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MOTION CONTROL SYSTEM FOR THE EUROPEAN SPALLATION SOURCE TARGET WHEEL

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Abstract

The European Spallation Source (ESS) linear accelerator will deliver high energy proton bunches to tungsten sectors on a rotating 'target wheel', which will produce neutrons for scientific research through a nuclear spallation process. The motion control system of the target wheel presents engineering challenges, such as: velocity and phase stability requirements to precisely align individual tungsten sectors with proton bunches from the accelerator; a high moment of inertia due to the composition and distribution of mass on the wheel; limitations on the physical space to integrate control components, and components for associated safety systems; and, some components being exposed to a high radiation environment. The motion control system being prototyped employs components that satisfy the constraints on the physical space and radiation environment. Precise velocity and phasing of the target wheel are achieved by using a grating disc incremental encoder coupled to the main wheel shaft, to enable the transit of each tungsten sector to be synchronised with a reference signal from the centralised ESS timing system, which also controls the production of proton bunches from the accelerator.

INTRODUCTION

The European Spallation Source (ESS) European Research Infrastructure Consortium (ERIC) is an ambitious project to build the world's most brilliant neutron source near Lund, Sweden. A 2 GeV 5 MW linear proton accelerator will deliver proton bunches to a rotating spallation target wheel with a pulse repetition rate of approximately 14 Hz. Interaction of the protons with the spallation material produces neutrons that will be utilised for research by a suite of 22 neutron instruments.

The target wheel and shaft systems are contained within the target monolith, which is located in the target building at the end of the accelerator-to-target area (see Fig. 1). The wheel is a disc composed of 36 sectors of tungsten blocks contained within a steel shroud and cooled by flowing helium. It is located deep within the target monolith at the base of a 7 m long shaft that positions the wheel at the level of the incoming proton beam. The target wheel is being produced by ESS partners in Spain, ESS Bilbao.

During normal operations, the wheel rotates around a vertical axis at a rate of 23 rpm to bring adjacent sectors into alignment with the impact consecutive proton bunches to optimize neutron production. The rotation of

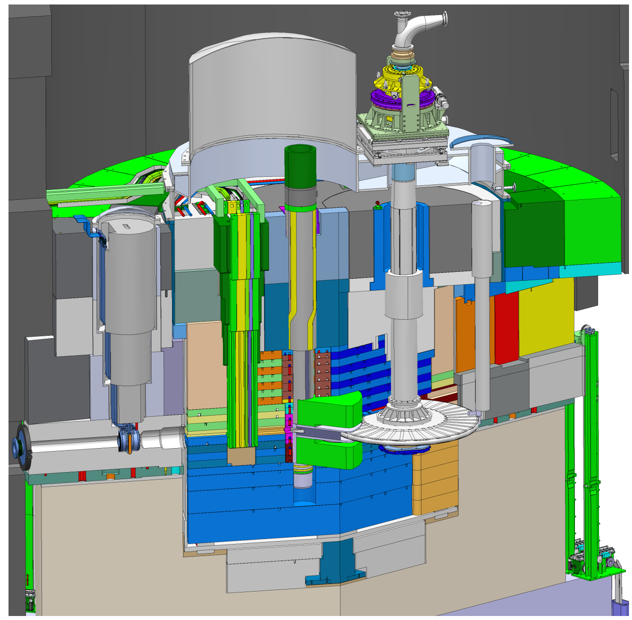

Figure 1: CAD model of the ESS Target, showing the target wheel, moderator and other components within the monolith.

the wheel is timed with the arrival of the proton beam such that the beam interacts with any given sector once every 2.6 seconds.

In the following sections we describe constraints on the design of the motion control system for the target wheel, the motion control solution that has been selected and the physical components of that solution, and finally we describe a mechanical test assembly which will facilitate development of the motion control system.

DESIGN CONSTRAINTS

Physical and environmental aspects of the overall target assembly influenced the design of the target wheel motion control system. Some constraints of particular relevance are described below.

