

Current Technology of Laser Beam Profile Measurements

Carlos B. Roundy, Ph.D.

Ophir-Spiricon Inc.

Logan, UT 84341

Phone: (435) 753-3729, Fax: (435) 753-5231, E-mail: sales@ophir-spiricon.com

1. Introduction

There are many applications of lasers in which the beam profile is of critical importance. When the beam profile is important, it is usually necessary to measure it to insure that the proper profile exists. For some lasers and applications this may only be necessary during the design or fabrication phase of the laser. In other cases it is necessary to monitor the laser profile continuously during the laser operation. For example scientific applications of lasers often push the laser to its operational limits and continuous or periodic measurement of the beam profile is necessary to insure that the laser is still operating as expected. Some industrial laser applications require periodic beam profile monitoring to eliminate scrap produced when the laser degrades. In other applications, such as some medical uses of lasers, the practitioner has no capability to tune the laser, and the manufacturers measure the beam profile in the design phase to ensure that the laser provides reliable performance at all times. However, there are medical uses of lasers, such as photo-refractive keratotomy, PRK, wherein periodic checking of the beam profile can considerably enhance the reliability of the operation. PRK is an example of laser beam shaping which is a process whereby the irradiance of the laser beam is changed along its cross section. In order for this laser beam shaping to be effective, it is necessary to be able to measure the degree to which the irradiance pattern or beam profile has been modified by the shaping medium.

This paper describes the general state of the art of laser beam profile analysis.¹⁻¹⁴ It introduces the general need for beam profile analysis, methods for measuring the laser beam profile, a description of instrumentation that is used in beam profile measurement, a discussion of the information that can be obtained simply by viewing the beam profile, and finally, how quantitative measurements are made on laser beam profiles, and the significance of those quantitative measurements.

2. Laser Beam Properties

There are many common sources of light, each providing a different function. Table 1 lists some of these. For example, the sun provides $1000\text{W}/\text{m}^2$ on the surface of the earth, a very high power, but spread over a large area. A typical incandescent light bulb may put out 100 Watts, but is radiating into a sphere, and much of the light is in the infrared where it is not visible. A fluorescent light bulb, on the other hand, may put out only 40 Watts, but since more of the light is in the visible region, it illuminates objects about 3 times more efficiently than an incandescent bulb. Flood lamps or collimated light bulbs simply have reflectors to redirect the light into a specific direction. Hot objects emitting radiation in the IR and near IR include everything around us: our own bodies, clouds overhead in the night, and all objects on the earth. Light emitting diodes (LEDs) produce light at fairly low intensity, but usually at specific wavelengths. Laser beam light, on the other hand, offers characteristics that are very different from other sources of light.

Table 1. Typical or common sources of light

The sun
A light bulb
A collimated light bulb (flood lights)
Hot objects
Light emitting diodes
A laser beam

2.1 Unique Laser Beam Characteristics

Some of the things that make laser beams unique are listed in Table 2. For example, the monochromatic nature of a laser beam means that it is typically a single narrow wavelength with very little light at wavelengths other than the central peak. The temporal nature of a laser beam enables it to vary from a continuous wave to an extremely short pulse providing very high power densities. The coherence of a laser enables it to travel in a narrow beam with a small and well defined divergence or spread. This allows a user to define exactly the area illuminated by the laser beam. Because of coherence a laser beam can also be focused to a very small and intense spot in a highly concentrated area. This concentration makes the laser beam useful for many applications in physics, chemistry, the medical industry, and industrial applications. Finally, a laser beam's unique irradiance profile gives it very significant characteristics. The beam profile is the pattern of irradiance that is distributed across the beam or its cross-sectional irradiance profile

Table 2. Unique characteristics of a laser beam

Monochromatic (Single wavelength)
Temporal (Continuous wave to femtosecond pulses)
Coherence (Consistent phase between all light elements)
Highly concentrated (Focusable to extremely small spots)
Beam irradiance profile (Unique cross-sectional spatial power or energy distribution)

2.2 Significance of the Beam Profile

The significance of the beam profile is that the energy density, the concentration, and the collimation of the light are all affected by it. Also the propagation of the beam through space is significantly affected by the beam profile. Figure 1 shows a number of typical laser beam profiles illustrating the variety that can exist. Since such a variety exists in laser beam profiles, it is essential to measure the profile in any application where the energy distribution affects the performance of the laser or its intended purpose.

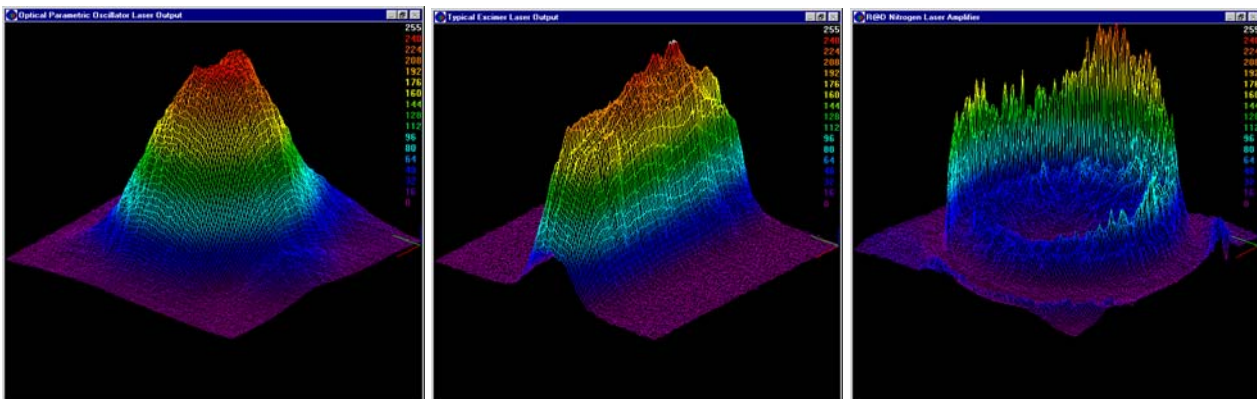


Figure 1. Various laser beam profiles: HeNe, Excimer, and Nitrogen Ring Laser.

Examples of two different types of ideal laser beams for different purposes are a Gaussian and a flat top beam. A Gaussian beam allows the highest concentration of focused light, whereas a flat top beam allows for very uniform distribution of the energy across a given area. These two idealized beams are shown in Figure 2.

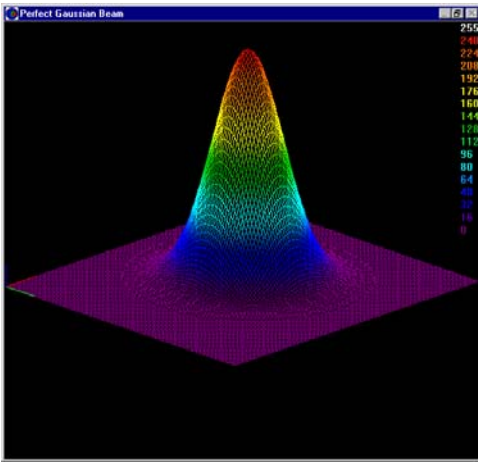


Figure 2a. Ideal Gaussian beam for highest concentration of energy.

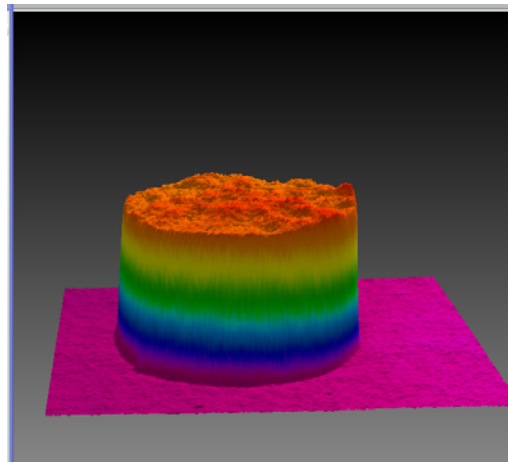


Figure 2b. Ideal flat top beam for uniform laser illumination.

2.3 Effects of Distorted Beam Profiles

However, lasers rarely exhibit the most uniform irradiance profile. Sometimes Gaussian beams are highly structured, and often-intended flat top beams are non-uniform across the top, or may be tilted in energy from one side to the other. Figure 3 illustrates some real world examples of distorted beam profiles. For example, in Figure 3a the highly structured beam would not focus nearly as well as the ideal Gaussian beam. The tilted flat top beam of Figure 3b would not give uniform illumination as intended, and could cause severe distortion in the process for which it is being applied.

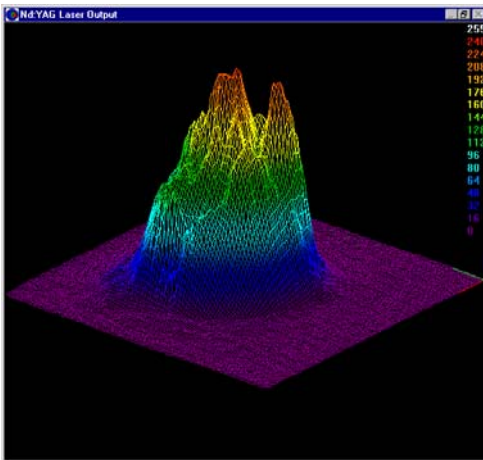


Figure 3a. Highly structured would-be Gaussian beam.

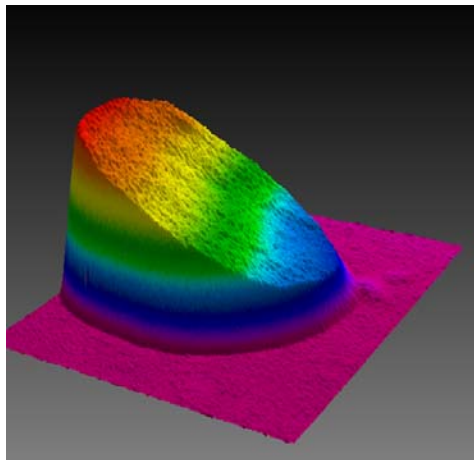


Figure 3b. Tilted or non-uniform flat top beam.

2.3.1 Scientific Applications

The significance of distorted beam profiles varies with the application. In scientific applications nonlinear processes are typically proportional to the irradiance squared or cubed. Thus a non-Gaussian profile may have peak energy as low as 50% of what a Gaussian beam would have under the same conditions of total power or energy. Therefore the nonlinear process may deteriorate to 25% or 12% of what is expected. This is a 300% to 700% error on an experiment that should be accurate to within $\pm 5\%$. Figure 4 shows the beam profiles of a Cr:LiSAF oscillator with subsequent amplifier outputs when the amplifier is properly aligned and when it is not.

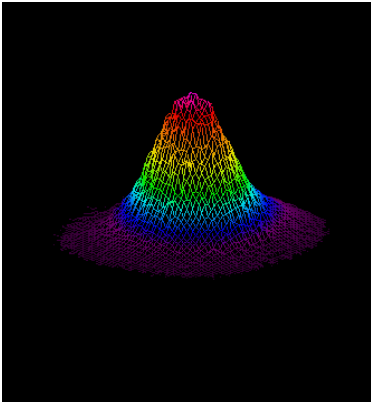


Figure 4a. Cr:LiSAF Laser Oscillator.

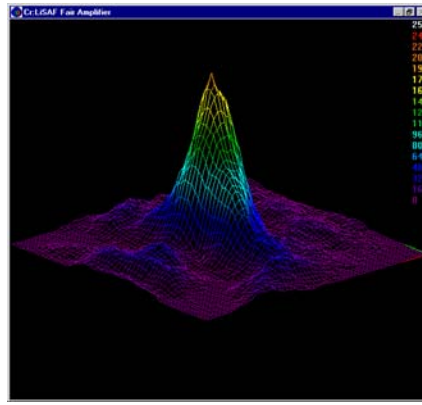


Figure 4b. Cr:LiSAF Laser with amplifier well aligned.

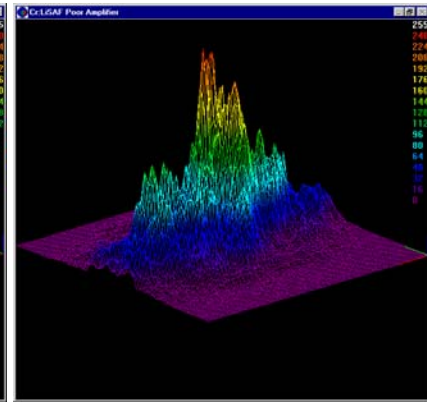


Figure 4c. Cr:LiSAF Laser with amplifier misaligned.

2.3.2 Instruments Using Lasers

Instruments using lasers, such as printers, fiber optics, communications, etc. require a high degree of control of the laser light to accomplish the intended task. The uniformity, pointing direction stability, and mode pattern of a typical laser diode used in instruments can be dramatically deteriorated by misalignment of the collimating optics or mounting, causing the instrument not to perform as expected. For example, Figure 5 illustrates a collimated laser diode beam being focused into a single mode fiber optic. In Figure 5b the Z axis of the focused laser diode is poorly aligned to the fiber, and much of the energy is fed into the cladding rather than to the inner fiber. Thus much of the energy does not come out of the central lobe. In Figure 5c the Z axis is adjusted slightly so that the major portion of the laser beam is coupled into the propagating mode of the fiber optic.

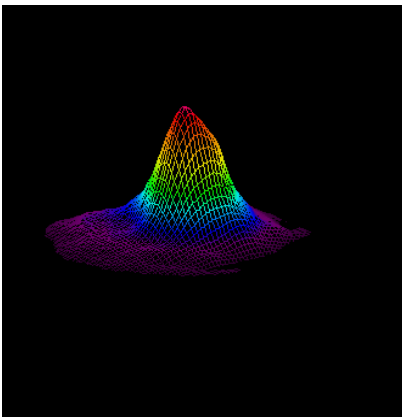


Figure 5a. Collimated laser diode beam.

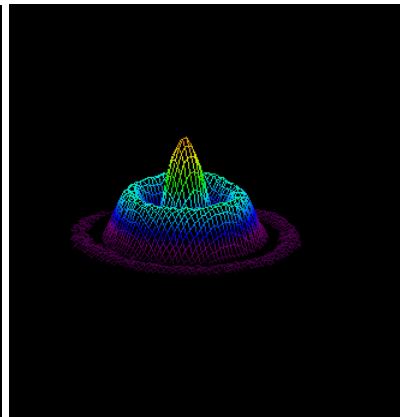


Figure 5b. Fiber output with diode poorly coupled into fiber optic.

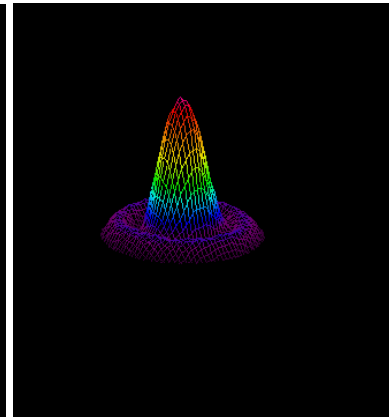


Figure 5c. Fiber output with diode well coupled into fiber optic.

2.3.3 Medical Applications

There are many medical applications of lasers.¹⁵ One of these is Photorefractive Keratotomy,¹⁶ in which a flat top beam is used to make vision corrections. If the homogenizer optics producing the flat top is out of alignment and there is a 50% tilt in the flat top, the correction to the eye may be 4 diopters on one side of an iris, with only 2 diopters on the opposite side. The flat top beam in Figure 2b would give expected results, whereas the tilted beam in Figure 3b would cause severe difficulty. This could account for some PRK operations causing the patient to end up with non-correctable vision after the operation. The flatness of the laser beam is also critical for aesthetic surgical applications such as; the remediation of port wine stains, hair removal, and other cosmetic surgery.

Tissue cutting and welding requires an extremely well controlled irradiance density to accomplish the task properly. Finally, many medical applications, such as Photo Dynamic Therapy, use fiber optics delivery systems, and the efficiency of these systems is strongly affected by the initial alignment of the laser beam into the fiber, as shown in Figure 5 above.

2.3.4 Industrial Applications

In industrial laser applications¹⁷⁻¹⁹ many high power Nd:YAG lasers and some CO₂ lasers are designed to produce multimode beams. The cutting, welding, and drilling efficiencies of these lasers are directly related to the beam profile. For example an Nd:YAG laser with a double peak at the focused spot can cause one cut width in the X direction, and a different cut width in the Y direction. Also, a beam with a poor profile can result in hole drilling of a different size than expected, and welds that are not as strong as necessary.

Figure 6 shows the beam profile of a poorly aligned and well-aligned CO₂ laser cavity. An industrial laser shop was using CO₂ lasers for scribing of ceramic wafers before breaking them into individual pieces. Most of the lasers in the machine shop gave extremely good results. However, one laser gave very inconsistent results which caused poor scribing, and therefore very erratic breaking of the ceramic. The laser had been measured by non-electronic mode burns in wooden tongue depressors, which gave the appearance that the laser had a uniform output. However, as soon as the laser was measured with an electronic pyroelectric camera, the high structure in the laser beam of Figure 6a became immediately evident. As soon as the technicians recognized this structure, they began adjusting the laser cavity mirrors, and within a short time the beam was improved to that of Figure 6b. Incidentally, the beam profile of Figure 6b was similar to that of the other lasers that were operating correctly.. Once the laser was tuned to the beam profile of Figure 6b, it gave consistent results in scribing the ceramic.

