Introduction to Lasers and High Power Lasers

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LUND UNIVERSITY

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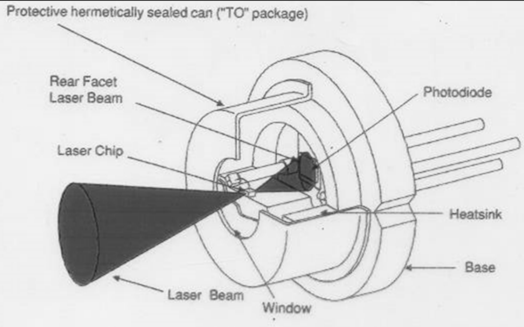
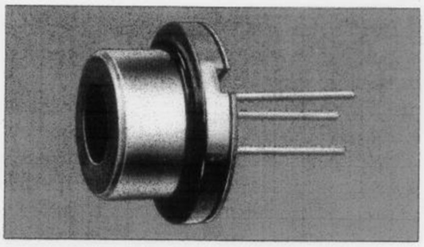
Laserlab Europe

Outline

- Laser basics and Applications
- Oscillators, Amplifiers, CPA
- Contrast, Gain narrowing, Thermal effects
- OPCPA
- Examples of high-power lasers, cost, size

Lasers can be small

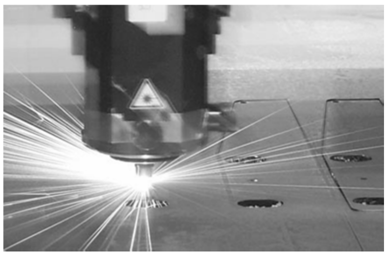




A typical compact disc style laser diode.

Lasers can be large

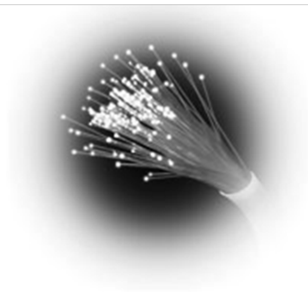
Lasers are used for Cutting and Welding



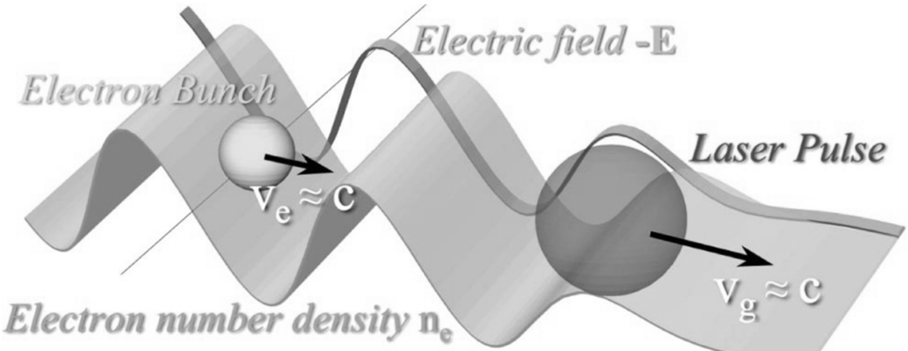
Lasers are used in Medicine

Optical Storage
CD-player, DVD-player, etc

Fiberoptic Communication



Lasers are used in Wakefield Accelerators



From Albert et al 2014 PPCF

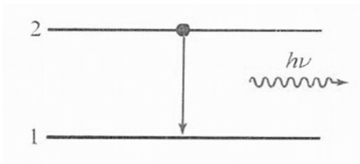
LASER

Light Amplification by Stimulated Emission of Radiation

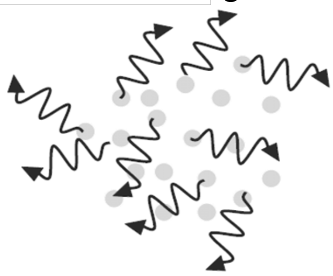
Einstein, 1916
Basov and Prokhorov, 1953
Schawlow and Townes, 1958
Maiman, 1960

