CAVITY LOSS FACTORS OF NON-RELATIVISTIC BEAMS FOR PROJECT X

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Abstract

Cavity loss factor calculation is an important part of the total cryolosses estimation for the super conductive (SC) accelerating structures. There are two approaches how to calculate cavity loss factors, the integration of a wake potential over the bunch profile and the addition of loss factors for individual cavity modes. We applied both methods in order to get reliable results for non-relativistic beam. The time domain CST solver was used for a wake potential calculation and the frequency domain HFSS code was used for the cavity eigenmodes spectrum findings. Finally we present the results of cavity loss factors simulations for a non-relativistic part of the ProjectX and analyze it for various beam parameters.

INTRODUCTION

Project X is a multi-MW proton source under development at Fermilab [1]. The facility is based on a 3 GeV superconducting CW linac [2]. The linac schematic is shown in Fig. 1. It includes three low energy sections based on 325 MHz single-spoke cavities and two high energy sections of 650 MHz elliptical cavities having geometrical beta values of 0.61 (low beta) and 0.9 (high beta).

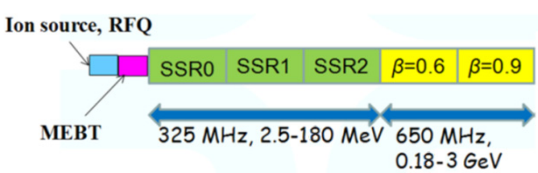

Figure 1: 3 GeV CW Project X linac schematic.

The linac provides beam with an average current of 1 mA and about 1 mm rms bunch length. Each bunch contains 9×10^7 H^- ions. In order to estimate the cavities' RF power losses in the high energy part of the Project X linac we performed a simulation of the incoherent beam energy loss in the 650 MHz cavities. Below we present the results of calculations made by two independent methods (in time domain and frequency domain) so as to achieve reliable results.

TIME DOMAIN ANALYSIS

The time-domain computation of beam energy loss factors is very common and well developed for relativistic beams. It can be done by variety of codes like MAFIA, GdfidL or ABCI [3,4,5]. However, when simulating non-relativistic beams passing through a cavity one needs to take into account the static Coulomb forces, and indirect methods of wake potential calculation and moving mesh techniques are not applicable. We used the CST Studio direct wakefield solver in order to calculate wake potentials for the 5-cell accelerating structure ($\beta=0.9$) for Project X [6]. The structure geometry is illustrated in Fig. 2. The direct method requires a meshing of the full structure volume, and the beam pipe length needs to be longer than a wake's catch-up distance. Therefore, the total number of mesh elements exceeds ten million for short bunches. The shortest bunch which we were able to simulate within a reasonable time was 3 mm rms length.

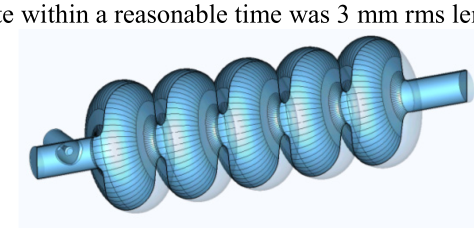

Figure 2: The 650 MHz, β=0.9 elliptical accelerating cavity for Project X

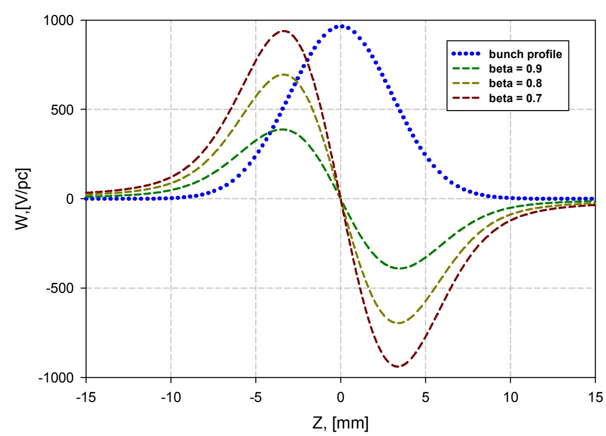

Figure 3: Primary result of time domain wake potential simulations in the high-beta Project X structure for a non-relativistic beam with 3 mm rms bunch size.

