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HARMONIC STRIPLINE KICKER FOR MEIC BUNCHED BEAM COOLER*

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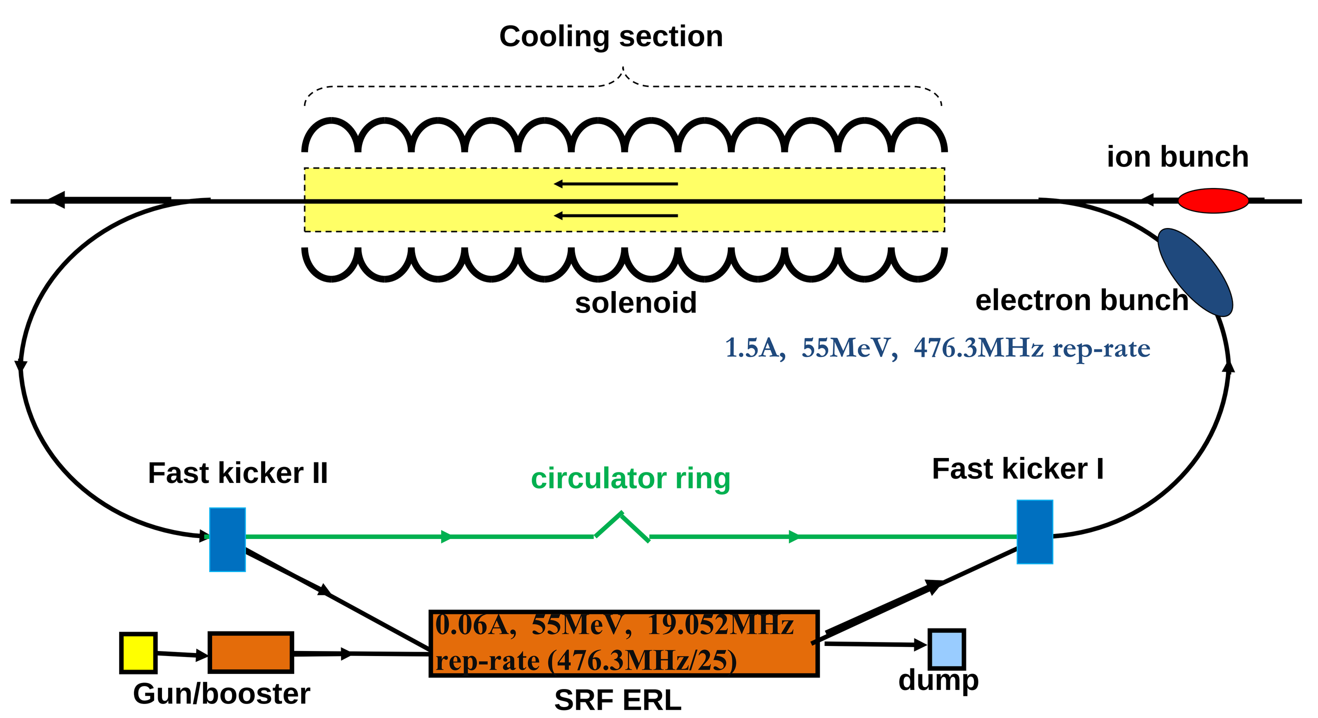
Abstract