1964

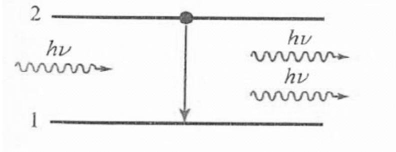
Spontaneous emission



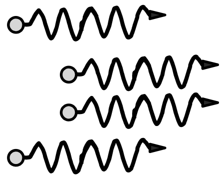
Incoherent light

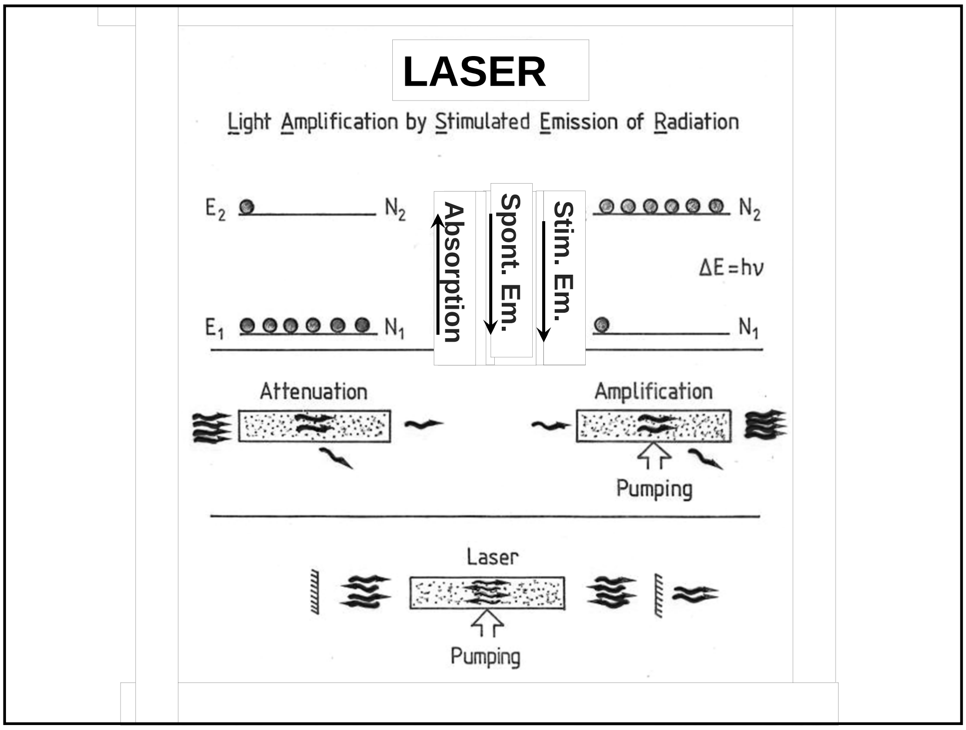


Stimulated emission

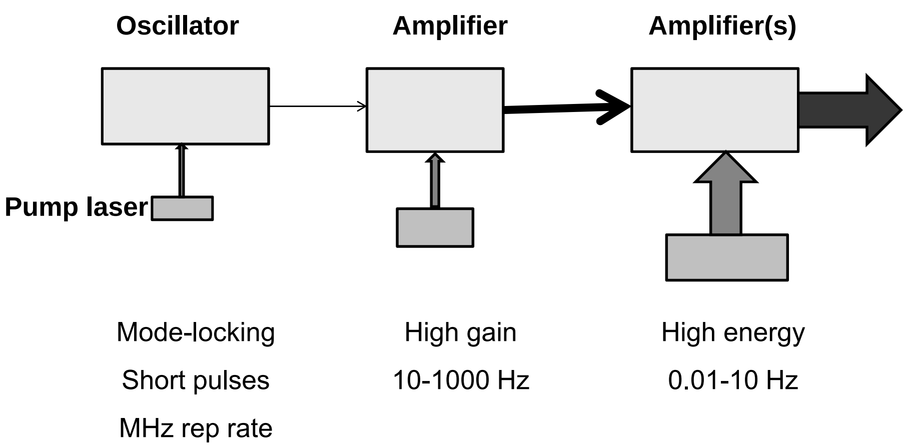


Coherent light

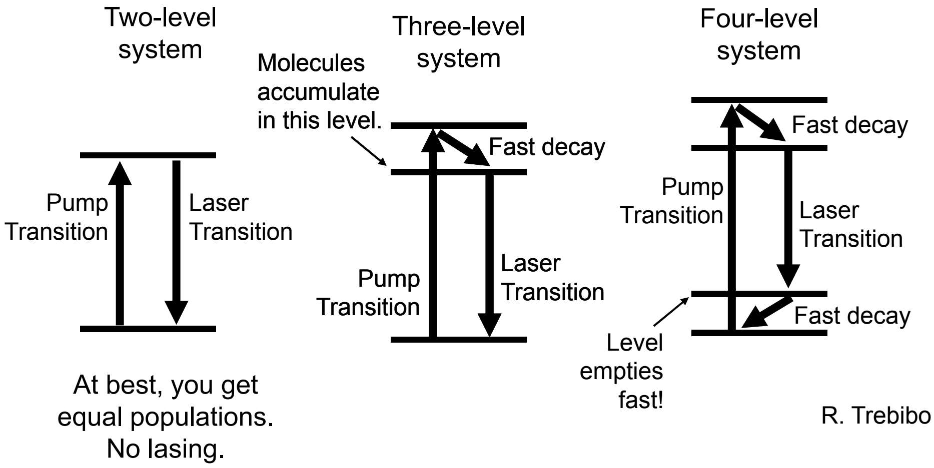




High-Power Laser Systems

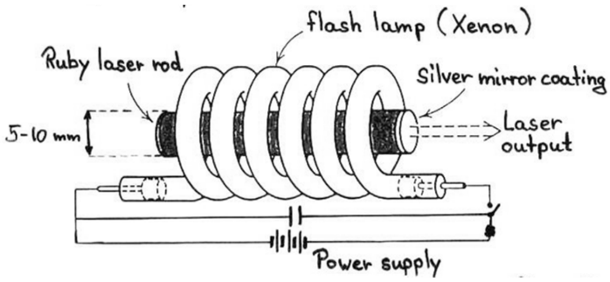


Pumping for Population Inversion

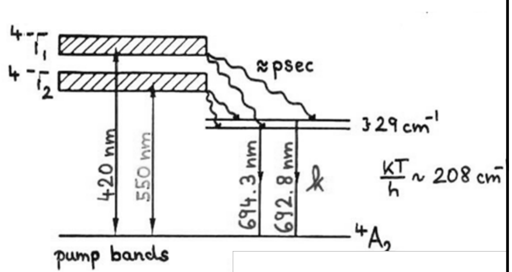


Pumps: Flash lamps,
CW or pulsed lasers, incl. laser diodes,
Gas discharges and charge transfer, etc

The first laser, a 3-level ruby laser (1960)



Theodore H. "Ted" Maiman



High-power lasers

$$P = \frac{E}{\tau}$$

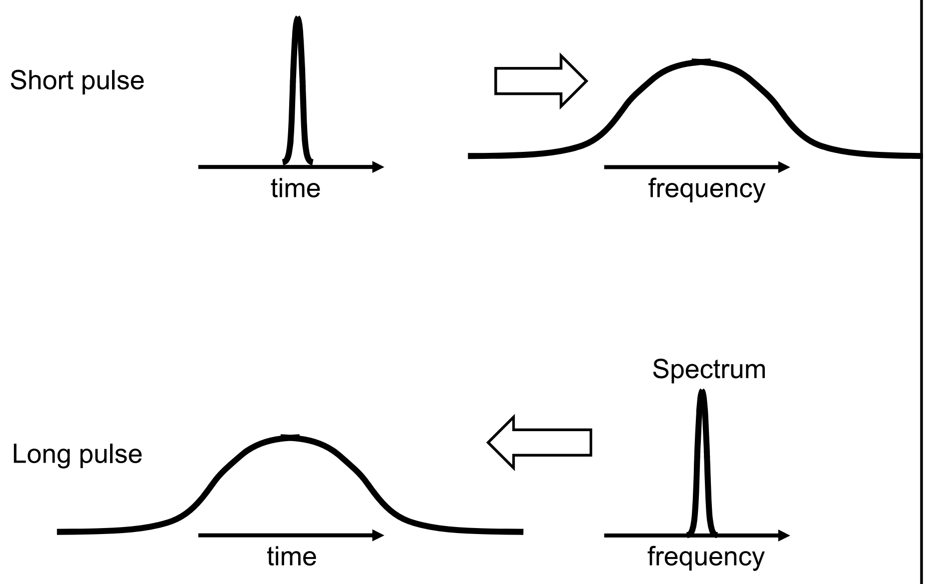
Two approaches:

ICF:	$\tau \sim$ **1 ns,**	$E \sim$ **100 kJ**	**100 TW**	**Few shots/day**
T³:	$\tau \sim$ **10's fs**	$E \sim$ **1 J**	**100 TW**	**10 Hz**

Use short pulses to get high power!

