BEAM ENERGY LOSS IN A BETA=0.09 SRF HWR CAVITY FOR 100 mA PROTON ACCELERATION*

F. Zhu#, H.T.X. ZHONG, S.W. Quan, F. Wang, K.X. Liu
Institute of Heavy Ion Physics & State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, 100871, China

Abstract

There's presently a growing demand for cw high current proton and deuteron linear accelerators based on superconducting technology to better support various fields of science. Up to now, high order modes (HOMs) studies induced by ion beams with current higher than 10mA and even 100 mA accelerated by low β non-elliptical Superconducting rf (SRF) cavities are very few. One of the main HOM related issues of the SRF linac is the HOM-induced power. HOM power is the important part of beam energy loss which is used to estimate the cryogenic losses. In this paper, we compare the beam energy loss induced by 100 mA beam passing through a β=0.09 HWR SRF cavity calculated from time domain solver and frequency domain cavity eigenmodes spectrum method.

INTRODUCTION

Compared to normal conducting accelerator, rf Superconducting accelerator has more advantages and the potential to accelerate super high current (for example 100 mA) cw ion beam. The beam pipes can be larger and the operation cost could be much less. Such high current SRF cavities have been adopted by some future facilities. For example, IFMIF has two 125 mA deuteron accelerators [1] and BISOL [2] recently proposed a 50 mA deuteron accelerator as a driver. Peking University (PKU) is developing a β =0.09 HWR SRF prototype cavity for BISOL deuteron acceleration or for 100 mA proton beam acceleration.

Compared to elliptical SRF cavities, quarter wave resonators (QWRs) or half wave resonators (HWRs) have much sparse high order modes. The modes are a little far from the accelerating mode and not easily activated. Normally the effect of the HOMs of QWRs or HWRs can be neglected and the studies of HOMs of HWRs are very few. But for 100 mA beam, whether the beam energy loss induced by the HOMs can be negligible or not still needs study.

All modes contribute to the additional cryogenic load. Cavity loss factor calculation is very important for the total cryo-losses estimation for the SRF cavities. In this paper, we will describe our efforts to characterize the beam-induced power in the β=0.09 HWR cavity for 100 mA beam acceleration, and present the results of calculations made by two independent methods (in time domain and frequency domain) so as to achieve reliable results.

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#zhufeng7726@pku.edu.cn

TIME DOMAIN ANALYSIS

The power deposited by the beam consisting of bunches following through the cavity with the bunch repetition rate f_{rep} is

$$P=k_{//}Iq= k_{//}q^{2}f_{rep}= k_{//}I^2/f_{rep} \quad (1)$$

Where $I=qf_{rep}$ is the average beam current, q is the bunch charge, and $k_{//}$ is the beam energy loss factor.

The time domain calculation of beam energy loss factors is very common and well developed for elliptical cavities and for relativistic beams. Code ABCI can calculate the loss factor of symmetric structure and for relativistic beams [3]. CST can calculate the loss factor of 3D structure, but normally also for relativistic beams. When simulating non-relativistic beams passing through a cavity, one needs to take into account the static Coulomb forces. CST Studio direct wake field solver was used to calculate wake potentials. The total wake potential includes both static (Coulomb forces) and dynamic (beam-cavity interaction) parts. Because static component is not perfectly symmetrical to the bunch centre, 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 components of the wake potential will change proportionally to the length while the dynamic part remains the same [4]. Thus, from these two solutions it is possible to subtract the static part and find the wake potential caused by beam-cavity interactions only. We used this method to calculate the wake potentials and further the loss factor for the high current taper type β=0.09 HWR cavity [5]. The structure geometry is illustrated in Figure 1.

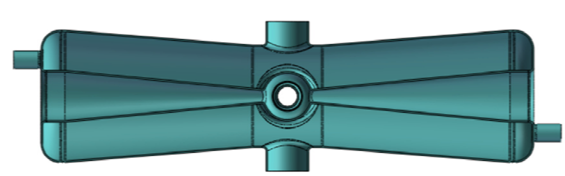

Figure 1: The 162.5 MHz, high current β=0.09 HWR cavity designed by Peking University.

Frequencies of HOMs excited by a non-relativistic beam bunch, passing through an SRF structure, depend on the characteristic size of the EM field distribution on the wall of the beam pipe at the cavity entrance, which is of the order of the beam pipe radius [6]. The beam pipe radius of the HWR cavity is 40 mm, frequencies below 7.5 GHz are present in the bunch field spectrum. It means

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the loss factor doesn't change as the bunch length for the β=0.09 HWR cavity.

CST calculation requires a meshing of the full structure volume, and the total number of mesh elements exceeds ten million for short bunches. The shorter is bunch, the calculation consumes more time. When the bunch length is shorter than 2.5 mm, the CST code can hardly execute the calculation because of time consuming. The beam bunch which we were able to simulate within a reasonable time was 3 mm rms length.

