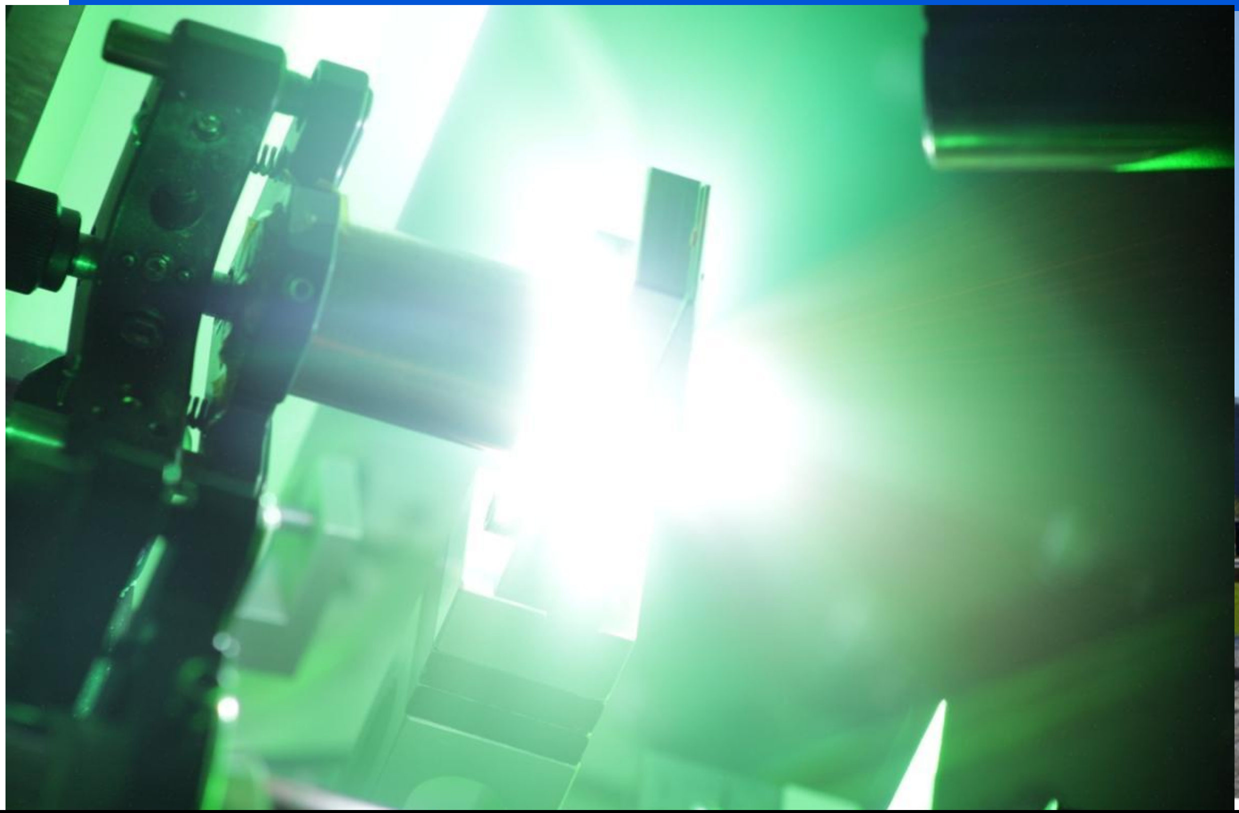
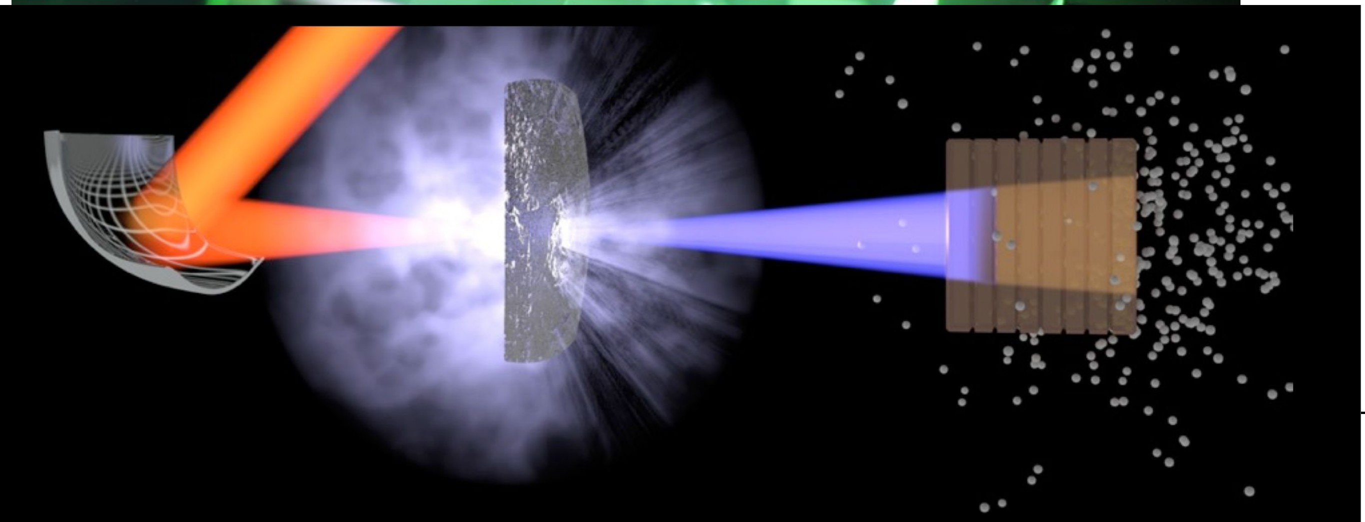
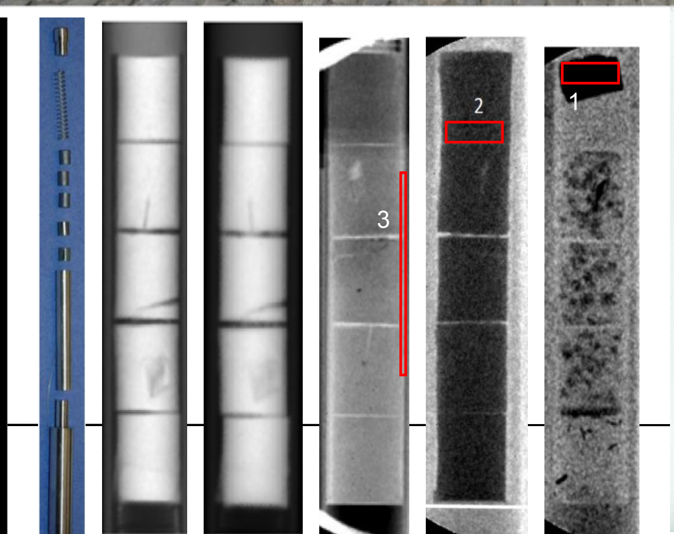
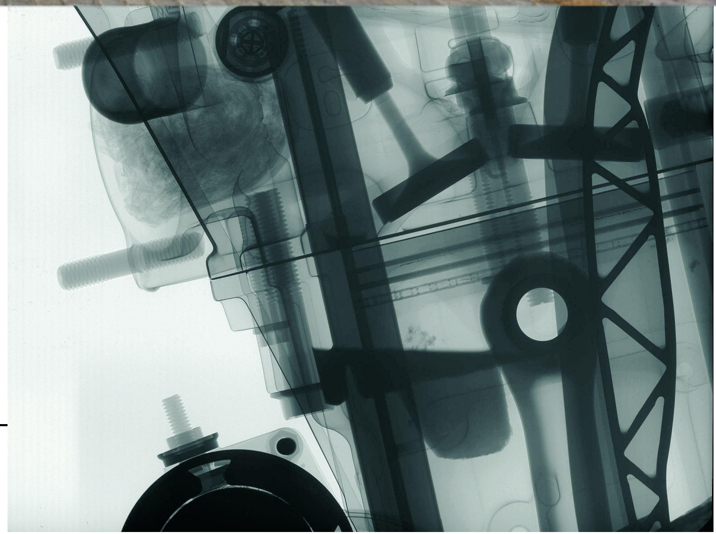
Ultra-Intense Lasers II

Design, technology proospects

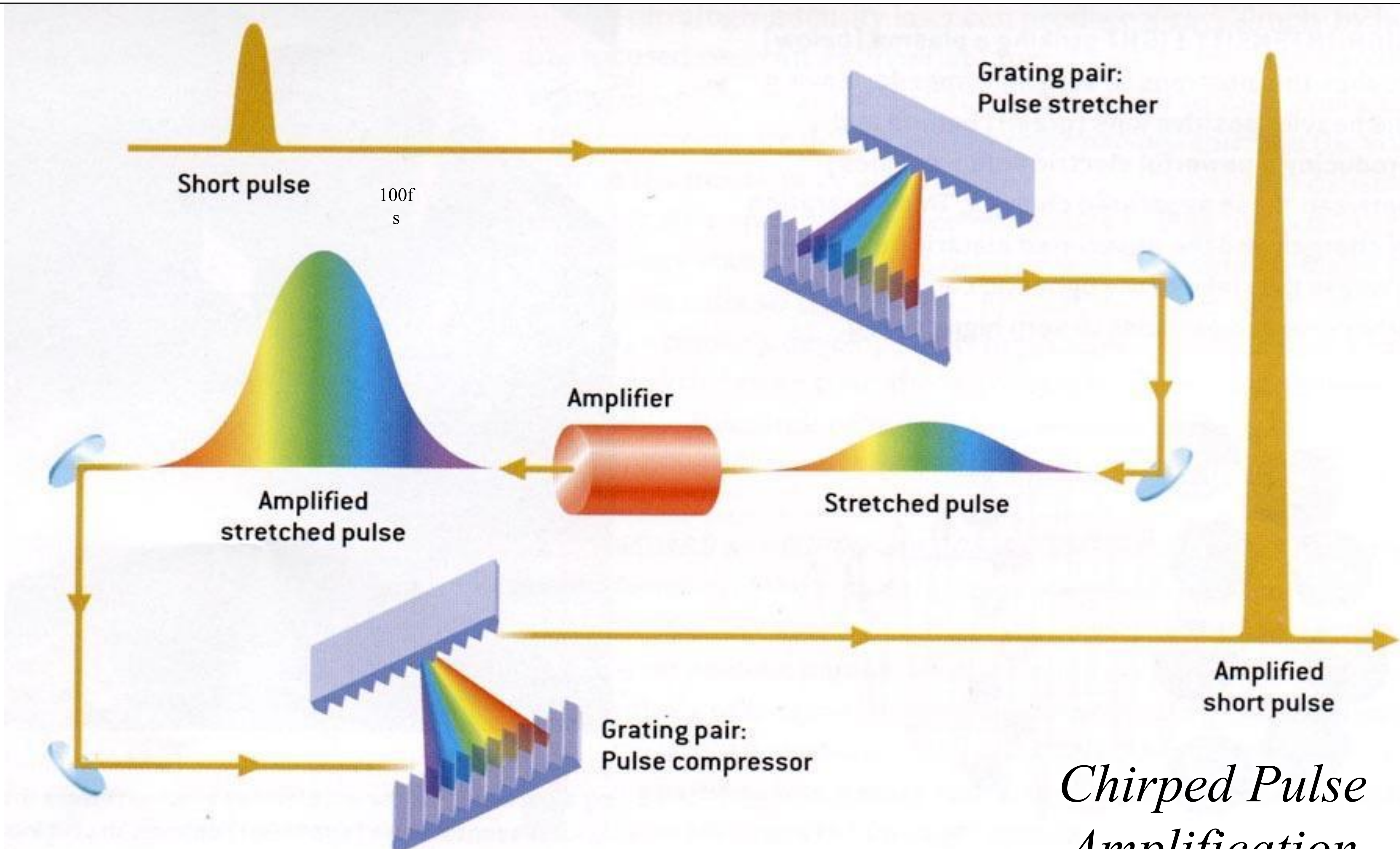








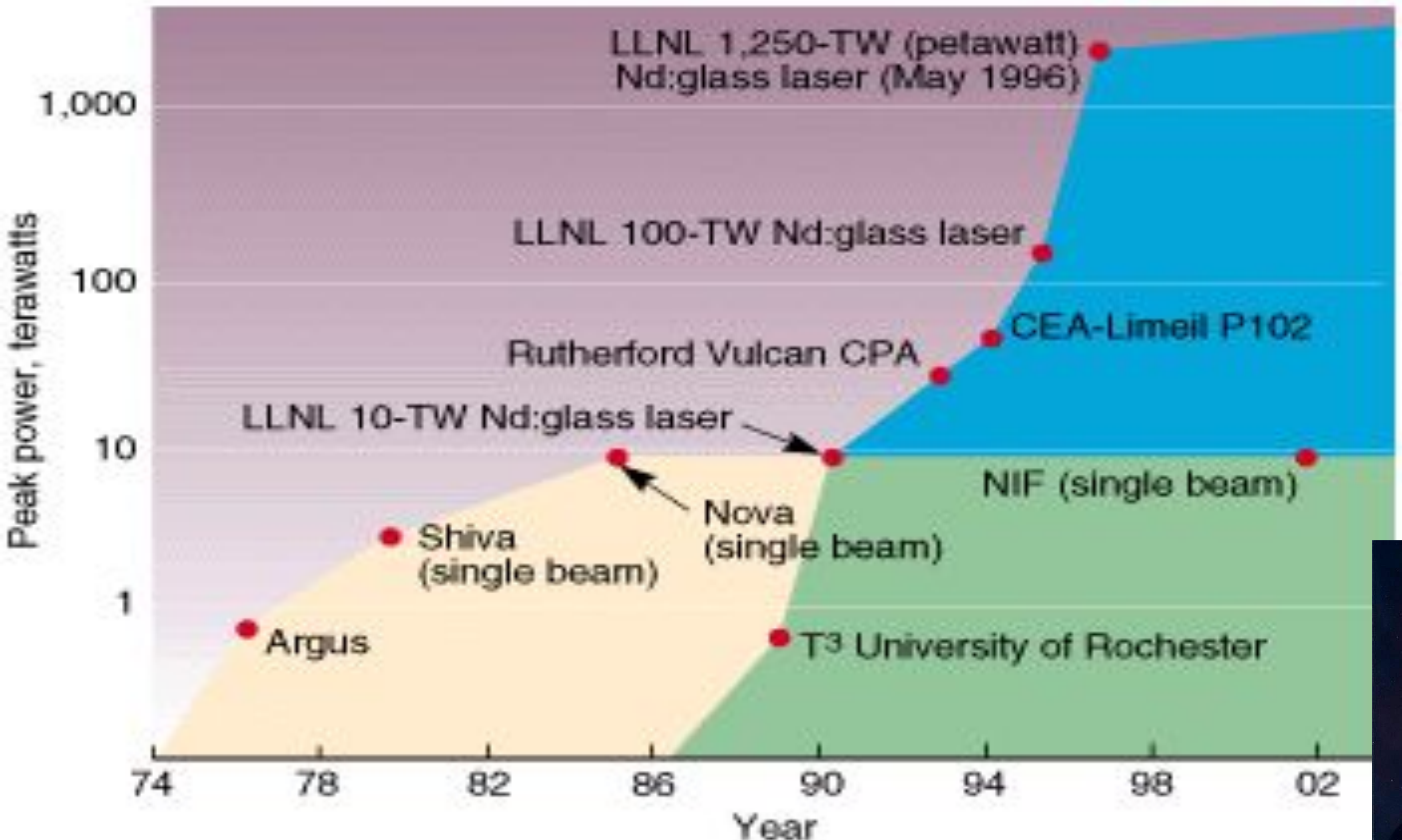
CPA technique

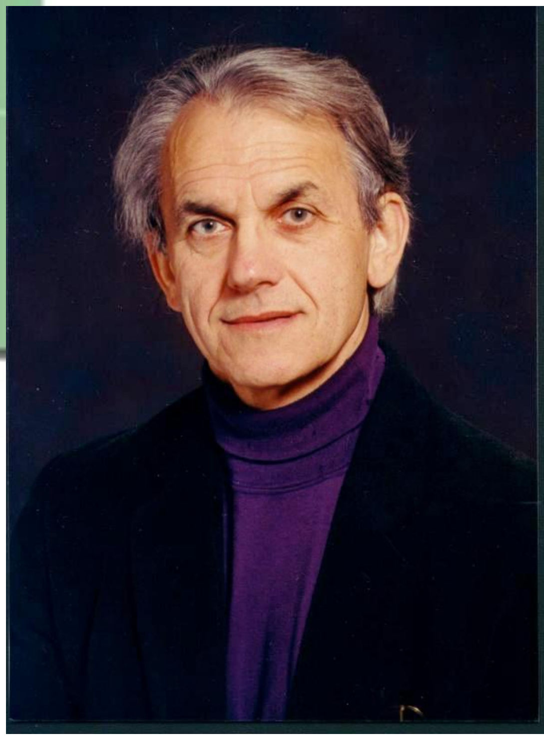


Chirped Pulse Amplification

D. Strickland and G. Mourou (1985)

CPA


LLNL 1,250-TW (petawatt)
Nd:glass laser (May 1996)
LLNL 100-TW Nd:glass laser
CEA-Limeil P102
Rutherford Vulcan CPA
LLNL 10-TW Nd:glass laser
NIF (single beam)
Nova
(single beam)
Shiva
(single beam)
Argus
T3 University of Rochester
1,000
100
10
1
Peak power, terawatts
74
78
82
86
90
94
98
02
Year



Generation of UHI laser pulses

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- Need to have a laser medium with sufficient bandwidth to support short pulses
- Need to provide save amplification without hig B- Integral
- Need to provide high contrast not to destroy the sample too early
- Need to be efficient and high rep rate
- Need to be compact

Materials (Examples)

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Laser Materials requirements:

- Right wavelength ($I\lambda^2$ – scaling)
- Lasing cross section – stored energy, gain, fluence limit
- Bandwidth
- Optical Quality
- Thermal properties
- Matching with pump sources

Each laser material consist of a host material and an active (lasing) material

Requirements:

Mechanical,	chemical and	optical properties
hard	inert	no innerer stress and variations of n

Good to shape

Host lattice structure must accompany guest atoms without disturbing the optical properties

Ti:Saphir (1)

$Ti{:}Al_2O_3$

Mostly used, tunable soliid state laser for short pulses.

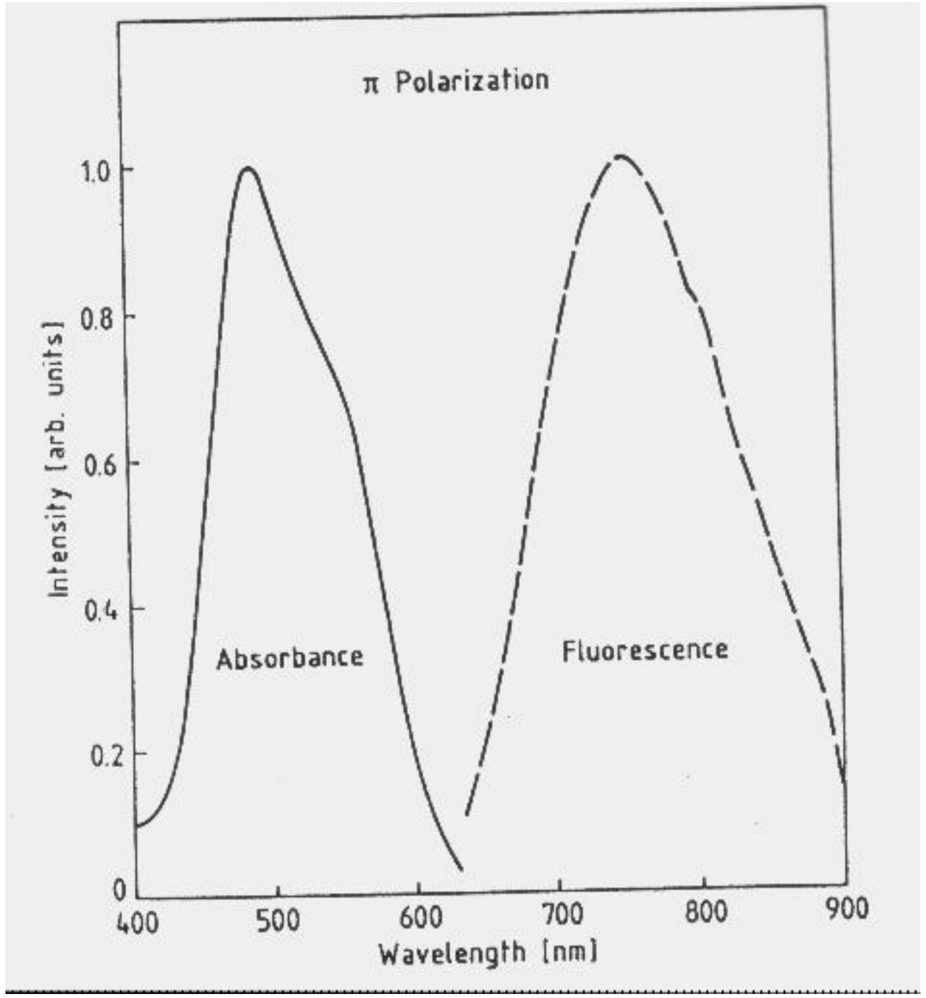
Tuning range 400 nm.

Energy levels of Ti unique in transition metals:

Czochralski crystal growth, doped with Sapphire
at 0.1% Ti^{3+} weigth percent.

Broad absorption spectrum, peaks at 490 nm.

Broad Vibrational-Fluorescence spectrum with
lasing between 670 – 1070 nm with peak at 800 nm.



Ti:Saphir (2)

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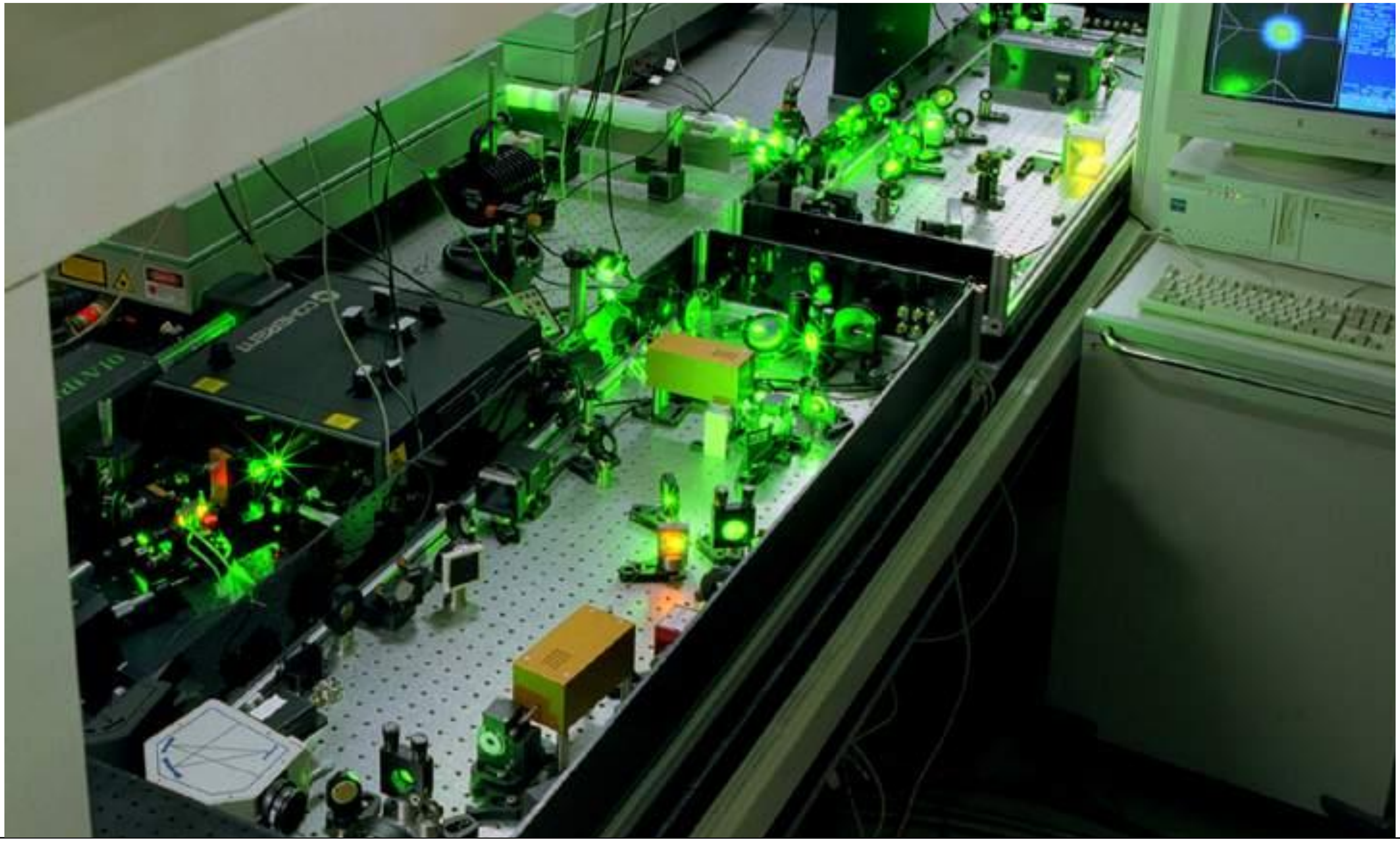
Index of refraction	1.76
Fluorescent lifetime	3.2 μs
Fluorescent linewidth (FWHM)	180 nm
Peak emission wavelength	790 nm
Peak stimulated emission cross section	
parallel to c-axis	$\sigma_{\parallel} \sim 4.1 \times 10^{-19}$ cm^2
perpendicular to c-axis	$\sigma_{\perp} \sim 2.0 \times 10^{-19}$ cm^2
Stimulated emission cross section	
at 0.795 μm (parallel to c-axis)	$\sigma_{\parallel} = 2.8 \times 10^{-19}$ cm^2
Quantum efficiency of	
converting a 0.53 μm pump photon	
into an inverted site	$\eta_Q \approx 1$
Saturation fluence at 0.795 μm	$E_s = 0.9$ J/cm^2

Further advantages:
High heat conductivity, exceptional chemical toughness, hard
Ti:Sa are pumped by Argon ion- and frequency-doubled ND:YAG and ND:YLF lasers and recently even with ND:glass lasers.

