# USER MANUAL

Beamage-M2 | Automated M² Measurement System

**gentec-e·o**
PARTNERS for ACCURACY

## WARRANTY

## First-Year Warranty

The Gentec-EO Beamage series beam profiler carries a one-year warranty (from the date of shipment) against material and/or workmanship defects, when used under normal operating conditions. The warranty does not cover damages related to battery leakage or misuse.

Gentec-EO Inc. will repair or replace, at Gentec-EO Inc.'s discretion, any Beamage that proves to be defective during the warranty period, except in the case of product misuse.

Any attempt by an unauthorized person to alter or repair the product voids the warranty.

The manufacturer is not liable for consequential damages of any kind.

**Contacting Gentec Electro-Optics Inc.**

In case of malfunction, contact your local Gentec-EO distributor or nearest Gentec-EO Inc. office to obtain a return authorization number. The material should be returned to:

Gentec Electro-Optics, Inc.
445, St-Jean-Baptiste Avenue, Suite 160
Québec, QC
Canada G2E 5N7

Tel: (418) 651-8003
Fax: (418) 651-1174
E-mail: service@gentec-eo.com
Website: gentec-eo.com

## CLAIMS

To obtain warranty service, contact your nearest Gentec-EO agent or send the product, with a description of the problem, and prepaid transportation and insurance, to the nearest Gentec-EO agent. Gentec-EO Inc. assumes no risk of damage during transit. Gentec-EO Inc. will, at its discretion, repair or replace the defective product free of charge or refund your purchase price. However, if Gentec-EO Inc. determines that the failure is caused by misuse, alterations, accident, or abnormal conditions of operation or handling, it would therefore not be covered by the warranty.

# SAFETY INFORMATION

Do not use a Beamage-M² if the device or the detector appears damaged, or if you suspect that a Beamage-M² is not operating properly.

**Note:**          This equipment has been tested and was found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation.  This equipment generates, uses, and can radiate radio frequency energy. If not installed and used in accordance with the instructions, it may cause harmful interference to radio communications.  However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception, which can be determined by turning the equipment off and on, try to correct the interference by taking one or more of the following steps:

- Reorient or relocate the receiving antenna.
- Increase the distance between the equipment and receiver.
- Connect the equipment to an outlet that is on a different circuit than the receiver.
- Consult the dealer or an experienced radio/TV technician for help.

**Caution:**        Changes or modifications not expressly approved in writing by Gentec-EO Inc. may void the user's authority to operate this equipment.

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# 1. BEAMAGE-M²

## 1.1. INCLUDED WITH YOUR BEAMAGE-M2

The following items are included with BEAMAGE-M2:

| Description | Part name | Part number |
|---|---|---|
| Beamage-M2 module | Beamage-M2 Module | 203616 |
| Beamage-4M camera with ND4.0 filter mounted | Beamage-4M | 202884 |
| 3 m elbowed USB-3 cable | 90° USB-3 cable | 105048 |
| USB-A to USB-B module control cable | M2 control cable | 203617 |
| Power supply 48V M2 | M2 Power Supply | 203465 |
| Fluorescent card and 85 mm alignment tube | Alignment kit | 203848 |
| 1/8" Flat head screwdriver | | |
| 3/32" L-key | | |
| 9/64" L-key | | |
| 1.5 mm L-key | | |
| Planoconvex lenses (f = 500, 400, 300, 250 and 200 mm) | | |
| Beamage-4M certificate of compliance | | |
| Beamage-M2 certificate of compliance | | |
| SM1-BNC adapter | | |
| USB stick | | |
| Pelican transport case | | |
| USB-A to USB-C adapter | USBA-C | 205915 |

## 1.2. INTRODUCTION

Gentec-EO's Beamage beam profiler now has a powerful ally in its quest towards $M^2$ measurement: The Automated $M^2$ Measurement System, Beamage-M². With its low profile and smart hardware, Beamage-M² is easy to set up on any optical table. Intended for use with a Beamage camera, equipped with a rapid translation stage, and integrated in the PC-Beamage software, an $M^2$ measurement can be done in less than 1 minute. It comes with a complete set of 2″ optics, the only one on the market allowing you to directly measure >1″ beams. No need to add uncertainties by further shrinking the beam!

The $M^2$ factor can be considered a quantitative indicator of a laser beam quality. In terms of propagation, it is an indicator of closeness to an ideal Gaussian beam at the same wavelength. Paired with a Beamage-4M beam profiling camera, the Beamage-M² module provides a very quick M² measurement directly in the PC-Beamage software.

### 1.3. SPECIFICATIONS

| M² System | Beamage-M² |
|---|---|
| Wavelength Range | 350-1100 nm |
| Attenuation Range | ND0 - ND0.5 - ND1 - ND2 - ND1.5 - ND2.5 - ND3 - ND3.5 |
| Beam Diameter Range | 55 µm to 11.3 mm (at Beamage) |
| Damage Threshold | See specifications for Beamage-4M |
| **Translation Stage** | |
| Travel Range | 200 mm |
| Effective Optical Path | 180 – 587 mm |
| Lens Focal Length | 200 mm<br>250 mm<br>300 mm<br>400 mm<br>500 mm |
| Optical Axis Height | 86 mm |
| Typical Estimated M² Accuracy (depending on the beam quality and optical configuration) | 5%<br>2% repeatability |
| Applicable Light Sources | CW and pulsed[1] |
| Typical Measurement Time | 45 sec |

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[1] Please contact Gentec-EO before using with a pulsed laser.

| Camera Specifications | See Beamage-4M manual |
|---|---|
| Sensor Technology | CMOS without cover glass |
| Pixel Dimension | 5.5 μm |
| Pixel Count | 4.2 MPixels |
| ADC | 12 bits |
| Frame Rate | See Beamage-4M Manual |
| Minimum and Maximum Exposure Time | 0.06 ms - 200 ms |
| USB Port | USB 3.0 ports for optimal performance<br>USB 2.0<br>USB-C (using the provided USB-A to USB-C adapter) |
| **General Specifications** | |
| Size | 602 mm (L) x 193 mm (W) x 172 mm (H) |
| Weight | 6.8 kg (15 lb) |
| Power Supply | 48V DC, 1.25A out |
| **Environmental** | |
| Storage Temperature | 10 °C to 60 °C |
| Storage Humidity | RH < 90% |
| Operating Temperature | 15 °C to 28 °C |
| Operating Humidity | RH < 80% (without condensation) |
| **Measurements** | |
| M-Square | $M_x^2, M_y^2$ |
| Beam Parameter Product | $BPP_x, BPP_y$ |
| Width at Waist | $w_x, w_y$ |
| Divergence angle | $\theta_x, \theta_y$ |
| Waists Location and Offset | $Z_x, Z_y, \Delta Z$ |
| Rayleigh Length | $Z_{Rx}, Z_{Ry}$ |
| Astigmatism | |

**Tip**

This guide contains the software information needed to operate the Beamage-M² automation. More information about the PC-Beamage software and interface can be found in the *Beamage User Manual*.

### 1.4. MECHANICAL DESCRIPTION

#### 1.4.1.Mechanical properties

The overall appearance of the fully assembled Beamage-M² is shown below. A casing covers the moving parts to protect them from dust and to prevent accidental misalignment of the factory-adjusted mirror (M4).



**Figure 1-1**: Assembled Automated M$^2$ Measurement System
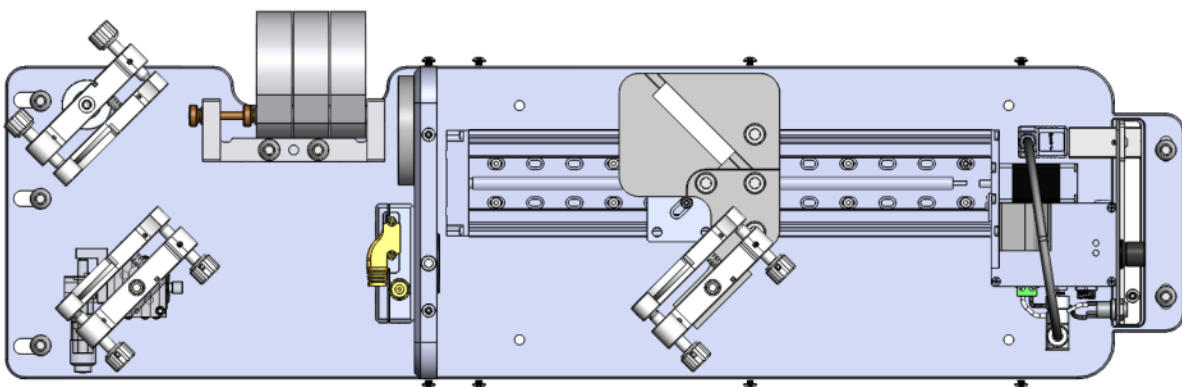


**Figure 1-2**: Complete mechanics top view

Automated M$^2$ Measurement System with the casing removed.

#10–32 Camera set screw (use 3/32" hex screwdriver)

50.40

192.60

159.83

75.60

168.81

111.83

33.35

602.49

124.46

174.04

135.94

211.82

10.16

360.31

10.16

SM2 Threaded

30.8mm Camera
Smooth bore hole

85.86

85.86

33.06

68
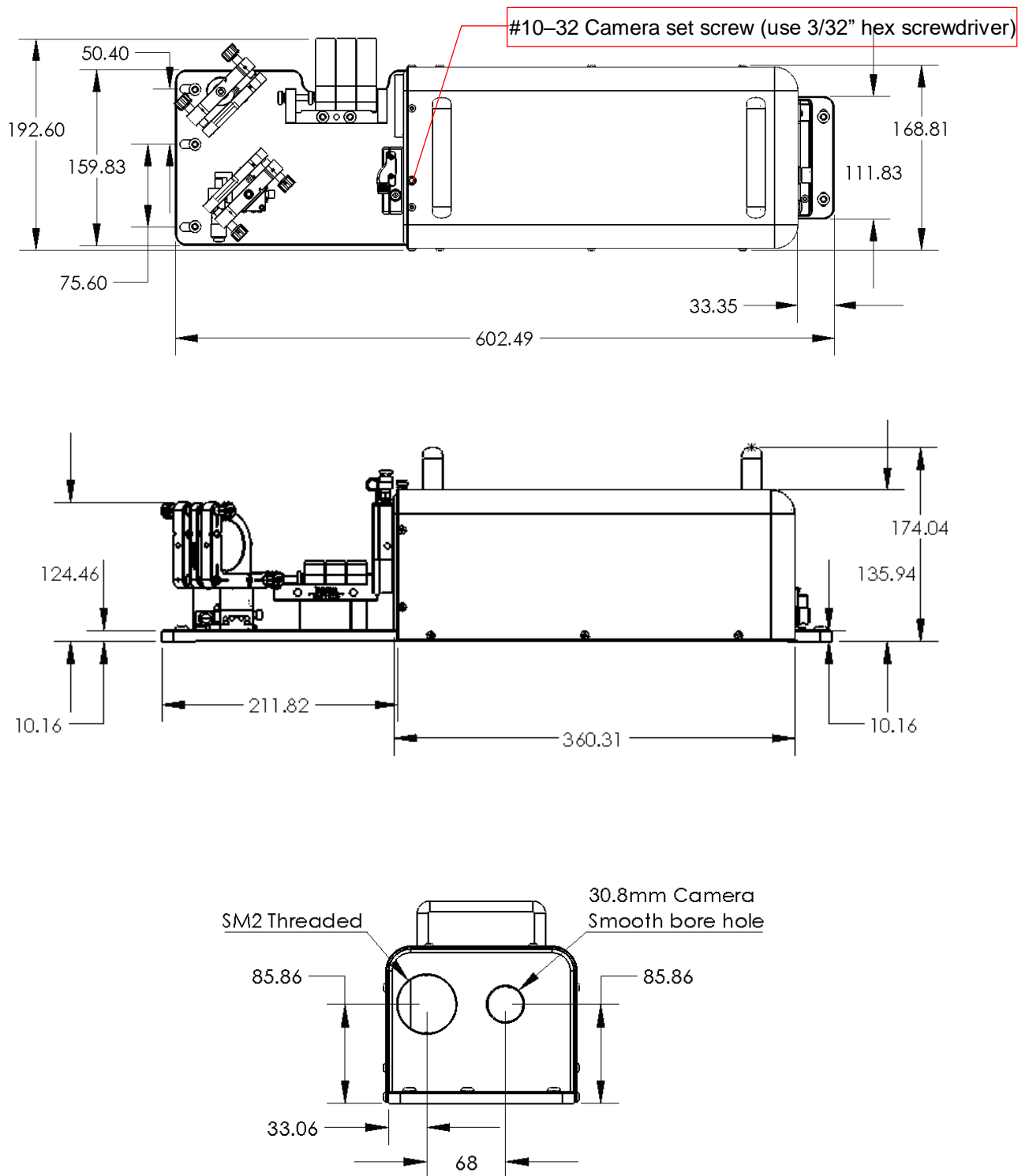
**Figure 1-3**: Beamage-M² module top, side and front view

### 1.4.2. Schematic
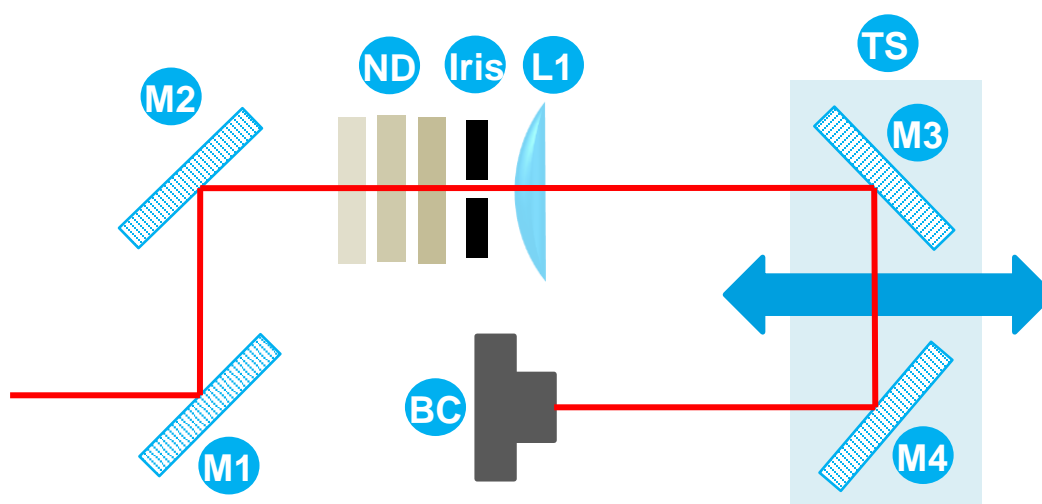


**Figure 1-4**: Automated M² Measurement System schematic

**M1**
**M2**
**Alignment mirrors**
M1 and M2 allow the user to align the beam through the lens and on the Beamage. M1 is mounted on a translation stage that allows a better centring on the mirror pair, while M2 is mounted on a fixed post. They both allow the usual "X" and "Y" angle alignment.

