Ultra-Fast Harmonic Resonant Kicker Design for the MEIC Electron Circular Cooler Ring

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Introduction

- Electron cooling is essential for achieving high luminosity for MEIC
- High energy bunched electron cooling is part of the multi-phased cooling scheme for MEIC
- To achieve very high current for bunched beam cooling in the future high luminosity upgrade, we adopt a circulator ring to reuse the electron bunches
- An ultra-fast kicker (less than 2.1 ns ,476.3MHz) is required for this circulator ring
- We start an R&D proposal to develop such a kicker
- Our approach is to generate a series harmonic modes with RF resonant cavities
- Every 10th bunch in a 476.3MHz bunch train will be kicked while all the other bunches un-kicked with the designed prototype cavities

MEIC Multi-Phased Electron Cooling

Reduce/maintain emittance

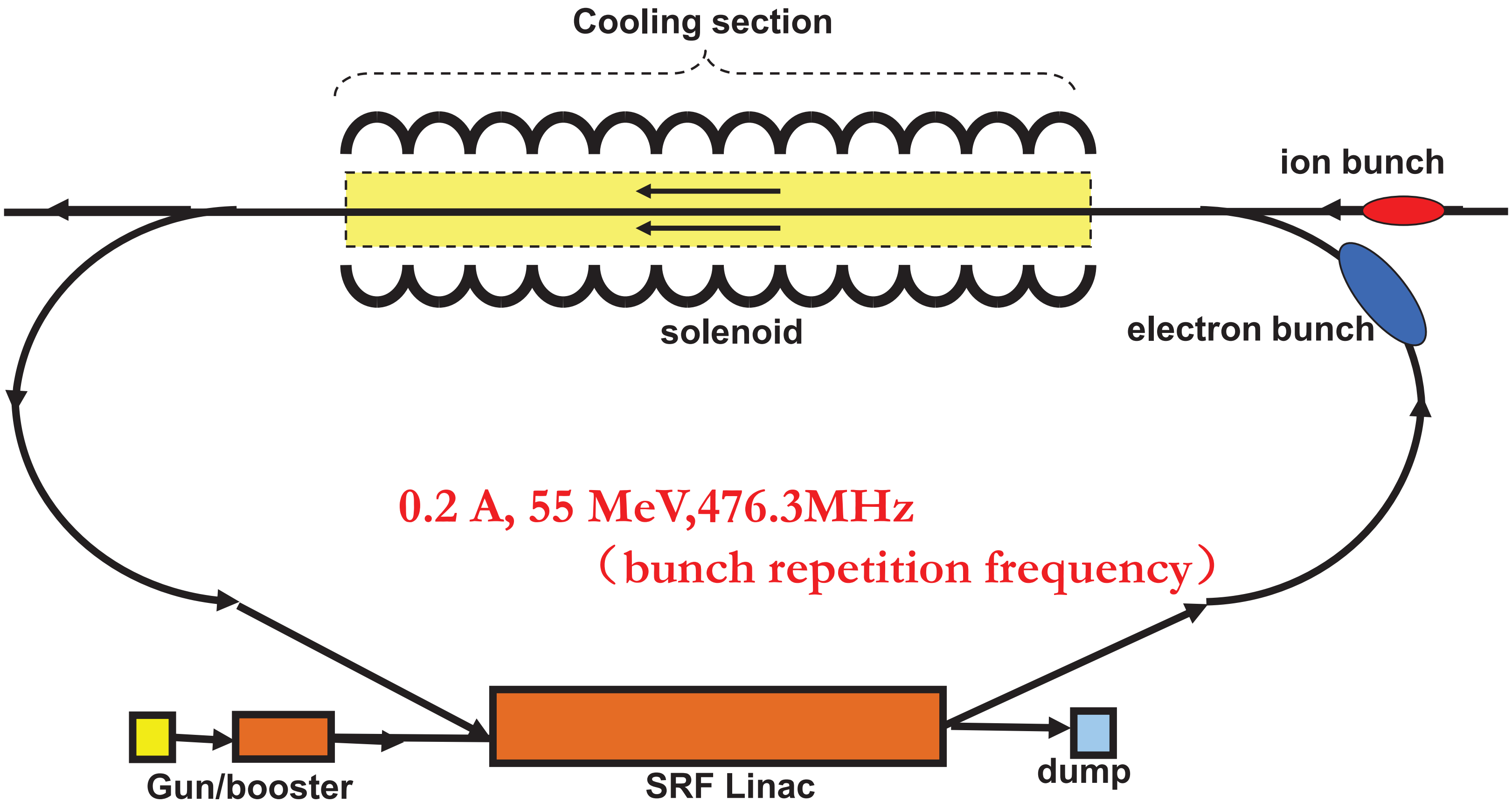
↓

High Luminosity!

