1 Introduction

A pre-print of Schuh's paper may be found at:
https://mschuh.web.cern.ch/mschuh/journalpaper/jphom.pdf

This paper uses home-brewed code (based on Root) to understand the effect of the various HOMs on the total phase space occupied by the pulse train at the end of the linac. That is, it considers each individual bunch to be a point charge, and simulates the total phase space occupied by the entire train by determining the effect of integrating the various HOMs across the pulse.

He begins with a discussion of the effect of RF errors (phase and amplitude noise), and uses the resulting phase space growth (a factor of ∼3.8) as the acceptable limit for the effect of HOMs on the beam.

In most cases he studies 1000 randomly generated machines, and reports the average and worst-case growth in the phase space. Occasionally, it is necessary for him to limit the number of random seeds used since several of the simulations are quite computationally intensive.

2 Longitudinal modes

2.1 A mode far from a machine line

Schuh concludes that HOMs far from machine lines are of no concern as there is no possibility of resonant amplification of these fields. Even in the (ridiculous) case of a beam current, I_b, of 400 mA, there is only a 4% growth in the phase space for a HOM with $Q_{ext} = 10^8$. Note that the $\frac{R}{Q}(\beta)$ used for this mode is not made clear in the paper.

At this point he notes that $Q_{ext} < 6 \times 10^7$ is a natural limit to use for these modes, since greater than this implies a decay time that would allow subsequent pulses to couple. The larger inter-pulse duration at ESS ($\frac{1}{14Hz}$ rather than $\frac{1}{50Hz}$) relaxes this tolerance by a factor of ∼3.

2.2 A mode close to a machine line

He finds that poorly damped ($Q_{ext} \sim 10^7$) modes that coincide with a machine line are quite destructive.

Their influence is moderated by their natural frequency spread causing some destructive intereference of the negative effect, but even a frequency spread of σ_f=1 MHz still induces an average growth of a factor of ∼5. The maximum growth he found for this frequency spread was a factor of ∼100.

He investigates how close it is possible to be to a machine line, and determined that maintaining a separation of $3\sigma_f$ is sufficient to maintain an effect that is less than that of the RF errors.

In the case of HOMs coinciding exactly with machine lines (he appears to use a frequency spread of 1 MHz, but it is not stated explicitly), a damping of $Q_{ext} \sim 10^5$ is necessary to limit the HOM–induced phase space growth to less than that caused by RF errors.

2.3 Conclusions

From this, it would appear that simply avoiding a machine line would allow us to relax the Q_{ext} tolerance to $\sim 10^8$, however pulse substructure complicates this. See section 4.

3 Transverse modes

He studies the effect of transverse modes on the horizontal phase space, including the effects of injection noise, and alignment errors. I note that he doesn't appear to have studied angular misalignments.

In all cases he reports very little impact due to these modes.

4 Effect of pulse sub-structure

He studies various chopping patterns, and notes that sub-structure adds additional Fourier sidebands to the primary machine lines. This increases the "danger zone" around the machine lines that should be avoided by HOMs. This is a larger concern for high frequency patterns (e.g. 5/8), than slower schemes (e.g. 500/800).

He concludes that $Q_{ext} = 10^5$ offers stable operation for any conceivable chopping pattern, although this may be relaxed for any modes more than $\sim$50 MHz from machine lines (remembering that machine lines are only separated by 352 MHz, and so this considerably shrinks the safe region).

5 Recommendations

Given the unknown status of the required substructure at ESS, it would seem that $Q_{ext} < 10^5$ is required for all modes. This will retain maximum flexibility for pulse substructure changes.

This, however, will require the installation of HOM couplers very close to the end cells of the cavity, thus adding to the expense, and the engineering complexity required in designing and constructing them. In addition, multipacting studies become more urgent in order to avoid the problems experienced by SNS.

Despite this, the default recommendation will be to maintain $Q_{ext} < 10^5$ for all HOMs.

6 Questions

1. Are there any significant differences between the SPL & ESS lattices (longitudinal and transverse) that mean it is inappropriate to apply his conclusions to ESS?

    - It appears to be non-trivial to directly translate SPL results to ESS, since it is not clear how differences in the focusing schemes will alter the conclusions from his note.
    - Therefore studies should be conducted on the ESS lattice.

2. The planned bunch substructure is an important input to these studies. If the machine will never be run with substructure faster than ∼5 MHz, then it may be possible to live with $Q_{ext} = 10^8$ HOMs (as long as they are more than ∼5 Mhz from a machine line). However a premature decision that this is the case may end up harming the flexibility of the machine. Should we design for maximum efficiency (i.e. $Q_{ext} < 10^5$ for all modes)?

3. When will we have access to cavity designs so as to investigate the HOM spectra, and determine how many modes lie within 100 MHz of machine lines?

4. We should look at the kicks induced by angular misalignments in the accelerating cavities. This isn't specifically a HOM problem, but needs to be looked at nonetheless.