High power beam analysis

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ABSTRACT

In various modern scientific and industrial laser applications, beam-shaping optics manipulates the laser spot size and its intensity distribution.
However the designed laser spot frequently deviates from the design goal due to real life imperfections and effects, such as: input laser distortions, optical distortion, heating, overall instabilities, and non-linear effects.
Lasers provide the ability to accurately deliver large amounts of energy to a target area with very high accuracy. Thus monitoring beam size power and beam location is of high importance for high quality results and repeatability.
Depending on the combination of wavelength, beam size and pulse duration , laser energy is absorbed by the material surface, yielding into processes such as cutting, welding, surface treatment, brazing and many other applications.
This article will cover the aspect of laser beam measurements, especially at the focal point where it matters the most. A brief introduction to the material processing interactions will be covered, followed by fundamentals of laser beam propagation, novel measurement techniques, actual measurement and brief conclusions.

Keywords: Beam profiling, Beam analysis, High power measurements, Material processing, Laser welding, Laser cutting, Knife edge.

1. FUNDAMENTALS OF LASER PROPAGATION

As a laser beam propagates, its width and spatial intensity distribution changes in space and time, due to changes in the laser cavity, divergence, and interaction with optical elements. Spatial intensity distribution is one of the fundamental parameters that indicates how a laser beam would behave in an application. Second fundamental parameter is the total laser power.
As output power increases, accurate and fast measurements are more and more difficult to perform. Theory can sometimes predict the behavior of a beam, but manufacturing tolerances in lenses and mirrors, and ambient conditions affecting the laser cavity, necessitate verification. Consequently, it is important to accurately measure power and its profile distribution along the propagation axis, especially at the focal point, where for material processing it counts the most. These parameters are covered by ISO standard 11146 , which defines approaches to be used in measuring of such beams.

1.1 Beam waist and divergence

Laser light waves diverge transversely as they propagate through space. Therefore accurate prediction of divergence, although possible, needs measurement verification.
The laser beam divergence is in accordance with the predictions of diffraction theory.
Under ordinary circumstances, the beam divergence might be very small, in a way not easy to discern, and thus requires several measurements along its propagation direction.
The following formulas accurately describe beam propagation through space, enabling engineering calculation predicting the laser beam's characteristics along its propagation axis. This model and notation is consistent with Siegman's pioneering work (Lasers, University Science Books).
A laser beam wave front diverges in space according to the below formula:

$$M^2=\P W_0\Theta/\lambda . \quad (1)$$

This value is the far-field angular radius (half-angle divergence) of the Gaussian and non-Gaussian beam.
It is important to note that, propagation variations of beam diameter and divergence with distance z are functions of a single parameter Wo, for cases where the beam is a perfect Gaussian and thus having $M^2=1$. For non-Gaussian laser beams the propagation is a function of two parameters Wo and M^2, where M^2 is always greater than 1.
Thus, M^2 parameter is a single value describing a general beam propagation with a known waist dimension Wo.

1.2 Near-field vs. far-field divergence

Laser beams, Gaussian and non Gaussian, do not diverge linearly as can be seen in bellow figure.

Near the Wo point, or waist position, the divergence angle is small, and far from the laser's waist the divergence angle approaches the asymptotic limit as described in Figure 3. The area along Z axis, where the divergence is low, is sometimes called depth of focus.
The Raleigh range is defined as the distance over which the beam radius diverges by a factor of $\sqrt{2}$ and is calculated from the same basic formula:

$$Z® = ¶W_0^2/\lambda \quad . (2)$$

- where Z® is the distance propagated from Wo plane,
- λ is the wavelength of light,
- Wo is the radius of the waist.

The Raleigh range is the dividing line between near-field divergence and mid-range divergence. Far-field divergence (the number quoted in laser specifications) must be measured at a point far from the Raleigh range. For a tightly focused beam, the distance from the waist (the focal point) to the far field can be a few millimeters or less. For beams coming directly from the laser, the far-field distance can be measured in meters.
Fundamental beam parameters to be measured, are :
-Total beam power
-Beam profile at the waist, or focal position
- A few beam profiles along propagation direction, including positions substantially away from Rayleigh distance

