Comparison of 5- & 6-cell Medium-β Linac based on the Nearest Passband Mode

Mohammad Eshraqi, Stephen Molloy*

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1 Introduction

A recent re-design of the ESS linac [1] has raised the question of the number of cells per cavity in the medium-β linac, with linacs of similar cost being designed making use of cavities with either 5 or 6 cells. The narrower velocity acceptance of the 6-cell cavities, as well as the broader velocity range that this section of the linac may have to accelerate, has raised questions of the influence of the nearest passband mode.

Beam dynamics studies were performed of these two linacs, with various assumptions of the stability of the accelerating RF and the injection jitter of the beam, and the effect of the passband modes was calculated. This is then used to make a recommendation as to which of the cavity types should be chosen for the medium-β linac.

2 Beam dynamics and cavity R/Q

Bunches passing through these cavities will excite the passband mode to an extent that is proportional to the R/Q of the mode, which is itself a function of the velocity of the bunch. The field excited for the passband mode will then decay at a rate given by its quality factor, $Q_{ex} \geq 10^5$, and will oscillate with its resonant frequency. Thus, it is possible that it will have sufficient amplitude when subsequent bunches arrive at the cavity that it will alter their momentum to a significant degree. They will also add a contribution to this field, thereby allowing the field to grow resonantly.

In addition, the alteration of the bunch's momentum will result in it arriving at the following cavities with the incorrect phase, and so the errors can accumulate throughout the length of the linac.

The code used for this study allows the injection of a long pulse of bunches, each represented as a point particle, which are then subject to this error accumulation. Further details may be found in [2].

3 Simulations

For each of the lattices that have been examined, only the superconducting portion of the linac was simulated; i.e. a file containing the the energy and phase of the bunches emerging from the DTL was used as an input, and the simulation code modelled the motion of this beam through the spoke, medium-β, and high-β sections of the linac. The voltage & phase profile for the two simulated linacs are shown in figure 1.

The input beam for these simulations was generated by tracking an initially perfect beam through a simplied model of a DTL that included RF errors of 0.5% and 0.5^o. A small error will arise in the results due to the fact that the RF errors were calculated for a beam emerging from the DTL with an energy of 75 MeV, while the simulations discussed here used a beam energy of 77.5 MeV, however this amounts to $\sim$3% of the total error, and so can be ignored.

*stephen.molloy@esss.se

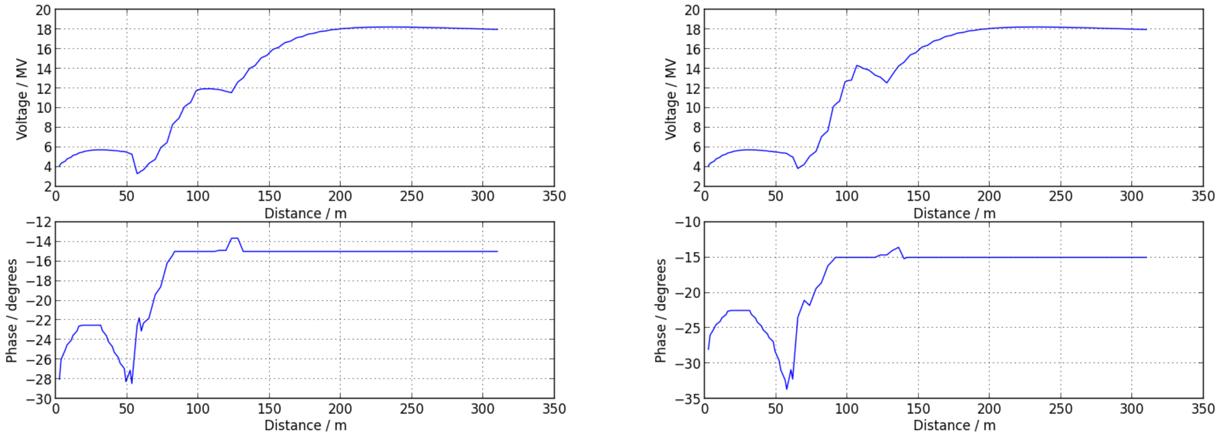

Figure 1: Voltage & phase profiles for the 5-cell lattice (left), and 6-cell lattice (right).

In both cases it was assumed that there was a 1% random jitter on the bunch charge. The plots in figure 2 show the output beam for the 5-cell & 6-cell linacs in the case where the only errors are on the input beam (i.e. no passband mode excitation, and no RF errors in the simulated linacs).