Ti:Saphir (3)

Short fluorescence lifetime: 3.2μs : high pump power required!

Most important application: Kerr-lens mode locking for generation of ultra-short pulses (6 fs) and their amplification (CPA-Systems).



Laser material (1) Nd:Glas

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Almost all high energy laser systems are made of Nd:glass

Reasons:

1. The absorption spectrum of Nd^{3+} in typical optical glasses goes from ≈ 350 nm in the UV to ≈ 900 nm in the infrared: overlap with cheap optical pump sources, like. Xe-flash lamps.

2. Laser wavelength of 1.06µm is of interest to laser fusion with acceptable coupling efficiency

3. By combining important energy levels large amoungs of eenergy can be stored at 1.06µm

4. Cross section for induced emission is in medium range:
   high enough for good gain at reasonable spatial scale
   small enough to handle ASE effects. (ASE we deal with later)

5. Properties of Nd^{3+} are well known: High predictive capability on systems and performance.
   Technologie of making the material is state of the art and can be tailored
   (High Average Power, High Bandwidth).

Laser material (2) Nd:Glas

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Downside:

1. Efficiency: Typical amplifier only convert 0.5-3% of electrical energy into laser radiation.

2. Low thermal conductivity and low efficiency : lots of energy lost in heat low repetition rate. Typical laser systems operate only once in 0.5-3 hours.

Lasermaterialien (3) Nd:Glas

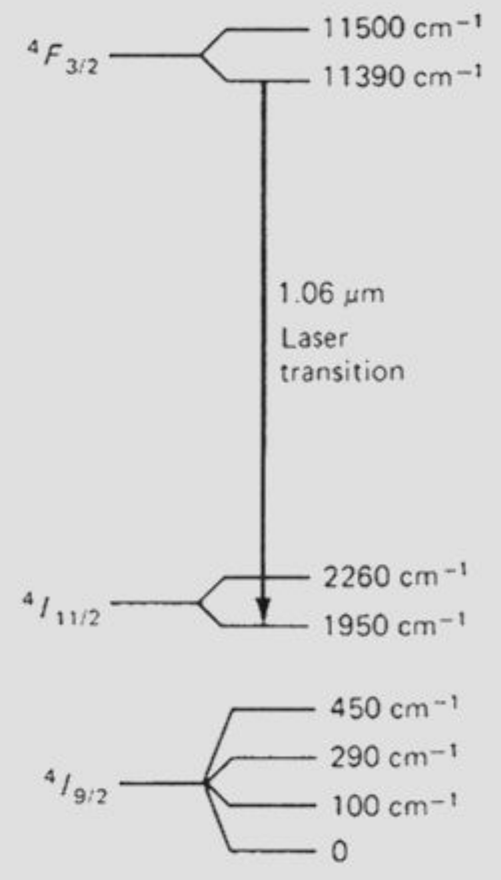


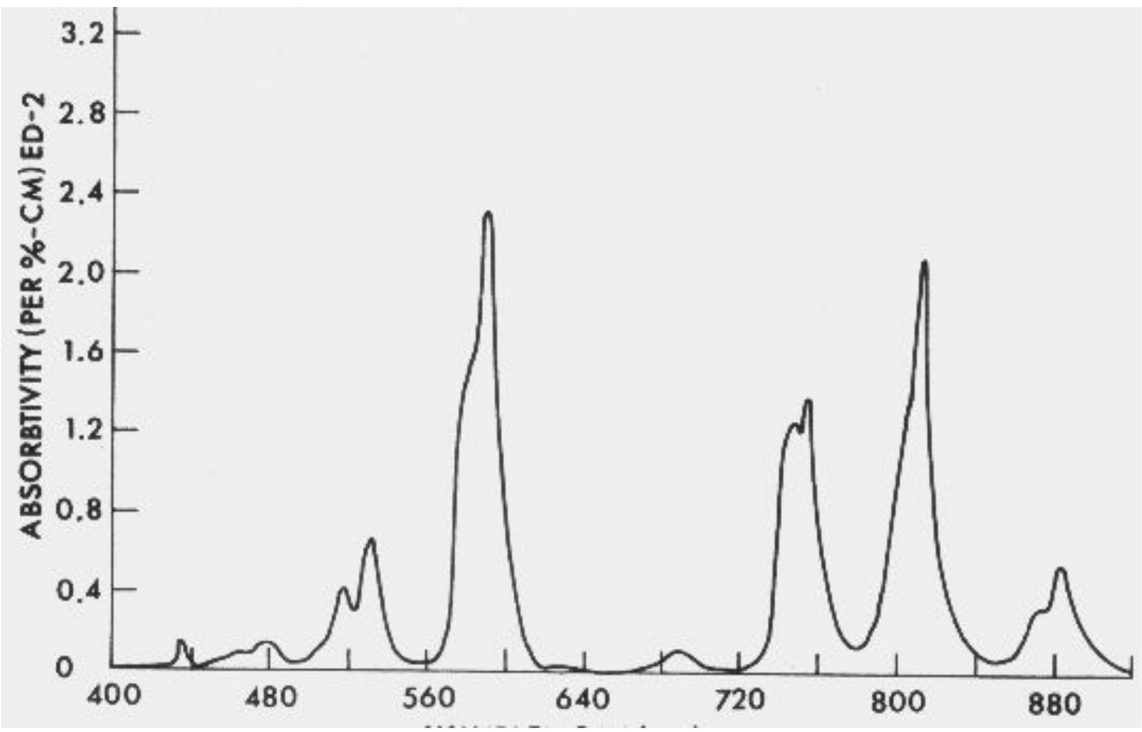
FIGURE 2.5. Partial energy level diagram of Nd^{3+} in glass.

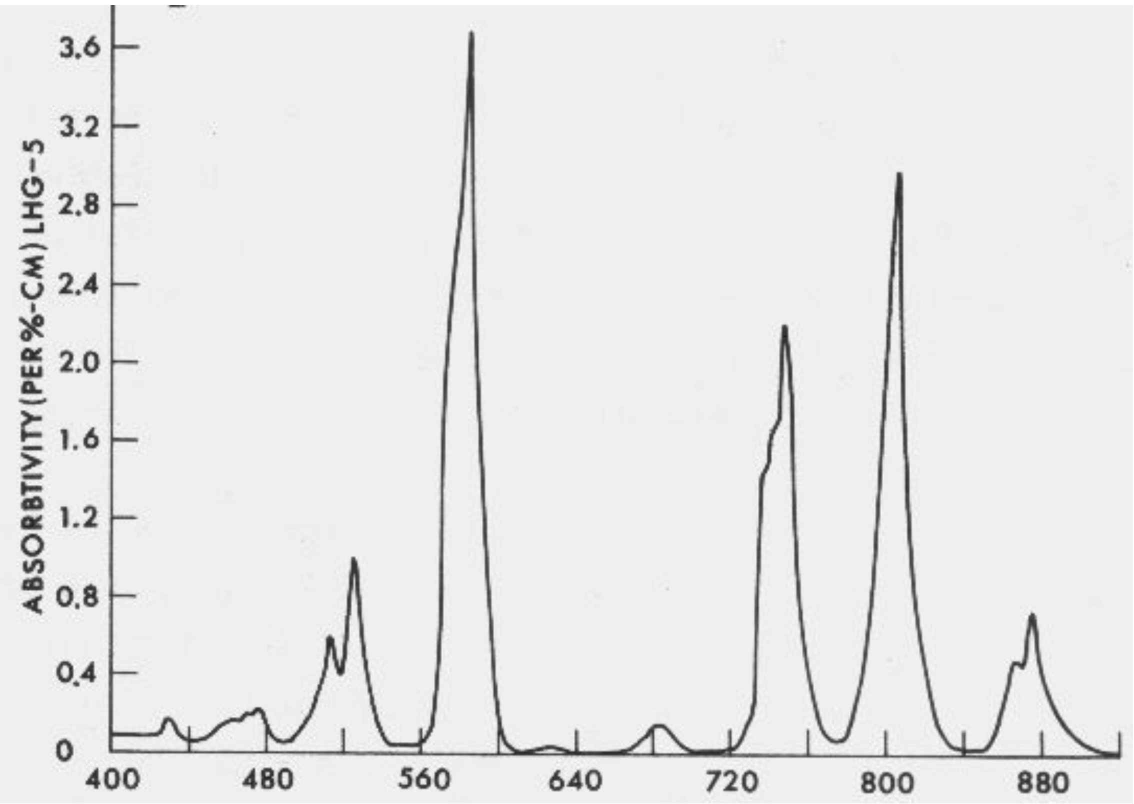
Commercially available: Phosphate and Silicate glasses: Rods up to 7.5 cm x 2m
Discs up to 90 cm x 5 cm

Phosphate glasses have 50% higher stimulated emission cross section t
(σ = 3.7-4.5 x 10^{-20} cm^{-3})

Lasermaterialien (4) Nd:Glas

Nd:Glass absorption spectra



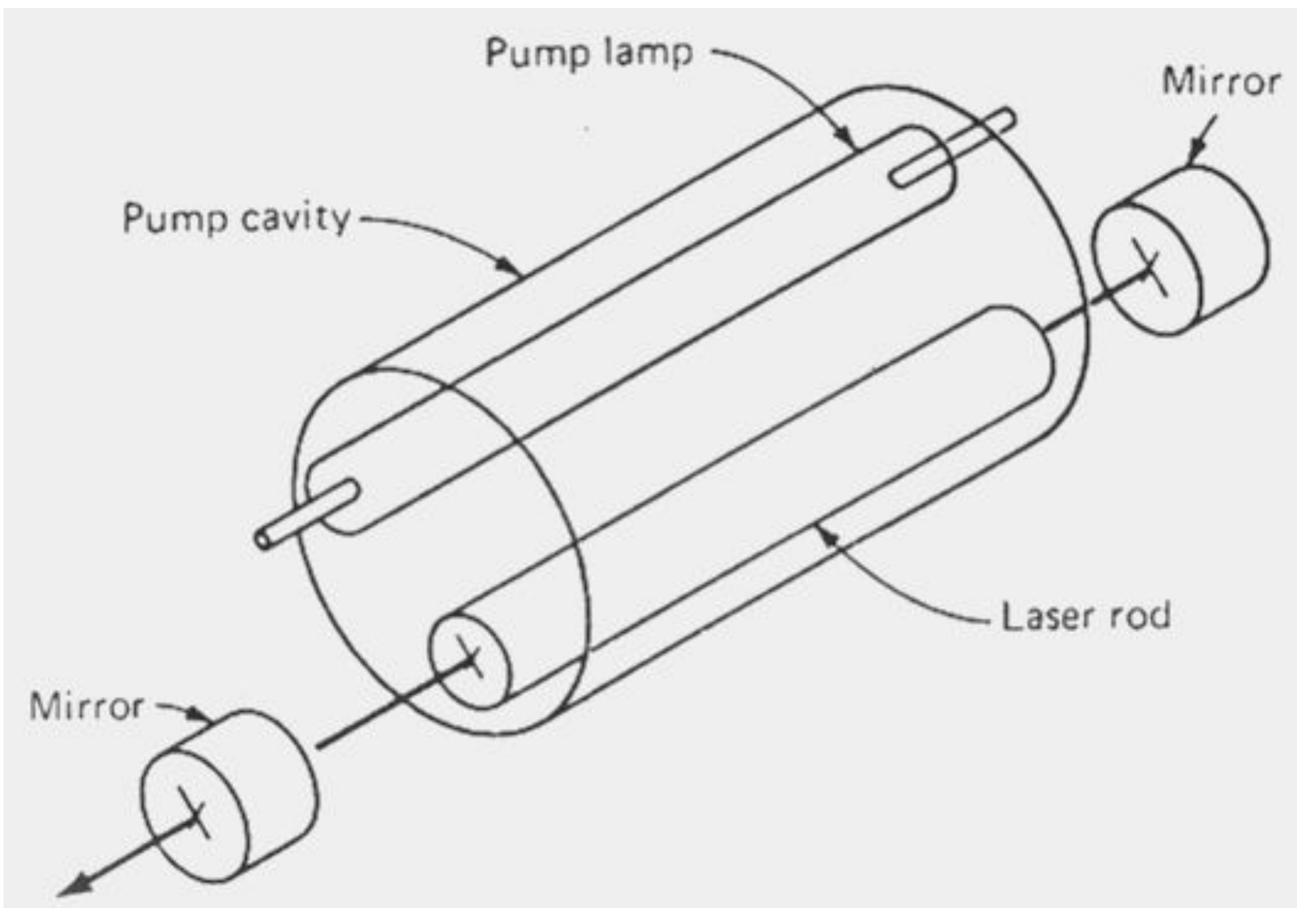


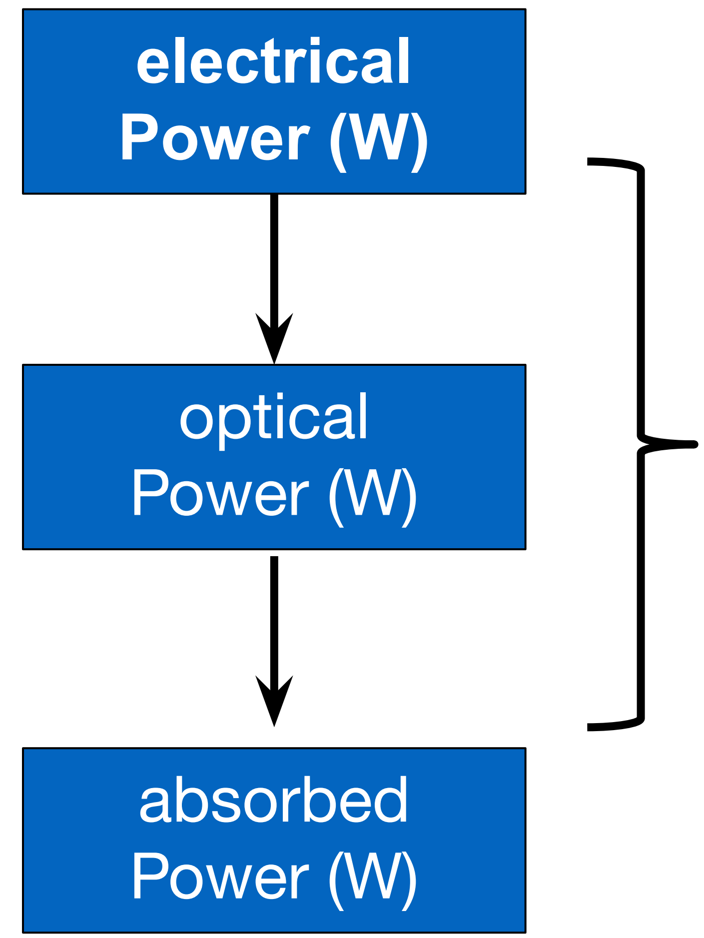
Absorption spectra of Nd in Silikate- (left) and Phosphate glasses (right)

Efficiency of laser pumping – flash lamps

(close coupled geometry).

Setup



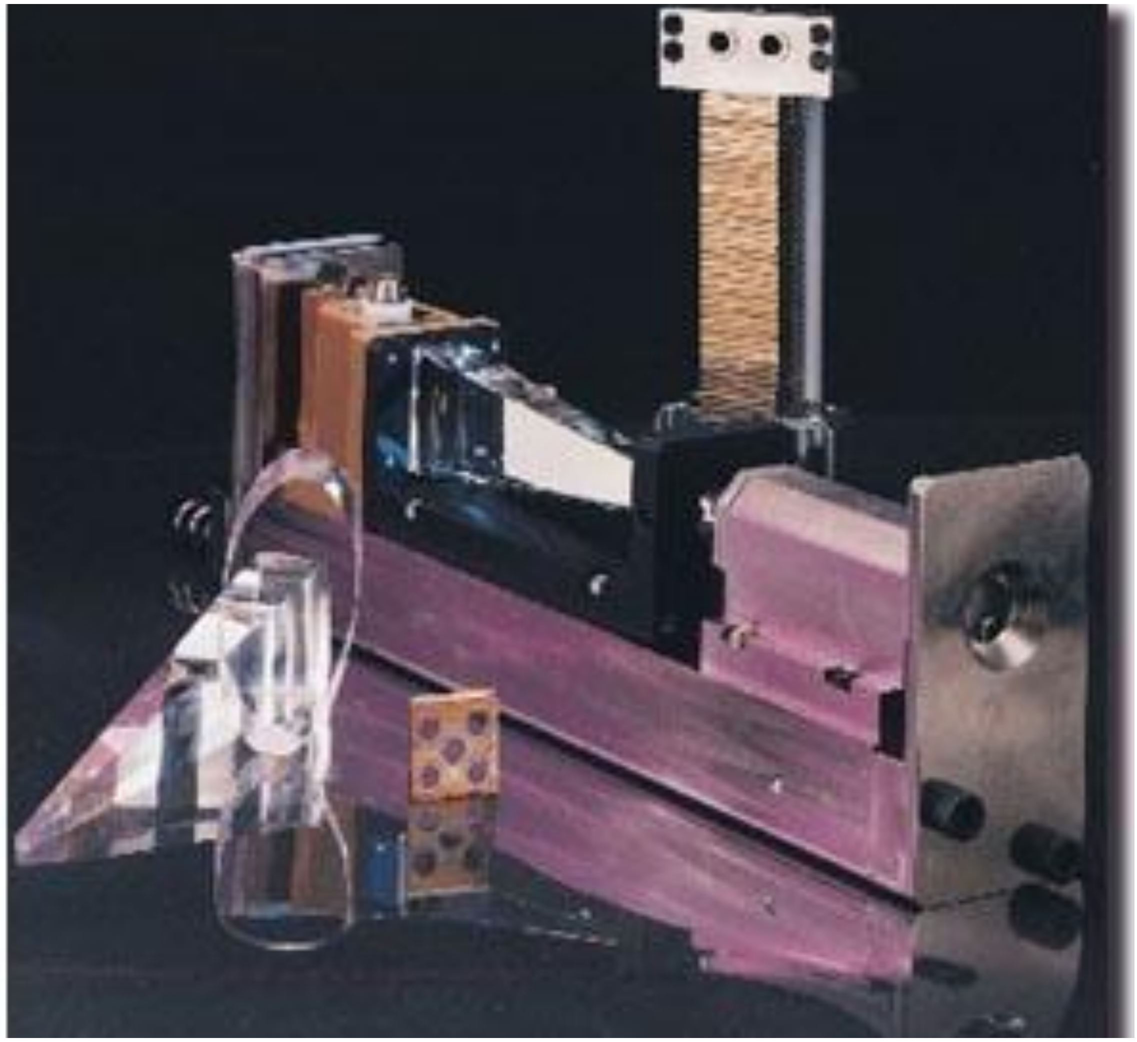


Mirros form the resonator, often named „Laser Cavity“ in contrast to „Pump Cavity“, combining the pump source with the laser medium.

Efficiency of laser pumping – diode pumping

In addition to flash lamps laser diodes are used more often to pump laser material

Fiber coupled laser diode
„End-pumped“ geometry



Pump efficiency η_P

Converting the electrical power to the pump into useable pump radiation:
Useable pump radiation: Radiation in the absorption band of the laser medium

η_P = part of el. power into optical radiation in the absorption band of the laser material

- **Laser diodes (array):**
  If matched, typical 0.3-0.5 (cw-oder quasi cw)

- **For flash lamps:**

$$\eta_P = P_\lambda / P_{in} = \int_{\lambda_1}^{\lambda_2} P_\lambda' d\lambda / P_{in}$$

With P_λ as spectral output power into absorption band of the laser material
P_{in} el. Input power and P_λ' spectral radiating power
and $\lambda_{1,2}$ the acceptance bandwidth to pump the upper laser level

Typical values for η_P are 0.04-0.08 for 5-10 mm thick laser material

Pump coupling efficiency- η_t

Transfer of radiation to the laser medium using the pump cavity.

Radiation transfer efficiency: η_t

$$P_e = \eta_t P_\lambda$$

with P_λ as usable pump power of the source and P_e the part transmitted into the laser medium

η_t combines capture efficiency and transmission efficiency.

Capture efficiency: part of the radiation hitting the laser
dep. on geometry of the pump cavity,
diameter and distance of source and laser.

Transmission -Efficiency: Wall reflectivity of the pump cavity, absorption in cooling liquid, losses at cavity windows.

$$\eta_t = (1 - R)$$

Typical values for close coupled cavities: η_t=0.3-0.6 (less in high energy lasers)

Diode pump cavities can reach higher coupling efficiencies up to η_t=0.85 – 0.98.

Absorption into upper laser level - η_a η_S η_Q

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Absorption of the pump radiation by the laser medium and transfer of the energy into the upper laser level.

2 Processes:

- **Absorption into Pump levels: η_a**
- **Transfer of the energy from pump level into upper laser level: $\eta_Q\eta_S$**

Absorption efficiency: ratio of absorbed power P_a into coupled power P_e

$$\eta_a = P_a / P_e$$

The efficiency of the upper laser level is defined as laser power per absorbed power into the pump levels. It consists of two factors:

Quantum efficiency η_Q : number of laser photons devided by number of pump photons
Quantum defect-efficiency or Stokes-Faktor η_S :

$$\eta_S = \left(\frac{h\nu_L}{h\nu_P}\right) = \frac{\lambda_P}{\lambda_L}$$

Ratio of photon energy of the laser light to photon energy of the pump light
e.g.: Diode-pumped YAG: Pump: 808nm; laser 1064nm; η_S=0.76 und η_Q=0.90.

Upper laser level and output – η_B η_e

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Spatial overlap of TEM modes in the resonantor with pumped volume
Part of the stored energy in upper laser level that can be used in the resonator.

η_B resonator mode volume divided by pump volume
Numbers smaller than 1 : part of the energy escapes by spontaneous emission.
Mode-matching efficiency.
Numbers vary between 0.1 und 0.95; TEM_{00} typ. 0.3-0.5; TEM_{xx} typ. 0.8-0.9

η_E part of the total stored energy in upper laser level that is emitted.

