Multipole effects of a harmonic kicker

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on behalf of

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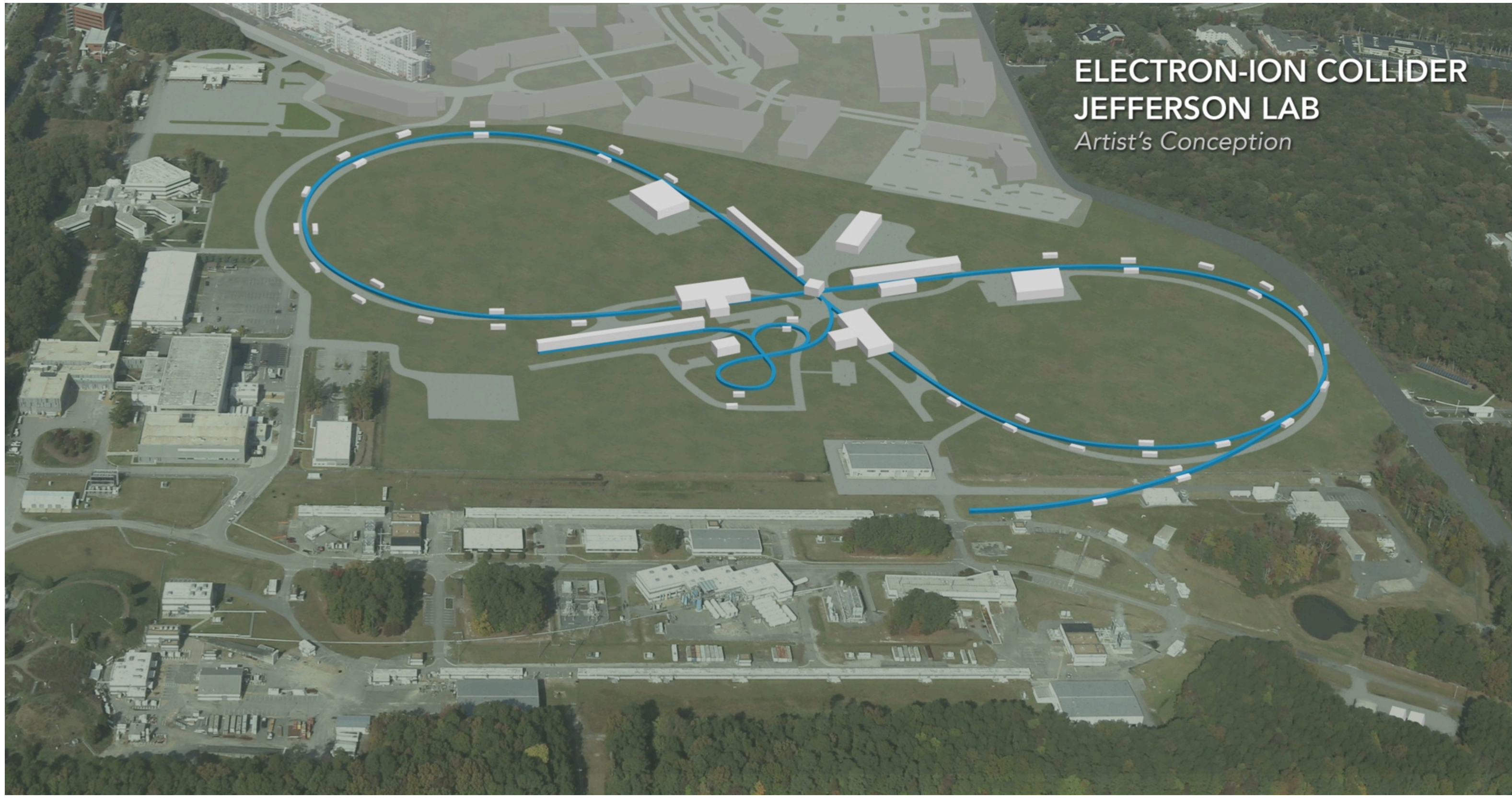

EIC Accelerator Collaboration Meeting

April 1 - April 3, 2019

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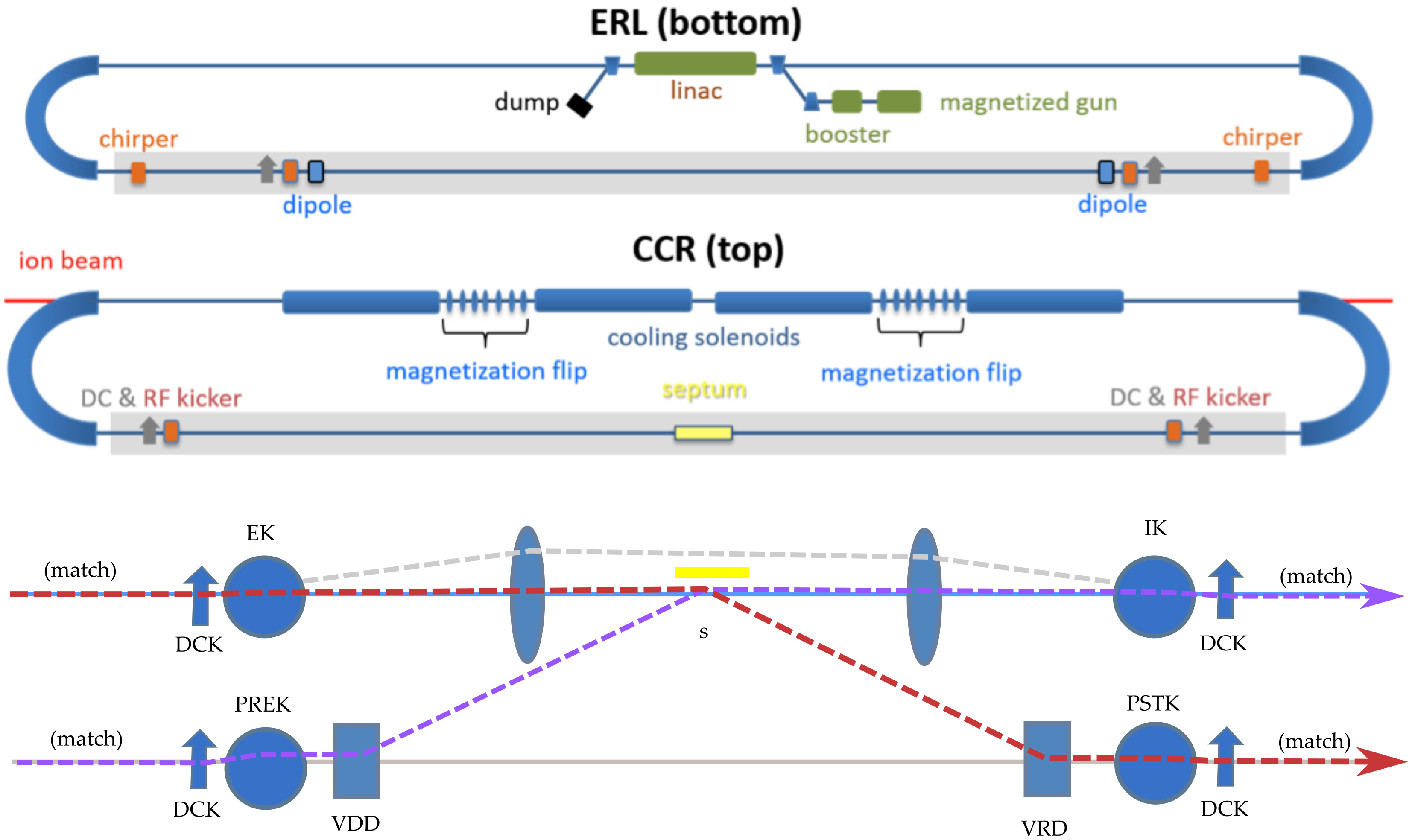
The harmonic kicker in Circulator Cooler Ring (CCR)

- A harmonic kicker system is a group of cavities that transit electron bunches between the ERL ring and the CCR.



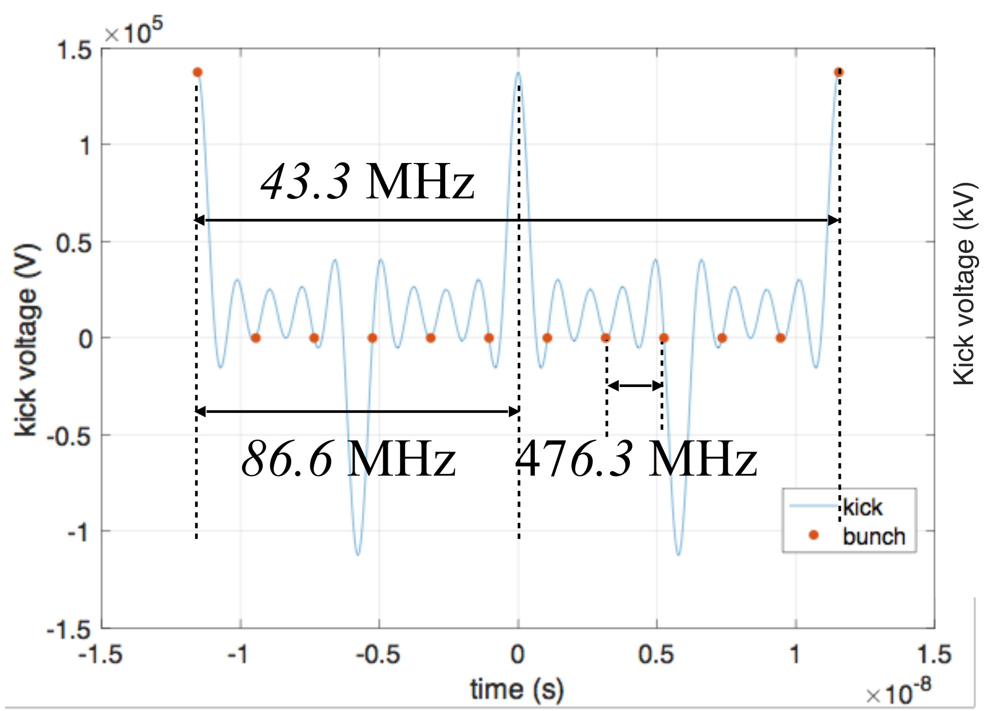
Parameters	Current
Beam energy	55 MeV
Kick angle	2.5 mrad
f_b	476.3 MHz
Q_b	1.6 nC
Turns	11
f_{kick}	86.6 MHz
Energy spread	3E-04
Bunch length	20 mm
$\alpha_x=\alpha_y$	0
$\beta_x=\beta_y$	120 m
$\varepsilon^n_x=\varepsilon^n_y$	36 μm
Beam distr.	Beer can

The requirements on harmonic kicker

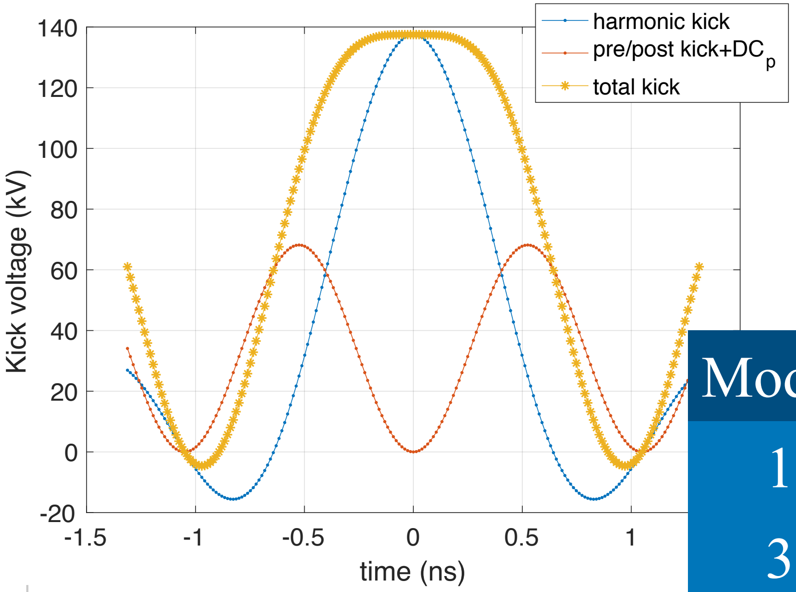
Requirements	Implementation
The kicked bunches are uniform (with no angular spread).	A single frequency pre-/post- kicker
The bunches between the kicks are not affected by residual kicks	A pair of the kickers are separated by π phase
The number of the modes and the kickers better be as small as possible.	The kick consists of 5 (odd) harmonic modes of 86.6 MHz (in one cavity).
The total dissipated power of the kicker must be minimized.	A careful RF/engineering design of the cavity
The kick must be stable against the various degrading conditions.	An efficient frequency tuning system and RF control.

