THE ESS ACCELERATOR

M. Lindroos*, S. Molloy, S. Peggs, K. Rathsman and R. Zeng, ESS AB, Sweden
R. Duperrier, CEA, France, R. Ruber, Uppsala University, Sweden, R. Ainsworth, RHUL, UK and
The ESS Accelerator Design Update collaboration

Abstract

In 2003 the joint European effort to design a European Spallation Source resulted in a set of detailed design reports. Lund was agreed as the site in 2009, and a company, ESS AB, has been created to design, build and operate ESS. A collaboration has been formed for the accelerator work and an update project has been agreed and financed. Detailed planning for the prototyping in a Prepare-to-Build (P2B) project has also started. The current status of the Design Update project for the accelerator will be presented, together with an outline of future work. The baseline for the updated design delivers 5 MW of 2.5 GeV protons to a single target, in 2.86 ms long pulses with a 14 Hz repetition rate. The linac will have a normal conducting front end with an ion source, an RFQ and a DTL. The superconducting part starts with spoke cavities followed by two families of elliptical cavities. It will be the first time that spoke cavities are used in a major accelerator. Work is being done to optimize the energy efficiency and to make further use of the heat from the cooling water coming out of the facility. Finally, potential future upgrades of power are considered.

INTRODUCTION

Spallation is a nuclear process in which neutrons of different energies are emitted in several stages following the bombardment of heavy nuclei with highly energetic particles. The spallation process is the most practical and feasible way of producing neutrons for a reasonable effort (or cost) of the neutron source cooling system. Spallation sources come in at least three types: short pulse sources (a few μs), long pulse sources (a few ms) and continuous sources. The future European Spallation Source (ESS) will be a long pulse source and the first spallation source with a time average neutron flux as high as that of the most intense research reactors.

The highest power spallation source currently in operation – the Spallation Neutron Source (SNS) in Oak Ridge – combines a full energy SC linear accelerator with an accumulator ring to provide very high intensity short pulses of neutrons to the instruments. The European Spallation (ESS) source will provide even higher intensities, but is developing instruments able to use longer linac pulses directly for spallation, avoiding the need for a costly and performance-limiting accumulator ring [1].

The obvious advantage of a linac is that beam passes only once through the accelerating structures, enabling it to accelerate a high current beam with a minimum of constraints. The current limit is mainly set by space charge effects at low energy, as well as the power that can be delivered to the beam in each accelerating cavity at medium and high energies, and by beam losses.

The spallation cross section for protons on heavy nuclei increases as a function of proton energy up to several tens of GeV [2]. 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 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 and the cryogenics systems and high-Q cavities are important issues.

THE ESS BASELINE

The ESS accelerator high level requirements are to provide a 2.86 ms long proton pulse at 2.5 GeV at repetiton rate of 14 Hz, with 5 MW of average beam power on target. The general lay-out of the ESS linac can been seen in Fig. 1.

Since there is no need for a charge injection schemes into an accumulator ring for a long pulse source, the ion source for ESS will produce a proton beam. The source is proposed to be a compact Electron Cyclotron Resonance source (ECR) similar to the VIS source [3] in Catania and the SILHI source [4] at CEA Saclay.

The beam from the ion source is transported through a Low Energy Beam Transport (LEBT) section to the RFQ for bunching and acceleration up to 3 MeV. The RFQ will be of four vane type [5] and a first test run at realistic ESS requirements will be performed at the IPHI RFQ which is presently under commissioning at CEA-Saclay in Paris. The beam is transported from the RFQ and matched to the first normal conducting Drift-Tube Linac (DTL) structures with a Medium Energy Beam Transport (MEBT) section. It is still an open issue if the MEBT will contain a fast buncher.

