FIRST MEASUREMENTS WITH CODED APERTURE X-RAY MONITOR AT THE ATF2 EXTRACTION LINE

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Abstract

The ATF2 extraction line is used as a test-bed for technologies needed for the ILC final-focus region. An x-ray extraction beam line has been constructed at the final upstream bend before the extraction line straight section, for development and testing of optics and readout systems for a coded aperture-based imaging system. The x-ray monitor is expected to eventually be able to measure single-shot vertical bunch sizes down to a few microns in size at its source location in the ATF2 extraction line. Preliminary scanned measurements have been made with beams in the ~15 micron range, and it is planned to make more measurements with further-tuned beam, and with fast read-out electronics. The details of the layout, expected performance, and preliminary measurement results will be presented.

INTRODUCTION

Coded aperture imaging is a technique well-developed among x-ray astronomers, which consists of using a pseudorandom array of pinholes, which project a mosaic of pinhole camera images onto a detector[1]. This image is then decoded using the known mask pattern to reconstruct the original image. One example of such a pattern is the Uniformly Redundant Array (URA)[2], which features an open aperture of 50% with an even sampling of spatial frequencies in the non-diffractive limit. This provides the spatial resolution somewhat better than that of a pinhole camera, but with much greater x-ray photon collection efficiency for single-shot measurements. Coded aperture x-ray imaging has been tested at CesrTA, with beam sizes down to about ~10 microns[3], and it is planned to use it at SuperKEKB[4]. An x-ray beam line has been constructed in the ATF2 extraction line, with the goal of testing coded aperture measurements with beam sizes down to ~4-5 μm.

BEAMLINE LAYOUT

The beamline is located off the last bend (BH3X) after the extraction point from the ATF ring, at the upstream end of the ATF2 line, as shown in Fig. 1. The bending radius of this magnet is 4.3 m, and the beam energy is 1.28 GeV, for a critical energy of 1.1 keV. The beam size at this bend is typically around 20 microns, but can be reduced, by lowering the beta function, to around 4-5 microns.[5] This bend is also used as the source for a visible-light SR monitor.

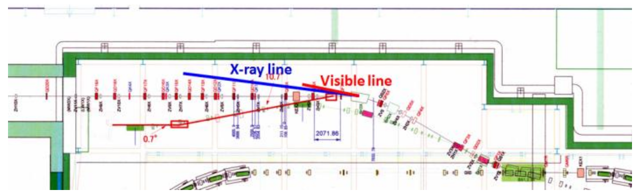

Figure 1: Location of x-ray beamline in the ATF2 extraction line.

The extraction chamber for the x-ray line has a 200 μm thick, polished beryllium window, with ATF2 vacuum on one side and atmosphere on the other side. Just downstream of the beryllium window is the coded aperture mask mounted on a rotating stage, which is then mounted on a 2-axis translational stage. Downstream of the mask is a vacuum chamber with 25 μm thick kapton at both the entrance and exit. There is a 6.4 cm air gap between the beryllium window, and entrance window of the second vacuum chamber, and a 1.5 cm air gap between the second chamber and the detector at the far downstream end, which is, like the mask, mounted on a rotating stage and 2-axis translational stage, on an optical table. Mask and detector mounts are shown in Fig. 3. The distance between the source point and the mask is 193.5 cm, and the distance from the mask to the detector is 835.7 cm.

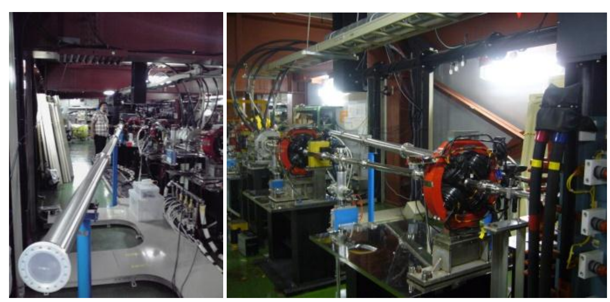

Figure 2: Views from downstream (left) and upstream (right) during construction of x-ray beamline at ATF2.

The downstream vacuum chamber is only pumped down to a few tens of Pa with a scroll pump; its function is to provide a low-loss path for the x-ray beam, and it is separate from the accelerator beam vacuum. The total effective air path length, including the air gap around the mask and between the downstream kapton window and the detector, is ~10 cm.

