IMPLICATIONS OF RESONANTLY DRIVEN HIGHER ORDER MODES ON THE ESS BEAM

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Abstract

The European Spallation Source (ESS) is under construction in Lund, Sweden, and once complete, will be a facility for fundamental physics studies of atomic structure using a spallation source of unparalleled brightness. To achieve this end, a 2.86 ms long pulsed proton beam will be accelerated up to a final energy of 2 GeV using three suites of superconducting cavities. If a Higher Order Mode (HOM) lies on a harmonic of the bunch frequency the HOM will be resonantly driven. This will dilute the beam quality significantly. Errors in fabricating these cavities are inevitable, and this sets a tolerance on how close the HOM can be within a harmonic of the bunch frequency. The baseline design for ESS requires HOMs to be at least 5 MHz from a machine line. Here we provide details of several finite element electromagnetic simulations on the HOMS anticipated in these ESS cavities. We analyse their impact on the beam emittance using a drift-kick-drift model with the potential for relaxed tolerances.

INTRODUCTION

The European Spallation Source (ESS) currently under construction in Lund, Sweden, will—upon completion—be the most intense source of cold neutrons for materials science research in the world [1]. The ESS is a proton driven spallation source which will utilise a 5 MW superconducting proton linac as its driver. The linac will take a 2.86 ms, 62.5 mA proton beam up to an energy of 2 GeV at which it will be collided with a solid rotating tungsten target.

The acceleration at low energy is achieved using normal conducting technology; including an RFQ and a DTL. Most of the energy however is gained in the superconducting section of the linac which consists of: 26 two-spoke cavities with an optimal beta of 0.5, 36 six-cell elliptical medium-beta cavities with a beta of 0.67 and 84 five-cell elliptical high-beta cavities with a β of 0.86. The spoke cavities operate at the bunch frequency of 352.21 MHz and the elliptical cavities at the second harmonic of 704.42 MHz [2].

The ESS has opted to forgo the usual practice of using Higher Order Mode (HOM) couplers to damp beam- excited fields and this introduces an element of risk into the design. It has been shown that in normal operation HOMs are not detrimental to the machine performance [3]. However a HOM in the vicinity of a harmonic of the bunch frequency may significantly degrade the beam quality.

Fabrication errors are of course inevitable in the production of a large number of cavities and these errors can shift the HOM frequency significantly from their design values. The baseline design for ESS specifies that all longitudinal HOMs located below the beam pipe cut-off frequency be at least 5 MHz from the nearest harmonic of the bunch frequency. This is a requirement on the final cavities after tuning of the accelerating mode has been performed [4].

Here we focus on the elliptical cavities and study the impact of HOMs closest to harmonics of the bunch frequency. Further, the effect of reducing the baseline tolerance is analysed.

THE ESS ELLIPTICAL CAVITIES

The two families of elliptical cavities designed for use at ESS both operate 704.42 MHz, with a quality factor of $Q_0 > 5 \times 10^9$, and at accelerating gradients of 16.7 and 19.9 MV/m [5].

Medium Beta Cavity

The ESS medium beta elliptical cavities each consist of six cells operating at a frequency of 704.42 MHz. We analysed the modal spectrum of these cavities using the ANSYS finite element code HFSS [6] to identify modes which lie near harmonics of the bunch frequency. It was found that the $\pi/6$ mode in the third band, although above the beam pipe cut-off, is trapped within the cavity and lies near the 5th harmonic of the bunch frequency. This mode has a frequency of 1749.57 MHz and an R/Q that ranges from 0.001 to 16.2 Ω as a function of bunch velocity.

The mode is primarily contained within the centre of the cavity and it is anticipated that the associated external quality factor Q_{ex} will be relatively high. This was verified by simulations which revealed $Q_{ex} > 10^6$ even when the fundamental power coupler (FPC) was terminated by a matched load. The field profile for this mode is shown in Fig. 1.

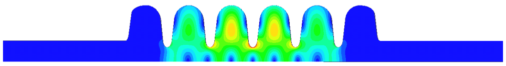

Figure 1: Electric field profile for the 1749.57 MHz HOM in the medium beta cavity. Red indicates a maximum value of the field.

A prototype of this cavity has been produced [7]. Tests at CEA Saclay, Paris, France, indicate that the HOM is much further away from the 5th harmonic of the bunch frequency than in simulations [8]. This is a result of the additional checks performed throughout the production process which

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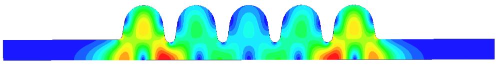
has allowed an optimal HOM frequency to be achieved by selecting the best dumbbells for the central cells [7].

