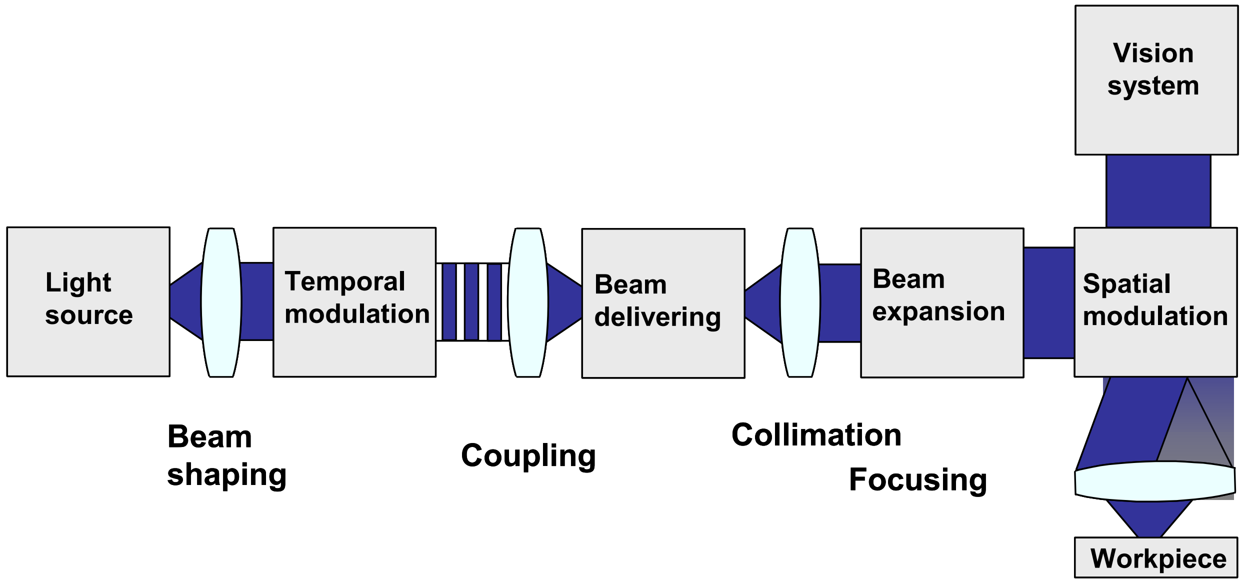
Laser Beam Expanders
Basics and Applications

In complex laser systems, such as those for material processing (Fig. 1), passive optical components and systems play a key role alongside active optical components such as Pockels cells for temporal modulation or galvo mirrors for spatial modulation of the laser beam used for processing. The tasks of the passive components range from changing the beam direction by mirrors, beam shaping, e.g. by using a cylindrical lens array, to final focussing of the laser beam on the workpiece by high-aperture laser objectives (HALOs) or scan objectives [1].

In addition to these components and systems, beam expanders (or BMX for short) are essential for adapting the beam diameter to the particular processing task.



Basic setup of optical systems for laser material processing (Fig. 1)

Beam Expanders: Large Beam Diameter for Small Laser Spots

For efficient production of the finest structures in laser material processing, a minimum laser focus with the highest possible energy density on the workpiece to be processed is required. In producing a focus by laser light, the 1/e^2 spot size d_f can be calculated using equation (1) as an approximation:

$$d_f \approx \frac{4}{\pi} \cdot \lambda \cdot \frac{f'}{d_1} \qquad (1)$$

Here, we assume that the Rayleigh length z_R of the focused laser beam is much smaller than f' and that the lens diameter is at least 1.5 times greater than d_1 [2]. *In this case,* λ is the laser wavelength, f' the focal length of the focusing lens system and d_1 the diameter of the laser beam at the first lens surface of the objective.
From equation (1), it is easy to see that a large beam diameter in particular results in a small laser spot. The laser beam is expanded to a suitable diameter using a beam expander. This is best located just before the spatial modulator or directly in front of the focusing optics to keep the optimal component dimensions small and thus inexpensive. Like telescopes, beam expanders are afocal systems. They consist of two optical sub

systems, the entrance and exit optics. Both sub systems are arranged so that the back focal point of the entrance optics F'_{in} coincides with the front focal point of the exit optics F_{out}.

