STUDIES OF PARASITIC CAVITY MODES FOR PROPOSED ESS LINAC LATTICES

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Abstract

The European Spallation Source (ESS) planned for construction in Lund, Sweden, will be the worlds most intense source of pulsed neutrons. The neutrons will be generated by the collision of a 2.5 GeV proton beam with a heavy-metal target. The superconducting section of the proton linac is split into three different types of cavities, and a question for the lattice designers is at which points in the beamline these splits should occur. This note studies various proposed designs for the ESS lattice from the point of view of the effect on the beam dynamics of the parasitic cavity modes lying close in frequency to the fundamental accelerating mode. Each linac design is characterised by the initial kinetic energy of the beam, as well as by the velocity of the beam at each of the points at which the cavity style changes. The scale of the phase-space disruption of the proton pulse is discussed, and some general conclusions for lattice designers are stated.

INTRODUCTION

The European Spallation Source is a facilty, currently in its design phase [1], for the generation of intense pulses of neutrons for studies in applied science. The neutrons are generated through the spallation process when a 5 MW (average) proton pulse is made to impact a heavy metal target.

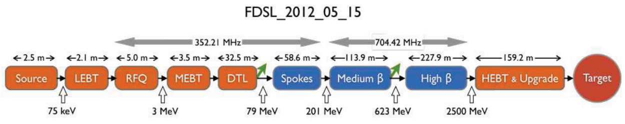

Figure 1: Block diagram of the ESS linac.

	Value	Unit
Final kinetic energy	2.5	GeV
Macropulse current	50	mA
Macropulse repetition rate	14	Hz
Bunch frequency	352.21	MHz

Table 1: Main ESS linac parameters.

A cartoon of the ESS linac is shown in Figure 1, and the main parameters of the proton beam are given in Table 1.

This note concerns the beam dynamics within the superconducting sections of the machine:

Spokes: Two–spoke cavities operating at 352.21 MHz. This section accelerates the beam from the exit of the DTL at 79 MeV to 201 MeV.

Medium β: Five–cell elliptical cavities operating at 704.42 MHz. The geometrical beta of this section is still under discussion, but is likely to be set at a value close to, $\beta_g = 0.65$. In this section, the beam is accelerated from 201 MeV to 623 MeV.

High β: Five–cell elliptical cavities operating at 704.42 MHz. As with the previous section, the geometrical beta is still under discussion, but the likely value is close to, $\beta_g = 0.92$. This section accelerates the beam to its final energy of 2.5 GeV

Given the high intensity of the beam, one major concern is that strong resonances will be excited in the superconducting cavities that will then act to disrupt subsequent bunches. In particular parasitic modes that lie close in frequency to that of the accelerating mode. They are of concern due to there small frequency spread and high R/Q relative to the accelerating mode. If they are found to be a problem, the geometric beta of the cavity may need to be altered or the velocity partitioning between the cavity families may need to be shifted.

LINACS

For the studies into Same Order Modes (SOMs), that is, modes that are part of the same passband as the fundamental accelerating mode, four linacs are investigated as shown in Table 2 where cavities per family denotes the number of cavities in the spoke, medium β and high β sections.

Linacs	Cavities per family	Energy In [MeV]
HS_2011_11_23	36-64-12	50
FD_SL_2012_04_13	32-60-120	79
FD_SSCL_2012_04_16	32-52-128	80
FD_SL_2012_05_15	28- 60-120	79

Table 2: Linacs investigated for SOM simulations.

