4 THE OPTICAL TRANSPORT LINE OF THE HGHG EXPERIMENT

4.1 The Optical Transport Line at Beam-line 2

We use a Helium Neon alignment laser (633nm red light) to align the whole system. It is crucial for the alignment of the laser through the wiggler to be accurate because it is used as a fiducial line onto which the CO_2 and the electron beams are coaligned. Upstream of beam-line 2 we have a small optical table to support the He-Ne laser and some associated optics. More elements are located on a 'breadboard' optical mounting-surface next to the beam-line entrance.

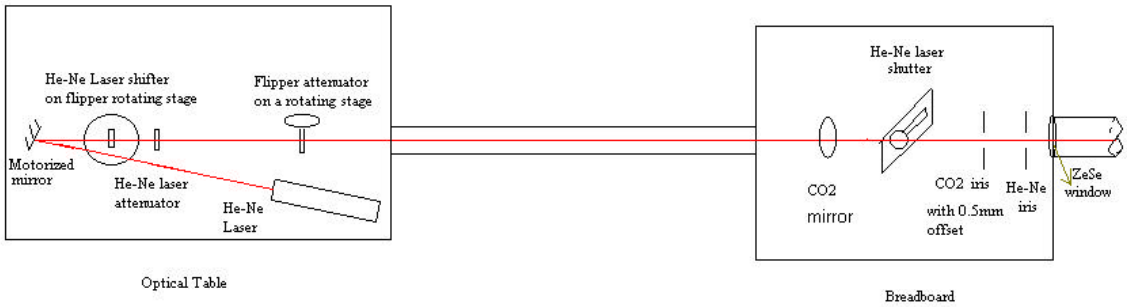

Figure 4-1 Top view of the He-Ne laser upstream transport line

As seen in Figure 4-1, the He-Ne laser is reflected to the beam-line axis by a remotely controlled motorized mirror. The beam line axis is defined by surveyed iris diaphragm. The first iris is located on the breadboard. The second is at the end of the beam line (as can be seen in Figure 4-2). We have horizontal and vertical tilt adjustments on the He-Ne mount. In order to align the laser through the two targets we use the laser mount and the mirror adjustments. We aim at the first target using the laser-mount adjustment and aim at the second target using the mirror adjustment. After several iterations, the alignment will converge and the laser will be aligned through both irises.

We have a CCD camera that images the beam transmitted through the second iris, thereby enabling the precision alignment. (Figure 4-2)

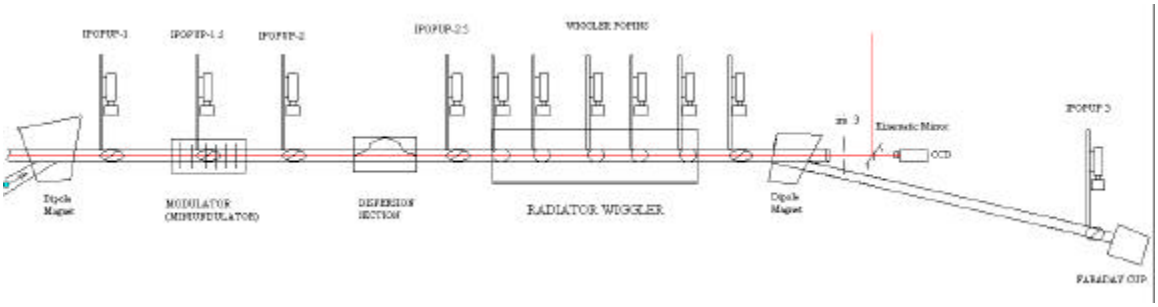

Figure 4-2 The electron beam diagnostics in BL-2

For diagnostic we have several cameras through the beam line which we image the electron beam and the He-Ne laser beam. I POPUP 1,1.5 and 2 cameras are dedicated to the modulator. We use these cameras to align the electron beam with the He-Ne laser. We have 5 pop-in cameras for the Radiator wiggler. Since the radiation is coming from the wiggler, we form a waist position of the He-Ne laser in the wiggler to be able to get more correlation.

