THE ESS ACCELERATOR

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The ESS Accelerator Design Update collaboration

Abstract. The European Spallation Source (ESS) is in the midst of an accelerator design update with plans to deliver a Technical Design Report at the end of 2012. Detailed planning for the Prepare-to-Build prototyping project has begun, and potential future power upgrades are being considered. First protons are expected in 2018, and first neutrons in 2019. 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, a Radio Frequency Quadrupole (RFQ), and a Drift Tube Linac (DTL). The superconducting section of the linac contains spoke cavities followed by two families of elliptical cavities. The ESS has the ambitious goal of being a sustainable research facility with zero release of carbon dioxide. This will be achieved through a combination of actions, with a focus on the linac. Care is being taken to optimize the overall energy efficiency.

1. 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.

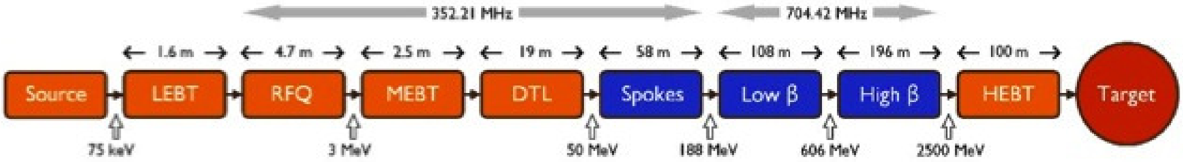

Figure 1. A block diagram of the ESS linac design. The Radio Frequency Quadrupole (RFQ) and Drift Tube Linac (DTL) are normal conducting while the spoke resonator and low beta and high beta elliptical cavities are superconducting

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				

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.

2. THE ESS BASELINE

The ESS accelerator high level requirements are to provide a 2.86 ms long proton pulse at 2.5 GeV at repetition 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 50-80 MeV. The first superconducting section will consist of double spoke cavities which will take the beam to close to 200 MeV MeV. Double spoke resonators have a large transverse and longitudinal acceptance and are mechanically very stiff, reducing their sensitivity to microphonics and to Lorenz force detuning 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 proposed RF system for ESS is described in [**?**]. 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.

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.

3. 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.

3.1. 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 2.

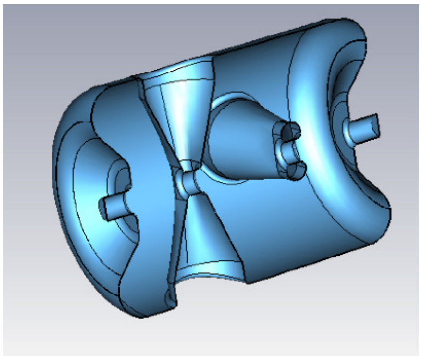

Figure 2. Double spoke resonator proposed for ESS.

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 [10] 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 [9].

3.2. 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 3.

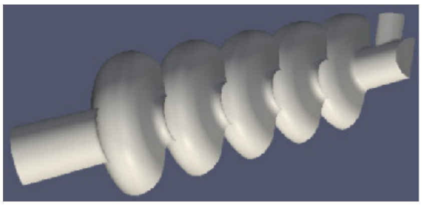

Figure 3. High β elliptical cavity proposed for ESS.

Note that figure 3 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.

