Bench Measurements of a Multi-frequency Prototype Cavity for the Fast Kicker in the JLEIC Circulator Cooler Ring

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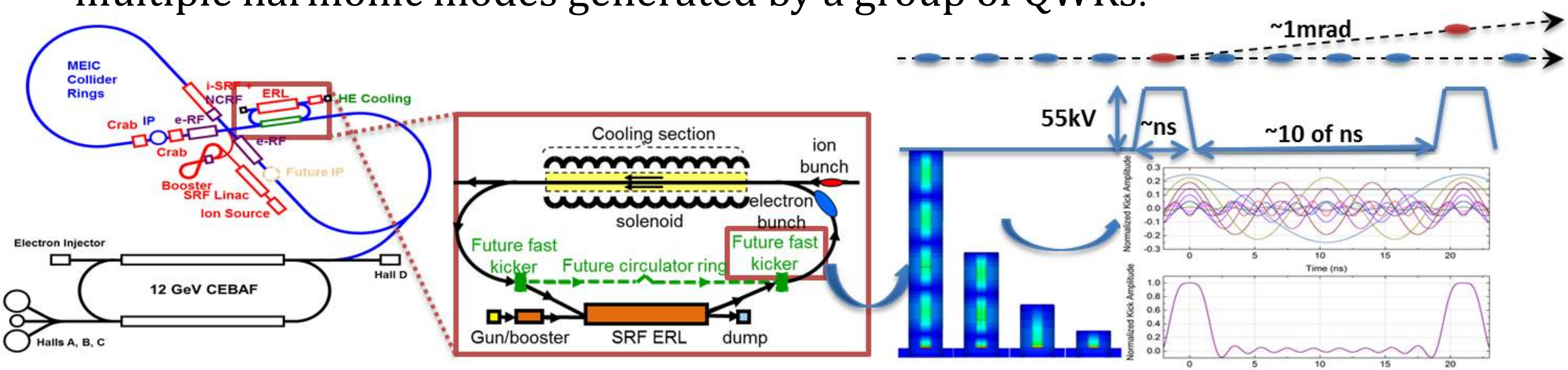
Outline

- ❑ **Fast Kicker in the JLEIC Circulator Cooler Ring**
- ❑ **RF Harmonic Kicker Design**
  - Harmonic Waveform Synthetize
  - Multi-Frequency Harmonic Deflecting Cavity Design
- ❑ **Half-Scale Copper Prototype**
  - Fabrication
  - Bench Measurements
- ❑ **Conclusion**
- ❑ **Acknowledgement**

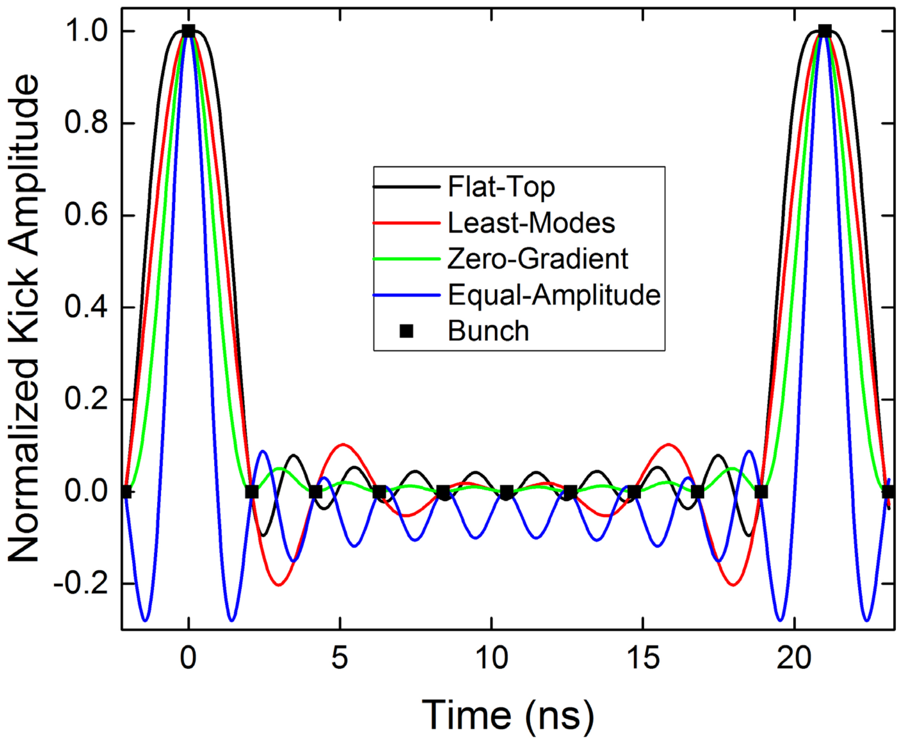
Fast Kicker in the JLEIC Circulator Cooler Ring

- **ERL-based electron cooler ring**
- **Single-pass ERL cooling**
  ~200mA,476.3MHz magnetized electron bunches
- **~1.5 A cooling electron beam current for powerful cooling**
  high current magnetized electron source; HOM damping in the SRF ERL;
  high beam power at the dump.
- **Multi-turn ERL-CCR Scheme**
  reuse electron bunches for 10~30 turns in the CCR,
  reduce the beam current and bunch repetition freq. to 1/10~1/30 in the ERL
- **Fast kicker for electron bunches exchange between ERL and CCR**
  multiple harmonic modes generated by a group of QWRs.



