THE EUROPEAN SPALLATION SOURCE

S. Peggs, ESS, Lund, Sweden
for ESS/AD and the ESS/ADU Collaboration

Abstract

The 5 MW European Spallation Source (ESS) – to be built in Lund, Sweden – is typical of the generation of mulit-MW superconducting proton linacs currently under design and discussion. The Accelerator Design Update (ADU) collaboration of mainly European institutions will deliver a Technical Design Report at the end of 2012. First protons are expected in 2018, and first neutrons in 2019.

HIGH POWER SPALLATION LINACS

Spallation is the nuclear process that emits neutrons at a spectrum of energies after highly energetic particles bombard heavy nuclei – for example, when the ESS proton beam strikes a liquid heavy-metal or rotating disk target. These neutrons are cooled in moderators adjacent to the target, before exiting target ports to be transported through neutron guides to experimental instruments [1].

Long Pulses

Pulsed neutron sources like the Spallation Neutron Source (SNS) and the ESS are more efficient than continuous sources, in a majority of applications [2]. The neutron time-of-flight, and therefore the neutron energy, are readily measured at a pulsed source. Unlike the SNS, the ESS does not need an accumulator (compressor) ring [3]; the ESS macro-pulse length is 2.0 ms rather than $\sim$1 μs. In addition to the advantage of eliminating the ring, a "long pulse" implementation permits H^+ operation, and maintains relatively low currents in all beamlines. High level ESS parameters are listed in Table 1.

Table 1: High Level Parameters in the ESS High Power Linac

Parameter	Unit	Value
Average beam power on target	MW	5.0
Proton kinetic energy on target	GeV	2.5
Average macro-pulse current	mA	50
Macro-pulse length	ms	2.0
Pulse repetition rate	Hz	20
Number of instruments		22
Number of target ports		44
Reliability	%	95
Maximum average beam loss rate	W/m	1.0
RF frequency: RFQ, DTL, spokes	MHz	352.21
RF frequency: elliptical cavities	MHz	704.42

Beam Energy

The spallation cross section increases as a function of proton energy up to several tens of GeV. Nonetheless, a kinetic energy of 1–3 GeV is optimal for practical target, moderator, and shielding designs and requirements. The ESS kinetic energy of 2.5 GeV enables an average macro-pulse current of 50 mA that is consistent with the need for high reliability, but still leaves some leeway for a potential energy (and power) upgrade. The current limit is mainly set by space charge effects at low energy, by the power that can be delivered to the beam in each cavity at medium and high energies, and by beam losses.

RF Frequency

Lower frequencies are favored at lower energies due to relaxed manufacturing tolerances in cavity components, and to the capacity for large beam apertures. Lower frequencies also reduce RF losses in superconducting cavities, and ameliorate Higher Order Mode (HOM) effects [4]. Higher frequencies keep the size of the superconducting cavities small, making them easier to handle and reducing manufacturing costs. Higher frequencies also reduce the cryogenic envelope and power consumption. A frequency of 600–800 MHz is a good compromise for elliptical structures like the Superconducting Proton Linac (SPL) and the ESS, which have both chosen frequencies of 352.21 MHz and 704.42 MHz, at low and high energies [5, 6].

Higher Order Modes

High energy efficiency requires superconducting RF structures with very high Quality Factors, Q. Consequently, each HOM tends to have a long damping time, with a significant risk that it will still be active when the next macro-pulse arrives. Two generic solutions are available to extract HOM energy – either mount couplers at cavity locations where the more destructive parasitic modes are expected to have large amplitudes, or include a low Q lossy material around the beam pipe to damp modes that extend into the volume between neighboring cavities. The ESS tentatively prefers HOM couplers, in part because they can also be instrumented to measure the 4D transverse location of the beam [7].