**ND**
**Variable neutral density filters (ND)**
Three ND filters are held in separate toggle mounts, allowing the user to rapidly change the beam attenuation factor. A sufficient attenuation factor set for the far field will usually be too weak around the focal spot for the camera to adjust its exposure time. The variable density filter eliminates the hassle of setting a cage system or multiple posts-mounted ND filters during the measurement.

**L1**
**Lens**
Five cage-mounted 2″ lenses are supplied with every M² system: 200 mm, 250 mm, 300 mm, 400 mm and 500 mm. The cages screw onto SM2 female thread.

**TS**
**Translation stage**
A 200 mm motorized rail allows a computer-controlled position of the folding mirrors (M3 and M4), which in turn allow a 400 mm beam path difference. The automation of the translation stage allowed by the software is the key to a fast measurement.

**M3**
**M4**
**Folding mirrors**
M3 is glued to the TS while M4 allows an angular adjustment. This enables the best possible beam alignment inside the translation chamber. M4 is factory-aligned.

**BC**
**Beamage camera**
A Beamage profiling camera (BC) is held in a smooth borehole by a set screw and can easily be removed when the M² measurement is completed. Use the provided 3/32" L-key to unscrew.

**Iris**
**Iris aperture**
An iris aperture is used in order to facilitate the alignment.

## 2.   BEAMAGE-M² SETUP

Before a measurement, make sure that the entire device is in good condition and ready to work. This section shows how to perform the set-up and verify that each component is working properly.

### 2.1.  MECHANICAL AND ELECTRICAL SETUP
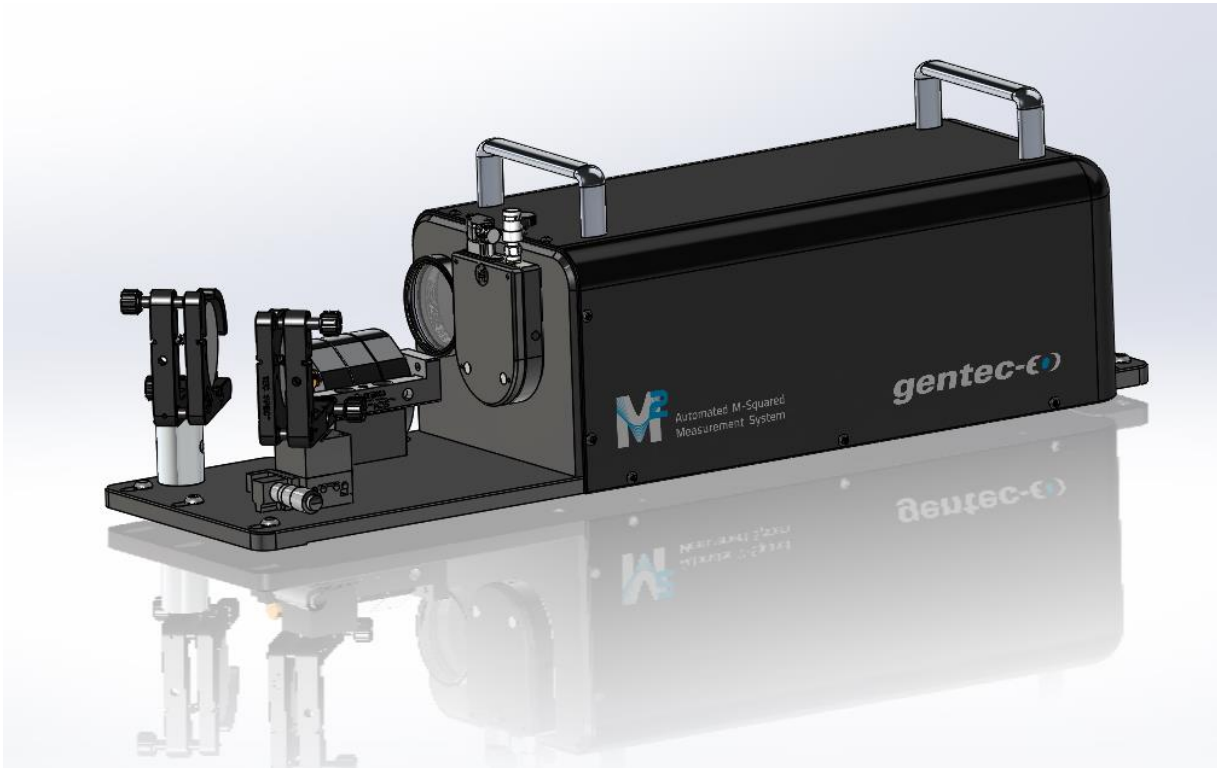


**Figure 2-1**: Complete assembly of Beamage-M² setup

1.  Make sure the Beamage-4M camera is in place as shown in the image above. The connectors must be facing upwards.

2.  Verify the focal length of the lens placed into the SM2 threaded hole.

3.  Plug the camera into a USB-3 port on your computer, equipped with the latest PC-Beamage software version.

4.  Connect the Beamage-M² rail to a USB-2 or USB-3 port. Note that the translation stage will only work with the provided USB cable.

5.  Connect the power cable to a power outlet. Upon connection, the rail should run by itself for a few seconds.

6.  Verify that the translation stage is in good working condition by turning the translation knob towards the "far" and "near" positions, respectively. "Far" and "near" refer to the position of the stage relative to the lens. Be sure to return the stage to the end of the "far" position prior to the laser alignment.

### 2.2. LASER ALIGNMENT

The first time the Beamage-M² is being used, the laser must be aligned correctly to ensure that the beam fits entirely on the camera's sensor.

The mechanics simplify this task by putting all the optics at the same height. The mirrors on the moving stage are factory-aligned so that the user should never need to adjust them. The only adjustment remaining is the entry angle, controlled by mirrors M1 and M2.

The beam must be centred on the lens and the Beamage camera at the same time; this is our success criteria.
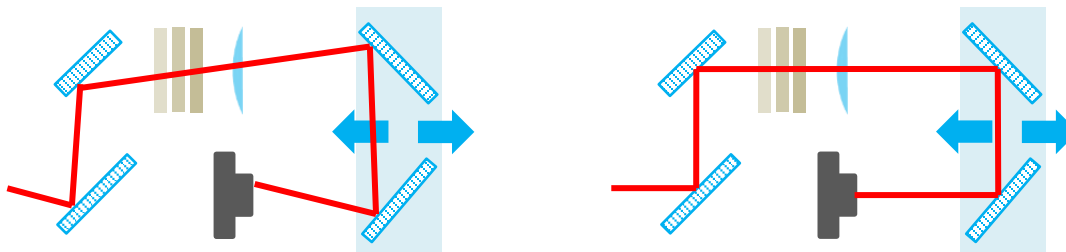


**Figure 2-2**: Bad alignment vs. good alignment.
Left side: Bad alignment, causes the beam to shift a great distance on the sensor when the stage is moving.
Right side: Good alignment, the beam is centered on both the lens and the camera.

1. Alignment:

    a. Place the Beamage-M² on an optical table.
    b. Fix at least two of the 5 anchoring points to the optical table in order to keep the module from moving during or after alignment.
    c. Install the Alignment Tube in front of the Iris (i.e., screw the tube on the Iris).
       Note: the orange surface on the disk is fluorescent from 800 nm to 1700 nm.
    d. Make sure the Beamage-M² mirrors are parallel to their mount prior to the alignment, it will make it easier.
    e. Block the output of the laser you wish to measure with the detector card or with a suitable beam blocker then turn it on.
    f. Be sure not to damage the system:
     i. If your laser beam has a power higher than 100 mW, put some attenuation in the beam path before mirror M1.
     ii. Use ND-Filters for beams with a power lower than 1 W.
     iii. Use a Beam Splitter for beams with a power higher than 1 W.
    g. Align the beam towards the center of mirror M1 while trying to have it as parallel as possible to the optical table. Use the detector card to help you align the beam from now on.
    h. Use mirror M1 to align the beam at the center of the mirror M2.
    i. Make sure the beam reaches the first disk of the alignment tube. Use mirror M1 to target the center of the disk P1 (see **Figure 2-3**)
    j. Once the beam passes through the disk P1, look through the tube's slot to find where it hits the disk P2.
    k. Use mirror M2 to center the beam on the disk P2.
    l. Repeat steps h. to k. until the beam is centred and passes through both the disks P1 and P2.
    m. Remove the alignment tube while keeping the iris in place.
    n. Turn on the PC-Beamage software, press *Start Capture* and click on *2D Display*.

o.  In the *Advanced* tab, click on the *M²* button. Two (2) new tabs open and the translation stage automatically connects to the computer.
p.  Click on the right arrow in the *Manual Settings*, this moves the stage to the farthest possible position.
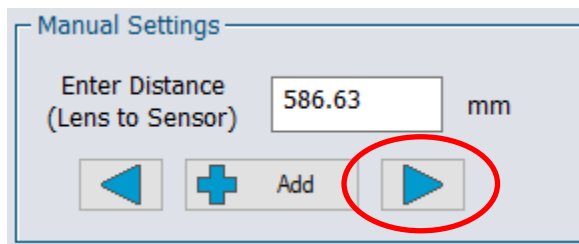


q.  Observe the beam in the *Display* screen and use mirror M2 (see **Figure 2-3:** Alignment tube) to center the beam on the sensor.
r.  Click on the left arrow in *Manual Settings*, this moves the stage to the closest possible position, then center the beam using mirror M1.
s.  Repeat steps q. to s. if needed.
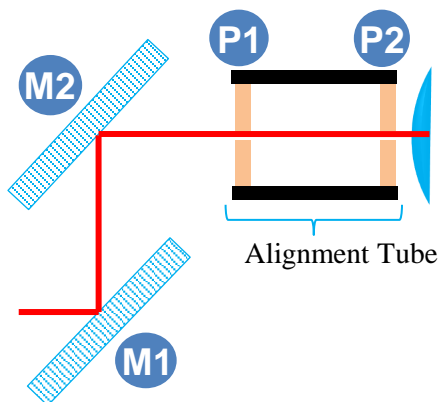


**Figure 2-3:** Alignment tube
On the left, the alignment tube mounted with its 2 fluorescent pinholes. On the right, schematics of the alignment tube with mirrors M1 and M2 aligning a laser beam.

### 2.3.  SOFTWARE AND DRIVERS SETUP

Always use the latest version of the PC-Beamage software to ensure an optimal operation of the Beamage-M² system and the most up-to-date automation features. The automatic control of the M² module requires at least the 1.04.00 version of PC-Beamage. Here, we will guide you through the software update/installation procedure. Note that the following software and firmware can also be found on the USB key provided.

1.  If PC-Beamage is already installed on your computer, the version is automatically verified at every software boot, provided you have an internet connection. The update begins automatically.

2.  Download the latest Beamage Installer at the following address:

    https://www.gentec-eo.com/resources/download-center.

3.  Click on the *Install All* button and follow the installation instructions.
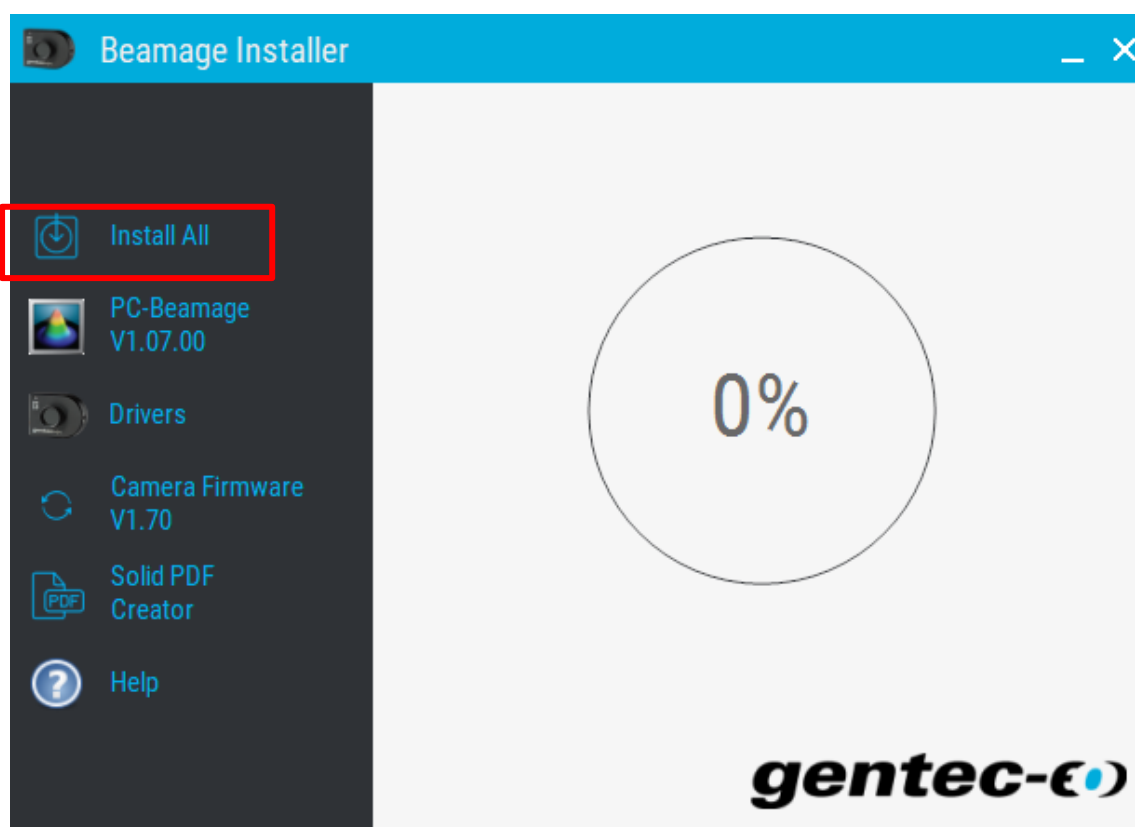


**Figure 2-4**: Beamage Installer

💡 **Tip**

By pressing the *Install All* button, you will install the latest version of the PC-Beamage software, the Beamage driver and the driver for the translation stage.