Harmonic Kicker Waveform Synthetize

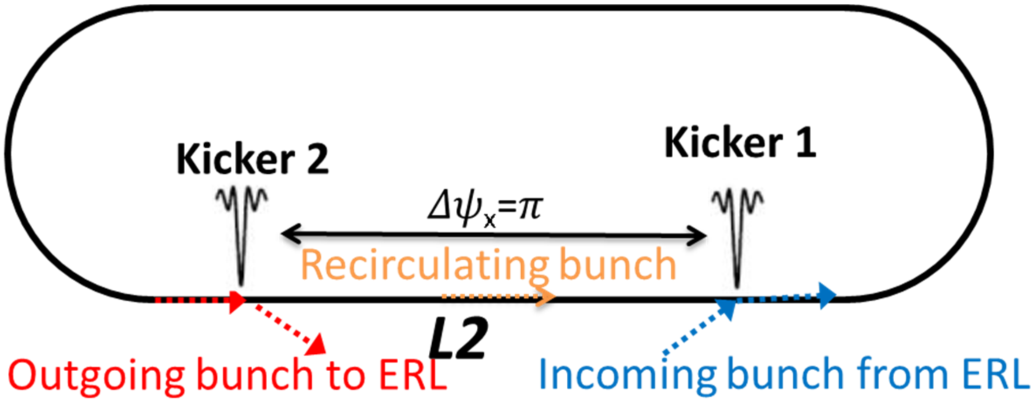
Kick every 10th bunch as an example



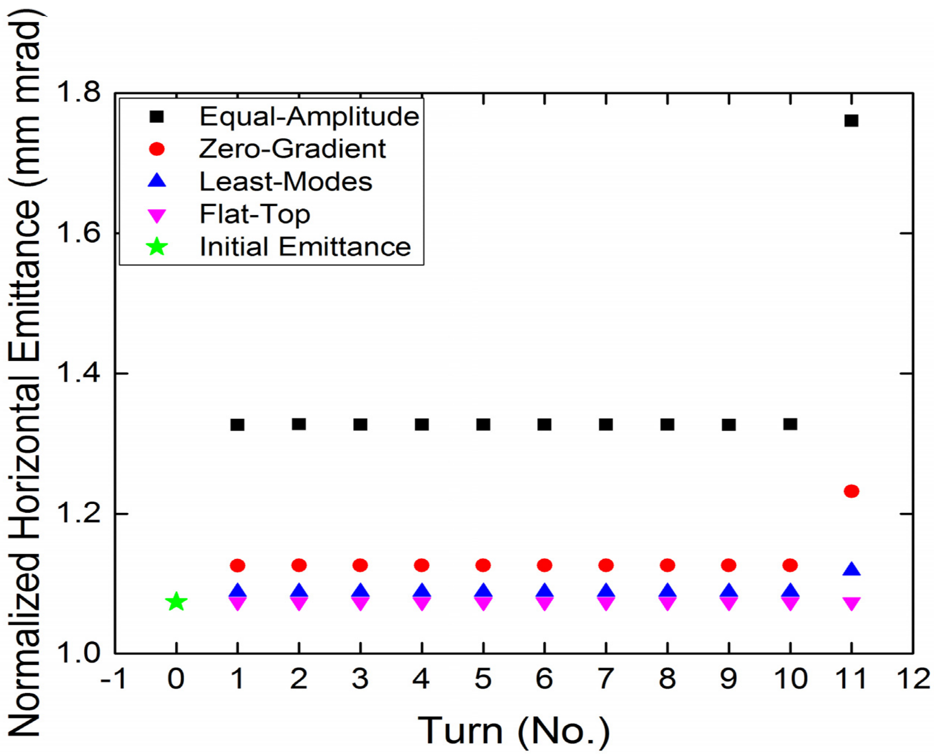
Mode (MHz)	Flat-Top	Zero-Gradient	Least-Modes	Equal-Amplitude
47.63	0.249	0.180	0.200	0.100
95.26	0.227	0.160	0.200	0.100
142.89	0.192	0.140	0.200	0.100
190.52	0.148	0.120	0.200	0.100
238.15	0.100	0.100	0.100	0.100
285.78	0.053	0.080	------	0.100
333.41	0.012	0.060	------	0.100
381.04	-0.022	0.040	------	0.100
428.67	-0.044	0.020	------	0.100
476.3	-0.055	------	------	0.100
DC	0.140	0.100	0.100	------
Total	1.000	1.000	1.000	1.000

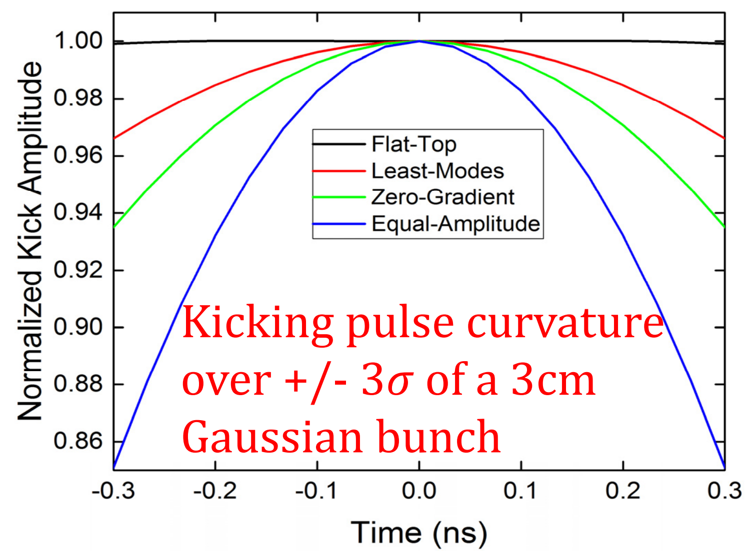
Ref: Y.Huang, H.Wang, R.A.Rimmer, et al. Phys. Rev. ST Accel. Beams 19, 084201 (2016)

Tracking Simulation in ELEGANT



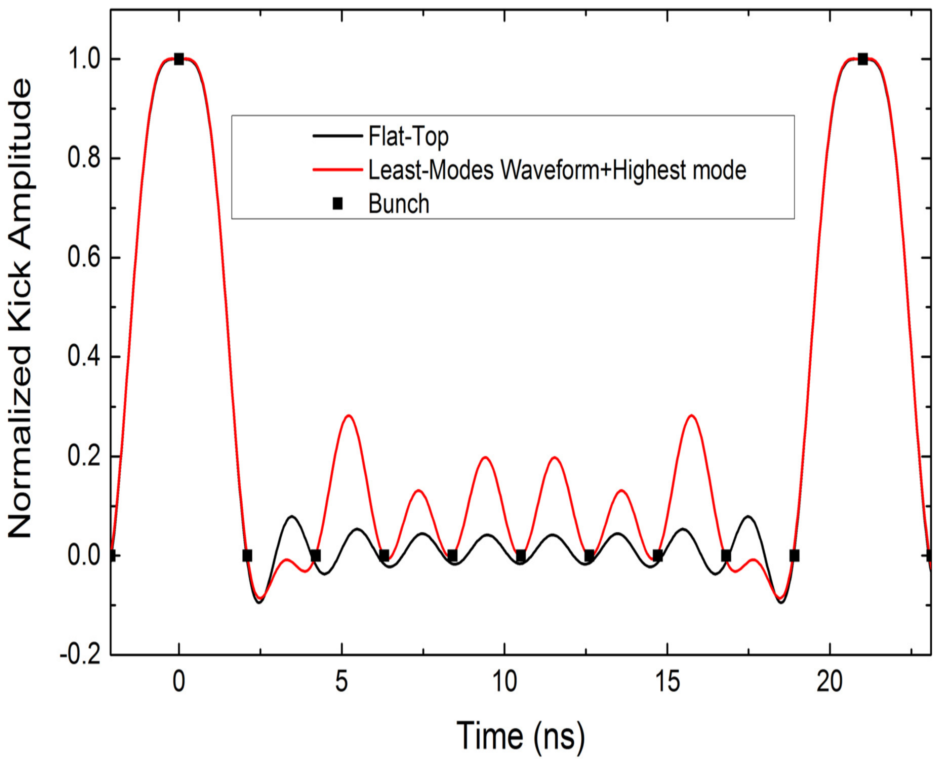
- With two kickers separated 180 degree in Betatron phase advance, emittance growth due to the residual wave slopes between the kicking pulse can be totally cancelled.
- Emittance growth mainly comes from the injection and ejection process, which is only determined by the kicking pulse curvature.





“Flat-Top” plus “Least-Modes”

Introducing the highest modes(476.3MHz, at the inverse phase) to the Least-Mode scheme, and adjusting the amplitude the DC offset.

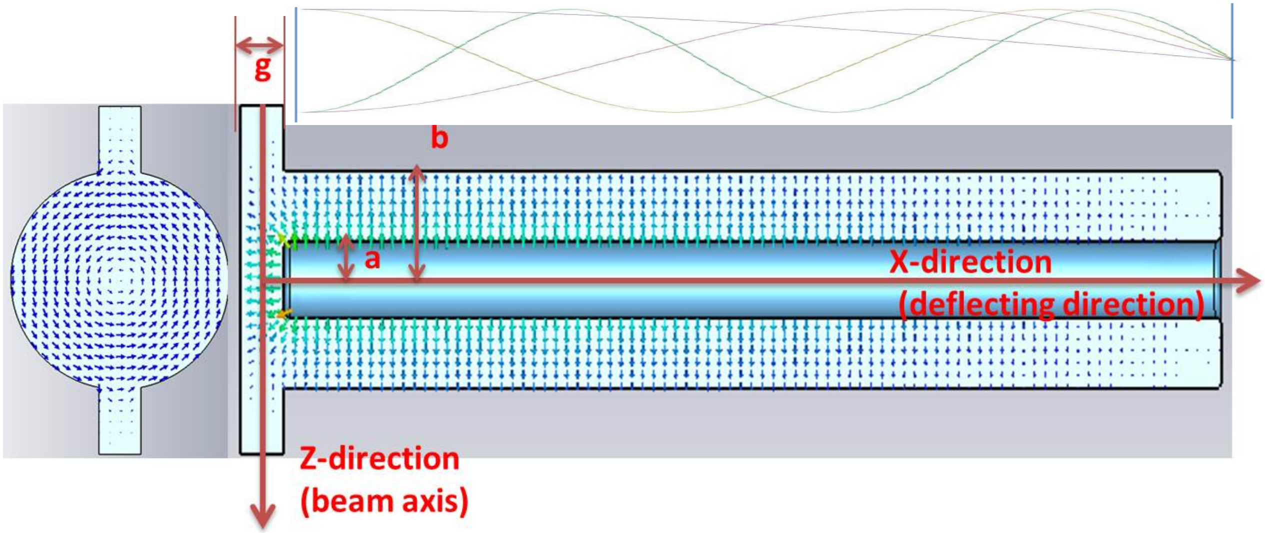


Mode (MHz)	Flat-Top	Least-Modes	Least-Modes +476.3MHz
47.63	0.249	0.200	0.200
95.26	0.227	0.200	0.200
142.89	0.192	0.200	0.200
190.52	0.148	0.200	0.200
238.15	0.100	0.100	0.100
285.78	0.053	...	...
333.41	0.012	...	...
381.04	-0.022	...	...
428.67	-0.044	...	...
476.3	-0.055	...	-0.090
DC	0.140	0.100	0.190
Total	1.000	1.000	1.000

10 Harmonic +DC **6 Harmonic +DC**

QWR-based Deflecting Cavities

The electron bunches traveling through the cavity will be deflected by both the transverse electric and magnetic fields.