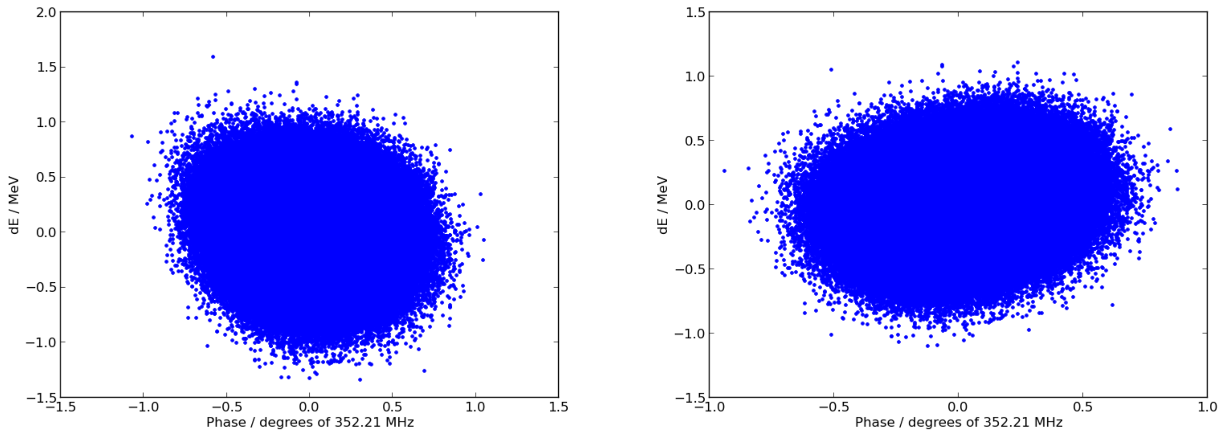

Figure 2: Bunch distribution in longitudinal phase space at the end of the 5-cell (left) & 6-cell (right) linacs for a beam with $0.5\%/0.5^o$ DTL-RF errors, but no passband modes or RF errors in the remainder of the linac.

Given a phase space distribution such as those shown in figure 2, it is possible to define a quantity that is very similar to the concept of the emittance of a single bunch, however with the averages taken over the phase space location of the centre of each of the bunches in the full machine pulse. For the remainder of this note, the term "emittance" will be used to indicate this quanity, ϵ, whose precise definition is as follows.

$$\epsilon \equiv \pi \cdot \sqrt{\langle dE^2 \rangle \cdot \langle dt^2 \rangle - \langle dE \cdot dt \rangle^2} \qquad (1)$$

Using this definition, the longitudinal emittances in figure 2 are 0.1998 & 0.1355 π.deg.MeV respectively, thus it can already be seen that the 6-cell linac is more resilient to certain errors than the 5-cell linac.

4 Results

4.1 RF Errors

The simulations were run with the effect of the passband modes eliminated in order to set a baseline. In this case, the only effects degrading the emittance are the injection jitter and the RF errors. A total of 1000 random linacs were simulated for each of the lattices, and the results are shown in figure 3 for the case of the smaller injection errors.

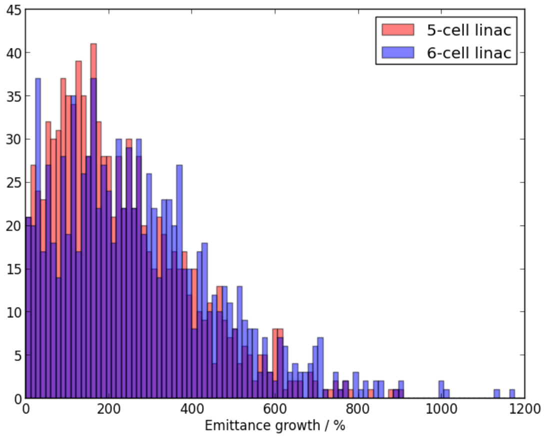

Figure 3: Distribution of simulated emittances for the two linacs.

In this figure, it can be seen that each of the lattices offers a similar performance from the point of view of resilience to RF errors, however it must be remembered that the absolute value of the unperturbed emittance is lower in the case of the 6-cell linac (see figure 2) and so the distributions of the absolute values are wider for the 5-cell lattice. This implies that this lattice might be more sensitive to errors, and so might be a more difficult linac to commission and run.

4.2 Passband Modes

With the exception of the injection errors, the RF errors were then switched off, and the action of the passband modes was simulated for each of the lattices.

