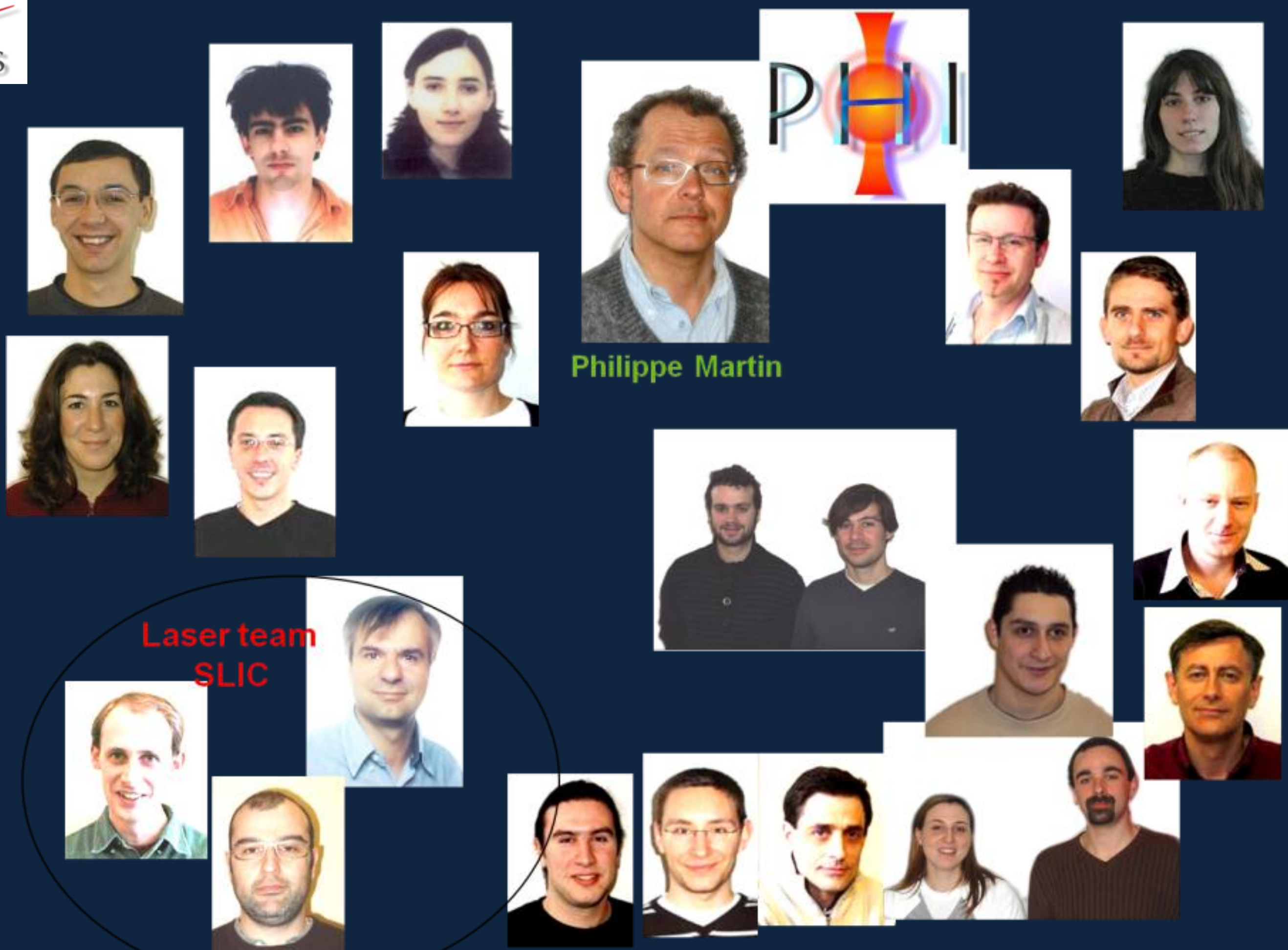
New Ionizing Sources
From Lasers to Particles and Applications

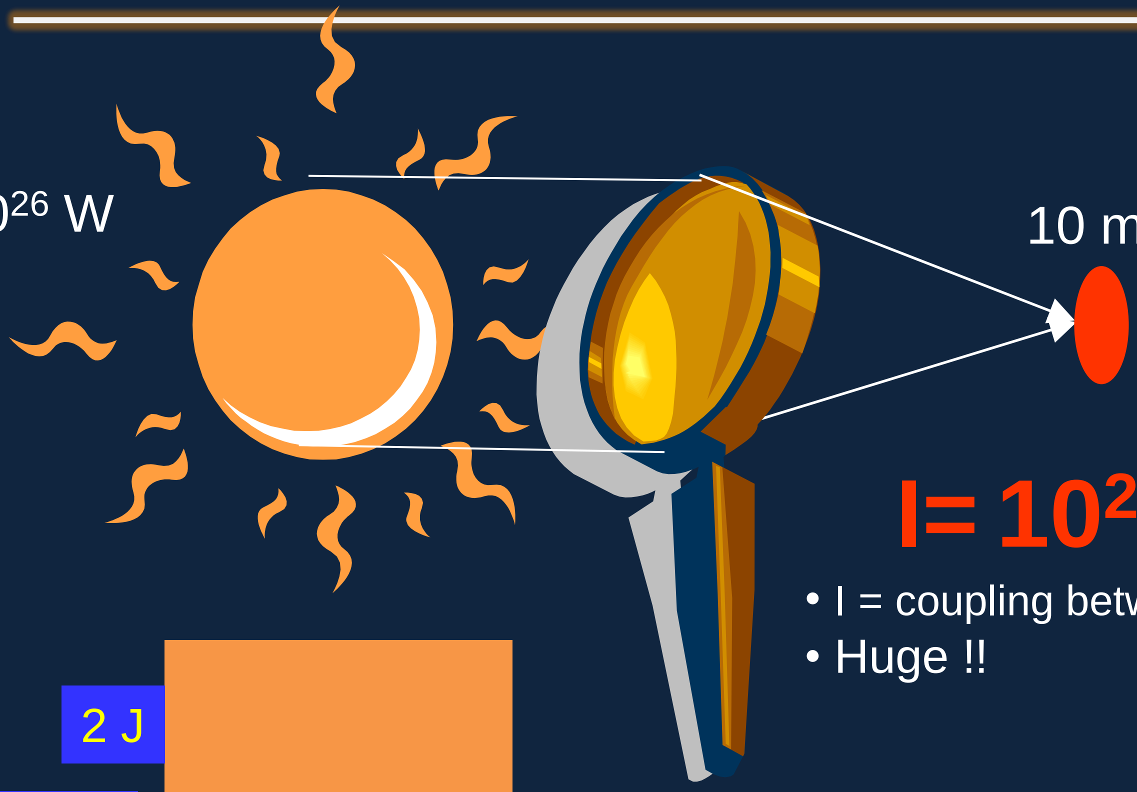


Philippe Martin CEA/DSM/ IRAMIS- Saclay

Colloque "Chimie sous Rayonnements", November 15th – 16th, Paris, Maison de la Chimie, France

What is Physics at High Intensity ?

P= 4x10^{26} W



I= 10^{20} W/cm^2

- I = coupling between light and matter
- Huge !!

10 µm

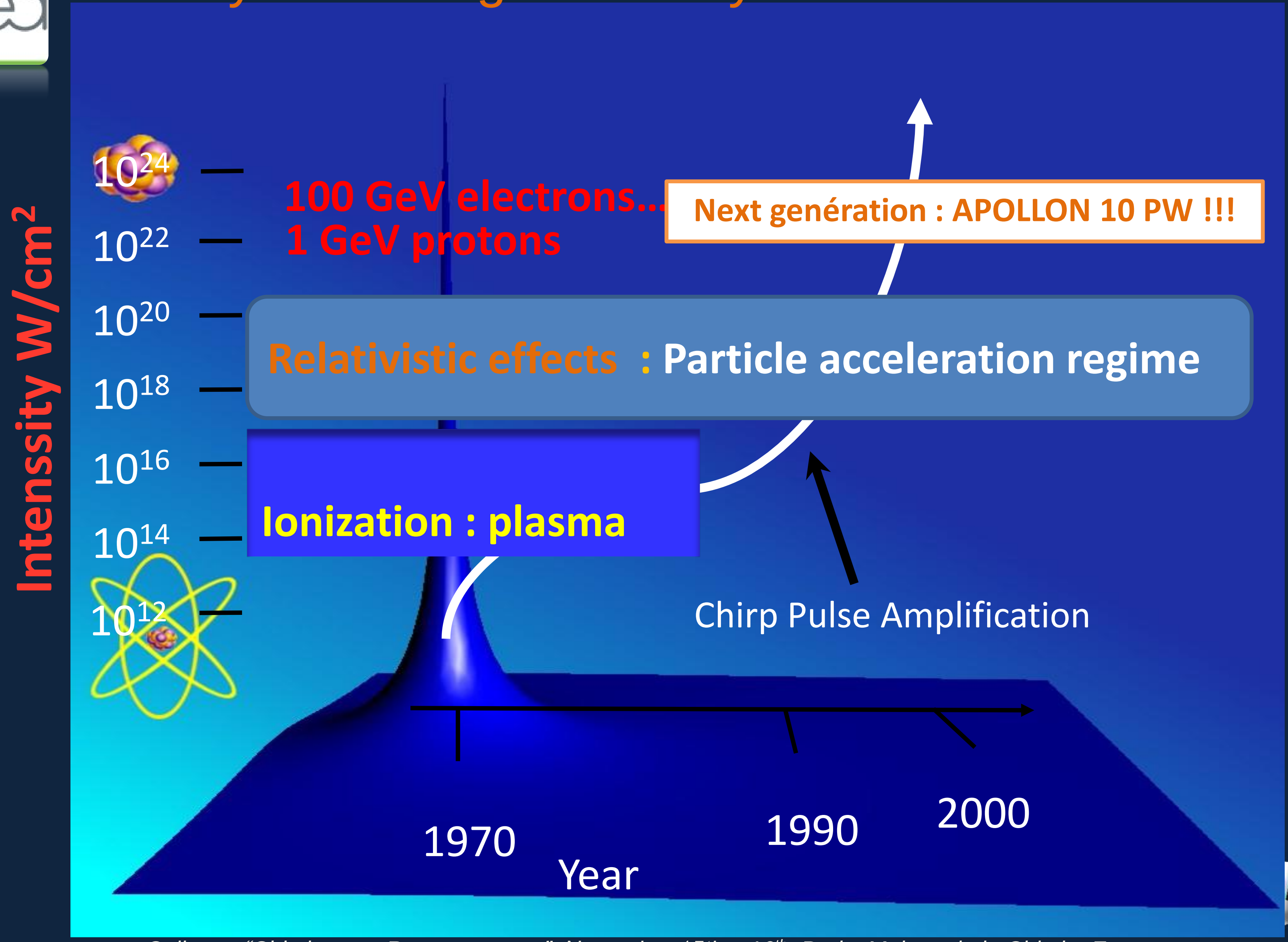
2 J

20 fs

P= 10^{14} W

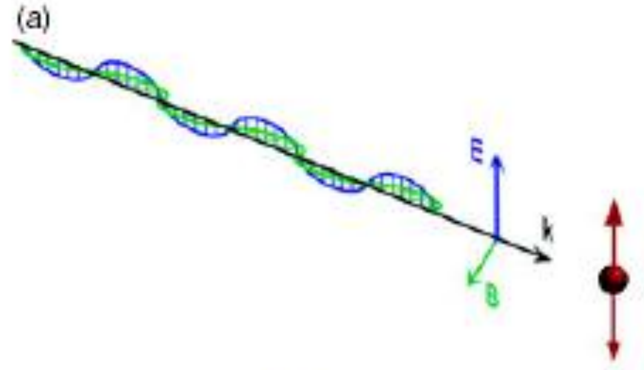
I > 10^{20} W/cm^2 !