The effective transverse kick voltage of the nth harmonic mode can be calculated from:

$$V_{tn} = \int_{-\infty}^{\infty} [E_{xn}(z)\cos(\frac{2\pi z}{\lambda_n}) + cB_{yn}(z)\sin(\frac{2\pi z}{\lambda_n})]dz$$

The total kick voltage from all harmonic modes is:

$$V_t = V_0 + \sum_{n=1}^{N} V_{tn} \cos(n\omega_0 t + \varphi_n)$$

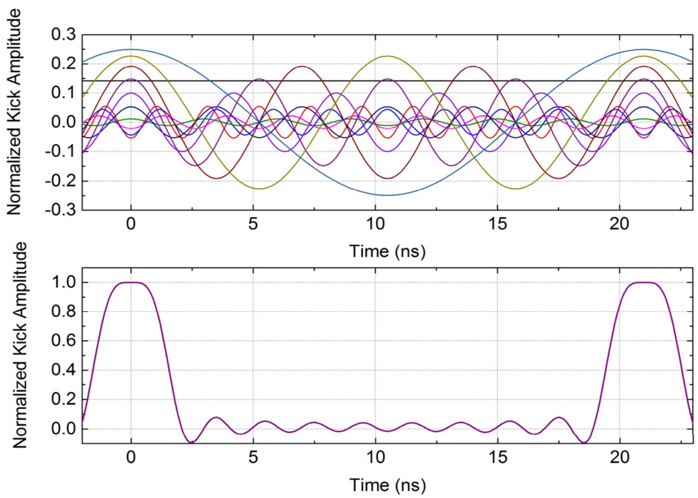
The relationship between cavity number M and maximum harmonic number N can be supported as:

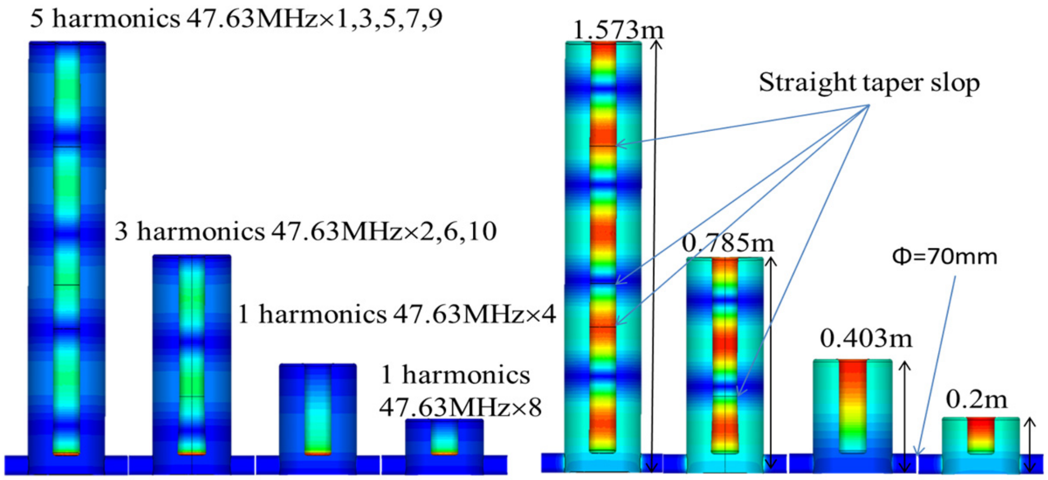
$$2^M - 1 \leq N$$

Discussion on the Recirculation Number, Harmonic Number, Cavity Number

	Flat-Top Scheme				Least-Mode +476.3MHz			
Recirculate Turn	10	15	25	30	10	15	25	30
Harmonic Number	10	15	25	30	6	8	13	16
Cavity number	4	4	5	5	3	3	4	4
Mode distribution	5:3:1:1	8:4:2:1	13:6:3:2:1	15:8:4:2:1	3:2:1	5:2:1	7:3:2:1	8:5:2:1
Mode in Cavity#1	1,3,5,7,9	1,3,5,7,9,11,13,15	1,3,5,7,9,11,13,15,17,19,21,23,25	1,3,5,7,9,11,13,15,17,19,21,23,25,27,29	1,3,5	1,3,5,7,15	1,3,5,7,9,11, 25	1,3,5,7,9,11,13,15
Mode in Cavity#2	2,6,10	2,6,10,14	2,6,10,14,18,22	2,6,10,14,18,22,26,30	2,10	2,6	2,6,10	2,6,10,14, 30
Mode in Cavity#3	4	4,12	4,12,20	4,12,20,28	4	4	4,12	4,12
Mode in Cavity#4	8	8	8,24	8,24			8	8
Mode in Cavity#5			16	16				

