B-integral and pulse duration in a 0.5× to 1.7× ultrafast zoom beam expander

Three-lens Galilean zoom behind a 1030 nm femtosecond laser, 7 variants, pulse propagated through the real system at each position

Application

A zoom beam expander sets the spot size of a femtosecond micromachining head. Its lenses also add a nonlinear phase to every pulse, and that phase grows as the beam gets smaller. This note finds the highest pulse energy that each zoom position accepts before the spectrum of the pulse starts to change, and the pulse duration at the output.

Modelling approach

The pulse of the laser was propagated through the lens prescription at each zoom position. The dispersion of every glass and air gap gives the output duration, and the beam size along the path gives the nonlinear phase, the B-integral. A position is accepted while the B-integral stays below 1 rad, the value under which the spectral change is insignificant [1].

1 The zoom and its positions

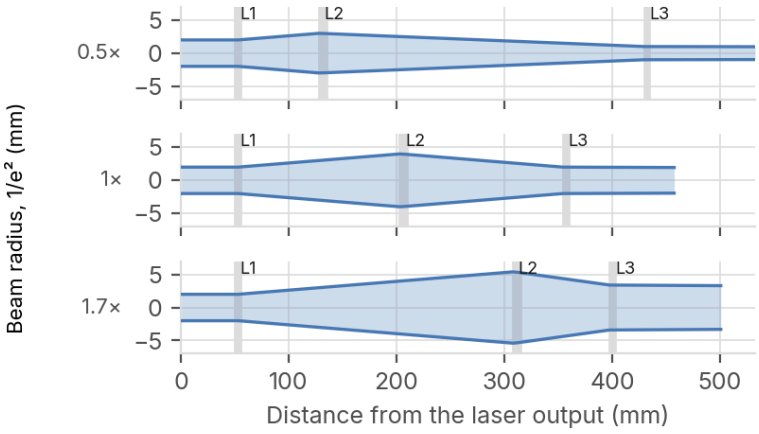


Figure 1. Beam radius along the zoom at its three positions, laser on the left; grey bands are the lenses: the negative first lens (fixed), the positive second lens and the negative last lens (both moving). The beam stays at least as wide as the input beam until the last lens. **Table 1.** The laser and the zoom as modelled.

PARAMETER	VALUE
Laser	1030 nm, 300 fs sech², 100 µJ at 200 kHz
Input beam	radius 2.0 mm at 1/e², M² 1.2
Lenses	f = −150 / +150 / −150 mm, fused silica
Zoom	L1 fixed; L2, L3 move; 308–383 mm long
Positions	0.5×, 1×, 1.7×

2 Nonlinear phase at each zoom position

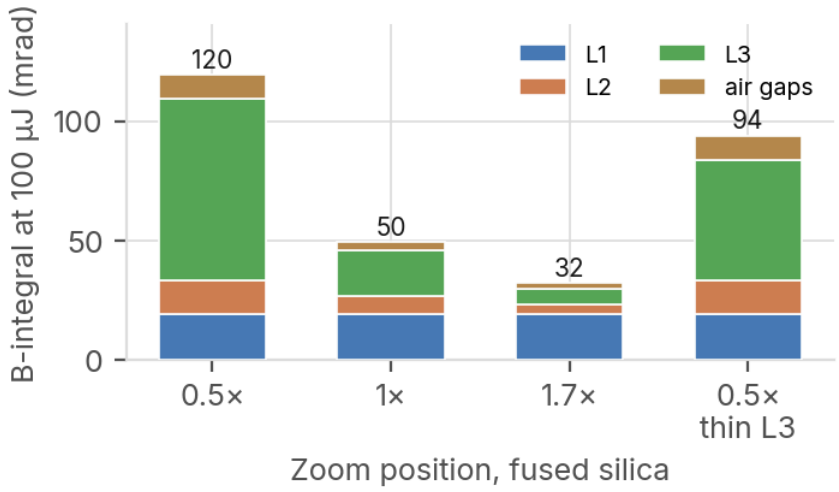


Figure 2. B-integral of a 100 µJ pulse at each zoom position, split between the three lenses and the air gaps. The last bar is the 0.5× position with a thinner last lens (2 mm instead of 3 mm).

837 µJ

Highest pulse energy at the 0.5× position for a B-integral of 1 rad. The 1× and 1.7× positions accept 2 018 µJ and 3 093 µJ.

64 %

Share of the B-integral taken by the last lens at 0.5×, where it carries the reduced output beam.

302 fs

Output pulse duration at that energy, for a 300 fs input: dispersion and self-phase modulation leave the duration unchanged.

The last lens sets the energy limit

The smallest beam of the zoom is the output beam at 0.5×, inside the last lens.