The expansion ratio m as a quotient of the exit diameter D_{out} to the diameter of the non-expanded focused laser beam D_{in} in front of the beam expander can be calculated using f'_{in} as the focal length of the entrance optics and f'_{out} as the focal length of the exit optics and with $h=D_{in}/2$ and $h'=D_{out}/2$ as follows:

$$m = -\frac{h'}{h} = -\frac{f'_{out}}{f'_{in}} \qquad (2)$$

Due to the general relation (3) between lateral expansion (expansion factor for afocal systems) m and angular magnification m_{ang}

$$m_{ang} = \frac{1}{m} \qquad (3)$$

a further effect can be easily derived for using beam expanders [3]: Divergences or collimation errors, which lie in the nature of the laser light source used or may have been introduced by the previous beam-shaping and delivering optics, are expressed as angular deviation of the rays that ideally travel parallel to the optical axis. Such errors prevent ideal focusing of the laser beams. For ray angles in object and image space, the following general relation applies to optical systems:

$$m_{ang} = \frac{\tan u'}{\tan u} \qquad (4)$$

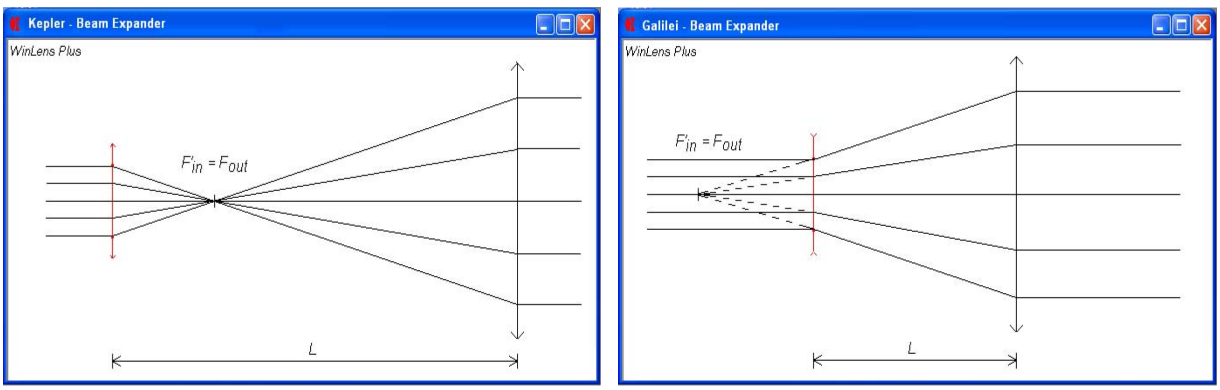
where u is the angular error before and u' the transferred angular error after expansion. For an expansion factor of $m>|1|$, all angular beam direction errors and beam divergences are thus reduced by the beam expansion factor!

Basic Types of Beam Expanders

As with telescopes, there are two basic ways of implementing beam expansion systems:

1.) The *Kepler arrangement* consisting of two positive lenses or groups of lenses
2.) The *Galileo configuration with a negative and a positive sub-system*.

The paraxial layouts of both configurations are illustrated in Figures 2 and 3.



Kepler and Galileo beam expander systems (Figures 2 and 3)

The real intermediate focus in the Kepler arrangement is advantageous for producing high-grade reference wave fronts with a homogeneous intensity (e.g., interferometry), because at the intermediate focal point, a pinhole can be positioned for spatial filtering.

To use a powerful laser, e.g., for material processing, the Galileo type is preferred, as the tremendous power densities in the intermediate focus of the Kepler system can cause air breakdown. Using spatial filters is impossible in any case because of the high energy in the focal point.

An additional general advantage of the Galileo arrangement is its reduced installation length *L* (see also *Figures 3* and *4*), which is approximately given by $L=|f'_{out}|-|f'_{in}|$, compared to the Kepler setup where $L=|f'_{out}|+|f'_{in}|$.