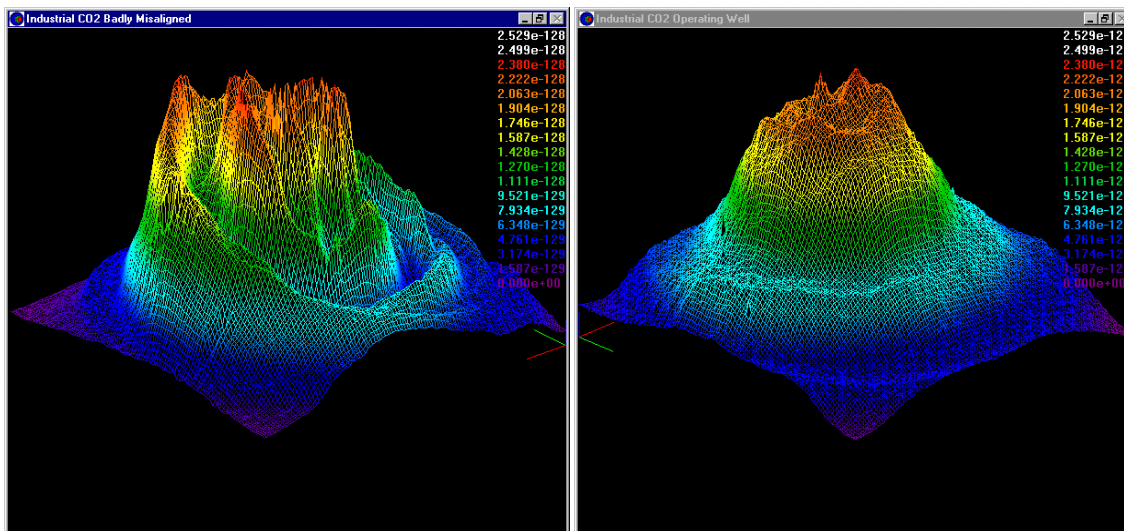


Figure 6a. Poorly aligned CO₂ laser cavity. Figure 6b. Well-aligned CO₂ laser cavity.

3. Laser Beam Profile Measurement Methods

3.1 Non-Electronic Methods

There are a number of non-electronic methods of laser beam profile measurement that have been used ever since lasers were invented. The first of these is observance of a laser beam reflected from a wall or other object. This is by far the simplest and least expensive method of measuring or observing a laser beam profile. The problem with this method is that the human eye is logarithmic, and can see many orders of magnitude difference in light irradiance. Even though it is logarithmic, the eye can only distinguish 8-12 shades of gray. Thus it is nearly impossible for a visual inspection of a laser beam to provide anything even approaching a quantitative measurement of the beam size and shape. Thus the beam width measurement by eye may have as much as 100% error. Figure 7a is a photograph of a HeNe laser beam being reflected off the wall. While photographic film has even less dynamic range than the human eye, the figure shows a very intense beam at the center, but a very large amount of structure far out from the center. This structure, which one might mistake as part of the laser beam, is less than 1% of the total energy in the beam. Yet the eye and the film are clearly able to discern this low energy. In addition, the eye cannot really distinguish structure in a laser beam with less than 2 to 1 magnitude variation.

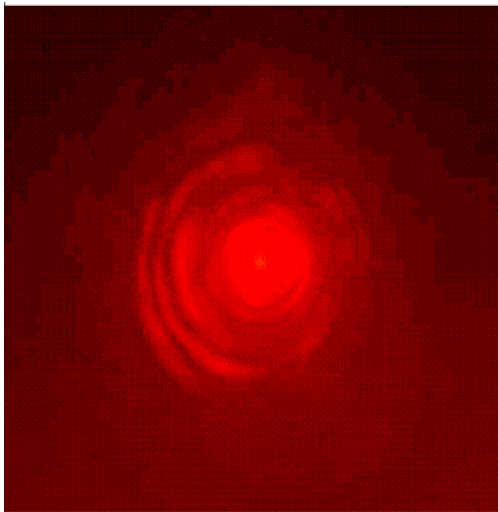


Figure 7a. Reflected laser beam.

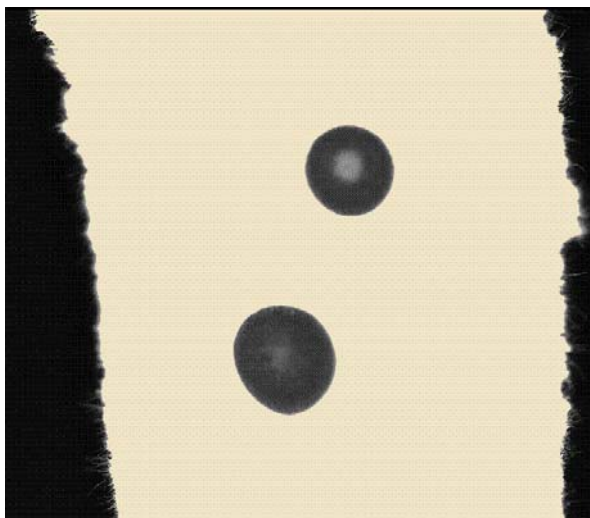


Figure 7b. Laser beam burn spots.

Burn paper and Polaroid film are often used for making beam profile measurements. Figure 7b illustrates thermal paper having been illuminated by a laser beam. The burn paper typically has a dynamic range of only 3, unburned paper, blackened paper, and paper turned to ash. Sometimes skilled operators can distinguish between levels, and give a dynamic range of 5. The main objection to this manual method is that the spot size is highly subjective to the integration time on the paper. With longer exposures the center may not change, but the width of the darkened area could change $\pm 50\%$ or more.

Wooden tongue depressors and burn spots on metal plates are used in similar methods as burn paper. Sometimes the depth of the burn gives additional insight into the laser irradiance. Sometimes operators learn from experience with these burn spots, such as which beam tuning gives a specific result in a specific application. Thus an operator might be tuning for one burn spot for cutting, and a different one for drilling holes. However, this measurement system is archaic, crude, and non-quantitative, thus subjective to the capability and experience of the operator, and therefore quite unreliable.

Fluorescing plates contribute to being able to see laser beams by converting UV and IR laser beams into the visible, where they can be seen by the human eye. These fluorescing plates have limited dynamic range, which adds to the dynamic range problem already described when viewing the reflected beam.

As shown in Figure 8 Acrylic mode burns provide quite representative beam profiles of CO₂ lasers. The depth of the acrylic burns clearly shows the irradiance profile of the beam, and it is often possible to see mode structure. This gives an excellent visual interpretation of the beam profile. However, the acrylic mode burns are not real-time, which makes it very cumbersome to tune the laser. They also do not enable one to see if there are short term fluctuations in the laser beam, which is quite common in CO₂ lasers. It is possible that fumes from the burning acrylic may form a plasma at the center of the hole, which blocks the incoming CO₂ beam. Unless care is taken to have a fan blowing the fumes away, the acrylic mode burn will contain a hole in the center of the image that is non-existent in the beam. An additional problem is that the fumes from burning acrylic are toxic to humans, and care must be taken to exhaust these fumes outside of the work area.

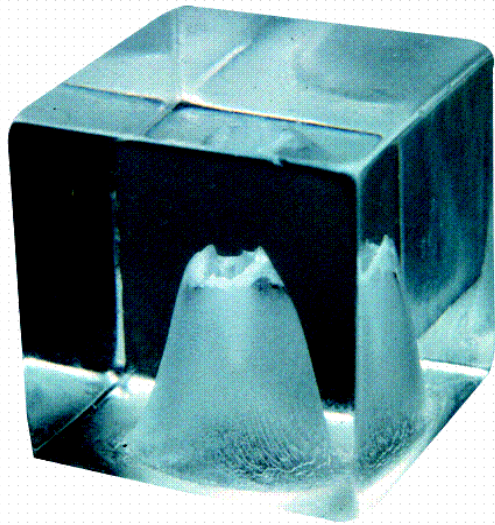


Figure 8. Laser beam acrylic mode burn.

3.2 Electronic Measurement Methods

For electronic laser beam profile analysis, it is nearly always necessary to attenuate the laser beam, at least to some degree, before measuring the beam with an electronic instrument. The degree of attenuation required depends on two factors. The first is the irradiance of the laser beam being measured. The second is the sensitivity of the beam profile sensor. Figure 9 shows a typical setup for the case where maximum amount of attenuation is required before the sensor measures the beam.

Typically when measuring the beam profile of a high power laser, i.e., in excess of 50-100W, the beam has enough energy to burn up most sensors that might be placed in the beam path. Therefore, the first element of Figure 9, the beam sampling assembly, is typically used regardless of the beam profiling sensor. It should be noted, however, that there are some beam profiling sensors, to be described later, which can be placed directly into the path of a high power beam of 10kW and greater.

For mechanical scanning instruments, the beam sampling assembly is usually sufficient to reduce the signal from high power lasers down to the level that is acceptable by such instruments. Also, if the original laser beam is in the range of 50W or less, then often mechanical scanning instruments can measure the beam directly without using the beam sampling assembly. The reason that mechanical

scanning instruments are able to be placed in the path of medium power beams, is that they usually consist of a single element detector with a rotating drum blocking the light from the sensor during most of the duty cycle of the sensor. The rotating drum either absorbs or reflects the incident laser beam during a significant part of the time, and thus high power is not placed on the sensing element.

For camera based beam analyzers, the beam sampling assembly does not perform sufficient attenuation to reduce the beam power low enough for the camera sensor. In this case, usually a set of neutral density filters is placed in the beam path to reduce the power to the level acceptable by the camera. In some cases the beam power, even after reflection from one sampling surface is too high, and would burn up neutral density filters. In this case a second reflecting surface is used to further reduce the incident power before impinging on the ND filter set. This is described in more detail in the section 4.5.1 titled “Camera Based Instrument Description”.

The neutral density filter assembly can be adjusted over a very wide dynamic range, as much as from ND0 to ND10 (or transmission of 1 to 10^{-10}) to reduce the beam power to a level acceptable by typical camera based systems. A detailed description of these ND filter assemblies is contained in section 4.5.2.

The fourth item in Figure 9, the beam profile sensor, can be either one of the mechanical scanning devices described in the next section, or it can be a CCD or other type of camera described, as in the following section. The beam profile readout device consists of either a dedicated monitor for reading out beam profile information, or in camera based systems, a PC style computer and monitor.

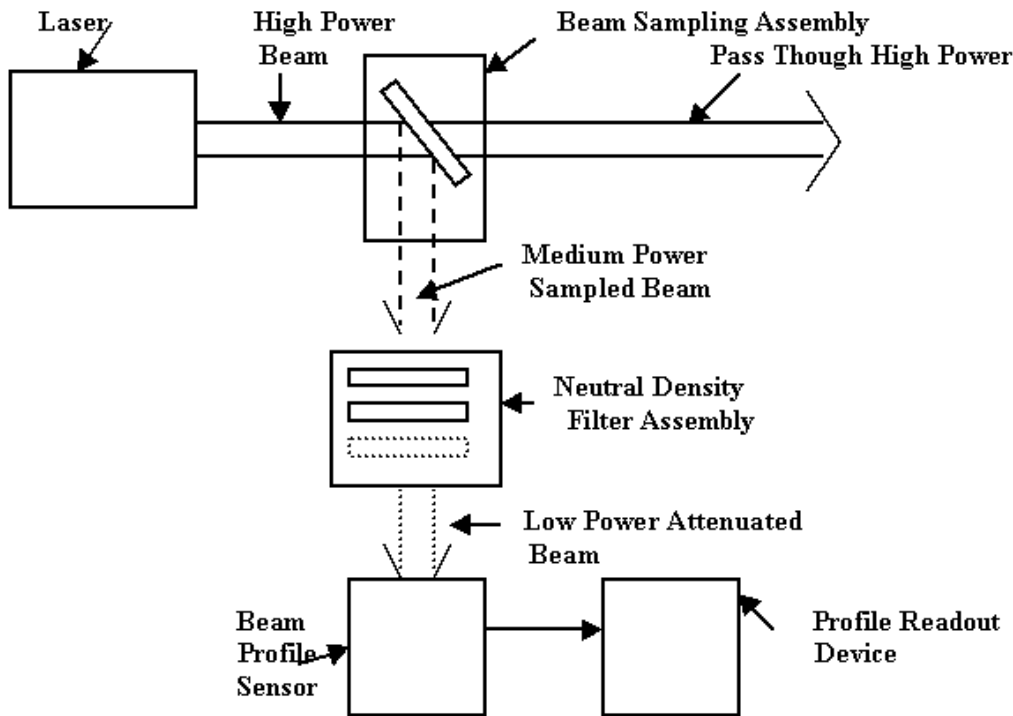


Figure 9. Optical setup for electronic laser beam analysis.

3.2.1 Mechanical Scanning Instruments

One of the earliest methods of measuring laser beams electronically was using a mechanical scanning device. This usually consists of a rotating drum containing a knife-edge, slit, or pinhole that moves in front of a single element detector. This method provides excellent resolution, sometimes to less than $1\mu\text{m}$. The limit of resolution is set by diffraction from the edge of the knife-edge or slit, and

1 μm is roughly the lower limit set by this diffraction. These devices can be used directly in the beam of medium power lasers with little or no attenuation because only a small part of the beam is impinging on the detector element at any one time. Most of the time the scanning drum is reflecting the beam away from the detector.

However, mechanical scanning methods work only on CW lasers, not on pulsed lasers. Also they have a limited number of axes for measurement, usually two, and integrate the beam along those axes. Thus they do not give detailed information about the structure of the beam perpendicular to the direction of travel of the aperture edge. However, there are rotating drum systems with knife-edges on seven different axes, which provides multiple axis cuts to the beam. This can assist somewhat in obtaining more detailed information about the beam along the various axes. These beam profile instruments are adaptable for work in the visible, UV, and infrared by using different types of single element detectors for the sensor. In addition, software has been developed which provides illuminating beam profile displays, as well as fairly detailed quantitative measurements from these scanning systems. This software now exists in the PC-based Windows operating system for easy use.

Figure 10a illustrates a commercial version of the knife-edge scanning slit beam profiling instrument. Figure 10b shows a typical Windows computer readout. Even though Figure 10b shows a 3D representation from a two-axis scanning system, it could be misleading, since it does not really give information about the beam structure off-axis. Figure 10c illustrates a typical mechanical diagram of a scanning slit beam profiler.

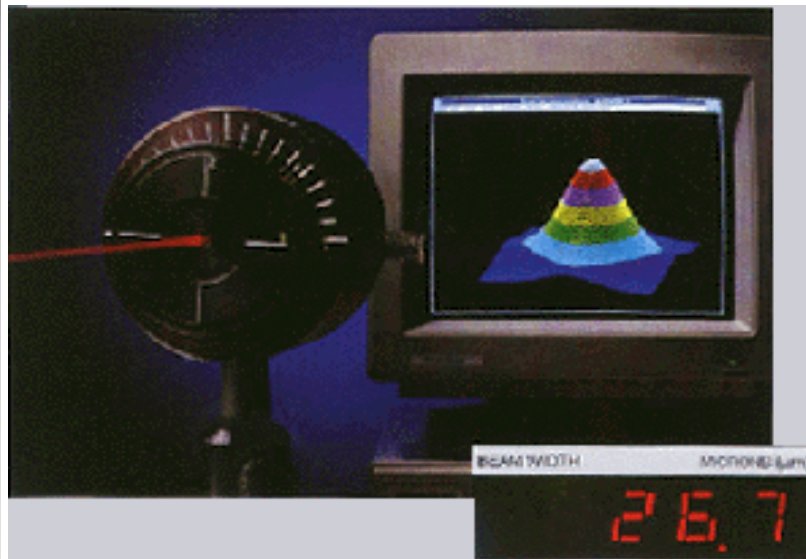


Figure 10a. Scanning knife-edge beam profiler. Figure 10b. Windows readout of scanning knife-edge system.

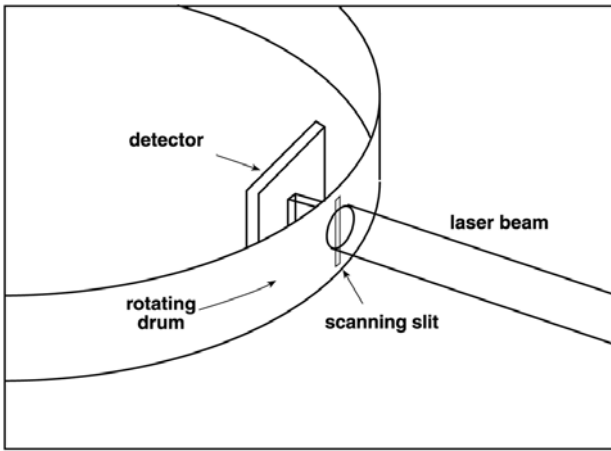


Figure 10c. Mechanical diagram of scanning slit or knife-edge beam profiler.

Figure 11a is a photograph of a seven-axis scanning blade system. Figure 11b illustrates a typical Windows readout from this seven axis system. The mechanical layout of the multi-axis profiler is similar to Figure 10c except that knife-edge apertures are used, and the angles of the knife-edges are varied so that the beam is scanned across multiple axes.



Figure 11a. 7 axis knife-edge Instrument.

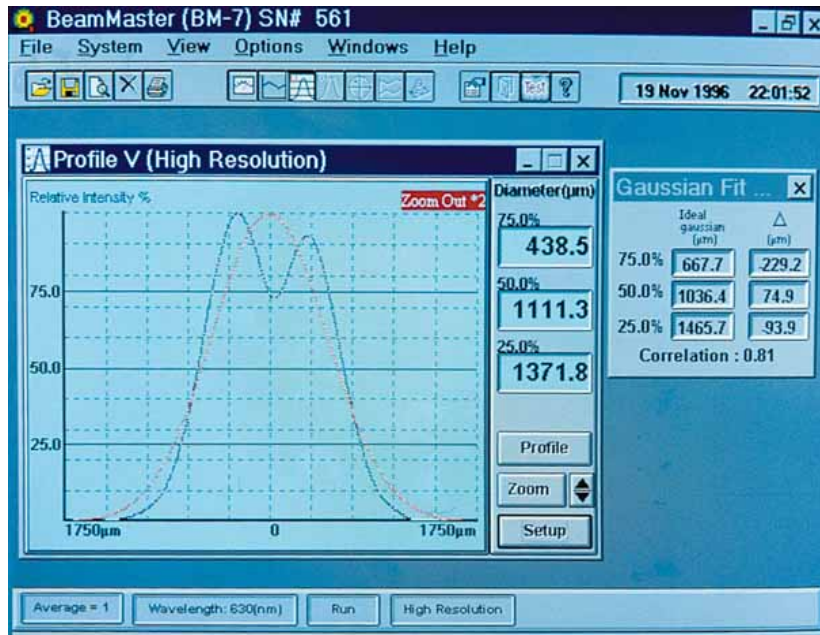


Figure 11b. Typical readout from 7 axis system.

A variation of the rotating drum system includes a lens mounted in front of the drum.²⁰ The lens is mounted on a moving axis, and thus focuses the beam to the detector at the back side of the drum. By moving the lens in the beam, a series of measurements can be made by the single element detector that enables calculation of M^2 . (A more detailed discussion of M^2 will be provided in a later section.) A photograph of this M^2 measuring instrument and readout is given in Figure 12a. A mechanical layout of the instrument is shown in Figure 12b.



