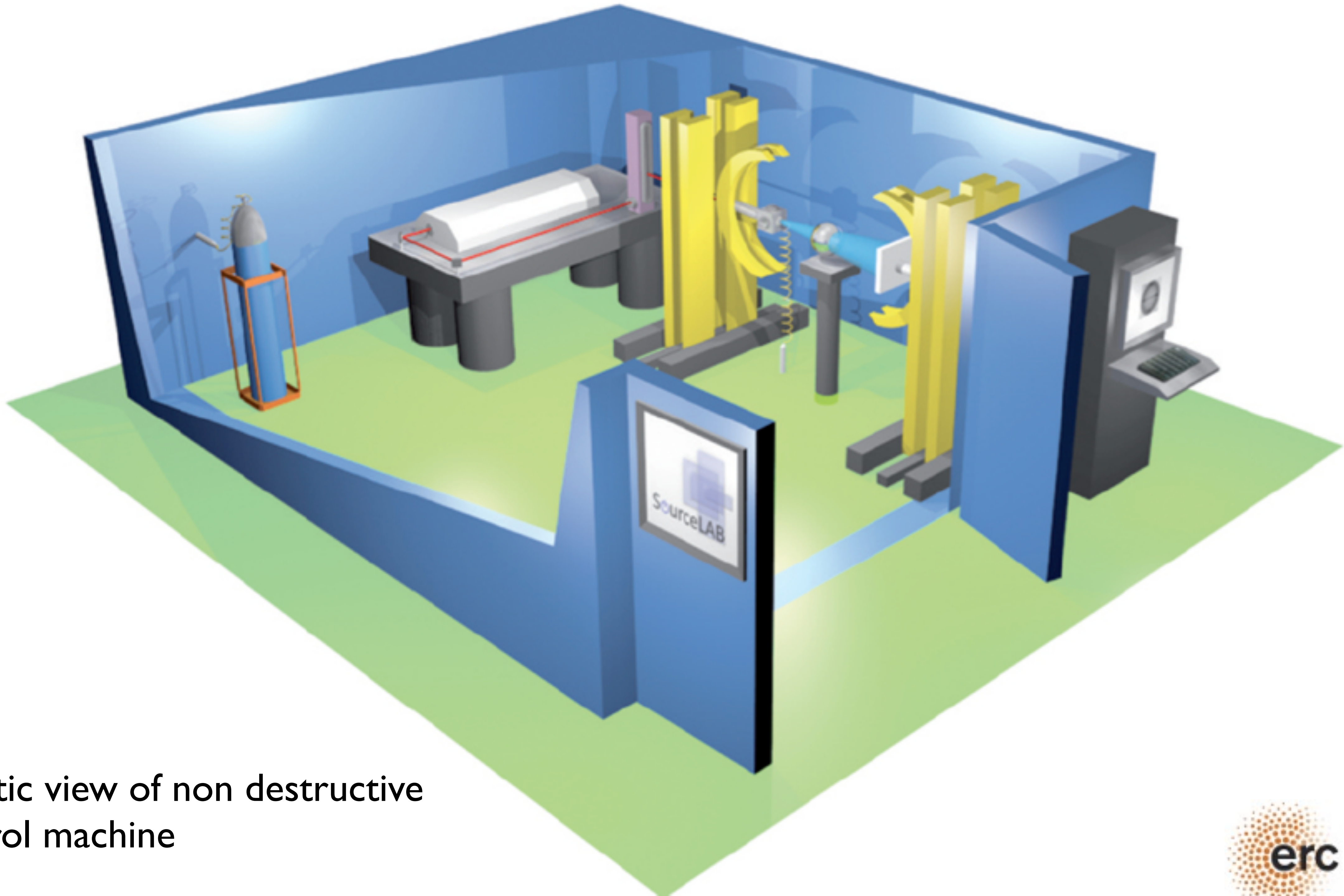
High resolution radiography of dense object with a low divergence, point-like electron source



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)