Physics at High Intensity : brief historical



Physics at High Intensity : relativistic effects

Courtesy G. Mourou



$$\Delta x \propto E$$

Low intensity : v << c

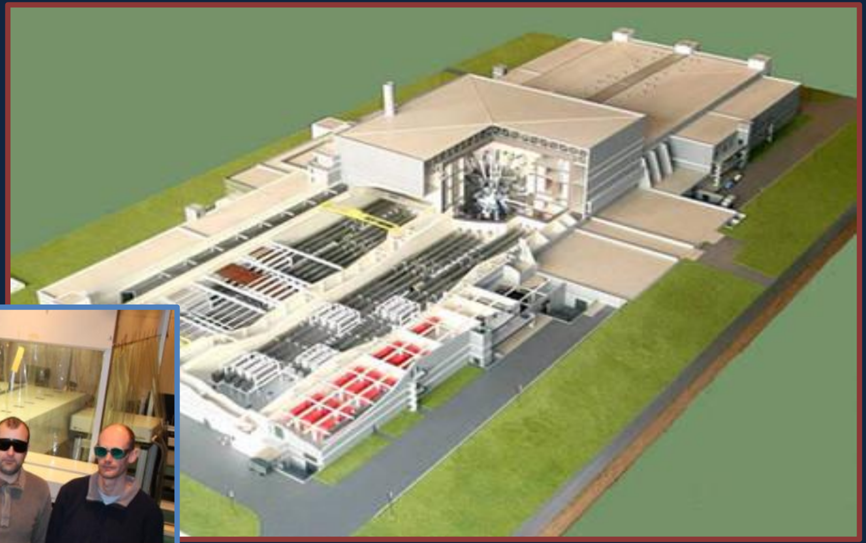
$$\vec{F} = q\vec{E}$$

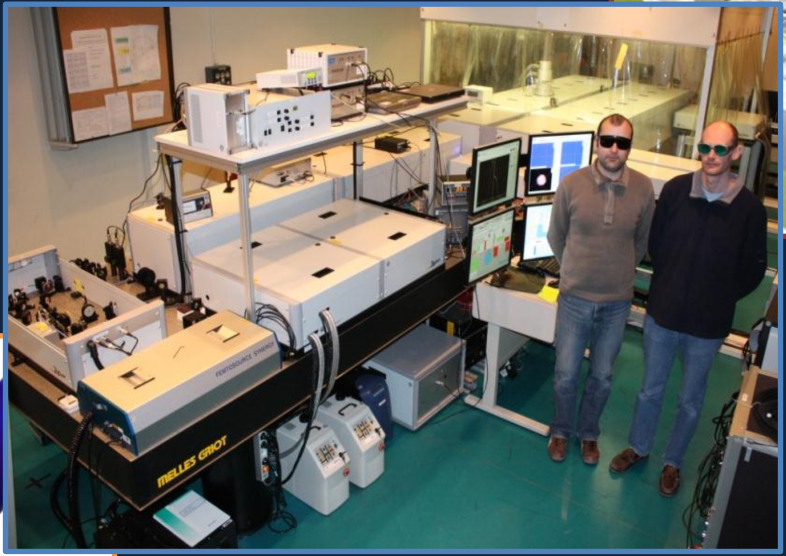
High Intensity : v ~ c

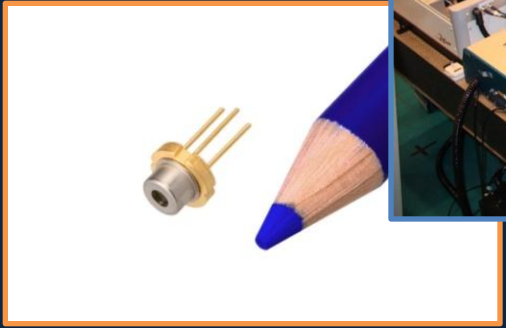
$$\vec{F} = q(\vec{E} + \frac{\vec{V} \times \vec{B}}{c})$$

Typical laser sizes

LMJ / NIF
A lot of Energy / Long pulses
Plasma Physics/ Ignition





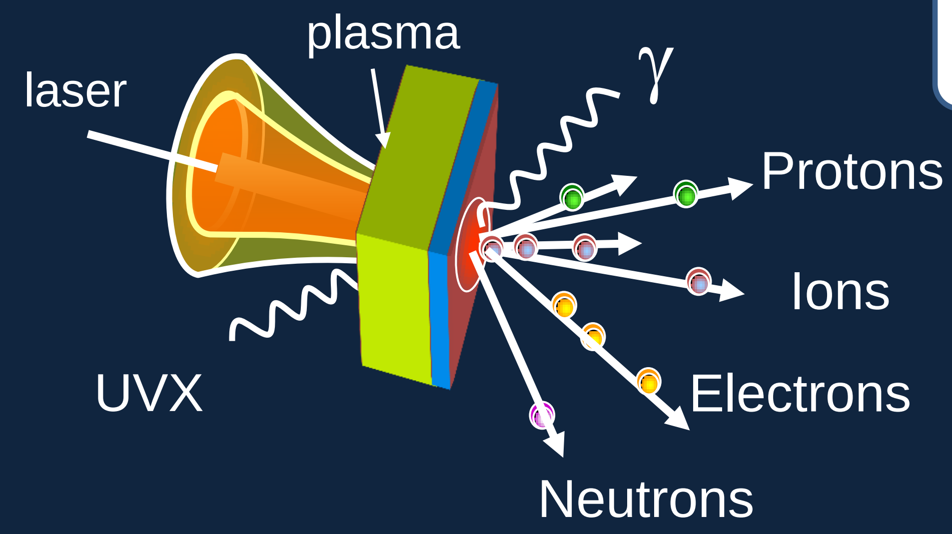


Laser diode
(telecom)

UHI T3 lasers : small Energy / ultra-short pulses :
Ultra-High peak power

Suitable for particle generation !

Relativistic Optics



Secondary particles : first source of information

- Photons diagnose the intantaneous response of matter
- Light electrons diagnose the femtosecond domain
- Heaviest protons give information on the 100 fs time scale

Complete description of interaction

The secondary sources inherit of the laser properties :
Duration, synchronization, coherence …

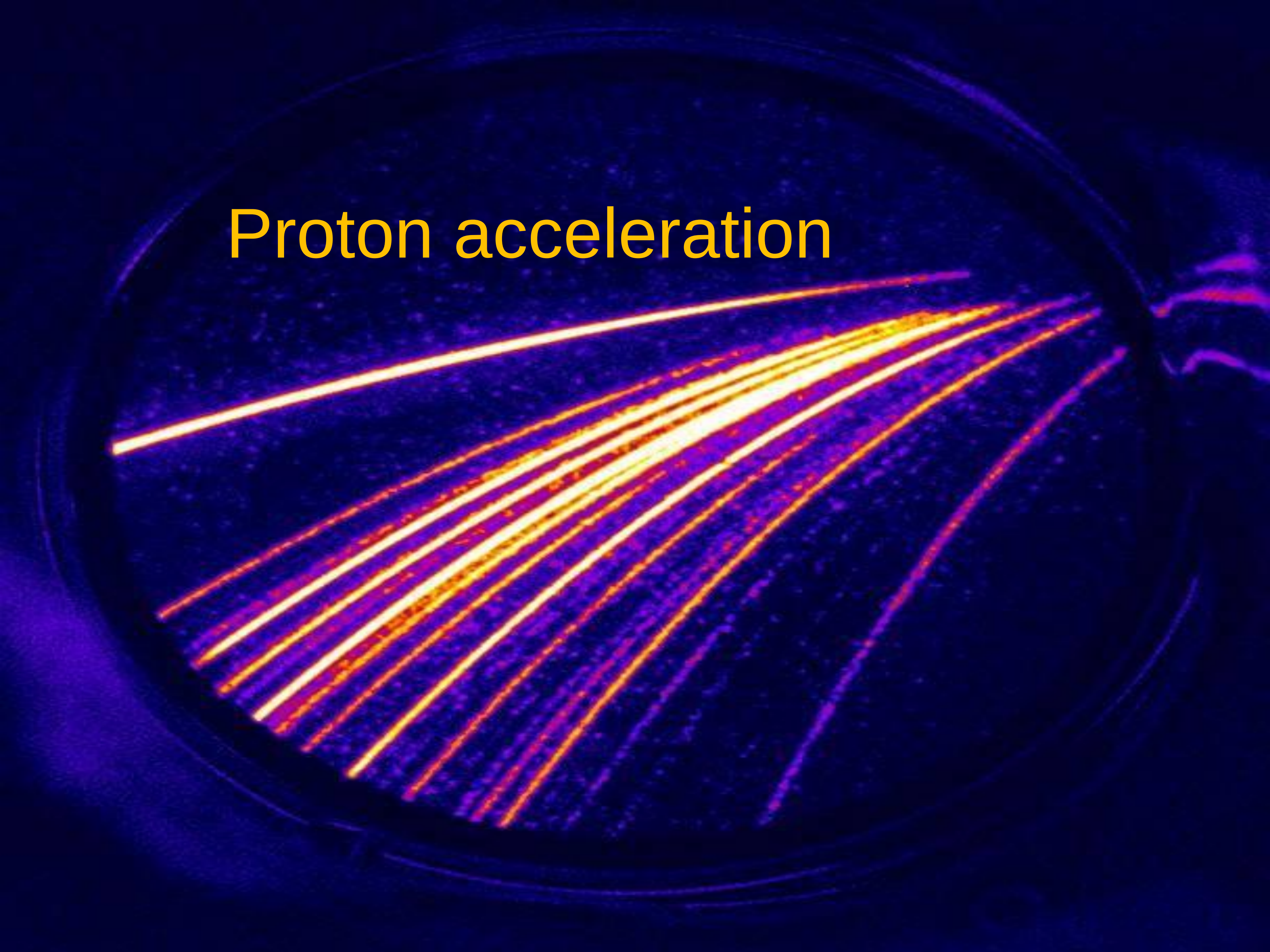
Developing these ultra-short sources **for applications :**
diagnostic inertial fusion, health technology, solid state physics, chemical physics, imagery,…

Outline

Sources	Possible applications
Proton	protontherapy
Electron	radiotherapy
Coherent XUV	imagery of nanoscale systems

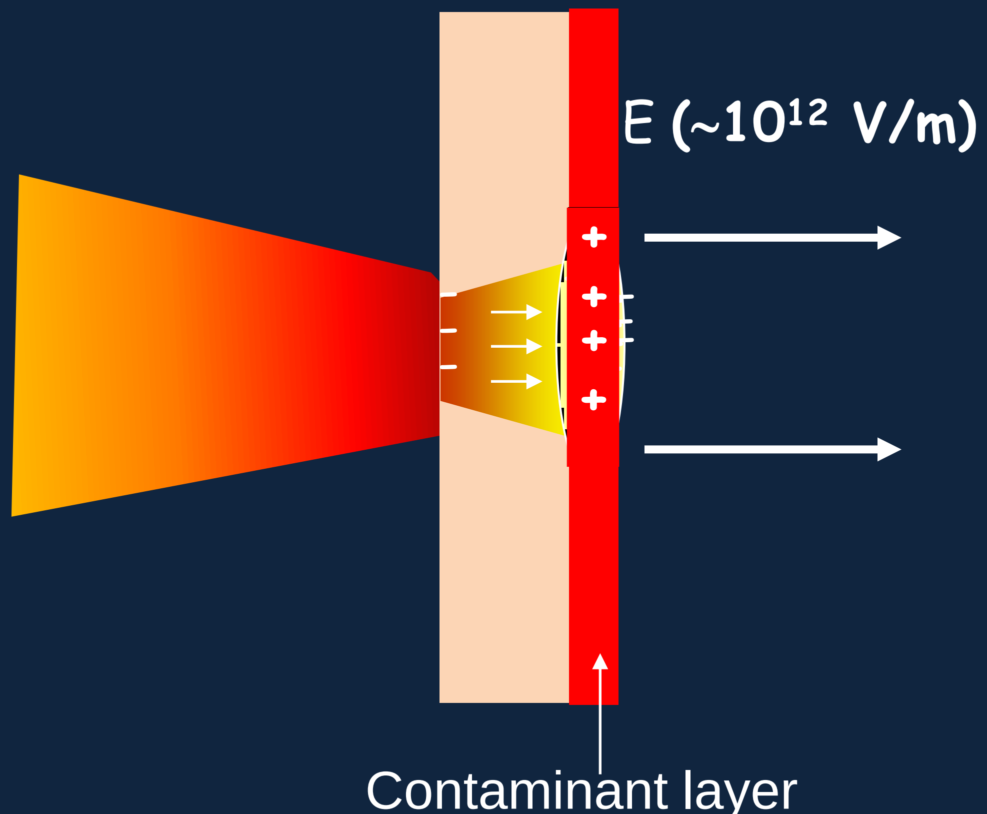
Perspectives

Proton acceleration



Ion acceleration mechanism

TNSA (Target Normal Sheath Acceleration) *S.C. Wilks et al., Phys. of Plasmas 8, 542 (2001)*

