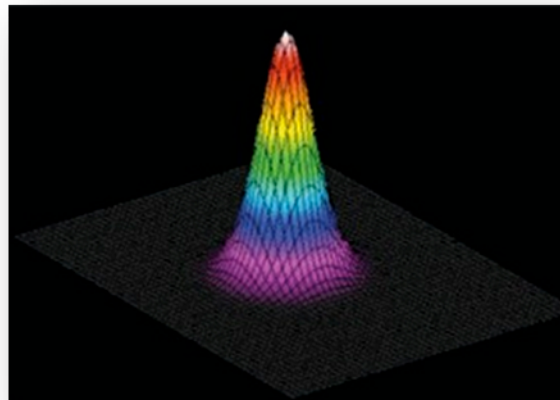


# Beam Profiling

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## Introduction

Lasers are ubiquitous in industry today. Carbon Dioxide, Nd:YAG, Excimer and Fiber lasers are used in many industries and a myriad of applications. Each laser type has its own unique properties that make them more suitable than others. Nevertheless, at the end of the day, it comes down to what does the focused or imaged laser beam look like at the work piece? This is where beam profiling comes into play and is an important part of quality control to ensure that the laser is doing what it intended to.

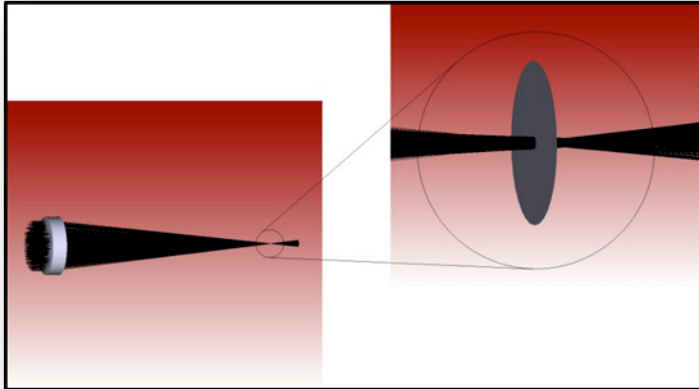
In a vast majority of cases the laser beam is simply focused to a small spot with a simple focusing lens to cut, scribe, etch, mark, anneal, or drill a material. If there is a problem with the beam delivery optics, the laser or the alignment of the system, this problem will show up quite markedly in the beam profile at the work piece.

## What is Beam Profiling?

Beam profiling is a means to quantify the intensity profile of a laser beam at a particular point in space. In material processing, the "point in space" is at the work piece being treated or machined. Beam profiling is accomplished with a device referred to a beam profiler. A beam profiler can be based upon a CCD or CMOS camera, a scanning slit, pin hole or a knife edge. In all systems, the intensity profile of the beam is analyzed within a fixed or range of spatial

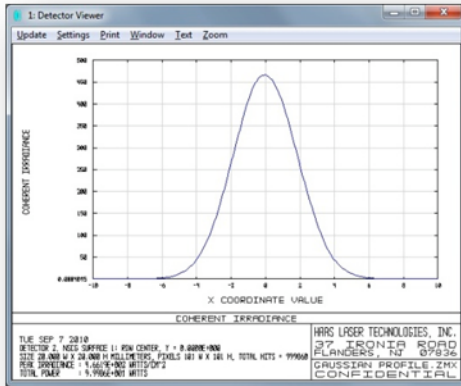


position. The CCD/CMOS camera based profilers provide a 3-D representation of the beam whereas the other methods provide a 2-D slice of the beam with the scanning of a slit, pin hole or knife edge across the beam while measuring the intensity with a photo diode.



**Figure 1: Focused Laser Beam and a Blow Up of the Focal Spot Where a Beam Profiler Would Measure the Profile.**

Within the Gaussian profile as shown in the figure 2, what is the beam diameter? The answer to that question is dependent upon the statistical reference it is measured to. In the laser industry the diameter can be measured to the full width of the beam at half its maximum intensity (FWHM),  $1/e^2$  point (0.135 times the maximum intensity,  $D4\sigma$  or second moment (which is 4 times the standard deviation of the horizontal or marginal distribution), Knife-edge width (the width of the beam is defined as the distance between the points of the measured curve that are 10% and 90% (or 20% and 80%) of the maximum value), D86 width is defined as the diameter of the circle that is centered at the centroid of the beam profile and contains 86% of the beam power.<sup>i</sup>



