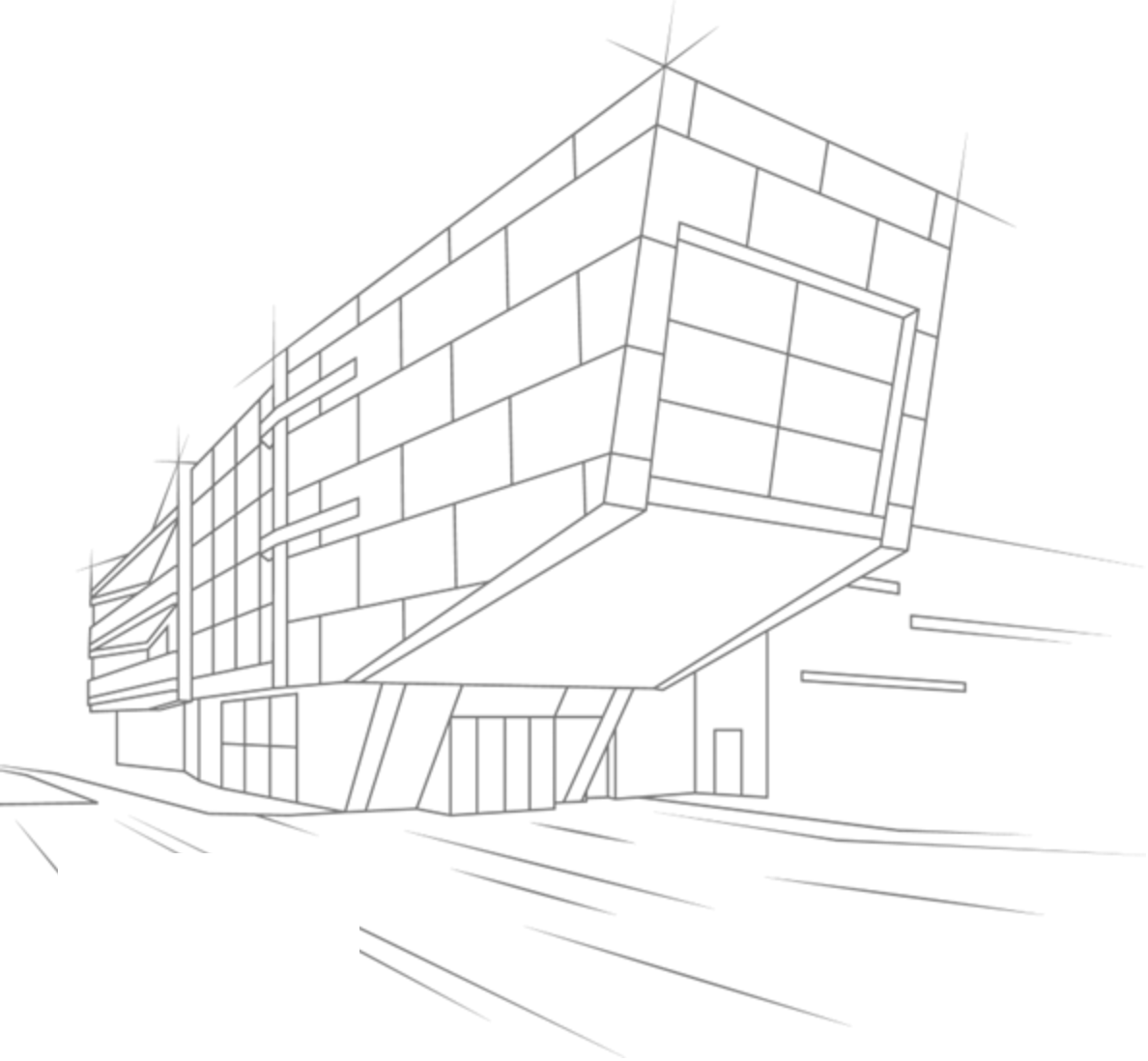
LASER TRAINING CENTRE

hilase



Introduction to cryogenically cooled multi slab lasers (Bivoj, Kazi)

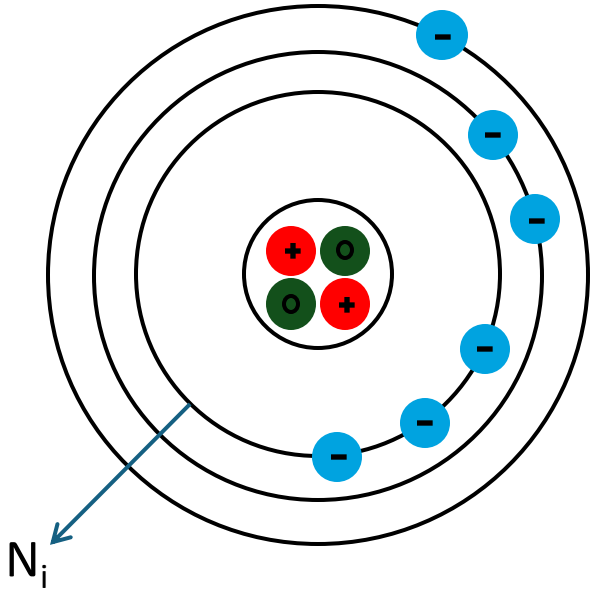
Martin Divoky

Outline

- Amplifier basics
  - Energy levels, storage and extraction efficiency
- Material selection
  - Pumping, lifetime, cross-sections
- Numerical modeling
  - Energy storage, heat load
- Bivoj / DiPOLE100
- KAZI / DiPOLE100Hz

Boltzmann distribution

Energy levels are thermally populated



Increase in the energy of the level

E_2 ——— N_2, g_2

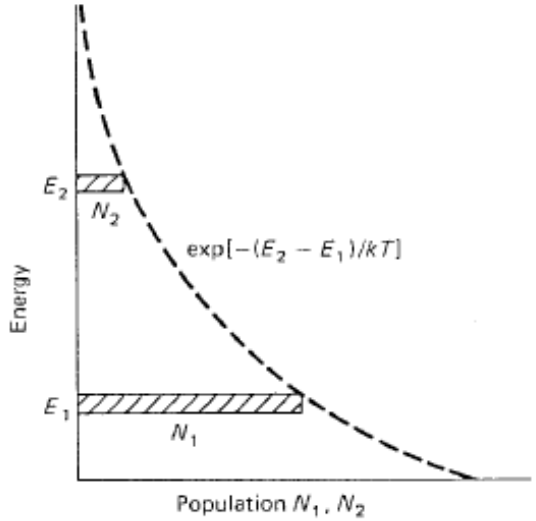
E_1 ——— N_1, g_1

E_i … energy level

N_i … population of the level

g_i … degeneration of the level

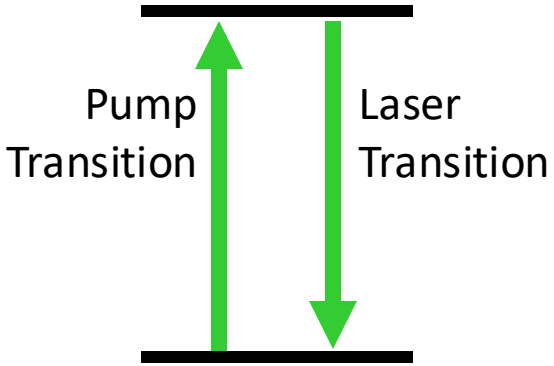
$$\frac{N_2}{N_1} = \frac{g_2}{g_1} e^{\left(-\frac{E_2 - E_1}{kT}\right)}$$



$$N_{tot} = N_1 + N_2$$

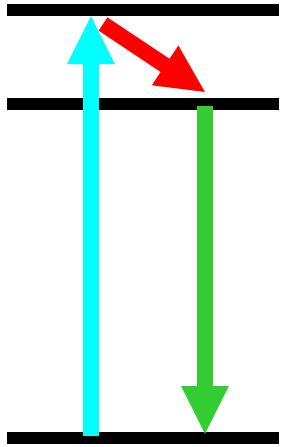
Types of gain media

Two-level system



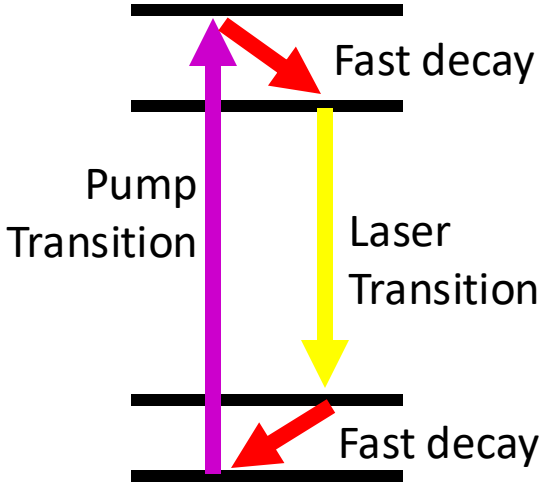
Population equilibrium. No lasing.

Three-level system



Lasing is possible

Four-level system

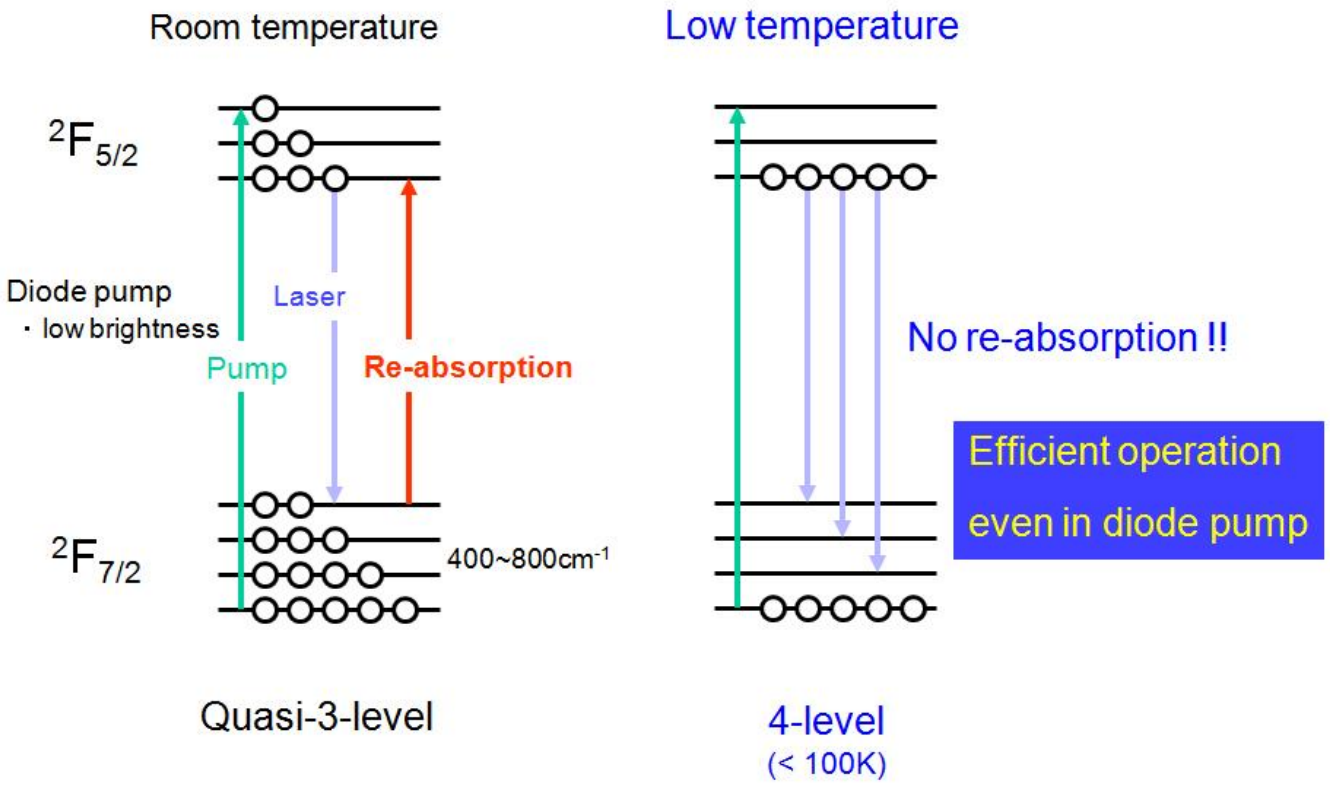


Lasing is easy!

Why do some people cool 3 level systems to cryogenic temperatures?

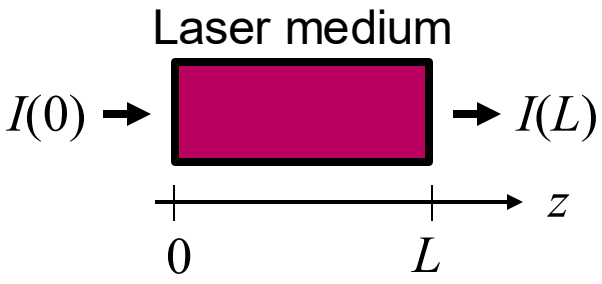
Cryogenic cooling of 3-lvl Yb:YAG makes it 4-lvl system

- less absorption
- energy extraction efficiency



* Kawanaka, HEC-DPSSL 2012

Gain



$$I(z) = I(0)\exp(\sigma \Delta N z) \qquad g = \sigma \Delta N$$

$$\Delta N = N_2 - N_1$$

Extraction efficiency – how much energy is extracted

$$\eta_{extr} = \frac{\phi_{stored_init} - \phi_{stored_\mathrm{final}}}{\phi_{stored_init}} = \frac{G_{init} - G_{final}}{G_{init}}$$

Amplified spontaneous emission

Not only the seed beam is amplified, but also all the spontaneous emission

Population inversion in the active medium:

$$\frac{dn}{dt} = \boxed{\left.\frac{dn}{dt}\right|_{P}} - \boxed{\left.\frac{dn}{dt}\right|_{SE}} - \boxed{\left.\frac{dn}{dt}\right|_{ASE}}$$

Pump

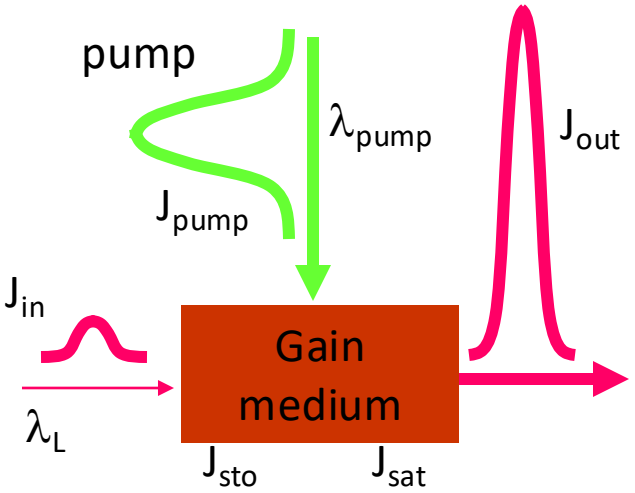
Spontaneous Emission

Amplified Spontaneous Emission

Energy of amplified photons changes with:

$$dJ = J(g_0 - \alpha)dl$$

Gain saturation



$\boldsymbol{J}$ ... Energy density

J_{sto}= stored energy density = J_{pump} (λ_{pump}/λ_L)
J_{sat}= saturation energy density

