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The Extreme Light Infrastructure ELI

A concerted community effort to push today's intensity frontiers

Wolfgang Sandner
Director General and CEO
ELI Delivery Consortium International Association (AISBL)

Extreme High-Intensity Laser Physics Conference
MPIK Heidelberg, Germany, July 21, 2015

Project supported by:
EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
INVESTING IN YOUR FUTURE

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Executive summary

2005: ELI is being initiated as a bottom-up project by the scientific community

2006: ELI is part of the first ESFRI Roadmap (single sited, 200PW laser user facility)

2007-2010: EU-funded “Preparatory Phase”

Design concept 2010

Result from the"Preparatory Phase":

- Not one, but three (later: four) ELI
- Use EU Structural Funds for construction
- Operation as international user facility
- Legal constitution/financing as "ERIC"
- Science case: the "*ELI White Book*"

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The challenges

ELI will be

- the world's first **international** laser research infrastructure,
- a **distributed** research infrastructure based initially on 3 facilities in CZ, HU and RO
- the first ESFRI project to be implemented **in the new EU Member States**
- pioneering a **novel funding model** combining, EU research funds (FP7), EU structural funds (ERDF), and contributions from an international consortium of countries (ERIC)

The product

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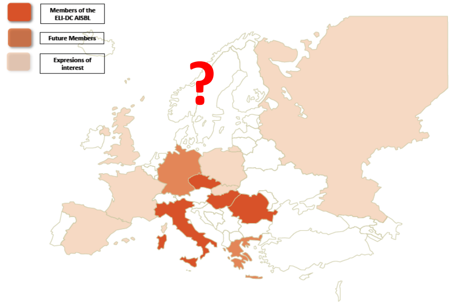
Attosecond Laser Science, will capitalize on new regimes of time resolution (*ELI-ALPS*, Szeged, HU)

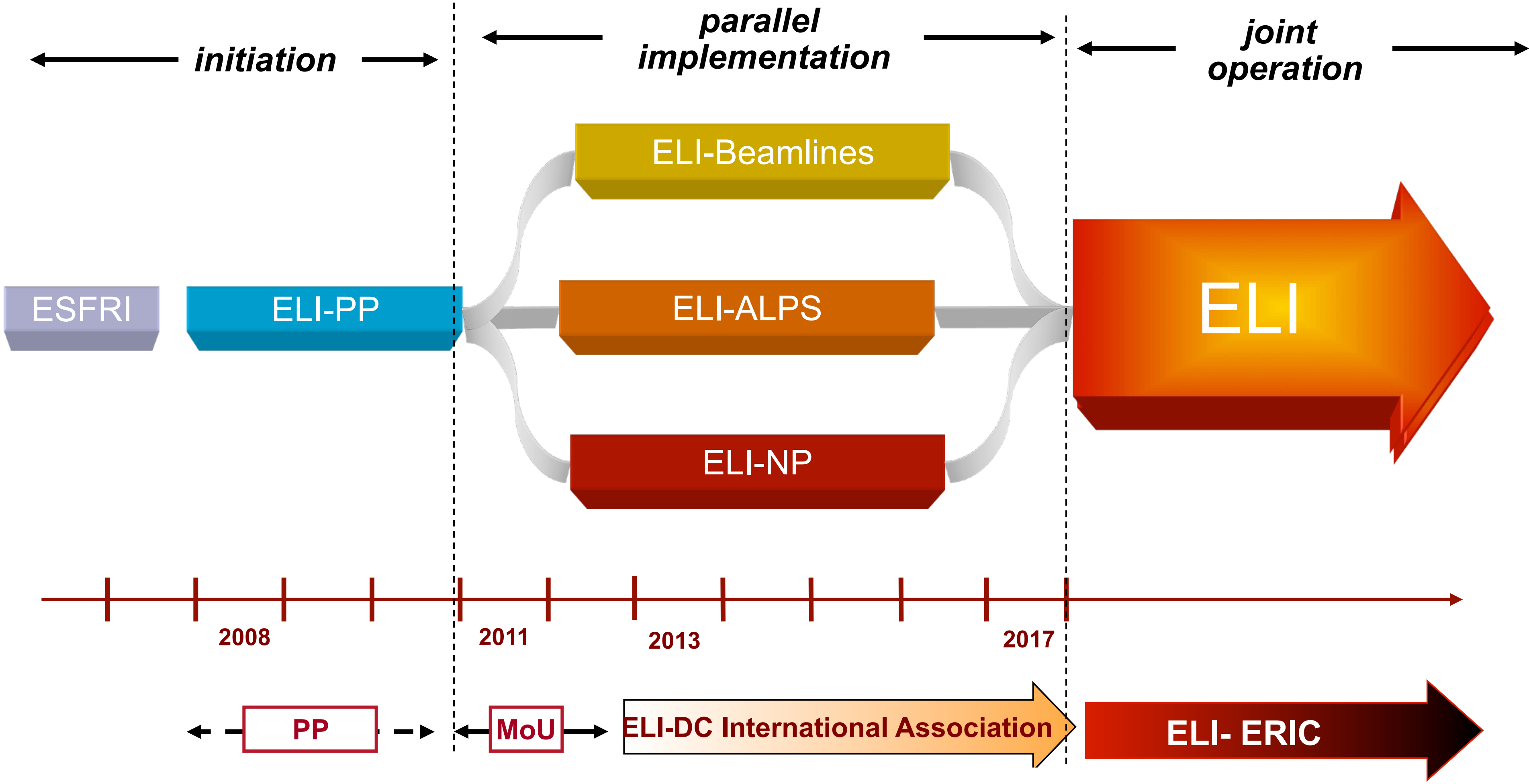
High-Energy Beam Facility, responsible for development and application of ultra-short pulses of high-energy particles and radiation (*ELI-Beamlines*, Prague, CZ)

Nuclear Physics Facility with ultra-intense laser and brilliant gamma beams (up to 19 MeV) enabling novel photonuclear studies (*ELI-NP*, Magurele, RO)

Ultra-High-Field Science centred on direct physics of the unprecedented laser field strength (*ELI 4*, to be decided)

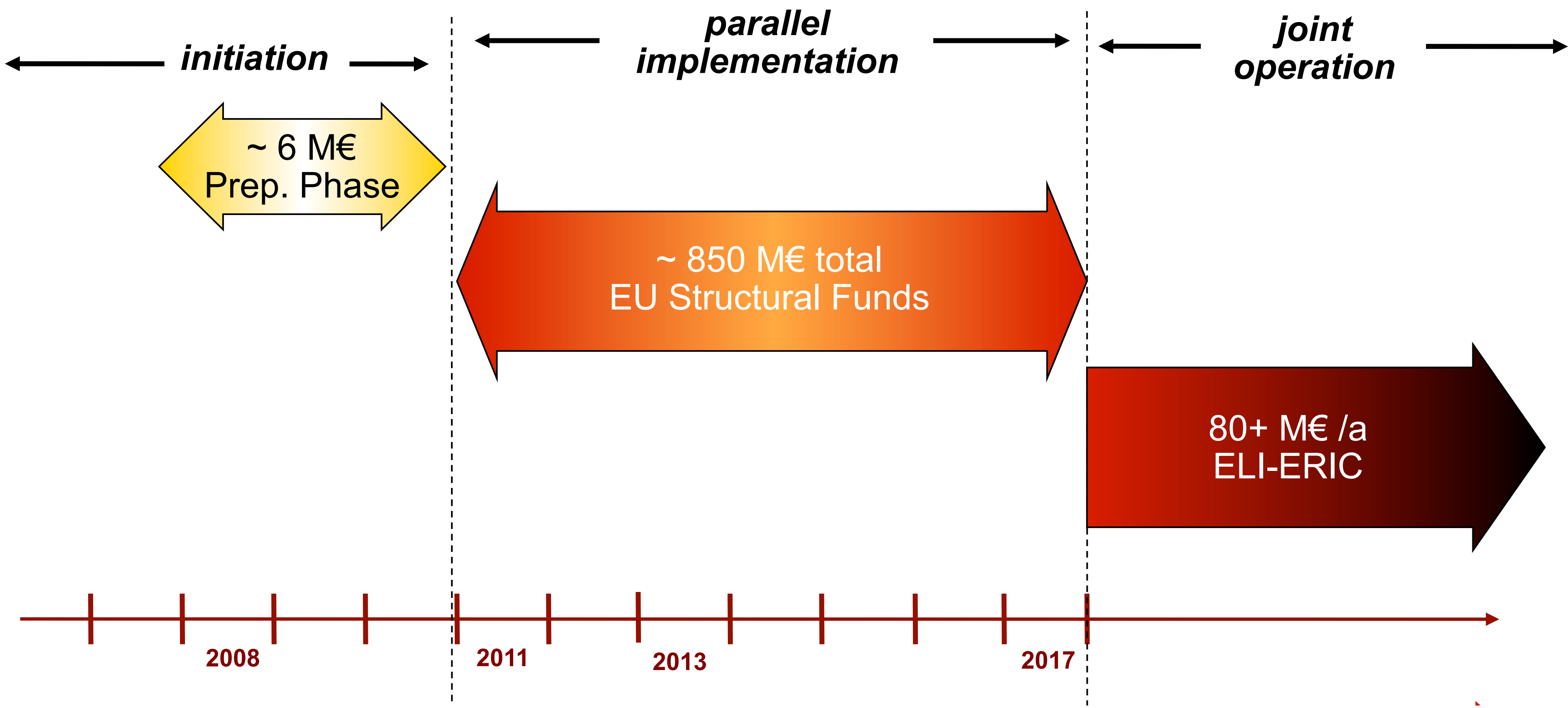


The implementation plan



Governing bodies

Financial plan



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ELI 2015-2018

Completion of the construction sites

Development of the business model / business plan for operation

Merger of 3 legally autonomous construction projects into one unified pan-European research infrastructure

Integration into the European landscape of national research infrastructures

Establishment of the ELI-ERIC Consortium

Operation as an international, open-access user facility

Completion of the construction sites

For a very comprehensive and up-to-date overview over the implementation status of the three pillars please consult:

JASPERS Network meeting
"ELI Pillars – status and way forward"
European Commission, Brussels, Belgium, May 5 & 6, 2015

http://www.jaspersnetwork.org/pages/viewpage.action?pageId=19464456

ELI Science

ELI science includes:

- **Creation** of laser pulses with highest power and intensity, at highest repetition rates

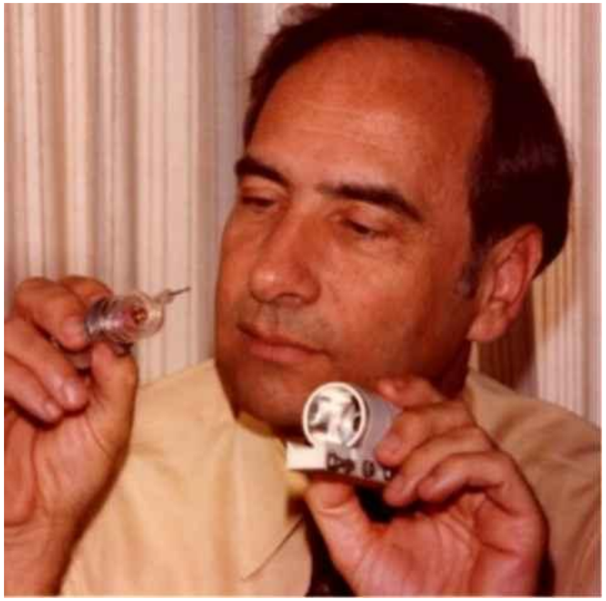
- **Interaction** of such pulses with matter: vacuum, nuclei, atoms, molecules, condensed matter and plasmas

- **Investigation and utilization of secondary radiation** of particles and photons from such interaction

