Ti:Sa lasers as drivers for laser-driven accelerators

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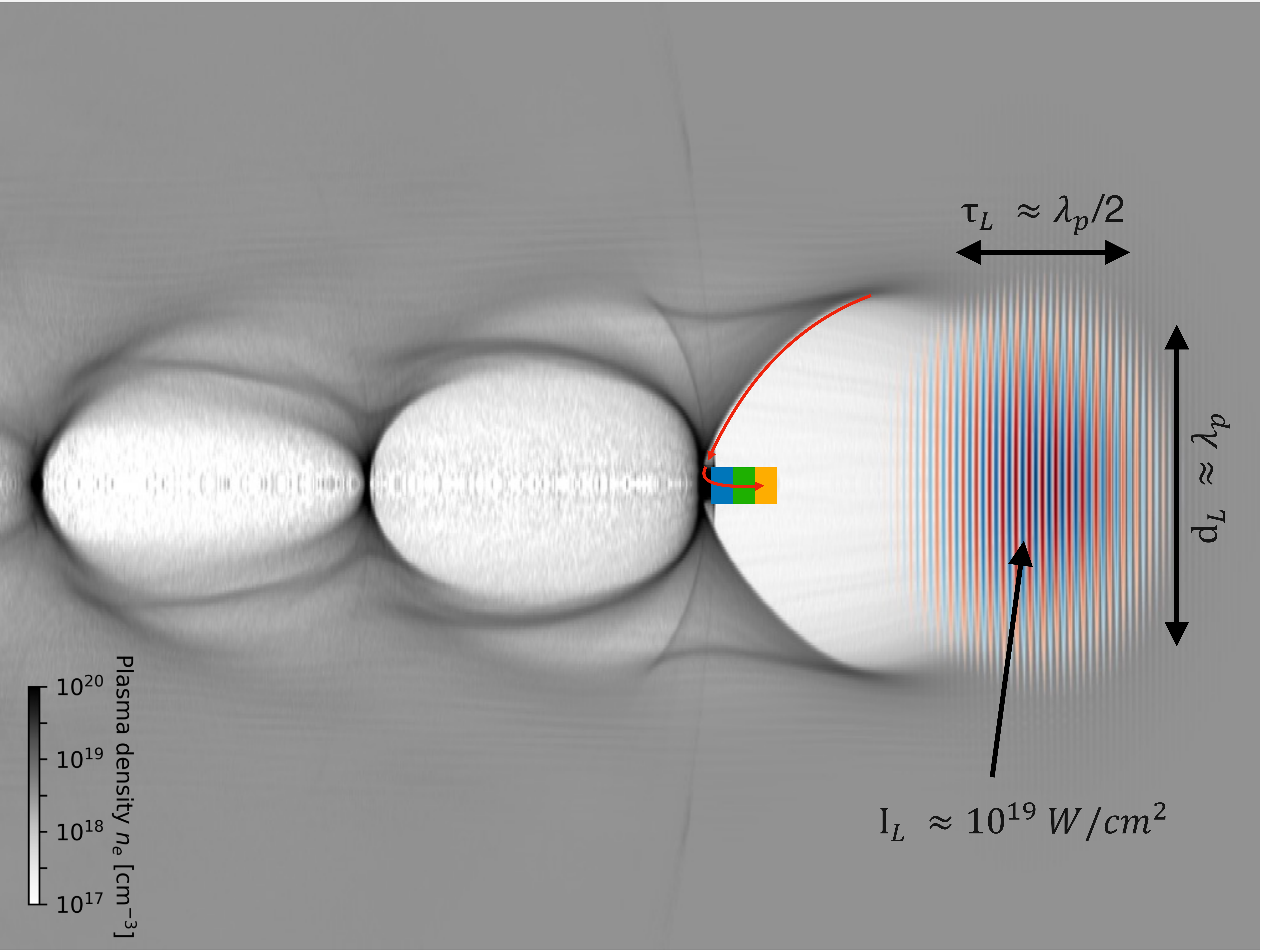
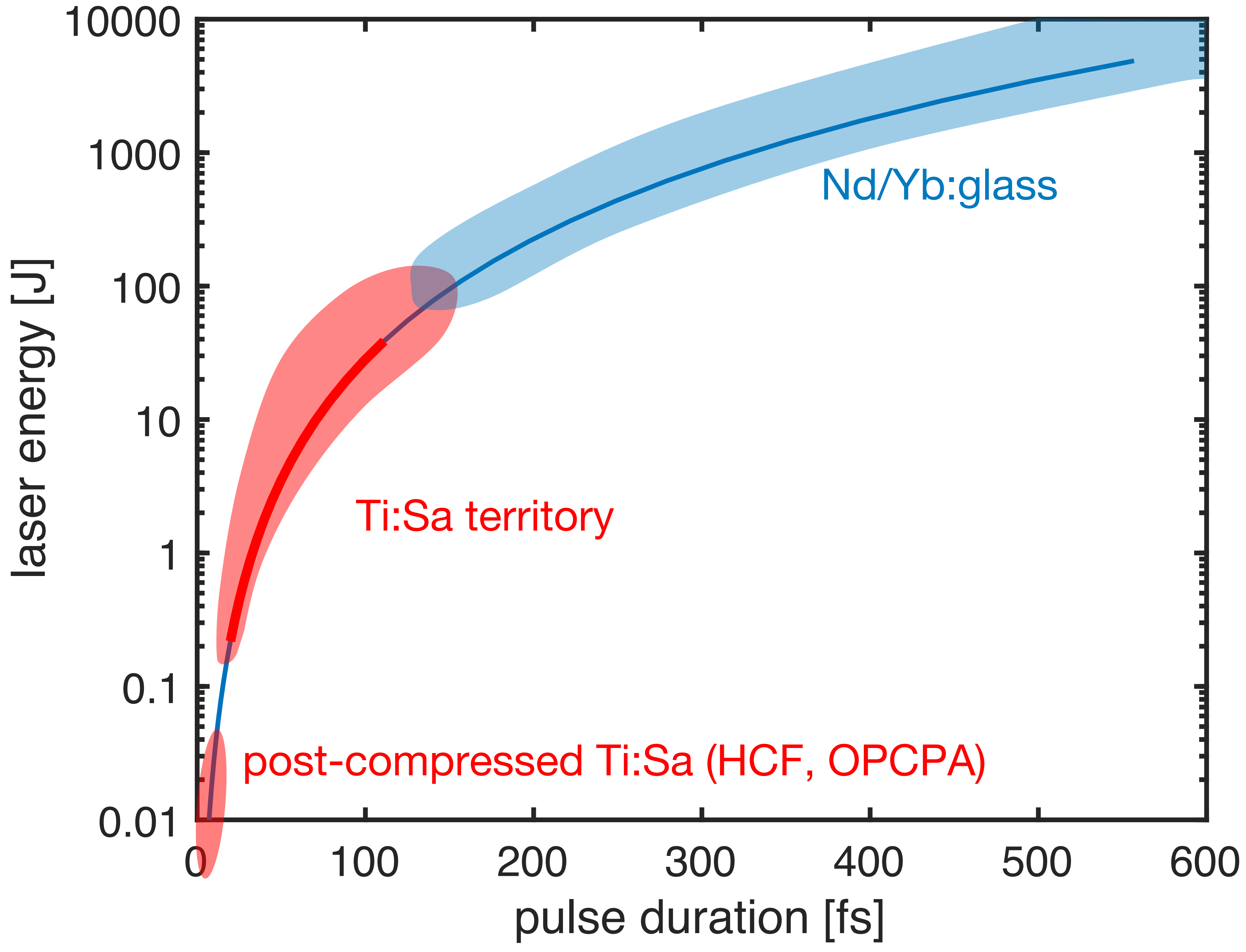
Laser Wakefield Acceleration (LWFA)



Assumptions:

- pulse duration ≈ plasma wavelength/2
- focus size ≈ plasma wavelength
- 4 x power / (π x focus size^2) > 10^{19} W/cm^2



Ideal drive laser for laser acceleration

High peak power	High average power	Good wall-plug efficiency	High reliability and control
• Short pulses ⇒ Broad bandwidth • High energy ⇒ Large gain medium ⇒ Practical saturation fluence ⇒ High damage threshold	• Efficient cooling ⇒ High thermal conductivity ⇒ Low thermal birefringence • Low quantum defect	• Low quantum defect • Efficient pump generation	• Long wavelength ⇒ Less influence of air turbulence ⇒ Less 2-photon absorption (less damage) • Short enough wavelength… ⇒ …for easy detection (silicon cameras)

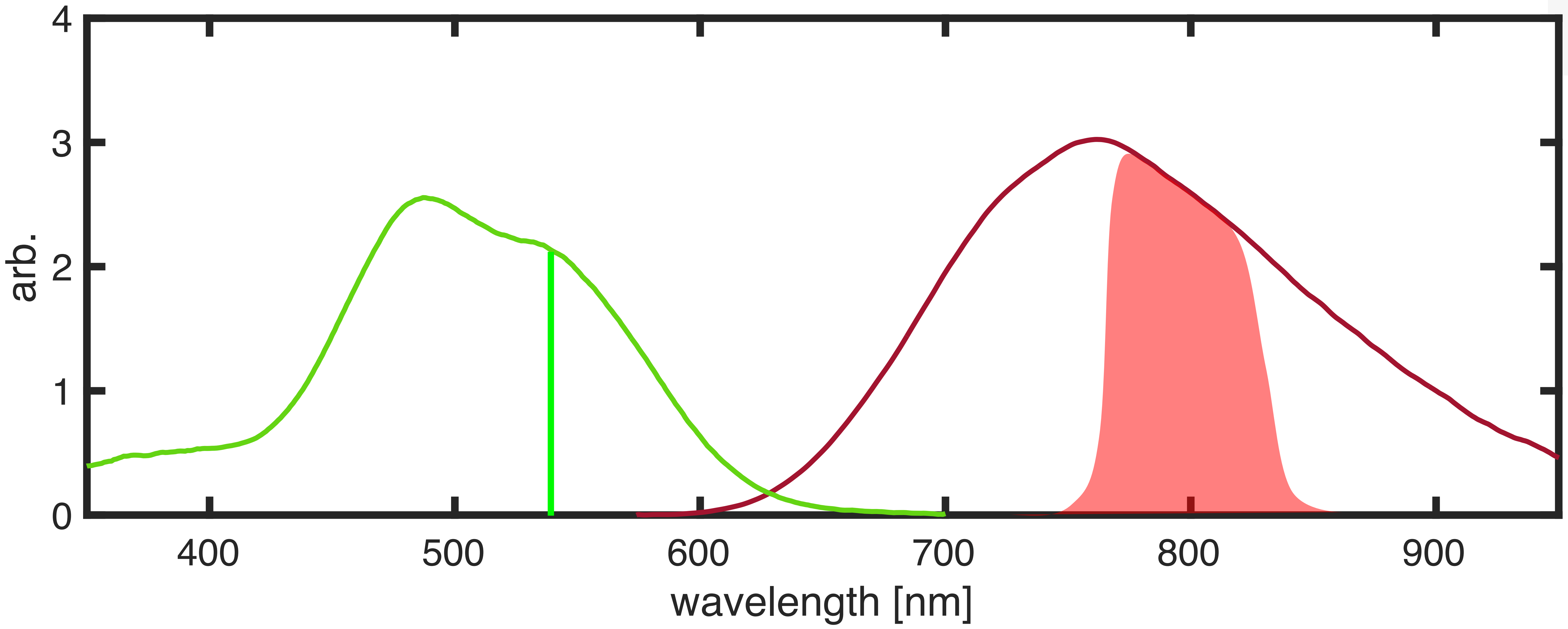
Ti:Sa laser material:

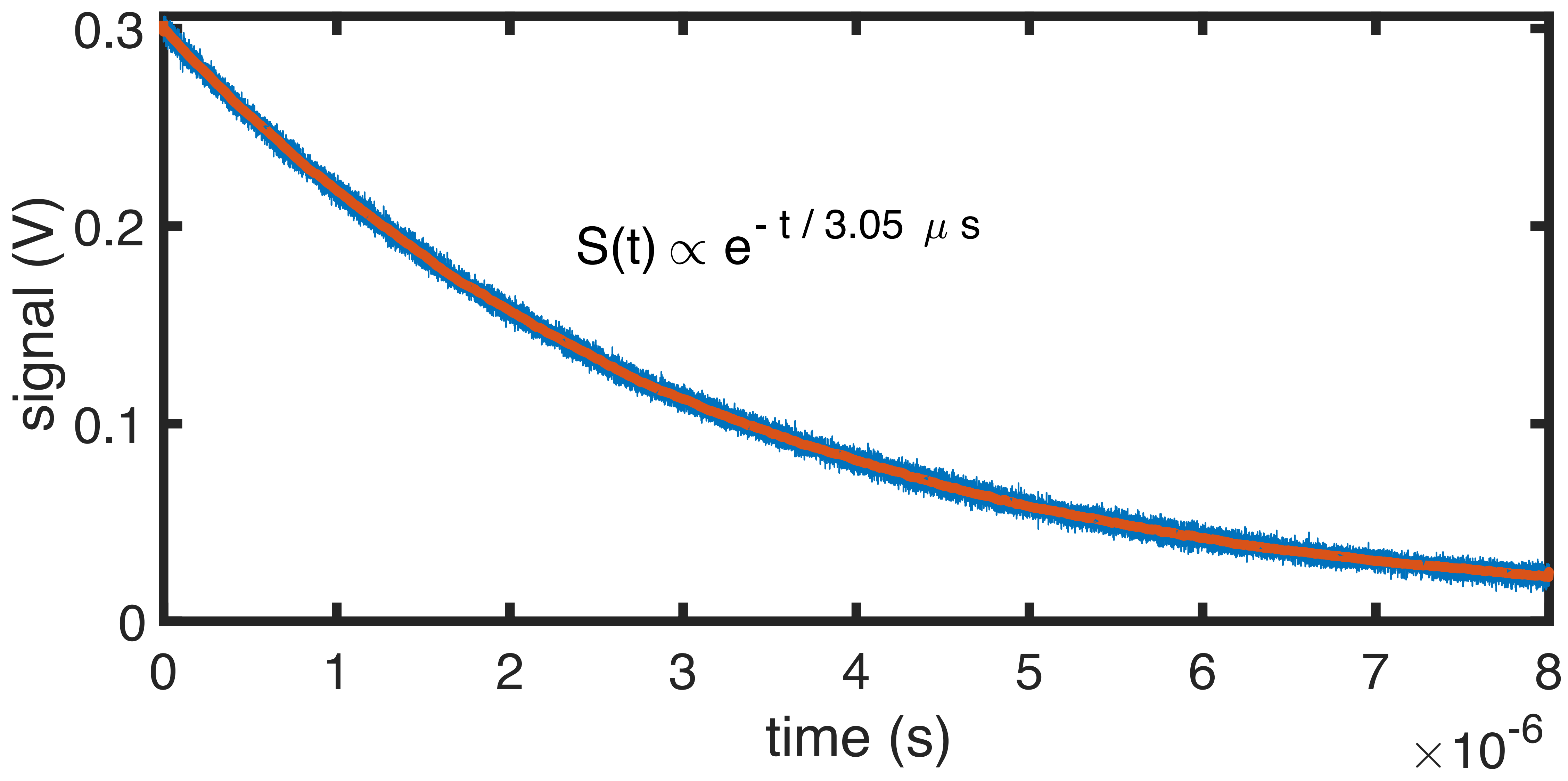
First demonstrated as a tunable laser medium in 1982 by Moulton

Well suited for ultraintense lasers:

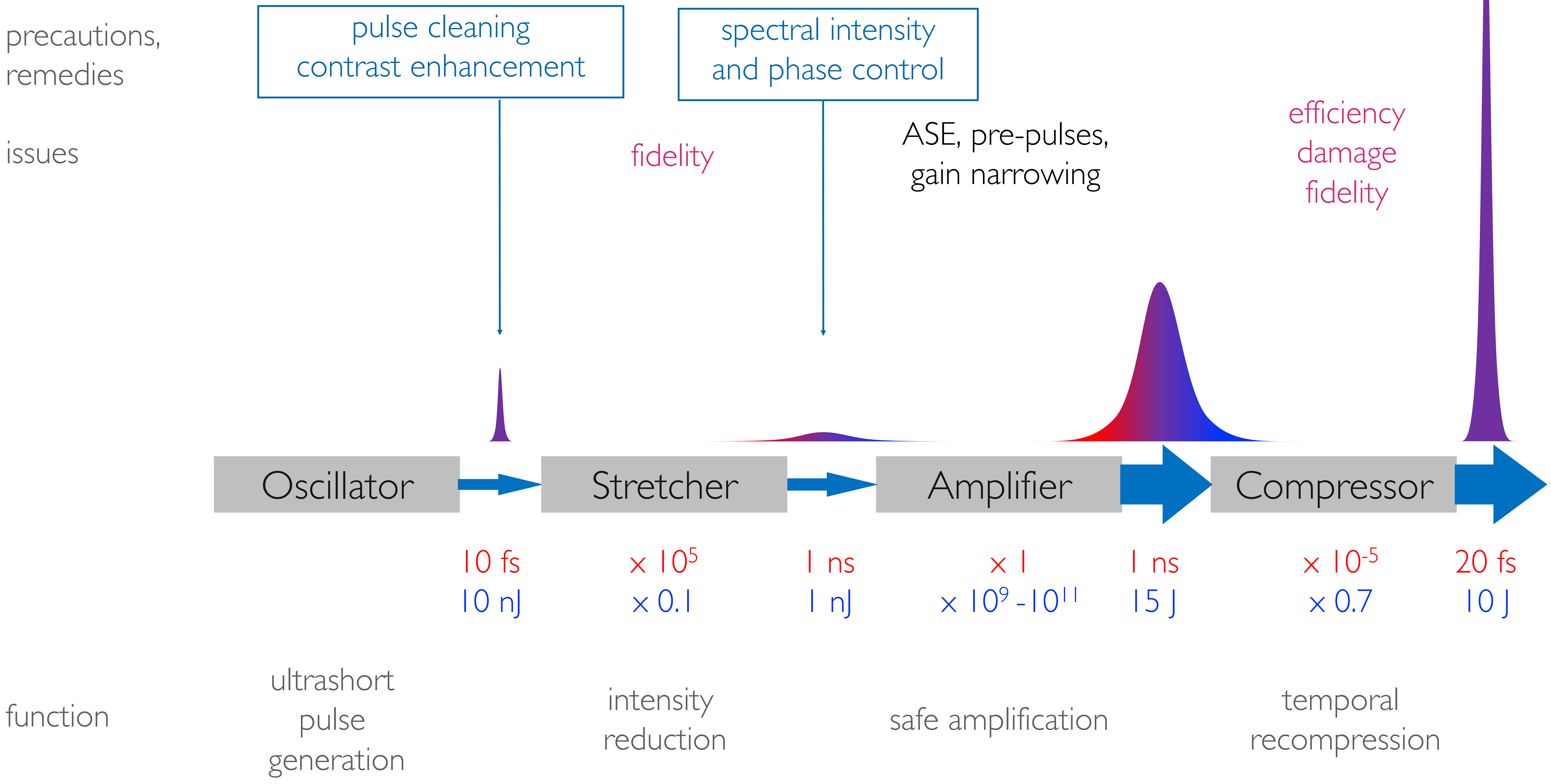
- \+ Extremely broad bandwidth – short pulses, > 15 fs
- \+ extremely durable – high thermal stress resistance
- \+ high thermal conductivity – decent heat dissipation
- \+ "practical" saturation fluence – efficient energy extraction

- – Short upper state lifetime – laser pumping required
- – Approx. 33% quantum defect – only moderate transfer efficiency

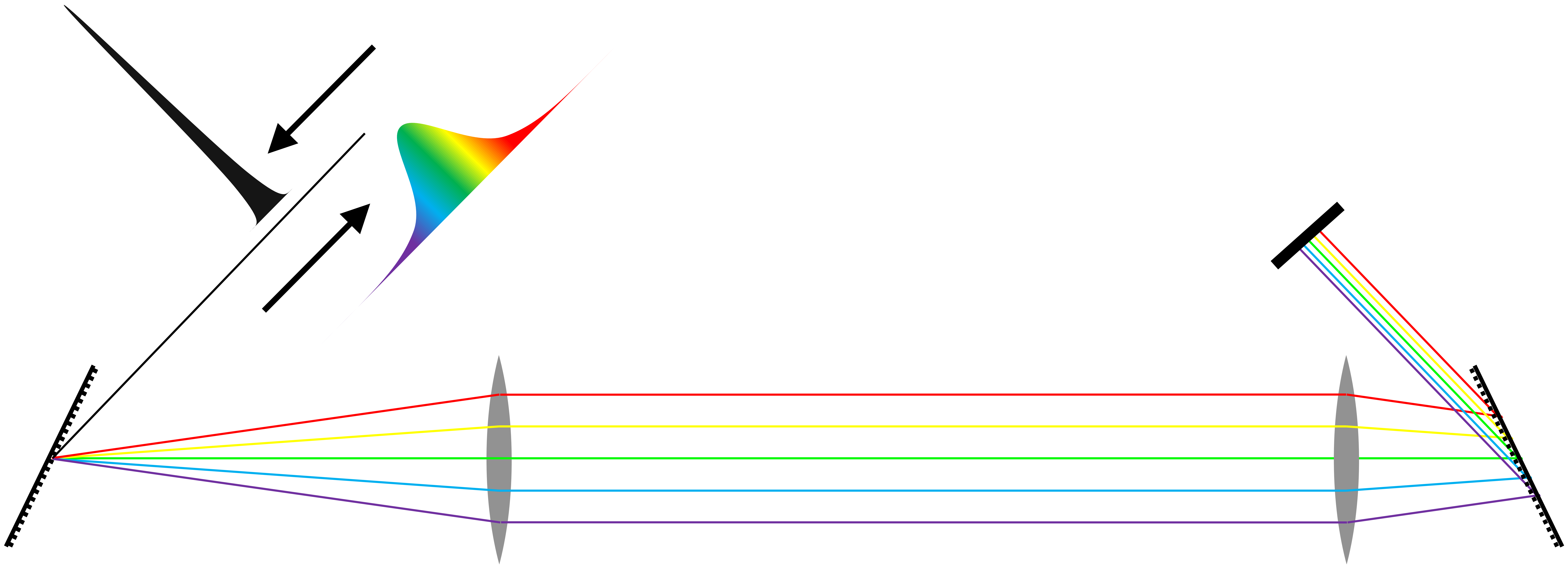




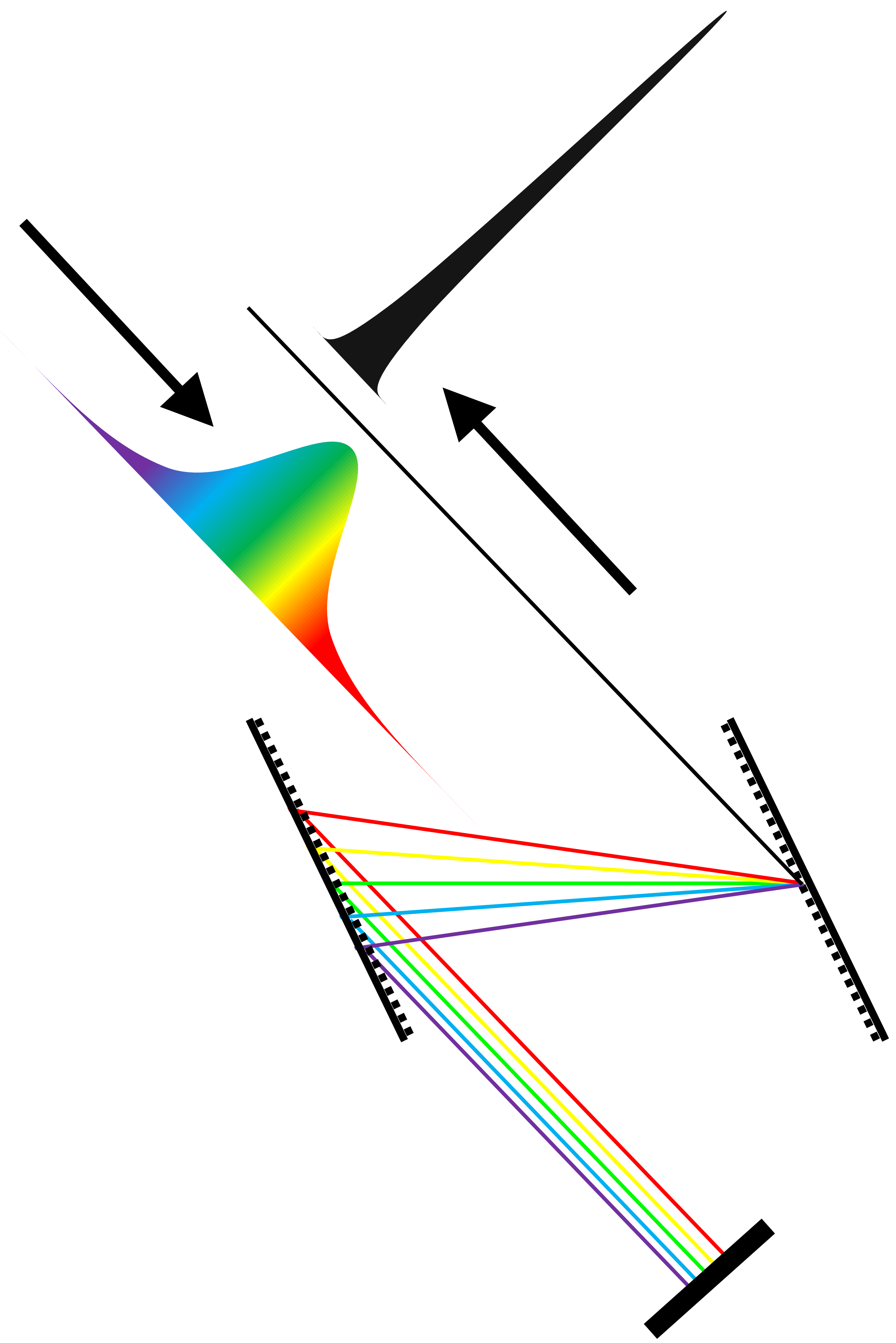
CPA principle: Avoid nonlinear propagation and damage issues



