Nuclear Instruments and Methods in Physics Research A 654 (2011) 580–587

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Reflective optical system for time-resolved electron bunch measurements at PITZ

K. Rosbach [a],*, J. Bähr [a], J. Rönsch-Schulenburg [b]

[a] DESY, Platanenallee 6, 15738 Zeuthen, Germany
[b] Hamburg University, Luruper Chaussee 149, 22761 Hamburg, Germany

ARTICLE INFO

Article history:
Received 11 January 2011
Received in revised form
14 June 2011
Accepted 14 June 2011
Available online 25 June 2011

Keywords:
Photo-injector
Longitudinal phase space diagnostics
Streak camera
Time-resolved imaging
Cherenkov imaging
Reflective optics

ABSTRACT

The Photo-Injector Test facility at DESY, Zeuthen site (PITZ), produces pulsed electron beams with low transverse emittance and is equipped with diagnostic devices for measuring various electron bunch properties, including the longitudinal and transverse electron phase space distributions. The longitudinal bunch structure is recorded using a streak camera located outside the accelerator tunnel, connected to the diagnostics in the beam-line stations by an optical system of about 30 m length. The temporal resolution is severely degraded by this optical system, mainly due to dispersion in the achromatic lenses. This article presents initial studies toward a system based on reflective optics which will restore the temporal resolution to a level close to the streak camera resolution of 2 ps FWHM. The study includes simulations and measurements of different mirror systems, with an emphasis on systems of parabolic mirrors. A hybrid system of lenses and mirrors, which can serve as a proof of principle, is discussed in detail.

1. Introduction

The Photo-Injector Test facility at DESY, Zeuthen site (PITZ), is a linear electron accelerator [1]. The main research goals for PITZ are the optimization of electron bunch parameters for driving short wavelength free electron lasers, in particular reaching a transverse emittance suitable for the European X-ray Free Electron Laser (European XFEL [2]), as well as extensive R&D on electron source design and diagnostics. In particular, several gun cavities of similar designs, with variations in cooling systems and surface treatments, were conditioned and characterized at PITZ, then delivered to the Free-Electron Laser in Hamburg (FLASH [3]).

The PITZ photo-injector produces electron bunches with a nominal charge of 1 nC by the photoelectric effect, using UV laser pulses with a flat-top temporal distribution of ~ 20 ps FWHM duration. The gun cavity accelerates the electron bunches to a momentum of about 6.5 MeV/c, which is then increased to about 15 MeV/c in a booster cavity [4]. Under these conditions a normalized projected emittance of 1.0 mm was measured taking into account 100% of the charge using the single slit scanning technique [5].

PITZ is also equipped for the diagnostics of the longitudinal phase space. In particular, the temporal bunch structure is recorded by a Hamamatsu C5680 streak camera [6], which provides a temporal resolution better than 2 ps FWHM in the full visible spectrum [7]. This sensitive device was placed in a separate room outside the accelerator tunnel to protect it from radiation and to allow camera handling during machine operation. Currently, four read-out ports along the electron beam-line are connected to the streak camera by an optical transmission line (OTL) of about 30 m length [8,9]. At every read-out port, a radiator can be moved into the beam tube. When passing the radiator, the electron bunches create light pulses, either as Cherenkov light (typically using Silica aerogel as radiator material) or as optical transition radiation (using, for example, silicon plates with aluminum coating). The transverse and temporal structure of the light pulse produced by a Cherenkov radiator resemble those of the original electron bunch, e.g. Silica aerogel with a refractive index of $n = 1.05$ and a thickness of 2 mm provides a temporal resolution of about 240 fs RMS at an electron beam energy of 6 MeV/c [10]. A significant part of the emitted light is contained in the visible spectrum and can be transported to the streak camera by conventional optical elements.