The result of CST Studio wake potential calculations for various beta values is shown in Fig. 3 for 3 mm bunch length. The total wake potential includes both static (Coulomb forces) and dynamic (beam-cavity interaction) parts. Theoretically the static part should vanish during the loss factor calculation. But the problem is that because of numerical noise present in the direct solution the static component is not perfectly symmetrical to the bunch center, and thus the convolution of the bunch profile with the wake potential gives the wrong result for the loss factor. The remedy is to run two consecutive simulations with slightly different pipe lengths, and then the static

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components of the wake potential will change proportionally to the length while the dynamic part remains the same. Thus, from these two solutions it is possible to subtract the static part and find the wake potential caused by beam-cavity interactions only. The final result after post-processing is demonstrated in Fig. 4. One can see that the wake potentials for low betas follow theoretical predictions; its profiles become wider and appear in the front of the bunch.

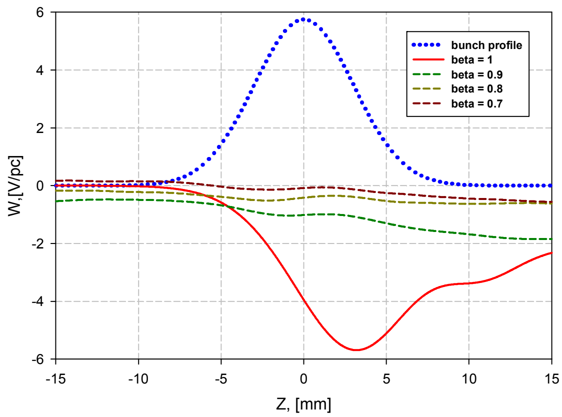

Figure 4: Reconstruction of wake potentials induced by beam-cavity interactions in the high-beta Project X structure for a non-relativistic beam with 3 mm rms bunch size.

We run a series of time-domain simulations for different bunch lengths and beam velocities. The results of the loss factor reconstructions are summarized in Fig. 5. For relativistic bunch ($\beta=1$) we did a crosscheck of the CST Studio result with trusted GdfidL code [4]. Both codes show similar dependencies of the loss factor on bunch length. Finally the convergence of the loss factor calculation was checked for two extreme mesh sizes. The result, in the form of a loss factor versus beta curve, is shown in Fig. 6 for a 20 mm bunch. One can estimate that the calculation errors are less than 10-15 % depending on the beta value.

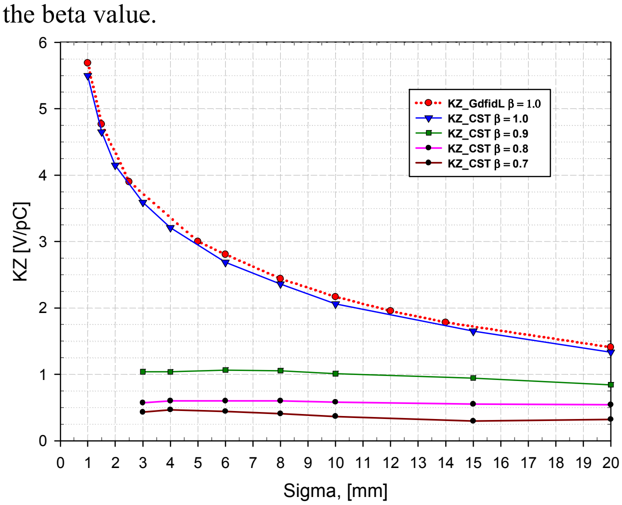

Fig. 5: The total loss factors for the high-beta Project X cavity versus bunch size (time-domain simulations).

