THE ESS SUPERCONDUCTING LINEAR ACCELERATOR

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Abstract

The European Spallation Source (ESS) is one of Europe's largest planned research infrastructures. The collaborative project is funded by a collaboration of 17 European countries and is under design and construction in Lund, Sweden. The ESS will bring new insights to the grand challenges of science and innovation in fields as diverse as material and life sciences, energy, environmental technology, cultural heritage, solid-state and fundamental physics. A 5 MW, long pulse proton accelerator is used to reach this goal. The pulsed length is 2.86 ms and the repetition frequency is 14 Hz (4 % duty cycle). The choice of SRF technology is a key element in the development of the ESS linear accelerator (linac). The superconducting linac is composed of one section of spoke cavity cryomodules (352.21 MHz) and two sections of elliptical cavity cryomodules (704.42 MHz). These cryomodules contain niobium SRF cavities operating at 2 K. This paper presents the superconducting linac layout and its requirements.

INTRODUCTION

The European Spallation Source (ESS) is one of Europe's largest planned research infrastructures and the world's leading facility using a 5 MW neutrons source [1-2]. The ESS will bring new insights to the grand challenges of science and innovation.

The ESS project is a collaborative project supported by seventeen European countries. This joint partnership build capacity and increase proficiency in scientific research mainly driven by applications related to material sciences.

The high level accelerator requirements are to design and construct a proton accelerator capable of delivering to the target a time averaged proton beam power of 5 MW at the completion with a stage at 1 MW in 2019.

The linear proton accelerator is composed of an ion source, Radio Frequency Quadrupole (RFQ), Drift Tube Linac (DTL), and beam transport sections as normal conducting sections plus the superconducting linac. The different energy gains for the linac are such that 95 % of the accelerator is superconducting. The superconducting linac is composed of 26 spoke cavities with an optimal β of 0.50, the medium-β elliptical section uses 36 six-cell elliptical cavities with a geometric β of 0.67 and finally 84 five-cell high β elliptical cavities with a geometric β of 0.86 bring the beam to its final energy. The nominal resonant frequency of the spoke cavity is 352.21 MHz whereas the centre frequency of the high power RF provided to the elliptical cavities is 704.42 MHz.

This paper introduces the ESS SRF linear accelerator requirements, its Optimus layout and a short description of the SRF components.

ESS ACCELERATOR REQUIREMENTS BASED ON THE OPTIMUS LAYOUT

Optimization of SRF Linac

To reduce the cost of the ESS accelerator Linac, the number of cryomodules and RF sources had to be reduced by decreasing the final energy from 2.5 GeV to 2.0 GeV and adjusting the beam current to compensate for it as well as increasing the gradients in the SRF cavities by 11.25 %. Consequently, using the Optimus lattice, the number of spoke and elliptical cavities have been reduced from 15 and 45 to 13 and 30, respectively [3].

To reach this lattice, the linac has undergone several rounds of iterations and optimizations, including the transition energies within the normal conducting frontend, i.e., between RFQ and DTL, and the transition energy from normal conducting to superconducting and those from one superconducting structure to the downstream one. On top of these, the beam current and final energy have been optimized to achieve the desired beam power on target while neither the beam quality nor transmission has been compromised.

Figure 1 shows the layout of the ESS linac.

The pulse length and the 4 % duty cycle (2.86 ms pulse at a maximum repetition rate of 14 Hz) must remain unchanged due to ESS instrument requirements.

The power to the coupler shall remain below 1.1 MW. Hence, the ESS accelerator has been redesigned to account for the peak beam current raised from 50.0 mA to 62.5 mA. Table 1 shows the length of the different section of the linac with their associated energy.

