1 Executive Summary

1.1 Motivation
The original design of the ESS Linac (2008 Baseline) was 1 GeV linac with a peak beam current of 150 mA. Forty percent of the energy gain was provide by normal conducting accelerating structures. At the beginning of the Accelerator Design Update (ADU), it was recognized that the beam current of 150 mA introduced considerable technical risk. Subsequently, in ADU, the beam current was reduced to 50 mA and the Linac energy increased to 2.5 GeV to compensate. Because of higher gradients, lower operational costs, and larger apertures provided by superconducting accelerating structures, it was decided in ADU that 98% of the ESS Linac would be superconducting. These features are reflected in the 2012 Baseline.

Although the 2012 Baseline has lower technical risk than the 2008 Baseline, it has an inherently higher construction cost because of the higher energy (but lower beam current) which requires a significantly longer linac with more accelerating structures of which a larger fraction are superconducting.

The equipment, services, and installation cost objective of the ESS linac is 497 M€ which is based on the cost estimate of the 2008 Baseline. This objective was provided in October of 2012. The current cost estimate of the 2012 Baseline is 589 M€. The only way to meet the cost target is to modify the 2012 Baseline design by adding technical risk or increasing the cost target. This note examines various design options for meeting the cost objective while having minimal impact on schedule and design work that has already occurred.

1.2 Cost Reduction Strategy
The cost drivers of the ESS linac are the superconducting cryomodules and the associated RF systems that provide power to the beam. For the same beam power the number of cryomodules can be reduced by a combination of the following:

- Increasing the beam current and lowering the energy of the linac.
- Increase the accelerating gradient by increasing the maximum allowable peak surface field in the superconducting cavities.
- Optimizing the cavity voltage profile for maximum energy gain
- Increasing the pulse length and lowering the energy of the linac at the expense of peak beam power.

1.3 Evaluation
To evaluate performance as a function of cost reduction, four different linac configurations where evaluated. These configurations are:
1. **2012:** The October 2012 baseline that includes 15 medium beta cryomodules and 30 high beta cryomodules

2. **Prius:** Includes a 22% increase in beam current, 10% increase in peak surface field, and a maximized voltage profile which results in requiring only 7 medium beta cryomodules and 24 high beta cryomodules. A uniform focusing period cell length in the medium and high beta sections is used which would permit interchange of cryomodules of different betas in the future.

3. **Smart:** The same parameters as the Prius but with 6 cell medium beta cavities. One less high beta cryomodule is required. The six cell medium beta cavities are 93% of the length of the five cell high beta cavities which could make much of the design of the high beta and the medium beta cryomodules similar.

4. **Yugo:** The same as the Smart but with an 18% increase in pulse length (and a corresponding decrease in peak beam power). The lattice requires 7 medium beta cryomodules and 18 high beta cryomodules.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>Prius</th>
<th>Smart</th>
<th>Yugo</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>Beam Current</td>
<td>50</td>
<td>61</td>
<td>61</td>
<td>61</td>
<td>mA</td>
</tr>
<tr>
<td>Pulse Length</td>
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<td>2.86</td>
<td>2.86</td>
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<td>mS</td>
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<td>14</td>
<td>14</td>
<td>14</td>
<td>Hz</td>
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<td>Energy</td>
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<td>2116</td>
<td>2077</td>
<td>1731</td>
<td>MeV</td>
</tr>
<tr>
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<td>5.07</td>
<td>5.0</td>
<td>MW</td>
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<tr>
<td>Peak Power</td>
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<td>129</td>
<td>127</td>
<td>106</td>
<td>MW</td>
</tr>
<tr>
<td>Number of elliptical cryomodules</td>
<td>45</td>
<td>31</td>
<td>30</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Linac Length</td>
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<td>340.3</td>
<td>332.4</td>
<td>292.7</td>
<td>meters</td>
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<td>Linac Cost</td>
<td>586</td>
<td>511</td>
<td>506</td>
<td>481</td>
<td>M€</td>
</tr>
</tbody>
</table>

