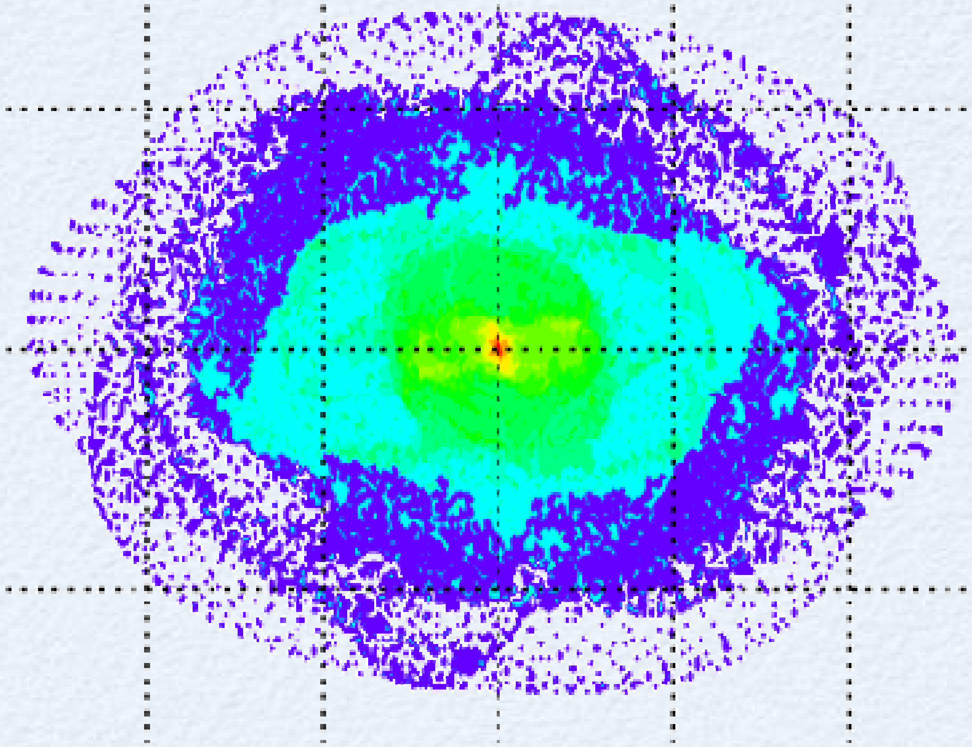
Higher Order Modes In The SPL, Transverse And Longitudinal Effects



Marcel Schuh
CERN-BE-RF-LR
CH-1211 Genève 23, Switzerland

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Outline

- HOM Bunch Tracking Simulation Code
- Simulation input parameters
- Simulation results
  - Chopping
- Conclusions & Outlook

Basic LINAC Simulation Model

- Drift kick model with **exact** cavity spacing (not transverse)
- $E_0T(\beta)$ 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 (σ = 1MHz) with no change over time
- $R/Q(\beta)$ 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

HOM Parameter

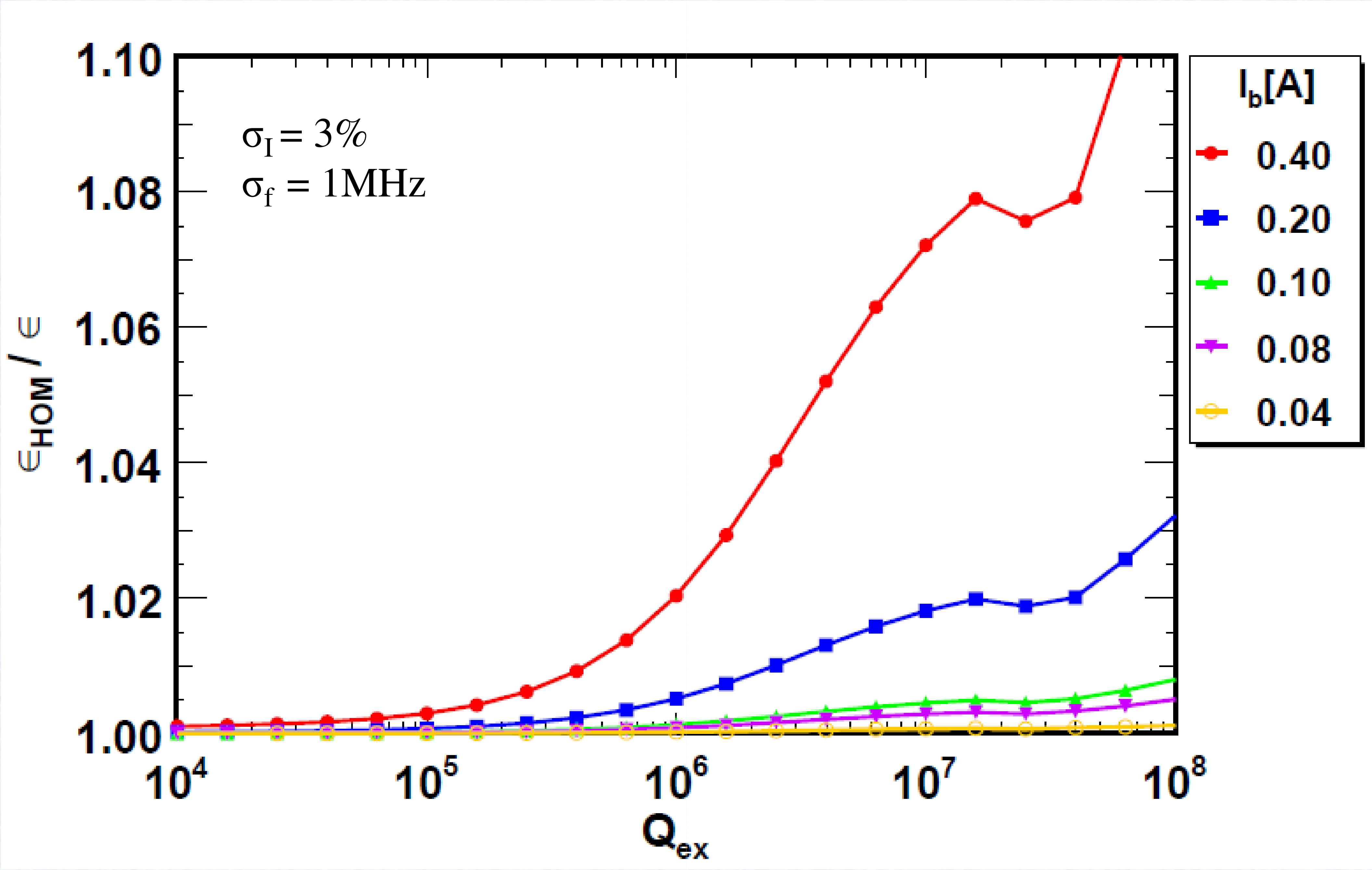
	Longitudinal		Transversal	
Section Parameter	**Medium β**	**High β**	**Medium β**	**High β**
f_{HOM} [MHz]	1783±1	1330±1	1015±1	915±1
R/Q(β) [Ω*] (avg)	12	114	60	48

* 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.**

Longitudinal - General Case

Longitudinal Bunch Center Emittance Growth Rate



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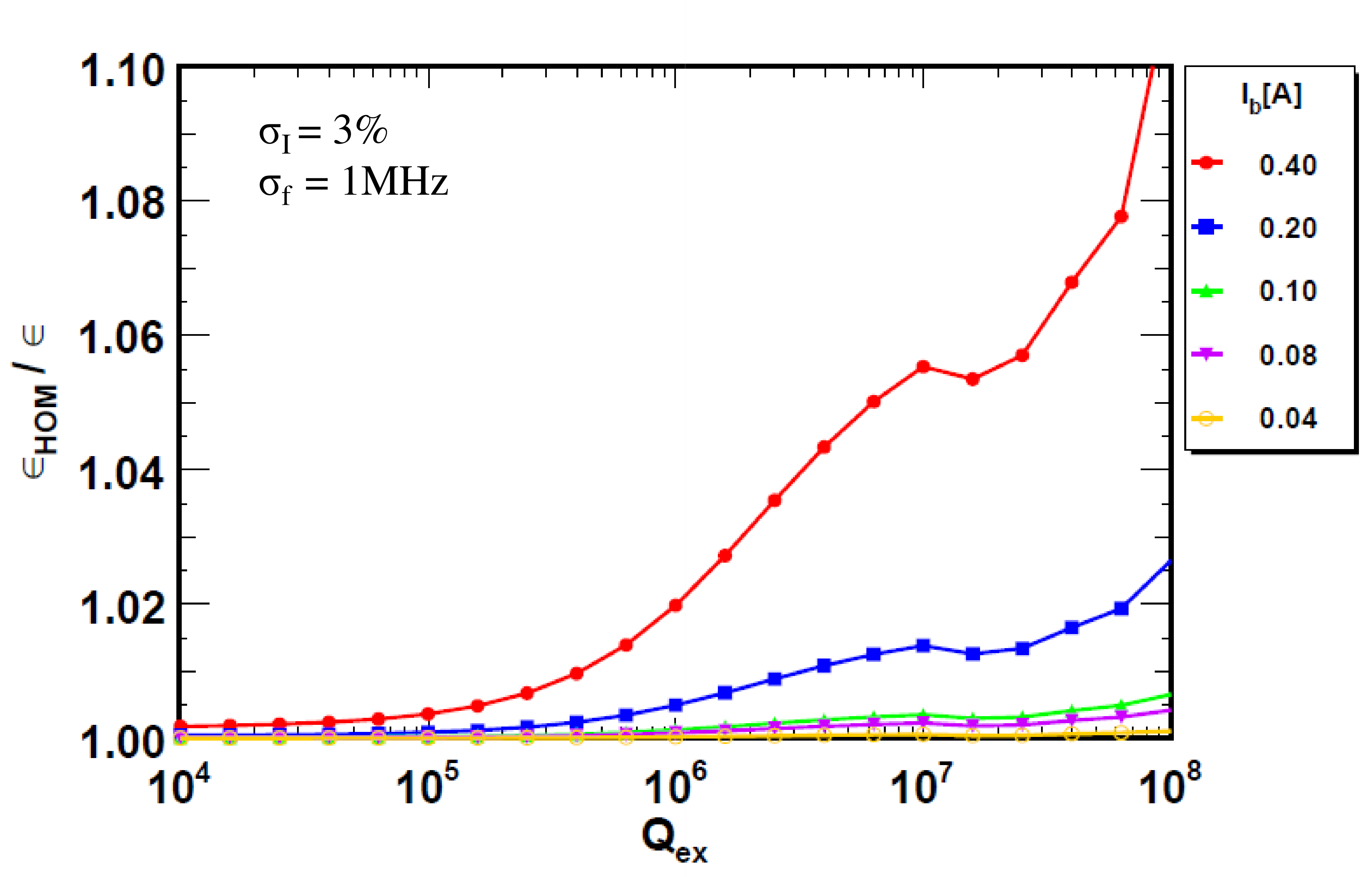
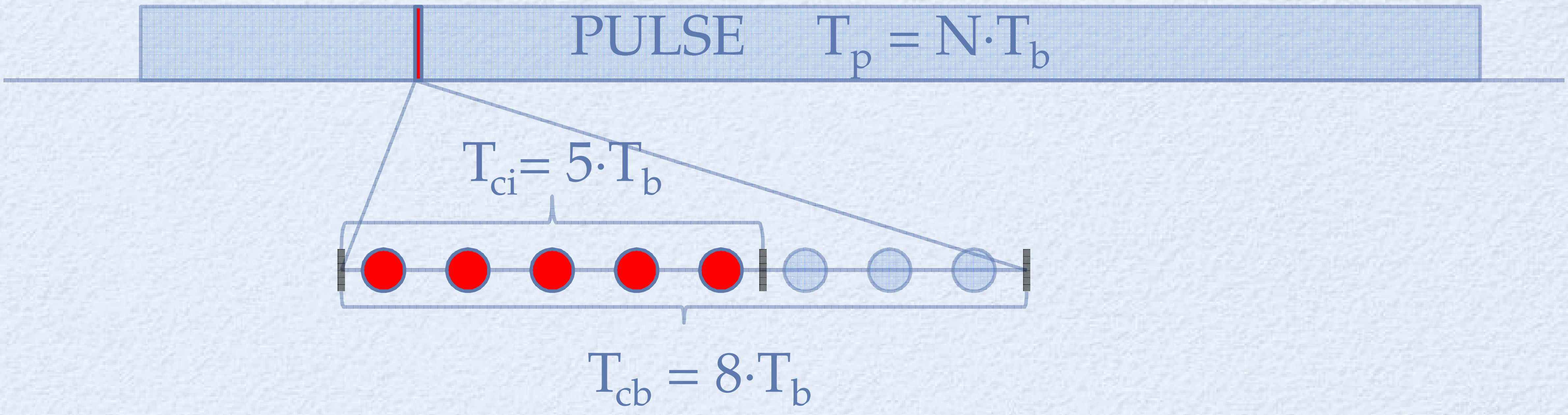
Transversal - General Case

Transversal Bunch Center Emittance Growth Rate



Chopping Modes



PULSE $T_p = N \cdot T_b$

$T_{ci} = 5 \cdot T_b$

$T_{cb} = 8 \cdot T_b$

New machine lines (created by chopping):

- N_{ci}/N_{cb}: $\boxed{f_{mcn} = n \frac{1}{T_{cb}} = n \frac{f_b}{N_{cb}} \quad ; n \in \mathbb{N}}$
- x/8 : $f_{mc1} = 44.025\text{MHz}$
- y/80 : $f_{mc1} = 4.4025\text{MHz}$
- z/800 : $f_{mc1} = 0.44025\text{MHz}$

N.B.: Charge per pulse stays const.
➔ charge per bunch increases

Effect Of Chopping Analytically (Longitudinal)

- Voltage induced by one pulse:

$$V_{Pulse} = V_b \frac{1-\exp\left(-\frac{T_p}{T_d}+i\omega_n T_p\right)}{1-\exp\left(-\frac{T_b}{T_d}+i\omega_n T_b\right)} \qquad T_d = \frac{2Q_{ex}}{\omega_n}$$

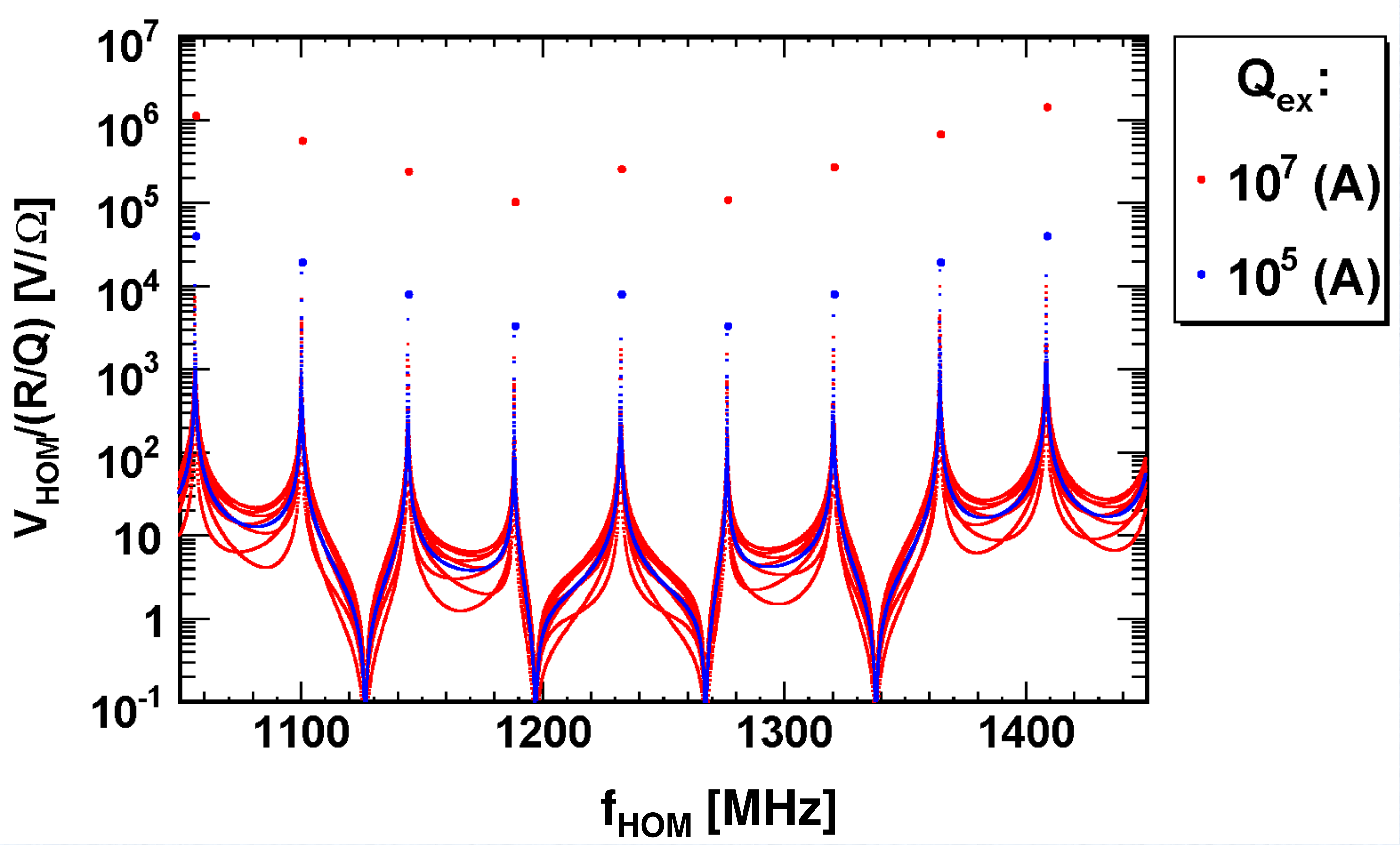
- Voltage induced by one pulse with substructure:

$$V_{Pulse} = V_b \frac{1-\exp\left(-\frac{T_p}{T_d}+i\omega_n T_p\right)}{1-\exp\left(-\frac{T_b}{T_d}+i\omega_n T_b\right)} \cdot \frac{1-\exp\left(-\frac{T_{ci}}{T_d}+i\omega_n T_{ci}\right)}{1-\exp\left(-\frac{T_{cb}}{T_d}+i\omega_n T_{cb}\right)}$$

