Research and technology development with ultra-intense lasers at ELI-Beamlines-Prague

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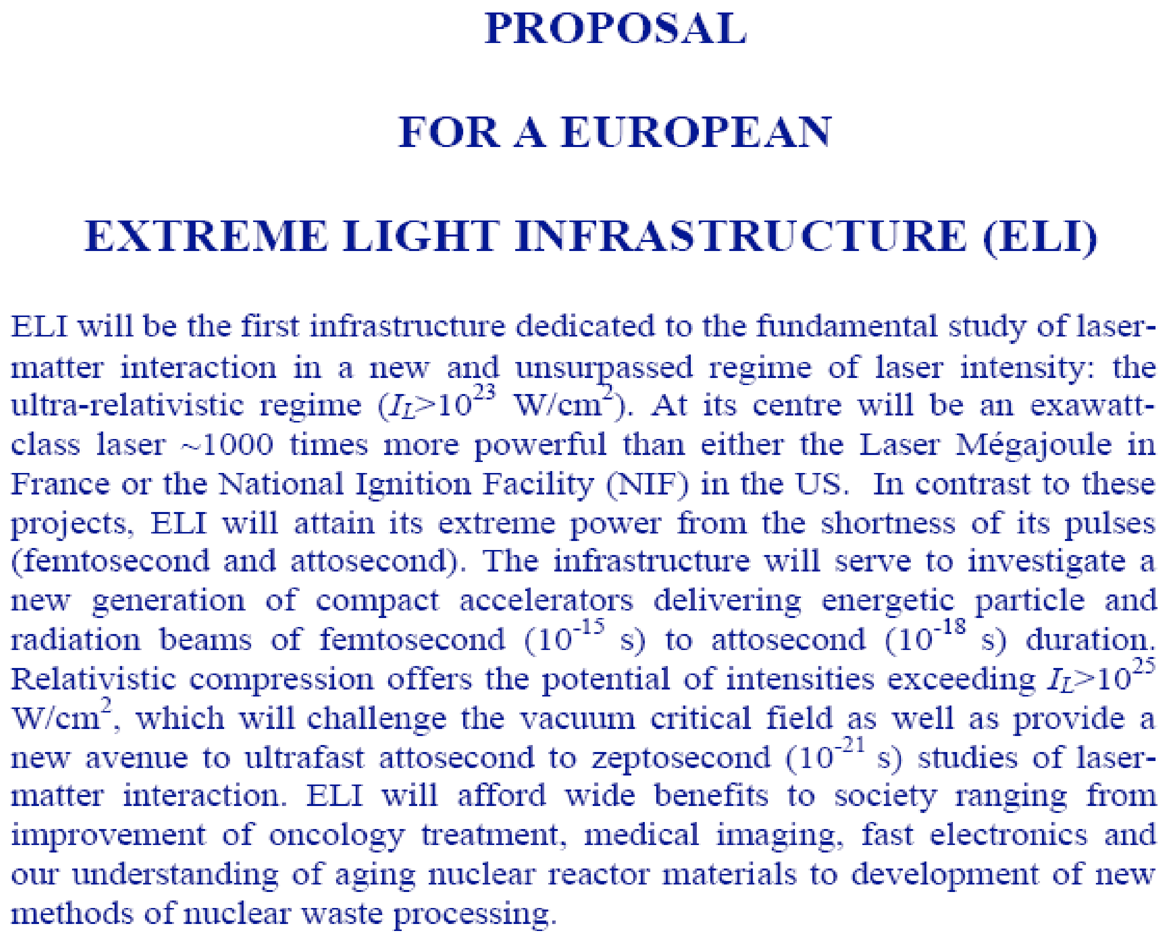
Outline

- ELI – Project development
- Ultra-intense laser-matter interaction
  - particle acceleration
  - x-ray generation
  - ultra-relativistic interaction
- ELI-Beamlines facilities
  - Projected Laser Systems
  - ELI experimental areas



PROPOSAL

FOR A EUROPEAN

EXTREME LIGHT INFRASTRUCTURE (ELI)

ELI will be the first infrastructure dedicated to the fundamental study of laser-matter interaction in a new and unsurpassed regime of laser intensity: the ultra-relativistic regime ($I_L > 10^{23}$ W/cm^2). At its centre will be an exawatt-class laser ~1000 times more powerful than either the Laser Mégajoule in France or the National Ignition Facility (NIF) in the US. In contrast to these projects, ELI will attain its extreme power from the shortness of its pulses (femtosecond and attosecond). The infrastructure will serve to investigate a new generation of compact accelerators delivering energetic particle and radiation beams of femtosecond (10^{-15} s) to attosecond (10^{-18} s) duration. Relativistic compression offers the potential of intensities exceeding $I_L > 10^{25}$ W/cm^2, which will challenge the vacuum critical field as well as provide a new avenue to ultrafast attosecond to zeptosecond (10^{-21} s) studies of laser-matter interaction. ELI will afford wide benefits to society ranging from improvement of oncology treatment, medical imaging, fast electronics and our understanding of aging nuclear reactor materials to development of new methods of nuclear waste processing.

The ELI-central laser facility will finally allow to go to the ultra-relativistic interaction regime,
Peak-Power 200 PW - the dream

www.eli-laser.eu

Today with careful design of dispersion and broad band laser materials pulses in the sub-20fs with 10s of Joules of energy can be generated direct laser amplification or through
CPA or
OPCPA (A. Piskarskas group, 1992)

PW- regime (I $>10^{22}$W/cm^2)

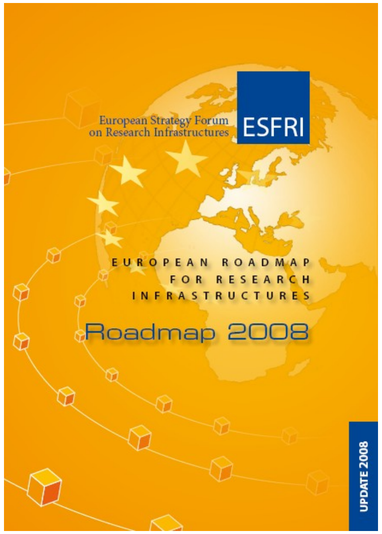
Extreme-Light-Infrastructure (ELI) European project
System with 200 PW is in planning (composed of 10-20 PW beamlines)

Exawatts may require new approaches using plasmas as a Nondestractible amplifying and reflecting medium (Raman amplification)

European Strategy Forum
on Research Infrastructures
ESFRI

EUROPEAN ROADMAP
FOR RESEARCH
INFRASTRUCTURES

Report 2006



European Strategy Forum
on Research Infrastructures
ESFRI

EUROPEAN ROADMAP
FOR RESEARCH
INFRASTRUCTURES

Roadmap 2008

UPDATE 2008

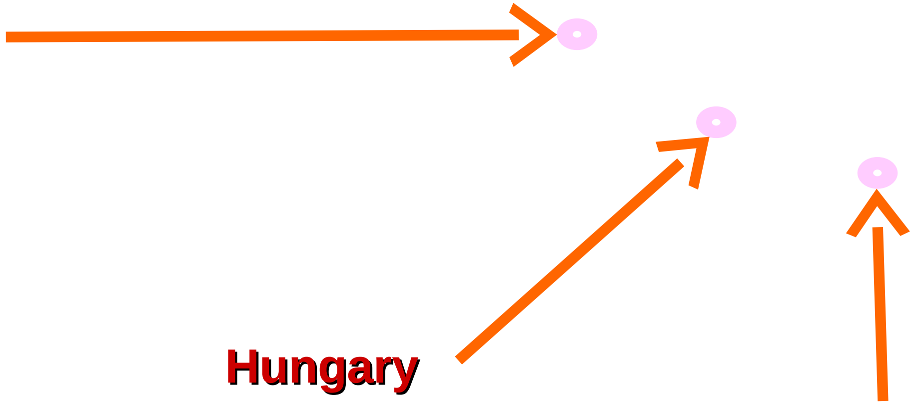
ELI-PP Start November 2007
End December 2010

13 countries on board:
CZ, Hu, Ro, Fr, Ge, UK, I, Lith., Gr, Pl
Sp, Bu, Po

Initial EU funding 6 Mio € to facilitate:

science program develop.
technical design (TDR)
safety&radioprotection
site choice
legal structure
governance
financial planning
funding

Site selection: decision on 1.10.2009

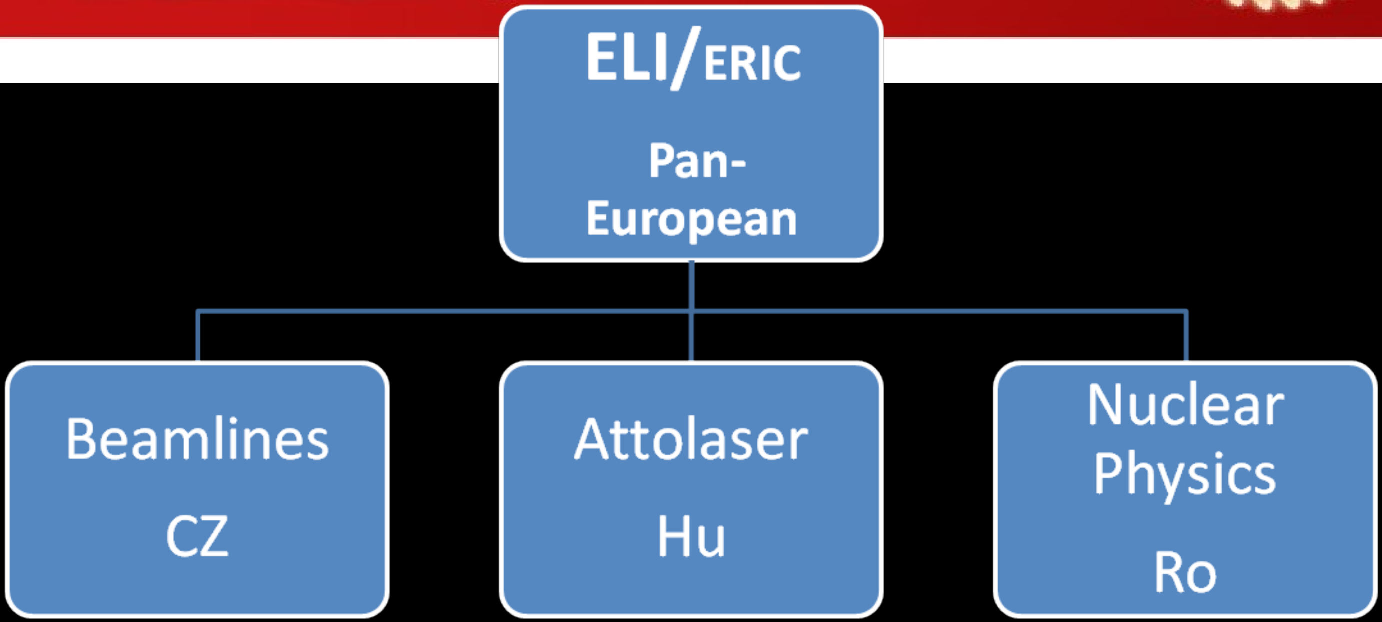


Czech Republic
Prague

Hungary
Szeged

Romania
Bucharest - Magurele

Overall cost: ≈ 750M€



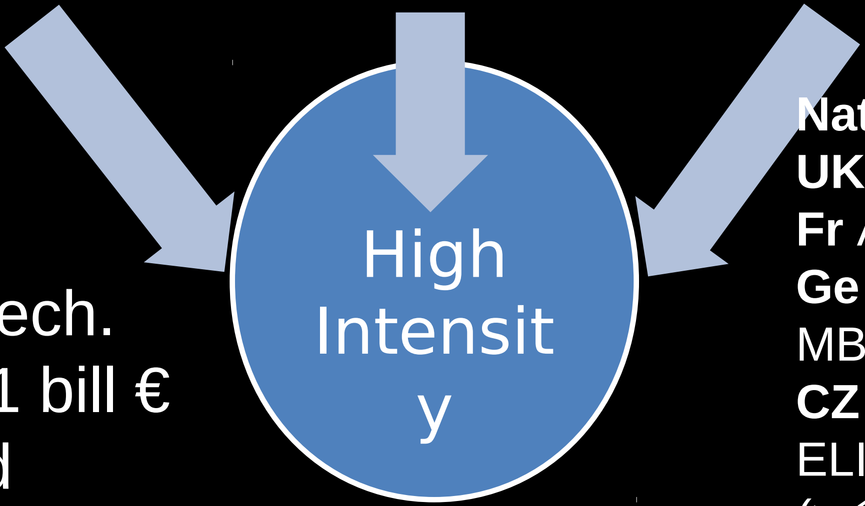
ELI/ERIC

Pan-European

Beamlines
CZ

Attolaser
Hu

Nuclear Physics
Ro



2012
Decision on Tech.
Extra-Funding 1 bill €
envisioned

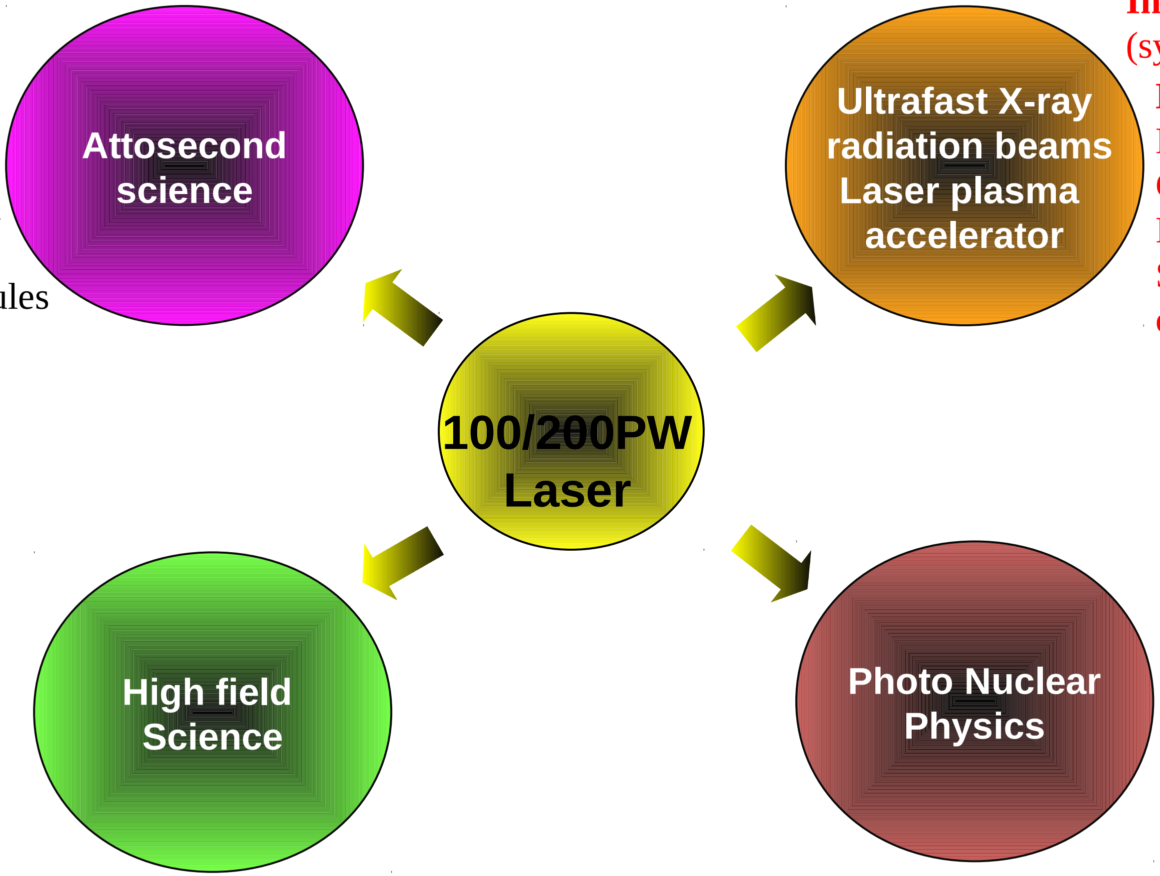
High
Intensit
y

National Projects
UK Vulcan, RAL
Fr Apollon, ILE
Ge PFS, PFSpro MPQ,
MBI, CALA, FZD
CZ HILASE
ELI-PP , Laserlab Europe
(> 163 Mio €)

Scientific ”pillars” of ELI

Attosecond
 to zeptosecond
Physics

Application
Ultrafast phenomena
Wave function
 in atoms and molecules


Attosecond science

Ultrafast X-ray radiation beams
Laser plasma accelerator

100/200PW
Laser

High field Science

Photo Nuclear Physics

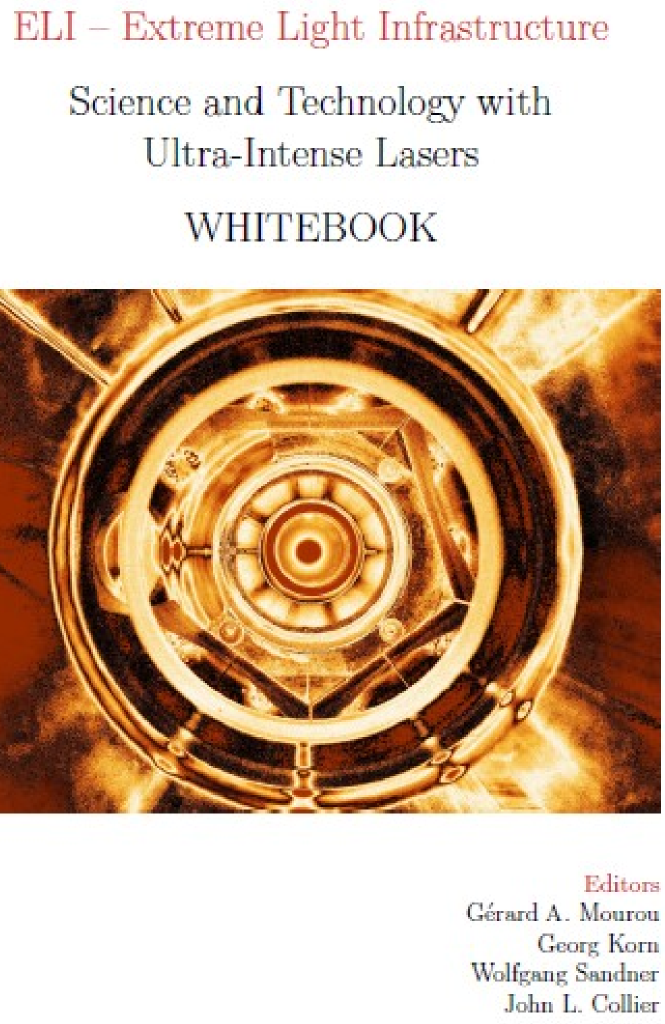
Coherent (X,g)-rays
(FEL, HHG & plasma)
Incoherent (X,g)-rayBeams
(synchrotron-like, atomic)

Beam lines facility
Electron beams
Gamma imaging
Proton beams
Synchronized with
optical driver beams

NLQED
Fundamental
 physics
Exotic physics

Nuclear Physics

530 pages
Science, technology and implementation strategies of ELI
FR !



ELI – Extreme Light Infrastructure

Science and Technology with
Ultra-Intense Lasers

WHITEBOOK

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The Extreme Light Infrastructure
European Project

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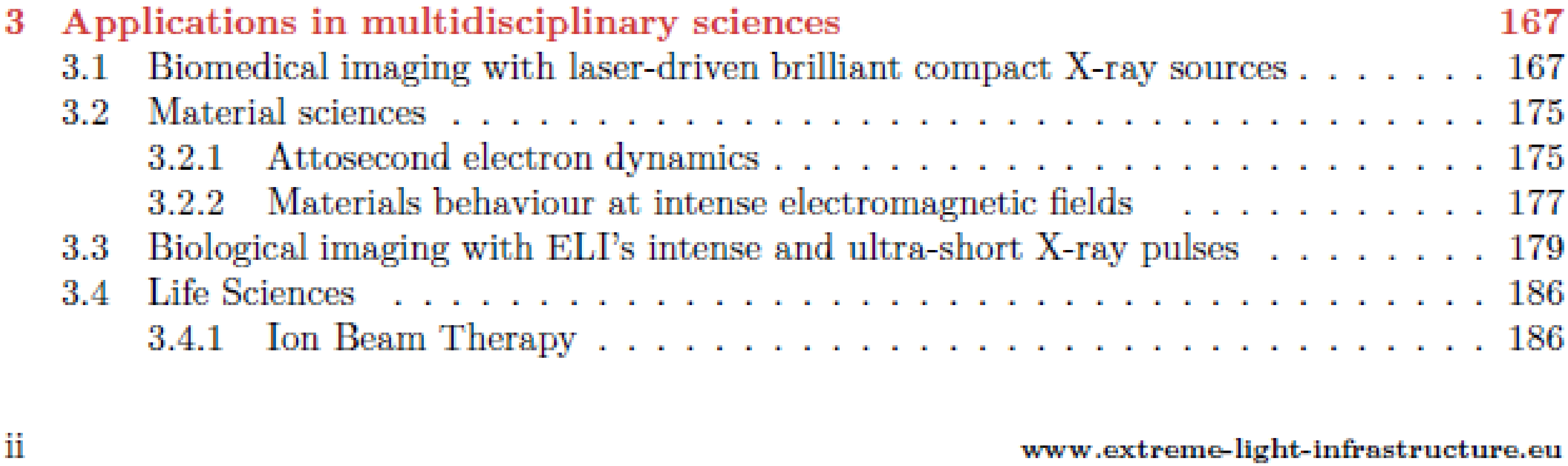
Electron-, Proton- and X-ray Beamlines developments
are directly connected with some applications



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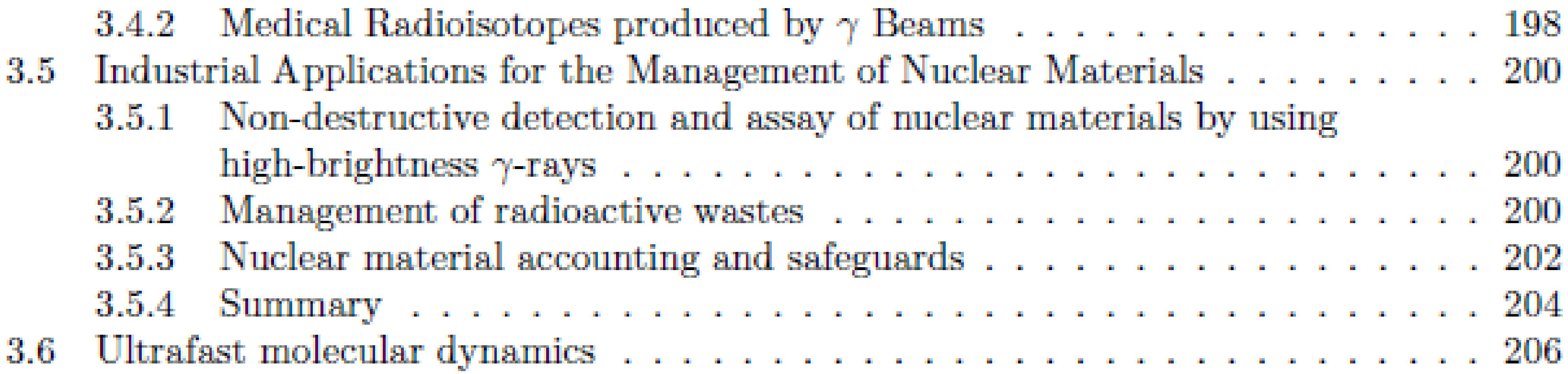

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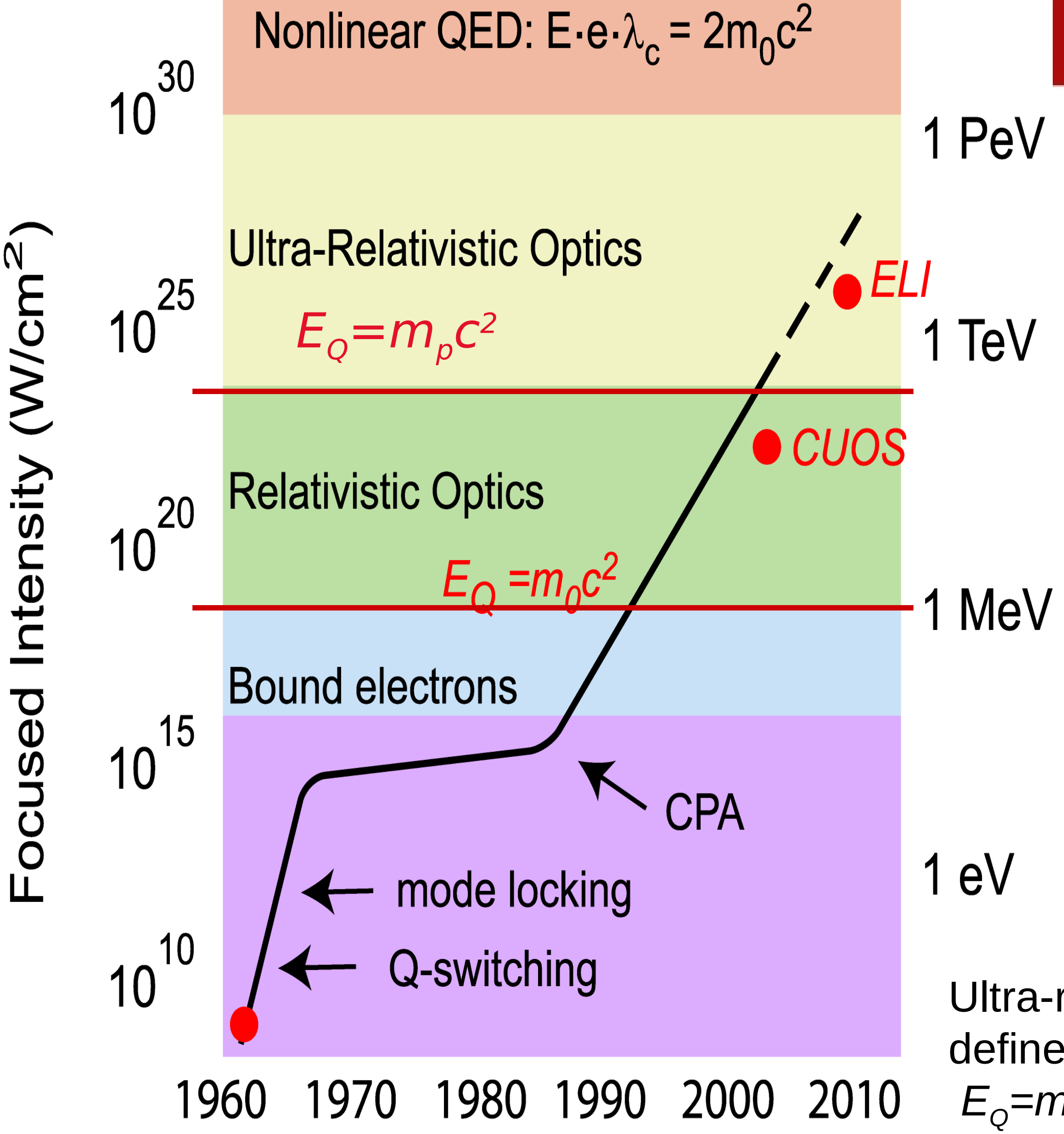
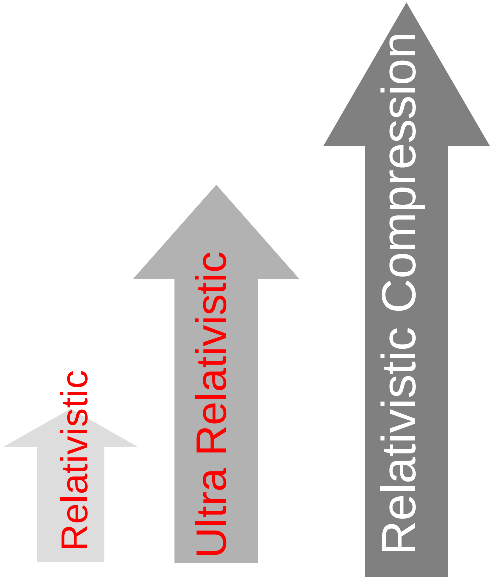
One of the big Challenges in Physics would be to built A laser powerful enough to breakdown vacuum.

Survey by "Science" 2005

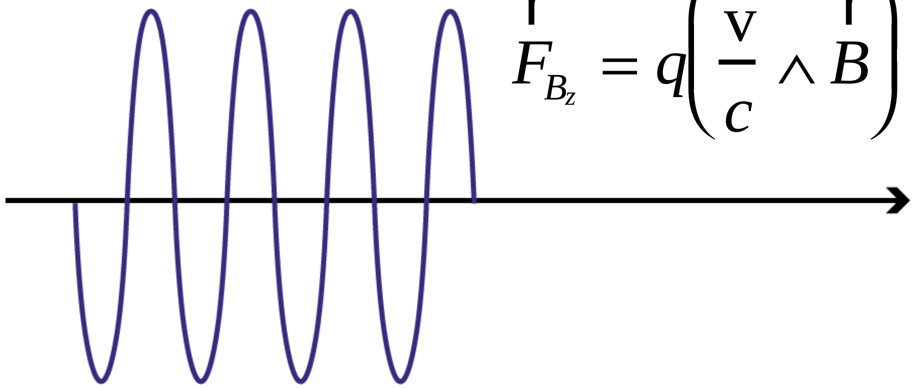




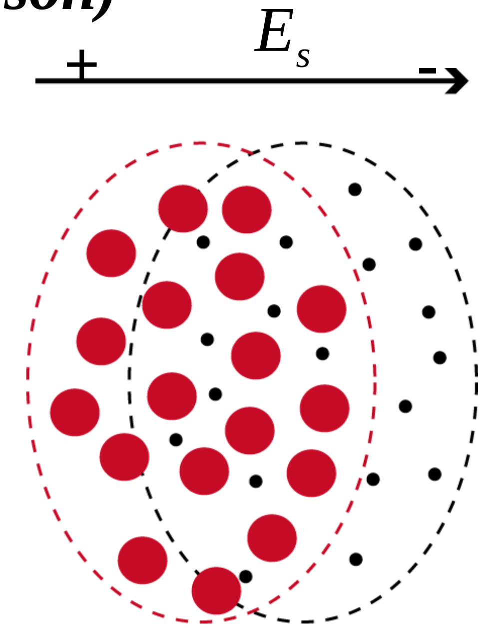
Ultra-relativistic intensity is defined with respect to the proton $E_Q=m_pc^2$, intensity~10^{24}W/cm^2

Relativistic Rectification

(Wake-Field Tajima, Dawson)



$$\vec{F}_{B_z} = q\left(\frac{\vec{v}}{c}\wedge\vec{B}\right)$$

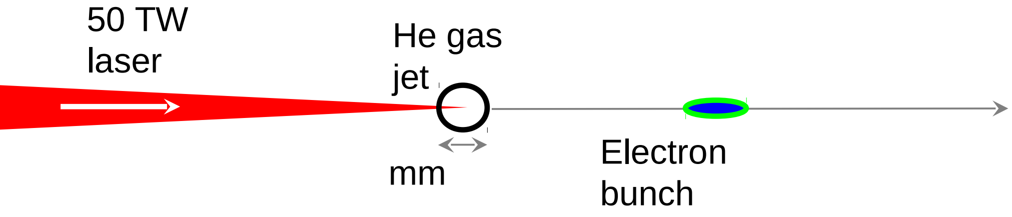


1) $\vec{v}\wedge\vec{B}$ pushes the electrons.

