Summer Student Report 2013

Commissioning of an optical set-up for laser beam diagnostics

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Abstract

FLASH is a free - electron laser (FEL) which produces coherent femtosecond pulses in the soft X-ray regime and enabling researchers to investigate the temporal evolution of processes happening in femtoseconds or picoseconds. There are two optical lasers in the FLASH experimental hall, that provide users with a unique possibility to conduct so called pump and probe experiments to explore physical, chemical and biological samples' dynamics.The idea of such experiments is to synchronize FEL pulses with the ultrashort pulses from an optical laser in such a way that both pulses can be used as pump or probe depending on the experiment type. Obviously, that success of the time-resolved experiments depends on the quality of synchronization and beam characteristics such as pulse duration, intensity stability and beam size. Till the FLASH upgrade in 2013 it was possible to analyze the beam parameters only in the laser hutch, where the optical beam is generated, from the laser hutch to experiments an evacuated laser beam delivery system transports the beam via beamlines and it is reasonable to purpose that during the transportation beam characteristics can be changed by energy losses or mechanical interruptions, such as cutting of the beam, what can lead to diffraction, or bending of the mirrors can induce an astigmatism.Thus, it was necessary to measure the beam parameters just before it goes into the target. In order to improve the user facility the diagnostic station for the optical laser at the beamline end BL2 was put into operation and the special software to automatize data processing was created. The main aspects of alignment of the diagnostic station with 500nm and 800nm wavelength lasers are discussed in this report. Detailed description of the installation of components and their calibration is presented.

Contents

1 Introduction

In this paragraph the free - electron laser is described.
Free - electron lasers are devices which transform the energy of ultrarelativistic electrons (their energy is much higher than rest energy 0,511 MeV) into electromagnetic radiation. FELs enable the prodution of the monochromatic radiation with almost any wavelength depending on electron energy.
In order to electrons interact with the electromagnetic wave in resonance, their trajectory should be a wavelike curve. The magnetic system with a magnetic field which is necessary to create such a trajectory is called undulator or wiggler.These are periodic arrangements of many short dipole magnets of altering polarity. The important role in the light amplification play so called microbunching, which is based on the following principle: electrons losing energy to the light wave travel on a wavelike trajectory of larger amplitude than electrons gaining energy from the light wave. The result is a modulation of the longitudinal velocity which eventually leads to a concentration of the electrons in slices that are shorter than the wavelength. These microbunches are close to the positions where maximum energy transfer to the light wave can happen, and the particles within a microbunch radiate like a single particle of high charge. This increase in the radiation field enhances the microbunching even further and leads to an exponential growth of the energy of the radiation pulse as a function of the length of the undulator. A key quantity for the technical realization of a high-gain FEL is the gain length, that is the length in which the FEL power grows by a factor e = 2.718. At FLASH the gain length is about 1 meter. The gain length depends critically on the electron beam parameters. To obtain a short gain length, the peak current in the bunch must be very high, in the order of several 1000 A, and the electron beam diameter must be less than 100 μm throughout a long undulator magnet. With increasing electron energy, and correspondingly decreasing FEL wavelength, the gain length grows, and longer undulators are needed. In order to achieve laser saturation at a sub-nanometer wavelength the undulator must be more than 100 m long.[6]

1.1 What is FLASH?

In this paragraph a short description of FLASH main components is presented.
FLASH is a free electron laser in Hamburg at DESY, operating in the wavelength range 4.5 nm to 40 nm. The pulse duration is in the range 30 to 200 fs. Noticeable, that FLASH was the first FEL to produce femtosecond pulses of soft X-rays.
The main components of FLASH are an 300-m-long accelerator providing a bunched relativistic electron beam and an 27-m-long undulator magnet. In free electron laser the role of the active laser medium and energy pump are both taken over by the relativistic electron beam which is accelerated to a maximum energy 1.2 GeV in seven accelerator modules, each containing eight superconducting cavities. The undulator consists of permanent NdFeB magnets with a fixed gap of 12 mm, a period length of 27.3 mm and peak magnetic field of 0.47 T. In the end of the tunnel the dipole magnet deflects the electron beam into the dump and FEL radiation propagates to the experimental hall,

which is 30 meters behind the last dipole magnet, with a help of a transport system operating under high vacuum conditions. However, only one experimental station can be served at a time.The FEL pulses are switched between the beamlines by 0.5-m-long plane mirrors reflecting the beam at grazing incidence angles of two and three degrees. The FEL optics system was designed to avoid the risk of damage, the mirrors consist of cooled silicon substrates with high density carbon coatings.

1.2 Pump and probe experiments and the FLASH optical laser

FLASH is a powerful tool to investigate ultrafast processes. To explore wide field of chemical reactions, atomic interactions, phase transitions and expansion of hot plasma the method of pump and probe experiments is used. Both pump and probe pulses could originate from the FEL itself, but the more flexible variant is to use the ultrashort pulses from an optical laser in combination with FEL pulses. The reason is that it is much easier to change the wavelength, the polarization and the angle of incidence with an optical laser.

The idea of pump-probe experiments is to start the reaction with a pump pulse, while the probe pulse investigates the state of the system after a defined time delay. In such a way the temporal evolution of the process could be observed. The fact that both FEL and optical pulses can be used as pump and as probe enables researchers to make various experiments in different areas of physics, biology and chemistry.

