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Beam dynamics in the ESS linac under the influence of monopole and dipole HOMs

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Abstract

The European Spallation Source (ESS), planned to be operational in 2019, is anticipated to be the worlds most intense neutron source. The total beam power will be 5 MW. We focus on the impact of manufacturing errors on the beam quality. In particular we assess the emittance dilution which occurs due to Higher Order Modes (HOMs) excited at a harmonic of the bunch frequency. We also discuss some alignment issues pertaining to the cavities.

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Keywords: Higher Order Modes (HOMs); Superconducting Cavity; European Spallation Source (ESS);

1. Introduction

The European Spallation Source (ESS) will be a facility for material science study, utilising neutron scattering techniques in Lund, Sweden[1]. The accelerator is utilised to produce a high intensity beam of neutrons. These will be produced via spallation caused by colliding a high power (5MW) proton beam with a solid tungsten target. The linac forms the heart of the machine and some of the main features of are illustrated in Fig. 1. In this paper we focus on the Higher Order Mode (HOM) issues issues pertaining to the spoke and elliptical superconducting (SC) cavities. Some of the properties of these cavities are given in table 1.

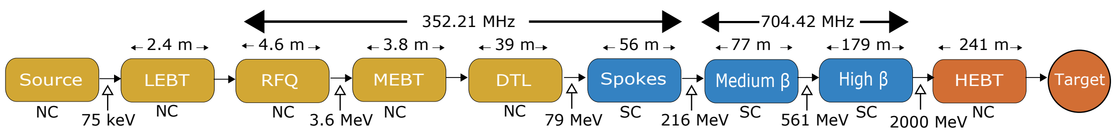

Fig. 1. An illustration of the Optimus+ design of the ESS linac. The normal conducting (NC) sections are in warm colours and the SC sections in cold colours [2].

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Table 1. Parameters for the ESS SC cavities.

Cavity Type	Number of Cavities	Frequency (MHz)	β_g	Energy Range (MeV)
Two-Spoke	26	352.21	0.5	89-216
Six-Cell Elliptical	36	704.42	0.67	216-561
Five-Cell Elliptical	84	704.42	0.86	561-2000

Introducing a charged particle beam to an accelerating cavity results in self-excitation of both a longitudinal and transverse wakefield. These wakefields are composed of, in principle an infinite series of HOMs. In a beam dynamics study only those modes which provide the largest momentum exchange with the charged particle beam will be on interest. In the ESS accelerating scheme a 2.86 ms long bunch train of approximately a million bunches is accelerated up to 2 GeV. Should one or more HOMs lie at a frequency which is an integer multiple of the bunch frequency, they will be resonantly driven and will have a significant impact on the beam quality. In order to minimise this it is important to ensure these modes are far enough from a harmonic of the bunch frequency –and this is achieved by tailoring the geometries of the cavities appropriately. An alternative means to suppress this resonant growth would be to couple out the deterious modes through the use of HOM couplers. However, the ESS design relies on a careful design of the cavities and dispenses with HOM couplers entirely. Manufacturing errors are nonetheless unavoidable in the process of producing 146 cavities. These errors can potentially shift the frequency of the HOMs onto a harmonic of the bunch frequency. To avoid such a problem with the HOMs, manufacturing tolerances are strictly observed –and both a minimum tolerance in random and systematic errors allowable for each type of cavity is specified.

Finally, we note that these HOMs can lead to heating of the walls of the cavities. This parasitic heating of the cavity walls can, in the worst case, lead to a quenching of the SC cavity. At the very least this can lead to an increased cryogenic load on the system, resulting in reduction in the overall efficiency of the facility.

This paper is arranged such that the next section discusses some properties of these HOMs, followed by implications on beam dynamics issues, a section on on simulation results and finally, a section on anticipated alignments for these cavities. The work concludes with some final remarks.

2. Aspects of Self Induced HOMs

In our simulations of the effects of HOMs on the beam dynamics of the ESS linac we consider both longitudinal and transverse effect. In the former we take into account the energy spread induced on the beam and the emittance dilution. In the transverse plane we make a multipole expansion of the beam-induced modes. Provided the beam is sufficiently close to the electrical centre the dipole component will be the dominant one, and we restrict our analysis to these modes.