**Figure 2: Intensity Profile of Gaussian Laser Beam**

One will find that laser manufacturers will provide the beam diameter as the  $1/e^2$  point for Gaussian, or "Gaussian Like" beams and excimer lasers are generally specified at the FWHM point since the beam is generally rectangular and has asymmetric beam divergence in the X and Y axes. It is therefore important to confirm with the laser manufacturer what their beam diameter is based upon and at what location from the output port of the laser. The distance from the laser, as we will see shortly, plays an extremely important role in size of the beam diameter. Without getting into the complex math of some of the beam diameter measurement definitions, beam profile device manufacturers provide in their software the ability to select the type of beam diameter measurement, i.e., FWHM,  $1/e^2$  point,  $D4\sigma$ , Knife-edge 90/10 or D86. This is convenient for the user as it avoids a high potential of calculation error.

### Where and What to Measure?

Not only is the type of beam diameter measurement method important but so is the location in space it is measured as regards its propagation through space. All lasers have a "beam waist" the beam waist of a laser is the location along the propagation direction where the beam radius has a minimum.

Two characteristics of beam propagation of great importance are the beam radius,  $w(z)$ , at any axial position,  $z$ , and the phase front radius  $R(z)$ , given below in mathematical terms:

$$w^2(z) = w_0^2 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right]$$

$$R(z) = z \left[ 1 + \left( \frac{\pi w_0^2}{\lambda z} \right)^2 \right]$$

where  $\lambda$  is the wavelength of the laser.

Graphically this is depicted in figure 3.

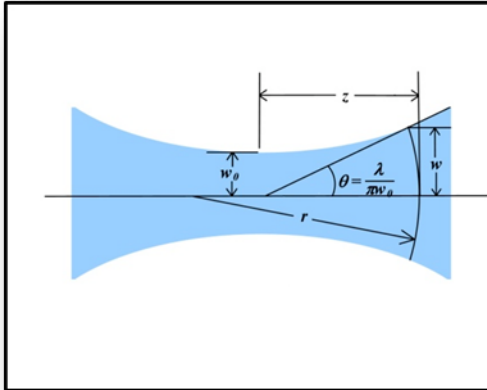


Figure 3: Gaussian beam propagation beginning from a waist  $w_0$ .

Referring now to figure 3 the beam expands as it propagates through space. The intensity distribution remains Gaussian at every beam cross section, with the width of the Gaussian profile changing along the axis. At the beam waist, where the phase front becomes plane, the beam contracts to a minimum diameter  $2w_0$  ( $z=0, R=\infty$ ). For most practical lasers, the location of the beam waist generally lies within the laser cavity itself.<sup>ii</sup>

For large values of  $z$  the beam expands linearly and has a far-field divergence angle ( $\theta$ ).

$$\theta = \lim_{z \rightarrow \infty} \frac{dw}{dz} = \frac{\lambda}{\pi w_0}$$

The focused spot size of a laser beam passed through a lens will then become:

$$w_2 = f \theta_1 = \frac{f \lambda}{\pi w_1}$$

This is simply the focal length of the lens times the measured, half angle beam divergence. More common, today, is the use of what is called  $M^2$  factor. This is the beam parameter product divided by the corresponding product for a diffraction-limited Gaussian beam with the same wavelength. This is represented as follows:

$$\theta = \frac{M^2 \lambda}{\pi w_0}$$



$$M^2 = \frac{\theta \pi w_0}{\lambda}$$

Consequently, a more accurate calculation of the spot radius, taking into account the  $M^2$  factor of a laser is as follows:

$$w_2 = \frac{f M^2 \lambda}{\pi w_0}$$

The laser beam profiler is therefore measuring the beam radiuses mentioned above and provide the numbers based upon the diameter method selected. It is therefore helpful to understand these basics to ensure an accurate measurement of a laser system under test.

### Why Measure Beam Quality?

In most laser applications some care has been taken to establish the best laser type and focusing optics to achieve a particular cutting speed, or drilling condition or whatever. Why worry after all this is done? Well, on day one everything is in good working condition: new laser, fresh and clean optics, good alignment, etc. In many applications there is a debris shield or other protective optic following a possibly expensive focusing lens. This debris shield serves as means to stop slag and other debris from getting on the lens. Debris on any optic will cause the wave front of the light to degrade which causes the  $M^2$  factor of the laser system to decline as well. By monitoring the  $M^2$  factor during a process, can greatly aid the performance of a system and its quality control.

