OPTICAL SYSTEM FOR MEASURING ELECTRON BUNCH LENGTH AND LONGITUDINAL PHASE SPACE AT PITZ: EXTENSION AND METHODICAL INVESTIGATIONS *

J.Bähr[1], H.Lüdecke, DESY, Zeuthen,Germany

J.Rönsch,University of Hamburg, Germany

Abstract

A complex optical system for measuring the electron bunch length and the longitudinal phase space using a streak camera is installed at PITZ. This system will be extended by two new branches in 2007. The physics design of the chambers containing the radiators and of the optical system is presented. The results of optical calculations of the whole system will be given. Results of methodical investigations will be shown as well, especially concerning transversal optical resolution and time dispersion.

INTRODUCTION

The Photo Injector Test facility at Zeuthen PITZ [1] is a dedicated facility for the developing rf guns for FELs as FLASH or the European XFEL at DESY. The experimental setup consists of a 1.5-cell L-band rf gun with a Cs_2Te cathode. The photocathode laser is capable to generate pulse trains up to 0.8ms length with a pulse to pulse separation of 1 µs. Besides diagnostics elements the gun is followed by a booster cavity which accelerates the electrons up to about 13 MeV. This booster will be exchanged in 2008 by a newly developed one. Then a beam energy of about 28 MeV will be reached. The whole electron beam line which is still under further development consists essentially of diagnostics elements. Besides several systems used for the analysis of the transverse phase space, which is crucial for the optimum running of any SASE-FEL, an extended system for the measurement and analysis of the longitudinal phase space is installed.

The longitudinal phase space [2] and the beam momentum are measured by screen chambers being part of magnet spectrometers whereas the electron bunch length is measured by use of screen stations in the main beam-line all containing special radiators. In both cases a streak camera for the detection of light created mainly by Cherenkov radiators is used. The typical bunch length in the gun is currently about 20 ps. The rise and fall time of the laser pulse creating the electrons of the bunch is about 7 ps later 2 ps. These numbers give the order of magnitude for the temporal resolution needed to be reached by the optical system including the streak camera, which is a device C5680 of Hamamatsu [3] with a resolution of about 2 ps FWHM.

*Work is partly supported by the European Community, contract numbers RII3-CT-2004-506008 and 011935, and by the "Impuls- und Vernetzungsfonds of the Helmholtz Association, contract number VH-FZ-005.

[1]juergen.baehr@desy.de

DESCRIPTION AND EXTENSION OF THE EXISTING OPTICAL SYSTEM

A specially developed optical system [4] transmitting the Cherenkov light [5] from the radiator in the e-beam to the streak camera about 27 m apart from the electron beam line is used at PITZ. Up to now three readout chambers are installed: DISP.scr1 (1) [2] in the low momentum spectrometer and LOW.scr3 (2). A further screen station HIGH1.scr2 (3) is mounted in PITZ just behind the booster cavity for measuring the bunch length and longitudinal bunch profile in the high energy section. Furthermore, a magnet spectrometer for the momentum measurement behind the booster cavity [6] is under development containing screen stations, one with optical readout (DISP2.scr1 (4)) for the streak camera. It will be installed in September 2007. The optical system for this spectrometer is essentially developed and described here.

The optical system is consisting of several branches of input optics, a commonly used optical transport system and a de-magnifying (matching) system. The system is modular and can easily be extended.

Two basic types of radiators are in use to convert the temporal electron bunch shape into that of a visible light pulse: Cherenkov radiators and radiators based on Optical Transition Radiation (OTR). Silica aerogel of different refractive indeces and a quartz plate are used as Cherenkov detectors. Up to now Silica aerogel is mostly used in the range of electron energy available up to now at PITZ (5-13 MeV) because of the higher amount of emitted light compared to OTR, see Fig. 1a.

Two types of optical schemes are used in the light collection systems. In the case that the bunch length is to be measured at a screen station in the main beam line, the so called "full cone"-approach is applied. All Cherenkov light is collected by the high aperture input optics. This method is not applicable in the case of rather extended input light distributions like momentum spectra. It is excluded in principle to transport light of an extended object field by a very high input aperture without remarkable light losses for off-axis object points. Therefore only a small fraction out of the Cherenkov cone of about one or two degrees is used. This scheme is called "partial cone". The light distribution of the momentum spectrum has to be imaged with appropriate spatial resolution onto the entrance slit of the streak camera which has dimensions about 0.05 mm x 6 mm. Therefore, for each screen station a suitable overall magnification has to be realized. In Tab.1 the radiators and related optical input schemes are shown for all screen stations in use or under development.

