PLANS FOR THE ESS LINAC

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Abstract

Lund was chosen as the site of the European Spallation Source in May 2009. The *Design Update* phase (January 2011 to December 2012) will be completed by the delivery of a Technical Design Report. After approval of the CDR, the ESS project will proceed to construction, installation, and commissioning. The superconducting linac is expected to begin delivering beam to users in 2019, eventually delivering an average beam power of 5 MW to a single neutron target station with a proton (H^+) macro-pulse current of (provisionally) 50 mA at 2.5 GeV in 2.0 ms long pulses at a repetition rate of 20 Hz .

INTRODUCTION

Table 1 shows the two tentative sets of primary ESS parameters that were presented at the ESS-Bilbao Initiative Workshop, in March 2009 [1]. Columns **B** and **S** show the close similarity between the parameters of the Bilbao and Scandinavia designs. In many cases the values are identical. Where they do deviate, the differences are relatively minor. In contrast, the average beam current and the final beam energy differ by at least a factor of two from the 2003 ESS design values (5 MW, 1 GeV, 150 mA, 16.7 Hz) [2]. Decreasing the beam current and increasing the beam energy simplifies the linac design and increases the reliability. Decreasing the beam current allows the cavity gradient to increase (at fixed power coupler strength), but keeps the linac length approximately unchanged from the 2003 values, despite the increase in beam energy.

The *Design Update* phase that begins in January 2011 will resolve most of the design issues and many of the lower level design parameters, for reporting in the Technical Design Report that will be delivered in December 2012. However, high level parameters and decisions that will hold their validity for at least two years need to be established even before that design effort can proceed. We have therefore committed to defining a *DU Baseline* by the end of December 2010. The issues affecting the evolution of this baseline from the current "provisional baseline" (column **S** in Table 1) are presented below, together with a description of some work already performed, and tentative conclusions already drawn for the control system.

DESIGN UPDATE BASELINE

In addition to parameters being further optimised in the transition to the Design Update (DU) baseline, design decisions and philosophies also need to be made and clarified.

Table 1: Primary ESS performance parameters in the long pulse conceptual design. Columns **B** and **S** show the minor differences between the ESS-Bilbao and ESS-Scandinavia nominal parameters (2009). The values in column **S** are called the "provisional baseline".

		B		S
INPUT				
Average beam power	[MW]		5.0	
No. of instruments			22	
Macro-pulse length	[ms]	1.5		2.0
Pulse repetition rate	[Hz]		20	
Proton kinetic energy	[GeV]	2.2		2.5
Peak coupler power	[MW]	1.2		1.0
Beam loss rate	[W/m]		<1.0	
OUTPUT				
Duty factor		0.03		0.04
Ave. current on target	[mA]	2.3		2.0
Macro-pulse current	[mA]	75		50
Ion source current	[mA]	~90		60
Total linac length	[m]		~420	

User Parameters and Potential Upgrades

The provisional repetition rate is 20 Hz, with a macropulse length of 2.0 ms, a length that is acceptable to most of the neutron user community, although some users would prefer it to be reduced towards 1.5 ms, while preserving 5 MW beam power. All users want high availability – few beam trips – in dynamic tension (for example) with an increase in beam current that could be necessary with shorter pulses. It is impossible to derive the availability of an ESS design from first principles, although there is empirical evidence from ISIS, LANSCE, PSI and SNS that the cumulative probability distribution of trip rate versus trip length follows a universal power law with an exponent of $-2/3$, for trips of less than one day in duration [3, 4].

The DU baseline will be optimised for a nominal beam power of 5 *MW*, with a provisional current of 50 mA and a provisional peak power (to the beam) of 0.9 MW in the elliptical cavity power coupler. This is consistent with the strategic philosophy that *upgrade options will be preserved where reasonably possible.* For example, the beam power may later be upgraded to 7.5 MW by increasing the average current to 75 mA and adding extra cryomodules in the "Upgrade and HEBT" section shown schematically in Figure 1. Other potential upgrade options that may or may not