same velocities → same γ factor

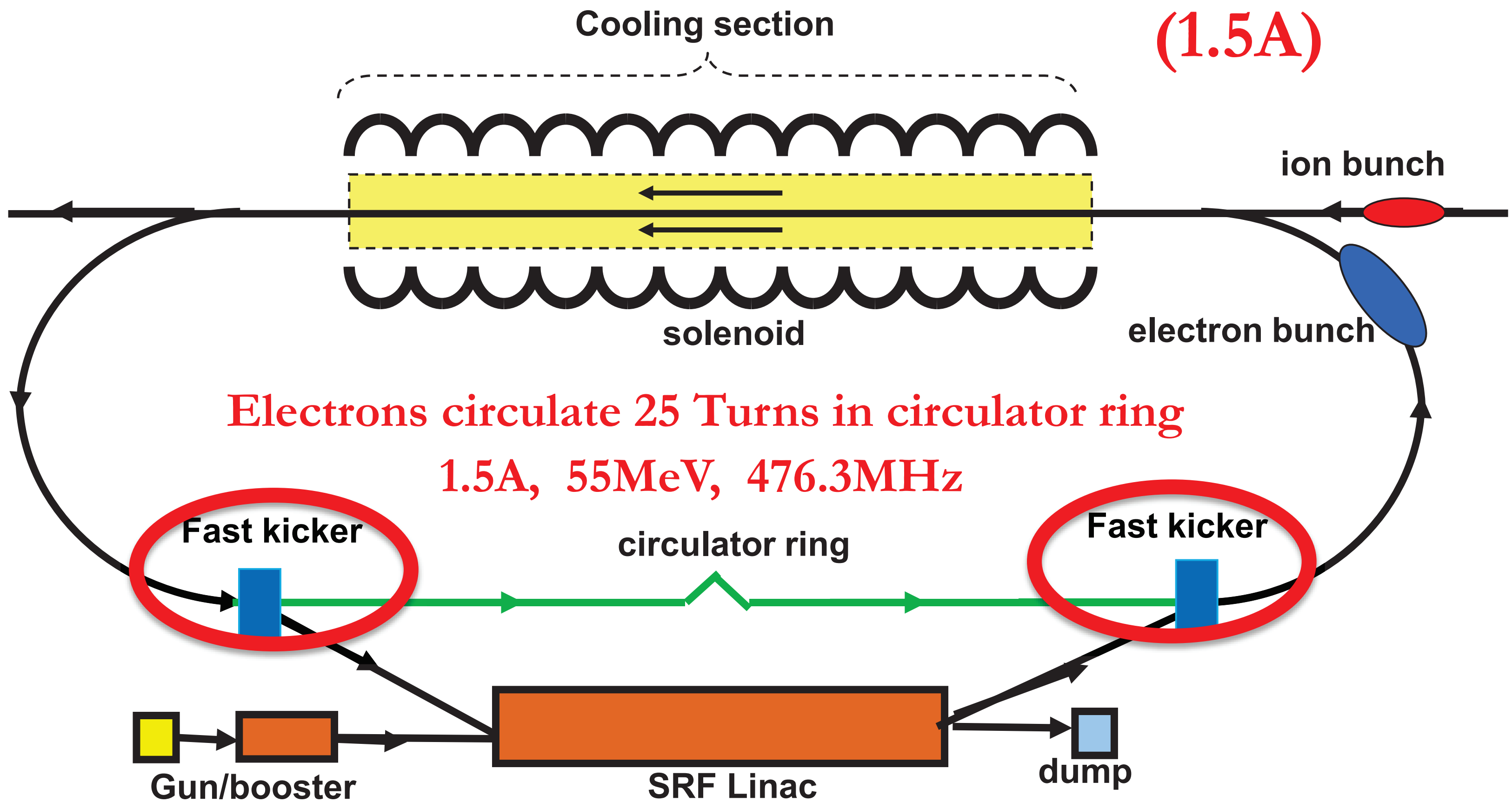
	Phase	Function	Proton kinetic energy (Gev/u)	Electron kinetic energy (MeV)	Cooler type
Booster	1	Assisting accumulation of injected positive ions	0.11 ~ 0.19	0.062 ~ 0.1	DC
	2	Emittance reduction	2	1.09	
Collider ring	3	Suppressing Intra-Beam Scattering and maintaining emittance during stacking of beams	7.9	4.3	Bunched Beam Cooler (ERL)
	4	Suppressing Intra-Beam Scattering and maintaining emittance during collision	100	55	

Single Turn ERL Cooler Scheme in MEIC Baseline Design



High Luminosity Upgrades

Need High Current! (1.5A)



