DEVELOPMENT AND COMMISSIONING OF THE NEXT GENERATION X-RAY BEAM SIZE MONITOR IN CESR *

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Abstract

The CESR Test Accelerator (CESRTA) program targets the study of beam physics issues relevant to linear collider damping rings and other low emittance storage rings. This endeavour requires new instrumentation to study the beam dynamics along trains of ultra-low emittance bunches. A key element of the program has been the design, commissioning and operation of an x-ray beam size monitor capable, on a turn by turn basis, of collecting single pass measurements of each individual bunch in a train over many thousands of turns. The x-ray beam size monitor development has matured to include the design of a new instrument which has been permanently integrated into the storage ring. A new beam line has been designed and constructed which allows for the extraction of x-rays from the positron beam using a newly developed electro magnet pair. This new instrument utilizes custom, high bandwidth amplifiers and digitization hardware and firmware to collect signals from a linear InGaAs diode array. This paper reports on the development of this new instrument and its integration into storage ring operation including vacuum component design, electromagnet design, electronics and capabilities.

INTRODUCTION

The Cornell Electron Storage Ring (CESR) provides electron and positron beams which are used for accelerator research and as a synchrotron light source. Both of these applications require diagnostic equipment and instrumentation to maintain particle beam and x-ray quality. The Next Generation x-Ray Beam Size Monitor (NGXBSM) is part of a suite of instrumentation developed for this purpose. The NGXBSM is a natural evolution of the instrument which was developed during the early stages of the CESRTA program. This instrument images x-rays from a bending magnet through a pinhole optical element on to a 32x1 pixel linear array detector. Figure 1 shows the basic concept of beam size measurement using x-rays.

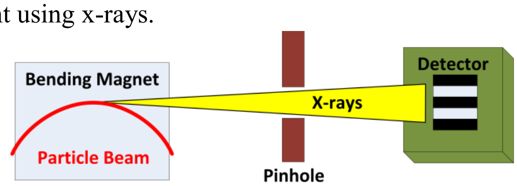

Figure 1: XBSM concept.

The development program has thus far leveraged the existing beam line and support structure of the experimental hutches at the Cornell High Energy Synchrotron Source (CHESS). While this arrangement was convenient, it was also temporary. The instrument was disassembled at the end of every CESRTA run and reinstalled, aligned and calibrated at the beginning of the next run. This prevented the use of the instrument during normal CHESS operations and limited development opportunities. The instrument provides valuable beam tuning information and an effort was undertaken to design and build a permanently installed instrument in CESR. The new instrument is a simplified application of the first generation technology. It provides vertical beam size measurements on a bunch by bunch and turn by turn basis. The available optical elements include a 35 micron vertical pinhole, a 200 micron vertical pinhole and an unlimited opening. These were chosen to support the typical operating energies of CESR, 2.085 GeV and 5.3 GeV. The instrument is capable of operating with CESR beam energies down to 1.8 GeV. First generation data acquisition electronics and software have been utilized to capture and process the x-ray images.

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ACCELERATOR INTEGRATION

In order to reduce the risk to the accelerator vacuum system, it was decided to pursue a windowed beam line design with the optical elements and detector outside of the CESR beam pipe. A beryllium window provides physical separation between the CESR and NGXBSM beam pipes. Usable x-ray intensity across the energy range of the accelerator is maintained by utilizing multiple x-ray sources. At 5.3 GeV an existing normal bend magnet is used as the x-ray source. At 2.085 GeV, a new two pole source magnet has been designed and constructed to provide the x-ray source. This new magnet is required to provide sufficient x-ray flux through the beryllium window at lower CESR beam energies. The spatial requirements of the new beam line coupled with the requirement for the installation of a new source magnet, limited potential instrument locations in the CESR tunnel. The location chosen for this new instrument forced an overall reduction in length of the x-ray path from optical element to detector when compared to the first generation instrument. Since the instrument is effectively a pinhole camera, this serves to reduce the effective magnification from source to detector. In order to offset this effect, the detector has been tilted at a 60 degree angle to functionally reduce the pixel height and increase resolution. The present configuration has a distance from source to optic of 4.4m or 6.76m, depending on which source is used, and a distance from optic to detector of 4.4m. Motorized stages are used to allow for precision alignment of the optical elements and the detector. Figure 2 shows a functional overview of the instrument and key CESR components.

