Alternative Estimate of the Required Power for the SLAC Transverse Stripeline RF Kicker to be Used in the MEIC Circular Cooler Ring by Analytics and CST Simulations

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Last Update on April 22, 2015

1. Analytical Calculation

The analytical calculation of a transverse stripline kicker's parameter can be found by Glen Lambertson's technical note [1] and his later publication in [2] for the kick constant $K_\perp$ and kick impedance $R_\perp$. The relationship between them can be written as;

$$R_\perp T^2 = Z_c|K_\perp|^2 \tag{1}$$

Here T is the beam Transient Time Factor (TTF. Z_c is the drive cable characteristic impedance. In most of the case, it is 50Ω. As the equation (4.9) in note [1] with an Errara corrected on October 24, 1986:

$$K_\perp = -\sqrt{\frac{Z_L}{2Z_c}}4g_\perp\frac{v}{h\omega}e^{-j\theta}sin\theta \tag{2}$$

Here Z_L is the stripline load impedance, v is the beam velocity. For 55MeV electron beam v=c, speed of light. The h is kicker electrode separation distance. ω is the RF drive angular frequency. $g_\perp$ is kicker's transverse geometry factor, which at the centerline the beam gets transverse kick:

$$g_\perp = tanh\left(\frac{\pi w}{2h}\right) \tag{3}$$

Where w is the parallel electrode width. H is the electrode separation distance. The beam transient angle θ can be written as:

$$\theta = \left(\frac{1}{v}+\frac{1}{v_L}\right)\frac{\omega l}{2} \tag{4}$$

Bring (2) (3) (4) into (1):

$$R_\perp T^2 = 8Z_L tanh\left(\frac{\pi w}{2h}\right)^2\frac{c^2}{h^2\omega^2}sin^2\theta \tag{5}$$

Here l is the kicker electrode longitudinal length. v_L is the wave velocity in the stripline. For the TEM mode propagation in the stripline, v_L=c, also in the speed of light. The equation (5) is exactly the same as equation (4.10) in reference [1] or the equation (8.17) in reference [2].

For the SLAC's arc electrode type of electrode, we use *h/2* as the beam line center to electrode arc distance. h=89.15mm. w uses the arc length=93.36mm. l=630.43mm. Then equation (3) gives $g_{\perp}$=0.928 (close to 1). The amplitude of kick factor as the function of drive frequency can be calculated as in Figure 1.

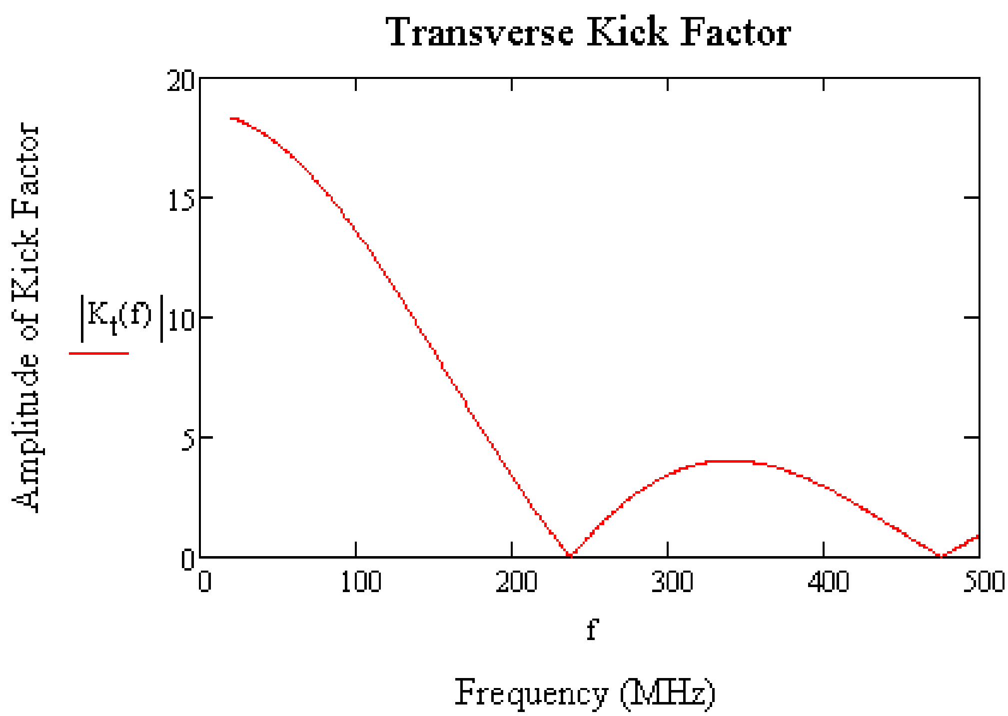

Figure1: SLAC transverse kicker's kick factor amplitude as the function of drive frequency.

