PHYSICS SPECIFICATIONS FOR THE INJECTOR PROFILE MONITORS (OTR AND YAG)

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Brief Summary
This document describes the location and performance requirements for the injector beam profile monitors using either fluorescent YAG crystals or optical transition radiation (OTR) from metal screens.

Change History Log

<table>
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<th>Rev Number</th>
<th>Revision Date</th>
<th>Sections Affected</th>
<th>Description of Change</th>
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<td>000</td>
<td>Sep. 26, 2005</td>
<td>All</td>
<td>Initial Version</td>
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PRD 1.2-021-r0  
1 of 14  
Check the LCLS Project website to verify that this is the correct version prior to use.
1. Overview

There are 7 YAG and 7 OTR profile monitors (view screens) in the injector whose specifications are given in Table 1. Their detailed locations are given in Figures 2 through 5.

Table 1

Numbers for the beam size in brackets refer to special modes of operation and specify the full extend of the beam whereas the numbers without brackets refer to the nominal rms beam size at 1 nC bunch charge. The minimum beam size $\sigma_{\text{min}}$ is for 0.2 nC and 5 pC (†) charge. $S_{\text{Position}}$ is the screen distance from the cathode, and Direction specifies either the axis in which the OTR light is reflected or a close to normal incidence reflection.

<table>
<thead>
<tr>
<th>YAG</th>
<th>Resolution [um]</th>
<th>Diameter [mm]</th>
<th>Thickness [um]</th>
<th>Nominal Energy [MeV]</th>
<th>$\sigma_{\text{min}}$ [mm]</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
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<td>20</td>
<td>100</td>
<td>6.2</td>
<td>0.040†</td>
<td>1.372</td>
<td>0.610</td>
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<td>20</td>
<td>100</td>
<td>6.2</td>
<td>0.080†</td>
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<td>YAG03</td>
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<td>64</td>
<td>0.289</td>
<td>0.408</td>
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<tr>
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<td>20</td>
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<td>135</td>
<td>0.157</td>
<td>0.220</td>
<td>0.381</td>
<td>8.440</td>
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<td>YAGG1</td>
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<td>50</td>
<td>100</td>
<td>6.2</td>
<td>3.339†</td>
<td>1.500</td>
<td>1.200</td>
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<td>20</td>
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<td>0.030</td>
<td>0.100</td>
<td>21.534</td>
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</table>
The YAG profile monitors consists of a YAG:Ce crystal mounted perpendicular to the electron beam and a mirror behind to reflect the light at 90 degree. A similar arrangement is used for the Cherenkov radiators (CR01 and CRG1), except the YAG crystal is replaced by a thin quartz plate which is frosted on the downstream surface to increase the scattering of Cherenkov light out of the plate (see PRD 1.2-109 Injector Cherenkov Radiators). The OTR profile monitor has a 1 µm thick aluminum foil mounted at 45 degree to the electron beam to radiate light at a direction of 90 degrees. These configurations are shown in Figure 1. Both types of profile monitors then have a vacuum window, attenuators, imaging optics, and a CCD camera to generate images of the transverse electron beam distribution. The images shall have the resolution given in Table 1 and sufficient dynamic range and noise level to determine the beam size and size of substructures in the distribution for a bunch charge of 0.2 to 1 nC. Measurements of the thermal emittance will require a charge as low as 5 pC at the profile monitors in the GTL section.

The specification for the resolution $\sigma_{\text{res}}$ of the profile monitors is based on the requirement to measure the expected minimum beam size $\sigma_{\text{beam}}$ at the respective locations with 5% accuracy. This requires for the resolution $\sigma_{\text{res}} = \sqrt{\frac{2}{3}} \times 5\% \times \sigma_{\text{beam}}$. The resolution for all YAG screens except the spectrometer screens YAGG1, YAGS1, and YAGS2 was set uniformly to 15 µm based on the requirement of YAG01 to enable a common design. The requirement for YAGG1 is chosen high enough to resolve features in the beam. The OTR screens will be mounted 45 degrees with respect

