The Terahertz Beamline at FLASH
DESY Hamburg

Ekaterina Zapolnova, NRNU MEPhI, Moscow, Russia
Markus Pötzlberger, TU Vienna, Vienna, Austria

September 11, 2014

The THz Beamline at FLASH

FLASH is a free electron laser. This term describes already its working principle. Flash accelerates bunches of electrons to relativistic velocities and uses them for the production of electromagnetic radiation. This radiation is obtained by forcing the electrons with magnetic fields on a slalom course. Each time when the electrons pass through one of the turnings of their winding course they experience a radial acceleration like any object on a circular trajectory. This acceleration leads, as in a Hertz dipole antenna, to emission of light. This light emitting process takes place in a part of the machine which is called undulator. This undulator hosts the magnets and is a massive construction in order to fix and control the magnets. This light production with undulator magnets benefits from the fact that the relativistic electrons emit their radiation under a narrow angle in electron beam direction. Up to this point the process is the same process which is nowadays used in synchrotrons to produce their synchrotron radiation.

The phenomenon which distinguishes a free electron laser from a synchrotron radiation source is abridged as SASE and stands for Self Amplified Spontaneous Emission. As mentioned before the electrons start to emit radiation when they enter the undulator. This "spontaneous" emission (its frequency composition and temporal profile) changes from run to run because it is created out of a statistical electron bunch. If this radiation becomes intense enough, than the electric field of the light and electrons start to interact. The result of this interaction is the formation of an electron bunch substructure, a so called micro-bunch structure. This means that the initial group of electrons is divided into subgroups of electrons as sketched in fig. 1.

Fig.1 *Left: Initial electron bunch, Right: electron bunch after SASE*

The electrons within these micro-bunches travel simultaneous through the undulator and coherently emit their radiation. This leads to a stronger electromagnetic field (more light), which leads to a stronger micro-bunching and so on. It amplifies itself and leads to the extremely high intensity and brilliance of free electron lasers. The mainly produced wavelength is affected by the electron energy, the magnetic field strength and the special periodicity of the undulator magnets. There is no principal limitation in the produced wavelength, which is one of major advantages of this technology. For example the FLASH facility produces radiation in the XUV wavelength range from 4 to 45 nm and THz radiation from 10 000 to 300 000 nm.

The part of the facility which creates this THz radiation is maintained by Nikola Stojanovic, Torsten Golz, Marc Temme and Daniel Espeloer. This "Team THz" maintains the existing machinery, continuously increases its abilities, performs experiments with it and supports external researchers during designing, setting up and measuring their experiments. Fortunately, such experiments were performed during our time at DESY.

Beamtime Experiment

An experiment at beam line 3 at FLASH where the whole THz team was strongly involved was performed together with the people around Leonard Müller. The aim of this experiment was to investigate the magnetization behavior of a cobalt platinum multilayer system, where the strong B field component of the THz radiation was used to influence the magnetization of the magnetic domains and the XUV pulse was used to record the changes in the magnetization. In order to record the dynamics of this process it was necessary to achieve a spatial and temporal overlap of both pulses and to perform a narrow scan over different delay times between the two pulses. Such an experiment needs an extensive preparation as illustrated by the design drawn in fig. 2. The beam travels from left from the end of the beam line, through the main vacuum chamber, towards a refocusing chamber where it is reflected back and focused to the actual experiment in the main chamber.

