Beam loading study of the harmonic kicker

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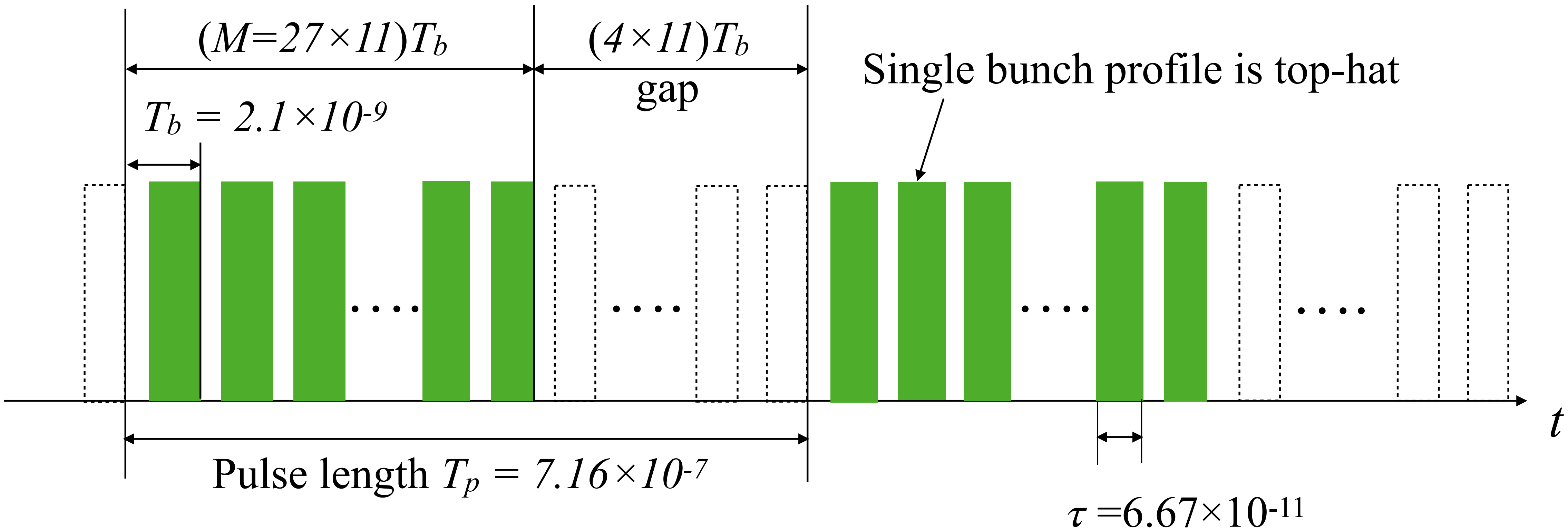
Contents

Introduction

Comments on impedance analysis

- The beam current of the CCR of the JLEIC is 0.76A (assuming CW modes).
- Due to beam loading with relatively high current, the power to maintain a constant kick voltage of the deflecting modes in the harmonic kicker cavity could increase dramatically.
- The dissipated power by the HOM's is also of concern. The transverse field of a High-Q_L mode could degrade beam quality.
- The goal of this study would be estimate the effects of beam loading and determine whether HOM damper for the kicker is needed.
- The study is an example of impedance analysis of transverse modes with beam current driven at different frequency from resonant frequency.
- The time structure of the beam current has gaps in otherwise CW mode (can be viewed as pulsed mode).
- Having a conclusion that induced power is not severe and HOM damper would not be needed, stability issues was not investigated.

Time structure of beam current in CCR



$$I(t) = \frac{2Q_b}{T_p} M + \Sigma\, A_n \cos(n\omega_p t) + B_n \sin(n\omega_p t)$$

n is not multiple of 31×11

$$A_n = \frac{4Q_b}{n\omega_p T_p \tau} \sin\left(\frac{n\omega_p\tau}{2}\right)\left[\cos\left(\frac{n\omega_p\tau}{2}\right)\left\{\frac{1}{2} + \frac{\sin(M-1/2)\delta_n}{2\sin\delta_n/2}\right\} - \sin\left(\frac{n\omega_p\tau}{2}\right)\left\{\frac{1}{2}\cot\frac{\delta_n}{2} - \frac{\cos(M-1/2)\delta_n}{2\sin\delta_n/2}\right\}\right]$$

$$= \frac{4Q_b}{n\omega_p T_p \tau} M \sin\left(\frac{n\omega_p\tau}{2}\right)\cos\left(\frac{n\omega_p\tau}{2}\right)$$ n is multiple of 31×11

