ESS Frequency Advisory Board Report **July 2010**

Executive Summary

The ESS Frequency Advisory Board meeting took place on July 10th in Lund following the ESS Technical Advisory Committee meeting on the preceding two days. The FAB charge, meeting agenda and membership are given in annex A. More detailed comments on the various elements of the charge are given in the other sections of this report.

The following comments are based on the main designs discussed; the nominal ESS baseline of a 5-cell 704 MHz design and a 9-cell 1.3 GHz design. Other parameters choices are possible but these two are representative of the various frequency related issues.

There is no completely dominant issue associated with the two frequency choices; either could be used to provide a high power spallation source. That said the FAB agrees with the Project that a lower frequency (600-800 MHz) produces a better optimized and a lower risk solution to meet the design goals. The baseline 704 MHz design is shorter, larger aperture (beneficial in regards to beam loss), and lower impedance.

With the present day limited experience of the lower frequency SRF cavities near the gradient limit, the FAB recommends that the project adopt a somewhat conservative approach to operating gradient to reduce sensitivity to gradient spread, and single point failures. HOM's are evidently a source of concern but the lower frequency/cell count reduces this effect. The FAB suggests that additional work in this area would be beneficial. Most areas of technical performance are similar for both frequencies.

The maturity of 1.3 GHz cavity industrial production is obviously better than the other frequencies but SRF technology is now less of an 'art form' than it used to be. With the right design, production should not prove to be a major technical obstacle. Cryomodules for high duty factor/average power will need development for either frequency. High power RF systems are demonstrated (SNS) at this point in time for the lower frequencies. While the component design obviously reflects the frequency choice the component availability does not appears to be strongly influenced by frequency.

From a technical perspective the FAB finds little difference for any frequency in the range of 600->800 MHz. In our opinion the exact frequency choice should be based on the project's collaborative strategy. We note in passing that at some point the Project will need to develop in-house technical expertise at the chosen frequency. The FAB believes that sufficient competencies exist at the EU labs for either frequency.

While upgrades are possible with either frequency choice, 5 MW itself represents a major technical challenge. An increase in power will require either a higher energy/gradient or more beam current. The lower HOM's suggest that higher currents

are more readily achievable with the lower frequency. Increasing power will probably require more cryomodules with lower gradient, which does not depend on frequency.

The FAB did not see any significant cost differences at the system level (factor of 2) in either approach.

Beam dynamics

The beam dynamics performance of different layouts based on two different frequencies was shown to the Committee. The designs were optimized with a high energy section based on a frequency for the elliptical superconducting cavities which was either a factor 2 or 4 the front end's frequency (352 or 325 MHz). In order to obtain similar accelerating voltages, the low frequency designs use 5 cell resonators while the high frequency layouts use 9 cells.

The results of these optimizations show that the low frequency layouts are shorter and use fewer different geometrical betas thanks to a larger transit time factor acceptance. It has been emphasized that the lower frequency jump induces a better accelerating efficiency when the longitudinal acceptance is kept continuous. Nevertheless, it has been difficult to quantify the gain, as the high frequency options didn't exactly include a factor 2 for the number of cells.

Both frequency options have been compared in terms of r.m.s. emittance growth for the nominal beam and its sensitivity to longitudinal errors. Transversely, the lattices are similar and no major differences for the transverse dynamics are expected. For both longitudinal and transverse planes, when each option is set up with the state of the art for the matching and the phase advance evolution rate and amplitude (resonances), no significant, (for a spallation source) emittance growth is observed for either frequency.

It was pointed out that the large aperture of the cavities in the range of 600-800 MHz is sufficient to reach one-megawatt beam operation (SNS) but there is no empirical evidence at this time that the aperture for frequencies close to 1.3 GHz is beam loss free.

The differences about the aperture and the numbers of cells will also have a relative impact on the sensitivity to the High Order Modes (HOMs). HOMs are excited by the passage of the beam and their amplitude is therefore directly proportional to the beam current. For long beam pulses and high peak currents, the amplitudes of HOMs can increase to levels where they influence the beam or even destroy the bunches. However, the SNS studies and feedback show that HOMs have no significant impact on this accelerator performance. No heating or significant signal through the HOM couplers has been observed. HOM studies tailored for ESS have been shown to the Committee and they claim that HOMs are not an issue for ESS too, with the possible exception of modes which are resonant with sources of excitation (the beam time structure for instance). It was shown to the FAB that a frequency shift of 10 kHz is sufficient to make this effect negligible. The FAB recommends that the ESS team carry out a strategy to mitigate this risk. This risk is lower for the low frequency scheme.

Technical Performance

This section briefly compares the technical performance between the two schemes (700 MHz, 5 cell vs. 1300 MHz, 9cell) in the context of high level scaling for cavity operating gradient, HOM/wake-field, cryogenics, and RF power, etc.

