EUROPEAN SPALLATION SOURCE

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Interface
LINAC
ID 4, ID 6 – LINAC design solutions

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SUMMARY

This document presents the alternatives considered and chosen for the Accelerator Design Update phase, which officially started 2011-01-01.

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1. INTRODUCTION

The aim of the European Spallation Source is to be the world leading facility for neutron science with long neutron pulses and ultra cold neutrons. The accelerator shall satisfy the needs of its future users, which could be summarised as [1]:

- Long pulses, 2.86 ms
- Repetition rates in the interval 14 Hz
- 5 MW beam power, for high neutron intensity

The accelerator is the unit of the facility that will be producing high-energy protons. These protons will drive the spallation process in the target. A linear accelerator (linac) [2,3] is the only type of accelerator that can deliver the long pulse proton beam needed. An electron cyclotron resonance (ECR) ion source is chosen to provide the protons. The linac will be built with both normal conducting and superconducting technologies. At low energy the accelerating structures will be normal conducting copper, while at higher energies the surface resistance of copper becomes too high and it is more economical to use superconducting niobium cavities. Therefore a fully normal-conducting linac is not considered.

Operating the accelerator produces radiation. Therefore, radiation protection considerations have a big impact on the physical design of the linac tunnel and its placement. Radiation protection studies have shown the feasibility of a linac tunnel structure that can provide sufficient shielding [4].

The design update will build on the baseline accelerator, which is presented in chapter 2.

Figure 1 shows an artist's impression of the ESS facility.

2. ESS-2010 BASELINE ACCELERATOR

By the end of 2010 the accelerator baseline was established. The design update, starting in January 2011, will build on this baseline and will produce the Technical Design Report (TDR) by the end of 2012 [5]. The baseline contains some parameters that are well established, some that are a bit more vague and subject to change, while others are not yet determined at all. Therefore, the current description is still sketchy, but it is the best estimate at the start of the design update phase.

2.1 High level parameters

Most of the high level parameters, as described in Table 1, are set since long, condensed from scientists' requests and technical achievability. They include the proton beam power of 5 MW and proton beam energy of 2.5 giga electron volt (GeV), which are chosen to produce the maximum number of neutrons. Proton pulse lengths of 2.86 ms at 14 Hz repetition rates have been requested, which sets the required beam current to 50 mA in order to reach the desired beam power. An average beam loss of 1 W/m along the linac is considered manageable from machine and radiation protection points of view, and has therefore been chosen as the limit.

The high level parameters are still subject to change.

Table 1: High-level parameters

High Level Parameters (CCB)		
Parameter	**Unit**	**Value**
Average beam power	MW	5
Number of target stations		1
Number of instruments in construction budget		22
Maximum number of instrument		44
Number of ports		50
Number of moderators		2
Separation of ports in degrees	°	5
Proton kinetic energy	GeV	2.5
Average macro-pulse current	mA	50
Macro-pulse length	ms	2.86
Pulse repetition rate	Hz	14
Maximum cavity surface field	MV/m	40
Maximum linac length (without 100 upgrade space)	m	392
Geometry of target (drawing)		
Beam size on target		
Annual operating period	h	5200
Reliability	%	95

2.2 Physical footprint

The linac is a very large machine; the estimated length from ion source to target is about 500 m. The main constituents of the superconducting section will be the cryomodules, mostly made from steel, housing the niobium cavities. The shorter warm section will primarily be made from copper. The linac is housed in a tunnel which might be about 5x5 m^2 in cross section. The tunnel will be made from concrete and covered by dirt, to provide sufficient shielding against radiation - according to the studies [4]. The baseline is to bury the tunnel up to 10 m below ground.

Apart from improving shielding, burying the linac also makes the least visible imprint on the landscape. Still, there will be the klystron gallery (a building housing RF power sources, klystrons and modulators) at the surface, running parallel with the linac for all its length. The klystron gallery could be between 20 and 40 m wide and 10 to 20 m tall, and situated either directly on top of the linac or to the side (but still aboveground).

2.3 Linac design

The ECR ion source has been proven to reliably produce proton currents in excess of the required 60 mA, for long periods of time, and is the chosen source for ESS. As losses occur, particularly in the low energy part of the linac, the source has to produce a higher current than what is required at the end of the accelerator (50 mA).

