

Beam Profiling

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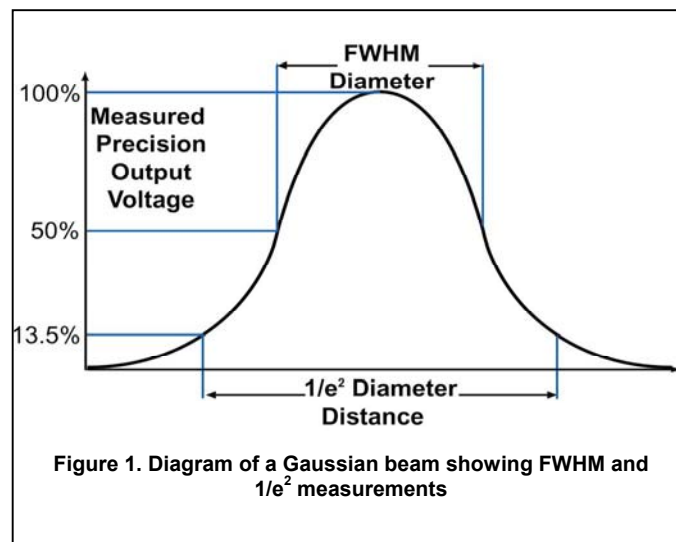
Introduction

In every laser application, whether in medical, industrial, laser printing, marking, welding and cutting, or fiber optics, the beam profile provides valuable information for the most efficient use of the laser. Although profiling is often not part of the Theoretical Optics curriculum taught in universities, beam profiles are very commonly the principal measurement in practical applications found in industry. The beam profile tells all about the beam's spatial characteristics, which in turn describe the propagation, beam quality and utility of the beam. In addition, it can tell how effectively optics are succeeding in modifying and shaping the laser's output. Profiling is particularly helpful in building optical systems for laser printers and fiber optic collimators. Until you know the beam profile, it is difficult or even impossible to put the laser light to use.

What is Beam Profiling?

Spatial characteristics describe the distribution of radiant energy across the wave front of an optical beam. The radiation can be shown as a plot of the relative intensity of points across a plane that intersects projected path of the beam.

The most basic measurement of the beam's irradiance is a single number defining its width or diameter. Since optical beams do not actually have sharp physical edges, the beam width is made between two points that contain a selected percentage of the "useful" energy. When beams are Gaussian, or at least approximately Gaussian, the common value for this measurement is at the $1/e^2$ diameter. This is the point at which the beam contains 4-sigma of the energy distribution and occurs where the beam's power is at 13.5% of the



maximum height. Another common measurement is at the full-width-half maximum (FWHM) level, where the power drops to one half of the maximum. The beam diameter measurement, by either method, allows one to determine other important features of the spatial irradiance pattern of the beam.ⁱ According to wave front propagation theory, light waves diverge, causing the beam diameter to increase as it travels along the beam path. The rate at which the beam diverges is an angular term known as the divergence, denoted as θ (*theta*). The point at which a beam width is at its minimum size is known as the beam waist (D_0). By measuring the beam diameter at various points along the axis of propagation, known as the z-axis, the divergence and waist characteristics of the beam can be determined. Beam profiling is the act of sampling the beam size along the z-axis and thereby determining its spatial characteristics. The net result of profiling yields an image of the beam's energy pattern. Techniques to make these measurements have included mode cups, phosphors, infrared cards, Plexiglas blocks, burn papers and film. These crude techniques do not provide numerical values and thus require a subjective evaluation of the image. More precise instruments for measuring a laser beam are scanning apertures and CCD array cameras. These sensors are preferred because they give a true numerical output that makes it easier to accurately quantify the nature of the beam. As William Thomson, Lord Kelvin, has said:

“... when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.”ⁱⁱ

Why is Beam Profiling Important?

