International Workshop on Higher-Order-Mode Damping in Superconducting RF Cavities

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HOMs in the Project-X CW linac

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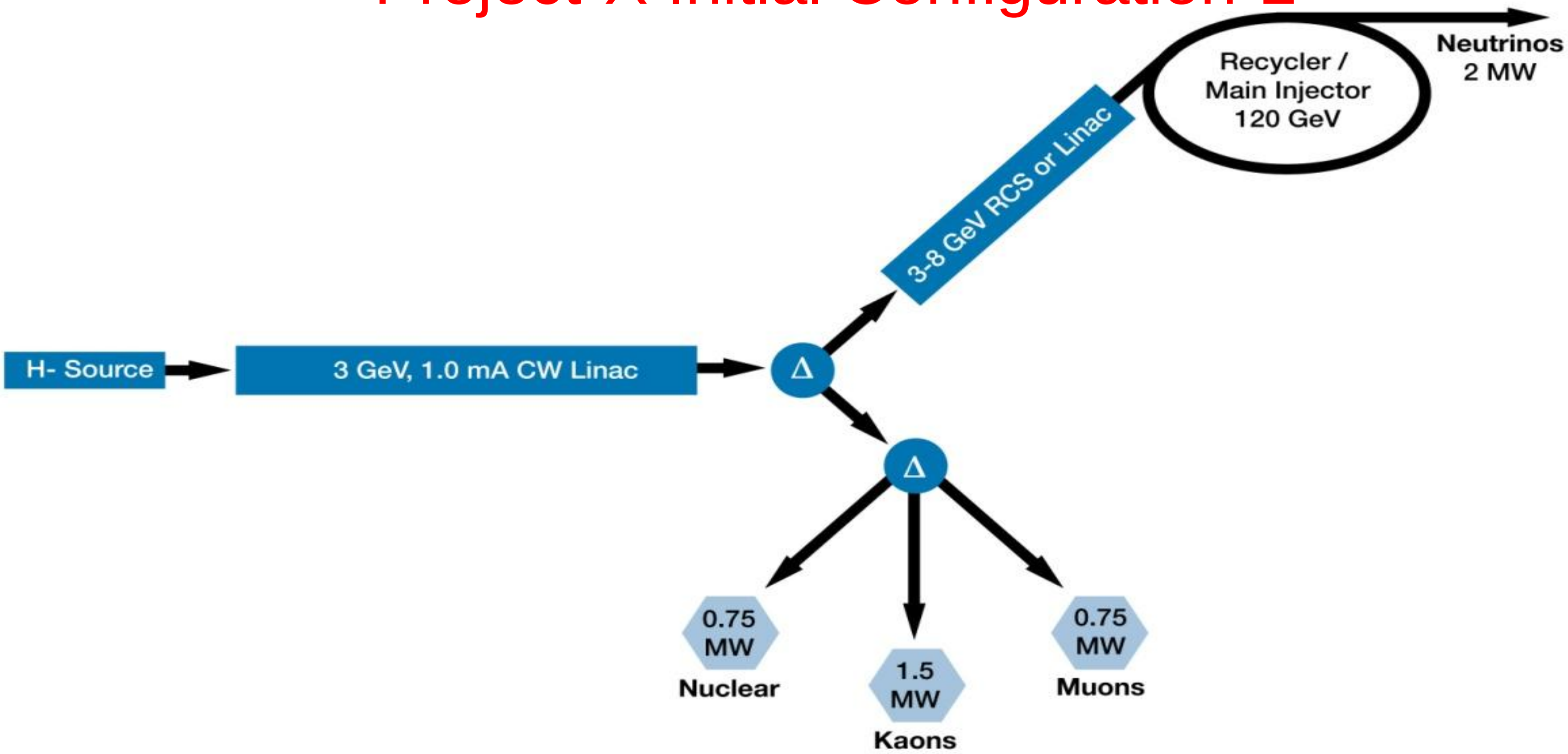
Project X

Fermi National Accelerator Laboratory

Project-X Initial Configuration-2

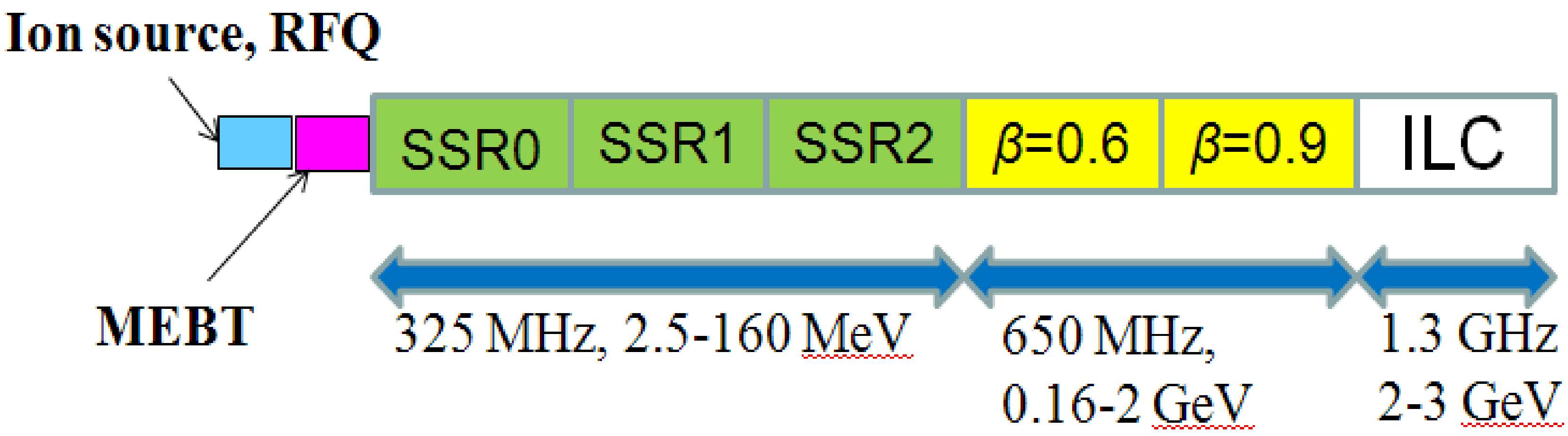


3-GeV, 1-mA CW linac provides beam for rare processes program

- ~3 MW; flexible provision for beam requirements supporting multiple users
- <5% of beam is sent to the MI

Options for 3-8 GeV acceleration: RCS or pulsed linac

- Linac would be 1300 MHz with <5% duty cycle



- The ILC-type 1.3 GHz cavities contain HOM couplers that reduce the loaded Q-factors for transverse and longitudinal HOMs down to 10^5.

- The 5-cell 650 MHz cavities are under development and it is necessary to formulate requirements for Qs of HOMs for these cavities.

Motivation:

•HOM dampers are an expensive and complicated part of SC acceleration structure (problems – multipactoring; additional hardware – cables, feedthrough, connectors, loads; leaks)

•SNS SC linac experience shows that HOM dampers may cause cavity performance degradation during long - term operation;

•SNS linac experience doesn't show necessity of the HOM couplers;

- Analysis of the BBU in SNS linac does not show critical influence of the HOMs on the beam dynamics;

- Our goal is to understand the HOM influence on the beam dynamics in Project X in order to decide whether we need the HPM dampers in high energy part of the linac and in the low energy part as well.

- In ILC linac HOM dampers are necessary. All 1.3 GHz ILC cavities are equipped by HOM couplers, that work successfully at DESY.

- In the case of future upgrade Project X couplers may become necessary.

HOM Damping Requirements

Project: Project X CW linac

Beam parameter

- Beam current: 1 mA
- Bunch charge: 14 pC
- Bunch length: 1 mm
- Bunch rep. rate: 70 MHz average (I/Qb)

Cavity / Linac parameter

- Total number of cavities: 194
- Cavity frequency: 650 MHz
- Number of cells per cavity: 5
- Longitudinal loss factor at design bunch length: <4 V/pC/cavity

HOM parameter

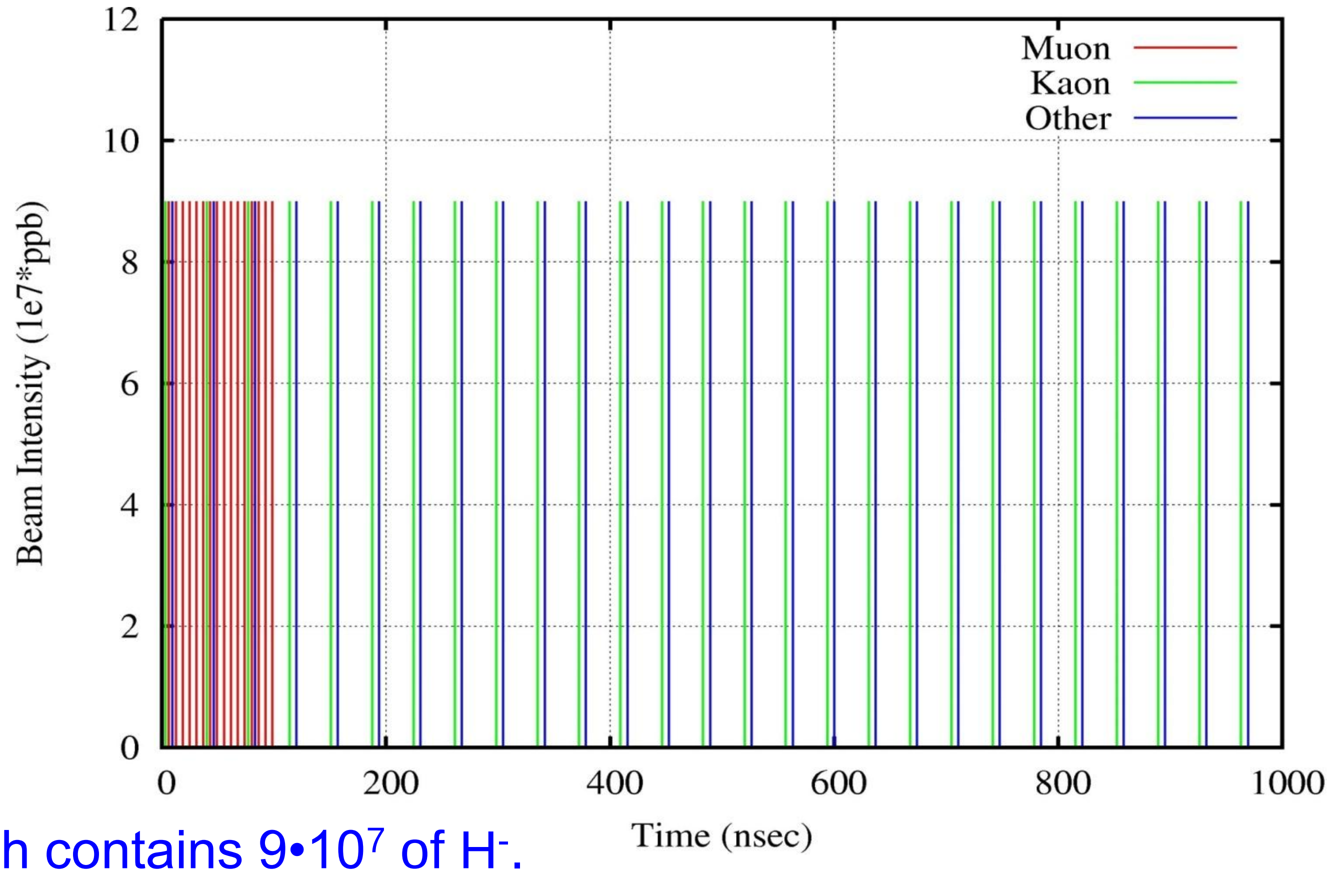
- Average HOM power per cavity ($k \cdot Q_b \cdot I$): 60 mW
- Worst case peak HOM power per cavity in case of resonant excitation of a mode: 2.6 kW (Q=2.e7*)
- 90% of HOM power below: 2.5 GHz