The profile of harmonic kick

The temporal profile of harmonic kick



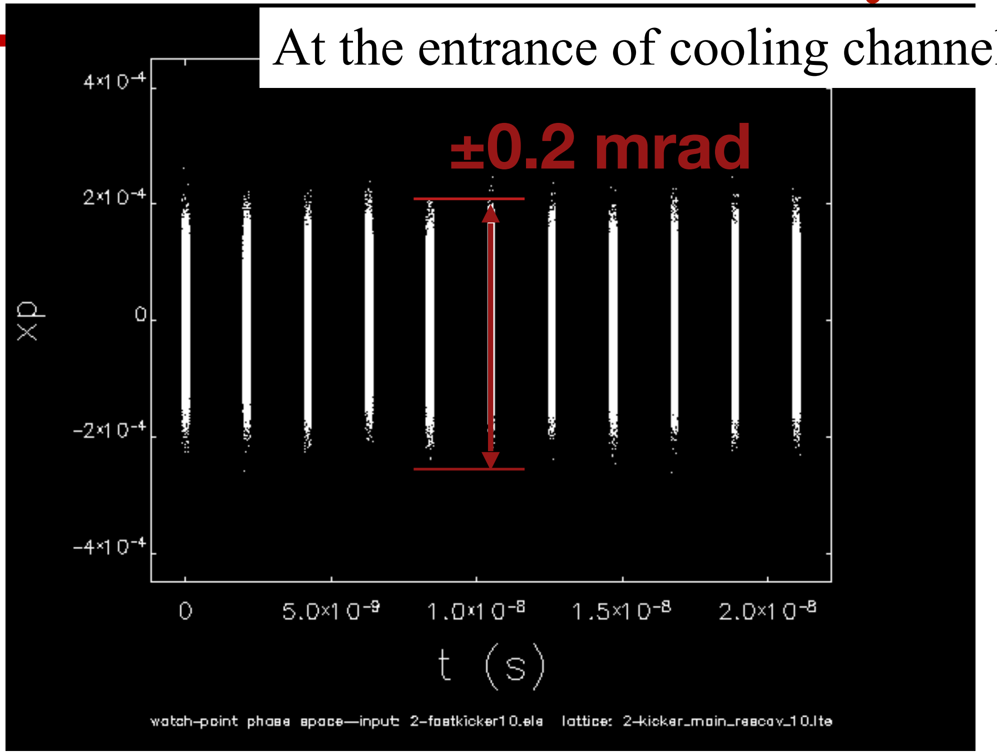
The temporal profile of pre-/post kick



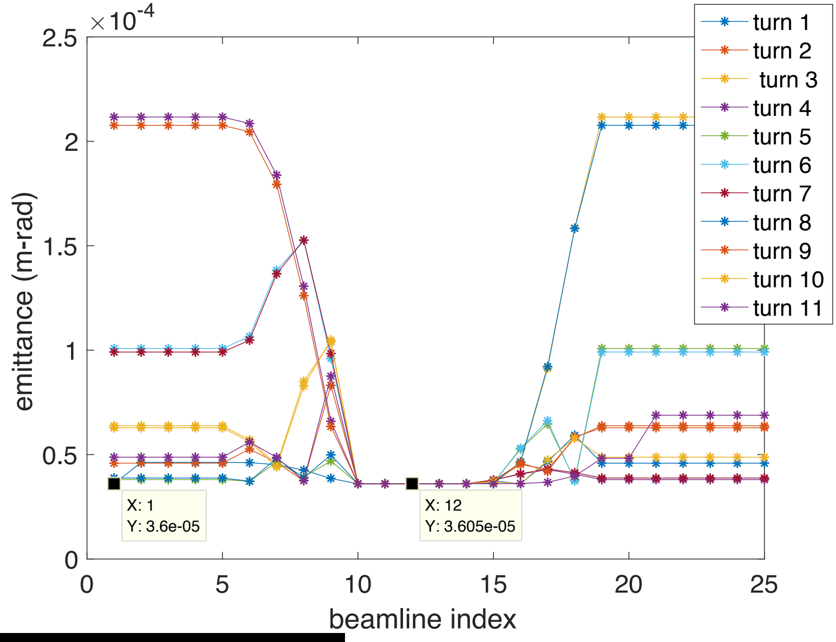
Modes	freq.	Amp.
1	86.6 MHz	25 kV
3	259.8 MHz	25 kV
5	433 MHz	25 kV
7	606.2 MHz	25 kV
9	779.4 MHz	25 kV
0	-	12.5 kV
11	952.6 MHz	-34.1kV
0	-	34.1 kV

The amplitude distribution of the kicker system

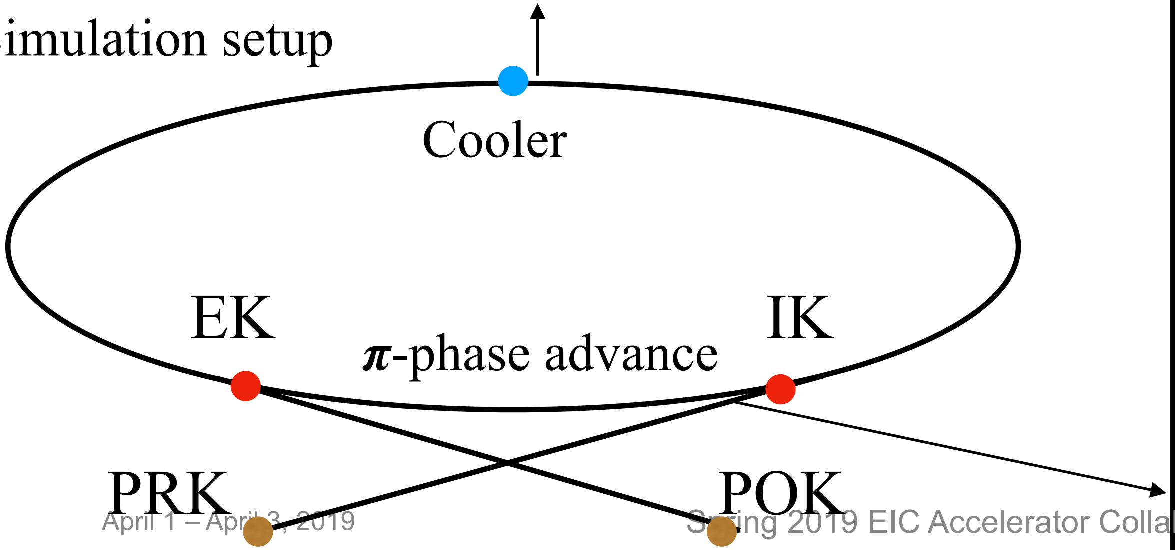
The beam dynamics simulation with ELEGANT



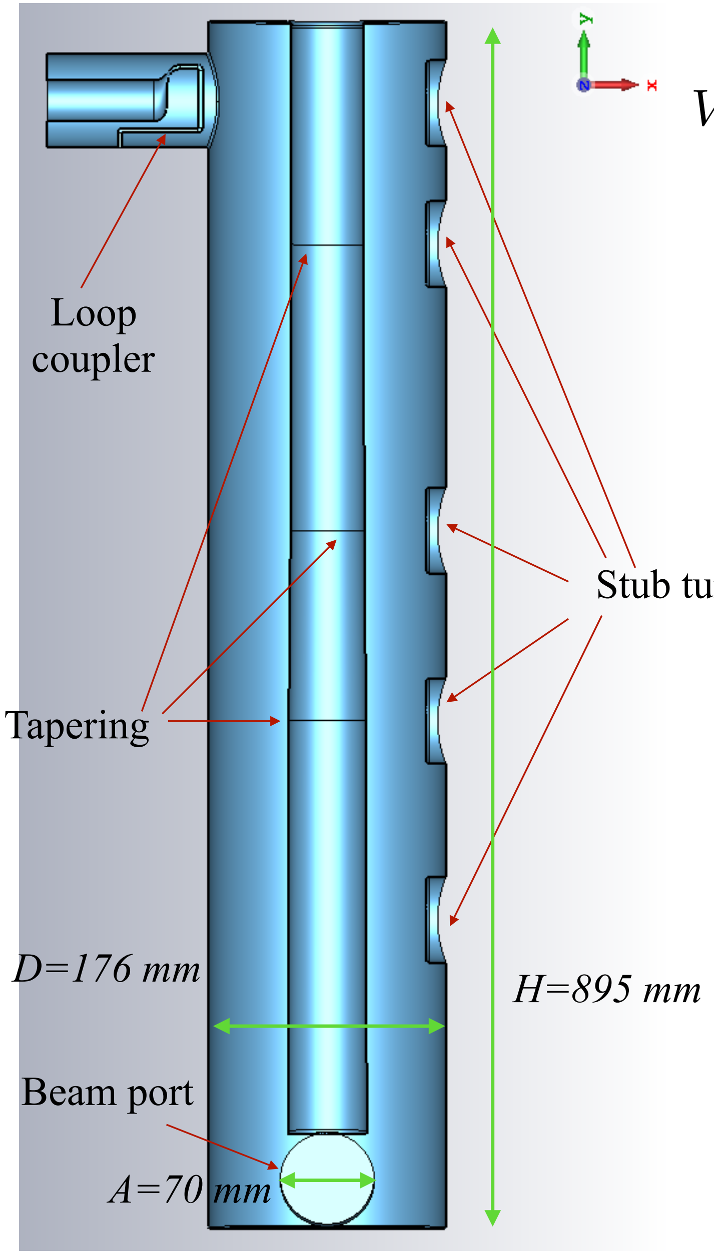
- To demonstrate longitudinal dynamics (Longitudinal profiles of angular divergence) through the kickers with pre/post kickers.
- Also checked is transverse emittance



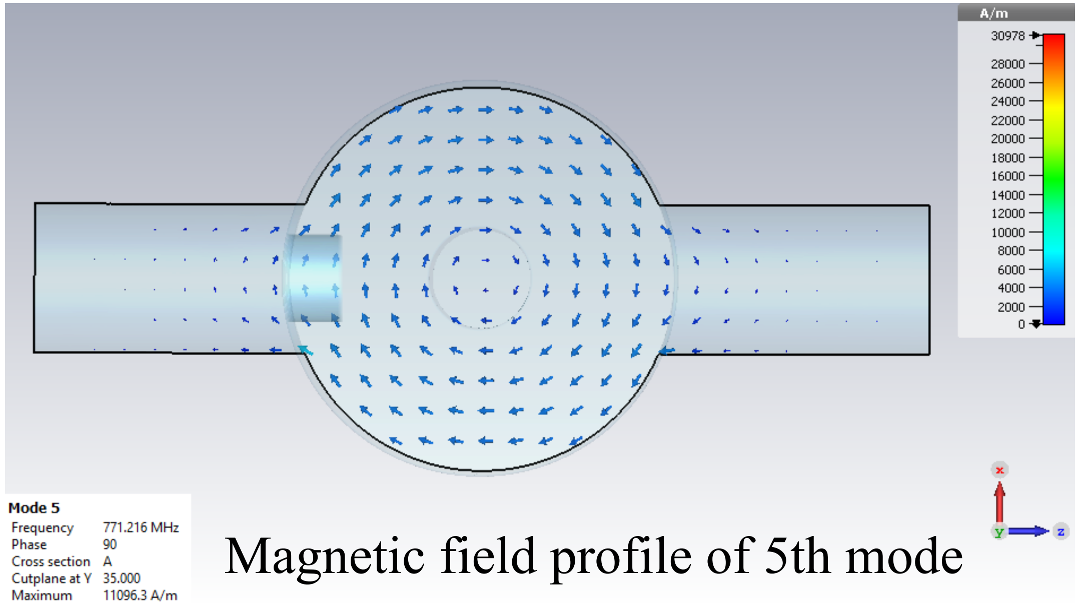
Simulation setup



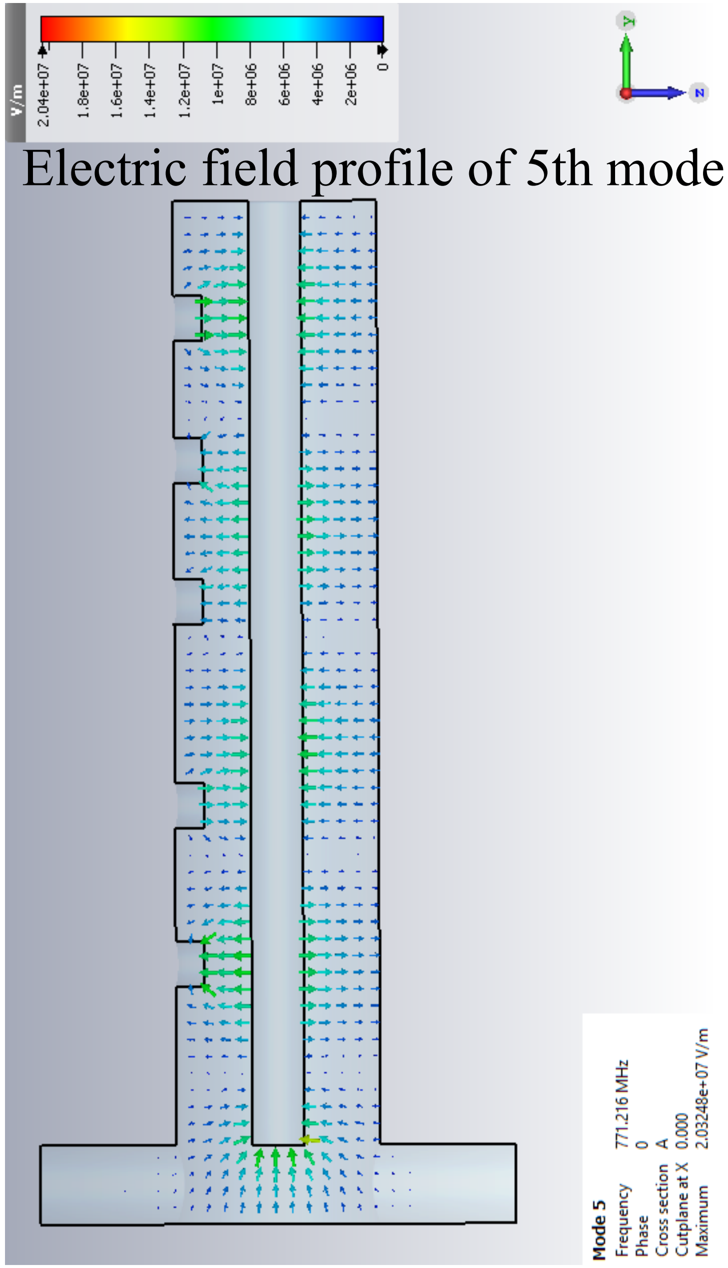
Quarter wave resonator as harmonic kicker



$$V_{kick} = \int_{-\mathcal{L}/2}^{\mathcal{L}/2} dz\, \vec{F}_{L,\perp} = \int_{-\mathcal{L}/2}^{\mathcal{L}/2} dz\, e(\vec{E} + \vec{v} \times \vec{B})_\perp$$



Magnetic field profile of 5th mode



Electric field profile of 5th mode

Tuner design

- Linear approximation of frequency response to the tuner insertion

$$\Delta f_k = \boldsymbol{T}_{ki} \Delta s_i$$

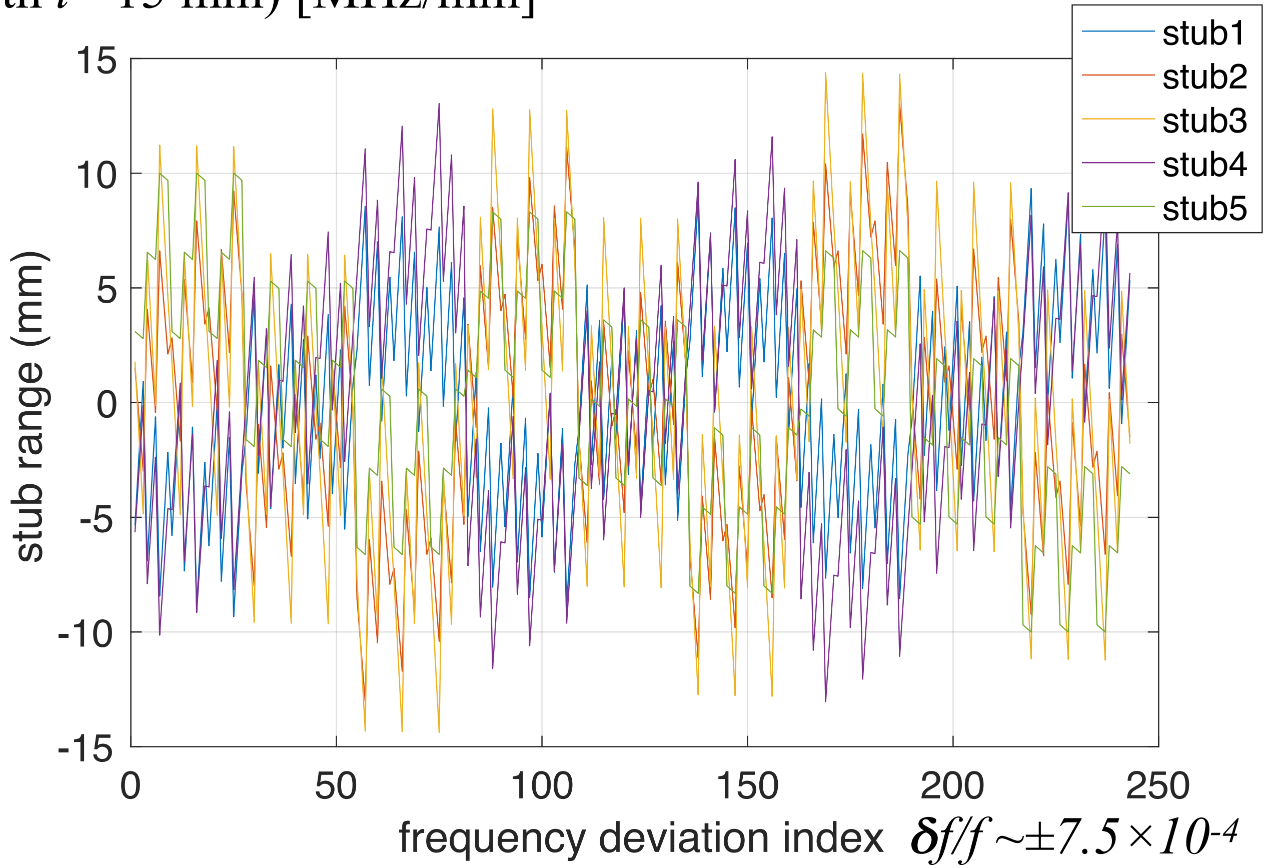
Δf_k is frequency deviation of k-th mode, $\boldsymbol{T}$ is tuning sensitivity matrix, and Δs_i is displacement of i-th stub.