Further details: S. Kim et al., Higher-order-mode (HOM) power in elliptical superconducting cavities for intense pulsed proton accelerators

5/8 Chopping

V_{HOM} after one pulse (5/8 chopping)



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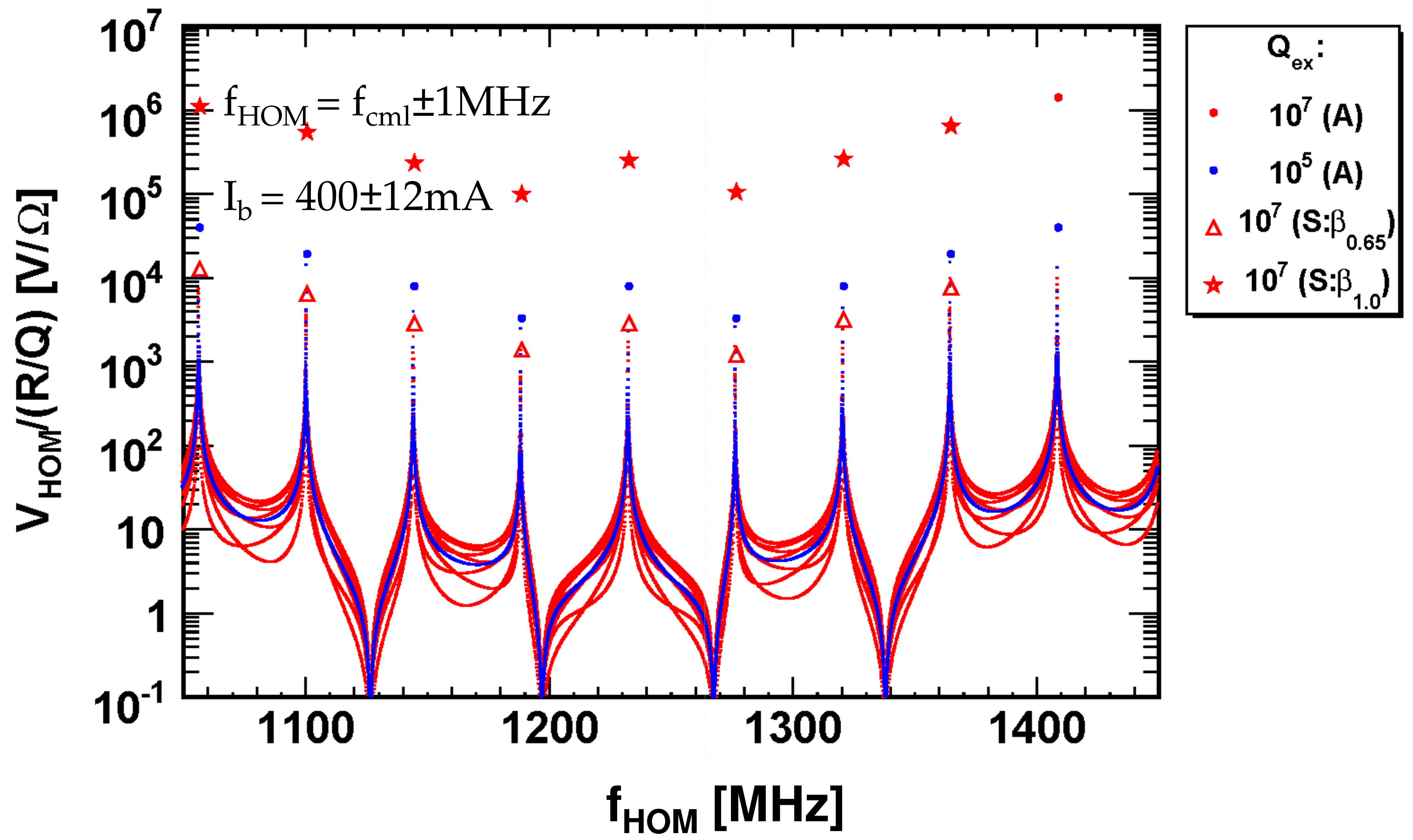
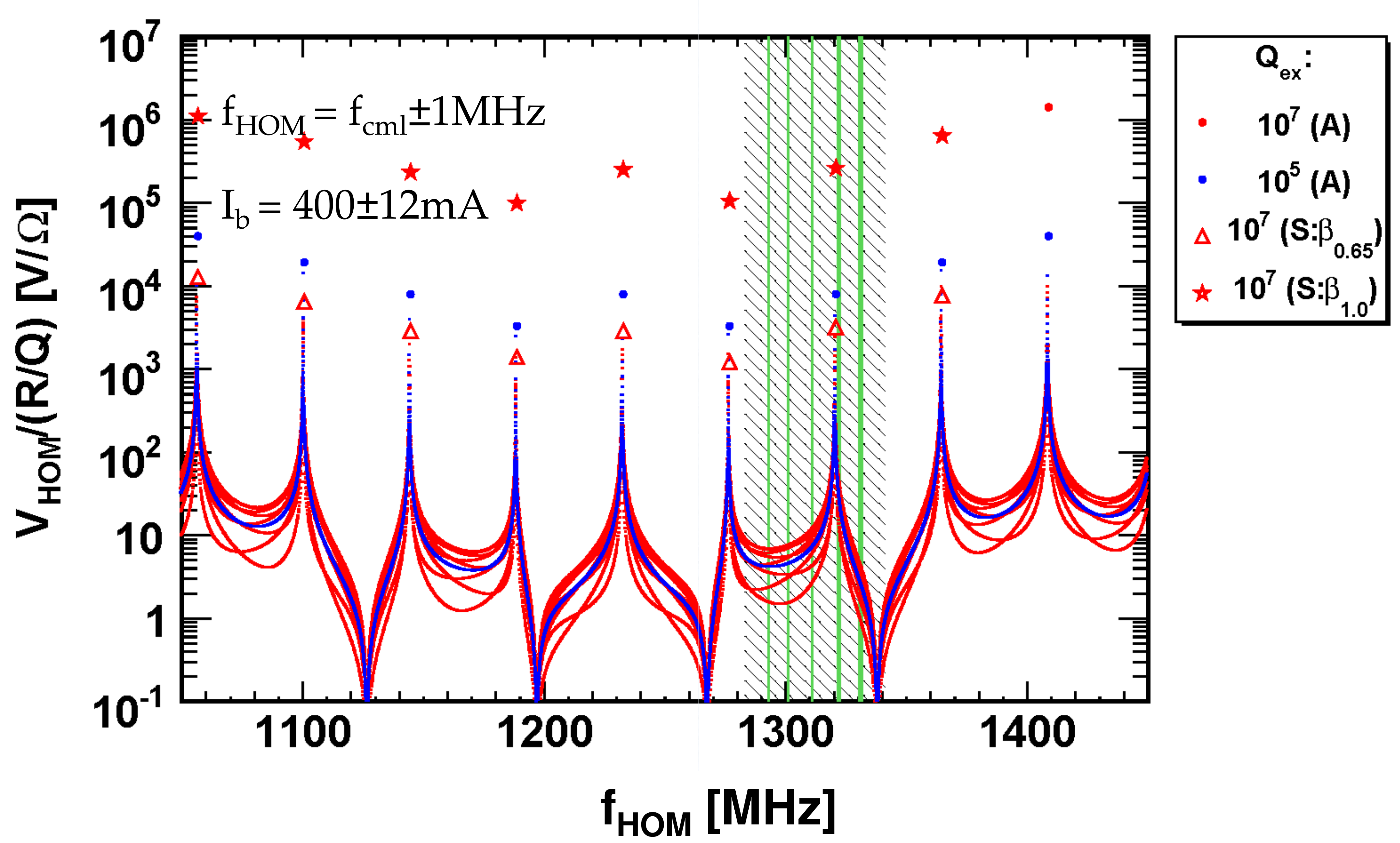
5/8 Chopping

V_{HOM} after one pulse (5/8 chopping)



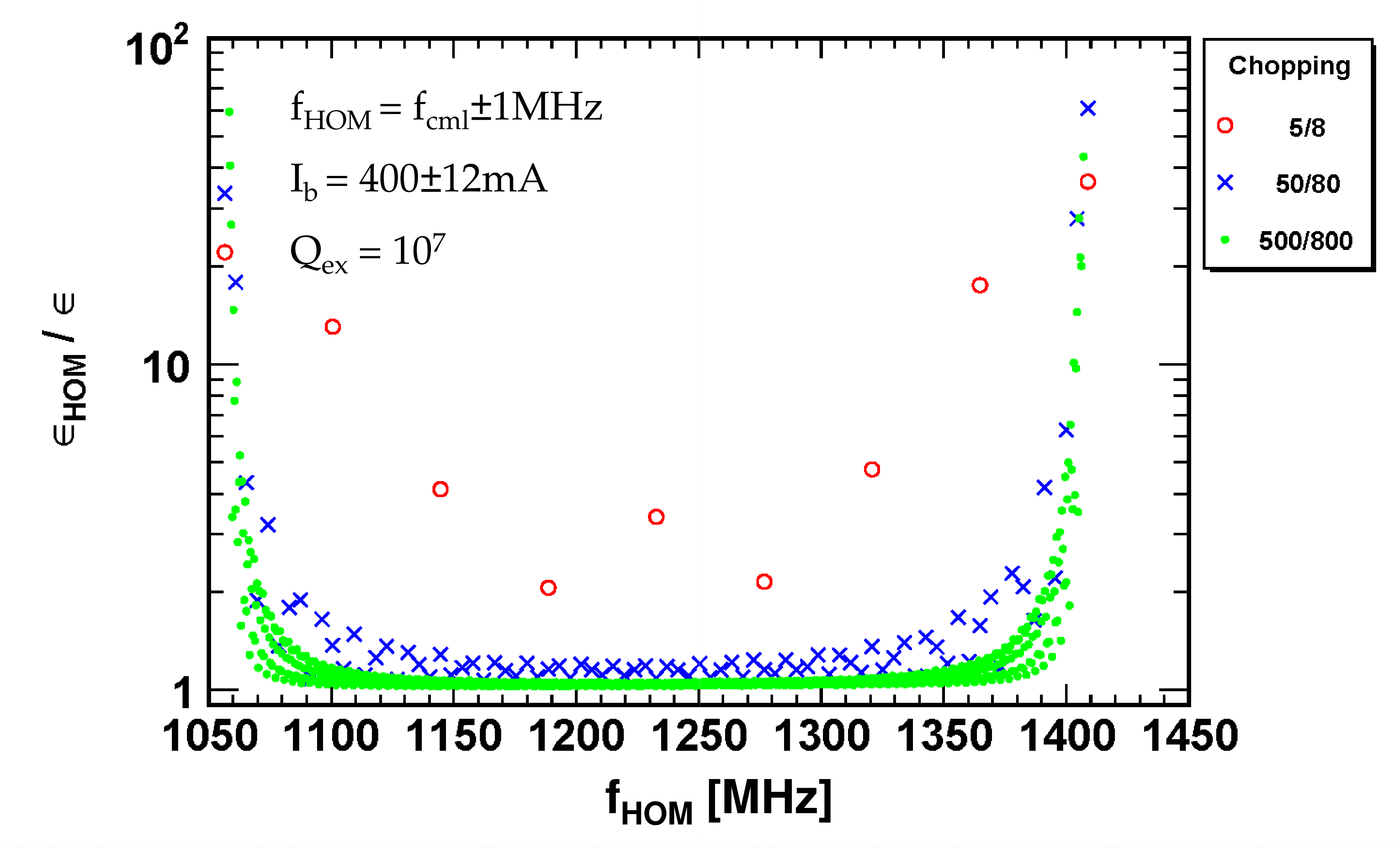
5/8 Chopping

V_{HOM} after one pulse (5/8 chopping)



