



Generation of terahertz radiation with femtosecond laser pulses

Summer student project at DESY-FLA

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Abstract:

Terahertz (THz) radiation with wavelengths in the mid- and far-infrared regime is used at the Free-Electron Laser in Hamburg (FLASH) for longitudinal electron bunch diagnostics. A laser-driven source of THz pulses, which is independent from the accelerator facility is expected to be a valuable tool for the development and commissioning of novel detection techniques for applications e.g. at a free-electron laser.

The generation process in ambient air is based on the frequency mixing of the fundamental frequency of intense laser pulses of femtoseconds length and the second harmonic produced e.g. in a non-linear crystal.

The goal of this project is to set up a THz source based on laser pulses, to characterize the pulses with spectroscopic techniques and the application on detector systems which are going to be used at FLASH

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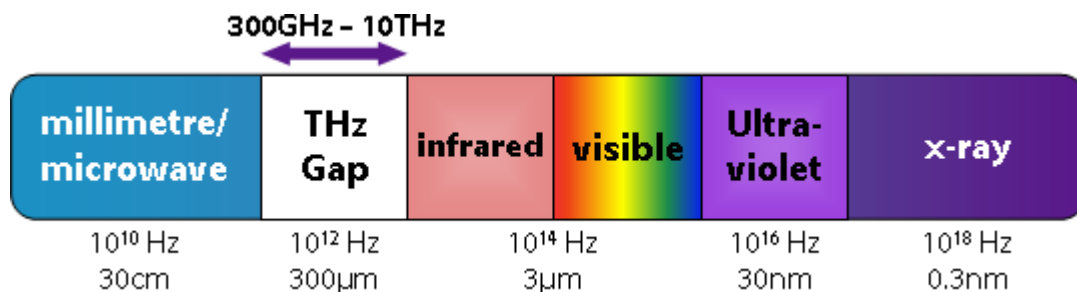
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1. Introduction

1.1 What is terahertz?

In physics, terahertz radiation consists of electromagnetic waves at frequencies from 100 GHz (10^{11} Hz) to the low frequency edge of the far-infrared light band, 10 THz (10^{13} Hz). Corresponding wavelengths of radiation in this band range from 1 mm to 0.1 mm (or 100 μm)

Terahertz radiation occupies a middle ground between microwaves and infrared light waves, and technology for generating and manipulating it is in its infancy, and is a subject of active research. It represents the region in the electromagnetic spectrum that the frequency of electromagnetic radiation becomes too high to be measured by directly counting cycles using electronic counters, and must be measured by the proxy properties of wavelength and energy. Similarly, in this frequency range the generation and modulation of coherent electromagnetic signals ceases to be possible by the conventional electronic devices used to generate radio waves and microwaves, and requires new devices and techniques [1].



Pic 1. Position of THz radiation in the spectrum of electromagnetic waves[1]

Currently there are a lot of fields of application for THz radiation.

The generation of intense sub-picosecond pulses in the terahertz (THz) spectral range (~ 0.1 –10 THz) is an important current direction in ultra-fast spectroscopy. Spectroscopy in terahertz radiation could provide novel information in chemistry and biochemistry. It can be applied in medical imaging because of relatively low energy of photons it would not damage any living cells or DNA. THz radiation can detect differences in water content. It can be applied for 3D imaging of teeth. THz can be applied in security screening because it can penetrate fabrics and plastics and can be used to detect concealed weapons on a person remotely. It also can be applied in submillimetre astronomy, communications and manufacturing.

1.2 Where we will use it

Terahertz radiation with wavelengths in the mid- and far-infrared regime is used at the Free-Electron Laser in Hamburg (FLASH) for longitudinal electron bunch diagnostics. When charged particles pass the boundary of two media with two different dielectric constants, transition radiation is emitted. For electron beam parameters at FLASH, in particular ultra-relativistic electron bunches with bunch lengths shorter than 500 fs, the coherent fraction of transition radiation provides frequency components in the THz regime.. By a system of mirrors this radiation is sent through pipes to an external laser laboratory

where the longitudinal shape and dimension of the electron bunches are investigated e.g. by spectroscopic methods.