4. Future upgrades for ESS accelerator

4.1. Introduction

All power upgrades beyond the original design goals will require enhancing the cooling capability of target and moderators, or/and the possible addition of a new target station. Enhancing the power to a target station increases both the time average and the peak neutron flux, which are the two basic characteristics of neutronic performance. Sharing the total beam power between two target stations means more beam lines with fewer neutrons than with a single target station, eventually with different beam pulse parameters. Furthermore, the macroscopic time structure of the proton beam at a pulsed spallation source is intimately linked to instrument design and location. The spallation cross section for protons on heavy nuclei increases as a function of proton energy up to several tens of GeV [**?**]. Nonetheless it is generally agreed that a kinetic proton energy between 1-3 GeV is optimal for practical target and moderator designs and accelerator power consumption. An upgrade based on an energy upgrade must consider this limitation and also take into account the change of target conditions at higher energies e.g. the peak of neutron production for the proton beam will move by a few cm for an energy increase from 2.5 to 3 GeV. This will influence the efficiency of the neutron moderators and possibly increase the number of protons scattered around and through the target. However, a pure energy upgrade using additional accelerating structures will have little influence on beam dynamics and will not require any major modification of the existing lattice. Increasing the current of the linac proton beam at ESS [12] is an upgrade option to enhance both the time average and the peak neutron flux, proportionally to the increase of the proton beam current. It requires no modification of the instruments and the optimal moderator positioning remains unchanged. It will demand more RF power to the beam, and will require a redesign of the front end, including the ion source, and of the RF sources for all accelerating structures. Since space charge increases, and the matching between RF sources and the accelerating structures will change, it is also likely to require a change of the accelerating structures, and of both the primary RF couplers and possible HOM couplers. For extreme cases it might be necessary to have two front-ends from which the beam eventually is funneled together at a higher energy when space charge is less of an issue. It will also have an overall impact on beam dynamics. Increasing the repetition rate or the pulse length will require new RF sources but will have little or no impact on beam dynamics and SCRF. However, in contrast to the above two options, it will not enhance the peak neutron flux and it will require new instruments or a redesign and possible relocation of existing instruments. A possible way around this is to add a second target station to which e.g. the additional pulses are extracted or part of the pulse is deviated. This option will add additional beam lines but will not be efficient for improving the neutronic performance of the beam lines. A radically different approach for enhancing the proton beam current to the target could be realized by an extension of the facility with a compressor ring for delivering the charge of each linac pulse in a shorter, higher current burst. This will proportionally enhance the peak neutron flux in the pulses as long as the proton pulse length is much longer than the response time of the neutron moderator systems (about 300 microseconds for cold neutrons and less for thermal and hot neutrons) and tend to saturate when the proton pulse length matches the moderator response time. Such a short linac pulse would require very high average pulse currents and space charge would make acceleration with low losses very difficult. Furthermore, the peak power requirements for couplers and RF sources would demand new technology and be prohibitively expensive.

4.2. Pulse compression for long pulses with enhanced peak flux

Increasing the linac beam power is the only way of increasing the total neutron flux for a spallation source. The long pulse concept is an excellent strategy of maximizing high beam power while limiting the peak power on the target. Chopping the neutron pulses provides in the long pulse concept the necessary, custom tailored resolution for neutron research applications. If the neutron pulse length matches the resolution requirement of the experiment (i.e. it is not too short, which would result in loss of beam intensity), the peak flux is a good measure of the neutronic performance. Within the long pulse approach the neutron peak flux can be increased by shortening the proton pulse while maintaining the proton beam energy per pulse. However, the thermalization process in neutron moderators acts as a time integrator which spreads the pulse response of the neutron flux from the target. Thus, shortening the proton pulse length less below 100 micros would not significantly increase the peak flux and would only serve to stress the target with higher incident peak power. At the power level of ESS 100 300 micros proton pulse lengths might eventually become manageable by future target technology. This would enable to upgrade ESS into a long pulse source with the same time average flux at equal repetition rate but up to an order of magnitude higher peak flux in neutron pulses with 300 400 micros pulse width, which is quite similar to that of the pulsed reactor in Dubna. To construct such linac pulse length the linac beam current would have to be increased by a factor of 10 30 from the present design. As discussed in the previous section, increasing the beam current would require a corresponding increase in installed RF power. More importantly, the beam current in the linac is limited by space charge effects, especially at the low energy end of the linac. Thus, the only to alternative to achieve a 100 ?s pulse at high beam power is to compress the long pulse in a storage ring. There are three main issues raised with using a storage ring for such a compression the linac beam pulse: i) H- acceleration in the linac, ii) Long pulse extraction from the ring and iii) Space charge tune shift in the ring.