Table 1. Summary of different ESS linac configurations

1.4 Comments on Risk

1.4.1 Technical Risk

Technical risk results from any issue that prevents the ESS linac from achieving 5 MW of average beam power. There are three main issues

1. **Emittance growth due to the increased beam current.** Increased space charge forces could result in emittance growth and halo generation. Too much halo will irradiate tunnel components to a point in which they need to be replaced or cannot be maintained. The proposed increase in current of 22% over the 2012 technical design is probably not significant enough to be of a concern. Finally, 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.

2. **Lower cavity yield due to increase requirements on higher average accelerating field.** The proposed increase on the peak surface field to 44 MV/meter in the superconducting cavities might be more difficult to achieve than the 40 MV/meter in the 2012 design. However, the value of 40-44 MV/meter for peak surface field is rather conservative as compared to many other superconducting accelerators that are being built such as XFEL (50 MV/meter) or are in the planning stages facilities such as SPL and the ILC. The need for ultra-high quality factors
required in such facilities as in Project X, FRIB, and XFEL are not important for the ESS linac because of the low duty factor of the ESS linac.

3. **Halo Formation due to discontinuities in the transverse and longitudinal phase advance.** A significant fraction in the reduction in the number of cryomodules arose from maximizing the voltage profile along the linac. This resulted in a 15% increase in transverse emittance. This is a small increase in comparison to the available aperture and is not likely to be noticed at the target station. The experience at SNS has shown that a smooth lattice is not required for high intensity operations.

1.4.2 **Schedule Risk**

Schedule risk results from any issue that prevents the ESS linac from providing beam by 2019. The propose changes in this note might actually accelerate the schedule. The main possibilities for this acceleration are:

1. The production of cryomodules and the associated RF station are not only cost drivers but on the critical path for the entire program as well. This note proposes to remove at least 15 cryomodules out of 45 from the 2012 design. This will greatly reduce the production time and since the cryomodules are installed serially, the installation period of the linac will be shortened.

2. The specifications for the tender for the prototype of the klystrons and klystron modulators have not been initiated. Therefore, there is no delay for the RF systems.

3. This note will show that to minimize the number of cryomodules the high beta cavities with a geometrical beta of 0.86 is superior to the choice of 0.92 that is in the 2012 design. There is no design for the 0.92 cavities. There exists only the design of 0.86 cavities and prototypes of these cavities are in the process of fabrication. Thus the choice geometrical beta of 0.86 proposed in this note not only reduces the number of cryomodules but actually accelerates the schedule.

4. This note proposes a uniform focusing cell length both the medium and high beta cavities so that the cryomodules could be interchangeable and possibly identical. The note also proposes 6 cell medium beta cavities that would be close to the same length of the high beta cavities. If 6 cell medium beta cavities are practicable, then the medium beta and high beta cryomodules could be identical. This would reduce the prototyping schedule (and cost) significantly because only one type cryomodule prototype would need to be constructed. Note that prototypes of each type of cavity string will still need to be constructed.

1.4.3 **Cost Risk**

Cost risk results from any issue that prevents the ESS linac construction from being on budget. The main focus of this note was to reduce cost. Cost models were used to predict the increased cost of having other systems provide more power because of the reduction in number of cryomodules. It could be possible that these models are inaccurate or not precise enough to forecast the actual cost savings. In addition, the cost implications on the cryomodules where not looked at the same depth as the investigation of RF sources.

It should be noted that there were some areas discounts on costs for the proposed changes were not taken. Chiefly among these was:

- the reduced manufacturing costs of having only one cryomodule design
• the reduced tunnel and gallery construction costs of having a uniform lattice cell length.

