RF MODELING PLANS FOR THE EUROPEAN SPALLATION SOURCE

Robert Ainsworth, Royal Holloway, University of London, UK
Mats Lindroos, Stephen Molloy*, Steve Peggs, Rihua Zeng, ESS, Lund, Sweden
Roger Ruber, Uppsala University, Uppsala, Sweden

Abstract

The European Spallation Source (ESS) will be the world's most powerful next generation neutron source. It consists of a linear accelerator, target, and instruments for neutron experiments. The linac is designed to accelerate protons to a final energy of 2.5 GeV, with a design beam power of 5 MW, for collision with a target used to produce a high neutron flux. Several stages of RF acceleration are required, each using a different technology. The high beam current and power require a high degree of control of the accelerating RF, and the specification that no more than 1 W/m of losses will be experienced means that the excitation and decay of the higher order modes must be very well understood. Experiences at other high power machines also imply that an understanding of the generation and subsequent trajectories of any field-emitted electrons should be understood. Thermal detuning of the HOM couplers due to multipacting is a serious concern here. This paper will outline the RF modeling plans - including the construction of mathematical models, simulations of HOMs, and multipacting - during the current Accelerator Design Update phase, and will discuss several important issues for ESS.

INTRODUCTION

The European Spallation Source (ESS), currently in an Accelerator Design Update (ADU) stage, will be the world's most powerful next generation neutron source, and is designed to accelerate bunches of protons to a final energy of 2.5 GeV for collision with a target designed to produce a large neutron flux for several instrument beamlines.

The time structure requires a repetition rate of 14 Hz, with 5 MW peak power on target, a beam current of 50 mA, and a duty cyle of 4% resulting in 2.86 ms long bunches.

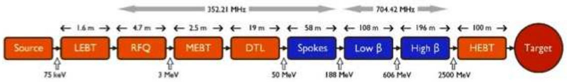

Figure 1: Schematic layout of the ESS accelerator.

The accelerator is a single pass linac without an accumulator ring and, as shown in Fig. 1, consists of several acceleration technologies.

The proton source is a compact Electron Cyclotron Resonance source (ECR) similar to the VIS source [1] in Catania and the SILHI source [2] at CEA Saclay. The 75 keV beam this generates is transported through a Low Energy Beam Transport (LEBT), and then accelerated to 3 MeV by a four-vane Radio Frequency Quadrupole (RFQ). A Medium Energy Beam Transport (MEBT) and Drift Tube Linac (DTL) take the proton's kinetic energy to 50 MeV.

From this point onwards, the accelerator uses superconducting RF (SRF) technology – spoke resonators, and two families of elliptical cavities – to accelerate the beam to its final energy of 2.5 GeV. A 100 m High Energy Beam Transport (HEBT) then transports the beam, and focuses it on the target, which is approximately 500 m from the source.

OPEN QUESTIONS

Several open questions will be directly addressed by the RF Modeling Work Unit:

Beam loss The specification for the beam loss limit is 1 W/m, and this is derived from a consideration of the load on the cryogenics due to absorption of the energy of the lost particles, as well as the avoidance of activation of beamline components. Since the maximum beam power observed in the machine is 5 MW, it is possible that only small perturbations are all that are required for the beam loss limit to be breached.

A primary concern related to the beam loss is that disruption of the phase space by Higher Order Modes (HOMs) may be sufficient to cause excessive beam loss, and therefore these will be directly studied by the RF Modeling effort.

Field emission / Multipacting It is known that field emission (FE) and multipacting (MP) can cause considerable problems with the operation of high power superconducting (SC) cavities [3], and so it is of significant importance for the successful operation of ESS to understand any issues arising.

The primary issues are related to the impact on the quality factor (Q) of the cavity due to absorption of the RF power by field emitted electrons, increased load on the cryogenic system due to FE electrons being lost in the cavity walls, and thermal detuning of the HOM coupler (if present) causing excessive power to be coupled out into the HOM electronics. In addition, excessive MP can result in cavity quenches, and disruption to the phase space of the beam.

LLRF stability The stability of the accelerating RF is fundamental in preserving the quality of the beam reaching the target, as well as to make sure that the previously mentioned beam loss limit is not breached. This is of particular

---

* stephen.molloy@esss.se

importance in the case of a proton linac, since the quasi-relativistic velocity of the particles implies that errors in phase/amplitude will result in a beam arrival time error at subsequent cavities, thereby allowing errors to accumulate along the length of the linac.