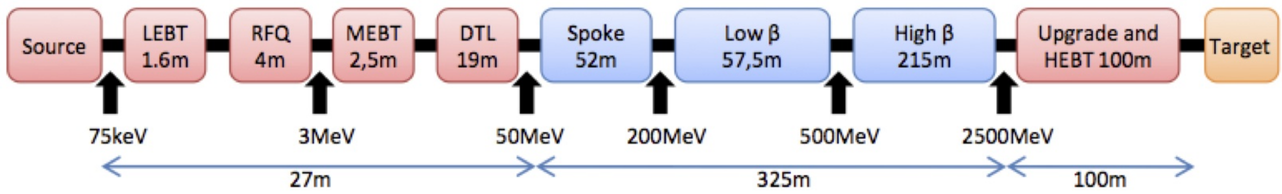

Figure 1: Provisional block layout of the ESS Linac (not to scale).

be "reasonably possible" include 1.3 ms long macropulses, a second target station, a 40 Hz repetition rate, and H^- beams.

Transition Energies and Beamline Components

Figure 1 and Table 2 show the provisional block layout of the linac, its transition energies between RF structure technologies, and the count of major components such as RF tanks and cryomodules. The transition energies may be further optimised for the DU baseline lattice, including the energy of the frequency jump between spoke resonators and elliptical cavities [5]. A more accurate representation of the ESS layout – for example, its length and its component counts – requires the inclusion of a full complement of beam instrumentation, collimation, magnets, correction systems, et cetera.

RF Frequencies

Two frequencies will be used in the normal and superconducting RF structures, 352.21 MHz and 704.42 MHz, the same frequencies that were selected for the CERN Linac4 and SPL [6]. According to the *ESS Frequency Advisory Board* report (2010) [7]:

> "... the FAB agrees with the Project that a lower frequency (600-800 MHz) produces a better optimised and a lower risk solution to meet the design goals. The baseline 704 MHz design is shorter, larger aperture (beneficial in regards to beam loss), and lower impedance"
>
> "... the FAB finds little difference for any frequency in the range of 600-800 MHz. In our opinion the exact frequency choice should be based on the projects collaborative strategy."

Table 2: Provisional block layout of RF structures, including the count of DTL tanks and superconducting cryomodules, after optimisation for operation with a beam power of 5 MW and a macropulse current of 50 mA.

Structure	**Energy** [MeV]	**Freq.** [MHz]	**Count**	**Length** [m]
Source	0.075	–	–	2.5
LEBT	0.075	–	–	1.6
RFQ	3 3	352.21	1	4.0
MEBT	3	–	–	2.5
DTL	50	352.21	3	19.0
Spokes	200	352.21	16	52.0
Elliptical 1	500	704.42	9	57.0
Elliptical 2	2500	704.42	14	215.0

Prototype Cryomodules

Circular superconducting accelerators have very few warm-to-cold transitions, usually connecting one magnet to the next with cold "spool pieces". In contrast, every cryomodule in the Spallation Neutron Source (SNS) linac is completely cryogenically "segmented" from its neighbor. Some superconducting linacs – those that are constrained in real estate length, such as the XFEL and the ILC – are designed with very little segmentation.

At ESS the two major technical drivers that will influence the level of cryogenic segmentation are the need to minimise the total site power through efficient energy engineering [8] and the need for high reliability (minimising the down time due to failed components). A preliminary study suggests that a fully-segmented linac would have 1.6 to 1.7 times the cryogenic power load of a fully non-segmented linac [9]. Other less crucial technical issues include the minimisation of linac length, the risk of accidental contamination, and the desirability of de-coupling the development and integration of magnets and beam instrumentation from SRF development.

The construction and testing of prototype elliptical cavity cryomodules is a crucial part of the Design Update phase, in an effort that will extend beyond the end of 2012. In all scenarios these prototypes will be designed to have static and dynamic heat loads that are as low as reasonably achievable. In some scenarios the prototype cryomodules could differ significantly from the production cryomodules, leaving open until later the decision on the level of cryogenic segmentation.

Also under consideration is the desirability of making ESS cryomodules "plug-compatible", consistent with the ILC philosophy, in order to make design integration easier across the collaboration. For example, this would make it easier to include cavities from different sources in the prototype cryomodules, and it would reduce the set of standard beam (and other) instrumentation, and magnets, that need to be developed [10]. It would also simplify the incorporation of cavities from multiple vendors in the production line cryomodules.

