Detection efficiency of the ESS Target Imaging System: Monte Carlo simulations

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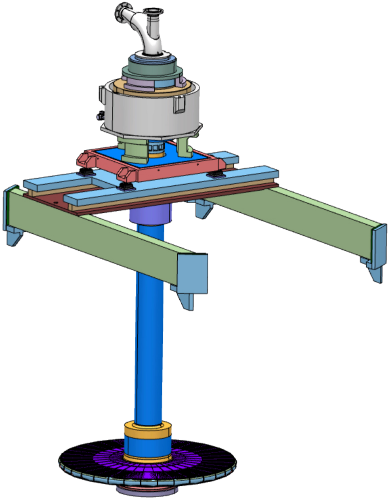
Outline

- The ESS target imaging system
  - Motivation and goals
  - Principle of target imaging
  - Proposed realization
  - Neutronic simulations
- Target image reconstruction
  - Methods and approximations
  - Monte Carlo simulations
  - Preliminary results
- Status and outlook
  - Code development
  - Test rig

Motivation and goals



The ESS Target Wheel…

- 2.5 m diameter
- suspended on a 6 m long shaft
- 36 sectors of 10° each
- 7000 tungsten bricks (3 tons)
- 2500 tons of shielding steel around

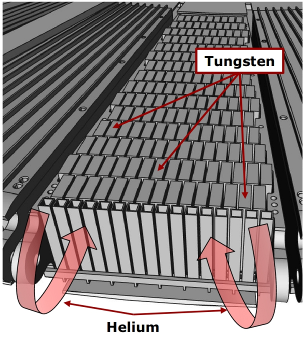
…will operate in extreme conditions

- 3 MW heat deposit from 5 MW proton beam
- 2.86 ms long proton pulses with 4% duty cycle
- 7 million 100°C thermal cycles per year

Motivation and goals

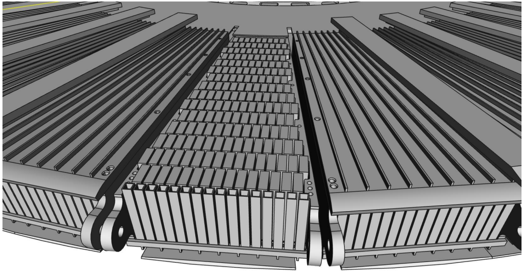
Tungsten bricks operate in a **brittle regime** after exposure to radiation

- Conditions may induce the **cleaving of the tungsten bricks**
- Local reconfiguration or accumulation of small debris may result in the **blocking of the coolant channels**
- **Thermal and pressure stresses may not be relieved**, affecting the actual lifetime of the target wheel



Important to know from an operations perspective if the tungsten geometry is preserved over the 5 years of expected lifetime of the target wheel

Principle of target imaging



Activation of the tungsten bricks is mainly due to hadrons.

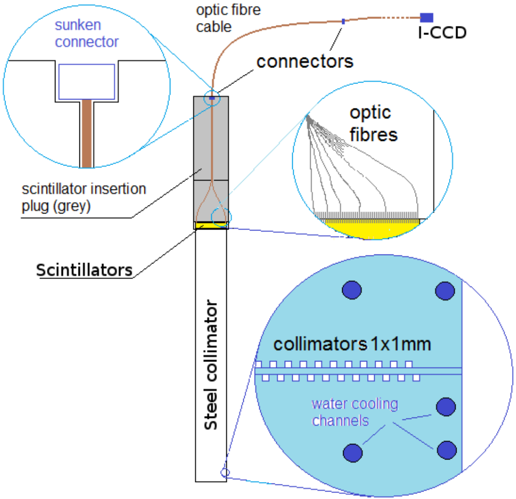
The **spatial distribution** of the decay gammas can be imaged through the target vessel.

The is TIS intended to provide high spatial resolution imaging of the decay gammas from the target wheel.

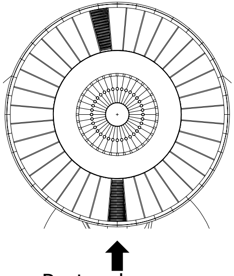
The image of the target **inner structure** can be used to confirm the **correct operation conditions.**

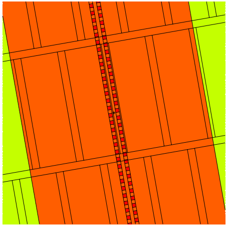
Proposed realization

- Brick size: $1\times3\times8$ cm^3
- Width of cooling channels: 0.2 cm
- Required maximum spatial resolution: 0.1 cm
- Gamma emission collimated by means of a **2.8 m steel block with syncopated 1x1 mm^2 grooves** to ensure complete radial coverage of the wheel
- **Azimuthal coverage** achieved by means of the wheel rotation
- **An array of scintillators** is placed on top of the collimator block
- Scintillators **coupled to optical fibers** to convey the scintillation light to a high-sensitivity I-sCMOS camera



