Commissioning of the THz beamline at FLASH: beam properties

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Abstract

We pretend to find some interesting properties of the FEL beam in the THz beamline at FLASH, DESY Hamburg. Based on transverse measurements of the beam profile, we aim to model its behavior, and later how does it propagate by calculating the so-called M factor.

1. Introduction

Which is Free Electron Laser (FEL) light behavior? Does it spread similar way to conventional laser beams? It's not a simple question since the physics principle behind these couple of light sources are completely different. This is our starting point, and we will try to find out whether this particular THz-beamline FEL-light does behave like conventional laser or it does not. To do so, one of the first problems we will face is the definition of the beam width. We will need to decide which and why. This will take us to the second-moment beam width definition, which is related to the *M-squared* factor. We will try to obtain this *M* factor. That finally gives us an idea how the beam propagates and, in the end, if we can conclude that our THz beam can be kind of modeled as conventional laser beams. Apart from this, we will check if the *M-squared* factor is actually wavelength independent as it is supposed to be, being this a big advantatge for future experiments since one doesn't need anymore to commission the beamline while changing the wavelength.

2. FEL vs conventional laser light

FEL light is based on synchrotron radiation emission, SASE principle and microbunching in the undulators. As a short summary, this is how it works: an electron bunch is shot from the RF gun. Bending magnets (chicanes) produce higher density bunches (bunch compressors). The electrons get fastly accelerated to relativistic velocities, emitting light. SASE principle permits the start-up at arbitrary wavelengths without the need for external seed radiation. Electrons produce spontaneous undulator radiation in the first section of a long undulator magnet which then serves as seed radiation in the main part of the undulator. The undulator makes them move through a sinusoidal path, so they are not only being linearly accelerated but they are also oscillating.

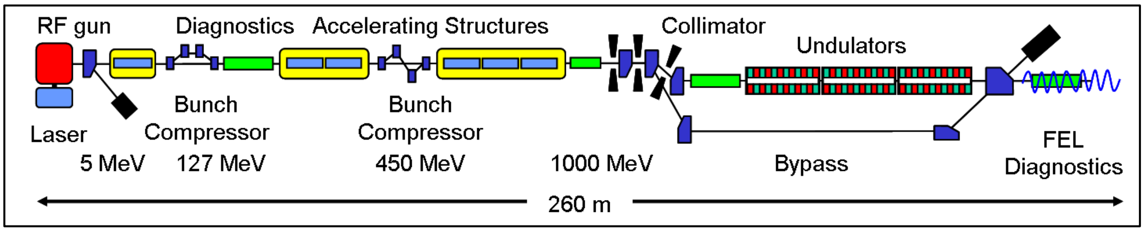

Figure 1: Schematic image of FLASH accelerator tunnel.

This undulator light interacts with the electron bunches in a way that it produces small packs of electrons all radiating as a single particle of high charge. So we have more photons. This increase in the radiation field enhances the microbunching even further and leads to an exponential growth of the energy of the radiation pulse. The final output is a very intense, coherent and short laser pulse.

So we got an insight, how different is FEL to conventional lasers, which are based in stimulated emission of light in three energy level atoms or molecules.

3. THz beamline

This beamline has been designed to provide coherent femtosecond – picosecond THz pulses for pump and probe experiments with the femtosecond VUV pulses from FLASH. The THz pulses are generated by a purpose built undulator implemented in series to the VUV undulators. The pulses should then be naturally synchronized. The pulse energies are around the μJ regime.

The spectral range goes from 10 up to 200 μm. The respective frequency range is from 1.5 up to 30 THz (1 THz = 10^{12} Hz).

Users at FLASH must apply for beamtime before their arrival. Then the accepted proposals are set in different shifts (even night-shifts), since only *one* beamline can be working at the same time.