Firstly, let us consider the issues pertinent to the longitudinal component. A charged particle, q passing through a cavity induces a voltage, ΔV_n in each mode of frequency ω_n[3]:

$$\Delta V_n = -2qk_{loss,n} \tag{1}$$

where $k_{loss,n}$ is the energy lost to mode n, per unit charge, and is given by

$$k_{loss,n} = \frac{\omega_n}{4}\left(\frac{R}{Q}\right)_n = \frac{\left|\int_{-\infty}^{\infty} E_{z,n}(r=0,z)e^{i\omega_n z/\beta c}dz\right|}{4U_n}. \tag{2}$$

Here $E_z(r = 0, s)$ is the axial electric field on axis, U_n is the energy of mode n and, β is the velocity as a fraction of c.

The cavity wall possesses a finite resistance and the voltage decays according to

$$V_n(t) = \Delta V e^{-t/T_{d,n}} e^{i\omega_n t} \tag{3}$$

where $T_{d,n} = 2Q_{L,n}/\omega_n$ is the decay constant and $Q_{L,n}$ is the loaded quality factor of the system:

$$\frac{1}{Q_{L,n}} = \frac{1}{Q_{0,n}} + \frac{1}{Q_{ext,n}}. \tag{4}$$

Here $Q_{0,n}$ is the ohmic quality factor ($\sim 10^{10}$ for the accelerating mode). For the SC cavities in the ESS $Q_{0,n}$ is at least four orders of magnitude larger than $Q_{ext,n}$. Hence, to an excellent approximation $Q_{L,n} \approx Q_{ext,n}$.

We now consider dipole modes. These are linearly proportional to the radial offset of the beam from the electrical centre of the cavity. These are excited by the head of the bunch and will deflect the remaining portion of the bunch –and indeed will deflect subsequent bunches in the train. The transverse momentum kick imposed to a bunch offset radially by x due to these modes is given by the Panofsky-Wenzel[4] theorem as

$$\Delta p_{\perp,n} = i\frac{q}{\omega_n}\frac{dV_{\parallel,n}}{dx}. \tag{5}$$

The transverse voltage is related to the momentum kick as $V_{\perp,n} = \frac{c}{q}\Delta p_{\perp,n}$ and as $V_{\parallel,n}$ is linearly dependent on the beam offset:

$$(R/Q)_{\perp,n}(\beta) = \frac{\left|V_{\perp,n}\right|^2}{\omega_n U_n}, \tag{6}$$

and hence the transverse voltage induced by a beam offset from the electrical centre by x is

$$\Delta V_{\perp} = \frac{1}{2}ixq\frac{\omega_n^2}{c}(R/Q)_{\perp,n}(\beta) = 2ixqK_n. \tag{7}$$

where K_n is the kick factor [5].

2.1. Longitudinal Beam Dynamics

The interaction between the beam and the HOMs within each cavity are tracked by applying a drift-kick-drift model [6], where each cavity is treated as a drift except for at the mid-plane where the bunches interact and receive an accelerating kick described by the equations shown previously. The size of the drifts between the cavity centres is defined by the lattice.

A difference in energy between bunches leads to a difference in the transit time from cavity-to-cavity which subsequently leads to a change in the accelerating voltage seen in the next cavity as it is equivalent to a phase error. This is combined with the additional errors caused by phase and amplitude errors from the various RF systems to give a net effect. The error in energy gained from the RF system is given by

$$dU_{rf} = qV_{RF}^{*}\cos(\phi_s^{*} + \omega_{rf}dt) - \Delta U, \tag{8}$$

where V_{RF}^{*} is the maximum accelerating voltage including amplitude errors, $\phi_s^{*} = \phi_s + \phi_{RFError}$ is the effective phase and ΔU is the energy gain of the synchronous particle without RF errors and is given by,

$$\Delta U = qV_0\cos\phi_s. \tag{9}$$

A charged particle passing through a cavity is also subject to an energy change caused by excited HOMs