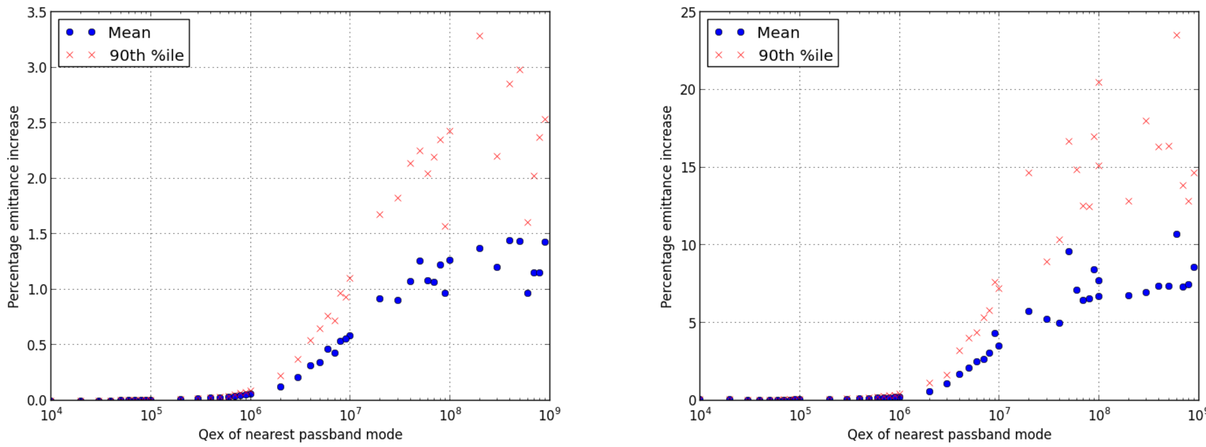

Figure 4: Q_{ex} scan for a 5-cell (left) and 6-cell (right) lattice with 0.5%/0.5^o injection errors. Blue points indicate the average emittance for the simulated linacs, while the red crosses show the 90th percentile.

For the plots in figure 4 the output emittance of the beam pulse is plotted for a range of simulated values for the Q_{ex} of the passband mode. In the case of a cavity without couplers, beam-pipe bellows, etc., it would be expected that the Q_{ex} of this mode could extend to 10^9, however in a cavity as installed in a cryomodule, it is more likely that this value will be approximately the same as that for the accelerating mode, $Q_{ex} \sim 10^5 - 10^6$. A range of values were simulated in order to allow a more detailed examination of the expected output.

5 Discussion

Figure 4 shows that the emittance increase for the 6-cell linac due to the passband modes is almost an order of magnitude greater than that for the 5-cell linac. This ≤10% increase, however, needs to be compared with the factor ∼240% increase due to RF errors shown in figure 3.

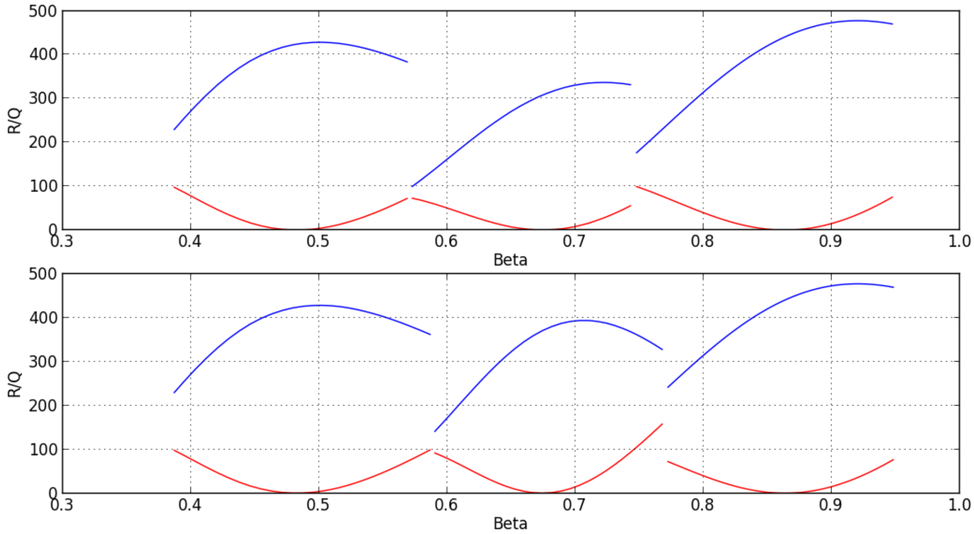

Figure 5: R/Q of the accelerating mode (blue) and passband mode (red) for the 5-cell linac (top) and 6-cell linacs (bottom) simulated in this note.

The fact that the 6-cell linac is influenced more strongly by the passband mode can be explained somewhat by examining the R/Q of the passband modes for the two linacs (see figure 5). The integral of this curve for the 6-cell linac is ∼15% greater than that for the 5-cell linac, which implies that the passband mode will be excited by a greater degree in this linac, and will therefore cause more disruption. That this mode is excited to a larger degree in the 6-cell linac is an expected result, and is what motivated this study.

6 Conclusions

Although it would appear that the 6-cell linac is slightly more resilient to errors relating to injection and RF errors, it has been shown that the larger R/Q at the beginning and end of the medium-β section cause a larger increase in the output emittance than in the 5-cell lattice. This ≤10% emittance increase should, however, be compared with the ∼240% increase due to the expected RF errors.

Therefore, although the behaviour with respect to the passband mode is almost an order of magnitude worse for the 6-cell linac, this increase is more than a factor of 20 less than the emittance increase caused by RF errors, and so can be considered to be negligible.

The conclusion of this note is that neither the RF errors nor the beam dynamics related to the passband modes are sufficient to distinguish between these linacs, and that the choice should be made based on other considerations.

References

[1] H. Danared, M. Eshraqi, D. McGinnis, “**Design Options of the ESS Linac**”, International Particle Accelerator Conference, IPAC2013.

[2] R. Ainsworth, S. Molloy, “**The influence of parasitic modes on beam dynamics for the European spallation source linac**”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2012.