Two conventional optical lasers are available to user groups coming to FLASH. The laser system consists of an ultrashort pulse oscillator synchronizes to the FEL and two different amplifiers seeded by this oscillator(Fig.1). First, a laser delivering a high energy pulse so called Hidra (up to 20mJ, 50 fs FWHM). The second laser provides trains of 10μJ pulses (70 fs FWHM).[1]

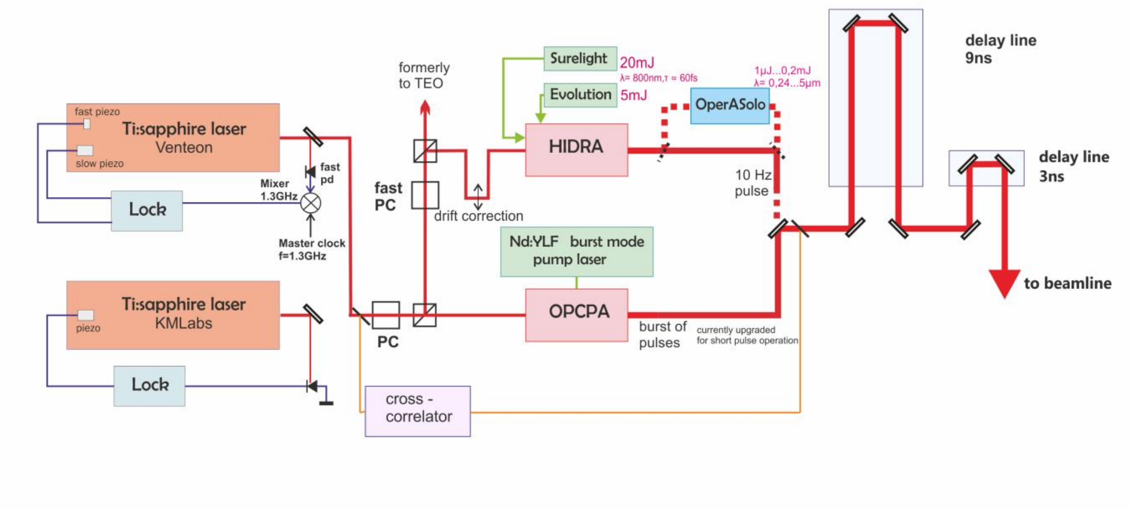


Figure 1: laser scheme

2 Theory

2.1 Gaussian beam

In optics, a Gaussian beam is a beam of electromagnetic radiation whose transverse electric field and intensity (irradiance) distributions is well approximated by a Gaussian function. The intensity distribution in any transverse plane is a circularly symmetric Gaussian function centered about the beam axis. The width of this function is minimum at the beam waist and grows gradually in both directions. The wavefronts are approximately planar near the beam waist, but they gradually become curved and get approximately spherical far from the waist. The angular divergence of the wavefront normals is the minimum permitted by the wave equation for a given beam width. The wavefront normal is therefore much like a thin pencil of rays. The mathematical function that describes the Gaussian beam is a solution to the paraxial form of the Helmholtz equation. The solution, in the form of a Gaussian function, represents the complex amplitude of the beam's electric field. The electric field and magnetic field together propagate as an electromagnetic wave. A description of just one of the two fields is sufficient to describe the properties of the beam. Other solutions to the paraxial form of the Helmholtz equation exist. Solving the equation in Cartesian coordinates leads to a family of solutions known as the HermiteGaussian modes, while solving the equation in cylindrical coordinates leads to the LaguerreGaussian modes. For both families, the

lowest-order solution describes a Gaussian beam, while higher-order solutions describe higher-order transverse modes in an optical resonator. Many lasers emit beams that approximate a Gaussian profile, in which case the laser is said to be operating on the fundamental transverse mode, or "TEM_0" of the laser's optical resonator.
A mathematical expression for its complex electric field amplitude is found by solving the paraxial Helmholtz equation, is given:

$$E(r,z) = \frac{E_0 w_0)}{w(z)} exp(\frac{-r^2}{w(z)^2} - ikz - \frac{ikr^2}{2R(z)} + i\zeta(z)) \quad (1)$$

where r - is the radial distance from the center axis of the beam, z - is the axial distance from the beam's narrowest point waist, i - is the imaginary unit, $k = 2\pi/\lambda$ - is the wave number, E_0 is determined from the boundary conditions:$|E(0,0)|$, $w(z)$ is the radius at which the field amplitude and intensity drop to 1/e and 1/e2 of their axial values, respectively, w_0- is the waist size, R(z) is the radius of curvature of the beam's wavefronts, $\zeta(z)$ - is the Gouy phase shift. For a Gaussian beam propagating in free space, the spot size (radius) $w(z)$ will be at a minimum value w_0 at one place along the beam axis, known as the beam waist. For a beam of wavelength at a distance z along the beam from the beam waist, the variation of the spot size is given by:

$$w(z) = w_0 \sqrt{1 + (\frac{z}{z_R})^2} \quad (2)$$

where $z_R = \pi w_0^2/\lambda$ - is Rayleigh range. At a distance from the waist equal to the Rayleigh range z_R, the width w of the beam is:

$$w(\pm z_R) = \sqrt{2} w_0 \quad (3)$$

The distance between these two points is called the confocal parameter or depth of focus of the beam:

$$b = 2z_R = \frac{2\pi w_0^2}{\lambda} \quad (4)$$

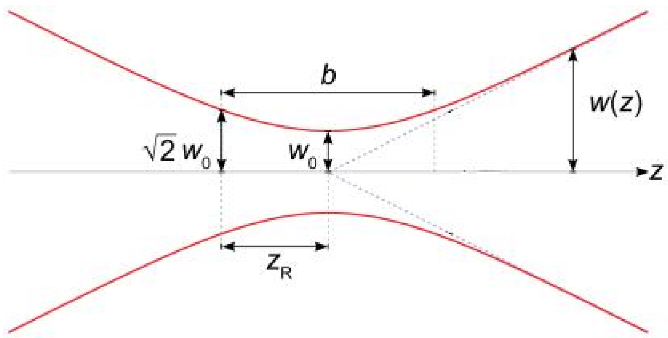


Figure 2: Gaussian beam width w(z) as a function of the axial distance z

The radius of curvature of the beam's wavefronts is given by:

$$R(z) = z(1 + (\frac{z_R}{z})^2) \tag{5}$$

And the Gouy phase shift is given by:

$$\zeta(z) = \arctan(\frac{z}{z_R}) \tag{6}$$

The corresponding time-averaged intensity (or irradiance) distribution is:

$$I(r, z) = I_0(\frac{w_0}{w(z)})^2 exp(\frac{-2r^2}{w(z)^2}) \tag{7}$$

where $I_0 = |I(0, 0)|$

2.2 Different definition of the beam width

The important question in developing a meaningful measure of beam quality for routine use is meaningful, practical, readily measurable definition for the width of a beam, given its time-averaged intensity profile I(x, y) at any given plane z. Possible definitions of beam width that have been suggested or used for optical beams in the past include:

- Width (or half-width) at first nulls.
- Variance σ_x of the intensity profile in one or the other transverse direction.
- Width at 1/e or $1/e^2$ intensity points.
- The "D86" diameter, containing 86% of the total beam energy.
- Transverse knife edge widths between 10% - 90% or 5% - 95% integrated intensities.
- Width of a rectangular profile having the same peak intensity and same total power.
- Width of some kind of best fit Gaussian fitted to the measured profile.

Note that the above definitions applied to different beam profiles can give very different width values, and in fact some of them cannot even be applied to certain classes of profiles. Its also important to understand that in general there are no universal conversion factors between the widths produced by different definitions. The conversion from one width definition to another depends (strongly in some cases) on the exact shape of the intensity profile. In all calculations of this work half width at half maximum of intensity (FWHM) definition was used.

2.3 M^2 parameter

In laser science, the parameter M^2 is defined as the ratio of the beam parameter product (BPP) of an actual beam to that of an ideal Gaussian beam at the same wavelength. BPP- is the product of a laser beam's divergence angle (half-angle) and the radius of the beam at its narrowest point, it quantifies the quality of a laser beam, and how well it can be focused to a small spot. M^2 parameter is often referred to as the beam quality factor, since its value can be used to quantify the degree of variation the actual beam is from such an ideal beam.The value M^2 is ≥ 1 for any arbitrary beam profile, with the limit of $M^2 \equiv 1$ occurring only for single-mode TEM_00 Gaussian beams.

2.4 Non-linear effects

The nonlinear optics studies processes of interaction between light and matter which depend on light intensity. Such effects are: optical harmonics generation, stimulated scattering, self-focusing of light beams and self-modulation of pulses, two-photon or three-photon absorption optical breakdown and so on. The theory of nonlinear optical effects is based on the constitutive and Maxwell's equations. Maxwell's equations for dielectric neutral nonmagnetic medium are:

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{H}}{\partial t}, \quad \nabla \times \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t}, \quad \nabla \vec{D} = 0, \quad \nabla \vec{H} = 0 \tag{8}$$

where: $\vec{D} = \vec{E} + 4\pi \vec{P}$

The wave equation follows from Maxwell's equations:

$$\nabla \times \nabla \times \vec{E} + \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = -\frac{4\pi}{c^2}\frac{\partial^2 \vec{P}}{\partial t^2} \tag{9}$$

Which in the case of isotropic medium takes form:

$$\triangle \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 \vec{P}}{\partial t^2} \tag{10}$$

Where $\vec{E}$ is electric field of the light wave, $\vec{P}$ is polarization of the medium, equations (9) and (10) are valid both for linear and nonlinear surroundings.According to this equations, polarization of the medium is a source of the light wave field and the polarization occurs under the action of incident light wave. The induced polarization is described by the material equation which describes the structure and propeties of medium:

$$\vec{P} = \vec{P}(\vec{E}) \tag{11}$$

The simplest material equation of the linear medium has a form:

$$P = \kappa E + \kappa^{(2)} E^2 + \kappa^{(3)} E^3 + ... \tag{12}$$

According to this equation, medium polarization is a nonlinear function of electric field of light. It is the reason of the superposition principle(light wave with different frequencies, polarizations and propagation directions propagate and interact with the medium independently) violation for light waves in the nonlinear medium. Noticeable, that the relative value of nonlinear summands raises with increasing of electric field strength of light wave that is with intensity increasing of light. Thus, nonlinear effects can be mostly observed in strong light fields. Coefficients $\kappa, \kappa^{(2)}, \kappa^{(3)}$ - depend on the medium properties and call optical susceptibilities. κ -is first-order linear optical susceptibility, $\kappa^{(2)}$ - is second-order nonlinear optical susceptibility, and so on.