For low intensities is gain linear:

$$\frac{dJ}{dz} = g_0 J \qquad \left(g_0 L = \frac{J_{sto}}{J_{sat}} > 0 \right)$$

For high intensities is gain constant:

$$\frac{dJ}{dz} = g_0 J_{sat}$$

Real case is in between:

$$\frac{dJ}{dz} = g_0 J_{sat} \left(1 - e^{-J/J_{sat}} \right)$$

Frantz-Nodvik equation

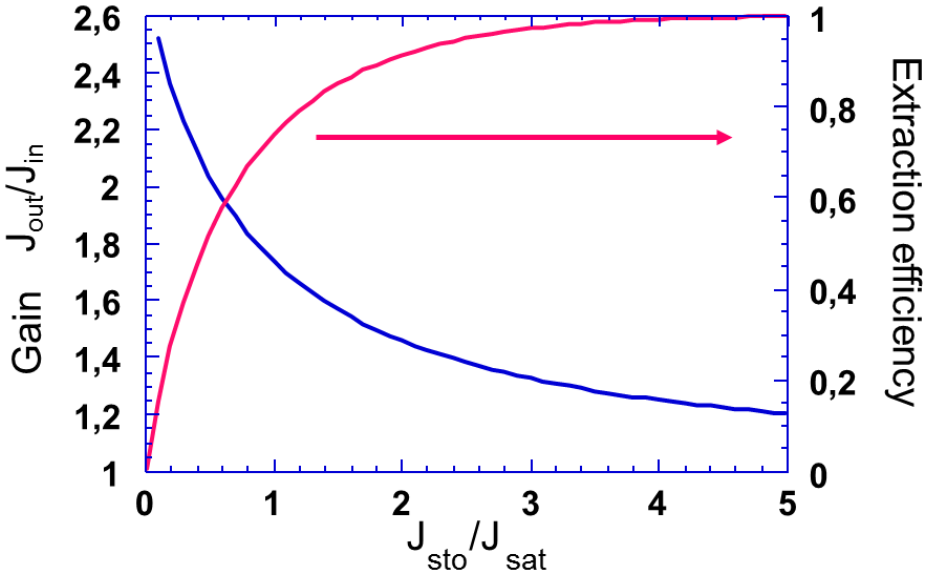
Last equation can be solved for square pulse as Frantz-Nodvik formula (4 lvl system)

$$J_{out} = J_{sat} \ln\left\{ G_0 \left[\exp\left(\frac{J_{in}}{J_{sat}} \right) - 1 \right] + 1 \right\}$$

Small signal gain:

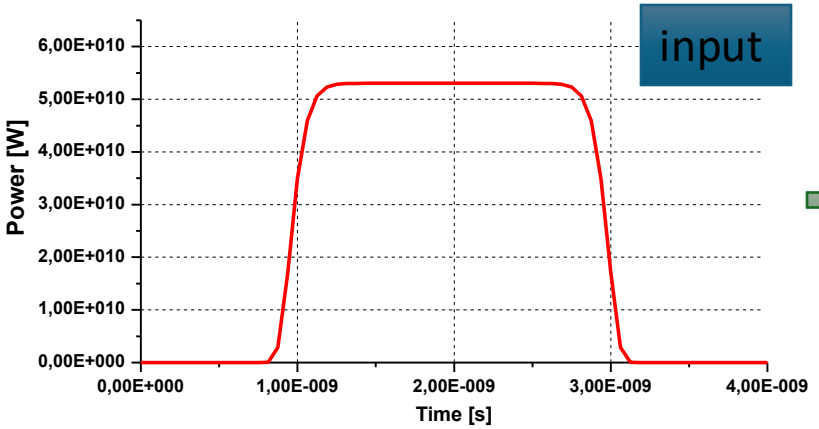
$$G_0 = \exp(g_0 L) = \exp\left(\frac{J_{sto}}{J_{sat}}\right)$$

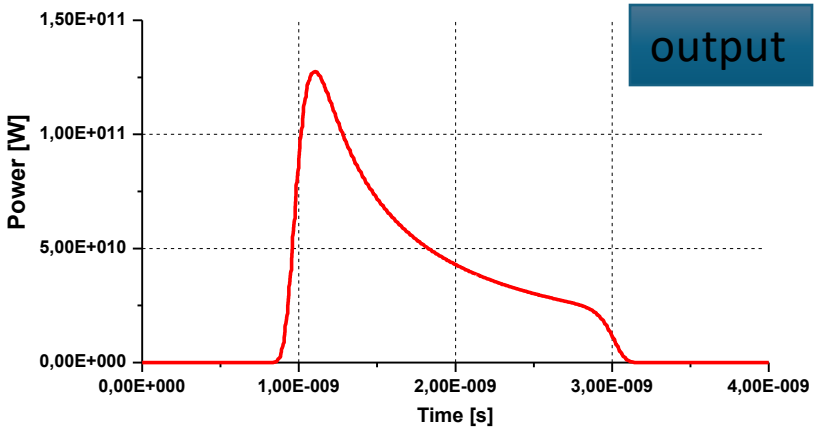
High gain or high extraction efficiency, not both



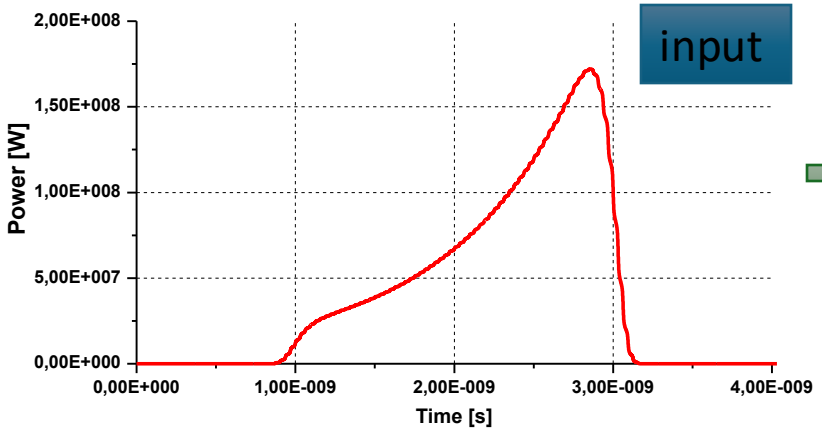
Pulse deformation by gain saturation (gain depletion)

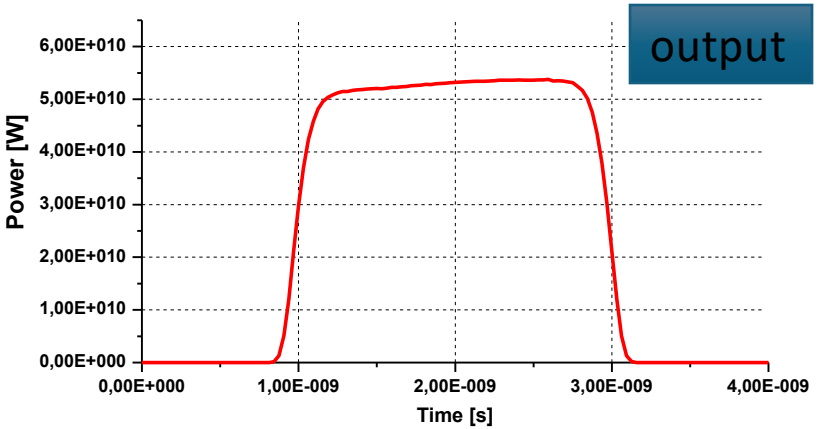
Front of the pulse experiences higher gain





This can be compensated by tailoring pulse shape

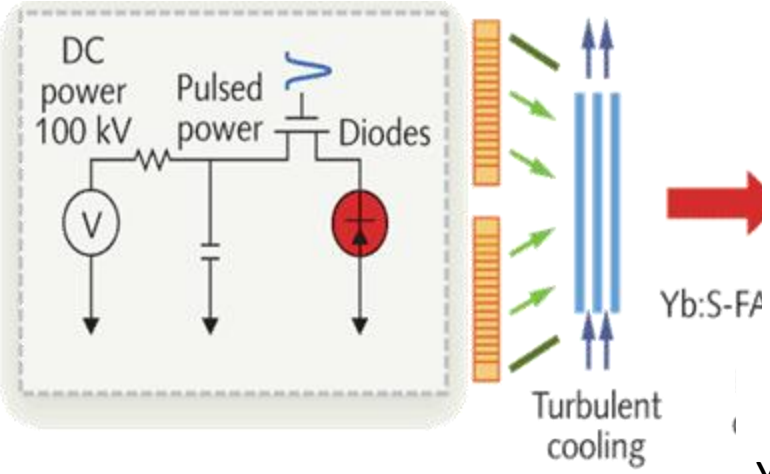


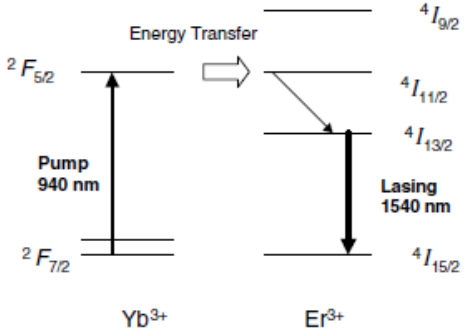


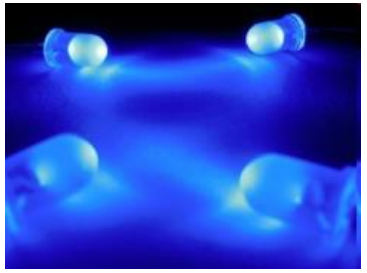
Diode pumping

Diodes

- whole spectrum usable
- low heating
- small emitting area
- expensive
- long pulse

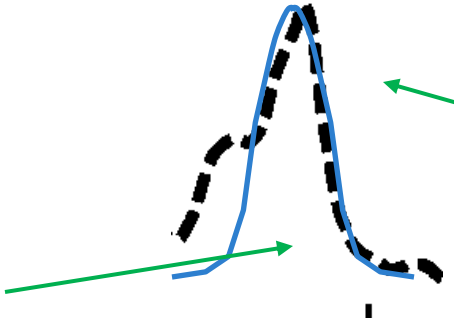




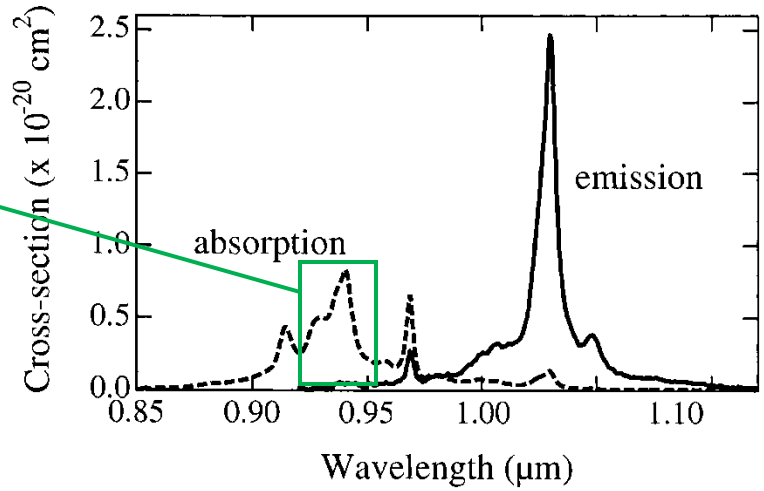


Usable radiation

Spectrum



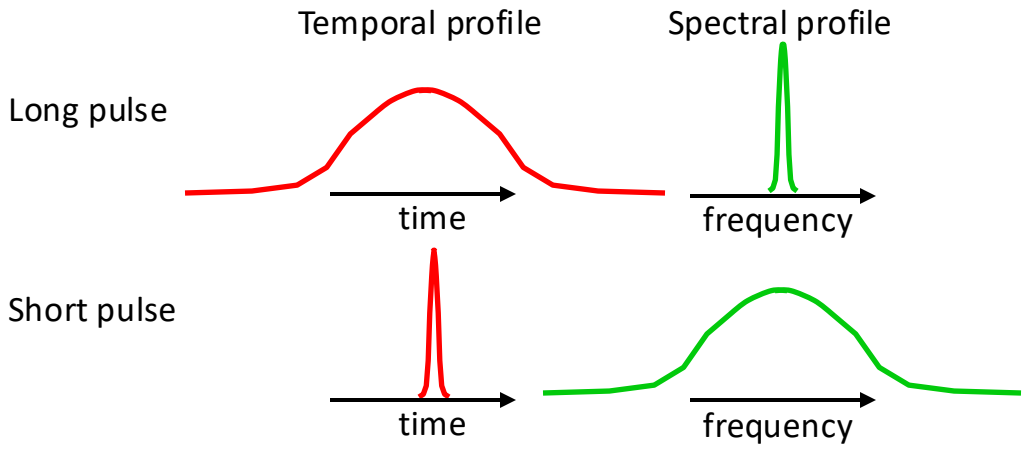
Yb:YAG

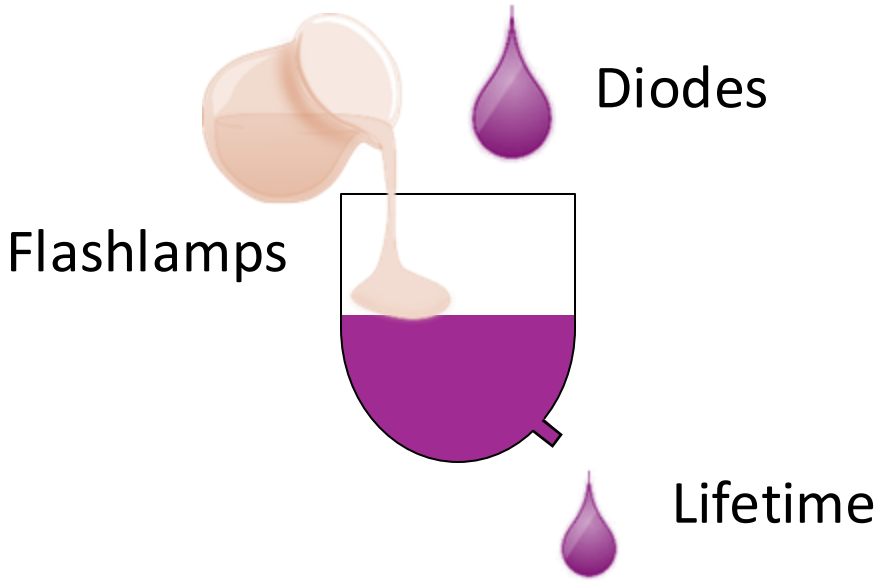


Bandwidth and lifetime

- Broader bandwidth supports shorter pulses
- Longer fluorescence lifetime allows pump diodes to pump longer

