# PROTON BEAM IMAGING OPTIONS FOR THE ESS TARGET

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## *Abstract*

Conceptual design of an imaging system for the ESS proton beam current density on target is presented. The window separating the linac HV from the 1bar He-filled target station will be used as a source for imaging by means of either OTR or luminescence. The system presents many challenges to be addressed. The window and the primary optics will be exposed to extremely high radiation doses, providing heat cycles and mechanical stresses near the engineering limits, but also may change the surface properties of the window and the optics. The window lifetime expected to be less than 1 year will have to be replace bi-annually, imposing remote handling design for the window but also for part of the optics. In addition, the imaging system should be able to form an image from low to high current beam operations, in order to retrieve beam profile distribution and power density distribution of both static and raster beam, imposing a large numerical aperture (NA), but also to transport the image at more than 15 m distance where radiation level is compatible with camera and pc stable operation and human access during commissioning and neutron production.

## INTRODUCTION

The ESS facility is composed of a high power pulsed proton beam, sent straight toward the spallation target for the production of neutrons. The extremely small normalised emittance of the proton beam [1], typically 0.7 mm.mrad, combined with the beam power, 5 MW, imposes a high level of control to the beam on target for the safety of the target area and components [2]. For this purpose a suite of diagnostics is been design to characterise the proton beam on target and to trigger machine protection system [2]. In particular, one of the diagnostics to be designed is an optical image of the proton beam density distribution through the window (later referred as Proton Beam Window, PBW) at the interface of the high vacuum Linac and the 1 bar He filled target area. The main information from the image will be the proton beam current density on the PBW, and by extension on target, although a similar optical system is been planed as a mirrored system of the one to be described bellow. In the following, we will present the conceptual design for the PBW optical imaging system, based on the required measurements on the images of the beam on target for the qualification of the pulses and for the detection of abnormal operation. We will also describe the constraints imposed by the shield integrity and the high radiation environment. The issue in terms of image quality and signal to noise ratio, comes from the necessity to perform an image at a large distance due to radiation safety, through very narrow apertures due to the radiation shield integrity, and with the highest possible transmission and resolution. In addition, the high radiation environment imposes constraints on the choice of materials for the optical elements, not only for stability of the optical properties, but also for the radiation waste management and lifetime of the optical elements. Finally, the heat-load due to energy deposition from the radiation into the optical elements, imposes to look at thermal deformation of the optical surfaces, but also heat cycles and thermo-elastic properties of the optical elements.

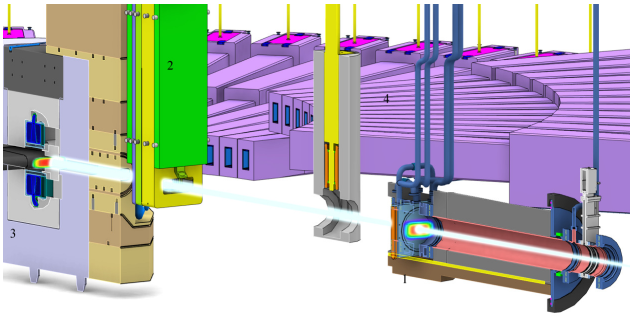

Figure 1: Layout of the proton beam through the target monolith. The beam passes from the high vacuum of Linac to the 1-bar He filled target area, through the PBW (1), then passes the Beam Instrumentation Plug (2) before reaching the Target Window and the rotating Tungsten target (3). The neutron Moderators (4) are represented setting the target in its neutron spallation context.

## BEAM ON TARGET PROPERTIES

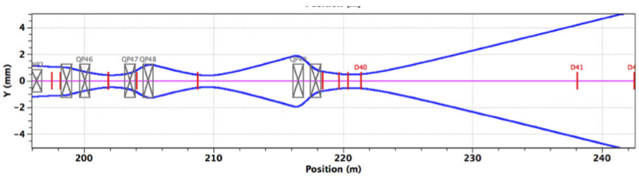

Figure 2: Layout of the beam optics before the target. The blue lines show the beam 10-$\sigma$ envelope.

The main strategy chosen to protect the target and target components is to firstly expand the beam by means of a set of quadrupoles, and then raster it in order to homogeneously paint the maco-pulse of 2.86 ms over a large surface. Figure 2 shows the layout of the beam optics and beam size before the target. The beam raster being done by a set of horizontal and vertical fast quadrupole kicker magnets, inducing a constant speed and linear transverse motion to the beam on the PBW and target. The beam is focused on a fixed point, and expands in size with its natural divergence. On the PBW, the beamlet size is 15 × 5 $\text{mm}^2$. The linear angular deflection from the raster magnets paints the beamlet fast enough so that the proton current density of a single 2.86 ms pulse is deposited onto the PBW over a 160 × 60 $\text{mm}^2$ area. The net result

