DESIGN OPTIONS OF THE ESS LINAC

M. Eshraqi, H. Danared, D. McGinnis,
ESS, Lund, Sweden

Abstract

The European Spallation Source, ESS, uses a linear accelerator to deliver the high intensity proton beam to the target station. The nominal average beam power is 5 MW with a peak beam power at target of 125 MW. During last year the ESS linac was costed, and to meet the budget a few modifications were introduced to the linac design, namely the final energy was decreased from 2.5 GeV to 2.0 GeV and the beam current was increased accordingly to compensate the lower final energy. As a result the linac is designed to meet the cost objective by taking a higher risk. This paper focuses on the new design options, beam dynamics requirements of the design and finally on the beam dynamics performance of the linac.

INTRODUCTION

The European Spallation Source, ESS, to be built in Lund, Sweden, will require a high current proton linac to accelerate protons to be used for the spallation process in which a high flux of pulsed neutrons will be generated. The accelerator is a 5 MW superconducting proton linac delivering beams of 2.0 GeV to the target in pulses of 2.86 ms long with a repetition rate of 14 Hz – corresponding to a duty cycle of 4%. Pulse length and repetition rate are high level parameters and affect the design of the instruments.

The final energy was recently reduced in a campaign to reduce the overall linac costs. One of the possible ways for reducing the total cost is to reduce the final energy of the linac. This reduces the number of required rf cavities, cryomodules and the the high power rf needed to feed the cavities. The latter has the biggest impact on the total cost of the accelerator.

Beam current is 62.5 mA, which at 352.21 MHz is equivalent to $\sim 1.1 \times 10^9$ protons per bunch. From ~ 200 MeV onward the acceleration is done at twice the frequency of the front end, 704.42 MHz, to improve the energy efficiency of the linac.

Hands on maintenance and machine protection set limits, 1 W/m and 0.1 W/m respectively, on beam losses and have been a concern in every high power linac [1–4]. Therefore it is crucial, specially for high power accelerators, to design a linac which does not excite particles to beam halo and also keeps the emittance growth to a minimum to avoid losing the particles that otherwise get too close to the transverse acceptance and eventually hit the beam pipe or escape the separatrix in longitudinal plane. The ESS linac is designed carefully to minimize such effects all along the linac and transport lines [5]. A recent study relaxed the losses in the low energy part of the linac, mainly in the RFQ and MEBT [6], from the conventional 1 W/m.

MOTIVATION

In 2009, at the beginning of the Accelerator Design Update phase of the ESS project, it was concluded that the 2003 accelerator design [7] with its high beam current of 150 mA had several technical risks, such as high beam losses and the need for funneling. The beam current was thus reduced by a factor of 3 to increase the reliability, where the overall goal of the ESS facility is 95%. The linac energy was at the same time increased to 2.5 GeV [8] to compensate for most of the current reduction. At the higher energy, superconducting structures that can have higher gradients at the relatively long ESS pulses and thus make the linac shorter for a given energy are a more economic choice. Their bigger aperture is another advantage. Nevertheless, first cost estimates of the 2012 linac showed that it was more expensive than the normal-conducing linac from 2003 because of its higher energy. A campaign to reduce the cost of the linac was thus started.

ESS is a long pulse machine and does not need a compressor ring, therefore one is not concerned about a space charge tune shift at the the ring and the peak beam current could be supplied at almost any energy. On top of this, since the ESS beam is not injected to a ring, the constraints on the emittance could be relaxed, specially if the the beam expansion system for the target is based on raster scanning of the beam on the target [9]. These facts and the cost distribution of the baseline linac, see Fig. 1, dictated a cost saving scheme based on lower final energy of the linac with a higher current at an expense of increased risk. The cost of the elliptical cryomodules and associated RF sys-

Table 1: Different ESS Design Main Parameters

Parameter	2003 (LP/SP)*	2012	2013
Ion	P / H^-	P	P
Energy [GeV]	1.334	2.5	2.0
Beam power [MW]	5.1	5	5
Rep. rate [Hz]	$16\frac{2}{3}$ / 50	14	14
Beam current [mA]	114	50	62.5
Beam pulse [ms]	2 / 0.48	2.86	2.86
Duty cycle [%]	3.3 / 4.8	4	4
Risk [Qualitative]	Highest	Lowest	Mod.

* Long pulse / Short pulse.

