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

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Outline

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- Time Domain Analysis
- Frequency Domain Analysis
- Conclusion

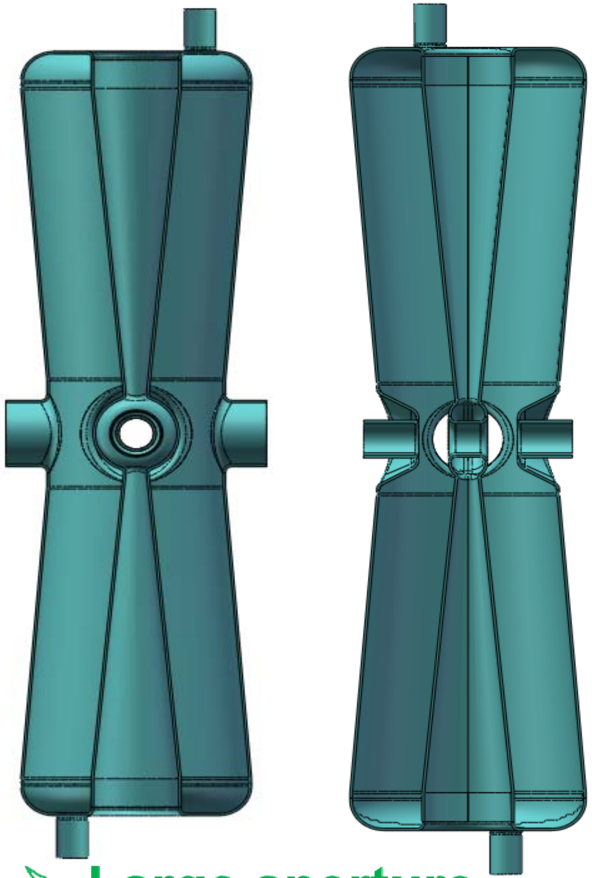
I Background

- **More and more projects based on high current ion linear accelerators have been proposed to better support various fields of science.**
- **Some future facilities adopt HWRs to accelerate seveal tens or hundred of mA ion beams.**
  IFMIF (125mA deuteron)
  BISOL (50mA deuteron)
- **Peking University is developing a beta=0.09 SRF HWR cavity for 100mA proton beam acceleration or for BISOL deuteron acceleration .**
- **Compared to elliptical SRF cavities, QWRs or HWRs have much sparse high order modes (HOMs). The HOMs are a little far from the fundermental mode and not easily excited.**
- **Normally the effect of the HOMs of QWRs or HWRs can be neglected for lower current ion beams and the studies of HOMs of HWRs are very few.**

I Background

- **One of the main HOM related issues of the SRF linac is the HOM-induced power.**
- **But for 100 mA beam, whether the beam energy loss induced by the HOMs can be negligible or not still needs study.**
- **Cavity loss factor calculation is very important for the total cryo-losses estimation for the SRF cavities.**
- **Loss factor of the beta=0.09 HWR cavity was calculated from time domain solver and frequency domain cavity eigenmodes spectrum method.**

High current β=0.09 HWR cavity developed at PKU



Parameter	HWR	Units
Frequency	162.5	MHz
Optimal β	0.09	-
R/Q	255	Ohm
Geometry factor	39	Ohm
B_{pk}/E_{acc}	6.4	mT/(MV/m)
E_{pk}/E_{acc}	5.3	-
Aperture	40	mm
Cavity diameter	260	mm
Lcav=βλ	166	mm
Cavity height	990	mm

- Large aperture
- Taper type
- Ring-shaped center conductor
- flat short ends

II Time Domain Analysis

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

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

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 loss factors is well developed for elliptical cavities and for relativistic beams.