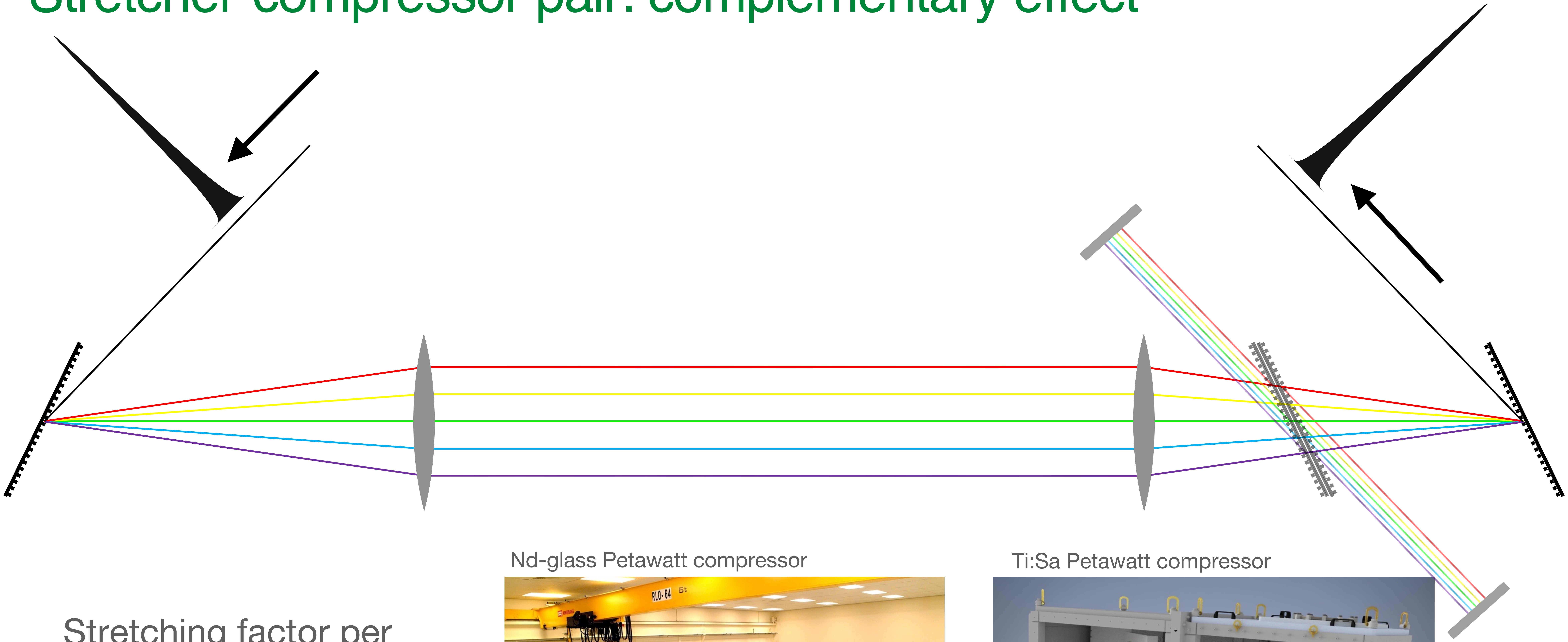
Stretcher:



Compressor:



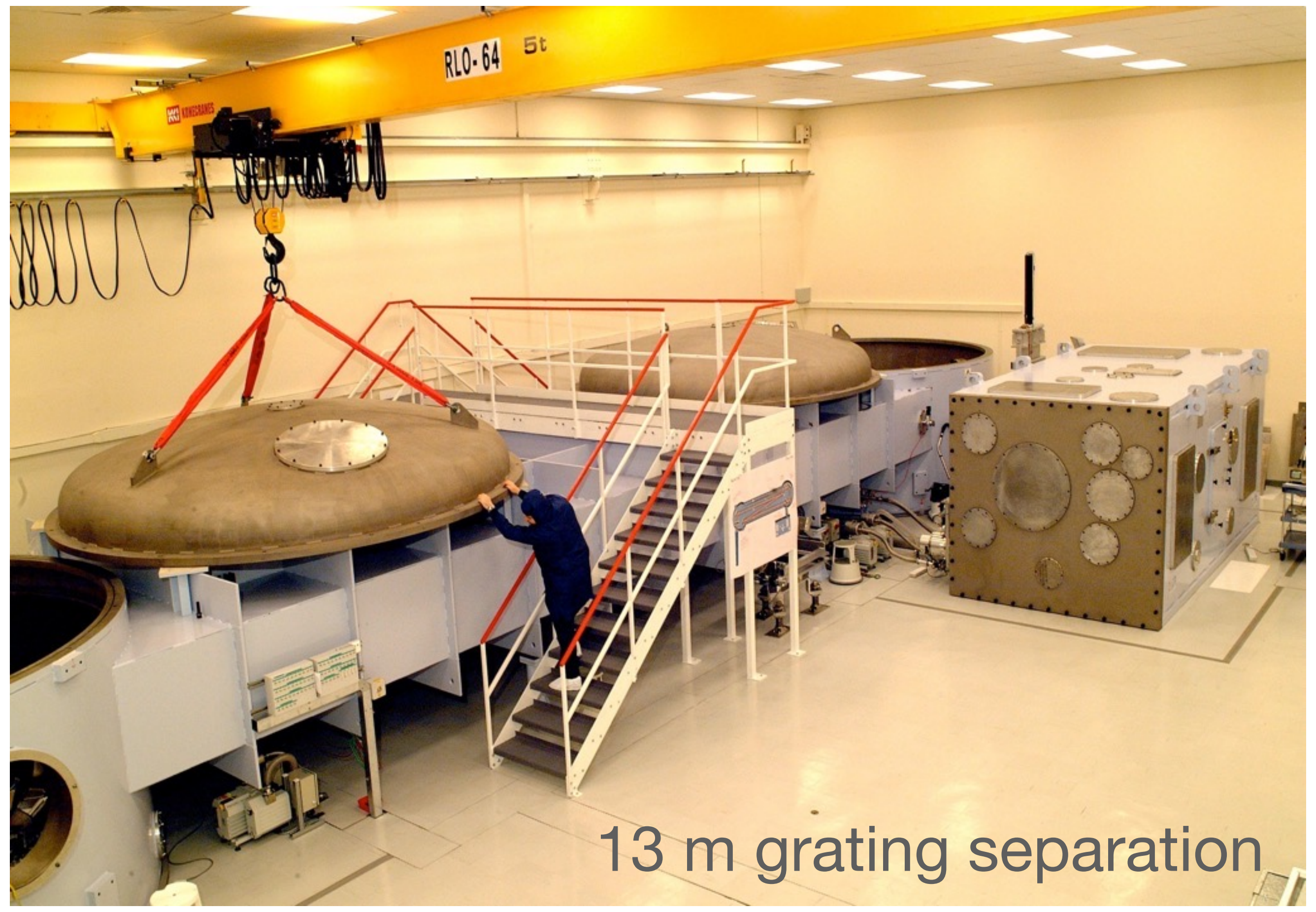
Stretcher-compressor pair: complementary effect



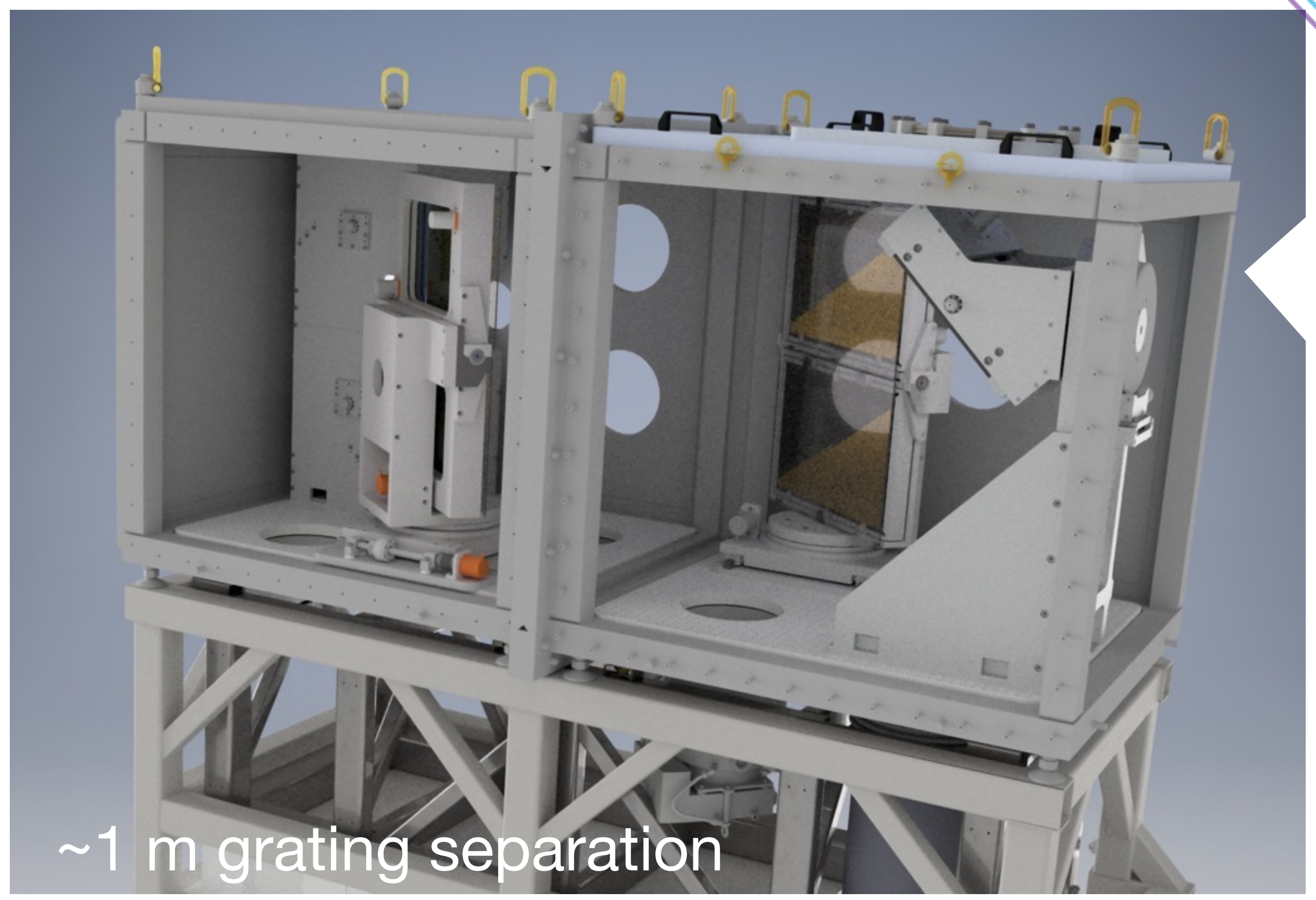
Stretching factor per bandwidth ~ size

⇒ Large bandwidth of Ti:Sa yields relatively compact setup

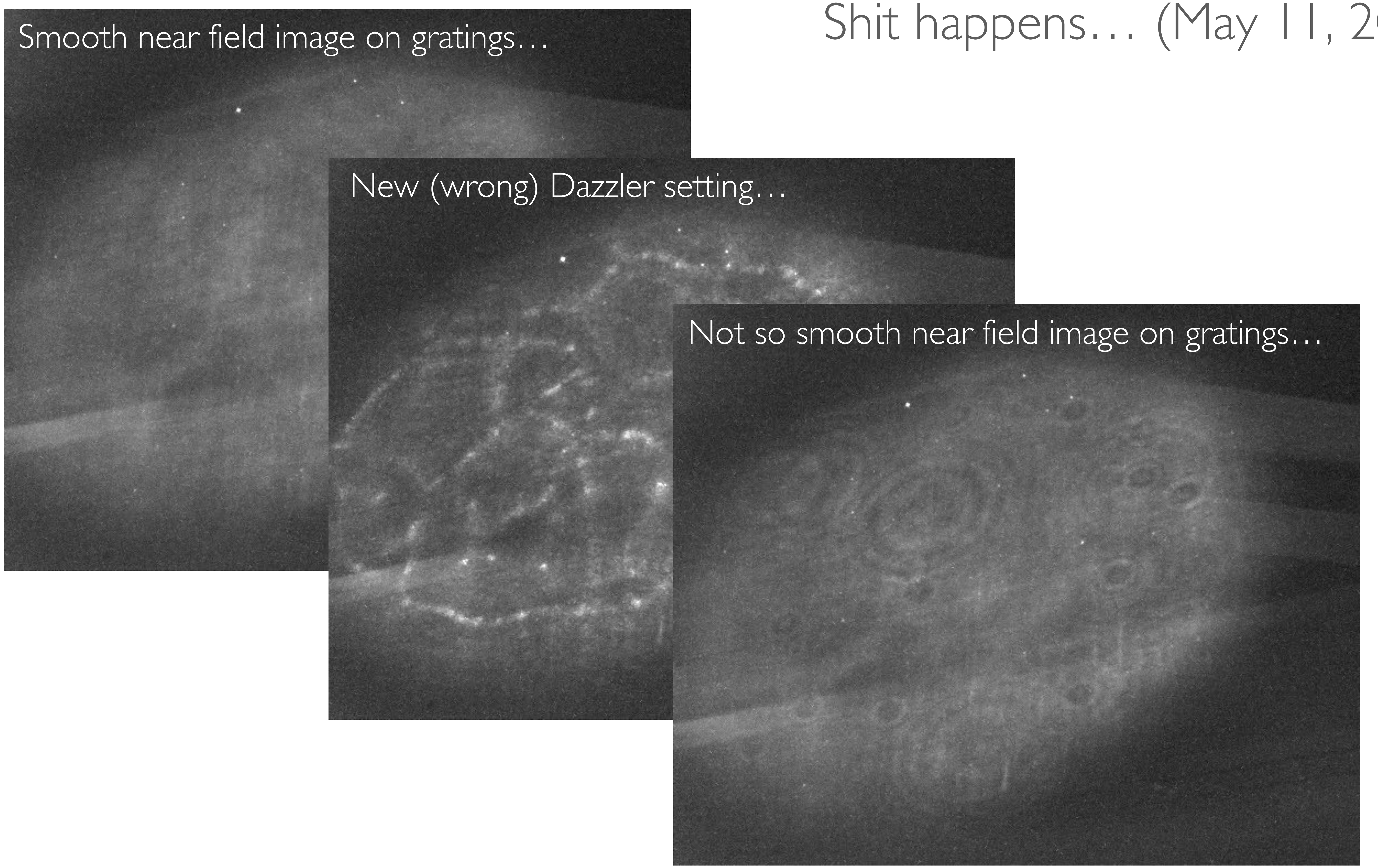
Nd-glass Petawatt compressor



Ti:Sa Petawatt compressor



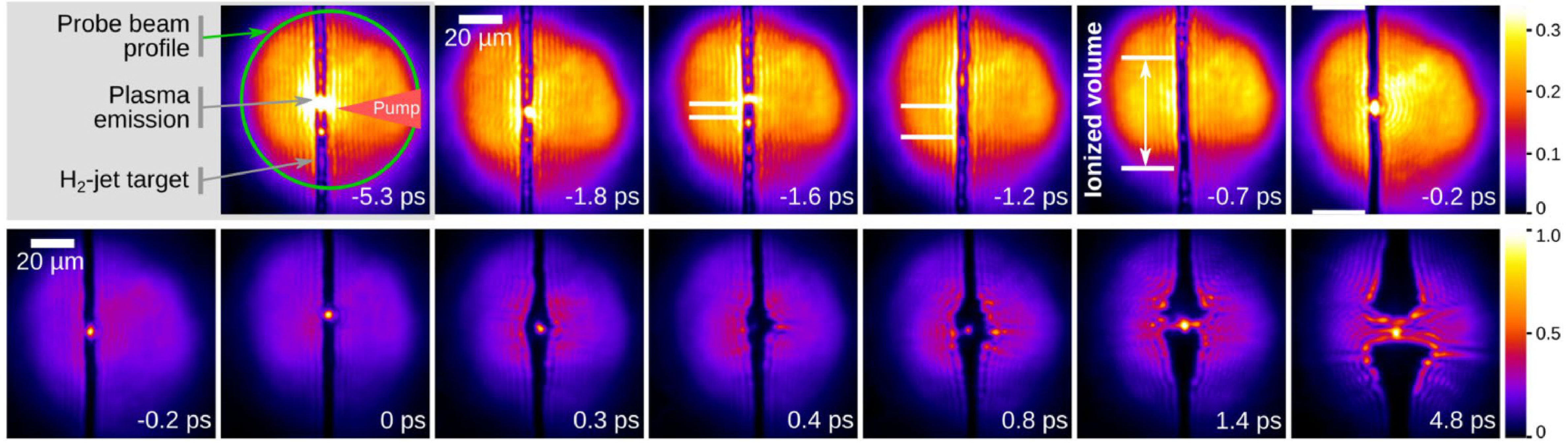
Shit happens… (May 11, 2021)



Temporal contrast: Why is it so important?

Ion acceleration/ Harmonic generation:

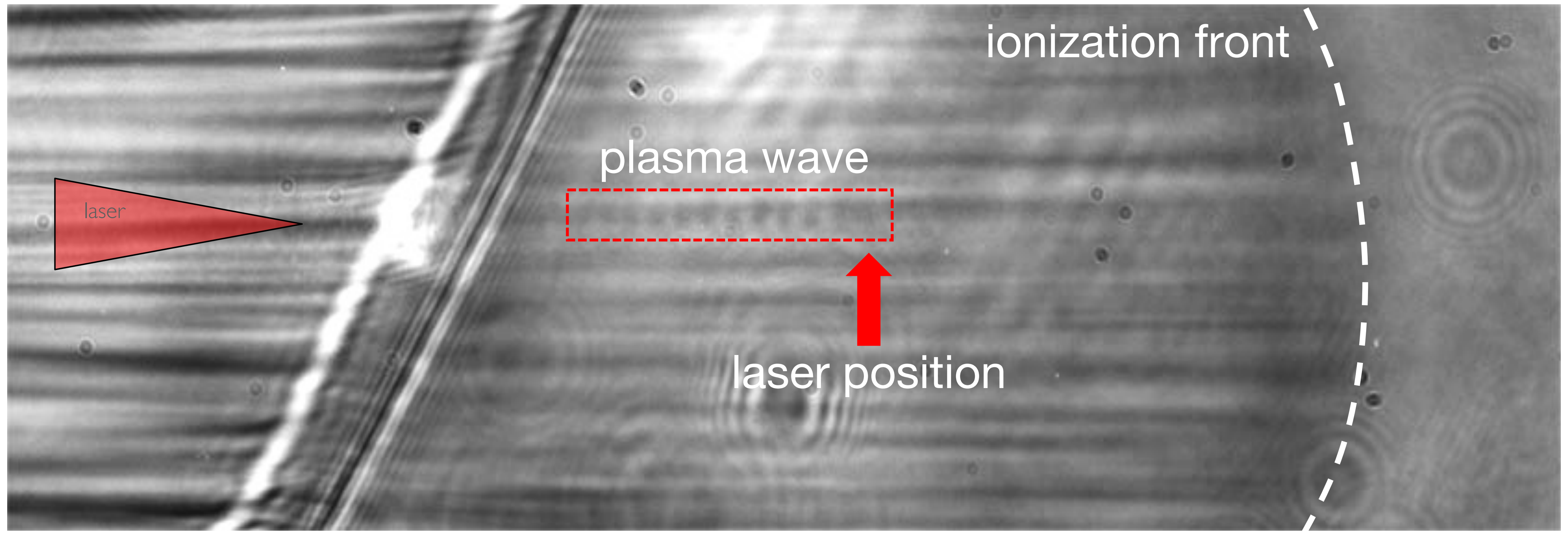
Causes premature plasma expansion



Bernert et al., Scientific Reports **12**, 7287 (2022)

Electron acceleration:

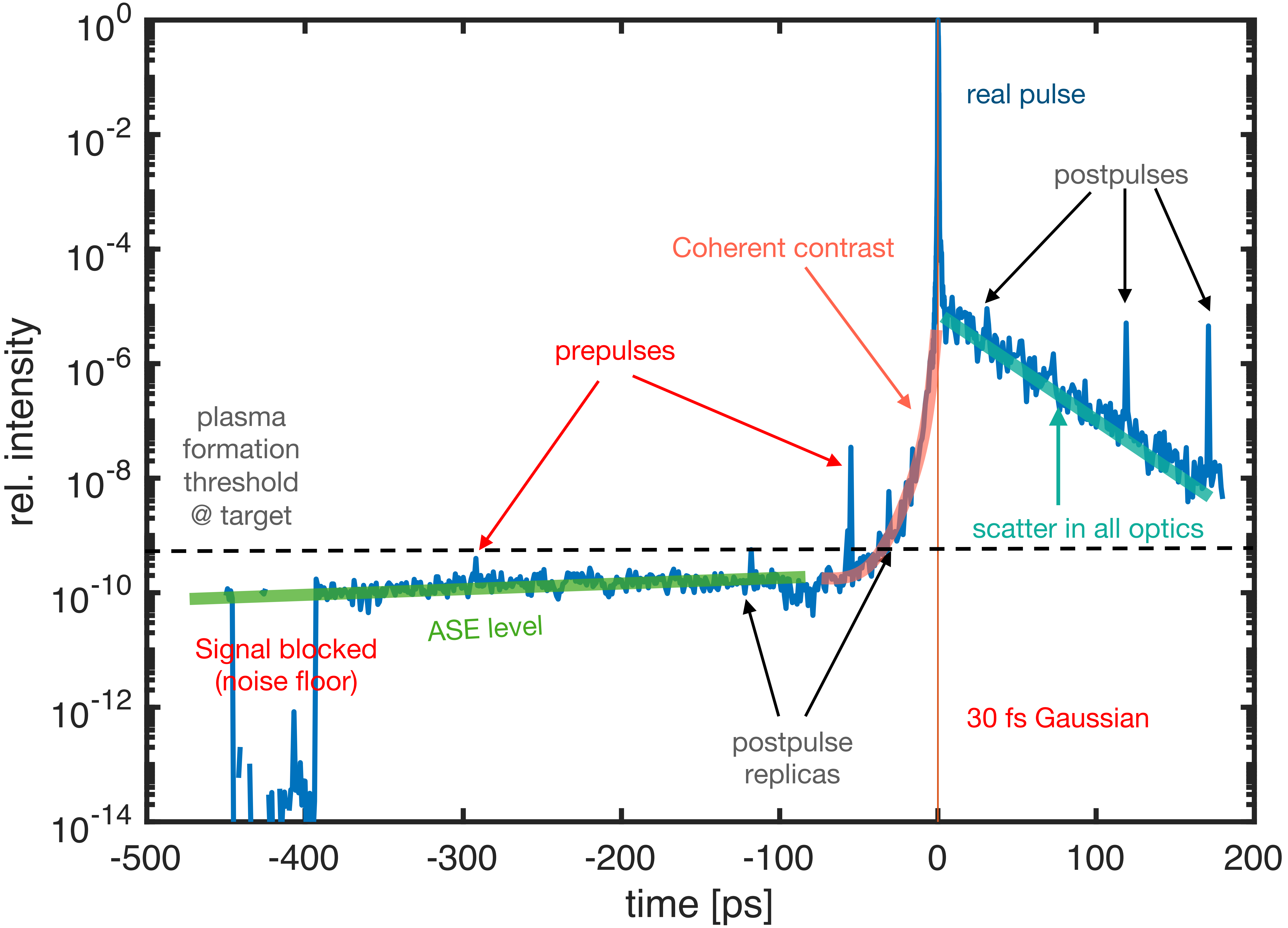
Causes co-moving, lateral density modulations in background plasma



See also: Haffa et al, Scientific Reports **9**, 7697 (2019)

See also: Mangles et al., Plasma Physics & Controlled Fusion **48**, B83 (2006)

Temporal contrast: causes



ASE (amplified spontaneous emission)

- Spontaneous light amplified in the laser chain
- optimized amplifier geometry, high seed level, low losses, spatial filtering, double CPA

Post pulses: reflections off mirror backside

- fine-ground or wedged substrates
- rotating periscopes instead of waveplates
- causes apparent replicas in measurement setup
- can turn into prepulses via nonlinear propagation and gain

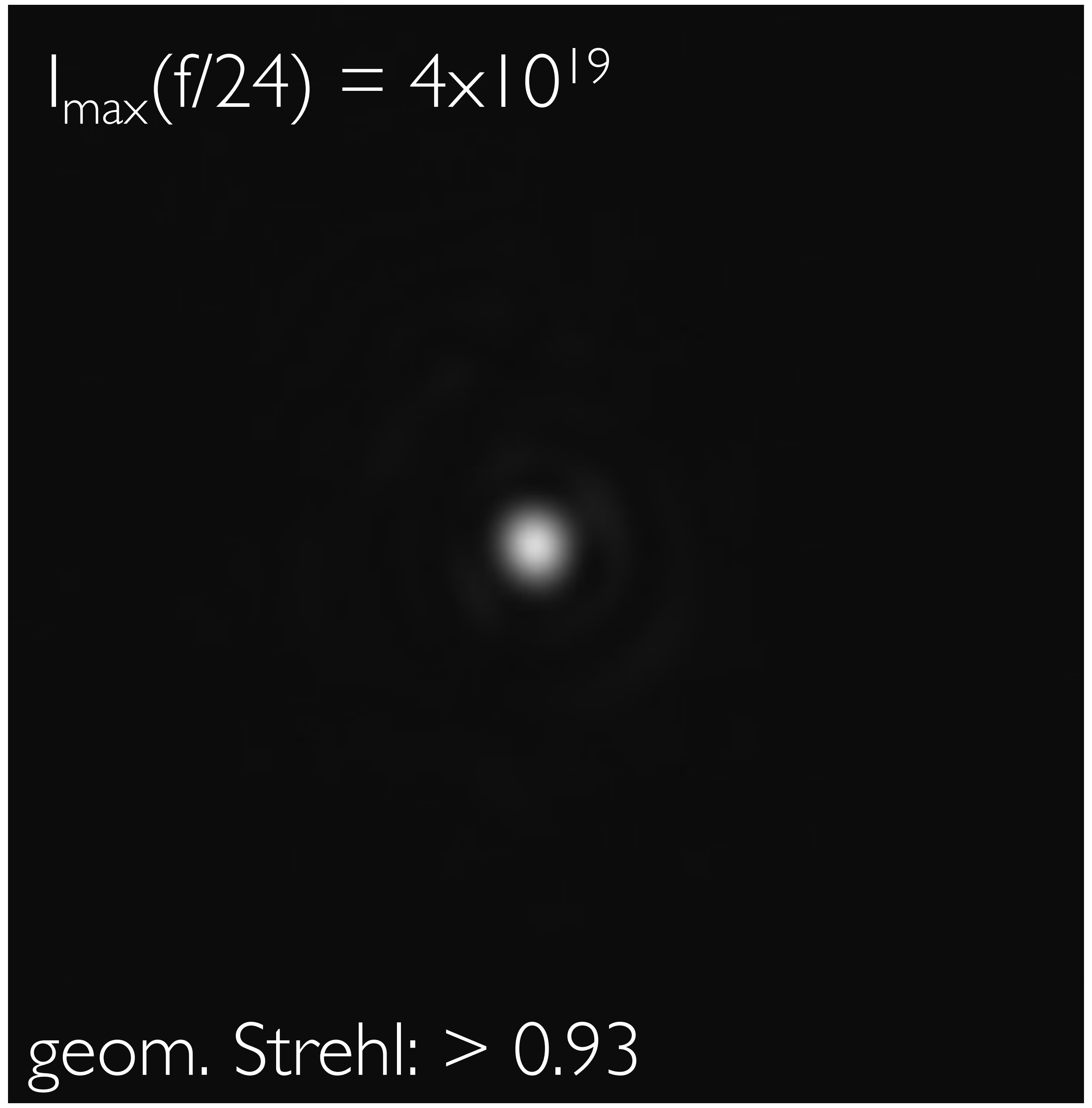
Scatter tail: stochastic delay of scattered light

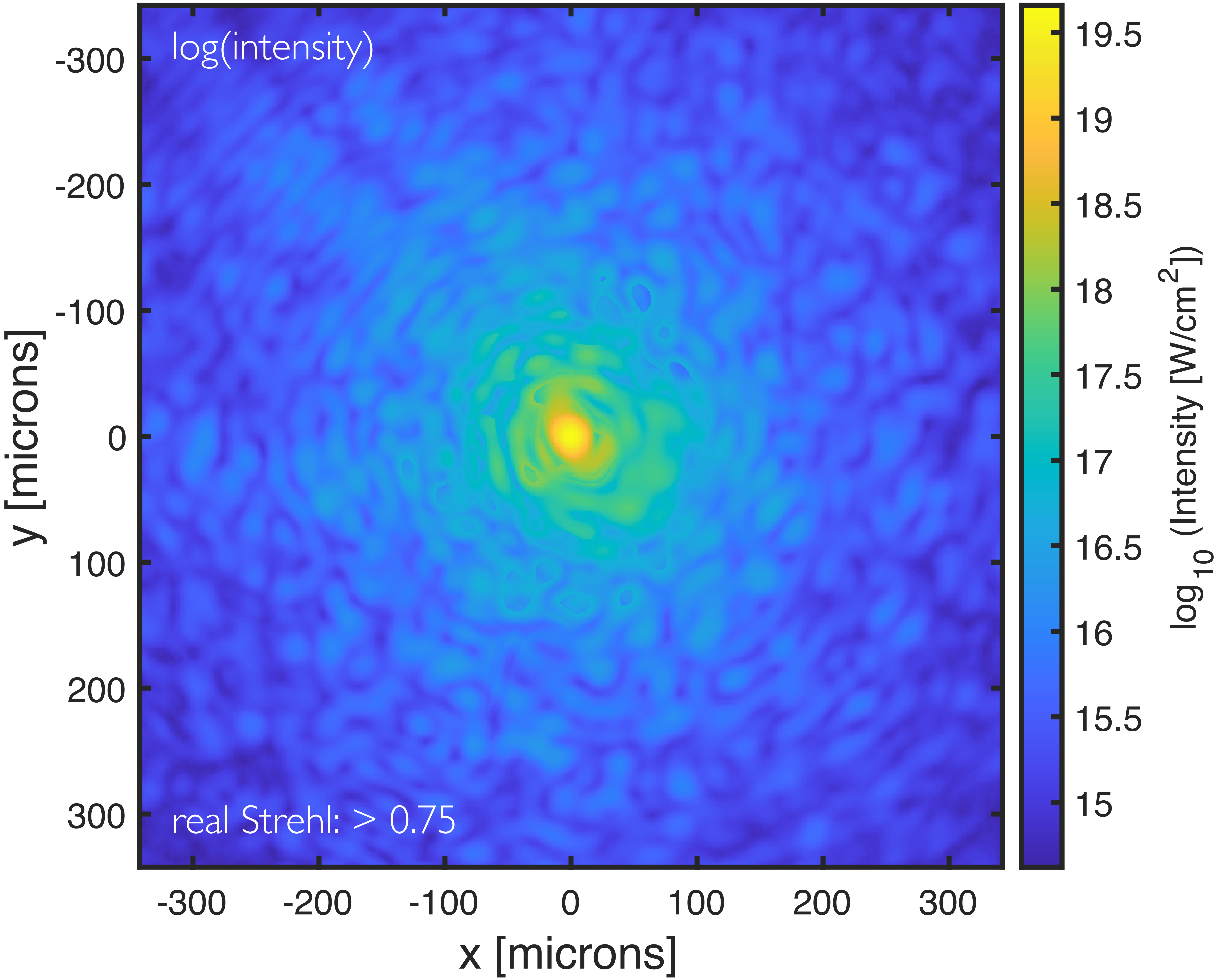
- clean optics, high-quality coatings

Coherent contrast: random phase errors from nonlinear propagation and scattering off gratings

- Low-scatter gratings, optimized geometry
- Avoid nonlinear propagation

Spatial contrast:





ASE: Transverse lasing

Laux et al., Optics Letters **37**, 1913 (2012)

- Disk geometry → large gain in direction of diameter.
- Birefringence favours gain ⊥ c-axis
- Fresnel reflection from disk edge sets up a cavity

→ Strong gain depletion ⊥ c-axis visible in fluorescence signal

- Index-matched absorptive liquid around crystal circumference destroys the lasing cavity.

- Short pump times of Ti:Sa facilitate ASE mitigation.

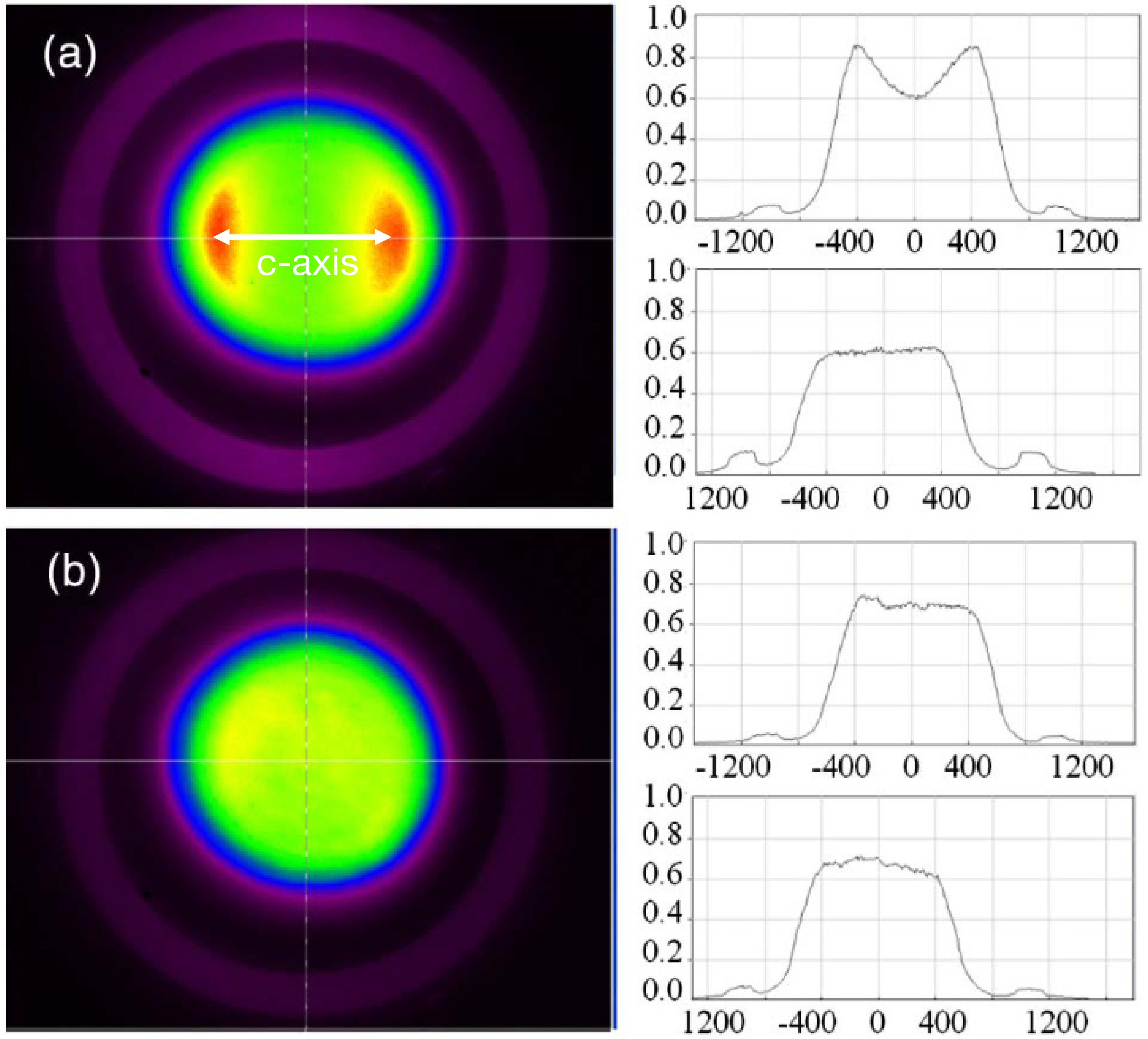
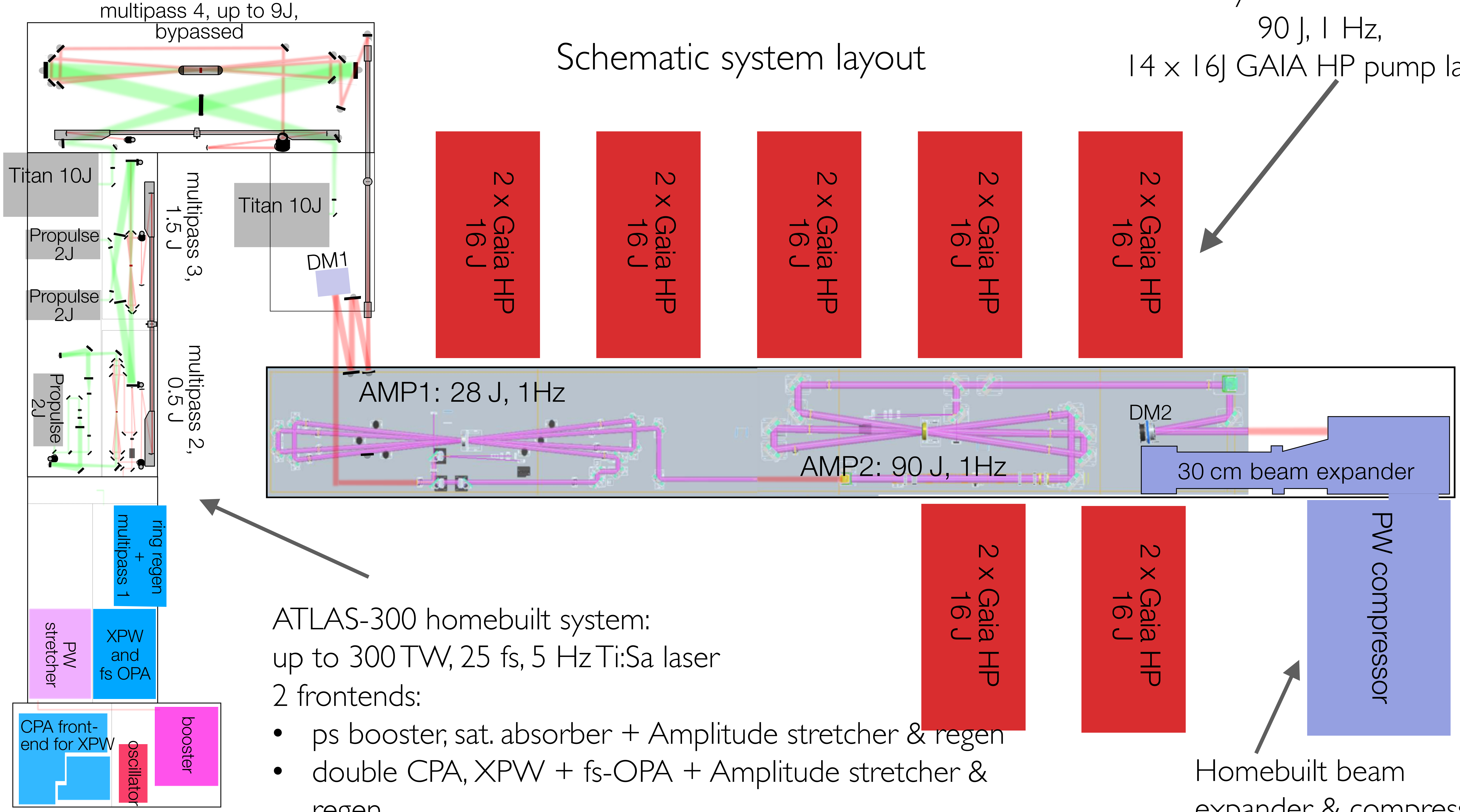


Fig. 4. (Color online) Fluorescence of the Ti:sapphire crystal with (a) ethanol and (b) refractive index liquid mixture. The C-axis is horizontal.

ATLAS-3000: 1 Hz, 3 PW system

ATLAS-3000 main amplifier
by THALES LAS
90 J, 1 Hz,
14 x 16J GAIA HP pump lasers

Schematic system layout



ATLAS-300 homebuilt system:
up to 300 TW, 25 fs, 5 Hz Ti:Sa laser
2 frontends:

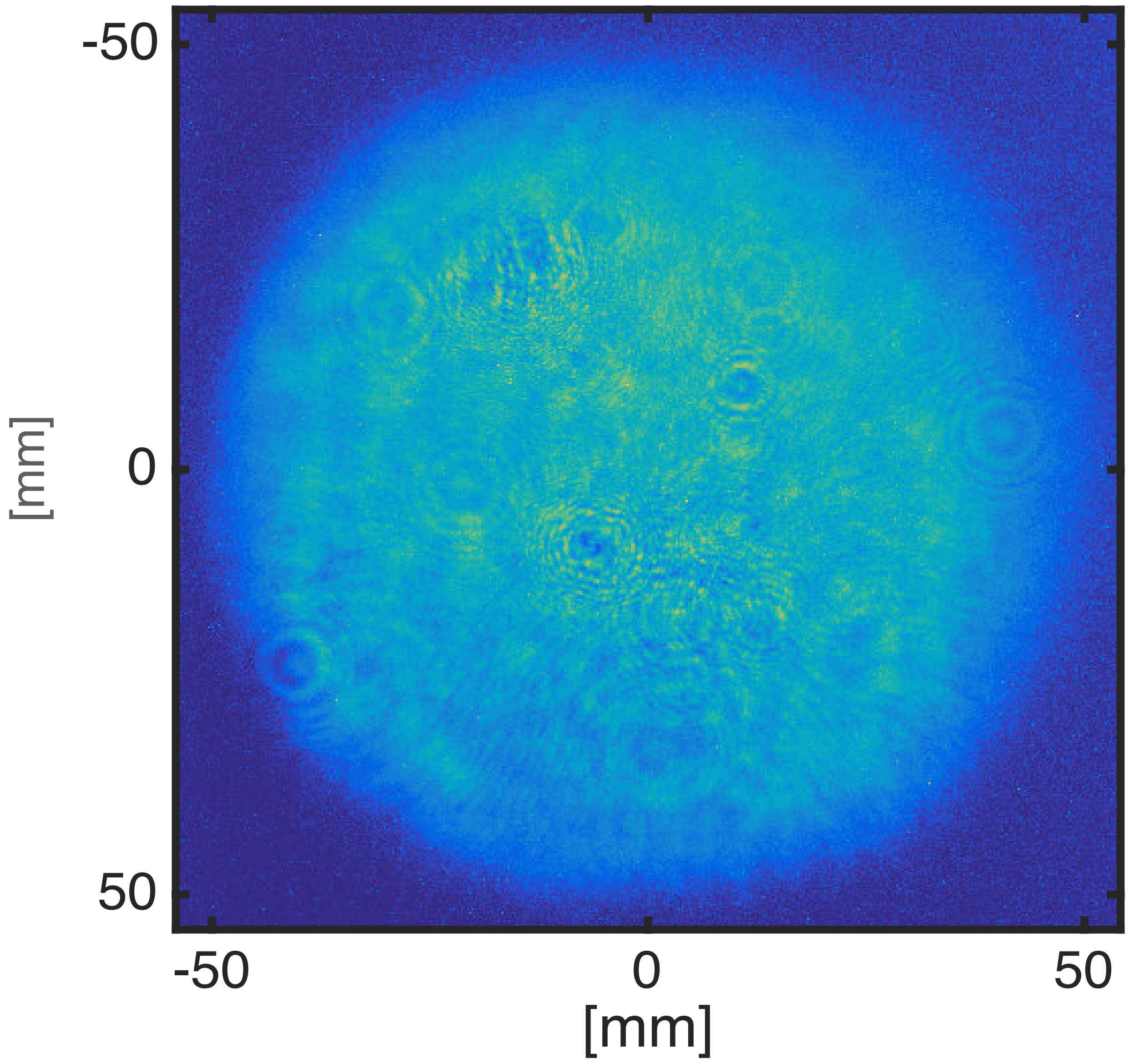
- ps booster, sat. absorber + Amplitude stretcher & regen
- double CPA, XPW + fs-OPA + Amplitude stretcher & regen