Numerous loss mechanisms, like:

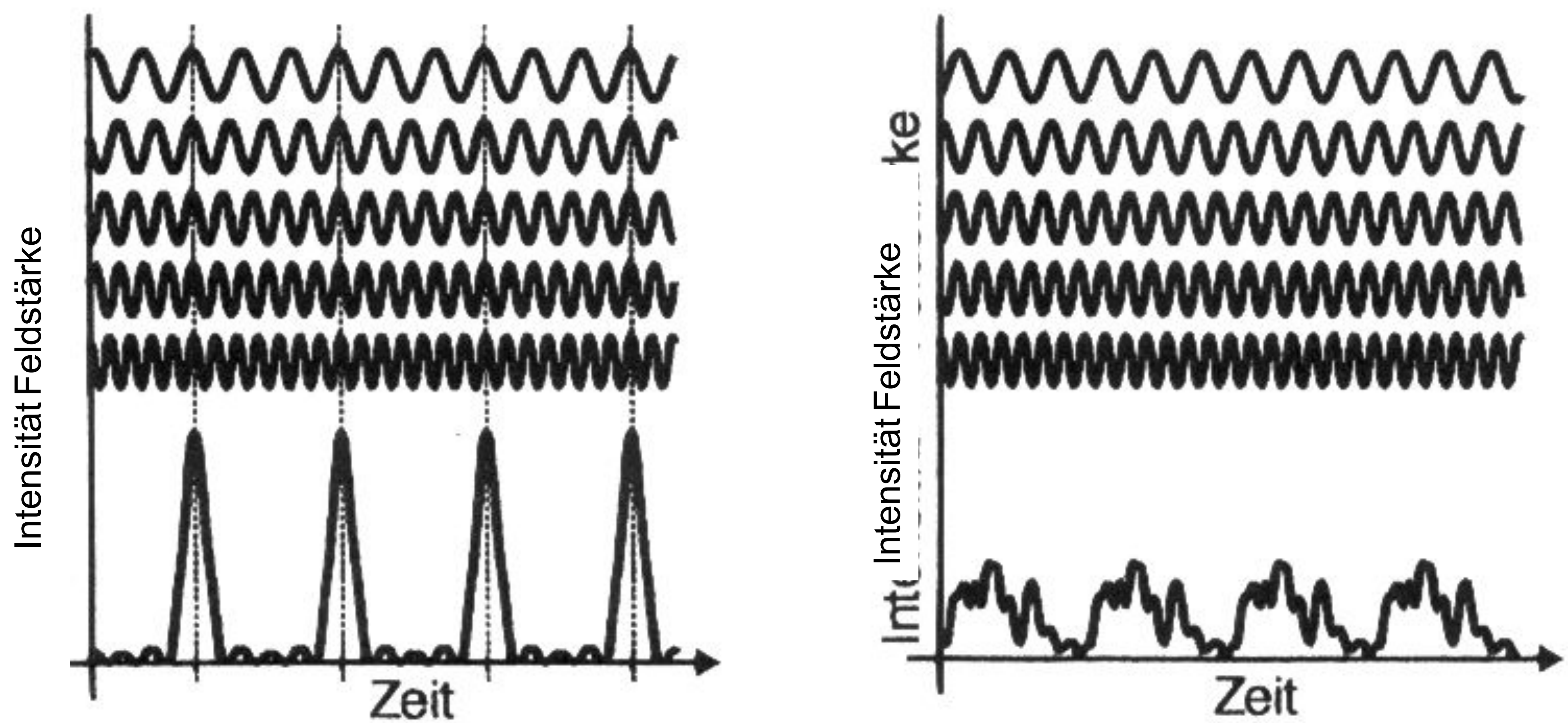
$$\eta_E = \eta_{St}\eta_{ASE}\eta_{EQ} \qquad (3.34)$$

Mit η_{St} loss by fluorescence and straggling; η_{ASE} Loss by amplified spontaneous emission and η_{EQ} extraction efficiency e.g. of Q-switching.

UHI Lasers: only by mode locking

Phase correlation of longitudinal modes in the resonator

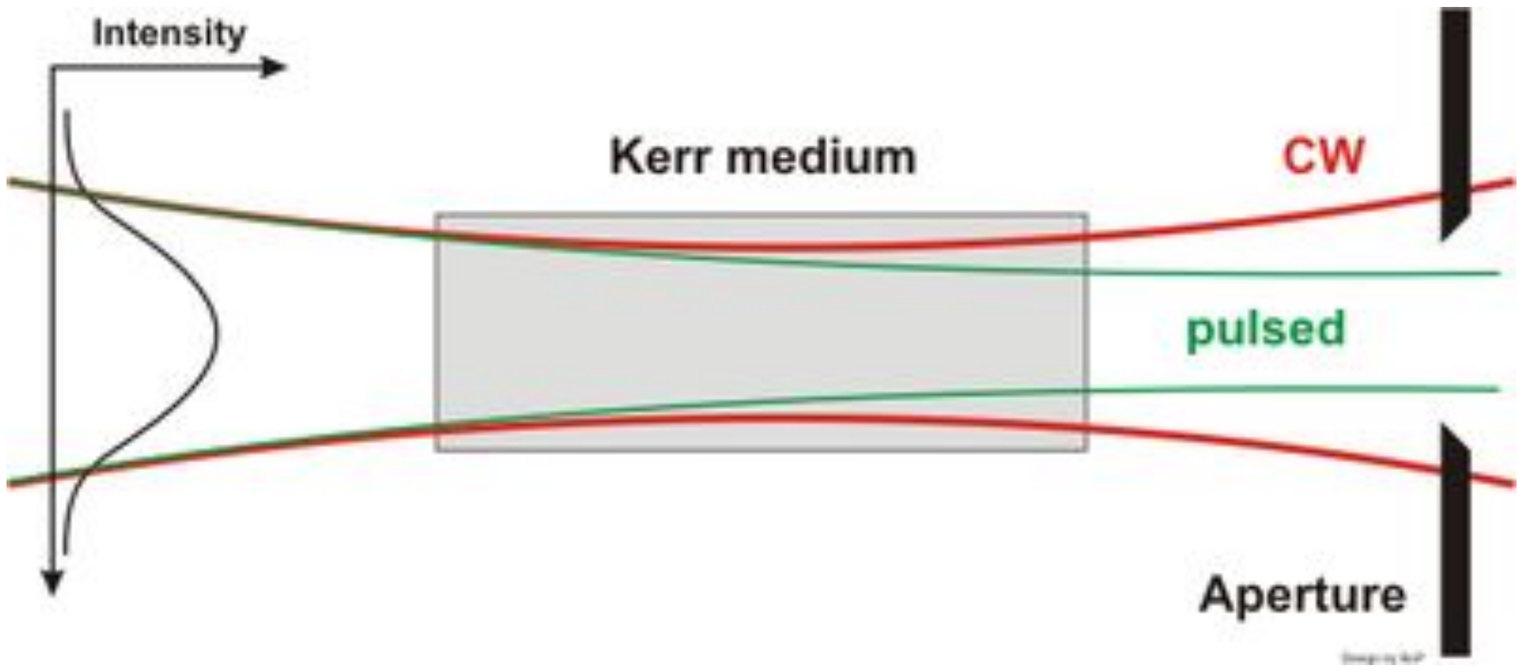
Idea: increase losses for all non-locked combinations. Those are of low intensity.



Mode-Locking

<u>Passive mode-locking:</u>

The KLM-Oscillator (Kerr-Lens-modelocking):



Switch by self – generated Kerr lansing and aperture

Intense light is passed through the aperture as suffers less losses.

Short pulses: Dispersion

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According to the Fourier Theorem short pulses have a large bandwidth.
All frequencies have a slightly different refractive index

The optical material hast normal dispersion in the visible and near IR range (for $\lambda_1 > \lambda_2$ yields: $n(\lambda_1) < n(\lambda_2)$) and creates positive chirp (d.h. $D_2 > 0$)

Mat.		n_0	D_0	D_1[fs]	D_2[fs^2]	D_3[fs^3]	D_4[fs^4]
Saphir		**1.76019**	**138245**	**59387**	**580**	**421**	**-152**
BK7		**1.51078**	**118656**	**50888**	**446**	**320**	**-96**
Quarz		**1.45332**	**114143**	**48905**	**361**	**274**	**-102**
SF14		**1.74294**	**136890**	**59558**	**1783**	**1144**	**-250**

Dispersion components for some optical media for λ_0=800 nm (central wavelength) and x = 1 cm (path in material)

To compensate positive Chirp we need optical arrangements to invoke negative ($D_2 < 0$)

Dispersion pulse lengthening

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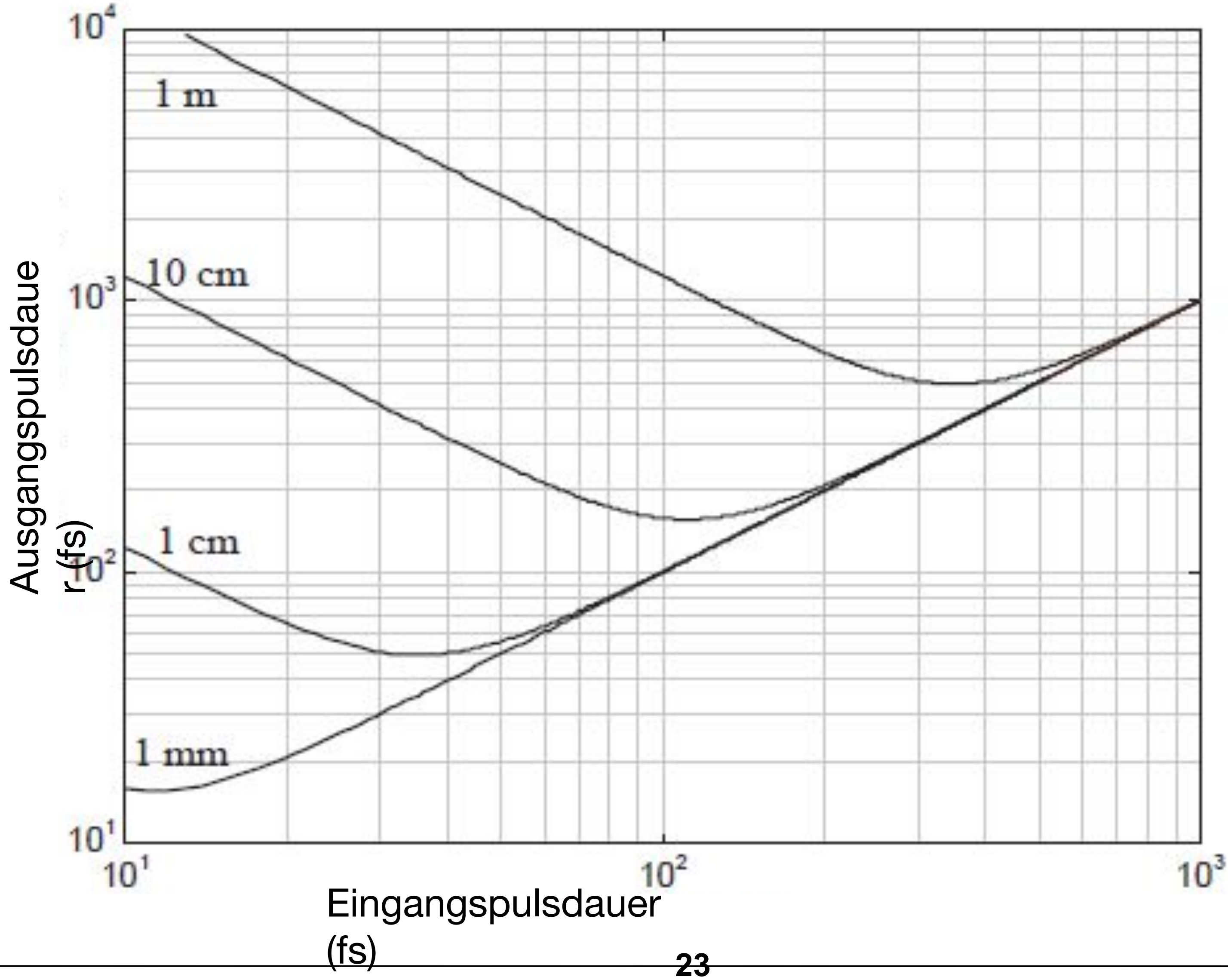
- Dispersion effects are specifically strong for fs pulses (highest bandwidth)
  - a 1-cm thick glass plate lengthen a 10-fs pulse to >100 fs
  - a 1-m thick glass plate has no effect on a 1 ps long pulse



Mode-Locking

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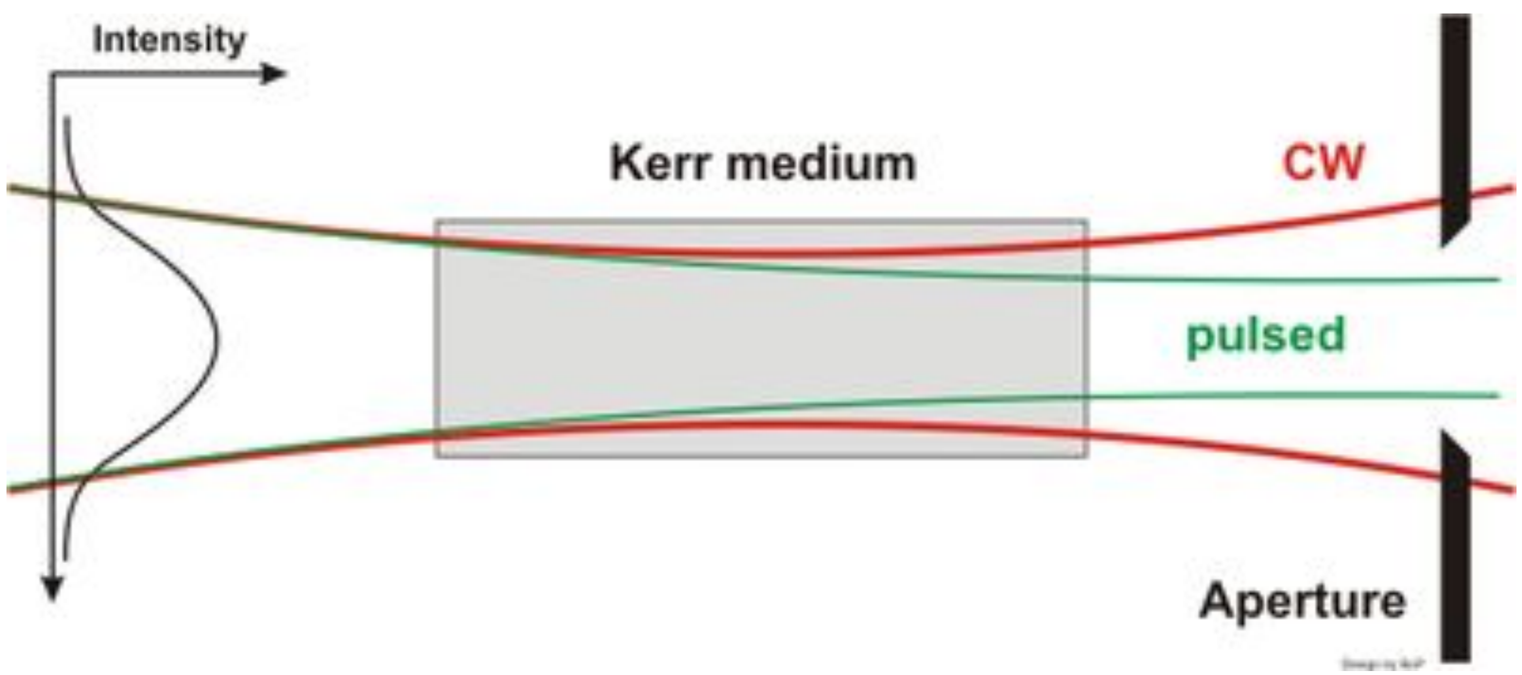
<u>Passive mode-locking:</u>

The KLM-Oscillator (Kerr-Lens-modelocking):

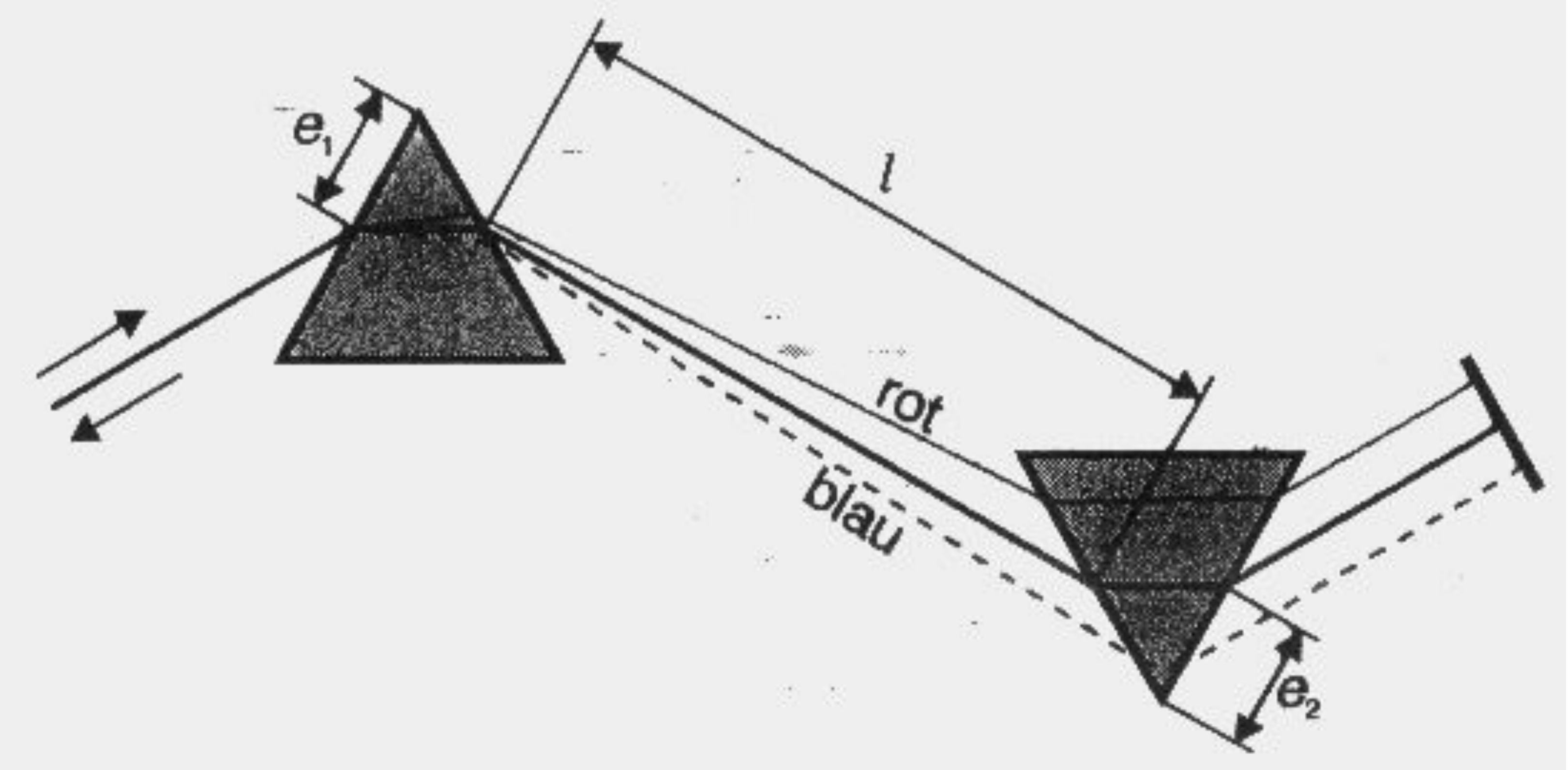


In a Kerr lens oscillator the pulse runs many times through the dispersive medium

Dispersion: compensation with prisms

•2 identical prisms exactly anti-parallel

•negative dispersion, as „blue“ passes less material then „red“

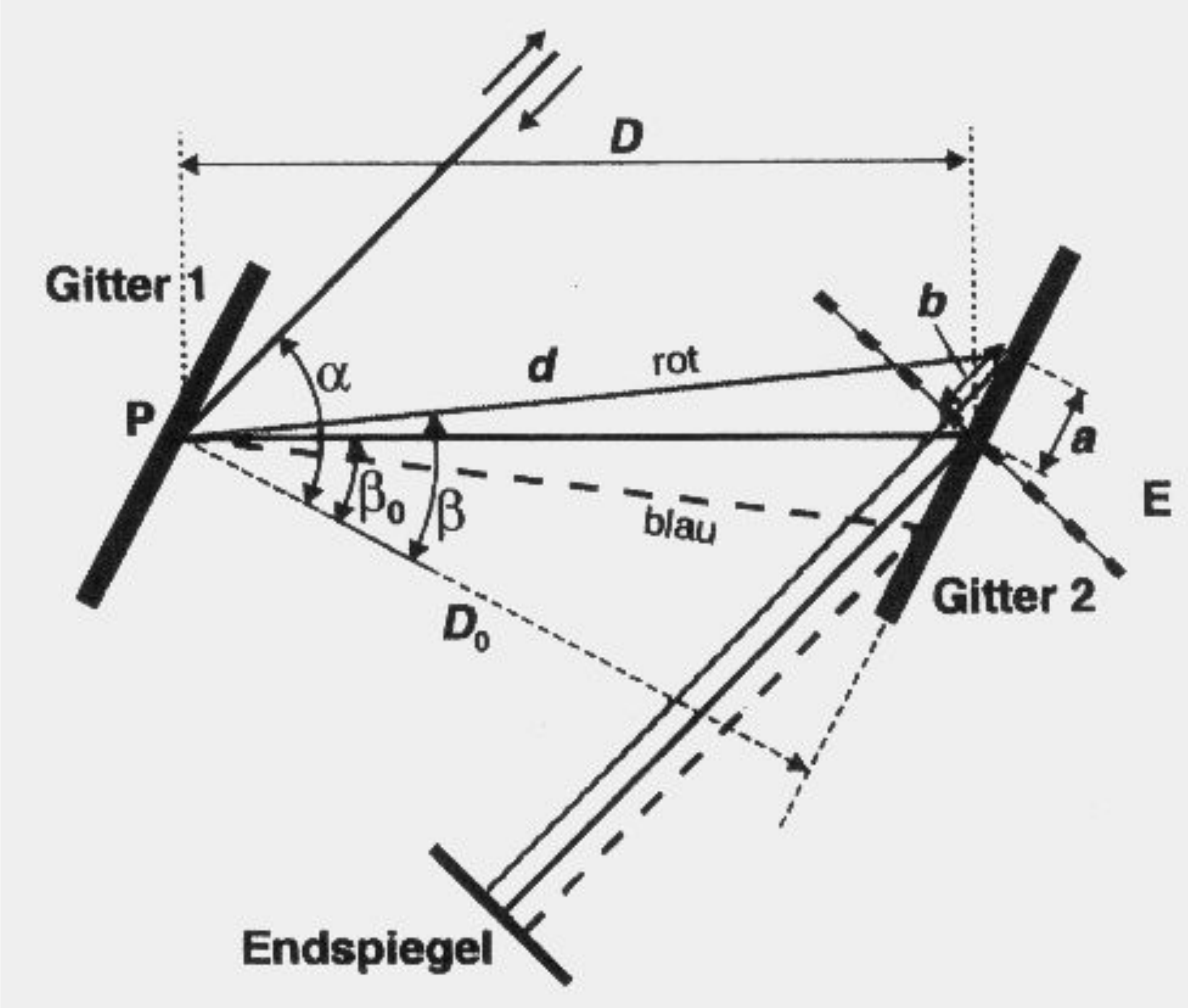


•Calculations: optical path through arrangement and find resulting phase and D_m

$$\varphi = \frac{2\pi}{\lambda} \cdot s_{opt}(\lambda) = \frac{\omega}{c} \cdot s_{opt}(\omega) \quad D_m = \frac{\partial^m \varphi(\omega)}{\partial \omega^m}$$

Dispersion: compensation with gratings

- 2 identical gratings, exactly anti-parallel
- $d = 1/p = N = 1200\text{-}1800$ l/mm
- blazed gratings: $R_{1.O} = 90 - 98$ %
- Characterized by:
  - Incident angle α,
  - Grating distance D(for $\lambda = \lambda_0$)
  - Grating equation for the first grating: $\sin \alpha + \sin \beta = N\lambda$ (see picture)



Short pulse oscillator

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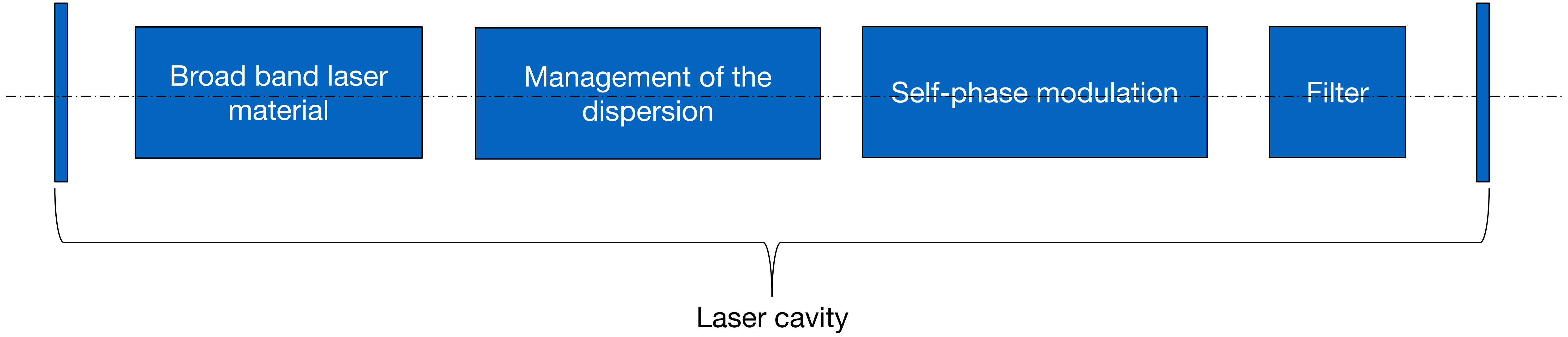
- Invention of the Kerr-Lens-Mode-locking (KLM) has revolutionized the short pulse laser busines

  - By KLM we can create (< 5fs) relatively easy.