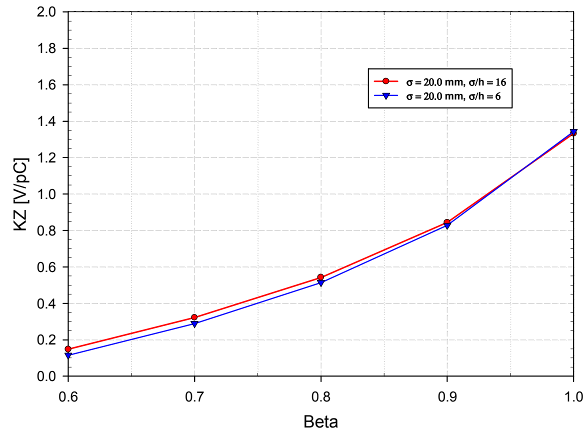

Fig. 6: Convergence study of loss factor calculation with CST Studio wake-field solver.

FREQUENCY DOMAIN ANALYSIS

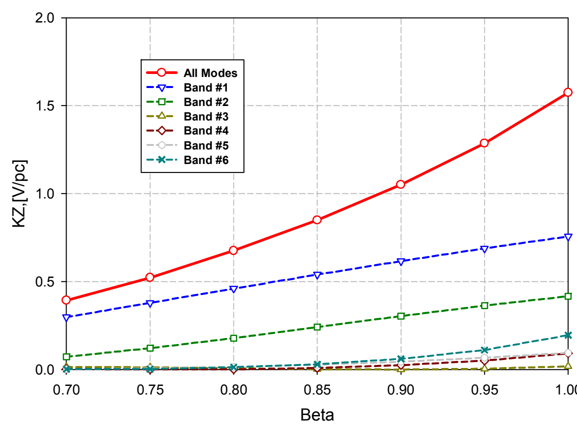

Fig.7: The solid line is the loss factor versus β for the high-beta Project X cavity (HFSS eigenmode simulations for all monopole modes below cut-off). The dashed lines show the inputs of individual passband.

Simulation in the frequency domain is the most straightforward method for finding the loss factor k in the accelerating structure. The bunch passing through the structure loses the energy $U=kq^2$, where q is the bunch charge. Here, the total loss factor k can be represented as an infinite series of all cavity modes' inputs. Apparently only modes below the beam pipe cut-off frequency can be taken into account because of the uncertainty in the boundary conditions for higher order modes. This is the main drawback of a loss factor calculation in the frequency domain, since we artificially limit the width of the beam spectrum and thus introduce an error into the final result. Nevertheless, the method is widely used for beam energy loss estimation in accelerating cavities due to its simplicity [7,8]. The problem reduces to the calculation of the cavity eigenmodes. The loss factor for an individual mode for a Gaussian bunch with rms length σ can be written in the form [8]:

$$k(\beta,\sigma)=\exp\left[-\left(\frac{\omega\sigma}{\beta c}\right)^2\right]\frac{\omega\rho(\beta)}{2Q}, \tag{1}$$

where ω is the circular eigenfrequency, $\rho(\beta)$ is the shunt impedance, Q is the eigenmode quality factor and $v=\beta c$ is the bunch velocity.

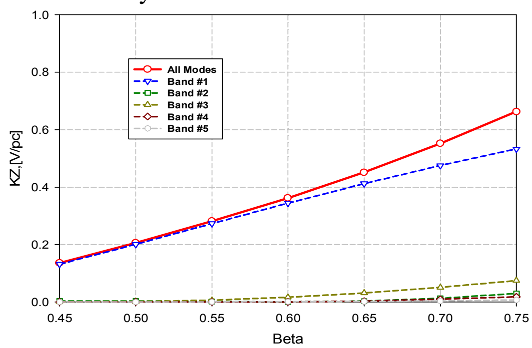

Fig. 8: The solid line is the loss factor versus β for the low-beta Project X cavity (HFSS eigenmode simulations for all monopole modes below cut-off). The dashed lines show the inputs of individual passbands.