Electrons circulate 25 Turns in circulator ring

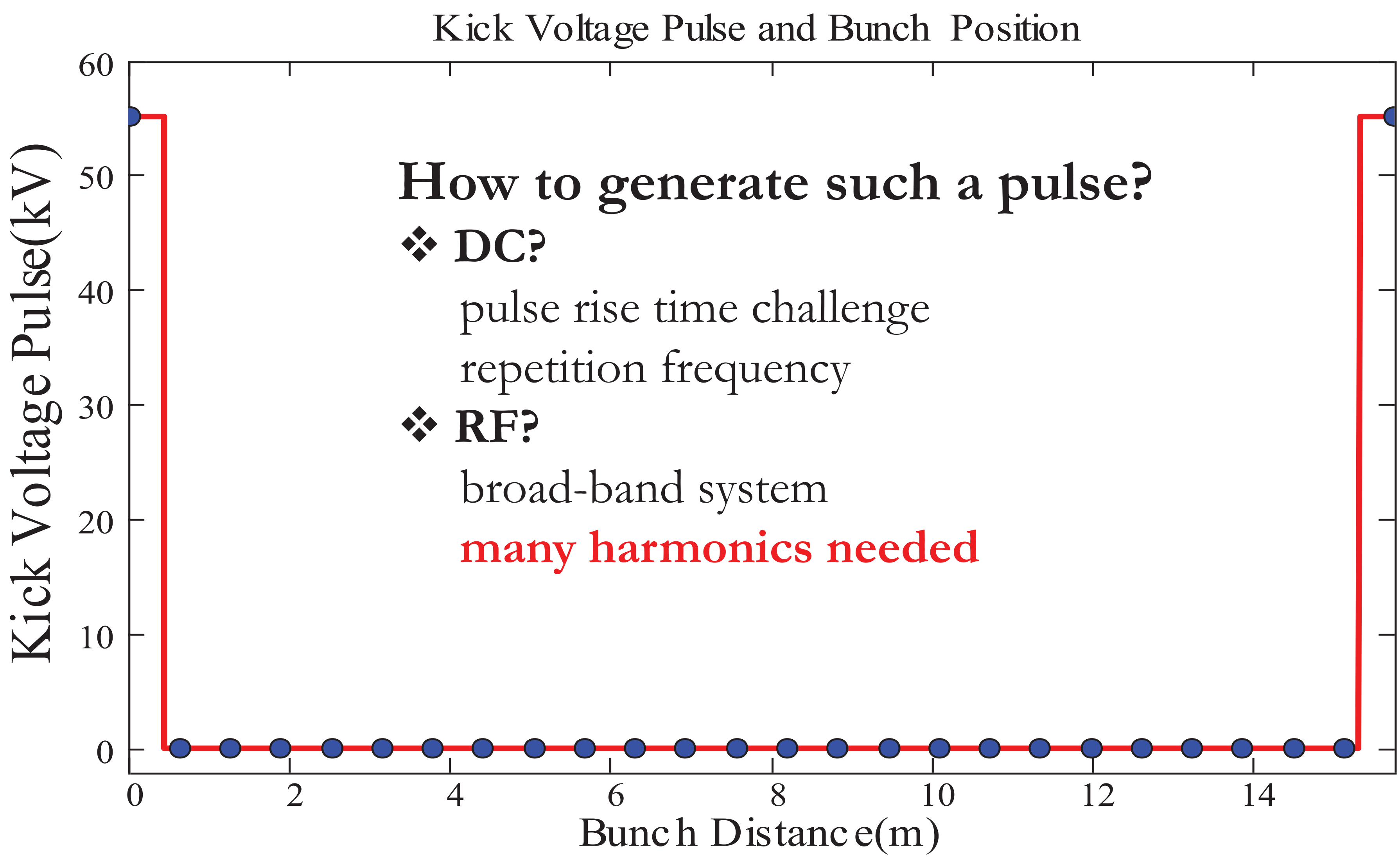
1.5A, 55MeV, 476.3MHz

- Periodically kick 1 in every25 bunches
- Ultra-fast ,2.1 ns
- 55kV(1 mrad kick angle)

0.06A, 55MeV, 19.052MHz(476.3/25)

(bunch repetition frequency)

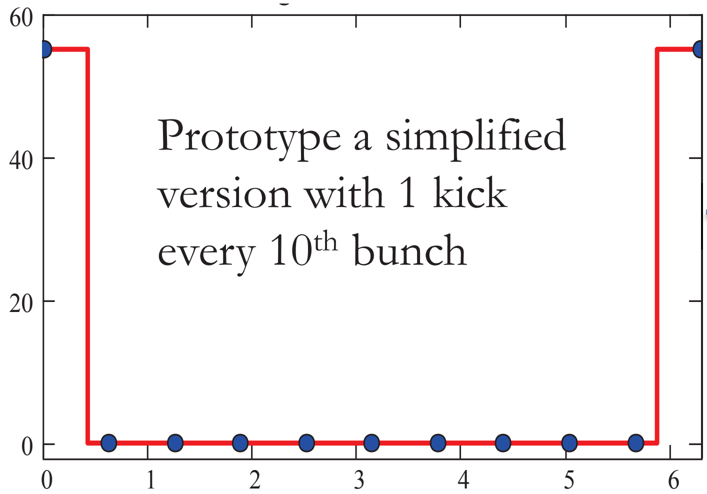
Ideal Kick Voltage Pulse Shapes



How to generate such a pulse?

- **DC?**
  - pulse rise time challenge
  - repetition frequency
- **RF?**
  - broad-band system
  - **many harmonics needed**