ISBN 978-3-95450-119-9

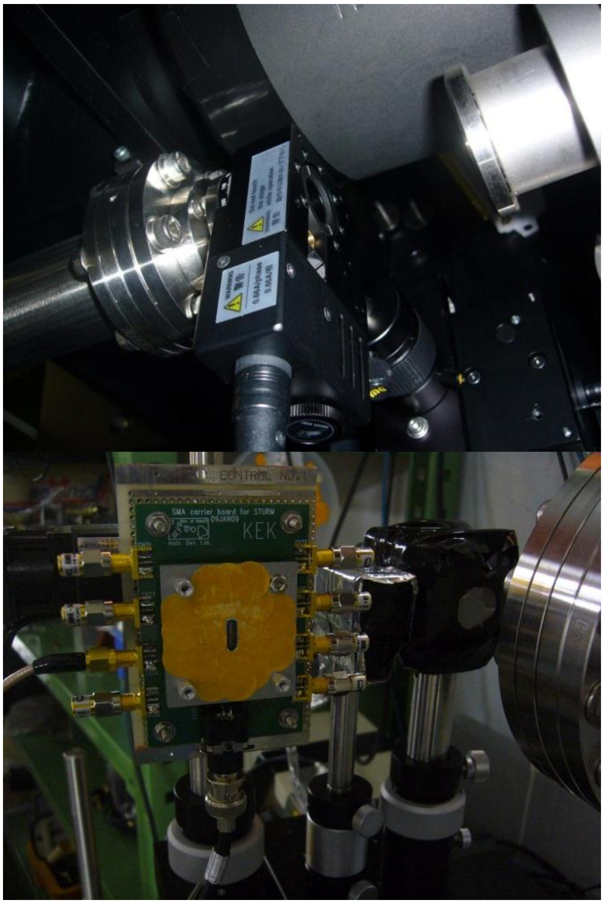

Figure 3: Rotating mask holder (above), and detector on rotating stage (below). Next to detector are a PMT with Ce:YAG scintillator and a CCD for initial alignment.

The detector is an InGaAs array produced by Fermionics, Inc., which features 25 μm ×500 μm pixels on a 50 μm pitch. The thickness of the InGaAs layer is 3.5 μm, which captures about 90% of the flux that reaches it after passing through the diamond window, and other layers on the chip above the InGaAs layer. For future bunch-by-bunch use at the ATF2 and SuperKEKB, a high-speed readout is being developed, but for preliminary checking of the x-ray system, a single Fermionics pixel was mechanically scanned across the imaging plane while being read out with an oscilloscope.

EXPECTED PERFORMANCE

At low intensities, the resolution of the system is limited by statistical fluctuations in the number of detected photons. To estimate the resolution of the system as a function of beam size, simulated images are calculated for Gaussian beams of various sizes. The simulated detector images for different-sized beams are then compared pair-wise against each other using residual weighting function for each channel proportional to the square of the signal height in that channel. The χ^2/ν value that corresponds to a confidence interval of 68% is chosen to represent the 1-s confidence interval.[6]

The calculated image pattern in the detector plane for vertical beam sizes of from 1 to 20 microns is shown in Fig. 4 The coded aperture mask is a 47-element array with 5-micron minimum feature size with a tantalum mask material on a 2.5 micron silicon carbide substrate, made by NTT-AT Nanofabrication.

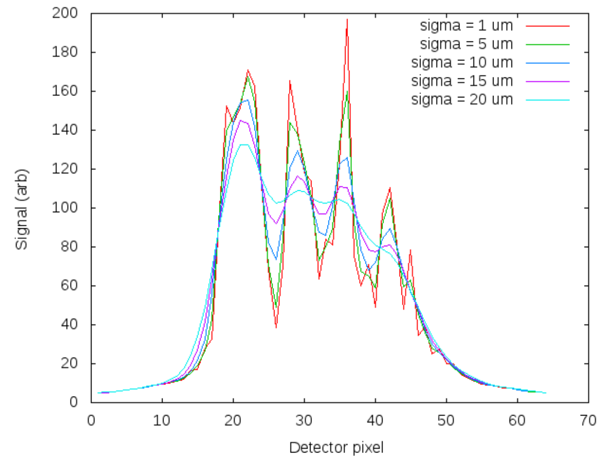

Figure 4: Simulation of expected beam patterns for 50-micron pitch detector at different beam sizes.

The minimum beam size possible at the x-ray monitor source point is expected to be around 4.5 μm. Figure 4 shows the resolution contours for the 47-element coded aperture mask, for 1 nC bunches, which produce an average of ~250 photons per pixel per shot on the Fermionics detector. As can be seen in Figure 5, single-shot statistical resolutions of ~1 μm can be expected for minimum beam sizes around 4 μm.

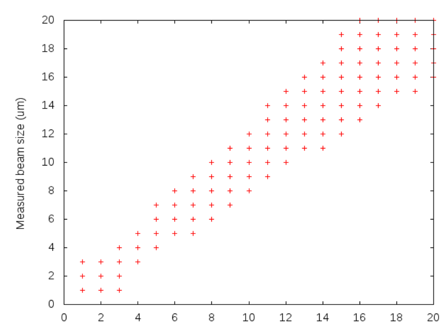

Figure 5: Calculated 1-σ statistical resolution contours for 47-element CA with 5 μm elements at the ATF2 with 1 nC bunches.