Emittance growth - chopping

Longitudinal Bunch Center Emittance Growth Rate



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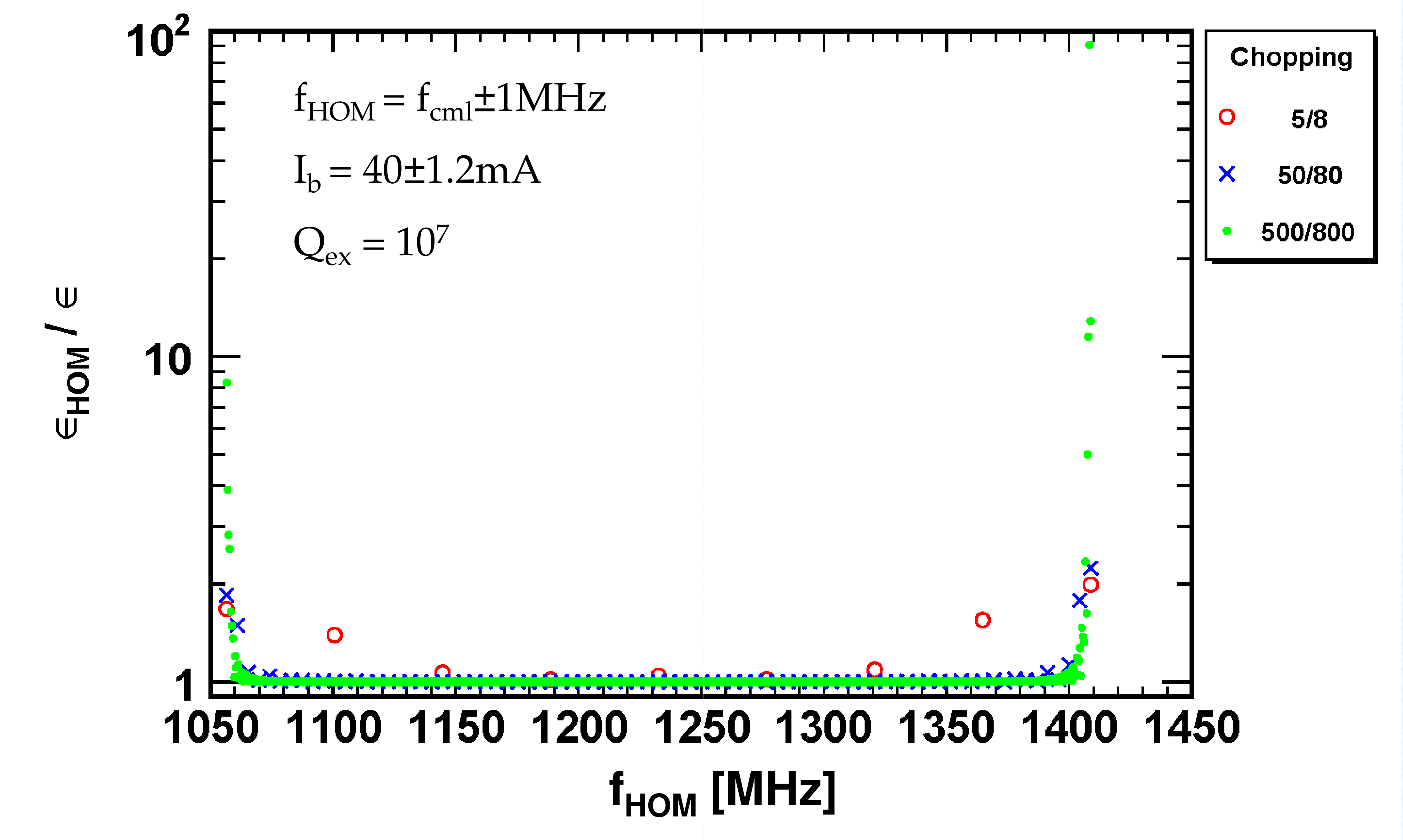
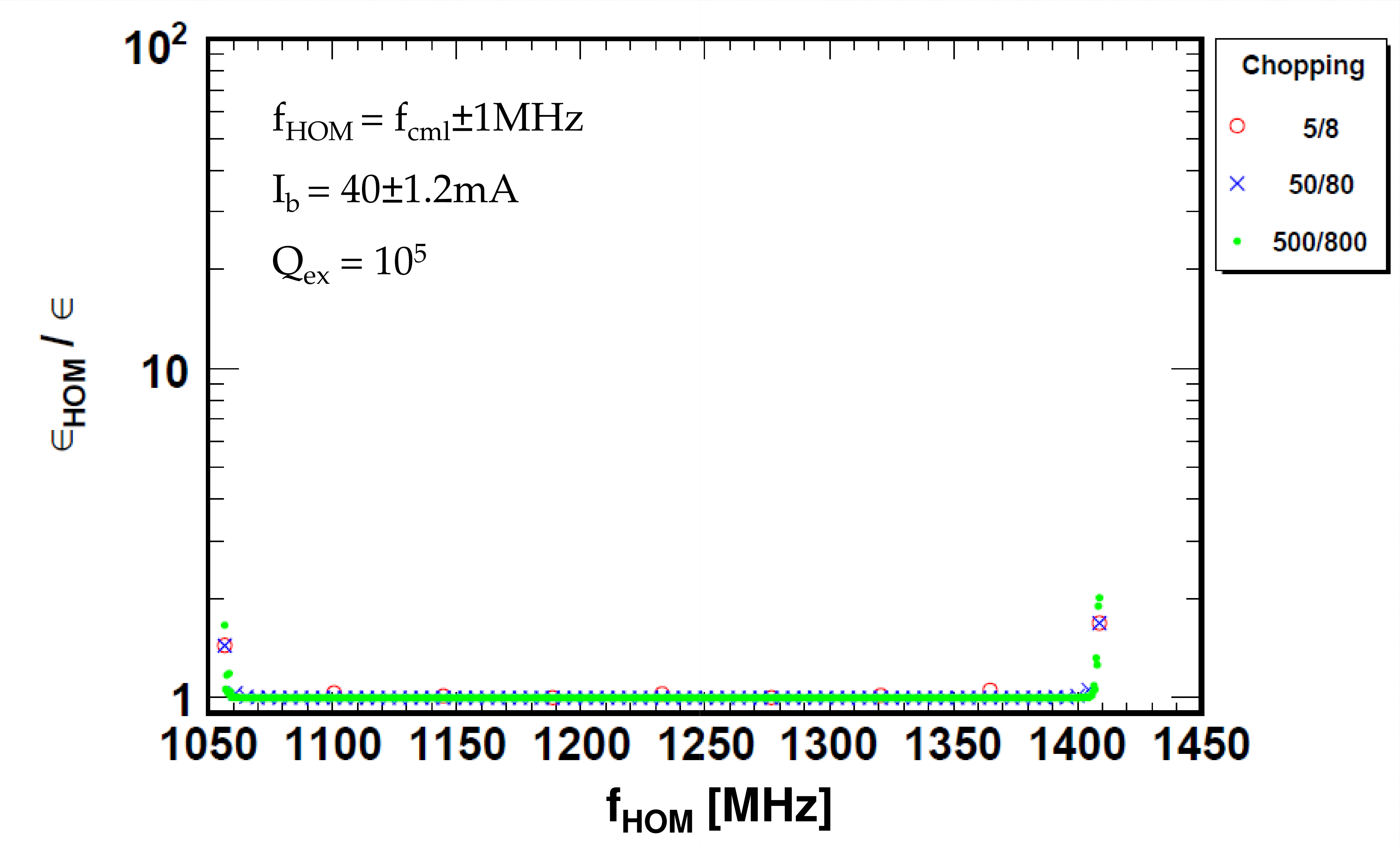
Emittance growth - chopping



Emittance growth - chopping

Longitudinal Bunch Center Emittance Growth Rate



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Effect Of Different Parameters

Parameter	LONG	TRANS
Frequency Spread	↘	↘
Charge Scatter	↗	→
Input Phase Space	→	→
I·R/Q	↗	↗
Machine Lines	↗ (no op.)	↗
Chopping	↗ (critical)	↗
Klystron Errors	→ (minor growth)	-
Cav. Alignment	-	→ (minor growth)
Pulse Length	→ ($Q_{ex}<10^6$)	→ ($Q_{ex}<10^6$)

Conclusions

- Tools developed to simulate influence of HOMs
- Simulations show HOM damping seeming to be necessary in order to provide a high brilliance beam!
- Chopping is a critical issue in the longitudinal plane
- **The limit of Q_{ex} based on the presented results:**

$Q_{ex} < 10^7$ (in case of chopping $Q_{ex} < 10^5$)

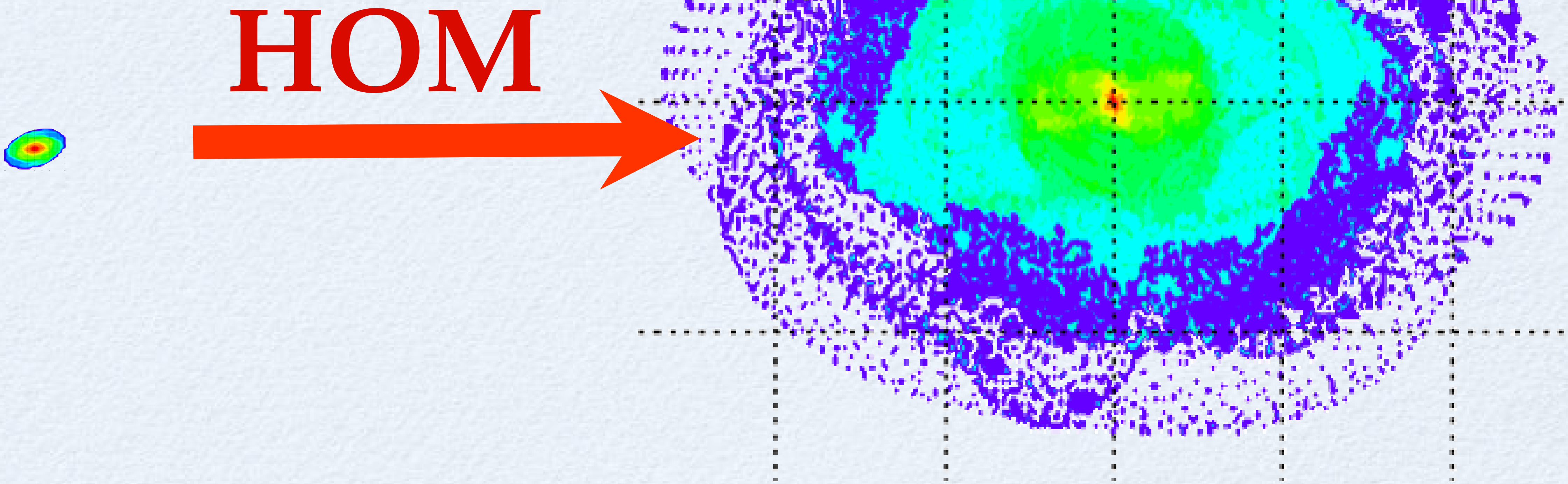
mschuh@cern.ch

Outlook

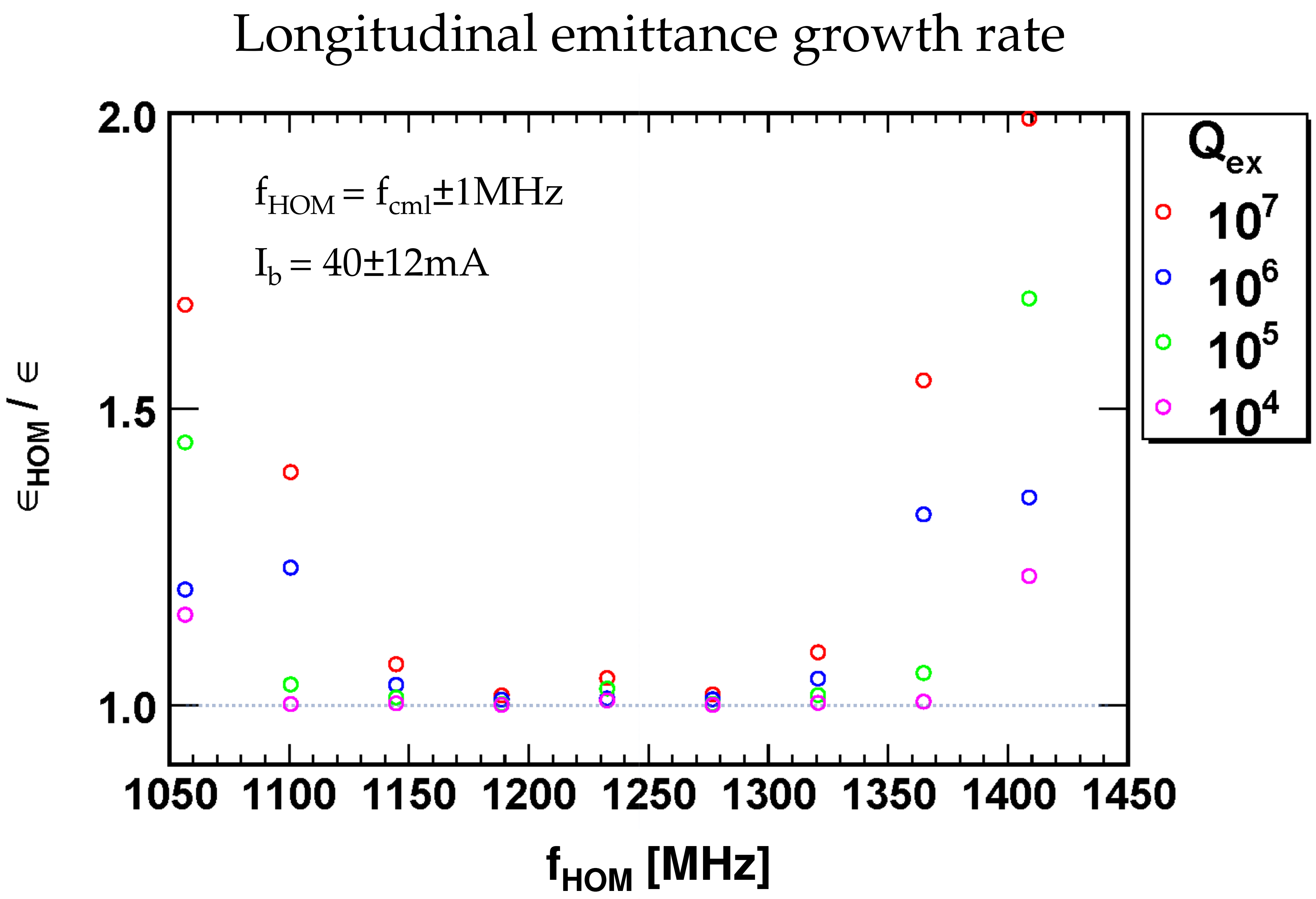
- Open beam dynamic issues:
  - Halo particles losses (activation issue)
  - Interaction of several modes in one cavity
  - e^- in the SPL (used as recirculating e^- linac)
- Can steel bellows provide enough damping?

Thank You!

Questions?