If the  $M^2$  factor is monitored, and limits set, a system can be stopped before laser machined parts become out of spec due to laser system degradation. There are many laser beam profilers on the market and many of them do not lend themselves to real time monitoring of the laser system. The Haas Laser Beam Analyzer is a compact unit that can be quickly inserted into a laser system between the focusing lens and work piece either before or after a product run to determine if the  $M^2$  value is within a specified limit.

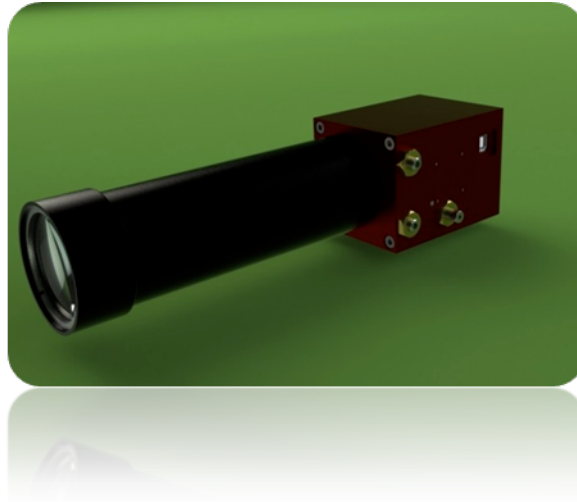


Figure 4: Haas Laser Beam Analyzer

## Haas Laser Beam Analyzer

Haas Laser Technologies has developed a compact beam profiling system that can measure the  $M^2$  values of very high power lasers in real time. The concept is based upon a patent pending optical design (USPTO 12/756,476) that simultaneously images multiple slices of the spatial profile through the beam waist onto a single CMOS camera. Each slice of the beam waist profile is evaluated as a region of interest (ROI) on the CMOS camera and ISO 11146 and 13694 standards are applied to the data collected from the images.

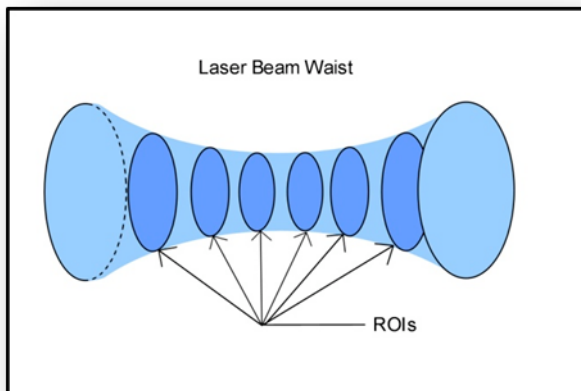


Figure 5: Beam Waist as Measured with Haas Laser Beam Analyzer Optics

The system can be adjusted so that the exact beam waist is contained with the 6 regions of interest generated by the camera and software. The separation of each ROI is uniform and dynamically adjustable for optimization of a given focusing system. This applies whether the



lens has a very short focal length or a very long focal length. The unit is so compact, it can be used with focusing lenses as short as 75mm.

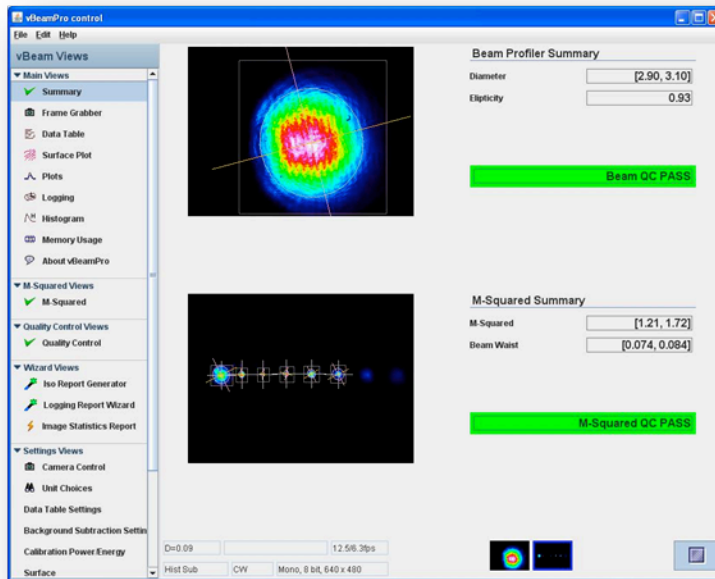


Figure 6: Haas Laser Beam Analyzer M2 QC Software

Figure 6 shows a typical quality control screen of a Haas Laser Technologies Laser Beam Analyzer. Here the raw beam is measure with one profiler camera where the light it picked off from the bleed light through the last turning mirror. The lower image is the profile of the focused light into the M<sub>2</sub> module camera. In a matter of seconds, the system computes the M<sub>2</sub> factor and then compares the number to the set limits to establish a Pass/Fail condition.