$$dU_n = q\left[\Re(V_n)\cos(\omega_n dt) - \Im(V_n)\sin(\omega_n dt)\right] - \frac{1}{2}\Delta V_{q,n} \tag{10}$$

where $\Re(V_n)$ and $\Im(V_n)$ are the real and imaginary part of the HOM voltage present at the time the mid-plane of the cavity is crossed. The factor of a half arises as a consequence of the fundamental theorem of beam loading[3]. Here the induced voltage acts back on the exciting charge. Summing these effects leads to the a total energy error evolution at cavity m of

$$dE^{(m+1)} = dE^{(m)} + dU_{rf}^{(m)} + dU_n^{(m)} \tag{11}$$

These energy errors result in an arrival time error at the next cavity given by

$$\Delta t^{(m+1)} = \Delta t^{(m)} + (dt/dE)^{(m)}dE^{(m)} \tag{12}$$

where the slope depends on the mass of the particle and also on γ, the relativistic factor of the synchronous particle,

$$(dt/dE)^{(m)} = -\frac{L^{(m)}}{cm_0c^2(\gamma^2-1)^{3/2}}. \tag{13}$$

2.2. Transverse Dynamics

In addition to longitudinal effects, bunches also get deflected by the fields of dipole modes inside a cavity, where to good approximation this depends on the magnitude of the radial offset. The change in transverse momentum of a bunch is given by,

$$\Delta p_x = q\frac{\Re(V_\perp)}{c}, \tag{14}$$

where $\Re(V_\perp)$ is the real part of the transverse voltage. This gives rise to a change in the angular particle trajectory, x' which in the small angle approximation is given by;

$$\Delta x' \approx \frac{\Delta p_x}{p_\parallel} = q\frac{\Re(V_\perp)}{cp_\parallel} \approx \frac{W_\perp x}{E}, \tag{15}$$

where $p_\parallel$ is the longitudinal momentum, $W_\perp$ is the transverse wakefield[5] and x is the radial offset of the bunch. The effects from the transverse focusing elements are included in the form of linear transfer maps taken from the lattice design.

3. Beam Dynamics Simulations

In these simulations we track a complete bunch train through all SC sections of the ESS linac by tracking the interaction of each bunch with the HOMs in each cavity. This is achieved by applying a drift-kick-drift model using a numerical code written in Python by Ainsworth and Molloy[7].

We track the full 2.86 ms train of approximately 1,007,320 bunches in this way. Each simulation has random errors on mode frequencies and bunch charge distribution included. In these simulations we consider the longitudinal and transverse planes separately. The input distribution used for these simulations is based on earlier simulations[7] and the result of these studies is a Gaussian profile of 78 keV RMS in energy and 1.26 degrees RMS in phase.

In order to assess the impact of HOMs over and above that of purely RF jitter errors we performed simulations both with and without HOMs. In each case we include RF jitter errors. Both longitudinal HOMs and transverse HOMs have independently been considered. In each case we compute the ratio of the emittance dilution due to HOMs or RF jitter to that of the injected emittance Fabrication errors can result in these HOMs lying on an integer multiple of the bunch frequency (352.21 MHz). Should this occur a resonant growth in the HOM voltage will result in a growth in emittance and this has been confirmed by simulations. These fabrication errors can result in both systematic and random errors in the cell frequencies. An empirical formula derived by Sundalin and discussed by Molloy[8] indicates that the standard deviation in measured frequencies for the n^{th} mode within the accelerating mode's passband is given by:

$$\sigma_n = 1.09 \times 10^{-3} \times |f_n - f_\pi|, \tag{16}$$

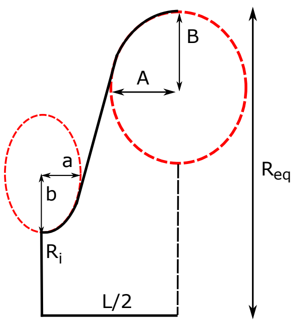
where f_n is the simulated frequency and f_π is the frequency of the accelerating mode. From Sundalin's study we also expect modes in all bands other than the accelerating modes band to have a maximum frequency shift of 0.38% from the simulated value and we assign this as a $5\sigma_n$ deviation. The frequency spread on the HOMs grows linearly with frequency. We apply these formula to both the longitudinal and transverse dynamics simulations. Prior to considering the beam dynamics effects of HOMs, we consider the effects of RF jitter errors. This is detailed in the next section.

