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PROGRESS OF THE ESS PROTON BEAM IMAGING SYSTEMS*

Erik Adli†, Håvard Gjersdal, Kyrre N. Sjøbæk, Grey Christoforo, Eric D. Fackelman, Ole M. Røhne,
Jonas S. Ringnes, Simen R. Solbak, Maren C. Lithun (University of Oslo, Oslo, Norway)
Cyrille Thomas, Yngve Levinsen, Kaj Rosengren, Thomas Shea (ESS ERIC, Lund, Sweden)
Gerard Bell (STFC), Mark Ibison (University of Liverpool and Cockcroft Institute, Daresbury, UK)
Shrikant Joshi, Stefan Björklund (University West, Trollhattan, Sweden)

Abstract

The ESS Target Proton Beam Imaging Systems has the objective to image the 5 MW ESS proton beam as it enters the spallation target. The imaging systems has to operate in a harsh radiation environment, leading to a number of challenges : development of radiation hard photon sources, long and aperture-restricted optical paths and fast electronics required to provide rapid information in case of beam anomalies. This paper outlines how main challenges of the imaging systems have been addressed, and the status of deployment as ESS gets closer to beam.

INTRODUCTION

The European Spallation Source (ESS) [1], currently under construction, has as objective 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], in order reduce the current density at the target. The Oslo in-kind contribution [3] consists of delivering the ESS target and tuning dump imaging systems. We report here on the recent progress on the two systems, including electronics development and related beam dynamics studies.

TUNING DUMP SYSTEMS: Two imaging systems are provided for the tuning beam dump, and are vital to characterise the beam on dump parameters. These will have insertable screens made of large, custom cut Chromox ceramic plates [4, 5], special camera inserts deep into the concrete walls to protect them from radiation, and an optical system design to give an optimal field of view. The tuning dump imaging system design is described in [6].

TARGET SYSTEMS: The two target 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 is 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, and the beginning of the optical path, are depicted in Fig. 1a). The target imaging system is further described in [3].

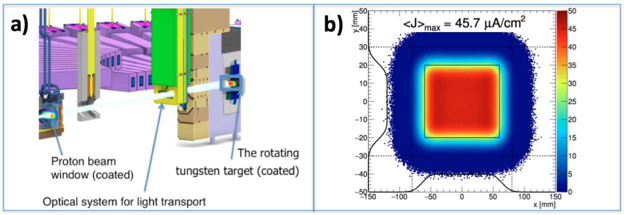

Figure 1: a) The target imaging systems, imaging the proton beam window and the target wheel, will operate in an intense neutron flux and must withstand the 5 MW proton beam. b) Beam density map of the rastered proton pulse at the target wheel. From [2].

TUNING DUMP SYSTEMS

Two tuning dump systems have been completed and were delivered to ESS in June 2022. One of systems is shown in Fig. 2, integrated in the vacuum vessel provided by STFC.

The vacuum vessel is fitted with an actuator that moves a frame that can hold two Chromox scintillating screens. When a screen is placed in the beam path, the beam footprint can be imaged from the emitted photons by a camera that is installed in the wall next to the chamber. Two mirrors are installed on the wall to transport the light from the Chromox screen to the camera. The images produced by the system will be used by the operators to tune the beam during commissioning.

Camera Insert

To minimise the radiation damage and increase the expected lifetime of the cameras, holes have been core drilled into the concrete wall next to the vacuum vessels. Pipes with rails will be installed and fixed in the holes. For each system, a camera with a lens, two neutral density (ND) filters, and a microcontroller are mounted on a custom camera insert.

The Allied Vision Manta G-419b PoE Gig-E camera is attached to an adapter at a tilted angle with respect to the optical axis as calculated from the Scheimpflug principle [7]. The Chromox screens are tilted 45 degrees to the optical axis, the camera tilt is there to make it possible to have the whole screen in focus. An off-the-shelf lens, Canon EF 135 F/2L, is also connected to the adapter. A microcontroller makes it possible to remote control the lens focus and aperture. Two ND filters (OD 2.0, 3.0) are installed on actuators in the adapter, so they can be moved in or out of the light-path.

The adapter is connected to a wagon and to rectangular pipes. The pipes are used as cable guides, as well as a handle

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[*] This work is part of the Norwegian in-kind contribution to ESS.