Figure 2 shows the wake potentials before and after the subtraction treatment. The primary wake potential is much higher than the treated one for the low β cavity. Figure 3 shows the dynamic wake potentials got from different lengths of beam pipes. The origin cavity length with beam pipes was 400 mm. The three curves were obtained by subtraction treatment between cavities with different beam pipes (460 mm, 520 mm and 580 mm) and the origin cavity of 400 mm long. These curves are in good consistency.

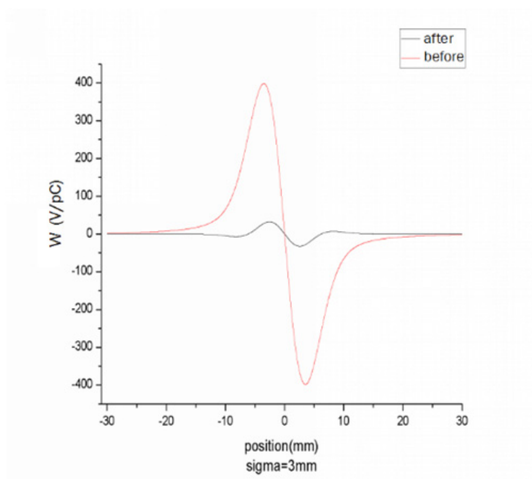

Figure 2: The wake potentials before (the direct result from the CST code) and after (the dynamic wake potential) the subtraction treatment.

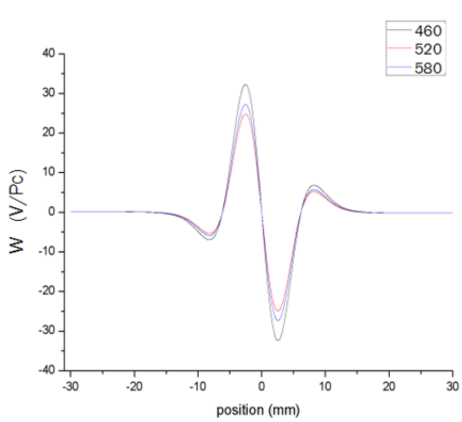

Figure 3: The wake potentials caused by beam-cavity interactions got from different beam pipes.

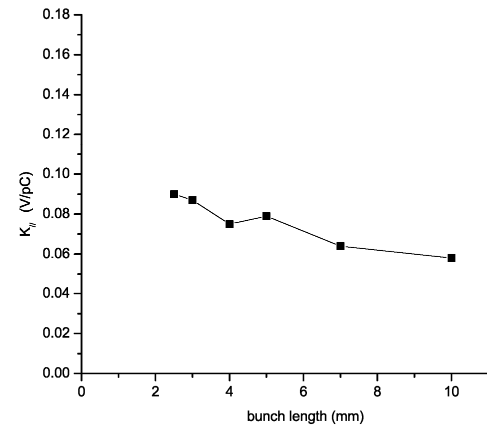

Figure 4: Loss factor $K_{//}$ versus bunch length for β =0.09 HWR cavity.

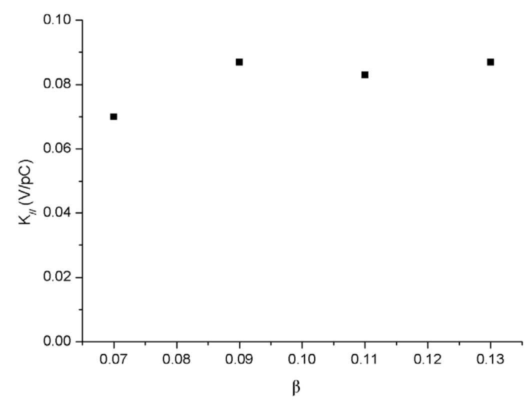

Figure 5: Loss factor versus velocity β for the HWR cavity.

Figure 4 shows the loss factor $k_{//}$ for the β =0.09 HWR cavity changes as the bunch length, $k_{//}$ is in the range of 0.06~0.087 V/pC. $k_{//}$ is about 0.087 V/pC when the rms bunch lengths are 2.5 mm and 3 mm separately. The real bunch which can be accelerated by the β =0.09 HWR cavity can be 2~3 mm. Figure 5 shows the loss factor changes as the beam velocity. The rms bunch length is 3mm. There is no much difference of the loss factors when the ion beam velocity β is in the range of 0.07~0.13. $k_{//}$ is near 0.09 V/pC.

If we choose $k_{//}$ =0.087 V/pC for the β =0.09 HWR cavity, the average beam current is 100 mA, and the bunch repetition rate is 162.5 MHz, then the bunch energy loss is about 5.3 W from equation (1).