Short pulses also good to drive plasma waves resonantly!

Pulses of Light



Short-Pulse Solid State Lasers

	$\tau_{pulse} \approx 1/\Delta\nu$	λ_{lasing}	τ_{upper}
Nd:YAG	**~10 ps**	**1064 nm**	**230 μs**
Nd:Glass	**~0.5 ps**	**1054 nm**	**300 μs**
Yb:Glass	**~100 fs**	**1035 nm**	**1.4 ms**
Ti:Sapphire ($Ti:Al_2O_3$)	**<5 fs**	**700-1000 nm**	**3.2 μs**

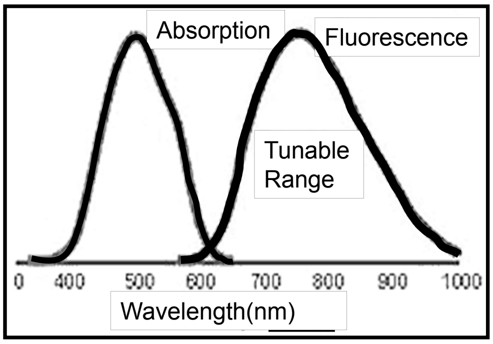
Titanium Sapphire $Ti:Al_2O_3$

Upper level lifetime: 3.2 μsec

Laser pumping required

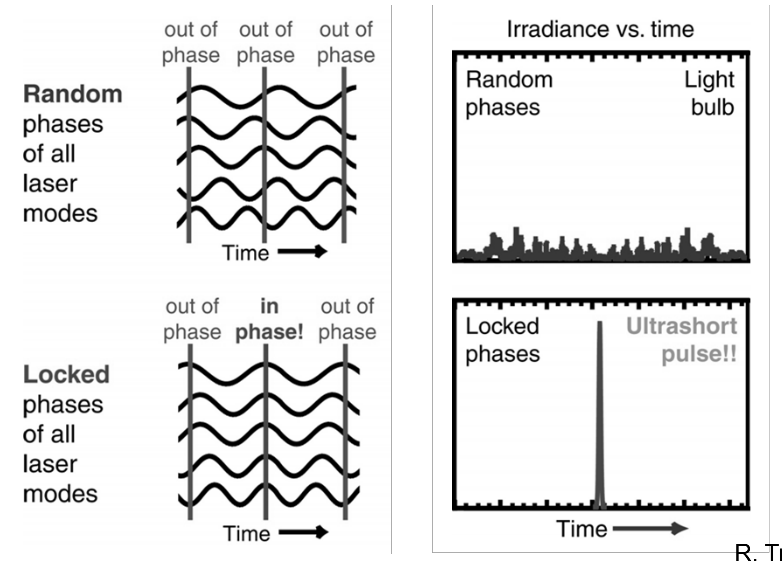
It can be pumped with a frequency doubled Nd laser (~532 nm).

Absorption and emission spectra



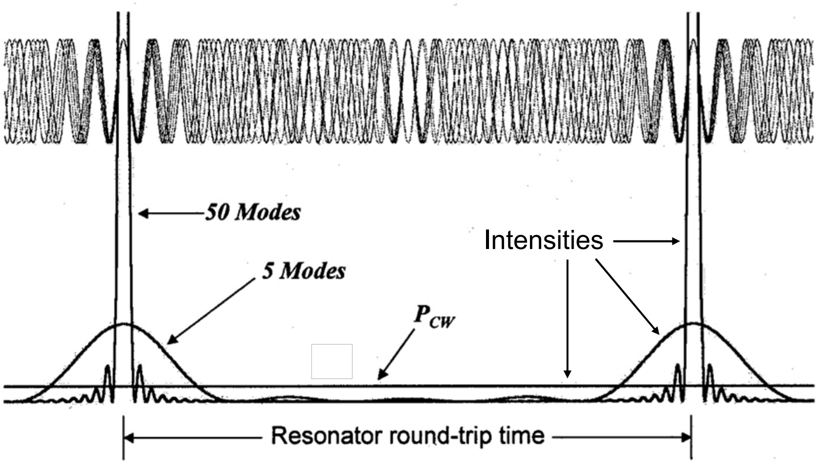
Ti:Sapphire lases from ~700 nm to ~1000 nm.

Generating ultrashort pulses = mode-locking



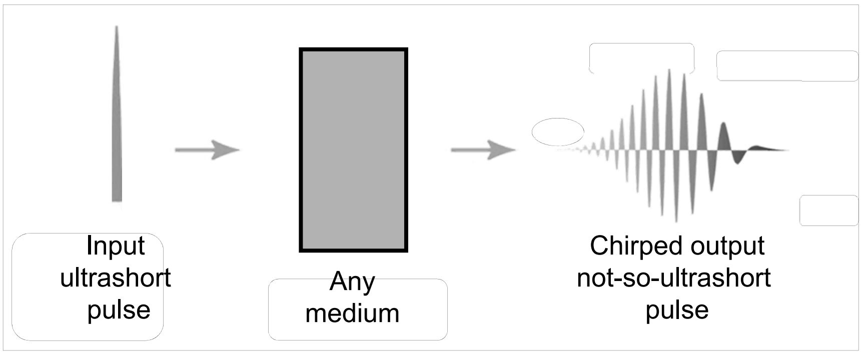
R. Trebibo

Phase-locked modes



Group velocity dispersion (GVD) broadens ultrashort laser pulses

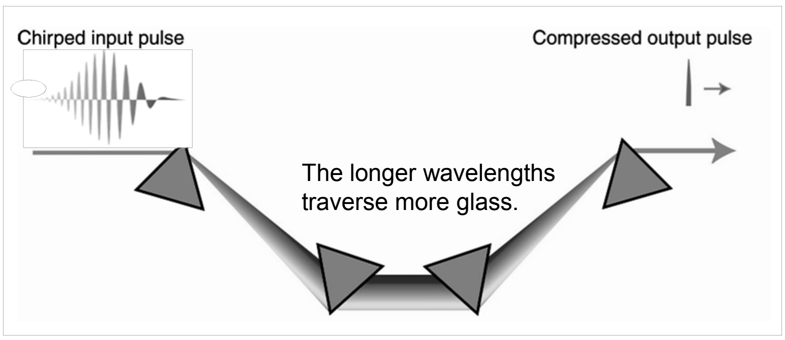
Different frequencies travel at different velocities in materials, causing pulses to expand to highly "chirped" (frequency-swept) pulses.



