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PROPOSED ENHANCED IMAGING STATION IN THE 6-GeV BOOSTER-TO-STORAGE RING TRANSPORT LINE FOR APS UPGRADE*

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Abstract

The high charge per micropulse of up to 17 nC in the booster to storage ring transport line for APS Upgrade will necessitate changes in the imaging station used to evaluate beam emittance in this key region. The original Chromox screen has recently been replaced by a YAG:Ce single crystal for immediate screen spatial resolution improvement down to <10 μm. However, the optical system also needs an upgrade with lenses and a digital camera to take full advantage of this. In addition, at the high areal charge densities expected, the YAG:Ce scintillator mechanism will saturate, or quench, leading to images larger than the actual beam size. To circumvent this effect, optical transition radiation (OTR) screens will be implemented. A proposed longer-range goal of a non-intercepting beam-size monitor using optical diffraction radiation techniques during top-up injection will also be addressed.

INTRODUCTION

One of the challenges of the injector for the Advanced Photon Source Upgrade (APS-U) [1] is the measurement and monitoring of the required high charge beam at 6 GeV between the booster synchrotron and the storage ring in the transport line (BTS). In APS-U, charges of up to 17 nC per micropulse are specified with a beam geometric emittance of 80 nm rad. One issue is the possibility of transverse emittance blow up at these high charges, and evaluations of this at station BTS:FS3 using a quadrupole field scan with downstream beam size measurements has been initiated. The anticipated lattice will result in vertical beam sizes at the imaging station BTS:FS3 of ~80 μm (sigma) so system resolutions of <30 μm are warranted. To address this need, a phased approach to enhance the imaging station performance has been initiated.

Recently, a 20-year-old Chromox screen oriented at 45 degrees to the beam was replaced by a 100-μm thick YAG:Ce screen with the surface orientation normal to the beam followed by a 45-degree backing mirror which resulted in an estimated screen resolution of <10 μm (σ). The optical magnification of the system still needs to be increased to take full advantage of this screen resolution, however. In addition, the high areal charge densities of APS-U are expected to exceed the scintillator mechanism's saturation threshold so an optical transition radiation (OTR) screen will be added to the station for high-charge studies. A final implementation phase under consideration is the use of an optical diffraction radiation (ODR) screen configuration as a non-intercepting beam-size monitor during top-up injections. Evaluations of the different imaging techniques will be presented.

EXPERIMENTAL ASPECTS

The APS Linac and Injector Rings

The APS linac is based on an S-band thermionic cathode (TC) rf gun which injects beam into an S-band linear accelerator with acceleration capability currently up to 450 MeV. This is an S-band pulse train with about 10 ns macropulse duration and 28 micropulses, presently delivering 1 to 1.5 nC per macropulse. Beam diagnostics in the linac include imaging screens, rf BPMs, loss monitors, and coherent transition radiation (CTR) autocorrelators [2].

The linac beam is injected into the particle accumulator ring (PAR) at 375 to 425 MeV at up to 30 Hz, and the macropulse is damped to about 300 ps pulse length at 3 nC normally. For APS-U however, up to 20 nC are stacked in the PAR, which in turn results in bunch lengthening, and some instabilities occur [3]. The beam is extracted and injected into the booster synchrotron which ramps the beam energy from the injection energy to 7 GeV currently, but 6-GeV for APS-U and machine injector studies. The beam is extracted from the booster and then enters the booster to storage ring transport line (BTS) as schematically shown in Fig. 1. The beam is then injected into the storage ring at full energy. One wishes to characterize the beam transverse emittance in normal conditions and at the high charges of APS-U in this transport line. Our injector studies are on the path to measure these beams with sufficient spatial resolution even at high charge. This objective has motivated the upgrade of the imaging station BTS:FS3 from the Chromox screen oriented at 45° to the beam direction to a YAG:Ce single crystal oriented with its surface normal to the beam and with a 45° mirror behind it (to redirect the light to the optical system). This crystal is a good solution for spatial resolution at low charge, but we address the potential saturation [4], or quenching [5], of the scintillator mechanism which occurs at charge areal densities of ~10 fC/μm^2. Note one reaches this regime with a 1 nC charge focussed in a 100 μm by 100 μm sigma-x,y beam size. We will show that APS-U parameters will exceed this value in the BTS line.