3.1. RF Errors

The baseline design for ESS initially specified a 1 degree phase and 1% amplitude error in the RF systems. The modified design is now more stringent as they have been reduced by a factor of 10 in both cases. We performed simulations to track the beam under the influence of these RF errors alone and found the dilution averaged over one thousand simulations to be 16%.

3.2. RF Cavity Eigenmode Simulations and Beam Dynamics Simulations

In order to track the beam down the length of the linac the modal characteristics of the SC cavities are investigated. Both the spoke and six-cell elliptical cavities were simulated by Ainsworth using the OMEGA3P component of the SLAC suite of codes known as ACE3P[9]. In addition, we obtained RF data on five-cell elliptical cavities from an unpublished design by Jain[10]. These latter cavities were designed to have similar, although by no means identical, characteristics (surface electromagnetic field, accelerating frequency and shunt impedance) to those of the baseline ESS five-cell cavities. The HOMs of these cavities were simulated using the HFSS[11] finite element code. The R/Q values found from these simulations are displayed in Fig. 2 as a function of the relativistic factor β. The functional dependence of R/Q on velocity is a direct consequence of the proton beam not being in the ultra-relativistic regime. In the following sections we perform beam dynamics simulations in which we track the beam down the linac under the influence of these computed HOMs.



Parameter	Length (mm)
A	67.2
B	67.2
a	17.5
b	26.7
L	91.5
R_i	57.0
R_{eq}	187.9

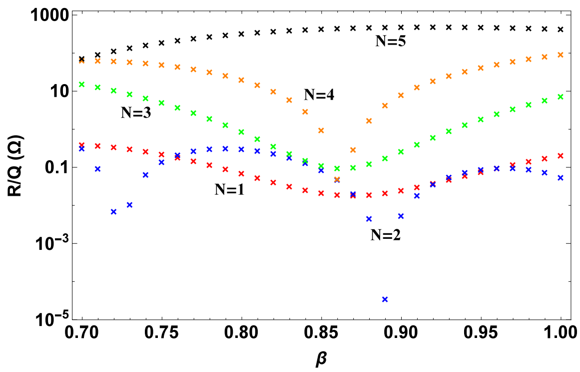


Fig. 2. Left: Cell geometry used for the five-cell elliptical cavities. These parameters are the result of a desing by Jain[10] which are similar, although by no means identical, to the ESS baseline five-cell cavities. Right: R/Q as a function of β for modes in the first passband of this five-cell cavity including end-cells and beam pipes. Each mode is labelled according to the phase advance per cell, $N\pi/5$.

3.2.1. Beam Dynamics Under the Influence of Monopole Modes Within the First Passband

Here we consider the effect of monopole modes which are in the first passband and lie close to an integer multiple of the bunch frequency. In this case we focus on one mode from each of the cavity types. In the spoke cavity we use the nearest mode to the accelerating mode (at 536.3 MHz). In the six-cell ellipticals we use the mode at a phase advance of $5\pi/6$ (at 703.9 MHz) and in the five-cell ellipticals we use the $4\pi/5$ phase advance mode (at 703.3 MHz). We then track the beam down the linac under the influence of these modes at different beam currents and Q's. The results of the average of one thousand simulations of emittance dilution as a function of Q is shown in Fig. 3. Also shown is the emittance growth which arises purely due to RF jitter errors. The transition point, in which errors due to the monopole modes start to dominate occurs at a Q value of 3×10^6. In practice the fundamental mode couplers will be tasked with ensuring these modes are damped to the $Q \sim 10^6$ level.

3.2.2. Influence of Monopole HOMs on Beam Dynamics

HOMs in SC cavities can be long lived (due to high Q values) and can be trapped inside the cavities. If a mode has a R/Q on the order of 10's to 100's Ω they can be a significant problem if the voltage is allowed to build up by being repeatedly excited. In the case of monopole modes this can result in bunches falling outside the RF bucket and being lost. Only modes with particularly large R/Q's were considered in the simulations. However little was seen in terms of emittance dilution due to their relatively low R/Q's (10-40 Ω) and the fact that they are well separated in frequency from the machine resonances.