4-Cavity Model Based on Flat-Top Scheme

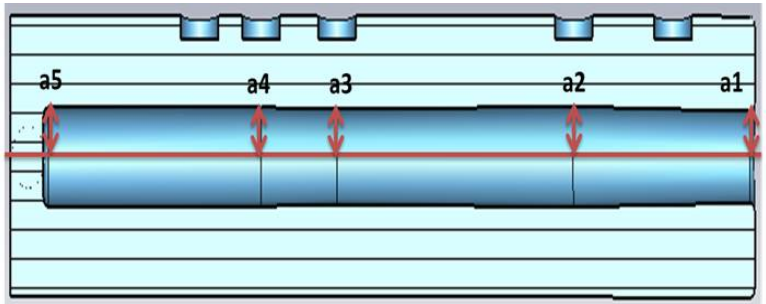


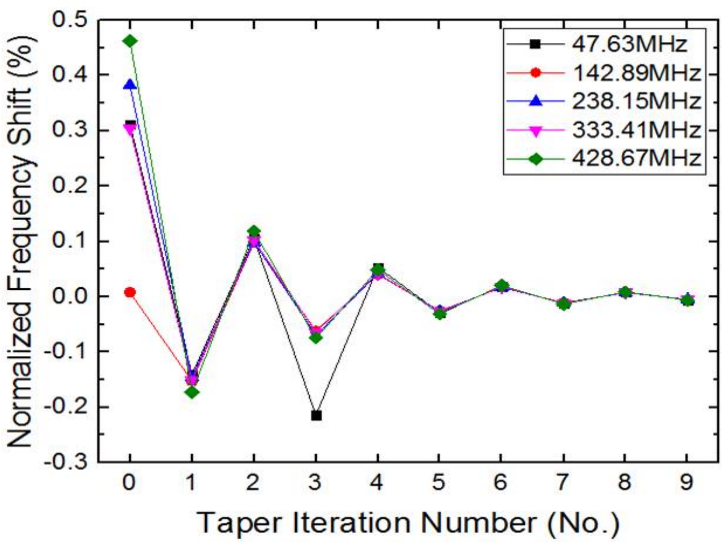


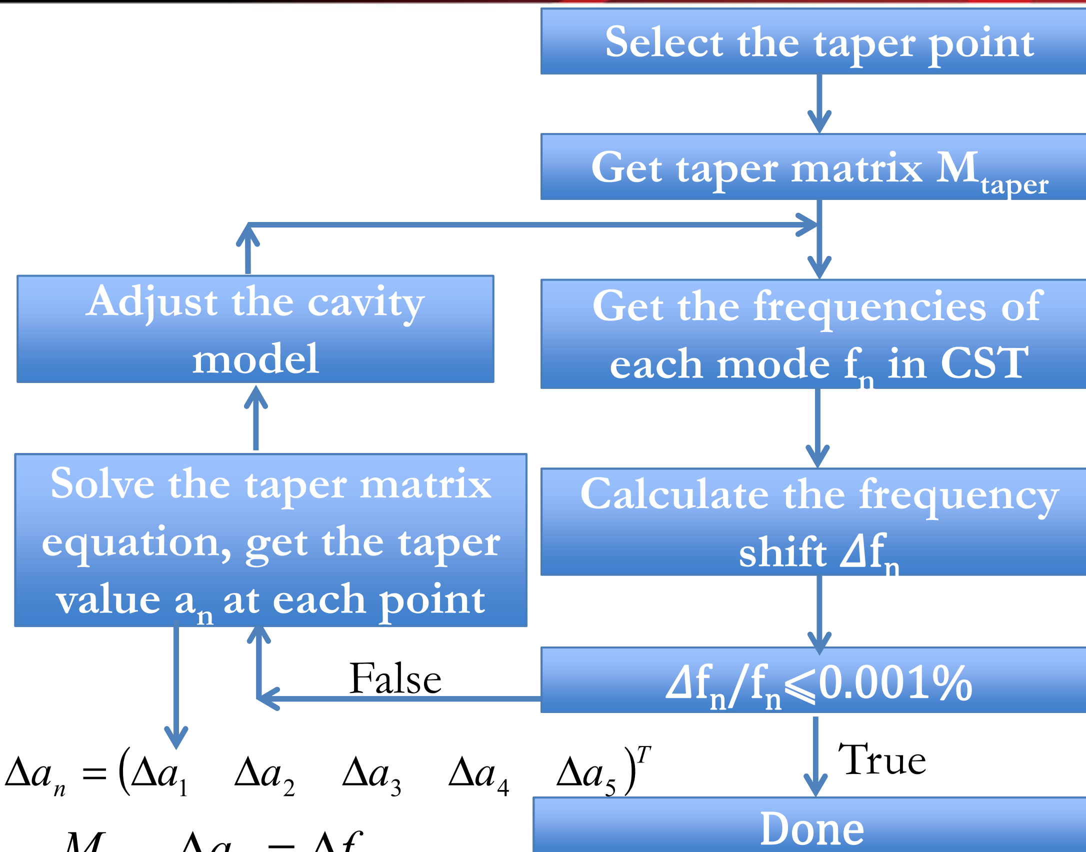
Calculated electromagnetic parameters of each mode for room temperature copper.

Cavity	Operation Frequency (MHz)	Q_0	Flat-Top Kick Voltage (kV)	Transverse Shunt Impedance (Ω)	Dissipated Power (W)
Five-Mode Cavity	47.63	8586	13.711	7.527E6	24.98
	142.89	14689	10.532	3.954E6	28.05
	238.15	18973	5.503	2.916E6	10.39
	333.41	22472	0.630	1.859E6	0.21
	428.67	25536	-2.432	1.131E6	5.23
Three-Mode Cavity	95.26	12002	12.462	1.080E7	14.38
	285.78	20784	2.917	4.082E6	2.08
	476.3	27056	-3.011	1.560E6	5.81
One-Mode Cavity	190.52	15298	8.129	1.153E7	5.73
One-Mode Cavity	381.04	19435	-1.209	8.861E6	0.17
DC Offset			7.768		
Total			55	3.117E7	97.03

Straight Taper and Stub Tuner Design







$$\Delta a_n = (\Delta a_1 \quad \Delta a_2 \quad \Delta a_3 \quad \Delta a_4 \quad \Delta a_5)^T$$

$$M_{taper} \Delta a_n = \Delta f_n$$

With taper design, the frequencies of all harmonic modes can be optimized to be odd multiple harmonics, the errors are within +/- 0.001% from their targets.

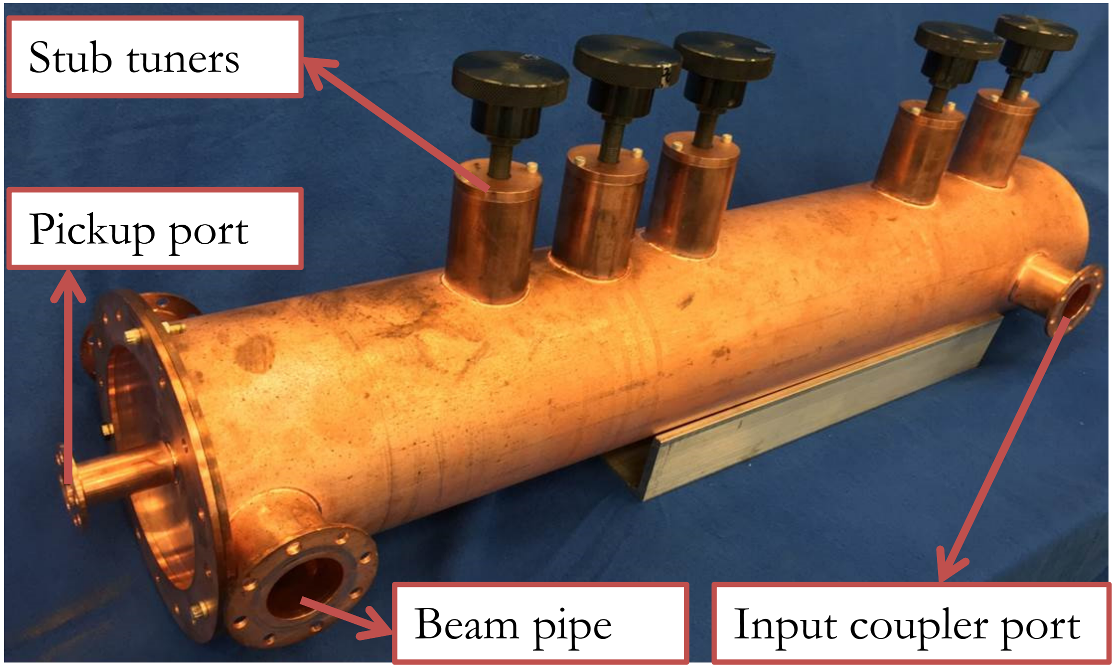
Manufacturing and other errors can be tuned back by the stub tuners with a similar process.

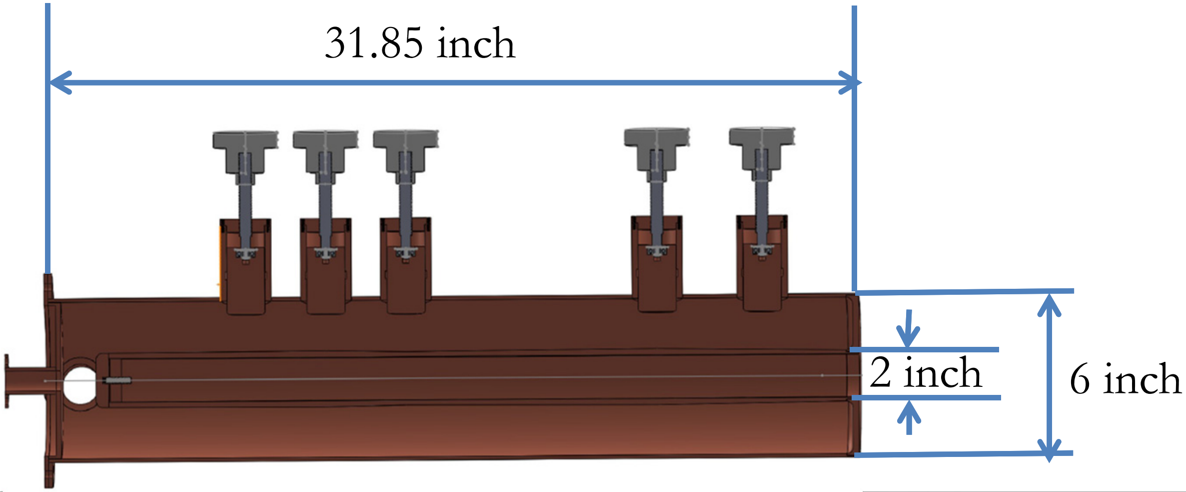
Stub tuners insert 25mm as the baseline of taper to get a bi-directional tuning range.

