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BEAM IMPEDANCE STUDY ON A HARMONIC KICKER FOR THE CCR OF JLEIC

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Abstract

The design of a high power prototype of the harmonic kicker cavity for the Circulator Cooler Ring (CCR) of Jefferson Lab's proposed Electron-Ion Collider (JLEIC) is complete and fabrication is underway. In this report we present some of the impedance studies assuming a high beam current of the JLEIC (∼ 0.76 A average) to estimate the HOM power dissipation and RF power requirement.

INTRODUCTION

A harmonic kicker cavity has been developed as a device that rapidly injects/extracts electron bunches into/out of the CCR of JLEIC [1], [2]. The engineering design of a high power prototype cavity based on a quarter wave resonator (QWR) is complete (See Fig, 1) [3], [4]. The cavity optimization took into consideration the higher order mode (HOM) impedance spectrum so that the HOM power induced by passing electron bunches is relatively low. In this report, we demonstrate that the beam-induced power due to the HOM's is below ∼ 15 W within a ± 10 mm transverse beam offset from the ideal orbit. Consequently, HOM dampers are not strictly needed. This analysis was carried out employing both analytical calculation with the knowledge of impedance of discrete eigenmodes and via a wake field simulation using CST-MWS and CST-PS respectively [5]. In addition, we estimated the required power from the RF source needed to maintain a constant kick voltage with five deflecting harmonic modes.

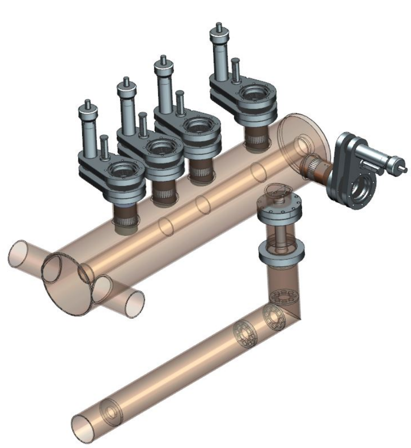

Figure 1: CAD model of the harmonic kicker cavity.

HOM POWER

The induced HOM power dissipated in the cavity can be evaluated in two ways. One is based on eigenmodes of the cavity computed numerically by the eigensolver of CST-MWS. Then the power associated with each eigenmode can be calculated analytically. The other is taking into account that the cavity modes are continuously fed by the beam bunch train. Therefore, the broadband coupling impedance spectrum (up to the first cutoff frequency of the beam pipe) has been evaluated using the wake field solver of the CST-PS, which allows to compute its power spectrum.

Time Structure of Beam Current in the CCR

The beam current in the CCR (for the parameters, see [6]) comes in a series of bunch trains with a gap (empty bucket) between the trains as shown in Fig. 2a. In addition to the periodicity of the bunch at a repetition rate of (f_b = 476.3 MHz), there is another periodicity arising from bunch train i.e., f_p = 1.4 MHz, which is very close to the CCR revolution frequency. The beam current can be expanded in a Fourier series, i.e.:

$$I(t) = \sum_m I_m e^{im\omega_p t} = c + id, \tag{1}$$

$$\text{where} \quad c(t) = \sum_m I_m \cos(m\omega_p t),$$
$$d(t) = \sum_m I_m \sin(m\omega_p t),$$

where I_m and $m\omega_p$ with $\omega_p = 2\pi f_p$ are the amplitude and angular frequency of each mode of the current. The Fourier spectrum of the current is shown in Fig. 2b.

Power Evaluation via Eigenmodes

For each eigenmode, the induced voltage with beam current as given in the CCR can be written as

$$\begin{aligned} V_{b,n,\parallel}(t) &= \int_{-\infty}^{t} dt'\, I(t') \frac{\omega_n R_{n,\parallel}}{2Q_{n,0}} e^{(i\omega_n - 1/\tau_n)(t-t')} \\ &= \frac{R_{n,\parallel}}{Q_{n,0}} Q_{n,L}\Big(a + ib\Big), \end{aligned} \tag{2}$$

$$\text{where } a(t) = \sum_m \frac{I_m}{\sqrt{1+\zeta_m^2}} \cos(m\omega_p t - \psi_m),$$
$$b(t) = \sum_m \frac{I_m}{\sqrt{1+\zeta_m^2}} \sin(m\omega_p t - \psi_m),$$
$$\zeta_m = 2Q_L(\frac{m\omega_p}{\omega_n} - 1), \quad \psi_m = \tan^{-1}\zeta_m.$$