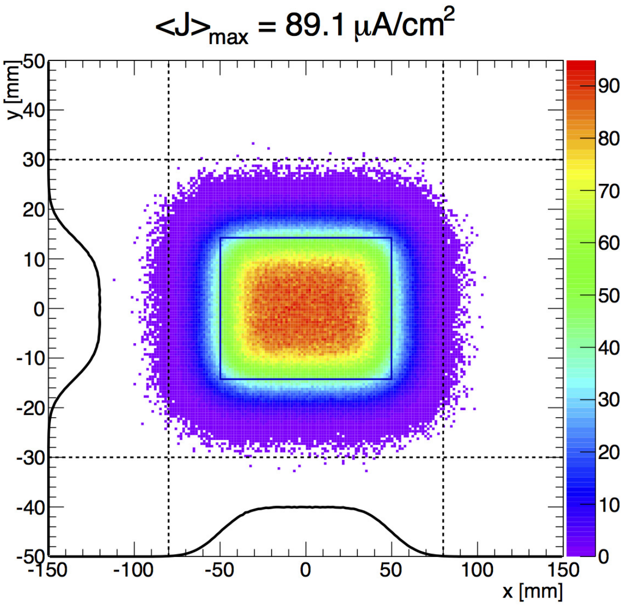

Figure 3: Image of the raster beam integrated current density of the 5 MW, 14 Hz, 2.86 ms pulse proton beam on the Target Window.

produces a dilution of the average current density on the PBW from approximately 10 mA/cm$^2$ to 89 μA/cm$^2$. Figure 3 (Courtesy of H. D Thomsen, ISA, Arhus, Denmark), shows the current density predicted by numerical simulation of beam dynamics with fixed focus point and raster motion.

The optical imaging of the beam distribution over the PBW is one of the essential diagnostics to assess the beam quality and the tuning of the beam onto the target. In addition, measurements on the image of the mean current density may provide assessment of the PBW lifetime.

## BEAM INSTRUMENTATION PLUG

Proton beam diagnostics in the target monolith are inserted through the radiation shield by a so-called Proton Beam Instrumentation Plug (PBIP). Its function is to allow the insertion of diagnostics, to maintain the shield integrity, and to allow remote handling on the diagnostics to be removed from the plug after been possibly activated by the scattered protons and neutrons. From the conceptual point of view, the PBIP is composed of slices, in which resides a unique diagnostics system so that it can be removed remotely. The path from the instrument's closest point to the proton beam to the external point outside the radiation shield cannot be straight, and cannot offer multi-lines of sight to a possible path for the scattered neutrons. The consequence for the optical system is a restricted space for the optics, and an optical path going firstly at 90 degrees up and side way up to outside the monolith shield (see Fig. 4).

## CONCEPTUAL DESIGN OF THE OPTICAL SYSTEM

Independently of the source, although assuming a non-coherent radiant source emitting over $2\pi$ sr, we started to design the optical path for imaging the PBW. The inputs for the design are the following: a large field of view, typically $250 \times 110$ mm$^2$, 1 mm resolution or less, and maximum possible transmission to the image sensor; but also the optical elements must be small enough to fit into one of the slices of the beam instrumentation plug.

The ideal optical system is well described by its cardinal points from which effective focal length and magnification can be derived, and effective NA which defines the geometrical best possible resolution, the depth of field and the geometrical transmission. To satisfy the requirements described above, the magnification should be between 0.05 and 0.2 to allow the image to match the size a commercial CCD/CMOS sensor, but also the effective NA should be large enough to not only match the expected resolution, but also the field of view. At the same time, NA should be small enough for the depth of field. In addition, geometrical aberration must be controlled in order to keep as close as possible from the geometrical aperture resolution.

From this, and recalling that the image must be at a large distance from the object, typically larger than 15 m, and that the shield integrity imposes narrow aperture, typically less than 100 mm, one can see that the effective numerical may not be matched to the required one. Also, having no refractive optics allowed in the high radiation environment zone, aberration control will be challenging, in particular for most of the image which will be off-axis. In addition, the first mirror should be placed far from the proton beam, so the PBW is seen from an angle and thus the object extents along the optical axis and imposes a minimum depth of field.

### *ZEMAX Preliminary Design*

In order to design the optical imaging system for the PBW with the requirements described above, we use ZEMAX, a specialised software for optical design[1]. This will help us not only to get a realistic optical design, but also optimise the mirror surfaces to minimise aberrations. Finally, the software exports CAD files, which can be used for integration of the optical system in the mechanical design of the target monolith, but also to communicate with manufacturers for quotation and to manufacture.