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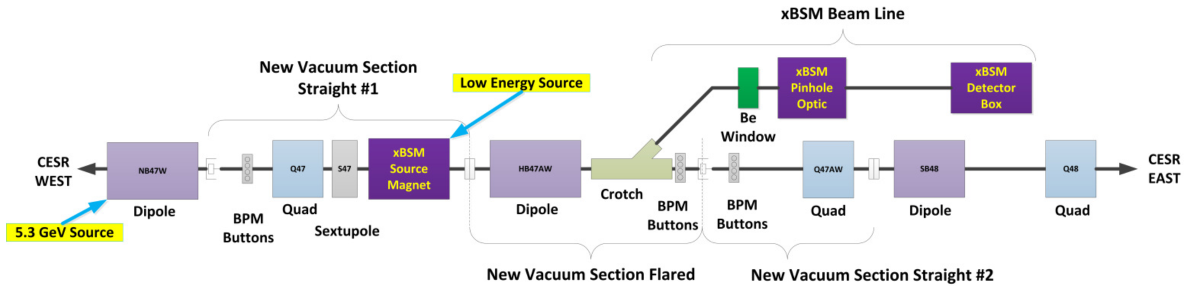

Figure 2: NGXBSM functional diagram.

VACUUM COMPONENTS

In order to transfer the x-rays from CESR to the detector, a flared vacuum chamber, beam line crotch, beryllium window and dedicated beam line have been designed and installed in CESR. The flared vacuum chamber is installed inside of a standard CESR hard bend magnet and has a large flange which mates with the beam line crotch. The beam line crotch is a water cooled copper device which absorbs the fan of synchrotron radiation while allowing the particle beam and the x-rays to pass down their respective lines. The shape of the crotch was carefully designed to absorb the synchrotron radiation energy across all operating parameters for CESR. The beryllium window is 200 microns thick, 38 mm in diameter and allows for the x-rays to pass from CESR vacuum into the NGXBSM beam line. The NGXBSM beam line is rough pumped and backfilled with helium. This provides a clean medium which minimizes x-ray scatter and contamination. The window provides vacuum isolation and filters out low energy x-rays. All vacuum components are cooled with 85 degree Fahrenheit water which is supplied from the main CESR cooling loop. Figure 3 shows these new components as installed.

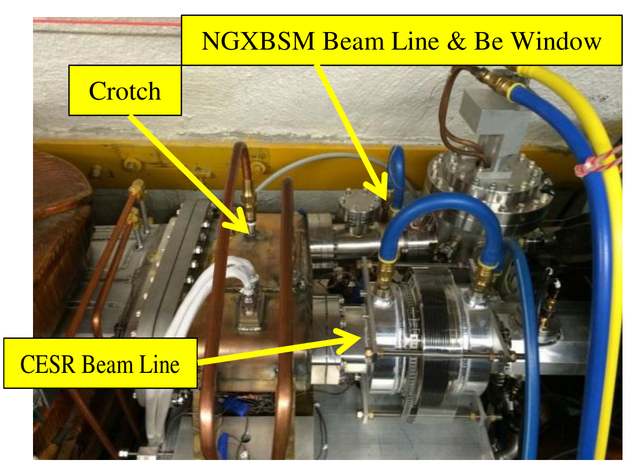

Figure 3: NGXBSM vacuum components.