Table 2. Energy accepted at each zoom position

Variant	Output radius (mm)	B at 100 µJ (mrad)	L3 share (%)	Highest energy (µJ)	Duration (fs)	Within 10 %
1× fused silica	2.0	50	38	2 018	303	pass
0.5× fused silica	1.0	120	64	837	302	pass
1.7× fused silica	3.4	32	20	3 093	304	pass
0.5× BK7-type crown	1.0	129	64	776	302	pass
1× BK7-type crown	2.0	53	39	1 869	304	pass
1.7× BK7-type crown	3.4	35	21	2 866	305	pass
0.5× fused silica, thin L3	1.0	94	54	1 062	302	pass

Highest energy: B-integral of 1 rad, glass and air. Duration: FWHM of the output pulse at that energy (300 fs input). Output radius at $1/e^2$; L3: last lens.

Table 3. Kerr lens at the highest energy of each position

Position	Energy (µJ)	Peak index change (×10⁻⁶)	Shortest Kerr focal length (m)	Output beam narrowing (%)
0.5×	837	35	2.4 (L3)	2.1
1×	2 018	21	15.7 (L3)	0.7
1.7×	3 093	32	10.3 (L1)	0.4

Fused silica. Largest on-axis index change of the three lenses; narrowing of the beam radius at the output plane.

Why the reduction limits

The first lens sees the input beam at every position and takes the same share of the B-integral. The last lens carries the output beam: at 0.5× its radius is halved and its intensity is four times higher. At 0.5× it takes 64 % of the total. The air gaps add 8 %.

What raises the limit

A last lens of 2 mm instead of 3 mm raises the energy accepted at 0.5× from 837 µJ to 1 062 µJ. A BK7-type crown instead of fused silica lowers it to 776 µJ.

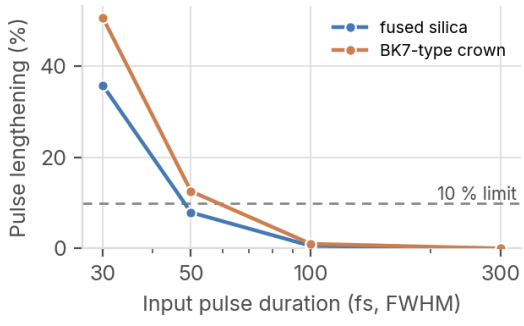
Above the critical power

The peak power is 59 times the critical power for self-focusing at 100 µJ, and 496 times at the limit of the 0.5× position. The beam does not collapse: the glass path stays below 8 % of the self-focusing distance [2].

Conclusion

With a 4 mm beam and 300 fs pulses, this zoom accepts up to 837 µJ at every position without pre-compensation, with an unchanged pulse duration. Above, avoid the 0.5× position or thin its last lens (1 062 µJ with 2 mm).

Figure 3. Dispersion at the 1× position



The zoom adds 209 fs² of group-delay dispersion in fused silica and 276 fs² in BK7-type crown, at every position. A 300 fs pulse is not lengthened; a 50 fs pulse comes out at 54 fs, a 30 fs pulse at 41 fs.

In etendue

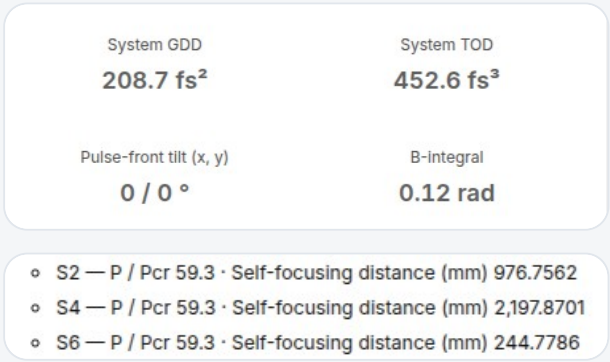


Figure 4. Results at 0.5× and 100 µJ: Laser pulse (top), Kerr effect (bottom; S2, S4, S6: L1, L2, L3). The zoom positions are variants of the library project « LAS10 - Ultrafast Zoom Beam Expander ».

Limits of the study. Gaussian beam without clipping; laser values are assumptions of this study [4]; the 10 % duration limit is a choice of this study; thermal effects of the average power and the coatings are not included. **References.** [1] S. Yu. Mironov et al., 100 J-level pulse compression for peak power enhancement, Quantum Electron. 47, 173 (2017). [2] V. Arévalo, A. Becker, Phys. Rev. A 72, 043807 (2005), Dawes-Marburger law; critical power after G. Fibich, A. L. Gaeta, Opt. Lett. 25, 335 (2000). [3] n2 of fused silica: S. R. Flom et al., Appl. Opt. 54, F123 (2015). [4] Laser parameters of the order of P. Balage et al., Micromachines 14, 1650 (2023).

B = (2π/λ)∫n2·I ds along the path, glass and air; pulse propagated through the real system.