<table>
<thead>
<tr>
<th>OTR</th>
<th>Resolution [µm]</th>
<th>Diameter [mm]</th>
<th>Thickness [µm]</th>
<th>Nominal Energy [MeV]</th>
<th>Direction</th>
<th>$\sigma_{\text{min}}$ [mm]</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mm]</th>
<th>$S_{\text{Position}}$ [m]</th>
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<td>Hor</td>
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<td>0.133</td>
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<td>1</td>
<td>135</td>
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<td>0.065 [8.000]</td>
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<td>1</td>
<td>135</td>
<td>Hor</td>
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<td>0.124</td>
<td>0.120</td>
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<td>1</td>
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<td>Hor</td>
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<td>0.161 [1.500]</td>
<td>0.116 [14.000]</td>
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<tr>
<td>OTRS1</td>
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<td>Norm.</td>
<td>0.021</td>
<td>0.030 [10.000]</td>
<td>0.100 [12.000]</td>
<td>21.534</td>
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to the electron beam, thus reflecting the radiation 90 degree towards the vacuum window. The 45-degree geometry of the OTR metal foil is necessary due to space restrictions in the injector and has the implication that with the camera mounted perpendicular to the light direction, not the entire OTR screen will be in focus. The imaging optics will only focus a vertical stripe across the OTR screen for horizontal reflection and vice versa. The width of the stripe in focus depends on the depth of field. Table 1 lists the optimum reflection direction depending on the electron beam size at the respective locations. For OTR2 the transverse cavity will streak the beam vertically. The large extent of the beam there is required to calibrate the vertical deflection of the beam induced by the transverse cavity versus time. At OTR4 and OTRS1 the electron beam is dispersed horizontally and can also be streaked vertically by the transverse cavity. The measurement of the energy spectrum requires vertical reflection of the OTR light. The vertically streaked beam will not be in focus in the geometry of 45 degree reflection. The OTRS1 screen should therefore be mounted close to perpendicular to the electron beam and the OTR light be reflected out of the vacuum with an upstream off-axis mirror inside the vacuum. The screen YAGS2 downstream of OTRS1 will enable beam profile measurements in case of insufficient OTR intensity, as may occur for a beam with low charge or with a large extent.

![Diagram of the GTL region showing the locations of three YAG view screens YAG01, YAG02, and YAGG1. The screens, CR01 and CRG1 are fused silica radiators for making streak camera measurements of the bunch length at these locations. The light from these locations is optically transported from the GTL upstairs to the drive laser room where the streak camera is located.](image)

Figure 2: The GTL (gun-to-linac) region showing the locations of three YAG view screens YAG01, YAG02, and YAGG1. The screens, CR01 and CRG1 are fused silica radiators for making streak camera measurements of the bunch length at these locations. The light from these locations is optically transported from the GTL upstairs to the drive laser room where the streak camera is located.
Figure 3: The region between the L0-a and L0-b linac structures showing the placement of YAG03.

Figure 4: The beamline between the end of L0-b and the shield wall has YAG04 at the linac exit; two OTR screens, OTRH1 and OTRH2, on both ends of the laser heater undulator; and OTR1 which is the first of the screens used for three screen emittance measurements.
Figure 5: The region at the end of the injector, showing the last two OTR’s, OTR2 and OTR3, for measuring the three screen emittance; OTR4 for energy and energy spread determination in the middle of the DL1 dog leg. In addition, there is a straight ahead beamline (SAB) for characterizing the beam without disturbing the main linac. The SAB has two YAG’s, YAGS1 and YAGS2, and one OTR, OTRS1. YAGS2 is located immediately after OTRS1.

1.1. OTR Yield and Resolution

The photon yield of transition radiation is critical for the specifications of the imaging system and the expected performance of the OTR beam profile monitors. The OTR yield is calculated by integrating the angular and frequency distribution of transition radiation at the injector energy of 135 MeV

$$\frac{d^2W}{d\omega d\Omega} = \frac{e^2}{\pi^2 c} \frac{\beta^2 \sin^2 \theta}{\left(1 - \beta^2 \sin^2 \theta\right)^2}$$

over the solid angle $\Omega$ (Fig. 6). The angle $\theta$ is measured with respect to the emission direction. Between an angle of 100 and 300 mrad the collected amount of OTR varies only from 45% to 65% of the total yield. This weak dependence provides flexibility in selecting the numerical aperture of the imaging system and to optimize resolution and depth of field.
Figure 6: Angular distribution of transition radiation at 135 MeV. The green curve is the double differential distribution, the red curve shows the distribution integrated over the solid angle and normalized to the total emitted radiation.