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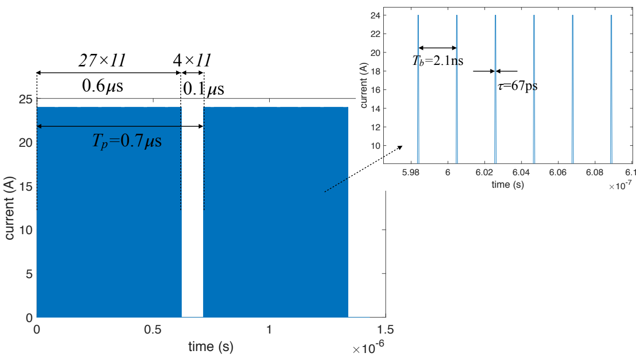
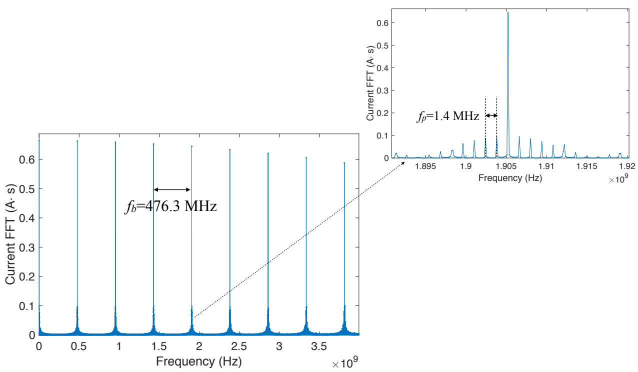


(a) The temporal profile. There are 27 × 11 bunches and 4 × 11 empty buckets (gaps) in a bunch train.



(b) The frequency spectrum.

Figure 2: The profiles of the beam current of the CCR

In Eq. (2), $I(t)$ is beam current, ω_n is a nth angular eigenfrequency of the cavity, $R_{n,\parallel}/Q_{n,0}$ is a longitudinal shunt impedance of the cavity, and $\tau_n = 1/Q_{n,L}$ with $Q_{n,L}$ being loaded quality factor is the natural decay time of the mode. Note that this is a voltage profile in time domain. From Eq. (2), the steady state induced power is computed straightforwardly according to

$$P_{ind,n} = \lim_{t\to\infty} P_{ind,n}(t) = \lim_{t\to\infty} \frac{|V_{b,n,\parallel}(t)|^2}{R_n}. \quad (3)$$

For a harmonic kicker, we add up the contribution from all the relevant eigenmodes to estimate the total power loss of the cavity, i.e., the ones that are confined within the cavity with the eigenfrequencies lower than TE_{11} cutoff frequency of the beam pipe (2.5 GHz). Because the eigenmodes are orthogonal modes to each other, we have

$$P_{tot} = \sum_{n}^{f_n<2.5GHz} P_{n,ind} \quad (4)$$

Here added n in the subscript refers to nth eigenmode. All the parameters needed in Eq. (2) and Eq. (5) were obtained from the CST eigensolver (up to 2.5 GHz). The power spectrum covering more than 100 eigenmodes (up to 2.5 GHz) is shown in Fig. 3. The summation of Eq. (4) yields $P_{tot} \sim 3.4$ W.

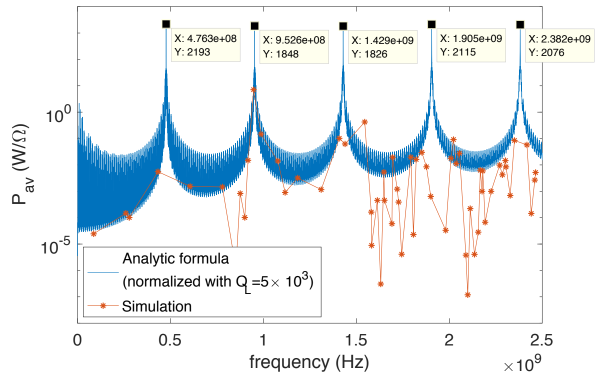


Figure 3: The power spectrum based on eignmode calculation. The red stars are the discrete spectrum of power while blue curve is continuous spectrum with a generic Q_L.