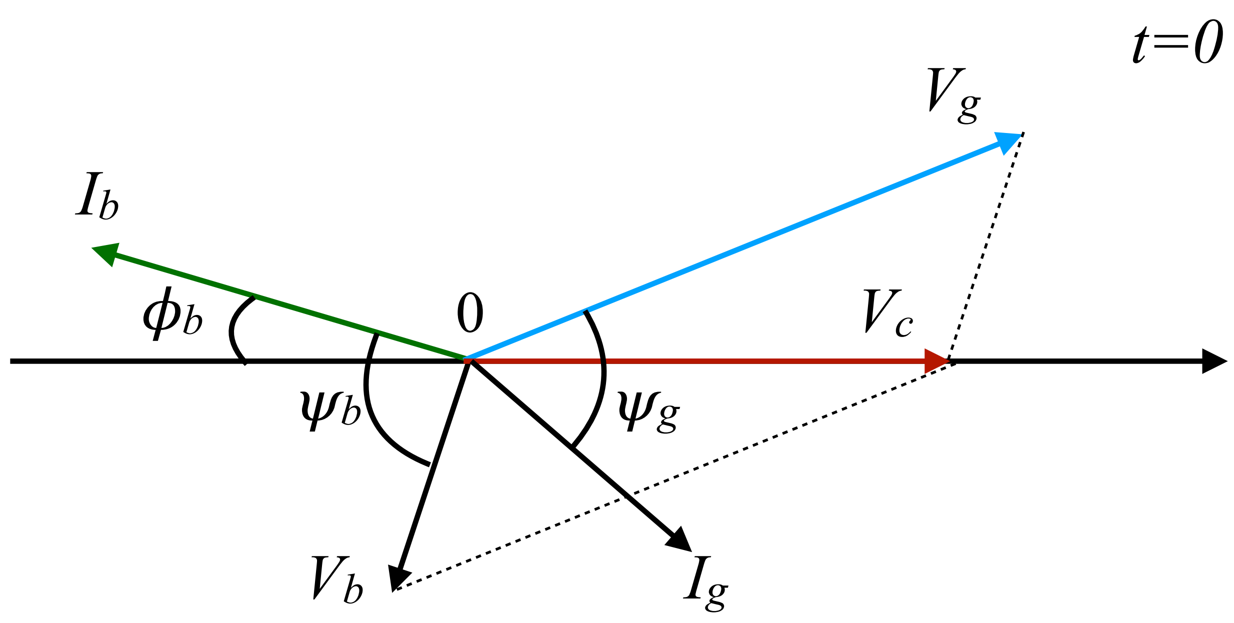
n is not multiple of 31×11

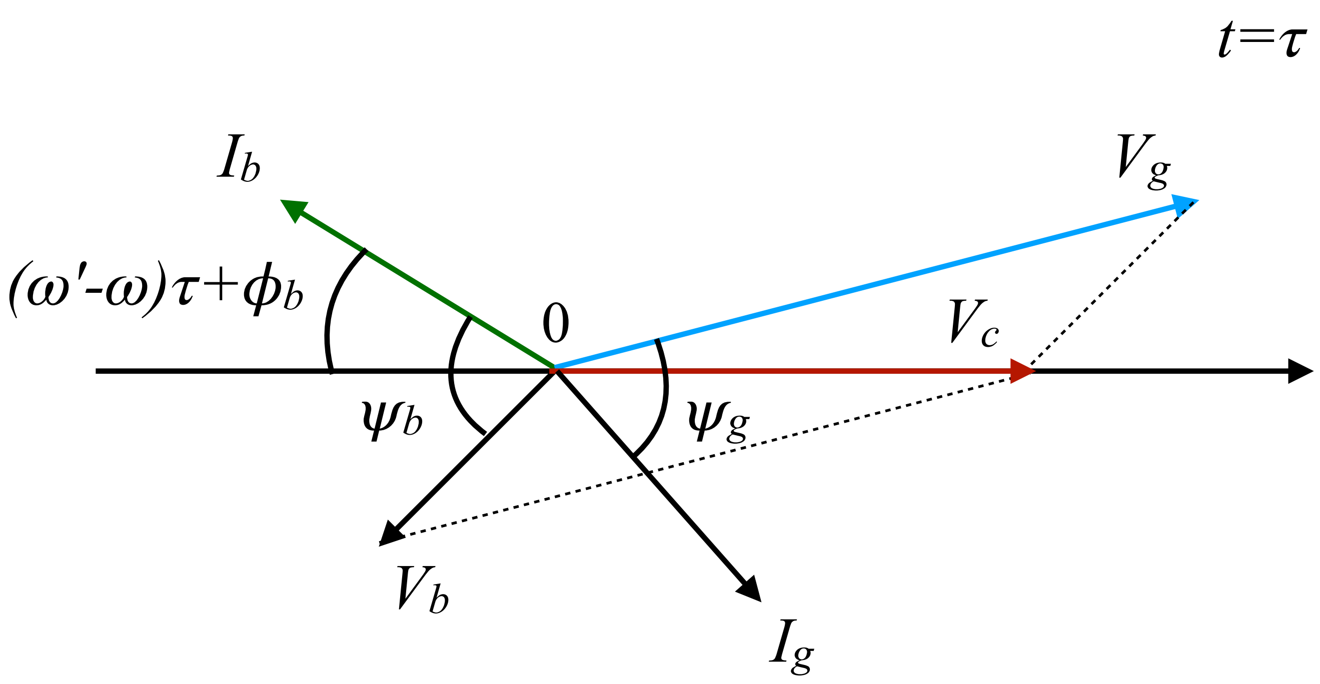
$$B_n = \frac{4Q_b}{n\omega_p T_p \tau} \sin\left(\frac{n\omega_p\tau}{2}\right)\left[\sin\left(\frac{n\omega_p\tau}{2}\right)\left\{\frac{1}{2} + \frac{\sin(M+1/2)\delta_n}{2\sin\delta_n/2}\right\} + \cos\left(\frac{n\omega_p\tau}{2}\right)\left\{\frac{1}{2}\cot\frac{\delta_n}{2} - \frac{\cos(M+1/2)\delta_n}{2\sin\delta_n/2}\right\}\right]$$

$$= \frac{4Q_b}{n\omega_p T_p \tau} M \sin^2\left(\frac{n\omega_p\tau}{2}\right)$$ n is multiple of 31×11

Deflecting modes

Phasor diagram





HOM

Issues on HOM impedance

- How much power would be induced by beam current?
  - Power splits to dissipation power on the kicker cavity wall and emitted power delivered to RF system.
  - How does power change with respect to misalignment of the beam?
- Would transverse field by induced high-Q_L HOM degrade beam quality?

HOM power analysis

- The general analytical formula for induced voltage by *n*th mode in the cavity is

$$V_n(t) = 2k_n e^{(i\omega_n - 1/\tau_n)t} \int_{-\infty}^{t} dt' \, I(t') e^{-(i\omega_n - 1/\tau_n)t'}$$

Available from eigenmode solver simulation in CST-MWS

V_n is induced voltage across the cavity, k_n is loss factor by a single charge, I is beam current, ω_n is angular frequency of the mode, and τ_n is decay time of the cavity.

