Creating Extreme Light: why, and how?

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EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
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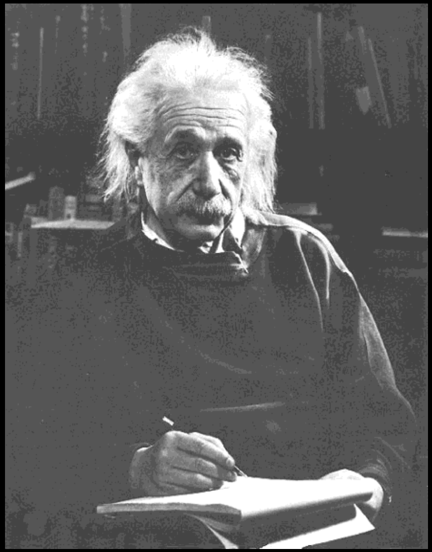
Lasers have changed the world ...

... by



controlling the coherence of light

Control of coherence by virtue of stimulated emission

The stimulated emission cross section is

$$\sigma_{21}(\nu) = A_{21}\frac{\lambda^2}{8\pi n^2}g(\nu)$$

where

A_{21} is the Einstein A coefficient (in radians per second),
λ is the wavelength (in meters),
n is the refractive index of the medium (dimensionless), and
$g(\nu)$ is the spectral line shape function (in seconds).

Stimulated emission can lead to amplification of light.

LASER: Light Amplification by Stimulated Emission of Radiation

Note for this talk:

“Control of coherence” is not necessarily the same as “high degree of coherence”

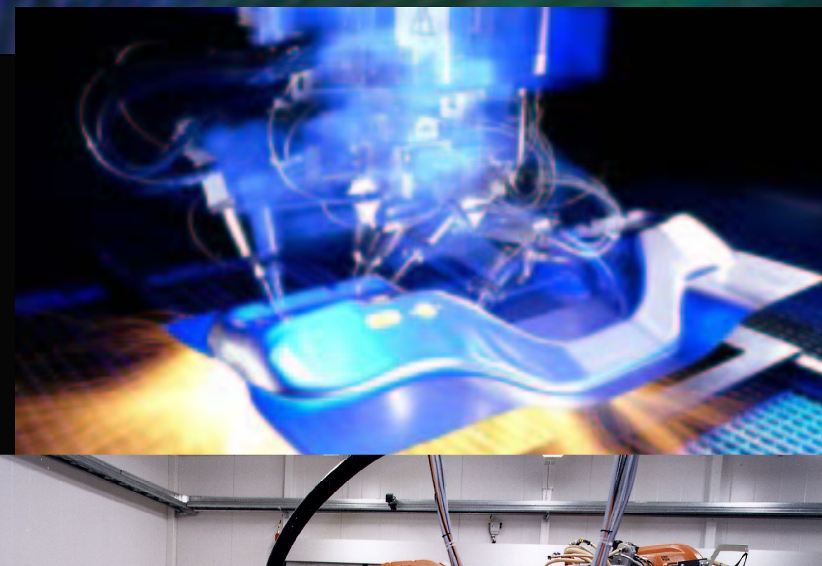
In particular, we will deal with broad-band, short-pulse lasers that have a low degree of (longitudinal) coherence, but excellent control over the phase relation between spectral components (“mode locking”).

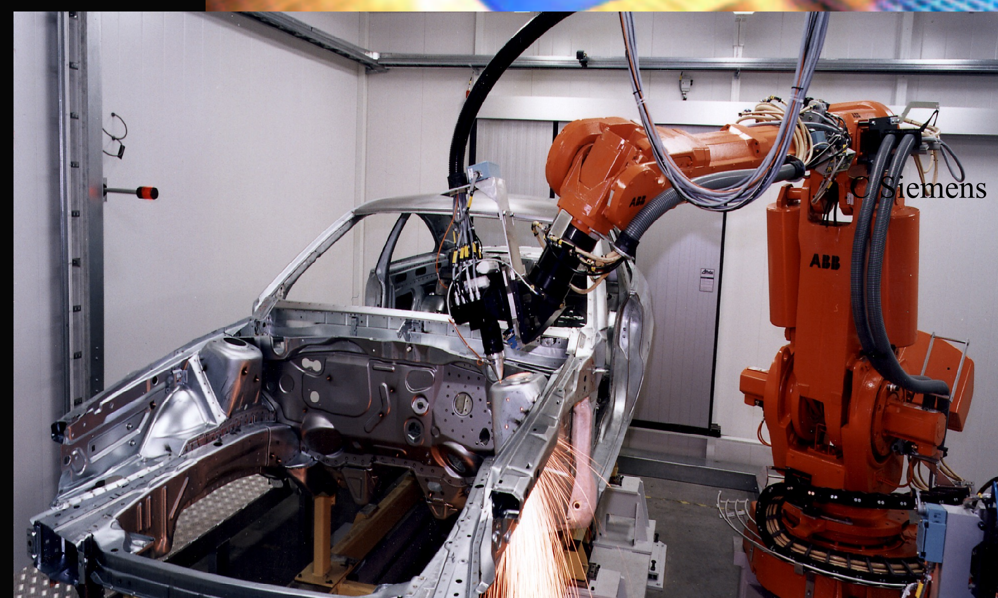
This is, again, possible by virtue of amplification through stimulated emission.

By controlling the coherence light can attain unprecedented properties:

Power:

Materials Processing

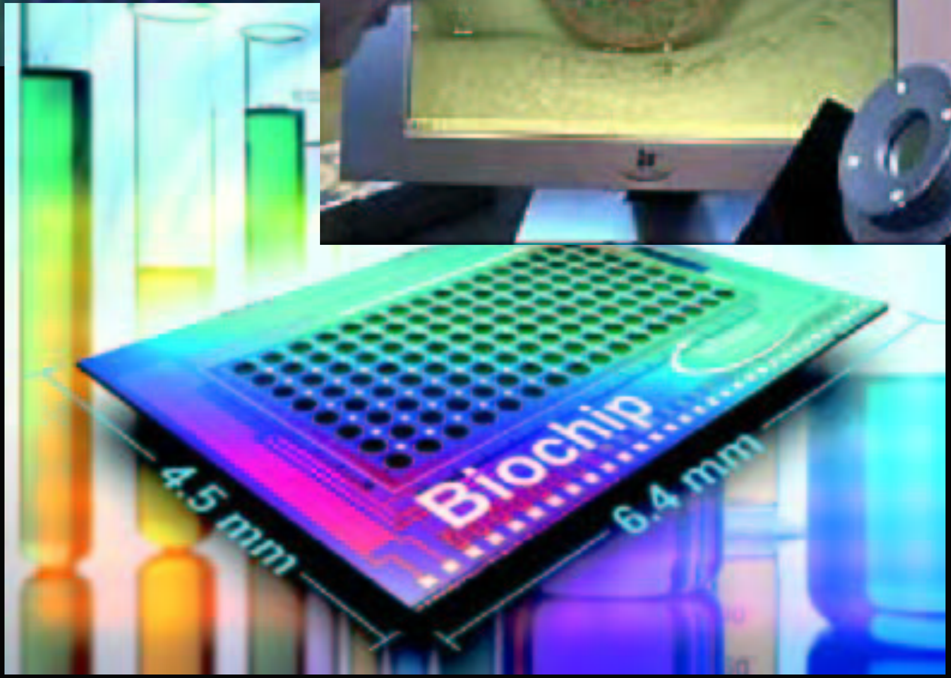


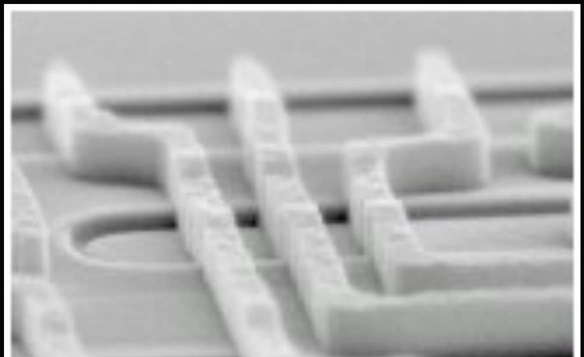


By controlling the coherence light can attain unprecedented properties:

Precision

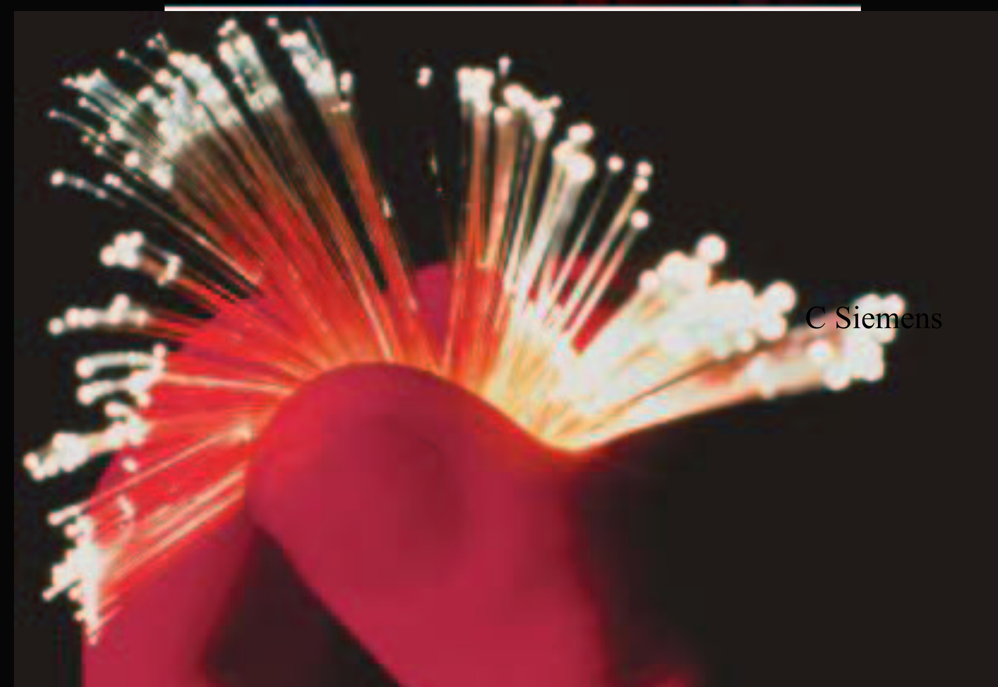
- Sensing
- Medicine
- Biology
- Micro- and nano- technologies





By controlling the coherence light can attain unprecedented properties:

Spectral purity or fastest modulation:

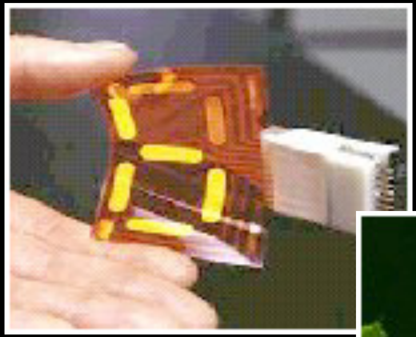


Information-Society Technologies,
Metrology,
Quantum Optics

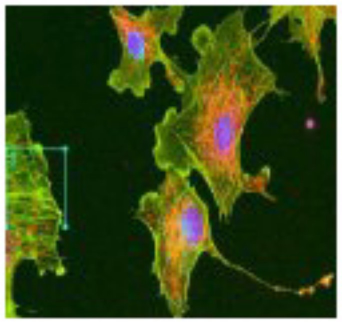
LOBO

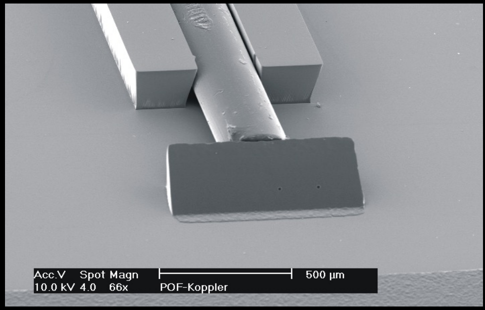
Lasers and Photonics:

A world market by itself (~400 billion € annually). Leverage in other technologies is MUCH larger.



→ **EU enabling key technology**



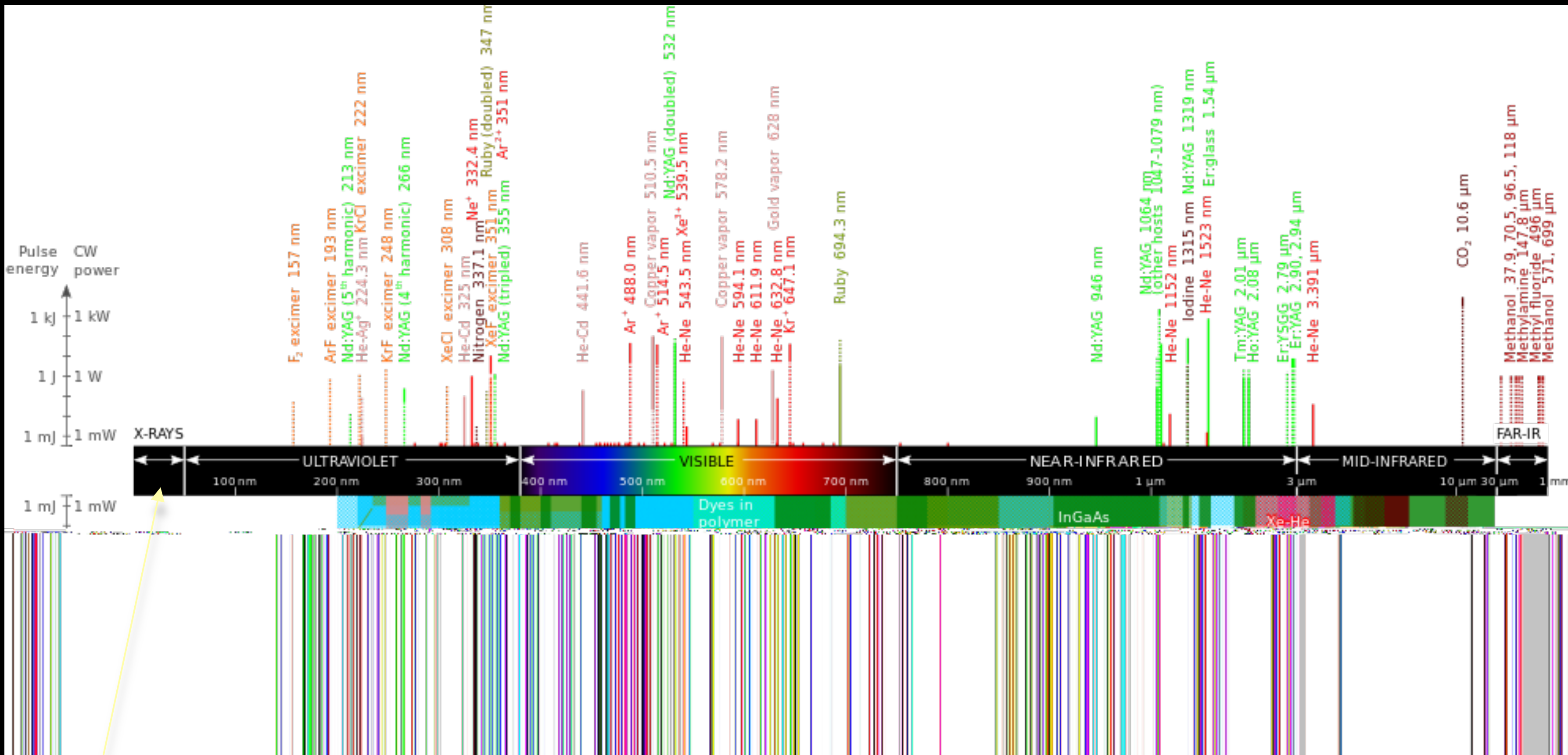


With all this success –

What is the need for “extreme light”?