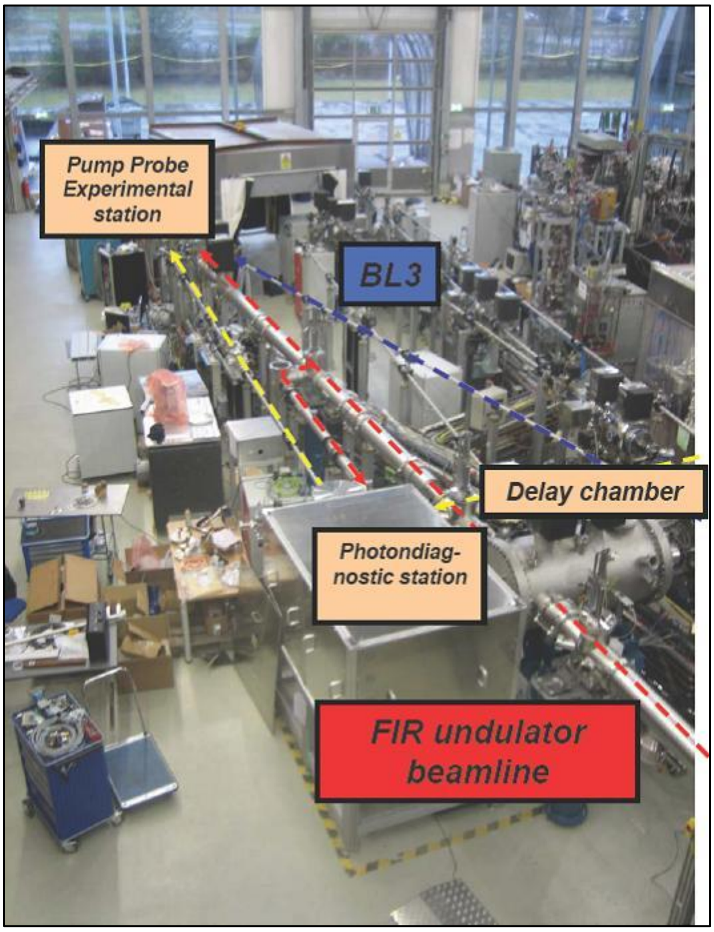

Figure 2: Picture of the THz beamline in the experimental hall.

4. How we define the beam width?

This has become nowadays a common problem in laser physics. Since the beam profiles can have many different shapes, it's hard to define an universal beam width. Some beam width definitions are:

- Width at first nulls.
- The 'D86' diameter, containing 86% of the total beam energy.
- Transverse knife edge widths between 10%-90% or 5%-95% integrated intensities.
- Width of rectangular profile having the same peak intensity and same total power.
- Variance σ_x of the intensity profile in one or other transverse direction.

This definitions can give very different values of the beam width when applied to the same beam profile, and in fact some of them cannot even be used to certain kinds of profiles. And moreover, in general there are no universal conversion from one width definition to another one; it usually depends on the exact shape of the intensity profile given. This topic is of main concern since any beam "quality" or propagation factor is based in a given beam width definition.

Thus, the inability to even define a standard and rigorous beam width means that there is no universal way in which one can evaluate the near-field far-field widths product, so there is no universal way or parameter to define the beam behavior – its propagation.

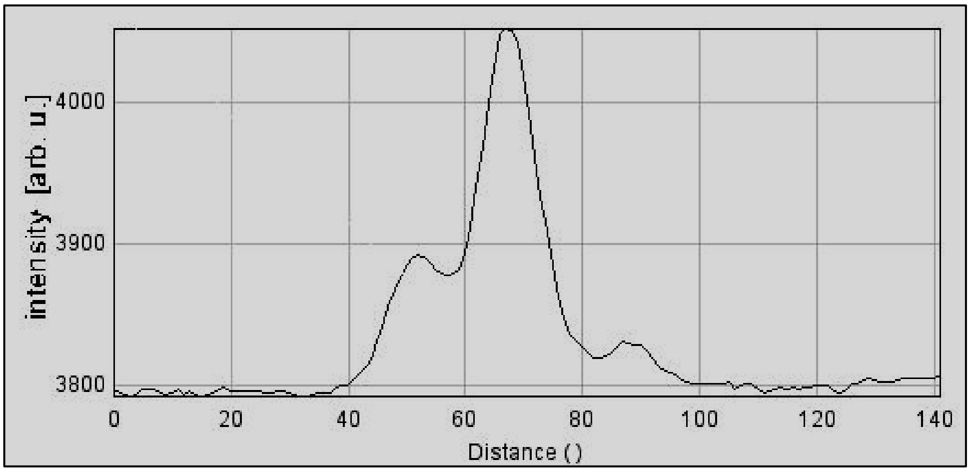

Figure 3: Intensity profile of a non-gaussian beam. This one, obtained of our own data.

5. Second-moment based beam width definition

Along all the beam width definitions existing, we choose the second-moment based beam width because it's the most mathematically rigorous formulation, and also because it takes us to the appearance of the *M-squared* factor.