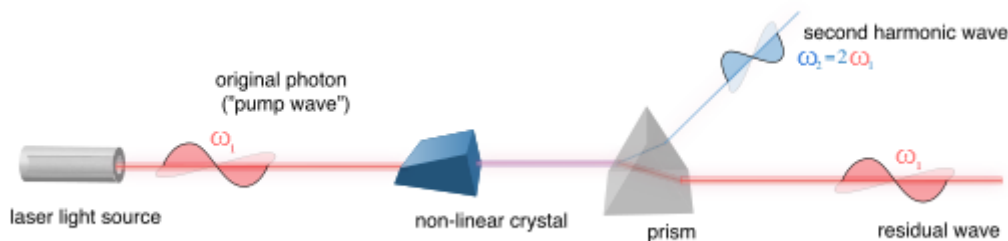
However, it is not always possible to generate coherent transition radiation, since it requires the operation of the accelerator and beam with certain parameters.

A laser-driven source of THz pulses, which is independent from the accelerator facility is expected to be a valuable tool for the development and commissioning of novel detection techniques like new detectors for infrared radiation. This source would be very useful for configuration of hardware; the adjusting of optical components and filters. It would be very convenient to have a source of terahertz radiation which will be independent from the accelerator facility.

1.3 Information about components

Barium borate is an inorganic compound, a borate of barium with a chemical formula BaB_2O_4 or $\text{Ba}(\text{BO}_2)_2$. It is available as a hydrate or dehydrated form, as white powder or colorless crystals. BBO is a common nonlinear optical material. BBO is a popular crystal for second harmonic generation [2].

Second harmonic generation is a nonlinear optical process, in which photons interacting with a nonlinear material are effectively "combined" to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons. It is a special case of sum frequency generation [3].



Pic 2. Second harmonic generation scheme[3]

Laser

The laser system used for the experiment is a commercial titanium-doped sapphire (Ti:Sa) laser amplifier Spectra Physics Spitfire Pro XP) pumped by a Ti:Sa oscillator (Coherent Micra-5). Key parameters are:

Table 1. Laser parameters	
Laser parameters	Value
Pulse duration, fs	50-150
Peak power, GW	30

Max pulse energy, mJ	2
Max average power , W	2
Repetition rate, kHz	1
Central wavelength, nm	800

Detecting of beam light

To detect the laser beam of 800 nm we used an infrared viewing scope and special wavelength shifting cards.



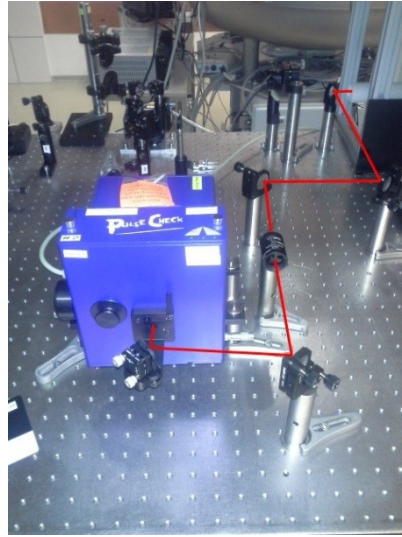
Pic 3. Infrared viewing scope and special wavelength shifting cards.

2. Preparation for the experiment

2.1 Pulse length measurement

Before we start the experiment we should make some measurement of most valuable parameters of our laser. One of the most important parameters of the laser for our experiment is the length of the laser pulse because it will largely determine the characteristics of the plasma that we need to for terahertz radiation producing. Experimental setup is shown below (Pic. 4).

The pulse length was measured with a help of a commercial autocorrelation device (blue box on Pic. 4) which works on the principle of a Michelson interferometer and second-harmonic generation. To avoid destruction of autocorrelator we decreased the power of laser beam with attenuators and provided the collimation of the laser beam.

