THE EUROPEAN SPALLATION SOURCE

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Abstract

The European Spallation Neutron Source project includes a 5 MW superconducting linac, and aims for initial operation at 1.5 MW in 2019 with 5 MW capacity installed for 2023. Design considerations including the work done to find the minimum cost for preserved beam power will be discussed. This will include discussions on lessons learnt from SNS regarding e.g. superconducting RF performance and RF power sources. The design and construction plans and status will be described.

NEUTRON USAGE AND HISTORICAL BACKGROUND

The neutron beams are being used extensively in science and industry to investigate the properties of matter. The beams of neutrons are used to monitor the structure of the matter in atomic levels using scattering methods. These methods give a high precision information about matter and the high penetration property of neutron makes it the only probe for these measurements.

Most existing neutron sources in Europe are based on nuclear reactors. This approach has been taken to its limits set by both technical issues such as cooling but also by licensing which is non-trivial for any facility using fissile material. Compared to existing spallation sources ESS will be 30 times brighter and it will be the first spallation source with a time averaged flux of neutrons as high as the best research reactors. Europe has today over 5000 researchers who use neutrons and this community is asking for a new intense source of neutrons.

The need for the European Spallation Source (ESS) [1] was articulated 20 years ago but a decision to build it in Lund in Sweden was only taken in May 2009. A series of meetings organized in 1991 and 1992 by Forchungszentrum Jülich (FZ-J) and Rutherford Appleton Laboratory (RAL) explored the basis for an advanced accelerator driven pulsed spallation source, which later formed the basis for the specification for ESS [2]. The decision to site it in Lund was the final stage of a process initiated by the European Commission and steered by the European Strategy Forum on Research Infrastructures (ESFRI). ESFRI was created in 2002 and is a strategic instrument of EC to develop the scientific integration of Europe and to strengthen its international outreach [3].

THE ESS FACILITY

The spallation cross section for protons on heavy nuclei increases as a function of proton energy up to several tens of GeV [4]. Nonetheless it is generally agreed that a kinetic proton energy between 1-3 GeV is optimal for practical target and moderator designs, and in order to keep the shielding requirements reasonable.

The ESS accelerator design has gone through several evolutions. In 2002 a fully normal conducting design was proposed [5] in parallel to a pre-dominantly superconducting design derived from the CONCERT project [6]. In 2003 a new design was presented [2] with two front-ends consisting of ion-source, Radio Frequency Quadrupole (RFQ) and a Drift-Tube Linac (DTL) up to 20 MeV. The beams of the two front-ends were merged at 20 MeV and further accelerated in normal conducting structures up to 400 MeV and superconducting structures up to 1334 MeV. The facility had both a long pulse target station and a storage and accumulation ring for a short pulse target. To enable low loss injection into the accumulator ring H^- ions were proposed to be accelerated at a total beam power of 10 MW. In 2009, the competing ESS-Bilbao [7] team and the ESS-Scandinavia [8, 9] team both proposed a simplified 5 MW design with protons accelerated to 2.5 GeV by a mostly supercondcting linac with only one front-end to avoid the complex merging stage and higher beam energy to lower the required beam current. The requirement for a short pulse target station was also dropped to reduce cost. This makes it possible to accelerate H^+ ions, which should reduce losses due to intra-beam stripping of H^- ions and simplifies the ion source design.

The last design iteration was undertaken after cost objectives were set in autumn 2012. The main changes were: i) the implementation of energy staging to ease installation and commissioning, ii) the removal of cryomodules with RF systems and compensate by using operational experience from SNS and run the linac more aggressively, iii) the removal of additional cryomodules with RF systems and compensate by increasing the peak field in the cavities from 40 MV/m to 45 MV/m and iv) introducing new Multi Beam (MB) IOT technology for the high beta linac RF system in the baseline. For the staged commissioning the plan is to start with 1.5 MW in 2019 and complete remaining installation of linac to 2.0 GeV to provide 5 MW of beam by 2022. The staging doesn't only leave more time for installation but it also creates more time for the development of MB-IOTs.

As a result of this series of optimization and iterations the ESS linac beam current is proposed to be 62.5 mA and the final energy is fixed to 2.0 GeV to provide 125 MW of

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peak power to the target. More than 95 % of acceleration is done in superconducting structures. The linac accelerates a 2.86 ms long pulse with a repetition rate of 14 Hz, resulting in a 4 % duty cycle and giving an average beam power of 5 MW with a high demand on availability of the facility (>95 %). The former two parameters are set by the experiments, instrument design and scientific performance of ESS.

The ESS has the ambitious goal of becoming a sustainable research facility with zero release of carbon dioxide. This will be achieved through a combination of actions, but with the linac being the most energy hungry part of ESS, the energy efficient design of the RF power sources, the cryogenics systems and high-Q cavities are important issues.

