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IMPLICATIONS OF MANUFACTURING ERRORS ON HIGHER ORDER MODES AND ON BEAM DYNAMICS IN THE ESS LINAC

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Abstract

The European Spallation Source (ESS) in Lund, Sweden, will be a facility for fundamental physics studies of atomic structure using a spallation source of unparalleled brightness. To achieve this end, protons will be accelerated up to 2 GeV using a suite of cavities. Here we focus on the medium beta (β=0.67) elliptical superconducting cavities and we assess the influence of potential errors in fabrication to shift eigenmode frequencies onto an harmonic of the bunch frequency. If this occurs, and countermeasures are not adopted, the beam quality will be appreciably diluted. We provide details on the geometrical parameters which are particularly sensitive to frequency errors from intensive finite element simulations of the electromagnetic fields. A circuit model is also employed to rapidly assess the shift in the eigenmodes from their anticipated design values due a variety of potential errors.

INTRODUCTION

The ESS is a material science research facility currently under construction in Lund, Sweden. It will provide an unparalleled neutron flux for neutron based experiments by colliding a 5 MW (average) proton beam with a solid Tungsten target [1]. To achieve this a superconducting (SC) linear accelerator (linac) will accelerate a 2.86 ms, 62.5 mA beam up to a final energy of 2 GeV. The beam will have a bunch frequency of 352.21 MHz and have a repetition rate of 14 Hz. The SC linac will consist of 146 SC cavities of which 26 are two-spoke resonators (β = 0.50), 36 medium-beta (β = 0.67) and 84 high-beta (β = 0.86) [2].

The introduction of a charged particle beam into an accelerating cavity results in the excitation of a wakefield. This has both longitudinal and transverse components which can be decomposed into a series of modes. Beam excited higher order modes (HOMs) can cause significant dilution in the beam quality as well as increased levels of beam loss by moving bunches outside the stable RF bucket. The affects of HOMs can be reduced by coupling out the radiation and damping them with appropriate absorbing materials. In the ESS, as the bunch charge (174 pC) is relatively small, the transverse HOMs are small enough [3] such that damping them by these means is considered unnecessary. Also the longitudinal HOMs have relatively small loss factors [4] and their impact on beam dynamics is in general quite benign. However, if the frequency of a longitudinal HOMs is close to an harmonic of the bunch frequency, it can have a detrimental impact on the beam quality and can give rise to enhanced cryogenic load.

In summary, due to the low bunch charge and frequency of the cavities the magnitude of the field excited will be small [5]. However if a monopole mode is resonantly excited due to lying on a harmonic of the bunch frequency (machine line) the induced voltage can build up significantly and have severe impact on the beam and also on the cryogenic system of the accelerator. Here we investigate this issue.

This situation can be avoided through carefully tuning the geometry of the cavity such that no mode below the cut-off frequency of the beam pipe (1.688 GHz) is within a specified frequency of a machine line, both in the design and production stages. In this case, 5 MHz is chosen as the tolerance.

This paper is arranged such that the first section considers the impact of geometrical errors in single cells. The following section assesses the change in the mode frequencies of complete cavities due to these geometric errors –both random and systematic are analysed. The last section entails a set of final remarks.

CELL FREQUENCY SENSITIVITY

The cavities in the medium-beta section of the ESS linac consist of six-cell elliptical cavities operating at a frequency of 704.42 MHz with an accelerating gradient of 15 MV/m and with a prescribed quality factor, $Q < 5 \times 10^5$. The medium beta cavities are particularly important as the transition in the accelerating frequency and also a large increase in gradient compared to the spoke cavities. These two issues will make the beam particularly sensitive to dilution effects from beam excited HOMs in these cavities.

The ESS elliptical cavities will be fabricated from high purity Niobium shaped using the deep drawing process. It is anticipated that the deviation of the internal shape will be at the 0.3 mm level. These deviations from the design will result in each cavity having HOMs at different frequencies and this shift may be large enough to move a mode to a machine line.

In the present series of simulations we use a quiet generic geometry for the medium beta cavity, driven by considerations of size, iris diameter, cell coupling, surface fields and field flatness; close, but by no means identical to the structure designed by CEA Saclay. A typical trapped HOM in this cavity is illustrated in Fig. 1.

To study, in detail, the effects of changes in geometry on the resonant frequencies of the individual cells we have simulated a cell with the code HFSS [6] in which we vary the

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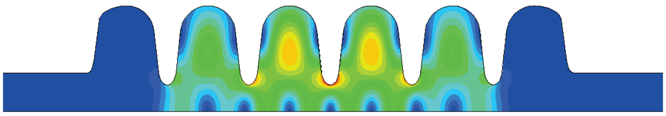
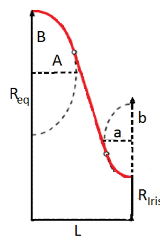


Figure 1: Monopole electric field profile at 1.750 GHz for an ESS-like medium beta cavity.