# 3. QUICK M² MEASUREMENT

1. Start-up the PC-Beamage software.



**Figure 3-1**: PC-Beamage logo

2. Select the serial number of the camera recognized on the *Beamage Selector* pop-up; click *OK*.
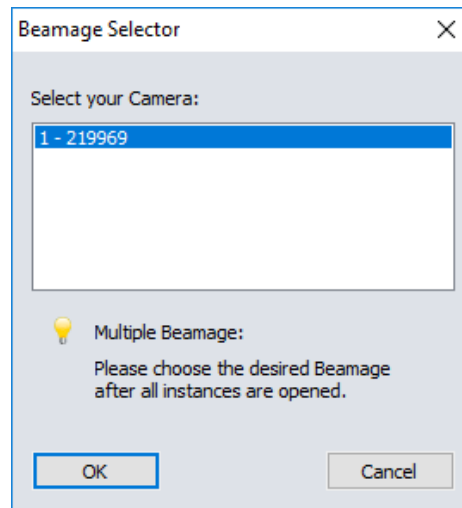


**Figure 3-2**: Beamage camera selector pop-up

3. Turn on the laser you want to measure and make sure it is aligned according to section 2.2.

4. In the software, under the *Advanced* tab, click the *M²* button to activate the M² measurement functions and the tabs *M² Results* and *M² Setup*.
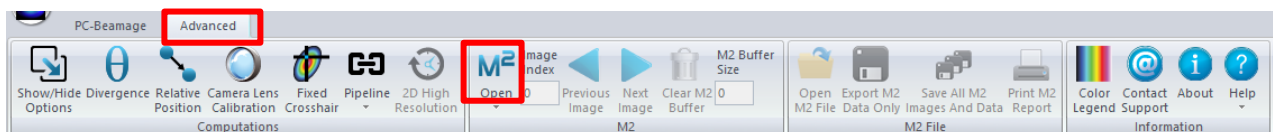


**Figure 3-3**: Software setup: step 4

**5.** Under *M² Setup*, fill in the *Laser Wavelength* and *Focal Length* fields.
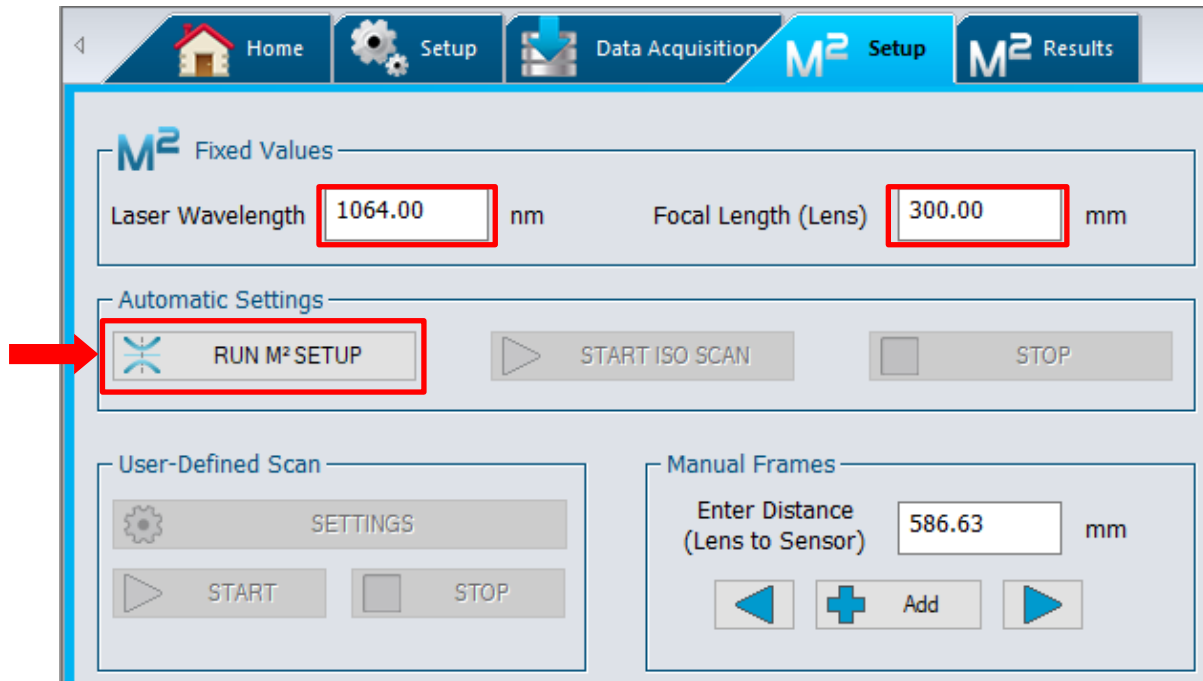


**Figure 3-4**: Software setup: step 5.

**6.** Click *RUN M² SETUP*.

**7.** Click *Yes* to automatically start an M² measurement once the *SETUP* phase is completed.
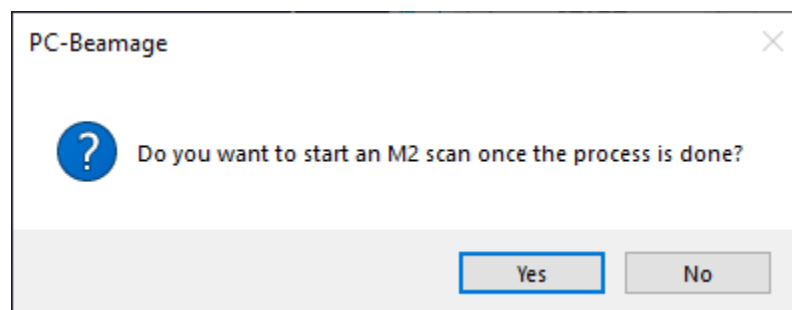


**Figure 3-5:** Select the action following the setup phase

**8.** Execute the tasks required to obtain good measurement conditions during the setup phase. The software might show pop-up windows when one of the following actions is required:

  a. Change lens

  b. Add attenuation

  c. Remove attenuation

9. Block the laser beam when the following pop-up appears:
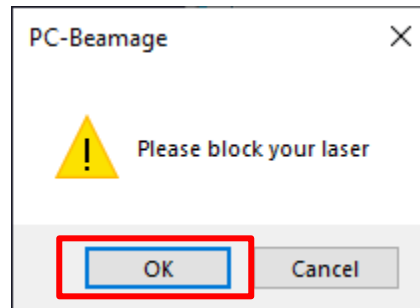


**Figure 3-6:** Software requires the laser beam to be blocked to execute the background noise subtraction

10. Release the laser blocking once the *Please block your laser* pop-up disappears to let the Beamage-M² device execute an automatic measurement.

11. Once the measurement is done, a window pops up. Press *OK* to reach the results tab.
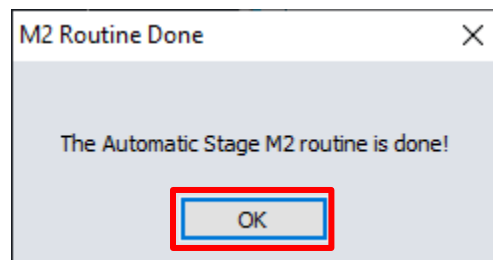


**Figure 3-7**: *M² routine done* prompt

# 4. THEORY

## 4.1. UNDERSTANDING THE M² FACTOR

The M² factor, which is unit-less, can be considered a quantitative indicator of a laser beam quality. It indicates the deviation of the measured beam from a theoretical Gaussian beam of the same wavelength. It can be mathematically defined as the ratio between the Beam Parameter Product (beam waist radius $w_0$ multiplied by divergence half-angle θ) of the measured beam with the theoretical Gaussian beam. Thus, for a single mode ideal TEM$_{00}$ theoretical Gaussian beam, the M² factor is exactly one. Since an ideal Gaussian beam diverges more slowly than any other beam, the M² value is always greater than one. An M² value very close to 1 indicates an excellent beam quality. This is associated with a low divergence and a good ability to focus. Multimode lasers have higher M² factors.

### 4.1.1. Propagation Parameters

*In the following equations, "th" refers to theoretical values and "exp" to experimental or real values.*

The beam waist is defined as the location along the beam propagation axis where the beam radius reaches its minimum value (see **Figure 4-1**). For a theoretical Gaussian beam, the beam radius $w_{th}(z)$ at any position $z$ along the beam axis is given by the following equation[1]:

$$w_{th}(z) = w_0 \sqrt{1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$

where $\lambda$ is the laser wavelength and $w_{0th}$, the theoretical beam waist radius.

As depicted in **Figure 4-1**, the theoretical Rayleigh Length $z_{R\,th}$ is the distance (along the propagation axis) between the beam waist and the position where the beam radius is $\sqrt{2}$ times larger than the beam waist (doubled cross-section).
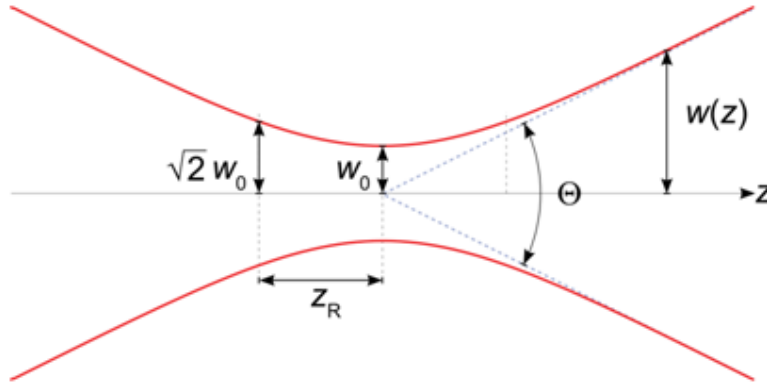


**Figure 4-1**: Gaussian beam parameters

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[1] Siegman, A. E., 1993. Defining, measuring, and optimizing laser beam quality. *Proceedings of SPIE, Volume 1868*, pp. 2-12.

Mathematically, it is given by the following equation:

$$z_{R\,th} = \frac{\pi\left(w_{0_{th}}\right)^2}{\lambda}$$

Far from the beam waist, the beam expansion becomes linear and the theoretical divergence half-angle $\theta_{th}$ (half of the angle shown in **Figure 4-1**) can be obtained by evaluating the limit of the beam radius's first derivative as the position tends towards infinity:

$$\theta_{th} = \lim_{z\to\infty}\frac{dw_{th}(z)}{dz} = \lim_{z\to\infty}\frac{d}{dz}w_{0th}\sqrt{1+\left(\frac{\lambda z}{\pi\left(w_{0_{th}}\right)^2}\right)^2} = \frac{\lambda}{\pi w_{0th}}$$

For a laser beam that passes through a focusing lens of focal length $f$, the theoretical radius of the beam $w_{fth}$ at the focal spot of the lens can be obtained by multiplying the beam divergence half-angle with the focal length $f$:

$$w_{f_{th}} = f\theta_{th} = \frac{f\lambda}{\pi w_{0th}}$$

As mentioned, all of the equations above describe theoretical ideal Gaussian beams. However, they can describe the propagation of real laser beams if we modify them slightly using the M² factor, which can be mathematically defined by the following equations:

$$M^2 = \frac{\pi\theta_{exp}w_{0exp}}{\lambda} = \frac{\theta_{exp}w_{0exp}}{\Theta_{th}\,w_{0th}} > 1 \quad because \quad \theta_{exp}w_{0exp} > \frac{\lambda}{\pi} = \Theta_{th}\,w_{0th}$$

With mathematics, it is easy to understand why small M² values correspond to low experimental divergences and small experimental beam waist radiuses.

The experimental beam waist radius $w_{exp}(z)$, the experimental half-angle divergence $\theta_{exp}$, and the experimental beam radius at the focal spot of the lens $w_{f_{exp}}$ are therefore given by the following equations:

$$w_{exp}(z) = w_{0th}\sqrt{M^2 + M^2\left(\frac{\lambda z}{\pi\left(w_{0_{th}}\right)^2}\right)^2}$$

$$\theta_{exp} = \frac{M^2\lambda}{\pi w_{0_{exp}}}$$

$$w_{f\,exp} = f\theta_{exp} = \frac{fM^2\lambda}{\pi w_{0_{exp}}}$$

### 4.1.2.Practical Measurement

In order to measure the M² factor, multiple slices of the beam within and beyond one Rayleigh Length along the propagation axis must be considered (see **Figure 4-2**). For each one, the second order spatial moment beam radius $w(z)$ is measured. A hyperbola, which recalls the beam radius equation, is then fitted with the results. The M² value is derived from that fit.
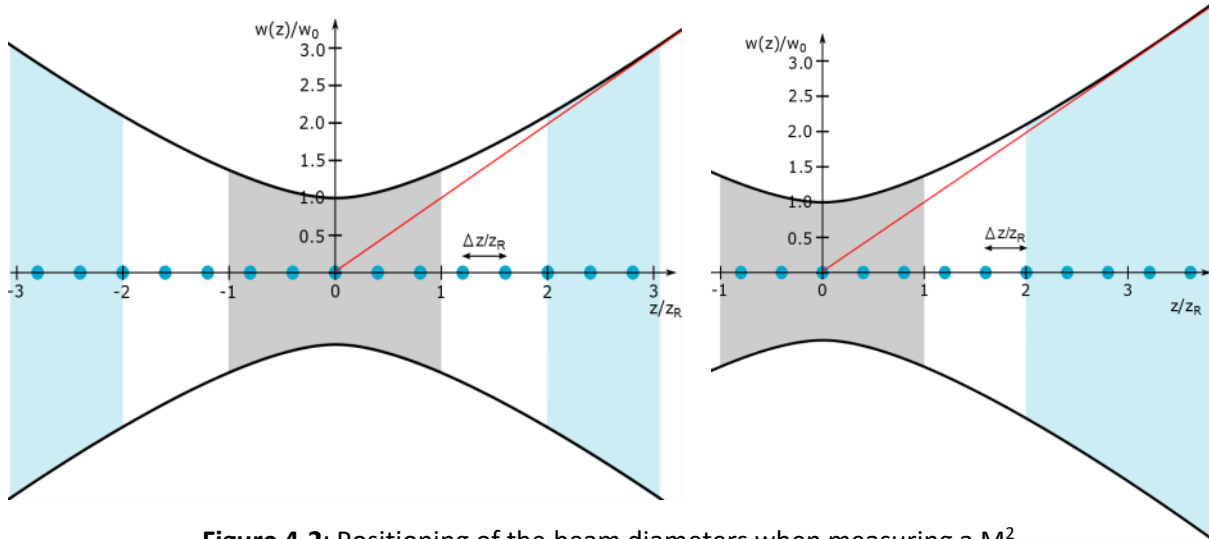


**Figure 4-2**: Positioning of the beam diameters when measuring a M²

**Left**: Five (5) beam diameters are taken in the focal region and three (3) beam diameters are taken at the far field on each side of the caustic. **Right**: Five (5) beam diameters are taken in the focal region and five (5) more beyond $2z_R$ on one side only. The grey zone is the focal region, between $-z_R$ and $+z_R$, the blue zones are for far field measurements and the white regions are the non-essential measurement zones. Blue dots represent the position along the Z axis where beam diameters are measured.

Since the distance range within which the measurements must be taken is too large (could be several meters), the use of a focusing lens is mandatory. It is also mandatory to comply with ISO standard. It helps to compress the slices of interest around the focal spot of the lens.

Please refer to ISO-11146 for more information.