2) The charge separation generates an electrostatic longitudinal field. (Tajima and Dawson: Wake Fields or Snow Plough) $E_s = \frac{c\gamma m_o \omega_p}{e} = \sqrt{4\pi\gamma m_o c^2 n_e}$

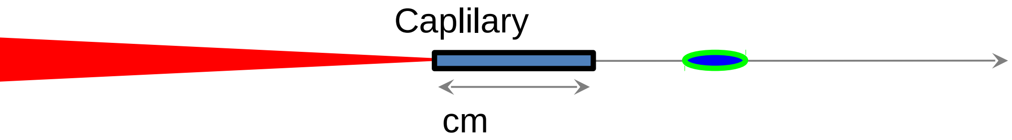
3) The electrostatic field $E_s \approx E_L$

Plasma wave acceleration : State of the art



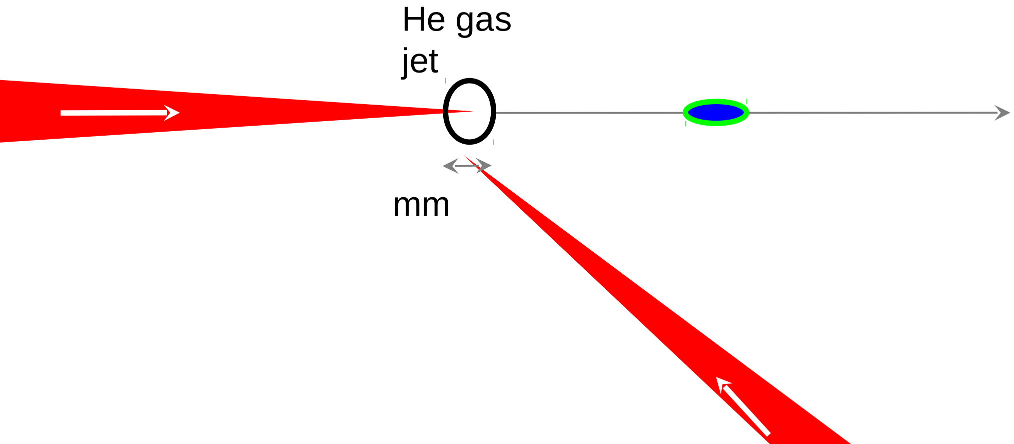
Energy: up to 200 MeV
Spectrum: Monochromatic or broadband
Charge: up to a few 100s pC
Divergence: a few mrad
Duration: fs

Faure et al., Nature 2004, Mangles et al, Nature 2004, Geddes et al, Nature 2004



Energy: up to 1 GeV
Spectrum: Monochromatic
Charge: up to a few 10s pC
Divergence: a few mrad
Duration: fs

Leemans et al, Nature Phys, 2006



Energy: up to 200 MeV
Spectrum: Monochromatic tunable
Charge: up to a few 10s pC
Divergence: a few mrad
Duration: fs

Faure et al, Nature, 2006

Goal ELI > 10 GeV

Secondary effects of electron acceleration:

X-rayBeam
(compact laser driven X-FEL, betatron radiation,..)

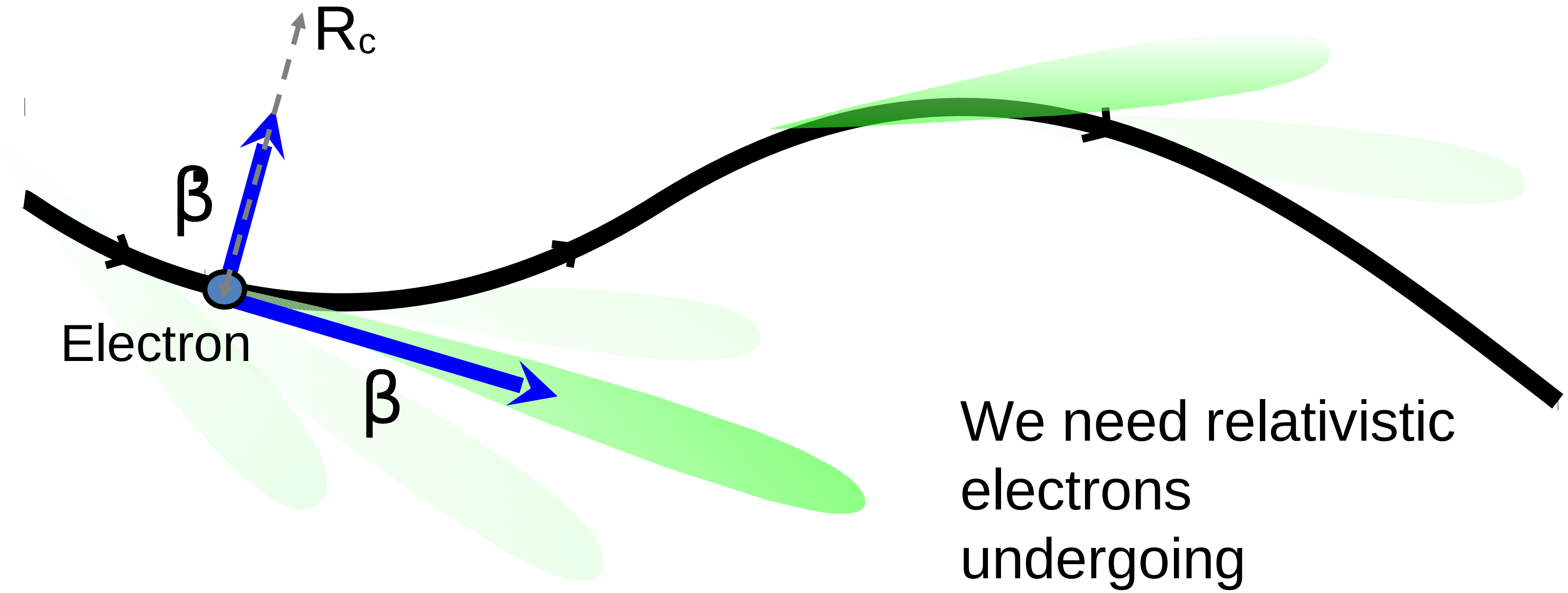
Moving charge radiation

Velocity

Acceleration

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c}\left|\int_{-\infty}^{+\infty} e^{i\omega[t-\vec{n}.\vec{r}(t)/c]}\frac{\vec{n}\times[(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}]}{(1-\vec{\beta}\,.\,\vec{n})^2}dt\right|^2$$

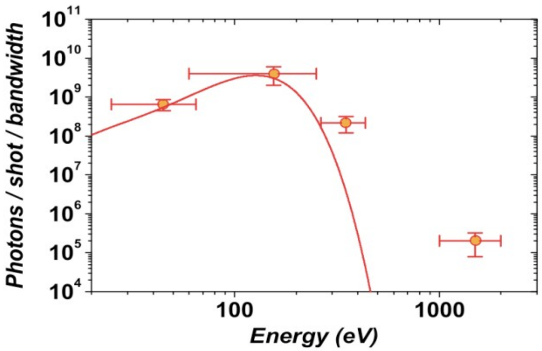
Radiated energy



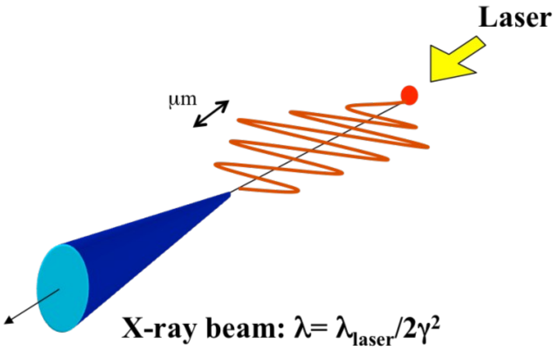
We need relativistic electrons undergoing oscillations

X-rays from relativistic e-beams : techniques

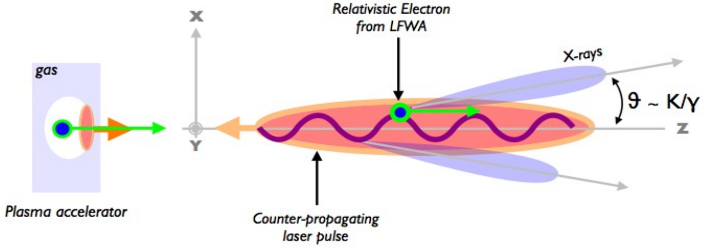
Non-linear Thomson scattering



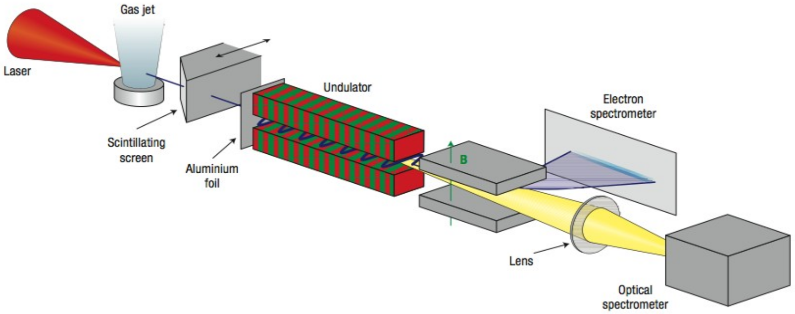
Betatron radiation



Thomson Backscattering

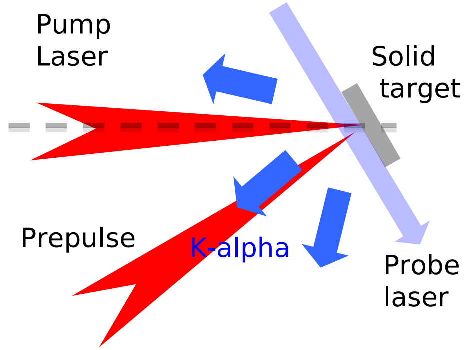


Classical undulator

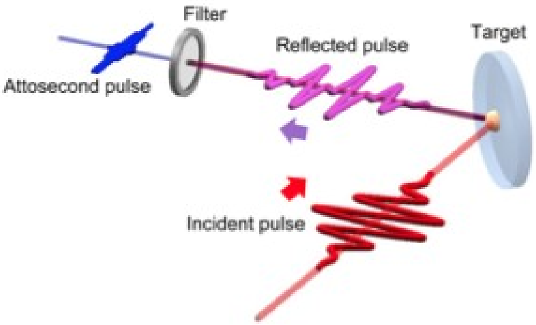


Laser-driven x-rays : several approaches

K-alpha emission

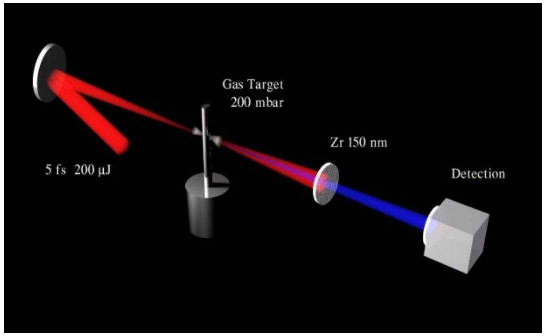


Harmonics (solid)

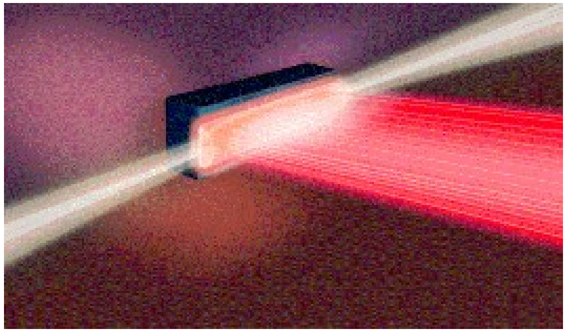


Relativistic mirror concept,
S. Bulanov.., PRL 2003

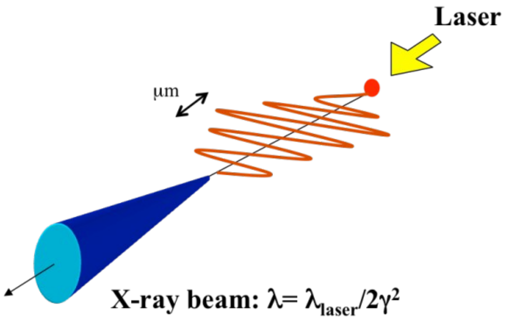
Harmonics (gas)



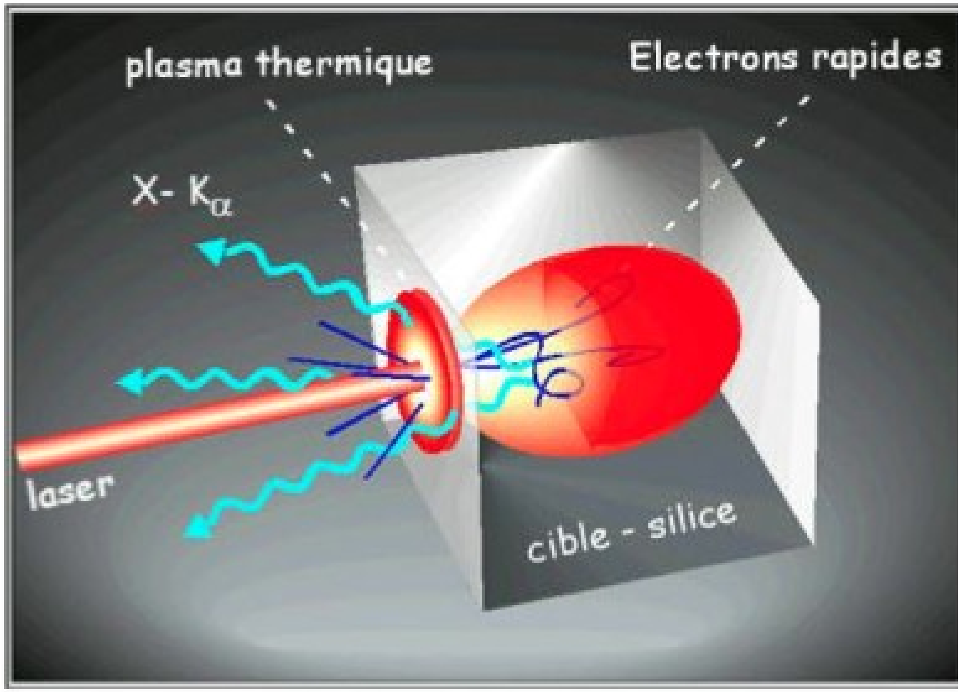
Plasma based x-ray lasers



X-rays from relativistic e-beams



K-alpha emission : easy and ultrafast x-ray source



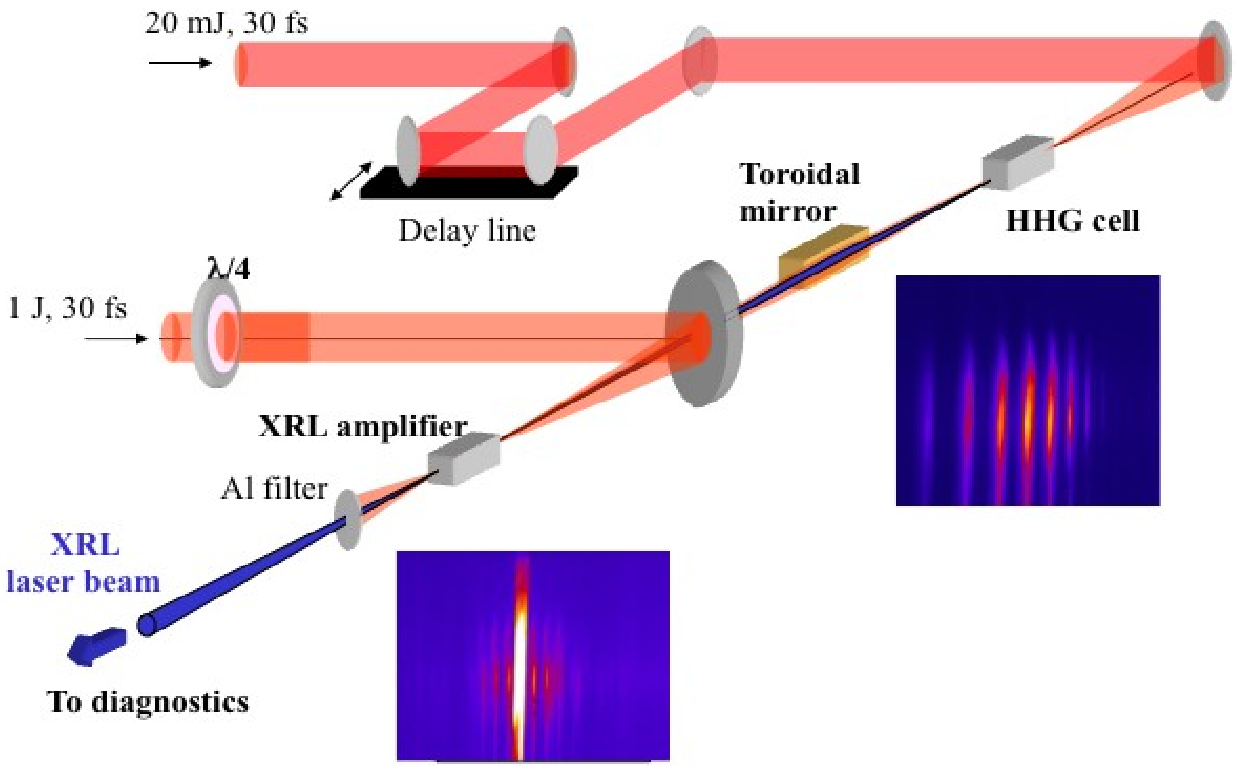
- Monochromatic
- Fully divergent
- Duration 100 fs
- KHz rep. rate
- Flux : 1e9 ph/shot

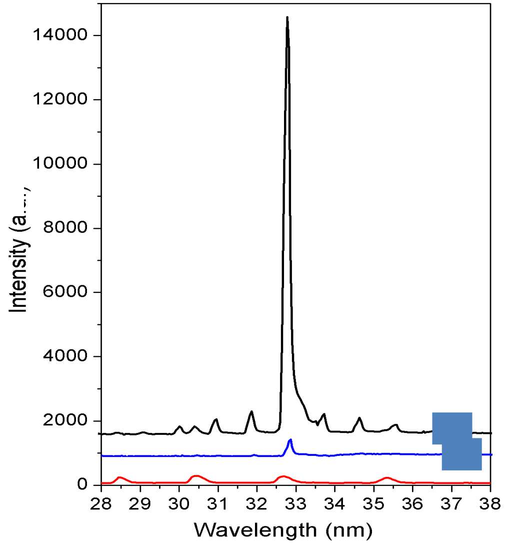
Main limitations : tunability, polychromaticity, divergence

Performances of HHG sources (gas)

	kHz, 1 mJ	**kHz, 100 mJ**
Wavelength	10 -60 nm	10 -60 nm
Photons/shot	10^7 to 10^9 at 10 Hz	few 10^{11} -10^{12}
$\Delta\lambda/\lambda$	10^{-2}	10^{-2}
Divergence	<1 mrad	<1 mrad
Spatial profil	Gaussian-like	Gaussian-like
Wavefront	$\lambda/10$	$\lambda/10$
Duration	Sub fs	Sub fs
Transverse coherence	High	High
Long. coherence	OK	OK
Polarization	Linear	Linear

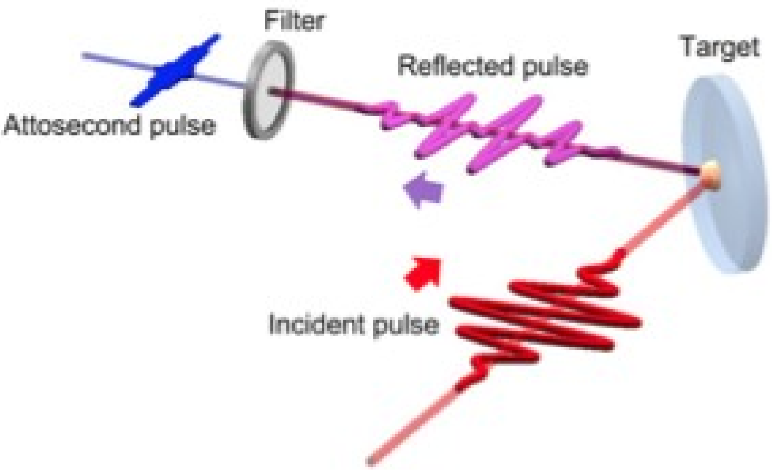
Seeded soft x-ray lasers : principle

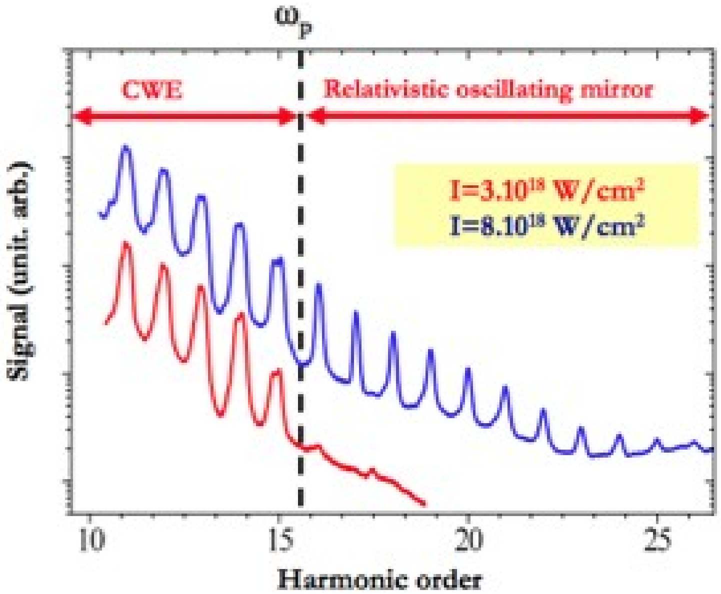


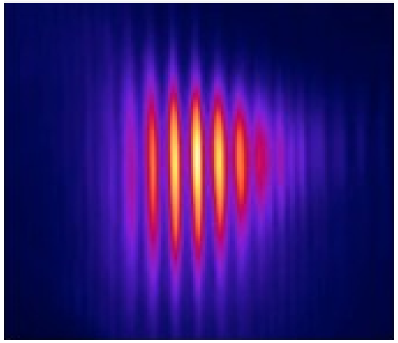


Harmonics from solid target plasma

S. V. Bulanov, T. Esirkepov, and T. Tajima, Phys. Rev. Lett. 91, 085001 (2003)







- Coherent and colimated down λ= 25 nm
- 10-20 µJ per pulse in H10-H12
- potentiality of attoseconde pulses (10^{-18} s)
- Potentialité de source kHz (démontré au LOA)

Harmonics from solids

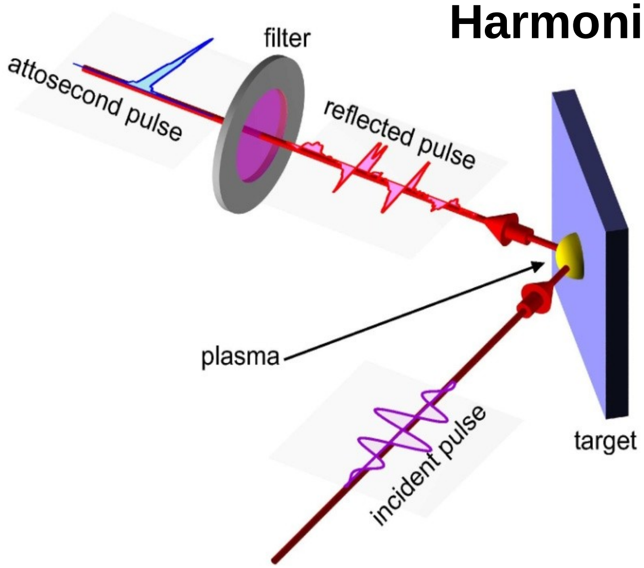


Fig. 1: *Schematic showing the proposed experimental configuration for the generation of attosecond pulses using*

Spectral range	Number of photons	Pulse duration
20-70 eV (Al filter)	$\sim 7 * 10^{15}$	~80 as
80-200 eV (Zr filter)	$\sim 2 * 10^{14}$	~40 as
400-1000 eV (Cu filter)	$\sim 2 * 10^{12}$	~5 as

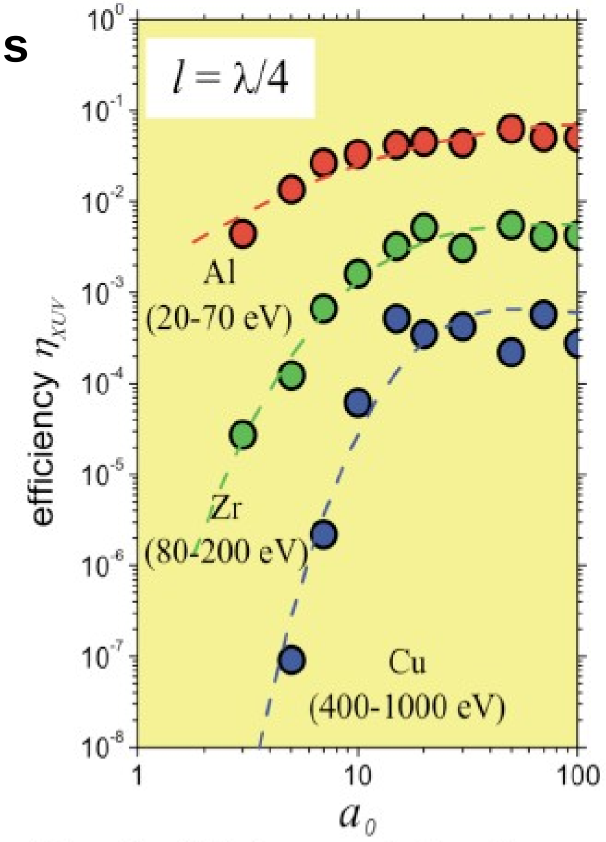
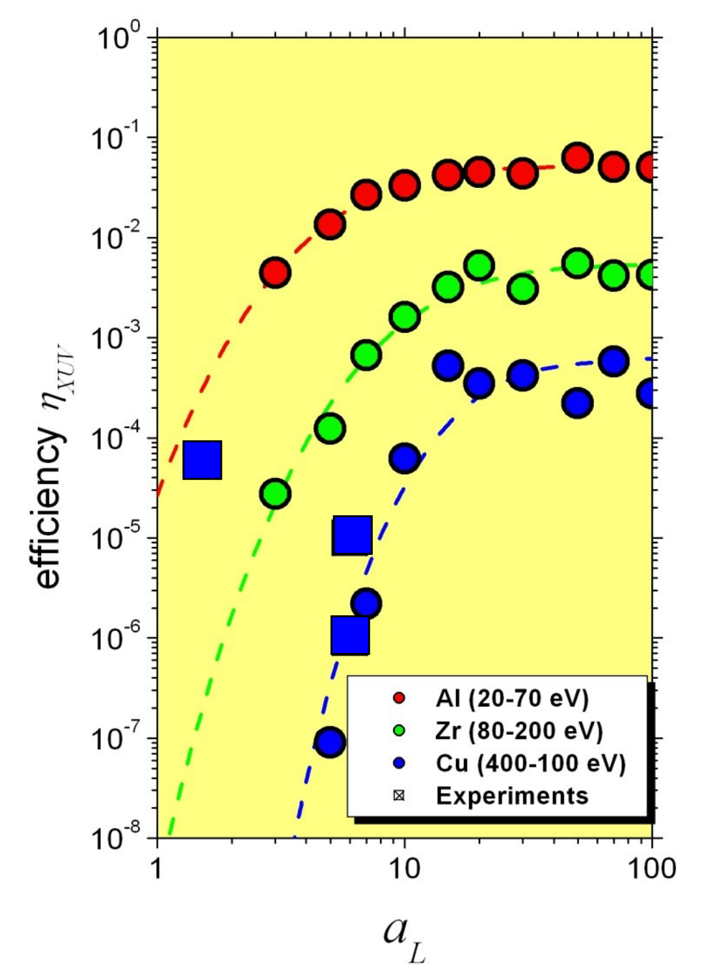


Fig. 3: *Efficiency of the laser into attosecond XUV pulse conversion as a function of the normalized field amplitude.*

Attosecond phase-locking of harmonics from laser dr. plasmas
Nature Physics 5, 124 - 128 (2009)



■ Y. Nomura *et al.*, Nature Phys. 5, 124 (2009)

■ B. Dromey *et al*, Nature Phys. 2, 456 (2006)

ELI front end unit: 1 J, 5 fs , 10 Hz

Focal spot d_s = 10 µm

I_L=2.5x10^{20} W/cm^2 ➔ a_L~11

Spectral range	**Number of photons**	**Pulse duration**
20-70 eV (Al filter)	**~7 *10^{15}**	**84 as**
80-200 eV (Zr filter)	**~2*10^{14}**	**38 as**
400-1000 eV (Cu filter)	**~2*10^{12}**	**5 as**

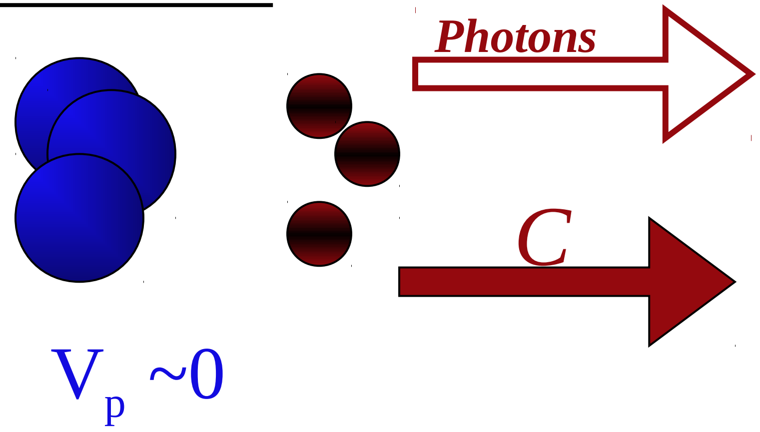
G. D. Tsakiris *et al.* New J. Phys. 8, 19(2006)

Secondary effects of electron acceleration:

Proton Acceleration

Relativistic Protons

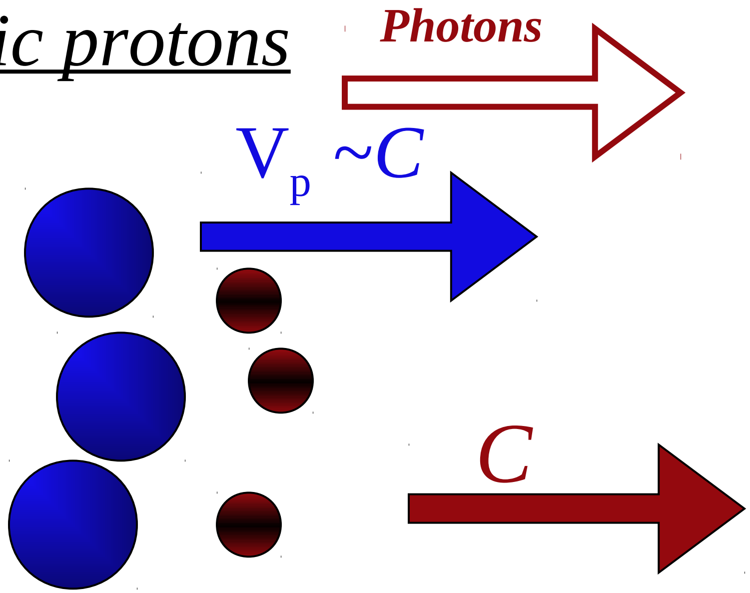
Non relativistic



$$E_p \sim I^{1/2}$$

Target Normal
SA

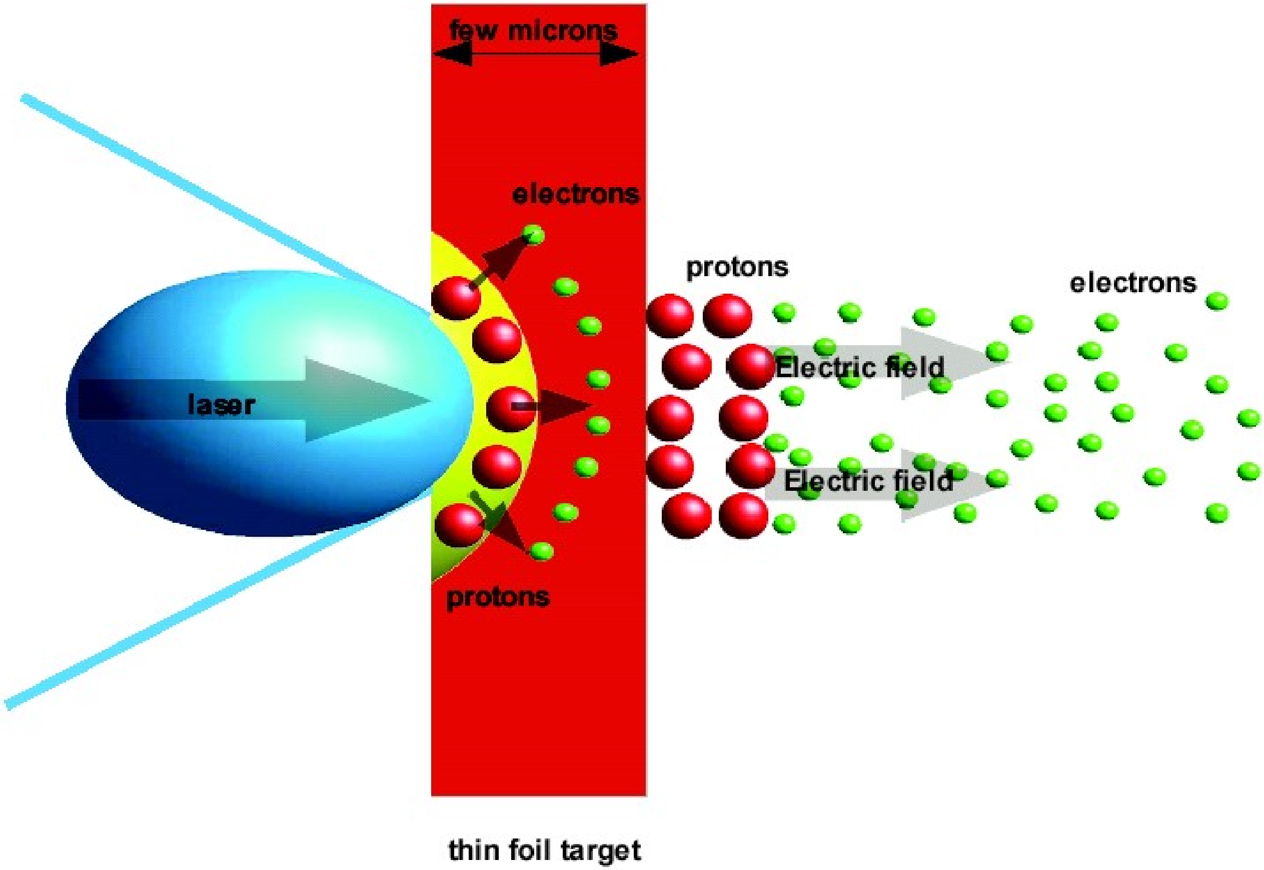
Relativistic protons



$$E_p \sim I$$

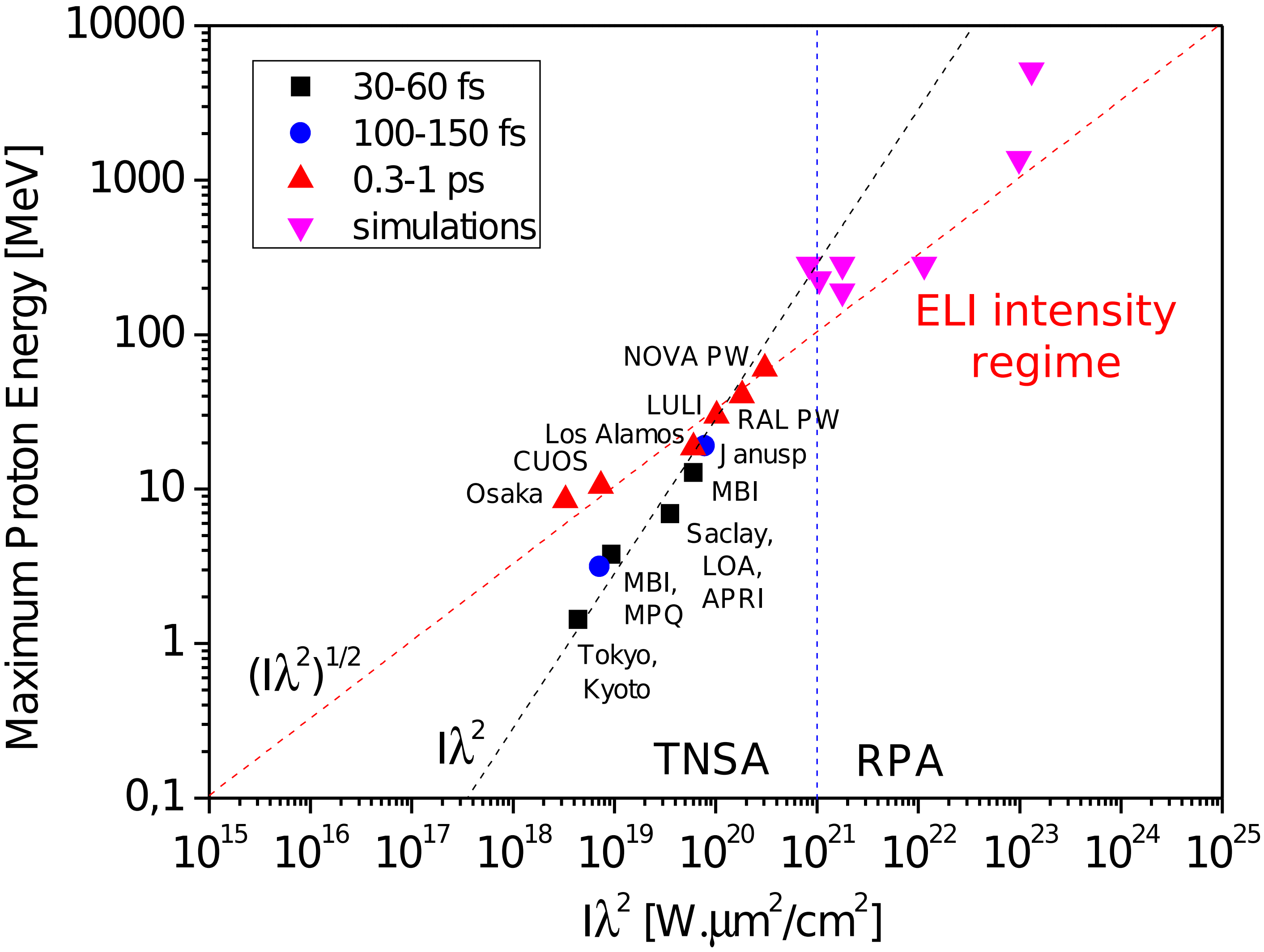
at very high intensitíes, light pressure accelerates
S. V. Bulanov …

Front and back acceleration mechanisms



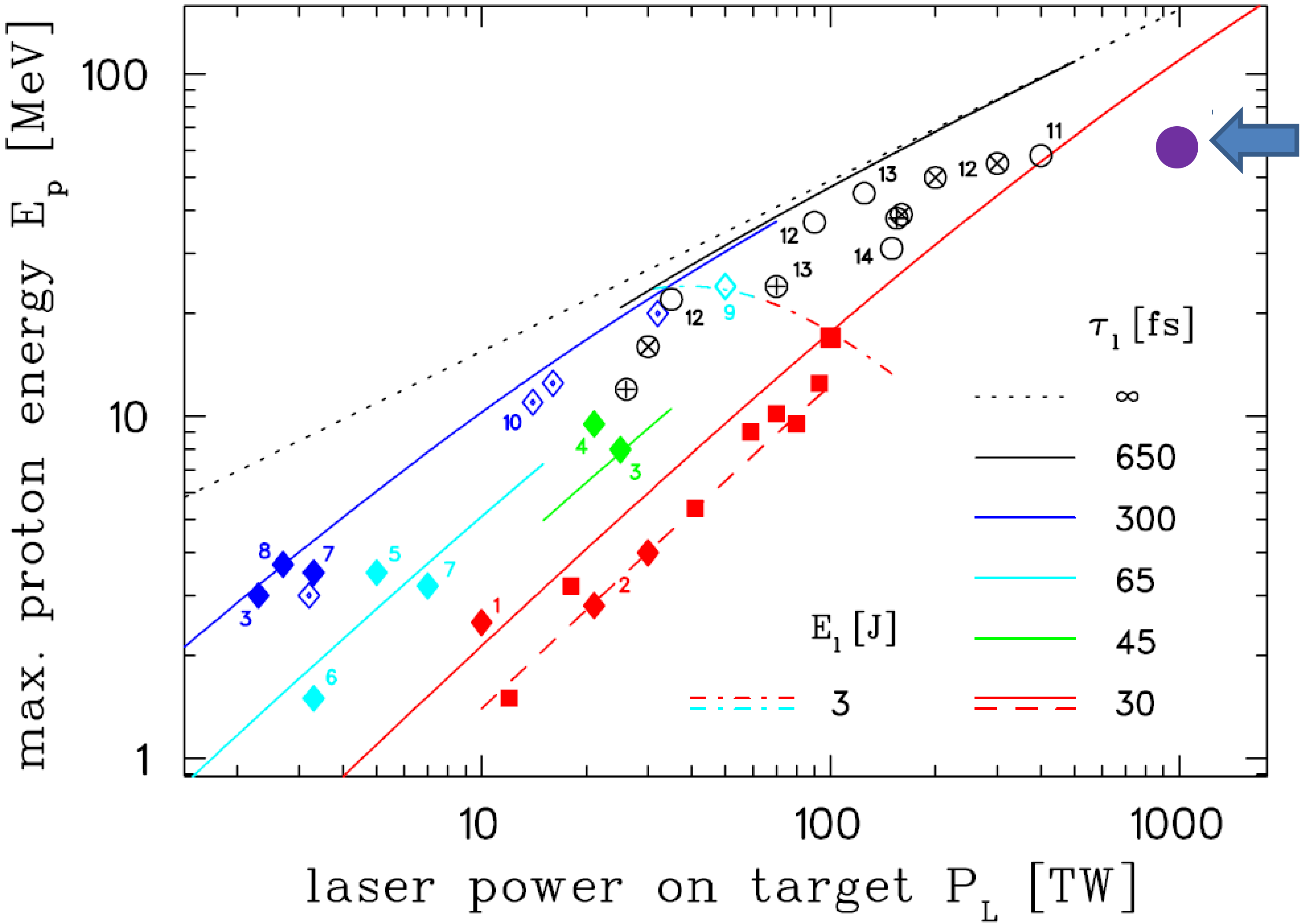
Peak energy scales as : $E_M \sim (I_L \times \neg\ )^{1/2}$

Proton acceleration scaling laws: experiment & theory



J. Fuchs et al., C. R. Physique 10 (2009) 176 and references therein

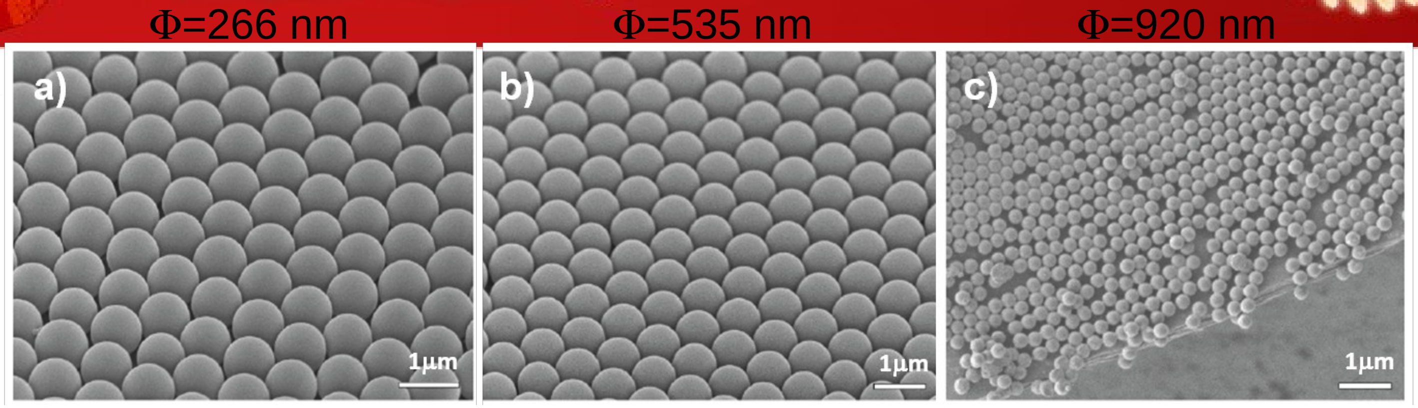
Proton acceleration scaling laws: TNSA experiments

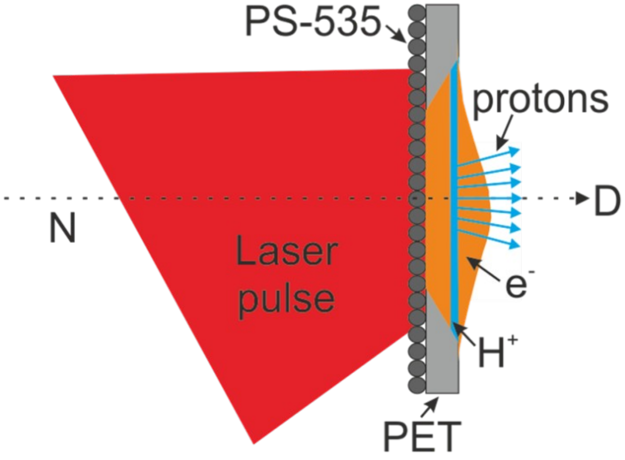


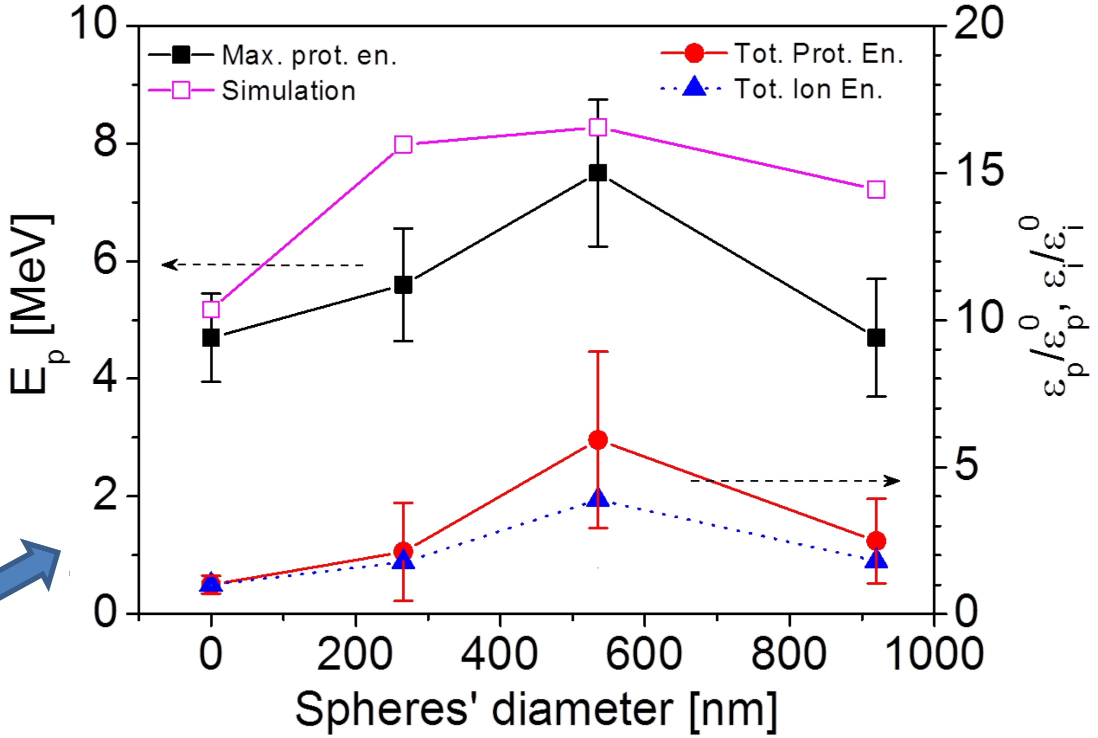
ELI-MED goal:
60 MeV
@ 1PW (10Hz)
~ 30fs

K. Zeil et al., New Journal of Physics 12 (2010) 045015

One way: enhanced TNSA by nanostructured thin foils







Laser: Ti:Sapphire @APRI-GIST
Power: 50 TW (on target)
Intensity: 5×10^{19} W/cm^2
Contrast: 10^{11} @1-ps

Another way: double-layer target in the Coulomb explosion regime

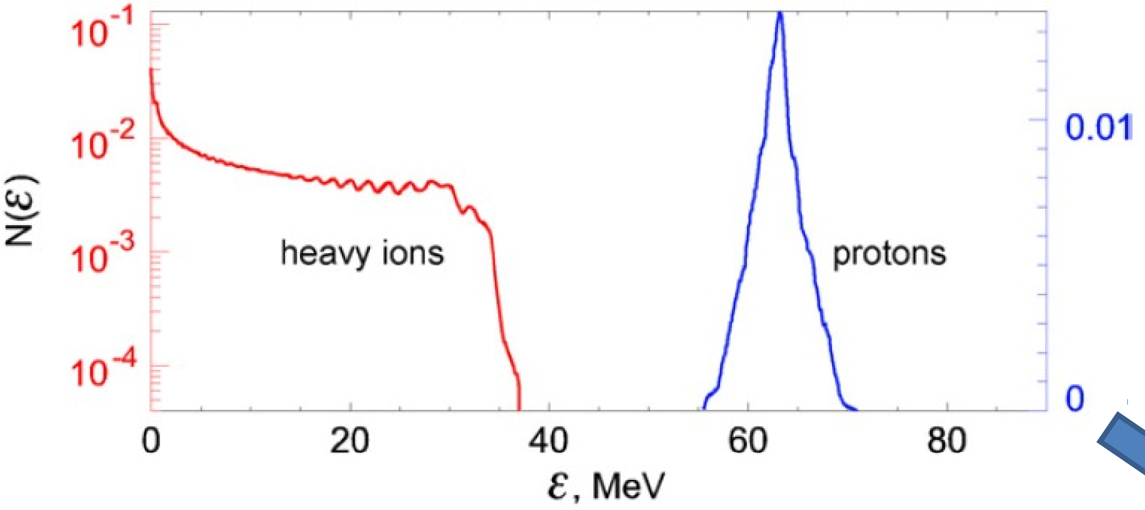


Figure 11. The proton (blue line) and heavy ion (red line) energy spectra at $t = 80 \times 2\pi/\omega_0$ from the 3D PIC simulations. The laser pulse is linearly polarized, $a_0 = 30$, $c\tau_0 = 15\lambda_0$, $r_0 = 12\lambda_0$, the incidence is normal. The mass-limited double-layer target consists of the first gold layer (a $10\lambda_0$ diameter disc with $l_1 = 0.5\lambda_0$, $m_\mathrm{i} = 195.4m_\mathrm{p}$, $Z_\mathrm{i} = 2$, $n_\mathrm{e1} = 9n_\mathrm{cr}$) and the second proton layer (a $5\lambda_0$ diameter disc with $l_2 = 0.03\lambda_0$, $n_\mathrm{e2} = 0.28n_\mathrm{cr}$). Reprinted with permission from Esirkepov *et al* (2002).

T. Esirkepov et al, Phys. Rev. Lett. 89 175003

H. Daido, M. Nishiuchi and A. Pirozhkov, Rep. Prog. Phys. 75 (2012) 056401

Energy requirement for eye tumor treatment!

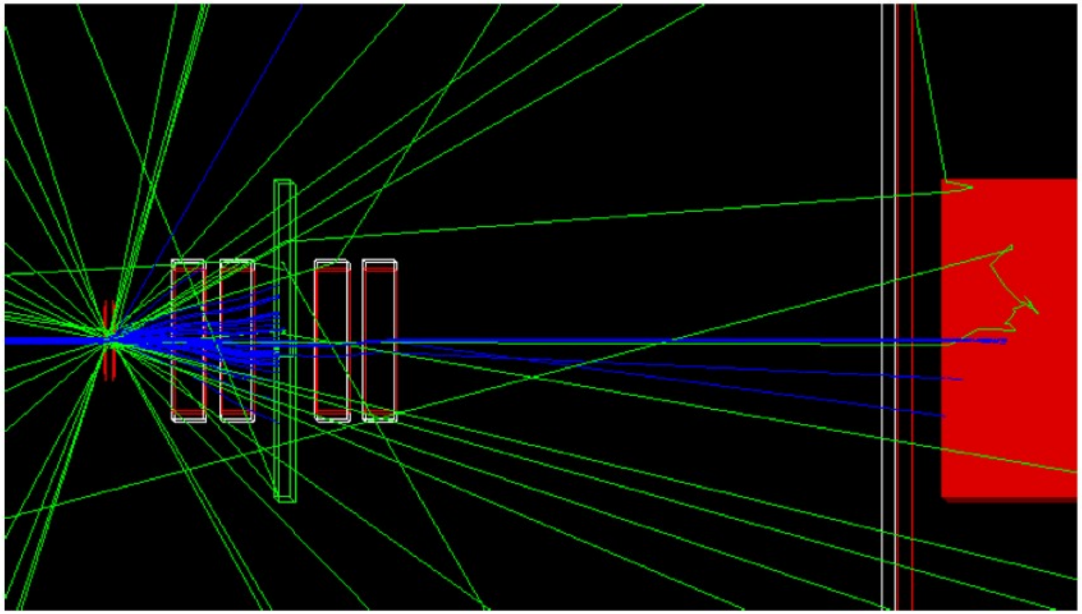
Preliminary experimental tests with our ultrathin double-layer targets performed @APRI-GIST have already shown **40 MeV in a recent campain** proton beams @ ~ **200 TW** laser power (on target)

ELI-MED:

Laser-driven proton beam transport and Monte Carlo simulations

Preliminary simulations of a possible particle selection system and first dosimetric studies

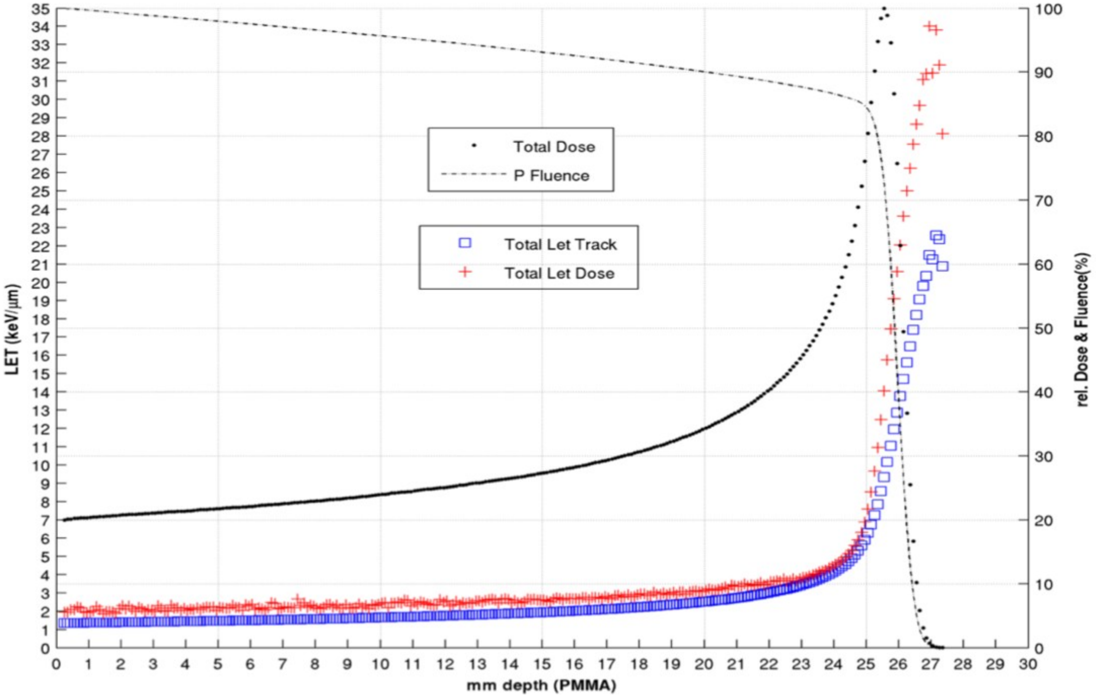
- Proton max energy up to 60 MeV
- Maximum energy spread 30% (in the first ELIMED phase)



- Gamma, neutrons production
- Any hadronic interaction can be taken into account
- Shielding evaluations
- Dose and biological effects evaluations

ELI-MED: dedicated Monte Carlo software tools in development

- Simulations for the design and optimisation of the in-air transport beam line (before the irradiation point)
- Dose distributions calculation (from primary beam and unwanted secondary radiations) at the irradiation point
- LET and RBE estimations



Example of fluence (dash), dose (dot) and LET (red and blue crosses) distributions in water calculated for a 60 MeV proton beam with the Monte Carlo tool dedicated to ELIMED

Strong Field Limits in the Ultra-Relativistic Interaction of Electrons with Electro-Magnetic Waves in Plasmas

Fundamental intensity dependent regimes of interaction

Amplitude $a_0 = \left[\frac{eE_0}{m_e c\omega}\right]$	Intensity $\left[\frac{W}{cm^2}\right]$	Regime
$a_{QED} = \frac{m_e c^2}{\hbar\omega}$	2.4×10^{29}	e^+, e^- in vacuum
$a_{QM} = \frac{2e^2 m_e c}{3\hbar^2\omega}$	5.6×10^{24}	quantum effects
$a_p = \frac{m_p}{m_e}$	1.3×10^{24}	ultra - relativistic p
$a_{rad} = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3}$	1×10^{23}	radiation damping
$a_{rel} = 1$	1.3×10^{18}	relativistic e^-

$$e\lambda E_{rel} = m_e c^2$$

$$e\lambda E_{ultrarel} = m_p c^2$$

$$e\lambda_{comp} E_{rel} = m_e c^2$$

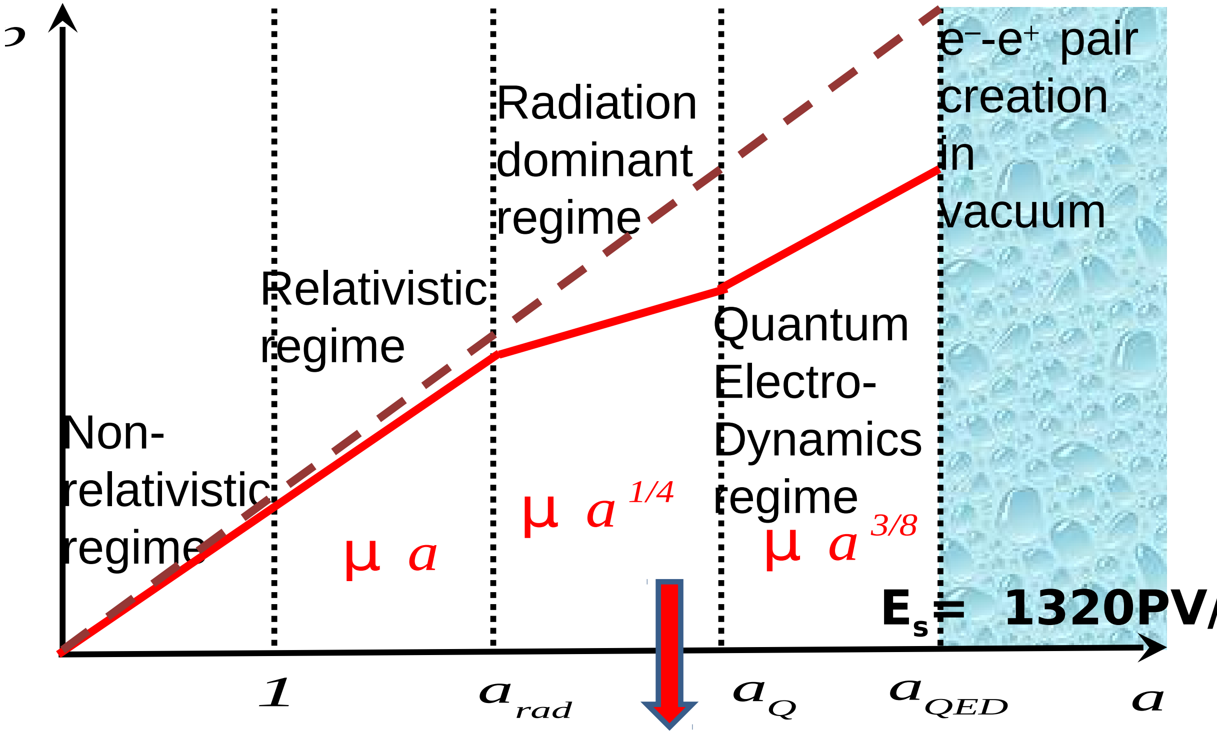
$$\lambda_{comp}(electron) = 2.4x10^{-6}\,\mu m$$

$$E_0[\mathrm{V/cm}] = 19\sqrt{I[\mathrm{W/cm^2}]}$$

Very compact accelerators can be built

SUMMARY of Laser-Plasma Interaction in "Radiation-Dominant" Regimes

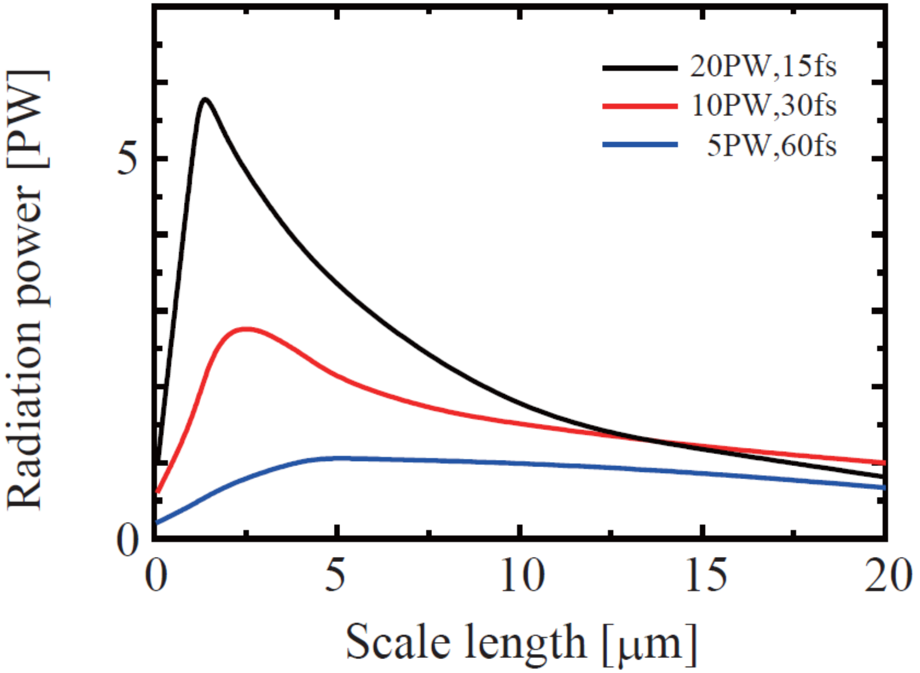
Amplitude $\left[a_0 = \frac{eE_0}{m_e c\omega}\right]$	Intensity $\left[\frac{\text{W}}{\text{cm}^2}\right]$	Regime
$a_{QED} = \frac{m_e c^2}{\hbar\omega}$	2.4×10^{29}	e^+,e^- in vacuum
$a_{QM} = \frac{2e^2 m_e c}{3\hbar^2\omega}$	5.6×10^{24}	quantum effects
$a_p = \frac{m_p}{m_e}$	1.3×10^{24}	ultra - relativistic p
$a_{rad} = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3}$	1×10^{23}	radiation damping
$a_{rel} = 1$	1.3×10^{18}	relativistic e^-



Currently
I_{max} = 10^{22} W/cm²
ELI will be pushing the limits by more than 1-2 orders but we

$a_{rad}^{c} = 408$ γ = 70 MeV

Ultrarelativistic ELI
a_0 > 2000, E= 4 PV/m

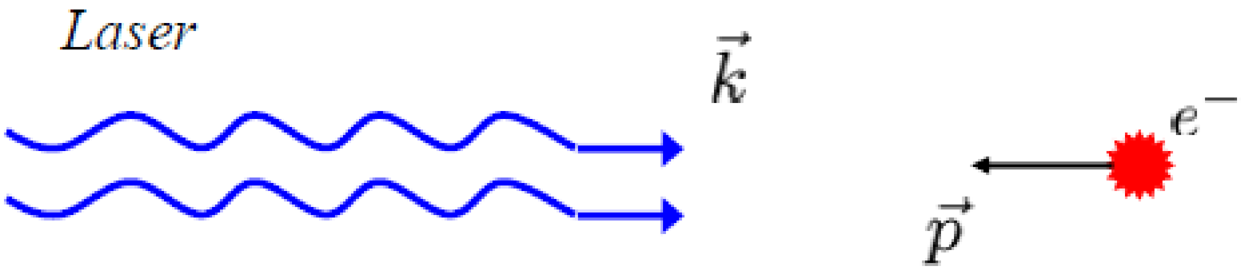


Dependence of the gamma-ray power (PW) on the plasma scale length, L ( ) for the laser pulse energy of 300 J and the laser power, , varying from 5 to 20 PW

Tatsufumi Nakamura[a], James K. Koga[a], Timur Zh. Esirkepov[a], Masaki Kando[a], Georg Korn[b,c], Sergei V. Bulanov[a,d], PRL April 2012

