Design Report for the TRIUMF e-Linac
View Screen beam profile monitors

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1 Summary

This document describes the design considerations of the mechanical components of the View Screen beam profile monitors based on the requirements presented in the next section and design studies performed. The design of this system was the subject of the author’s MSc thesis project and more information can be found in the author’s MSc Thesis [1].

This document is organized into the following sections.

- Section 1: Introduction and Document Structure
- Section 2: Requirements
- Section 3: View Screen Beam Targets
- Section 4: Design of the View Screen
- Section 5: Image Distortion, Calibration and Corrections
- Section 6: Simulation Results
- Section 7: Optics Bench Tests
- Section 8: Conclusion
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2 Requirements

Successful operation of the e-linac requires accurate measurements of the beam properties. The View Screens have been designed to meet a series of requirements, as specified in [2].

The nominal beam size in the different areas of the beam-line are shown in Table 1. The size of the beams may change by up to a factor of 5 times larger and down to 10 times smaller than the nominal sizes during the tuning of the e-linac [3]. The beam transport pipe in all sections of the e-linac are 50 mm in diameter and to ensure that the mounting structure of the target holder will not intercept the beam or its halo, the beam targets for the View Screens have been specified to also be 50 mm in diameter.

In the ELBT, where beam sizes are the largest, the field of view of the camera will cover the entire area of the beam targets. The nominal beam sizes in the higher energy sections of the e-linac are smaller, so even though the target size is specified as the same size in all areas of the e-linac, the field of view is smaller in the EMBT and EHBT sections, covering only 25 mm at the center of the beam targets.
Table 1: Summary of the nominal beam sizes expected in the different areas of the e-linac and the corresponding requirements on the View Screens.

<table>
<thead>
<tr>
<th>Area</th>
<th>Nominal Beam Size, $\sigma$</th>
<th>Screen Size</th>
<th>Field of View</th>
<th>Imaging Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELBT</td>
<td>3 mm</td>
<td>50 mm</td>
<td>50 mm</td>
<td>150 $\mu$m</td>
</tr>
<tr>
<td>EMBT</td>
<td>2 mm</td>
<td>50 mm</td>
<td>25 mm</td>
<td>100 $\mu$m</td>
</tr>
<tr>
<td>EHBT</td>
<td>1 mm</td>
<td>50 mm</td>
<td>25 mm</td>
<td>50 $\mu$m</td>
</tr>
</tbody>
</table>

The requirement on imaging resolution comes from the need to resolve substructure within the beam profile down to a scale of $\sim$5% of the nominal beam size. The key factors affecting the imaging resolution are the pixel resolution and the ability of the imaging optics to focus the light emitted from the beam targets.

The location of the centroid of the beam must be determined relative to the other elements of the beam-line to an absolute uncertainty of 200 $\mu$m and a relative uncertainty of 25 $\mu$m. The required uncertainty in the measurement of the beam size depends on the transverse size of the beam and should be 10% of the nominal beam size, 300 $\mu$m, 200 $\mu$m, or 100 $\mu$m in the ELBT, EMBT, and EHBT respectively. The uncertainty in the measurement depends on both the image resolution, as well as the geometric calibration and the application of correction factors applied to remove artificial distortions in the images.

Beam losses must be kept below 2 W per device by limiting the current or duty factor of the beam when the beam targets are inserted into the beam. At low beam energy, less than a few MeV, the beam targets are completely intercepting and destructive to the beam. The entire beam is stopped within the target, with few electrons scattered out, mostly in the backwards direction. At higher energies, the beam will pass right through the target, losing some energy and undergoing multiple scattering.

Upon exiting the target, the beam must be able to be safely directed towards a beam dump to be safely disposed. The momentum aperture is the maximum deviation from the design momentum that an electron may have such that the focusing and steering elements along the beam-line can contain the particle. The relative momentum aperture of the e-linac is estimated to be 2%.

Any elements of the View Screens that will be inserted into the beam-line have to be vacuum compatible from $10^{-9}$ Torr near the electron gun to $10^{-7}$ Torr in the EHBT. Materials that outgas are not permitted within the vacuum. The beam-line is held under high vacuum to minimize interactions of the beam with residual air molecules that would result in energy losses of the beam and unnecessary radiation.

Due to radiation produced by the e-linac, beam dumps, and target stations,
the View Screens are required to withstand up to 10 mSv per hour of radiation, predominantly X-rays, γ-rays, and neutrons. The camera and lenses are especially susceptible to radiation damage and will be replaced as required, but should last for at least one year to minimize downtime and replacement costs.

Control of the View Screens will be provided through the EPICS software from within the e-linac Control Room. Images will be acquired at rates of up to 10 Hz with the ability to synchronize image acquisition the arrival of beam pulses. Further information on the image acquisition system can be found in a separate document.

3 View Screen Beam Targets

The basic elements of the beam profile monitor are the beam targets, which emit visible light as beam particles pass through them, and an imaging system to acquire images of the emitted light, resulting in a two dimensional image of the beam intensity as a function of position.

There are two main types of beam targets that are used in beam profile monitors. Targets that scintillate as beam particles pass through them (i.e. produce a flash of light when they absorb ionizing radiation) are called scintillation targets. These are generally used for low current measurements as they can produce a relatively high amount of light. For use at higher beam currents, Optical Transition Radiation (OTR) targets can be used. These emit transition radiation in the optical spectrum at the interface between vacuum and target material and the response is generally very linear with respect to particle density. The properties of these two targets types as well as some commonly used target materials will be discussed in this section.

3.1 Scintillation Targets

Scintillation targets, or screens as they are sometimes called, are beam targets whose atoms emit visible radiation when excited by the passage of ionizing beam particles. The light is emitted close to the point where the beam particle passed through the screen, resulting in a pattern of light on the screen corresponding to the density profile of the beam.

There are many types of scintillating materials that are used for View Screen beam targets. A few commonly used materials are Chromox, YAG:Ce, and deposited phosphor screens. Chromox is the trade name for a chromium enhanced aluminum ceramic manufactured by Morgan Technical Ceramics with a composition of 99.5% Al₂O₃ (alumina) and 0.5% Cr₂O₃. There are other manufacturers that supply materials similar to this that are also commonly referred to as Chromox.

Chromox is a ceramic material composed of many small grains, 10 - 15 μm or larger in size. Chromox is mostly opaque, so most of the scintillation light is emitted
from the surface, although some light disperses through the bulk of the material, resulting in a lower limit to the achievable imaging resolution. For a 0.5 mm Chromox screen at 45°, this resolution limit has been reported as approximately 300 µm [4].

The emission spectrum of Chromox is peaked at around 700 nm [5] resulting in a reddish coloured scintillation light. The decay time of the scintillation is given in the range of several milliseconds [6], making it a relatively slow scintillation screen. This property limits the usefulness of Chromox for the e-linac View Screens as the ARIEL electron beam is expected to have important time varying characteristics at the scale of tens of µs which would be washed out with a long scintillation decay time.

YAG:Ce is a cerium doped yttrium aluminum garnet, Y₃Al₅O₁₂. The amount of cerium dopant included varies but is typically on the order of 0.2%. YAG:Ce screens are prepared in one of two ways, either in single-crystalline form or as a thin layer of powder deposited on a substrate, known as a phosphor screen. On a phosphor screen, YAG:Ce is commonly referred to as P46. YAG:Ce is a very fast scintillator, with a decay time of approximately 70 ns, and the emission spectrum is peaked at a wavelength of 550 nm [7].

In crystalline form, YAG:Ce is transparent and scintillation photons are visible from points throughout the thickness of the screen. Therefore if the screen is oriented at an angle with respect to the camera, as is common procedure with View Screens, a broadening of the beam size would be apparent due to the viewing angle as shown in Figure 1. In phosphor screens, the individual grain size determines a lower limit to the resolution, however, grain sizes of less than 10 µm are common.

![Figure 1](image.png)

Figure 1: Artificial broadening of the beam profile image caused by a transparent YAG:Ce screen mounted at 45°.

In some applications an intensity dependent beam enlargement of the imaged
beam size have been reported for YAG:Ce screens with high brilliance electron beams, when compared to other diagnostics equipment, such as wire scanners and OTR screens. This phenomenon has generally been observed for beams with charge densities of $\Sigma > 0.01 \text{ pC}/\mu\text{m}^2$ [8, 9, 10].

For the ARIEL e-linac, the maximum charge density for a 1 mm electron beam at 1 $\mu$A is then $\Sigma_{\text{max}} = 1.6 \times 10^{-8}$ pC/$\mu$m$^2$. This is much less than 0.01 pC/$\mu$m$^2$ and therefore this resolution limit for YAG:Ce screens should not be reached under normal operating conditions.

At high energies, the electrons pass directly though the targets. However, at low energy, such as at 300keV and less, electrons hitting the beam targets do not have enough energy to pass through the entire thickness and stop within the bulk of the target. This can potentially lead to issues if the material is not conductive enough to allow this charge build-up to drain away. A target may fracture due to the internal stress caused by a large internal charges. If the charge arcs to a nearby conductive surface, the arc can burn a permanent mark into the target.