It may be seen that the beam loss and FE/MP questions are tightly correlated, and that they are part of the larger question on the installation, or not, of HOM couplers.

RF-RELATED BEAM DYNAMICS

It has been shown [4] that HOMs may cause significant disruption to the quality of the beam in high power proton linacs, and that this disruption is primarily caused by the coincidence of highly coupled RF modes with the frequency content of the beam.

Figure 2 shows the R/Q spectrum calculated for a high β elliptical cavity proposed for ESS where multiples of the bunch repetition rate (the "machine lines") have also been indicated. Note that these cavities will accelerate a range of particle velocities, and that the coupling, R/Q, is a function of the velocity, so it is the maximum value of the coupling within the beta range that is plotted.

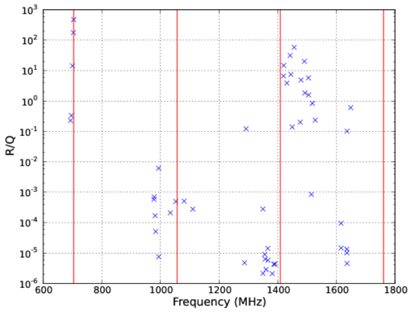

Figure 2: Maximum R/Q within the beta range used by the cavity plotted against the frequency of the mode. The red lines indicate multiples of the 352 MHz bunch repetition rate.

In Fig. 2 it can be seen that several modes lie close to primary machine lines, and may therefore be considered to be a risk to the quality of the beam. In particular, the highly coupled modes lying just above the machine line at 1408 MHz require further investigation.

Beam dynamics studies mirroring those in [4] will commence soon, and their results will form an important part of the decision on the installation of HOM couplers.

FE/MP IN HOM COUPLERS

Design proposals for HOM couplers for the elliptical cavities are shown in Figs. 3 and 4. Both of these rely on the standard technique of providing a broadband acceptance, but designing the structure to have a certain inductance and capacitance in order to strongly reject the frequency of the fundamental accelerating mode.

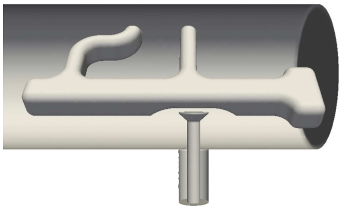

Figure 3: A re-scaled, "TESLA-style" HOM coupler.

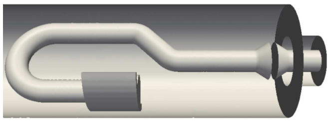

Figure 4: The "Rostock design" for a HOM coupler.

The position of the so-called "notch" rejection frequency is very sensitive to the geometry, and so it is possible for thermal expansion induced by absorption of FE/MP electrons to alter this in such a way that significant amounts of the high amplitude accelerating mode are coupled out through these ports, resulting in Q-droop and electronics damage.

FE/MP simulations using the ACE3P codes [5] have begun. The trajectories of electrons emitted around the inner walls of the couplers were simulated, with a postprocessing step involving scaling any resonances by a typical[1] Secondary Electron Yield (SEY) for niobium (see Fig. 5).

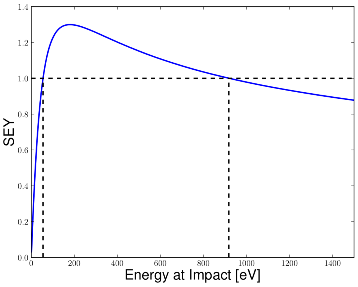

Figure 5: SEY curve used in the postprocessing of the simulation results.

Figure 6 shows a comparison of the MP behaviour of the two HOM couplers. It can be seen that the coupler shown in Fig. 3 displays a large band of MP, this is of a much lower amplitude that the narrow band observed for the coupler in Fig. 4.

Remaining questions for this study are:

1. To what extent may the MP bands in Fig. 6 be lessened by RF processing during commisioning of the accelerator?
2. Through the addition of ridges, or by some minor

---

[1] Data taken from the Fishpact [6] tutorial.