Laser-induced Nonlinear QED

For head-on collision at laboratory reference frame:



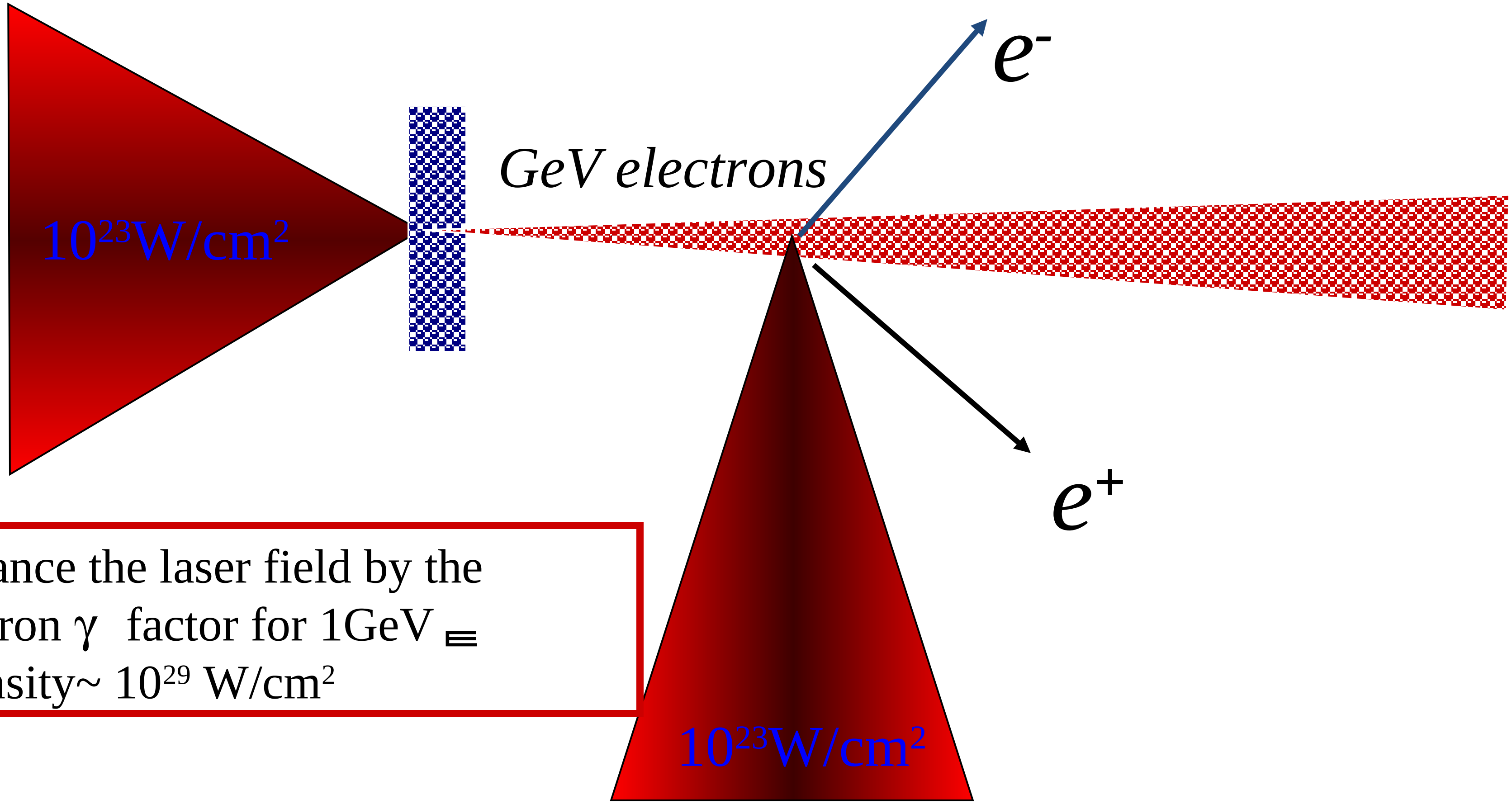
$$E_R = E_L\sqrt{\frac{1+v/c}{1-v/c}}, \qquad v = pc/\varepsilon$$ - electron velocity

for ultrarelativistic particle $1 - v/c \ll 1$, or

$$\gamma = \frac{1}{\sqrt{1-v^2/c^2}} = \varepsilon/mc^2 \gg 1 \qquad E_R \approx 2\gamma E_L$$

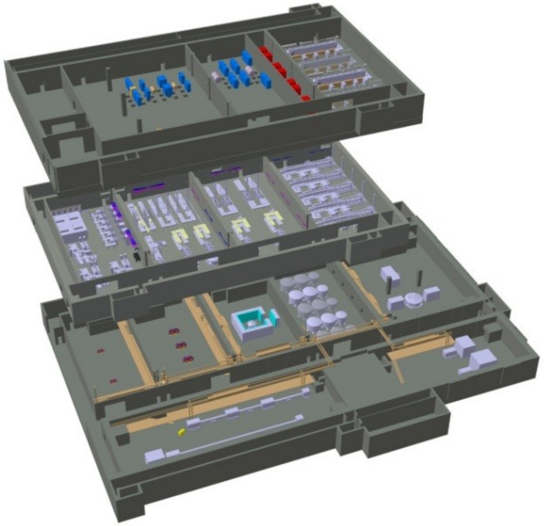
Laser-induced Nonlinear QED

$$e^- + \omega \rightarrow e^{-'} + e^+ e^-$$



enhance the laser field by the electron γ factor for 1GeV ≡ Intensity~ 10^{29} W/cm^2

Outline of the ELI-Beamlines facility



B. Rus, F. Batysta, J. Čáp[2], M. Divoký, M. Fibrich, M. Griffiths, R. Haley[3], T. Havlicek, J. Hrebicek, P. Homer,
P. Hribek, J. Jandourek, L. Juha, G. Korn [4], P. Korouš, M. Košelja, M. Kozlová, D. Kramer, M. Krus,
J.C. Lagron [4], J. Limpouch[6], L. McFarlane[3], M. Malý, D. Margarone, P. Matlas, L. Mindl, J. Moravec [7],
T. Mocek, J. Nejdl, J. Novák, V. Olšovcová, M. Palatka [8], J.P. Perin [9], M. Pešlo, J. Polan, J. Prokupek,
K. Rohlena, M. Sawicka, L. Scholzová, D. Snopek[2], P. Strkula, L. Švéda[2]

Project background and status

ELI-Beamlines mission, Prague

Generation of femtosecond secondary sources of radiation and particles

- XUV and X-ray sources (monochromatic and broadband);
    plasma based x-ray lasers and amplified HHG (100 µJ – 10 mJ)
- Accelerated electrons (2 GeV 10 Hz rep-rate, >10 GeV low rep-rate),
    protons (trying to enter 50-70 MeV 10 Hz rep-rate, >1 GeV low-rep-rate)
- ELI Betatron beamline
- preparation for a future laser driven, LUX and later X-FEL
- Gamma-ray sources (broadband); entering the radiation driven regime

Programmatic applications of the femtosecond secondary sources

- Medical research including proton therapy (1 PW-Laser, 10 Hz), detectors time, spat. res
- Molecular, biomedical and material sciences
- Physics of dense plasmas, WDM, laboratory astrophysics (radiographic images)

High-field physics experiments with focused intensities 10^{22}-10^{24} Wcm^{-2}

- Exotic plasma physics (e.g. electron-positron pair plasma), non-linear QED
  proton and electron acceleration at high intensities and high energies, careful studies of
  different intensity regimes, proof of achieved intensities and the corresponding interacti

Participation in prototyping technologies for the high-intensity pillar

Compression & coherent superposition of multi-10-PW ultrashort pulses (>100 PW far fut

Science Case in the ELI-Beamline

ELI-Beamlines bid: balance between fundamental science and applications

ELI-Beamlines will be international user facility, partnership experiments & projects

Research Program 1
Lasers generating rep-rate ultrashort pulses & multi-petawatt peak powers

Research Program 2
X-ray sources driven by rep-rate ultrashort laser pulses,

Research Program 3
Particle acceleration by lasers , MED-ELI

Research Program 4
Applications in molecular, biomedical, and material sciences

ogram 5
a and high-energy-density physics (PALS kJ laser synchronized to 40 TW laser)

rch Program 6
eld physics and theory (steps to 10^{23}W/cm^2, radiation reaction plays role)

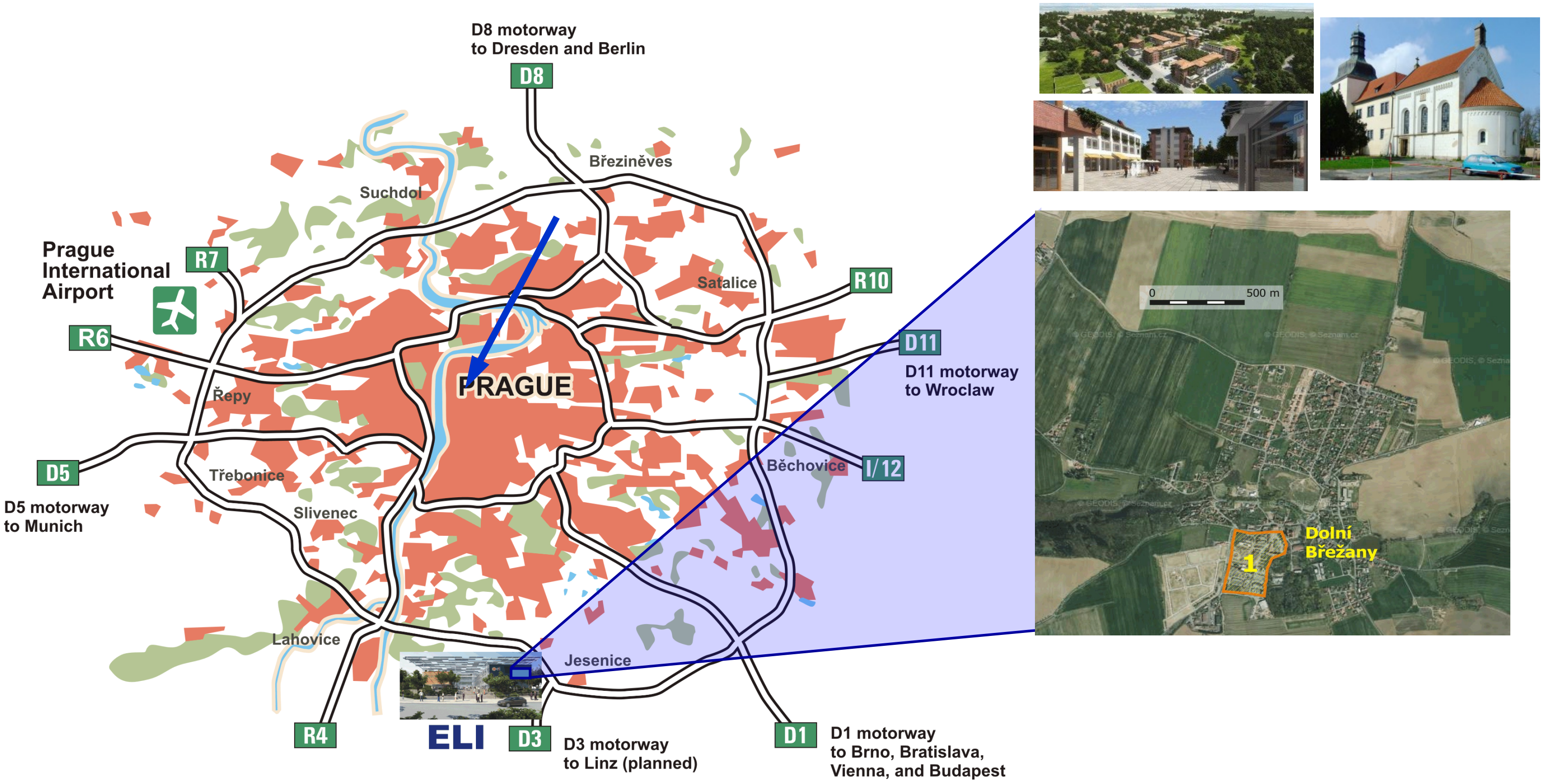
ELI Beamlines budget and steps towards funding

Total investment: 265 mil. Euro, Structual funds (85% EU, 15%-State)

Timeline:

Nov 12, 2009	Submission of ELI-Beamlines bid into the national funding call ("Research & Development for Innovations")
Feb 2010	ELI-Beamlines bid assessed by the national expert panel (industrial applications, national synergies, financial sustainability)
March 19, 2010	ELI-Beamlines bid assessed by the international expert panel (quality of research, quality of management, human resources strategy)
May 20, 2010	National negotiations on funding successfully concluded
June 28, 2010	Project receives OK note by JASPERS (Joint Assistance to Support Projects in European Regions)
June 30, 2010	**Request for funding submitted to EC**
Sept 13, 2010	Construction permit to build ELI-Beamlines issued
Dec 2010	Project approved by EC's DG Research, DG Regio and DG Environ, additional issues raised by DG Competition
Feb 2011	Project approved by EC's DG Competition

ELI-Beamlines location: South of Prague



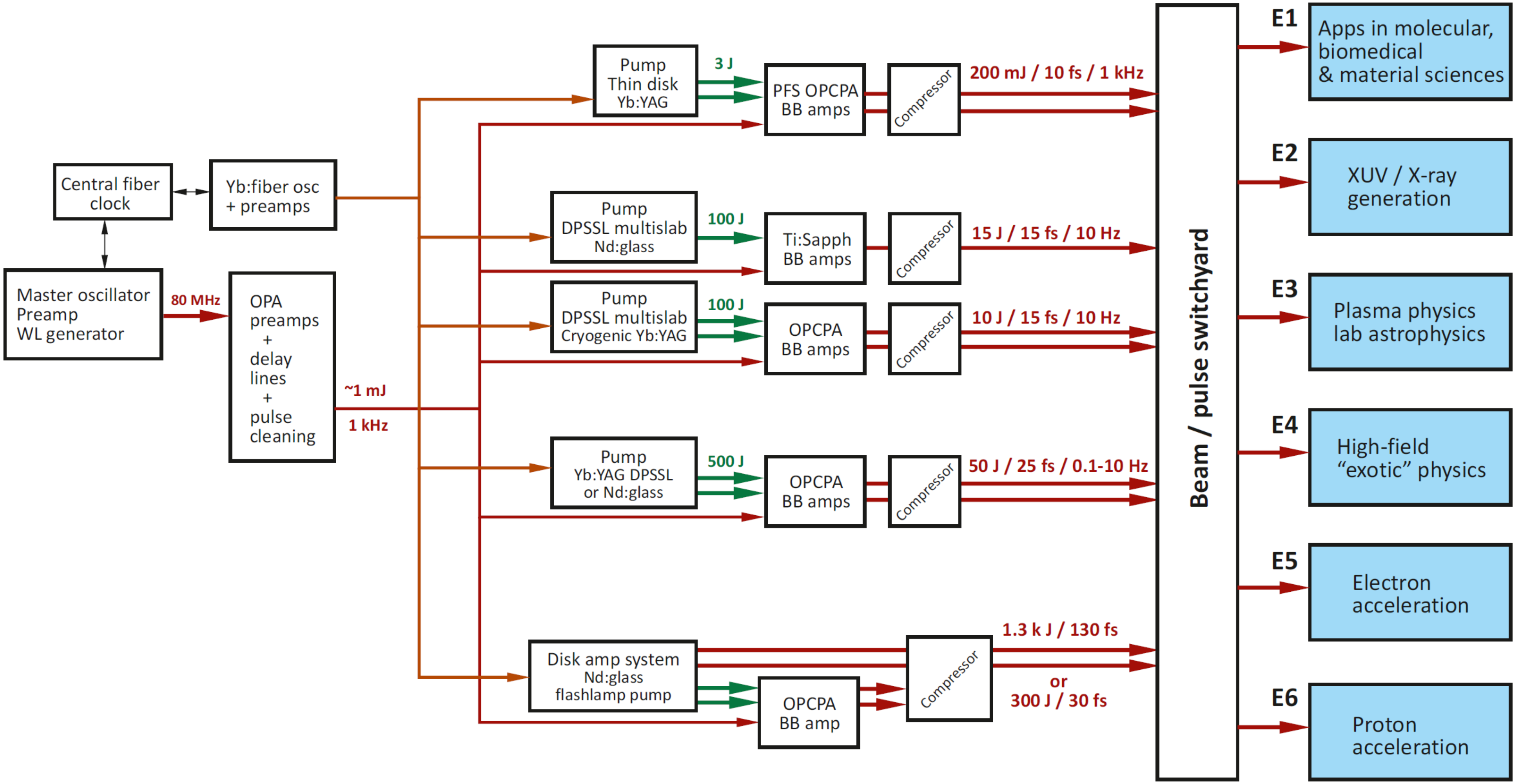
- Proximity of international airport (15 min drive), enjoyable surroundings, behind the border of Prague (funding issuses)
- Synergy with planned large biotechnology center BIOCEV (2 km distance)
- Direct connection to Prague outer ring and the European motorway network

2. Laser and experimental facilities

ELI Beamlines facility laser

Laser system

Exp. areas



Central fiber clock

Yb:fiber osc + preamps

Master oscillator
Preamp
WL generator

80 MHz

OPA preamps + delay lines + pulse cleaning

~1 mJ

1 kHz

Pump
Thin disk
Yb:YAG

3 J

PFS OPCPA
BB amps

Compressor

200 mJ / 10 fs / 1 kHz

Pump
DPSSL multislab
Nd:glass

100 J

Ti:Sapph
BB amps

Compressor

15 J / 15 fs / 10 Hz

Pump
DPSSL multislab
Cryogenic Yb:YAG

100 J

OPCPA
BB amps

Compressor

10 J / 15 fs / 10 Hz

Pump
Yb:YAG DPSSL
or Nd:glass

500 J

OPCPA
BB amps

Compressor

50 J / 25 fs / 0.1-10 Hz

Disk amp system
Nd:glass
flashlamp pump

OPCPA
BB amp

Compressor

1.3 k J / 130 fs

or

300 J / 30 fs

Beam / pulse switchyard

E1 Apps in molecular, biomedical & material sciences

E2 XUV / X-ray generation

E3 Plasma physics lab astrophysics

E4 High-field “exotic” physics

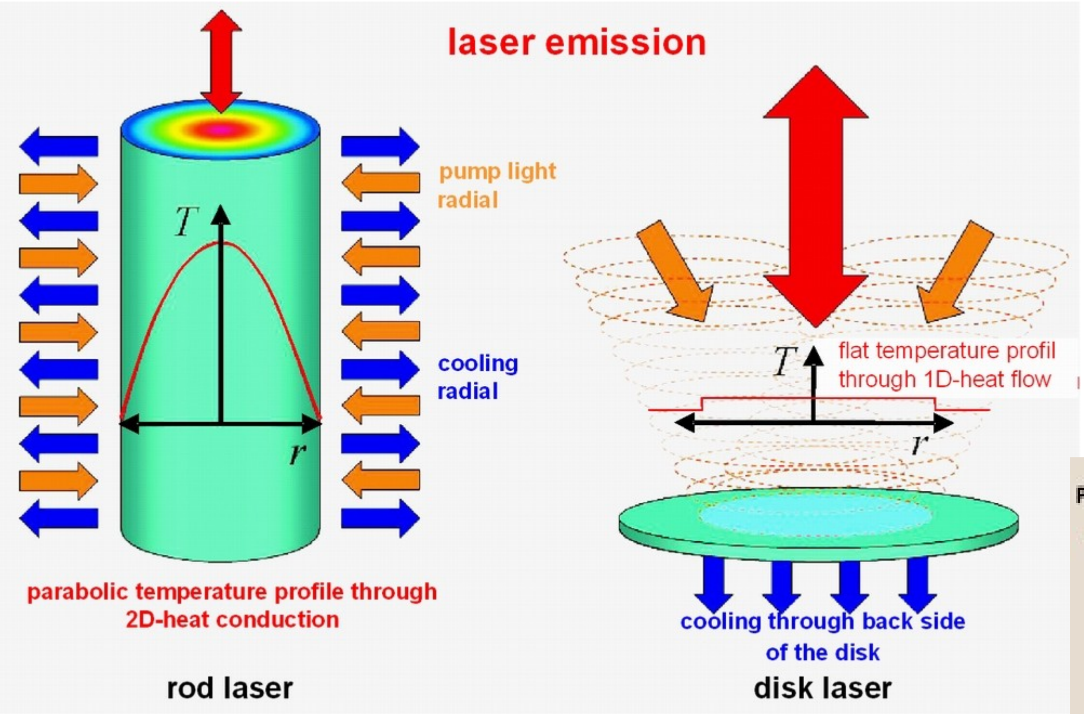
E5 Electron acceleration

E6 Proton acceleration

L1– thin disk technology

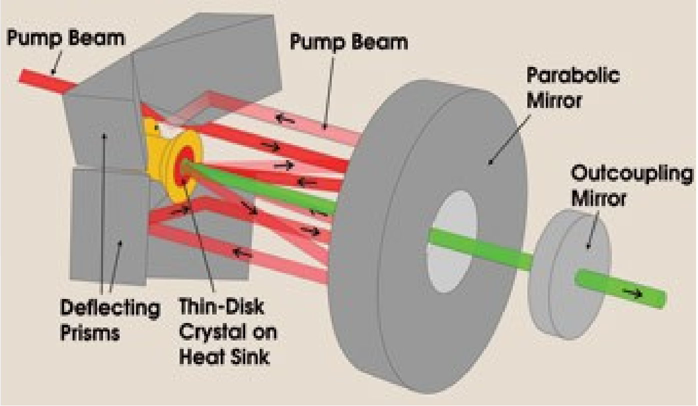
Enabling kHz repetition rates and high pulse energies

L1 pump lasers need to reach 1.5 J/pulse at 1kHz repetition rate and 2 ps pulse duration



Disk parameter
thickness: 100 - 900 µm

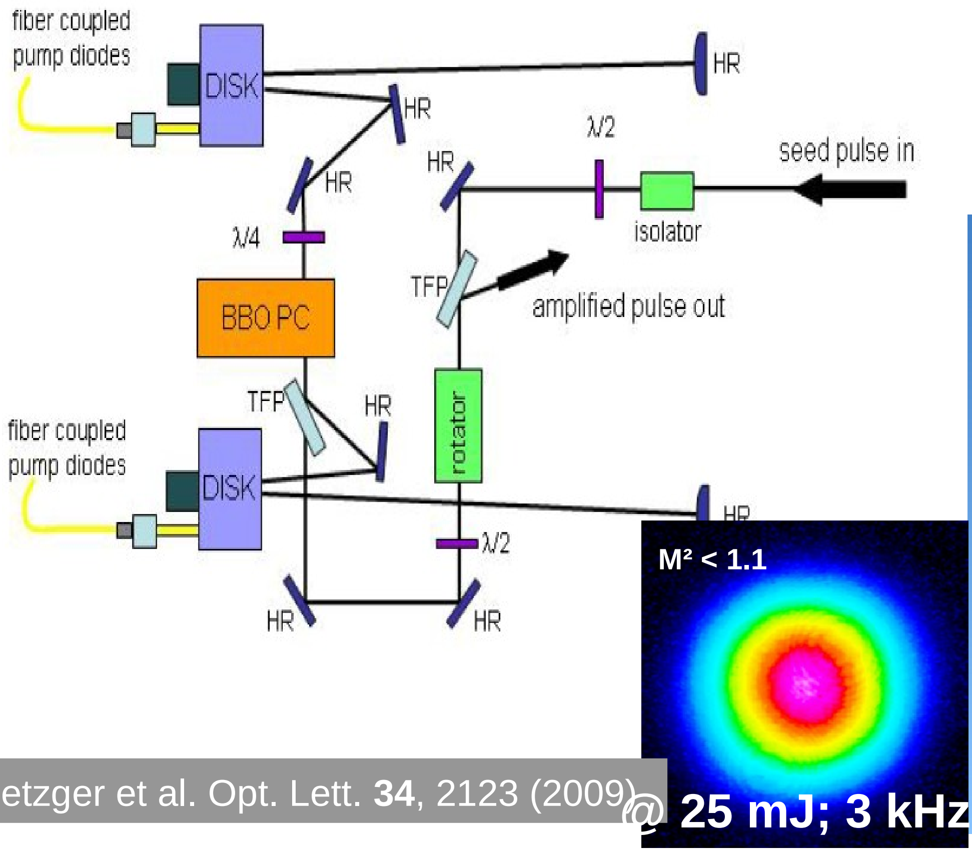
diameter: 10 - 35 mm



Thomas Metzger, MPQ
500 W achieved with short 1.5 ps pulses

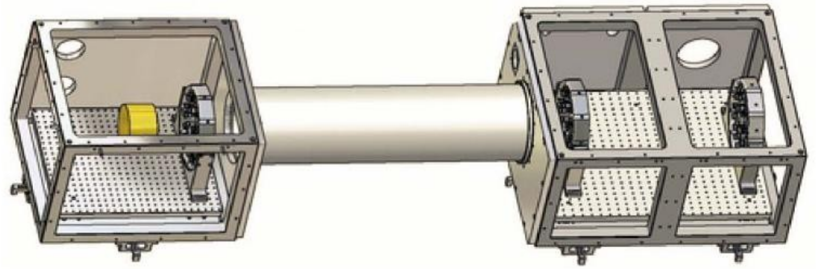
L1: Thin disk :Pump laser 1030 nm

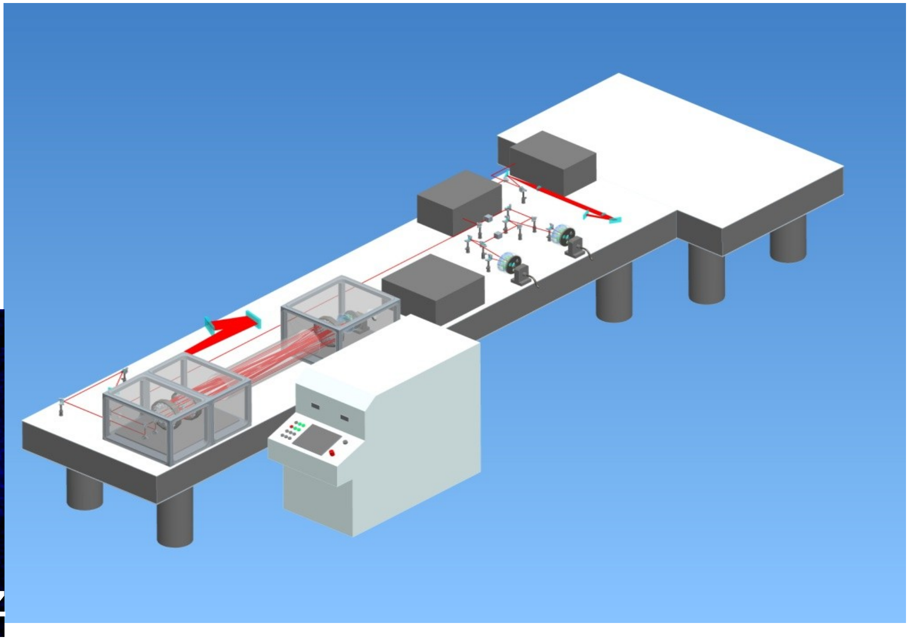
Regenerative amplifier



Metzger et al. Opt. Lett. **34**, 2123 (2009)

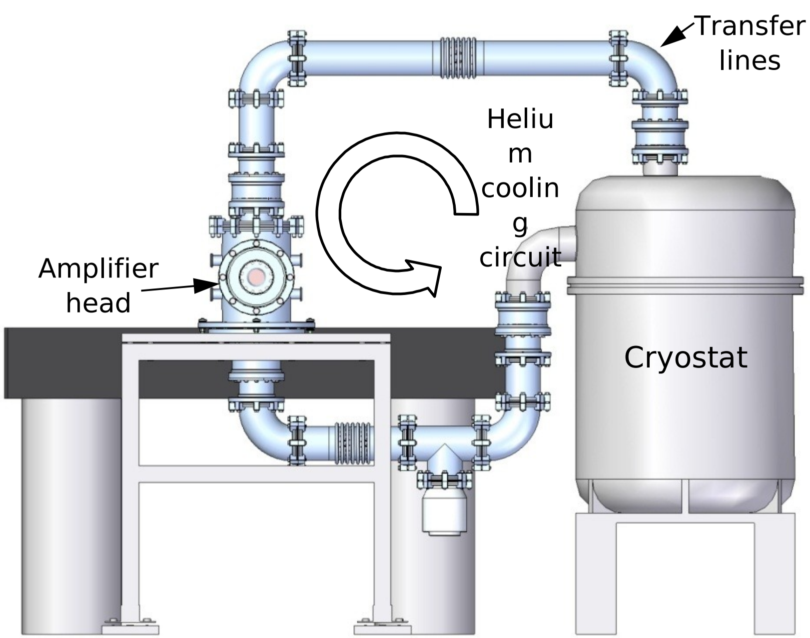
Multipass amplifier

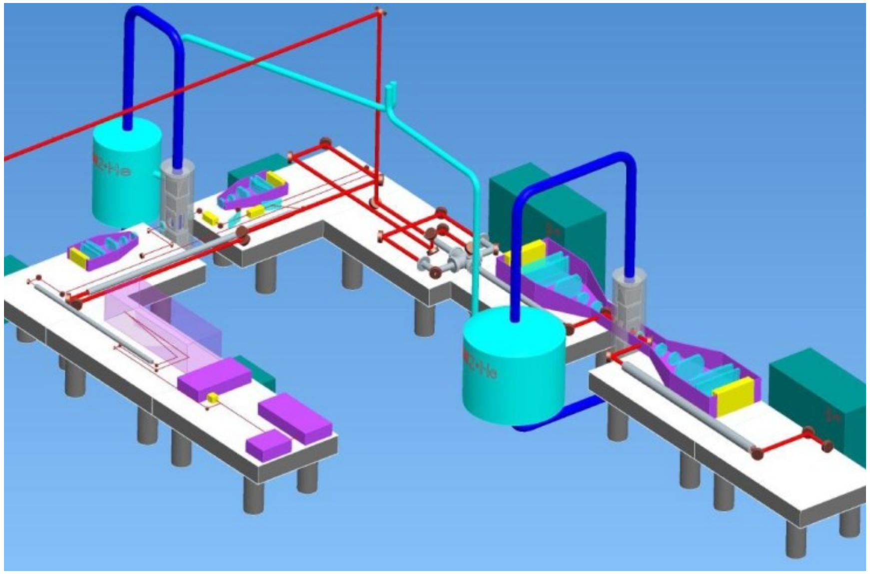




L2 : Cryo cooled multislab Yb:YAG

Development of cryogenic Yb:YAG amplifier technology at RAL/STFC essential for ELI-Beamlines
ELI-Beamlines & HiLASE project : cooperation on development of Yb:YAG technology



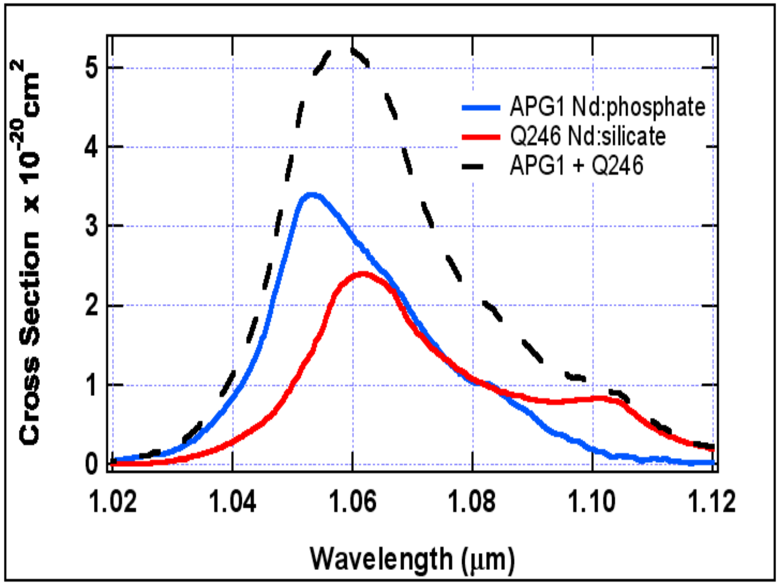


Study of layout of a Yb:YAG 100 J system for ELI-Beamlines and HiLASE
According to RAL/STFC (courtesy of K. Ertel and J. Collier)