LOW ENERGY SOURCE MAGNET

The normal bend magnet which is used as a source at 5.3 GeV has a field strength of 0.972 kG when CESR is operated at 2.085 GeV. This is not sufficient to provide usable x-rays. Therefore an electro-magnet pair has been designed and constructed to support operation at low energy. This pair, in conjunction with an additional CESR magnet, provides the horizontal beam trajectory necessary to generate x-rays which are of useful energy and direction. This trajectory requires a minimum of three poles to close the horizontal orbit bump which is created at the source point.

The new magnet was limited to two poles due to spatial constraints. An additional trim winding, which is part of a normal CESR bending magnet, is used to close the beam orbit disturbance created by the NGXBSM source magnet. Maximum horizontal beam orbit displacement within the source magnet is calculated to be 5.2 mm radially outward.

The two magnet poles are powered by a common 60 Volt, 300 Amp switched power supply. The current provided by the supply is controlled via the CESR control system. This allows for a design field of 4.5 kG in the shorter pole and 1.5 kG in the longer pole. The ratio between these two magnet poles provides the proper CESR beam trajectory for x-ray transmission. A 25 Amp active shunt is connected around the long pole and allows for precision adjustment of this ratio. The x-ray source point is provided by the short pole. Figure 4 shows the magnet as installed. The design magnetic field characteristics for the new source magnet are shown in Figure 5.

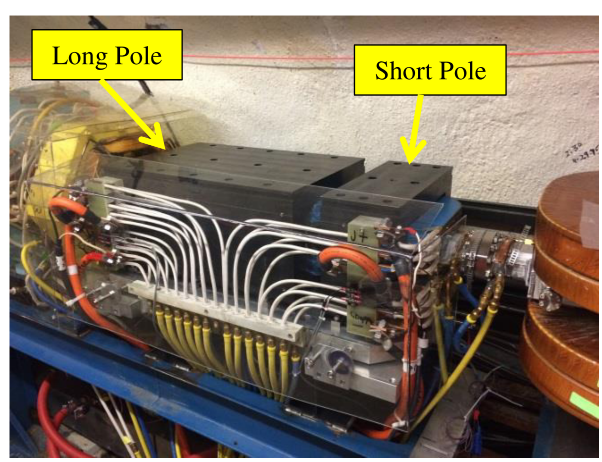

Figure 4: NGXBSM source magnet.

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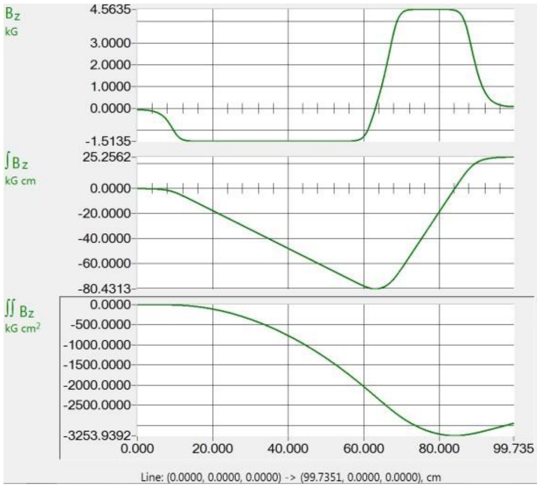

Figure 5: Magnetic field map of NGBSM magnet.

X-RAY SPECTRUM

The NGXBSM utilizes the same detector as the original instrument. This detector was used in conjunction with an existing hard bend magnet in CESR with a field of 5.1 kG at 5.3 GeV and 2.0 kG at 2.1 GeV. The detector response has been extensively studied over the course of the CESRTA program. Figure 6 shows the inferred detector response as well as the transmission characteristics of the 200 micron beryllium window. The detector response was determined empirically by using a variety of filters with a constant x-ray source.