Figure 12a. M^2 measuring instrument and readout.

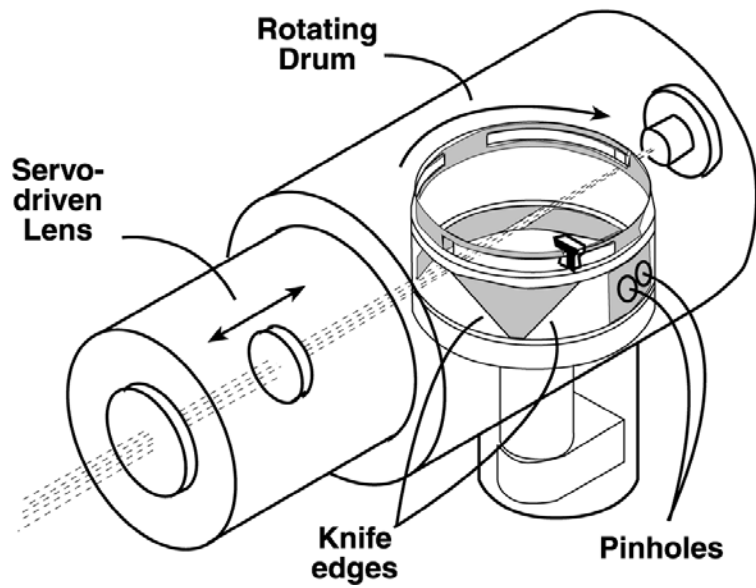


Figure 12b. Mechanical diagram of M^2 measuring instrument.

Another mechanical scanning system consists of a rotating needle that is placed directly in the beam. This needle has a small opening allowing a very small portion of the beam to enter the needle. A 45° mirror at the bottom of the needle reflects the sampled part of the beam to a single element detector. The needle is both rotated in the beam, and axially moved in and out of the beam to sample it in a complete 2-dimensional manner. The advantage of a rotating needle system is that it can be placed directly in the beam of high power industrial lasers, both Nd:YAG and CO₂. It introduces a very small distortion in the beam, and so can be used in the beam while on-line. In addition, the translation of the needle can be made extremely small for focused spots, or large for unfocused beams. It has, however, some characteristics of the rotating drum mentioned above. Specifically, it is not very useful for pulsed lasers because of the synchronization problem between the position of the needle and the timing of the laser pulse. These rotating needle systems also have extensive computer processing of the signal with beam displays and quantitative calculations in Windows based systems.

3.2.2 Camera Based Systems

Cameras are used to provide simultaneous, whole two-dimensional laser beam measurements. They work with both pulsed and CW lasers. There are silicon based cameras that operate in the UV region to the near IR at 1.1μm, which are useful with a great majority of lasers. In addition, there are other types of cameras that operate in the X-ray and UV regions, and other cameras that cover the infrared from 1.1μm to greater than 400μm. A drawback of cameras is that the resolution is limited to approximately the size of the pixels. In CCD cameras this is roughly 10μm, and for most infrared cameras the size is somewhat larger. However, a focused spot can be re-imaged with lenses to provide a larger waist for viewing on the camera, which provides a resolution down to approximately 1μm. Again the resolution of a camera system is limited by diffraction in the optics. Cameras have been interfaced to digitizers to connect the signal into a computer. Now digital interfaces such as USB and Firewire (IEEE1394) provide easy connection to the PC environment. Current computer software provides very illuminating 2D and 3D beam displays as shown in Figure 13. They also provide very sophisticated numerical analysis on the beam profile. A drawback of camera based systems is that the cameras are extremely sensitive relative to the energy in laser beams. Thus nearly all lasers must be significantly attenuated before the cameras can be used for beam profile analysis.

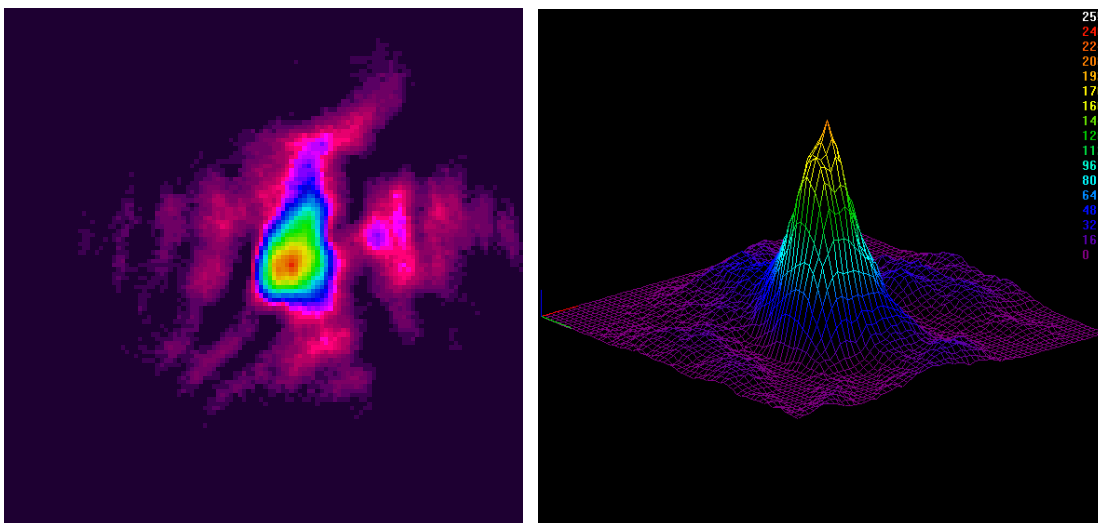


Figure 13. Highly structured laser beam measured with a CCD camera and shown in both 2D and 3D views.

4. Camera Based Instrument Description

Complete instrumentation for a camera-based beam profiling system includes a modern computer, a framegrabber card to digitize the signal or a camera with a digital signal interface such as USB or Firewire, and software for controlling the camera, displaying beam profiles and making quantitative calculations. A camera such as a CCD is used for the visible, while a pyroelectric or other camera is used for longer wavelengths. Attenuation is almost always needed to either split off part of the beam, or at least attenuate the beam before going on to the camera. Often the beam is either too large or too small, and beam sizing optics or other techniques must be used to size the beam for the camera.

4.1 Frame Grabbers

The frame grabber is an analog to digital converter, normally placed inside the computer, which digitizes the signal from the camera, and presents it to the computer for signal processing. There are many brands of commercial framegrabbers available that have characteristics that are useful for beam profile analysis.

However, measuring parameters of a laser beam presents many unique challenges that do not exist in measuring parameters of other items such as are common in machine vision. As Tom Johnston of Coherent once said, "Measuring the width of a laser beam is like trying to measure the size of a cotton ball with a caliper." This difficulty in measuring laser beam width comes from the fact that laser beams never cut off at the baseline to zero, but almost always have energy that extends out into the wings. Thus processing of very low level signals becomes critical in measurement of laser beams. Therefore it is essential that the framegrabber used for beam profile analysis has the capability for very accurate baseline adjustments, and the capability for special processing of the noise in the baseline of the camera. The section on quantitative measurements discusses the details of accurate baseline control, and sophisticated noise processing in order to make accurate beam profile measurements.

4.2 Computers

Computers that are currently used for laser beam profiling range from the standard desktop to a portable laptop to a small tablet PC. With the advent of high speed digital interfaces, frame grabber cards are no longer required. USB and Firewire cameras provide easy connections to any PC environment. Active X protocol permits information from a beam profile application be made instantly available to other applications operating on the same PC.

4.3 Beam Analysis Software

Laser beam analysis software now typically runs on Windows. It provides extremely sophisticated signal processing, very detailed views of the laser beam, and highly accurate quantitative beam profile measurements. This software also must control the camera and be able to control the baseline and noise of the signal coming into the analysis system. In addition to providing beam displays and calculations, software also provides the capability for versatile file and data transfer and management, either to the hard disk, to other computers as a means of logging the acquired laser beam characteristics. The capabilities of the software including very intuitive beam profile displays is given in more detail in Section 9.5. Details regarding the quantitative calculations made by the software are provided in Section 9.6.

4.4 Cameras Used in Beam Profile Measurement

There are currently many types of cameras that are used in beam profile analysis. Each of these has advantages and disadvantages for various applications. The most common type of camera used for laser beam diagnostics incorporates a silicon-based sensor. These cameras consist of two types, charge injection devices, CID, and charge coupled devices, CCD. Silicon based cameras cover the wavelength range from 190nm to 1.1 μ m when the normal glass window is removed, which would otherwise attenuate the UV. These cameras are fairly inexpensive, and since they cover the visible region, which includes many lasers, they are the most common cameras used. At slightly longer wavelengths lead sulfide vidicon tubes cover the region from the visible to 2.2 μ m. Also a new solid state camera, InGaAs, covers the range from visible to about 2 μ m. The most common cameras for infrared lasers of wavelengths longer than 1 μ m are pyroelectric solid state cameras. These are fairly low resolution at 124X124 pixels and 100 μ m elements, but cover the wavelength range all the way from 1 μ m to beyond 400 μ m, as well as work in the UV range from 190nm to 350nm. Formerly pyroelectric vidicon tubes were used for the visible to 12 μ m range. However, their characteristics were never very satisfactory, and they are now seldom used for laser beam profiling. Finally, there are many cooled infrared cameras that can be used for the wavelength range from 1 μ m to about 12 μ m. These are discussed in the concluding paragraph of the next section.

4.4.1 Characteristics of Cameras

One of the initial camera technologies used for beam profile analysis was a charge injection device, CID. CID cameras are very versatile in that they have an X/Y readout rather than a sequential readout, and can thus be programmed to readout only a part of the camera matrix. This Region of Interest or ROI mode enables them to operate at high frame rates. CID cameras are no longer typically used for laser beam profiling applications except where the cameras exposure to ionizing radiation is an issue

CCD cameras are the most common type of cameras used in beam profile analysis today. Because they are used so extensively, a more detailed analysis of CCD cameras is provided in the paragraphs below. In addition to standard CCD cameras, there are CCD cameras with coolers attached to the sensor. This significantly reduces the electronic noise of the CCD, and allows it a much greater signal-to-noise ratio. A typical uncooled CCD has 8 to 16 bits of dynamic range, whereas cooled CCD cameras can be obtained with 16, 24, and even 32 bit signal-to-noise ratios. However, these cooled cameras are a factor of 5 to 20 times more expensive than uncooled units.

Lead sulfide vidicon cameras, PbS-PbO, have been used with near infrared lasers from 1 μ m to 2.2 μ m. The advantage of these vidicon tubes is that they are relatively inexpensive, for coverage at this wavelength range where silicon based CID and CCD cameras do not function. One drawback of these vidicon cameras is that they have a long image lag of up to 1 second, and thus cannot be effectively used to profile laser pulse occurring at faster than 1Hz. In addition, they typically have some baseline shading which reduces the useable dynamic range.

Pyroelectric vidicons have been in existence for many years, and were once used extensively for beam profile analysis, particularly of CO₂ lasers. They had the advantage of providing relatively high resolution for a CO₂ beam in the far infrared at 10.6 μ m. However, they had many of the disadvantages of lead sulfide vidicons, in that they have a slight image lag in the readout, some nonlinearity, and baseline shading.

Cameras made from solid-state pyroelectric arrays have been manufactured for many years. Recently high resolution cameras have become available. Because these cameras, as with CCD cameras, are commonly used in beam profile analysis, more details will be given in a later paragraph.

Another camera that is particularly useful for beam profile analysis of lasers in the 1 to 2 μ m region is the solid-state InGaAs. These cameras have the advantage of being solid-state, and thus do not

suffer from the problems of vidicon tube cameras. Probably their only drawback is that they are somewhat expensive compared to CCD cameras, although they are in the same price range as the solid-state pyroelectric cameras mentioned in the preceding paragraph.

Another type of solid-state camera useful for far infrared is a camera containing an infrared micro-bolometer array. These infrared cameras are designed primarily to operate in the 8-12 μ m range for thermal imaging, but nevertheless can be useful for long wavelength laser beam analysis. In addition to infrared bolometers is an infrared ferroelectric type of camera. This camera is designed for thermal imaging in the 8-12 μ m region, but potentially useful for laser beam analysis as well. Both of these cameras provide higher spatial resolution than the solid-state pyroelectric camera mentioned above. However, the technology is still being developed to make them sufficiently stable to make accurate laser beam profile measurements.

Finally, there are cooled infrared cameras that could be used for laser beam analysis. This includes cameras made from material such as Indium Antimonide, InSb, and Mercury Cadmium Telluride (HgCdTe). These cooled infrared cameras, however, require significantly more cooling than cooled CCDs, and typically use liquid nitrogen as the cooling mechanism. In addition, they are extremely expensive, costing between 20 and 50 times as much as CCD cameras, and 2-3 times as much as solid-state pyroelectric cameras. Another drawback of these cooled IR cameras is that they are made for thermal imaging, and thus are extremely sensitive. This requires additional attenuation over and above what would be required for uncooled, solid-state pyroelectric cameras.

4.4.2 Characteristics of Cameras Relevant to Beam Profile Analysis

There are a number of characteristics to evaluate in choosing one camera over another, or in specifying a given type of camera. The most significant characteristic is the wavelength response of the camera. This was alluded to in the section above. For example, CCD cameras are the most useful cameras in the visible and near IR wavelength (190 – 1,300nm). A second essential factor is that the sensor on the camera be windowless to eliminate interference fringes between the two surfaces. Alternatively, if a window is required, then the window should be configured to minimize these interference effects. This can either be done by AR coating the window for the wavelength of use, or by making the window a bulk absorbing ND filter which attenuates the second surface reflection keeping it from interfering with the incoming irradiation of the first surface. The dynamic range of the camera is another factor for serious consideration. This subject is discussed in more detail when describing the CCD and pyroelectric cameras below.

Another useful feature to consider in choosing a camera is that some CCD cameras have electronic shutters. This feature enables the CCD to integrate only during a short time of each frame period, for example, 1/1000th of a second (1.0mS). This enables the camera to select a single laser pulse out of a kHz pulse train, and display that single pulse. The frame rate of the camera should be considered. In the U.S. the standard for video monitors is called RS-170 and operates at the line frequency at 60Hz. In Europe and most of the rest of the world, the standard is CCIR for 50Hz operation. Neither of these factors is very significant in measuring beam profiles but may affect the maximum update rate at which new beam profile data will be available. However, if the camera is also going to be used for direct display on a monitor, then the user must choose the type of camera for the part of the world in which he lives.

Fill factor or the ratio of the active area to the total area of the detector should be considered in the choice of a camera. Normally CCD and most other cameras have a relatively high fill factor, and thus do not lose signal in between the active parts of the pixel.

Shading can be a serious factor in some cameras. Shading is defined as a non-flat baseline offset. This means, for example, that a center region of the camera could have an offset of 10 or 20 digital counts out of 1024, whereas perhaps one edge of the camera could have a baseline offset of as

much as 50-100 counts. Even Most CCD cameras have very little shading, but do have enough that it needs attention in terms of signal processing.

Linearity of the camera output is another factor to be considered. Most solid-state cameras have nonlinearity of less than 1% over the specified dynamic range of the camera, which enables accurate profile measurements. Lead sulfide vidicons and some CCDs are nonlinear, but have a typically known gamma. The gamma factor means that for a given change in the input signal magnitude there is not a proportional change in the output magnitude. If the gamma is 1, then the output is linear relative to the input. However, many vidicons have a typical gamma of 0.6, meaning that for a 10 times increase in input signal, for example, only a 6 times increase in the voltage output would occur. Beam profile software and hardware corrects for this gamma, and converts the nonlinear signal from the vidicon into a linear signal.

A useful feature of some cameras is that they can be triggered externally. This enables an electronic trigger from the laser to synchronize the camera to the laser pulse. A more common feature is that the camera is free running, and synchronization must be obtained by triggering the laser from the camera. When this is impossible, and the laser and camera run asynchronously, the user takes a slight chance that the camera will be in a reset mode when the laser pulse arrives. However, this typically occurs less than 1% of the time with most CCD type cameras.

The sensitivity of the relative types of cameras is another consideration because of the optical laser attenuation needed. Almost all of the silicon based cameras, such as CCD, CID, etc. have very similar sensitivity. The solid-state uncooled pyroelectric cameras are about 6 orders of magnitude less sensitive than CCDs, and thus require less attenuation than CCD cameras. Many of the other cameras mentioned under Section 4.4.1 "Types of Cameras" have sensitivity somewhere between the solid-state pyroelectric and the CCD cameras, and thus the attenuation requirement falls somewhere between these two.

4.4.3 CCD Type Cameras

CCD cameras are the most common type of cameras used in beam profile analysis. There are very inexpensive CCDs typically used in camcorder and consumer type applications. These CCDs typically have a very large proportion of bad pixels, as well as a poor signal-to-noise ratio, and thus are not very suitable for laser beam profile analysis. Industrial grade CCD cameras have fewer bad pixels, and the electronics in the camera are typically designed to mask any bad pixels that do exist, which makes it easier for beam analysis software to process the signal.

The specifications given by camera manufacturers for the signal-to-noise ratio of CCD cameras must be understood in order to properly measure laser beams. A typical specification is a signal-to-noise ratio of 50 to 60db. This specification is arrived at by dividing the saturated signal level by the RMS noise. Thus 50-60db implies a signal-to-noise ratio of 300 to 1000. However, the RMS noise of a camera is equivalent to the 2-sigma standard deviation, with significant noise peaks out to 3 standard deviations. When you consider both positive and negative noise transitions, the peak to peak noise becomes 6 times the RMS. Thus a CCD camera with a specification of 50 to 60db signal-to-noise ratio typically has a peak to peak signal-to-noise ratio of only about 50 to 180. Thus framegrabbers utilizing 8-bit digitizers with 256 counts of resolution have typically been sufficient for beam analysis. It may be noted that with a 256 count digitizer, and a 50-180 signal-to-noise ratio, the bottom 2 to 6 counts from the digitizer will be noisy. There are cases when a 10 or 12-bit digitizer can provide an advantage over 8 bits, in beam profile analysis, in that the noise of the cameras is divided into smaller increments, thus it is better understood. This enables the software to provide signal summing and averaging to a greater accuracy in order to improve the signal-to-noise ratio from the beam profile measurement.