Cavity operating gradient

20 MV/m is a reasonable operating gradient for the future high power proton machine. The major efforts for the highest gradients have been put for the 1.3 GHz ILC/TESLA cavities. The SNS cavities represent the only corresponding experience of the lower frequency SRF cavities for a production machine. The operating gradients of the SNS cavities range from 8 to 15.5 MV/m for various reasons. The major limiting factors of the SNS cavities are heating from field emission and their interplay between cavities at a duty factor higher than 3 %. The committee recommends that the ESS adopt a conservative approach to gradient for the baseline design. Also energy margin during the machine operation will be essential in mitigating single point failures.

HOM & wake-fields

As mentioned in the Beam Dynamics section, the damping requirements for the low frequency scheme becomes less severe mainly due to the reduced number of cells per cavity and larger bore.

Even under conservative assumptions like about 1% white beam noise (in fact, beam noise decreases exponentially with frequency), no significant impact on beam quality is expected. HOM induced power right on the beam lines could be big, but the chance is very low.

There's a presentation about wake-field driven power deposition that is one of the major issues for the CW, high intensity case like ERL. The heat load from the wake-field looks very high. Committee recommends one should carefully check the input conditions for the ESS case including r/Q(v) of modes, necessity for r/Qs beyond cut-off frequencies, beam charge and duty, etc. In SNS case, additional cryogenic load for all cavities at 1 MW operation (bunch intesity~85 pC/bunch, average current~1mA) ranges from 10-40 W. Most of this additional load comes from the beam loss depending of linac tuning/optics, which implies the loss/cavity from the wake-field is much less than 1W/cavity.

In any case, much less concerns are expected with the low frequency scheme in this regard.

Cryogenic load

The cryogenic load depends on many physical parameters and component design such as static loss (cryomodule design, size of cryostat), dynamic loss (surface resistance, field emission, additional thermal radiation from fundamental power coupler, beam loss, etc). The lower frequency is better for some aspects and worse for some others. There's no significant difference on cryogenic requirement between two schemes. Any difference should be well within the margin of the cryogenic system design. Since the cryogenic plant has to run at a fixed load, which includes the design margin, the highest overall efficiency is not necessarily achieved at design conditions.

RF pulse width and power requirements

The required RF power is about the same between two schemes since it is mainly determined by the beam loading.

The cavity filling time is shorter at higher frequency assuming driving RF power and Qex are about the same between two schemes. The difference of required RF pulse length including filling will be less than 10 % since filling time can be much shorter than the RF flattop in ESS case by utilizing the fully available RF power for the filling.

Component Availability

Component availability must be considered when choosing the operating frequencies for the ESS Linac. The relevant components include the RF cavities, HOM couplers, power couplers, cavity tuning system, cryomodule components, RF power amplifiers, RF transmission lines, high-voltage modulators, low-level RF control systems, and the cryogenic plant and distribution system. In general, the availability of these components is weakly influenced by the frequency choice. The main points for each mentioned component are listed below.

Production of superconducting cavities by industry is relatively mature at this point with established vendors in Europe and North America. There are two potential problems: capacity at the cavity vendors and availability of high-purity niobium. These are both schedule issues, not technical performance issues. The cavity production schedules for the European XFEL and the FRIB projects should be monitored as they may impact ESS cavity prototyping and production. The cavity availability is not impacted by the frequency choice.

The HOM couplers will likely be an integral part of the cavities. Hence their availability will be the same as for the cavities.

The power couplers will have to be developed specifically for the ESS project. It is likely that design features from one or more existing designs will be adopted for this application. Past experience and basic principles suggest the coupler development is readily achievable. There are a few vendors worldwide building power couplers at this time. Industrial capacity and expertise will likely be sufficient for prototyping and production of the ESS power couplers independent of frequency.

The cavities will require a slow tuning system for frequency adjustment. They may also require fast piezo-electric tuners that can be used to compensate Lorentz force detuning and/or microphonics. However, the gradient specifications and relatively low external Q may eliminate the need for the fast tuner. In any case, the cavity tuning systems can be produced by a variety of vendors. Availability is not impacted by frequency and should not be a problem.

The cryomodule design does depend somewhat on the frequency choice, with the lower frequencies generally requiring cryomodules of larger diameter. The cryomodule components, such as vacuum vessels, thermal shields, piping, supports, etc. are readily available from industry.

It would be convenient, of course, if existing RF power amplifiers could be utilized. For example, there are a variety of klystrons operating at 805 MHz at ORNL/SNS, some of which might be directly applicable to an ESS at 805 MHz. However, given sufficient development time, the required amplifiers can be developed for any of the frequencies under consideration. Development and production costs are likely comparable regardless of the chosen frequency. There are at least three vendors engaged in the development and production of klystrons at this time.

RF transmission line components are readily available from industry regardless of frequency. The transmission lines will generally be larger in cross section for the lower frequencies. This may impact the design of penetrations from the RF gallery to the Linac tunnel.

