SYNCHROTRON RADIATION MONITOR FOR BUNCH-RESOLVED BEAM ENERGY MEASUREMENTS AT FLASH

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Abstract

A synchrotron radiation monitor based on a multi-anode photomultiplier tube (PMT) has been installed in the first magnetic bunch compressor chicane at the Free-electron LASer in Hamburg (FLASH). The synchrotron radiation emitted in the third dipole of the magnetic chicane is imaged by a telescope onto two anodes of the PMT. In this way the horizontal beam position of the electron bunches is recorded which corresponds to the beam energy as the beam position is governed by the beam energy in the dispersive section of the magnetic chicane. The fast PMT signals are digitized by analog -to-digital converters which enables bunch-resolved beam energy measurement within the trains of the up to 800 bunches generated by the superconducting linear accelerator of FLASH. In this paper we describe the experimental setup of the synchrotron radiation monitor and present first commissioning results for various accelerator settings.

INTRODUCTION

Various diagnostic techniques based on the detection of synchrotron radiation (SR) have been utilised for decades for the characterisation of electron and proton beams in storage rings [1, 2]. In single-pass free-electron lasers (FEL), off-crest acceleration in combination with magnetic dipole chicanes is a common scheme for longitudinal bunch compression to produce ultra-short electron bunches with high peak currents. Due to the relatively large dispersion of these magnetic chicanes, the beam energy and energy spread can directly be deduced from a beam position measurement in the dispersive section of the magnetic chicane.

In the first bunch compressor (BC) at the Free-electron LASer in Hamburg (FLASH), a SR monitor based on photomultiplier tube (SR-PMT) has been added to an existing SR monitor based on an intensified CCD camera (SR-camera) [3]. The super-conducting linear accelerator of FLASH is capable of generating trains of up to 800 bunches with a spacing of 1 μs at a repetition rate of 5 Hz. By adjusting the gate and delay of the SR-camera, the full x-y projection of a single bunch (or any number of subsequent bunches) out of a bunch train can be recorded. However, the readout of the CCD is too slow to resolve more than one electron bunch within a bunch train. In contrast, by recording the signals of the two adjacent anodes of the SR-PMT the centre-of-gravity beam position for all individual bunches can be measured.

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SR MONITOR SETUP

A schematic overview of the SR monitor installed in the first BC at FLASH is presented in Fig. 1. The BC, which consists of 4 horizontally deflecting dipole magnets, is located downstream of a RF photo-cathode gun and a super-conducting 1.3 GHz accelerating module (ACC1) which accelerates the electrons to a beam energy of typically 130 MeV. The large horizontal aperture of the flat vacuum chamber (200 mm $\times$ 8 mm cross section) allows one to operate the BC at bend angles in the range 15° - 21°. The critical wavelength of the emitted SR lies in the visible at around 400 nm for a bend angle of 18°.

An Ag-coated laser mirror (Linos, 20 mm $\times$ 30 mm) deflects the SR emitted at the entrance of the third dipole downwards by 90° (not shown in Fig. 1) onto a beam splitter. The transmitted SR is imaged by a camera lens (Sigma, f = 180 mm) onto an intensified CCD camera (PCO, dicam pro). The part of the SR that is reflected by the beam splitter is deflected by another mirror by 90° and then imaged by a camera lens (Tamron, f = 300 mm) with a teleconverter (3x) onto two anodes of a multi-anode photomultiplier tube (PMT). The PMT of type Hamamatsu R5900U-00-M4 comprises four anodes each having a size of 8 x 8 mm^2. The PMT was operated at a voltage of 720 V for which a linear dependence between the output signal and the electron bunch charge, i.e. SR intensity, was measured. The fast current signal of the PMT have a pulse height of about 1 V (with 50 Ohm input impedance) and a width of 4 ns (FWHM). The signals are broadened to 20 ns (FWHM) by Gauss filters with a cut-off frequency of 15 MHz to eliminate high-frequency noise and reduce the effect of timing jitter ($\sim$ 1 ns) of the 14-bit analog-to-digital converters (ADC). The ADCs are synchronised to the bunch repetition rate of 1 MHz and can be read out by the machine control system. The normalized difference signal s of both ADC channels gives then the centre-of-gravity beam position $s = (I_1 - I_2)/(I_1 + I_2)$, where I_1 and I_2 are the signal intensities of both anodes measured with the ADCs. The whole SR monitor setup is mounted on a mover which can be moved horizontally to be able to adjust to the electron beam trajectory for different bend angles of the BC.