There are basically two types of CCD camera technology currently in use. One is called frame transfer, and the other is called interline transfer. In frame transfer cameras there is only one sensor site for both interlaced fields of the signal frame. Thus on a pulsed laser, since there is only one cell. This

cell is read out during the first field, and no signal remains for the second field. Thus frame transfer cameras have only one half the resolution for pulsed lasers that they do for CW lasers.

Some CCD cameras have been shown to have signal response beyond the normal $1.1\mu\text{m}$ cutoff of silicon sensors, out to $1.3\mu\text{m}$, even though the sensitivity is typically 1000 times less than it is at $.9\mu\text{m}$. This slightly reduces the dynamic range of the camera when used in this wavelength range. Interline transfer sensors have individual pixels for each field of the camera frame. Thus they maintain twice the resolution of frame transfer cameras with pulsed lasers. An interline transfer camera can pick out a single pulse from pulse rates up to 10kHz with a $1/10,000^{\text{th}}$ second shutter speed. Interline transfer cameras typically have higher speed shutters than with frame transfer cameras. However, a problem exists with interline transfer cameras in that the readout electronics are typically on the backside of the silicon wafer behind the sensor cells. For infrared lasers with wavelengths approaching $1.06\mu\text{m}$, the absorption of all the radiation does not occur in the sensor cells on the front, and some of the radiation is absorbed in the transfer electronics on the back side of the cell. This absorption of radiation creates a ghost image in the beam, which distorts the view of the beam profile. Even more significantly, it greatly distorts measurements on the beam, since this ghost image appears as a low-level energy in the wings of the beam. Thus interline transfer cameras are recommended for pulsed lasers wherein the wavelength is less than $1\mu\text{m}$. Frame transfer cameras are recommended for YAG lasers at $1.06\mu\text{m}$, even though on pulsed lasers they have only half the resolution as interline transfer cameras.

4.4.4 Pyroelectric Solid State Cameras

Pyroelectric solid-state cameras²¹ have been developed that cover the wavelength range from $1.1\mu\text{m}$ to greater than $400\mu\text{m}$. These cameras are solid-state with a very stable and linear output. They have a flat baseline with no excessive shading and no image lag (as is present in pyroelectric and PbO-PbS vidicon tubes). Also, pyroelectric cameras interface to computers and software much as do CCD cameras, and provide the same viewing and numerical capability. However, pyroelectric cameras have a lower resolution of $100\mu\text{m}$ per pixel, and a 124×124 matrix. Figure 14 shows a pyroelectric camera with the output of a CO_2 laser displayed on a computer monitor.

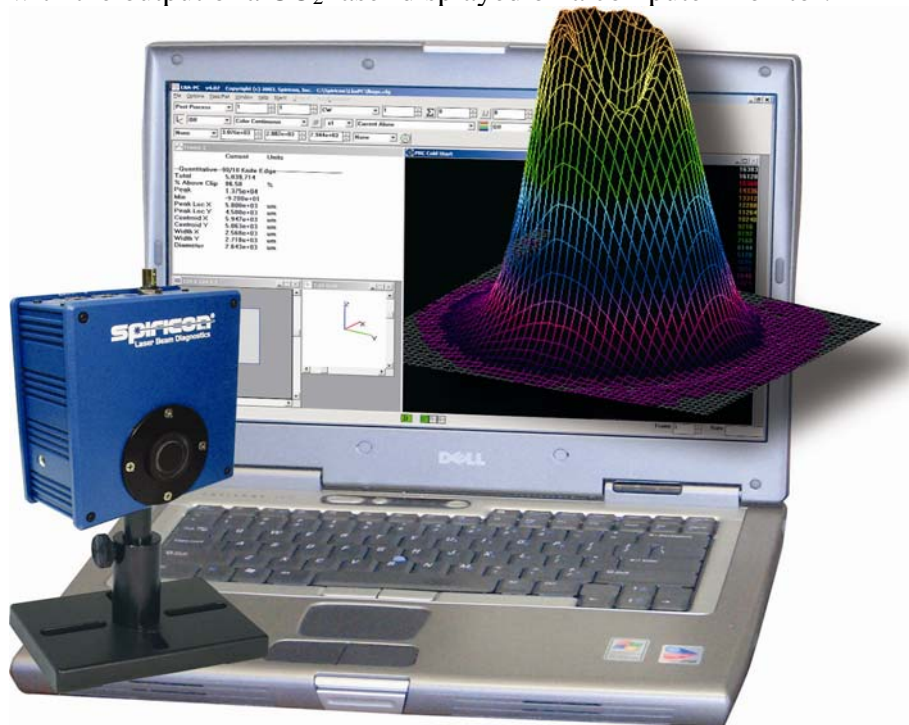


Figure 14. Pyroelectric camera and beam profile display with numerical analysis.

Pyroelectric solid state cameras work well with pulsed laser radiation. However, it is necessary that the camera be triggered from the laser to synchronize the scanning. The reason for this is that the pyroelectric sensor is a thermal sensor, and after the signal is read out from the heating radiation pulse, the heated area of the sensor cools and generates a signal of the opposite polarity. It is necessary to read out this negative polarity signal and reset the sensor before the next laser pulse. This is done by having the camera sense a short series of pulses, calculate the interval between pulses, and then adjust the resetting scan to occur just before the next laser pulse. Depending on the pulse rate of the laser, whether it is single shot, very low frequency below 5Hz, intermediate frequency between 5 and 50Hz, or high frequency between 50Hz and 1 kHz, this resetting operation is performed differently in the pyroelectric camera.

For CW operation the sensor must be optically chopped to provide an alternating heating and cooling cycle. This typically is done with a 50% duty cycle between heating and cooling, and is normally performed by a rotating chopper blade. The chopper blade is usually incorporated into the camera such that the blade crosses the camera sensor from top to bottom. The camera readout is then triggered to read out each row from the camera just as the blade crosses that row of pixels. In this manner every row of pixels in the pyroelectric sensor has the same integration time, is read out immediately after being covered or uncovered, and thus gives optimum uniformity of the signal. If chopping synchronization is not performed properly, the pyroelectric sensor can give a distorted output signal.

Because the pyroelectric sensor is a thermal device, there is some distortion that occurs from thermal and electrical crosstalk. Thermal crosstalk occurs when some heat spreads from one element into adjacent elements. This is minimized by either chopping at a relatively high frequency, or with pulsed lasers by resetting the array just prior to an incoming laser pulse. With chopped radiation the maximum distortion occurs in the corners of the array, because the chopper blade is not parallel to the row on the top and bottom edges. Even so, the non-uniformity in the corners is only about 5%. At the same time, the linearity and uniformity of the corner areas usually has the least impact on measuring a beam. There is some distortion from electrical crosstalk coupling between pyroelectric detector elements. However, with high-resolution elements in current pyroelectric solid-state arrays, this electrical crosstalk is typically less than 5%. Since laser beams do not typically have very sharp irradiance changes from one element to the next, this crosstalk is seldom a problem in obtaining relatively accurate analysis of the structure in a laser beam.

4.5 Laser Beam Attenuation

Laser beam profile measurements are made on lasers that vary from less than 1mW to greater than 10kW average power. This typically corresponds to a power density of less than $10^{-1}\text{W}/\text{cm}^2$ to greater than $10^5\text{W}/\text{cm}^2$. A CCD camera typically saturates at a power density in the range of $10^{-7}\text{W}/\text{cm}^2$. Solid state pyroelectric cameras typically saturate at approximately $1\text{W}/\text{cm}^2$. Thus the necessary attenuation arranged for CCD cameras varies from 10^5 to 10^{12} . For pyroelectric cameras the attenuation range is a little more modest at about 10^4 . This laser beam attenuation is usually performed by one of two methods. The first is using a beam splitter to pick off a small percentage of a beam, allowing the main part to pass through the beam splitter. The second method is inline attenuation in which the beam is reduced in power by the absorption of neutral density filters.

4.5.1 Beam Pickoff

The first step in attenuating a high power laser beam is to pick off or sample a small percentage of the beam from the main beam, without affecting the beam profile of the sampled beam. There are basically three ways to perform this pickoff. The most common is to have a beam splitter that is mostly transmitting and partially reflecting. The beam splitter is typically put in the beam at 45° , so that a small percentage of the beam is reflected at 90° to the incident beam. However, this beam sampling surface

can be placed at any angle, and there is an advantage is to placing the pickoff surface nearly perpendicular to the beam so that the reflection becomes less polarization sensitive.

The other type of pickoff is to use a mostly reflecting and partially transmitting surface. In this case the surface is placed in the beam at an angle to reflect the majority of the beam, and then transmit a small part through the surface to be measured by the beam analyzer.

A third method of beam pickoff is to use a diffraction grating. This can either be a reflecting or a transmitting type. In the transmitting type of diffraction grating the beam is typically incident upon the grating perpendicular to the surface, and most of the beam passes directly through the diffraction grating. However, a small percentage of the beam is transmitted at an angle offset from the output angle of the main pass through beam. The portion diffracted typically has multiple modes, whereas for example, 1% of the beam may transmit at, for example, 15° from the emitting main beam. Second order diffraction may be 0.01% at 30° , and even a third order beam may be 10^{-6} of the input beam at 45° . The angle and the diffraction percent depend upon the manufacturing characteristics of the diffraction grating, as well as the wavelength of the beam incident upon the grating.

A reflection type of diffraction grating works in a similar manner, except that the beam incident on the diffraction grating is at an angle other than perpendicular. For example, instead of at 90° to the plane of the grating, it may be 30° from normal incidence. The main reflected beam is then reflected at 30° from normal incidence in the opposite direction. Now the first order, second order, third order beams are reflected at angles other than the angle of the main reflection. As in the case of the transmitted reflection beam, these refracted and attenuated beams might be 5° , 10° , or 15° away from the main reflected beam, and will typically be 1%, 0.01%, or 10^{-6} of the main beam, etc. The diffracted low intensity beam maintains all of the beam profile characteristics of the main beam. This small intensity beam can then be used for beam analysis.

The most commonly used beam pickoff surface is fused silica or quartz, usually used at a 45° angle to the incoming beam. If the quartz is not AR coated, it reflects an average of 4% of the beam per surface. However, at 45° the quartz becomes polarization sensitive, and one polarization is reflected at about 2%, and the other can be as high as 8-10%. Thus the reflected sample beam does not truly represent the incoming laser beam. This problem can be solved by placing a second quartz surface in the path of the initially sampled beam, but angled in a perpendicular plane that reflects the two polarization's opposite of the first surface. (I.e., the first surface may reflect the beam 90° in the horizontal, and the second surface reflects 90° in the vertical.) After two such reflections the sampled beam once again has the same characteristics as the initial beam.

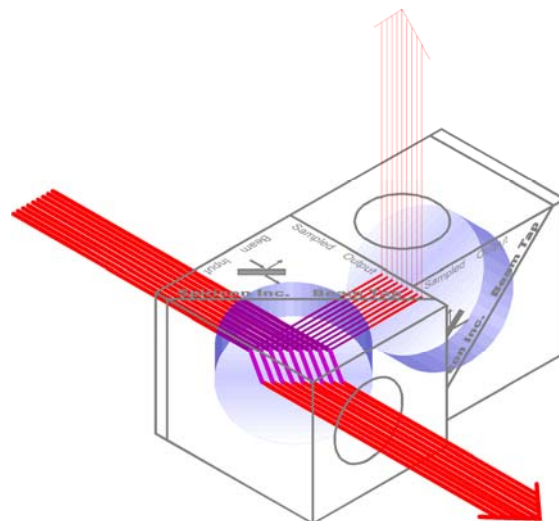
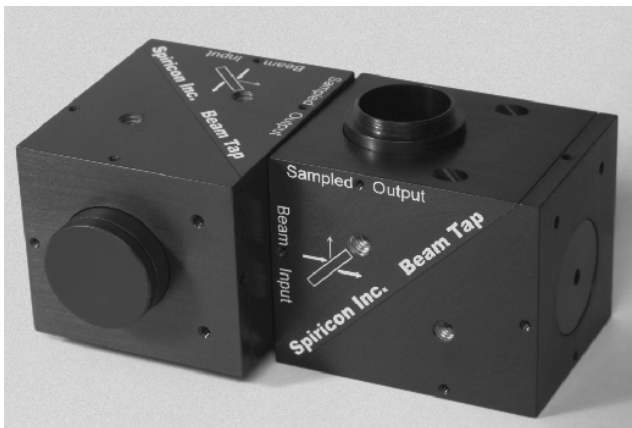


Figure 15a. Beam Tap II reflecting beam splitter. Figure 15b. Beam Path of Beam Tap II.

The quartz sampling plates have two configurations. One is a wedge, so that the back surface of the quartz reflects at a different angle than the front surface, and keeps the beams from the two surfaces from interfering from each other. The other configuration uses a very thick, flat quartz plate such that the reflection from the back surface is displaced sufficiently far from the front surface reflection that it does not overlap. Flat pickoffs have the advantage that the throughput beam, while being slightly displaced in position from the input beam, exits the quartz flat at the same angle as the entrance, and is not distorted. Figure 15a shows a commercially available quartz sampling device using a thick flat as the reflector. The beam path is shown in Figure 15b. With the wedge, the exit beam is displaced in position and angle, as well as being slightly elongated. Thus if a beam pickoff were to be used in process and left permanently in place, then the flat would have superior characteristics to a wedge. Figure 16a shows a commercially available attenuation device using a wedge as the reflecting mechanism. Figure 16b shows the mechanical layout of the device, with indents for mounting the wedge on the right side and slots for ND filters on the left side. For infrared lasers ZnSe commonly replaces the quartz as the reflecting material. ZnSe can be AR coated for the specific wavelength of interest, and achieve reflection lower than 1% per surface.



Figure 16a. Combined beam splitter and ND filter holder.

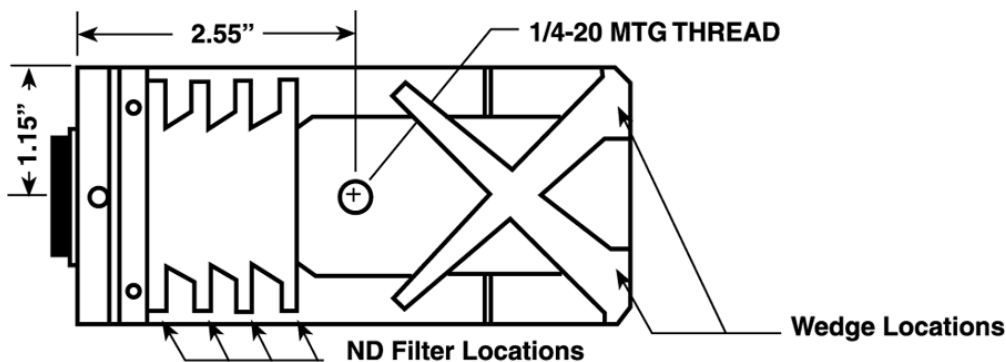


Figure 16b. Mechanical diagram of combined beam splitter and ND filter holder.

An advantage of reflecting gratings is that they can be made from metal, and then the back side cooled with water to enable them to withstand very high powers. Some gratings are of a transmitting

type, either from quartz for visible radiation, or from ZnSe for infrared radiation, and have the advantage that the main beam continues along the same path as its entrance.

Sometimes a thin pellicle, of 10-50 μ m thick, is used for a beam sampler. This is so that the back side reflection is so close to the front side that the interference effects can sometimes be negligible. However, a pellicle as thin as 10 μ m can still cause interference fringes that could be seen with a 10 μ m pixel camera.

Finally, for industrial Nd:YAG lasers a good pickoff scheme is the use of the dichroic mirror that is normally employed as a turning mirror for the laser. This dichroic mirror is typically made of quartz or fused silica with an AR coating and placed at 45° to reflect nearly the entire 1.06 μ m beam at 90° from the input. The dichroic mirror is configured so that visible light passes through the filter, so an operator can either see through the filter to the work surface, or a camera can be mounted behind the filter to monitor the industrial process being performed. These dichroic filters transmit a small percentage of the YAG laser beam directly through the filter, so that it is used as a sampling mechanism. Dichroic filters used in this manner are also very polarization sensitive, and so once again, two filters must be placed at 90° to each other in order to obtain a true representation of the input beam.

4.5.2 In-Line Attenuation

There are a number of methods of further attenuating a laser beam once reflection has reduced the power or energy low enough that it does not damage the in-line attenuators. One type of in-line attenuators consists of glass or quartz with a broad band neutral density reflecting surface coating. When these neutral density filters are made of quartz, they are particularly useful for ultraviolet radiation. However, when the multiple surface reflecting neutral density filters are used in conjunction with each other, there is the danger of causing interference between the multiple surfaces. This interference can cause interference fringes, which completely distort the ability to measure the beam profile. This problem can be somewhat alleviated by tilting the filters so that the reflected beam bounces away from the camera sensor.

Another type of surface reflecting ND filter consists of circular variable filters, in which the attenuation varies around the surface of a circular disk. This type of filter is very useful for single element detectors, but is not very useful for beam profilers, in that the attenuation is continuously varying, and therefore will attenuate one side of the beam more than the other.

The more common in-line attenuation filters for beam profile analysis consist of bulk absorbing neutral density filters. Bulk absorbing filters are usually made of BK7 glass impregnated with an absorbing material. The range of attenuation achievable with these filters varies from a neutral density, ND, of 0.1 to an ND of greater than 4. The ND number is defined by

$$ND = \log (1/T) \tag{1}$$

Where: T is the transmission ratio of output divided by input.

Since the absorption is within the material, there is very little danger of reflection from one surface bouncing back and interfering with the reflection from the other surface. Nevertheless, when two filters are stacked together, the back surface of one, and the front surface of the next, need to be slightly angled so that interference does not occur in this region where there is no attenuation between the surfaces. Bulk absorbing filters are very useful for the entire visible and near infrared. However, they cut off at about 350nm in the UV, and are not useful for Excimer or other UV lasers

Bulk absorbing ND filters are commercially available in a number of forms. One common form is simply a flat plate, 2" square, which can be stacked one after another in any mechanism to hold them in place. Figure 16 shows 2" square ND filter flat plates used to attenuate the beam. This same instrument could also accommodate surface reflecting filters for the UV. A second commercially available type is to have individual round filters mounted on a wheel so that the wheel can be turned,

enabling the user to change attenuation simply by rotating the wheel. Often these wheels can be stacked one behind another, so that multiple ND filters can be selected. Typical filters have an attenuation range between 0 and 10^{-10} . Figure 17 shows a commercially available rotating wheel neutral density filter set.