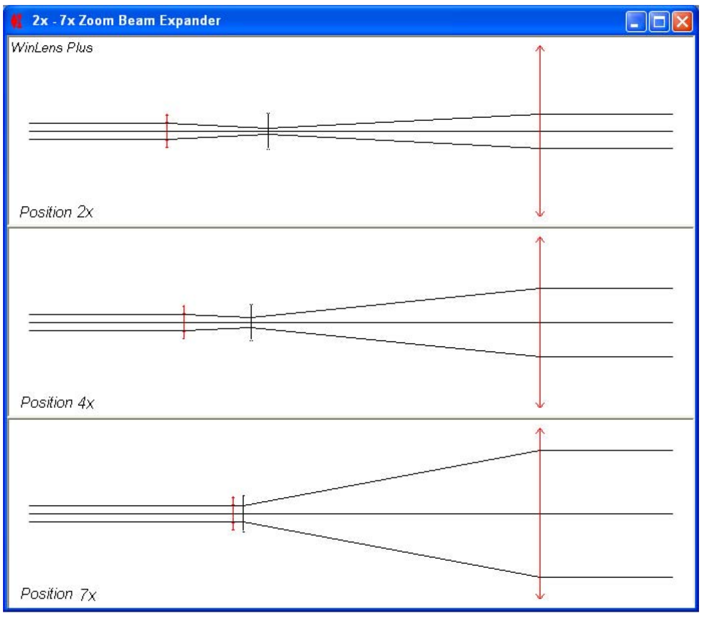
Flexibility from Zoom and Modular Systems

If particular flexibility is required, e.g., in the trial phase of a laser processing system, *variable (zoom) beam expander systems* are practical. Here, in the case of a beam expander system of the Galileo type, the negative entrance optics is typically split into two subgroups (e.g., positive and negative groups). By varying the distance e_{12} of both subgroups with their individual focal lengths f'_1 and f'_2, the total focal length f'_{in} of these entrance optics can be adjusted according to equation (5):

$$f'_{in} = \frac{f'_1 f'_2}{f'_1 + f'_2 - e_{12}} \qquad (5)$$

By shifting the two groups with respect to the exit optics, it is possible to continuously vary the expansion factor. As in the case of photographic zoom lenses, a good compromise between image quality, expansion range and the engineering work entailed must be found when designing such a system.

Figure 4 shows schematic paraxial setup of a variable 2x to 7x beam expander system.



Paraxial layout of a 2x-7x zoom beam expander (Figure 4)

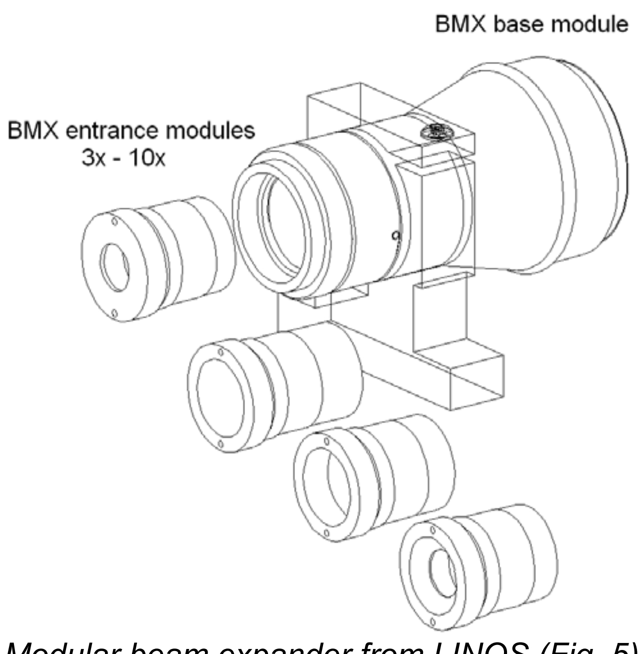
The relation between the individual focal lengths f'_n, the lens distances $e_{n,n+1}$ and the expansion factor m is given by equations 6 and 7 [4] for paraxial expansion systems with three elements:

$$e_{12} = f'_1 + f'_2 + \frac{f'_1 f'_2}{f'_3 m} \quad (6)$$

and

$$e_{23} = f'_2 + f'_3 + \frac{f'_1 f'_2 m}{f'_1} \quad (7)$$

If the spot size of the laser system needs to be adjusted only once for an application, *modular beam expanders* from LINOS are a suitable alternative. These beam expanders allow easy interchange of the smaller beam entrance lens (basic module) thanks to their modular design. Therefore, they enable the operator to easily adapt the expansion ratio of the system to new applications using just one beam exit element (basic module). The operator can choose from expansion ratios of 3x, 5x, 8x and 10x *(Fig. 5)*. Each entrance unit, supporting a single expansion ratio, is optimised to match the basic module, thus guaranteeing optimal imaging quality. The focussing capability of the entrance element permits additional adjustment of the axial focus position and size beyond the following focussing lens system. The optics can be shifted without rotation during focussing, and thus the required focusing stability is obtained.