Beam Losses

Excessive radio-activation from beam losses larger than about 1 W/m can hinder hands-on maintenance. Beam losses from aperture limitations, transition regions and misalignment are readily simulated, yielding mechanical tolerances for cavity designs, supporting infrastructure and other equipment [8]. Intra-beam stripping is plausibly an important source of beam losses in H^- linacs like the SNS, but not in the H^+ ESS [9]. Other beam loss sources are Hoffman space charge resonances [10], transverse overfocusing [11], and uncollimated low energy beam halo. Attaining the ability to confidently predict the relative importance of loss mechanisms is a fundamental challenge to our ability to design multi-MW proton linacs.

BASELINE-2010 DESIGN

Figures 1 and 2 show the *Baseline-2010* design, optimized for 50 mA operation with a single cavity per klystron. Some baseline parameters (such as the 5 MW beam power) are very solid, while others (such as the source-to-target length ∼420 m) are subject to modest evolution. Parameters will fluctuate somewhat as the design converges, through baseline releases at the end of 2011 and in the Technical Design Report at the end of 2012 . Live parameters, continuously maintained and under configuration change control, are publicly available on-line [12].

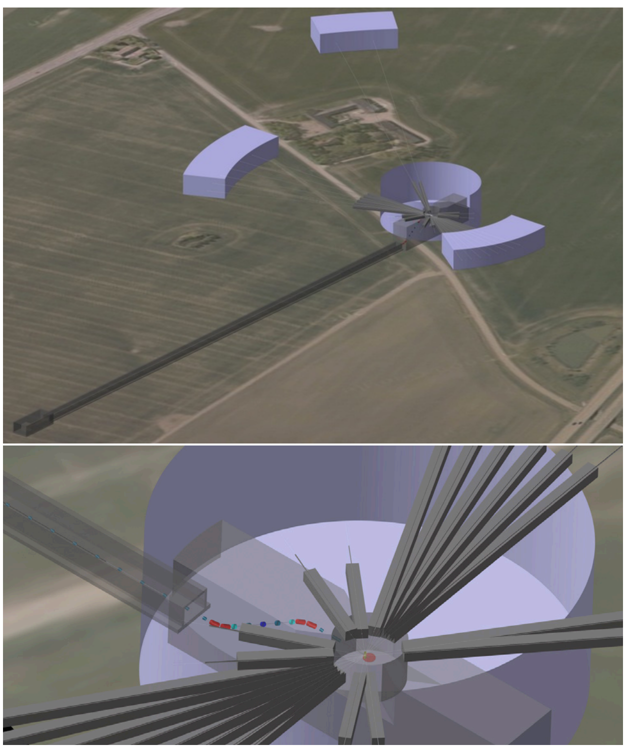

Figure 2: Tentative layout of the linac, HEBT, and 4 experimental halls containing 22 neutron lines and experiments.

The exact locations of the target and experimental halls shown in Figure 2 is being optimized, for example with respect to ongoing geo-technical measurements. The 4 halls, at about (35,80,160,300) meters from the target, will accommodate (6,8,6,2) instruments. In general, the ESS design incorporates features that provide upgrade potential, so long as their day-one inclusion is inexpensive. Thus, the target monolith is equipped with 44 neutron beam ports, providing a potential path towards additional instruments. Similarly, provision may be made for parasitic proton extraction lines, for a beam current increase to 75 mA, and for a modest energy upgrade, while no provision will be made for a second full-power target station, nor for future short pulse operation with H^- beam.

