Study of Superconducting Accelerating Structures for Linac Applications

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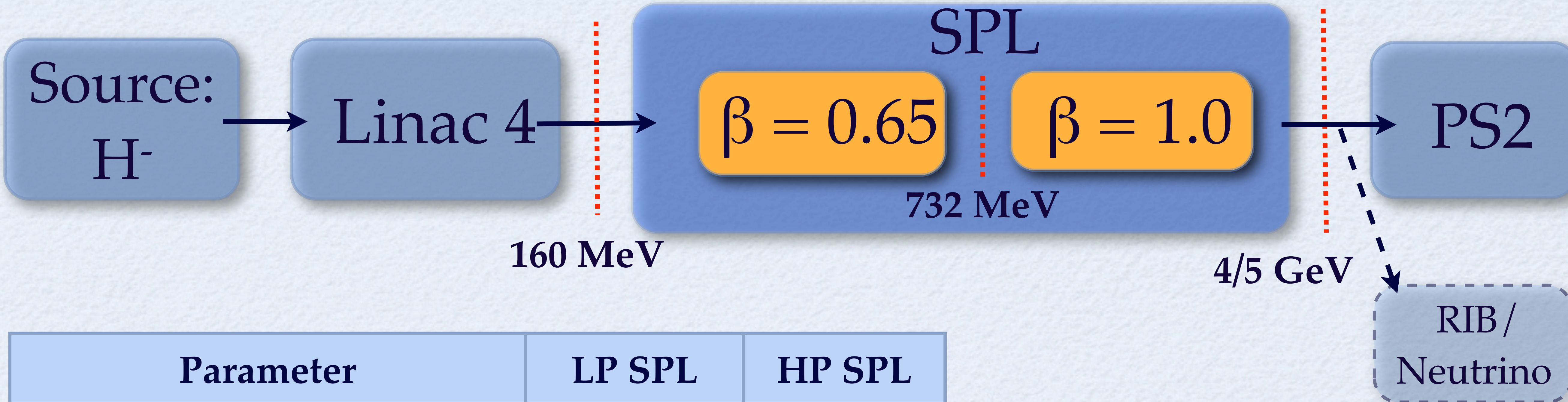
OUTLINE

- Superconducting Proton Linac (SPL)
- HOM Bunch Tracking Simulation Code
- Latest Results
- Conclusions & Outlook

THE SPL PROJECT

https://twiki.cern.ch/twiki/bin/view/SPL/WebHome



Parameter	LP SPL	HP SPL
Energy [*GeV*]	4	5
Beam power [*MW*]	0.19	4 - 8
Rep. frequency [Hz]	2	50
Bunch frequency [*MHz*]	352.2	
Operation frequency [*MHz*]	704.4	
Cavities (β = 0.65/β = 1.0)	54/152	54/192
Physical length [m]	~430	~500

Milestones:

- 2006: CDR
- 2012: TDR
- 2019: Operation LP

Higher Order Modes (HOMs)

- Present in each cavity
- Divide modes in monopole, dipole ...
- Characteristics depend on cavity shape
- Excited by the beam itself ($V \propto I \cdot R/Q$)
- Bunch train structure is important
- Interact with cavity and beam

Basic Linac Simulation Model

- Drift kick model with **exact** cavity spacing
- $E_0T(\beta)$ via field integration (**only sync. particle**)
- Phase and field controlled individually for each cavity
- Transfer matrix between cavities (transverse) using phase advance per period (**no magnets modeled**)
- Longitudinal and transverse plane are independent

➡ Bunch (point charge)/particle tracking without space charge effects

Basic HOM Model

- One HOM per cavity (monopole or dipole)
- Gaussian or Uniform HOM frequency distribution with no change over time
- $\boldsymbol{R/Q(\beta)}$ applied in each cavity according to beam β
- Global Q_{ex}

➡ **Load HOM via bunch tracking (Bunch ⇔ HOM interaction)**

Beam Input Parameters

Basic beam settings used in all simulations:

Parameter	Mean	Variance	Simulation
Bunch period [ns]	$1/f_b \approx 3$	0.00315	long
Pulse length [ms]	1.0	0	both
Period length [ms]	20	0	both
Beam current [mA]	40...400	3%	both
W_{Input} [MeV]	160	0.078	long
Tr. position [mm]	0	0.3	trans
Tr. momentum [mrad]	0	0.3	trans