2.5 Index of refraction which depends on the light intensity

Usually, in the isotropic nonlinear medium the lowest nonzero nonlinearity - is cubical. The equation of such medium is looks like:

$$P = \kappa E + \kappa^{(3)} E^3 \tag{13}$$

In this approximation the index of refraction is defined by: $D = E + 4\pi P = \epsilon E = n^2 E$, whence:

$$n = \sqrt{1 + \frac{4\pi E}{P}} \tag{14}$$

Substituting the (13) into the (14) and considering the smallness of nonlinear summand we obtain:

$$n = n_0 + \frac{2\pi E^2 \kappa^{(3)}}{n_0} \tag{15}$$

where

$$n_0 = \sqrt{1 + 4\pi\kappa} \tag{16}$$

Let us now express the square of electrical field in terms of intensity, using the formula: $I = \frac{cE^2}{8\pi}$, we obtain

$$n = n_0 + n_2 I, \tag{17}$$

where

$$n_2 = \frac{16\pi^2 \kappa^{(3)}}{n_0 c} \tag{18}$$

here c - speed of light, n_0 - linear index of refraction. The formula (17) shows us that the index of refraction depends on light intensity in the matter with cubic nonlinearity. This effect leads to self-action of light waves, in particular, to such effect as self-focusing of light beams.n_2 is a convenient parameter for characterization of nonlinear medium, e. g. for fused silica $n_2 = 3.2 \cdot 10^{-16} cm^2/W$. The refraction index dependency on light intensity is called Kerr effect.

2.6 B integral

B integral is a measure of the nonlinear phase shift of light. It is defined as:

$$B = \frac{2\pi}{\lambda} \int n_2 I(z) dz \tag{19}$$

where the I(z) is the optical intensity along the beam axis, z the position in beam direction, n_2 is nonlinear index quantifying the Kerr nonlinearity.As n_2 is the nonlinear change in the refractive index, one easily recognizes the B integral to be the total on-axis nonlinear phase shift accumulated in a passage through the device. This parameter can be used to quantitatively characterize nonlinear effects.For high optical intensities the B integral can become larger than 1. For values above $\sim$ 3 - 5, there is a risk that self-focusing may occur: the nonlinear lensing effect can become so strong that the beam collapses to a very small radius, so that the optical intensities are strongly further increased and easily exceed the damage threshold. A single pulse in this regime may be sufficient for destroying component on it's way.

3 Description of the optical set up

For users coming to FLASH it is important to know the parameters of the optical laser beam they are using at experiment. For this purpose the diagnostic station at beamline end BL2 was designed and built. The idea was to redirect the incident beam which goes to the experiment with the mirror in the vacuum cross through an additional window to the diagnostic station, where beam is split into two different beams with the help of the glass beam splitter with 50% reflecting coating. After the beam splitter first the beam with reduced intensity is directed to the second mirror and then to the 500mm lens to focus beam in the plane of the CCD(Charge-coupled device) camera. To avoid damage of the camera, between the beam splitter and second mirror the motorized wheel with holders for six different order neutral density filters was mounted. The second beam propagates through the beam splitter to the spectrometer.

3.1 Selecting the optimal focus distance of the lens

The lens has a movable platform, that is possible to move the lens along the beam axis and take pictures of the beam profile above and below the focus point. The special interest has a switching between far and near field positions with one lens, but the problem was that the limit of the motor movement is 79mm while to switch between far and near field is needed a distance 3 times the Rayleigh range. At the same time the smaller focus distance of the lens the smaller waist spot of the beam.Thus, it is necessary to choose the lens with the optimal focus distance when the compromise is reached between the smallest beam waist spot which can be seen at the camera (resolution 2592×1944 pixels, the size of each pixel 2.2×2.2 μm) and the distance which is available with motorized platform of the lens. The calculations of the beam waist spot were made and it was assumed that for focus distance f=300mm , wavelength λ= 800nm, initial

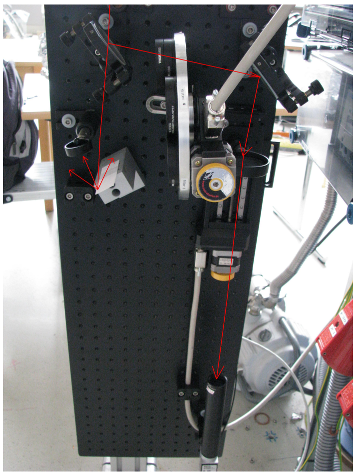


Figure 3: Diagnostic station.Beam direction is marked with red

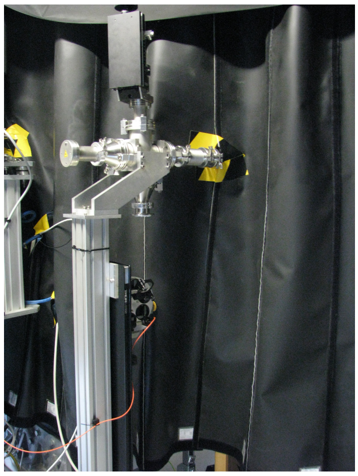


Figure 4: The output window on the top of the image.

beam diameter ρ_0= 15mm(FWHM) the beam diameter at the smallest point will be only w_0= 3 pixels(6.6μ) - it is not enough to observe such effect as astigmatism of the beam. The same calculations showed that for f=500mm beam diameter should be w_0= 6 pixels, this value was considered as sufficient, thus lens with 500mm focus distance was selected.

