Investigations towards an optical transmission line for longitudinal phase space measurements at PITZ

Sergei Amirian
Moscow institute of physics and technology
DESY, Zeuthen, September 2005
Email:serami85@yahoo.com

Abstract

The Photo Injector Test facility at DESY Zeuthen was built for research and development on sources of high brightness electron beams for free electron lasers and linear colliders. The RF-gun approaches to produce electrons with a momentum of about 7 MeV/c. It is the goal to measure the temporal characteristics of the electron bunch train and single bunches with high accuracy by using a Cherenkov radiator optical transmission line and a streak camera. The problem to be solved is the light transport over a distance of about 27 m. The actual optical transmission line consists of achromats and photo lenses, which increase the chromatic dispersion. To avoid the dispersion effect in the optical transmission line completely reflective optics has to be used. The investigation of Seidel aberrations of different mirror types will be presented. The results of simulations of the optical system with different parameters of optical elements will be shown. The study of a transverse resolution, magnification and pulse elongation during propagation through the system will be discussed.

1. Introduction

The photo injector PITZ at DESY Zeuthen is a dedicated facility for the investigations of RF-guns for future FEL-s and linear colliders. Different diagnostic methods are used to investigate the characteristics of the produced electron beam. One important goal is the measurement of the bunch length and longitudinal phase space with a temporal resolution of 2 ps and 0.2 ps respectively limited by the streak camera to be used as basic tool.

A large fraction of the light created by the electron beam hitting or penetrating a radiator has to be transported by the optical transmission line onto the entrance slit of the streak camera. The light transport has to be performed creating minimum time dispersion, good transverse resolution and a minimum light loses.

The light to be transported by the optical transmission line is produced by Cherenkov radiator. It transforms electron bunches into pulses of light with wavelength in the visible range. A silica aero-gel of a refractive index of n = 1.03 and a thickness of 2 mm is used at PITZ experiment. Consequently the divergence angle of photon bunch is about 13 deg. The photon bunches produced by silica aero-gel have approximately the same temporal distribution as the electron bunch.

The streak camera can measure the temporal profile of the photon pulse. The light enters through a small horizontal slit and propagates through the entrance optics into the streak camera. The entrance optics projects the photon distribution at the slit plane onto a photo cathode, which transforms the light into electrons. These electrons are accelerated in the direction of a micro channel plate by passing a streak tube, where a high frequent electrical field is applied, so that electrons are reflected in vertical direction. Depending on the moment of arrival at the streak tube the electrons are differently deflected. The vertical direction displays the temporal distribution of the photon pulse.

2. Simulation

The simulations presented in this work were done with WinLens4.3 and RAY. The WinLens4.3 is a free version software of LINOS company. With this program the investigations of Seidel aberrations for different mirror types were done. The significant disadvantage of this program is that one cannot study the influence of the whole system on the final picture. It is impossible to design the system with an optical element, which has an off-axis position of its vertex. This program can be used for investigation of optical line with refractive optics. Hence in required case only one mirror system can be investigated. The results of simulation with Winlens4.3 are presented in Fig.1-Fig.4.In this paper the plots of only two mirror types are presented: parabolic and spherical. One can notice that a parabolic mirror doesn't have spherical aberration unlike spherical, hyperbolic and elliptic mirror. For all this mirrors the spherical aberration plays the most important role. Increasing the object size one can see that spherical aberration becomes one order of magnitude larger than astigmatism and coma.

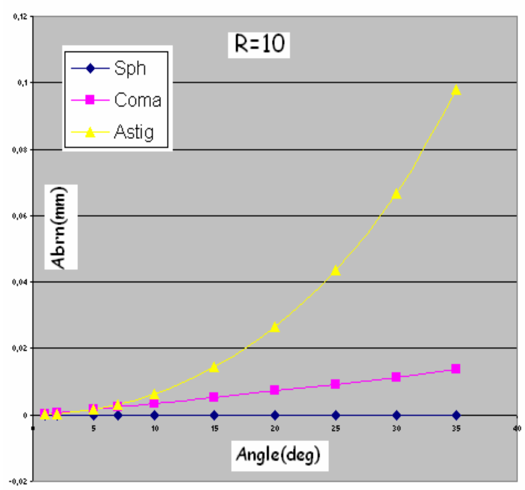

Fig.1: *The simulation for parabolic mirror. Seidel aberrations vs angle of divergence*