FFT of the Kick Voltage Pulse

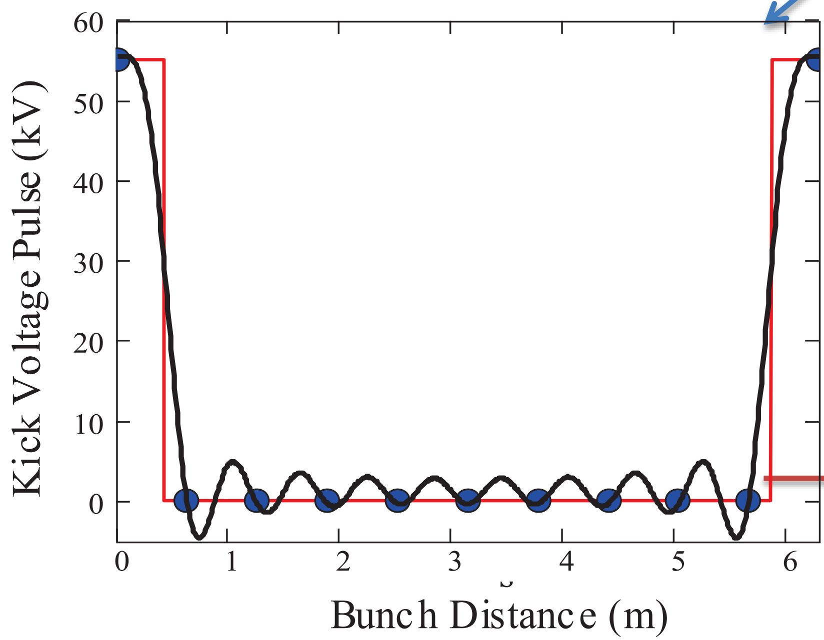


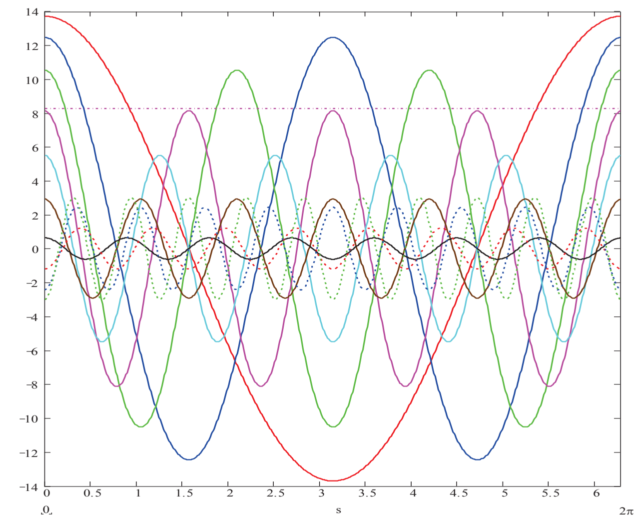
FFT

$$V_t = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega_0 t + \varphi_n)$$

Reconstruct the square pulse with first 10 modes

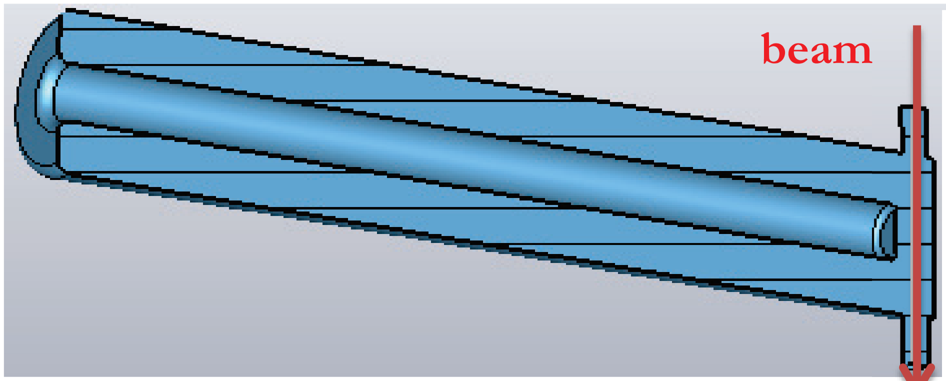
Flat top kick can be got by adjusting the pulse width before FFT

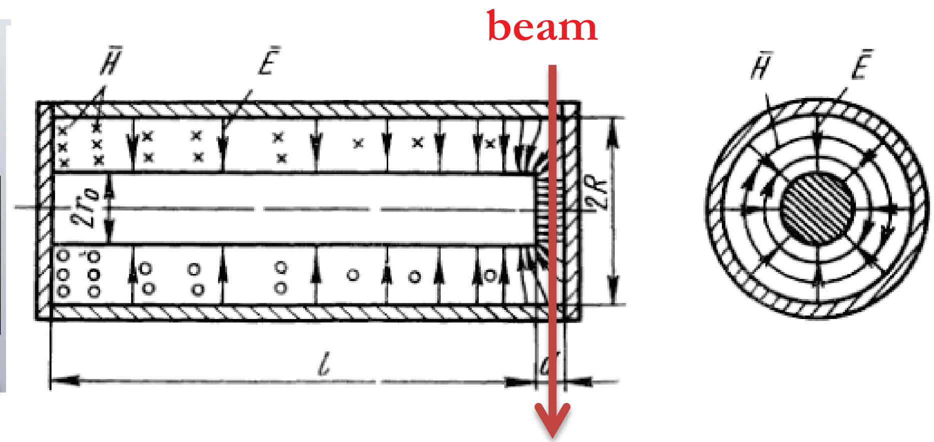




Head tail difference can be canceled by a 180⁰ betatron phase advance between two kickers

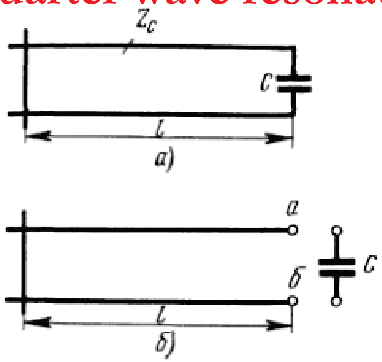
How to Generate Harmonic Modes?