YAG:Ce has a low conductivity which leads to significant damage to the target under these conditions. One way to avoid this issue is by applying a thin conductive coating directly to the front surface of the target. A thin layer of gold, 10-20nm, is almost completely transparent but is conductive enough to drain the charge.

In a Phosphor screen, most of the electrons stop within the substrate material. If it is conductive, such as an aluminum substrate, the charge harmlessly drains off the target.

The optical properties of scintillating materials such as the light yield are affected by the temperature of the beam target. This temperature dependence causes a non-linearity in light yield for high beam currents. The effect of this distortion will generally cause the width of beam to appear wider as viewed by the View Screen. A correction may be applied to attempt to correct for the decrease in light yield with temperature, but would be heavily dependent on the temperature distribution of the beam targets which cannot be measured directly.

The light yield of YAG:Ce decreases with temperature by approximately 0.1% per $^\circ$C up to $\sim 200^\circ$C as shown in Figure 10. The quenching temperature of YAG:Ce luminescence is around 430$^\circ$C [11].

### 3.2 Optical Transition Radiation

When a charged particle crosses the the boundary between two materials with different relative permittivities, electromagnetic radiation called transition radiation is emitted. This radiation has a broad spectrum, covering the entire visible regime, hence the name Optical Transition Radiation (OTR).

As a charged particle approaches the boundary between two media, the moving fields of the charged particle induce a time varying polarization at the interface.
The radiated fields from this polarization combine coherently to form the emission of transition radiation [12, 13]. The process is a surface phenomenon with the radiation being emitted within the first 100 Å of the surface [14].

When a charged particle crosses a thin foil in a vacuum, it crosses two boundaries. As it passes the first boundary from vacuum to foil material, optical transition radiation is emitted in the direction of specular reflection and is referred to as the \textit{backward radiation}. As the charged particle exits the other side of the foil, crossing from foil material to vacuum, the \textit{forward radiation} is emitted in the direction of the exiting particle’s velocity. The optical transition radiation is peaked at an angle, $\theta_{\text{peak}}$, as measured from either the reflection axis for backward radiation or the particle’s velocity for forward radiation, as shown in Figure 2.

![Figure 2: The Optical Transition Radiation emitted as an electron beam passes through a beam diagnostics foil](image)

The OTR emission distribution is dependent on the energy of the charged particle, the relative permittivity of the two materials, $\epsilon_1$ and $\epsilon_2$, and the orientation of the surface boundary, $\psi$, defined as the angle between the incoming velocity vector and the normal to the surface interface.

For low energy electrons, $E < 50\text{ MeV}$, the OTR emission distribution has been derived from Maxwell’s Equations [15]. The expression obtained here is for the backward radiation from electrons crossing the boundary between two semi-infinite planes. It is possible to apply this result to a foil with finite dimensions provided that the conductivity is sufficiently high and because the emission takes place primarily within the first 100 Å of material, which is much less than the thickness of the foils.

Defining $\kappa$ as the wave vector of the emitted radiation, then the two angles that describe the direction of the emission are $\theta$, the angle between the normal to the surface, $\hat{n}$, and $\kappa$, and $\phi$, the angle between the projections of the velocity vector and the wave vector $\kappa$ on the interface. A summary of these variables is illustrated in Figure 3.
The expression for the backward OTR emission distribution is then given in terms of the horizontal and vertical polarization components:

\[
\frac{d^2I_\parallel}{d\Omega d\omega} = \frac{e^2\sqrt{\epsilon_1}}{\pi^2 c} \frac{1}{4\pi\epsilon_0} \frac{\beta^2 \cos^2 \psi \cos^2 \theta |\epsilon_2 - \epsilon_1|^2}{\left[ \left(1 - \sqrt{\epsilon_1} \beta \sin \theta \cos \phi \sin \psi \right)^2 - \epsilon_1 \beta^2 \cos^2 \theta \cos^2 \psi \right] \sin^2 \theta} \frac{1}{\left(1 - \sqrt{\epsilon_1} \beta \sin \theta \cos \phi \sin \psi + \sqrt{\epsilon_2 - \epsilon_1 \sin^2 \theta \beta \cos \psi - \epsilon_1 \beta^2 \cos^2 \psi} \right) - \ldots}
\]

\[
\frac{d^2I_\perp}{d\Omega d\omega} = \frac{e^2\sqrt{\epsilon_1}}{\pi^2 c} \frac{1}{4\pi\epsilon_0} \frac{\beta^6 \cos^4 \psi \sin^2 \psi \sin^2 \phi \cos^2 \theta |\epsilon_2 - \epsilon_1|^2}{\left[ \left(1 - \sqrt{\epsilon_1} \beta \sin \theta \cos \phi \sin \psi \right)^2 - \epsilon_1 \beta^2 \cos^2 \theta \cos^2 \psi \right] \sin^2 \theta} \frac{1}{\left(1 - \sqrt{\epsilon_1} \beta \sin \theta \cos \phi \sin \psi + \sqrt{\epsilon_2 - \epsilon_1 \sin^2 \theta \beta \cos \psi} \right) \left(\sqrt{\epsilon_2 - \epsilon_1 \sin^2 \theta + \cos \theta}\right)^2}
\]

The backward OTR emission distribution for 10 MeV electrons crossing from vacuum, \(\epsilon_1 = 1\), to pyrolytic graphite, \(\epsilon_2 = 13.5\), at an angle of 45° is shown in Figure 4, where both the distance from the emission point and the surface color indicate the intensity of the emitted radiation. The electron beam is indicated by the vertical red line and the blue line represents the direction of the reflection axis.

The emission of OTR light from Pyrolytic Graphite is peaked in two lobes, on either side of the reflection axis at \(\phi = \pm \pi/2\). For highly reflective materials, the two lobes join together, forming a cone of emission about the reflection axis. The direction of maximal emission is located at an angle \(\theta_{\text{peak}}\) from the reflection axis. This angle is related to the Lorentz factor, \(\gamma\) by \(\theta_{\text{peak}} \approx 1/\gamma\). At 10 MeV \(\theta_{\text{peak}}\) is approximately 2.8°, while at 50 MeV the radiation is peaked at \(\sim 0.6°\).
The OTR emission distribution depends strongly on the properties of the foil material, mainly the relative permittivity. For the backward radiation, the intensity of the emitted OTR light can be shown, through the expressions (1) and (2) with $\beta \sim 1$ and $\epsilon_1 \sim 1$, to be approximately proportional to the reflectivity of the material

$$I \propto \left| \frac{\sqrt{\epsilon_2} - 1}{\sqrt{\epsilon_2} + 1} \right|^2 \quad (2)$$

Other important properties of the foil material are the melting temperature and thermal conductivity, which are important when determining the maximum current the foils can withstand without damage, and the atomic number of the element, which reflects the degree of energy loss and scattering of the beam as it passes through the foil. These properties are summarized in Table 2 for some common OTR foil materials: aluminum, titanium, and pyrolytic graphite [16, 17, 18].

Aluminum has the highest OTR light output of the three materials presented, however its low melting temperature make it an unsuitable choice for the high average current of the e-linac. Titanium has a much higher melting point than Aluminum and a fairly high light output, but has a high atomic number and therefore contributes to significantly higher beam losses than either Aluminum or Pyrolytic Graphite. Although Pyrolytic Graphite has a low reflectivity, its high melting temperature and thermal conductivity make it robust for use at relatively high beam currents, and with it’s low atomic number causes less interference to the passing electron beam.
Table 2: Material properties of the candidate OTR foil materials.

<table>
<thead>
<tr>
<th>Atomic Number, $Z$</th>
<th>Aluminum</th>
<th>Titanium</th>
<th>Pyrolytic Graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_R$</td>
<td>-42$+12i$</td>
<td>-7$+7i$</td>
<td>13.5</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>$\sim$ 90%</td>
<td>$\sim$ 65%</td>
<td>$\sim$ 35%</td>
</tr>
<tr>
<td>Melting Temperature</td>
<td>660$^\circ$</td>
<td>1670$^\circ$</td>
<td>$&gt;2500^\circ$</td>
</tr>
<tr>
<td>Thermal Conductivity (300 K)</td>
<td>230 W/m-K</td>
<td>220 W/m-K</td>
<td>345 W/m-K</td>
</tr>
</tbody>
</table>

4 Design of the View Screens

The following is a description of the main components of the View Screen system. This includes the beam targets, target holders and actuator, imaging optics, calibration light sources, and the mechanical support and shielding.

4.1 Targets

Two types of beam targets will be used for the View Screens to provide usage over a wide range of beam currents. Scintillation targets will be used for low currents as these have a higher light output than OTR targets, but must be thicker and will contribute to higher beam losses and scattering. OTR targets can be used at beam energies of 10 to 50 MeV. Additionally, a calibration target will also be installed on each device, to perform geometric calibration and distortion correction.

The beam targets will be circular with a diameter of 50 mm, approximately the same size as the beam transport tube. This is to ensure that the electrons pass through the beam targets, rather than striking the target holder, causing increased beam losses.