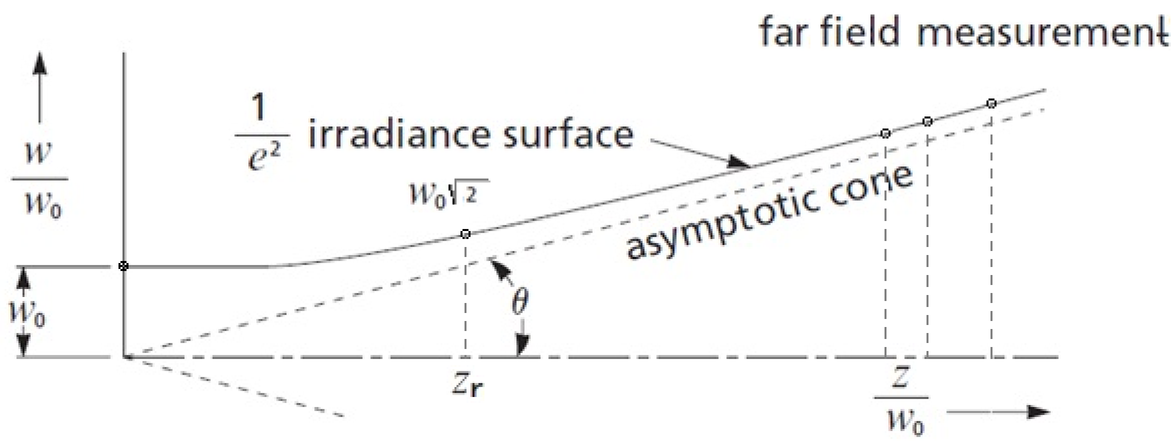

Figure 1 Describes the laser beam propagation along Z axis and possible locations for beam profile measurement

2. MEASUREMENT FUNDAMENTALS

As we have shown above, fundamental to all measurements, enabling laser beam full characterization, is the capability to measure and define beam width and beam profile along several intersections. As such, defining beam width, is of outmost importance for measurements and analysis.

2.1 Defining the beam width
Optical beams are not clearly defined and, in theory the beam profile at a certain location Z extends to infinity. Thus, the dimensions of a beam cannot be defined by a single number as easily as some mechanical object.
The commonly used definition of beam width is the width at which the beam intensity has a value of $1/e^2$ (13.5%) of its peak value, when measured in a plane that is orthogonal to the optical axis. This is derived from the propagation of a Gaussian beam and is appropriate for lasers operating in the fundamental TEMoo mode .
Many lasers, however, significantly differ from a perfect Gaussian beam, and applying this simple definition causes problems. Therefore, the IS011146 Standard specifies the beam width as the point of the second moment of intensity, a value that is calculated from the raw intensity data distribution.

2.2 Methods of measuring beam width

There are four main types of beam-profiling instrumentation: camera-based systems, knife-edge scanners, slit scanners, and pinhole scanners. Each has specific advantages and disadvantages. Different measurement techniques may result in slightly different profiles.

Scanning profilers are, to some extent, regarded as same family, and are usually mechanical devices using an aperture scanned across the laser beam and thus generating the transmitted power vs. the aperture position. These scanner devices have several advantages in the area of resolution, beam size (very small and large beams measurement capability), and their large wavelength measurement range from deep UV to far IR. Their main disadvantage is their poor performance for pulsed lasers.

Development in Knife-edge scanners offers the capability of accurate power measurement and for multiple scanning knife-edges the capability of beam reconstruction by Tomographic algorithms.

Camera type beam profilers will be excellent for imaging laser beams, both CW and pulsed beams, with some limitations regarding resolution, power measurement and wavelength range.

For the purpose of this article, we'll concentrate on knife-edge scanners and camera type beam profilers.

2.3 Scanning Knife-Edge Beam Profilers

Knife-edge profilers use a blocking metal strip to block an aperture, large enough to pass the entire beam. The strip's edge (knife-edge) has one sharp, straight edge. As the knife-edge scans the aperture the beam is partially blocked, and the system measures the portion of the beam that is not blocked, see figure 2. The differential change of the unblocked beam is directly proportional to the laser beam measured width.

This has several advantages, when compared to a slit or pinhole scanners. First of all, accurate power measurements of the total unblocked beam are possible. Moreover, the beam resolution is not limited by the size of the pinhole nor the slit width, so the signal-to-noise ratio is very high.