The testing of actual performance rather than relying on theoretical assumptions is basic to any good quality control plan. Nearly all optical systems use optical elements to affect the path or distribution of the output from a source (laser, LED or incoherent light). The system designer must know what the initial distribution is in order to select the necessary optical components. System fabricators must know whether their components achieve the desired result. They also must have real-time feedback on the beam performance to make the necessary adjustments. End users need an easy means to confirm that their systems are providing acceptable performance. Optical design engineers face the challenge of working with a vast set of variables. The fact that the beam's spatial characteristics can change as a result of the drive current, source temperature, internal apertures, or mirror sets compounds the problem. By knowing the value of the beam waist D_0 and the actual divergence angle θ , the designer can predict the beam diameter at any position (z) along the axis of propagation by the propagation formula:

$$D_z^2 = D_0^2 + \theta^2 z^2$$

By combining the results with the thin lens equations or ray tracing, it is possible to model the beam path for Gaussian or mixed mode laser beam. The savings to the design cycle in time and dollars can be substantial.ⁱⁱⁱ The analysis of results from non-numerical sampling methods can lead to a host of differing opinions about the laser beam, but a beam profiler provides a numerical value for the beam diameter. An XY scan or 2D array image of the beam can provide numerical measurements of the beam's shape and

ellipticity. Modern profilers also provide accurate measurements of the beam's position, and thus any pointing error in the optical system. In addition, profilers give a rapid, real-time feedback that assists in adjusting the optical system. Beams can be focused while the profiler provides an image of the exact result of the adjustments. Coupling a beam profiler with a multi-axis nano- or micro-positioning stage allows for the automation of precise assembly of optical components.

Laser Manufacturing

Beam profiling has been a standard technique for the traditional laser manufacturers for many years. The quality of a radially symmetrical laser beam can be defined by a parameter called the times-diffraction-limit-factor M^2 , or its inverse, k-factor, which can be derived from the location of the beam waist z_0 , the waist diameter $d_{\sigma 0}$, and the far-field divergence angle, θ .

$$k = 1/M^2 = (4\lambda_0/\pi) \cdot (1/nd_{\sigma 0}\theta_{\sigma}) = (4\lambda/\pi) \cdot (1/d_{\sigma 0}\theta_{\sigma})$$

Where:

λ_0 = Vacuum wavelength

λ = wavelength in medium with index of refraction n

k = beam propagation factor

M^2 = times-diffraction-limit-factor

n = index of refraction

The propagation M^2 or k-factor gives a theoretical measurement of how finely the laser beam can be focused. This is important to determine how well the beam can be put to use for various applications. An M^2 or $k=1$ describes a perfectly diffraction-limited beam. In other words, its behavior will be directly related to the diffraction limit of the wavelength and the lens system, without any additional effects from the laser itself.

Laser diodes and VCSELs are semiconductor lasers with divergent rather than paraxial beams. Testing these lasers is quite different from testing typical cavity lasers. In general, the important parameters are the power-input-to-light-output curve, called the *LI* or *LIV curve*, the spectrum of the beam, and its divergence angle. Because semiconductor lasers have such divergent beams, lenses are necessary to collimate them into useful beams. Characterizing the beam shape and divergence makes it possible to understand how these devices will work with the optics designs. The LI curves provide information on the efficiency of the laser output and detect any flaws in the manufacturing process of the diodes. Unlike cavity lasers where standard emission comes from the lasing medium, the wavelengths of diode lasers are dependent on the physical configuration of the crystal lattice and how this makes up the laser cavity. For this reason, systems to measure diode lasers also do a spectrum test, along with the LI curve and divergence angle profile.

Medical/Biotechnology Applications

In the medical and biotechnology industries there are many laser applications ranging from light scalpels to scanners to read the genetic code on a DNA chip. Each of these applications requires that laser beams be shaped and adjusted with optics to make them function properly. Beam profiling directly checks the beam-shaping optics to see that

they are performing as expected and allows real-time adjustments if they are not. The FDA and state health regulatory agencies have rigorous requirements for the testing of medical devices. “Good Manufacturing Practices” (GMP) and “Good Laboratory Practices” (GLP) are the foundations of regulatory approval. These both require tests to be both repeatable and traceable to guarantee performance. Traceable, calibrated beam profilers are essential to the maintenance and calibration of medical laser systems, whether they be Lasik® eye surgery, light scalpels for laparoscopic surgery or other patient-care laser applications.