https://twiki.cern.ch/twiki/bin/view/SPL/SplHom

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HOM Parameter

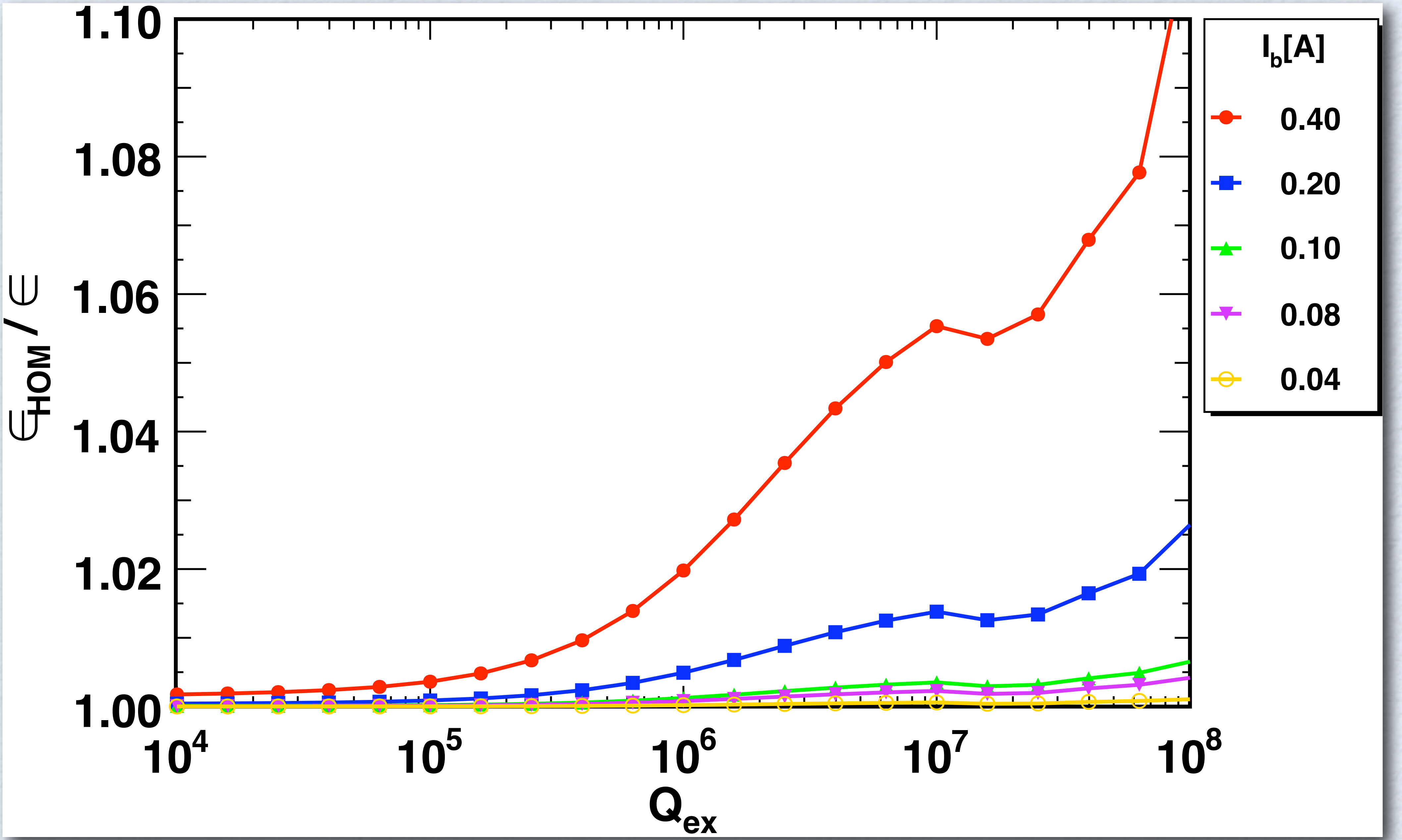
Transverse setup

Parameter \ Section	Medium β	High β
f_{HOM} [MHz]	1015±1	915±1
R/Q(β) [Ω*] (avg)	60	48

* linac def.

➡ Compare phase space (ε) of one pulse (350.000 bunches) with (loaded HOM) and without HOM interaction at the exit of the linac.

Transversal



RESULTS

Effect of different parameters:

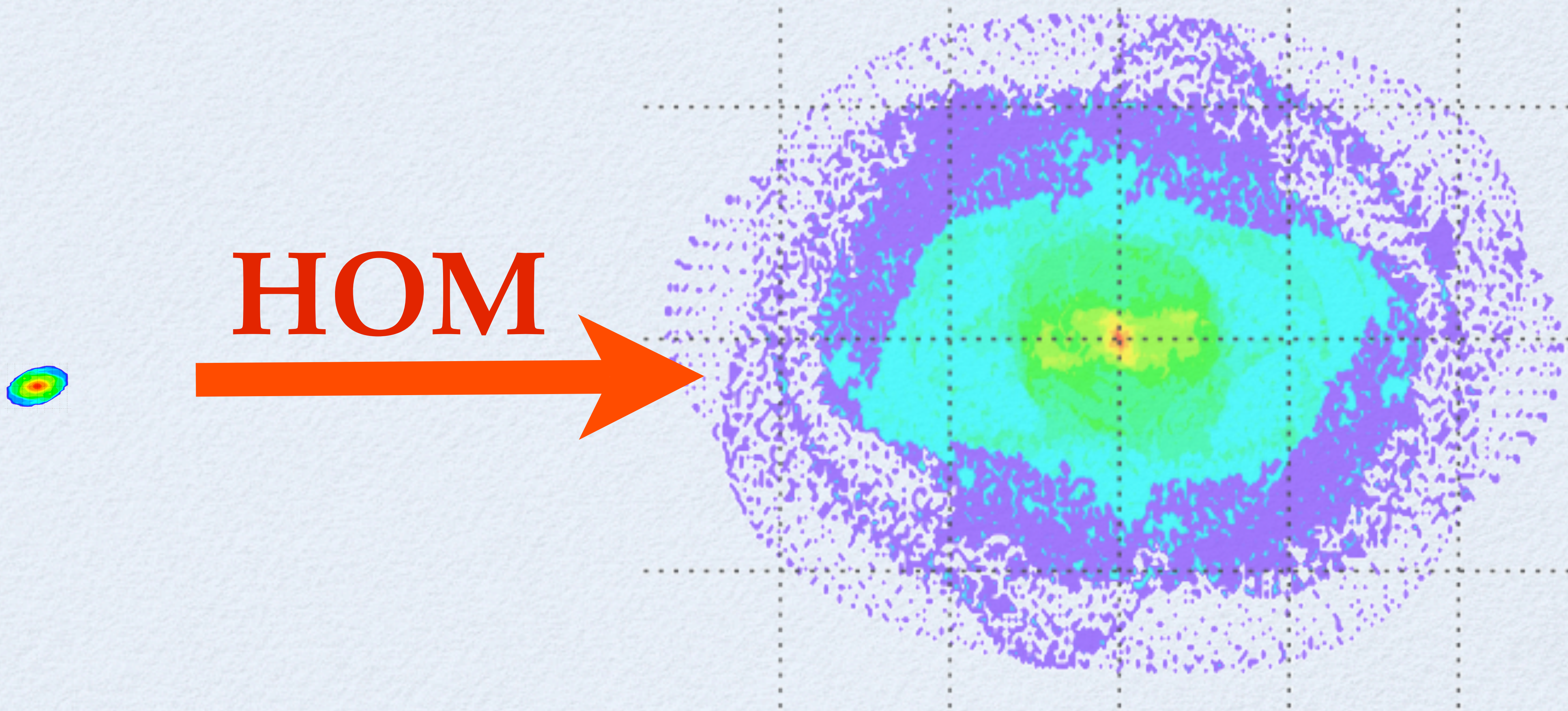
Parameter	LONG	TRANS
frequency spread	↘	↘
machine lines	↗	↗
I · R/Q	↗	↗
charge scatter	↗	→
chopping	tbc	↗
input phase space	→	→