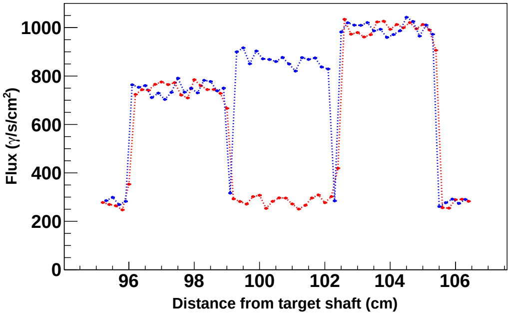
Neutronic simulations





Simulation workflow:

- MCNPX simulation with **protons** on the first sector
- CINDER'90 to calculate **nuclide inventory after 1 s** on the **first sector**
- **Gamma source** (bricks+vessel) copied to the imaged sector
- MCNPX simulation to calculate the **gamma flux** at scintillators
- Independent MCNPX simulation for gamma and neutron **background** evaluation

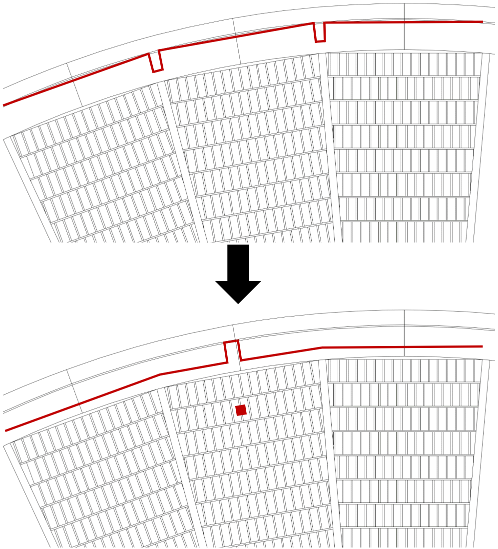


Methods and approximations

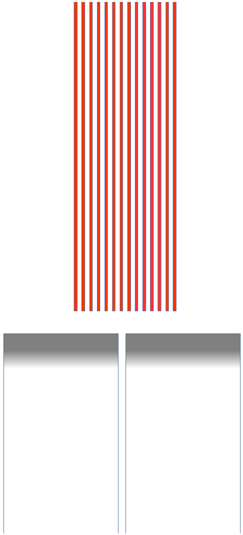
Target imaging is done in **two stages**:

- Normal operation: **full-arc**, **time-averaged** acquisition for each individual sector;
- High-resolution operation: narrow gating **contouring** the problematic spot.

During high-resolution operation, **on-chip data accumulation** across successive rotations is performed to limit the final readout noise.



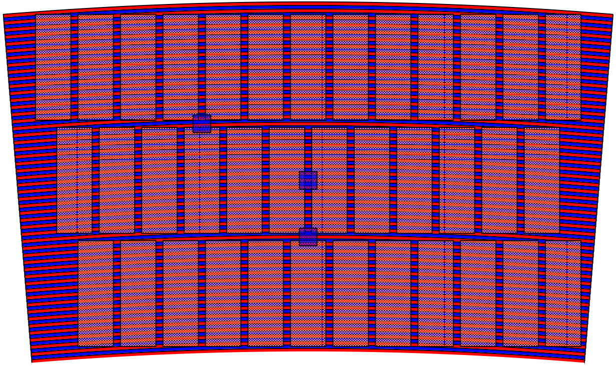
Methods and approximations



The first implementation of the code is based on **two approximations**:

- **thin-layer (2D)**: given the attenuation length for 686 keV photons in tungsten, **only the top cm** is responsible for the measured signal;
- **cell rejection**: the collimator allows only gammas perpendicular to the target surface to reach the scintillators, so **no blurring** is included in the simulations.