Energy Calibration

The horizontal beam size in the BC is governed by the beam energy spread as an energy deviation $\Delta E/E$ transforms into a horizontal displacement Δx by 1st-order transport theory via $\Delta x = R_{16} \cdot \Delta E/E$ due to the large horizontal dispersion of about $R_{16} \approx 300 - 400$ mm [4].

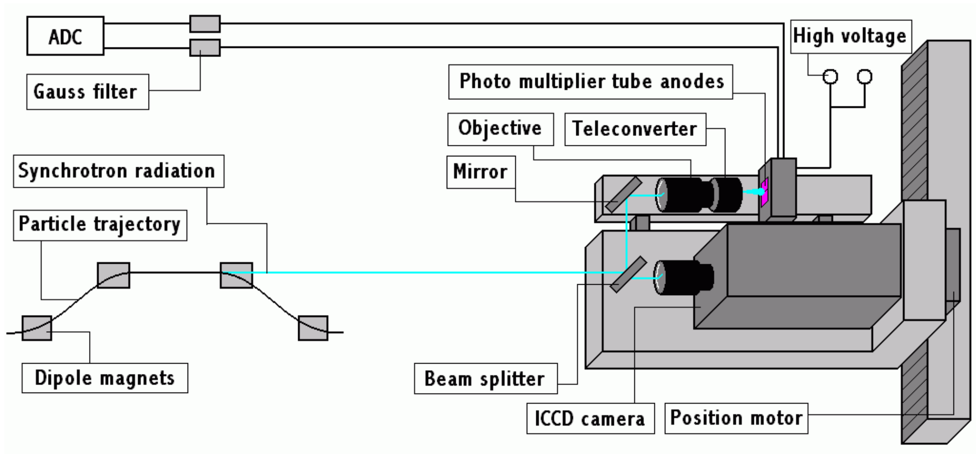

Figure 1: Schematic overview of the SR monitor setup. For further explanation see text.

Figure 2(a) shows the horizontal beam profile recorded with the SR-camera for 3 different accelerating phases of module ACC1. The corresponding calibration curves for the SR-PMT signal s are shown in Fig. 2(b). The calibration was accomplished by changing the dipole current - a relative change in the magnetic field corresponds to a relative change in beam energy - and recording simultaneously the SR-PMT signal. As can be seen, the calibration curve of the SR-PMT depends on the horizontal beam profile. The horizontal beam profile is dominated by the accelerator optics and phase of ACC1. Hence, after changing accelerator settings a re-calibration of the SR-PMT becomes necessary.

A calibration curve has been constructed from a horizontal beam profile recorded with the SR-camera by dividing the beam profile shown in Fig. 3(a) into two parts, calculating the normalised difference signal s for the integral intensity of each part and moving the parting line across the profile. This calibration curve (solid red line) is shown in Fig. 3(b) together with the corresponding calibration measurement with the SR-PMT (blue dots). A crosstalk of 8% between the two parts was assumed for the dashed line which is in good agreement with measurement points. This crosstalk may be due to crosstalk in the PMT, crosstalk in the electronics or a broadened profile, e.g. if the PMT is not positioned exactly in the image plane.

