THE ESS TARGET PROTON BEAM IMAGING SYSTEM AS IN-KIND CONTRIBUTION*

E. Adli†, H. Gjersdal, O. M. Røhne, O. Dorholt, D. M. Bang, University of Oslo, Oslo, Norway
C. Thomas, T. Shea. R. Andersson[1], ESS ERIC, Lund, Sweden
M.G. Ibison, C.P. Welsch, University of Liverpool and Cockcroft Institute, Daresbury, UK
S. Joshi, University West, Trollhattan, Sweden
[1]also at University of Oslo, Oslo, Norway

Abstract

The ESS Target Proton Beam Imaging System will image the 5 MW ESS proton beam as it enters the spallation target. The system will operate in a harsh radiation environment, leading to a number of challenges: development of radiation hard photon sources, long aperture-restricted optical paths, and fast electronics to provide rapid response to beam anomalies. The newly formed accelerator group at the University of Oslo is the in-kind partner for the Imaging System. This paper outlines the main challenges of the Imaging System and how they are addressed within the collaborative nature of the in-kind project.

INTRODUCTION

The European Spallation Source (ESS), currently under construction, is expecting to deliver first beam around the year 2020 and to reach its full design specifications in 2025, with a suite of 22 research instruments. The facility consists of a 600 m long linear accelerator, sending a 2.86 ms long pulse of 2 GeV protons with 14 Hz repetition rate onto a rotating, helium cooled, tungsten target. This spallation source distributes thermal and cold neutron beams to a large variety of state-of-the-art neutron instruments [1].

ESS' key tasks is to deliver neutron beams with a 95% overall availability (average beam power of 5 MW) for ~5000 h per year. In order to achieve these goals it is critical to monitor all aspects of the spallation process and the proton beam characteristics. The beam will be rastered (painted) onto the rotating target by specially designed rastering magnets [2]. It would damage the target if the beam hits the target un-rastered. Two imaging systems are key diagnostics for monitoring the proton beam in the target region, including verifying that the rastering is functioning correctly. A thin layer of luminescent coating will be thermal sprayed on the target surface and on the proton beam window surface. Optical systems will image the photons emitted when the proton beam passed through the coated surfaces. The two surfaces together with the start of the optical path are depicted in Fig. 1a). Software and electronics will be developed for robust and fast processing of the beam images, with the aim of providing information about beam profile anomalies in time to shut down the next pulse. Figure 1b) illustrates a rastered beam profile as will be measured by the imaging system as the beam enter the target.

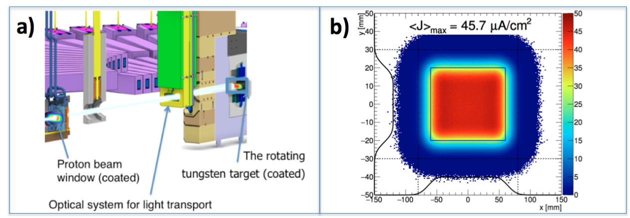

Figure 1: a) The two target-region imaging systems that will operate in an intense neutron flux and must withstand the 5 MW proton beam. b) Beam density map of the rastered proton pulse at the target wheel. From [2].

CHALLENGE

The target proton beam imaging systems will be installed in the ESS target region. As the ESS average beam power is 3.5 higher than that of SNS, with a corresponding higher neutron flux from the spallation, intense radiation is the main challenge for the development of the ESS imaging systems. Research for luminescent coatings with improved radiation hardness is required in order to ensure the correct functioning of the imaging system at full power. The optical paths to cameras placed in an area accessible during operation are ~12 m long, with mirror positions heavily constrained due to the need for shielding. The imaging system should be able to respond quickly enough to disable a subsequent pulse in case of beam anomalies, at 14 Hz rep. rate.

LUMINESCENT COATING RESEARCH

Luminescent materials have been used for imaging of high-energy proton beams accelerators for several decades, for example in form of sintered Cr:Al_2O_3 (Chromox) widely used at CERN [3,4]. However, there has been comparatively little research on luminescent materials that can withstand intense neutron or ion irradiation, with exception of the development done for the Spallation Neutron Source at Oak Ridge National Laboratory (SNS). At SNS, a luminescent coating is used to image the proton beam in a similar way [5]. This coating consists of Alumina doped with chromium (Cr:Al_2O_3), generated by combustion flame spraying powder with 1.5% chromia and 98.5% Alumina onto the SNS target. The chromium dopes the alpha-phase Alumina. The

* This work is part of the Norwegian in-kind contribution to ESS.
† Erik.Adli@fys.uio.no

resulting crystal structure, known as Ruby, has fluorescent light emission around 694 nm, as illustrated in Fig. 2b).