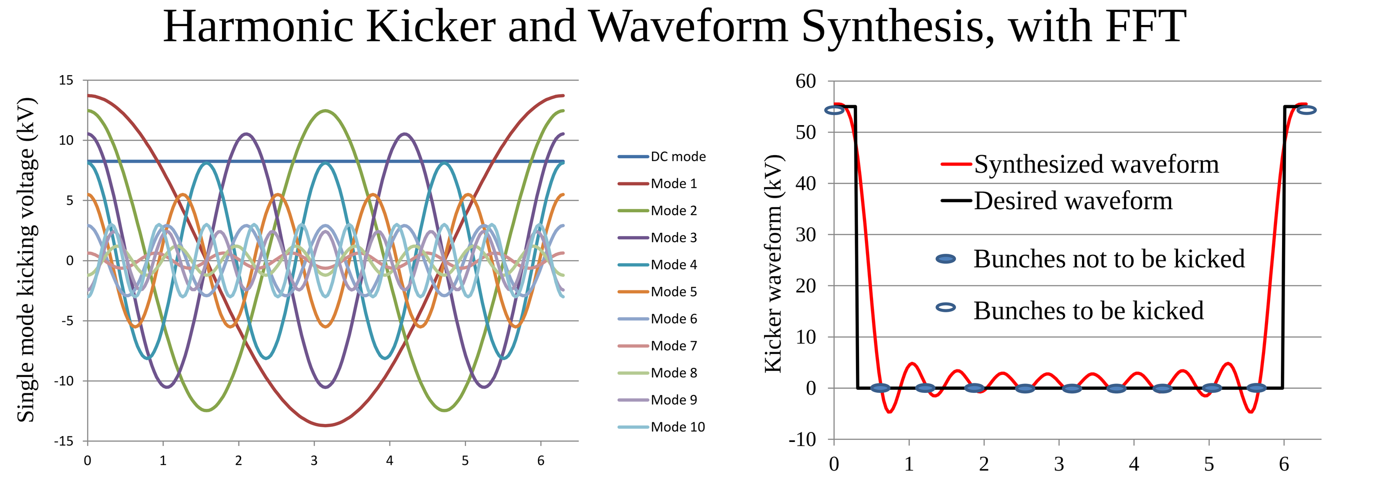
In the current MEIC design, the ion collider ring needs to be cooled by a bunched electron beam of up to 200 mA 55 MeV, with the possibility to upgrade to 1.5 A. Although it's not impossible to design and build an ERL to provide such a beam, the technical risk and cost associated with such an ERL would be very high. An alternative is to recirculate the electron bunches in a ring for up to 25 turns until the bunch's quality is degraded, reducing the beam current in the ERL by a factor of 25. This scheme requires a pair of fast kickers that kick one in every 25 bunches. In this paper, we will analyze the electrodynamics of a harmonic stripline kicker for this circulator ring, and compare to the harmonic resonator kicker.

Circulator Ring for MEIC Bunched Electron Cooler



Electron beam will be accelerated to 55MeV in the ERL, injected into the circulator ring by kicker I, circulates M passes (M=25 in this case) in the circulator ring and perform cooling, then extracted back to the ERL by kicker II, deaccelerated and dumped.
The bunch repetition rate in the ERL (and the gun/booster) will be reduced to 1/25 of that in the cooling channel, as well as the beam current.
Kicker rise/fall time is required to be <<1 ns, and repetition rate needs to be 19 MHz. This set of parameters will be prohibitive for switching DC pulse kickers, but could be achieved with harmonic kickers.
A simplified version of kicker with M=10 and repeats at 47.6MHz will also be used in the discussion.

Harmonic Kicker and Waveform Synthesis, with FFT



A harmonic kicker utilizes the harmonic alternating EM field to synthesize the desired periodic waveform. For a particle with different initial position z_0 (which determines the phase when the particle arrives at the kicker), the total kick it receives from N RF modes will be

$$V_\perp(z_0) = V_{\perp 0} + \sum_{n=1}^{N} V_{\perp n} \cos\left(\frac{n\omega_0 z_0}{c} + \phi_n\right)$$

We can use FFT to find the kicking voltage of each mode that approximates the desired waveform with finite number of N modes, usually N≈M. Waveform shown above kicks one in every 10 bunches using 10 RF modes plus DC offset. The crabbing effect of voltage slopes can be canceled by a 180° betatron phase advance between two kickers. The table below shows the voltage and power of each mode for a stripline kicker with d=70mm and L=432mm (this length minimizes the total power for this set of $V_{\perp n}$). The total power is 47.2kW, about 500 time of the power needed for the resonator kicker (MOPF13). If M and N goes to 25, the total power can be reduced to ~19kW.