The single-shot readout electronics for the 64-channel detector are under development. For the present time, a single pixel is scanned across the beam to make a slow-scan image. The shot-to-shot vertical orbit jitter of the ATF2 beam is about 10% of the beam size[7], which is sufficient for basic beam size measurements. When the single-shot readout system is ready, we can then proceed to measurements of the single-shot resolution, as determined by photon statistics and readout noise.

ISBN 978-3-95450-119-9

PRELIMINARY MEASUREMENTS

Optics

T. Okugi of the ATF optics group designed a set of optics for the ATF2 extraction line which minimized the beam size at the x-ray source bend, BH3X, shown in Fig. 6. The vertical beta function at the source point is 1 m, which for a vertical emittance of 20 pm-rad (1% of the horizontal emittance) gives a vertical beam size of 4.5 μm. (The horizontal beam size is 260 μm.) The set of optics required to reach these parameters is incompatible with regular ATF2 operations, which are targeted at minimizing the beam size at the end of the ATF2 line, so dedicated machine time is needed to carry out this measurement. One shift was allotted for this purpose on 23 Feb., 2012.

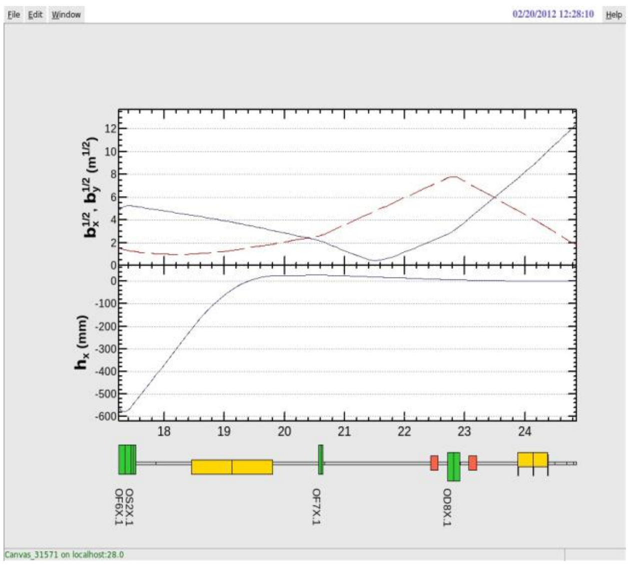

Figure 6: Small beam-size optics at BH3X (Courtesy of T. Okugi).

Measurements

A dispersion knob and rotation knob were available to tune the beam at the source point, along with an x-y coupling knob. After setting up the initial optics, and before tuning the knobs, the coded aperture mask was aligned with the x-ray beam, and a detector scan was taken to verify the coded aperture pattern was detected, as shown in Fig. 7. The initial, unturned beam size at this point was about 15 microns (hand fit, based on peak-valley modulation).

Next, a dispersion knob scan was carried out, maximizing the peak-valley ratios using 50-micron-step scans. The dispersion knob was set to the value which maximized the peak-valley ratio (+0.25 machine units). The measurements taken during the dispersion scan are shown in Fig. 8.

Following this, the coupling knob was scanned, and set to the optimum value (0 machine units). The measurements taken during the coupling scan are shown in Fig. 9.

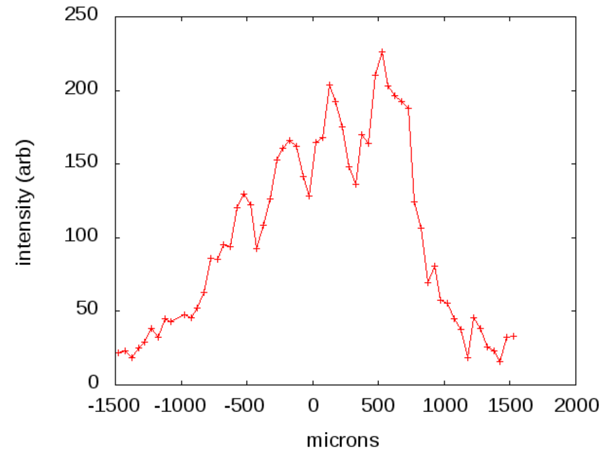

Figure 7: Pre-tuning scan, corresponding to about 15 micron beam size (hand fit).