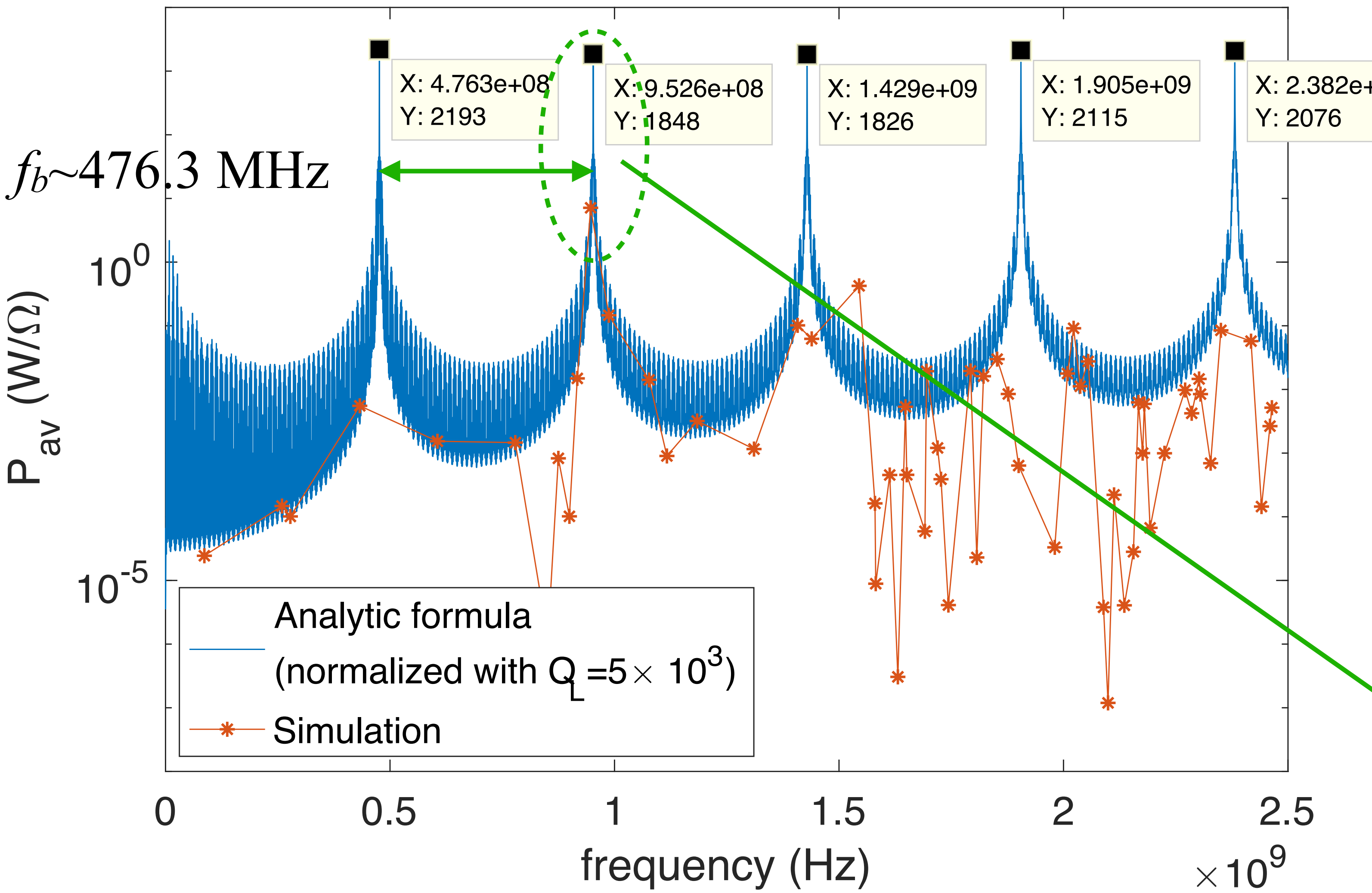
- The total power formula by n-th mode in the cavity and total average power are

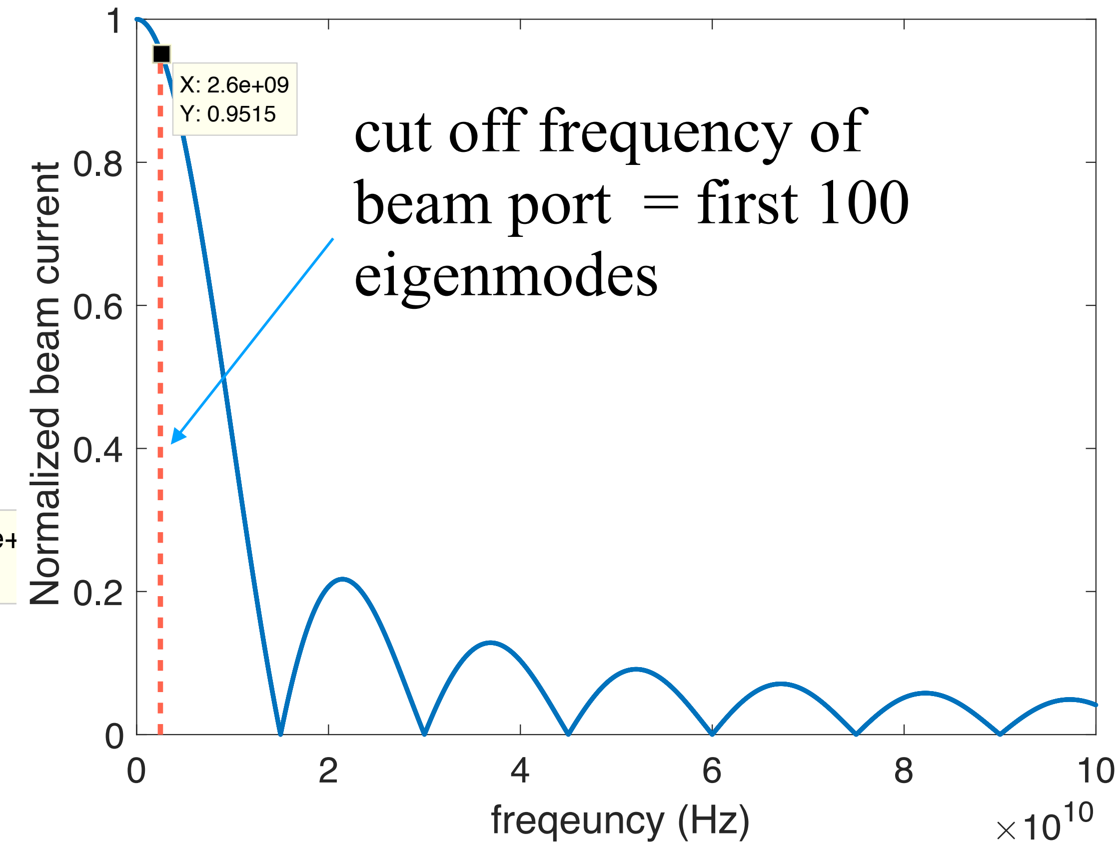
$$P_n(t) = \frac{V_n^2(t)}{Q_L \cdot R_{\parallel,n}/Q_0}$$