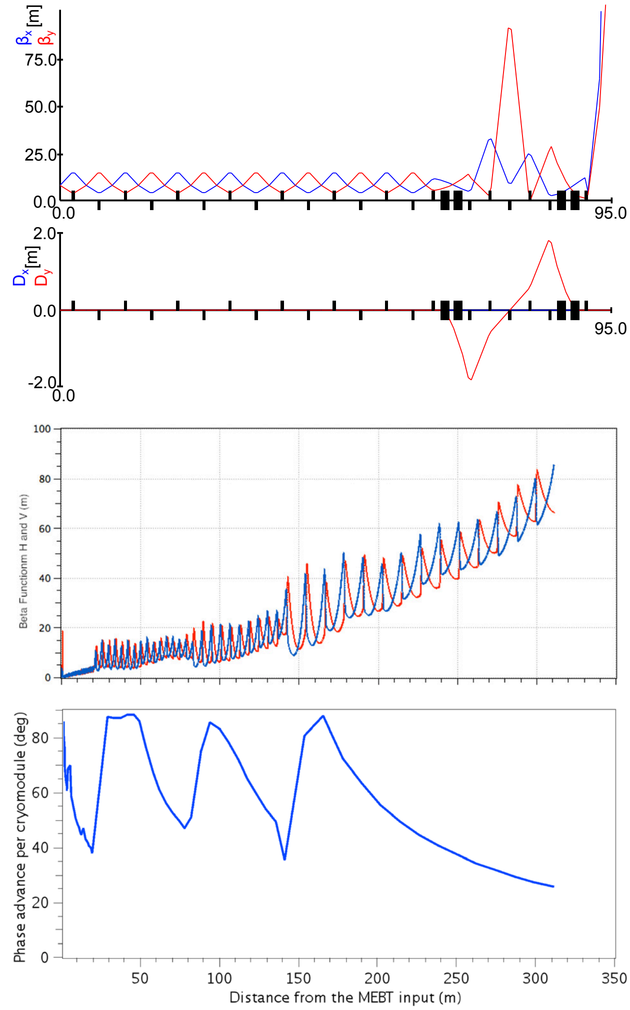

Figure 3: Transverse and longitudinal optics in the HEBT (top plots) and in the linac (bottom plots).

Optics

Figure 2 (bottom) indicates how the end of the HEBT rises vertically 10 m (with no horizontal bend) to the target, which sits 1.6 m above ground level. The optical functions shown in Figure 3 (top) confirm that this vertical transition is achromatic, matched out of a FODO channel with a 14.0 m period. The uphill straight is available for momentum and betatron collimation. Octupolar beam profile flattening at the end of the HEBT reduces the peak intensity on the target window by 45%, leaving 7 m of free space from the last magnet to the target. Not shown in Figure 2 is the tune-up dump that receives beam when the vertical dipoles are turned off. These dipoles may use high-temperature superconductor technology to achieve high performance in a high-radiation environment. Figure 3 (bottom) also shows the doublet optics of the linac, with transverse and longitudinal optics that become significantly weaker as the energy of the beam increases.

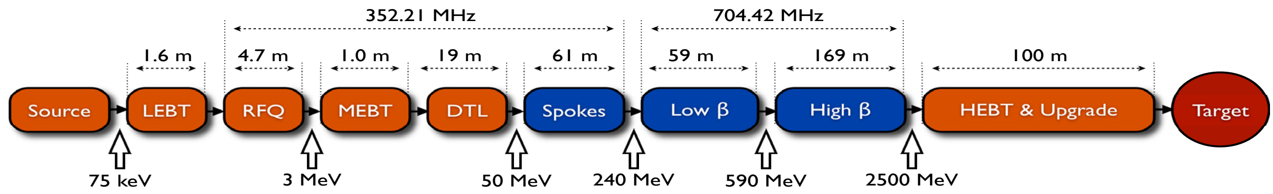

Figure 1: The *Baseline-2010* accelerator layout of the ESS linac and the High Energy Beam Transport (HEBT).