We also investigated the implications of systematic errors shifting the mode frequency to be coincident with that of an harmonic of the bunch frequency. This is expected to make a significant impact on the beam emittance as it is a resonantly driven effect. We identified all modes in each type of cavity that could be shifted onto a machine line.

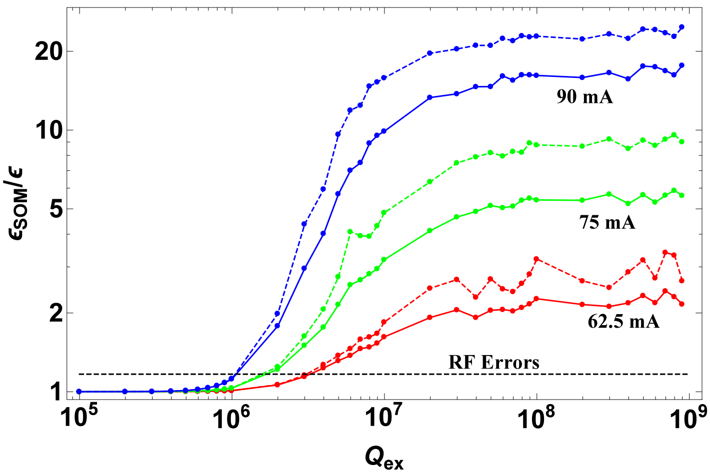


Fig. 3. Growth due to monopole modes in the first passband for several beam currents 62.5 mA (Red), 75 mA (Green) and 90 mA (Blue). The mean values and RMS values are plotted with solid and dashed lines respectively. The horizontal dashed line shows the growth purely due to RF errors.

Here we focussed on the five-cell ellipticals as they make up the bulk of the linac. We shifted the frequency of one of these modes in a single cavity to lie exactly on the nearest machine line and studied at the effect that the mode has on the beam. We then relocated the position of this resonant mode along the complete linac. In each case the emittance dilution was recorded. As the beam moves downstream the corresponding β value increases. Hence we map the spatial value to the corresponding β. The results of these simulations are illustrated in Fig. 4.

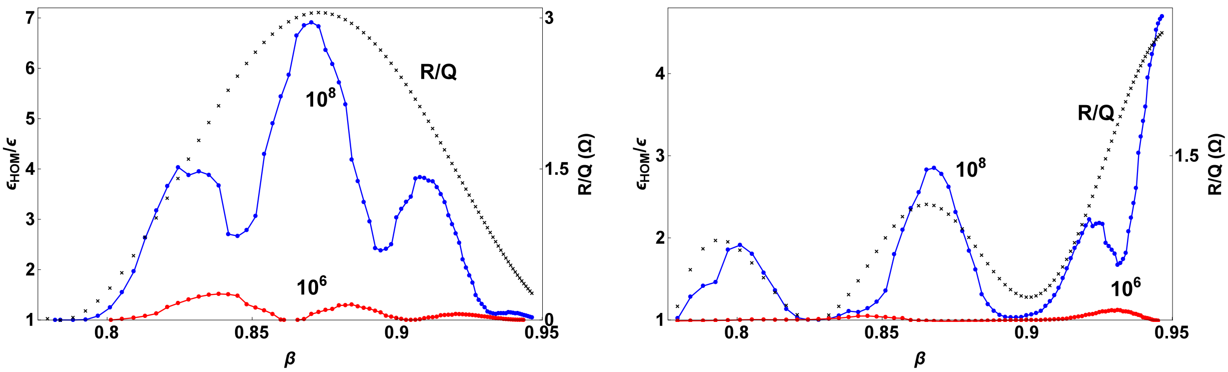


Fig. 4. Emittance dilution due to a single HOM in a single cavity which lies exactly on a machine line, where the position (equivalent to β) of this cavity within the linac is varied. This was repeated for two levels of damping Q 10^8 (Blue) and 10^6 (Red) for a monopole mode at 1.410 GHz (left) and 2.465 GHz (right). Additionally, R/Q as a function of β is included as a dotted line.

