A High Resolution Electron Beam Profile Monitor and its Applications

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Abstract. A beam diagnostic to measure transverse profiles of electron beams is described. This profile monitor uses a cerium-doped yttrium:aluminum:garnet (YAG:Ce) crystal scintillator to produce an image of the transverse beam distribution. The advantage of this material over traditional fluorescent screens is that it is formed from a single crystal, and therefore has improved spatial resolution. The resolution is ultimately limited by the diffraction of visible light to approximately 1 micron. The application of these scintillators in a very compact three-screen emittance monitor is also described.

INTRODUCTION

The high-brightness electron beams now being produced for short wavelength FELs and high-energy colliders have focused sizes as small as a few microns. Resolution below this is necessary for accurate reproduction of the transverse beam profiles. Fluorescent screens based on phosphors have been widely used to measure the transverse profiles of electron beams at high-energy accelerator facilities. Traditional fluorescent screens [1], such as ZnS, produce a bright image but have relatively poor resolution. Phosphors have an individual grain size of 50–100 microns. Internal scattering of the fluorescence limits the image resolution to the same scale. A newer technology with improved resolution is the use of optical transition radiation (OTR) [2] produced by the electron beam passing from vacuum through a material such as a thin carbon or aluminum foil. This technique has excellent spatial resolution but suffers from very weak light output (more than two orders of magnitude less intense than phosphors in the visible spectrum). The YAG:Ce scintillators described here produce an image as bright as a good phosphor screen with a resolution comparable to that of an OTR screen.

Several devices based on these crystals have been built at the NSLS. They will be the main profile monitors installed in the Source Development Lab, a new free electron laser laboratory. A periscope pop-in monitor [3] now uses them for high precision beam profiles inside a small-gap undulator installed at the BNL Accelerator Test Facility. The crystals are also used in a compact three-screen emittance

Table 1. Summary of YAG:Ce properties

YAG:Ce Physical Properties	
Density	4.55 gm/cm^3
Rise Time	5 ns
Fast Decay Time	90 ns
Slow Decay Time	300 ns
Photon Yield	18,000 photons/MeV
Peak Fluorescence Wavelength	560 nm

monitor installed in the Smith-Purcell experiment at ATF. This monitor is described in detail below.

SCINTILLATOR PROPERTIES

The crystals used to date have been cut as cylinders 0.5 mm thick by either 6 or 10 mm in diameter. They are available in a wide range of sizes and shapes. The thinnest standard size we have found is 0.2 mm, available from Preciosa Crytur. Crystals 0.1 mm thick are available on special order from the same manufacturer.

The photon yield is dependent on the type of exciting particle [4]. The yield is approximately 45% of NaI(Tl) [4] at 1.8×10^3 photons/MeV. This is more than two orders of magnitude brighter than screens utilizing optical transition radiation.

There is a finite rise time of the scintillator light of about 5 ns which may be due to a time constant of the lattice-to-activator energy transfer. The decay time is marked by two exponentials which depend on the method of excitation [5]. The fast time component has a decay constant of 90 ns and accounts for about 80% of the emitted light. The slow decay has a time constant of 300 ns and accounts for the remaining 20% of the light.

We initially coated the crystals with a 60%/40% Au/Pd metal layer a few tens of nm thick. This is to drain adsorbed charge from the electron beam. However, light reflections from flaws in the coating caused intensity variations in the beam image. Subsequent tests of an uncoated crystal using an electron microscope beam indicated that the bare YAG:Ce is adequately conducting, and we now routinely use uncoated crystals in high-energy beams.

The beam at BNL's Accelerator Test Facility has been used to test damage resistance. Several thousand pulses of charge of 0.5 nC each were run through the crystal in spot sizes ranging from tens of microns to 1 mm. There has been no measurable deterioration in light output. Visual inspection of the crystal also indicates no damage. The crystals have also been tested with large amounts of charge [6] (40 nC/pulse, 200,000 nC integrated charge) at the Argonne Wakefield Accelerator facility and have shown no damage.