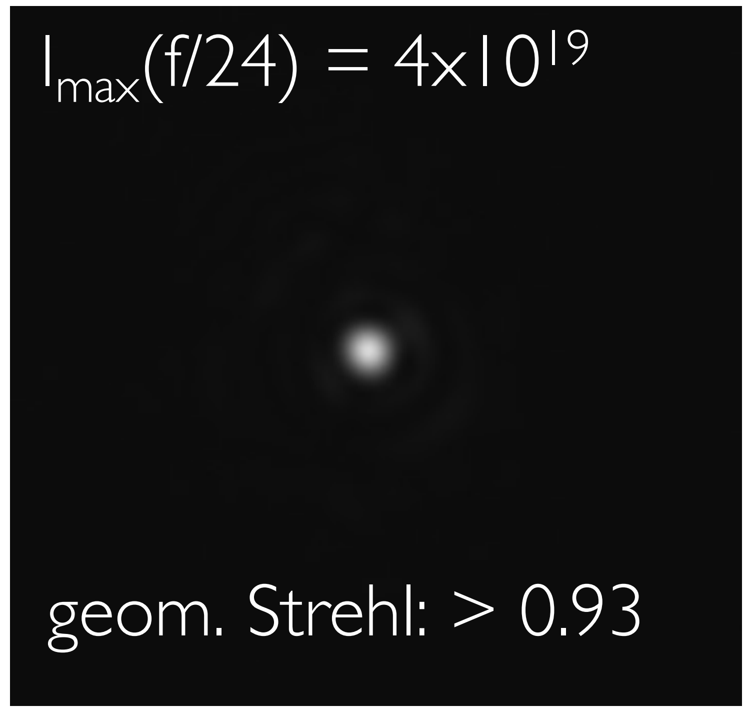
Homebuilt beam expander & compressor

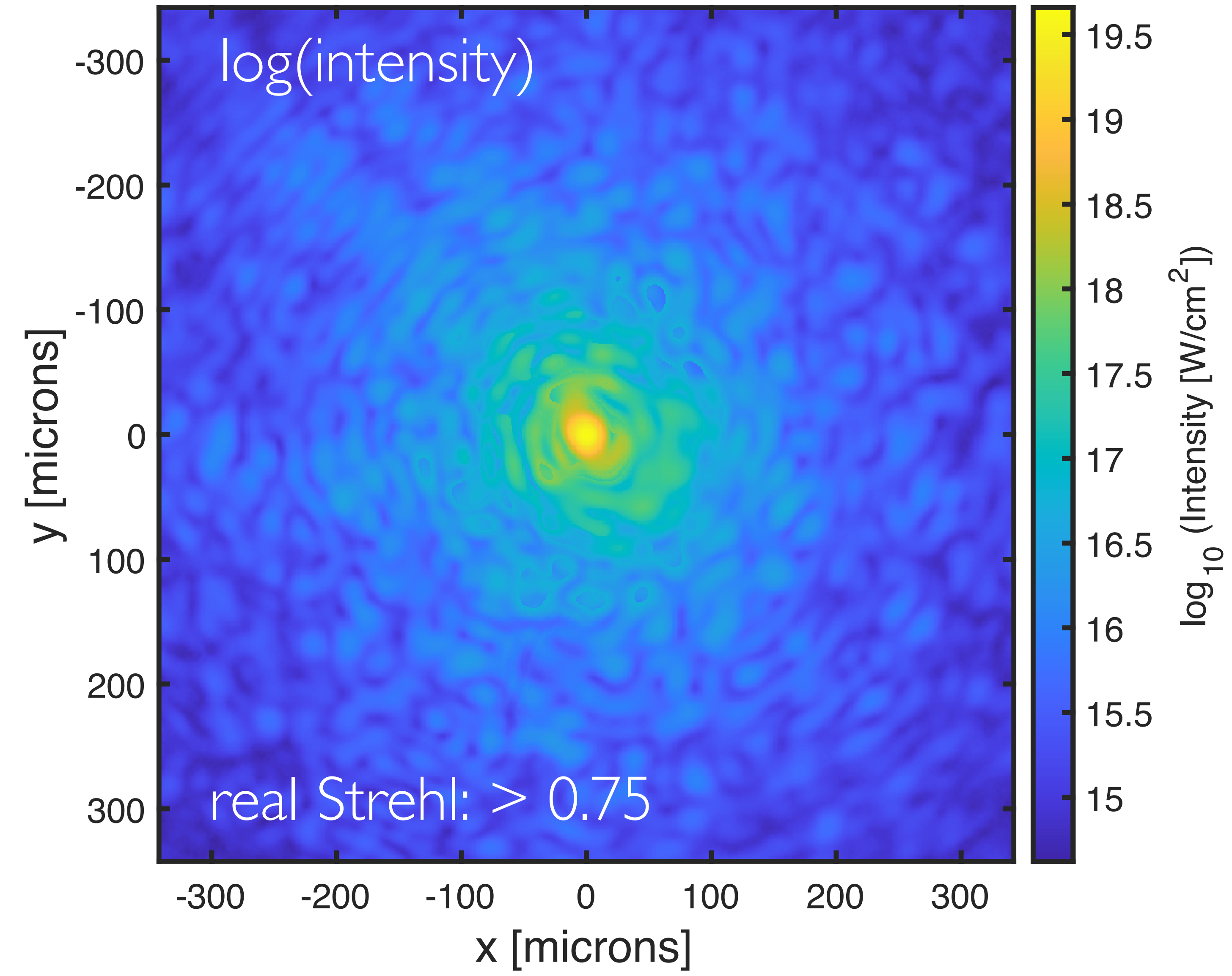
ATLAS-3000: current performance

near field | far field | contrast

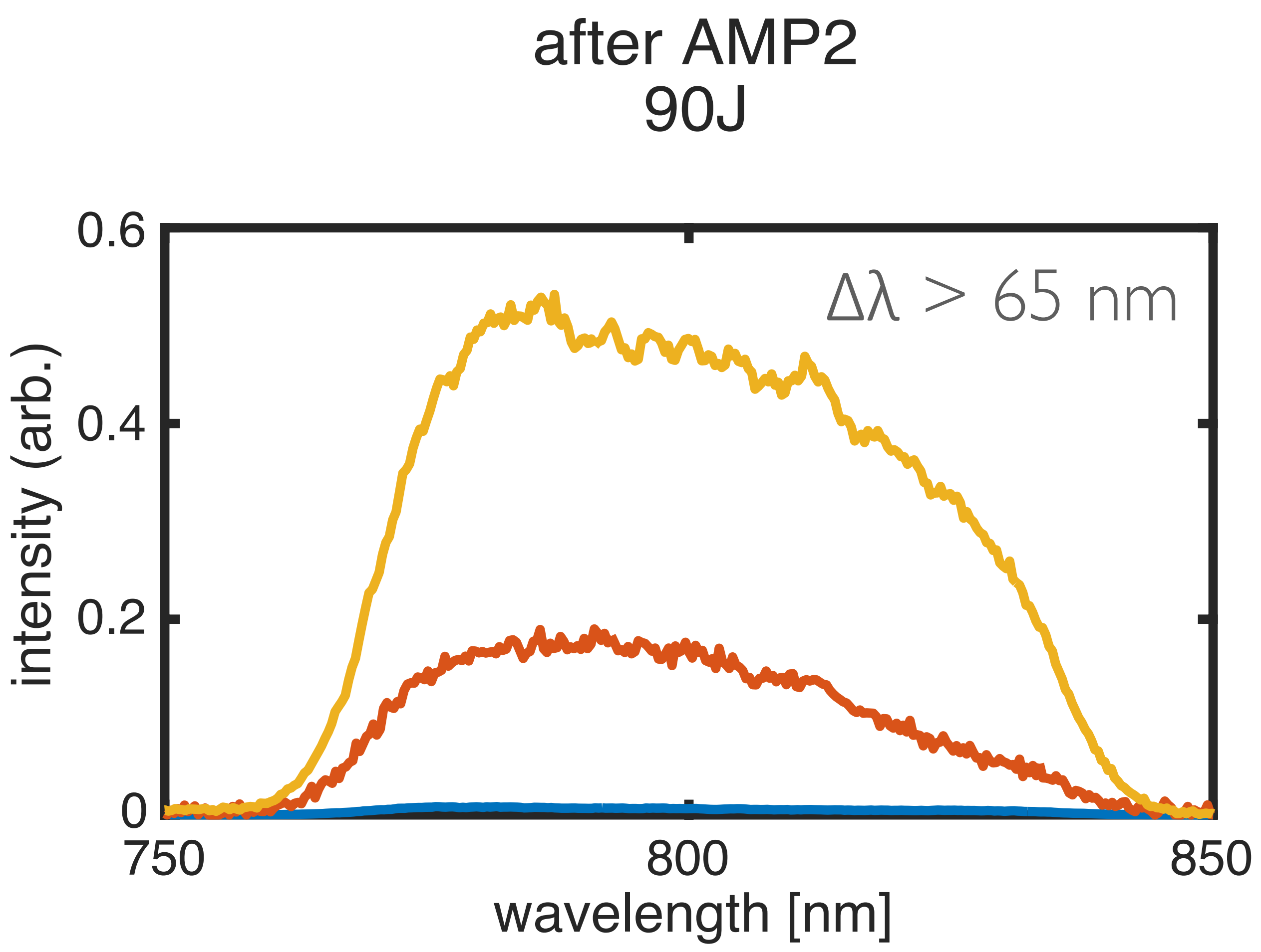
spatial

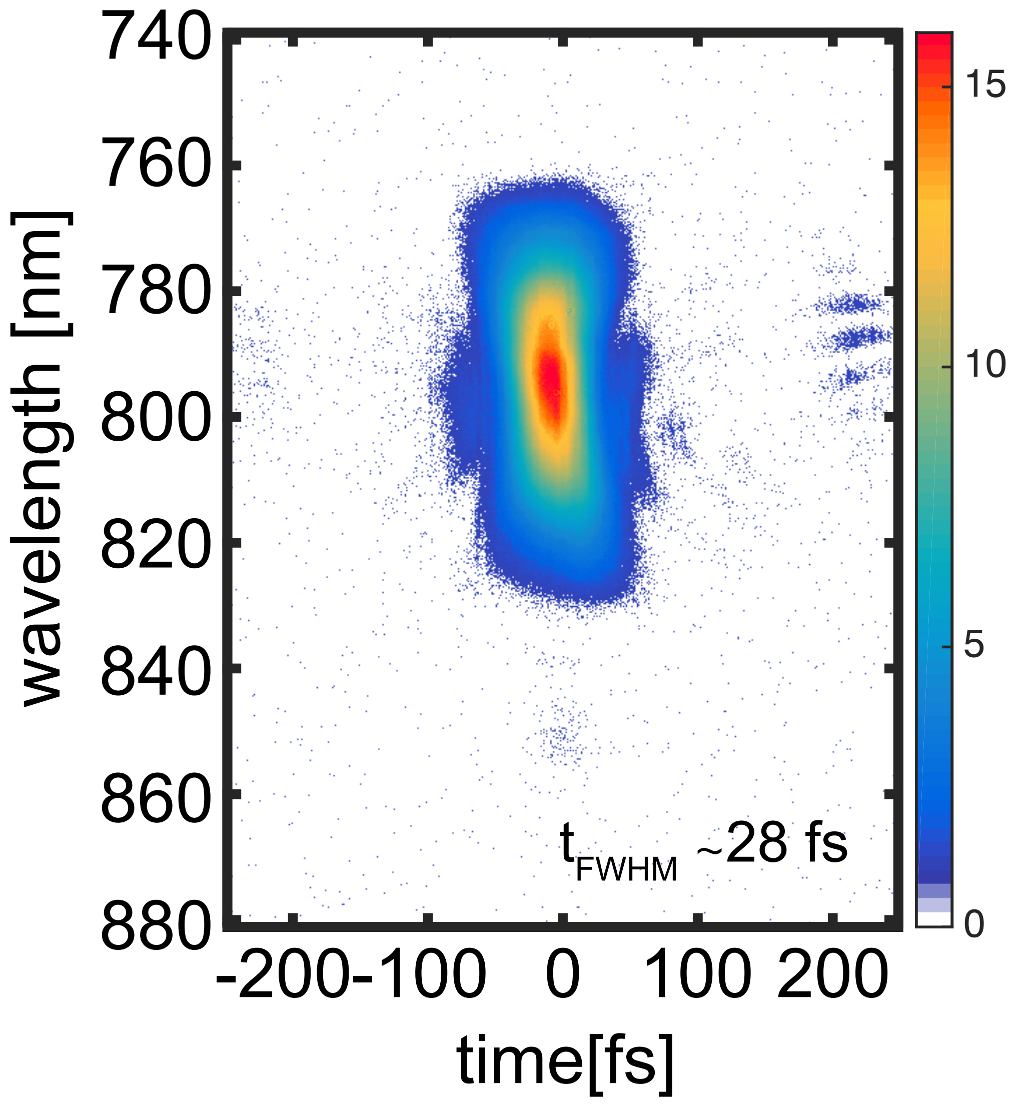


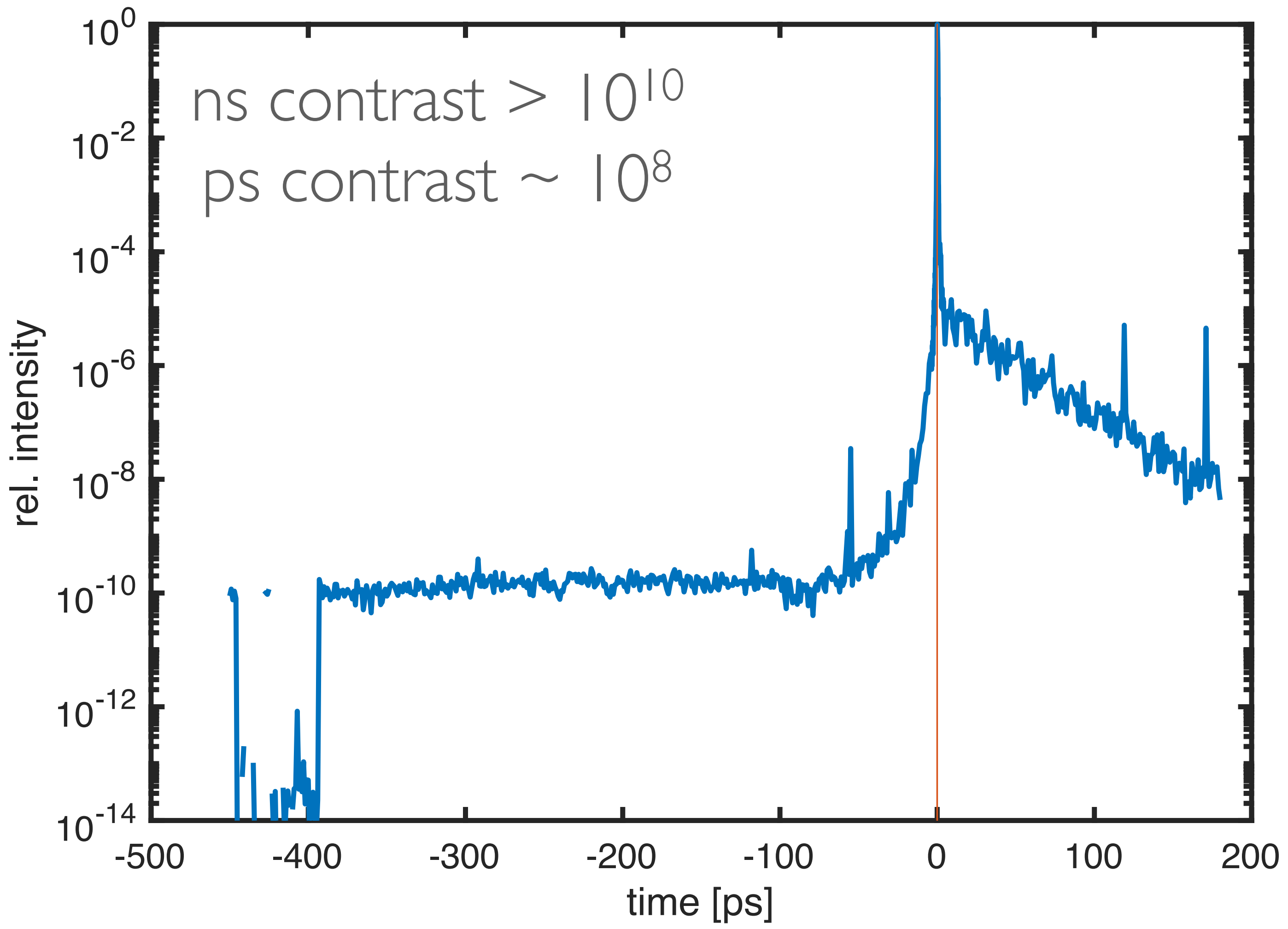




spectro-temp.

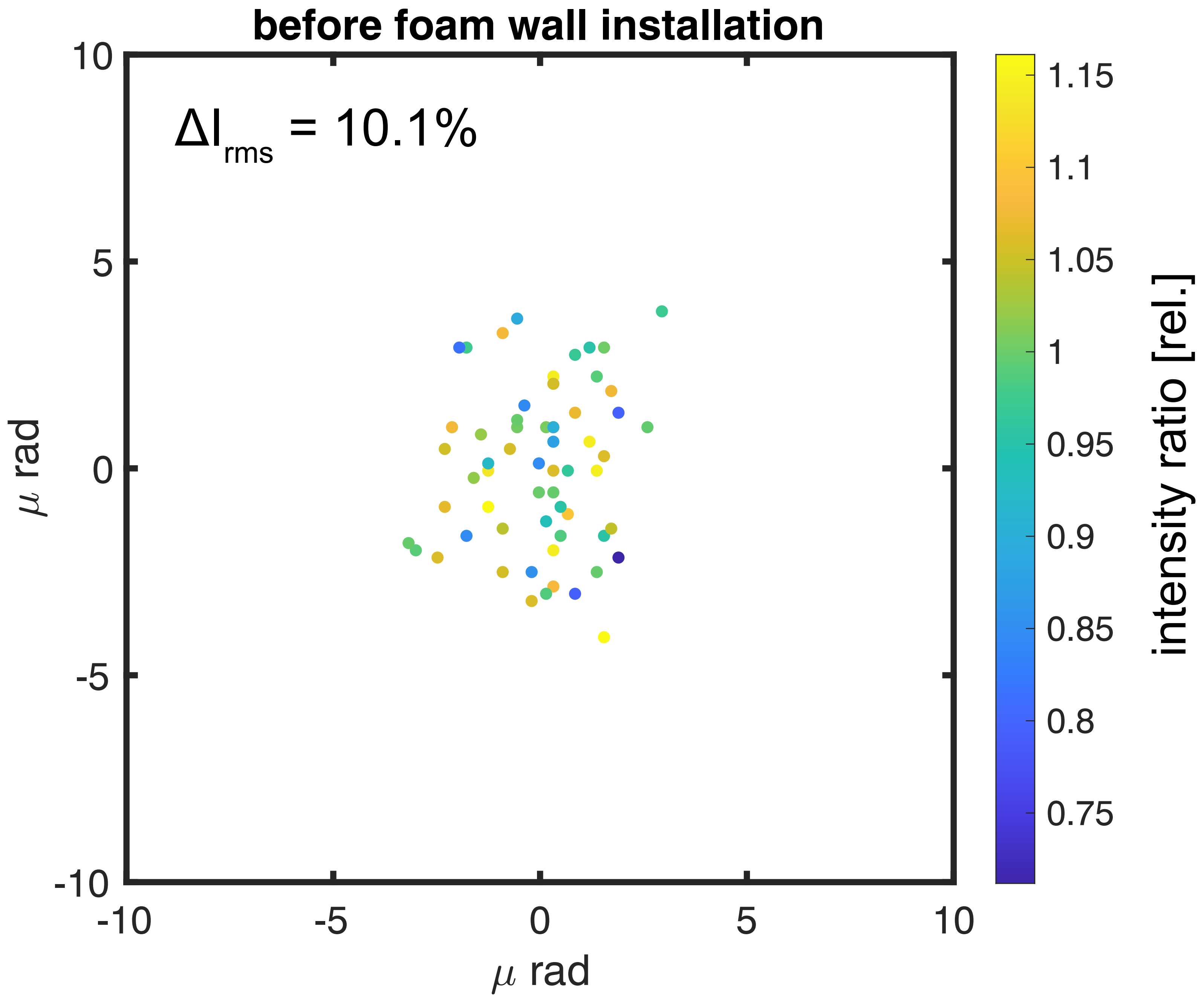


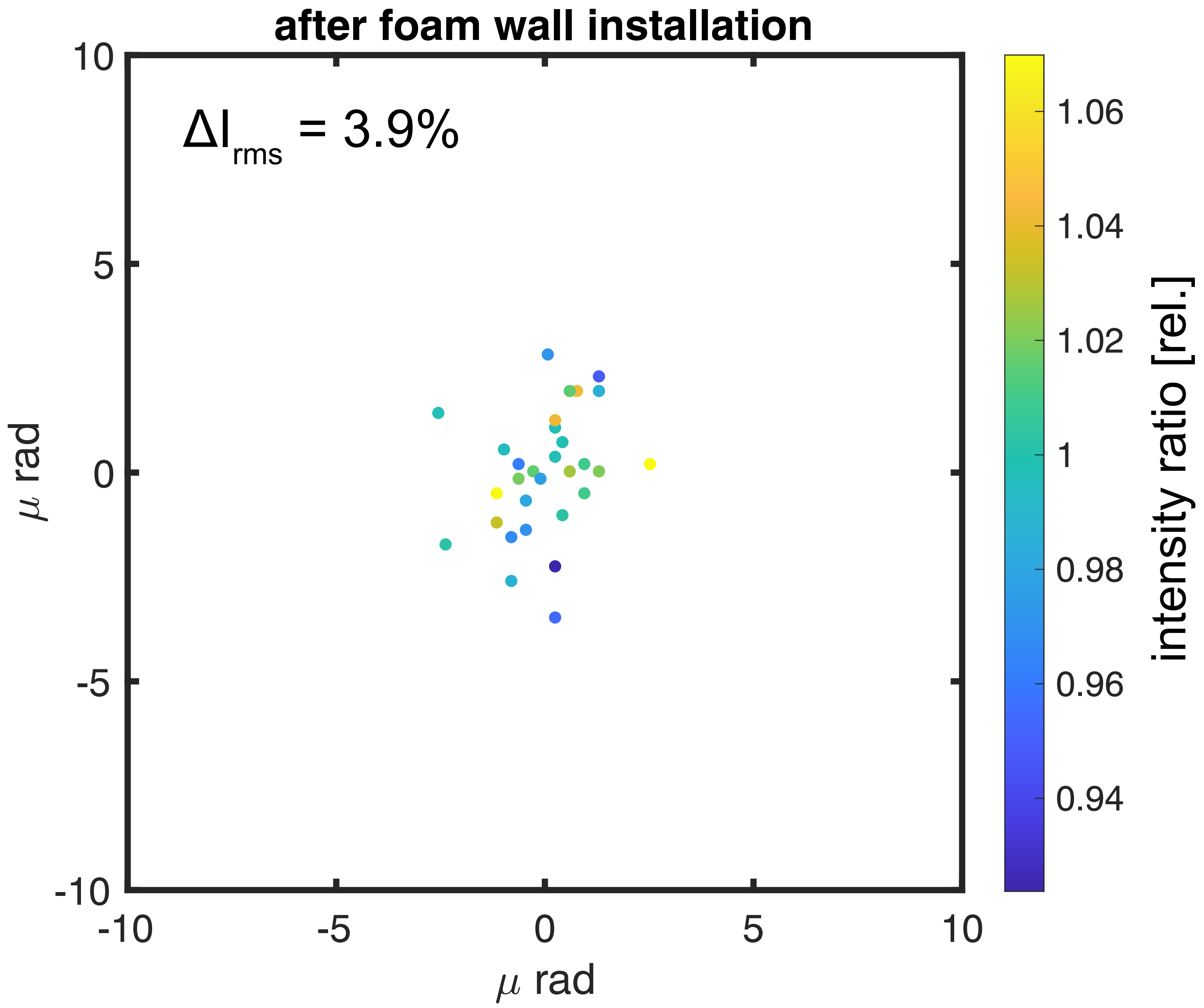


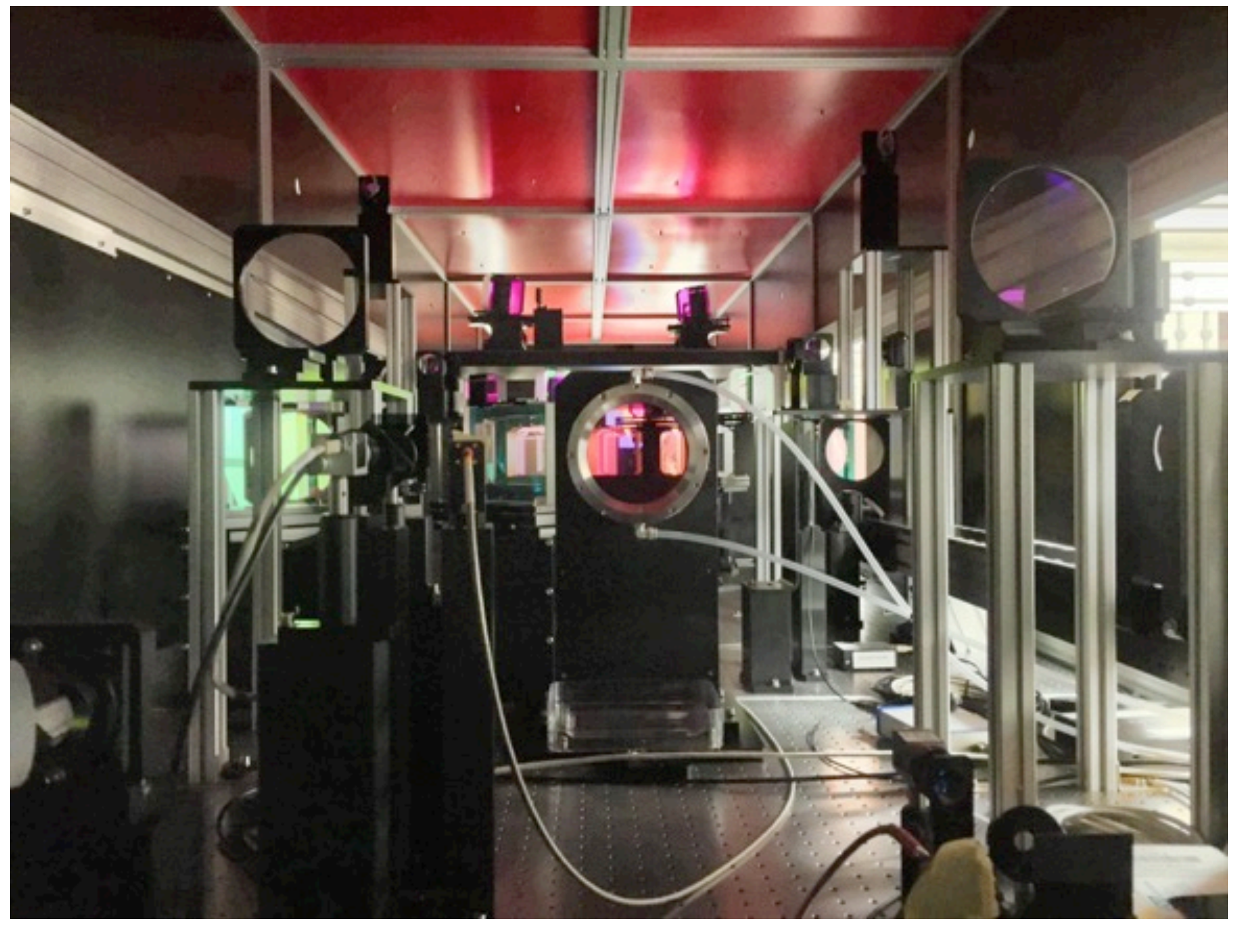


Air turbulence:

Moving from 100 TW to PW: as beam size and optical path increase, so does susceptibility to air turbulence.