High Beta Cavity

The high beta section consists of five-cell elliptical cavities operating at 704.42 MHz. A similar analysis to that of the medium beta cavity was performed and two HOMs, at 1419.23 and 1419.82 MHz, were found to be in vicinity of the 4th harmonic of the bunch frequency. The R/Q values of these modes are in the ranges of 0.002 to 7.66 Ω and 0.001 to 10.19 Ω.

Simulations made with HFSS indicated a large concentration of electromagnetic fields within the end-cells and hence damping from the FPC may be present. The field profiles for each of the modes are plotted in Fig. 2



(a) 1419.23 MHz HOM

(b) 1419.82 MHz HOM

Figure 2: High beta cavity electric field HOM profiles. Red indicates a maximum value of the field.

Two prototypes of the high beta cavity have been produced and tested [5]. It was found that the cavities meet the ESS specifications for both Q_0 and accelerating gradient. However the experimental measurements indicated that the HOMs in these two cavities had shifted by up to 16 MHz toward the 4th harmonic of the bunch frequency. This was attributed to deviations of up to 1.2 mm from the design geometry in the vicinity of the equator in the end-cells.

In order to investigate the impact of the HOMs on the beam quality we used a code written in the Python programming language by R. Ainsworth [4], and this is described in the next section.

BEAM DYNAMICS CODE

The code utilises a drift-kick-drift scheme where each bunch is treated as a point charge as the bunch length is small compared to the wavelengths considered. In the case of longitudinal HOMs, the interactions with the cavity occurs at the cavity mid-plane. At this point the bunch receives a kick from the accelerating mode and the change in energy relative to the synchronous particle is given by;

$$\Delta U_{RF} = qV_0 \Re(\exp(j(\omega_{RF}\Delta t + \phi_s)) - \exp(j\phi_s)) \quad (1)$$

where V_0 is the peak cavity voltage, ϕ_s is the phase of the synchronous bunch, ω_{RF} is the accelerating mode frequency and Δt is the time arrival difference between the bunch and the synchronous bunch.

The interaction of the beam with the HOM is also calculated at this point using the equation

$$\Delta U_n = q\Re(V_n \exp(j\omega_n \Delta t)) - \frac{1}{2}\Delta V_{q,n} \quad (2)$$

where V_n is the complex HOM voltage in the cavity, $\omega_n/2\pi$ is the frequency of the n^{th} HOM and $\Delta V_{q,n}$ is the change in the HOM voltage caused by a particle of charge q and arises from the fundamental theorem of beam loading,

$$\Delta V_{q,n} = -q\frac{\left|\int E_z(z)e^{i\omega_n z/\beta c}\, dz\right|^2}{2U_n} = -q\frac{\omega_n}{2}(R/Q)_n(\beta). \quad (3)$$

where U_n is the energy stored in mode n. These energy difference due to the RF system and HOMs are are added to the particles energy error prior to the interaction. The time of flight error at the next cavity is also calculated and added to the bunches current time of flight error.

In each simulation the relative growth in the beam emittance is calculated using [9]

$$\epsilon = \pi\sqrt{\langle \Delta E^2\rangle \langle \Delta\phi^2\rangle - \langle \Delta E \Delta\phi\rangle^2} \quad (4)$$

where $\Delta\phi$ is the difference in phase at 704.42 MHz and ΔE the difference in energy from the synchronous bunch. The ratio of the emittance with and without the HOMs present was calculated. For each simulation the bunch distribution is generated using the Mersen-Twister generator following a Gaussian distribution of phase width 1.26 degs at 704.42 MHz and energy width of 78 keV. As a base-line for acceptable emittance dilution the average growth due to 10,000 simulations with only RF errors present has been calculated to be 1.17 and will be used as a baseline the subsequent analysis.

HOM-BASED TOLERANCES

Here we investigate the emittance dilution due to longitudinal HOMs. The worst case corresponds to a HOM laying exactly on a harmonic of the bunch frequency. If the appropriate level of damping is present then the impact of the HOM will of course be mitigated. To set a limit on Q_{ex} which achieves this, the HOM closest to the machine harmonic in each of the 120 elliptical cavities was shifted, one-by-one, to lie exactly on the nearest harmonic and the Q_{ex} was varied. The results are displayed in Fig. 3.

These results indicate that if the $Q_{ex} < 9 \times 10^4$ in the medium beta cavity and below 3×10^5 in the high beta cavities, even in this worst case, produces an emittance dilution less than that due to RF errors alone. Detailed simulations of the cavity, with couplers and the waveguide system are needed to determine the final Q_{ex} of the HOMs.

