HOM issues in the ESS SC linac
Beam dynamics due to HOMs

Marcel Schuh

LABORATORY FOR APPLICATIONS OF COHERENT SYNCHROTRON RADIATION

Outline

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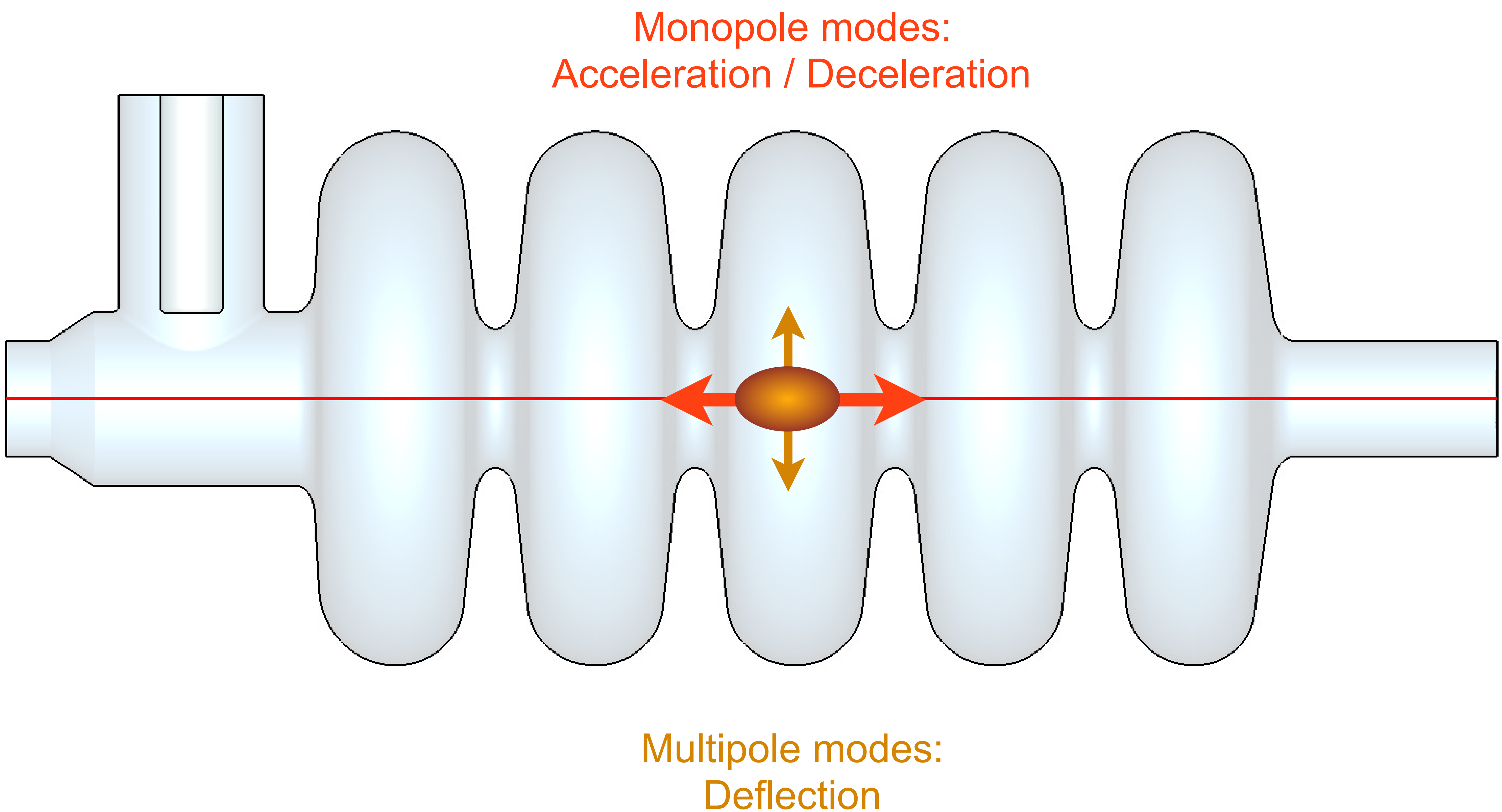
- Introduction: Beam - HOM interaction
- Important parameters based on different studies (SPL, SNS, ESS)
  - choice of the cavities's geometrical beta
  - mode frequency spread
  - resonances
- Power dissipation due to HOMs - probably more critical than the beam dynamics
- Conclusions

Effects of HOMs



Higher Order Modes - My Definition

- All modes beside the accelerating one
  - Typically the accelerating mode is the $TM_{010,\pi}$ - hence, there are modes below this mode in a multi-cell cavity
- Divide into monopole, dipole, ... according to the field profile
- Focus on monopole modes :
  - Protons travel with $\beta<1$ ➜ more sensitive to errors in longitudinal plane
  - Deflecting forces less efficient due to higher mass compared to electrons
  - Accelerator length small compared to planed e± colliders - influence of deflecting modes increases with the linac length

Mode characterization

- Type: TE, TM,...
- Frequency f_n
- Quality factor $Q_{0,n}$
- Damping $Q_{ex,n}$, Q_L
- R/Q(β)$_n$:
  - Monopoles:

$$(R/Q)_n(\beta) = \frac{\left| \int_{-\infty}^{\infty} E_{n,z}(r=0,z) \exp\left(i\omega_n \frac{z}{\beta c}\right) dz \right|^2}{\omega_n U_n}$$

  - Dipoles:

$$(R/Q)_{\perp,n}(\beta) = \frac{c^2}{x_0^2 \omega_n^2} \frac{\left| \int_{-\infty}^{\infty} E_{n,z}(r=x_0,z) \exp\left(i\omega_n \frac{z}{\beta c}\right) dz \right|^2}{\omega_n U_n}$$

Mode excitation

- Monopole modes
  - Induced Voltage (fundamental theorem of beam loading)

$$\Delta V_{\mathrm{q},n} = -q\frac{\omega_n}{2}\left(R/Q\right)_n(\beta)$$

  - Exponential voltage decay

$$T_{\mathrm{d},n} = \frac{2Q_{\mathrm{L},n}}{\omega_n} \approx \frac{2Q_{\mathrm{ex},n}}{\omega_n}$$

  - Sum over voltage taking into account phase, charge jitter
  - Half of the induced voltage act back on the same bunch
- Dipole modes
  - Only bunch of axis excite HOM

$$\Delta V_{\perp,\mathrm{q},n} = \frac{1}{2} ixq\frac{\omega_n^2}{c}(R/Q)_{\perp,n}(\beta)$$

Longitudinal Beam Dynamics

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- **Energy error change in cavity *m*:**

$$dE_{m+1} = dE_m + dU_{\mathrm{RF},m} + dU_{n,m}$$

$$dU_{n,m} = q\left(\Re(V_{n,m})\cos(\omega_{n,m}dt_m) - \Im(V_{n,m})\sin(\omega_{n,m}dt_m) + \frac{1}{2}\Delta V_{\mathrm{q},n,m}\right)$$

$$dU_{\mathrm{RF},m} = qV^*_{\mathrm{RF},m}\cdot\cos(\phi^*_{\mathrm{s},m} + \omega_{\mathrm{RF}}dt_m) - \Delta U_m \qquad \Delta U_m = qV_{0,m}\cos(\phi_{\mathrm{s},m})$$

- **Phase error change in cavity *m*:**

$$dt_{m+1} = dt_m + (dt/dE)_{\mathrm{E},m}\cdot dE_m$$

$$(dt/dE)_{\mathrm{E},m} = -\frac{L_m}{c\cdot m_0c^2\cdot(\gamma_m^2 - 1)^{3/2}}$$

ANKA THZ GROUP

Transverse Beam Dynamics

- **Transfer Matrix between cavities:**

$$\begin{pmatrix} x_{m+1} \\ x'_{m+1} \end{pmatrix} = \begin{pmatrix} \cos\left(L/\beta\right) & \beta\sin\left(L/\beta\right) \\ -\frac{1}{\beta}\sin\left(L/\beta\right) & \cos\left(L/\beta\right) \end{pmatrix} \cdot \begin{pmatrix} x_m \\ x'_m \end{pmatrix}$$

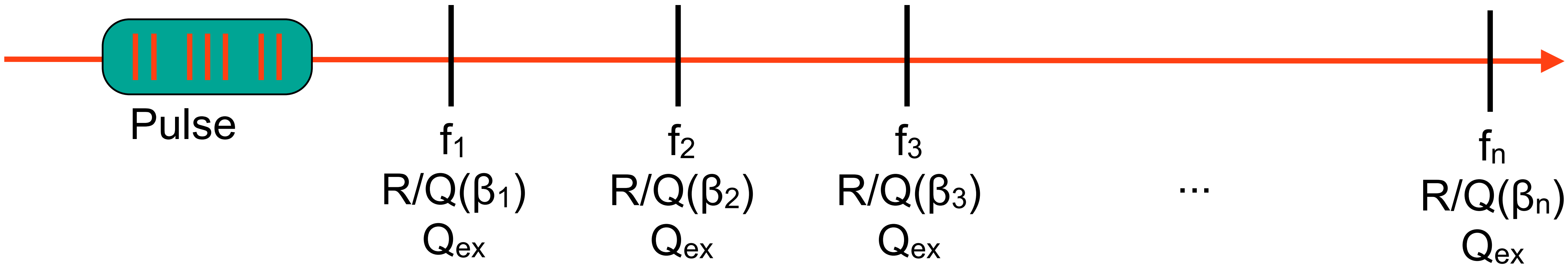
- **Bunch induce a imaginary voltage:**

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

- **HOM kicks bunch/particle - momentum change:**

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

Simulation of higher order mode Dynamics (SMD)



- **One HOM per cavity (monopole or dipole)**
- **Gaussian HOM frequency distribution**
- **$R/Q(\beta_{beam})$**
- **Set global Q_{ex} (Damping)**

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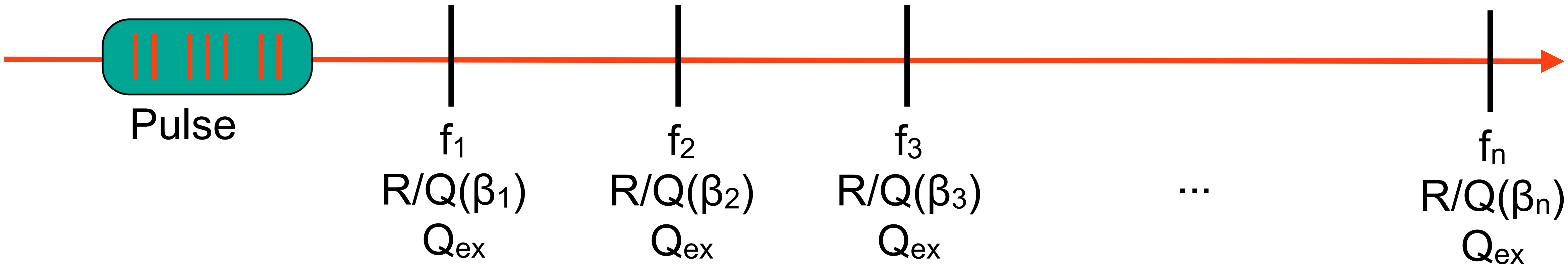

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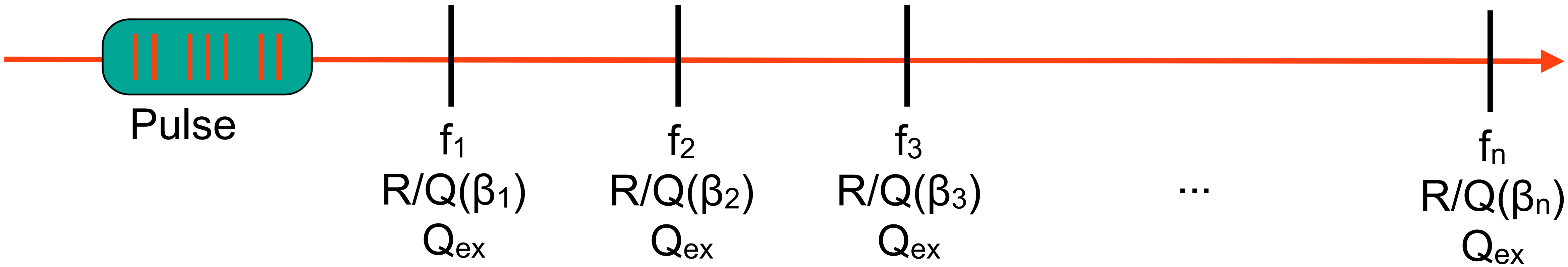

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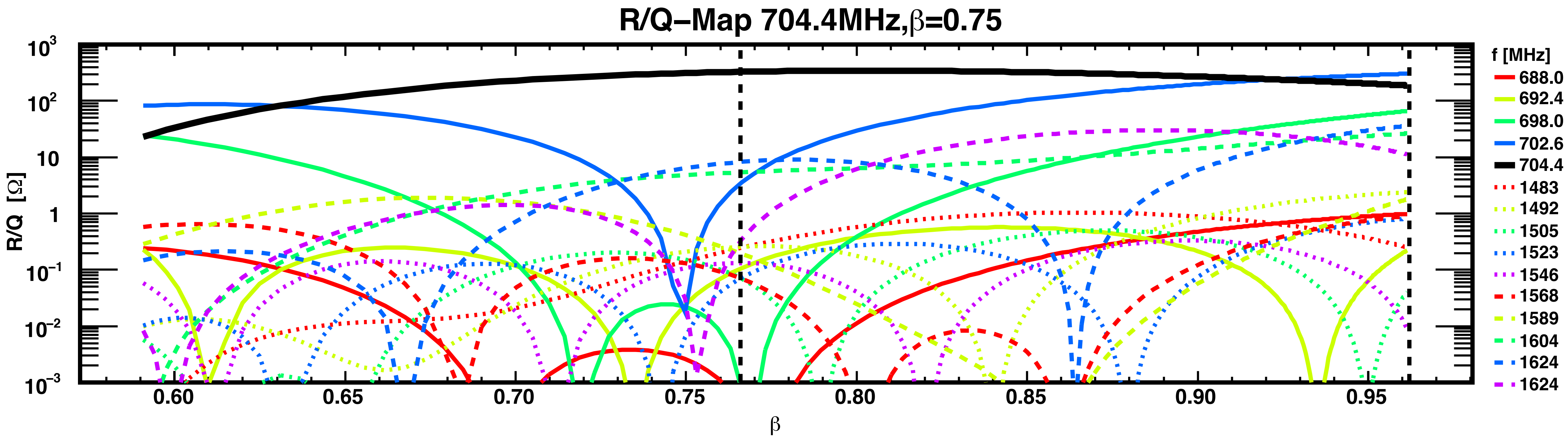
GOAL: Define upper limits for Q_{ex}

Simulation Input Data

- Linac layout (cavity spacing, V_{acc}(cavity), ϕ_s)
- Beam noise at injection
- HOM data
  - HOM frequencies
  - (R/Q)(β) map



Beam Dynamics Simulations
Studied effects

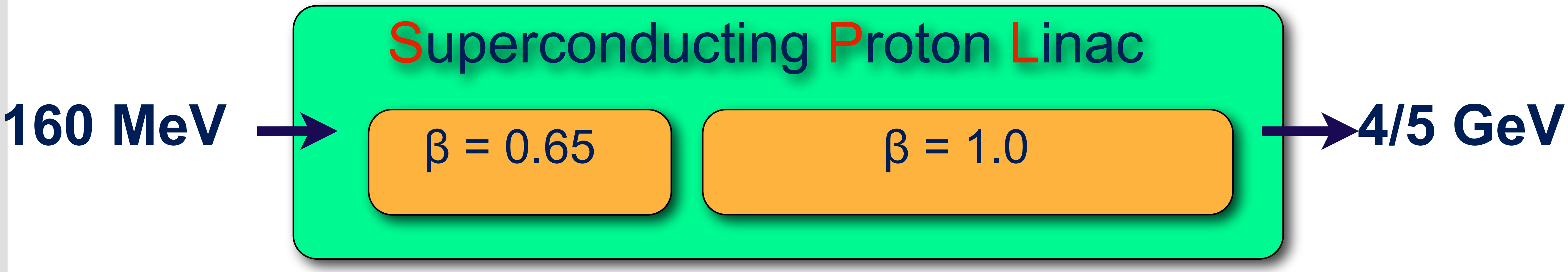
- High R/Q, I_b, as function of Q_{ex}
- HOM frequency spread
- Beam noise
  - Bunch to bunch charge scatter
  - Injection
- Resonances
- RF errors
- TM_{010} modes
- Alignment (transverse)
  - Injection position
  - Cavity alignment

▸ **Details see: Phys. Rev. ST Accel. Beams, 2011, 14, 051001**

The SPL R&D Project

Karlsruhe Institute of Technology

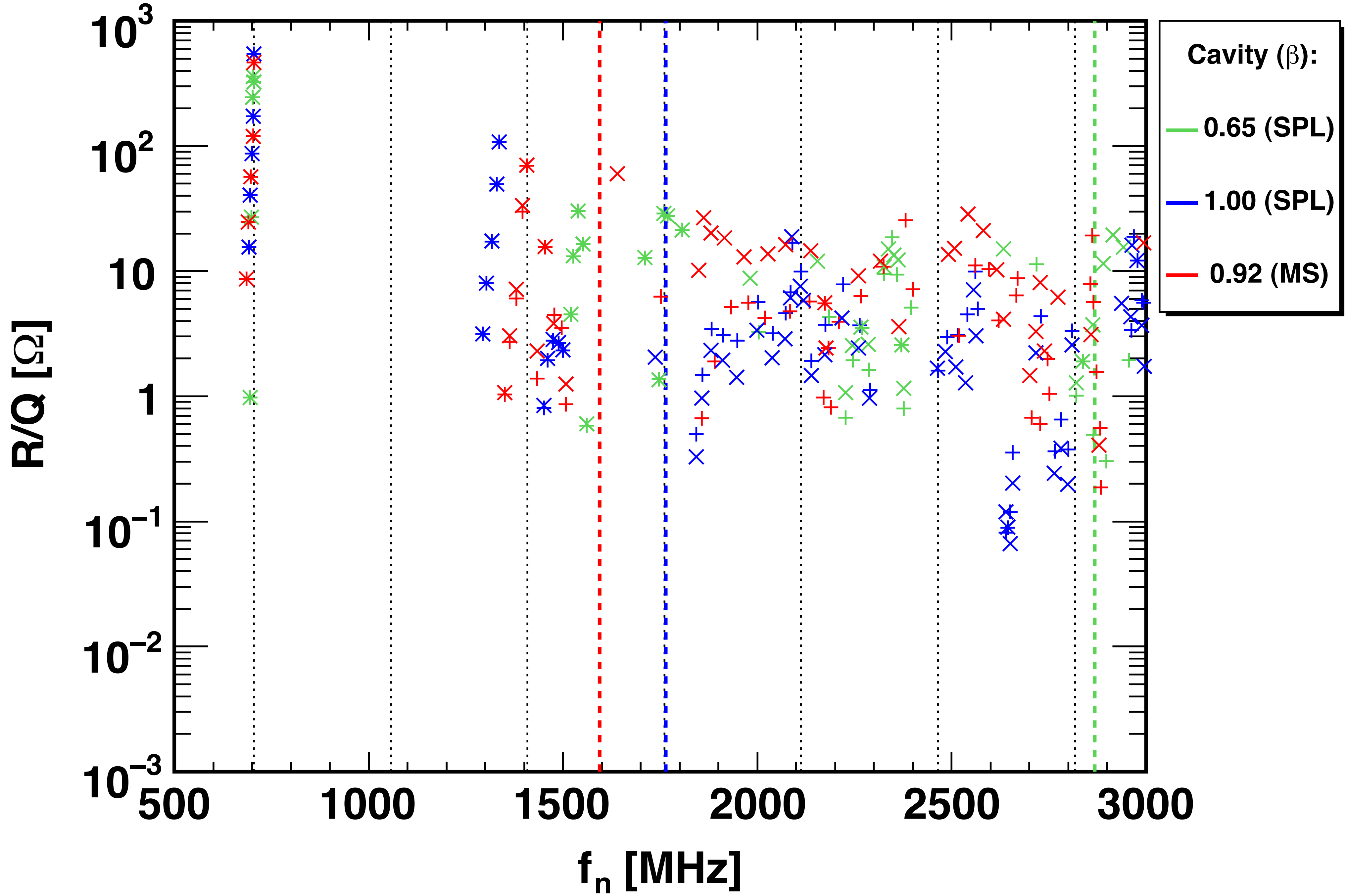
www.cern.ch/project-spl



General parameters	
Beam power [MW]	4
Beam current [mA]	20 - 40
Pulse length [ms]	≤ 1.0
Rep. frequency [Hz]	50
Physical length [m]	~500

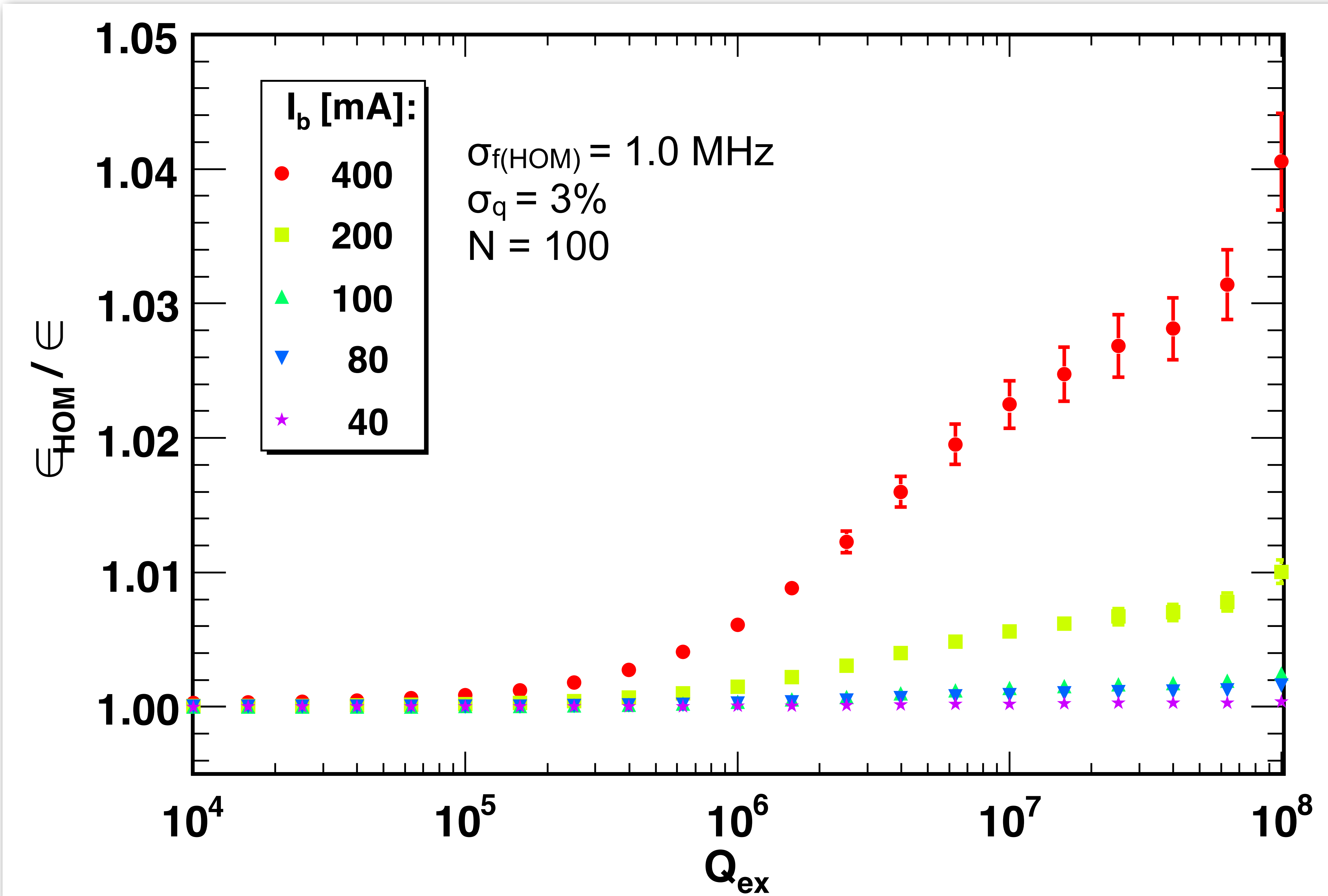
Cavity parameters	$\beta_g = 0.65$	$\beta_g = 1.0$
Operation Frequency [MHz]	704.4	704.4
Cells per cavity	5	5
Design gradient @ β_g [MV/m]	19	25
R/Q(β_g) [linac Ω]	320	560
Cavities installed (5 GeV)	~54	~192

R/Q(β)max Monopoles



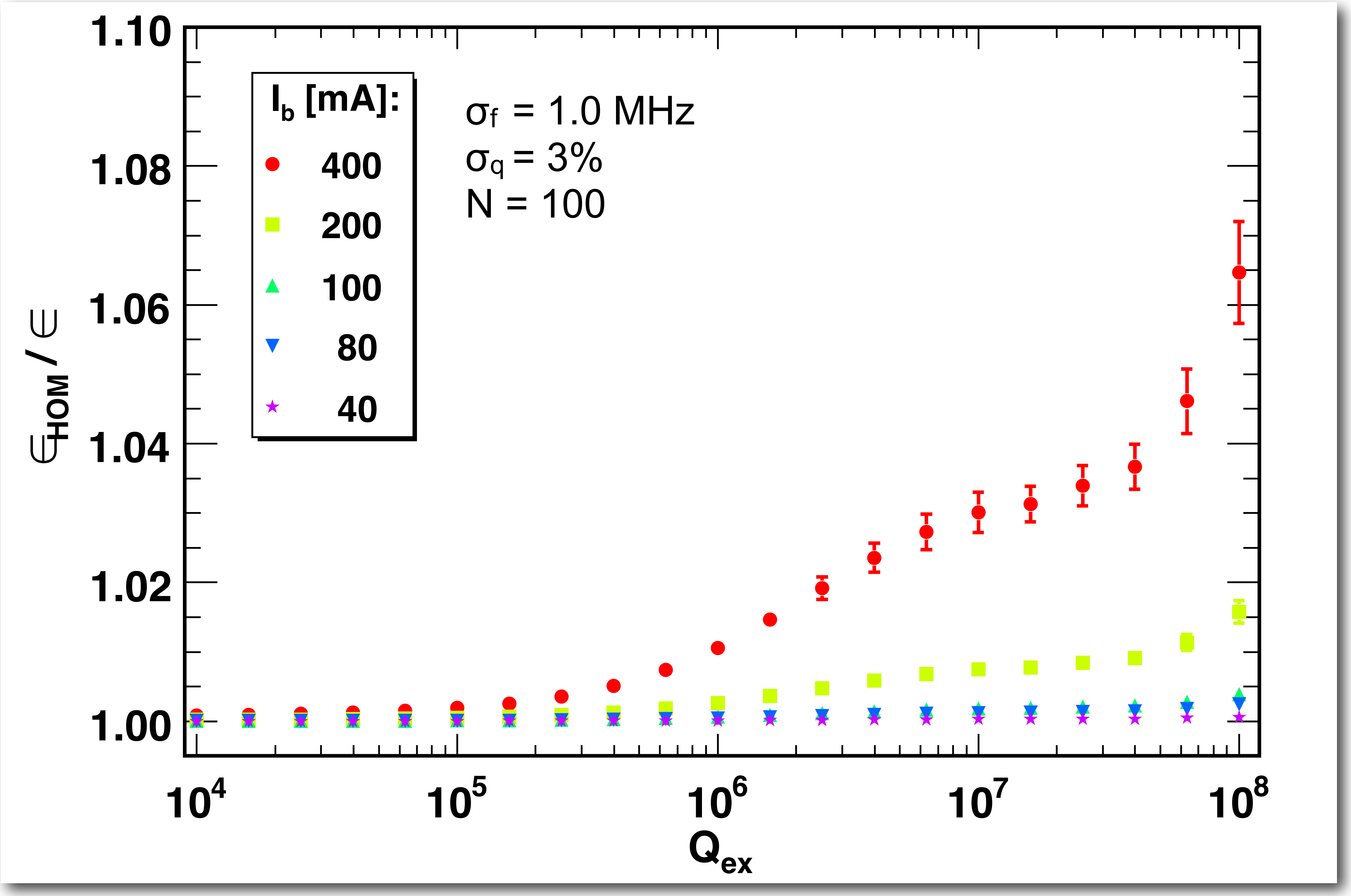
Longitudinal: SPL example

$$\epsilon = \pi\sqrt{\langle dE^2\rangle\langle d\phi^2\rangle - \langle dE d\phi\rangle^2}$$