As can be seen in figure 2 that, the SLAC stripline kicker only works more efficiently at low frequency, say less than 150MHz. At 238MHz and 476MHz, the impedance drop to nearly zero.

2 CST Time Domain Simulation

A full 3D geometry model of SLAC PEP-II transverse stripline kicker has been generated in the CST modeler by using SLAC provided drawings and bench surveying on the actual kicker device. Two electrodes made of Molybdenum (Mo) are suspended by separated thin Mo triangle sheets and connected through the Anchor brackets. With two matching disc blocks at both ends, the stripline kicker is formed to kick the beam in Y direction when the RF power is driven through the Ports 1 and 2 (same amplitude but with 180^{o} relative phase) and dumped thought Ports 3 and 4. The electron beam has to travel in +Z direction in order to avoid E and M kick force cancellation. Figures 3 and 4 have shown this CST time domain simulation setup.

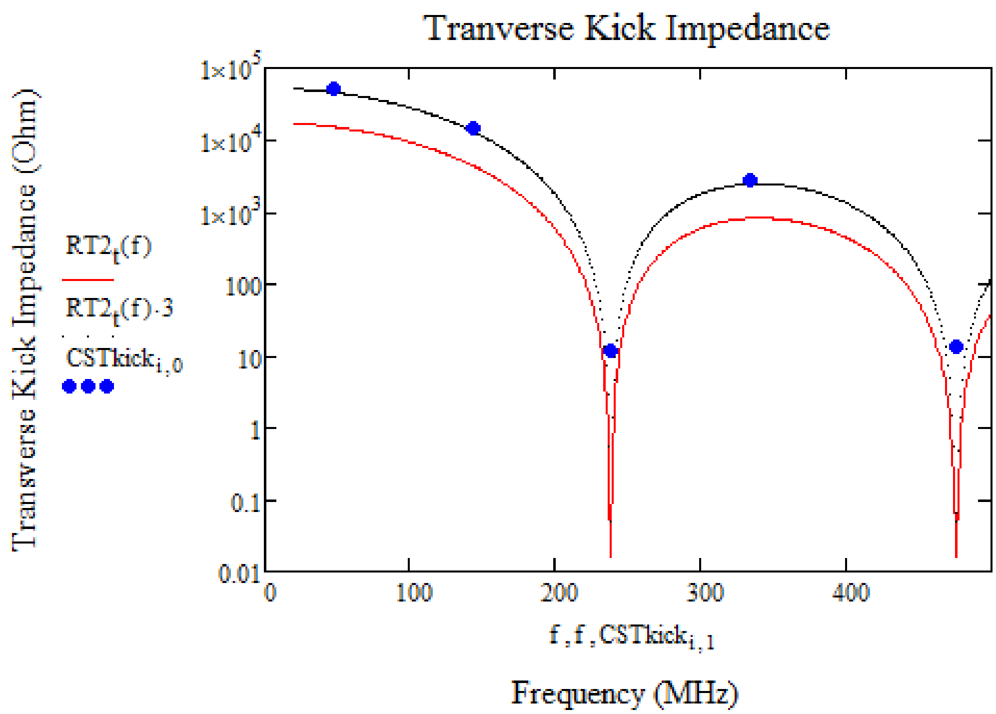

Figure 2: Transverse kick impedance including TTF as function of drive frequency. Analytical verses CST time domain simulation result.

