OPTICAL SYSTEM DESIGN FOR THE ESS PROTON BEAM AND TARGET DIAGNOSTICS

M. G. Ibison†, C. P. Welsch, Cockcroft Institute and The University of Liverpool, UK*
E. Adli, H. Gjersdal, University of Oslo, Norway**
N. de la Cour, T. Shea, C. Thomas, ESS, Lund, Sweden

Abstract

The high power and low emittance of the ESS proton beam require a robust protection strategy for the spallation target and its surroundings. For this, a suite of instruments has been established, including an imaging system for the beam on target. It will be imaged by scintillation on passing through thin screens coating both the proton beam window (PBW) on exit from the accelerator, and also the entry window to the target (TW). Light from the screens must be transported to remote cameras through a 4m high shielding plug with a restricted aperture. At the same time, the optical path must not compromise the integrity of the shield against neutrons and other beam interaction products. We present the theory underlying the design of the reflective optics for efficient transmission of high-quality images to provide the desired level of protection to the machine, and describe the implementation of the design in Zemax OpticStudio software, as well as the predicted performance of the imaging system. We also consider how the requirements of environment (thermal and radiation), initial alignment and ongoing maintenance for the optical system can be met. We conclude with comments on the applicability of optics of this type for diagnostic systems in similar situations at other neutron sources and elsewhere.

OPTICAL DIAGNOSTIC REQUIREMENT FOR THE TARGET

The optical diagnostic is designed to capture an image of the PBW [1], through which 2 GeV protons will exit the

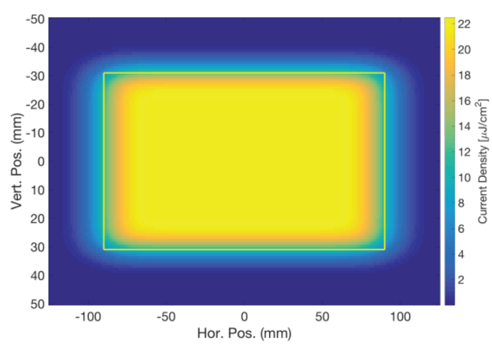

Figure 1: Beam on Target image simulation. Colour scale indicates the current density. The yellow rectangle shows the footprint enclosing a 99.9% beam fraction.

accelerator and enter the target area, as shown simulated in Fig. 1. To protect the target, the beam will be raster-scanned to spread the 5 MW average power load; the system must collect images within the 2.86 ms duration of the macro-pulse at 14 Hz repetition.

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†e-mail address mark.ibison@cockcroft.ac.uk

The current density derived from the image will provide a continuous assessment of beam quality, triggering the Machine Protection System (MPS) if errant conditions are detected [2]. An almost identical optical system will image the beam on the TW downstream of the PBW.

Image acquisition must take place remotely, in a room shielded so that it is accessible during normal operation. Optical elements to transport the image vertically upwards from proton beam level must be housed inside the shielded structure, into a penetration known as the Proton Beam Instrumentation Plug (PBIP). This contains several vertical 'slices', one for the PBW optics, another for the TW optics and three for other diagnostics [3]. The radiation environment imposes severe constraints on the optical systems. Firstly, radiation shielding integrity restricts physical and therefore numerical aperture; also, the first elements are exposed to thermo-mechanical stress, with the potential for structural changes.

The light source will be a luminescent coating on the PBW and TW, excited by the incident protons. Studies are in hand to improve on the standard Cr-doped alumina [4], for adequate photon yield, spectrum, lifetime & linearity.

OPTICAL SYSTEM PARAMETERS

The principal parameter values to be achieved by the system are summarised in Table 1 below.

Table 1: Summary of the Main Optical Parameters Required of the System, with their Sources

Parameter	Value	Origin
Field of View	250x110 mm^2	dimensions of raster pattern on PBW and target; fiducials
Depth of Field	$\geq$22 mm	viewing angle; offset from proton beam axis (160mm)
Physical Aperture	<100 mm	Limited PBIP slice thickness; shield integrity
Resolution	$\leq$1 mm	Ability to detect beam raster failure; beam on target tuning
Magnification	0.05 - 0.15	Object extent, sensor dimensions

DESIGN METHODOLOGY

Because of the hostile radiation environment in the target area, a system based on reflective optics has been selected, rather than lenses or optical fibres which are known to suffer rapid damage [4]. Even so, some degradation of the first mirror - closest to the proton beam - is expected; six-monthly access for possible replacement is provided for, although the optics slices have a 2-year projected lifetime.