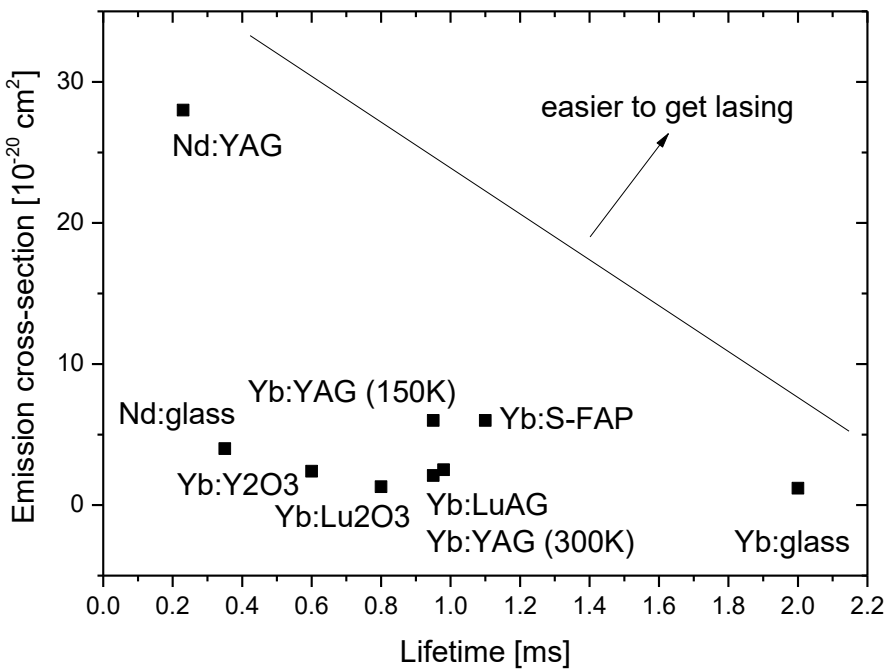
Gain medium	Laser wavelength [nm]	Emission bandwidth [nm]	Fluorescence lifetime [µs]
Nd:YAG	1064.1	0.45	230
Yb:YAG	1030	6	960
Ti:Al_2O_3	600 - 1100	320	3
Yb:S-FAP	1047	4	1100
Yb:CaF_2	1033	8	2400
Nd:glass	1054	28	300
Yb:Lu_2O_3	1032	13	820
Yb:LuAG	1031	7.5	1250
Cr:LiSAF	800 - 1050	257	67
Ho:YAG	2098	0.65	8500

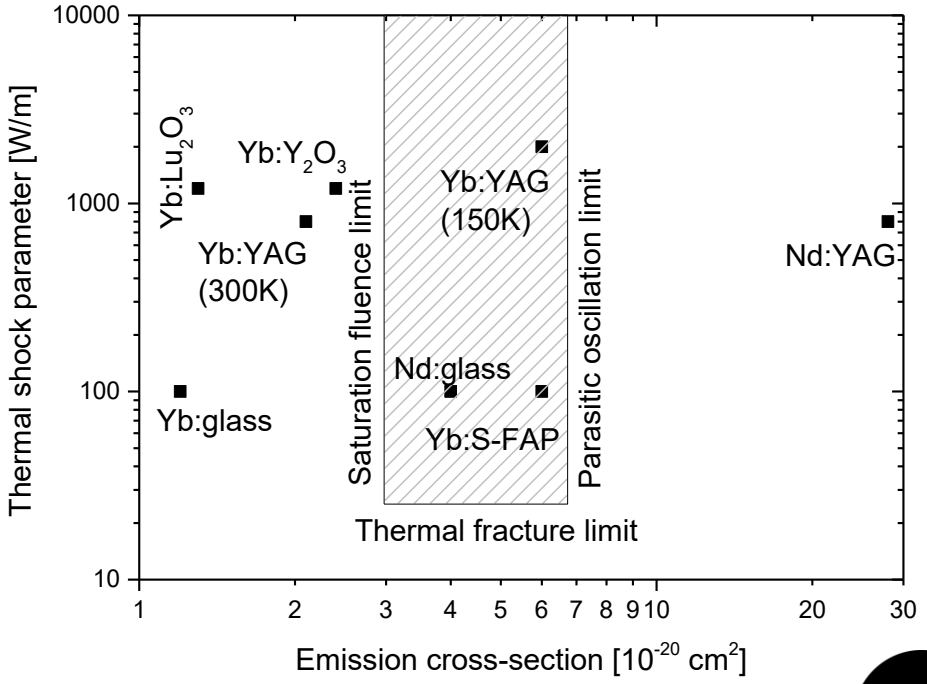




Lasing conditions

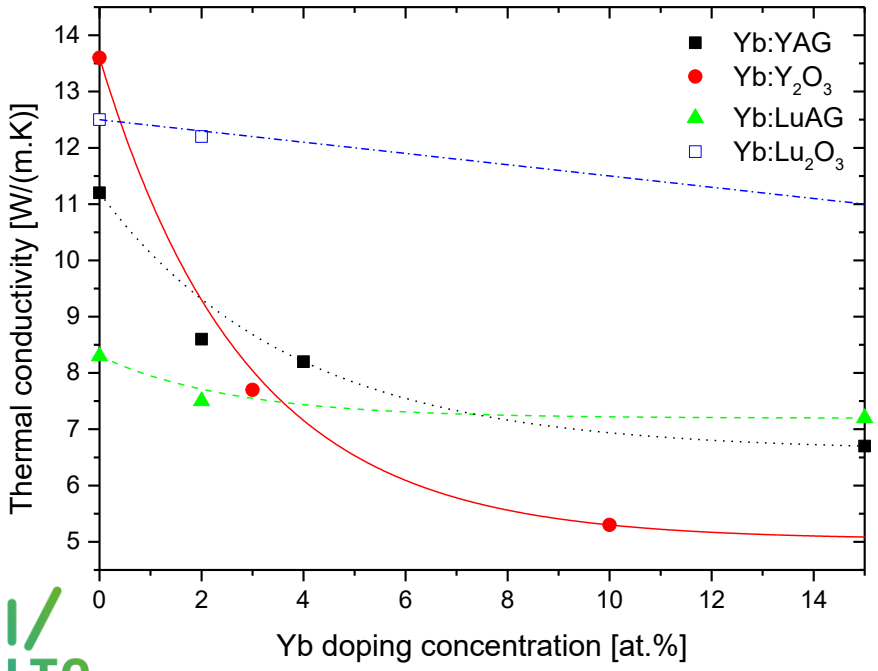
- Higher gain, but ASE
- Lower gain, but saturation fluence

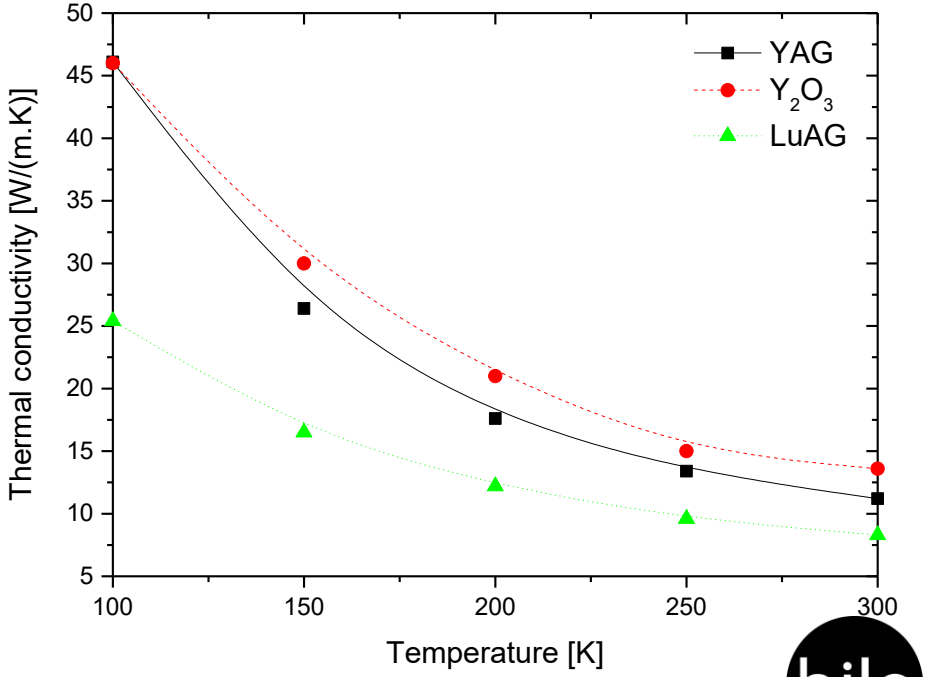




Thermal conductivity

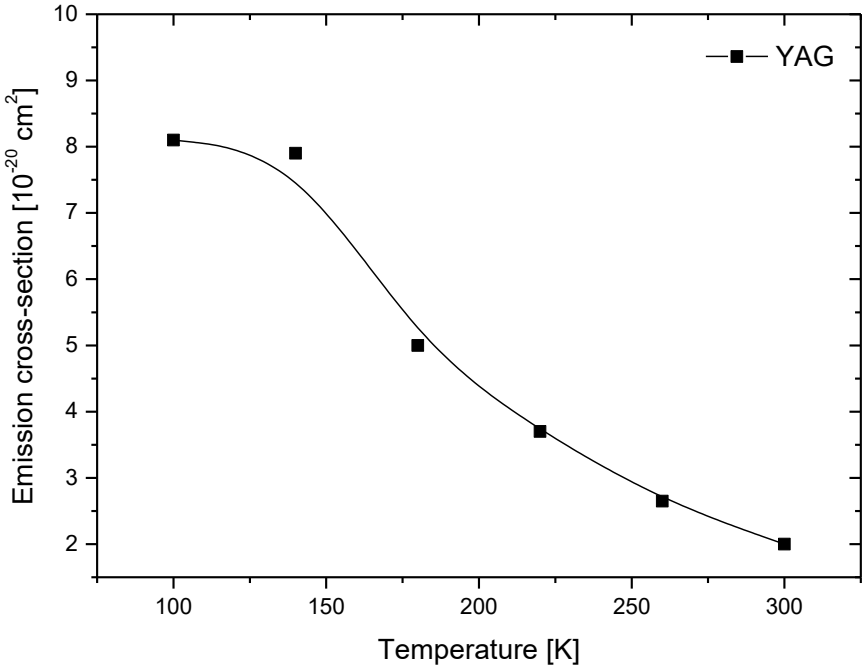
- Gain influenced by doping, but thermal conductivity
- Thermal conductivity and temperature