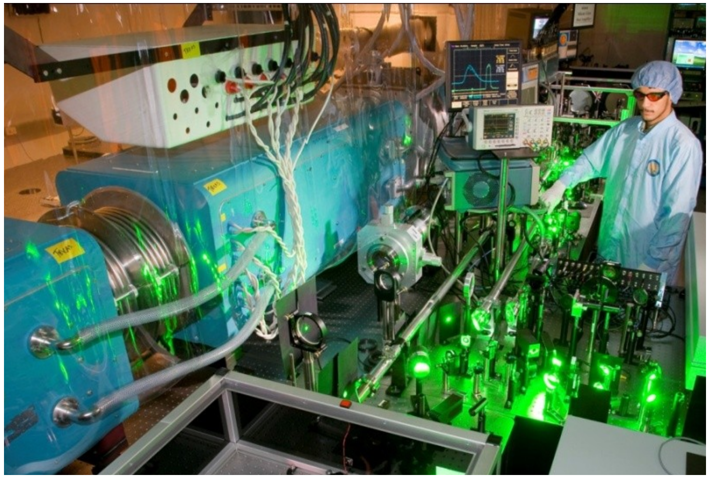
L4 (10PW): mixed glass system

Mixed glass technology: high energy & bandwidth equivalent to <130 fs FWHM *

Nd:phosphate glass 1053.9 nm
Nd:silicate glass 1061 nm



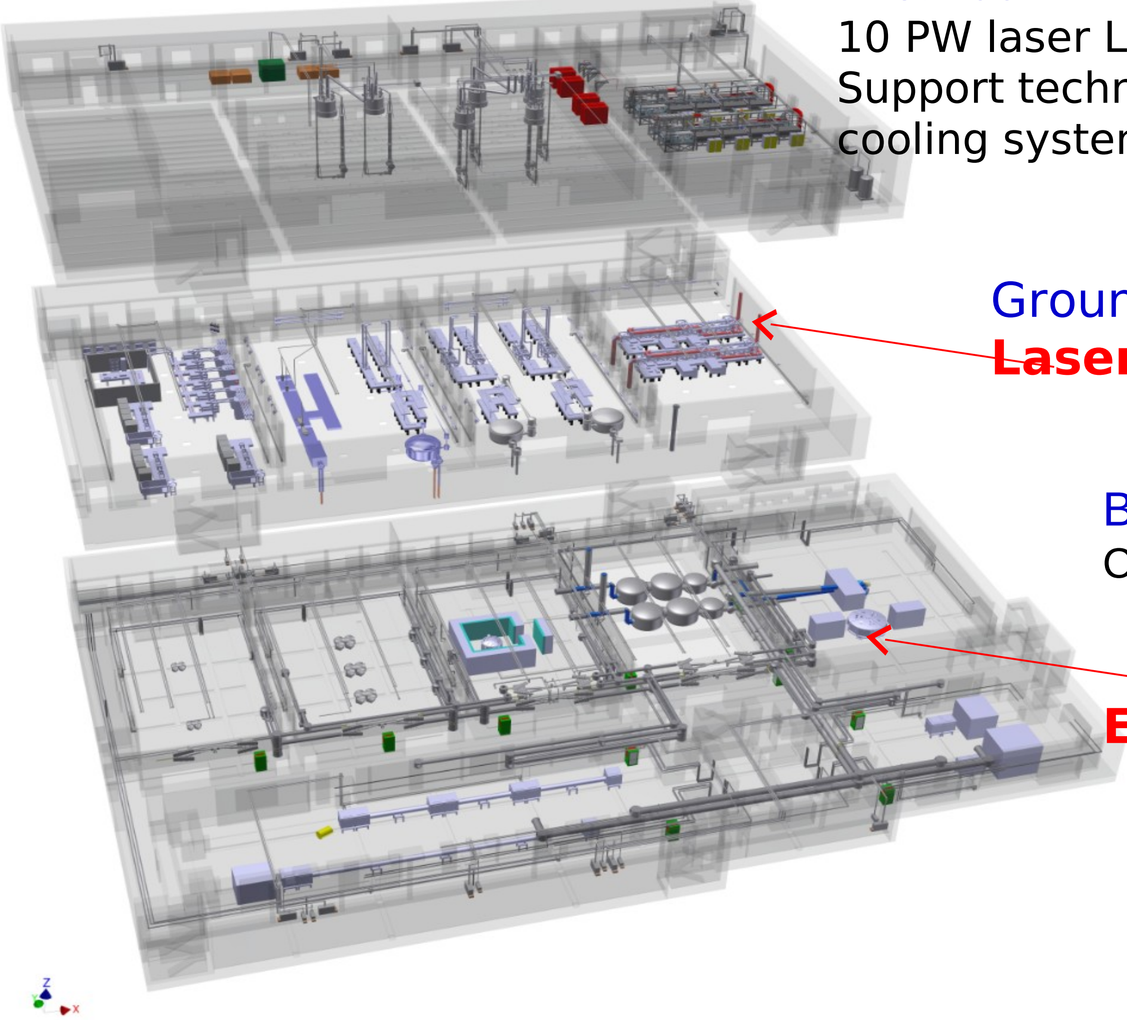
Texas Petawatt laser:
185 J / 130 fs – scalable -> 1900 J /130 fs



- Straightforward choice for e- acceleration
- The laser can be used as a pump of an OPCPA chain (Vulcan 10 PW solution)

* ELI: Extreme Light Infrastructure White Book: *Science and Technology with Ultra-Intense Lasers*
edited by G. Mourou, G. Korn, W. Sandner and J. Collier (2011)

Laser building layout



First floor

10 PW laser L4

Support technologies, cryogenic systems, cooling systems

Ground floor

Laser halls (L1 – L4)

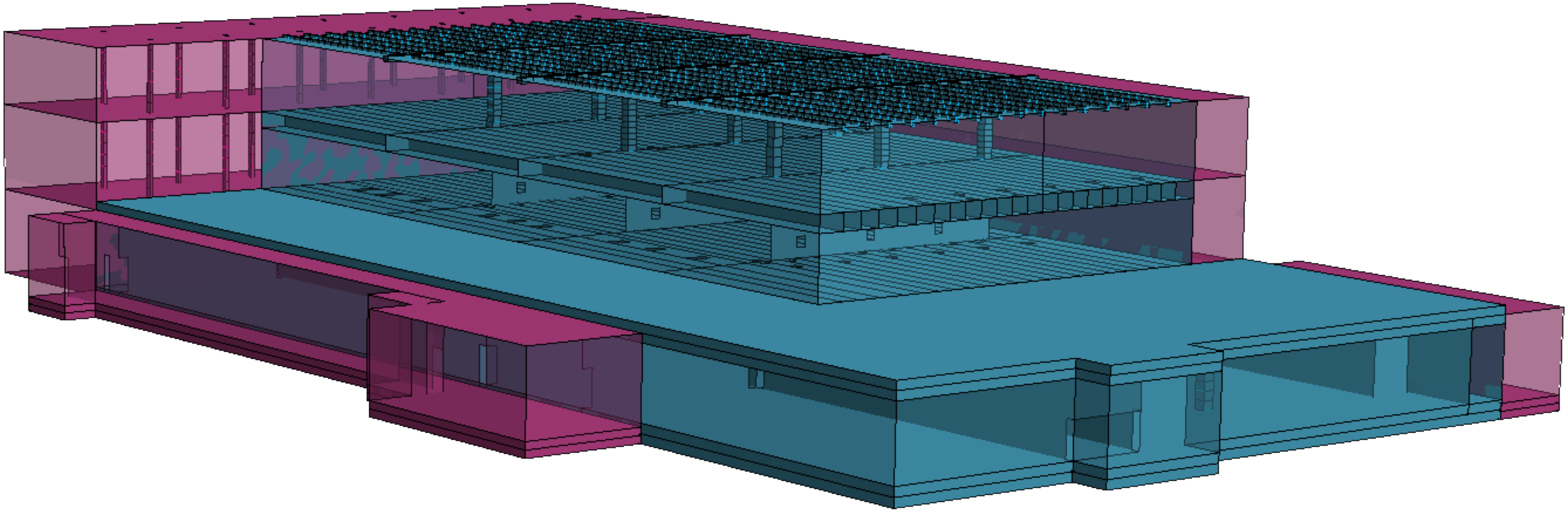
Basement

Compressor hall for 10-PW lasers

Pulse distribution in vacuum

6 specialized Experimental halls

Building structure

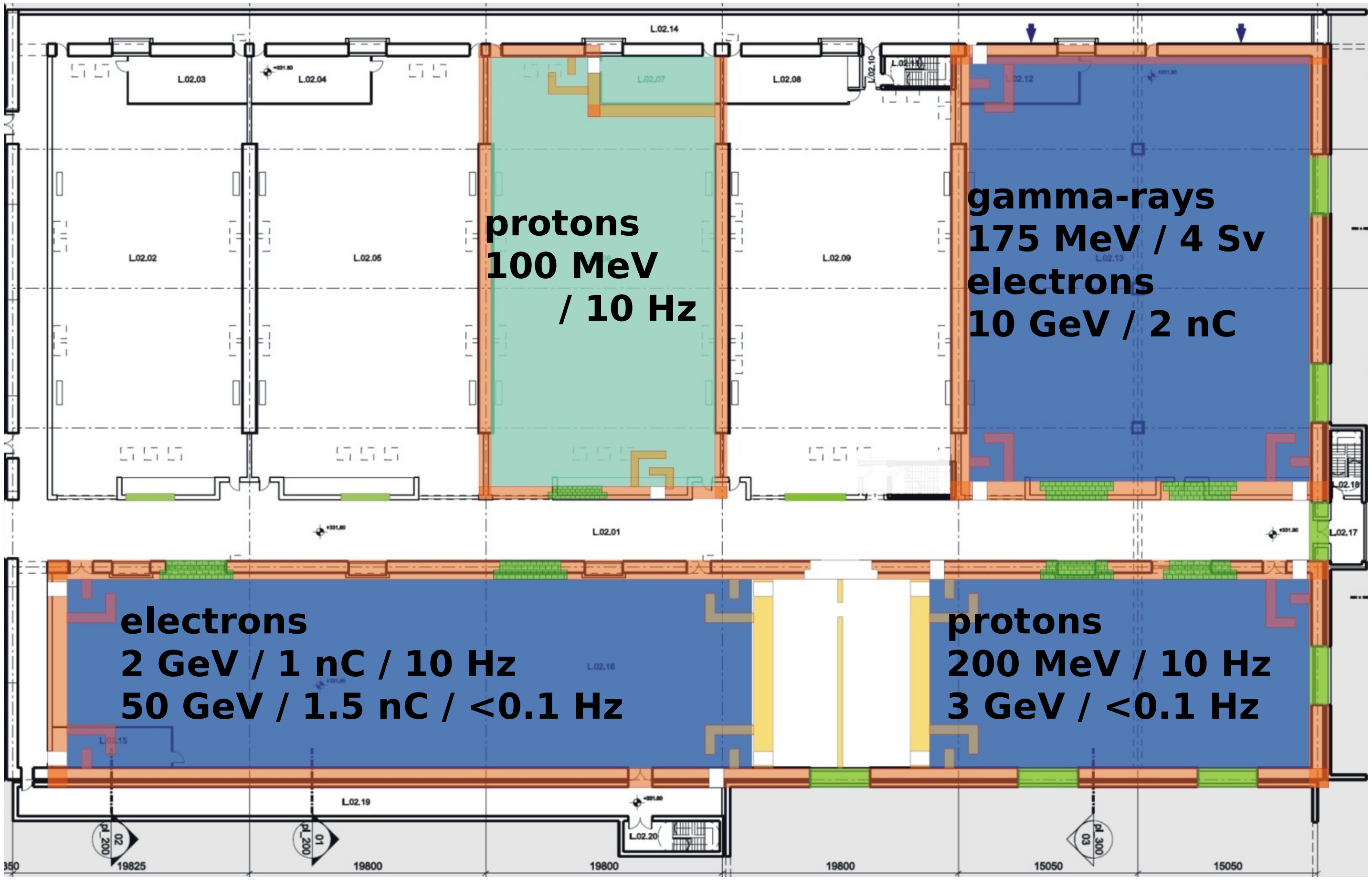


🟦 **Monolithic structure** (laser and experimental areas) – vibration analysis model

🟥 **Supporting technologies** (air conditioning, vacuum pumps, etc.) **& auxiliary laboratories**

The analysis accounts for actual sources of vibration measured on the site

Experimental areas



protons
100 MeV / 10 Hz

gamma-rays
175 MeV / 4 Sv
electrons
10 GeV / 2 nC

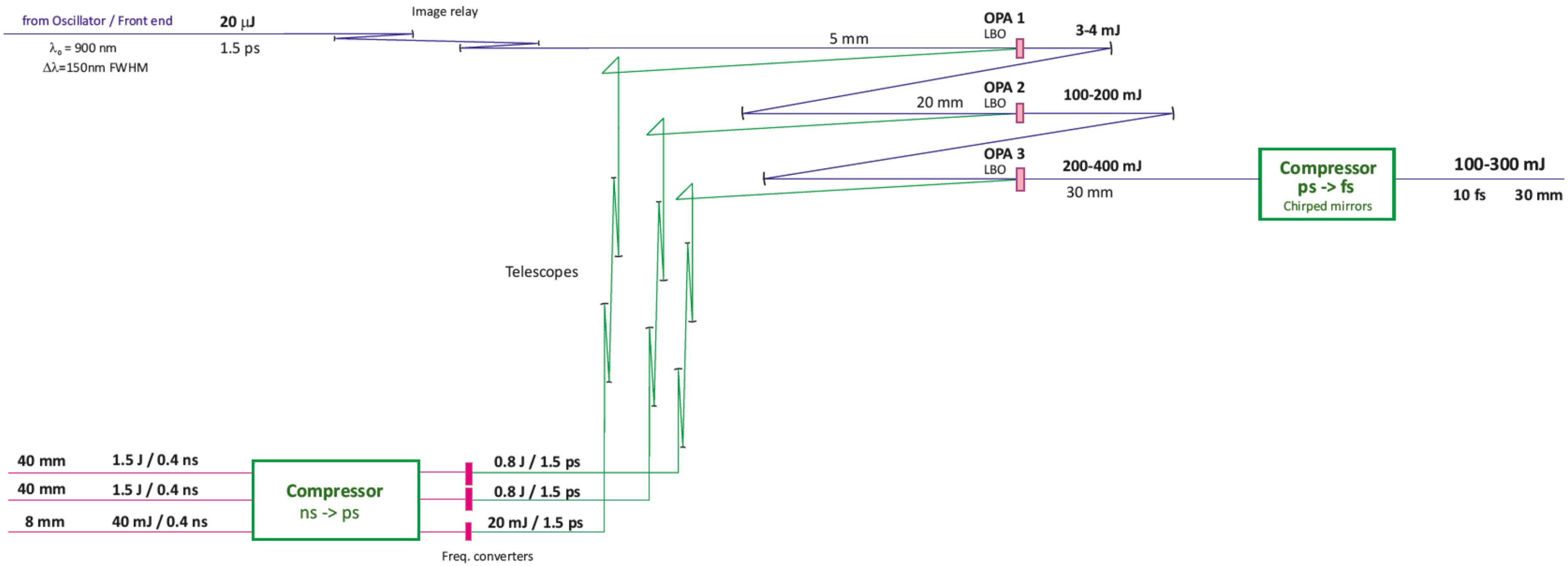
electrons
2 GeV / 1 nC / 10 Hz
50 GeV / 1.5 nC / <0.1 Hz

protons
200 MeV / 10 Hz
3 GeV / <0.1 Hz

L1.1 – kHz OPCPA

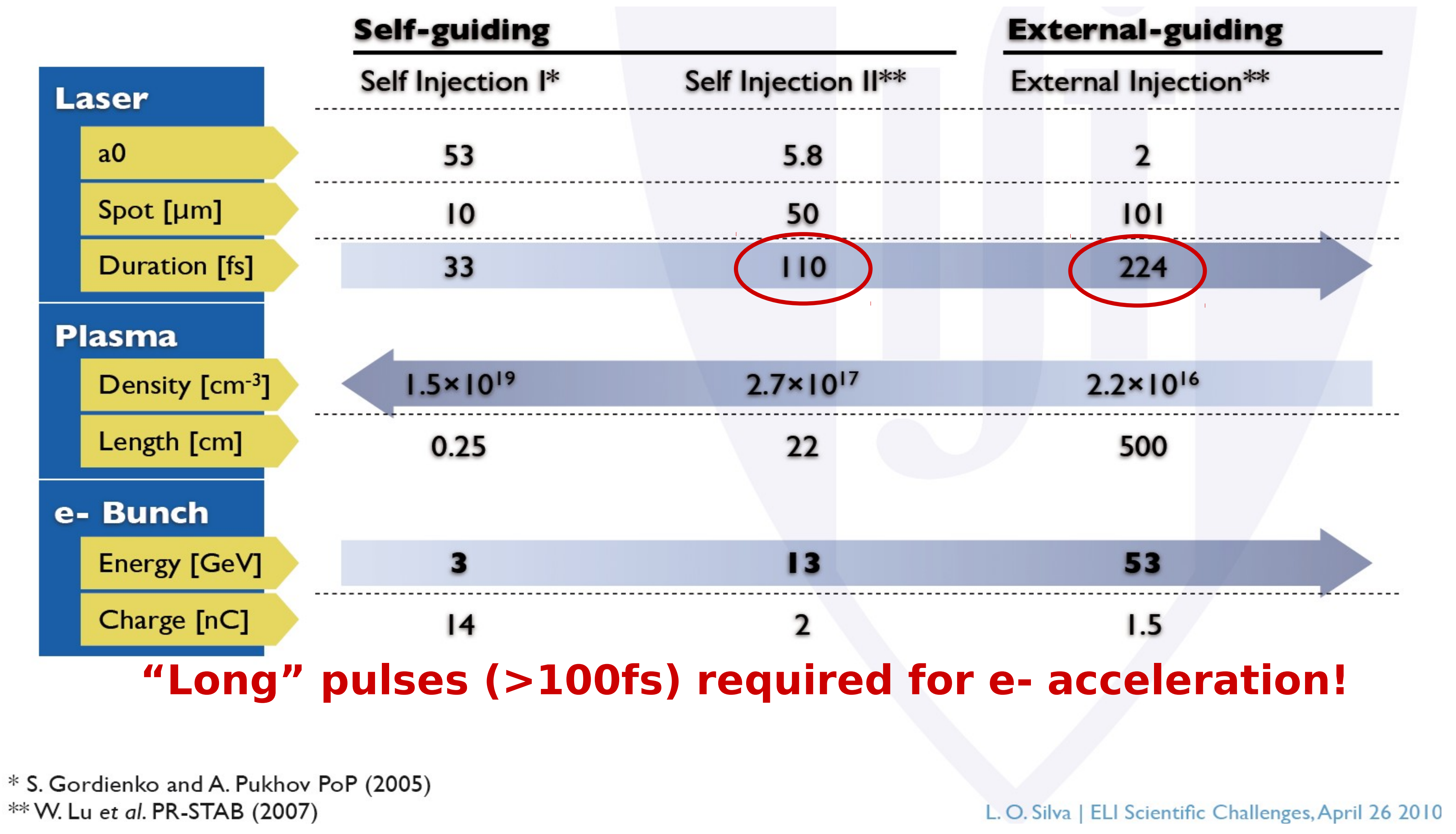
PFS: Technique proposed and developed by MPQ Garching

ELI-Beamlines: cooperation on the design of the 200 mJ / kHz amplifier chain



Electron acceleration (LWFA) with 250 J laser pulses

Luis Silva, IST Lisbon, ELI-Beamlines Scientific Challenges Workshop, Prague 26-27 April, 2010



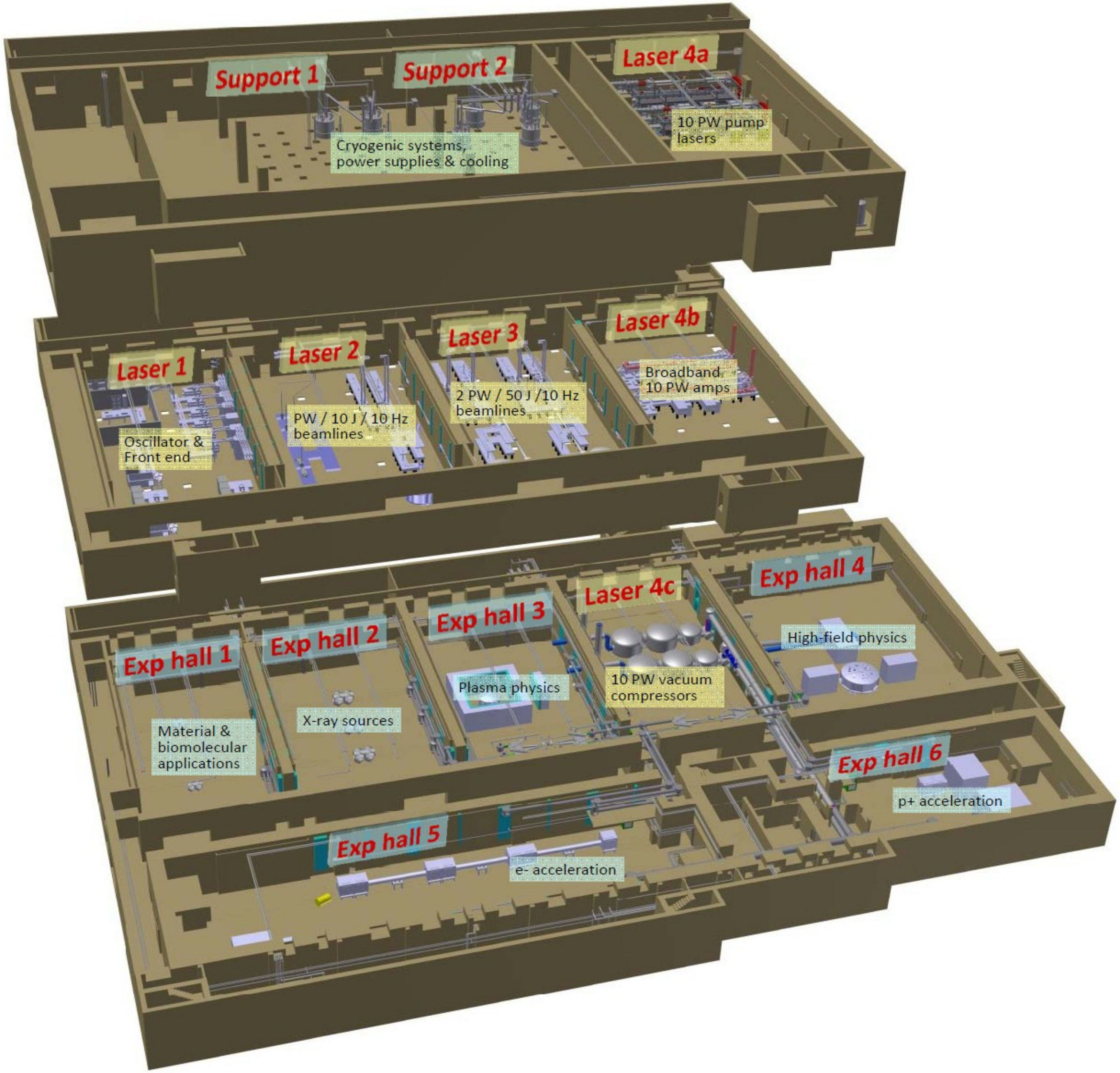
	Self-guiding		External-guiding
	Self Injection I*	Self Injection II**	External Injection**
Laser			
a0	53	5.8	2
Spot [μm]	10	50	101
Duration [fs]	33	110	224
Plasma			
Density [cm^{-3}]	1.5×10^{19}	2.7×10^{17}	2.2×10^{16}
Length [cm]	0.25	22	500
e- Bunch			
Energy [GeV]	**3**	**13**	**53**
Charge [nC]	14	2	1.5

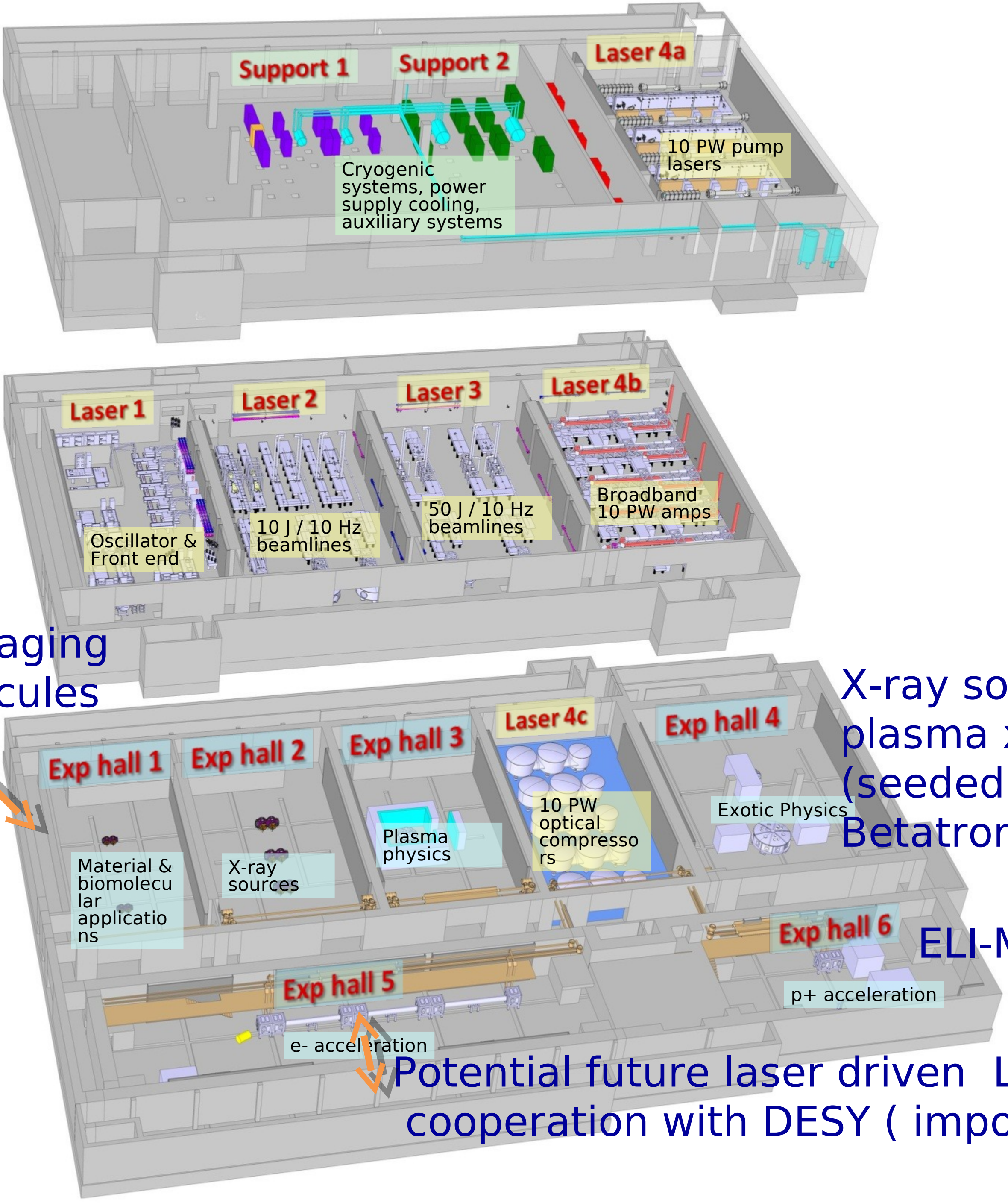
“Long” pulses (>100fs) required for e- acceleration!

* S. Gordienko and A. Pukhov PoP (2005)
** W. Lu *et al.* PR-STAB (2007)

L. O. Silva | ELI Scientific Challenges, April 26 2010

Detailed organization of the building





otential future
D diffractive imaging
f complex molecules

X-ray sources:
plasma x-ray laser
(seeded), k-alpha,
Betatron

ELI-MED

Potential future laser driven LUX and X-FEL
cooperation with DESY (important)

ELI-Beamlines mission

ELI Betatron beamline 100 TW- 1 PW, ELI- white book

S. Kneip, IC

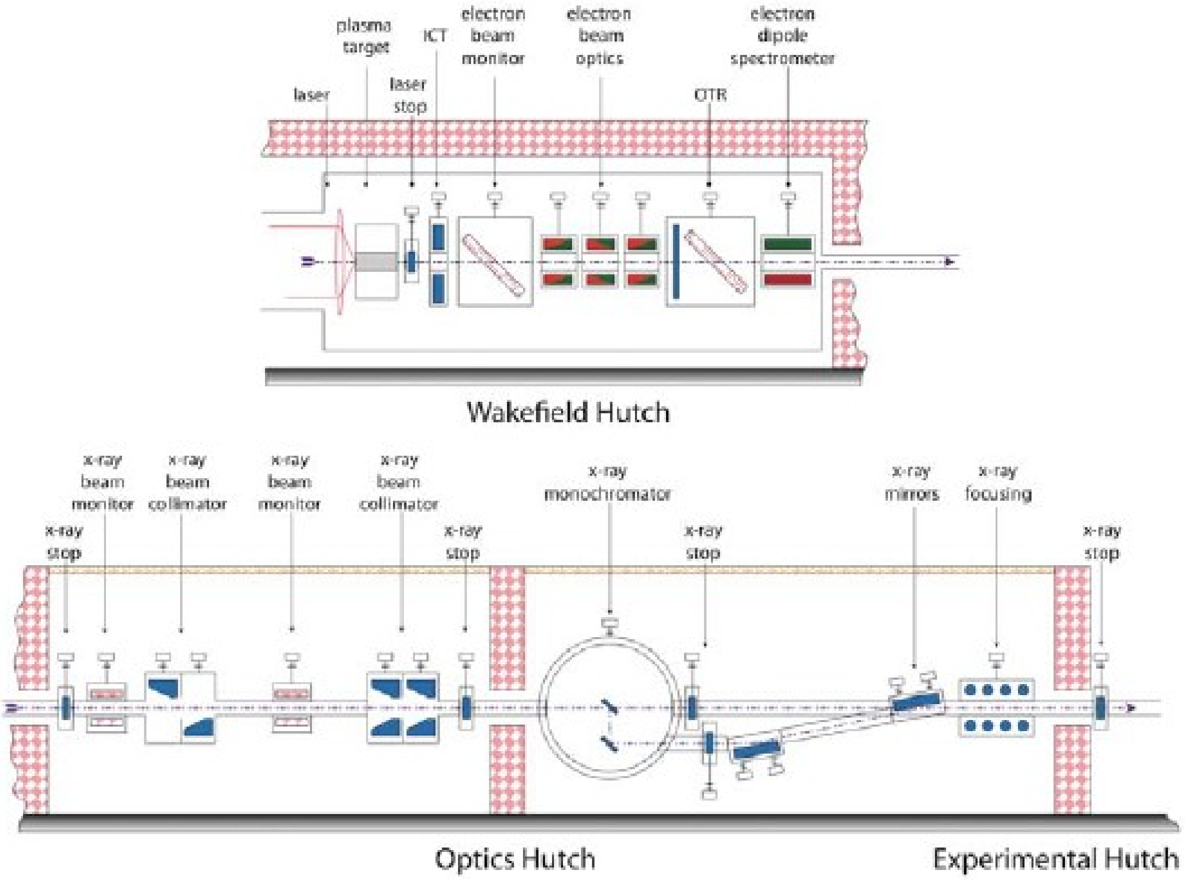


Figure 6.40: Schematic layout of the plasma wiggler beam line for the ELI-100-PW or ELI-1-PW laser.