$$P_{ave} = \sum_n P_{n,ave} = \sum_n \frac{1}{T} \int_0^{1/f_b} dt \, P_n(t)$$

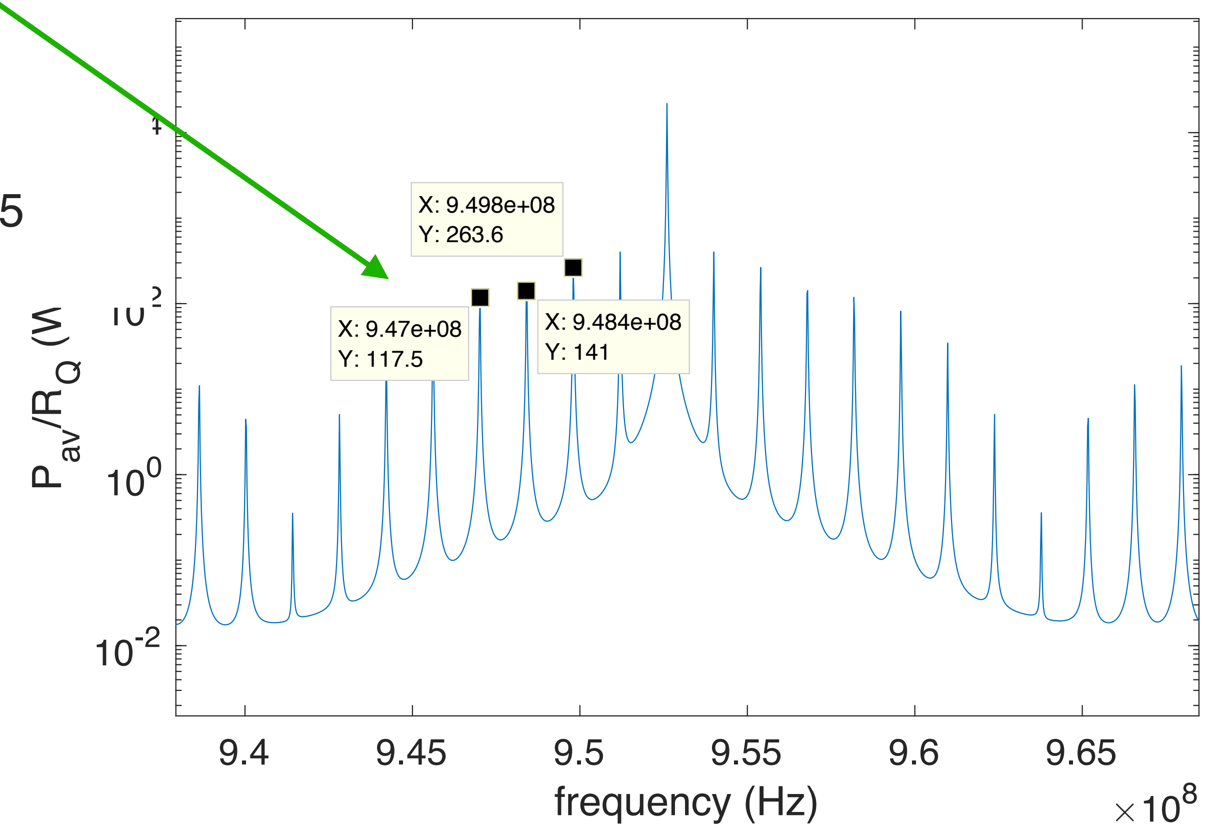
- (average) Power of HOM

$P_{\text{ave,total}} \sim 10\text{W}$ ($P_{\text{ave,loss}} \sim 4\text{W}$)





Frequency spectrum of top-hat beam current



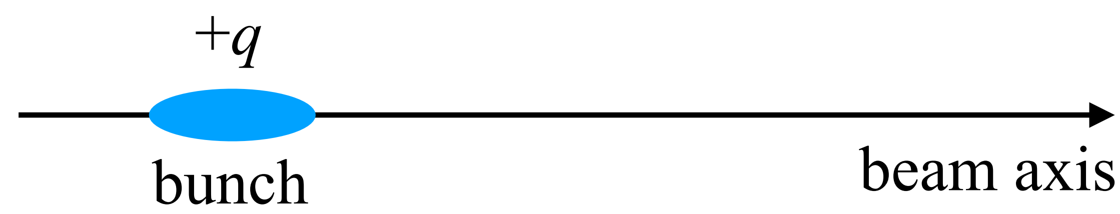
Setup for impedance simulation

	On-axis	Off-axis	ACE3P
Beam size σ	6cm	2cm	3cm
Wall material	PEC	PEC	PEC
Beam position	35mm	45mm/25mm	45mm/25mm
Bunch charge	1 nC	±1nC	±1nC

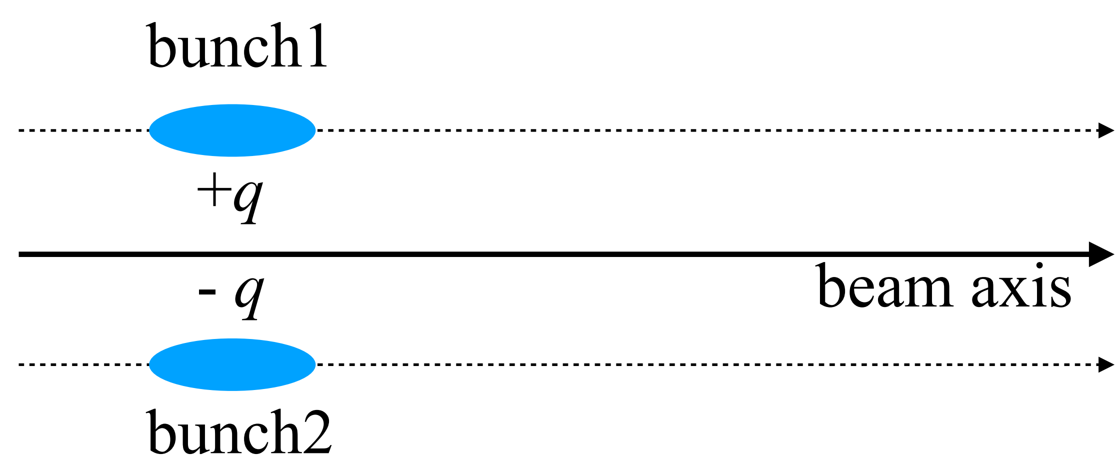
Frequency range was set to be

$f_{\max}$ = 2.5 GHz (cut off frequency of the beam ports)
Δf < 68 kHz (bandwidth of the lowest HOM)
Mode 7 : f = 851.5 MHz, Q_L = 12600

$t_{\max} > 15\mu$s ($s_{\max} > 4.5$ km)
Due to simulation time, $t_{\max}$=8.34 μs ($s_{\max}$ =2.5 km)
Δt = 4ps (σ = 2cm)