Radiation Environment

One important design constraint is to shield the motion control components from the intense neutron flux and other radiation generated by the target.

The required level of shielding from fast neutrons (>0.1 MeV) is achieved through locating as much steel as possible between the target and the motor and other control components, to close all possible gaps and finally to employ neutron-absorbing material in the monolith lid structure, on which the target rotation and motion control components rest.

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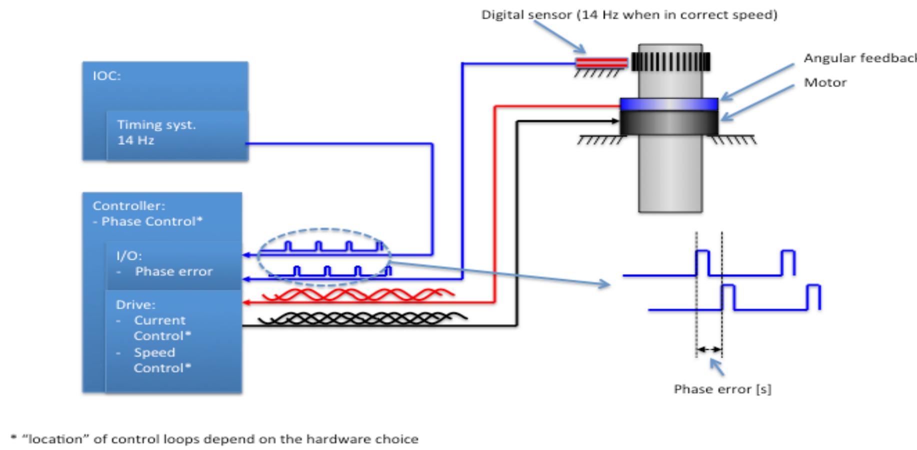

Figure 2: Equipment foreseen to control the target wheel.

The shielding has been based on the ability to provide sufficient lifetime to the NdFeB magnets for the drive motor. A lifetime limit for total fast neutron exposure has been defined as $1{,}8 \times 10^{12}$ n/cm^2. The currently suggested geometry with a 25 cm layer of borated concrete in the monolith should provide a 42 year technical lifetime for a standard, off the shelf, permanently magnetised motor.

Mechanical Space

The height of the drive unit is limited by the need for heavy shielding between the highly activated connection cell area and the open area above it, the so-called high-bay.

The speed and phase measurement system, described further below, is therefore designed with a limited axial space. Notable is that that speed will be monitored, apart from by the motion control system described here, also by Target Safety System (TSS) and the Machine Protection System For Target (MPSFT), each of them requiring independent, redundant and diversified sensor configuration.

Rotor-Dynamics

Important motives have been to design the rotor suspension to be sufficiently stiff to be able to operate below the first natural frequency. Some rotor-related data are presented in Table 1. The rotor is very heavy and has a very high inertia.

Phasing Accuracy

Requirements on accuracy for the motion control system are based on the need to synchronise the rotation of the target wheel with the operation of the accelerator, such that tungsten sectors are located within +/-2 mm, on the circumference of the wheel, of the required position at the moment of the accelerator proton pulse.

Absolute Positioning

The motion control system shall also be able to place the target wheel in an arbitrary angular position, and to maintain that position at zero velocity, with the same precision of +/-2 mm on the circumference.

Table 1: Dynamical Properties of the Rotor

Property	Value
Total mass	19752 kg
Rotating mass	11300 kg
Moment of inertia	4500 kgm^2
Thrust bearing	718/630 MPB
Bearing load (C/P)	338 kN/92 kN = 4
Estimated friction	100 Nm
Number of pole pairs	35
Cogging torque	TBD
Cogging frequency	TBD
Motor rotor moment of inertia	1.25 kgm^2

MOTION CONTROL STRATEGY

The target wheel has three operational modes: phasing; positioning; and parking. The phasing mode is used when the wheel needs to be synchronized to the proton pulse (normal operation mode). The positioning mode is used for rotating the wheel to a certain angle and maintaining that position. The parking mode is used to lower the wheel such that it rests on the bottom of the monolith.