However, this note does not propose any drastic technology change so the risks in increased cost are mostly the same as for the 2012 design.
2 Motivation

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3 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. Finally to satisfy the tight schedule requirements of the facility users, an availability of 95% is desired. (In this note, availability will be defined as the ratio between the mean time to failure to the sum of the mean time to failure and the mean time to repair.)

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.

4 Design Evolution

4.1 2008 Design

The current ESS linac design has evolved significantly over the years. Since the current cost targets are based on cost estimates of these previous designs, it is worthwhile to examine the tradeoffs on the linac design that have already been decided. Figure 1 shows a schematic of the 2008 design that was the basis for the current ESS site selection. This design is a 1 GeV linac with a 3.3% duty factor (16.6 Hz repetition rate and 2.0 mS pulse length). The linac is normal conducting to 400 MeV and superconducting for the remaining 600 MeV. To obtain an average beam power of 5 MW, an intense peak beam current of 150 mA is required. The resulting peak beam power is 150 MW. The large beam current is provided by two sources that are merged in a funnel system at 20 MeV. The superconducting accelerating cavities operate at frequency of 1.3 GHz. At this high frequency, the bore radius of the superconducting cavities is 3.5 cm. The average accelerating gradient of the superconducting part of the linac is 12 MV/meter. With the relative low accelerating gradient and duty factor, the dynamic heat load of the superconducting part of the linac is 25% of the total cryogenic heat load.

The radio frequency (RF) power sources of the superconducting section feed two superconducting cavities for each klystron as shown in Figure 2. This produces a significant cost savings at the risk of requiring 1.8 MW peak and 60 kW average powers in the cavity couplers. The very large accelerating gradients available in superconducting cavities cause the cavities to de-tune via electromagnetic radiation pressure on the walls of the cavities (Lorentz detuning). Since the pulse length is about a factor of two larger than the Lorentz detuning time constant of the superconducting cavities, the individual performance of the cavities in a pair would have to be very close to identical.
4.2 2012 Design

The 2012 design made a number of substantial changes to enhance the availability of the ESS facility. A significant feature of the 2008 design is the very high peak current of 150 mA that was required to obtain the 5 MW average beam power. This large beam current could exacerbate beam loss via space charge blowup of the emittances in the low energy section of the linac. The large beam loss might preclude the required beam power which is the hallmark of the ESS facility. The space charge can be partially ameliorated by having two lower current sources but with the added complication of the combining the sources in a funnel section.

In the 2012 design, the beam current was reduced by a factor of three to a more manageable level of 50 mA. However, to compensate the decrease in beam current, the energy of the linac has to be raised to 2.5 GeV. Since the operational cost of normal conducting accelerating cavities is much higher than superconducting cavities, the 2012 design is 98% superconducting with only the first 80 MeV of the linac composed of normal conducting cavities. Since it has been observed that the Lorentz detuning properties can vary significantly from cavity to cavity, the 2012 design takes a more conservative approach to Lorentz detuning compensation. In the 2012 design, individual RF power sources are required for the regulation of the accelerating field in each cavity.
In addition, the resonant frequency of the superconducting linac in the 2012 design is 352.21 and 704.42 MHz. The lower frequency permits a much larger beam pipe bore radius of 6 cm which is almost double bore radius of the 2008 design. With the large aperture and a factor of three reduction in beam current, much lower beam loss is expected in the 2012 design.

Finally, the maximum accelerating gradient in the 2012 design is 18 MV/meter compared to 12MV/meter for the 2008 design. The increase gradient makes more efficient use of RF sources reduces tunnel length. In addition, for the same cavity quality factor, the higher gradient raises the dynamic heat load to static heat load for more efficient use of the cryogenic system.