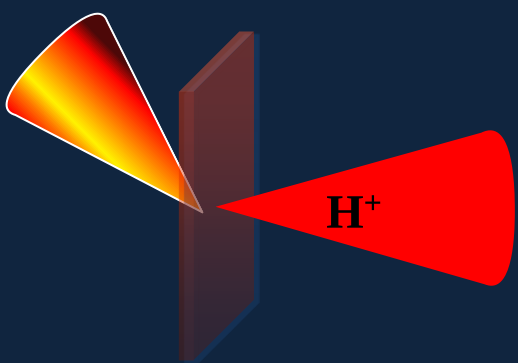


ARTICLES

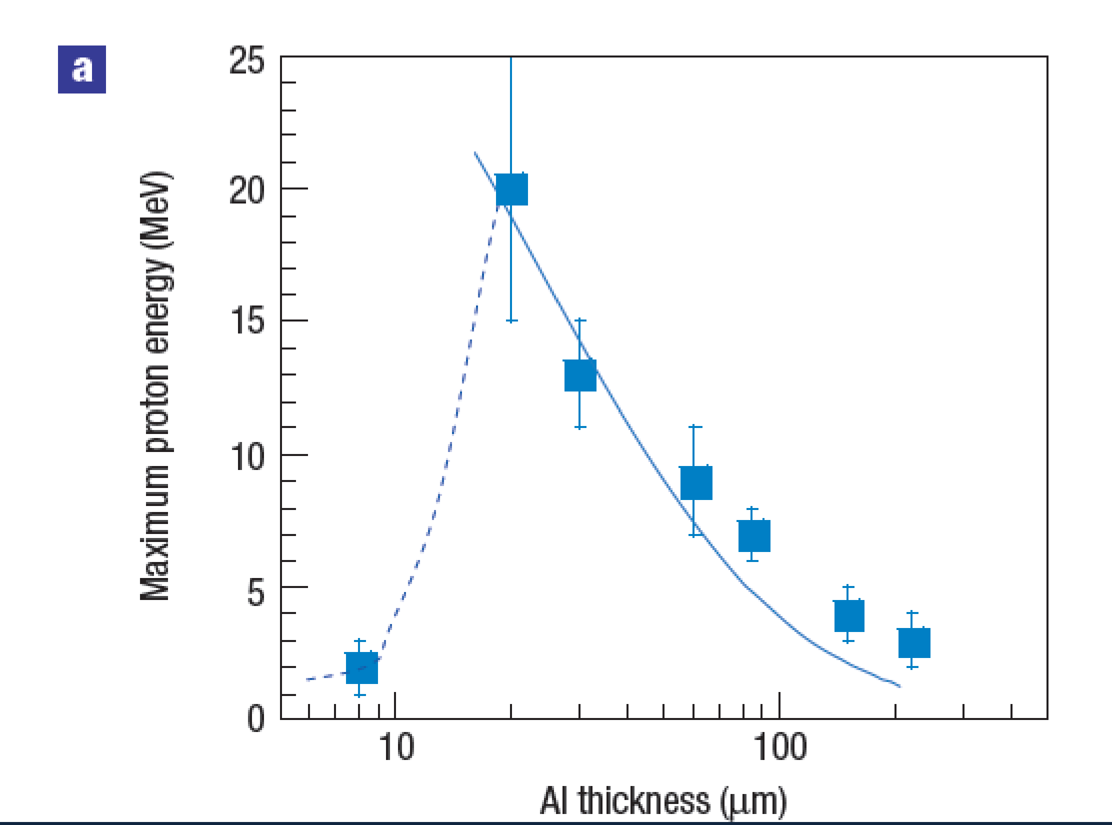
2006

Laser-driven proton scaling laws and new paths towards energy increase

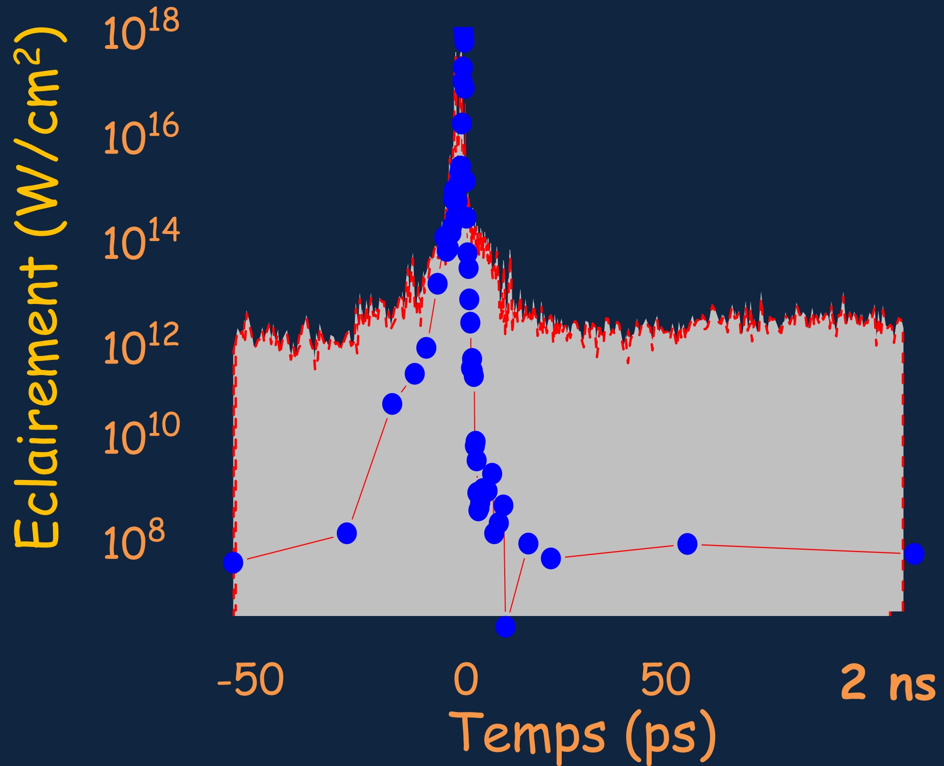
J. FUCHS[1,2*], P. ANTICI[1,2,3,4], E. D'HUMIÈRES[5], E. LEFEBVRE[5], M. BORGHESI[6], E. BRAMBRINK[1], C. A. CECCHETTI[6], M. KALUZA[7], V. MALKA[8], M. MANCLOSSI[8,9], S. MEYRONEINC[10], P. MORA[11], J. SCHREIBER[7], T. TONCIAN[12], H. PÉPIN[3] AND P. AUDEBERT[1]

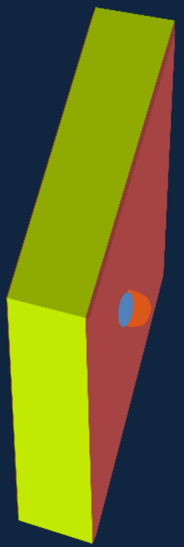


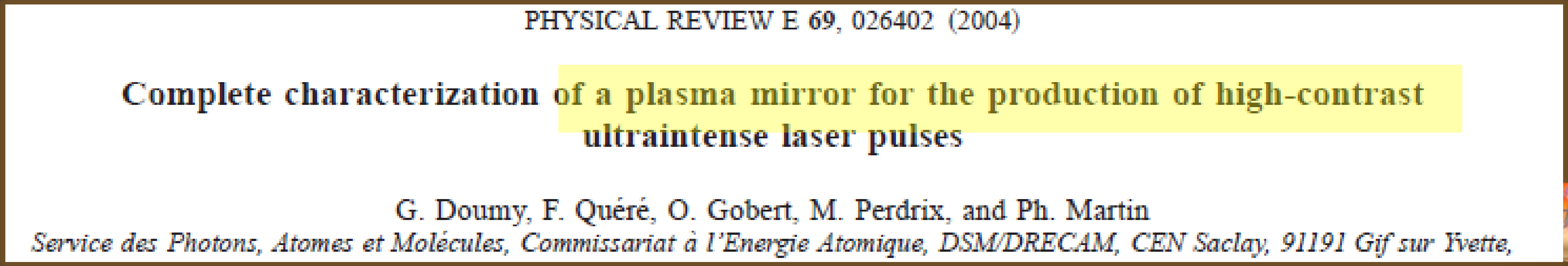
4×10^{19} W/cm^2



The contrast issue



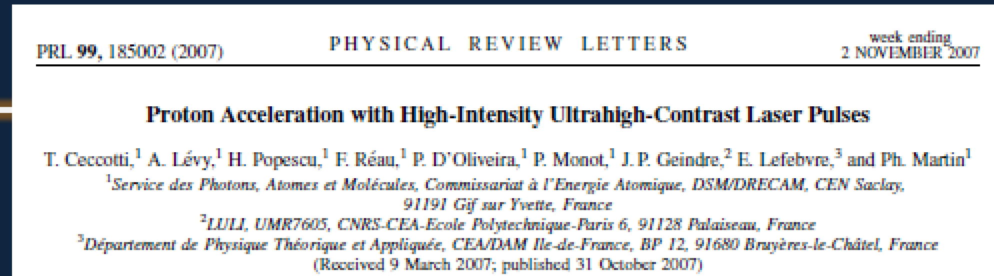



PHYSICAL REVIEW E 69, 026402 (2004)

Complete characterization of a plasma mirror for the production of high-contrast ultraintense laser pulses

G. Doumy, F. Quéré, O. Gobert, M. Perdrix, and Ph. Martin

Service des Photons, Atomes et Molécules, Commissariat à l'Energie Atomique, DSM/DRECAM, CEN Saclay, 91191 Gif sur Yvette,


PRL 99, 185002 (2007) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2007

Proton Acceleration with High-Intensity Ultrahigh-Contrast Laser Pulses

T. Ceccotti,[1] A. Lévy,[1] H. Popescu,[1] F. Réau,[1] P. D'Oliveira,[1] P. Monot,[1] J. P. Geindre,[2] E. Lefebvre,[3] and Ph. Martin[1]
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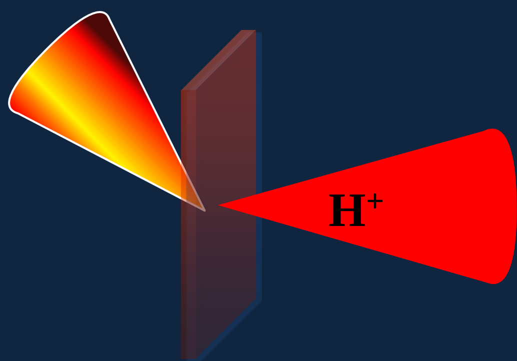
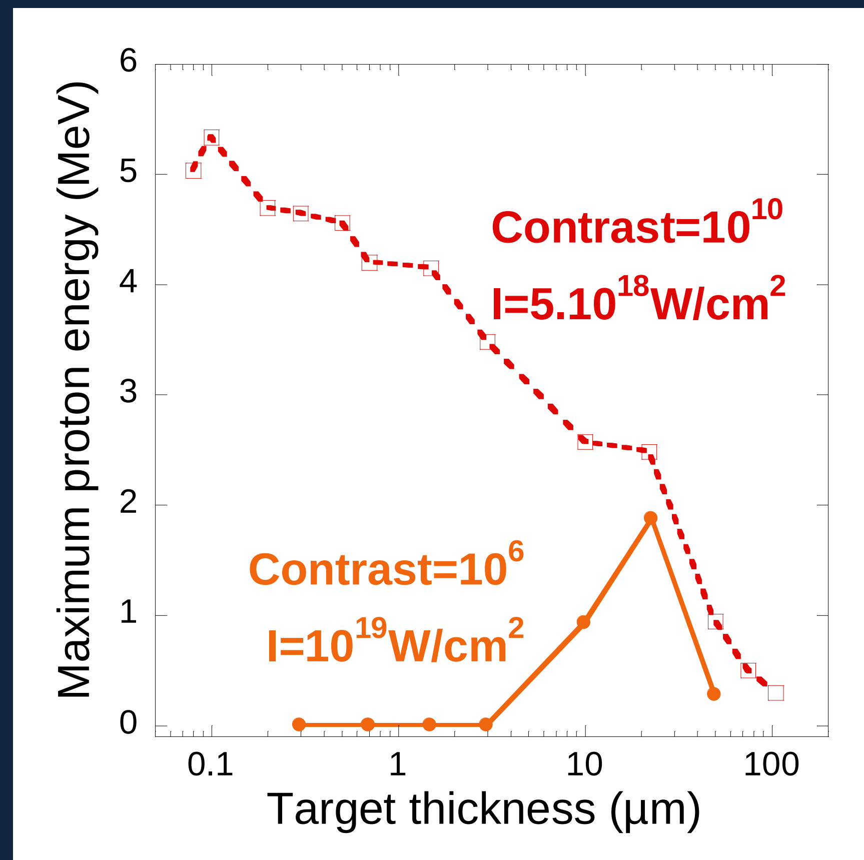
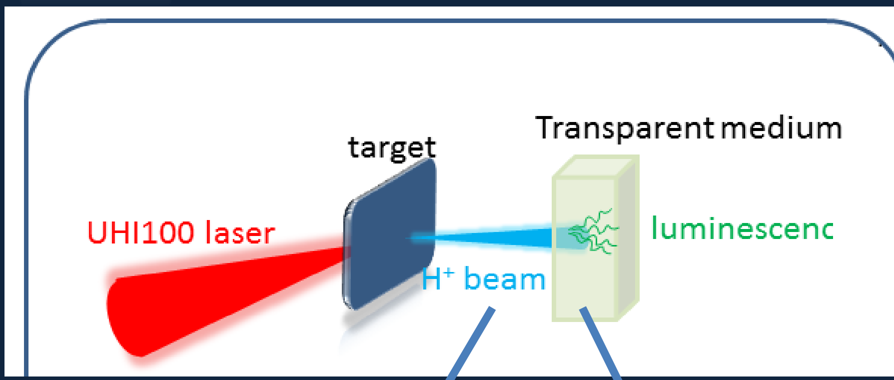
(Received 9 March 2007; published 31 October 2007)