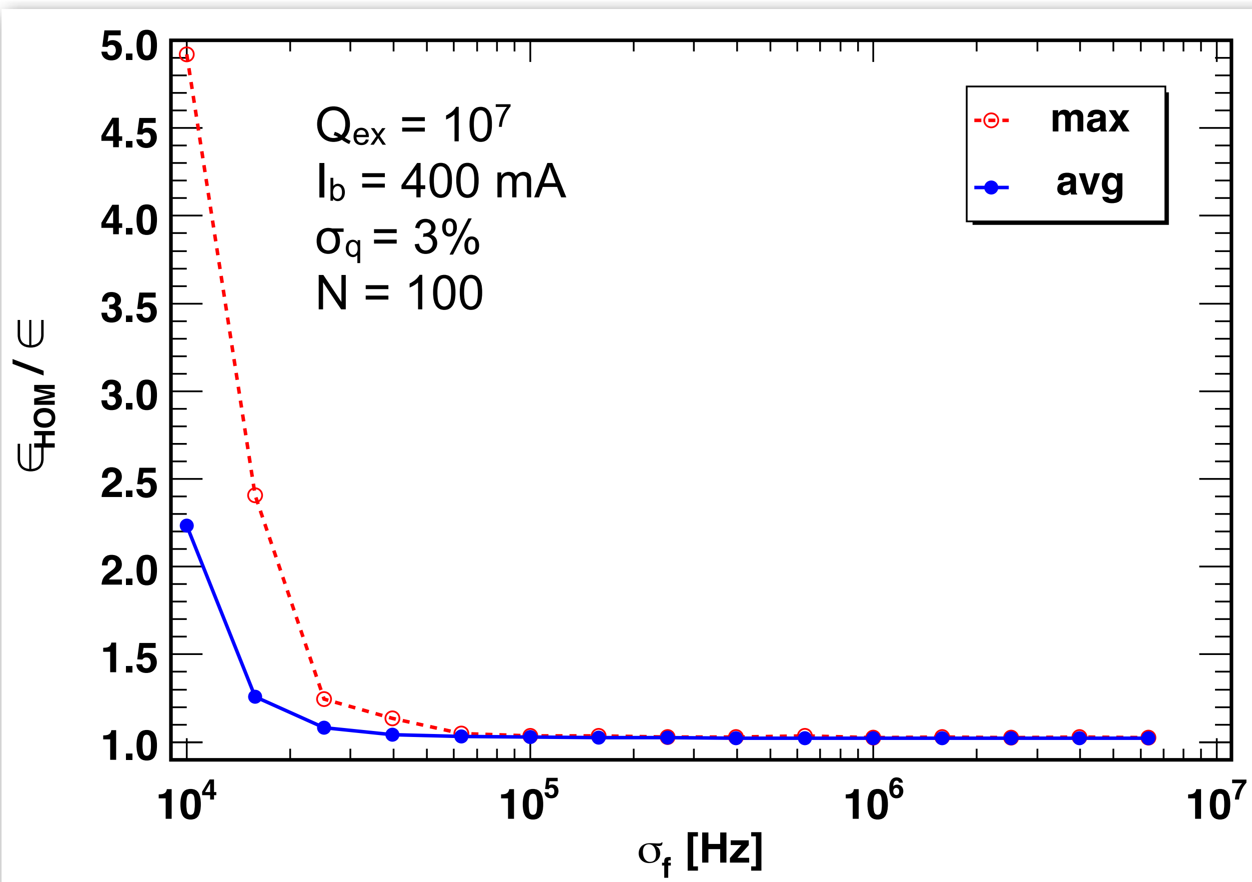
Transversal: SPL example

$$\epsilon = \pi\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

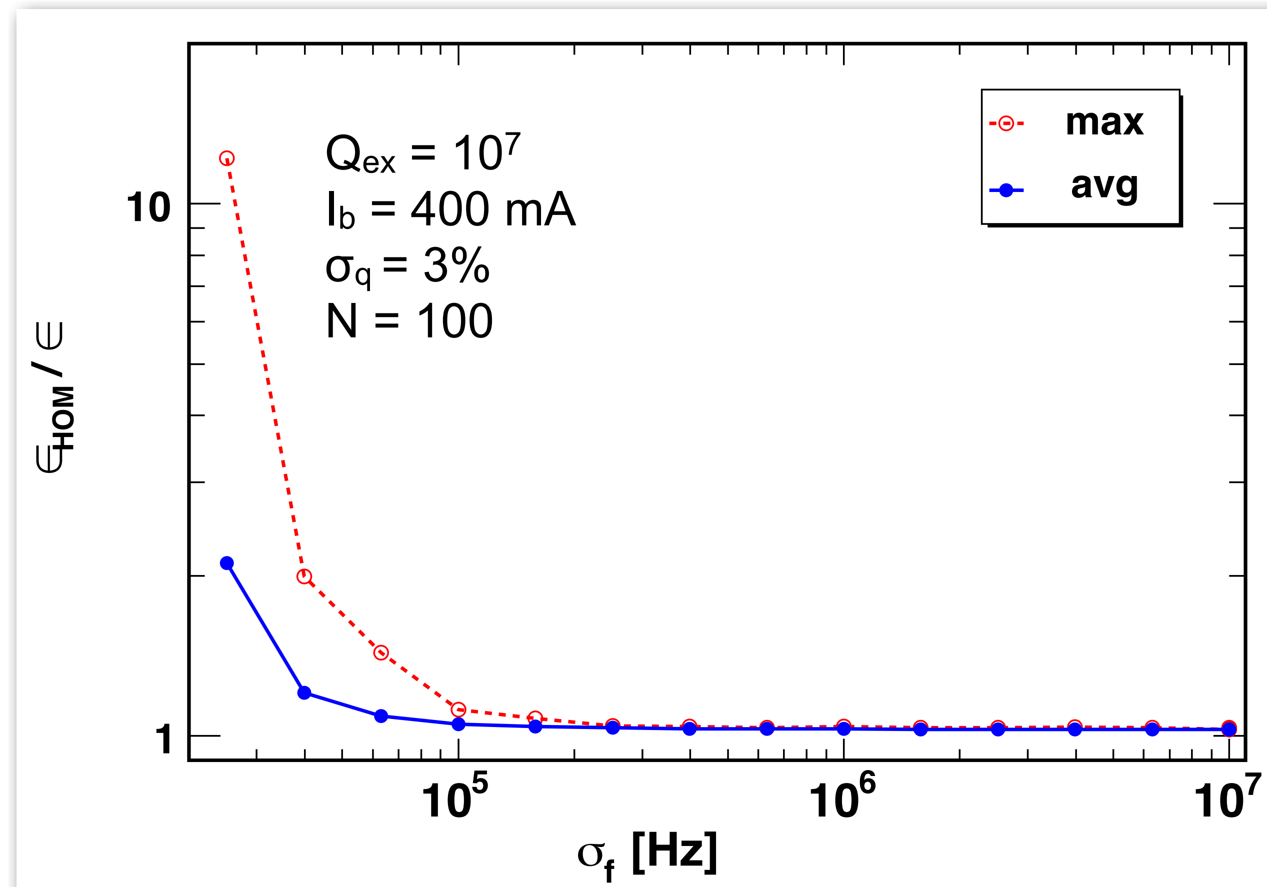


HOM frequency spread (SPL)

Longitudinal



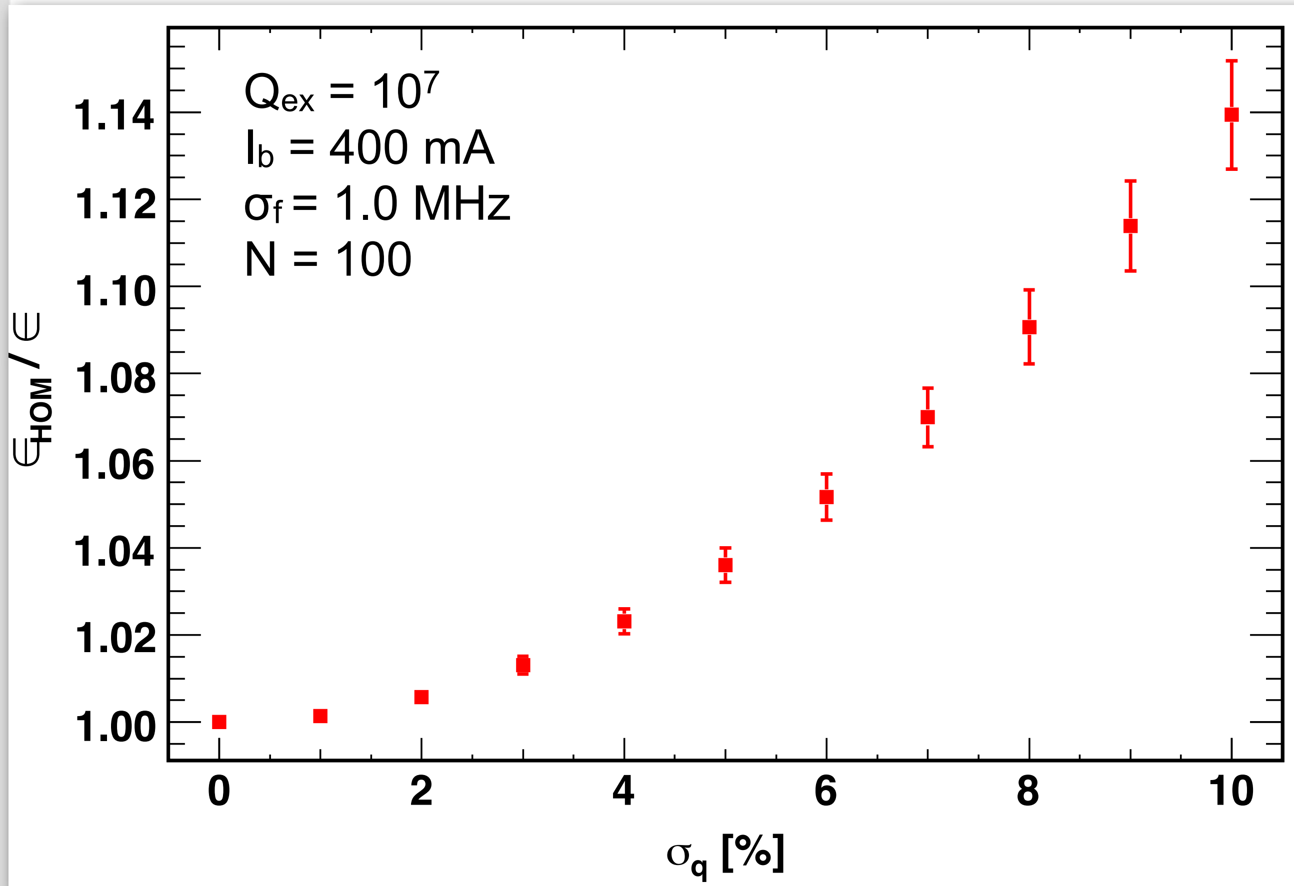
Transversal



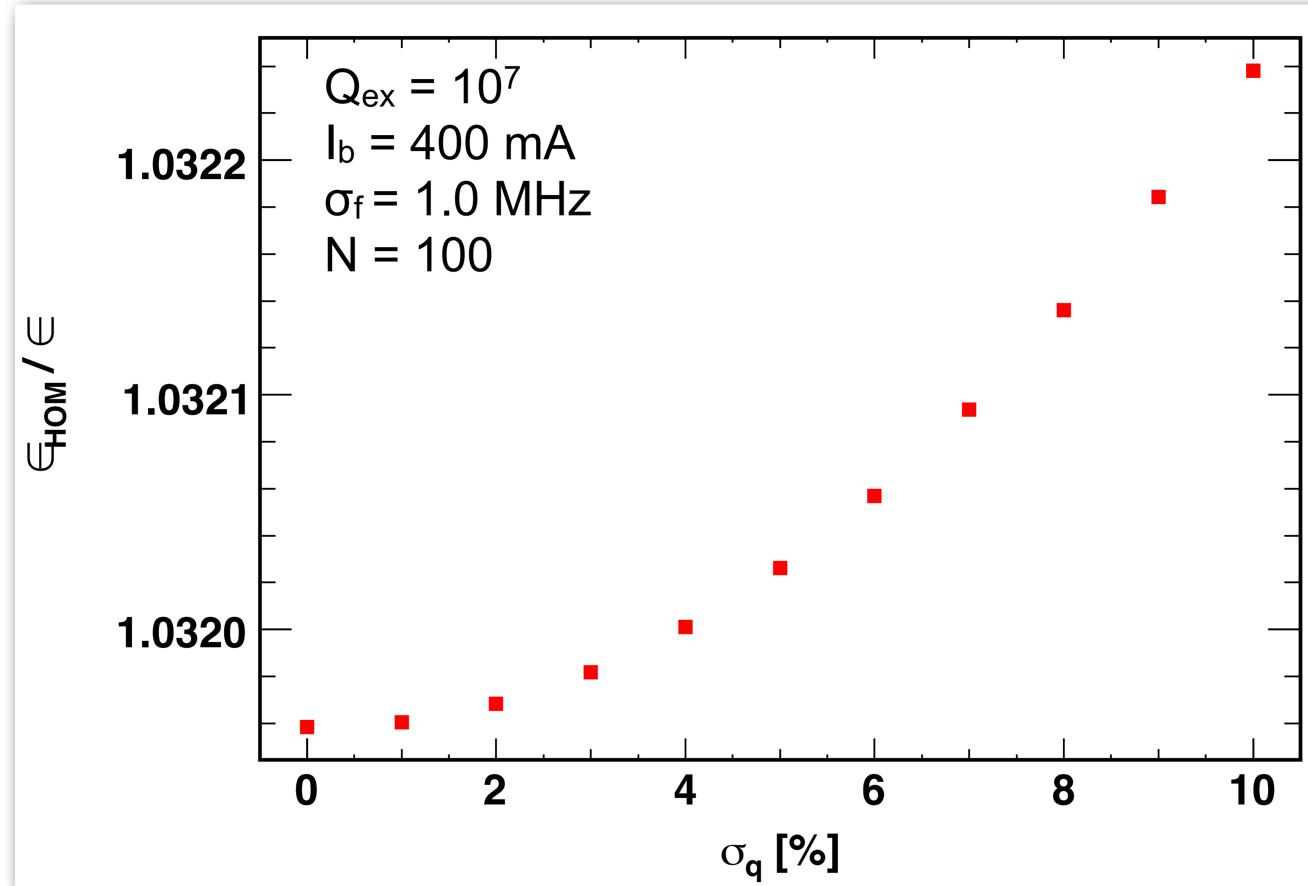
- Higher HOM frequency spread decreases growth

Bunch Charge Scatter (SPL)

Longitudinal

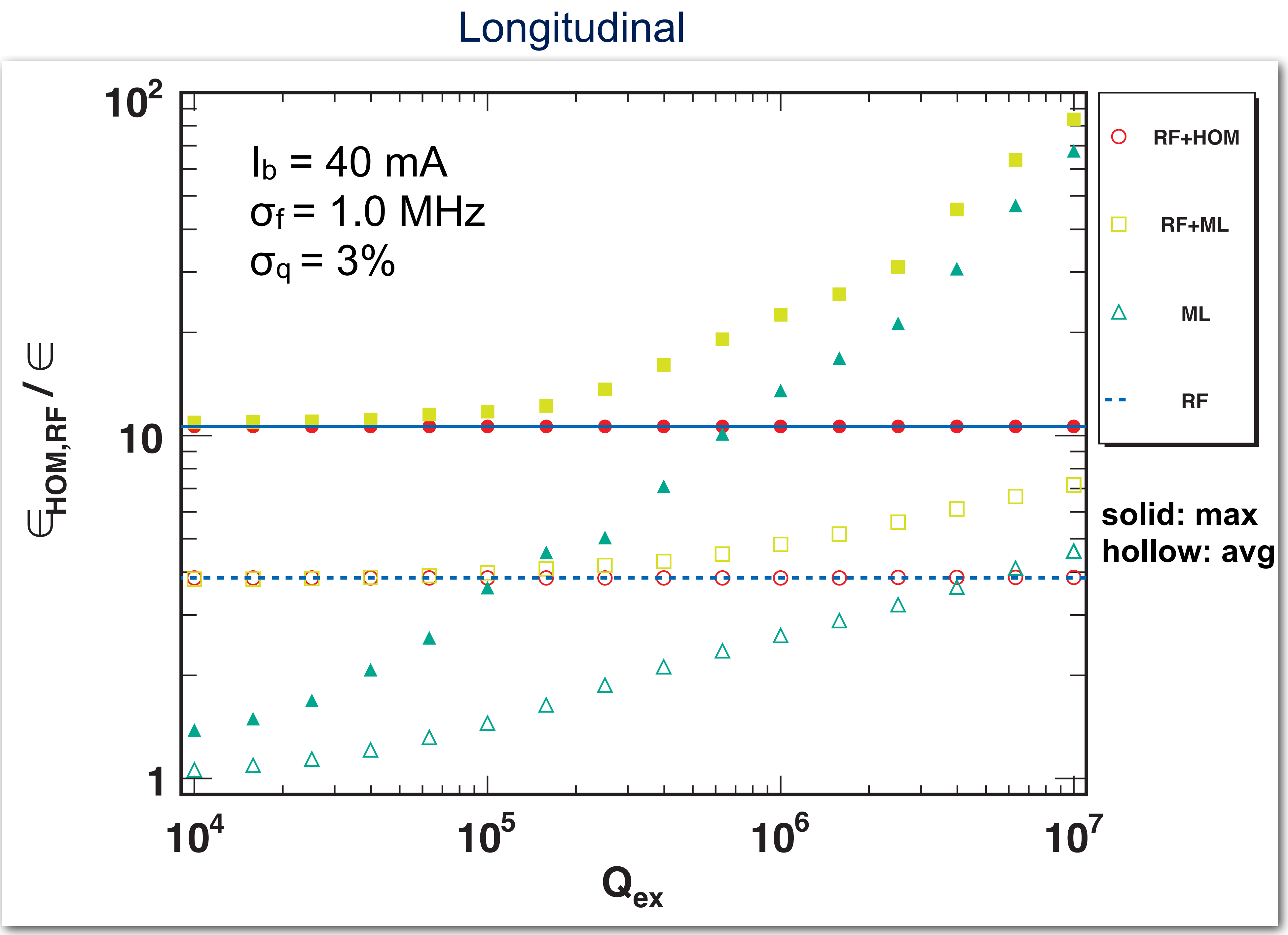


Transversal



- Bunch charge scatter drives HOM in longitudinal plane

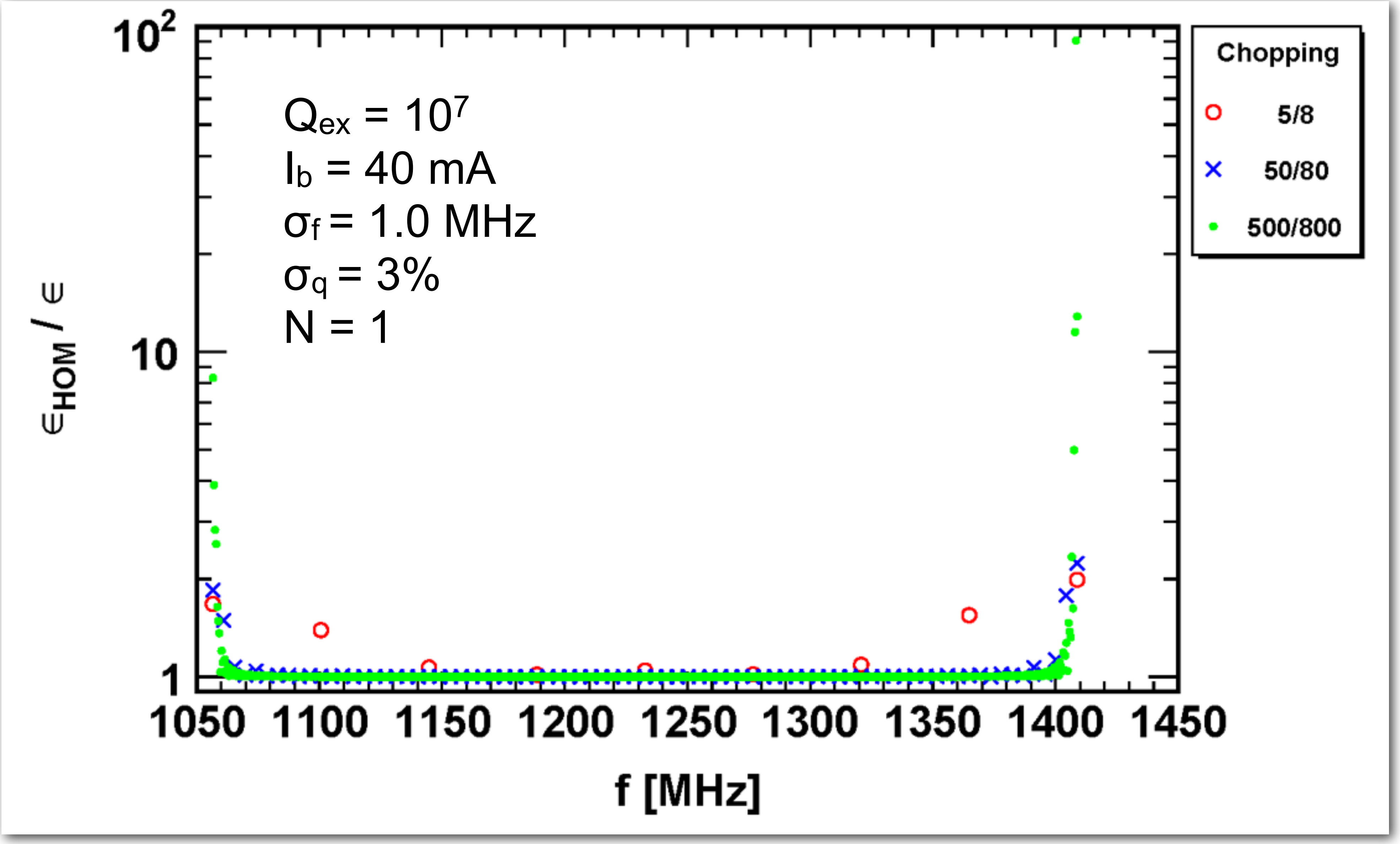
Machine Lines (SPL)



- Use RF-Errors as reference to judge impact of HOM

Chopping - Longitudinal

- New machine lines, created by the pulse substructure
- Can resonantly excite HOMs



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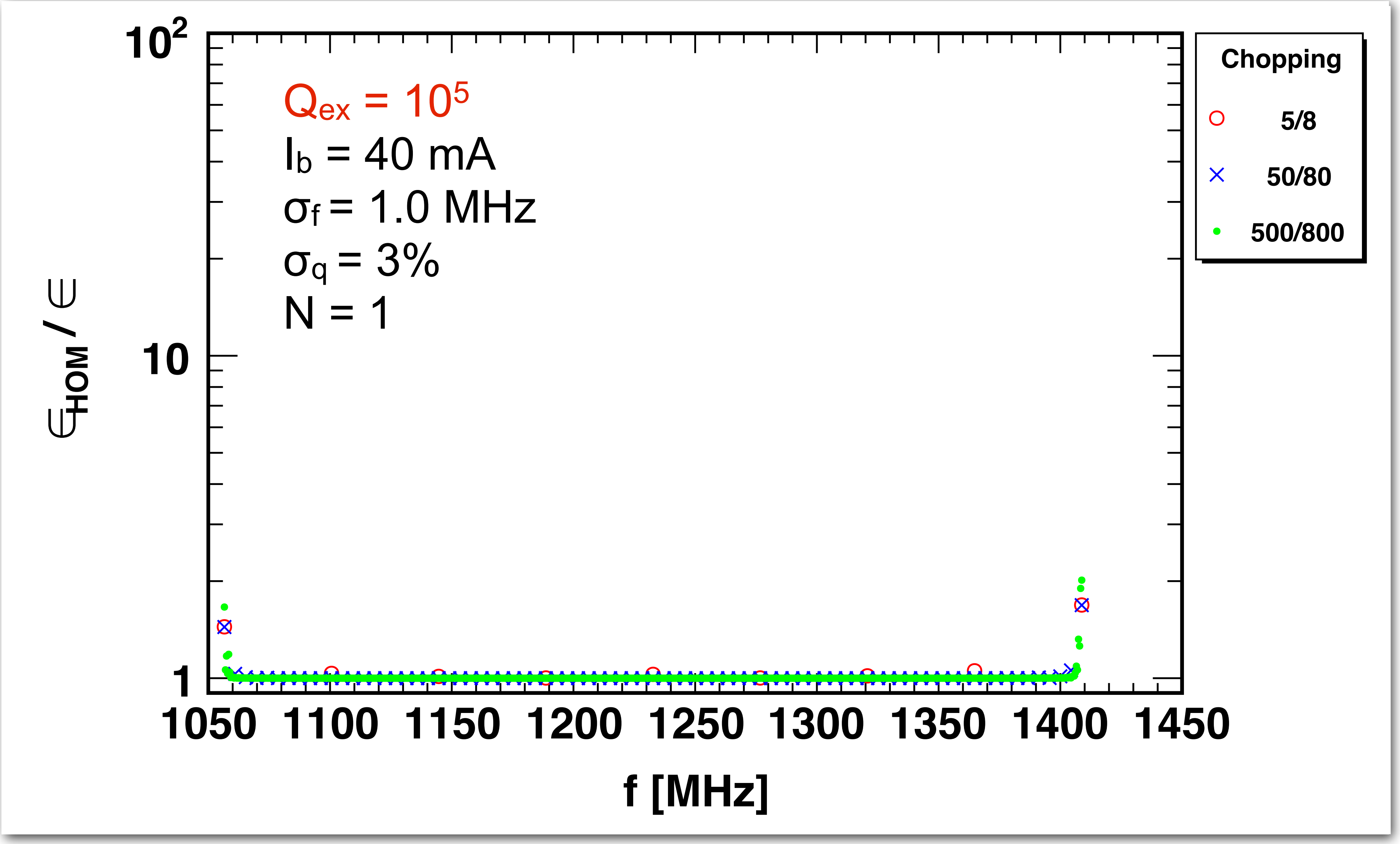