The other factor which can significantly affect the impact of HOMs is their R/Q values. This varies significantly on a cavity-by-cavity basis along the ESS linac, due to the changing beam velocity and depends strongly on the cavity design. To assess the impact of R/Q, the frequency of one HOM is shifted onto the nearest harmonic of the bunch frequency

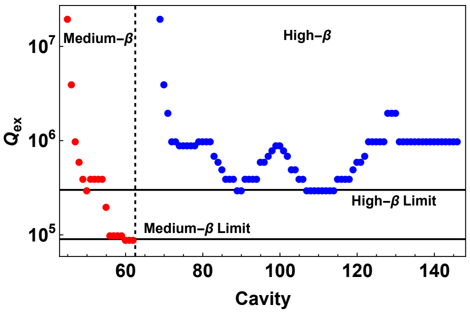


Figure 3: Q_{ex} required to mitigate the impact of a resonantly driven HOMs in each of the elliptical cavities to a level below that due to RF errors.

in a single cavity. The average relative growth is calculated from 1,000 simulations at various Q_{ex} and R/Q's. This was done for each cavity—including the spoke cavities—and the value at which the growth is equal to that due to RF errors was taken to be the maximum allowable. The resulting data is plotted in Fig 4.

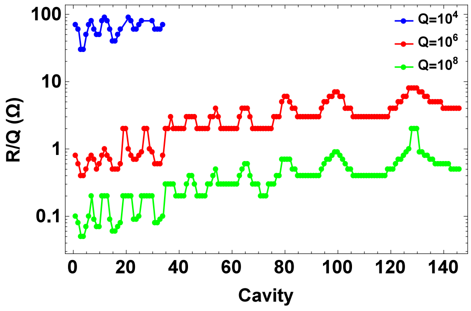


Figure 4: R/Q budget in each cavity at several values of Q_{ex} with a growth limit of 17% set according to that prescribed on the baseline ESS design for RF errors.

The results in Fig. 4 show that at a fixed Q_{ex}s there are regions where the impact on the beam is minimised. Furthermore, the impact of a particular R/Q and Q_{ex} reduces along the linac. Larger R/Q is more tolerable as the rigidity of the beam is increasing concomitantly. In addition, a fluctuation within the same cavity families can be seen which is caused by the width of the phase distribution at specific cavities.

To assess the ESS HOM criteria, simulations of each cavity for each HOM of concern have been performed in which the frequency of the HOM is set to lie on the machine harmonic and is then shifted away at several values of Q_{ex}. An example of the data from the $\pi/6$ mode in the last medium beta cavity—which exhibits the worst degradation characteristics—is shown in Fig. 5. The data shown is for the cavity which has the largest R/Q and a β of 0.78. The width of the resonance varies as a strong function of Q_{ex} as expected for a damped driven system.

The emittance dilution is unappreciable provided the HOM frequency is more than 5 kHz away from a bunch harmonic, and this is irrespective of the anticipated Q_{ex}'s.

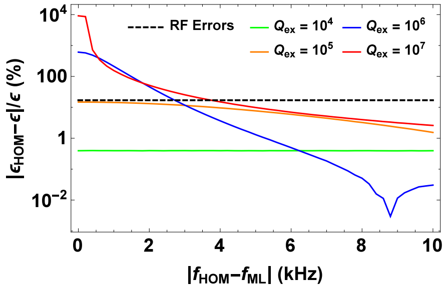


Figure 5: Emittance dilution due to the $\pi/6$ mode in the last medium beta cavity as a function of HOM frequency.

As this is three orders of magnitude smaller than the baseline ESS design of 5 MHz it indicates the potential for a looser tolerance. However, tuning up the cavity during routine operation is liable to shift these modes considerably also. Hence the baseline design is particularly conservative.

CONCLUDING REMARKS

The impact of resonantly driven longitudinal HOMs on the emittance of the ESS beam has been investigated using a suite of simulations. Varying the R/Q, Q, and separation of the HOM frequency from the nearest harmonic of the bunch frequency have been the focus of this study. These simulations indicate that, provided the HOMs are more than 5 kHz away from a machine line little impact on the beam dynamics is anticipated. As the ESS baseline is set to 5 MHz, then this provides a robust design for the overall machine operation. However, tuning the fundamental mode of the cavities also shifts the location of their associated HOMs.

Further simulations are in progress studying the implications of cavity tuning on the behaviour of these eigenmodes.

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