Standard shipping containers have an inside length of approximately 12.03 m [11]. Insisting that elliptical cryomodules are shorter than this could limit them to 6 cavities, although 8 may still be possible. This, too, is a consideration in arriving at a DU baseline configuration.

RF System Parameters

Table 3 shows the provisional parameters for the RF structures. The three geometric betas (for the spoke resonators, low-energy, and high-energy elliptical cavities) depend strongly on the baseline macropulse current, but depend only weakly on sub-scenarios that leave module transition energies unchanged. The values shown correspond to operation with a 50 mA beam, consistent with the philosophy of optimising for the nominal beam power of 5.0 MW. Error bars of ± 0.01 indicate the small size of changes that may occur in the move to the DU baseline. Spoke resonator and elliptical cavity designs will be optimised within the design update collaboration, after their geometric betas has been determined. It is not impossible that the production of low-energy elliptical cavities could be eliminated, proceeding with a single geometric beta of (say) 0.83 ± 0.01, if the advantages of a more relaxed schedule and reduced costs outweigh the potential disadvantages of inefficient Higher Order Mode suppression.

Table 3: Provisional RF system parameters, optimised for the 50 mA nominal macropulse current. Voltages and gradients are the maximum operational values per cavity, with little or no headroom.

Structure	**Geometric beta** β_G	**Maximum voltage** [MV]	**Maximum gradient** [MV/m]
Spokes	0.54 ± 0.01	5.6	8.0
Elliptical 1	0.67 ± 0.01	10.1	14.1
Elliptical 2	0.83 ± 0.01	18.5	21.1

The provisional maximum operating voltages and gradients shown in Table 3 are somewhat relaxed, since linac performance is mainly constrained by power coupler throughput, rather than by voltage or gradient. However, these values do not include any headroom, which must be included not only to ensure robust routine operations, but also to ensure that the cavity-to-cavity fluctuations are minimised, maximising the longitudinal acceptance and decreasing transverse beam losses. Detailed modeling and simulation studies are required before headroom specifications will be possible for spoke and elliptical cavity production lines, and for operations.

LINAC STRUCTURES

Source, LEBT, RFQ, MEBT and DTL

The Electron Cyclotron Resonance proton source will deliver macropulses up to 2 ms in length with currents of up to 90 mA. Pulse repetition frequencies as high as 40 Hz may be viable, permitting interleaved delivery to two target stations at 20 Hz.

The Low Energy Beam Transport uses two magnetic solenoids to match the beam coming from the source into the Radio Frequency Quadrupole. Dipole steerers in the LEBT adjust the beam position and angle at injection into the RFQ, and beam diagnostics monitor performance.

The RFQ – the first structure to shape the bunches – has a significant effect on the quality of the beam throughout the rest of the machine. Special care must be taken in its design, to simultaneously maintain transverse and longitudinal emittances while also maximising the transmission efficiency. Any beam losses will reduce the output beam intensity, and can cause microscopic deformations of the vanes to initiate sparking. A low Kilpatrick ratio of 1.8 preserves the ability to adjust the pulse length and the repetition rate, and minimises power consumption.

The Medium Energy Beam Transport uses four quadrupoles and two bunching cavities to match the beam in all three dimensions into the Drift Tube Linac, in the shortest possible length. Neutron production is not an issue at these low energies (~ 3 MeV), and so pre-collimation could easily be performed.

The DTL accelerates the proton beam in three tanks, each fed by a single klystron of (1.3, 2.5, 2.5) MW, respectively. Fixed post couplers installed before every (3, 2, 1) drift tubes in the (1st, 2nd, 3rd) tanks compensate for static manufacturing errors. Permanent or electromagnetic quads in an FFDD lattice perform transverse focusing.

Spoke Resonators and Elliptical Cavities

One family of superconducting double-spoke resonators provides large longitudinal and transverse acceptances, thanks to the relatively low frequency of 352.21 MHz and their relatively large apertures. This helps to reduce beam losses and associated radio-activation. Superconducting spokes have relatively low power consumption, and have the advantage of enabling independent tuning, so that operations can continue if one – or more – cavities go off-line. Each of the 14 cryomodules contains a quadrupole doublet followed by three double-spokes cavities.