The second-moment of a beam profile is defined by:

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty} (x - x_0)^2 I(x,y) dxdy}{\int_{-\infty}^{\infty} I(x,y) dxdy} \quad ; \quad (1)$$

The third reason for using this definition is that any beam characterization based on the second-moment will automaticly follow the next quadratic propagation rule:

$$W_x^2(z) = W_{0x}^2 + M_x^4 \left(\frac{\lambda}{\pi W_{0x}}\right)^2 (z - z_{0x})^2;$$

where the general beam width W_x is related with the variance of the laser beam:

$$W_x = 2\sigma_x;$$

finally obtaining:

$$\sigma_x^2(z) = \sigma_{0x}^2 + M_x^4 \left(\frac{\lambda}{4\pi\sigma_{0x}}\right)^2 (z - z_{0x})^2; \quad (2)$$

which is analogous for the y coordinate, just by changing y in x. This quadratic propagation dependence holds for any arbitrary laser beam, whether gaussian or non-gaussian, fully coherent or partially incoherent. Moreover, at least so far as anyone has proven, this quadratic dependence of beam width is rigorously true only for the second-moment width and not for any other width definitions.

One of the most useful features of the second-moment based method is that the M^2 values and their associated W_0 and z_0 parameters can be directly applied in the design of real laser beams. We can envision an "embedded gaussian" beam with spot size *w* given by:

$$w_0 = W_0/M \qquad at\ z = 0 \qquad \text{and} \qquad w(z) = W(z)/M \qquad at\ any\ z.$$

This embedded gaussian beam does not necessarily have any physical reality, but we can however design calculations in which one propagates this hypothetical embedded gaussian through multiple lenses and paraxial elements, finding the focal points and other properties. Then, we can assure that the real optical beam will propagate through the same system in exactly the same fashion, except that the spot size *W(z)* of the real beam at every plane will be exactly *M* times larger than the calculated spot size of the hypothetical gaussian beam at every plane along the system.

6. Experimental data

The measurements were made by my supervisors prior to my arrival. They consist in an array of pictures taken with a CCD camera transverse to the direction of propagation of the beam, in the surroundings of the focusing point z_0. So they are like beam slices. Two differents measurements at two different wavelengths were made, later on we will see why. Also, in order to measure the background, pictures in each point were taken both with the beam on and the beam off. This is very important since second-moment calculations are extremely sensitive to background, due to the fact that its value depend on squared distance. Therefore if we have any level of noise - background radiation on the edges of our camera, we will get results strongly deviated from these ones with the background subtracted.

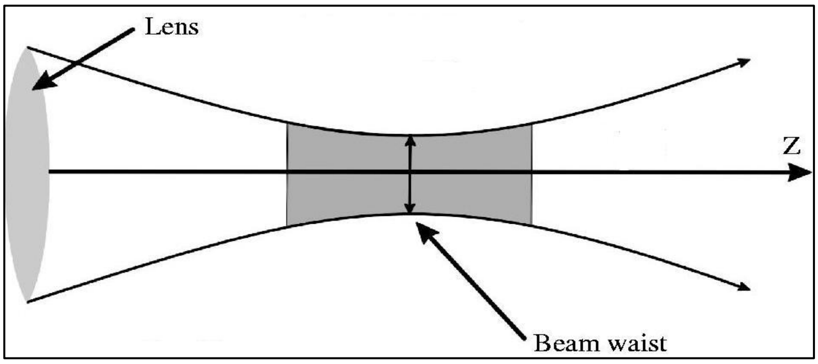

Figure 4: beam convergence to the focal point.

This point above mentioned is one of the main problems to deal with when we calculate *M-squared* factor. Other error sources are baseline drift or camera nonlinearity. For the reasons and the formalism so far explained, we should consider *M* factor not as a beam "quality" factor but as a **beam propagation factor**, since it gives a rigorous and useful measure of how the beam will propagate through free space or any kind of optical system.

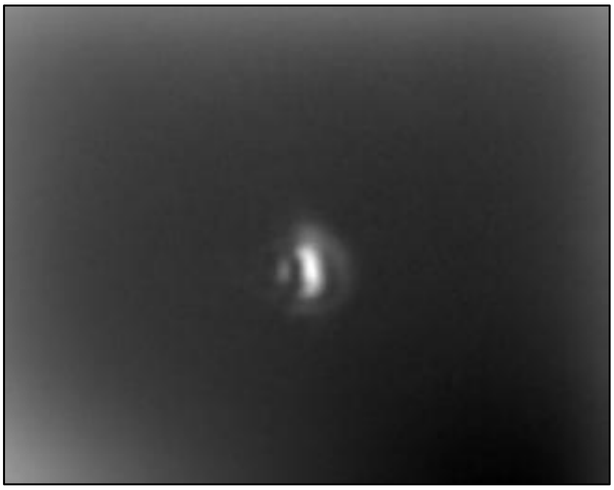

Figure 5: real picture obtained with the CCD camera at $z = 25mm$ ($\lambda = 52\ \mu m$).