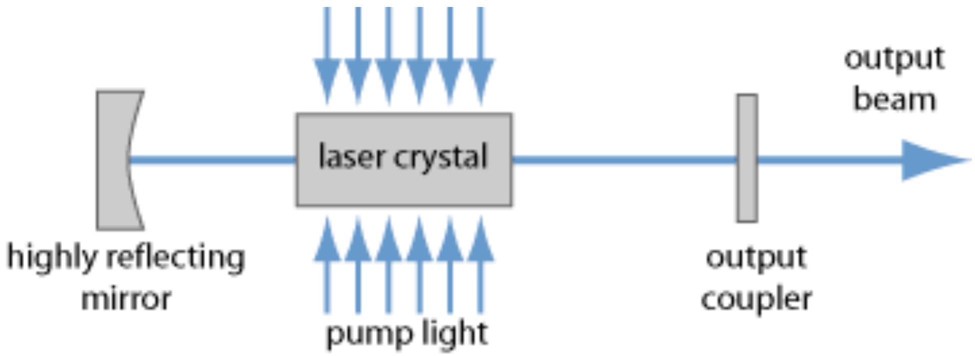
- **Application** of all this in societally relevant areas

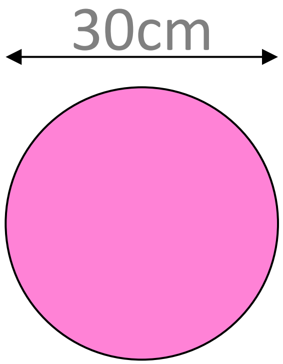
I Creation of extreme laser pulses:

Taking Theodore Maiman's laser concept to the extreme



The ultimate high-power solid state laser:





1000 PW = 1 Exawatt ?

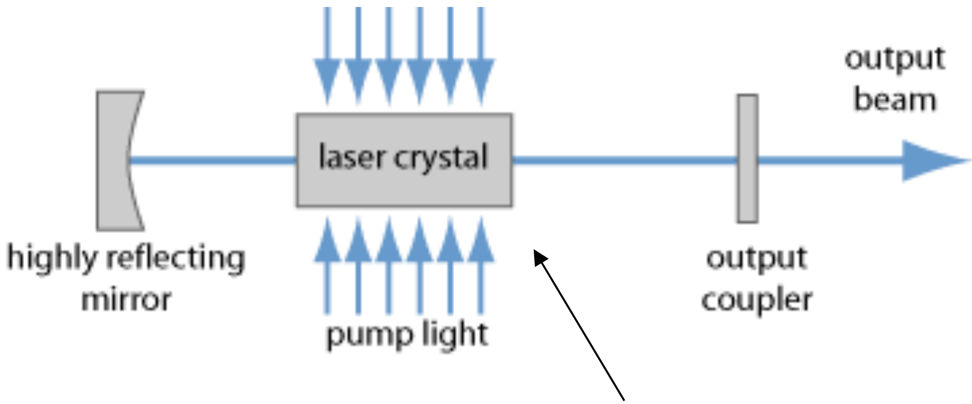
Active material physical limits :

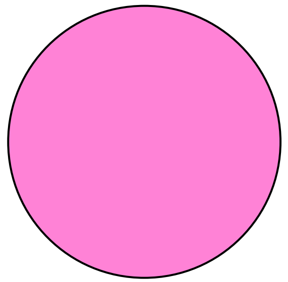
- Saturation fluence = 1 $h\nu / \sigma$ ~ 1J / cm^2
- Amplification bandwidth $\Delta\lambda$ < few 100nm => Pulse duration ~ fs
- maximum extractable power density ~ 1J / cm^2 fs ~ **1 PW /cm^2**

derives from basic materials constants only:

$h\nu$, σ, $\Delta\lambda$

The ultimate high-power solid state laser:





P_{max} < 10TW

Beam propagation limits:

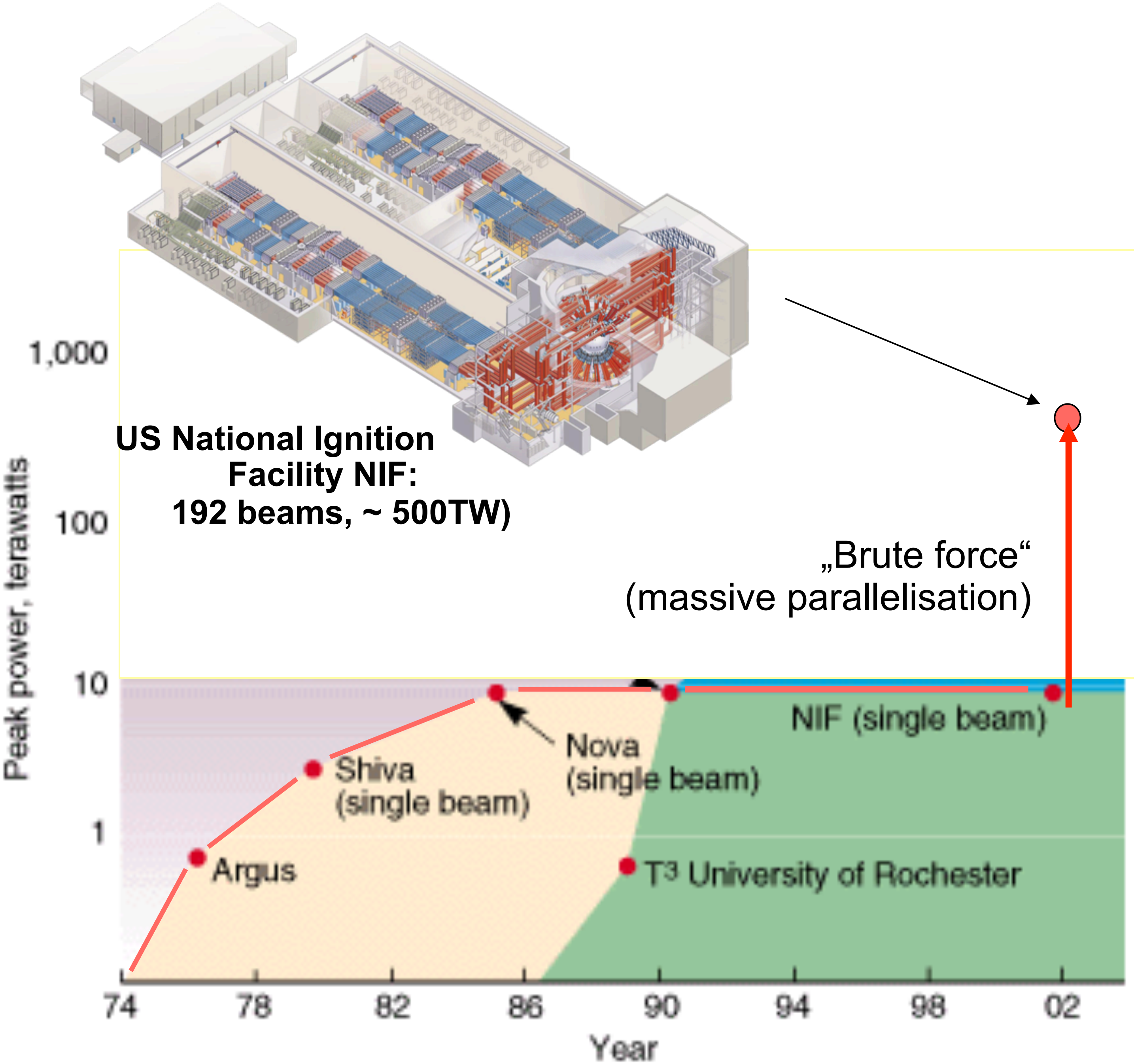
- Intensity– and n_2-dependent phase accumulation along the beam propagation z, the „B-Integral"

$$B \equiv \frac{2\pi}{\lambda} \int_0^L n_2(z) I(z) dz$$

- => Gauß beam self focusing above the critical power: $P_{cr} = \alpha \frac{\lambda^2}{4\pi n_0 n_2}$

- P_{crit} ~ 1 MW for usual λ, n_0, n_2 (materials constants again!).

- Special design „tricks" allow up to ~ 10TW single beam power



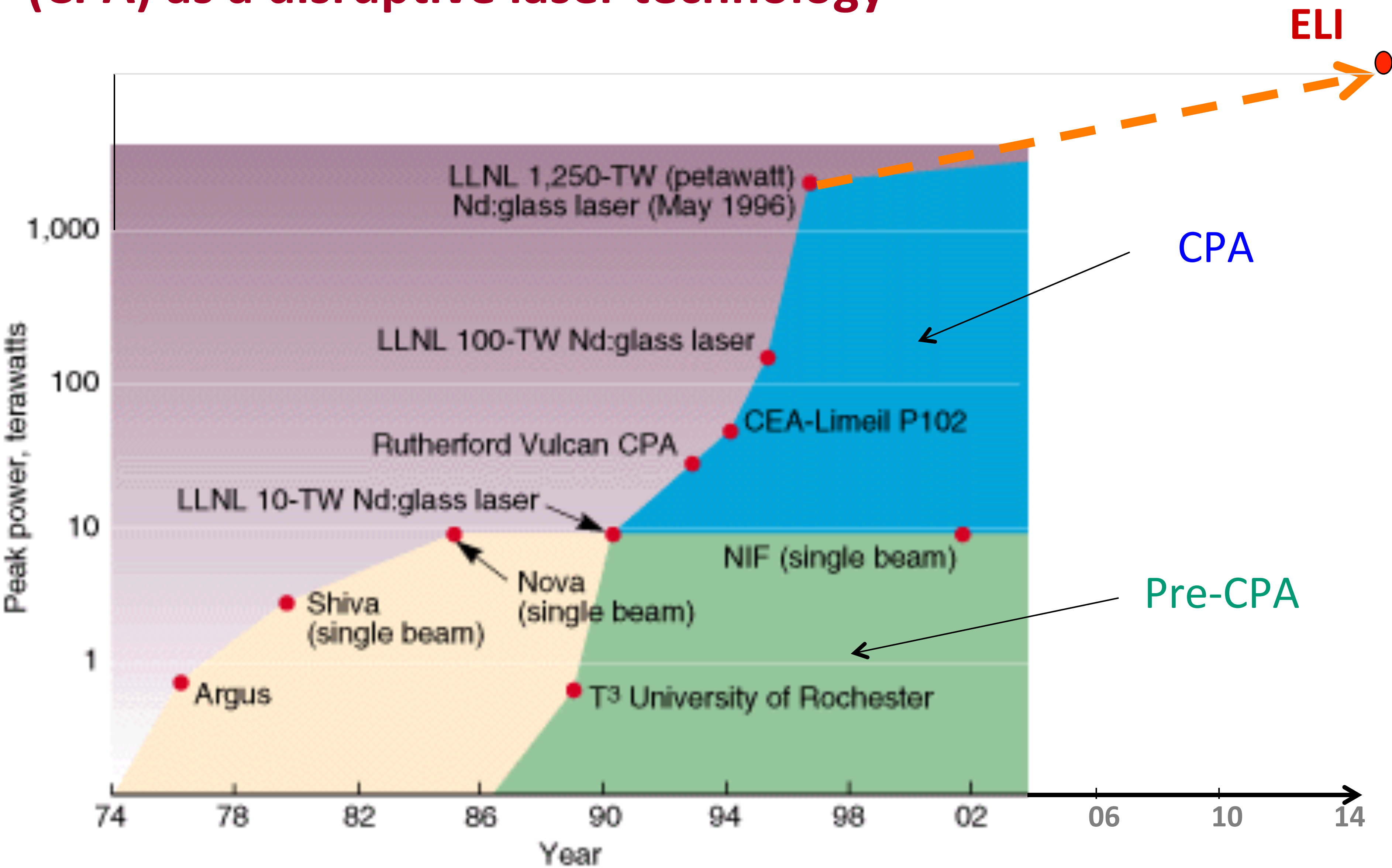
Milestones in laser development: early lasers (yellow), long-pulse technology (green),

Picture: LLNL

The need for disruptive technologies:

- **Chirped pulse amplification**: overcoming the B-Integral barrier (self-focusing)