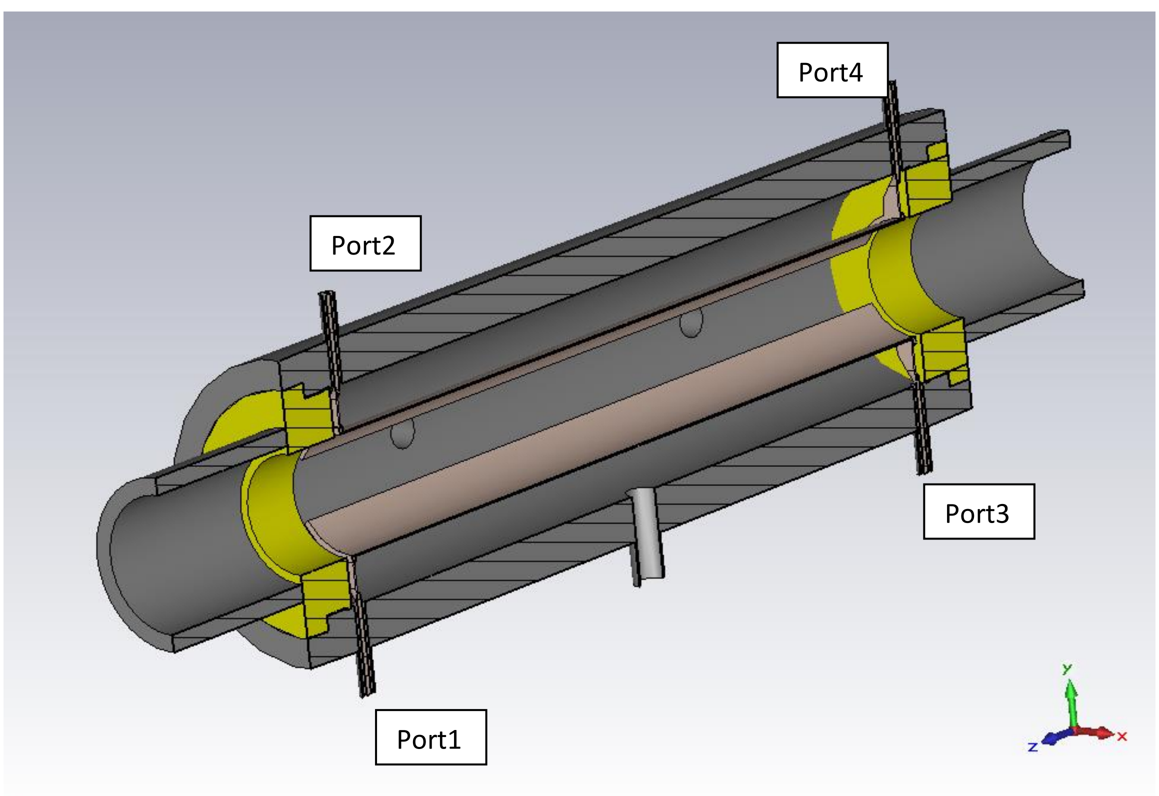

Figure 3: SLAC PEP-II Transverse Kicker geometry model for the time domain simulation

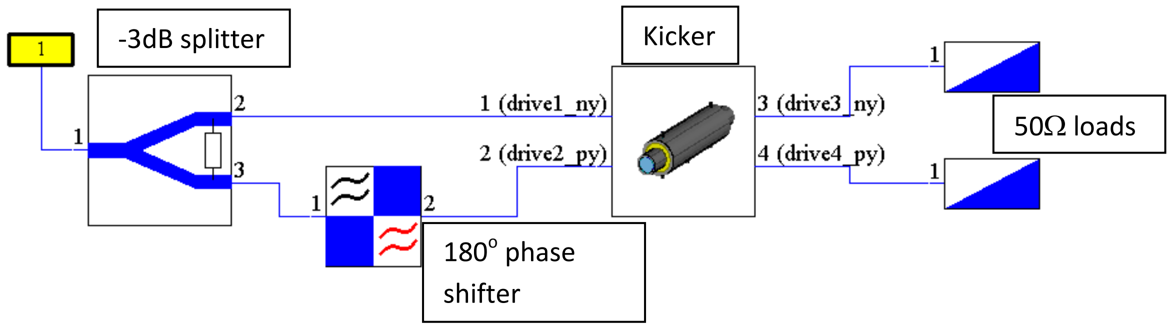

Figure 4: External circuit setup for the SLAC PEP-II Transverse Kicker impedance simulation.

The excitation signal is launched through Port1 and Port2 with an amplitude of 1W (or 1 $\sqrt{Watt}$ with a normalized line impedance) In other words, Port1= $\sqrt{50}$ V, Port2=- $\sqrt{50}$ V amplitude for 50Ω impedance line with 180° relative phases are excited simultaneously using a reference frequency for each sub-harmonic. The excitation signal source is chosen in the default mode which is a broadband excitation with the signal pulse length of ~10ns for the frequency band from 47.6MHz to 476MHz.

The full cavity field monitors of both E and H field were recorded at each sub harmonics of 476MHz, i.e. from the frequency of 47.6MHz, 95.2MHz, 142.8MHz, … 476MHz.

The kicker device in RF circuit works like a RF directional coupler. That is from Port 1 to Port 3 is a matched circuit, S31 is nearly 0dB attenuation. S42 is also near 0dB. But all other ports have -15dB to -55dB isolations.