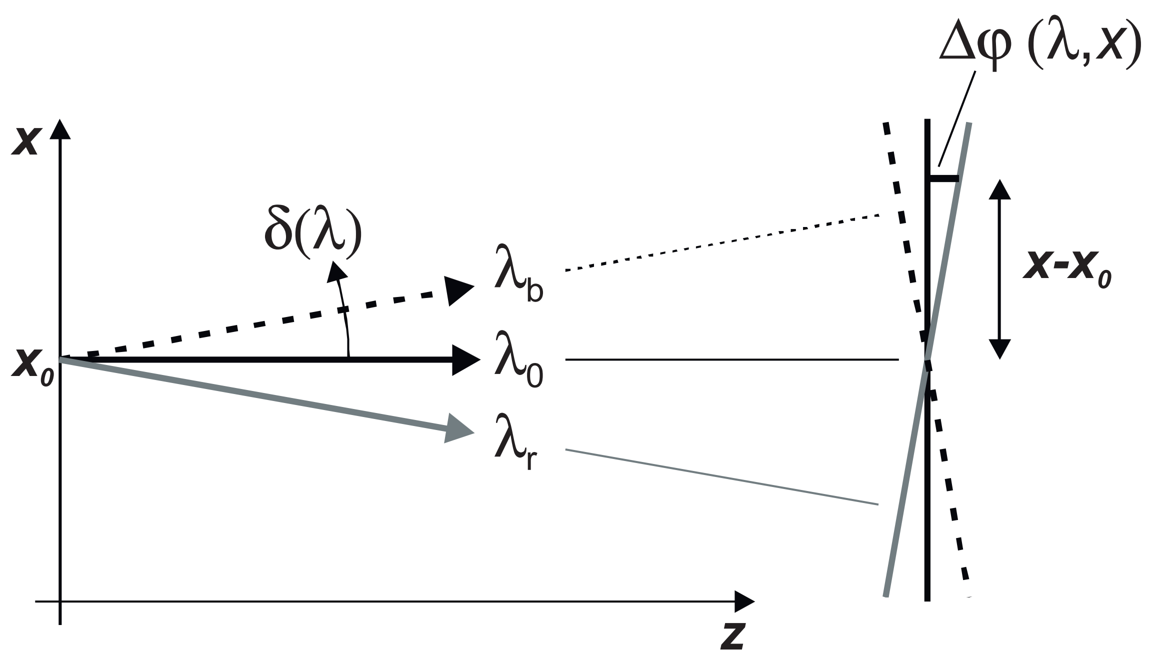


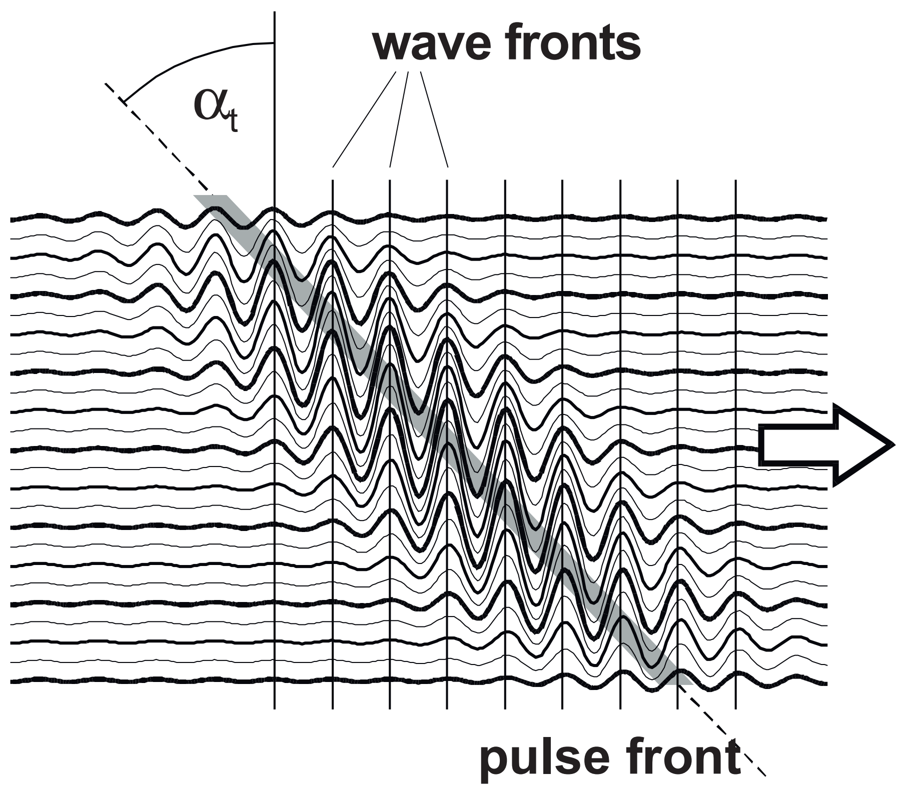




Spatio-temporal couplings: large broadband laser beams exhibit them due to chromatic aberrations

Lowest order effect: Angular chirp causes pulse front tilt:

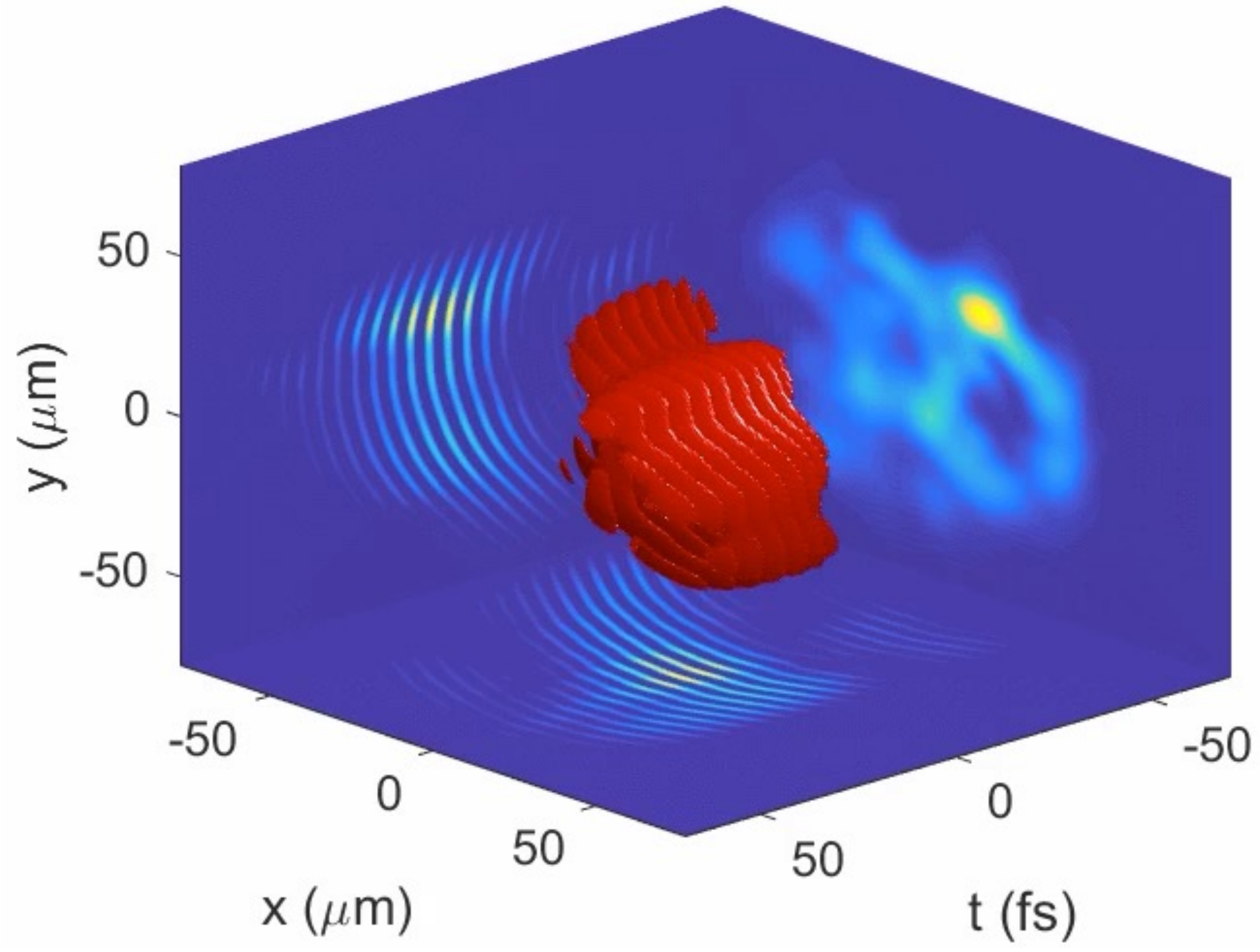




Pulse arrives at different time at different positions in space
⟹ STCs

static wavefront aberrations + chromatic optics (gratings)
⟹ higher order STCs

fluctuating wavefront aberrations (air turbulence) + chromatic optics
⟹ fluctuating high-order STCs: Crucial for stability



A. Borot, F. Quere, Optics Express 26, 26444 (2018):
Spatio-temporal E-field of the UHI100 laser

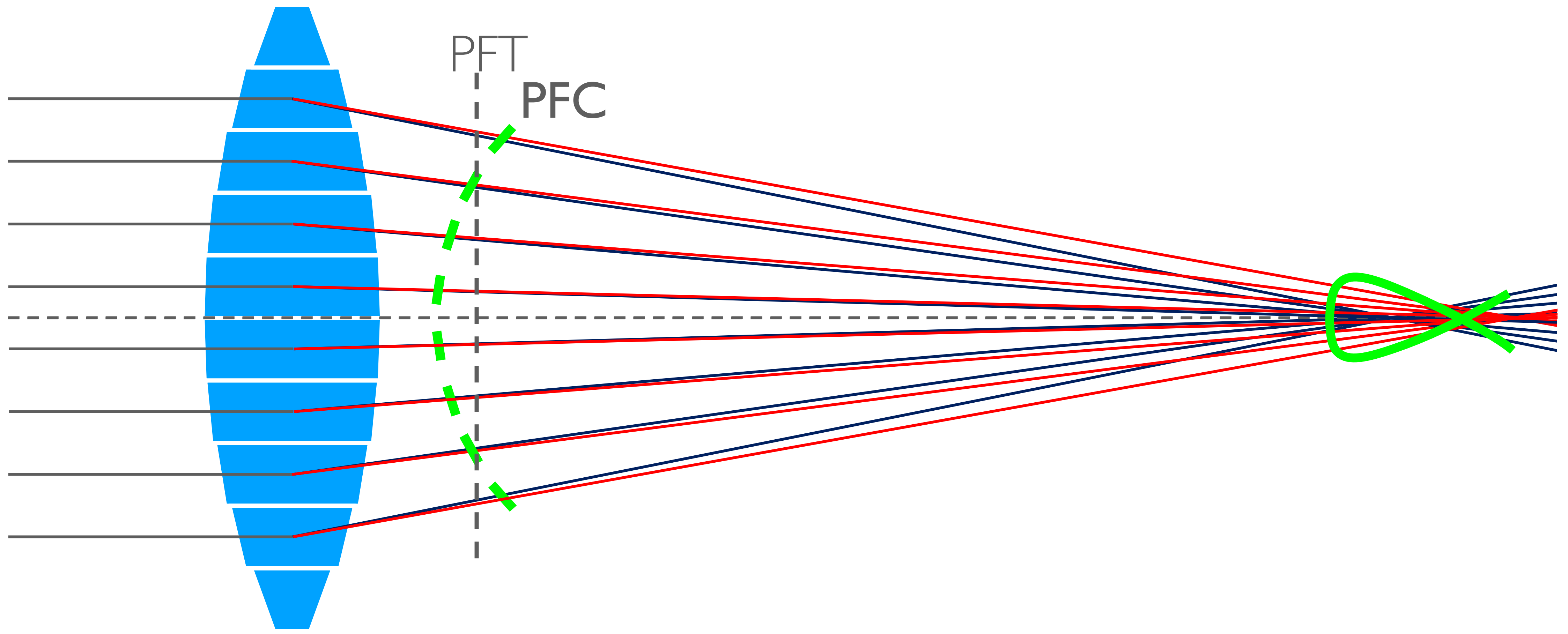
Scanning methods (INSIGHT, TERMITES) cannot detect the fluctuations

⬇

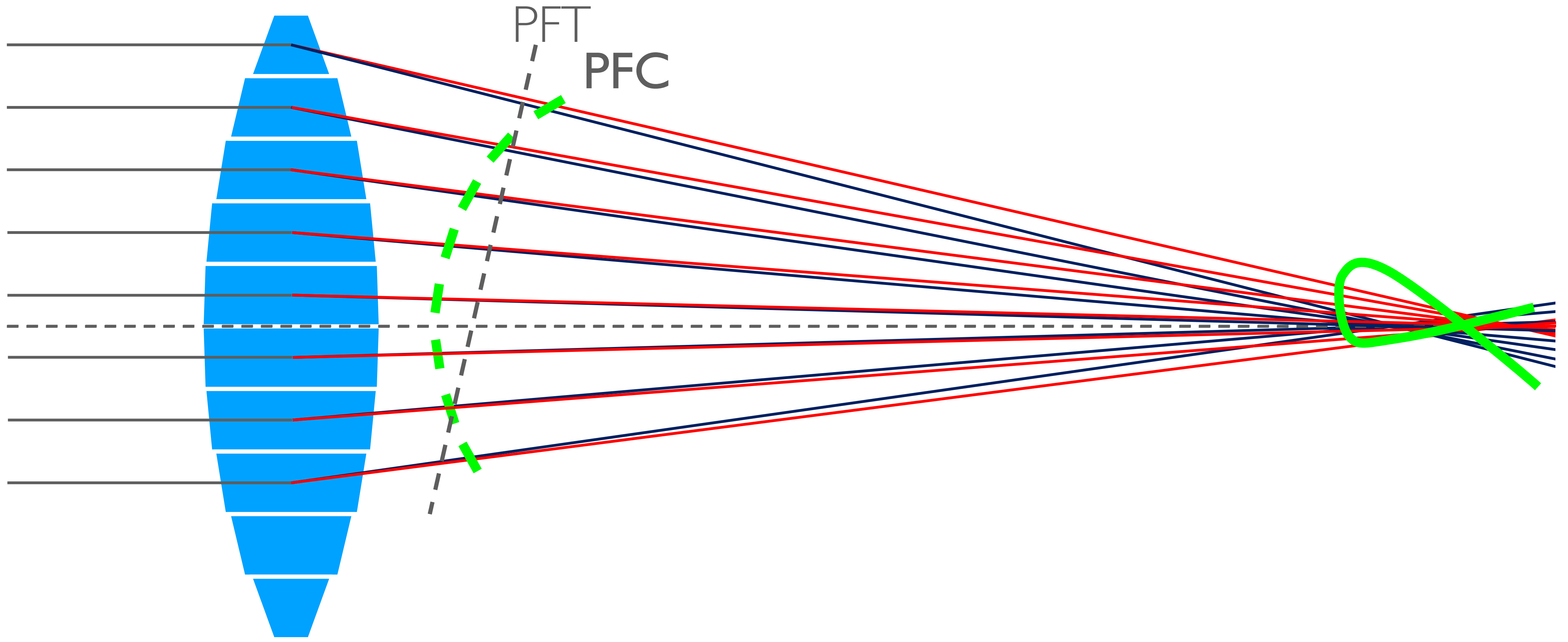
We are working on single-shot approaches

STCs by chromatic optics

Chromatic lens causes pulse front curvature (PFC)



Off-center bundle in chromatic lens causes PFC and pulse front tilt (PFT)

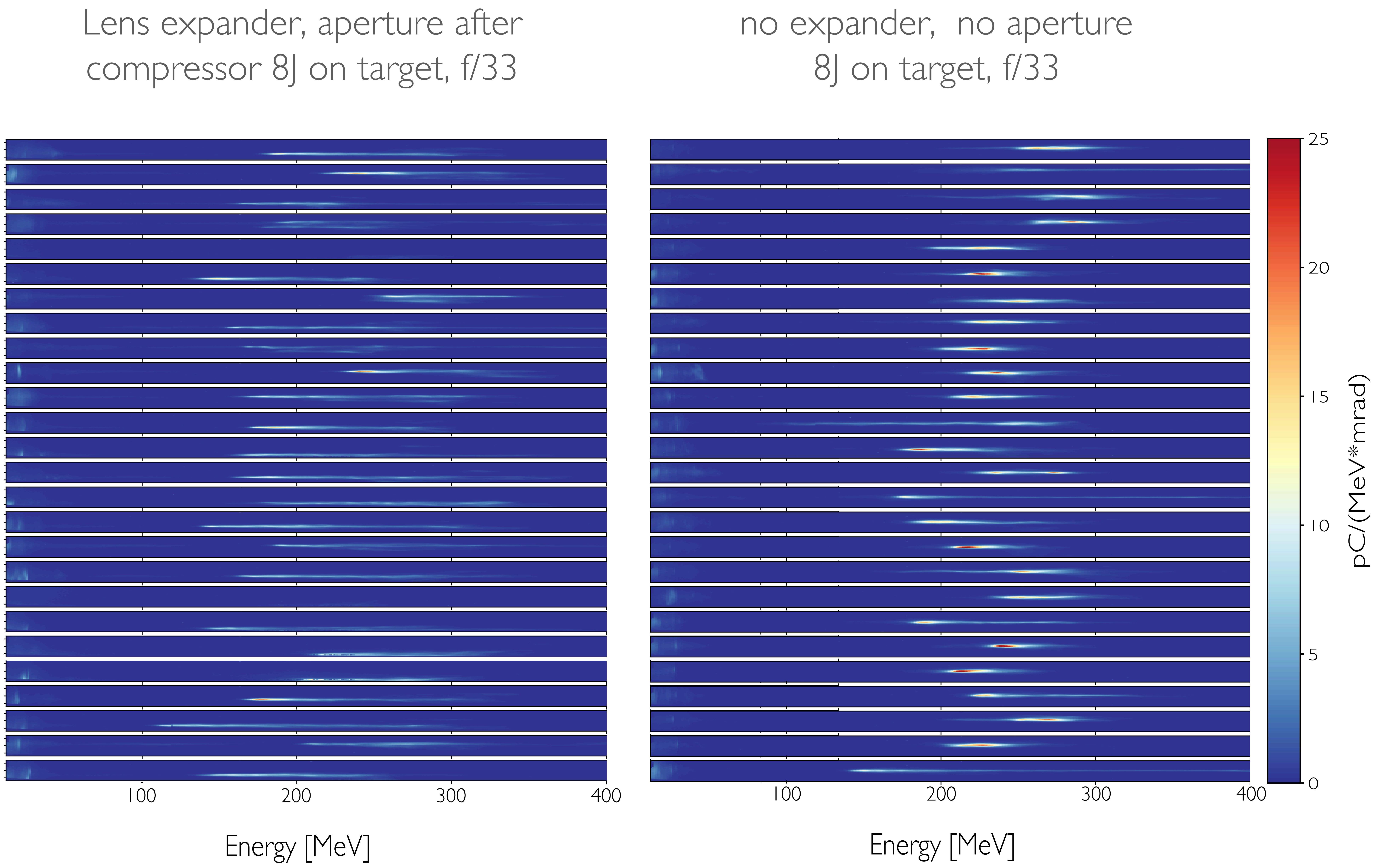


"A(po)chromatic lenses are free from PFT/PFC" ⇒
Triplet lens expander between AMP1 and AMP2 is designed as apochromatic within lambda/50

Yet still detect PFT after beam shift ⇒ expander in practice is not free from STCs