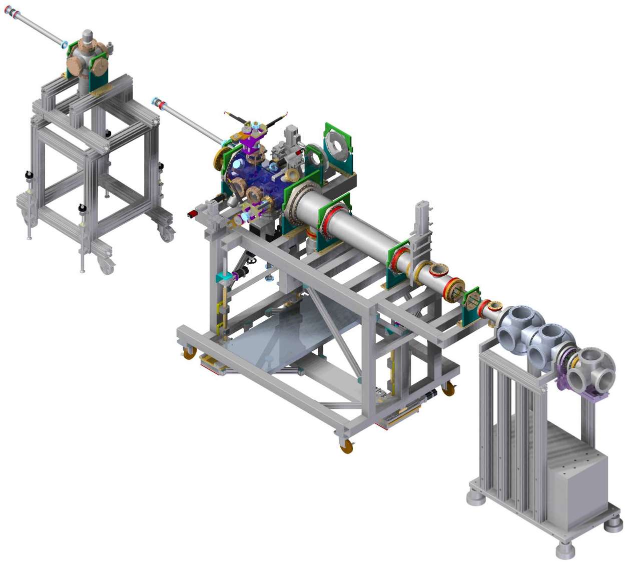
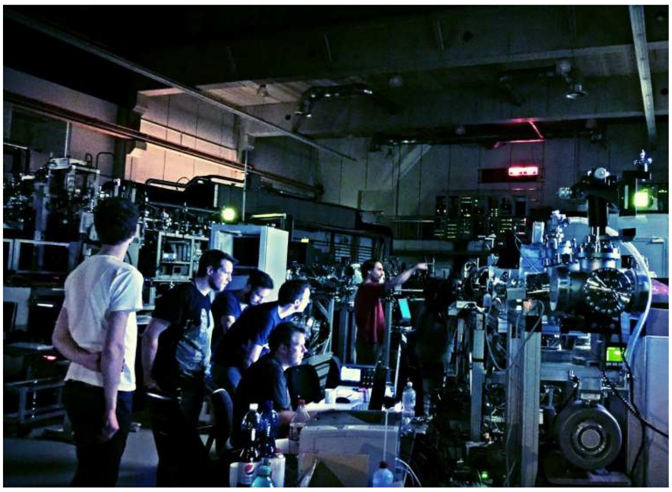
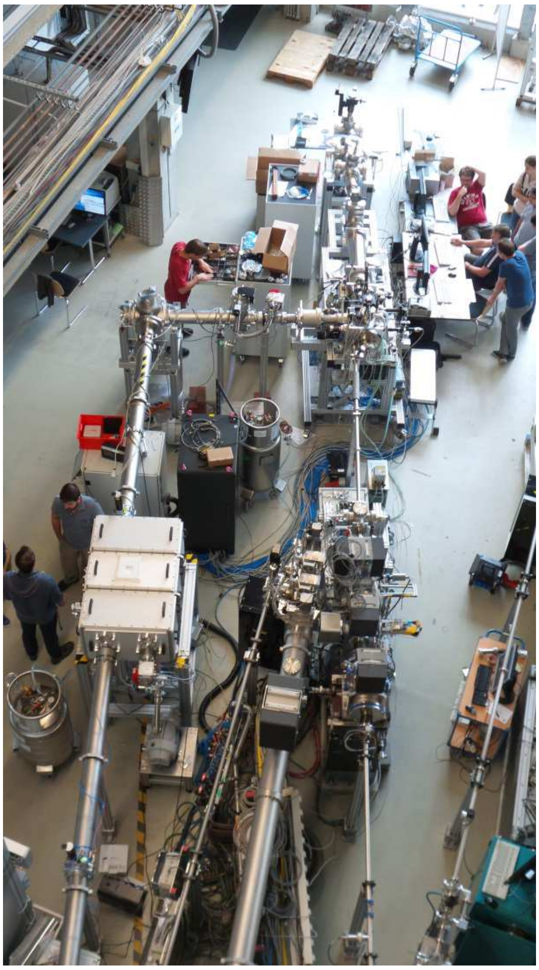


Fig. 2 *Technical drawing of the experiment*

The main vacuum chamber was already constructed for previous experiments. Therefore our task was to build the connections towards FLASH and the needed XUV refocusing chamber. The refocusing chamber was needed due to two reasons. First, it was necessary to compensate a technical given path length difference between the XUV and the THz beam in order to reach the temporal overlap. Second, the used multilayer mirror was a curved mirror in order to focus the light onto the small samples. The chamber was designed by Mark Temme and the setup was finished within days. The result can be seen on the picture to the right.

The complete experimental setup is shown on the picture to the right. The experiment received a beam time of more than 80 hours spread over several different shifts. Hence we had the opportunity to participate in day- and night shifts. The image below gives an impression of one of our night shifts.





Focal Length of Spherical Mirror

The usage of the spherical refocusing mirror in the refocusing chamber led to our next project. For the set-up of the experiment it was necessary to figure out the focal length of the used curved mirror. The only practical way to do this was to illuminate the mirror with a collimated beam and to reflect some of the incident light under a slight angle. The focal length was then measure as the distance between the mirror and the so produced focal point of the reflection. The measured focal length was 349cm. One should keep in mind that a reasonable small amount of effort was invested into the measurement of the exact value. Especially the long Rayleigh length makes the measurement fault-prone, since the position of the focal point was jugged based on visual inspection. The achieved precision was sufficient to adapt the experimental set-up accordingly.

Shearing Interferometer

For the previous mentioned measurement of the focal length it was necessary to use a collimated beam. A possible way to ensure that the beam is collimated is the use of a device called shearing interferometer.

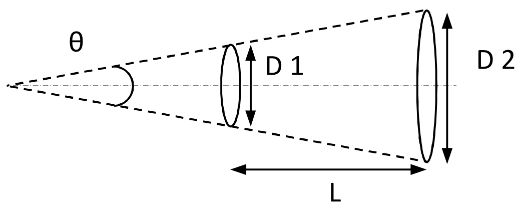
"Das Scher-Interferometer eignet sich sehr gut, um schnell und einfach die Ebenheit einer Wellenfront zu untersuchen.
Der Vorteil des Scher-Interferometers ist sein einfacher und robuster Aufbau."
Quotation: Handbuch Bauelemente der Optik, H. Naumann et al., 7th version, Carl Hanser Verlag, 2014