We have a kinematic mirror after the dipole to send the radiation in to the Free Electron Laser room (FEL room) to be analyzed. The reason we have kinematic mirror here is that we need to align He-Ne laser with CCD camera. Kinematic mirror gives us the ability to move the mirror back and fourth without changing the alignment.

In the first optical table in Figure 4-1 we have a quarter inch thick glass window on a rotating base. We use this to calibrate the cameras along the beamline. By changing the angle of the glass we shift the beam by a known amount and measure it using the frame grabber in terms of pixels. These glasses are on a remote controlled flipper stage so that we can insert and retract remotely during the experiment. Also we have some attenuators in this table for He-Ne because the laser is too bright for the cameras.

Wiggler cameras have their own attenuators on a rotating wheel, which can also be controlled remotely. These attenuators are set for the electron beam. Once these attenuators are set we have to put additional attenuators for He-Ne laser upstream of the beamline to be able to see both electron beam and the He-Ne laser. However this attenuated He-Ne is still bright for the cameras around the modulator. We put another attenuator on a flipper stage on the first optical table, thus we can look at the modulator

cameras when we insert the flipper attenuator and we can look at the wiggler cameras when we retract it.

4.2 The Optical Transport Line to the FEL Diagnostic's Room

During the experiment we cannot be present in the ATF Experiment Hall due to the ionizing radiation generated by the electron beam. Since the SASE signal is exponential in the longitudinal direction, most of the radiation is coming from the last part of the wiggler. Therefore, in order to analyze the FEL radiation coming from the wiggler, we need to form the image of the wiggler in the FEL room. To obtain this image we use two long focal length Zn-Se lenses. Their design focal length values are 2.75m. However we need the precise focal lengths for the simulation of the transport system. For this reason we measured the focal lengths of the lenses.

4.2.1 Focal Length Measurement

We used two methods to measure the focal lengths.

1. **Imaging method**

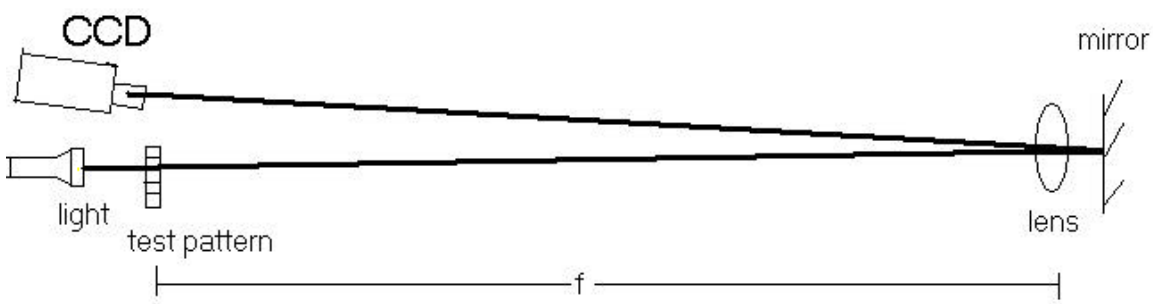

Figure 4-3 The set up for focal length measurement of a lens using a light source, test pattern, a mirror and a CCD camera

In this method we used a test pattern, which has parallel lines and letters to test the imaging. We set up a flashlight, the test pattern and the lens as shown in Figure 4-3

and placed a mirror after the lens, thus the light passes two times through the lens. The lens and the mirror are placed on a rail to allow easy change of the distance between the lens and the test pattern. Our purpose is to form an image of the test pattern on the CCD camera. The test pattern and the CCD camera are equidistant from the lens. Let *f* be the focal length of the lens. The equivalent optics consists of two lenses next to each other, equivalent to a single lens with a focal length *f*/2. Thus a object placed at a distance *f* on one side of the combined lens will be imaged at a distance *f* on the other side, as shown in Figure 4-4.

