Tomography module for transverse phase-space measurements at PITZ

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Abstract

The Photo-Injector Test Facility at DESY in Zeuthen, PITZ, is used to test and optimize high brightness electron sources for free electron lasers. A key issue for such studies is the accurate determination of the beam emittance on which dedicated measurements take place. The development of a tomography module at PITZ aims to measure the phase-space distribution of the electron beam for the two transverse planes simultaneously with improved signal-to-noise ratio. Specific features of the produced electron beam - low emittance, high charge density, moderate energy - and limited linac length, require a special design and operation. A dedicated quadrupole setup is used for FODO structures able to provide the needed for the tomographic procedure rotations of the beam in the phase space and for matching of the necessary beam parameters at the entrance of the FODO lattice. Measurement of the wanted projections is possible using a system of YAG/OTR screens and a readout system. Further processing of the acquired data using basic tomographic principles allows then reconstruction of the transverse phase-space distribution.

This work presents the final design of the tomography module installed and operated at PITZ.

INTRODUCTION

Photo-Injector Test Facility at DESY in Zeuthen, PITZ, aims to deliver a normalized rms emittance smaller than 1 mm·mrad [1] operating at beam energies smaller than 30 MeV with nominal bunch charge of 1 nC. Electrons are produced via photo effect from a $\mathrm{Cs_2Te}$ cathode and accelerated by a $1^1/_2$-cell L-band rf gun cavity up to about 6.6 MeV. Further acceleration is then achieved by a 14-cell Cut Disk Structure booster cavity. The transverse and longitudinal properties of the electron bunches are measured after the final energy is reached.

A tomography module, as part of diagnostics at PITZ, was assembled to reveal a detailed depiction of the phase-space distribution of the electron beam. The advantages of the tomography method are the capability to resolve both transverse planes simultaneously, an improved signal-to-noise ratio and the possibility of single shot measurements. This module makes use of the basic principle of tomography, which requires a number of rotated projections of a sample in order to reconstruct it. Snapshots of the beam rotating in the phase space are used to reconstruct the transverse phase-space distribution. In order to achieve and control these rotations, quadrupole magnets are used in the form of FODO cells preceded by a matching section, that together with screen stations and an optical readout system comprise altogether the tomography module described in this paper.

QUADRUPOLE MAGNETS

The quadrupole magnets at PITZ serve two purposes regarding tomography: they are used along the matching section responsible to deliver the design beam parameters in front of the tomography module and then as components of the FODO lattice that provides the different projections of the beam.

The matching section is located upstream the tomography module, as illustrated in Fig. 1. The current setup includes five quadrupoles, with four more available to use depending on the beam characteristics and the number of the wanted projections.

Along the FODO lattice the quadrupoles cause a rotation of the beam in the phase space, so that the beam meets each screen at a certain phase advance value. These values, controlled by the strength of the pair of quadrupoles, are determined by the number of the wanted projections so that they are equidistantly distributed over 180°. This ensures that the reconstruction procedure is utilized and the systematic uncertainty is minimized [2]. Basic parameters of the magnets used are given in Table 1.

Average effective length	0.043 [m]
Average required current	7.3 [A]
Physical length	0.063 [m]
Maximum gradient	7.5 [T/m]
Bore radius	0.02 [m]

Table 1: Main parameters of the quadrupole magnets.

FODO CELLS

A FODO cell comprises a combination of two identical quadrupole magnets with opposite polarity and a drift space of certain length after each other. Such a setup can control the opposite focusing effect the quadrupoles have on the two transverse planes, allowing symmetric betatron oscillations, so that equidistant rotations in the phase space can be achieved for both planes simultaneously.