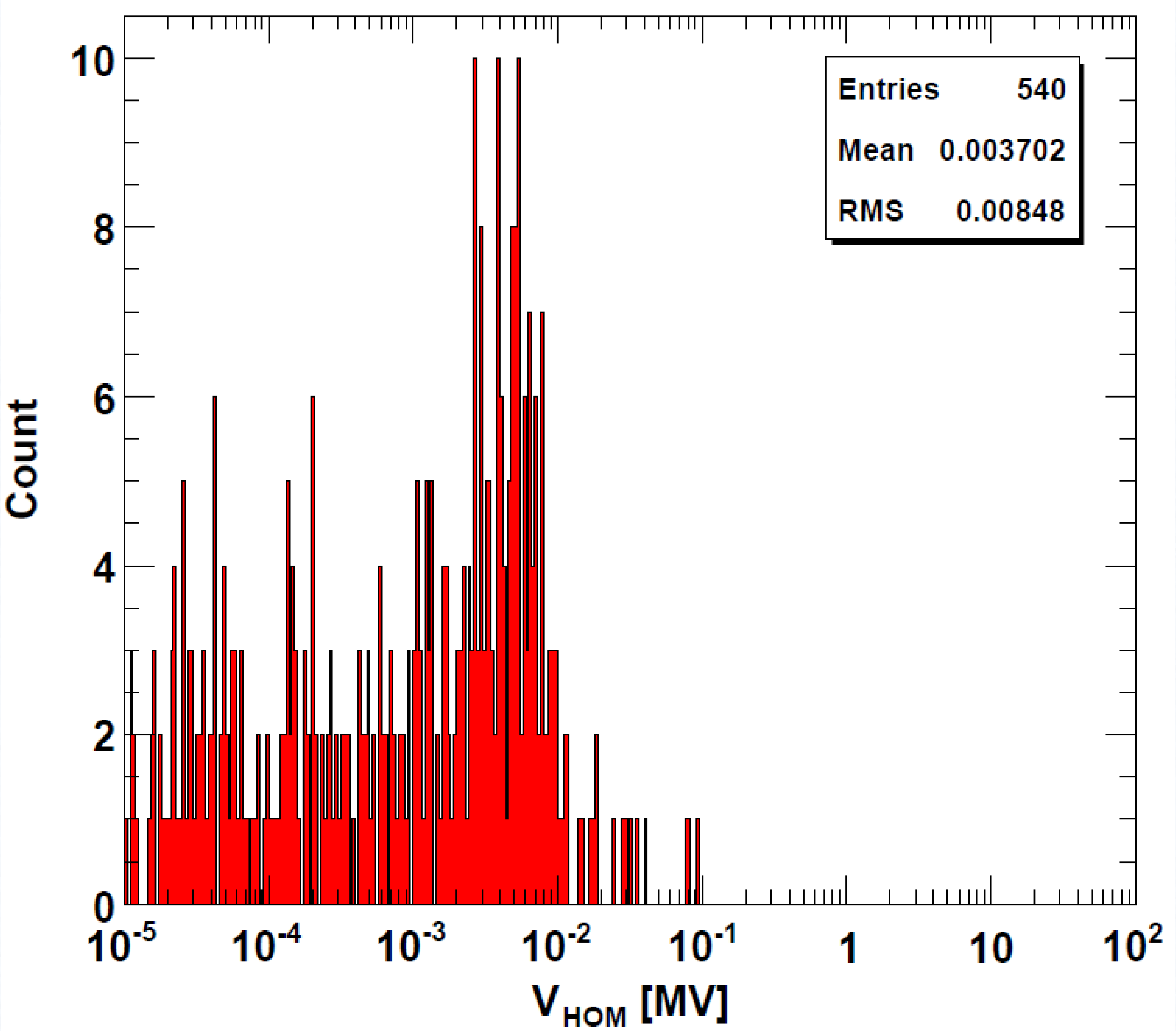
Emittance Growth – 5/8 Chopping



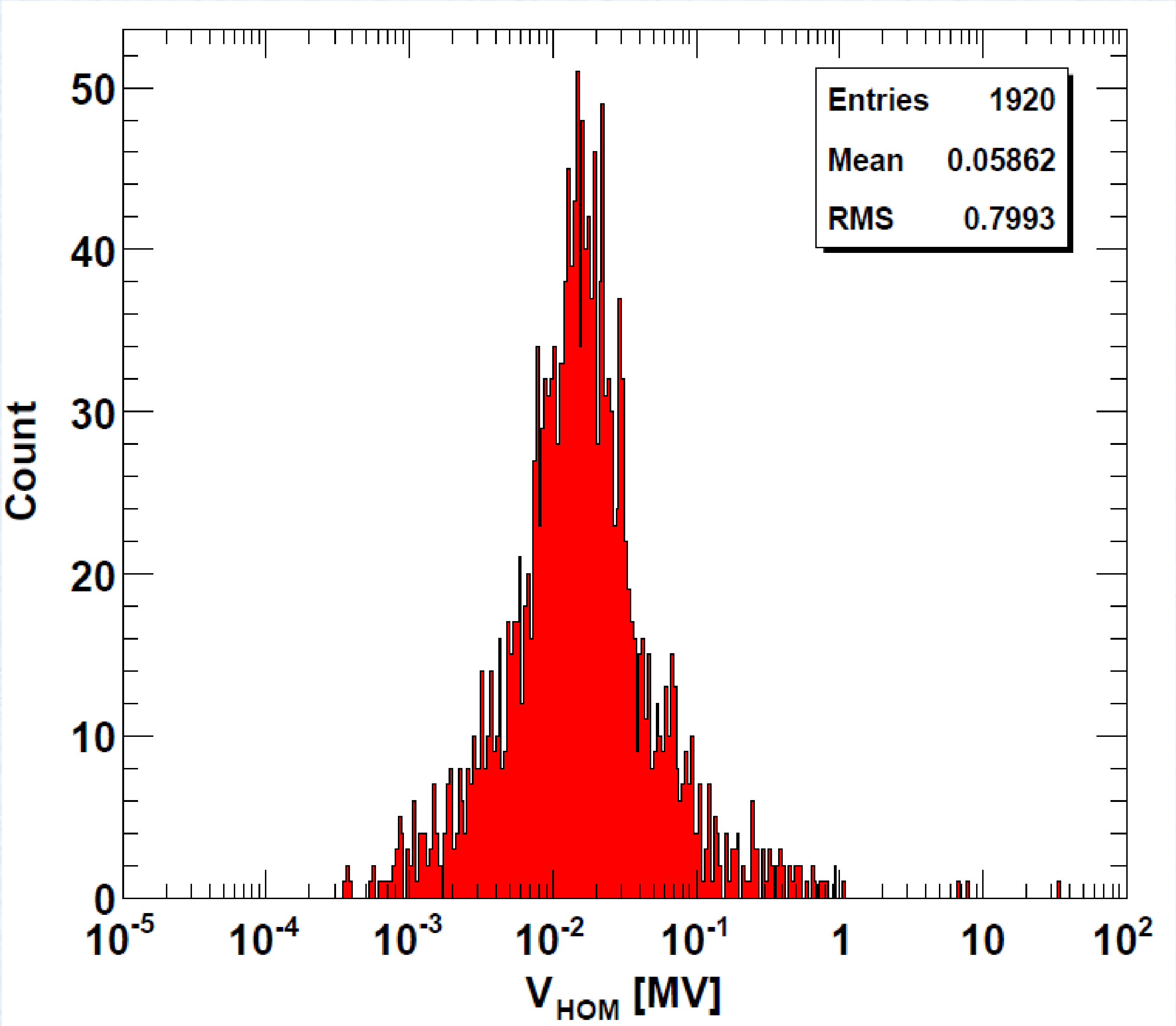
Induced HOM Voltage – 5/8 chopping

$f_{HOM} = 1321 \pm 1\text{MHz}$, $I_b = 0.4\text{A}$, $Q_{ex} = 10^7$

β= *0.65* cavities



β= *1.0* cavities



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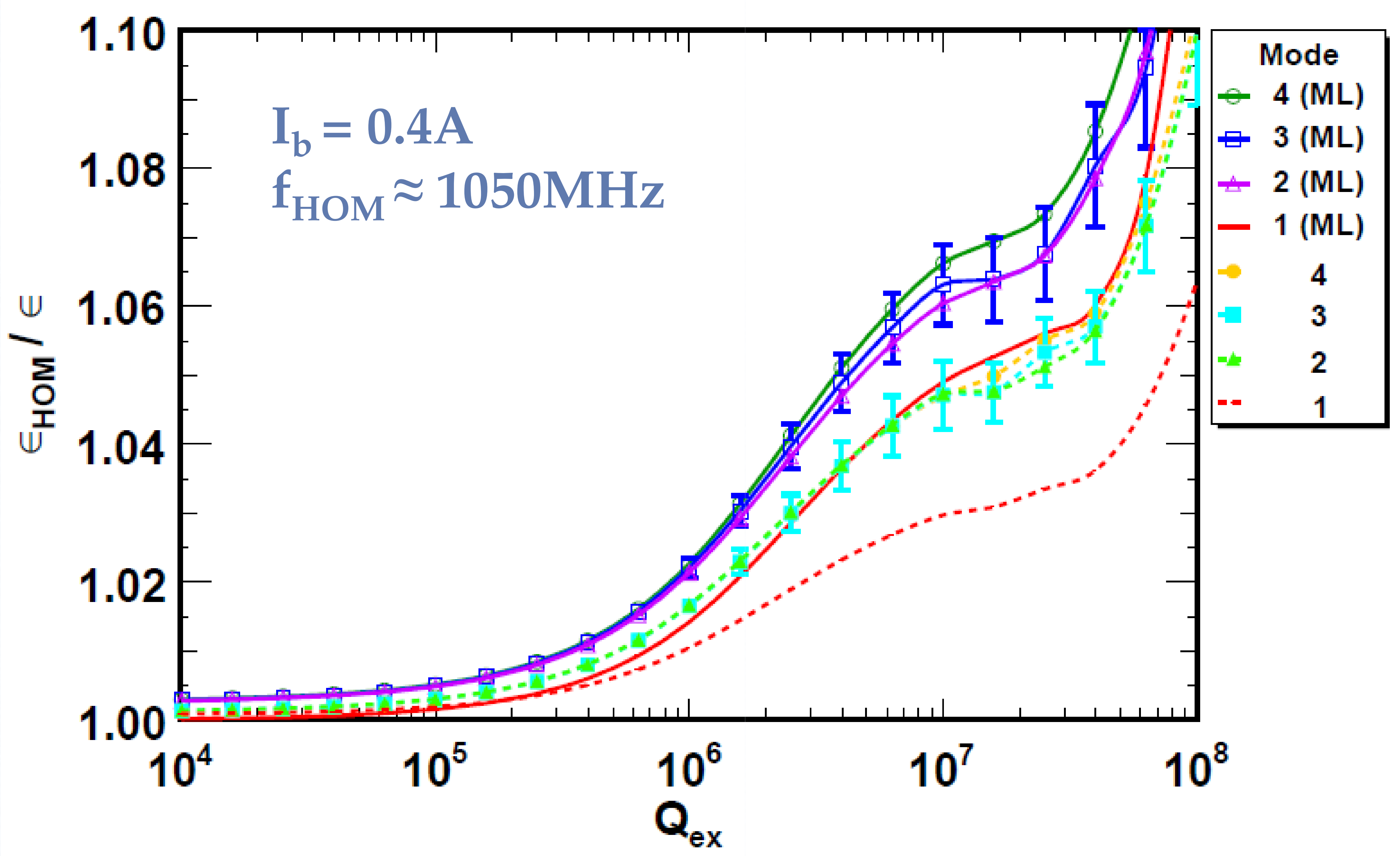
Tr. Emittance growth – chopping

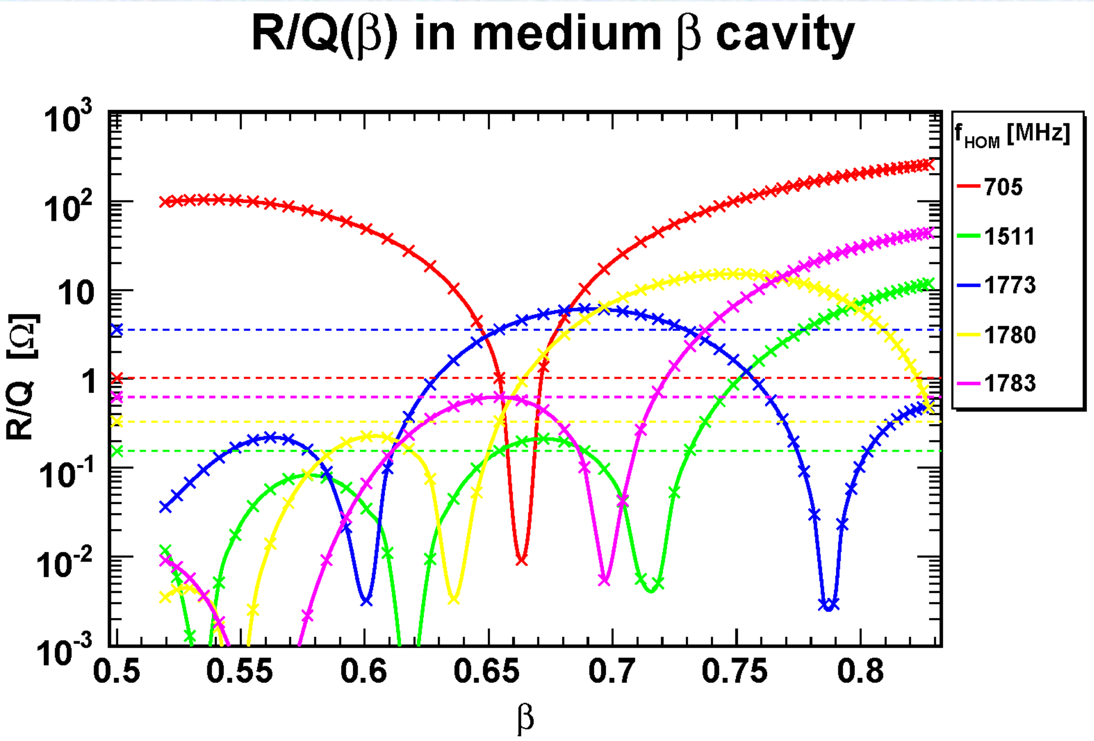


$I_b = 0.4A$

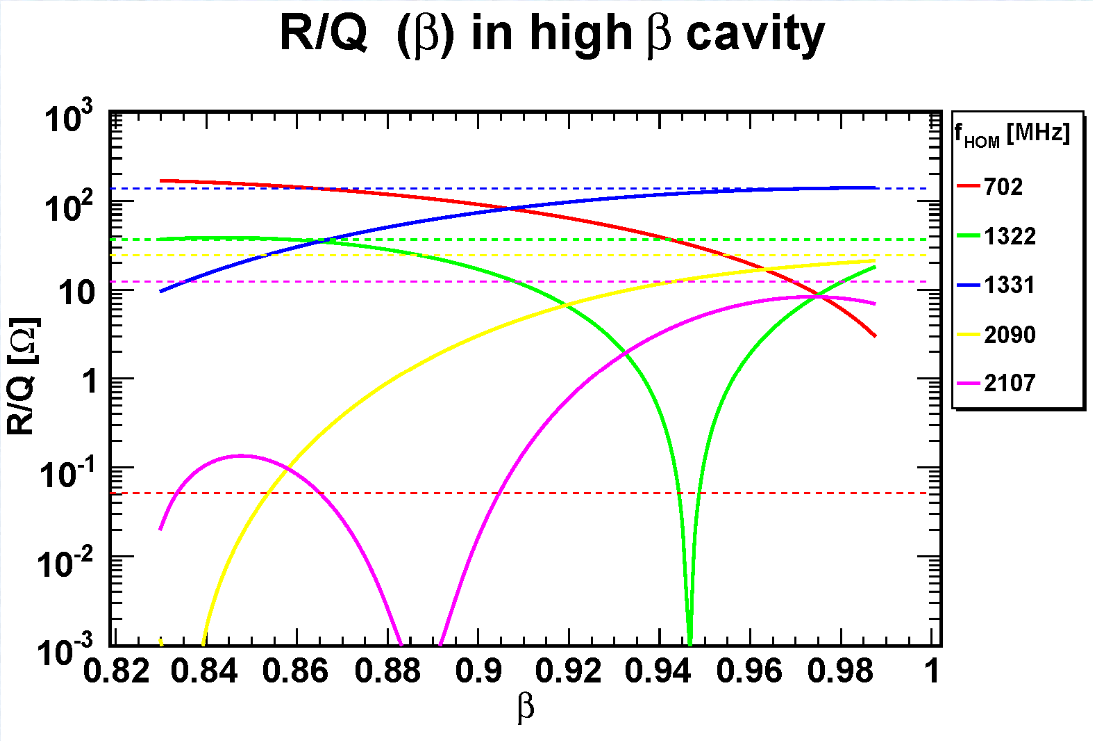
$f_{HOM} \approx 1050MHz$

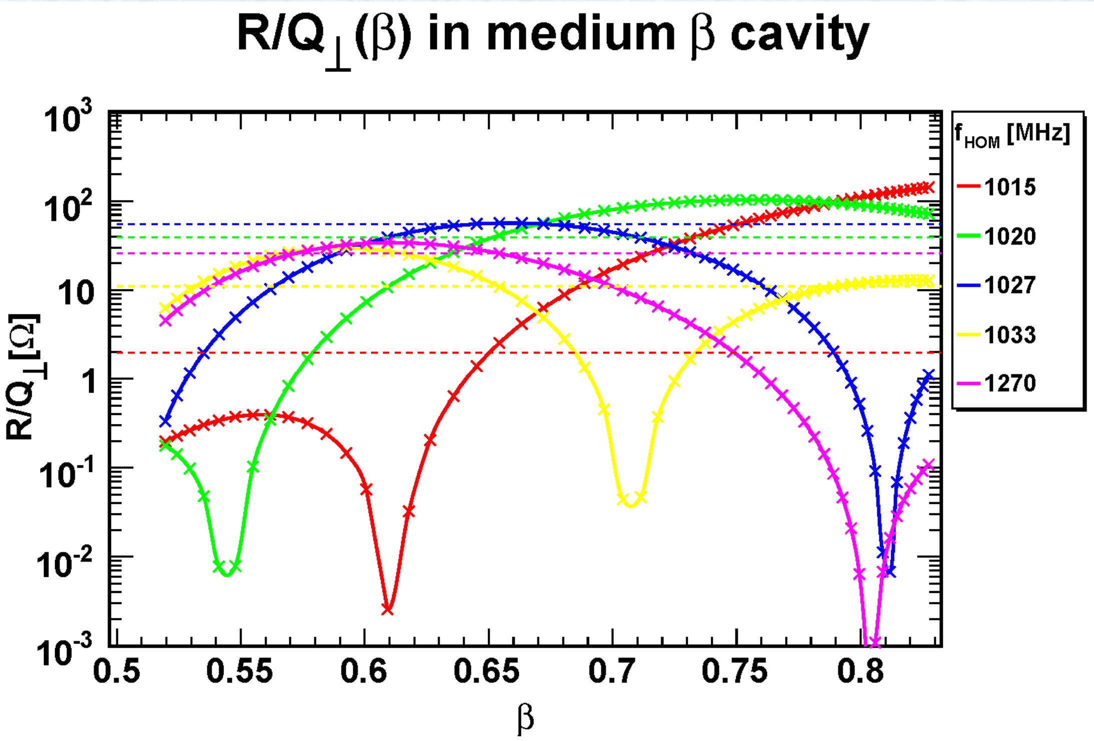
Chopping:
500/800
50/80
5/8
1/1
500/800
50/80
5/8
1/1

