Neutron Scattering Collimation Wheel Instrument for Imaging Research

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Abstract. The design of a state-of-the-art selector wheel instrument to support the area of neutron imaging research (neutron radiography/tomography) is discussed. The selector wheel is installed on the DINGO Radiography instrument at the Bragg Institute HB2 beamline at ANSTO in Sidney Aus. The selector wheel consists of a single axis drum filled with a wax/steel shielding mixture and six square cutouts for neutron optics and a larger solid shielding sector to act as a shutter. This paper focuses on the details of design and shielding of the selector wheel.

1. Introduction

The DINGO Radiography instrument is the first at the Bragg Institute to use the HB2 thermal neutron beam with an estimated flux of up to 4.7 x 107 [n/cm2s] at the sample [2]. The main components of the DINGO instrument consist of a primary collimator, collimation wheel, Tertiary & Fast Shutter, sample stage; detector camera and beam stop (Figure 2). The collimation wheel is a single axis drum filled with a wax/steel shielding mixture and six square cutouts for neutron optics and a larger solid shielding sector to act as a shutter.

The DINGO instrument covers a large area of scientific research such as medical applications, biology and environmental science, geology and engineering science as well industrial application, which are key areas for future technology and industrial developments in Australia. The selector wheel shutter unit, shown in figure 1 below, combines two different functions in one item. The first function is to work as an instrument shutter and the second one is to work as a selector wheel. The selector wheel assembly component provides selective aperture options for high resolution or phase contrast imaging and separates the two beams coming from the in-pile collimator. One beam is blocked and the other passes the selector wheel insert and is used for an imaging experiment. A positioning accuracy of 0.01° step width is achieved. The selector wheel was designed with a stepped housing to mate with the inserts and prevent direct shine from the beam.

The main component of the selector wheel is a 2.5 ton aperture wheel filled with a shielding mixture. It provides six openings, which are equipped with various neutron beam optics plus a solid 'shutter' section to block the beam. Utilizing the solid section as a shutter requires complex interaction between the safety [1] interlock and motion control systems. A standardized Galil based motion system controls the movement of the wheel while a Pilz safety PLC specifies the desired position and handles other safety aspects of the instrument. A shielded absolute SSI encoder is employed to give high accuracy feedback on the position in conjunction with a number or limit switches.

Figure 1. ANSTO Selector Wheel Shutter Unit

The selector wheel is located in the DINGO beamline just after the neutron guides but before the window slits and collimator leading up to the sample stage. Please see figure 2 below showing the beamline layout as well as a photo of the actual sample stage area.