Mode frequency (MHz)	Transverse impedance $R_\perp$ (Ω)	Kicking voltage (kV)	Power (kW)
DC	∞	8.256	0
47.63	40134	13.711	4.665
95.26	33148	12.462	4.670
142.89	23665	10.532	4.680
190.52	14084	8.129	4.697
238.15	6442	5.503	4.730
285.78	1802	2.917	4.808
333.41	78	0.63	5.677
381.04	318	-1.209	4.384
428.67	1271	-2.432	4.566
476.30	1942	-3.011	4.631
Total/Avg	**65228**	**55.488**	**47.2**

Two Technical Approaches

Stripline Kicker (details discussed in this poster)

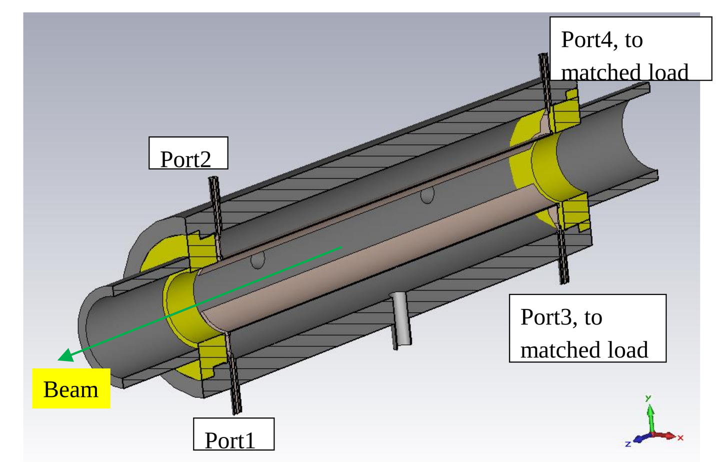


Fig. 2a. 3D model

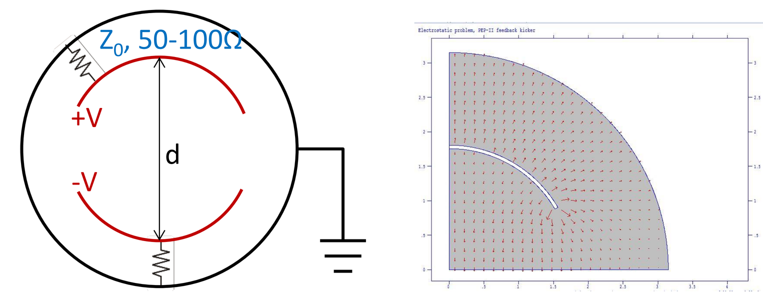
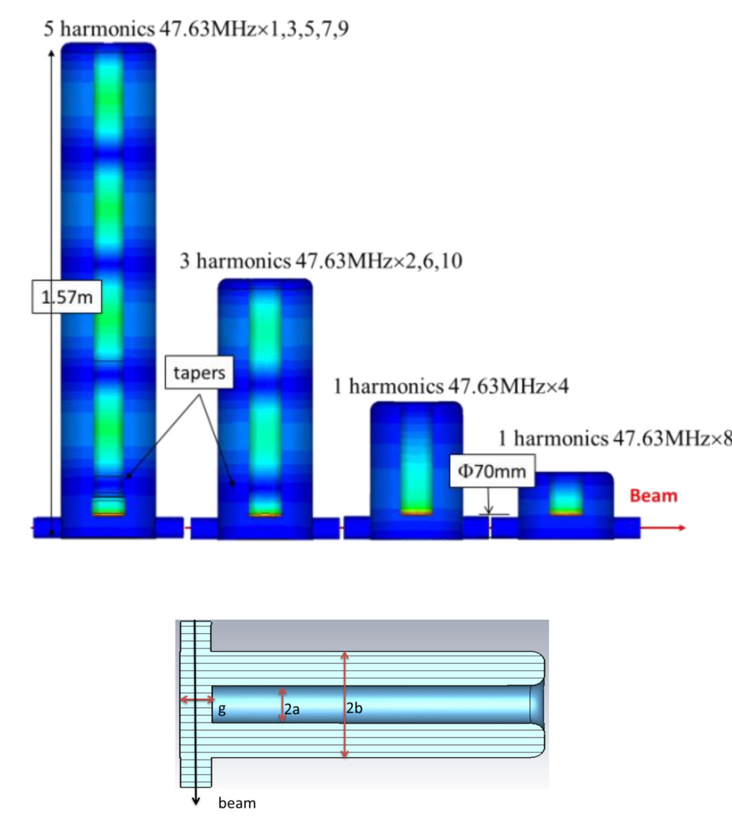