3.2 Calibration of the movable platform

Next step after the selection of the focal length was mounting the lens platform to the diagnostic station. The mounting was done in such a way that the beam focuses at the plane of the camera when the position of the lens is approximately in the middle of it's motion limit. Such option allows to investigate the beam profile at different planes as well as the far field. For the calibration of the motor it was moved by 2 518 135 steps and the travel distance was 79mm thus conversion factor was:

$$conversion\ \ factor = \frac{end\ \ position\ \ in\ \ mm}{end\ \ position\ \ in\ \ motor\ \ steps} = 31nm/step$$

3.3 Calibration of the filter wheel

Even reduced intensity of the beam by the beam splitter is enough to damage the camera, moreover, if move the lens along the beam axis in the direction of focus the intensity will grow significantly and for different positions of the lens different attenuation should be used. Thus, to do possible further decreasing of beam intensity the motor wheel was designed and mounted between the beam splitter and mirror, that directs the beam to the lens and camera. The motorized wheel with diameter(d=put here diameter) has 6 holes with a thread for neutral density filters. As in the case with the linear motor of the lens a special calibration procedure was needed. As the wheel motor type is rotational it has one end - switch, which sends a command to the motor controller the end - switch. Because of the reason that the end - switch did not coincide with the position when the beam is exactly in the middle of the filter center, the fist position was not zero, but - 40 000steps, second position had a value - 420 000, whence the step between two positions was found.The recurrent formula to find the each position in steps:

$$position = position\ number \cdot 380000 + 40000$$

It is planning to create the the new GUI for this motor which will include this calibration and will do all calculations automatically, so the user will only choose the needed position with definite neutral density filter.

4 Measurements

4.1 Measurements with the alignment laser

The first alignment was done with the 500nm wavelength laser. The first images of the beam profile were not successful.The first reason was that all optics was designed for 800nm wavelength, so strips could be seen. The second problem interference rings in the beam profile and inhomogeneous distribution of the intensity, also there was a second beam in the picture - it came from back side reflection from the beam splitter. Obviously, the pictures showed problems of the alignment, so it became clear what should be improved.

4.2 Measurement of the Hidra beam spot

Note that the Hidra laser has bigger beam diameter as compared to the alignment laser, so the beam profile for 800nm was different. Thus, further alignment was done with the 800nm wavelength laser. The first step was to determine which spot comes from what surface of the beam splitter and find out how to avoid back side reflection. For this purpose a test with the iris was performed: the iris was mounted before the splitter to reduce the beam diameter, so the distance between two spots became bigger- it was easy to block one of them with the paper card and to determine which comes from a front side of the splitter(Fig.8a). The attempt was done to avoid backside reflection by replacing the glass beam splitter with pellicle, but beam profile became unstable(Fig.8b).

4.3 Alignment of the lens platform

Another problem was that the motorized platform of the lens was not exactly parallel to the beam axis, so it was observed that while moving the lens along the beam axis the beam moves across the screen. Evidently, that accurate manual alignment of the lens platform by unscrewing it and moving was impossible. For fine - tuning were used screws for horizontal and vertical tune - up of the beam splitter and the mirror. All alignment was done with the help of the camera. A circle was put into the center of

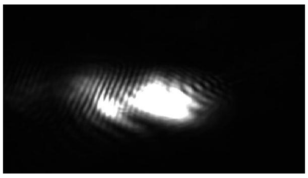


Figure 5: The beam profile of the alignment laser. Intensity distribution is inhomogeneous

Figure 6: Two spots can be visible with alignment laser.

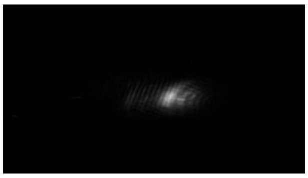
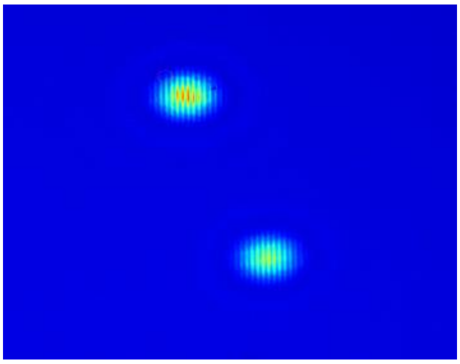
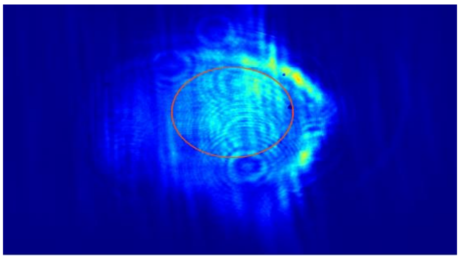