R/Q(β) maps

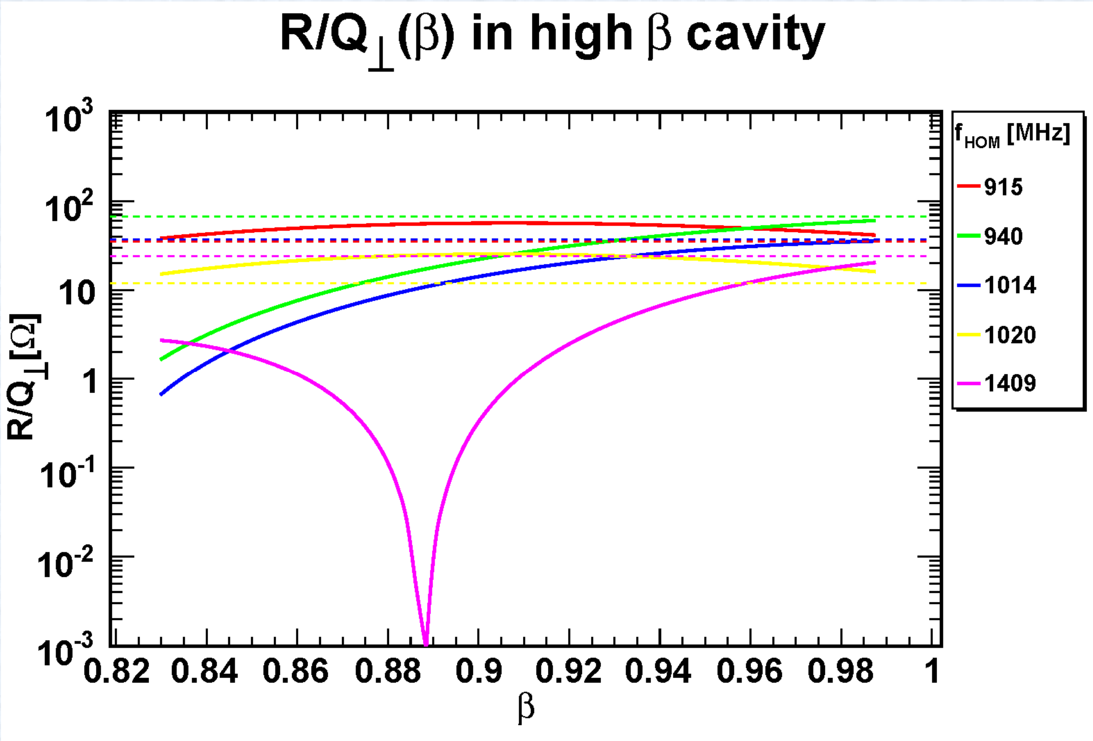

R/Q(β) in medium β cavity

Mono-pole


R/Q (β) in high β cavity

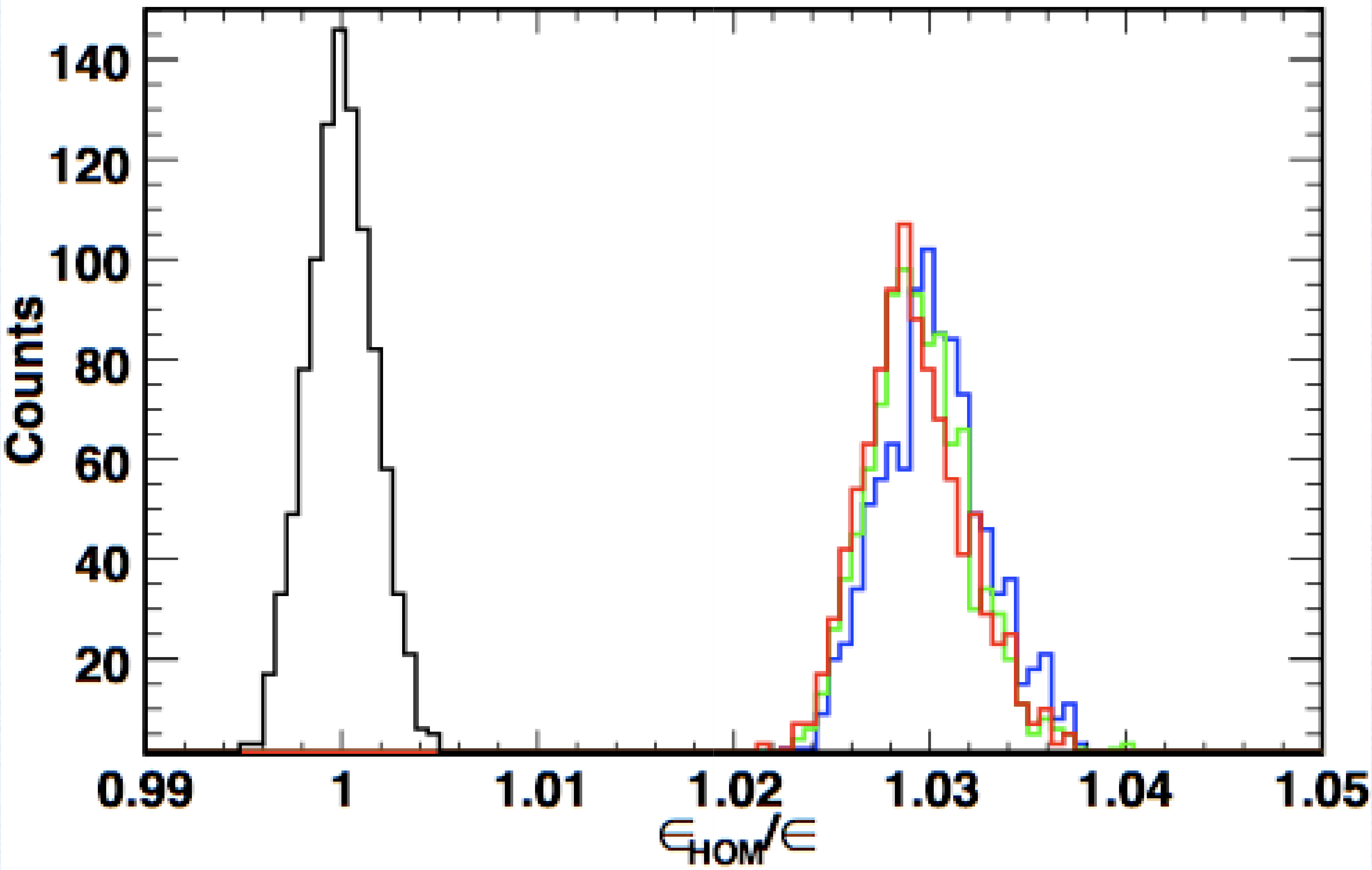

R/Q$_\perp$(β) in medium β cavity

Dipole

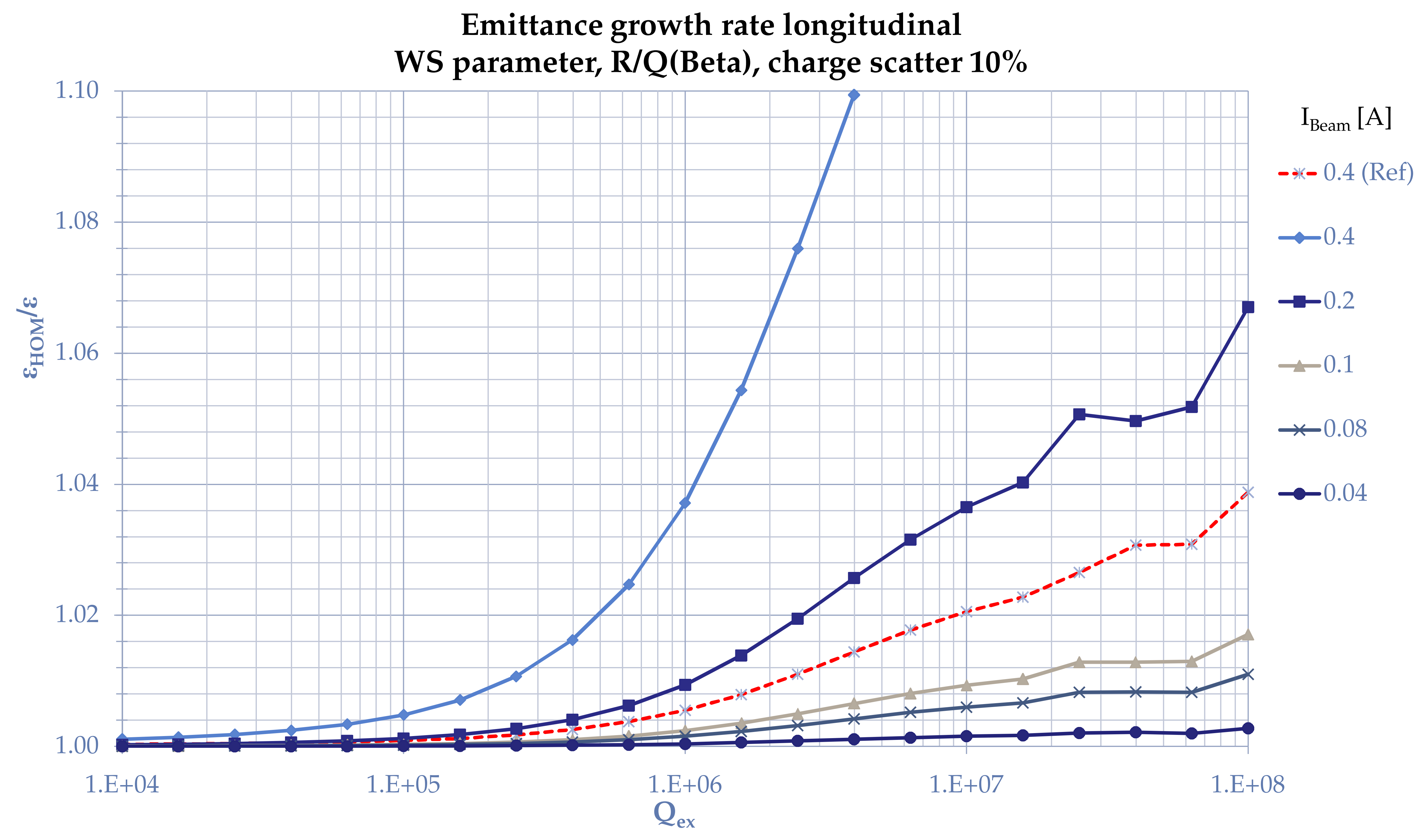

R/Q$_\perp$(β) in high β cavity

Statistic: 1000 linacs

Influence of input beam and
cavity to cavity frequency distribution



Long. charge scatter



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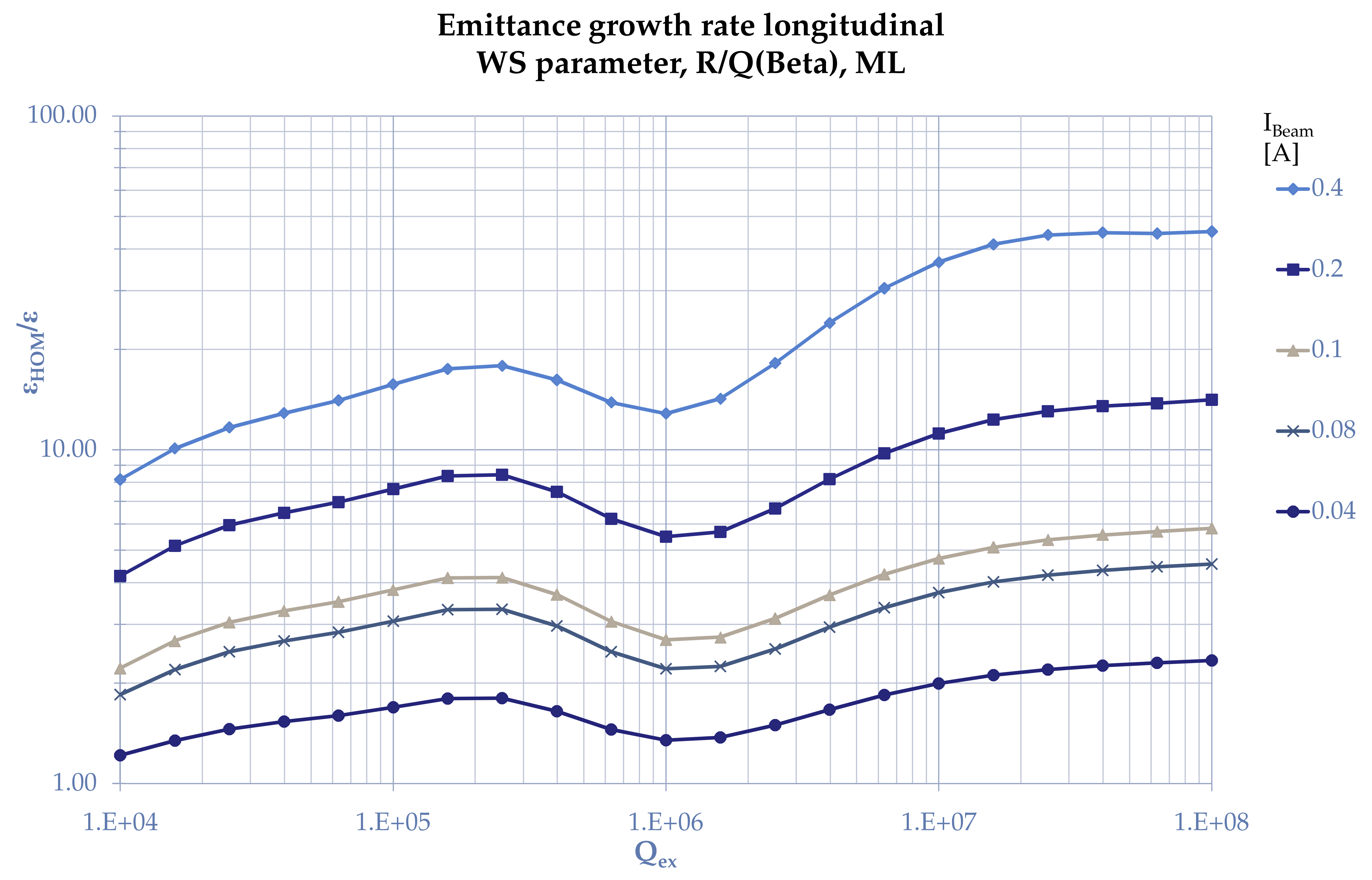
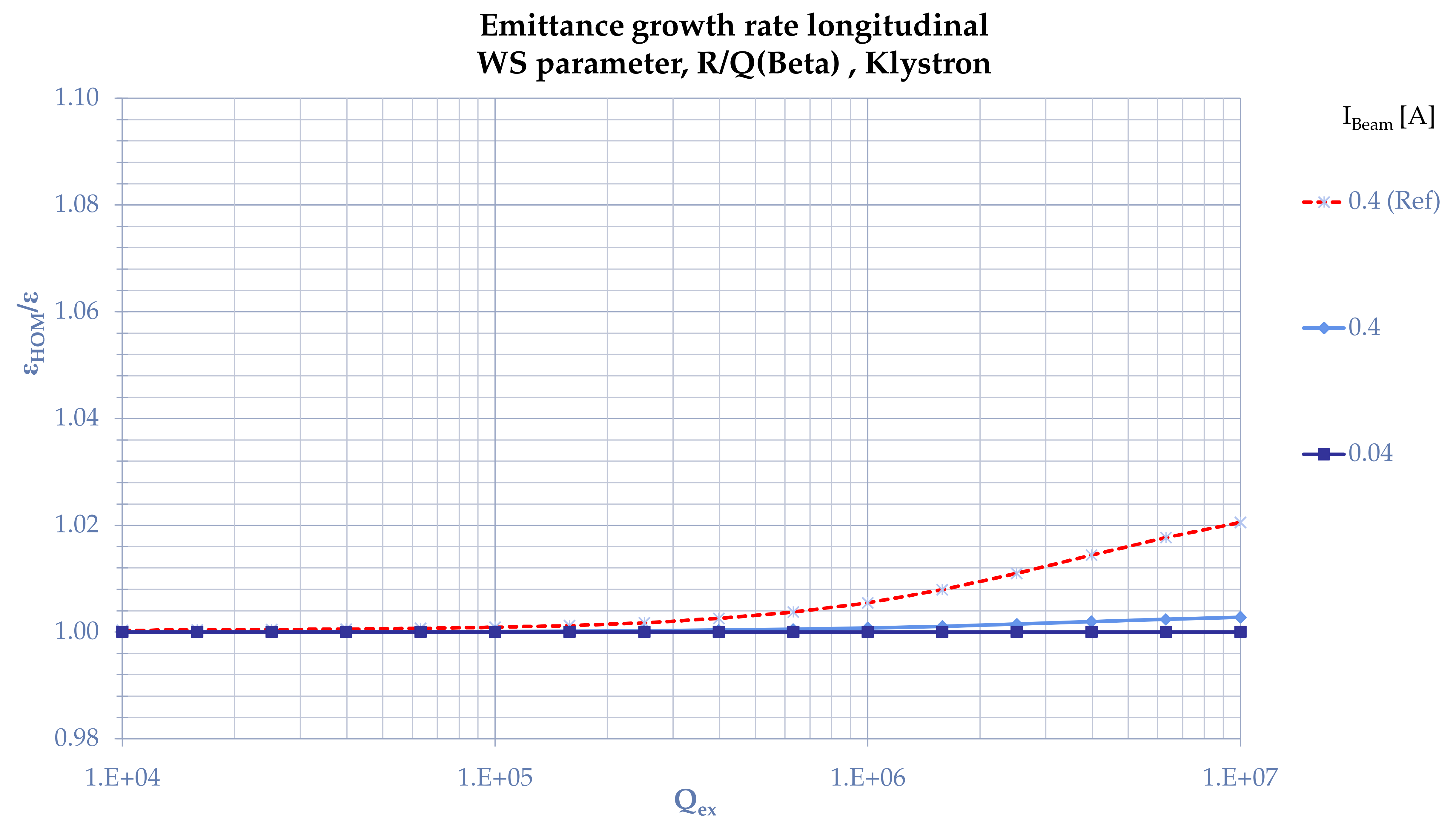
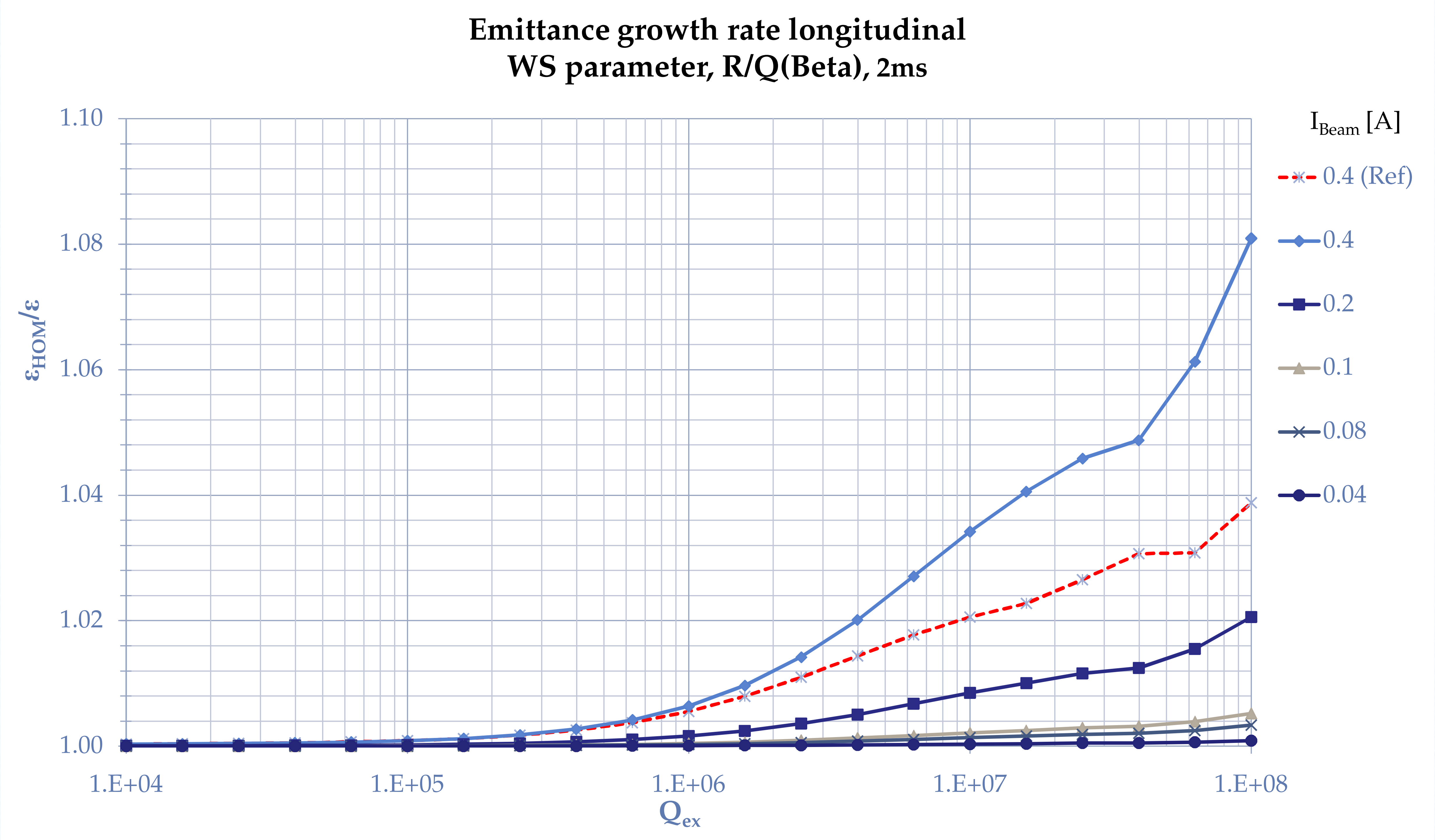
Long. Machine Line