7 parameters which characterise the geometry individually. This was done in 0.1 mm steps and ranging from ±2 mm of the design values. The frequency shifts were found to vary linearly with the of the size of the geometry change and the results are summarised in Table 1.

Table 1: Frequency sensitivity of various cavity parameters for the first three monopole bands (B_1, B_2, B_3) resonant frequencies in the mid-cell (MHz/mm)

Param.	B_1	B_2	B_3
A	-3.31	0.40	-18.7
B	0.90	0.75	2.67
L	2.38	-2.04	-7.77
a	-2.46	1.15	6.66
b	0.39	0.04	-0.26
R_{eq}	-4.34	-8.81	-3.20
R_{Iris}	1.32	2.68	1.17



We highlight the large sensitivity of the third band to changes in the elliptical eccentricity, A. In several parameters (L, a, b) the behaviour is opposite to that of the first band. The data in table 1 indicates that it is straightforward to tune up the accelerating mode to its required value. However, in this tuning process the HOMs can readily become detuned, and potentially shifted to lay upon a machine line.

Upon manufacturing the cavities for ESS we anticipate random errors from manufacturing tolerances to modify the cell frequencies and also the mode frequencies. To investigate the effects of random errors we use the SUPERFISH [7] code to simulate the cell frequencies rapidly. We apply errors according to a uniform (or Top Hat) distribution extending from of $-\sigma_e$ to $+\sigma_e$ individually to each parameter in our geometry characterisation. The values for the random errors are calculated using the Mersenne-Twister generator [8]. The resulting data was found to be Gaussian in shape and centered on zero, with a standard deviation, σ which varied linearly with the width of the random errors applied.

The frequency sensitivity due to the randomly generated errors is illustrated in Fig. 2. The sensitivity of the cell frequencies to geometry changes increases as we move up in mode frequency as expected. Utilising these frequency spreads we will estimate the likely spread in HOM frequency for the three modes of most concern, namely the accelerating mode and the $\pi/6$ modes of the second and third bands which lie closest to machine lines.

MODE FREQUENCY SENSITIVITY

Simulating the full structure to assess the potential effects of errors is computationally extremely expensive due to the large numbers of degrees of freedom in the geometry of the full structure. In the parametrisation we have used we have 73 degrees of freedom assuming all of the half cells match up correctly. However, we use an alternative approach in which we model our cavity as a series of coupled LC circuits as illustrated in Fig. 3. C_k are the capacitors through which

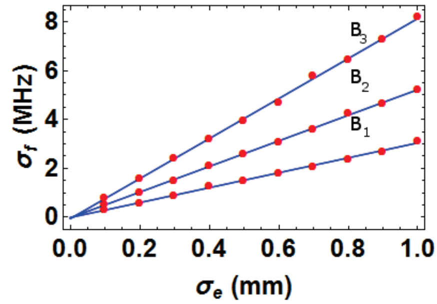


Figure 2: The standard deviation, σ_f of the Gaussian frequency distribution from 500 simulations due to uniform random geometrical errors of width σ_e for the first three monopole bands.

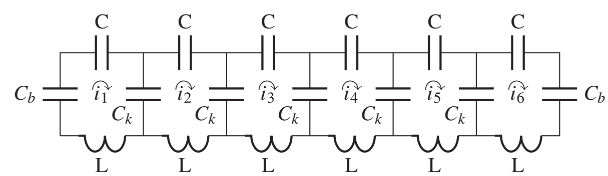


Figure 3: Equivalent circuit for monopole modes.

the cells are coupled and L and C are the inductance and capacitance of each cell respectively. At this point we define the cell resonant frequency to be, $\omega_r = \frac{1}{\sqrt{LC}}$. To add errors to the cell frequency we let $C \rightarrow \frac{C}{1+e_j}$, where e_j is an error in the capacitance of a cell. Applying Kirchoffs voltage rules we obtain:

$$(1 + k + \gamma + e_1)I_1 - kI_2 = \Omega_r I_1 \quad (1)$$
$$(1 + 2k + e_n)I_n - k(I_{n+1} + I_{n-1}) = \Omega_r I_n \quad (2)$$
$$(1 + k + \gamma + e_N)I_N - kI_{N-1} = \Omega_r I_N \quad (3)$$

where $k = \frac{C_k}{C}$ to be the cell-to-cell coupling and $\Omega_r = \frac{\omega^2}{\omega_r^2}$. Further e_1 and e_N also contain an additional term $\gamma = \frac{C_b}{C}$ due to coupling to the beam pipe which is effectively a shift in the end cell frequency.