THE ESS LINAC

The configuration of the current baseline linac is shown schematically in Fig. 1, and selected linac parameters are listed in Tab. 1 [10].

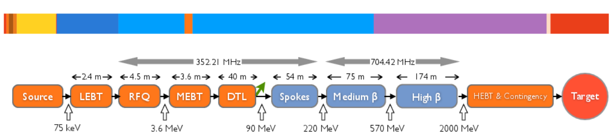

Figure 1: Top: Scaled Layout of ESS. The normal conducting structures are indicated by warm colors and the blue themes sectors indicate the superconducting structures. From left: Ion source, LEBT, RFQ, MEBT, DTL, Spoke, Medium β, High β, and HEBT (consisting of Contingency and beam transport, Dogleg, and Expander). Bottom: blob layout of the ESS linac.

The warm linac design has been done in a collaboration consisting of ESS, INFN Catania, CEA Saclay, ESS-Bilbao and INFN Legnaro, the superconducting cavities and their cryomodules are developed at IPN Orsay and CEA Saclay, and the HEBT is designed by ISA in Aarhus.

A proton beam of less than 80 mA is produced in a pulsed microwave-discharge source on a platform at 75 kV. A low-energy beam transport, LEBT, with two solenoid magnets as focusing elements brings the beam to the entrance of the RFQ. The LEBT has a chopper that cuts away the beam while the proton pulses from the ion source stabilize, preventing a beam with off-nominal parameters from being accelerated in the RFQ and lost at high energy. The 4-vane RFQ accelerates the beam to 3.6 MeV with small losses and a minimal emittance growth. It is designed specifically for ESS but it is based on the IPHI RFQ at Saclay. The RF frequency of the RFQ and the warm linac is 352.21 MHz. After the RFQ there is a medium-energy beam transport, MEBT, with three buncher cavities and 11 quadrupole magnets. The MEBT has several different functions: it has optics to match and steer the beam from the RFQ into the drift-tube linac, it has a comprehensive set of beam-instrumentation devices, it has a chopper which acts faster than the LEBT chopper since space-charge neutralization is not an issue in the MEBT, and it allows collimation of the transverse particle distribution. A drift-tube linac, DTL, with five tanks which each are $\leq$8.0 m long takes the beam from 3.6 MeV to 90 MeV. It has a FODO structure with permanent-magnet quadrupoles. Every second drift tube is empty or used for steering magnets and beam-position monitors.

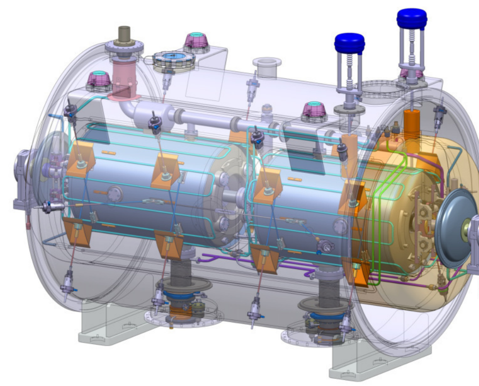

Figure 2: Spoke cavity cryomdoule for ESS

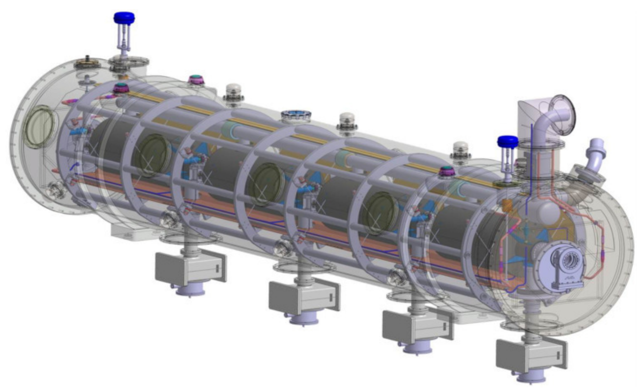

Figure 3: Elliptical cavity cryomdoule for ESS

The superconducting linac has three types of cavities: double-spoke resonators, six-cell medium-beta elliptical cavities and five-cell high-beta elliptical cavities. The linac has 13 spoke cryomodules (see Fig. 2) with two double-spoke resonators in each, and between the cryomodules there are warm quadrupole doublets. The spoke resonators operate at 352.21 MHz like the warm linac, but then there is a frequency doubling to the 704.42 MHz at the elliptical cavities. There are a total of 30 elliptical cavity cryomodules (see Fig. 2) with 9 medium-beta cryomodules with four cavities in each and 21 high-beta cryomodules with four cavities in each. There are quadrupole doublets between every cryomodule. The period length in the medium-beta and high-beta section is exactly the same to allow swapping the cryomodules in case of low performing medium-beta cavities.