The transfer to the first superconducting structures will be at 50 MeV. The first superconducting section will consist of double spoke cavities which will take the beam to 188 MeV. Spoke resonators have a large transverse and longitudinal acceptance and are mechanically very stiff, reducing their sensitivity to microphonics and to Lorenz force detun-

* mats.lindroos@esss.se

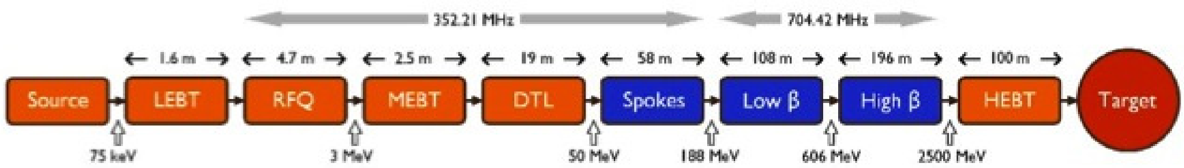

Figure 1: A block diagram of the ESS linac design. The Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) are normal conducting while the spoke resonator and low beta and high beta elliptical cavities are superconducting

Table 1: The ESS RF parameters

	Length m	Input energy MeV	Frequency MHz	Geometric β	No of sections	Temp K
RFQ	4.7	75×10^{-3}	352.2		1	RT
DTL	19	3	352.2		3	RT
Spoke	58	50	352.2	0.57	14 (2c)	≈ 2
Low β	108	188	704.4	0.70	16 (4c)	≈ 2
High β	196	606	704.4	0.90	15 (8c)	≈ 2
HEBT	100	2500				

ing compared to elliptical resonators in this energy range. Beyond this, the first family of elliptical cavities will take the beam to some 600 MeV and the second to the full energy of 2.5 GeV.

The optimum frequency for accelerating structures is determined by a number of factors. At lower energies, lower frequencies are favoured due to tolerance that can be achieved when manufacturing cavity components. Lower frequencies also have the advantage of reducing RF losses in superconducting cavities, of decreasing beam losses through larger apertures, and of ameliorating Higher Order Mode (HOM) effects [6] from the high current beams. Higher frequencies are encouraged by the desire to keep the size of the superconducting cavities small, making them easier to handle and reducing the manufacturing costs. The cryogenic envelope and power consumption are also reduced at higher frequencies. It is generally agreed that a frequency of 600-800 MHz is a good compromise for elliptical structures [7, 8].

The pulsed beam structure of a long pulse source requires the use of klystron modulators to drive the klystrons if the energy consumption is to be kept reasonable. Special care has to be taken with the design of the RF power source, distribution system and controls due to severe space limitations, reliability and safety concerns and high investment and operational costs. The ESS baseline design is for one modulator and klystron stage per cavity. This will give a maximum flexibility for beam tuning and robustness against faults. First studies show that the linac should after retuning be capable of operating with any individual cavity in the SC sector failing. In Fig. 2 the power requirement for the RF sources are shown based on beam dynamics requirements for a smooth acceleration transition between the different types of structures.

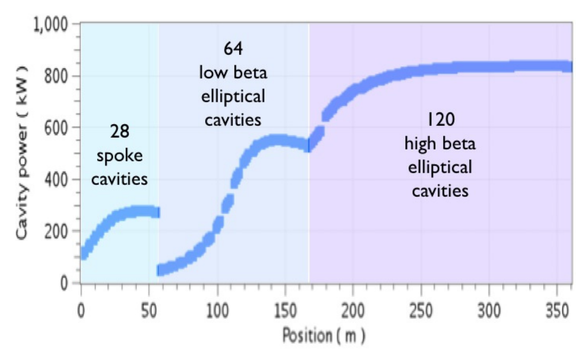

Figure 2: The power to beam of the superconducting part of the linac [9] as calculated from the lattice in [10]

The ESS design goal of being a sustainable research facility requires minimisation of power consumption and the re-use of all heat from the cooling water. The plan is to divide the facility into different categories depending on the cooling need and the temperature range in which the equipment can operate reliably. According to experience from SNS, the highest temperature zones will be the RF loads, circulators, compressors, and the klystron's collectors. These systems can operate at higher temperatures permitting ESS to boost the temperature of the cooling water leaving the facility to a value (>70 degree Celsius) that is commercially viable for re-sale to the district heating system of the region.