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Applying established theory of geometrical optics, it is well known [5] that systems of three (or more) curved mirrors can be configured to provide desired imaging properties while minimising the most severe third-order aberrations. For the ESS Target Imaging System (ETIS), this theory has been implemented to calculate mirror configurations in a simple MS-EXCEL spreadsheet and in MATLAB, with results of each compared for validation.

'Block' Design Concept

A design concept was developed to build the complete system from three-mirror 'blocks', one interfaced to the next via intermediate images having specific locations and parameters. This approach allowed rapid assessment of candidate designs to meet some of the dimensional constraints of the optical paths within the PBIP, but it had deficiencies: it could not compensate for those aberrations due to the inherently off-axis nature of the system, nor could all relevant mirror properties be included in the calculation. It was therefore used only as a starting point, to suggest approximate mirror placements and curvatures.

All design work has been performed in the industry-standard optics software tool Zemax OpticStudio [6], using theoretical values as initial parameters. Only in Zemax could all requirements of the system be incorporated, especially the detailed geometry. Pure ray optics was sufficient, as diffractive effects were expected to be negligible. As an intermediate design stage between a parameter set derived from theory, and Zemax model-building, manual ray-tracing based on prints of the detailed Computer-Aided Design (CAD) model of the PBIP was used to provide an envelope for the optical paths and mirror placements.

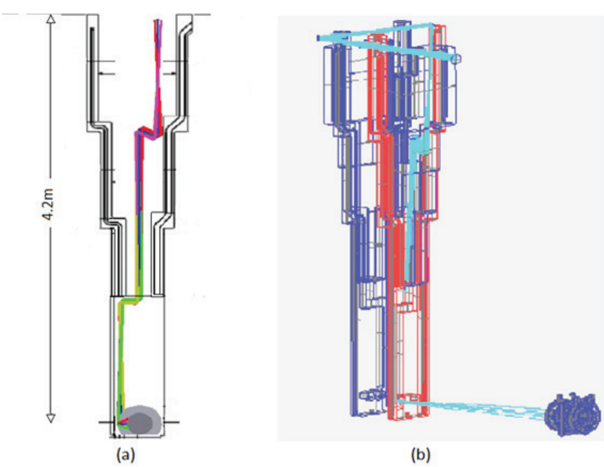

Figure 2: Optical Path from the PBW, inside the PBIP.
(a) ZEMAX Implementation of original sketch design, superimposed onto a CAD drawing. Colours indicate rays from different object fields.
(b) CAD wireframe model with highlighted PBW 'slice' (red) showing its optical path (blue).

This technique allowed alternative configurations to be explored relatively quickly, without concern for the technicalities of data entry into modelling software.

Encoding into Zemax requires the relative positions and orientations of all optical elements between the source object and the final image to be specified. The software then automatically traces an end-to-end ray-path, if one is geometrically possible. The designer uses the various analysis tools to diagnose any problems and makes manual adjustments until a satisfactory configuration is found, as illustrated in Fig. 2. For the ETIS, this process was carried out block-by-block, so reducing the number of free parameters - and hence complexity – at each stage. Initially this philosophy worked successfully for the first block of the design, but often failed on adding a second block; geometrical restrictions caused ray-tracing breakdown, or at least severely limited the available aperture or created incompatible divergence at the blocks' interface. The problem then required another design iteration, trying out an alternative starting configuration for the first block.

Optimisation with Zemax

The solution has been to combine approaches: first, to simplify the design to just one block, placing additional flat mirrors to fit the path into the PBIP geometry; second, to allow the Zemax *optimiser* tool to determine mirror configurations itself. An outline of the procedure is:-

1. Start from 'paper' optics estimates for the block, with image positions, and desired path for best shielding
2. Enter operands to control mirror geometry and ray-path
3. Run optimiser until targets are met; if not, reduce operands and/or relax constraints, and repeat.

The optimiser works within user-specified constraints – typically on mirror & beam sizes & positions - to find an optimal system, at least in local solution space. Variables available to the optimiser include, but are not limited to:-

- vertices and rotations of mirrors and other surfaces;
- curvatures and conic constants of curved mirrors.

The preferred criterion for the optimiser is the minimum *radial spot size* at the final image, as image quality is limited by geometrical aberrations rather than diffraction. This approach has successfully optimised the vertical section of the path, i.e. within the PBIP itself, and seems to work even with two images, in the two-block system.

Optical design geometry is confirmed by exporting from Zemax into CAD format, then merging with the full PBIP mechanical model. This checks that the ray-path and mirror positions are within acceptable bounds and do not interfere with other essential structures or services.