Figure 17. Rotating wheel ND filter set.



Figure 17a. LBS-300 Compact Beam Attenuator

A third type of bulk absorbing ND filter consists of two filters made in the form of wedges. An individual wedge would be like a circular variable filter, and attenuate more on one side than another. However, an opposing wedge is placed behind the first wedge, and the entire beam passes through the same amount of attenuating material. These wedges enable a user to make continuous changes in attenuation in small increments, which can be very convenient. However, in some instances beam distortion has been observed from these filters.

Numerous beam attenuator systems are now commercially available that utilize various combinations of beam splitters and neutral density filters for camera based beam profiling. Some units such as the LBS-300 (figure 17a) provide a sufficiently compact beam path and high degree of attenuation to permit the analysis of focused spots. These devices finally allow the laser user to see the actual beam that is interacting with material being processed.

None of the in-line filters discussed thus far is useful for infrared lasers beyond $2\mu\text{m}$. It turns out that for CO_2 lasers, the use of CaF_2 flats is very useful. A 1mm thick CaF_2 plate absorbs roughly 50% of $10.6\mu\text{m}$ radiation impinging upon it. Thus by stacking CaF_2 flats, CO_2 lasers can be attenuated so that the signal is reduced in fine increments to within the range of the infrared camera.

Crossed polarizers are popular for in-line attenuation of laser beams. However, it would be difficult to assure that the cross polarizers are attenuating each polarization of the beam identically. Therefore, they are not commonly used in beam profile analysis, even though they work very well to attenuate beams for power measurement.

Finally, the last method of attenuating a laser beam is to allow the beam to impinge upon a scattering surface. The beam must first be attenuated by beam sampling, so it does not burn or damage the scattering surface. Once the beam impinges upon the scattering surface, the camera can use a lens to image the reflection of this surface. The image reflection is typically very representative of the beam profile. A problem that can exist is that speckle always occurs from scattering surfaces. Speckle is a situation in which the roughness of the scattering causes interference to create both bright and dark spots in the image reflection. Having the scattering surface move at a rate faster than the camera integration frame rate can solve this problem. There exists a commercial product called a "speckle eater", which is simply a scattering surface mounted to a small vibrating motor. An advantage of imaging scattered

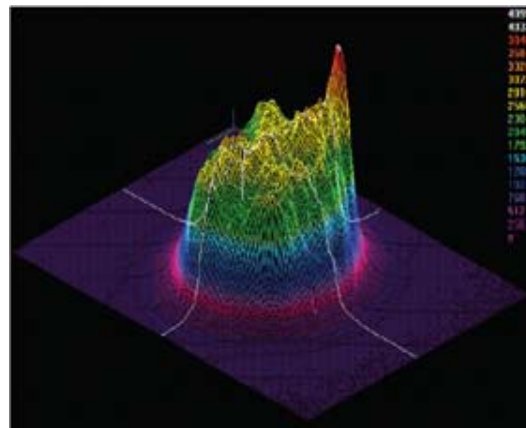
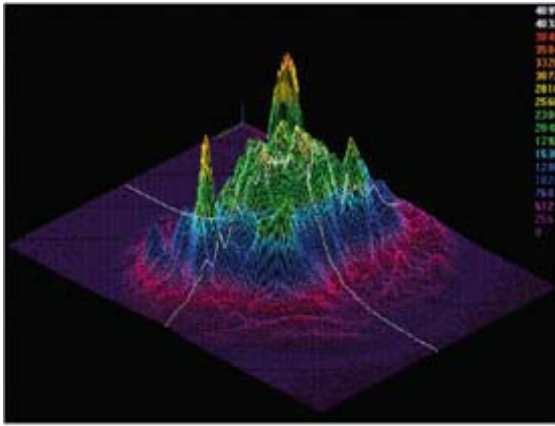
beam reflection is that the iris in the camera lens can be used for attenuation to achieve a fine degree of beam irradiance reduction.



Figure 17c. ND Filters in Stackable C-mount Rings



Filters are angled to reduce interference



View focal spot changing with laser power level with Focal Spot Adapter

4.6 Beam Size

Laser beams typically vary from 1mm in beam width to 40mm, and in many applications, much larger. Focused laser beam spots can be as small as $1\mu\text{m}$ in width. Since camera pixels at the smallest, are approximately $4\mu\text{m}$, cameras are not very useful for measuring the smallest of focused spots. In addition, typical commercial grade cameras have an overall sensitive area of roughly 6mm, with 10mm being the size of 1000X1000 large area CCD cameras. Thus there are many cases when the beam is much too small to be measured with the camera pixels and other cases when the beam is much too large to fit onto the camera sensor.

When the beam is too small for the pixels on a camera system, one of the most straightforward solutions is to use one of the mechanical scanning devices instead. Both the rotating drum and the rotating needle systems can measure small beams. However, these systems are still plagued with the problem that they do not work with pulsed lasers, and do not give instantaneous whole beam analysis.

A second solution that is used especially when looking at a laser emitter such as a laser diode is to use a microscope objective and focus the camera onto the emitter surface. This images the laser output aperture on the array.

A third solution is the use of focused spot analysers that attach to the camera and sample the beam in a compact path length. These devices may employ a negative lens to extend the focal plane of the laser system under test. This technique allows the laser user to observe the laser at focus where power densities are typically too intense for direct measurement with scanning slit or other mechanical devices.

An indirect method of measuring a small focused spot is to allow the beam to go through focus, and then use another lens to collimate the beam. A third lens with a long focal length then refocus the beam to a much larger waist that can be resolved by the camera pixels. If the beam is not a tightly focused spot, but rather a long waist, then a beam expander can perform the same function to increase the size of the beam. Finally, a small focused spot can be scattered from either a reflecting or transmitting surface, and imaged with a camera lens. Difficulty with this technique is that if the spot is very small, it is difficult to obtain scattering surfaces with structure small enough to accurately scatter the beam, rather than simply reflect off one of the facets of the scattering surface. Magnification of the beam can also be achieved in the computer, however at the loss of resolution. An example of the magnification capability in the computer software is shown in Figure 18.

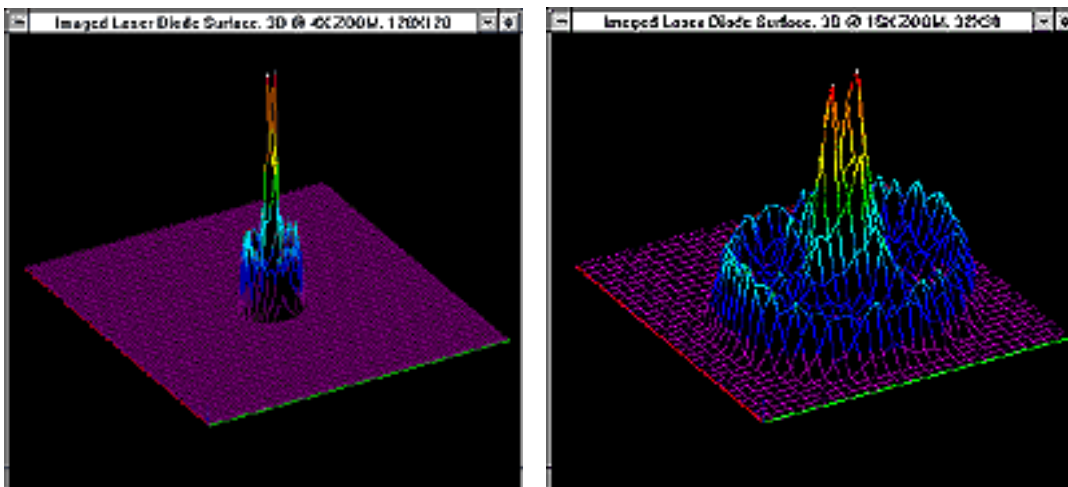


Figure 18. Focused laser diode beam shown at 4X computer magnification and 16X magnification.

When the beam is too large for the camera, the first solution is to use a beam expander in reverse. A beam expander can typically give beam reductions in the order of 10 to 1. Thus a 5cm beam could be reduced to 5mm, which would fit nicely on a CCD camera.

A second method with large beams is to use large area sensors. This is limited to approximately 1cm² for silicon type sensors.

Finally, the most common method of viewing very large beams is to reflect the beam from a scattering surface and image the beam with a lens. A scale can be used to calibrate the pixel pitch of the lens/camera system. This is the same technique as is used for beam attenuation, but now the primary purpose is to be able to image a large area beam, rather than attenuate a large energy. All the same techniques described above must be used to minimize speckle and other problems.

5. Viewing Beam Profiles

A tremendous amount of information can be gained about the beam profile simply by being able to clearly see it on a computer screen. Mode structure and distortion of the beam are immediately

recognized. Examples are a Gaussian beam distorted into an elliptical shape, or the introduction of spurious multimode beams into the main beam. The beam splitting up into multiple spots or clipping of the beam on an edge is immediately seen. In Top Hat beams an electronic display can show hot and cold spots in the flat top, as well as distortion in the ideal vertical sides of the beam.

5.1 Two Dimensional Beam Profile Displays

A 2D view of the beam enables the user to see the entire beam simultaneously. A false color or a grayscale plot is given which enables the user to tell intuitively where the hot and cold spots are in the beam. Cross-sections or slices through the beam, set either manually or automatically at some part of the beam such as Centroid to Peak., provide displays of beam irradiance in the vertical axis, which help interpret the lasers energy distribution. Shown in Figure 19 is the 2D display of a beam profile with the cross section vertical displays drawn through the peak of the beam. The cross section profiles can be drawn at any other part of the beam as well, or rotated from the X/Y axis to the major/minor, or any axis of an elliptical beam.

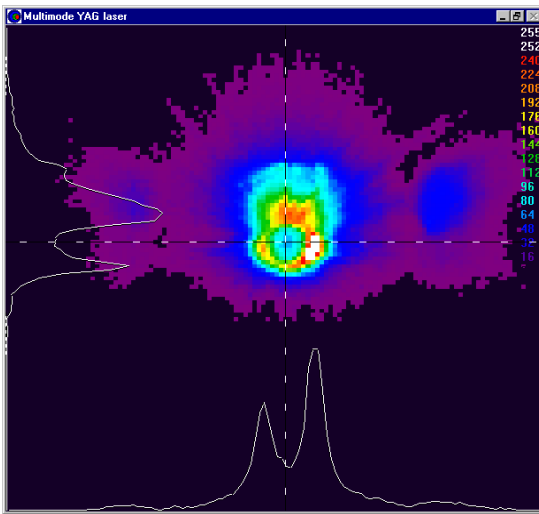


Figure 19. 2D Beam profile display with cross section on the X/Y axis.

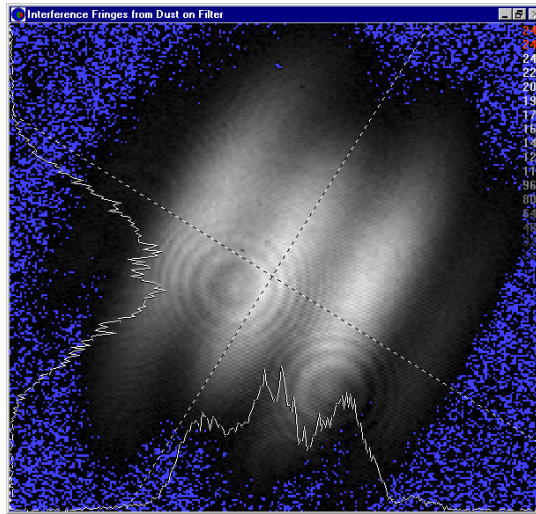


Figure 20. 2D gray scale beam profile display showing interference fringes from dust particles.

Sometimes color can have a significant effect in providing intuitive beam profile information. Other times a grayscale image can show information that color does not. Figure 20 shows a 2D beam profile display created as a grayscale image. Notice the interference rings that show up dramatically in the shades of gray. If this were in color, one might not even notice the interference rings. These interference rings are reflections from small specks of dust on one of the neutral density filters.

5.2 Three Dimensional Beam Profile Displays

3D views of the beam profile give a higher level of intuition of what the beam profile really looks like. The user has the option of rotating and tilting the beam, changing the resolution and color, etc. to maximize his ability to obtain intuitive information from the beam display. However, while 2D displays give all the beam profile information simultaneously, 3D displays hide the backside of the beam. Nevertheless, the 3D view is still often useful in gaining greater intuition from the beam profile. Shown in Figure 21 is a 3D beam profile at different angles of rotation, illustrating how the beam looks from different sides.

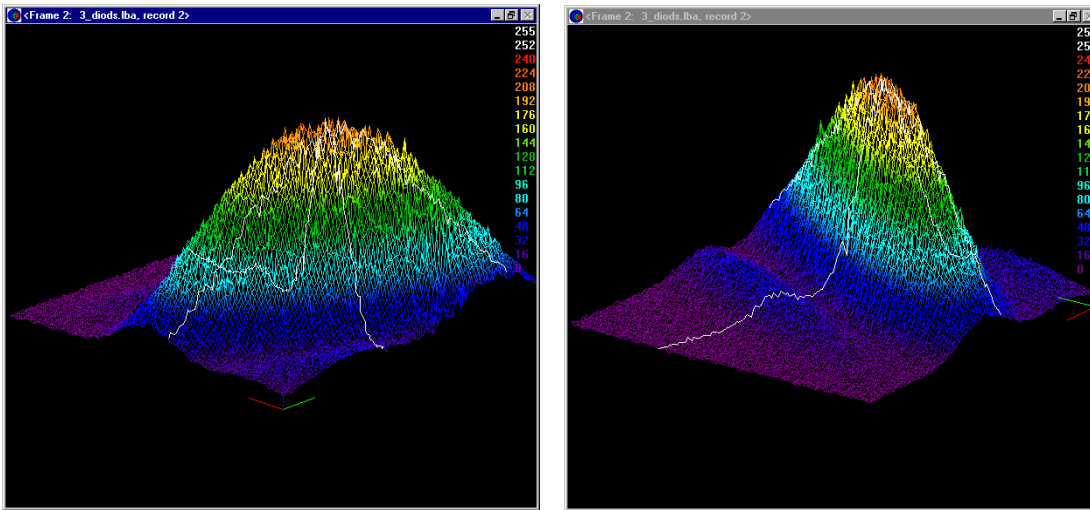


Figure 21. 3D Beam profile shown at various rotation angles. a. 135 Degrees, b. 225 Degrees.

There are many view processing features now available that assist in enhancing the intuition gained from seeing the beam. These include choices of resolution in the 3D display; that is, the number of lines displayed. Also adjacent pixel summing and convolution are available to reduce the visual signal-to-noise ratio, and thus enable a user to more clearly see the major features of the beam, especially in the presence of noise.

6. Quantitative Measurements

One of the most important features of modern beam profilers is the ability to make very accurate measurements of the beam characteristics. Two important laser characteristics, the wavelength of the laser, and the temporal pulse width, are unrelated to beam profile measurement, and are easily measured by instruments other than beam profile measuring instruments. Nearly all other qualities of a laser beam are related to the beam profile. One additional measurement that is not measured directly by beam profile instrument is the total power or energy, which also must be measured by a separate instrument. However, the total power or energy can be measured with a power or energy meter at the same time that the sampled beam profile is measured. When this is done then the beam profiling system can be calibrated to the total power or energy measurement, and from then on the beam profiler is able to track the total power or energy, being calibrated to the power meter reading. New products offer the ability to automatically calibrate the laser power or energy with a beam profiling system. A laser power or energy meter interfaces to the computer running the beam profiling application. The software application then matches-up time stamps from both instruments to provide an accurately calibrated beam profile,.

Characteristics of a laser that are directly related to beam profile measurements include the pulse to pulse relative power or energy, as discussed above, the peak power or energy, the location of the peak, the location of the centroid of the power or energy, and the beam width. The beam width can be measured either on an X/Y axis, or for an elliptical beam, can be measured along the major and minor axis. Each of these characteristics is discussed below.

6.1 Relative Beam Power or Energy

Cameras are seldom able to give a direct measurement of the total energy or power in a laser beam. Two reasons for this are as follows. First, the camera follows a long chain of attenuation so that it does not see the total beam directly. Since this attenuation is put in place for the purpose of getting the energy down to the level of the camera, and can be as much as a factor of 10^{11} , it is not practical to calibrate each element of attenuation. Thus the absolute power fed to the camera is unknown relative to the total power of the beam. Secondly, cameras do not have uniform wavelength absorption. Therefore

they would have a different calibration factor for every wavelength of laser that is used. It would be impractical to attempt to calibrate the camera as a function of wavelength.

6.2 Peak Power or Energy

Peak power or energy is a relatively easy measurement that is derived from the total power. Since the total power on a camera is a summation of the irradiance on each pixel, it becomes relatively easy to determine what part of this total power is contained within each pixel, and thus the energy on the pixel with the highest power is derived in software. This is a useful measurement in that it tells whether there are hot spots in the beam, and what the magnitude of these hot spots is. This can be particularly useful when the laser power or energy is approaching the damage threshold of optics through which the beam must pass. A hot spot in the beam could cause damage even when power averaged over the area of the beam may be well below the damage threshold.

6.3 Peak Pixel Location

When the software in the beam analyzer finds the magnitude of the pixel with the highest irradiance, it also can provide the location of this pixel. This may be useful to track the stability of the hot spot or peak irradiance, and determine whether or not this highest irradiance is stable or is moving back and forth across the beam. The actual peak irradiance location seldom is useful in telling where the majority of the energy of the beam is located, however.

6.4 Beam Centroid Location

Quite often, more significant than the peak pixel location is the location of the centroid of the beam. The centroid is defined as the center of mass or first moment of the laser beam, and is described in Equation 2.

$$X = \iint x E(x,y,z) dx dy / \iint E(x,y,z) dx dy \quad (2a)$$

$$Y = \iint y E(x,y,z) dx dy / \iint E(x,y,z) dx dy \quad (2b)$$

The centroid of the beam can be more significant than the peak pixel because it is independent of hot spots in the beam. This is where the energy center is located. Usually pointing stability of a beam is measured by doing statistical analysis on the centroid rather than on the peak pixel. This pointing stability provides significance in showing the stability of the laser beam position.