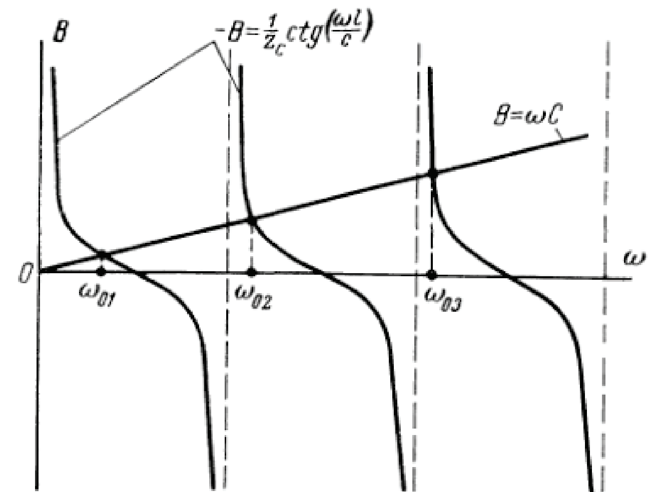


Quarter wave resonator with loading capacitor

Electric Field Deflection



$$\omega C = \frac{1}{Z_0}\cot\left(\frac{\omega l}{c}\right)$$



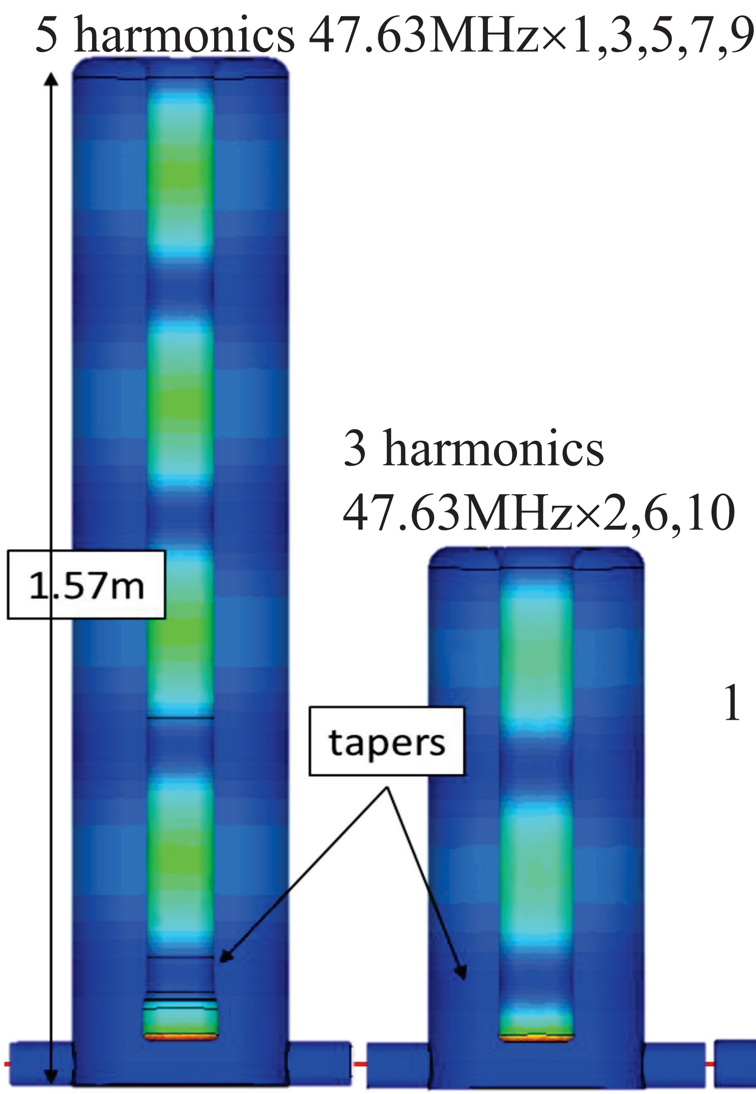
l≈(2n+1)λ/4

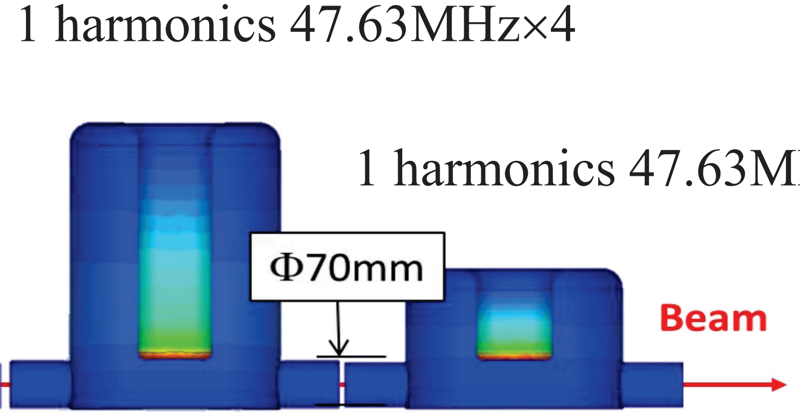
Cavity Length related with Frequency

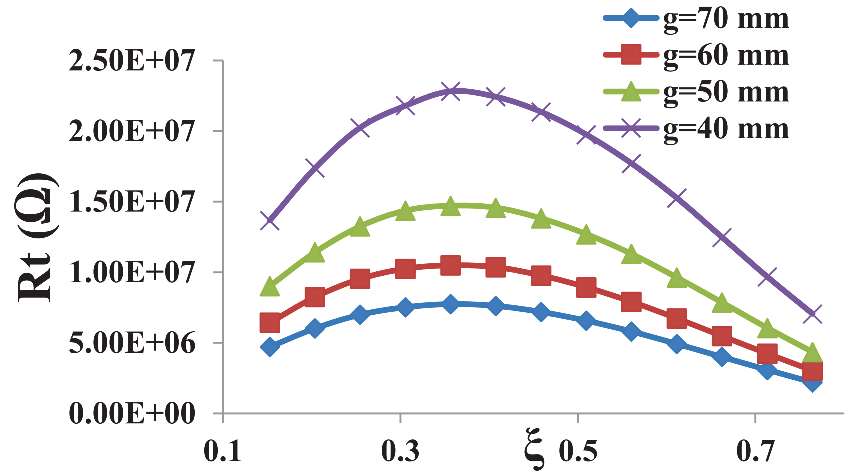
Fix the cavity length, the gap distance, and the outer conductor radius

Taper the inner conductor (change Z_0)to make the frequencies to be harmonics.