This method allows beams of a few microns to a few millimeters in diameter to be measured.

Like the slit scanner, the accuracy of a scan depends upon the geometry of the beam. For best results, the beam should be circularly symmetric and near Gaussian. To overcome this limitation, a special knife-edge / drum mechanism was developed, which scans the beam with several knife-edges, each one differently oriented on its circumference.

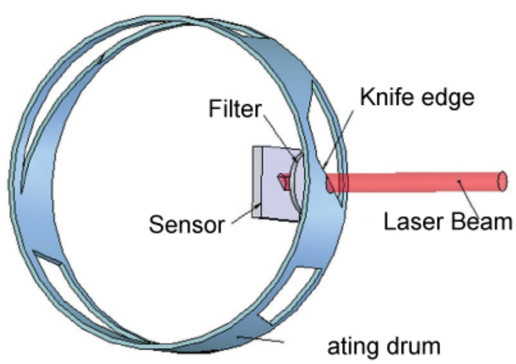

Figure 2 Simplified mechanics of a knife-edge beam profiler

As the blade is scanned across the beam, the knife-edge blocks off an increasingly larger portion of the beam power. The power sensor measures this change in power versus knife-edge position creating a power/position plot as shown below.

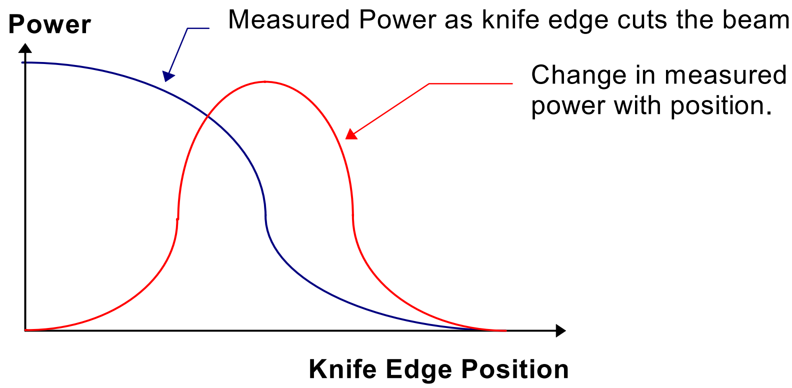

Figure 3 Profile generating by a knife-edge device

The obtained profiles from multiple knife-edges at different orientations are used to create information on 2D and 3D plots of the beam, using a mathematical process called "*Reconstructive Tomography"*.

2.4 Camera-based beam profilers

Camera-based beam profilers use a two-dimensional array of pixels as the imaging device. They sense and store the power distribution of an incoming beam as an electronic signal.

The intensity distribution of a laser beam is recorded, pixel by pixel, and displayed as either a topographic or three-dimensional contour plot.

The advantage of such profilers is that they sense in a matter similar to a photographic device, and will reveal any special structure such as hot spots, that may exist on the profile. They can display 2D and 3D plots of the beam profiles, and they can be used with both CW and pulsed lasers.

The main disadvantage of these instruments is that their measurement resolution is limited by their pixel size (usually between 5 µm and 10 µm). Additional limiting factor is their sensitivity, usually 190nm - 1100nm for other wavelength tend to be very expensive.

A new class of camera-based profiler, overcomes the minimal beam size limitation by magnifying the laser beam, in a calibrated manner, by a factor of up to 50 x.

This allows profiling of beams less than 5 µm diameter.

3. FUNDAMENTSALS OF LASER MATERIAL PROCESSING

Advances in manufacturing technology, and the trends of faster and more accurate procedures, opened the door for new metal welding and cutting applications, based on high power lasers. Laser welding and cutting technologies are now being used to replace old processes, often with increased productivity and lower overall cost.

Moreover, the demand for greater precision in high-performance applications, especially in the automotive industries, has increased the use of these lasers as a higher quality - more effective technology. Also, since laser welding and cutting is a noncontact process, metal deformation of the component parts is practically eliminated.

Of a special interest are the fiber lasers, where the good beam quality coupled with high CW power offers deep penetration welding, as well as superior metal cutting capabilities. Modulating these CW lasers achieves pulsed lasers with high peak and low average power for low heat input applications.

