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NEW DESIGN APPROACHES FOR HIGH INTENSITY SUPERCONDUCTING LINACS - THE NEW ESS LINAC DESIGN

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Abstract

The cost of the next generation of high intensity accelerators has become so large that no single institution can solely afford to fund the construction of the project. To fund these large projects, institutions have embarked on forming ambitious collaboration structures with other laboratories. For example, 60% of the European Spallation Source linac will be funded with in-kind contributions. To induce other laboratories to join the collaboration, compromises must be made in the accelerator technical design to offer interesting and challenging projects to partner institutions.

The cost of high intensity hadron accelerators is largely driven by RF system. Emittance preservation is often less of an issue as long as beam losses are kept low. A new design philosophy different from the traditional approach at particle and nuclear physics machines is emerging for the high intensity frontier machines. During last year the ESS linac was costed, to meet the budget, modifications were introduced to the linac design. One of the major changes is the reduction of final energy from 2.5 GeV to 2.0 GeV and an increase of gradient and therefore beam current was increased. As a result the design now meets the cost objective but for the price of a higher risk. The accelerator system designer must then try to balance the cost and technical risks while also satisfying the interests and external goals of the partner laboratories. This paper illustrates how this balance was achieved with the ESS design.

DESIGN DRIVERS

While considering different design options it is important to keep in mind the chief requirements of the ESS Linac. For large neutron flux, an average proton beam power of 5 MW is required. To explore rare processes with neutrons, a large peak proton beam power of 125 MW is needed.

The ESS facility is based on the long pulse concept. The long pulse concept does not require the typical compressor storage ring found in many other spallation sources and permits a very flexible design strategy that could not be considered in compressor ring based spallation source. To understand this inherent flexibility of the long pulse concept, a few of the constraints imposed by a compressor ring will be examined.

- Due to the phenomenon of space charge tune shift, the amount of beam that can be stored in a compressor ring is approximately inversely proportional to the square of the energy at the proton beam energies of interest. Without the need of a compressor ring, the ESS linac can provide the design peak current at almost any energy to the neutron production target. This flexible requirement of beam energy provides many avenues of staging the construction of the linac.
- In addition, since the ESS linac does not have to inject into a ring, the requirements on beam quality (e.g. beam emittance) can be relaxed. This is especially true if the beam expansion system for the target is based on raster scanning of the beam on the target.
- Finally, a compressor ring requires the acceleration of H- ions so that the linac beam can be merged with the circulating beam in the compressor ring. The acceleration of H- ions produces beam loss in the linac due to intra-beam stripping of the H- ions. Also injection losses on the required injection stripping system can be a dominant limitation for the intensity in a compressor ring. These loss mechanisms will be completely absent in the ESS design.

However, the disadvantage of the long pulse concept from an accelerator design point of view is that the user requirements of pulse length and repetition rate are imprinted on the linac beam structure. The duty factor of the ESS linac, which is defined as the product of the beam pulse length and the linac repetition rate, is 4%. This number yields rather high operational costs for a normal conducting linac. Conversely, the duty factor of 4% is rather small for a superconducting linac to provide significant operational cost savings in contrast to the larger construction costs.

DESIGN OPTIONS

There is always uncertainty in cost estimates, especially in such a complex project as the ESS linac. To reduce this uncertainty, prototyping some of the major cost drivers such as the cryomodules, klystrons, and modulators has started. In addition, the linac design should be examined to identify possible sources of design contingency that will cope with market fluctuations and design alterations as a result of prototype results for the major cost drivers.

The primary figure of merit of the ESS linac is average beam power. The average beam power, <Pb>, is the product of the peak beam power, P_{bpk}, and the duty factor, D. The duty factor is the product of the pulse length, τ_p, and the repetition rate, f_r.

$$\langle P_b \rangle = P_{bpk} D = P_{bpk} f_r \tau_p. \quad (1)$$

The equation for peak beam power can be written to emphasize the different design options for the superconducting section of the linac:

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$$P_{bpk}=I_b\left(E_{pk}\sum_{n=1}^{N}\left(M_{cell}\frac{E_{acc}T}{E_{pk}}\frac{\beta_g\lambda}{2}\cos(\phi_s)\right)_n+\frac{E_{FE}}{q}\right). \quad (2)$$

where I_b is the peak beam current, E_{FE} is the energy of the normal conducting front end linac, q is the charge of a proton, N is the number of superconducting cavities, E_{pk} is the maximum surface electric field in the superconducting cavities, $E_{acc}T$ is the acceleration gradient including the transit time factor T along the beam axis for a cavity, and M_{cell} is number of cells in a cavity, β_g is the geometrical beta of the cavity, λ is the RF wavelength in the cavity, and ϕ_s is the synchronous phase.

