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Development of a target imaging system for the European Spallation Source

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Abstract. At the European Spallation Source (ESS) neutrons will be produced by a proton beam impinging on a rotating target wheel. The technology of the target wheel, which comprises a large number of closely spaced tungsten bricks and is cooled by helium, is largely untested. The durability of the target wheel and hence the overall ESS neutronic performance depend on the integrity of the tungsten bricks. In order to monitor whether the target geometry is preserved over the expected 5 year lifetime of the target wheel, we propose a Target Imaging System (TIS). The TIS consists of a scintillator array detecting the collimated single photon emission (decay gammas) from the activated tungsten bricks. Preliminary Monte Carlo simulations support the feasibility of this imaging system. As a proof-of-principle, an experimental test-rig is being constructed allowing to test the main aspects of the imaging system under conditions relevant to ESS.

1. Introduction

The European Spallation Source (ESS) will be the most powerful spallation neutron source in the world. Neutron production is initiated by a 2 GeV, 5 MW proton beam impinging on a rotating target wheel, comprising a large number of closely spaced tungsten bricks encased in a steel vessel [1]. The technology of the helium-cooled tungsten wheel, however, is largely untested and the durability of the target wheel depends *inter alia* on the integrity of the tungsten bricks. The tungsten bricks will operate in a brittle regime after exposure to radiation and thermal stresses, both of which may induce erosion or cracking of the bricks, eventually resulting in the blocking of the coolant channels, unwarranted heating and loss of mechanical stability of the wheel.

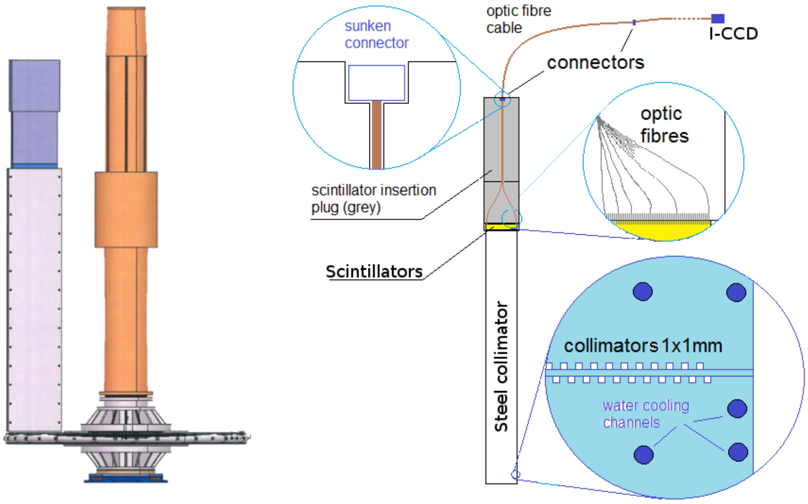
2. The Target Imaging System

Among several diagnostic systems currently under development, we propose a Target Imaging System (TIS) in order to investigate whether the target geometry is preserved over the expected 5 year lifetime of the target wheel. The TIS is intended to provide a means for a high spatial resolution recording of the decay gammas from the target wheel.

During operation, the target with the tungsten bricks is exposed to intense particle irradiation, especially protons and neutrons, giving rise to highly radioactive bricks, encased in a steel vessel of somewhat lower activity. By recording the decay gammas from the tungsten bricks, the TIS will be able to detect changes to the brick layout, especially the presence of brick fragments in the cooling channels between the bricks.

The TIS is not a safety system but is intended as a monitoring instrument capable of providing support to issues of target maintenance and operation, as well as future design development.

As shown in figure 1(a), the TIS is positioned in the vertical target diagnostic plug that lies above the target wheel, on the side opposite to the incoming proton beam and forming a 15° angle (azimuthal) with respect to the proton beam axis.



(a) **(b)**

Figure 1. (a) Target diagnostic plug positioning relative to the target system; (b) schematic representation of the main components of the TIS.