Tuning sensitivity matrix (around the default insertion depth l =15 mm) [MHz/mm]

$$\boldsymbol{T} = \begin{matrix} -0.0169 & -0.0101 & -0.0032 & 0.0067 & 0.0082 \\ 0.0050 & 0.0215 & -0.0270 & -0.0212 & 0.0141 \\ 0.0375 & -0.0885 & -0.0001 & -0.0935 & -0.0135 \\ -0.0630 & -0.0116 & -0.0955 & -0.1116 & -0.0708 \\ -0.1909 & -0.0055 & 0.0316 & -0.0337 & -0.1513 \end{matrix}$$

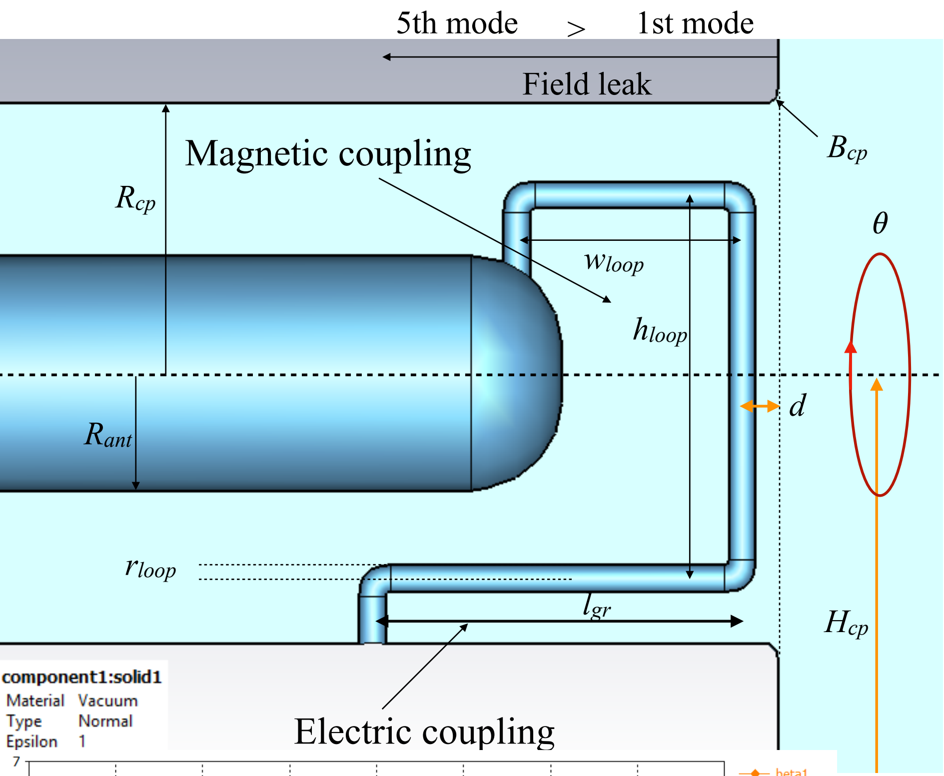
freq. sensitivity of the 4th mode.

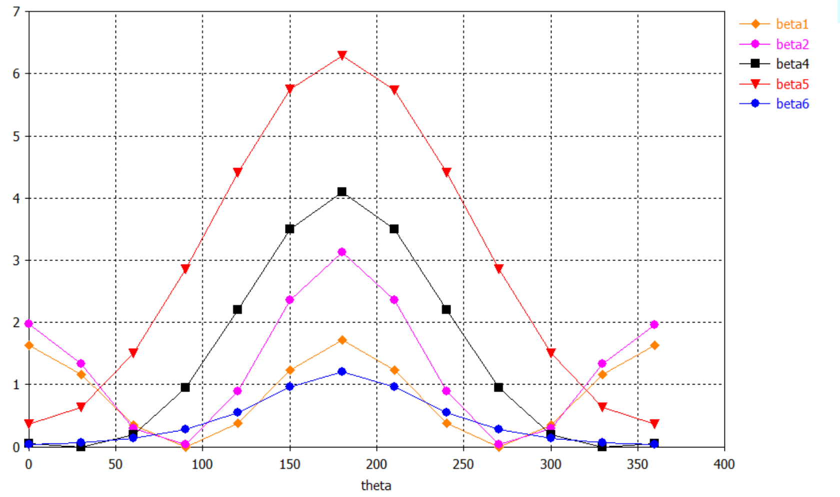
by the 2nd tuner stub



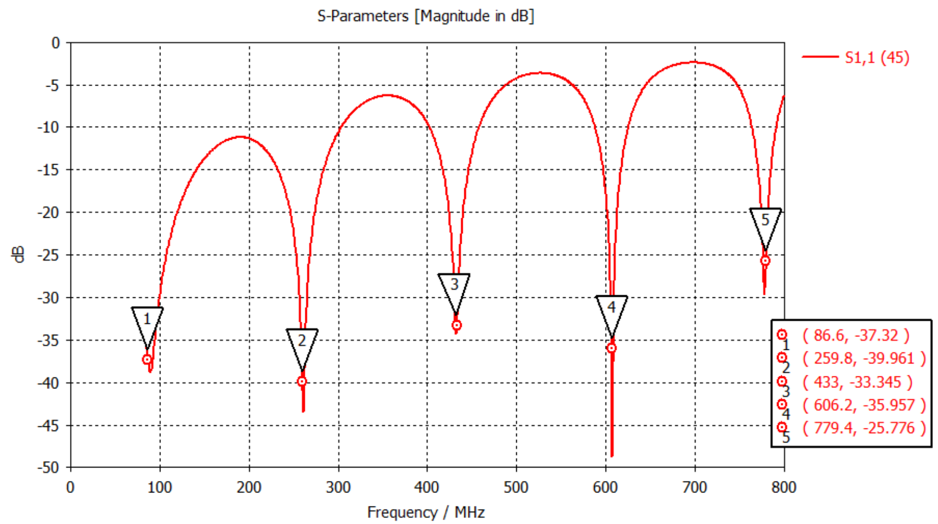
$\delta f/f \sim \pm 7.5 \times 10^{-4}$

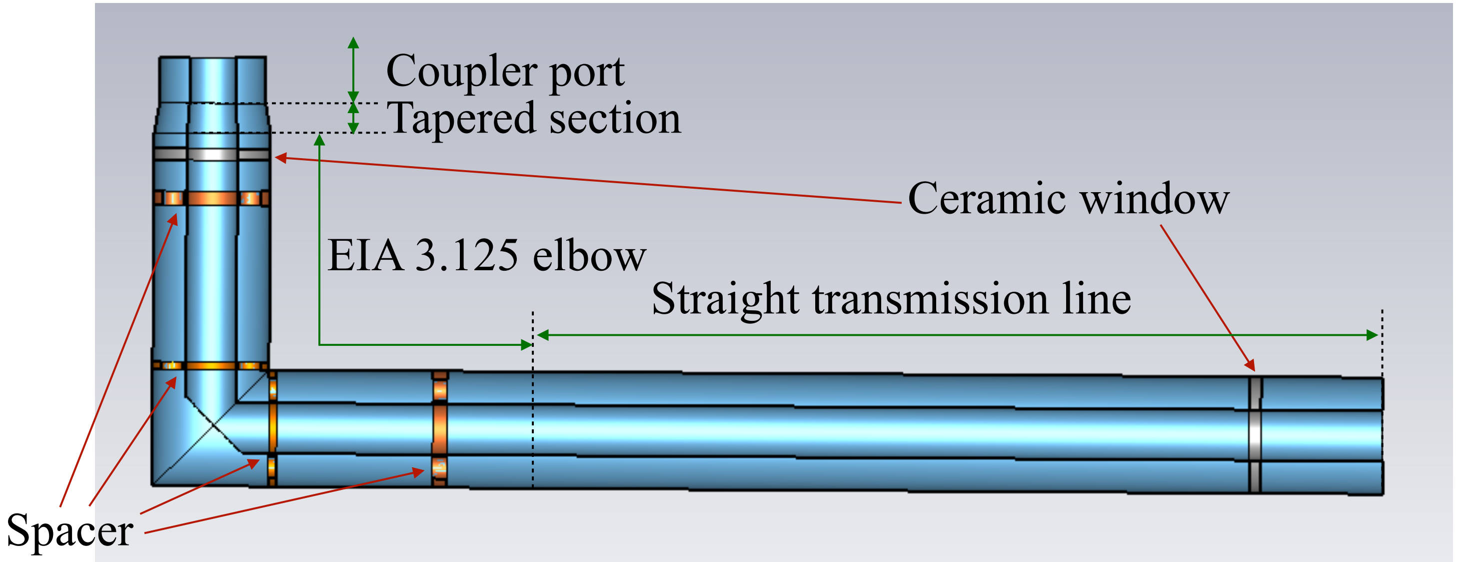
Power coupler design





- 5 harmonic modes are critically coupled to the cavity by a loop coupler in predominantly magnetic region.
- Broadband coupler using double window is used to deliver 5 harmonic modes.





RF Power and figures of merit

With beam loading, RF power from the RF source that maintains constant voltage in the cavity is given as

$$P_g = \sum_{n=1}^{5} \frac{V_{\perp,n}^2}{R_{\perp,n}} \frac{(1+\beta_n)^2}{4\beta_n} \left[\left(1 + \frac{kaR_{\perp,n}}{1+\beta_n} \frac{I_b}{V_{\perp,n}} \sin\phi_s \right)^2 + \left(2Q_{L,n} \frac{\delta f_n}{f_n} - \frac{kaR_{\perp,n}}{1+\beta_n} \frac{I_b}{V_{\perp,n}} \cos\phi_s \right)^2 \right]$$

With $I_b = f_k Q_b = 0.35$ mA, $\phi_s = 0$ (deflecting phase),

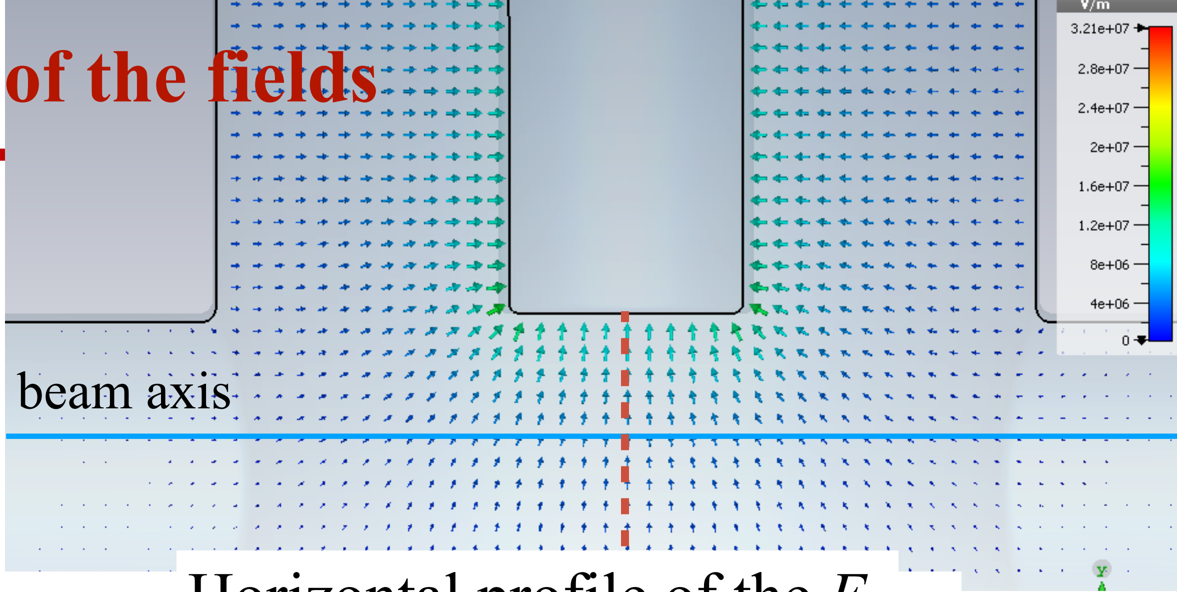
$$\approx \sum_{n=1}^{5} \frac{V_{\perp,n}^2}{R_{\perp,n}} \frac{(1+\beta_n)^2}{4\beta_n}$$

Figures of merit

Modes	f (MHz)	TTF	R_{sh} (MΩ)	P_d (kW)	Q_0	$\Delta f/f$	β	P_g
1	86.6	1	0.95	0.37	6.47E+03	±4E-04	0.7	0.38
2	259.8	0.98	0.87	0.69	1.11E+04	±2E-04	1.2	0.70
3	433	0.94	0.61	0.99	1.44E+04	±2E-04	1.2	1.00
4	606.2	0.88	0.42	1.44	1.67E+04	±1E-04	1.1	1.44
5	779.4	0.80	0.23	2.52	1.58E+04	±1E-04	1.1	2.53