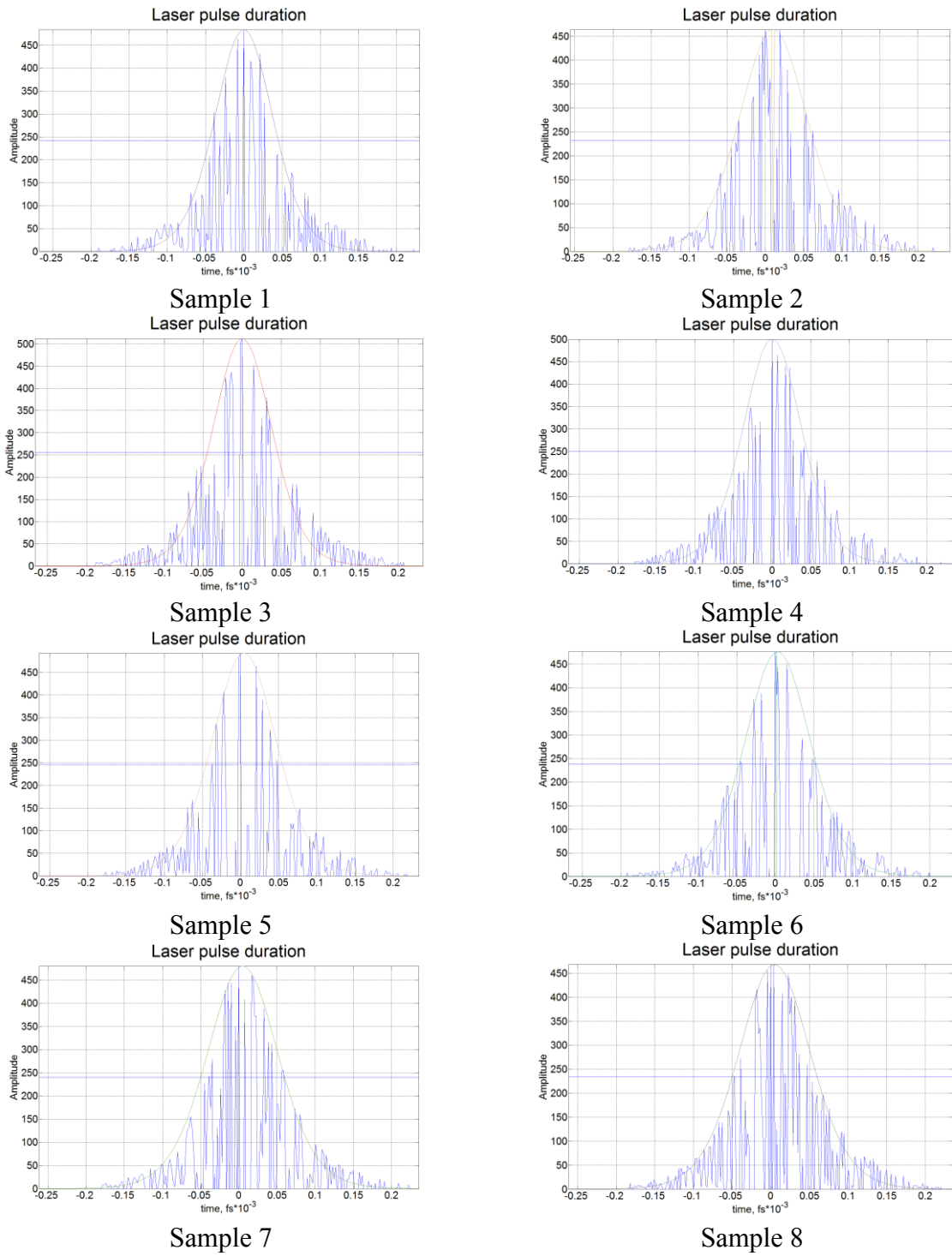


Pic 4. Beam length measurement experiment scheme

Processing of data obtained from the interferometer was carried out using a script written for MATLAB. For every graph autocorrelation function (with the most suitable value of $\Delta\tau_A^{FWHM}$) for pulses providing a hyperbolic secant-like shape was constructed (pic 5).

$$A(\tau) = \frac{3}{\sinh^2 \left(2.7196 \frac{\tau}{\Delta\tau_A^{FWHM}} \right)} \left[\frac{2.7196\tau}{\Delta\tau_A^{FWHM}} \coth \left(\frac{2.7196\tau}{\Delta\tau_A^{FWHM}} \right) - 1 \right]$$

$\Delta\tau_A^{FWHM}$ – Full width half maximum pulse length



Pic 5. Autocorrelation results

For each sample the beam length was calculated. Results can be observed in a table below.

