WAKE FIELD EFFECTS 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 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. Here we concentrate on two features specific to the APT linac: loss factors for the design $\beta < 1$ and CW beam structure.

1 INTRODUCTION

A wake-field analysis for a high-intensity accelerator includes wake computations, followed by calculations of loss factors and heating due to various elements of the vacuum chamber. The wake fields are typically computed with time-domain codes like ABCI [2] or MAFIA [3]. However, these codes are only applicable for ultrarelativistic bunches with $\beta = v/c = 1$. Two specific features of proton (or H^-) high-intensity linacs are essential for the wake-field analysis: first, β is significantly less than 1 for the most part of the machine, and second, the beam is either CW (in APT) or consists of macropulses containing many regularly spaced bunches (spallation neutron sources). Usual $\beta = 1$ estimates, while useful, can be quite different from those for the design β values, e.g., [4]. In particular, the resonance impedances and corresponding loss factors can strongly depend on β. Frequency-domain calculations can provide an answer for a given $\beta < 1$, but they require information on individual modes, and are typically limited to just a few lowest ones. In Sect. 2, we consider β-dependence of the loss factors for lowest modes in the APT 5-cell superconducting (SC) cavities.

Due to the CW beam structure, the beam frequency spectrum is concentrated only near the multiples of the bunch repetition frequency f_b. While the spectrum envelope is still defined by the bunch shape, it rolls off at frequencies many times higher than f_b, due to a very short bunch length. Therefore, an important question is whether any higher-order mode (HOM) 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. One can use time-domain computations with multiple bunches to answer this question. The idea is to apply a 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 Sect. 3 we compute the wakes in the APT 5-cell SC cavities varying the number of bunches in the bunch train, and look for coherent wake-field effects.

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2 LOSS FACTORS VERSUS β

For a Gaussian bunch of rms length $2l$, the loss factor k_s for the s-th cavity mode having the frequency ω_s depends on β as (see [4] for more details)

$$\frac{k_s(\beta,l)}{k_s(1,l)} = \exp\left[-\left(\frac{\omega_s l}{c\beta\gamma}\right)^2\right]\frac{|I_s(\beta,\omega_s)|^2}{|I_s(1,\omega_s)|^2} \ . \qquad (1)$$

Here $I_s(\beta,\omega) = \int_L dz \exp(-i\omega z/\beta c) E_{sz}(0,z)$ is the overlap integral, $\gamma = 1/\sqrt{1-\beta^2}$, and $E_{sz}(0,z)$ is the mode longitudinal electric field on the chamber axis.

For 5-cell APT SC cavities the lowest resonances are split into 5 modes which differ by phase advance per cell $\Delta\Phi$, and their frequencies are a few percent apart [5], see Table 1. MAFIA-computed on-axis fields of these modes [5] are used to calculate numerically overlap integrals in Eq. (1) and to find the loss factors for a given β. The results for the lowest monopole modes are presented in Table 1. We are mostly concerned about only these two resonance bands, since the higher modes are above the cutoff and can propagate out of the cavity depositing most of their energy in the beam pipes. Our results for the design values of β are in agreement with those obtained in [5]. Remarkably, the total loss factors for a given resonance band in Table 1 are lower for the design β than at $\beta = 1$, which is not always the case, see [4] for detail. The only exception here is the TM_{020} band for the $\beta = 0.82$ cavity, but it includes some propagating modes, and its contribution is very small.

Time-domain simulations with ABCI [2] give us the loss factor of a bunch at $\beta = 1$. The loss factor spectrum for the $\beta = 0.64$ cavity, integrated up to a given frequency, has two sharp steps, 0.5 V/pC near 700 MHz, and about 0.1 V/pC near 1400 MHz. They correspond to the two bands of the trapped monopole modes in the cavity, cf. Table 1. The totals for the TM_{010} and TM_{020} bands for $\beta = 1$ in Table 1 agree very well with the time-domain results.

The β-dependence of the loss factor for two TM_{010} modes — 0-mode and fundamental, π-mode — is shown in Fig. 1. Obviously, the shunt impedance (and the loss factor) dependence on β is strongly influenced by the mode field pattern.