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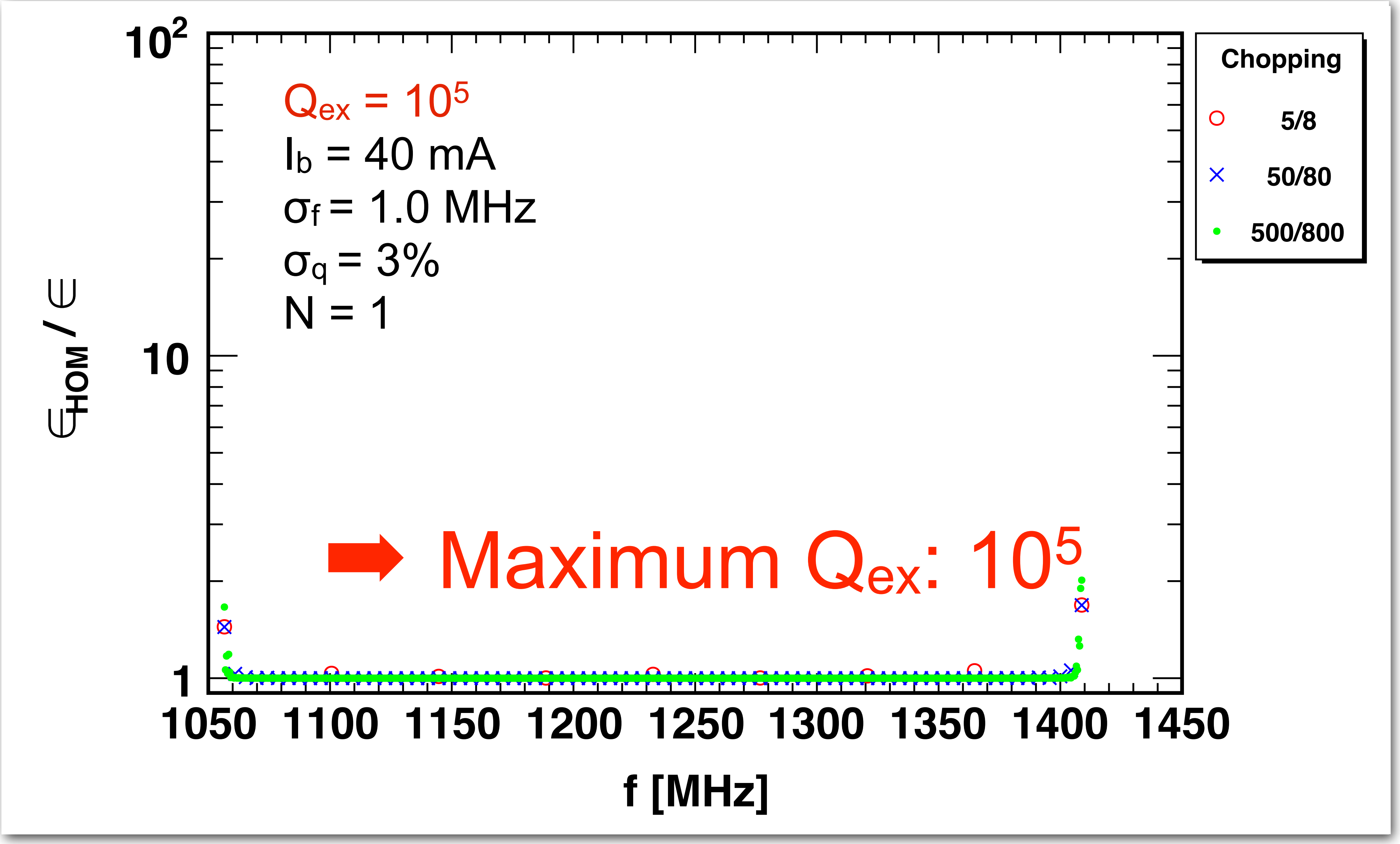
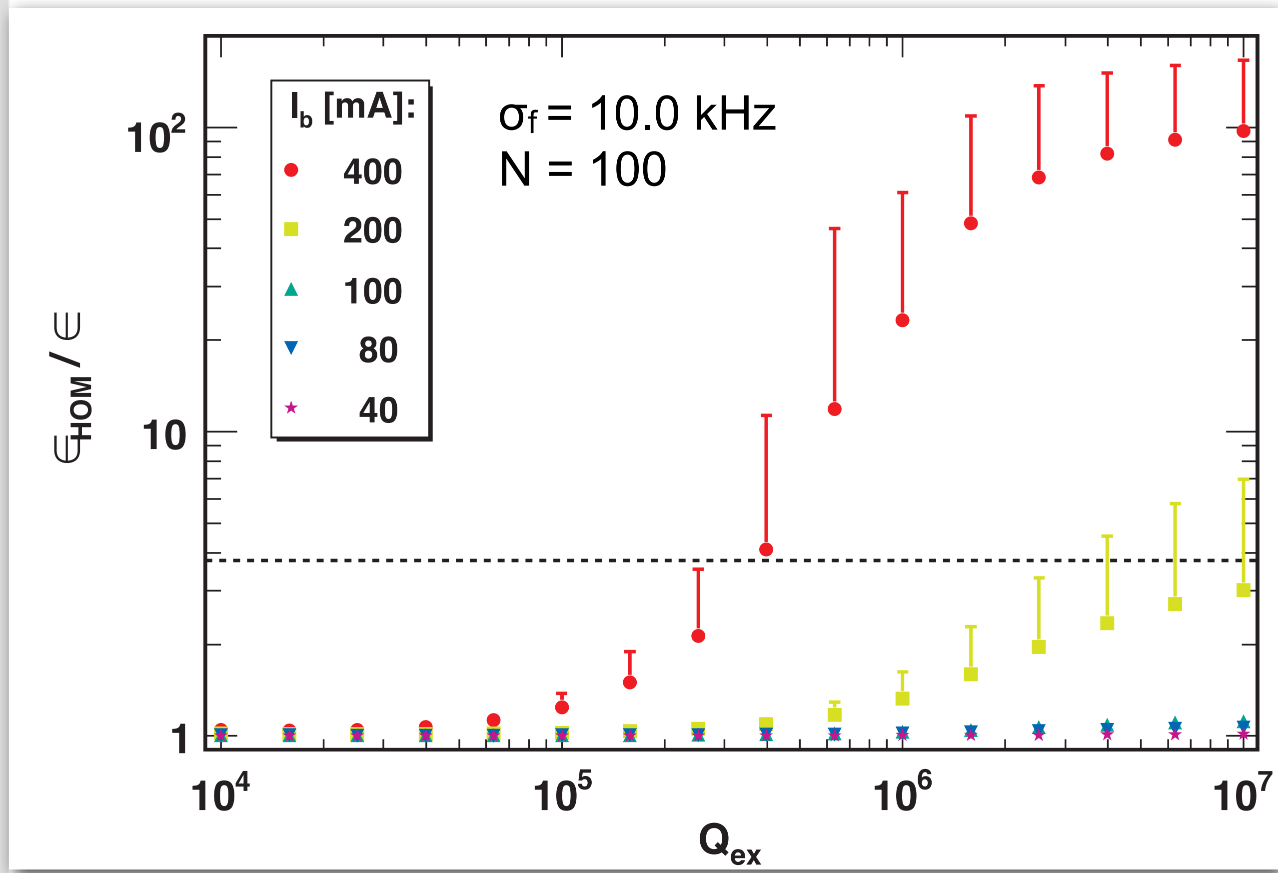
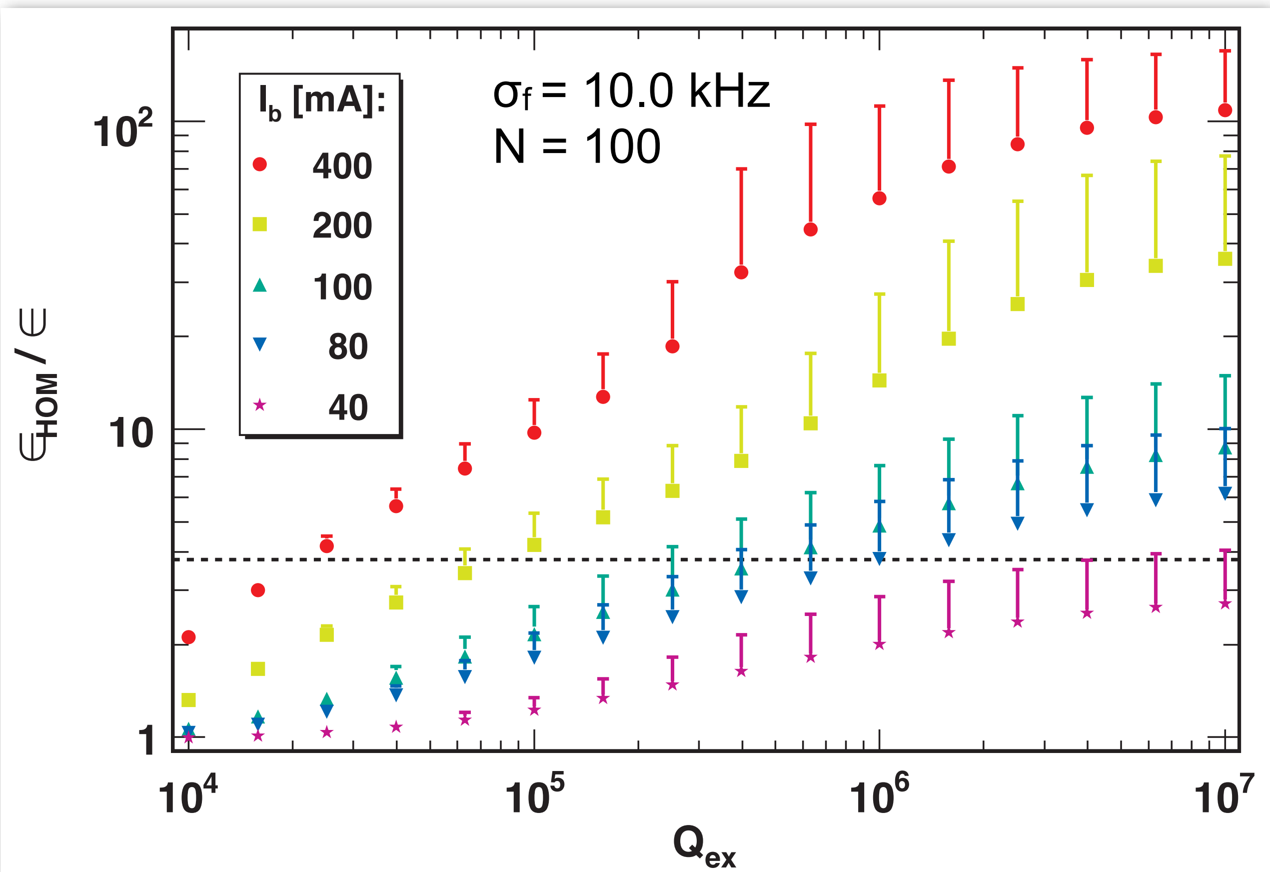


Passband modes

TM_{010},4/5π



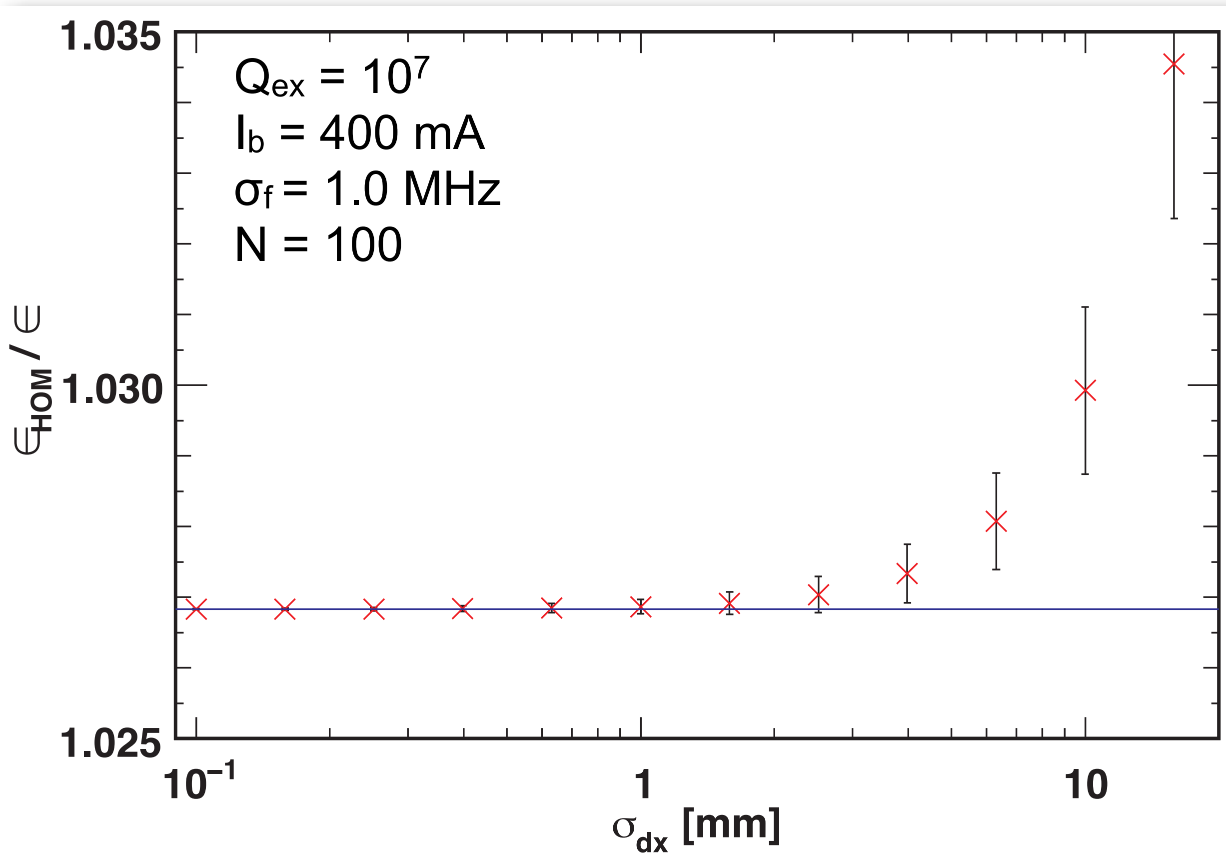
TM_{010},3/5π (chopping)



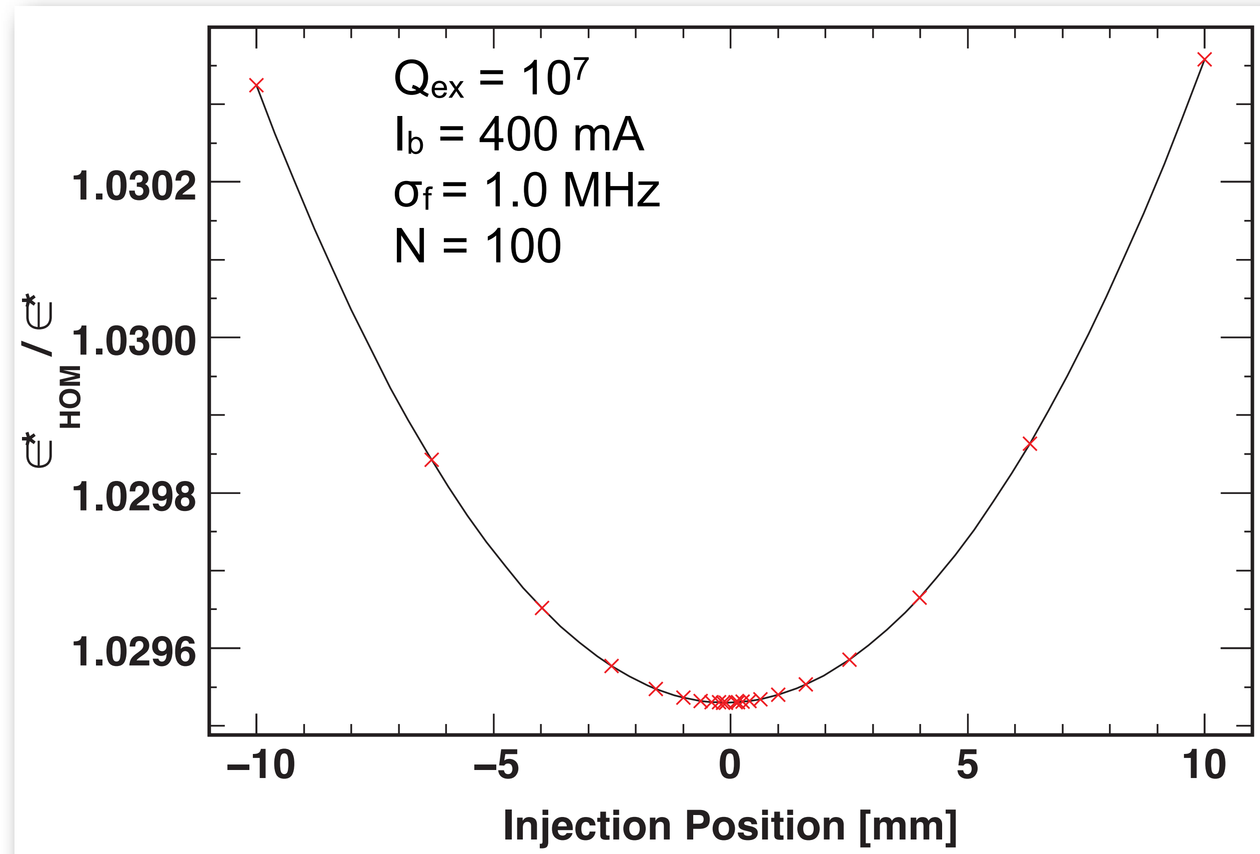
- Passband modes can drive instabilities at high currents or if they get resonantly excited

Transverse alignment

Cavity alignment



Injection position



- **Not a concern in the used simulation model**

Impact of different effects
SPL case study

Effect	Longitudinal	Transversal
HOM Frequency Spread	↘ (>100kHz)	↘ (>1MHz)
Machine Lines	↗	→
I·R/Q	↗	↗
Charge Scatter	↗	→
Chopping	↗	↗ (bunch charge)
Passband Modes	↗ (Chopping)	-
RF-Errors	→	-
Alignment Errors	-	→

➡ Maximum Q_{ex} between 10^4 and 10^7 dependent on the operation mode (chopping)

Differences SPL, SNS & ESS

Parameter	SNS	SPL	ESS
Beam power [MW]	1,44	~4	5
Output E_{kin} [GeV]	1	4-5	2.5
Beam current [mA]	26	20 - 40	50
Pulse length [ms]	1	0.4 - 0.8	2.86
Pulse substructure	yes	yes (high freq.)	no
Cavity freq. [MHz]	805	704,4	704,4
Pulse rep. [Hz]	60	50	14
β_g	0.61/0.81	0.65/1.0	0.7/0.9
Cells	6/6	5/5	5/5
$E_0T(\beta_g)$	10.1/15.8	19.3/25	~15(?)/~18.1
Lenght Ell. Cav Sec. [m]	~160	~525	~300

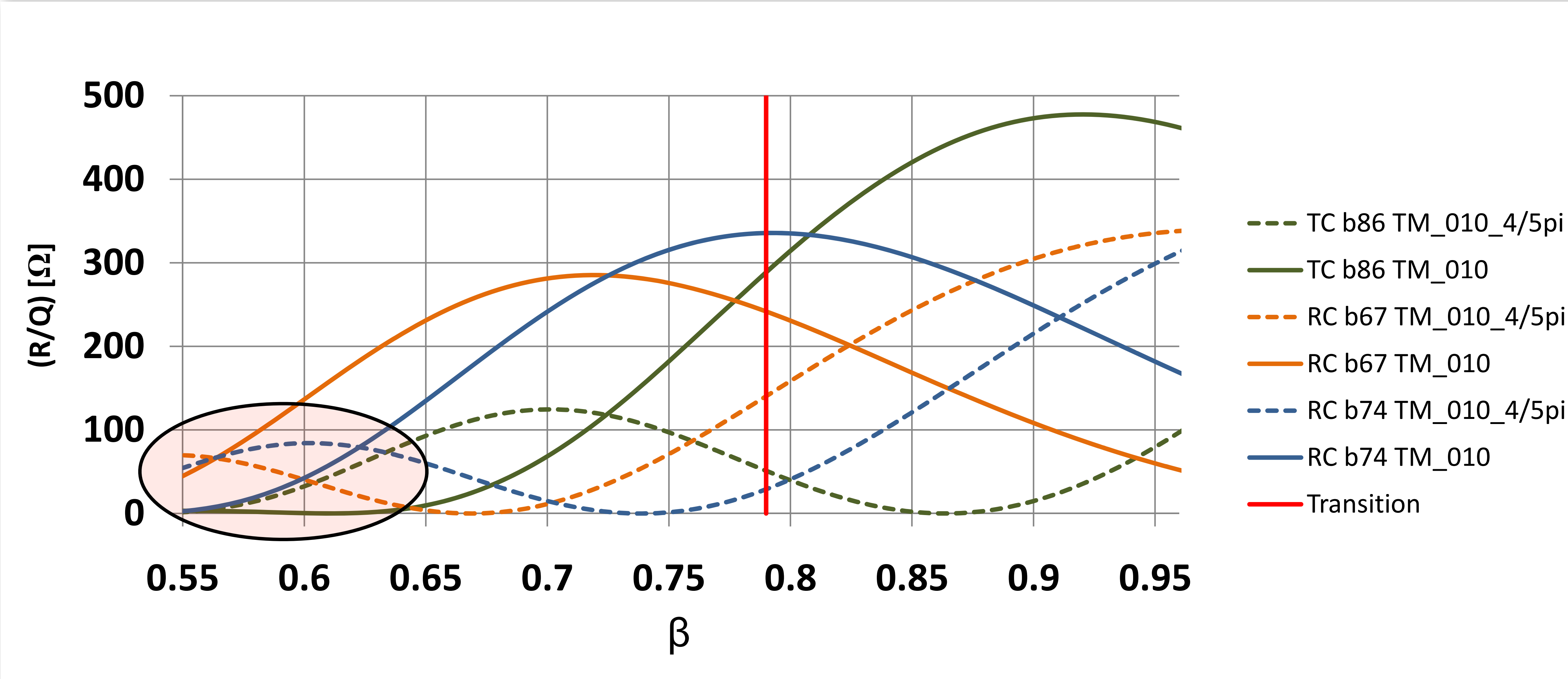
To be studied in ESS linac

- Passband modes, especially $TM_{010,4/5\pi}$ mode - to be considered in choice of geometrical beta
- Resonances - only fundamental machines (integer multiples of the bunch frequency) lines are a concern
- Effect of long pulses (higher HOM voltage can build up)
  - Power dissipation
- Beam noise is to weak to drive instabilities - assuming same values as SPL

- Problems at the moment
  - No cavity design of the proposed geometrical beta is available
  - HOM frequencies and R/Q values have to be estimated
  - No dedicated beam dynamics simulations carried out so fare

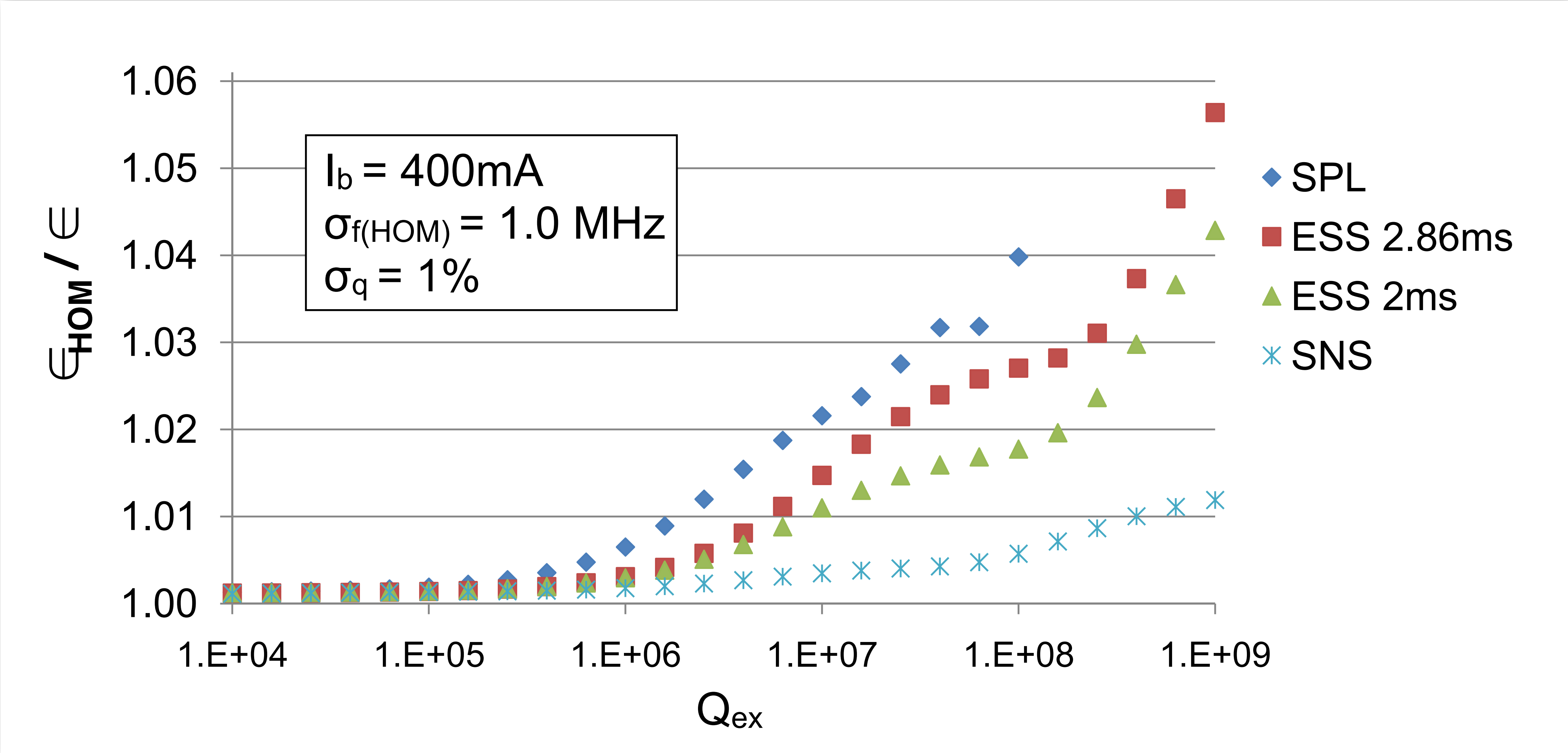
- Analytic studies based on the experience with SPL study...

Passband modes



- High R/Q values at injection could cause instabilites
- Lower β_g is preferable in medium beta section

Longitudinal: Mode with high R/Q, not resonant



- ESS linac with old layout and cavities - used in frequency review meeting
- R/Q_{max} of test cavity a factor two higher

Power dissipation

- Average Power dissipation:

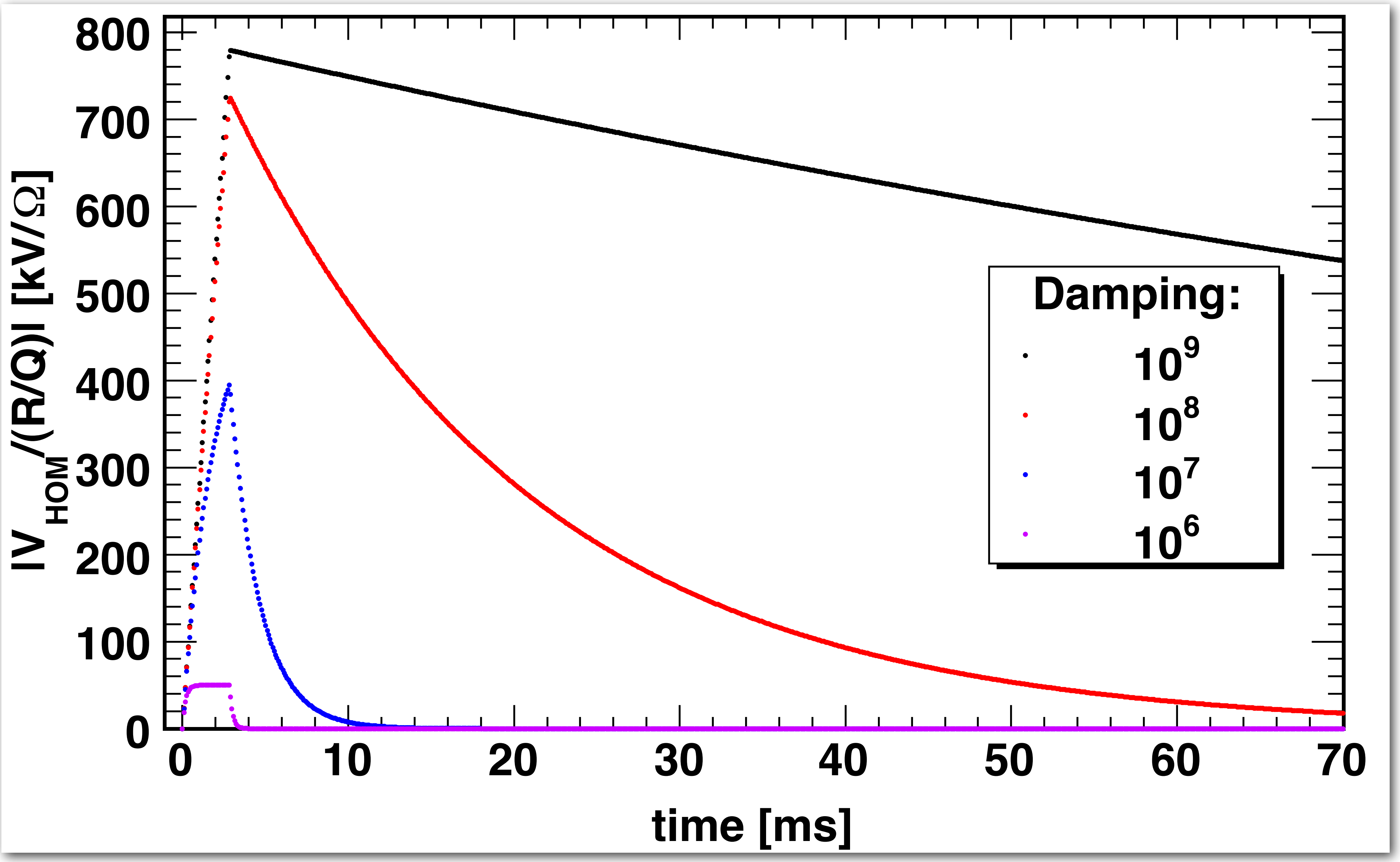
$$\langle P_{\mathrm{ex},n} \rangle = \frac{1}{T_\mathrm{p}(R/Q)_n Q_{\mathrm{ex},n}} \int_{t_1}^{t_1+T_\mathrm{p}} |V_n(t)|^2 \, dt$$

- Analytic formulae for HOM voltage (no noise considered)

$$V_{\mathrm{p},n} = \Delta V_{\mathrm{q},n} \prod_{j=0}^{M} \frac{1-\exp\left(-k_j T_j/T_\mathrm{d} + i k_j \omega_n T_j\right)}{1-\exp\left(-T_j/T_\mathrm{d} + i\omega_n T_j\right)}$$

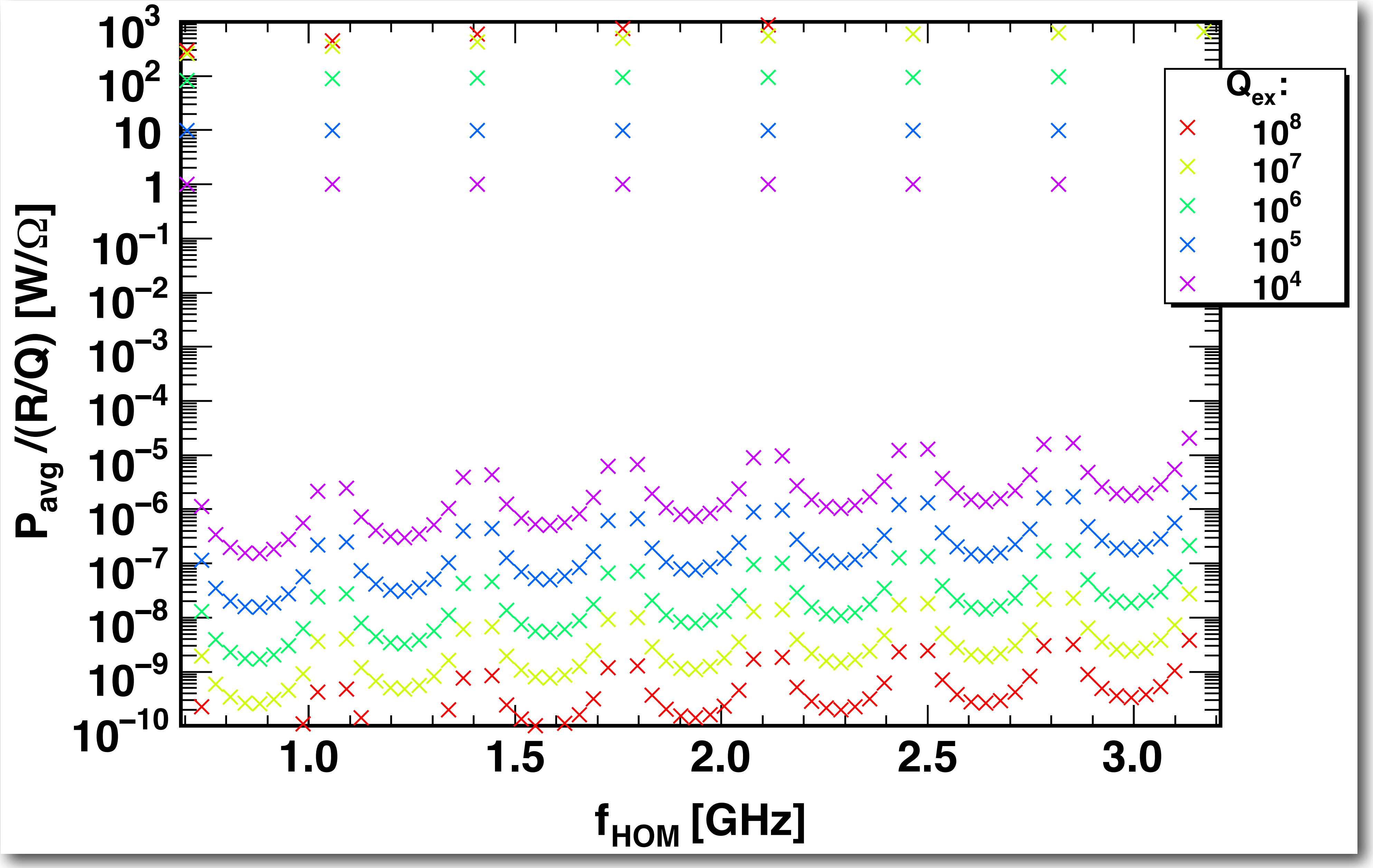
- Most power is dissipated in load
- Dissipated power scales
  - linear with R/Q
  - linear with frequency
  - quadratic with I_b