Table 2. Measured pulse duration	
Number of sample	Laser Pulse Duration, fs
1	68.1
2	68.1
3	58.3
4	58.3

5	64.2
6	71.9
7	69.3
8	61.6

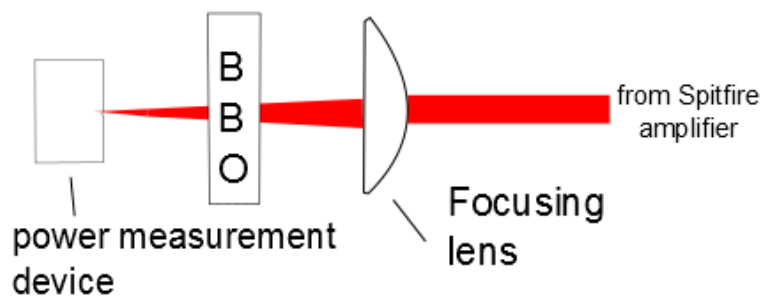
From this result we calculated mean value $T=65\pm 5$ fs. This data correlate well with our information about laser and former measurements.

2.2 Power Measurement

The second important parameter for our experiment is the power of the laser beam. We provided two experiments for power measurements: one for measurement of the total beam light energy and another for measurement of the power of the second harmonic (400 nm, blue light).

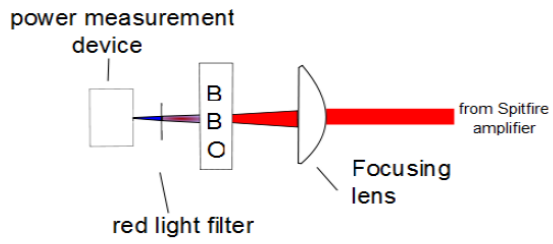
The first experiment was provided by the setup depicted in Pic. 6. After a focusing lens that focuses our beam light into a small point where plasma will be created we place a BBO crystal, which serves as a source of the second harmonic (blue light). In view of the high power laser beam to prevent surface damages of the crystal we put it on a distance from the focal point. It is also possible to measure the energy of the laser beam without BBO in this scheme, but for a more accurate measurement, it was decided to put it into the experiment because a fraction of the energy goes into heating of the crystal and reflections. The laser power was measured with a thermal power meter (pic 9) that we put also on a distance from focal point.

We place the BBO crystal after the focusing lens and not vice versa because the lens that we used is not transparent for 400 nm light.

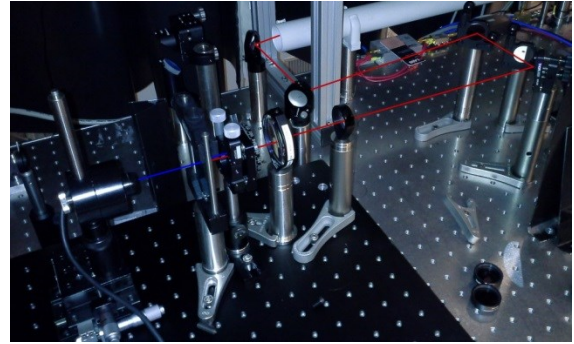


Pic 6. Total light power measurement scheme

For the measurement of blue light converted by BBO from red light we provide next experiment. For a scheme of the setup, refer to pic 7. A laser beam passing through the lens was directed onto the surface of the crystal. Behind, the crystal, we set a band pass filter Schott BG 39 that is transparent for blue light but not for the red. As long as only blue light can pass through this filter we assumed that measured power corresponds to energy of the blue light. Thus, knowing the value of the total power and the power of the second harmonic, the conversion efficiency has been calculated.



Pic 7. Blue light power measurement scheme



Pic 8 Photo of scheme for measurement of blue light power

Measured total power $P_{\text{total}}=173 \text{ mW}$, and power of blue light $P_{\text{blue}}=3 \text{ mW}$. So the power of red light is $P_{\text{red}}=170 \text{ mW}$.