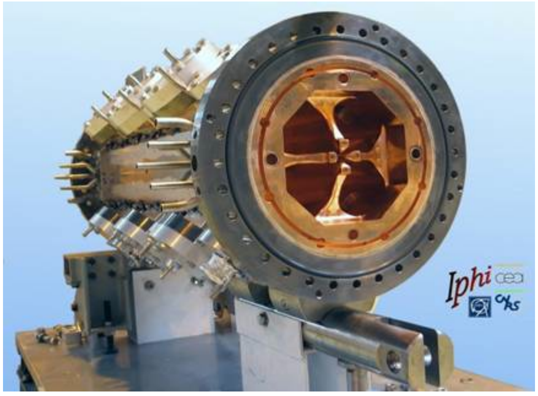

Figure 1: IPHI RFQ at CEA Saclay

The source is followed by a low energy beam transport (LEBT) to the first accelerating structure, the radio frequency quadrupole (RFQ), see Figure 1. The medium energy beam transport (MEBT) leads the protons to the drift tube linac (DTL), see Figure 2. The LEBT and MEBT will contain beam diagnostics and beam shaping capabilities. All these structures are at room temperature.

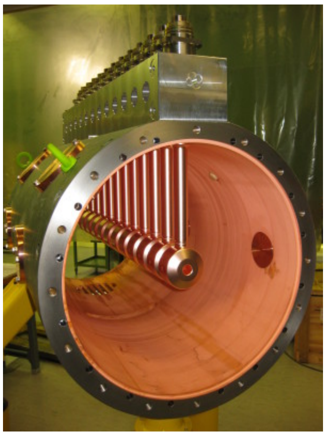

Figure 2: Open DTL tank

After the DTL begins the superconducting linac, first with double spoke cavities, followed by two families of elliptical cavities (low β and high β). The types of accelerating structures are chosen for what is best suited for the speed of the protons at the different stages (expressed in $\beta=v/c$). All technologies, except for the spoke cavities, have been proven and are extensively used in other accelerators. The spoke cavities are being developed at a number of different laboratories, but have not been tested in an actual accelerator yet. Still they are deemed a mature technology that can be trusted to work by the time ESS is constructed.

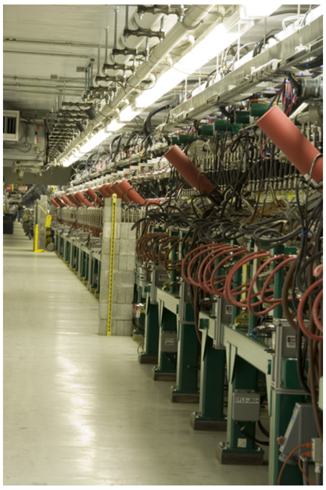

Figure 3: SNS superconducting linac (segmented)

The superconducting linac could look similar to the one at SNS, see Figure 3. It will be made up of around 45 cryomodules. The design of the cryomodules has not been chosen yet, but a preferred variant is the so called hybrid design, which allows for either cold or warm gaps between the modules. This creates a welcome flexibility for the placement of beam instrumentation, while at the same time managing to keep the overall energy consumption low. Other plausible options are completely segmented designs (as at SNS) or completely continuous designs (as at XFEL).

The last 100 m of the linac tunnel are housing the high energy beam transport (HEBT) and can be used for future upgrades, too. If the HEBT were shorter, future upgrades would be incredibly difficult and expensive. The HEBT also serves to lead the beam from the tunnel up to the target situated 1.6 m above ground, while giving the beam the right shape.

For the warm section and the spoke cavities the radio frequency (RF) is 352 MHz, while for the elliptical cavities it is 704 MHz. These frequencies are within a range suitable for proton acceleration. The particular choice is made to be compatible with RF infrastructure existing at other labs.

Figure 4 shows a block diagram of the linac with the lengths and energies for all the sections, while the baseline lattice design is summarised in Table 2.

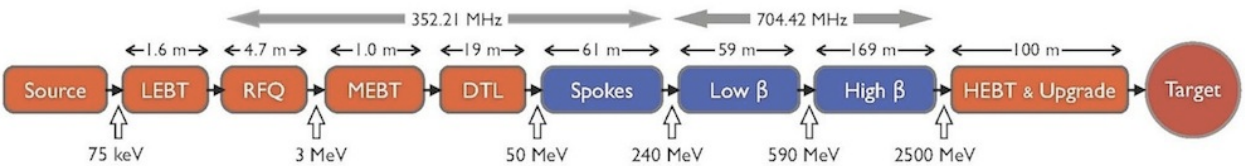

Figure 4: Block diagram of the ESS accelerator

Table 2: Baseline lattice parameters

LATTICE & ACCELERATOR SCIENCE (H. Danared)