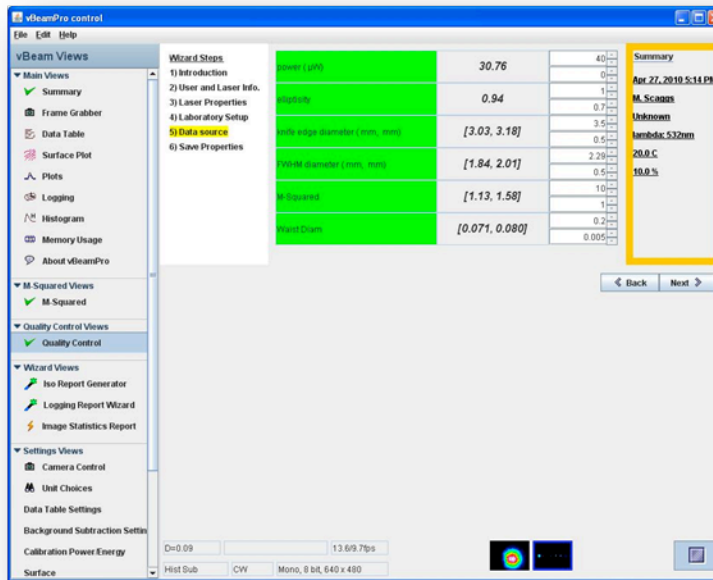


Figure 7: QC Control Window for Beam Quality Monitoring

Figure 7 shows the software screen where the limits for critical beam parameters are set for quality control purposes. As a process is developed, these values can be optimized to provide the best performance and reliability for a given laser process.

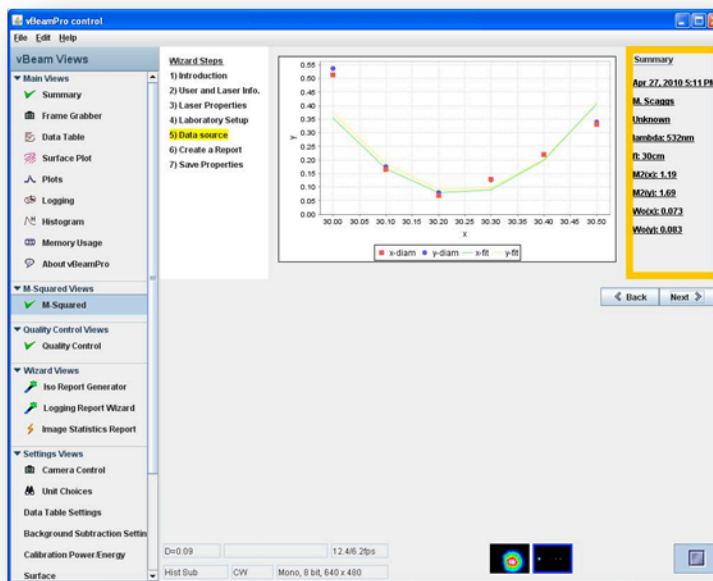


Figure 8: Beam Waist Measurement.





Details of the actual beam waist measurement can be reviewed as shown in the graphic in figure 8. Here the entire beam waist and its Raleigh length (depth of focus) can be seen, along with astigmatism of the focused spot. The measurements from the HLBA system can provide the focused spot size, circularity, astigmatism, and  $M^2$  factor. The unit is compact enough that it can be inserted virtually at any location in a beam delivery system to help locate poorly performing optics. A simple beam bending mirror, for example, can be deformed mechanically in its mount to cause sufficient beam distortion to show up as astigmatism and degrade the focused spot to the point it is out of spec. Without a beam profiler, this can be very difficult to locate and correct.

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<sup>i</sup> ISO 11146-3:2005(E), "Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 3: Intrinsic and geometrical laser beam classification, propagation and details of test methods."

<sup>ii</sup> Gagliano, et al., Chapter 3, Laser Processing Fundamentals, Lasers in Industry, 1972, Western Electric Company.