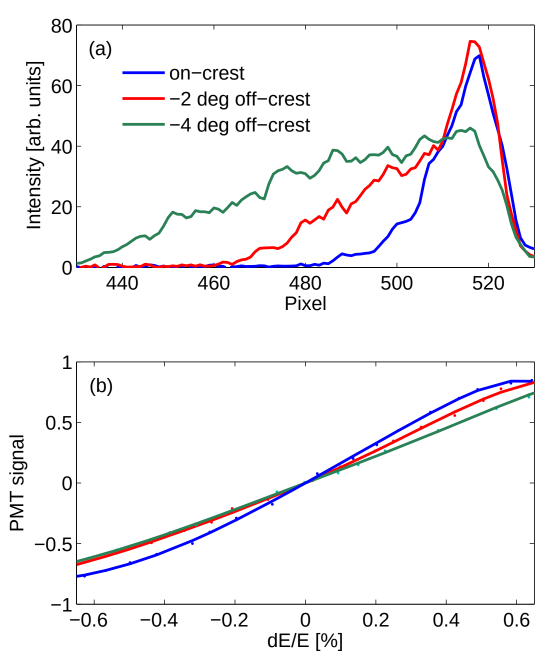

Figure 2: (a) Horizontal beam profiles measured with the SR-camera for 3 ACC1 phases; (b) Corresponding energy calibration of SR-PMT signal.

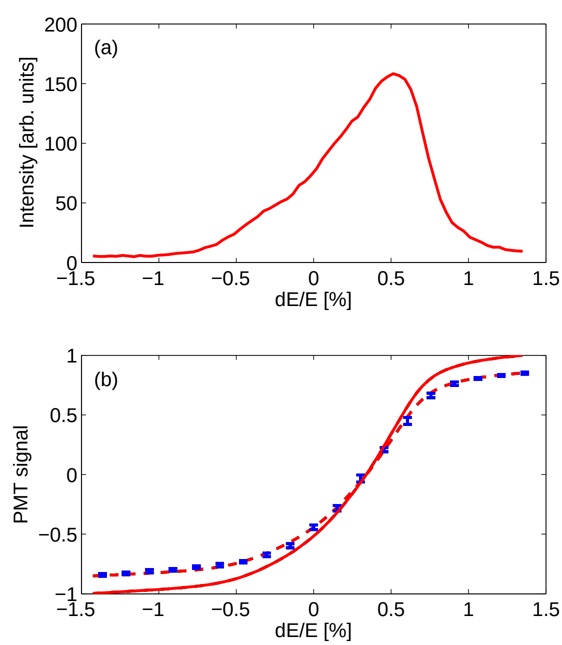

Figure 3: (a) Beam profile measured with the SR-camera; (b) Calibration curves of SR-PMT (dots) and deduced from beam profile (solid) with 8% crosstalk (dashed).

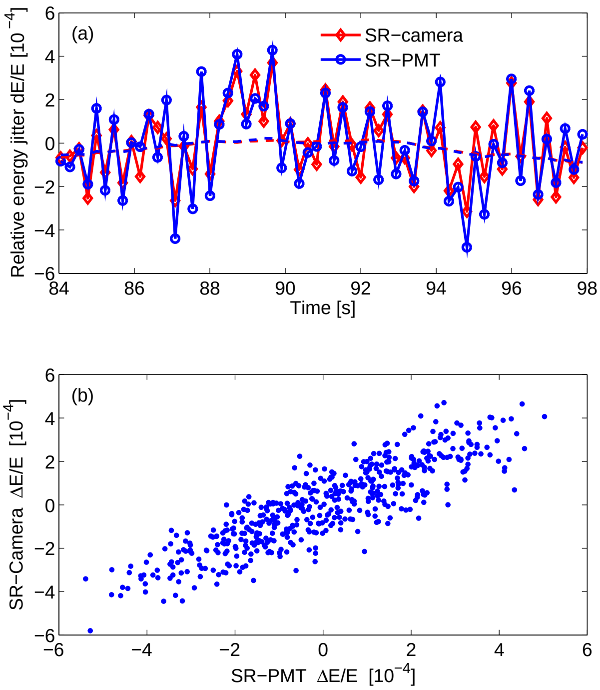

Figure 4: (a) Beam energy of single bunches measured with the SR-PMT and SR-camera for 60 subsequent bunch trains; (b) Correlation plot for 500 measurement points of the SR-PMT and SR-camera.