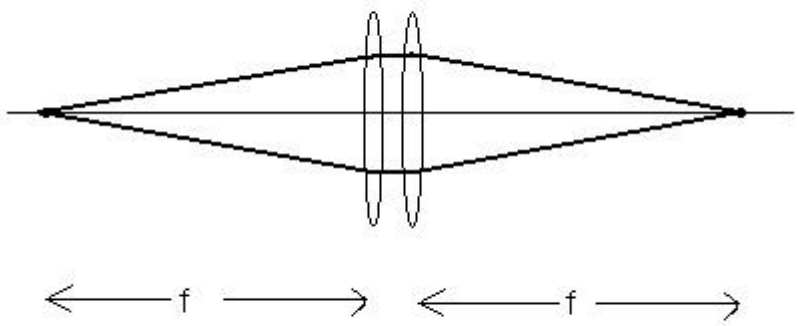

Figure 4-4 Equivalent optics of the set up shown in Figure 4-3

We verified the method with a known lens. One Zn-Se lens produced a sharp image at 264cm. The other Zn-Se lens and produced an image at about 241cm, however the image was not clear. We suspected stigmatism, and applied another method to clarify the lens characteristics.

4.2.2 Waist Measurement of the Beam

In this method we used a collimated He-Ne laser to measure the beam size at a few positions downstream of the lens. This method provides horizontal and vertical beam sizes independently. In order to improve the precision of the measurement we used a

simple telescope, consisting of two focusing lenses, to expand the beam (See Figure 4-5). The separation between the lenses is the sum of the two focal lengths of the lenses.

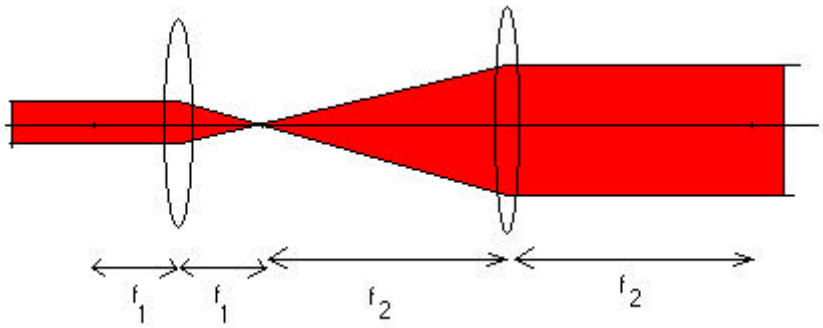

Figure 4-5 Optical schematic of a telescope

In this case the beam expansion ratio is f_2/f_1. The main significance of the telescope is its ability to improve the collimation of the He-Ne laser, which has some divergence coming out of the cavity. One of the lenses was placed on a micrometer stage, allowing a precise adjustment of the distance. The telescope allows us to create a bigger beam with a Rayleigh range much longer than the focal length of the ZnSe lens, and precise positioning of the telescope lens allows us to place the waist of the collimated beam at the lens position for best measurement accuracy without more elaborate beam simulation. The Zn-Se lens is placed as shown in Figure 4-6. After double passing we form a waist at $\frac{f}{2}$ distance from the lens instead of f.

Figure 4-6 The waist method for the measurement of a focal length

The CCD camera is placed on a rail, and moved along the laser path. The beam size is measured at a few positions to find the smallest spot size in vertical and horizontal directions.

The lens suspected of stigmatism had horizontal and vertical waist positions which were different by about 5 cm. In horizontal we got $\frac{f}{2} = 124.5cm$ whereas in vertical $\frac{f}{2} = 119.5cm$. That means this lens has $\pm 2\%$ error if we assume the focal length is 244 cm as an average of both axes.

The other lens measurement produced f=267 cm in both directions, in good agreement with the previous method.