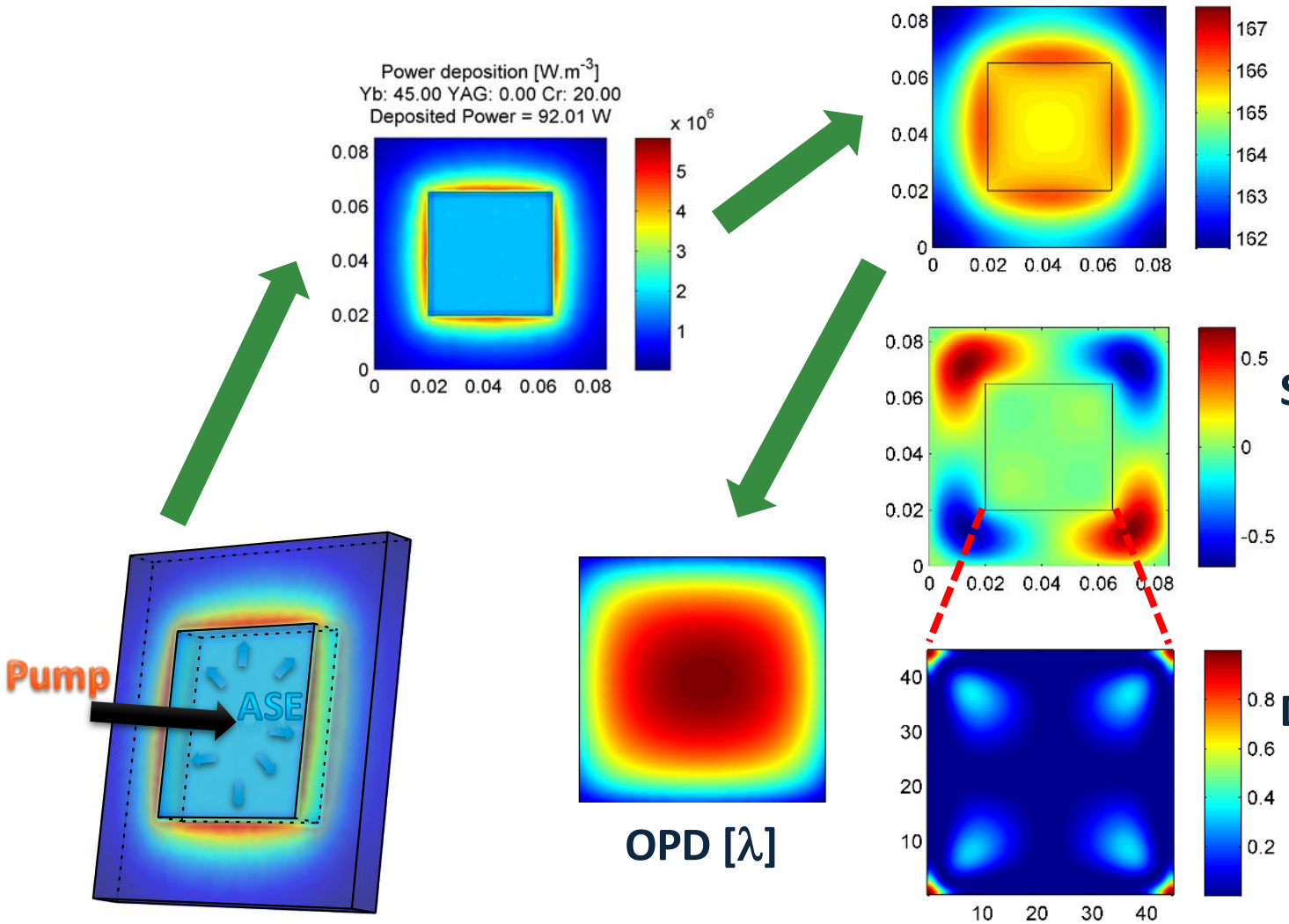


Thermal effects

- Emission cross section, 3 level system



Numerical modeling



Temperature [K]
FEM

Stress-strain [MPa]
FEM

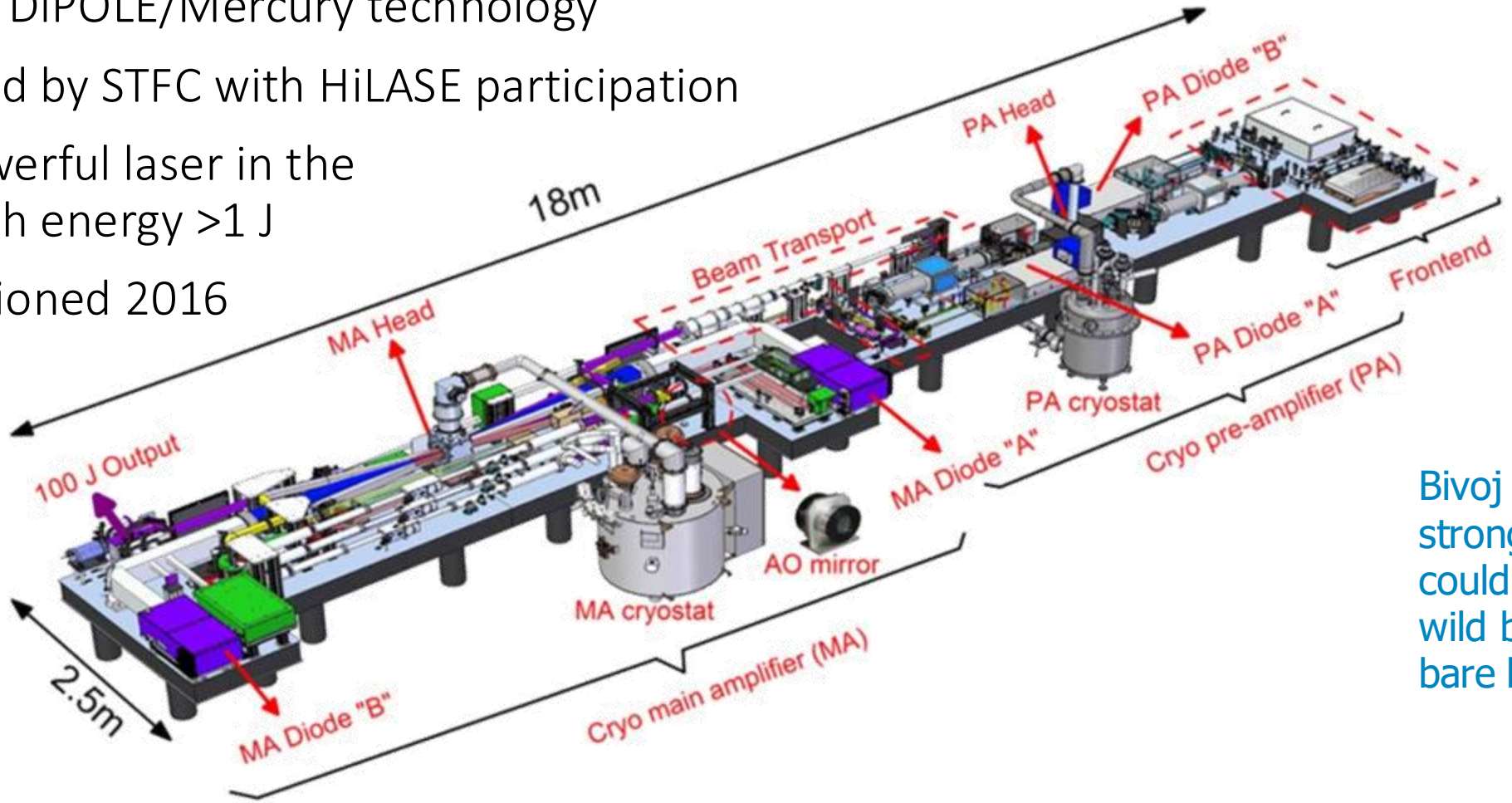
Depolarization loss
(after 64 passes)
Jones matrices

K(T) and *α(T)* from Brown (IEEE J. QE. **33**,861 (1997)), Aggarwal (J. App. Phys. 98, 103514 (2005))

Bivoj laser

Bivoj laser

- Bivoj system – DPSSL – 150 J, 10 Hz, 2-14 ns
  square flat top beam, shaped pulses, multi-slab
- Based on DiPOLE/Mercury technology
- Developed by STFC with HiLASE participation
- Most powerful laser in the world with energy >1 J
- Commissioned 2016



Bivoj was so strong that he could catch a wild boar with his bare hands

Front - end

1

Temporally-shaped fibre seed

- 1 nJ, 10 kHz, 1029.5 nm
- 2 to 14 ns, programmable < 200 ps steps

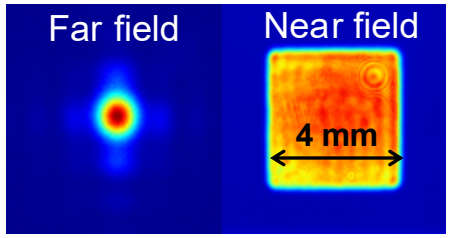
2

Regenerative amplifier

- Yb:CaF_2, 4.5 mJ, 10 Hz

3

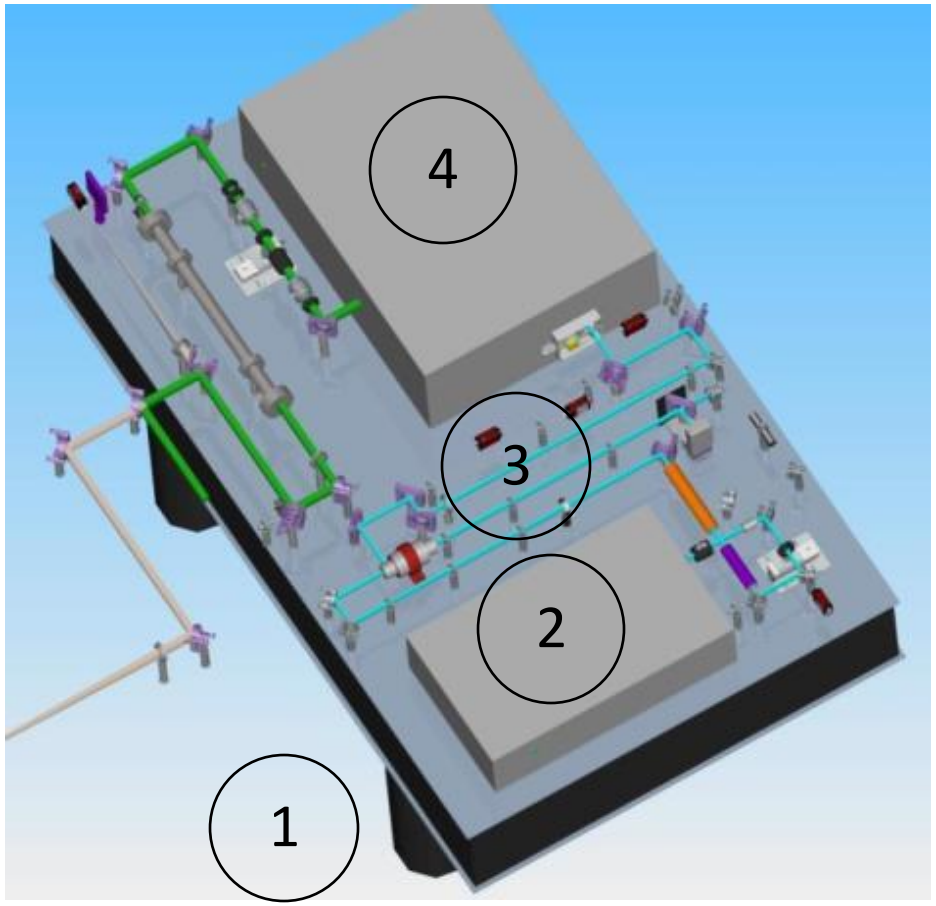
Spatial shaping



4

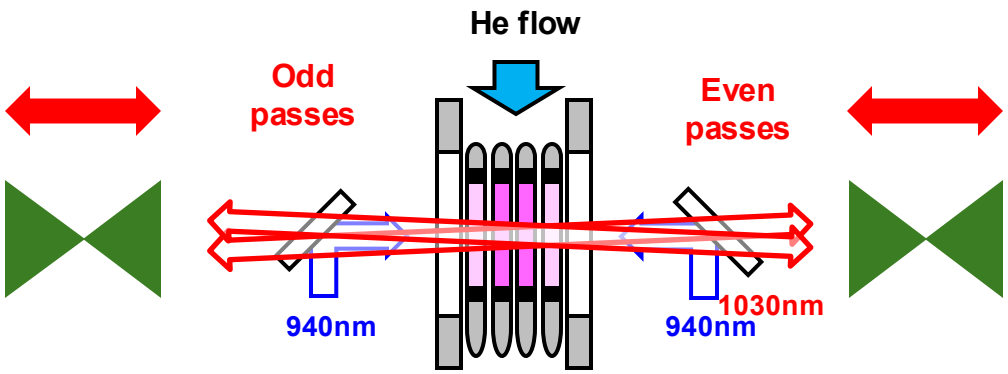
Multi-pass amplifier

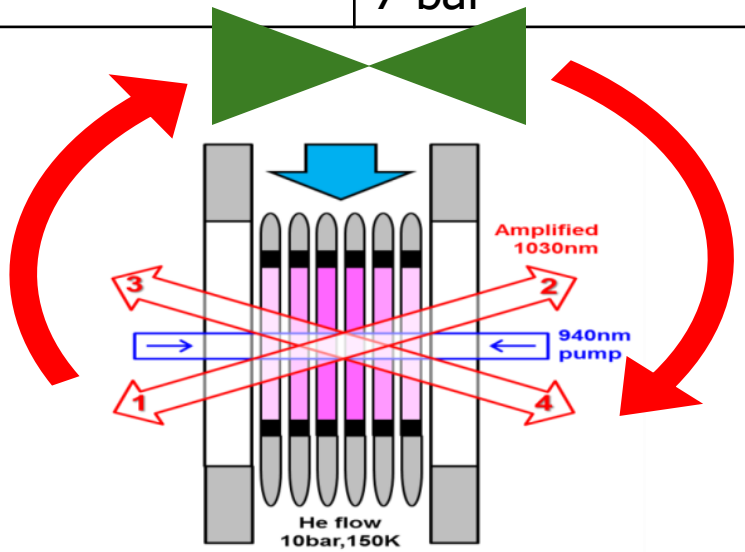
- Yb:YAG (crystal), 6 passes
- 1 mJ to 100 mJ, 10 Hz



Power amplifiers

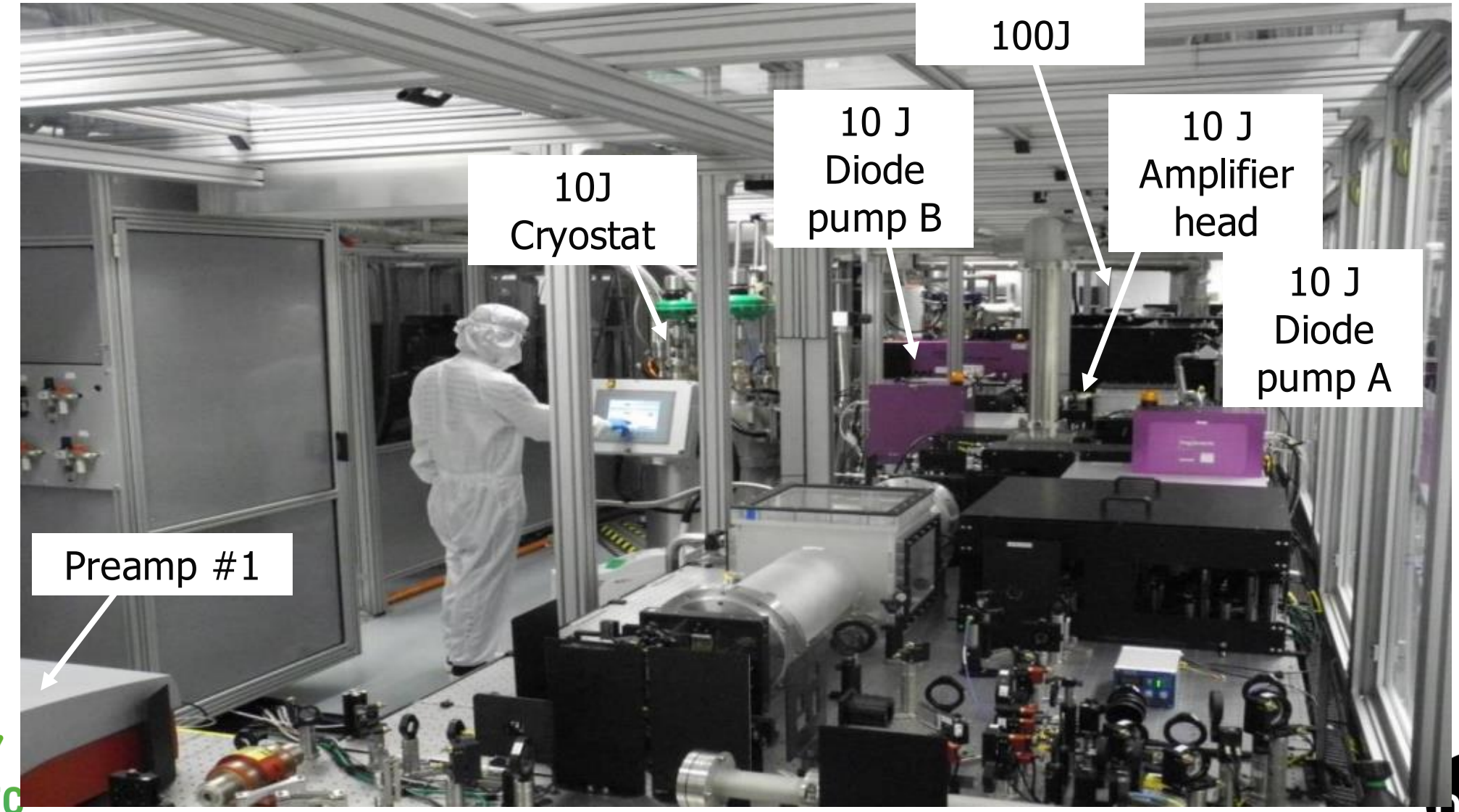
Properties	10 J preamplifier
Beam	20 x 20 mm^2
Yb:YAG Size	D45 mm x 5 mm
4 slabs	7 passes
Pump	60 kW, 1 ms, 10 Hz
Cooling	He, 150K, 16 g/s, 7 bar



