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Theory and Conceptual design of kickers

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Introduction

We design dipole and quadrupole stripline kickers to study the effect of echoes in the Integrable Optics Test Accelerator (IOTA) ring. We need to use these kickers to generate an echo: a recoherence of particle motion in phase space. To produce an echo, we use an electromagnetic pulse to kick the beam in a controlled manner. To prevent unwanted reflections and ringing, the characteristic impedance of the kicker should match both the line coming from the pulse generator and some terminating load(s).

Goals:

1. Kickers must be compact
2. Dipole: strong center electric field
3. Quadrupole: strong field gradient
4. Matched characteristic impedance

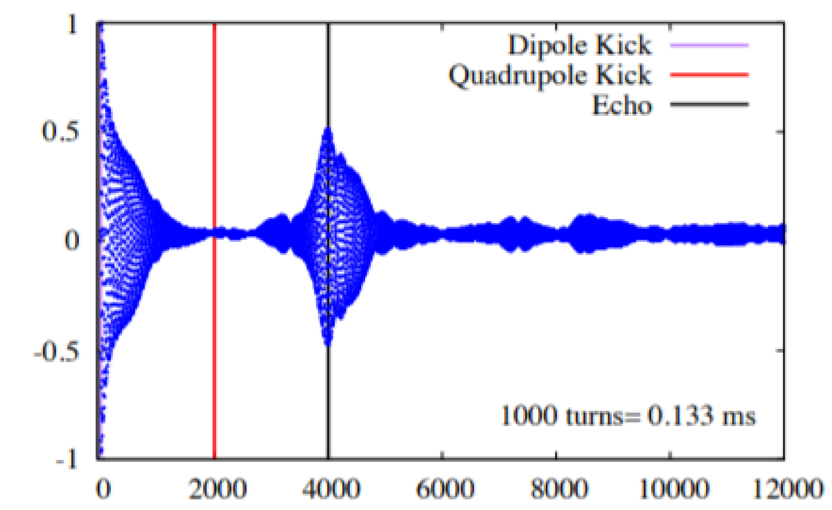


Figure 1: Example echo, adapted from [1]

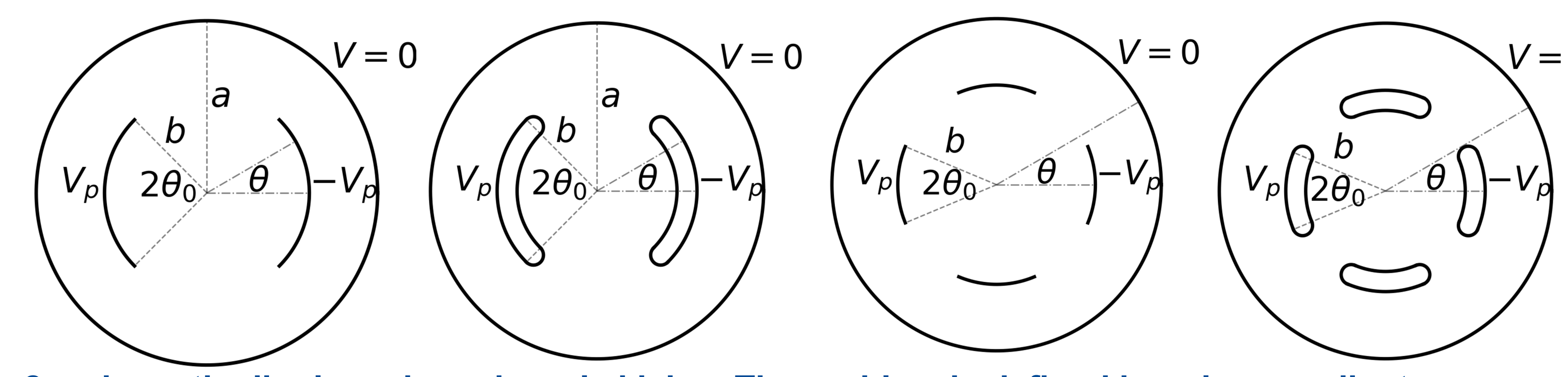


Figure 2: schematic dipole and quadrupole kicker. The problem is defined in polar coordinate. Dimension of the kickers are as shown in the figure. For plates with finite thickness, b is defined to be the outer rim of the electrode. In the case of parallel plates, b is defined as the distance between the center and parallel plate tip