In order to enable operation in these modes the actual phase error and the actual position need to be measured. The actual phase is determined by measuring the time difference between a pulse train generated by a digital sensor, sensing on a grating disc incremental encoder (described below), and a reference pulse train generated by the ESS timing system. Alternatively, the phase error can also be measured by latching positions from an absolute encoder for each trigger signal from the timing system. A phase PID controller then alters the speed set point of the speed controller, resulting in a controlled phase. In the positioning mode, the angular feedback sensor is used as actual value for the position control.

Fig. 2 show the equipment foreseen to be used to control the target wheel.

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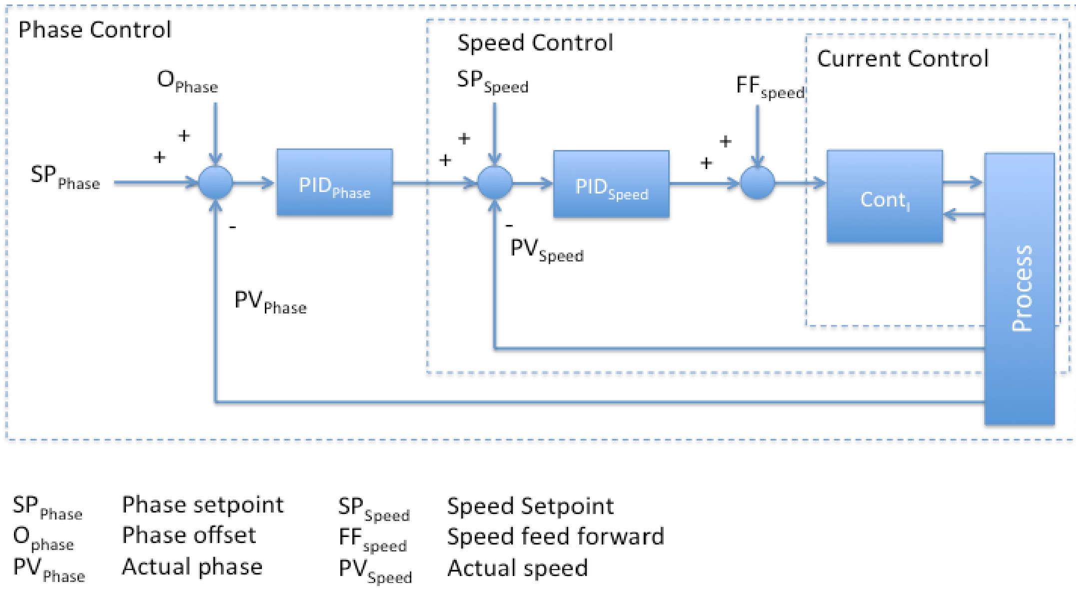

Figure 3: Cascaded control loops.

Motor

A direct drive torque motor was selected since it allows a compact solution that could be well integrated into the mechanical design. This kind of motor can be operated directly on the main shaft without a gearbox and thereby avoids grease in the radiation area and also minimizing maintenance.

Encoder

An encoder is needed for commutation of the motor and for the positioning, phasing and safety related algorithms. In order to withstand the radiation environment an encoder with separate electronics of an inductive type was chosen. The chosen encoder can accommodate multiple heads reading from the same measurement scale which results in a compact and flexible mounting. The multiple heads allow independent wheel position measurements to be taken by the TSS and MPSFT systems.

Grating Disc and Digital Sensors

The grating disc is a mechanical part of the target wheel assembly and is used to provide information about the location of each sector to the phasing algorithm.