One of the most painful limits:

Even 50 years after their invention LASERS cover only a limited spectral range around the visible and near infrared.



157nm ⟵⟶ 1 mm

X-rays (the light of micro- and nano- technologies, and of many research areas) is still outside the range of the direct LASER concept.

Source: wikipedia

Think of it:

The scientific and economic success story of "visible lasers" could be repeated by controlling the coherence of X-rays.

Besides fundamental research this could lead to revolutions in micro- and nano-technologies, and in the investigation of biological structures.

In addition, only X-rays open the door to shorter pulses than fs. Hence, the interplay between structure and dynamics at micro- and nano- scales – and, eventually, the secrets of life – could be investigated in real time.

Lasers could change the world again ...

... by

controlling the coherence of x-rays

However, today's LASERS don't create coherent X-rays.

Possible ways out:

1. Create coherent X-rays by **other methods** than LASER (stimulated emission from a population-inverted medium) => X-ray free electron lasers (Giga-Euro investment)

2. Create coherent X-rays by **nonlinear conversion** of longer-wavelength light in suitable media => "n photons in, one X-ray photon out"

3. Create coherent X-rays by **directly forcing free electrons into relativistic oscillatory** motions through powerful lasers => relativistics dynamics causes the necessary anharmonicity of the motion

In any case:

The secret behind compact coherent short-wavelength sources seems to lie in **(ultra-) high intensity / power driver lasers**

Having said that:

Besides generating X-rays, such lasers offer **unprecedented other applications** in science and technology if providing a combination of:

- highest peak power / intensity
- highest average power (repetition rate)
- shortest pulse duration (=> attoseconds)
- broadest wavelength range (MIR, NIR, UV, x-rays, Gamma) through non-linear conversion
- largest amplitude and phase control

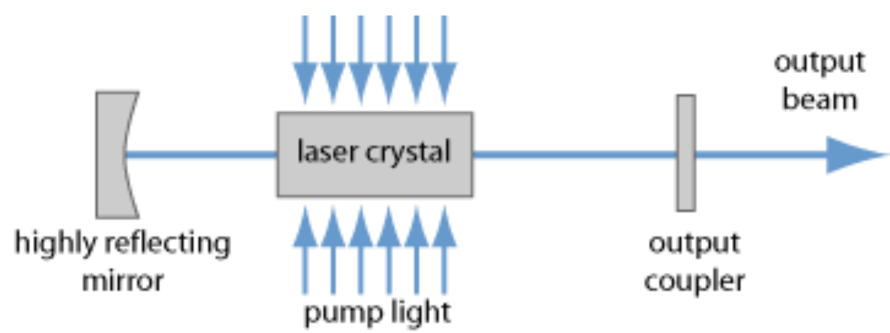
This – a combination of highest-power lasers, together with unprecedented secondary sources - is essentially the concept of „extreme light“ that lies behind ELI

How?

Creation of high-power laser pulses:

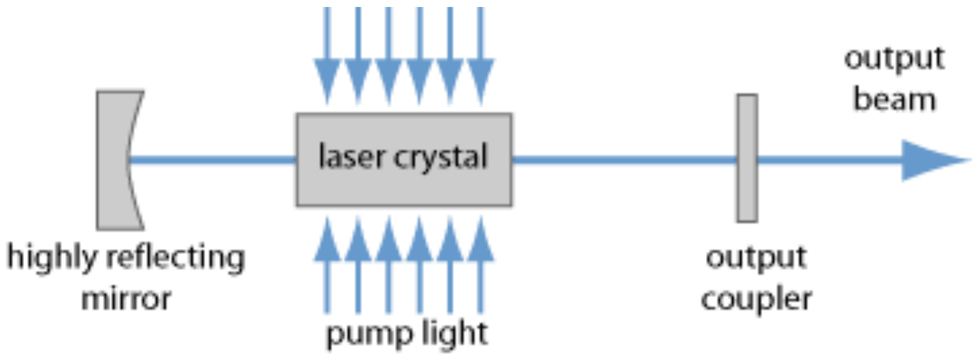
Taking Theodore Maiman's laser concept to the extreme

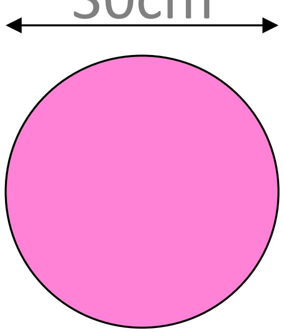
Theodore H. Maiman
1960



delivery consortium

The ultimate high-power solid state laser:





1000 PW = 1 Exawatt ?

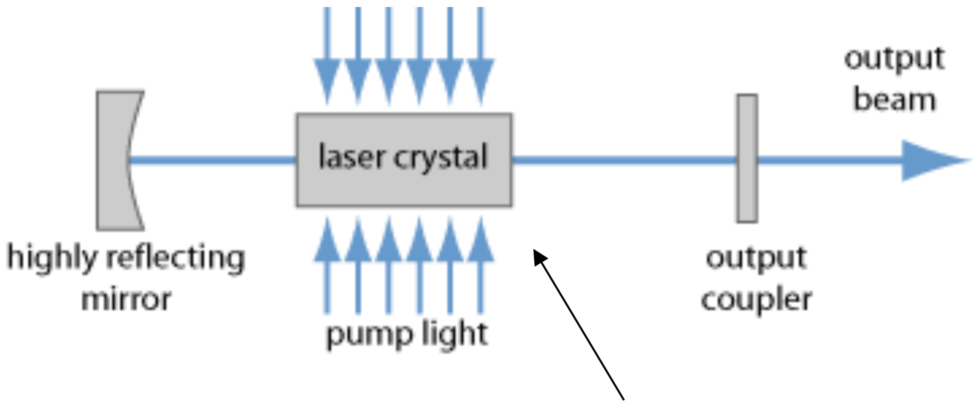
Active material physical limits :

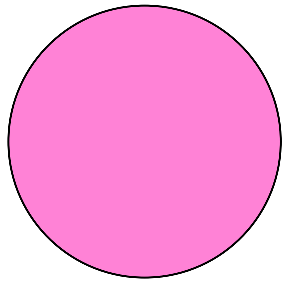
- Saturation fluence = 1 $h\nu / \sigma$ ~ 1J / cm^2
- Amplification bandwidth $\Delta\lambda$ < few 100nm => Pulse duration ~ fs
- maximum extractable power density ~ 1J / cm^2 fs ~ **1 PW /cm^2**

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"

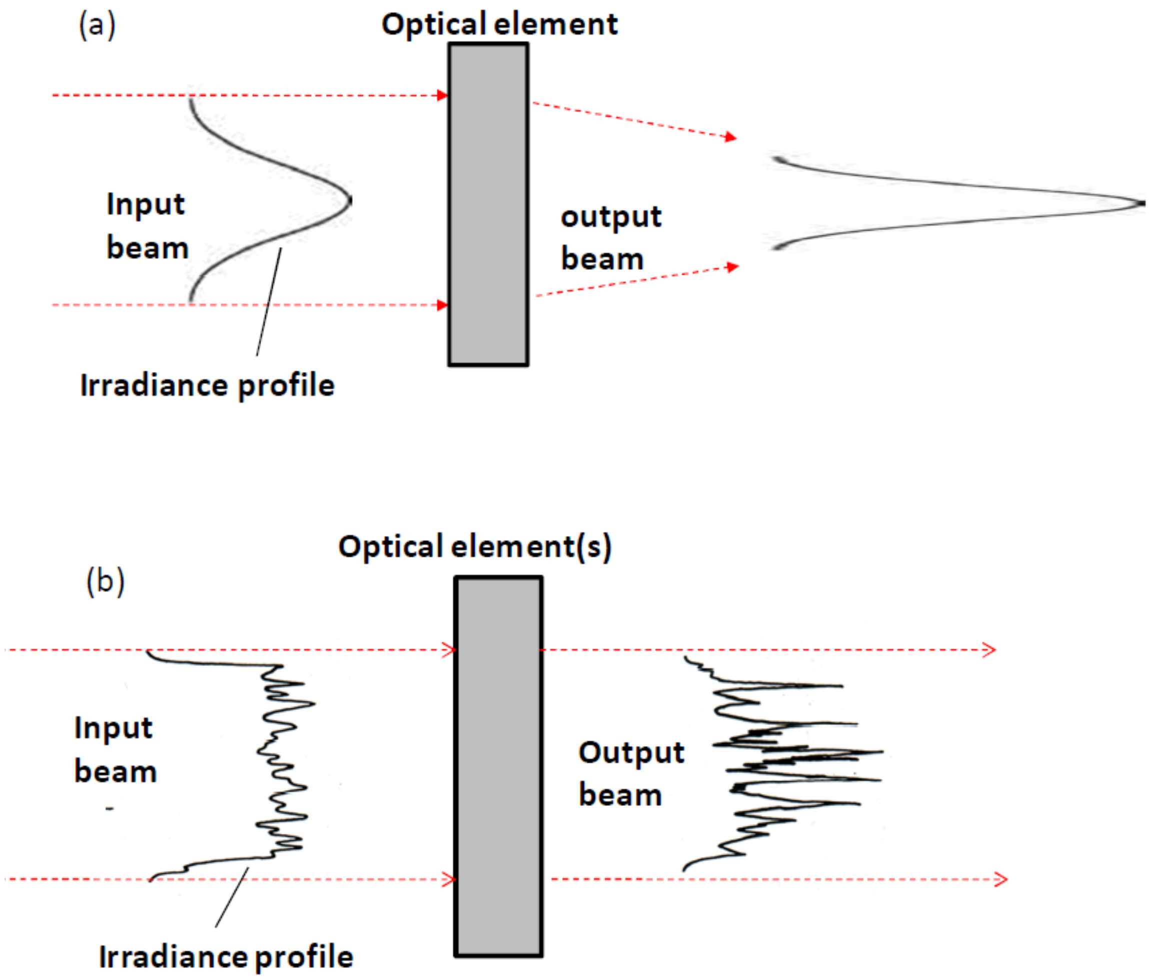
$$B \equiv \frac{2\pi}{\lambda}\int_0^L n_2(z)\, I(z)\, dz$$

- => 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!).

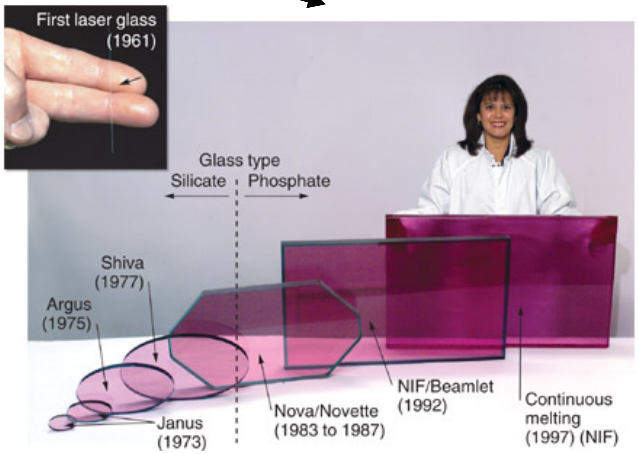
- Special design „tricks" allow up to ~ 10TW single beam power

Effect of the „B-Integral“



Common techniques to fight B:

(0) flat top beam profile (NIF: flat region 33x33cm, out of 37x37 cm beam area)



Glass disk amplifiers 1973 - today

(1) using spatial filters and relay imaging devices;

(2) eliminating the effect of Fresnel diffraction by means of apodization;

(3) using diverging beams;

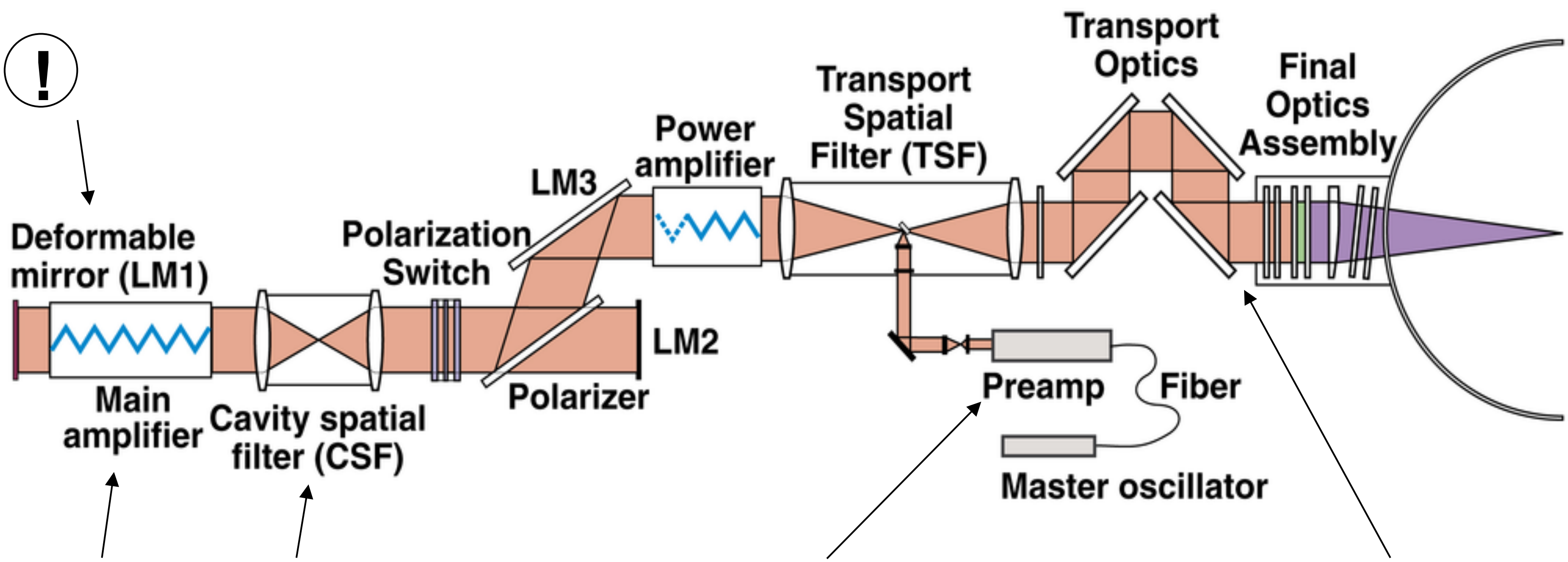
(4) insertion of air-spaces into nonlinear medium; (self-focusing lower in disk elements than in rods due to the defocusing action of the air gaps (due to diffraction) on small-scale perturbations.)