Some examples of applications : Non Destructive Control

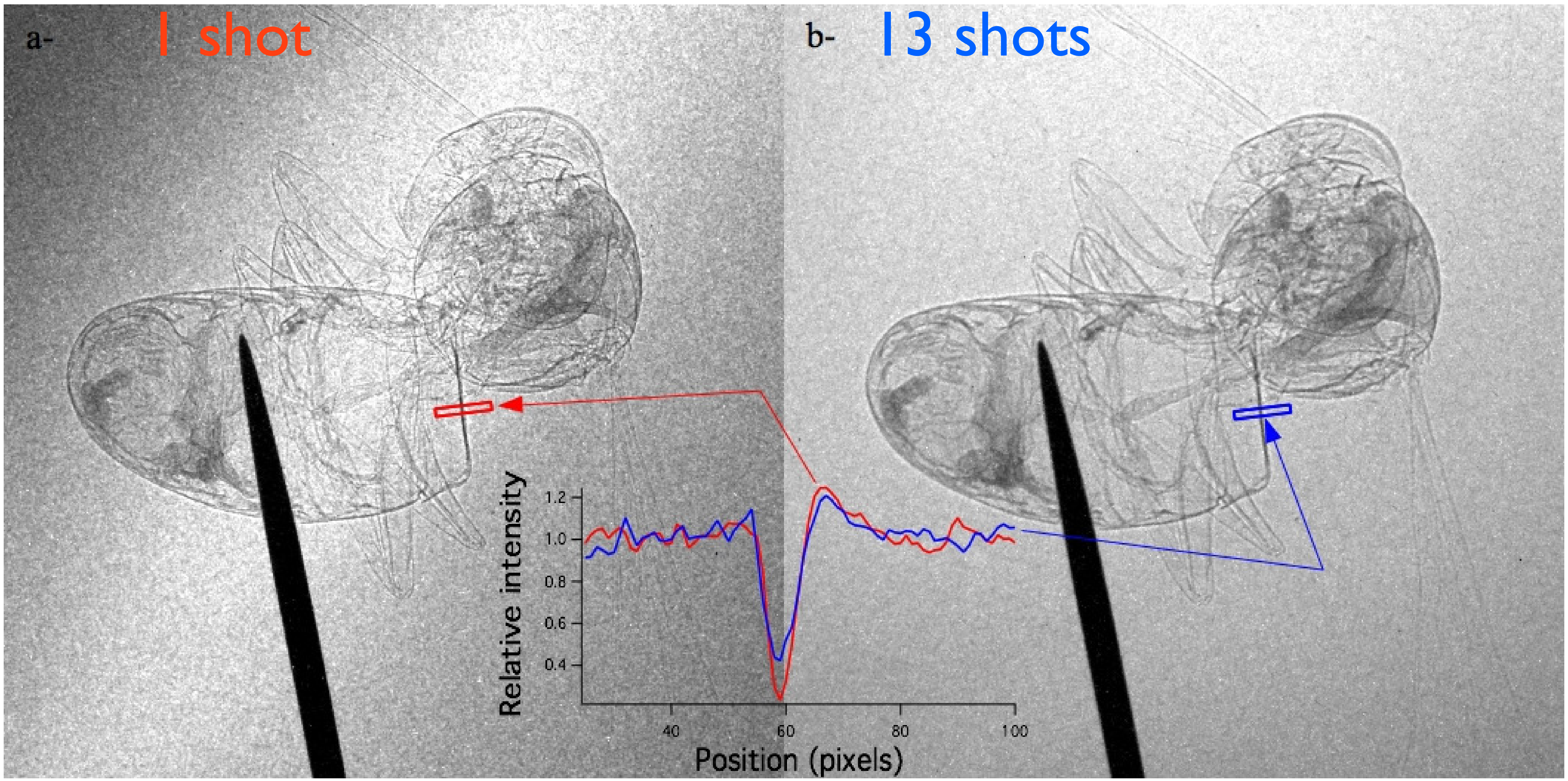


Artistic view of non destructive control machine

Phase contrast imaging : results

Bee contrast image :