Long. Klystron



Long. Pulse length



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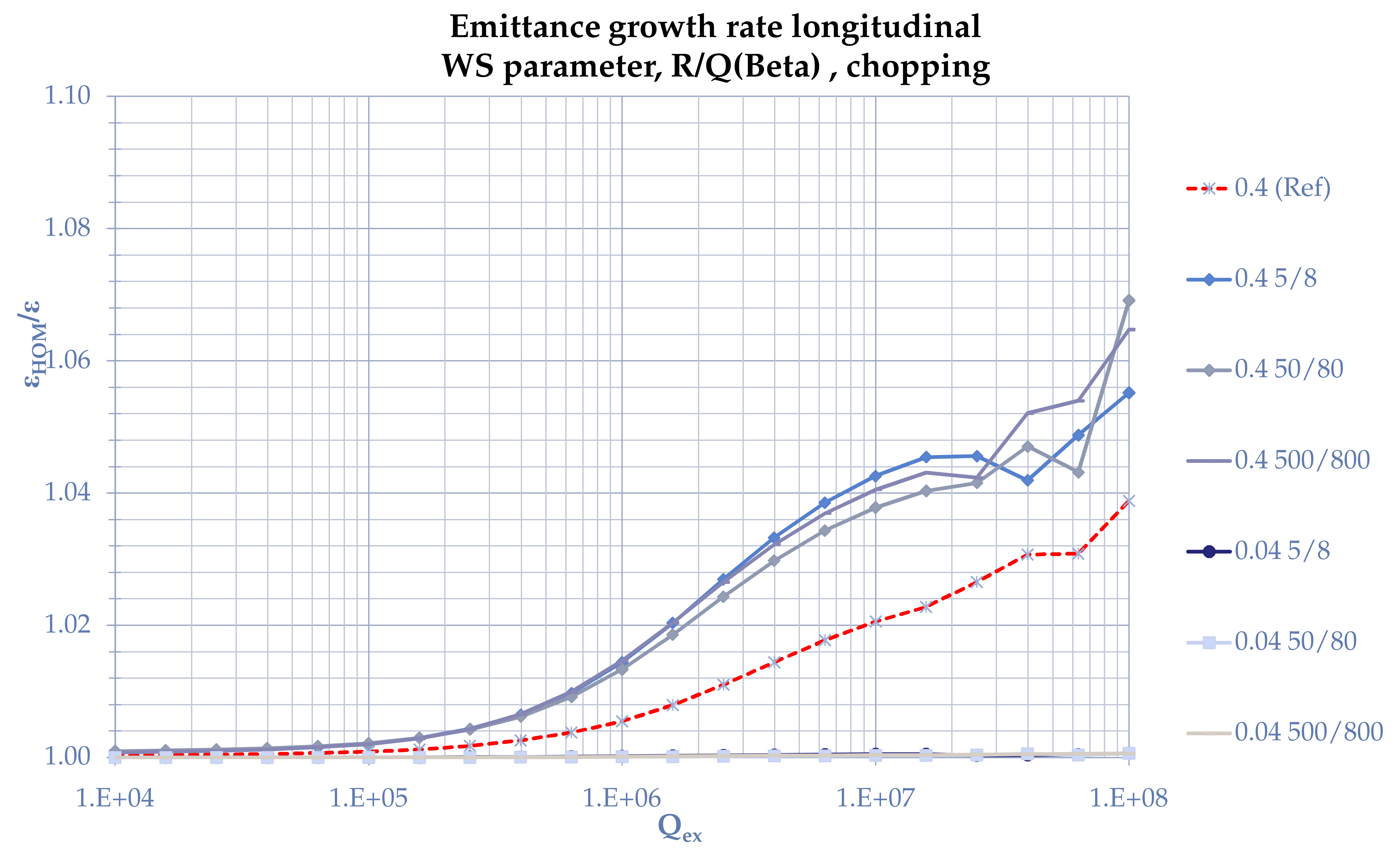
Long. Chopping



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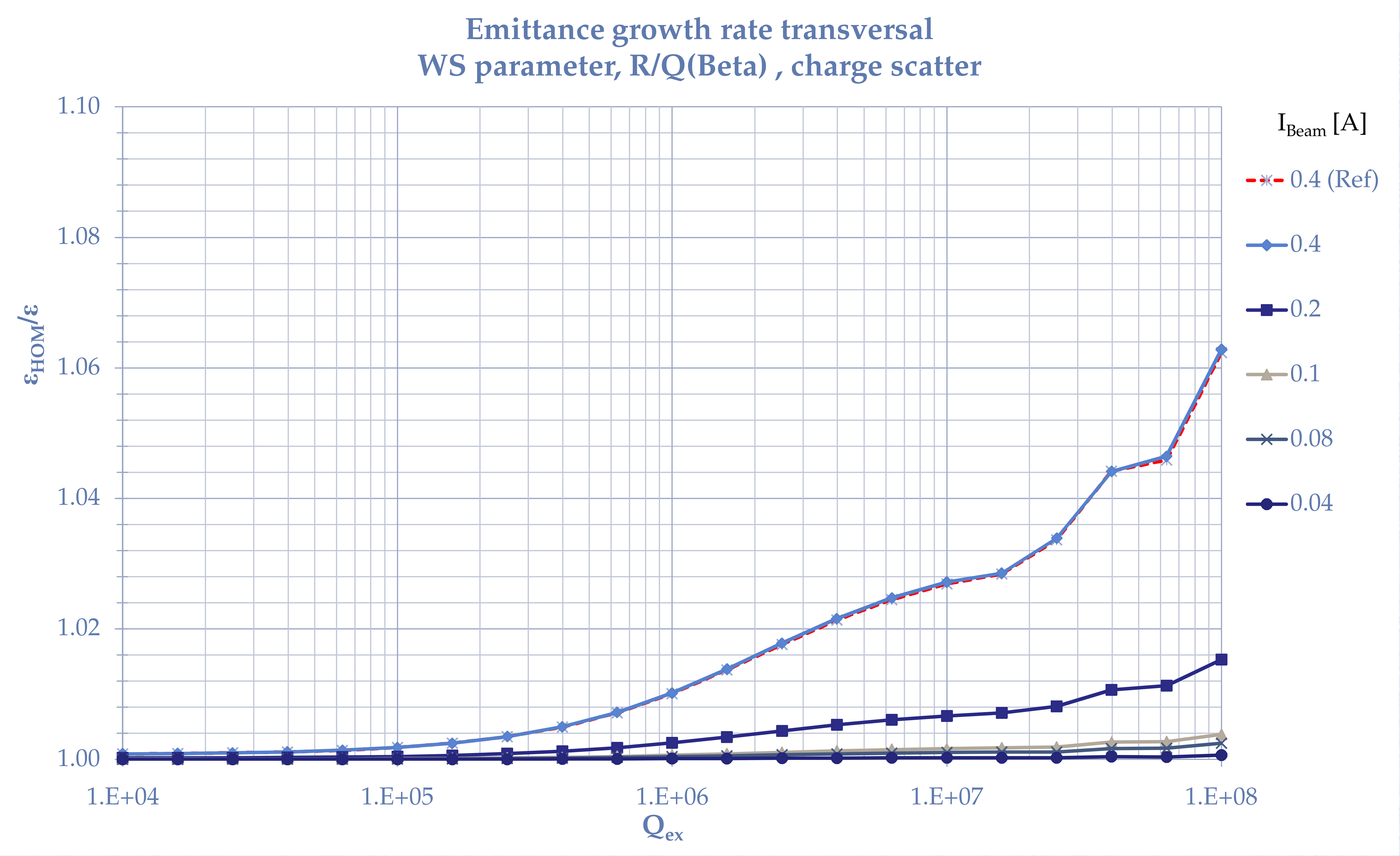
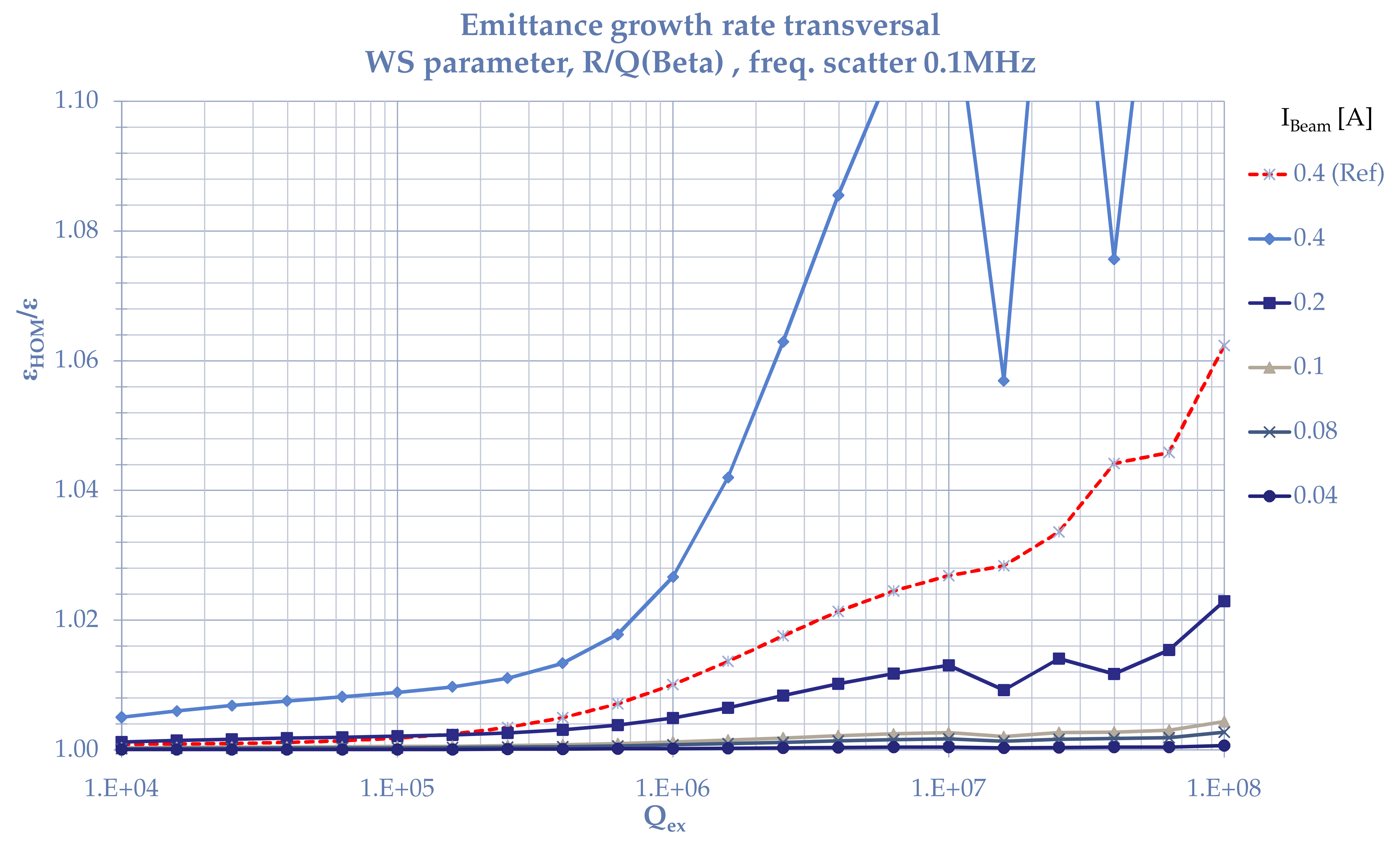
TR. charge scatter