Conversion efficiency of BBO crystal:

$$\eta_{\text{BBO}} = \frac{P_{\text{blue}}}{P_{\text{red}}} = 1.73\%$$



Pic 9. Thermal power measurement device

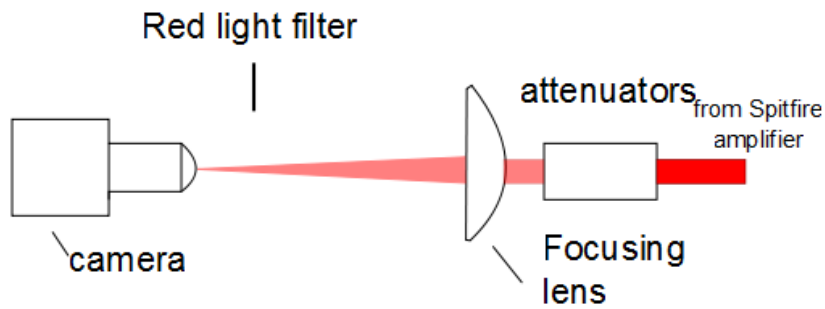
1.3 Transverse sizes measurements

Another important parameter is the size of the beam in the focal point, since this parameter will determine the size of the transverse dimensions of the plasma channel.



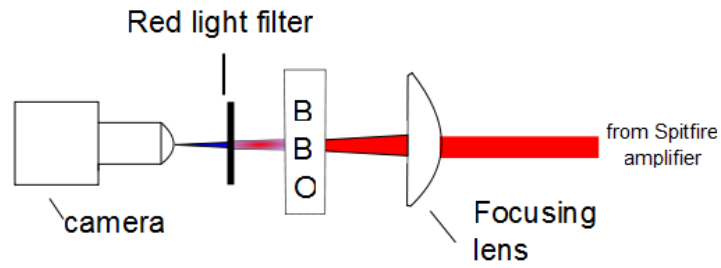
Pic 10. Camera Basler acA1300-30gm[4]

To measure the size of the beam we used the commercial camera Basler acA1300-30gm (pic 10). The scheme of experiment presented on pic 11. To prevent damaging of the sensitive camera matrix while measuring the transverse dimensions of the red laser focus we used a large number of neutral density (ND) filters which serve as attenuators for our beam light. Before fixing the camera we measured the decreased beam power to make sure that camera would not get harmed. For this experiment we used lenses with focal lengths of 60 and 100 mm. The Beam sizes are presented in table 3.



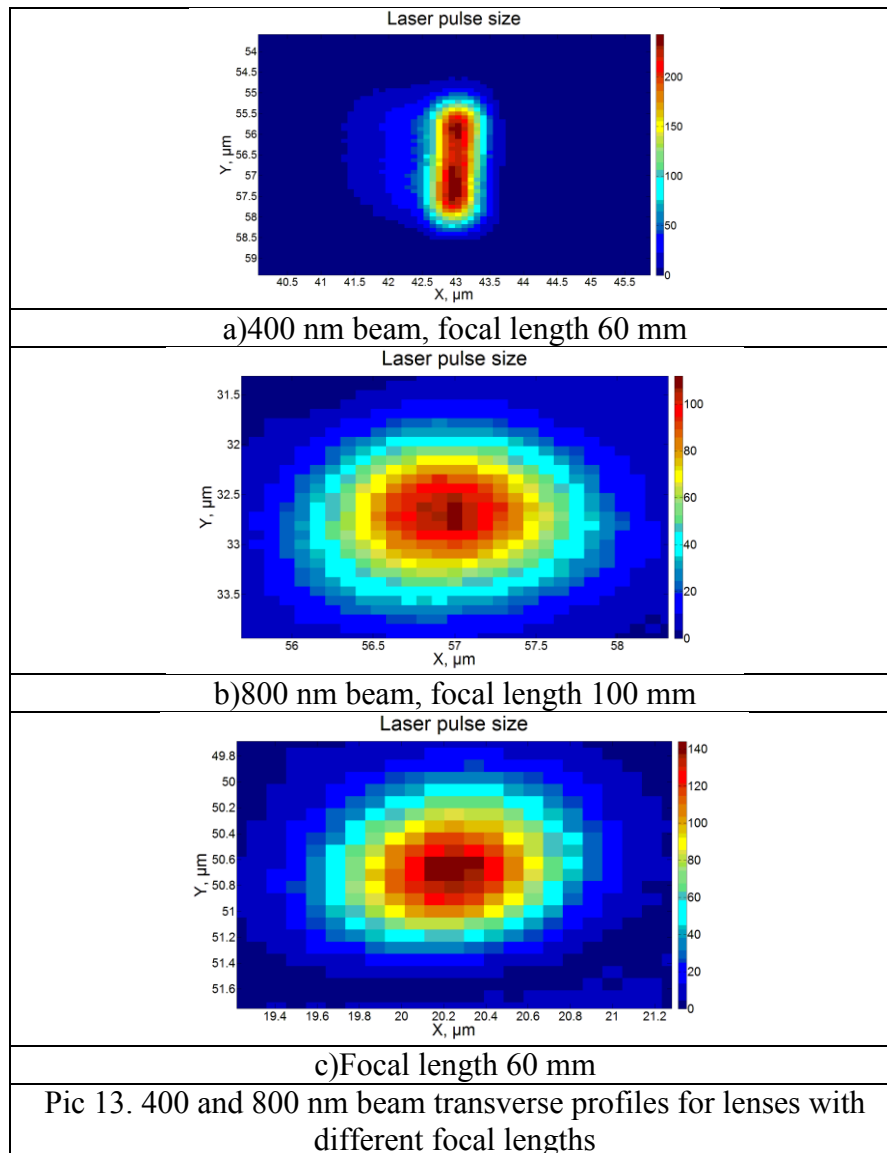
Pic 11. Red light transverse sizes measurement scheme