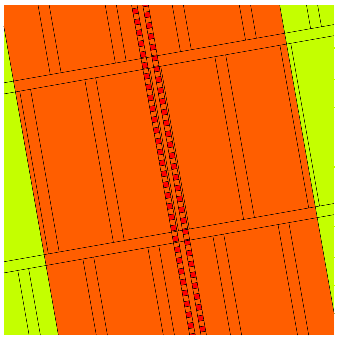


Figure 2. MCNPX model of the horizontal cross section of tungsten bricks superimposed with collimator grooves.

The TIS is composed of four main components, outlined in figure 1(b):

- a 2.8 m steel collimator suspended 2 cm above the target wheel and normal to its plane. A total of 500 1×1 mm^2 grooves are machined into the collimator structure, aligned along two rows, offset by 1 mm with respect to each other and separated by a 1 mm septum;
- on top of the collimator, a scintillator cartridge housing 500 $1 \times 1 \times 10$ mm^3 scintillators. Each scintillator is precisely coupled to a single collimator groove;
- an optical fiber bundle, where each fiber is coupled to a scintillator. The fiber bundle is $10 - 15$ m long and will be routed outside the ESS target monolith. To comply with ESS requirements, extra shielding material is surrounding the optical fiber bundle;
- a fast-switching (3 ns) image-intensified CCD camera coupled to the optical fiber bundle, to register the scintillation photons.

The TIS can be seen as the collection of 500 independent read-out channels, each composed of a collimator, a scintillator, a fiber and a CCD detector. Each of these channels will detect decay gammas emitted by the tungsten bricks, allowing for a high spatial resolution image.

In figure 2, details of the MCNPX geometry are shown, where the horizontal cross section of the tungsten bricks has been superimposed on the collimator grooves. The two rows of collimators allow the desired spatial resolution (1 mm) to be achieved while ensuring radial coverage of the target wheel; the imaging along the azimuthal direction is achieved through rotation of the wheel.

3. Data acquisition and imaging

With the high spatial resolution required for proper monitoring of the target wheel, each of the scintillators will have a count rate of about 10 γ/s. For each of the collimators, the passing time for a collimator across the gap between the bricks (that act as cooling channels) is of the order of 300 μs during normal operation, hence real-time image reconstruction is not possible. However, by taking advantage of fast image-intensified CCD cameras, several accumulation techniques may be envisaged to gather sufficient statistical significance in a relatively short time during ESS operation. This includes sector-averaging, in which only high-spatial resolution is maintained in the radial direction, supplemented by intelligent gating procedures allowing for high-spatial azimuthal angular resolution covering smaller sections of the wheel.

Two main sources of noise will affect the measurements:

- prompt γ background, resulting from the spallation process. This can effectively be avoided by limiting the acquisition time to the beam-off intervals;
- delayed gamma background, resulting from the activation of all the components within the monolith, including the scintillators themselves. This background can be limited with specific shielding.

4. Neutronic simulations

Extensive Monte Carlo simulations and activation calculations, performed with MCNPX [2] and CINDER'90 [3], respectively, are carried out to investigate the signal-to-noise ratio of the TIS.

The MCNPX and CINDER'90 simulations are carried out in three phases: (i) MCNPX simulation of a 2 GeV proton beam impinging on the target wheel to calculate the neutron fluxes in one sector of the wheel; (ii) CINDER'90 activation calculation. For the latter, we employed the following time structure:

- 1 year irradiation at 5 MW i.e., average power of the proton beam;
- 30 irradiation cycles comprising 2.86 ms irradiation at peak power (125 MW) interleaved with 2.57 s cooling time;
- cooling time of 1 s.

The 1 s cooling time corresponds to the time needed for the wheel to move from the irradiation position to the imaging position, i.e. the measurement of a sector of the target wheel is performed 1 second after the proton pulse. Finally, an MCNPX simulation is performed to calculate the instantaneous gamma flux at the scintillators.

In figure 3, the result of the simulation is shown, corresponding to the layout of figure 2. The figure shows the gamma flux at the position of the scintillators; each point corresponding to one of 113 scintillators included in the simulation. The cooling time is 1 s.