As stated above the shearing interferometer is very simple and robust in use and generates an interference pattern in dependence on the beam divergence. This is experimentally achieved by shining the beam of interest in x-direction onto a slightly wedged glass plate. This glass plate is 45° tilted against the beam, such that a part of the beam is reflected on the first surface upwards in z-direction. The second reflection from the second surface of the plate experience a shear in x- and tilt in y-direction, due to the thickness of the plate and the wedge of the plate in y-direction. Both reflections travel in z-direction and overlap each other to a certain extent. In the area of overlap an interference fringe can be detected with a diffuse screen. The observed pattern for collimated coherent light is an interference fringe parallel to the incident beam as shown in fig. 3 a), whereas for non-collimated beams a tilted pattern is observed. How much this pattern is tilted against the incident direction depends on the degree of collimation of the beam. Throughout this report we describe this tilt of the pattern against the beam direction with its tilt angle. As depicted in fig. 3 b) and c) it is possible to distinguish between a convergent and a divergent beam, because they are tilted in the opposite direction.

a) b) c)

***Fig 3**. Interference pattern for collimated, convergent and divergent beam*

The open question was if it is possible to use the shearing interferometer for quantitative measurements, or expressed in another term, if we can find the relation between beam divergence and tilt angle of the interference pattern. In order to measure this relation we used a knife-edge method to define the beam diameter. To do so it was necessary to assume our laser beam to be of Gaussian shape. Once we know the beam diameter at two different distances from the source, we are able to calculate the beam divergence θ out of it, see fig. 4. This allows us to record the relation between the divergence and the tilt angle.



$$\theta = 2\tan^{-1}\left(\frac{D2 - D1}{2\,L}\right)$$

***Fig 4**. Geometrical relation between the beam diameter and the divergence angle*

For the experiment we used a red diode laser with beam size of 4 mm as light source. The shearing interferometer that we used needed a beam diameter between 10 and 25 mm. Therefore we had to expand the beam. For this purpose we used a Keplerian telescope with magnification of 4. This allowed us to observe the interference on the shear interferometer screen. Moreover the telescope allowed us to collimate the beam and to produce beams with various diameter evolutions by adjusting the distance between the lenses with a linear stage. Figure 5 shows a scheme of the set-up and figure 6 a) shows a picture of the real version. Due to technical limitations is was necessary to use a focusing optics in front of the detector, to cut the focused beam instead of the original and to add a mirror, as shown in Figure 6 b).

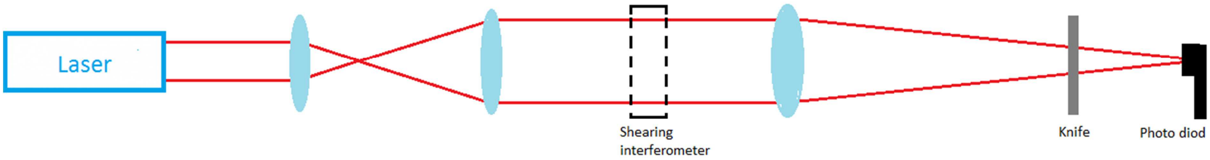
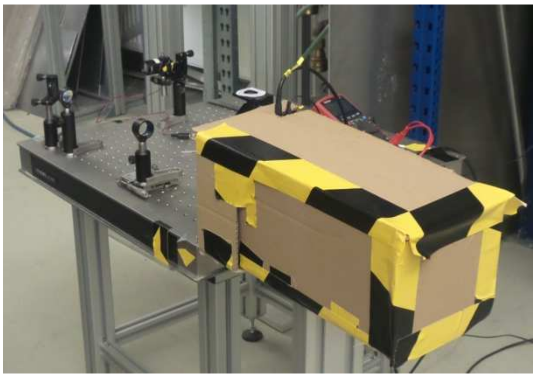


Fig 5. *Beam diameter measurement scheme*



a) b)

Fig 6. *a) The real set-up b) The knife-edge detection unit*

The measurement procedure was the following. The shear interferometer was inserted at a defined position after the telescope. Then the telescope was tuned in order to get a certain tilt angle of the interference patter. We equipped the shearing interferometer with a measuring scale in order to ease the angular measurement. Then the shearing interferometer was removed again and the diameter of the beam at a defined distance from the table was measured.

The measurement principle of the knife-edge method is based on the principal knowledge of the intensity beam profile. For the case of a Gaussian beam profile one can integrate one dimension and obtains a Gaussian power per length profile. The integration of this profile over the remaining dimension gives the transmitted power in dependence of this dimension (the blade position). The integral of a Gaussian function is an error function. Therefore if one cuts a beam like in fig. 7, then one observes a blade position dependent power which behaves like an error function.

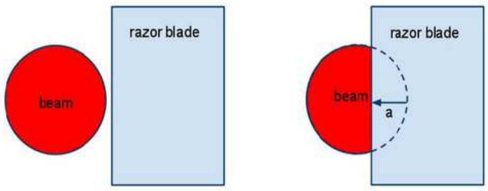


Fig 7. *Principle of the sharp edge method*

For tilt angles 0, 10, 20, 30, 40 and 50 degrees we cut the beam with the sharp edge and measured the amount of light (power) with a photo diode for knife position from completely closed beam until completely opened. The knife was attached to a micrometer-linear stage. We moved in steps of either 4 or 6 mm. We made these measurements for 2 different distances from the optical breadboard: 25 mm and 2910 mm. All together we recorded approximately 800 data points. The amount of points was chosen according to the needs of the fitting function.