- Generic short pulse oscillator



Resonator Design

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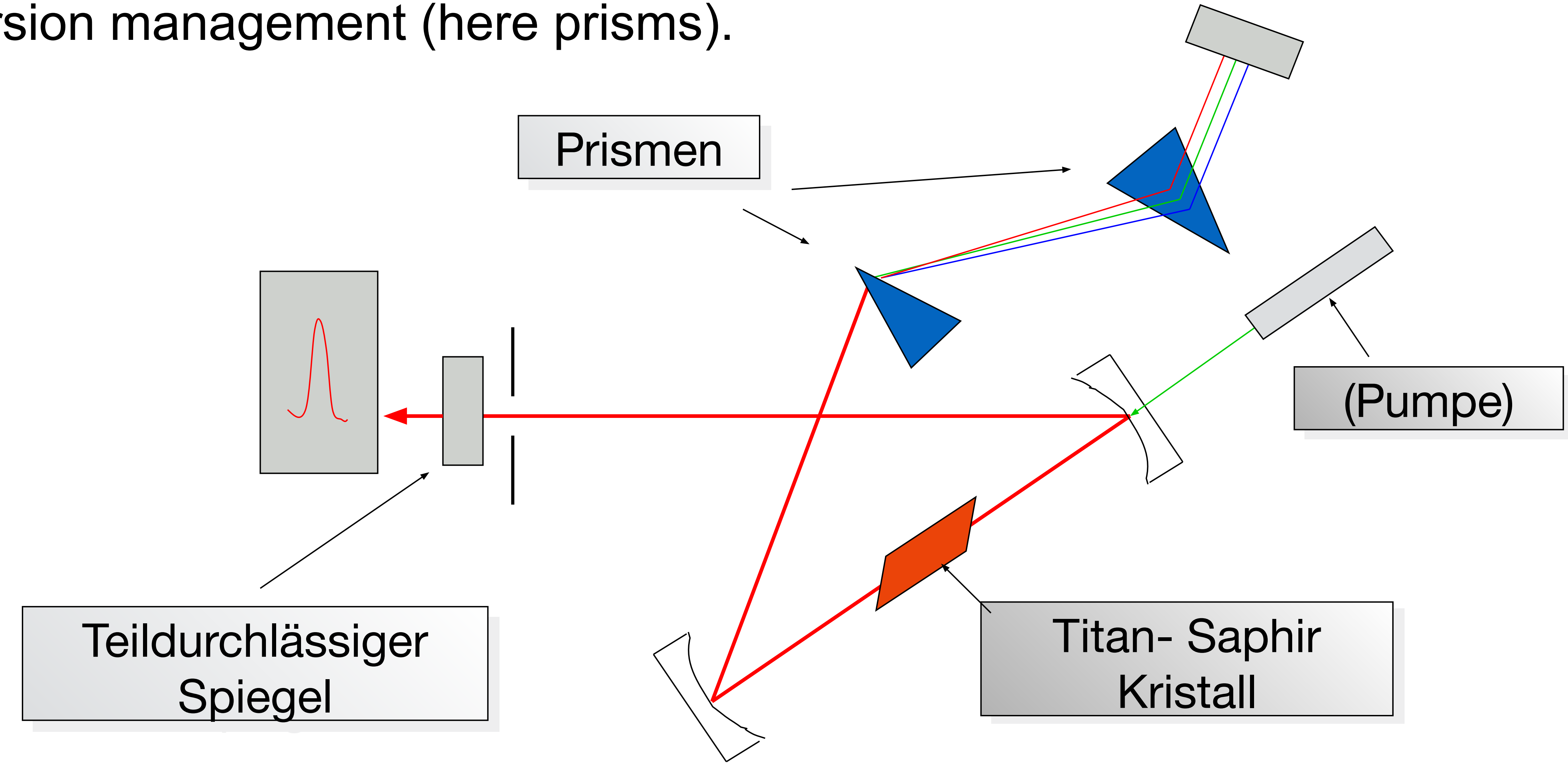
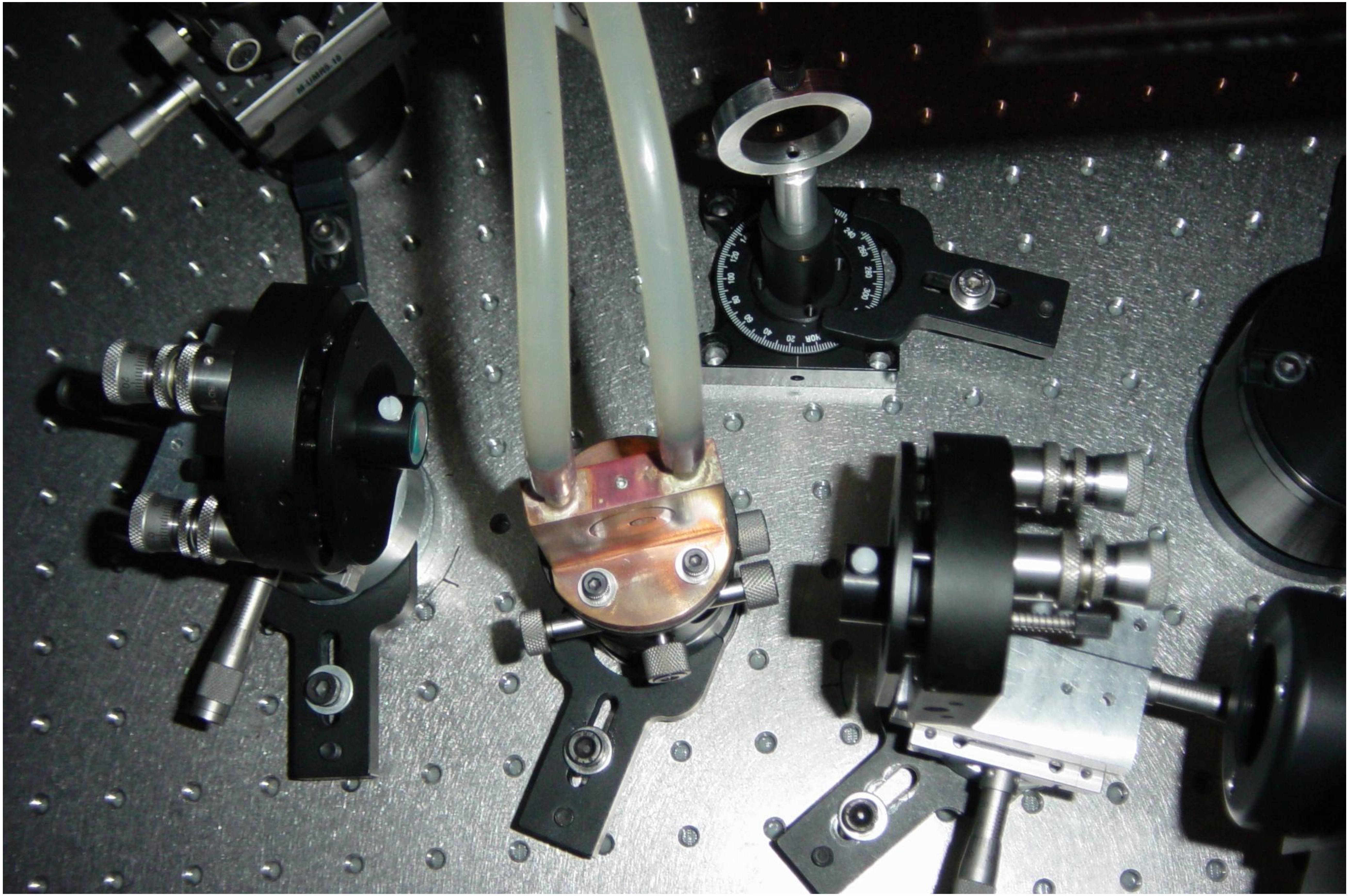
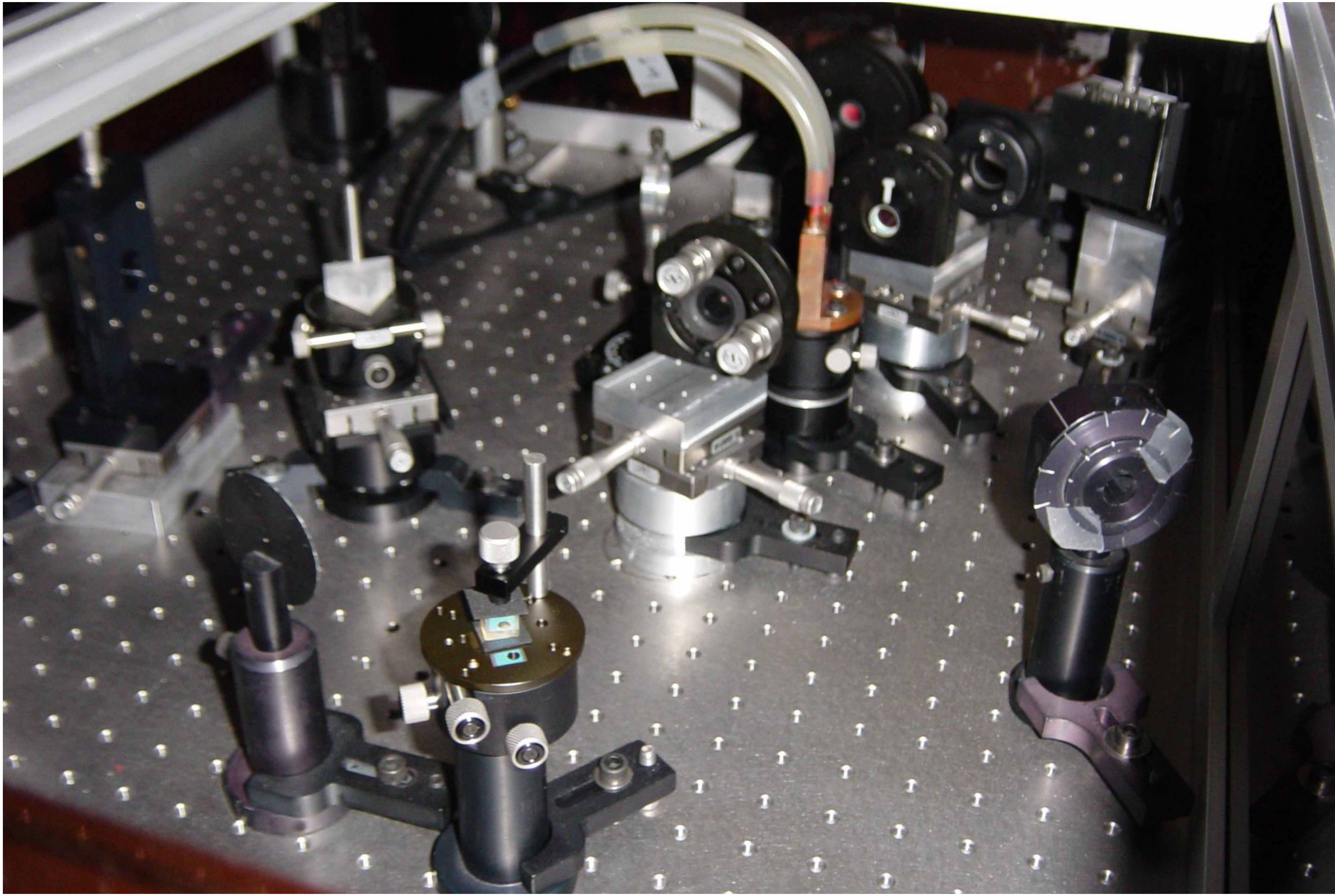
- High non-linearity in Kerr medium: Medium in focus of the mirrors – SPM.
- Astigmatic compensated resonator (Sub cavity) made of 2 focusing and 2 planar resonator mirrors.
- Dispersion management (here prisms).







Modern laser concepts, architecture,
Pulse shaping

CPA Method UHI laser amplification

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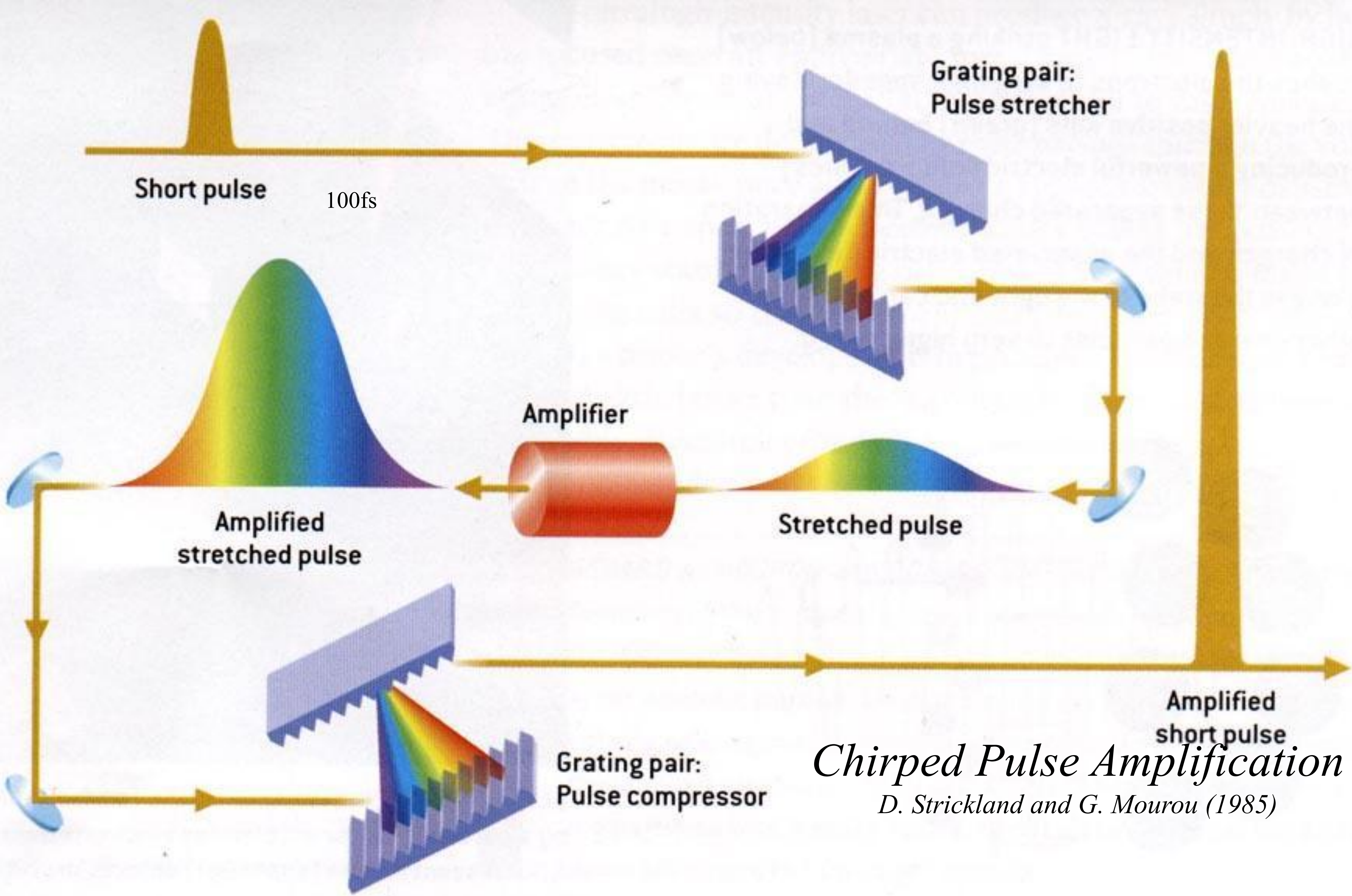

Chirped Pulse Amplification

D. Strickland and G. Mourou (1985)

Laser architecture: the MOPA concept

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Master Oscillator: short pulse (ns) nJ - mJ → Pulse shaping Spectral shaping beam shaping → Pre-amplifier: high-gain multipass → Amplifier: high-energy multipass linear amplification

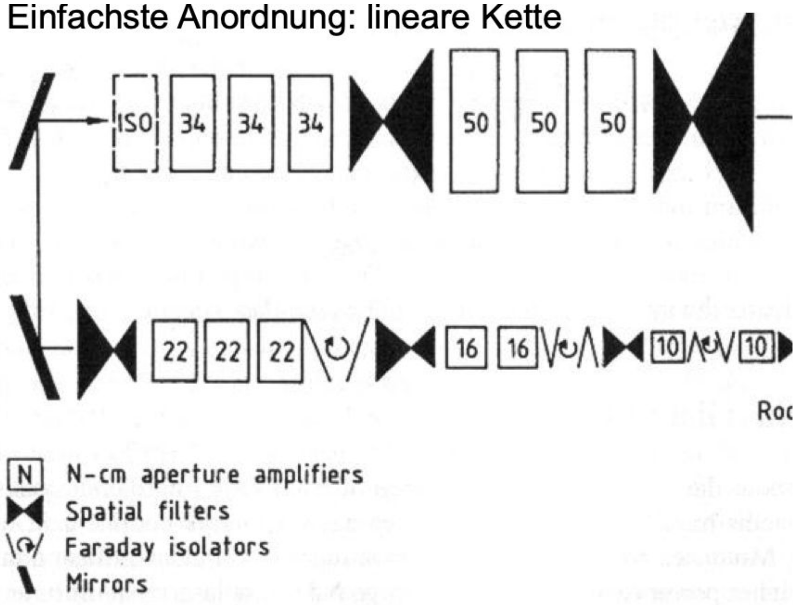
- Oscillator creates the pulse
- Pulse will be shaped (spectrum, beam shape)
- One or more preamplifier
  Low distortion
  High effincy
  High energy storage capacity
  Now noise

- Beam gets injected into main amplifier as boosters

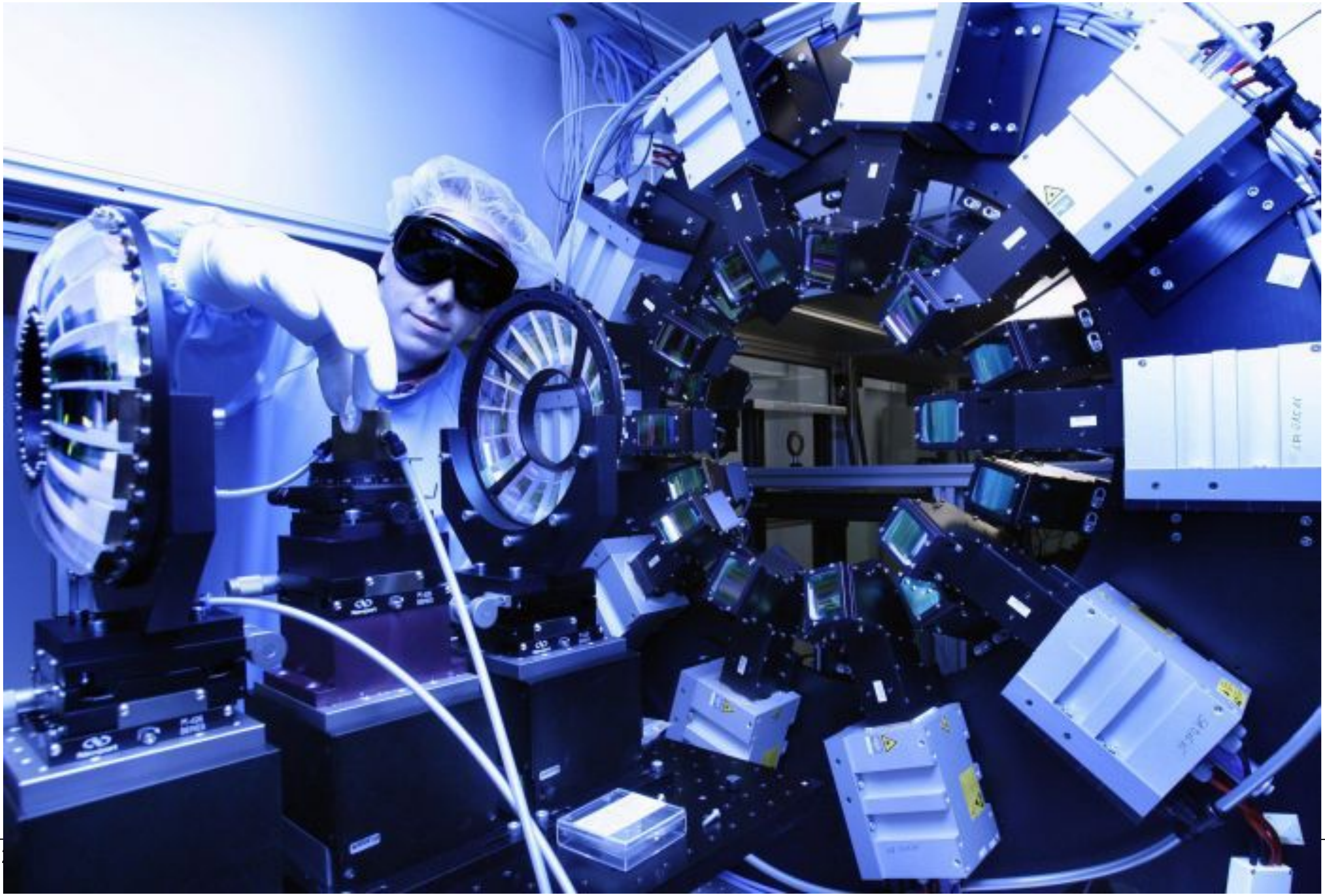
Example: NOVA Laser

- **NOVA 10 Strahlen, 100 kJ @ 10 ns (1984-1999)**

Einfachste Anordnung: lineare Kette

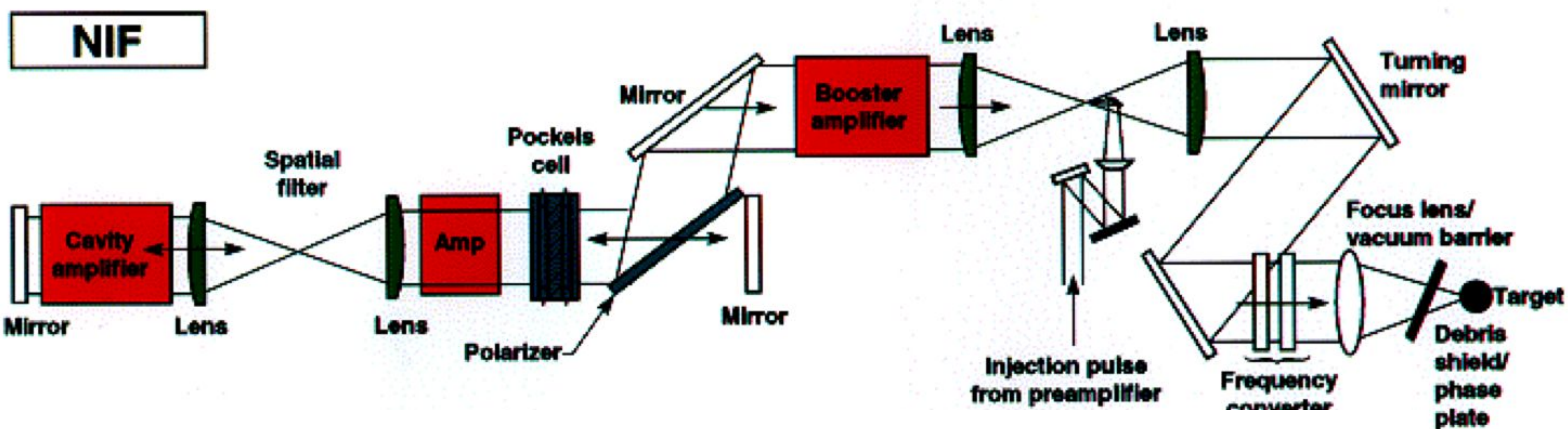


Amplifier Design



Example

Example of a multipass amplifier



Schematic descritption of the NIF Beamline without preamplifier

Idea: Multipass amplification including PEPC

regenerative amplification

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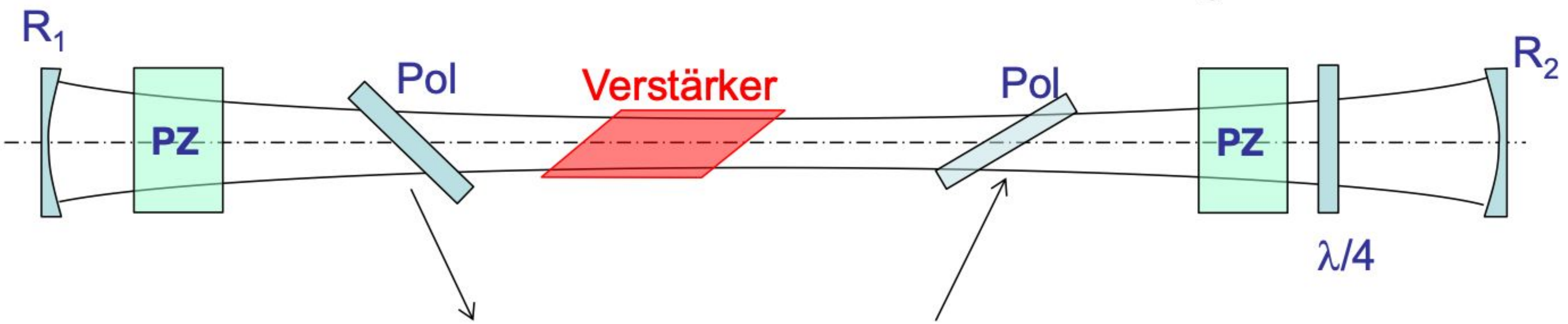
•Beam is inserted and extracted actively



