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CHARACTERIZING OPTICAL SYNCHROTRON RADIATION IN THE GEOMETRIC OPTICAL PHASE SPACE AND OPTIMIZING THE ENERGY TRANSPORT TO A PHOTO DETECTOR

M.-D. Noll*, E. Bründermann, E. Huttel, D. El Khechen, M. Schuh, J. L. Steinmann, and A.-S. Müller, Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

At the Karlsruhe Research Accelerator (KARA) facility, an electron beam is generated by a thermionic electron gun, pre-accelerated to 53 MeV by a microtron and then ramped up to 500 MeV in a booster synchrotron before being injected into the storage ring, where a final electron energy of 2.5 GeV is reached. Compared to a 2D camera, when using 1D photodetectors either directly at the synchrotron light port or after a fiber optics segment, the optic design goal is to maximize the optical intensity at the photo detector, rather than to keep spacial coherence. In this field of non-imaging optics the emitter, optical setup and sink can be modeled in the optical phase space, with the etendue being the conserved quantity and position and angle the independent variables. In this contribution we describe the synchrotron radiation emitted at a dipole in the KARA booster synchrotron and the imaging setup into an optical multimode fiber with this formalism and compare the results with measurements at the synchrotron light port of the booster synchrotron.

INTRODUCTION

Using the synchrotron radiation emitted from a dipole magnet is well established for transversal and longitudinal diagnostics of circular accelerators. To protect the optical detectors from x-rays and secondary radiation, they can be placed perpendicular to the beam orbit plane, which requires mirrors and/or they can be shielded with lead. Another approach is the usage of a beamline or optical fibers [1] to guide the visible to infrared portion of the synchrotron radiation spectrum to a detector placed away from the accelerator. In test scenarios with low synchrotron light power, the coupling efficiency to the detector is a crucial design goal to achieve high enough signal to noise ratios at the detector output. The coupling efficiency describes only the power transfer, not the spacial coherence. This poses a challenge in the area of non-imaging optics, for which a phase-space representation, similar to the phase space of transversal beam physics, exists.

Here, we show measured synchrotron radiation profiles in this phase space, compare them with optical elements for light guiding and find areas for optimization. The upcoming compact STorage ring for Accelerator Research and Technology (cSTART) features a storage ring where LPA-like electron bunches are only stored for about 100 ms. Because equilibrium is not reached during the storage time [2, 3], the bunch profiles change significantly during one revolution. Therefore optical beam diagnostic systems will be used at different locations around the ring. As the KARA booster covers similar electron energies, it can be used as a test bed for such diagnostics.

* marvin-dennis.noll@kit.edu

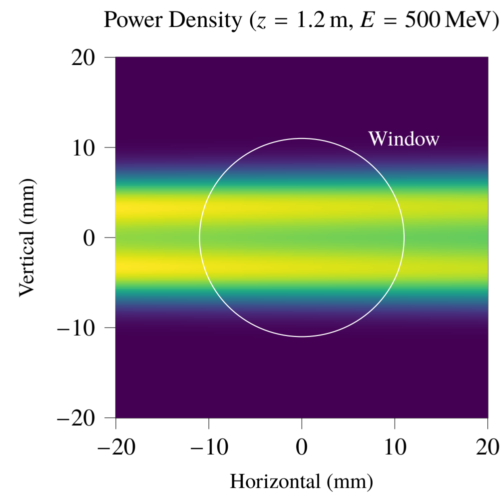

Figure 1: Simulated 2D profile of the synchrotron radiation expected at the location of the synchrotron light port window for 500 MeV and $\lambda = 830$ nm; the free opening of the window is marked with a white circle.

SYNCHROTRON RADIATION AT THE KARA BOOSTER

With the (x, y)-2D power density calculation feature of SPECTRA [4], we estimate the 2D distribution of the synchrotron radiation at the location of the synchrotron light port window ($z = 1.2$ m) of one of the KARA booster dipole magnets. The simulation is done without taking the geometry of the dipole magnets, the beam pipe and the synchrotron light port into account. Thus it is unaware of light blocking apertures and the simulation results in a wide streak of light in Fig. 1. With the geometry of the window added to the plot, it becomes apparent that the radiation is only clipped horizontally and will be reflected by the stainless steel beampipe in the horizontal plane.