[†] Erik.Adli@fys.uio.no

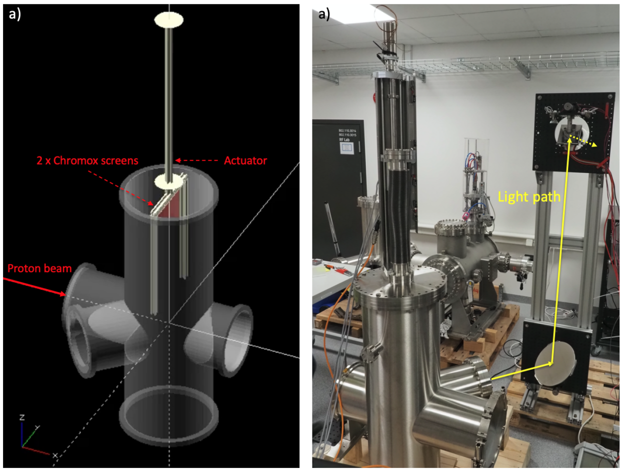

Figure 2: Two tuning dump imaging systems will be installed. a) Design drawing showing the screen frame in the vacuum vessel. b) One complete imaging systems as delivered to ESS.

to install or remove the camera inserts by sliding it along the rails in the pipe. The mechanical parts have been designed and made at the workshop at the University of Oslo.

The University of Oslo has delivered three complete camera tube systems, with camera, electronics and mechanical components. Two tubes for the two installed imaging systems, and one tube as hot spare. Fig. 3 shows details of the camera insert.

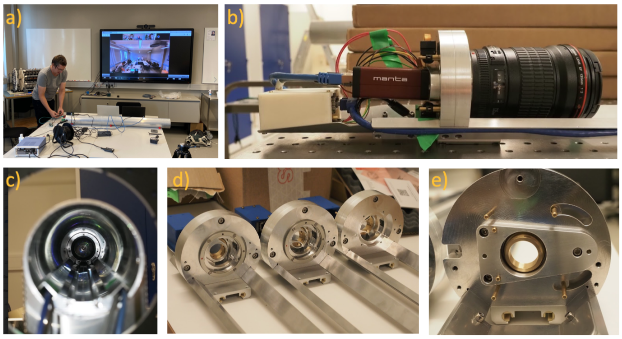

Figure 3: a) The tuning dump camera insert inside a tube. b) A camera insert with all electronics mounted and connected c) View from the tube front. d) ND filter holders. The ND filters, along with control of the camera aperture, makes it possible to limit the amount of light on the camera by 7 orders of magnitude. e)A wedge adds a tilt to the camera to optimize the focus plane.

Optical System

For each optical system, two mirrors are mounted on the wall. A 290 mm diameter circular mirror is mounted outside a viewport in the vacuum vessel. A 150 mm x 110 mm rectangular mirror is mounted directly in front of the hole for the camera. Both mirrors are custom made by UQG optics.

Mirror clamps have been designed and made at the workshop at the University of Oslo for both mirrors. The mirrors are attached to breadboards that are attached to the wall. The breadboard that is attached in front of the camera tube has a hole in the middle. The mirror clamps are attached to the breadboards using Polaris mounts and Thorlabs parts. The Thorlabs parts allow for rough alignment of the mirrors, the Polaris mounts allow for accurate adjustments of the angles.

Four halogen lamps are attached to the mirror outside the camera insert. When the lamps are on, it is possible to make sure the Chromox screens are in the correct position and undamaged, by looking at the images from the camera.

A complete mirror mount assembly is shown in Fig. 2b).

TARGET LUMINESCENT COATING

The Target Proton Beam Imaging Systems will be installed in the ESS target region. 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 reach cameras 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 the 14 Hz rep. rate.

For its first target, ESS has adopted the same principle and will mainly use the same powder to deposit the luminescent coating as used by the Spallation Neutron Source at Oak Ridge National Laboratory (SNS). At SNS, a luminescent coating, flame sprayed on the target, is used to image the proton beam [8]. The SNS powder consists of alumina doped with chromium ($\mathrm{Cr{:}Al_2O_3}$), in a mixture of 1.5% chromia and 98.5%. alumina. The powder has been tested by the ESS-Oslo collaboration and shows a luminescence yield of the order of 10,000 photons per MeV, it has a lifetime of about 3ms; the yield decreases by about 50% at 230°C and is expected to quench thermally over 350°C. The radiation damage will rapidly decrease the luminescence yield down to 5-10% of fresh material, keeping a sufficient luminescent level. For ESS the thermal spraying process has been developed in collaboration with University West, Sweden. The process allows spraying a luminescent material on a large surface, typically larger than 100 mm x 200 mm. The characterisation of the material showed it satisfied most requirements for the imaging system.

In March 2022 a major milestone was achieved with the coating of the ESS target with the qualified luminescent material. In parallel, ESS has developed the process for manufacturing custom luminescent chromia alumina powder that can be flame sprayed. Figure 4 shows two sectors of the ESS target wheel, one coated with the SNS chromia alumina and the other with the ESS manufactured powder. With the coating of the target wheel, one of the critical milestones

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for the delivery of the beam on target imaging systems is achieved.