Longer wavelengths almost always travel faster than shorter ones.

R. Trebibo

Prism Pulse Compressor



R. Trebibo

High-power and high-intensity lasers

$$P = \frac{E}{\tau}$$

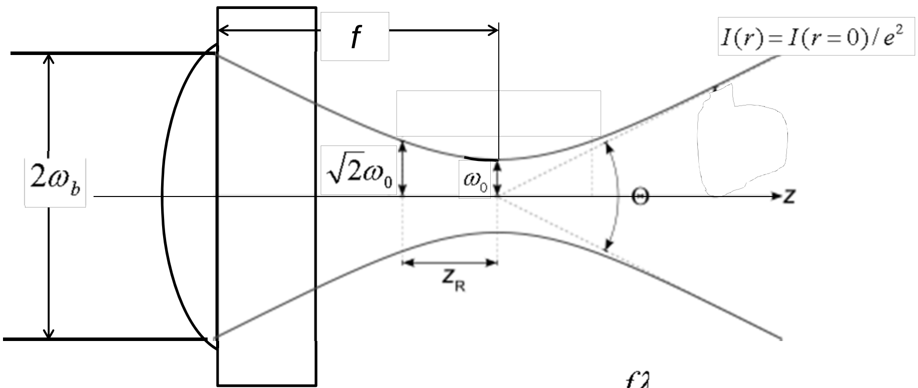
Two approaches:

ICF:	$\tau \sim$ **1 ns,**	$E \sim$ **100 kJ**	**100 TW**	**Few shots/day**
T[3]:	$\tau \sim$ **10's fs**	$E \sim$ **1 J**	**100 TW**	**10 Hz**