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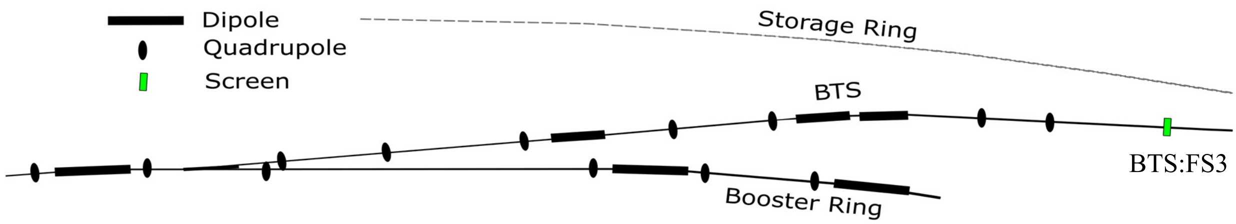

Figure 1: Schematic of an arc of the APS Booster synchrotron and the BTS line with the imaging screen BTS:FS3 (green rectangle).

Radiation Converter Screens for Beam Imaging

The basic task of imaging a relativistic electron beam has been accomplished for many years in accelerator laboratories. The imaging system includes a converter screen, optical transport, a CCD camera, and digital image processing. The first task is to have the optical system spatial resolution preferably 3x smaller than the beam size to be measured. For 1-mm size beams in older machines, 300-µm resolution would be more than adequate. It is relatively straight forward to proceed down to ~10 µm with present day technology, but care is needed. The converter screen has been a key performance factor in this change. Historically, powder screens or polycrystalline forms had been used. Due to light scattering off the grains, the delivered spatial resolution was much larger than the grain size. The "rule of thumb" in the x-ray imaging world was that the full width at half-maximum intensity (FWHM) spatial resolution was about the same as the screen thickness [6]. For relativistic electrons, this resolution rule is measurably worse than this guideline. This is graphically illustrated by the plot in Fig. 2 showing a compilation of different thickness powder screens and their deduced resolutions based on comparisons to OTR, single crystals, or wire scanners [7, 8]. For example, the 250-µm thick Chromox screen at 45 deg to the beam direction has about 200 µm (sigma) or 470 µm (FWHM) resolution, which is 34 % larger than the thickness. The plot here also shows where a grain size of 5 µm would fit, but the light scattering prevents the attainment of that resolution. The other point is that the single crystal samples have superior spatial resolution by a factor >5 compared to a powder version of the same thickness. This is why one has moved to such crystals at many laboratories in recent years. A comparison of screen properties is given in Table 1. Note the clear advantages of the YAG:Ce over Chromox and OTR over both at high areal charge densities. It is also noted that the beams are extracted from the booster synchrotron ring so they are Gaussian shaped and would have no microbunching instability effects for the OTR or ODR imaging [9]. They would still have the linear polarization effects on OTR image size reduction of ~15 % to address [10].

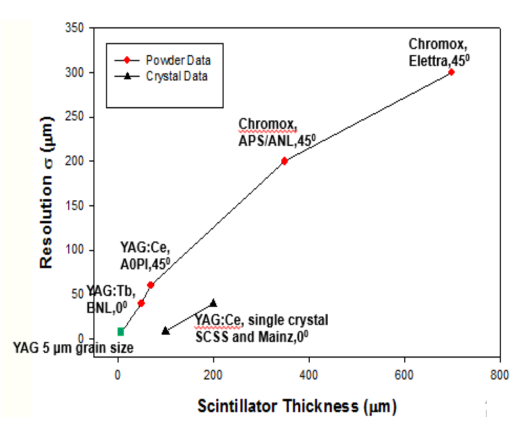

Figure 2: Comparison of powder screen and single crystal scintillator spatial resolutions vs. thickness. The different accelerator facilities where data were obtained are indicated [7, 8].