Resonant HOM voltage growth



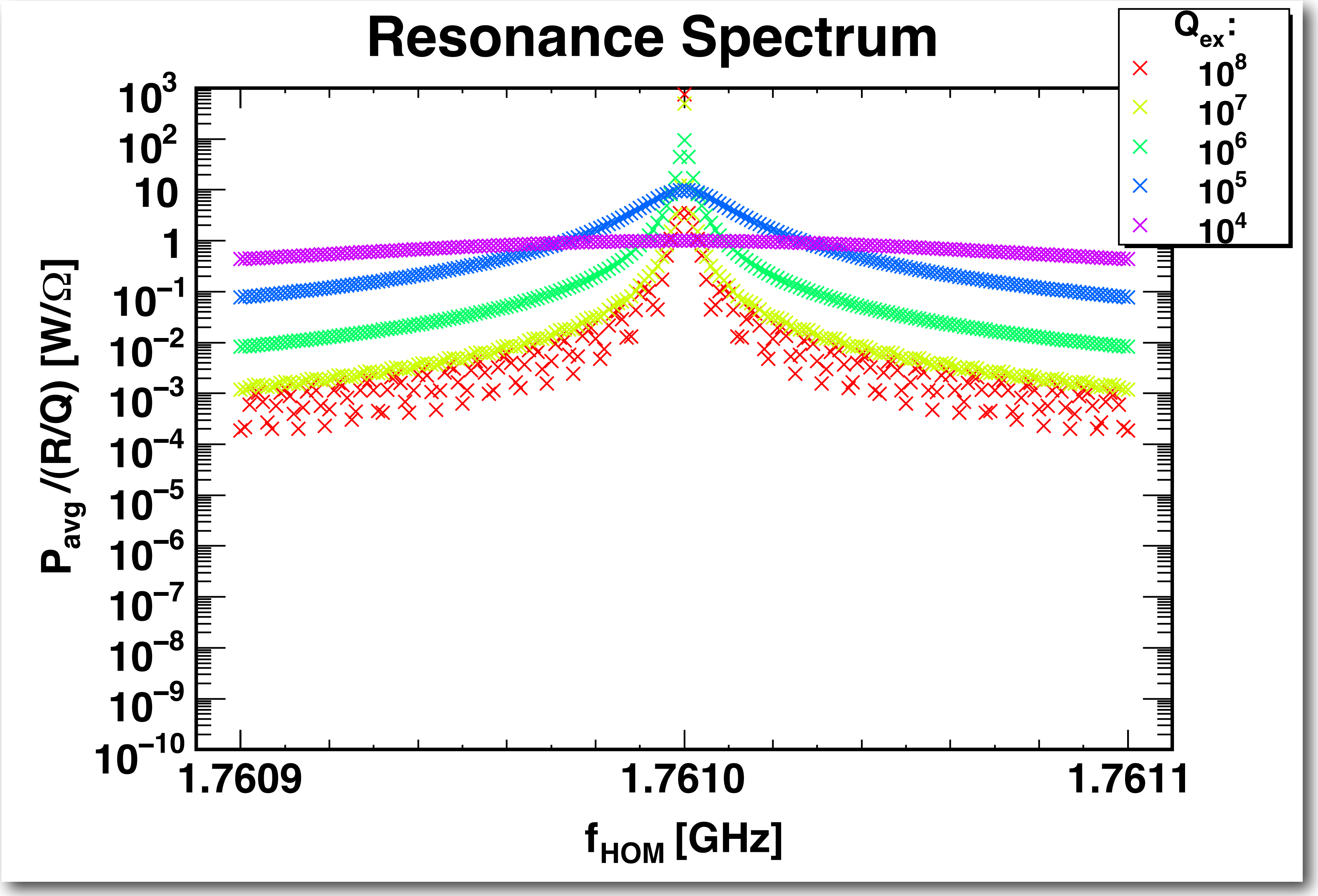
- RF voltage error about 100kV → $(R/Q) \cdot Q_{ex} \sim 10^6$ in case of resonant excitation

Power dissipation spectrum



- Power dissipation is only high at a resonance

Power dissipation close to a resonance



- Sharp resonance

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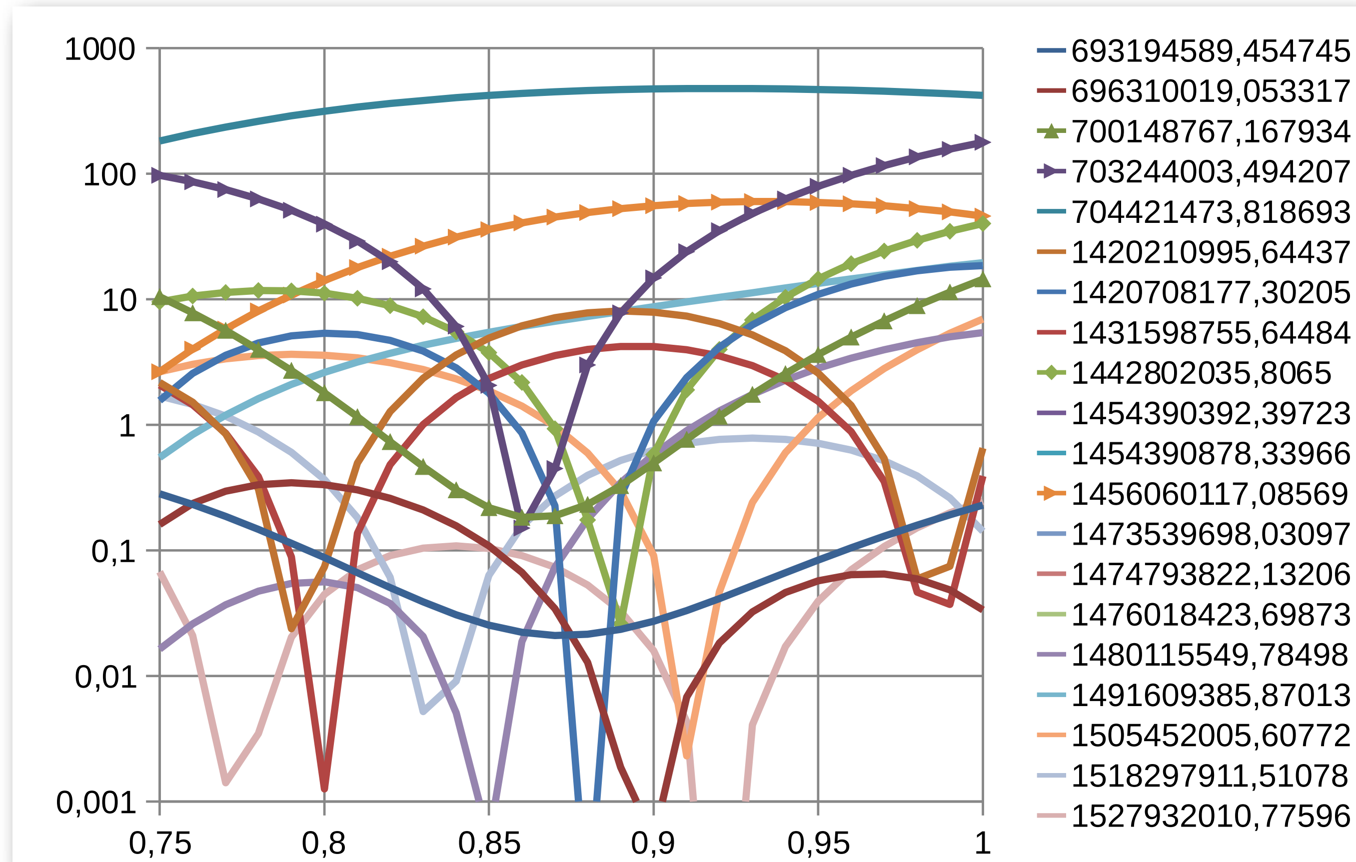
ESS Test Cavity
Data from G. Devanz

Frequency (MHz)	Max. r/Q (Ohm)	Q
First monopolar band		
1420.3	8	$1.58\ 10^{5}$
1421.9	17	$4.30\ 10^{3}$
1431.7	4	$3.22\ 10^{4}$
1442.8	29	$3.30\ 10^{4}$
1456.0	60	$4.41\ 10^{4}$
Second monopolar band (TM02)		
1480.1	5	$1.98\ 10^{4}$
1491.5	17	1.3310^{4}
1431.7	4	$1.40\ 10^{4}$
1518.2	4	1.8710^{4}
1527.9	0.2	4.5710^{4}



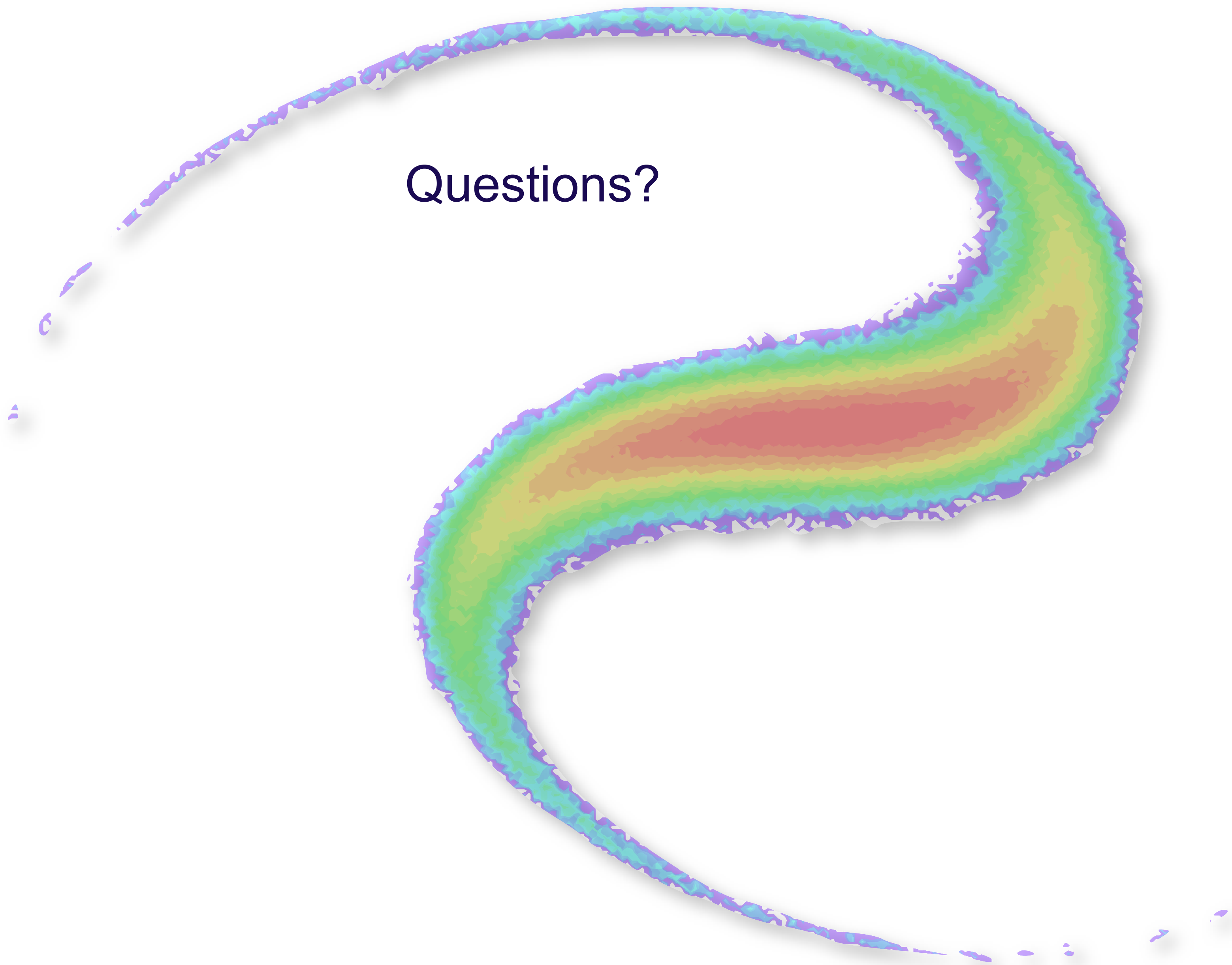
- **No mode below cut-off close to machine line**
- **R/Q values are moderate - no noise induced instabilities are expected**

Conclusion

- Based on the analytic analysis only Resonances are a real concern
  - Damping has to be very strong $Q_{ex} \sim 10^4$ to enable operation with a HOM directly at HOM
  - Resonances are very sharp at weak damping - probability to hit a resonance is very small. If so the mode can be shifted by cavity detuning
  - Dedicated HOM couplers are not needed from the beam dynamics point of view
- Check, if a lower geometrical beta in the medium beta section could be used

- Proposed studies:
  - Analyze final cavity geometry - exclude mode close to resonances
  - Beam loss studies in the context of HOMs - all simulations showed assume a point charge

Thank You!



Questions?

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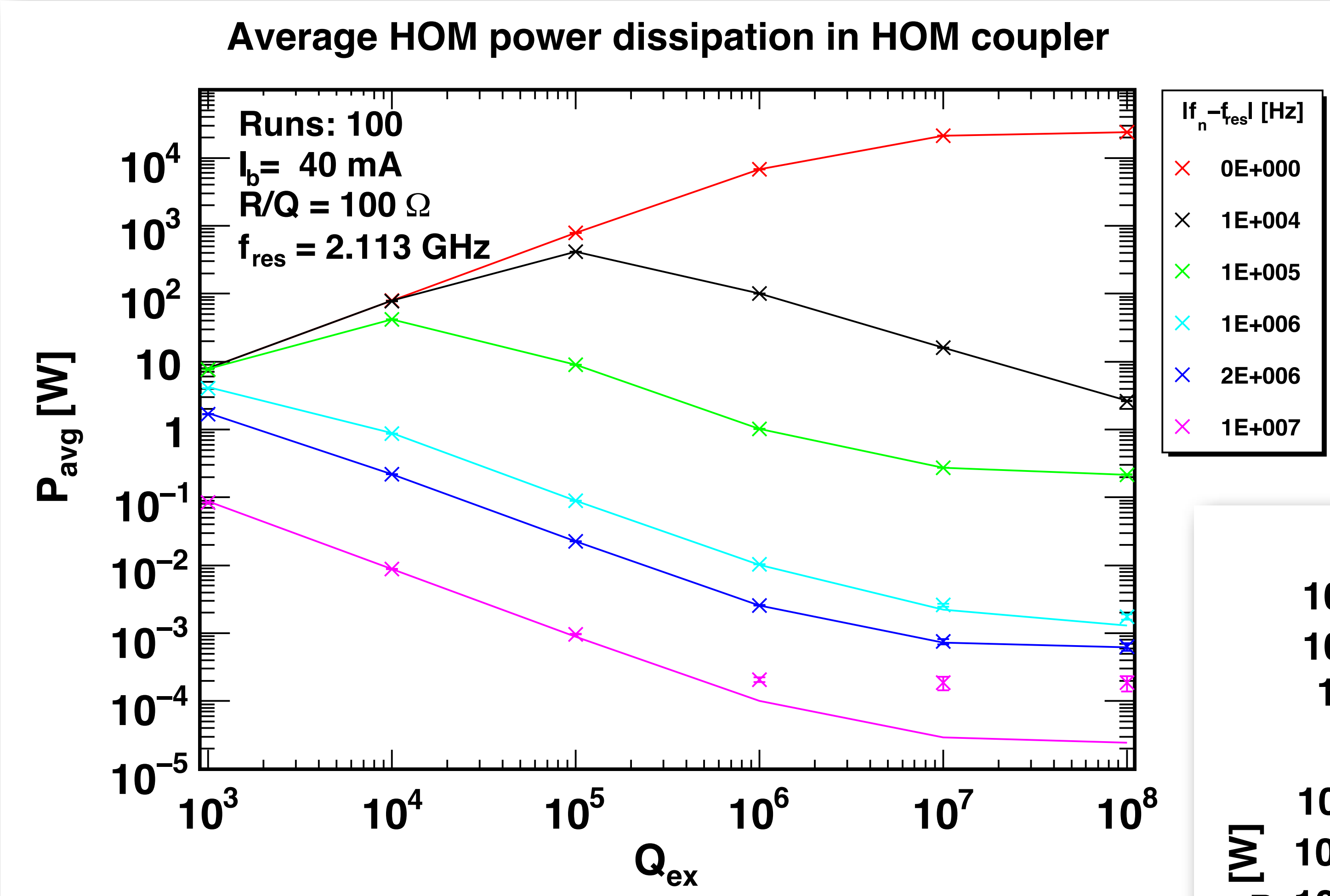
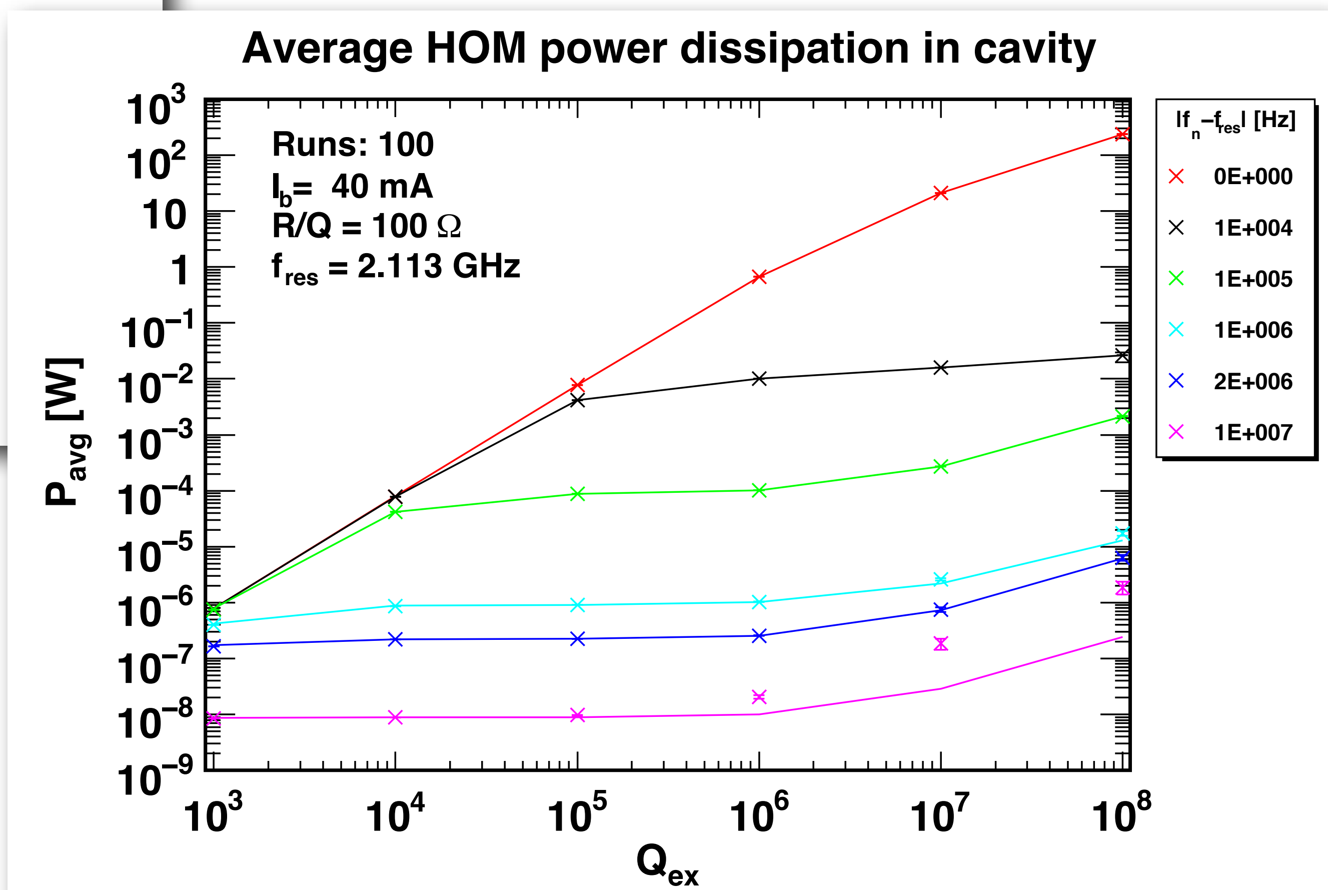
HOM Power Simulation with Beam Noise (SPL)



Beam noise:

- σ_q = 1%
- $\sigma_\varphi \approx$ 0.4 ps (not const. during pulse)

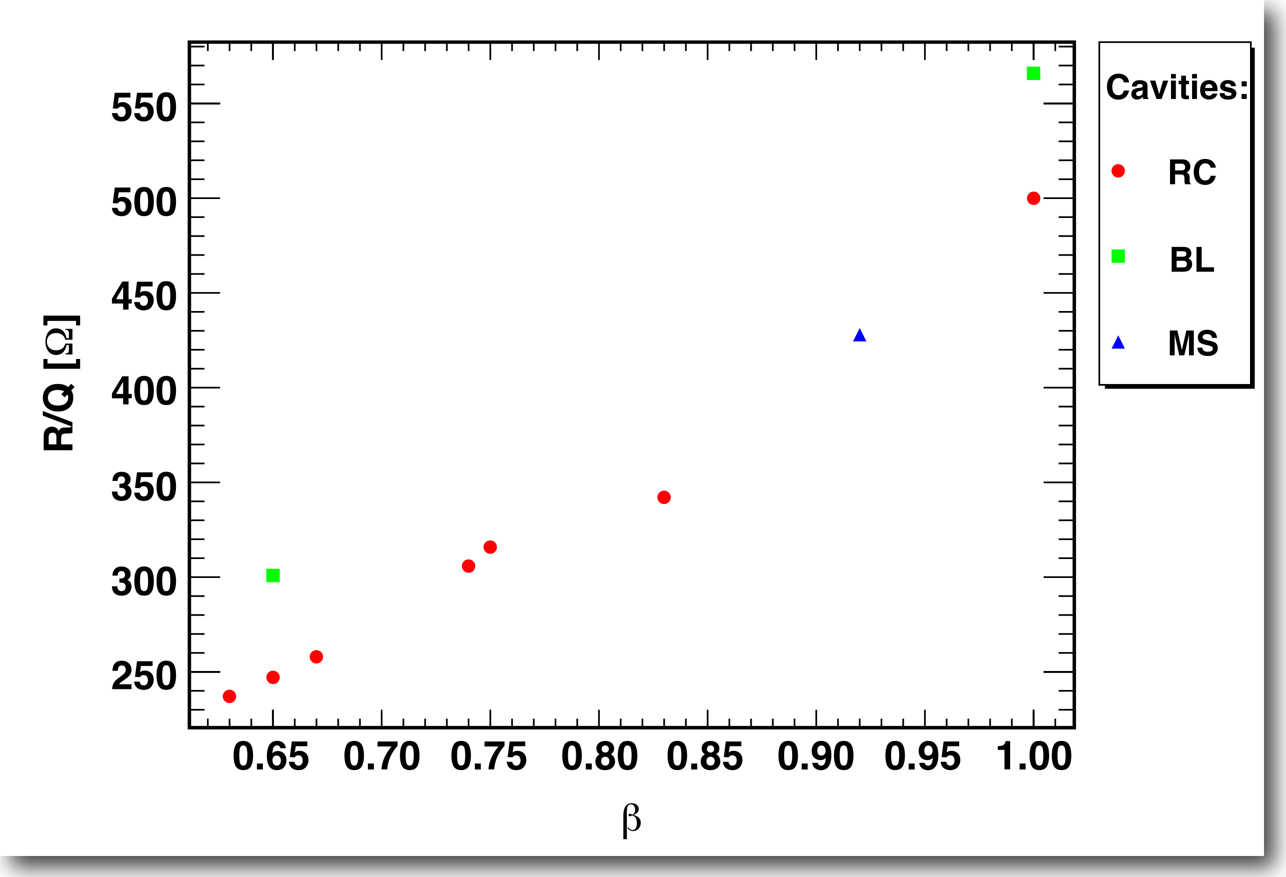


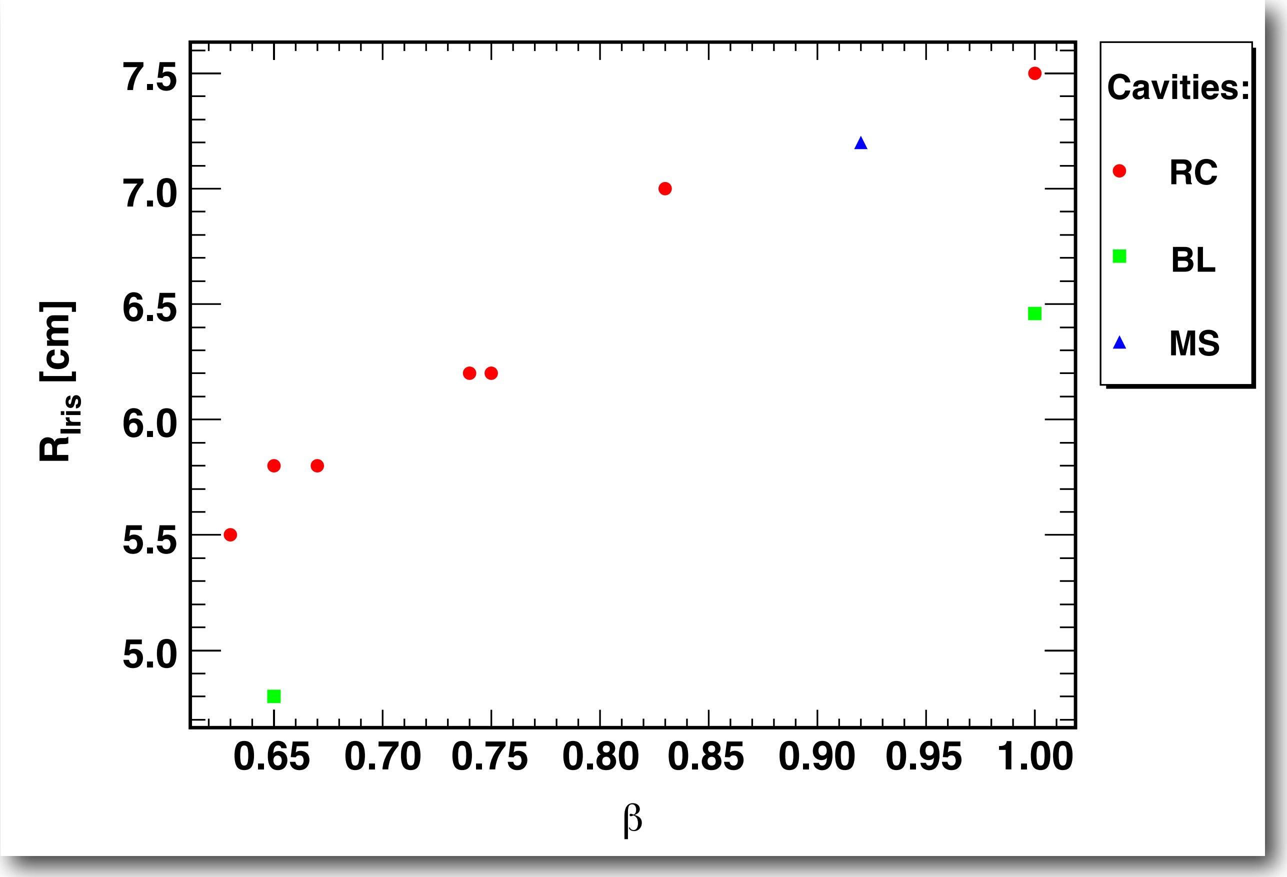
Solid lines are analytic values without noise.

Deviation only off resonance!

