PROTON BEAM MEASUREMENT STRATEGY FOR THE 5 MW EUROPEAN SPALLATION SOURCE TARGET

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Abstract

Approaching construction phase in Lund, Sweden, the European Spallation Source (ESS) consists of a superconducting linear accelerator that delivers a 2 GeV, 5 MW proton beam to a rotating tungsten target. As a long pulse neutron source, the ESS does not require an accumulator ring, so the 2.86 ms pulses, with repetition rate of 14 Hz arrive directly from the linear accelerator with low emittance. To avoid damage to target station components, this intense beam must be actively expanded by quadrupoles that produce a centimetre size beamlet, combined with a fast rastering system that paints the beamlet into a 160 mm by 60 mm footprint. Upstream of and within the target station, a suite of devices will measure the beam's density, halo, position, current, and time-of-arrival. Online density measurements are particularly important for machine protection, but present significant challenges. Diverse techniques will provide this measurement within the target station, based upon secondary emission grids, ionisation monitors, luminescent coatings, and Helium gas luminescence. Requirements, system descriptions, and performance estimates will be presented.

INTRODUCTION

As a 5 MW long pulse neutron source, the ESS facility presents significant challenges for beam transport to the target and for beam instrumentation in the target region. Unlike a short pulse source, no accumulator ring is employed, so the transport line must expand the low emittance beam of the linac, and the beam instrumentation systems must assure that the beam remains safe for the target.

During commissioning and setup, the instrumentation systems will see a wide range of beam current, pulse length, and transverse size. With short pulses, measurement performance must support qualification of the transport system and synchronisation of the target wheel. Only then can beam power be increased to production levels. During neutron production, the instrumentation protects the target components by detecting any off-normal beam conditions, and via the machine protect system, inhibiting beam before damage occurs. Because of this function, the instrumentation system must exhibit very high reliability even though some devices live within the harsh environment of the target station.

PROTON BEAM PROPERTIES

The beam transport line to the target fulfils several goals. Primarily, it expands the small beam from the linac into a size that the target components can survive. While serving this function, it keeps beam loss to a minimum, thus reducing component activation and allowing hands-on maintenance. At full power, beam losses above a part in 10^7 per meter can produce too much residual activity. Because existing techniques cannot convincingly simulate beam properties as this level, the transport line retains the small beam size throughout much of its length, only expanding the beam in a shielded drift region downstream of the last magnet.

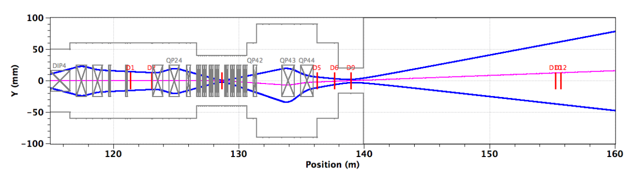

Figure 1: Plot of the vertical beam centroid (magenta) and the 10 sigma envelope (blue) along the transport line to the target. The raster magnets are located at about 128 m, the neutron shield wall at 139 m, and the target at 160 m.

A beam line design based on linear raster scanning achieves these goals [1] with the layout shown in Figure 1. The line focusses the beam through a final waist, thus producing a centimetre-size beamlet at the target. A raster magnet system then scans this beamlet across the target face. The intensity of the moderated neutrons depends on beamlet position. Given the finite moderation time, a raster frequency of tens of kHz will minimise this effect. A neutron shield wall with a small aperture isolates the beam line from target back shine. The beamlet waist and the stationary point about which the beamlet pivots both reside within this aperture.

Table 1 summarises the beam parameters in the transport line and the resulting beam properties at the target station, while Figure 2 depicts the 2-dimensional current distribution at the target face, averaged over time. This distribution represents full power beam during neutron production.