The scintillation targets will be P46 phosphor screens. Scintillation screens will provide coverage up to several $\mu$A of average beam current. The targets will be mounted at 45$^\circ$ to the beam to be in the same plane as the OTR and calibration targets.

The OTR beam targets will be constructed from 10 $\mu$m (or less) pyrolytic graphite foil or a similar deposited carbon foil produced by AAPS at TRIUMF. The OTR targets will be mounted at 45$^\circ$ to the beam such that the reflection axis, and therefore the peak of the emitted backwards radiation, will be oriented at 90$^\circ$ to the beam, and directed out the view-port window and towards the optical imaging components.

The OTR targets will only be included in the diagnostics stations with beam energies of 10-50 MeV. Below this energy, the intensity of the OTR radiation is too low and the emission distribution too spread out to provide adequate levels of light.
to perform imaging of the beam profile. The field of view will cover only the central 25 mm of the 50 mm diameter OTR foils.

The calibration target is an aluminum sheet with holes located on a grid pattern. This target will only be used when the beam is off as it would damage the target and create unacceptable beam losses. The pattern on the target will be illuminated by either the front or back light. By imaging this target, the image coordinates can be calibrated to the measured locations of the corresponding target markings.

In addition to the grid pattern, there will be an extra hole on the calibration targets located at a non-grid location that can be used to confirm the orientation of the target image. This off-grid hole is positioned such that it cannot be misinterpreted through any rotations or mirror transformations that may occur in the image acquisition or post-processing. Figure 5 shows the layout of the calibration target holes and their locations with the target center as the origin.

![Diagram showing calibration target layout](image)

(a) ELBT calibration target pattern, covering the entire 50 mm field of view. (b) EMBT / EHBT calibration target pattern, covering the reduced 25 mm field of view.

Figure 5: The layout and locations of the calibration markings on the calibration target.

In the ELBT, the calibration target will be the same size and shape as the beam targets, 50 mm in diameter, to cover the entire field of view. The holes will be 0.8 mm in diameter and spaced 7 mm apart. In the EMBT and EHBT, the field of view covers approximately a 25 mm by 25 mm area of the beam targets, and the calibration target need only cover this reduced area. The holes will be slightly smaller at 0.5 mm in diameter and spaced at 5 mm apart.

As the calibration target will also be mounted at 45°, the thickness of the material will partially block the opening on one side, as is shown in Figure 6. This will cause a shift in the location of the centroid of the opening by a distance of \( t/\sqrt{8} \), where \( t \) is the thickness of the material. The specified hole thickness is 0.15 mm, which results
in a shift of the centroid of 53 µm in the horizontal position of the hole locations. Without adjusting the positions of the target markings by this correction factor, the reconstructed beam position would be biased in one direction.

![Figure 6](image_url)

Figure 6: The view of one of the calibration target markings, oriented at 45°, as seen by the camera. The centroid of the opening is shifted to the left by a distance of $t/\sqrt{8}$ due to the thickness of the material blocking a portion of the hole.

Also located on the calibration target is a survey marker scribed onto the aluminum surface. Before installation onto the target holder, the locations of each of the target markings will be measured in reference to this survey marker. Upon installation of the target holder onto the actuator assembly, the survey marker on the calibration target will be measured in reference to another survey marker on the outside of the actuator housing. This marker’s position will be determined after installation onto the diagnostics box, providing a means of translating positions determined by the View Screen to a coordinate system referenced to the rest of the beam-line.

### 4.2 Target Holder and Actuator

The targets are mounted onto a target holder which is attached to the target actuator. The actuator moves the entire assembly in and out to insert the various targets into place in the beam-line, and retracts the holder out of the beam-line when not in use.

The targets are all mounted on the holder in the same orientation, at 45° to the beam axis, such that when in place, each target will be in focus across the entire field of view of the imaging acquisition system. This is also required so that the geometric calibration is consistent among targets.

In the ELBT section of the beam-line, there is only need for the scintillation and calibration targets as the beam energy is too low to use OTR. The calibration target
here is the same size as the scintillation target as the field of view in this section covers the entire 50 mm target.

At 10 MeV view screen locations, all three targets: OTR, scintillation, and calibration; will be employed to offer a greater dynamic range of operating currents. For energies of 20 MeV and greater, generally only the OTR and calibrion targets will be employed as there is significant overlap of the operating currents of the scintillation and OTR targets.

Since the image calibration need only be performed periodically, the calibration target will be located at the top of the target holder to reduce the travel distance of the actuator to extend the lifetime of the mechanical components of the actuator. In locations that include an OTR target, it will be located in the middle position to place it closer to the top of the holder to improve thermal conduction.

The beam targets will each have a clearance hole through the target holder in the direction of the beam axis to allow the beam to pass through without hitting the holder. Because the targets are mounted at 45°, the clearance hole is elliptical in shape relative to the beam direction with dimensions 34 mm by 48 mm. The calibration target also has a clearance hole which is oriented 90° to the beam to be parallel to the optics axis to allow light from the back-light to shine through the target markings.

In addition to holding the targets in place, the target holder must also dissipate the heat deposited in the targets from the electron beam. Since the beam profile monitors may only contribute up to 2 W of total beam losses of the electron beam, the amount of thermal energy energy gained by the beam targets will always be less than this. Therefore, the target holder will be required to dissipate no greater than 2 W of thermal power. This is to be achieved through passive cooling through the copper actuator rod to which the target holder attaches to. If the thermal load is increased, a water cooling option is available by pumping cold water through the hollow copper rod to increase thermal conduction.

Since the targets will be in vacuum, heat dissipation through convection is non-existent and radiative thermal cooling is minimal. Good thermal contact between the targets and holder is therefore imperative as thermal conduction down the target holder is the only significant means of removing heat in the targets.

The YAG:Ce scintillation targets and Phosphor screens are rigid free-standing discs. The target will be held in place on the target holder by a retaining ring, fastened over the edge of the disc, and held by 8 fasteners. By tightening the ring in a large number of places, a higher degree of thermal contact is ensured. In addition, this provides electrical contact allowing charge build-up to be harmlessly drained away at low beam energies.

Design efforts for mounting the thin OTR foils are ongoing. It is important to ensure good thermal and electrical contact and that the foil be held flat as to not disturb the OTR emission distribution.
Since no beam will pass through the calibration target, no special mounting is required. The calibration target is simply a flat sheet of aluminum and can therefore be attached with fasteners along the edge of the target.

The actuator will move the target holder at a rate of $\sim 50\, \text{mm/s}$ and will take approximately 3 to 4 s to completely insert or retract. The actuator has been designed so that the stepper motor may be removed to allow the target holder to be retracted by hand in case of failure without breaking the vacuum inside the beam-line.

The requirement on the absolute uncertainty of the beam center position measured with the beam profile monitor is 0.2 mm. This requires that the positioning accuracy of the actuator when inserting the calibration target into the beam-line to be less than this. For this reason, the actuator includes a linear potentiometer to provide positional feedback with a resolution of $< 0.1 \, \text{mm}$ and limit switches at the beginning and end of the travel.

### 4.3 Imaging Optics

The light emitted by the beam targets is collected and focused onto a CCD sensor for image capture through the optical imaging elements located within the camera box, as shown in Figure 7. The light emitted from the beam targets passes through the view port window of the diagnostics cross (not shown), through the light tube shown in yellow in the figure, and into the camera box. Inside the camera box, the light is reflected off a mirror, through an iris, and is focused by the lenses onto the camera’s CCD sensor.

The nominal RMS beam-size in the ELBT is 3 mm and the required field of view is 50 mm wide such that the entire beam target is in view. In the EMBT and EHBT the size of the beam is smaller and even though the size of the targets is the same as the ELBT, the field of view need only cover 25 mm at the center of the target. The two different field of views require different optics configurations to provide the correct magnification of the image.

Since the targets are mounted at 45° to the beam-line, the circular beam targets appear elliptical in shape when viewed from the location of the camera. The size of the camera’s CCD sensor, as discussed in the next section, is 6.4 mm $\times$ 4.8 mm. To fit the entire image of the 50 mm target onto the camera’s CCD will require demagnification by a factor of $M_{50} = 0.128$. In the EMBT and EHBT, the field of view is half the size, 25 mm, and requires a less demanding demagnification of $M_{25} = 0.256$.

Lenses are used to collect as much of the light emitted from the beam targets as possible and focus it onto the CCD sensor of the camera. For this reason, it is advantageous for the lenses to have a large diameter and to be as close to the beam targets as possible to collect the most light. However, the sensitivity of the glass lenses to radiation and the selection of commercially available lenses must also be
4.3.1 Mirror

A mirror, mounted at 45° to the optics axis, is used to reflect the visible light emitted from the beam targets out of the direct line-of-sight of the beam-line. This is done so that the radiation sensitive optical elements, the lenses and camera, can be protected from the damaging radiation emanating from the beam-line behind lead and polyethylene shielding. The mirror is a first surface polished aluminum mirror on a glass substrate. The glass substrate will darken over time from radiation exposure, however this will not affect the performance of the mirror as the radiation hard aluminum is mounted on the front facing surface.