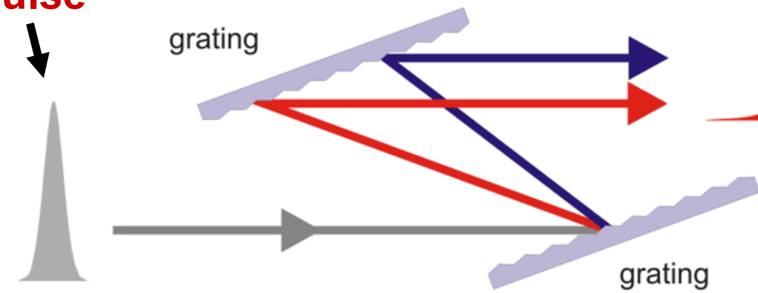
Chirped Pulse Amplification (CPA) as a disruptive laser technology

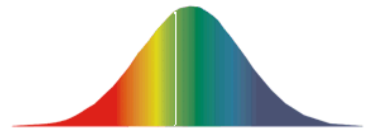


Picture: LLNL

CPA = Chirped Pulse Amplification

Ultra-short pulse





Carrier frequency:
$\omega = \omega_0 + \beta t$

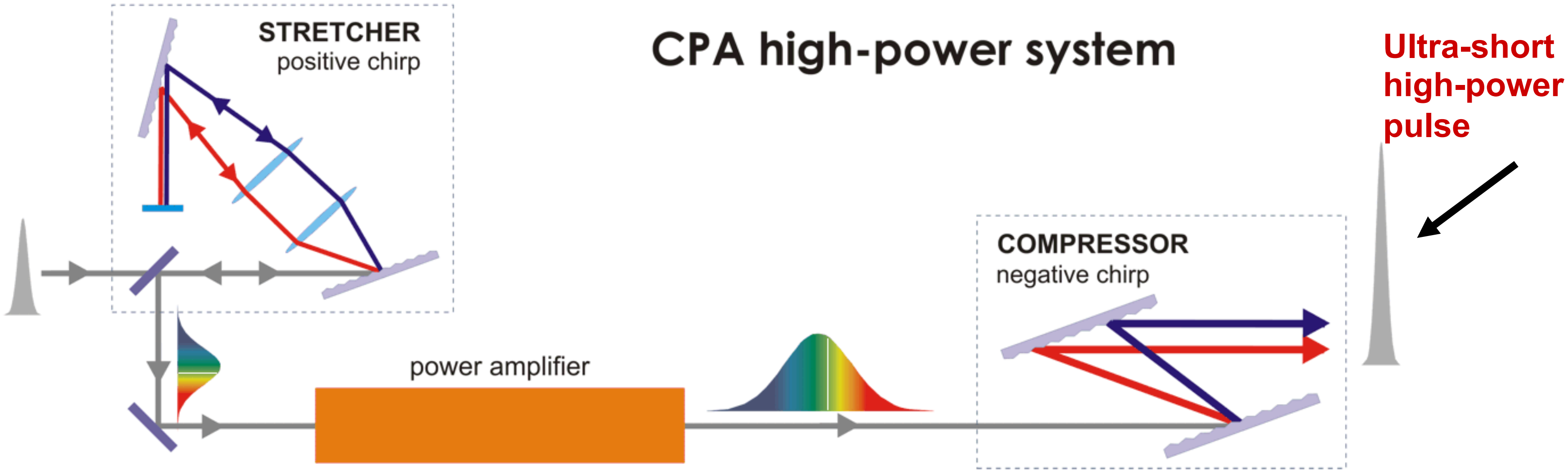
the gratings introduce a frequency dependent time delay

chirp = a linear frequency sweep, $d\omega/dt$

The "blue" frequency component appears ahead of the "red" component = NEGATIVE CHIRP

* E.B. Treacy, Optical Pulse Compression With Diffraction Gratings, IEEE J. Quant. El., Vol QE-5, pp. 454-458 (1969)
D. Strickland and G. Mourou, Compression of amplified chirped optical pulses, Opt. Commun. 56, 219 (1985)

CPA = Chirped Pulse Amplification



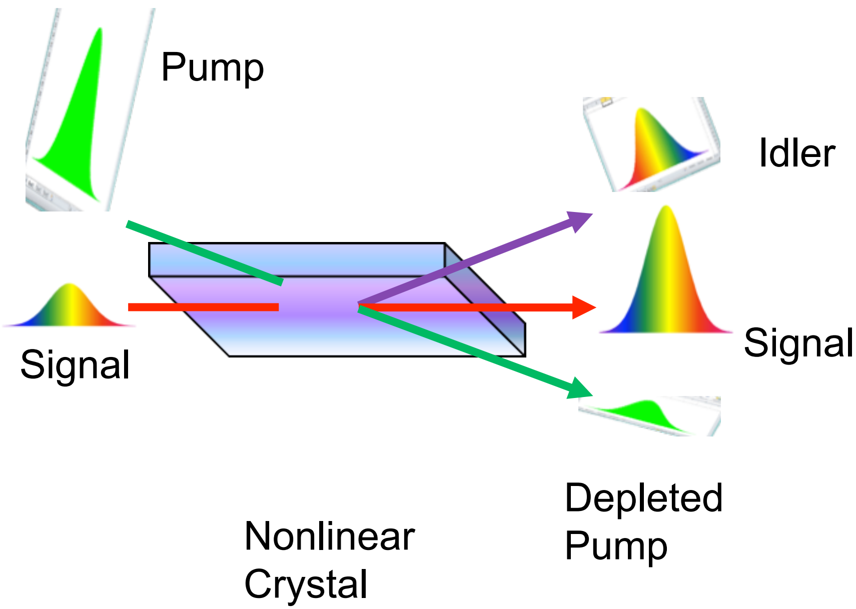
* E.B. Treacy, Optical Pulse Compression With Diffraction Gratings, IEEE J. Quant. El., Vol QE-5, pp. 454-458 (1969)
D. Strickland and G. Mourou, Compression of amplified chirped optical pulses, Opt. Commun. 56, 219 (1985)

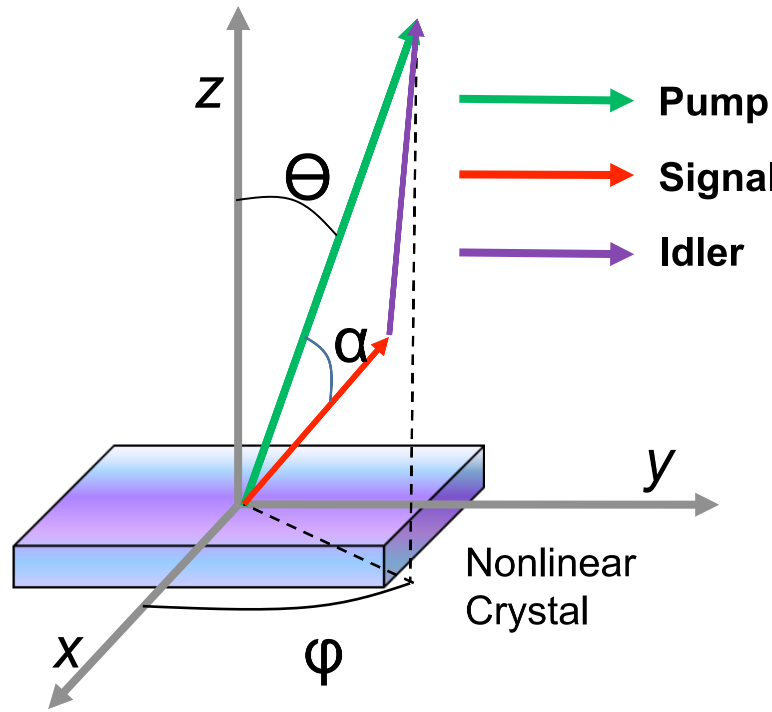
The need for disruptive technologies:

- **Chirped pulse amplification**: overcoming the B-Integral barrier (self-focusing)
- **Optical parametric amplification**: overcoming intermediate energy storage (population inversion => stimulated emission)

OPA = Optical Parametric Amplification

- Another disruptive technology: "Laser" without electronic population inversion and stimulated emission.
- Going beyond Einstein's (and Maiman's) LASER principle.





* A. Dubietis et al., Opt. Commun. 88, 433 (1992)
I.N. Ross et al., Opt. Commun. 144, 125 (1997)

The need for disruptive technologies:

- **Chirped pulse amplification**: overcoming the B-Integral barrier (self-focusing)

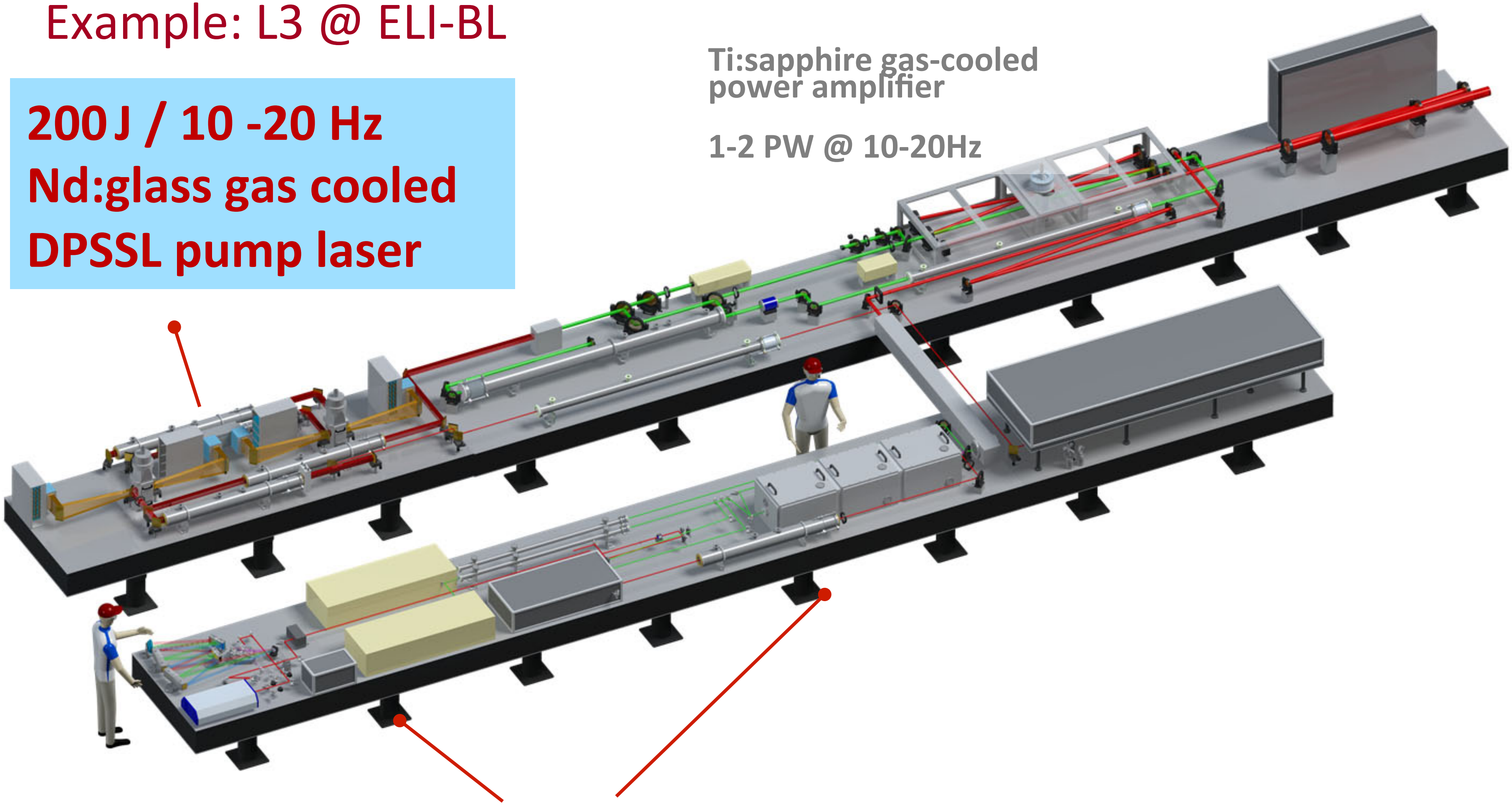
- **Optical parametric amplification**: overcoming intermediate energy storage (population inversion => stimulated emission)

- **Diode pumping**: overcoming the average power problem P_{av} ~ 1 W

Finally: high-repetition-rate diode pumping of high-power lasers

Example: L3 @ ELI-BL

200 J / 10 -20 Hz
Nd:glass gas cooled
DPSSL pump laser



The challenge after the petawatt
is the kilowatt !