Since these results are obtained at the 633 nm wavelength of the He-Ne laser, we have to correct for the change in the index of refraction to 5.3 μm. For the correction we use the relation:

$$\frac{1}{f} = (n-1)(\frac{1}{R_1} - \frac{1}{R_2})$$

Eqn 4-1

The focal length is inversely proportional to n-1. Therefore for 5.3 μ the focal length will be 11 % larger, so the focal lengths at 5.3 μm are 271 cm and 296 cm.

4.2.3 The Transport Line

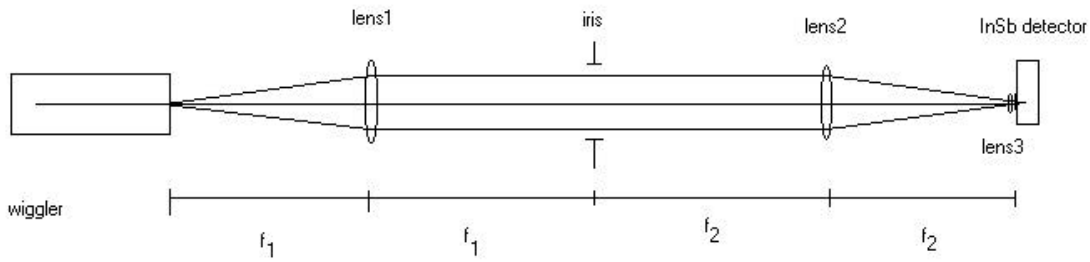

Figure 4-7 The schematic layout of the optical transport line

Figure 4-7 shows the layout of the transport line from the wiggler to the FEL room. The system forms a one to one image of the end of the wiggler at the diagnostic station. As shown in Figure 4-7 we put the first lens at a distance f_1=271cm from the end of the wiggler. The second lens is placed f_1+ f_2=271+296=567cm from the first lens. The image is formed at a distance f_2 away from the second lens. Thus the beam forms a waist at the detector position.

An iris placed at a distance f_1 from the first lens provides a new feature – angular distribution analysis. At the iris position, almost in the mid-point of the lenses, size corresponds to the angular divergence at the wiggler. So by varying the aperture of the iris we can analyze the angular distribution of the radiation.

The simple estimate of the magnification was tested with an optical transport simulation code, the BeamCad program [17]. BeamCad is simply a Gaussian beam propagation code, and does not take into account aberrations. It confirms that the magnification is about 1 (see more below). To be conservative in our signal collection, we assumed the full beam size in the wiggler to be 3 mm. Since the detector's sensitive area is 1mm in diameter, a short focal-length lens is needed to reduce the beam size on the detector. We use a meniscus lens with1 cm diameter and 1.6 cm focal length, located just in front of the detector to avoid aberration. Aberrations are minimum when the lens positioned as shown in Figure 4-8.

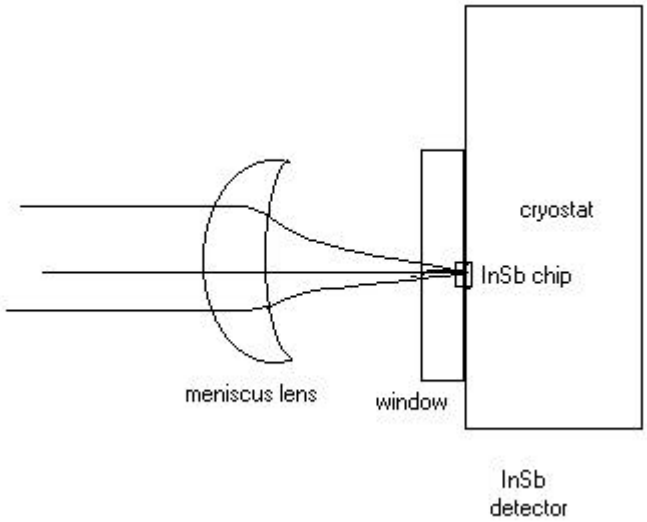

Figure 4-8 In-Sb[18] detector and collecting lens

Distance. From Reference, m		Beam Dia. mm
Wiggler position	0	3.000002
First lens position	2.71	9.129972
Second lens position	8.38	9.230839
Meniscus lens position	11.34	3.276755
Detector position	11.356	0.046628