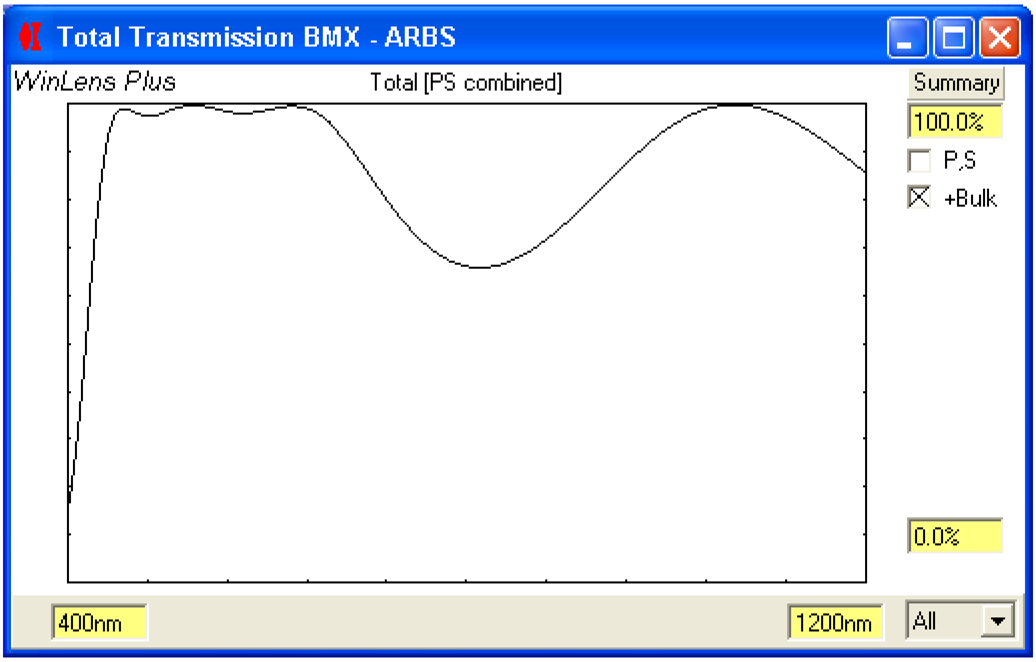
Modular beam expander from LINOS (Fig. 5)

Wide waveband expanders

Any beam expander must introduce minimal wavefront distortion otherwise the post connected focusing lens will not be able to produce the smallest spot. Beam aberrations, such as spherical aberration make exact focusing difficult and the smallest spots impossible to obtain!

Normally beam expanders are designed for a single wavelength, to simplify the optical design task. Indeed creating a wide band beam expander adds a whole new dimension to the optical design task. But avoiding this extra work means that a new expander is usually required if the laser wavelength is changed.

The innovative optical design of the LINOS BMX series now makes minimal wavefront distortion from 458nm to 1064nm a reality. Slight refocusing of the front lens is all that is needed if the wavelength is changed within this waveband. The exceptionally broadband anti-reflection coating of the lenses support applications in the wavelength range of 458nm to 635nm (residual reflection less than 0.5%) and additionally at 1064nm (residual reflection less than 0.3%)



Total transmission of a LINOS BMX expansion system (Fig. 6)

Combination of high-grade materials and appealing design

To enable the use of beam expander systems at high laser powers, the choice of materials for the individual optical components of the system is critical. Lenses, through which especially high-powered laser beams are focused, e.g., through small beam cross-sections, should be manufactured from high-grade fused silica as this material exhibits a particularly high damage threshold. All other lenses used should also be made of glass that has the lowest possible absorption. The use of these kinds of materials in combination with high-grade coatings yields a laser resistance in LINOS BMX systems of more than $100 J/cm^2$ at a laser pulse width of 20ns (S-O-1 measurement), e.g., for a laser wavelength of 1064nm.

Last, but not least, LINOS beam expanders feature an appealing external design.

Sources:

1. *T. Thöniß, S. Dreher, R. Schuhmann: >Photonik-Puzzle, optische Komponenten und Systeme für Laseranwendungen< (Photonics Puzzle, Optical Components and Systems for Laser Applications); Laser+Photonik 2 (Juni 2003), pp. 14-21.*
2. *W. Demtröder: >Laser Spectroscopy<; Springer-Verlag, Berlin, Heidelberg, New York 1982.*
3. *C. Hofmann: >Die optische Abbildung< (The optical image); Geest & Portig, Leipzig 1980.*
4. *F.-M- Chuang, M.-W. Chang : >Solution areas of three-component afocal zoom systems<; Optik 101. No. 1 (1995), pp.10-16.*