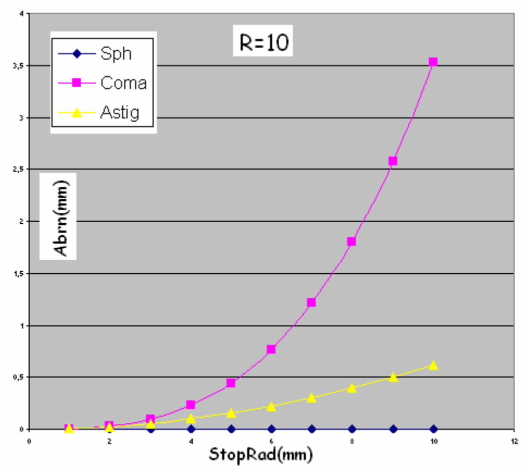

Fig.2: *The simulation for parabolic mirror. Seidel aberrations vs object size.*

From this plots it is obvious that only parabolic mirrors should be used in optical transmission line.

RAY is the BESSY ray tracing program to calculate synchrotron radiation beam lines. This program was used in this work to investigate optical transmission line, study pulse elongation during passing through the system, transverse resolution and magnification

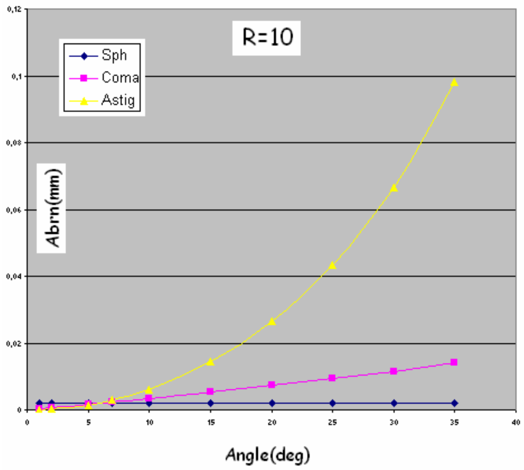

Fig.1: *The simulation for spherical mirror. Seidel aberrations vs angle of divergence*

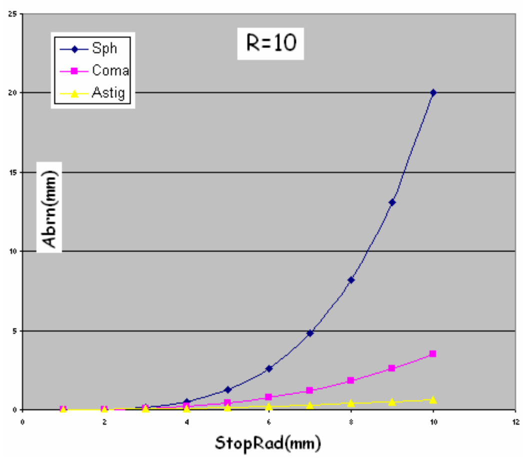

Fig.2: *The simulation for parabolic mirror. Seidel aberrations vs object size.*

of the picture at the entrance of the streak camera.

The optical transmission line should fulfill definite requirements. It should collect a maximum of created light, transmit the light over 27 m, project the transported light onto the entrance slit of the streak camera, minimize the number of optical elements, maximize the number of transmitted photons, optimize optical resolution, fix maximum object distribution, minimize the photon pulse elongation. The general example of the optical transmission line is presented in Fig.5. To simulate the Cherenkov cone the slit with a bagel shape was placed behind the radiator at the distance of 10 mm. The maximal and minimal radii of the slit are respectively equal to 2.6 and 2.4 mm. The angle range in this case is 0.23÷0.25 rad. The size of radiator is taken to be 2x2 mm which corresponds to a typical size of the electron beam. The energy of photons lays in the range of 1.5÷3.5 eV corresponding to the visible light photons.