Transverse profile of the fields

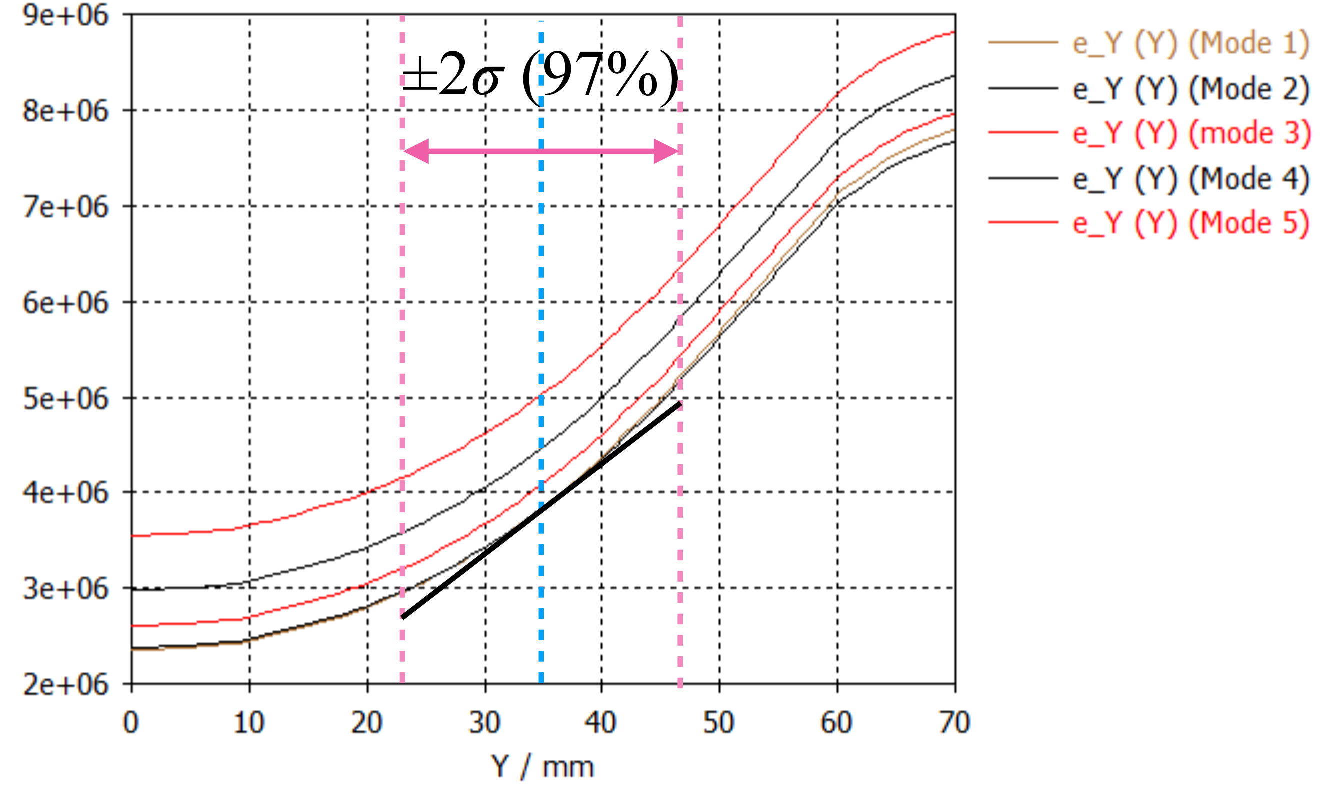
- Because of lack of vertical symmetry of the QWR, the kick is expected to have some multipole components.



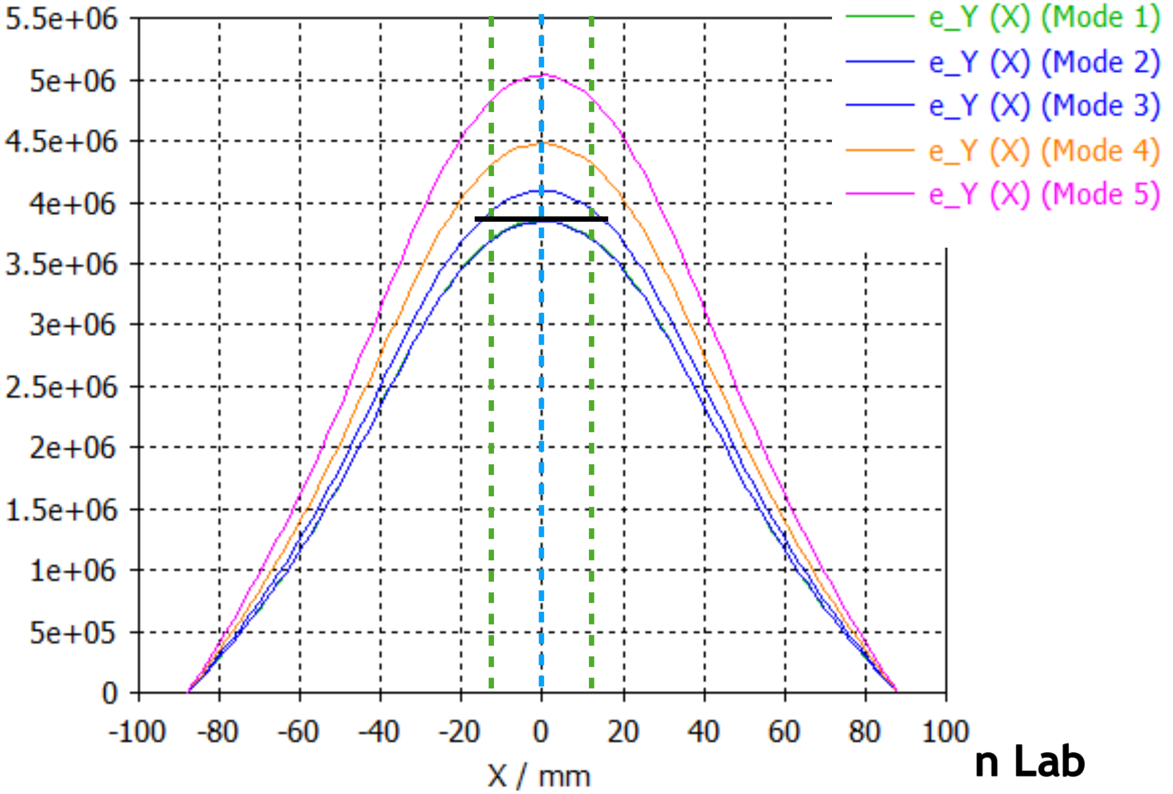
Beam size: $\sigma = 6.25\text{mm}$

Assuming γ=110, β=120m, ε_n=36 μm @kicker

Vertical profile of the E_y



Horizontal profile of the E_y



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Multipole fields of the QWR

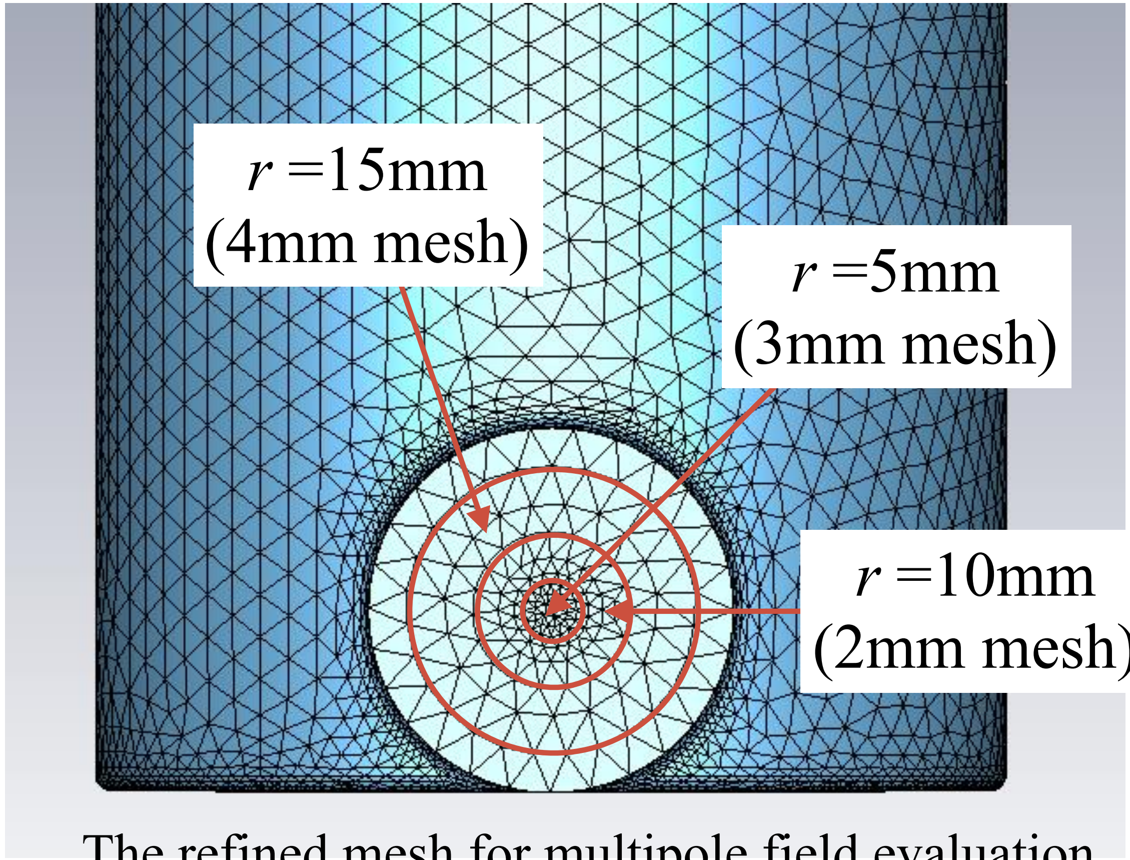
- We evaluate multipole transverse fields in terms of multipole coefficients of longitudinal fields via Panofsky-Wenzel theorem.

$$\Delta p_y = -\frac{e}{\omega} Re\left\{ i \int_{-\infty}^{\infty} dz\, \nabla_y E_z \Big|_{\vec{r}=\vec{r}_0} \right\}$$

$$= \frac{e}{\omega} \sum_n n r_0^{n-1} Re\left[i e^{i(n-1)\phi_0} c_n \right]$$

Spatial factor obtained from 3D field map (CST simulation)

$$c_n = \frac{1}{\pi} \int_{-\infty}^{\infty} \left[\int_0^{2\pi} E_z(\vec{r}) e^{-in\phi} d\phi \right] \frac{1}{r^n} \sin\left(\frac{2\pi f z}{c}\right) dz$$



The refined mesh for multipole field evaluation

Multipole fields coefficients

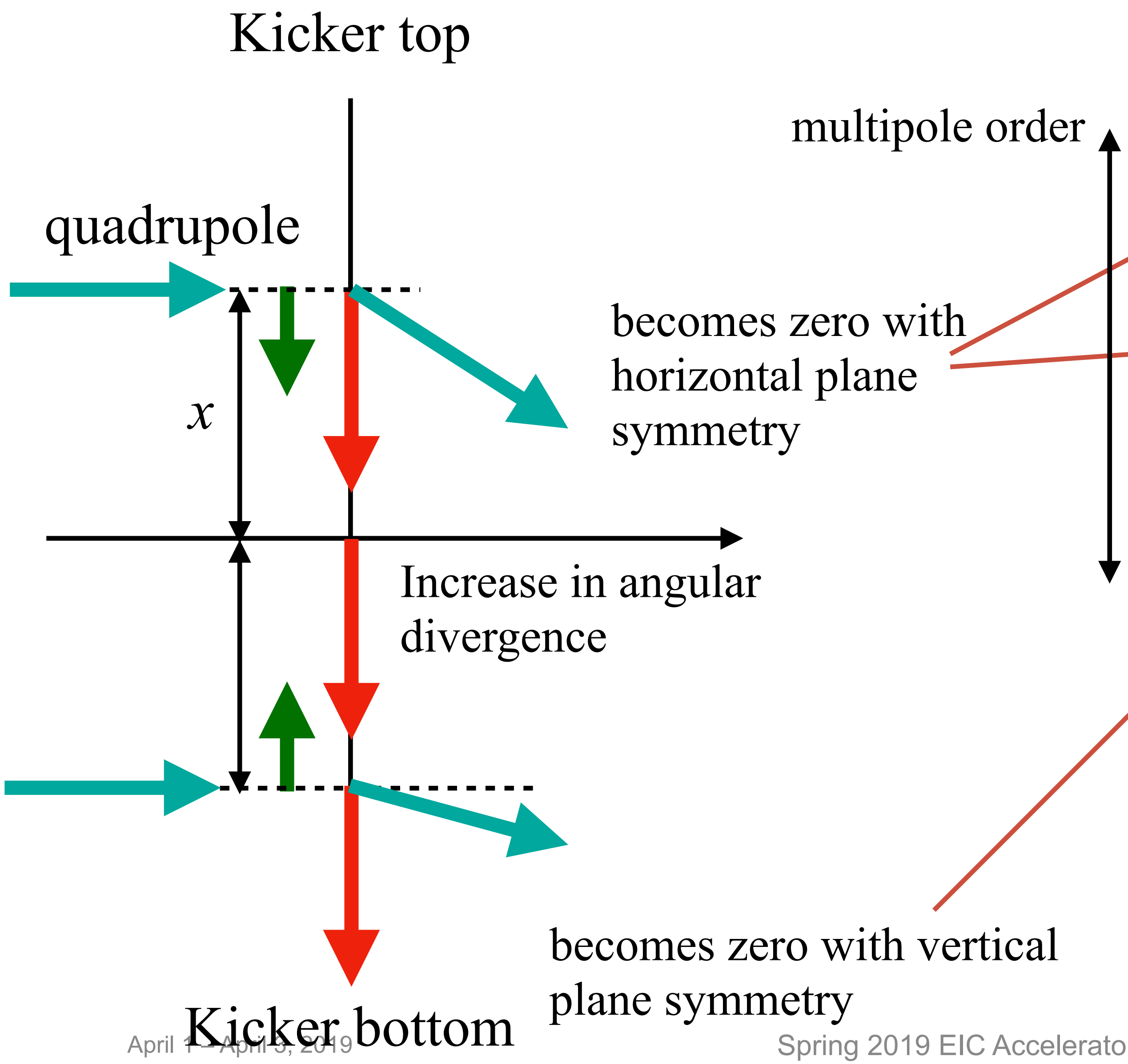


Table 1

b = frequency

1E+09 *

0	0.0004	0.0053	0.0366	0.2086
-0.0001	-0.0013	-0.0162	-0.1106	-0.6314
0.0002	0.002	0.0268	0.182	1.0461
-0.0003	-0.0028	-0.0375	-0.2529	-1.4841
-0.0004	-0.0035	-0.0488	-0.3279	-2.0345
-0.0008	-0.0063	-0.0983	-0.6677	-4.852

