

WAKE FIELD EFFECT ANALYSIS IN APT LINAC

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Abstract

The 1.7-GeV 100-mA CW proton linac is now under design for the Accelerator Production of Tritium (APT) Project [1]. The APT linac comprises both the normal conducting (below 211 MeV) and superconducting (SC) sections. The high current leads to stringent restrictions on allowable beam losses (< 1 nA/m), that requires analyzing carefully all possible loss sources. While wake-field effects are usually considered negligible in proton linacs, we study these effects for the APT to exclude potential problems at such a high current. Loss factors and resonance frequency spectra of various discontinuities of the vacuum chamber are investigated, both analytically and using 2-D and 3-D simulation codes with a single bunch as well as with many bunches. Our main conclusion is that the only noticeable effect is the HOM heating of the 5-cell SC cavities. It, however, has an acceptable level and, in addition, will be taken care of by HOM couplers.

1 INTRODUCTION

A wake field analysis for a high-intensity accelerator typically includes wake and/or coupling impedance computations, and following calculations of loss factors and heating due to various elements of the vacuum chamber, as well as a study of possible instabilities. Beam coupling impedances and loss factors can be obtained from wake fields computed by time-domain codes like ABCI [2] and MAFFIA [3]. However, this approach works only for an ultrarelativistic bunch, with $\beta = v/c = 1$, because of difficulties formulating open boundary conditions for $\beta < 1$ in time domain.

There are two specific features of the wake-field analysis in proton (or H^-) high-intensity linacs. First, β is significantly less than 1 for the most part of the machine. Results at $\beta = 1$, while provide useful estimates, can be quite different from those at the design β values in some cases, see, e.g., [4]. In particular, the resonance impedances and corresponding loss factors can strongly depend on β . Frequency-domain calculations provide an accurate answer for a given $\beta < 1$, but typically they are limited to just a few lowest modes. Second, the beam in high-intensity linacs is either CW, or consists of macropulses containing many regularly spaced bunches. As a result, the beam frequency spectrum is concentrated only near the multiples of the bunch repetition frequency f_b . Of course, the spectrum envelope is defined by the bunch shape, but due to short bunch length it rolls off at frequencies many times higher than f_b .

Therefore, an important question to consider is whether any higher mode has its frequency close to a multiple of

f_b . The presence of such modes, especially at relatively low frequencies, can lead to undesired coherent effects. We use time-domain computations with multiple bunches to answer this question. The idea is to apply a standard time-domain code with a few identical bunches at $\beta = 1$, but to set the bunch spacing s to $s = c/f_b$ for having the correct bunch repetition frequency. Since the resonance frequencies are essentially independent of β , so is a conclusion from such simulations. In this note, we concentrate only on this aspect of the wake-field studies for the APT. Specifically, we apply the code ABCI [2] to compute longitudinal and transverse wakes in axisymmetric models of the APT 5-cell superconducting (SC) cavities using a varying number of bunches and looking for coherent wake-field effects.

2 MULTIPLE-BUNCH EFFECTS IN APT SC CAVITIES

Wake potentials of a train of a few identical Gaussian bunches passing through a 5-cell APT SC cavity have been computed with the code ABCI [2]. Geometrical parameters of the APT cavities are given in [5]. The bunch rms length was chosen to be 4.5 mm in the $\beta=0.82$ section, and 3.5 mm for $\beta=0.64$. While these bunches have $\beta=1$, their separation is set to $s=0.85657$ m, which gives the proper bunch repetition frequency $f_b=350$ MHz.

We study the loss factor for the 5-cell APT SC cavities as a function of the number of bunches N_b in the bunch train. We expect that the loss factor per bunch tends to a constant for incoherent wakes, but it should increase linearly when wakes are coherent. The coherent effects occur if higher-mode resonances are close to multiples of f_b . Correspondingly, the loss factor for the total train is proportional to N_b if there are no coherent effects, or increases faster, up to N_b^2 , otherwise.