ELI-Beamlines mission, x-ray Betatron, ELI-white book

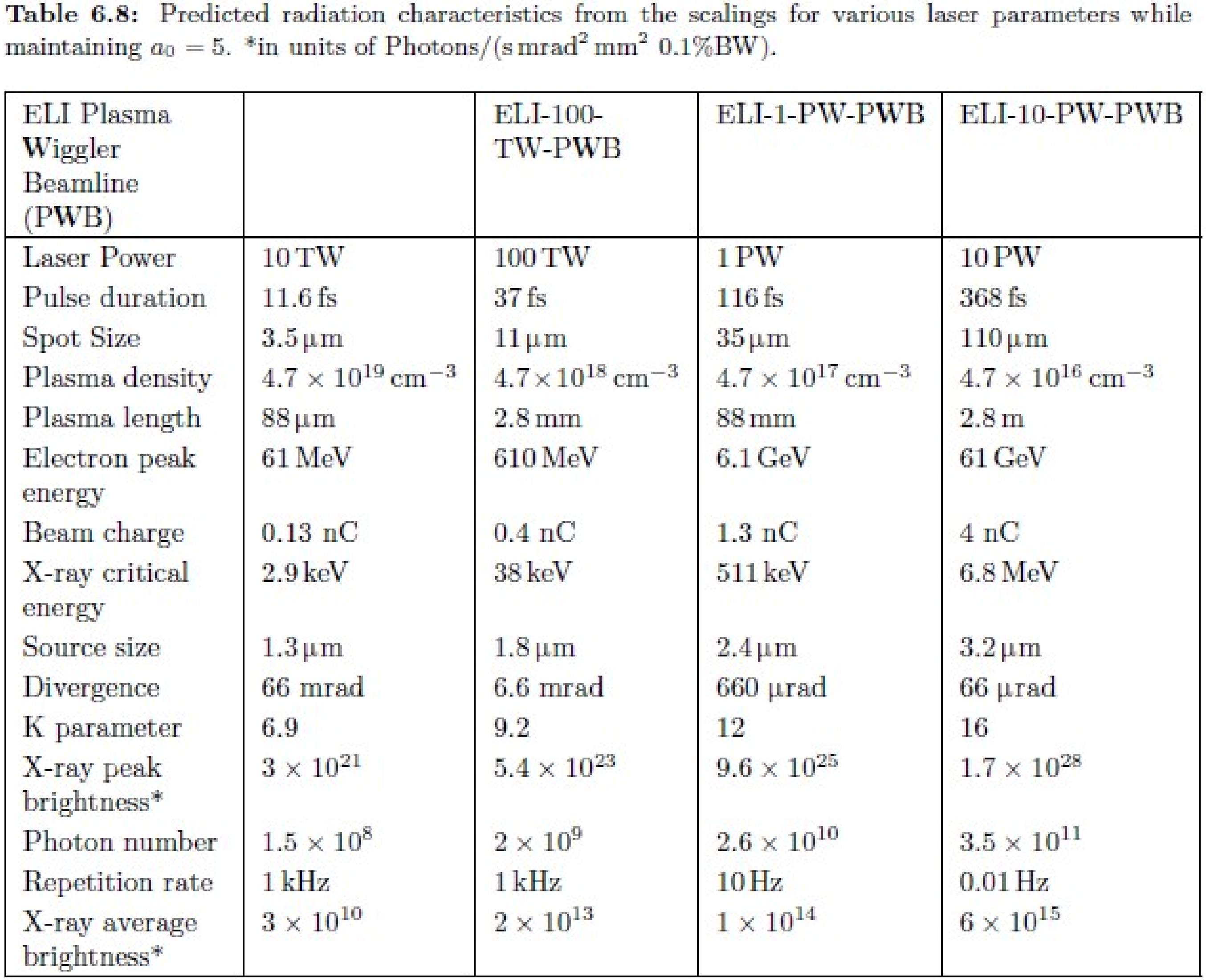


Table 6.8: Predicted radiation characteristics from the scalings for various laser parameters while maintaining $a_0 = 5$. *in units of Photons/(s mrad^2 mm^2 0.1%BW).

ELI Plasma Wiggler Beamline (PWB)		ELI-100-TW-PWB	ELI-1-PW-PWB	ELI-10-PW-PWB
Laser Power	10 TW	100 TW	1 PW	10 PW
Pulse duration	11.6 fs	37 fs	116 fs	368 fs
Spot Size	3.5 µm	11 µm	35 µm	110 µm
Plasma density	4.7×10^{19} cm^{-3}	4.7×10^{18} cm^{-3}	4.7×10^{17} cm^{-3}	4.7×10^{16} cm^{-3}
Plasma length	88 µm	2.8 mm	88 mm	2.8 m
Electron peak energy	61 MeV	610 MeV	6.1 GeV	61 GeV
Beam charge	0.13 nC	0.4 nC	1.3 nC	4 nC
X-ray critical energy	2.9 keV	38 keV	511 keV	6.8 MeV
Source size	1.3 µm	1.8 µm	2.4 µm	3.2 µm
Divergence	66 mrad	6.6 mrad	660 µrad	66 µrad
K parameter	6.9	9.2	12	16
X-ray peak brightness*	3×10^{21}	5.4×10^{23}	9.6×10^{25}	1.7×10^{28}
Photon number	1.5×10^{8}	2×10^{9}	2.6×10^{10}	3.5×10^{11}
Repetition rate	1 kHz	1 kHz	10 Hz	0.01 Hz
X-ray average brightness*	3×10^{10}	2×10^{13}	1×10^{14}	6×10^{15}

Applications:

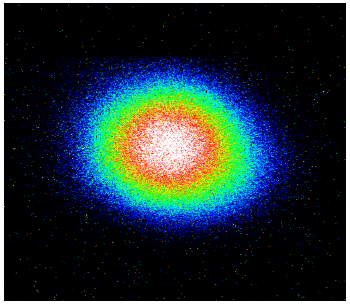
3D phase or absor. contrast imaging possible with different projections

High spatial coherence

Betatron : extrapolation using multi- PW laser

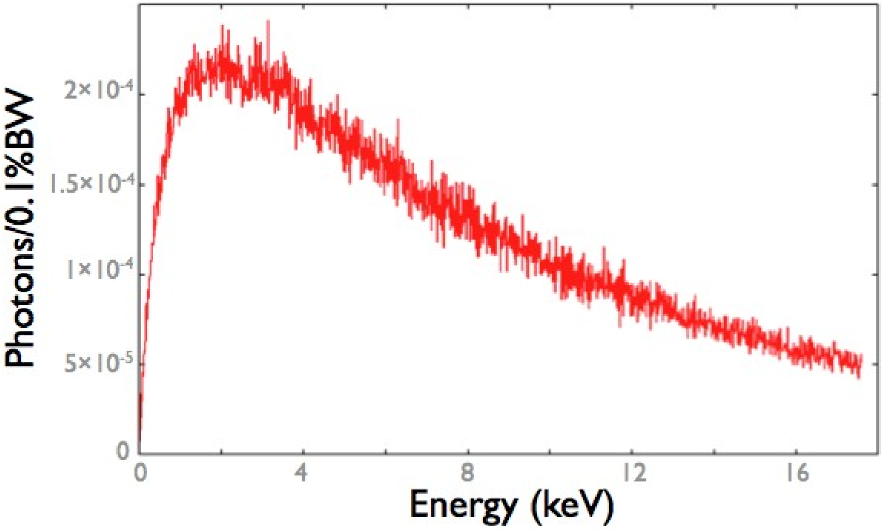
100 TW RANGE (E-BEAM AT 200 MeV)

1-10 PW RANGE (E-BEAM AT 2.5 GeV)



e-beam

E_{e-} = 2.5 GeV, R_{β}= 5µm, K=3



X-ray -beam

E_X = 325 keV

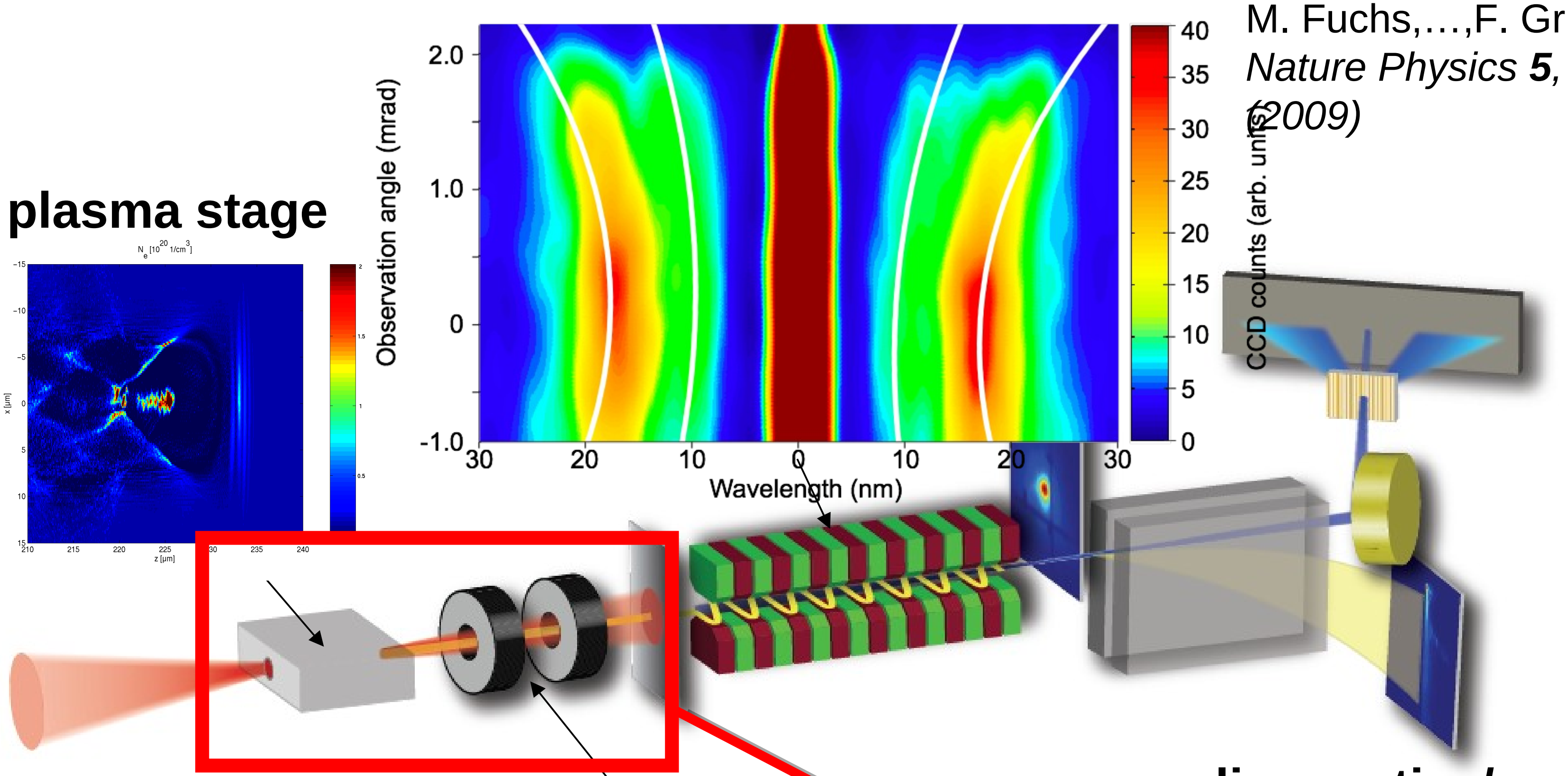
10^{10}-10^{11} photons

mrad divergence

fs duration

basic setup LUX- Laser undulator

M. Fuchs,…,F. Grüner, *Nature Physics* **5**, *826 (2009)*



high-intensity laser

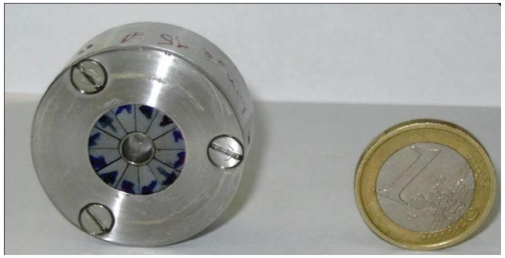
energy ~ **J**

pulse length ~ 25 fs

power: 100 TW → few PW

magnetic lenses

500 T/m gradient



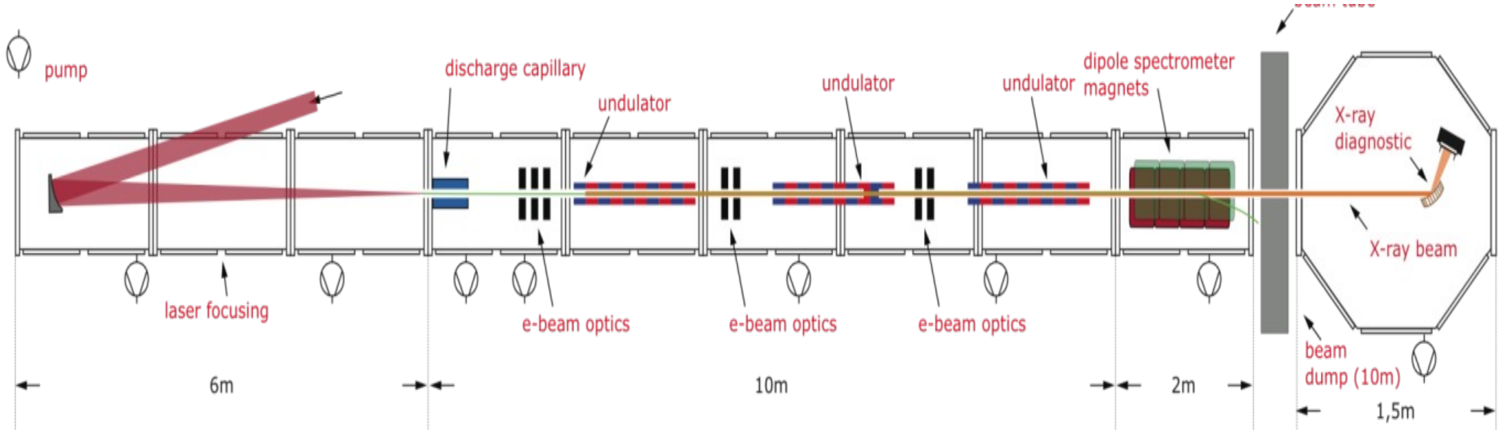
diagnostics/ applications

key challenges for **FEL**:
energy spread, charge, emittance

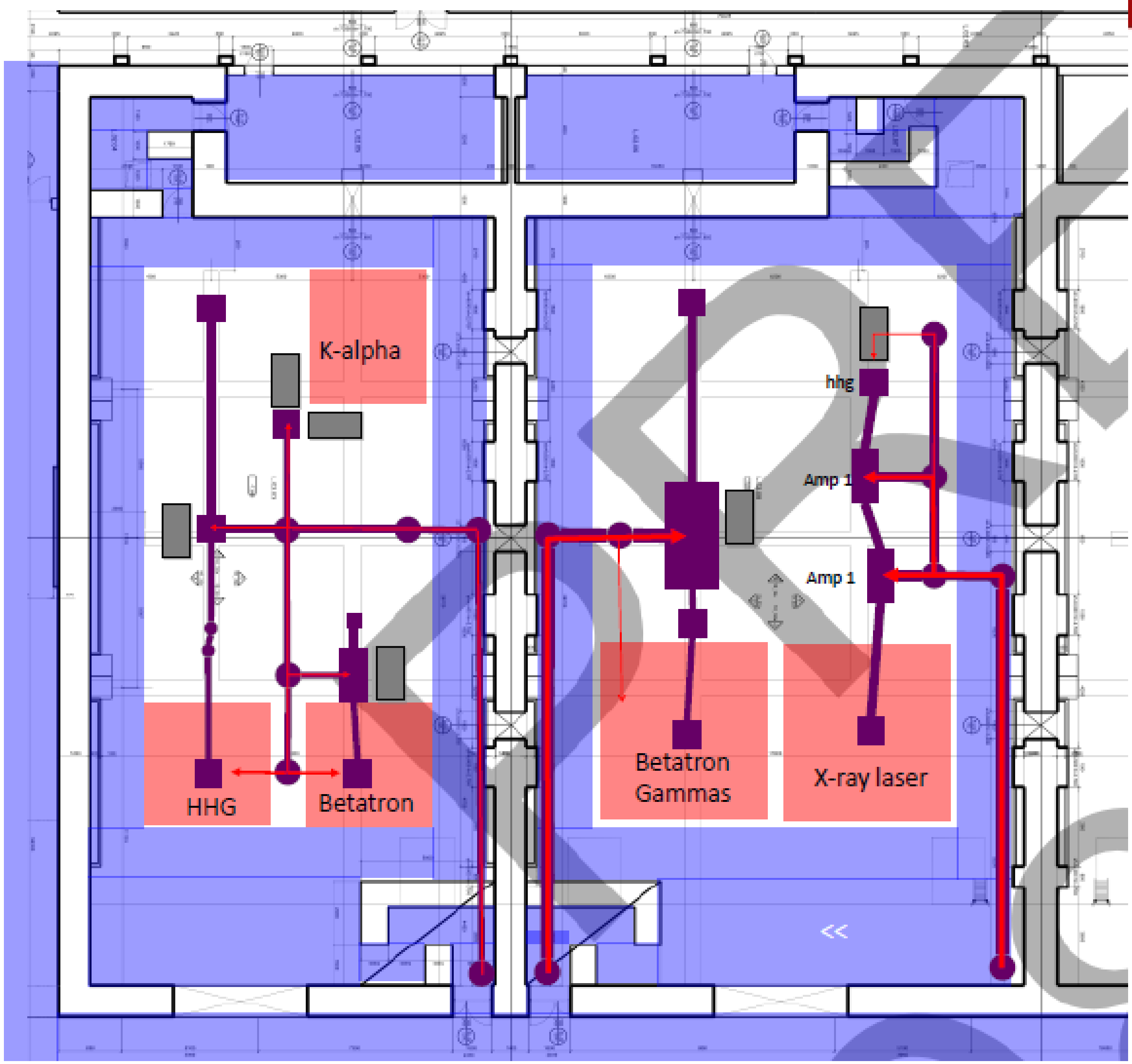
→ **combine conventional and plasma acceleration at DESY**

ELI-Beamlines mission

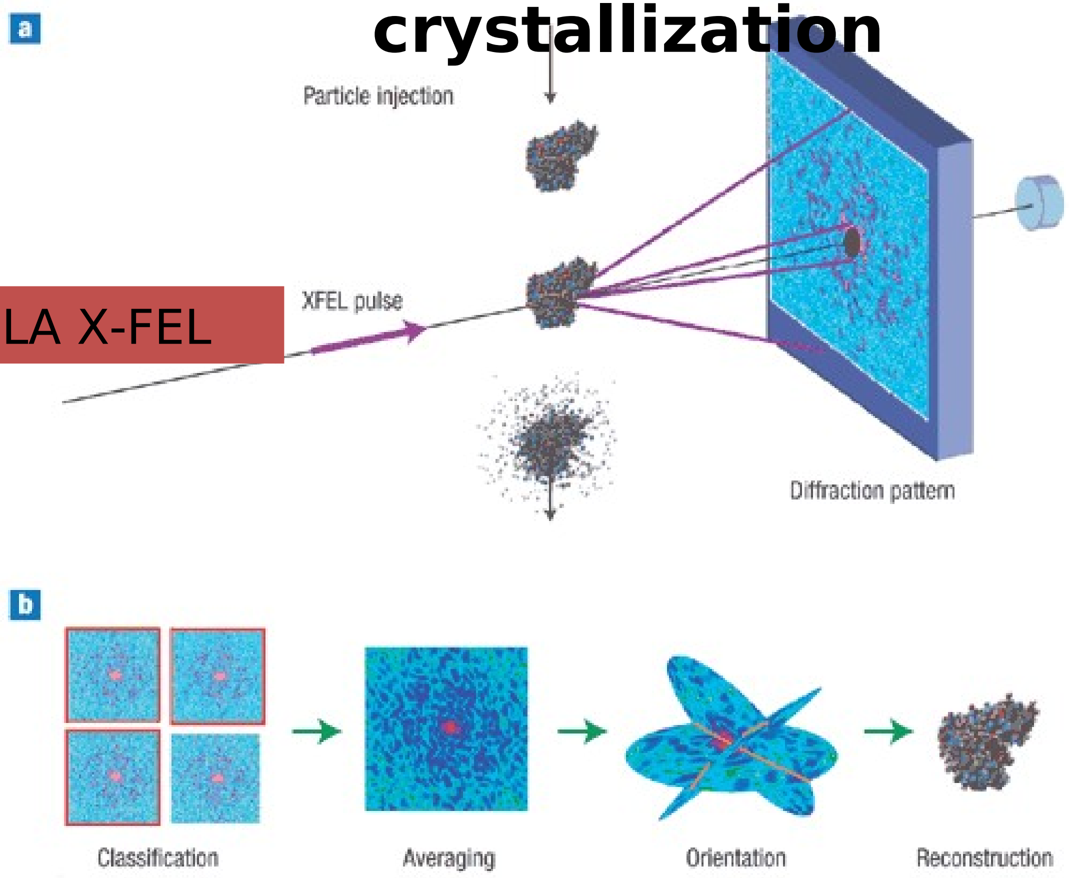
Laser driven LUX and x-FEL (F. Grüner et al.)
Long term vision, ELI-white book
200 TW -1 PW @ 5-10 Hz
Cooperation with DESY using accelerator know-how



2 GeV electrons, 5 keV, short and tunable x-ray pulses,
Diagnostics of short bunches
Detector development
Common team generated


K-alpha
HHG
Betatron
hhg
Amp 1
Amp 1
Betatron
Gammas
X-ray laser
<<

Single- particle diffraction imaging of biological particles without crystallization



ELI-LAOLA X-FEL

Kirz,Nature Physics 2, 799 - 800 (20

LCLS 10^{11} photons per shot, 3 keV

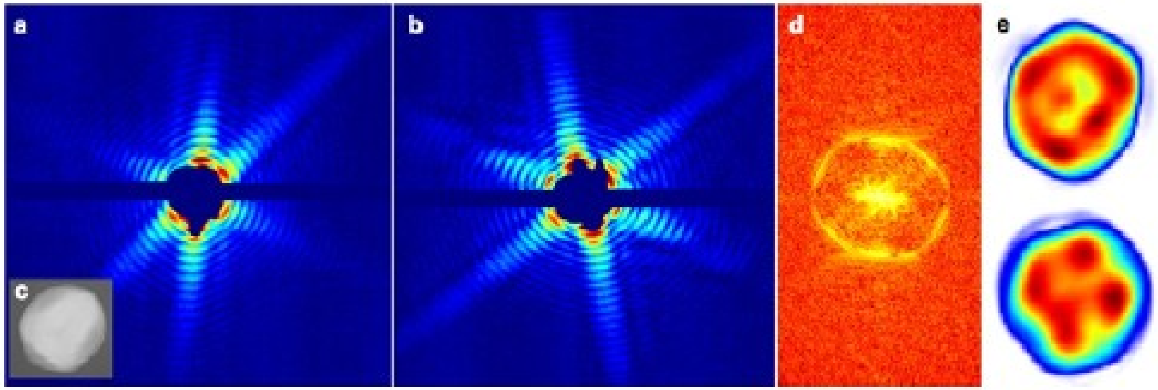
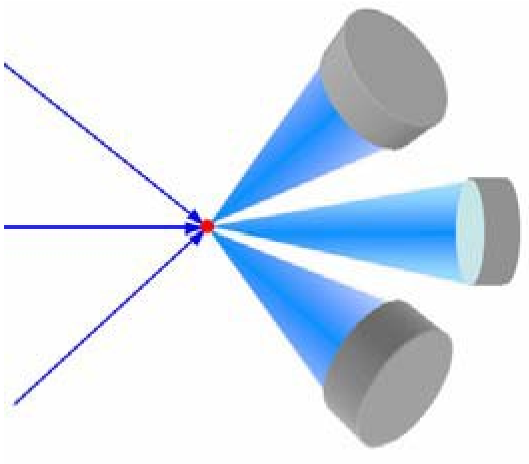


Figure 3.13: Diffraction patterns and reconstructed exit wave fronts (images) for mimivirus particles. For more detail see text and ref. [20].

[20] Chapman, H.N. et al., Nature 470, 73–77 (2011)

From projection images to (almost) 3d structures

3 D diffractive imaging using synchronized ELI x-ray pulses



Timing synchronization of 30 fs should allow to go for µm samples diffraction
Explosion happens over many ps (Hajdu et al.)

Development works steps

- Laser development

- Complete System integration including target areas

- proof of principle experiments showing the anticipated laser power and intensity parameters in the different research areas

- user facility mode for different research areas step

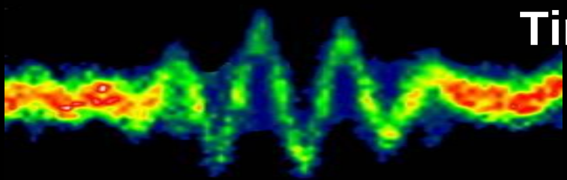

eti

Thank you for your attention

and for the kind invitation !

For more info about the ELI Beamlines facility see
http://www.eli-beams.eu

Time-resolved Attosecond spectroscopy



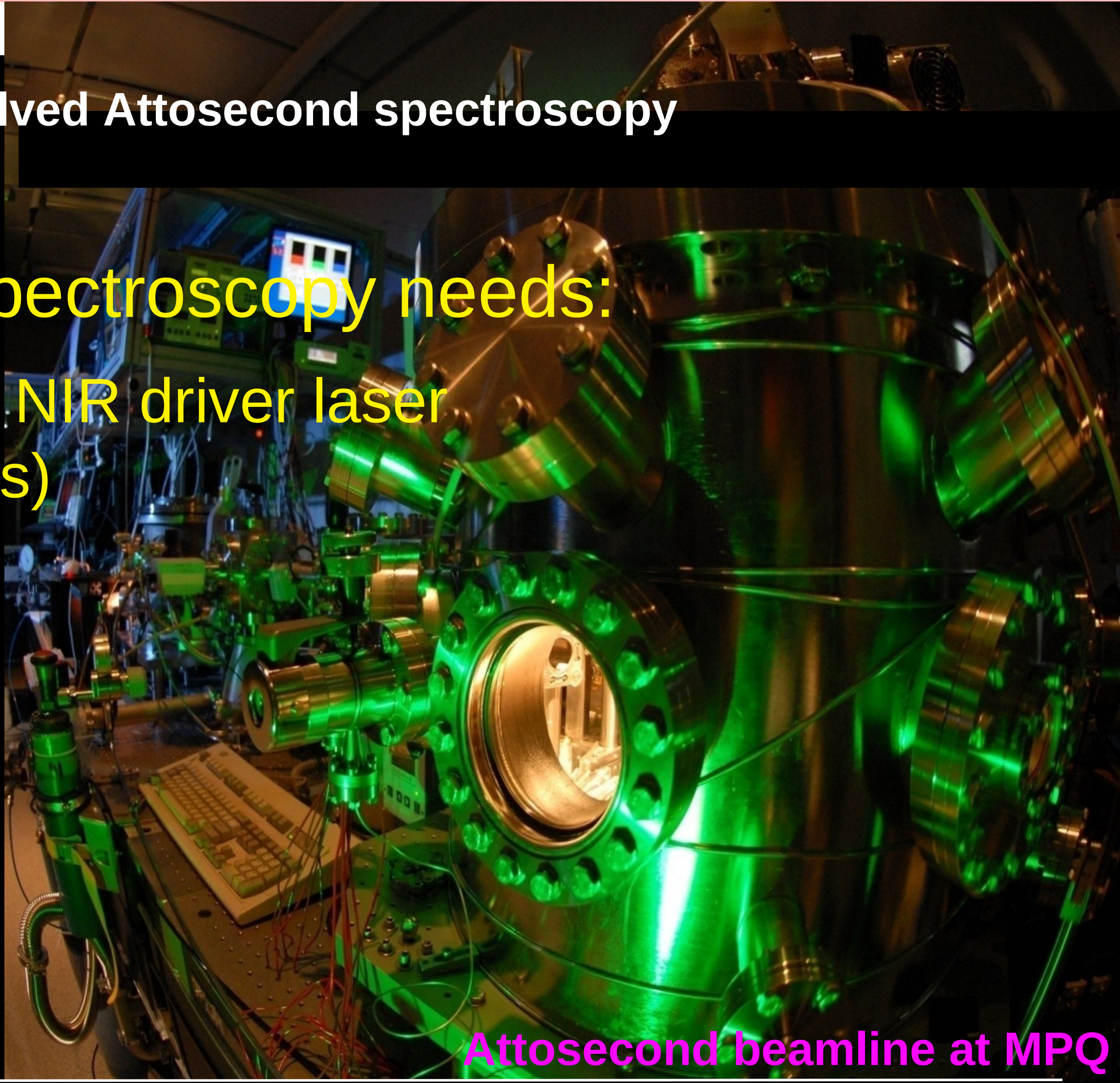
ELI xuv- Attosecond-Spectroscopy needs:

- Femtosecond-high-power NIR driver laser
- „few cycle“ Pulses (5-10 fs)
- high repetition rates
- I = 10^{20} W/cm^2

Solution:

OPCPA (provides large bandwidth for ampl. high aver. power)

more info:
www.attoworld.de



Attosecond beamline at MPQ

ELI Beamlines Facility laser

Thin disk pump technology

0 kW short pulse

00 mJ /1 kHz/10fs

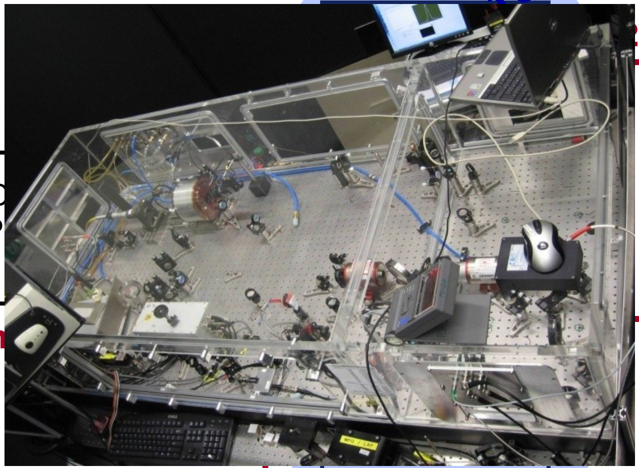
Multislab pump

ology

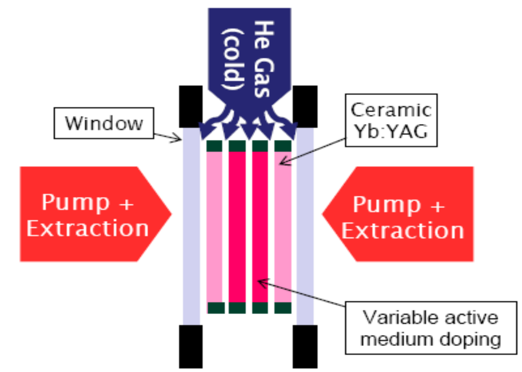
O

+ P

10 m



fs



Flashlamp pump

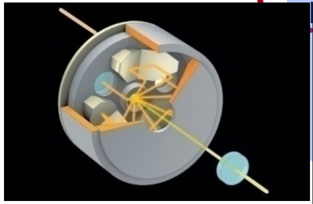
Beam/pulse switchyard

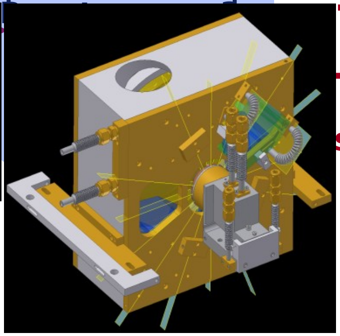
Applications (molecular, biomedical & material sciences)

XUV / X-ray generation

e- and p+ acceleration

Plasma physics WDM





s

pump

High-intensity test & user facility Exotic physics

Pump: Flashlamp

echnology

Science Case in the ELI-Beamline

Research Program 1
Lasers generating rep-rate ultrashort pulses & multi-petawatt peak powers

Research Program 2
X-ray sources driven by rep-rate ultrashort laser pulses,

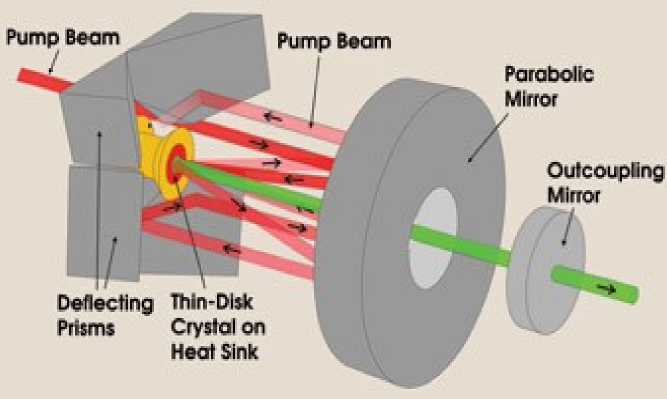
Research Program 3
Particle acceleration by lasers

