THE ESS LINAC DESIGN

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Abstract

The European Spallation Source (ESS) is a 5 MW, 2.5 MeV long pulse proton machine. It represents a big jump in power compare to the existing spallation facilities. The design phase is well under way, with the delivery of a Conceptual Design Report published in the beginning of 2012, and a Technical Design Report in December 2012. Why and how the 5 MW goal influences the parameter choices will be described.

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 configuration of the current, May 2012 Baseline linac is shown schematically in Fig. 1, and selected linac parameters are listed in Tab. 1 [3]. The warm linac has contributions from INFN Catania, CEA Saclay, ESS-Bilbao and INFN Legnaro, the superconducting cavities and their cryomodules are designed at IPN Orsay and CEA Saclay, and the HEBT will come from ISA in Aarhus. The 50-mA proton beam 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 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 10 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 four tanks takes the beam from 3 MeV to 79 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. The superconducting linac has three types of cavities: double-spoke resonators, five-cell medium-beta elliptical cavities and five-cell high-beta elliptical cavities. The May 2012 linac has 14 spoke cryomodules 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 of the elliptical cavities. There are 15 medium-beta cryomodules with four cavities in each and

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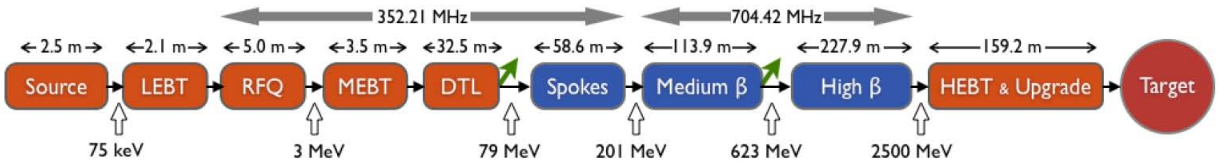

Figure 1: A block diagram of the ESS linac design. The Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) are normal conducting while the spoke resonator and low beta and high beta elliptical cavities are superconducting

Table 1: The ESS RF parameters

	Length m	Input energy MeV	Frequency MHz	Geometric β	No of sections	Temp K
LEBT	2.1					
RFQ	5.0	75×10^{-3}	352.2		1	RT
MEBT	3.5					
DTL	32.5	3	352.2		3	RT
Spoke	58.6	79	352.2	0.50 (optimal)	14 (2c)	≈ 2
Medium β	113.9	201	704.4	0.67	15 (4c)	≈ 2
High β	227.9	623	704.4	0.92	30 (4c)	≈ 2
HEBT	100	2500				

quadrupole doublets between, and there are 30 high-beta cryomodules with four cavities in each and quadrupole doublets between every second cryomodule. All accelerating structures will be powered by klystrons, except the spoke resonators where tetrodes will be used. With one klystron per elliptical cavity plus a few for the warm linac, there will be close to 200 large klystrons and almost 100 modulators since one modulator will drive two klystrons. 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. After the last cryomodule there is 100 m of tunnel where additional cryomodules can be installed for an energy upgrade. Then the beam is brought from the tunnel to the spallation target at the surface through two vertical bends and an expansion section. Quadrupole and octupole magnets are used to blow the beam up onto the desired profile of the proton-beam window and the target window.

SUPERCONDUCTING LINAC

The superconducting part of the linac consists of three families of SC cavities. The beam dynamics has been discussed in the previous section. We will here give some insight to the specific issues relating the superconducting technology for a high power linac like ESS.

Cryomodules

The cryomodules are installed in a $\approx$ 400 m long ESS cold linac section. There are three families of cryomodules: the spoke resonator cryomodules, the medium- and the high-beta elliptical cavity cryomodules. The cryomodules are composed of the cavity packages, the supporting system, the alignment system, the thermal and magnetic shieldings, the internal cryogenic piping and the diagnostic instrumentation. Each elliptical cryomodule contains four superconducting cavity packages, which include cavities (or resonator), fundamental power coupler, cold tuning system, its helium tank and the RF pick-up coil. Each spoke cryomodule contains two spoke resonator packages. The main functions of the cryomodules are to provide the positioning and alignment of the cavity package w.r.t. the beam axis, and to reduce the thermal losses to the 2 K helium tank. The cryomodules have the capacity 1) to transfer energy from RF system to the beam, 2) to confine the protons longitudinally and 3) to steer the protons longitudinally. To lower the construction and operating risk, the ESS cold linac take advantage of the de-velopment done on the cryomodules design and the procedures developed at the Spallation Neutron Source (SNS), Desy (X-FEL) and CEA for module integration. In an effort to standardize the solution and to lower the technical unknown/risk, the ESS has contracted the same institute (IPNO) to design the cryomodule of both the spoke and the elliptical cavities. The design of the cryomodules and its jumper connection are in compliance with the European Pressure Equipment Directive 97/23/EC and is driven by the ALARA principle.