Conclusions & Outlook

- Tools developed to simulate influence of HOMs
- Simulations show HOM damping seeming to be necessary in order to provide a high brilliance beam!
- **The limit of Q_{ex} based on the presented results: 10^7 !**
- Further simulations:
  - Chopping (longitudinal)
  - Klystron and field errors

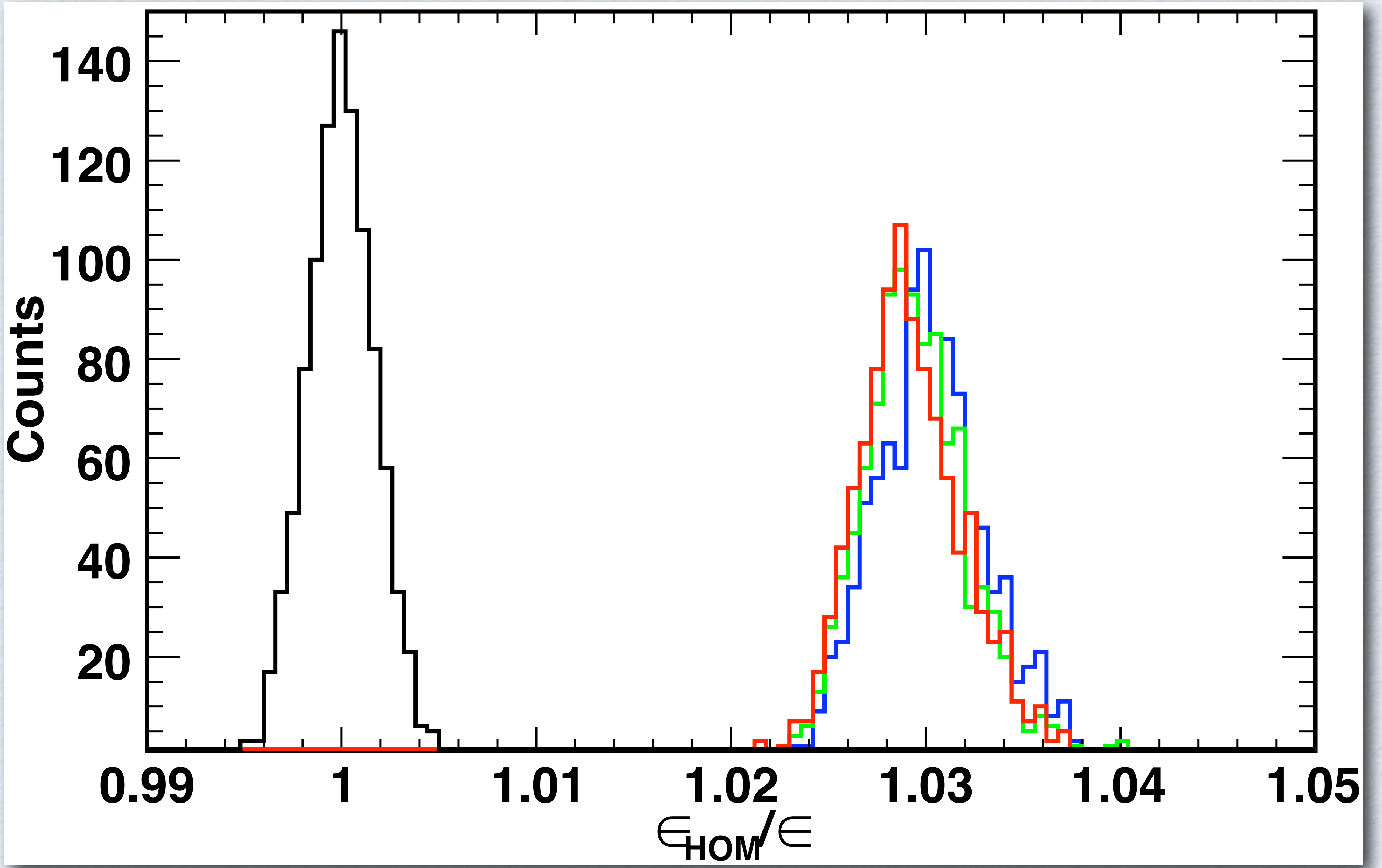
THANK YOU!

Questions?