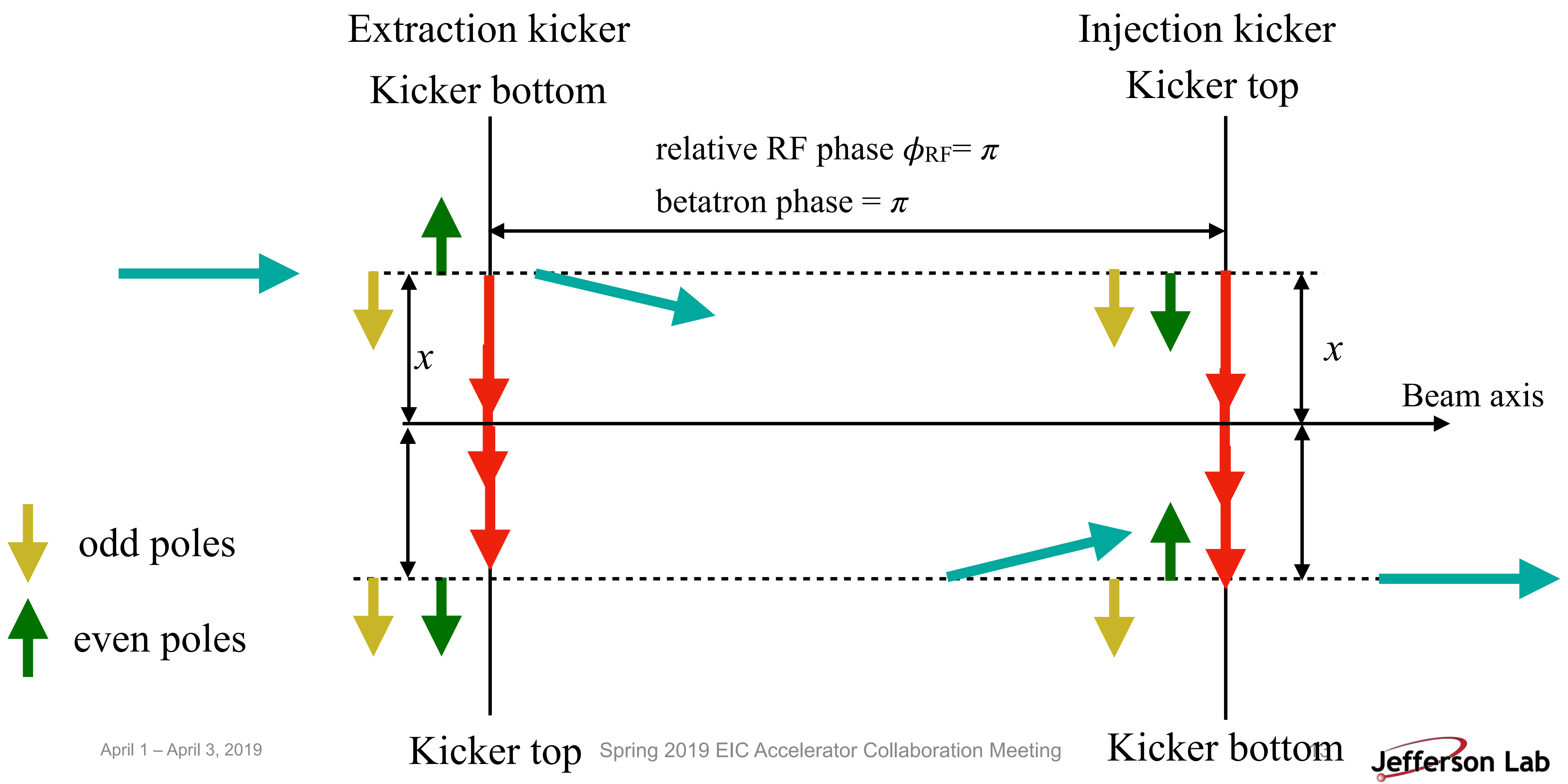
Table 1-1

a =

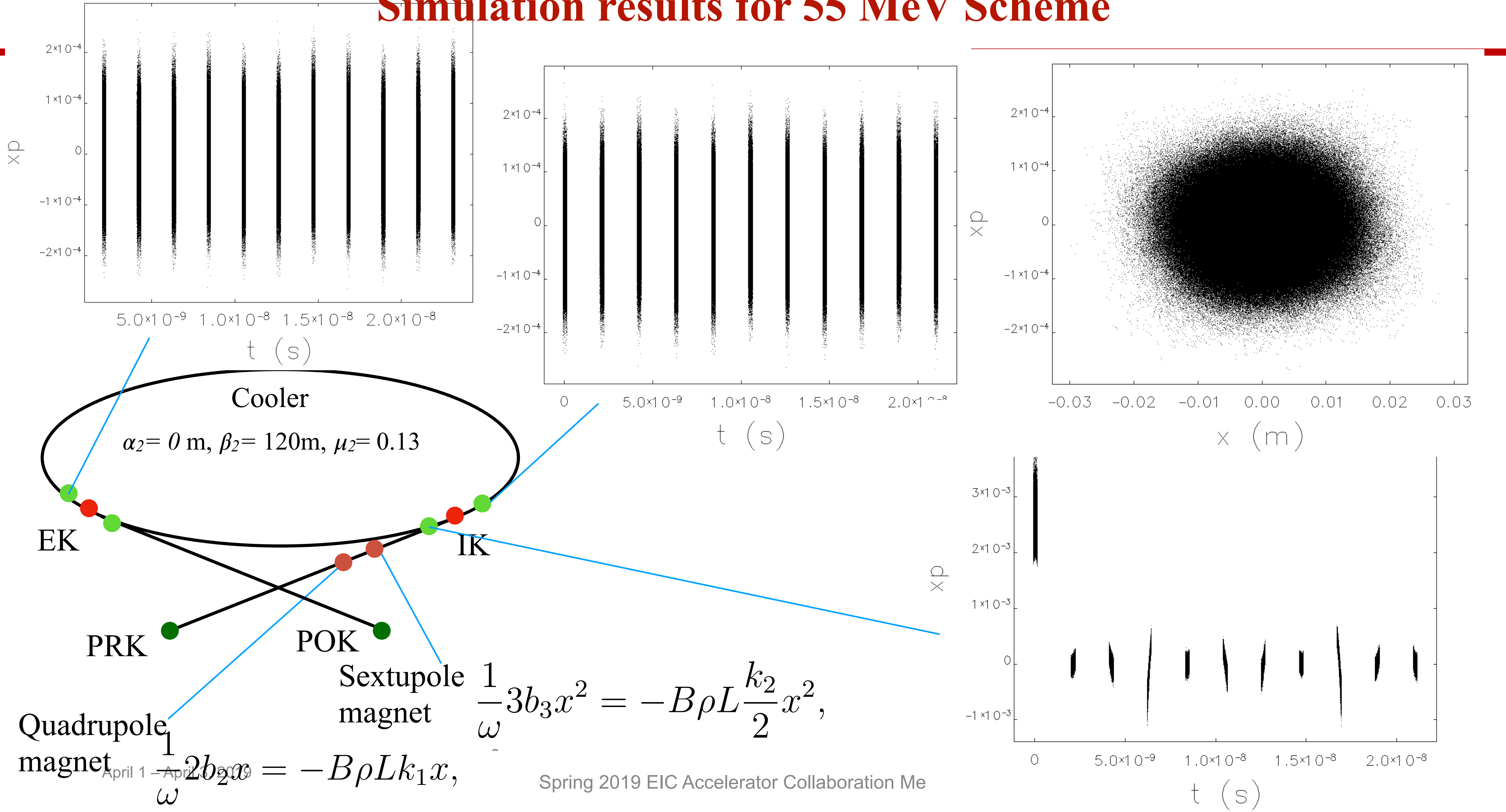
1E+08 *

0	0	0	-0.0004	0.0651
0	0	0.0001	0.0008	-0.2008
0	0	0	0.001	0.3535
0	-0.0001	-0.0007	-0.0128	-0.6061
0	-0.0005	-0.0053	-0.088	-1.5279
0	-0.0006	-0.0057	-0.0972	-2.1107

Multipole fields cancellation scheme (@ E_e= 55 MeV)



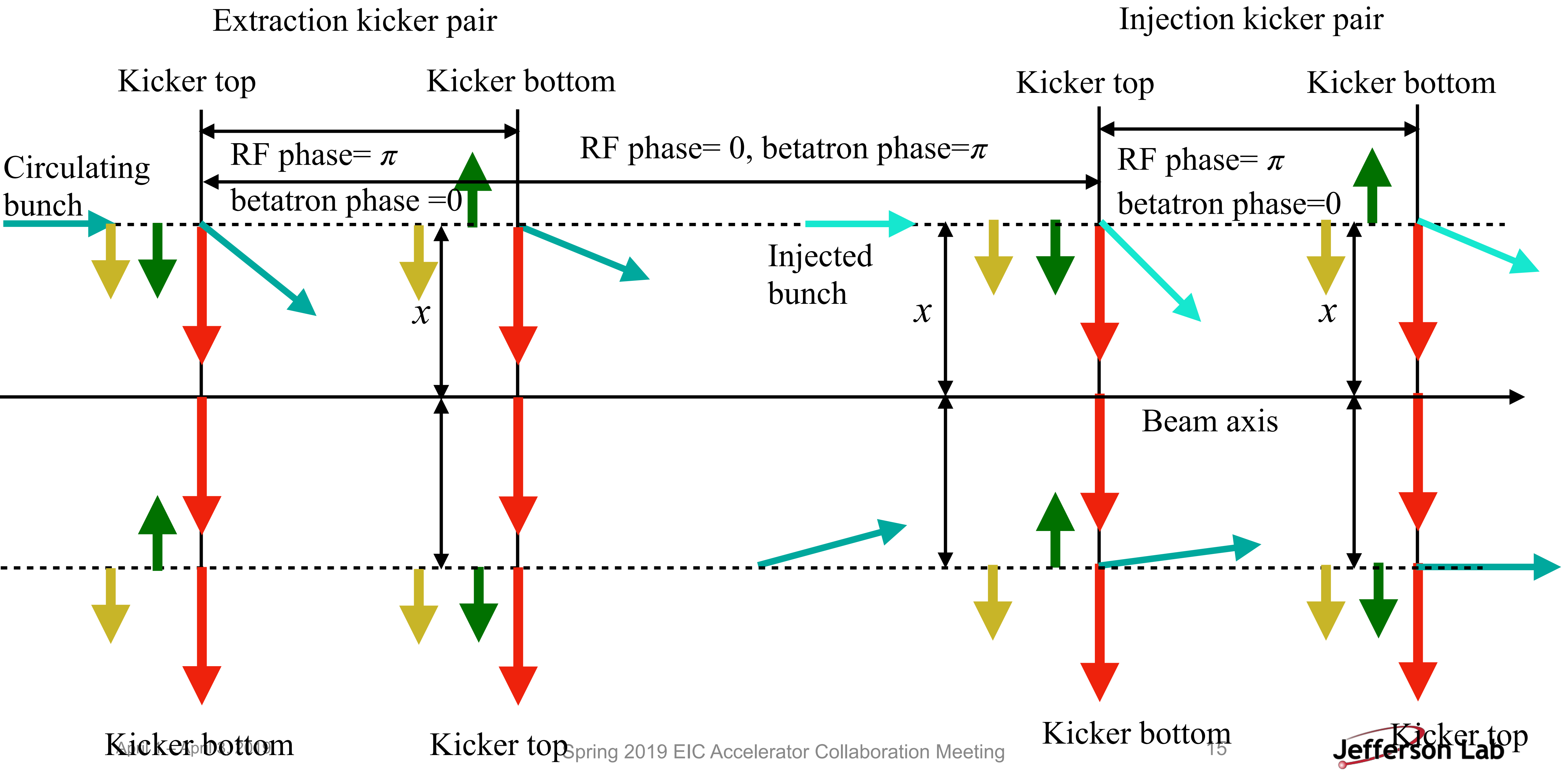
Simulation results for 55 MeV Scheme



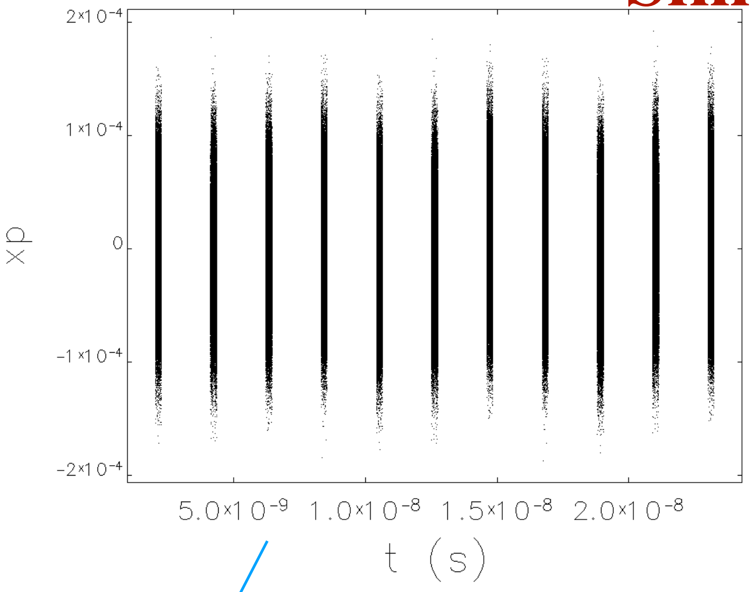
$$\frac{1}{\omega}3b_3x^2 = -B\rho L\frac{k_2}{2}x^2,$$

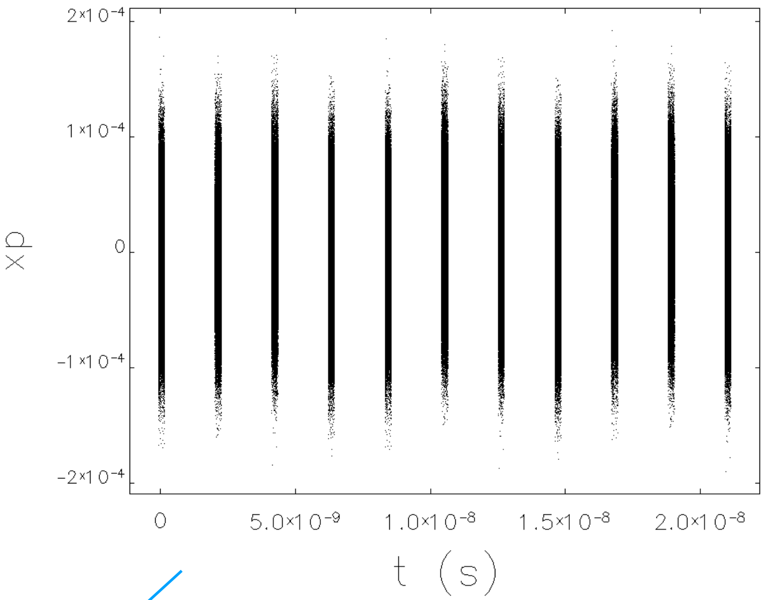
$$\frac{1}{\omega}2b_2x = -B\rho Lk_1x,$$