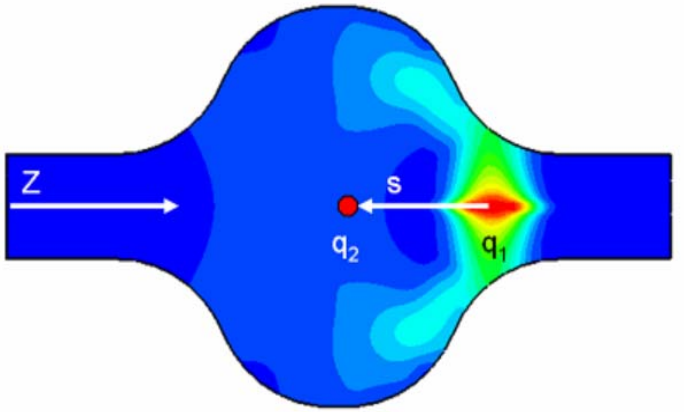
Code ABCI can calculate the loss factor of symmetric structure and for relativistic beams.

CST can calculate the loss factor of 3D structure, but normally also for relativistic beams.

Wake potential

q1 moves along the axis of the accelerating structure, the position is r1. q2 is a checking charged particle, the position is r2. s is the distance between q1 and q2. The wake potential caused by the charged particle q1 is:

$$\vec{W}^{\delta}(r1,r2,s)=\frac{1}{q1}\int_{-\infty}^{\infty}dz[\vec{E}(r1,r2,z,t)+\beta c\,\vec{ez}\times\vec{B}(r1,r2,z,t)]_{t=(z+s)/\beta c}\quad(\frac{V}{C})$$



longitudinal loss factor $K_{//}$

When a bunch with spectrum λ(s) passing through a SRF structure, The wake potential caused by the bunch is:

$$\underset{\mathrm{w}}{\rightarrow}(\mathrm{r1},\mathrm{r2},\mathrm{s})=\int_{-\infty}^{\infty}\mathrm{ds}'\,\lambda(\mathrm{s}-\mathrm{s}')\,\underset{\mathrm{w}}{\rightarrow}(\mathrm{r1},\mathrm{r2},\mathrm{s}')\qquad\left(\frac{\mathrm{V}}{\mathrm{C}}\right)$$

The longitudinal loss factor get from the convolution of the bunch profile and the wake potential:

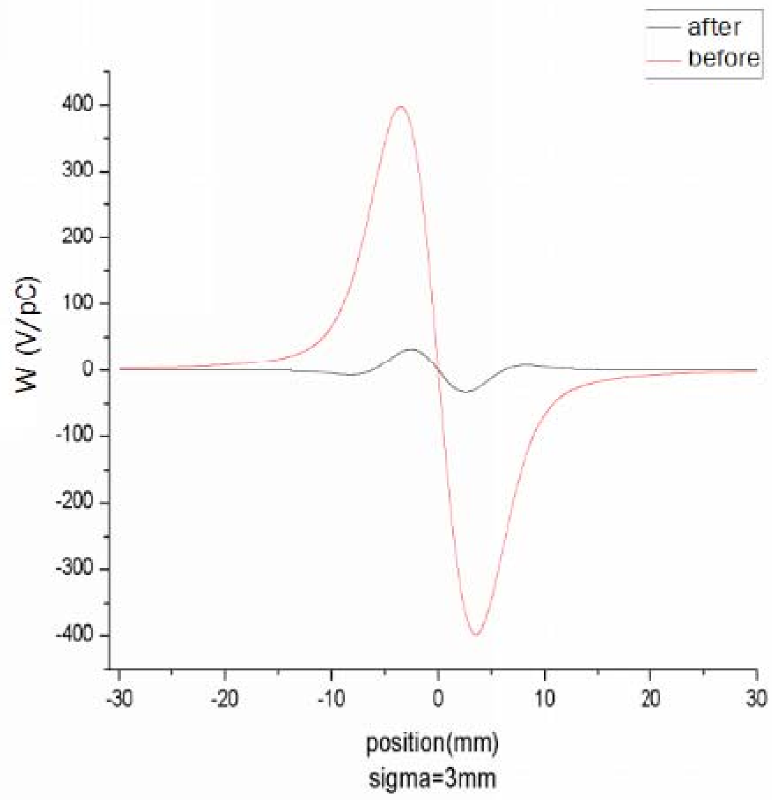
$$\mathrm{k}_{\|}=\int_{-\infty}^{\infty}\mathrm{ds}\mathrm{W}_{\|}(\mathrm{s})\,\lambda\,(\mathrm{s})\qquad\left(\frac{\mathrm{V}}{\mathrm{C}}\right)$$