The mirror is mounted on a two-axis adjustable mirror mount attached to the
camera box. The mount has two adjustment knobs to adjust the mirror angle in two dimensions for optical alignment to center the image on the CCD sensor.

### 4.3.2 Lenses

The light is focused through two achromatic doublet lenses. These are lenses constructed of two layers of different types of optical glass which have been designed to minimize on-axis spherical and chromatic aberrations. Spherical aberrations are the errors in focusing caused by lenses being constructed with spherical surfaces, rather than the ideal parabolic shape. Lenses are made this way to reduce manufacturing costs, although it decreases the performance of the lenses. Chromatic aberrations are due to the dependence of the index of refraction on the wavelength of light, causing light of different colors to be focused to different locations. By pairing two surfaces of different materials together, this color separation is minimized, and light across the visible regime is focused in approximately the same way.

<table>
<thead>
<tr>
<th>Lens</th>
<th>Composition</th>
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</thead>
</table>
| ELBT   | 300 mm FL N-BaK4 Barium Crown glass  
         75 mm FL N-BaF10 Barium Flint glass  
         N-SF10 Dense Flint glass          |
| EMBT / EHBT | 500 mm FL N-BK7 Borosilicate (Crown) glass  
                N-SF5 Dense Flint glass         
                150 mm FL N-BaK4 Barium Crown glass  
                N-SF10 Dense Flint Glass       |

Table 3: The types of optical glass within the achromatic lenses used in the imaging optics.

Within the different lenses employed in this design, there are several different types of optical glass, each containing slightly different components. The glass types are given a number and letter designation based on their chemical makeup as listed in Table 3. The lenses also have an anti-reflection MgF$_2$ coating. Some of these materials, such as N-BK7 due to its boron content, will darken over time with radiation exposure making it important for the lenses to be shielded behind lead and polyethylene to extend this lifetime.

The lenses are 50 mm in diameter, although the use of an iris will limit the illuminated area as will be discussed shortly. The pair of lenses are held in place within a holding tube by threaded retaining rings which are tightened up against
the lenses. In the ELBT optics, a 300 mm focal length and 75 mm focal length lens are used, and in the EMBT and EHBT, 500 mm and 150 mm focal length lenses are used to provide the proper focusing and image magnification. The placement of these lenses is discussed in Section 4.4.

### 4.3.3 Iris

Before entering the lenses, the light must first pass through an iris. The iris is used to control the area through which the light passes to minimize spherical aberrations, and the amount of light collected and to control image intensity. When wide open, the iris aperture has a maximum diameter of 41 mm and can close down to a 1.2 mm diameter, however it is not expected that such a small iris diameter would ever be required.

With the iris wide open, a large amount of light would be collected, resulting in a brighter image. However, using a large fraction of the lenses increases spherical aberrations in the focused image, decreasing the imaging resolution. Since the lenses are spherical lenses, instead of the ideal parabolic shape, the farther from the center of the lens that the light hits, the larger the focusing error. This is most significant in the ELBT optics configuration as it requires the most extreme focusing.

When the iris diameter is closed down, the imaging resolution is increased at the expense of collecting less light. The amount of light allowed to pass through the iris decreases approximately with the square of the iris diameter. By decreasing the iris diameter by half, the image intensity is decreased to approximately one fourth. The image intensity may also be adjusted through the exposure time of the camera.

The iris is mounted directly in front of the lenses and is attached to the lens holder as shown in Figure 7. The iris diameter is controlled remotely with the stepper motor.

### 4.3.4 Camera

A CCD camera, the Allied Vision Technologies (AVT) Manta model G-046B, is used to acquire the images, the specifications of which are listed in Table 4 [19, 20]. The advantages of CCD cameras are that they are generally much more sensitive than other imaging technologies such as Charge Insertion Device (CID) cameras, and are relatively cheap. Camera cost is an important consideration as there will be approximately 14 View Screens required, some with cameras that will require periodic replacement. CCD cameras are also generally simpler to use and to readout images as they do not require Frame Grabber hardware and can communicate directly with a computer through Ethernet or FireWire connections. Unfortunately, CCD sensors are more sensitive to radiation damage, and require local radiation shielding to extend camera life.
### Feature Specification

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD sensor</td>
<td>Sony ICX 415</td>
</tr>
<tr>
<td>Resolution</td>
<td>$780 \times 580$ pixels</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>$8.3 \times 8.3 , \mu$m</td>
</tr>
<tr>
<td>CCD Size</td>
<td>$6.4 \times 4.8 , \text{mm (1/2&quot; sensor format)}$</td>
</tr>
<tr>
<td>Full Well Capacity</td>
<td>15 000 electrons</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>$26 , \mu$s - 60 s</td>
</tr>
<tr>
<td>Maximum Frame Rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Trigger</td>
<td>External or Software</td>
</tr>
<tr>
<td>Camera Interface</td>
<td>Gigabit Ethernet (GigE Vision)</td>
</tr>
<tr>
<td>Maximum Power Input</td>
<td>3.6 W</td>
</tr>
</tbody>
</table>

**Table 4:** AVT Manta, G-046 camera specifications.

The camera is capable of receiving image acquisition triggers either through software commands or through external triggers. External triggering allows for synchronization of image acquisition with the beam pulses. This can be very useful in low duty factor imaging or to avoid imaging the transient response of a beam pulse. The external trigger input accepts TTL logic signals, and can be accessed from either of two input pins located on the camera’s 12-pin Input/Output connector.

Output signals from the camera may be used to indicate performance of different processes within the camera [19]. These signals may provide useful information in diagnosing faulty cameras and can also be accessed through the camera’s Input/Output connector.

The CCD cameras are expected to undergo degradation over time as radiation effects cause damage to the camera’s CCD sensor and electronics. The main effect of radiation damage is expected to cause changes in the gain of the individual pixels and increase dark currents in the sensor. This will decrease the well capacity and the signal to noise ratio of the camera. The cameras are meant to be an expendable item, to be replaced when degradation of image quality demands it, but should last for at least one year of usage.

Focusing of the cameras is to be done manually during their installation. After all the elements are fixed in place and the mirror orientation adjusted to center the image onto the camera’s CCD sensor, the camera can then be focused. With the calibration target in place and the camera connected to a computer within view of the person performing the focusing, the focusing knob is rotated, moving the camera back and forth, until the size of the calibration target markings are clearest and smallest across the entire field of view. The camera is then locked into this position with a set screw to hold the camera rigidly in place.
4.4 Optics Layout

The different field of view and image resolutions required in the ELBT and EMBT/EHBT are achieved through different optics configurations. This involves the use of different focal length lenses and different spacings between the lenses and camera. The selection and positioning of the lenses was optimized through the use of a ray tracing simulation, Section 6.3, to maximize both light collection and resolution.

The positioning of the optical elements are defined by three distances, $d_1$ refers to the separation between the center of the beam target and the first surface of the first lens that the light reaches. $d_2$ is the spacing between the front face of the first lens to the front face of the second lens, and $d_3$ is distance from the front face of the second lens to the center of the camera’s CCD sensor. These values are given in Table 5 along with the lens focal lengths (FL) for both optics layouts.

<table>
<thead>
<tr>
<th>First Lens</th>
<th>Second Lens</th>
<th>$d_1$, mm</th>
<th>$d_2$, mm</th>
<th>$d_3$, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELBT</td>
<td>300 mm FL</td>
<td>75 mm FL</td>
<td>534</td>
<td>20</td>
</tr>
<tr>
<td>EMBT / EHBT</td>
<td>500 mm FL</td>
<td>150 mm FL</td>
<td>558</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5: Spacing of the lenses and camera in the two optics configurations.

In order for the image to be in focus across the entire field of view, the camera is mounted at an angle to offset the $45^\circ$ angle of the beam targets, which results in one side of the targets being located closer to the imaging optics than the opposite side. Light emitted from points closer to the lenses will be focused at shorter distances than light emitted from points which are further from the lenses. The image plane is therefore rotated with respect to the imaging optics, at an angle referred to as the *Scheimflug angle*, Figure 8. For the ELBT optics, this angle is $7.0^\circ$ as measured from the vertical orientation, and in the EMBT and EHBT View Screens, $14.5^\circ$.

4.5 Calibration Light Source

Illumination for the calibration targets will be provided from a light source located either in front of or behind the targets. Back illumination would involve light emitted from a port in the diagnostics cross directly opposite the camera. The light would shine through the holes in the calibration target to be imaged by the imaging optics. By retracting the target holder completely, the light source would become visible to the camera, provided a method for diagnosing radiation damaged pixels, discussed further in Section 5.1.

A front light design would shine light from in front of the target holder, onto the front face of the calibration target. Light would reflect off the calibration target to
be imaged by the imaging optics. The calibration markings would be visible as dark spots on the image where the light was not reflected at the locations of the holes on the calibration target. A front light also provides the ability to view the beam target surfaces or other devices inserted in the diagnostics boxes with the camera. The back lights may also be used for this purpose by using long exposure images and imaging the light that has reflected around the diagnostics boxes or along the beam pipe.