Power Evaluation via Impedance Spectrum

To take into account transient modes for power estimation, we use wakefield solver of the CST-PS to obtain the full. First, the cavities' wake potential has been computed as excited by a single bunch of Gaussian shape (line current) passing on the beam axis (The induced power is dominated by monopole modes). Then the wake potential is Fast Fourier transformed (FFT) to result in the broadband impedance spectrum using a customized FFT [7], which can resolve the peaks more accurately than via CST's embedded post-processing (up to a factor of 3 compared to the results (R/Q_0) of eigenmodes at resonance). In Fig. 4a, the real part of the longitudinal impedance spectrum $Z_\parallel$ is shown. By combining $Z_\parallel$ with the current spectrum shown in Fig. 2b, the beam-induced power can be calculated via

$$P(\omega) = \int_0^{\omega_c} d\omega\, I^2(\omega) Z_\parallel(\omega), \quad (5)$$

The resulting power spectrum is shown in Fig. 4b. The spectral density sums up to $P_{tot} = 3.6$ W (slightly more than the one based on eigenmode results). In addition, longitudinal loss factor has been calculated resulting in $k = 0.003$ V/pC.

Wake Fields by Dipole Charge

In addition to the HOM power excited by monopole modes, one would need to know the power induced by the beam traveling off-axis through the cavity, while this could also affect the transverse beam dynamics. But the effect on the beam dynamics is limited by a small number (11 turns) of circulation for each bunch. This aspect has been addressed by computing the transverse coupling impedance due to a dipole excitation, i.e., the electron bunches were offset vertically by a certain amount r_s from the beam tube axis. According to the Panofsky-Wenzel theorem, the transverse impedance at r_0 is related to the longitudinal impedance according to

$$Z_\perp(r_0,\omega) \quad = \quad \frac{c}{\omega r_s} \nabla_\perp Z_\parallel(r,\omega)\Big|_{r=r_0}, \quad (6)$$

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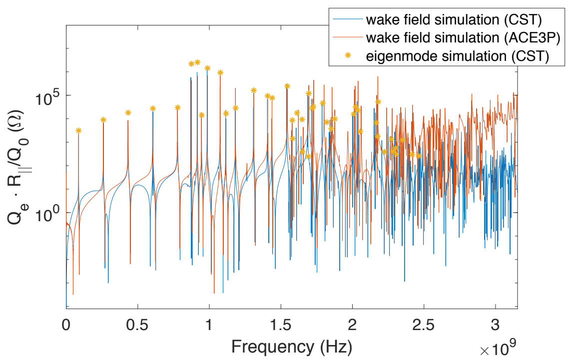
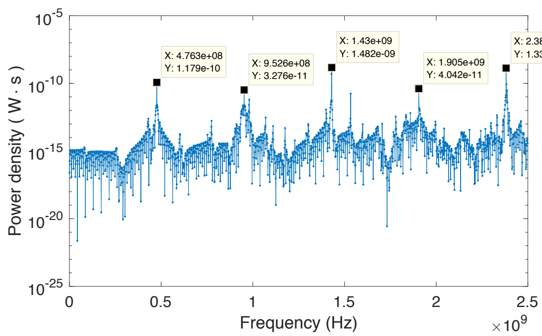


(a) The longitudinal impedance spectrum.



(b) The power spectrum by monopole excitation.

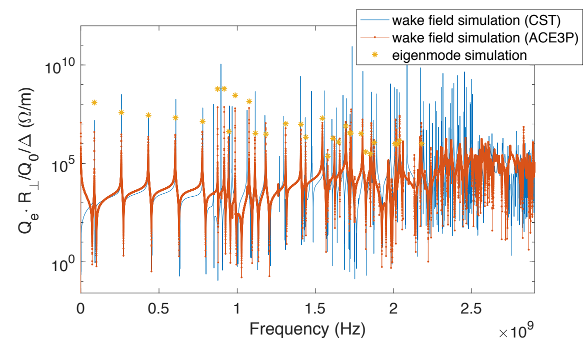
Figure 4: The impedance spectrum by monopole excitation.