Figure 7: Stripes can be seen with alignment laser because all optical elements are designed for 800nm wavelength.

screen in the camera GUI. The lens was set at zero position - a current position of the beam on the screen was below and to the right of control circle, the screws for accurate tuning of beam splitter were used to realign the current position with the position of control circle in the middle of the screen. The same alignment of the current position with the control circle was done for the end position of the lens, but with the screws of the mirror. So the procedure of tuning was to switch between zero and end positions of the lens and alignment the actual position with the drawing circle in the middle of the GUI screen. It was important to use the correct screws for each position each time. This should be repeated until the beam stops it's motion across the screen. Ideally the beam should stays at the same point during the moving of the lens and only changes of the diameter should be visible. This alignment was done as the last alignment at diagnostic station because it is very sensitive to any change of components.



(a) Glass beam splitter.Alignment laserThe upper spot is a front - side reflection.



(b) Beam profile of the Hidra laser with pellicle instead of the glass beam splitter

4.4 Position improving of the mirror in the vacuum cross

The mirror which redirects the beam to the diagnostic station has a movable platform. The mirror has a limit position when it is out of the beam. Then it propagates to the experimental chamber and the second limit position is when the mirror is fully in the beamline. Between these two positions there are several positions for which the mirror is still in the beam, thus the optimal option can be chosen. It was found that the initial position(14 in the terms of the ruler of the platform) of the mirror was not successful it gave a clipping of the lower edge of the beam. The position was changed and the series of the pictures was recorded corresponding to each position of mirror. But the best position was not found: before the clipping of the lower edge of the beam could disappear a clipping on the top of the beam arose (Fig. 9, 10).

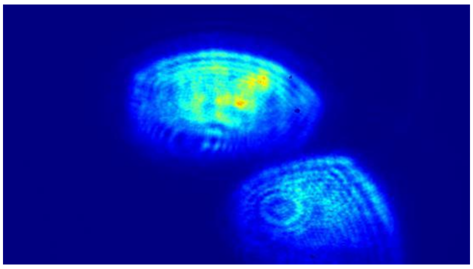


Figure 9: Hidra laser.Cutting on the top.

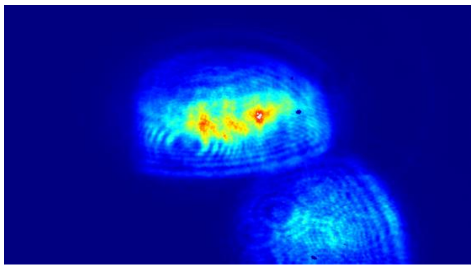


Figure 10: Hidra laser.Cutting on the down.

Two extreme positions of the mirror are presented. There was no better position between them. Thus,when the mirror was unscrewed and shifted disappeared.

4.5 Measurements of M^2 parameter

First tests showed that there are some interference rings and an inhomogeneous distribution in the beam profile. It was decided that such effect could be caused by random

fluctuations and scattering, to remove them from the intensity profile of a laser beam the spatial filters of different diameter were used. To estimate the beam quality the parameter M^2 was calculated for the cases of different spatial filters as well as without filters.
Spatial filters are installed at the position between the laser hutch and mirror which switches between different beamlines, at the focus position of the beam. The plate with the spatial filters is motorized and has two degrees of freedom - horizontal and vertical. The fist step was to find exact positions when the beam is centered to the each pinhole. The approximate coordinates of the pinholes were known, thus in the range where the pinhole was expected the motor was moving with small steps in vertical direction and along the all perpendicular direction per each vertical step. The pinhole was centered according to the maximum throughput.
When all pinholes were found the series of images of the beam profile at different positions of the lens and with three different pinholes was done. Then all images were processed with MATLAB and the FWHM for each image was found. The curve FWHM(z), width as a function of the lens position z was built, according the theory experimental curve should be well fit to the theoretical curve:

$$w(z) = w_0\sqrt{1 + (\frac{z}{z_R})^2} \tag{20}$$

but for a not ideal laser the M^2 parameter should be considered:

$$w(z) = w_0\sqrt{1 + (\frac{M^2\lambda}{\pi w_0^2})^2(z - z_0)^2} = A\sqrt{1 + (\frac{z - z_0}{B})^2} \tag{21}$$