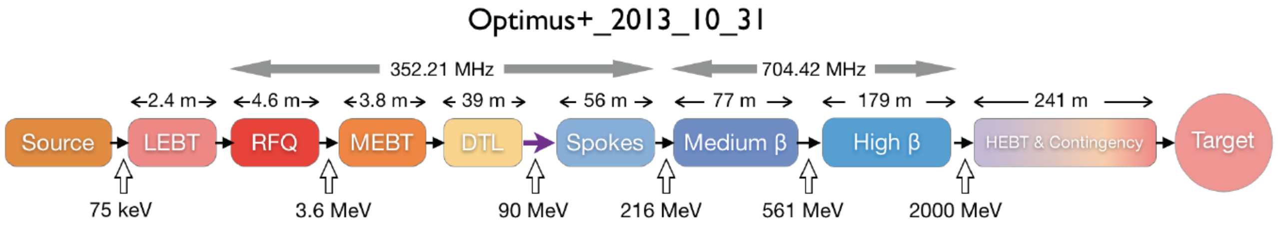

Figure 1: Block diagram of the Optimus layout

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Table 1: Length and Energy along the Linac

Item	Length (m)	Energy (MeV)
Ion source	2.5*	0
LEBT	2.38	0.075
RFQ	4.50	0.075-3.6
MEBT	3.62	3.6
DTL	38.88	3.6 to 90
Spoke	55.62	90 to 216
Medium-β	76.68	216 to 561
High-β	176.92	561 to 2000
Contingency	119.28	2000
High-β upgrade	59.64	2000
HEDP	6.32**	2000
A2T /DogLeg	14.16	2000
A2T / Expander	44.4	2000
Sum	602.4	-

* This length is excluded from the length calculations.
** This length is adjusted to keep the source (exit) to target distance at 602.4 m.

At 90 MeV of beam energy at the beginning of spoke section the beam is energetic enough to be accelerated in a double spoke cavity, and the optimum β of these spoke cavities have been chosen to transfer the RF power most efficiently to beam in the range where spoke cavities accelerate. It has to be mentioned that the transition energies and the optimum β of the cavities are correlated and both optimizations have to be performed simultaneously. Both of these are a function of the available power, accelerating gradient of cavities, beam physics requirements and number of cells per cavity, which itself is another optimization parameter. Figure 2 shows the accelerating gradient over the SRF linac.

To achieve a uniform lattice and increased reliability of the superconducting linac as a whole, the period length, i.e. the length of cryomodule plus a quadrupole doublet, in the elliptical section, medium and high-β is the same, and is also equal to twice of spoke period length, permitting their replacement in the unfortunate case where the gradient in one structure is not achieved by the sequence of installed cavities.

Each double spoke cavity has three gaps with an accelerating gradient of 9 MV/m. Each pair of these cavities is housed in a cryomodule separated from the following cryomodule by a quadrupole doublet used for transverse beam control. Elliptical cavities are having a surface peak field of 45 MV/m and are grouped in four and housed in identical cryomodules.

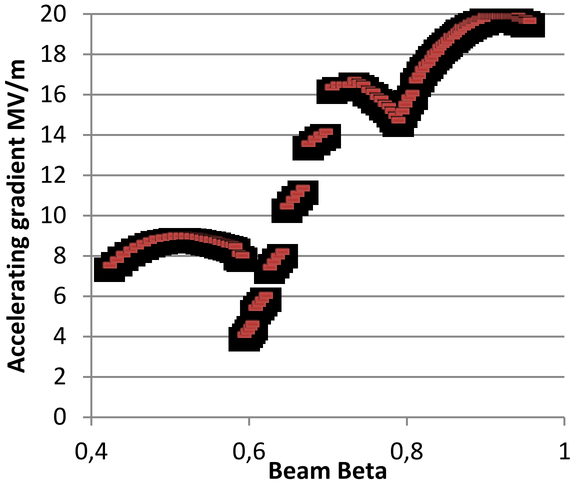

Figure 2: SRF Linac accelerating gradient profile

Risk Assessment and Sustainable Infrastructure

Even if the major impact of the accelerator redesign lays in the front-end normal conducting component operation, it also leads to larger operational risks to SRF linac components. For instance, the SRF cavities accelerating voltage must handle an additional 30 %. Hence, the probability of thermal breakdown and field emission are larger since SRF cavities are operating at a higher surface field.