Cavity Model



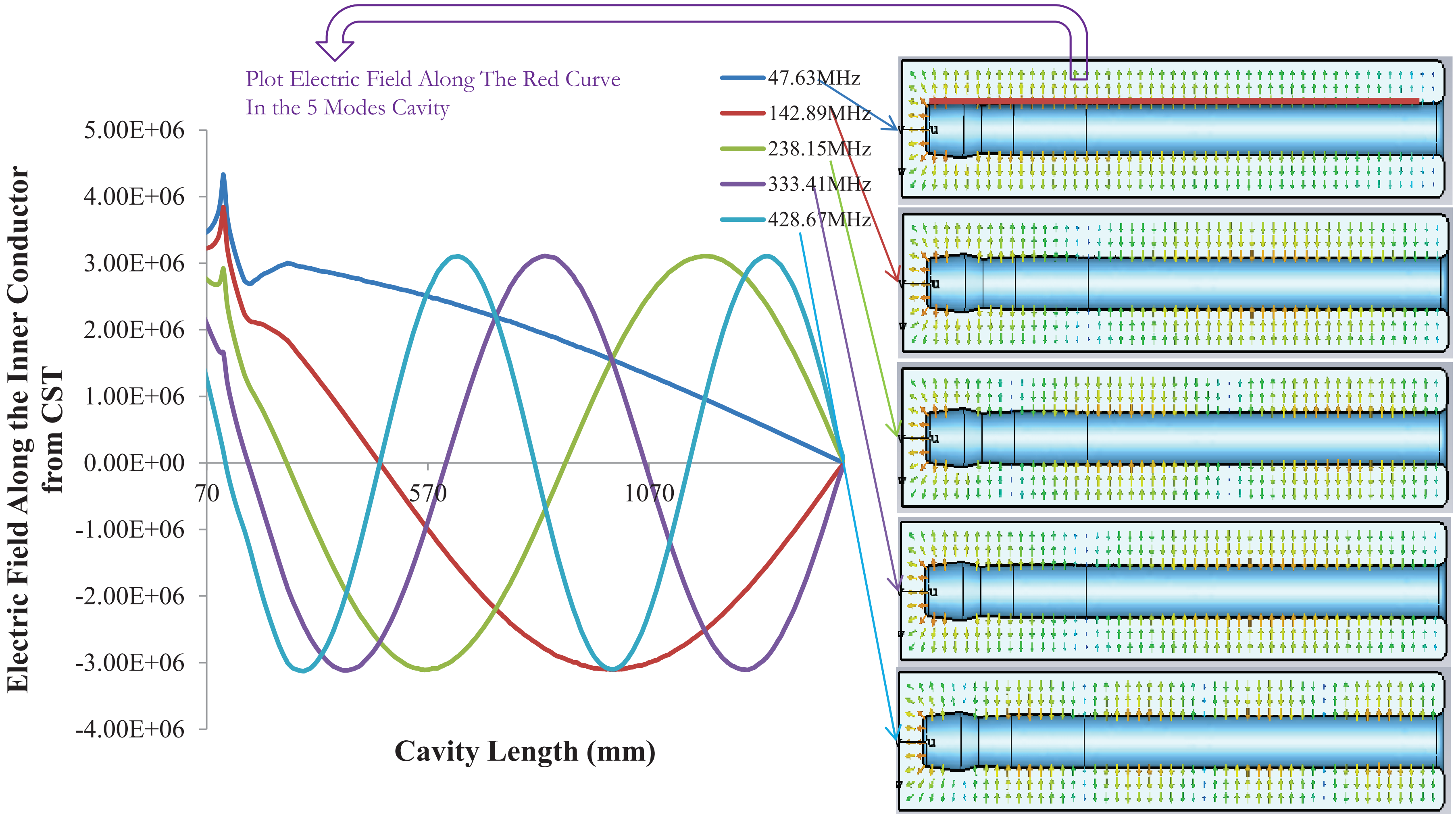




$$\xi = \frac{a(inner\ conductor\ radius)}{b(outer\ conductor\ radius)}$$

g is the end gap(beam pipe diameter)

Boundary Conditions



Just odd-integer multiples of the fundamental mode can be generate in one cavity!

M Cavities Needed for N Harmonics

Cavity #1	Cavity #2	Cavity #3	Cavity #4	Cavity #5
$(2n+1)\frac{f_0}{N}$	$(2n+1)\frac{2f_0}{N}$	$(2n+1)\frac{4f_0}{N}$	$(2n+1)\frac{8f_0}{N}$	$(2n+1)\frac{16f_0}{N}$

Here f_0 is the bunch repetition frequency in the Cooler ring (476.3MHz).
n=0,1,2,...