The choice of frequency will have very little impact on modulator availability. There are several vendors worldwide that can produce modulators. The key is to have a good modulator design so that high-reliability operations can be achieved.

The availability of LLRF control systems is not influenced by the frequency choice.

The availability of the cryogenic system is not influenced by the frequency choice. However, the frequency choice does impact the capacity of the system and the segmentation and temperature optimization. Therefore it will affect the cost of the cryogenic system.

Potential for Collaboration

The ESS facility design is well suited for a collaborative approach since the design is quite modular with well-defined equipment interfaces. The SNS was successful using this approach but did demonstrate that the overall design ownership must reside with the central team since this is where the technical interfaces are specified and controlled. The central team is also crucial in defining equipment acceptance criteria and ultimately commissioning and operations. The creation of this central team will be one of the initial challenges facing the project but is not impacted directly by frequency choice.

The FAB believes that sufficient competencies exist in the EU laboratories to allow either frequency choice. While endorsing the lower frequency design from a technical perspective, the FAB finds little difference for any frequency in the range of 600-800 MHz. In our opinion the final choice should be based on the project’s collaborative strategy.

The upstream portion of the linac, while needing to be consistent with the overall design, is not strongly influenced by the exact frequency of the final high-beta section.

The 704 MHz baseline is based on the frequency choice of the CERN SPL proposal and the European R&D program CARE/High Intensity Pulsed Proton Injector. This ESS relevant R&D program provided expertise in EU and allowed the construction of test stands at the two frequencies 352 and 704 MHz. The ESS needs to understand the impact should the SPL project not receive approval or be subject to delay. The XFEL cryomodule schedule is such that cryostat fabrication infrastructure at Saclay and cavity test facilities at DESY will become available on the requisite time frame for the ESS construction phase whatever the frequency. All of these laboratories have proven track records in these technologies.

Upgradability

The FAB did not have sufficient time to focus on upgradability to any great extent. While upgrades a possible with either frequency choice the FAB believes that 5 MW itself represents a major technical challenge.

An increase in power will require either a higher energy/gradient or more beam current. The lower HOM’s suggest that higher currents should be more readily achievable with the lower frequency option although SNS experience to date with ~1MW operation suggests that HOM’s are not a significant issue. With higher power, the ESS needs better understanding of the impact of HOM’s than appears to be the case at present.

The FAB believes that increasing power beyond 5 MW will probably require more cryomodules with lower gradient, which does not depend on the frequency choice.

Annex A

FAB Charge:

The frequency of most of the superconducting RF structures in the ESS baseline design is 704 MHz (some operate at 352 MHz). This is also the frequency of the CERN SPL baseline design. Other frequencies at superconducting linacs under design or in operation include 652 MHz, 805 MHz, and 1.3 GHz.

- The FAB is asked to report on the advisability of the choice of 704 MHz, from the perspectives of beam dynamics, technical performance, component availability, potential for collaboration, and upgradability (beyond 5 MW at 2.5 GeV).

- The FAB is asked to deliver a final documentary report before July 31, 2010. It is also asked to deliver a preliminary assessment at the close of business on July 10, in a closed or open door session, as appropriate, to the TAC chair and the Director of ESS.

- The FAB is also welcome to address issues that they consider to be important, which are connected to the choice of frequency, but which are not explicitly addressed by the charge.

- To the extent that it is possible the FAB is invited to give advice on costs for construction and operation.

FAB Membership:

FAB members are Mike Harrison (BNL/ILC, chair), Mark Champion (FNAL/Project-X & ILC), Romuald Duperrier (Saclay/ESS), and Sang-ho Kim (ORNL/SNS).

The TAC chair is Kurt Clausen (PSI/Directorate), and the chair of the TAC/Linac sub committee is Roland Garoby (CERN/SPL). The FAB will report to the TAC chair Kurt Clausen. Clausen & Garoby are ex-officio observers at FAB sessions, while FAB members are ex-officio observers at the accelerator TAC sessions.

Meeting Agenda:

8.30	Executive Session	
9.00	Welcome and ESS overview	M Lindroos (ESS)
9.45	Choosing the frequency of SC Proton Linacs	F Gerigk (CERN)
10.30	COFFEE BREAK	
10.45	HOMs in elliptical cavities at 704 MHZ & 1.3 GHz	R Calaga (BNL)
11.30	HOM issues in 704MHz and 1.3GHz cavities	M Schuh (CERN)
12.00	1.3 GHz performance & component availability at XFEL & ILC	W-D Moeller (DESY)
12.30	WORKING LUNCH – Board in Executive Session	
13.30	Open and/or closed discussions & additional presentations	
15.00	COFFEE BREAK	

15.15	Committee deliberations	
16.30	Closeout Comments	M Harrison (BNL)
Farewell comments		P Carlsson (ESS)