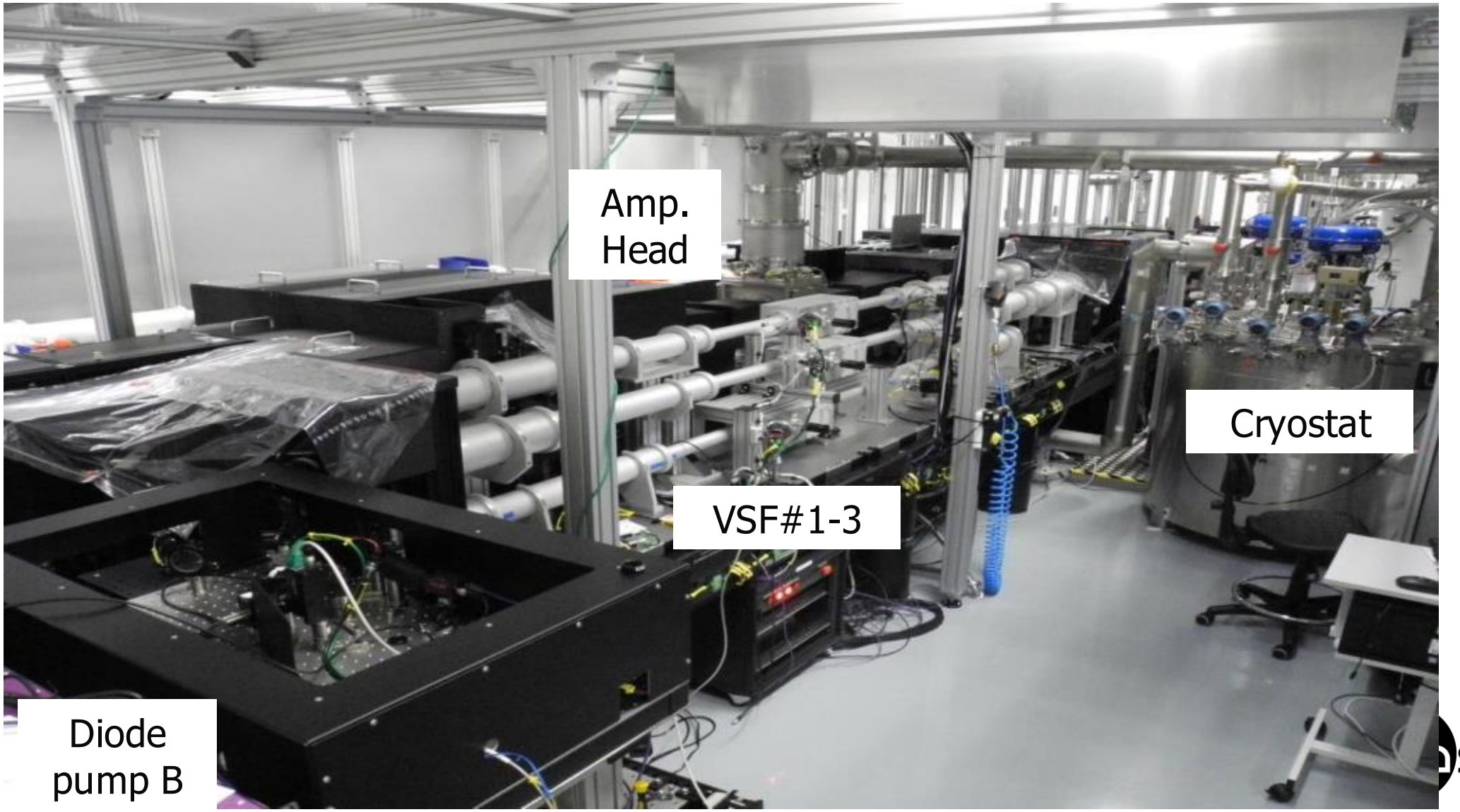


Properties	100 J preamplifier
Beam	75 x 75 mm^2
Yb:YAG Size	100 mm x 100 mm x 8.5 mm
6 slas	4 passes
Pump	500 kW, 1 ms, 10 Hz
Cooling	He, 150K, [illegible] g/s, 10 bar

Bivoj laser at HiLASE – 10 J

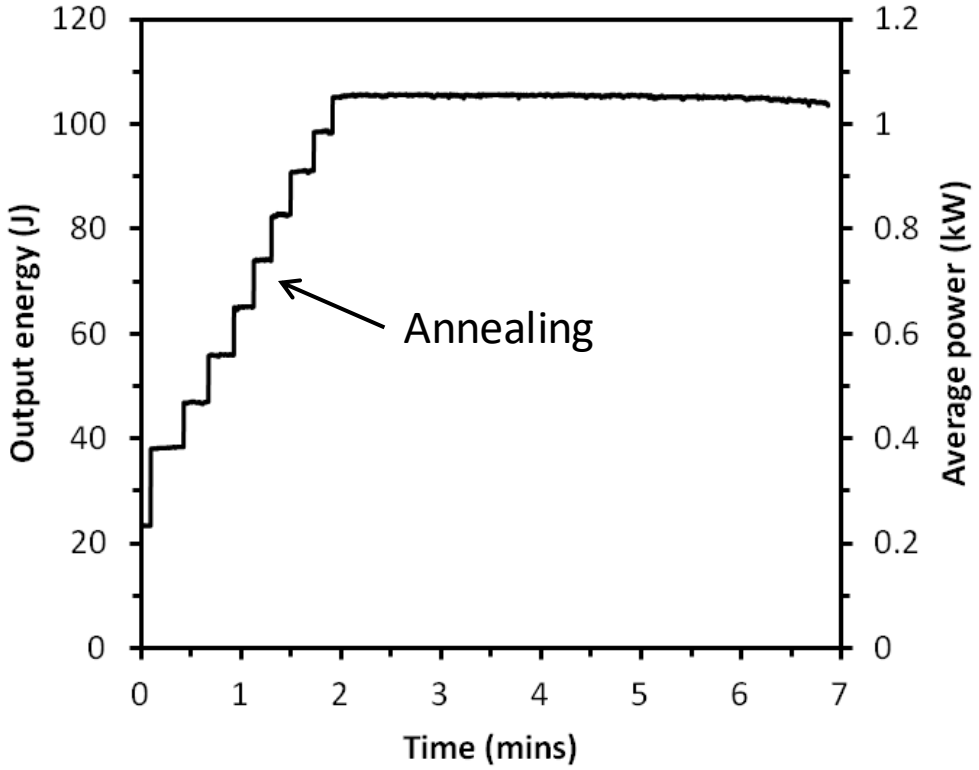


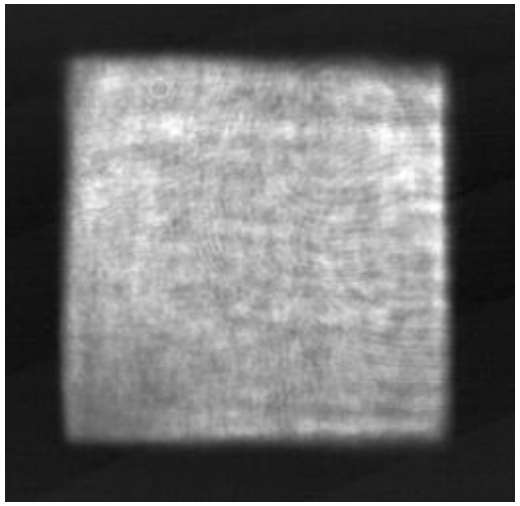
Bivoj laser at HiLASE – 100 J

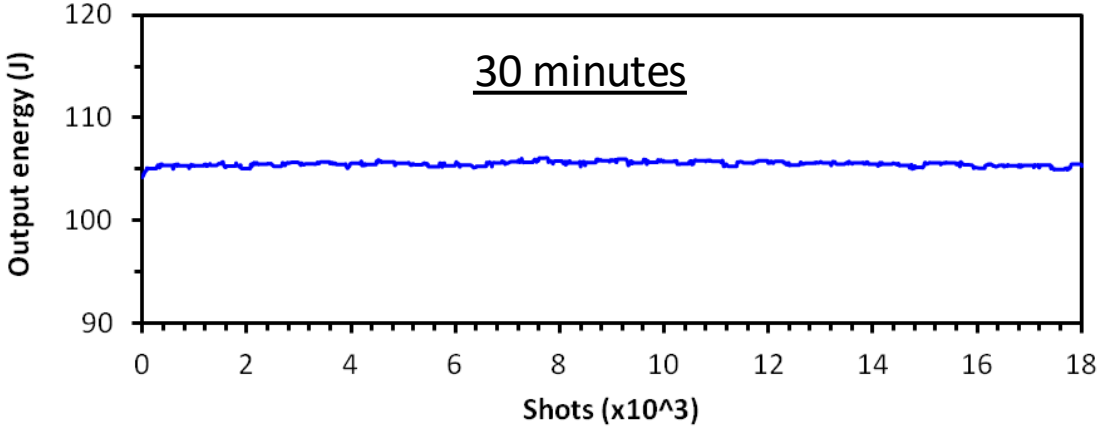


Bivoj record in 2016

- Bivoj system achieved 105 J @ 10 Hz for 6 J input
- Joint effort of STFC and HiLASE

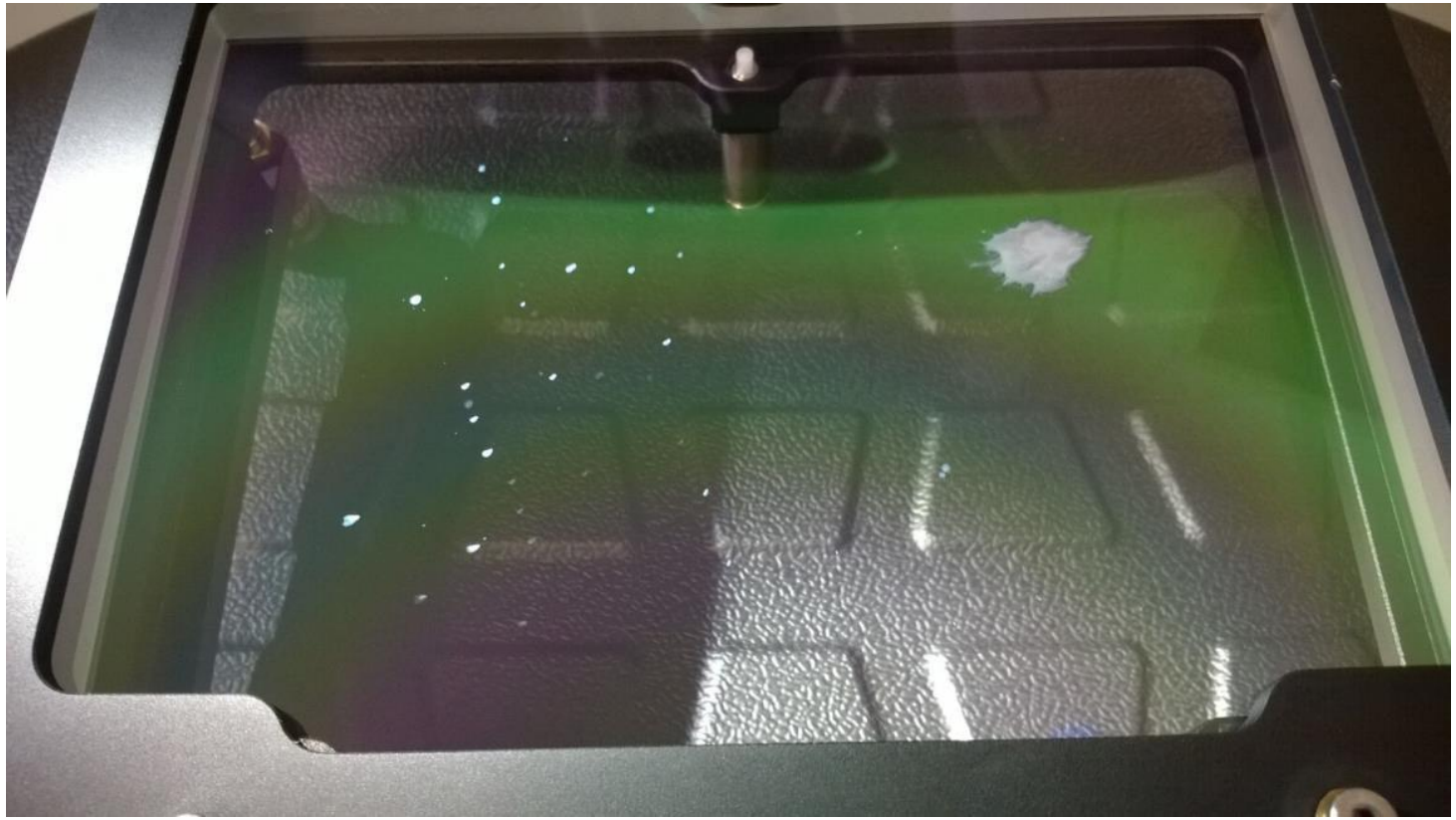






LIDT issues

- Optics rated to 20 J/cm^2 failed at 1.5 J/cm^2
- 1030 nm, 10 ns pulses, 10 Hz repetition rate

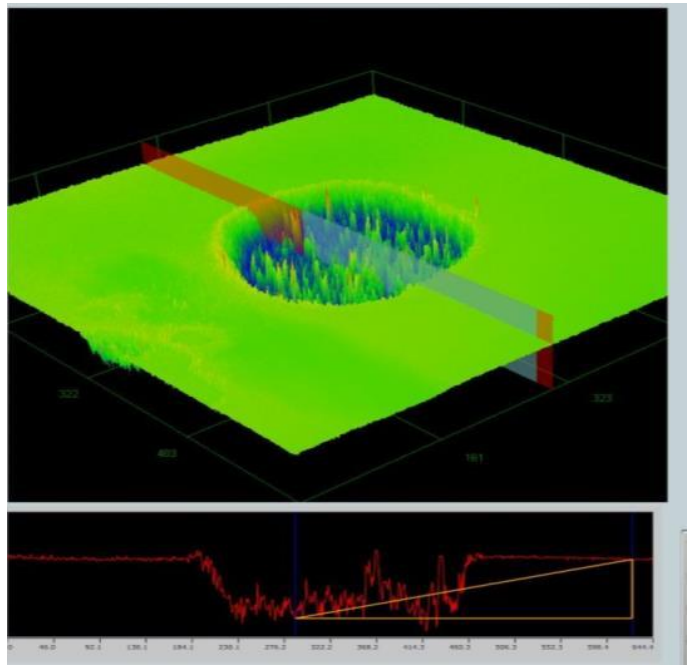


LIDT tests – size matters

- Tests of various optics at 1030 nm, 10 ns pulses, 10 Hz

- Sample 1 – 2”
- 1-on-1 22 J/cm2 (0.25 mm beam)
- 1000-on-1 13 J/cm2 (0.25 mm beam)
- Raster scan 7.5 J/cm2 (1 mm beam)
- Field test 3.1 J/cm2 (10 mm beam)

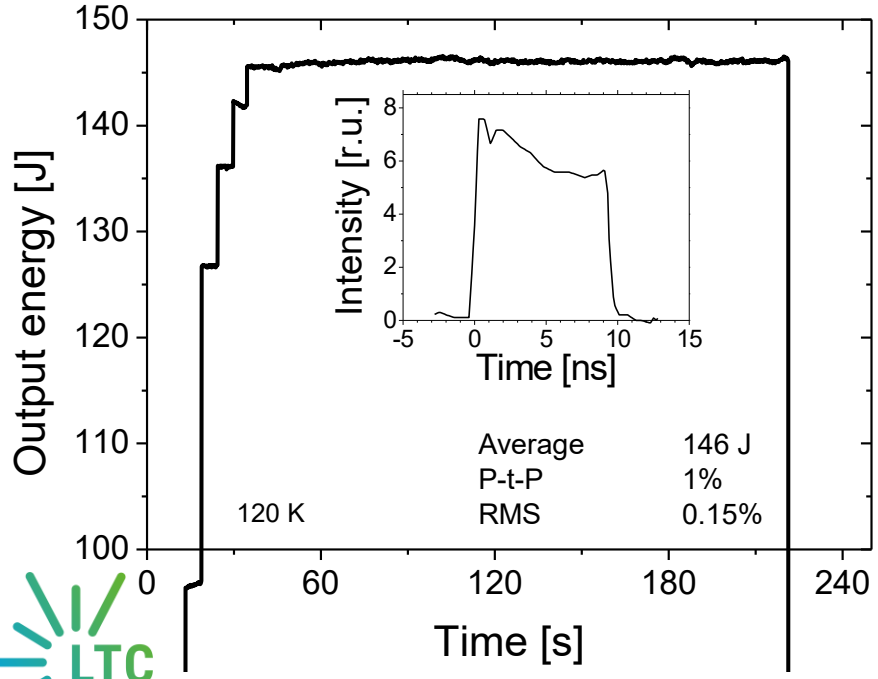
- Sample 2 – 6”
- Field test 3.1 J/cm2 (10 mm beam)
- Field test 1.4 J/cm2 (75 mm beam)