# 5. M² MEASUREMENT CONTROLS

The controls allowing an M² measurement are toggled by clicking on the *M²* button, under the *Advanced* tab. It also adds an *M²* display button.
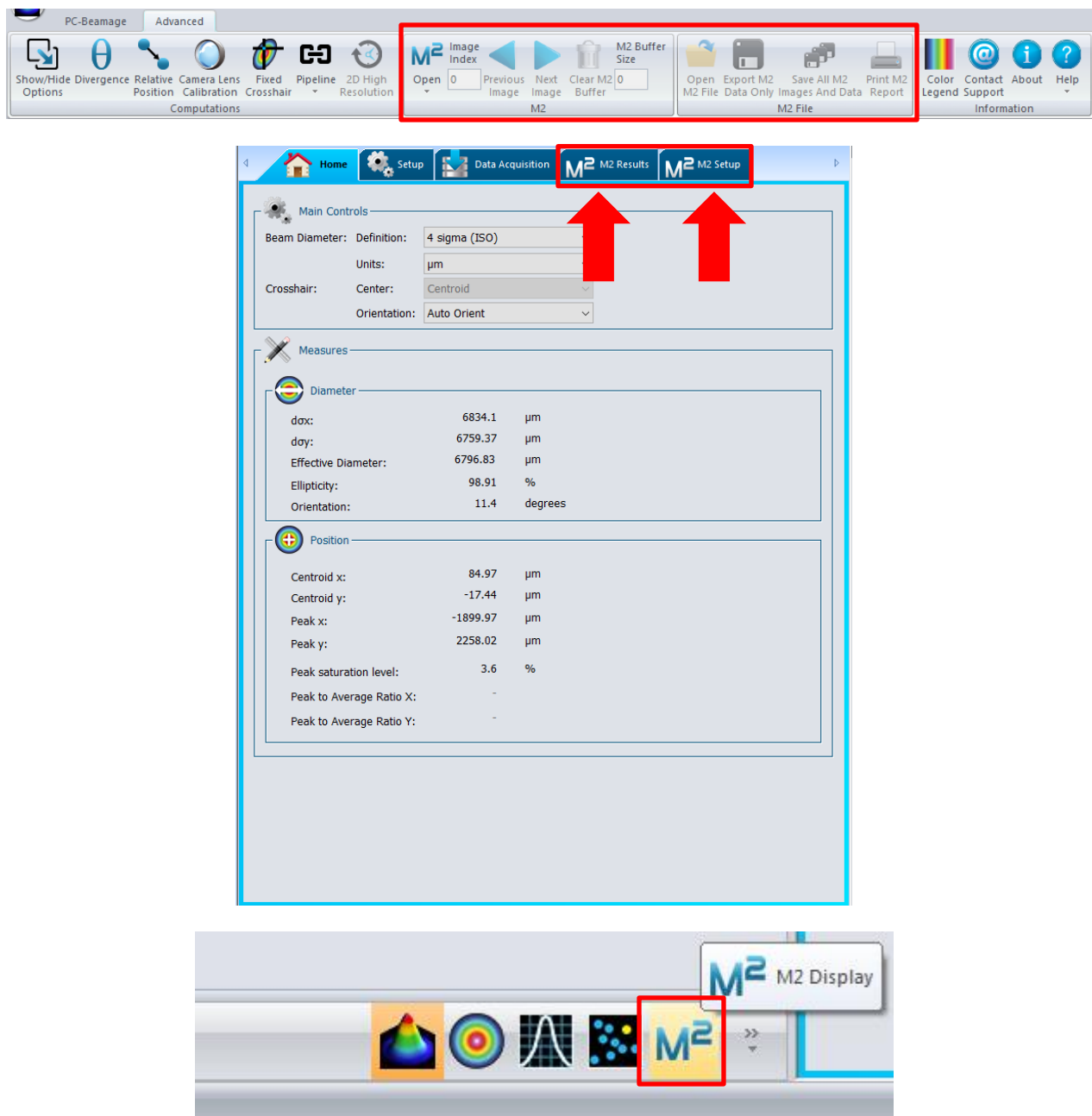


**Figure 5-1**: M² main control buttons

### 5.1. M² IMAGES CONTROLS

The PC-Beamage software saves the images of each beam slice on the hard drive of your computer. These images facilitate the analysis of the results by allowing the user to consult them once the measurement is completed.
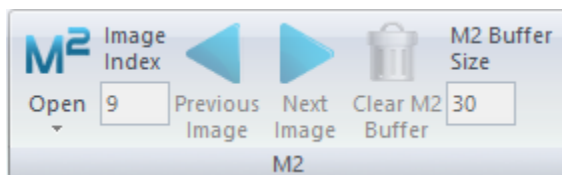


**Figure 5-2:** M² Images controls



**Tip**

The PC-Beamage Software provides an automatic management of the *.bmg files saved on the hard drive which will be used for the calculation of M². These files will be deleted every time the application starts up or every time you use the "Clear all" button.

#### 5.1.1. *M²* button

The *M²* button activates the M² mode by giving access to the *M² Results* and *M² Setup* panels. By default, the *M²* button is inactive. Upon successful connection, the stage will move the carrier to the "far" end of the rail (far from the lens), and the other buttons will become clickable.
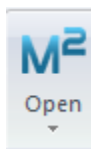


**Figure 5-3:** *M²* button



**Tip**

It is not necessary to have a connected camera to use the M² mode. For more information, please see the "*load a *.m2man file*" section.

### 5.1.2. *M² Advanced* button

The *M² Advanced* button, under the *M² Open* button, activates the advanced M² mode. This mode can be used to measure the M² factor of nearly Gaussian laser beams. It must be used carefully as it can return erroneous values if the beam undergoes many modifications along its path. As most of the measured beams emerge from laser systems in which beams are transformed in many ways, ones most likely measures the M² factor of laser systems rather than laser beams. For this reason, by default, the *M² Advanced* button is inactive.



**Figure 5-4:** *M² Advanced* button

### 5.1.3. Image index

The *Image Index* edit box displays the current image index in reference to the beam data list (see **Figure 5-29:** Data Box). When the Beamage is not streaming, it is possible to access different frames by typing the desired image index.
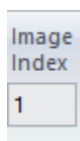


**Figure 5-5:** Image Index

### 5.1.4. *Previous Image* and *Next Image* buttons

The *Next Image* and *Previous Image* buttons access the next and previous images of the list containing M² measurements.
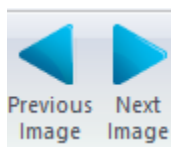


**Figure 5-6:** *Previous Image* and *Next Image* buttons

### 5.1.5. *Clear M² Buffer* button

The *Clear M² Buffer* erases all the beam slices currently stored into the *Data* box. It will also delete the current M² calculations executed from the data being erased.
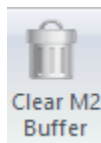


**Figure 5-7:** Clear M² Buffer

### 5.1.6. *M² Buffer Size*

The *M² Buffer Size* displays the number of images stored on the list containing $M^2$ measurements. By default, the $M^2$ buffer size is 1. The $M^2$ buffer size dynamically increases every time a new beam measurement is added to the list regrouping $M^2$ beam data.
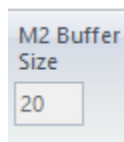


**Figure 5-8:** M² Buffer Size

### 5.2. M² FILE CONTROLS
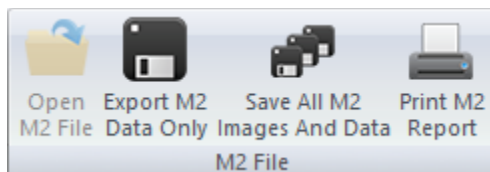


**Figure 5-9:** M² File Controls

M² File controls allow the user to save a current measurement for further use, load a previously saved set of data or generate a print report of a measurement.

### 5.2.1. Open M² File

Load an *.m2geo file containing the complete information of a saved $M^2$ measurement: the beams and the images that correspond to these measurements will be loaded. This process can take several seconds.

The PC-Beamage Software uses hard drive space to load the *.m2geo files that contain M² measurement information; if your hard drive has less than 20% of its total capacity available, a pop-up window will appear, notifying this information. Press OK to keep on using the PC-Beamage software (see **Figure 5-11**).
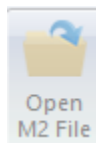


**Figure 5-10:** Open M² File
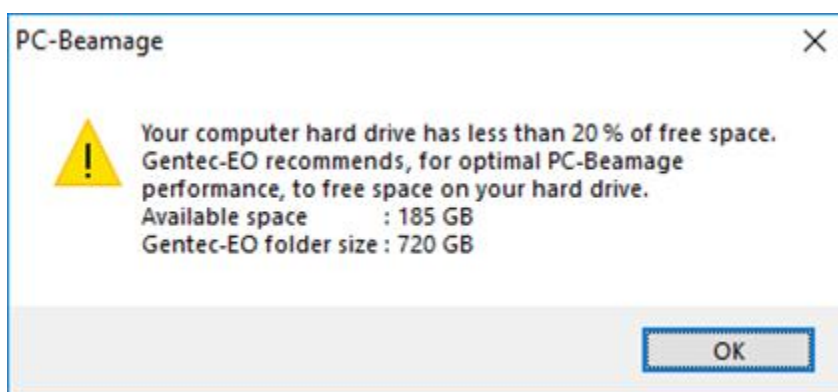


**Figure 5-11:** Less than 20% of available space on the hard disk

If your hard drive has less than 10% of its total capacity available, a pop-up window will appear, notifying this information. Press OK to keep on using the PC-Beamage software (see Figure 5-12).
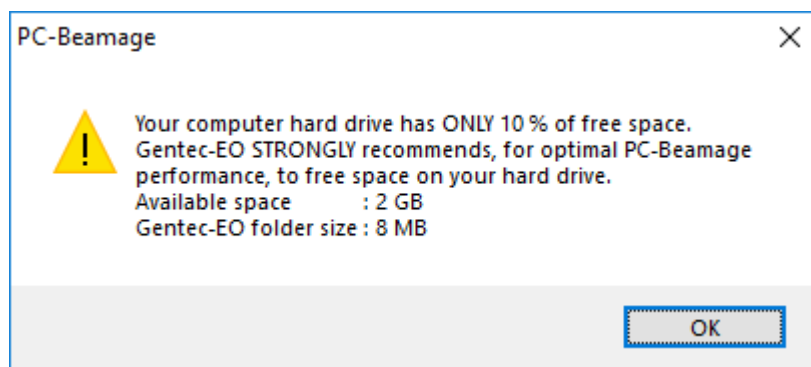


**Figure 5-12:** Less than 10% of available space on the hard disk

But, if your hard drive has less than 255 Mb of available space, a pop-up window will appear, notifying this information. You should free some space on your hard drive to continue to save or load a file. This includes * .m2geo files, * .m2man files and * .bmg files (see **Figure 5-13**).
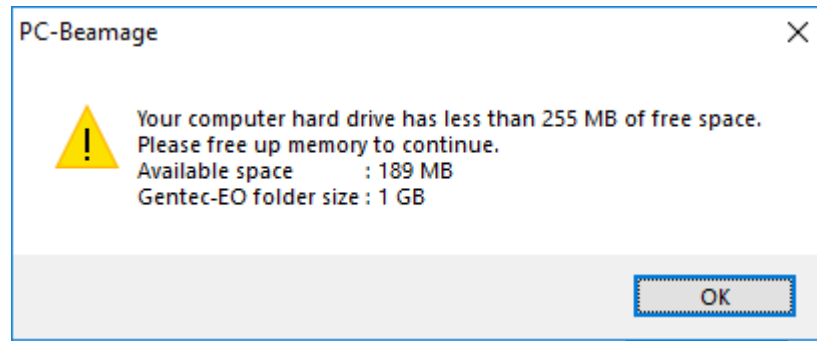
**Figure 5-13:** Less than 255 Mb of available space on the hard disk

 **Warning**

- You will be notified when you start the PC-Beamage software and you will have a notification when you press on the load button as well as each time that you restart the PC-Beamage software. If you receive this message, please free up some hard drive space to avoid errors during recording.
- After loading a file, the *Load* button becomes unavailable. To load another *.m2geo or *.m2man file, press the *Clear All* button and then the *Load* button.

### 5.2.2. *Export M² Data Only* button

Exports all the calculated and measured M² data as a *.txt file that can be used in an Excel spreadsheet. The file contains the following information:

- Measurement parameters:
    - Wavelength of the laser beam
    - Focal length of the lens
    - Diameter definition mode
    - Diameter orientation mode
- Interpolated values in X and Y axis:
    - z0
    - d0
    - ZR
    - Divergence
    - Delta Z
    - Astigmatism
    - BPP
    - M²
- Beam slices data:
    - Beam number
    - Distance along Z axis (propagation)
    - X diameter
    - Y diameter
    - Exposure time
    - Beam orientation (degrees)
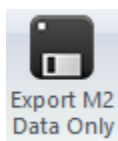


**Figure 5-14:** *Export M² Data Only* button

### 5.2.3. *Save All M² Images and Data* button

Creates an *.m2geo file containing a complete set of beam slices and their data. Such a file allows the reconstruction of a complete measurement. This process can take several seconds.
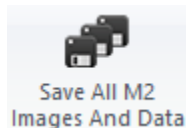


**Figure 5-15:** *Save All M² Images and Data* button

### 5.2.4. *Print M² Report* button

A customized print report has been created for the **M²** mode.
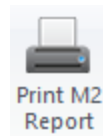


**Figure 5-16:** *Print M² Report* button
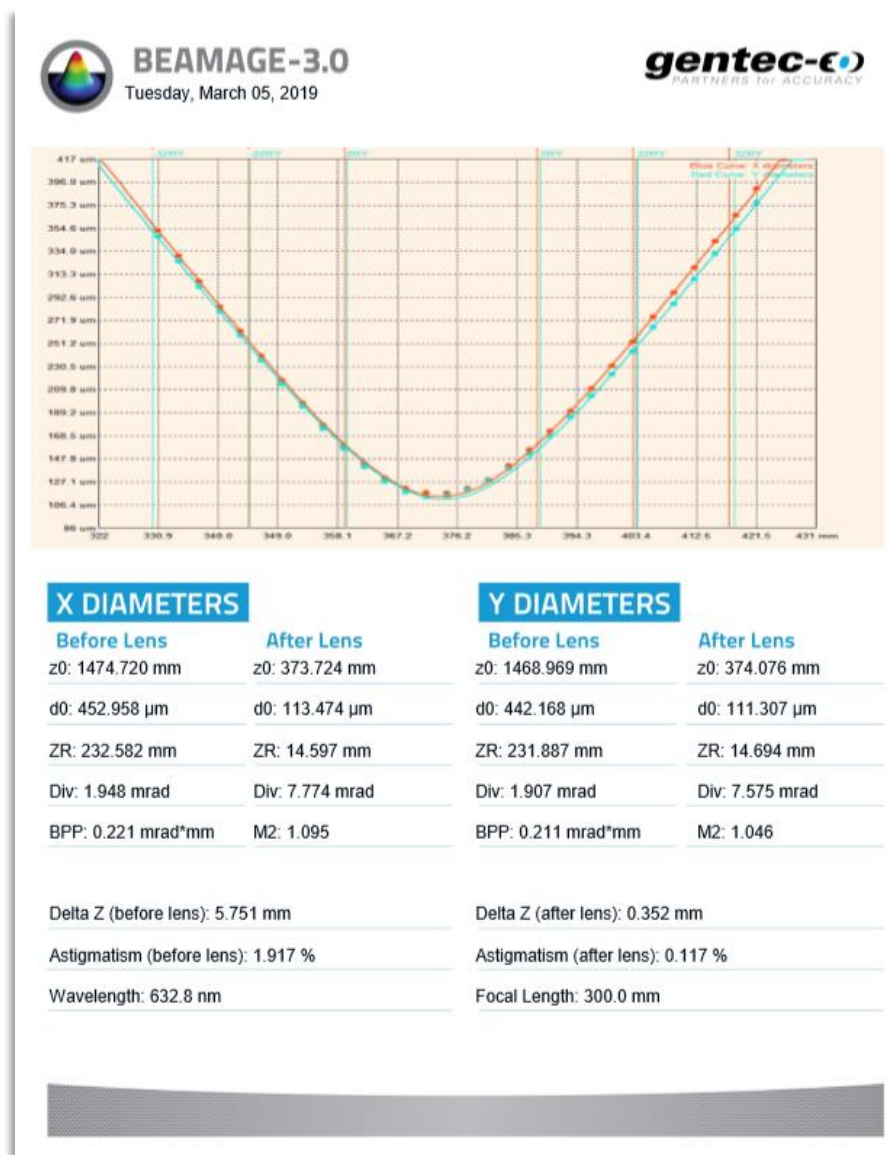


**Figure 5-17:** M² print report


**Tip**

You can print the M² report even without a connected Beamage camera.
Just load a * .m2geo file and press the *Print M² Report* button.