The currently installed optical system (Fig. 1) comprises about one dozen lenses per branch and can be used to measure the electron bunch length [11] and the electron distribution in the longitudinal phase space spanned by longitudinal position z and

---

Abbreviation: DESY, Deutsches Elektronen-Synchrotron; IS, Input section; MTF, Modulation transfer function; OAP, Off-axis parabolic; OTL, Optical transmission line; PITZ, Photo-Injector Test facility at DESY, Zeuthen site.

* Corresponding author. Now at CERN, 1211 Genève 23, Switzerland. Tel.: +41 22 7675048.
E-mail address: Kilian.Rosbach@cern.ch (K. Rosbach).

0168-9002/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.06.072

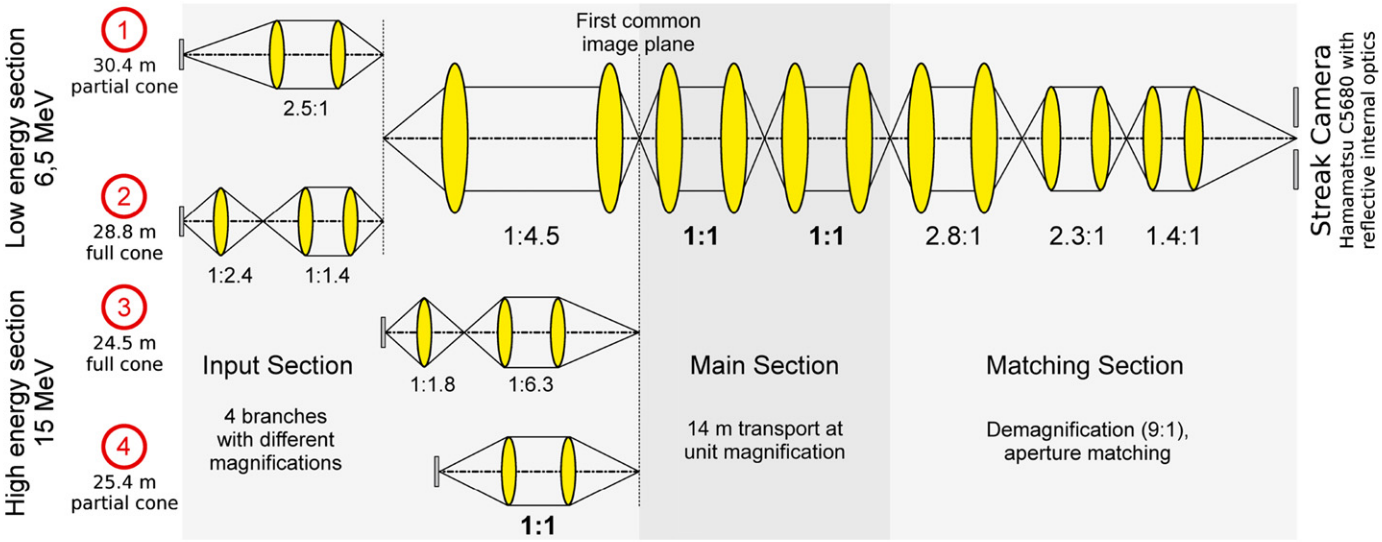

Fig. 1. Simplified scheme of the current optical transmission line (OTL), not to scale. Only the most commonly used elements are included for clarity. The dashed lines indicate positions of movable mirrors that allow switching between read-out ports. There are three subsystems with unit magnification (1:1). The branches labeled "partial cone" use only a fraction of the Cherenkov cone for imaging (see Fig. 2).

longitudinal momentum p_z [12]. However, the temporal resolution deteriorates during transport due to dispersion in the lenses, since the glass introduces a wavelength-dependent delay, with light at 400 nm arriving about 100 ps later than the corresponding 700 nm component. This leads to a distortion of the recorded temporal distribution.