In addition, risk assessment studies have been performed in order to identify the requested interlock systems and to define the Machine Protection System [4].

One of the most stringent requirements for the ESS project is the requested reliability of 95 % per hour, which in other words means that the mean time between failures of the accelerator shall exceed 22 hours.

During operations, the electrical power consumption of the accelerator should not exceed 28 MW. The recycled waste heat from the accelerator will be optimized. The design and operating process of accelerator components comply with the ESS sustainability program. The ESS accelerator makes use of renewable, recyclable, responsible and reliable equipment design and operations.

SRF LINAC COMPONENTS

The ESS layout is composed of 13 spoke cavity cryomodules, 30 elliptical cavity cryomodules with four cavities in each and quadrupole doublets between cryomodules. The spacing and location of the power coupler ports are the same for the high-β and medium-β cryomodules, providing capability to be interchangeable in the tunnel. The details of the spoke and elliptical cryomodules are shown in [5-10].

The SRF cavities are aligned within 1.5 mm of the beam axis. The nominal accelerating voltages at the optimal betas and the maximum loaded quality factor of the cavity coupler system are listed in Table 2.

The dynamic heat loads at 2 K per medium and high-β cavities at nominal operation are 4.9 W and 6.5 W, respectively. They match the ESS estimated average electricity (45 MW) and cooling needs (44 MW). As well, the maximum forward power supplied to the fundamental power coupler is an important constraint to reasonably optimize the technology used the accelerator redesign. Those two later requirements are also listed in Table 2 together with the baseline parameters.

Table 2: Summary SRF component parameters

Style	Spoke	Medium-β	High-β
Freq. (MHz)	352.21	704.42	704.42
Cavity #	26	36	84
Velocity range	0.42 to 0.58	0.58 to 0.78	0.78 to 0.95
Nom. Acc. Voltage (MV)	5.74	14.3	18.2
Loaded quality factor	2.85×10^5	8×10^5	7.6×10^5
Dynamic heat load (W)	0.8	4.9	5.5
Max. forward power (kW)	335	1100	1100
RF (baseline)	Tetrode	Klystron	IOT

The expected mechanical time constant of the cavities is about 1 ms compared to the pulse length of 2.86 ms. This constraint has a large impact on the tuning scheme of the SRF cavities. Because of the enormous gradients in superconducting cavities, we expect over 400 Hz of detuning. The static frequency tuning requirements are possible using a cold tuning system (CTS) installed on each SRF cavity. The piezo needs to compensate the Lorenz force detuning. In the ESS long pulse configuration, the static pre-detuning as done in SNS will not be sufficient and the dynamic de-tuning compensation using piezo-electric tuners is crucial. For this matter, the resonant frequency of the fundamental mode of the cavity is controllable over a range exceeding 10 kHz. Due to the heavy beam loading, it is only necessary to hold the resonant frequency of the fundamental mode constant to within an accuracy of ~100 Hz over the entire pulse.

All other cavity modes are at least 0.45 MHz and 1 MHz away from the fundamental accelerating mode for the medium and high-β cavities. In the case of the elliptical cavity design, all higher order modes (HOMs) are at least 5 MHz away from integer multiples of the beam-bunching frequency (352.21 MHz) for any HOMs whose resonant frequencies are below the cut-off frequency of the beam-pipe.

CONCLUSION

The ESS accelerator lattice has been modified in order to reduce the overall cost of the ESS project, while reducing the number of cryomodules and RF sources. As a result the beam current has been raised from 50 to 62.5 mA. Additional risks are handled by the cavity operating at a higher surface field. The cryomodule design has been standardized to allow flexibility in the lattice.

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