Replace "perfect" lens telescope by reflective expander

Residual STCs adversely affect electron performance

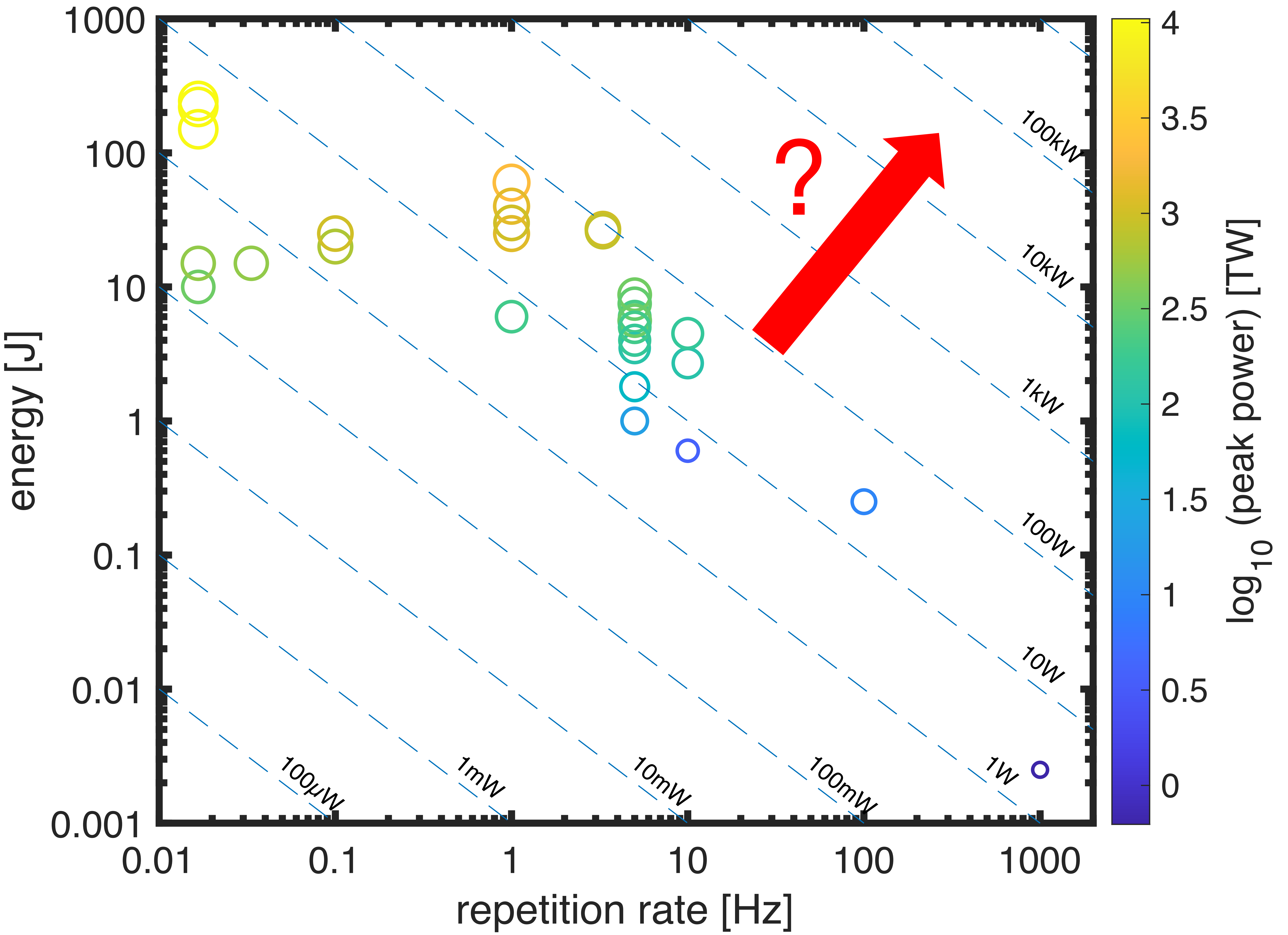


Ti:Sa laser systems worldwide:

Cover broad range of parameters:

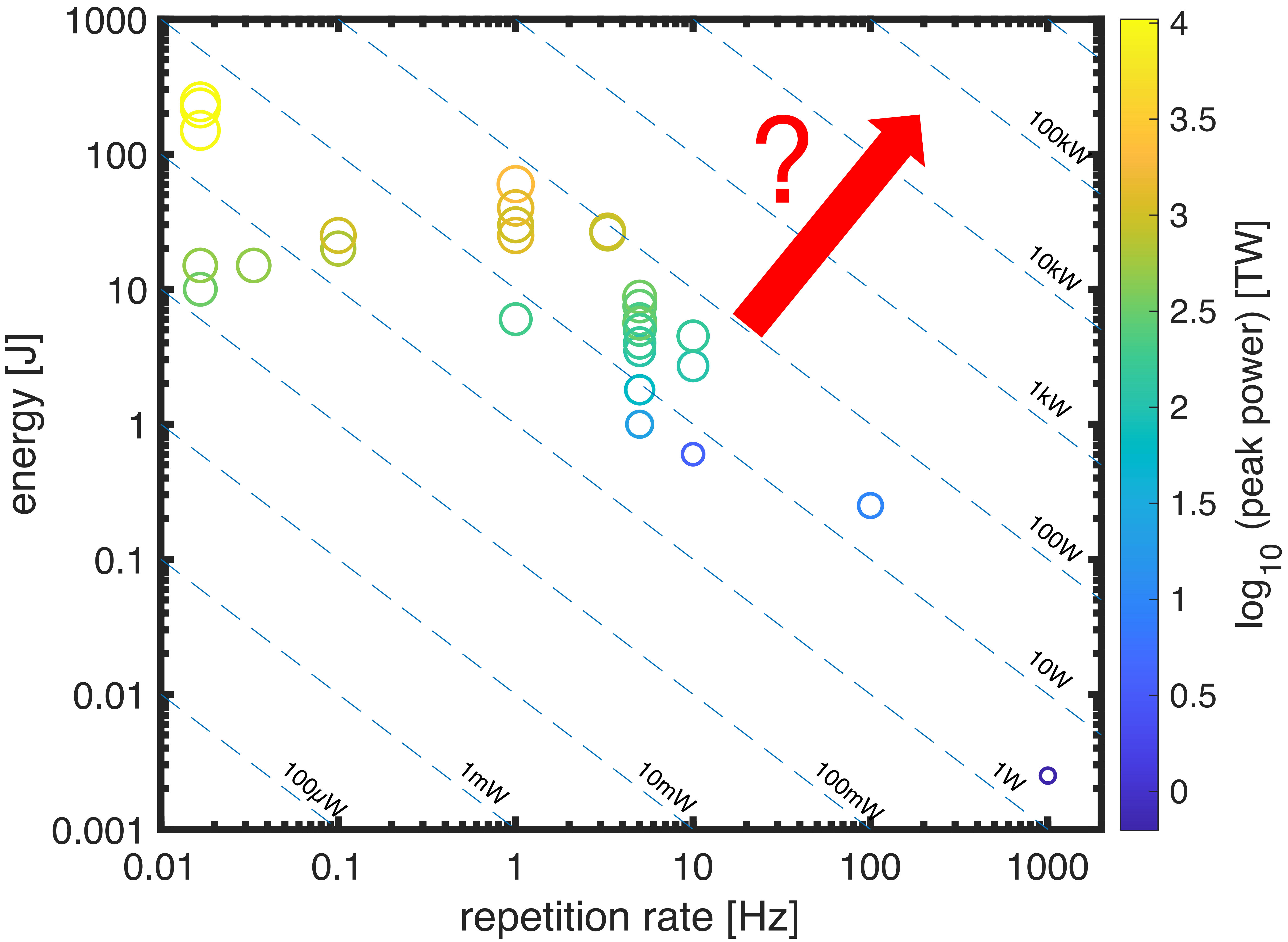
+ kHz to single-shot
+ mJ to 100J+
+ sub-TW to multi-PW
+ pulse duration 15-50 fs

- Average power limited to below 100 W



Ti:Sa laser scalability issues:

- High average power pump lasers
- Cooling of multi-kW amplifiers
- Heating of optics
- Contamination of optics
- Targetry
- Radiation safety



KALDERA project at DESY - 100TW @ kHz LPA Drive Laser

Science Case

Fig: SciCom Lab

Science Case
- Active feedback
- Competitive repetition rate
- Technology demonstrator

Goal:
- 100 TW @ kHz, 3J @ 30 fs laser pulse
- FEL-quality electron beams: sub-percent energy spread, sub-percent energy stability

Andi Maier, Project Leader

Initiated by Wim

High Average Power Pump Laser

Technology Candidates

Massively parallel fibre lasers (LLE Rochester)

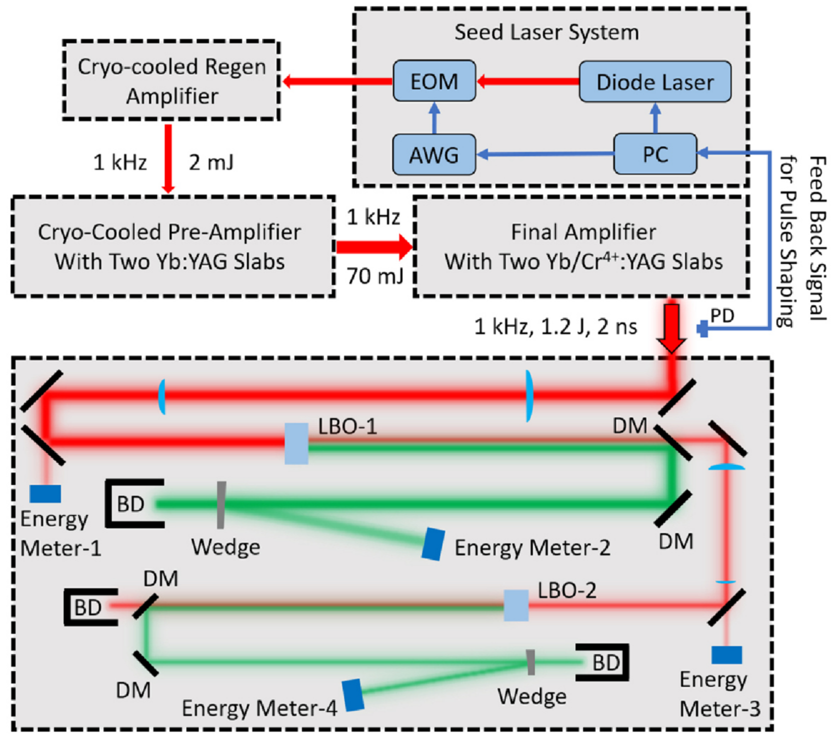
> Based on cheap few-mJ fibre
> Massively parallel architecture with ~3000+ fibers

Room-temperature Yb:YAG thin disk lasers (Trumpf Scientific)

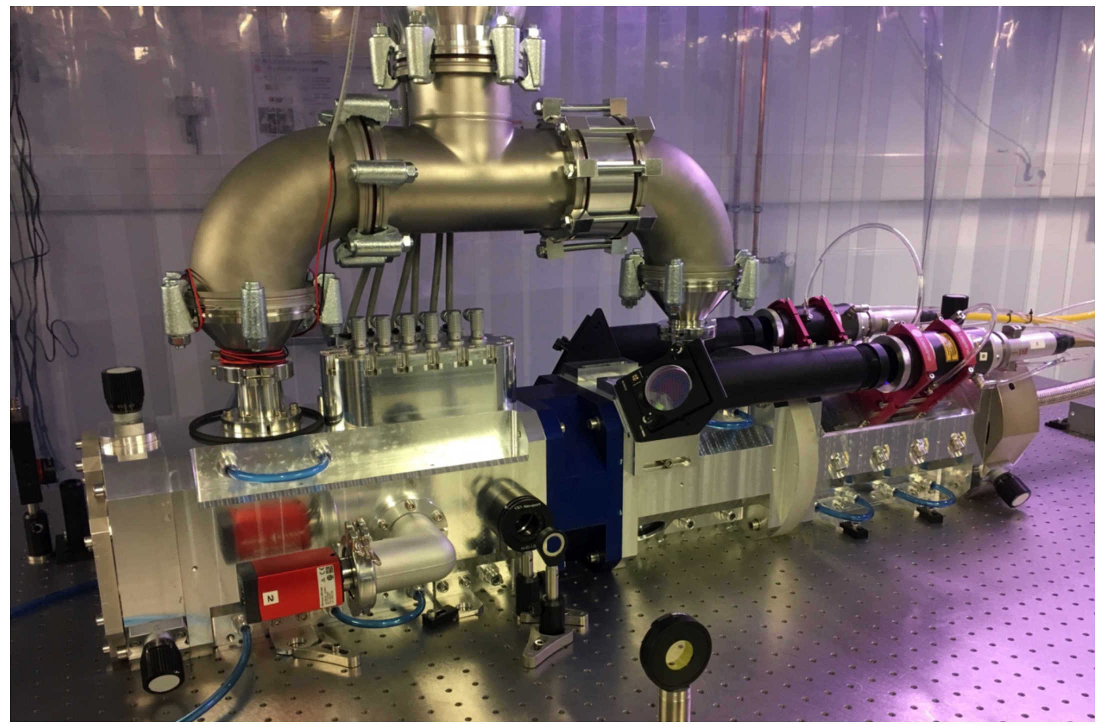
> Based on industry-grade thin-disk modules
> 1J green @ 1 kHz

Cryo-cooled Yb:YAG disk lasers (J. Rocca, CSU / M. Pergament (DESY))

> Joule class pulses @ kHz demonstrated:
Opt. Lett. 45, 6803 (2020)



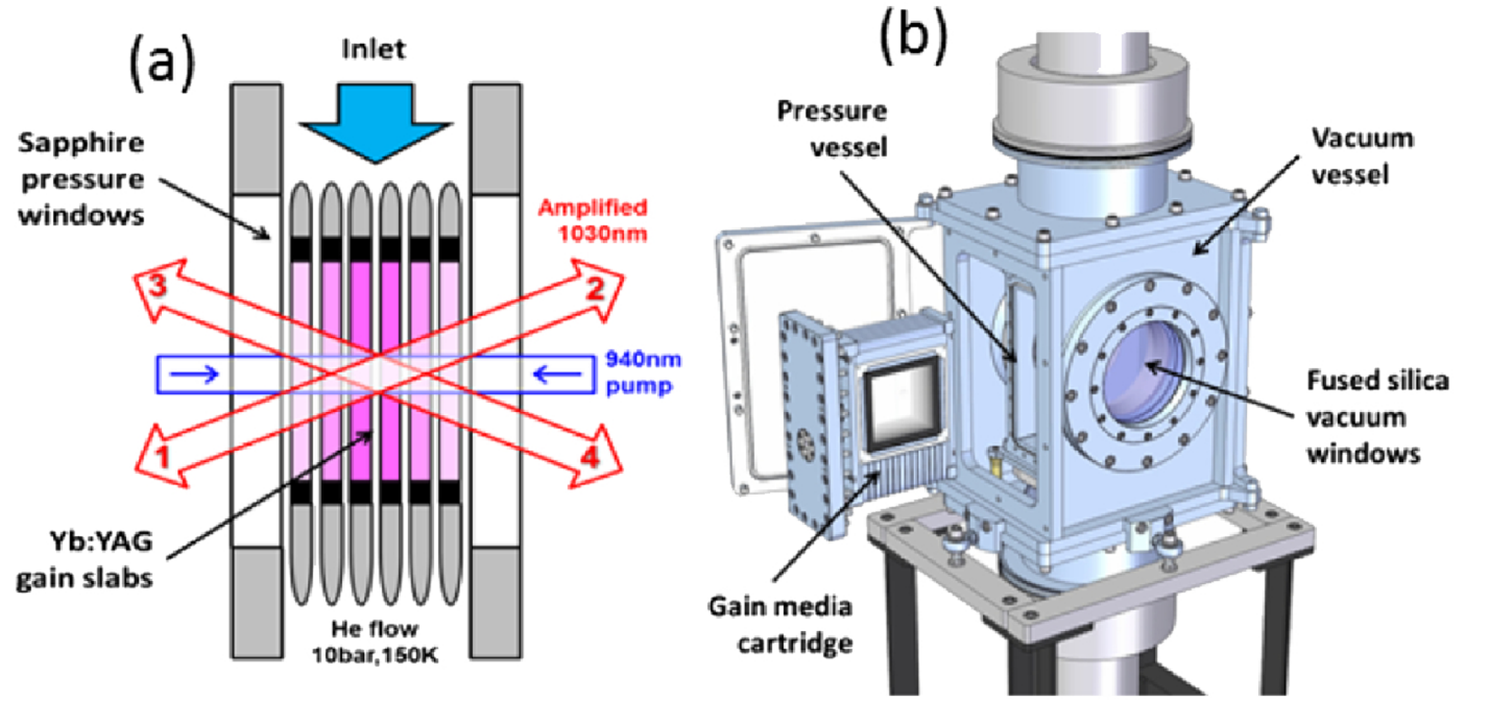
J. Rocca et al.



M Pergament et al.

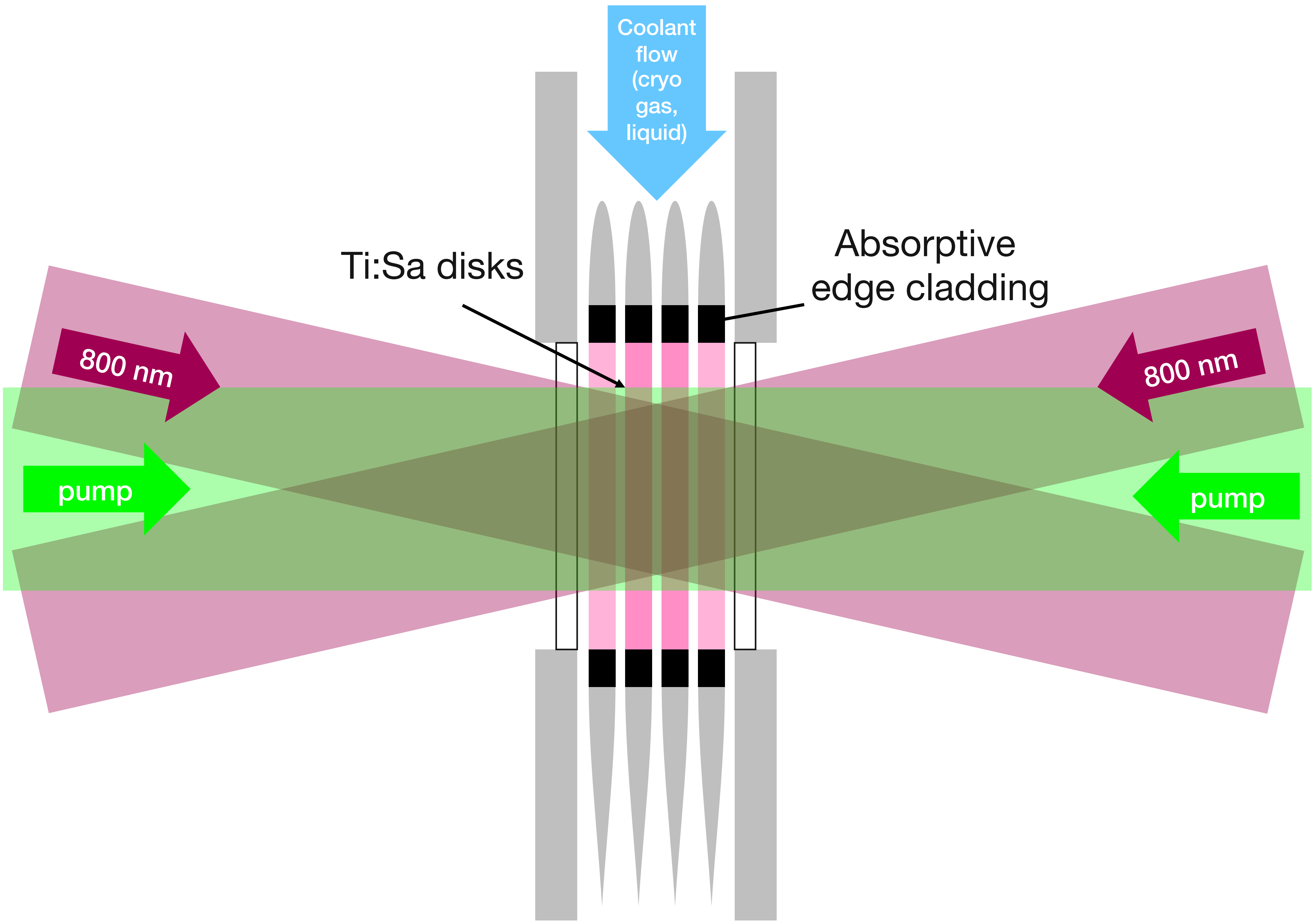
(Cryo) gas-cooled multi-slabs (DIPOLE (RAL/STFC) / HAPLS pump laser (LLNL/ELI))

> Opt. Lett 41, 2089 (2016)



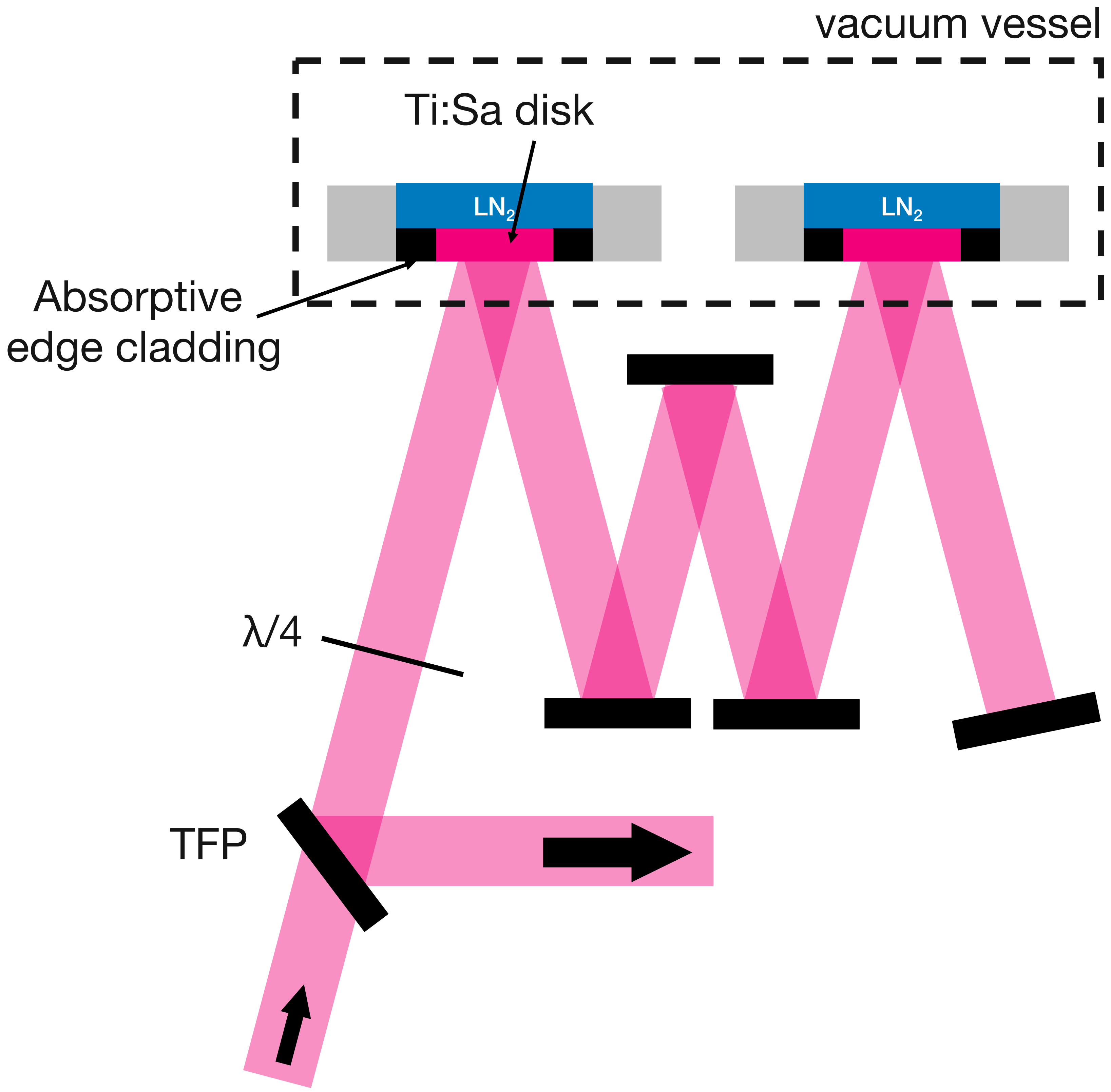
Amplifier Cooling:

Liquid or gas-cooled multislabs:



V. Chvykov, Crystals 11, 841 (2021)

Active mirror:



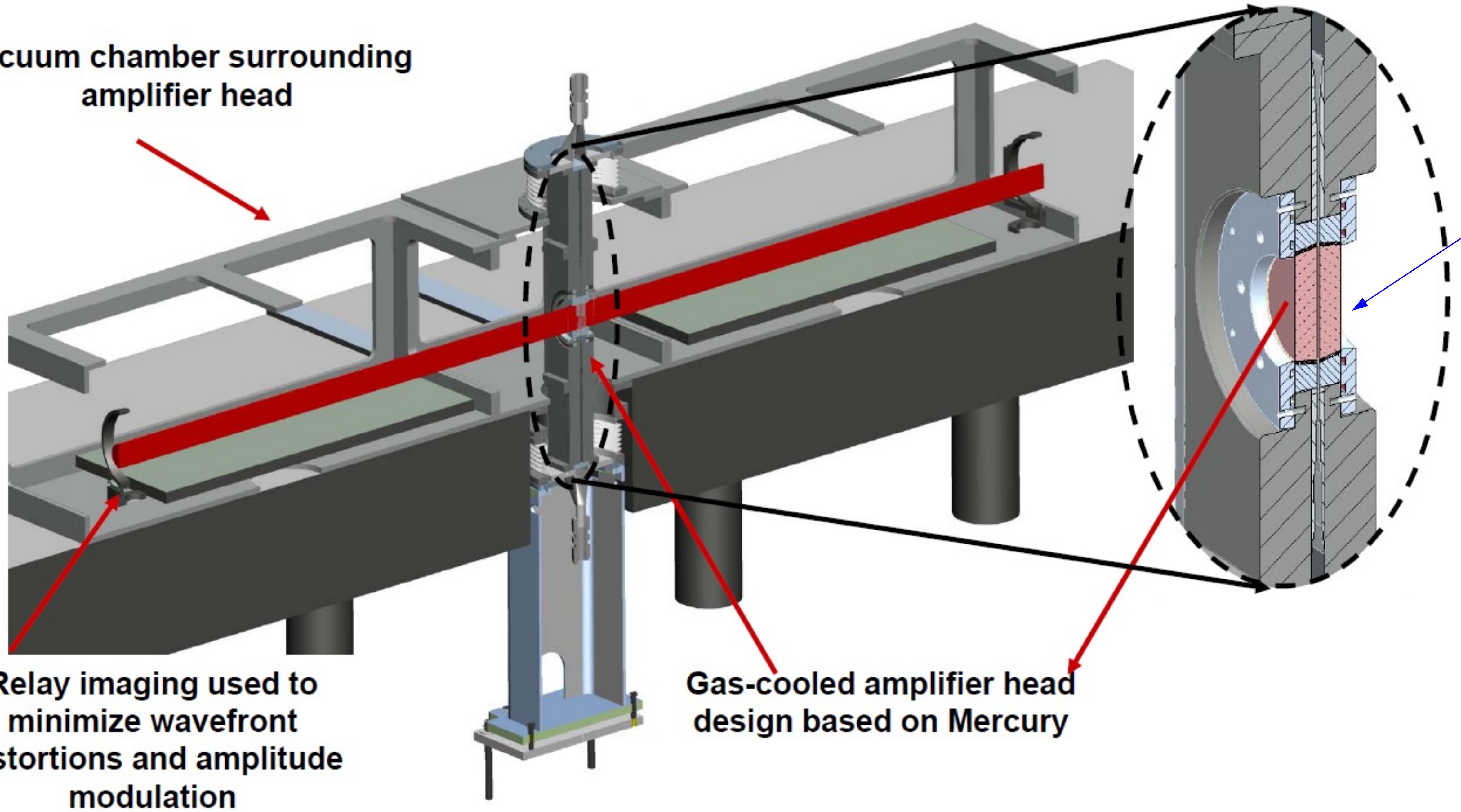
Sketch similar to C. Baumgarten et al., Optics Letters 41 3339 (2016)
M.Krüger et al., in preparation

He gas-cooled Ti:sapphire PW amplifier head in L3-HAPLS

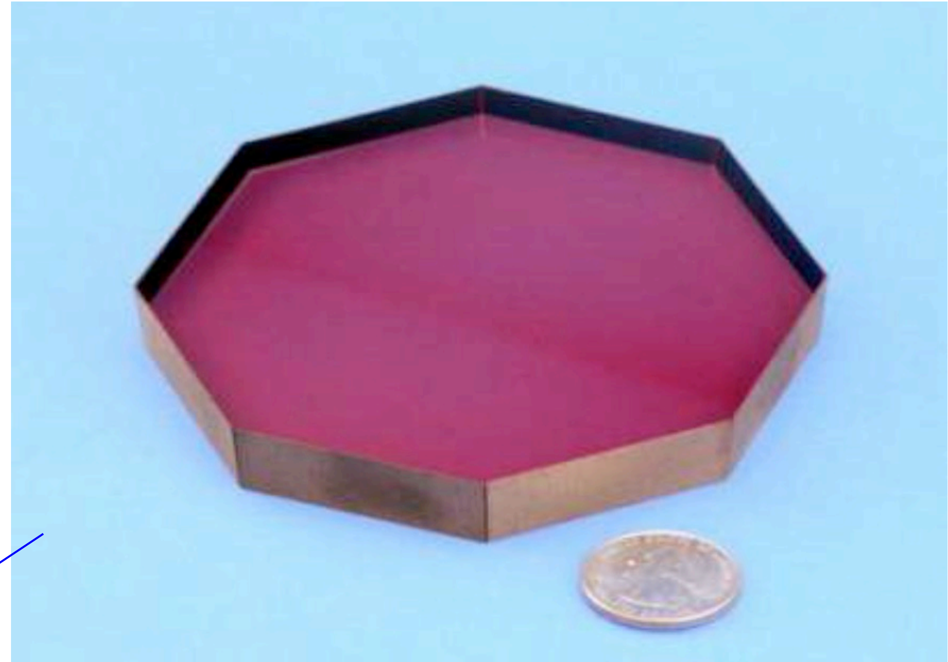
Beam size in the power amplifier 5x5 cm

Approx. 30% of the pump incident to Ti:sapphire dissipated into heat,
up to 200 W must be rejected into cooling

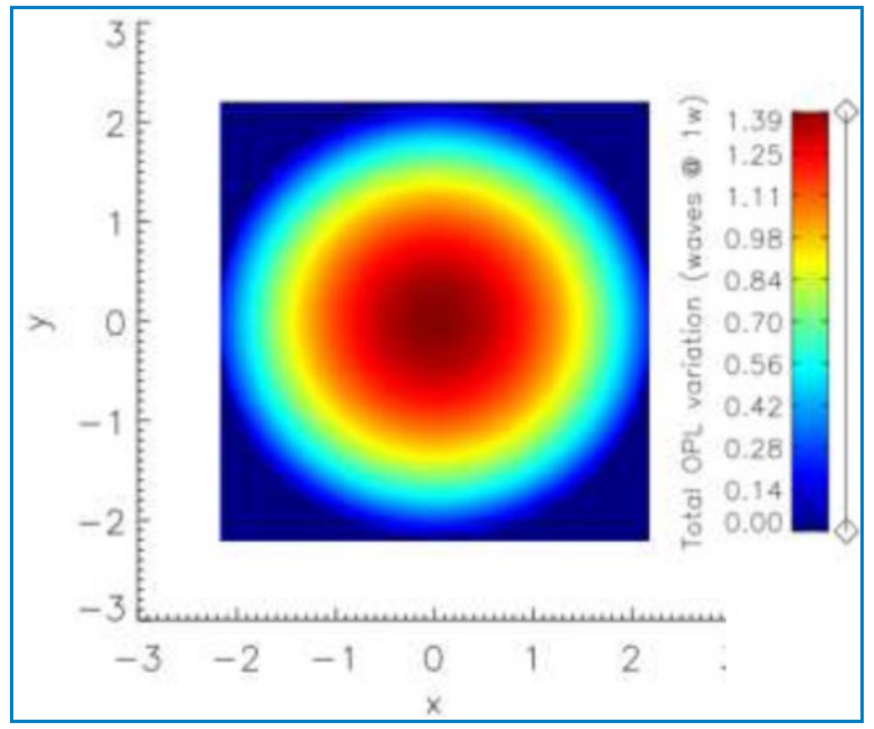
Solution: High-speed flow of helium gas at room temperature



Hard edge cladding (LLNL proprietary) compatible with average power loading ~1 W/cm^2 and vacuum environment



Thermal wavefront distortion is low (<1.4 λ), almost entirely spherical



Lawrence Livermore National Laboratory

Slide courtesy Bedrich Rus, ELI-BL

Amplifier Cooling: cryogenics

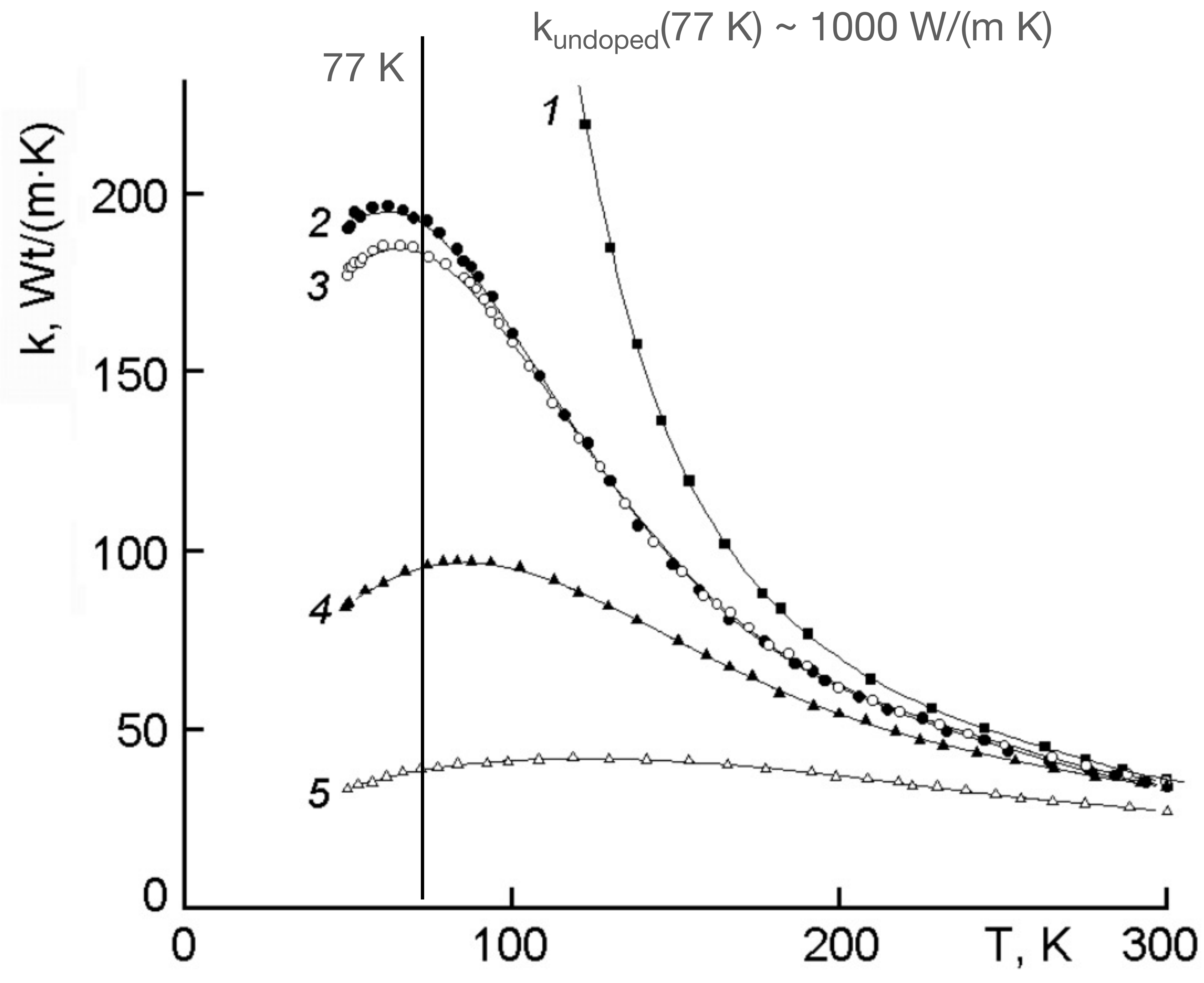
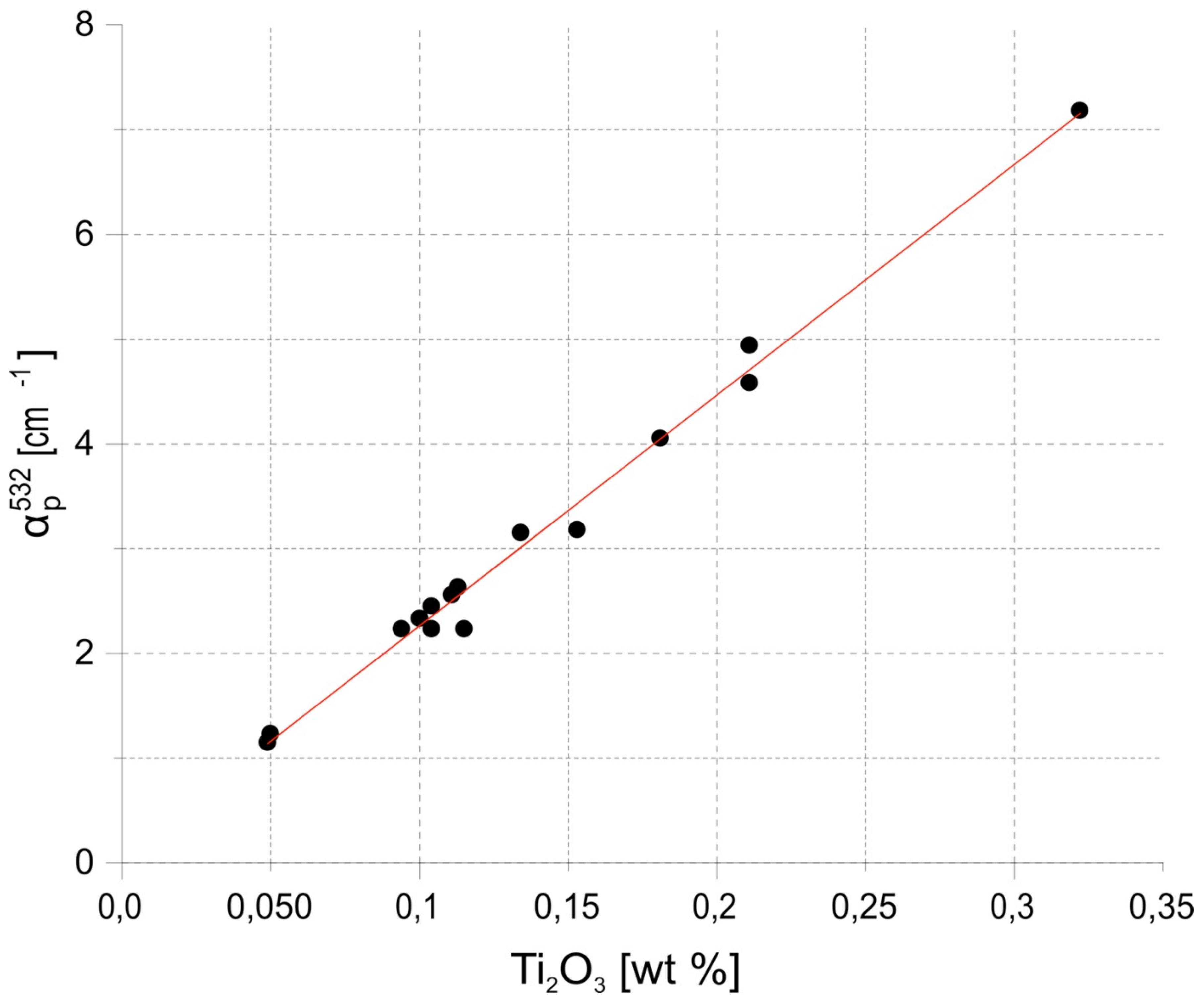


Fig. 4. Temperature dependences of thermal conductivity of ticor with different titanium content: *1* — nominally pure, *2* — 0.06 %; *3* — 0.08 %; *4* — 0.2 %; *5* — 0.5 %.

Popov et al., Functional Materials 18, 476 (2011)

Dependance of α_p on Ti_2O_3 concentration



α L = 2.3 ≙ 90% pump absorption

Longer crystal allows lower doping concentration and better conductivity

greater length offsets this benefit: optimization game

Data from Crytur website,
https://www.crytur.com/materials/tisapphire/

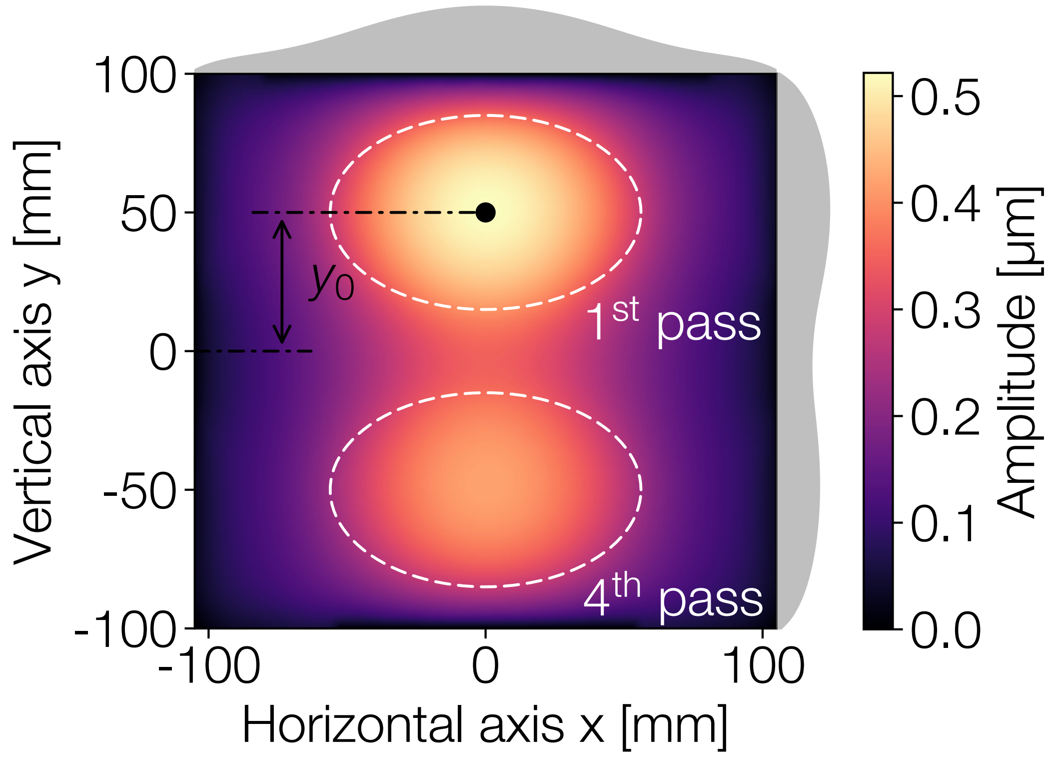
Pulse Compressor

Well-known issues at high average power

T. Eichner et al.

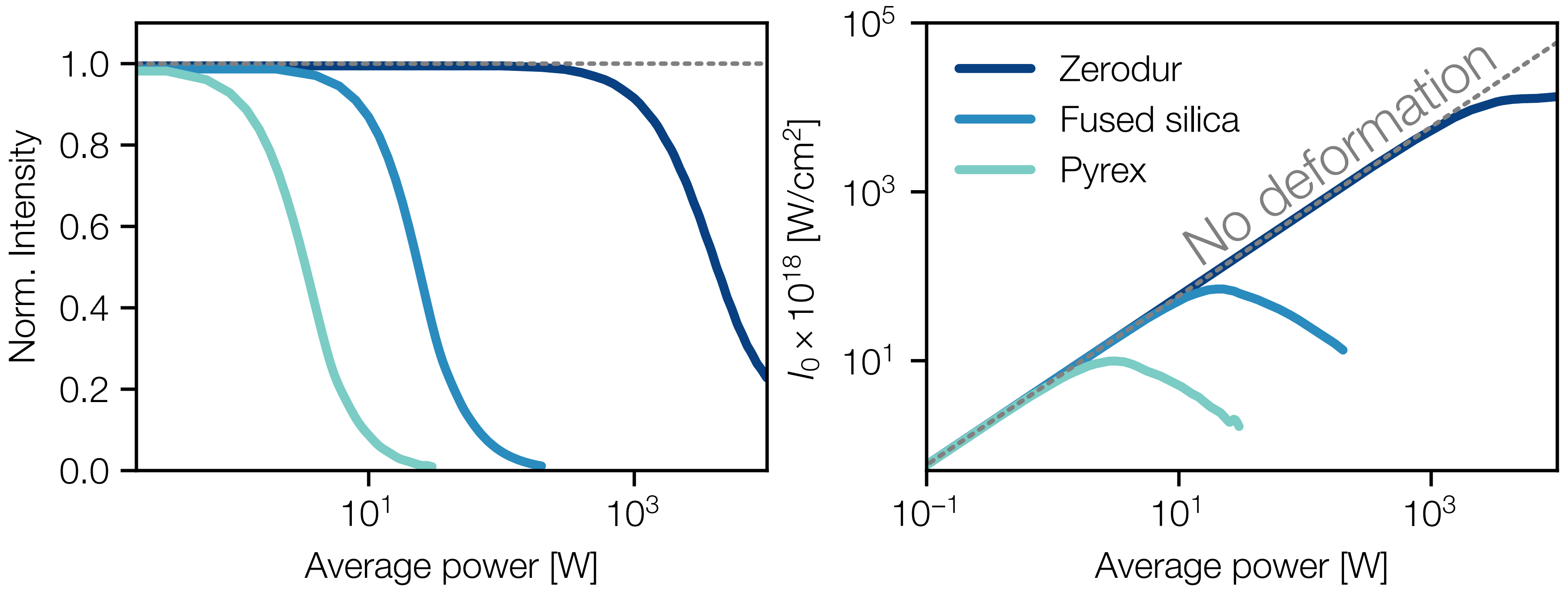
> Heat-induced substrate deformation causes spatio-temporal couplings