=> ELI

Extreme power => ELI

- Today's most powerful lasers achieve
  ~ 1PW (50J/50fs) @ 1Hz (BELLA laser, LBL)
- There exist a handful of PW-class lasers world-wide

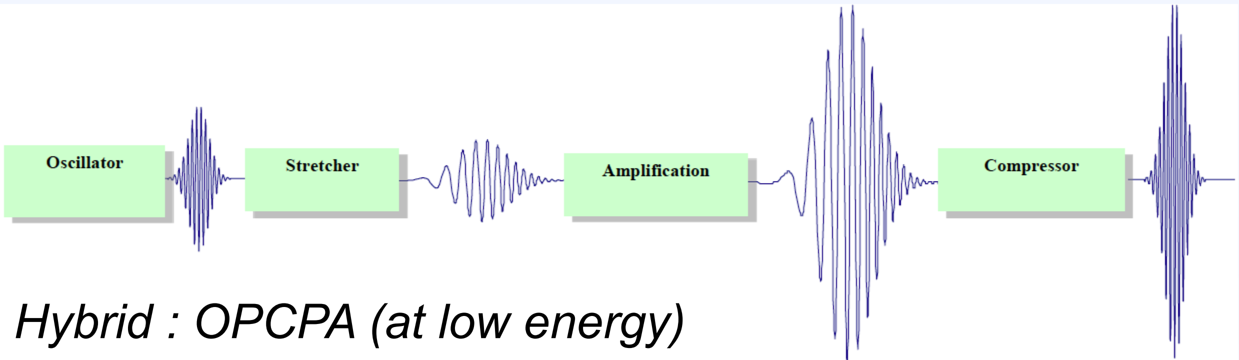
- **ELI** will have by 2018

  - Two coupled 10PW lasers (ELI-NP)
  - One 1-2PW laser @ 10-20Hz (ELI-Beamlines)
  - One 1PW laser (OPCPA, <20fs) @ 10Hz (ELI-Beamlines)
  - One 10PW laser (1.5kJ, 150fs) (ELI Beamlines)
  - One multi-PW laser @ <10Hz (ELI-ALPS)

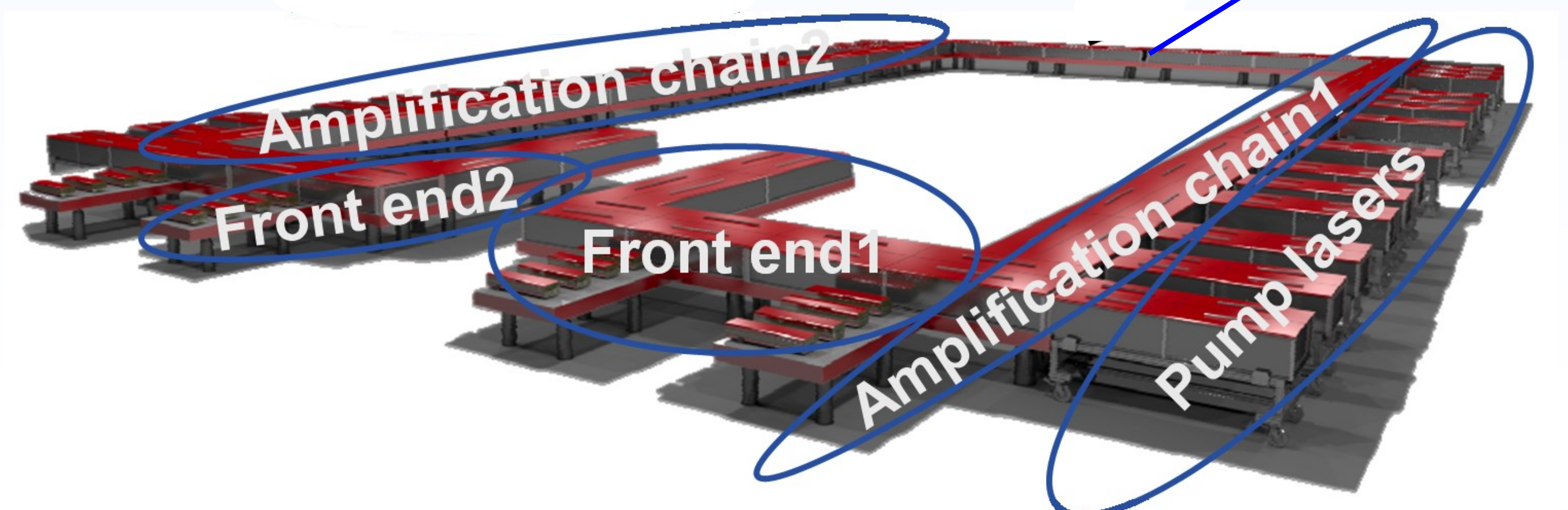
Each of these exceeds today's state-of-the-art by a factor of ~10 !

THALES Optronique– France
THALES – Romania

2 x	0.1 PW	10Hz
2 x	1 PW	1 Hz
2 x	10 PW	0.1 Hz

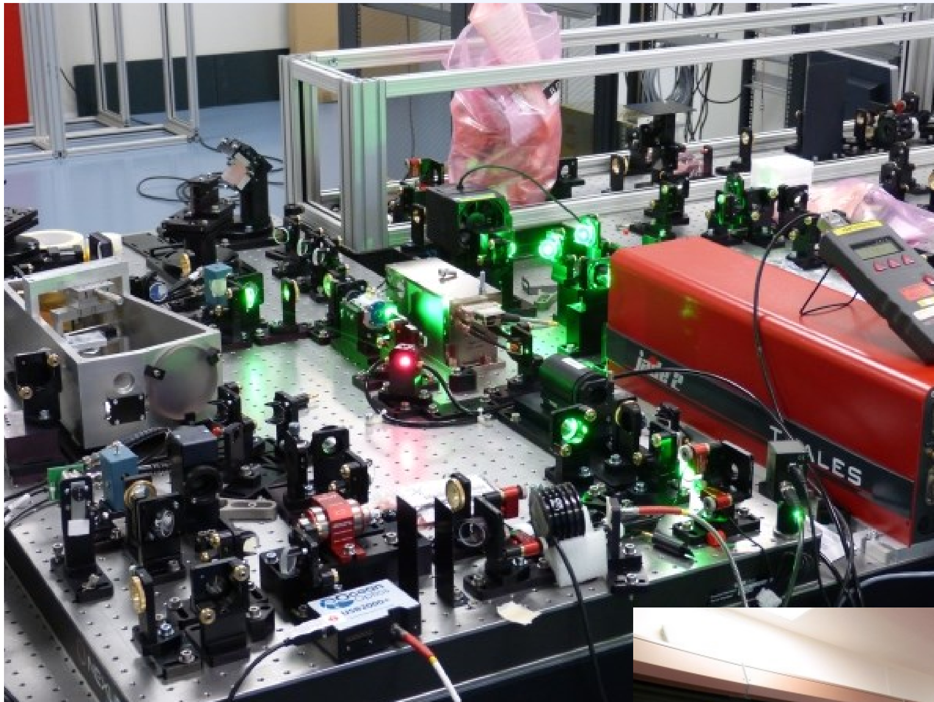


Hybrid : OPCPA (at low energy)
Ti: Sa CPA (at high energy)



eli Nuclear Physics

High Power Laser System



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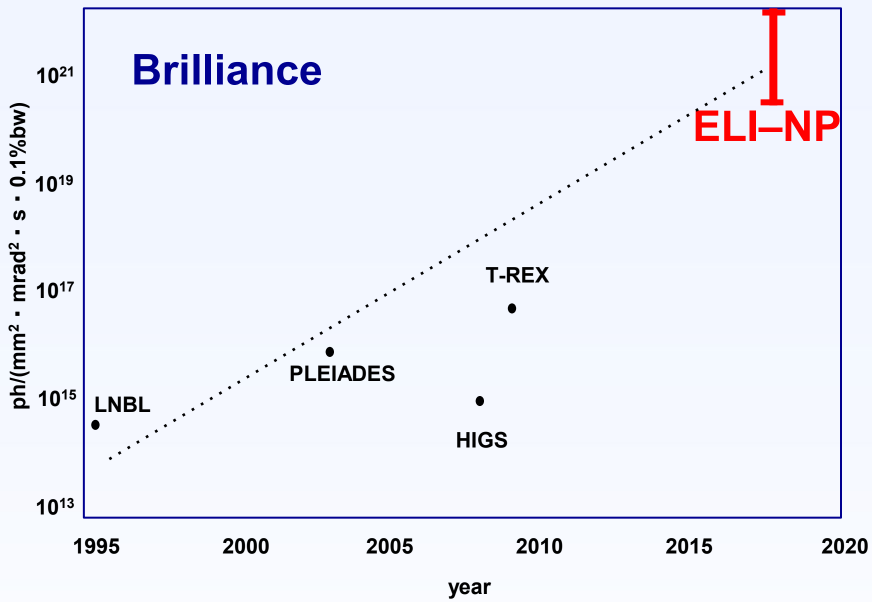
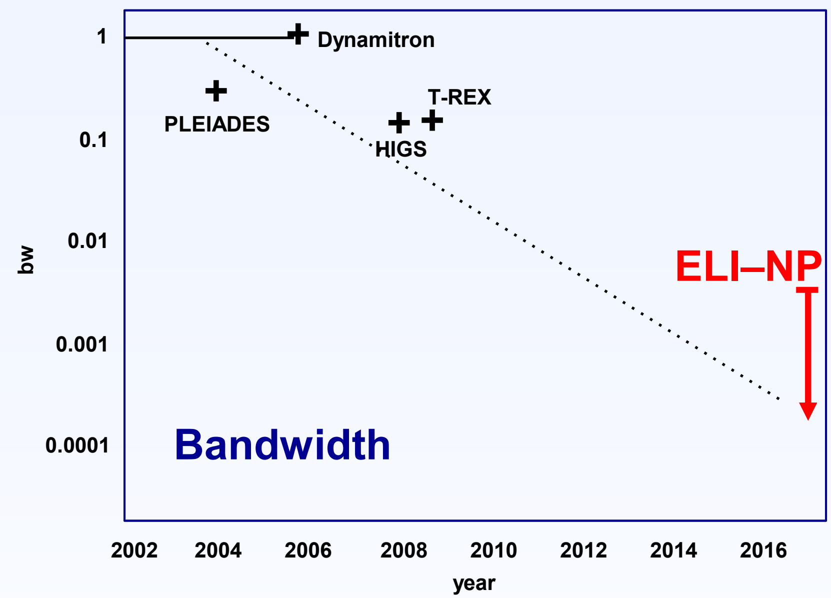
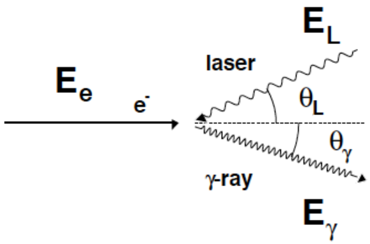
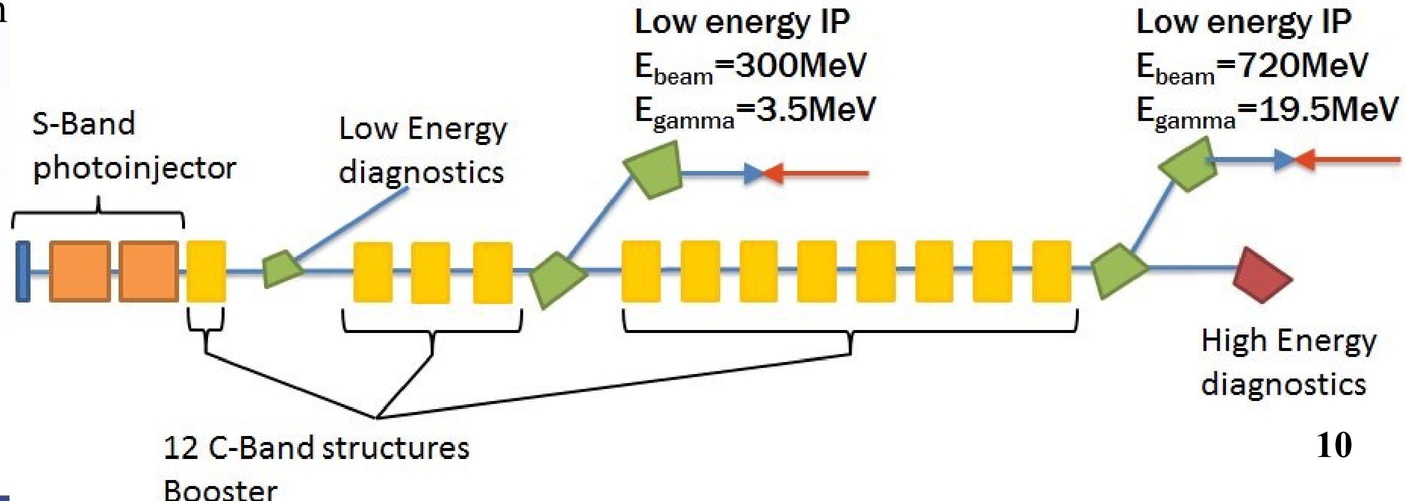
Gamma Beam System