The situation with blue laser is totally different. To block the red laser we added red light filter after the lens. In view of the low conversion rates of the BBO crystal, all attenuators were subsequently removed and only in such a configuration we were able to detect the blue light.



Pic 12. Blue light transverse sizes measurement scheme

To analyze data coming from the camera for determining of the transverse dimensions of the laser beam another script for the MATLAB was written. The radius of the laser beam is defined as the distance from the position of the maximum amplitude up to half of this amplitude (FWHM). The results presented below also take into account the magnification factor of the camera.



Pic 13. 400 and 800 nm beam transverse profiles for lenses with different focal lengths

During the experiment we found that the shape of the blue light beam is completely different from red light shape (pic 14). We also found that the power of the blue laser is very strongly dependent on the angle of rotation of the crystal BBO.

Table 3. Transverse sizes of beam light in focus			
Wavelength, nm	Focal length, mm	X, micron	Y, micron
800	60	1.03	1.03
800	100	1.4	1.3
400	60	0.8	2.9

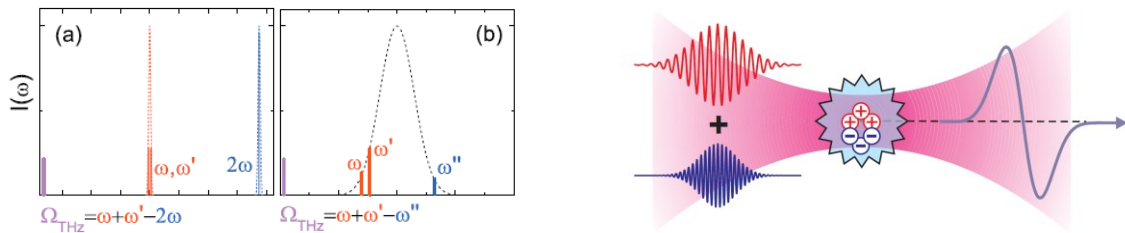
3. Experiment

3.1 Four wave mixing scheme

As long as all pre-measurements are done we can start our experiment.

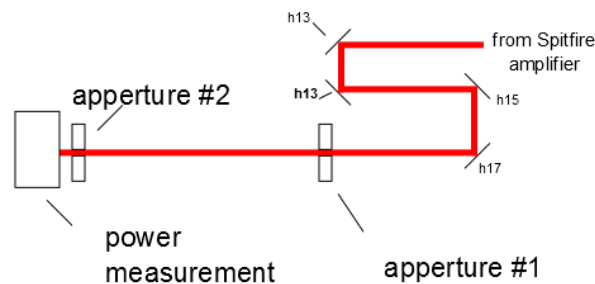
The first experimental scheme that was used called four wave mixing scheme (in analogy to the second-order optical rectification).