The grating disc has 36 holes that are aligned with the 36 sectors of the target wheel, in a way that the beginning of each hole of the grating disc represents the beginning of the allowed area on each of the sector on the target wheel. The grating disc also has one index hole to be used as reference for a homing procedure. The TSS and MPSFT systems require higher resolution signals, so an additional row of 360 notches were added on the outer diameter of the grating disc. This will generate 10 pulses for each sector of the target wheel.

The grating disc will be mounted directly on the shaft of the target wheel.

Digital sensors will be used to detect the holes in the grating disc while the shaft is rotating. Different sensor technologies were considered for this task, with main constraints being the response time and radiation environment. Sensors that were considered include:

- Optical sensor with radiation hard and heat resistant fibres.
- Capacitive sensor with separate electronics.
- Inductive sensor with separate electronics.
- Hall effect sensor.

The initial estimates of radiation levels were very high (10 MGray levels over the intended lifetime of the sensors). It was very difficult to find a supplier that would guarantee their product will work in that environment, even with products with separate electronics. The digital sensor approach considered at that time was to have an amplifier in an area with lower radiation and radiation hard optical fibres with special glass lenses located at the grating disc that would transmit the signal.

After improved shielding was included in the design, estimated radiation levels became significantly lower, around 1 kGray total dose in 5 years. An optical sensor with heat resistant fibres and adequate response time has now been chosen as the most practical solution. Work of this sensor will be tested on the target wheel motion control test assembly, described later.

Future tests will also include testing the performance of the heat resistant fibres after being exposed to expected radiation levels in one of the ESS partner facilities.

Drive

The drive needs to handle commutation, current and velocity control of the motor. A servo drive was chosen since it, in addition to the required tasks, also can handle position control resulting in high flexibility.

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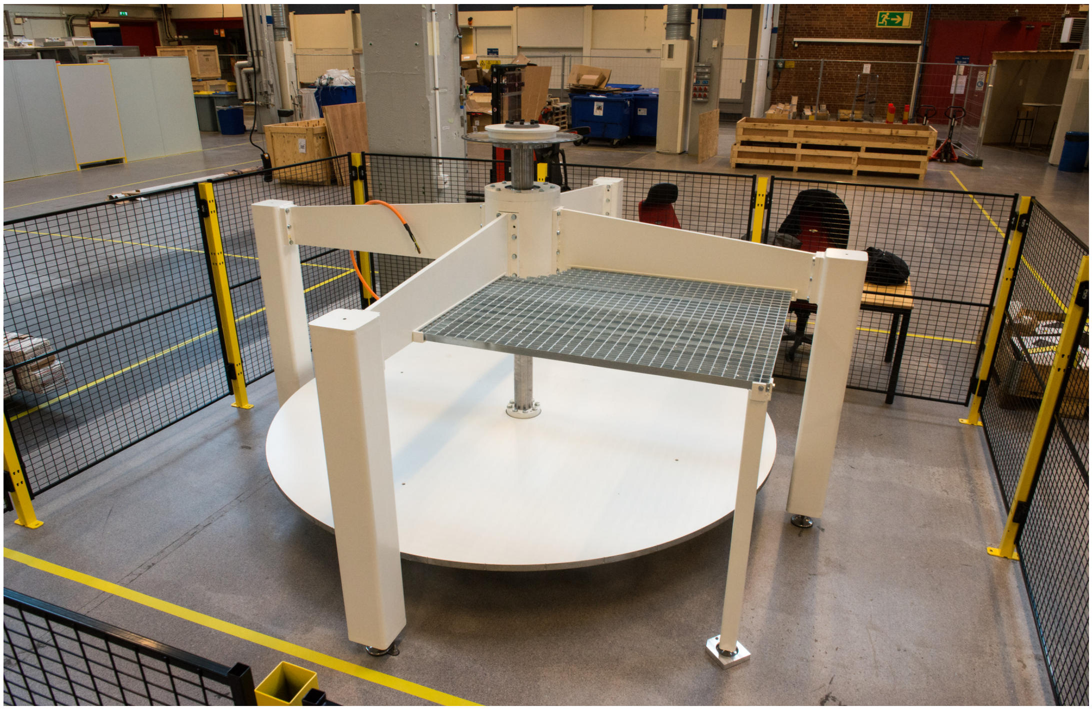

Figure 4: The target wheel motion control test assembly.