Linearity of the light output with beam charge is good [7]. Results from Argonne [6] also show good linearity for larger beam charges.

RESOLUTION LIMITS

The ultimate spatial resolution is set by both the minimum object size that can be produced by the crystal and by the optical transport of visible light. The minimum object size for high-energy electrons is limited by multiple Coulomb scattering of the beam through the crystal and by the generation of bremsstrahlung. The multiple scattering angle through the material is given approximately by [8]:

$$\theta_{ms}(z) = \frac{13.6\text{MeV/c}}{p}\sqrt{z/Z_0}\,[1 + 0.20\ln(z/Z_0)] \tag{1}$$

where z/Z_0 is the material thickness in radiation lengths and p is the electron momentum. The radiation length for YAG is 5.2 cm. For a 50 MeV beam traveling through a 0.5 mm thick crystal, $\theta_{ms} = 1.9$ mrad, yielding a minimum possible spot size of

$$x_{ms} = \int_0^{0.5\text{mm}} \theta_{ms}(z)dz = 0.6\mu\text{m}. \tag{2}$$

The critical energy, where energy losses due to ionization and radiation of bremsstrahlung are equal, is about 50 MeV. Above this energy the x-rays generated by electrons passing through the material will also cause scintillation, limiting the minimum measurable beam size. The characteristic emission angle of the x-rays is $1/\gamma = 10$ mrad at 50 MeV. Thus $x_{brem} = 2.5$ μm at 50 MeV.

The minimum spot size limits due to either multiple scattering or bremsstrahlung are both dependent on the electron beam energy. The limits are reduced at higher energies (Fig. 1).

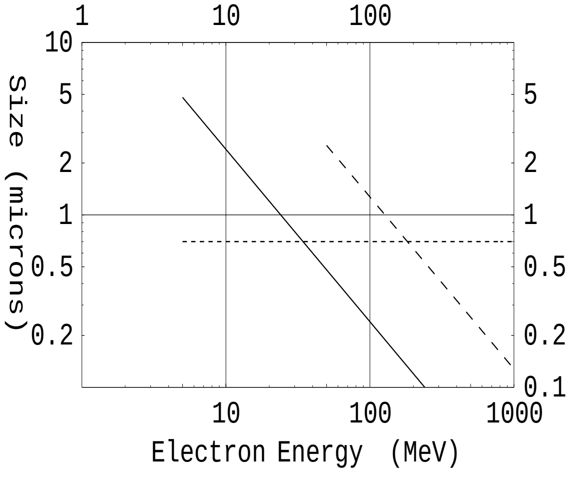


FIGURE 1. Effects that limit minimum spot size are plotted as a function of electron beam energy for a 0.5 mm thick crystal. Solid line is multiple scattering, dashed line is bremsstrahlung, dotted line is diffraction limit.

In addition to the intrinsic limits set by the electron beam passing through the crystal, the final image quality is also determined by the transport of visible light through the optical focusing system. The diffraction-limited diameter of a lens focus is $d_0 = 2.44\lambda(f/D)$, where the wavelength, λ, of the light is 560nm, f is the lens focal length, and D is the lens diameter. This is the diameter of the zeroes of the Airy disk. For reasonable working distances of a few centimeters, the lowest diffraction-limited f/D that can be achieved is about 3. Therefore the optics of visible light limit our resolution to beam spots of 4 microns diameter, or 0.7 microns rms size. Figure 1 summarizes the rms spot size limits due to multiple scattering, bremsstrahlung, and diffraction.

Spherical aberration, chromatic aberration, and depth of field are the most important lens effects that will distort the image and prevent diffraction-limited performance. The crystals are transparent so that the beam image is created along the entire depth of the crystal. This produces an extended longitudinal object that must be accurately focused at the plane of the camera. The crystals should be as thin as possible to reduce the depth of field and the amount of electron beam scattering. A lens system that is telecentric (magnification is the same for all conjugate planes, see Figure 2) will reduce the depth of field problem.