β_g dependency of R/Q

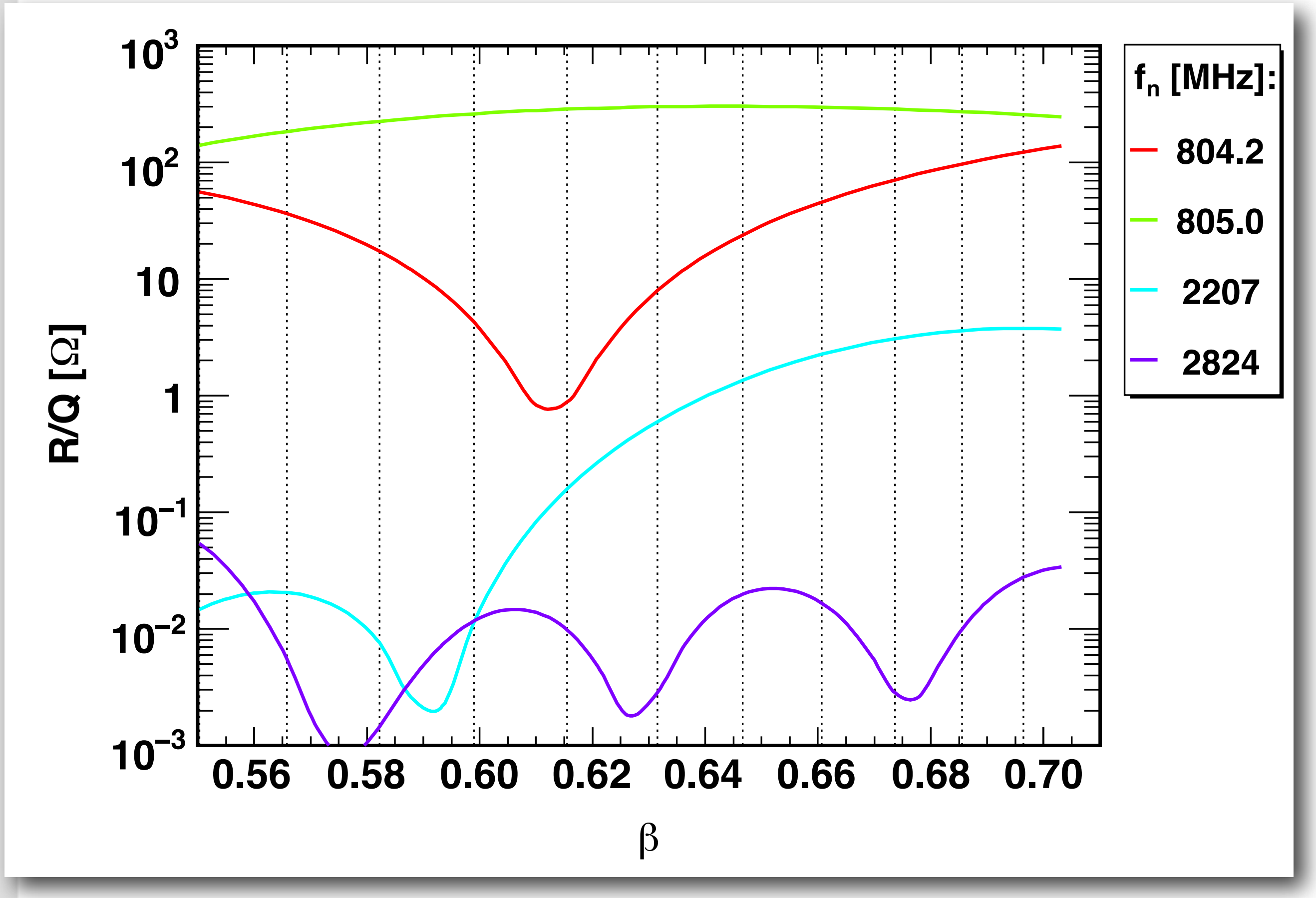
- To keep B_{peak}/E_{acc} small, R_{iris} has to be reduced with β_g and so also $R/Q(\beta_g)$ decreases.



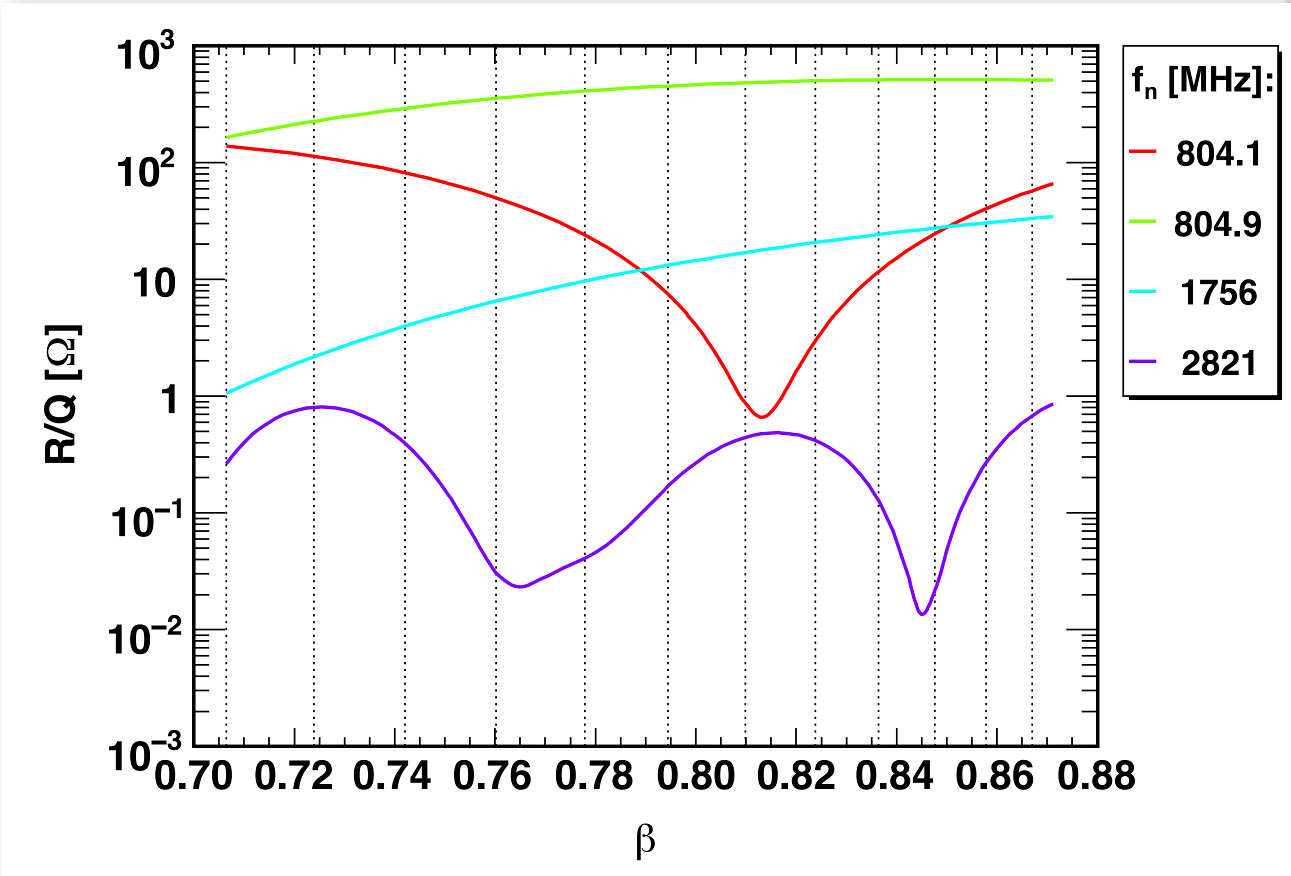


R/Q -maps SNS linac

$\beta_g = 0.61$



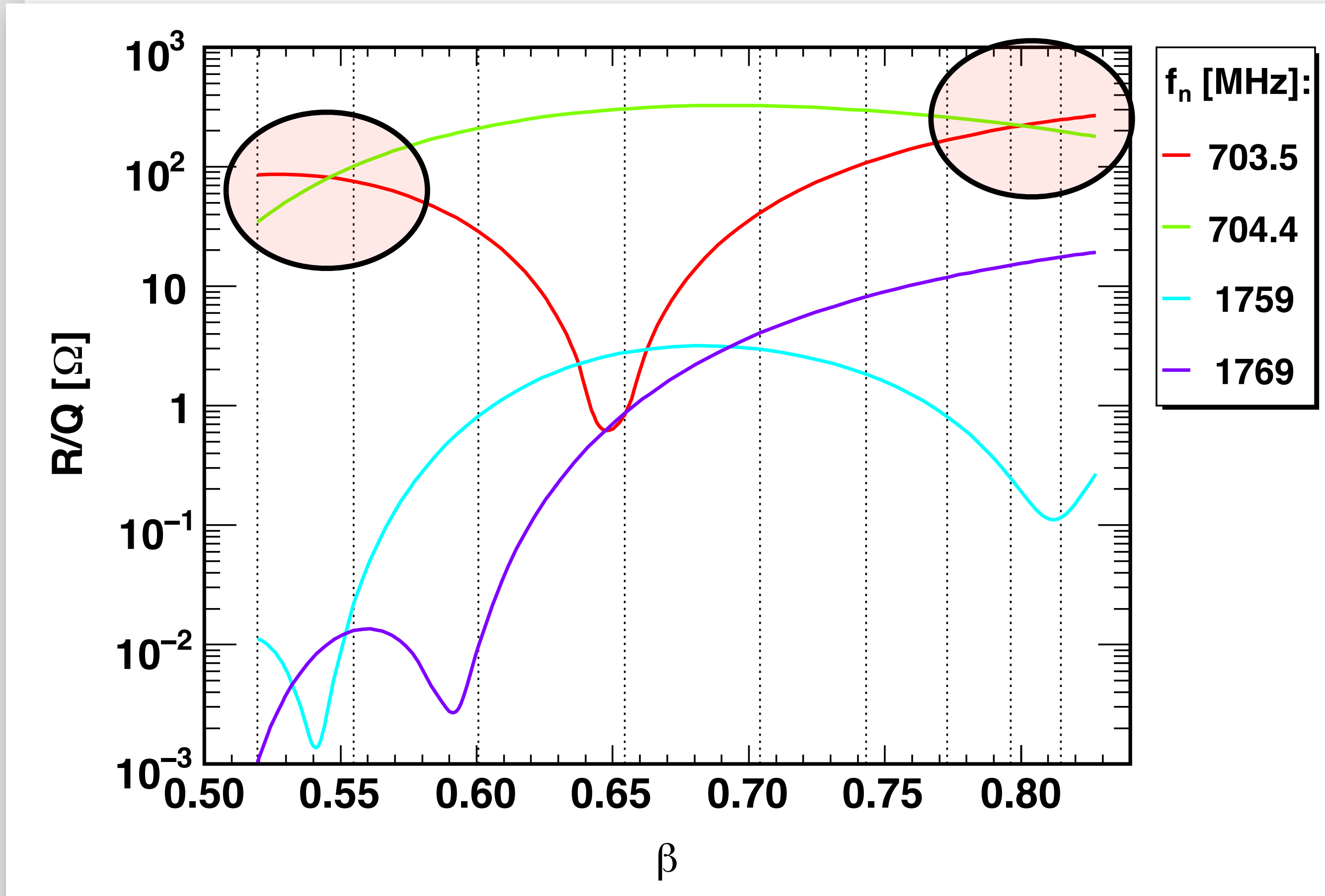
$\beta_g = 0.81$



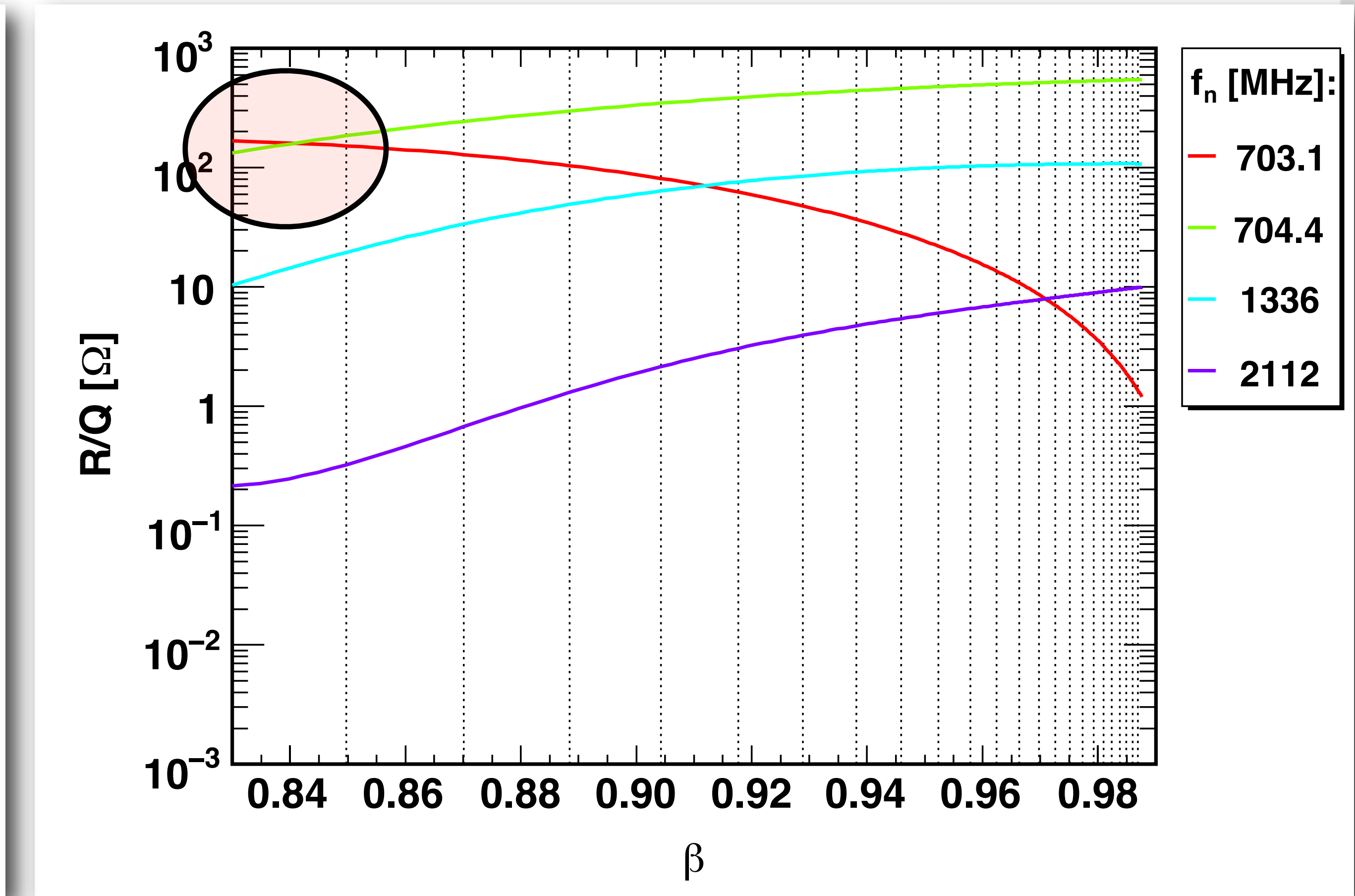
805	f_{acc} [MHz]	805
6	cells	6
33 (3)	cavities (per module)	48 (4)

R/Q -maps SPL

$\beta_g = 0.65$



$\beta_g = 1.0$

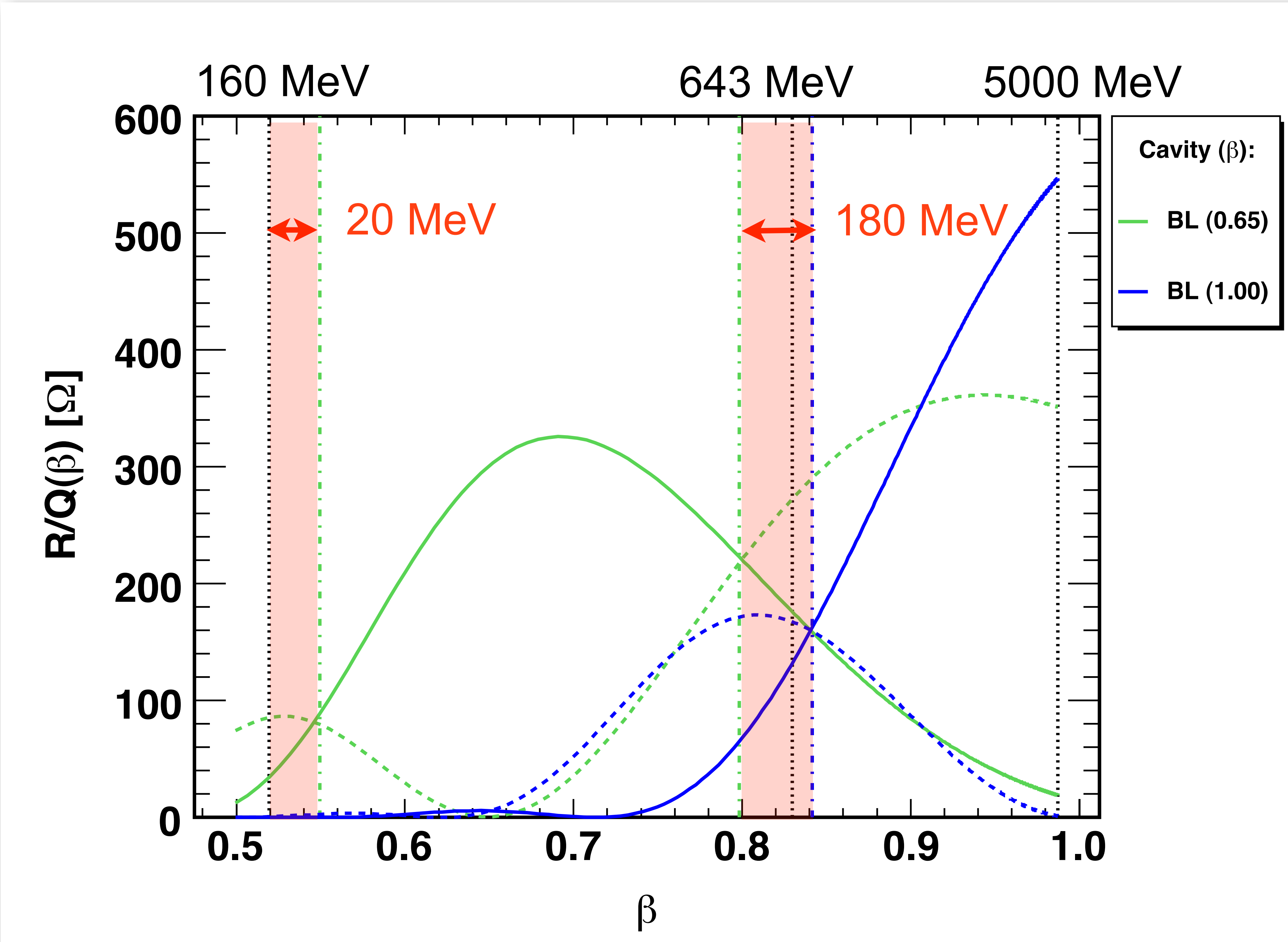


704,4	**f_{acc} [MHz]**	**704,4**
5	**cells**	**5**
54 (6)	**cavities (per module) ***	**196 (8)**

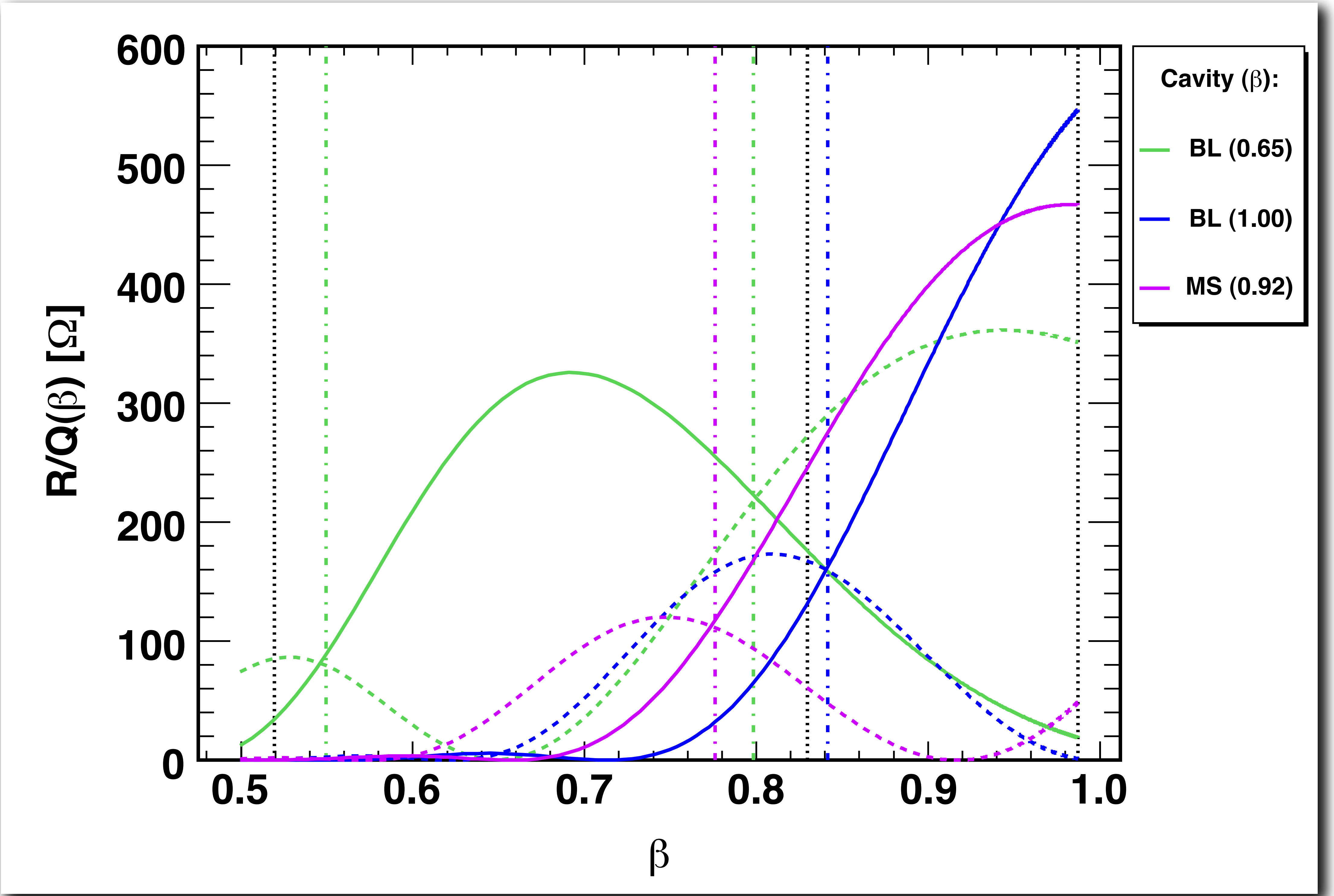
* old CDR2 layout

SPL baseline

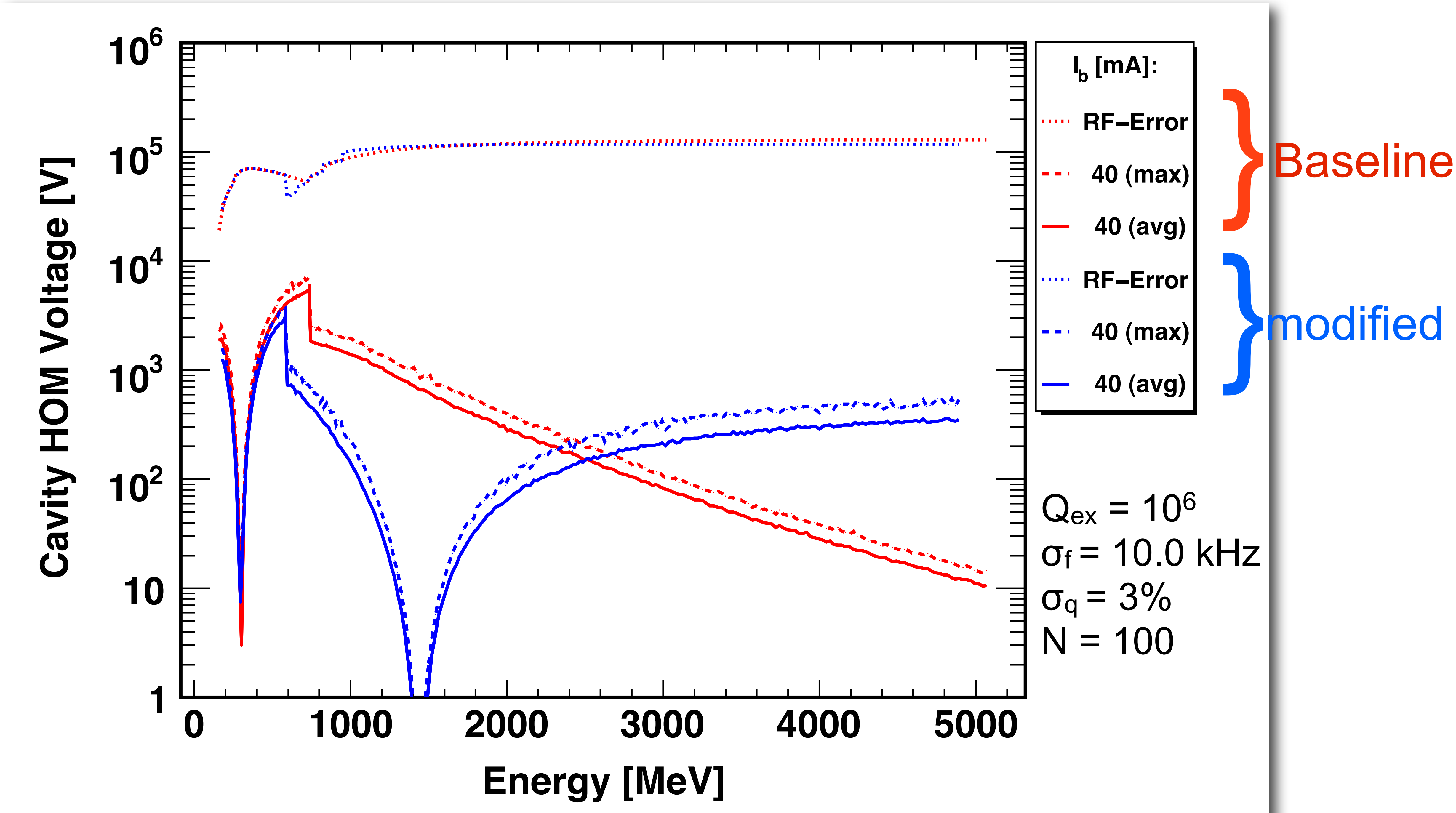
Define operation β limit, where R/Q(β) of other TM_{010} mode exceeds R/Q(β) of operation mode.