In the ELBT, where space in the diagnostics cross is limited due to the large number of diagnostics devices required, the port opposite the camera will not always be available for use as a back light. In these cases, the front light will be used. Radiation damage is expected to be low here, reducing the need for a back-light. At higher energies, there is less competition for ports in the diagnostics cross and the back-light solution should always be available.

4.6 Support Structure and Shielding

The camera box shields the camera from outside light and keeps the optical surfaces free of dust. The camera, lenses, and mirror are fastened to the inside of the box, providing the fixed alignment and spacing of the elements as described in the previous sections. The lens holder and camera are mounted onto the front inside face of the box with the central vertical optics axis located 50 mm from the wall.

The light enters the camera box through the light tube which bridges the gap between the box and the view-port in the diagnostics cross. The light tube has an inside diameter 52.5 mm such that it will not interfere with the light that will enter the imaging optics and is constructed out of black anodized aluminum to minimize internal reflections along the tube. The light tube is also constructed such that it blocks out any outside light from interfering with imaging.

Power and data connections for the camera and iris control are fed into the
camera box through bulkhead feedthrough connectors located on the top of the box. An ethernet port on the outside of the box provides access to the camera data. Four BNC connections are available for the camera trigger inputs and diagnostics outputs. Power for the camera and for the iris control are fed into the box through a single multi-pin circular connector. There are several empty pins available on this connector for future unforeseen usage.

In the ELBT beam-line, the diagnostics box is mounted on a support frame which rolls on a rails to assist with beam-line assembly and alignment. The View Screen camera box is mounted directly to the diagnostics box so that it moves along with it, eliminating the need to refocus the camera if the diagnostics box is moved.

Due to the lower levels of radiation in the ELBT, little shielding is required to protect the camera and lenses. Approximately 16 kg of lead will be mounted around the faces of camera box. The light weight of the camera box allows the box to be supported solely by the light tube, as shown in Figure 9.

Figure 9: The ELBT camera box supported entirely by the light tube. An adapter plate on the diagnostics box viewport allows for the removal and reinstallation of the camera box to the same position and alignment.

The camera box and light tube will be removed during the bake-out procedure to avoid damage. This is the process where the entire beam-line, while under vacuum, is heated to a temperature of ∼ 200°C to remove absorbed gases (i.e. H₂O, O₂, N₂, CO₂, etc) from the surfaces of the vacuum envelope. The accelerator beam-line must be baked-out whenever it has been brought up to atmospheric pressure and returned to vacuum. The light tube mounts over the view-port window with an adjustable adapter plate that allows for alignment of the box. There is an additional set of
screws and dowel pins that allow the camera box to be removed during bake-out without affecting the mounting position and camera focus when re-installed.

In the EMBT and EHBT, space is not so constrained and the beam-line will not be undergoing frequent repositioning. This allows the View Screen to be mounted directly to the floor, providing the support required to hold up the weight of the several centimeters of lead and polyethylene shielding required.

The outside faces of the camera boxes are lined with lead and polyethylene panels to protect the lenses and camera from the damaging radiation emitted from the beam-line and beam dumps. Polyethylene is an efficient neutron absorber, while the lead is used to stop photons and electrons. Additional shielding may be incorporated as required based on localized radiation measurements.

5 Image Distortion, Calibration and Corrections

Upon acquisition, images must go through a series of image calibration and correction procedures. The purpose of these procedures are to:

- Perform a pixel-by-pixel intensity calibration to correct for pixel to pixel variability and changes due to radiation damage,
- Convert image coordinates to positional coordinates in the plane transverse to the beam,
- Correct for geometric distortions in the images due to the 45° orientation of the beam targets and other optical effects,
- For scintillation targets operating under high beam currents, adjust the pixel intensity to account for temperature dependent light yield, and
- Adjust pixel intensity to account for the position dependency of the optics to collect light emitted from different locations on the beam targets.

The following is a brief description of each issue. A detailed account of how the view screen control system performs the image calibrations and corrections will be described in a separate document.

5.1 Radiation Damage Calibration

The main effect of the radiation damage on the cameras is to decrease the gain and signal to noise ratio of individual pixels. By acquiring images of a known light distribution, the damage can be characterized and partially corrected for.
With the target holder completely retracted and the back-light on, the camera will see an unobstructed view of the light distribution of the back-light. Images will be acquired of the light source, which can then be compared to a reference image acquired when the camera was first installed, before it has been affected by the radiation. The light source was designed to be as uniform as possible but still exhibits a difference in intensity of several percent across the field of view.

Images should be taken at several light intensities to fully characterize pixel damage. Pixels with large deviations from the reference images can be adjusted in future images to correct for pixel damage. Analyzing a series of images acquired at the same intensity will provide a measure of the signal to noise ratio for individual pixels.

5.2 Geometric Calibration

A geometric calibration performs two functions. Firstly, it translates image coordinates into their corresponding positional coordinates in transverse beam space, and secondly, it corrects geometric distortions caused by the viewing angle and imaging optics.

As acquired from the camera, raw images will have a slight geometric distortion across the field of view. Since the targets are placed at a 45° angle to the beam-line, one edge of the target will be closer to the lenses and camera than the other. The camera is mounted on an angle so that the entire image is in focus, however this still causes a slight difference in the magnification in one side of the image compared to the other. The effect of this is that the image will appear slightly more compressed on one side.

By acquiring an image of the calibration target, lit either from the front or the back, the locations of the target markings can be used to convert the image to corrected positional coordinates.

5.3 Thermal-Dependant Intensity Correction

The decrease in light yield of the scintillation targets with temperature may be partially corrected for by applying an appropriate correction map. Through the use of simulations to model the deposition of energy within the scintillating targets and the resulting temperature rise, a theoretical correction map may be determined to adjust the intensity appropriately. These simulations are described in more detail in the following chapter.

The accuracy of such a correction factor depends strongly on the relevancy of the corresponding simulation studies and the temperature dependence of the light yield of YAG:Ce, as reported in [11] and shown in Figure 10.
It is desirable to keep the applied correction factor minimal by operating under the lowest beam currents possible. At beam currents under 5 µA, the 0.5 mm thick ELBT YAG:Ce targets will stay below 100°C for nominal beam sizes.

5.4 Light Collection Efficiency Calibration

The amount of light collected by the imaging optics, referred to here as the light collection efficiency, differs for light emitted from different locations across the beam targets, causing some areas of the targets to appear artificially brighter than others. This effect is present for both the isotropic emission distribution of the scintillation screens, where light is emitted in all directions uniformly, and the emission of OTR light, although the effect is much more apparent for OTR emission.

The optics system covers a slightly larger solid angle for points on the closer edge of the target than for the farther points. For isotropic emission, this results in a maximum difference of ~12% or ~6% in the light collection efficiency across the field of view in the ELBT optics and EMBT/EHBT optics respectively, as shown in Figure 11. Without calibrating the image to correct for this difference, would cause a 24 µm bias in beam center location for a nominal beam size in the ELBT, and a 10 µm bias error in the EMBT/EHBT for a 2 mm beam.

A correction map is created for the light collection efficiency for the isotropic emission distribution by calculating the solid angle subtended by the iris aperture as a function of target position and iris diameter.

The light emitted from the OTR beam targets is emitted with an angular distribution described by Equations 1 and 2, and shown in Figure 4. The light is directed in two lobes on either side of the reflection axis of the beam target and depending
on the location of the emission of light from the OTR target, varying amounts of light will be collected by the optics.

A correction map can be calculated from the theoretical OTR emission distribution to correct for the differing light collection efficiencies across the OTR target. The collection efficiency is shown for 10 MeV OTR light across the foil in the \( x \) and \( y \) directions in Figure 12. For 30 and 50 MeV OTR emission, the maximal light collection is achieved at the center of the target, as the light is more sharply peaked towards the reflection axis.

![Figure 11](image1.png)

(a) ELBT optics  
(b) EHBT optics

Figure 11: The light collection efficiency for points across the scintillation beam targets in the \( x \) and \( y \) axes.

When imaging the OTR light distribution, it is most desirable to operate with the optics aperture as wide as possible to decrease the dependency on the applied correction factor. From Figure 12, for 10 MeV OTR emission with the iris opened to 41 mm, there is an approximately 25% difference in intensity of the light collected from the center of the foil to light from the edge of the field of view. With the iris closed to 30 mm, this difference increases to approximately 75%.

Applying a correction map also requires a tight angular tolerance on the mounting angle of the beam targets. If the angle used to generate the correction map is not the same as the angle the OTR target is actually mounted at, an error will be introduced, biasing the image to one side or the other.

The error on the computed beam center with the beam target mounting angle varied from 44.7° to 46° is shown in Figure 13 for 10 MeV and 50 MeV OTR distributions and a 2 mm Gaussian beam. With the iris aperture at 41 mm, the tolerance...
Figure 12: The light collection efficiency for points across the OTR beam target in the $x$ and $y$ axes, with a 41 mm iris aperture (top), 30 mm iris (middle), and 15 mm iris (bottom).

on mounting angle is quite loose, with the error on the reconstructed beam position approaching the 0.2 mm requirement on absolute uncertainty at approximately 0.7° offset for 50 MeV OTR and much later at 10 MeV. With a small iris diameter the tolerance is much tighter, with the error in the beam center location reaching 0.2 mm with only a 0.1° offset for 10 MeV OTR, or 0.2° at 50 MeV. This effect is stronger for wider beams that cover a larger area of the foils.