In four waves mixing scheme producing of terahertz can be explained by mixing of frequencies of three input components. The first component is the laser central frequency with wavelength of 800 nm. Second component is a 400 nm blue light that can be produced by BBO crystal. And the third component is the plasma frequency of laser-induced plasma by focusing the laser beam into a certain point. This mechanism for a multi-cycle two-color pulse is schematically represented on pic. 15.



Pic 15. Schematic of generated THz spectra in a four-wave mixing picture for the AC-bias $(\omega-2\omega)$ method with multicycle [5]

In the beginning, the laser beam alignment with respect to two alignment apertures was held. To do this, at the very end of the experimental setup (pic 16) we set the laser power meter, one aperture before the power meter and another one in the front of the setup. By changing the angle of two mirrors in front of the experimental setup, we have worked to ensure that the power level was at highest rates. Maximum power corresponds to an aligned beam.



Pic 16. Adjusting of collimated beam scheme

After beam alignment we set up all other components. Because of the focal length of the lens we put lens and BBO crystal inside a protection box so the plasma spot will stay inside the box. This box serves to prevent the contact with plasma spot which can be very harmful for the skin.

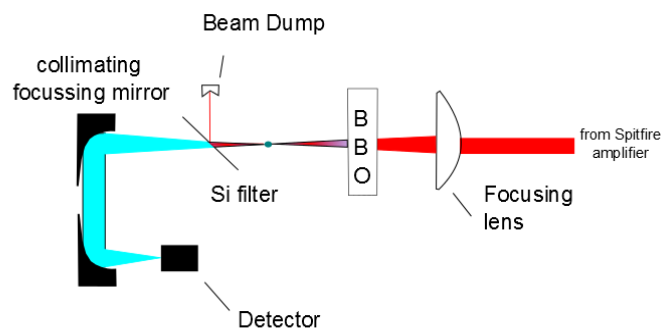
Also inside the box we placed a silicon filter that provides a high transmission for THz radiation, but reflects both the laser's fundamental and second harmonic.

After the box we placed two parabolic mirrors that guide THz radiation directly to detector.

During this experiment we used lenses with different focal lengths, different type of detectors (pyro-electric detectors and MCT (mercury cadmium telluride) detectors) and filters like silicon, high-density polyethylene (HDPE) and gallium arsenide (GaAs).

Unfortunately, a big amount of reflected laser radiation escapes from the protecting box and passes through the wavelength-separating filter and hit the detector.

So, no conclusive statement could be made if low-intensity THz pulses or just laser radiation hit the detector and resulted in the detector signal observed. The angle of Si filter and beam dump was set up to decrease the reflected beam as much as possible. There was another possibility to block the laser beam: to use more filters but it was not very effective due to possible absorption of terahertz radiation.



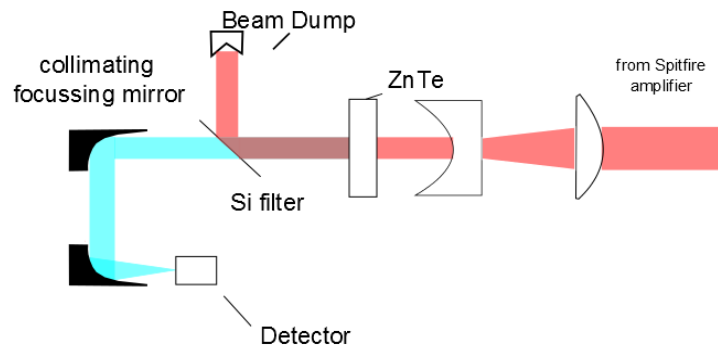
Pic 17. Scheme for four wave mixing terahertz producing

3.2 Optical rectification scheme

Another method for producing THz radiation based on optical rectification [6] effect in ZnTe crystal. This experimental scheme is very similar with 4 wave mixing scheme. But BBO crystal in this scheme replaced with ZnTe crystal. We made two different experiments with this scheme of radiation generation. The first one with collimated beam and another with focused beam.

In first scheme (pic 18) beam light pass through a telescope system (focusing and defocusing lens). It is necessary to decrease the beam size to increase the power density and to avoid losses on borders of the crystal.