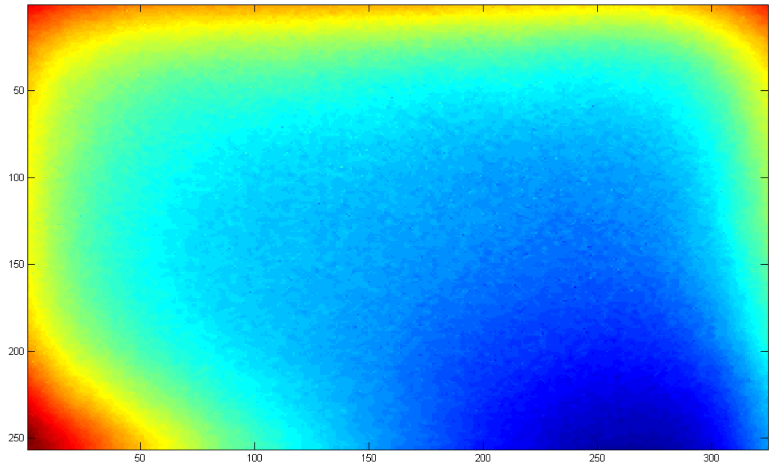

Figure 6: MATLAB background (beam off) image processed.

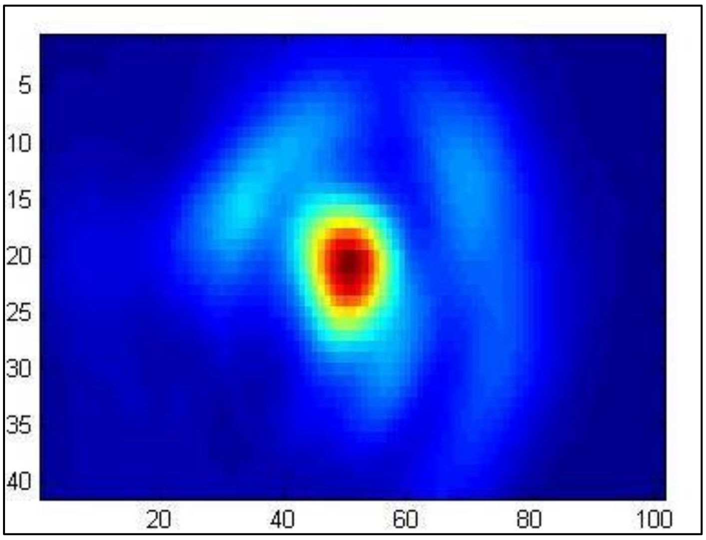

Figure 7: MATLAB beam image processed.

Once we got above's picture, we were running a MATLAB program which was working following the next steps:

- Reading the picture, calculating the intensity of each pixel and colouring them in function of intensity.
- Subtraction of the beam on – beam off pictures.
- Centre of gravity (highest intensity peak) calculation of the beam.
- Once the background is subtracted, zoom on the center of the image (picture above).
- Sigma values are obtained using formula (1) within the program, and saved in a .txt file for further analysis.

7. Fitting our data. Results

Now, since we want to fit that expression with a quadratic approximation, i.e.:

$$y(z) = a + bz + cz^2;$$

we need to arrange (2) separating the linear and the quadratic terms. By doing that, we obtain the coefficients *a,b* and *c*:

$$a = \sigma_{0x}^2 + z_{0x}^2 M_x^4 \left(\frac{\lambda}{4\pi\sigma_{0x}}\right)^2 \; ; \; (3)$$

$$b = -2z_{0x} M_x^4 \left(\frac{\lambda}{4\pi\sigma_{0x}}\right)^2 \; ; \; (4)$$

$$c = M_x^4 \left(\frac{\lambda}{4\pi\sigma_{0x}}\right)^2 \; ; \quad (5)$$

Once that is done, and taking into account that we know the values of these coefficients since we are fitting the function to an array of experimental values, we just need to solve the system, being M_x^2, σ_{0x} and z_{0x} the unknown parameters.