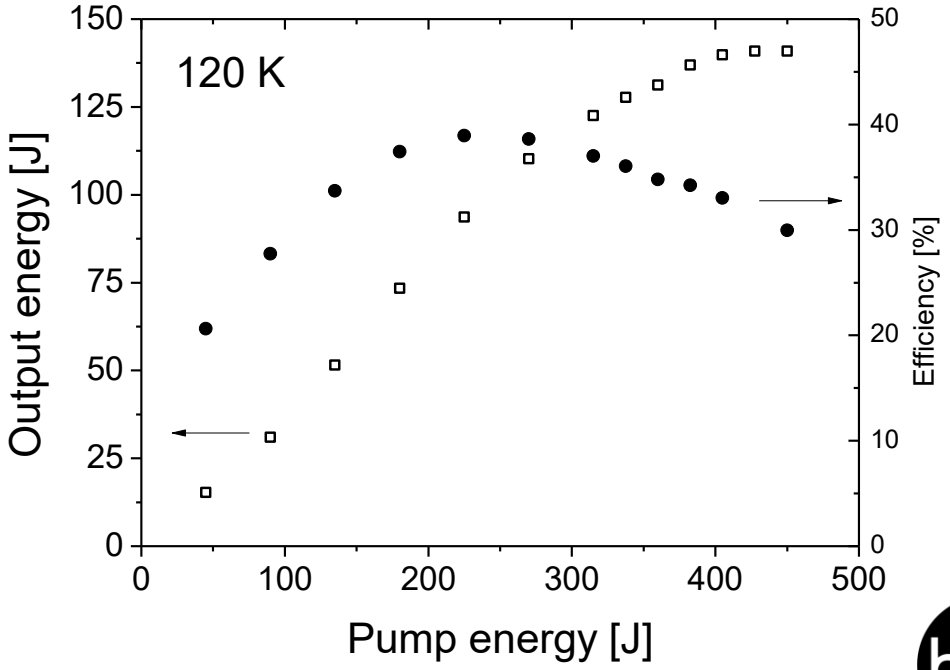


LIDT of large samples depends more on surface preparation then on coatings

146 J @ 10 Hz in 2021

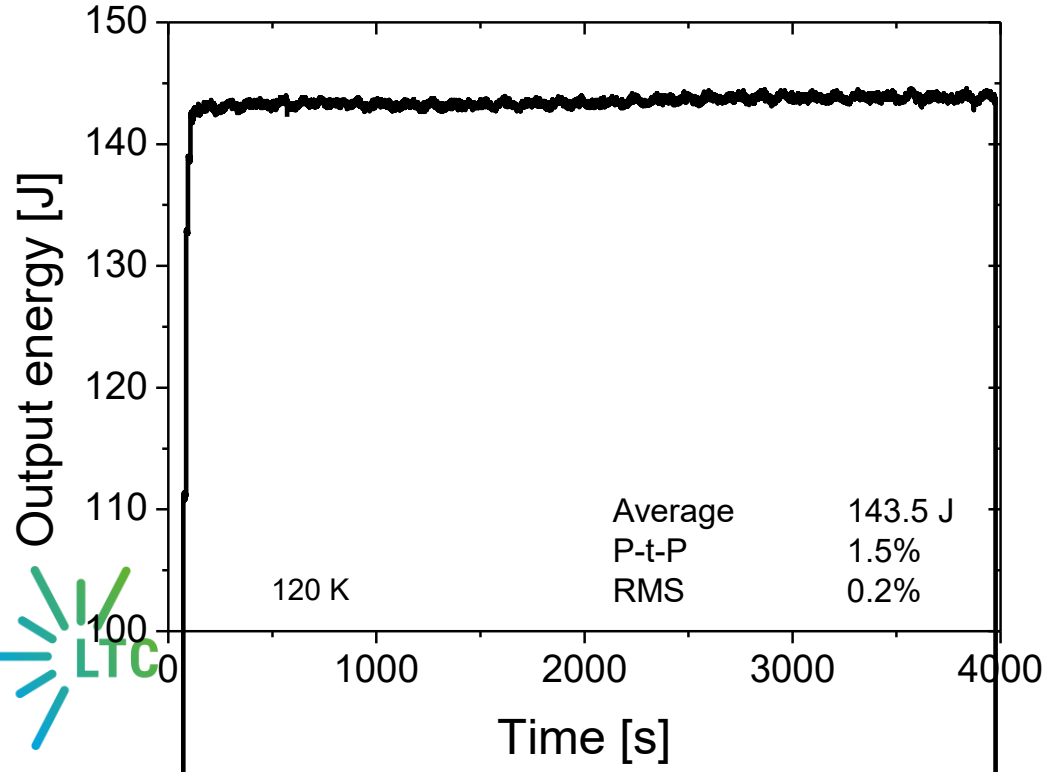
- 146 J @ 10 Hz for 13 J input
- 30% optical – to – optical efficiency
- 120 K coolant temperature

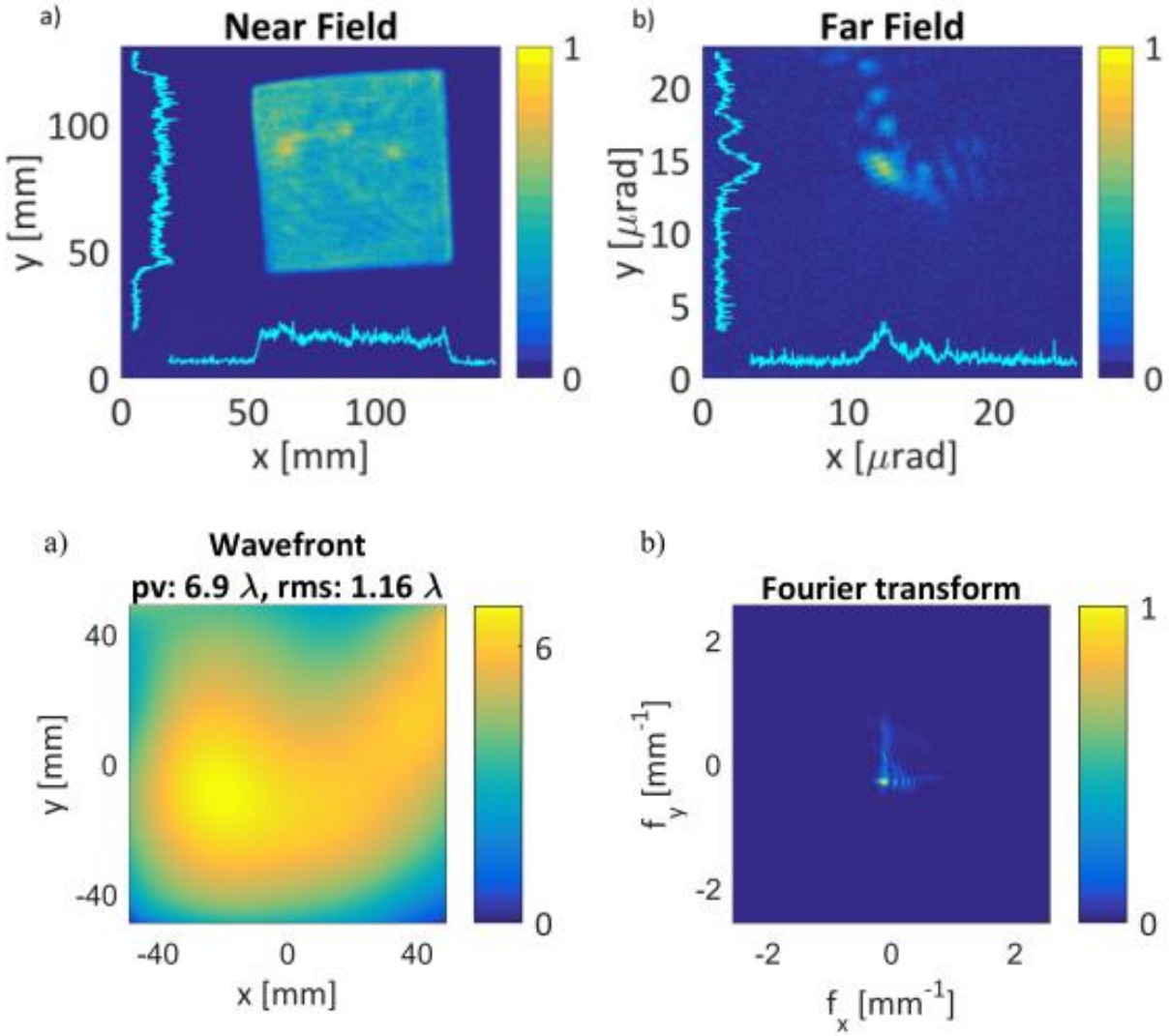




143 J @ 10 Hz for 60 mins

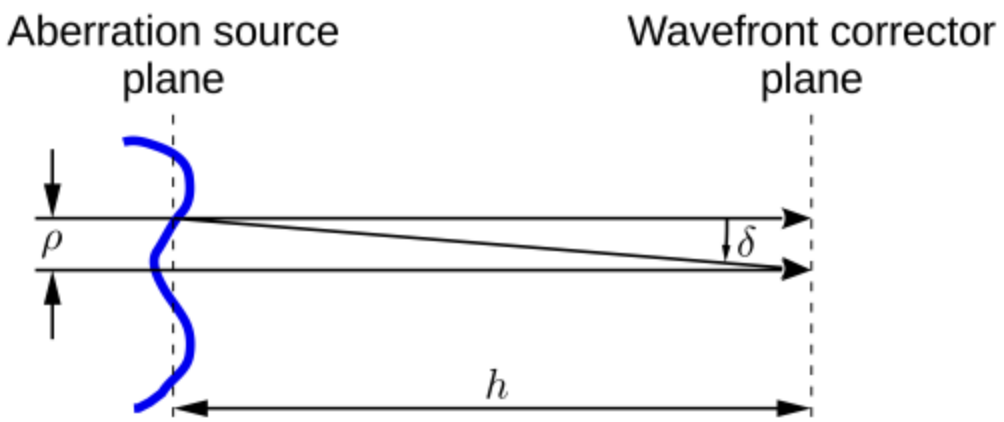
- 143 J for 60 mins
- without deformable mirror
- No damage, no power drop

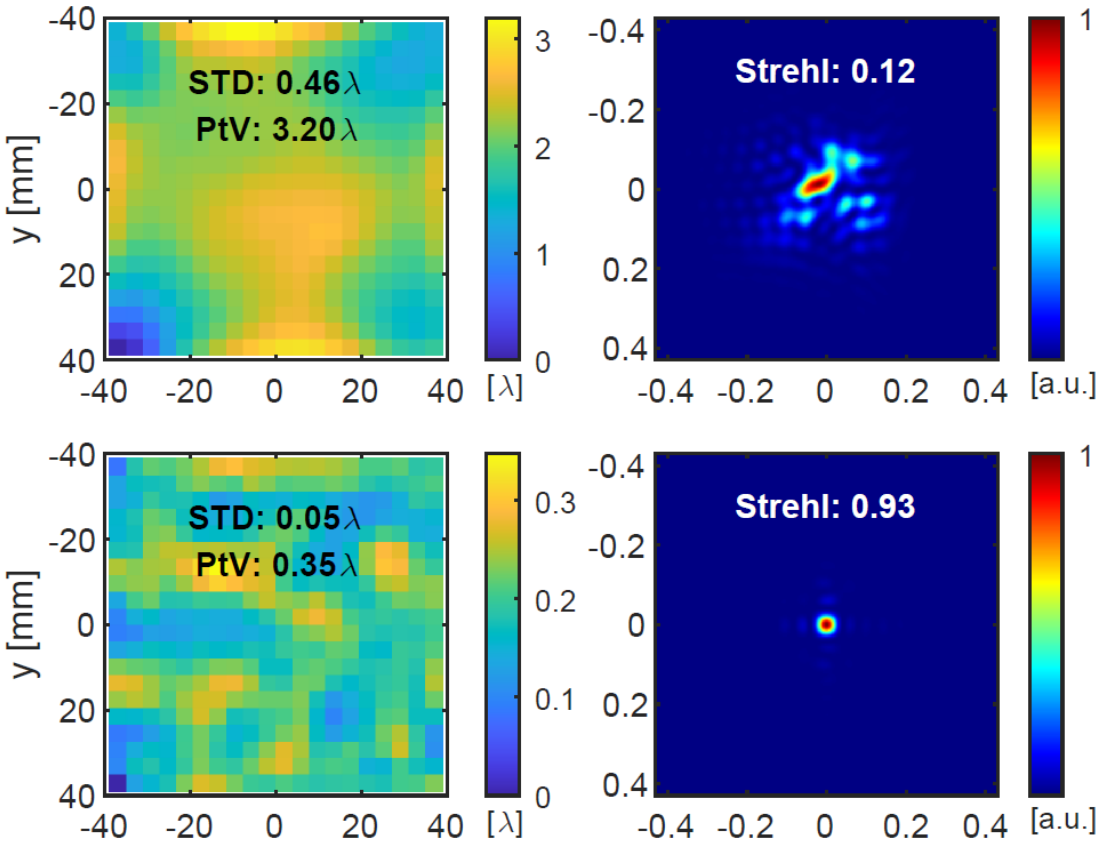




Wavefront correction

Wavefront correction must happen in the image plane, otherwise its not possible to compensate