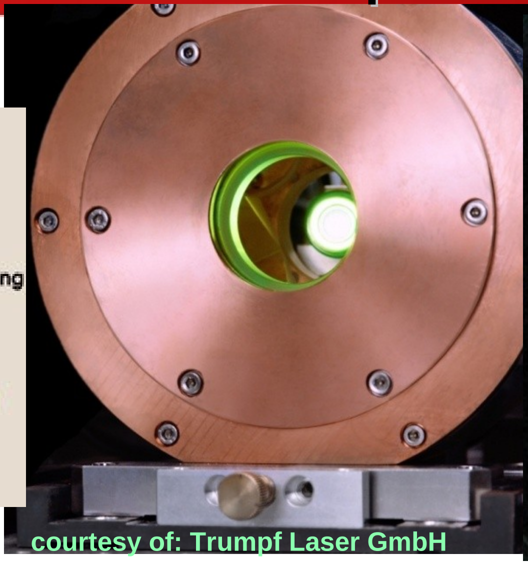
Research Program 4
Applications in molecular, biomedical, and material sciences

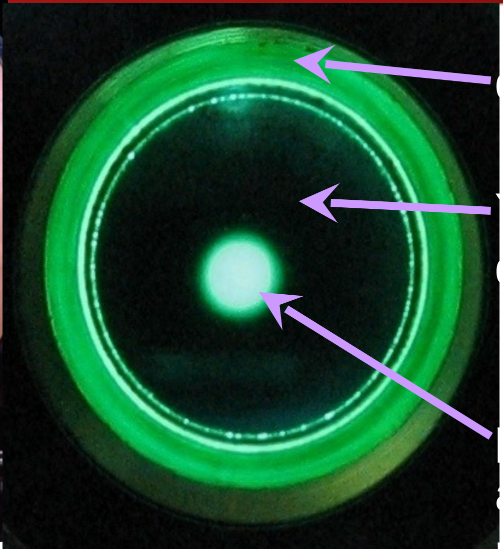
ogram 5
a and high-energy-density physics (PALS kJ laser synchronized to 40 TW laser)

rch Program 6
eld physics and theory (steps to 10^{23}W/cm^2, radiation reaction plays role)

Energy scaling via disk based amplifiers




courtesy of: Trumpf Laser GmbH



• scaling factor	1	10
• pump spot Ø	3 mm	9.5 mm
• pump power	300 W	3 kW
• pulse energy	30 mJ	300 mJ
• gain 1,2 @ 0,3 kW	1,2	1,2
• required V-	80 regen	13 multi pass

1J OPA @ 1 kHz

5 J @ 515 nm

1 x 10 J @ 1030 nm

100 kW pump diodes

100 mm Ø disk

large disk head

Budget and timeline

Total investment: 268.8 mil. € Cz

244.5 mil. € Hu

280.0 mil. € Ro

793.3 mil. € (15% country, 85% IS-funding)

ELI will be an international facility:

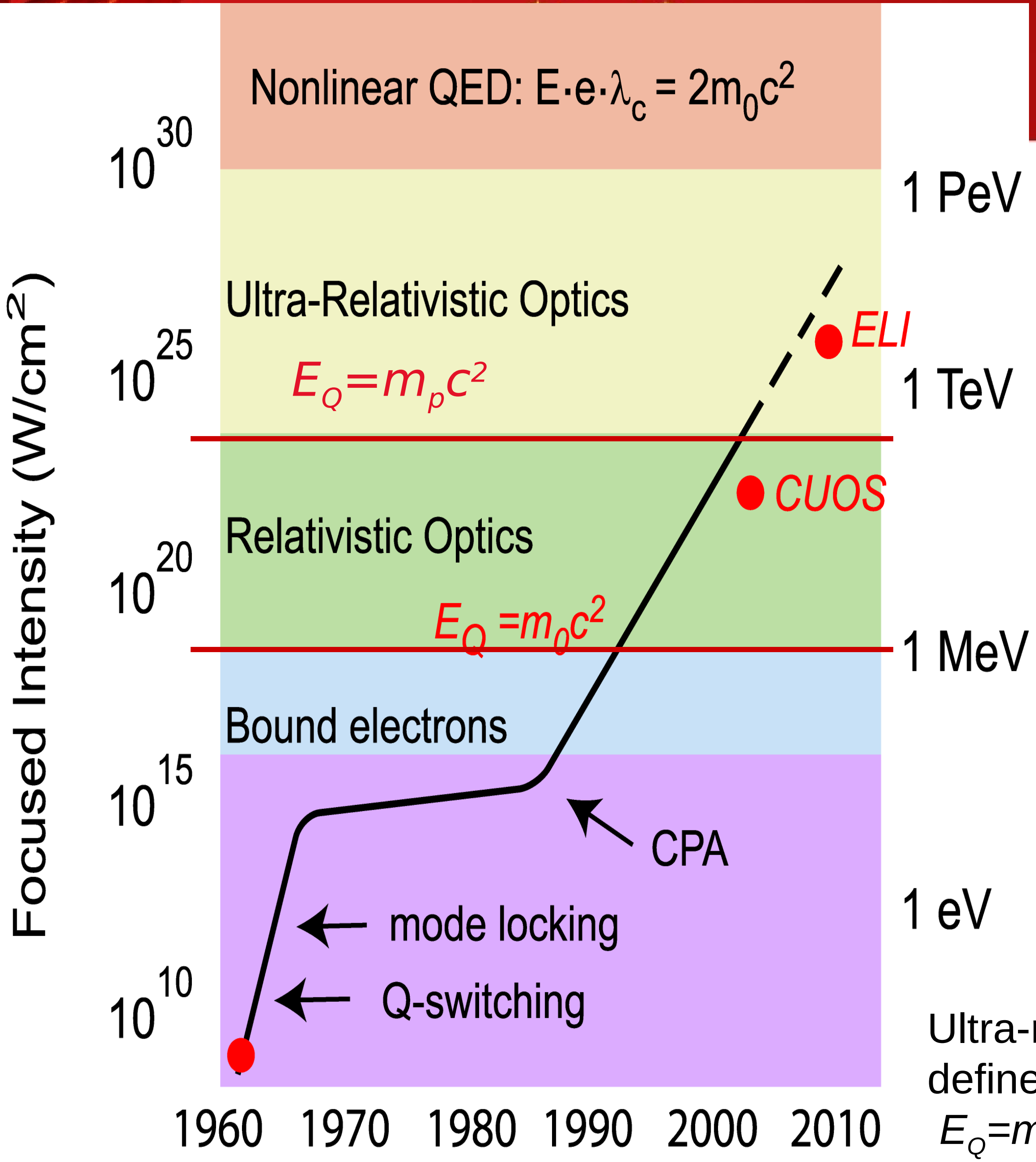
European Research Infrastructure Consortium (ERIC)

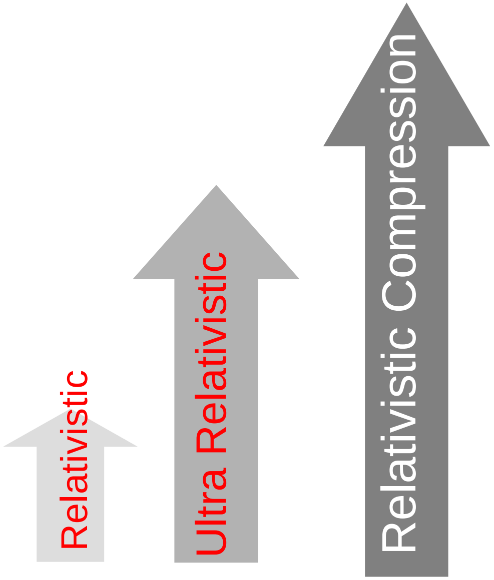
Timeline:

October 1, 2009	ELI-Preparation Phase Steering Committee (13 countries) giving Hu, Cz, Ro mandate to implement ELI-sites
Jan 29, 2010	Legally effective zoning permit to build ELI-Beamlines issued
June-Sept. 2010	Transmission of the IS-funding request for to EC
End 2010-2011	Official approval of EC expected
2010 – 2015	Construction, development &installation of laser systems

Thank you for your attention!

For more info about ELI see
http://www.eli-laser.eu





Ultra-relativistic intensity is defined with respect to the proton $E_Q = m_p c^2$, intensity~10^{24}W/cm^2

(Legal) Implementation of ELI

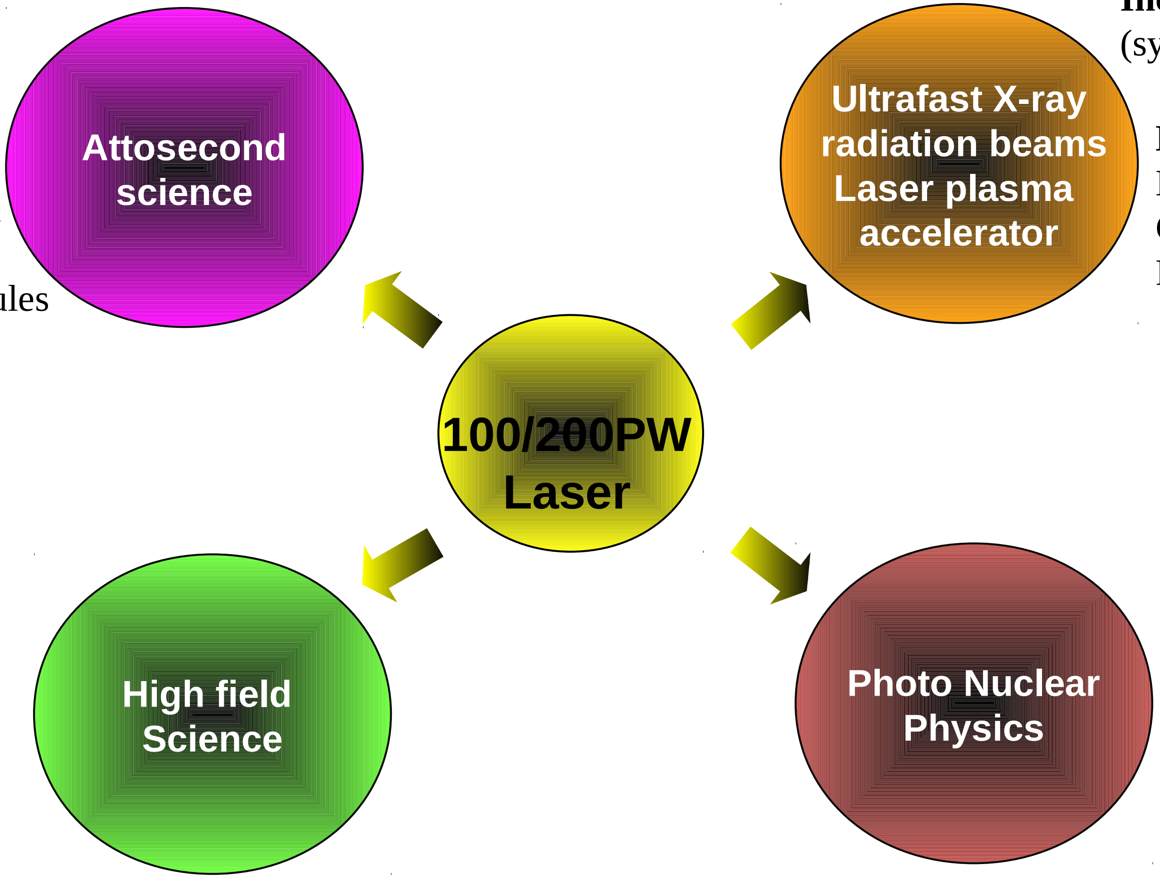
Single governance, three-site research infrastructure:

ELI-ERIC

(European Research Infrastructure Consortium)

… is to be formed in 2011

Scientific ”pillars” of ELI



Attosecond
to zeptosecond
Physics

Application
Ultrafast phenomena
Wave function
in atoms and molecules

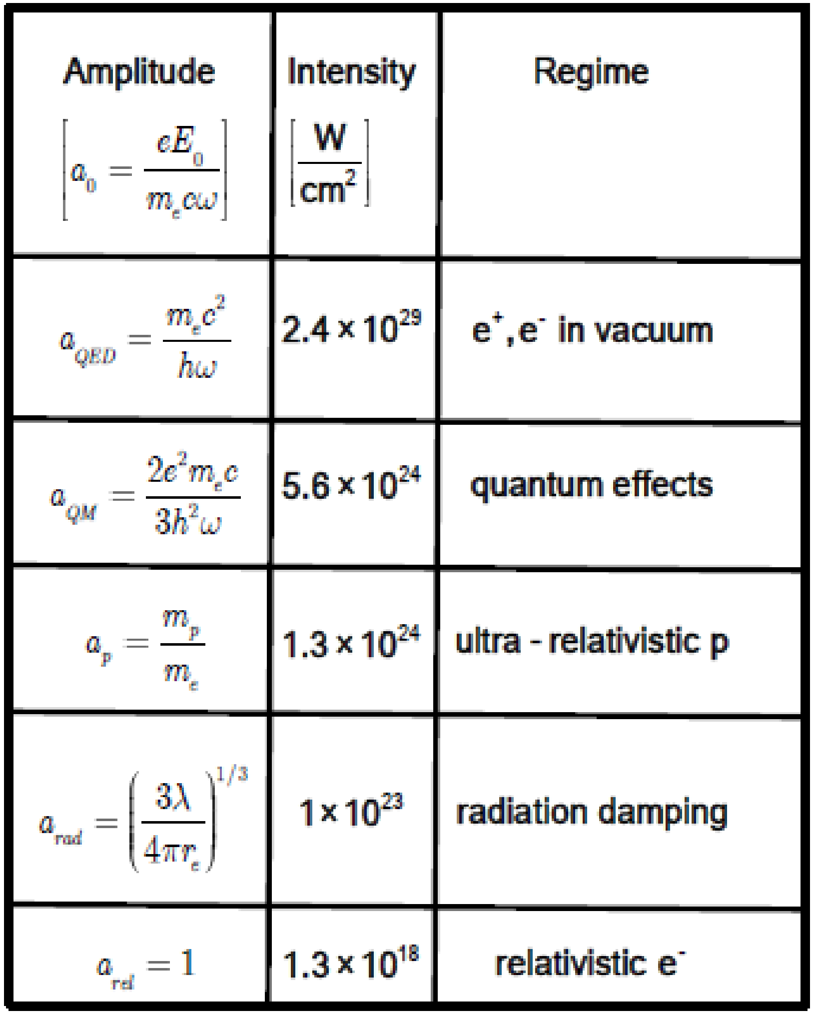
Coherent (X,g)-rays
(FEL, HHG & plasma)
Incoherent (X,g)-rayBeams
(synchrotron-like, atomic)

Beam lines facility
Electrons beam
Gamma imaging
Protons beam

NLQED
Fundamendatl
physics
Exotic physics

Nuclear Physics
Transmutation

Fundamental intensity dependent regimes of interaction



Amplitude $\left[a_0 = \frac{eE_0}{m_e c\omega}\right]$	Intensity $\left[\frac{\text{W}}{\text{cm}^2}\right]$	Regime
$a_{QED} = \frac{m_e c^2}{h\omega}$	2.4×10^{29}	e^+, e^- in vacuum
$a_{QM} = \frac{2e^2 m_e c}{3h^2\omega}$	5.6×10^{24}	quantum effects
$a_p = \frac{m_p}{m_e}$	1.3×10^{24}	ultra - relativistic p
$a_{rad} = \left(\frac{3\lambda}{4\pi r_e}\right)^{1/3}$	1×10^{23}	radiation damping
$a_{rel} = 1$	1.3×10^{18}	relativistic e^-

$$e\lambda E_{rel} = m_e c^2$$

$$e\lambda E_{ultrarel} = m_p c^2$$

$$e\lambda_{comp} E_{rel} = m_e c^2$$

$$\lambda_{comp}(electron) = 2.4x10^{-6}\,\mu m$$

$$E_0[\mathrm{V/cm}] = 19\sqrt{I[\mathrm{W/cm^2}]}$$

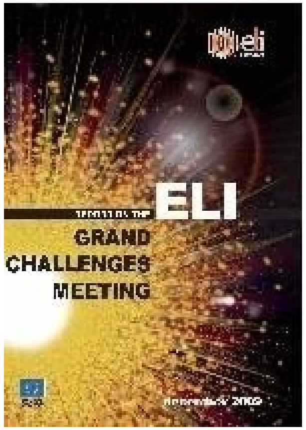
Very compact accelerators can be built

The European Strategy Forum on Research Infrastructures (ESFRI) has been set-up to help facing important challenges in science:

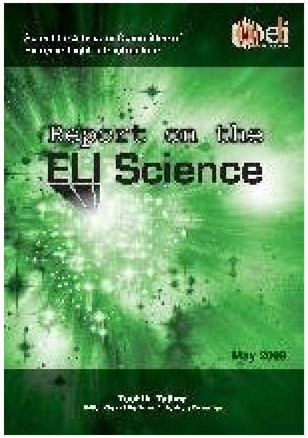
Roadmap of Europe
for Research Infrastructures

For the scientific case please visit the web-page

www.eli-laser.eu



ELI
GRAND
CHALLENGES
MEETING



Report on the
ELI Science

Laser acceleration
Towards 100 GeV (electrons, ions)

Investigation of Vacuum Structure
Towards Schwinger Fields
    e-, e+ pair production,
    colliding fast electrons (γ >1000) with ultra-intense laser fields

Attosecond science
Coherent x-rays: going beyond 1-10 KeV

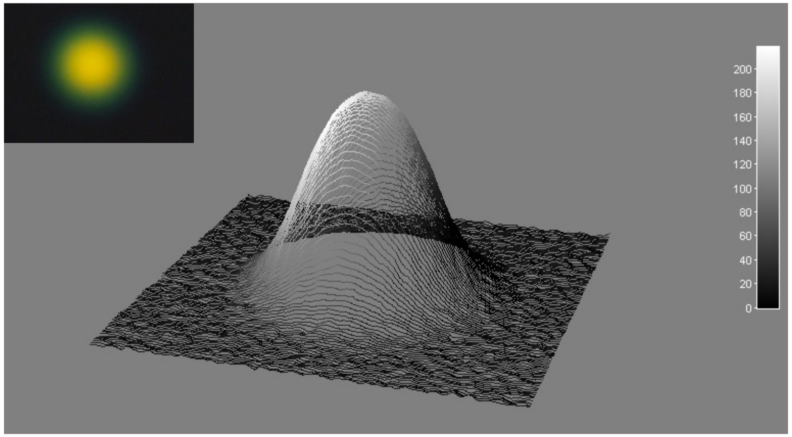
Nuclear Physics
Explore nuclei with photons

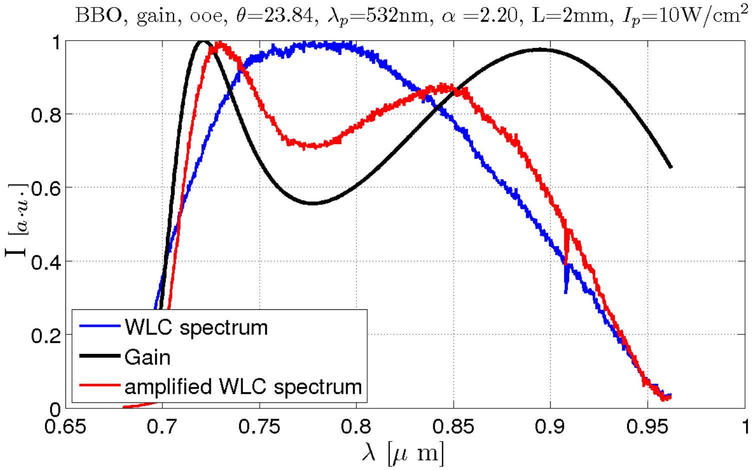
Pulse shortening and frequency conversion to Attoseconds and shorter Generation of light (photons)

ELI generates unique, perfectly synchronized sources
of particle and photon beams
from GeV (TeV) to visible THz , x-ray
and $\gamma-$ beams

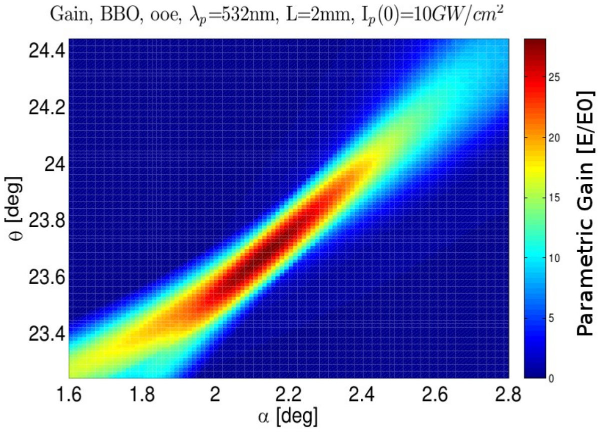
Front end development: Generation and amplification of WLC

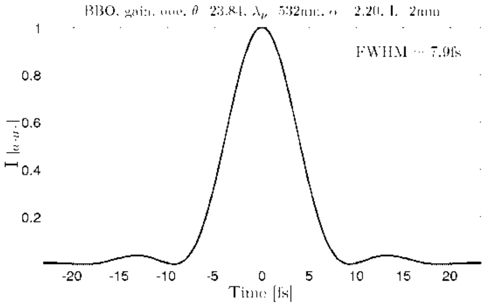
WLC beam profile (Sapphire), 1 kHz   710-900 nm





Dependence of OPA gain on pump-signal and synchronisation angle





SPIE, Prague 18th of April

F. Batysta et al.   Ultra-broadband OPA of White Light Continuum for ELI front end

HiLASE center in 2

www.hilase.cz

We are now looking for Technicians, Ph.D. students, Junior Researchers, Senior Researches

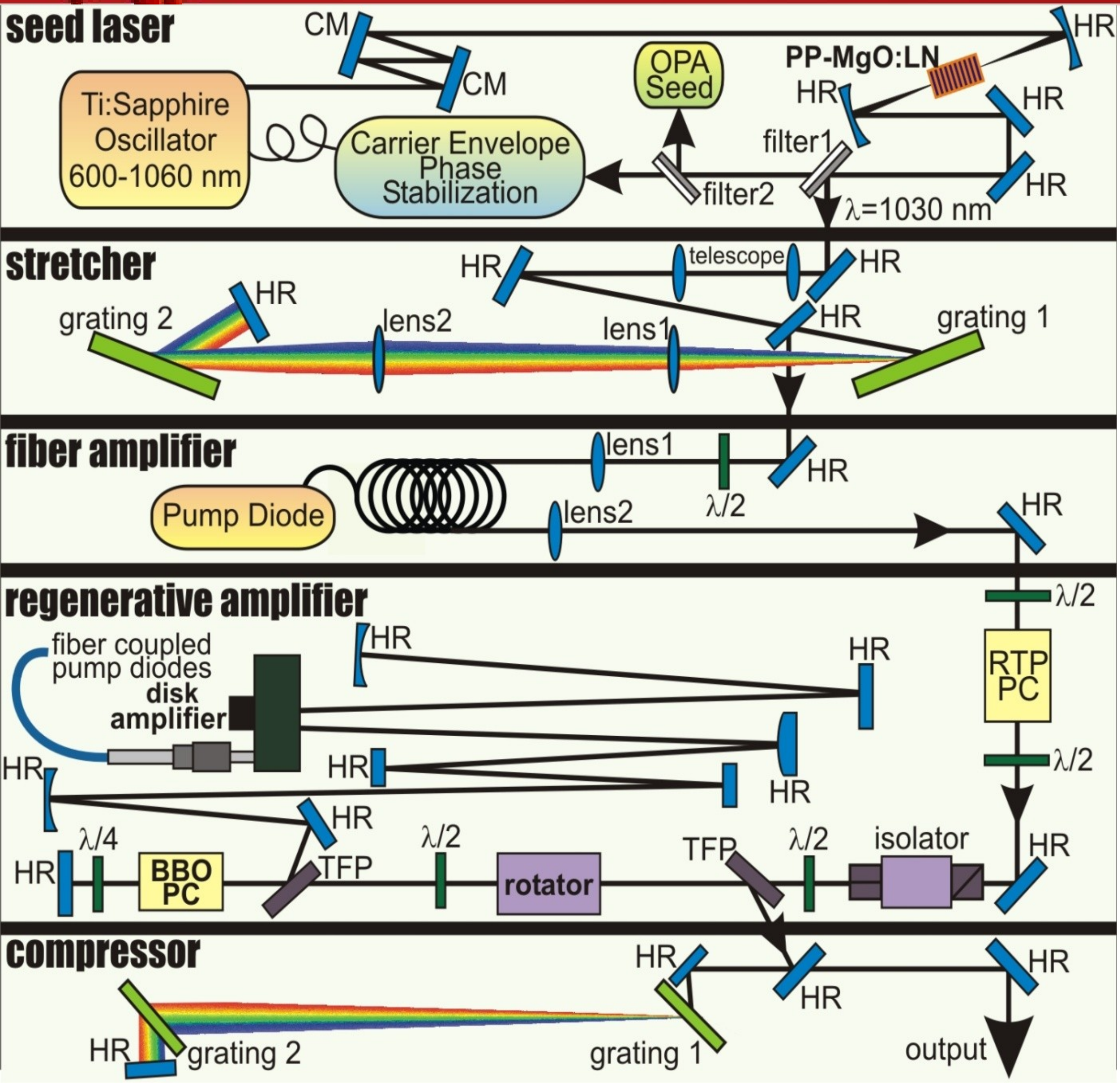
HiLASE project

Institute of Physics AS CR

30 M € Diode pumped Lasers for applications

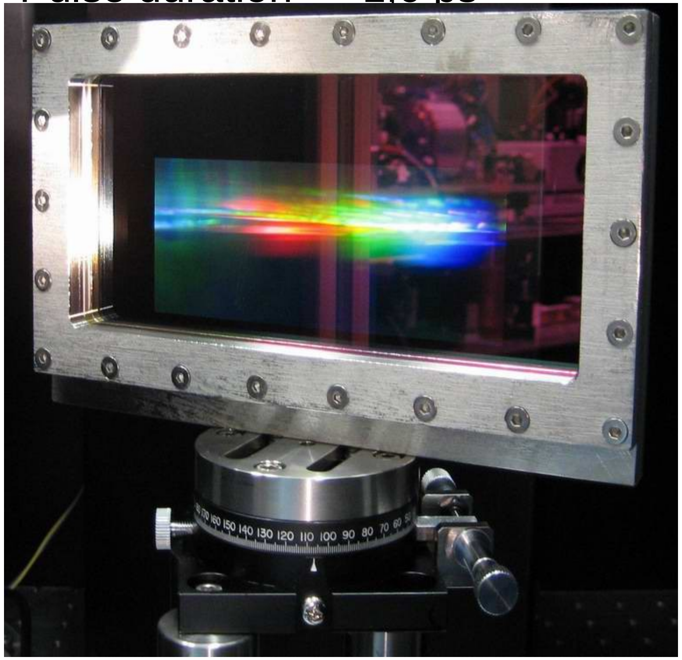
New lasers for industry and research

- **High average power pulsed LASErs**
- **Czech national project on development of advanced solid-state laser technologies based on diode pumping**
- **Motivated by strong need for head-start laser technology development & prototyping for the next generation of high rep. rate laser facilities**
- **Potential of industrial applications using rep. rate, high-peak and high-average power lasers**
- **Implementation phase: 4 years (fully supported)**
- **Operational phase: ALAP (institutional/grants/contractual)**



Compressor (negative GDD)
(Uni Jena 1400 Lines/mm):

Bandwidth	~1 nm @ 1030 nm
GDD	~ -10^8 fs^2
Efficiency	~ 77 %
Pulse duration	1.6 ps



0.5 kW ; 1J-2 J, 1 kHz staging for pumping the OPCPA, 1 kHz, Common effort, MPQ, court.T. Metzger

Intensity of radiation emitted by electron is given by

$$I = \frac{2e^2}{3m_e^2c^3}\left(\frac{dp_i}{ds}\frac{dp_i}{ds}\right)$$

In circularly polarized EM wave (**in plasma**), whose

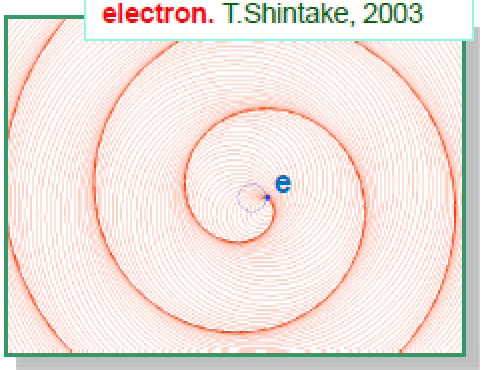
amplitude is equal to $a_0 = \frac{eE_0}{m_e\omega_0 c}$ electron energy

losses are

$$\dot{\mathcal{E}}^{(-)} = \frac{2e^4E_0^2}{3m_e^2c^3}\left[1+\left(\frac{eE_0}{m_e\omega_0 c}\right)^2\right]$$

For linearly polarized wave we have

$$\dot{\mathcal{E}}^{(-)} = \frac{e^4E_0^2}{3m_e^2c^3}\left[1+\frac{3}{8}\left(\frac{eE_0}{m_e\omega_0 c}\right)^2\right]$$



Pattern of field emitted by electron. T.Shintake, 2003

L.D.Landau & E.M.Lifshitz
«The Classical Theory of Fields»

Quantum Effects become important, when the recoil due to photon emission becomes of the order of the electron momentum, i.e. At

$$\gamma_e \geq \gamma_Q = \left(\frac{m_e c^2}{\hbar \omega_0} \right)^{1/2}$$

For electron gamma-factor $\gamma_e = \left(a_0 / \varepsilon_{rad} \right)^{1/4}$ it yields the quantum limit:

$$a_Q = \frac{2e^2 m_e c}{3\hbar^2 \omega_0} = \frac{2\alpha}{3} \frac{m_e c^2}{\hbar \omega_0}$$

EM wave amplitude and intensity correspond to

$$E_Q = \frac{2e m_e^2 c^2}{3\hbar^2} = \frac{2\alpha}{3} E_{QED}, \quad \alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

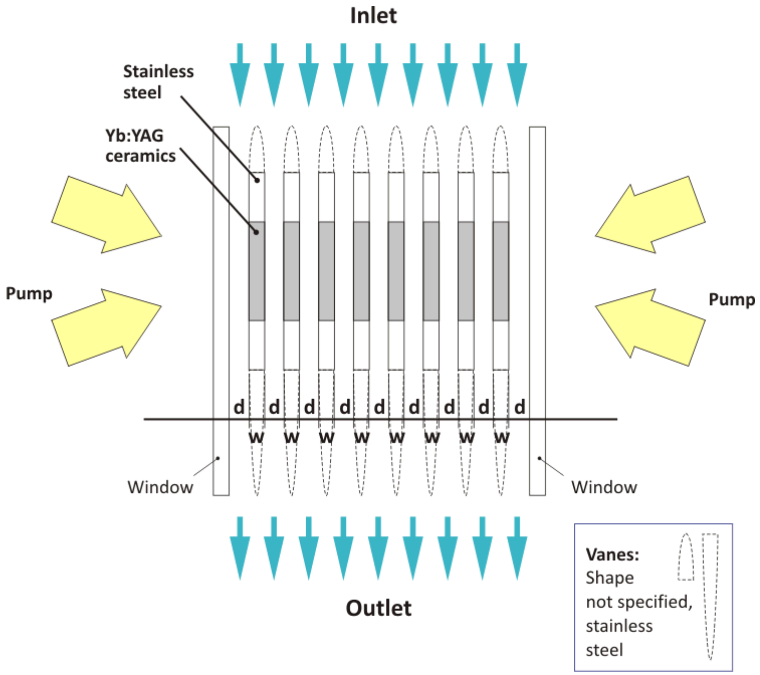
and $I_{las} = 8.5 \times 10^{24}\, W/cm^2$

Here E_{QED} is the Schwinger field $E_{QED} = \frac{m_e^2 c^3}{e\hbar}$

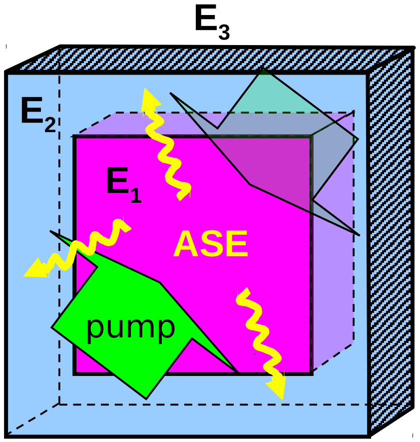
Modelling of ASE losses and energy budget in multislab lasers

Design phase of 500 J/ 10 Hz multislab amplifiers
(collaboration with Rutherford Appleton Laboratory)

Baseline model



8 Yb:YAG slabs, each 8 mm thick
Nominal operation temp. 170K



Heat sources in the crystal:

- Transition (>11 %):
  - Stokes defect
  - Quantum efficiency (non-radiative)
- Radiative (>35 %)
  - Absorption on impurities
  - Absorption on the ASE absorber
  - Higher orders effects (colective absorption)
- ASE losses can be limited by MLD absorptive coating or Cr:YAG absorber
- Heat conduction calculations predict < 4 K temperature non-uniformity

M. Divoký et al. Numerical evaluation of heat deposition in cryogenically cooled multi-slab amplifier

Two other important steps:

Phase control in stretchers and compressors including higher order material dispersion of the amplifier system

Regenerative pulse shaping

enabled the first 18fs TW pulse generation in 1996

October 1, 1993 / Vol. 18, No. 19 / OPTICS LETTERS

Quintic-phase-limited, spatially uniform expansion and recompression of ultrashort optical pulses

B. E. Lemoff and C. P. J. Barty

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Received April 15, 1993

Design of an expansion and recompression system for amplification of sub-20-fs optical pulses to multiterawatt peak powers is presented. The system allows one to eliminate spatial inhomogeneities and cubic and quartic phase errors that make existing designs unsuitable for use with pulses much shorter than 100 fs. We experimentally demonstrate $>10{,}000$ times expansion and recompression of $\sim$25-fs optical pulses.