* Q of the most dangerous monopole HOM is determined by the main coupler (coupler window is optimized to provide good transmission for ~1250 MHz)

- Required HOM damping for strongest modes (typical Q-values only!)
  - Monopole modes Q < 2e7**
  - Dipole modes Q < 1.e9
  - Quadrupole modes Q < 1.e10

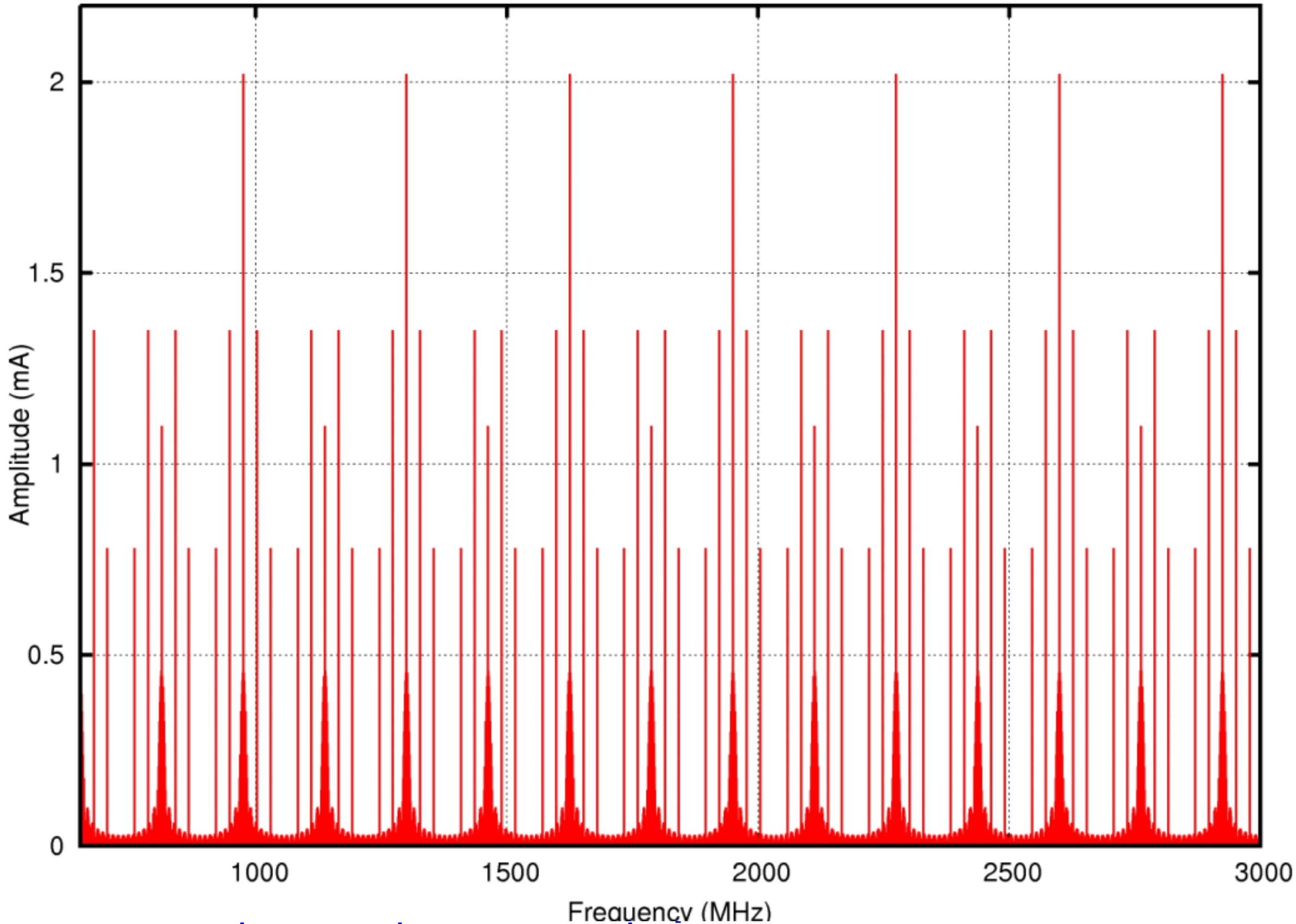
**HOM doesn't dilute emittance even in resonance.

The beam time structure:

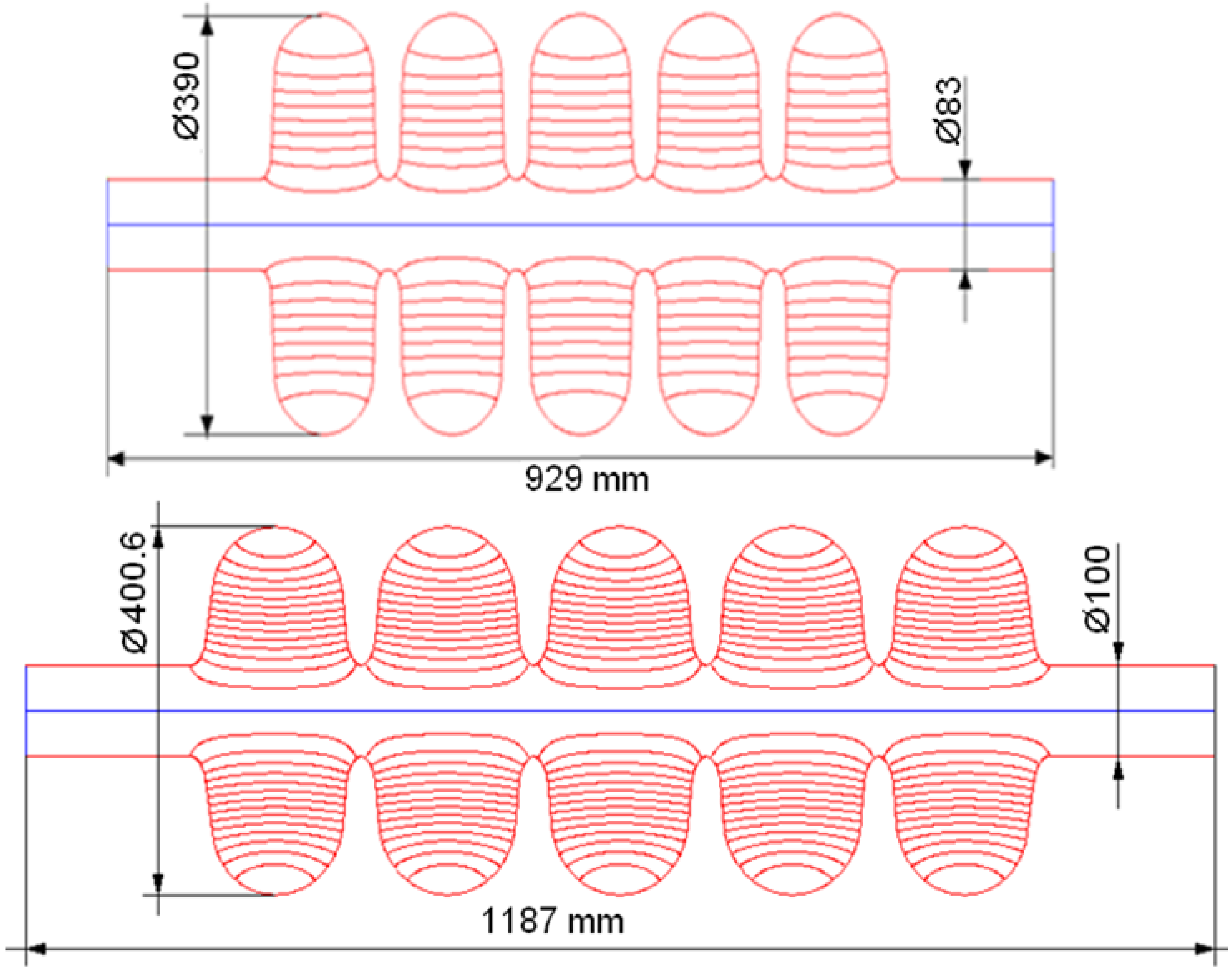


- Each bunch contains $9 \cdot 10^7$ of H^-.
- The bunch sequence frequency for the Mu2e is 162.5 MHz (for the RFQ frequency of 325 MHz) and the bunch train width is 100 nsec when the train repetition rate is 1 MHz.
- The bunch sequence for Kaons and other experiment is 27.08 MHz.
- The beam power for Mu2e is 400 kW, and 800 kW for each other experiment.