5 Cost Drivers

Figure 3 shows the distribution of costs for the major systems for the 2012 ESS linac design as of October 2012. The main cost driver is the RF systems which comprise 37% of the cost. In second place, the 704.42MHz elliptical cryomodules occupy 19% of the cost and in third place; the cryogenic plant absorbs 14% of the total cost. The RF costs are distributed over five major systems as shown in Figure 4. The 704 MHz elliptical section comprises 82% of the RF system cost. The cost break down for the RF systems for the 704.42MHz elliptical section of the linac is shown in Figure 5. The high
power RF amplifiers (klystrons in this case) and the power convertor that energizes the amplifiers (modulators) comprise 80% of the RF system cost. Figure 6 shows the cost distribution for a high beta cryomodule. The cost of a single high beta cryomodule along with the associated RF systems accounts 1.2% of the total cost of the linac.

6 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, \( <P_b> \), 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, \( \tau_p \), and the repetition rate, \( f_r \).

\[
\langle P_b \rangle = P_{bpk}D = P_{bpk}f_r \tau_p \tag{1}
\]

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

\[
P_{bpk} = I_b \left( E_{pk} \sum_{n=1}^{N} \left( M_{cell} \frac{E_{acc} T \beta_g \lambda}{E_{pk}} - \frac{1}{2} \cos(\phi_s) \right) + \frac{E_{FE}}{q} \right) \tag{2}
\]

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, \( \beta_g \) is the geometrical beta of the cavity, \( \lambda \) is the RF wavelength in the cavity, and \( \phi_s \) 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 \( \beta_g \)
- energy of the front end linac, \( E_{FE} \)
6.1 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.

6.1.1 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. Table 2 and Equation 3 demonstrate a simple scaling model for a solid state bouncer modulator where \( C(P) \) is the cost at power level \( P \) and \( C_{P_o} \) is the cost at the reference power \( P_o \).

<table>
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<tr>
<th>Modulator Part</th>
<th>Symbol</th>
<th>Cost (%)</th>
<th>Power Factor</th>
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<tr>
<td>Capacitor Charger</td>
<td>( R_{cc} )</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Capacitor Banks</td>
<td>( R_{cb} )</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Solid State Switch</td>
<td>( R_{ss} )</td>
<td>15</td>
<td>0.33</td>
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<td>Cabinets &amp; Controls</td>
<td>( R_{cab} )</td>
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</tr>
<tr>
<td>Assembly &amp; testing</td>
<td>( R_{at} )</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Cost Coefficients for Solid State Bouncer Klystron Modulator

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

6.1.2 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 7. 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 [2] for a 704 MHz klystron is:

\[
C(P) = C_{P_o} \left( 0.87 + 0.13 \frac{P}{P_o} \right)
\]

Where \( C_{P_o} \) is the cost of the klystron at power level \( P_o \).

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1 “Cost Model of Long Pulse and high Voltage Klystron Modulators”, Carlos Martins, August 2012
2 “Simple cost Model: Klystrons”, Anders Sunesson, October 2012
6.1.3 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:

\[
P_{dn} = \left( \frac{E_{pk}}{E_{pk}} \frac{E_{acc} T M_{cell}}{E_{pk}} \frac{\beta_g \lambda}{2} \right)^2 \frac{R}{Q_{acc}} Q_0 f_r \tau_p
\]  

where \( Q_o \) is the internal quality factor of the cavity and \( \frac{R}{Q_{acc}} Q_0 \) is the accelerating shunt impedance of the cavity. Comparing Equation 5 to Equation 1, the power dissipated in the walls for cavity \( n \) is:

\[
P_{dn} = \frac{E_{pk}}{E_{pk}} \frac{E_{acc} T M_{cell}}{E_{pk}} \frac{\beta_g \lambda}{2} \frac{R}{Q_{acc}} Q_0 l_b \cos(\phi_b) \left( P_{bpkD} \right)_n
\]  

Summing over all the cavities,

\[
P_d \propto \frac{E_{pk}}{l_b} \langle P_b \rangle
\]  

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 \( l_b \) 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 cooling 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.
6.1.4 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 3.4 ms. 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 (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 be 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%.