The total yield is obtained by multiplying the wavelength dependent OTR with the reflectivity of the OTR screen material and integrating over the respective wavelength range. The resulting quantum efficiencies for an aluminum screen are listed in Table 2. The yield for the LCLS linac energy is also given here for reference and is only about a factor two higher compared to the injector. The yield for titanium is only half of the one for aluminum due to titanium’s lower reflectivity. For a charge variation from 0.1 to 1 nC, between $10^7$ and $10^8$ photons will be available for detection.

<table>
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<tr>
<th>Energy (MeV)</th>
<th>QE (%)</th>
<th>450-650 nm</th>
<th>QE (%)</th>
<th>400-750 nm</th>
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<td>0.75</td>
<td></td>
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<td>4300</td>
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<td></td>
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<td>14000</td>
<td>1.17</td>
<td>1.99</td>
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</table>

The nature of transition radiation being a directed light source rather than an isotropic point source has implications on the tolerances of the angular screen alignment and the maximum field of view. Figure 7 shows the OTR yield as a function of angular misalignment of the OTR screen for 100 mrad acceptance angle of the imaging optics. The yield drops to 50% at that angle and to 95% at 50
mrad. It holds in general for the acceptance angles and energies considered here that at an angular deviation of half of the collection angle at least 95% of the maximum light will still be transmitted. The field of view with at least 95% transmission is then half the diameter of the aperture of the imaging optics.

Figure 7: OTR yield vs. angular misalignment of OTR screen in respect to optical axis of imaging optics for 135 MeV and 100 mrad collection angle.

The OTR resolution is determined by the OTR point spread function. The rms size is 
\[ \sigma = \frac{4.55 \lambda}{2 \pi \theta} \]
for a collection angle \( \theta \). To meet the lowest resolution requirement of 10 µm at 550 nm wavelength, a collection angle of at least 40 mrad is required. For the resolution over an extended spectral range, as required to get a sufficient photon yield, the depth of field and the change in focal length of the imaging optics due to chromaticity has to be taken into account. A simulation of the transverse OTR distribution imaged by a 4-f optics with 150 mm focal length and an f/# of 5 (0.1 rad collection angle) resulted in a minimum spot size of 10 µm and a depth of field of 0.8 mm within 20 µm spot size for a spectral range from 450 nm to 650 nm.

1.2. YAG Yield and Resolution

The photon yield of the YAG fluorescence is generally at least a factor 100 larger than that for OTR. The yield can be estimated from the number of photons per energy loss of 18,000/MeV, the energy loss of an electron per density and per length of 1.7 MeV/(g/cm²), the YAG density of 4.55g/cm³, the crystal length \( l \), and the collection half angle \( \theta \) to 
\[ \eta = 1.4 \times 10^5 \ cm^{-1} \ l \ sin^2(\theta/2). \] For a 100 µm thick
crystal and a total collection angle of 0.3 rad this is about 10 ph/e-, which is a factor 10³ higher than OTR. The ratio benefits from a large collection angle because for scintillation the yield scales quadratic with the collection angle whereas it scales only logarithmic for OTR.

The resolution of the YAG screen is limited by a number of factors besides the diffraction limited spot size of about 1 µm. Both the effect of multiple scattering and of bremsstrahlung are below the diffraction limit if the crystal thickness is less than 100 µm at beam energies above 5 MeV. The resolution is also limited by the fact that the light is emitted from the entire depth of the crystal. The resolution is then given by \( \sigma = d / n \tan(\theta/2) = 10 \mu m \) for a total collection angle of 0.3 rad and a 100 µm thick crystal. The accuracy of the measured distribution can be affected by saturation of the scintillation in the crystal which occurs at a charge density of 0.04 pC/µm² at 100 MeV beam energy. This gives a minimum Gaussian beam size of 63 µm at 1 nC. Therefore a YAG screen is not suitable to measure the smallest beam sizes in the injector at the full charge. The feasibility of a beam size measurement with a 100 um thick YAG crystal was shown at the GTF where at 70 pC the same emittance was measured both from OTR and YAG with minimum beam sizes of 50 µm.