MEASUREMENT REQUIREMENTS

Analysis of the reference design described in the previous section resulted in a set of measurement requirements

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Table 1: Proton Beam Parameters

Parameter	Value
Nominal Power	5 MW
Energy	0.5 to 2 GeV
Pulse current	6.2 to 62.5 mA
Pulse Length	5 to 2860 µs
Repetition rate	14 Hz
Bunching frequency	352 MHz
RMS width in linac	2 mm
RMS width at waist	200 µm
RMS width at target	6 mm
Scanning frequency	up to 40 kHz
Footprint width at target	160 mm
Footprint height at target	60 mm
Peak density at window	90 µA cm^{-2}
Peak density at target	55 µA cm^{-2}

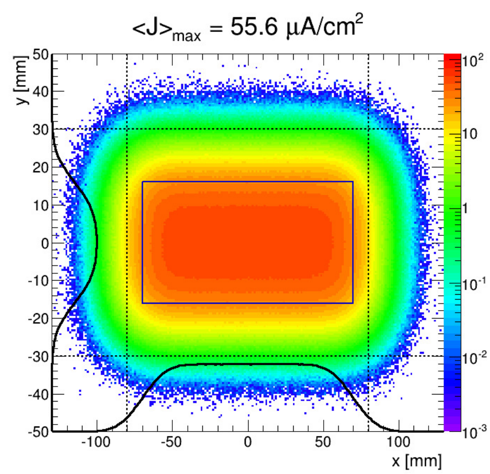

Figure 2: Predicted beam density at target surface.

summarised in Table 2. Errant beam and damaging pulse conditions represent two timescales for off-normal conditions that may damage equipment. Beamline and target hardware should survive a full pulse of errant beam; for example, a current density at the target up to one order of magnitude higher than nominal. If instrumentation detects and reports this condition within 60 ms, the machine protection system could inhibit beam before the next pulse arrives. Damaging beam represents a worst credible beam condition, and all hardware should survive this condition for 20 µs. The accelerator from ion source to target contains about 4 µs of beam and the machine protection system will inhibit beam at the source within 5 µs. Therefore, 10 µs remain for detection of the damaging condition.

The accuracy requirements on density and centroid position measurements are about one half of the allowed variation of these parameters. During the pulse, measurement of the beamlet position versus time will verify proper operation of the raster scanning system. These pulses occur every 71 ms, and in that time, the 33-sector target wheel rotates to the next sector. The instrumentation systems will verify that the beam pulses hit the centre of each sector. Finally, the instrumentation that must be operational during neutron production must have high availability.

Table 2: Beam-on-Target Measurement Requirements

Parameter	Value
Errant beam detection	60 ms
Damaging pulse detection	10 µs
Density accuracy	20%
H centroid accuracy	3 mm
V centroid accuracy	2 mm
Beamlet centroid precision	2 mm
Beamlet measurement interval	1 µs
Target position accuracy	6 mm
Availability goal	99.9%

BEAM INSTRUMENTATION SYSTEMS

Figure 3 shows a schematic layout of the beam instrumentation along with the magnets of the beam delivery system. A proton beam window (PBW) isolates that transport line vacuum on the left from the helium (at atomspheric pressure) within the target monolith on the right. As seen in Figure 4, this window is located near the edge of the monolith, 4.4 m upstream of the target surface. Within the monolith, the beam instrumentation is concentrated in the proton beam window plug and the proton beam instrumentation plug.

In addition to the requirements, the following guidelines informed the development of this instrumentation layout:

- Enough redundancy to meet the availability goal
- Beam Loss Monitors (BLM) located to allow full coverage with no blind spots
- Wire Scanners (WS) and Non-invasive Profile Monitors (NPM) co-located to allow cross calibration
- Beam Current Monitors (BCM) at each end to measure transmission and support redundant reporting of beam on target measurements; BCMs located uptream of interceptive devices to reduce impact of charged particle showers.
- A Beam Position Monitor (BPM) on nearly every quad with three BPMs in a row to measure trajectory into monolith
- No instrumentation between neutron shield wall and the target, a region activated by back shine and difficult to maintain.
- Outside of monolith, no interceptive devices continuously in beam as this could increase local activation in the beam line and background in the neutron instruments.