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Table 1: ESS Linac Parameters

	Energy (MeV)	No.$_{modules}$	No.$_{cavities}$	β_G	T (K)	L$_{Period}$ (m)
Source	0.075	1	0	–	$\sim$ 300	–
LEBT	0.075	–	0	–	$\sim$ 300	–
RFQ	3.6	1	1	–	$\sim$ 300	Not fixed
MEBT	3.6	–	3	–	$\sim$ 300	Not fixed
DTL	90	5	5	–	$\sim$ 300	Not fixed
Spoke	220	13	26	0.50*	$\sim$ 2	4.14
Medium β	570	9	36	0.67	$\sim$ 2	8.28
High β	2000	21	84	0.86	$\sim$ 2	8.28
HEBT	2000	–	0	–	$\sim$ 300	Not fixed

* β_{opt}

All accelerating structures will be powered by klystrons or IOTs, except the spoke resonators where tetrodes might be used. The possibility of using Solid State Amplifiers is still under study. With one klystron per elliptical cavity plus a few for the warm linac, there will be more than 120 large tubes and more than 60 modulators depending on how many tube each modulator is feeding. A tube could be a klystron, an IOT or a tetrode. The density of components in the klystron building would become too high if these were to be positioned linearly. Instead they will be located in groups of eight klystrons and four modulators across the klystron building Fig. 4.

After the last cryomodule there is the contingency and

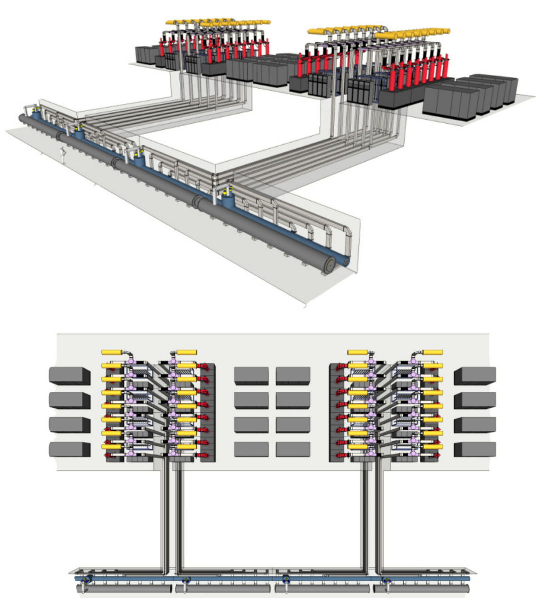

Figure 4: The ESS RF sources in and the RF waveguide stub lay-out. The 3D view on top and the view from top on bottom.

upgrade section where additional cryomodules can be installed to compensate for a shortfall in linac performance and/or a power upgrade of the facility. The additional tunnel would also make it possible to bend the beam out for a second target station.

Then the beam is brought from the tunnel to the spallation target at the surface through two vertical bends and an expansion section. A raster scanning system is used to blow the beam up onto the desired profile of the proton-beam window and the target window.

RF SOURCES

The vast majority of structures in the ESS linac are superconducting cavities, therefore the dominant feature of the ESS RF system is the number of RF stations. The enormous gradients in the superconducting cavities is strong enough to deform the 4 mm thick niobium cavities by exerting a significant radiation pressure. This deformation is called Lorentz detuning and must be compensated, otherwise the deformed cavity will resonate at a different frequency which will destroy beam quality and induce losses. To handle variations in cavity coupling and Lorentz detuning there is one RF power amplifier per superconducting resonator; totaling 146 individual RF stations for the superconducting cavities. The core of each RF station is an RF power amplifier which is typically a klystron. For the high beta section of the linac consisting of 84 stations, the peak power required for the cavities is 1100 kW, Fig. 5.

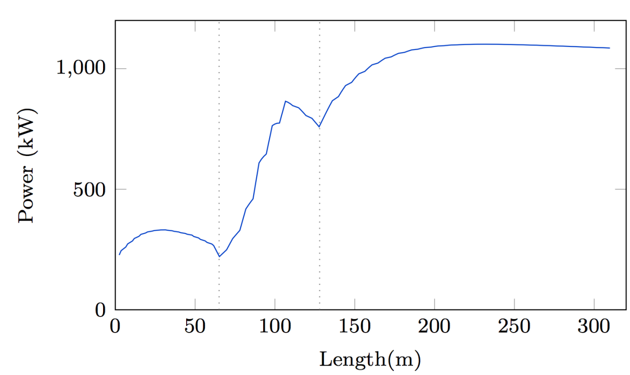

Figure 5: Power profile in the superconducting linac of the ESS, the three section divided by vertical dotted lines are the spoke, medium beta and high beta section.