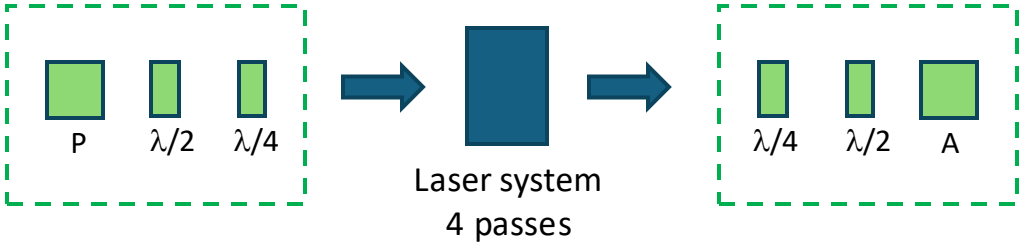




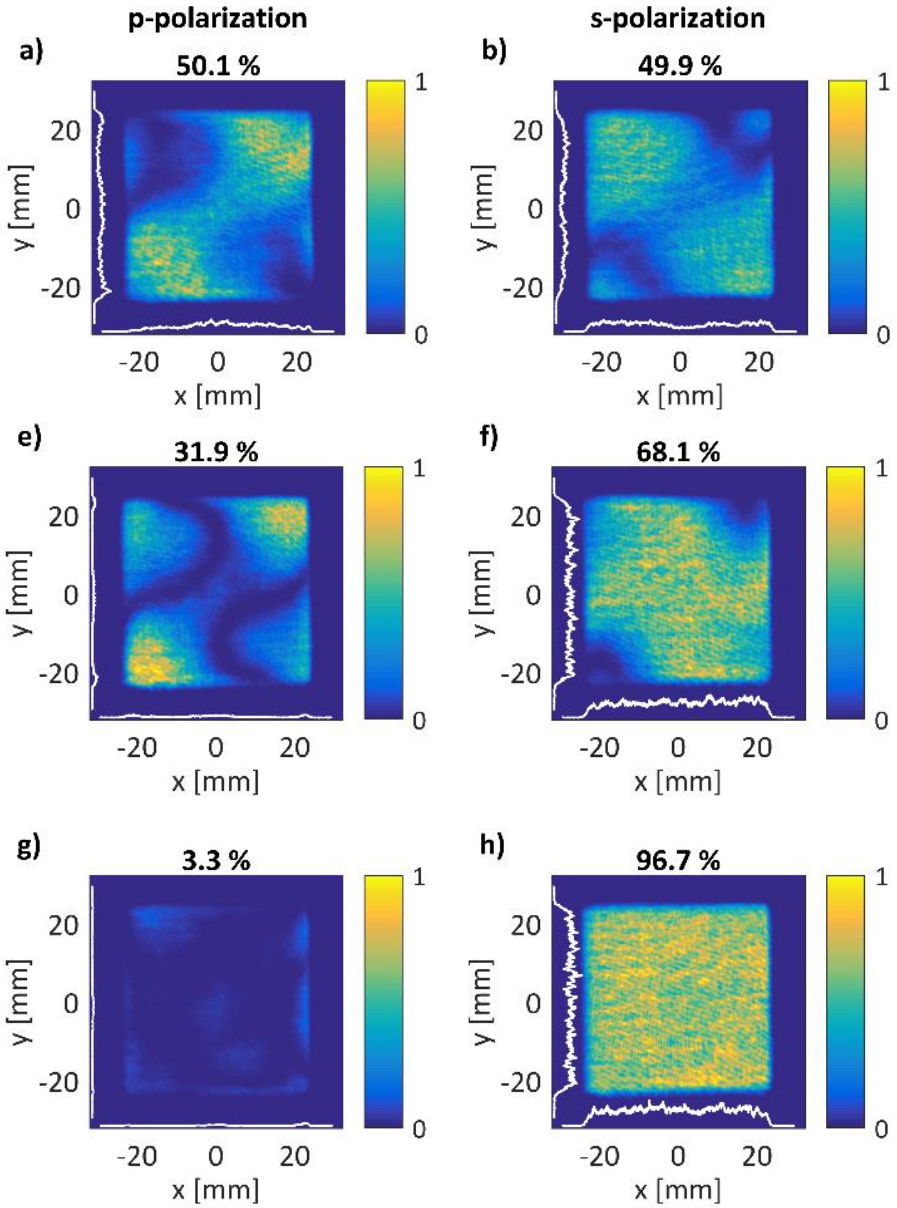
Relay imaging is needed to achieve good beam quality

Compensating polarization changes

- Obtain full information about polarization properties of the system by polarimetry



- Numerically finds the best input and output polarization to minimize polarization losses
- Polarization losses
  - Unoptimized – 50%
  - Post compensation – 32%
  - Input/output optimization – 3%

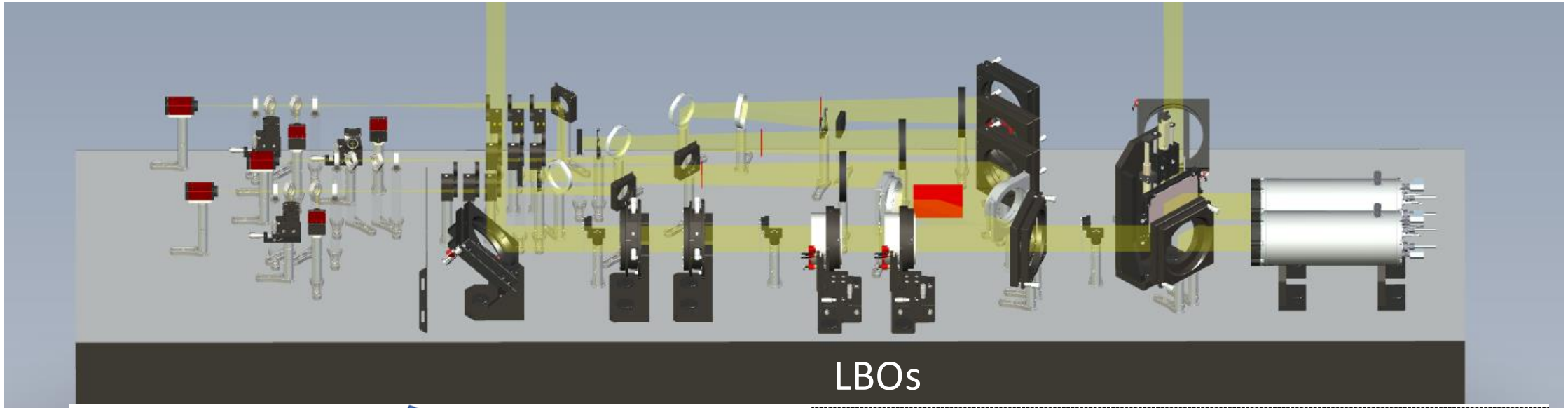


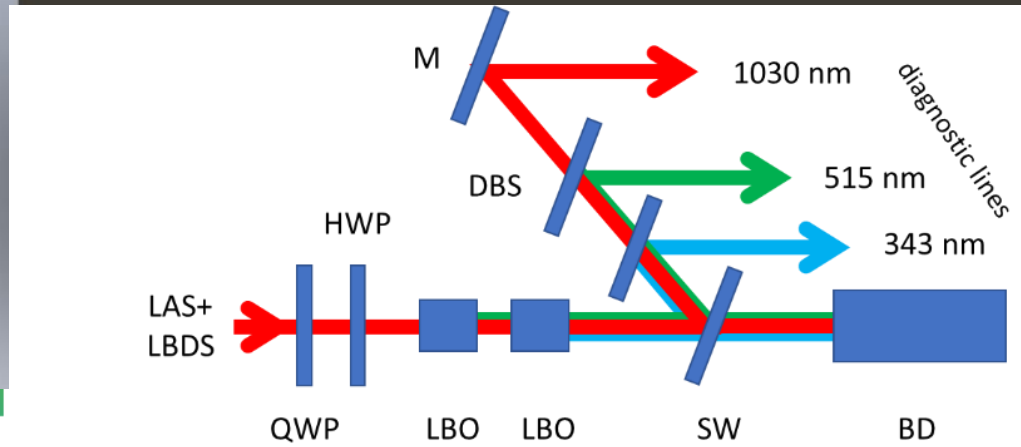
Slezak SciRep 2022, Divoky HPLSE 2023

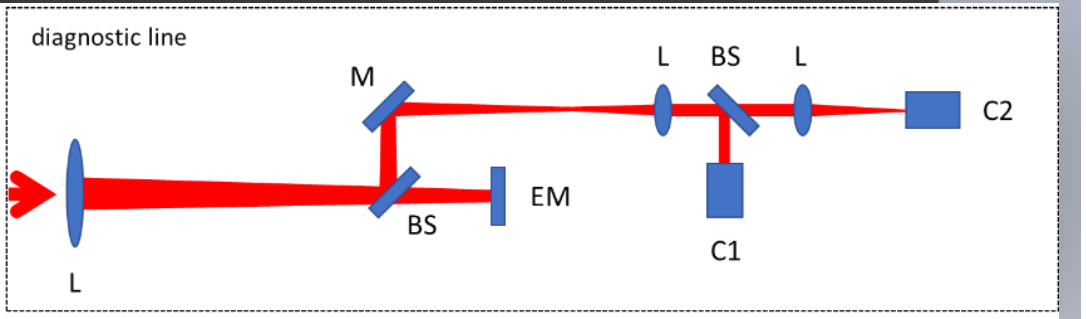
Harmonic generation setup

input

output

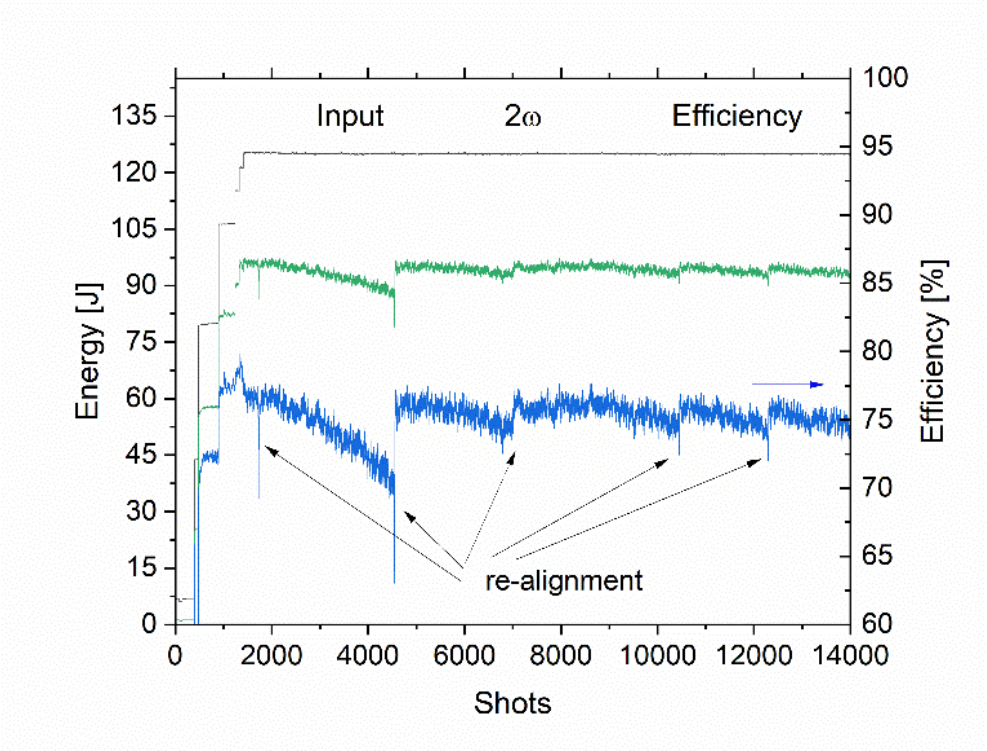


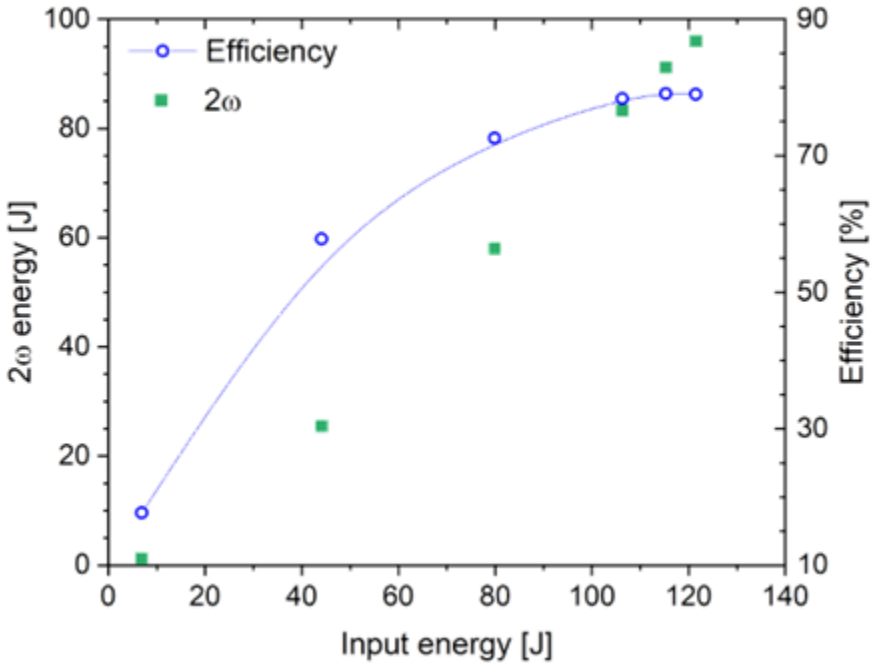




Second harmonic generation

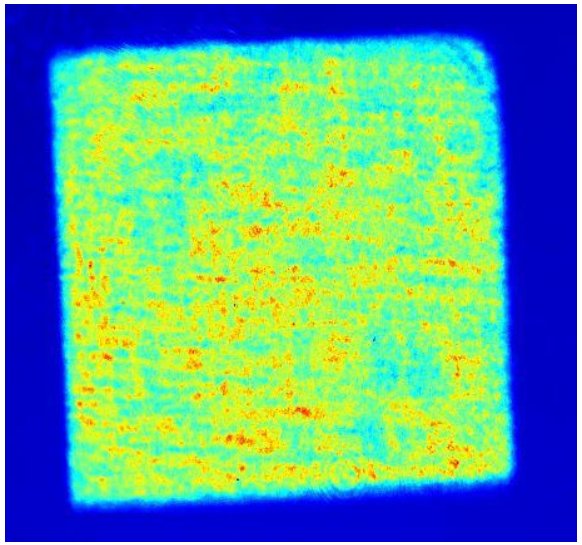
- SHG 515 nm, 10 Hz
- Output 95 J (1.4x world record power for > 1 J)
- Efficiency >75% (peak 80%)
- After long thermalization, excellent stability (0.5% RMS, 2% P-t-P)





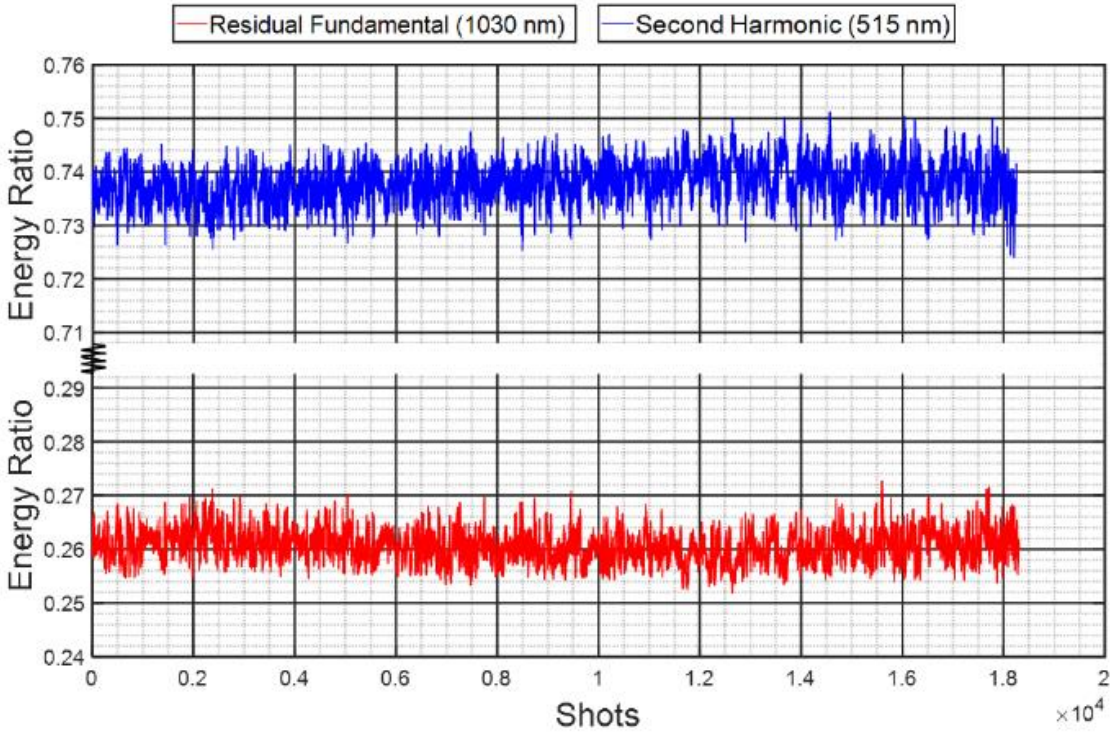
Second harmonic generation

- Excellent beam homogeneity
- Upgraded temperature stabilization oven (TEC, sealed)
- Excellent stability from the start (0.5% RMS)