Fig. 1b. Cross section model and E-field from 2D electrostatic solver

- TEM mode, travelling wave propagating opposite to the beam
- Lower impedance and efficiency (but could be efficient enough?)
- Possible to excite all the 25 modes in one device to synthesize the desired waveform, making the system compact.
- No frequency tuning needed
- Can be scaled from the PEP-II feedback kicker design (Z_0=50Ω)
- **E=2V/g/d** around the longitudinal axis, g is a geometry factor
- g=0.843 for the PEP-II kicker, g=1 for large parallel plates

QWR Cavities (MOPF13)



- TEM mode, standing wave in Quarter Wave Resonators with capacitor loaded at the beamline end
- Higher efficiency
- Each cavity can only excite odd harmonics of the cavity's fundamental mode. Needs 5 different cavities to generate 25 modes to synthesize the desired waveform.
- Frequency tuning of multi modes in one cavity might be difficult

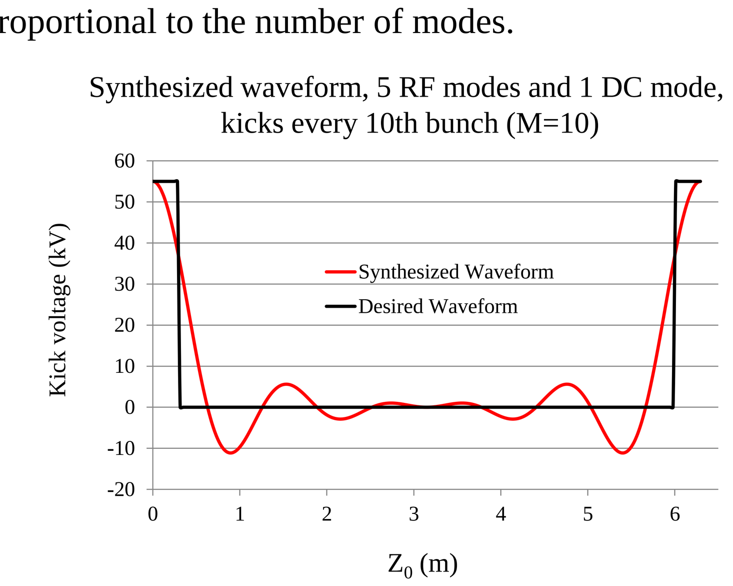
Waveform Synthesis with Constraint Method

Minimum Number of Modes

We can't, and don't have to make a perfect square wave with finite harmonic modes. For a waveform that kicks one in M bunches, the synthesized voltage only need to meet constraints (shown below) at the center of each bunch, plus an optional flat top requirement near the kicked bunches.

$$V_\perp(z_0) = \begin{cases} 55kV, & \frac{M\omega_0 z_0}{2\pi c} = 0 \\ 0, & \frac{M\omega_0 z_0}{2\pi c} = 1, 2, \ldots, M-1 \end{cases}$$

By setting ϕ_n=0, the system of linear equations with N+1 variable $V_{\perp n}$ defined by the constraints will have a rank of M/2+1 or (M+1)/2 due to symmetry, so we can reduce the number of modes to ~M/2.
As shown below, we can generate the waveform satisfying aforementioned constraints for M=10 with 5 RF modes. The total power can be optimized to 25kW with kicker length 416mm (0.66×λ_M). If we increase M to 25 and N to 12, the power can be reduced to 11.6kW, roughly inversely proportional to the number of modes.