Tab1: Screen stations, their physical tasks, radiators, optical input schemes, OTR: optical transition radiation, YAG: Yttrium-Aluminium garnet, F: full cone, P: partial cone

Port	Physical task	Radiator	F/P
1	TV (momentum)	YAG	
	Long. phase space	Aerogel, n = 1.05, quartz	P
	Long. Phase space	OTR	F
2	Bunch length	Aerogel n=1.03, OTR	F
	TV,Beam size	YAG	
	Bunch length, test of partial cone	Quartz	P
3	TV, beam size	YAG, OTR	
	Bunch length	Aerogel n=1.008, OTR	F
4	TV: momentum	YAG	
	Long. Phase space	Aerogel n=1.05	P
5	TV(slice emittance)	YAG	
	TV:momentum, long.phase space possible	OTR	F

Further demands to the optical imaging are a high light collection and transmission efficiency and a minimum time dispersion of the light passing the optical transport line. Generally, achromatic lenses of large focal length forming telescopes with 4-F geometry are used for the imaging over large distances. These lenses have usually a low aperture. Therefore the aperture of the light coming from the light collection system has to be matched to the lenses by magnification. The matching system at the end of the beam line de-magnifies the intermediated images so that the final image fits to the slit dimensions and a maximum of light is passing through the slit of the streak camera. The system is optimized to have minimum of light losses and minimum of optical elements. An image rotating box [9] using switch-able mirrors is used to turn the image of the low energy momentum spectrum by 60 degrees to fit to the streak camera slit orientation.

Port (2) is used for the bunch length measurement [7] in the low energy section. The mostly used configuration is aerogel n=1.03 and will be 1.008 in future (to match the foreseen higher momentum after the gun) and full cone optics.

DESIGN OF TWO NEW RADIATOR CHAMBERS AND RELATED OPTICS

The screen station (3) allows the determination of the longitudinal distribution in the high energy section just behind the booster cavity. It contains an OTR screen and an aerogel radiator with refractive index n = 1.008 and a thickness of 9 mm for bunch length measurements. The full light cone has to be transported. Further screens are installed to measure the transverse distribution by a CCD camera. A detailed description of the design considerations of radiators in screen station (3) can be found in [8].

The High Energy Dispersive Arm HEDA1 (port (4), (5)) is used for momentum and longitudinal phase space measurements [9] in the high energy section of PITZ and includes two screen stations. The first one (4) contains a Silica aerogel radiator (n=1.05, 80mm x 20mm x 5mm) for streak readout. The "partial cone" optical input scheme is used because of the dimensions of the spectrum. The thickness of the aerogel of 5 mm leads to a contribution of about 0.6 ps to the temporal resolution for a momentum of 15 MeV/c. Fig. 1a and Fig.1b show the number of photons and the temporal resolution vs. beam momentum.

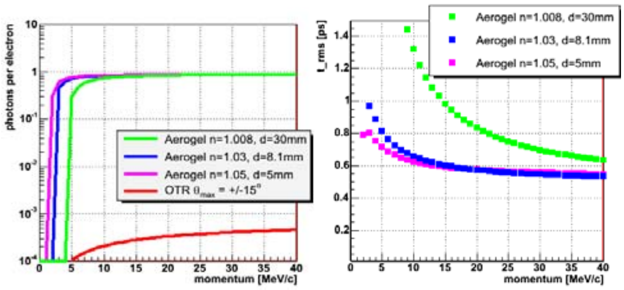

Fig.1a: Number of photons produced by different aerogels and OTR vs. beam momentum, Fig. 1b: Temporal resolution of different Silica aerogels vs. beam momentum

All the suggested aerogel solutions produce about the same number of photons at about 30 MeV/c, but for n =1.05 the resolution in the range from 5 to 15 MeV/c is at minimum compared to the other options and the number of photons for lower energies is higher.

The second screen station (5) in HEDA1 contains an OTR-screen and will initially be used for TV readout. Streak optics can be added later easily. For about 30 to 40 MeV/c the emission angle of an OTR radiator is rather small, so the full cone can be measured.

CHARACTERIZATION OF THE WHOLE OPTICAL SYSTEM

Several quantitative characteristics are used to describe the whole system:

- collection efficiency ε(coll)
- transmission efficiency ε(Tr)
- Modulation Transfer Function (MTF)
- spatial resolution R
- time dispersion Δt

The design of the optical system for "full cone" is such that the collection efficiency is about 100%, while in case of "partial cone" it is <1%. All subsystems are designed such that the transmission efficiency is maximized and any vignetting is avoided. For example the transmission efficiency at screen 3) for a beam of 2 mm diameter is 98% for a central ray and 85% for a ray with 1.4 mm off-set. The other characteristics will be used to compare measurements and simulations shown in Tab. 2.