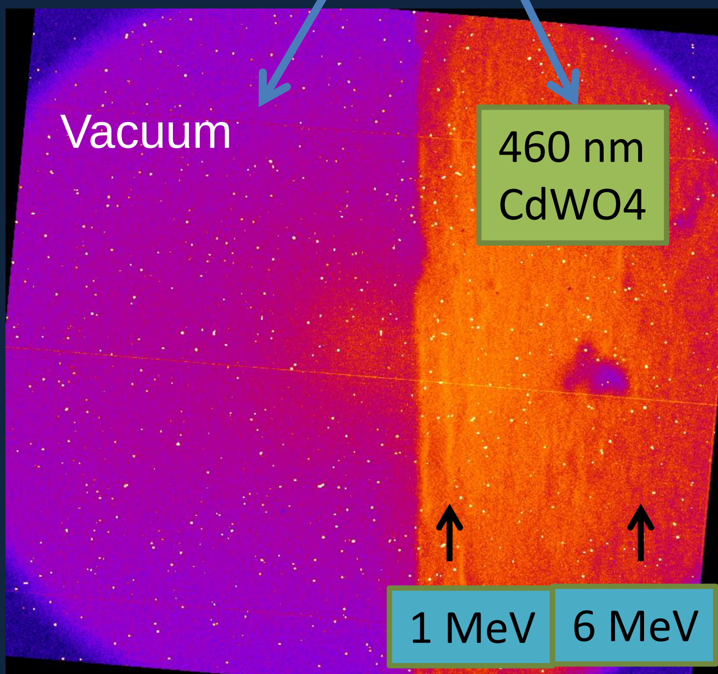




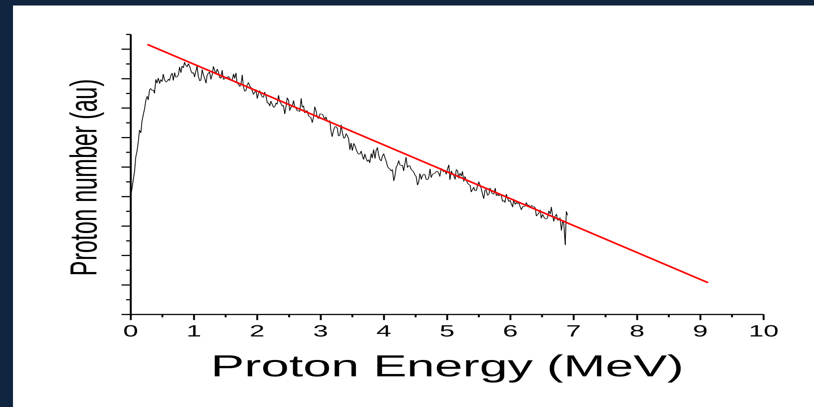
First laser induced proton luminescence imagery

Coll : G. Baldachino, JP. Renault, S. Pommeret





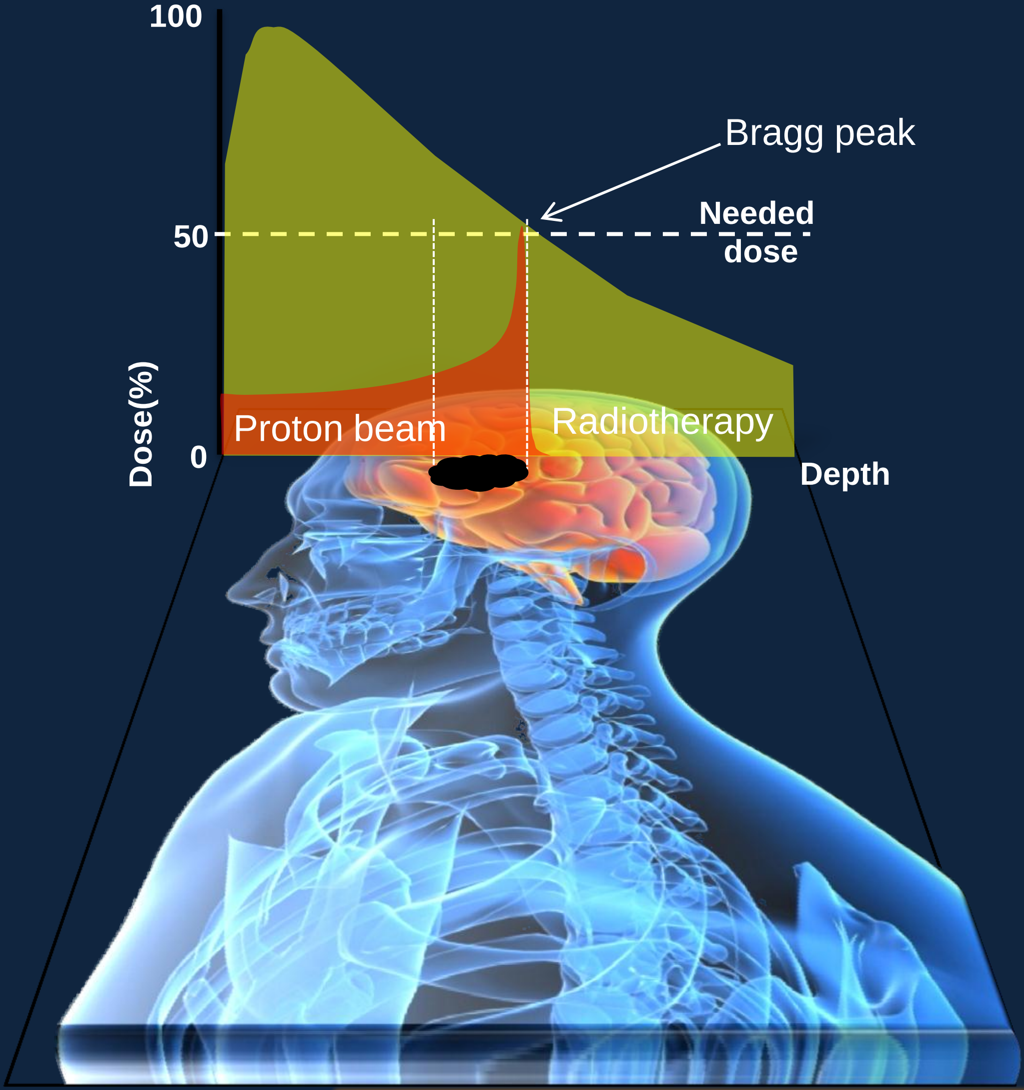
Single shot proton energy release in the material



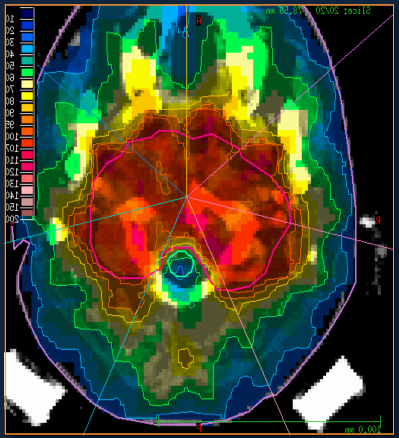
- Single shot diagnostic for energy and divergency measurement

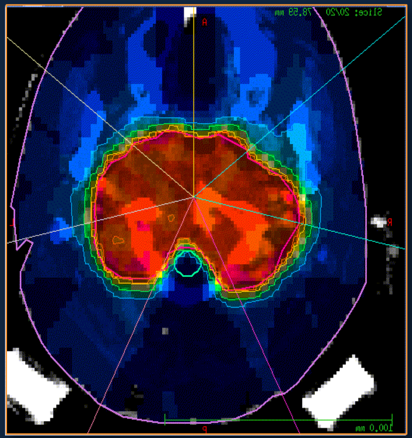
- First step for up coming ps time scale Defect formation studies (coll DEN) and Ultra-fast radiolysis experiments (coll Labo de Radiolyse- Saclay)

Are UHI lasers Suitable for laser-protontherapy ?

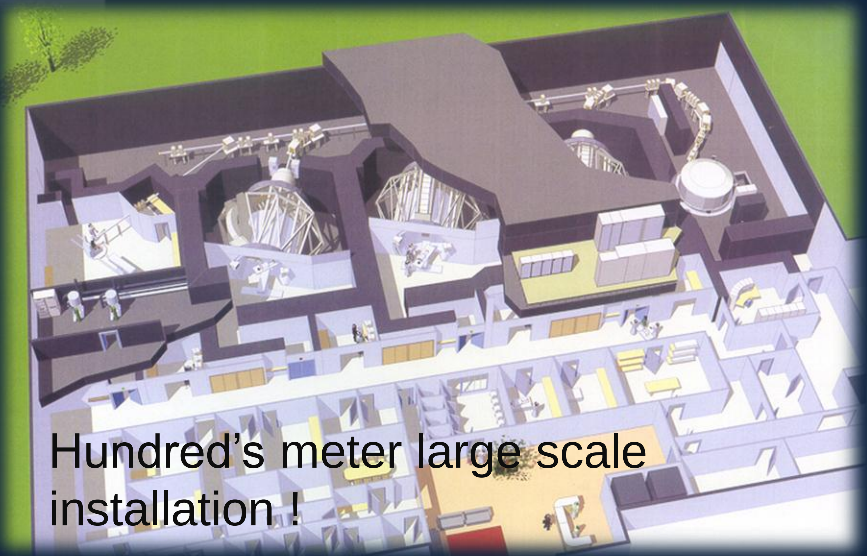


•*dose deposition optimised*



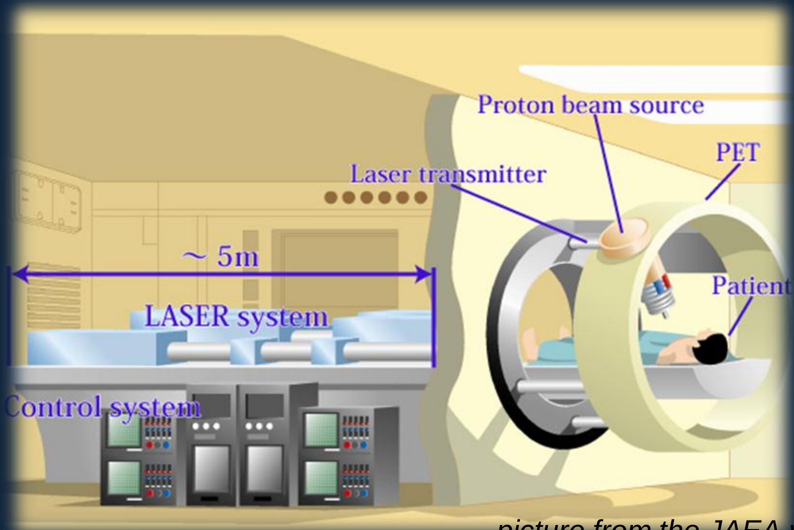


Proton therapy centers : typical sizes



Cost : 80 to 140 M€
(~2.5 times a photon based center)
Size : 1000 to 2000 m²

More affordable installations
↓
more clinical centers
↓
more treated patients



picture from the JAEA web site

How far are we with lasers ?

	Energy max	ΔE/E	Shot / shot Variability	dose	divergency
Requested	200 MeV	0.1 %	0.1 %	1 liter @ 2 Gy ⇨ $10^{E}12$ protons/2 min	Controlled !

A laser driven ion beam for medical therapy: a real challenge !!

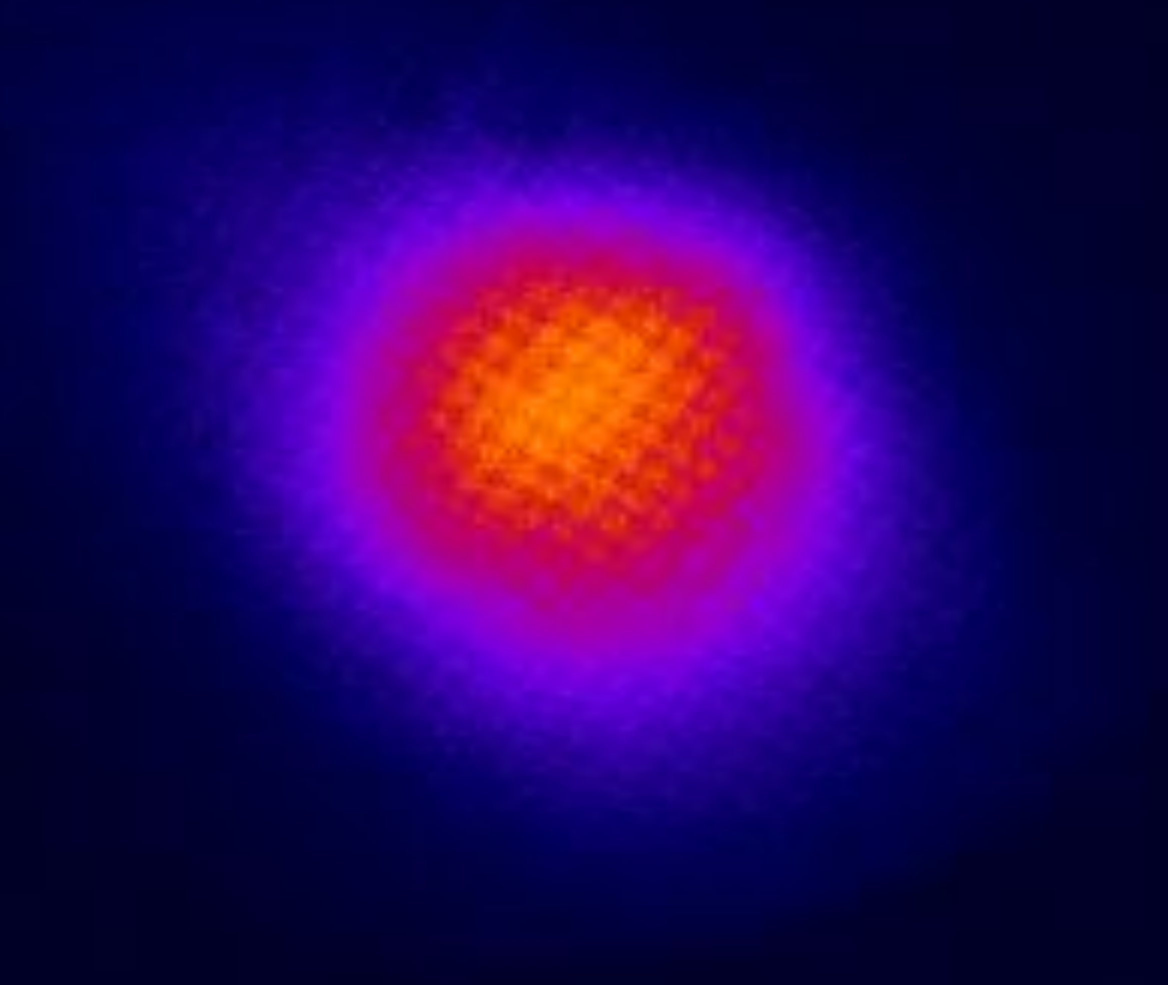
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 10, 094801 (2007)

What will it take for laser driven proton accelerators to be applied to tumor therapy?