DESCRIPTION OF CURRENT DESIGN

A Zemax design built under the principles described above is shown at Fig. 3. Essentially it comprises two blocks: a lower block of 5 mirrors, two of which are flat (or 'fold') mirrors, and an upper block of 4 mirrors, all of which are curved. As previously explained, the PBIP contains two sets of optics, for PBW and for TW imaging, which are very nearly mirror images of each other, one looking up-beam and the other down-beam; the principal difference is the source-object-to-first-mirror distance of 1.82 and 1.36 m respectively. Above the PBIP, they follow parallel optical channels out of the target vessel and through a shield wall, into the experimental room where the imaging cameras are located.

To provide much better aberration control, curved mirrors in these designs are specified as *biconic* surfaces, that is, their curvatures and shapes are allowed to differ in the two principal orthogonal planes. Through the optimiser tool, limits are set to avoid extreme values in these parameters, which could make manufacture of the mirrors very difficult and/or expensive.

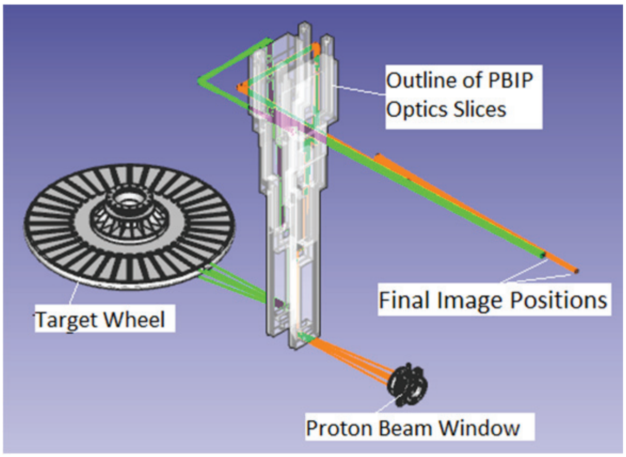

Figure 3: CAD view, with Zemax models of the PBW (red) and Target (green) system end-to-end optical paths. Only the target wheel, PBIP & PBW are shown; for clarity other structures around the target monolith are omitted.

PERFORMANCE OF THE DESIGN

The Zemax toolset has features to characterise the optical properties of the design, and these are listed in Table 2 for comparison with required values.

Table 2 Performance Measures Predicted by Zemax, for the PBW and Target Systems

Parameter	PBW system	Target system
Total Mirror Count	9 (inc 2 flats)	9 (inc 2 flats)
Working F/#	*45.3*	36.5
Numerical Aperture (NA) - Object Space	~0.002‡	0.0017‡
Depth of Field (mm)	>20	*>40*
Spot Size (µm)	*180*	208
Magnification (paraxial)	0.48†	-0.30†

‡provisional estimates from (non-circular) pupil areas
†optimised for image quality, not yet camera sensor size

It will be seen that the PBW system is significantly closer to specification than the Target; but as the PBW is better developed than the TW, further refinement on the Target side is expected to achieve similar performance.

The Modulation Transfer Function (MTF), plotted in Fig. 4 for the PBW system, is a standard measure of how well the optics can image fine detail. It is expressed as the image-to-object modulation intensity ratio of closely-spaced light/dark sinusoidal cycles, over a range of spatial frequencies.

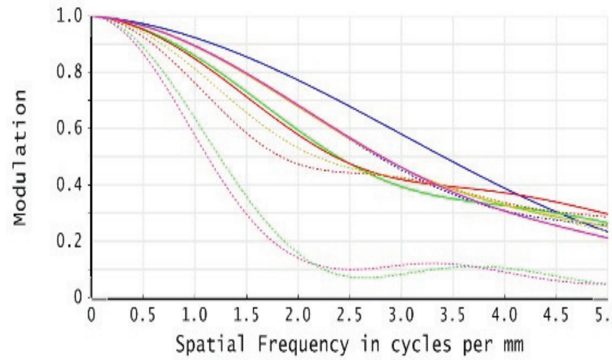

Figure 4: MTF Plot of full PBW optical system. Colours denote different Object field points. Broken lines show the blur in a vertical pattern, full lines in the horizontal.

CONCLUSION

Two optical systems have been designed, to form images of the ESS proton beam on the PBW and the TW. The design of both systems has been developed and optimised using the Zemax toolset, to meet performance requirements under severe radiation environment constraints. The total mirror count has been minimised while maintaining acceptable image quality. The design will now undergo tolerancing studies of the effects of thermal expansion, misalignments, and production uncertainties, to enable detailed specifications for all mirrors and their mountings to be generated. These will be essential to confirm costings and manufacturability with suppliers. A further detailed design phase will lead to refinements based on the tolerancing studies and the manufacturing and alignment constraints.

Models will be used to construct a full-scale mock-up of the optics, to verify the design and to devise a workable alignment procedure, both for initial assembly and installation of the system, and for its later maintenance.

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