SPL Baseline + $\beta_g = 0.92$



Induced HOM voltage



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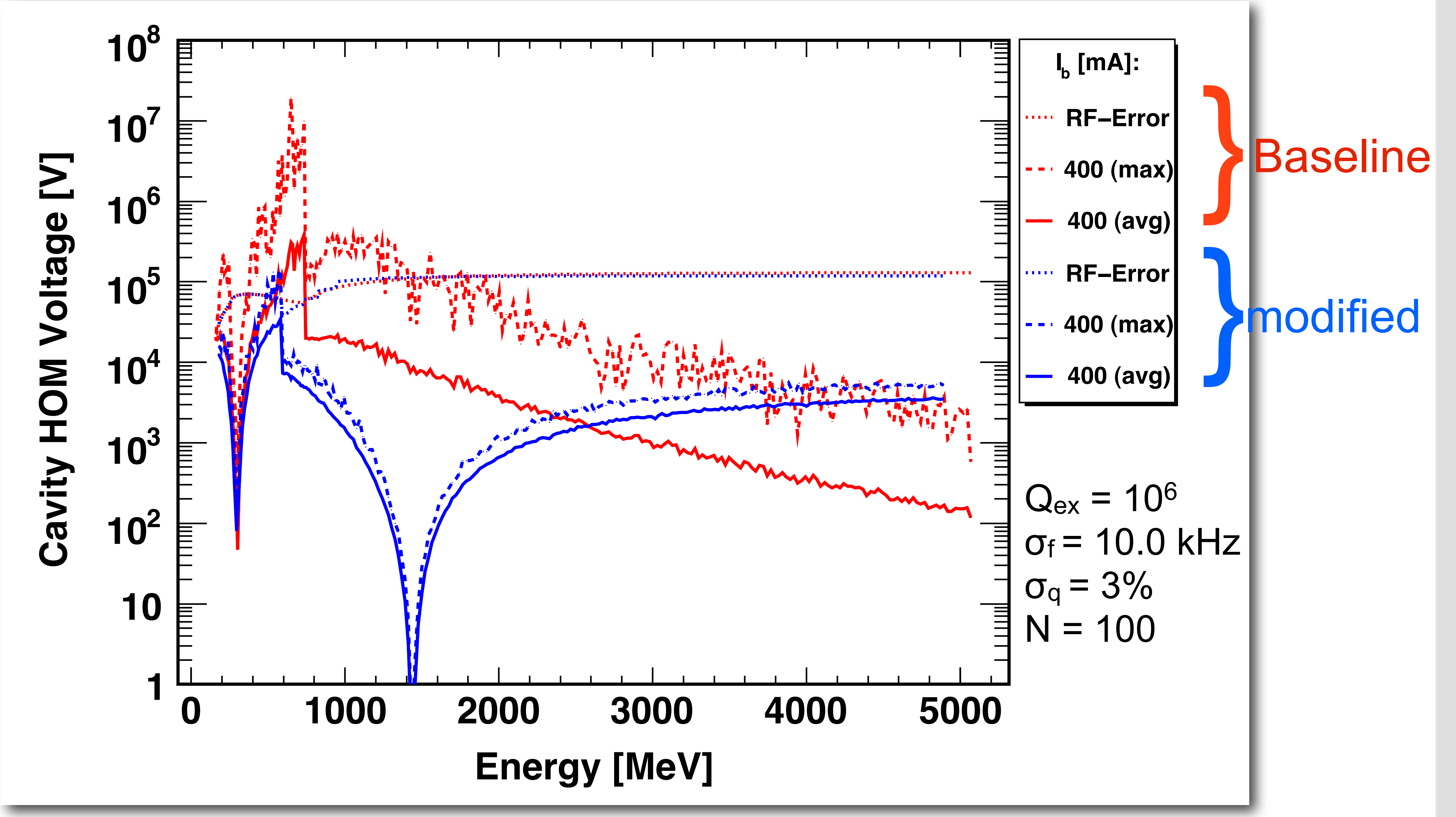
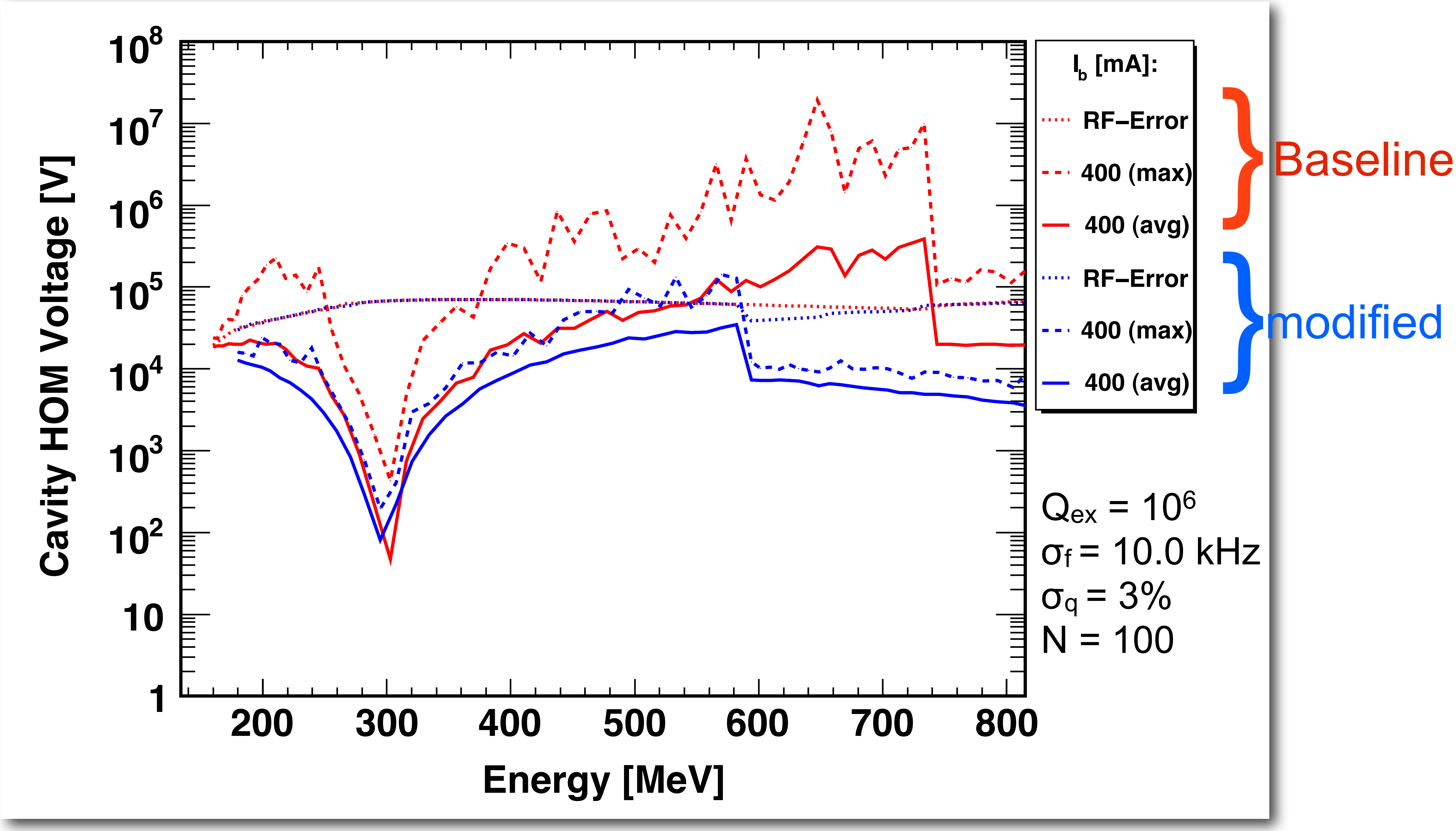
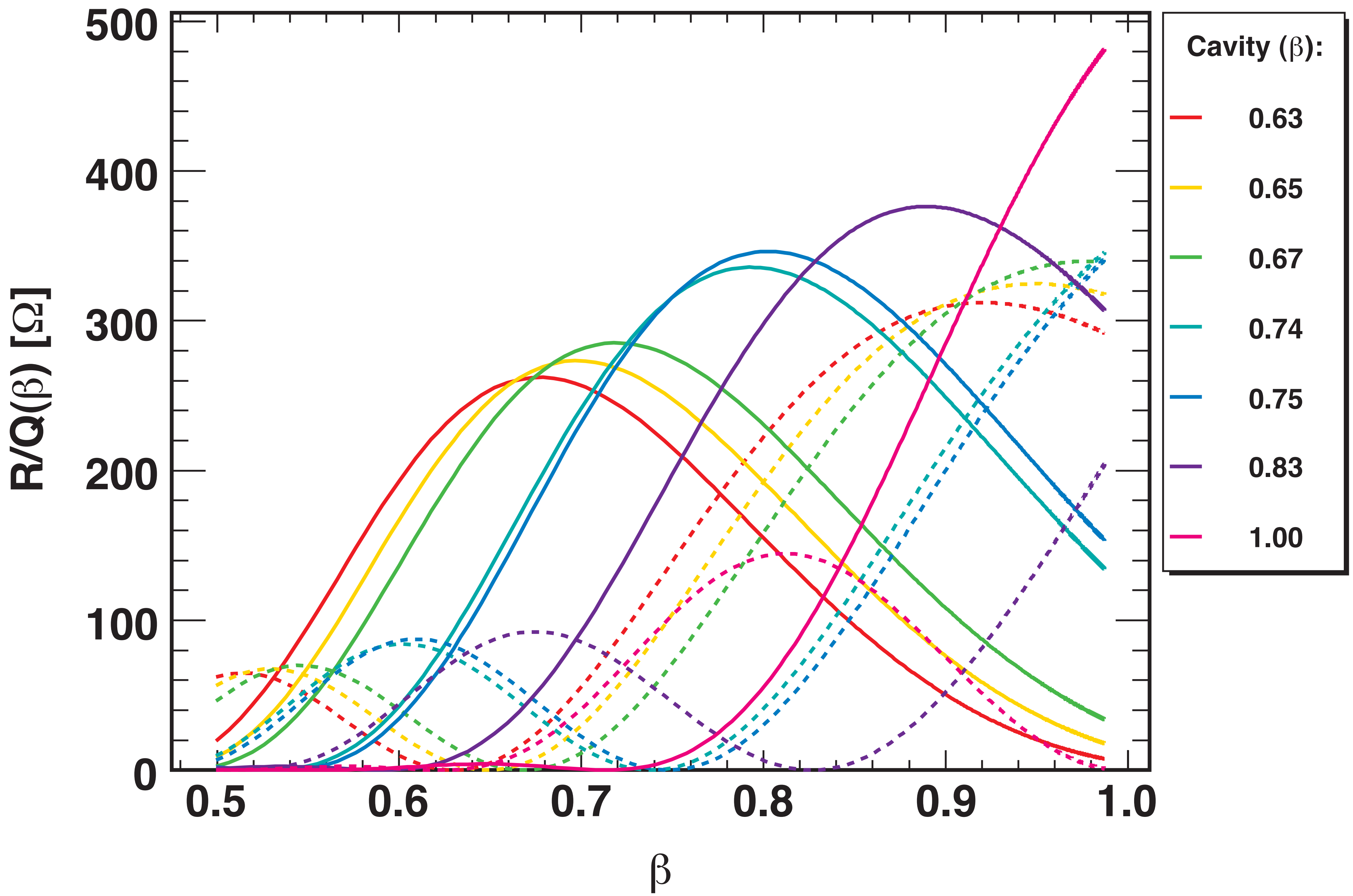


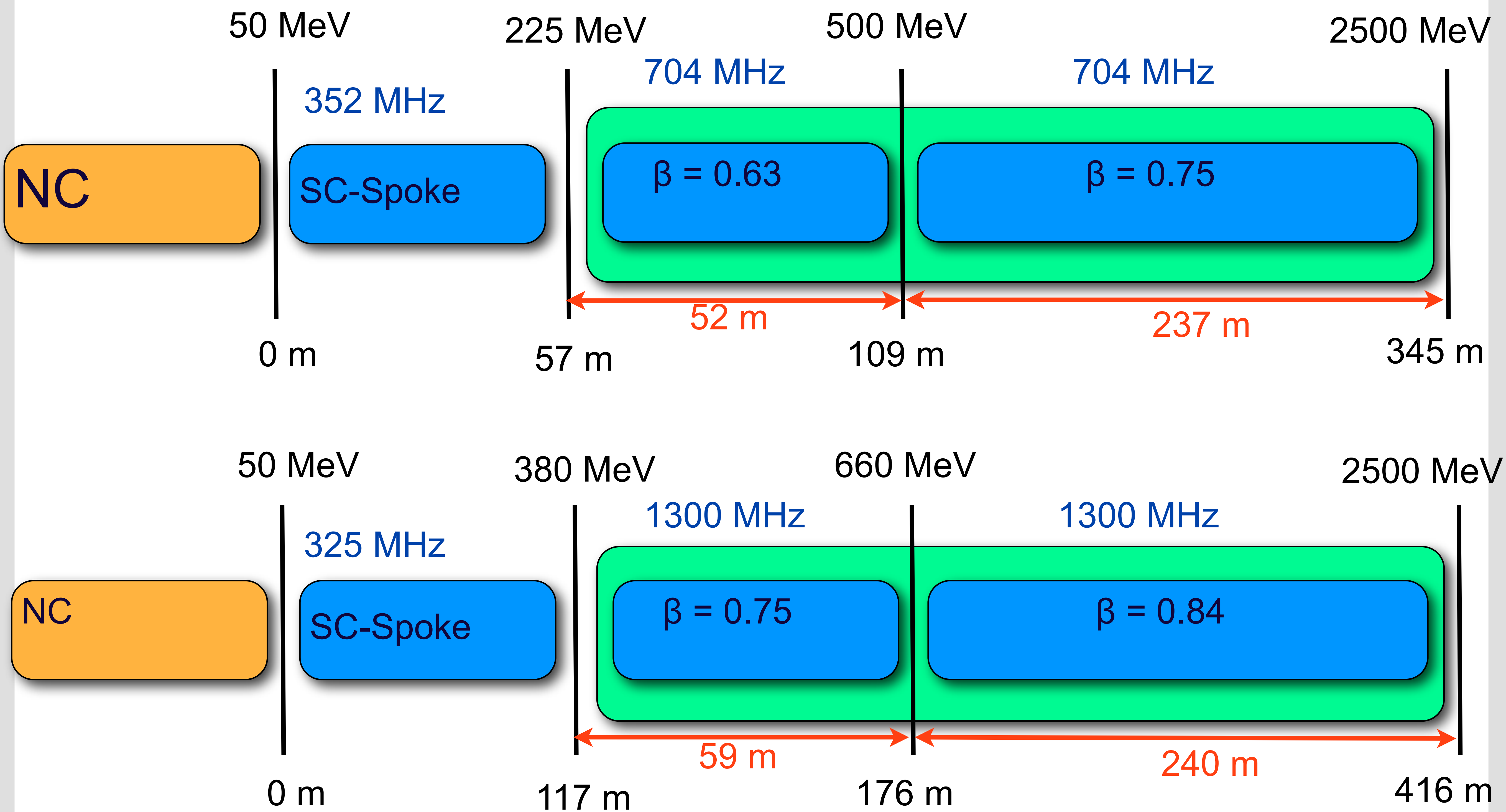
Induced HOM voltage



RC Cavities: R/Q(β)



LINAC Layout



Gradient and Phase Along Linac

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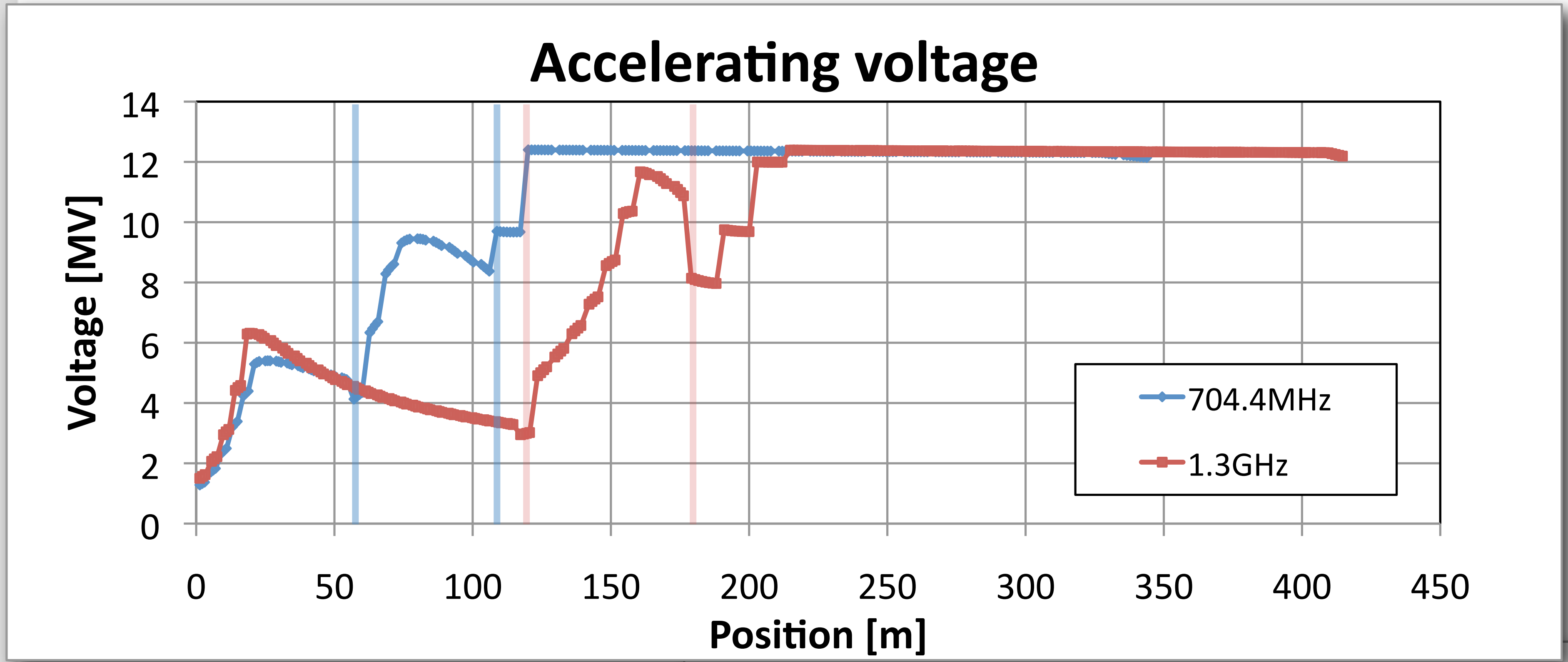
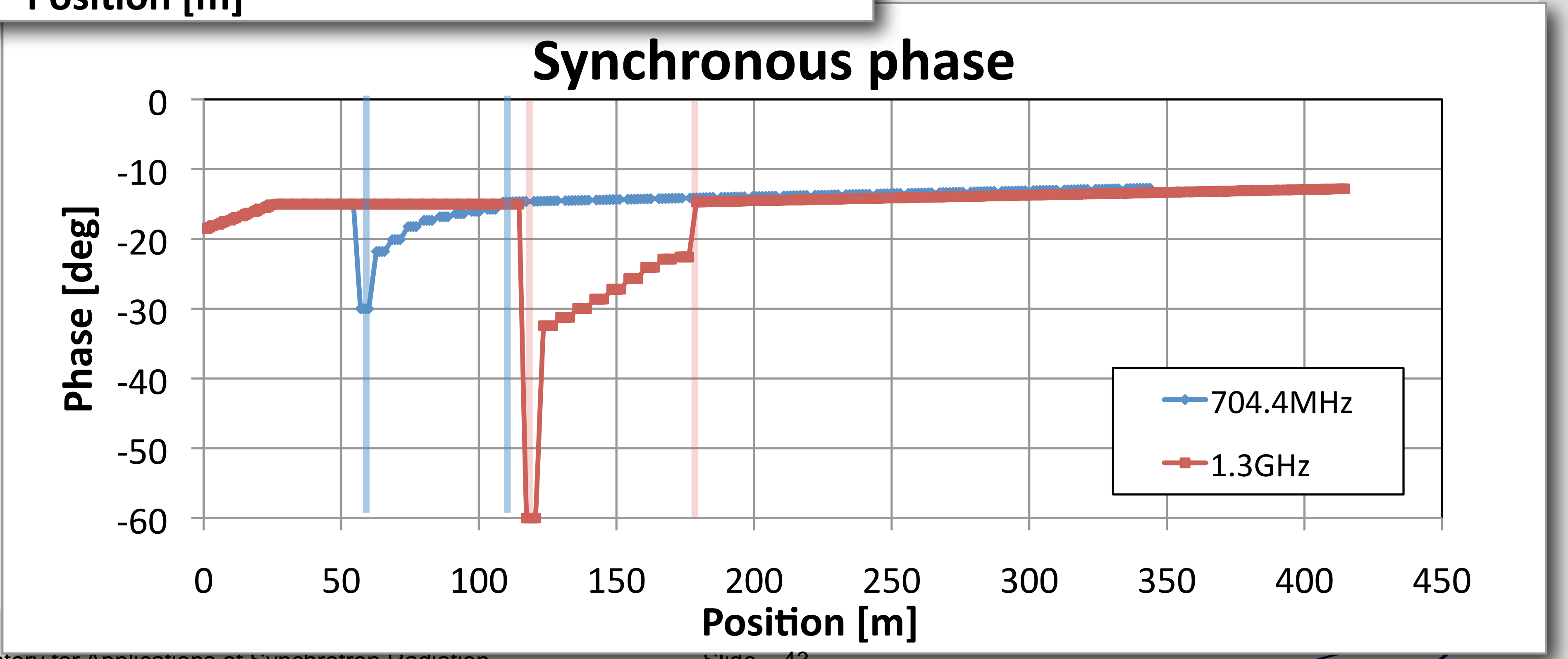
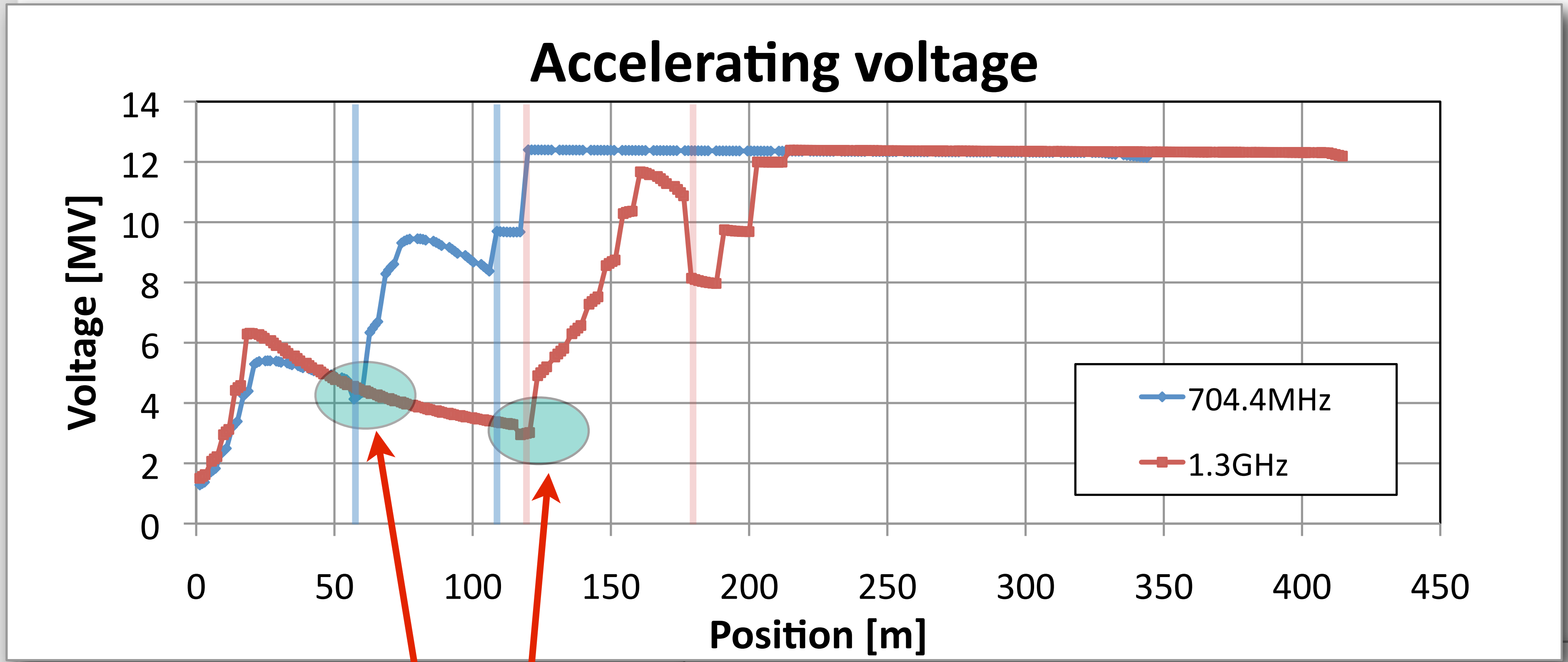


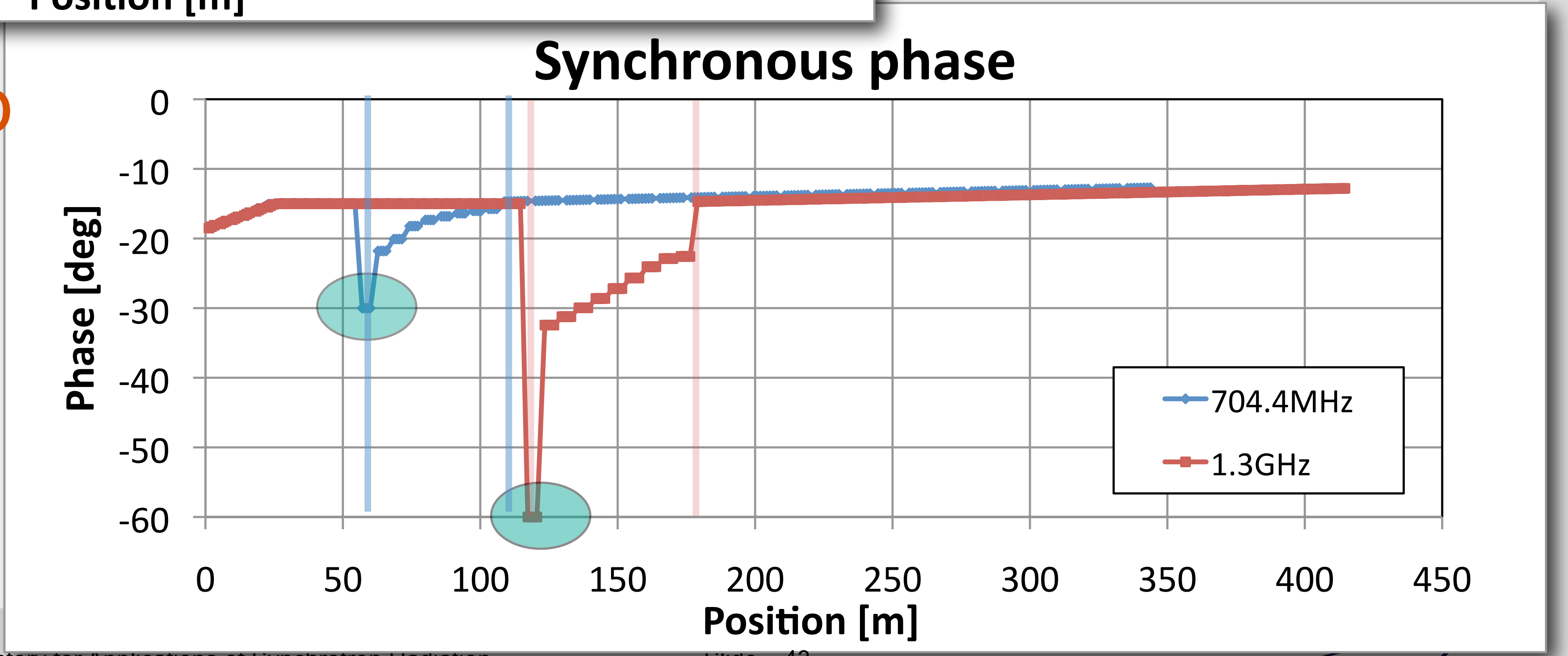


Gradient and Phase Along Linac



Frequency Jump

The sync. phase is reduced at the frequency jump.



Gradient and Phase Along Linac

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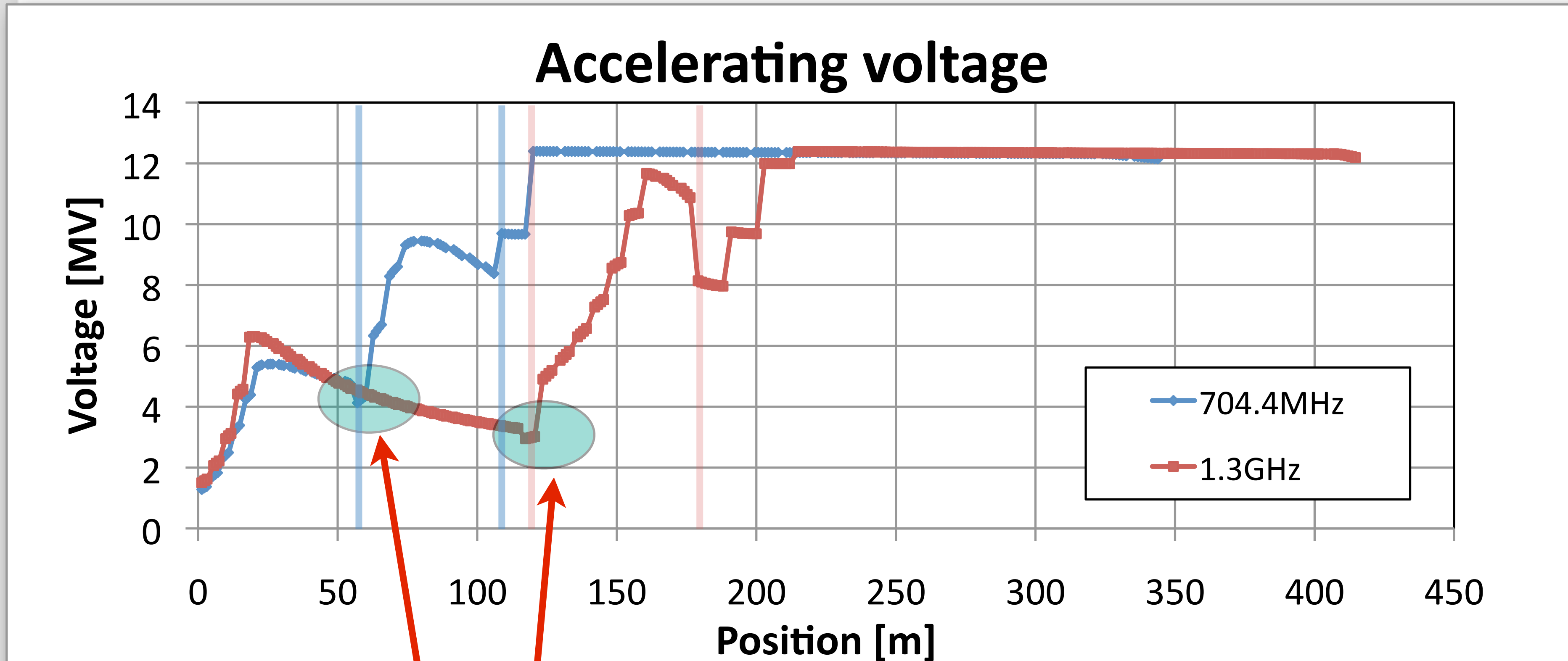


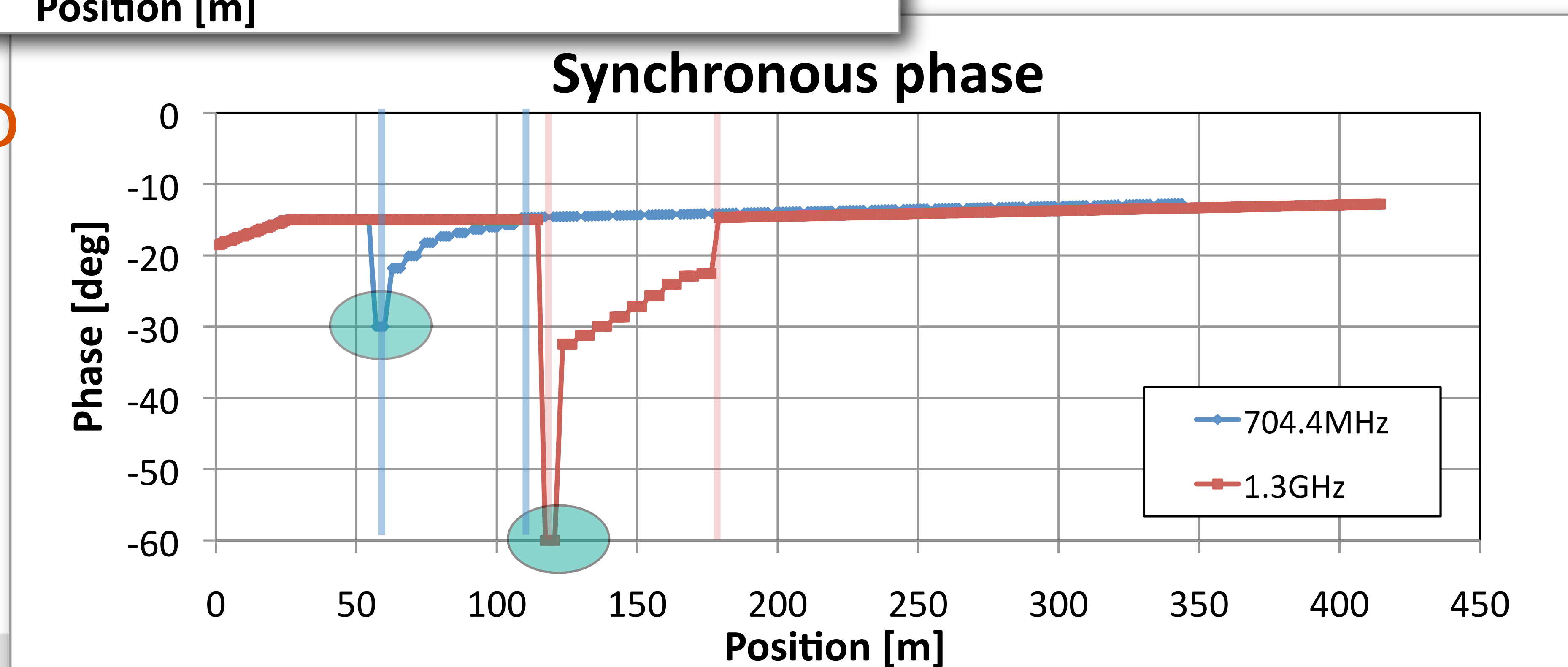
In both cases power per cavity is limited to **0.9 MW** (≙12MV@75mA).