Reducing the number of superconducting cavities will have the largest impact on cost and design contingency because each cavity that is removed from the design not only removes the cost of the cavity but also removes the need (and cost) for the RF power sources that feed the cavity. Therefore, the design contingency strategy will hold the average beam power constant while looking for avenues to minimize the number of superconducting cavities. Examining Equations 1 and 2, the different options to decrease the number of superconducting cavities is to increase a combination of the following list:

- duty factor, D
- peak surface field, E_{pk}
- peak beam current, I_b
- average value of $E_{acc}T$ sum by adjusting the power profile
- ratio of $E_{acc}T/E_{pk}$ by appropriate choice of β_g
- energy of the front end linac, E_{FE}

Increasing the Duty Factor

As discussed earlier, the choice of a superconducting linac becomes obvious as the duty factor increases. Additionally, from an accelerator design point of view, increasing the duty factor has the least impact on the configuration of the accelerator. As the duty factor is increased by either increasing the pulse length or the repetition rate, the final energy of the linac can be decreased and still provide the same average beam power.

Modulator Cost Model

When the duty factor is increased, the remaining RF systems need to provide more RF power to compensate for the higher duty factor. The increase in RF power will incur additional cost due to such factors as requiring larger capacitor banks in the klystron modulators, more powerful switch assemblies in the modulators, larger klystron cathodes and collectors, etc. Simple cost models for the RF systems have been developed to give a feel on how much impact an increase in RF power will have on cost. A major cost driver for the RF systems is the klystron modulators. There are many different configurations of klystron modulators and the cost scaling of a klystron modulator will depend on the particular topology. Equation 3 demonstrates a simple scaling model for a solid state bouncer modulator where C(P) is the cost at power level P and C_{Po} is the cost at the reference power P_o

$$C(P)=C_{P_o}\left(R_{cc}\frac{P}{P_o}+R_{cb}\frac{P}{P_o}+R_{ss}\left(\frac{P}{P_o}\right)^{\frac{1}{3}}+R_{xt}\left(\frac{P}{P_o}\right)^{\frac{2}{3}}+R_{cab}+R_{at}\right)$$

where R_{cc} is the cost of the capacitor charger (30%), R_{cb} is the cost of the capacitor banks (5%), R_{ss} is the cost of the solid state switch (15%), R_{xt} is the cost of the transformers (15%), R_{cab} is the cost of the cabinets and controls (10%) and R_{at} is the cost of assembly and testing (25%).

Klystron Cost Model

Since there are very few klystron vendors, the cost models for the klystron are much vaguer and klystron costs can be the result of many other intangible variables such as market conditions. A sample of klystron costs is shown in Figure 1. Also for a given frequency and power range, the cost of a klystron is fairly insensitive to power. Based on a sampling of a few vendors a simplified cost model for a 704 MHz klystron is:

$$C(P)=C_{P_o}\left(0.87+0.13\frac{P}{P_o}\right). \quad (4)$$

where C_{Po} is the cost of the klystron at power level P_o.

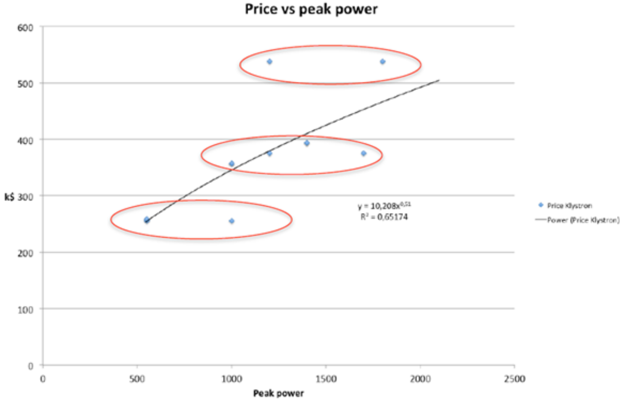

Figure 1: Klystrons costs as a function of peak power.