Relationship between Cavity number and Harmonics number:

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

4 cavities, 15 harmonics
5 cavities, 31 harmonics

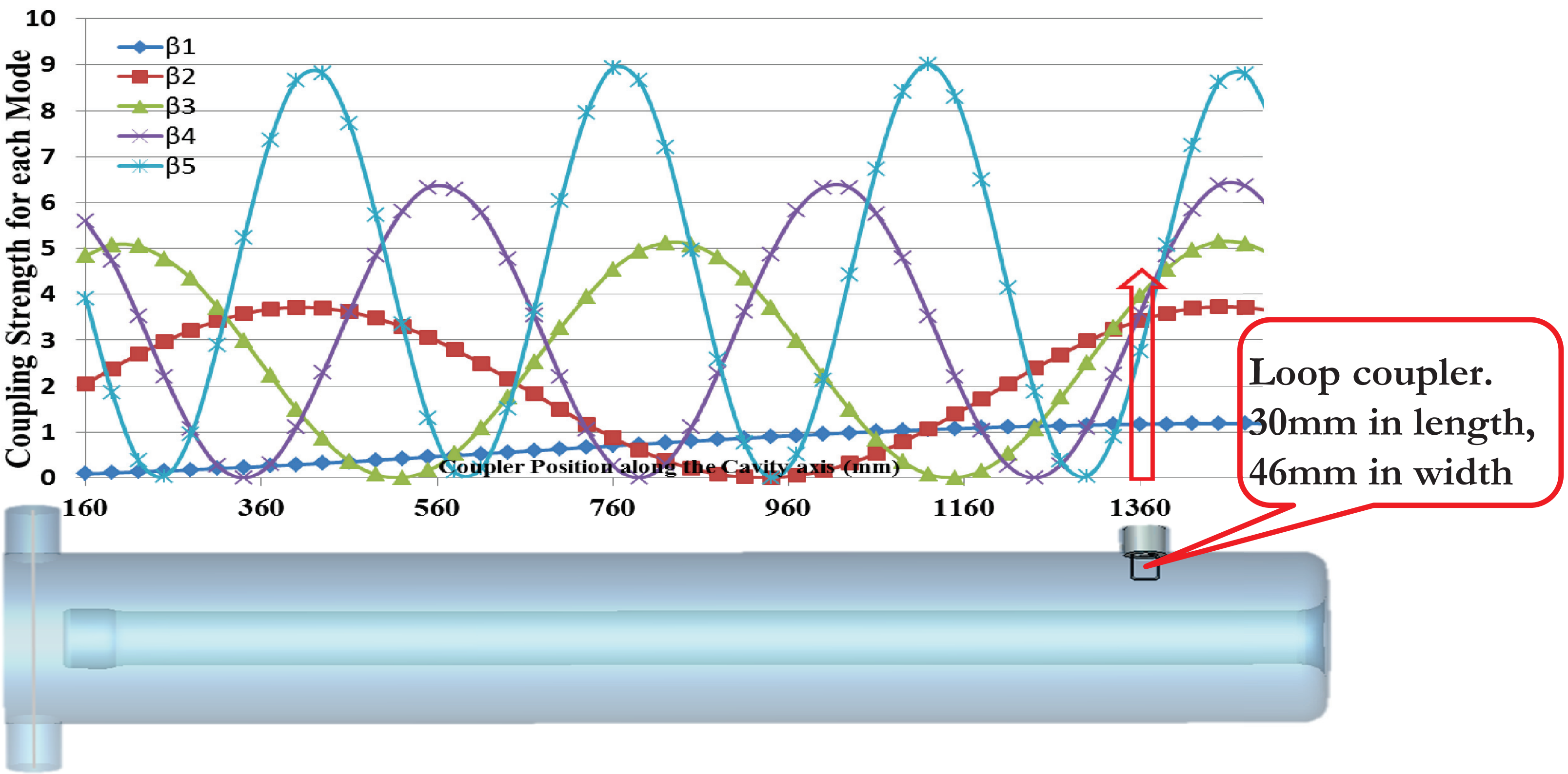
Shunt Impedance and Power

Mode (MHz)	FFT Kick Voltage (kV)	CST Trans. Shunt Impedance (Ω)	Dissipated Power (W)
47.63	13.711	7.13E6	26.37
95.26	12.462	1.14E7	13.62
142.89	10.532	4.09E6	27.12
190.52	8.1290	1.35E7	4.89
238.15	5.5030	3.14E6	9.64
285.78	2.9170	6.09E6	1.40
333.41	0.6300	2.65E6	0.15
381.04	-1.2090	1.65E7	0.09
428.67	-2.4320	2.40E6	2.46
476.3	-3.0110	4.57E6	1.98
DC	8.2760		
Total	**55.508**	**3.56E7**	**87.72**

Two to Three orders of magnitude lower than a strip-line kicker

The **kick voltage** (amplitude with phase) is come from the FFT result.
Transverse shunt impedance with TTF is calculated with CST Microwave Studio.
(Cavity model is simplified, **straight line taper with no blending** is used to achieve the target frequency for each mode, beam pipe is not optimized)

Input Loop Coupler Design



Fundamental mode has a lowest coupling strength but requires the highest power.**1360mm** is selected, the fundamental mode is critically coupled, and the higher modes are slightly over-coupled