4.3. H- injection

Injection into a compressor ring will require that H- ions are accelerated in the ESS linac. This would demand a new ion source, a new RFQ, a chopper in the MEBT section of the linac and an accelerator design which keeps the magnetic field in all accelerator elements below the magnetic stripping limit for H- ions. With such large beam power, injection would be done with laser stripping to avoid problems with the life time for the stripping foils normally used for H-stripping injection schemes. Laser stripping becomes easier at higher beam energies because the required frequency of the laser light would begin to approach optical frequencies.

4.4. Long Pulse Extraction

Resonant extraction is a well-known technique in high energy physics for extracting the beam from a storage ring when the required extraction time is much greater than the revolution period of the ring. To extract the beam resonantly, the machine is pushed close to a betatron resonance where particles begin to increase in betatron amplitude. Wire septums in the beam place an added kick on the particles which causes the particles to stream out of the machine. Because of the wire septum, the process is inherently lossy and extraction for a 5 MW beam would be problematic. Single turn extraction, while lossless, would require a ring with a revolution period of 100 micros or a circumference of 29 km. Besides the enormous cost of such a ring (unless suddenly one became available on the western edge of Switzerland) the average bending field would be some 25 Gauss. Such a low field would make the ring inoperable due to stray fields. One could consider smaller multiple rings occupying the same tunnel and stagger the single turn extraction from the rings over a 100 micros period. As noted previously, the pulse structure of the multiple extractions would be obscured by the moderator response. Multiple rings would also reduce the burden of space charge tune-shift. To reduce the cost, the bend magnets in the rings could be constructed from permanent magnets. Based on the Fermilab Recycler experience, a permanent magnet ring could have a radius substantially less than 250 meters. One could consider 3-4 permanent magnet rings in the same tunnel. However, even with multiple rings, single turn extraction would leave a relatively large gap between sequential extractions giving rise to concerns about peak power on the target. The figure of merit for target shock waves is based on transit time of sound waves out of the target. This transit time is on the order of 25 microseconds. It would be better if the beam can be extracted at shorter intervals. With four rings in the same tunnel of 5 microseconds in circumference (240 meters radius), an RF system of 5 MHz would provide a total of 100 bunches (25 bunches per ring) with a bunch spacing of 200 ns. To extract a single bunch with a bunching factor of 2, the required rise and fall of the kicker would need to be less than 50 ns. This rise and fall time is certainly achievable with strip-line kickers such as proposed for the ILC damping rings [13, 14] . With the advent of high voltage solid state switches, a solid state switch driven kicker could be considered as an alternative. An additional advantage of the single bunch extraction would be that bunches could be extracted with different time spacing permitting tailoring of the neutron pulse through the time structure of the proton pulses hitting the target.

4.5. Space Charge Tune Shift

Space charge would be a major issue for a high intensity compressor ring. For an average beam power of 5 MW with energy of 2.5 GeV and a repetition rate of 14 Hz, the required pulse intensity is 900×10^{12} protons. At this intensity and energy, a space charge tune shift of at least 0.75 would result from a normalized beam emittance (95%) of 100-mm-mrad for a single ring. With four rings, the tune shift would be reduced to less than 0.2. Since the proton beam is only required to be stored in the rings for less than 3 ms, this tune shift might be permissible. However advanced tune-shift compensation techniques such as electron beam compensation [15] could also be investigated. The enhancement of the ESS long pulse peak flux with the help of a ring system would require major R&D on e.g. the ring itself, the laser injection scheme, the fast kickers, target and not at least the instruments. However, it is a tantalizing long term upgrade path for the facility which would require that ESS continuous to invest in accelerator, target, moderator and instrument R&D beyond the design phase of the present facility.

4.6. 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 phase which has been named Prepare-to-Build (P2B) and 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 2019. The projects are being performed in a collaboration between European universities and institutes with important contributions from overseas laboratories and universities. It is possible to envisage upgrades to higher power operation of ESS and also towards boosting the long pulse proton beam current on the target at a given power. Further detailed studies will set the path and limit for possible upgrades. However, it is clear that major savings and flexibility can be gained from wise base line choices for ESS.

4.7. Acknowledgements

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