=> Real estate gradient:

704.4 MHz: 8.5 MV/m

1.3 GHz: 8.1 MV/m

Frequency Jump



The sync. phase is reduced at the frequency jump.

Simulation ParamEter General Beam Dynamic

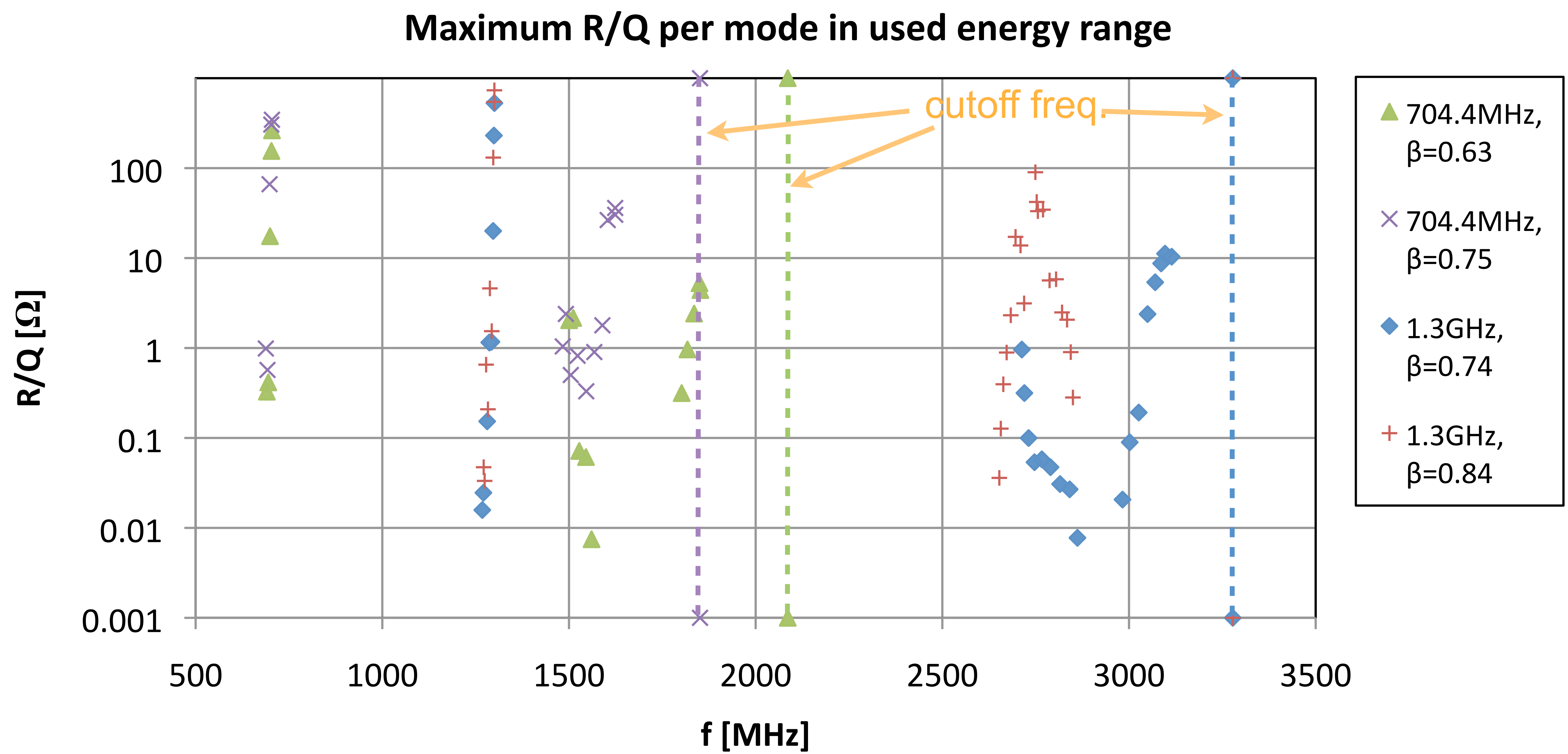
	704.4 MHz	1.3 GHz
Current	50 mA	50 mA
NC Frequency	352.2 MHz	325 MHz
Input Energy	50 MeV	50 MeV
No. Particles	50,000	50,000
Distribution	Gaussian 3xσ	Gaussian 3xσ
e.x. norm. rms	0.2455 pi.mm.mrad	
e.y. norm. rms	0.2419 pi.mm.mrad	
e.z. norm. rms	0.6464 pi.mm.mrad	

Elliptical Cavities

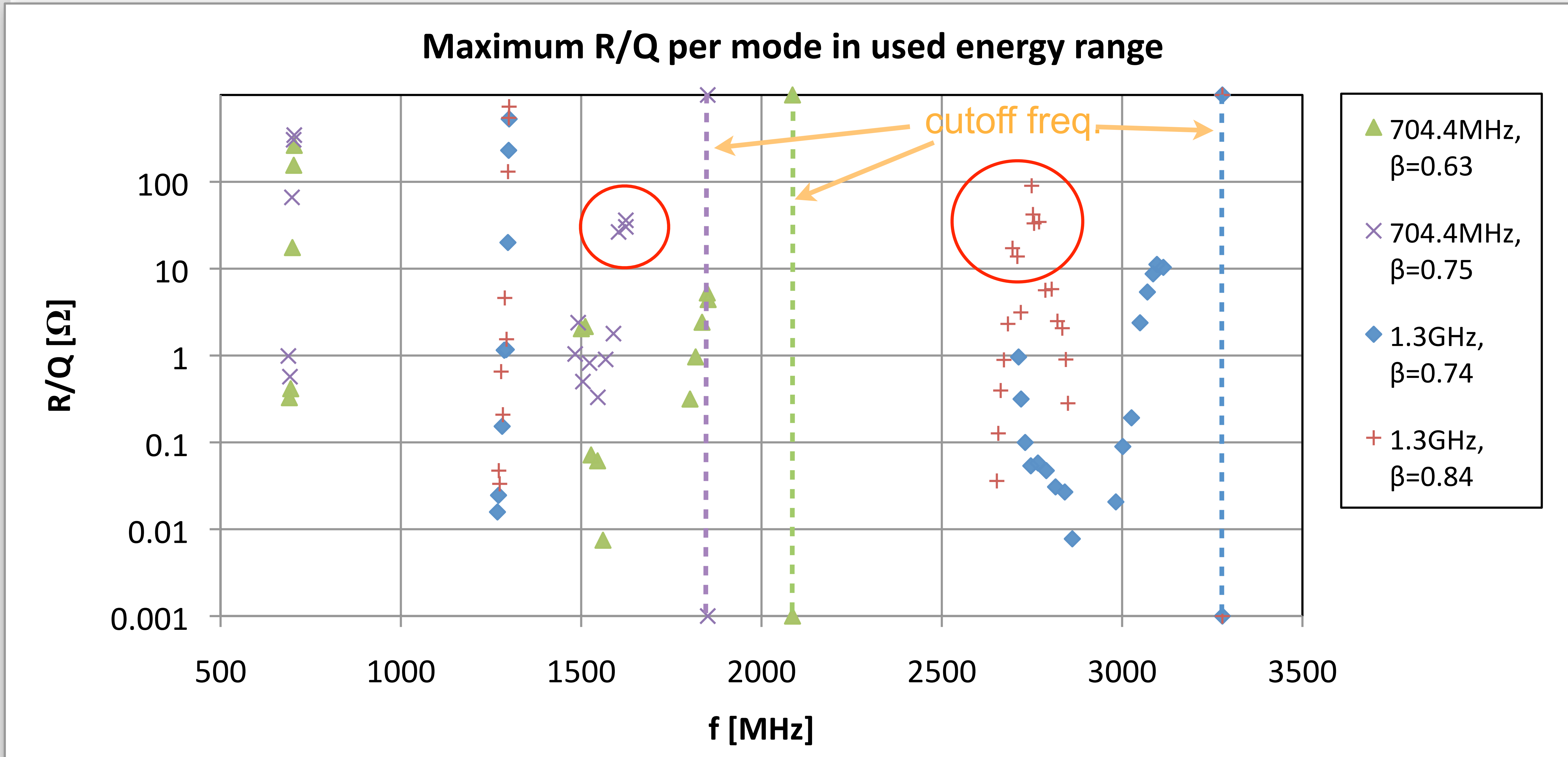
	704.4 MHz		1.3 GHz	
β_g	0.63	0.75	0.74	0.84
Cells	5	5	9	9
L (L_{active}) [m]	0.99 (0.67)	1.11 (0.79)	1.09 (0.77)	1.19 (0.87)
R_{iris} [cm]	5.5	6.2	3.5	3.5
$R/Q(\beta_g)$ [$\Omega^\dagger$]	238	307	513	715
Gradient [MV/m]	14	20	15	21
f_{Cutoff} [GHz]	2.09	1.85	3.28	3.28
Installed	36	168	40	160

†linac definition

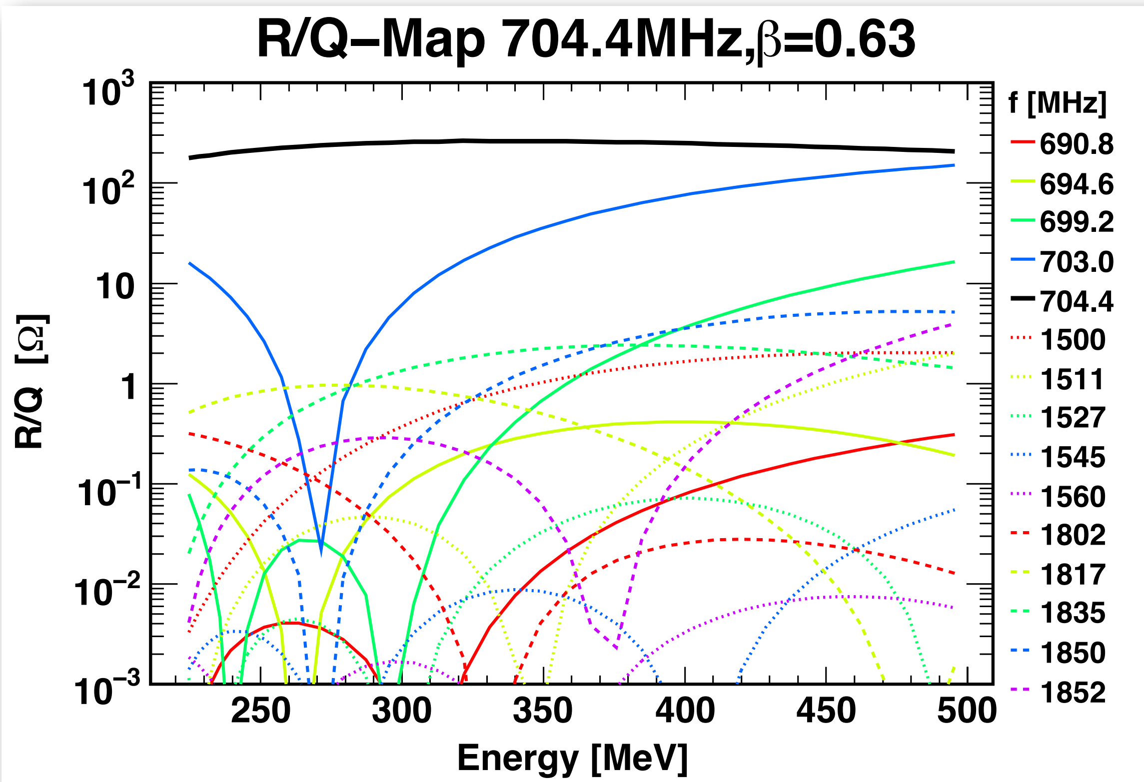
Monopole Spectrum



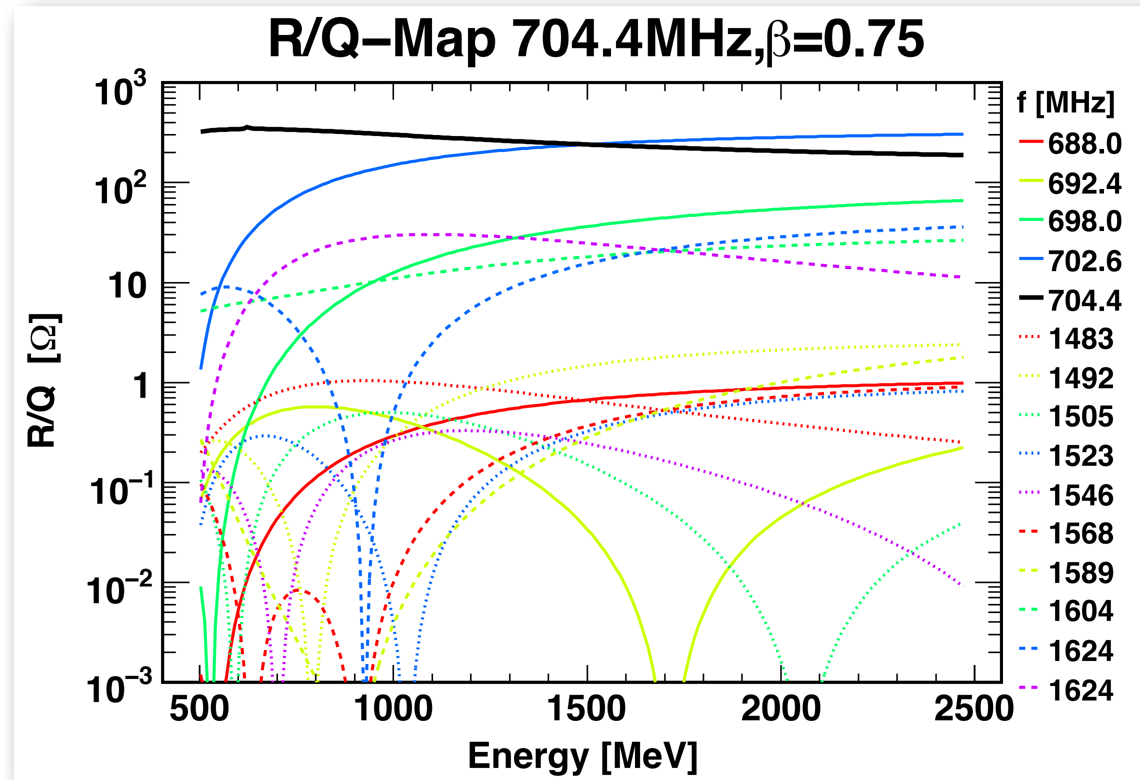
Monopole Spectrum



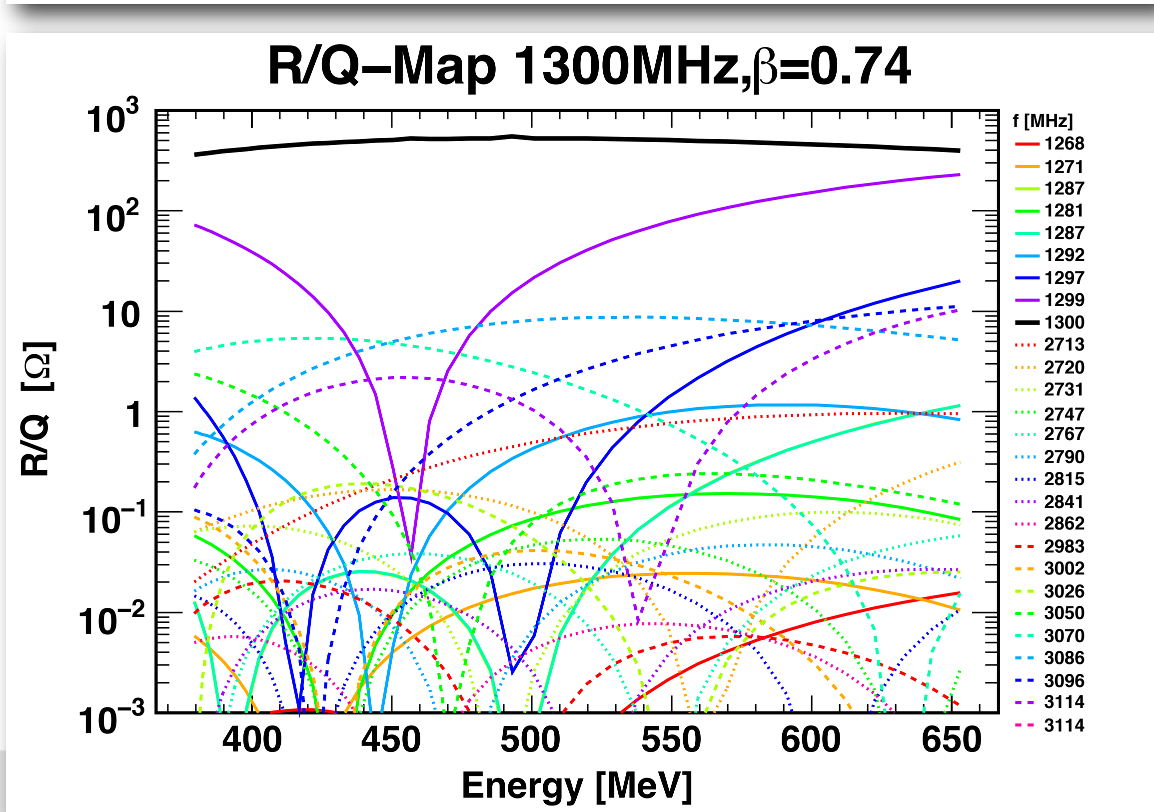
R/Q -MAP



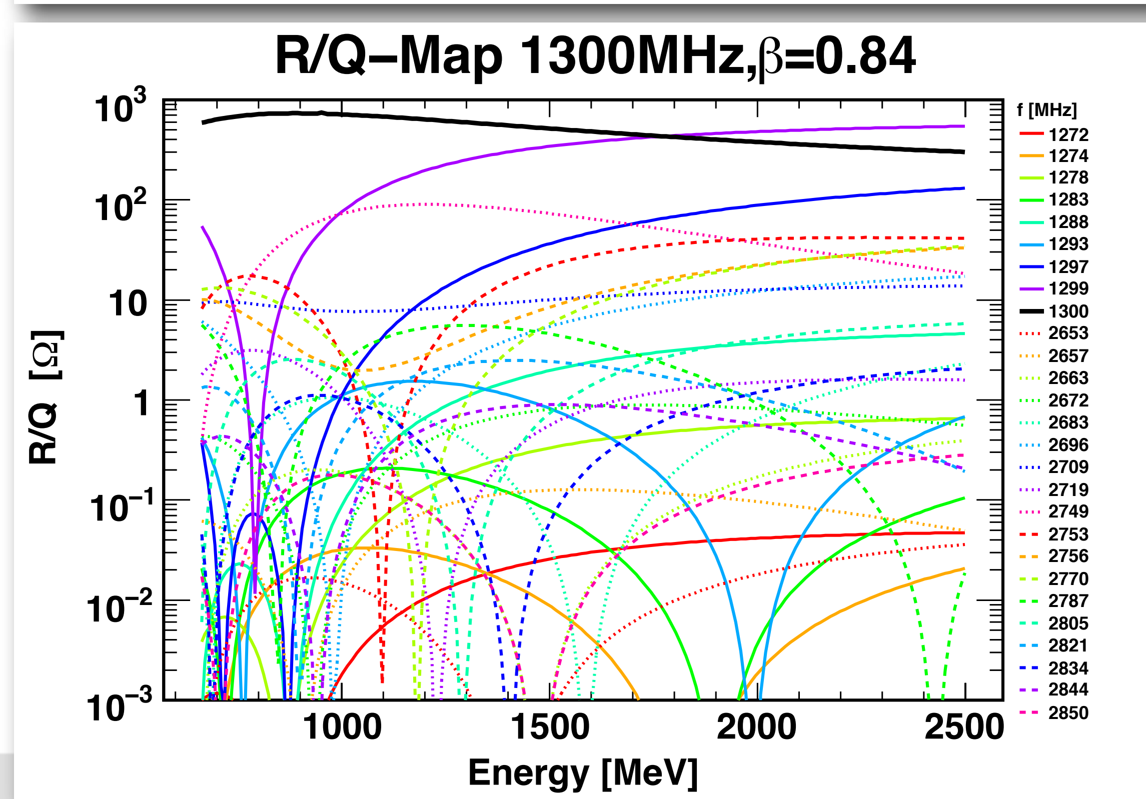
R/Q–Map 704.4MHz,β=0.63
R/Q [Ω]
Energy [MeV]
10^3
10^2
10
1
10^-1
10^-2
10^-3
250
300
350
400
450
500
f [MHz]
690.8
694.6
699.2
703.0
704.4
1500
1511
1527
1545
1560
1802
1817
1835
1850
1852



R/Q–Map 704.4MHz,β=0.75
R/Q [Ω]
Energy [MeV]
10^3
10^2
10
1
10^-1
10^-2
10^-3
500
1000
1500
2000
2500
f [MHz]
688.0
692.4
698.0
702.6
704.4
1483
1492
1505
1523
1546
1568
1589
1604
1624
1624



R/Q–Map 1300MHz,β=0.74
R/Q [Ω]
Energy [MeV]
10^3
10^2
10
1
10^-1
10^-2
10^-3
400
450
500
550
600
650
f [MHz]
1268
1271
1287
1281
1287
1292
1297
1299
1300
2713
2720
2731
2747
2767
2790
2815
2841
2862
2983
3002
3026
3050
3070
3086
3096
3114
3114



R/Q–Map 1300MHz,β=0.84
R/Q [Ω]
Energy [MeV]
10^3
10^2
10
1
10^-1
10^-2
10^-3
1000
1500
2000
2500
f [MHz]
1272
1274
1278
1283
1288
1293
1297
1299
1300
2653
2657
2663
2672
2683
2696
2709
2719
2749
2753
2756
2770
2787
2805
2821
2834
2844
2850

R/Q -MAP

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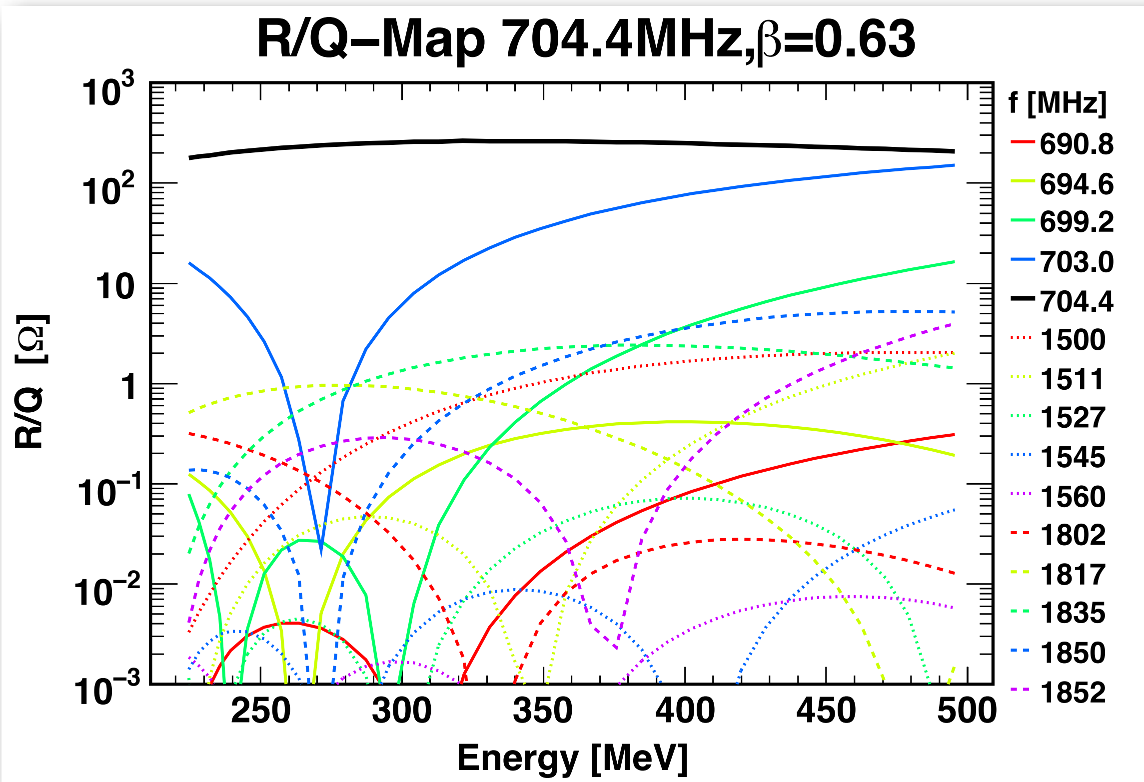

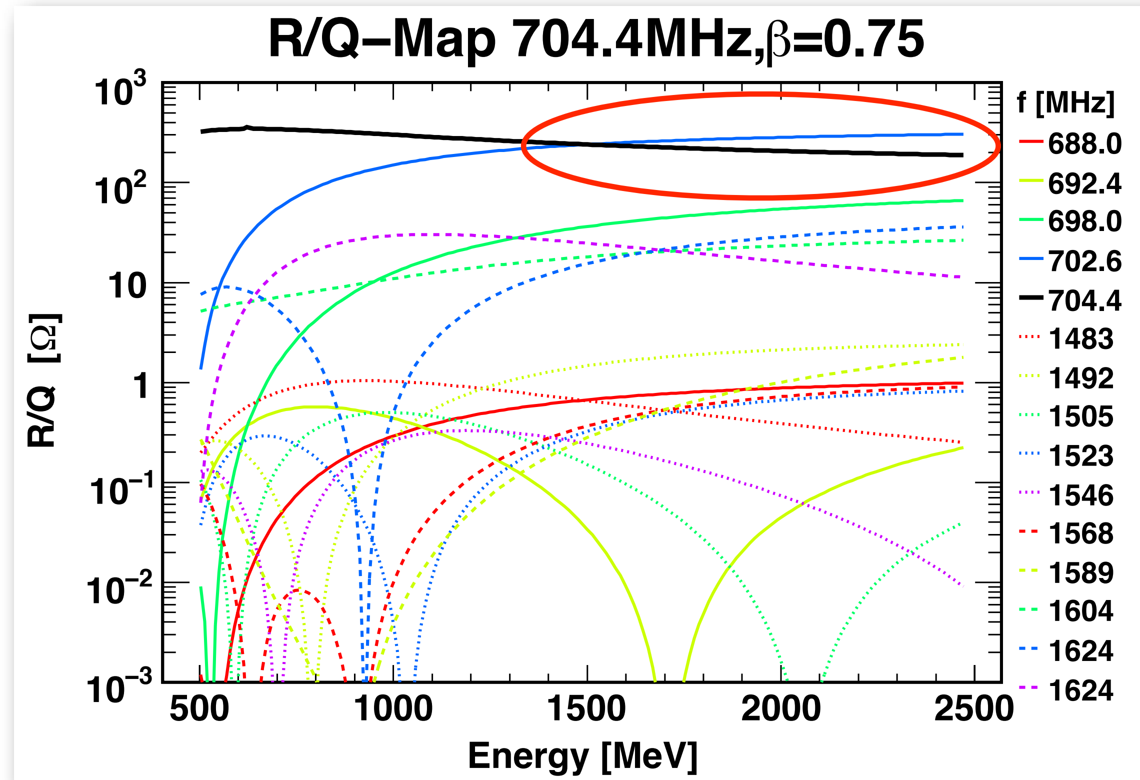

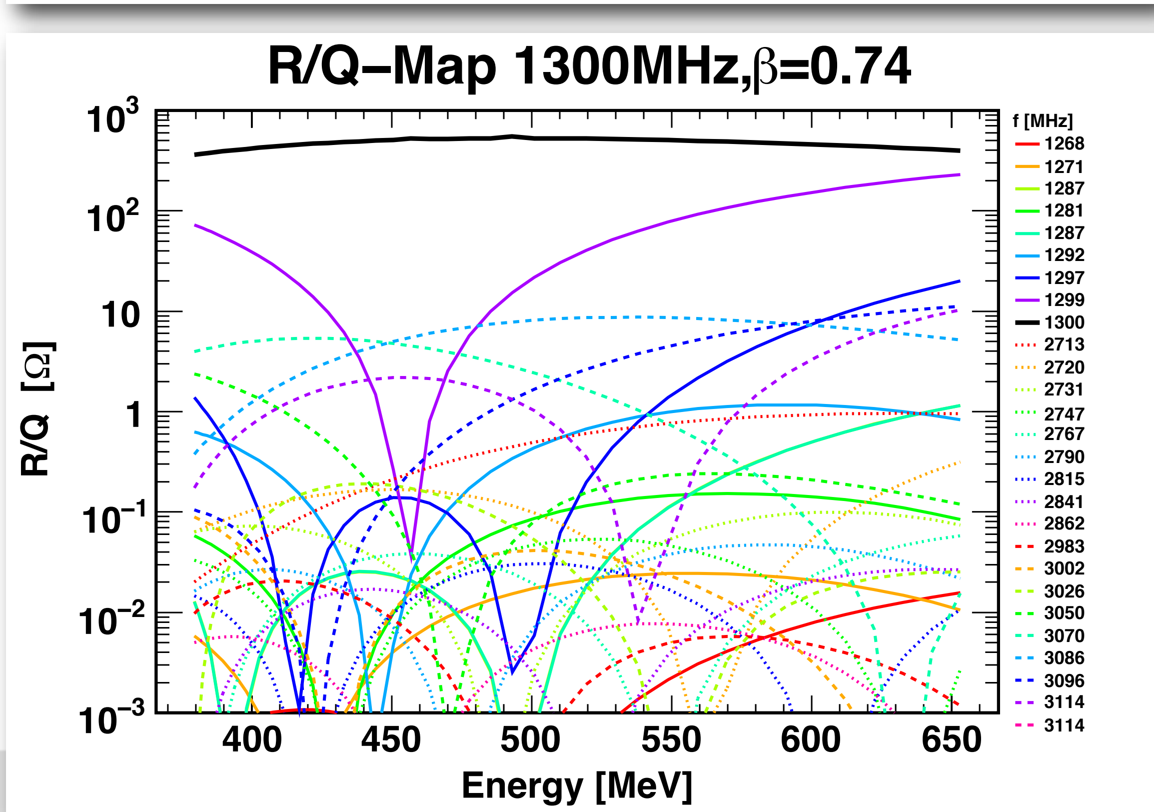

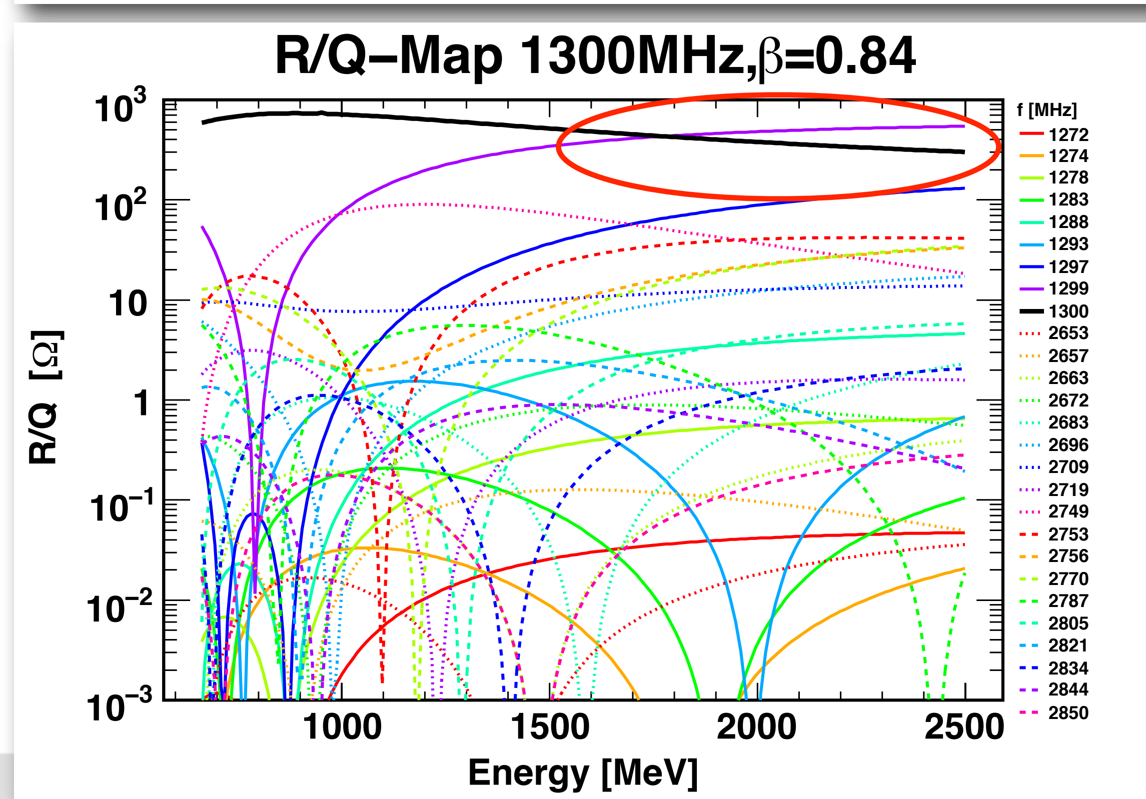

ANKA THz GROUP

Beam Parameter HOM Simulations

Parameter	Mean (704.4 MHz/1.3 GHz)	σ
Bunch frequency [MHz]	352.2 / 325	-
Pulse length [ms]	~2 (700,000 bunches)	-
Period length [ms]	50	-
Beam current [mA]	50...400	1 %
W_{Input} [MeV]	225 (380) /380	$2 \cdot 10^{-5}$
Phase [deg]	-30 (-16) / -60	0.3 (0.2)/ 0.4