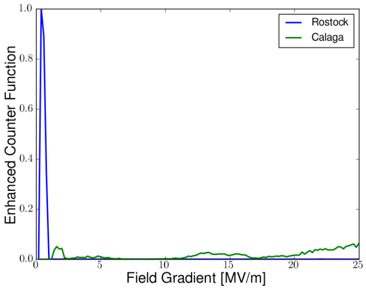

Figure 6: Comparison of the MP found in the two proposed HOM couplers [7]. The green line refers to the HOM coupler shown in Fig. 3, and the blue to that in Fig. 4.

tweaks in geometry, is it possible to lessen the MP bands to acceptable levels?

3. Are these studies affected by limitations of the simulation code? For example, the ACE3P codes always emit electrons normally to the cavity wall, and do not implement a statistical spread in the emission energy. In addition, they do not take account of space charge when tracking the emitted particles. Each of these effects may have a considerable effect on the outcome of the calculations.

MULTI-CAVITY FE/MP

As seen in [3], the statistics of the FE electrons impacting in the end-groups of a particular cavity are correlated with the settings of neighbouring cavities, implying that FE electrons are being transported throughout the cryomodule.

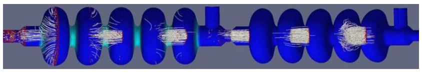

Figure 7: A simulation of FE trajectories in two cavities.

Figure 7 shows a frame from an animation of the transport of FE electrons by the accelerating field from the "most upstream" cell of one cavity into a neighbouring structure.

Figure 8 shows the dependence on phase difference of the current emerging from the downstream cavity. The ESS cavities will operate between ∼-80°and +10°, and so should expect to see a high degree of FE activity spread throughout the cryomodules.

LLRF

Investigations [8] of the variations in phase and amplitude of the klystron output due to cathode voltage changes related to modulator ripple & droop have begun, and proportional and proportional–integral (PI) controllers have been studied for the normal–conducting and superconducting cavities.

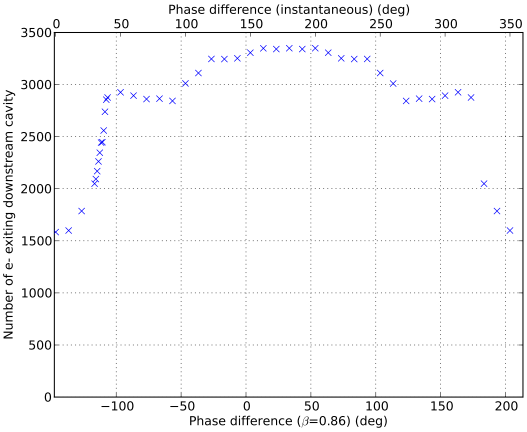

Figure 8: The integrated current emerging from the downstream end of a two-cavity system plotted against their phase difference. The instantaneous phase difference (top axis), and that observed by a particle with β=0.86 (bottom axis) is plotted.

It is found that wideband modulator droop and ripple of 1% induces changes of more than 10° in the output phase of the klystron, and 1.25% in amplitude. Calculations show that the PI controller struggles to deal with high frequency and high amplitude klystron noise due to the loop delay and the necessity to keep proper phase margin.

It is suggested that the low frequency (<1 kHz) modulator droop/ripple is kept <1%, and that the high frequency (>1 kHz) is tightened to <0.1%.

At very low frequency (<100 Hz) the tolerances may be significantly relaxed (∼3%), but this results in the consumption of more power and dynamic range.

REFERENCES

[1] F. Maimone, et al, "Status of the Versatile Ion Source VIS", EPAC08, Genoa, Italy (2008).

[2] R. Gobin, et al, "First plasma analysis of the CEA-Saclay ECR hydrogen negative ion source", Rev.Sci.Instrum. 73, 983985 (2002).

[3] I. E. Campisi, et al, "Status of the SNS Cryomodule Test", 2511 (2007).

[4] M. Schuh, et al, "Influence of Higher Order Modes on the Beam Stability in the High Power Superconducting Proton Linac", Phys.Rev.ST Accel.Beams 14, 051001 (2011).

[5] K. Ko, et al., "Advances in Parallel Electromagnetic Codes for Accelerator Science AND Development", LINAC2010, Tsukuba, Japan, 2010

[6] E. Donoghue, et al, "Studies of electron activities in SNS-type superconducting RF cavities", (2005).

[7] R. Ainsworth, S. Molloy, R. Ruber, "Multipacting Analysis for the Superconducting RF Cavity HOM Couplers in ESS", this conference, 2011

[8] R. Zeng et al, "Influence of the Droop and Ripple of Modulator on Klystron Output", Tech Note ESS/AD, 2011