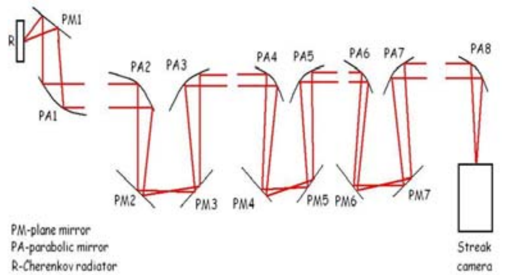

Fig.5: The *optical transmission line*

The influence of the slit on the aperture of photon beam is not significant. Fig.6 shows the slight change in the beam diameter gradient at the position of the slit.

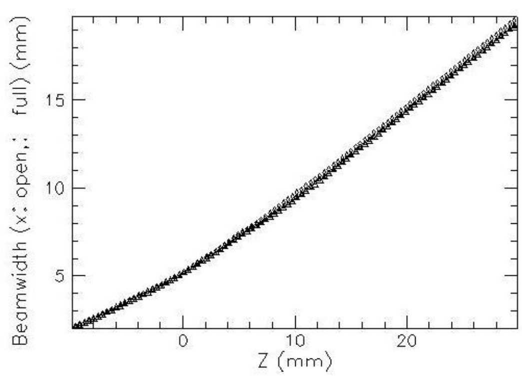

Fig.6: *The influence of the slit on the photon beam aperture*

The transverse distribution of source is shown in Fig.7:

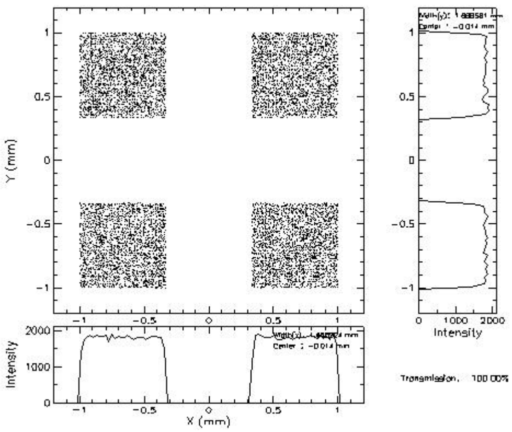

Fig.7: *The transverse distribution of source*

The bunch length in this simulation is taken infinitesimal to obtain elongation due to the optical beam line.

To minimize the number of optical elements, parabolic mirrors in our case, one has to take the grazing angle of the mirrors to be 45 deg. RAY has a severe restriction on the maximal number of optical elements to 10 elements. At the same moment it is clear that the decreasing of grazing angle decreases the transverse resolution. The number of mirrors with the same parameter of parabola necessary to transport the light over the distance L can be derived from the obvious formula:

$$\frac{Nl\sin(2\alpha)}{2}+(2N-1)f(\alpha)=L \qquad (1)$$

here, α is grazing angle, N is number of optical elements, l is the distance between collimating and focusing mirror and f(α) is a focal length of the mirror as a function of grazing angle. This dependence for parameter of parabola p=200 mm is shown in Fig.8:

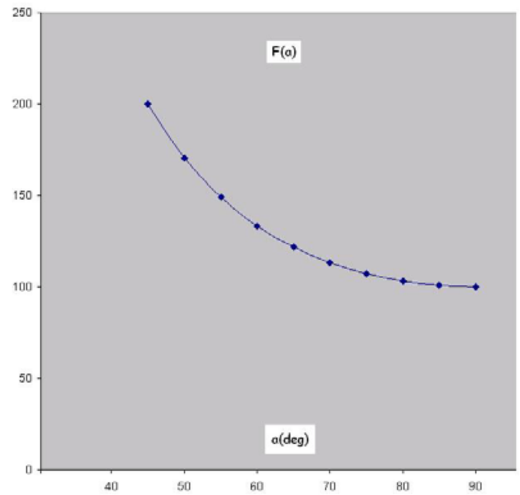

Fig.8: *Focal length vs grazing angle*

The first mirror in the transmission line should have a small focal length, otherwise one will obtain a wide beam and its transport requires a large diameter mirrors to be used in the optical line. One example of simulations with RAY is presented below.

In Table 1 the mirror parameters of simulated system are presented:

	PA1	PA2-PA8
Radius	100 mm	150 mm
Grazing angle	-45 deg.	±45 deg.
Parameter of parabola	200 mm	1000 mm

Table 1: *Optical system parameters*

The distance between collimating and focusing mirror l is equal to 5000 mm.