Theory of Stripline kickers - Dipole & Quadrupole

Figure 2 shows two infinitesimal electrodes held at potential $\pm V_p$. The beam pipe was held at 0 potential. Since there is no charge interior to the plates, the potential obeys Laplace's equation

$$\nabla^2 \Phi = 0$$

The general solution to Laplace's equation assuming cylindrical symmetry is

$$\Phi(r,\theta) = a_0 \ln r + b_0 + \sum_{m=1}(a_m r^m + b_m r^{-m})(c_m \cos m\theta + d_m \sin m\theta)$$

Define $X_m = \frac{b^m c_m}{V_p}$ and $g_m = \frac{1}{1-(b/a)^{2m}}$,

By solving for the region $r < b$ and for the region $r > b$, matching the solutions in both region,

$$\sum_{m=\text{ind}} X_m \cos m\theta = -1 \quad \text{(eq1)} \qquad \sum_{m=\text{ind}} m g_m X_m \cos m\theta = 0 \quad \text{(eq2)}$$

(Eq. 1 applies on the plates; eq. 2 applies in the gaps between the plates)

Where $\text{ind} = 1, 3, \ldots$ for dipole and $\text{ind} = 2, 6$ ... for quadrupole.

These equations must be truncated and solved numerically.

Method 1: Least square method

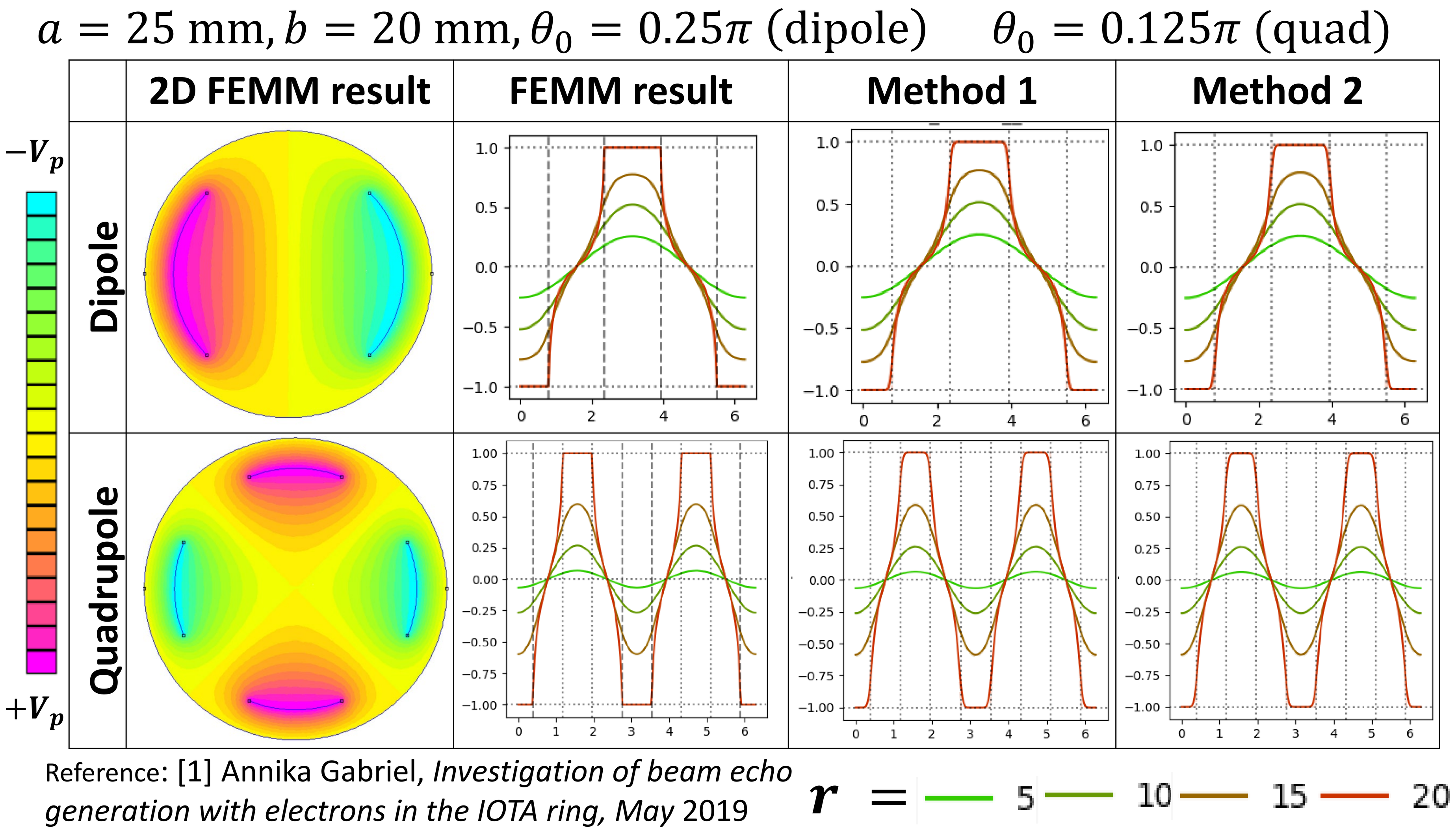
Define an error function by taking the square of the difference of either sides of equation1 and 2, they solve for the case where the global error is at minimum (derivative = 0)