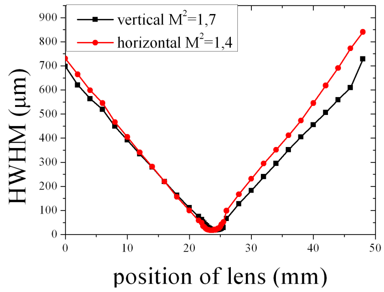
where $B = \frac{\pi w_0^2}{\lambda M^2}$ and:

$$M^2 = \frac{\pi w_0^2}{\lambda B} = \frac{\pi A^2}{\lambda B} \tag{22}$$

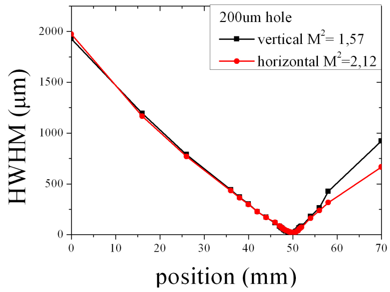
Thus, all experimental curves were fitted to the eq.(21) with free parameters A, B and the z_0 and M^2 parameters were found. Results showed that the beam quality does not vary significantly. The problem was that pinhole were not exactly at the waist, so the filtering did not work as intended. To understand what is the shift of current position relatively to the waist position special measurements of intensity with a power-meter were done. The intensity was measured for each spatial filter.
According to theory the experimental curve $I(r)$ intensity as a function of filters radius can be fitted to the theoretical:

$$\frac{I}{I_{max}} = 1 - e^{-\frac{4ln(2)r^2}{w(z)^2}} \tag{23}$$

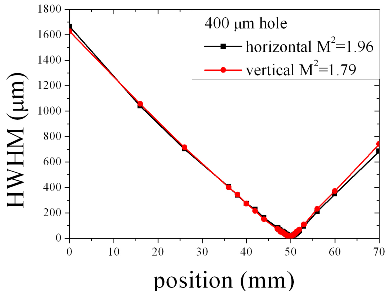
where $w(z)$(FWHM) is a free parameter which was found from fitting w =386±26. It was calculated that for the 4,5m lens which focuses the beam at the plane, where pinholes are mounted, for the initial beam diameter $d = 16$ mm, wavelength $\lambda = 800$nm and for $M^2 = 2$ (average value from measurements) the waist size is $w_0 = 281$ μm.



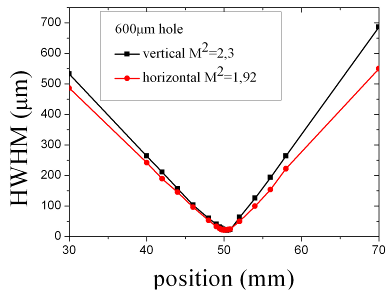
(a) without pinhole



(b) 200μm pinhole



(a) 400μm pinhole



(b) 600μm pinhole

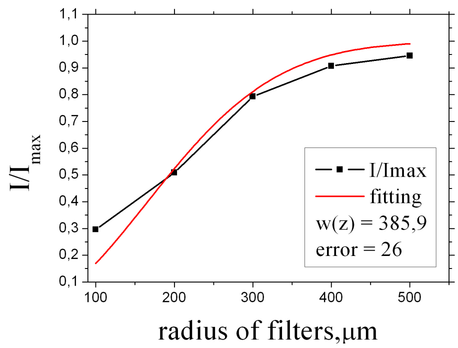
With $w(z)$ and w_0 parameters it is possible to calculate the shift of the current position of the spatial filters relatively to the waist position of the beam, making mathematical conversions with eq.(21):

$$(z - z_0) = \frac{\pi w_0^2}{\lambda M^2}\sqrt{(\frac{w(z)}{w_0})^2 - 1} \tag{24}$$

For $M^2 = 2$, λ=800nm, w_0=281 μm(FWHM), w=385μm(FWHM), but in the terms in which formula(24) is valid the $1/e^2$ definition of the beam width should be used: w_0=240 μm and w=329μm, so the position shift $(z - z_0) = 10$ cm, but the direction of the shift was not clear.
To shift the waist spot to the point where spatial filters were the 4 m lens in the laser hutch was replaced with a 5 m lens and was shifted in two directions relatively initial position to find the best position, where intensity was the highest. The test was repeated with the 5m lens. The beam profile became "cleaner", but interferece rings were still in the beam profile. The images of the beam profile at the near and far field with the 5 m lens are presented, the astigmatism of the beam is visible at far field (Fig.13, 14a, 14b, 14c).
In order to better understanding where these rings came from the temporary diagnostic station which consisted of the camera and 400mm lens were built at the strait output of the beamline end BL2. Images from this camera showed that the problem of interference rings came from diagnostic station(Fig.15a,15b,15c).

Table 1: Measurements of intensity decreasing with different spatial filters

Radius of a filter	Intensity
100 μm	207 μJ
200 μm	356 μJ
300 μm	555 μJ
400 μm	635 μJ
500 μm	662 μJ
without pinhole	700 μJ



4.6 Power variations

Till this moment the laser was operated with the pulse energy of 700 μJ, but at the real experiment the laser should work at full power. Thus, several tests with power varying were performed.
First test was to understand where the losses of the pulse energy come from at the beamline end. Measurements of beam intensity at the laser hutch and at the beamline end were compared.