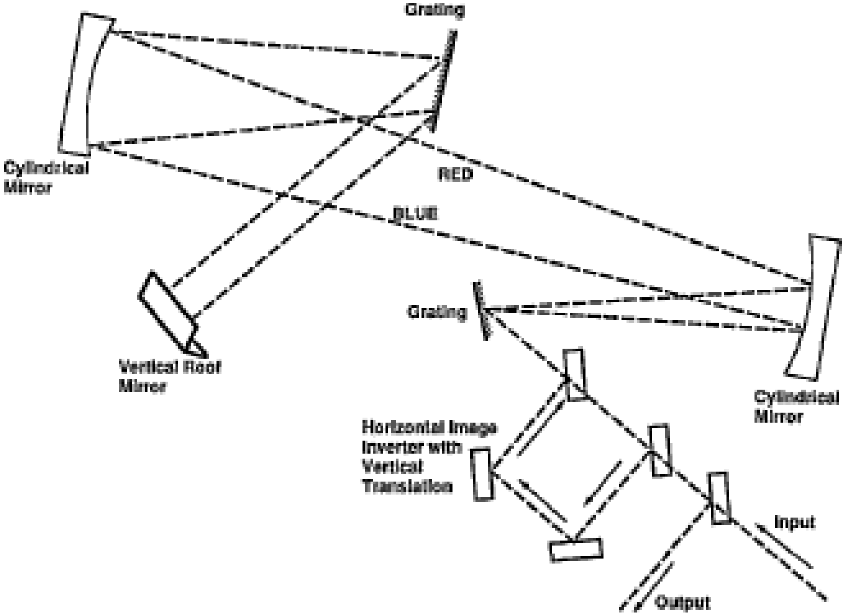


Fig. 1. Schematic of the all-reflective pulse expander. The beam is vertically multiplexed four times, with vertical displacement occurring twice at the roof mirror and once at the horizontal image inverter.

February 1, 1996 / Vol. 21, No. 3 / OPTICS LETTERS

Regenerative pulse shaping and amplification of ultrabroadband optical pulses

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Received August 3, 1995

Regenerative pulse shaping is used to alleviate gain narrowing during ultrashort-pulse amplification. Amplification bandwidths of ~100 nm, or nearly three times wider than the traditional gain-narrowing limit, are produced with a modified Ti:sapphire regenerative amplifier. This novel regenerative amplifier has been used to amplify pulses to the 5-mJ level with a bandwidth sufficient to support ~10-fs pulses.

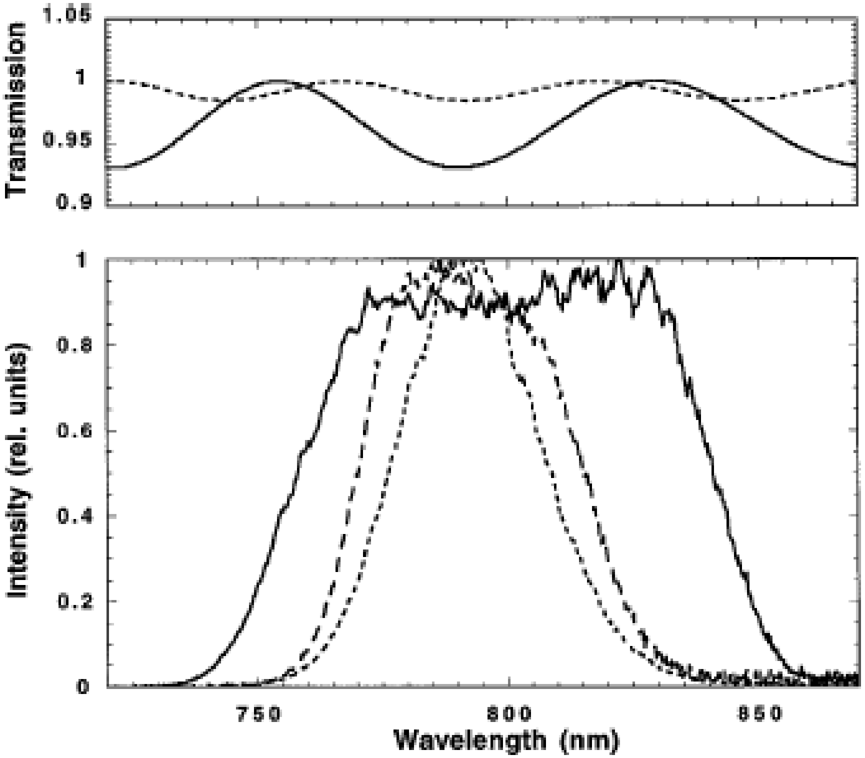


Fig. 2. Bottom plot: ASE spectra from the free-running amplifier without a filter (dotted curve, 33 nm FWHM), with a 5-μm étalon (dashed curve, 45 nm FWHM), and with a 3-μm étalon (solid curve, 84 nm FWHM). Top plot: representative single-pass transmission curves for a 3-μm (solid curve) and a 5-μm (dashed curve) nitrocellulose étalon oriented to be antiresonant at ~790 nm (angles of incidence 5.6 and 11.5 deg, respectively).

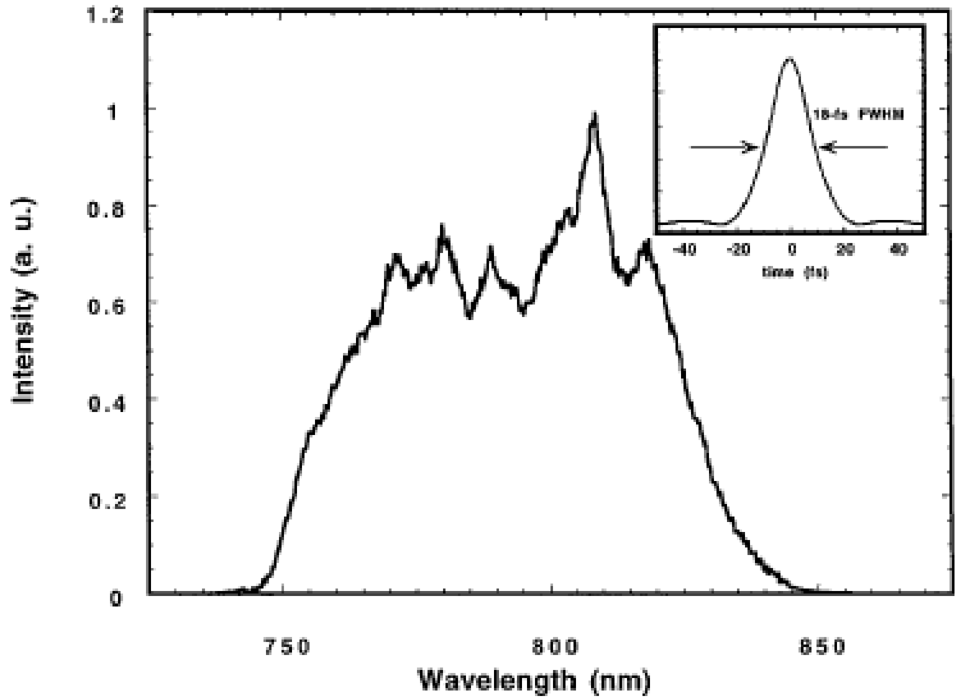


Fig. 3. Measured amplified spectrum. Inset: transform-limited pulse shape corresponding to this spectrum (FWHM 18 fs).

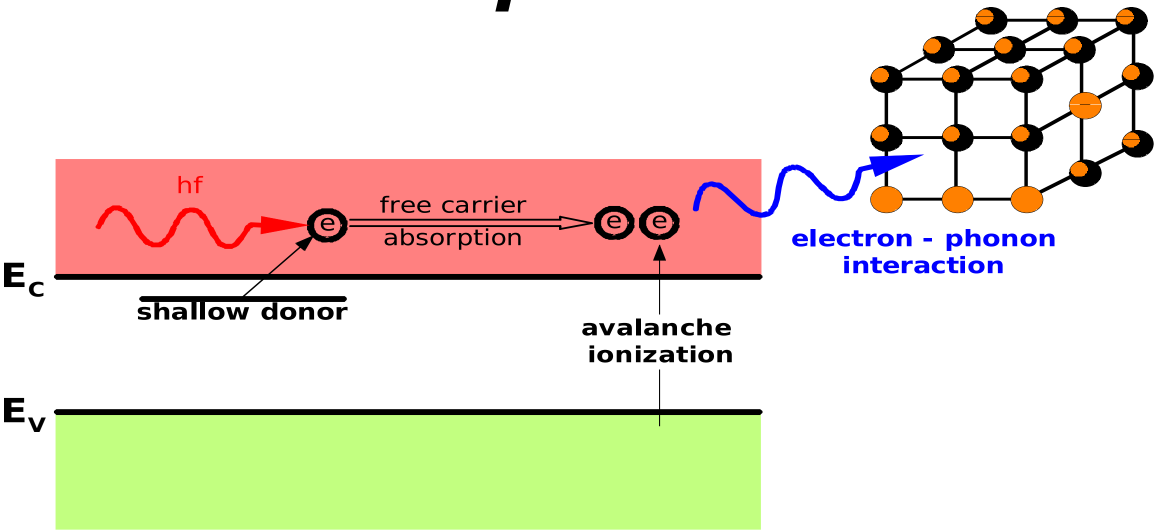
C. P. J. Barty et al Optics Letters V.21, May 1, pp. 668
„Generation of 18fs multiterawatt pulses by regenerative pulse shaping and CPA“

Micromachining with fs-pulses

little collateral damage (pulse shorter than the electron-phonon coupling time in most media)

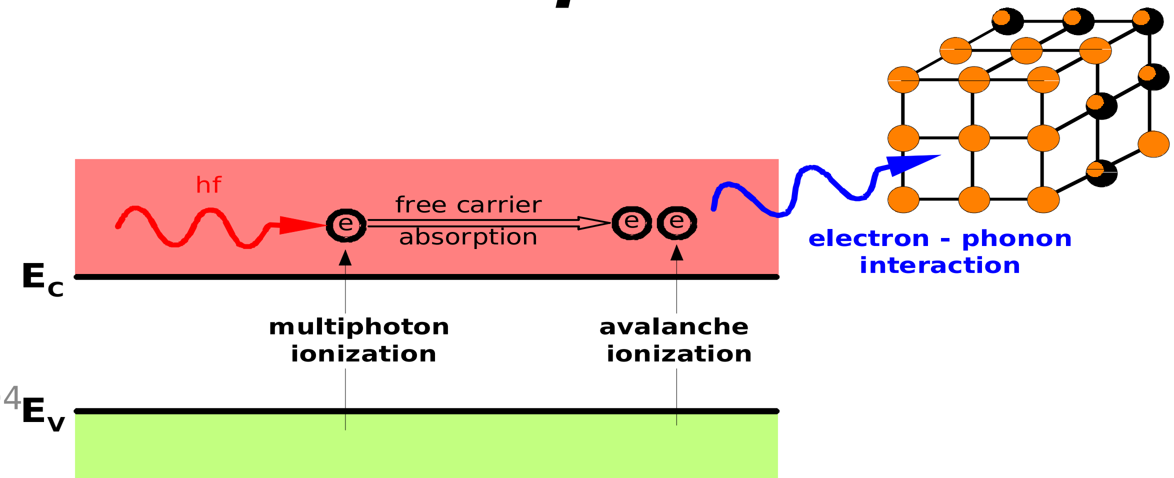
very precise, allows structering inside transparent materials (Ophthalmolgy, LASIK and Cataract Surgery)
FR !
the process is deterministic, starts from seed electrons generated by multiphoton ionization
not from impurities which are statistically distributed

Nanosecond pulses:



statistical proc.
by heat transfer to
the lattice affects
Bigger zones

Femtosecond pulses:



highly deterministic
no heat transfer to
the lattice; well
defined and precise
micromachining

Laser-induced breakdown by impact ionization in SiO_2 with pulse widths from 7 ns to 150 fs

D. Du, X. Liu, G. Korn, J. Squier, and G. Mourou
Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, Michigan 48109-2099

(Received 13 September 1993; accepted for publication 16 March 1994)

Results of laser-induced breakdown experiments in fused silica (SiO_2) employing 150 fs–7 ns, 780 nm laser pulses are reported. The avalanche ionization mechanism is found to dominate over the entire pulse-width range. Fluence breakdown threshold does not follow the scaling of $F_{\text{th}} \sim \sqrt{\tau_p}$, when pulses are shorter than 10 ps. The impact ionization coefficient of SiO_2 is measured up to $\sim 3 \times 10^8$ V/cm. The relative role of photoionization in breakdown for ultrashort pulses is discussed.

Appl. Phys. Lett.. Vol. 64. No. 23. 6 June 1994

Micromachining with fs-pulses

little collateral damage (pulse shorter than the electron-phonon coupling time in most media)

very precise, allows structering inside transparent materials (Ophthalmolgy)

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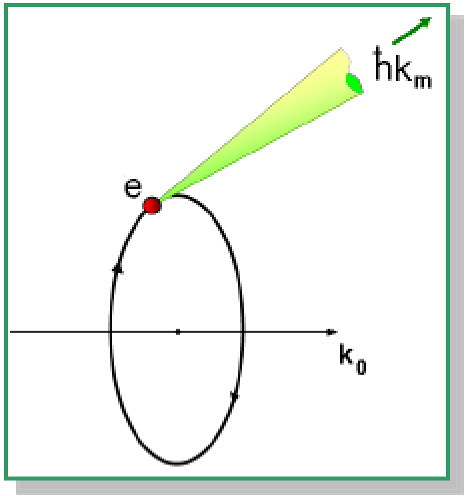
not from impurities which are statistically distributed

Equations of electron motion are:

$$m_e c \frac{du^i}{ds} = \frac{e}{c} F^{ik} u_k + g^i$$



Radiation friction force is given by

$$g^i = \frac{2e^2}{3c}\left(\frac{d^2u^i}{ds^2} - u^i u^k \frac{d^2u_k}{ds^2}\right)$$

Here $i = 0,1,2,3$, s is proper time: $ds = c\dfrac{dt}{\gamma}$

4-velocity is $u^i = \dfrac{dx^i}{ds} = \left(\gamma, \dfrac{\mathbf{p}}{m_e c}\right)$

and $F_{ij} = \dfrac{\partial A_j}{\partial x^i} - \dfrac{\partial A_i}{\partial x^j}$ is 4-tensor of EM field

The EM wave can provide energy gain rate not higher than

$$\dot{\mathcal{E}}^{(+)} \approx \omega_0 m_e c^2 a_0$$

Energy Balance Condition $\dot{\mathcal{E}}^{(+)} = \dot{\mathcal{E}}^{(-)}$ yields

$a^c_{rad} = (3\lambda_0 / 4\pi r_e)^{1/3}$ for circular polarization

$a^l_{rad} = (4\lambda_0 / \pi r_e)^{1/3}$ for linear polarization

where $r_e = e^2 / m_e c^2 \approx 2.8 \times 10^{-13} cm$ is classical electron radius

For laser wavelength of $\lambda_0 = 0.8 \mu m$ we obtain

$a^c_{rad} = 408$ and $a^l_{rad} = 713$

which corresponds to laser intensity $I_{las} = (4.5 - 7.0) \times 10^{23} W/cm^2$

Emitted γ- photon energy: $\hbar\omega = \hbar\omega_0 a^3_{rad} \approx (70 - 350)\ MeV$

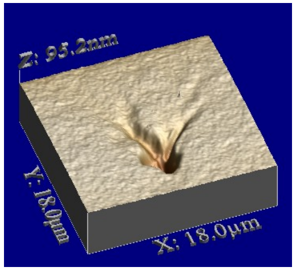
Ya. B. Zel'dovich, Sov. Phys. Usp. 18, 79 (1975); A. G. Zhidkov,etal, PRL 88, 185002 (2002); S. V. Bulanov, etal Plasma Phys. Rep. 30, 221 (2004); J. Koga et al., PoP 12, 093106 (2005); N. M. Naumova etal., PRL (2009)

Secondary effects of electron acceleration:

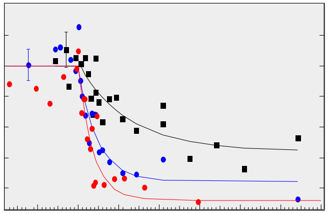
X-ray Beams
(compact laser driven LUX, X-FEL, betatron radiation, gamma..)

Motivations : brigth fs sources for applications

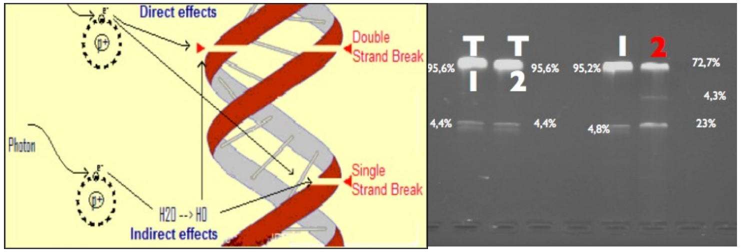
Ablation



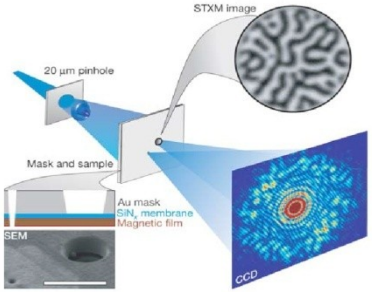
Phase transitions



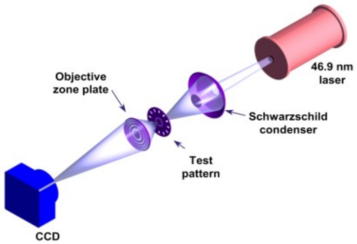
Bio structures, damage

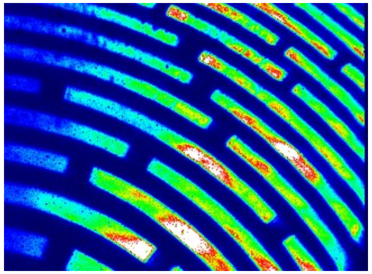


Magnetism

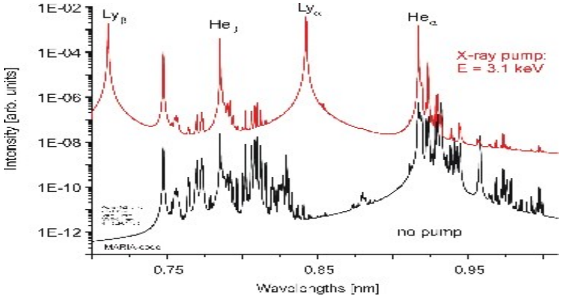


X-ray microscopy

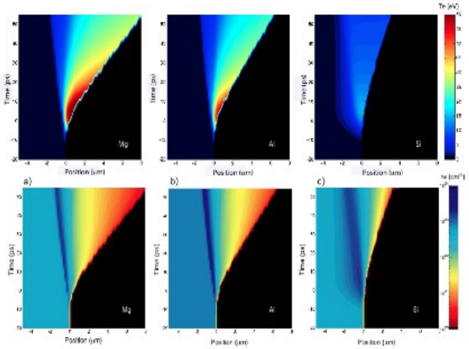




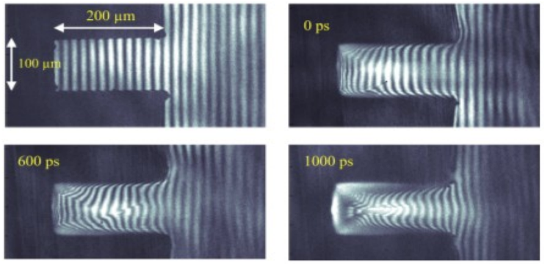
Atomic physics



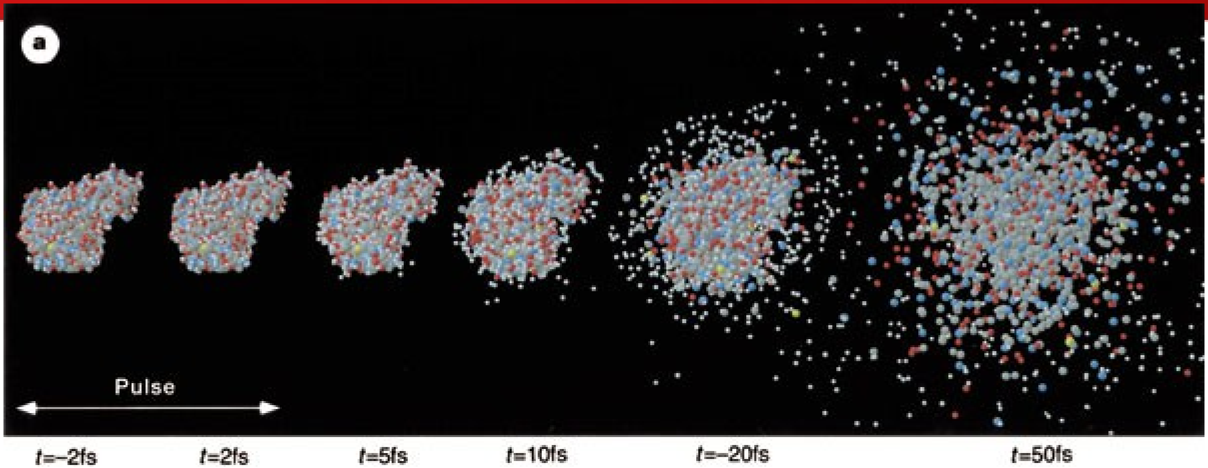
Warm dense matter

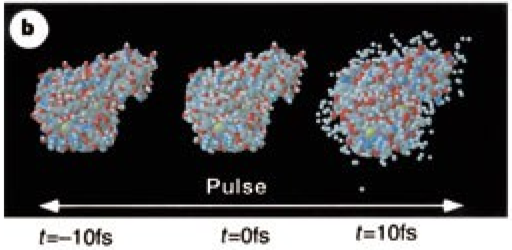


Plasma diagnostics

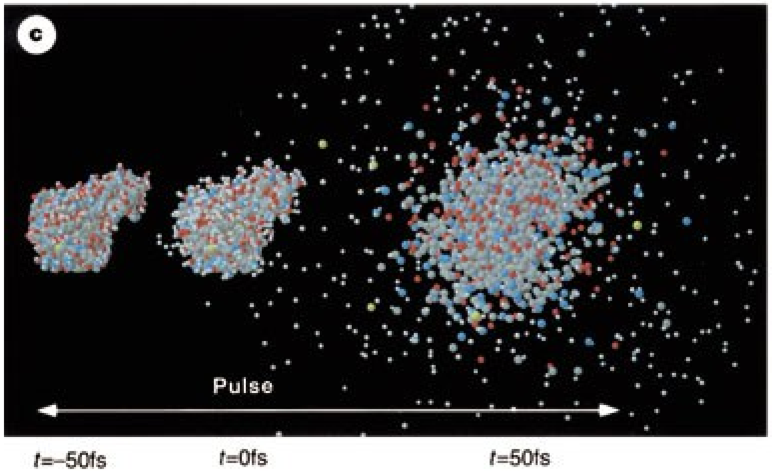


Explosion of T4 lysozyme (white, H; grey, C; blue, N; red, O; yellow, S) induced by radiation damage.



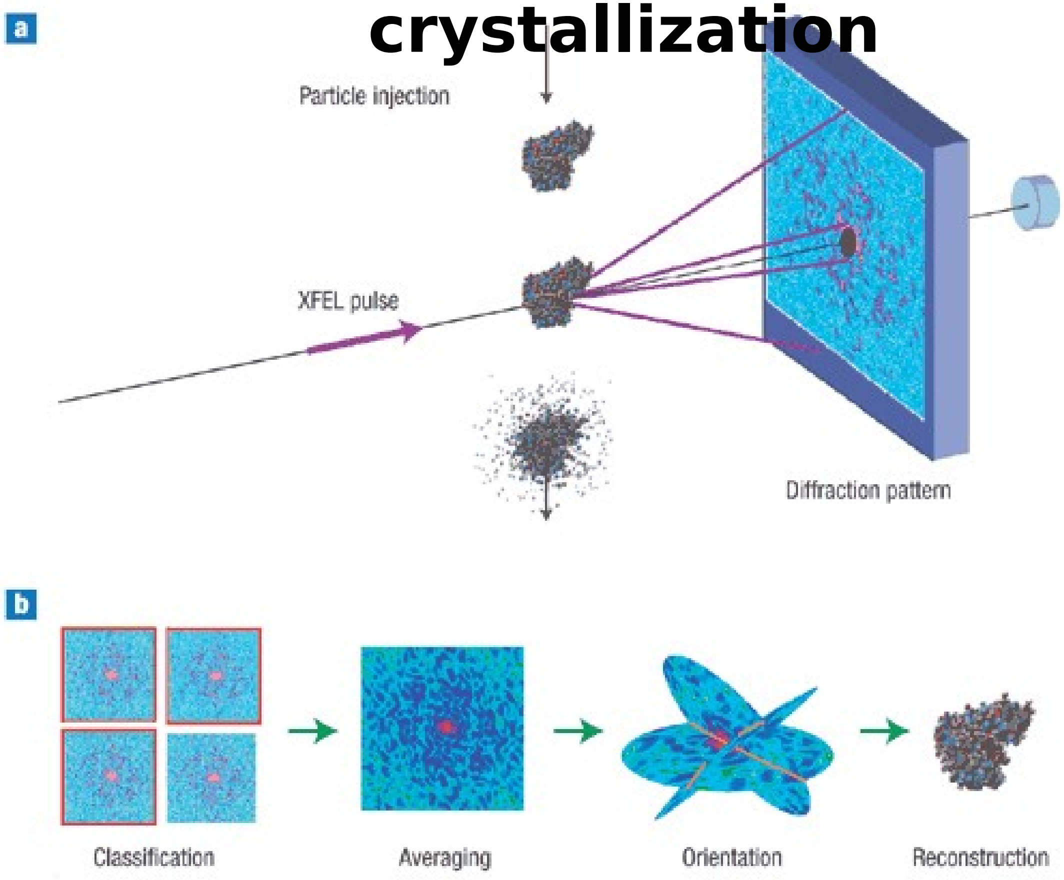


The integrated X-ray intensity is 3 x10^{12} (12 keV) photons per 100-nm diameter spot (3.8 10^{6} photons per Å^{2}) in all cases.



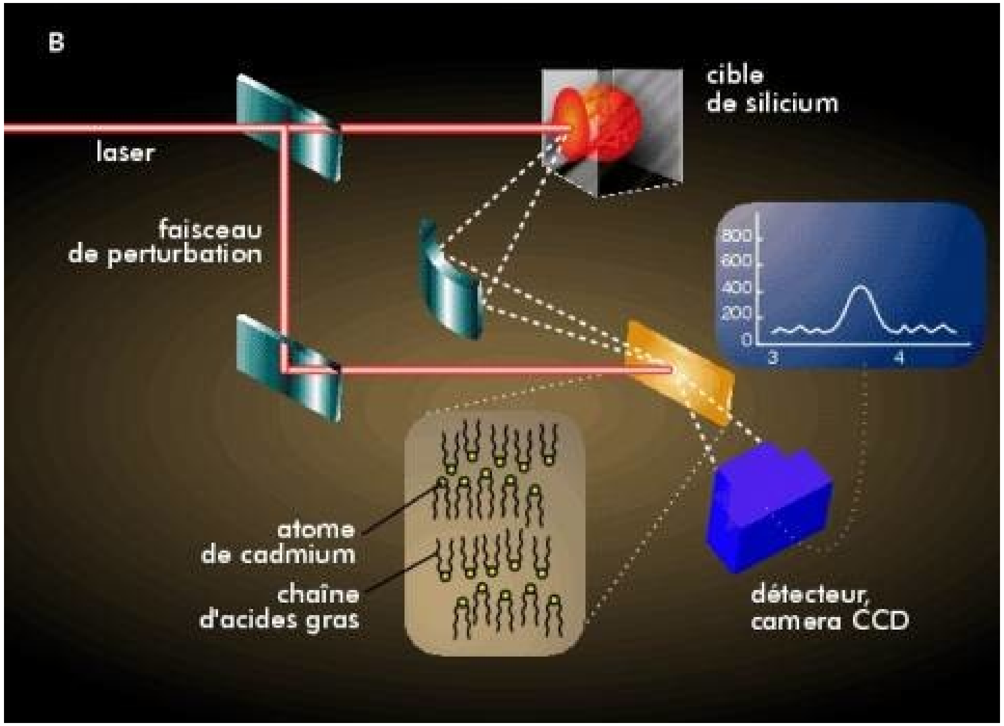
Richard Neutze, Remco Wouts, David van der Spoel, Edgar Weckert and Janos Hajdu
Nature 406, 752-757(17 August 2000)

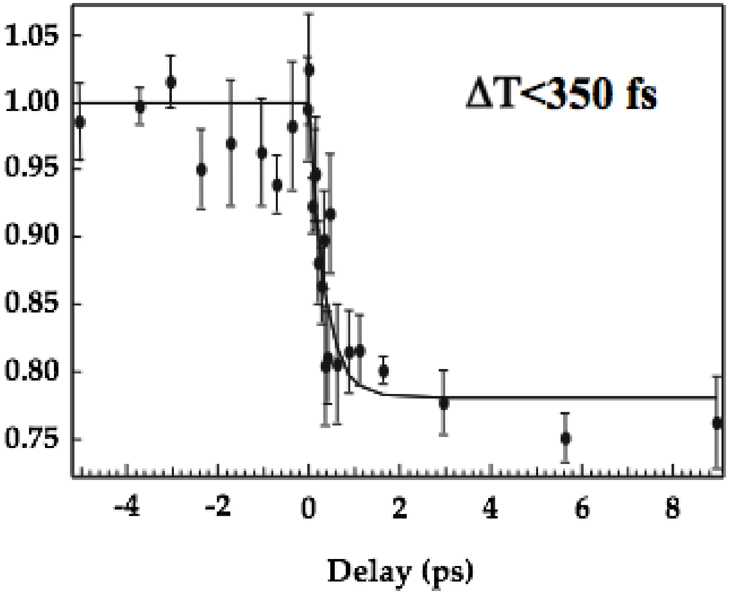
Single- particle diffraction imaging of biological particles without crystallization



Kirz,Nature Physics 2, 799 - 800 (20

K-alpha emission appropriate for pump-probe experiments with 100 fs time resolution





Rousse et al. Nature 410 (6824) 65 (2001)

RPDA Particle-In-Cell simulation

code REMP

Initial configuration

$$a = 316, \quad I = 10^{23} W/cm^2$$

$$20\lambda \times 10\lambda, \;\; s - pol$$

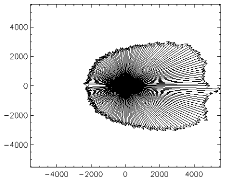
$$l_0 = 0.25\lambda, \quad \frac{\omega}{\omega_{pe}} = \frac{1}{4}$$

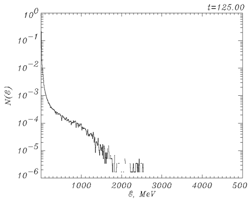
$$\frac{m_p}{m_e} = 1836$$

$E_z(x, y)$

electrons

$n_e(x, y)$

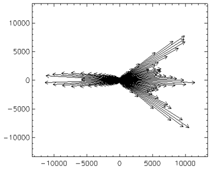


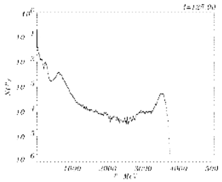


$N_e(E)$

ions

$n_p(x, y)$





$N_p(E)$