(5) using circular polarization (lower n_2)

(6) limiting the degree of coherence

Powers of 10^3 - 10^4 x $P_{critical}$ are possible

NIF-amplifier: playing all tricks

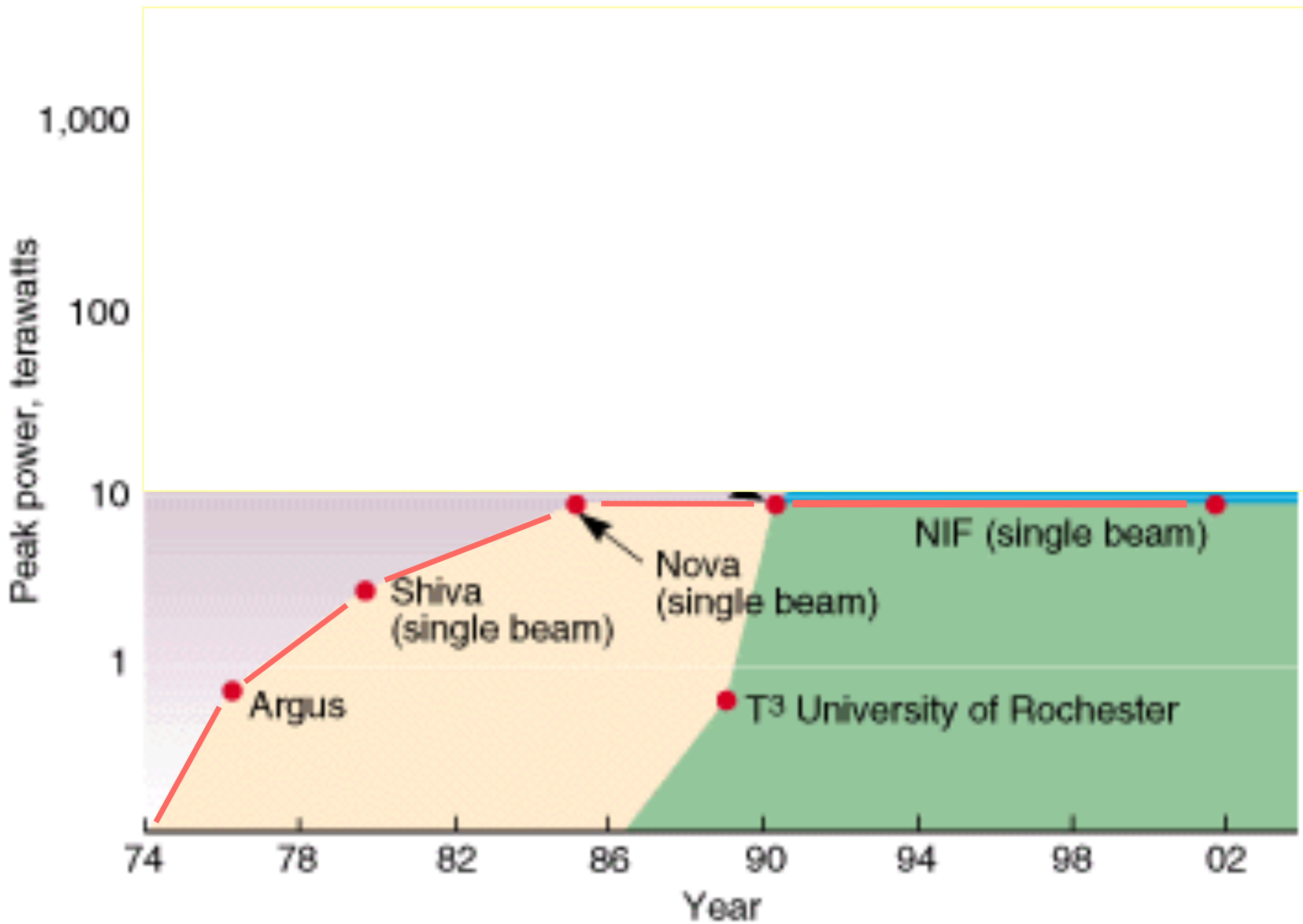


! !

! Flat – top
Beam shaping!

Single beam power
10 Terawatt
> 10^6 x $P_{critical}$

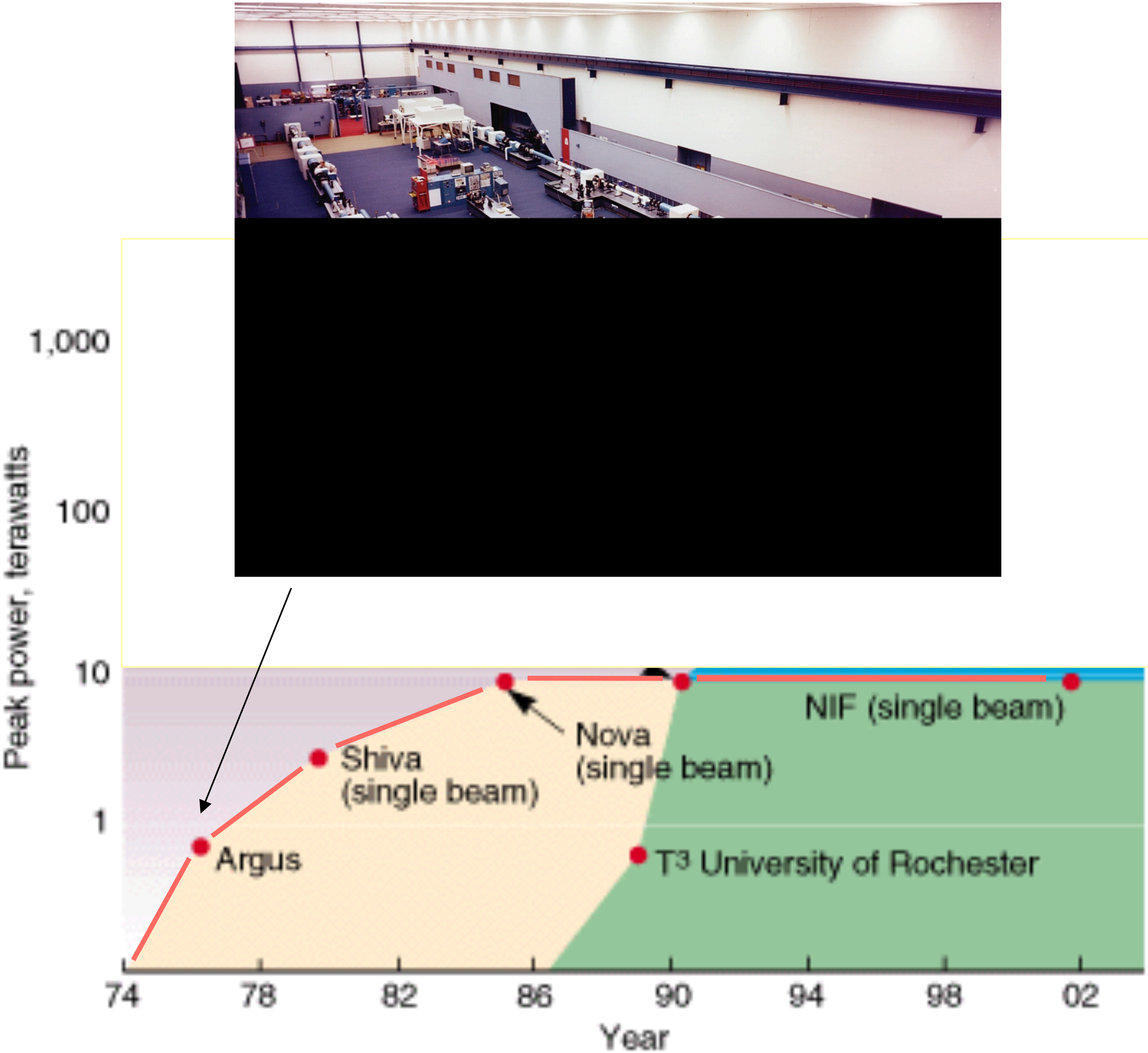
Total NIF power (192 beams): 500TW @ 3ω



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

The B-limit

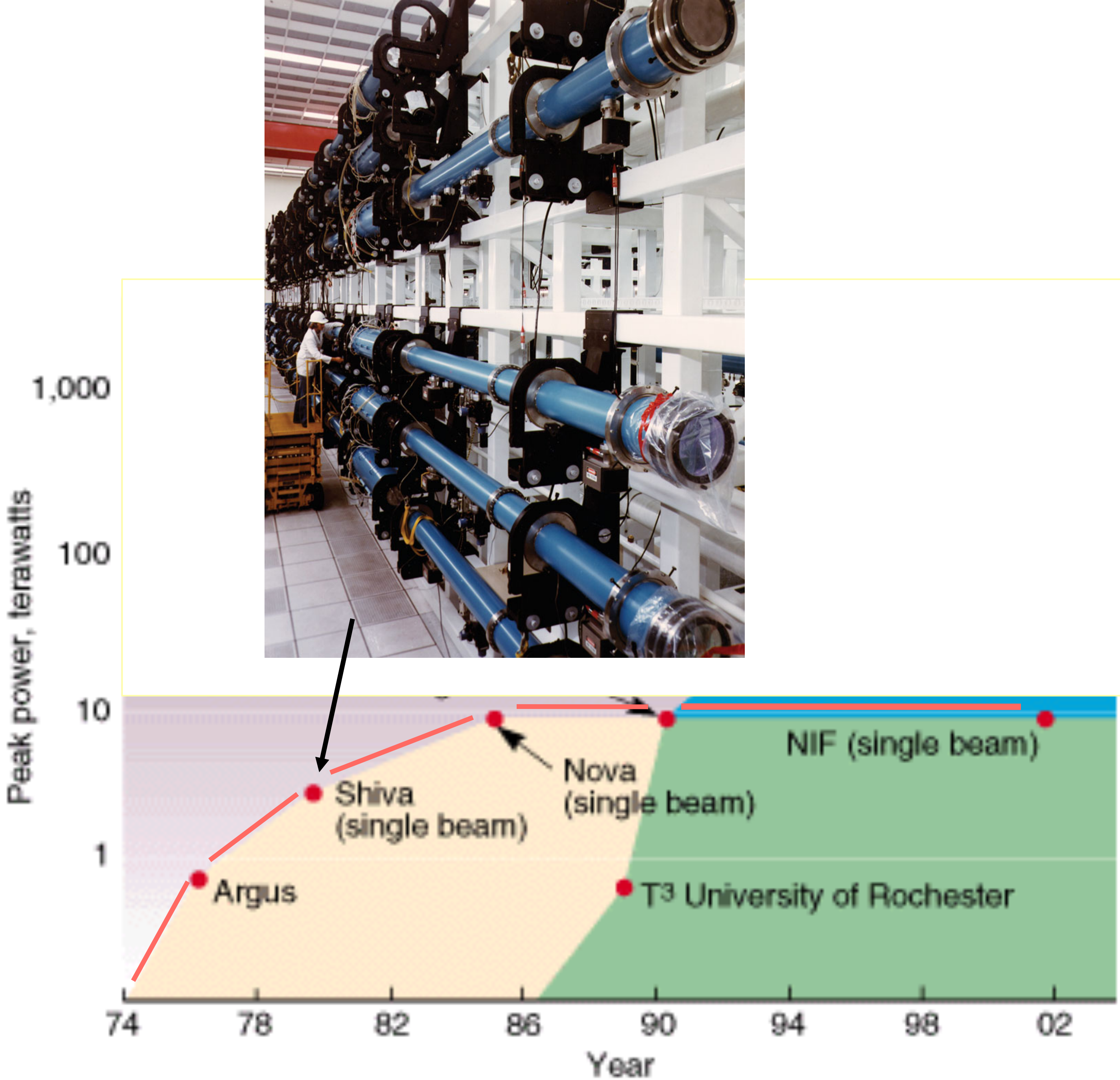
Picture: LLNL



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

The B-limi

Picture: LLNL



Milestones in
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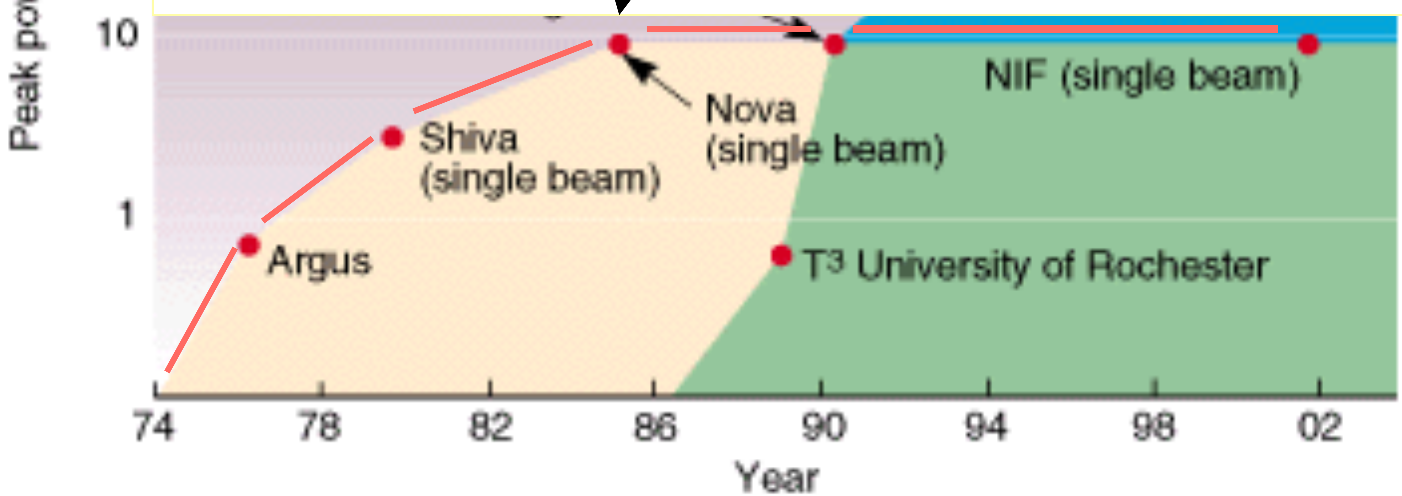
The B-limi