Two types of analysis were made: 1) finding beam diameter and 2) finding tilt angle - divergence dependence. To find the beam diameter we used least squares method. When finding the beam width by the least squares method one has the problem that the theoretical function (integral of a Gaussian) can not be written as a formula and thus cannot be directly compared to the data. The integral in fact defines the "error function", or erf(x). We performed our fit by fitting our data to an error function of the following type:

$$A + B * \mathrm{erf}(\frac{x - C}{D})$$

The variables A, B, C and D were our fitting parameters. After our Matlab code found the appropriate values for these parameters, we took the derivative of this error function and got the Gaussian. We did this for each tilt angle at 2 different distances. For each Gaussian we calculated its FWHM value and consider this value as its beam diameter.

For 25mm distance from the optical breadboard we got the following beam diameters:

Degree [°]	0	10	20	30	40	50
FWHM [mm]	2,4691	2,4713	2,4882	2,5202	2,5104	2,5929

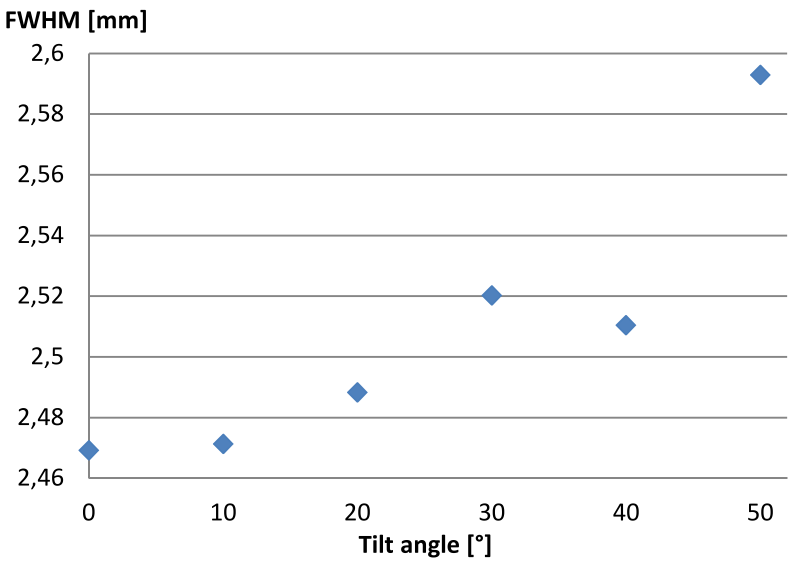


Fig. 8 *FWHM values of the beam at the distance of 25mm*

For 2910 mm distance:

Degree [°]	0	10	20	30	40	50
FWHM [mm]	2,7658	2,7938	2,8502	2,9215	3,0524	2,8973

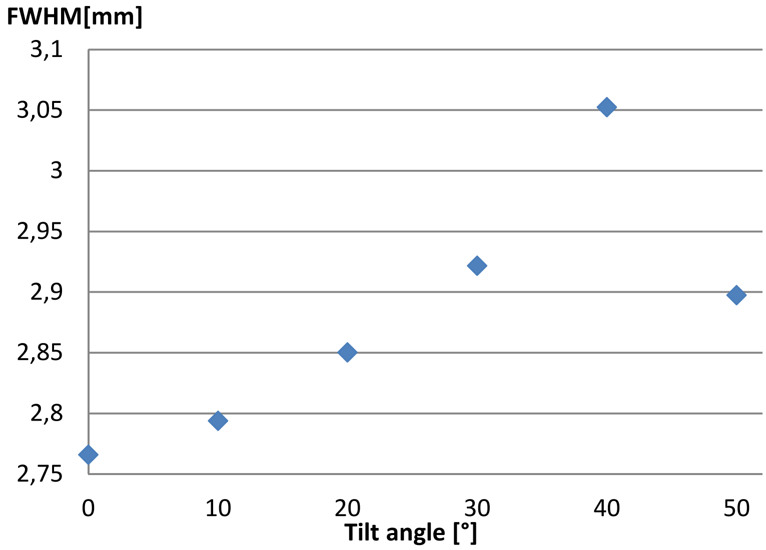


Fig. 9 *FWHM values of the beam at the distance of 2910mm*

One can see in fig. 8 and fig. 9 that there are two points which don't follow the tendency. We analyzed how our data for these points fit the error function and on the graphs below it can be seen that they fit well. Fig. 10 shows the fitting results of 40° tilt angle at 25 mm distance, fig. 11 the result of 50° at 2910mm and fig. 12 the result of 10° at 2910mm. The first two figures belong to the corrupted data points, whereas the last figure belongs to a reasonable point. The comparison of these figures indicates that the tendency violations are not caused by a bad fit of the data. A possible reason could be the observed intensity instabilities of the laser. Therefore we neglected the results of the tilt angles 40° and 50°.