The result for transverse distribution is shown in Fig.9. Fig.10 shows longitudinal distribution, i.e. pulse elongation.

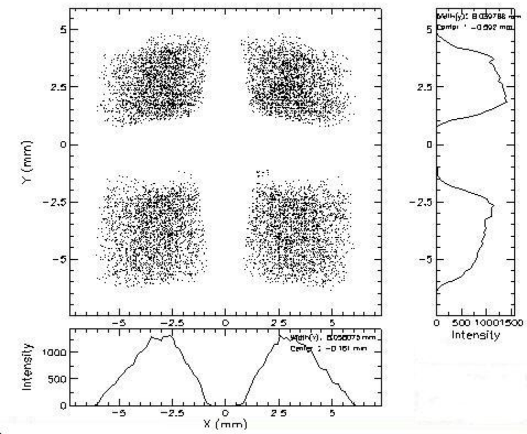

Fig.9: *Transverse distribution at the entrance of the streak camera. Grazing angle is 45 deg.*

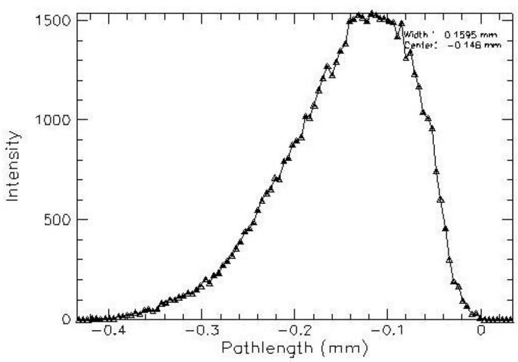

Fig.10: *Longitudinal distribution at the entrance of the streak camera. Grazing angle is 45 deg.*

The pulse is elongated by 0.5 ps, i.e. less than the temporal resolution of the streak camera. But at the same time the picture of transverse distribution is visible with a significant shearing. The transmission of the line is equal to 84.3%. The transmission in this case is called a quantity which shows the fraction of rays which achieved the slit of the streak camera. This photon loss is explained by the value of the mirror diameter, some photon miss the mirror plane. By increasing the mirror diameter one may increase the transmission.

Remaining the grazing angle equal to 45 deg. and changing other mirror parameters one is not able to improve significantly transverse distribution pattern. Fig.11 and Fig.12 show the results for transverse and longitudinal distribution respectively for the same system but with grazing angle equal to 85 deg. and distance between mirrors l=2500 mm:

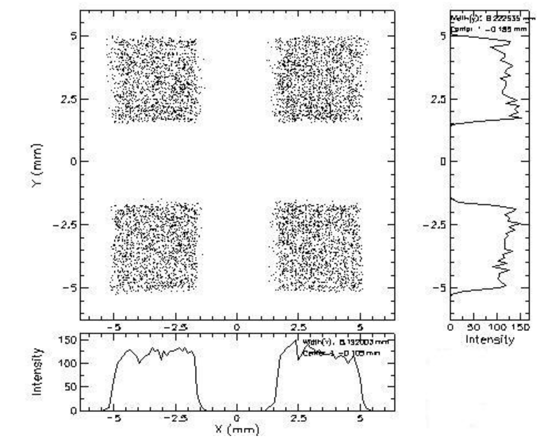

Fig.11: *Transverse distribution at the entrance of the streak camera. Grazing angle is 85 deg.*

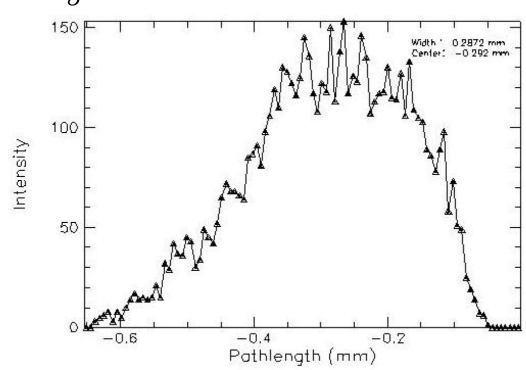

Fig.12: *Longitudinal distribution at the entrance of the streak camera. Grazing angle is 85 deg.*