Parameter	Unit	Value
Ion source output energy	MeV	0.075
RFQ output energy	MeV	3
DTL output energy	MeV	50
Spoke resonator output energy	MeV	188
Elliptical low beta output energy	MeV	606
Elliptical high beta output energy	MeV	2500
Proton kinetic energy on target	MeV	2500
Ion source length	m	2.5
LEBT length	m	1.6
RFQ length	m	4.0
MEBT length	m	2.5
DTL length	m	19.0
Spoke resonator section length	m	58.0
Elliptical low beta section length	m	108.0
Elliptical high beta section length	m	196.0
HEBT length, to first vertical bend	m	100.0
Length, source-to-first vertical bend	m	491.6
Depth of linac below ground level	m	10
Number of accelerating gaps per spoke cavity		3
Number of cells per low beta elliptical cavity		5
Number of cells per high beta elliptical cavity		5
Spoke resonator cavities per cryomodule		2
Low beta elliptical cavities per cryomodule		4
High beta elliptical cavities per cryomodule		8
Geometric beta, spoke resonators		0.57
Geometric beta, low beta elliptical cavities		0.70
Geometric beta, high beta elliptical cavities		0.90
Operational gradient, spoke resonators	MV/m	8
Operational gradient, low beta elliptical cavities	MV/m	15.44
Operational gradient, high beta elliptical cavities	MV/m	18.17
Elliptical power coupler power, to beam	MW	0.9

3. ALTERNATIVE DESIGNS

The design chosen as the baseline for the Design Update is not the only conceivable option, there are many alternatives that have been and are still being evaluated.

3.1 Baseline evolution

The current baseline evolved from the earlier 2003 design, where 150 mA would have been accelerated to 1 GeV [2]. In this case the proton beams from two ECR sources would have been funneled together to reach sufficient current, a technique that has never been routinely operated at a facility. Cavity design, manufacturing and quality assurance have advanced through the years and 2.5 GeV can be reached with the same linac length as was foreseen for the 1 GeV design. It has also been shown that the beam power, proportional to current times energy, is the important parameter for neutron production. Due to these facts it was deemed feasible to eliminating the double ion sources.

In the 2003 design an accumulator ring was included, for short pulse production. Since ESS has now been announced a long pulse facility, the accumulator ring has been dropped.

3.2 Physical footprint

While putting the linac below ground is convenient from the direct radiation protection point of view, it might constitute a problem with activated ground water. The problem would be smaller, if the linac were at ground level. Putting the linac underground also disturbs the ground water flow, which then has to be corrected for. This might be both complicated and expensive.

Additional radiation protection studies are necessary, both concerning ground water activation in the different scenarios, and concerning prompt radiation. If the linac is placed at the surface, it could be considered to build the tunnel with thicker concrete walls and no soil covering. This might be more expensive up front, but cheaper if decommissioning costs are considered, because activated concrete is much easier to handle than activated soil. With the linac at ground level, the infrastructure - e.g. waveguides for RF power transmission - could be simplified.

In any configuration, above or below ground, there must be a bend in the HEBT, to avoid direct back streaming of neutrons, and to provide the possibility for a beam dump in the forward direction for commissioning or errant beams. If the linac is below ground, the bend is ideally vertical – if the linac is above ground, the bend can be horizontal.

3.3 Linac design

There is no experience to date with operating spoke cavities. In parallel to the Design Update phase, there will be an R&D program for these cavities. In case the spoke cavities turn out not to be feasible, the fall-back option would be a prolonged DTL. Since a DTL is a fairly conventional device it could be designed with relatively short notice.

There are still considerations if one klystron per cavity is the optimal choice in terms of value for money. The alternative would be to use one klystron for two or more cavities. The price of klystrons does not scale linearly with power, so fewer klystrons of higher power could be cheaper than more klystrons of lower power. However, there are a number of issues with high power klystrons [9]. For instance:

- there are no klystrons with sufficient power for two elliptical cavities on the market today, R&D is needed;
- high power klystrons have shorter lifetimes and are less efficient than low power klystrons;
- the RF distribution system would become more complex and costly.

Therefore, having more than one cavity per klystron would actually be more expensive. The baseline is therefore one klystron per cavity, at least for the elliptical cavities, which constitute the bulk of the accelerating structures. For the lower power spoke resonators it might still be wise to investigate other configurations.

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