Picture: LLNL



Milestones in
laser development
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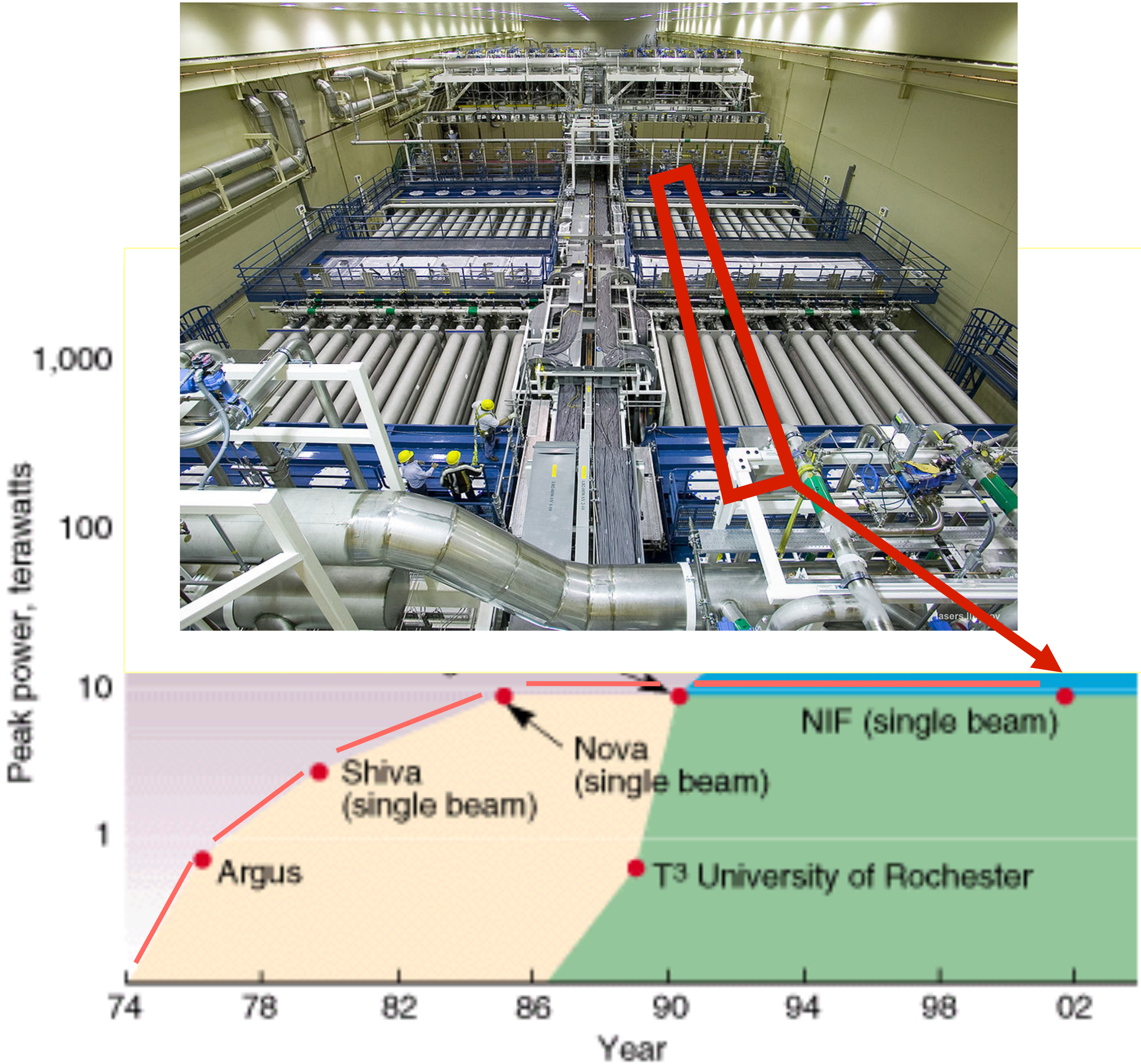
The B-limi

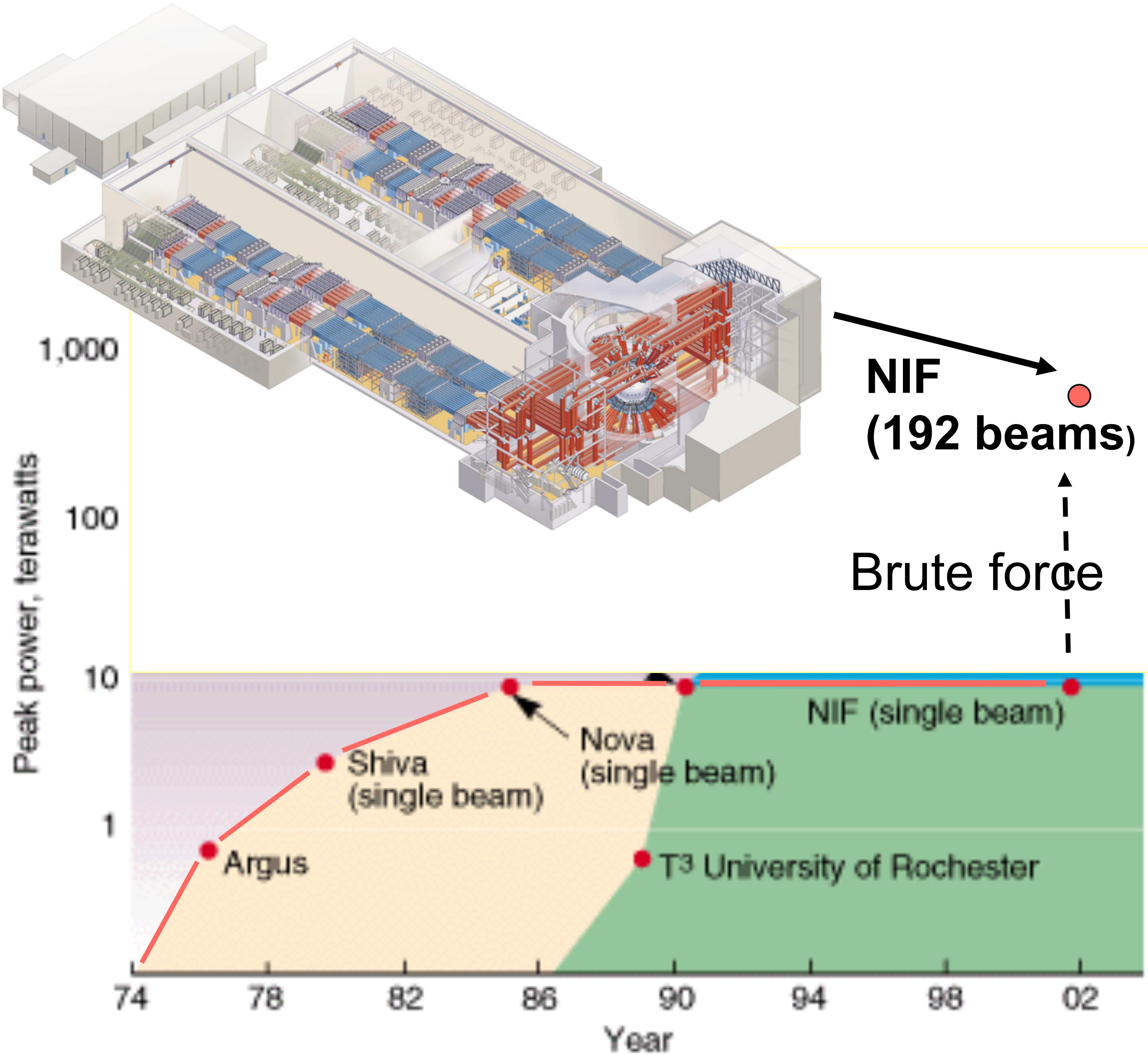
Picture: LLNL



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

The B-limi

Picture: LLNL



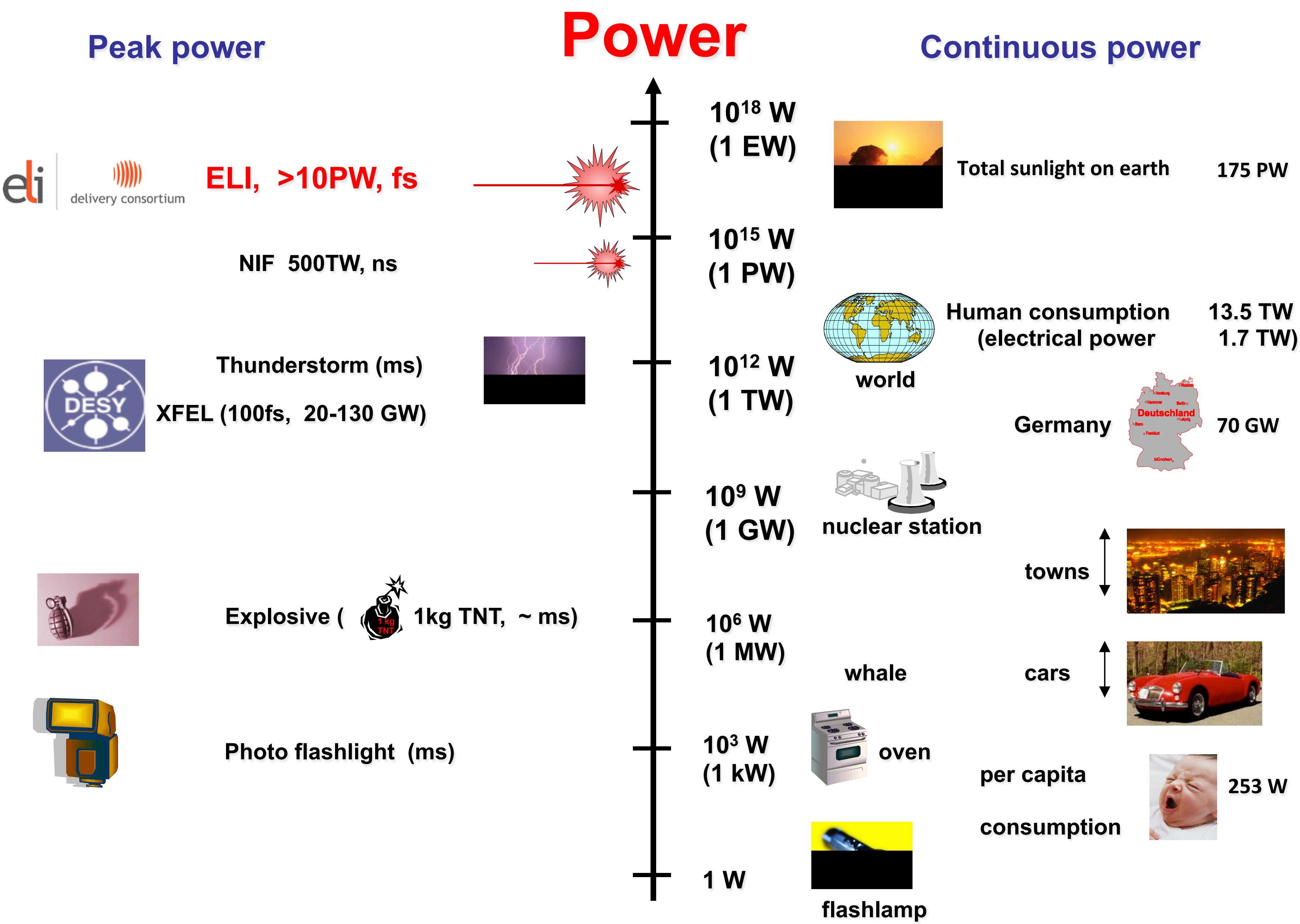
Milestones in laser development: early lasers (yellow), long-pulse technology (green),

Picture: LLNL

~2.5 MJ, the NIF single light pulse energy, is the energy of a 10-ton truck traveling at ~100km/h

So, NIF has energy.

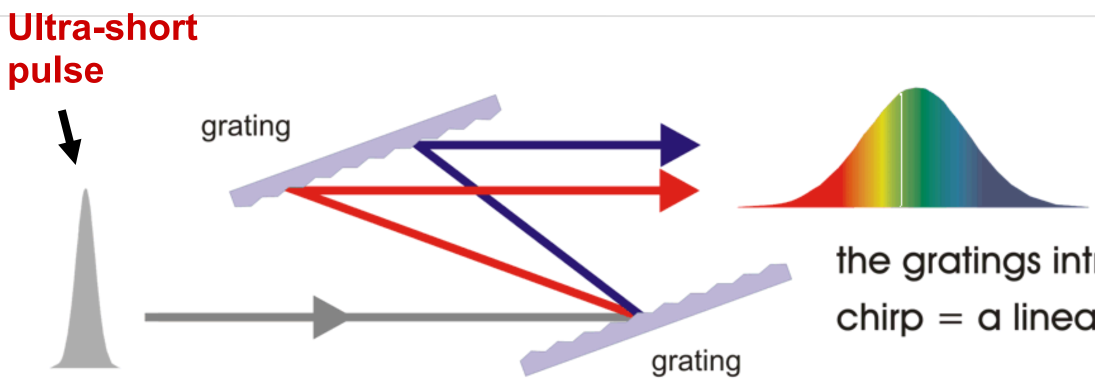
But what about power?


Power
Peak power
Continuous power
10^{18} W
(1 EW)
eli
delivery consortium
ELI, >10PW, fs
Total sunlight on earth
175 PW
10^{15} W
(1 PW)
NIF 500TW, ns
Human consumption
(electrical power
13.5 TW
1.7 TW)
world
Thunderstorm (ms)
10^{12} W
(1 TW)
DESY
XFEL (100fs, 20-130 GW)
Germany
Deutschland
70 GW
10^{9} W
(1 GW)
nuclear station
towns
Explosive (1kg TNT, ~ ms)
1 kg TNT
10^{6} W
(1 MW)
whale
cars
Photo flashlight (ms)
10^{3} W
(1 kW)
oven
per capita
consumption
253 W
1 W
flashlamp

Conclusion:
The NIF approach – massive parallelization of beam-lines limited to 10 TW each – appears not suitable to be scaled up to ELI-powers of 10PW and beyond.

=> Need for a “disruptive technology”