2D PROFILE MEASUREMENTS AT THE KARA BOOSTER

Previous 2D camera setups for measurement of the transversal profile of synchrotron radiation at the KARA booster used a lens configuration with a focal point near the

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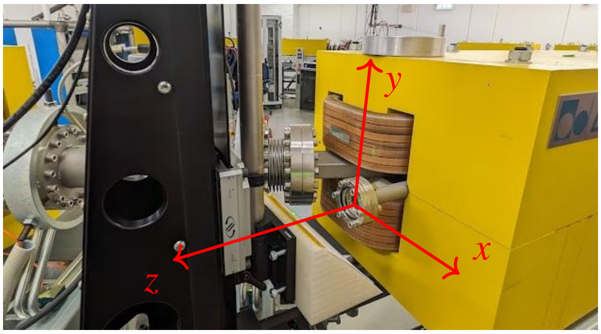

Figure 2: 2D profile measurement setup at the KARA booster; camera and lens are not shown (0.5 m above the white wedge).

electron orbit [5]. While this "near field" setup is useful for studying the electron beam, it is not easily possible to extrapolate the field of light a detector would see outside the synchrotron light port window from those measurements.

Therefore, here, a 45 degree polymer wedge is used as a screen and is placed in front of the window. The wedge surface angled towards the window has 1 cm spaced grooves cut into it horizontally and vertically to help with alignment and calibrating pixels to millimeters. An industrial camera and macro lens is placed 0.6 m above the wedge. The camera features a 1/3.7" silicon CMOS sensor with 1920 by 1080 pixels. Without a color matrix, the camera captures black and white images only. The 35 mm macro lens is focused to the center of the wedge and the lens aperture is closed in until the visible grooves on the wedge surface are fully inside the depth of field. The image acquisition can be triggered with an external input. This trigger is shifted in time along with the booster cycle to capture the evolution of the 2D profile when the magnets are ramped.

To keep the images comparable, the same gain and integration time (of about 5 ms) is used for all images. To avoid overexposure on some images, the settings are tuned for the $t = 500\,\mathrm{ms}$ ($E \approx 430\,\mathrm{MeV}$) point in time, because there the profile is most narrow with the highest peak brightness. At earlier times, because of lower brightness of the synchrotron light beam, the images have a low signal to noise ratio. To counteract this and to reduce the effects of the shot-to-shot variations of the booster cycles, the average of ten images is calculated for each time step on the ramp. The resulting images are plotted in a false-color representation encoding the normalized intensity in Fig. 3.

The profiles show the overall shrinking and growing of the spot size and at time $t = 600\,\mathrm{ms}$, i.e. shortly before extraction, the reflection on the stainless steel pipe become clearly visible.

REPRESENTATION IN THE OPTICAL PHASE SPACE

The etendue ϵ of a source or of a sink (then more accurately called acceptance) can simplified as the volume in the phase space representation. In the case here, it is the area in the (y, θ) plane, that is occupied by an optical ray.

For components with known geometry and emitting/receiving properties, the, often correlated, extend in y and θ can be given analytically. This is drawn for the fiber, fiber-coupled detector and free-space detector in Fig. 4 and Fig. 5.

For the synchrotron radiation, the measurements in Fig. 3 are used to determine first the y extend from one z position. Then the same is done for the second z position. The difference is used to calculate the angle scope $\Delta\theta$:

$$\Delta y = 5\,\mathrm{mm} \tag{1}$$

$$\Delta\theta = \tan\frac{\Delta\Delta y}{\Delta z} = \tan\frac{10\,\mathrm{mm} - 5\,\mathrm{mm}}{225\,\mathrm{mm}} = 22.23\,\mathrm{mrad} \tag{2}$$

With the approximation

$$\epsilon \leq \Delta y \cdot \Delta\theta, \tag{3}$$

the required detector acceptance is about

$$\epsilon = 0.1\,\mathrm{mrad\,m}. \tag{4}$$

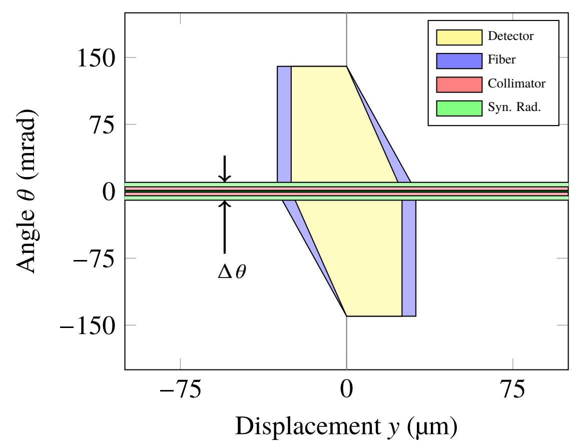

Figure 4: Optical phase space representation of the acceptances in position and angle for a fiber-coupled detector.