$$z_{0x} = -\frac{1}{2}\frac{b}{c}; \quad (6)$$

then:

$$a = \sigma_{0x}^2 + z_{0x}^2 c = \sigma_{0x}^2 + \frac{1}{4}\frac{b^2}{c};$$

which leads to:

$$\sigma_{0x} = \sqrt{a - \frac{b^2}{4c}}; \quad (7)$$

And finally, with this parameters calculated, we obtain the value of M_x^2 from (5):

$$M_x^2 = \sqrt{c}\frac{4\pi\sigma_{0x}}{\lambda}; \quad (8)$$

where λ is the wavelenght, which has a fixed value (in our case, 47 μm or 52 μm). Then we only need the square root of that value.

The software used in calculations were *Microsoft Excel*, *OriginPro 8.0* and *Gnuplot 3.7*, and of course *MATLAB* as we mentioned before.

With the fit values, and using formulas in (6), (7) and (8) we finally obtain the *M factor* for each axis, and allow us, at the same time, to plot the graphs below:

$\lambda = 52\ \mu m$:

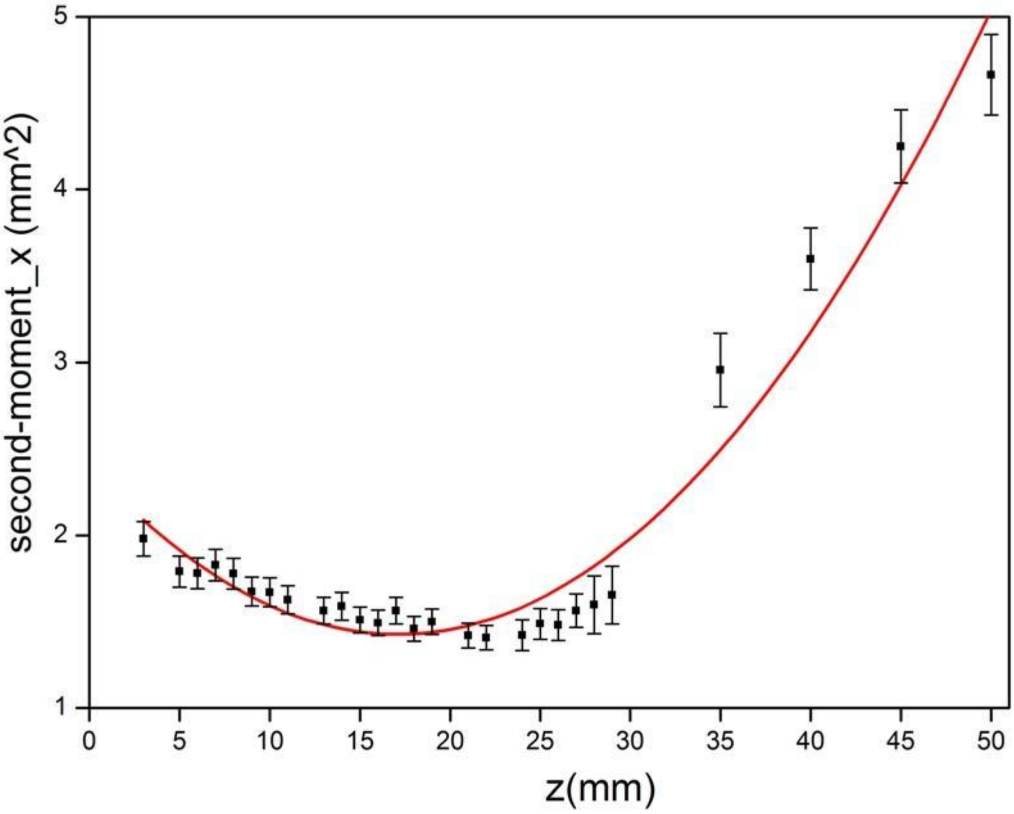

Figure 8: experimental values for σ_x ($\lambda = 52\ \mu m$) and its quadratic function fit.