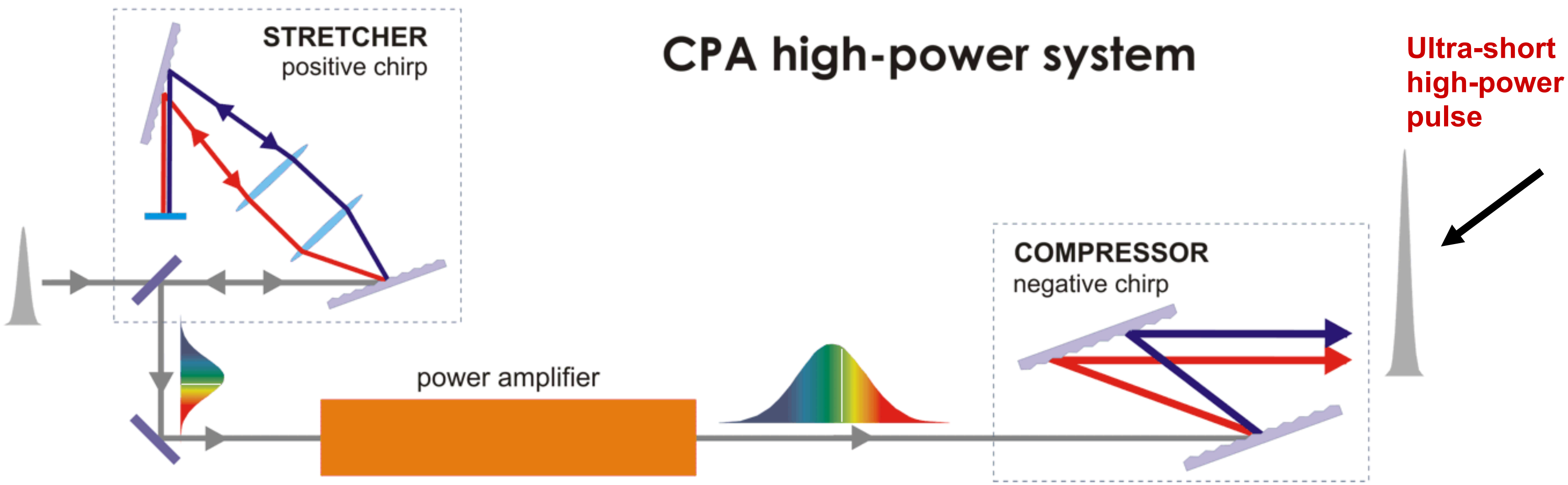
Meet CPA = Chirped Pulse Amplification



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

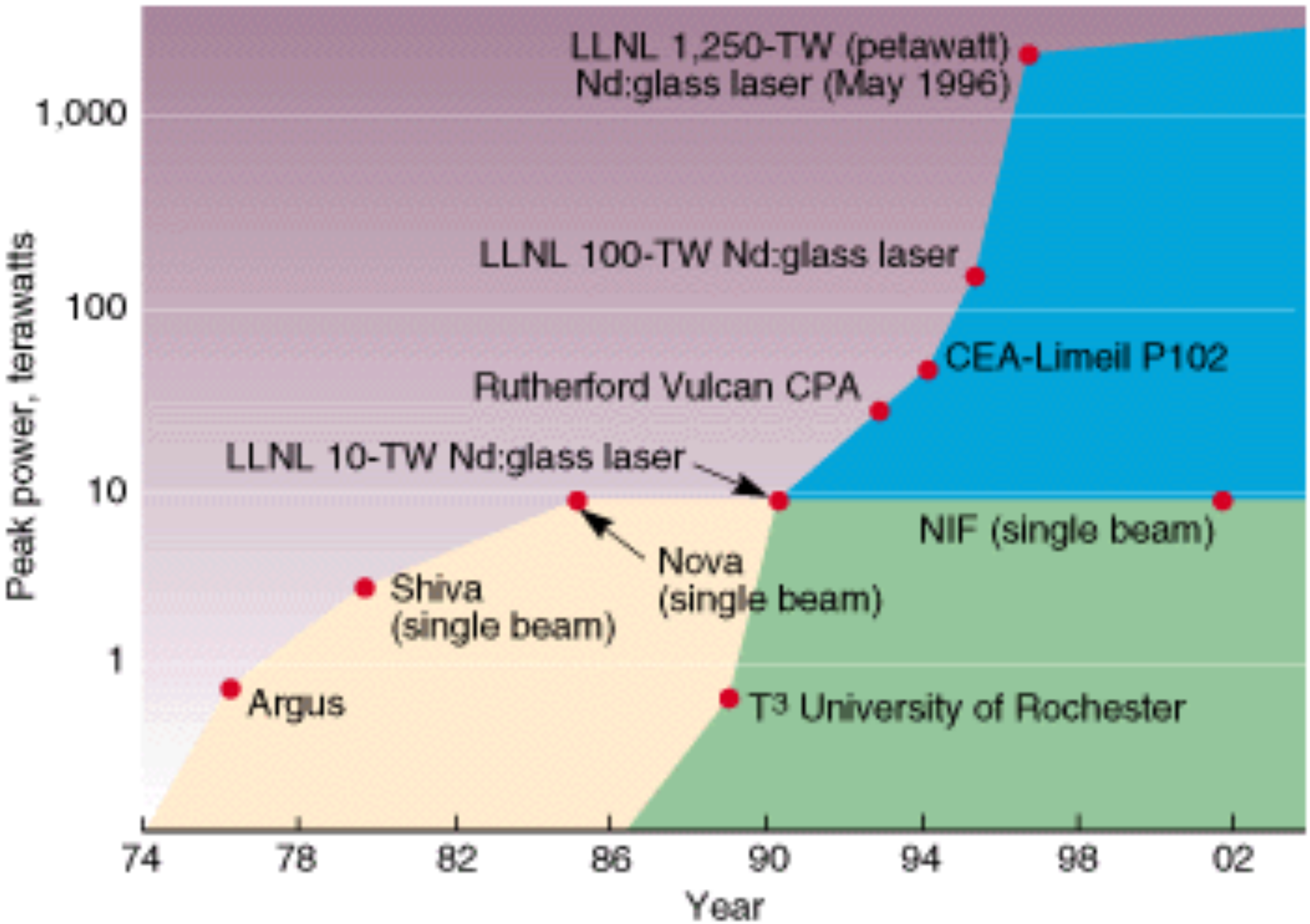
the gratings introduce a frequency dependent time delay
chirp = a linear frequency sweep, $d\omega/dt$

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 as a disruptive technology

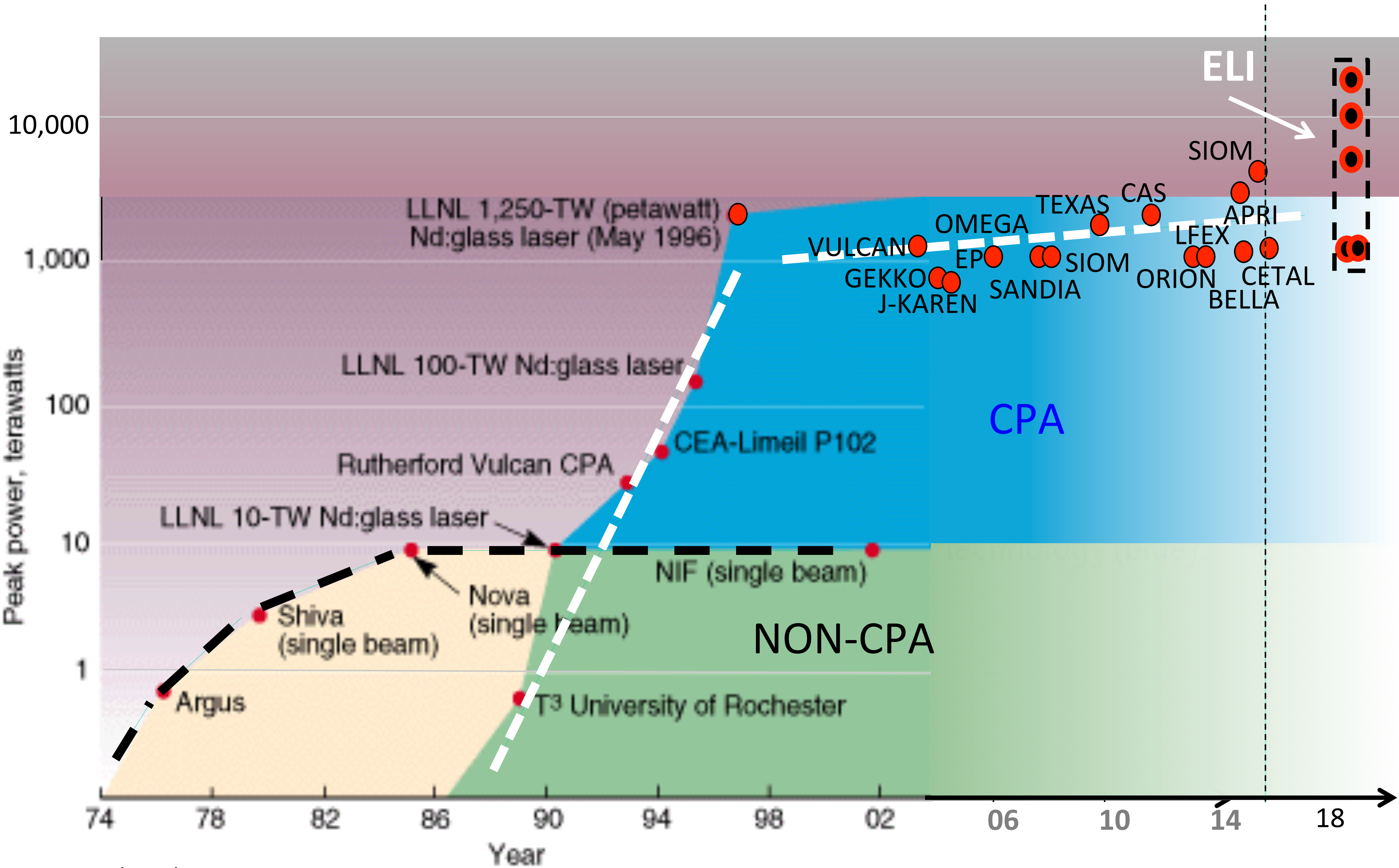


Milestones in laser development: early lasers (yellow), long-pulse technology (green), and chirped-pulse amplification technology (blue).

Picture: LLNL

How did the story continue?

HIGH - POWER LASERS 2015



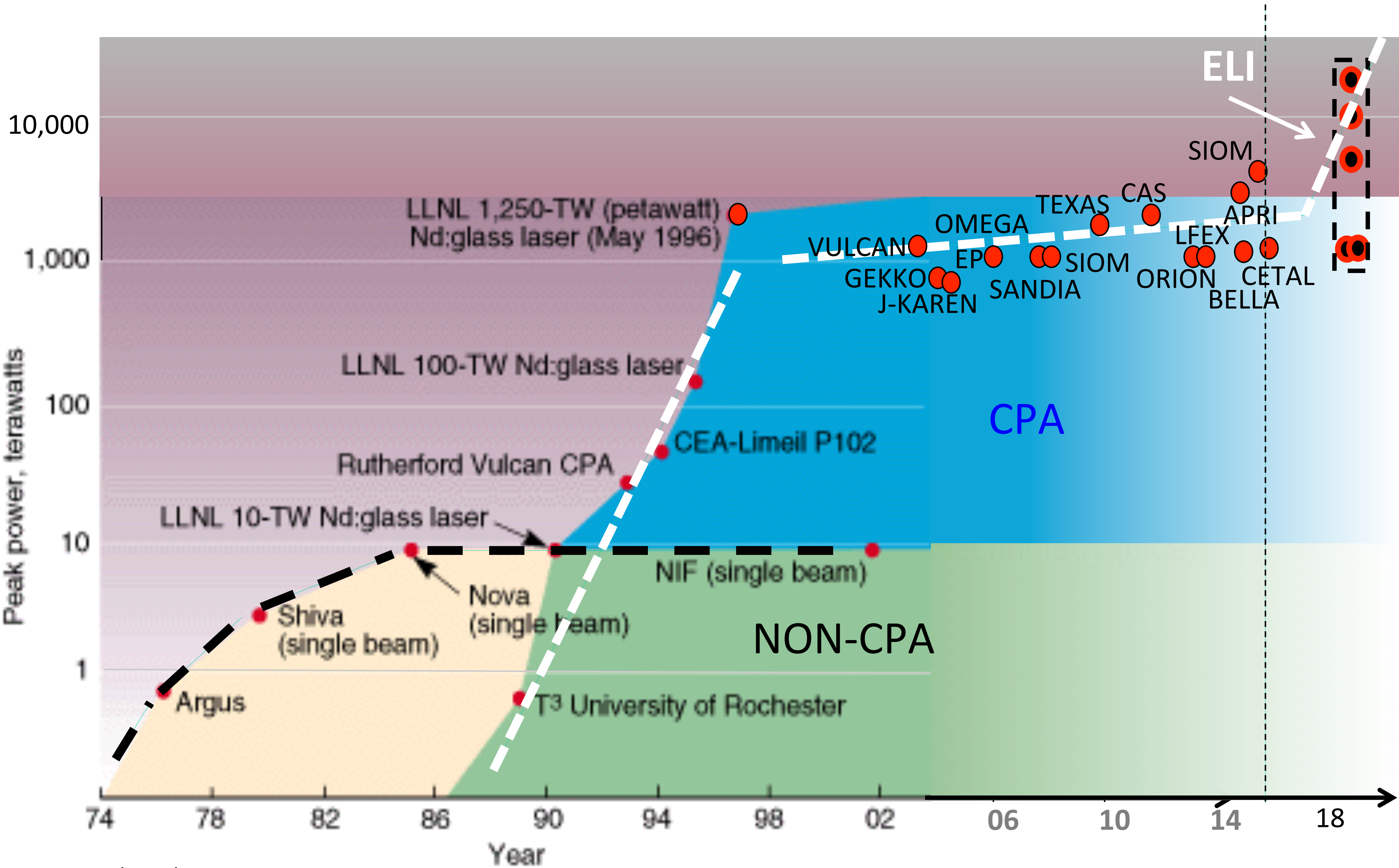
Original graphics: LLNL

Recent data: Colin Danson, David Hillier, Nicholas Hopps and David Neely (2015). **Petawatt class lasers worldwide**. High Power Laser Science and Engineering, 3, e3 doi:10.1017/hpl.2014.52

Two decades of near-stagnation at the PW level - time for new disruptive technologies!

- **Chirped pulse amplification (1986)**: overcoming the B-Integral barrier (self-focusing).The basis of today's PW-lasers.
- **Optical parametric amplification**: potentially overcoming intermediate energy storage, contrast-, bandwidth- & thermal problems (=> ELI-BL, ELI-ALPS, ELI-NP)
- **Coherent beam superposition:** potentially overcoming size limitations in optical components (ICAN, "Nexawatt") => ELI-NP
- **Others?** Damage-resistant surfaces, crystals, gratings, new amplifier concepts (e.g. Raman) or compressor concepts
- **Diode pumping**: overcoming the average power problem ("*the next challenge after multi-PW is multi-kW*")=> ELI-BL

ELI – starting a new era in high-power lasers?



Original graphics: LLNL

Recent data: Colin Danson, David Hillier, Nicholas Hopps and David Neely (2015). **Petawatt class lasers worldwide**. High Power Laser Science and Engineering, 3, e3 doi:10.1017/hpl.2014.52

Extreme peak power @ ELI

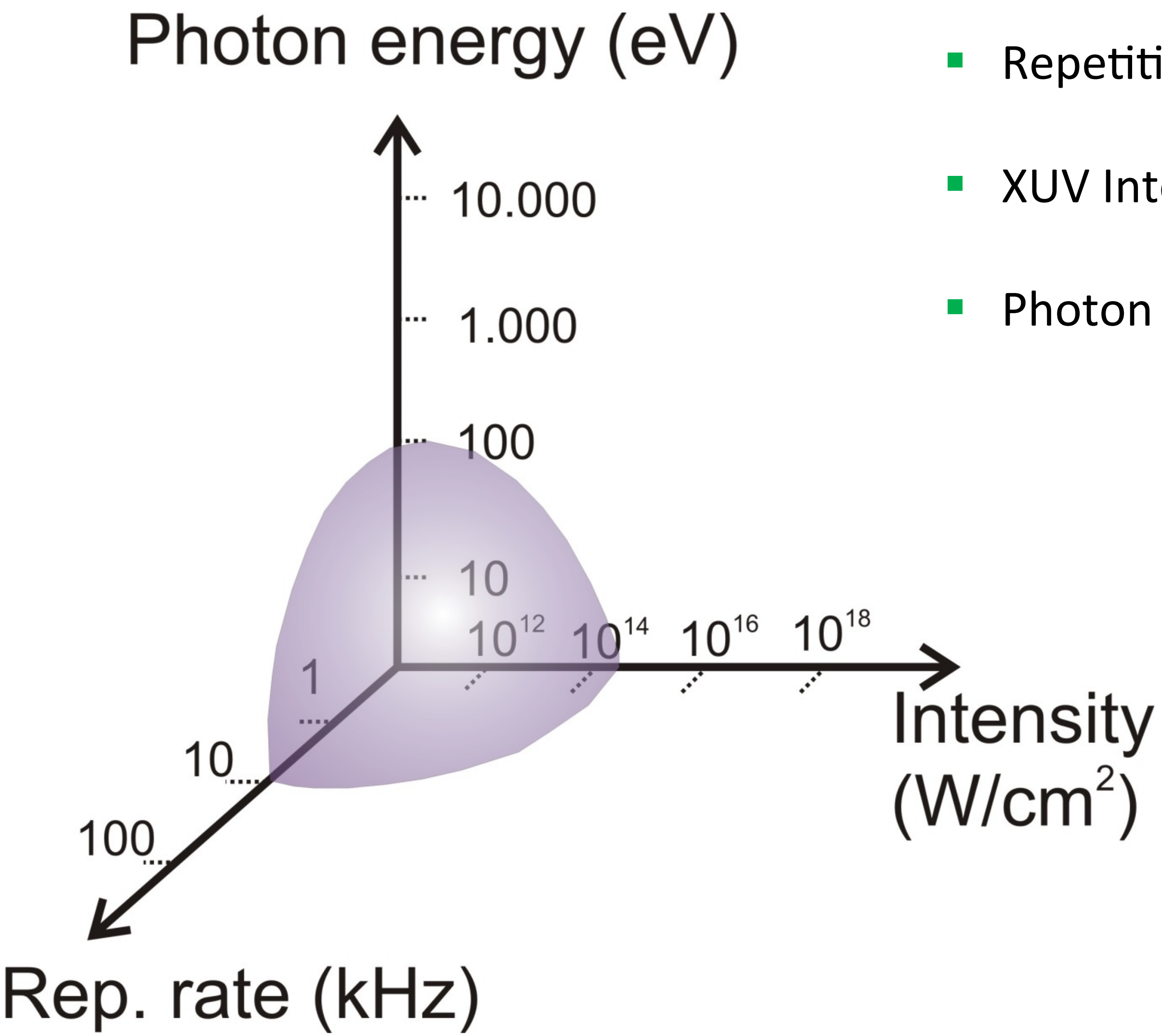
- Today's most powerful lasers achieve max. few PW @ max. 1Hz (typically << 1Hz).
- There exist about a dozen PW lasers world-wide, more are planned