Mode frequency (MHz)	Transverse impedance $R_\perp$ (Ω)	Kicking voltage (kV)	Power (kW)
DC	∞	5.5	0
47.63	37525	11	3.225
95.26	31417	11	3.851
142.89	23005	11	5.260
190.52	14292	11	8.466
238.15	7059	5.5	4.285
Total/Avg	**120579**	**55**	**25.1**

Zero Gradient Waveform

We can also use M-1 RF modes to construct the waveform and apply additional zero gradient constraints at the bunches, avoiding the emittance growth due to crabbing [TUYAUD04].

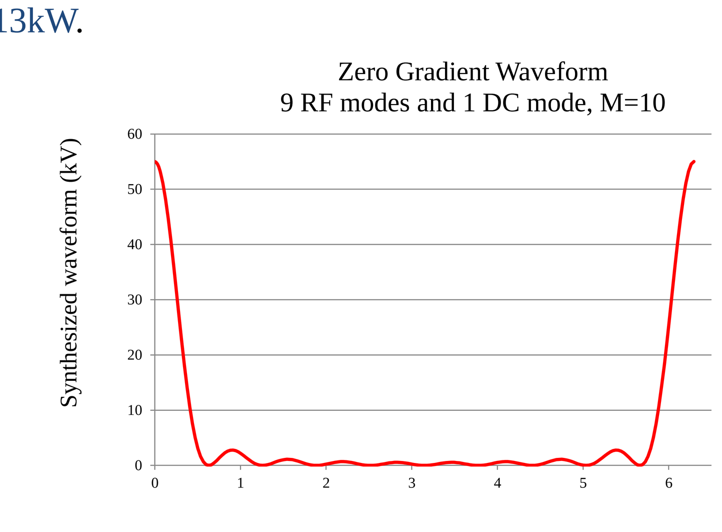
$$\frac{dV_\perp(z_0)}{dz_0} = 0, \qquad \frac{M\omega_0 z_0}{2\pi c} = 0, 1, 2, \ldots, M-1$$

In this case, the rank of the constraint matrix is M. The solution will be

$$V_{\perp 0} = V_\perp / M$$

$$V_{\perp n} = \frac{2V_\perp(M-n)}{M^2}, n = 1, 2, \ldots, M$$

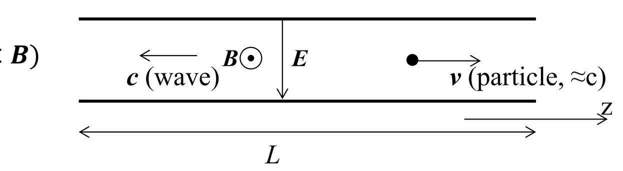
The waveform for the case M=10 is shown below. The total RF power needed is 30.7kW when optimized with 289mm kicker length (0.46×λ_M). With M=25, the power reduces to 13kW.



Mode frequency (MHz)	Transverse impedance $R_\perp$ (Ω)	Kicking voltage (kV)	Power (kW)
DC	∞	5.5	0
47.63	18662	9.9	5.252
95.26	17151	8.8	4.515
142.89	14851	7.7	3.992
190.52	12047	6.6	3.616
238.15	9071	5.5	3.335
285.78	6241	4.4	3.102
333.41	3820	3.3	2.851
381.04	1975	2.2	2.451
428.67	765	1.1	1.581
Total/Avg	**98550**	**55**	**30.7**

Single Mode Transverse Shunt Impedance in a Stripline Kicker

$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$



For TEM modes in a stripline, travelling wave propagates at speed of light with **E**=-**c**×**B**
If the electron travels close to speed of light and opposite to the wave propagation direction, the electric force and the magnetic force will be equal and add up, ***F***=*2e**E***.
The transverse E-field of one traveling harmonic with amplitude $\bar{E}$ and angular frequency ω is a function of time and position $E_{wave} = \bar{E}\cos(\omega(t+z/c))$
Particle location is a function of time $z=ct+z_0$
Total kick field (E-field equivalent) from the traveling wave for the particle at location z is

$$E = 2\bar{E}\cos\frac{\omega(2z-z_0)}{c}$$

The kicking voltage of single mode is the field integral along z axis

$$V_\perp = \int_{-L/2}^{L/2} 2\bar{E}\cos\left(\frac{\omega(2z-z_0)}{c}\right)dz = \frac{2c\bar{E}}{\omega}\sin(\omega L/c)\cos\left(\frac{\omega z_0}{c}\right)$$