Two families of five cell superconducting elliptical cavities that are very similar to SPL cavities [12] will be used, except that SPL and ESS cavities have different geometric βs. ESS low-energy elliptical cryomodules contain four 5 cell cavities, while the high-energy cryomodules nominally contain eight 5 cell cavities. Each cavity is fed by a single power coupler that can deliver 1.0 MW of power, from which 0.9 MW is available for acceleration. An intercavity distance of about 400 mm eliminates crosstalk between cavities, and accommodates both the main power couplers and also HOM dampers. Transverse focusing in elliptical cryomodules is achieved by quadrupole doublets which may be warm (with segmented cryomodules) or cold (without segmentation). Superconducting quadrupole doublets could be installed either inside the same cryo-module or inside separate cryomodules.

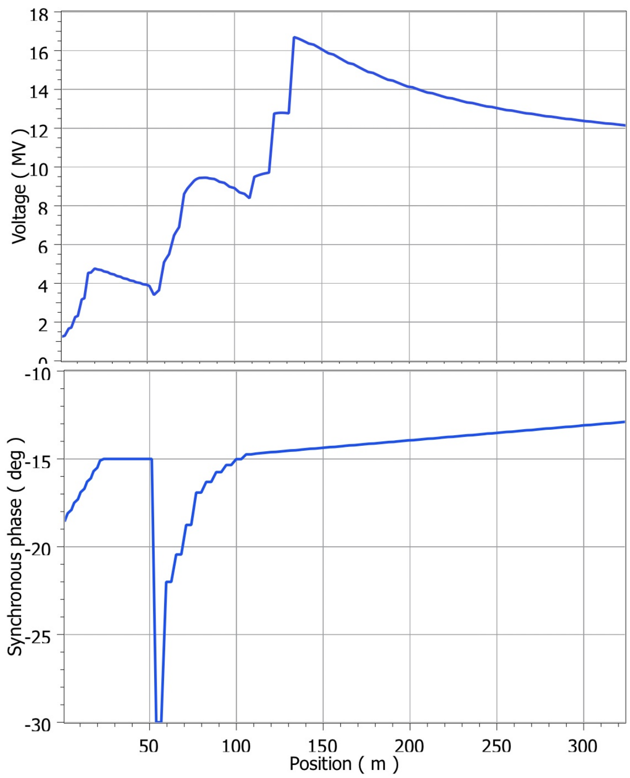

Figure 2: Spoke resonator and elliptical cavity voltage (TOP) and phase (BOTTOM) optics settings for the simulation of a 50 mA beam under ideal conditions. (Phase is everywhere reported with $f = 352.21$ MHz.)

BEAM DYNAMICS

A preliminary set of end-to-end beam dynamics simulations has been performed for a 60 mA beam with a normalised RMS emittance of 0.2 μm, using the Toutatis and TraceWin multi-particle simulation codes [14], to check for aperture bottlenecks, emittance growth, and halo production.

Optics

A transverse to longitudinal zero current phase advance ratio of 1.7 was chosen to give the best transverse confinement of the beam within the DTL apertures. The synchrotron phase at the entrance to the first tank is −30 deg, permitting a large longitudinal acceptance. The phase gradually increases to −20 deg in the middle of first tank for better acceleration. Figure 2 shows the idealised optics that were used for the spoke resonators and elliptical cavities, where adiabatic phase space shrinkage has reduced the required longitudinal acceptance. This permits the phase setting to increase from −20 deg to −15 deg in the spoke resonators. The RF bucket size is held constant across the frequency transition (in order to minimise damaging the beam distribution [5]) by initially doubling the phase to −30 deg before increasing it rapidly to −15 deg, and then smoothly increasing it to −13 deg towards the end of the linac.