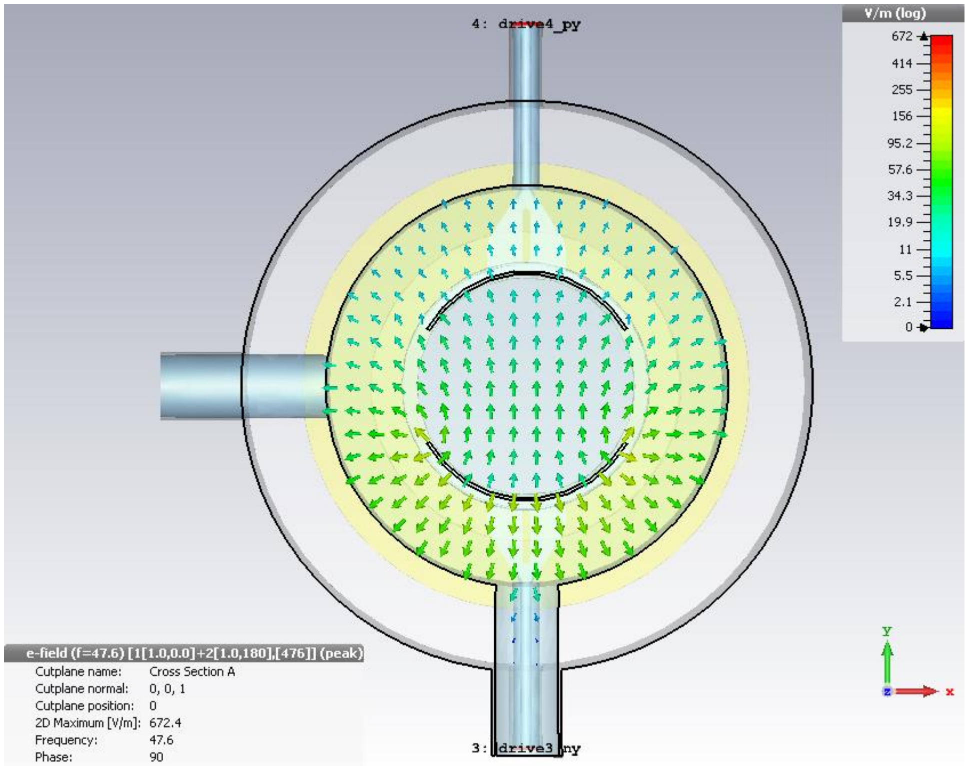

Figure 5: Electric field arrow plot cross-section in X-Y cut at the middle of the kicker z=0 position at phase of 90^o. The drive and monitor frequency is at 47.6MHz. Ports 3 and 4 are terminated with 50Ω loads. The RF power is driven at Ports 1 and 2 with 1W at phase of 0 and 180^o each.

In order to get frequency domain shunt impedance correctly, the time domain runs have to set up at each sub harmonic frequency, so the simultaneous drives at 180^o relative phases have correct meaning and the field monitor at each sub harmonic frequency has the correct field amplitudes and phases. All solution recorded are complex field, i.e. real and imaginary parts. The travelling fields run from Port1 and Port2 to Port 3 and Port4. The beam on axis will also experience this travelling wave. A special CST macro program in Visual Basic language has been developed for the calculation of transverse impedance $R_{b\perp}T^2$ by an integration of (E_y+βCB_x) transverse fields when the electron beam traveling in $+Z$ direction:

$$V_{b\perp}T = \int_{-l/2}^{l/2}[E_x + \beta c B_x]exp(ikz)dz \tag{6}$$

Since each E_y and B_x field component contains the real and imaginary parts, so the calculation (5) can be summed up in real and imaginary parts separately also:

$$re(V_{b\perp}T) = \sum_{z=-l/2}^{z=l/2}\left[\left(E_{yre} + \beta c B_{xre}\right)\cos\left(\frac{2\pi f}{\beta c}z\right) - \left(E_{yim} + \beta c B_{xim}\right)\sin\left(\frac{2\pi f}{\beta c}z\right)\right]\Delta z \tag{7}$$