Idealized beam spectrum



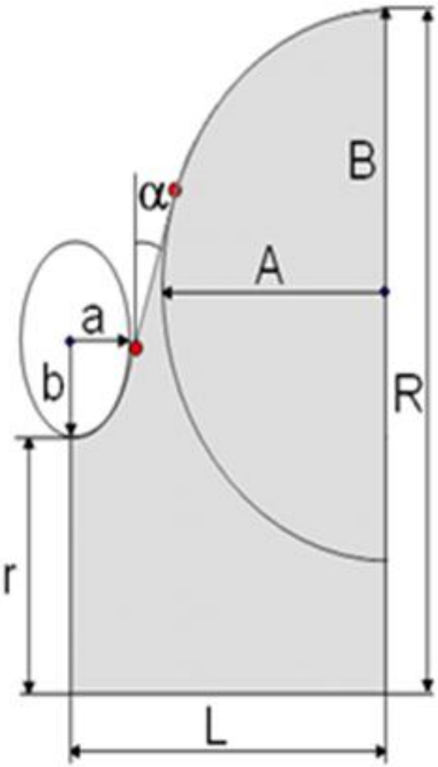
The beam current spectrum contains
(i)harmonics of the bunch sequence frequency 27.08 MHz and
(ii)sidebands of the harmonics of 162.5 MHz separated by 1 MHz.



Layout of 650 MHz cavities.
Beta=0.61 (top) and beta=0.9 (bottom).

Dimensions of the 650 MHz cavities

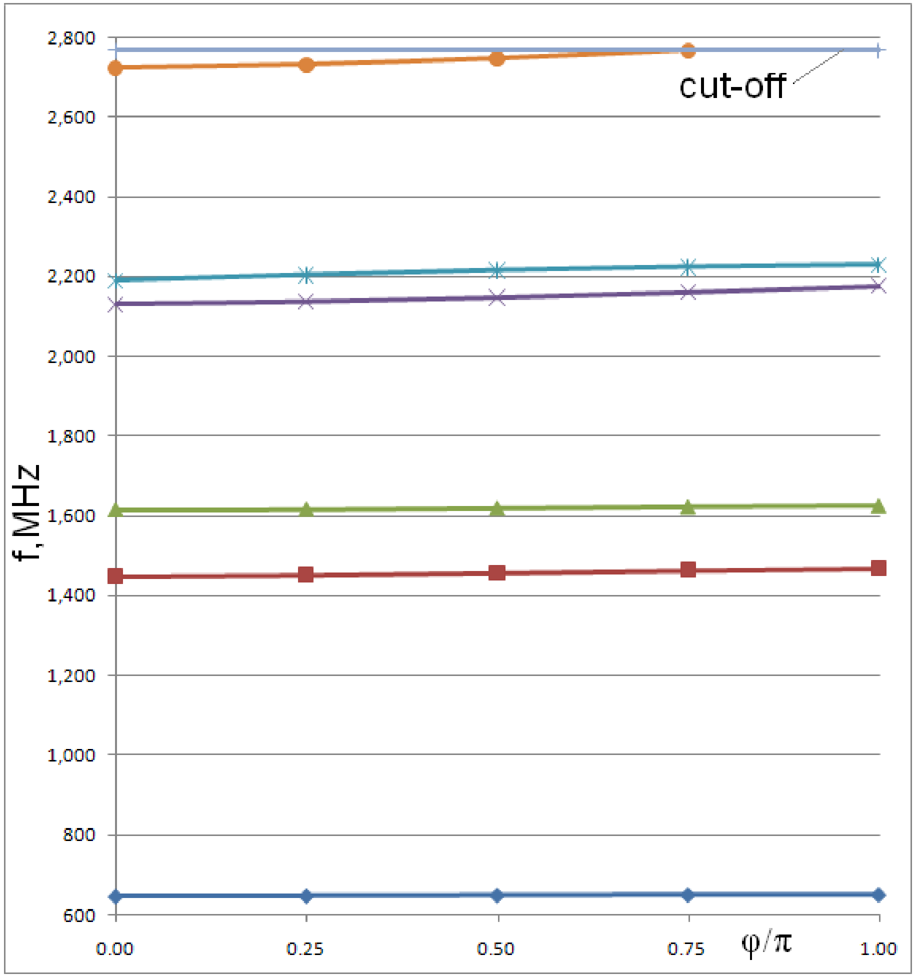
Dimension	Beta=0.61		Beta=0.9	
	Regular cell	End cell	Regular cell	End cell
r, mm	41.5	41.5	50	50
R, mm	195	195	200.3	200.3
L, mm	70.3	71.4	103.8	107.0
A, mm	54	54	82.5	82.5
B, mm	58	58	84	84.5
a, mm	14	14	18	20
b, mm	25	25	38	39.5
α,°	2	2.7	5.2	7

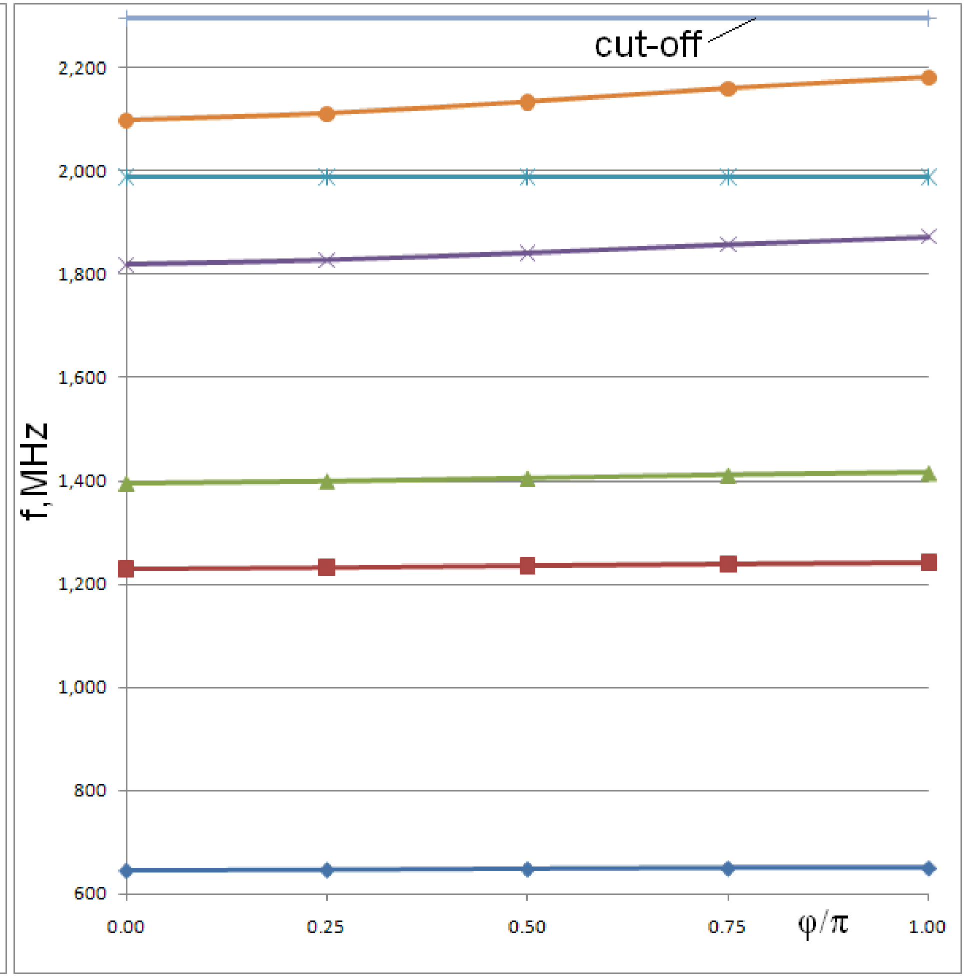


RF parameters of the 650 MHz cavities

Beta	0.61	0.9
R/Q, Ohm	378	638
G-factor, Ohm	191	255
Max. gain per cavity, MeV(on crest)	11.7	19.3
Gradient, MeV/m	16.6	18.7
Max. Surface electric field, MV/m	37.5	37.3
E_{pk}/E_{acc}	2.26	2
Max surf magnetic field, mT	70	70
B_{pk}/E_{acc}	4.21	3.75
Coupling, %	0.68	0.75