For the accelerating mode $\gamma = 2k$ which causes the field to be flat [9]. This set of equations can readily be cast into a matrix equation and the values which correspond to the modes frequencies found. To apply this model the resonate frequency and coupling constants for each mode were found by fitting the infinite periodic solution found by applying Floquet's theorem to Eq. 2 to single cell data at fixed phase advances found using HFSS.

This method of determining the shift in the mode frequencies was tested by simulating a three cell pillbox cavity in SUPERFISH and varying the radii of the cells to change the cell frequency. For the higher bands tested the agreement

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was within 0.5 MHz. In this validation and when looking at the medium beta cavity we have made the assumption that the coupling between cells does not vary with the changing geometry and the frequency change is dominated by the cell frequency errors.

We now use the data in Fig. 2 to generate a set of random cell frequencies according to normal distribution. These cell frequencies are fed into the circuit model and the resulting eigenvalues are calculated. This process is repeated 5000 times for each value of geometrical error. The resulting frequencies were found to be normally distributed with a means shifted significantly away from the original values. The resulting data for the three full cavity modes of particular concern can be seen in Fig. 4.

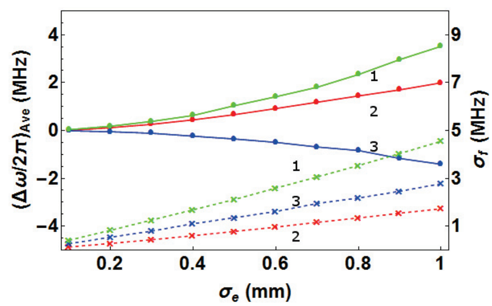

Figure 4: Mean(solid line) and standard deviation, σ_f (dashed line) of the frequencies of three modes. The accelerating(2/red) at 704 MHz, the first mode from the second band(3/blue) at 1.516 GHz and the first mode of the third band(1/green) at 1.750 GHz.

The increase in the spread of the data in Fig. 4 is clear to see for each of the modes, we also note the significant shifts in the mean value as the magnitude of the errors applied increases. This shift is was observed to be more significant the further the mode is from the $\pi/2$ mode as the mode density increases correspondingly. This indicates that if the random errors introduced from manufacturing tolerances are less than ±0.5 mm the risk of a mode being shifted to a machine line is very low. If this is the case the three modes of concern will lie over 4σ away from the nearest machine line.

Random shifts are not the only concern, it is possible for cells to have a systematic difference in geometry from the design. This is emphasised by the data in table 1, which clearly illustrates that a deviation 1 mm in a parameter could cause shifts on the order of 10 MHz. A systematic error of this size could cause the highest frequency mode in the third band to shift onto a machine line when additional random errors are included. To confirm this with the circuit model first the single cells were simulated with both a systematic error to the eccentricity A and random errors on all parameters in the same way as before. The resulting frequency distributions were passed into the circuit model and the shifts in the zero mode of the third band were calculated. In Fig. 5 we can see that with a systematic error of 0.2 mm once we approach a

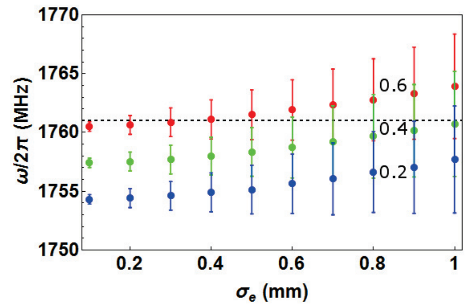

Figure 5: Mean mode frequency as a function of random geometrical errors. In addition we apply three systematic errors indicated: 0.2 mm (blue), 0.4 mm (green) and 0.6 mm (red). The dashed horizontal line denotes the fifth harmonic of the bunch frequency (1.761 GHz).

random error of 0.4 mm we have a significant potential to be on an harmonic of the bunch frequency. This highlights that care must be taken to avoid systematic errors of 0.2 mm or in the case of the ellipse eccentricity A.

FINAL REMARKS

An analysis of the expected spread in mode frequencies in medium beta cavities due to typical manufacturing errors have been presented. In particular we considered modes that are below or near the beam pipe cut-off that if shifted have the potential to have a significant impact on machine performance. In most cases we found the shifts due to random errors to be unable to shift modes to to be coincident with a machine line. Based on the model presented there is a potential for some of the monopole modes to be close to an harmonic of the bunch frequency. This initial study will be continued in the future utilizing additional finite element codes to accurately predict the frequency and field profiles of the HOMs.

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