The results for the transverse loss factor k_{tr} per bunch are shown in Fig. 1, both for $\beta=0.64$ and $\beta=0.82$. As one can see from Fig. 1, k_{tr} reaches its asymptotic already for N_b between 5 and 10 in the case of $\beta=0.82$. This asymptotic value, in fact, is lower than k_{tr} for a single bunch. For $\beta=0.64$, however, we observe an almost linear growth up to N_b about 20, and only after that the behavior changes and the transverse loss factor per bunch saturates. Therefore, in the $\beta=0.64$ cavity higher-order dipole resonances are closer to multiples of f_b than those for $\beta=0.82$. For comparison, the total longitudinal loss factor for both cavities depends quadratically on N_b , while the loss factor per bunch increases linearly as N_b increases. This is, of course, due to the fundamental accelerating mode of the cavity, whose frequency is 700 MHz.

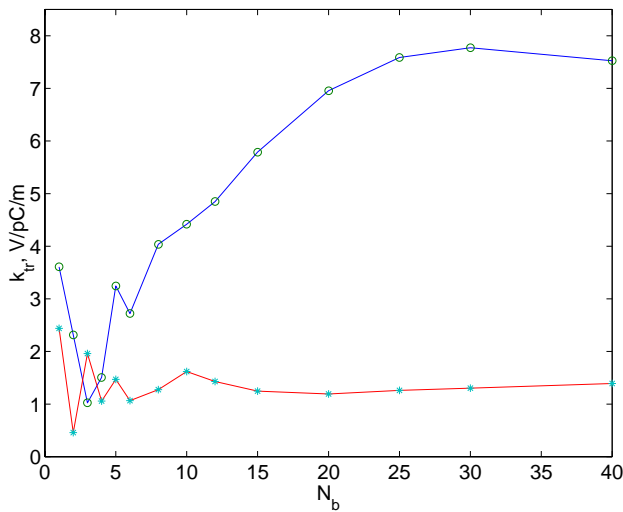


Figure 1: Transverse loss factor per bunch for 5-cell APT SC cavities versus the number of bunches: circles for $\beta = 0.64$, stars for $\beta = 0.82$.

The wake potentials for a bunch train with a monopole (on-axis beam) and dipole (off-axis beam) excitation look quite differently. There is a strong coherent build-up of the amplitude of the longitudinal wake as long as bunches travel through the cavity. The bunches in the train interact with each other through the excitation of the cavity fundamental mode. On the contrary, no apparent increase is observed for the transverse wake potential; wakes left by individual bunches are incoherent in this case. Therefore, one can use a maximal value of the transverse wake from these simulations as a reasonable estimate of that for a very large number of bunches, cf. Fig. 2. The maximum wakes from Fig. 2 allow to estimate the strength of beam-induced deflecting fields in the cavities for use in beam-dynamics simulations.

To identify the frequency range where a higher dipole resonance in the APT SC $\beta=0.64$ 5-cell cavity has its frequency close to the multiple of the bunch frequency $f_b=350$ MHz, we plot in Fig. 3 the power spectrum of the wake potential produced by a 30-bunch train in the cavity. One can see in Fig. 3 a regular structure of peaks at multiples of f_b , as well as a peak near 950 MHz, which corresponds to the band of the TM110 dipole mode [6]. Comparison of the wake power spectra for different N_b shows that the magnitude of this last peak decreases quickly as one goes to longer and longer bunch trains, since there is a smaller and smaller excitation at this frequency. However, it is the strong peak near 1750 MHz — the multiple of the bunch frequency — that produces a coherent increase of the dipole loss factor. Fortunately, its resonance frequency is close to the cutoff frequency of the pipe, which means this resonance can be effectively damped by HOM power couplers. Nevertheless, a more detailed analysis of this frequency range with frequency-domain codes is required to identify the corresponding eigenmode(s), and take its