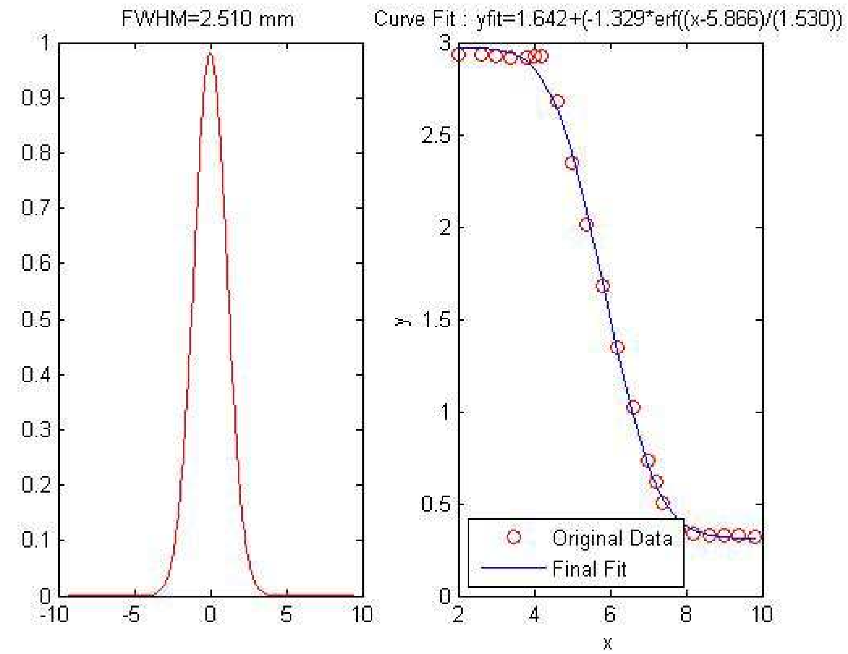


Fig. 10 *Data fit for 40° tilt angle at 25mm distance*

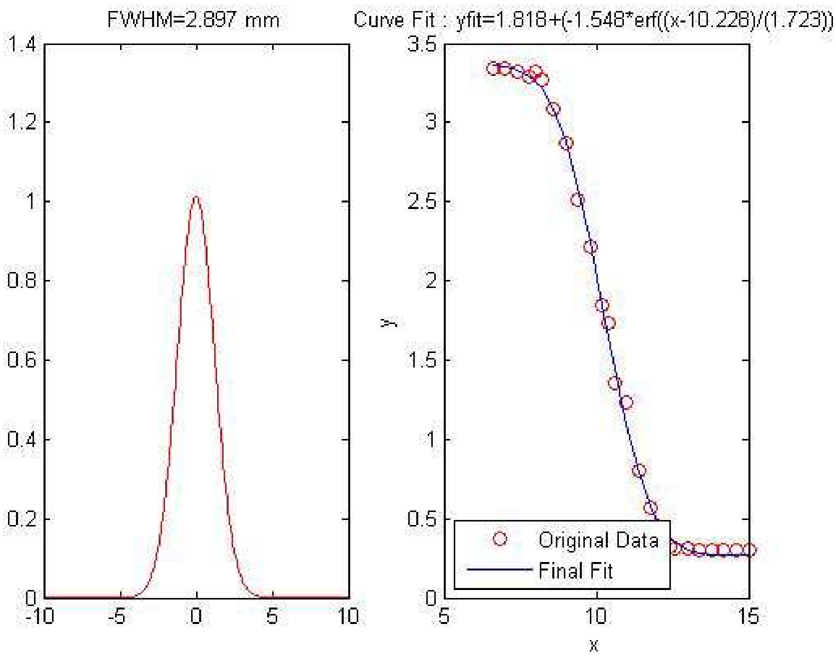


Fig. 11 *Data fit for 50° tilt angle at 2910mm distance*

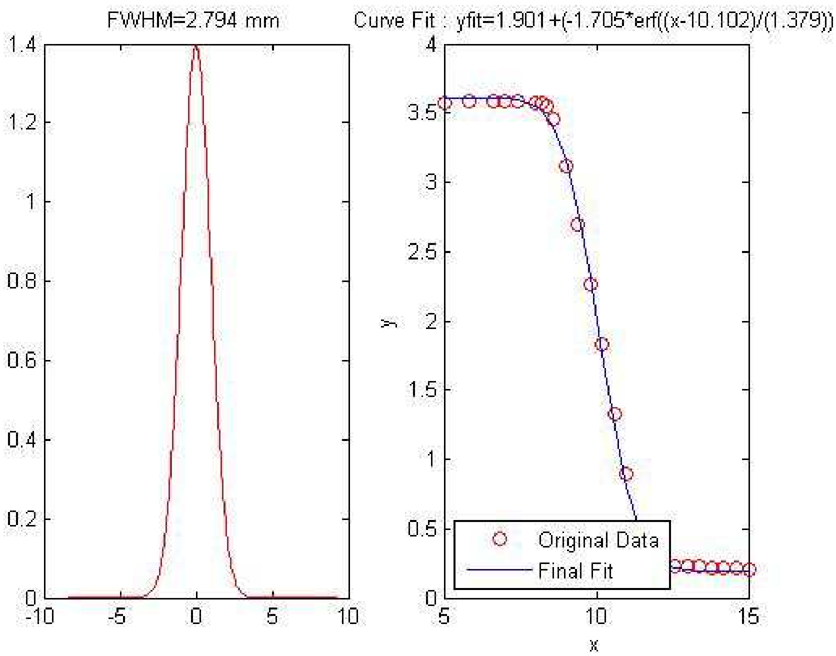


Fig. 12 *Data fit for 10° tilt angle at 2910mm distance*

The finally obtained relation between the beam divergence and the interference pattern tilt angle is:

Tilt angle [°]	0	10	20	30	40	50
Θ [°]	0,0059	0,0064	0,0072	0,0079	0,0108	0,0060

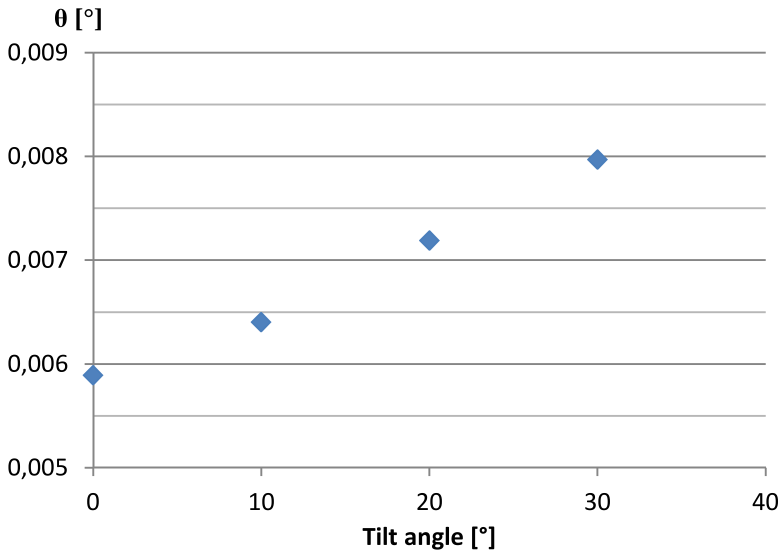


Fig. 13 *Beam divergence angle θ against the tilt angle of the shearing interferometer pattern*

From the graph in fig. 13 we can see a well behaved tendency, which relates larger tilt angles to larger beam divergences. The divergence offset of 0.0059° for the parallel pattern could imply that the absolute precision of the measurement with the shearing interferometer is limited or that we made a systematical error.

LED

The main aim of the LED experiment was to focus the light from an LED surface in such a way that the highest possible intensity on a spot larger than 0.04 mm^2 is obtained. The requested intensity was at least 200 W/cm^2. The set-up which would fulfill these specifications would be used for the manipulation of terahertz radiation with germanium.