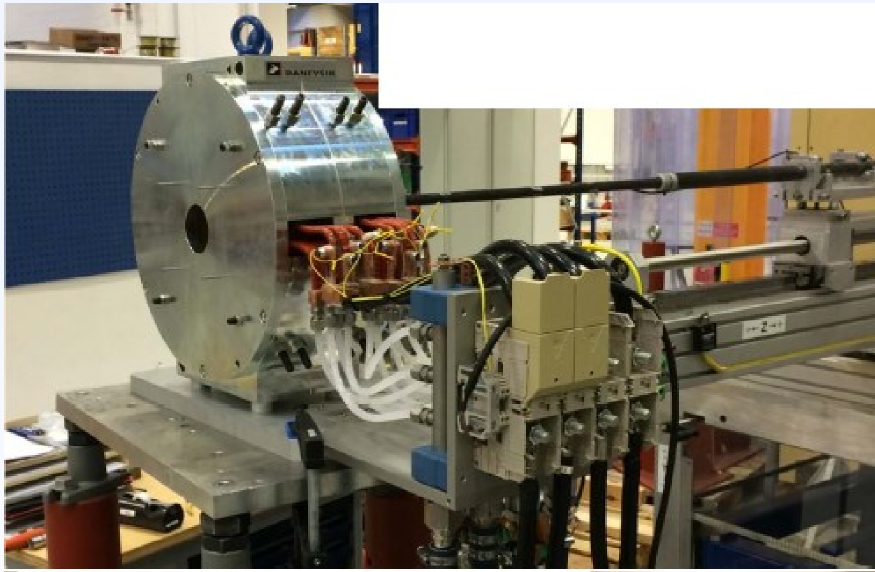


EuroGammas Consortium
Lead by INFN Italy
Research Institutes and
HighTech Companies
from 8 Countries





Gamma Beam System



SOLENOID B
Module 2
Factory Acceptance Test

Alignment test at Danfysik have been performed, that will be demonstrated on 3rd March, when LNF & STFC Daresbury staff visit

Technology

- 4 Laser beamlines

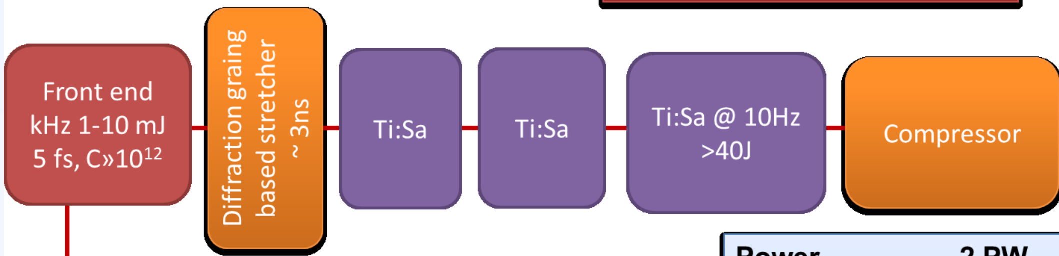
Beamline	L1	L2	L3	L4
Peak power	>5 TW	PW	≥PW	10 PW
Energy in pulse	100 mJ	≥15 J	≥30 J	≥1.5 kJ
Pulse duration	<20 fs	≤15 fs	≤30 fs	≤150 fs
Rep rate	kHz	10 Hz, >10 Hz	10 Hz	1 per min
Delivery	In-house	External supplier + in-house development	Major contractor	Major contractor

- 7 Experimental stations (beamlines) with 6 extra multipurpose end-stations
- K-alpha, LUX (Laser Undulator X-ray beamline), ELIMAIA (Multidisciplinary Applications of Laser-Ion Acceleration, HELL (High Energy Electron Acceleration by Lasers), Plasma betatron, High Harmonic Generation, P3 Plasma Physics Platform

Laser system

ELI-ALPS Lasers – Procured

Amplitude Technologies



Seed for HF 100

Rep.rate	100Hz
Pulse duration	<10fs
Energy	1 mJ
CEP	250mrad

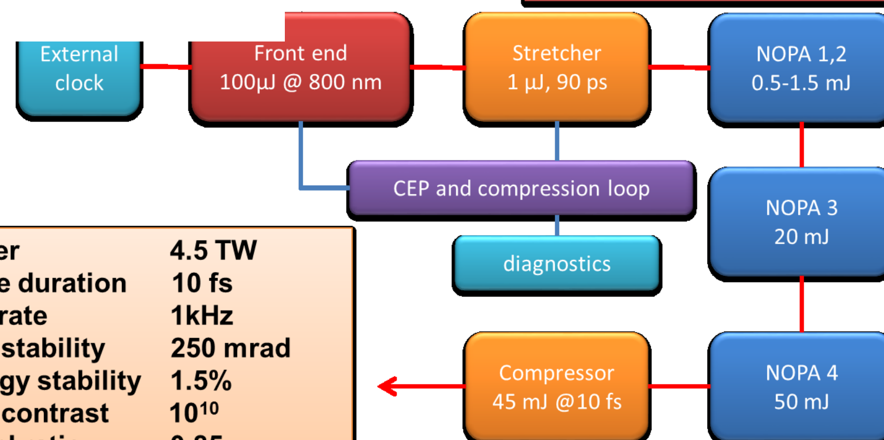
Power	2 PW
Pulse duration	17fs
Rep.rate	10Hz
Energy stability	1.5%
ASE contrast	10^{11}
Strehl ratio	0.9
Central λ	800 nm
Beam ∅	240 mm
Optics ∅	300 mm

FAT: Sept, 2016, SAT: March, 2017

PP for 500 mJ @ < 100Hz, 10fs -> in 2016

HF PW laser
Value: 6BHUF

EKSPLA + Light Conversion consortium



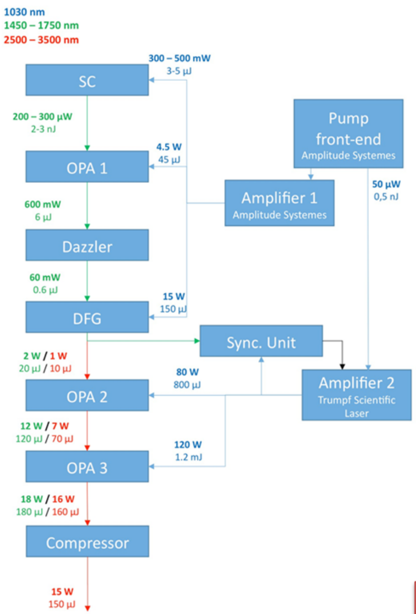
Power	4.5 TW
Pulse duration	10 fs
Rep.rate	1kHz
CEP stability	250 mrad
Energy stability	1.5%
ASE contrast	10^{10}
Strehl ratio	0.85
Central λ	800 nm
Beam ∅	60 mm
Optics ∅	100 mm

FAT: March, 2016, SAT: June, 2016

PP for SYLOS II 100 mJ @ < 7 fs -> in 2015

SYLOS 1 laser
Value: 1.25 BHUF

ELI-ALPS Lasers – Procured



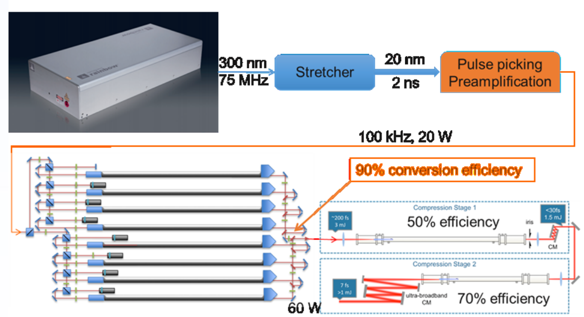
Fastlite (+AmplitudeSystems+Trumpf SL)

Wavelength	3.1 µm
Energy	150 µJ
Pulse duration	<4 cycles
Rep.rate	100 kHz
CEP stability	100 mrad
Energy stability	1.5%
Strehl ratio	0.5
Tuning range	1500 nm

MIR laser
Value: 492 MHUF

FAT: Nov, 2016, SAT: Jar

IAP FSU Jena + Fraunhofer IAF + Active Fiber Systems GmbH



Wavelength	1030 nm
Energy	>1 mJ
Pulse duration	<6.2 fs
Rep.rate	100 kHz
CEP stability	<100 mrad
Energy stability	0.8%
Strehl ratio	0.9