**5.3. M² SETUP TAB**

The *M² Setup* tab allows you to control the beam path length for every spot size you need to measure.



**Figure 5-18**: *M² Setup* tab
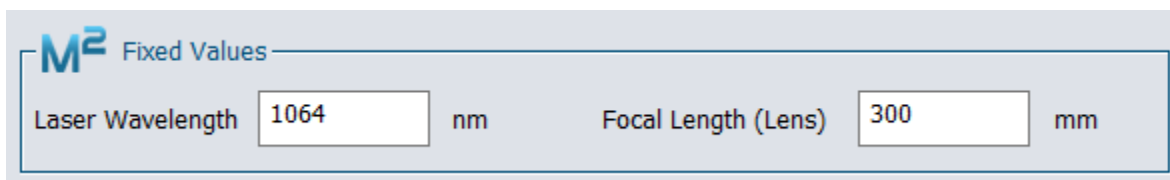
- $M^2$ Fixed Values : Input fields required for identifying the laser and lens used in order to obtain correct calculations.
- Automatic Settings : Simplified automatic data acquisition. These buttons trigger the automatic data acquisition algorithms for rapid M² measurement or ISO measurement from existing data.
- User-Defined Scan : Section allowing a user to manually define several data points and their measurement domain along the propagation axis.
- Manual Frames : Allows manual data collection and/or provides you with a method for adding points that were not included in the automatic scan.
- Data : Section used to manage the data. You can delete some or all of the current data, sort them and calculate the M² value of a modified/new data set.

### 5.3.1. M² Fixed Values

As seen in Section 4 (Theory), the wavelength of the laser plays a crucial role in the calculation of the waist position and minimal beam radius ($w_0$). Note that if you change the laser and/or the lens, it is necessary to update these values manually.

To do so, just click the on the corresponding field and change the required values, keeping in mind that the wavelength is expressed in nanometers ($10^{-9}$ m) and the focal length in millimeters ($10^{-3}$ m).

By default, the wavelength value is 1064 nm and the focal length value is 300 mm.



**Figure 5-19**: Fixed parameters

### 5.3.2. Automatic Settings

RUN M² SETUP: Triggers a fast measurement with 10 data points to estimate values such as the beam waist width and location. This automation will also check whether the lens and/or the attenuation values need to be modified in order to execute the proper background subtraction and will pop messages accordingly. The user is prompted to block the laser beam before the M² measurement starts.
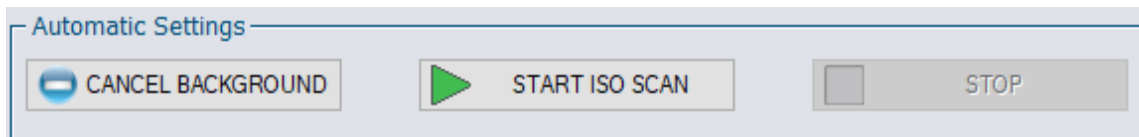


START ISO SCAN: Becomes clickable once a first M² value is calculated. This function erases all the data from the *Data* section and begins a new 30 points measurement on the calculated $-3.5zR$ to $+3.5zR$ domain along the propagation axis, using the background subtraction pattern determined from the *RUN M² SETUP* routine. The *START ISO SCAN* function is useful for data points captured far beyond $\pm 3zR$ OR when fewer than 5 data points are found between $-zR$ and $zR$.

CANCEL BACKGROUND: Is shown instead of *RUN M² SETUP* if any background subtraction is currently applied. Using *CANCEL BACKGROUND* cancels the actual noise subtractions and allows the capture of a new background noise pattern.

STOP: Stops a running algorithm. It becomes active when an algorithm is running.

### 5.3.3. User-Defined Scan

*User-Defined Scan* is employed to set the optical path lengths at which beam slices are to be measured by the Beamage-M² measurement system. Note that a background subtraction must be executed before the *User-Defined Scan* buttons can be used.
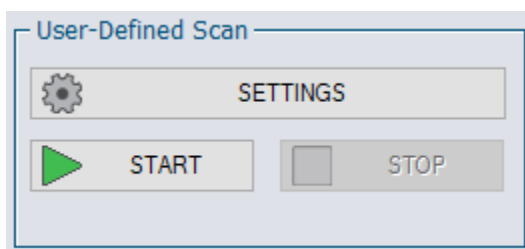


**Figure 5-20**: Translation stage user-defined scan controls

**Settings button**

Displays the *Stage Settings* window which allows the setting of the *Specified Distance,* which possesses a default value of 14.0 mm, or *Specified Step*, which presents a default value of 30 steps. Also allows setting the *Start Position,* which has as default value 180.23 mm, and *Stop Position*, with a default value 586.63 mm. All data points acquired via the *Stage Settings* window are added to the existing data set.
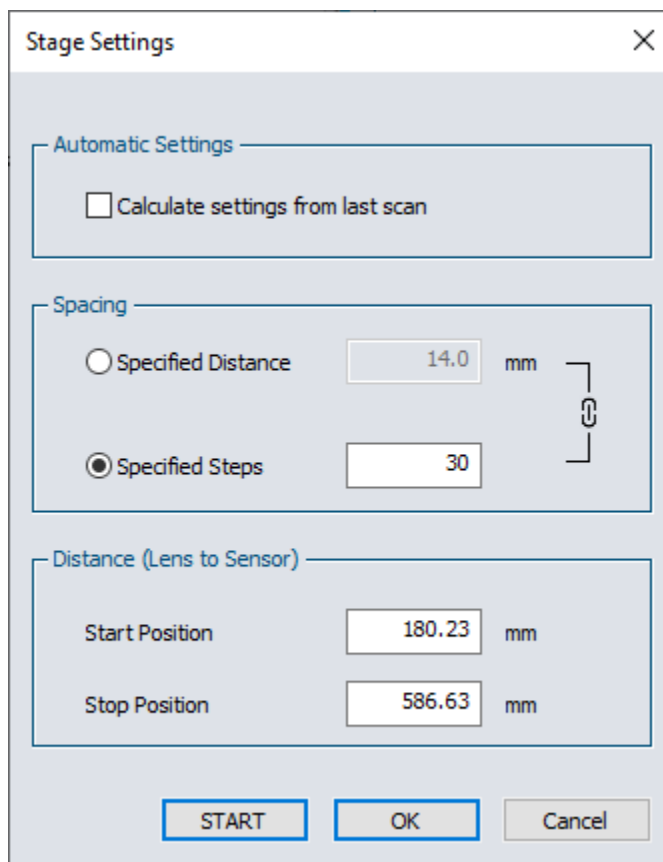


**Figure 5-21**: *Stage Settings* window

- The **Automatic Settings** checkbox, when activated, uses $-3.5zR$ and $+3.5zR$ values calculated from the last data set as the *Start Position* and *Stop Position* inputs for a next measurement.

- The **Spacing** options let you choose whether you prefer to have a **Specified Distance** between two measurements or a specific number of steps (**Specified Steps**) in the chosen interval.

- The **Distance (Lens to Sensor)** determines the limits of the carrier's travel and is expressed in millimetres. A short $Z_R$ value brings the **Start Position** and the **Stop Position** closer to the beam waist position $Z_0$ in order to capture a "zoomed" measurement. It prevents problems such as a highly diverging beam being too big for the sensor.

- The **Start** button starts an M² measurement using the parameters from the window.

- The **OK** button saves the current settings without starting a measurement.

- The **Cancel** button ignores the modified values from the fields

- 

### *Start* button

Quick starts an M² measurement using the parameters from the stage settings. The beam slices will be added to those already recorded without erasing any acquired data.



**Figure 5-22:** *Start* button

### *Stop* button

Stops a running M² measurement. The button is only active when the translation stage moves.



**Figure 5-23:** *Stop* button



> When you press the *Stop* button, the current process stops. If you press the *Start* button again, the measurements will start over from the beginning.

### *Events following a measurement*

At the end of a scan, a window pops up. Click the *OK* button to force the calculation of the beam parameters based on the acquired data; PC-Beamage switches to **M² Results** tab and **M²** display.
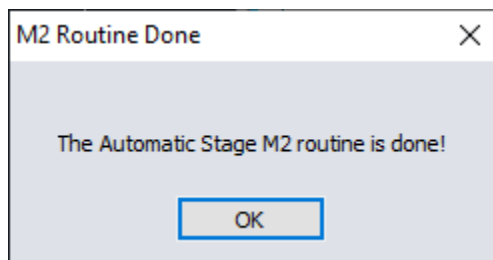


**Figure 5-24**: Routine done pop-up window

If the quadratic fit curve passes under zero, the PC-Beamage software will try to solve the problem by deleting the measurements farthest from $Z0$ and by automatically recalculating the value of M². The PC-Beamage software will also offer a recommended travel distance between $-3.5zR$ and $3.5zR$ to correct the problem (see Figure 5-25).
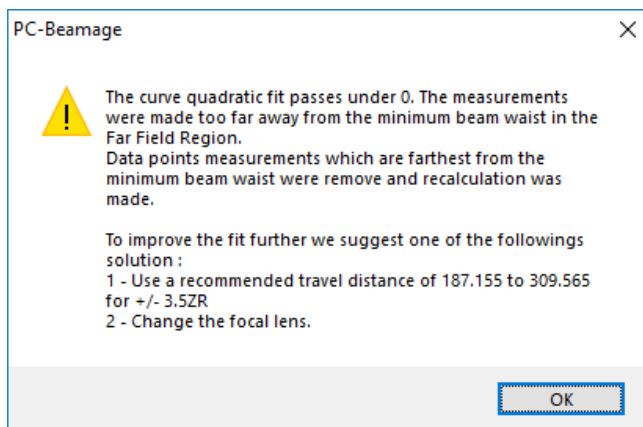


**Figure 5-25:** Curve Fit Passes Under Zero.



A minimum of 5 beams must be detected to calculate M².

Upon clicking the *START ISO SCAN* button, click *Yes* if you want to save previous data or *No* to ignore them. The data erase themselves and then a new M² measurement begins automatically.
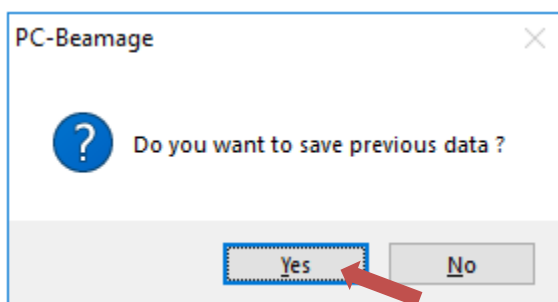


**Figure 5-26:** Save previous data

Once the new measurement is completed, click the *Calculate M²* button to display the *M² Results* tab.
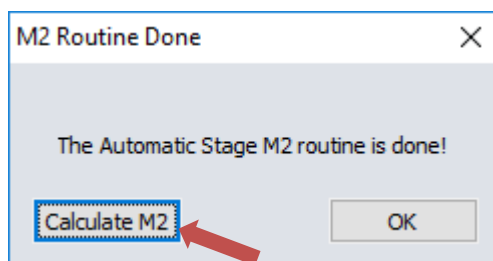
**Figure 5-27:** *Calculate M²* button

### 5.3.4. Manual Frames

In case you wish to add points at specific beam path lengths, write the distance (in millimeters) at which the data must be taken and click the *Add* button. This can be done several times if needed. The arrow buttons allow you to go quickly at one end or the other of the moving stage. These are useful when aligning the laser.

You can find more details about manual measurements in section **6. M² Manual method**.
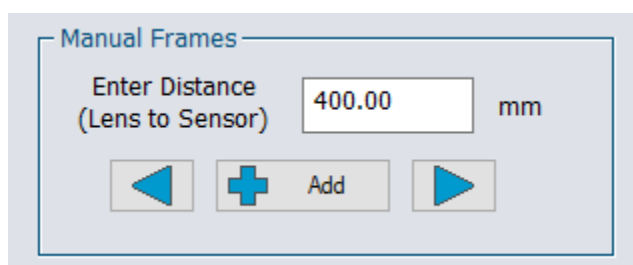


**Figure 5-28**: Manual distance setting

### 5.3.5. Data

The **Data** box allows visualization and manipulation of the data.



| Index | Distance | X Diameter | Y Diameter | Exposure Time |
|---|---|---|---|---|
| 2 | 250.0 | 822.9 | 806.8 | 13.98 |
| 3 | 300.0 | 574.6 | 566.0 | 7.17 |
| 4 | 350.0 | 341.2 | 344.5 | 2.55 |
| 5 | 375.0 | 240.6 | 245.3 | 1.19 |
| 6 | 400.0 | 179.7 | 185.2 | 0.66 |
| 7 | 425.0 | 198.7 | 199.9 | 0.80 |
| 8 | 450.0 | 271.7 | 265.2 | 1.35 |
| 9 | 475.0 | 367.5 | 355.3 | 2.22 |
| 10 | 586.6 | 902.7 | 872.9 | 14.69 |

**Figure 5-29:** Data Box

Click on any data on the list to select it. When the camera is not streaming, the corresponding beam measurement will be shown on the *Display* panel.



**Tip**

- The values *X diameters* and *Y diameters* are calculated according to the chosen definition **4 sigma (ISO)** or **1/e² along crosshairs (13.5%)**. You can change the definition from **4 sigma (ISO)** to **1/e² along crosshairs (13.5%)** or vice versa, at any time, but when the measurement is in progress. These diameters will be recalculated automatically and updated on the list.