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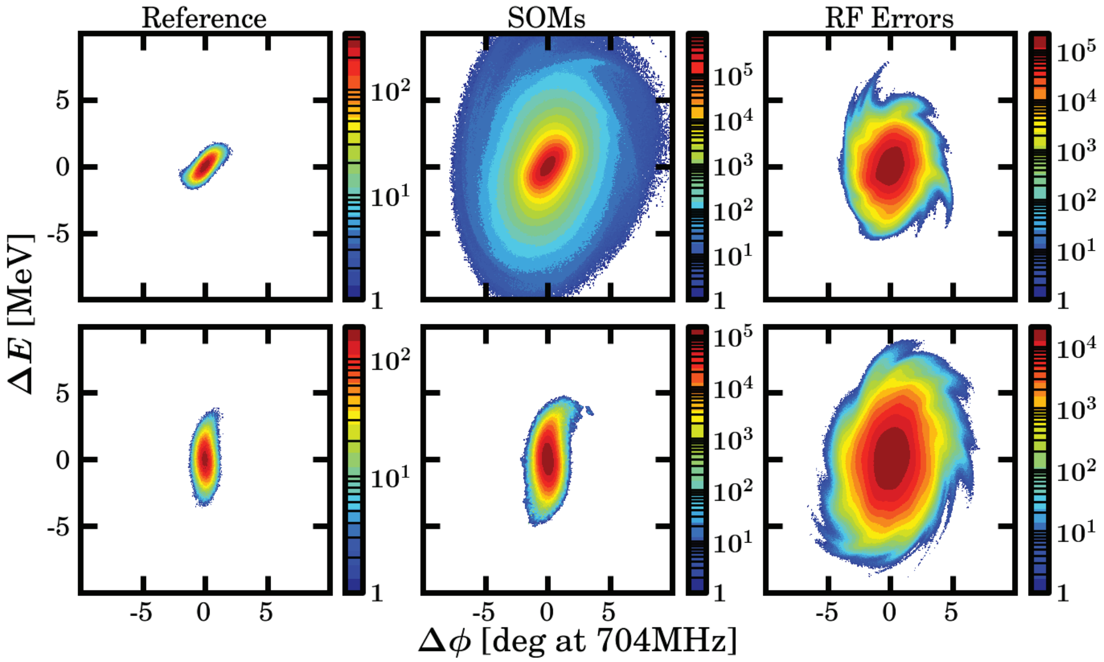

Figure 3: The Pulse phase space distribution at the end of the linac due to different effects.

SIMULATIONS

To explore the effect of these modes, a pulse train of one million point-like bunches was tracked through the superconducting section of the linac. Each bunch adds to the induced fields, these act on subsequent bunches through a kick-drift-kick model [2], and the resulting bunch energy and time errors are calculated.

For each cavity family, the SOM with the highest R/Q is used for simulations. For the spokes, the second mode is used and for the ellipticals, the $4\pi/5$ mode is used. The R/Q that will be seen in each cavity for the whole HS_2011-11-23 linac is shown in Figure 2. Of particular concern are the regions at the beginning of the spoke and medium beta sections where the R/Q of the SOMs are larger than that of the accelerating mode.

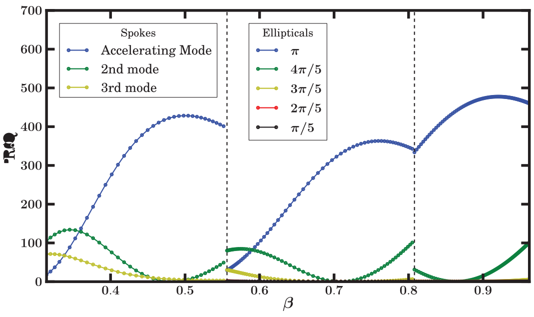

Figure 2: The R/Q for each cavity as a function of particles velocity.

The simulation is performed 1000 times using a different seed for the random number generator to set the frequencies of the SOMs. All other parameters are left constant. In addition, a charge scatter of 1% was also used [3].

Jitter from the RF system will also lead to energy and phase errors. Uniformly distributed errors of $1\%, 1^\circ$ are used in each linac with the exception of the HS_2011_11_23 linac which uses errors of $0.5\%, 0.5^\circ$. Each linac is simulated 1000 times with a different set of uniformly distributed random errors each time. The growth due to RF errors will be used as the acceptable limit in order to gauge the effect of the SOMs.

FREQUENCY SPREAD

The frequency spread of the SOMs will have a large effect on their influence. A smaller frequency spread will result in a larger coherence resulting in a larger influence on the beam. Therefore, it is important to use an reasonable value. In the late 1980's, Ron Sundelin performed a series of studies measuring the distribution of resonant frequencies of SCRF cavities [4]. The frequency spread based on empirical results is given by

$$\sigma = 1.09 \times 10^{-3} \cdot |f_n - f_0|. \qquad (1)$$

This means that for the elliptical cavities where the $4\pi/5$ mode is only ~ 1 MHz away from the accelerating mode, the frequency spread will be ~ 1 kHz.