Monte Carlo simulations



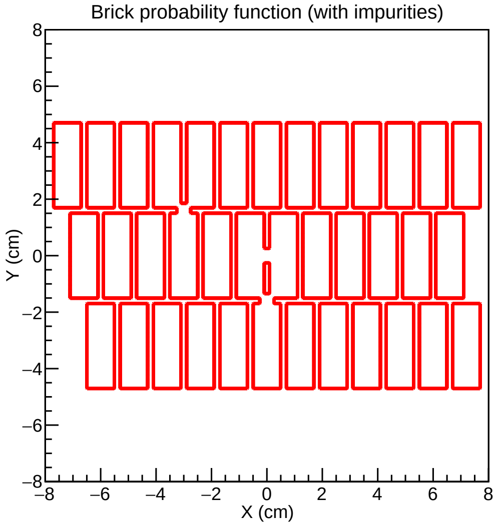
The code is fully-integrated with the ROOT framework:

- Bricks and impurities are instances of **TBox objects**, thus 3D-ready;
- No limit to the number, position or shape of the simulated objects;
- Collimators are instances of TArc objects grouped into a **TH2D** $(\mathbf{r}, \theta)$ **histogram**.

Monte Carlo simulations

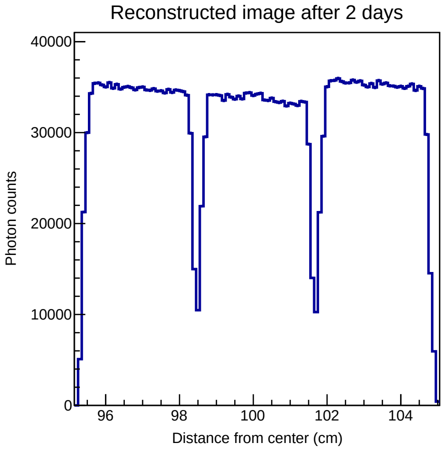
From the objects in the geometry, a Probability Distribution Function is defined:

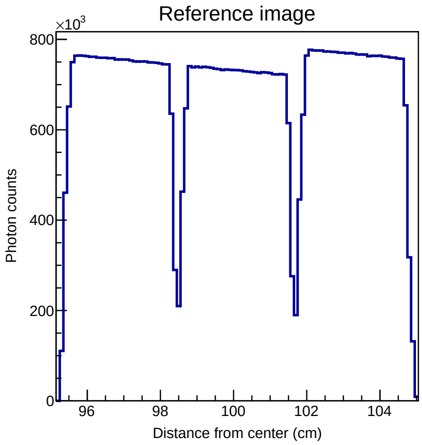
- points, corresponding to emitted gammas, are **sampled uniformly** within the domain (wheel segment);
- hits in the detectors (arcs) are recorded if the sampled point is within the a brick or impurity;
- the number of sampled points is proportional to the **TIS acquisition time**;
- by default, the **specific activity** of each object is the same, i.e. impurities are fragments of the spallation tungsten;
- the relative intensity of the emission from each object can be adjusted to **simulate different materials**;



Preliminary results

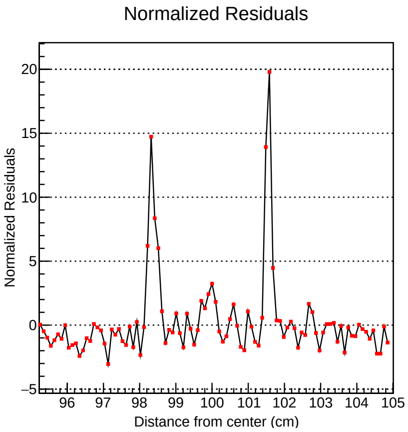
After the chosen exposure time (2 days), the collected image (left) is compared to a **higher-statistics ideal image** (right) obtained from a clean PDF, representing a healthy target.

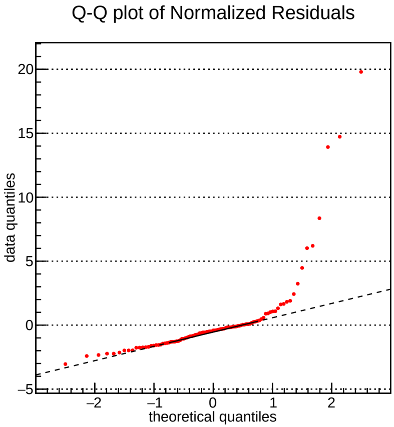




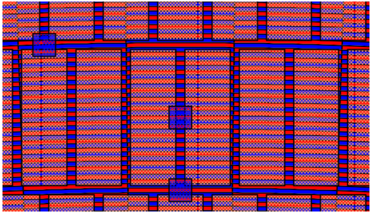
Preliminary results

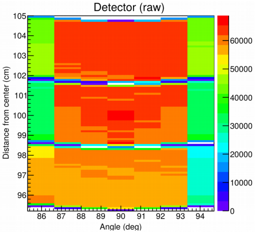
The images are compared by means of the **Pearson's χ^2 homogeneity test**, which calculates the probability for the **hypothesis of identity** to hold. The analysis of the **normalized residuals** locates the anomalous bins and the **Q-Q plot** estimates the probability for the residuals fluctuations to be normally distributed.