•Components:

•End Mirrors: curved, high reflective, form a resonator

•Amplifying medium often at Brewster angle (no losses for p-polarized light)

•Polarizing beam splitter: transmission for p-polarized light >80%
reflectivity for s-polarized light >80%
for the entire bandwidth of the pulse

•Resonator:

•Only resonator modes are amplified: great beam profile

•Requires mode matched injection of the pulse

Features of a regen

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On the spectrum:

optical medium: many roundtripsäufe, high dispersion
=> for ultra short pulses (<25fs) a regenerative amplifier is fairly useless

Saturation effects: low spectral deformation if gainis low and J_{Sat} is not reached

Gain-narrowing, as losses require a higher total gain

Influence on pulses:

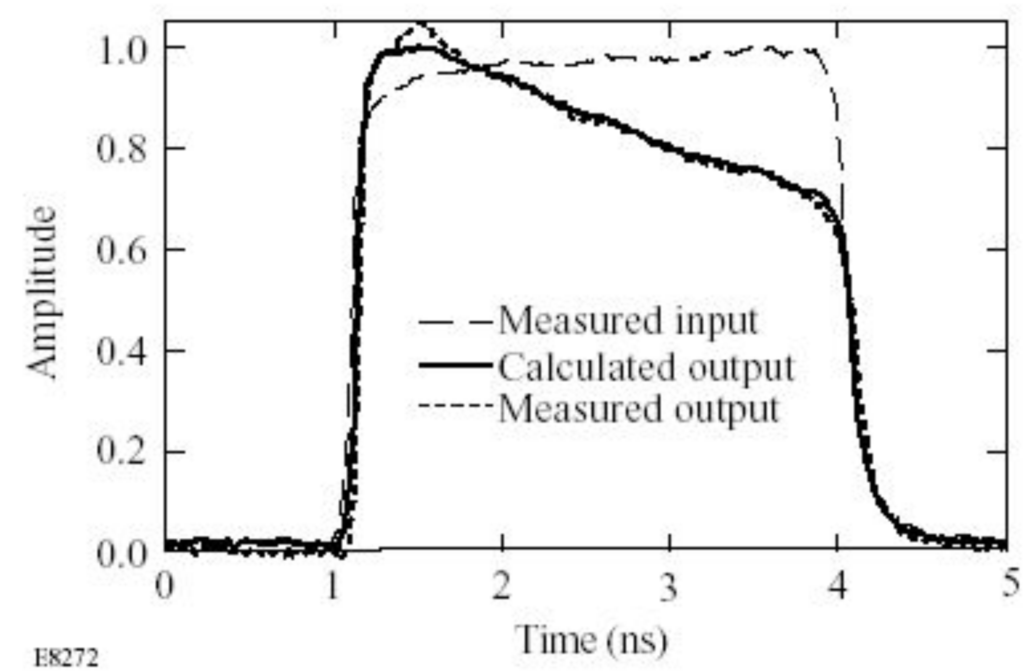
Amplifier in saturation: high energy yield

Energy stable

Square-Pulse-Distortion

Pre-pulses

ASE noise



Example of a regen

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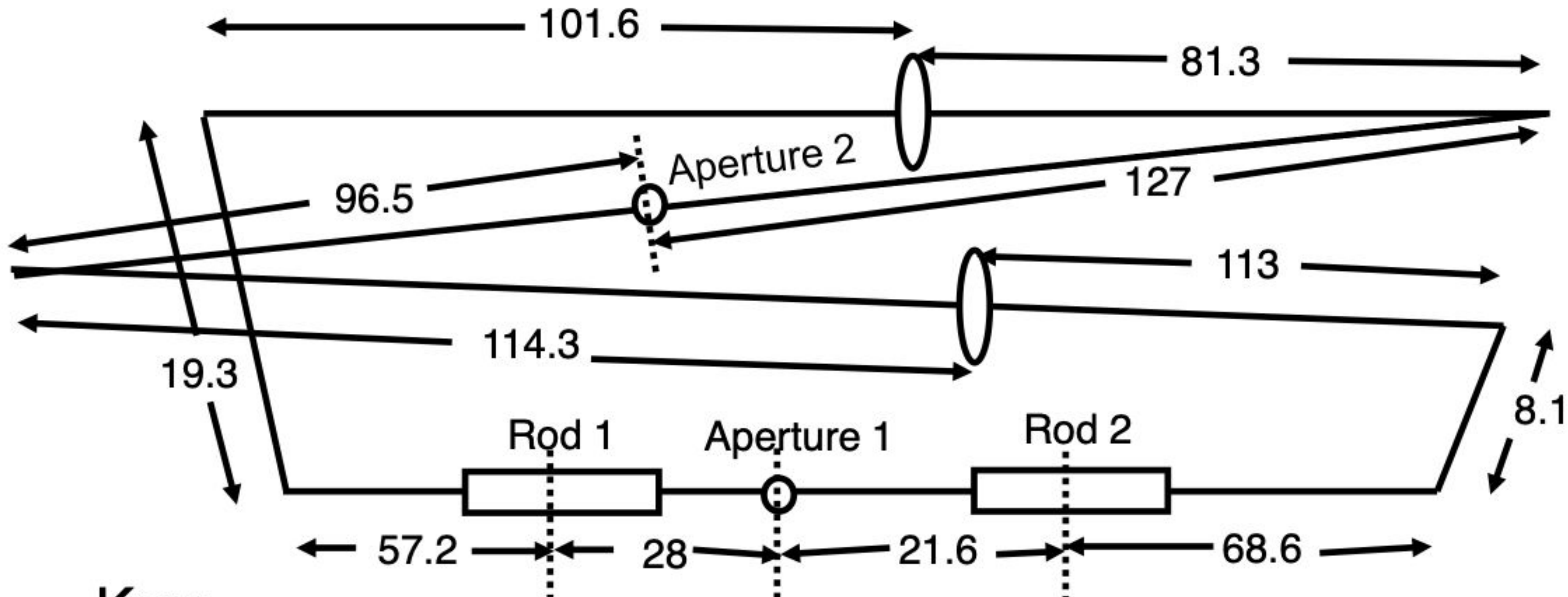
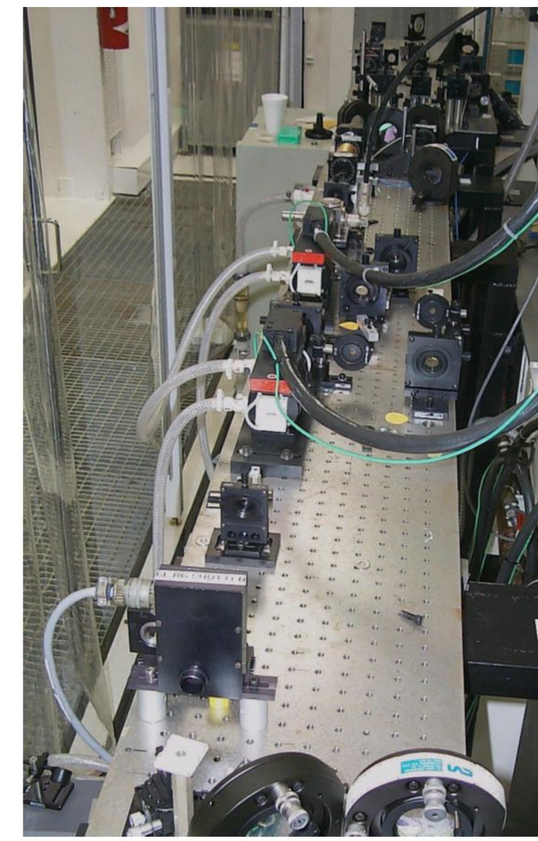
Z-Beamlet (Sandia NL, Ca. USA)





<u>Key:</u>

- aperture
- 213-cm focal-length lens
- laser rod

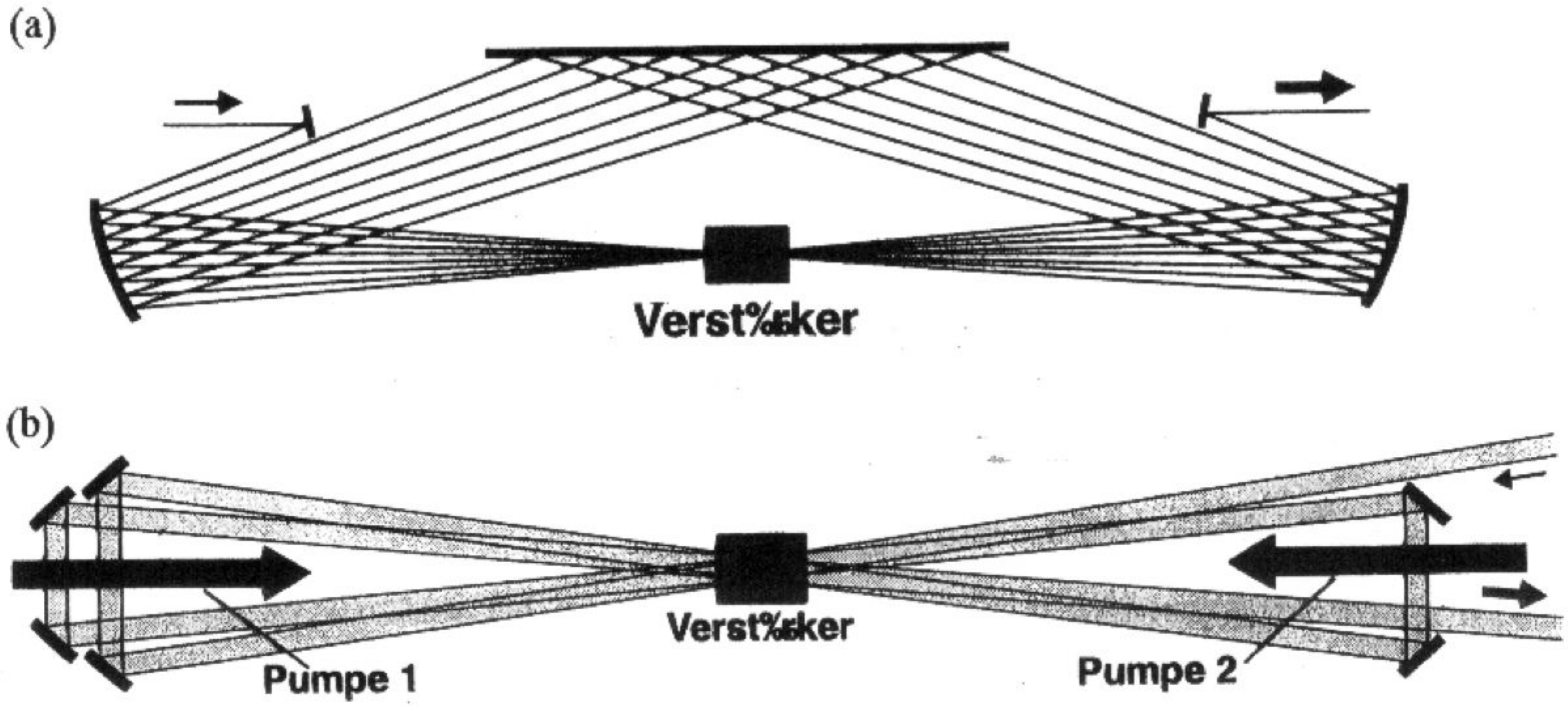
<u>Beam waist (radius):</u>

Rods 1and 2, at ends: 1.13 mm
Aperture 2: 0.63 mm

- calculations by Eric Honea and PARAXIA

Multipass Amplifier

Beam is sent through active material multiple times with different angles



„Bow-Tie“ Verstärker

Multipass Amplifier (active mirror)

Amplifier design with high potential,
especially diode pumped

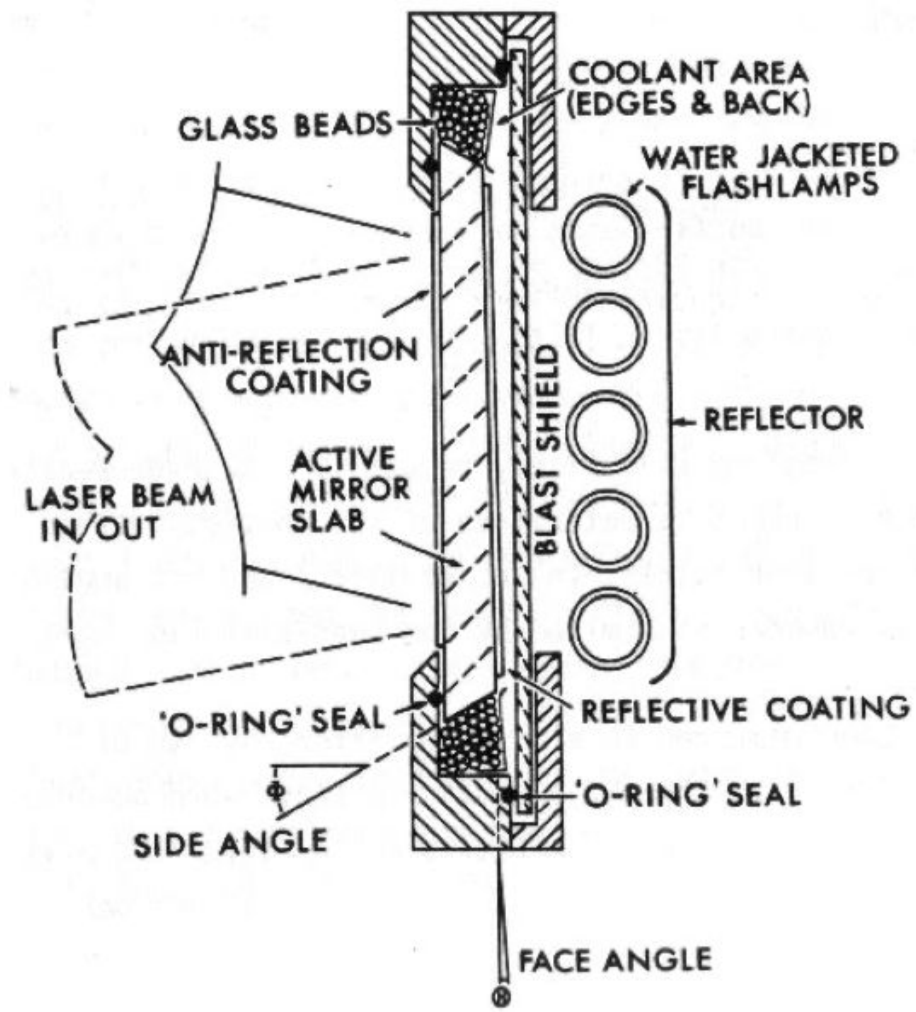
Coating issues in the past (multilayer coating)

Frontside AR coated for laser wavelength

Backside HR coated for laser wavelength

Backside transparent for pump light
(hard for flash lamps)

Limit in aperture: Transverse lasing



Multipass Amplifier (active mirror)

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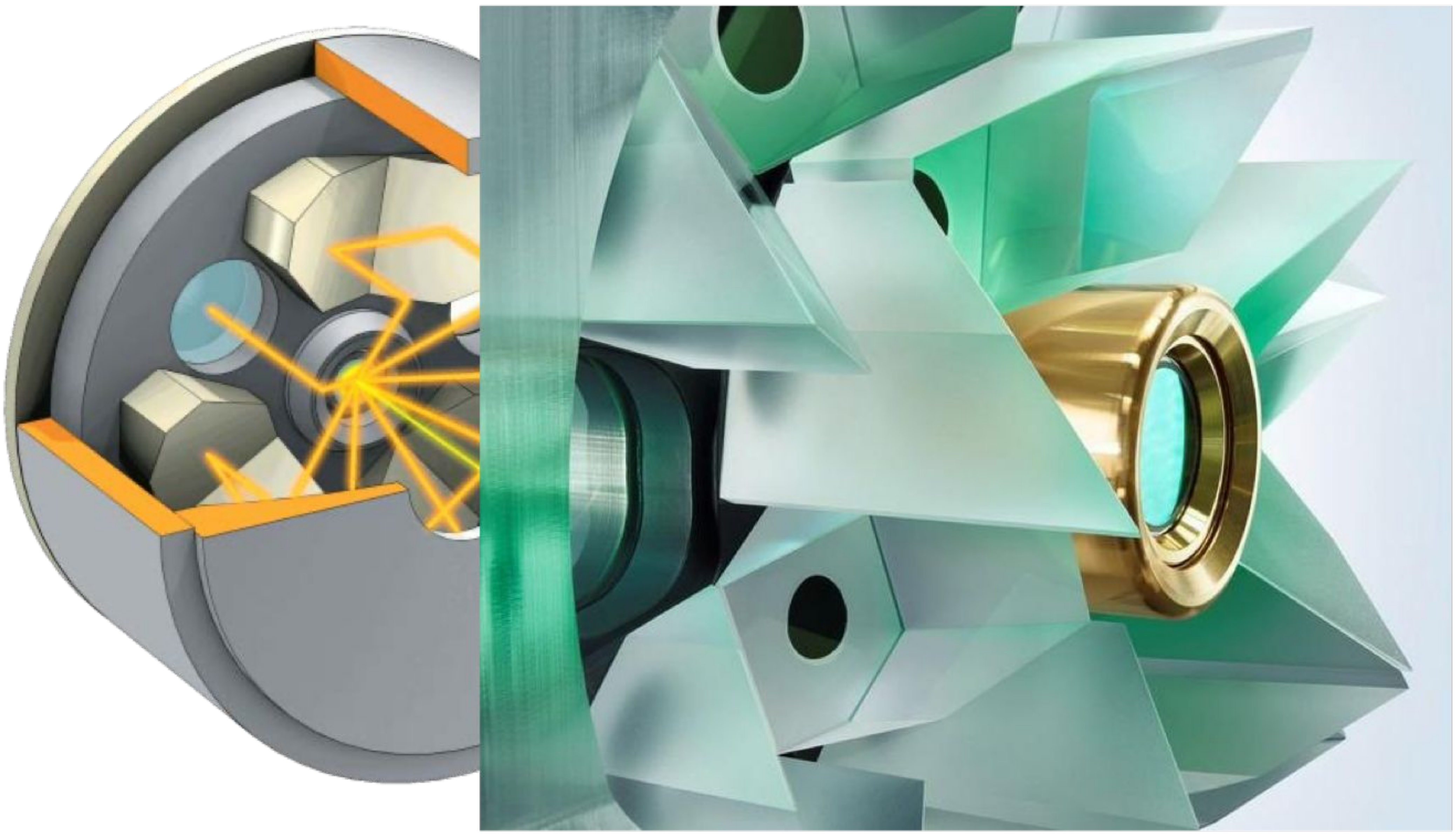
Disk Laser Principles

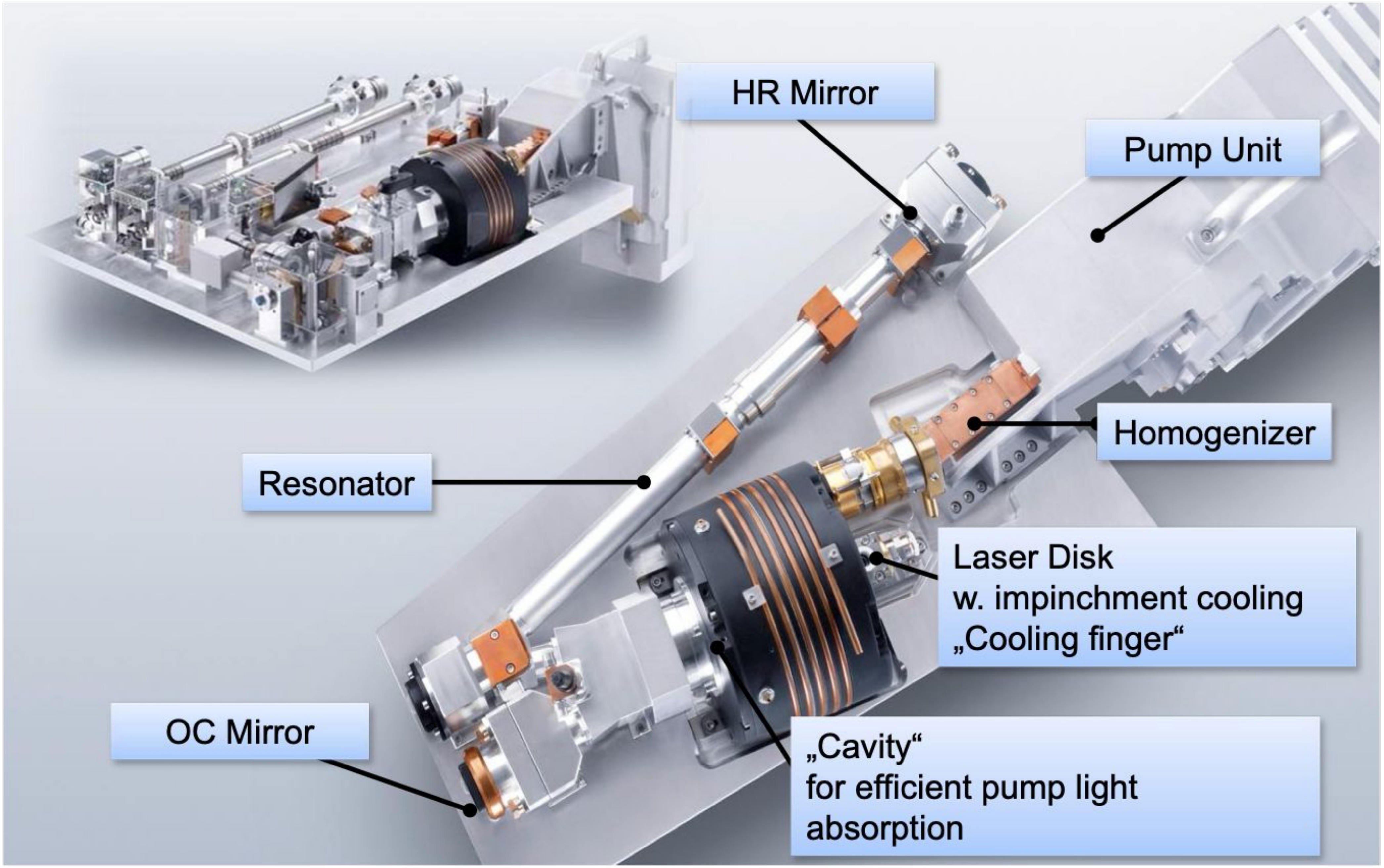
TRUMPF

Pump Light Absorption



Multipass Amplifier (active mirror)