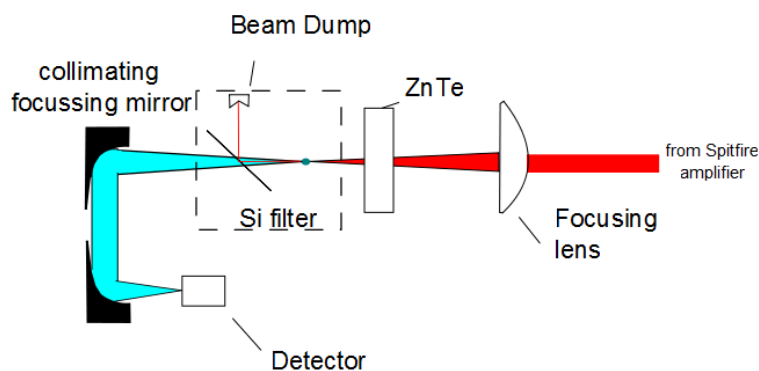
After the crystal we placed a filter and parabolic mirrors as in 4 wave mixing scheme. But the alignment of mirrors was changed because now we use collimated beam instead of focusing.



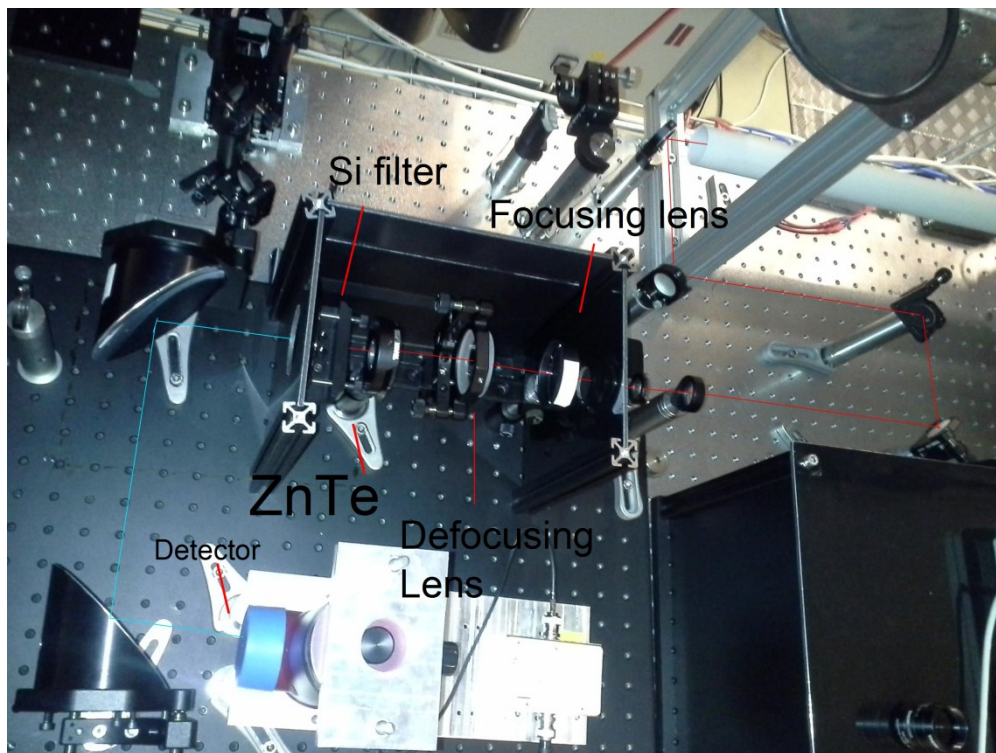
Pic 18. First ZnTe scheme for THz radiation generation

In second scheme (pic 19) beam was focused on surface of ZnTe. We put the crystal on the distance from focal point to avoid damaging it.

After the crystal we placed a filter and parabolic mirrors as in 4 wave mixing scheme.



Pic 19. Second ZnTe scheme for THz radiation generation



Pic 20. Photo of second ZnTe scheme for THz radiation generation

As in the four-wave rectification scheme, we observed a signal from the detector on the oscilloscope, but we can't make a reliable statement on the detection on THz radiation.

Conclusion and outlook:

- Both schemes (four-wave mixing and optical rectification) didn't allow an assured statement on the detection on THz radiation.
- The THz intensity is expected to be too low to be detected.
- Suspected reason: distortion of the laser beam like pulse front tilt / angular chirp
- Measurements are on the way for further laser characterization.

References

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