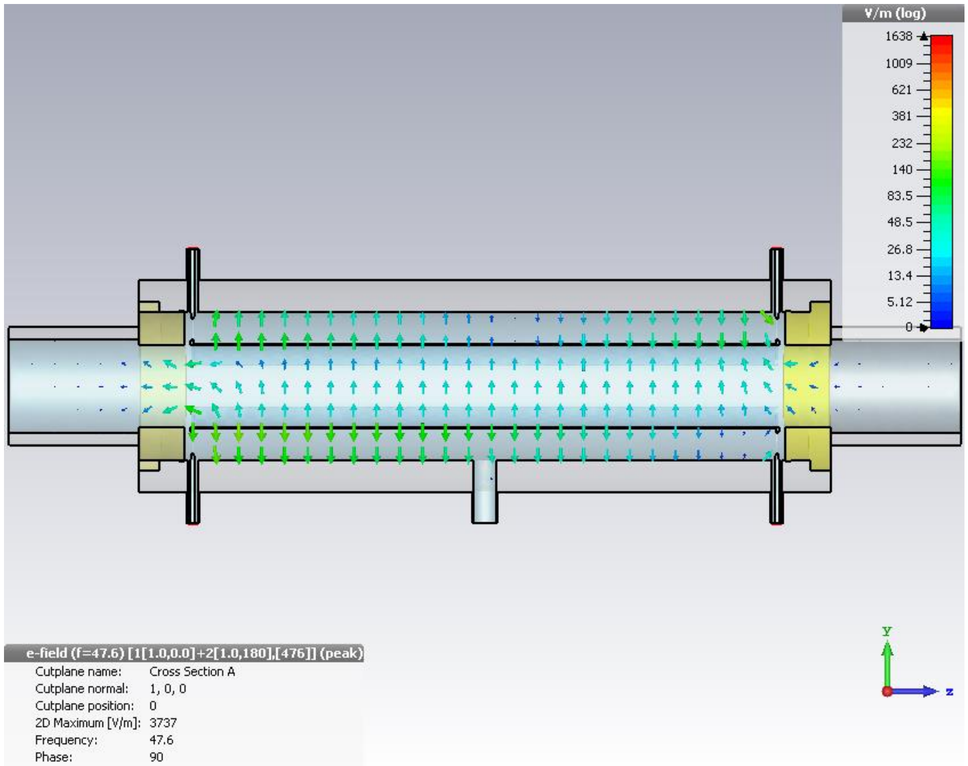

Figure 6: Electric field arrow plot cross-section in X-Z cut at the middle plane of the kicker x=0 position at phase of 90^o with the same condition of Figure 5.

$$im(V_{b\perp}T) = \sum_{z=-l/2}^{z=l/2} \left[\left(E_{yim} + \beta c B_{xim}\right) \cos\left(\frac{2\pi f}{\beta c} z\right) + \left(E_{yre} + \beta c B_{xre}\right) \sin\left(\frac{2\pi f}{\beta c} z\right) \right] \Delta z \qquad (8)$$

$$V_{b\perp}{}^2 T^2 = [re(V_{b\perp}T)]^2 + [im(V_{b\perp}T)]^2 \qquad (9)$$

The transverse kick impedance (including TTF) defined by equation (1) implies the transverse kick voltage $V_\perp$ is related by the kick factor $K_\perp$ which is geometry dependent only. That means the transverse kick impedance has different definition from the cavity type of kick impedance. Normally the cavity type kicker has the transverse impedance definition of:

$$R_{cav\perp} = \frac{V_{b\perp}{}^2 T^2}{P_{loss}} \qquad (10)$$

Here P_{loss} (W) is the RF power loss at the kicker wall (electrodes and end blocks). The $R_{cav\perp}$ (Ω) includes the TTF. The kick factor is defined as:

$$K_\perp = \frac{V_\perp T}{V_K} \qquad (11)$$

V_K (V) is the RF peak voltage on the drive line. It is related the single line drive power P_K by:

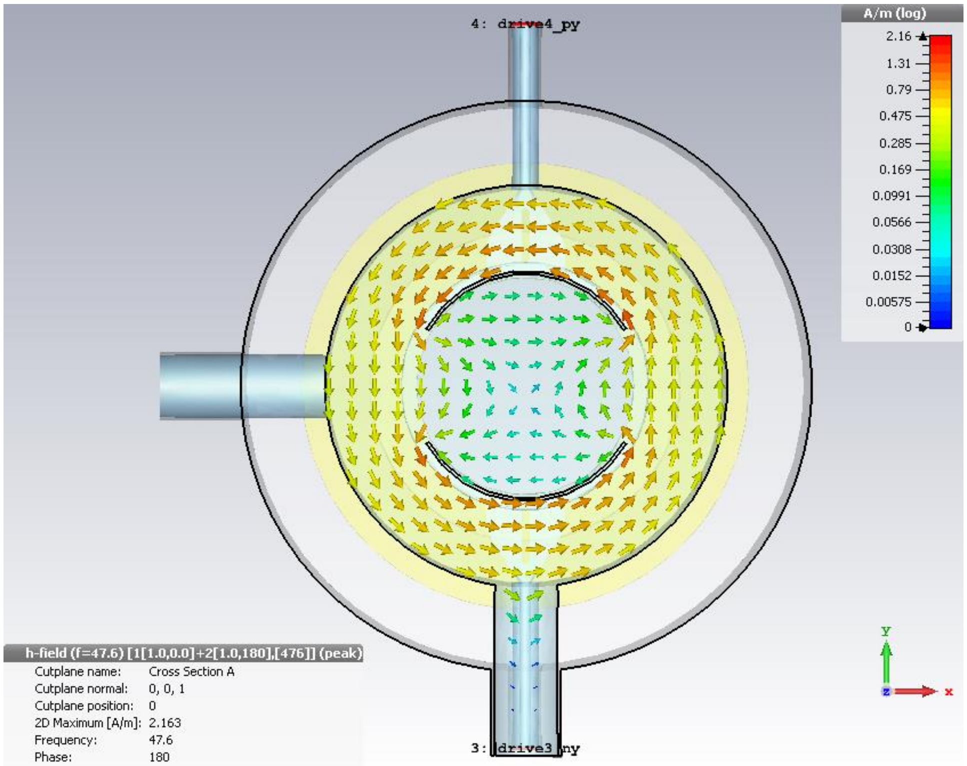

Figure 7: Magnetic field arrow plot cross-section in X-Y cut at the middle of the kicker z=0 position at phase of 180^{o} with the same condition of Figure 5.

$$P_K = \frac{V_K{}^2}{2Z_c} \tag{12}$$

Then:

$$R_{\perp}T^2 = \frac{V_{\perp}{}^2T^2}{2P_K} \tag{13}$$

Since the CST calculated $V_{b\perp}{}^2T^2$ is based on equations (6)-(9) and also generated by driving Port1 and Port2 with 1W peak power each or 0.5W rms average power each, but the equation (13) implies the P_K power is from the average value from one port only, So $V_{b\perp}{}^2T^2/(2\times0.5)=R_{\perp}T^2$ is the number of transverse kick impedance defined by equation (1) and its relation to the drive power P_K by equation (13). We have found the CST calculated beam impedance including TTF ($V_{b\perp}{}^2T^2$) is always a factor of ~3 larger than the $R_{\perp}T^2$ value calculated by equation (5). After carefully inspecting all places possibly having a factor of 2 missing by definition or deviation, we concluded that this factor of 3 come from two places. One is related to the $g_{\perp}$ factor from the original kicker device by parallel plate electrodes described in [1] and [2] to the SLAC type kicker which electrodes are curved surface. After doing a 1D line plot at $x=0$ and $z=0$ for the E_y field magnitude (include real and imaginary) from Figure 5, ignoring the wavelength effect since it can be treated as the electrostatic field case, we have found from Figure 8 that the electric field at beam axis position (*x=0, y=0, z=0*) does have a higher value than at the plate surface. The ratio between mark 1 and mark 2 value is 1.732. If we integrate this E_y field, we should get $V(r=b)<E_y(r=0)h/2$. An estimate of such an integration is V(r=b)=1.25*E_y(r=0)h/2. Derive this factor into the kick impedance will be 1.25^2=1.563 factor. Another place is the problem in the definition of equation (1). If the kick impedance is the beam impedance generated by two set of transmission line channels with each line impedance of Z_c and kick factor of P_K is for one line drive power. Then equation (1) should have a factor of 2 on the right. The impedance calculation discrepancy between using equation (5) and CST (6)-(9) must be in both places. So in order to use equation (5) for an analytical calculation for the SLAC type stripline kicker, we should use a factor of 3 multiples original impedance expression for the parallel plates.