Statistic: 1000 Linacs

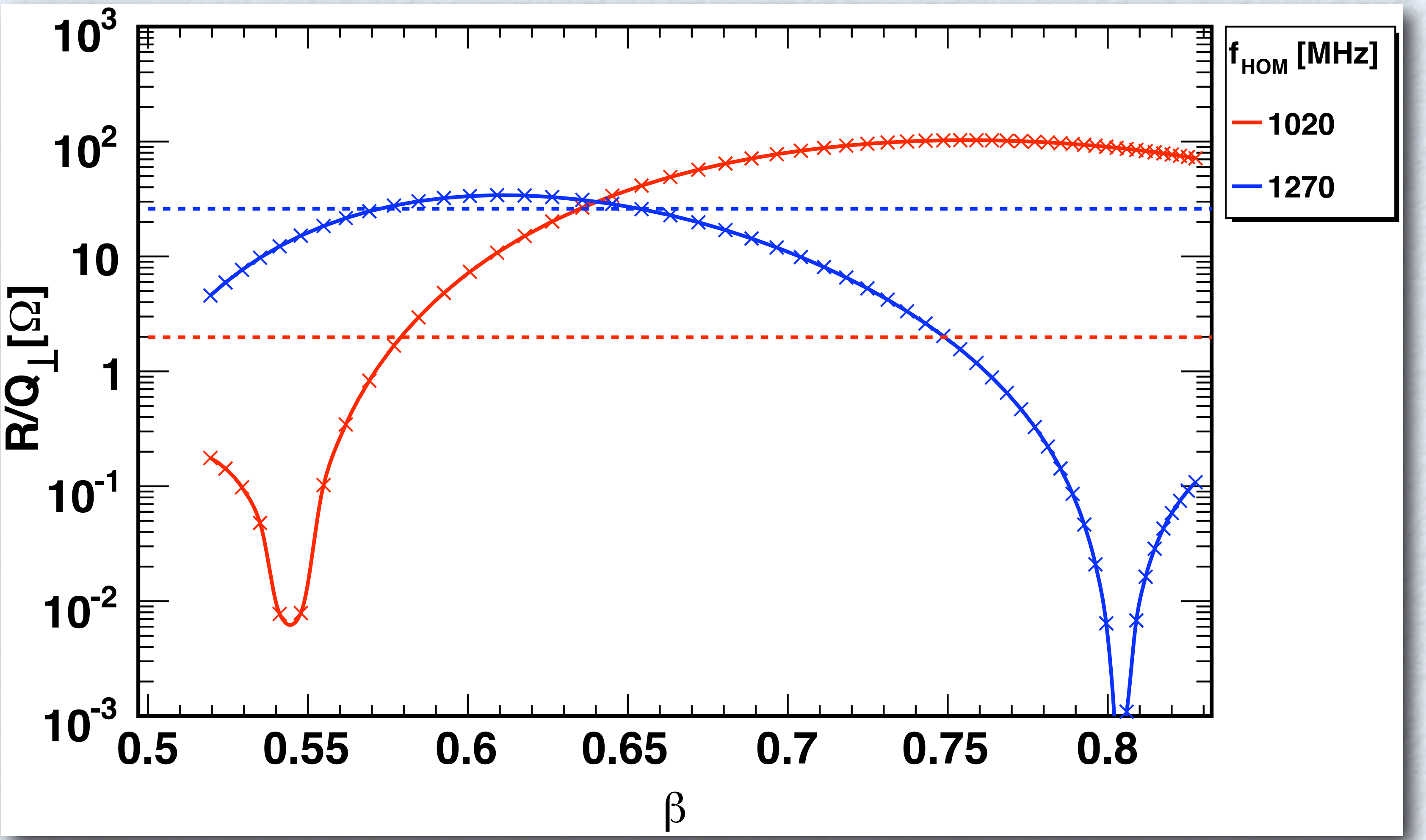
Influence of input beam and cavity to cavity frequency distribution