$$I = \frac{P}{A}$$

focus diameter **~ 10 μm** $I \sim 10^{20}$ **W/cm²**

Laser focus



Beam waist radius $\omega_0 = \frac{f\lambda}{\pi\omega_b}$

Rayleigh range $Z_R = \frac{\pi\omega_0^2}{\lambda}$

Spot size

Nonlinear Refractive Index

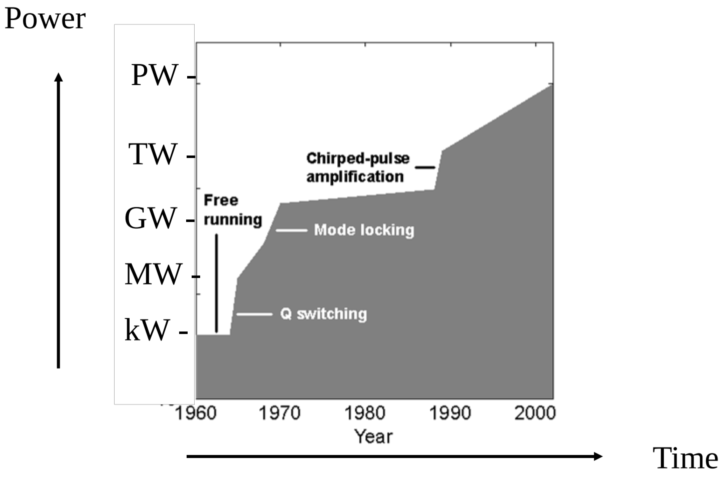
$$n=n_0+n_2I$$

$I=I(r,t)$ ⇒ $n=n(r,t)$

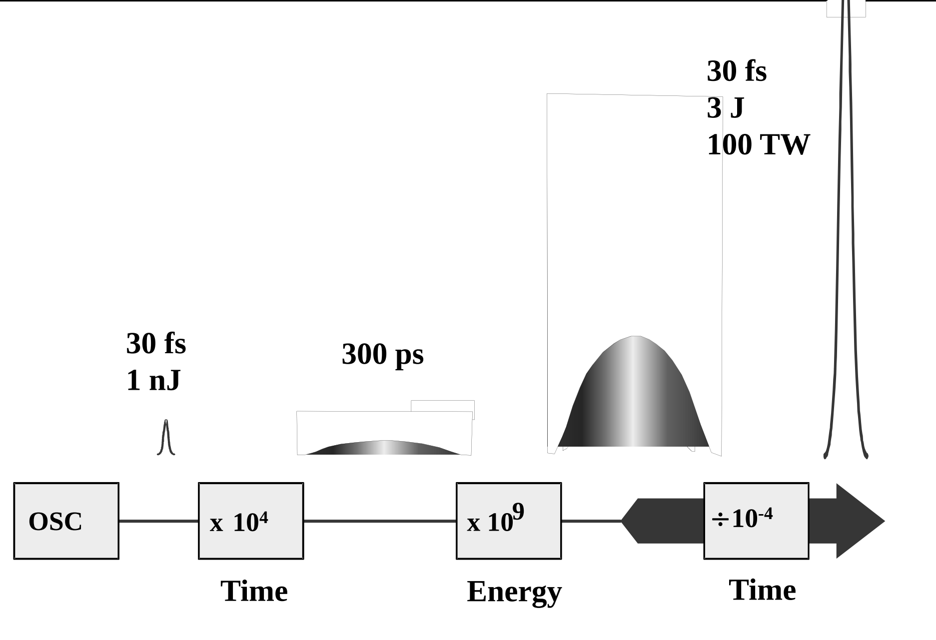
$n(t)$ ⇒ **Self Phase Modulation, SPM**

$n(r)$ ⇒ **Self Focusing ⇒ DAMAGE**

Laser Power Development

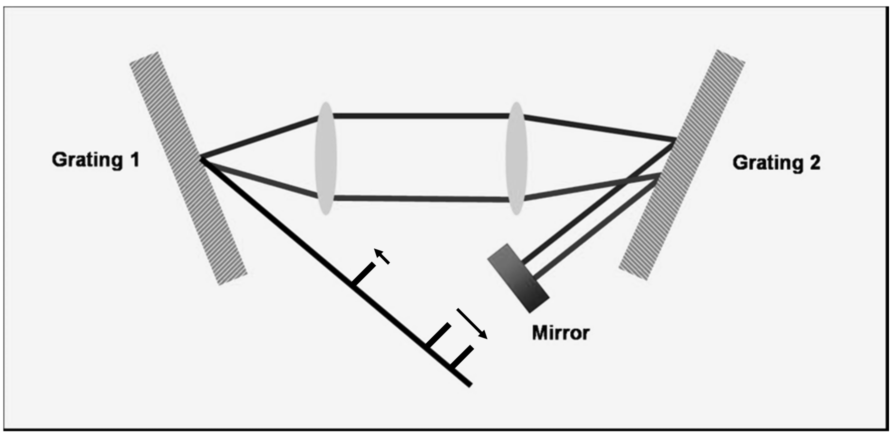


Chirped Pulse Amplification CPA



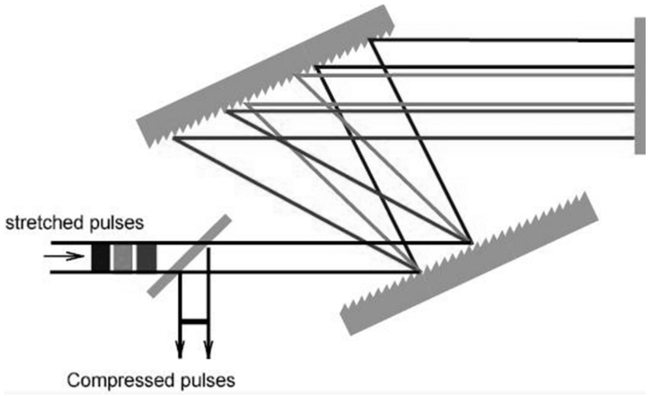
Grating Stretcher

•***Shorter*** optical path for longer wavelength

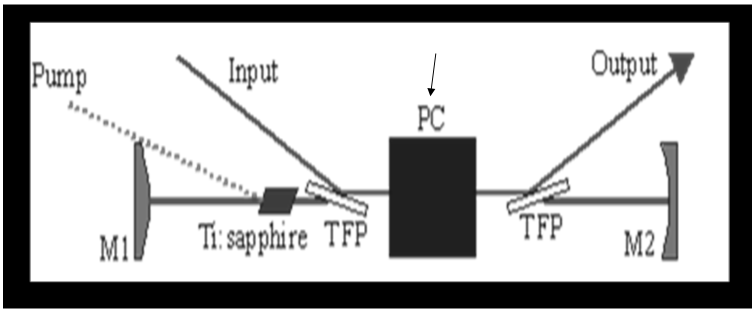


Pulse Compression by Gratings

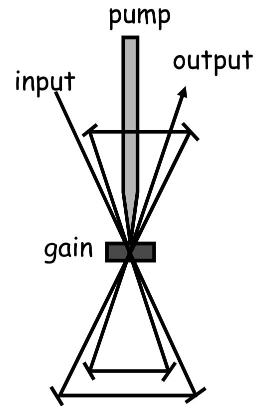
- ***Longer*** optical path for longer wavelength



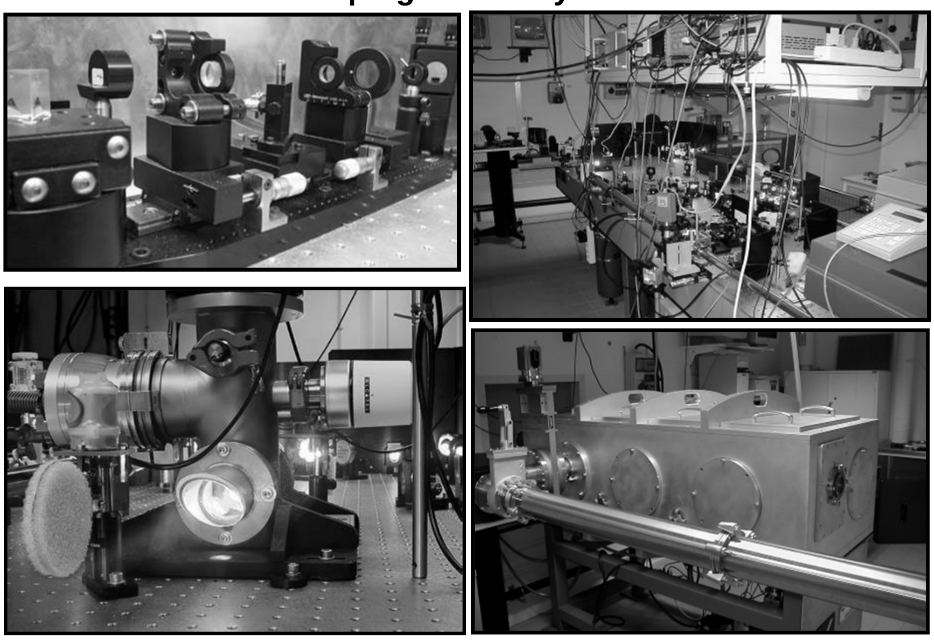
Regenerative Amplifiers



Multipass Amplifiers



Lund 40 TW, 35 fs, 10 Hz, CPA Terawatt Laser
wall-plug efficiency <1%

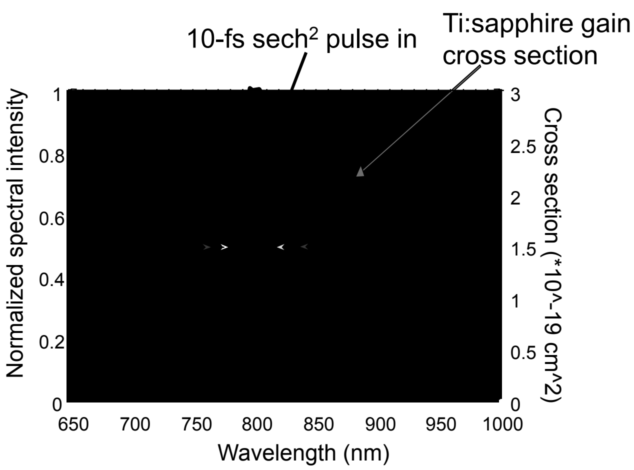


CPA works well!