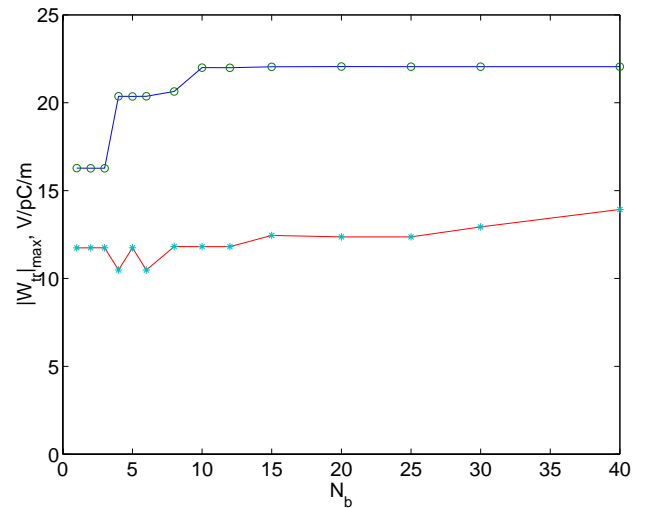


Figure 2: Maximum transverse wake potential for 5-cell APT SC cavities versus the number of bunches: circles for $\beta = 0.64$, stars for $\beta = 0.82$.

(their) properties into account in designing HOM couplers.

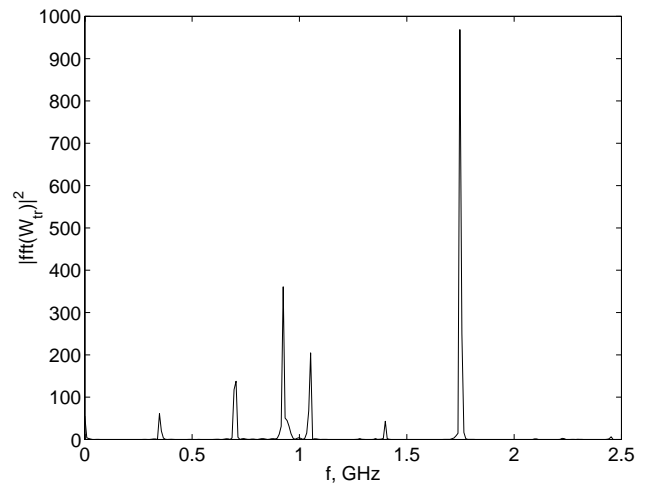


Figure 3: Power spectrum of the transverse wake potential for 30 bunches in the 5-cell $\beta = 0.64$ cavity.

As the number of bunches in the train increases, its frequency spectrum is getting more and more concentrated near the multiples of the bunch repetition frequency. Stronger peaks in the wake power spectrum for a relatively long bunch train indicate the frequency regions where the cavity resonances are close to multiples of f_b . We show in Figs. 3-6 the power spectra of both the transverse and longitudinal wake potentials for 30-bunch trains. The wake potentials have been calculated for 30 m after the leading bunch in all cases, they include about 60,000 points, and their Fourier transforms have been performed with $N = 2^{16} = 64K$. A logarithmic scale is used for the longitudinal spectra, otherwise the pictures would be dominated completely by the cavity fundamental mode at 700 MHz.

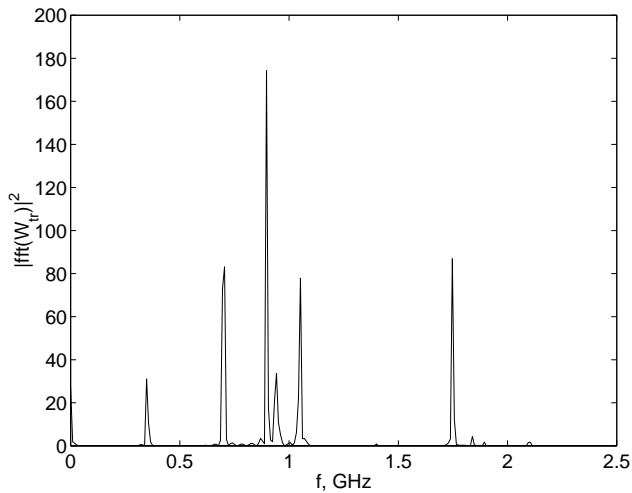


Figure 4: Power spectrum of the transverse wake potential for 30 bunches in the 5-cell $\beta = 0.82$ cavity.