Tab. 2 gives the length of the individual cryomodule types and the length of different SC sections. Warm quadrupole doublets and beam instrumentation systems are installed in between the cryomodules to correct and to monitor the beam profile. Fig. 2 shows the conceptual de-

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Table 2: The ESS Cryomodule parameters

Section	Cryomodule length [m]	Cavities count per section
Spoke	≈ 2.9	28
Medium-beta	≈ 6.7	60
High-beta	≈ 6.7	120

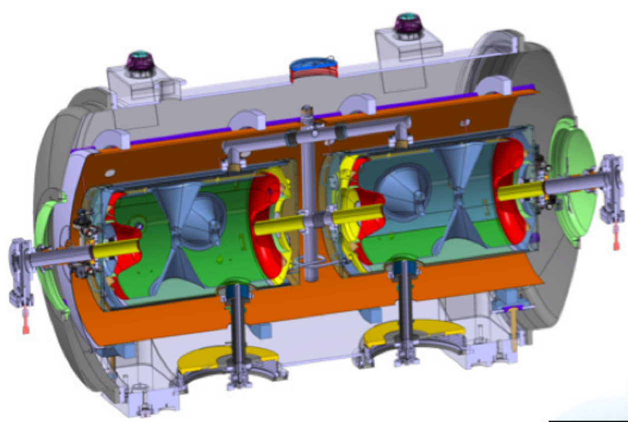

Figure 2: Spoke cavity cryomdoule for ESS

sign of the spoke resonator cryomodule and Fig. 3 shows the conceptual design of the RF elliptical cavities cryomodule. A space-frame is used to position and align the elliptical cryomodules.

Cavities

The three families of SC cavities intended for use in the ESS linac are:

1. Double spoke cavities operating at 352.21 MHz
2. Medium-β elliptical cavities operating at 704.42 MHz
3. High-β elliptical cavities operating at 704.42 MHz

Double spoke cavities The proton beam will be accelerated from 79 MeV to 201 MeV by 28 spoke cavities. These will be installed in 14 cryomodules (i.e. 2 cavities per cryomodule), operating at 2 K.

It should be noted that ESS will be the world's first accelerator to make use of spoke cavities.

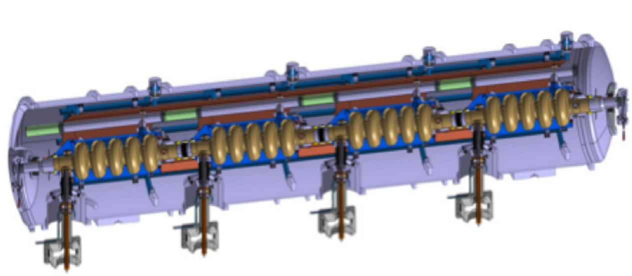

Figure 3: Elliptical cavity cryomdoule for ESS

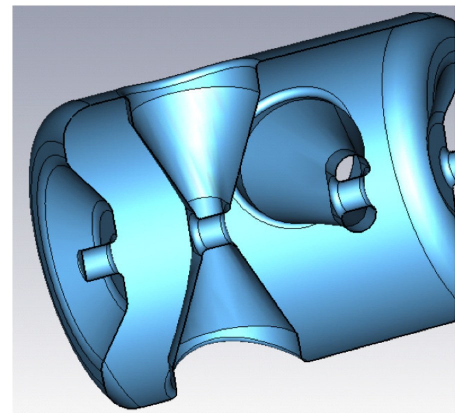

Figure 4: A cross-section through a spoke cavity design for ESS.

Figure 4 shows a cross-sectional view through a spoke cavity designed for use in ESS.