6.2 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.

6.3 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 in Section 6.2, 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 in Section 6.2. 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.

6.4 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 8. The maximum voltage permitted for a 5 cell elliptical cavity with a $\beta_g$ of 0.92, a maximum surface field of 40 MV/meter with an $E_{\text{peak}}/E_{\text{acc}}$ 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 9 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.
Figure 8. October 2012 Baseline Cavity Voltage. The blue diamonds is the cavity voltage profile as published in the TDR. The red squares are the maximum voltage permitted for a 5 cell elliptical cavity with a $\beta_g$ of 0.92 and a maximum surface field of 40 MV/meter. The green triangles are the adjusted profile that does not exceed the maximum limit.

It is clear in the “High Beta Removed” trace in Figure 9 that at the transition between medium to high beta sections, the high beta cavities can produce substantially more voltage. As shown in Section 6.1, the cost of producing the extra voltage is weak function of the extra power required. Thus, as long as the impedance of the cavity $\pi$ mode is dominant over a given energy range, it makes economic sense to remove the lower voltage medium beta cavities in favor 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.

6.5 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 (see Figure 10) 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. Using the curve in Figure 10, 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.
In Sections 6.2 and 6.3, 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 11 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 11. 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 10. Peak Field ratio for elliptical cavities compiled by P. Pierini

Figure 11. Cavity Power profile to achieve 5 MW average beam power for different values of geometrical betas in the high beta section.
6.6 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 in Section 6.5 that is more efficient to reduce the number of medium beta cryomodules because they produce less acceleration than the high beta cryomodules. Also in Section 6.5, 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. A possible configuration of a uniform cell is shown in Table 3.

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 ($\beta_g=0.92$) cryomodules. The design proposed in Section Error! Reference source not found. includes 14 two cavity spoke cryomodules, 7 four cavity medium beta cryomodules, and 24 four cavity high beta ($\beta_g=0.86$) 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 proposed in Table 3, 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
- Smooth 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
6.7 Lattice Performance

In Sections 6.4 and 6.5, it was shown that the number of required cryomodules can be reduced substantially if the requirement on smooth phase advance is relaxed. However, as noted earlier, the lifting of this requirement might cause emittance growth. This section will try to quantitatively examine how much emittance growth could result.

To evaluate lattice performance as a function of cost reduction, four different linac configurations where evaluated. These configurations are:

- **2012 Baseline:** The October 2012 baseline that included 15 medium beta cryomodules and 30 high beta cryomodules
- **Prius:** Includes a 22% increase in beam current, 10% increase in peak surface field, and a maximized voltage profile which resulted in requiring 7 medium beta cryomodules and 24 high beta cryomodules. A uniform cell length in the medium and high beta sections is used which would permit interchange of cryomodules of different betas in the future.
- **Smart:** The same parameters as the Prius but with 6 cell medium beta cavities. One less high beta cryomodule is required. The six cell medium beta cavities are 93% of the length of the five cell high beta cavities which could make much of the design of the high beta and the medium beta cryomodules similar.
- **Yugo**: The same as the Smart but with an 18% increase in pulse length (and a corresponding decrease in peak beam power). The lattice requires 7 medium beta cryomodules and 18 high beta cryomodules.

The major parameters of these configurations are shown in Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>Prius</th>
<th>Smart</th>
<th>Yugo</th>
<th>Units</th>
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<td>Linac Cost</td>
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<td>511</td>
<td>506</td>
<td>481</td>
<td>M€</td>
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*Table 4. Major parameters of four different linac configurations*
Figure 12 - Figure 14 show selected lattice plots of the superconducting section for the various linac configurations. The October 2012 Baseline is the most expensive but has the best emittance performance with almost no emittance growth observed in the superconducting section. The next three configurations (Prius, Smart, and Yugo) all have maximized voltage profiles. This results in a rapid longitudinal shrinking of the bunch length in the transition from the spoke to medium beta section with a corresponding increase of 15% in transverse emittance. A fair amount of effort was made to smooth the phase advance per meter of these configurations but with little success in reducing the emittance growth in the medium beta sections.