The fiber delivery offers flexibility to integrate into conventional weld head, Galvo heads, robotic arms and remote welding systems. Whatever the beam delivery technique is used, fiber lasers offer un-parallel performance. Keeping reliability and reproducible results, real time measurement of beam profile at its focal point is of outmost importance and a challenging task.

Laser material processing is especially sensitive to beam characteristics, and process results are strongly dependent on laser beam quality. Laser cutting and ablation characteristics, such as depth and edge quality, are determined by beam diameter and its surrounding, diffraction rings or pedestal. In laser welding the weld characteristics are dictated by material type, beam's power density and stability, depth of focus and so on. Moreover effects such as thermal lensing will directly influence beam quality and stability.

For further understanding the complexity of high power beam profiling we will shortly describe the characteristics of two main applications: **welding** and **cutting**.

3.1 Laser welding
There are many welding methods, however we will concentrate our attention on deposition welding where a filler material is applied to fill the gap between two parts.
Deposition welding is a also a useful process applied for surface finishing as well as repairing or modifying existing components.
In automated deposition welding, the machine guides the filler material to the area to be welded. After cooling, a metal layer will solidify and can be mechanically machined.

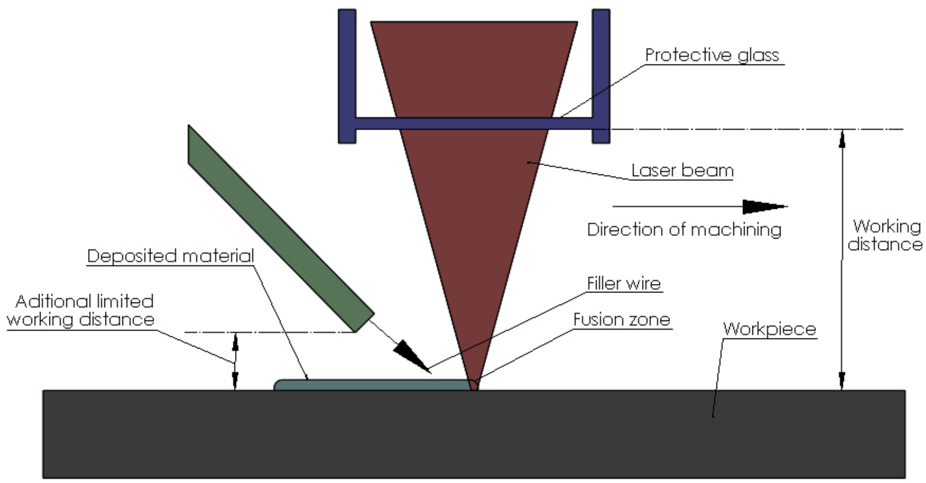

Figure 4 Describes a typical deposition welding head.
Measuring the laser beam directly in its mechanical enclosure might be very difficult due to limited working distance between protective glass and spot location. Moreover the filler wire guide will protrude into the free space between laser head and work-piece to limit the working distance even further.

3.2 Principle of laser welding
The focused laser beam strikes the filling wire and heats the material. It heats the filling material to its melting point and fuses to the surfaces to be welded or filled. Once it has completely welded or filled the work piece, the process is sustained by moving the laser head along the intended welding contour. The laser beam moves along the part contour, melting the filler material and welding as it goes.

3.3 Laser cutting
Cutting is one of the biggest applications of lasers in materials processing. The wavelength, power, beam quality and spot size are some of the parameters that determine the cutting dynamics. As for applications, pulsed lasers are used for fine cutting of thin metals and non ferrous materials, where CW lasers are used for cutting wide range of thick materials.
Ytterbium fiber lasers operating at the 1070 nm wavelength are perfect for laser cutting.