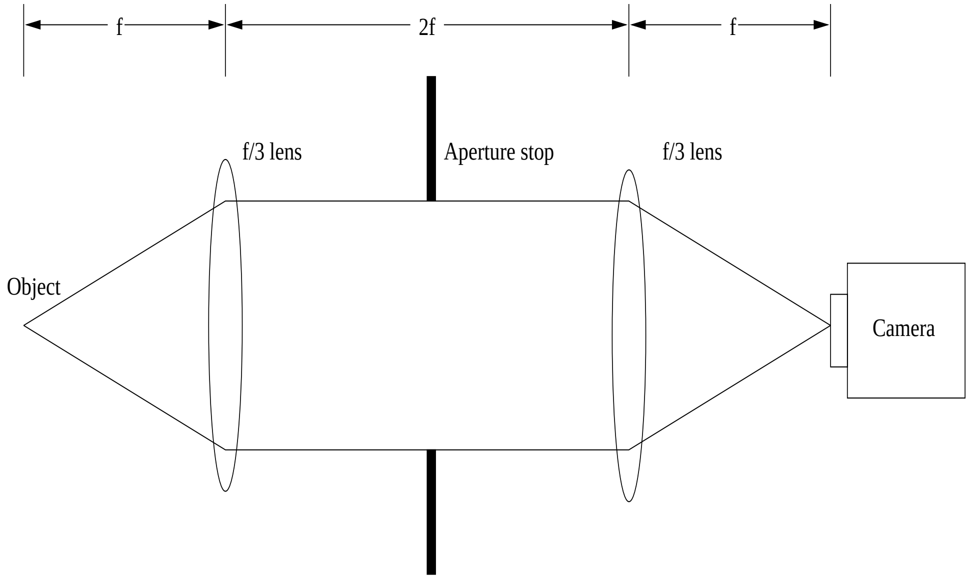


FIGURE 2. A telecentric lens arrangement reduces distortion due to depth of field and has minimum distortion if doublet achromatic lenses are used.

Spherical and chromatic aberration may then be reduced by choosing achromatic doublets for the lenses, which can be made diffraction-limited over a range of wavelengths.

THREE-SCREEN EMITTANCE MONITOR

The layout of the three-screen emittance monitor is shown in Figure 3. It is installed in beamline 1 of the BNL Accelerator Test Facility in an experiment to