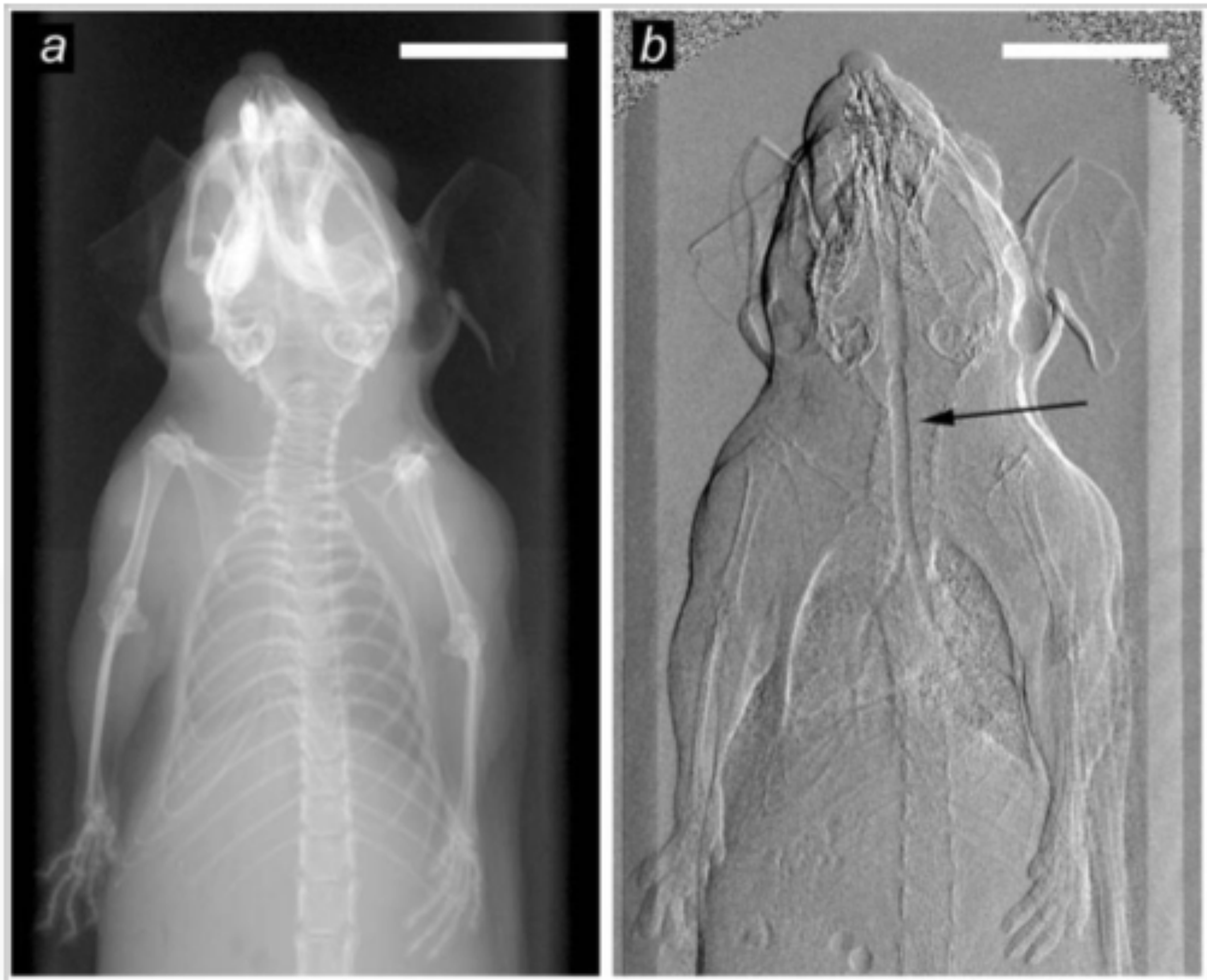
- Contrast of 0.68 in single shot.
- Very tiny details can be observed in single shot that disappear in multi shots.