3.4 Principle of laser cutting

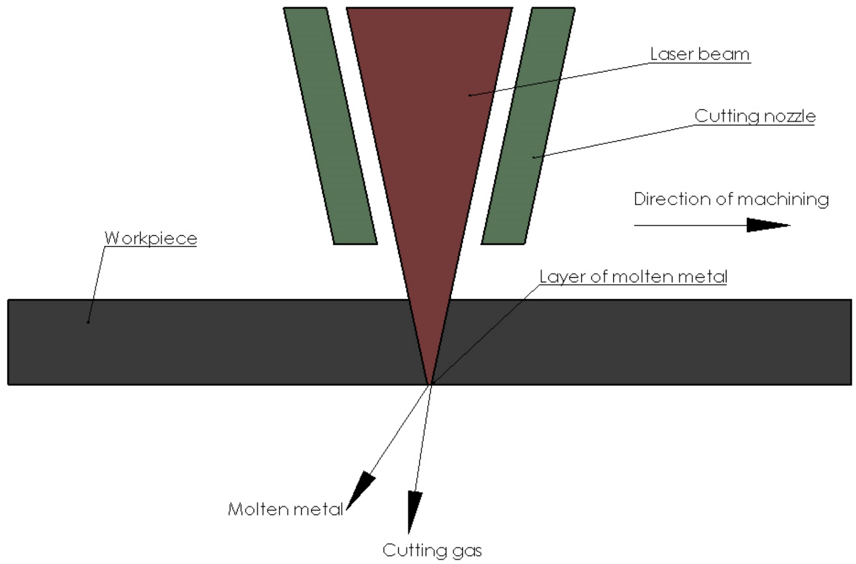

Figure 5 Describes the laser cutting procedure.

The focused laser beam incidents the work piece, heating the material to its melting point or even vaporization point. Once penetrating the work piece, the cutting process is sustained by moving the laser beam across the part contour. Usually, a pressurized gas blows the melted material downwards, out of the cut. In laser drilling, a short laser pulse melts and vaporizes the material with a high power

To summarize, the laser can handle a variety of material processing tasks. Cutting application ranges from micrometer-precise cutting joints in paper-thin semiconductor chips to quality cuts in 30-millimeter-thick steel.

4. HIGH POWER BEAM PARAMETERS MEASUREMENTS

High power laser technology has made a dramatic progress in total output power and beam quality focusing capabilities.
This progress calls for more and more difficult measurements to be implemented in order to periodic and on-line improvement of manufacturing processes.

The main parameters to be measured are:

- Total output power and its stability
- Beam size and its distribution
- Beam pointing stability
- Overall position accuracy

In today's manufacturing procedures it is not standard to measure any of the above mentioned parameters. Most of the measuring devices are not constructed for use in industrial environment, especially when on-line measurement is required. This is especially the case where high power laser measurements are involved.
Even for the most basic laser beam parameter, the optical power, measuring devices are on an acceptable standard, but their response time and mounting is inadequate for fast or on line measurements.
Most of the available measuring devices for the rest of the above parameters are not made for use with high power lasers in industrial environment. Those devices do not allow measurements at full power especially not at the focal point. They are too fragile, the handling is too complicate and the results are not reproducible.
Recent development of sophisticated non polarizing beam sampling device solves most of these obstacles, allowing real time measurements of beam parameters. The practical approach that was implemented partially samples a small part of the beam, and performs the measurement with a standard beam profiling equipment, such as a camera-based beam profiler or a scanning knife-edge beam profiler system.
Key requirements for this beam sampler element, are:

- Active cooling and aperture cleaning,
- High thermal stability,
- Non distorting sampling and constant sampling ratio, regardless of the input power .

In Figure 6 a practical measurement using a device for characterizing high power beam propagation is presented. The incoming beam is split into two parts, most of it exits the beam sampler and a small portion is directed to the sensor head. The sampled beam could be a focused beam or a parallel beam.

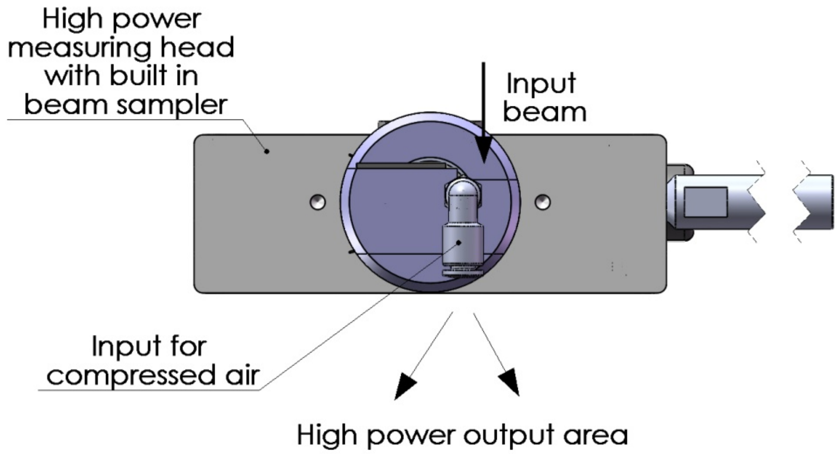

Figure 6 A multiple knife-edge measuring head equipped with custom beam sampler and compressed air cooling.