Table 1: Loss Factors (in V/pC) in APT 5-cell Cavities

$\Delta\Phi$	f, MHz	$k(\beta)$	$k(1)$	$k(\beta)/k(1)$
$\beta=0.64$, TM_{010}-band				
0	681.6	$7.2\,10^{-6}$	$3.7\,10^{-4}$	0.020
$2\pi/5$	686.5	$4.8\,10^{-5}$	$2.9\,10^{-2}$	0.0016
$3\pi/5$	692.6	$1.1\,10^{-4}$	0.218	0.0005
$4\pi/5$	697.6	$1.2\,10^{-3}$	0.250	0.0049
π	699.5	0.184	$9.2\,10^{-3}$	19.92
Total		0.185	0.507	0.365
$\beta=0.64$, TM_{020}-band				
0	1396.8	$6.5\,10^{-4}$	$5.4\,10^{-4}$	1.187
$2\pi/5$	1410.7	$1.2\,10^{-6}$	$9.0\,10^{-4}$	0.0014
$3\pi/5$	1432.7	$1.8\,10^{-5}$	0.0173	0.0011
$4\pi/5$	1458.8	$8.0\,10^{-7}$	0.0578	$1.4\,10^{-5}$
π	1481.0	$3.5\,10^{-7}$	0.0095	$3.7\,10^{-5}$
Total		$6.7\,10^{-4}$	0.086	$7.8\,10^{-3}$
$\beta=0.82$, TM_{010}-band				
0	674.2	$0.3\,10^{-6}$	$6.9\,10^{-4}$	$4.5\,10^{-4}$
$2\pi/5$	681.2	$7.3\,10^{-5}$	$1.6\,10^{-5}$	4.64
$3\pi/5$	689.9	$1.8\,10^{-6}$	0.034	$5.1\,10^{-5}$
$4\pi/5$	697.2	$1.3\,10^{-3}$	0.220	$5.9\,10^{-3}$
π	699.9	0.285	0.240	1.188
Total		0.286	0.494	0.579
$\beta=0.82$, TM_{020}-band				
0	1357.7	$4.2\,10^{-5}$	$0.8\,10^{-6}$	52.4
$2\pi/5$	1367.7	$1.4\,10^{-4}$	$8.0\,10^{-5}$	1.71
$3\pi/5$	1384.5	$1.6\,10^{-6}$	$1.4\,10^{-4}$	0.011
$4\pi/5$*	1409.6	$8.0\,10^{-7}$	$1.3\,10^{-3}$	$5.6\,10^{-3}$
π**	1436.9	$1.6\,10^{-2}$	$2.2\,10^{-3}$	7.5
Total		$1.6\,10^{-2}$	$3.7\,10^{-3}$	4.32

*Mode near the cutoff.

**Propagating mode, above the cutoff.

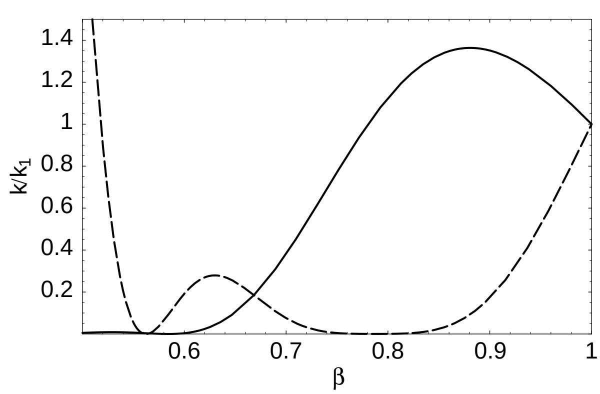

Figure 1: Loss factor ratio (1) versus β for 0-mode (dashed) and π-mode in the 5-cell APT $\beta = 0.82$ cavity.

3 MULTIPLE-BUNCH EFFECTS

Wake potentials of a train of a few identical Gaussian bunches passing through 5-cell APT SC cavities have been computed with the code ABCI [2]. Cavity parameters are given in [6], the bunch rms length was chosen to be 4.5 mm in the β=0.82 section of the linac, and 3.5 mm for β=0.64. While these bunches have β=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 factors for the 5-cell APT SC cavities as a function of the number of bunches N_b in the bunch train. The loss factor per bunch is expected to tend to a constant for incoherent wakes, but it should increase linearly when wakes are coherent. The coherent effects would occur if higher-mode resonances are close to multiples of f_b. The results for the transverse loss factor k_{tr} per bunch are shown in Fig. 2, both for β=0.64 and β=0.82 cavities. As one can see, k_{tr} reaches its asymptotic already for N_b between 5 and 10 in the case of β=0.82. This asymptotic value is, in fact, lower than k_{tr} for a single bunch. For β=0.64, however, we observe an almost linear growth up to N_b about 20, and only after that the transverse loss factor per bunch saturates. Therefore, in the β=0.64 cavity higher-order dipole resonances are closer to multiples of f_b than those for β=0.82. For comparison, the longitudinal loss factor per bunch for both cavities increases linearly as N_b increases. This is, of course, due to the fundamental accelerating mode of the cavity at 700 MHz. The maximal values of the transverse wake potentials also saturate as N_b increases, unlike the longitudinal ones, see [7].

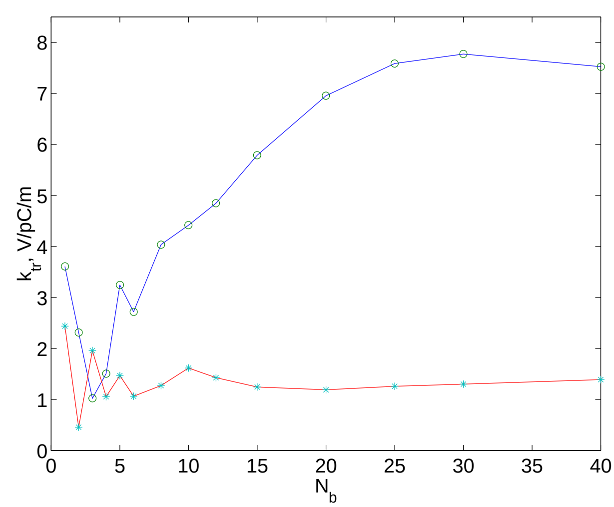

Figure 2: Transverse loss factor per bunch for 5-cell APT SC cavities versus the number of bunches: circles for $\beta = 0.64$, stars for $\beta = 0.82$.