The pulse is elongated by 0.96 ps, i.e. more than in previous case, but still less than the temporal resolution of the streak camera. Transmission is equal to 100%. Concerning the transverse resolution one can mention a significant improvement. The pattern is rather sharp. The disadvantage of the increasing of grazing angle is that in this case one should increase the number of mirrors according to formula (1). To obtain the fine transversal resolution and collect all reflected light one should also decrease the distance l or increase the diameters of the mirrors. The necessary number of mirrors in this case is equal to 22. One should keep in mind that the increase of mirror numbers increases the pulse elongation. Study of a system containing more than 10 optical elements is impossible with RAY. The resolution dependence on the grazing angle is presented in Fig.13. The resolution is defined as a ratio of top and bottom length of transverse distribution.

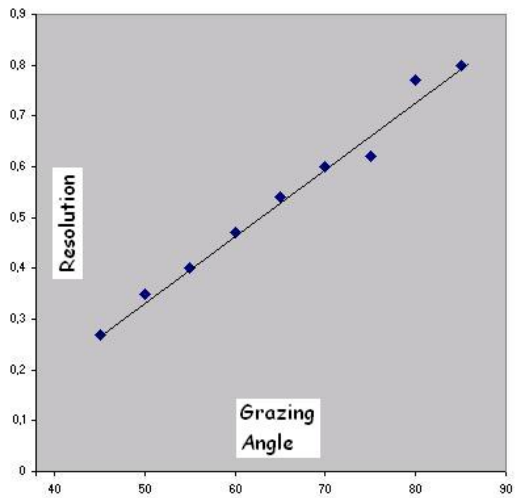

Fig.13: *The transverse resolution vs grazing angle*

In Table 2 the list of mirrors available in laboratory is presented:

Number	Focal length mm	Diameter mm
2	660	100
1	900	150
1	1200	200
2	1500	250

Table 2: *Mirrors available in laboratory*

Unfortunately there was no enough space in laboratory room to construct the system containing the mirrors with large focal length. To simulate the system with available mirrors and with grazing angle different from 90 deg. one should use spherical mirrors. For an inclined parabolic mirror RAY uses the plane which does not contain the vertex of the paraboloid. The mirrors available in the laboratory have their vertexes in the plane of the mirror. Hence to simulate the similar system one should replace the parabolic mirrors by spherical ones. The result of the simulation of the system constructed in laboratory (see Fig.14), but with spherical mirrors is presented in Fig.15:

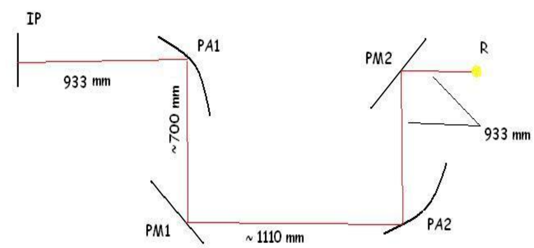

Fig.14: *The laboratory setup*

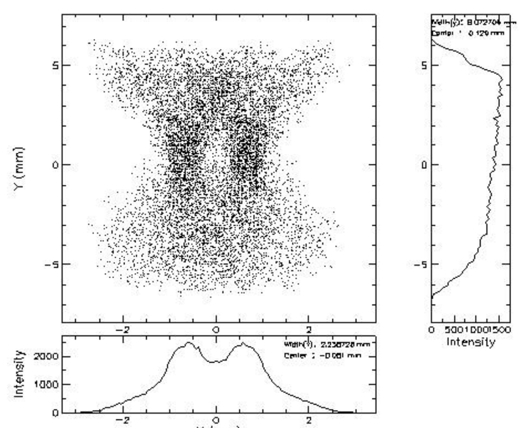

Fig.15: *The simulated transverse resolution at the image plane for the laboratory setup with spherical mirrors*

The image is sheared so much that one cannot even see the object shape. The simulations with spherical mirrors are not reasonable because of the high value of spherical aberration.