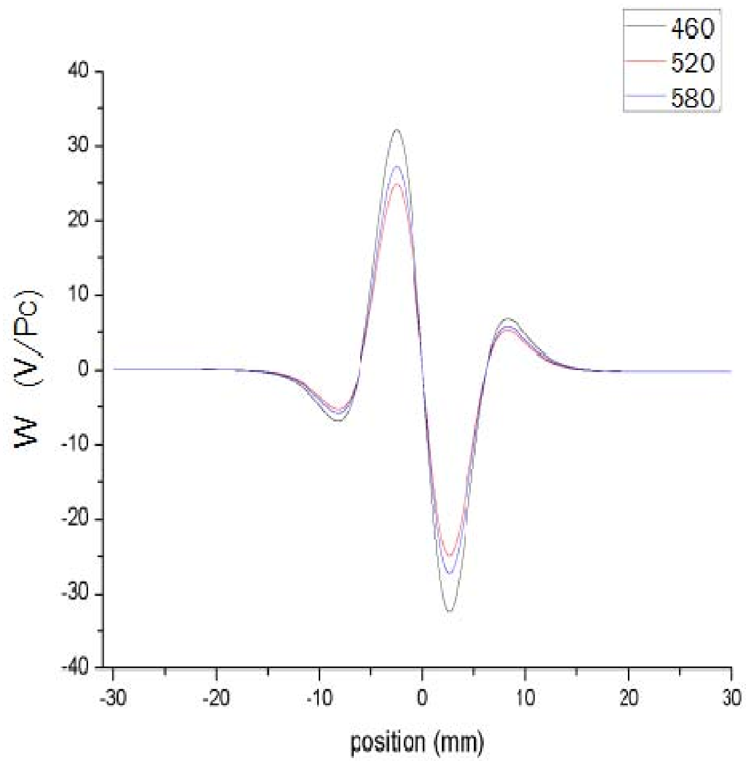
Time Domain Analysis

- **CST Studio direct wake field solver**
- **The total wake potential includes both static (Coulomb forces) and dynamic (beam-cavity interaction) parts.**
- **The direct result of 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 the static components of the wake potential will change proportionally to the length while the dynamic part remains the same, we can get the wake potential caused by beam-cavity interactions only by subtraction treatment. [1]**