Table 4-1 Calculated beam sizes using the Beam Cad program

As we see on Table 4-1 the beam size at the detector position is reduced to 50μ in diameter, thus we can safely fit the whole beam into the detector.

The complete transport line from the experimental hall to the FEL room schematic diagram is shown in Figure 4-9 below.

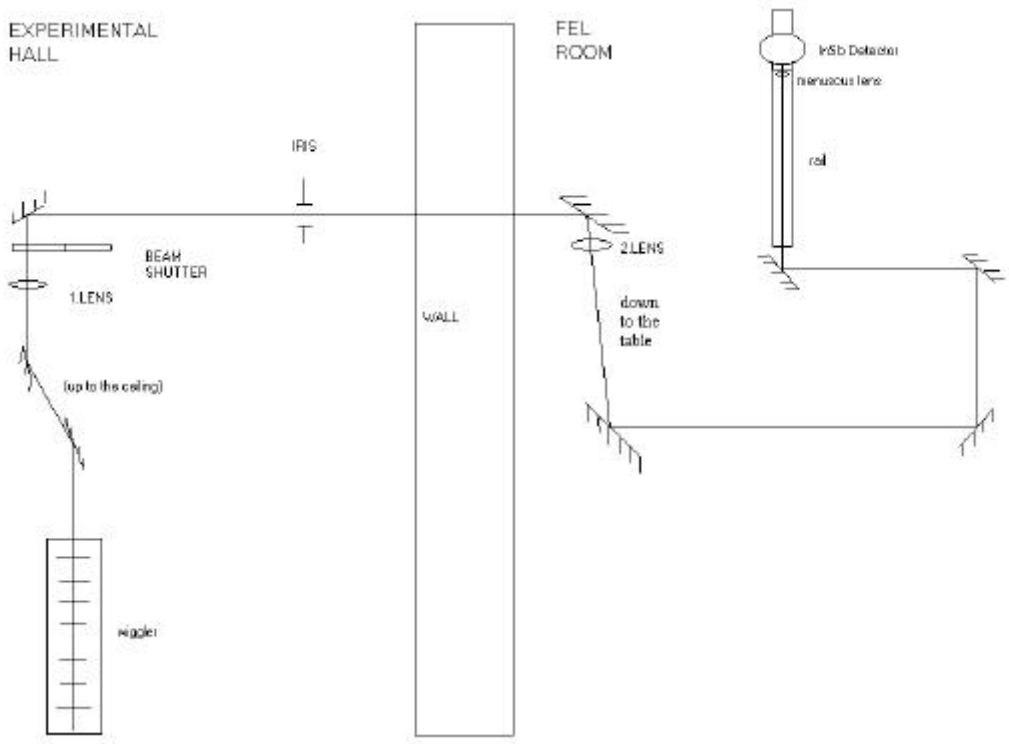

Figure 4-9 A schematic view of the optical transport line leading from the HGHG beam line to the optical analysis room.

In this schematic drawing we describe both horizontal and vertical portions of the transport line. The radiation emerging out of the wiggler is reflected up to the ceiling. Then the first lens is positioned nearby, in a horizontal section. The next element is a beam shutter, which is required for the safety interlock system. This shutter can be opened only when the two rooms are simultaneously secured for laser operations, therefore preventing laser radiation exposure. Downstream of the shutter the beam is reflected towards the FEL room and then reflected down to the table. The second lens is located in this vertical drop. The beam passes through four mirrors on the optical table on its way to the detector. The choice of lens locations has been discussed above.