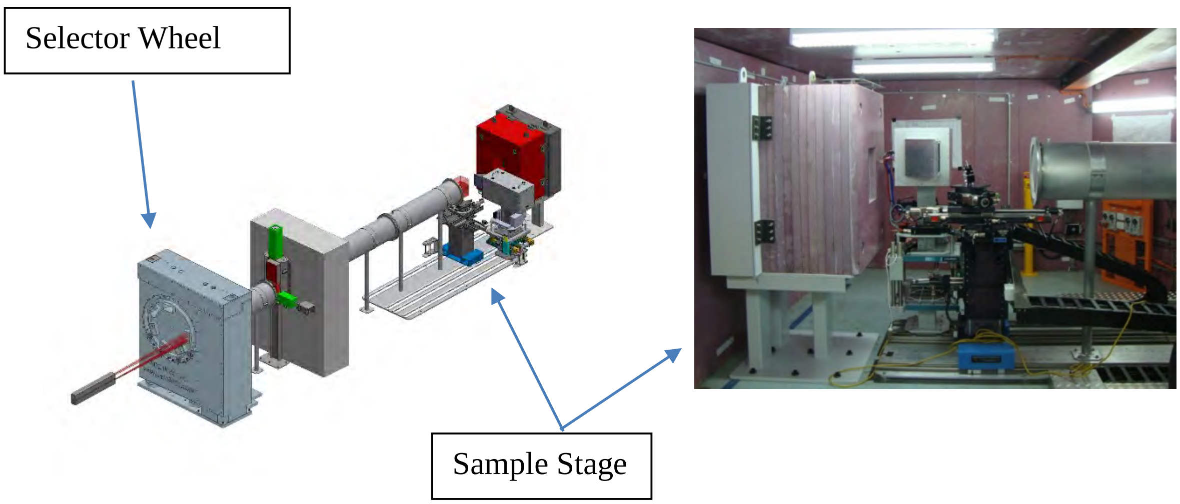

Figure 2. DINGO instrument layout

2. Shutter Wheel Design Parameters

The design criteria for shutter wheel instrument includes: an indexing wheel with six insert locations; inserts that are adjustable in all 6 degrees of freedom; a wheel that rotates at a speed of 6º per sec; end of travel limit switches and safety switch; neutron shielding; and finally no direct neutron path was allowed. Major components of the selector wheel include; slew bearing driving the rotational motion; radial bearing constraining the upstream end of the indexing wheel; precision machining on large diameter components; stepped chambers filled with neutron shielding to eliminate direct neutron paths; inserts that were designed to adjust in all 6 degrees of freedom and can be flipped. The engineering, FEA modeling, design, and detail of the system from concept to final design took 5 months.

The range of rotation was 360 degrees to allow access to all apertures. The radial resolution of position was 0.1^{O} with repeatability of 0.2^{O} and absolute accuracy of 0.01^{O}. These specifications were chosen to ensure the beam passed consistently through the center of the optics. The drive motor is located in radiation and must be radiation hard. The rotation speed is 6^{O}/min. All structural components are non-magnetic. These parameters are summarized in Table 1 below.

Table 1. Collimation Wheel Instrument Design Requirements

Range	360°
Resolution	0.1°
Repeatability	0.2°
Absolute Accuracy	0.01°
Travel Speed	6°/min
Radiation Hardness	Yes
Vacuum Rating	not required
Non-Magnetic Material	Yes

A heavy duty rotation bearing from a German manufactured supplier was used. Upon arrival at ADC, inspection showed errors in manufacturing of the bearing. The bearing was returned to the manufacturer for corrective action. A radiation hard motor was used but also failed initial QA testing and was returned.. Each of these issues was properly document as part of ADC ISO 9001 quality control and corrective actions were taken immediately to meet project requirements.

3. Neutron Shielding Mix Prototyping

A prototype of the neutron shielding for the shutter wheel assembly was performed at ADC. ANSTO had provided requirements for the shielding mix including materials and density Specifications include: mild steel shot, boron carbide, and refined paraffin. ADC was required to develop a process to implement the shielding mix.

ADC first constructed a steel chamber with a right triangular cross section, 197 mm by 203 mm, and with a height of 404 mm, for a volume of 8.08×10^6 mm^3, or approximately 8 liters. The shape was chosen to test sharp angles due to the angles among braces inside the main housing assembly, and the depth is comparable to the internal depth of the main housing piece, at 550 mm. The structure was welded together and all joints were sealed with a silicon based caulk. Aluminum plates where attached to the chamber with cable ties, with approximately 80 mm extending above the top of the steel chamber to act as a reservoir for molten wax. The mold was filled with the steel shot, boron carbide, and paraffin wax. Figure 3 below shows the prototype vessel.

Figure 3. Triangular cross section steel test chamber with aluminum plate reservoir and heating tape.

A thermocouple was inserted as deep into the mix as possible. The steel mold was wrapped in heating tape and then covered with aluminum foil in half width strips, covering the top third, middle third, then lower third and base. The mold was wrapped in foam insulation as shown in figure 4 below, and then slowly heated.

Figure 4. The steel mold filled with proper mixtures while heating with tape heaters

The internal temperature was recorded, close to the center of the steel and boron carbide mixture, and on the outside of the aluminum foil sheathing. After melting, the temperature of the paraffin was monitored, to ensure that it reached the required specification. The lower portion was removed of the aluminum foil, exposing the bottom third of the mold to air. The mold was supported on three feet allowing air to pass under the chamber to facilitate bottom up cooling and solidification.

Results

The top couple centimeters of the shielding mix are not as hard or regular as the rest, and were not fully wetted by the wax. This is a result of a leak which did not permit us to have an adequate reservoir of molten wax. The surface of the shielding block looked smooth over half its area. In figure 5 below, one can clearly see shot which has stuck to the walls of the mold when it was split open. The entire surface was solid, although grit could be chiseled or cut away. This bock had a volume of approximately 7780 cm^3, and a mass of 40.5 kg for a density of 5.2 g/cm^3. The shielding density specification was greater than 5.0 g/cm^3, thereby exceeding requirements.

The block of shielding material was removed from the mold and then split open, approximately on one third and two thirds up, along what was the horizontal axis while pouring. Figure 6 below shows sections of shielding material after removal from the block.

The final result was quite satisfactory, other than near the pouring surface which was partially depleted of wax. When a portion of the block was exposed it was solid, *i.e.* all the shot were well held in the matrix and only became loose directly from cutting or chiseling. The block was both solid and homogeneous.