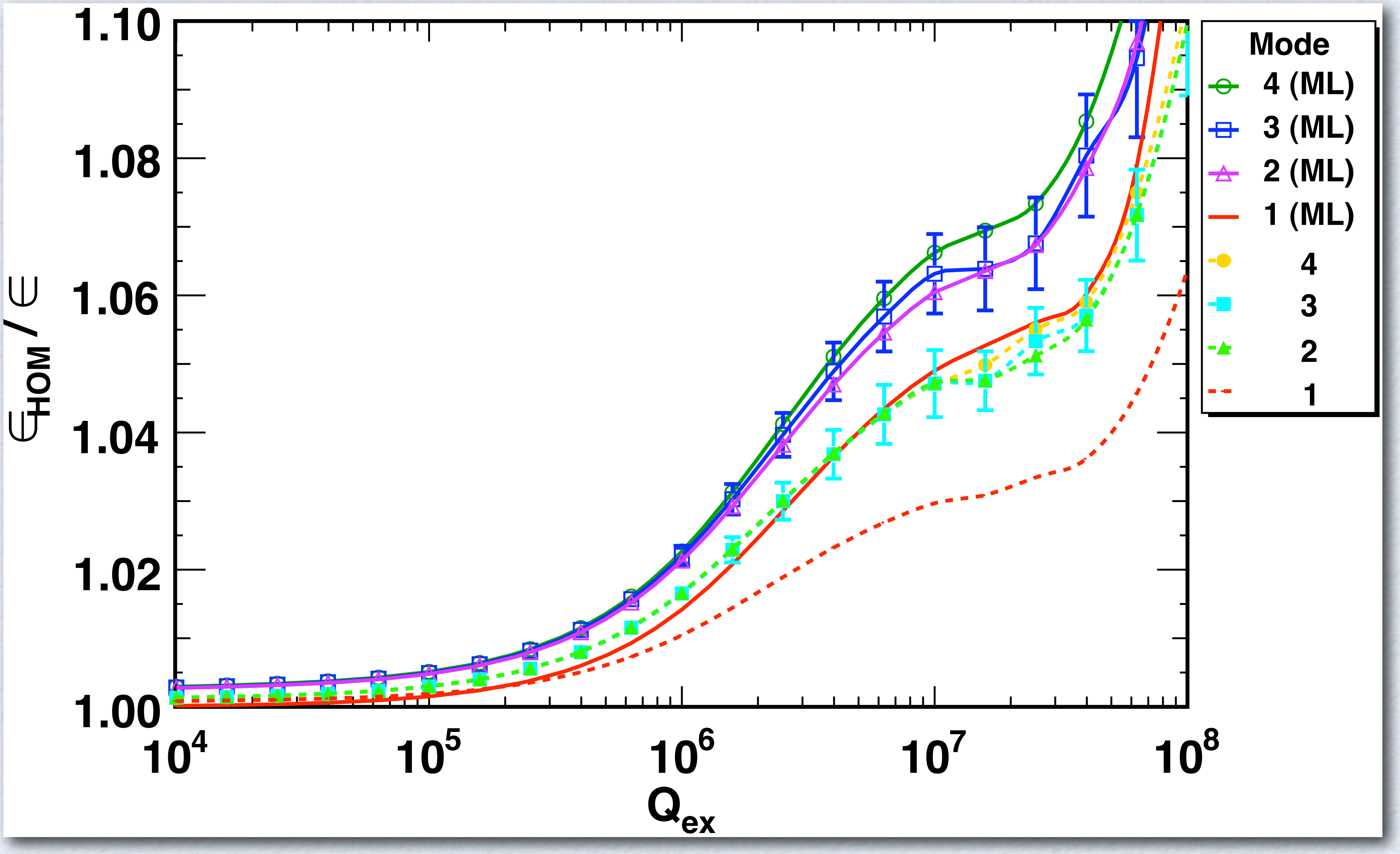
HOM Characteristics

HOM Parameter needed in simulation:

- HOM frequency f_n
- $R/Q(\beta)$ map:



Transversal: Chopping



Monopole modes:

- Each bunch sees half of its self-induced voltage V_b:
- Energy error caused by HOM:

$$dU_H = e\left(\Re(V_H)\cos(\omega_H dt) - \Im(V_H)\sin(\omega_H dt)\right) - \frac{1}{2}V_b$$

- Iteration over linac:

$$dE^{(n+1)} = dE^{(n)} + dU_{RF} + dU_H$$

$$dt^{(n+1)} = dt^{(n)} + (dt/dE)_E \cdot dE$$

Longitudinal Beam Dynamic

- Particle velocity: $\beta < 1$
- Energy error causes arrival time / phase error:

$$dt = -\frac{L}{c \cdot m_0 c^2 \cdot (\gamma^2 - 1)^{3/2}} dE$$

- Phase error causes a different energy gain in next cavity:

$$dU_{RF} = eV_{RF}^* \cdot \cos(\phi_s + \omega_{RF} dt) - \Delta U$$

Transverse Beam Dynamic

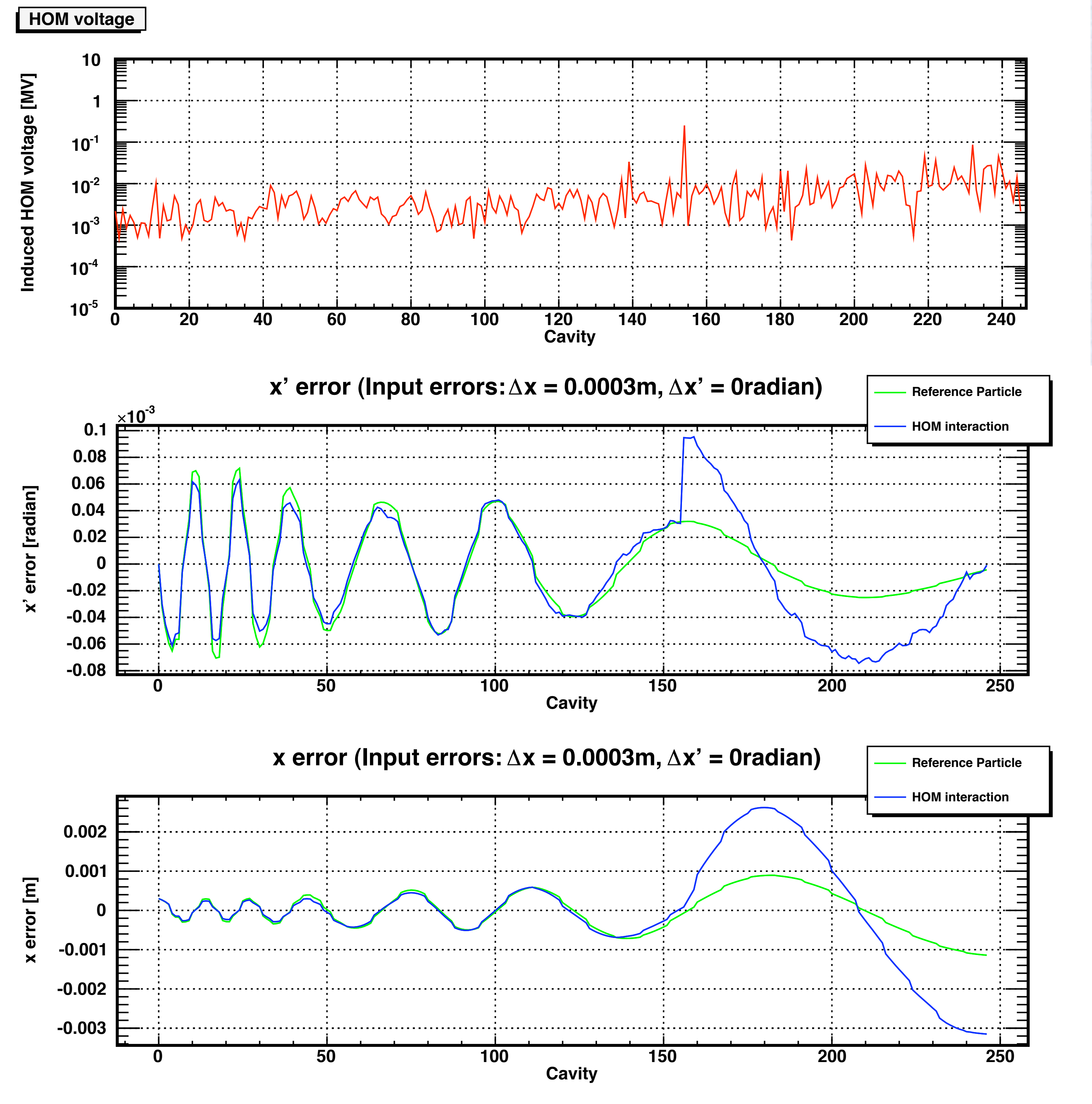
- Transfer Matrix between cavities
- Bunch induce a imaginary voltage:

$$\Delta V_{\perp} = ixq\frac{\omega^2}{c}(R/Q)_{\perp}$$

- HOM kicks bunch/particle - momentum change:

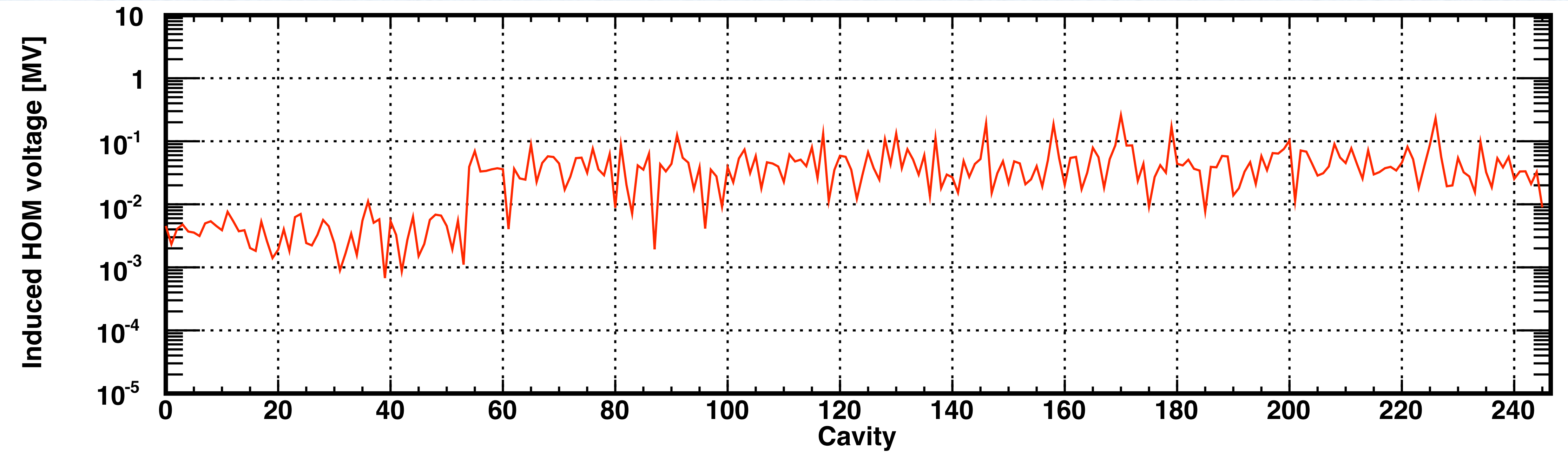
$$\Delta x' = \frac{e\Re(V_{\perp})}{c \cdot p_{||}}$$

Observed Dipole Kick

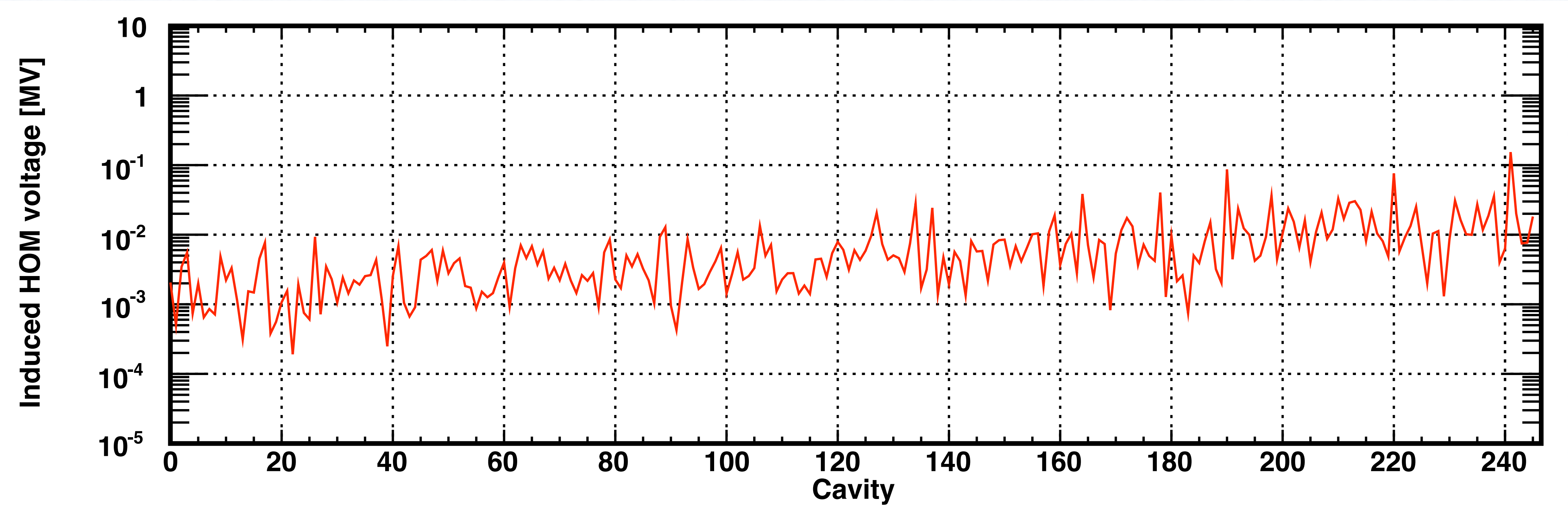


HOM Voltage Distribution

Mono-pole:

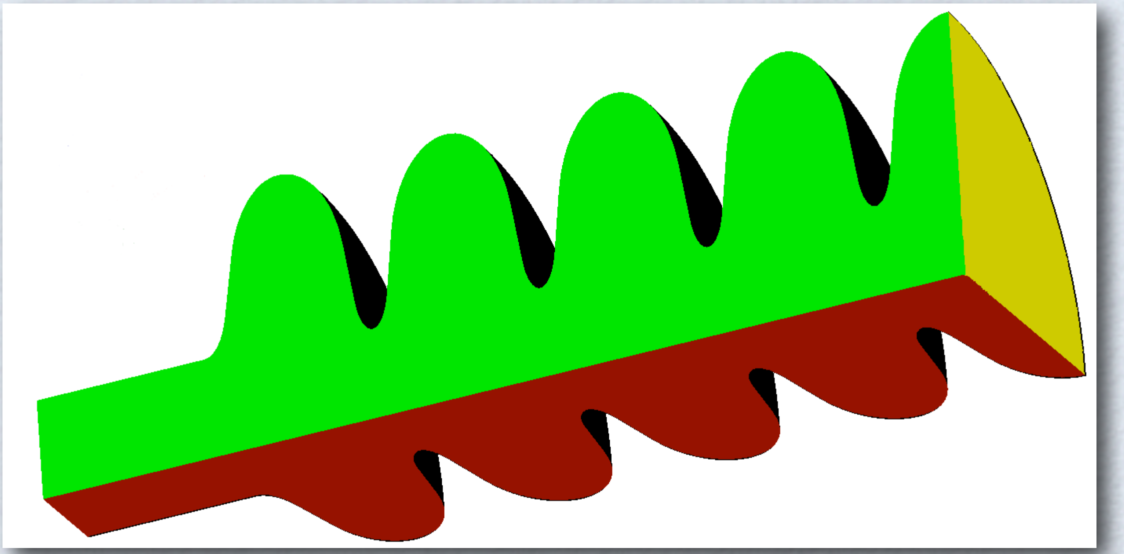


Dipole:



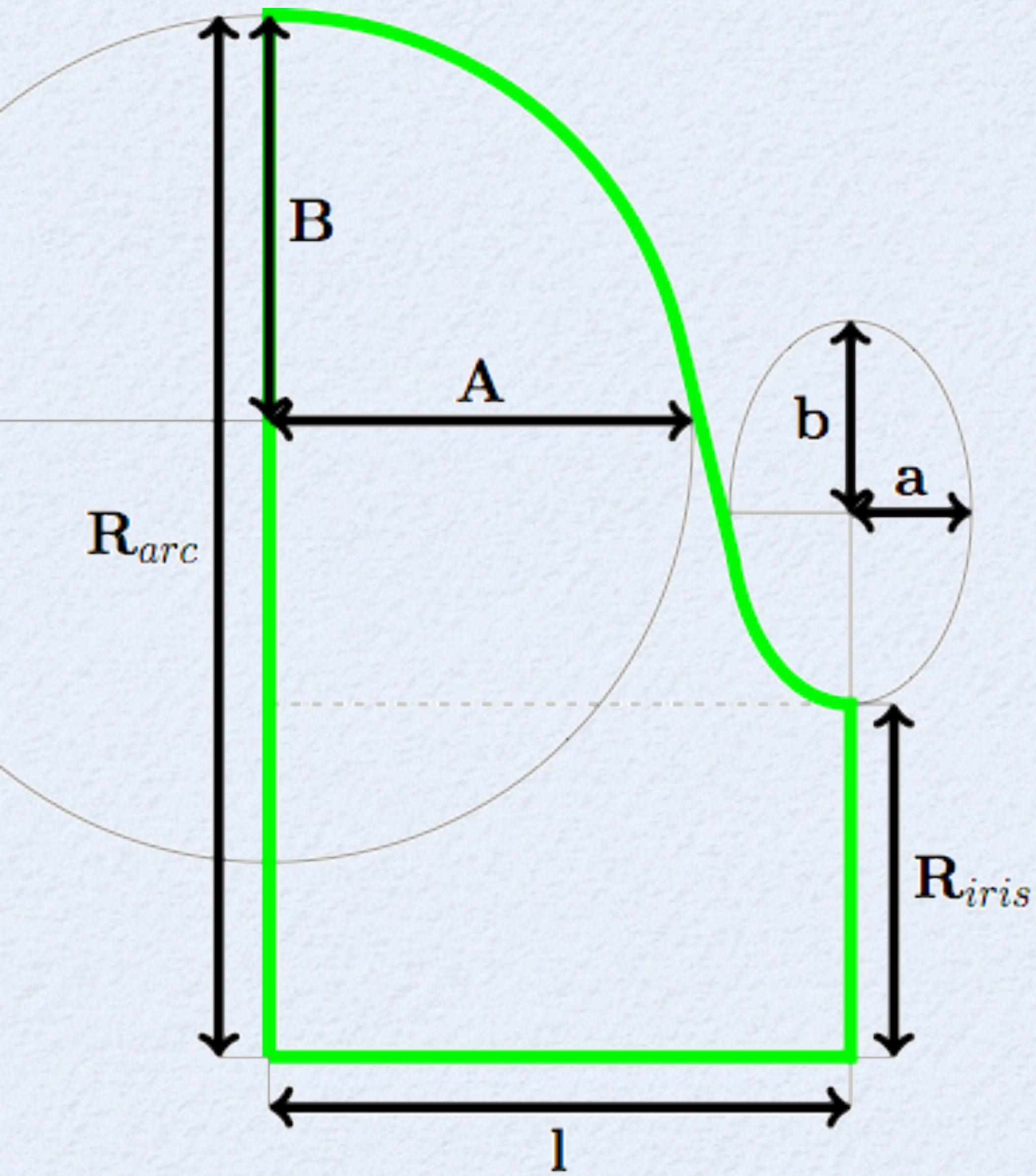
Cavity Modeling

- 2d Superfish model
- 3d HFSS model
    - half cavity length
    - quarter rotation
    - boundary conditions