The quality of the reconstruction improves with respect to the number of the available projections, as proved by basic principles of tomography. In this module four cells

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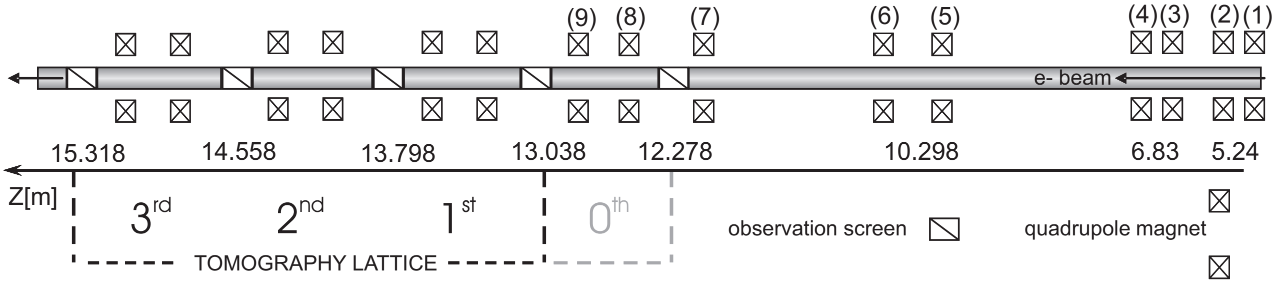


Figure 1: Layout containing the matching section and the tomography module of PITZ. The numbers of the quadrupoles are indicated at the top side (1-9) and the numbers of the FODO cells at the bottom (0-3).

were implemented due to the limited space in the accelerator tunnel. Currently three of them are used for projection data (1^{st} to 3^{rd} in Fig. 1) and one to assist the matching of the beam (0^{th} in Fig. 1).

The position and dimensions of the components, shown in Fig. 2, were chosen considering requirements for motion stability [3] and the foreseen installation of kicker magnets in the drift space that will be used for single bunch measurements. A beam position monitor (BPM) and a rotating steerer surround each screen station to control the orbit of the beam.

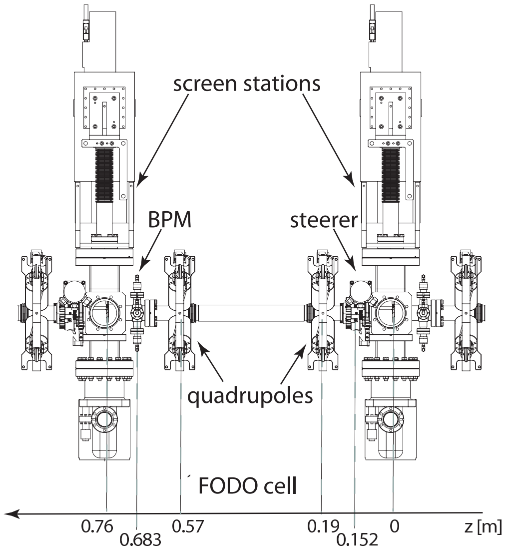


Figure 2: Top view of a FODO cell with its quadrupoles, screen stations, a BPM and a steerer. The coordinate axis shows the middle positions of the components with respect to the beginning of the cell. Image courtesy [3].

SCREEN STATIONS

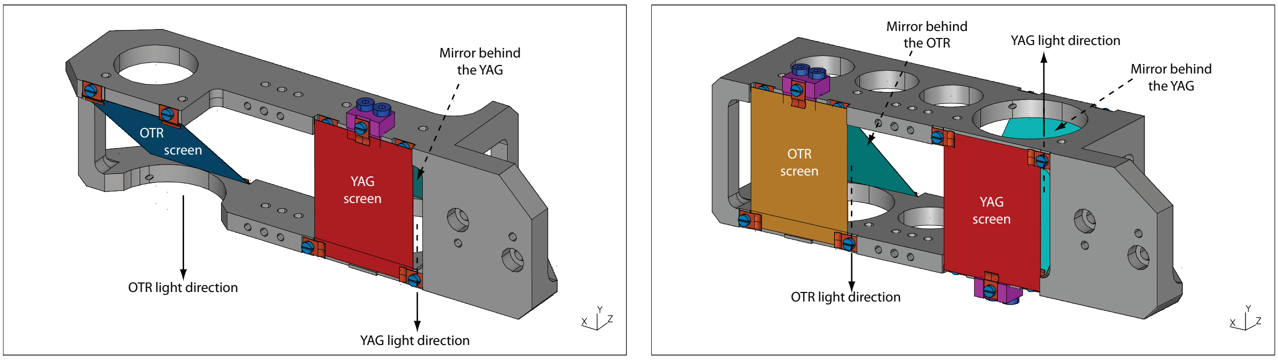
Each FODO cell is surrounded by two screen stations (Fig. 1 and Fig. 2) which host the observation screens. The screens map the six-dimensional transverse phase space (x, x', y, y', z, p_z) onto a spatial projection (x, y), thus allowing the available spatial distribution to be used as input for the reconstruction of the phase-space distribution.