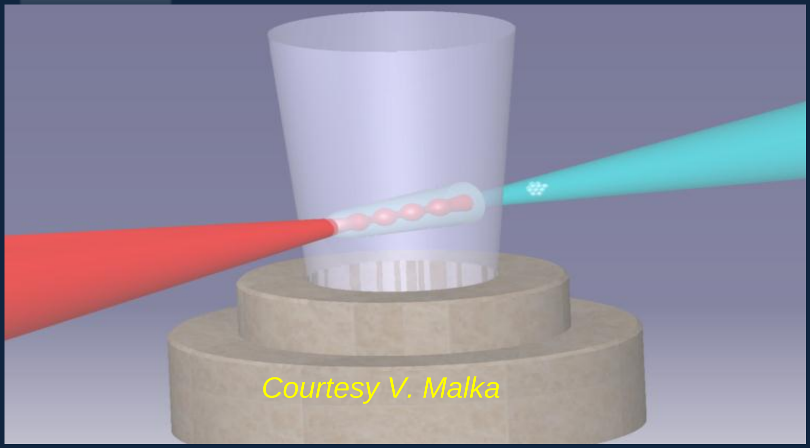
Ute Linz[1,*] and Jose Alonso[2,†]
[1]Forschungszentrum Jülich, D-52425 Jülich, Germany
[2]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 27 April 2007; published 24 September 2007)

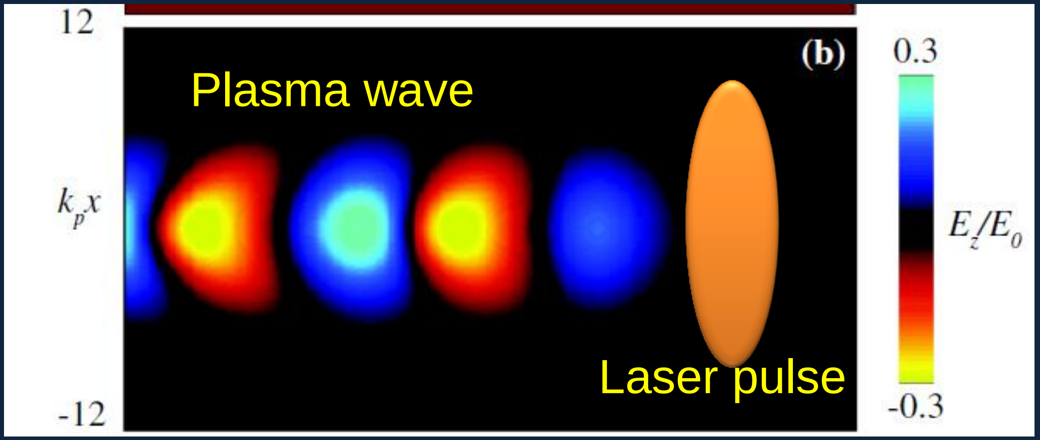
quality-assurance and patient-safety aspects. This is not to say that one should not work towards solving these tremendous problems! After all, it was realized over 100 years ago that orthovoltage x rays could be used for treating malignancies, but it took many decades—plus the development of a number of enabling technologies—be-

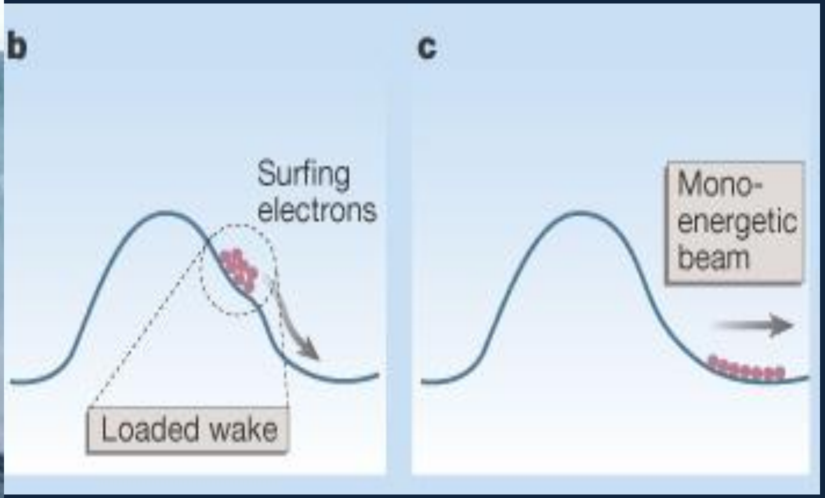
Electron acceleration



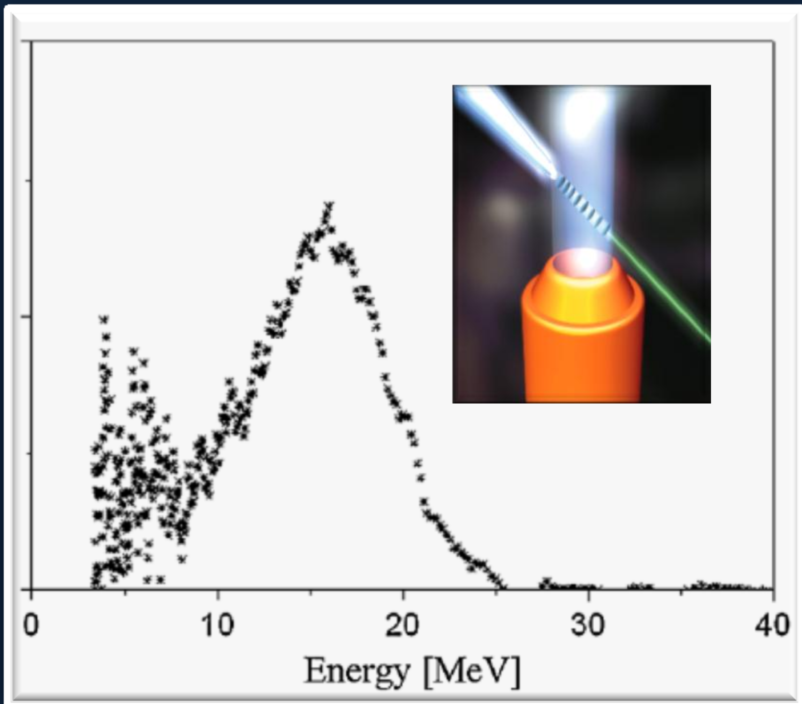
Electron acceleration mechanism - under-dense plasmas -

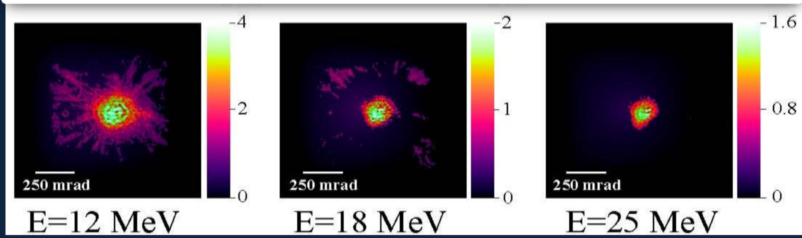






Saclay Laser driven electron accelerator performances





10^{10} electrons (with **E ≥ 8 MeV**)
per Joule record efficiency ≥ 10^{-2}

1.6 nC, 10Hz of ~15MeV e^- !!

PRL **101,** 105002 (2008) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2008

Intense γ-Ray Source in the Giant-Dipole-Resonance Range Driven by 10-TW Laser Pulses

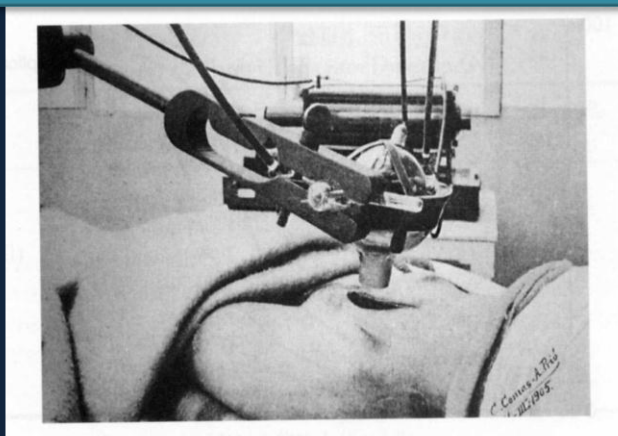
A. Giulietti,[1,2] N. Bourgeois,[3] T. Ceccotti,[4] X. Davoine,[5] S. Dobosz,[4] P. D'Oliveira,[4] M. Galimberti,[1,*] J. Galy,[6] A. Gamucci,[1,2] D. Giulietti,[1,2,7] L. A. Gizzi,[1,2] D. J. Hamilton,[6,+] E. Lefebvre,[5] L. Labate,[1,2] J. R. Marquès,[3] P. Monot,[4] H. Popescu,[4] F. Réau,[4] G. Sarri,[1] P. Tomassini,[1,8] and P. Martin[4]

[1]*Intense Laser Irradiation Laboratory, IPCF, Consiglio Nazionale delle Ricerche, CNR Campus, Pisa, Italy*
[2]*INFN, Sezione di Pisa, Italy*
[3]*Laboratoire pour l'Utilisation des Lasers Intenses, CNRS UMR 7605, Ecole Polytechnique, Palaiseau, France*
[4]*CEA-DSM/DRECAM/SPAM, Gif sur Yvette Cedex, France*
[5]*Département de Physique Théorique et Appliquée, CEA/DIF, 91680 Bruyères-le-Châtel, France*
[6]*European Commission, JRC Institute for Transuranium Elements, Karlsruhe, Germany*
[7]*Dipartimento di Fisica, Università di Pisa, Pisa, Italy*
[8]*INFN, Sezione di Milano, Italy*

Suitable for IORT?

The *Intra-Operative Radiation Therapy* is a particular class of radiotherapy which consists in irradiating the tumour bed just after its surgical ablation and before the end of operation.

First intra-operative treatment (**1909**)



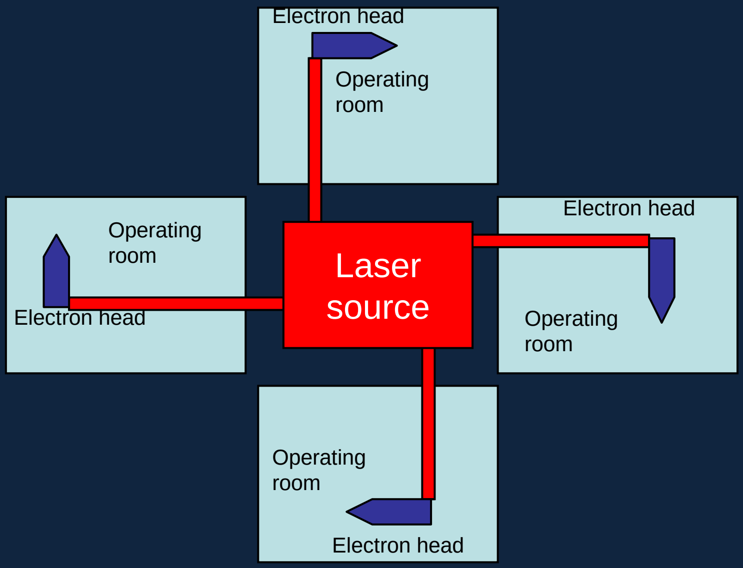
A modern IORT device

	Energy	ΔE/E	Rep Rate	Bunch charge, bunch duration	Beam divergency	cost
LIAC *(SORDINA)*	12 MeV	Non critical	5-20 Hz	1.8 nC, 1.2 μs	Non critical	2 M€

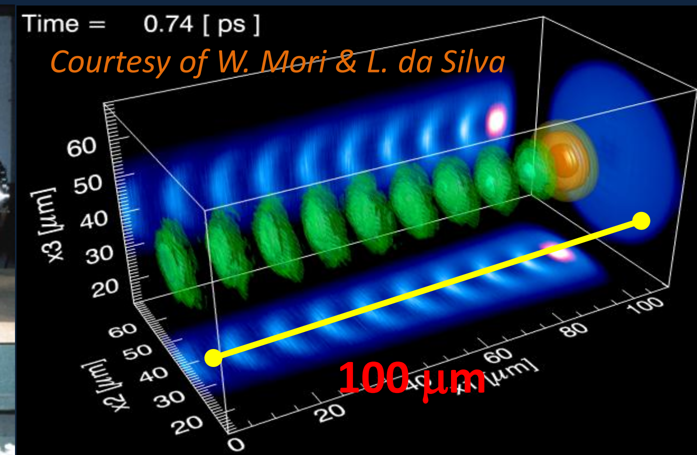
Main laser advantages

- Laser in a dedicated technical room : daily operation and servicing is performed **outside** the operating **sterile rooms** : **save time**