We used a rather larger bunch length (= 6 cm) in the simulation than actual beam bunch length in the CCR, but this is small enough to reach 2.5 GHz. The wake potential is calculated up to 2.5 km in order to resolve within the bandwidth of each resonance.

where r_s is the distance of the driving charge from the beam axis. By setting $r_0 = 0$, longitudinal impedance $Z_\parallel$ can be Taylor-expanded as

$$Z_\parallel(r,\omega) = Z_\parallel(0,\omega) + \frac{\omega r_s}{c} Z_\perp(0,\omega) r + \mathcal{Z}(\omega) r^2 + \cdots, \quad (7)$$

where the coefficient of the linear term was fixed by making use of Eq. (6). With Eq. (7) and $Z_\parallel(0)$ obtained from the monopole excitation, one can evaluate $Z_\parallel$ at an arbitrary offset up to the linear term (dipole contribution) by evaluating $Z_\perp(0)$. To obtain a spectrum exclusively comprised by dipole modes, we setup a pair of oppositely charged bunches at opposite offsets, which cancels all the even-multipoles including $\mathcal{Z}$. In Fig. 5a, the resulting dipole impedance spectrum is shown. Utilizing the impedances plotted in Fig. 4a and 5a, and Eq. (7) and Eq. (5), the computed HOM power at an arbitrary offset up to linear order term, which resulted in $P(r) = (3.6 + 904.5r)$ W (with r in units of eter [m]). E.g. at an offset $r = \pm 1$ mm, the expected power is 3.6 ± 0.9 W.



(a) The transverse impedance spectrum.

Figure 5: The impedance spectrum by dipole excitation.

DEFLECTING MODE POWER

Unlike the parasitic HOM's, the operating deflecting modes are excited by the RF generator as well as the beam. Because the resonant frequencies of the harmonic kicker are incommensurate with the bunch repetition rate of the CCR beam current, the phase relation between the generator mode and induced mode is dynamical, i.e., changes in time. The longitudinal kick voltage $V_{c,n\parallel}$ associated with the nth resonant mode in the cavity with phase ϕ_n can be written as

$$V_{c,n,\parallel} e^{i(\tilde{\omega}_n t + \phi_n)} = \tilde{V}_{g,n,\parallel}(t) + \tilde{V}_{b,\parallel}(t), \quad (8)$$

where $\tilde{V}_{g,n,\parallel}(t), \tilde{V}_{b,\parallel}(t)$ are complex voltages of the generator and beam induced mode, respectively. $V_{g,n,\parallel}(t)$ is adjusted so that $V_{c,n,\parallel}$ remains constant in time. The induced voltage by a train of $\mathcal{N}$ bunches with the period of $1/f_b$ is given via Eq. (2) as

$$\tilde{V}_{b,n,\parallel} = V_{b,n,\parallel} \left\{ \sum_{k=1}^{\mathcal{N}} e^{ik\tilde{\omega}_n/f_b} - \frac{1}{2} \right\} \quad (9)$$

$$= V_{b,n,\parallel} \left\{ \left(\frac{1 - e^{i\mathcal{N}\tilde{\omega}_n/f_b}}{1 - e^{i\tilde{\omega}_n/f_b}} \right) - \frac{1}{2} \right\}, \quad (10)$$

where $V_{b,n,\parallel}$ is the induced voltage by a single bunch. With $\mathcal{N} = 11$, the first term in the curly bracket of Eq. (10) vanishes with $11\omega_n = 4\pi n f_b$ for any n. A factor of half integer in the curly bracket is due to the voltage seen by the electron due to beam loading. This implies that the contribution from the beam loading remains at a few bunch-to-bunch fluctuations, which are negligible. Accordingly, the total power would be very close to ~ 7.4 kW as evaluated previously without beam loading in ref. [3].

CONCLUSION

The impedance study for a high power prototype of the harmonic kicker for the CCR of JLEIC has been completed. The results based on two different methods are consistent and yield HOM power levels lower than 20 W. This is insignificant compared to the RF power dissipated in the cavity walls for the operating, deflecting modes, for which we have

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designed a proper water cooling layout. Consequently we do not contemplate using HOM dampers. Also the required additional RF power due to beam loading is not significant compared to the cavity wall loss.

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