Excites only monopole field of each mode

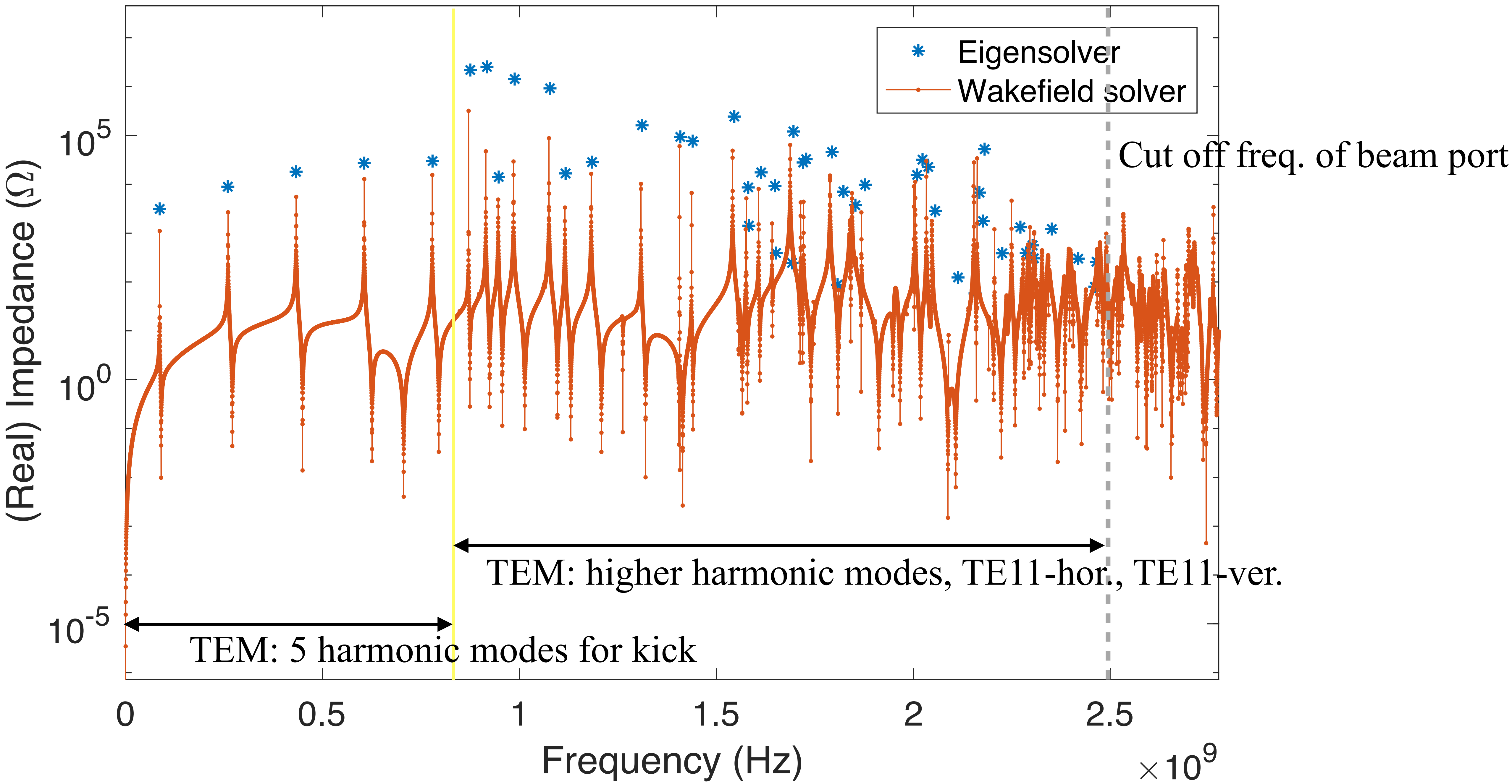


Excites only dipole field of each mode, doubling its magnitude

Impedance spectrum (real value) by charge on beam axis

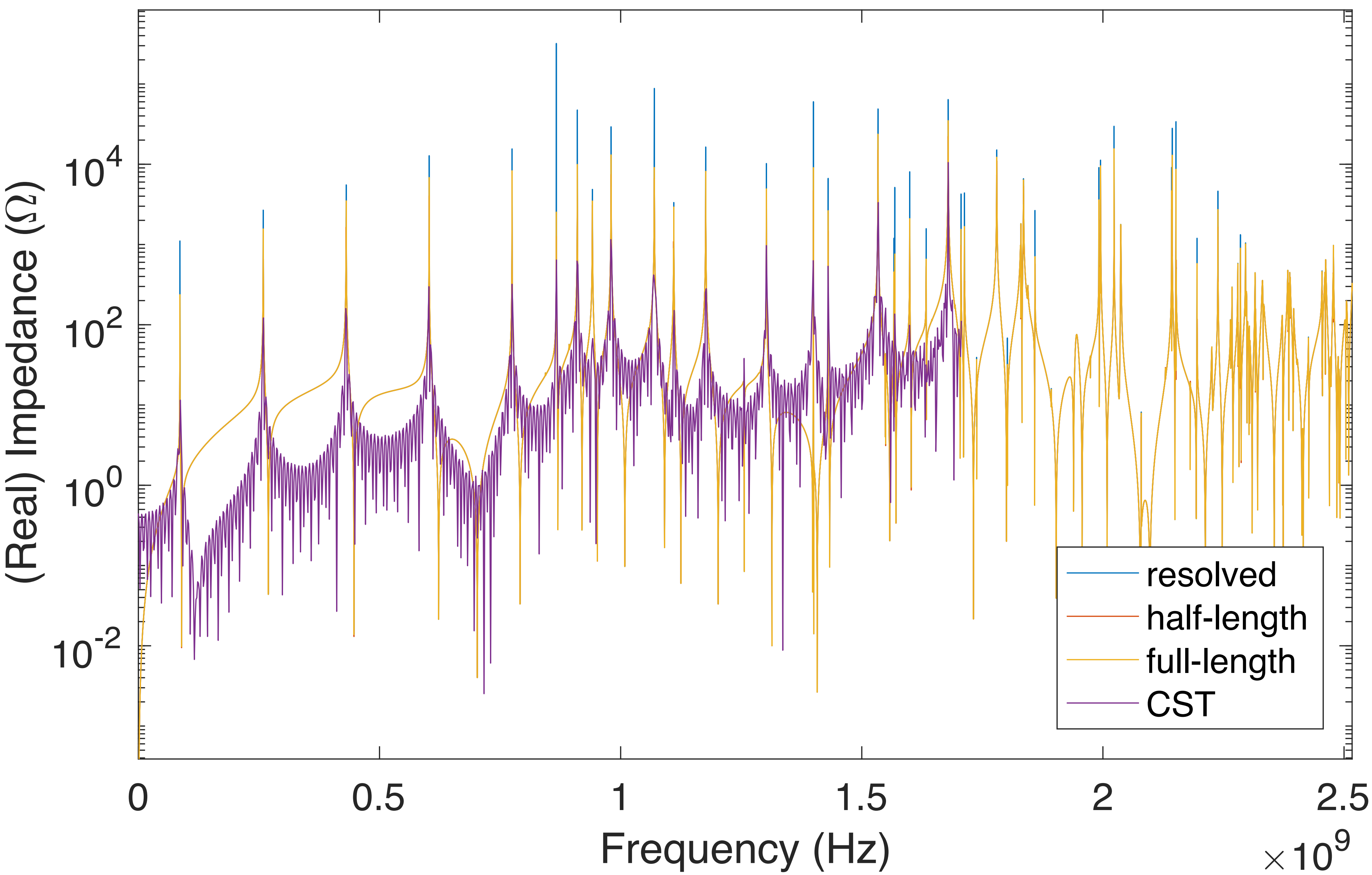
- the peak locations in (real) impedance spectrum are identified with resonant frequencies and the peak values are the effective shunt impedance, which is more accurately evaluated by CST-MWS (Eigensolver).