Monopole mode spectrum

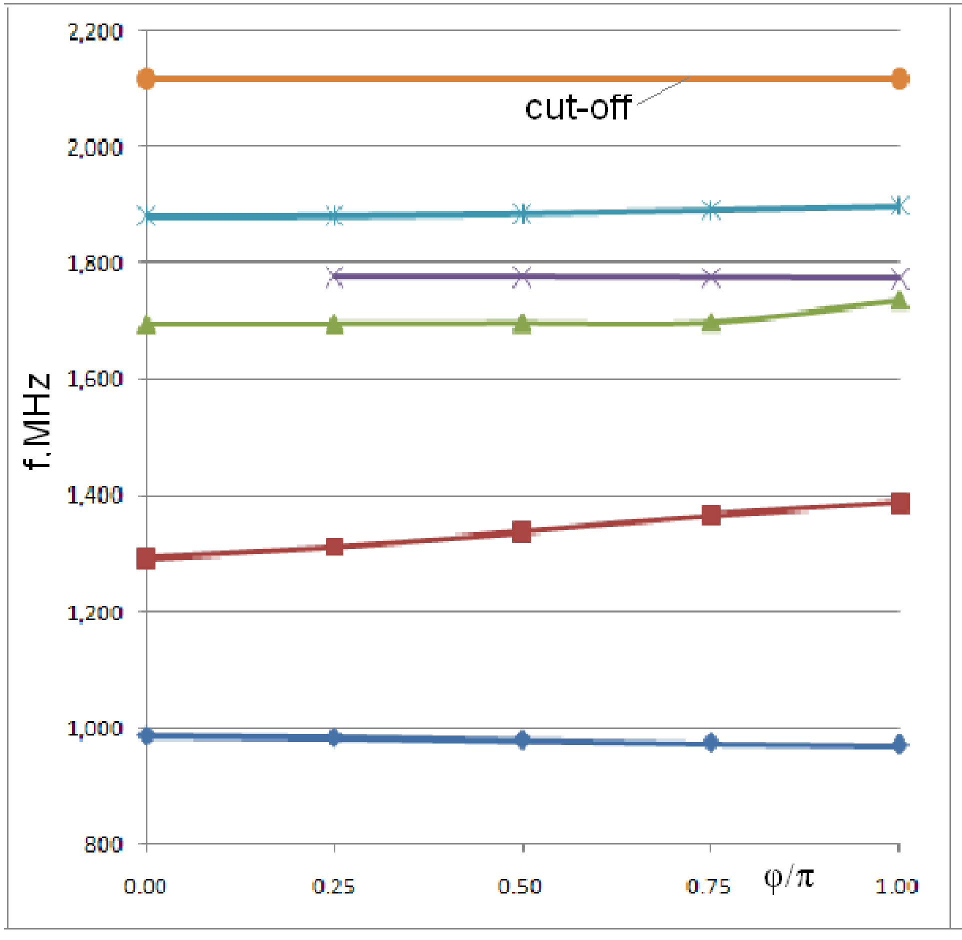


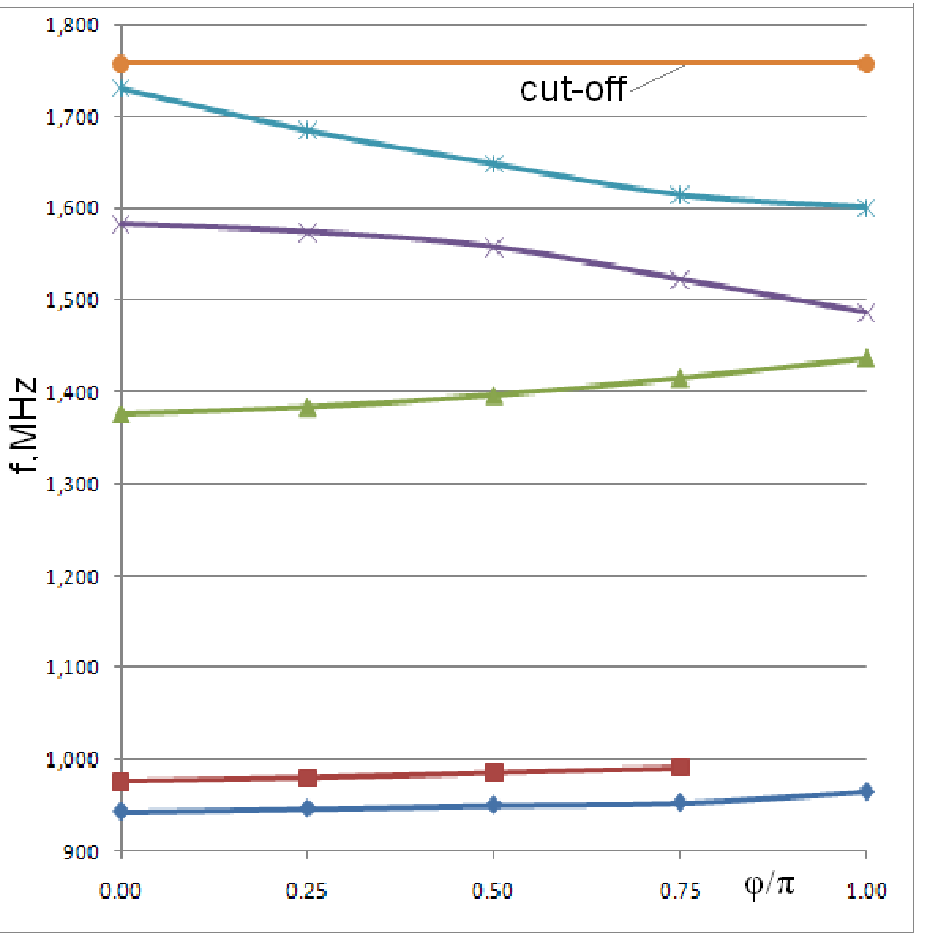


β = 0.61

β = 0.9

Dipole mode spectrum

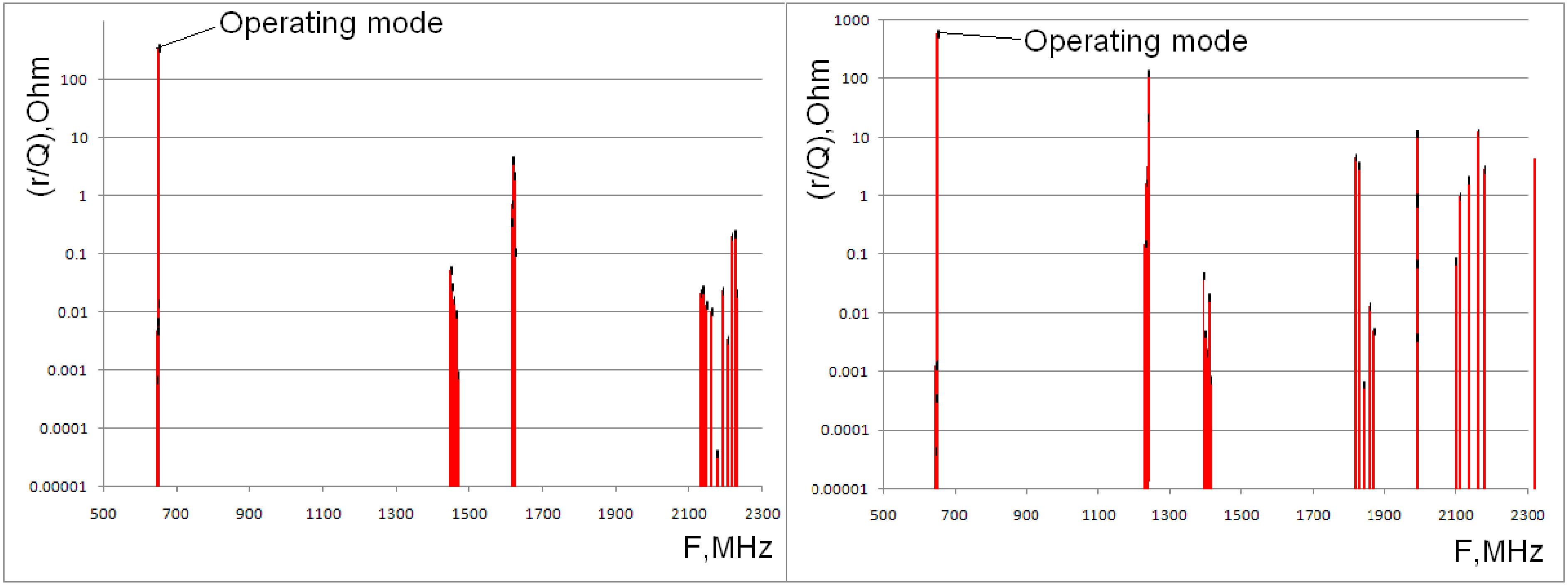




β = 0.61

β = 0.9

Impedances of monopole modes



β = 0.61 β = 0.9

- For β = 0.61: all the modes have (r/Q) below 10 Ohms;
- For β = 0.90:

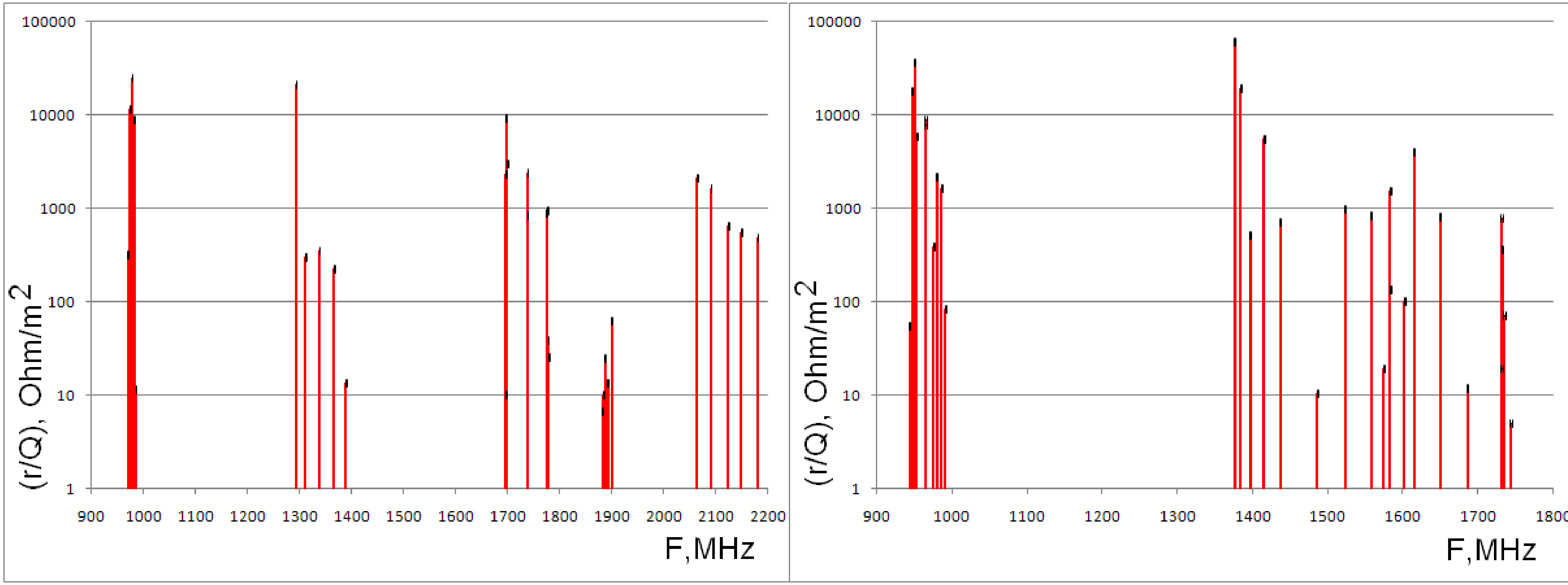
-two modes have (r/Q) ~10 Ohm: F=1988 (df=11 MHz) and 2159 MHz (df=7 MHz),

-one mode has (r/Q) = 22 Ohm: F=1238.6 MHz (df=7 MHz) , and

-one mode has (r/Q) = 130 Ohm: F=1241 MHz (df=5 MHz)

df is the difference between the HOM frequency and nearest main beam spectrum line.