The theoretical OTR emission distribution depends strongly on the properties of the foil material, such as the relative permittivity. Since the correction maps are calculated based on the theoretical distribution, it is beneficial to verify the accuracy of the calculated correction factor. Providing that the beam spot characteristics are sufficiently stable, the profile can be imaged with varying iris diameters, comparing the resulting images to simulated images produced from the theoretical OTR distribution. Provided that the parameters of the theoretical OTR distribution are correct, the measured beam properties should be reproducible with any iris diameter.
Figure 13: The errors incurred from the OTR light collection calibration with the mounting angle offset from 45° for a 2 mm Gaussian beam.

6 Results of Simulation Studies

Simulation studies have been performed to study potential materials for scintillation and OTR beam targets. A GEANT simulation was used to study the energy losses and scattering of the beam and a COMSOL thermal simulation was used to look at the thermal response of the beam targets to the deposited energy. An optics simulation was also developed to aid in the design of the imaging optics through the selection and placement of optical elements.

This section describes the results of these studies, of which the View Screen system described in the previous sections has been designed by. These simulation studies also provide the operational range of the different beam targets and the visibility of the beam profiles with the View Screen under different operating conditions.
6.1 GEANT Simulations of the Beam Targets

A GEANT4 simulation was written to study the energy losses occurring for electrons passing through various scintillation and OTR beam targets. The simulation work focused on the energy losses by the beam electrons, the energy deposited within the targets, and the scattering distribution of the emerging beam.

Studies were performed on several different potential beam targets; Chromox, YAG:Ce, or LYSO:Ce scintillating targets, and Pyrolytic Graphite or Titanium OTR targets, mounted at 45° to the beam axis. The beam was assumed to be composed of electrons with zero energy and angular spread. Electron beam energies of 300 keV, 10 MeV, 30 MeV, and 50 MeV were included in this study.

As electrons pass through the beam targets, they lose energy through ionization and excitation of the media, and the emission of bremsstrahlung photons. A portion of this energy loss is deposited in the target with the rest leaving the target carried by scattered electrons, and bremsstrahlung photons. The energy deposited in the targets contributes to heating and in the scintillation targets, the emission of scintillation photons, although this represents a small fraction of the total energy deposited.

The electrons undergo multiple scatters while traversing the beam targets and exit scattered at an angle with respect to the beam axis. The particle flux, as a function of scattering angle, approximately follows a Gaussian distribution with a large number of particles scattered at low scattering angles.

The results presented here were determined using $10^5$ events in each scenario studied. Each event comprised of a single beam electron passing through the beam target material, along with any subsequent electrons or photons scattered or produced in the process.

6.1.1 Results

The average total energy loss per electron by the primary electrons as they traverse the beam targets in the GEANT4 simulation closely follows a Landau distribution, as shown in Figure 14. The Landau distribution is generally used to describe the energy losses of charged particles traversing a thin layer of material [21], such as a beam target. The energy spread of the electron beam after the foil can be characterized by the width of the Landau distribution, $\sigma$, which has been determined to be equal to approximately one quarter the FWHM.

For electrons at 300 keV, only the scintillation screen is required as the energy is too low to employ the OTR technique. At this energy, almost the entire electron beam is stopped completely by the screens, with a small fraction of the electrons being deflected backwards. Most of the electrons are stopped within the first 100 µm of the beam target and almost no electrons make it through a 200 µm target. The aver-
Figure 14: The distribution of total energy loss per electron for 10 MeV electrons after traversing a 0.2 mm YAG:Ce screen, fit with a Landau distribution.

...age energy deposited within a 0.5 mm YAG:Ce target is approximately 237 keV per electron at 300 keV, with the remaining energy carried away by the back-scattered electrons. Other materials will also result in similar energy deposition since most of the electrons are stopped quickly at this energy.

At the higher beam energies, 10, 30 and 50 MeV, the electrons have enough energy to pass through the entire thickness of the beam targets. At these energies, either the scintillation target or the OTR target may be used. The total energy loss, energy deposited, and energy exiting the target as photons, all given as an average per beam electron, and the energy spread are listed in Table 6.

As the electron beam is highly relativistic at these energies, the ionization energy losses, and therefore the energy deposited in the beam targets, is approximately the same for a given beam target across the range of beam energies. Therefore the thermal heating of the beam targets is fairly independent of beam energy. The energy loss through bremsstrahlung photons does however depend strongly on the beam energy resulting in different total energy losses at different beam energies.

The distribution of the average total energy loss per electron is shown as the fraction of electrons with average total energy loss greater than a given energy, as shown in Figure 15. This shows the fraction of electrons that fall outside of a given longitudinal acceptance after passing through the beam targets.

The angular distribution of the emerging electron beam can also be represented in a similar way, as the fraction of electrons scattered outside of a given scattering angle, as shown in Figure 16. This provides a measure of the number of electrons that cannot be captured by the quadrupole focusing magnets of the e-linac and collide with the downstream beam pipe wall.

In order to keep the total beam losses less than 2 W through each device, the beam profile monitors are limited to a maximum operating current set by the total...
Figure 15: The fraction of electrons with average total energy loss per electron greater than a given energy for YAG:Ce scintillation screens and Pyrolytic Graphite OTR foils.
Figure 16: The fraction of electrons scattered outside a given scattering angle for YAG:Ce scintillation screens and Pyrolytic Graphite OTR foils.
Table 6: Summary of the average energy losses per electron through 0.2 mm YAG:Ce and LYSO:Ce scintillation screens, 10 µm Pyrolytic Graphite, and 5 µm Titanium OTR foils.

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>Average energy deposited (keV)</th>
<th>YAG:Ce</th>
<th>LYSO:Ce</th>
<th>Graphite</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>300 keV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total average energy lost (keV)</td>
<td>236.5</td>
<td>191.0</td>
<td>- - -</td>
<td>- - -</td>
<td></td>
</tr>
<tr>
<td>Average energy deposited (keV)</td>
<td>262.7</td>
<td>473.8</td>
<td>6.14</td>
<td>6.55</td>
<td></td>
</tr>
<tr>
<td>Energy exiting as photons (keV)</td>
<td>58.7</td>
<td>189.1</td>
<td>0.37</td>
<td>1.34</td>
<td></td>
</tr>
<tr>
<td>Energy spread, $\sigma$ (keV)</td>
<td>13.7</td>
<td>23.1</td>
<td>0.44</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td><strong>10 MeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total average energy lost (keV)</td>
<td>402.5</td>
<td>835.1</td>
<td>8.17</td>
<td>9.72</td>
<td></td>
</tr>
<tr>
<td>Average energy deposited (keV)</td>
<td>189.5</td>
<td>266.1</td>
<td>5.03</td>
<td>4.55</td>
<td></td>
</tr>
<tr>
<td>Energy exiting as photons (keV)</td>
<td>187.7</td>
<td>543.5</td>
<td>1.87</td>
<td>4.18</td>
<td></td>
</tr>
<tr>
<td>Energy spread, $\sigma$ (keV)</td>
<td>13.5</td>
<td>19.6</td>
<td>0.44</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td><strong>50 MeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total average energy lost (keV)</td>
<td>552.1</td>
<td>1279</td>
<td>8.68</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>Average energy deposited (keV)</td>
<td>190.1</td>
<td>267.0</td>
<td>4.96</td>
<td>4.50</td>
<td></td>
</tr>
<tr>
<td>Energy exiting as photons (keV)</td>
<td>334.7</td>
<td>978.4</td>
<td>2.51</td>
<td>8.33</td>
<td></td>
</tr>
<tr>
<td>Energy spread, $\sigma$ (keV)</td>
<td>13.5</td>
<td>19.1</td>
<td>0.44</td>
<td>0.40</td>
<td></td>
</tr>
</tbody>
</table>

The energy loss experienced per electron as they traverse a beam target. The total beam losses can be determined by multiplying the average total energy loss per electron, by the number of electrons passing through the foil per second. Table 7 summarizes the maximum operating currents for the different beam targets at each profile monitor station.

### 6.2 Thermal Simulations of the Beam Targets

The effects of target heating were modeled in a COMSOL simulation. COMSOL is a Finite Element Analysis (FEA) tool used to provide numerical simulations of physical processes. The Heat Transfer Module provides tools for analyzing heat transfer through the processes of conduction, convection, and radiation. The mesh was determined by decreasing the mesh size for a fixed parameter set until the solution no longer depended on the characteristics of the mesh.
Several materials were included in this study YAG:Ce, LYSO:Ce and Chromox scintillation screens, and Pyrolytic Graphite and Titanium OTR foils. Above 300 keV, the temperature distribution does not depend strongly on the target thickness. However in the low energy regime where the electron beam is stopped almost entirely by the target, decreasing the target thickness would result in less material, but the same amount of energy deposition leading to higher target temperatures.