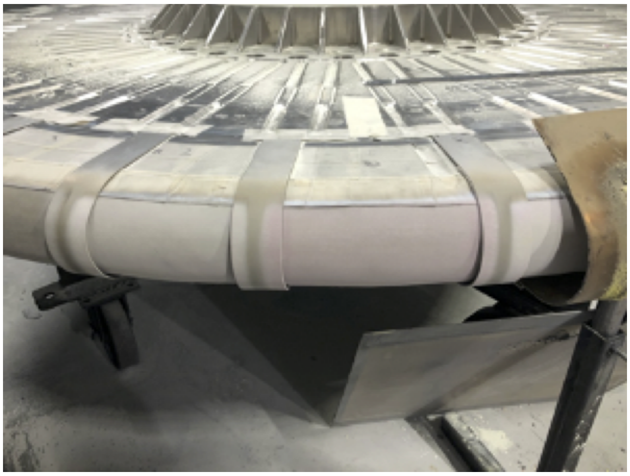

Figure 4: Two sectors of the ESS target wheel, one coated with the SNS chromia alumina and the other with the ESS chromia alumina.

BEAM DYNAMICS

The effect of the Aluminium Proton Beam Window (PBW) [9] on the proton beam has been simulated using MiniScatter [10], based on GEANT4. From Fig. 5 we see that the beam size, σ, at the target changes significantly due to the PBW Al thickness. Analytical expressions for Twiss parameter change due to a thin scatterer [11, Eq. 7, 8] agree with the simulations to within 2% at the planned PBW Al thickness of 2.25 mm, which surrounds the standard 2.0 mm of water in the center [9, Figure 2]. We can compensate for the increase in beam size by decreasing the amplitude of the raster magnet scan.

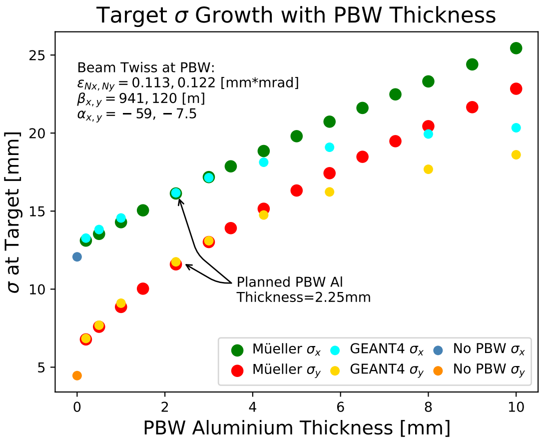

Figure 5: Beam size (σ) at target with respect to PBW Aluminium Thickness

ELECTRONICS AND SOFTWARE

The imaging systems will extract key beam parameters including centroid, peak current density and beam-outside-99%-footprint. In addition, the image system may 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 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.

Figure 6 shows a block diagram of the planned solution for the imaging system camera read-out and processing. After receiving the image from the camera, the raw image is to be made available to the Linux running on the embedded SOC using a VDMA and the Xilinx Video4Linux2 (V4L2) drivers. Images received through V4L2 are made available for EPICS AreaDetector using the ADV4L driver. Further image processing and analyses are also done by the FPGA, with the resulting data published through EPICS via the SOC. The SOC is also used for configuring parameters of the FPGA and camera, as well as for less time-critical and more high-level analyses for which higher programming flexibility is desired. In addition to the images from the camera, the system would require to know the current screen number and beam-current for calibration of the measured light intensity into charge density.

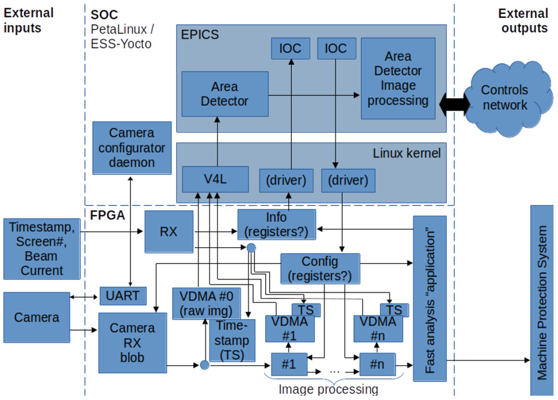

Figure 6: Block diagram for the camera read-out and processing.

SUMMARY

The ESS Target Proton Beam Imaging System poses unique challenges, which have been addressed by the collaboration of ESS, Oslo, STFC, and University West. The tuning dump systems have been delivered to ESS and are ready for installation. The target has been successfully coated using a custom developed process for precision flame spraying of the target wheel. The target optical system is awaiting completion as the different ESS subsystems are coming to completion in the coming year.

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