Half Scale Copper Prototype

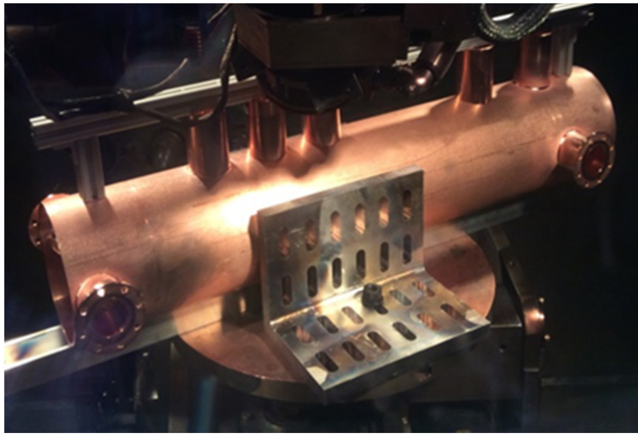
Half scale copper prototype with 5 odd harmonic modes:

95.26 MHz
285.78MHz
476.3MHz
666.82MHz
857.34MHz

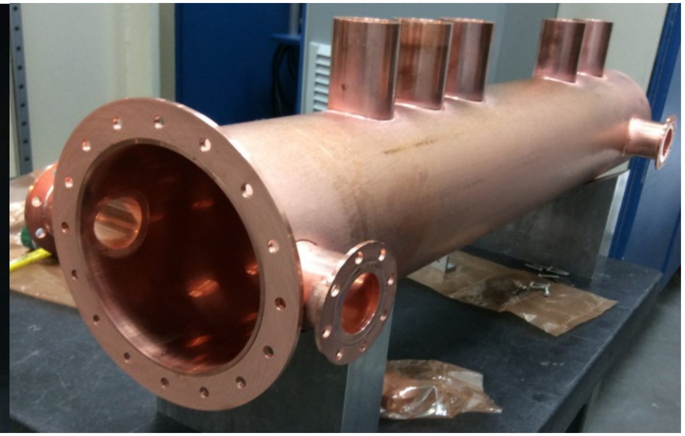




Some Fabrication Detail

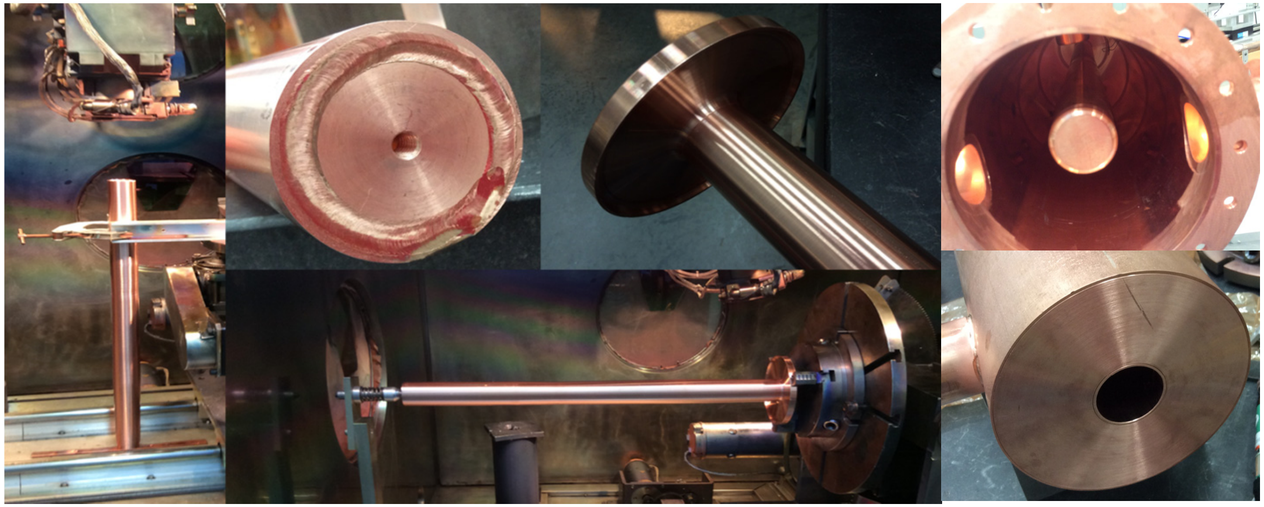


EBW of the outer conductor with the tuner pipes

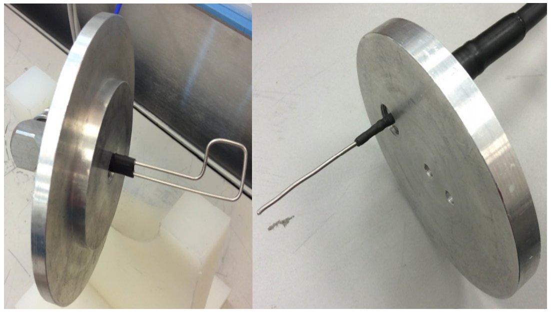


EBW of the outer conductor with electric end flange

Stub tuners detail



EBW of the inner conductor to the Magnetic End flange and thread connection with the Electron End Cap



Loop coupler and pickup antenna

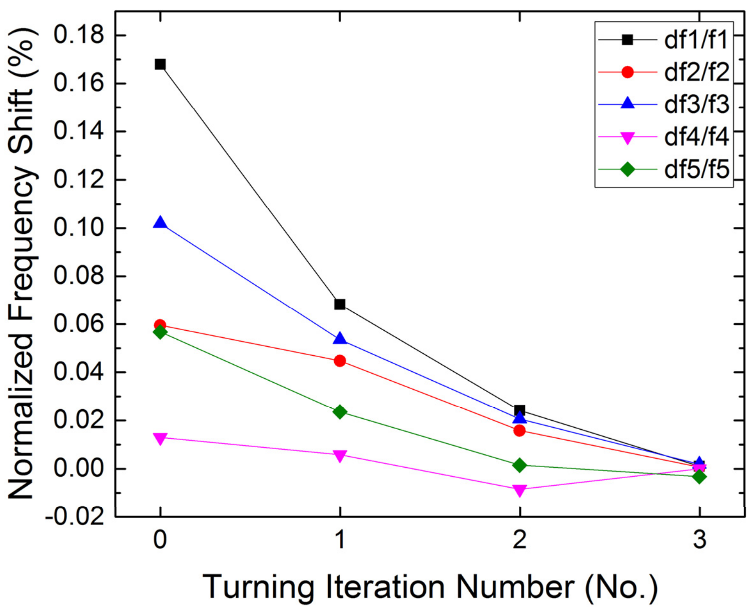
Resonant frequencies and tuning sensitivity

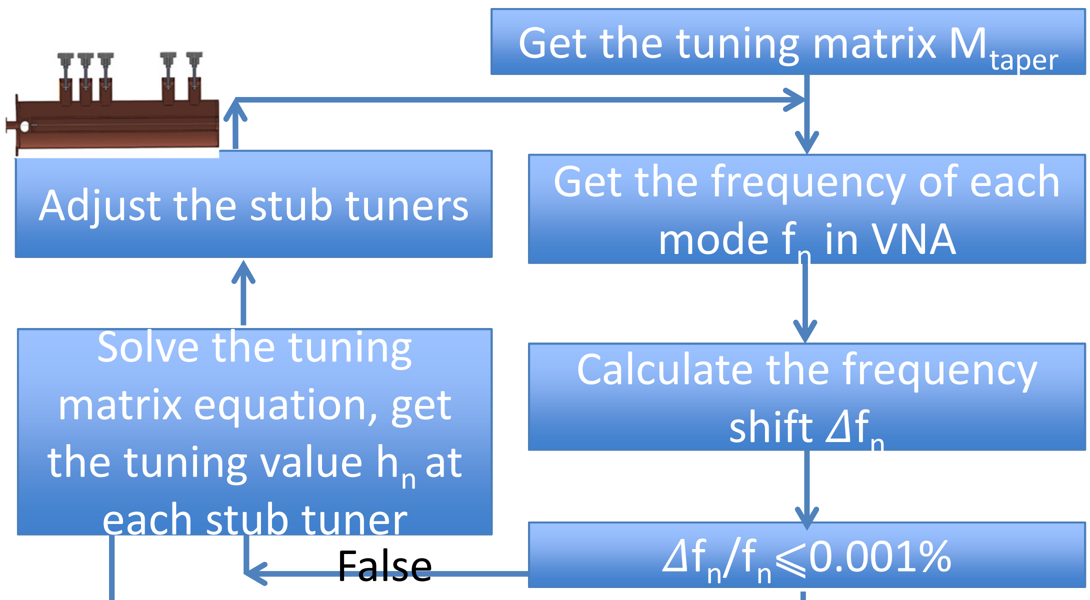
Resonant frequency measurements.