A biotechnology application for lasers is in the scanning of genomic and proteomic “lab-on-a-chip” detectors. These systems use a laser beam to identify, or “read,” the building-block “letters” of the DNA and RNA sequences or the amino acid components of proteins. The finer the laser spot, the smaller the sample that the scanner can read. Beam profiling helps in fine-tuning the beam optics for these types of scanners.

Graphics and Printing

The laser printing industry was one of the earliest adopters of beam profilers for the design and manufacture of the laser scan unit (LSU) that is the heart of the laser printer engine. Understanding the spot size, alignment and jitter of these systems is essential for the continued improvement of the laser printers. Competition and price pressure in the laser printer industry is intense, and therefore reducing the cost to produce the LSU is paramount. Nonetheless, each LSU must be adjusted and tested to ensure its proper operation. The laser beam optics must be tested to be sure that the laser spot is delivered to the proper points across the scan plane of the paper platen. In many cases the method for doing this is to operate the laser with the scanning polygon mirror stopped. The mirror is then aimed to deliver a stationary laser spot to various points along the scan path. The spots are measured either by moving a beam profiler or placing multiple profilers along this path to measure the spots at the appropriate points. In order to measure the performance of all the mirror facets on the polygon, this must be done numerous times at each location, and may take up to twenty minutes to accomplish. A new instrument technology that allows the LSU to be tested with the polygon running at full speed can reduce this test time to several seconds. The productivity increase for LSUs is more than tenfold, and therefore the actual cost of the testing is dramatically lower.

Bar Code Scanning and Optical Memory

Both bar code scanning and optical memory techniques use a laser beam to read or write information. As with biotechnology scanning techniques and printing applications, the smaller the laser beam, the more precisely it can read and write the information. However, bar code readers require that the operating range of the beam be fairly long in order to allow the scanner to work over a convenient range of working distances. The extent of the waist region of the beam is called the Rayleigh range. This is defined as the area over which the beam diameter is $\pm\sqrt{2} \cdot D_0$, where D_0 is the waist or smallest diameter of the beam.^{iv}

A beam profiler will allow the direct measurement and adjustment of the optics to provide a long Rayleigh region consistent with good scanner performance. For optical

memory, on the other hand, the beam is generally optimized to create a very small spot. Since spot size and Rayleigh range are inversely proportional, the focal point of the optical memory laser beam is very critical. The following formula shows this

$$\text{mathematically: } D_0 = \frac{4\lambda}{\pi\theta} .$$

Since for any given wavelength, λ , $D_0\theta$ equals a constant, $\frac{4\lambda}{\pi}$, thus $D_0 = \frac{K}{\theta}$

For a small spot the angle must be large; for a small angle (i.e., long Rayleigh range, collimated beam) the waist must be large.^v

Welding and Cutting

Many high-power welding and cutting laser applications take advantage of the finesse of the laser because a laser can deliver precise power density to the work piece. In order to be sure that this precision is maintained during the process, it is necessary to monitor the laser's performance. Until now, this has generally been done either by checking the parts being worked on for flaws, or by monitoring the unfocused beam and extrapolating the focused beam's performance.

Both of these methods are less than optimal. The first, because one has to waste material and time by making a bad part, in order to discover that the laser is not working properly. Sometimes the flaw is difficult to discover until some later step in the manufacturing process, when further value has been added, increasing the scrap and rework expense. Monitoring the raw laser beam has the disadvantage of only checking the laser, not the actual delivery optics. It does not really tell you what is going on at the work piece. With a properly designed scanning slit beam profiler, such Photon's High Power NanoScan, it is possible to measure the beam that is actually doing the work. It can measure precisely the beam diameter, shape and power distribution at the actual work surface. It provides a numerical value for the beam diameter, measures ellipticity, and centroid position. It will give early warning of problems with the laser and the focusing optics and delivery system.

