MEASUREMENT OF THE LONGITUDINAL PHASE SPACE AT THE PHOTO INJECTOR TEST FACILITY AT DESY IN ZEUTHEN (PITZ)*

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Abstract

PITZ generates electrons with an energy of about 5 MeV. To optimize the RF-gun parameters and to fulfill the requirements of the bunch compressor the longitudinal phase space behind the gun has to be studied. A measurement of the longitudinal phase space comprises a correlated measurement of momentum and temporal distribution. The momentum distribution is measured by deflecting the electron bunch using a spectrometer magnet. A subsequent Cherenkov radiator transforms the electron bunch into a light pulse with equal temporal and spatial distribution, which is imaged onto a streak camera by an optical transmission line to measure the longitudinal distribution. The longitudinal phase space was measured for different temporal photo cathode laser distributions, bunch charges and phases between RF field and laser. Physical effects in the dipole magnet, optical transmission line and streak camera, which influence the longitudinal phase space measurements, are taken into account. The measurement results were compared with simulations and with directly measured momenta and temporal distributions.

INTRODUCTION

The main goal of PITZ is the test and optimization of photo injectors for Free-Electron Lasers (FELs). The demands on such a photo injector are a small emittance, short bunches and a charge of about 1 nC. The linac of a FEL incorporates a RF gun, capable of producing a high bunch charge, followed by an acceleration section and a magnetic bunch compressor. For an effective bunch compression detailed studies of the longitudinal phase space have to be performed. Besides the projections of the longitudinal phase space, i.e. temporal and momentum distribution of the electron bunch, the correlation between the positions of the particles in the bunch and their longitudinal momenta has to be understood. The non-linearities of the longitudinal phase space have to be analysed. Typical high energy diagnostics for longitudinal phase space tomography can not be used, therefore a special apparatus for an energy around 5 MeV was developed.

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SETUP

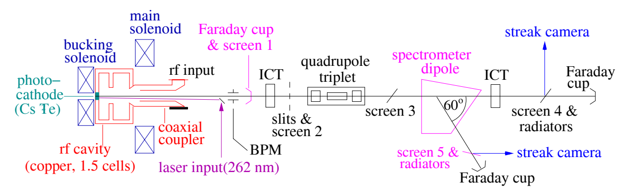


Figure 1: Schematic of PITZ1 setup.

Fig. 1 shows a schematic of the PITZ1 setup. To measure the longitudinal distribution of the electron bunch a Cherenkov radiator (silica aerogel) [1] is used to transform the bunch into a light distribution at screen station 4 in the straight section (SS). This light distribution is imaged by an optical transmission line onto the entrance slit of a streak camera. The momentum distribution is measured with a YAG-screen at screen station 5 in the dispersive arm (DA). To measure the longitudinal phase space both methods are combined. The YAG-screen in the DA can be replaced by silica aerogel using a movable actuator. The light pulse which presents the longitudinal phase space is transported to the streak camera. The momentum axis of the longitudinal phase space measured by the streak camera is scaled using the momentum distribution directly measured at the YAG-screen.

Several physical effects of the main components of the apparatus (as dipole magnet, streak camera and optical transmission line) impact the results of the measurements of the longitudinal phase space. These effects will be described in the following subsections. They have to be corrected successively, but reversely, i.e. starting from the streak camera.

Spectrometer Dipole

The dipole magnet at PITZ1 deflects the electron bunches by 60° in vertical direction to transform the momentum distribution into a spatial one. The vertical position y of an electron behind a hard edge sector dipole is given by the first order transport matrix of a dipole [2]:

$$y = \cos\alpha \cdot y_0 + \rho_{\text{eff}} \cdot \sin\alpha \cdot y_0' + \rho_{\text{eff}} \cdot (1 - \cos\alpha) \cdot \frac{\delta p_0}{< p_0 >}, \quad (1)$$

where α is the angle of deflection, ρ_{eff} is the radius of curvature in the dipole, $\frac{\delta p_0}{<p_0>}$ is the relative momentum deviation, y_0 is the initial vertical position and y_0' is the initial vertical divergence of the electron. To have a good resolution $\cos\alpha \cdot y_0 + \rho_{\text{eff}} \cdot \sin\alpha \cdot y_0'$ should be small in comparison to $\rho_{\text{eff}} \cdot (1-\cos\alpha) \cdot \frac{\delta p_0}{<p_0>}$. Furthermore, the edge fields of the dipole and drift spaces have to be included into the equation by multiplication of the transport matrices.