Method 2: Projection method

By projecting each equation using basis functions, we get two matrix equations that need to be satisfied simultaneously. Then combine the matrix equations and solve numerically.

Result and comparison with FEMM. (plots are as a function of θ)

$a = 25$ mm, $b = 20$ mm, $\theta_0 = 0.25\pi$ (dipole) $\quad \theta_0 = 0.125\pi$ (quad)

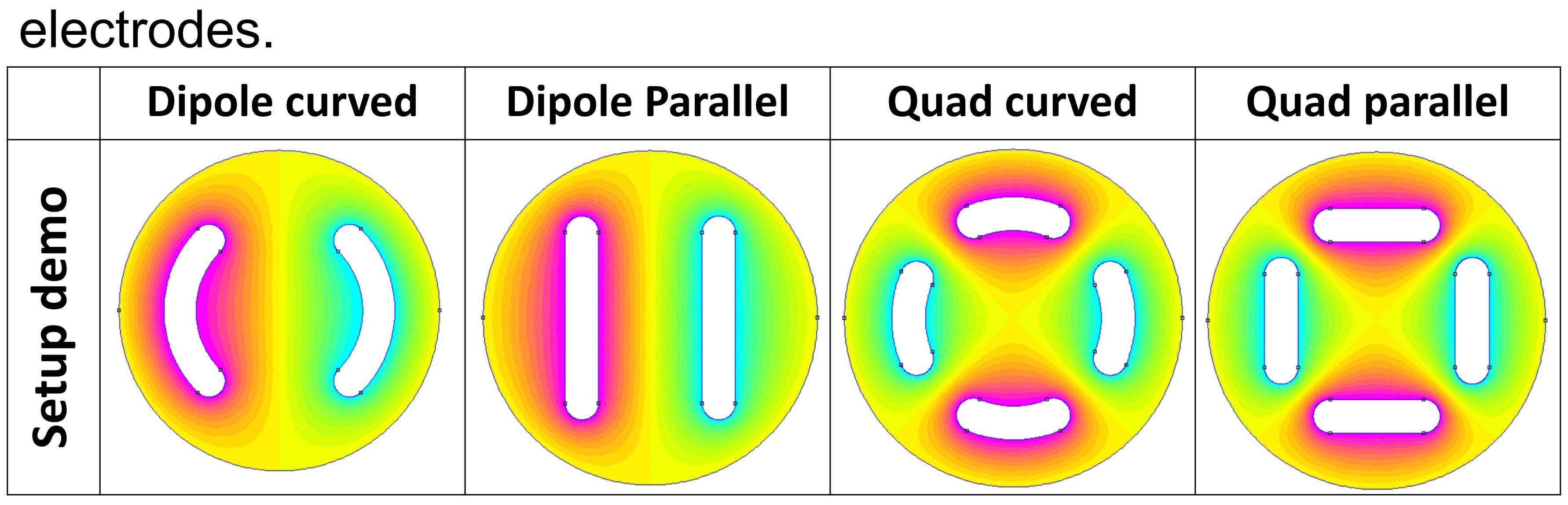


Reference: [1] Annika Gabriel, *Investigation of beam echo generation with electrons in the IOTA ring*, May 2019

Kicker design with Finite Element Method Magnetics (FEMM)

Definition of characteristic impedance for a multi-conductor transmission line mode: $Z_c = \frac{V_c}{I_c}$

where V_c and I_c are the voltage and current on one of the electrodes.