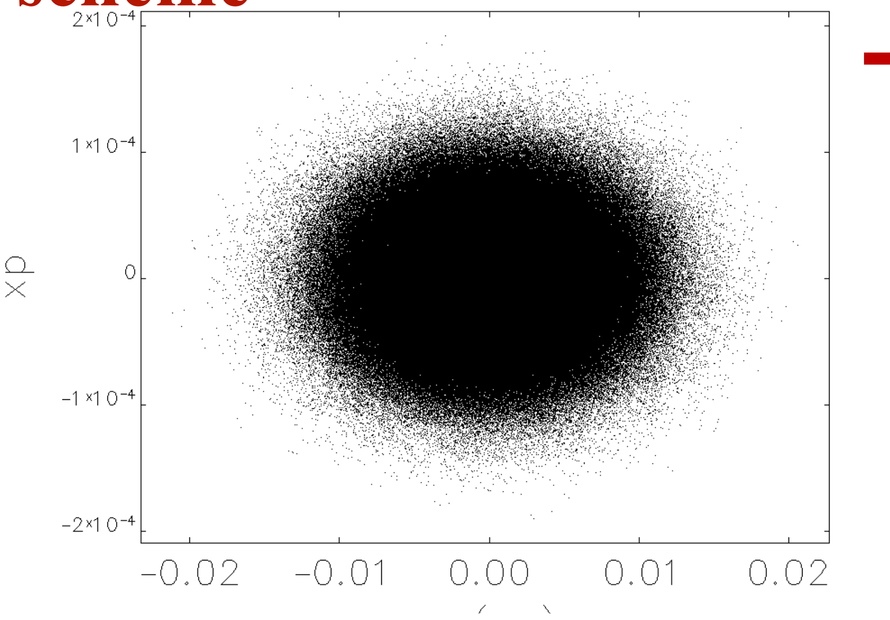
The double-kicker cancellation scheme (@ E_e=110 MeV)

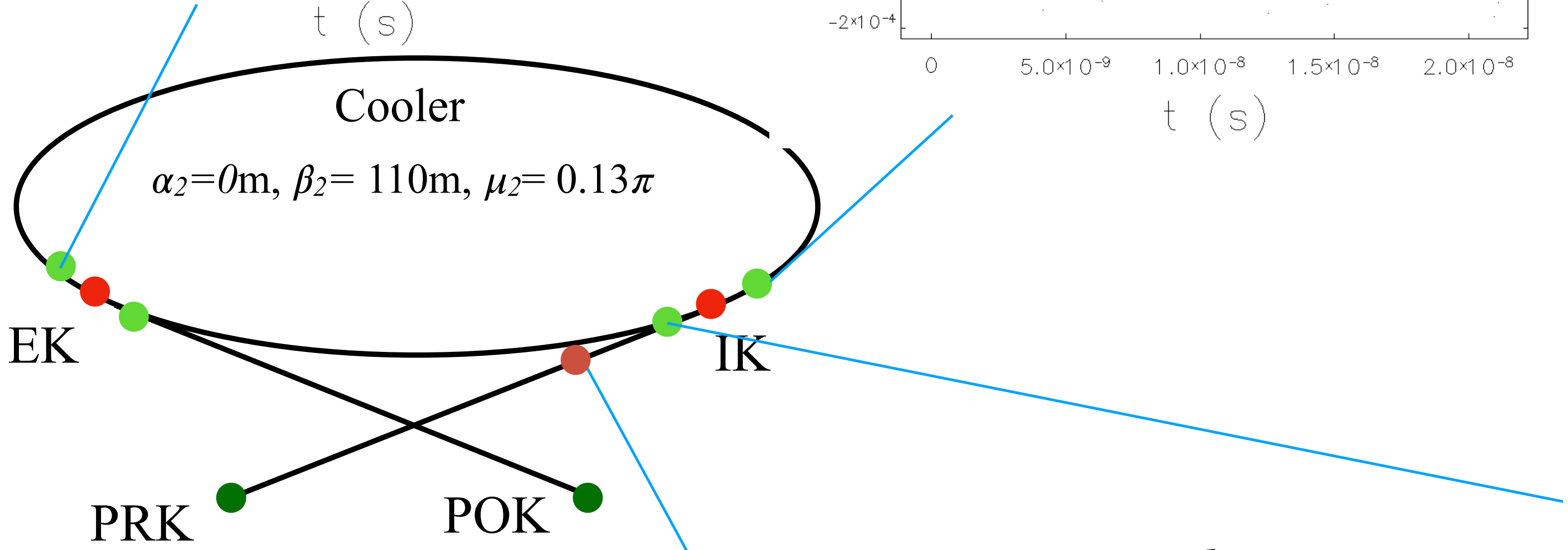


Simulation Scheme for 110 MeV scheme



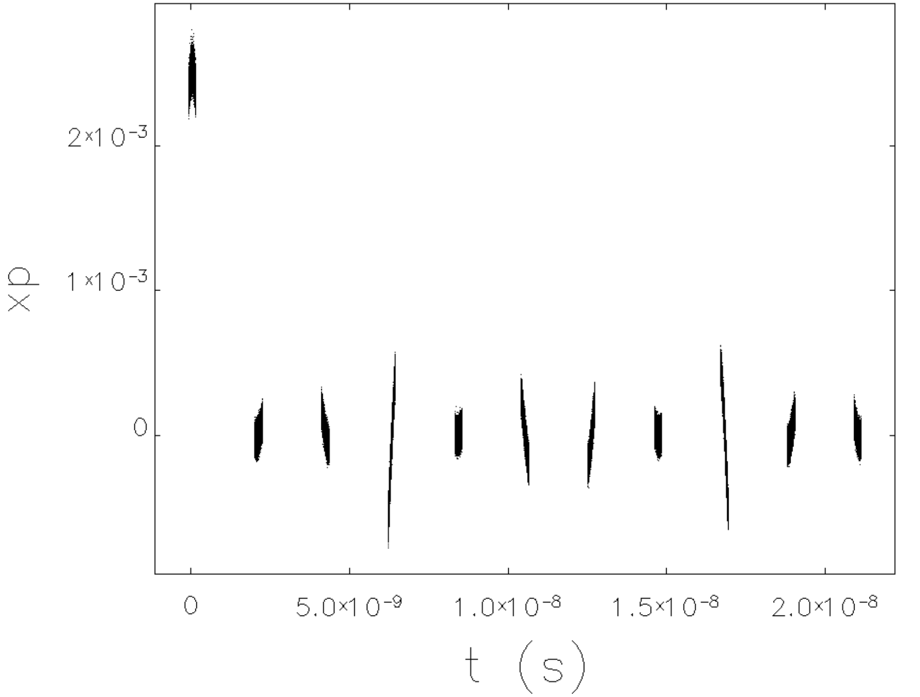






Sextupole magnet

$$\frac{1}{\omega}3b_3x^2 = -B\rho L\frac{k_2}{2}x^2,$$

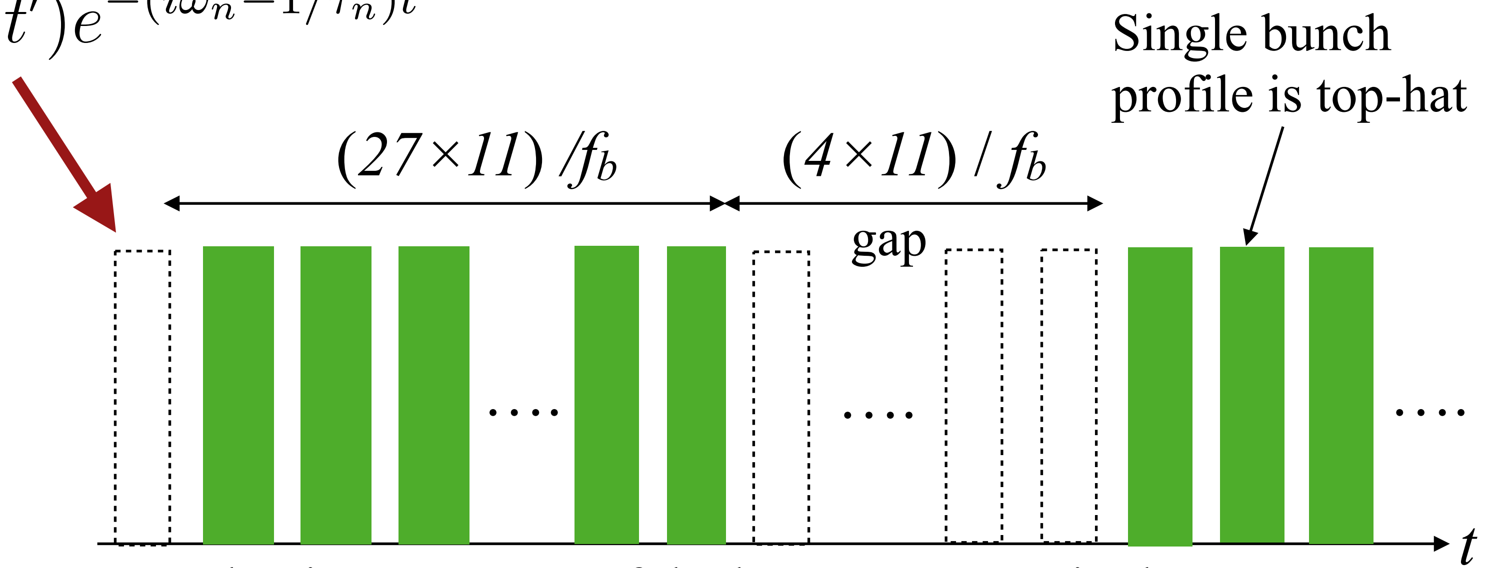


HOM power spectrum

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

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

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 time structure of the beam current I in the CCR

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

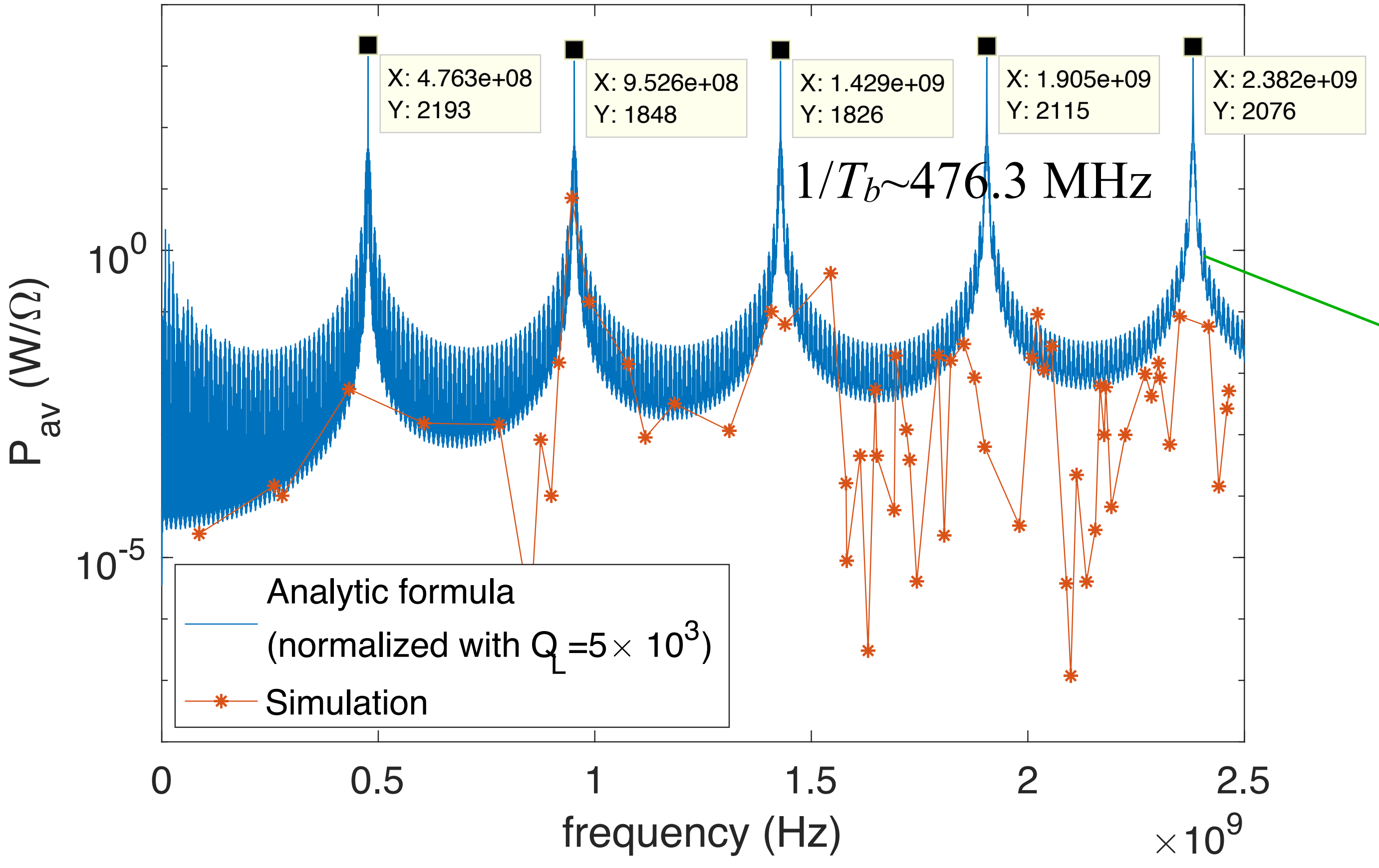
$$P_n(t) = \frac{V_n^2(t)}{Q_L \cdot R_{\parallel,n}/Q_0}$$

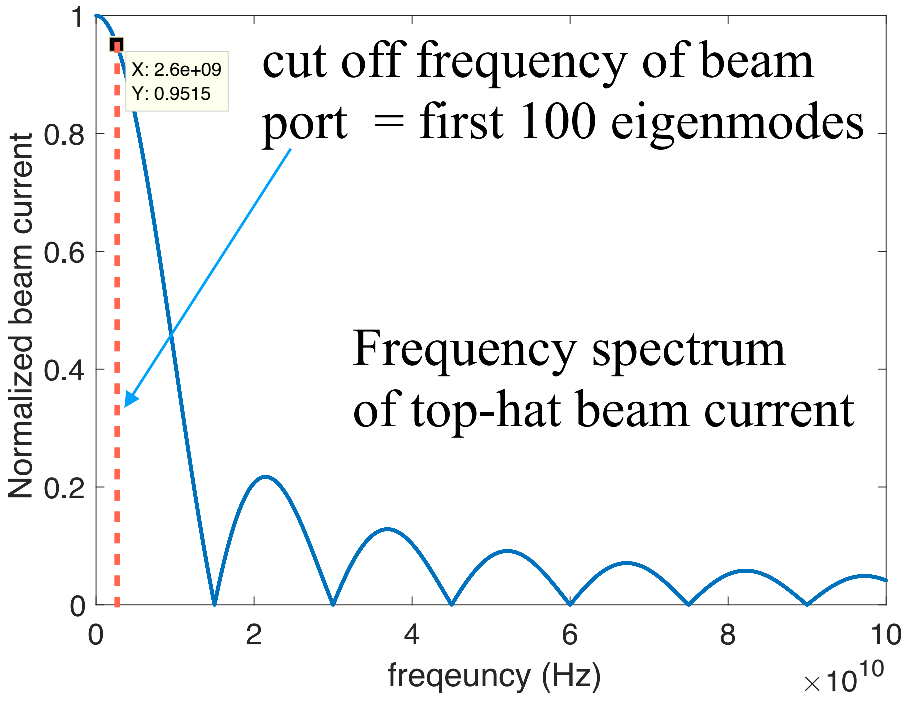
$$P_{ave} = \sum_n P_{n,ave} = \sum_n \frac{1}{T} \int_0^{1/f_b} dt\, P_n(t)$$