For the center of 0th bunch with z_0=0 (arriving at center of kicker at t=0 and "on phase")

$$V_\perp = \frac{2c\bar{E}}{\omega}\sin(\omega L/c), \qquad \bar{E} = \frac{2V}{gd}$$

The wall loss is negligible as most of the power is dumped into the load. RF power needed to excite that mode will be

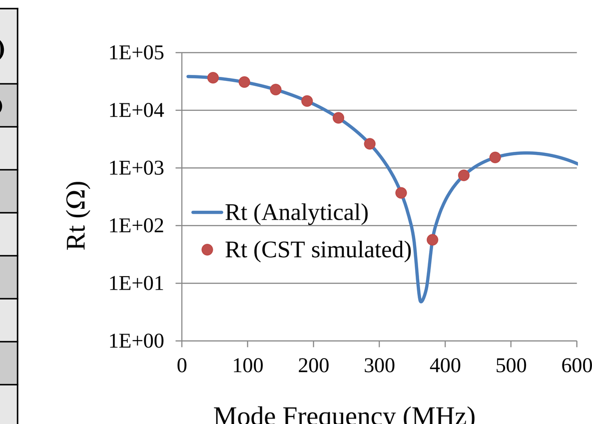
$$P = 2\frac{(V)^2}{2Z_0}$$

The resulting transverse shunt impedance for single mode on the kicked (0'th) bunch is

$$R_\perp = \frac{V_\perp^2}{P} = Z_0\left(\frac{V_\perp}{V}\right)^2 = Z_0\left(\frac{4\sin(\omega L/c)}{g\omega d/c}\right)^2$$

Benchmark Impedance calculation with CST MWS

Frequency (MHz)	Transverse impedance $R_\perp$ (Ω)	
	CST	Analytical+2D
47.63	36529.4	36363.34
95.26	30767.7	30627.88
142.89	22780.6	22677.02
190.52	14417.9	14352.37
238.15	7354.6	7321.18
285.78	2613.9	2602.04
333.41	367.9	366.22
381.04	56.8	56.59
428.67	740.9	737.53
476.30	1515.8	1508.95



- Cross-section scaled from the PEP-II kicker to d=70 mm.
- Length 409mm, minimizing the total power for a certain set of mode amplitudes
- Shunt impedance will be 0 when kicker length is half wavelength. Need to avoid when optimizing the kicker length.
- The other parameters are kept same: g=0.843, Z_0=50Ω
- Results from both methods agree very well

CONCLUSION

We analyzed the dynamics of the stripline RF kicker and derived the analytical equation to estimate the shunt impedance; the result well agrees with numeric simulation. We are able to optimize the length of such a kicker, so that the RF power needed to construct a waveform using certain set of harmonics can be minimized. To generate 55kV kick in every 25th bunches with 12 modes in the MEIC recirculating electron cooler, the power needed is 11.6kW for a kicker scaled from the PEP-II feedback kicker to 70mm beampipe. To generate 55kV "zero gradient" kick with 24 modes, the power increases slightly to 13kW. The power requirement for the stripline kicker is 2-3 orders of magnitude higher than a set of resonant kickers, but is not prohibitive. The shunt impedance of the stripline kicker can be further improved with higher characteristic impedance, if we can match with the loads and sources.

REFERENCES

[1] A. Sy et al., "Development of an Ultra Fast RF Kicker for an ERL-based Electron Cooler", TUYAUD04, this workshop.
[2] J. Guo et al., JLAB-TN-15-020
[3] Y. Huang et al., Ultra-fast Harmonic Resonant Kicker Design for the MEIC Electron Circular Cooler ring, WEICLH2063, ERL2015 workshop.