Table 1: Comparison of radiation converter screen parameters for Chromox (Al2O3:Cr), YAG:Ce, and OTR assuming screen thicknesses of 250 µm, 100 µm, and 10 µm, respectively.

Parameter	Al_2O_3:Cr	YAG:Ce	OTR
Spatial resolution σ (µm)	200	<10	<10
Response Time	300 ms	80 ns	10 fs
Polarization effect	No	No	Yes
Saturation effect	Yes	Yes	No

EXPERIMENTAL RESULTS

Previous Scintillator Saturation Results

We have made the case for improved spatial resolution at low charge areal densities, but there is a caveat at high charge. Scintillator mechanism saturation [4], or quenching [5], can occur at high charge areal densities. Using a linac beam at 600 MeV previously [4], we identified beam image size blurring in the YAG:Ce 0.5-mm thick crystal compared to the OTR images taken under the same charge conditions from the TC rf gun as shown in the updated plots of Fig. 3. The beam x,y sigma sizes were 40 µm x 400 µm with the total charges varied from 1-7 nC by lengthening the S-band macropulse generated by the TC rf gun. The response time of the crystal is 80 ns so the macropulse appeared as a single bunch to the scintillator. It is noted that the light yield per electron may reduce at the higher charge densities as well as the image broadening observed. In the European XFEL case with LYSO crystals, smoke-ring-like images were observed at 14 GeV, but less so at the ~200-MeV point for ~1-nC micropulse charge [5]. This was modelled as a quenching effect on the excitation carriers. They also reported the YAG:Ce crystal has a better performance than LYSO in this aspect. At 6-7 GeV in the BTS and 10-17 nC per micropulse, we will look for the two effects in the YAG:Ce crystal images.

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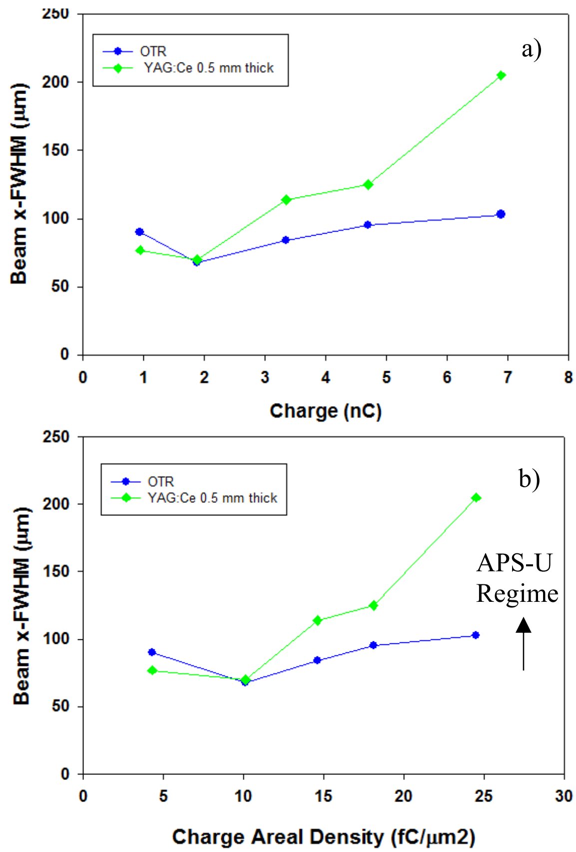

Figure 3: (a) Measured beam image sizes with OTR (blue) and YAG:Ce (green) as a function of charge. (b) Measured beam image sizes with OTR (blue) and YAG:Ce (green) as a function of charge areal density. At 25 fC/µm^2, the YAG:Ce image is twice as large as the reference OTR image due to presumed saturation effects. APS-U exceeds this density value with 17 nC and the expected beam sizes.

Recent YAG:Ce Scintillator Results

Examples of the beam images with Chromox and YAG:Ce screens are shown in Fig. 4 on two different machine runs with different lattices (β's). The YAG:Ce image is the more recent and also includes optics revisions. In addition, an example of the measurement of vertical emittance with the latter screen using a quadrupole field scan technique is shown in Fig. 5. A vertical emittance of ~1.5 nm rad was obtained indicating a low vertical coupling of around 1.5%.