Tab.2: Results of measurements and simulations of the optical systems of four branches: R: spatial resolution, ΔT: time dispersion, F: full cone, P: partial cone, M: magnification

No. port	R/ Lp/mm	R/Lp/mm at λ/nm	ΔT/ ps	ΔT/ ps	M
	Meas.	Calcul.	Meas.	Calcul.	
1	3 [‡]	>9 (550)	68	58	0,2
2	12[§**]	170 (550) 20 at (400-700)	73	52	1,6
3	15	9	-	45	1.4
4	-	20	-	40	0.07

The measured time dispersion is larger than the calculated one. This can be explained with facts like dispersion in air, that lenses in reality are mostly thicker than their values in the catalogues and misalignment of optical elements. The values of spatial resolution are mostly better than the design values.

For screen station 1 the calculated Modulation Transfer Function MTF is shown in Fig. 2. The figure shows the high transverse spatial resolution of at least 8 Lp/mm.

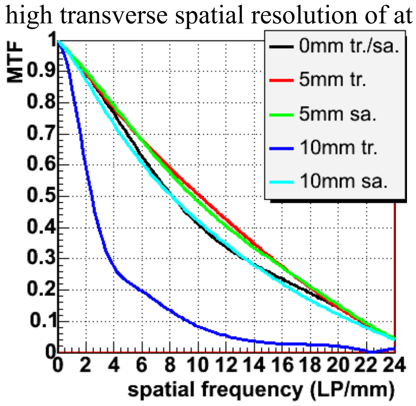

Fig 2: MTF for screen (1), different conditions for the range of 545-555 nm, offset from optical axis in mm, sa: sagittal, tr: transversal

REFLECTIVE OPTICS

The goal of the design of the optical system is to reach a temporal resolution of the whole system which is comparable to the temporal resolution of the streak camera, i.e. about 2 ps. As earlier measurements have shown [5], the temporal resolution of the system is about 60 ps caused by dispersion in the lenses. It is necessary to restrict the spectral bandwidth essentially to reach the wanted time resolution. This results of course in a large loss of light. To improve the situation significantly, refractive elements (lenses) must be exchanged by reflective elements (mirrors) because these do not cause any dispersion. We consider the use of aspheric mirrors to avoid, beside a large chromatic aberration also spherical aberration at the same time. A simple ansatz was tested experimentally and by simulation as a first step for an improved system. It is based on telescopes formed by mirrors in 4-F configurations see Fig. 3. The mirrors are aspheric on-axis with rather high aperture. Also a system consisting of two telescopes of such mirrors was investigated. The spatial resolution was measured to 30 Lp/mm for a scheme of four parabolic mirrors (two 4-F schemes, magnification = 1, f1 = f2 = 660 mm, f3 = f4 = 1500 mm, overall length about 12 m).

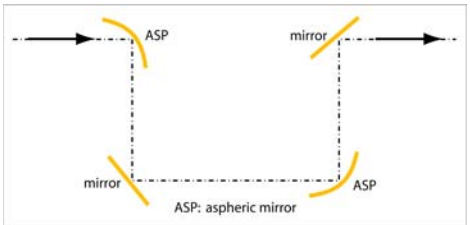

Fig.3: Scheme of a telescope formed by aspheric mirrors (ASP)

CONCLUSION

The optical system for the measurement of bunch length and longitudinal phase space by streak camera has been described and evaluated. In 2007 it will be extended by two new branches. The transverse resolution, the time dispersion and further characteristics are measured and simulated. Most of theses are better than the design goals. The basic problem of the time dispersion caused by use of lenses is going to be solved by aspheric mirrors.

REFERENCES

[1] F.Stephan et al., Photo Injector Test Facility and Construction at DESY, FEL 2000, Durham.

[2] J.Rönsch et al., Longitudinal Phase Space Studies at PITZ, FEL ’05, SLAC, Stanford, USA, 2005.

[3] Hamamatsu Photonics, Hamamatsu city, Japan

[4] J.Bähr et al., Optical Transmission Line for Streak Camera Measurements at PITZ, DIPAC ‘03, Mainz, Germany 2003

[5] J.Bähr et al., Measurement of the longitudinal phase space at the Photo Injector Test Facility at DESY Zeuthen DIPAC ’03, Mainz, Germany 2003.

[6] S.Khodyachykh et al., Design and Construction of the Multipurpose Dispersive Section at PITZ, DIPAC’07, Venice,Italia.

[7] J.Bähr et al., Measurement of the Longitudinal Phase Space at the Photo Injector Test Facility at DESY Zeuthen, FEL ’03, Tsukuba, Japan.

[8] J.Rönsch et al., Investigations of the Longitudinal Beam Properties at the Photo Injector Test Facility in Zeuthen, FEL’06, Berlin, Germany.

[9] J.Rönsch, Measurement of the Longitudinal Phase Space at the Photo Injector Test Facility at DESY in Zeuthen (PITZ), DIPAC’05, Lyon, France, 2005

[‡] resolution measurements limited by pixel size of used CCD camera

[§] resolution measurements limited by pixel size of used CCD camera

[**] without first lens f = 80mm