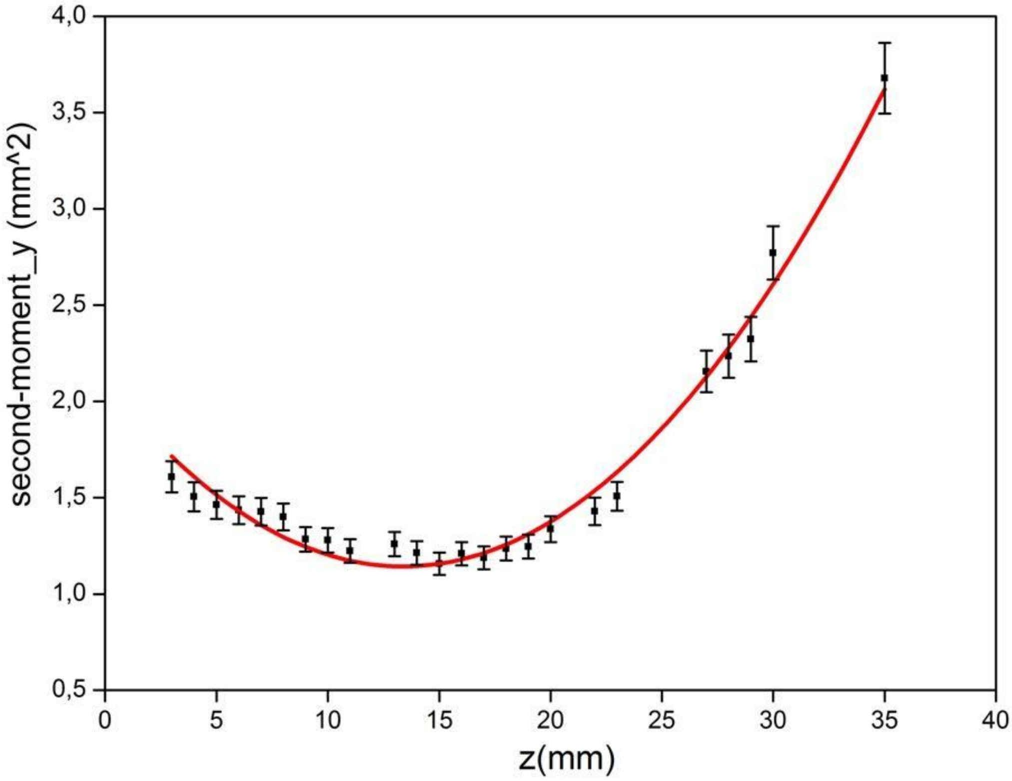

Figure 9: experimental values for σ_y ($\lambda = 52\ \mu m$) and its quadratic function fit.

$\boldsymbol{\lambda = 47\ \mu m}$:

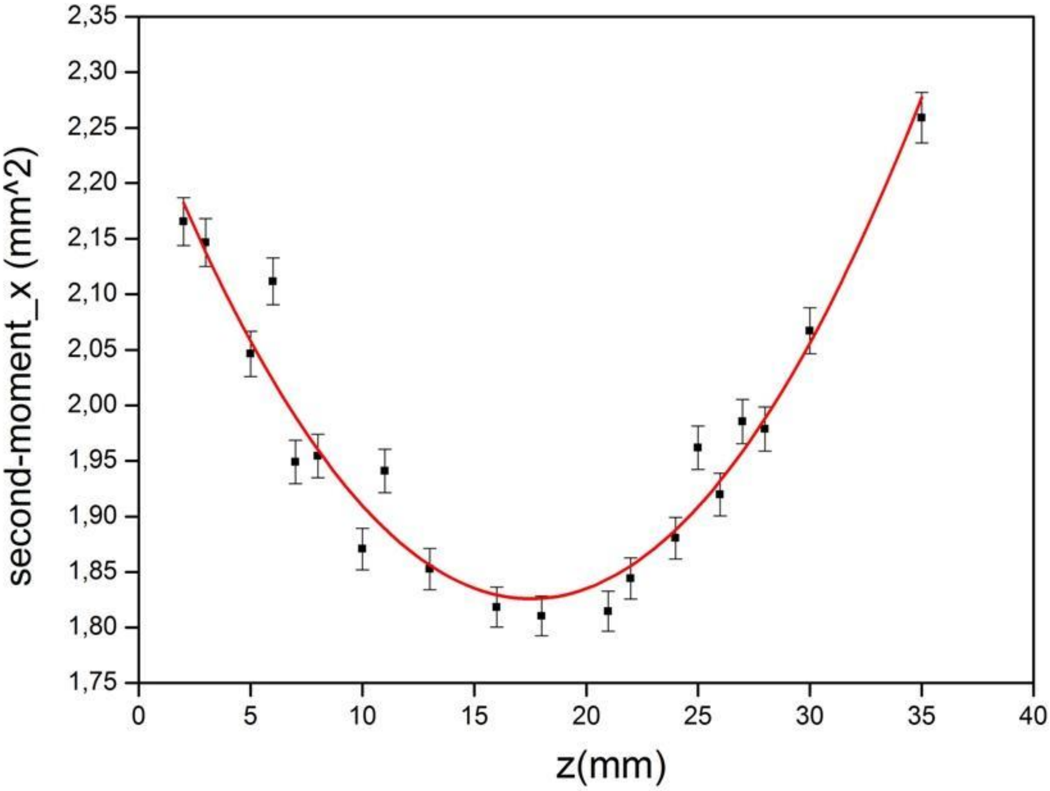

Figure 10: experimental values for σ_x ($\lambda = 47\ \mu m$) and its quadratic function fit.

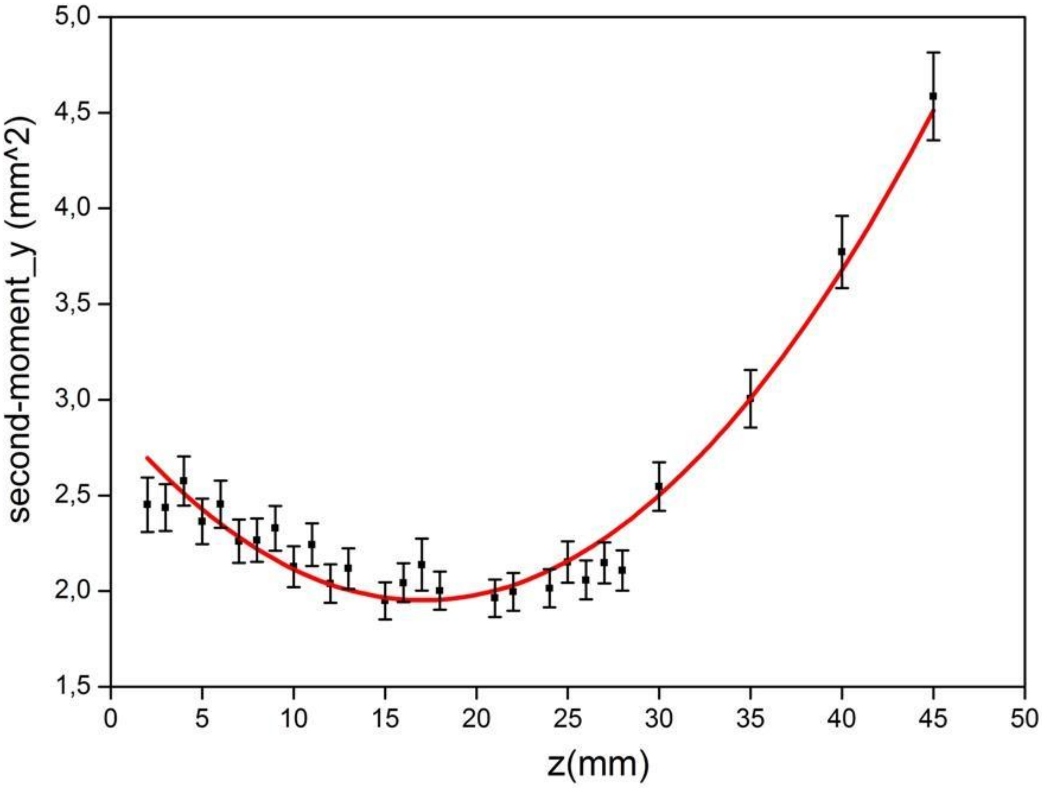

Figure 11: experimental values for σ_y ($\lambda = 47\ \mu m$) and its quadratic function fit.

$\boldsymbol{\lambda = 47\ \mu m}$:

$$z_{0x} = 25{,}36\ mm;\ \sigma_{0x} = 1{,}46\ mm;$$

$$\boldsymbol{M_x^2 = 21{,}8;\ M_x = 4{,}66}$$

$$z_{0y} = 15{,}89\ mm;\ \sigma_{0y} = 1{,}42\ mm;$$

$$\boldsymbol{M_y^2 = 22{,}52;\ M_y = 4{,}74}$$

$\boldsymbol{\lambda = 52\ \mu m}$:

$$z_{0x} = 14{,}73\ mm;\ \sigma_{0x} = 1{,}25\ mm;$$

$$\boldsymbol{M_x^2 = 17{,}71;\ M_x = 4{,}21}$$

$$z_{0y} = 13{,}37\ mm;\ \sigma_{0y} = 1{,}07\ mm;$$

$$\boldsymbol{M_y^2 = 18{,}81;\ M_y = 4{,}34}$$

The values on each axis are usually different, due to the so-called astigmatism effect: the intensity peaks (maximums) in both x and y axis belong to different z points.