MEASUREMENTS

An upper limit for the energy resolution of both SR monitors can be estimated by recording simultaneously the relative energy jitter with the SR-camera and SR-PMT.

Figure 4(a) shows the beam energy of single bunches measured with the SR-camera and SR-PMT during user operation of FLASH for 60 subsequent bunch trains out of a measurement of 500 bunch trains. The correlation of the measured beam energies for all 500 measurement points is shown in Fig. 4(b). The difference of the measured beam energy is $1.08 \pm 0.04\ 10^{-4}$ which gives an upper limit for the resolution of both SR monitors. Assuming that both SR monitors have the same resolution, the resolution of each detector would be $1.08 \pm 0.04\ 10^{-4}/\sqrt{(2)} = 7.6 \pm 0.3\ 10^{-5}$. Very similar values were obtained by correlating the beam energy measured with the SR-PMT for two adjacent bunches. The energy difference for adjacent bunches in a bunch train is very small due to the very high quality factor, i.e. very narrow bandwidth, of the superconducting cavities.

Figure 5(a) shows the beam energy measured with the SR-PMT for 300 subsequent bunch trains with 30 bunches (black dots). The mean values of each of the 30 bunches (blue dots) represent the energy slope along the bunch train (mean value of first bunch was normalised to zero). The measurement was recorded during the application of an adaptive feedforward algorithm to compensate beam loading effects (see Ref. [5] for more details). The rms beam energy jitter measured for each of the 30 bunches is about $1.6\ 10^{-4}$ and shown in Fig. 5(b).

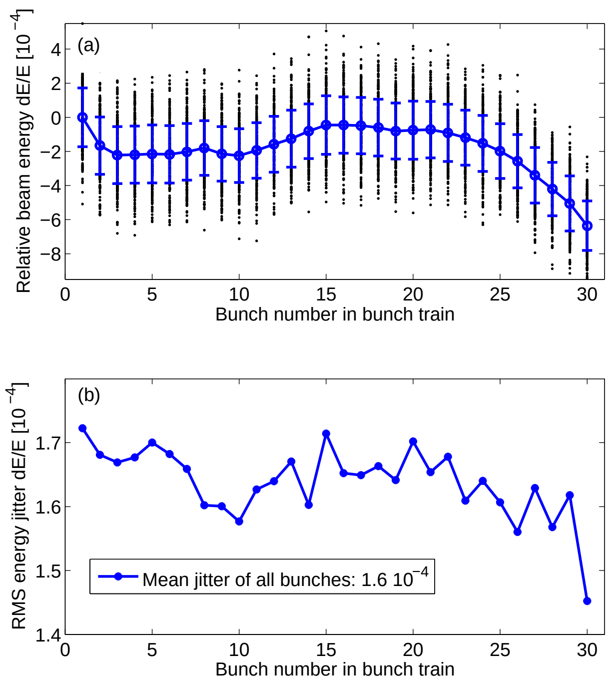

Figure 5: (a) Beam energy measured with the SR-PMT for 300 subsequent bunch trains with 30 bunches; (b) Corresponding rms energy jitter of each bunch.

SUMMARY

A new type of synchrotron radiation monitor based on a multi-anode photomultiplier tube has been installed in the first bunch compressor chicane at FLASH for bunch-resolved beam energy measurements. A relative energy resolution of about $1 \cdot 10^{-4}$ or below was achieved.

REFERENCES

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[5] Ch. Gerth *et al.*, "Beam Based Measurements of the RF Amplitude Stability at FLASH using a Synchrotron Radiation Monitor", DIPAC'09, Basel, TUPD22, `http://www.JACoW.org`.