Time Domain Analysis

Calculation of loss factor $K_{//}$

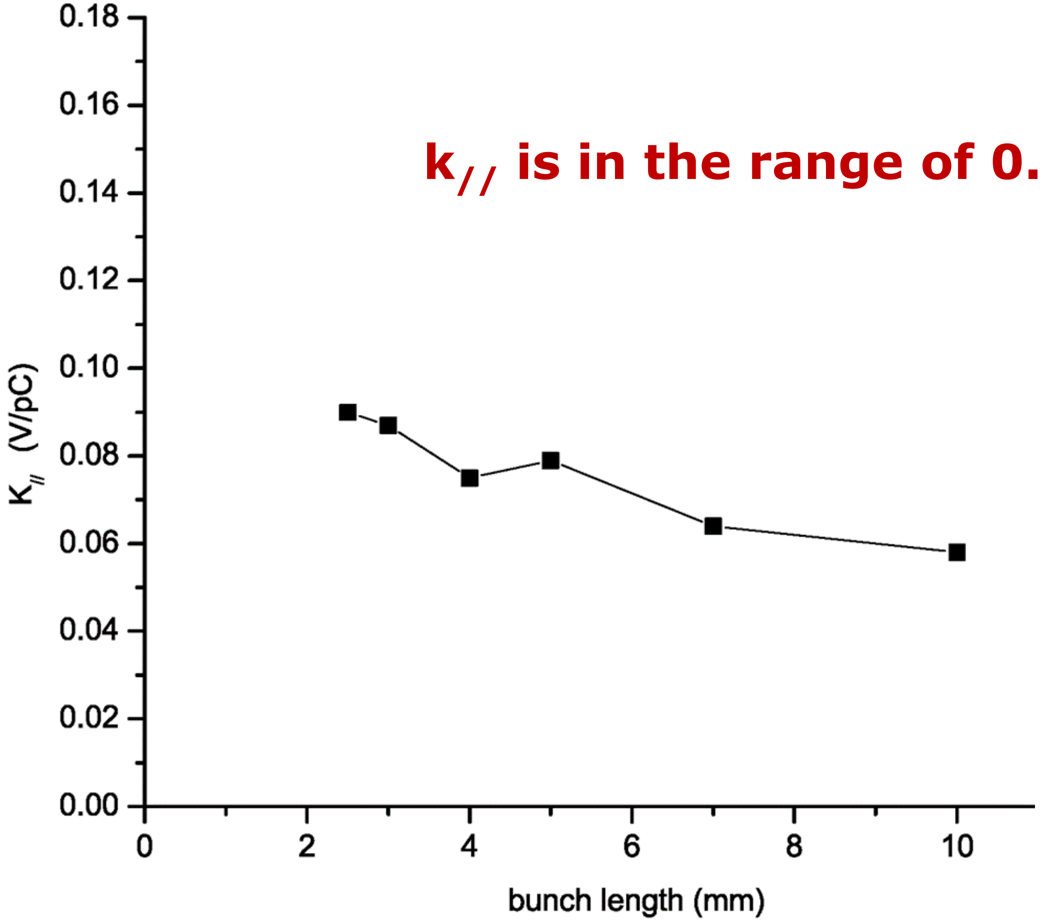




The wake potentials before (the direct result from the CST code) and after (the dynamic wake potential) the subtraction treatment.

