Collimation and thermal lens of a 1×–4× zoom beam expander at 1 kW

Galilean zoom with three fused-silica lenses, four zoom positions optimized together, 1030 nm continuous laser from 100 W to 1 kW

Application

A zoom beam expander sets the beam diameter, and therefore the focused spot, of a laser machine for cutting, drilling or micromachining. The machine builder needs the magnification shown on the dial to be the real one, the beam to leave collimated at every position, and both to hold when the laser runs at full power. This note answers these questions for a 1 kW fibre laser.

Modelling approach

Each zoom position is a variant of the same system. The four positions were optimized together: each keeps its own lens spacings, while the lens shapes are shared. The magnification was written as a formula, the ratio of the output and input heights of a real ray. Each position was then heated by the laser until the temperature of every lens stopped changing.

1 The expander at its four positions

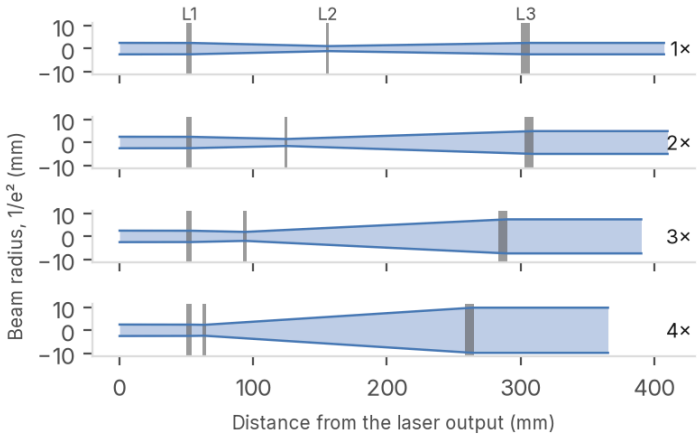


Figure 1. Beam radius through the expander at each position, with the three lenses in grey. The beam narrows between L1 and L2 but never comes to a focus: its smallest radius is 1.07 mm, at 1×. **Table 1.** Main parameters.

PARAMETER	VALUE
Laser	1 kW CW, 1030 nm, M^2 1.1
Input beam	5 mm diameter ($1/e^2$)
Output beam	5 to 20 mm diameter
Lenses	three, fused silica, AR coated
Moving lenses	L2 and L3; L1 fixed
Housing length	215 to 260 mm

2 Collimation from 100 W to 1 kW

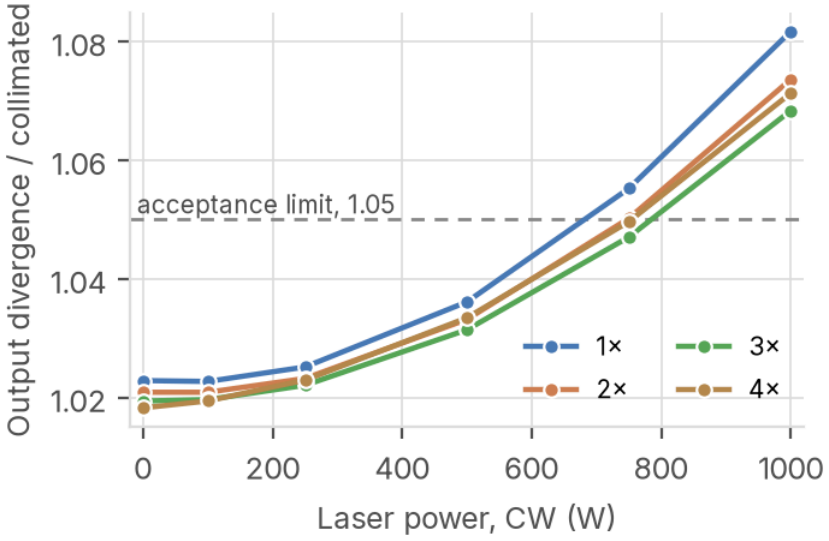


Figure 2. Divergence of the output beam divided by the divergence of a perfectly collimated beam of the same diameter, against laser power, without any adjustment. The dashed line is the acceptance limit of this study.

680 W

Highest power at which the output beam stays collimated within 5 % at all four zoom positions, without adjustment. The 1× position limits it.

85 µm to 1.3 mm

Movement of L3 towards L2 that restores collimation at 1 kW, from 4× to 1×.

λ/80

Largest RMS wavefront error over the four positions (at 4×), far below the λ/14 of a diffraction-limited beam.

Optical specification met cold; above 680 W, L3 moves

Magnification within 0.2 %, wavefront below λ/80; the thermal lens of L2 sets the power limit.

Table 2. Each zoom position, cold

POSITION	MAGNIFICATION	DIVERGENCE / COLLIMATED	WAVEFRONT RMS	M² OUT	OPTICAL SPEC
1×	0.999	1.023	λ/347	1.10	pass
2×	2.001	1.021	λ/141	1.11	pass
3×	3.001	1.019	λ/161	1.11	pass
4×	3.993	1.018	λ/80	1.14	pass

Magnification: ratio of real-ray heights. Wavefront: RMS of a Zernike fit without piston, tilt and defocus. Input M²: 1.10. Acceptance: magnification within 1 %, divergence ratio up to 1.05, wavefront up to λ/14, M² growth up to 5 %.