It is evident in Fig. 4 that the variation in the growth is intricately related to the variation of R/Q with β. There are however some clear deviation that are due to the shape of the phase space in that area of the linac mitigating some of the effect of the HOM. In the region where these dips occur it was found that there is a narrower profile (within $\pm 1^o$ at 704 MHz) in phase compared to the other regions (within $\pm 3^o$ at 704 MHz) and hence the spread in energy gained from the HOM is reduced at these points.

3.2.3. Dipole Modes

As indicated earlier, provided the beam is close to the electrical centre of the cavity only dipole modes, in a multipole modal expansion of the transverse wakefield, will be of significance. The transverse wakefield experienced by the beam $W_\perp$ is given by the imaginary component of $\tilde{W}_\perp$ directly behind the exciting point charge,

$$\tilde{W}_\perp(s) = 2\sum_{n=1}^{N} K_n exp[i\omega_n(1 + i/2Q_n)s/c], \quad \forall s > 0. \tag{17}$$

Ahead of the driving charge there is no wakefield as a direct consequence of causality. This formula is only valid for an ultra-relativistic charged particle ($v \approx c$). However in our case $\beta < 1$ and this is taken into account by ensuring the kick factors in eq.(17) are evaluated with an explicit velocity dependence. We neglect the influence of the wakefield ahead of the driving bunches though. This effect is expected to small compared to the wakefield left behind by each bunch in the train.

In each summation we include modes from the first six dipole bands, which in this case includes 26 modes all with values above 0.1 μV/pC/m/mm. The kick factors, shown in Fig. 5, indicate that the dominate contributions are concentrated in the first and third dipole bands. A straightforward calculation indicates that 93% of the wakefield is concentrated in the first and third bands. The envelope of the wakefield, $|\tilde{W}_\perp|$ is illustrated in Fig. 6 for a Q of 10^6, which is the anticipated to be provided by the fundamental mode couplers.

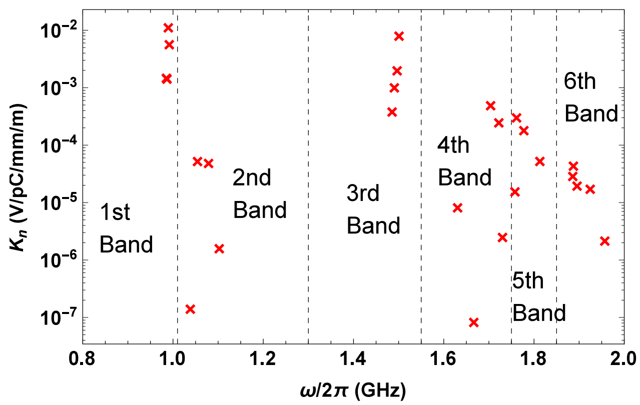


Fig. 5. Distribution of kick factors with frequency. The individual bands are separated by dashed lines

The sum wakefield,

$$S(n) = \sum_{i=0}^{n} W_\perp(ns_b) \tag{18}$$

is also shown in Fig. 7. The corresponding to an e-folding length of the wakefield is ~ 90 km, both the wakefield and sum wakefield are well damped by 100 km. The RMS of the sum wakefield is ~ 0.017 V/pC/mm and this is ~ 3.0 V/mm which is expected to have little effect on the beam dynamics. To verify this analysis we tracked the bunch train down the linac using Ainsworth's Python code[7]. No appreciable dilution in the beam emittance was observed.