The lateral chromatic aberration resulting from dispersion is corrected by using achromatic lenses in the system, but the distortion of the temporal distribution cannot be compensated in this way. This effect can be mitigated, and the temporal resolution can be restored to an acceptable level of about 3 ps, by inserting an interference filter of narrow bandwidth (typically: 10 nm FWHM transmittance, centered at 500 or 550 nm) into the optical path, but the loss of light at the filter leads to an intensity reduction by about 96%. This necessitates an integration over several pulses to reach an adequate signal-to-noise ratio, and the temporal structure of an individual bunch cannot be recorded. Furthermore, the lenses are sensitive to the radiation in the accelerator tunnel: notably in periods of conditioning new components, the lenses become brown and lose in transmittance, leading to a further reduction of recorded intensity at the streak camera [13].

This article presents an investigation toward a new optical system based on mirrors. Since the law of reflection is not wavelength-dependent, the temporal resolution will not be diluted by dispersion. Also, mirrors do not suffer from the radiation in the tunnel. Several plane mirrors of borosilicate glass with a reflectivity coating ($\mathrm{Al}+\mathrm{SiO_2}$) are present in the current optical system, and no discoloration was observed for them. Therefore, a reflective optical system intrinsically avoids the loss of temporal resolution due to dispersion and is resistant to radiation damages. On the other hand one has to deal with a more challenging geometry and a more difficult adjustment.

2. General considerations for reflective optics

The longitudinal electron phase space distribution contains the temporal structure of the bunch as well as its momentum distribution. At PITZ, it is measured using a dipole spectrometer in conjunction with a streak camera [14]. The optical system between the radiator in the spectrometer and the streak camera has to maintain the spatial and temporal information of the light pulses. Fortunately, spatial and temporal resolutions are closely related for optical systems which operate independently of wavelength, as can be seen from Fermat's principle: from all the possible paths connecting two points $\mathcal{A}$ and $\mathcal{B}$, any optical path $\mathcal{P}$ realized in nature is an extremum of the optical path length $\mathcal{L}$. On the other hand, $\mathcal{L}$ is directly proportional to t, the traveling time of the ray along $\mathcal{P}$:

$$\mathcal{L}=\int_{\mathcal{P}} n(\vec{s})\,\mathrm{d}\vec{s} \tag{1}$$

$$t=\int_{\mathcal{P}} \frac{1}{c_n(\vec{s})}\,\mathrm{d}\vec{s}=\frac{1}{c_0}\mathcal{L} \tag{2}$$

where $\vec{s}$ is an element of the path $\mathcal{P}$, and c_0 and c_n are the speed of light in vacuum and in a medium with refractive index n, respectively. Assuming that all physical optical paths connecting $\mathcal{A}$ to $\mathcal{B}$ are related by a continuous transformation parametrized by α, then t is constant for all of these paths, since

$$\frac{\mathrm{d}}{\mathrm{d}\alpha}t=\frac{1}{c_0}\frac{\mathrm{d}}{\mathrm{d}\alpha}\mathcal{L}=0 \tag{3}$$

where in the final step Fermat's principle is used again. This means that a system with a perfect spatial resolution, i.e. a system in which all the rays originating from $\mathcal{A}$ are arriving at $\mathcal{B}$, will also have a perfect temporal resolution due to identical traveling times of all rays. The argument is true only for the two points in consideration and might not hold for an arbitrary pair of points in the vicinity of $\mathcal{A}$ and $\mathcal{B}$, respectively. Typically this is improved by demanding that the derivatives of $\mathcal{L}$ with respect to lateral displacements of $\mathcal{A}$ and $\mathcal{B}$ vanish, which then leads to the Abbe sine condition [15]. Since this condition is often met in well-corrected optical systems, a mirror system with a good spatial resolution is likely to exhibit a good temporal resolution. This provides suitable starting points for the following investigation. It is important to notice that the whole argument does not hold for lenses or any other system where dispersion cannot be neglected. In those systems, the extremal path is a function of the wavelength—but the extremum of Fermat's principle is found with respect to a variation of the path for a fixed wavelength (as opposed to a variation of wavelength itself).