$$\mathrm{Re}\,[\,Z\,] = Q_e \times R_{\mathrm{long}}/Q_0$$



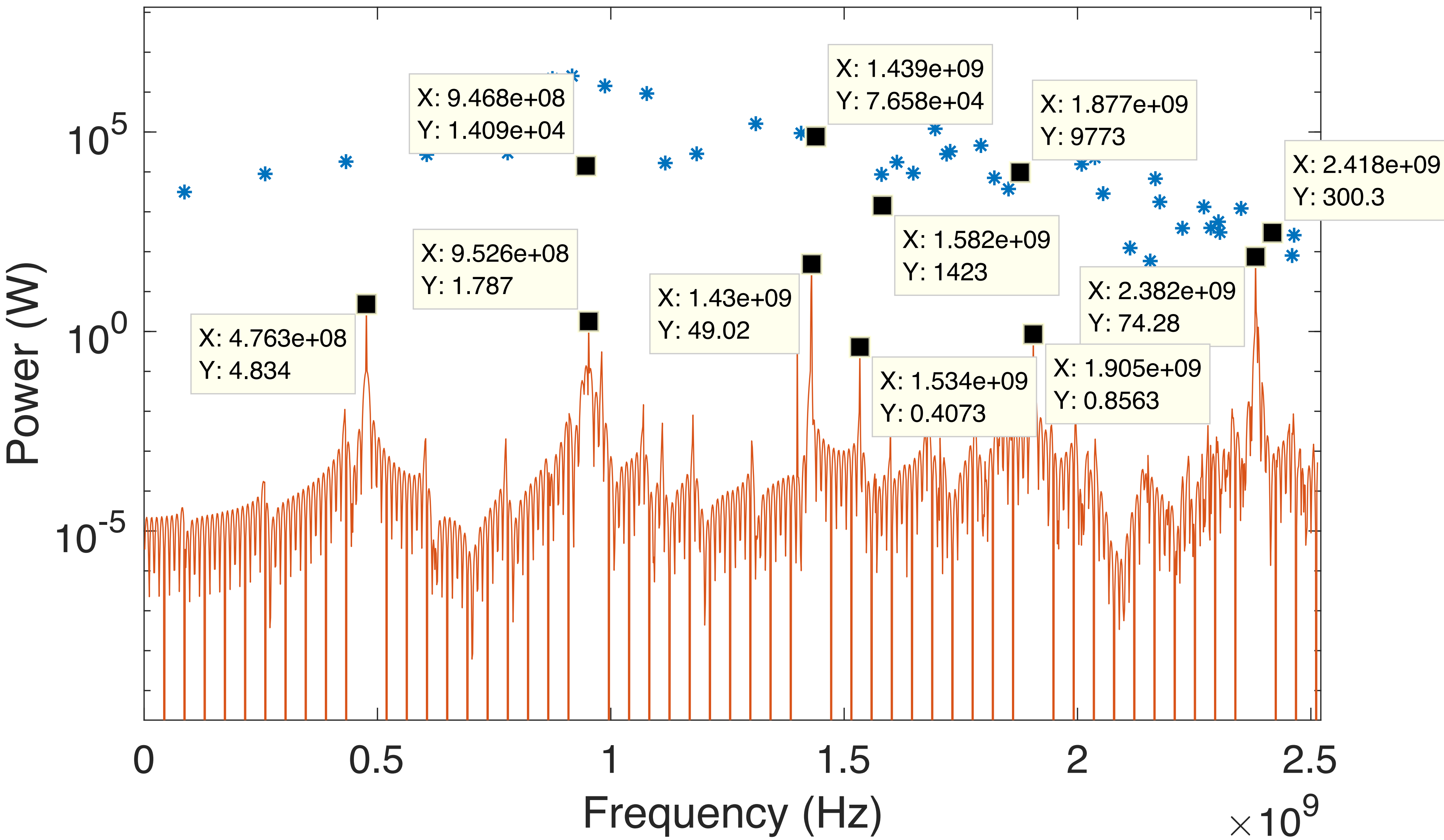
Evaluation accuracy of impedance spectrum

- The resolved values of impedance (using Daerun Li's technique) approaches close to those obtained by Eigensolver, but still there exits a factor of 3~5 difference between the two.



- Loss factor is evaluated as

$$k = \frac{2}{q^2} \int_0^\infty d\omega \, Re[Z(\omega)] I^2(\omega) \qquad U = 2 \int_0^\infty d\omega \, Re[Z(\omega)] I^2(\omega)$$

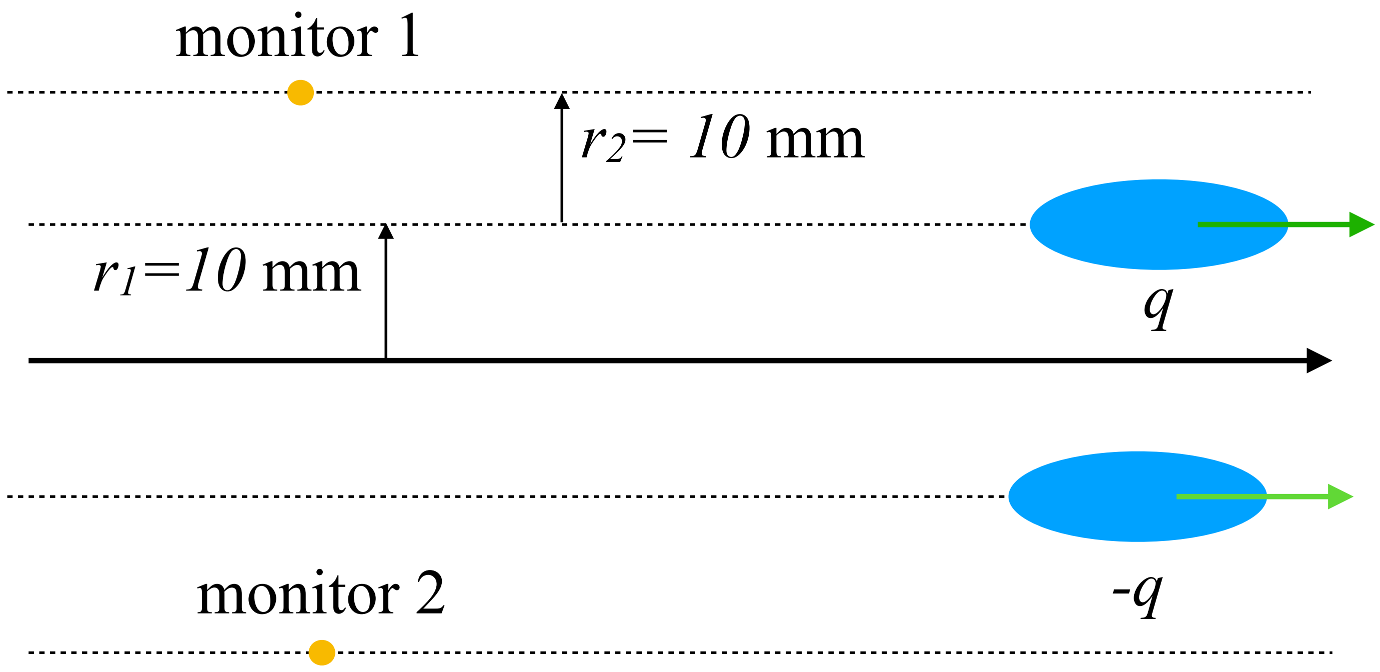


$P_{loss} = 311$ W.