HOM Voltage along the linac after one Pulse

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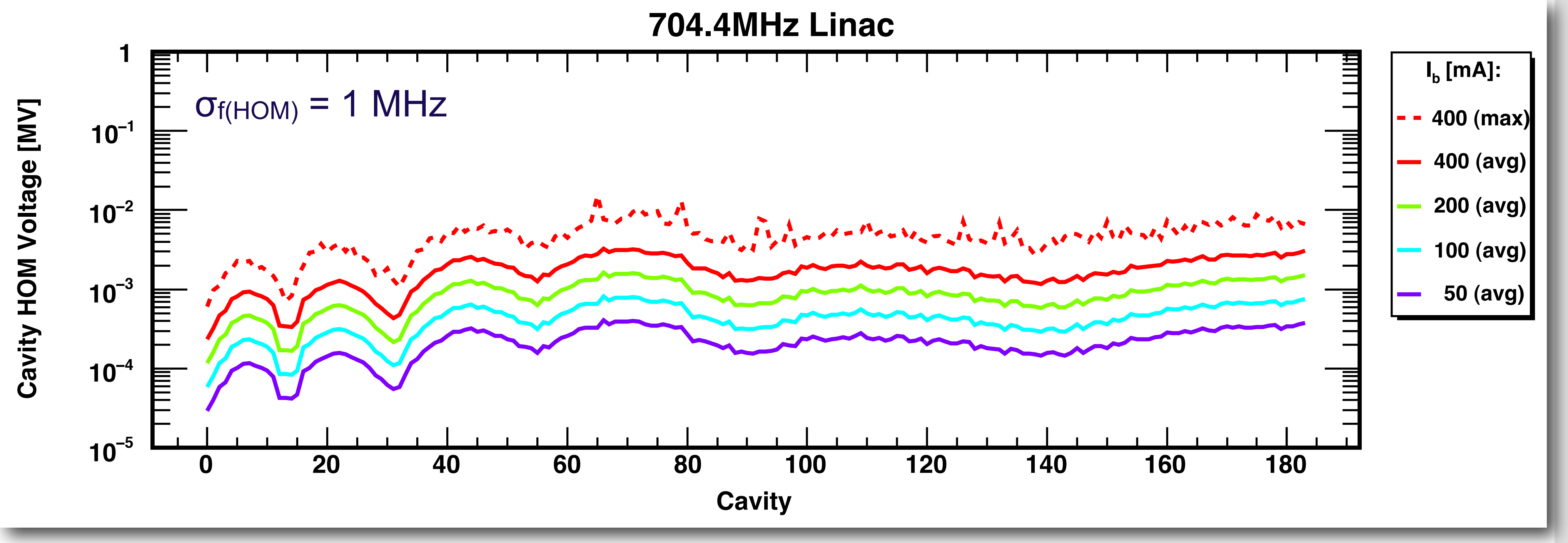
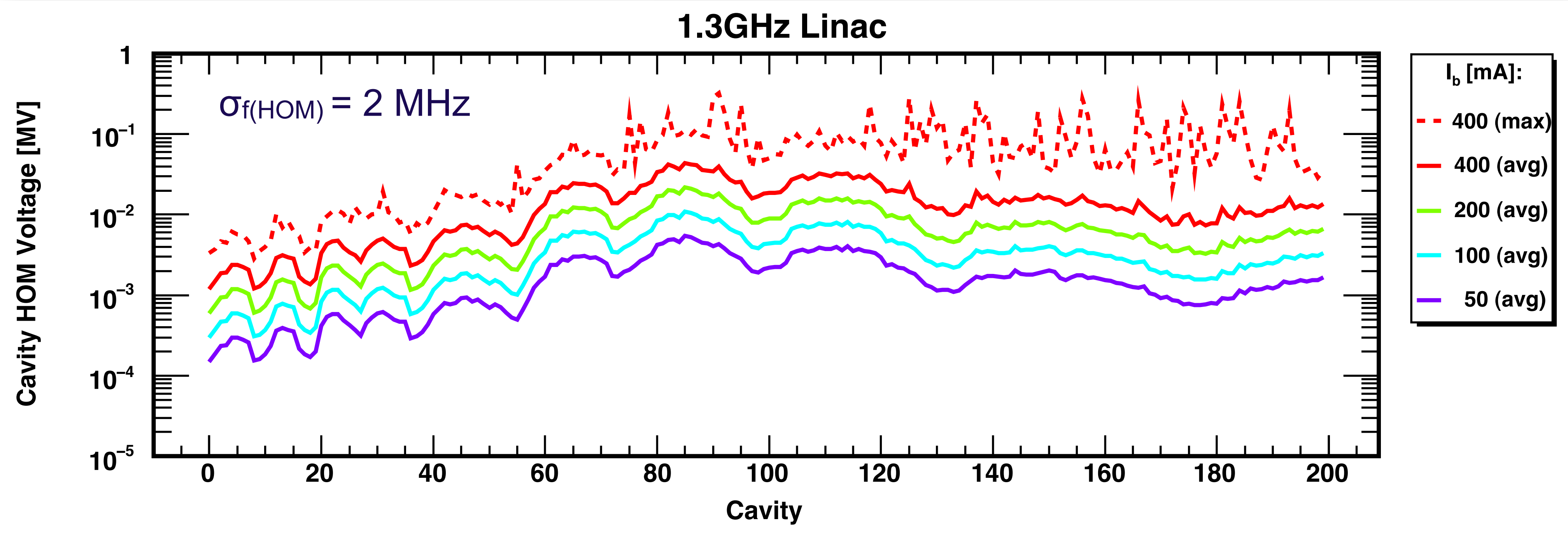
100 linacs simulated:

- mode with highest R/Q (β) present in each cavity
- different HOM frequency patterns along linac
- no HOM voltage present at start
- one pulse simulated
- same injection noise
- same damping in all cavities: $Q_{ex}=10^8$

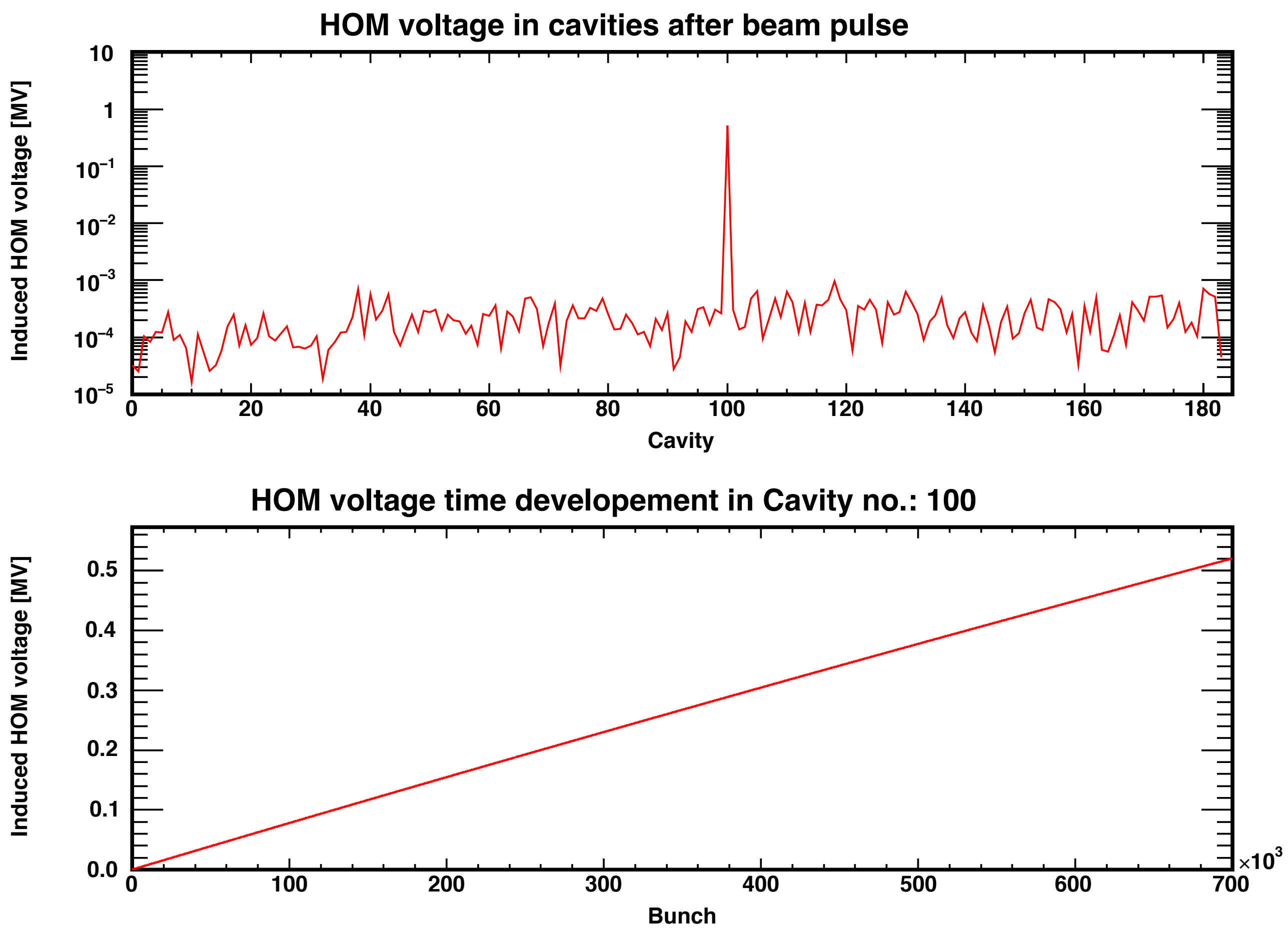


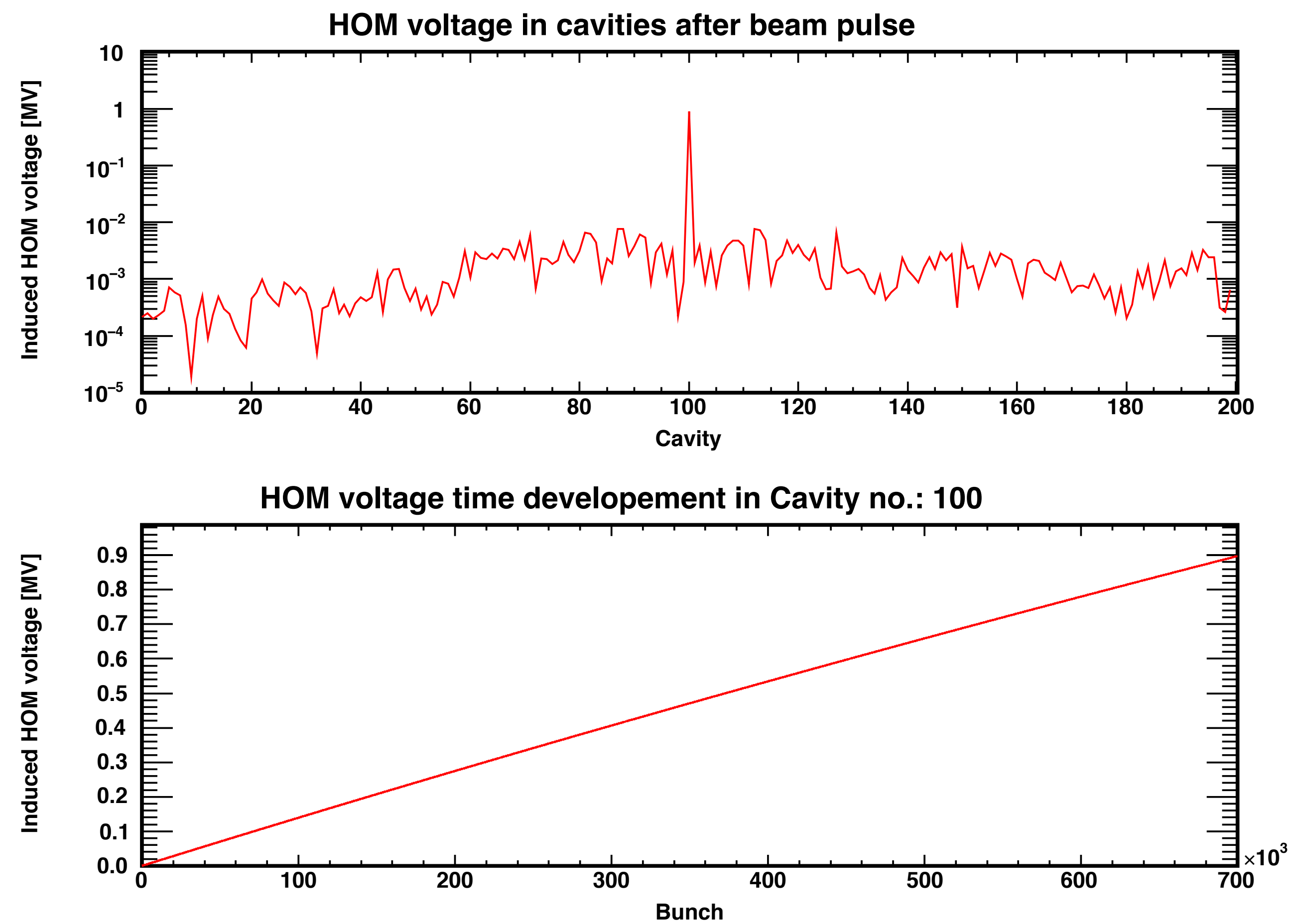


ANKA THZ GROUP

Machine Line

704.4 MHz		1.3 GHz

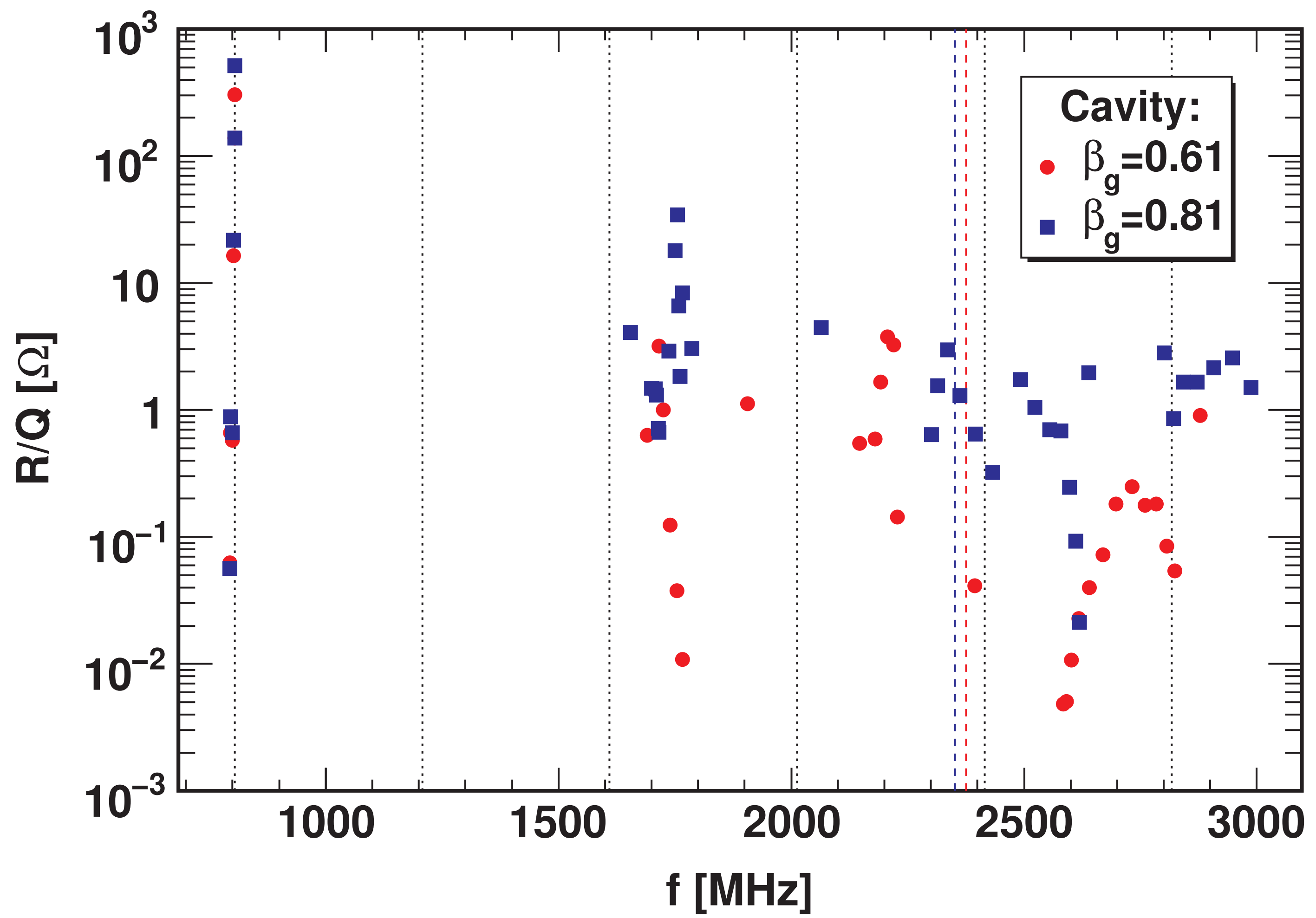




1.761 GHz, 1Ω	f_{res}, R/Q	2.925 GHz, 1Ω
50mA	I_b	50mA
0	Δf	0
10^8	Q_{ex}	10^8

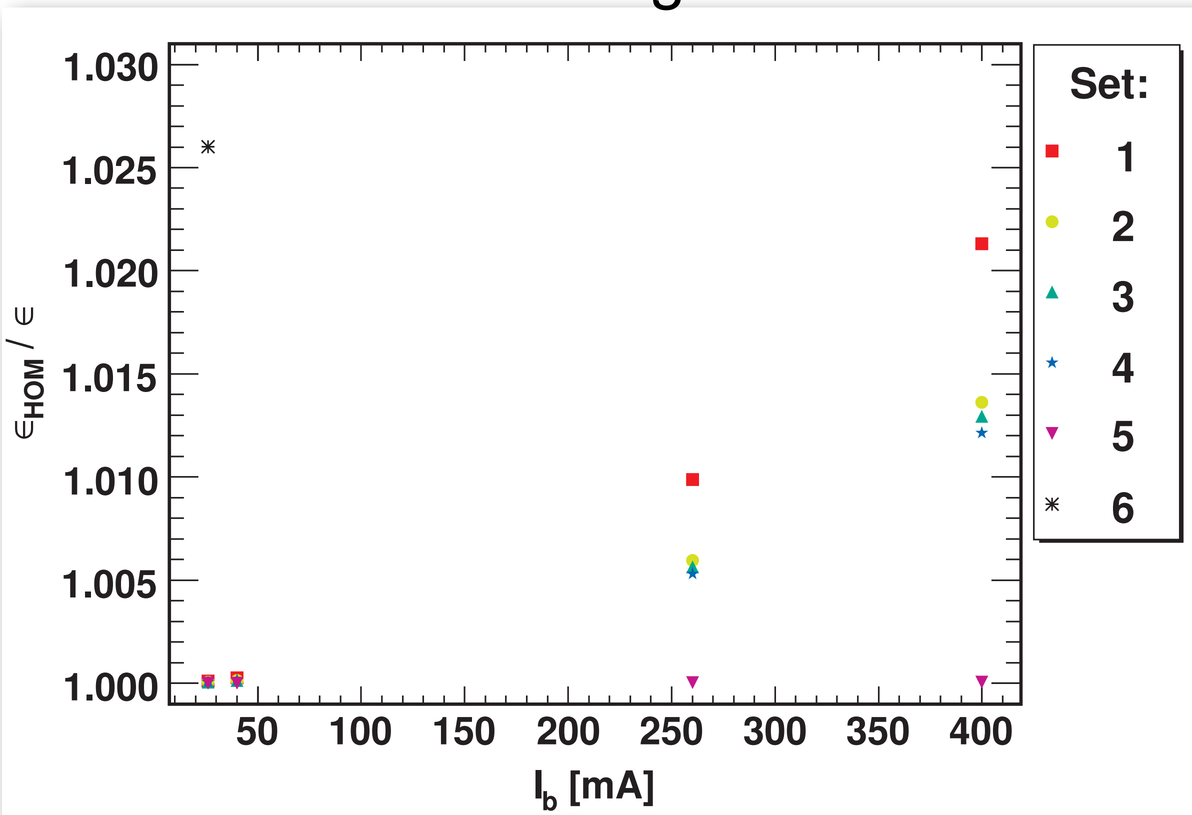
SNS - Parameters

Parameter	Unit	Value	
Beam power	[MW]		1.0
Repetition rate	[Hz]		60.0
Average pulse current	[mA]		26
Peak pulse current	[mA]		38
Beam pulse length	[ms]		1
Sub-pulse length	[μs]		645
Sub-pulse repetition rate	[MHz]		1.059
Bunch frequency	[MHz]		402.5
Sections		$\beta_g = 0.61$	$\beta_g = 0.81$
Output energy	[MeV]	379	1,000
Number of cavities		33	48
Cavities per cryostat		3	4
Period length	[m]	5.839	7.891
Operation phase	[deg]	-20.5	-19.5
Q_{ex} Power Coupler		$7.3 \cdot 10^5$	$7.0 \cdot 10^5$
Q_{ex} HOM Coupler		10^4	10^4
Length	[m]	64	95
Cavities		$\beta_g = 0.61$	$\beta_g = 0.81$
Cells		6	6
Frequency	[MHz]	805	805
Geometrical beta β_g		0.61	0.81
$(R/Q)(\beta_g)$	[Ω]	279	483
$E_0T(\beta_g)$	[MV/m]	10.1	15.8
Beam	Unit	Value	Variation
Injection energy	[MeV]	185.6	0.07
Injection phase	[deg @ 805 MHz]	-20.5	0.225
Beam current	[mA]	0.26-0.4	0.3%
RF Errors			
Amplitude			0.5%
Phase	[deg @ 805 MHz]		0.5

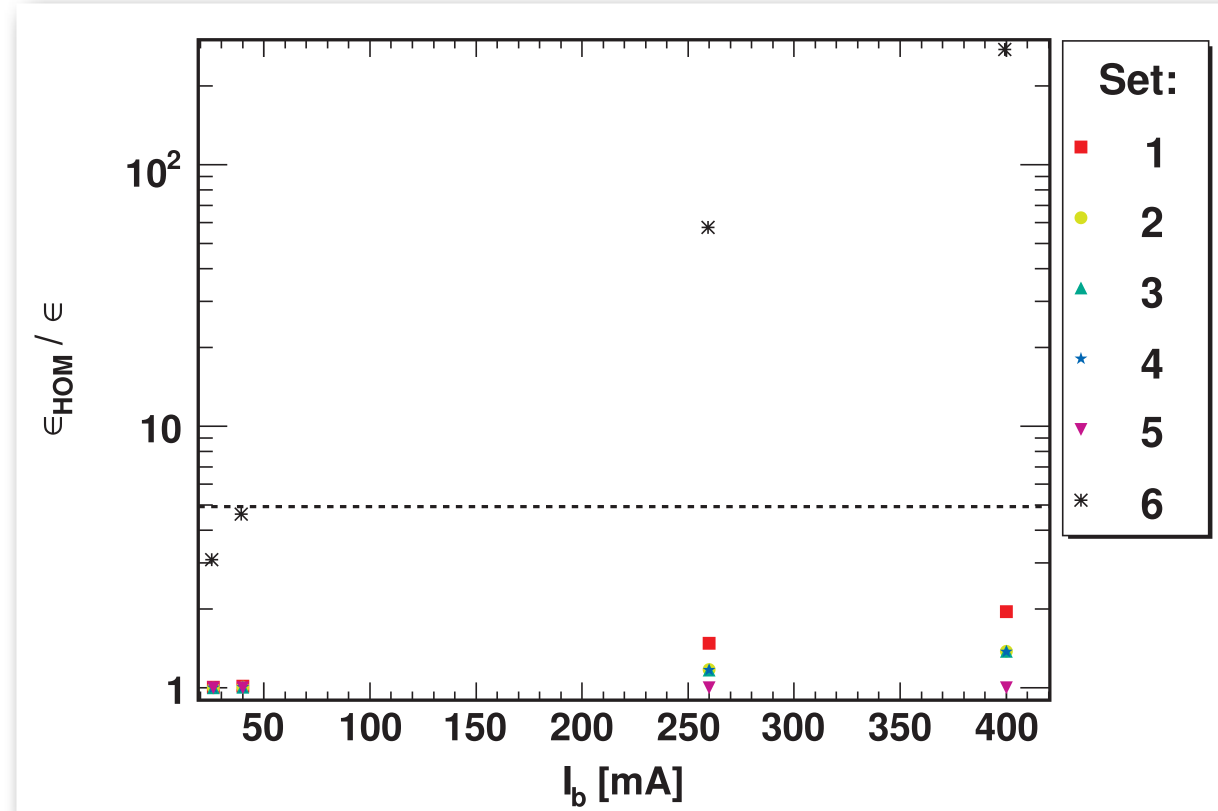


SNS Simulations

Average



Max



	Q_{ex}			
Set	$\beta_g = 0.61$	$\beta_g = 0.81$	σ_q [%]	comment
1	10^8	10^8	1	f_n shifted to chopping machine line
2	10^8	10^8	1	
3	10^8	10^8	0.3	
4	10^4	10^8	0.3	
5	10^4	10^4	0.3	
6	10^8	10^8	1	SPL 5/8 chopping and f_n shifted to chopping machine line

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