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The requirement to detect errant beam will be met with multiple techniques. A primary concern is a failure of the raster system leading to elevated current density. Integrating over all or most of a pulse, this density can be observed directly by the profile monitor systems including imaging, multi-wire grids, and the non-invasive monitors based on gas luminescence. Also, BPMs and some of the profile monitors will observe operation of the raster magnets by recording beamlet position versus time within the pulse. Increasing the beam current density to even more damaging levels would result in the waist moving toward the target station. Since the beam size in the shield wall aperture would simultaneously increase, the loss monitors could detect this damaging condition within the requisite short time. The same loss monitors also catch most mis-steered beam although the BPMs could also be used. Two instrumentation systems will help synchronise the beam pulses with the the target wheel's angular position. Beam time of arrival from the BCMs will be compared to target angular position and more directly, images of the beam will be compared to fiducial marks on target surface. The following sections briefly describe the instrumentation systems.

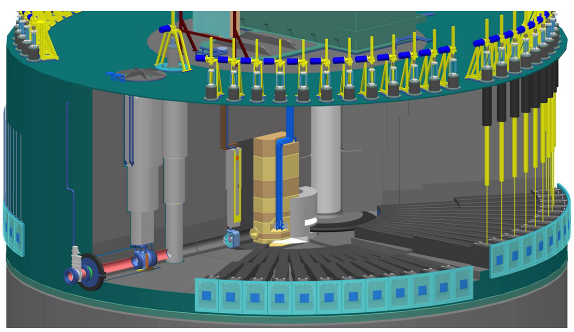

Figure 4: The target monolith. Beam arrives from the left, passing through the proton beam window, then the instrumentation plug, and finally hitting the edge of the rotating target located near the monolith center.

Imaging

Two imaging systems will measure the 2-dimensional current density on the proton beam window and the target wheel surface. In Figure 3, the measurement locations marked"Im" represent luminescent coatings applied to these two surfaces and observed via optical systems installed in the instrumentation plug. Building on the success of the target imaging system originated at SNS [2], development focusses on addressing the unique challenges of the ESS application. These include: higher current densities, higher surface temperatures, and the thinner coating required for the proton beam window. To calibrate the system as well as to monitor target synchronisation, the imaging system will provide an image of each beam pulse relative to fiducial marks on the target surface.

The objective mirrors and both of the coated surfaces reside within the helium gas environment of the monolith. Luminescence from this gas will provide a strong signal for the luminescence profile monitor described in the next section. For the imaging systems, this light only provides an undesirable background. With the long pulse of ESS, time-gating will not isolate the coating emissions from the gas emissions, but spectral filtering will accomplish this.

Gas Luminescence

Residual gas luminescence [3, 4] offers the most promising non-invasive profile measurement technique for this region. At the JESSICA experiment in Jülich, this method was successfully tested near a spallation neutron source [3, 5]. At the ESS, observation of the rastered beamlet within the pulse will require a rather fast readout with µs integration time. The expected residual gas pressure is about 10^{-6} Torr (Nitrogen) in the transport line, and atmospheric pressure (Helium) in the target monolith. The 2 GeV proton energy results in a luminescent cross section for Nitrogen in the transport line of about $2.35 \cdot 10^{-20}$ cm^{-2}, and by extrapolation from cross sections in the lower MeV-range, for Helium, of about $5 \cdot 10^{-21}$ cm^{-2}. This will lead to an estimated signal rate of 10 counts per µs in the transport line. This low count rate makes acquisition of sufficient statistics challenging, so a local pressure bump will be considered. In contrast, the atmospheric pressure within the monolith leads to a signal rate near 10^9 counts per µs. The next steps in system development include experimental verification of the luminescent cross section for Helium, studies focussed on measuring the sub-mm beam waist, and conceptual design of the optical system for the instrumentation plug.

Grids

Due to the reduced current density of the expanded beam, wires near the target will survive in the full production beam. Wire grids will monitor the beam profile at two locations within the monolith: just upstream of the proton beam window, and near the centre of the instrumentation plug. Each will contain both horizontal and vertical planes of 100 µm diameter Tungsten wires with a spacing of about 2 mm. They will remain in the beam at all times, and reach a maximum temperature of less than 900 degrees K, safely below Tungsten's melting point and also low enough to avoid thermionic emission. This temperature estimate only takes credit for radiative cooling and is therefore realistic for the wires in the vacuum upstream of the proton beam window, but conservative for the wires in the Helium environment surrounding the instrumentation plug.