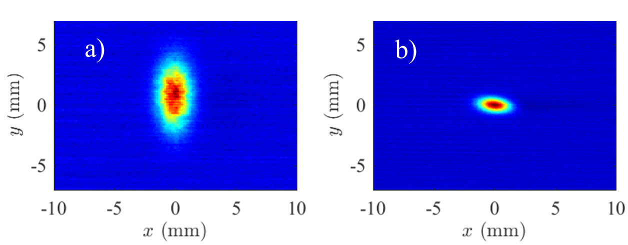

Figure 4: Chromox (a) and YAG:Ce (b) beam images taken at BTS:FS3 with different lattices and optical imaging.

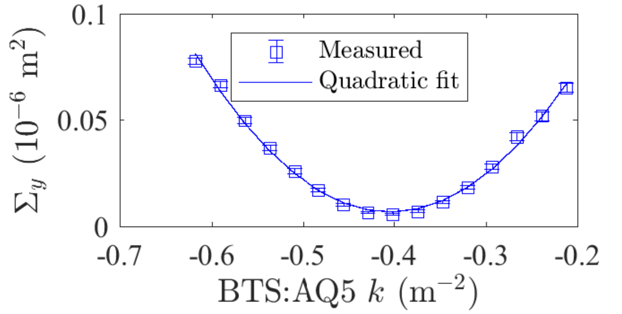

Figure 5: Example of vertical emittance measurement data using the YAG:Ce crystal.

Previous OTR and ODR Imaging Results:7 GeV

Both OTR and ODR imaging were demonstrated at APS at 7 GeV in the booster extraction/beam dump line (BTX) [11]. In this case, a polished Al metal mirror on a stepper actuator could be inserted into the beam for OTR imaging or positioned with its edge above the beam line axis for ODR imaging. This is shown schematically in the inset in Fig. 6. In Fig. 7a we show an example of the OTR image from this station with Q = 0.4 nC and an ~1200-µm x size. The ODR image was then taken with Q = 3.3 nC and the metal edge 1.25 mm above the beam axis as shown in Fig. 7b. This provided a *non-intercepting* monitor of this image size at the <20 % level, or better using corrections.

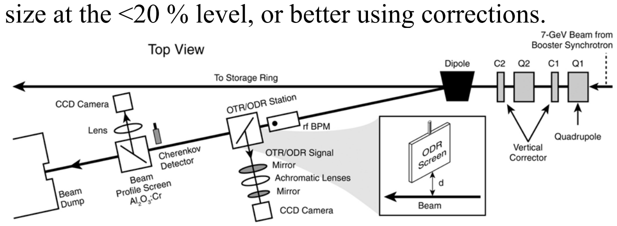

Figure 6: Schematic of the OTR/ODR station in the nearby BTX line [11].

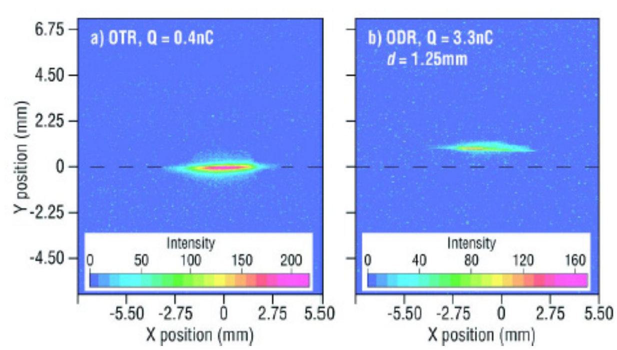

Figure 7: (a) Example of an OTR image at 7 GeV taken in the BTX line at APS. (b) Example of the ODR image taken with a screen edge offset of 1.25 mm from beam axis [11].

SUMMARY

In summary, the BTS:FS3 imaging station upgrade paths have been described with supporting demonstrations of imaging techniques. These indicate the beam imaging can meet the desired performance goals for APS-U and even provide a non-intercepting beam-size monitor online during the top-up injections of 17 nC at 1 Hz.

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