Two types of screen are installed in each screen station: Optical Transition Radiation (OTR) and Yttrium-Aluminum-Garnet (YAG) - powdered screen, doped with Ce atoms on a Si substrate. The first is used for higher and the second for lower beam energies and charge densities. The OTR screen meets the beam at an incidence angle of 45°, guiding its forward radiation cone to the readout system, except from the 0^{th} cell which was adjusted to be used for optical and screen test purposes. In that case an orthogonal with respect to the beamline OTR mirror radiates backwards to a 45° tilted mirror facing the readout system. The YAG screen is always placed orthogonally to the beam direction with a 45° inclined mirror behind it guiding the light output futher to an optical path. Considering the desired minimum resolvable spot size due to high charges and possibilities of multiple scattering within the Si layer, the thickness of the Si is chosen to be 100 μm [3]. Both setups mounted on can be seen in Fig. 3.

A gap between the two screens is to be used for single bunch measurements when the installation of the kickers would allow only a single bunch from the bunch train to be deflected towards a screen located one cell downstream, while the rest of the train would continue straight without a kick. The dimensions of the gap and the screens are selected with respect to the desired resolution of a transverse deflecting cavity, which will be installed in future allowing the projection of the longitudinal profile of the beam on the transverse plane [4]. The complex of screens is mounted on an actuator which, inserted across the beamline with a linear stage drive, allows precise positioning with respect to the applied deflection angle from the kicker magnet.

OPTICAL READOUT SYSTEM

After the beam hits a screen, the emitted light is guided and collected by an optical readout system. A set of mirrors is available to direct the light outside the vacuum chamber to a CCD camera. An extra movable mirror is used to compensate the additional distance the light has to travel in the case of the inclined OTR screen compared to the YAG, due to the fact that they both share a common horizontal but not vertical axis, as seen in Fig. 3(a). For this case one common readout system is used for both cameras which is located below the vacuum chamber, while in front of the 0^{th}



(a) Movable screen holder with mounted 90° YAG and 45° OTR screens along the tomography module. The two screens share a common optical readout system.

(b) Movable screen holder with mounted 90° YAG and 90° OTR screens in front of the 0th cell from Fig. 1. There are two physically different optical readout systems used for the two screen types.

Figure 3: Two different actuator designs along the tomography and matching sections.

cell each screen is served by a dedicated readout system, located on opposite directions - Fig. 3(b).

Two lenses with fixed magnification are available for each camera, one for alignment purposes able to image the full area of the screen and one offering bigger magnification for better resolution. The installation of a third lens with bigger magnification for beams with lower charges and respectively smaller spot sizes is currently under discussion.

MOUNTING TOLERANCE OF COMPONENTS

The performance of the tomography module strongly depends on the precision with which the components are mounted along the beamline, as the cell dimensions are small and the focusing is rather strong. PITZ aims to measure emittances with a systematic uncertainty better that 10% and this corresponds to an uncertainty of about 10% in the measured spot size or about 0.05 m uncertainty in the Twiss β-function in absolute units (about 5% for the four-cell set-up).

The considered misplacements are: an offset along the z axis and a rotation around the x and y axis for the screen stations supplemented by an offset in the transverse planes and a rotation around the z axis for the quadrupoles. Single misalignment tolerances for each type in RMS units are given in the Table 2. More details on mounting and alignments of the components can be found in [5].

OUTCOME

The tomography module described in this paper, assembled and installed at PITZ, is a unique implementation of the tomographic principle in the diagnostics of electron beams with the characteristics mentioned above. It was successfully operated since November 2010 and its functionality was proven with experimental data [6, 7].

Element	Misalignment type	Range (RMS)
Quadrupole	offset along z	0.1 [mm]
	offset in x/y planes	0.1 [mm]
	rotation around x axis	20 [mrad]
	rotation around y axis	20 [mrad]
	rotation around z axis	10 [mrad]
Screen	offset along z	0.1 [mm]
	rotation around x axis	10 [mrad]
	rotation around y axis	10 [mrad]

Table 2: Alignment tolerances of the components along the tomography and matching sections.

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