We used a high power LED from the company Luminus. We did our measurements with the green LED, because it has the highest luminance - about 3900 lm in continuous mode. The emitting area of the LED was three times four millimeter large. We used different approaches from geometrical and non-imaging optics in order to concentrate the light. It appeared to be absolutely not trivial to get the needed intensity.

Our first attempt was to collimate the LED light. We used different lenses with different focal lengths and diameters. We have found that the most suitable lens was a Fresnel lens with diameter of 1 inch and focal length of 1.6 inch, because it has the highest diameter to focal length ratio. The principle idea of this experiment is shown at fig. 14.

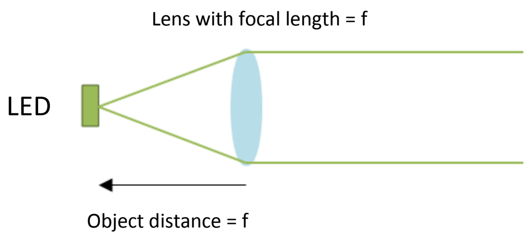


Fig. 14 *Beam divergence angle θ against the tilt angle of the shearing interferometer pattern*

This idea would work out for a point source. But since the LED has a large emitting area it was not possible to obtain a collimated beam with the optics we have used.

Our next try was to use two lenses of different diameters to get a small image of the source. The set-up is illustrated on fig. 15. We were able to get a spot size of 3 mm^2 by using an aspherical lens with f = 10 mm and a Fresnel lens with f = 1 inch. The amount of light was measured with a photodiode and a neutral density filter of strength 3. The measured voltage was 2V, where 0,34V is noise and the total output of the LED was 3V. These are by now the best results with this kind of set-up.