Tr. Frequency scatter



3rd SPL Collaboration Meeting

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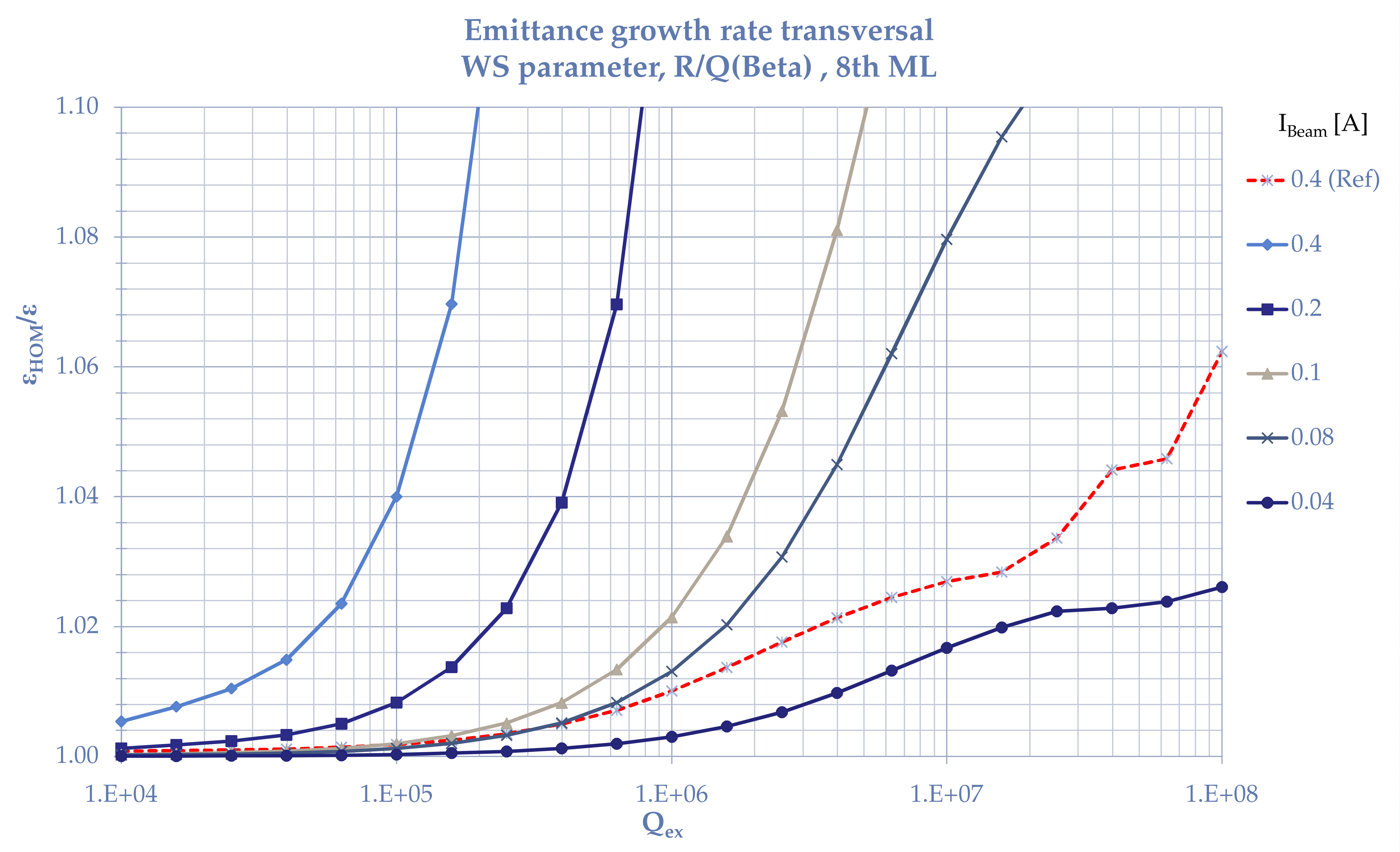
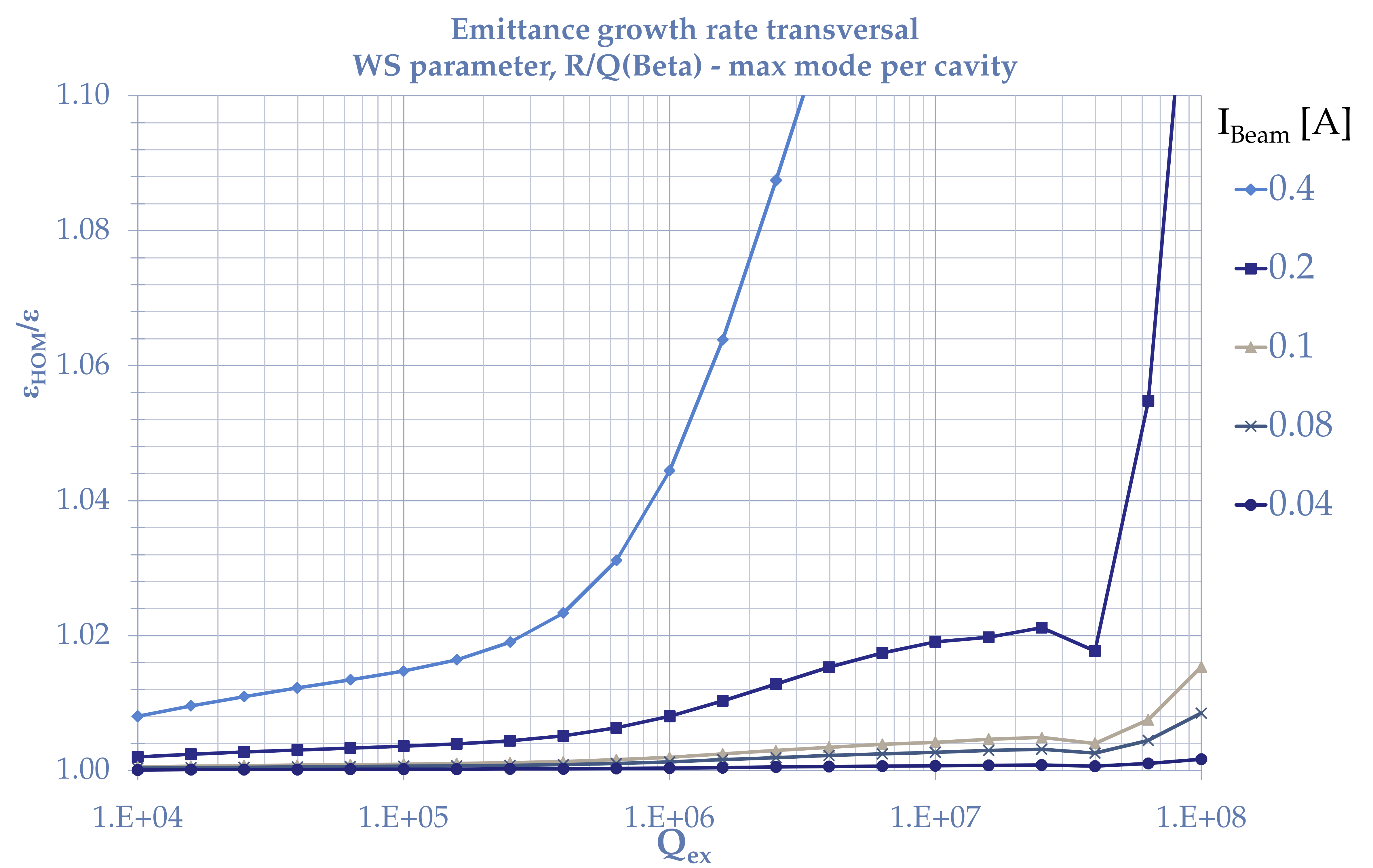
mschuh@cern.ch

Tr. Machine line



Tr. Max mode per cavity



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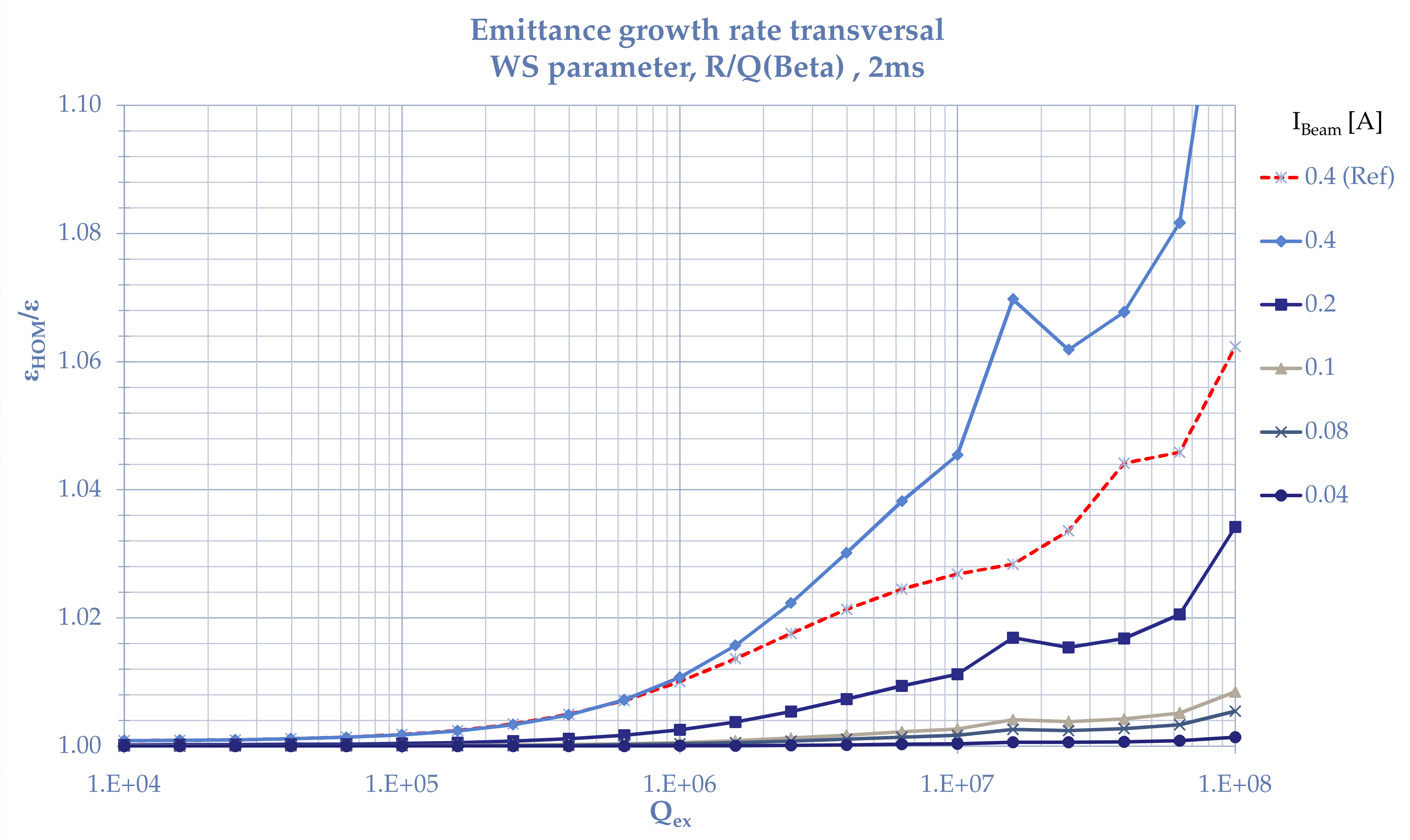
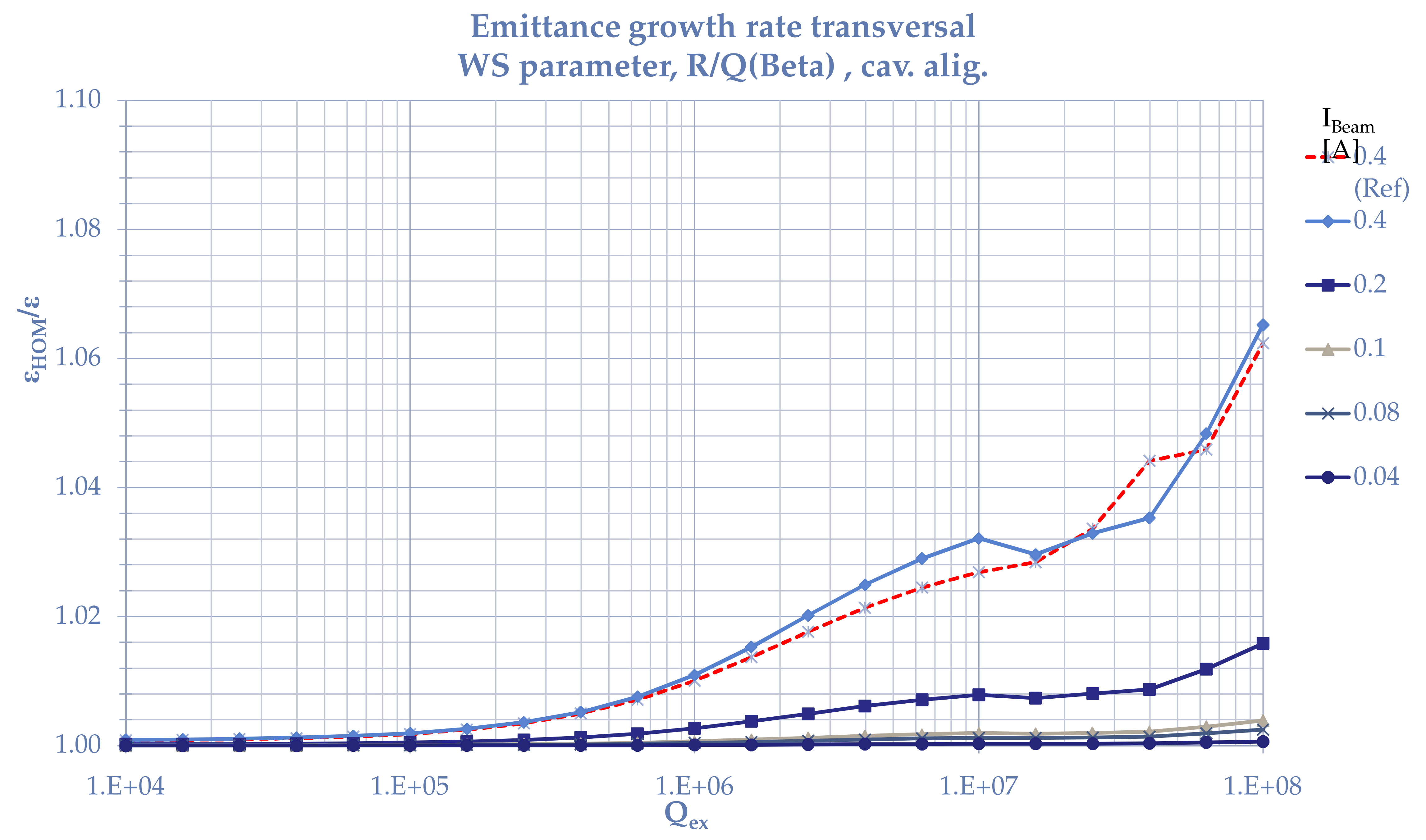
Tr. Pulse length