It should be noted that all these configurations used the same normal conducting front-end lattices which was optimized for the October 2012 Baseline configuration. It is possible that better emittance performance could be obtained if the front-end lattice is optimized for each configuration. Additional work should also be carried out to understand the effect of cavity pass-band modes and the maximized voltage profiles have on longitudinal emittance.
Figure 13. Selected lattice plots for the superconducting section of *Prius*. 
Figure 14. Selected lattice plots for the superconducting section of Smart.
7 Summary

The cost drivers of the ESS linac are the superconducting cryomodules and the associated RF systems that provide power to the beam. For the same beam power the number of cryomodules can be reduced by a combination of the following:

- Increasing the beam current and lowering the energy of the linac.
- Increasing the maximum allowable peak surface field in the superconducting cavities.
- Optimizing the cavity voltage profile for maximum energy gain.
- Increasing the pulse length and lowering the energy of the linac at the expense of peak beam power.

To evaluate lattice performance as a function of cost reduction, four different linac configurations where evaluated. These configurations are:

1. **2012**: The October 2012 baseline that included 15 medium beta cryomodules and 30 high beta cryomodules.
2. **Prius**: Includes a 22% increase in beam current, 10% increase in peak surface field, and a maximized voltage profile which resulted in requiring 7 medium beta cryomodules and 24 high beta cryomodules. A uniform focusing period cell length in the medium and high beta sections is used which would permit interchange of cryomodules of different betas in the future.
3. **Smart**: The same parameters as the Prius but with 6 cell medium beta cavities. One less high beta cryomodule is required. The six cell medium beta cavities are 93% of the length of the five cell high beta cavities which could make much of the design of the high beta and the medium beta cryomodules similar.
4. **Yugo**: The same as the Smart but with an 18% increase in pulse length (and a corresponding decrease in peak beam power). The lattice requires 7 medium beta cryomodules and 18 high beta cryomodules.

Table 5 lists the major parameters of the different configurations and Figure 15 provides a synopsis of the major cost drivers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012</th>
<th>Prius</th>
<th>Smart</th>
<th>Yugo</th>
<th>Units</th>
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<tbody>
<tr>
<td>Beam Current</td>
<td>50</td>
<td>61</td>
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<td>61</td>
<td>mA</td>
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<tr>
<td>Pulse Length</td>
<td>2.86</td>
<td>2.86</td>
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<td>Rep. Rate</td>
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<td>5.17</td>
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<td>129</td>
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<td>106</td>
<td>MW</td>
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<tr>
<td>Number of elliptical cryomodules</td>
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<td>Linac Length</td>
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<td>Linac Cost</td>
<td>586</td>
<td>511</td>
<td>506</td>
<td>481</td>
<td>M€</td>
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</table>

*Table 5. Design Summary Table*
8 Comments on Risk

8.1 Technical Risk
Technical risk results from any issue that prevents the ESS linac from achieving 5 MW of average beam power. There are three main issues

1. **Emittance growth due to the increased beam current.** Space charge forces will increase as the beam current increases. The space charge forces could result in emittance growth and halo generation. Too much halo will irradiate tunnel components to a point in which they need to be replaced or cannot be maintained. The beam intensity would have to be limited. The proposed increase in current of 22% over the 2012 technical design is probably not significant enough to be of a concern. It should be noted that the 2008 design had a factor of three times more beam current in an aperture at least one fourth the size of the 2012 design. Also future upgrades proposed for the ESS facility all rely on significant increases in beam current well beyond the increase proposed in this note. The value of 50 mA chosen for the 2012 design was somewhat arbitrarily chosen without regard to quantitative studies of halo formation and emittance growth and it will be hard to judge the added risk of going from 50 to 61 mA. Finally, 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.