The significance of the beam centroid can be very important in alignment of laser beams. This is true in optical trains, on research tables, and in industrial laser applications where it is important to know that the beam is positioned correctly in the optics. It is also significant in aligning lenses to laser diodes to collimate the beam. The beam centroid must also be accurately known when aligning beams into fiber optics. Many beam-shaping systems require alignment of the beam, usually the centroid, to the shaping optics.

6.5 Beam Width

One of the most fundamental laser profile measurements is the beam width. It is a measurement of primary significance because it affects many other beam parameters. For example, the beam width gives the size of the beam at the point where measured. This can be significant in terms of the size of the elements that are in the optical train. Measurement of beam width is also a part of measuring divergence of laser beams, which is significant in predicting what size the beam will be at some other point in the optical train. The beam width is critical for the performance of most non-integrating beam shaping systems. Statistical measurement of the width of the beam is also a significant factor in determining the stability of the laser output. Finally, measurement of the beam width is essential in calculating the M^2 of the laser. This is an important characteristic of laser beams that will be discussed later in this section. Even though fundamental and important, this beam width is sometimes a very difficult measurement to perform accurately.

6.5.1 Considerations in Accurate Beam Width Measurement

A number of considerations in the characteristics of a camera used for beam profile measurement must be carefully considered and accounted for in accurately measuring beam width. Among these considerations is the signal-to-noise ratio, i.e., the magnitude of the beam relative to the background noise in the camera. The amount of attenuation used for the camera is usually adjusted to enable the peak pixel in the camera to be as near to saturation as possible without overdriving the camera. Also if the beam is of a very small size in a very large field of camera pixels, this may be a very small amount of signal compared to the random noise of all the pixels. Proper treatment of this noise is discussed below.

The camera baseline offset is another factor that must be accurately controlled. Because the energy of a laser does not abruptly go to zero, but trails off to a width roughly 4 times the standard deviation, or twice the $1/e^2$ width, there is a lot of low power energy that must be accounted for in accurately measuring the width of the beam.²²⁻²⁴ (The percent of energy in a Gaussian beam is 68% in $\pm 1\sigma$, 95% in $\pm 2\sigma$, and 99.7% in $\pm 3\sigma$. Nevertheless, experiments performed by the author have shown that as an aperture cuts off the beam at less than $\pm 4\sigma$ the measured beam width begins to decrease.) Correct and incorrect baseline control is illustrated in Figures 22a, 22b, and 22c. In Figure 22a the baseline is set too low, and the digitizer cuts off all the energy in the wings of the beam. The beam is seen to rise out of a flat, noiseless baseline. This means that without the wings of the laser beam, a measurement would report a width much too small. In Figure 22b the baseline offset is too high, as seen by observing the beam baseline relative to the small corner defining mark. In this case the software will interpret the baseline as part of the laser beam. A calculation of beam width will be much too large. In Figure 22c the baseline is set precisely at zero. Both positive and negative noise components are retained out beyond the wings of the beam where there is no beam energy. The software will interpret the average of the positive and negative signal as nearly zero.

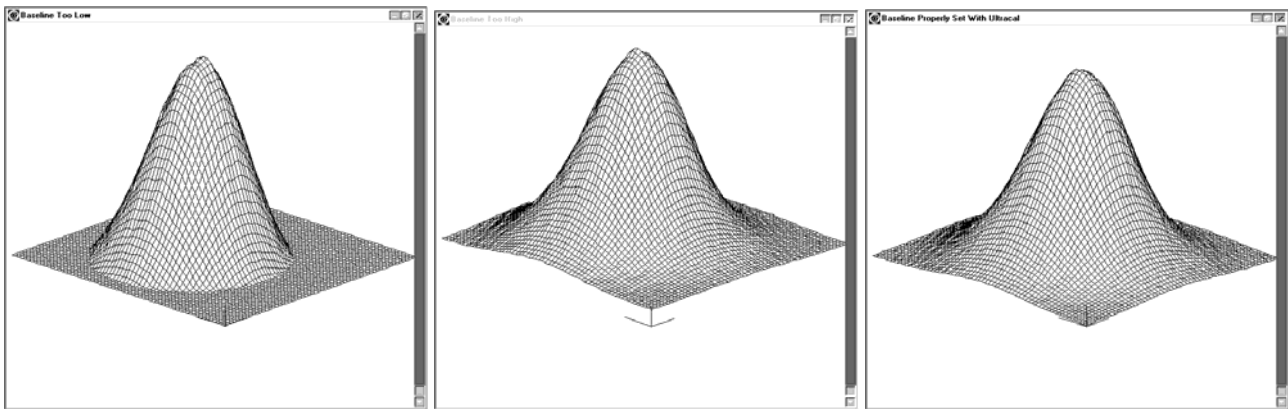


Figure 22. Camera baseline set too low, set too high, and set properly. (Low baseline shows beam rising out of a flat background, which would cause a beam width calculation too small. High baseline would cause a beam width measurement too large.)

Because the low power energy in the wings of a laser beam can have a significant effect on the width measurement, it becomes necessary to be able to characterize the noise in the wings of the beam. Both the noise components that are above and the noise components below the average noise in the baseline must be considered. The noise below the average baseline will hereafter be called negative noise.

Since the size of the beam measurement is affected by the total amount of laser beam energy relative to the noise of the camera, it has been found that software apertures placed around the beam can have a very strong effect in improving the signal-to-noise ratio. For a non-refracted beam, an aperture approximately 2 times the $1/e^2$ width of the beam can be placed around the beam, and all noise outside the aperture can be set to zero in the calculation. This greatly improves the relative signal-to-noise ratio when small beams are being measured in a large camera field. Finally, the measurement algorithm that is used to measure the beam width can have a notable effect on the accuracy and significance of the measurement.

6.5.2 Beam Width Definitions

There are various traditional definitions of beam width, which may or may not contribute to knowing what the beam will do when focused or propagated into space. Some of these include

measurements of the width at some percent of the peak, full width/half max, which would be 50% of peak, a percent of energy, or the $1/e^2$ width. Software equivalent knife-edge measurements are also used as means of determining the beam width. Finally, a more recent definition of beam width is called the Second Moment.²⁵

The software equivalent knife-edge measurement and the Second Moment measurement are becoming the most widely accepted means of measuring laser beams. Both measurements are independent of holes or structure within a beam. When the knife-edge measurement is performed correctly, it does an excellent job of approximating a Second Moment measurement.²⁶ The knife-edge measurement with a camera is simply a software algorithm simulating the motion of an actual moving knife-edge. One advantage of cameras over actual mechanical scanning knife-edges is that the software can quickly find the major and minor axis of an elliptical beam, and perform the knife-edge measurement along these axes without having to actually reposition the mechanical device.

6.5.3 Second Moment Beam Width Measurements

Recent ISO standards²⁶⁻²⁹ have defined a Second Moment beam width, abbreviated $D4\sigma$, which, for many cases, gives the most realistic measure of the actual beam width. The equation for the second moment beam width is given in Equation 3. Equation 3 is an integral of the irradiance of the beam multiplied by the square of the distance from the centroid of the beam, and then divided by the integrated irradiance of the beam. This equation is called the second moment because of the analogy to the second moment of mechanics, and is abbreviated $D4\sigma$ because it is the diameter at $\pm 2\sigma$ which is $\pm 1/e^2$ for Gaussian beams. This second moment definition of a beam width enables a user to accurately predict what will happen to the beam as it propagates, what is its real divergence, and the size of the spot when the beam is focused.

$$D4\sigma_x = 4 \left(\iint (x-X)^2 E(x,y,z) dx dy / \iint E(x,y,z) dx dy \right)^{1/2} \quad (3a)$$

$$D4\sigma_y = 4 \left(\iint (y-Y)^2 E(x,y,z) dx dy / \iint E(x,y,z) dx dy \right)^{1/2} \quad (3b)$$

Where:

(x-X) and (y-Y) are the distances to the centroids X and Y.

Sometimes there are conditions of laser beams wherein the Second Moment measurement is not an appropriate measurement to make. This is particularly true when there are optical elements in the beam smaller than twice the $1/e^2$ width that causes diffraction of part of the energy in the beam. This diffraction will put energy further out into the wings of the beam, which when measured by the Second Moment method, will cause a measurement of the beam width much larger than is significant for the central portion of the beam. By Equation (3), the $(x-X)^2$ term overemphasizes small signals far from the centroid. This requires judgment on the part of the user as to whether or not measurement of this diffracted energy is significant for his application. If the diffracted energy, which typically diverges more rapidly than the central lobe, is not significant, it is possible to place a physical or software aperture around the main lobe of the beam and make Second Moment measurements only within this aperture, and disregard the energy in the wings. However, if the application is dependent on the total amount of energy, and it is important to know that part of this energy is diffracted, then one would want to place this aperture such that it includes all the beam energy in making the calculation.

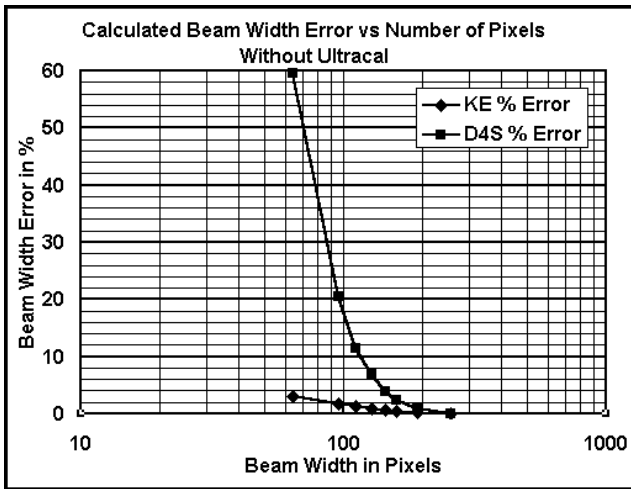


Figure 23a. Simulated beam width error vs. number of pixels without a 2X aperture.

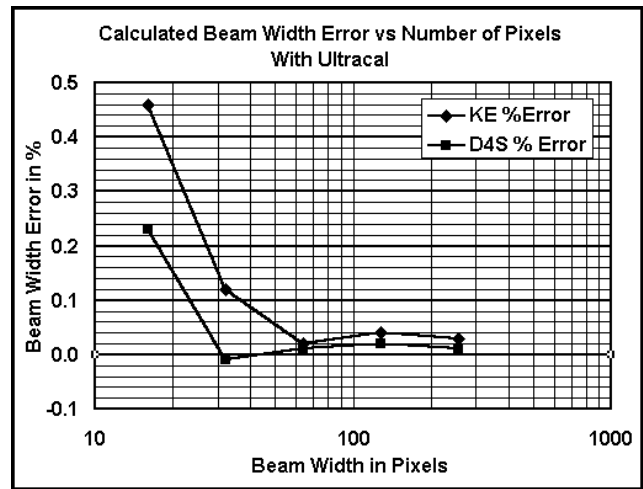


Figure 23b. Simulated beam width error vs. number of pixels with a 2X aperture.

Second Moment measurement, however, is very difficult to make with CCD cameras because the high camera noise out in the wings of the beam is multiplied by $(x-X)^2$ producing a large error component. Also any offset or shading of the camera in the wings of the beam causes very large errors because these small energy numbers are multiplied by $(x-X)^2$. For example, Figures 23a and 23b illustrate the difficulty of making Second Moment measurements. These figures are from theoretical calculations based on creating a perfect Gaussian beam, adding random noise to the mathematically derived beam, then using beam width measurement algorithms to calculate the beam size. In Figure 23a it is seen that a knife-edge measurement can measure a beam of 64 pixels in a 512 field with only 3% error. However, using Second Moment measurement and random camera noise, the beam width error rises to over 60%. For this reason, a few years ago, theoreticians believed that it was not possible to make an accurate Second Moment beam width measurement with a commercial grade CCD camera. However, as shown in Figure 23b, using a knife-edge can initially calculate a relatively accurate beam width. Then by placing a 2X software aperture around the beam, the Second Moment measurement can make very accurate beam width calculations down to a beam containing as few as 13 pixels.

In the following comparisons, Figures 24 to 26, measurements were made to determine the effect on beam width measurement accuracy of various parameters. Since there is no “traceable standard beam width” the beam was first measured under the most ideal conditions. This includes a large beam of high intensity, and using 2X apertures and negative noise components. Then as measurement conditions are changed the “error” is calculated as the percent change in measured beam width from the measurement made under the ideal conditions. All measurements in Figures 24 to 26 were made on the same beam and in the same time frame.

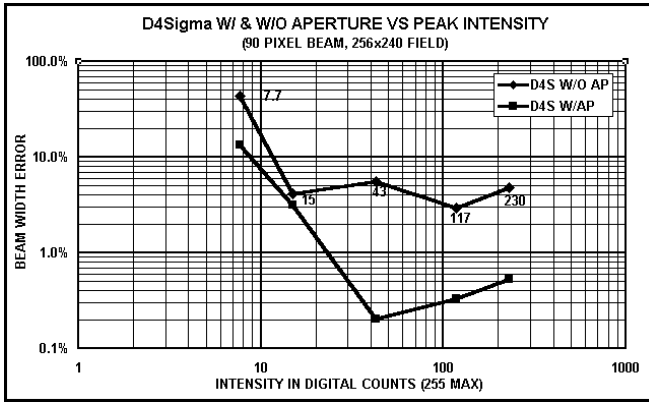


Figure 24a. Measured beam width error vs. Irradiance with and without a 2X aperture.

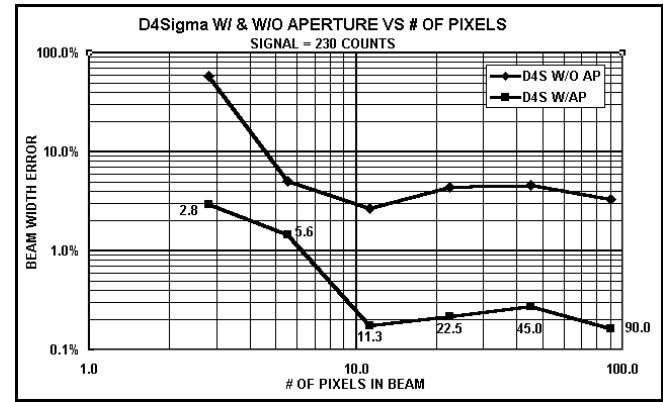


Figure 24b. Measured beam width error vs. Number of Pixels with and without a 2X aperture.

Figure 24a and 24b illustrate the measured experimental accuracy of making Second Moment beam width measurements with and without a 2X software aperture. Figure 24a illustrates the accuracy vs. the irradiance of the peak pixel on the camera. Notice that with the 2X software aperture around the beam, the irradiance can be reduced to as low as 16 counts out of 256, or roughly 5% of saturation, and the beam width measurement error is still only about 3%. Without an aperture the beam width measurement error is in the 3-5% range, regardless of the irradiance of the beam. In Figure 24b it is shown that the number of pixels in the beam can be reduced to about 3X3 pixels before the beam width error measurement rises to 3%. Without an aperture in the beam the beam width error is always in the 3-5% range, and at 3 pixels the error rises to over 60%.

Other conditions that are necessary to accurately measure the Second Moment beam width include accurate baseline control. This is done by having the software perform a multiple frame average of each individual pixel in the camera while the camera is not illuminated. This baseline is then subtracted from the signal when the laser is being measured. This baseline subtraction not only eliminates total offset of the baseline, but also any shading in the camera. (Shading is defined as the offset in the baseline not being uniform across the camera, but varying from one side to the other.)

In addition to accurate baseline control and 2X software apertures mentioned in the previous paragraph, it is also very important to maintain the negative numbers derived from background subtraction as described previously. The following figures illustrate measurements made on an actual laser beam to determine the relative accuracy of making beam width measurements using both Second Moment and knife-edge under varying conditions. Figures 25a and 25b illustrate the ability of Second Moment algorithm to accurately measure beam width with and without negative numbers in the baseline. Notice that in Figure 25a where the beam is reduced in irradiance, the beam can be as low as 15 counts or 5% of saturation, with only 3% error. However, without negative numbers in the baseline, at 15 counts the beam width error is 100%. Figure 25b illustrates the ability to accurately measure beam width as a function of the number of pixels in the beam with and without negative numbers in the baseline. Having the negative numbers improves the accuracy by about a factor of 5 for larger beams. At 3X3 pixels the accuracy is 3% with negative numbers, and just over 7% without negative numbers.

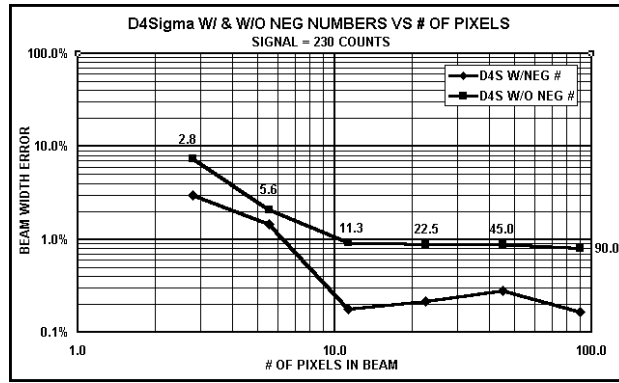
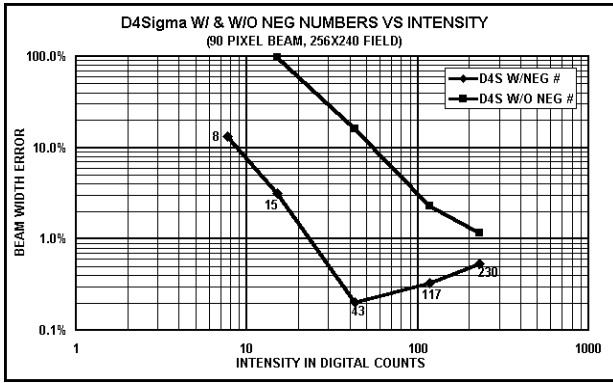


Figure 25a. Measured beam width error vs. Irradiance with and without negative baseline numbers.

Figure 25b. Measured beam width error vs. Number of Pixels with and without negative baseline numbers.

Figures 26a and 26b illustrate the measurement accuracy of the Second Moment beam width method compared to the accuracy of the knife-edge algorithm. In Figure 26a the measurements are compared vs. irradiance of the beam. In Figure 26b they are compared vs. the number of pixels in the beam. In both cases an aperture and negative numbers are used. Note that both Second Moment and knife-edge have approximately the same measurement accuracy in these conditions.