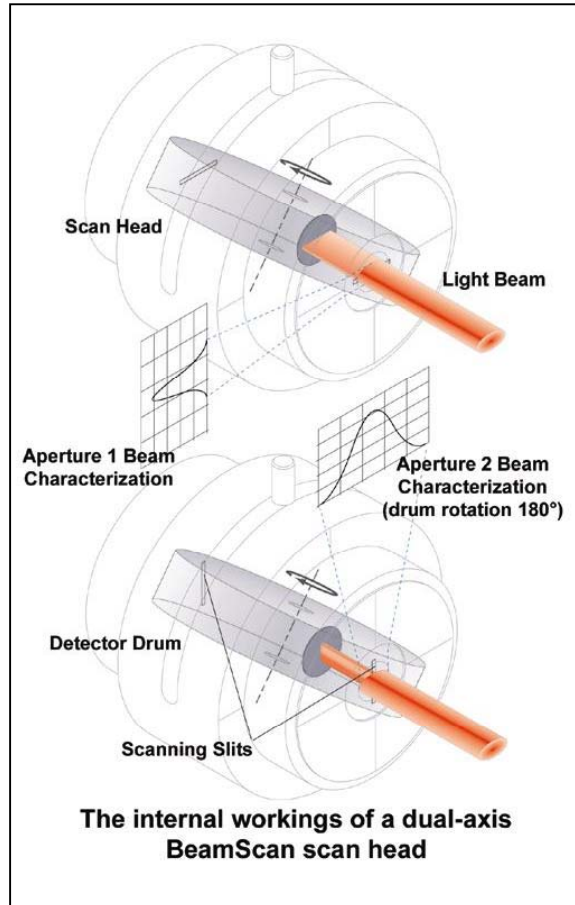
What is a Beam Profiler, and How Does it Work?

Gaussian Beam Profiling

The standard beam profiler is a device comprising a photo detector with a scanning pinhole, knife-edge, or slit, or a 2-dimensional array, such as a CCD (charge coupled device) camera. The laser spot is focused on the profiler and measurements taken. For the purposes of discussion we will describe the scanning slit profiler for measurement of Gaussian paraxial beams. The slit has some distinct advantages over the pinhole, knife-edge and camera methods.

Why Use a Slit?

The scanning slit is a natural attenuator, which makes it possible to measure a fairly high-powered beam directly without the need for external attenuation. By comparison a CCD camera array can only accept a few picowatts of direct power. By using two mounted slits it is quite simple to align them to measure the x and y axes of the beam. If the profiler is rotated to have the slits pass through the long and short axes, the ellipticity of a beam can be accurately measured. It is this XY orthogonal scan that is the basis of the Photon BeamScan and NanoScan instruments. The advantage that the slit has over the knife-edge profiler is twofold. First, because the knife edge only blocks one side of the beam—it does not attenuate it—additional attenuation will be necessary to avoid detector saturation. Second, to observe a profile from a knife-edge the trace must be differentiated. The differentiated noise contained on the laser is amplified and must be filtered to arrive at a legibly smooth profile. This smoothing may remove important information about the structure of the beam, thus making the beam look better than it actually is.^{vi}



Pinholes also attenuate the beam, but they are much more difficult to align in order to obtain a good profile. A pinhole will give better spatial detail than a slit, but only marginally so, and it must be aligned to pass through the maximum chord of the beam. This is difficult to do, particularly with a focused beam.^{vii}

The beam width is determined by measuring the profile between the clip level points on either side of the maximum energy of the beam. Although clip levels are arbitrary, they do define the beam. By setting the desired clip level (usually $1/e^2$ or 13.5%), the scanning slit instrument will then report a direct beam width reading. With the XY scan head, the slit method reports a beam diameter for both the x- and y-axes. Computer graphics programs can then extrapolate these data into a pseudo 3-dimensional representation of the beam profile.

Why Use a CCD Camera?

