Laser Focus Spot Size Control

Interaction of a laser beam with any material is a function of energy density, which in turn is a function of laser beam power and spot size. While laser power is easy to change on the programming pendant/screen, changing the spot size takes more of an effort, and in some cases, advanced planning. In this document, we will review various options to reduce spot size and costs associated with such a change. Spot size can also be increased by reversing the steps, but is not a common requirement.

Laser spot size can be calculated by the following formula (Equation 1):

\[ d = \frac{4\lambda f M^2}{\pi D} \]

Where,
- \( d \) = spot diameter (microns)
- \( \lambda \) = wavelength (microns)
- \( f \) = focal length of the focus lens (cm)
- \( M^2 \) = Measure of beam quality (1 is ideal)
- \( D \) = beam diameter coming into the focus lens (cm) [not the lens diameter]

Figure 1. Shows focusing of beam down to smallest spot size, \( d_{00} \), corresponding to an ideal single mode beam (\( M^2=1 \), TEM\(_{00}\)).
With suitable optics and excluding any lens errors, a 1-micron wavelength gaussian beam ($M^2=1$) can be focused down to a theoretical spot diameter of about 1 micron, which is considered the absolute smallest spot size possible, also known as diffraction limited spot size. In practice, lens errors and limitations to beam size and optical hardware will limit the spot size to order of 10-30 microns. Such small spot sizes are commonly used for cutting, marking, and drilling applications. Examples include stent cutting, 2D barcode marking on practically anything, and drilling of fine holes for fuel injectors.

For applications where larger spot sizes are employed such as welding (50-500 microns), good beam quality is not a major requirement. In such applications, energy is usually delivered to a focus head through a fiber, core diameter of which is typically in the range of 50-300 microns. The welding spot size is then essentially an image of the core diameter (which can be changed by fiber selection), as seen in the schematic below.

![Optical Fiber Collimator Focus Lens Spot Size](image)

Figure 2. Schematic shows the optical path of laser beam through the beam delivery optics. If the collimator and focus lens are of the same focal length, then the spot size is an image of the core diameter.

Based on simple optical imaging effect from your high-school physics text book, the spot size can be defined as (Equation 2):

\[
\text{Spot size} = \text{Core Diameter} \times \frac{\text{Focus Lens Focal Length}}{\text{Collimator Focal Length}}
\]

Depending on the application and optical hardware employed, different factors will come into play in determining the spot size; those factors are discussed in the following sections.
Laser **wavelength** is fundamental property of the lasing atoms and is of the order of 1 micron for YAG and Fiber laser, and 10 microns for CO2 lasers. Wavelength can be halved by sending the beam through a frequency-doubling crystal (as was implemented in the patent on green welding laser) or even tripling or quadrupling crystal where the wavelength is reduced to a third or fourth of original. The main reason for reducing wavelength is to improve laser absorption to match the material being processed; reduction in spot size is a secondary benefit. Changing wavelength by frequency changing crystals is an expensive proposition as it involves the crystals themselves (and replacement costs) as well as laser energy loss as the beam passes through the crystal. The decision to use frequency changing crystals has to be made upfront as the laser has to be configured accordingly; not a second thought option.

Spot size can also be reduced by installing a focus lens of shorter **focal length**. This change is relatively easy in most focus heads, and is a common option in welding applications. The downside of a shorter focal length is a shorter depth-of-focus (see Figure 2, below), which is the distance along the optical axis where the spot size is relatively unchanged. Shorter depth-of-focus raises the risk of the spot going out-of-focus with minor changes in part shape or fixture variations. An out-of-focus spot will have lower energy density and likelihood of insufficient weld depth.

![Figure 2. Comparison of short and long focal lengths on depth of focus. Shorter focal length lens will have smaller spot size and shorter depth-of-focus.](image)

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Spot size can also be reduced by improving beam quality for cutting/marking/drilling applications, and is measured by a factor referred to as $M^2$. An ideal beam where the energy distribution is perfectly gaussian has a $M^2$ value of 1. To achieve an $M^2$ of 1 in a conventional YAG/Vanadate solid-state laser requires use of a very small diameter YAG rod and/or a very small aperture in the resonating cavity; both methods limit the power output. Fiber lasers are not so constrained and are able to produce good beam quality even at high power levels of the order of multiple kW. Same is true with CO$_2$ gas lasers which have lost some of their market for welding applications to fiber lasers, but continue to be popular for cutting applications. Even though beam quality is not an issue to control spot size in welding applications, good beam quality allows fiber lasers to be focused to a reasonable spot size at distances of the order of 200-1000 mm, greatly expanding the scope and applications for laser welding including remote galvo-welding.

The last option to reduce spot size is to increase the beam diameter as the beam enters the focusing lens. Beam diameter can be increased with beam expanders placed between the collimating lens and focus lens. Increasing beam diameter reduces beam divergence and allows beam to focused to a smaller spot size. This strategy is commonly used in marking lasers to control spot size, but can also be used in welding lasers. The downside is the added expense of beam expanders and the energy loss as the beam travels through additional lenses.

Figure 3. Beam expander uses a combination of lenses to increases diameter of the collimated beam; it is placed between the collimating and focusing lenses.
With so many choices to produce the desired spot size, a laser engineer has to carefully balance the pros and cons before choosing a particular strategy. Some of the options have to be planned in advance as they are not easy to implement without suitable hardware design. Engineers will do well to give spot size some serious thought, else the process will put them on the spot!

If you have any questions about the contents of this newsletter or any other question about welding, please contact us at WJM Technologies.