Optical setup of cw disk laser



Multipass Amplifier (active mirror)

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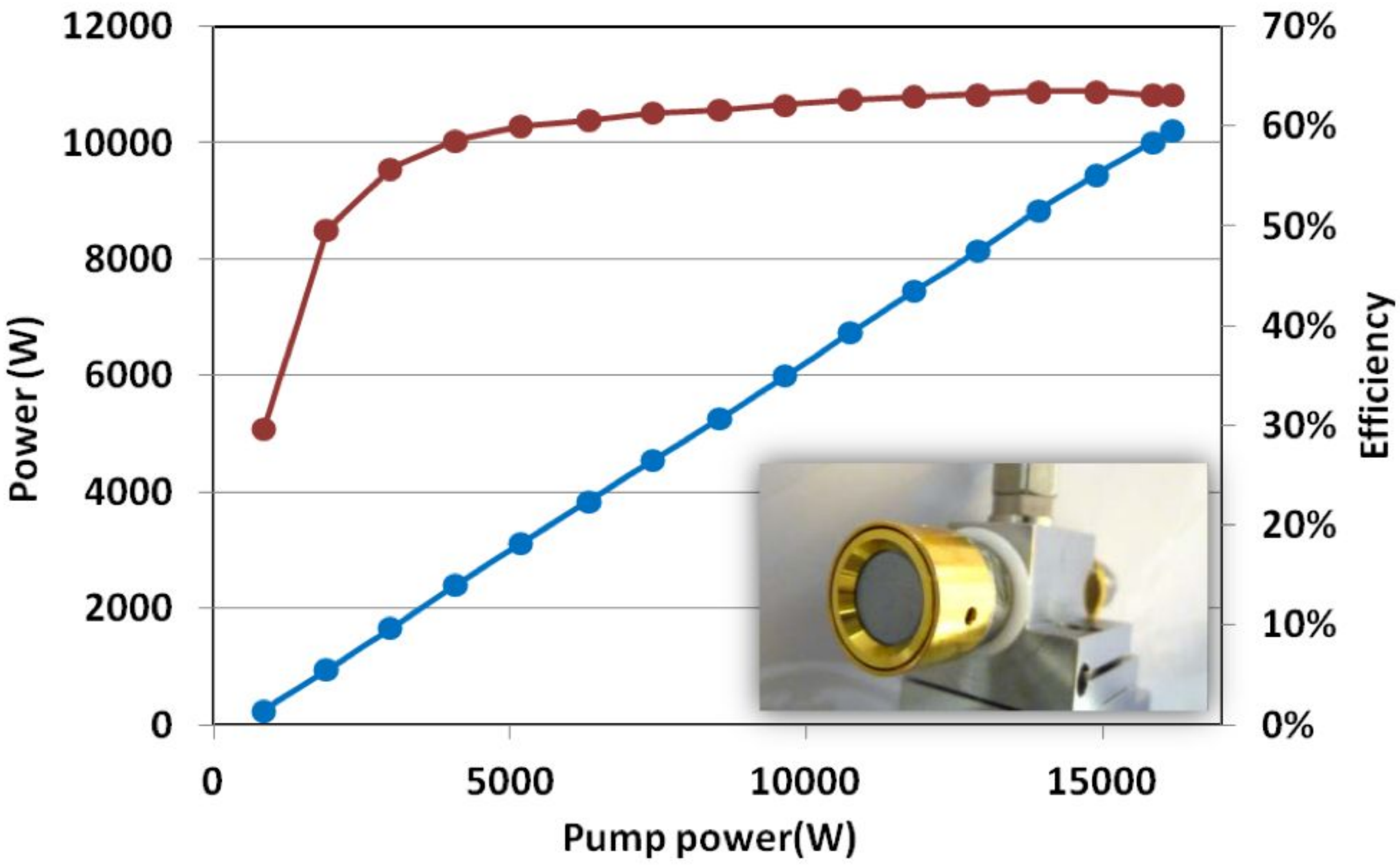
Record performance: 10 kW per Disk / 62 % optical efficiency

→ There are no barriers to scale power/disk beyond current power levels



Multipass Amplifier (active mirror)

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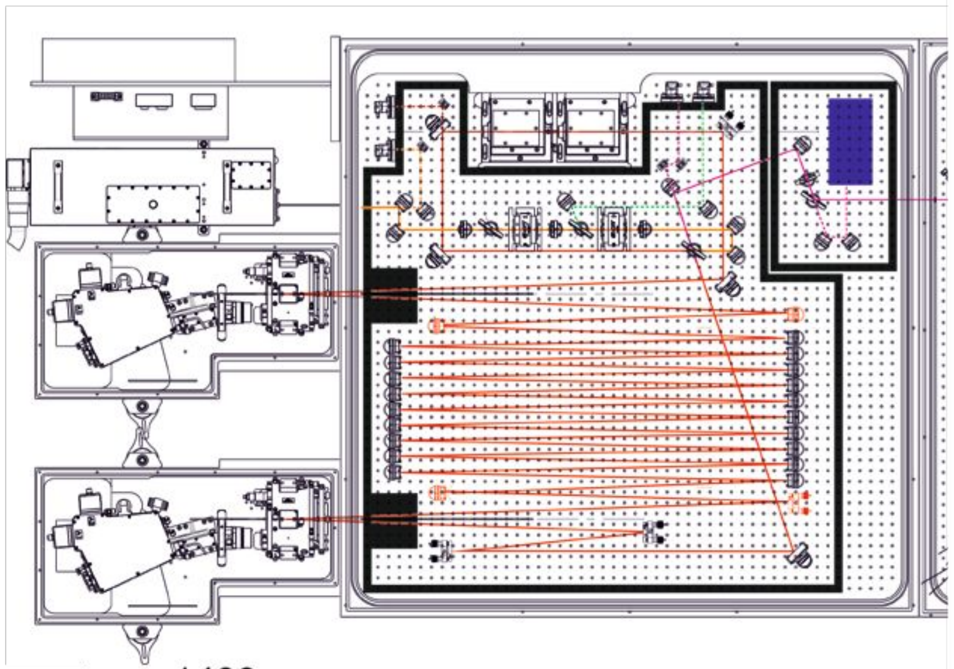

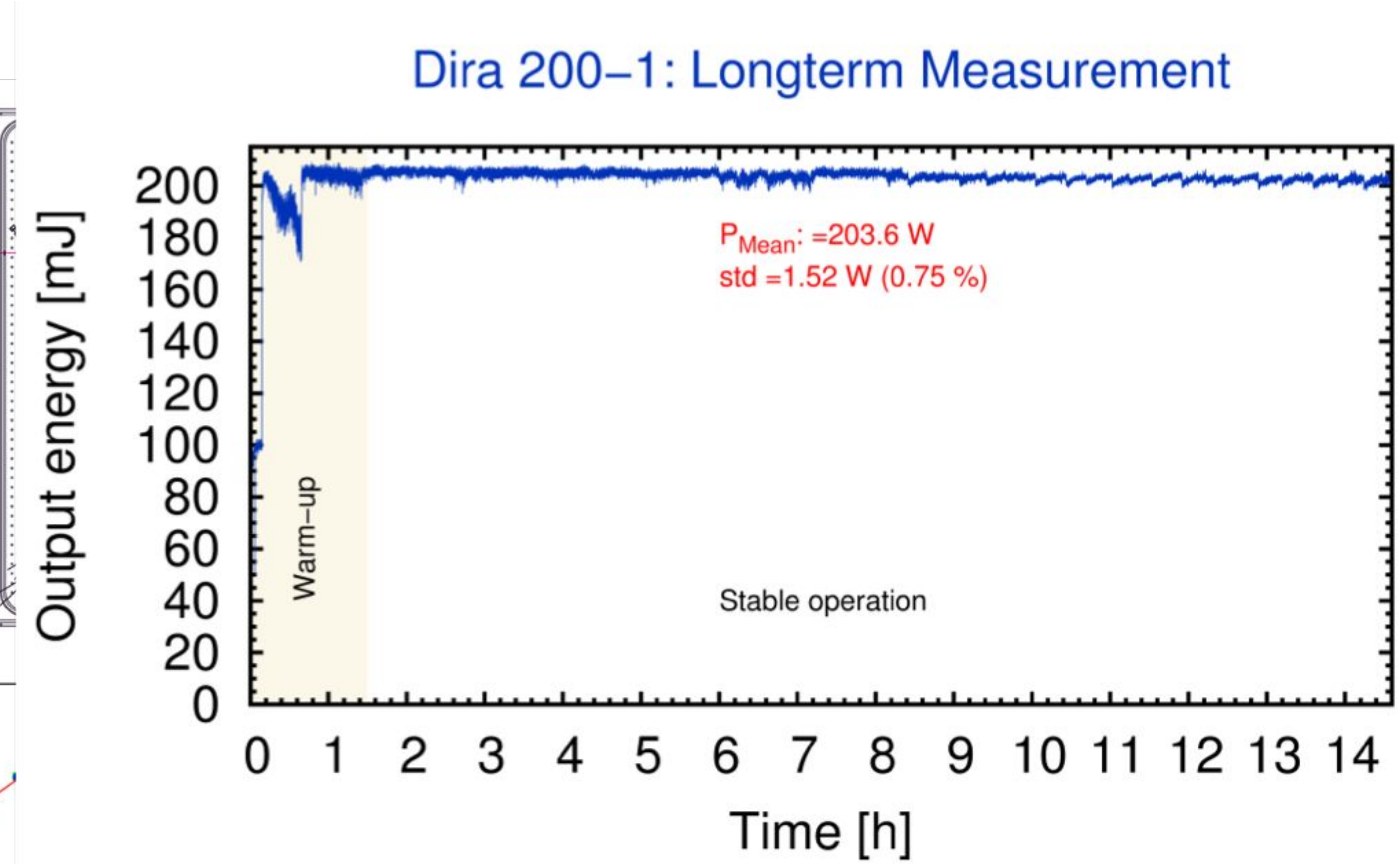

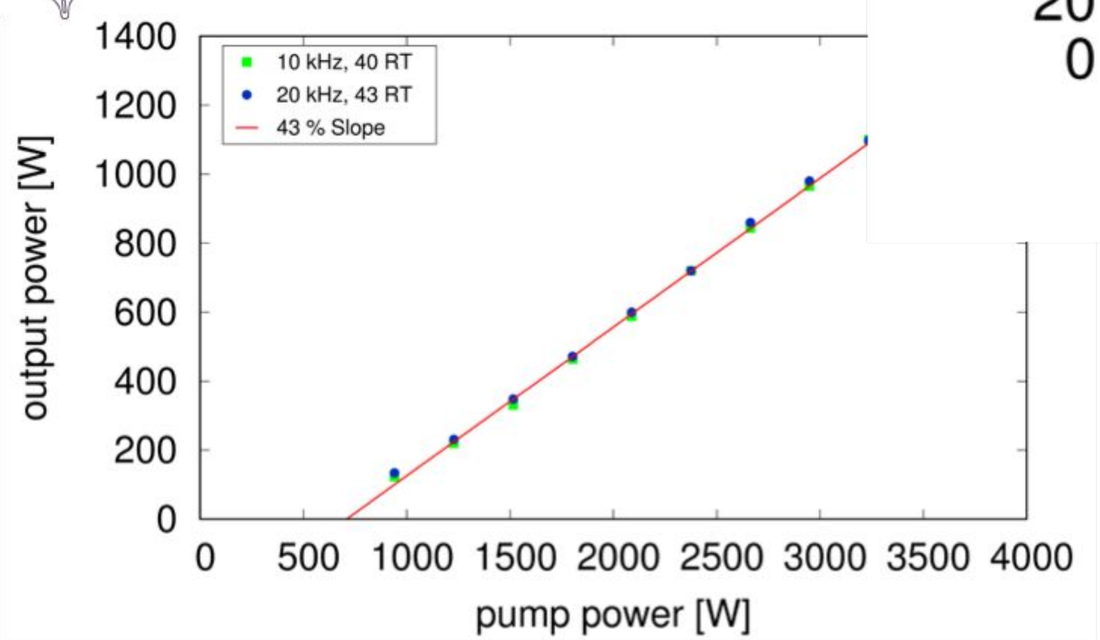

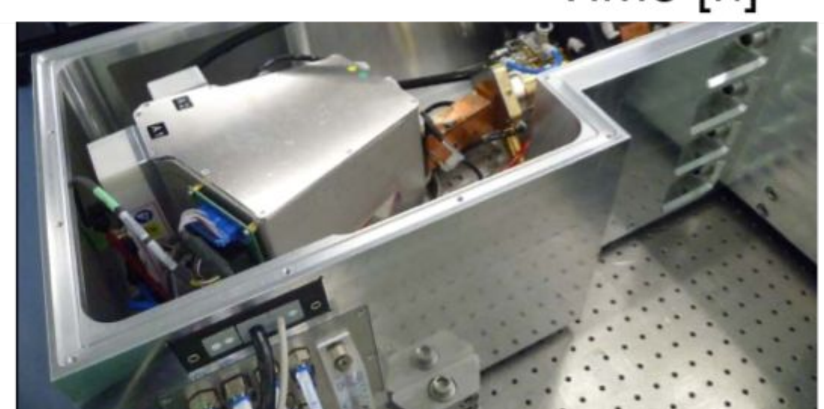

Multipass Amplifier (active mirror)

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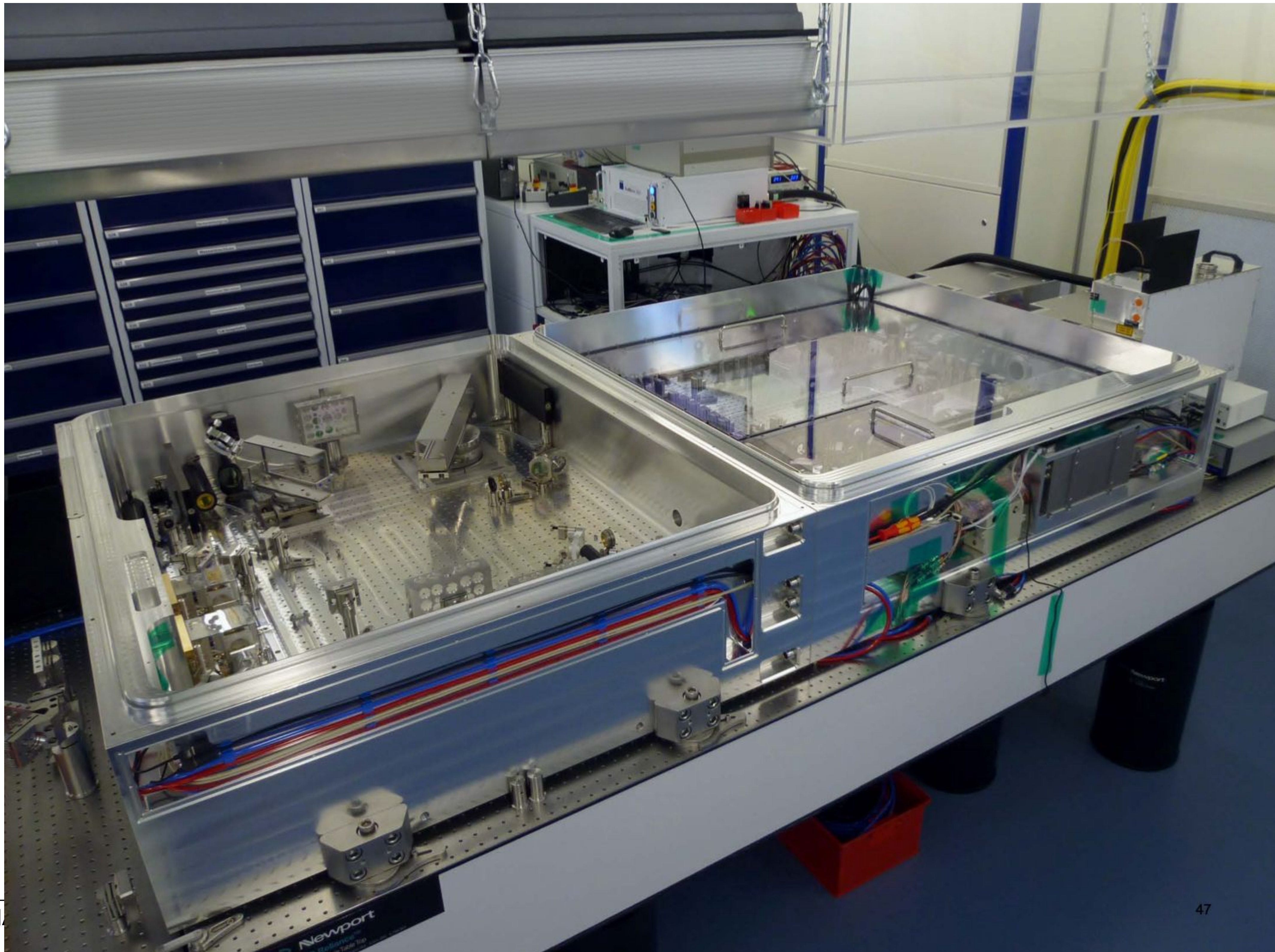

Multipass Amplifier (active mirror)

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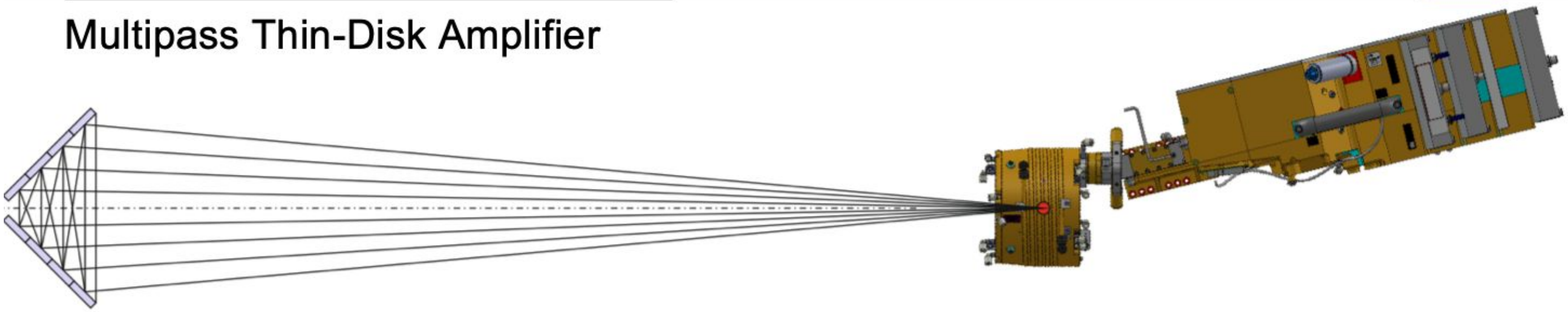
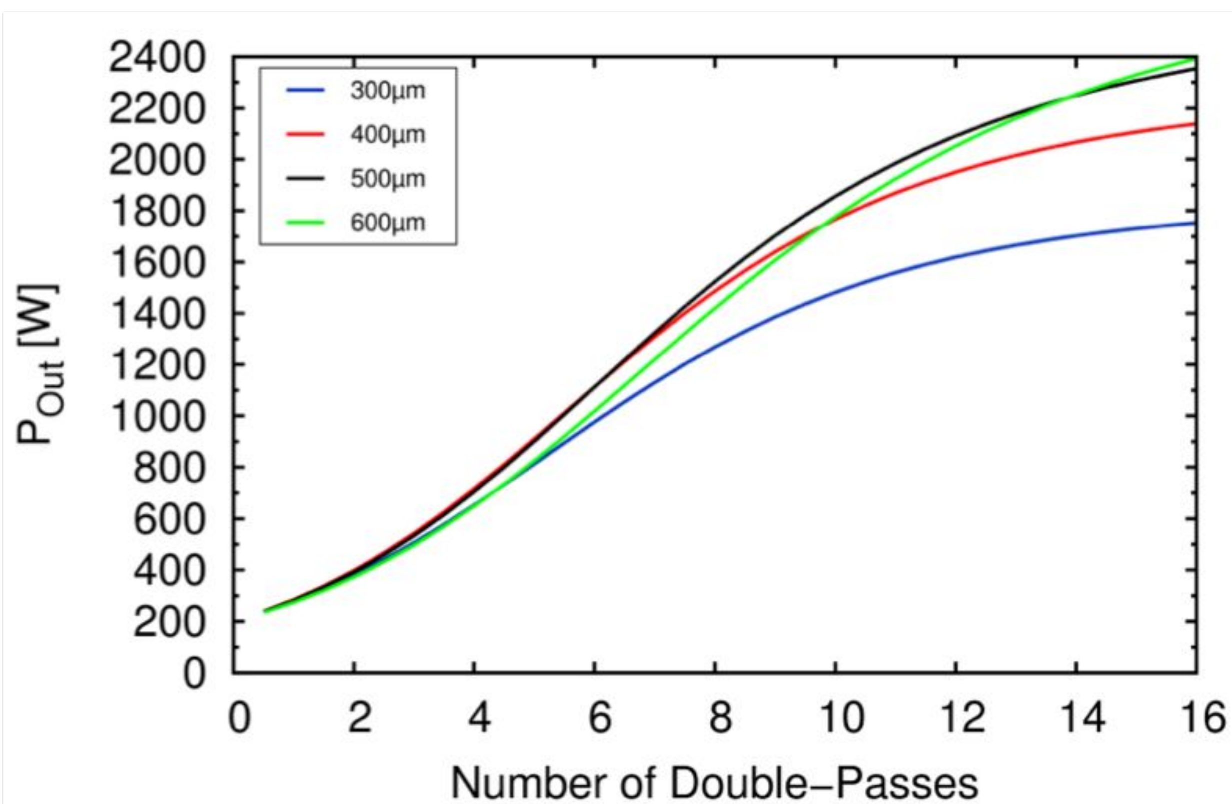
TRUMPF