Both YAG:Ce and LYSO:Ce have melting temperatures close to 2000°C, although the maximum operating temperature is much lower than this. The aluminum substrate for the phosphor screens have a much lower melting temperature of around 660°C.

For the OTR targets, Pyrolytic Graphite is stable up to 2500°C and Titanium has a melting temperature of 1670°C. However at these temperatures, the intensity of blackbody radiation becomes comparable to or greater than the emission of OTR. The relative permittivity also has some temperature dependence.

### 6.2.1 Thermal Model Assumptions

In general the thermal properties of a material are dependent on temperature. For example, while Pyrolytic Graphite has a high thermal conductivity of approximately 345 W/m K at room temperature, at temperatures greater than 2000 K this drops to almost 100 W/m K. Such a large change in material properties must be taken into account while attempting to analyze the thermal response across such a temperature range. If temperature dependent properties are unavailable, then across relatively smaller temperature changes, such as the scintillation beam targets are limited to, the thermal properties may be assumed constant with little loss of accuracy.

The thermal conductivity and heat capacity of Pyroid, a form of Pyrolytic Graphite, is shown for temperatures between 300 K and 2000 K in Figure 17. The thermal conductivity is greater in the plane parallel to the target surface than for the perpendicular axis. The density is approximately constant over this range at

<table>
<thead>
<tr>
<th>Energy</th>
<th>YAG:Ce</th>
<th>YAG:Ce</th>
<th>Graphite</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 keV</td>
<td>6.5 µA</td>
<td>6.6 µA</td>
<td>- - -</td>
<td>- - -</td>
</tr>
<tr>
<td>10 MeV</td>
<td>- - -</td>
<td>7.5 µA</td>
<td>320 µA</td>
<td>300 µA</td>
</tr>
<tr>
<td>30 MeV</td>
<td>- - -</td>
<td>5.0 µA</td>
<td>240 µA</td>
<td>200 µA</td>
</tr>
<tr>
<td>50 MeV</td>
<td>- - -</td>
<td>3.5 µA</td>
<td>230 µA</td>
<td>140 µA</td>
</tr>
</tbody>
</table>

Table 7: The maximum beam currents to keep the total losses below 2 W for the candidate beam targets.
Figure 17: The thermal properties of Pyroid as a function of temperature.

2220 kg/m$^3$ [17].

The temperature dependent properties of YAG:Ce were taken to be equivalent to those of undoped YAG, whose temperature dependent properties are available within the COMSOL materials library. The thermal conductivity is 10.8 W/m K, the heat capacity 590 J/kg K, and the density 4550 kg/m$^3$.

The following assumptions were applied in the construction of the COMSOL FEA thermal model.

1. The initial temperature of the beam targets and holder is 300 K.

2. The edges of the beam targets are held at a constant temperature of 300 K. This is based on two more fundamental assumptions, mainly that there exists good thermal contact between target and target holder around the edge of the targets to allow for the heat to flow freely between them in a vacuum environment, and that the target holder is capable of dissipating up to 2 W of thermal energy without a significant rise in temperature.

3. The only mode of thermal transport modeled is the thermal conduction within the beam target itself. As the targets are located in vacuum there will be no medium to provide convective cooling, and even at the maximum operating temperatures, energy losses through radiation are minimal relative to conductive cooling. This emphasizes the importance of achieving an effective thermal contact between target and target holder.
4. The energy deposited within the targets is taken from the GEANT simulation results as summarized in Table 6. For electron energies of 10-50 MeV, the average energy deposited per electron is mostly independent of beam energy. Therefore the thermal response is likewise independent of beam energy for 10-50 MeV beams.

5. The energy deposited within the beam targets is uniform over time. This of course is not truly the case as the electron beam will contain a pulsed time structure which is most apparent when operating at a low duty factor. The results acquired by assuming a uniform time structure correspond to the time averaged temperature distribution of a pulsed beam.

6. The mesh size was decreased until the simulation provided a stable solution and the size of the mesh elements were much less than the width of the beam such that the properties across a single mesh could be assumed approximately constant.

6.2.2 Time Structure Response

Figure 18 shows the effect of a pulsed beam on the thermal response for the first 100 ms. In this study, a relativistic 10 mA electron beam operating in 10 µs pulses at 100 Hz corresponds to a duty factor of 0.1% and a time averaged current of 10 µA. The beam was assumed to be circular with a Gaussian distribution and a width of $\sigma = 0.335 \text{ mm}$.

![Figure 18: The maximum temperature of a Pyrolytic Graphite foil in a 0.1% duty factor electron beam, showing the thermal response to both the pulsed beam structure and the time averaged beam current for the first 100 ms.](image)

Within less than 3 seconds, the temperature distribution reaches a dynamic equilibrium state with the maximum foil temperature oscillating between $\sim 335 \text{ K}$
immediately after a beam pulse and cooling to $\sim 307\,\text{K}$ between pulses. The time averaged maximum temperature of the foil after reaching this equilibrium state is approximately $310\,\text{K}$.

Using a pulsed beam structure for all of the thermal simulations is not possible as it requires a prohibitively higher computation time. By assuming the energy deposited into the beam targets is uniform over time with the appropriate time average beam current, the calculated temperature distribution is approximately equal to the time average of the pulsed beam temperature distribution. This is shown as the blue line on the plots in Figure 18. For the remaining thermal studies, the energy deposition is assumed uniform in time and it must be understood that the peak temperature of the beam targets will actually oscillate above and below the values calculated. The true peak temperature depends both on the pulse length and bunch charge.

6.2.3 Results

In the ELBT, a 0.5 mm single crystal YAG:Ce screen would reach a temperature of $100^\circ\text{C}$ at a beam current of $5\,\mu\text{A}$ for a nominal beam size. Due to the much higher thermal conductivity of aluminum, a Phosphor screen on an aluminum substrate would reach lower temperatures under the same conditions.

The peak time-averaged temperature that a YAG:Ce screen will reach as a function of beam current and beam size in the ELBT is shown in Figure 19. For nominal beams sizes, the maximum temperature reached by the YAG:Ce screen is $\sim 130^\circ\text{C}$. Smaller beam sizes heat the screen to higher temperatures, leading to a higher loss in light output due to the temperature dependant light yield.

![Figure 19: Maximum target temperatures for a 300 keV, 3 mm beam on a 0.5 mm YAG:Ce target.](image-url)
The peak temperatures for the scintillation beam targets in the EMBT and EHBT are shown in Figure 20(a). As discussed earlier, the thermal response is independant of beam energy for 10-50 MeV beams. The YAG:Ce screens reach their thermal quenching temperature of around 430°C at beam currents of 6 to 8 µA for nominally sized beams. The light output will be significantly decreased before this point, limiting the usage of the scintillation targets to up to only a few µA’s for the EMBT and EHBT View Screens.

Figure 20: Maximum target temperatures in EMBT and EHBT of the scintillation and OTR beam targets.

From Figure 20(b), the Pyrolytic Graphite target reaches a peak temperature
of 650 °C at its highest operating current of 320 µA, corresponding to 2 W of total beam losses at 10 MeV. This is well below the melting temperature for Pyrolytic Graphite and is cool enough that the emission of thermal radiation should not interfere with imaging.

The ELBT View Screen may be operated with nominal beam sizes without requiring the application of a thermal correction factor. For a 3 mm beam at 6 µA of beam current on a YAG:Ce target, the beam would appear only ~3 µm larger due to the temperature dependant loss in light output. However, since the scintillation screens in the EMBT and EHBT may reach much higher temperatures, a correction factor could be required in order to properly characterize the beam properties.

6.3 Simulation of the Imaging Optics

An optical simulation was designed to determine the optimal selection and configuration of the optics elements within the imaging optics system. This allowed for the evaluation of a great number of lens configurations to determine which ones would produce the clearest and brightest images of the beam profiles.

The simulation is based on a ray tracing routine, tracking individual rays of light emitted from the target, through the surfaces of the optical components, and striking a pixel on the CCD sensor. Since the routine is based on determining the path of individual rays through the optics system, the phenomenon of diffraction and interference are not modeled in this simulation. Each ray was assigned a weighting factor based on the emission direction. For scintillation light the weighting factor is equal for every ray as the light is emitted with no angular preference. For OTR light, the weighting factor is determined by the OTR emission distribution, Equations 1 and 2.

The initial positioning of the lenses and CCD was determined through calculations using the thin lens equation to achieve the correct magnification factor. Fine adjustment of the CCD sensor location was then studied using the ray tracing simulation to achieve the optimal focus, as the lenses are not ideal thin lenses. The Point Spread Function (PSF) is used to characterize the focus of the system.