Figure 5. The mold with the finished shielding block, opened for testing

Figure 6. Faces of the shielding block after being broken open

4. Factory Acceptance Testing

A factory acceptance test (FAT) document describing the tests and methods was developed by ADC to the satisfaction of ANSTO. At the FAT, the selector wheel was verified to meet all specifications. Open loop and closed loop positioning tests were performed and the wheel was rotated more times than was expected in its lifetime. Rotational position accuracy, resolution, and repeatability, were verified using an electronic tilt meter mounted to the face of the wheel which compared the actual position with the measured position. The results of the FAT are listed below in Table 2. Please note that each of the items in this list were verified with independent instruments and were found to exceed specifications.

Other than density measurements, the effectiveness of the shielding can only be tested in a neutron beam. For this reason, we relied on ANSTO's experience regarding the density of the mix for adequacy of neutron shielding.

Table 2. Summary of FAT

No	Areas of testing	FAT Conclusion
1	Dimensional requirements	Comply*
2	Accuracy	Comply*
3	Repeatability	Comply*
4	Adjustable inserts	Comply*
5	Multiple revolutions	Comply*
6	Total time for one complete revolution at various speeds	Comply*
7	Motion Control Cam and limit switches activated	Comply*
8	All cams have sufficient adjustability	Comply*
9	All limit switches have sufficient adjustability	Comply*
	Safety home cam activates safety limit switch	Comply*
	Backlash is within a requirement range	Comply*
	Stopping time at various speeds	Comply*
	Acceleration/deceleration times sufficient such that the cams do not overshoot limit switches	Comply*
	Check each position	Comply*
	The wheel is able to be moved from a position where the motion control cam is activating motion control limit switch 1 through 355 degrees where it contacts motion control limit switch 2.	Comply*
	Provisions for cabling	Comply*
	Use a probe for repeatability so something comes down and touches the probe, goes away and then comes back.	Comply*
	Does the wheel lock?	Comply*

*During the Factory Acceptance Test (FAT) extensive test were conducted and the results showed the Neutron Scattering Collimation Wheel Instrument was in compliant or exceeded the design requirements.

Additional data supporting the FAT results is provided in figure 7 below. This is an actual acceptance sheet required by ANSTO.

Item	Type of Control	Design Parameter	Range of provided motion (This is the range of this motion that will be provided in the adjustment system) - i.e. Adjustability	Absolute Accuracy (This is the level to which you will be able to repeatadly get to the same spot as last time)	Importance Level
1	Selector Wheel & Base plate alignment	Height	± 1mm		B
		Length	± 1mm		B
		Width	± 1mm		B
		Tilt (Roll)	± 1º	± 0.1º	B
		Tilt (Pitch)	± 1º	± 0.1º	B
		Yaw	± 1º	± 0.1º	B
2	Selector Wheel Housing Proximity Location with existing Walls.	Clearance between existing infrastructure: Range	± 10mm		A
3	Selector Wheel	Range	360º		A
		Resolution	0.1º		B
		Precision	0.01º		B
		Repeatability	0.2º		B
		Travel Speed	6º / min.		C
4	Shutter Inserts (*) *Refer to Figure Below:*	X, Y and Z	± 2mm	± 0.2mm	B
		Tilt (Roll)	± 1º	± 0.1º	B
		Tilt (Pitch)	± 1º	± 0.1º	B
		Yaw	± 1º	± 0.1º	B
5	Distance Between Reactor Face and Inserts	Length	<50mm (close as possible)		A

* the absolute accuracy required for the shutter inserts with respect to the position of the neutron beam may be found using a fixed insert solution,

Definitions:

Resolution - *This is the minimum change on the axes that can be detected on the encoder*

Preciosion - *This is the minimum change that you will receive when one step is sent to the motor*

Figure 7.Selector Wheel Housing Unit Accuracies

5. Conclusions

The DINGO instrument was successfully commissioned during 2013 and saw its first neutron radiography image during August of that year. The ADC selector wheel has been shown to be a robust and reliable component of this beamline.

5. References

[1] The Interaction Between Safety Interlock And Motion Control Systems On The Dingo Radiography Instrument At The Opal Research Reactor; Proceedings of ICALEPCS2013, San Francisco, CA, USA

[2] The Neutron Beam Expansion Program at the Bragg Institute; International Workshop on Neutron Optics and Detectors (NOP&D 2013) Journal of Physics: Conference Series 528 (2014) 012026