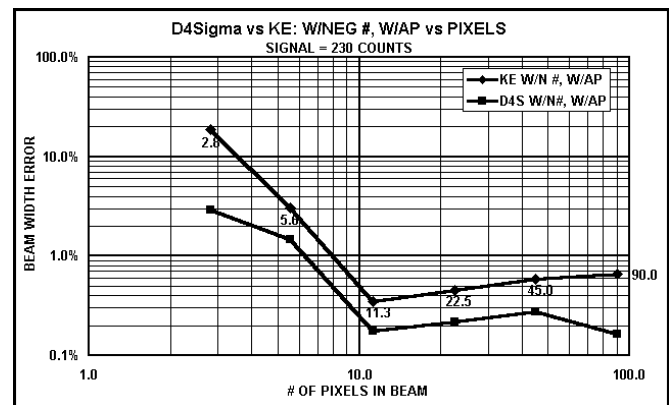
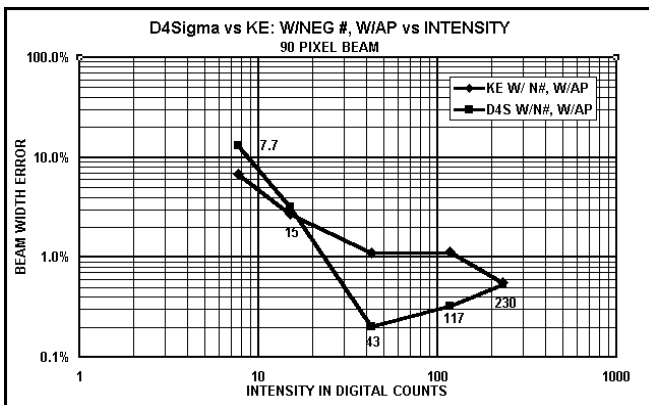


Figure 26a. $D4\sigma$ vs. KE beam width error vs. Irradiance. (With aperture and negative numbers)

Figure 26b. $D4\sigma$ vs. KE beam width error vs. Number of Pixels. (With aperture and negative numbers)

6.6 Other Important Beam Profile Measurements

6.6.1 Beam Ellipticity

With camera based beam-profiling systems it is relatively simple for the software to measure the ellipticity of laser beams. The software typically finds the major axis of a beam, and then sets the minor axis perpendicular to the major axis. Once the major axis is found, the angle that the major axis deviates, typically from the X-axis, is given, and the ratio of the major to minor axis widths is calculated. This is an extremely useful measurement in laser beam alignment. It is particularly useful in aligning lenses to laser diodes, which are highly elliptical. Typically a special lens is used with diodes to circularize the beam. The alignment of this lens to the diode is extremely critical. With mechanical scanning systems it is very cumbersome to find the major and minor axes. Whereas with a camera

based system the entire beam profile is obtained in every frame of the camera, so the ellipticity can be found instantaneously. This makes it extremely rapid to do beam and component alignment real-time.

Another important reason for knowing the ellipticity of the laser beam is in industrial applications. Typically if the beam becomes elliptical, a laser used for cutting irregular shapes will have a different cut width in one axis than in the other. By measuring the ellipticity and correcting it when it goes beyond acceptable limits, industrial users can eliminate creating scrap materials.

6.6.2 Gaussian Fit

In many cases the desired beam irradiance profile is a Gaussian beam with its irradiance at any point in the X/Y plane corresponding to Equation 4. There are a number of ways to perform a fit of the real beam to the Gaussian equation. One of these is to minimize the deviation, which is defined in Equation 5. This fit can either be along an X/Y axis, a major/minor axis, or can be performed over the entire laser beam. Being performed over the entire beam is useful in that it means that any energy off axis contributes to determining how well the beam fits a perfect Gaussian. In addition to these equations, the actual data of beam profile irradiance can be exported to a spreadsheet and a user can perform the calculations according to his own method.

Gaussian equation:

$$J = J_o e^{-2 \left[\left(\frac{x-\bar{x}}{w_x} \right)^2 + \left(\frac{y-\bar{y}}{w_y} \right)^2 \right]} + A \quad (4)$$

where:

- J = amplitude at the point (x, y)
- J_o = amplitude at the Gaussian center
- x = x location of pixel
- \bar{x} = x location of the Gaussian center
- w_x = horizontal radius at $1/e^2$ of energy
- y = y location of pixel
- \bar{y} = y location of the Gaussian center
- w_y = vertical radius at $1/e^2$ of energy
- A = offset

Minimization of the deviation can be performed by varying the parameters of Equation 4 using the spreadsheet solve feature. A is an offset term which is set to zero, i.e. disregarded in beam analyzers, because as stated above, the background is carefully set to zero. The definition of the Deviation is:

$$\sigma = \sqrt{\frac{\sum (Z - s)^2}{n - 2}} \quad (5)$$

where:

- σ = standard deviation
- Z = pixel irradiance
- s = Gaussian surface irradiance
- n = number of pixels

Gaussian fit as a measure of the quality of a laser beam is becoming less important. It has been shown that a multimode beam with the right combination of modes can look Gaussian,²⁶ and can very closely fit to a Gaussian curve. Nevertheless, the beam has many modes, and is far from true TEM₀₀ mode. A multimode will not follow the propagation laws of a perfect Gaussian beam, and a user can be misled by the Gaussian fit. Instead, the parameter, M², has become more popular as representing the reality of how close the beam is to a true TEM₀₀ Gaussian. M² will be discussed in more detail below.

6.6.3 Top Hat Measurement

Many real beams are intended to be flat top. Some beam techniques discuss how to obtain uniform flat tops from Gaussian and other input beams. A flat top beam is useful in many applications where the irradiance should be uniform over a given cross section. Some applications include medical process such as wine spot removal and photorefractive keratotomy, wherein a uniform portion of the cornea of the eye is removed. Industrial applications in which a flat top is useful include cleaning of surfaces and marking.

Camera based systems enable easy and accurate measurements of flat top beams. The software is programmed to give a readout of the average irradiance, or the mean across the flat top, the standard deviation of the variations from the mean, and the standard deviation divided by the mean, which gives a percentage flatness. Also the minimum and maximum can be provided, which give additional information about the relative flatness of the beam. The flat top factor³⁰ is a way to give a quantitative and intuitive measure of how flat a top hat beam is. (The equations are given in reference 30.) A typically square beam would have a top hat factor of 1. A Gaussian beam has a top hat factor of 0.5. Therefore, most beams will fall somewhere between 0.5 and 1. In addition to measuring the flatness of the top hat, the software can also calculate the top hat area and the size or width of the top hat beam. Figure 27a shows a typical Top Hat and typical calculations from our BeamGage software.

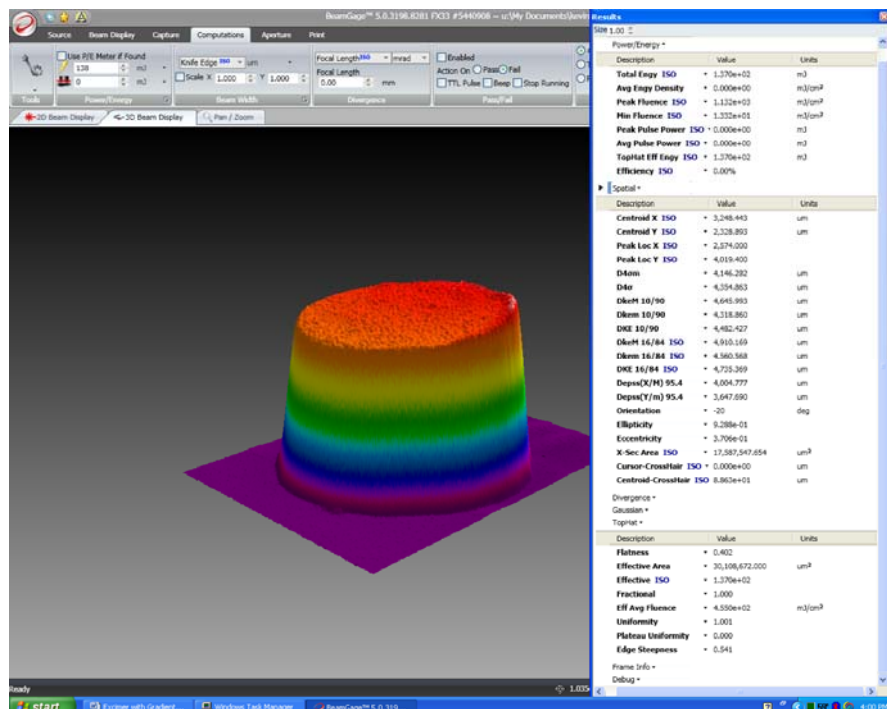


Figure 27. Typical Top Hat beam with Top Hat calculations.

6.6.4 Divergence Measurement

Divergence is an important characteristic of laser beams. It gives the angle at which the beam is diverging from a collimated parallel beam. It is important because the lower the divergence, the longer the beam will remain at a given diameter. Typically when low divergence is necessary, a beam is often expanded to a large width, and then the divergence of this large width beam is smaller. Nevertheless, beam divergence by itself does not provide the true characteristics of a beam, since as just mentioned; simply expanding the beam to a larger waist can change it. This will be explored in more detail in the M^2 section to follow.

6.6.5 Statistical Measurement

Statistics on all measurements can provide information on long term stability of the laser beam. A typical example of statistical measurement is shown in Figure 28. This figure illustrates a number of the basic measurements possible from the software, along with the statistics provided by sampling twenty calculations to determine the beam stability. Statistics can be performed in a large variety of ways. For example, software can be arranged so that only one measurement is made out of every few hundred frames, then statistics are calculated on thousands of such frames. This enables one to track the stability of a laser with respect to time, temperature fluctuations, or other characteristics of interest. Statistics typically provide the mean or average measurement of a parameter, the standard deviation, and the minimum and maximum to which that characteristic has drifted.

	Current	Mean	Deviation	Minimum	Maximum	Units
Statistics						
Samples	20	20	20	20	20	
Quantitative						
90/10 Knife Edge						
Total	5.002e+05	5.100e+05	5.094e+05	5.088e+04	2.006e+06	mw
% Above Clip	86.76	87.19	.94	86.50	90.68	%
Peak	1.490e+02	1.458e+02	6.172e+01	4.600e+01	2.450e+02	mw/cm ²
Min	-1.200e+01	-8.050e+00	5.463e+00	-1.500e+01	0.000e+00	mw/cm ²
Peak Loc X	5.300e+03	6.680e+03	1.263e+03	4.000e+03	8.400e+03	um
Peak Loc Y	8.100e+03	7.530e+03	1.584e+03	5.200e+03	1.060e+04	um
Centroid X	6.584e+03	6.734e+03	9.008e+02	5.484e+03	8.534e+03	um
Centroid Y	5.980e+03	6.456e+03	7.703e+02	5.478e+03	8.287e+03	um
Width X	1.005e+04	8.464e+03	2.209e+03	5.186e+03	1.403e+04	um
Width Y	1.183e+04	1.059e+04	1.615e+03	7.608e+03	1.330e+04	um
Diameter	1.094e+04	9.527e+03	1.670e+03	6.890e+03	1.367e+04	um

Figure 28. Statistical measurement of the basic laser beam parameters.

6.6.6 Pass/Fail Measurements

Figure 29 shows a typical dialog for a pass/fail measurement. Essentially all of the quantitative measurements being made on the laser beam can have pass/fail limits set in one of these dialog boxes. Thus, for example, if the centroid location is critical in a manufacturing or other environment, a maximum radius from a given position can be set. The software can then be programmed to provide an alarm if the parameter of interest drifts outside the limits. This feature can be used in many environments, including industrial, instrument design, laser stability and design, and others.

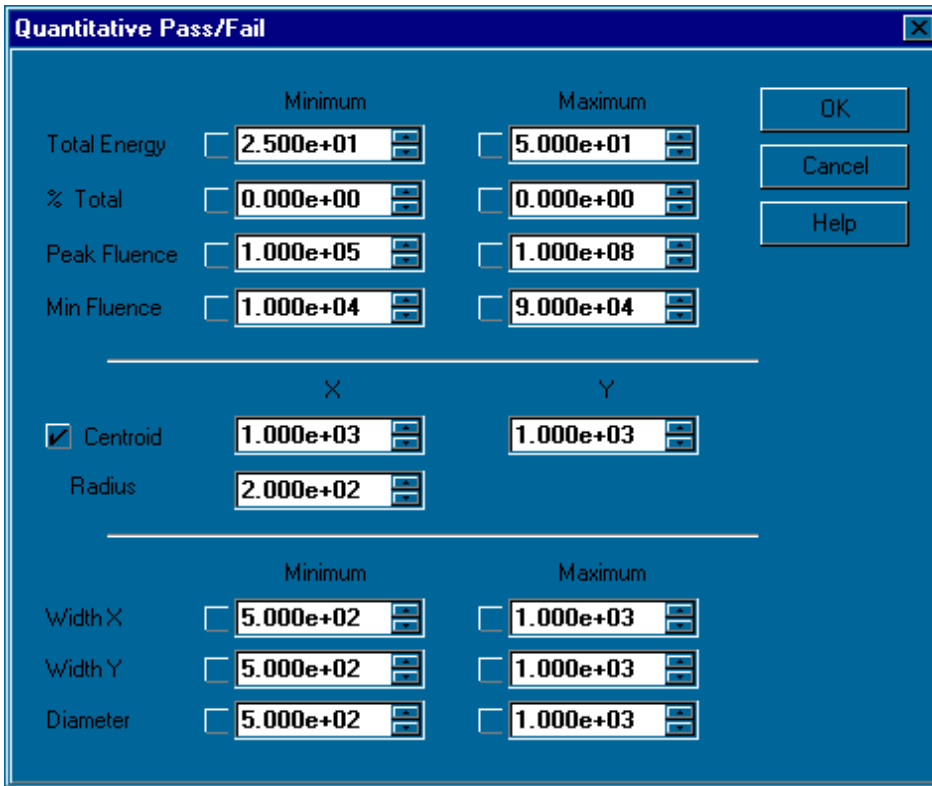


Figure 29. Pass/Fail dialog box.

6.7 M² Measurements

M², or the factor $k = 1/M^2$ in Europe, has become increasingly important in recent years in describing the beam propagation characteristics of a laser beam.³¹⁻⁴² In many applications, especially those in which a Gaussian beam is the desired profile, M² is the most important characteristic describing the relative characteristics of the beam. Figure 30 illustrates the essential features of the concept of M² as defined by Equations 6a and 6b. As shown in Figure 30, if a given input beam of width D_{in} is focused by a lens, the focused spot size and divergence can be readily predicted. If the input beam is a pure TEM₀₀, the spot size equals a minimum defined by Equation 6a and d_{00} in Figure 30. However, if the input beam D_{in} is composed of modes other than pure TEM₀₀, the beam will focus to a larger spot size, namely M² times larger than the minimum, as shown mathematically in Equation 6b, and d_0 in Figure 30. The ISO definition for the Beam Propagation Factor of a laser beam uses M² as the fundamental measurement parameter.

$$d_{00} = 4\lambda f / \pi D_{in} \quad (6a)$$

$$d_0 = M^2 4\lambda f / \pi D_{in} \quad (6b)$$

Where:

λ = the wavelength

f = the focal length of the lens

D_{in} = the width of the input beam at the waist

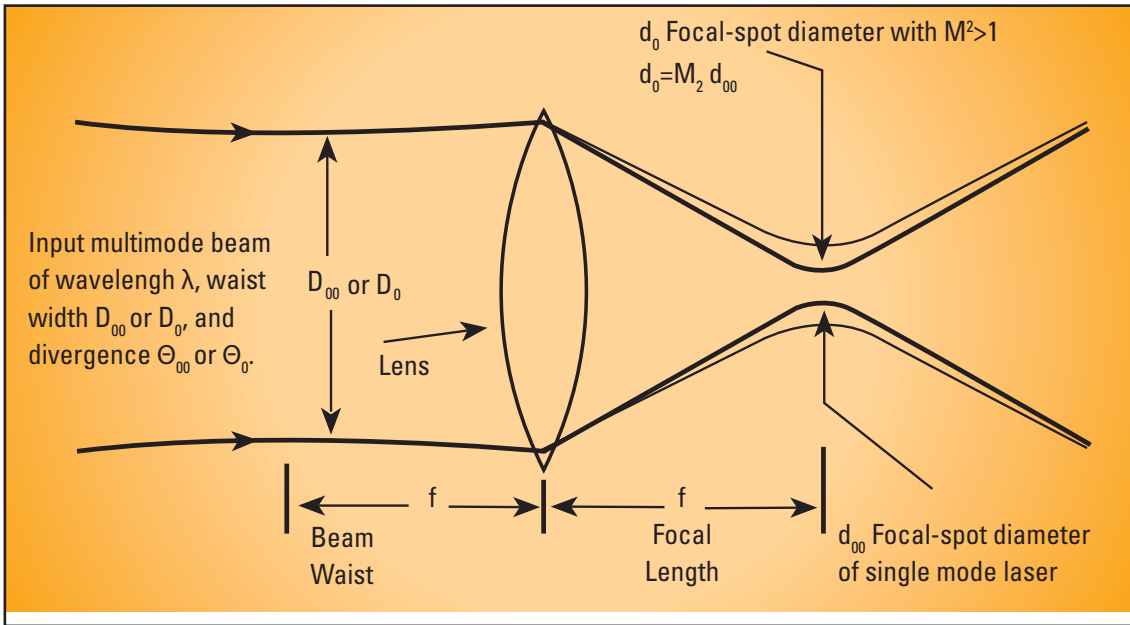


Figure 30. Curve showing M^2 . (Characteristics and equations relating M^2 to the beam focused spot size.)

In measuring and depicting M^2 , it is essential that the correct beam width be defined. The ISO standard, and beam propagation theory indicate that the Second Moment is the most relevant beam width measurement in defining M^2 . Only the Second Moment measurement follows the beam propagation laws so that the future beam size will be predicted by Equations 6a and 6b. Beam width measured by other methods may or may not give the expected width in different parts of the beam path.