- Room multiplexing possible : **save budget**

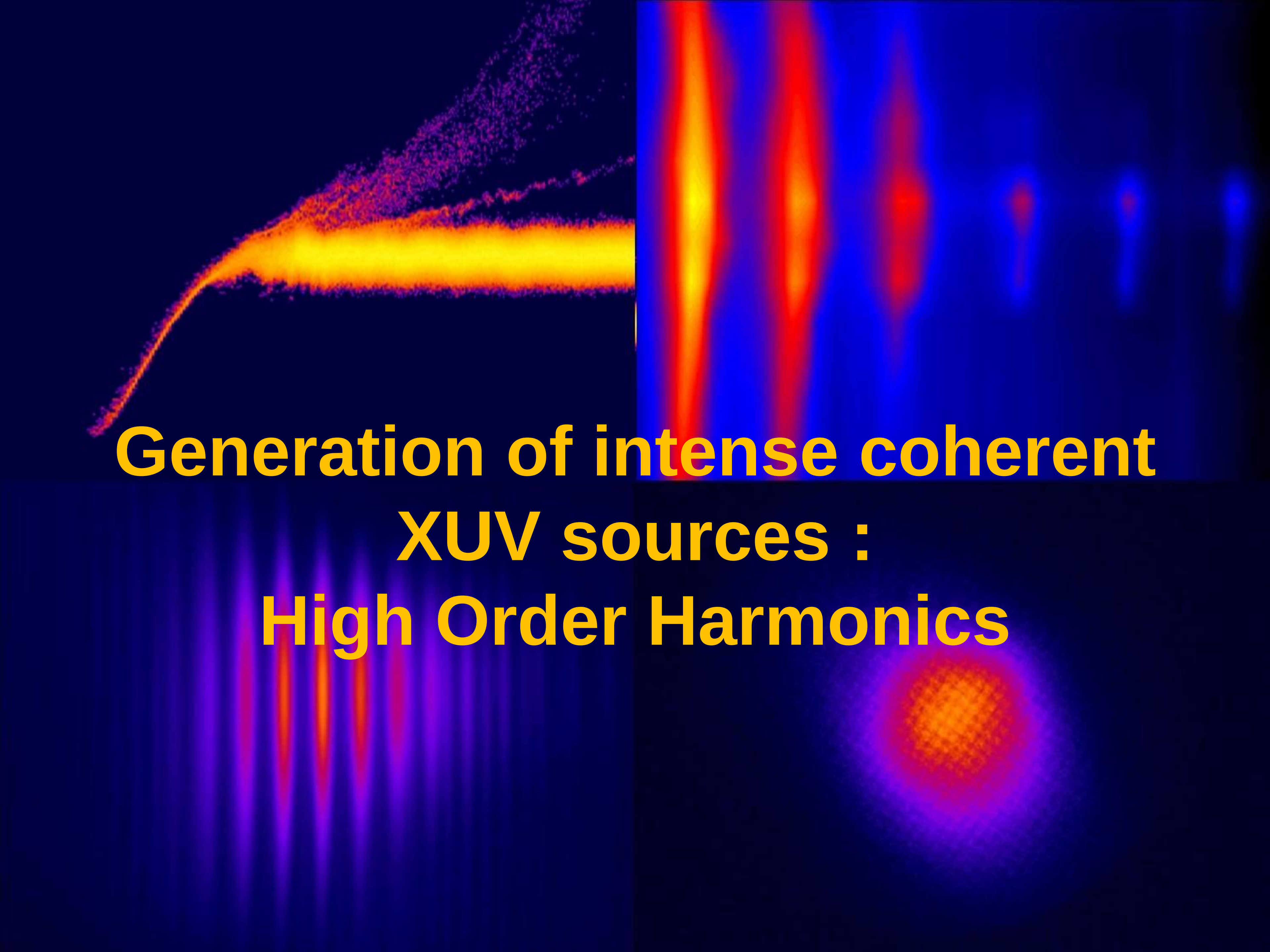


Best supraconducting cavities : *E* = 50 MV/m : **100 MeV in 2 m**
LPA : E > 100 GeV/m : **100 MeV in 1 mm !!**

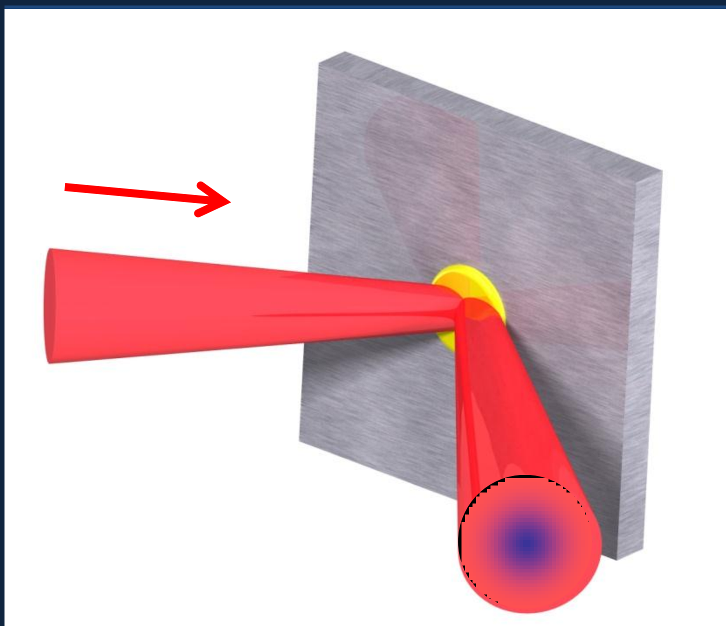


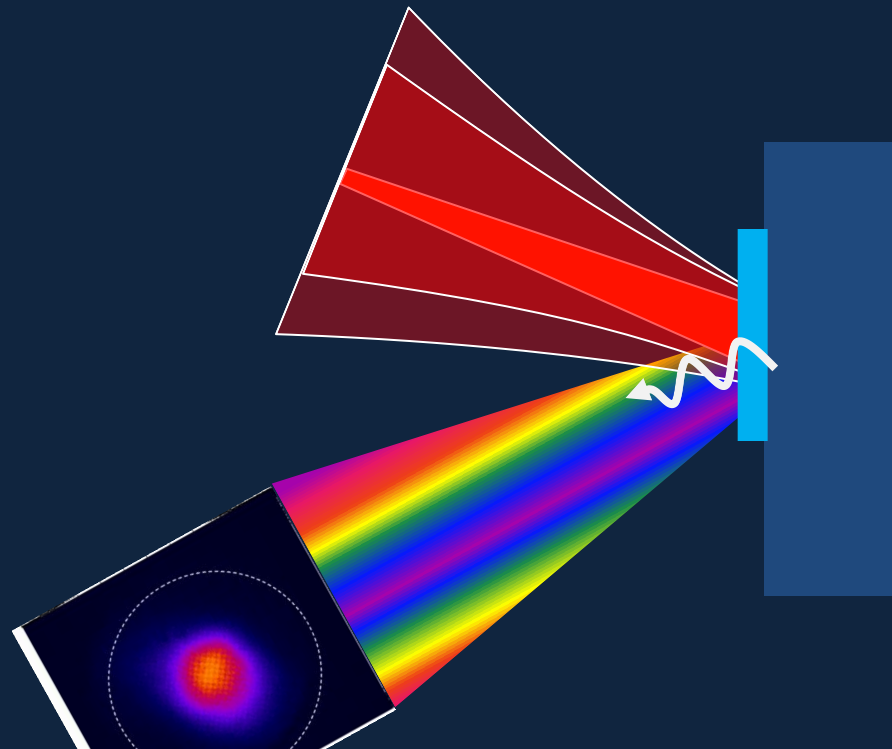
Record 2006 : 1 GeV over 3 cm distance, W. Leemans et al, Nature Phys 2, 696, 2006

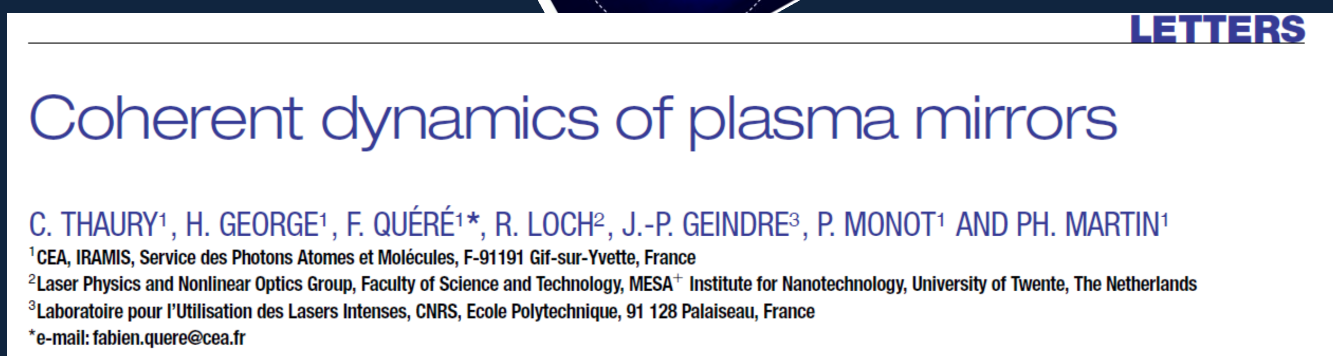
Generation of intense coherent XUV sources : High Order Harmonics



HHG from solid targets







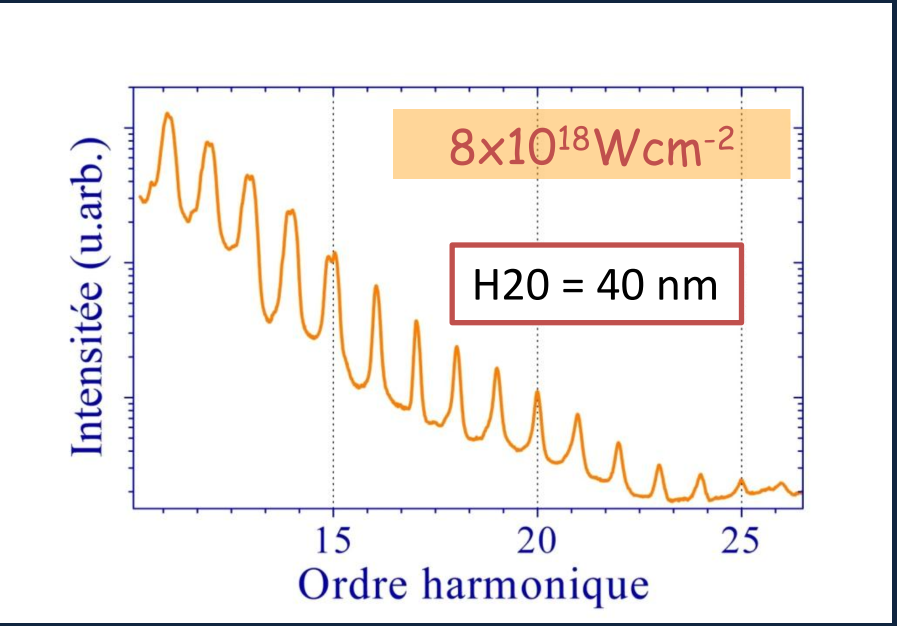
LETTERS

Coherent dynamics of plasma mirrors

C. THAURY[1], H. GEORGE[1], F. QUÉRÉ[1]*, R. LOCH[2], J.-P. GEINDRE[3], P. MONOT[1] AND PH. MARTIN[1]

[1]CEA, IRAMIS, Service des Photons Atomes et Molécules, F-91191 Gif-sur-Yvette, France
[2]Laser Physics and Nonlinear Optics Group, Faculty of Science and Technology, MESA+ Institute for Nanotechnology, University of Twente, The Netherlands
[3]Laboratoire pour l'Utilisation des Lasers Intenses, CNRS, Ecole Polytechnique, 91 128 Palaiseau, France
*e-mail: fabien.quere@cea.fr