Impedances of dipole modes

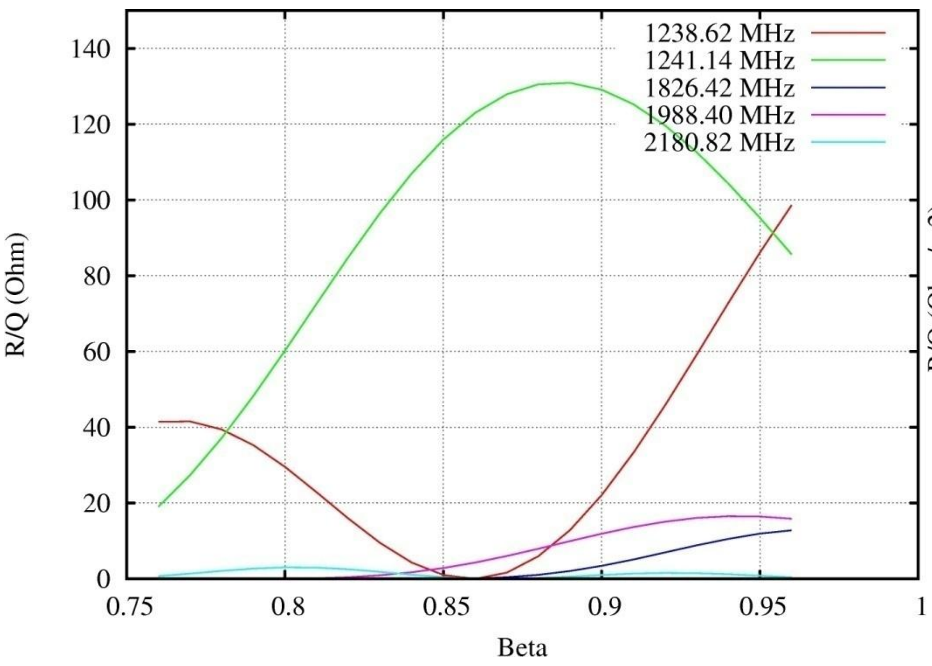


β = 0.61 β = 0.9

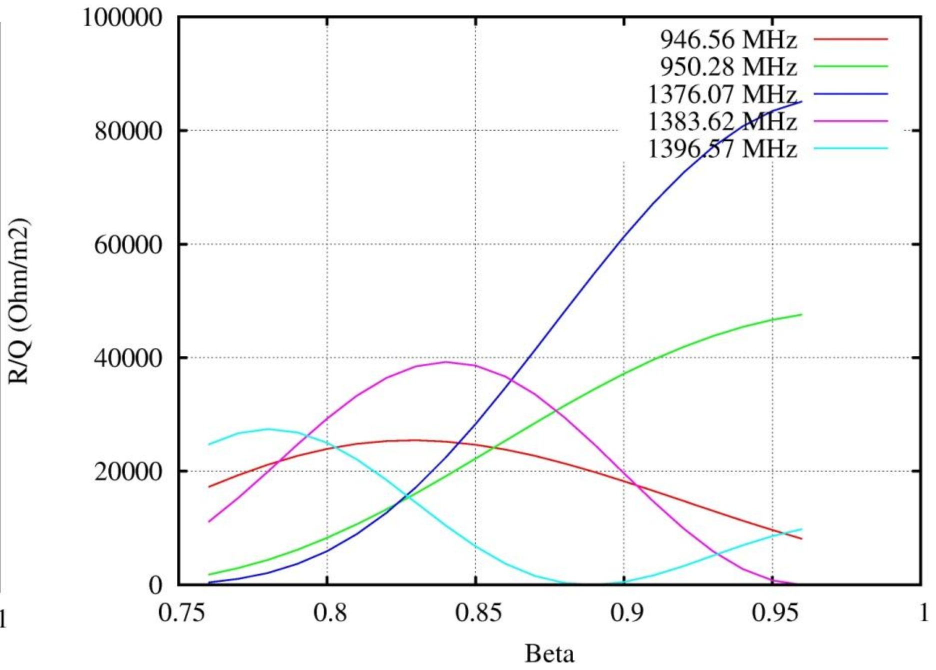
- For β = 0.61 three modes have (r/Q) above 10^4 Ohm/m^2 (F=974, 978.6 and 1293 MHz);

- For β = 0.90 four modes have (r/Q) above 10^4 Ohm/m^2 (F=946.6, 950.3, 1376 and 1383 MHz).

(r/Q) for HOM modes depends on the particle velocity β: 650 MHz, β=0.9 cavity



a)



b)

Monopole (a) and dipole (b) impedances of "the most dangerous" modes for beta=0.9 cavity versus accelerated particle velocity.

HOM have frequency spread caused by manufacturing errors.

❖For ILC cavity r.m.s. spread of the resonance frequencies is 6-9 MHz depending on the pass band, according to DESY measurement statistics:

J. Sekutowicz, HOM damping," ILC Workshop, KEK, November 13-15, 2004.

❖However, in a process of "technology improvement" r.m.s. frequency spread for HOMs reduced to ~1 MHz:

Effect of the HOMs:

- Resonance excitation;
- Collective effects.

❖Resonance excitation, monopole modes.

Monopole modes should not increase the beam longitudinal emittance ε_z (ε_z= 1.6 keV*nsec):

$$\hat{U}_{HOM}\sigma_t \ll \varepsilon_z,$$

$\hat{U}_{HOM}$ is average energy gain caused by HOM, σ_t is a bunch length. For high-Q resonances

$$\hat{U}_{HOM} \approx \frac{\tilde{I}(R/Q)}{4\sqrt{2}\delta f / f}, \quad \text{and thus,} \quad \delta f >> f\frac{\tilde{I}(R/Q)\sigma_t}{4\sqrt{2}\varepsilon_z}$$

δf is the deference between the HOM frequency f and the beam spectrum line frequency ($\delta f/f \gg 1/Q$). $\tilde{I}$ Is a beam spectrum line amplitude.

The worst case: beginning of the high-beta 650 MHz section.
σ_t *= 7.7e-3 nsec (or 1.8 deg). For* $\tilde{I}$*= 0.5 mA and (R/Q)= 130 Ohm (HOM with the frequency of 1241 MHz) one has*

δf *>> 70 Hz*

- *When the distance between the beam spectrum line and the resonance frequency is 5 MHz, and the frequency spread is 5 MHz too, the probability that the cavity has the resonant frequency close enough to the beam spectrum line is ~1e-5.*
- *The gain caused by the HOM is <300 keV, that is small compared to the operating mode gain, ~20 MeV, and does not contribute to the cryogenic losses*

$$\delta P_{loss} \approx \frac{U_{HOM}^2}{(R/Q)Q_0} < 0.15\ W$$

because 1241 MHz mode is TM_{011} mode in a cell, and, thus, it's surface distribution is "orthogonal" to one of the operating mode. Q_0 ~ 5e9.

- If the HOM mode is in resonance, it's Q_{loaded} << 1.8e7.

One should take care on the 2d band monopole HOMs in order to avoid resonance accidental excitation!

❖Resonance excitation, dipole modes.

- Dipole modes should not increase the beam transverse emittance (ε= 2.5e-7/$\beta\gamma$ m).
- Transverse kick caused by the HOM is:

$$U_{kick} \approx \frac{f}{4\delta f}\left(\frac{x_0}{k}\right)\tilde{I}(R/Q)_1, \quad \delta f/f \gg 1/Q$$

($k=2\pi/\lambda$)

- Emittance increase $\delta\varepsilon$ may be estimated the following way:

$$\delta\varepsilon \approx \Delta x' \sigma_x = \frac{U_{kick}}{\sqrt{2}p_{||}c}\sqrt{\varepsilon\beta_f}$$

β_f is beta-function near the cavity.

- Thus,

$$\delta f \ll \frac{c x_0 \tilde{I}(R/Q)_1}{8\sqrt{2}\pi\beta\gamma U_0\sqrt{\varepsilon/\beta_f}}$$

U_0 is proton rest mass in *eV*.

- For f=1376 MHz, $(R/Q)_1$=60 kOhm/m^2 (worst case), proton energy of 500 MeV, β_f=2.5 m and x_0=1 mm one has

δf >> 1 Hz.

Does not look to be a problem.

- If the HOM is in resonance, Q << 1.4e9.

What to do if the HOM has resonance frequency close to the beam spectrum line*?

- Even in the case when it happens, it is possible to move the HOM frequency away from the spectrum line simply detuning the cavity by tens of kHz, and then tune the operating mode back to the resonance.

- A special test was made with the 1.3 GHz, 9-cell ILC cavity. The cavity was tested **at 2 K**.

- The operating mode was detuned by Δf=90 kHz, and then was tuned back.