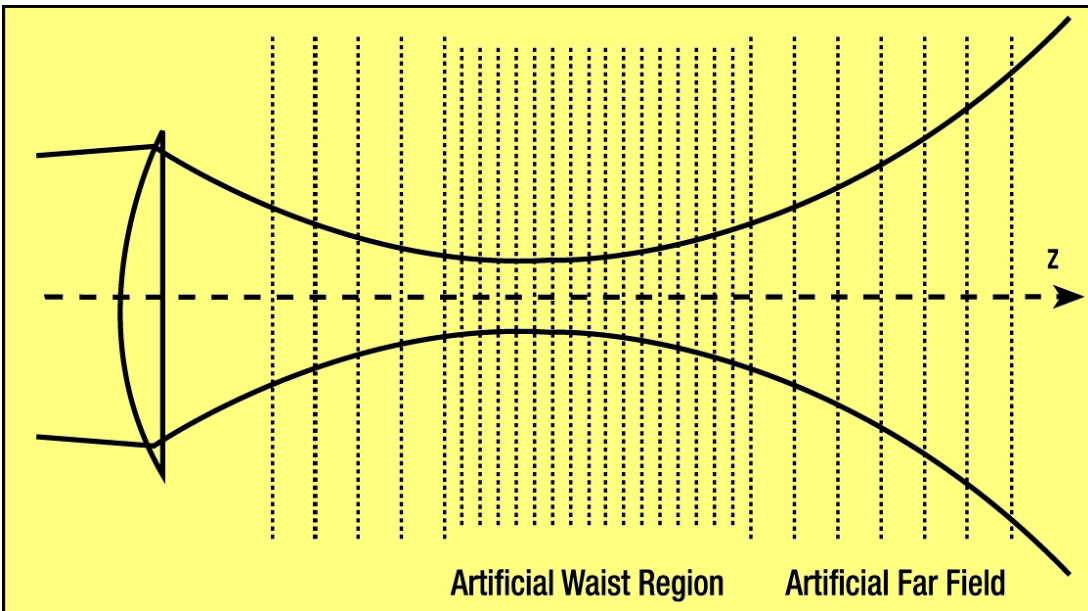


Figure 31. Multiple measurements made to measure M^2 .

M^2 is not a simple measurement to make. It cannot be found by measuring the beam at any single point. Instead a multiple set of measurements must be made as shown in Figure 31 wherein an artificial waist is generated by passing the laser beam through a lens with known focal length. One

essential measurement is to measure the beam width exactly at the focal length of the lens. This gives one measurement of the divergence of the beam. Other measurements are made near the focal length of a lens to find the width of the beam and the position at the smallest point. In addition, measurements are made beyond the Rayleigh range of the beam waist to confirm the divergence measurement. With these multiple measurements one can then calculate the divergence and minimum spot size, and then going backwards through Equation 6b, one can find the M^2 of the input beam.

The measurement shown in Figure 31 can be made in a number of ways. In one commercial instrument, shown in Figure 12, a detector is placed behind a rotating drum with knife edges, and then the lens is moved in the beam to effectively enable the measurement of the multiple spots without having to move the detector. This instrument works extremely well as long as the motion of the lens is in a relatively collimated part of the laser beam. However, if the beam is either diverging or converging in the region where the lens is moving, the resultant M^2 measurement can be misleading.

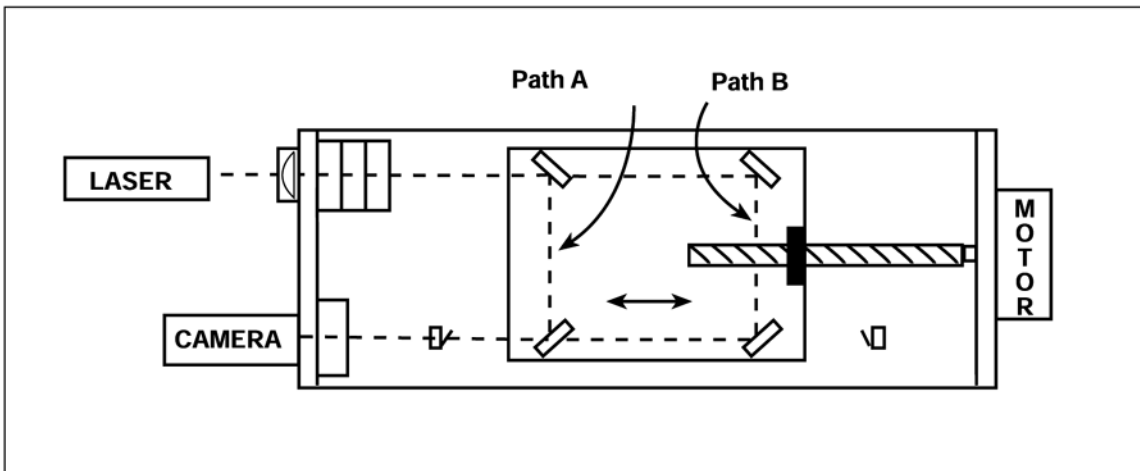


Figure 32. Instrument with fixed position lens for measuring M^2 .

The ISO method²⁸ for measuring M^2 is to have the lens in a fixed position, and then make multiple detector position measurements as shown in Figure 31. This can be done by placing a lens on a rail and then moving the camera along the rail through the waist and through the far field region. Spiricon manufactured instruments perform this measurement automatically without having to manually position the camera along the rail. One of these is shown in Figure 32, wherein the lens and the camera are fixed, but folding mirrors are mounted on a translation table, and moved back and forth to provide the changing path length of the beam. A typical readout of an M^2 measurement is shown in Figure 33. In this case a collimated laser diode was measured, which gave a much greater divergence in the X axis than in the Y axis. The steep V curve displayed is the X axis of the beam coming to a focus following the lens. The more gradual curve is the focus of the less divergent Y axis. Notice that while for most of the range the X axis has a wider beam width, at focus the X axis focuses smaller than the Y axis. Also, the X-axis M^2 was 1.46, whereas the Y-axis M^2 was only 1.10. The M^2 reported in the numbers section is calculated from the measurements of the beam width at the focal length, the minimum width, and the divergence in the far field according to the equations in the ISO standard.

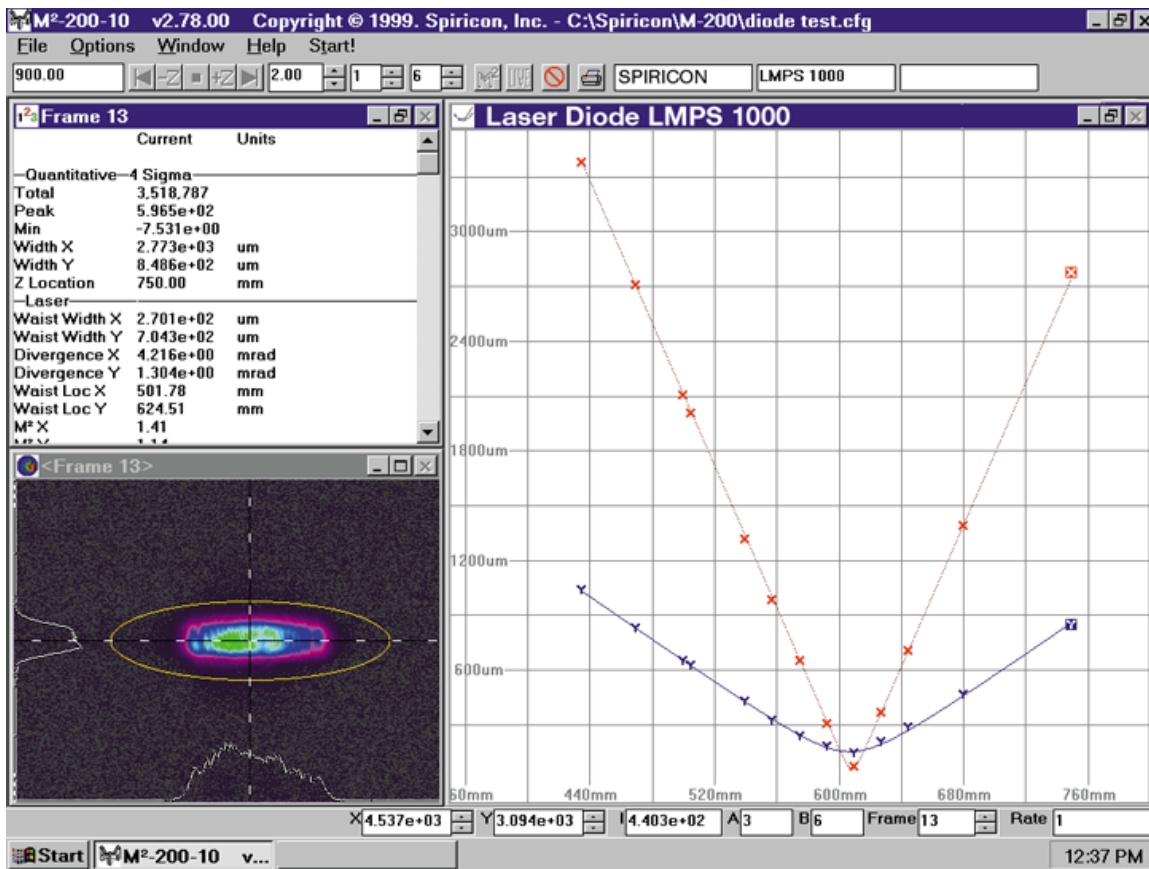


Figure 33. M^2 measurement display and calculation readout.

One of the difficulties of accurately measuring M^2 is accurately measuring the beam width. This is one of the reasons that so much effort has been made at Spiricon to define the Second Moment beam width, and create algorithms to accurately make this measurement. Another difficulty in measuring this beam width is that the irradiance at the beam focus is much greater than it is far from the Rayleigh length. This necessitates that the measurement instrument operates over a wide signal dynamic range. Multiple neutral density filters are typically used to enable this measurement. An alternative exists with cameras or detectors that have extremely wide dynamic range, typically 12 bits, so that sufficient signal-to-noise ratio is obtained when the irradiance is low, and still not saturate the detector near the focused waist.

There are some cases when M^2 is not a significant measure of the functionality of a laser beam. For example, flat top beams for surface processing typically have a very large M^2 , and M^2 is not at all relevant to the functionality of the beam. Nevertheless, for many applications in nonlinear optics, industrial laser processing, and many others, the smallest possible beam with the M^2 closest to 1 is the ideal. Some flat top beam shapers are designed for an input Gaussian beam and then the M^2 of the input beam should be very close to 1, and the beam widths should closely match the design width.

6.8 Signal Processing

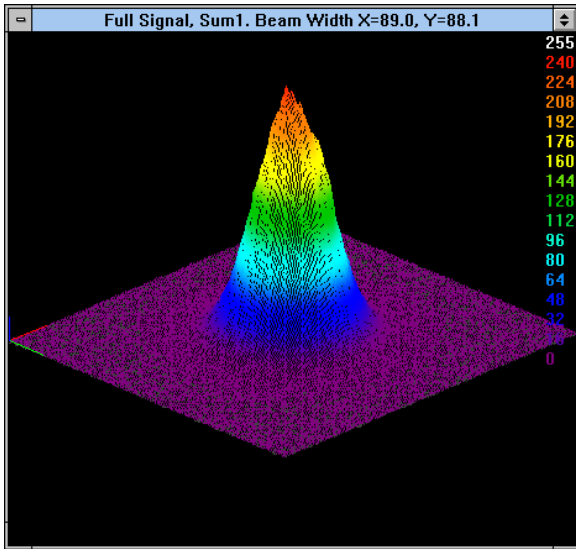


Figure 34. HeNe laser beam used in signal processing experiment.

Careful control of the camera baseline and proper treatment of both positive and negative going noise enable signal processing that would not otherwise be possible. Figure 34 shows a HeNe laser beam at near saturation of a CCD camera. This beam was then blocked, and signal summing of 256 frames was performed to determine the noise distribution under summing conditions. This noise is shown in 3D in Figure 35a. The darker components of noise at the bottom of the distribution are the negative going components. With accurate baseline control and treatment of negative noise components, Figure 35b shows that the distribution of the noise is roughly Gaussian, and is centered at zero. This is what would be hoped for from summing many frames of random noise.

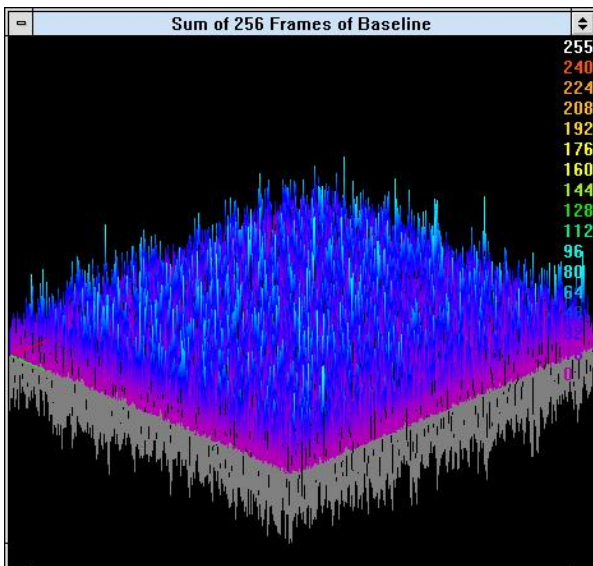


Figure 35a. CCD camera noise after sum of 256 frames.

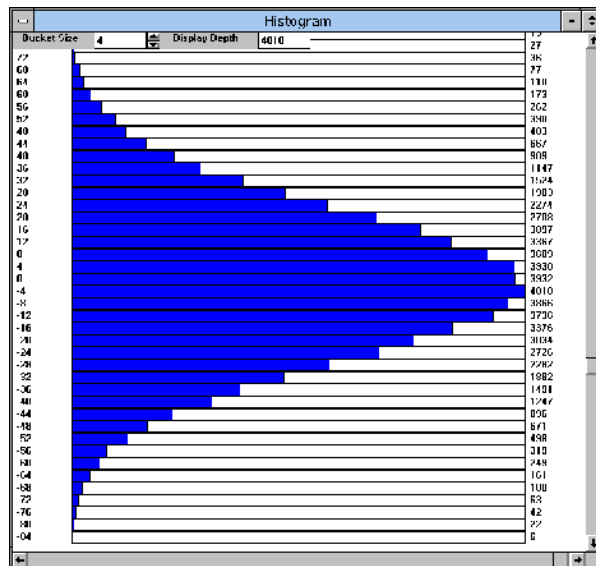


Figure 35b. Distribution of noise shown in Figure 35a.

The laser beam of Figure 34 was then passed through an ND2 filter, which attenuated it by a factor of roughly 100. At this point the laser beam was completely buried in the random noise for each single frame. Again 256 frames of signal were summed, and the signal rose out of the noise as shown in Figure 36a. In this case, the signal sums as the number of frames, whereas the noise sums roughly as the square root of the number of frames. Thus the signal-to-noise ratio is improved by approximately the square root of the number of frames summed. Note that this is possible only when negative noise components are used. Otherwise if negative components are clipped at zero, the noise will sum to a positive DC offset. Figure 36b shows the beam profile of 36a when adjacent pixels in a 4X4 matrix are summed together. Notice a tremendous noise cancellation leaving a much cleaner view of the beam profile. This results from the summing of adjacent positive and negative noise components. Figure 36c shows a similar way of providing a clearer beam profile picture by using convolution to average out the noise in the background. In all three cases of Figure 36 the beam width measurement, from the measurement of the beam in Figure 34, was in error by only about 5 to 7%. This is quite phenomenal for a beam that started out buried in the noise.

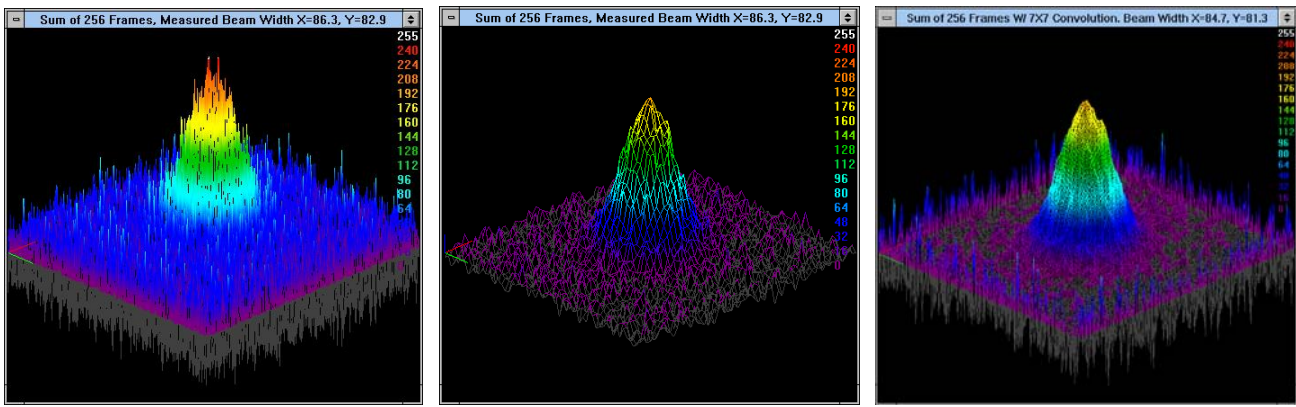


Figure 36a. Beam of Figure 34 after attenuation of about 100 and summed for 256 frames.

Figure 36b. Beam of Figure 36a with summing of pixels in a 4 X 4 matrix.

Figure 36c. Beam of Figure 36a with convolution over a 7 X 7 array.

6.9 Wavefront Phase

A more advanced measurement on laser beam profile is the wavefront phase of the laser beam. The profile simply measures the irradiance, but does not predict what the irradiance will be at any point further along the propagation path. A measurement of M^2 tells how much more rapidly a beam will diverge, but does not give any information about the manner in which this divergence will occur. A measurement of wavefront phase gives the details of the beam distortions that are reported as a simple number in M^2 . However, wavefront phase is a more complicated measurement to make, as well as to make use of. It is likely that as users become more sophisticated, that wavefront phase will become an increasingly important measurement related to the beam profile. Currently there are two methods of measuring the wavefront phase in which commercial instruments are available. One is to use an interferometer, and the second is to use a Hartman array of individual detectors. For some beam shaping problems, knowledge of the wavefront phase is important.

7. Summary

Electronic measurements of laser beams using CCD and other solid state cameras yield very detailed information on laser beams. Using such beam profilers, scientists and laser users in many fields are able to greatly enhance the operation of these powerful tools. Giving an accurate view of the beam

profile, and making precise measurements of beam parameters, such as beam width and other characteristics, provides this important information thus advancing the successful use of lasers.

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