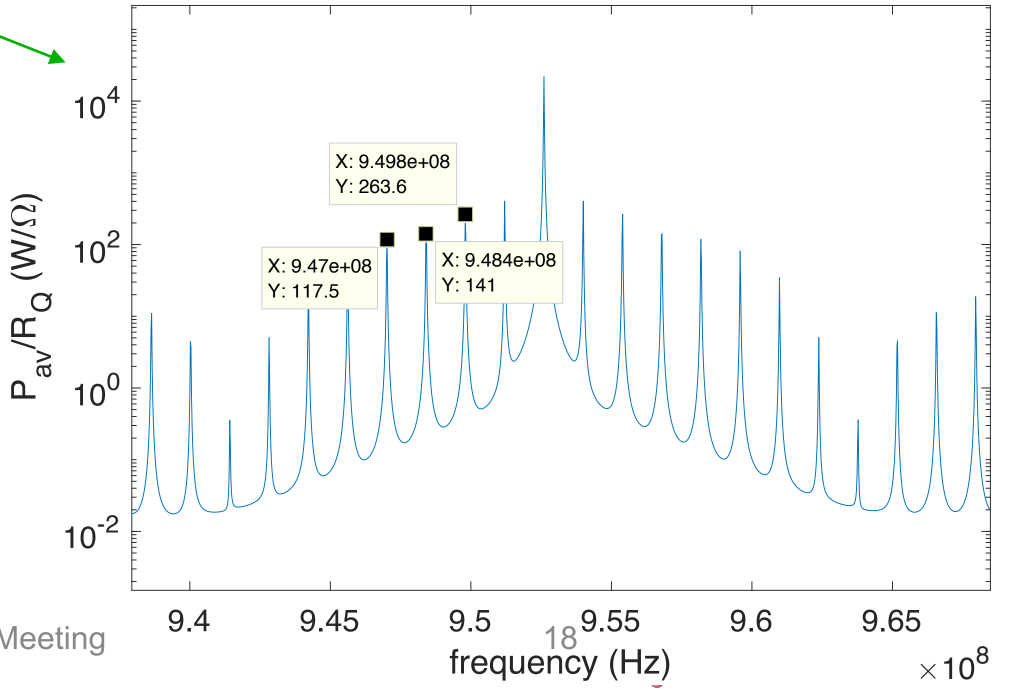
HOM power estimation

- (average) Power of HOM

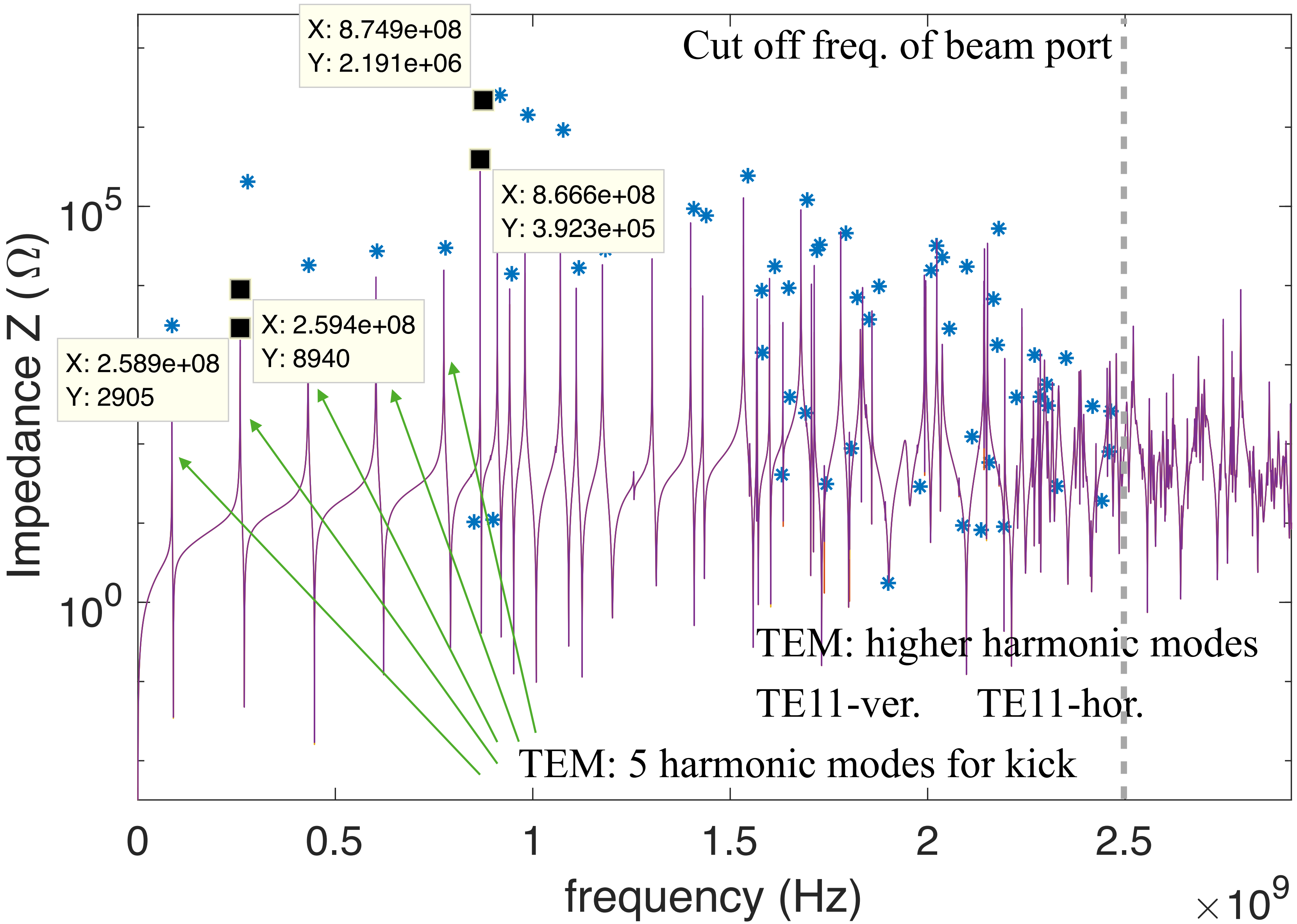
$$P_{\text{ave,total}} \sim 10\text{W} \; (P_{\text{ave,loss}} \sim 4\text{W})$$







Impedance spectrum



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

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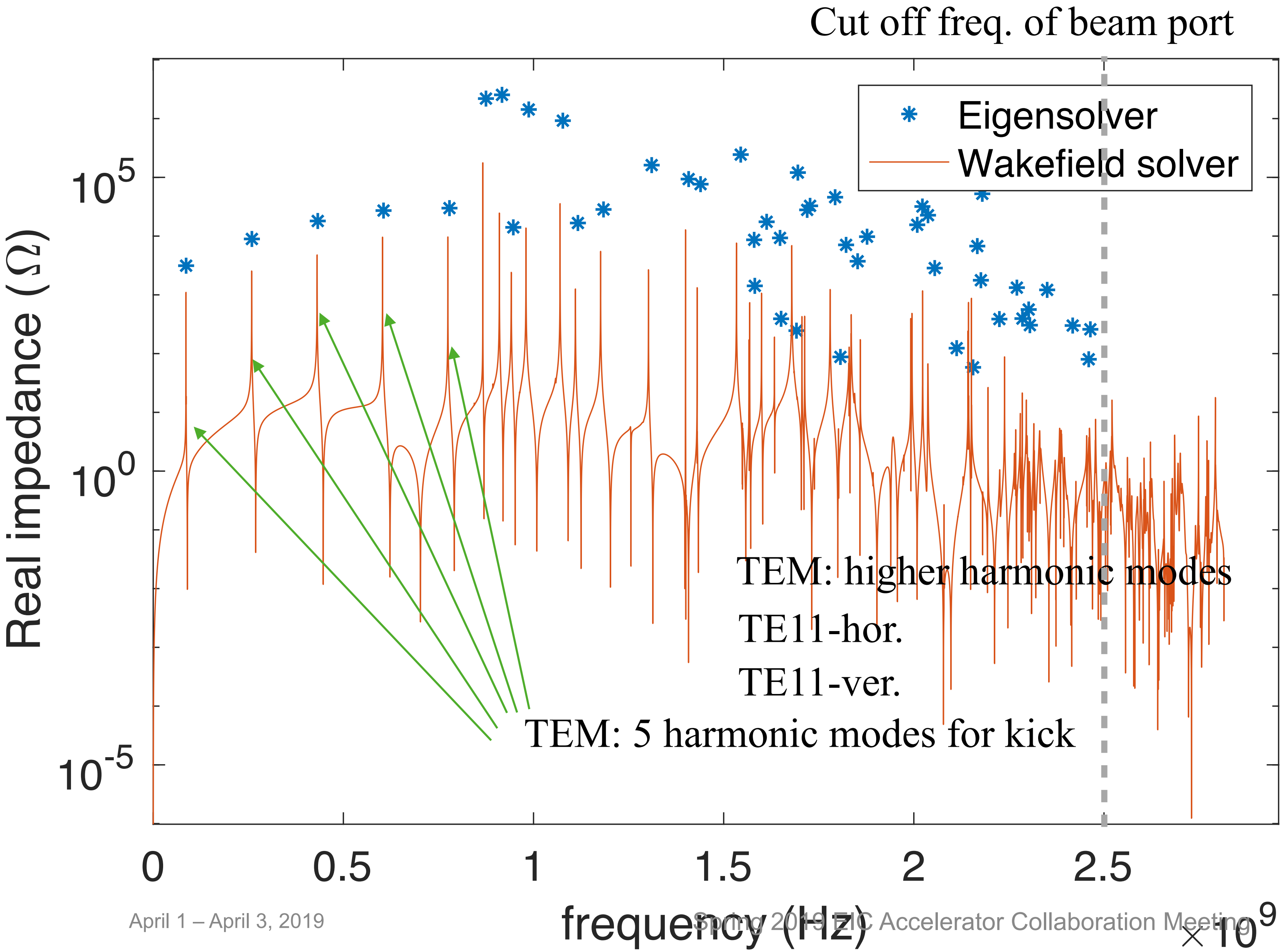
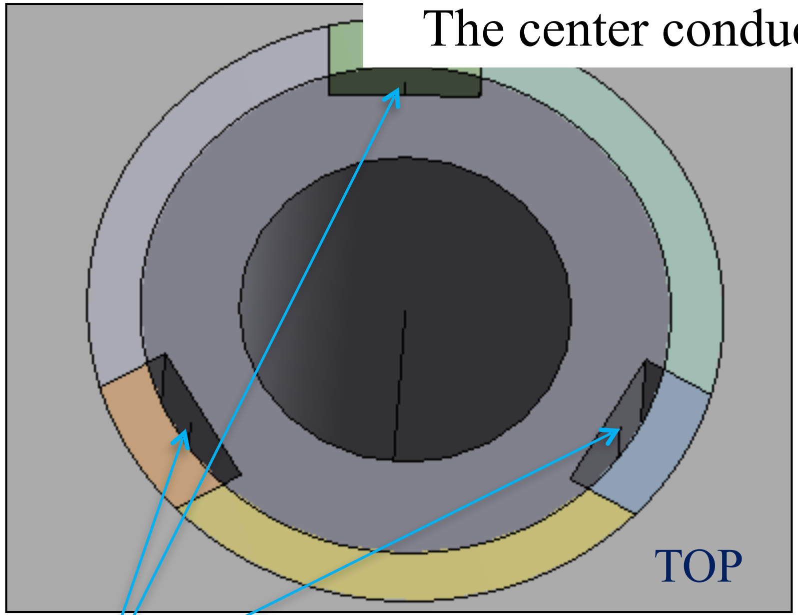
Impedance spectrum

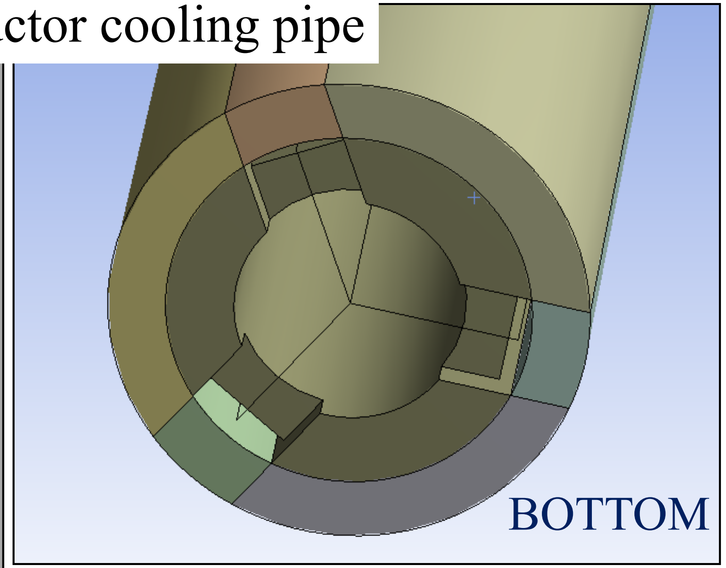


- In wake field simulation, the locations of the peaks in (real) impedance spectrum were identified with resonant frequencies and the peaked values were with the shunt impedance, which is more accurately computed by CST Eigensolver. .