HHG from solid targets



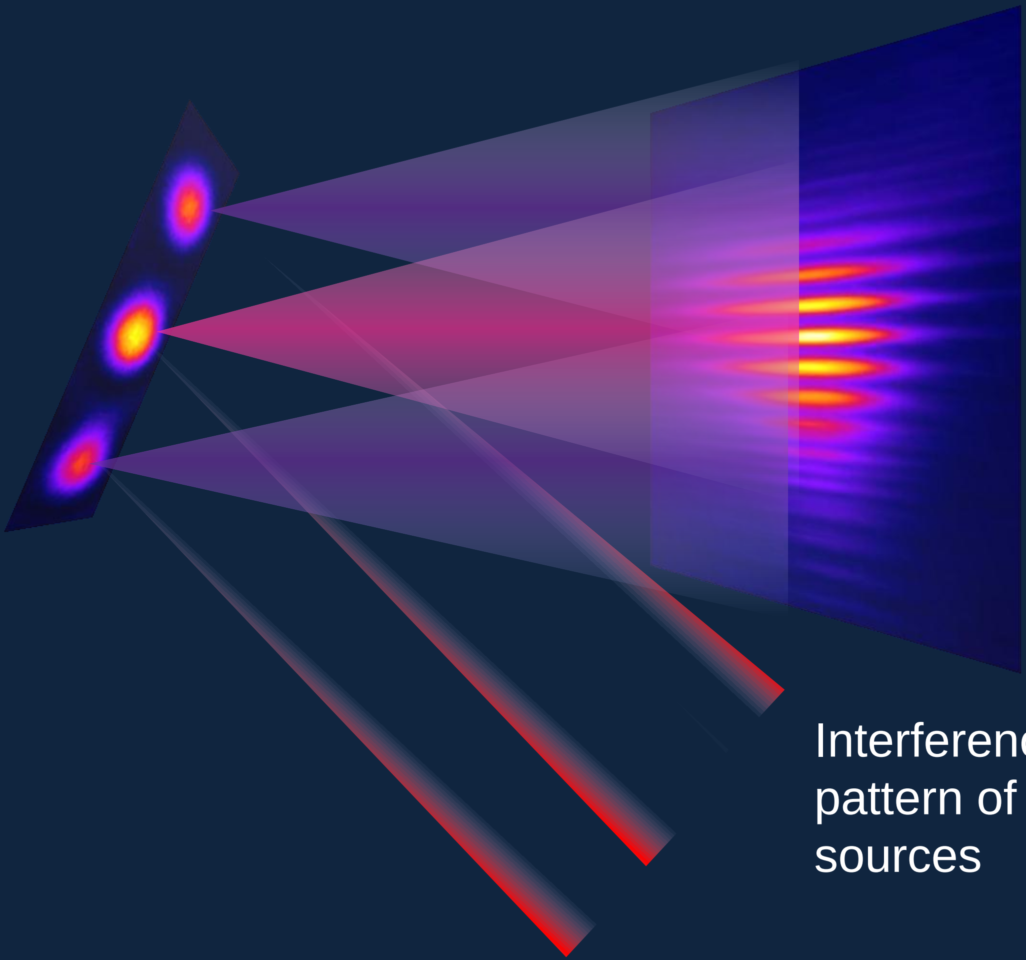
ARTICLES

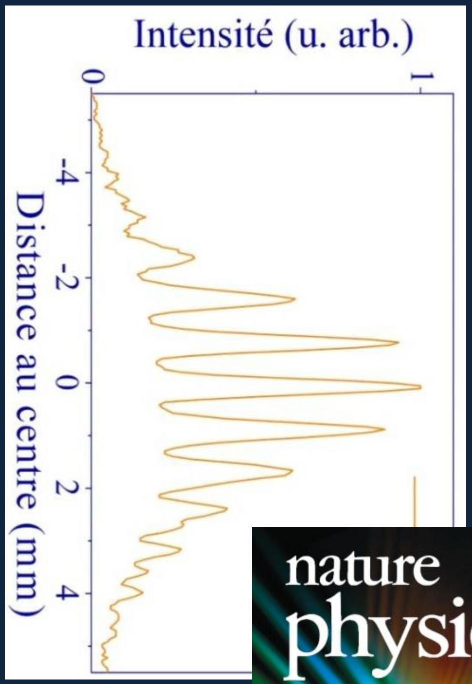
Plasma mirrors for ultrahigh-intensity optics

C. THAURY[1], F. QUÉRÉ[1]*, J.-P. GEINDRE[2], A. LEVY[1], T. CECCOTTI[1], P. MONOT[1], M. BOUGEARD[1], F. RÉAU[1], P. D'OLIVEIRA[1], P. AUDEBERT[2], R. MARJORIBANKS[3] AND PH. MARTIN[1]

[1]Service des Photons, Atomes et Molécules, Commissariat à l'Energie Atomique, DSM/DRECAM, CEN Saclay, 91191 Gif-sur-Yvette, France
[2]Laboratoire pour l'Utilisation des Lasers Intenses, CNRS, Ecole Polytechnique, 91128 Palaiseau, France
[3]Department of Physics and Institute for Optical Sciences, University of Toronto, 60 St George Street, Toronto, Ontario M5S 1A7, Canada
*e-mail: fabien.quere@cea.fr

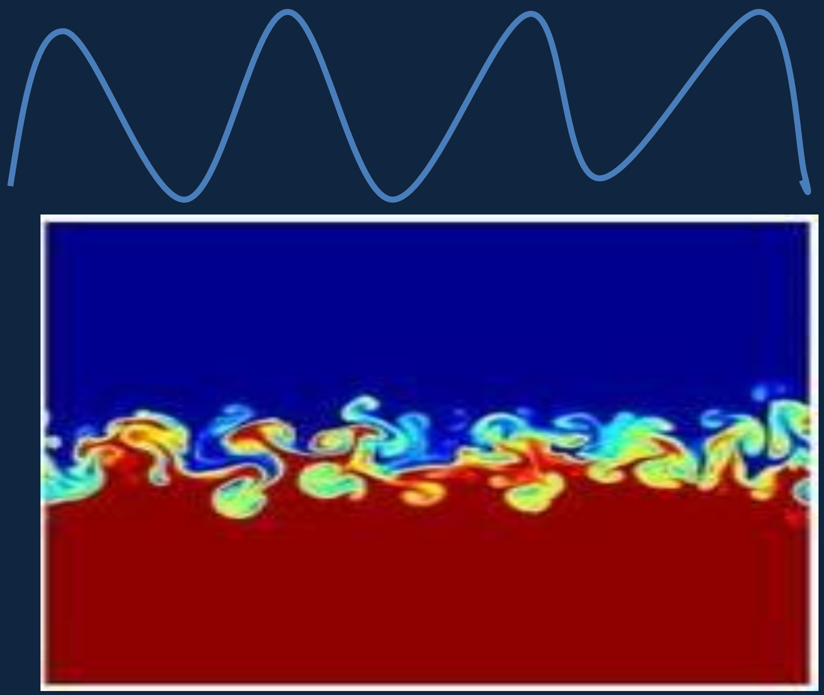
Is the Beam Spatialy coherent ?



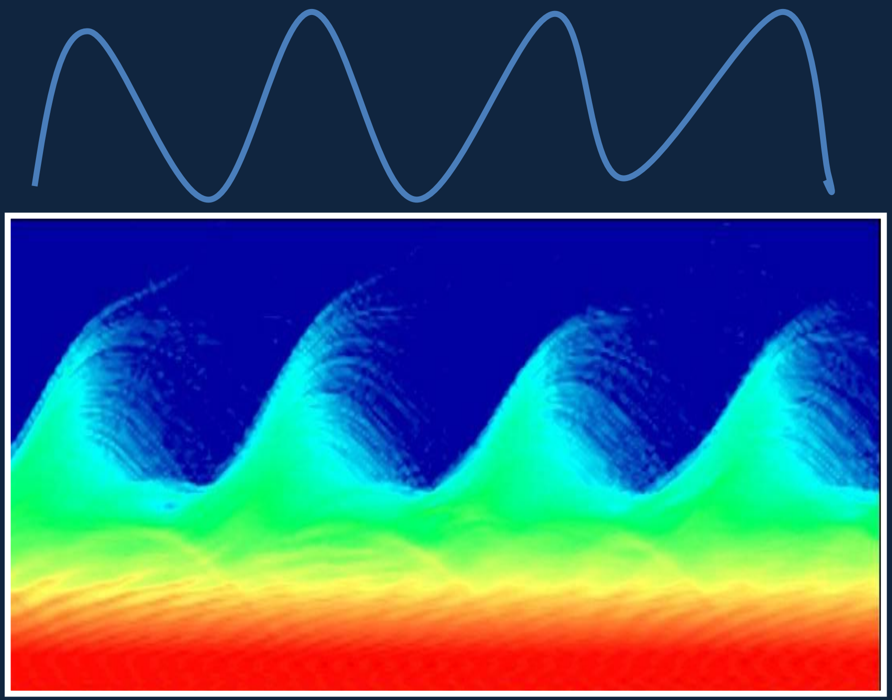


Interference pattern of 3 XUV sources

Coherent response of the matter at the femtosecond time scale



Usual plasma



Laser- driven femtosecond plasma

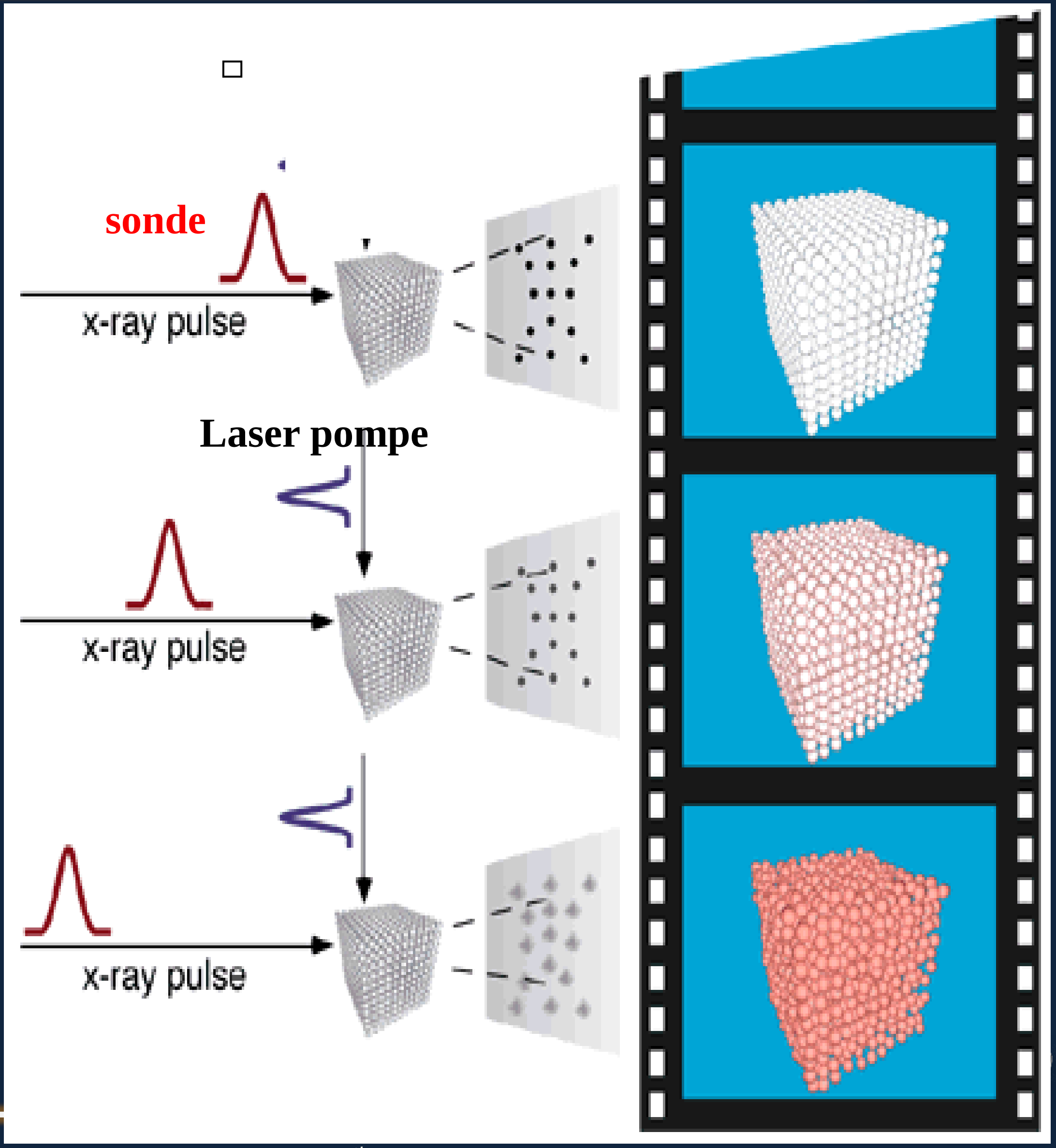
Dream application : Imaging a macromolecule and following its dynamics of on the femtosecond time scale

'Watching matter rearrange'
K. Nelson Science (1999)

Principle :
coherent diffraction imaging
pump-probe experiments

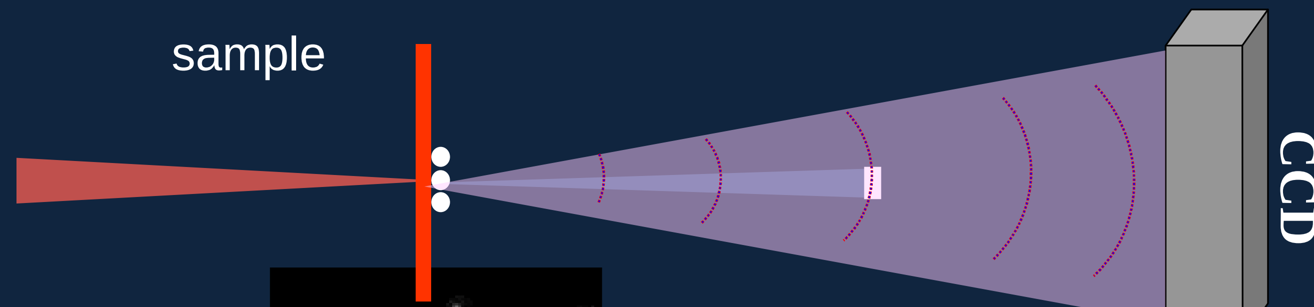
Necessary properties on the imaging source :

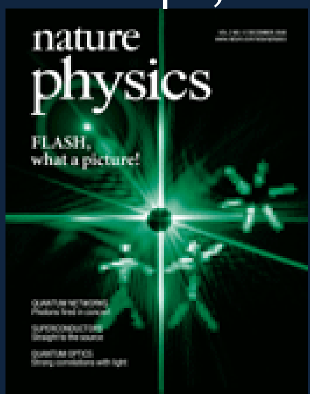
- coherent
- short wavelength-spatial resolution
- ultra-short - temporal resolution
- intense-image small size objects
- single shot !