SCRF

From the exit of the DTL, where the proton beam has been accelerated to a kinetic energy of 50 MeV, the ESS linac makes use of several families of superconducting technology.

Spoke Resonators

The spoke resonator proposed for ESS is of a double–spoke type operating with a frequency of 352.21 MHz, with an accelerating gradient of 8 MV/m, and is shown in figure 3.

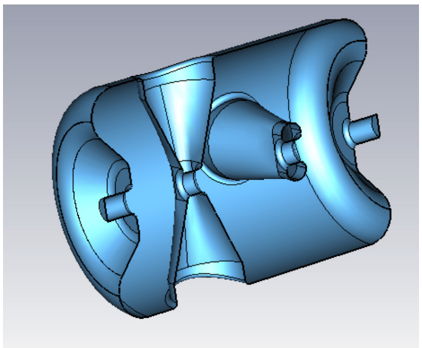

Figure 3: Double spoke resonator proposed for ESS.

Spoke resonators will be used to accelerate the proton beam from 50 MeV to 188 MeV, and will have a geometric β_{geo}=0.57. This value, despite being greater than the maximum beam velocity observed by these cavities (β_{max}=0.55), has been chosen to optimise the coupling of the accelerating RF to the beam.

Although spoke cavities have never been used to accelerate particles, recent tests at Fermilab [12] have demonstrated that accelerating gradients significantly in excess of the 8 MV/m proposed for ESS are achievable.

The remaining concern for the operation of these cavities is excitation of HOM power by the passage of the beam, and this is currently the subject of an ESS Work Unit [11].

Elliptical Cavities

The five-cell elliptical cavities come in two families – β_{geo}= 0.70 and β_{geo}= 0.90 – to accelerate the beam from 188 MeV to 606 MeV, and from 606 MeV to 2.5 GeV respectively. These values have been chosen based on beam dynamics considerations, with minimisation of the total number of cavities as a goal of the optimisation. A proposed design for the high β family is shown in figure 4.

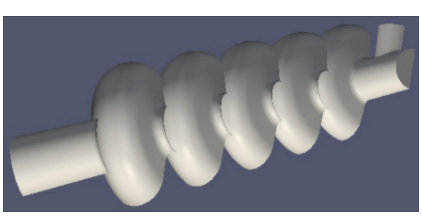

Figure 4: High β elliptical cavity proposed for ESS.

Note that figure 4 only shows the fundamental power coupler and not any HOM couplers since it has not yet been decided whether it is necessary to extract this excited power.

Higher Order Mode (HOM) Concerns

Simulations of the proposed cavity result in the R/Q details shown in figure 5. This shows the calculated coupling for each of the five modes in the fundamental passband plotted against the relativistic velocity, β, of the beam, with the accelerating π-mode having the strongest coupling to the beam throughout the entire region. Note, however, that the increased coupling of the $4\pi/5$ mode at the low and high energy ends of this region has implications for the HOM mitigation strategy.

The spectrum of the maximum coupling found for each of these modes is shown in figure 6 along with multiples of the primary beam frequency. Note that several modes lie close to these multiples, and, based on studies on a similar proton linac [13], are of concern for the quality of the accelerated beam.

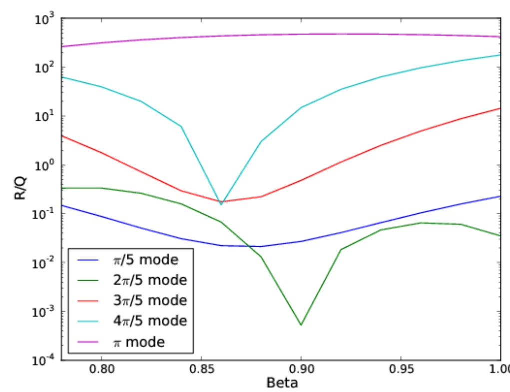

Figure 5: Beam coupling for the simulated modes of the fundamental passband over the range of βs expected to be accelerated by the cavity.