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

Cancer detection with X Contrast Phase Imaging

Early detection of cancer tumour with an 10 micrometers resolution



X ray Absorption Imaging

X ray Contrast Phase Imaging

M. Bech *et al.*,
Scientific reports (2013)

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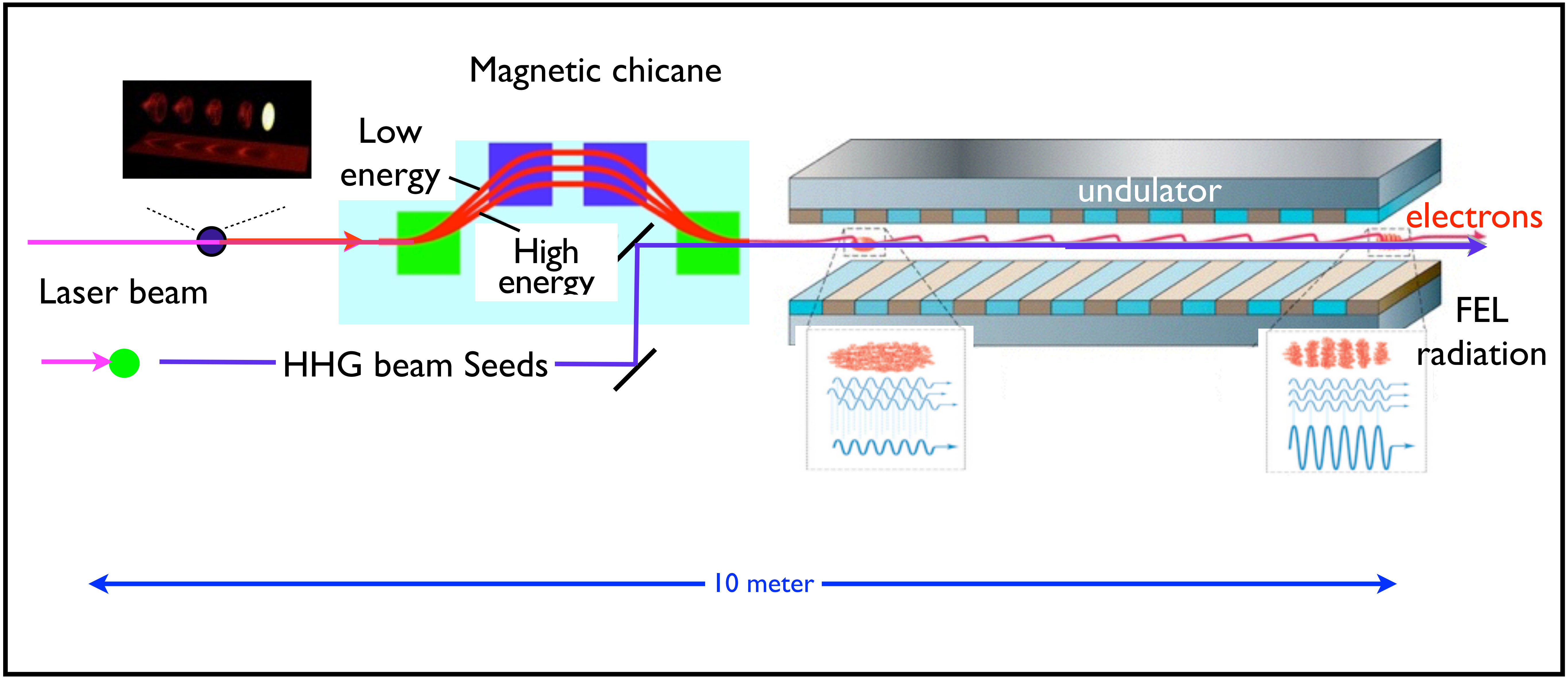
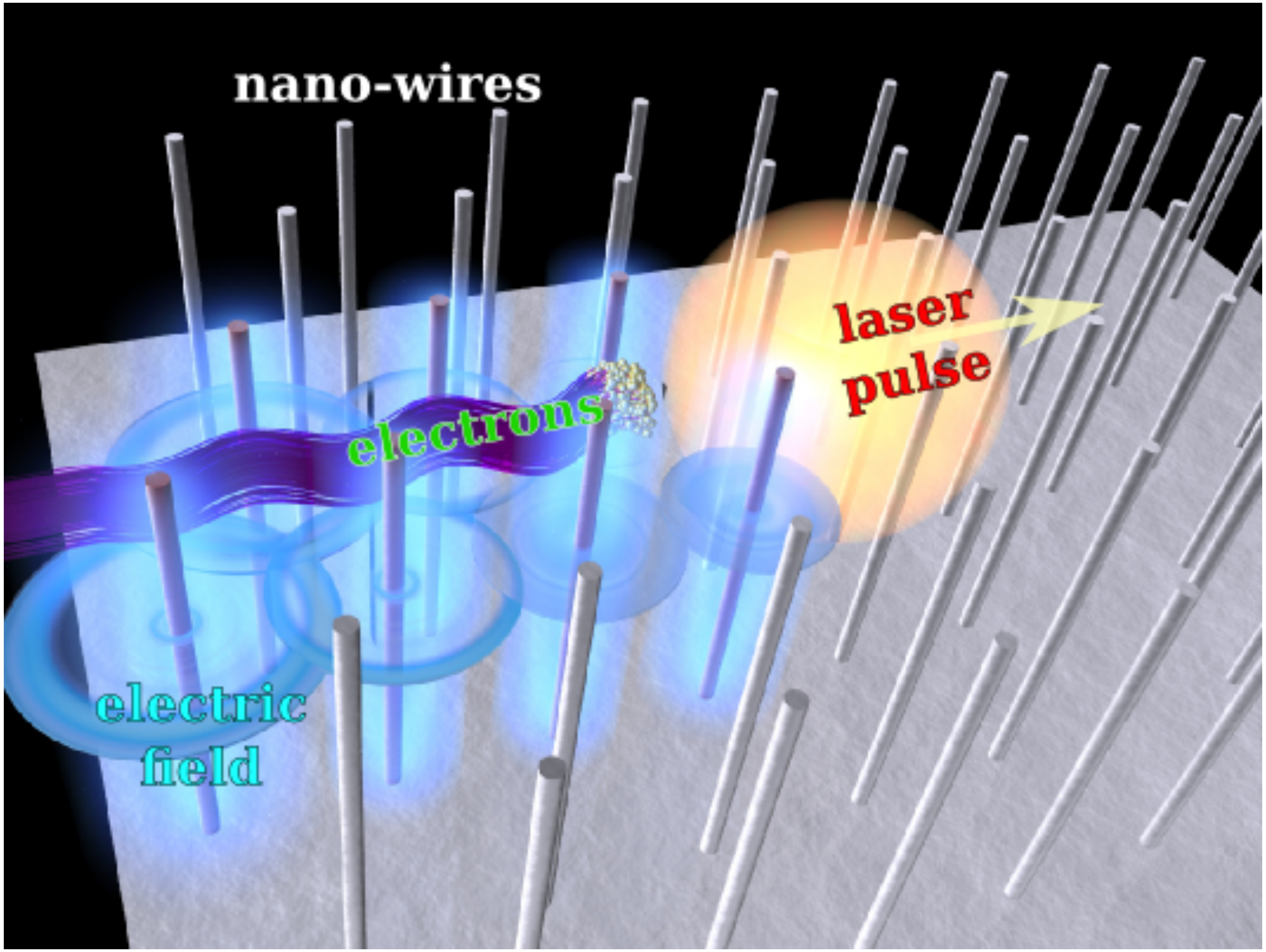
FEL experiment on Seeding mode with LPA