CAVITY GEOMETRY

Cavitiy shapes at 704.4MHz (symmetrical):



	Medium β		High β	
5 Cells	mid	end	mid	end
β	0.658		1.0	
R_{arc} [mm]	186.4		190.8	
R_{iris} [mm]	45	45	64.6	70
l_{cell} [mm]	70	70	106.47	103.07
A [mm]	45.1	45.06	77.5	76.89
B [mm]	45.1	49.56	77.5	74.45
a [mm]	12.14	12.11	22.1	18.5
b [mm]	15.79	15.74	35.1	24.9

Cavity Geometry

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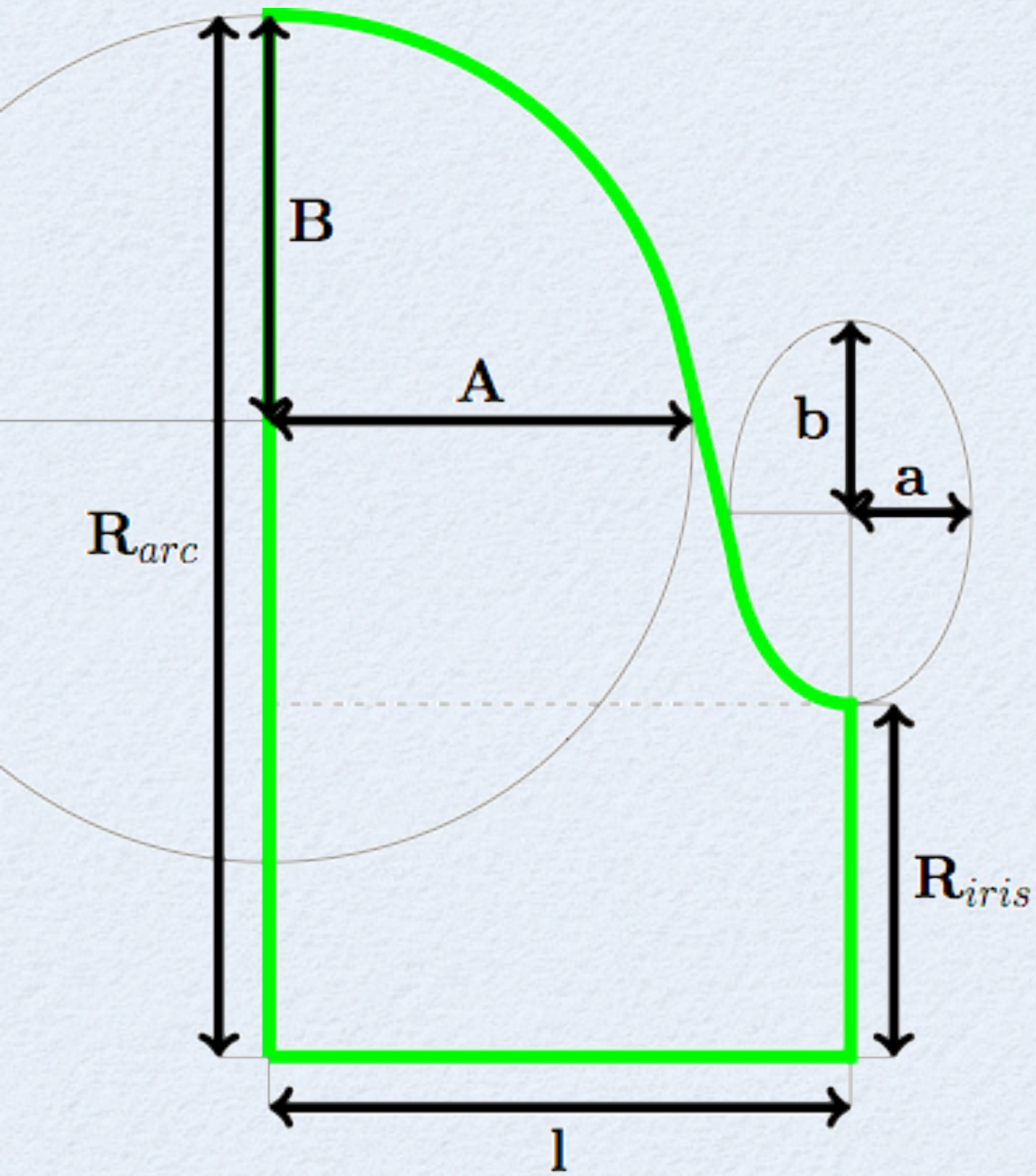

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Monopole Modes

β	Mode	f [MHz]	HFSS (R/Q)† [Ω]	Superfish (R/Q)† [Ω]
0.65	TM_{010} 4/5π	703.7	1	1
0.65	TM_{010} π	704.4	318	330
0.65	**TM_{011} 3/5π**	**1765**	**3**	**4**
0.65	TM_{010} 4/5π	1774	4	3
0.65	TM_{01} cuttoff	2550		
1	TM_{010} π	704.4	525	562
1	TM_{011} 4/5π	1328	37	36
1	**TM_{011} π**	**1332**	**137**	**135**
1	TM_{021}	2090	25	21
1	TM_{01} cuttoff	1639		

†linac definition

Dipole Modes

β	Mode	f [MHz]	HFSS (R/Q)† [Ω]
0.65	TM_{110} 2/5π	1020	19
0.65	**TM_{110} 3/5π**	**1027**	**28**
0.65	TM_{110} 4/5π	1033	6
0.65	TE_{111} 1/5π	1270	13
0.65	TE_{11} cuttoff	1952	
1	TE_{111} 3/5π	915.1	18
1	**TE_{111} 4/5π**	**939.8**	**33**
1	TE_{111} π	966.4	13
1	TM_{110} 3/5π	1014	19
1	TE_{11} cuttoff	1255	

†linac definition