Moreover, the field of a hard edge sector dipole shifts the position of an electron inside the bunch by Δl [2] and changes consequently the temporal distribution of the longitudinal phase space:

$$\Delta l = \sin\alpha \cdot y_0 + \rho_{\text{eff}}(1-\cos\alpha) \cdot y_0' - \rho_{\text{eff}} \cdot (\alpha - \sin\alpha) \cdot \frac{\delta p_0}{< p_0 >}. \quad (2)$$

To correct the effects due to the finite beam size and divergence a deconvolution has to be performed. The influence of momentum spread on the longitudinal position in the bunch can be rectified by shearing the longitudinal phase space.

Cherenkov Radiator

To measure the bunch length (in the SS) the silica aerogel with a refractive index $n = 1.03$ and a thickness of $l = 2$ mm was used. It has a contribution to the time resolution of 0.13 ps for an energy of 5 MeV. Whereas the full Cherenkov cone is used to determine the longitudinal distribution (SS), for the measurement of the longitudinal phase space (DA) only a segment of the cone is used, because the aperture angle would be too big for the optical transmission line. Due to this, the number of photons is reduced to a small fraction. To reach a sufficient number of photons aerogel with $n = 1.05$ and $l = 2$ mm was installed. The contribution to the time resolution of this aerogel plate is 0.22 ps for 5 MeV. In the energy range of 5 MeV the number of photons produced by aerogel is on the order of 10^3 higher than for optical transition radiation (OTR) [3]. But the disadvantage of aerogel is the danger of outgassing molecules.

Optical Transmission Line

The Cherenkov light distribution produced by the radiator has to be imaged onto the entrance slit of the streak camera. The optical transmission line consists of several mirrors and lenses with a large focal length and a small focal number, arranged as a chain of telescopes [4]. To measure the longitudinal distribution the conservation of the temporal light distribution has to be ensured. For the measurement of the longitudinal phase space the spatial distribution has to be preserved in addition.

There are two different input systems (for SS and DA), which match into a common transmission line. To transport the full Cherenkov cone, the first lens of the optical input system needs a small focal number, to collect a moderate part of the cone. The measurement of the partial cone needs the transport of a quasiparallel bundle of light. The last lenses demagnify the distribution to match with the streak camera slit size. Although achromates are used to minimize dispersion in the transmission line, the pulse length is elongated in the optical transmission line. Fig. 2 shows the mean arrival time of photons with different wavelength produced by the same bunch passing the optical transmission line.

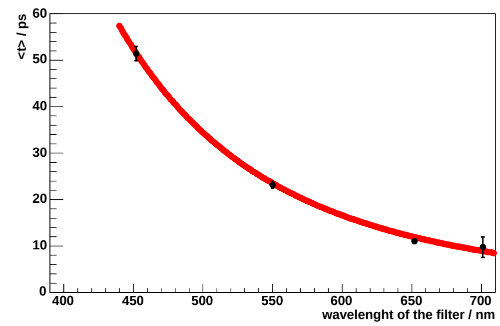


Figure 2: Mean arrival time of photons with different wavelength, measured by using different spectral transmission filters.

This behavior is caused by residual dispersion of the lenses and scattering effects. Narrow spectral transmission filters (10 nm) are used for suppressing the light pulse lengthening.

Rotating Box The dispersive arm is inclined under 60°. Therefore, the image of the momentum distribution is not parallel to the streak camera slit. A rotating box is included into the optical transmission line to rotate the light distribution in such a way, that the image of the light distribution of the momentum spectrum is parallel to the slit. A schematic of the rotating box is shown in Fig. 3, it consists of 11 mirrors. In fact, the rotation is executed by only 3 mirrors (S5-S7). Two light paths lead to mirror S5, one transports the image of the light distribution of the momentum spectrum without rotation (S1-S4) and the other with 180° rotation (S8-S11). The toggle between these two light paths allows the analysis of the influence of the image rotating and the momentum spread to the longitudinal distribution in the bunch. Depending on the path the effects are subtractive or additive.

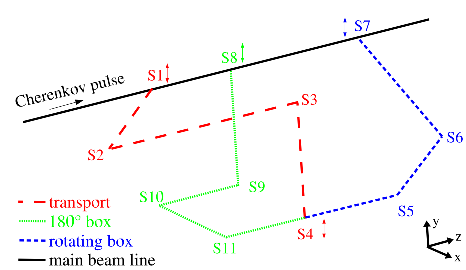


Figure 3: Schematic of the rotating box.