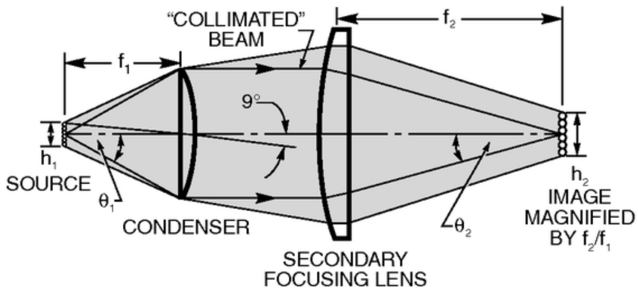


Fig. 15 *Focusing method with two lenses*

Our next approach was to use a Compound Parabolic Concentrator (CPC). On the fig. 16 our set-up for this experiment is depicted.

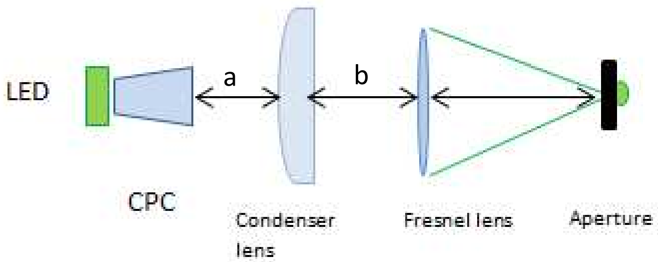


Fig. 16 *Set-up with CPC*

With the CPC we faced the problem that the image that we got consists of a halo and the image of the LED. We put an aperture after the Fresnel lens. This time we used a power meter for power measurement. For a = 4cm, b = 6.5cm we got the following results:

Spot size, mm^2	Power, W	W/cm^2
2	0.15	7.5

The usage of the aperture was necessary because the surrounding halo contains a not negligible amount of light. The measurement without aperture would result in a much higher power and intensity. If one would still measure the image together with its halo, then one would have to use the halo size as spot size and one would end up with a much lower intensity. Further the spot is not homogeneous, so we do not measure in this way. To place the aperture into the beam after the Fresnel lens is also not the best way how to measure the spot intensity. The reason is that the aperture also cuts away beams belonging to the image and thereby reduces the spot intensity. The way how it should be done is to place the aperture right in front of the power meter. Maybe one should try to re-measure the spot intensity of this set-up again with this improved measurement configuration.

Another idea was to place a lens in a distance larger than 2f from the source in order to create a small image of the LED. We used different Fresnel lenses. In the table below we summarized our results for this set-up. We used different Fresnel lenses and different distances from the object. One can see that the power that we got is not enough for our goal, but these results are at least better than of previous set-ups.

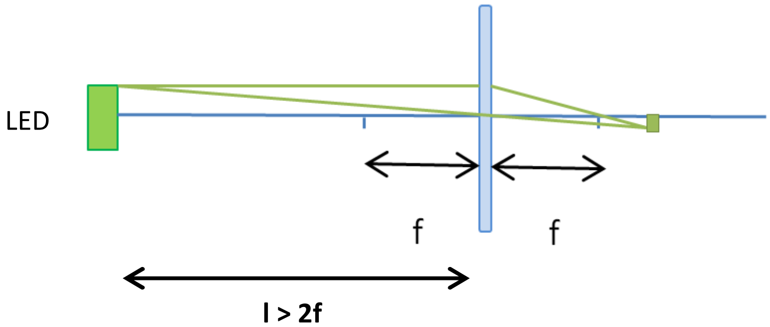


Fig.17 *Set-up with one Fresnel lens*

Spot size, mm^2	Power, W	W/cm^2
2.4	0.102	4.25
1.5	0.051	3.4
6	0.2	3.33
16	1.58	9.875
2	0.25	12.5
5	0.37	7.4
1.5	0.17	11.33
2	0.24	12

We had the best result for the Fresnel lens with f = 15 mm (0.6 inch) and the distance from LED to Fresnel lens l = 5.5 cm.

Then we used a combination of 2 Fresnel lenses. The first approach was to use the following scheme:

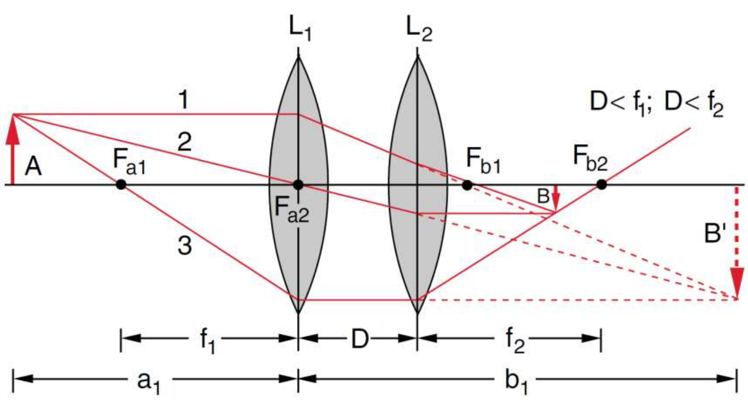


Fig. 18 *Set-up with 2 Fresnel lenses*

So we placed the first lens in a distance larger than f_1 from the LED and the second lens in the optimized distance to get the best results possible. The results are:

Spot size, mm^2	Power, W	W/cm^2
2	0.06	3
3	0.088	2.93
3	0.545	18.16
8	1.25	15.625
2	0.5	25
2	0.36	18
2	0.388	19.4
2	0.372	18.6
2	0.392	19.6

We got the best value for this experiment with the following set-up: a_1= 40 mm, f_1 = 21 mm, D = 15 mm, f_2 = 15 mm.