2. **Lower cavity yield due to increase requirements on higher average accelerating field.** The proposed increase on the peak surface field to 44 MV/meter in the superconducting cavities might be more difficult to achieve than the 40 MV/meter in the 2012 design. This would lower the energy of the linac with the associated reduction in beam power. However, the value of 40-44 MV/meter for peak surface field is rather conservative as compared to many other superconducting accelerators that are being built such as XFEL (50 MV/meter) or are in
the planning stages facilities such as SPL and the ILC. Superconducting RF technology especially in the area of material processing and development has advanced rapidly over the preceding decade and is likely to continue in the future to the point where the difference between 40 MV/meter to 44 MV meter will be seen as a modest increase in peak surface field. Finally, it should be noted that the duty factor of the ESS linac is very low (4%) and significant contribution to the heat load is static. The need for ultra-high quality factors required in such facilities as in Project X, FRIB, and XFEL are not important for the ESS linac because of the low duty factor of the ESS linac.

3. **Halo Formation due to discontinuities in the transverse and longitudinal phase advance.** A significant fraction in the reduction in the number of cryomodules arose from maximizing the voltage profile along the linac. This resulted in a 15% increase in transverse emittance. This is a small increase in comparison to the available aperture and is not likely to be noticed at the target station. However, increase emittance gives fear to halo formation that might limit the beam intensity as discussed above. It is not clear that large emittance increases halo formation. Larger emittance might actually be beneficial because it reduces the strength of space charge forces. The experience at SNS has shown that a smooth lattice is not required for high intensity operations.

8.2 Schedule Risk

Schedule risk results from any issue that prevents the ESS linac from providing beam by 2019. The propose changes in this note might actually accelerate the schedule. The main possibilities for this acceleration are:

1. The production of cryomodules and the associated RF station are not only cost drivers but on the critical path for the entire program as well. This note proposes to remove at least 15 cryomodules out of 45 from the 2012 design. This will greatly reduce the production time and since the cryomodules are installed serially, the installation period of the linac will be shortened.

2. The specifications for the tender for the prototype of the klystrons and klystron modulators have not been initiated. Therefore, there is no delay for the RF systems.

3. This note has shown that to minimize the number of cryomodules that high beta cavities with a geometrical beta of 0.86 is superior to the choice of 0.92 that is in the 2012 design. There is no design for the 0.92 cavities. There exists only the design of 0.86 cavities and prototypes of these cavities are in the process of fabrication. Thus the choice geometrical beta of 0.86 proposed in this note not only reduces the number of cryomodules but actually accelerates the schedule.

4. This note proposes a uniform focusing cell length both the medium and high beta cavities so that the cryomodules could be interchangeable and possibly identical. The note also proposes 6 cell medium beta cavities that would be close to the same length of the high beta cavities. If 6 cell medium beta cavities are practicable, then the medium beta and high beta cryomodules could be identical. This would reduce the prototyping schedule (and cost) significantly because only one type cryomodule prototype would need to be constructed. Note that prototypes of each type of cavity string will still need to be constructed.
8.3 Cost Risk

Cost risk results from any issue that prevents the ESS linac construction from being on budget. The main focus of this note was to reduce cost. Cost models were used to predict the increased cost of having other systems to provide more power because of the reduction in number of cryomodules. It could be possible that these models are inaccurate or not precise enough to forecast the actual cost savings. In addition, the cost implications on the cryomodules where not looked at the same depth as the investigation of RF sources.

It should be noted that there were some areas discounts on costs for the proposed changes were not taken. Chiefly among these was:

- the reduced manufacturing costs of having only one cryomodule design
- the reduced tunnel and gallery construction costs of having a uniform lattice cell length.

However, this note did not propose any drastic technology change so the risks in increased cost are mostly the same as for the 2012 design.