TR. alignment



Beam HOM Interaction

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

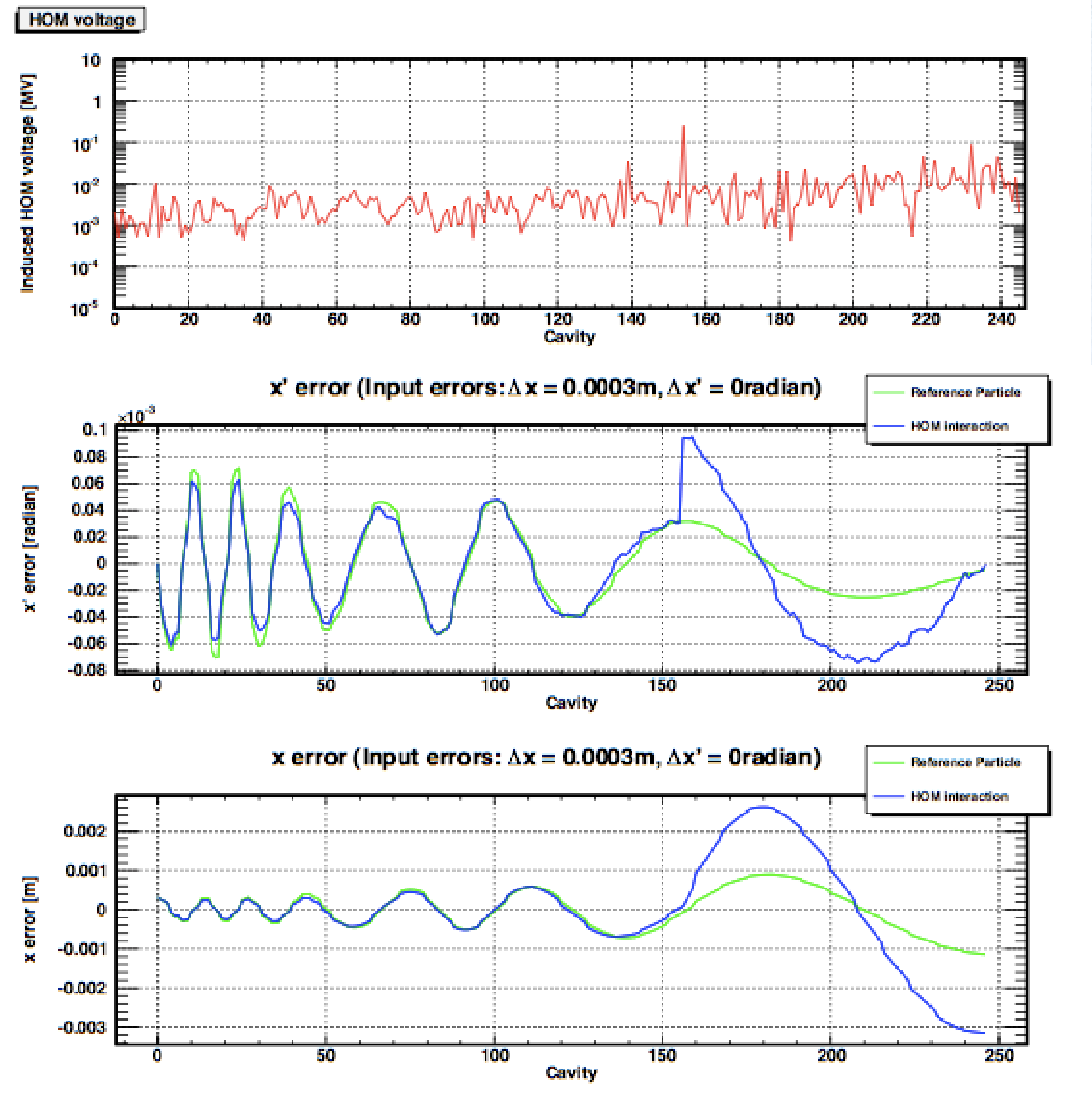
- Transfer Matrix between cavities
- Bunch induce an imaginary voltage:

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

- HOM kicks bunch/particle - momentum change:

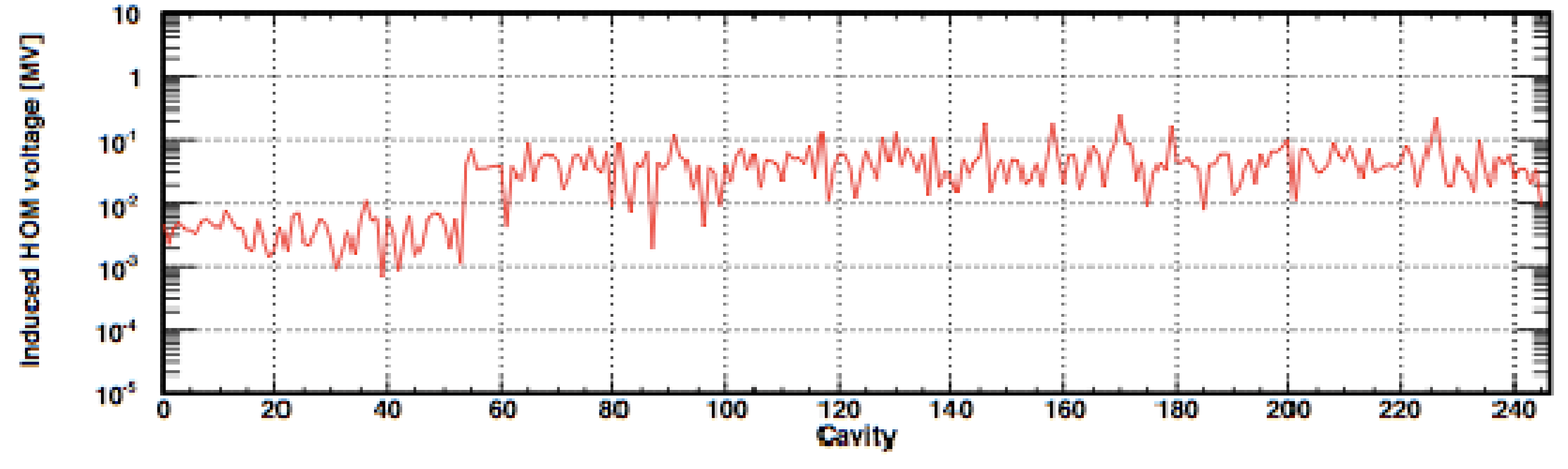
$$\Delta x' = \frac{e\Re(V_{\perp})}{c \cdot p_{||}}$$

Observed Dipole Kick

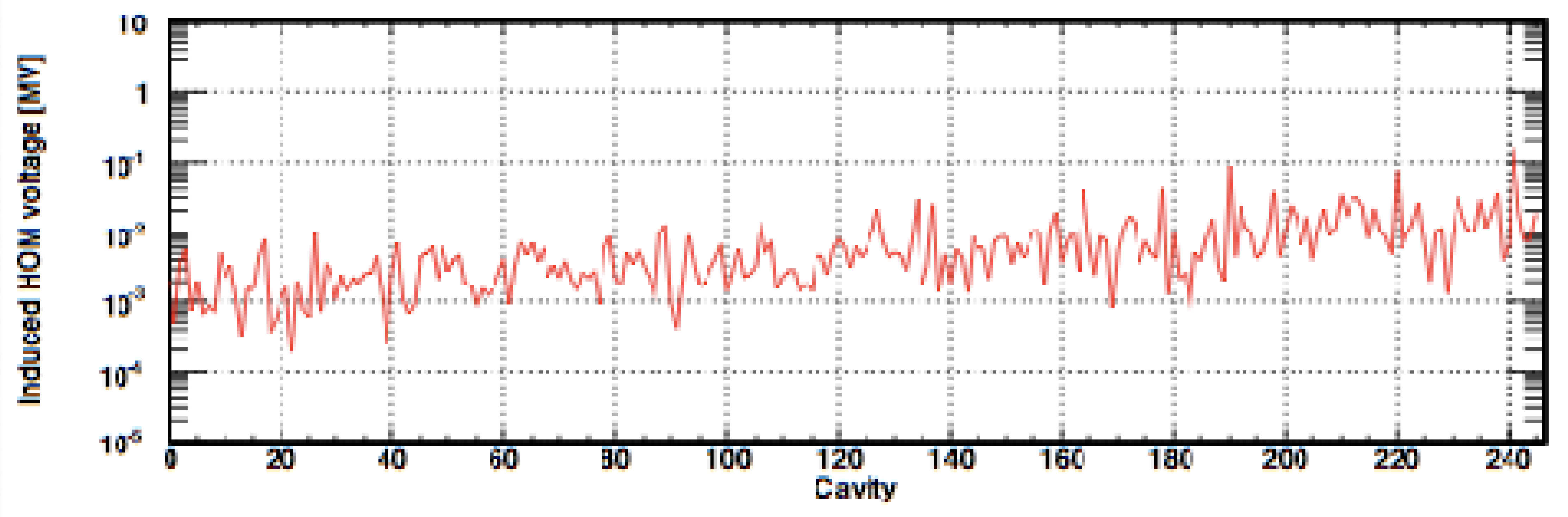


HOM voltage distribution (const R/Q)

Mono-pole:

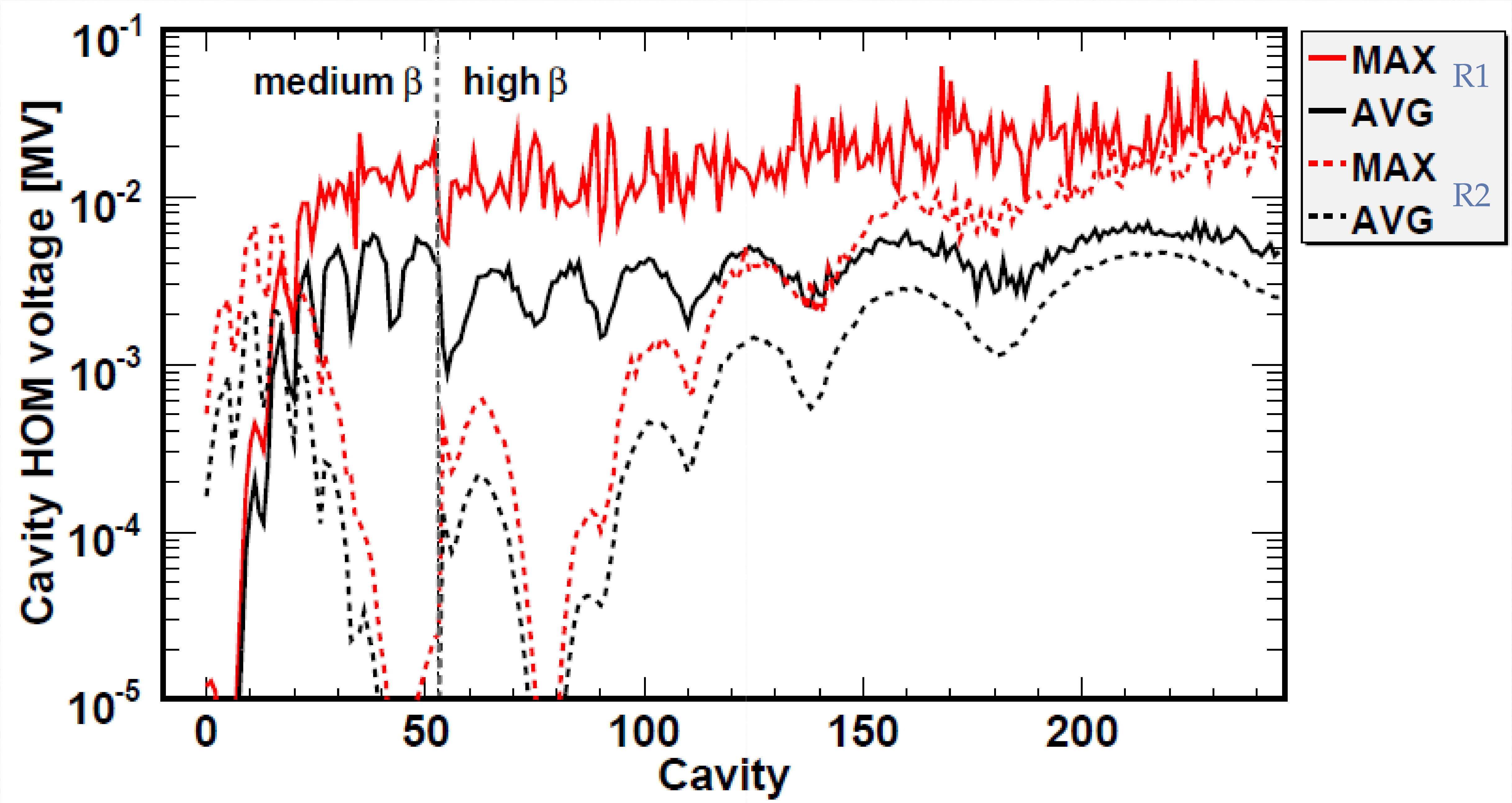


Dipole:



HOM voltage distribution ($R/Q_\perp(\beta)$)

Dipole mode – 1000 simulations: I_b=0.4A, Q_{ex}=10^7



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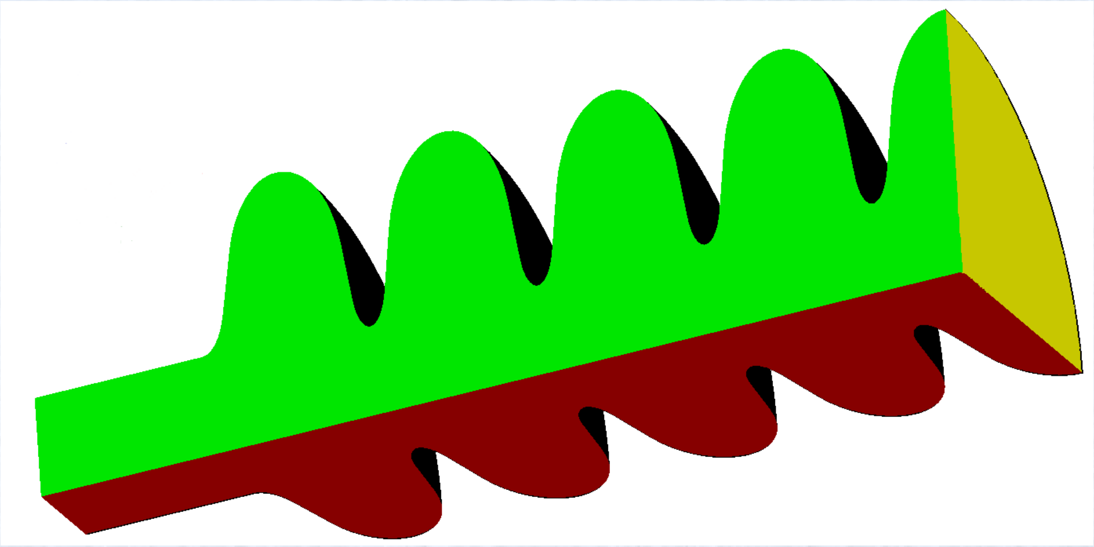
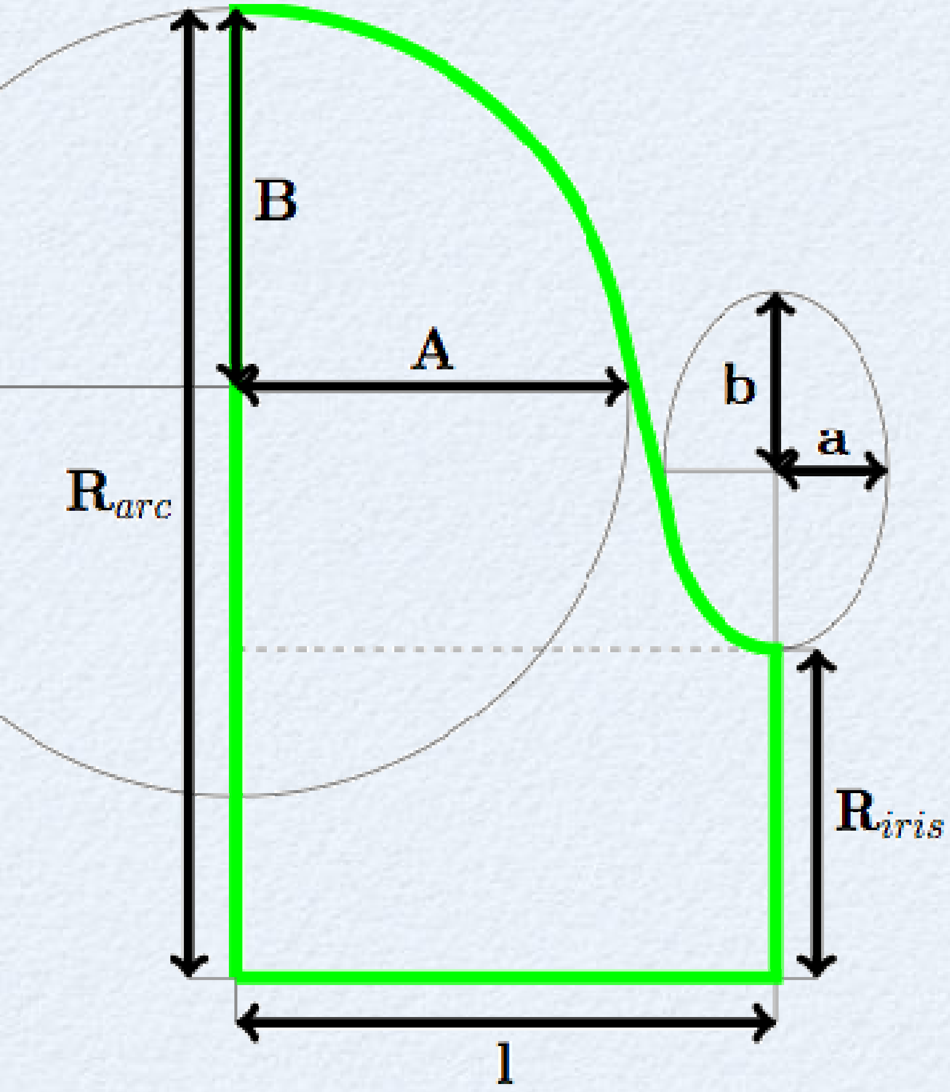
Cavity modeling

- 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

Preliminar

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