Target Frequency (MHz)	Measured Frequency (MHz)	Frequency Shift (%)
95.26	95.420	+0.17
285.78	285.950	+0.06
476.3	476.785	+0.10
666.82	666.906	+0.01
857.34	857.827	+0.06

$$M_{tuner} = \begin{pmatrix} -31.26 & -26.93 & -17.80 & +3.465 & +9.370 \\ -4.803 & +33.07 & +8.583 & -100.3 & -9.134 \\ +47.09 & -126.9 & -180.2 & -150.2 & -104.3 \\ -153.5 & -216.8 & +74.25 & +20.08 & -265.5 \\ -404.6 & +97.17 & -401.0 & +14.33 & -422.1 \end{pmatrix}$$

Tuning matrix form measurement, m_{ij} is the 1rst order (linear) frequency response of mode i to tuner j in units of Hz/mm.

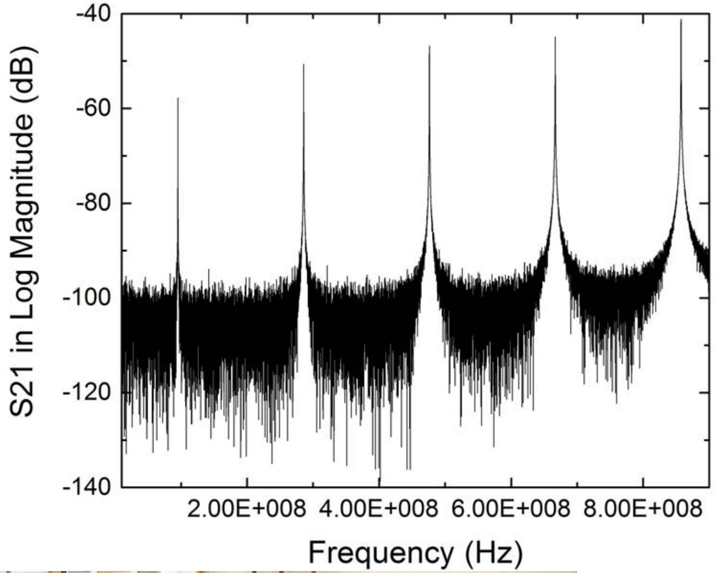


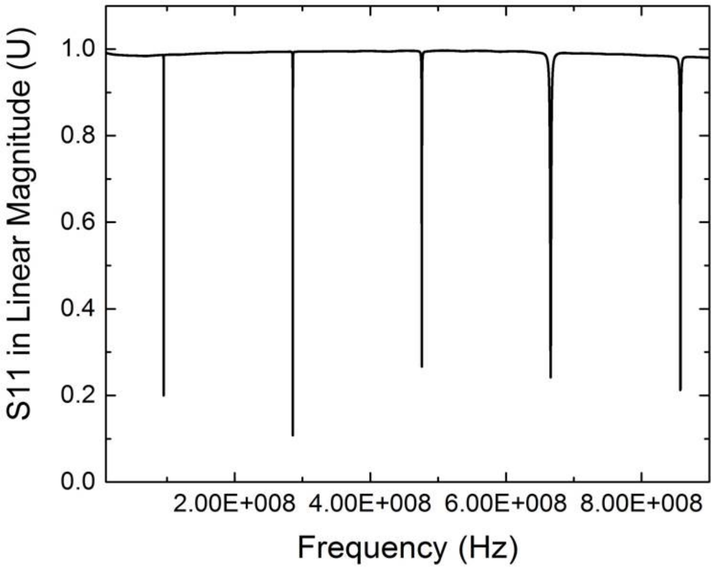


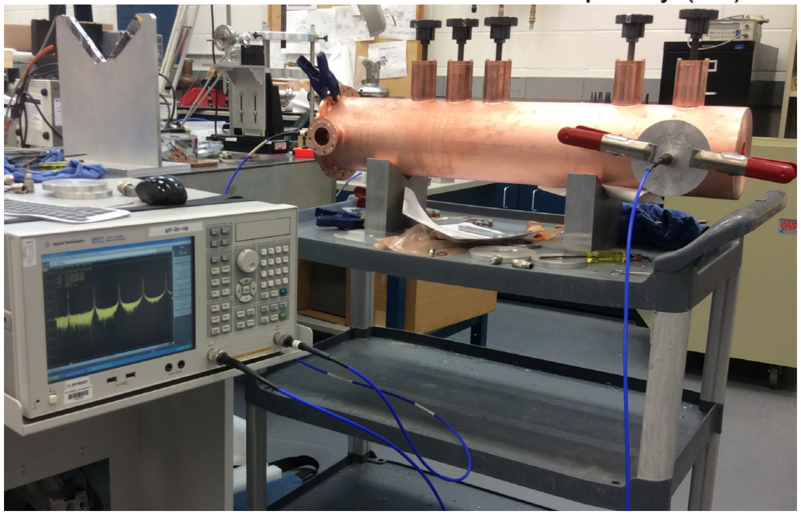
$$\Delta h_n = (\Delta h_1 \quad \Delta h_2 \quad \Delta h_3 \quad \Delta h_4 \quad \Delta h_5)^T$$

$$M_{tuner}\Delta h_n = \Delta f_n$$

Transmission and Reflection Coefficients, Unloaded Quality Factor Q Measurements



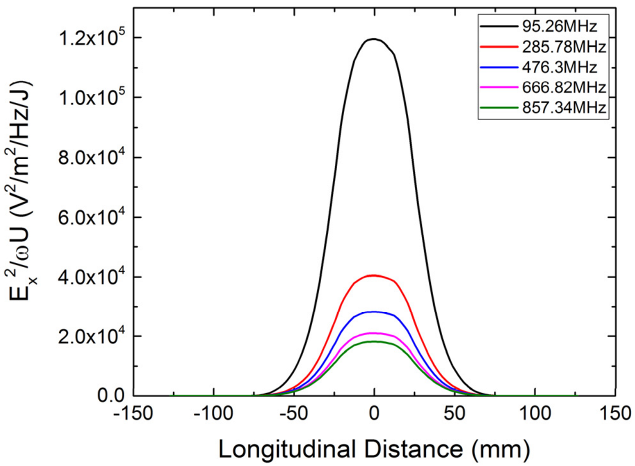


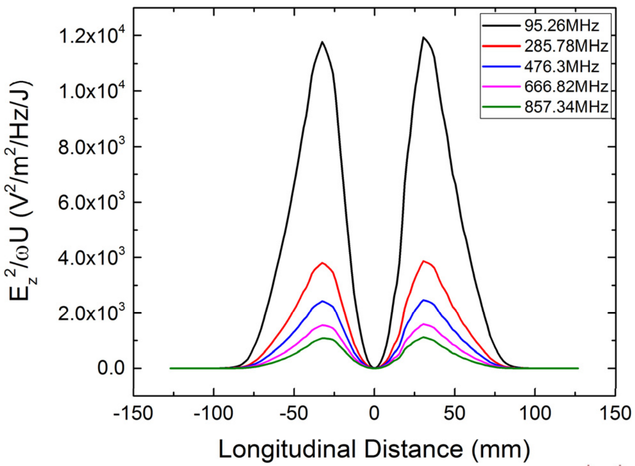


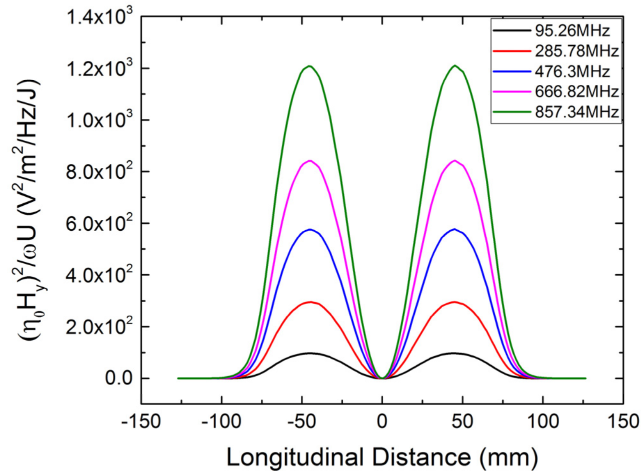
Unloaded quality factors from the simulation and measurement.