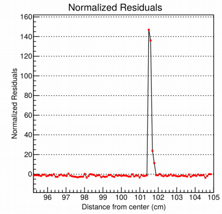


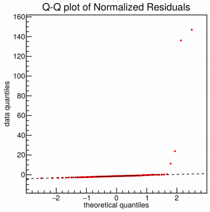
Preliminary results

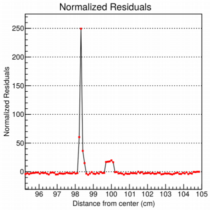


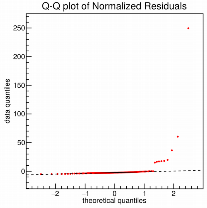


Bin	pValue
1	0.1
2	0.93
3	0
4	0
5	0.64
6	0.79
7	0.84



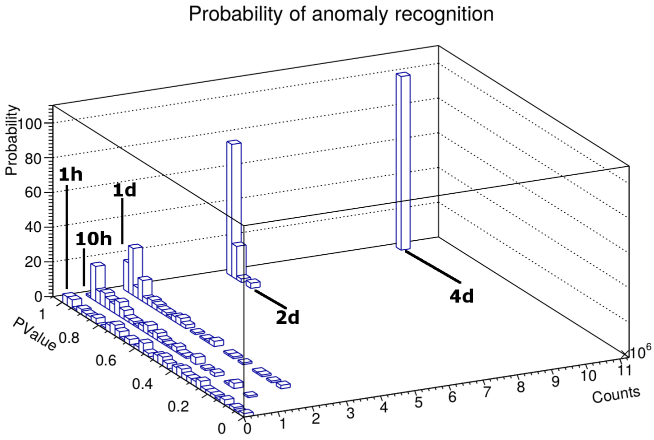






Increasing the number of angular bins (7 bins) and iterating the χ^2 test allows to **identify the location of the anomaly** and provides a **2D reconstruction** of the imaged target sector. The image spatial resolution is proportional to the number of angular bins.

Preliminary results



The Pearson's test is a statistical estimator and its reliability must be evaluated to **avoid false positive errors**:

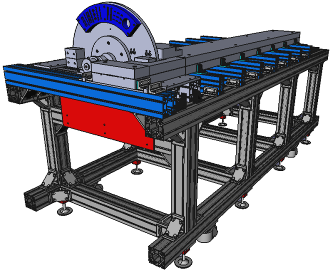
- after **1h of acquisition**, the test is not able to identify any of the anomalies introduced (**14%**);
- after **10h**, the probability of getting a reliable answer is **41%**;
- after **1d**, the probability is increased to **65%**;
- **above 2d** of acquisition, the adopted test is **completely reliable**.

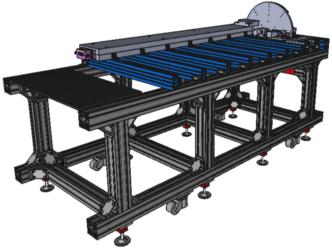
Code development

The code presented is the first step in the development of an **image reconstruction and anomaly detection protocol** and will serve as the basis for the future design of the TIS data acquisition software. However, several aspects of the image reconstruction methodology require further investigation:

- introduce **background and noise effects**;
- simulate impurities of **different size and specific activity**;
- **automate the algorithm** for blind analysis (splitting and re-iteration);
- **randomize the anomaly placement** to fully test the blind analysis procedure;
- implement **different statistical checks** to cross-verify the Pearson's test;
- introduce a realistic **description of the camera gating**, mainly in terms of dead-time and maximum achievable fps.

Test rig





A **test-rig** specifically designed for the DTU ^{60}Co Terabalt source is currently under construction and will be used as a **proof of principle** for the imaging system.

The **gamma intensity** of the ^{60}Co source is comparable to that of the ESS target wheel.

It will allow to perform tests under conditions **relevant to the actual ESS system**.

Test rig

The test-rig will give the opportunity to investigate several aspects:

- **Spatial resolution** of the system: 1 mm, 0.5 mm grooves and several resolution targets on the wheel
- **Scintillator and fiber efficiency** in detection and transmission of the signal (losses due to attenuation, couplings and connections, radiation damage, etc.)
- Heating elements and temperature sensors to study the **signal degradation** at ESS operating conditions
- **Gating techniques and software controls**:
    1. Intelligent gating
    2. Signal processing
    3. Image reconstruction
    4. LabView for device controls (motors, encoders, sensors, heating elements, etc.)

Thank you for your attention

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