HR 1 laser
Value: 895 MHUF

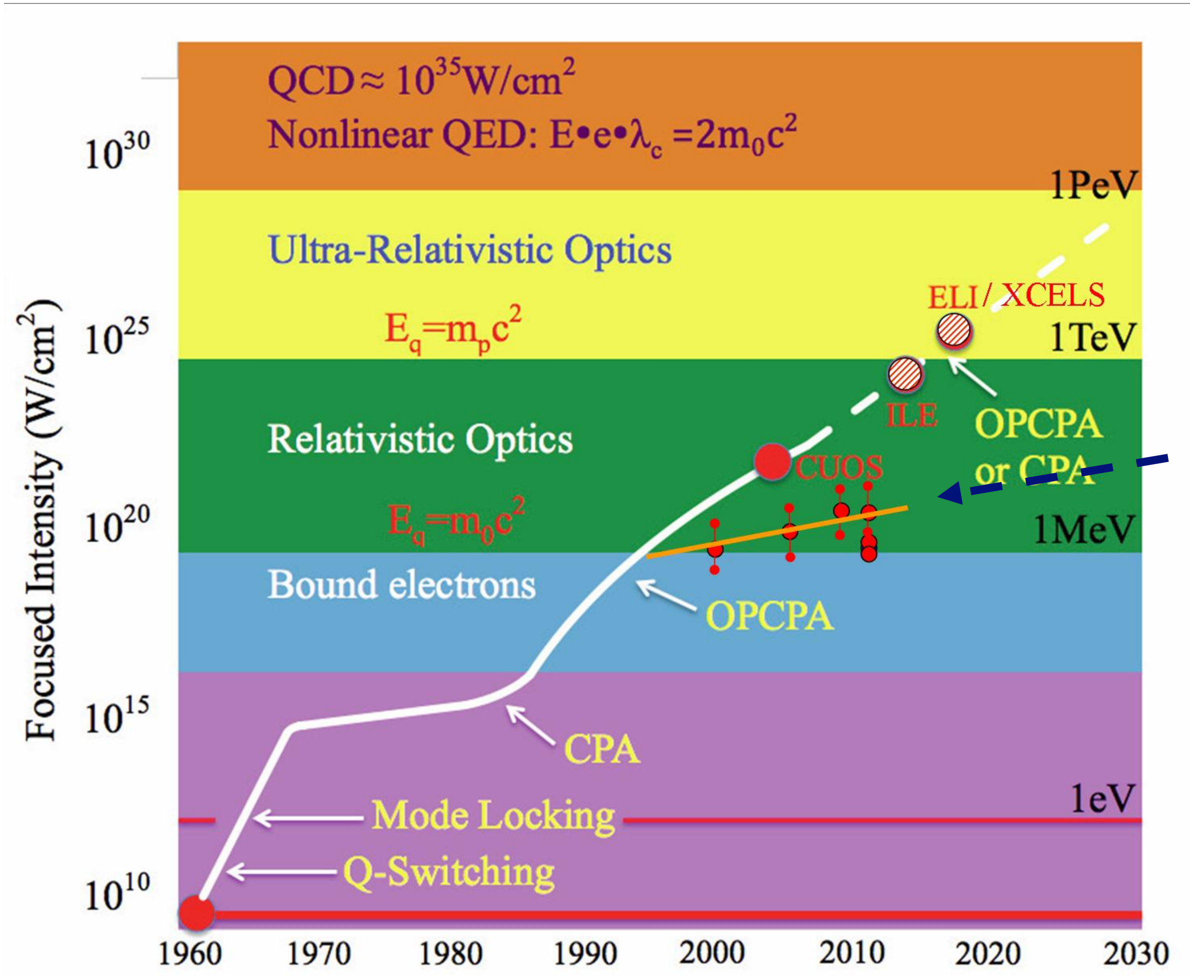
FAT: May, 2016, SAT: July, 2016

PP for 5 mJ, <5 fs -> in 2016

The remaining challenges:

- **Technology challenges:** => global collaborations / industrial suppliers
- **The "facility challenge":** reliability and availability for users
- **The socio-economic challenge:** High-power lasers and the "Grand Societal Problems"

The facility challenge: Laser top specifications versus useability

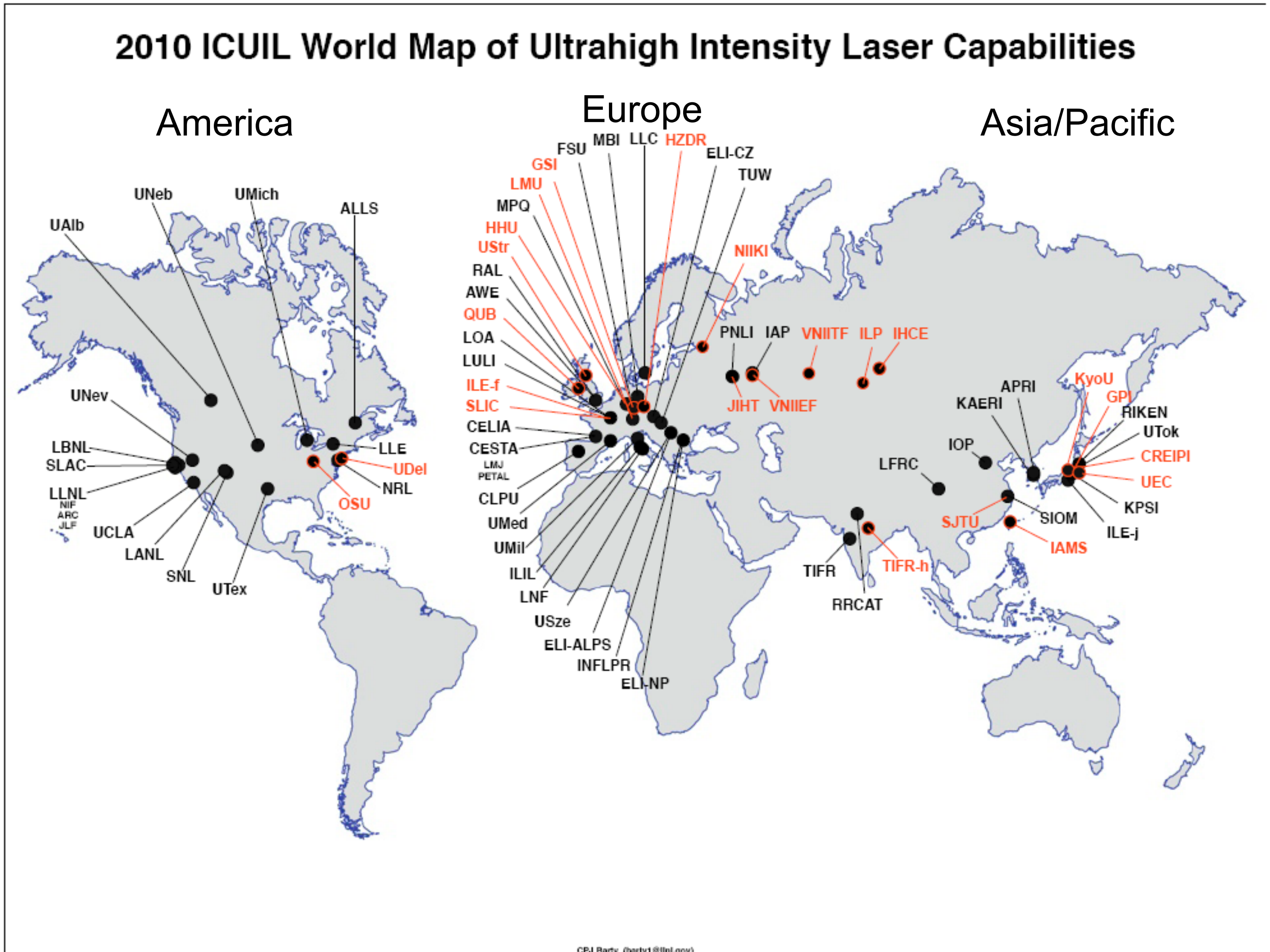


Top laser specifications

Highest reported intensities
used in experiments

(graphics from the “ELI White Book”)

National Research Infrastructures High Power Lasers (P > 100TW)



2009
2010

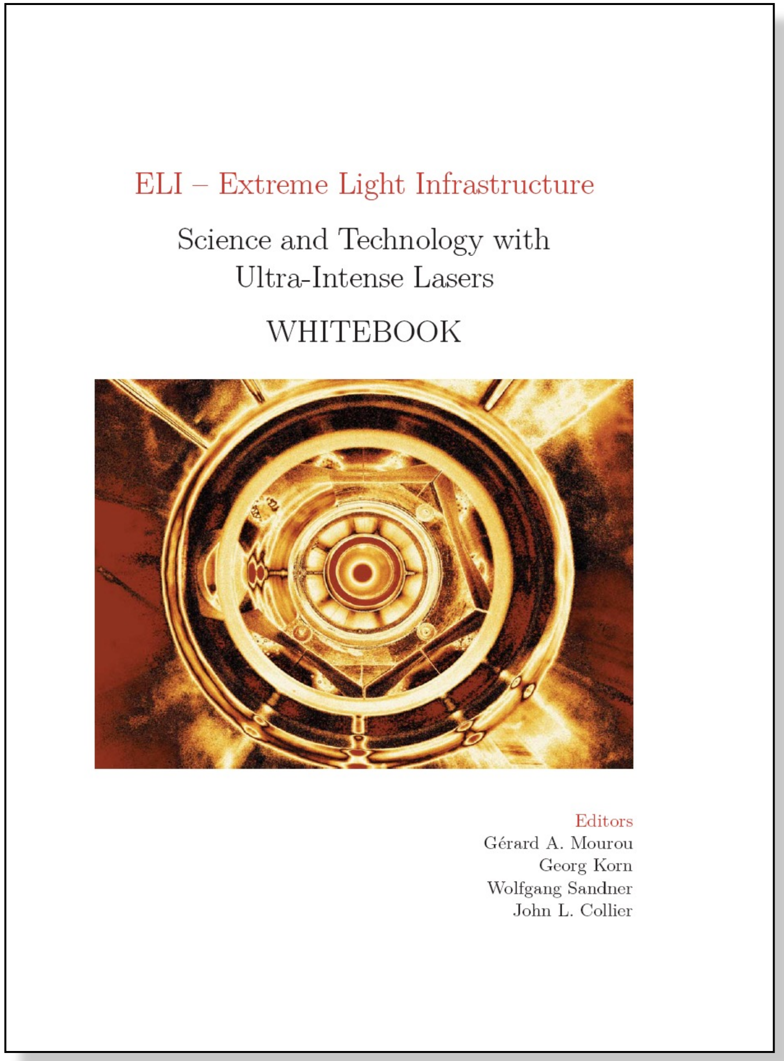
Christopher P.J. Barty, 2011
http://www.icuil.org

The socio-economic question:
Why do nations invest so much in high-power lasers?

The driver is science and the scientific community

The ELI „White Book“

530 pages
172 authors
10 major
interdisciplinary fields


ELI – Extreme Light Infrastructure

Science and Technology with
Ultra-Intense Lasers

WHITEBOOK

Editors
Gérard A. Mourou
Georg Korn
Wolfgang Sandner
John L. Collier

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The quest for extreme light

Science	Application
• Investigation of Vacuum Structure	
• Electron Acceleration	X-rays => Materials Research
• Ion sources	Medical, Materials Research
• Neutron sources	Materials research
• Terahertz sources	Analytics
• Ultrafast-laser driven X-ray sources	Micro-, Nano-Techn.
• Attophysics	Chemistry
• Nuclear & Photonuclear Physics	Mat. Res., Med., Environm.
• Physics of dense plasmas	X-rays, Fusion
• Laboratory Astrophysics	

(from the “ELI White Book”)

More than basic science

With nations or continents spending such amount of public money there must be an expected return - ***not only in pure science but also in applications of societal relevance*.**

ELI, with a Structural Funds background and genetic roots in optics and photonics, will contribute to regional development in the host countries through technology transfer and substantial socio-economic impact.