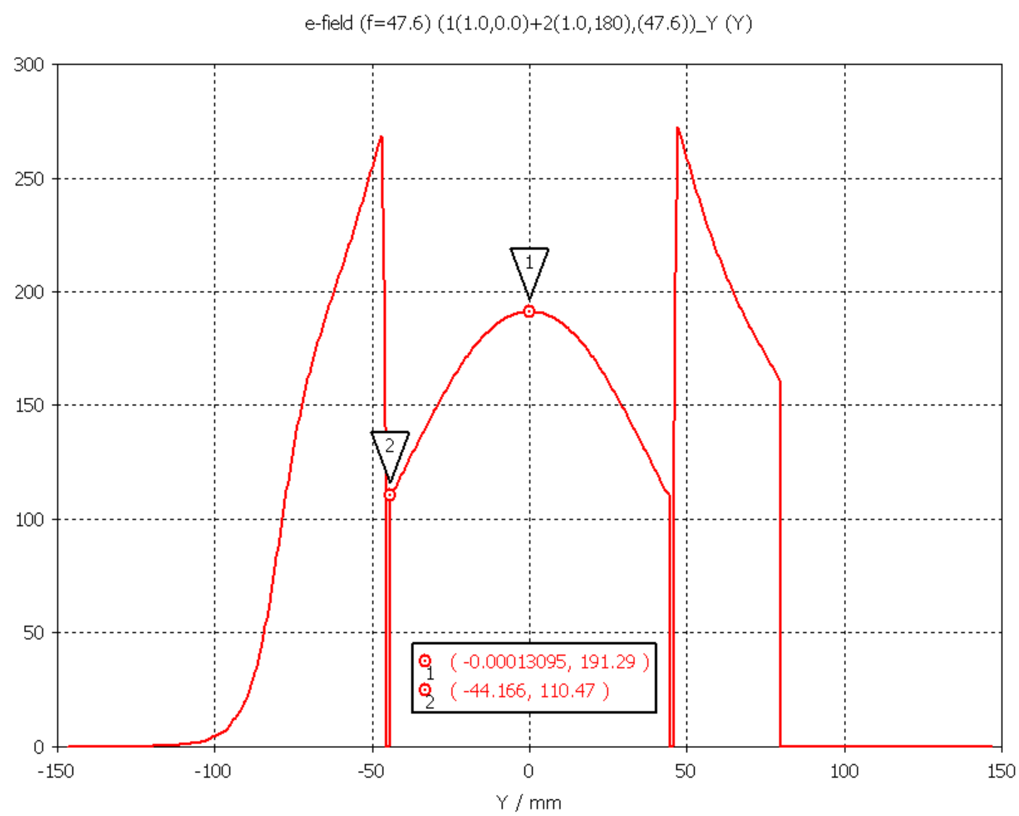

Figure 8: E_y field magnitude in *V/m* along y line at *x=0, z=0* from Figure 5 arrow plot.

In Figure 2, the comparison of the CST calculated impedance (in blue dots) to the analytical formula (5) (in red curve) and 3 times of red curve (in black) have been shown. So we can use equation (5) times 3 and (16) for the harmonic kicker power estimate.

3 Harmonic Kicker Power Estimate

To use this kicker for the MEIC ERL based Circular Cooler Ring with harmonic drive of 10 modes, we have used FFT analysis using 10 modes of sub-harmonic of 476MHz which requires the electron bunches circulate in the cooler ring in 2.1ns bunch spacing (0.63m). The ten harmonics combined pulse will kick the bunches every 1 out of 10 with a flat top of the pulse voltage in 1.4e-3 from the head or tail to the centroid of the bunch in plus and minus 3 σ, here bunch length of 1 σ is 2cm. To achieve this flat top voltage pulse in 55kV, the voltage amplitude and phase of each harmonic have to be as following table which is calculated by Yulu for the cavity type of harmonic kickers' design to kick the beam bunch in 1mrad's angle.

Table 1: RF power estimate for generating 10 harmonic modes on the SLAC's PEPE-II kicker

Frequency f (MHz)	Kick Voltage $V_{\perp}$ (kV)	Voltage Phase (rad)	Impedance $R_{\perp}T^2$ (Ω)	Power $2P_K$ (kW)
47.63	13.895	-0.003	45229.9	4.269
95.26	12.595	-0.006	29577	5.363
142.89	10.59	-0.009	13119.2	8.548
190.52	8.101	-0.012	2803.1	23.412
238.15	5.396	-0.015	0.049	5.939E5
285.78	2.751	-0.018	1267.0	5.973
333.41	0.439	-0.001	2419.2	0.080
381.04	1.396	3.117	1841.2	1.058
428.67	2.576	3.114	549.0	12.087
476.3	3.086	3.111	0.049	1.943E5
DC offset	8.348			
Total	55.056		4.986E4	60.790*

* Due to the inefficiency of this kicker at 238.15MHz and 476.3MHz, the total power calculation doesn't include these two modes.

You can see that by using SLAC's PEP-II kicker to get the 1mrad's kick angle for the 55MeV electron beam, one needs total of ~60kW of CW RF power. It is too much power for the port feedthroughs.

To redesign this type of kicker for the same kick performance, a different electrode length l has been suggested, for example, by Jiquan [3], ϕ=0.13π which in turn of the l is:

$$l = \frac{\phi c}{\omega_1} = \frac{0.13c}{2f_1} = 0.40938m \tag{14}$$

Using l=0.40938m and 3 times of equation (5), the new data of $R_{\perp}T^2$ impedance has been calculated for h=70mm (beam center to electrode arc surface distance=35mm). Figure 9 shows the kick impedance has a notch at f=366MHz, but more in efficiency due to using smaller aperture h and shorter electrode length l. This modification saves the drive power by 30%.