But there are some issues to pay attention to:

- Gain Narrowing
- Temporal contrast
- Thermal aberrations

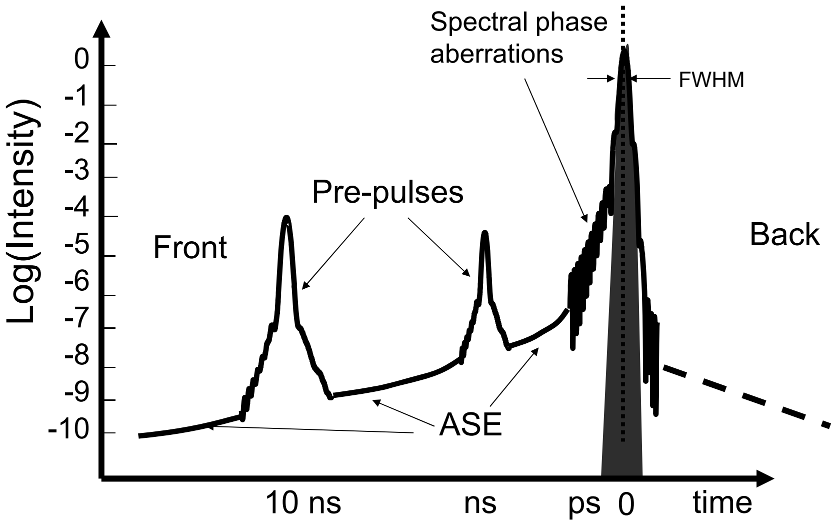
Gain Narrowing (Ti:Sapp)



Factor of 2 loss in bandwidth for 10^7 gain

10 fs oscillator is OK, but sub 30 fs at TW level is tough

Temporal Contrast of Amplified Pulses



Contrast Improvement Methods

One or several fast Pockels cells to suppress prepulses

Reduced amplifier gain to minimize ASE

High pulse energy oscillator

Preamplifer + nonlinear pulse cleaning before stretching

Double-CPA system with nonlinear pulse cleaning

OPA

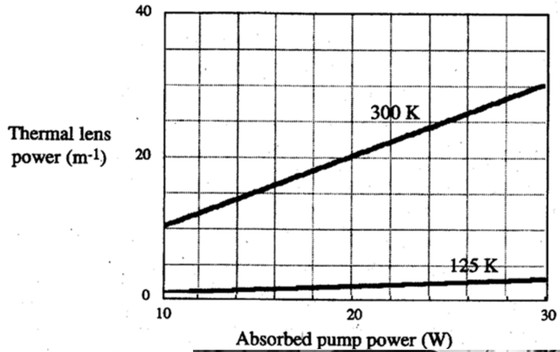
Thermal Effects in Amplifiers

Heat deposition causes lensing and small-scale self-focusing. These thermal aberrations increase the focus spot size and reduce the intensity

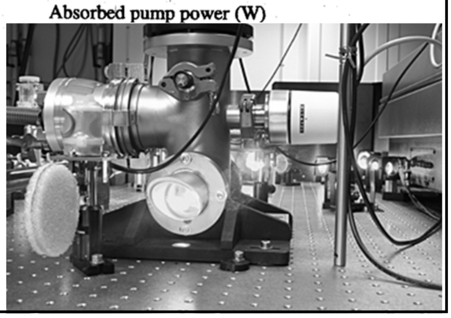
$$I_{peak} = \frac{E}{A\ \tau}$$

Low Temperature Minimizes Lensing

In sapphire, conductivity increases and d*n*/d*T* decreases as *T* decreases.



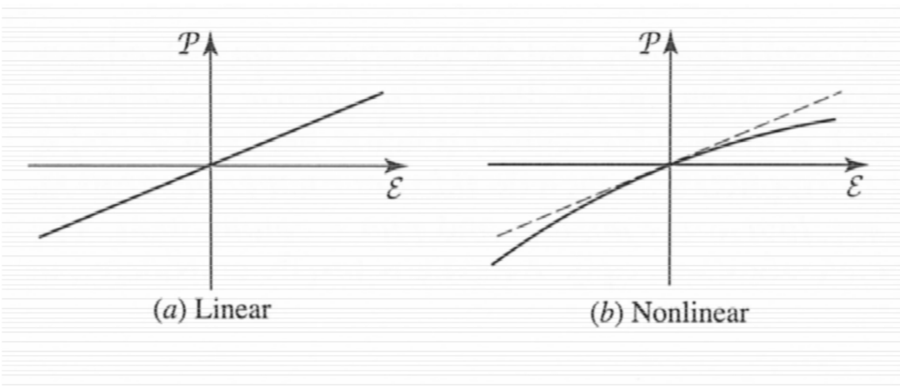
Cryogenic cooling results in almost no thermal lensing



OPCPA

Chirped Pulse Amplification
+
Optical Parametric Amplification

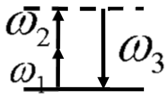
Basic Nonlinear Optics



$$\mathcal{P} = \boxed{\epsilon_o \chi \mathcal{E}} + 2\mathrm{d}\mathcal{E}^2 + 4\chi^{(3)}\mathcal{E}^3 + \cdots$$

Wave Mixing

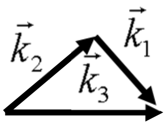
$$\mathcal{P} = \epsilon_o \chi \mathcal{E} + \boxed{2\mathrm{d}\mathcal{E}^2} + 4\chi^{(3)}\mathcal{E}^3 + \cdots$$



$\omega_1 + \omega_2 = \omega_3$

Frequency Matching

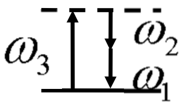
Conservation of energy



$\vec{k}_1 + \vec{k}_2 = \vec{k}_3$

Phase Matching

Conservation of momentum



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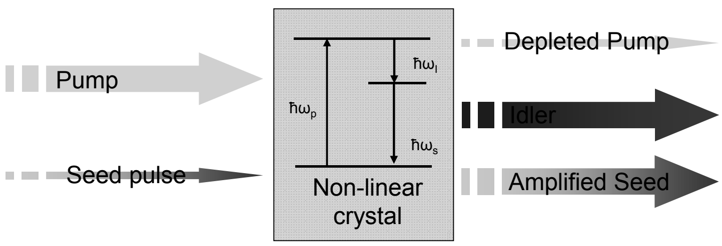
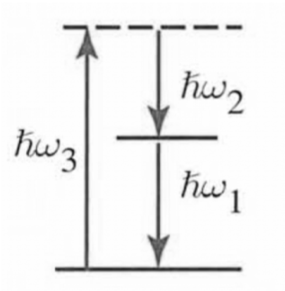
Optical Parametric Amplification OPA

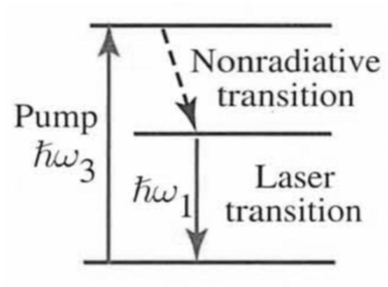


OPA vs Laser

OPA



Laser



No energy stored in the medium.