$k_{loss} = 0.02$ V/pC (for single bunch)

Transverse impedance spectrum (real value) by charge off axis

- The wake field is excited by a pair of charges off axis, with positive charge above and negative charge below by the same offset.
- This configuration excites only dipole (longitudinal) field of each mode, equivalent to the transverse mode by PW theorem.



$$Z_\perp(s,0) = \frac{1}{kr_1^2}\Big[-kr_1r_2Z_\perp(r_1+r_2) + Z_\parallel(s,r_1+r_2) - Z_\parallel(0)\Big]$$

In pure dipole field,

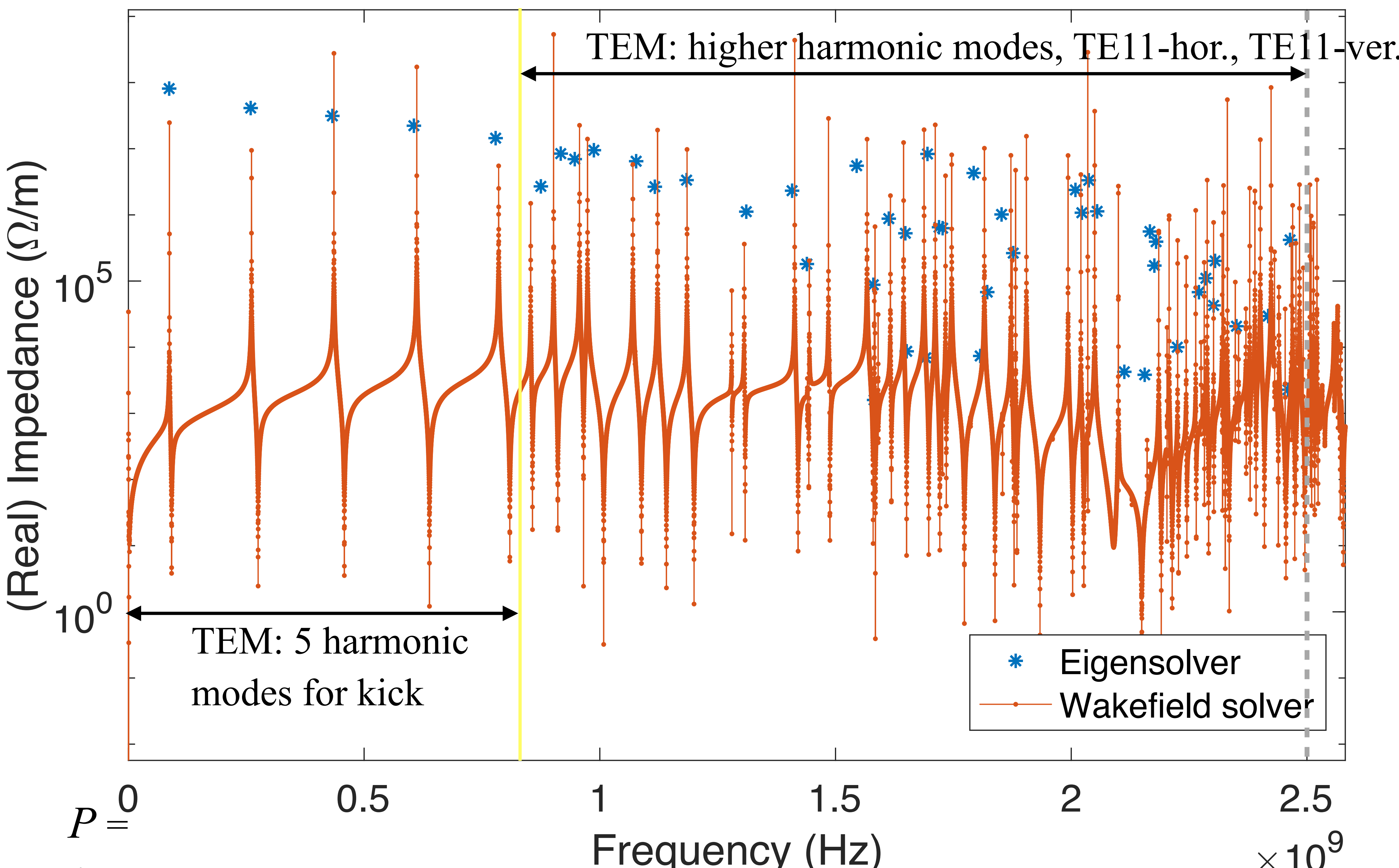
$$Z_\perp(s,0) = \frac{1}{k(r_1+r_2)r_1}\Big(Z_\parallel(r_1+r_2) - Z_\parallel(0)\Big)$$

Transverse impedance spectrum (real value) by charge off axis

- Unlike elliptical cavities, the same modes are excited by off-axis charges (as those by on axis charges).