These cavities are designed to have an optimal beam velocity, $\beta_{opt} = 0.50$, and a peak accelerating gradient, $E_{acc} = 8$ MV/m.

The design of these cavities is driven by some quite conservative limits on the maximum surface fields – $B_{peak} \leq$ 70 mT, $E_{peak} \leq 35$ MV/m – in order to minimise the risk associated with this new technology.

The expected quality factor, $Q_0 \geq 2 \times 10^9$, at the nominal gradient.

Medium-β cavities Following the spokes, the proton beam is then accelerated from 201 MeV to 623 MeV by 60 SC elliptical cavities. This is the first section to use the higher accelerator frequency of 704.42 MHz

These cavities contain five resonant cells operating in the π-mode, and they are designed with a geometric beta, $\beta_G = 0.67$.

At the nominal gradient, $E_{acc} = 15$ MV/m, the cavity surface will be treated such that a quality factor, $Q_0 \geq 5 \times 10^9$, is achieved.

High-β cavities The final section of the ESS linac consists of 120 high-β cavities that are used to accelerate the protons from the 623 MeV with which they exit the medium-β section, to the final energy of 2.5 GeV.

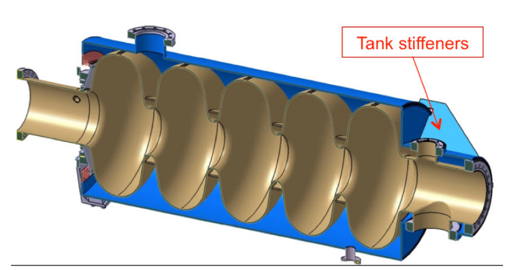

Figure 5: A cross-section through a high-β elliptical cavity installed within its cryo-vessel.

As with the medium-β section, these are also π-mode cavities with five resonant cells, however their geometric beta, $\beta_G = 0.92$ in the current baseline.

At the nominal gradient, $E_{acc} = 18$ MV/m, the cavity surface will be treated such that a quality factor, $Q_0 \geq 6 \times 10^9$, is achieved.

RF SOURCES

Because the vast majority of accelerating structures in the ESS linac are superconducting, the dominant feature of the ESS RF system is the number of RF stations. To handle variations in cavity coupling, Lorentz detuning, there is one RF power amplifier per superconducting resonator; totaling over 208 individual RF stations. 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 120 stations, the peak power required for the cavities is 900 kW. 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 50 degrees of RF phase during the beam pulse. In addition, the beam pulse for the ESS linac is very long (2.86 ms) which is about a factor of three longer than the mechanical response time of the cavity to the Lorentz detuning. To save on RF power overhead, all superconducting cavities will be equipped with fast piezo-electric tuners to negate the Lorentz detuning of the cavities. The klystrons are operated with 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 1.2 MW. The klystron is energized with a modulator. For stability, reliability and economic reasons, the klystrons will be powered in the pulsed cathode configuration. The modulators must supply a 3.5 ms long pulse at a rate of 14 Hz. The cathode voltage is for each klystron is about 100kV 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 decide 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 modulator topology will not be imposed by ESS but functional specifications will be given to vendors. 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-foward 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 un-economical 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 Figure 6. 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 35kV 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 [4]

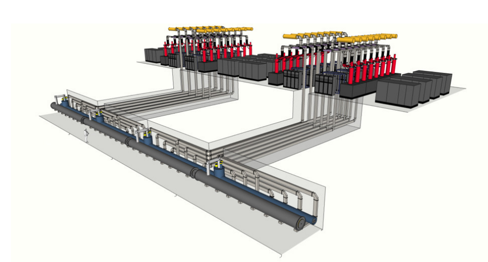

Figure 6: The ESS RF sources in stub lay-out

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DISCUSSION

The ESS accelerator design update is approaching completion. Work is being done in all areas from ion-source, thorough accelerating structures to the target. We have here reported on the work on RF, cavities and cryomodules but major progress has also been made for the normal conducting magnets, the Low, Medium and High energy beam transsport, controls and instrumentation. The design update work for the accelerator and for all other areas of the project will enable ESS to enter construction in early 2013 provided the negotiations between ESS member states can complete in time.

ACKNOWLEDGMENT

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