DESIGN CONSIDERATIONS FOR THE ESS ACCELERATOR-TO-TARGET REGION

Thomas J. Shea, Eric J. Pitcher, Ken Andersen, Phillip Bentley, Paul Henry,
Pascal Sabbagh, Alan Takibayev, ESS, Lund, Sweden
Heine Dølrath Thomsen, Søren Pape Møller, ISA, Aarhus, Denmark

Abstract

When the European Spallation Source (ESS) is completed in Lund, Sweden, a superconducting linac will deliver a 5 MW proton beam to a rotating tungsten target. Moderated neutrons from this target will be delivered to a suite of 22 neutron instruments. In the accelerator-to-target region, design choices must balance the demands of the accelerator, the target, and the neutron instruments. For example, the transport line upstream of the target station expands and shapes the small, low emittance linac beam into a large beam that is safe for the target components. It must do this with low loss in order to reduce activation of the beam line and minimize a potential source of background in the neutron instruments. To meet availability goals, beam-induced damage to critical components must be avoided by instrumenting beamline components, deploying a suite of beam instrumentation within the target monolith, and interfacing some of these devices to the machine protection system. This paper will describe recent design changes in this region, highlighting considerations that are applicable to most high power facilities and also those that are unique to a long-pulse source like the ESS.

GOALS

The accelerator-to-target region serves three primary stakeholders: Neutron Science, Target, and Accelerator. Because the long pulse concept couples these stakeholders, the design must balance the needs of all three.

Neutron Science

Neutron instrumentation at a long-pulse source requires a reproducible pulse, both in terms of the time structure and the brightness. Most long pulse instruments under development for ESS use a combination of choppers and the instrument's total flight path length to tailor the neutron pulse and the available wavelength band to the desired characteristics. For example, a truncated pulse will lead to a hole in the wavelength band at the sample position during the time-frame. Therefore, during neutron production, the facility should provide full length pulses with reproducible structure.

The long pulse places additional unique requirements on the neutron instrumentation in terms of dimensions and background. The optimal arrangement of the instrument geometry to exploit the long pulse requires measurement across a frame boundary. In other words, the instruments will perform measurements with slow-moving, meV-energy neutrons at the same time that the proton pulse hits the target for the next pulse. Any contamination from MeV particles emitted by the accelerator and target that can be picked up by the instrument appear as a time-dependent background superimposed on the weak meV signals of interest. This background manifests itself as a systematic error that is correlated with the measurement time (e.g. [5]), and is most efficiently mitigated at its source.

Target

To survive between reasonably long replacement intervals, target components that intercept the proton beam core impose restrictions on the beam's density. These components include the rotating tungsten target, and the proton beam window that separates this target's atmosphere from the accelerator's vacuum. In addition, surrounding components can only receive a limited volumetric power density, and this imposes a limit on beam outside of the core footprint.

Neutron moderator and reflector assemblies also reside within the target system. Because neutron intensity can depend on proton beam position and current, the time to moderate neutrons from the spallation spectrum down to desired energies will determine that timescale for allowable fluctuations in proton beam position and current.

Accelerator

To meet the target requirements above, the transport line leading to the target must expand the bright beam from the linac into an acceptable footprint. To meet the requirements for the neutron pulse, fluctuations in beam position and current must be repeatable and also limited in magnitude and/or characteristic timescale. The transport line should also allow hands-on maintenance by limiting beam loss to well under 1 W/m and by enabling isolation of the components from target back shine.

PROTON BEAM TRANSPORT

Table 1 summarizes the proton beam parameters at the output of the ESS linac. The accelerator-to-target line receives the beam with these parameters and transform it into a beam with the parameters at the proton beam window (PBW) and target (Tgt) listed in Table 2. It accomplishes this by scanning or rastering an expanded beamlet across the target surface.

ISBN 978-3-95450-138-0

Table 1: Proton Beam Parameters at the End of the Linac

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

Table 2: Beam Parameters at the Target Station, Horizontal (H) and Vertical (V)

Parameter	Location	H	V
RMS size	CO	0.2 mm	0.4 mm
	PBW	10.0 mm	5.00 mm
	Tgt	12.6 mm	6.32 mm
Max. deflection	PBW	55.4 mm	12.7 mm
	Tgt	70.0 mm	16.0 mm
Avg. current density	PBW	88 μA/cm^2	
	Tgt	56 μA/cm^2	

Transport line optics are shown in Figure 1. The design proposal for the LANL MTS line [1] inspired this concept. The upstream matching quads, Q1–Q4, set the beamlet size on the target and provide a beam waist at the crossover (CO), where the beam deflections are minimized by design. Eight raster magnet dipoles (RMs) scan the beamlet, and they are centered on the action point (AP) with 4 acting in each plane. Downstream of the raster magnets, a quadrupole doublet, Q5+Q6, not only ensures the final beam size expansion, but imposes a transverse phase advance of π between the AP and the CO which becomes a pivot point for the deflections. In the presented optics, the peak integrated field per raster magnet is $\int B_y dL = 2.2\,\mathrm{mT.m}$ or $\int B_x dL = 3.8\,\mathrm{mT.m}$. To reduce modulation of the neutron intensity, the a rather high raster frequency of up to 40 kHz is specified.