ISBN 978-3-95450-122-9

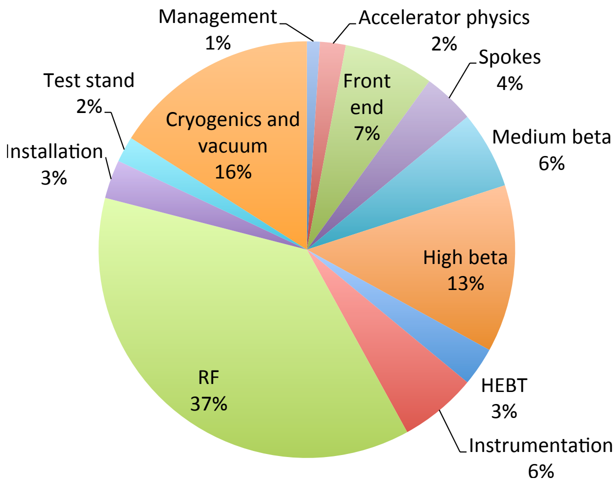

Figure 1: Cost distribution for the 2012 baseline linac [10].

tems are the largest cost driver in the ESS Linac and reducing the number of superconducting cavities will have the largest impact on cost. Each cavity that is removed from the design not only removes the cost of the cavity, but it also removes the need (and cost) for the RF power sources that feed the cavity. However, for any given strategy, as the number of cryomodules is reduced, the remaining cryomodules require more RF power to keep the linac peak and average power constant. A set of simple models have been developed to predict the increased cost of more powerful RF power sources.

DESIGN

There are several other factors which could be changed in the design to save the cost, each of which being accompanied by a certain amount of added risk. The only factor that does not require a redesign of the accelerator and could save cost without affecting the performance of the accelerator itself is the duty factor, (Pulse length × Rep. rate). However, both pulse length and repetition rate are crucial factors for the neutron instruments and experiments and could not be changed. The other possible parameters to vary are the beam current, the peak accelerating gradient in the superconducting accelerating cavities, the average of $\sum E_{acc}.T$ by pushing the power profile, the ratio of $E_{acc}.T/E_{acc}.T_{max}$ by reoptimizing the transition energies and geometric βs of the cavities, and finally the energy of the front end (normal conducting) linac.

BEAM PHYSICS

The beam physics design of the cost optimized linac was performed in two steps. Initially the beam physics constraints were relaxed to the extreme limit, and even broke a few rules, to determine the absolute minimum number of cavities and structures needed to bring the beam to the final energy of 2 GeV. This first linac was called “Smart”, see [11]. The preliminary studies showed significant rms emittance growth in this linac and a 99% emittance growth with a higher rate, indicative of halo generation.

To avoid these unwanted defects the beam dynamics rules were re-applied to the Smart linac trying to keep the number of required cavities at the minimum if possible or with the fewest extra cavities. The beam physics rules applied to the design are:

- The phase advance per period in transverse and longitudinal must be less than 90°.
- The phase advance per meter variation should be smooth and continues.
- The relative tune spread, $\zeta = 1 - \sigma_{sc}/\sigma_0$, must stay below 0.6 in all the three planes along the accelerator [5].

Architecture

For improved matching and smoothness of the phase advance per meter as well as reduced cost and increased reliability of the accelerator the period length in medium and high β elliptical cavities made equal. This increased the intercavity distance in the medium β section. The number of cells in medium β cavities was increased from 5 to 6 in order to reduce the amount of unused spaces. The additional advantage of this modification is that in case of low performing medium β cavities, the first few modules in high β section could easily be replaced a by few medium β modules to have the right energy at the transition. At the same time the length of the medium and high β periods were adjusted to be exactly twice the length of the spoke section periods in order to have the possibility of switching the cryomodules at that transition.

Table 2: Comparison of the Main 2012 Baseline and 2013 Design Parameters

Parameter	2012 BL	2013
Surface field [MV/m]	40	45
N_{cell} (Spoke/Mβ/Hβ)	3/5/5	3/6/5
β_g (Spoke/Mβ/Hβ)	0.50/0.67/0.92	0.50/0.67/0.86
$E_{Transition}$ [MeV]	200/627	223/532
L_{period} [m]	4.14/7.12/15.2	4.14/8.28/8.28
N_{cav} (Spoke/Mβ/Hβ)	28/60/120	30/32/88
$L_{SClinac}$ [m]	393	310

Performance

The beam dynamics performance of the 2013 linac is studied using multiparticle simulations. In these simulations 100,000 particles are generated at the beginning of the superconducting linac and transported through the linac using the code TraceWin [12], from the CEA suite of beam physics codes. The matching between the structures was done by smoothing the phase advance to remove the dependence on beam current, and keeping the relative tune spread below 0.6 was another criteria in the matching process. The relative tune spread along the linac is plotted in

ISBN 978-3-95450-122-9

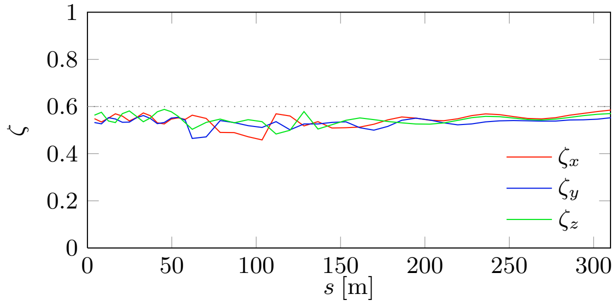

Figure 2: Relative tune spread (ζ) in the ESS SC linac.