Further Scaling to > 1J @ 1kHz

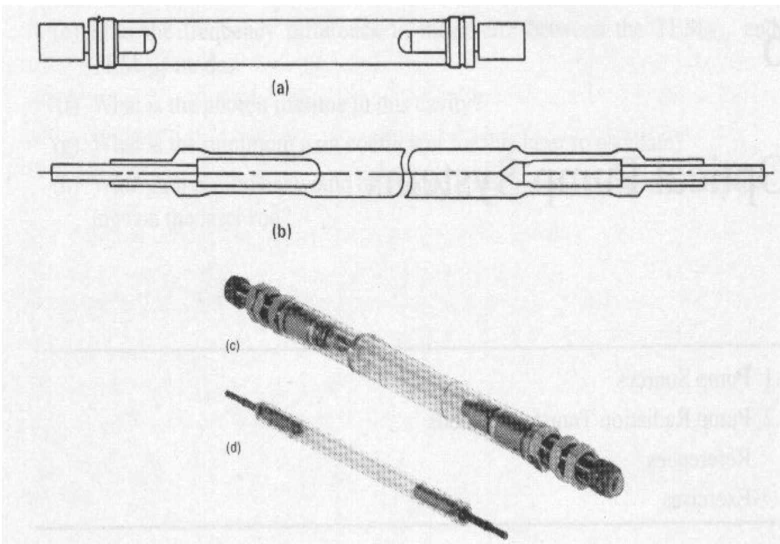
Multipass Thin-Disk Amplifier



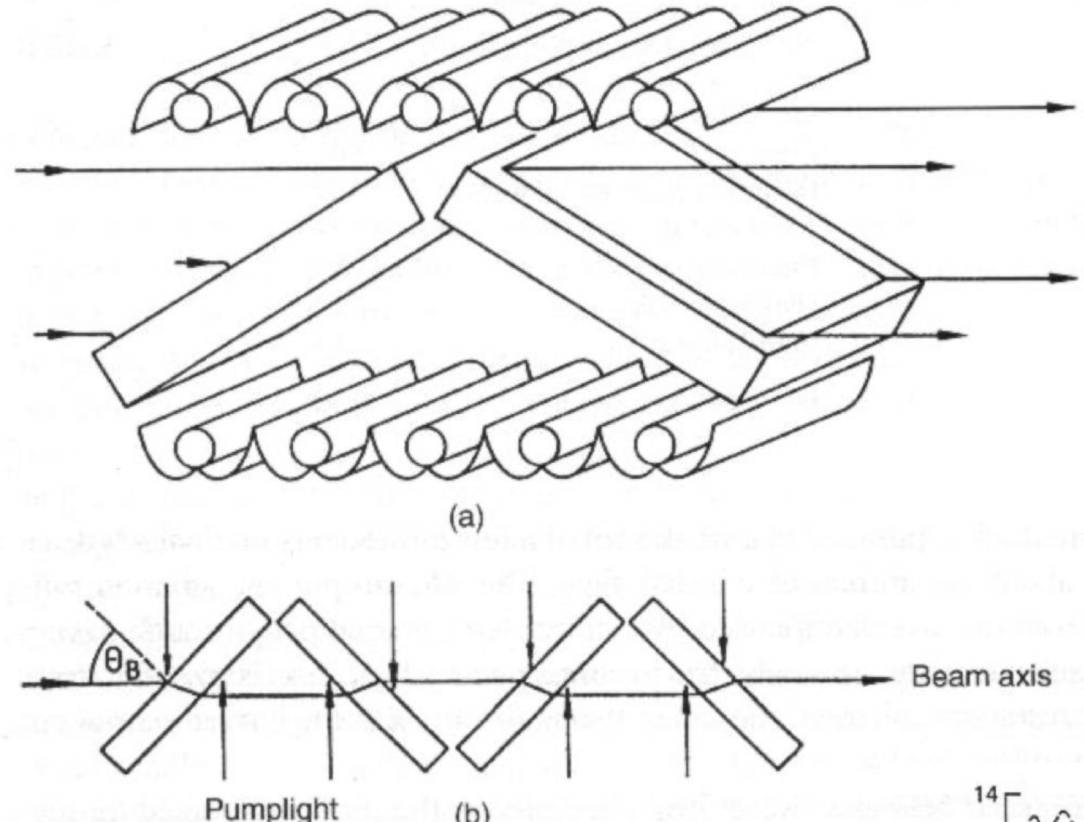


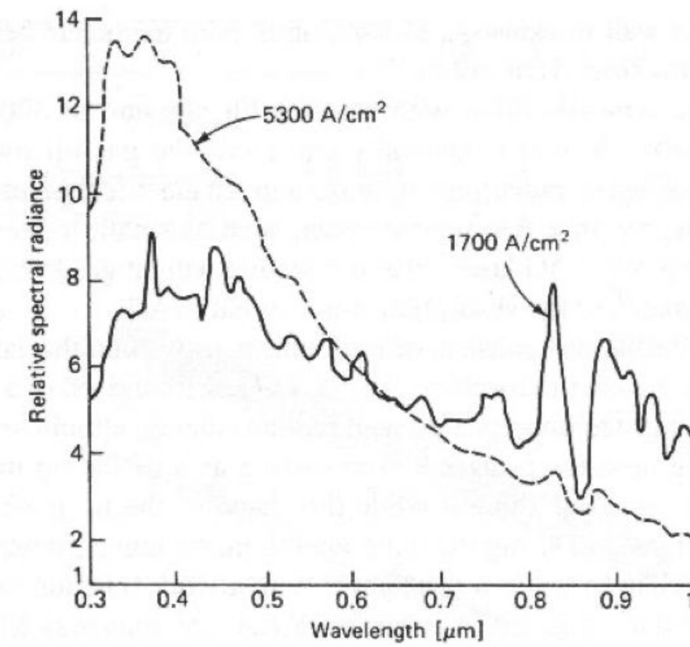
- 20 mm disk diameter
- 20 kW of pump power
- 8 kW average pump power (40% duty cycle)
- 220 mJ seed laser
- 8 – 10 passes expected

Pump sources (flash lamps)



7680 flashlamps, each 6 feet long
30 kJ energy each





Pump sources (Laser diodes)

Diodes can convert up to 60-70 of the electricity into radiation

Better spectral match to the laser medium absorption band:
almost full conversion of the diode light into population inversion

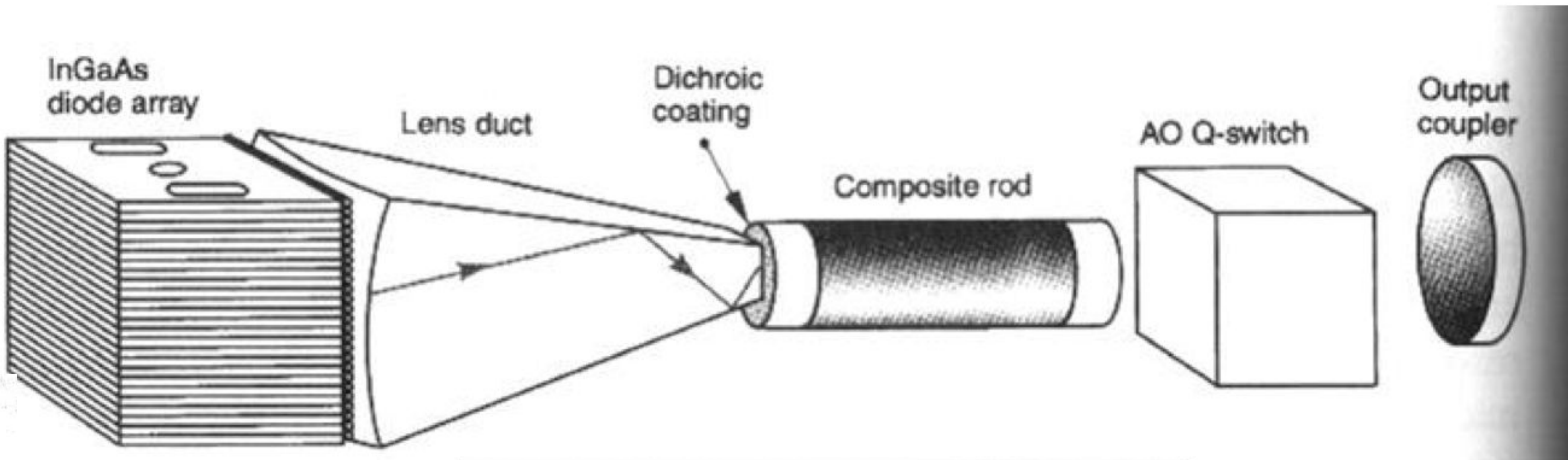
Individual emitters: very small (200µm-1mm wide and 0.4 µm high, 500µm length).

Emitted radiation different in divergence => matching optics

1cm Diode bars ca. 10 – 50 independent emitters.

Small size limits the power via damage threshold of the micro optics in the resonator

Pump sources (Laser diodes)



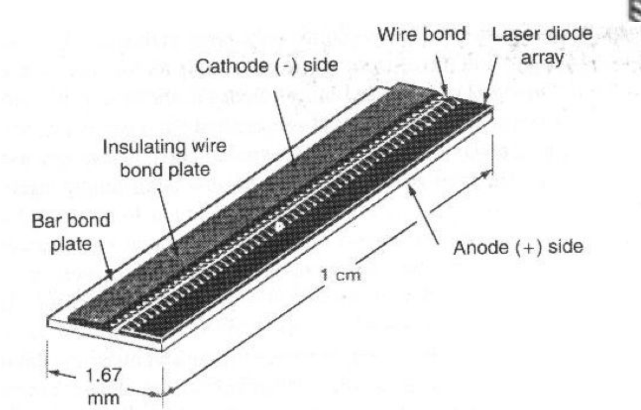
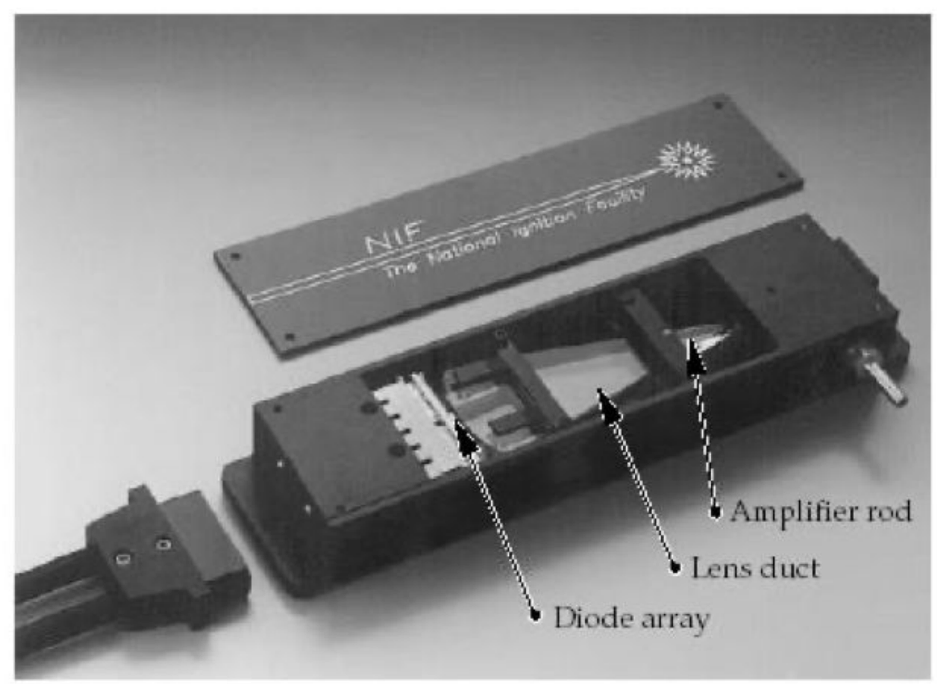


FIGURE 6.11. Basic structure of a 1 cm bar.



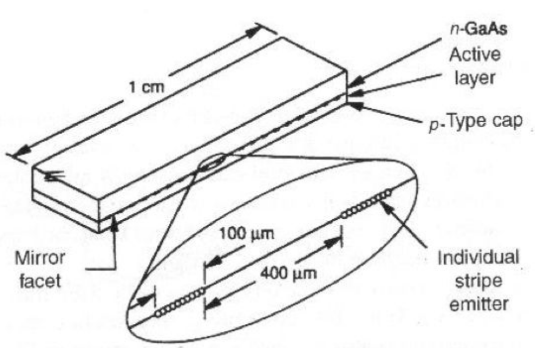
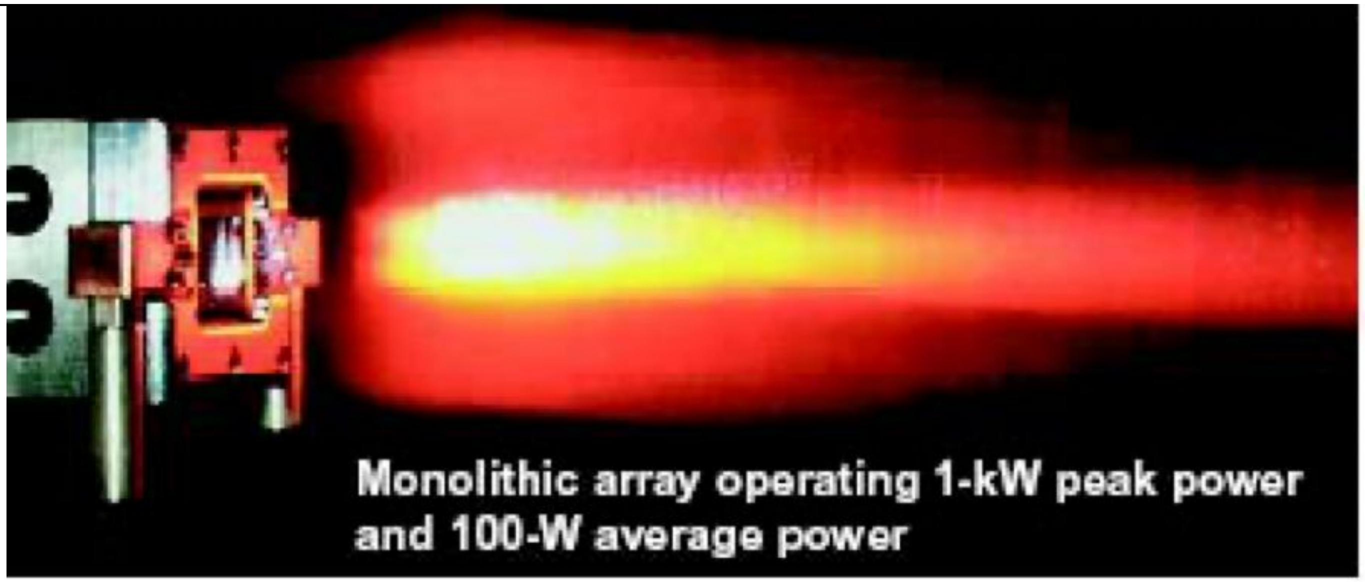
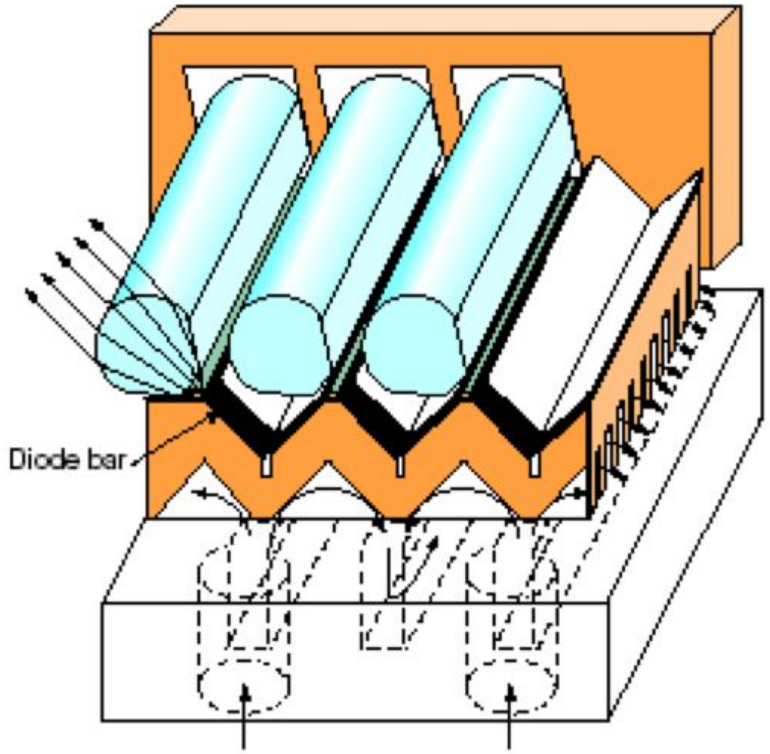


FIGURE 6.12. Monolithic 1 cm bar for cw operation [9].

Pump sources (Laser diodes)

2-D array





Diode array
1kW from 4 cm^2 surface

Pulsed array with 30% duty cycle

Peak power up to 30 kW
And cw power up to several kW

6. Moderne Laserkonzepte, Architektur, Pulsformung

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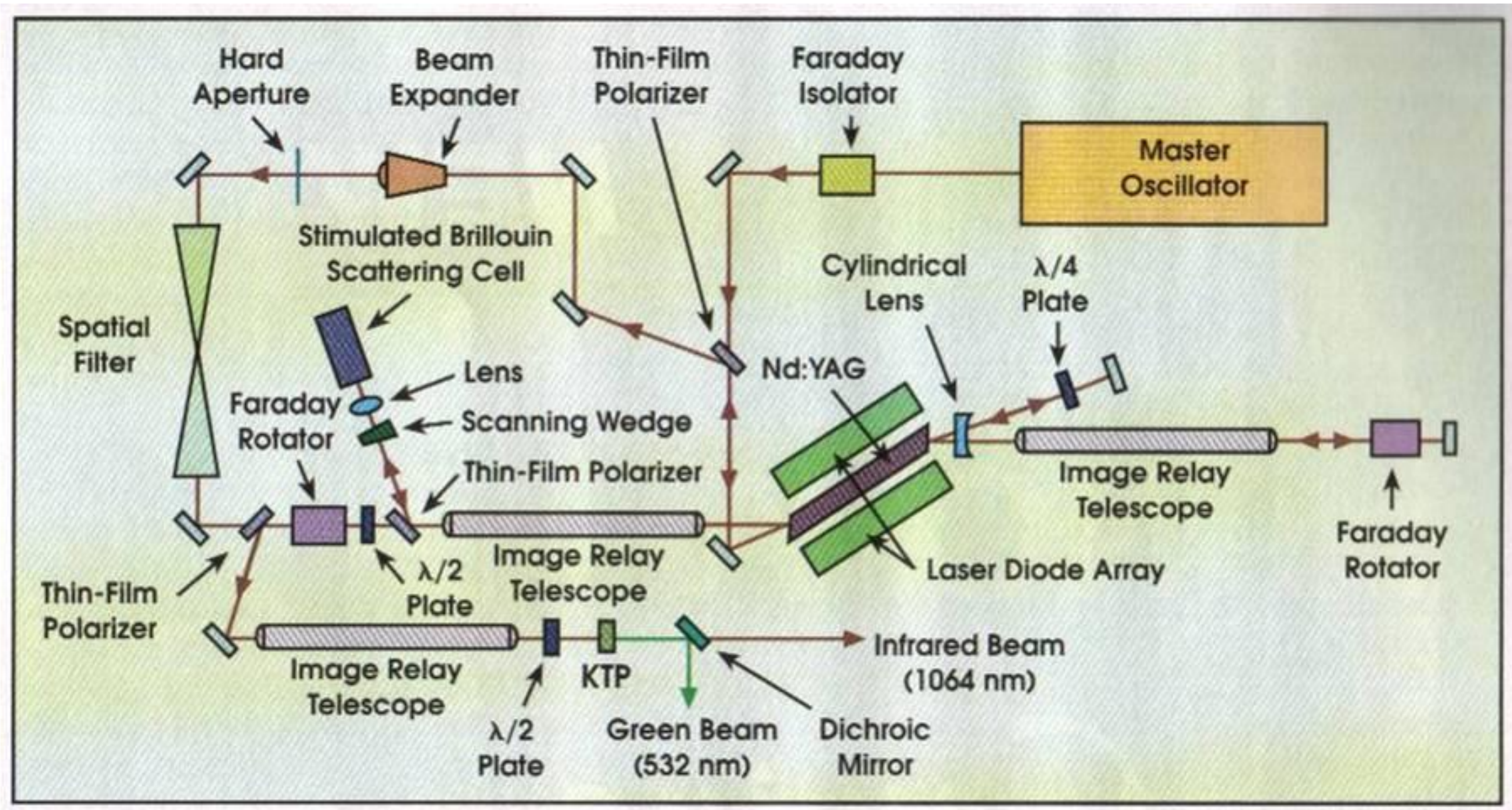
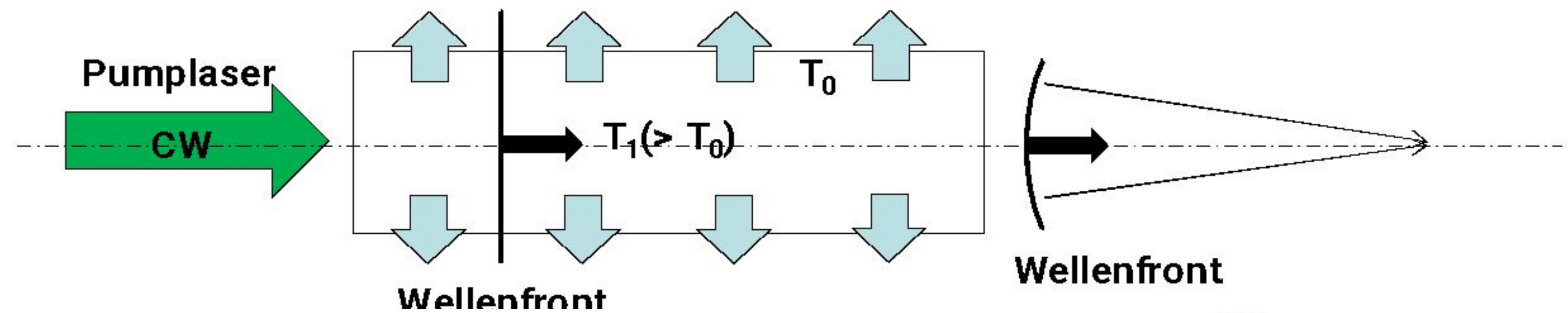


Laser system (132 W; 1 kHz) JAERI: 1.5 x 1m Footprint
Pulse from oscillator double pass through λ/4 plate; magnified and filtered image relayed;
2 double pass with Faraday-Rotator (compensate thermal biefringence);
SBS cell reflects the pulse 3. time into amplifier (double pass)
In SBS cell pulse phase conjugated (phase distortions compensated)
ZigZag Nd:YAG amplifier (5mm X 25cm; 0.85%);
2 pump arrays 9kW peak power in 200µs pulses