$$\mathrm{Re}\,[\,Z_\perp\,]\,/\Delta x = Q_e \times R_\perp / Q_0\,/\Delta x$$

Cut off freq. of beam port

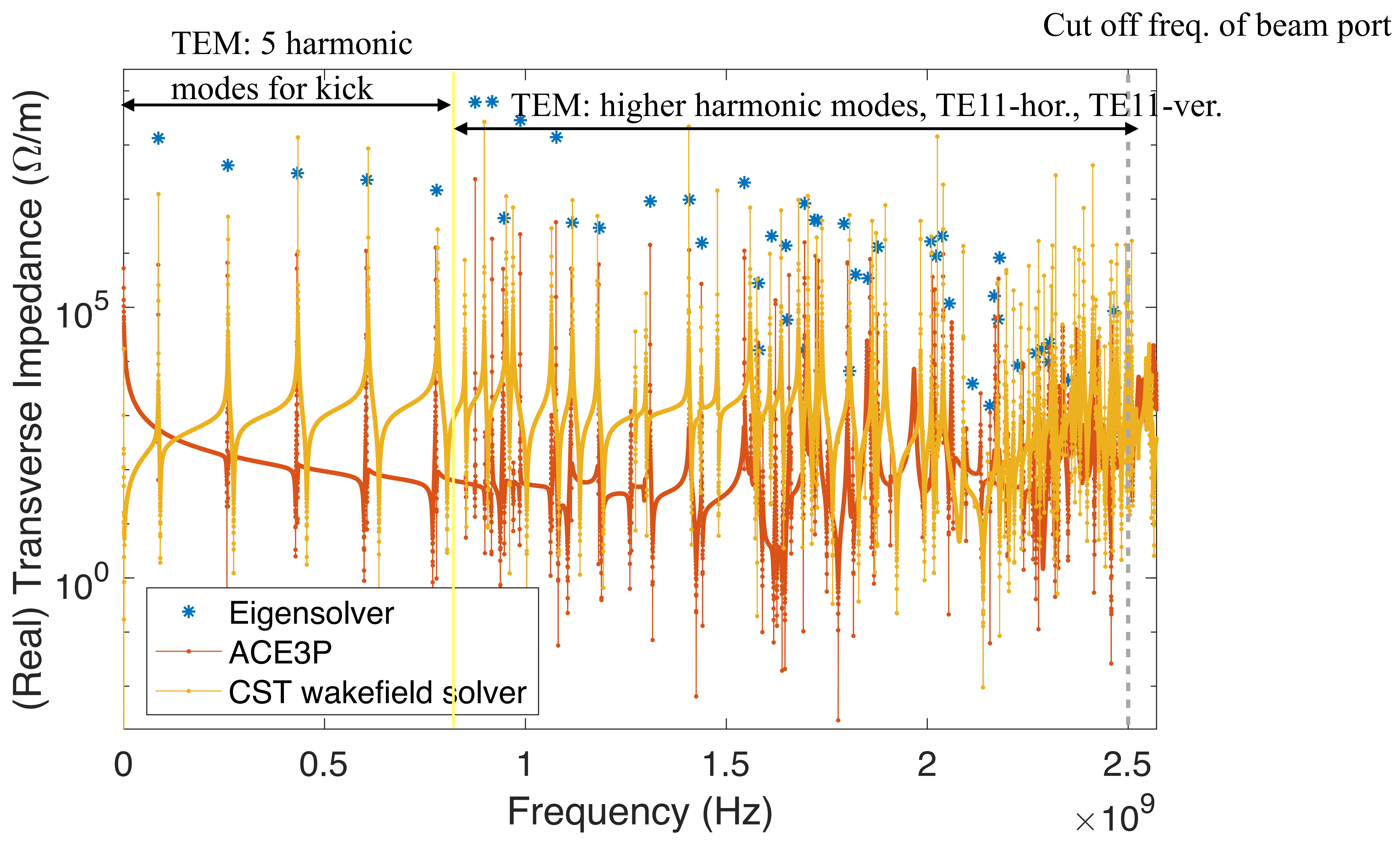


$P =$

$k =$

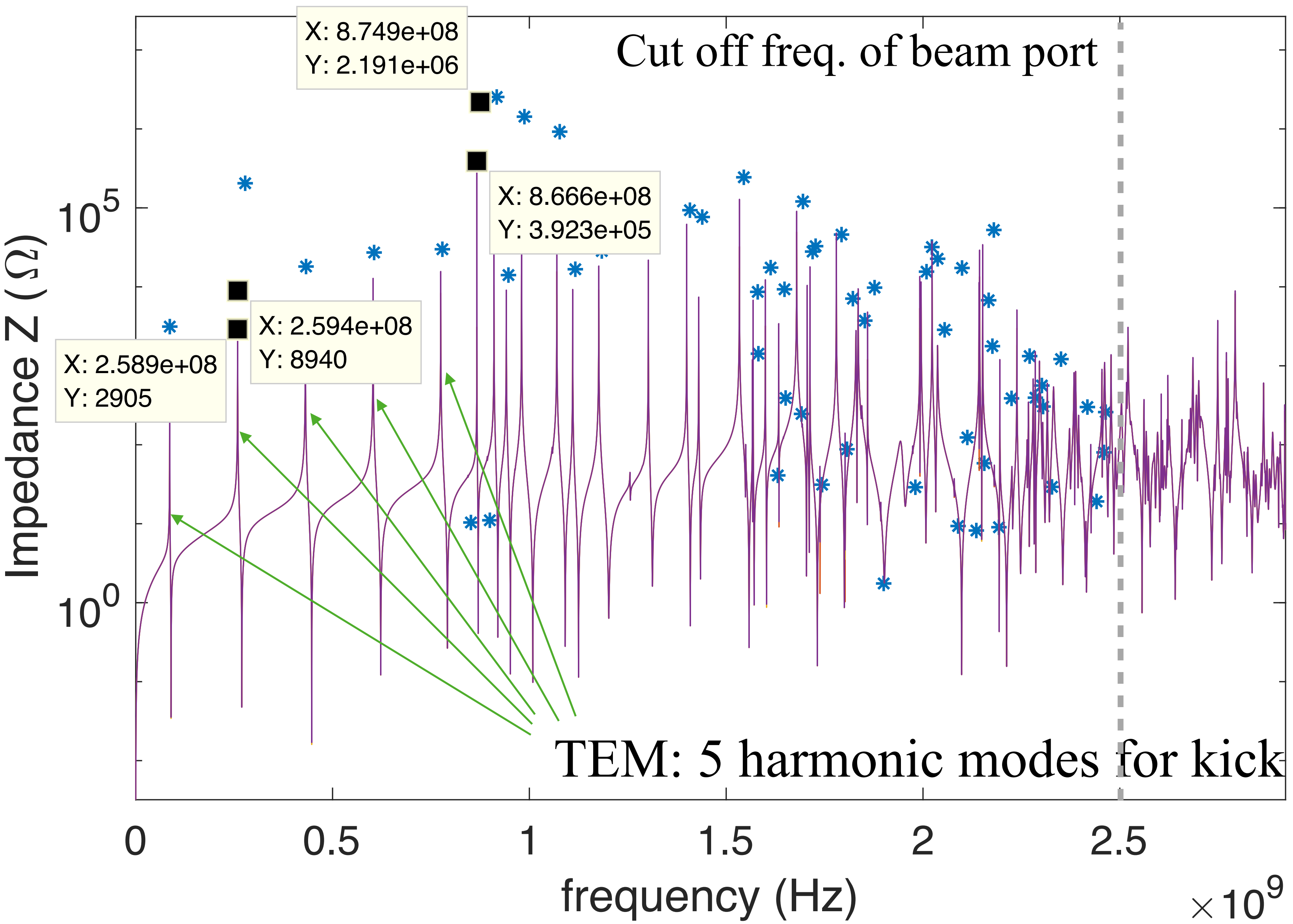
Transverse impedance spectrum (real value) by charge off axis: Comparison with ACE3P results

- The peak values of ACE3P are much lower in deflecting modes but similar in HOM's.



Impedance spectrum (absolute value) by charge on beam axis

- In wake field simulation, the locations of the peaks in (absolute) impedance spectrum were identified with resonant frequencies and the peaked values were with the shunt impedance, which is more accurately computed by CST Eigensolver. .



TEM: higher harmonic modes

TE11-ver.

TE11-hor.