GROWTH

To quantify the growth, the area, ϵ, of the phase space created all the bunches are compared where the area is given by

$$\epsilon = \pi\sqrt{\langle\Delta E^2\rangle\langle\Delta\phi^2\rangle - \langle\Delta E\Delta\phi\rangle^2}, \qquad (2)$$

where ΔE and $\Delta\phi$ are the energy and phase error of the bunch with respect to the synchronous bunch. The growth ϵ_{RF}/ϵ is used to determine the effects of the RF and set the tolerable growth due to SOMs.

RESULTS

Figure 3 shows the effect of these modes on the pulse phase space of two linacs with different velocity partitioning over the three cavity families. The first column shows the phase space distribution with no external effects such as SOMs or RF errors acting providing a reference distribution to compare to. The middle column shows the case where a SOM is present in each cavity. The last column shows the case when RF errors are applied to the linac in form of amplitude and phase errors. The growth due RF errors is used as an acceptable limit It can be seen that the linac of the top row, which represents an earlier ESS layout, is susceptible to these modes. The bottom row, corresponding to the May 2012 linac layout, shows significantly better performance.

Table 3 shows the growth in due to SOMs and RF errors for each of the linacs simulated. It can be seen that all linacs due except the HS_2011_11_23 linac show negligible growth due to SOMs. It is thought that increasing the Energy input to the spoke section from 50 MeV to 79 MeV was the main reason the effect of SOMs was less in the other linacs. This is because at 79 MeV, the R/Q of the SOMs no longer crossed the accelerating mode in the spoke section.

SOMs	Average Growth	Max Growth
HS_2011_11_23	3.1	56.6
FD_SL_2012_04_13	1.02	1.2
FD_SSCL_2012_04_16	1.01	1.5
FD_SL_2012_05_15	1.02	1.47
RF Errors	Average Growth	Growth
HS_2011_11_23	3.3	13
FD_SL_2012_04_13	4.24	16.2
FD_SSCL_2012_04_16	3.9	14.5
FD_SL_2012_05_15	3.7	16.6

Table 3: Growth in each linac due to SOMs and RF errors.

CURRENT AND DAMPING SCAN

The final investigation was to vary the current, Ib and Q_{ex} for the simulations involving the May Baseline linac FD_SL_2012_05_15. The current was varied from the nominal current of 50 mA to a relatively high current of 150 mA in order to determine a threshold if there is one and how close the nominal current is to the threshold. The Q_{ex} is also varied from 10^4 to 10^9, previous simulations used a relatively high value of 10^8 as the actual value will not be known however it is expected to be similar to that of the fundamental mode which has a $Q_{ex} \sim 10^6$. The results are shown in Figure 4 where the dashed line represents the growth due to RF errors. At the nominal current, negligible growth is observed and it is not until 90 mA where the growth starts to exceed that of RF errors. Losses are also seen at this current for $Q_{ex} > 10^7$.

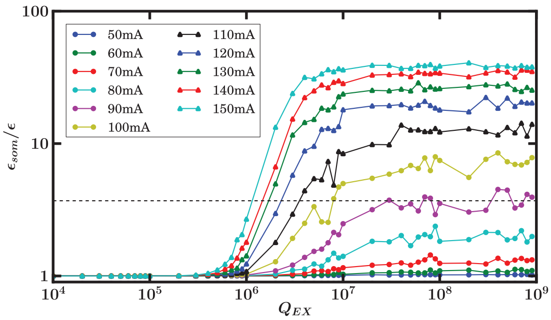

Figure 4: The average longitudinal phase space increase for 100 linacs at varying currents and Qex of the SOMs.

SUMMARY

The influence of parasitic modes in the ESS linac have been investigated with emphasis on modes that lie in the same passband as the fundamental mode. It has been shown that although it is possible to design a linac susceptible to modes in the fundamental passband, the current baseline is not affected at the nominal current and should operate up to currents on 100 mA if upgrades are desired in the future. Therefore, no change is needed to the velocity partitioning of the linac nor the geometric beta of the cavities.

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