The blue dots correspond to the left row of scintillators in figure 2, imaging three bricks, whereas the red dots are for the right row, imaging two bricks only. The cooling channels in between the bricks are associated with the reduced gamma fluxes at around 300 $\gamma/\text{cm}^2/\text{s}$. Note that the overall gamma intensity grows with the distance from the target shaft, since the primary proton beam intensity is larger at the wheel edge. The constant values of the gamma flux across each of the bricks is an artifact of the simulation where each brick is treated as a single cell.

5. The test-rig

As a proof-of-principle for the TIS, a test-rig is being constructed at DTU. A 3D view of the setup is provided in figure 4(a). The test-rig will be equipped with 60 collimator grooves; 30 with 1 mm^2 cross section and 30 with 0.5 mm^2 cross section, allowing for different spatial resolutions. A scaled model of the wheel, shown in figure 4(b), will be fitted with several resolution targets

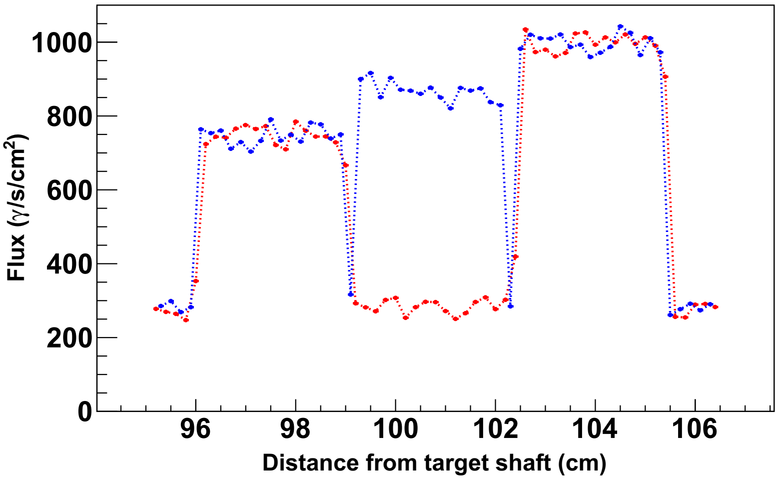


Figure 3. Simulated gamma flux at the scintillators 1 s after irradiation: left row (blue), right row (red). Background due to activation of the monolith has not been included. Dotted lines are to guide the eye.

made of lead. While the lead targets will not be activated themselves, measurements will be performed using the DTU Nutech medical radiation source (^{60}Co, 450 TBq).

The test-rig will allow assessment of the detector performance of the proposed TIS in terms of spatial resolution, temperature-dependent signal degradation, radiation damage of the components, etc. In addition, data acquired from the measurements of the test-rig will be used for the development of the control and data analysis software.

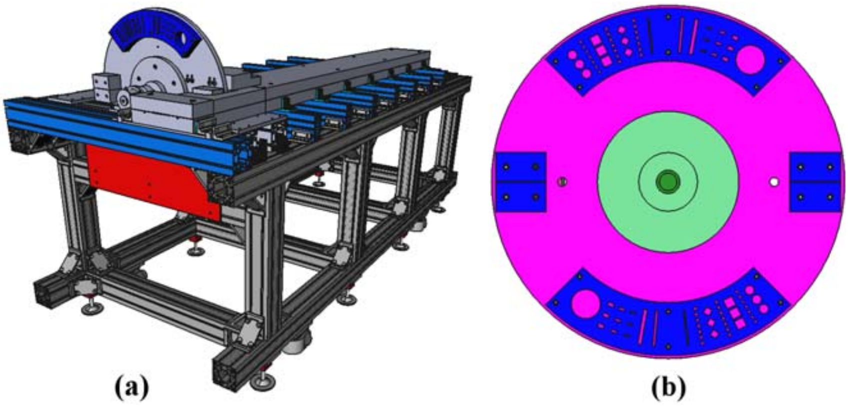


Figure 4. (a) The DTU test-rig: 3D rendering of the entire setup; (b) detail of the model wheel with resolution targets.

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