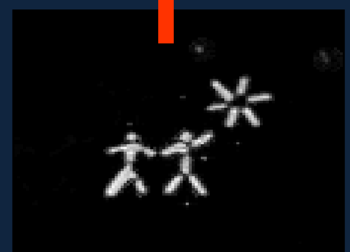


First step : Single shot diffractive imaging using soft X-ray : 2006

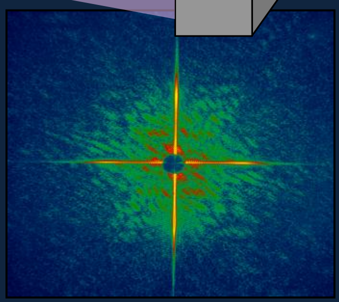
$\lambda = 32$nm
20µJ, 30 fs



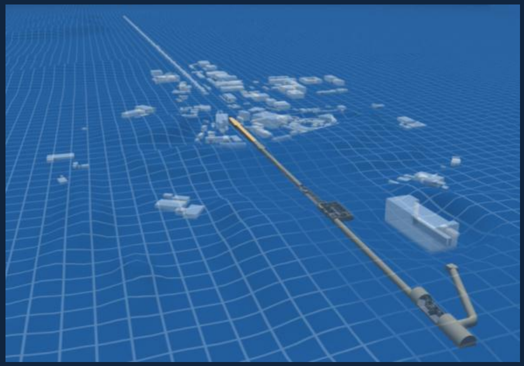


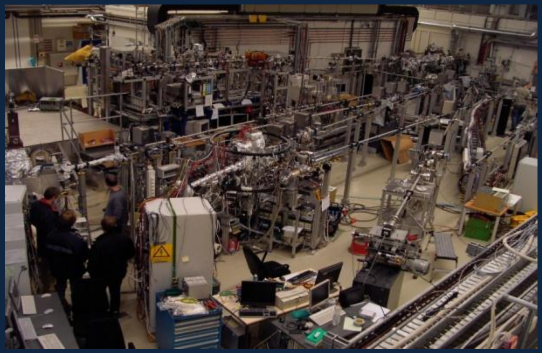


Resolution = 60 nm

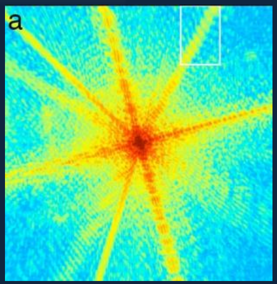


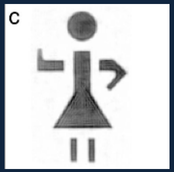
First demonstration using a FEL – FLASH (large scale facility)





Seconds step : the same BUT using HHG from a T3 laser





1 Hour acquisition

PRL 99, 098103 (2007) PHYSICAL REVIEW LETTERS week ending 31 AUGUST 2007

Lensless Diffractive Imaging Using Tabletop Coherent High-Harmonic Soft-X-Ray Beams

Richard L. Sandberg,* Ariel Paul, Daisy A. Raymondson, Steffen Hädrich, David M. Gaudiosi, Jim Holtsnider, Ra'anan I. Tobey, Oren Cohen, Margaret M. Murnane, and Henry C. Kapteyn
JILA and Department of Physics, University of Colorado and NSF Engineering Research Center in Extreme Ultraviolet Science and Technology, Boulder, Colorado 80309, USA
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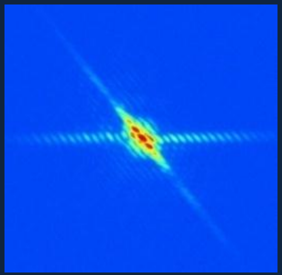
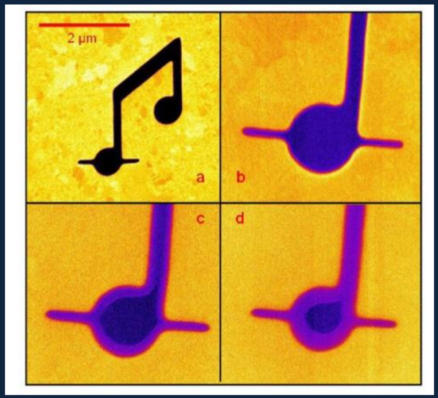
Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 18 April 2007; published 29 August 2007)

Decisive step ! Single shot diffractive imaging using HHG from a T3 laser





Resolution = 120 nm

PRL 103, 028104 (2009) PHYSICAL REVIEW LETTERS week ending 10 JULY 2009

Single-Shot Diffractive Imaging with a Table-Top Femtosecond Soft X-Ray Laser-Harmonics Source

A. Ravasio,[1] D. Gauthier,[1] F. R. N. C. Maia,[2] M. Billon,[1] J-P. Caumes,[1] D. Garzella,[1] M. Géléoc,[1] O. Gobert,[1] J-F. Hergott,[1] A-M. Pena,[1] H. Perez,[1] B. Carré,[1] E. Bourhis,[3] J. Gierak,[3] A. Madouri,[3] D. Mailly,[3] B. Schiedt,[3] M. Fajardo,[4] J. Gautier,[5] P. Zeitoun,[5] P. H. Bucksbaum,[6] J. Hajdu,[2,6] and H. Merdji[1,6,*]
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(Received 30 January 2009; published 8 July 2009)

PRL 105, 093901 (2010) PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2010

Single-shot Femtosecond X-Ray Holography Using Extended References

D. Gauthier,[1] M. Guizar-Sicairos,[2] X. Ge,[1] W. Boutu,[1] B. Carré,[1] J. R. Fienup,[2] and H. Merdji[1,3,*]
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(Received 4 February 2010; revised manuscript received 15 July 2010; published 24 August 2010)

Coulombic explosion of an isolated single molecule
Time resolution 1 fs !

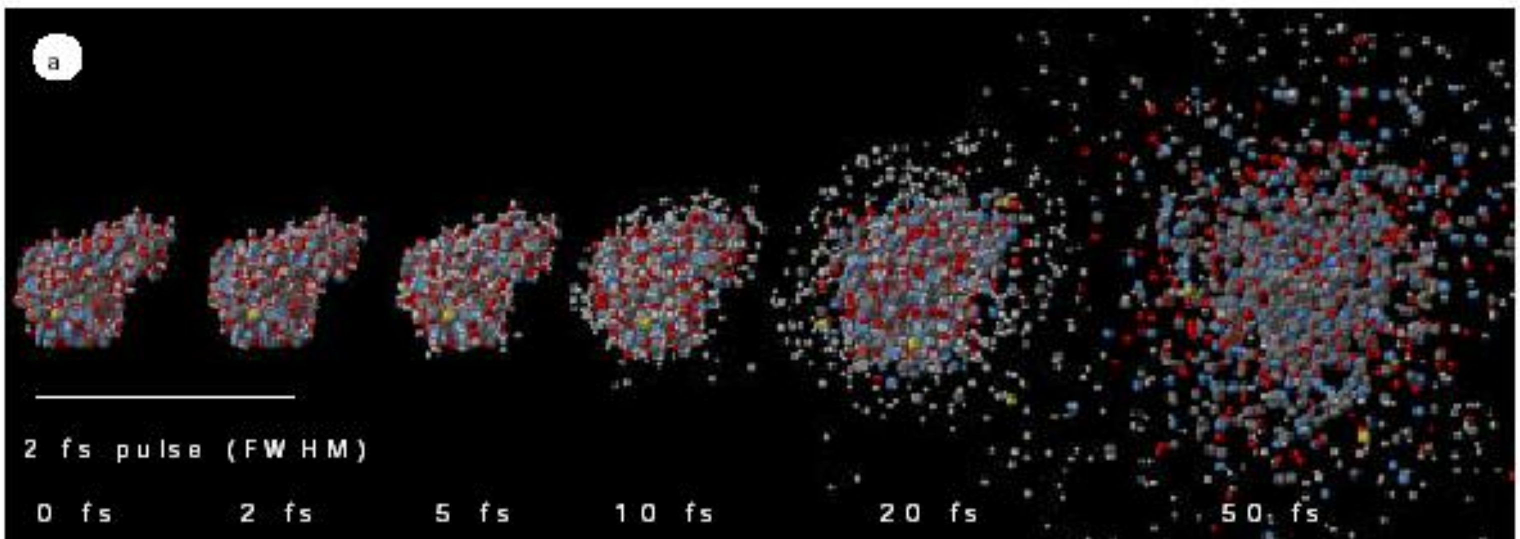
letters to nature

Potential for biomolecular imaging with femtosecond X-ray pulses

Richard Neutze*, Remco Wouts*, David van der Spoel*, Edgar Weckert†‡ & Janos Hajdu*

NATURE | VOL 406 | 17 AUGUST 2000 |

Simulation !!!!

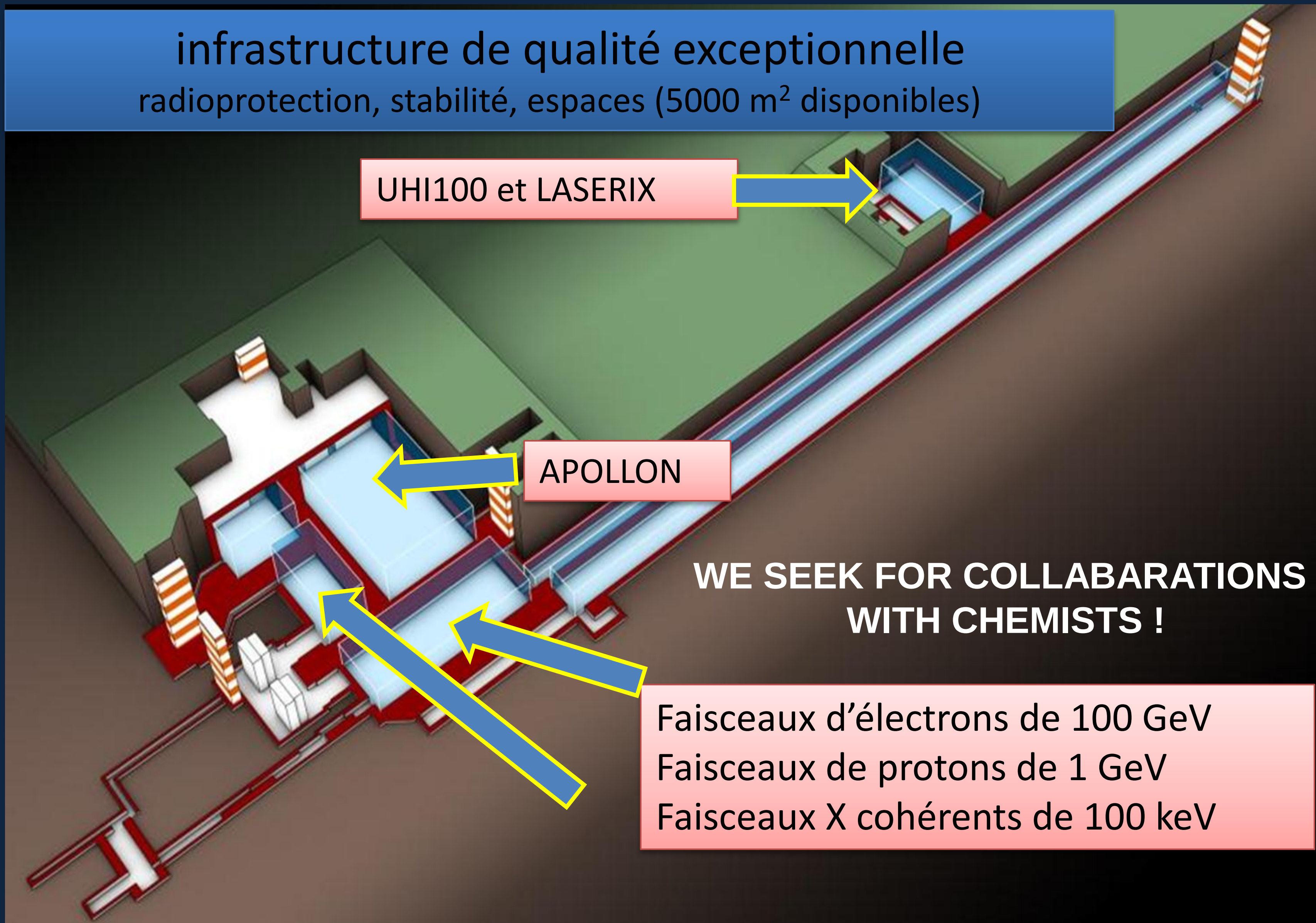


Conclusions/ perpectives

Laser driven particle acceleration or hard photon generation using relativistic ultra-high field effects is of considerable interest !!

- **Laser Proton-therapy : still a long way !**
- **Laser Electro-therapy (IORT) : not so long !**
- **Dynamical evolution of isolated molecules with a unprecedented time resolution : not so long !**

French Project CILEX @ Orme des merisiers



Above PW projects in EU > 1 B€

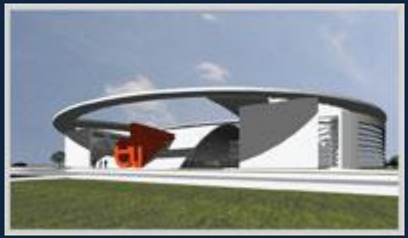
ELI in Tcheque Republic

ELI in Hongria

ELI in Romania

FLAME- PLASMONX in Italy

CLPU : Salamanca



Vulcan 10PW / Gemini projects in UK

SCAPA project in Scotland

MPQ project in UHI physics on PW lasers

Jena projects in UHI physics on PW lasers

European XFEL projects with PW lasers

Dresden projects in UHI physics with PW lasers