Conclusions

The most important thing here is not the *M* value itself but the shape of the data. As we have seen, the data fits clearly and quite well to a quadratic function, which means that our beam behaves like conventional laser light since the model we started with is the one used for any known (conventional) laser beam. So despite the fact that the THz (and any FEL) light is not generated at all like common lasers, we can model it like that. This means that we don't need any new FEL light model yet, but we can use the so-known nowadays laser theory (i.e. second momentum) to predict and simulate how our THz beam will propagate and which is going to be its shape.

Ideal gaussian beams have *M=1*, and TiSa laser system at FLASH has *M=3*. We obtained that our THz beam is roughly *M=4.3*, which is a big result if we take into account that the light source is completely different than laser's, since it's generated by different processes we mentioned before. But still, we can use laser models with more than acceptable parameters and be able to perform good-quality experiments, since we will know the optical behavior (i.e. focal point, beam spot at any given point, and so on) of our THz beam.

Last, but not least goal was to prove that the *M* factor does not depend on the wavelength. The results, taking into account the error propagation, allow us to confirm that. So far as we know, these measurements are extremely sensitive to background, but we still got very good shapes of our data, so the deviation of our results is totally justified. This is a very important point, because our beamline will be fully characterized by only one *M* value, with no need to re-calculate it each time we want to change the wavelength.

Acknowledgments

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I would specially thank Nikola for all the hours of explanations and all the patience he got with me.

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Last but not least, I'd like to thank my friends there for all the funny and intense time I shared with them.

References

[1] M. Gensch et al.: *New infrared undulator beamline at FLASH*, Infrared Physics & Technology 51, 2008, 423-425.

[2] A.E. Siegman, Stanford University*: How to (Maybe) Measure Laser Beam Quality,* 1997. Tutorial presentation at the Optical Society of America, Annual Meeting.

[3] http://www.rp-photonics.com/beam_parameter_product.html

[4] http://www.rp-photonics.com/m2_factor.html

[5] http://hasylab.desy.de/facilities/flash/

Annexe: data

Table 1: Experimental values of the second momentum for $\lambda = 47\ \mu m$.

z(mm)	sigma_x^2(mm^2)	sigma_y^2(mm^2)
2	2,778	2,452
3	2,785	2,437
4	2,838	2,576
5	2,774	2,365
6	2,806	2,455
7	2,742	2,262
8	2,733	2,267
9	2,764	2,329
10	2,653	2,129
11	2,680	2,244
12	2,597	2,040
13	2,592	2,119
14	2,656	2,298
15	2,465	1,949
16	2,484	2,044
17	2,505	2,138
18	2,413	2,002
19	2,592	2,330
20	2,581	2,366
21	2,304	1,963
22	2,169	1,996
23	2,299	2,341
24	2,088	2,015
25	2,120	2,153
26	2,014	2,059
27	2,043	2,148
28	1,963	2,108
29	2,810	3,098
30	2,318	2,547
35	2,535	3,005
40	2,821	3,771
45	3,635	4,586
50	4,295	5,332

Table 2: Experimental values of the second momentum for $\lambda = 52\ \mu m$.

z(mm)	sigma_x^2(mm^2)	sigma_y^2(mm^2)
2	1,935	1,598
3	1,972	1,608
4	1,863	1,505
5	1,847	1,464
6	1,844	1,436
7	1,863	1,427
8	1,852	1,400
9	1,743	1,284
10	1,741	1,279
11	1,701	1,224
12	1,830	1,356
13	1,743	1,260
14	1,689	1,213
15	1,586	1,157
16	1,622	1,210
17	1,539	1,189
18	1,533	1,237
19	1,472	1,247
20	1,524	1,337
21	1,739	1,542
22	1,439	1,429
23	1,468	1,508
24	1,848	1,885
25	2,394	2,261
26	2,457	2,339
27	1,939	2,156
28	1,969	2,234
29	1,979	2,323
30	2,893	2,770
35	3,534	3,679
40	3,892	4,017
45	4,936	4,477
50	5,445	4,643