To avoid the notch frequency falls on any harmonic frequency, making two separated kickers with different electrode lengths is suggested. Their optimum lengths need to be further studied.

Making a single kicker device with a shorter length (like $l=245$mm) is possible, but the power is still too much for two 50Ω feedthroughs to handle.

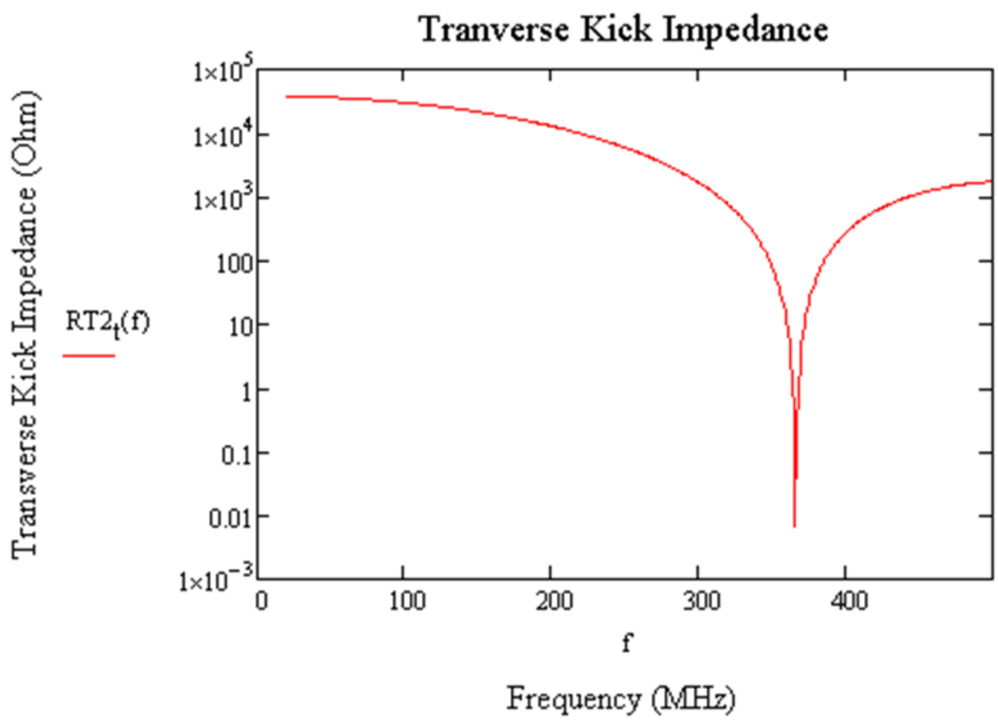

Figure 9: Kick impedance for $h=70$mm, $l=409.4$mm for the arc type electrode kicker. Notch frequency is at 366MHz.

Table 2: RF power estimate for generating 10 harmonic modes on the SLAC's type h=70mm kicker

Frequency f (MHz)	Kick Voltage $V_\perp$ (kV)	Voltage Phase (rad)	Impedance $R_\perp T^2$ (Ω)	Power $2P_K$ (kW)
47.63	13.895	-0.003	36529.4	5.285
95.26	12.595	-0.006	30767.7	5.156
142.89	10.59	-0.009	22780.6	4.923
190.52	8.101	-0.012	14417.9	4.552
238.15	5.396	-0.015	7354.6	3.959
285.78	2.751	-0.018	2613.9	2.895
333.41	0.439	-0.001	367.9	0.524
381.04	1.396	3.117	56.8	34.285
428.67	2.576	3.114	740.9	8.956
476.3	3.086	3.111	1515.8	6.283
DC offset	8.348			
Total	55.056		7.112E4	42.533*

* Due to the inefficiency of this kicker at 366MHz, the total power calculation doesn't include the 381.04MHz mode.

4 References:

[1] G. R. Lambertson, Dynamic Devices – Pickups and Kickers, LBL-22085, BECON-63, LBL, UC Berkeley, August, 1986.

[2] D. A. Goldberg and G. R. Lambertson, Dynamic Devices, A Primer on Pickups and Kickers LBL-31664, November, 1991.

[3] Jiquan Guo, Haipeng Wang, First Estimate of the Required Power for the Stripeline RF Kicker, to be published with this note, April, 2015.