Cross-comparison between parallel and curved plate

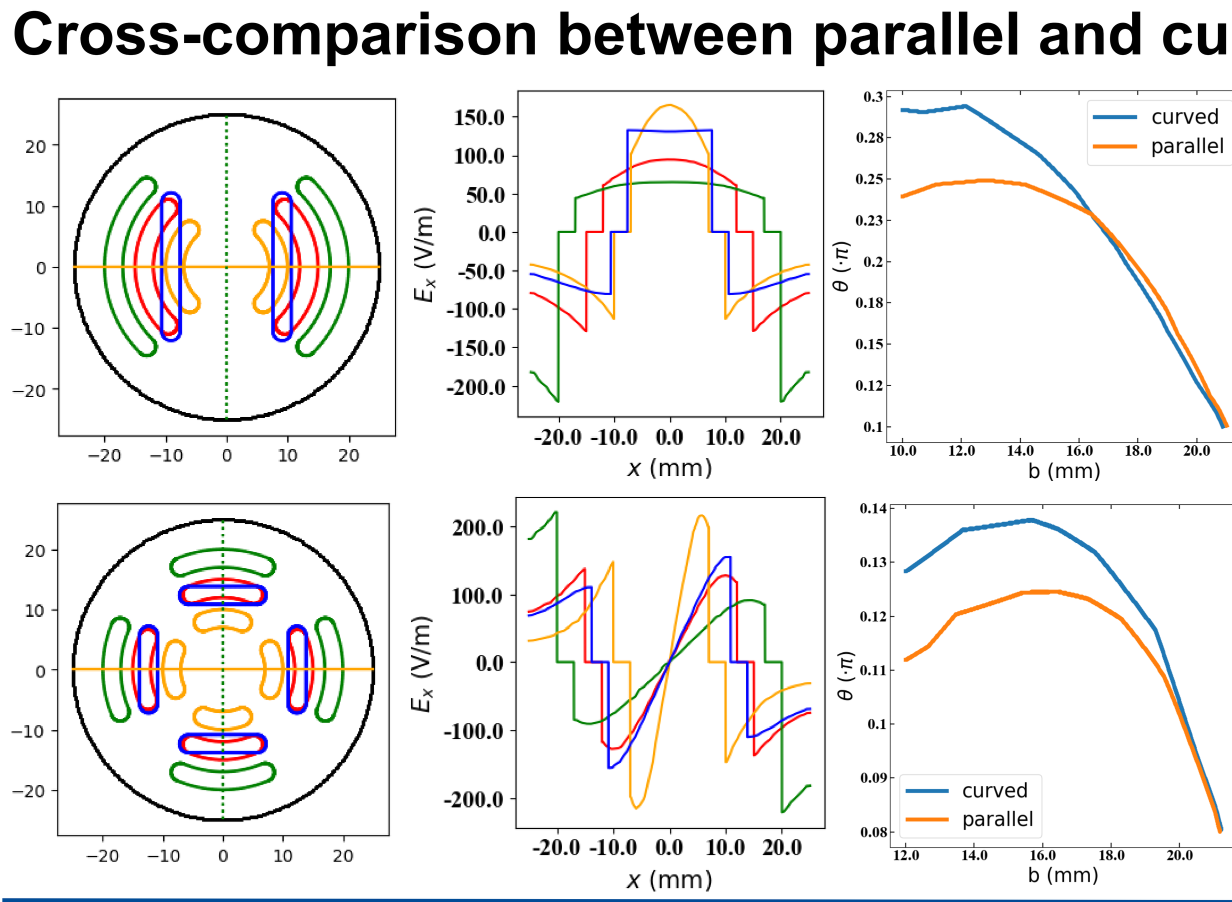


Figure 2:

Upper row: comparison in dipole case.

Lower row: comparison in quadrupole case.

Left most: schematic

Center: electric field at $y = 0$, the lines are color coded with the left most figure (blue is parallel and the rest are curved)

Right: values of b and θ_0 when $Z = 50\Omega$. Blue denotes curved plate, orange denotes parallel.

Conclusion and future work

We developed analytic solution to the Stripline kicker

1. Solver converges with ~ 100 terms and agrees with FEMM
2. Required electric field gradient achieved in quadrupole with V ~ 2 kV, L ~ 0.2 m

We also used FEMM to design kickers meeting our requirements.

1. (Dipole) Parallel plates produce more linear field at the center
2. (Quadrupole) Curved and parallel plate don't differ by much

Future work: Use the result obtained from this study to study echoes in IOTA ring

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