- If the Beamage is not streaming, you can select a row in the list using the mouse and the image corresponding to this measurement will be shown in all displays. The row index corresponds to the image index (see **Figure 5-5**: Image Index).
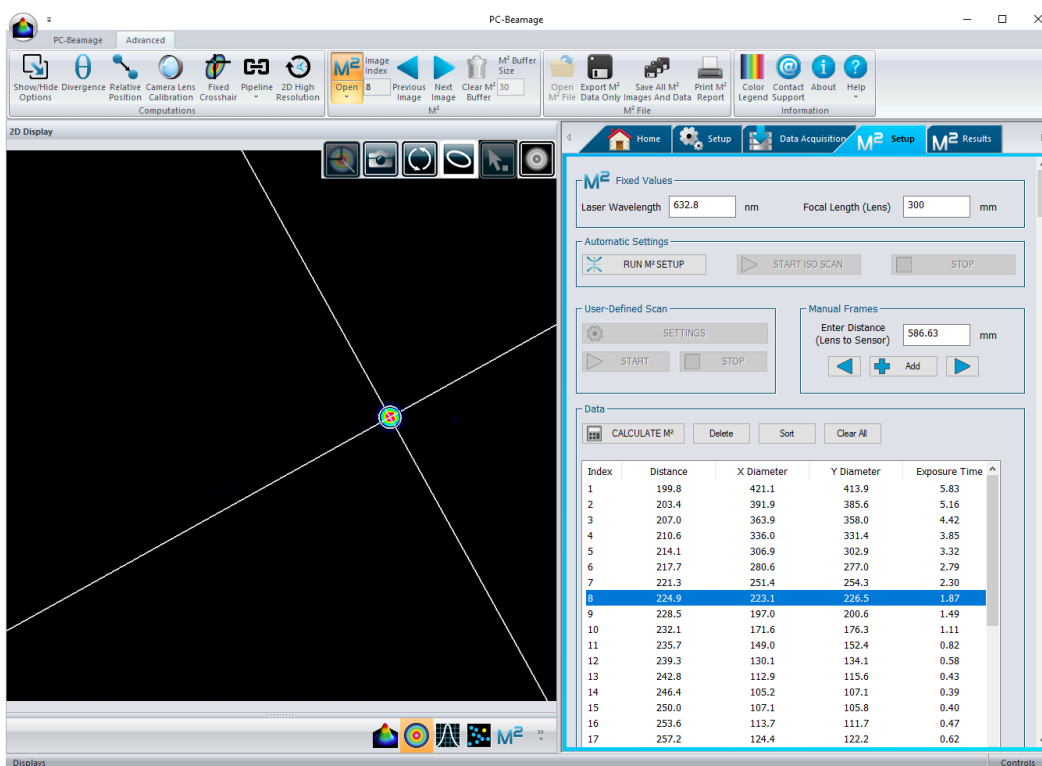


**Figure 5-30**: Data section

When the camera is not streaming, click any data row in the list and the corresponding beam image will show in the *Display* panel.

**Calculate M² button**

Clicking this button forces the calculation of the beam parameters based on the acquired data and makes PC-Beamage switch to *M² Results* tab and *M²* display.
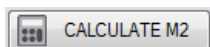


**Figure 5-31**: *Calculate M²* button

***Delete* button**

The *Delete* button removes the selected (highlighted) row(s) from the *Data* box.
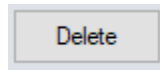


**Tip**

To delete more than one row in the list, select multiple rows using the mouse and the *Ctrl* key. To do so, hold the *Ctrl* key on your keyboard and select the rows to be deleted with the mouse. Delete them by pressing the *Delete* button or the *"delete"* key on your keyboard.

***Clear All* button**

Removes all the data from the *Data* box.
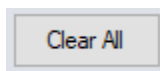


***Sort* button**

This button can be employed to refresh the *Index* numbers (left column) and rearrange the rows by *Distance* (propagation axis – second column).
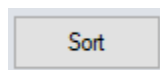


For example, upon deleting row 5 and manually adding a data point around the center of the distribution, the only indexed numbers remaining will be "1, 2, 3, 4, 6, 7…" and the last row's *Distance* will not match its position. Clicking the **Sort** button reallocates the numbers to the remaining rows and places them in order of increasing *Distance*.

**5.4. M² RESULTS**

Calculations executed from the acquired data are centralized in the *M² Results* tab.
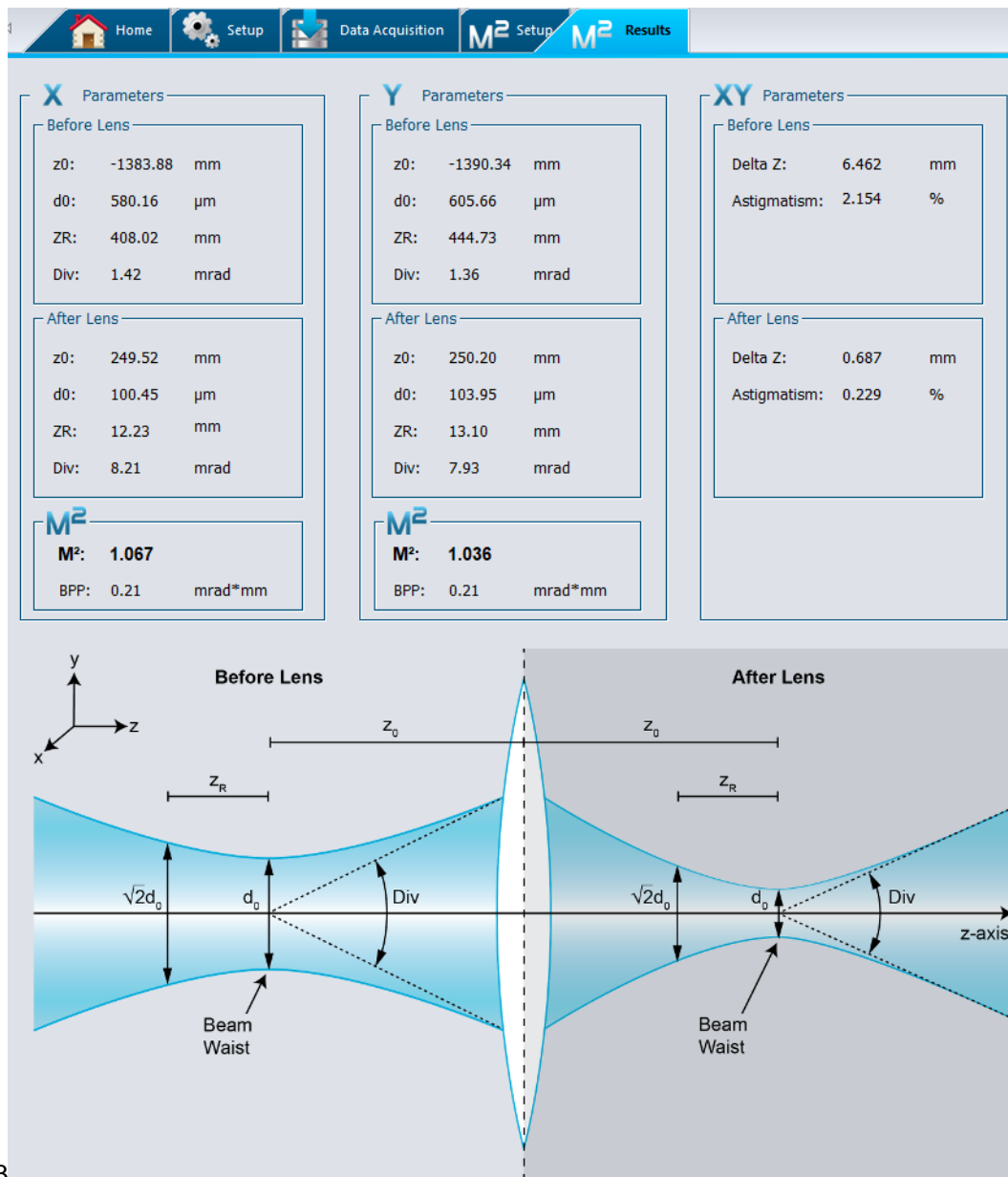


**Figure 5-32**: *M² Results* tab

- **X Parameters**: Results of the calculations for the beam profile on the "X" axis.

- **Y Parameters**: Results of the calculations for the beam profile on the "Y" axis.

- **XY Parameters**: Summary of the comparisons between data on "X" and "Y" axis.

- **M²**: Value of the *M²* and the *Beam Propagation Parameter* (*BPP*) obtained from data.

- **Graph**: A reminder of the meaning of every parameter shown above.

### 5.4.1. Before lens

These are the beam parameters derived from those measured and calculated in the *After Lens* box in either "**X**" or "**Y**" axis:

**z0**: Position of the "natural" beam waist relative to the lens.

**d0**: Diameter of the "natural" beam waist where $d_0 = 2w_0$.

**ZR**: Rayleigh length of the "natural" beam.

**Div**: Divergence of the original beam.

The section beneath *XY Parameters* is slightly different as it shows a comparison of the parameters on "**X**" and "**Y**" axies.

**Delta Z**: Distance between $z_{0x}$ and $z_{0y}$ on the propagation axis.

**Astigmatism**: How far apart the **X** and **Y** waists are, compared to the focal length $f$: $\frac{|z_{0x}-z_{0y}|}{f}$.

| Before Lens | | |
|---|---|---|
| z0: | 1468.97 | mm |
| d0: | 442.17 | µm |
| ZR: | 231.89 | mm |
| Div: | 1.91 | mrad |

| Before Lens | | |
|---|---|---|
| Delta Z: | 6.482 | mm |
| Astigmatism: | 3.241 | % |

**Figure 5-33**: Calculation results of the natural beam *before lens*

### 5.4.2. After Lens

Calculated parameters of the beam after the lens:

**z0**: Position of the focused beam waist relative to the lens.

**d0**: Diameter of the focused beam waist where $d_0 = 2w_0$.

**ZR**: Rayleigh length of the focused beam.

**Div**: Divergence of the focused beam.

The *XY Parameters* shows a comparison of the "**X**" and "**Y**" parameters.

**Delta Z**: Distance between the focused $z_{0x}$ and $z_{0y}$ on the propagation axis.

**Astigmatism**: Value of the focused **Delta Z** compared to the focal length $f$: $\frac{|z_{0x}-z_{0y}|}{f}$.

| After Lens | | | | After Lens | | |
|---|---|---|---|---|---|---|
| z0: | 374.08 | mm | | Delta Z: | 0.352 | mm |
| d0: | 111.31 | µm | | Astigmatism: | 0.117 | % |
| ZR: | 14.69 | mm | | | | |
| Div: | 7.57 | mrad | | | | |
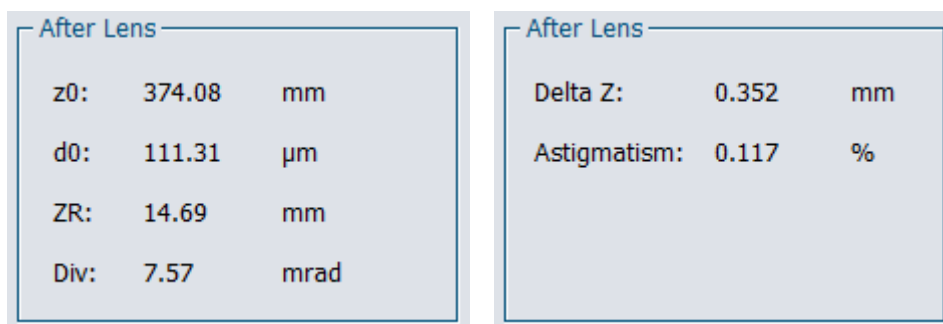
**Figure 5-34**: Calculation results of the focused beam after the lens

### 5.4.3. M² Calculation

**M²**: Calculated $M^2$ value of the beam as defined in section 4.

**BPP**: Beam Parameter Product, defined as the product of the measured divergence times the waist diameter size: $BPP = \theta * w_0 = \frac{Div}{2} * \frac{d_0}{2}$.

$M^2$
**M2:** 1.090
**BPP:** 0.22        mrad*mm

**Figure 5-35** : M² and BPP results

### 5.4.4. Definition scheme

Illustration detailing the values found in the **M² Results** tab.
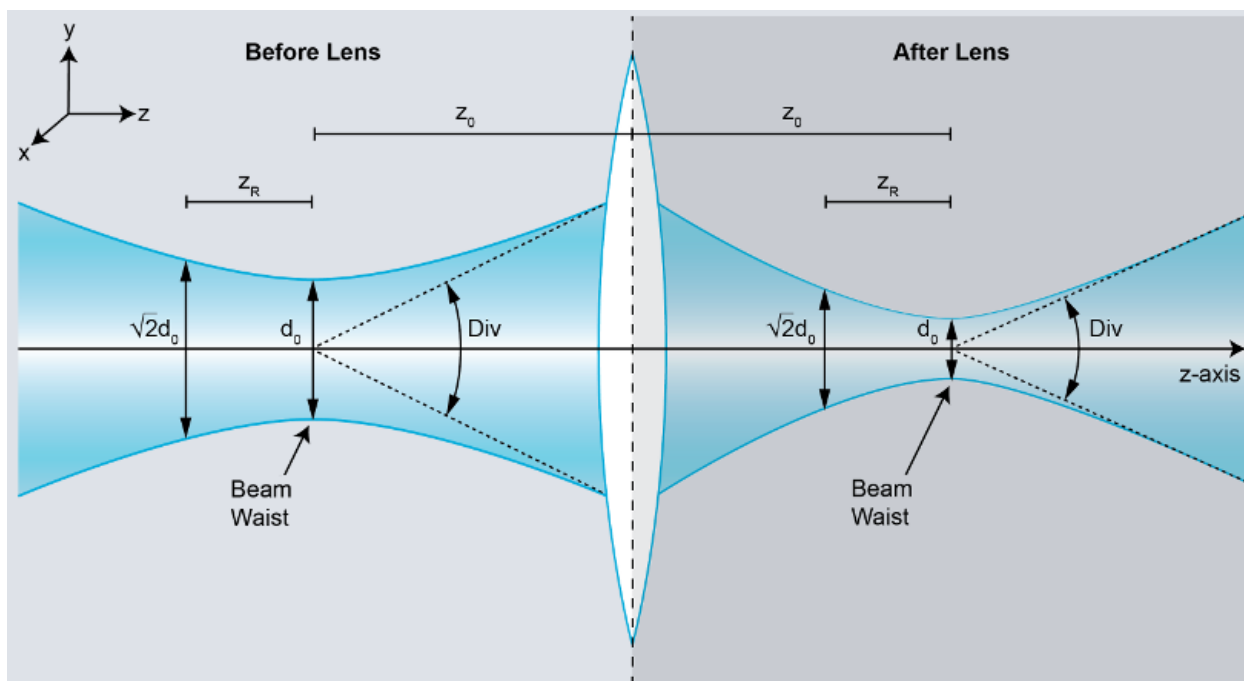


**Figure 5-36** : Gaussian beam parameters schematic before and after the lens

### 5.5. DISPLAY WINDOW

After an acquisition, the data points and the paraboloids approximating them appear on the M$^2$ display window. The graphic shows beam diameters (μm) as functions of the lens to sensor distance (mm).

The graphic is automatically generated when you press the **Calculate M$^2$** button.

Save an image of the current graph as a bitmap (.bmp) or JPEG (.jpg) file.

Use mouse pointer to zoom over an area.