### 1.3. Imaging Simulation

The number of photons available from the OTR, and to a lesser extent from the YAG, sets a limit to the size and charge of the electron beam that can still reliably be measured due to photon shot noise and readout noise in the CCD image sensor. In a typical CCD sensor, the quantum efficiency is between 30% and 60%, the readout noise is in the order of 10's of electrons per pixel, and the full well capacity is 10000's of electrons. This range determines the dynamic range of the CCD together with the bit depth of the digitizer. For the simulation shown in Figure 8, the steps were as follows. The OTR photon distribution was calculated from a smooth electron distribution using a quantum efficiency of 0.5% with an added photon shot noise of \( \sqrt{N} \) of the photon number reaching each image sensor pixel. The photons were then converted into CCD electrons using a CCD quantum efficiency of 30% and a read out noise of 30 e⁻ was added. Losses in the imaging optics were not considered. The image was then created by digitizing the electrons with 8 e⁻/count. The resulting images and projections for OTR1 are shown in Fig. 8 for the 0.1 nC case with 260 µm being twice the nominal beam size and for the 1 nC charge case with the nominal beam size of 130 µm. The low charge case just meets the 5% accuracy criterion for the beam size, whereas the 1 nC case is very accurately measured with only 0.3% error. The errors in beam size from the simulation agree well with the analytical estimation of the error of

\[
\frac{\Delta \sigma_x}{\sigma_x} = \frac{N_{ROI} N_{bb}^3}{4\pi \sqrt{2} N_{roi} \eta \sigma_{cal} \sqrt{\sigma_x \sigma_y}}
\]

(2)

with \( \eta \) as the conversion efficiency from electron beam electrons \( N_i \) into CCD electrons and \( \sigma_{cal} \) is the camera calibration factor (e.g. µm/pixel). \( N_{bb} \) is the size of the bounding box for the beam profile integration in units of the rms beam size and was set to 10 to include wings in the distribution. If the bounding box is sliced vertically into \( N_{slice} \) slices, the beam size error increases by \( \sqrt{N_{slice}} \). The simulation code was benchmarked with good agreement to an actual OTR image taken at the GTF with 60 pC charge, a beam size of 140 µm by 340 µm, a photon yield of 0.15% due to the energy of 32 MeV and a small optical aperture, a read out noise of 10 e⁻, and a pixel calibration of 20 µm. The estimated error in beam size was 5% in this case.
2. Component Specifications

Based on the measurement requirements and the physical constraints outlined in section 1, the following specifications for the components of the beam profile monitors have been set.

2.1. OTR Screen

A metal surface of optical quality will be used to produce optical transition radiation for imaging. It needs to survive the intense electron beam while maintaining its optical quality.

2.1.1. Screen Material

A low Z material of 1 µm thickness is needed to minimize the interaction between foil and electron beam. This both minimizes the beam loss and emittance growth of the electron beam so that it is still usable for downstream diagnostics as well as minimizes the amount of radiation that damages the camera. The two suitable materials are Aluminum and Titanium. Aluminum has a reflectivity...
which is about a factor of two higher and should therefore be selected to obtain the highest OTR yield.

2.1.2. Screen Surface

The requirements for the surface flatness are to reflect an alignment laser beam off the foil and to collect the same amount of TR from everywhere on the foil. As mentioned above, this requires that the surface flatness is better than 50 mrad or 2.7 degrees. The same requirement applies to the actuator alignment reproducibility. In contrast to the OTR, the alignment laser will be a collimated beam at the foil and hence has to be reflected from a surface with optical quality to maintain the laser beam quality for the alignment of the imaging optics. This will require a tensioned foil of 1 µm thickness. The surface flatness shall be at least 3λ.

The heating of the foil from the electron beam and a possible resulting distortion of the foil surface due to much lesser heat conductivity in the foil than in the bulk material is a concern, but has not been studied or taken into consideration.

2.2. Mirrors and Windows

The mirrors placed behind the YAG screens and the in-vacuum mirror for OTRS1 shall be diamond turned aluminum substrate mirrors with a surface quality of λ/4 and a diameter larger than the YAG screen diameter. For the YAG screens also equipped with a Faraday cup, the surface of the cup can serve as the mirror if machined to the same quality. The vacuum window for all beam profile monitors shall have at least λ/4 flatness to maintain the imaging quality and a diameter of at least 35 mm to enable the required acceptance angle of the imaging optics. The diameter for the YAGG1 window shall be at least 75 mm.