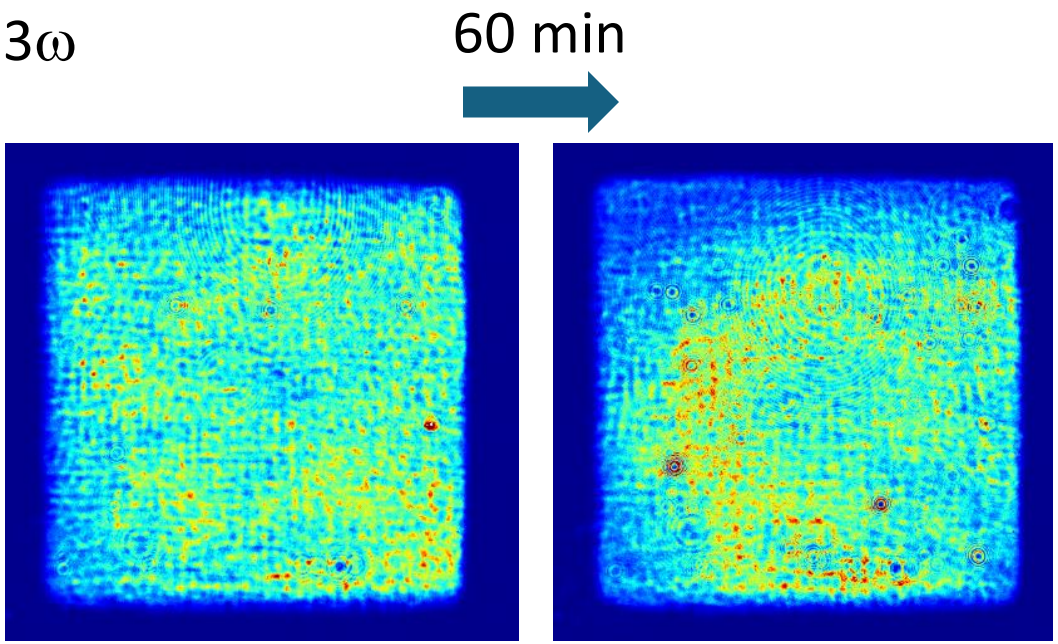
2ω

1ω



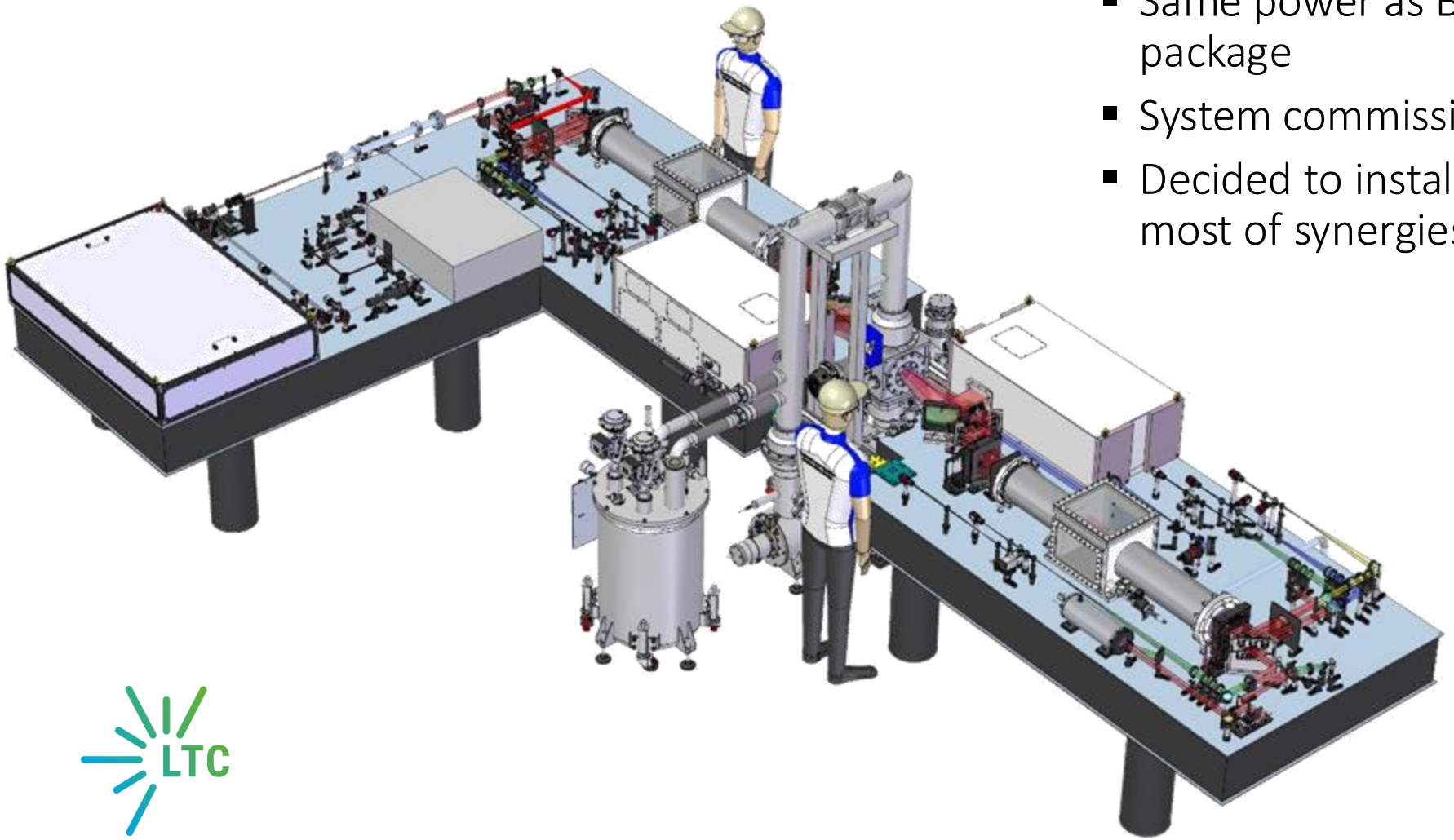
Third harmonic generation

- THG 343 nm, 10 Hz
- Output 49.5 J (4x world record power)
- Efficiency >55% (peak 60%)
- Thermal feedback from THG to SHG (reflected beams)
- After very long thermalization, good stability (1% RMS, 6% P-t-P), but bad homogeneity



Kazi laser (Bivoj 100 Hz)

KAZI laser



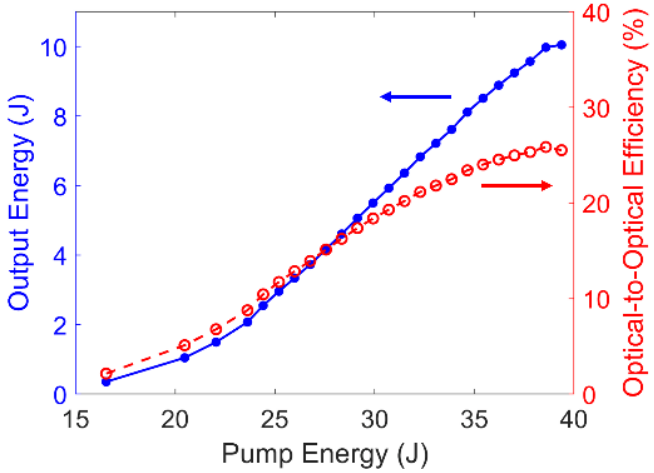
- 10 J, 100 Hz nanosecond pulse DPSSL, based on STFC's DiPOLE technology
- Same power as Bivoj in smaller, cheaper package
- System commissioned in the UK
- Decided to install at ELI-Beamlines to make the most of synergies between HiLASE and ELI

10 x power density

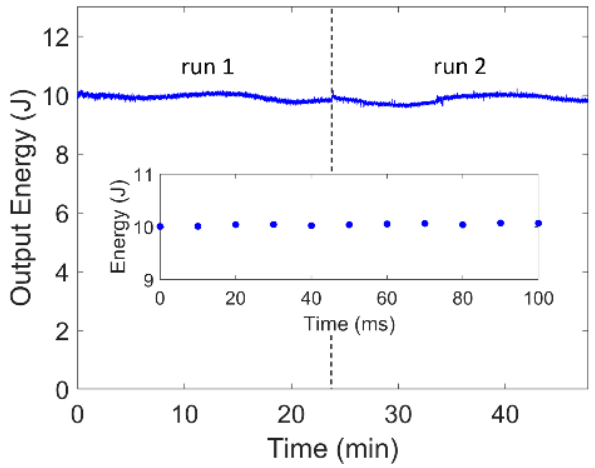
KAZI results obtained by STFC

- 25.4% optical-to-optical efficiency
- ~300,000 shots @ 10 J, 100 Hz
- 1.44·106 shots @ 7J, 100 Hz
- 1% rms energy stability

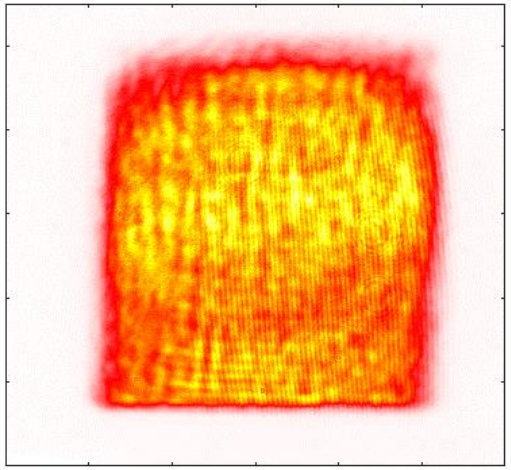
- World's first demonstration of stable, long-term amplification of a 1 kW average power, high energy laser operating at 100 Hz.
- Expansion of parameter range of high energy lasers, benefitting:
  - manufacturing;
  - materials testing;
  - development of high peak power lasers operating at high pulse rates.



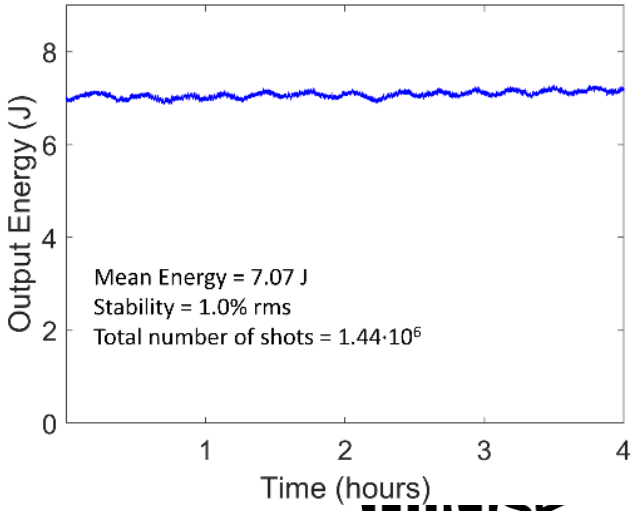
10 J, 100 Hz for 45 minutes



Near-field @ 10 J, 100 Hz

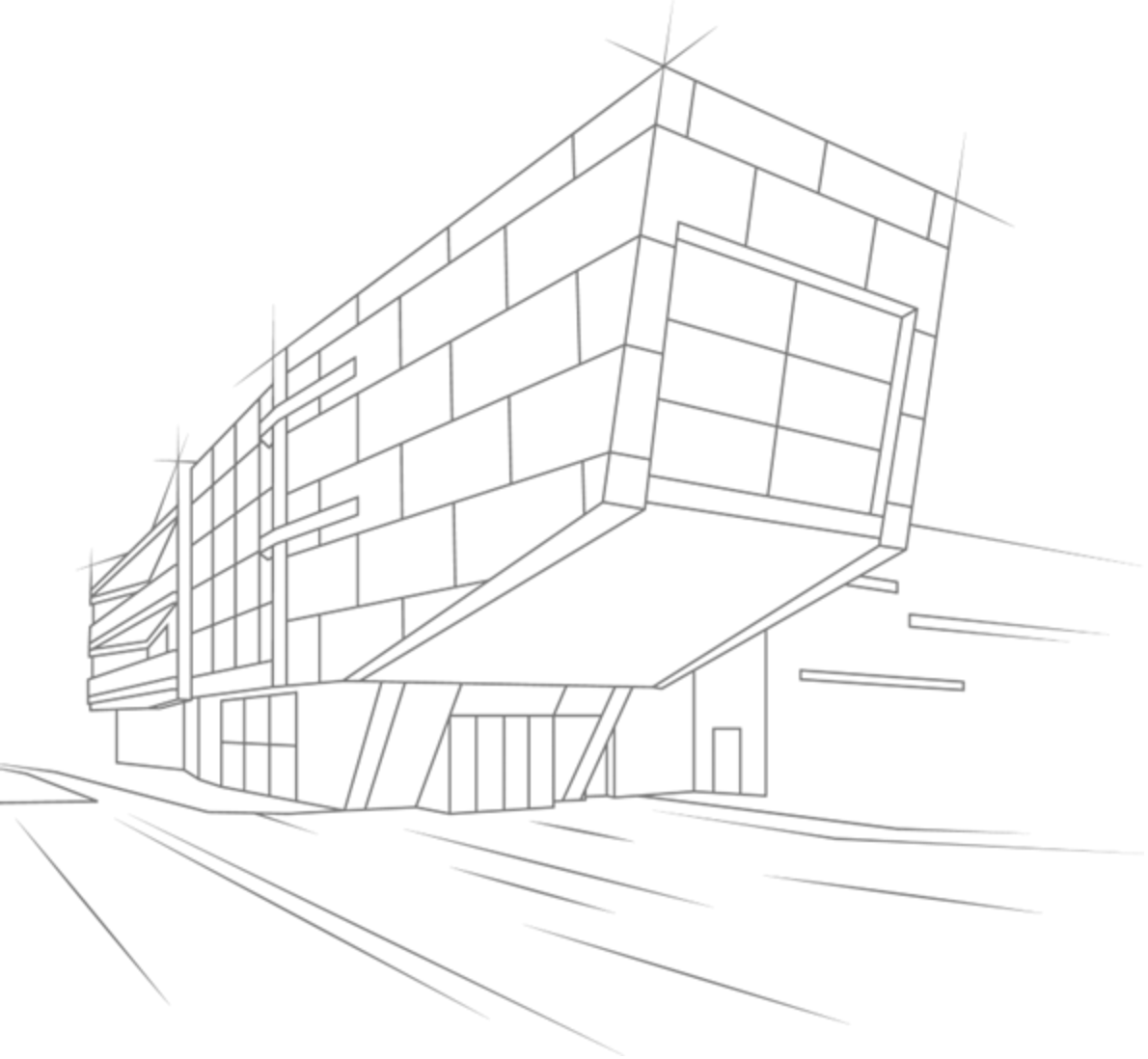


7 J, 100 Hz for 4 hours



LASER TRAINING CENTRE

hilase



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