FREQUENCY DOMAIN ANALYSIS

Because of the rapid decay of HOM spectrum, the effective HOMs below few GHz will be excited by the non-relativistic beam in the β=0.09 HWR cavity. Table1 gives information of the lowest modes.

The total loss factor k can be represented as an infinite series of all cavity modes' inputs. The loss factor for an individual mode for a Gaussian bunch with rms length σ can be written in the form [7]:

$$k(\beta,\sigma)=\exp\left[-\left(\frac{\omega\sigma}{\beta c}\right)^2\right]\frac{\omega r(\beta)}{4Q} \tag{2}$$

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Table 1: Loss Factors (in V/pC) of the Lowest Modes in the β =0.09 HWR Cavity

Mode	f (MHz)	r/Q	$r_\perp$/Q (1mm)	$r_\perp$/Q (10mm)	k (0.09)
1	162.20	255	-	-	0.064
2	315.29	2.8×10^{-7}	6.5×10^{-3}	7.1×10^{-5}	0
3	422.28	16.6	-	-	0.011
4	633.03	7.8×10^{-9}	4.5×10^{-5}	6.7×10^{-7}	0
5	697.30	1.57	-	-	0.0015
6	715.39	0.93	-	-	8×10^{-4}
7	720.03	2.8×10^{-6}		0.32	3×10^{-4}
8	724.25	2.9×10^{-5}	0.13	2.2×10^{-3}	1.5×10^{-4}
9	724.42	1.2×10^{-8}	3.4×10^{-4}	3.2×10^{-4}	0
10	759.78	0.15	-	-	1.2×10^{-4}
11	858.61	1.3×10^{-7}	1.69	2.35	0.0019
12	929.72	1.5×10^{-10}	6.7×10^{-6}	1.4×10^{-6}	0
13	930.07	1.5×10^{-6}	3.9×10^{-3}	8.5×10^{-5}	0
14	944.53	6.9×10^{-11}	1.5×10^{-7}	9.8×10^{-11}	0
15	973.15	0.026	-	-	0
16	1004.43	3.7×10^{-8}	0.098	0.15	1.2×10^{-4}
17	1023.67	1.9×10^{-4}	0.45	0.042	4.4×10^{-4}
18	1226.76	3.6×10^{-4}	0.55	0.008	5×10^{-4}
19	1283.84	-	0.054	-	4.5×10^{-5}
Total					0.078

The definitions of the shunt impedance r/Q of the longitudinal modes and deflecting modes are: $\frac{r}{Q} = \frac{Vacc^2}{\omega U}$ for longitudinal modes and $\frac{r_\perp}{Q} = \frac{\left|\int_0^d E_z(\rho = a)e^{i\omega z/v}dz\right|}{(ka)^2\omega U} = \frac{R_a}{Q}\frac{1}{(ka)^2}$ for deflecting modes which has no E_z along the beam axis.

where ω is the circular eigenfrequency, r(β) is the shunt impedance, Q is the eigenmode quality factor and βc is the bunch velocity.

The total loss factor of the HWR cavity for β=0.09 from the frequency domain is 0.078 V/pC. The majority is from the fundamental mode and the contribution of all the other modes gives 0.014 V/pC. The beam energy loss induced by 100 mA beam passing through the cavity obtained by the frequency eigenmodes approach is 4.8 W, and the majority is from the fundamental mode of 3.9 W. The CST eigenmode solver only gives 20 modes for the reference frequency near the fundamental mode frequency. When the reference frequency is much higher than the fundamental mode frequency, the results are not precise even though the program can give more modes. In superconducting cavities, the contribution of the lowest modes is a major concern. Loss factor of 0.078 V/pC does not include those modes with frequencies higher than 1.3 GHz. The time-domain approach is more acceptable. By comparing the frequency domain analysis and the time domain analysis, we can conclude that the beam energy loss induced by the high order modes of the β=0.09 HWR cavity is about 1.4 W. Of all the HOMs, the mode with frequency of 422.28 MHz has the highest r/Q, and the deposited power by this mode is about 0.7 W. Special HOM coupler could be designed to absorb this particular harmful mode.

CONCLUSION

The estimation of the total incoherent beam energy loss of 100 mA beam passing through the PKU β=0.09 HWR cavity was made using two independent methods (in time and frequency domains) for loss factor calculation. Because of the limited modes calculated from the frequency domain approach, the time domain result is a little higher than the frequency domain result. The final amount of incoherent RF losses calculated for a single cavity is about 5.3 W. The energy loss induced by the HOMs is 1.4 W, which gives a little effect on the total cryo-loss budget. The mode with frequency of 422.28 MHz contributes the majority. Thus HOM coupler could be designed to absorb this most harmful mode.

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