As the location of the beamlet waist and also the pivot point for deflections, the CO becomes a suitable location for a small-aperture shield that absorbs most of the back-streaming neutrons. TraceWin [2] simulations including 3D space charge, demonstrate transport of 5×10^6 multi-particles through a $\lesssim$ 0.4 mm RMS waist with no loss in the line or the aperture. This is an improvement over the previous design that was based upon nonlinear magnets [3]. Due to the limited magnification of the linac beamlet and the raster pattern's smearing of the beamlet, any transverse halo generated by the linac has a limited effect on the accumulated beam footprint at the target.

A suite of beam instrumentation supports tuning of the beam line [4]. During high power operations, a subset of this instrumentation also provides inputs to an interlock system that can suppress beam production upon detection of potentially damaging conditions.

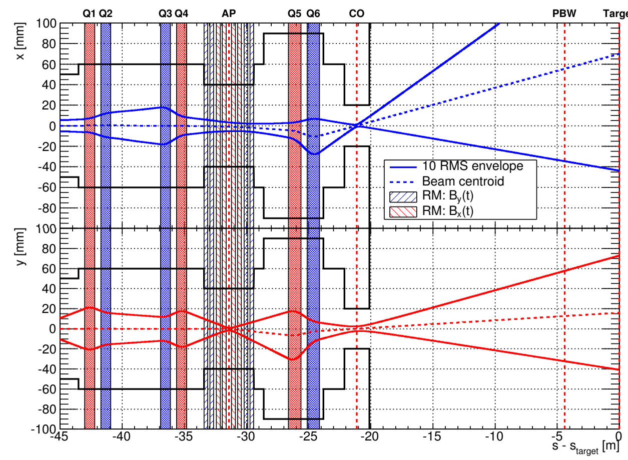

Figure 1: The final 45 m of the HEBT before the target surface. The optics are shown at maximum deflection.

TARGET

Rastering the beam the provides benefits described above, and with normal beam conditions, calculations show that the proton beam window, most delicate interceptive component, should provide the desired lifetime of about one year. However, off-normal situations must be considered and one of the most dramatic would be the simultaneous, undetected failure of all 8 raster magnet systems. In this case, a stationary beamlet with the parameters listed in Table 2 remains on the window. Beam instrumentation detects this condition and suppresses beam production before the arrival of the next pulse, but the window must survive the original errant pulse.

Finite element analysis has been used to analyse this situation. The calculations were performed using ANSYS and results were then post-processed using the RCC-MRx design standard, considering a dose up to 10 DPA. The calculation has been performed for a PBW made either from Al6061T6 or Ti6Al4V. The goal is indeed to fulfill RCC-MRx criteria from level A, meaning that the PBW can be used without inspection or replacement. The start values for this transient thermal analysis are those of a window subjected to nominal beam. A full unrastered pulse then induces a new temperature profile that is coupled one way to a transient structural analysis used for the RCC-MRx post-processing. The results summarized in Table 3 show that an aluminum window would require a replacement whereas a titanium window would not.

NEUTRONICS

As discussed above, the beam transport line employs a dynamic rastering system that scans a beamlet across the target surface. The impact on neutron beam characteristics has been assessed by incorporating time-dependent raster beams into a full MCNPX model of the target sta-

ISBN 978-3-95450-138-0

Table 3: Usage Factors According to the RCC-MRx

	Al 6061T6		Ti6Al4V	
Criteria	**A**	**D**	**A**	**D**
$\overline{P_m}$	0.39	0.19	0.21	0.10
$\overline{P_L}$	0.26	0.12	0.14	0.07
$\overline{P_L + P_b}$	0.31	0.15	0.15	0.07
$\overline{P_m + Q_m}$	1.28	0.69	0.27	0.14
$\overline{P_L + P_b + Q + F}$	1.06	0.12	0.17	0.09
	unirr.	**irr.**	**unirr.**	**irr.**
J	4.8	4.8	9.4e-3	8.5e-2

tion monolith. Each moderator-reflector assembly in the ESS target station contains 3 moderators: a cold para-hydrogen moderator, an upstream thermal water moderator, and a downstream thermal water moderator. Time-dependent brightness was tallied for all 3 moderators. With a horizontal rastering frequency of about 40 kHz and a vertical rastering frequency of 29 kHz, fluctuations for cold neutrons (i.e. 2.5 Å) are very small - less than a few percent. Maximum fluctuations were observed out of the downstream thermal moderator, about 6% RMS at 0.8 Å.