4.1 Measurement principle

The focused laser beam incidents the Beam Samplers Input aperture, where by reflected beam is sampled and its power is greatly reduced. A second reflection further reduces the beam power and restores the original beam polarization. Further on the double sampled beam reaches the detection area, as usually is done by a regular laser beam profiler. In this application we used a knife edge beam profiler made by Duma Optronics.

For CW high power measurements this will be the preferred measuring device due to its accuracy in power and multiple profile measurements. Moreover, due to its special power handling capabilities, whatever additional power attenuation is required, it can be performed without distortion based on a special attenuation configuration.

Most of the beam passes through the sampling device and strikes a Beam Dump. The sampling ratio is about .0.1% of the main beam power.

Input [W]	97	274	450	620	760	955	1030
Output [mW]	1.04	2.964	4.8	6.657	8.561	10.4	11.3

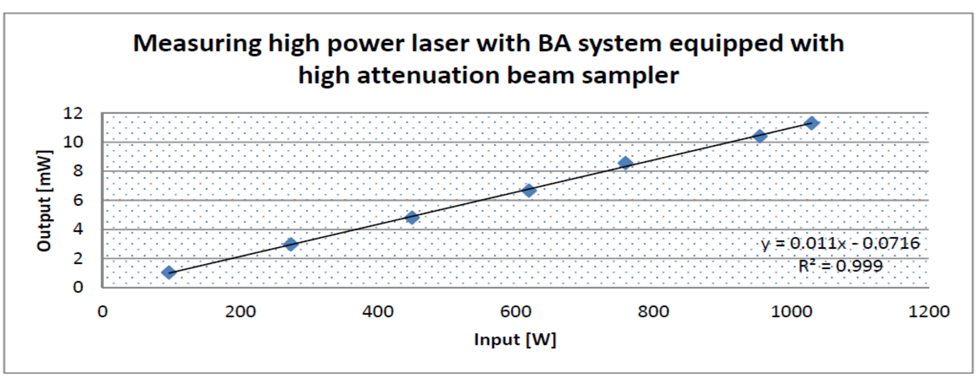

Figure 7 Test sampling ratio as a function of power for a typical beam sampler

The figure below presents a typical application, where the laser beam generated by the fiber laser is first collimated and then focused by the focusing lens. The focused beam is sampled by the laser beam sampler and presented to the knife-edge beam profiler.
Along its propagation axis, several regions can be measured by the same arrangement.
Those locations could be right after the fiber laser output, at the collimated region, or at the focal plane after the focusing lens.
Pressurized air is used to actively cool and remove excess heat from the beam sampler, as well as a mean to blow dust particles and to prevent air Thermal Lensing. A built-in cooled beam dump will prevent unwanted radiation to escape from the instrument.