As estimated by a FLUKA simulation, the central wires in the proton beam window assembly will produce a peak signal of about 0.3 µA. Energetic charged particles dominate this signal. The grid located in the instrumentation plug will operate in ionisation mode and with a wire plane spacing of 10 mm, central wires will produce peak signals above 3 mA. Saturation effects remain to be studied, but even with this issue, the device could probably measure beamlet position within the pulse.

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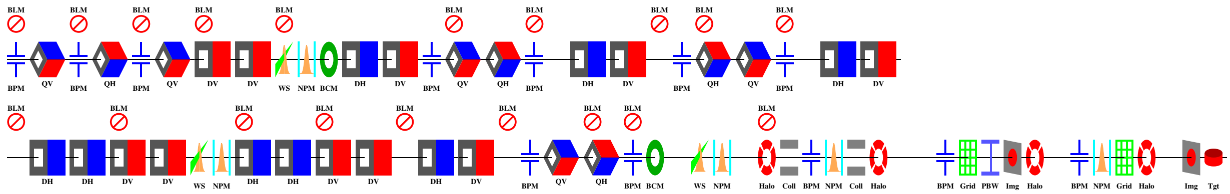

Figure 3: Schematic layout of the beam instrumentation upstream of and within the target monolith. The 8 raster magnets are shown on the lower left, and the neutron shield wall (marked "Col") is shown surrounding a BPM and NPM. The proton beam window is marked "PBW" and appears on the lower right.

Position and Current

In most of the linac, button electrodes will provide signals for beam position and phase measurements, but in the target region, additional challenges merit consideration of alternative designs [6]. These challenges include the large rectangular aperture, the reduced high frequency content of debunched beam, and the requirement to measure beamlet position at 1 μs intervals. Arrays of electrodes could provide coverage of the entire aperture at the cost of increased electronic complexity. Striplines could enhance signal strength over that of the buttons. Special electrodes must also be integrated within the aperture of the neutron shield wall.

Fast toroids will provide current measurements in the accelerator-to-target transport line. Concerns about radiation damage to the magnetic core restricts their use to regions upstream of the neutron shield wall. Redundant devices will provide peak current measurements and accumulated charge measurements to assure that the facility operates within its allowed envelope. Combined with time-of-flight energy measurements from the BPM system, the current monitors measure power delivered to the target, an important performance metric for a high power facility such as ESS. As an additional monitor of target synchronisation, the target wheel position will be measured at the pulse arrival time provided by the last BCM. Finally, the BCM system will deliver pulse waveforms to the neutron instruments. To be conveniently included in an instrument's event stream, this data from each pulse will be delivered before arrival of the next pulse.

Halo and Loss

Throughout the accelerator, beam loss monitors based on ionisation chambers provide the primary machine protection input to guard against beam-induced damage. The system will detect total beam loss within 2 μs after the loss commences, and will have the sensitivity to detect 10 mW/m of distributed beam loss. The transport line to the target introduces some special machine protection situations. Two severe faults have been previously introduced: off-nominal settings of the final quad doublet, and total failure of the raster system. Detection of the first fault can rely upon beam loss and halo monitors, while detection of the second fault depends on direct measurements of the beam density, or time resolved beamlet position measurements.

The final doublet focusses the beam through a waist in the neutron shield wall. In the worst case scenario, the beam could instead be focussed downstream, possibly damaging a beam window within one pulse. This situation would result in an increased beam size within the shield wall, leading to easily detectable beam loss in that region. As usual, loss monitors could then provide the primary fast protection input to interrupt beam production within the time of the damaging pulse. If the beam is focussed too strongly, the location of the waist moves upstream, producing a larger beam footprint in the target station. The halo monitors, based on robust thermocouples would detect this situation, but with a response time much longer than that of the loss monitors. Faster signals, such as those induced by the charged particle shower will also be considered.

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