3. Measurement

The picture of the setup is presented in Fig.16:

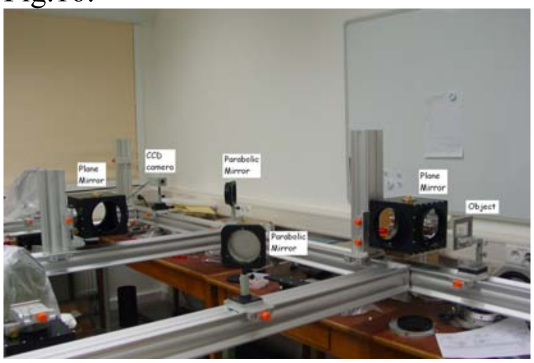

Fig.16: *The picture of the setup*

There were only two parabolic mirrors with focal length f (90) = 660 mm used in the experiment. The distance between mirrors was approximately equal to $2f(45) = 2\sqrt{2}f(90)$, where f (45) is the focal length when grazing angle is equal to 45 deg. The setup with large focal length mirrors requires more space. The CCD camera was positioned in the image point, so one could observe the picture on the PC.
The best resolution we have achieved by adjustment of the setup is presented in the Fig.17:

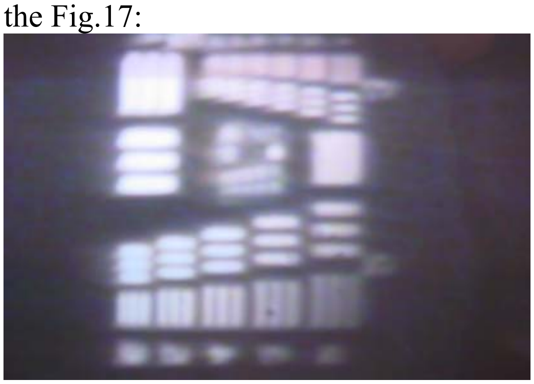

Fig.17: *The picture to estimate the resolution of the setup recorded by a CCD camera*

From this picture one can find the resolution to be ~ 8 L/mm.

4. Summary

The simulations of different optical lines were done with RAY. The main disadvantage of this software is that one cannot simulate the parabolic mirrors with the vertex of parabolic function in the mirror plane. The simulations with grazing angle close to 90 deg. and measurement show that mirrors with vertex in the mirror plane will give better result for transverse resolution. For this reason some other software should be used and further simulations with grazing angle equal to 45 deg. should be done. In the RAY simulations the longitudinal distribution was obtained to be less than temporal resolution of the streak camera. Nevertheless, increasing the number of optical elements and grazing angle one also increases the pulse elongation. This fact points out that to improve the longitudinal resolution in the optical line the mirrors with a large optical length and grazing angle close to 45 deg. should be used.

Acknowledgements

I want to thank Mr. Hiller and Mrs. Baer for organizing the summer student program. It was a great experience for me in a scientific work. Also I want to thank Mr. Hiller and DESY administration for very interesting excursion to Hamburg. I want to give thanks to all lecturers during this summer program, especially to Mr. Lohmann.

Also I want to thank the whole PITZ group for letting me take part in the meetings.
I want to give thanks to my supervisor Juliane Rönsch who introduced me in the project and supported me during the work. Also I want to thank Mr. Bähr who was willing to answer my questions and helped in running the experiment. Thanks for useful discussions to Dirk Lipka, who has introduced RAY to me and was always glad to answer my questions.
Finally, I want to thank all summer students for being such nice colleagues.

References

[1] J.Bähr et al.: Optical transmission line for streak camera measurements at PITZ, DEZY Zeuthen, Germany
[2] J.Rönsch: Selected studies of the longitudinal phase at the photo injector test facility at DEZY Zeuthen, Diploma Thesis, 01 March 2005, DEZY Zeuthen, Germany
[3] D.Lipka: Optical transmission line with parabolic mirrors, DEZY Zeuthen, Germany
[4] F.Schäfers: RAY the BESSY ray trace program to calculate synchrotron radiation beamlines,05 April 2004, BESSY GmbH, Berlin, Germany
[5] M.Krasilnikov et al.: Recent developments at PITZ, DEZY Zeuthen, Germany
[6] D.Korsch: Reflective optics, Academic Press, INC., Harcourt Brace Jovanovich, Publishers, 1991