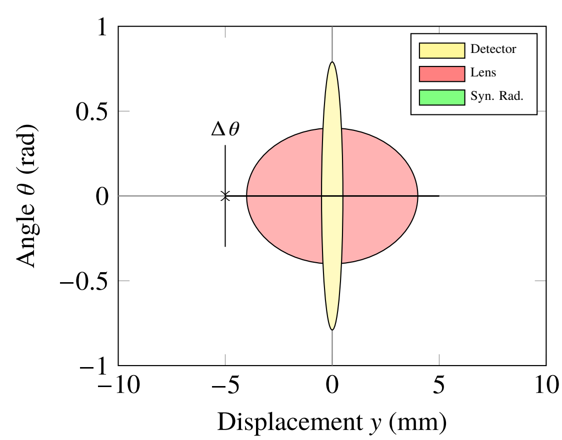

Figure 5: Optical phase space representation of the acceptances in position and angle for a free-space detector.

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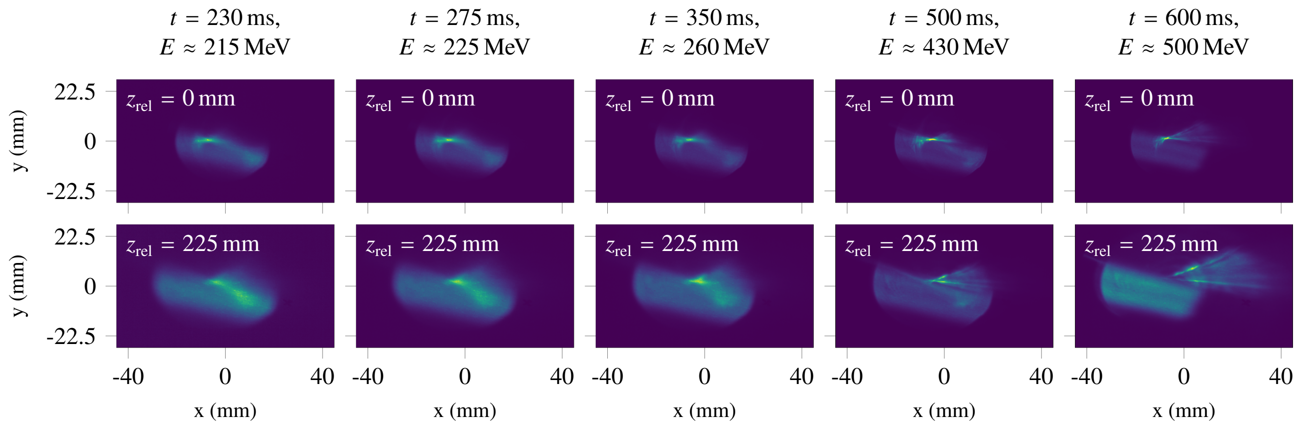

Figure 3: 2D profiles measured at the synchrotron light port of one KARA booster dipole for different times of the booster cycle and two different z positions (spaced 225 mm); fixed gain and integration time (5 ms) for each image; $z_{rel} = 0$ mm is 100 mm away from the window.

Fig. 4 and Fig. 5 show that the sizes and aspect ratios of the phase space areas of the optics are not matched to that of the synchrotron radiation. This causes coupling losses. As the etendue is a conserved quantity, it can not be reduced without clipping the profile with additional apertures. However by the use of properly selected focusing optical elements, the aspect ratio can be changed to better match synchrotron radiation and detector.

OUTLOOK

We showed that the currently used collimator optics do not capture large parts of the synchrotron radiation and thus they do not reach the detectors. To optimize the energy flow, more sophisticated optics are needed. As a first step we will switch to a remotely focusable fiber collimator. Alternatively a lens-free collimator setup using focusing mirrors is possible, which would also reduce absorption losses and eliminate chromatic aberrations.

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