- ELI will have, based on contracts with international suppliers:

  - Two coupled 10PW Ti:Sa lasers (ELI-NP)
  - One 1-2PW DPSSL @ >10Hz (ELI-BL)
  - One 1PW OPCPA DPSSL, <20fs, 10Hz (ELI-BL)
  - One 10PW mixed-glass laser (1.5kJ, 150fs) (ELI BL)
  - One multi-PW Ti:Sa laser @ few Hz (ELI-ALPS)

Each of these exceeds today's state-of-the-art (power and/or repetition rate) by a factor of ~10

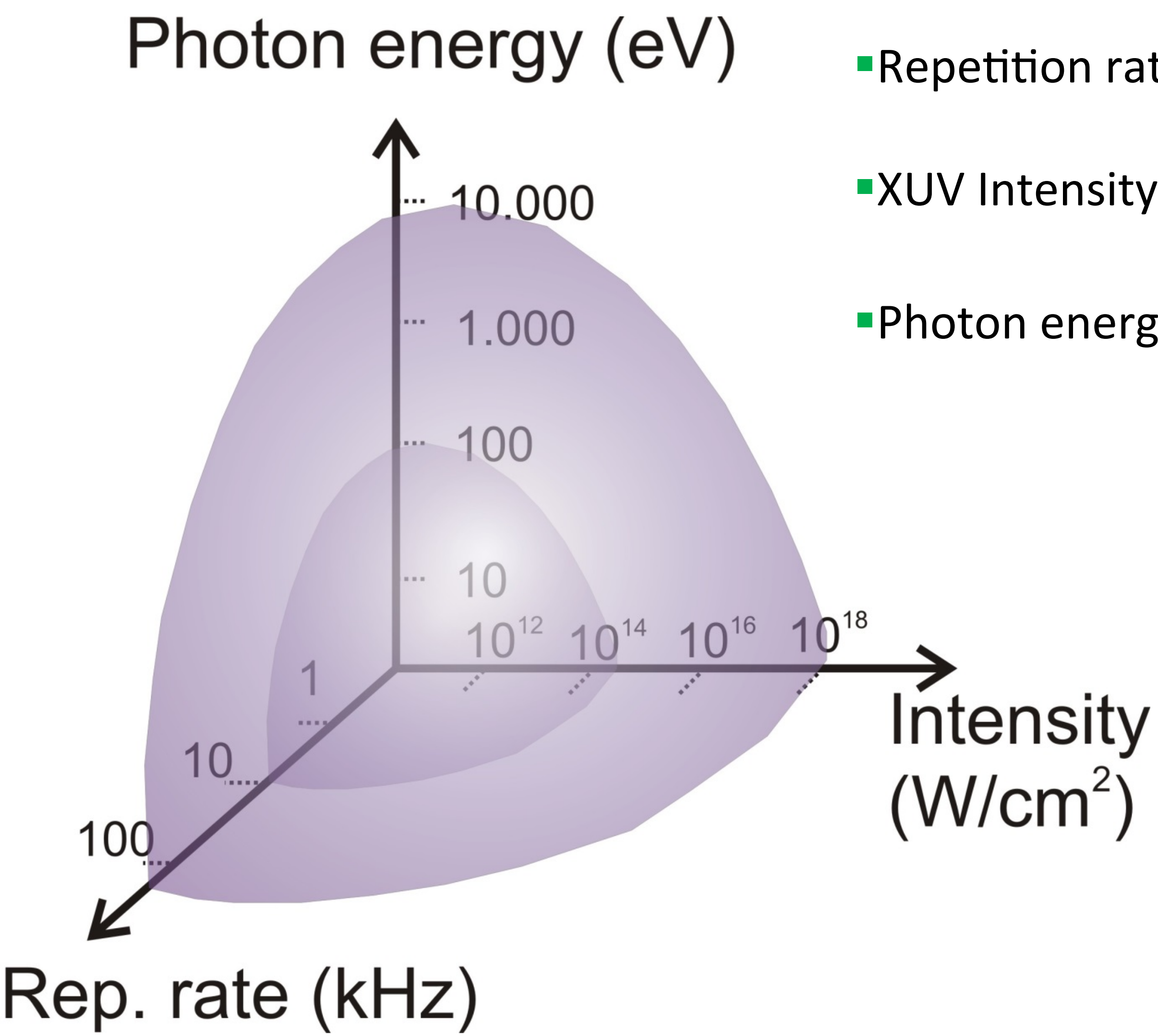
Today's spectral coverage, ultra-short intensity and repetition rate



- Repetition rate (few Hz-10 kHz)
- XUV Intensity (10^9-10^{14} W/cm^2)
- Photon energy (10-100 eV)

delivery consortium

ELI: spectral coverage, ultra-short intensity and repetition rate

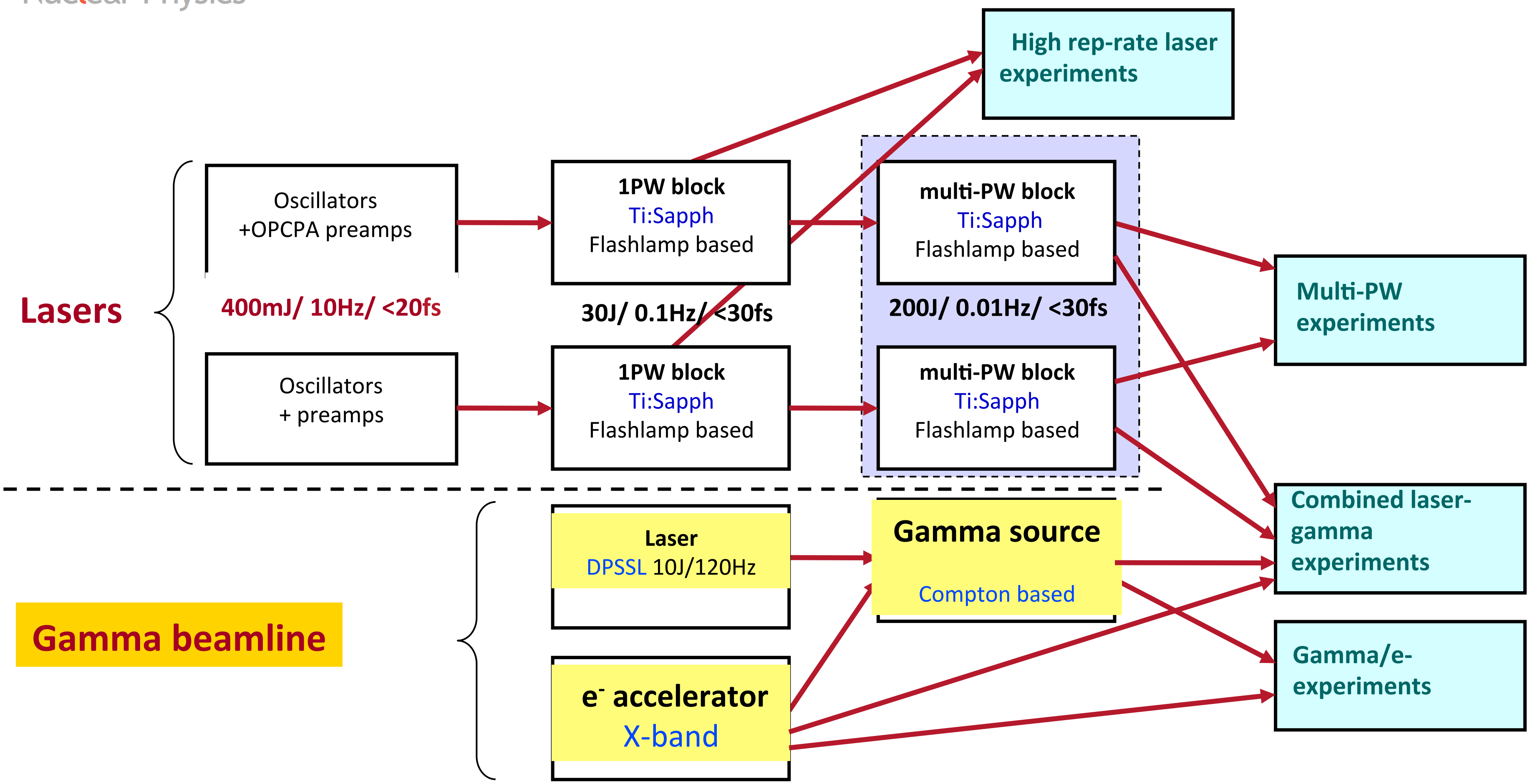


- Repetition rate (few Hz-100 kHz)
- XUV Intensity (10^9-10^{18} W/cm^2)
- Photon energy (10-10.000 eV)

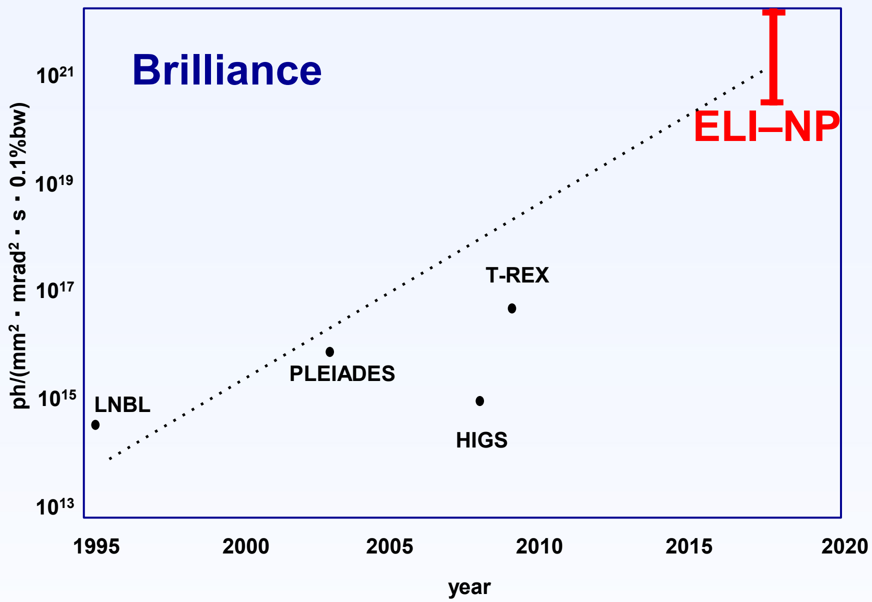
(*specs from ELI-ALPS*)