Mode(MHz)	CST	Measurement	Error
95.26	5665	5301	-6.43%
285.78	9770	9277	-5.04%
476.3	12531	11282	-9.96%
666.82	14834	13152	-11.34%
857.34	17109	14095	-17.62%

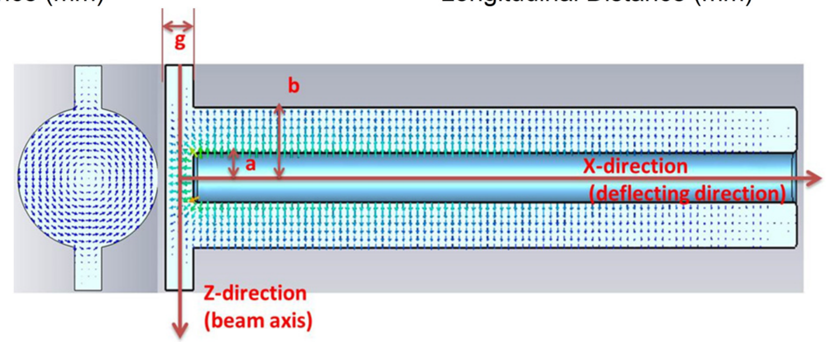
Distribution of Different Field Components Along the Beam Axis form CST





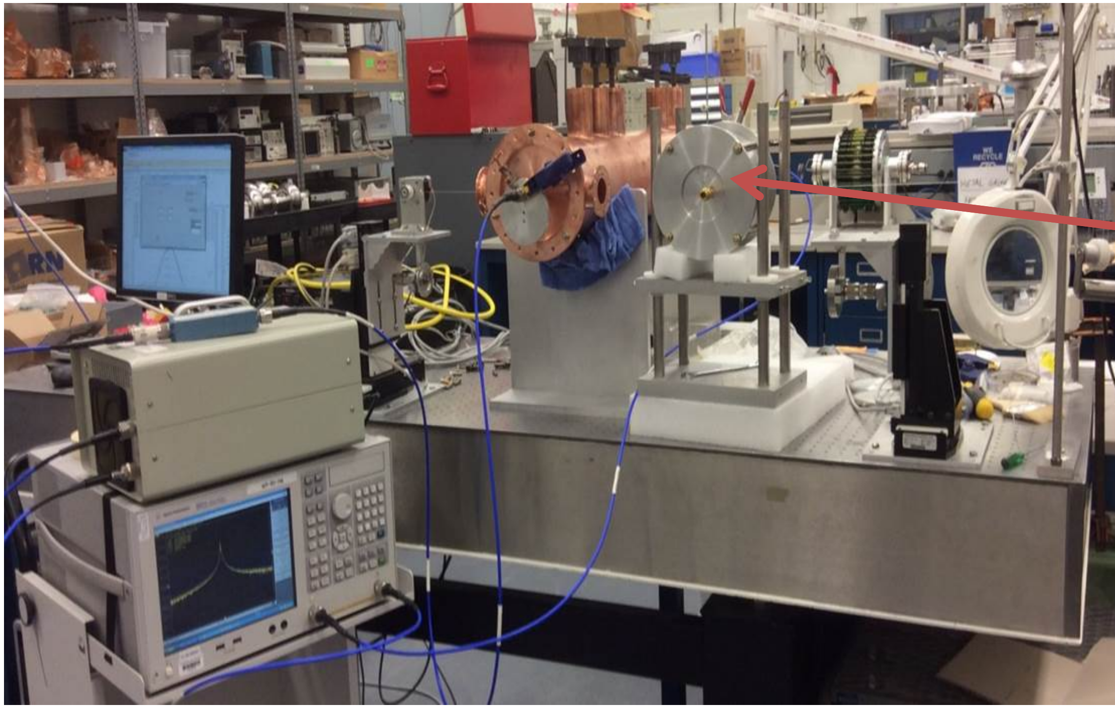


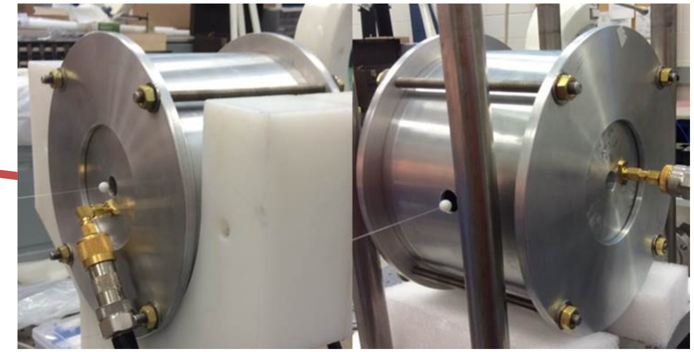
- **The dominant Field component is the deflecting electric field Ex**
- **The longitudinal field Ez is much smaller than the deflecting field(maximum 10% in magnitude squared).**



- **The magnetic field Hy is much weaker, and much smaller for the lowest harmonic mode (0.1% in magnitude squared) and relatively larger for the highest harmonic mode (6% in magnitude squared).**

Bead-pull Measurements





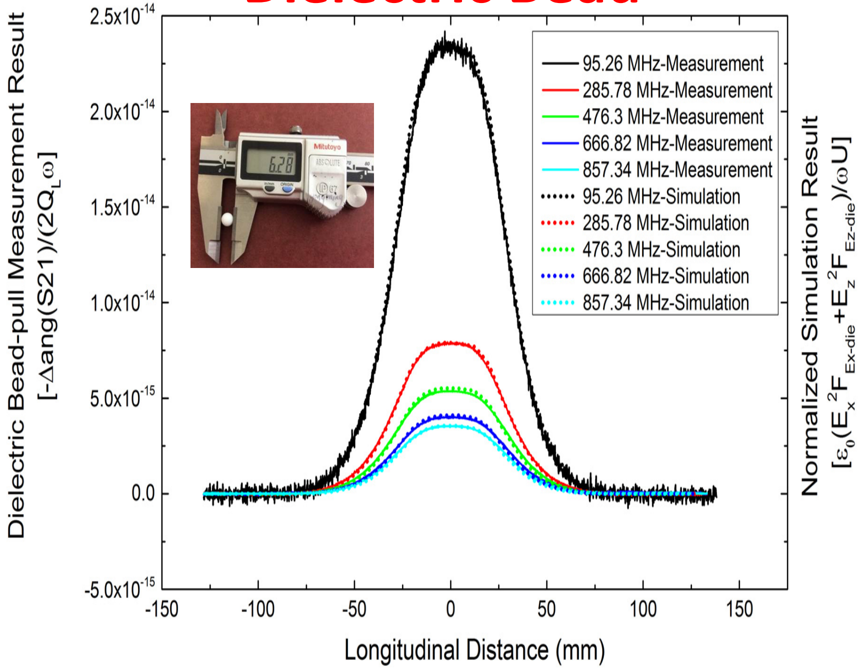
Aluminum pillbox cavity operated in TM010 is employed to calibrate the bead form factor.
Left: Longitudinal factor
Right: Transverse factor

$$\frac{\Delta\omega}{\omega} = -F_E \frac{\varepsilon_0 |E|^2}{U} + F_H \frac{\mu_0 |H|^2}{U}$$