Cryogenic System Cost Model

Neglecting the fill and fall time of the cavity in long pulse operation, a simple expression for the power dissipated in the walls of a superconducting cavity n is:

$$P_{d_n}=\frac{\left(E_{pk}\frac{E_{acc}T}{E_{pk}}M_{cell}\frac{\beta_g\lambda}{2}\right)^2}{\frac{R}{Q}_{acc}Q_0}f_r\tau_p. \quad (5)$$

where Q_o is the internal quality factor of the cavity and $[\![R/Q]\!]_{acc}$ Q_0 is the accelerating shunt impedance of the cavity. Comparing Equation 5 to Equation 1, the power dissipated in the walls for cavity n is:

$$P_{d_n}=\frac{E_{pk}\frac{E_{acc}T}{E_{pk}}M_{cell}\frac{\beta_g\lambda}{2}}{I_b\cos(\phi_s)\frac{R}{Q}_{acc}Q_0}\left(P_{bpk}D\right)_n. \quad (6)$$

Summing over all the cavities,

$$P_d \propto \frac{E_{pk}}{I_b} \langle P_b \rangle. \quad (7)$$

where P_d is the total amount of power lost in the superconducting linac. Since the average beam power is to be kept constant, the total dynamic heat load of the cryogenic system will be constant if the ratio of E_{pk} to I_b is kept constant. In fact it will be shown later that it will be advantageous to decrease this ratio. In addition, reducing the number of cryomodules will decrease the total static heat load, but a conservative approach would be to not to take credit for the reduction in the static heat load. It will be assumed that the cost cryogenic cooing plant will be independent of small changes in the duty factor.

As the duty factor is increased, the dynamic heat load on a given cryomodule will increase and the cryogenic cooling of the cryomodule will have to be increased. However at the design duty factor of 4%, the dynamic heat load of a cryomodule is about two thirds the total heat load. This ratio will temper the increased the cost of additional cooling for an individual cryomodule.

Example Analysis

Increasing the duty factor for a given average beam power will decrease the peak proton beam power with a corresponding decrease in peak neutron flux. A decrease in peak neutron flux is probably undesirable from a user point of view. However, because of the simplicity of this scenario, it is worthwhile to examine the effects on cost of increasing the duty factor. This section will examine the example scenario of increasing the duty factor from 4.0% to 4.8%. To increase the duty factor by this amount, the pulse length can be increased from design value of 2.86 mS to 3.4ms. An increase of pulse length of this magnitude would decrease the peak neutron flux by 20%.

For the current baseline design documented in the ESS Technical Design Report[1] (TDR), the energy gain per cryomodule is 68.7 MeV averaged over the last ten cryomodules. Thus six cryomodules can be removed and the final energy of the linac reduced from 2500 MeV to 2087 MeV. The amount of RF power in the remaining cryomodules will have to increase by 20% to compensate for the larger duty factor. Using the cost models described above, the cost of the remaining modulators will increase by 10% and the cost of the klystrons will increase by 2.6%. The effective cost of a cryomodule system (cryomodule + RF) increases by 3.2%. This increase in cryomodule cost must subtracted from the cost savings of removing the six cryomodules. Thus only 82% of the cost of the six cryomodules removed is recovered in cost savings. In summary, increasing the pulse length by 20% reduces the cost of the linac by 5.9%.

Increasing the Peak Surface Field

In the October 2012 baseline design for the ESS linac, the accelerating gradient in the 704 MHz elliptical superconducting cavities was limited to so as not to exceed a peak surface field of 40 MV/meter. This rather conservative limit was set to ensure a high yield in the manufacturing of the cavities. However, many other superconducting linacs are designed for substantially higher surface fields of 50 MV/meter or higher. If the limit on the maximum surface field was increased by 10% to a value of 44 MV meter, then three high beta cryomodules could be removed and still have the output energy of the linac exceed 2500 MeV. With this higher accelerating gradient, the 10% more RF power would be required by the remaining RF sources which would increase the cost of the modulators by 5% and the cost of the klystrons to increase by 1.3%. However 81% of the cost of the removed cryomodules and RF systems could be recovered to provide a cost reduction of almost 3% for the entire linac. The advantage to the cost reduction strategy is that the peak beam power remains unchanged.