Toggle to show/hide the ZRX (blue) and ZRY (red) vertical lines.
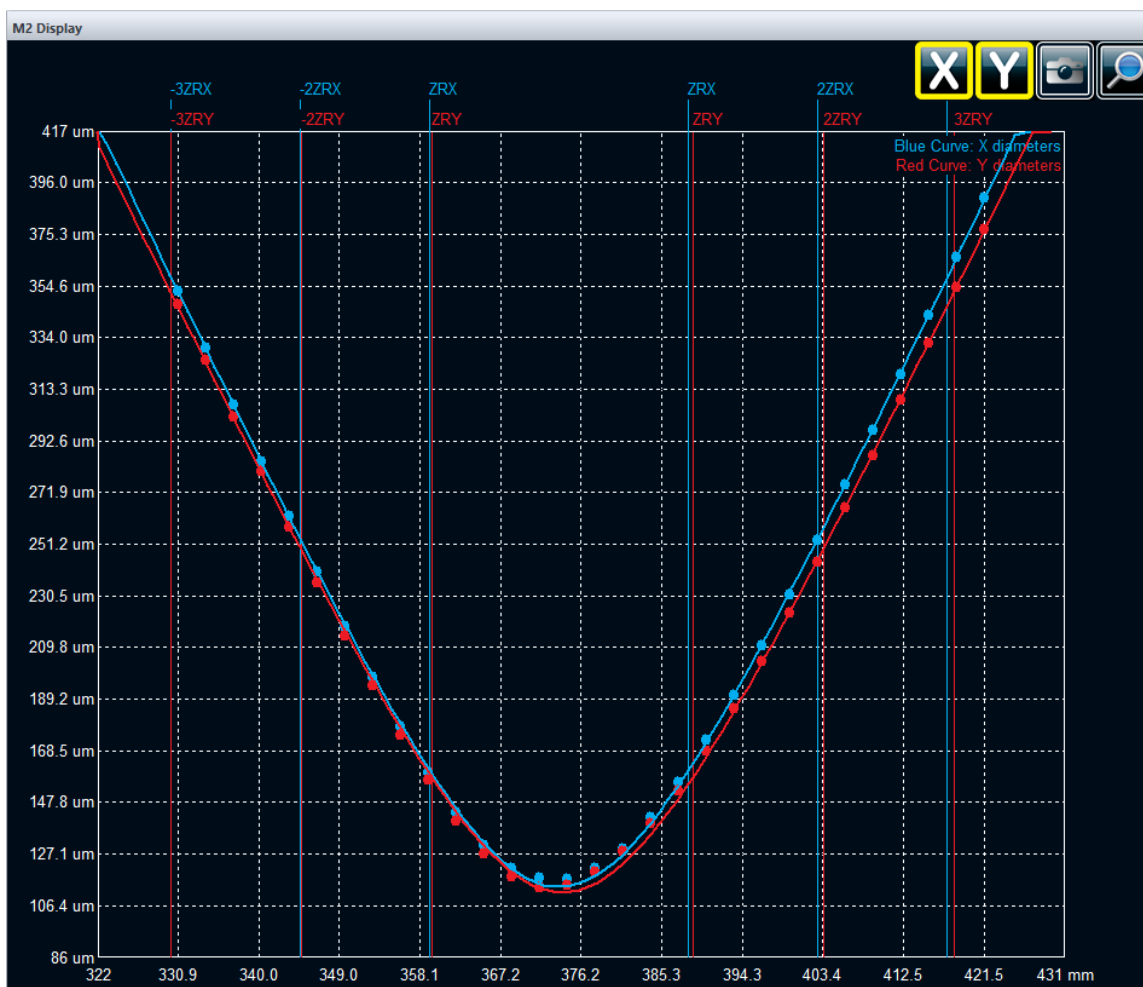


**Figure 5-37**: Display window showing the measured data, their Gaussian fit and the -3ZR to +3ZR regions

## 6. M² MANUAL METHOD

The Manual M² method is the simplest of the M² measurement methods and is ideal for stable laser beams. To manually measure the M² factor of your laser, you will need an imaging lens and a system to measure the distance between the lens and the sensor plane of the camera. Ideally, you should use a graduated optical rail system to get the most accurate measurement, but a simple ruler or a caliper can be employed. The optical setup of the Manual M² method reimages the laser beam waist and captures different slices of the laser beam propagation *within at least 3 Rayleigh lengths*. Here is a simplified setup to measure the M² factor. Please make sure to properly attenuate the laser beam before the lens, as the beam power density will be higher at the waist position, after the lens.
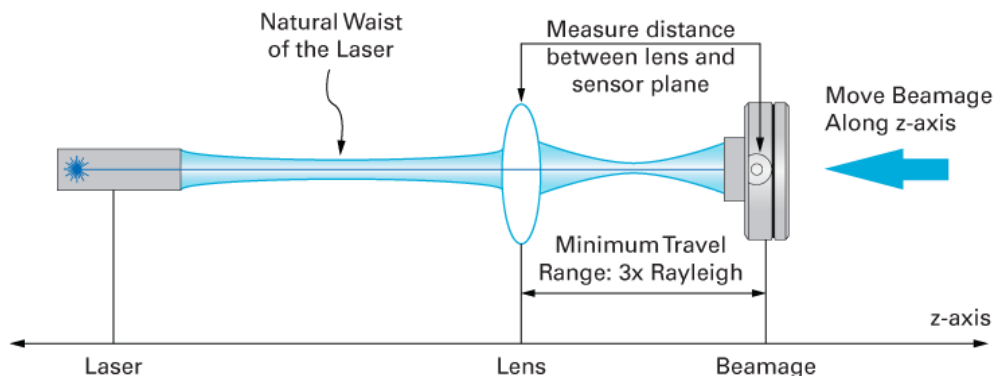


**Figure 6-1:** Optical setup for the M² measurement

**Tips**

- Make sure to place a lens after the beam waist in order to be able to reimage it.
- Choose a lens that allows a travel distance that is within your workable space.
- You can use laser viewing cards along the z-axis to make sure you have an appropriate waist and get a rough idea of its position.
- Align the Beamage and the Z-axis to make sure the laser beam stays within the sensor perimeter along the entire travel range. Due to minimal misalignment, the beam might not always be perfectly centered. Although not ideal, this is not an issue, as long as the beam stays within the sensor perimeter.

### 6.1. PROCEDURE FOR MANUAL MEASUREMENT

This procedure explains how to execute an M² measurement with a Beamage camera without the need to use a Beamage-M² system. It requires the use of a lens, a Beamage camera, some hardware to align and keep them on the laser beam's optical axis, and a ruler.

1) Start the image capture.

2) Ensure that the following conditions are met to maximize the accuracy of the M² measurement:
   a. Set the Beam Diameter Definition at **4 sigma (ISO)**
   b. Set the Crosshair position at:
      i. Centre: **Centroid**
      ii. Orientation: **Auto Orient**
   c. Execute **Subtract Background** to minimize the noise[1]

3) Click the **M²** button in the main menu.
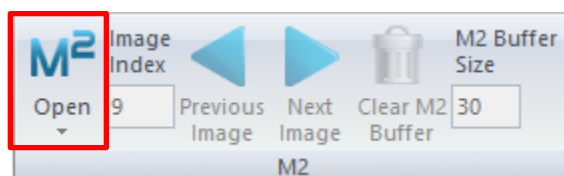


**Figure 6-2:** *M²* button

4) Go to the **M² SETUP** panel and enter the parameters of your setup:
   a. Enter the laser wavelength
   b. Enter the focal length of the lens chosen for the installation
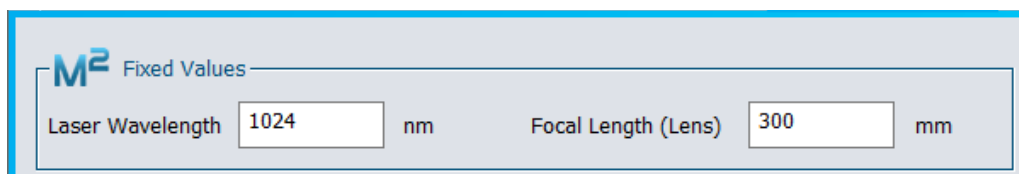


**Figure 6-3:** *M² Fixed Values* window

5) Measure the distance between the lens and the sensor of the Beamage. The sensor is positioned at 7.8 mm from the front of the casing. Enter the distance in *Manual Settings* (see 5.3.4)

6) Click on the **Add** button. The measured X and Y widths, the exposure time and the image will automatically be saved.

7) Move the Beamage and repeat steps **5** and **6** as you go along the Z-axis. You will notice that, as you get closer to the waist, the diameters and exposure times will decrease.

---

[1] Note that, in theory, the background subtraction is only valid for one exposure time. For rigorous measurements, the subtraction should be performed for every measurement as they will be executed at different exposure times. However, making a background subtraction at the highest exposure time and then using the *Auto Exposure* will greatly minimize the error. It is thus a very acceptable method in standard environments.

8) To obtain an accurate M$^2$ measurement, you must add images of the beam from the *Far Field* (beyond 2 Rayleigh lengths) and from either side of the waist in the *Near Field* (within 1 Rayleigh length). Please, refer to ISO-11146 for more information.

9) Available functions are detailed in section 5. Here is a quick reminder of the available functions for manual measurement:
   a. **Distance**: Distance between the lens and the camera sensor.
   b. **Add**: Add the current beam diameter to the list.
   c. **Delete**: Remove the selected rows from the list. The rows must be selected before deleting them.
   d. **Clear All**: Remove all the data from the list.
   e. **Sort**: All beams will be sorted by distance.
   f. **Calculate M²**: M$^2$ measurements will be done with the current data.
   g. **Open M² File**: Open saved beams from a * .m2geo or *.m2man file.
   h. **Save All Images and Data**: Save all beams from the list to a * .m2geo file.
   i. **Export M² Data Only**: Export all the data to an Excel compatible *.txt file.

10) When a minimum of 5 beams have been entered, you can use the **Calculate M²** function. A curve fit will then be available on the **M² Display** window and all M$^2$ measurement results will be available in the **M² Results** tab. See section 5.4 for more details about the results.

11) At any time during the process:
   a. More beams can be added to the list by using the **Add** button. When using this function, all previously added beams will be kept.

   b. A beam can be deleted by using the **Delete** button. The corresponding beam row must be selected before using this function.

   c. New M$^2$ calculations can be performed by using the **Calculate M²** button. If a new beam has been added or deleted, the **Calculate M²** button must be used to provide the new result of the M$^2$ measurement.

12) To retrieve previously saved data, click on the *Open M2 File* button, in the ribbon. Click on *Calculate* to see the M$^2$ results in the *M2 Curve Display* and *M2 Results* tabs.

# 7. TROUBLESHOOTING AND TIPS

### 7.1. THE PROGRAM CANNOT START BECAUSE MSVCR100.DLL IS MISSING […]

You must download the missing dll from Microsoft software and install it on your computer:
32-bits: http://www.microsoft.com/download/en/details.aspx?id=5555
64-bits: http://www.microsoft.com/download/en/details.aspx?id=14632

### 7.2. BEAMAGE IS NOT DETECTED

Make sure the Beamage is connected to a USB 3.0 Super Speed port. The Beamage will work if plugged directly into a USB 2.0 port at a slower transfer rate.

On modern computers with USB-A and USB-C ports, we recommend connecting the Beamage in one of three ways, trying them in the order listed:

1. Option 1: Connect the Beamage to your PC via the cable (#103642) in a USB-A 3.0 SuperSpeed port;
2. Option 2: Use the USB-A to USB-C adapter (#205915) to connect the Beamage to a USB-C 3.0 SuperSpeed port;
3. Option 3: Use the powered USB3.0-HUB (#202829) to connect the Beamage to a USB-A 3.0 SuperSpeed port on your PC.

Close the software application, disconnect and reconnect the USB 3.0 to the Beamage, then reopen the software application. The LED indicator on the Beamage should blink green, and then red, before turning green. If the LED does not turn on upon software startup, or if it does not turn on completely, please contact your Gentec-EO representative or contact us at service@gentec-eo.com.

### 7.3. THE DISPLAY AREA IS COMPLETELY WHITE

Press the *Refresh* button and the display should return to its operational state.

### 7.4. THERE IS NO SERIAL NUMBER DISPLAYED ON THE *BEAMAGE SELECTOR* WINDOW

- Please close the PC-Beamage software, wait a few seconds, then reopen PC-Beamage.

- If the problem persists, please verify in the Task Manager menu of Windows if only 1 PC-Beamage.exe instance is running. If more than one is running, interrupt all processes and reopen PC-Beamage.

- If the problem persists, please disconnect the Beamage and connect it again.

- If the problem still persists, please contact your Gentec-EO representative or contact us at service@gentec-eo.com.

### 7.5. TIPS TO INCREASE THE FRAME RATE

The Beamage's frame rate greatly depends upon the computer's performance. Here are a few tips to increase the frame rate:

- Use a USB 3.0 port.
- Use a high-performance computer (Beamage manual, PC Requirements, section 0).

- Use Windows 7, Windows 8, or Windows 10.
- Follow the PC operating state for optimal conditions (Beamage manual, refer to section 0).
- Use the smallest attenuation possible (refer to Beamage manual).
- Do not use *Image Averaging* (refer to Beamage manual).
- For a large beam, use *Pixel Addressing* (refer to Beamage manual).
- For a small beam, use an *Active Area* (refer to Beamage manual).
- Make sure you use a short exposure time.
- Do not stream multiple Beamage units simultaneously.

## 7.6. THE BEAM DISAPPEARS FROM THE SENSOR

When the beam disappears from the sensor, it must be realigned. The conditions for a good alignment on the whole carrier travel are:

- While the carrier is in its farthest position, the beam must be centred on the Beamage's sensor.
- The beam must be centred on the lens.

Make sure your laser does not move relative to the Beamage-M² setup during the experiment.

For more details about the beam alignment, see section 2.2 Laser alignment.

## 7.7. ACTUAL SETTINGS DO NOT ALLOW AN M² MEASUREMENT

Measuring the $M^2$ of a diverging laser may pull the beam waist position beyond the reach of the system. In this case, using a lens with a shorter focal length will bring the waist closer to the measured span and therefore, allow the $M^2$ measurement.

In case you find Z0 to be out of the range or ZR to be too high, you will need to change the lens. Here is the procedure to replace a lens. Different cases of bad focal length choice are presented right after.
1. Replacing the lens:
    a. Lower all the ND filters.
    b. Unscrew the iris and the iris adapter.
    c. Unscrew the lens tube and put it in a clean plastic bag.
    d. Take the lens you need from the transport case and screw it in place of the one you just took away.
    e. Screw the iris and the adapter in front of the new lens.

## 7.8. LENS CHOOSING GUIDE

Here is a quick guide to help you choose a suitable lens.
In case you get:
1.  Z0 < 186 mm
    a.  The focal length is too short, change for a longer focal length.
2.  Z0 > 580 mm
    a.  The focal length is too long, change for a shorter focal length.
3.  ZR > 100 mm
    a.  The Rayleigh length is too long to return an ISO M² value.
    b.  This means the divergence is too low.
    c.  Change the lens for a shorter focal length to raise divergence.
4.  ZR > 58 mm
    a.  The Rayleigh length is too long to return a Gentec approved commercial M² measurement (7 ZR must fit within the stage's range).
    b.  This means the divergence is too low.
    c.  Change the lens for a shorter focal length to increase the divergence.