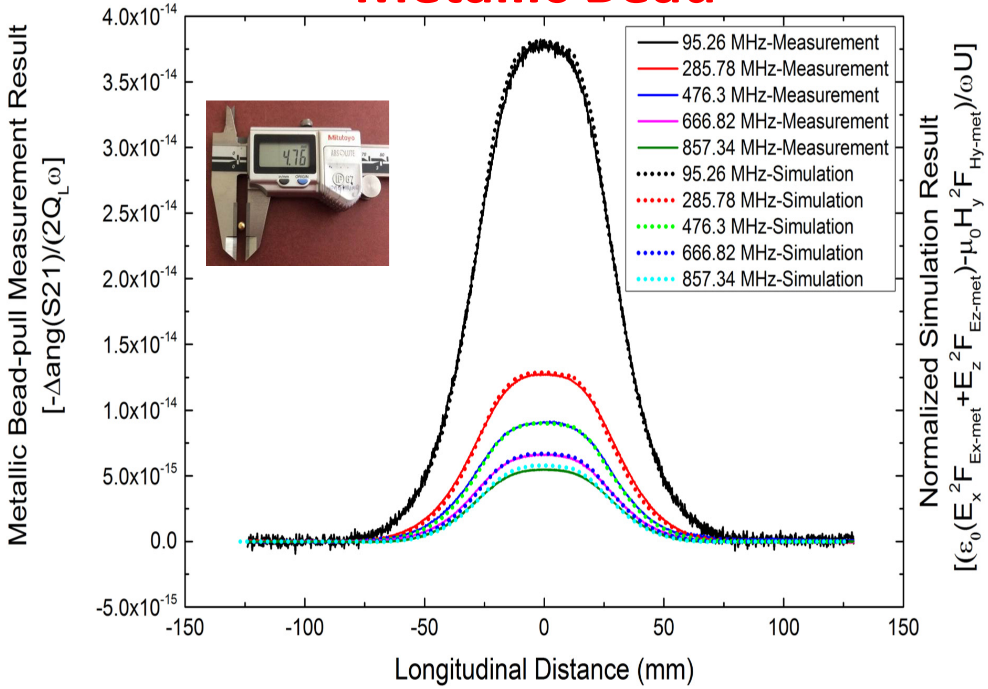
$$\frac{\Delta\omega}{\omega} = \frac{1}{2Q_L}\tan(\varphi)$$

Bead-pull Results Compared with the Simulation Results

Dielectric Bead



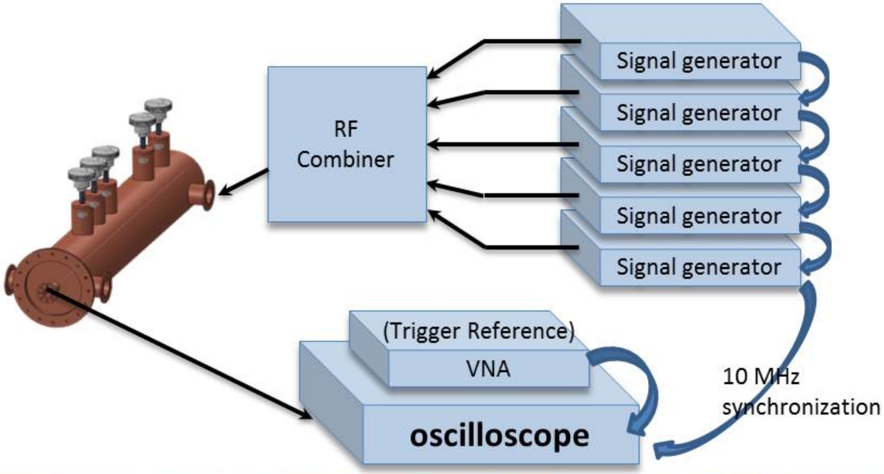
Metallic Bead

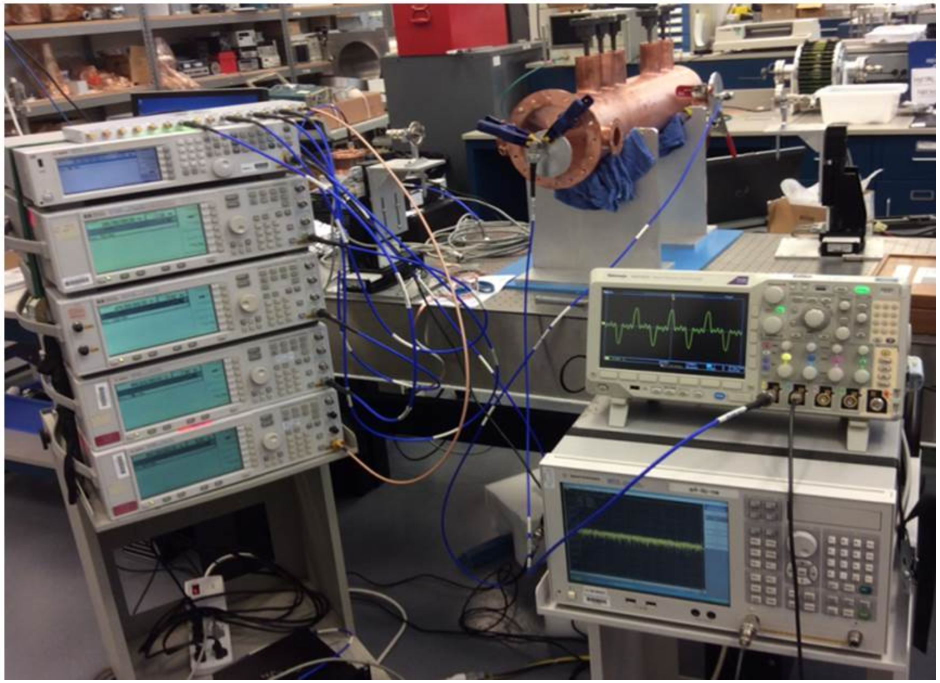


Measurement results agree well with the simulation results.

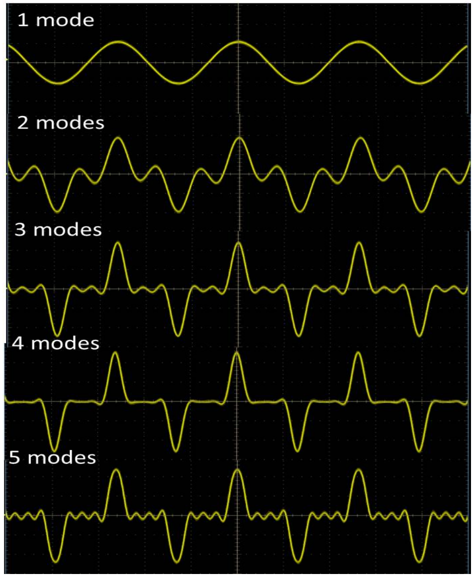
The longitudinal electric field Ex and the magnetic field Hy are too weak to be separated out.

Modes Combination Experiment

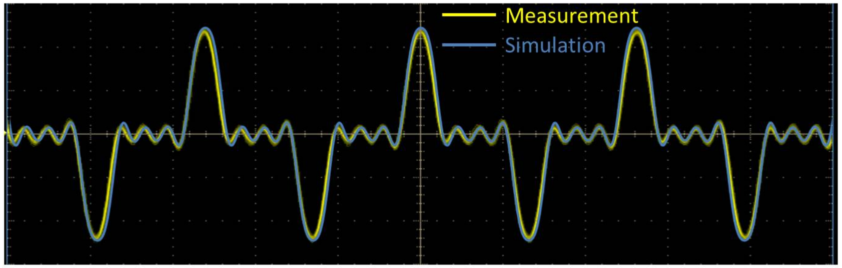




The mode combination results with each mode added in turn starting with the lowest mode.



Comparison of the combined kick pulse captured from the oscilloscope display with the simulation



Conclusions

- An ultrafast RF kicker concept suitable for the JLEIC bunched beam electron cooler ring has been demonstrated.
- By using four QWR based deflecting cavities, 10 harmonic modes with the distribution 5:3:1:1 can be generated, with an additional DC offset, a Flat-Top kicking pulse can be synthesized.
- The cavity was designed and optimized to get high transverse impedances so the sum of the RF wall losses in all four cavities is less than 100 W for a kicking voltage of 55 kV.
- A half scale 5-mode prototype copper cavity was fabricated and bench measurements were taken on this prototype cavity, which showed good agreement with the simulation result.
- Further investigations on the HOM damping for high current operation is under way.
- Real vacuum compatible cavities are planned to be designed and fabricated in the near future to measure the actual kicking effect on an electron beam.

Acknowledgements

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Especially we would like to thank **Larry Turlington**, **Steven Castagnola**, **Jim Follkie** and **Teena Harris**, **Bill Clemens**, **Damon Combs** and **Robert Martin**, **Stephen Dutton**, **Curt Hovater**, **John Musson** and **Ramakrishna Bachimanchi** for help during the construction and bench measurements on this harmonic kicker prototype cavity.