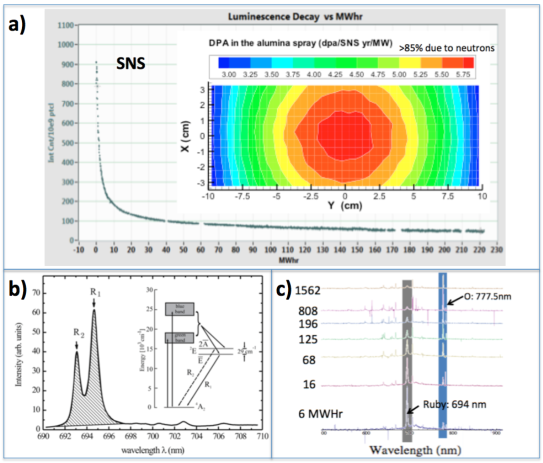

Figure 2: a) A plot of SNS Luminescence decay vs. integrated beam power, adapted from [5]. b) Ruby lines for the SNS Cr:Al_2O_3 coating. c) Evolution of the Ruby and possible Oxygen lines with integrated SNS beam power.

The luminosity of the SNS coating decays rapidly with integrated beam power on target [5], as shown in Fig. 2a), adapted from [5]. However, some luminescence remains towards the end of the SNS target lifetime (6 months), enough to provide a reduced quality image of the proton beam. As demonstrated by SNS/Stony Brook University the luminescence of the coating depends on a large range of factors; parameters related to the feedstock powder (chemistry, particle size distribution, grain size), spraying technique (flame spray, plasma spray), spraying parameters [6]; the coating has to be sprayed with the right powder composition and with fine-tuned spraying parameters, if not, the coating shows little or no luminescence, especially after irradiation. This fine dependence on powder- and spraying parameters is not fully understood. An unconfirmed hypothesis is that the Chromia continues to re-dope the Alumina after the Alumina cores have been damaged by slow neutrons. Also unexplained is the appearance of possible Oxygen lines around 777 nm with intensity increasing with irradiation, see Fig. 2c). While these lines could be beneficial to maintain luminosity, this effect must be better understood before it can be eventually exploited as baseline for the ESS target.

Extrapolating the measured SNS performance to the expected ESS neutron flux, and considering the higher ESS target temperature, the SNS coating is not expected to give measurable luminescence at the ESS at full beam power. An international collaboration has been formed with the objective of identifying more radiation resistant luminescent thermal coatings. The collaboration consists of ESS and Oslo, the University West which will be the ESS thermal spray partner, SNS and Stony Brook University. The collaboration will study performance limitations of the SNS coating, identify alternative chemistries and/or spraying techniques with improved performance, and conduct beam tests, including at Oslo and at high irradiation test facilities like BLIP at Brookhaven National Laboratory. More details about the on-going and planned coating studies is found in [7].

OPTICAL SYSTEM

The optical system should have a field of view larger than 250x100, with a resolution better than 1mm across the beam window. Refractive optics (lenses) are not used in the target area for several reasons; the high radiation will quickly discolor or otherwise damage the lenses, the photon source spectrum is not yet decided upon, and may be broadband. Fiber optics will not be used based on negative experience from SNS, and poor availability of long radiation hard fibers. Instead reflective optics will be used, although the implementation is expected to be challenging due to long optical paths, the limited apertures and chicanes imposed by shielding requirements. After installation of the mirrors in the proton beam instrumentation plug, the mirrors will not be accessible. Due to the radiation environment, motorized adjustment of mirrors after installation has been ruled out. As result there are tight mechanical tolerances on the proton beam instrumentation plug during installation and operation. Earlier optics designs [8] used curved mirrors with optical power to increase numerical aperture. It was found that due to strong geometrical constraints on the placements of the mirrors, it was challenging to cancel aberration sufficiently, and therefore to achieve the 1 mm resolution. All optics calculations, including estimations of aberrations and tolerances, have been done with the software package Zemax OpticStudio (ZOS) [9].

Recently a simpler design was adopted, with a single chicane in the proton beam instrumentation plug, designed to have the minimum number of mirrors needed to fulfill the requirements. The first mirror facing the object is curved in order to achieve the required field of view. The rest of the mirrors are flat. This design achieves the target resolution with a numerical aperture of about 0.001, comparable to that of the previous concept with curved mirrors. The system with flat mirrors will be significantly simpler to produce, install and align. One disadvantage is that a camera lens is needed in order to image onto the camera chip, requiring the spectrum of the luminescent coating to be within the bandwidth of the lens. Since lenses with adequate chromatic corrections within the spectral range of the sensor are commercially available this was not judged to be a determining factor. Figure 3a) shows the optical system integrated into the target region, while Fig. 3b) shows the locations of the mirrors more precisely. For the tuning beam dump, a simpler imaging system is envisaged, based on cameras with lenses installed in a shielded enclosure within the dump tunnel.