### 7.9. THE BEAM IS TOO WEAK TO START AN AUTOMATIC ACQUISITION

There may be many causes for a weak beam: too much attenuation in the optical path, a measurement taken too far from the waist, and more.

Some beams will lose too much intensity to be correctly measured when they get far from the waist. In these cases, stream the camera output in PC-Beamage, set 2D view, and turn the translation stage knob to find the waist. From there, start an acquisition and use the software to find the maximum measurement range. Repeat in the other direction and verify that $6Z_R$ fits in the measured zone. Otherwise, use a lens with a shorter focal length or lower attenuation.

If you turned off the 3 ND filters already and the beam continues to be too weak, you can change or remove the ND filter mounted directly on the Beamage camera. Refer to the Beamage Manual for changing the Beamage ND filter.

### 7.10.        OTHER ISSUES

NOTE: The Beamage must not be disconnected while streaming.

1. Curve fit passes below 0
   a. The measurement is made too far away from the waist:
      i. We have too many points beyond -3.5Zr and 3.5Zr.
      ii. We do not have enough points between –Zr and Zr.
      iii. Solutions:
         1. Remove points far from the waist, one by one, and then recalculate.
         2. Note the values of Z0 and Zr, clear all results and remeasure a set of points expanding ONLY from -3.5Zr to +3.5Zr, not beyond.
         3. Take more points around the waist.
   b. The software cannot find the waist:
      1. See section 7.8 Lens choosing guide above.

2. The value of M² is below 1
   a. The system (not laser) affects the beam:
      i. Check and clean every mirror and ND filter.
      ii. Dust can change drastically a M² measurement.
      iii. Broken optics or mirrors can change drastically a M² measurement.
      iv. Look and ask for collimator adjustment.
   b. ISO minimum requirements are not respected:
      i. Look at the M² display for ISO minimum requirements.
      ii. If not respected, add more data points (MORE THAN REQUIRED BY ISO).
   c. The measurements were made too far away from the waist:
      i. See section 7.8 Lens choosing guide above.

3. The software continually asks to change attenuation and take no measurement
   a. Make sure the laser beam illuminates the camera's sensor.
   b. The laser beam might be so intense that it saturates the sensor near the focus. Possible solutions:
      i. Change the lens for a longer focal length, this will widen $w_0$.
      ii. Add attenuation before M1; a beam that has a power beyond 100 mW might have some saturation issues near the focus.
   c. The computer might be too slow (very low frame rate):
      i. See section 7.5 Tips to increase the frame rate.
      ii. Use the *Image averaging* function to stop the flickering.

4. Other things to double-check:
   a. The mirrors are well set.
   b. The camera is securely fastened.
   c. The filter on the camera is completely screwed.
   d. The moving stage is plugged with a **special** USB cable.
   e. The beam is sufficiently attenuated.
   f. The drivers and software are up to date.
   g. In case of uncertainty, uninstall everything with Windows control panel and install the latest versions.

## 8.  DECLARATION OF CONFORMITY

Application of Council Directive(s):          2014/30/EU          The EMC Directive

Manufacturer's Name:                              Gentec Electro Optics, Inc.
Manufacturer's Address:                          445, rue Saint-Jean Baptiste, suite 160
                                                              Québec (Canada)  G2E 5N7

European Representative's Name:              Laser Components S.A.S.
Representative's Address:                          45 bis, route des Gardes
                                                              92190 Meudon (France)

Type of Equipment:                                  Laser Beam Diagnostic Equipment.
Model No.:                                              Beamage-M²
Year of test & manufacture:                      2017

Standard(s) to which Conformity is declared:
EN 61326 :2005/EN 61326: 2006/ Emission generic standard

| Standard | Description | Performance Criteria |
|---|---|---|
| CISPR 11 :2009 +A1 2010 | Industrial, scientific, and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement | Class A |
| EN 61326 :2005/EN 61326 : 2006 | Limits and methods of measurement of radio interference characteristics of information technology equipment. Testing and measurements of radiated emission | Class A |
| IEC 61000-4-2:2001 | Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques - Section 2: Electrostatic discharge. | Class B |
| IEC 61000-4-3:2002 | Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques - Section 3: Radiated, Radio Frequency immunity. | Class A |
| IEC 61000-4-4:2012 | Electromagnetic compatibility (EMC) - Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test | Class B |
| IEC 61000-4-5:2014 | Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test | Class B |
| IEC 61000-4-6:2013 | Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields | Class A |
| IEC 61000-4-8:2009 | Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test | Class B |
| IEC 61000-4-11:2004 | Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions, and voltage variations immunity tests | Class C |

I, the undersigned, hereby declare that the equipment specified above
conforms to the above Directive(s) and Standard(s).

Place:  Québec (Québec)

Date :  July 14, 2017

(President)

# 9.  UKCA DECLARATION OF CONFORMITY

Application of Council Directive(s):        2014/30/EU        The EMC Directive

Manufacturer's Name:                       Gentec Electro Optics, Inc.
Manufacturer's Address:                     445 Saint-Jean Baptiste, suite 160
                                            Québec (Canada) G2E 5N7

European Representative's Name:             Laser Components S.A.S.
Representative's Address:                    45 bis, route des Gardes
                                             92190 Meudon (France)

Type of Equipment:                          Laser Beam Diagnostic Equipment.
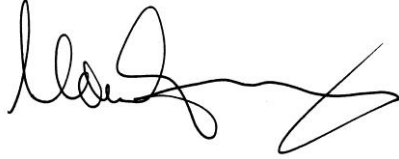Model No.:                                  Beamage-M²
Year of test & manufacture:                 2017

Standard(s) to which Conformity is declared:
EN 61326 :2005/EN 61326: 2006/ Emission generic standard

| Standard | Description | Performance Criteria |
|---|---|---|
| CISPR 11 :2009 +A1 2010 | Industrial, scientific, and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement | Class A |
| EN 61326 :2005/EN 61326 : 2006 | Limits and methods of measurement of radio interference characteristics of information technology equipment. Testing and measurements of radiated emission | Class A |
| IEC 61000-4-2:2001 | Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques - Section 2: Electrostatic discharge. | Class B |
| IEC 61000-4-3:2002 | Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques - Section 3: Radiated, Radio Frequency immunity. | Class A |
| IEC 61000-4-4:2012 | Electromagnetic compatibility (EMC) - Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test | Class B |
| IEC 61000-4-5:2014 | Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test | Class B |
| IEC 61000-4-6:2013 | Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields | Class A |
| IEC 61000-4-8:2009 | Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test | Class B |
| IEC 61000-4-11:2004 | Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions, and voltage variations immunity tests | Class C |

I, the undersigned, hereby declare that the equipment specified above
conforms to the above Directive(s) and Standard(s).

Place:    Québec (Québec)

Date :    December 7, 2021

(President)

## APPENDIX A. ISO11146 AND ISO11670 DEFINITIONS

The beam centroid coordinates are given by:

$$\bar{x}(z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)x\,dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)dxdy}$$

$$\bar{y}(z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)y\,dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)dxdy}$$

The beam widths are defined as an *"extent of a power density distribution in a cross section of beam based on the centered second-order moments of the power density distribution."*

The second-order moments of the power density distribution are given by:

$$\sigma_x^2(z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(x-\bar{x})^2\,dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)dxdy}$$

$$\sigma_y^2(z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(y-\bar{y})^2\,dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)dxdy}$$

$$\sigma_{xy}^2(z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(x-\bar{x})(y-\bar{y})\,dxdy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)dxdy}$$

The beam widths are given by:

$$d_{\sigma_x} = 2\sqrt{2}\left\{(\sigma_x^2 + \sigma_y^2) + \gamma\left[(\sigma_x^2 - \sigma_y^2)^2 + 4(\sigma_{xy}^2)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}$$

$$d_{\sigma_y} = 2\sqrt{2}\left\{(\sigma_x^2 + \sigma_y^2) - \gamma\left[(\sigma_x^2 - \sigma_y^2)^2 + 4(\sigma_{xy}^2)^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}}$$

where:

$$\gamma = \frac{\sigma_x^2 - \sigma_y^2}{|\sigma_x^2 - \sigma_y^2|}$$

The major axis is the width's maximum whereas the minor axis is the width's minimum.

The effective diameter of the beam is an *"extent of a circular power density having an ellipticity greater than 0.87. […] If the ellipticity is larger than 0.87, the beam profile may be considered to be of circular symmetry at that measuring location and the beam diameter can be obtained from:"*

$$d_\sigma = 2\sqrt{2}(\sigma_x^2 + \sigma_y^2)^{1/2}$$

The beam ellipticity is the *"ratio between the minimum and maximum widths"*.

The beam orientation is the "*angle between the x-axis […] and that of the principal axis of the power density distribution which is closer to the x-axis.*" From this definition, the angle is comprised between 45° and -45°:

$$\varphi(z) = \frac{1}{2}\arctan\left(\frac{2\sigma_{xy}^2}{\sigma_x^2 - \sigma_y^2}\right)$$

The beam's divergences transformed by an aberration-free focusing element of focal length *f* are provided by the following equations:

$$\theta_x = \frac{d_{\sigma_x}}{f}$$

$$\theta_y = \frac{d_{\sigma_y}}{f}$$

$$\theta_\sigma = \frac{d_\sigma}{f}$$

In the laboratory or usual system of coordinates (X', Y', Z'), the coordinates of the latest calculated position of the centroid for both X' and Y' axes are given by the following equations:

$$\bar{x}'(z) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x',y',z')x'\,dx'\,dy'}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x',y',z')\,dx'\,dy'}$$

$$\bar{y}'(z) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x',y',z')y'\,dx'\,dy'}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x',y',z')\,dx'\,dy'}$$

The coordinates of the mean position of all computed centroids for both X' and Y' axes are thus defined by the following equations, which are simple arithmetic means:

$$\bar{x}'_M = \frac{\sum_i \bar{x}'_i}{n}$$

$$\bar{y}'_M = \frac{\sum_i \bar{y}'_i}{n}$$

where $\bar{x}'_i(z)$ and $\bar{y}'_i(z)$ are the centroid coordinates for the X' and Y' axes already saved in the buffer, and $n$ is the number of computed centroid positions saved in the buffer.

The azimuth angle, which is the angle between the usual X' axis and all computed centroids, is given by the following equation:

$$\psi = \frac{1}{2}\arctan\left(\frac{2s_{\widetilde{xy}}^2}{s_{\tilde{x}}^2 - s_{\tilde{y}}^2}\right)$$

where we have the following definitions:

$$s_x = \sqrt{\frac{\sum_i \bar{x}_i^2}{n-1}}$$

$$s_{\tilde{y}}^2 = \frac{\sum_i (\bar{y}'_i - \bar{y}'_M)^2}{n-1}$$

$$s_{\widetilde{xy}}^2 = \frac{\sum_i (\bar{x}'_i - \bar{x}'_M)(\bar{y}'_i - \bar{y}'_M)}{n-1}$$

In the beam axis coordinate system (X, Y, Z), the beam positional stability values in the azimuthal direction (X) and perpendicularly to the azimuthal direction (Y), which are 4 times the standard deviations of all computed centroid values, are given by the following equations:

$$\Delta_x(z) = 4s_x$$
$$\Delta_y(z) = 4s_x$$

The overall positional stability is given by:

$$\Delta(z) = 2\sqrt{2}s$$

In the three previous equations, the standard deviations are defined by the following equations:

$$s_x = \sqrt{\frac{\sum_i \bar{x}_i^{\,2}}{n-1}}$$

$$s_y = \sqrt{\frac{\sum_i \bar{y}_i^{\,2}}{n-1}}$$

$$s = \sqrt{\frac{\sum_i \bar{x}_i^{\,2} + \bar{y}_i^{\,2}}{n-1}}$$

$\bar{x}_i^{\,2}$ and $\bar{y}_i^{\,2}$ are derived from $\bar{x}'^{\,2}_i$ and $\bar{y}'^{\,2}_i$ by transformation of coordinates. Here, (X',Y',Z') represent the usual or laboratory coordinate system and (X,Y,Z) is the beam axis coordinate system.

The RMS standard deviation value of the centroid position, which is not an ISO standard, is given by the following equation:

$$RMS = \sqrt{\left(\frac{\sum_i x_r^2 + y_r^2}{n}\right)}$$

where $x_r^2$ and $y_r^2$ are relative values.

## APPENDIX B. RECYCLING AND SEPARATION PROCEDURE FOR WEEE

This section is used by the recycling center when the Beamage-M² reaches its end of life. Breaking the calibration seal or opening the Beamage's case will void the warranty.

The complete Beamage-M² contains:

    1 Beamage-4M camera
    1 USB 3.0 cable with screw locks
    1 BNC to SMA connector
    1 Software USB key
    3 Circular 2" Al-coated mirrors
    1 Square 2" Al-coated mirror
    2 Moving stages
    1 48 V power supply
    1 USB 2 cable
    3 2" ND filters
    4 Mirror mounts
    1 Aluminum housing with mounting pieces
    3 Lenses, 2"
    3 Lens holding tubes, 2"

### SEPARATION

Plastic: Aperture cap, SMA cap, USB key housing
Metal: Beamage case, screws, SMA connector, BNC to SMA connector, ND filter holders, mirror holders,
        Beamage-M² casing, connector plate, mirror posts, lens holding tubes
Wires: USB cables, power supply
Printed circuit board: Inside the Beamage-4M and inside the electrical moving stage
Glass: ND filters and mirrors

### DISMANTLING PROCEDURE

Remove all housing screws.
Separate the round mirrors from their mounts by unscrewing their holding screws.
Remove the square mirror by sliding a fine flat head screwdriver behind it.
Remove the 2" ND filters and the 2" lenses with a spanner wrench.
Use a Philips screwdriver to unscrew the electrical moving stage's circuit housing.
Remove the PCB and motor.
Unscrew the #10-32 set screw to remove the Beamage-4M camera.
Unscrew every other screws to completely unmount the assembly.

**For the Beamage camera:**
Remove the 3 screws on the BEAMAGE's back cover with an Allen key (1/16'').
Remove the 1 screw holding the PCBs with a flat screwdriver.
Cut the wire between the PCB and the SMA connector.
Remove the ND filter and remove the glass with a spanner wrench.

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**CANADA**

445 St-Jean-Baptiste, Suite 160
Quebec, QC, G2E 5N7, Canada

T (418) 651-8003
F (418) 651-1174

info@gentec-eo.com

**UNITED STATES**

5825 Jean Road Center
Lake Oswego, OR, 97035, USA

T (503) 697-1870
F (503) 697-0633

info@gentec-eo.com

**JAPAN**

Office No. 101, EXL111 building,
Takinogawa, Kita-ku, Tokyo
114-0023, Japan

T +81-3-5972-1290
F +81-3-5972-1291

info@gentec-eo.com

**CALIBRATION CENTERS**

• 445 St-Jean-Baptiste, Suite 160
  Quebec, QC, G2E 5N7, Canada

• Werner von Siemens Str. 15
  82140 Olching, Germany

• Office No. 101, EXL111 building,
  Takinogawa, Kita-ku, Tokyo
  114-0023, Japan