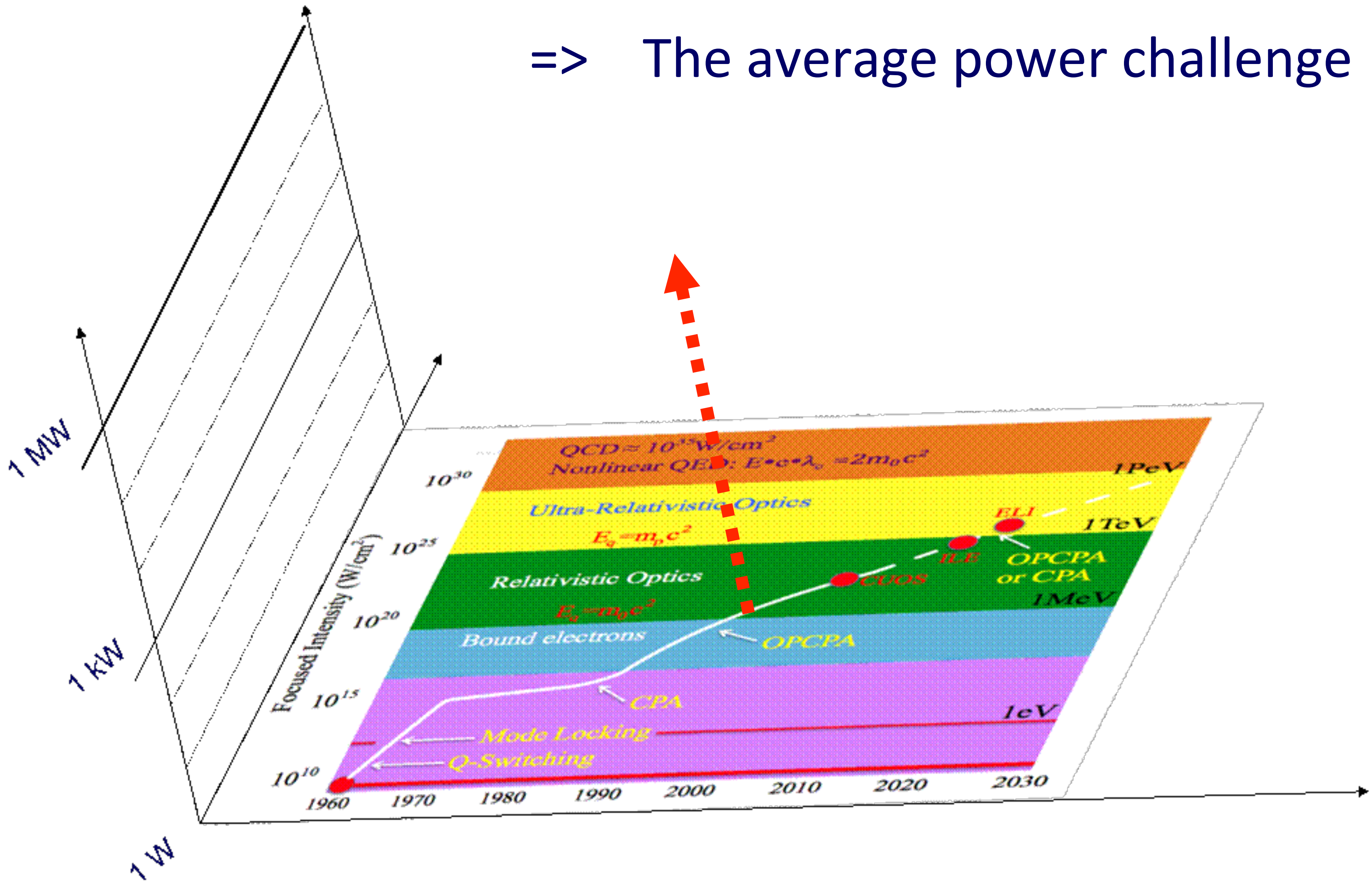
Photonics – A EU Key Enabling Technology

- Total Photonics market € 350 bn (2010) / € 600bn (2020)
- Average annual growth 6,5% (= 2x GDP growth)
- **European Photonics market ~ € 65 bn**
- **European market share 18%** (in 2011)
- Many market-leading industrial players
- Market shares of European companies

Production technology	55%
Optical components & systems	40%
Measurement & automated vision	35%
Medical technology & life sciences	30%

- More than 5000 SMEs in Europe
- **~ 300,000 employees**

=>   The average power challenge



Science with extreme light

or

The physics of the interaction of ELI light pulses with matter

Three key phenomena for the interaction of extreme light with matter:

- Electromagnetic peak fields
- Time-averaged „quiver energy" of free electrons
- Light pressure on a reflecting plasma surface

Electromagnetic peak fields

ELI @ 10^{22} W/cm^2

$$E_{max} = \left[\left(\frac{V}{cm}\right)\right] \cong 2.75\times10^{9}\left(\frac{I_L}{10^{16}W/cm^2}\right)^{1/2} \longrightarrow$$ **10^{12} V/cm**

$$B_{max} = [Gauss] \cong 9.2\times10^{6}\left(\frac{I_L}{10^{16}W/cm^2}\right)^{1/2} \longrightarrow$$ **~ 3G Gauss**

Time-averaged „quiver energy" of free electrons:

$$U_p[eV] = 9.33\times10^{-14}\underbrace{I[W/cm^2]\lambda^2[\mu m^2]}_{\text{time-averaged intensity !}} \longrightarrow$$ **1 GeV @ 1µm**

Light pressure on a reflecting plasma surface:

$$P_L = \frac{I_L}{c}(1+R) \approx 3.3Mbar\left(\frac{I_L}{10^{16}W/cm^2}\right)(1+R) \longrightarrow$$ **~ 1000 Gbar (@ R=30%)**

Sequence of light-matter interaction processes at ELI intensities:

1. Electromagnetic peak fields (10^{12} V/cm / 3G Gauss)

$\Rightarrow$ Immediately ionization, => free electrons and ions

2. Time-averaged „quiver energy“ of free electrons (1 GeV):

- hot electrons + cold ions
- plasma heating processes
- electrons get expelled from the center of the laser pulse
  => charge separation between electrons and ions

3. Light pressure on a reflecting plasma surface (~1000 Gbar):

- electrons get pushed in forward direction
- charge separation may drag ions behind

Example: creating unprecendented secondary radiation of particles and photons

Particles: laser accelerated ions and electrons

Photons: from table-top XFELs to Gamma rays

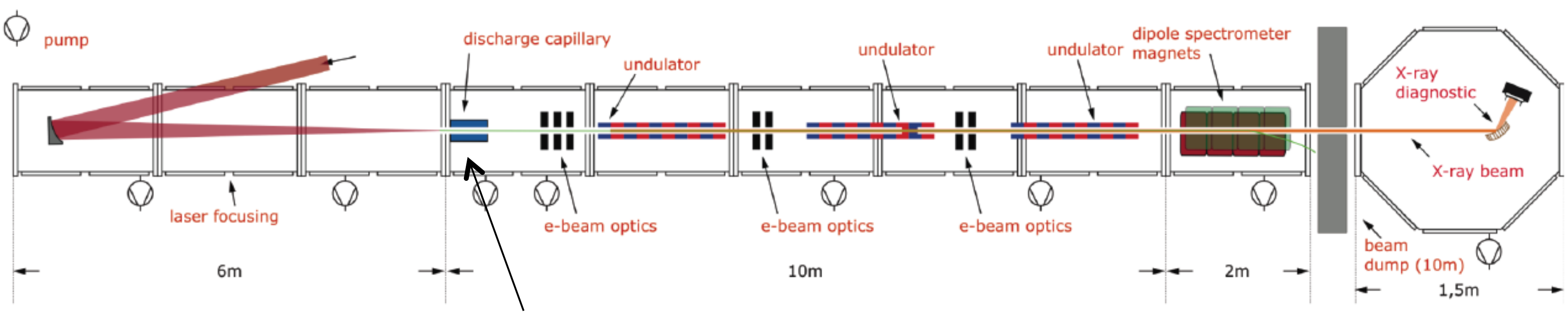
from meV (THz) to MeV

from pico- to attoseconds

VUV Photons: Towards “table-top” X-ray FEL (ELI-BL)

The LUX beamline:

Photon yield:	10^{12} photons per shot	
Photon energy	up to 5 keV	
Pulse width:	general:	few fs
	advanced:	below 1 fs



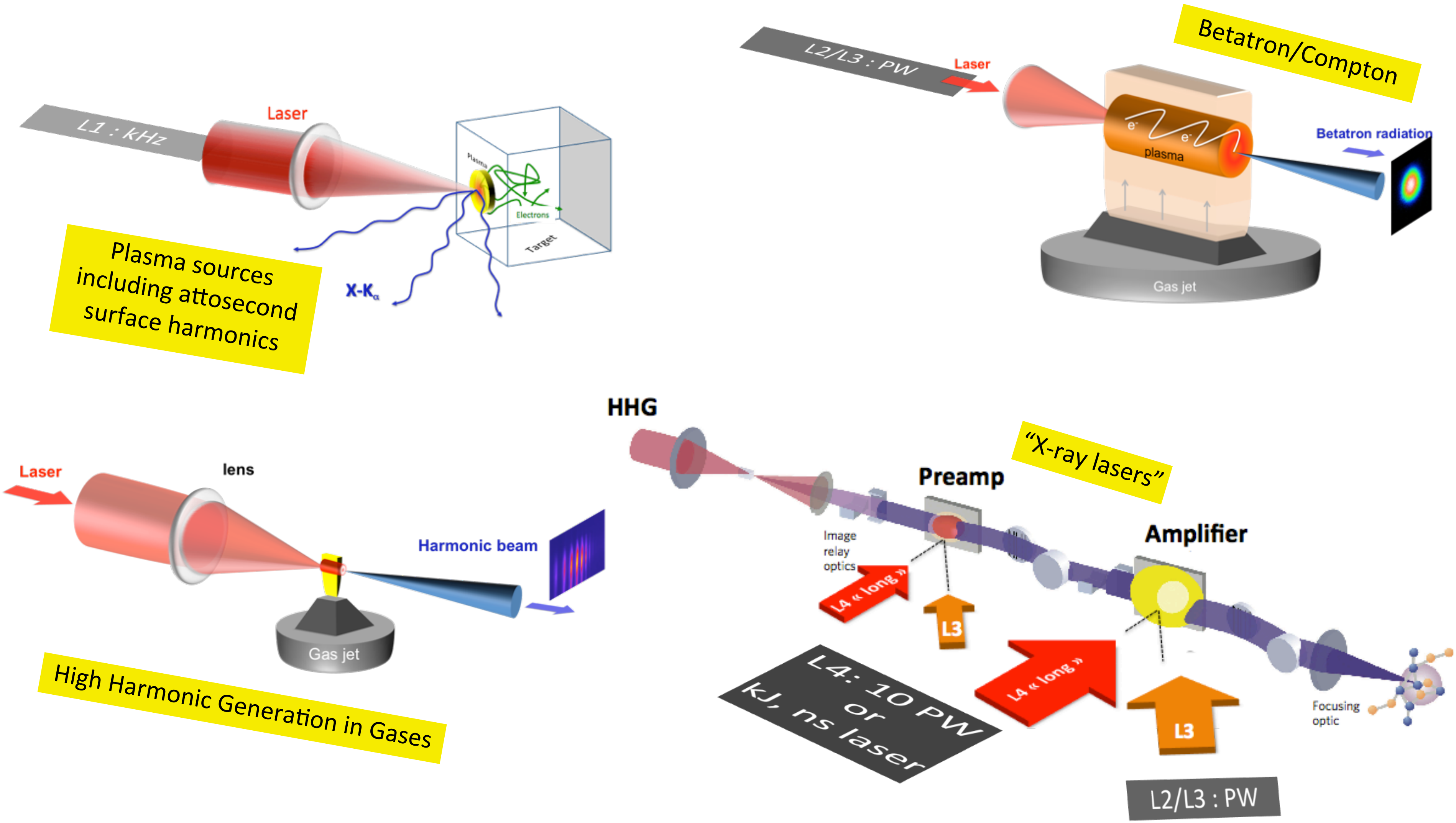
Driver Laser

Wakefield electron accelerator

Undulators

Experiments

VUV and x-rays: short pulse, intense laser driven sources (ELI-BL & ELI-ALPS)



ELI Scientific Missions

Scientific Mission

- **Nuclear Physics experiments to characterize laser – target interaction**

- **Photonuclear Physics**

- **Exotic Nuclear Physics and astrophysics**

  complementary to other ESFRI Large Scale Physics Facilities (FAIR- Germany, SPIRAL2- France)

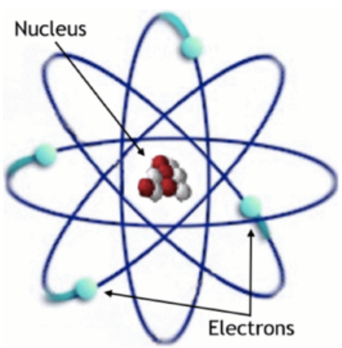
- **Applications based on high intensity laser and very brilliant γ beams**

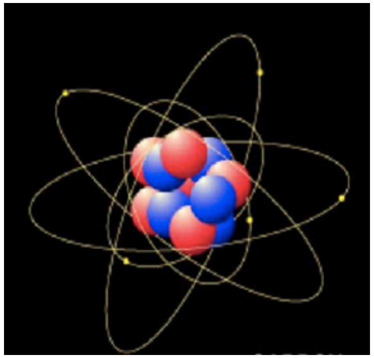
ELI-NP in ‘**Nuclear Physics Long Range Plan in Europe**’ as a major facility

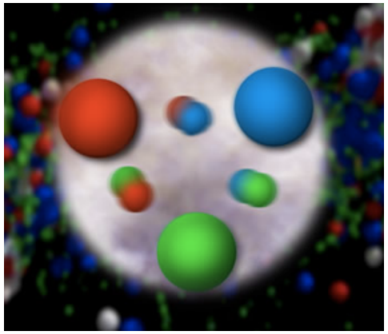
ELI-NP in Magurele, Romania:

Study matter from atom to vacuum

Fundamental Research & Applications of Laser & Ion beams







S. Gales for the ELI-NP team, Brussels 07-03-2014

Scientific mission of ELI-ALPS

1) To generate X-UV and X-ray femtosecond and atto pulses, for temporal investigation at the attosecond scale of electron dynamics in atoms, molecules, plasmas and solids.