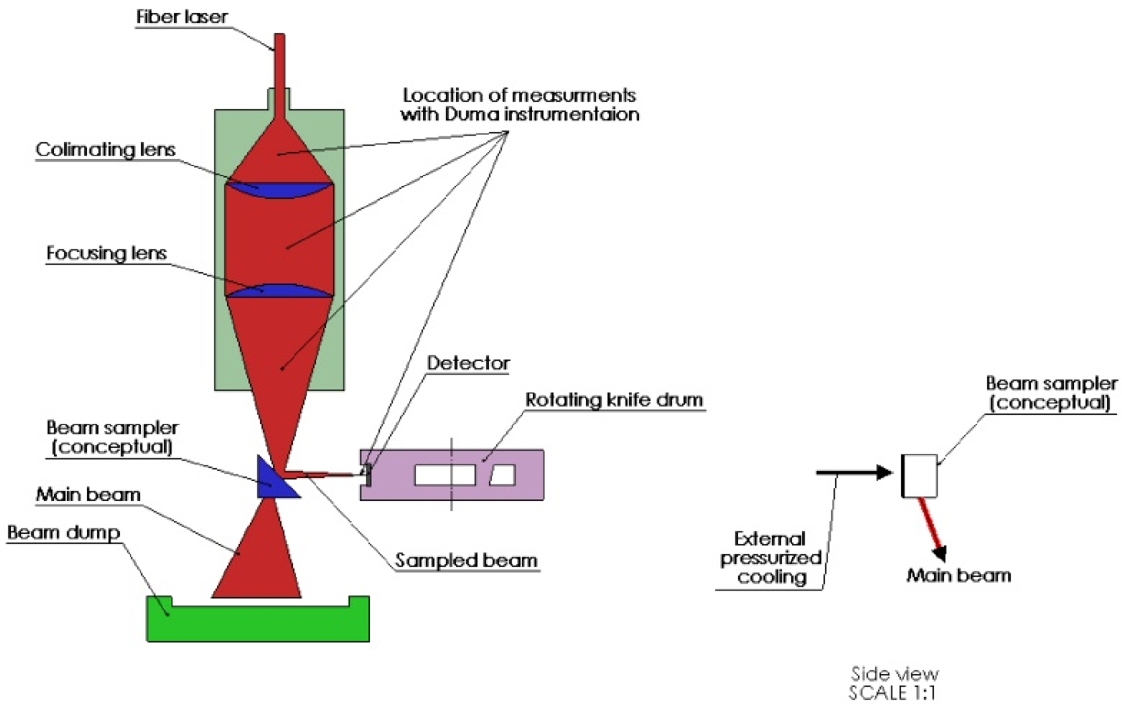

Figure 8 Schematic layout showing laser beam propagation and its measuring device
In some cases, where the work distance is limited, a different configuration as shown in figure 9 is presented. Here the beam is sampled after its focal point, however the focal point is imaged and magnified by a special objective lens to perform remote measurement.

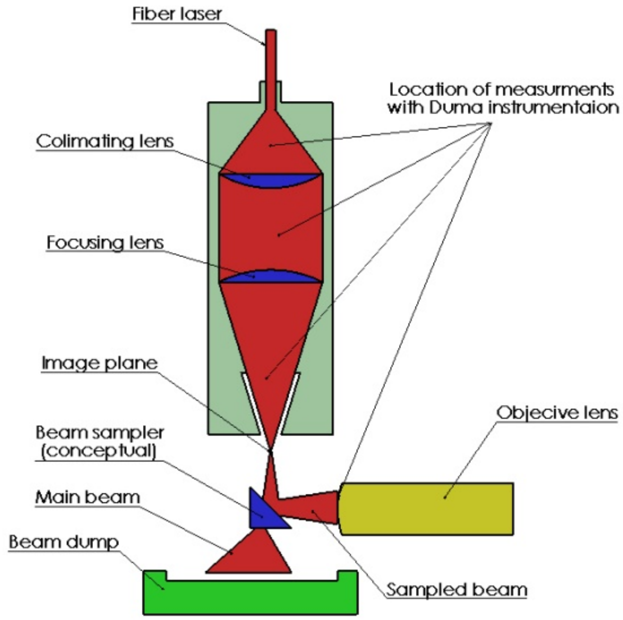

Figure 9 Schematic layout showing a typical measurement for a small work distance laser

The below figure 10 presents a typical application, where the high power laser beam profiler system can be used in a production floor. Here the robotic arm continues working on a work piece (not shown), and from time to time is directed to the beam analyzing system for power, position and profile measurement.

The configuration could be such that the measuring device is used by several robotic arms in different times. Moreover, moving the robotic arm along its Z axis, M-Squared and depth of focus values could be calculated as well.

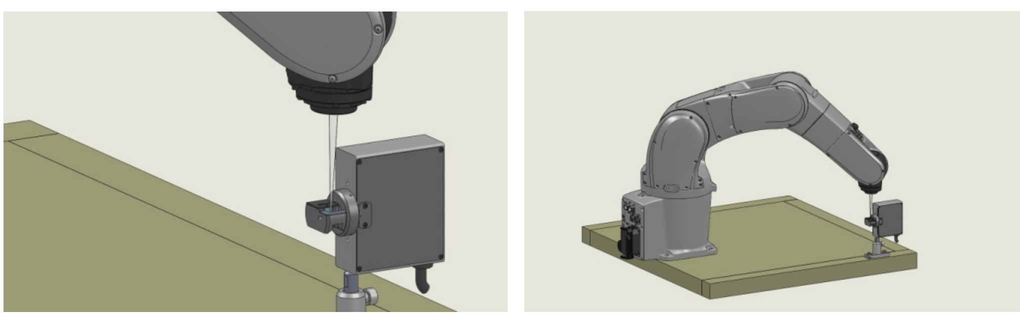
Figure 10 Beam analysis for a high power robotic laser