Increasing the Peak Beam Current

In the October 2012 baseline design for the ESS linac, the peak beam current was limited to 50 mA. Because the ESS linac accelerates protons instead of H- ions, substantially higher beam current sources are available. Increasing the beam current would permit a reduction in the energy of the linac and still provide the same average and peak beam power. However, increasing the beam current can cause emittance increase due to higher space charge forces.

In addition to a the higher acceleration gradient proposed earlier, increasing the beam current will require more peak power from the RF sources. The couplers on the elliptical 704 MHz cavities have been tested to 1200 kW of peak power. It is unknown whether substantially higher peak RF power in the couplers can be tolerated. In the October 2012 baseline design, the peak RF power is 860 kW. Increasing the accelerating gradient by 10% would leave margin of 25% in the peak RF power to not exceed 1200 kW. In this section an increase in beam current of 10% to 55 mA will be considered in addition to the increase of peak surface field to 44 MV/meter already discussed earlier. This would provide a maximum power in the RF coupler of 1040 kW which gives 13% of headroom in the maximum power rating of 1200 kW in the couplers.

With a peak surface field of 44MV/ meter and a beam current of 55 mA, six cryomodules can be removed from the baseline configuration and still achieve an average beam power of 5 MW and a peak beam power of 125 MW. The energy of the linac is reduced from 2500 MeV to 2300 MeV. The amount of RF power in the remaining cryomodules increases by 21% which raises the cost of the modulators by 10% and the cost of the klystrons by 2.7%. However 81% of the cost of the removed cryomodules and RF systems could be recovered to provide a cost reduction of almost 5.8% for the entire linac.

Adjusting the Power Profile of the Linac

The cavity voltage profile for the superconducting section of the ESS linac as published in the TDR is shown in "Oct 2012 Baseline" trace in Figure 2. The maximum voltage permitted for a 5 cell elliptical cavity with a β_g of 0.92, a maximum surface field of 40 MV/meter with an E_{peak}/E_{acc} ratio of 2.13 is represented with "Maximum Voltage" trace. There is an inconsistency in which the design voltage profile exceeds the maximum value for the middle of the high beta section. The profile shown in "Adjuster Oct 2012" trace rectifies this inconsistency and as a result the final energy of the linac is reduced from 2523 MeV to 2491 MeV.

Examining the adjusted cavity voltage profile, the design voltage is substantially lower than the maximum voltage permitted at the beginning of the medium beta and high beta sections. The reason for this reduction is the lattice matching between preceding sections of the linac where a smooth longitudinal phase advance per cell is desired. The goal of smooth phase advance is to produce a lower longitudinal and transverse emittance. As noted earlier this note, the ESS linac sends the beam directly to the target and does not inject into a compressor ring. Also, there is an effort underway to study a raster scanning system for the beam on target to replace the current octopole beam expansion system outlined in the TDR. Then, the only issue facing larger emittance is halo generation and beam loss. It is not always clear that larger emittance produces more halo. In fact, a large emittance reduces space charge forces and halo generation could in fact be smaller with a larger emittance beam. Thus, the requirements on beam emittance could be relaxed.

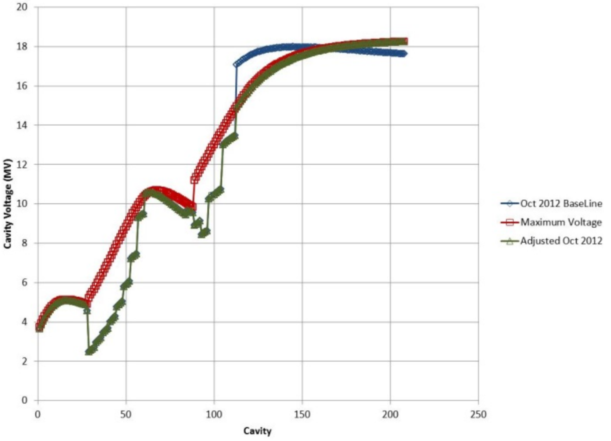

Figure 2: October 2012 Baseline Cavity Voltage.