Field Emission (FE) & Multipactor (MP)

Due to the SNS experience with SCRF elliptical cavities [14], there is considerable concern that FE & MP will significantly limit the performance of the ESS cavities.

This is of particular concern in the case where it is decided that HOM couplers are required since the tuning of the notch filter used to reject the accelerating mode is particularly sensitive to thermal detuning. The nature of the FE/MP that caused this problem in SNS is particularly complex [14], and several different simulation–based calculations have commenced.

Individual coupler Electrons emitted from the vacuum wall of the HOM coupler are tracked as they move throughout the cavity, and a typical SEY curve for Nb is used to determine the magnitude and location of any MP regions.

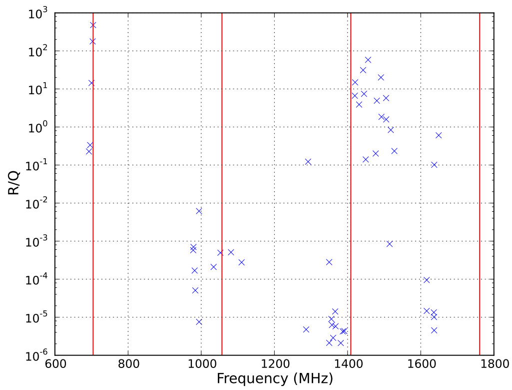

Figure 6: Beam coupling spectrum for the modes of the proposed cavity. Note that the values given here for R/Q are the maximum values found over the range of beam velocities expected to be accelerated by these cavities. The red horizontal lines indicate multiples of the beam repetition rate (325 MHz).

Full cavity Electrons emitted within the cavity are tracked for several RF cycles to determine if any may propagate through to the expected locations of the HOM coupler.

Multiple cavities One important observation made in the SNS cavities [14] was that FE electrons may travserse multiple cavities, before depositing their energy in the cryogenic system. In order to determine how this effect may be mitigated in the ESS cryomodules, simulations involving the tracking of FE electrons throughout multiple cavities have commenced.

These simulations are currently being performed using the SLAC ACE3P suite [15], however alternative codes are also under discussion in order to complement these initial simulations.

LLRF

Investigations [16] of the variations in phase and amplitude of the klystron output due to cathode voltage changes related to modulator ripple & droop have begun, and proportional and proportional–integral (PI) controllers have been studied for the normal–conducting and superconducting cavities.

It is found that wideband modulator droop and ripple of 1% induces changes of more than 10° in the output phase of the klystron, and 1.25% in amplitude. Calculations show that the PI controller struggles to deal with high frequency and high amplitude klystron noise due to the loop delay and the necessity to keep proper phase margin.

It is suggested that the low frequency (<1 kHz) modulator droop/ripple is kept <1%, and that the high frequency (>1 kHz) is tightened to <0.1%.

At very low frequency (<100 Hz) the tolerances may be significantly relaxed (∼3%), but this results in the consumption of more power and dynamic range.

DISCUSSION

The design goal of ESS is a 5 MW long pulse facility. A first analysis of the user requirements shows that any upgrade should focus on the beam power with a preserved time structure as the latter, together with moderator scheme and chopper positioning, determines the instrument design and location. It is too early to state what the maximum achievable power of the ESS linac can be. Nevertheless, the power couplers will be designed for up to 2 MW maximum RF power of which only 900 kW are required at the highest power part of the elliptical SC linac section in the baseline design.

The on-going Accelerator Design Update (ADU) project will result in a Technical Design Report with associated costing and scheduling at the end 2012. It should also produce interface and requirement documents for the next project which has been named Prepare-to-Build (P2B), which will deliver all manufacturing specifications and detailed integration plans in a timely fashion, and permit orders to be placed, testing and construction and assembly to start so that protons can be delivered to the target station in 2018. The projects are being performed in a collaboration between European universities and institutes with important contributions from overseas laboratories and universities.

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