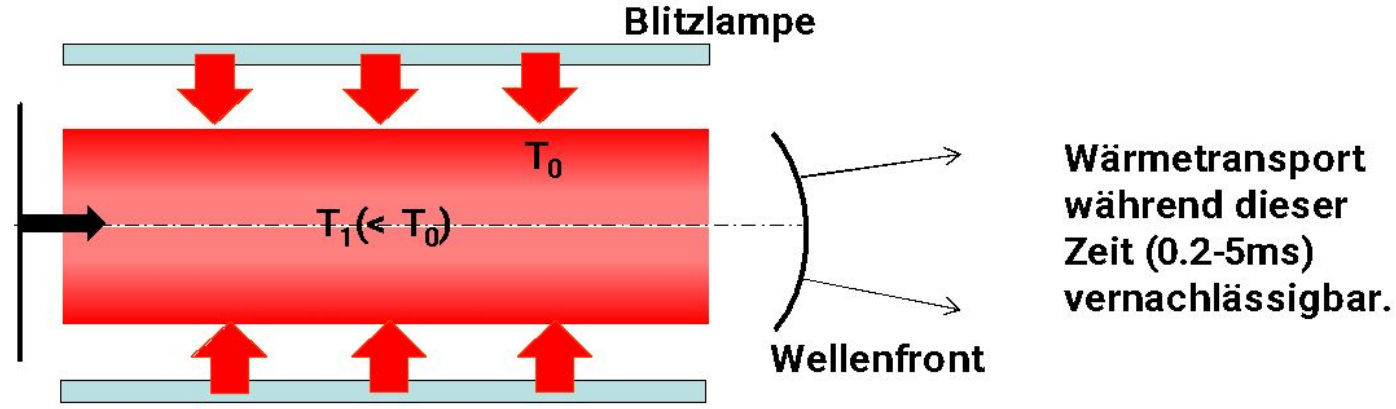
Other important effects

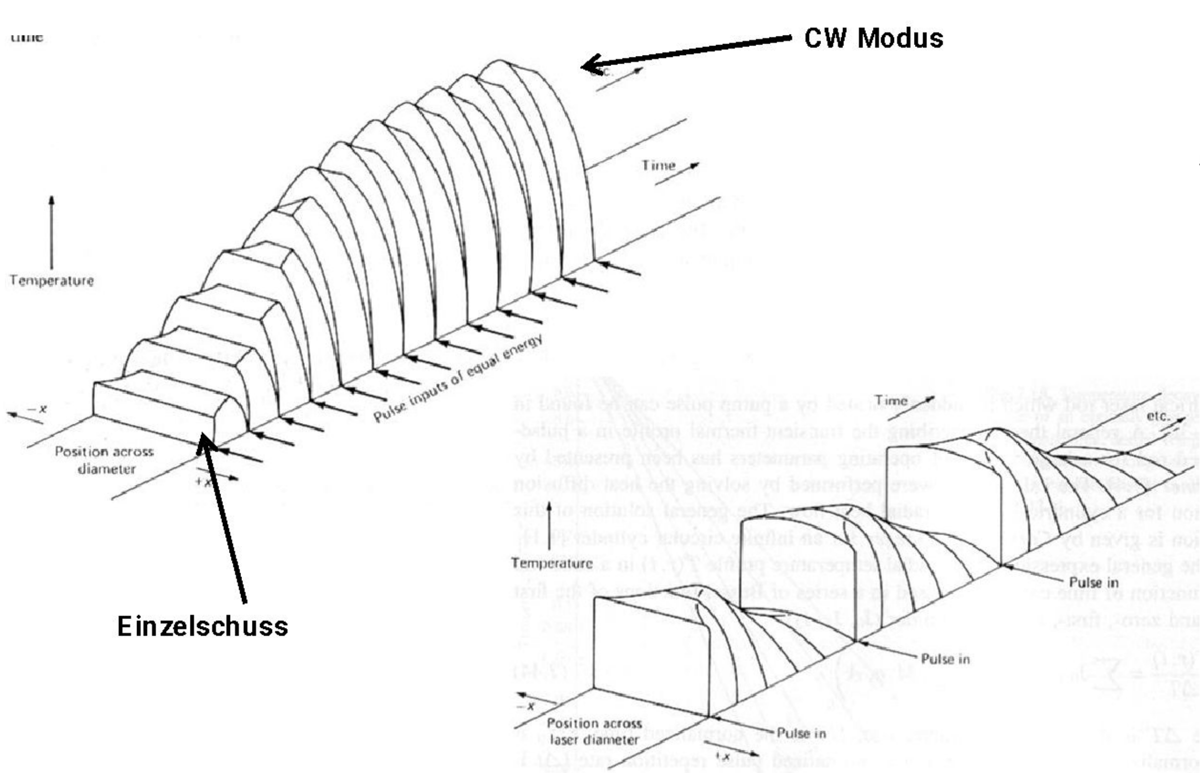
Heat management and thermal effects

In cw mode: converging lens effect if [illegible]/[illegible] > 0



- **In pulsed mode: diverging lens effect if [illegible]/[illegible] > 0**





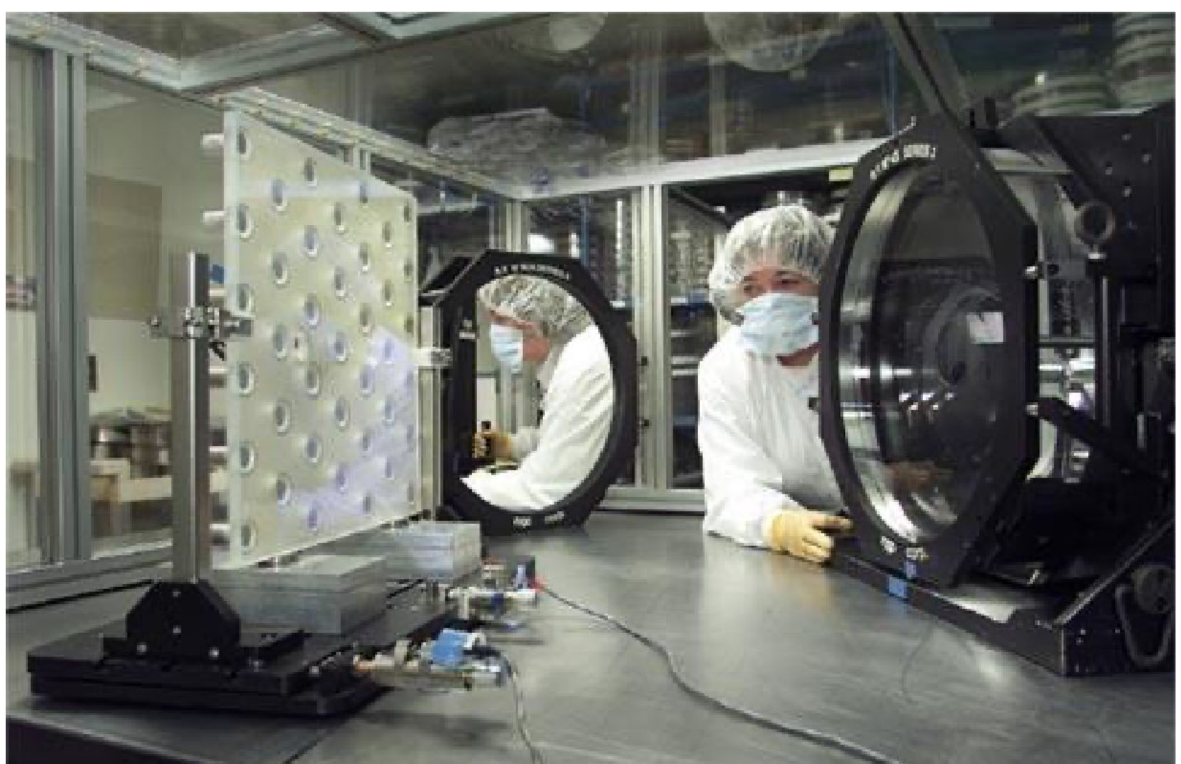
Other important effects

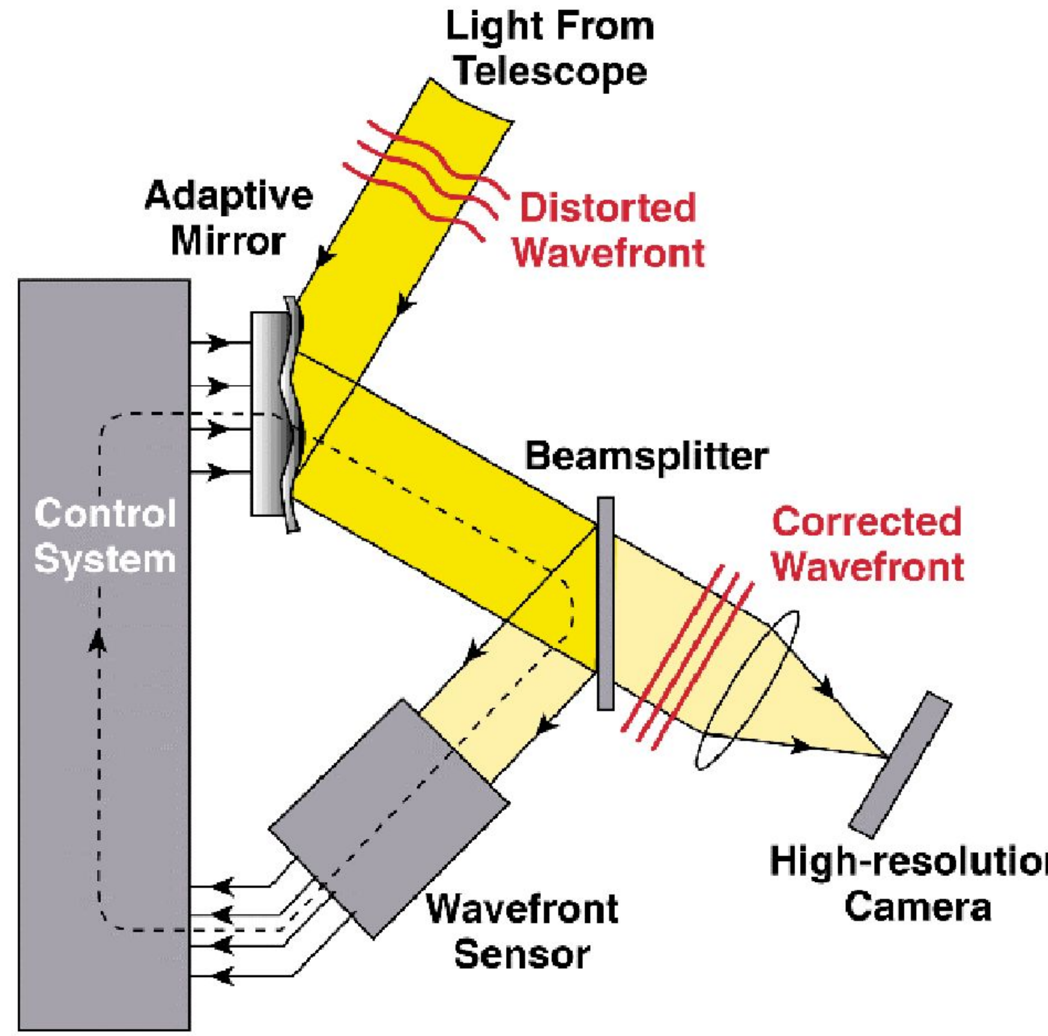
Wavefront distortions

•**A thin mirror can deformed by micro-actuators**

•**Deformable mirrors have been invented for SDI, astronomy and later biology**

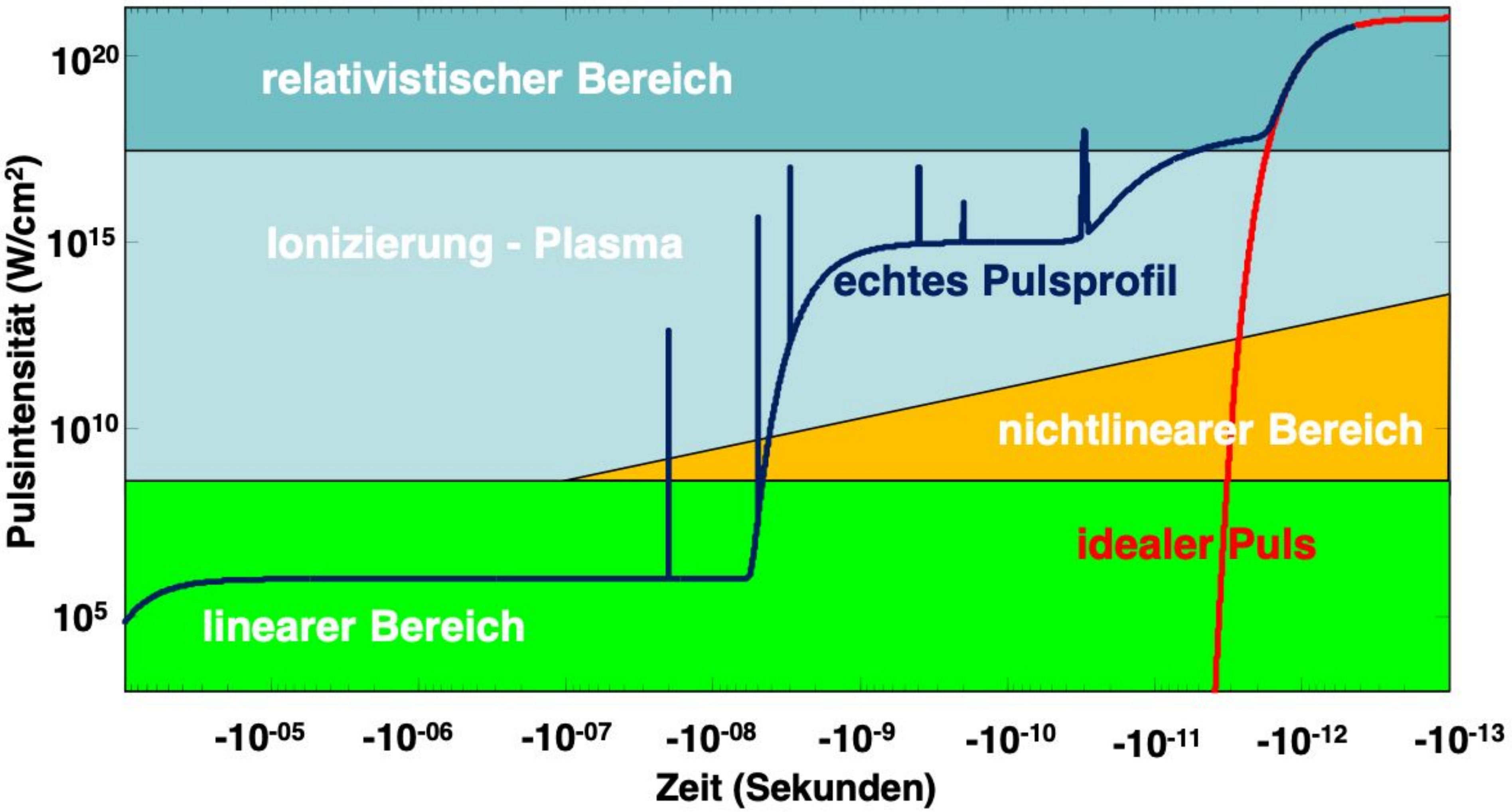
•**Deformable mirrors are used for the last 25 years in lasers successfully**





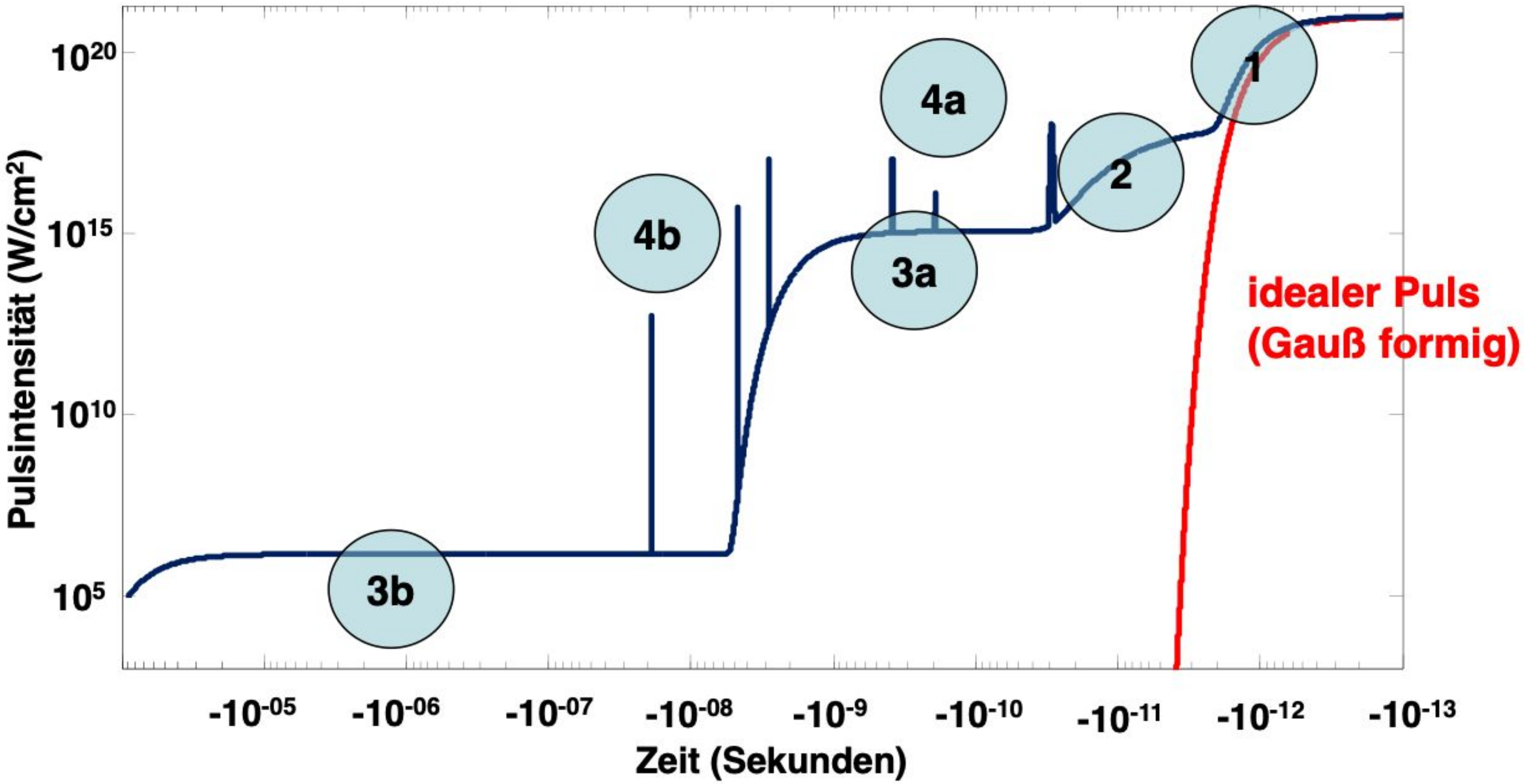
Temporal contrast

The interaction of a laser pulse with the target can start way before the arrival of the main pulse die

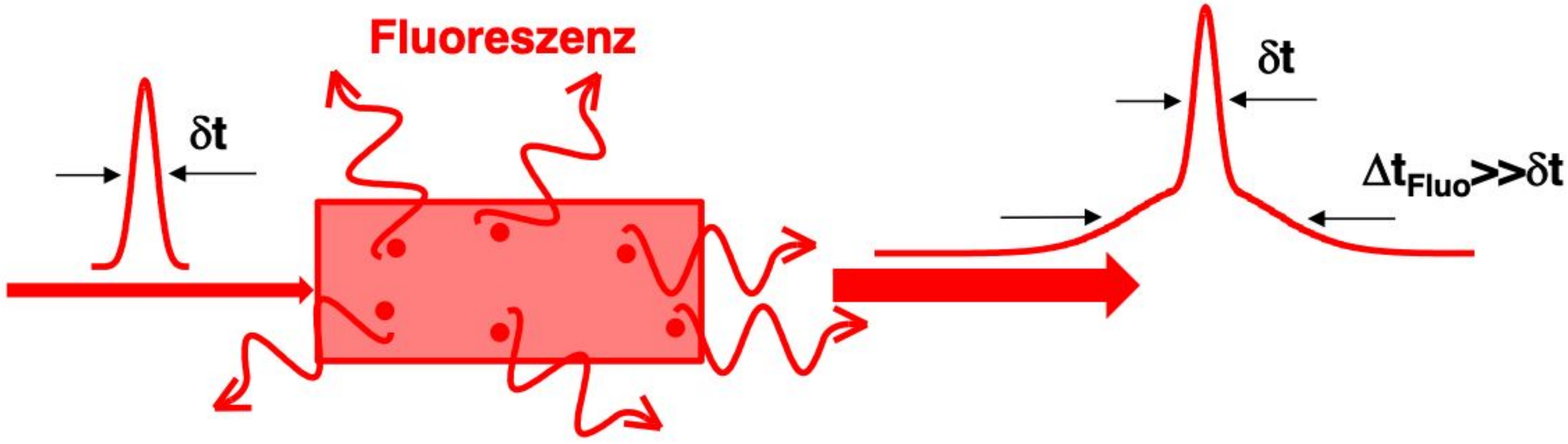


Topology of a laser pulse

1. **Deviation of ideal temporal shape (spectral phase)**
2. **Coherent contrast (origin not quite clear, maybe surface roughness)**
3. **ASE in preamplifiers (3a) and main amplifier (3b)**
4. **Pre pulses in ps range (4a) and nanoseceond range (4b)**



Limited contrast is of multiple origin



ASE: Amplified Spontaneous Emission

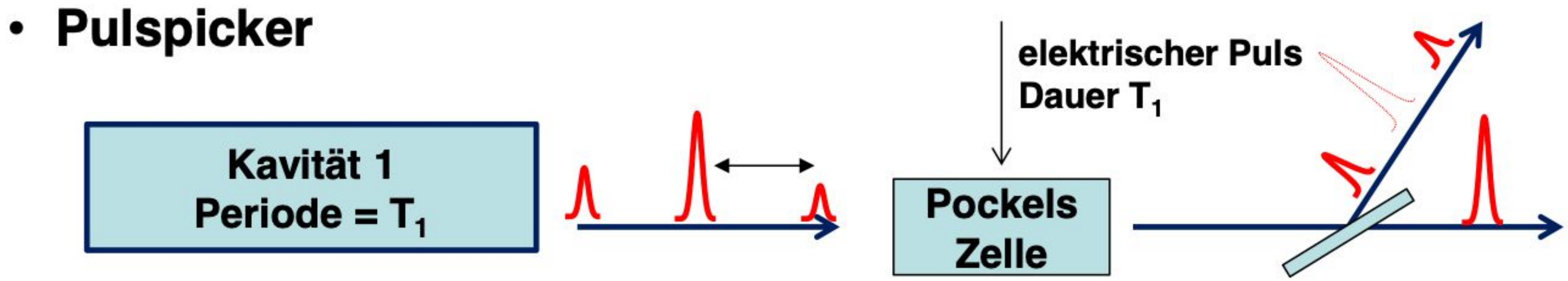
$$\frac{A}{B} \propto \omega^3$$

Improvement on pre pulse contrast

•Pulse picker (Pockels Cell)

•Dependend on TFP efficiency is 10^{-2} to 10^{-4}

•Time to switch up to 0.1 ns



Improvement for CPA systems

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In CPA systems pulse picker cannot be used below a nanosecond
stretched pulse and ASE overlap

Solution:
Pulse is amplified in a first stage, compressed, cleaned
and stretched again
Double CPA concept
cleaning by non-linear effects

XPW (Kerr-effectt based tilt of polarization)
saturable absorbers

PHELIX Laser

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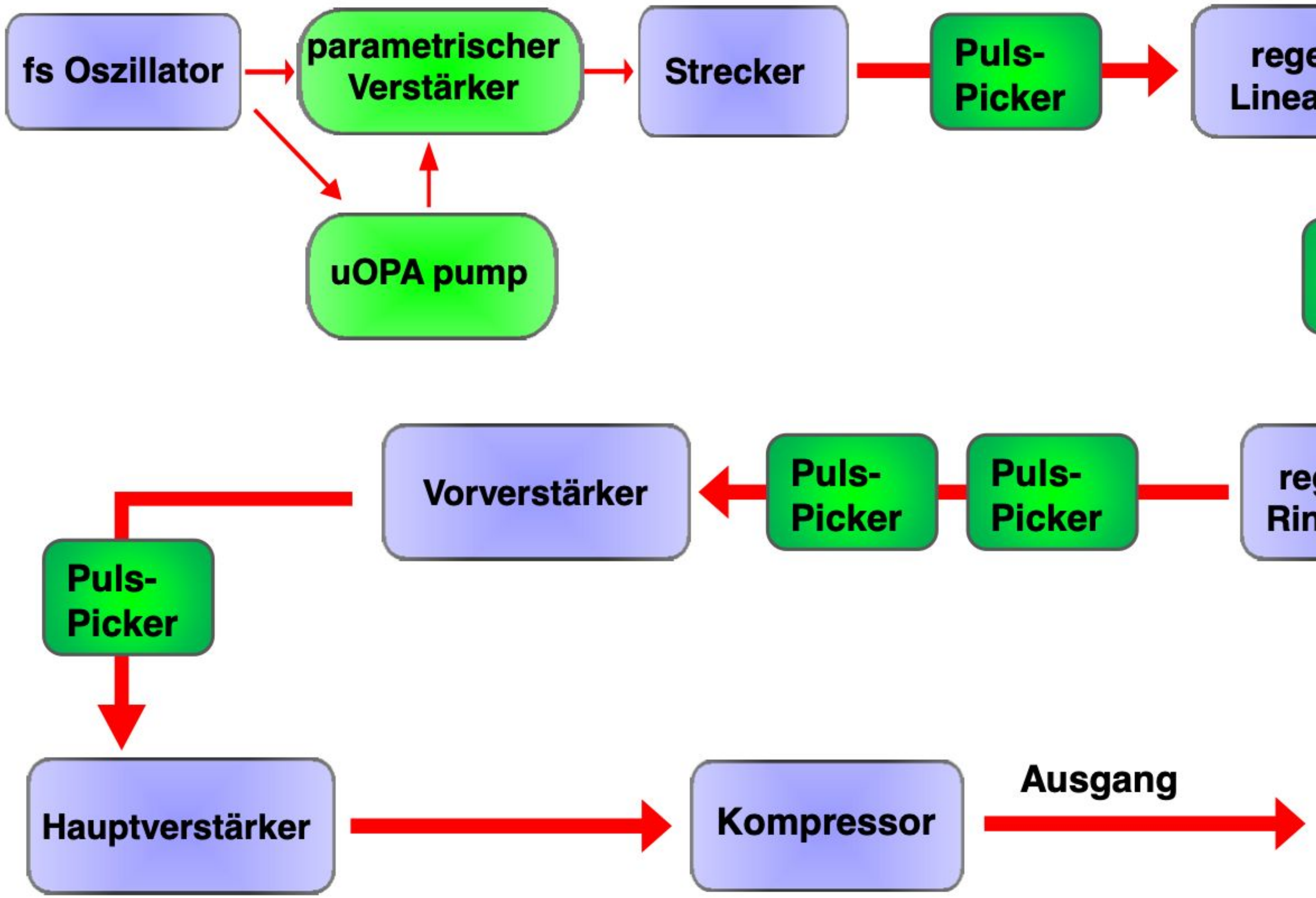

end