Simulation results

More than 95% of the beam is transmitted to 3 MeV through the LEDA RFQ that was simulated, with 18% transverse emittance growth, as recorded in Table 4. It is expected that the transmission of a more realistic ESS RFQ could be more than 99%, with negligible emittance growth. The halo that is generated even for a perfectly matched beam could be removed by a collimator integrated into the MEBT. In the absence of errors there are no losses through the DTL, where the FFDD lattice is expected to be resilient to quadrupole misalignments [15]. Table 4 shows that the RMS emittances increase only modestly through the linac, so that the downstream apertures are relatively larger, justifying the reduction of transverse phase advance per period to (in general) 1.25 times the longitudinal phase advance per period. More than 99.9% of the particles are confined within 5 mm and the outermost particles do not exceed a radius of 10 mm, according to Figure 3. The RMS transverse beam size remains approximately constant at ∼ 3 mm, as shown in Figure 4.

Table 4: Simulated normalised RMS emittances at the injection point of each structure, for an injected beam of 60 mA beam passing through an idealised linac.

Structure	ϵ_x [μm]	ϵ_y [μm]	ϵ_z [13] [μm]
RFQ	0.200	0.200	–
DTL	0.239	0.234	0.617
Spoke	0.245	0.242	0.645
Elliptical 1	0.248	0.260	0.634
Elliptical 2	0.257	0.267	0.623
HEBT	0.262	0.270	0.620

CONTROL SYSTEM

Control system risks for the ESS are mainly technical and organisational. The *technical risks* are relatively low, in part because major control system software platforms have matured significantly in the last decades, so that the development focus has shifted towards ease of adoption and usability. Also, large improvements of CPU performance have simplified software and hardware development. Standard commercial off the shelf hardware components are increasingly available. *Organisational risks* are incurred because the ESS will be constructed by a number of geographically dispersed partner institutions, so that controls

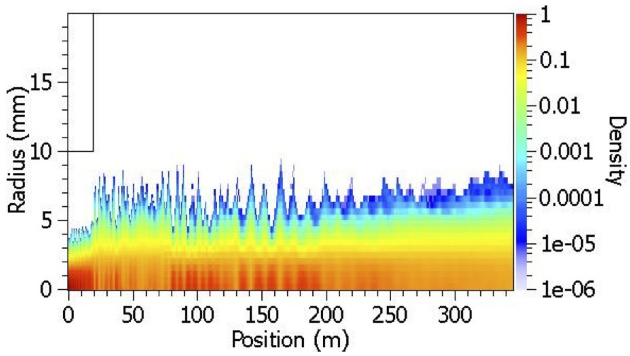

Figure 3: Simulated beam density and halo generation along an idealised linac.

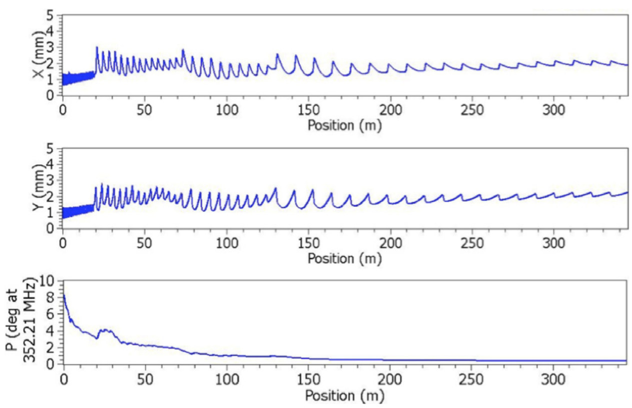

Figure 4: RMS beam sizes along the linac: horizontal (top), vertical (middle), and longitudinal (bottom). The RMS longitudinal phase spread is plotted at 352.21 MHz

development will be performed by a large number of quasi-independent teams. Further, control system integration comes late in the project and integrates with all other subsystems, so that problems could affect the critical path of the overall project.

Nominal assumptions have already been made about the control system [16]. In some cases their application is immediate, in others at the end of the Design Update phase (end of 2012), and still others only need to be applied in time for the construction phase (2016):

1. Use the EPICS control system.
2. Linux will be the service tier operating system.
3. Use the Oracle relational database system extensively.
4. Collaborate with similar projects, e.g. SNS, ITER, FRIB, XFEL and JLab 12 GeV Upgrade.
5. Join the XAL application development framework collaboration.
6. Introduce a naming convention early in the project.
7. Provide a standardised *Control Box* platform to partner institutions, with first prototype delivery in 2010, based on the philosophy adopted by ITER [17].
8. Integrate the control system of the linac and the target.

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