Table 3. Each zoom position at 1 kW

Position	Hottest lens, L2 (K)	Divergence / collimated	Power limit	L3 shift (µm)	After the shift
1×	12.3	1.082	682 W	-1323	1.034
2×	10.7	1.074	747 W	-335	1.025
3×	9.8	1.068	785 W	-146	1.021
4×	9.2	1.071	754 W	-85	1.019

Rise at the centre of L2, the hottest lens. Power limit: where the divergence ratio reaches 1.05. L3 shift: movement that gives the hot beam its smallest divergence; negative is towards L2.

Why 1× limits the power

Each lens absorbs about 41 mW at 1 kW. The negative lens L2 sees the narrowest beam, so it heats the most, and most at 1×, where the beam on it is smallest. Its weak positive thermal lens makes the output beam diverge about 5 % more than when cold.

Above the limit

Up to 680 W the expander needs no adjustment. Above, moving L3 towards L2 (Table 3) brings the beam back within the limit at every position. A material with negative dn/dT in the beam is the passive alternative [3].

Ghosts

Each double reflection carries about 4 mW at 1 kW. All focus in air except one, inside L2 near 3×: harmless at a few milliwatts of continuous power, but a pulsed laser would call for another lens bending. Transmission: 98.8 %.

In etendue

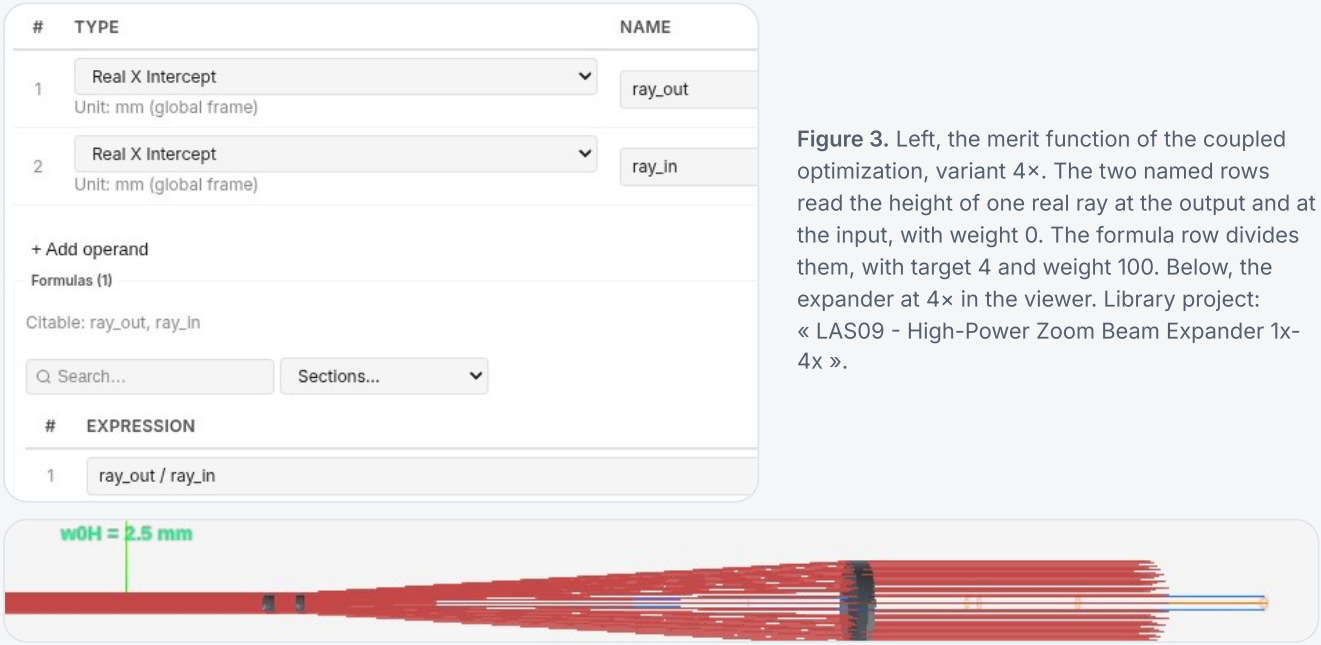


Figure 3. Left, the merit function of the coupled optimization, variant 4×. The two named rows read the height of one real ray at the output and at the input, with weight 0. The formula row divides them, with target 4 and weight 100. Below, the expander at 4× in the viewer. Library project: « LAS09 - High-Power Zoom Beam Expander 1x-4x ».

References. [1] US 5,134,523 (Galilean zoom beam expander). [2] A. E. Siegman, Analysis of laser beam quality degradation caused by quartic phase aberrations, Appl. Opt. 32(30), 5893 (1993). [3] M. Stubenvoll, B. Schäfer, K. Mann, Measurement and compensation of laser-induced wavefront deformations and focal shifts in near IR optics, Opt. Express 22(21), 25385 (2014). [4] M. Born, E. Wolf, Principles of Optics, Cambridge University Press (Maréchal criterion, λ/14 RMS). **Limits.** Absorption from data sheets, lenses cooled by air only, acceptance limits chosen for this study.

Thermal lens from the beam second moments (ISO 11146) of the heated system; M² from a wave-optics propagation [2].