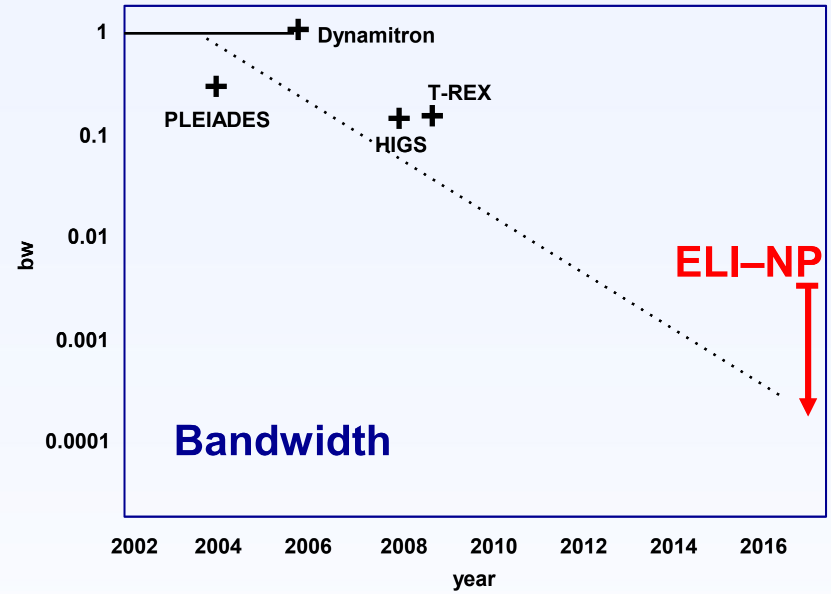
The implementation

ELI-NP Facility Concept

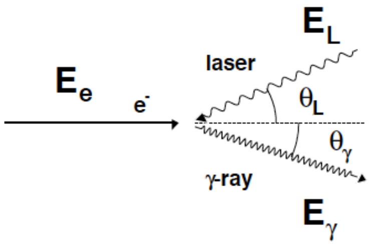


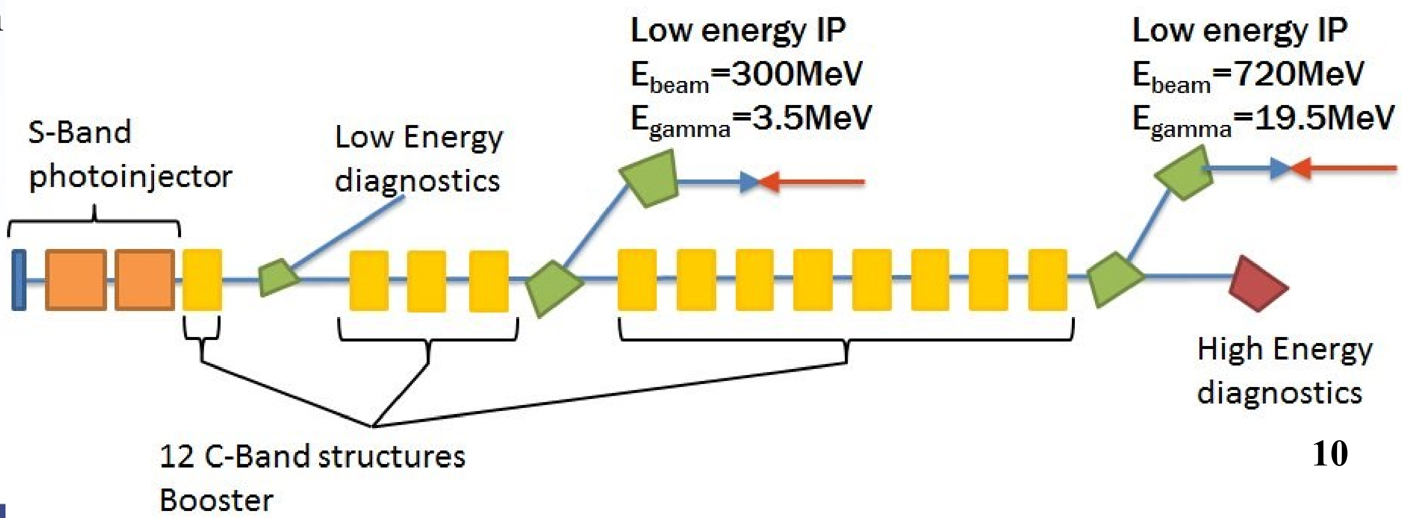
Gamma Beam System



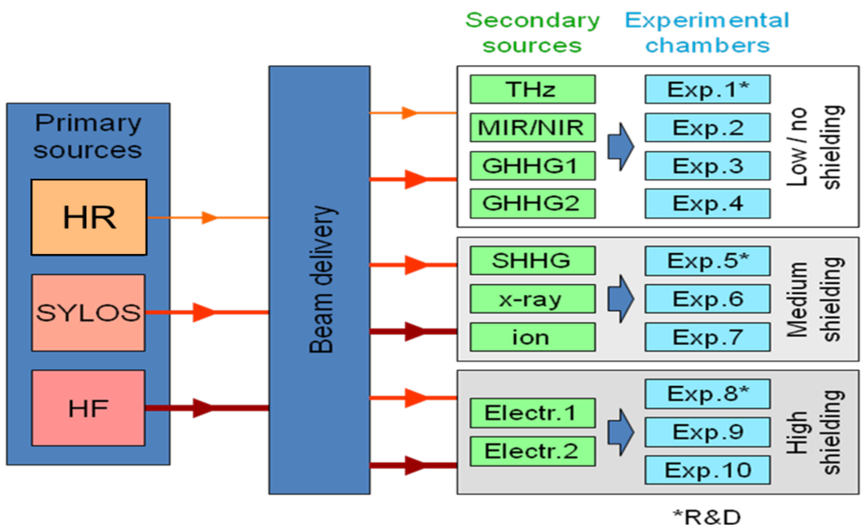


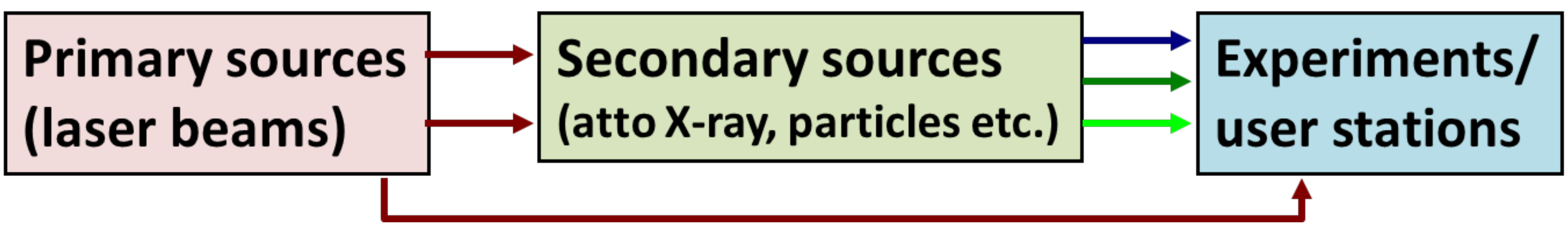
EuroGammas Consortium
Lead by INFN Italy
Research Institutes and
HighTech Companies
from 8 Countries





Schematics of ELI-ALPS

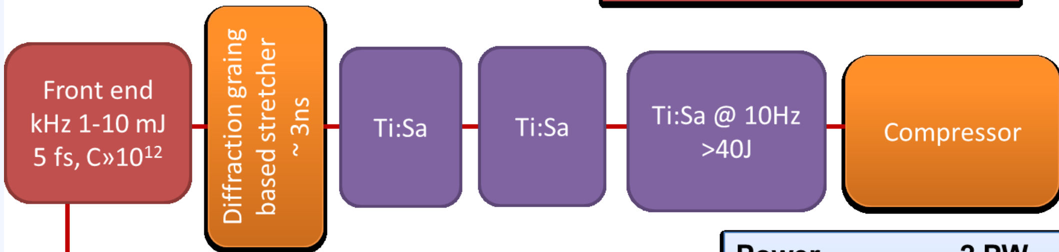




ELI-ALPS will provide the shortest pulses (femto- and atto-second duration), with highest power, highest repetition rate, in the broadest spectral range

ELI-ALPS Lasers – Procured

Amplitude Technologies



Seed for HF 100

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

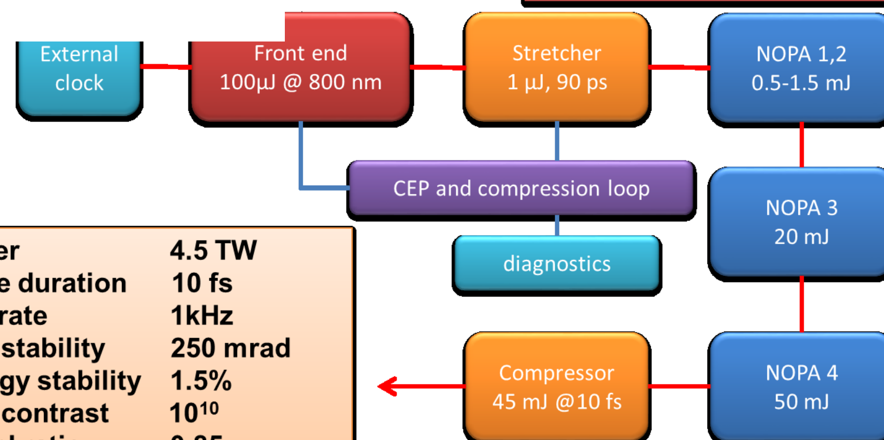
FAT: Sept, 2016, SAT: March, 2017

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

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

HF PW laser
Value: 6BHUF

EKSPLA + Light Conversion consortium



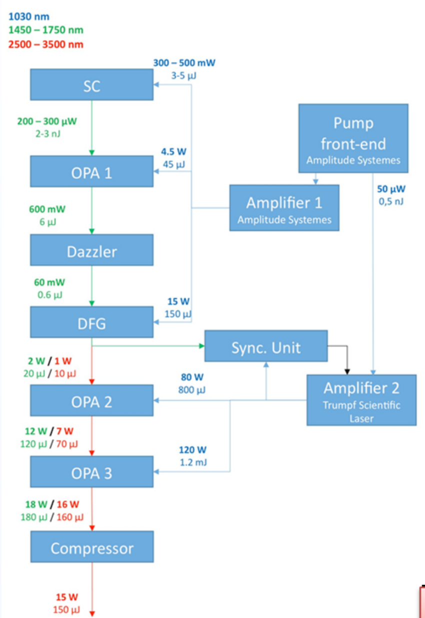
Power	4.5 TW
Pulse duration	10 fs
Rep.rate	1kHz
CEP stability	250 mrad
Energy stability	1.5%
ASE contrast	10^{10}
Strehl ratio	0.85
Central λ	800 nm
Beam ∅	60 mm
Optics ∅	100 mm

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



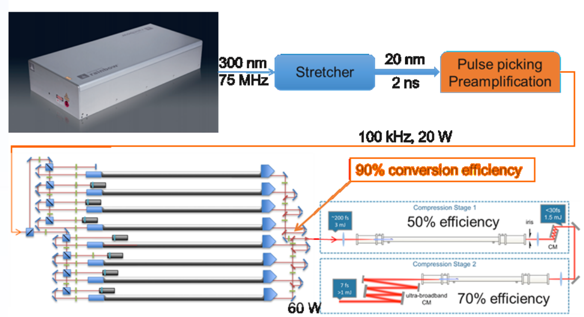
Fastlite (+AmplitudeSystems+Trumpf SL)

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



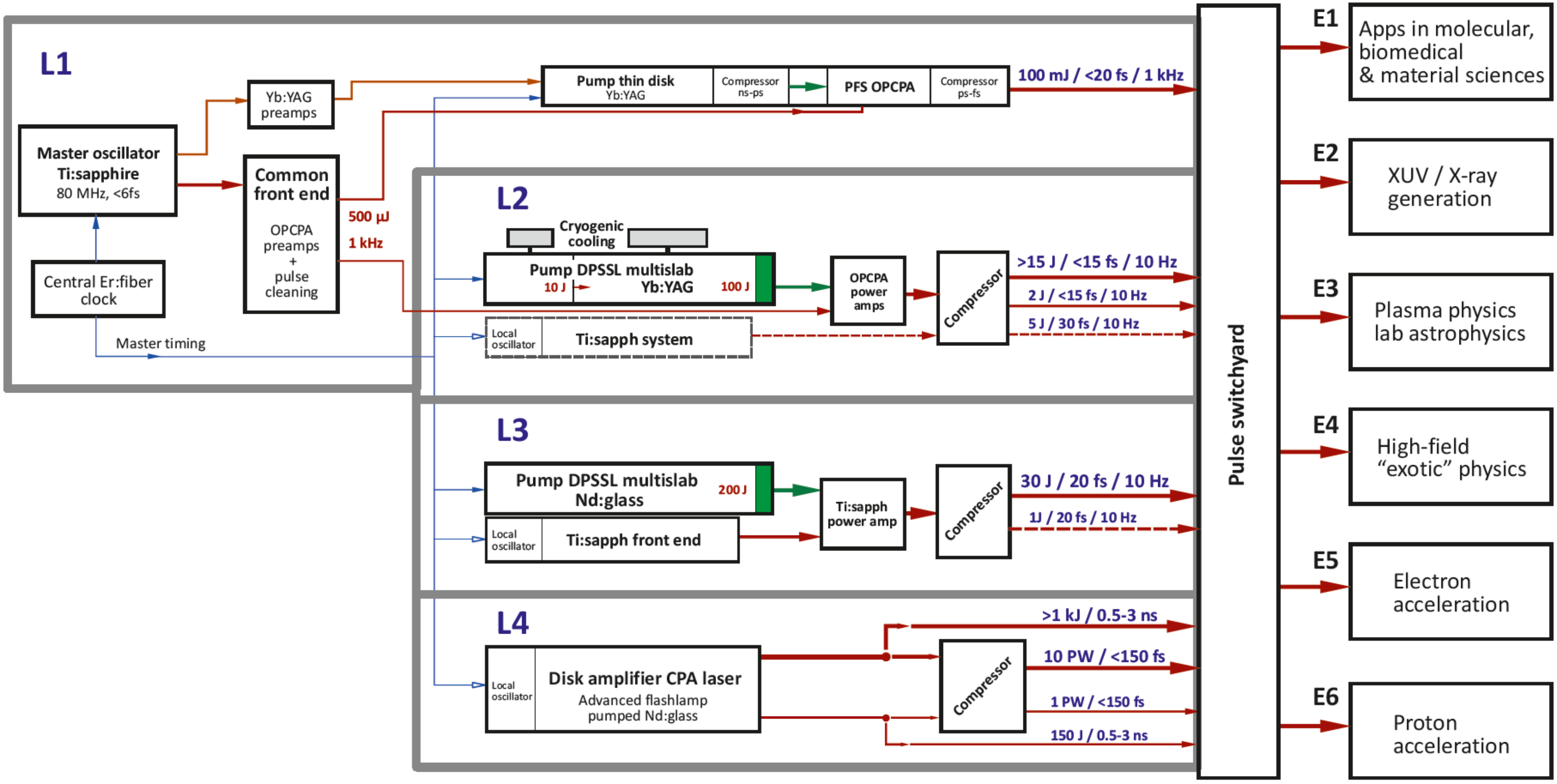
Wavelength	1030 nm
Energy	>1 mJ
Pulse duration	<6.2 fs
Rep.rate	100 kHz
CEP stability	<100 mrad
Energy stability	0.8%
Strehl ratio	0.9

HR 1 laser
Value: 895 MHUF

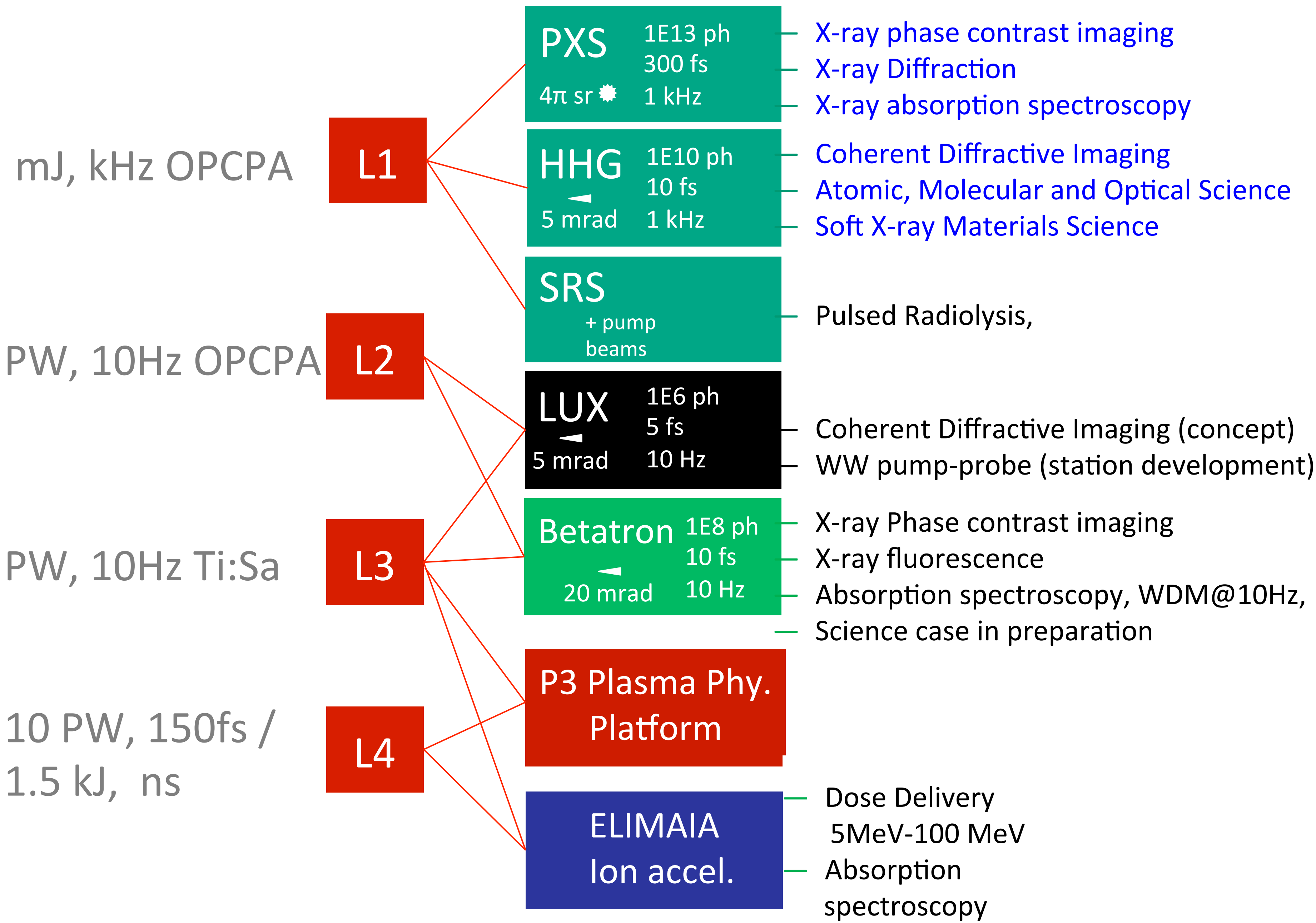
FAT: May, 2016, SAT: July, 2016

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

ELI-Beamlines master scheme



ELI-BL: What users get



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Why?