No heat loading

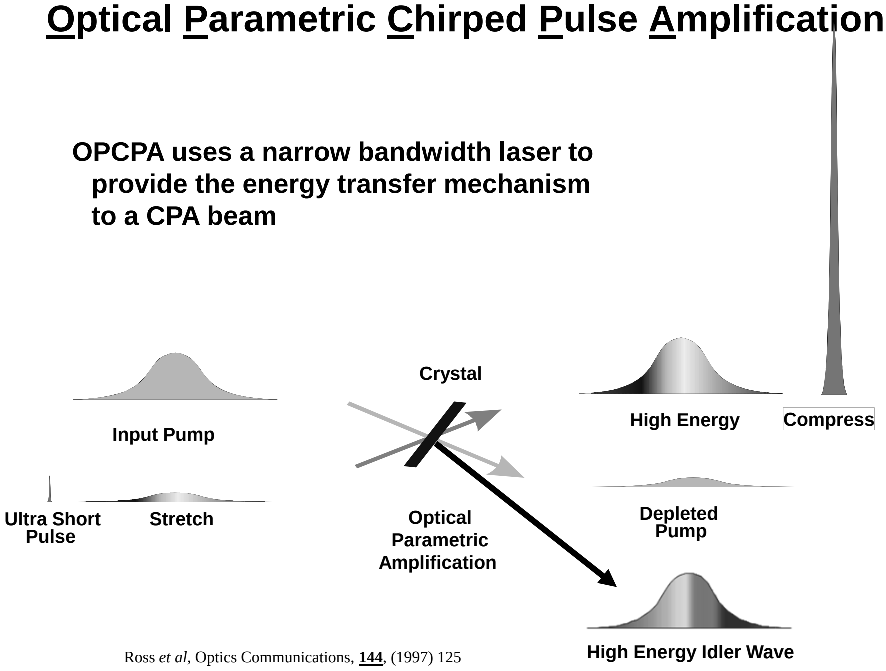
BW given by phase matching

Laser Integrates pump energy prior to lasing

BW given by laser transition

Optical Parametric Chirped Pulse Amplification

OPCPA uses a narrow bandwidth laser to provide the energy transfer mechanism to a CPA beam



Ross *et al*, Optics Communications, **144**, (1997) 125
Dubietis *et al*, Optics Communications, **88**, (1992) 437

OPCPA "Magic List" of Properties

- **Very High Gains (eg 10^{12}) - Little Material (cm's)**
- **Ultra Broad Bandwidth, No gain narrowing, Short pulses**
- **High Energy - pump limited**
- **No Thermal Loading and Excellent Beam Quality**
- **High Efficiency**
- **Good Contrast (shorter ASE duration)**
- **Directional Gain – no transverse ASE**

Disadvantages…

- **Non-storage gain medium**
- **High efficiency only if pump duration less than few ns**
- **Accurate synchronization to pump pulse required**
- **Careful control of pump shape required for maximum bandwidth and efficiency**
- **Critical Phase Matching**

A few examples of "compact" high-power lasers suitable for LWFA

Amplitude

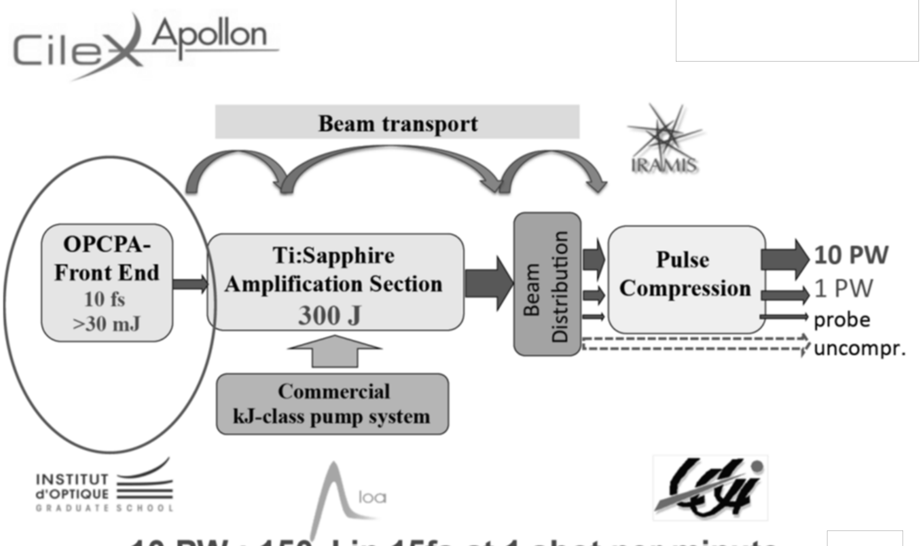
1 PW: DRACO in Dresden, Germany and VEGA in Salamanca, Spain
~25 J in 25 fs, at 1 Hz (soon!)