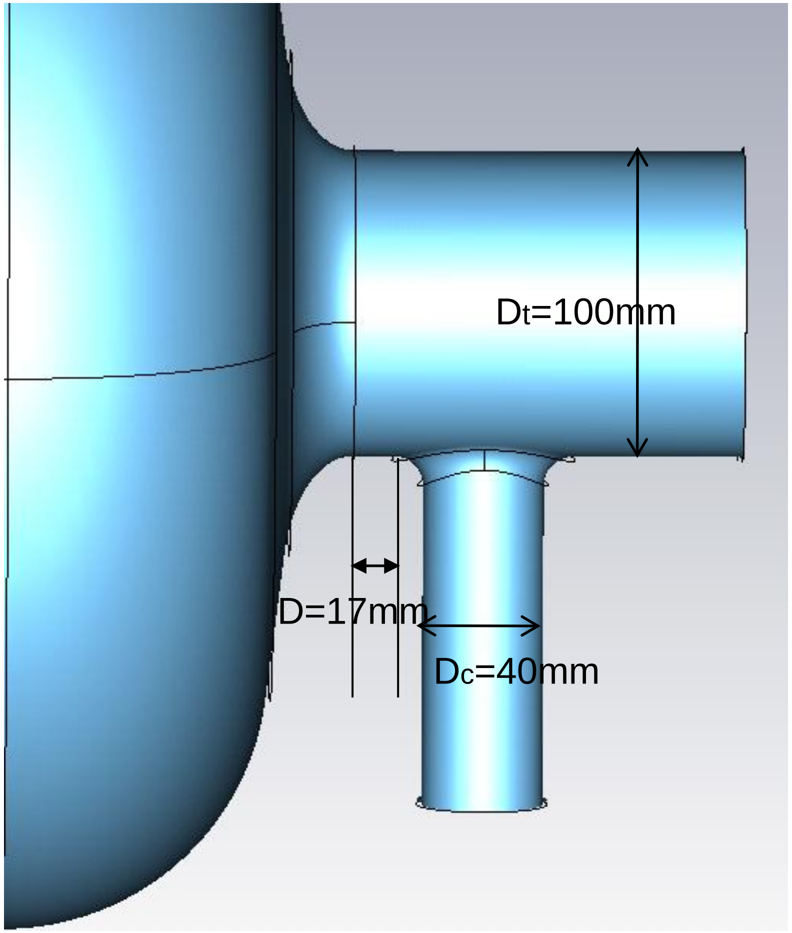
- The frequencies of HOMs moved after this procedure by δf=100-500 Hz because of small residual deformation of the cavity.

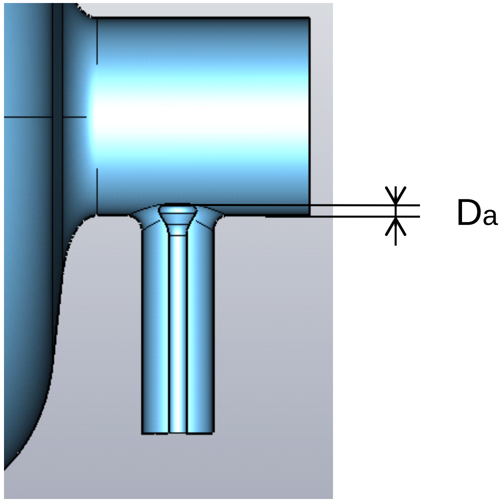
f, MHz	Δf, kHz	δf, Hz	Passband
1300	90	0	1Monopole
1600.093	-218	360	1Dipole
1604.536	-215	240	1Dipole
1607.951	-214	360	1Dipole
1612.189	-210	360	1Dipole
1621.344	-211	240	1Dipole
1625.458	-208	370	1Dipole
1830.836	-185	370	2Dipople
1859.882	-36	120	2Dipople
2298.807	-278	480	1Quadrupole
2299.346	-278	490	1Quadrupole
2372.333	-224	490	2Monopole
2377.333	-221	490	2Monopole
2383.575	-213	240	2Monopole
2399.289	-210	490	2Monopole

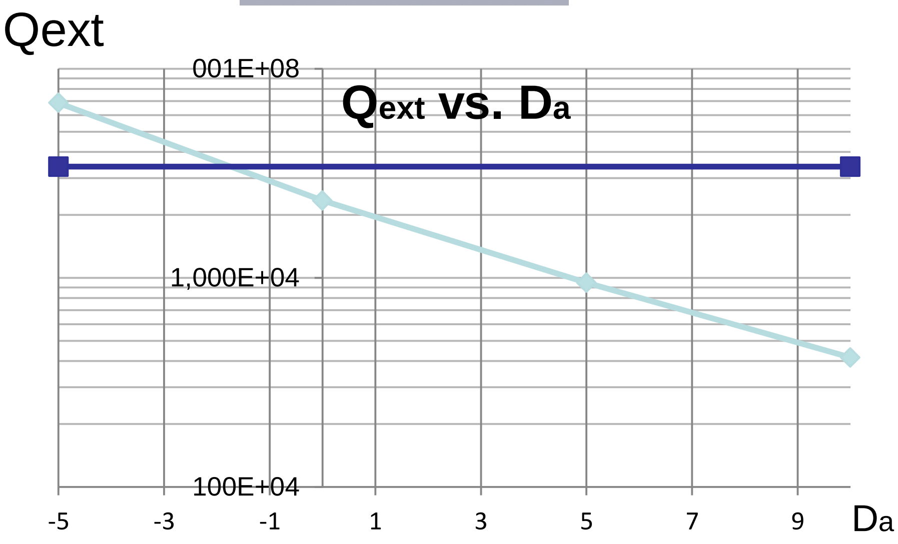
**Timergali Khabiboulline, this workshop*

HOM damping through the main coupler.

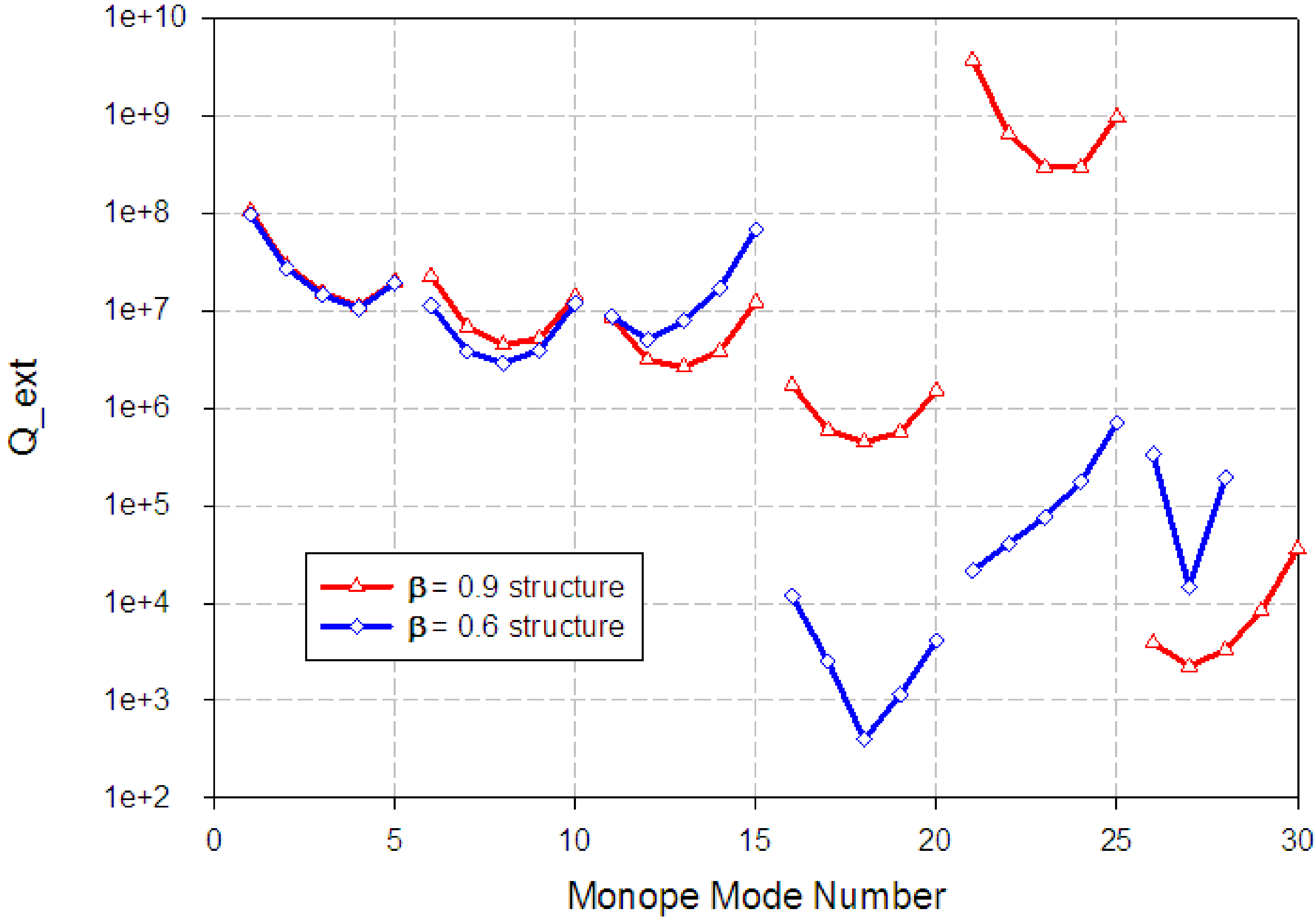
Main coupler should provide Q_{ext} ~ 2-3e7 for the operating mode.