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Even though the loaded Q of the cavities is quite low (7×10^5) to compensate for heavy beam loading, the Lorentz detuning for ESS can be quite severe. Without any Lorentz-detuning compensation, the resonant frequency of the cavities could shift up to 400 Hz. The bandwidth of the cavity in the absence of the beam, the unloaded cavity bandwidth, is 0.07 Hz, and the bandwidth in the presence of beam is almost 1 kHz. Comparing to the number of oscillation of the RF wave during the 2.86 ms of pulse length one can calculate that even this small difference in frequency can shift the RF wave with respect to bunches by more than one whole RF period. In addition, the beam pulse for the ESS linac is very long and is about a factor of three longer than the mechanical response time of the cavity to the Lorentz detuning. Other methods like predetuning of the cavity as done in the SNS linac is not sufficient in the case of ESS. To save on RF power overhead and maintain the beam quality, all superconducting cavities will be equipped with fast piezo-electric tuners to negate the Lorentz detuning of the cavities.

The klystrons are operated 30 % below the maximum saturated power so that variations in the RF system such as modulator droop, cavity coupling, residual Lorentz detuning, and power loss in the waveguide distribution system can be compensated. Also part of the overhead is used for stable regulation of the feedback loop. The target efficiency of the klystrons at maximum saturated power is 60 % which will give an operational efficiency of about 45 %. The required maximum saturated power for the klystrons is 1.5 MW. For stability, reliability and economic reasons, the klystrons will be powered in the pulsed cathode configuration.

The klystrons are energized using modulators. The modulators must supply a 3.5 ms long pulse at a rate of 14 Hz. The cathode voltage for each klystron is about 100 kV with a peak current of about 20 Amperes. For a modulator efficiency of 90 % and a power factor of 0.9, 120 kVA will be required for each klystron. For economical and space reasons, it has been decided to power two klystrons per modulator which limits the required power per modulator to 240 kVA. To handle the long pulse length of 3.5 ms, the modulators will implement solid-state switches at relatively moderate voltages and the output voltage pulse will be stepped up by a pulse transformer or equivalent technology.

The regulation of each RF system will be done independently with the low level RF system. Using modern digital technology, most of the regulation will be done with adaptive feed-forward algorithms. Feedback regulation will play a secondary role to the adaptive feed-forward so the required power overhead can be minimized.

With the large number of RF systems, it will be uneconomical for the high power waveguide of each RF system to have its own penetration to the tunnel. ESS will use a “stub” concept for distributing 16 RF systems into the tunnel as shown in Fig. 4. The stubs will provide access to additional conventional services such as water and power as well. In addition, the radiation shielding issues are best handled with the stub concept.

ESS is also considering the use of Inductive Output Tubes (IOTs) in place of klystrons for the high beta section of the linac. IOT shows the promise of high efficiency and much lower capital cost. IOTs can be thought of as a cross between klystrons and tetrodes. As in tetrodes, IOTs employ a grid to control electron flow from cathode to collector. These grids are very robust with the advent of pyrolithic carbon technology. Since IOTs are gridded tubes, no pulsed modulation system is needed to energize the cathode. This eliminates costly high voltages switches in the power supply for the IOT. Also a gridded tube can be run in deep class C that can produce very high efficiencies (less than 70 %). Also IOTs do not exhibit the severe saturation effect of klystrons. This permits the operation of IOTs at the maximum rated power in feedback loops which increases the efficiency of the RF system significantly. It is estimated that 3-4 MW of power consumption can be saved if klystrons are replaced by IOTs. Like klystrons, IOTs use a resonant output cavity to efficiently couple power from the electron beam at high frequencies. However the gain of an IOT is much lower than a klystron because an IOT uses a single output cavity while a klystron may employ 4-5 stages of cavities. With the advent of low cost solid stage RF amplifiers as pre-drivers, the high gain provided by multi-cavity klystrons is not required. Because of this low gain, IOTs require cathode voltages on the order of 35 kV as compared to 100 kV for high gain klystrons. The lower cathode voltage also reduces the cost of the power supply that energizes the IOT. Current estimates for a power supply for an IOT is 60 % the cost of a klystron modulator of comparable power. Currently there are no commercially available IOTs for the ESS power range. However there has been very good progress made in higher order mode multi-beam IOTs in which power levels of 1 MW have been achieved [11]. For a more detailed discussion on the ESS RF system and the potential of IOTs we refer to [12, 13].

SUMMARY

The European Spallation Source to be built in Lund will be the most powerful linac worldwide. Design and construction of ESS is done through an international collaboration and benefits from the experiences of the similar facilities. The construction of the ESS will start in 2014 and the accelerator will be operational in 2019. The beam power will be increased after the start up and will reach its nominal value of 5 MW by 2025 and scientists will be welcomed to perform experiments at the facility.

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