4. Cavity Alignment Issues

In constructing a linac, consisting of 146 cavities it is important to ensure the cavities are aligned with respect to beam axis of the system. This includes translational and angular alignments in particular. The cavity-to-cavity, and cell-to-cell alignment tolerances are relatively loose due to the small kick factors of these cavities. However an angular misalignment gives rise to a transverse kick from the vertical component of the accelerating field. These of course

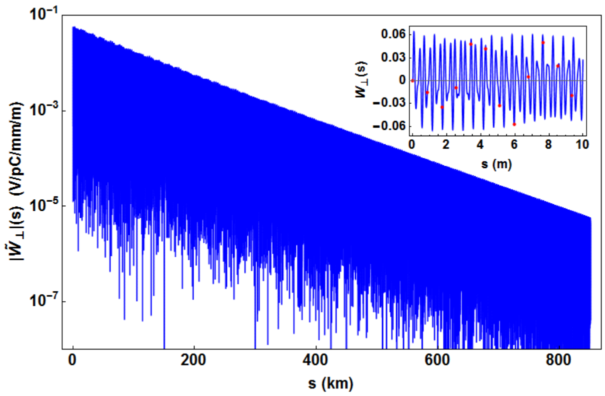


Fig. 6. Envelope of the wakefield for the five cell elliptical cavity. Inset is the short range wakefield with the arrival point of subsequent bunches plotted in red.

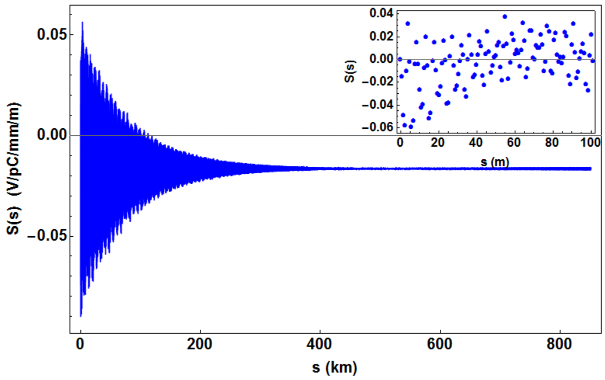


Fig. 7. Sum wakefield over the full bunch train. All modes are damped with a Q of 10^6 Shown inset is the first 116 bunches.

have far tighter tolerances than those associated with wakefields. For example, an 18 MV/m accelerating cavity field with a cavity angle of 1 mrad gives rise to a transverse voltage of 18 kV and this has the potential to markedly impact the beam dynamics. To confirm this analysis we performed a beam dynamics study using Ainsworth's computer code[7]. Here we tracked the progress of the proton beam down the linac under the influence of angular errors which we randomly distributed along the complete machine with a uniform distribution. The results of these simulations, averaged over 1000 machines, is displayed in fig. 8. The standard error of the sampled mean is 3.2% for each data point. For example, the 1 mrad error indicated gives rise to a 24% emmitance dilution of the beam.

5. Final Remarks

The ESS facility will include a 5 MW proton accelerator that will act as a driver for the spallation source. The accelerator will take a high intensity beam with normalised emittance of 0.2 π mm mrads[1] from 89 MeV to 2 GeV with minimal dilution in the emittance. The longitudinal component of the wakefield excited by the beam has the potential to seriously dilute the beam emittance and also to quench the SC cavities. The wakefield can be decomposed into a series of modes. Should the frequency of one or more of these self excited modes lie on a harmonic of the bunch frequency (352.21 MHz) then the mode will be resonantly driven. Detailed simulations presented here indicate that these monopole modes must be damped with a quality factor of 10^6 or less. This is at the level anticipated to be achieved through coupling provided by the fundamental power coupler.

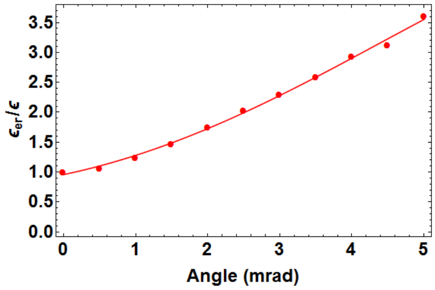


Fig. 8. Emittance dilution due to the dipole like kick from the accelerating mode averaged over 1000 simulations (solid line) due to the cavity being angularly offset from the beam axis.

In addition we investigated the impact of angular misalignment between the beam and cavity axis. These misalignments provide a transverse kick to the beam and relatively small angles can result in large dilution.

Measurements are in progress on the HOM spectra of a series of cavities. Our future studies will incorporate the results of these experiments and we will assess their impact on on the beam dynamics. However initial simulations have indicated that their effect on the beam quality will be minimal –provided that they are not resonantly driven.

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