- ATTOSECOND Beamlines & User Facility

2) To contribute to the laser science and technological developments

ELI Attosecond Light Pulse Source

attosecond

Providing the international scientific community with unique ultrafast coherent light sources,

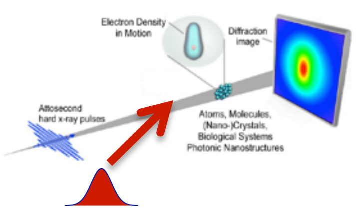
with special emphasis on attosecond pulses in the XUV- and X-ray spectral range

1) 4D attosecond imaging

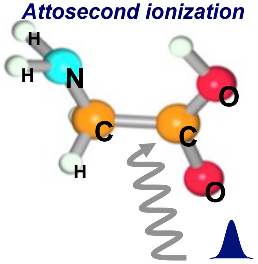
2) New directions in chemistry

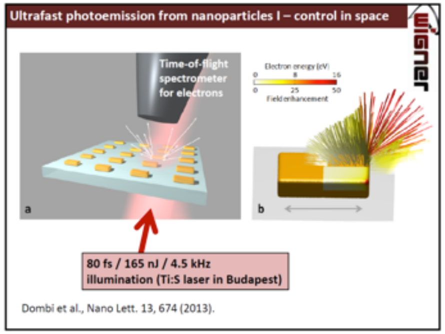
3) Nano-plasmonics

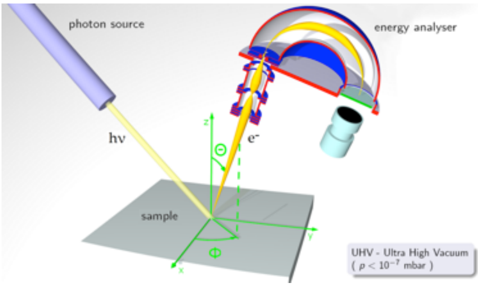
4) Interface processes (charge dynamics)



4D (space+time) attosecond/Å scale imaging of atoms and molecules







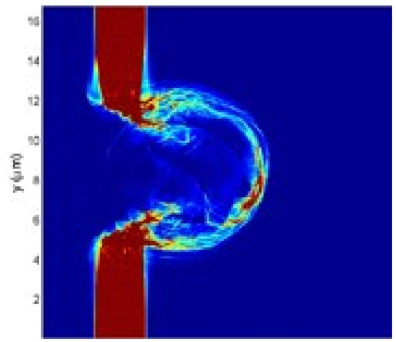
ELI Beamlines
Scientific mission

User facility for fundamental & applied research

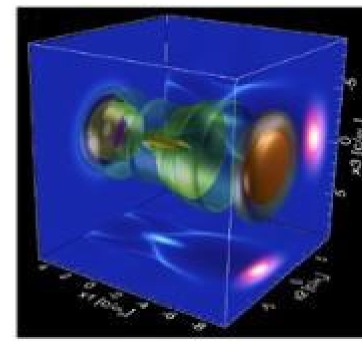
- Generation of high repetition-rate laser-driven sources of radiation and particles
- Programmatic applications of laser-driven femtosecond secondary sources of X-rays and accelerated particles: medical and biomolecular research, material research
- High-field physics using unique combination of synchronized laser pulses and laser-generated secondary sources
- Development of high-repetition rate laser technologies

Research Areas

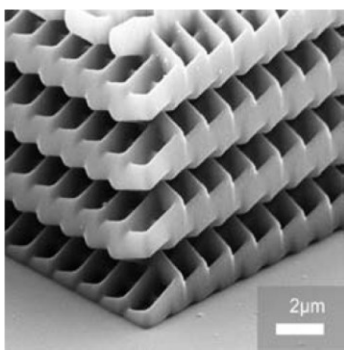
Roentgen and gamma sources,
laboratory astrophysics



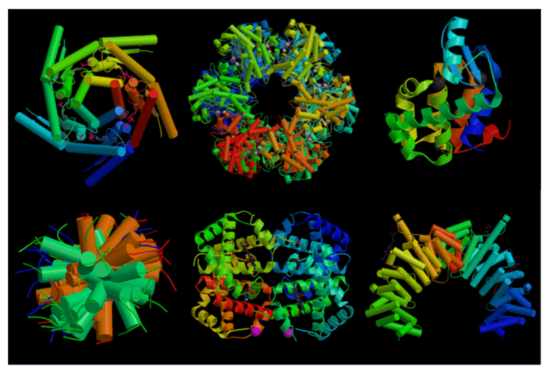
Proton acceleration



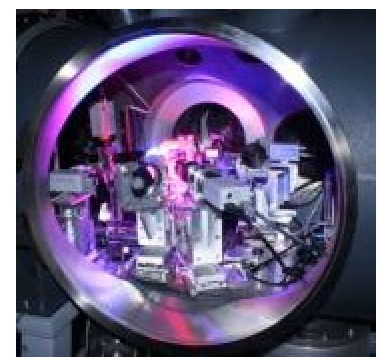
Electron acceleration



Nanotechnology
and advanced materials



Biology and biochemistry



Medical diagnostics
and treatment technology

eli delivery consortium

Where do we stand?

Project supported by:

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
INVESTING IN YOUR FUTURE

Construction in Szeged (HU)

National Development Agency
www.ujszechenyiterv.gov.hu
06 40 638 638

HUNGARY'S RENEWAL

The projects are supported by the European Union and co-financed by the European Regional Development Fund.

attosecond

Construction in Szeged (HU)

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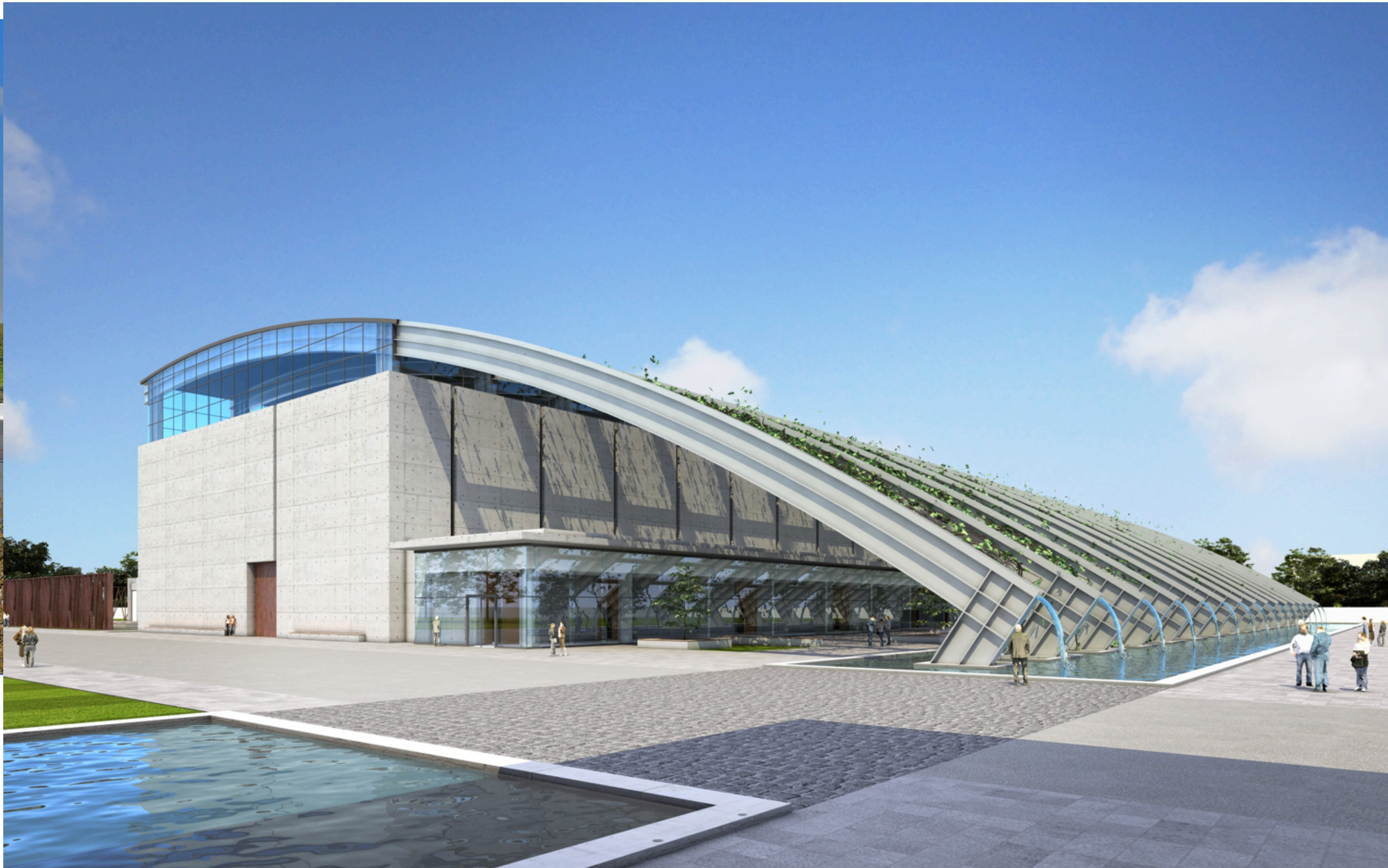
Construction in Dolny Brezany (CZ)

Construction in Dolny Brezany (CZ)

Construction in Magurele (RO)

Nuclear Physics

Construction in Magurele (RO)



ELI‘s fourth pillar?

ELI‘s „fourth pillar“ will be a sub-exawatt (~200PW) laser facility, again by a factor of 10 more powerful than the present state-of-the-art (ELI)

- Strategy:
  - **Implement** the present three pillars, already having world-leading specifications
  - **Gain experience** with new technologies (10 PW Ti:Sa, OPCPA, phase-correct beam superposition etc.)
  - **develop funding model** for construction and operation
  - **then decide** on fourth pillar technology and site

Summary

eli delivery consortium

ELI will be

- a distributed research infrastructure based initially on 3 facilities in CZ, HU and RO
- the first ESFRI project to be implemented in the new EU Member States
- pioneering a novel funding model combining structural funds (ERDF) for the implementation and contributions to an ERIC for the operation

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
INVESTING IN YOUR FUTURE

ELI's new sources, science and applications…

are essentially based on three key phenomena for the interaction of extreme light with matter:

- Electromagnetic peak fields: ~1000 GV/cm / 3 G Gauss
- Time-averaged „quiver energy“ of free electrons: ~ GeV
- „Light pressure“ on a plasma surface: ~ 1000 Gbar

With all this, ELI will be **the world's first international laser user facility,** providing unique research opportunities for the future:

"*The CERN of laser research*"