Control Algorithm

The needed control algorithm can be dived into three cascaded control loops, see Fig. 3:

1. Current control (commutation)
2. Speed control
3. Phase / Position control

Depending on hardware choice these control loops can be executed in different locations. The current control loop needs to be the fastest and is normally executed inside the motor drive. Due to the high inertia of the target wheel and the mechanical resonance frequencies, special considerations are needed in tuning and adapting the control loops.

Facility Integration

ESS have elected to use a distributed, delay-compensated timing system produced by Micro-Research Finland. This system provides the signals required to synchronise the operation of the entire facility, from the proton source at one end, through to the neutron detectors on the neutron science instruments at the other.

An industrial computer, equipped with a timing receiver, will be integrated with the other target wheel motion control electronics. A digital pulse train, running at the accelerator pulse repetition rate, can be configured with an appropriate phase to provide a reference to specify the desired speed and phase of the target wheel motion control system.

The signal from the digital sensors on the grating disc will be used by the motion control algorithms, but also timestamped directly in hardware by the timing receiver in the industrial computer. This will provide an independent measurement of the phase and speed stability of the target wheel and will be published as metadata for ingest by software agents and machine operators.

ESS controls will be based on the Experimental Physics and Industrial Control System (EPICS) and, ultimately, control of the target wheel will be managed by machine operators though this EPICS backbone.

PROTOTYPING ACTIVITIES

A test assembly, approximating some essential mechanical characteristics of the ESS target wheel, has been manufactured to facilitate development of the motion control system. The test assembly is shown in Fig. 4. This test assembly will enable early development and verification of the motion control system without requiring the actual ESS target system to be available.

The test assembly has been slightly scaled down from the full-scale target wheel, drive and shaft to reduce costs. However the wheel diameter and operating speed are the same as for the real target. To ensure reasonably representative conditions the scaling has been done with the aim to keep certain key relations constant. Table 2 shows a comparison between the test assembly and for the full-scale target wheel.

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Table 2: Mechanical Comparison of the Target Wheel and the Target Wheel Motion Control Test Assembly

Property	**Full- scale**	**Test Rig**
Total mass	19752 kg	2034 kg
Rotating mass	11300 kg	1250 kg
Moment of inertia	4500 kgm^2	894 kgm^2
Thrust bearing	718/630 MPB	7220 BECBM
Bearing load (C/P)	338 kN/ 92 kN = 4	87 kN/7,4 kN= 11
Estimated friction	100 Nm	25 Nm
Motor (Siemens)	MST530C-0010-F	MST210E-0027-F
Number of pole pairs	35	20
Cogging torque	TBD	TBD
Cogging frequency	TBD	TBD
Motor rotor moment of inertia	1.25 kgm^2	0,024 kgm^2
Rated torque/Max torque at 25 rpm	1200 Nm/2700 Nm	240 Nm/500 Nm
Rated torque/ Estimated friction	12	10
Rated torque/ Inertia	0,3	0,3
Rotor inertia/ Motor rotor inertia	3600	21000
First bending natural frequency	2,2 Hz	6,0 Hz
First torsional natural frequency	9,0 Hz	4,0 Hz

CONCLUSION

The European Spallation Source target wheel will be a critical component of the world's most brilliant neutron science facility. A motion control system to ensure accurate synchronisation of the target wheel with the rest of the facility is required. Here some of the main design constraints have been described, as has the proposed solution to the motion control problem. Future development will now be facilitated by the construction of a test assembly specifically for this purpose.