Thermal/Structural Analysis of the QWR

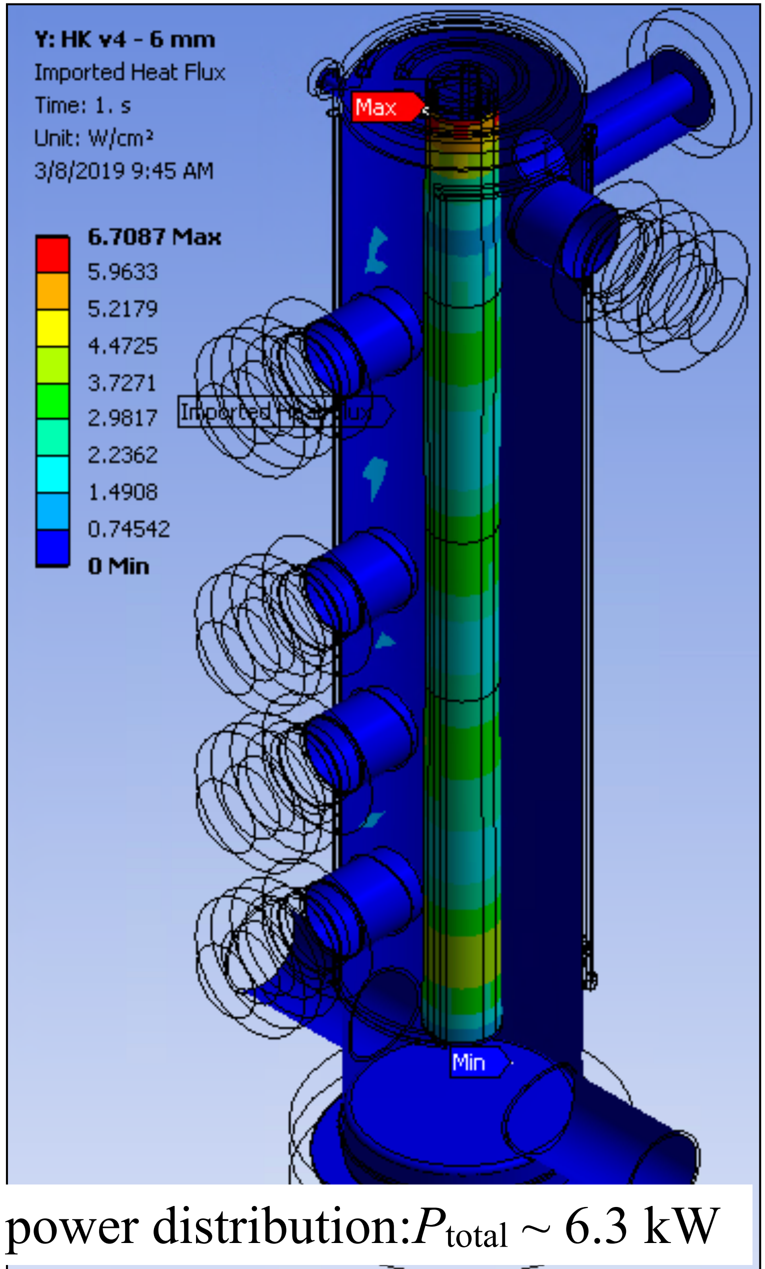
The center conductor cooling pipe



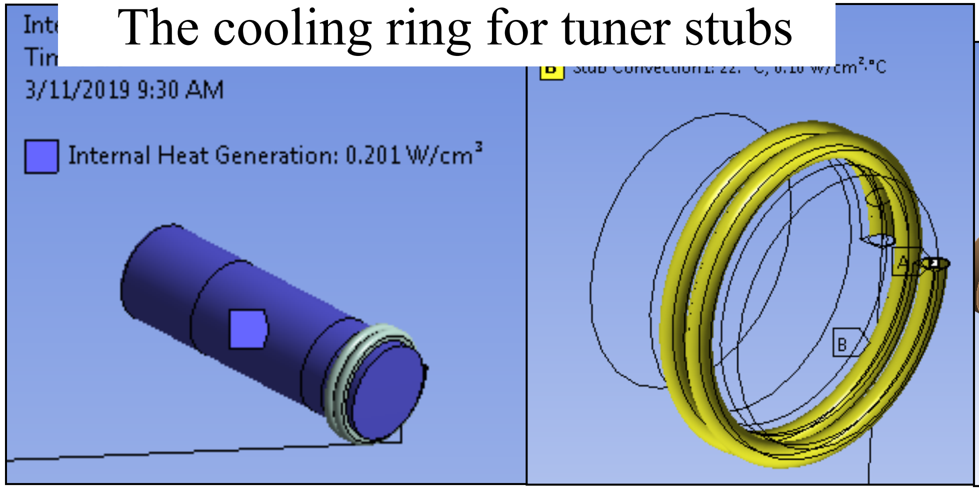


Channels @ 1.25 *l*/min

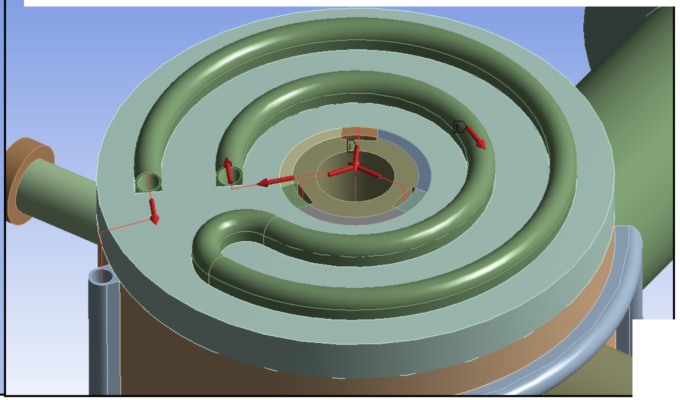
Supply pipe flow diverts to the three channels at the bottom



The cooling ring for tuner stubs

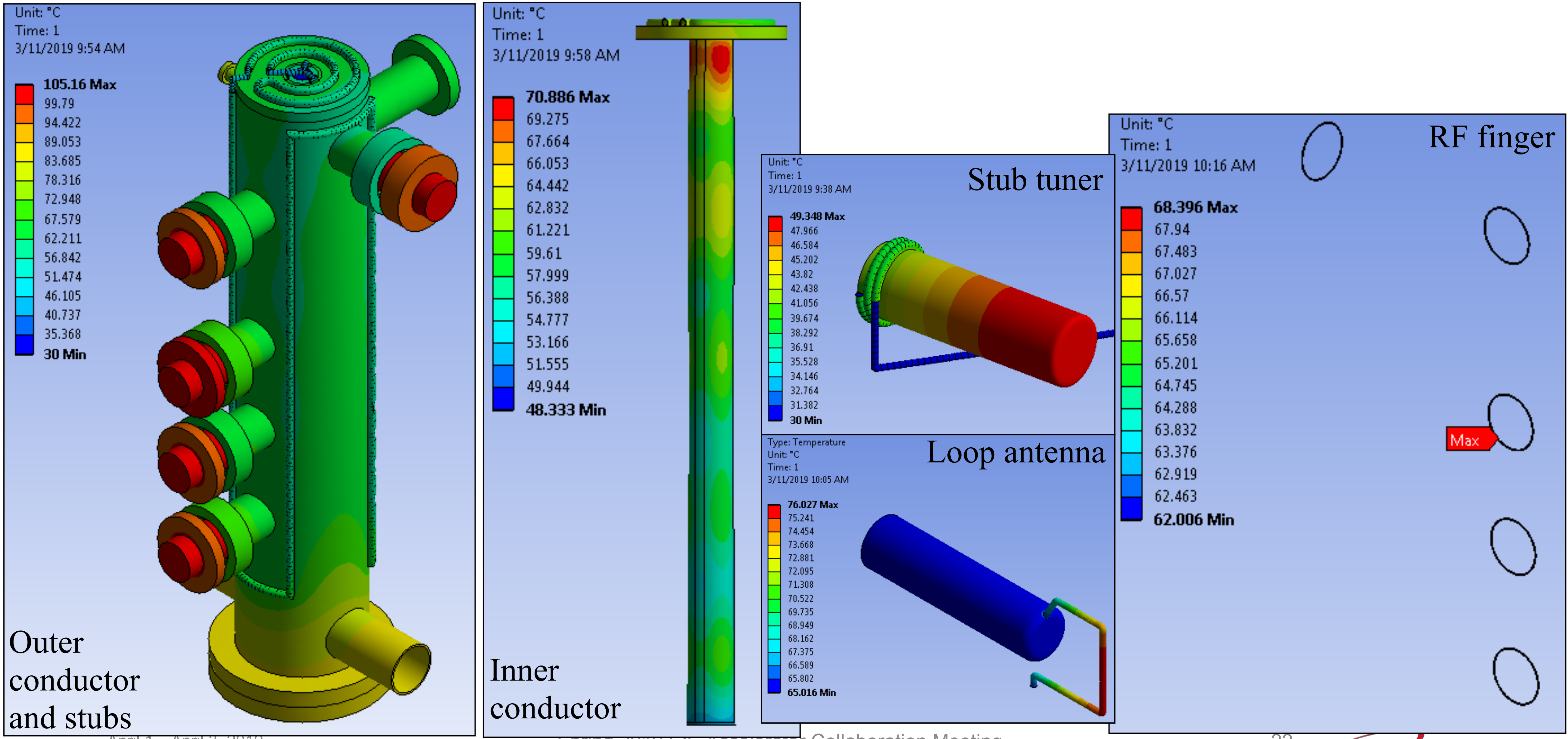


Top plate cooling channel on the outer conductor



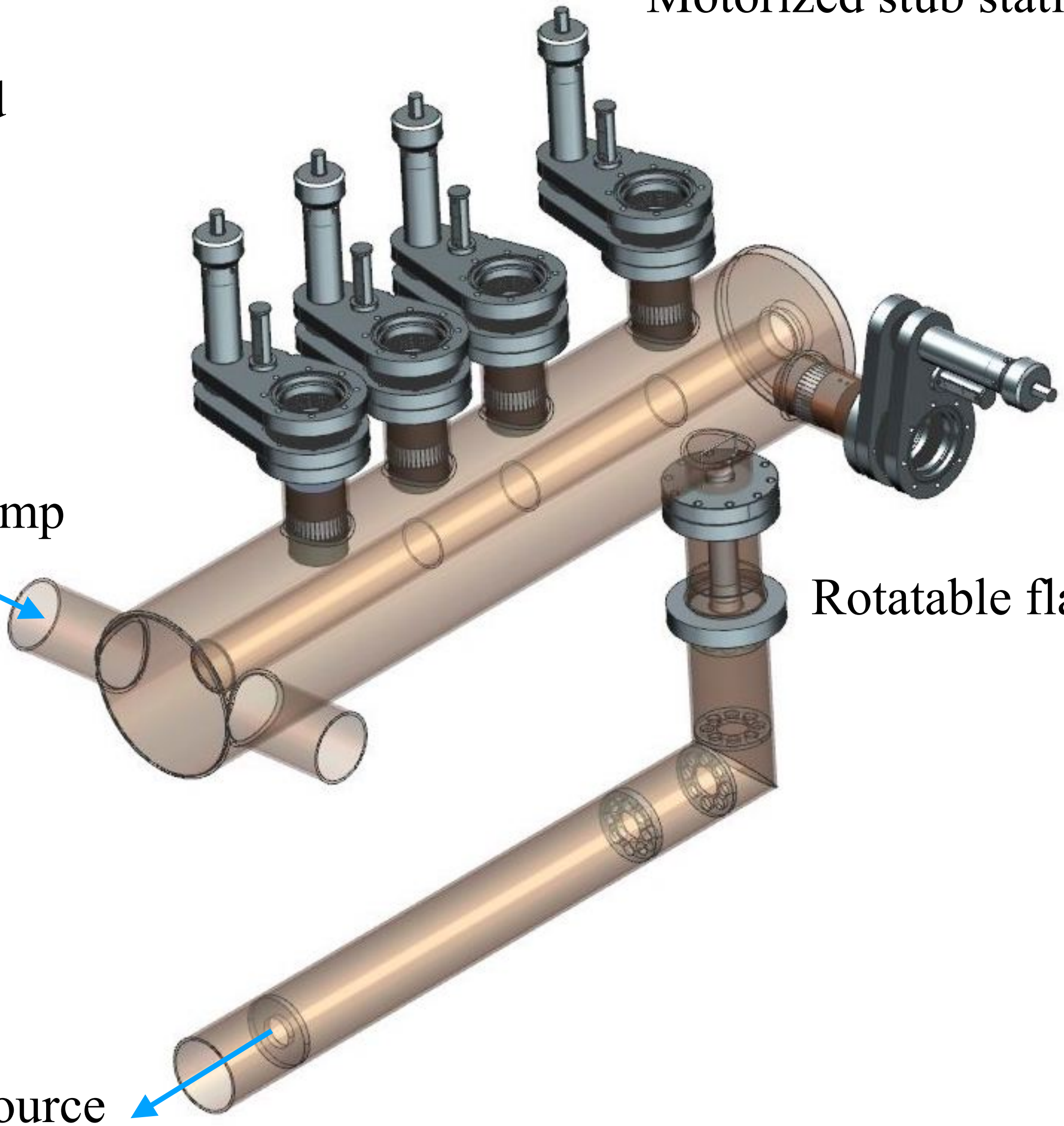
The power distribution: $P_{\text{total}} \sim 6.3$ kW

Temperature distribution @ power ~ 6.3 kW



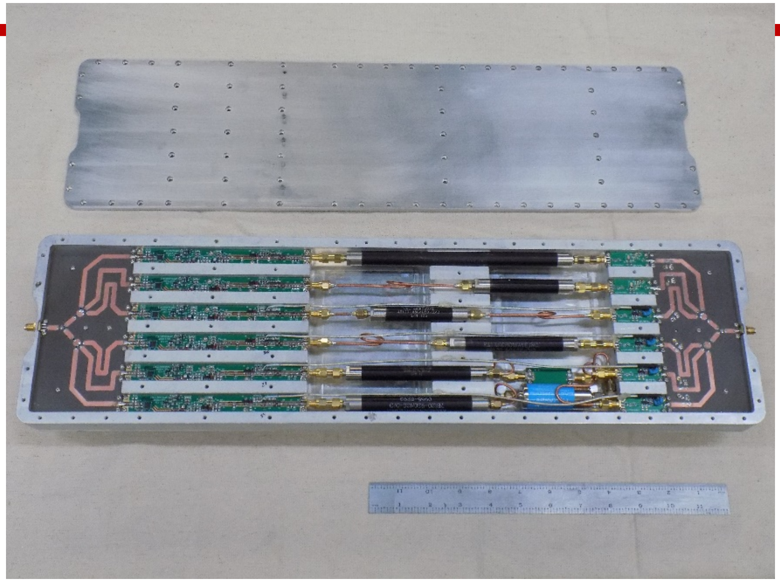
Fabrication Plan

- Design review is upcoming and kicker cavity will be fabricated soon.
- The subsequent development would be about the power (and pickup) coupler, tuning system, RF source (SSA), vacuum system, and control system.
- In particular, one option for power supply is 5 narrow band amplifier for 5 harmonic modes and high-power harmonic combiner.



Low Level RF Harmonic Driver Developed by Electrodynamics, SBIR-I Project

Electrodynamics developed stand-along HAWG with a Tektronix oscilloscope and a PC based LLRF controller



6-channel 1W Harmonic Arbitrary Waveform Generator (HAWG)