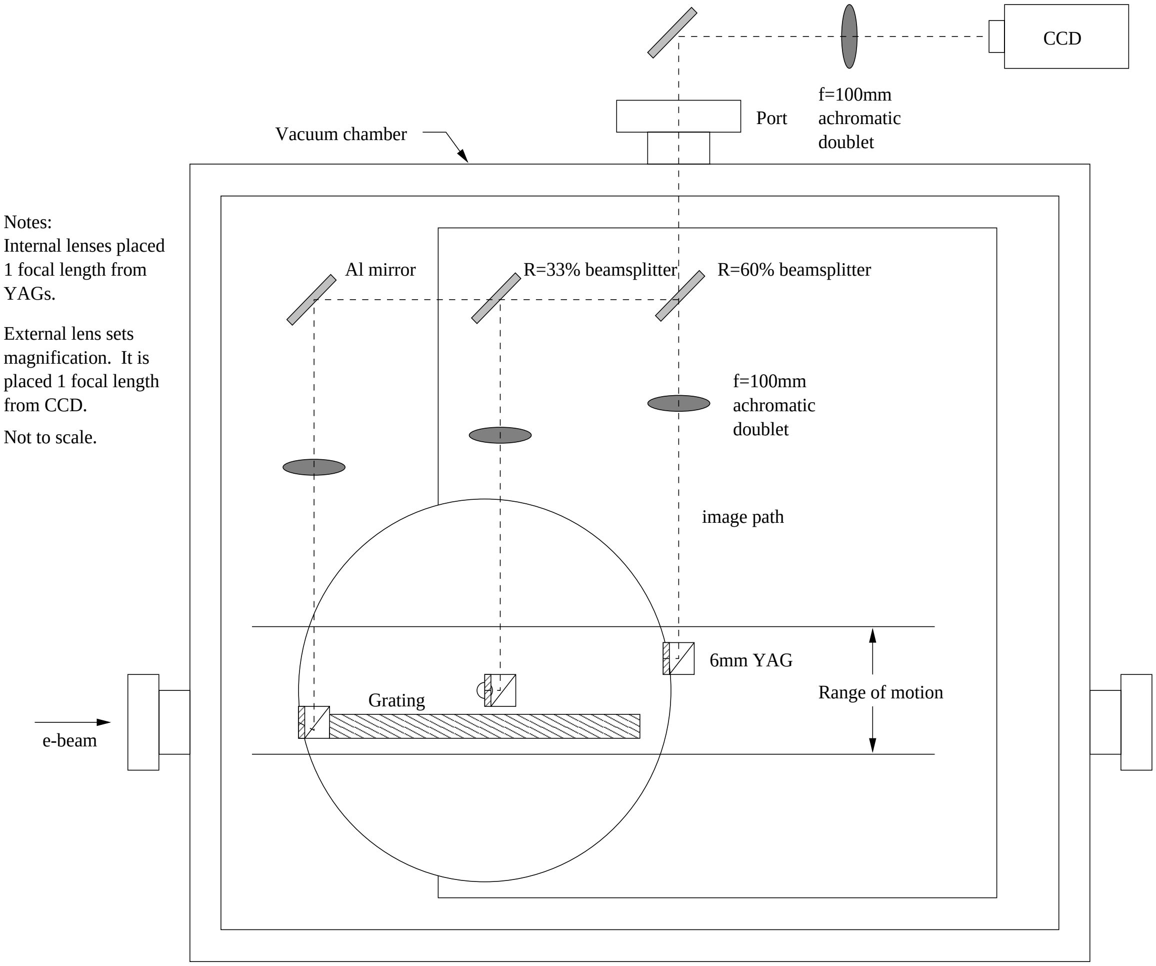


FIGURE 3. Layout of optics of three-screen emittance monitor. Spacing between screens is just 6 cm.

measure Smith-Purcell radiation from a relativistic electron beam [9]. The infrared Smith-Purcell radiation is transported by optics that are not shown. In this experiment the YAG:Ce crystals act purely as an electron beam diagnostic and do not affect the generation of Smith-Purcell radiation. The table on which the crystals are mounted translates across the beam direction. This enables the table to be placed so that the beam skims the surface of the grating or intercepts any one of the three screens. The table also rotates so that the grating may be made parallel to the beam. The YAG:Ce crystals facilitate the precise positioning of the grating with respect to the beam because the distances from each screen to the grating and to each other are known with high accuracy. Thus, position measurements allow the beam to be placed just off the surface of the grating and parallel to it. The crystals also indicate when the upstream focusing magnets are properly tuned to produce a beam waist at the grating center. Finally, they are used to measure the emittance using the three-screen technique.