2.3. Attenuators

Neutral density filters will be used to attenuate the amount of OTR light to prevent saturation of the CCD image sensor. This also enables the detection of the full light level in contrast to rotating polarizers with a minimum of 50% attenuation. The implementation of 2 different stacked filters with optical densities of 0.5 and 1.0 provides four distinct levels of attenuation from a factor of 1 to a factor of 30. The filters have to be replaced with equal thickness glass flats when the filters are retracted to maintain the optical path length. The attenuation of the YAG fluorescence of the screens in the GTL will be done with rotating polarizers to cover the larger dynamic range required for the 5 pC to 1 nC operation.
2.4. Imaging Optics

Two different designs will be necessary for the YAG and OTR imaging optics. The YAGG1 screen needs a variable magnification by a motorized zoom lens because of two different modes of operation for the gun spectrometer. An achromatic close up lens with at least 70 mm diameter close to the vacuum window is needed to reduce the working distance of the zoom lens. The magnification range shall be at least from 1 to 1/7. The remaining screens will have a single telecentric lens. The whole assembly is shown schematically in Fig. 9 for the OTR and in Fig. 10 for the standard YAG profile monitor.

Figure 9: Sample design of the OTR beam profile monitor showing the arrangement of all of the components.

Figure 10: Sample design of the YAG beam profile monitor.

The minimum numerical aperture for both designs shall be 0.2. The lens diameter shall be at least 40 mm, which is twice the standard YAG and OTR screen diameter of 20 mm. The diameter and avoids vignetting. Additionally, to protect the CCD camera from radiation, the YAG screens shall have a mirror between the vacuum window and the lens to reflect the light by 90 degrees and to avoid a direct line of sight between the camera and the YAG screen.
2.5. **Camera Specifications**

A digital camera will be used for reading out the OTR and YAG image.

2.5.1. **Image Data Rate**

The OTR imager will be used at reduced bunch rate (10 Hz) to minimize the scattered radiation. Accordingly, the minimum image data rate is set at 10 full frames per second. Higher frame rates up to 120 Hz in partial scan mode are desirable to capture beam profiles at the full bunch rate.

2.5.2. **Camera Interface**

The camera will use a standard interface that supports the data transfer rate, such as CameraLink or Gigabit Ethernet.

2.5.3. **Pixel Sizes and Number**

The camera shall be of ½” format to keep the dimensions of the lens system small. The number of pixels shall be at least 1000 in each direction. The pixels shall have square shape and a maximum size of 6 µm.

2.6. **Profile Monitor Alignment**

Since optical transition radiation is produced into a narrow cone centered at the spectral angle with respect to the electron beam, it is necessary to have a good alignment technique for the optics and cameras. This alignment is facilitated by the use of an on-axis alignment laser which is injected into the injector beamline at the cross containing YAG01(FC01), see Figure 2. This laser beam travels the full length of the injector exiting the vacuum at the BXS vacuum chamber through a vacuum view port. At this view port is an alignment target upon which the laser beam is centered using mirrors where it enters the beamline at YAG01. A camera at this exit port whose video is sent to a display near YAG01 allows the operator to perform this alignment. Details of the target and camera are illustrated in Figure 5. Straight through ports are also required on the DL1 vacuum chambers for injection of a laser to align OTR4 and its optics, this is also shown in Figure 5.

2.7. **Camera Calibration and Focusing**

In addition to pre-calibration and alignment of the cameras in a test lab, calibration aids shall be provided to permit in situ calibration of the camera. They consist of suitable pinhole pattern on the OTR screen and remotely controlled illumination. Pinholes in the corners of the minimum field of view area will have minimum impact on the image acquisition. Additional pinholes at the edges of
the line of focus will enable to properly set the imaging optics into focus. The calibration aid for the YAG screens will be a fiducial. Additionally, a beamsplitter can be introduced into the imaging optics to view a calibration target at the same distance as the YAG screen.

2.8. **Camera and Optics Shielding**

The camera shall be shielded against upstream radiation with a suitable thickness of lead where necessary. The camera and imaging optics shall be contained in a protective housing to prevent deterioration of both from dust and other contaminants.

2.9. **Wake Field Shield**

When removed from the beam, the beam profile monitor will be replaced by a wake field shield which maintains the wall current continuity and minimizes wake field effects on the beam.

2.10. **Equipment Protection Interlock**

The design is based on the assumption that, when the OTR screen is inserted and removed from the beam, the electron beam will be turned off by the LCLS machine protection system interlocks to avoid damage due to beam scattering on the OTR profile components.