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=350 MHz. To identify such frequency ranges we plot in Fig. 3 the power spectra of the wake potentials produced by a 30-bunch train in the cavities. The wake potentials have been calculated for 30 m after the leading bunch; they include about 60,000 points, and their Fourier transforms have been performed with $N = 2^{16} = 64K$. One can see 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 [5]. 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. Comparing relative peak heights in the frequency spectra shows where higher-order modes are close to multiples of the bunch frequency. Obviously, it is the strong peak near 1750 MHz — the multiple of the bunch frequency — that produces a coherent increase of the dipole loss factor in the APT SC β=0.64 5-cell cavity. 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 (their) properties into account in designing HOM couplers.

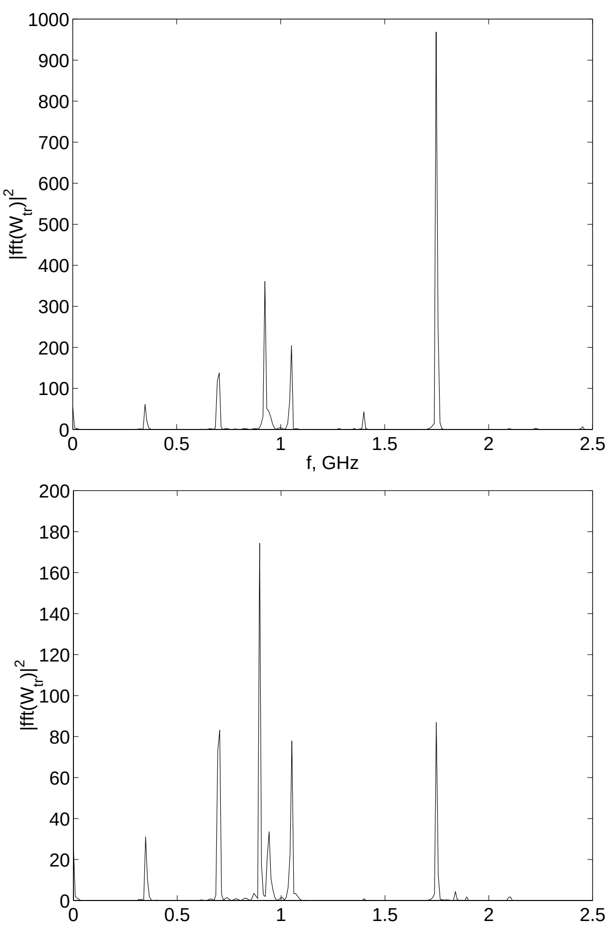

Figure 3: Power spectra of the transverse wake potentials for 30 bunches in the APT 5-cell cavities: $\beta = 0.64$ (top) and $\beta = 0.82$ (bottom).

Clearly, the potentially dangerous regions for the 5-cell β=0.64 APT SC cavities with respect to the dipole modes are around 1750 MHz and 1050 MHz, and for 5-cell β=0.82 cavities they are around 1750, 700, and 1050 MHz (but all those contributions are relatively weak). Also, some additional attention is probably required to the transverse modes near 950 MHz for β=0.64 and in the range 900–950 MHz for the β=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.

A similar analysis has been performed for the longitudinal wakes, see [7] for detail. The power spectra of the monopole wakes are dominated by the fundamental mode at 700 MHz, but in a log plot one can see higher-mode peaks. There is one near 2100 MHz for β=0.64 cavities (since 2100 MHz is above the beam-pipe cutoff, one should expect a trapped monopole mode near this frequency), and two, near 1750 and 1050 MHz, for the β=0.82 case.

4 CONCLUSIONS

A simple approach to study HOM effects in cavities for CW or long-pulse non-ultrarelativistic ($\beta < 1$) beams is developed. Time-domain simulations with standard codes are applied to the bunch trains moving with β=1, but having a correct bunch repetition frequency f_b. As the number of bunches N_b increases, the details of the beam frequency spectrum, dependent both on β and N_b, become unessential since the cavity is excited mostly at multiples of f_b. This allows us to find potentially dangerous frequency ranges where HOM frequencies are close to multiples of f_b.

A further analysis with frequency-domain codes should be used to identify the modes in these frequency ranges. Computed fields of these HOMs are used then to calculate their loss factors for the design value of β and to take their properties into account in designing HOM couplers, if required.

Our main conclusion for the APT linac is that the only noticeable wake-field effect is the HOM heating of the 5-cell SC cavities. It has, however, an acceptable level and, in addition, will be taken care of by HOM couplers.

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