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

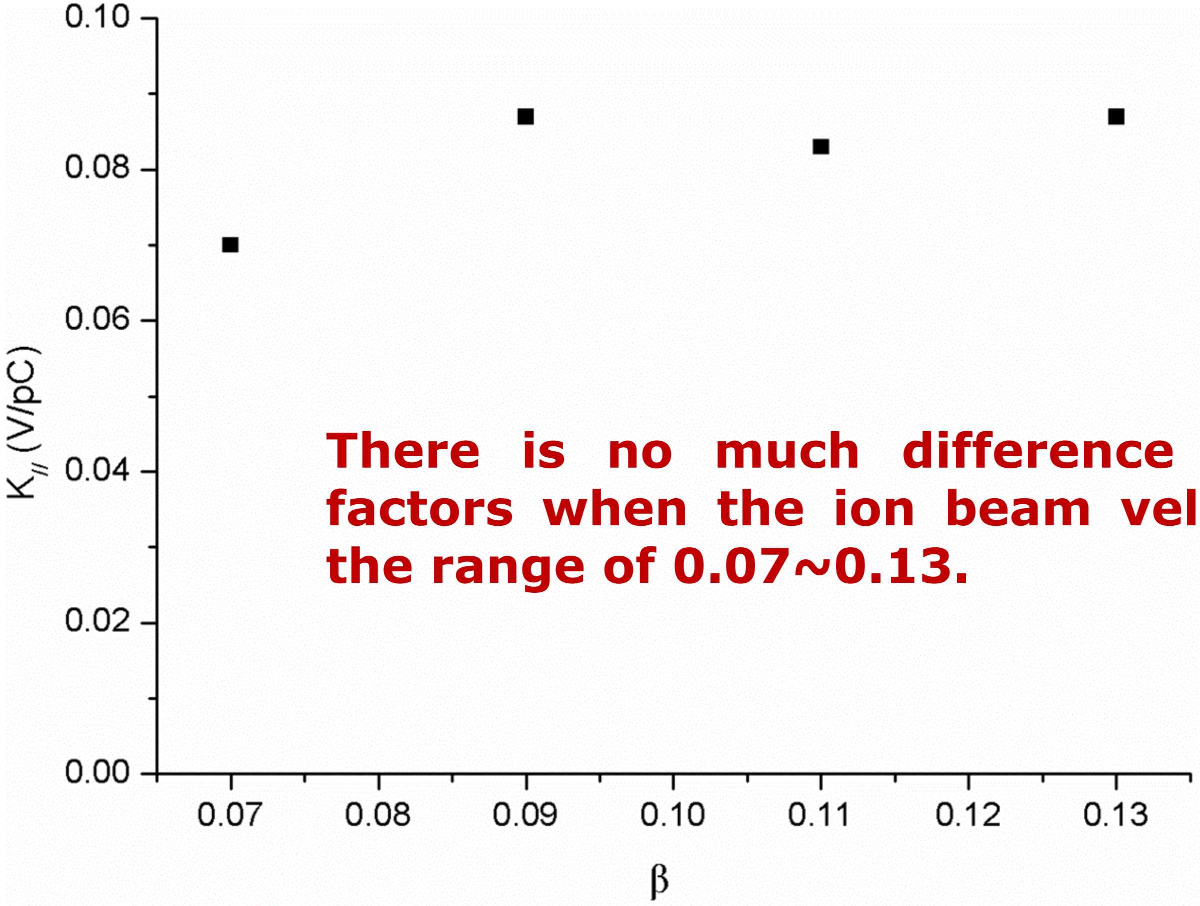
Calculation of loss factor $K_{//}$



$k_{//}$ is in the range of 0.06~0.087 V/pC

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

Calculation of loss factor $K_{//}$



There is no much difference of the loss factors when the ion beam velocity β is in the range of 0.07~0.13.

Loss factor versus velocity β for the HWR cavity.

III Frequency Domain Analysis

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 [2]:

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

$$\frac{r}{Q} = \frac{Vacc^2}{\omega U}$$

$$\frac{r_\perp}{Q} = \frac{\left|\int_0^d E_z(\rho = a)e^{i\omega z/v}dz\right|}{(ka)^2\omega U} = \frac{R_a}{Q}\frac{1}{(ka)^2}$$

Frequency Domain Analysis

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	1303	7.7×10^{-4}	1.02	0.004	9×10^{-4}
20	1503	3.9×10^{-4}	0.04	0.003	3×10^{-5}
Total					0.082

Frequency Domain Analysis

- **The calculated modes below 1.6GHz, about 40modes, there are other 20modes with much less r/Q and we did not put them in the table.**
- **In superconducting cavities, the contribution of the lowest modes is a major concern.**
- **Because of the limited modes calculated from the frequency domain approach, the time domain result is a little higher than the frequency domain result.**
  0.087V/pC for time domain result
  0.082V/pC for frequency domain result

Beam Energy Loss Analysis

- **The majority is from the fundamental mode and the contribution of all the other modes gives 0.018 V/pC.**

- **The beam energy loss induced by 100mA beam passing through the cavity with the repetition rate of 162.5MHz obtained by the frequency eigenmodes approach is 5.0 W and by the time domain approach is 5.3W. The majority is from the fundamental mode of 3.9 W.**

- **Of all the HOMs, the most harmful mode with frequency of 422.28 MHz has the highest r/Q, and the deposited power by this mode is about 0.7 W.**

IV 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.
- 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 of all the HOMs.

References

[1] A. Lunin, V. Yakovlev and S. Kazakov, Cavity Loss Factors of Non-relativistic beams for Project-X, Proceedings of 2011 Particle Accelerator Conference, NewYork, USA 2011.

[2] S.S. Kurennoy, Phys. Rev. ST - Acc. Beams, v.2, 032001, 1999.

Thank you!