1 PW: BELLA, in Berkeley, USA
40 J in 40 fs @ 1 Hz

THALES

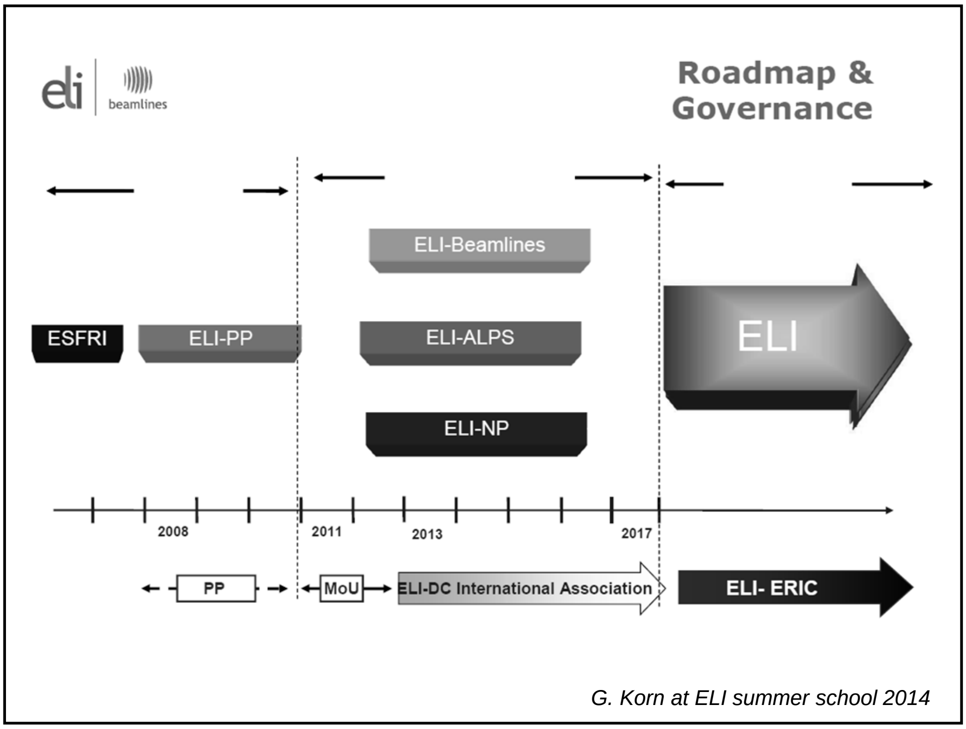
Building etc more expensive

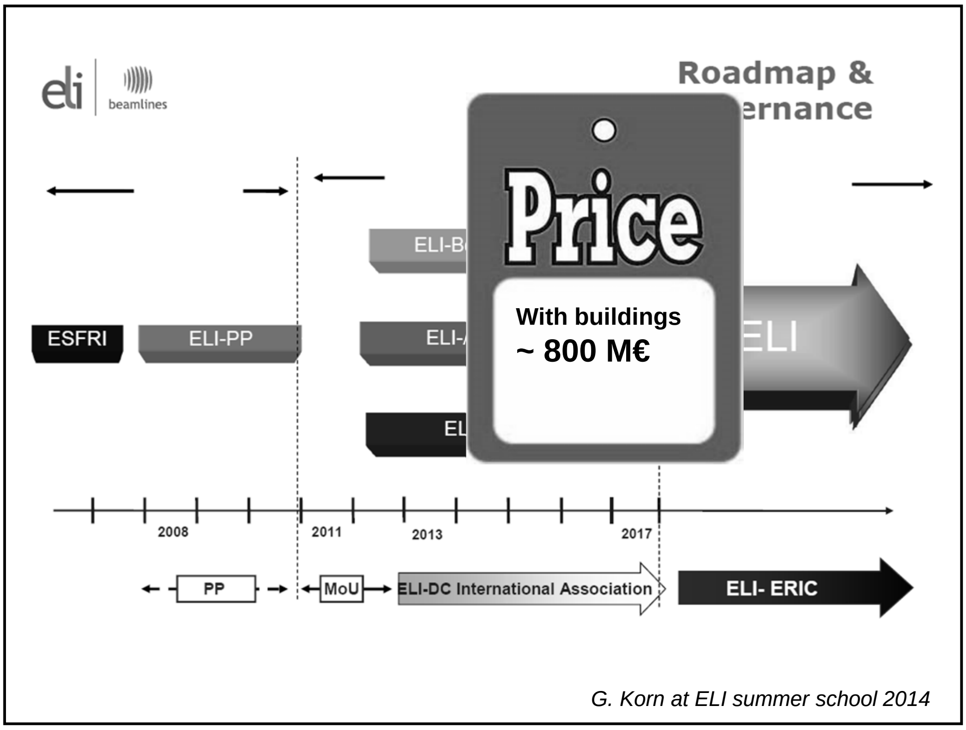
<u>10 PW:</u> Apollon at CILEX, Plateau de Saclay, France



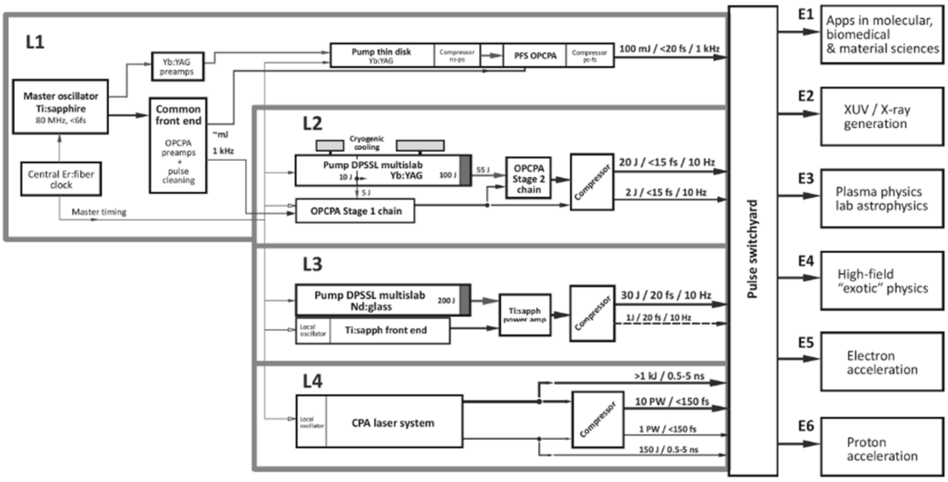
10 PW : 150 J in 15fs at 1 shot per minute

C. Le Blanc


Roadmap &
Governance
ELI-Beamlines
ESFRI
ELI-PP
ELI-ALPS
ELI
ELI-NP
2008
2011
2013
2017
PP
MoU
ELI-DC International Association
ELI- ERIC
G. Korn at ELI summer school 2014


Roadmap &
Price
With buildings
~ 800 M€
ESFRI
ELI-PP
2008
2011
2013
2017
PP
MoU
ELI-DC International Association
ELI- ERIC
G. Korn at ELI summer school 2014

ELI-Beamlines master scheme



B. Rus at ELI summer school 2014

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