Table 2: Power losses

Directly at the output of the laser	Beamline end	Losses
835 μJ	722 μJ	13.54 %
1.81 mJ	1.56 mJ	13.82%

Second type of tests was to measure how the beam size varies when the 4 and 5 lenses are in the laser hutch with the energy of 3.12mJ. For this purpose measurement with iris were performed with following steps:

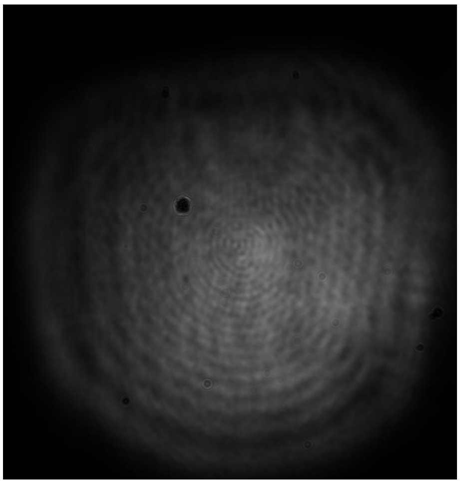
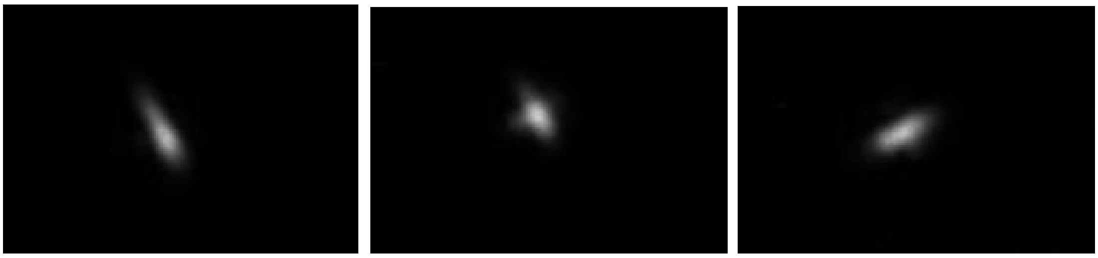


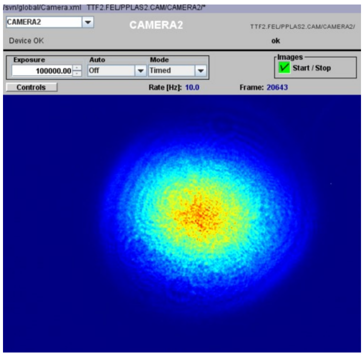
Figure 13: near field



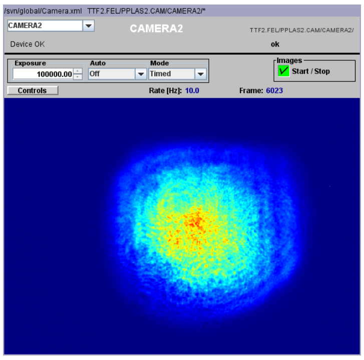
(a) below the focus (b) focus (c) above the focus

- The picture of the beam profile without iris was recoded and a measure fot the intensity of the beam was calculated in MATLAB (sum of all pixels' values).
- The value which corresponds to the half of intensity was found.
- The series of images of beam profile reduced by iris were done and processed for full intensity.
- The diameter of iris which gives an image with full intensity equal to a half of initial intensity is exactly a beam width(FWHM).

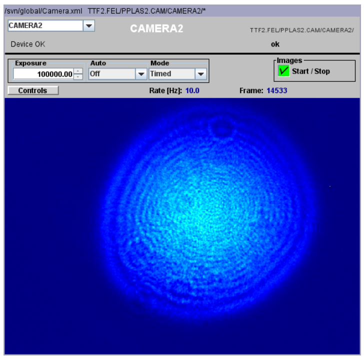
For the 5m lens the diameter of the beam was measured as d = 11mm and for 4m lens d = 11.5 mm. It was expected that the difference should be bigger.
In order to investigate how the beam properties of the beam changes depending on the power changes the M^2parameter was measured for 15.6 mJ and for 700μJ but results showed that M^2parameter is always in the range of two. A series of spectra was recorded with the spectrometer for different power values:
For operating with pulse energy in the range 1.56-15.6 mJ the pulse duration was elongated from 50 fs to $\sim$ 2-3 ps.



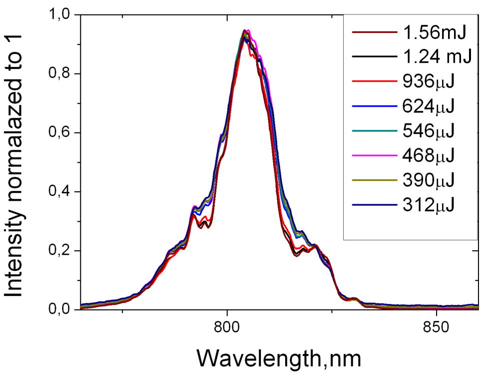
(a) Strait output.5m lens in the lase hutch,600μm pihole is in

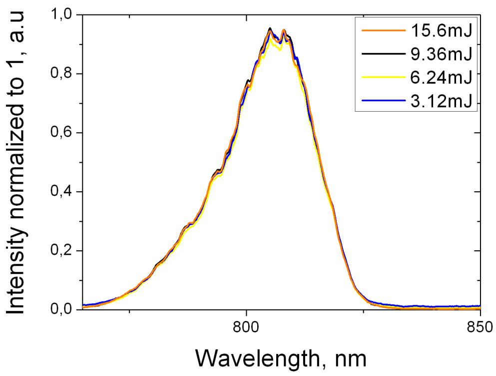


(b) Strait output.5m lens in the lase hutch,without pinhole



(c) Strait output.5m lens in the lase hutch,400μm pinhole is in





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