For low repetition rate pulsed beams, it is usually necessary to use a 2-dimensional array to profile the beam. For single pulsed lasers, the short duration of the beam precludes the use of the slit to profile it. A CCD camera can be synchronized to “catch” the pulse. It will give a true 2D image of the beam. All the same clip level parameters can be used with CCDs to give good value for the peak diameter. The principle disadvantage of the CCD camera approach is that the direct power that the CCD can accept without saturation is very small. This means that one will necessarily have to use external attenuators to control the amount of light hitting the array. In addition, the pixels on the

array determine the precision of the measurement. The best CCDs available for profiling have pixels that are 5-10 μm in diameter. For very small beam diameters, fine detail may be invisible. CCD based profilers are fine for beams that are greater than 100 μm in diameter. Although silicon CCDs are quite inexpensive, their spectral response is confined to the visible range. For the “telecom wavelengths” between 1300-1700nm, it is necessary to use InGaAs arrays, and these are very costly and still have fairly large pixel sizes (>30 μm), which limit their spatial resolution. Longer wavelengths require even more costly approaches to measure them with arrays.

Lasers with kHz pulse rates can be measured with slit profilers provided the beam widths are sufficient to provide enough data. Many CO₂ lasers use pulse width modulation (PWM) to control the power level of the laser. This uses pulsed operation to reduce the duty cycle and lower the average power. The beam operates as if it were CW, and many operators do not even realize that the laser is pulsing. To measure lasers operated in this mode the slit profiler must have a pulsed operation mode; the laser’s pulse frequency must be at least several kHz; and the combination of the frequency and beam size must provide a sufficient number of pulses across the beam to generate a meaningful profile. Eight to ten pulses are a reasonable minimum. PWM lasers usually operate around 10kHz. The relationship of the beam size and frequency is a fairly simple mathematical model. For pulsed beam operation the drum should be run at the lowest speed, (e.g., 1.25Hz on the Photon NanoScan). At this speed the slits are moving at ~115mm per second, or 115 μm per msec. This means that each slit would take 1.7msec to traverse a 200 μm beam. At 5kHz the laser would pulse ~8 times during this time. This would provide just enough data to generate a meaningful profile. A smaller beam would require a faster pulse rate, a larger one could run at a lower repetition rate.

Pulse rates above 500kHz can be treated as CW for purposes of profiling. Slit scanning profilers equipped with pyroelectric detectors can profile the entire wavelength range

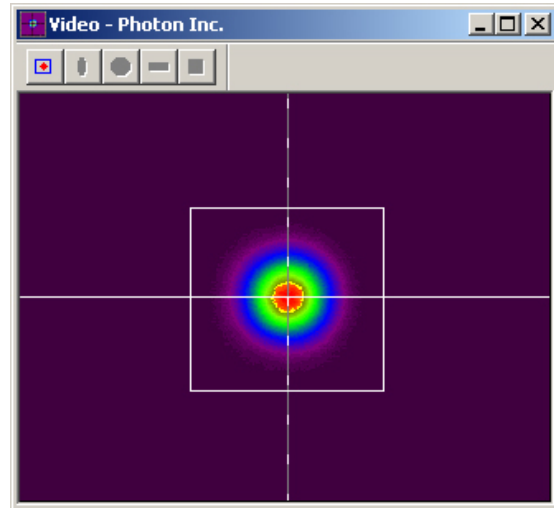


Figure 3. Typical 2D profile of the Photon CCD camera, BeamPro_{filer}

from UV to far infrared beyond 20 μ m, making them the closest thing to a universal profiler.

For more information on profiling and various profiling instruments, please visit www.photon-inc.com.

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- i. "Six Benefits of Characterizing the Spatial Performance of your Optical System," Photon Inc, 1997
 - ii. William Thomson, Lord Kelvin, Popular Lecture, 1883.
 - iii. "Six Benefits", *op.cit*
 - iv. O'Shea, Donald C., Elements of Modern Optical Design, John Wiley & Sons 1985, pp. 232-2
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 - vi. Fleischer, J.M., "Beam Profiling Monitors Laser Health" Industrial Laser Solutions, September 1999
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