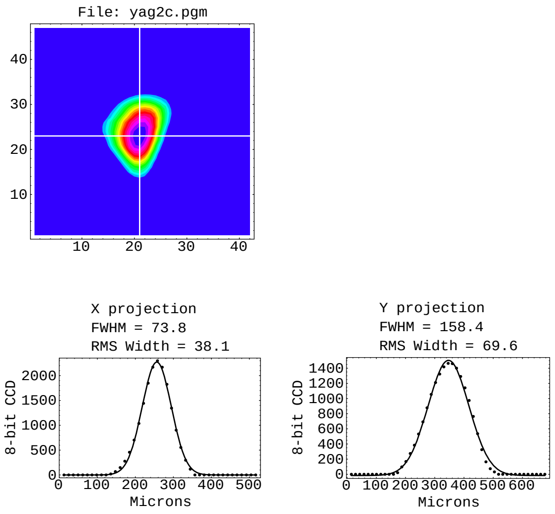
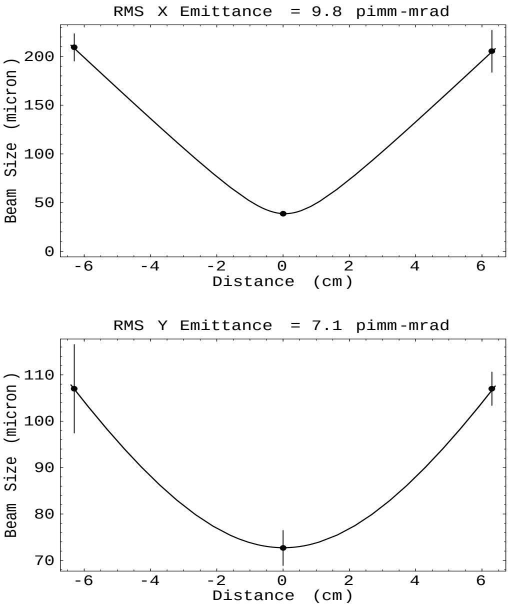


FIGURE 4. Image of the electron beam on the center profile monitor in Smith-Purcell experiment.

For this experiment the resolution requirements are not difficult (beam size greater than 40 μm). The doublets were arranged to be approximately telecentric. This arrangement proved useful for decoupling the lens focus from the translation table position. The vacuum window was used as an aperture stop. All lenses were 25 mm diameter and 100 mm focal length. The beam splitter reflectivities shown in Figure 3 were chosen to transport approximately equal amounts of light intensity from each screen to the camera. A Cohu 4910 CCD camera and a PC-based framegrabber were used to record the image [7]. Note that the short decay time of the scintillator (much less than a camera frame time) requires that the camera be synchronized to the beam arrival. Alignment and focusing of the optical transport was done by placing a pinhole successively at each screen until it was in focus at each and the images overlapped to with 1 or 2 pixels. With this arrangement, illuminating the apparatus with an external light allows all three screens to be seen on the CCD simultaneously. The grating shown in the illustration is 10 cm long, and the total spacing from the first crystal to the last is just 12 cm.

To accurately measure emittance, the beam's phase space ellipse should be sampled via profiles at equal intervals of betatron phase advance [10] as it rotates through 180 degrees. If three screens are available, then the ideal spacing is 60 degrees of phase advance between screens. This requirement is met when there is a beam waist at or near the center screen *and* the beam is a factor of two larger


RMS X Emittance = 9.8 pimm-mrad

RMS Y Emittance = 7.1 pimm-mrad

FIGURE 5. Horizontal and vertical emittance measurements using three screens in the Smith-Purcell experiment.

at each of the outer screens. Note also that if more than three screens are used, or the quadrupole-tuning method of single screen emittance measurement is employed, that the requirement that the screens be spaced at equal intervals of phase advance implies that the screens (or quadrupole tuning points) are not equidistant from each other.

A typical beam image and its horizontal and vertical projections are shown in Figure 4. This image is of a beam waist at the center screen of the experiment. Figure 5 shows horizontal and vertical profiles for all three screens and gives the calculated normalized rms horizontal emittance as 9.8π mm-mrad and the vertical emittance as 7.1π mm-mrad. The betatron advance between screens is not ideal for either transverse plane. The beam was tuned to give a minimum horizontal waist at the grating center as the best condition for producing Smith-Purcell radiation.

CONCLUSIONS

The performance of YAG:Ce scintillator crystals was described. These crystals are bright, have linear response, are highly damage resistant, have a fast decay time, and have excellent spatial resolution.

A three-screen emittance measurement using a very compact arrangement of these crystals was described. The novel aspects of this beam diagnostic are its compact size and placement directly in another experiment that is critically dependent on accurate knowledge of the beam size, position, angle, and divergence.

An important aspect of beam profile monitors based on these crystals is the low system cost. The crystals themselves are very inexpensive and the visible light produced is well matched to current silicon-based detectors.

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