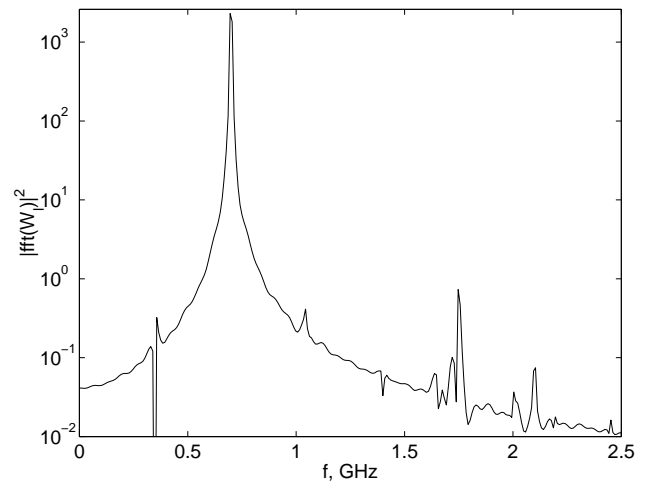


Figure 6: Power spectrum of the longitudinal wake potential for 30 bunches in the 5-cell $\beta = 0.82$ cavity.

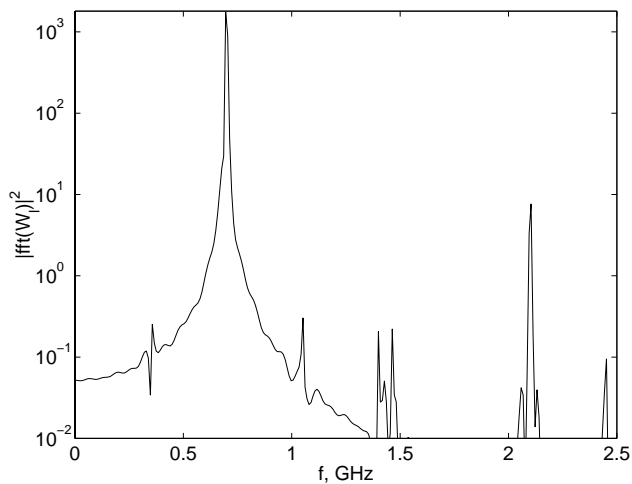


Figure 5: Power spectrum of the longitudinal wake potential for 30 bunches in the 5-cell $\beta = 0.64$ cavity.

Comparing relative peak heights in the frequency spectra shows where higher-order modes are close to multiples of the bunch frequency. Clearly, the potentially dangerous regions for the 5-cell $\beta=0.64$ APT SC cavities are: around 1750 MHz and 1050 MHz with respect to the dipole modes; and near 2100 MHz for the monopole ones (of course, apart from 700 MHz). Since 2100 MHz is above the beam-pipe cutoff, one should expect a trapped monopole mode near this frequency. For 5-cell $\beta=0.82$ APT SC cavities these regions are: around 1750, 700, and 1050 MHz for the transverse modes (but all those contributions are relatively weak) and near 1750 and 1050 MHz for the longitudinal ones. Also, some additional attention is probably required to the transverse modes near 950 MHz for $\beta=0.64$ and in the range 900–950 MHz for the $\beta=0.82$ cavities. While these frequencies are not close to a multiple of f_b , the corresponding dipole resonances are strong enough that their effects are observed even for rather long bunch trains.

3 CONCLUSIONS

A new approach to study higher-order mode effects in cavities for non-ultrarelativistic ($\beta < 1$) CW or long-pulse beams is proposed. It utilizes time-domain simulations using bunch trains which have $\beta=1$, but a correct bunch repetition frequency f_b . As the number of bunches N_b increases, the details of the beam frequency spectrum, which are dependent both on β and N_b , become unessential since the cavity is excited mostly at multiples of f_b . The approach allows applying standard time-domain codes, for example, [2].

Using this method we have found a few potentially dangerous frequency ranges of higher-order modes for the APT superconducting cavities. More details can be found in [7]. A further analysis with frequency-domain codes is required to identify the modes in these frequency ranges, and to take their properties into account in designing HOM couplers.

The author would like to thank Frank Krawczyk and Thomas Wangler for useful discussions.

4 REFERENCES

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