ELI's science & research opportunities

Project supported by:

EUROPEAN UNION
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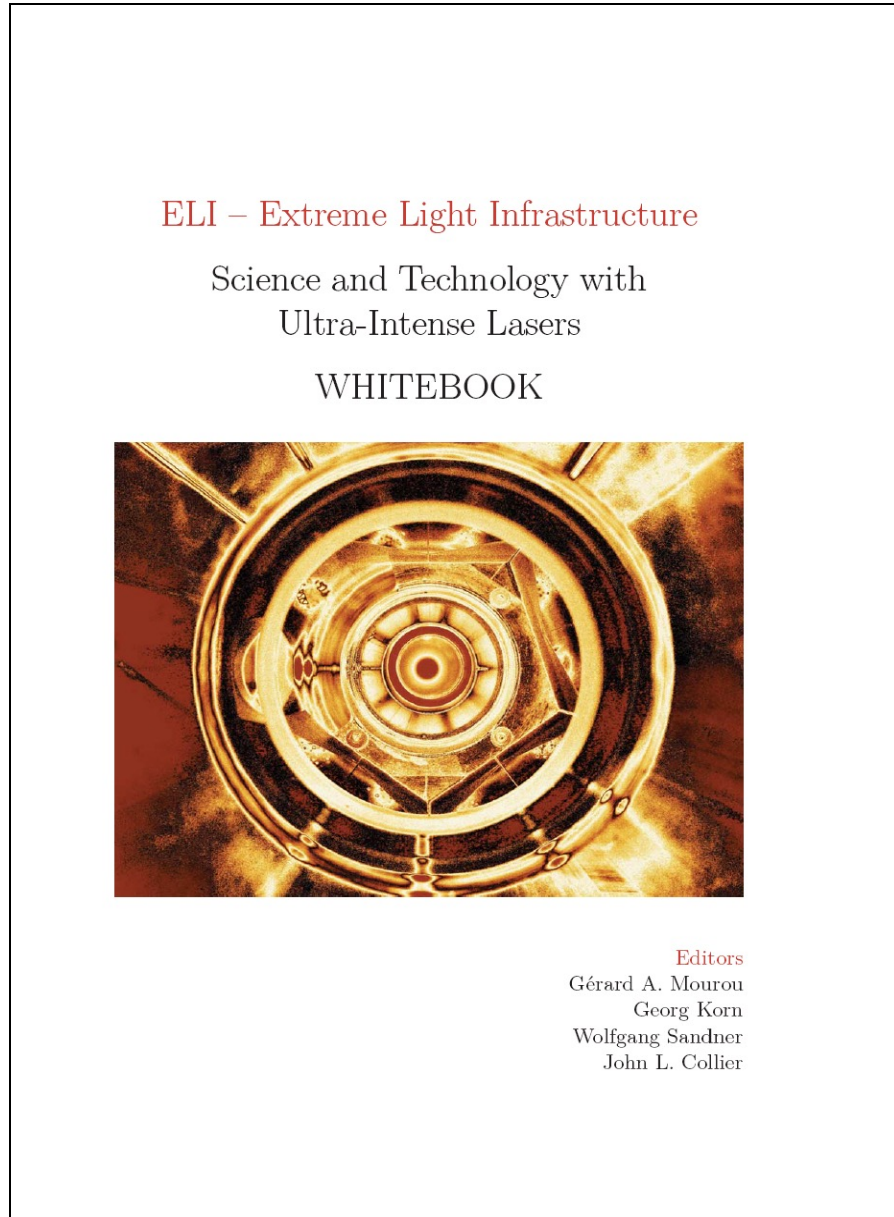
INVESTING IN YOUR FUTURE

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

Physics behind

Some key phenomena for the interaction of extreme laser intenisities 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:

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

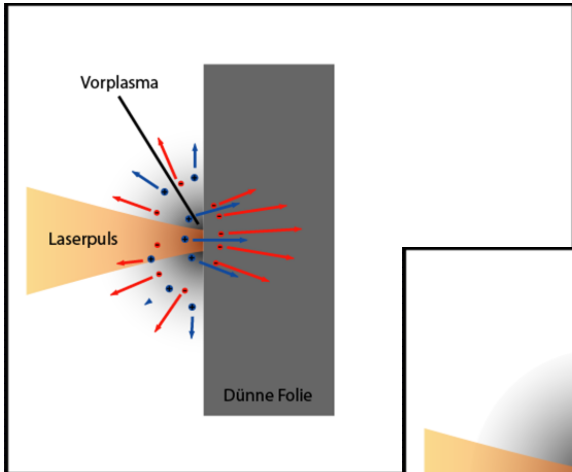
Particles: laser accelerated ions and electrons

Photons: from table-top XFELs to Gamma rays

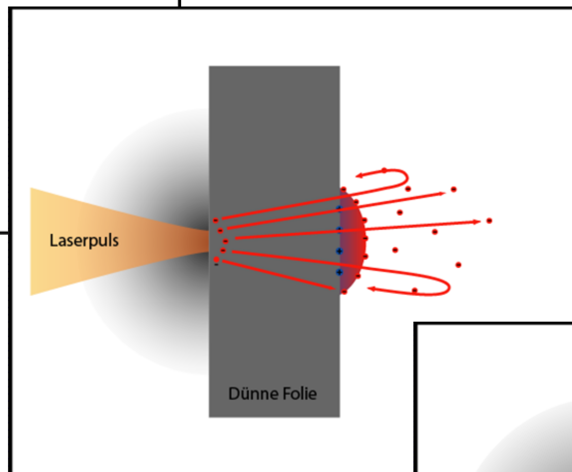
from meV (THz) to MeV

from pico- to attoseconds

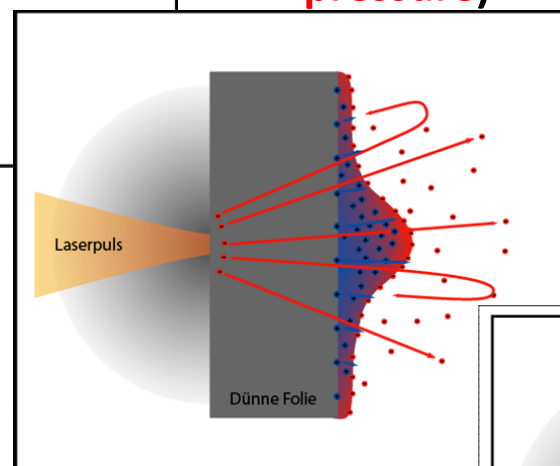
Ions: Target Normal Sheath Acceleration (TNSA)



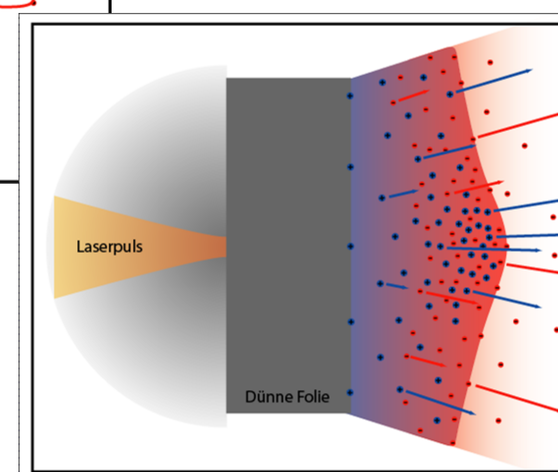
Pre-plasma creation on thin foil (ionisation and heating)



Main pulse energy and momentum transferred to plasma electrons, electrons leave on the back (light pressure)

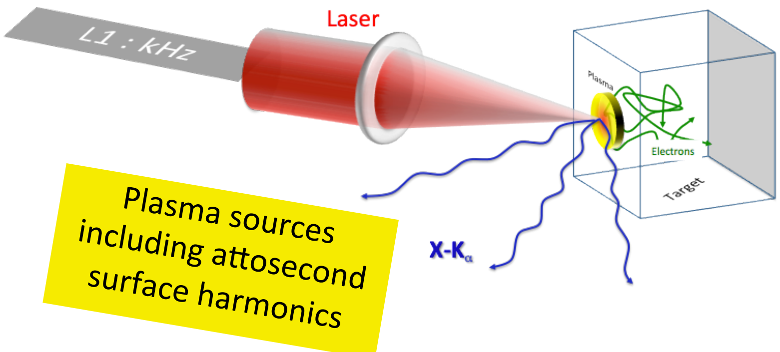


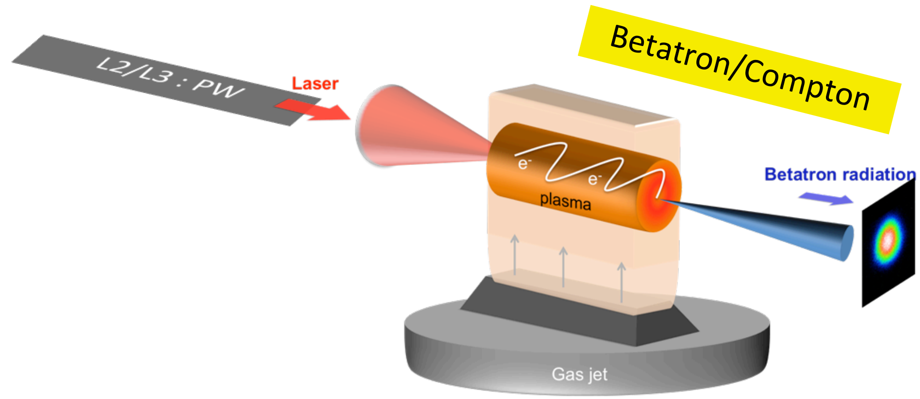
Formation of an electron sheath
⇒ quasi-equilibrium electric field (MV/µm)
⇒ Rectification of laser fields

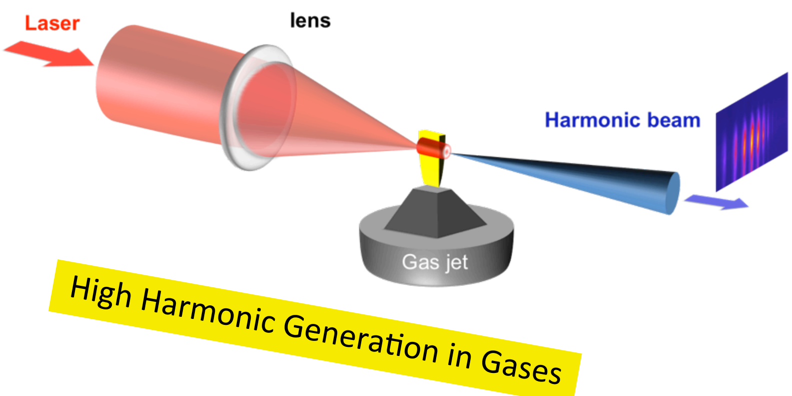


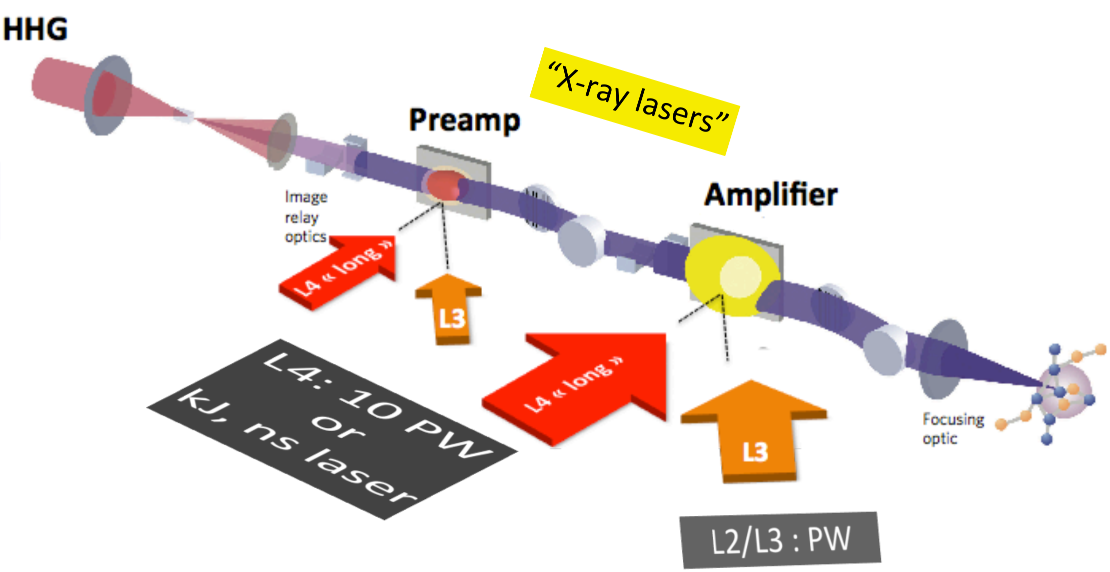
Ion acceleration by the static electric field

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









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Science and applications

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")

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The facilities

Attosecond Light Pulse Source (*ELI-ALPS*, Szeged, HU): new regimes of time resolution

High-Energy Beam Facility (*ELI-Beamlines*, Dolni Brezany, CZ): development and application of ultra-short pulses of high-energy particles and radiation

Nuclear Physics Facility (*ELI-NP*, Magurele, RO): novel photonuclear studieswith ultra-intense lasers and brilliant gamma beams (up to 19 MeV)

Ultra-High-Field Facility (*ELI 4*, to be decided): physics with unprecedented laser field strengths

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ELI's fourth pillar?

ELI's „fourth pillar" will be a sub-exawatt (~ 200PW) laser facility - by a factor of 100 more powerful than today's state-of-the-art, and 10 times more powerful than the present ELI lasers

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, site and funding

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How to benefit from all this?

How to become an ELI user?

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- Get involved! Join ELI user meetings and user consortia. Encourage your government to join ELI-DC (and later ELI-ERIC) for the benefit of national users.
- Get prepared for ELI's science & research opportunities. Expect ELI calls for user proposals in 2017.
- Attend ELI conferences: *International Conference on Extreme Light* ICEL, November 23-27, 2015, Bukarest, Romania.
- **Thus, become part of one of the most exciting laser projects of global dimension.**

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