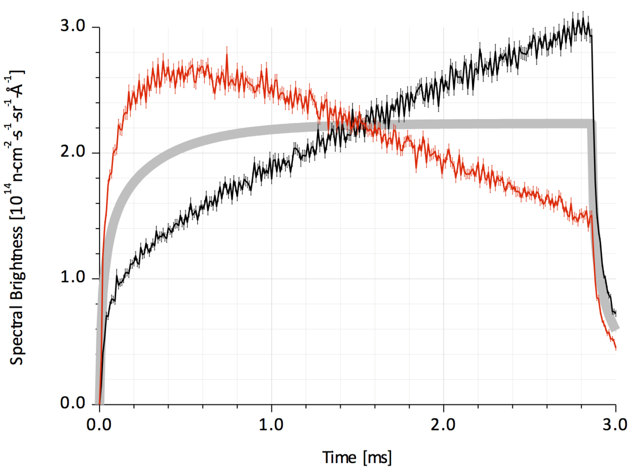

Figure 2: One example of an alternative scanning scenario. The beam is rastered vertically at 29 kHz and swept once horizontally during the 2.86 ms pulse. Thermal neutron pulses (0.8 Å) from upstream (red) and downstream (black) moderators are shown with the reference output from a square proton pulse shown in grey.

This effect on downstream thermal moderators can be exploited by using raster patterns like, for example, slow painting of the proton beam over the target in a horizontal direction while maintaining the rapid scanning in the vertical direction. In this case, high frequency deviations due to horizontal rastering are eliminated, while neutron pulse shapes exhibit rather interesting temporal features as depicted in Figure 2. Additionally, the study of the impact of beam rastering on updated conceptual designs of ESS moderators is underway.

NEUTRON INSTRUMENTS

The variations in the pulse structure as a result of the rastering of the proton beam onto the target offers several opportunities, particularly for thermal instruments, as the effect is most pronounced for short wavelength neutrons. By siting thermal instruments in the correct sector, the enhanced brightness of short wavelength neutrons at the end of the pulse can be harnessed by, for example, high-resolution diffraction instruments or a thermal chopper spectrometer. For example, through the use of a pulse-shaping chopper at 6-7m from the moderator surface, a wavelength band and wavelength uncertainty ($\Delta\lambda/\lambda$) is selected by a diffraction instrument. At the sample position, within the time-frame given by the 14 Hz repetition rate, the short wavelength neutrons (with a higher velocity) are selected from the end of the initial pulse, with enhanced intensity as shown in Figure 2. These neutrons give access to high Q at close to backscattering from the sample, which reveal the subtle structural details. As a general remark, boosting the neutron brightness for the short wavelengths will be very useful for all thermal instruments that employ pulse-shaping.

Delivery of the proton beam to the target with lower loss could also benefit neutron instruments. Reducing the potential for beam losses in this region by orders of magnitude could bring a proportional reduction in that contribution to the background. Other sources are now being investigated, with a focus on emission of particles from the accelerator berm that are transported as sky shine, and mechanisms of illumination of the instruments directly from the target, both external and internal to the neutron beamlines. Particular attention is being paid to the types of materials that can be used and the energies of the particles that illuminate them, and the physics processes that convert these transport mechanisms into measurable signals for detectors that are typically only sensitive up to 100s keV.

CONCLUSION

Particularly in a long pulse neutron source such as the ESS, the optimisation of the accelerator to target region can significantly enhance neutron source performance. Recent updates to the design, including the addition of raster scanning appear to provide performance benefits. This work is ongoing. In the near future, we plan to model updated moderator designs, and improve our understanding of neutron background with additional beam loss simulations.

REFERENCES

[1] B. Blind *et al.*, LINAC 2006, MOP055, p. 171 (2006).
[2] R. Duperrier *et al.*, ICCS'02, LNCS2331, p. 411 (2002).
[3] A.I.S. Holm *et al.*, IPAC'12, MOPPD049, p. 475 (2012).
[4] T. J. Shea *et al.*, IBIC 2013, TUPC02, Oxford (2013).
[5] B. Winn *et al.*, http://neutrons.ornl.gov/hyspec/_media/HYSPEC_Status_June_2012.pdf (2013).