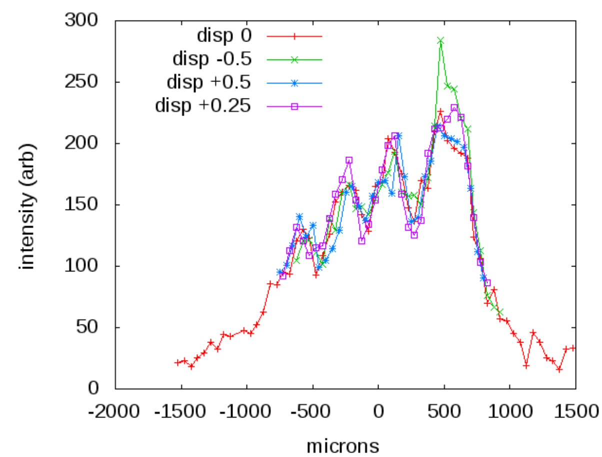

Figure 8: Dispersion knob scan.

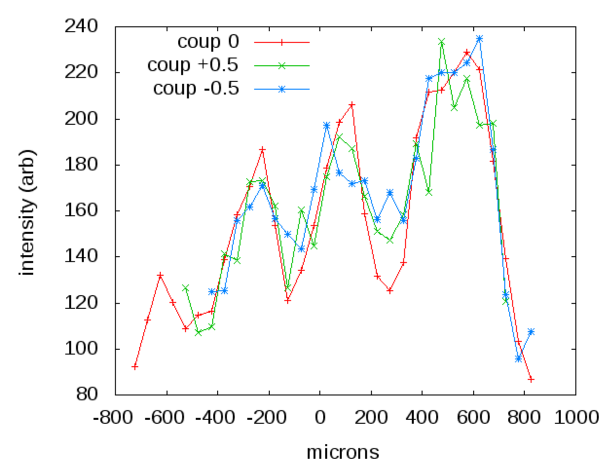

Figure 9: Coupling knob scan.

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Finally, a mask angle scan was performed, and the mask angle set to the optimum angle, which was found to be at 1 degree from the initial orientation. The mask scan measurements are shown in Fig. 10.

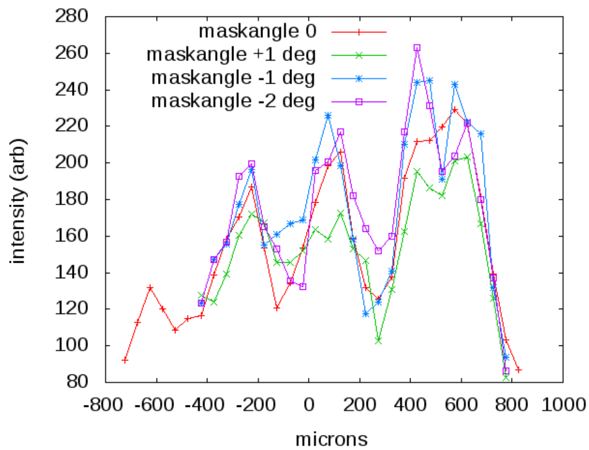

Figure 10: Mask angle scan.

At the end of the knob scans and mask angle scan, a detector slow-scan data set was taken using 25-micron steps (Fig. 11). The final beam size was around 10 microns, based on maximum peak-valley ratio (hand fit).

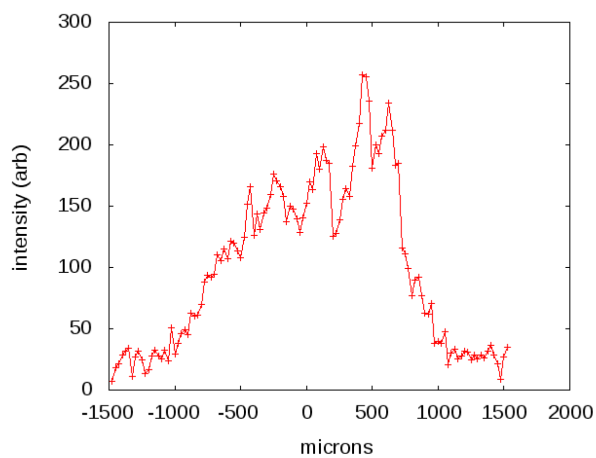

Figure 11: Final scan, using 25-micron steps, corresponding to about 10 microns (hand fit).

SUMMARY AND PLANS FOR THE FUTURE

Preliminary measurements have been taken with a coded aperture mask at the ATF2 in slow-scanning mode. Beam sizes of around 10-15 microns were measured. Further improvements to the optics are considered possible, and will be tried in future studies in order to try to reach and demonstrate measurements of ~4-5 micron beams. In addition, a 64-channel fast-readout is being developed, which will enable the quantitative measurement of the predicted ~1 µm single-shot statistical resolution at such small beam sizes. The beam line will also continue to be used for testing detector and readout systems for SuperKEKB.

ACKNOWLEDGMENTS

We would like to thank the ATF/ATF2 group for allowing us to set up a beamline there, and for allowing a dedicated run to take the preliminary data. In particular, we would like to thank T. Naitoh for his help with set-up issues, and T. Okugi for his optics calculations and tuning efforts during the study.

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