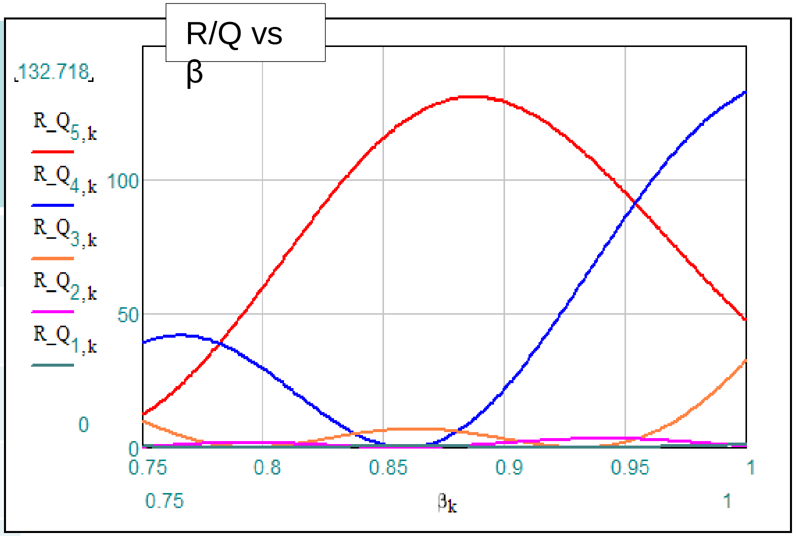
HOM damping through the main coupler (perfect window transmission).

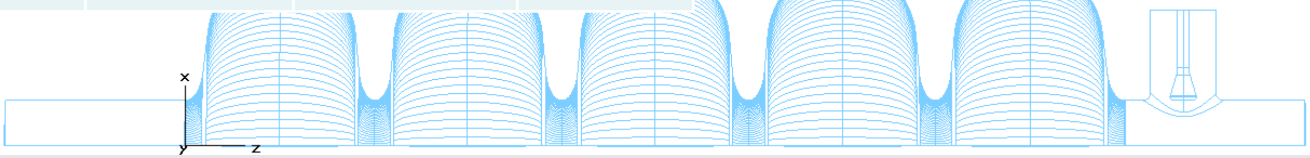


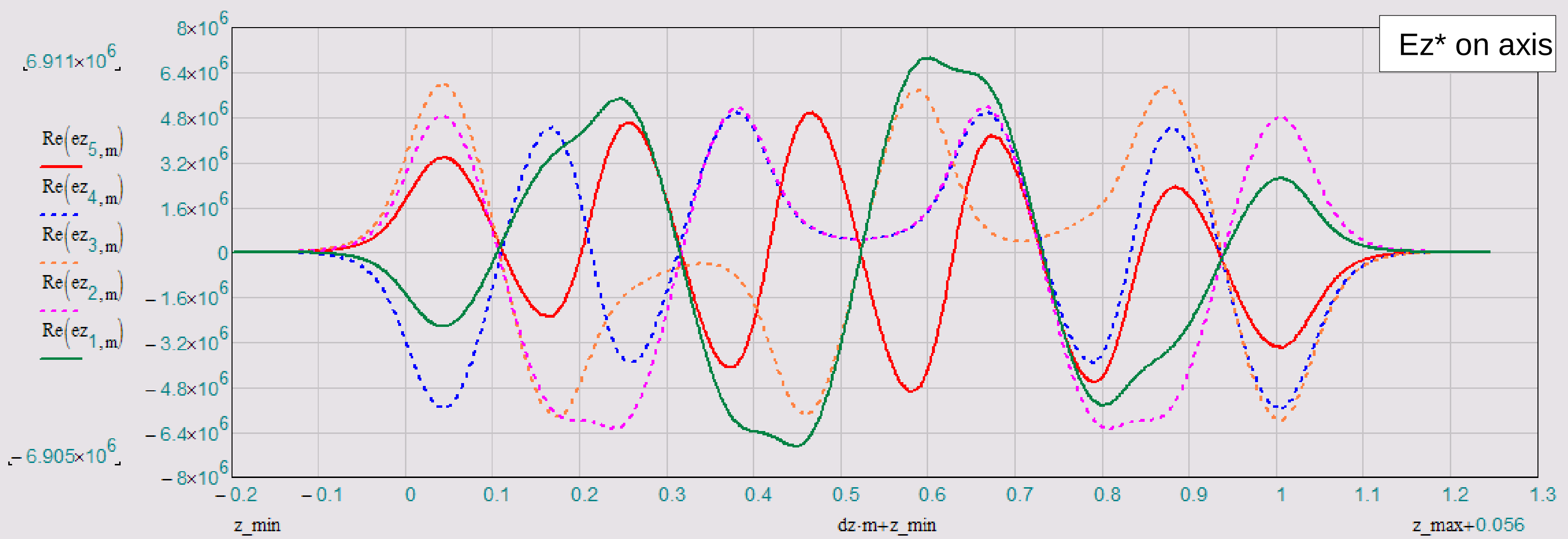
The coupler window is optimized to provide a good transmission for the 2d pass band

Monopole Band #2

Mode #	Freq [GHz]	Q_ext	R/Q max [Ω]	β max
1/5π	1.229017	2.27E+07	1.0	1
2/5π	1.231639	6.83E+06	3.4	0.941
3/5π	1.235158	4.46E+06	32.8	1
4/5π	1.238620	5.19E+06	132.6	1
π	1.241131	1.41E+07	130.9	0.887

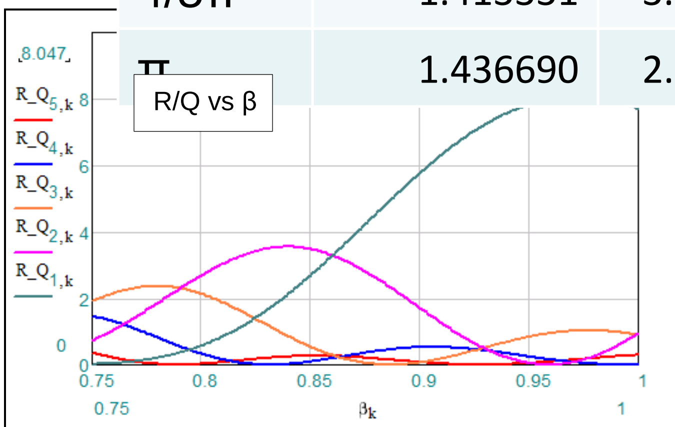


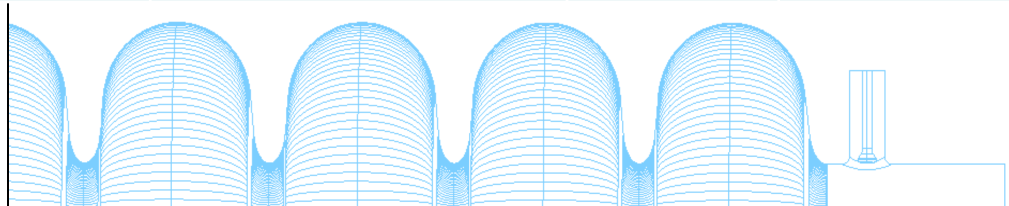


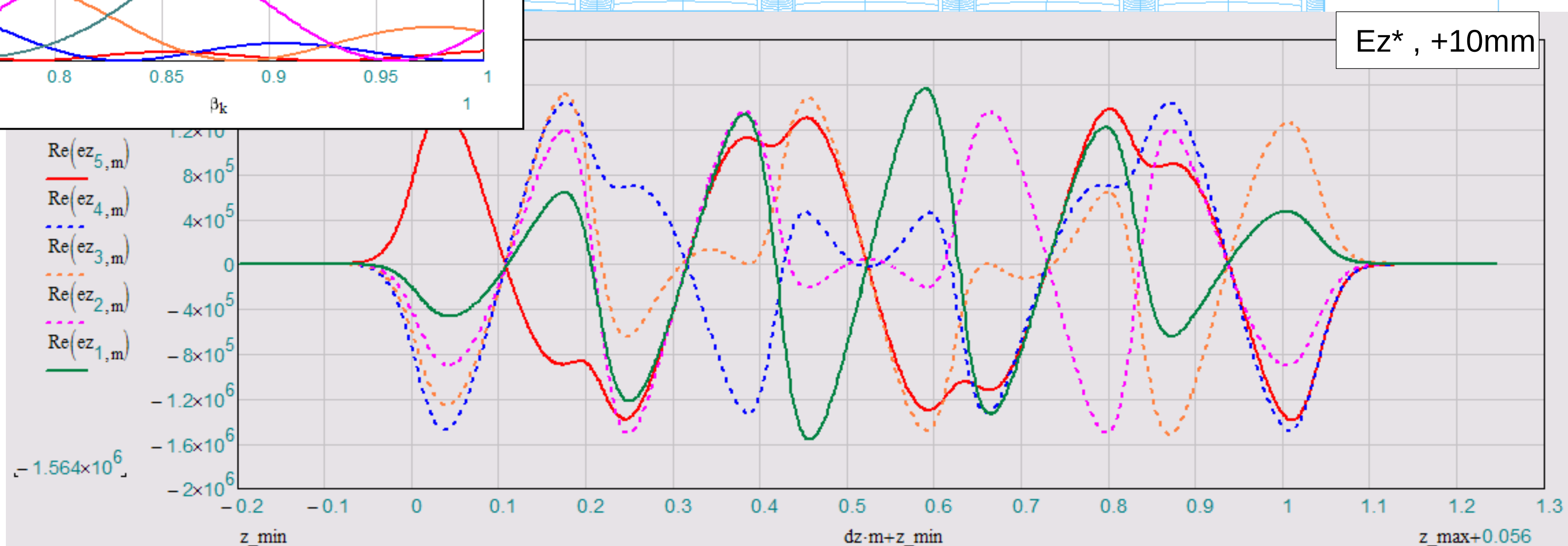


Dipole Band #3

Mode #	Freq, [GHz]	Q_ext	R/Q (max), [Ω/cm]	β (max)	W, [J]
1/5π	1.373530	9.86E+06	8.0	0.972	7.180E-16
2/5π	1.381113	2.10E+06	3.5	0.839	1.649E-16
3/5π	1.394238	7.58E+05	2.4	0.779	6.676E-17
4/5π	1.413331	3.57E+05	1.5	0.75	3.589E-17
π	1.436690	2.62E+05	0.4	0.75	2.996E-17







*Optimal polarization

Incoherent losses:

K_{loss} = 4V/pC (sigma=1 mm, beta=0.95)

P_{ic} ~ K_{loss}*Q*I=**60** mW for Q=14.4 pC (beam intensity 9e7 ppb), I=1 mA.