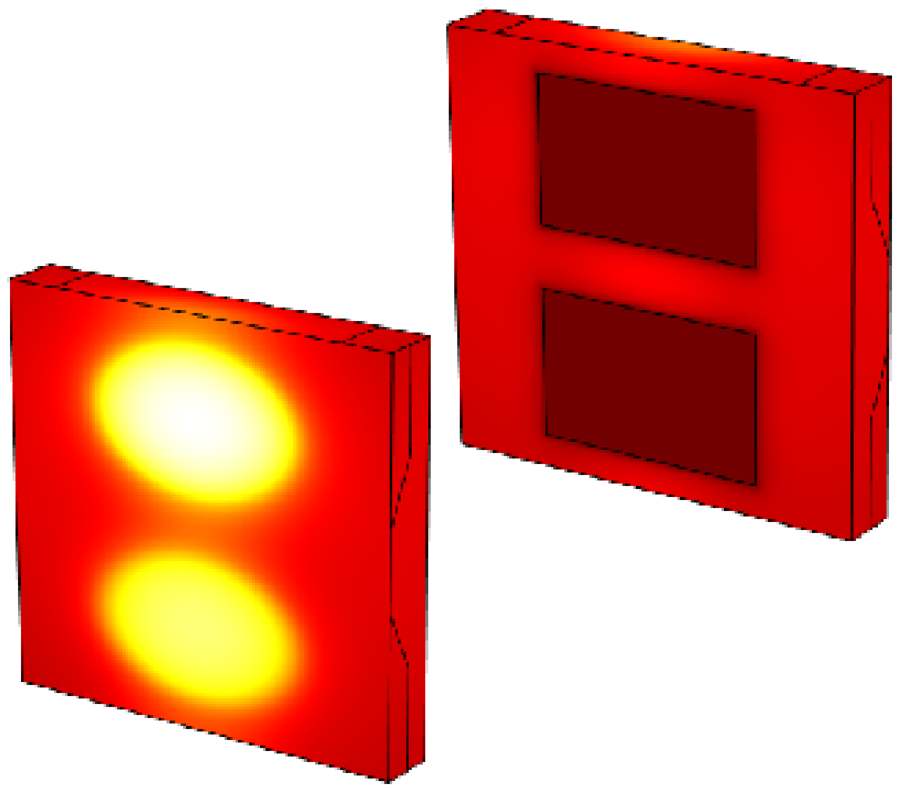
COMSOL Simulation



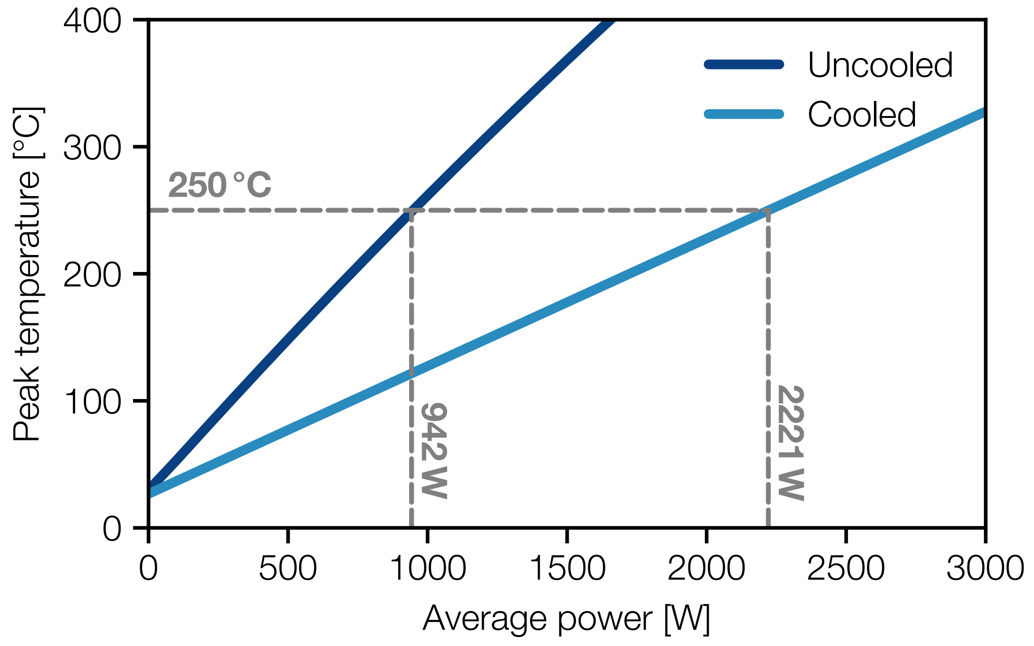
V. Leroux et al., Opt. Express 28, 8257 (2020); V. Leroux et al., Opt. Express 26, 13061 (2018); Li et al., Optics Express (2018); Li et al., Appl. Physics (2017); Opt. Express 24, 30015 (2016)

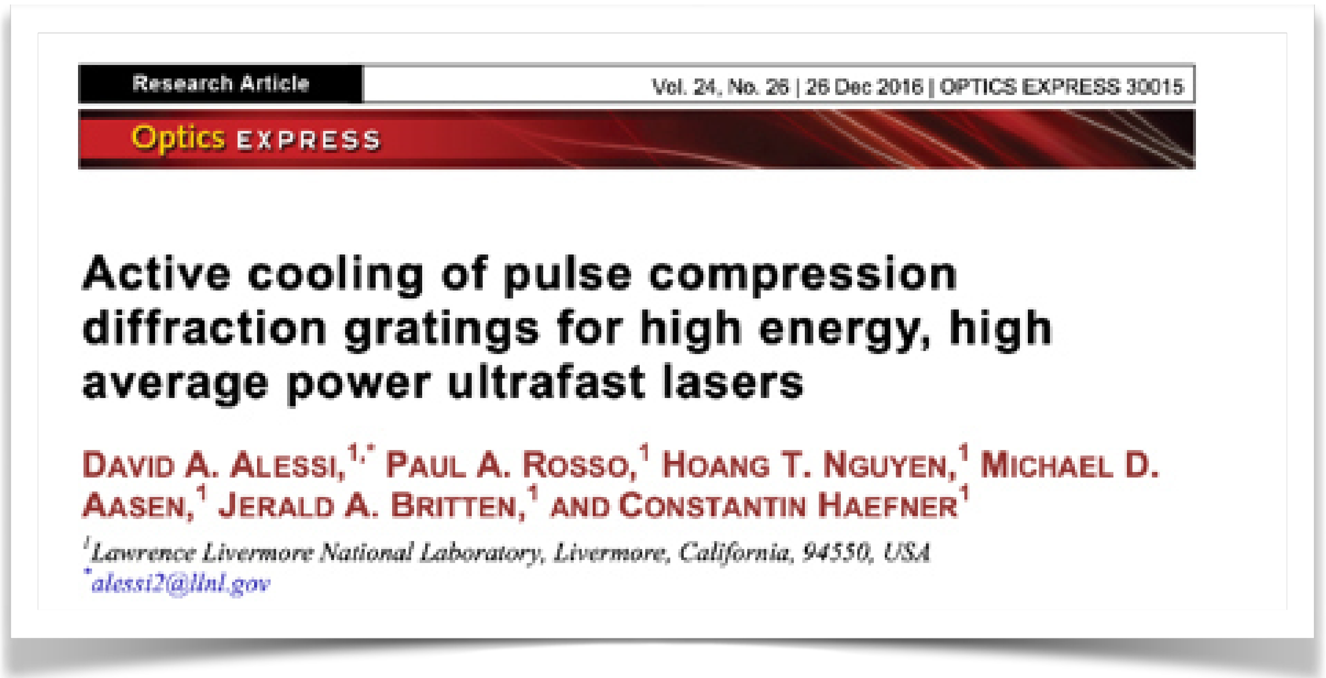
> ULE type substrate helps





> (Simple) active cooling helps
> But surface temperature increases





Research Article | Vol. 24, No. 26 | 26 Dec 2016 | OPTICS EXPRESS 30015

Optics EXPRESS

Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers

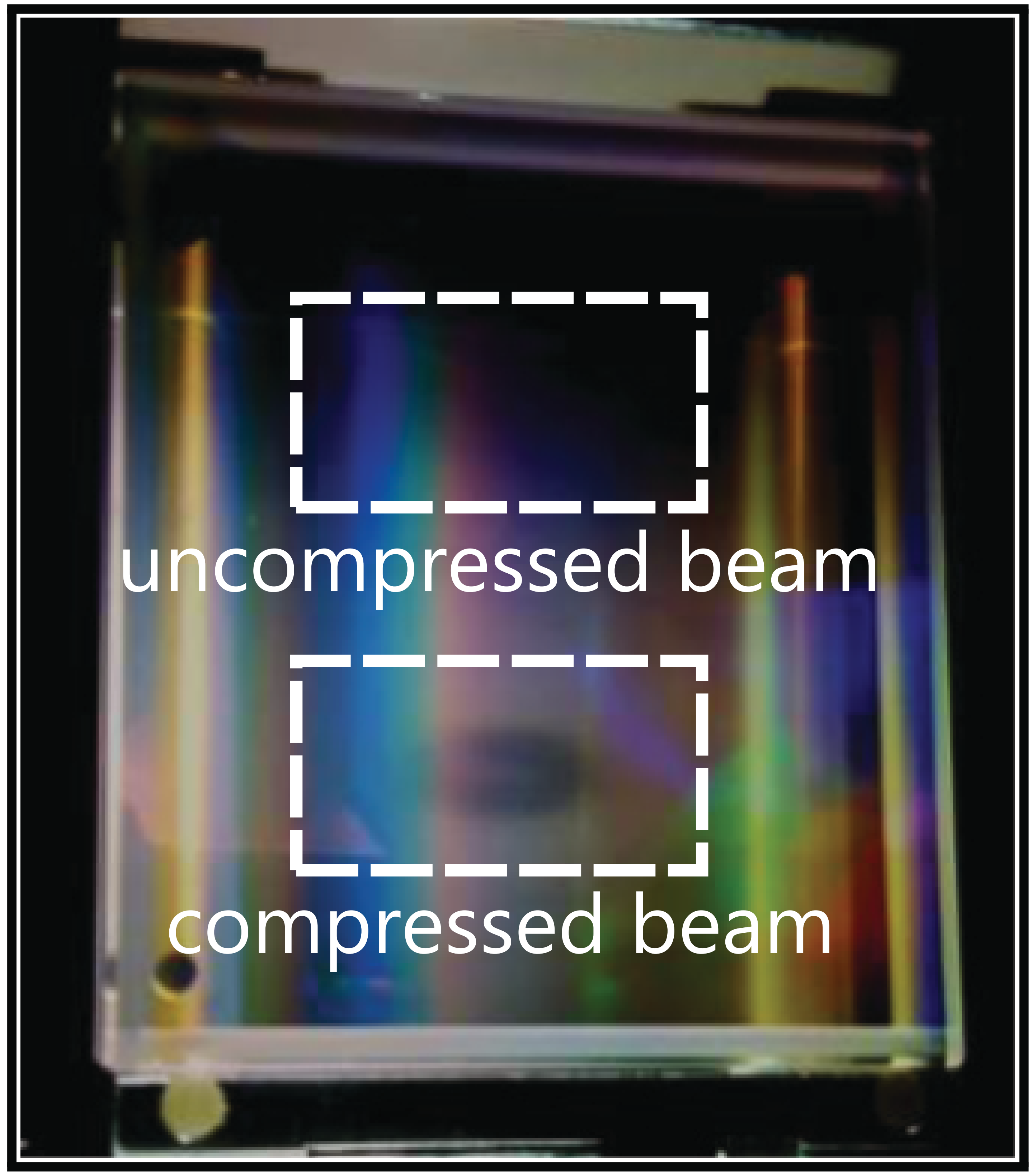
DAVID A. ALESSI,[1,*] PAUL A. ROSSO,[1] HOANG T. NGUYEN,[1] MICHAEL D. AASEN,[1] JERALD A. BRITTEN,[1] AND CONSTANTIN HAEFNER[1]

[1]Lawrence Livermore National Laboratory, Livermore, California, 94550, USA
[*]alessi2@llnl.gov

Optics contamination:

Blackening of gratings at high intensity

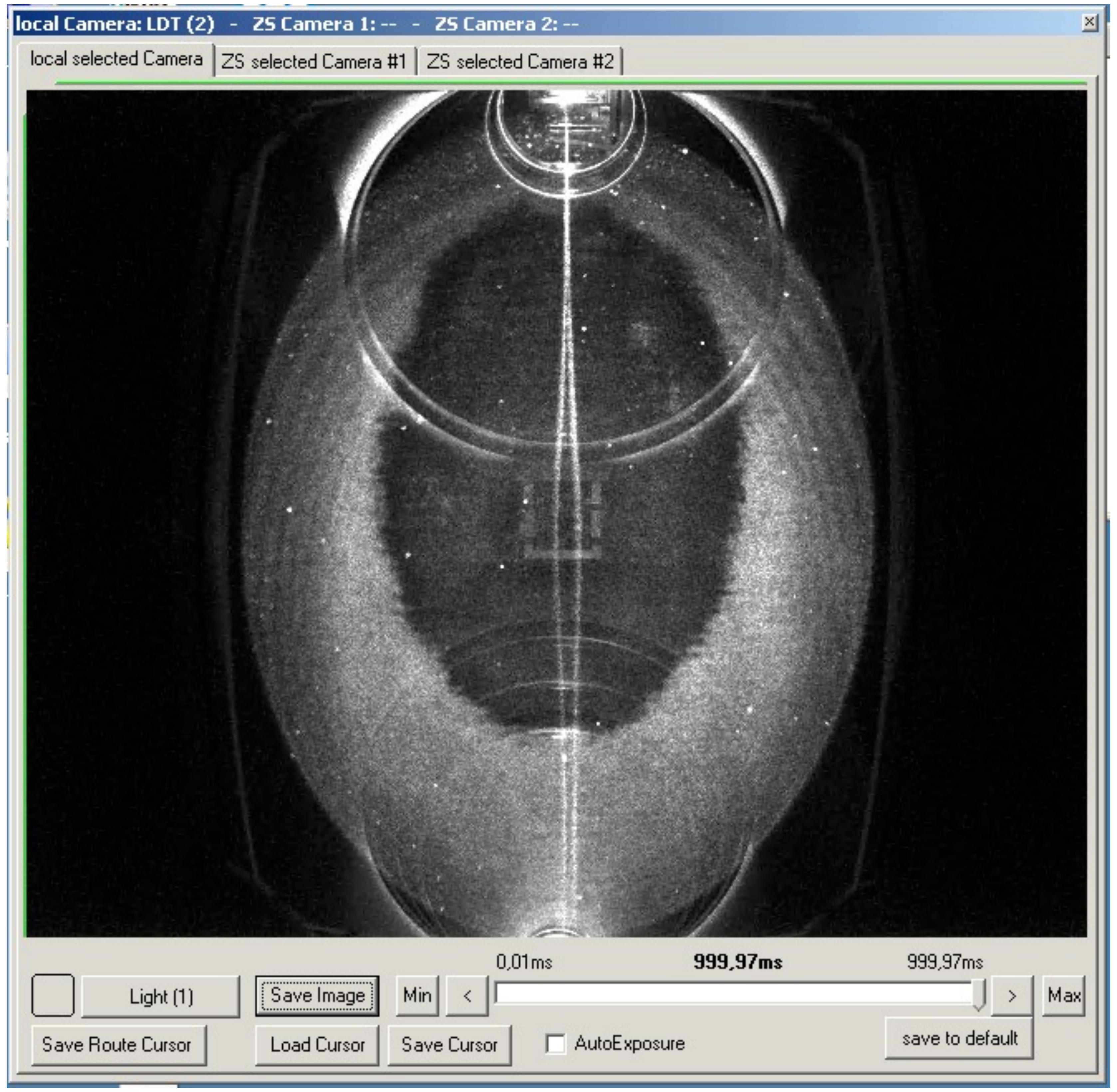
Affects last compressor grating,
10^6 shots at 100 mJ/cm^2 @ 5Hz
10^7 shots at 6.5 mJ/cm^2 @ 1 kHz



Hubka et al, Applied Optics 60, 533 (2021)
R.B.Gillette,et al, J. Vac. Sci. Technol. 7, 534–537 (1970)

Blackening of dielectric mirrors is less well known

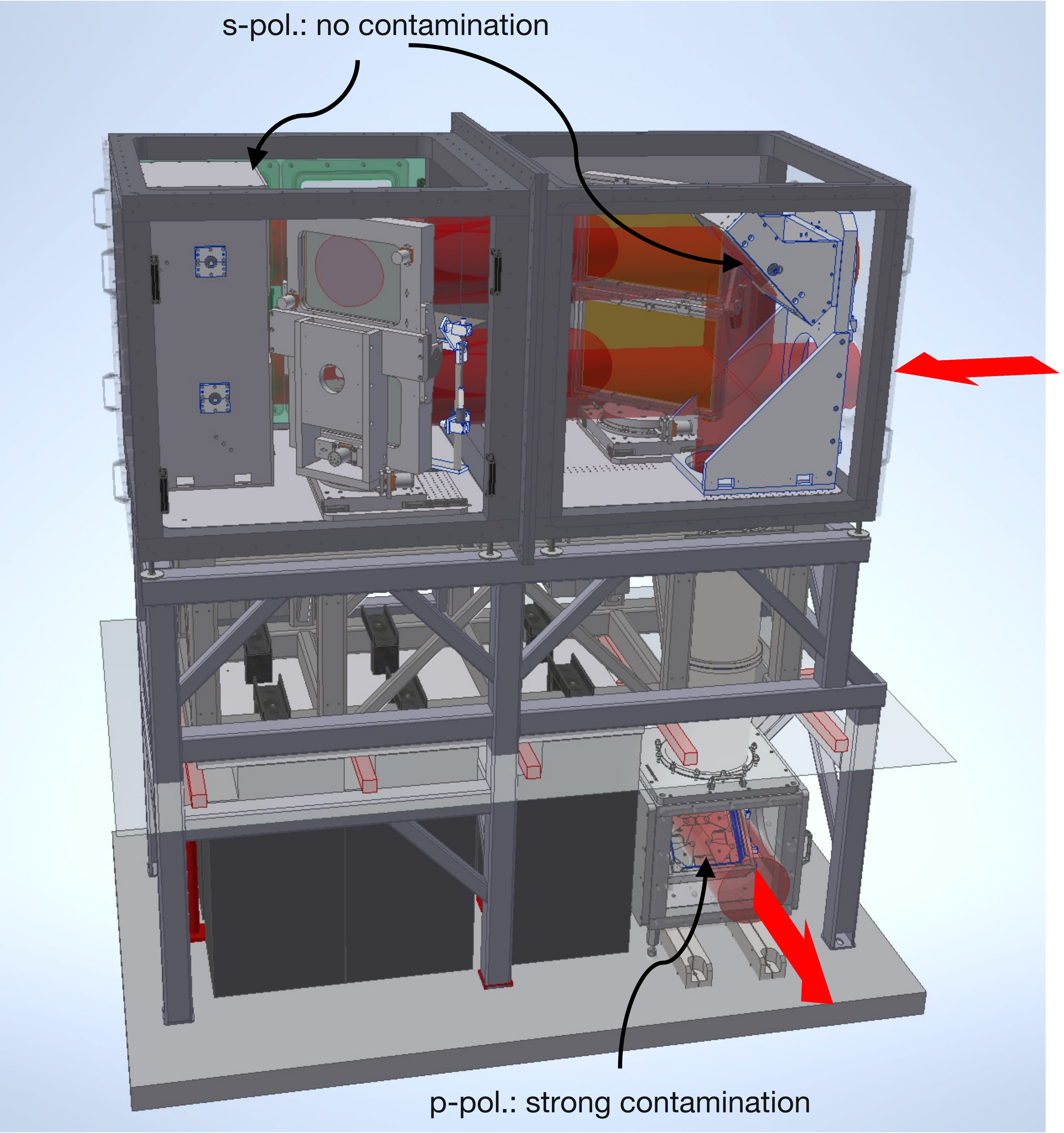
typically 10^4 shots at 35 mJ/cm^2 @ ¼ Hz



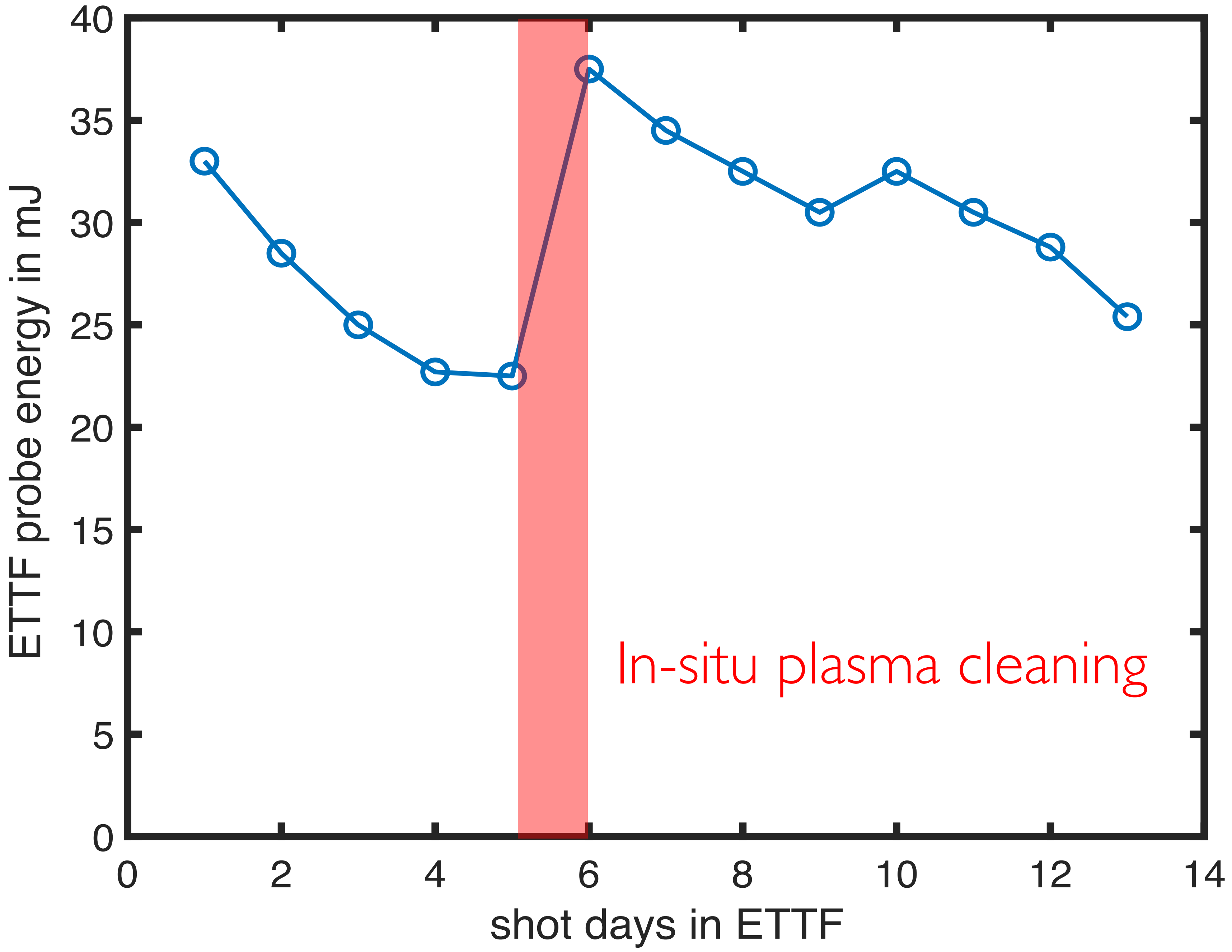
Happens long before grating shows contamination

Optics contamination:

ATLAS-3000 compressor



Vacuum quality ($<10^{-9}$ abs. for m>45) is comparable with other laser facilities (Jena, DESY)



Coating/surface	Degradation	Cleaning strategy
Gold grating (p to surface, s to grooves)	Hardly noticeable (many months)	in-situ plasma
E-beam HR coating (s-pol)	Weak (several weeks)	in-situ UV
E-beam HR coating (p-pol)	Strong (days)	in-situ plasma
Enhanced silver (sputtered)	none	(in-situ UV)

- Oil in porous surface (manufacturer's guess)?
- Electrostatic charge-up (from p vs. s)?

Ti:Sa pros and cons:

- Broad bandwidth required for 100TW-class lasers
- Relatively efficient energy storage and extraction
- Cryogenic operation does not limit bandwidth
- Very tough laser material
- Compact stretcher and compressor setups
- ns laser pumping allows better ASE control than ms diode pumping
- Availability and technological maturity

- ns-laser pumping required – efficiency, cooling
- Broad bandwidth increases sensitivity for spatio-temporal couplings and high order phase terms
- Full bandwidth too broad for MLD gratings
- Quantum defect larger than Nd, Yb or Tm materials
- Shorter wavelength than Nd, Yb or Tm makes optics more susceptible to damage from 2-photon absorption.