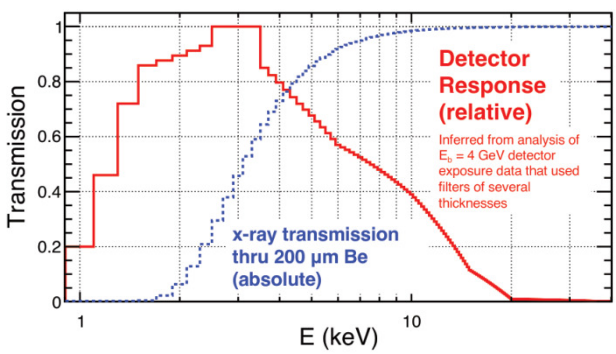

Figure 6: Detector response and be window transmission.

For CESR operations at 2.085 GeV the new source magnet has a calculated output spectrum as shown in Figure 7. For CESR operations at 5.3 GeV, the existing bend magnet has a calculated output spectrum as shown in Figure 8. Here, intensity is defined to be electromagnetic energy per unit time per unit area per unit current perpendicular to the x-ray beam in arbitrary units which are the same for both cases. A 1.5 mm aluminium filter is required at 5.3 GeV to lower the intensity so as to not saturate the detector. This filter is removable for operation at lower CESR beam energies.

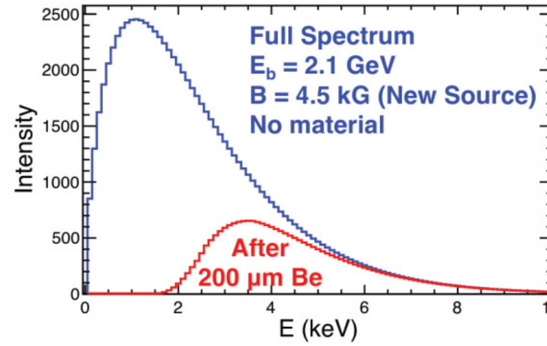

Figure 7: 2.085 GeV x-ray spectrum.

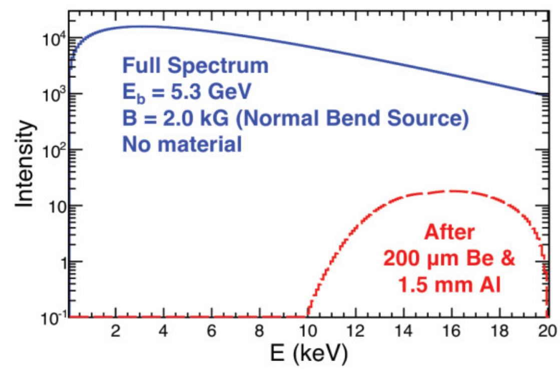

Figure 8: 5.3 GeV x-ray spectrum.

ACCELERATOR OPTICS

In order to create enough physical space in CESR for the installation of the new source magnet, several quadrupole magnets were moved. These changes coupled with the effect of the two pole source magnet at 2.085 GeV forced a redesign of the CESR magnetic optics. The trim winding of the closest CESR bending magnet is used to close the horizontal bump which is introduced by the two pole source magnet. After correction, we are left with an RMS orbit ripple of 111 microns and an RMS horizontal dispersion ripple of 1.9 mm. This results in an increase in horizontal emittance of 1.5% in our low emittance optics. This increase is deemed acceptable.

At 5.3 GeV the existing normal bend magnet is used with no impact on beam characteristics for CHESS operations.

MEASUREMENTS

At this point in the project, x-rays have been delivered to the detector at both 2.085 GeV and 5.3 GeV. The pinhole optical elements have been manufactured but have not yet been used to image the beam. During alignment, a digital camera was used to capture the x-ray beam position on the aluminium flag. Figure 9 shows the x-ray fluorescence on the aluminium filter at 5.3 GeV.