Figure 3 shows a couple of possible cavity voltage profiles. The October 2012 baseline design contains 28 spoke cavities in 14 cryomodules, 60 medium beta cavities in 15 cryomodules, and 120 high beta cavities in thirty cryomodules. The "High Beta Removed" trace shows a voltage profile with 60 medium beta cavities and 108 high beta cavities that reaches and energy of 2524 MeV. This profile would save three high beta cryomodules. One noticeable feature of this profile is the large jump in voltage at the beginning of the high beta section. This jump arises from the larger transit time factor of the high beta cavities as compared to the medium beta cavities at this energy. A large jump in voltage like this is a very large discontinuity in the longitudinal phase advance and would certainly induce longitudinal oscillations. A number of high beta cavities would probably have to run at a lower voltage to match this large jump as was done with the October 2012 baseline design.

It is clear in the "High Beta Removed" trace in Figure 3 that at the transition between medium to high beta sections, the high beta cavities can produce substantially more voltage. As shown earlier, the cost of producing the extra voltage is weak function of the extra power required. Thus, as long as the impedance of the cavity π mode is dominant over a given energy range, it makes economic sense to remove the lower voltage medium beta cavities in favour of the high beta cavities at the transition. The trace with "Med. Beta Removed" is a possible voltage profile in which 12 medium beta cavities (4 cryomodules) have been removed and an energy of 2510 MeV can still be achieved. This solution has the advantage that no cavities need to be sacrificed for providing a matching section between the medium and high beta sections.

Choice of Geometrical Beta

At an energy of 2500 MeV, the beam beta is 0.96. In the October 2012 baseline, the high beta cavities have a geometrical beta of 0.92 which have an optimum beta of 0.985. The main reason for this choice is there is experimental evidence that for a given peak surface field, higher accelerating gradient that can be achieved for higher geometrical beta cavities. For example, the 0.86 cavity designed for ESS by CEA has an accelerating gradient of 17.9 MV/m for a peak surface field of 40 MV/meter. A 0.92 cavity could have an accelerating gradient of 18.7 MV/meter for a surface field of 40 MV/meter. The higher gradient could reduce the number of high beta cryomodules. However, this increased gradient has to be weighed against the mismatch of beam beta to optimum beta.

Earlier, it was proposed that the peak surface field and peak beam current be increased by 10% to 44MV/meter and 55 mA. To provide 5 MW of average beam power, the required energy of the linac is reduced to 2273 MeV and the corresponding beam beta becomes 0.956. Figure 4 shows the power per cavity required to achieve an average beam power 5 MW. For the profile with the geometrical beta of 0.92, 40 medium beta cavities (10 cryomodules) and 96 high beta cavities (24 cryomodules) reach an energy of 2295 MeV. For the profile with the geometrical beta of 0.86, even fewer medium beta cavities are required because of the higher transit time factor of the 0.86 cavities at lower energies. Only 28 medium beta cavities (7 cryomodules) are required. However, 112 high beta cavities (28 cryomodules) are needed to reach an energy of 2333 MeV. Thus the higher geometrical beta of 0.92 requires one less cryomodule than the 0.86 cavities.

The 0.92 cavities require 1060 kW of peak RF power compared to 960 kW required for the 0.86 cavities. Since the coupler design is independent of geometrical beta, it is possible to run 1060 kW of power into the 0.86 cavities if the beam current is increased to 61 mA as shown in the green trace in Figure 4. A beam current of 61 mA requires a final energy of only 2049 MeV for the linac. To achieve this energy, the number of 0.86 high beta cavities can be reduced to 96 cavities (24 cryomodules). Thus for the 0.86 design, 31 elliptical cryomodules (7 medium beta and 24 high beta) are needed compared to 34 elliptical cryomodules (10 medium beta and 24 high beta) for the 0.92 design