We performed the monopole spectrum calculation for both types (low and high beta) of 5-cell superconducting structures designed at Fermilab for Project X [6]. The HFSS eigenmode solver was used for the individual mode computation [9]. The final results of loss factor post-processing are shown in Fig. 7 and Fig. 8 for $\beta=0.6$ and $\beta=0.9$ cavities respectively. The solid lines represent the total loss factor, while the dashed lines show the input from a particular passband. One can see that the first two passbands provide about 90% of the total energy loss.

DISCUSSION

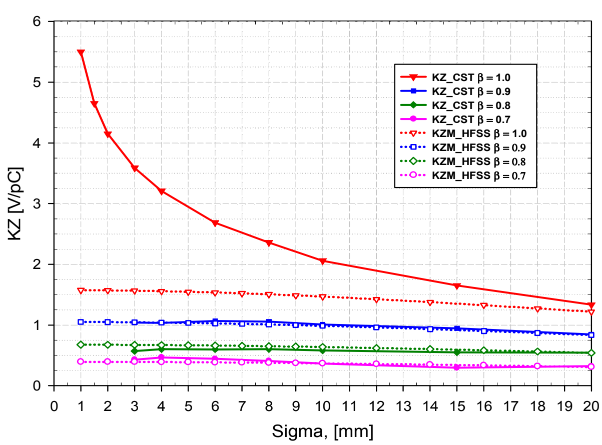

Figure 9: The loss factor for the high-beta Project X cavity versus bunch length calculated in time (solid) and frequency (dashed) domains.

We summarize the results of both time and frequency domain loss factor analyses of the high-beta Project X structure in Fig. 11. Evidently, for a weakly relativistic electron beam both curves are very flat and repeat each other within an error of ±10% in the full range of overlapping bunch lengths. Thus, we can safely extrapolate the time domain results to the linac parameter of 1 mm rms bunch length. The coincidence of the two methods indicates that the spectrum of a non-relativistic bunch is limited and its contribution to the high frequency modes' (above cutoff) excitation is negligible. This fact can be explained due to the widening of the electromagnetic pulse envelope carried by a charged particle that moves inside a hollow metal pipe with a speed less than c. The effective EM field width of a weakly relativistic particle is roughly the order of the pipe radius, limiting the spectrum of excited modes. On the contrary, in the ultra-relativistic case the EM field of a Gaussian bunch repeats the bunch profile itself.

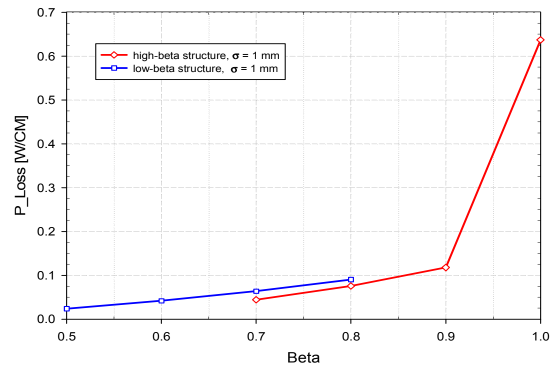

Figure 10: Incoherent beam energy loss per cryomodule in the high energy part of the Project X linac.

Finally we made an estimation of the total incoherent beam energy loss in the high energy part of the Project X linac. The beam power dissipated in a single structure is $P= kqI_0$, where I_0 is the average current and q is the bunch charge. The calculated losses normalized for a single cryomodule is shown in Fig. 10. The amount of loss is less than 0.5 W/CM, and thus can be neglected in the total cryo loss budget (200 W/CM). The HOM absorbers between cryomodules also may not be necessary.

CONCLUSIONS

The estimation of the total incoherent beam energy loss in the high energy part of the Project X linac was made using two independent methods (in time and frequency domains) for loss factor calculation. The results obtained by both methods are in good agreement. The final amount of incoherent RF losses calculated for a single cryomodule is small, and thus doesn't affect the total cryo loss budget. The effect of possible resonance losses is described in a separate paper presented at this conference [10].

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