Then we put two Fresnel lenses very close to each other in order to obtain a reduced focal length. We used a CCD camera for measuring the spot size and a power meter, as before. And in this way we got the best results by now:

Spot size, mm^2	Power, W	W/cm^2
1.8	0.39	21.66666667
1.0795	0.272	25.19685039
0.821	0.247	30.08526188
0.7	0.186	26.57142857

The best result was obtained for the following configuration: distance from LED to Fresnel lens d = 5.3cm, f=12cm. Although the achieved intensity is not sufficient for the intended purpose of switching and modifying THz pulses.

The last optical design used a kind of parabolic mirror, which we added to a Fresnel lense set-up. We placed this reflecting metallic surface which looked like a parabolic mirror in front of the LED to redirect some of the stray light. It turned out that the mirror increases the spot intensity by several percent, but the draw back for measurement is that it creates a halo around the bright image.

Possible further attempts:

One of our ideas was to try special optics for the collimation of LED light. These are LED collimators, which are mainly used in torches or similar illumination devices. The principle idea of such collimator is shown on the fig. 19. The reason why we have not tried it is only the lack of time. This approach is very promising, because this kind of collimator is used in torches in order to illuminate objects at the distance of 200 meters and more. For this purpose the light should be well collimated. There are different types of collimators. But we are mostly interested in ones with the smallest beam divergence. Once we have such a less divergent beam, then we would try to focus it down again.

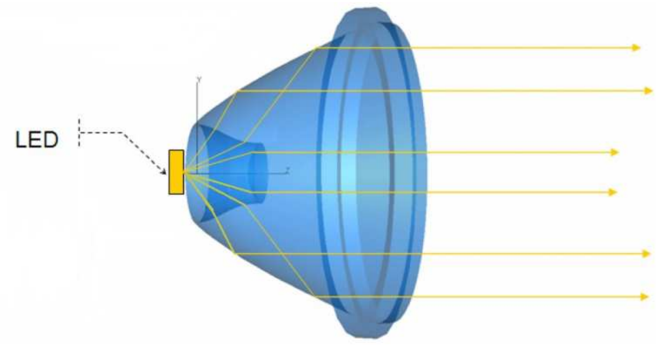


Fig. 19 *LED Collimator*

Other optical components that one could try are parabolic reflectors. We used a reflector, but the results are not clear, because the reflector that we used was a "hand-made" one. To get some significant results a reflector should have a very smooth surface, which we could not achieve during the Summer Student Program.

Fig. 20 *Parabolic reflector*

If the attempt with the collimation of light is successful, than it is possible to use an off-axis parabolic mirror to focus the light onto a tiny spot. But for this kind of experiment one should have well collimated light, otherwise it's not possible to have a small spot with the mirror. It's not possible to use this method directly for LED light, because these mirrors introduce significant aberrations for extended sources.

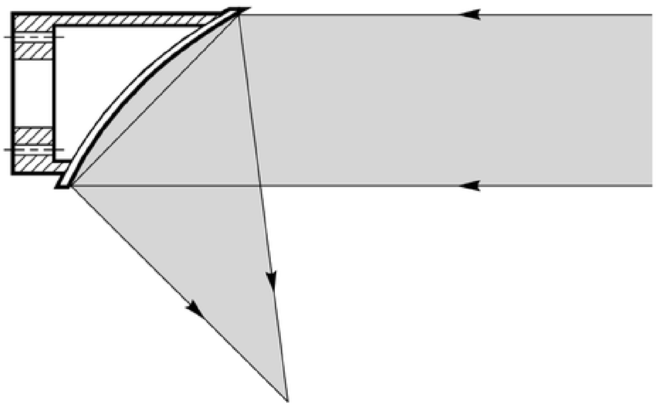


Fig. 21 *Off-axis parabolic mirror*

Conclusion

We enjoyed our stay at DESY and learned a lot during this time. We especially gained a lot of practice in making scientific decisions.
Regarding our projects one can conclude that the shearing interferometer is a very sensitive and useful device. The measured relation between the interference pattern tilt angle and the beam divergence should be used carefully. Because we do not know it this relation depends on the initial beam diameter and if we made a systematic error in our knife-edge measurement.
The LED project made quite some progress during our stay. Though I was not possible to reach the requested properties jet. Maybe the new components will allow one to push the intensity even further. In principle it could be possible to reach the needed intensity, because one is still far away from the minimal accepted spot size.