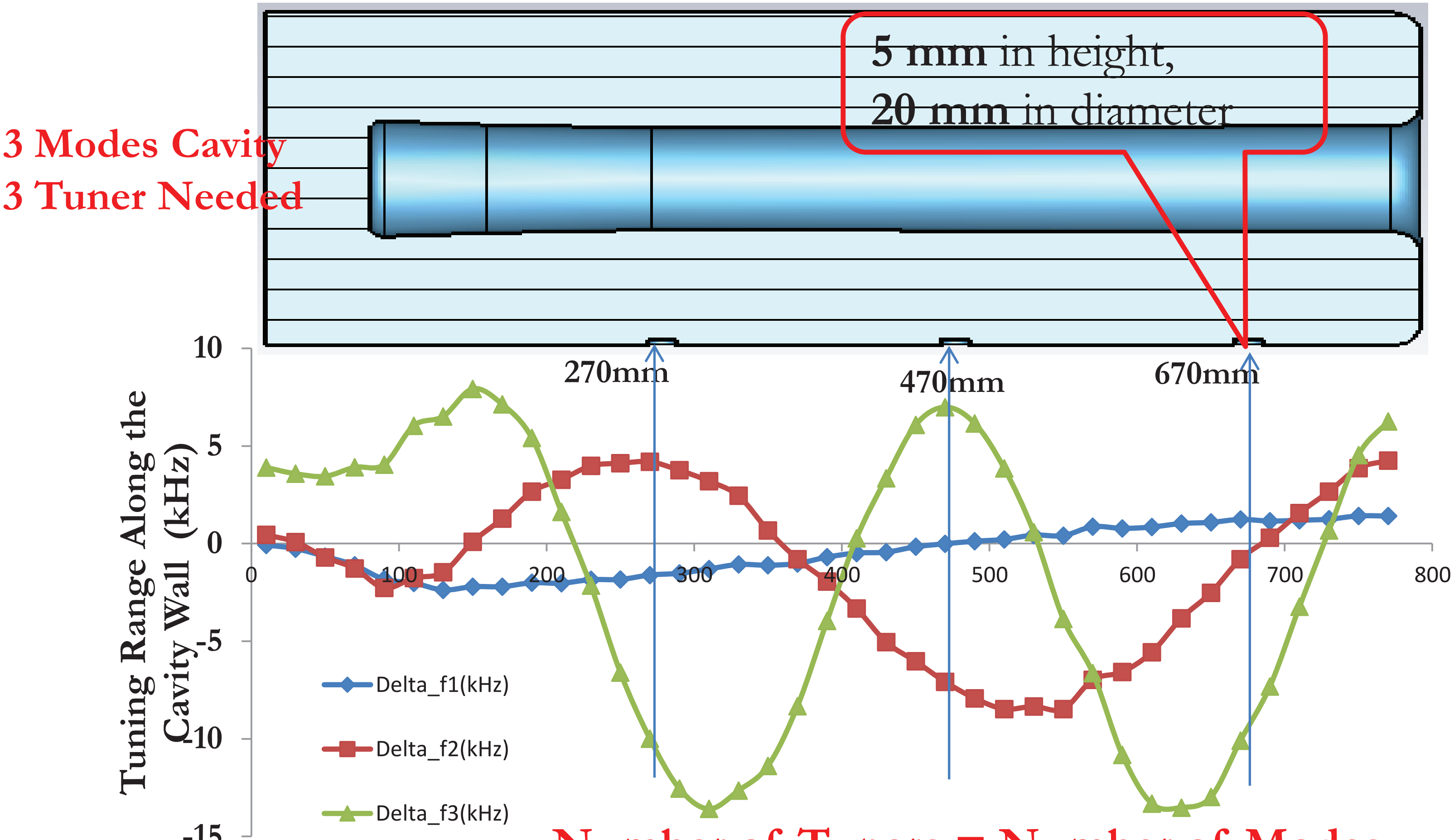
Cavity Tuning Need Estimation

	Operation Frequency (MHz)	Q_0 For 300K Copper	β	Bandwidth For 300K Copper (kHz)	Designed Frequency with Taper (kHz)	Error Frequency by Design (kHz)
Five Modes Cavity	47.63	8586	≈1	≈11.09	47.62991	-0.09
	142.89	14689	≥1	≥19.46	142.8915	0.15
	238.15	18973	≥1	≥25.10	238.153	3
	333.41	22472	≥1	≥29.67	333.4117	1.7
	428.67	25536	≥1	≥33.57	428.6718	1.8
Three Modes Cavity	95.26	12002	≈1	≈16.04	95.26267	2.67
	285.78	20784	≥1	≥27.50	285.7868	6.8
	476.3	27056	≥1	≥35.21	476.3087	8.7
One Mode Cavity	190.52	15298	≈1	≈24.91	190.5267	6.7
One Mode Cavity	381.04	19435	≈1	≈39.21	381.0361	3.9

- Bandwidth is calculated for one-coupler system $\Delta f_n = \frac{f_n}{Q_{0n}}(1+\beta_n)$
- Fundamental mode in each cavity is critical coupled, higher modes in the 5 modes and 3 modes cavities is over coupled.
- With an optimized taper design, harmonic frequencies without the tuner tunings can be designed within the bandwidths of operation modes.

Stub Tuner Design

Mistuning due to **manufacturing tolerance** can be tuned by **stub tuners** inserted into the cylinder wall.



Number of Tuners = Number of Modes

Conclusions

- An Ultra-fast , high repetition rate(2.1ns,476.3MHz) kicker was conceptual developed.
- It's great power efficiency, just 87.72W.
- Cost-effective, just copper cavities in room temperature.
- Cavity RF design and Concept design of the stub tuner and loop coupler is done.
- Beam dynamics tracking is being study.
- Mechanical design, HOM damping will be studied.
- Prototype Cavity will be made
- Bench RF Measurement
- Future beam experiment?