Table 2: *Baseline-2010* Parameters for the Superconducting Spoke Resonators and Elliptical Structures in the ESS Linac

Parameter	Unit	Value
No. of accel. gaps per spoke cav.		3
No. of cells per low beta ellipt. cav.		5
No. of cells per high beta ellipt. cav.		5
Spoke resonator cavs. per cryomod.		3
Low beta ellipt. cavs. per cryomod.		3
High beta ellipt. cavs. per cryomod.		6
Geometric beta, spoke resonators		0.53
Geometric beta, low beta cavities		0.65
Geometric beta, high beta cavities		0.86
Operational voltage, spokes	MV	6.0
Operational voltage, low beta	MV	10.5
Operational voltage, high beta	MV	18.5
Expected gradient, low beta, horz.	MV/m	15
Expected gradient, low beta, V test	MV/m	17
Expected gradient, high beta, horz,	MV/m	18
Expected gradient, high beta, V test	MV/m	20
Elliptical coupler power, to beam	MV/m	1.2

Hybrid Cryomodules

The superconducting RF parameters shown in Table 2 for *Baseline-2010* are based on the assumption of fully non-segmented (continuous) cryomodules that minimize cryogenic load and hence site power. This has the disadvantages of requiring cold beam instrumentation, increasing the time to replace RF cryomodules, and deterring the inclusion of occasional sections of room temperature beamline.

Under study is the possibility of avoiding most of these disadvantages, while maintaining low cryogenic heat-loads, through the use of short utility modules in the *hybrid cryomodule* scheme illustrated in Figure 4. Standard length utility modules of various styles placed between cold doublet quadrupoles would typically contain instrumentation and other beamline hardware – represented by the white box in Figure 4 – at the temperature of the cryomodule thermal shield, about 50 K. In a limited number of cases the utility module beamline would be at room temperature.

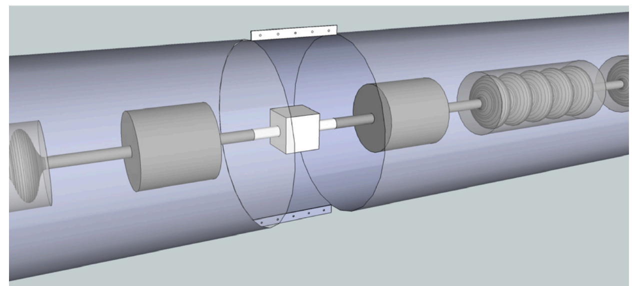

Figure 4: Sketch of the *hybrid cryomodule* concept currently under study, in which a short *utility module* is placed between neighboring accelerator cryomodules..

REFERENCES

[1] B.T.M.Willis and C.J.Carlile, "Experimental neutron scattering", Oxford University Press, ISBN 978-0-19-851970-6 (2009).

[2] "Scientific Prospects for Neutron Scattering with Present and Future Sources", proc. ESF Exploratory Workshop, Autrans, (1996).

[3] F. Mezei, "The raison detre of long pulse spallation sources", J. Neutron Research 6 3-32 (1997).

[4] H. Padamsee, J. Knobloch and T. Hays, "RF Superconductivity for Accelerators", Wiley-vch, ISBN 978-3-527-40842-9, (2008).

[5] F. Gerigk et al, "Choice of Frequency, Gradient, and Temperature for a Superconducting Proton Linac", CERN-AB-2008-064, (2008).

[6] M. Harrison et al, "ESS Frequency Advisory Board Report", (2010).

[7] S, Molloy et al, "High precision superconducting cavity diagnostics with higher order mode measurements", PRST-AB 9, 112802 (2006).

[8] R. Duperrier, D. Uriot, "Application of the extreme value theory to beam loss estimates in the SPIRAL2 linac based on large scale Monte Carlo computations", PRST-AB 9, 044202 (2006).

[9] V. Lebedev et al, "Intrabeam stripping in H^- linacs", IPAC'10, Tsukuba, (2010), `http://www.JACoW.org`.

[10] I. Hofmann, K. Beckert, "Resonance Crossing in the Presence of Space Charge", IEEE Trans. Nucl. Sci. NS-32, 2264 (1985)

[11] Y. Zhang et al, "Measurement of longitudinal acceptance and emittance of the Oak Ridge Spallation Neutron Source Superconducting Linac", PRST-AB 11, 104001 (2008).

[12] Live parameters under ESS configuration control are available at `http://esss.se/linac/Parameters.html`