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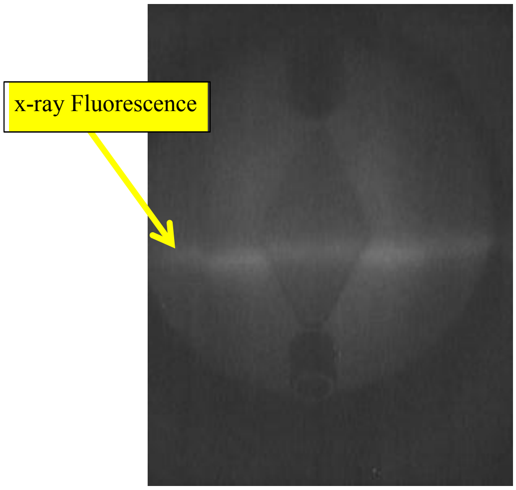

Figure 9: X-ray fluorescence at 5.3 GeV.

Once basic alignment was achieved, the detector and accompanying electronics were used to capture an x-ray profile of the straight through beam. Careful timing calibrations were performed to align the sampling electronics with the revolving bunch in CESR. This calibration positions the sampling point on the peak of the induced signals produced by each diode segment. Typical alignment procedures produce temporal alignment within 50 picoseconds. Figure 10 shows the detector response of straight through beam at 2.085 GeV.

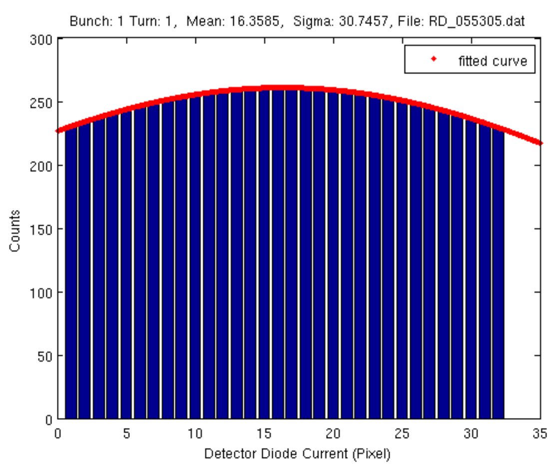

Figure 10: Straight through beam Image at 2.085 GeV.

FUTURE EFFORTS

The motorized pinhole stage has been completed and will be installed prior to the CESR accelerator start up in October 2016. It is expected that alignment will be completed and measurements at 5.3 GeV will be made using the 35 and 200 micron pinhole optics. Figure 11 shows the pinhole stage prior to installation.

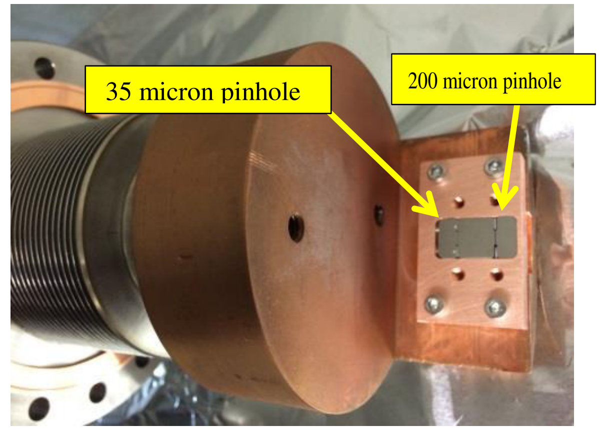

Figure 11: NGXBSM pinhole stage.

The instrument will then be used for experimental measurements as part of normal CHESS operations. 2.085 GeV alignment and measurements will be made during the December 2016 CESRTA run. Additional efforts to improve the quality of the detector itself are being planned.

CONCLUSION

The transition of the xBSM instrument from temporary prototype to permanently installed instrument has required significant intellectual and physical investment. New hardware, software and operating procedures have been developed and are presently being tested. It is expected that the instrument will be commissioned and placed into regular operation by the end of 2016.

ACKNOWLEDGMENT

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