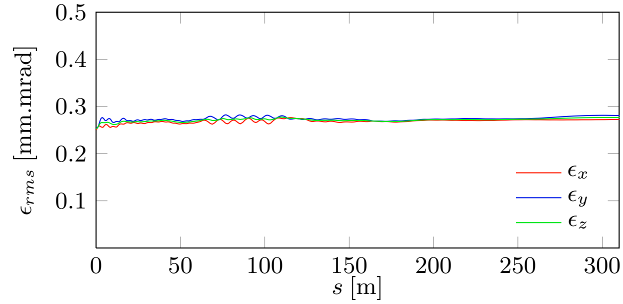

Figure 4: RMS normalized emittance evolution.

Fig. 2. Due to the equal period length and smooth phase advance variation between the medium and high β sections the transition is transparent for the beam, Fig 3.

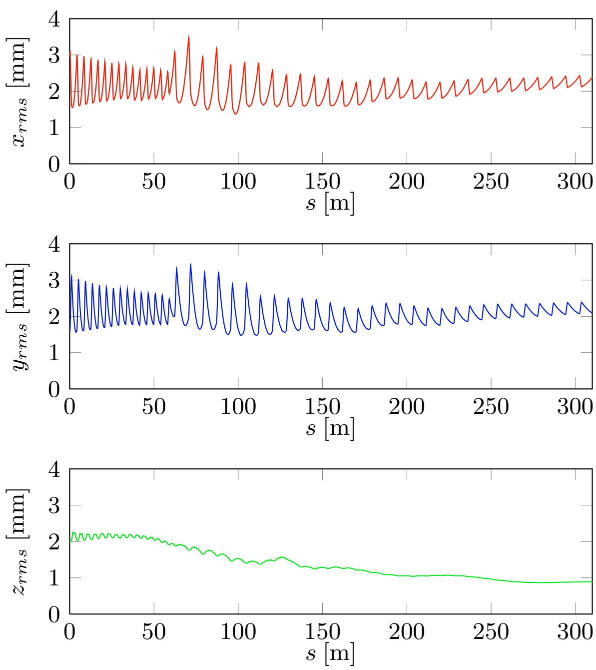

Figure 3: RMS envelopes in x (top/red), y (middle/blue) and z (bottom/green) along the SC linac.

The beam emittance stays almost constant along the superconduting linac, Fig. 4. The same is valid for the 99.00% emittance and the halo parameter. The emittance by itself is not a major concern for the ESS linac since the beam will be rastered on a tungsten target, but since the halo particles can significantly influence the losses the 99.00% emittance should be considered carefully.

CONCLUSION

The 2013 ESS linac uses one more spoke cryomodule than than the absolute minimum. However the beam performance is significantly improved with respect to a bare minimum linac, and the halo production and losses are highly decreased. The choice of uniform period length for the elliptical sections results in a very smooth transition between the structures which is transparent for the beam. The front end for the 2013 ESS linac has to be finalized and the probable higher energy at the injection to the superconducting linac will further improve the beam performance and reduce the cost.

Compared to the 2012 baseline, the 2013 linac is under two major risks, the 25% increase in beam current and 10% increase in the cavity gradient. None of these risks is posing a threat to the linac functionality and in the worst case will decrease the beam power at target until additional cryomodules in the contingency area are installed and operational. On the other hand, the smooth lattice design is an advantage of the 2013 design with respect to prior designs.

REFERENCES

[1] R. A. Jameson, "Design for low beam loss in accelerators for intense neutron source applications", PAC 1993.

[2] T. P. Wangler *et. al.*, "Basis for low beam loss in the high-current APT linac", LINAC 1998.

[3] J. L. Biarrotte *et. al.*, "Accelerator reference design for the MYRRHA European ADS demonstrator", LINAC 2010.

[4] D. Raparia *et. al.*, "Reducing losses and emittance in high intensity linac at BNL", HB 2010.

[5] M. Eshraqi, J-M. Lagniel, "On the choice of linac parameters for minimal beam losses", IPAC 2013.

[6] L. Tchelidze, J. Stovall, "Estimation of residual dose rates and beam loss limits in the ESS linac", IPAC 2013.

[7] "ESS Volume III Update: Technical report status", 2003, `http://ess-scandinavia.eu/documents/VolIII.pdf`.

[8] S. Peggs, Ed., "The conceptual design report", 2011, `http://ess-scandinavia.eu/ess-documents/589-cdr`.

[9] H. D. Thomsen, A. I. S. Holm, and S. P. Møller, "A Linear Beam Raster System for the European Spallation Source?", IPAC 2013.

[10] S. Gysin, *private communication.*

[11] M. Eshraqi, D. McGinnis, "ESS linac design options", 3rd SLHiPP collaboration meeting, `https://indico.esss.lu.se/indico/conferenceDisplay.py?confId=61`.

[12] R. Duperrier, N. Pichoff and D. Uriot, Proc. International Conf. on Computational Science, Amsterdam, The Netherlands, 2002.

ISBN 978-3-95450-122-9