4.2 Actual measurement results for a 4 KW tested beam

Typical results for 4000watts measurements are presented in Figure 11. Here we see a measurement of 3921 Watt, two beam profiles in perpendicular directions, one with 559 microns and the second with 579 microns. The laser power and profile were measured from about 400 Watt to about 4000 Watt. There are several noticeable interesting things as a direct result of this measurement:

- Real time profile and power measurements at a rate of 5 times per second.
- Profiles and position were very stable during the power up procedure
- There is a significant pedestal around main lobe with about 50% percent of total power

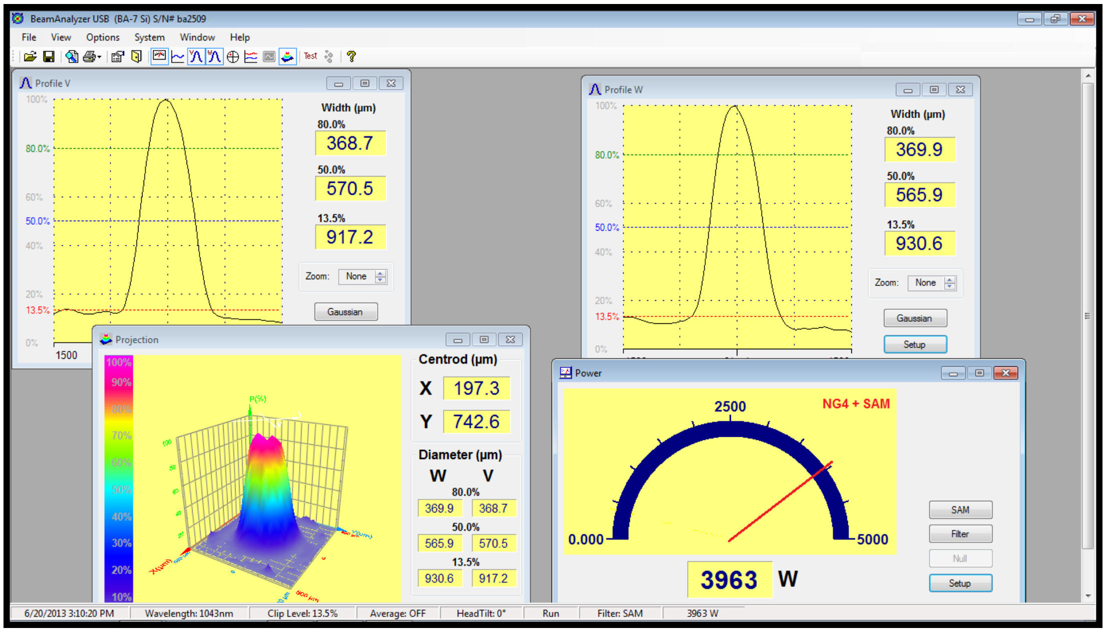

Figure 11 High Power laser beam profiler screens

5. CONCLUSIONS

A practical real time method of high power laser measurements was demonstrated.
Measurements were performed at the laser's focal point, where it matters the most.
Further development of an innovative beam sampler can lead to real time accurate measurements of 50 or even 100 Kilowatts of laser power.
Various measuring beam profilers should be adapted to measurements needs, such as power, CW or Pulsed lasers, wavelength etc. For pulsed lasers, a camera based beam profiler is advantageous over a knife-edge based beam profiler.

The performance of a high power CW or pulsed fiber-delivered laser systems has to be assessed. At powers of 4000W and up measuring the laser parameters is a taunting mission.
For best results, measurements should be performed periodically under different working environments, preferably on a manufacturing line.

Main parameters to be measured are:
- Total output power and its stability
- Beam size and its distribution
- Beam pointing stability
- Overall position accuracy

To make things even more difficult measurements should be performed fast with fast data transfer to a laser controlling computer for on line corrections.

Footnotes
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References
[1] Anthony Siegman, [Lasers], University science books, Sausalito, (1986).