Streak Camera

The streak camera C5680 from Hamamatsu is used to measure the longitudinal distribution and the longitudinal phase space with a resolution of about 2 ps. The streak camera itself shows inhomogeneities in intensity of the signal in the direction perpendicular to the streak direction (horizontal). Furthermore, light entering into the transmission line, stray light and dark current, can produce an unequal background. Therefore, the background has to be determined and subtracted for all measurements.

The streak camera exhibits a non-uniform horizontal sensitivity. Possible reasons are: slight variations of the slit width, of the amplification of the Multi-Channel Plate, of the thickness of the fluorescent material and of the cathode sensitivity, also effects due to internal streak camera optics and the CCD chip as well as a misalignment of the accelerating mesh or of the output optics. The sensitivity for different horizontal positions was determined and corrected.

On the edges of the sensitive area of the streak camera in horizontal direction a temporal delay was observed, when the RF-field was applied on the streak tube. The effect stayed unchanged when the camera was shifted, but without streak RF field it disappeared. It seems that the streak camera does not deflect homogeneously, due to a slightly varying RF-field in horizontal direction. The curvature of mean time value as a function of the horizontal position on the streak image was determined to correct the data.

The smearing of the streak signal in the temporal direction due to slit width and space charge in the streak camera can be described as a convolution, using the signal taken without streak RF-field on the streak tube as response function. To correct these effects the smeared signal has to be deconvoluted.

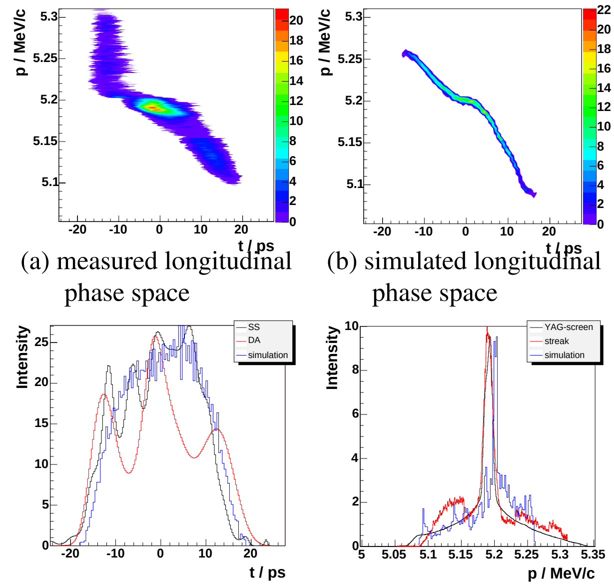
MEASUREMENT RESULTS

The first measurements were done for flat-top and gaussian temporal laser distributions, bunch charges from 30 pC up to 1 nC and different phases between RF field and laser. The conditions were not optimized to some degree when this data were taken. The vertical divergence and beam size of the bunch were not measured, therefore simulated data had to be used for the corrections of dipole effects. In general the measured and simulated longitudinal phase spaces are similar, but for small longitudinal emittance values the longitudinal phase space could not be fully resolved. Fig. 4 shows the results for 1 nC, phase with the highest momentum and flat-top laser distribution of about 20 ps FWHM pulse length. It displays the measured longitudinal phase space in comparison to the simulated one and their projections compared to the direct measurements.

CONCLUSION

An apparatus to measure the longitudinal phase space for an energy around 5 MeV was successfully developed and tested. This method allows the measurement of the correlations between the longitudinal and momentum distribution, but the elements of the apparatus contribute systematical errors, therefore an extensive data evaluation is required.

Further systematic studies of the longitudinal phase space at 5 MeV are foreseen and improvements of the data analysis are ongoing. In addition, the design of a high energy longitudinal phase space tomograph is ongoing. Another goal is the replacement of the lenses in the optical transmission line by reflective optics.



(a) measured longitudinal phase space (b) simulated longitudinal phase space

(c) longitudinal distribution (d) momentum distribution

Figure 4: Measured (a) and simulated (b) longitudinal phase space and their projections: longitudinal (c) and momentum distribution (d) for 1 nC bunch charge, phase with the highest momentum and flat-top laser distribution with about 20 ps FWHM bunch length. In (c) and (d) the black curves are direct measurements, the red ones are the projections of the measured longitudinal phase space and the blue ones are simulations.

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