For the design, we proceed in several steps. Firstly, we design a primary set of mirrors to performe and intermediate image the PBW. The first mirror and the others must be placed in the PBIP, at 2.65 m from the PBW. The intermediate image is positioned between 0.5 m and 1 m above the proton beam axis. The magnification of this intermediate image should be less than 0.5 to match the 100 mm entrance of the plug on the way up, and to minimise the angular magnification. This prepares the second stages of optics which

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[1] www.zemax.com

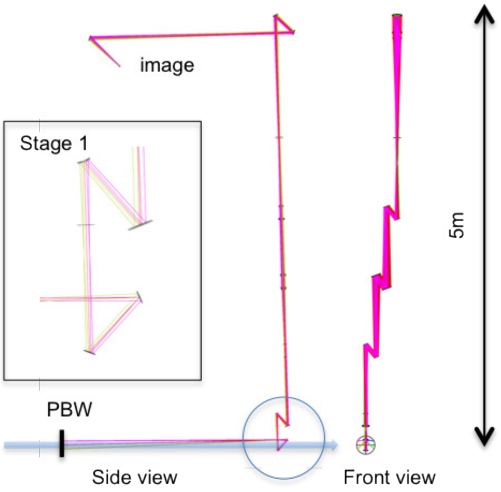

Figure 4: Optical imaging system primary design. The beam is shown by the semi-transparent arrow. First focusing stage of the optical imaging system is shown in the inset. The distance between PBW and first mirrors is 2.65 m. On the top, the visible beam exits the monolith through a viewport (not shown) and then is finally focused on the image sensor.

will be afocal to transport the beam far away. Before designing the afocal stages the primary one is optimised for the best resolution and transmission. After they are designed and optimised, a final stage is introduced for focusing the image and adjusting magnification and NA.

The overall optical imaging system is shown is Fig. 4. The inset of Fig. 4 zooms on the primary stage. It is composed of 4 bi-conic mirrors, to minimise aberration in both planes. The afocal stages are additional to the first one. As shown in the front view, the optical path goes side-way to prevent line-of-sight to the scattered neutrons and protons.

From the requirements derived above, it is possible to use the effective NA, which depends on the magnification, to derive the resolution (R), the depth of field (DoF), and the transmission (T) of the optical imaging system[2] at the observed light wavelength $\lambda$. These values are reported in Tab. 1. We also retrieve these values as calculated by ZEMAX for the presented preliminary design (also in Tab. 1). In addition, we give in the table the geometrical r.m.s Point Spread Function (PSF) as calculated by ZEMAX, taking into account all the system aberrations and the magnification. We find that PSF to varying across the image from 2 to 4 mm. Its seems to be rather large compared to the expected value. However, here we present a preliminary design, which is not fully optimised. So we believe that the final design will match the expected resolution value.

The requirements, as shown in Tab. 1, are all related to the NA. As is well-known, the resolution and the transmission are large for large NA, but the DoF is just the opposite. Thus there exists a range for which NA may satisfy all the requirements. In the table, we showed a large expected T=1%, at a NA = 0.14. This value would be indeed satisfying all the requirements. But the geometry of the system, and the shield integrity requirement may prevent the system to reach such an ideal NA. In the presented design NA is not even close to 0.05, which would make only T=0.1%.

Table 1: Summary of the optical system properties as given by the ZEMAX primary design and compared to the expected conceptual approach.

| | Expected Values | | ZEMAX Design |
|---|---|---|---|
| Magnification | 0.05 - 0.2 | | 0.085 |
| object NA$_{eff}$ | R < 1 mm | > 0.004 | 0.00995 |
| | DoF > 1 mm | < 0.022 | |
| | T > 0.01 | > 0.14 | |
| DoF (mm) | | | 5 |
| R (μm ) | | | 30 |
| PSF (mm) | | | 2-4 |
| Geometric T | | | $5 \cdot 10^{-5}$ |

## CONCLUDING REMARKS

A conceptual design for an optical imaging system of the proton beam current density across the PBW has been presented. To perform reliable measurements on single macropulse images, the optical system should have a large numerical aperture, but not too large to keep the DoF larger than the depth of the PBW. In addition, the radiation shield of the target monolith may limit the NA. Further development of the design may show this and which NA can be achieved. In addition, further requirements, not mentioned here, on imaging system of the target window will be designed too. Therefore, the first stage will have to be redesigned: only one mirror should be close to the beam, and also it will have to reside within one slice of the PBIB. This second optical system is foreseen to be simply mirrored to the PBW one. This second phase of the design is already ongoing. However, is it not mature enough yet to be presented.

## REFERENCES

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[2] T. J. Shea, C. Bohme, B. Cheymol, S. Gallimore, H. Hassanzadegan, E. J. Pitcher, and H. Thomsen. Proton beam measurement strategy for the 5mw european spallation source target. In *IBIC*, pages 349–352, 2013.

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[2] The formula used here are: $R = 0.61\ \lambda\ /\ NA_{eff}$ ; $DoF = \lambda\ /\ NA^2_{eff}$ ; $T = 1 - (1 - NA^2_{eff})^{0.5}$, with $\lambda$ the wavelength