The PSF is the response of the optics system to a point source of light, originating from the object plane. Due to spherical and chromatic aberrations, non-uniformities in the lenses, and diffraction effects, the focal point of a ray has a small dependency on how far from the center of the lens the light ray passed and on the wavelength of the light. This creates a spreading of the focal point, therefore illuminating a number of CCD pixels.
6.4 Modes of Operation

The range of operation of the Beam Profile Monitor depends on a number of factors. The lower limit is set by the minimum beam current which produces an image on the camera with enough intensity to determine beam properties from. On the other end of the scale, the maximum beam current depends on one of the following: the maximum tolerable beam losses of 2 W per device, the loss of electrons scattered at large scattering angle, or the heating of the beam targets beyond operational limits.

The intensity of the light emitted by the beam targets varies with beam current, size, and energy. The size of the electron beam affects the amount of light that will illuminate a single pixel. In a larger beam, the light will be spread out over a larger number of pixels so that even though the total amount of light may be equal to that of a smaller electron beam, the individual pixels will be dimmer.

For scintillation targets, the light output is dependent on the energy deposited within the beam target by the passing electron beam. The light output is approximately proportional to beam intensity, with the light yield decreasing at higher target temperatures.

For OTR beam targets, the emission distribution depends on the beam energy. Higher energy electrons result in more light output and a larger fraction of light emitted within the angular aperture of the optics. The intensity of OTR emission scales very linearly with beam intensity.

The amount of light collected by the imaging system depends on the optics aperture, which is set by the iris diameter, and the exposure time of the camera. In the ELBT, it is most desirable to acquire images with the iris held at 15 mm and use the camera’s exposure time to adjust the image intensity in order to minimize spherical aberrations. The iris may be opened to 41 mm to increase light collection at the expense of losing imaging resolution. In the EMBT and EHBT, where spherical aberrations are much less of an issue, imaging should be performed with the iris wide open as much as possible to maximize the angular acceptance when imaging OTR light.

The camera is sensitive to visible radiation within the range of approximately 300 nm to 1000 nm with the quantum efficiency of the CCD given in [19]. The emission spectrum of the scintillation light emitted by the YAG:Ce beam target is peaked at ~ 550 nm, while the OTR light emission is broadband, emitted across the entire visible spectrum.

The range of operation of the OTR and scintillation beam targets is shown in Figure 21. The minimum current was determined using the theoretical light output of the targets, the iris opened to its maximum diameter, and the camera exposure set to 50 ms. The maximum operating current was determined from either the current that resulted in 2 W of total losses for the OTR beam targets, or from thermal considerations for the scintillation targets. The maximum current may be limited
further as a result of beam dynamics calculations determining the acceptance of scattered electrons.

At 300 keV, with a nominal beam size of $\sigma = 3\text{ mm}$, the minimum operating current will be determined with operation as limited data is available for the phosphor screen. The upper limit for a beam stopping screen is $6.5\text{ µA}$ when the beam losses reach 2 W.

For a 10 MeV beam with a nominal beam size of $\sigma = 2\text{ mm}$, either the Phosphor or OTR targets may be used. At low currents, from around 10 nA up to several µA the Phosphor screen may be used. The OTR light should become visible at approximately $2\text{ µA}$, with the beam losses reaching 2 W at around $320\text{ µA}$.

At the highest energies, 30 to 50 MeV, the nominal beam size is smaller yet, $\sigma = 1\text{ mm}$, so the Phosphor screen will become visible at lower beam currents. The operable range of the Pyrolytic Graphite target overlaps the range of the Phosphor screen significantly and can be used from $\sim 0.1\text{ µA}$ up to $230\text{ µA}$.

### 7 Optics Bench Tests

Tests were performed using a prototype version of the optical elements mounted on an optics test bench to characterize the performance of the imaging system and to test image acquisition procedures.

A resolution test target was used to characterize the resolution of the imaging system. This target was a glass slide printed with the National Bureau of Standards 1963A Resolution Pattern in negative as shown in Figure 22. The pattern consists of series of dark and light line groupings, each with a different spacing between pairs of lines. The spacing is measured in line pairs per mm (lp/mm).
A grid target pattern was used to determine the cross field of view imaging characteristics and to test the focusing algorithms. The grid consisted of a series of 0.4 mm diameter holes on a 5 mm grid pattern drilled onto a $\sim 150\mu m$ thick bronze sheet. To measure the PSF of the imaging system, a sheet of aluminum foil with a very small hole was used to imitate a point source of light. The size of the hole was measured under a microscope and determined to be $<10\mu m$ in diameter, which is much less than the size of a single pixel on the focal plane.

The targets were lit from behind with a halogen bulb placed behind a translucent diffuser. The targets were mounted either perpendicular to the optical axis, or at an angle of 45°, the same as the beam targets will be oriented.

The mirror was mounted on the adjustable mirror mount to provide optical alignment. The iris was held on the front face of the lens holder and was controlled manually throughout the bench tests. The camera mount allowed for angular adjustment with the rotation axis aligned with the CCD position within the camera. This allowed the camera mounting angle to be adjusted without changing the distance to the center of the CCD, which would change the focus. The camera mount had an adjustable slide to provide manual focus of the camera, similar to the camera mount that will be used in the final design.

### 7.1 Point Spread Function

The PSF measured with the ELBT optics is shown in Figure 23 for iris diameters of 15, 41 mm. The PSF is seen to have a halo surrounding it when the iris is opened wide to 41 mm, due to spherical aberrations. By closing the iris to 15 mm, the central portion of the PSF remain unchanged, but the halo is removed, significantly.
improving image quality, but decreasing the total amount of light collected. If the camera were to be focused with an ideal focus at an iris diameter of 41 mm, then the PSF would actually worsen as the iris was closed, resulting in poorer resolution images.

Figure 23: The PSF measured with ELBT optics.

Figure 24: The PSF measured with EMBT/EHBT optics.

Figure 24 shows the PSF for the EMBT and EHBT imaging optics. Due to the less demanding optics, the PSF covers a significantly smaller number of pixels than for the ELBT optics, resulting in much clearer images. The PSF becomes slightly smaller as the iris is closed from 41 mm to 15 mm. This has a small effect on the resulting image quality as will be discussed in the next section, but the main effect
is the reduction in the amount of light collected, which is not apparent in these images.

Optimization of the imaging optics through the use of the ray tracing optics simulation was verified by comparison of the PSF acquired on the optics bench to the results obtained through the optics simulation. Figure 25 shows a cross section of the pixel intensity across the PSF for both the simulated result and the image of the PSF. The close agreement of the two indicates the optics simulation provides an accurate representation of the imaging system.

![Figure 25: Cross section of the simulated and measured PSFs for the ELBT optics with a 41 mm iris aperture.](image)

7.2 Contrast Transfer Function

The contrast and resolution are two very closely related qualities of an optical imaging system. Because the PSF is spread over a range of pixels, when two bright spots on an image are brought closer together, the space in between will become illuminated by the tails of the PSF, decreasing the contrast between the bright spots and the dark in between. The resolution test target is used to quantify this relationship. The CTF is the plot of the contrast as a function of line pair spacing.

In a series of alternating light and dark lines, the contrast refers to the difference in the intensity between a bright line and a dark line in the acquired image. If the intensity of an illuminated pixel within a bright line is $I_{\text{max}}$ and of a pixel between bright lines, $I_{\text{min}}$, then the contrast between them is defined as

$$\text{Contrast} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

(3)
The minimum separation that can be determined within a pixelated image is fixed by the size of the pixels. This minimum separation occurs when the width of a single line within a line pair is same width as a pixel. If the line pairs are smaller than this, a single pixel would correspond to both a light and dark line and the lines would be indistinguishable. With a camera with a $580 \times 780$ pixel resolution, then the minimum distinguishable line pair spacing would be 7.5 lp/mm in the ELBT where the field of view is 50 mm wide, and 15 lp/mm in the EMBT and EHBT where the field of view is 25 mm wide.

![Figure 26: The Contrast Transfer Function measured with the resolution test target.](image)

The CTF measured with both the ELBT and the EMBT/EHBT optics is shown in Figure 26, acquired with the iris diameter at 15 mm and 41 mm. The contrast improves as the iris aperture is decreased, resulting in clearer images. In the ELBT, this effect is very clear, the contrast for a 2.5 lp/mm line spacing is 65% with the iris at 15 mm, but drops by a factor of 6, to 11% with the iris opened all the up to 41 mm. With the EMBT/EHBT optics, the effect is not quite as dramatic, but at the smallest line spacing, 14 lp/mm, there is still a decrease in contrast from 18% to 8% when opening the iris from 15 mm to 41 mm.

### 8 Conclusion

The design study reported here forms the basis for fabrication and assembly of the view screens for e-linac. The design provides coverage over a range of beam currents from nA’s of average current with scinitillation screens up to 100’s of µA’s with the OTR targets.
Necessarily, the designs were completed before view screen implementation at the ISAC/VECC Injector test facility, which is the subject of a collaboration between TRIUMF and the Variable Energy Cyclotron Centre, Kolkata India, since 2009. The scintillator-based design has been tested with beam energies up to 90 keV at the VECC ELBT.

The 100 keV view screens are now in routine operation and perform admirably. The scintillator targets will be tested at the VECC ELBT at energies of 300 keV and 10 MeV; and the OTR target at 10 MeV in the VECC EMBT after the injector cryomodule.

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References