PROTOTYPING

A full prototype of the optical system for the target wheel has been built up at Oslo. Apart from a few different folding directions, in order to have a smaller prototype footprint, the

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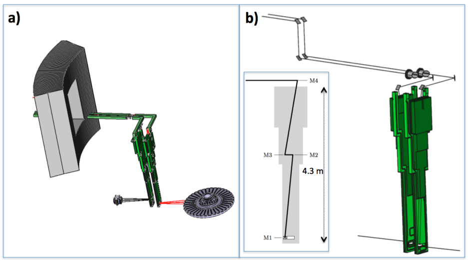

Figure 3: a) the optical system integrated into the main target region components. Light collected from the proton beam window and the target wheel passes through the proton beam instrumentation plug, the connection cell, and a wall to the camera systems. b) locations of the mirrors.

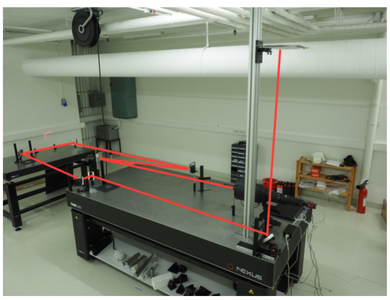

Figure 4: The target wheel optical system prototype built up in Oslo. The optical path in is red. The object (target wheel) is at the top of the picture.

prototype optical design is very similar to the ESS system. Figure 4a) shows a picture of the Oslo prototype, with the light path in red. The object (target wheel entrance window) is at the top of the picture. The system resolution and distortions can be found experimentally by imaging a custom target, as shown in Fig. 5a). Each square is one mm large, which allows to verify in practical way whether the resolution target of 1 mm is met by the system. Figure 5b) shows the target as imaged by the camera. The image confirms that features of size of 1 mm can be imaged. The measured resolution, field of view and deformations correspond well to what is predicted by ZOS, giving confidence in the design calculations. An illumination system based on collimated LED light is foreseen to uniformly illuminate the target surface and fiducials, and has been tested with the prototype.

ELECTRONICS AND SOFTWARE

The foreseen post-processing of the raw image from the camera includes: noise suppression and filtering, calibration and aberration correction, correction for target wheel motion followed by extraction of key beam parameters including centroid, peak current density and beam outside footprint. In addition, the image system will be used to monitor changes in the optical system itself by tracking the position of fiducials on the target wheel. Time-critical operations are planned to

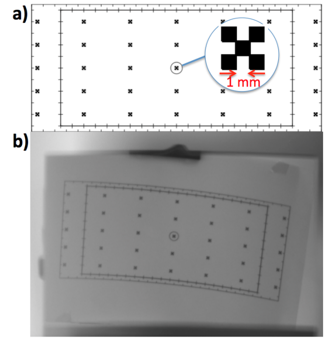

Figure 5: a) a custom target placed at the prototype object position. The squares have a size of 1 mm. b) The custom target as imaged by the system. The performance is close to the expected from the ZOS calculations. The 1 mm squares can be resolved.

be performed in FPGA hardware. The analysis should be rapid enough so that in case of anomalies the next beam pulse can be stopped. Less critical operations like fiducial tracking will likely be performed in software only. Algorithm design is taking advantage of open source OpenCV software, for which EPICS areaDetector plugins already exist. The first image processing algorithms have been designed and implemented on FPGA. Figure 6 shows the results of correction of geometric aberrations of the beam image, originating from the curvature of the target wheel (calculated analytically), and from the distortion of the optical path (estimated by ZOS).

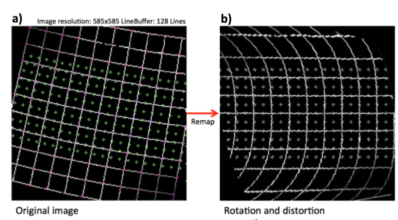

Figure 6: Correction of geometric aberrations of the beam image. a) Original image. b) Image after FPGA-correction. Only the parts with green stars contain the beam.

SUMMARY

Design of the ESS Target Proton Beam Imaging System poses unique challenges that makes close collaboration between the in-kind provider, ESS experts and world wide expertise necessary. Weekly online meetings and frequent visits by Oslo to ESS and partners, as well as visits by ESS to Oslo, has been key to the rapid progress of the project. The work to design, construct and deliver the optical systems is on schedule, with the CDR planned for Fall 2017. The main remaining challenge is to successfully develop novel luminescent coatings necessary to image the proton beam at ESS full power operation.

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