in collaboration with Marie Emmanuelle Couprie from Soleil (talk of A. Loulergues)

Advanced concept for ultra compact X rays beam



I. Andriyash *et al.*, Nat. Communications, 5736 (2014)

Undulating with plasma fields

Varying electron energy

Energy 200 / 400 / 600 MeV

Undulator emission

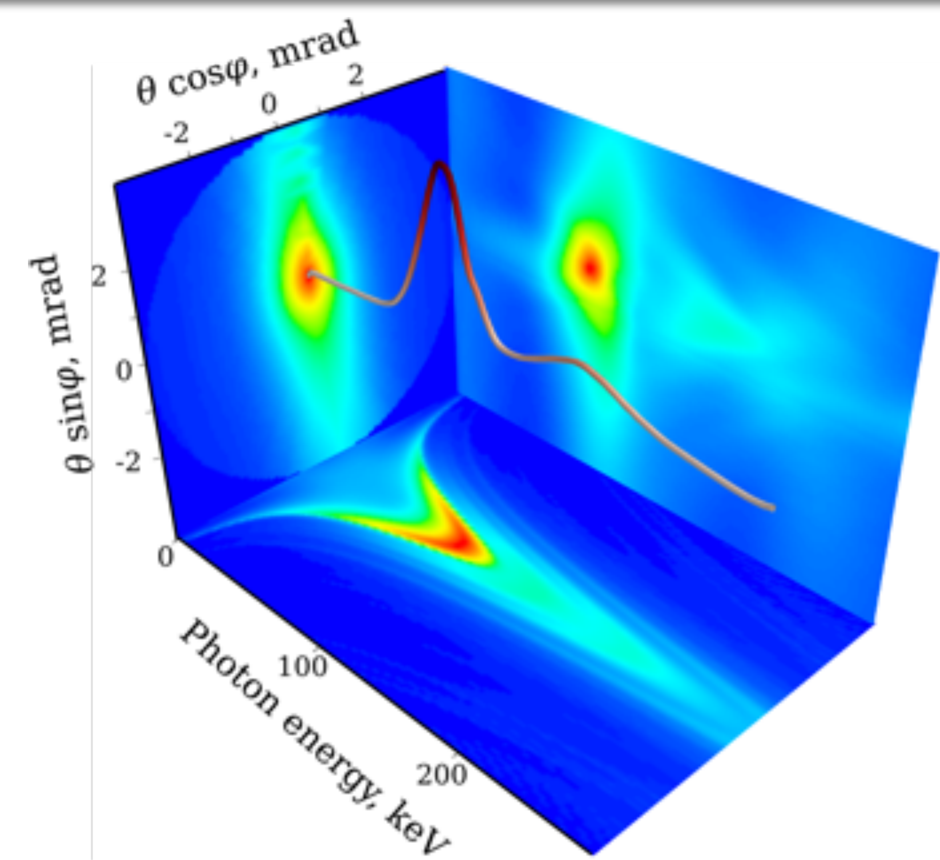
Photon energy 12 / 47 / 106 keV

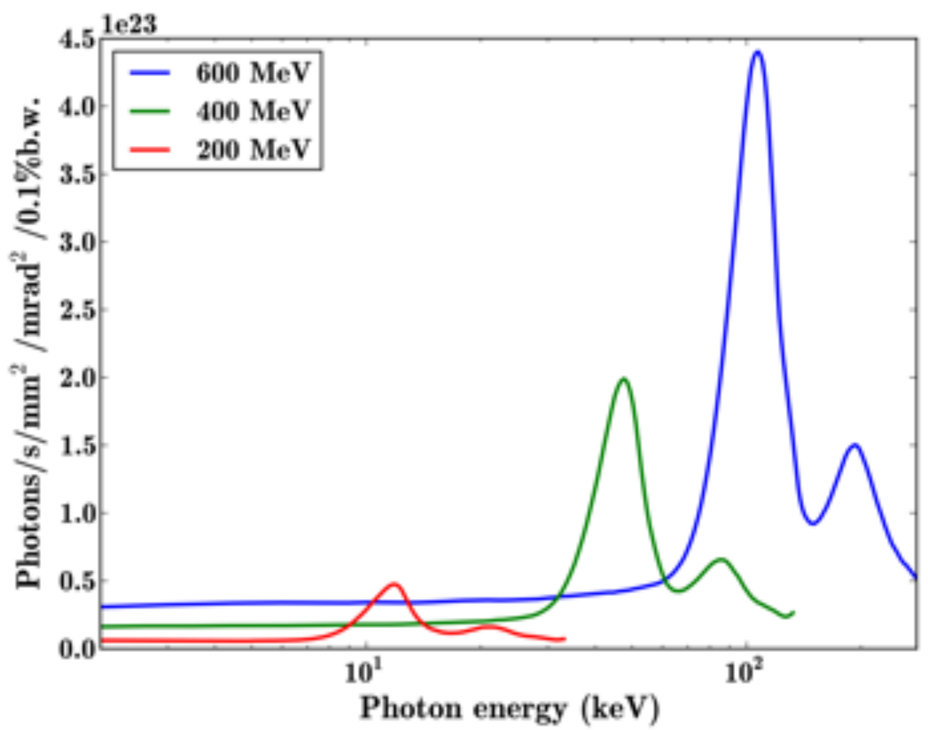
Brightness 0.5 / 2 / 4.5×10^{23}s.u.

Angular sizes 0.85×1.7 mrad

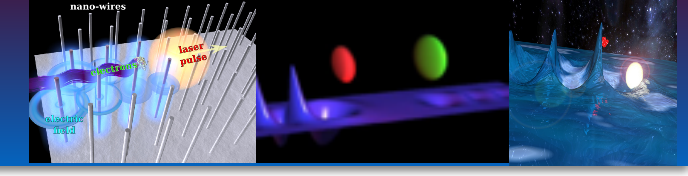
Laser plasma nanostructured SR source

- Quasi-monoenergetic collimated spectrum
- Tunability λ_u, ε_e
- Brightness ~ γ_b^2
- Source brightness level 10^{23} s.u.
- Interaction length ≲ 1 mm





Conclusions and Perspectives



Laser Plasma Accelerators have made significant progresses delivering stable, reliable high quality and high current e-beams.

Applications in medicine (radiotherapy, cancer imaging, security) are almost here.

Compact FEL based on LWFA is one very important challenge that has been identified by the community. Maturity of LWFA and of beam transport with supports from fundings agency can make this goal a reality.

Plasma undulators can play in the future an important role.

Acknowledgements

Sebastien Corde, Remi Lehe, Kim Ta Phuoc, Cédric Thaury, Agustin Lifschitz, Igor Andriyash, Olle Lundh, Jérôme Faure, Antoine Rousse, Stephane Sebban

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