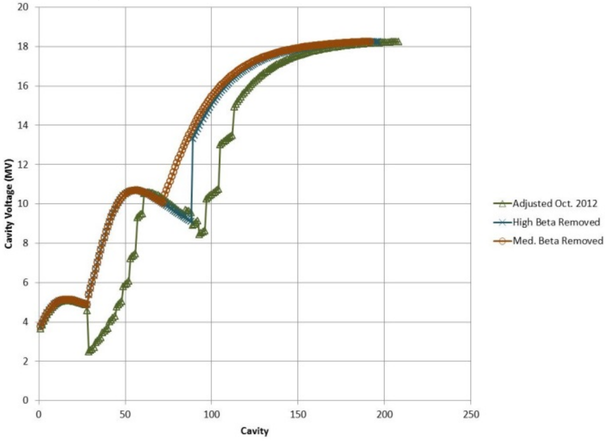

Figure 3: Maximum Cavity Voltage Profiles.

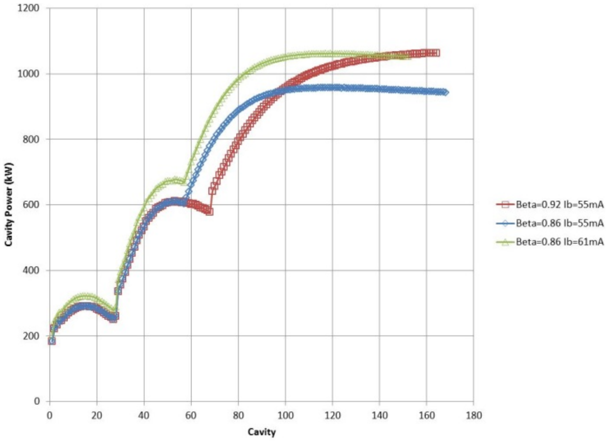

Figure 4: Cavity Power profile to achieve 5 MW average beam power for different values of geometrical betas in the high beta section.

Lattice Cell Length

In the October 2012 baseline design, the cell length along the linac changes substantially. In the spoke region, the cell length is 4.18 meters, in the medium beta section it is 7.12 meters with one cryomodule per cell, and in the high beta section it is 15.19 meters with two cryomodules per cell. It was shown earlier that is more efficient to reduce the number of medium beta cryomodules because they produce less acceleration than the high beta cryomodules. Also, it was proposed to eliminate over one half of the medium beta cryomodules. If the medium beta cells are replaced with the current high beta cells which have over twice the length, then the transverse focusing provided by the long high beta cells is too weak at to provide the desired phase advance per cell of 87 degrees with reasonable gradients in the quadrupoles. Thus a fourth type of cell with one high beta cryomodule per cell would be needed in this region.

At this point the linac layout is becoming very complicated. From a simplicity standpoint, it would be better if all the high beta cells had only one cryomodule per cell. Although this would require 12 more doublet quadrupole packages, the cost impact would be minimal because a doublet quadrupole package is only a few percent of the total cost of a cryomodule and associated RF systems.

A tunnel design with many different cell lengths is very undesirable with the perspective of considering future upgrades. In the future, it might be advantageous to interchange medium beta cryomodules with high beta cryomodules. As the October 2012 baseline currently stands, this would be difficult. To enhance the flexibility of the ESS linac design, it is proposed that the length of a lattice cell in the elliptical section of the linac is uniform and independent of the geometrical beta of the cavities.

The length of the superconducting section of the linac in the October 2012 baseline is 393 meters. This length includes 14 two cavity spoke cryomodules, 15 four cavity medium beta cryomodules and 30 four cavity high beta (β_g=0.92) cryomodules. The design proposed earlier includes 14 two cavity spoke cryomodules, 7 four cavity medium beta cryomodules, and 24 four cavity high beta (β_g==0.86) cryomodules. If non-uniform cell lengths are used in the elliptical section, then the superconducting section in the new design could be as short as 284.5 meters. With a uniform cell length, the length of the superconducting section would be 304 meters.

In summary, a uniform cell length for the elliptical cryomodules provides the following advantages:

- Common elliptical cryomodules independent of cavity beta
- Uniform spacing of the tunnel stubs
- transverse focusing at the medium beta – high beta transition
- Stronger focusing and higher phase advance at the end of the linac
- Ability to interchange medium beta and high beta cryomodules

REFERENCES

[1] S. Peggs, "European Spallation Source Technical Design Report"; http://eval.esss.lu.se/cgi-bin/public/DocDB/ShowDocument?docid=274