Q is the bunch charge,
I is a beam current.

Collective effects:

- Beam break –up (BBU) , transverse.

- “Klystron-type” , longitudinal.

Why collective effects may not be an issue:

1. No feedback as in CEBAF;
2. Different cavity types with different frequencies and different HOM spectrum are used;
3. Frequency spread of HOMs in each cavity type, caused by manufacturing errors;
4. Velocity dependence of the (R/Q);
5. Small beam current.

Transverse dynamics.

BBU estimations for 650 MHz part of the Project – X linac:

Simple model:

- Short bunches;
- Current lattice design - N. Solyak, et al;
- Two types of the 650 MHz cavities, beta=0.61 and beta=0.9;
- Five dipole pass bands are taking into account;
- Random transverse misalignment of the cavities;
- Beam time structure – S. Nagaitsev (see above)
- Model:

$$U'_{n+1} = U'_n e^{i\omega_{HOM}T - T/\tau} - \frac{1}{2} Q R_{\|}^{(1)} \omega_{HOM} (x - x_{cavity});$$

$$\Delta p_{\perp} c = Re(i\frac{v}{\omega}U'); \quad U' \equiv \nabla_{\perp} \int_{-\infty}^{\infty} E_z(z,x) e^{i\omega z/v} dz$$ (P-W)

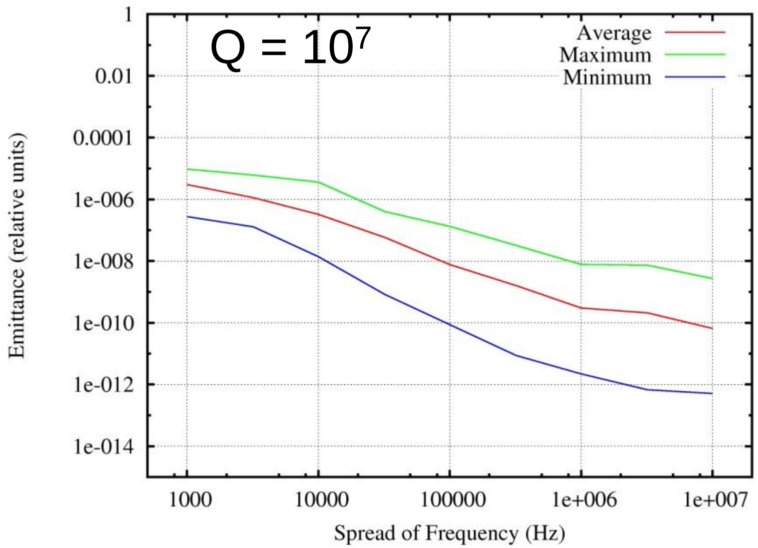
Parameters:

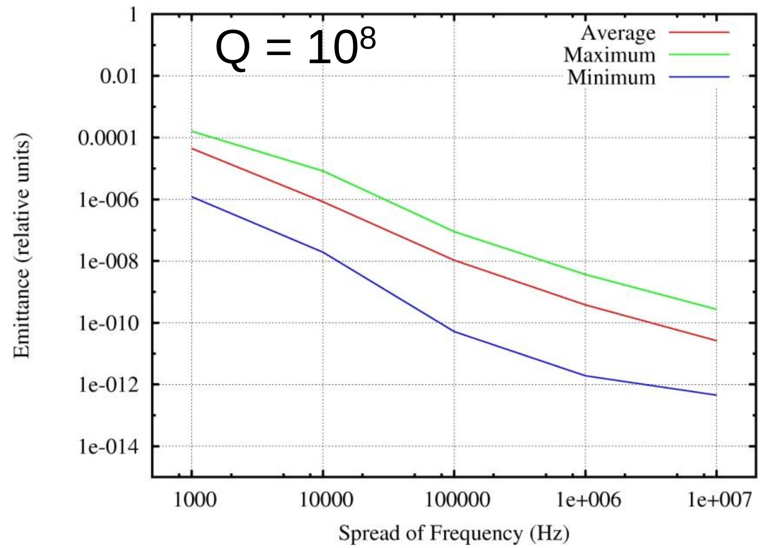
- Beam current: 1 mA;
- RFQ frequency: 325 MHz;
- r.m.s cavity off-set: 0.5 mm;

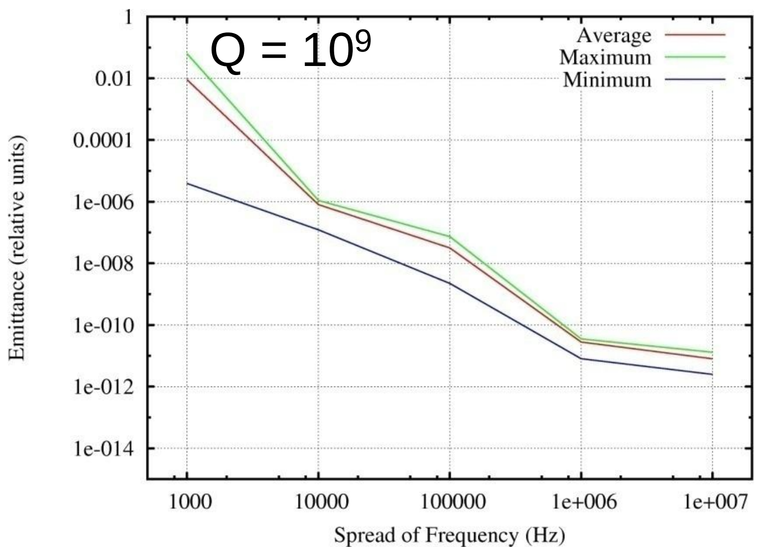
Transverse emittance dilution vs. HOM frequency spread Δf.

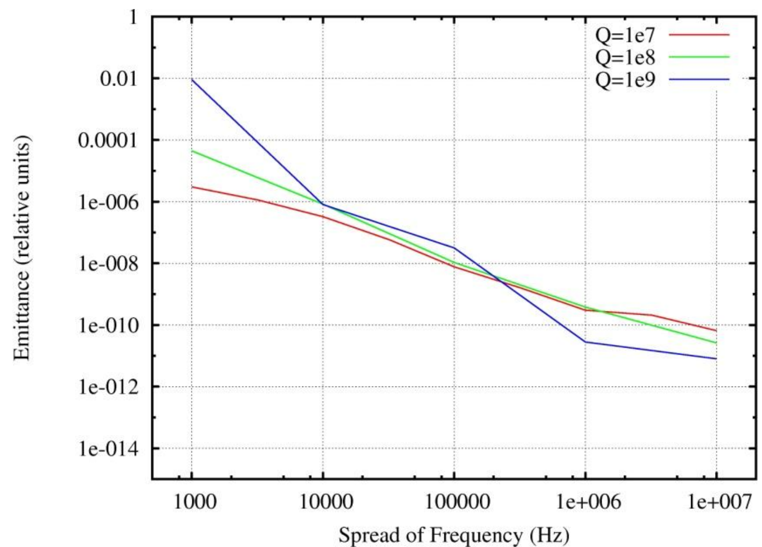
- Low beta section,
- Resonance case,
- One HOM only, (978.5 MHz, 24 kOHm/m^2)
- No dependence of (R/Q) on beta.

$\Delta\varepsilon \sim \Delta f^{-2}$

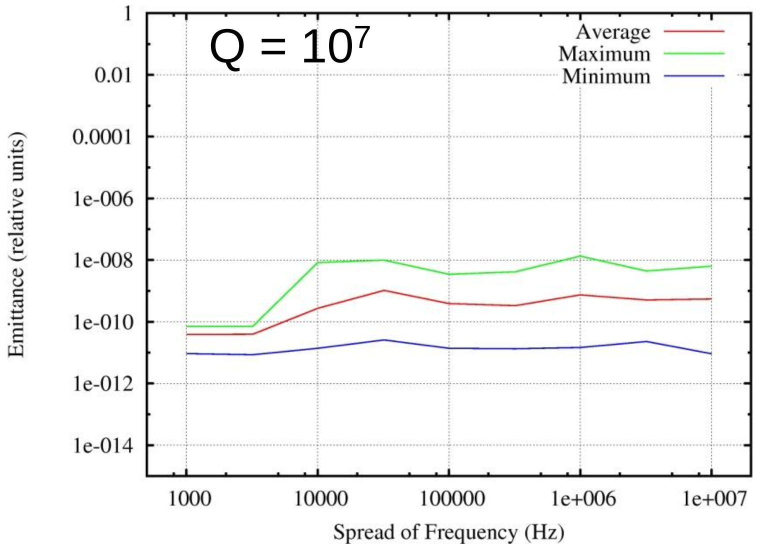


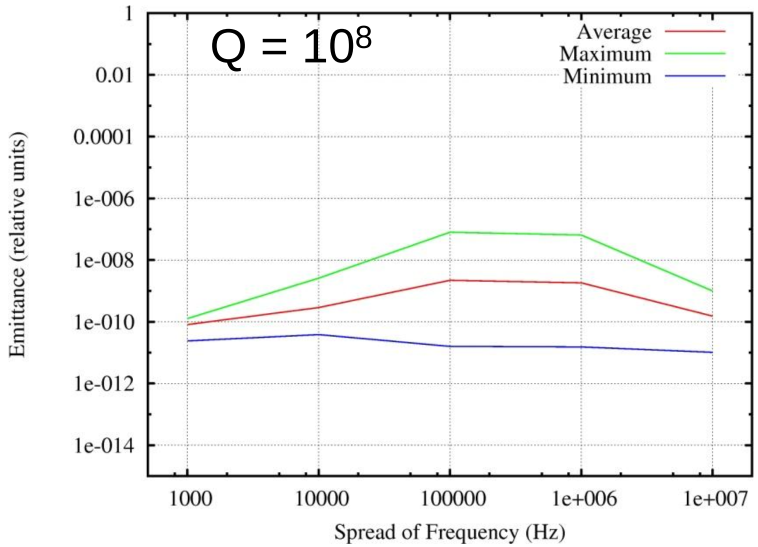


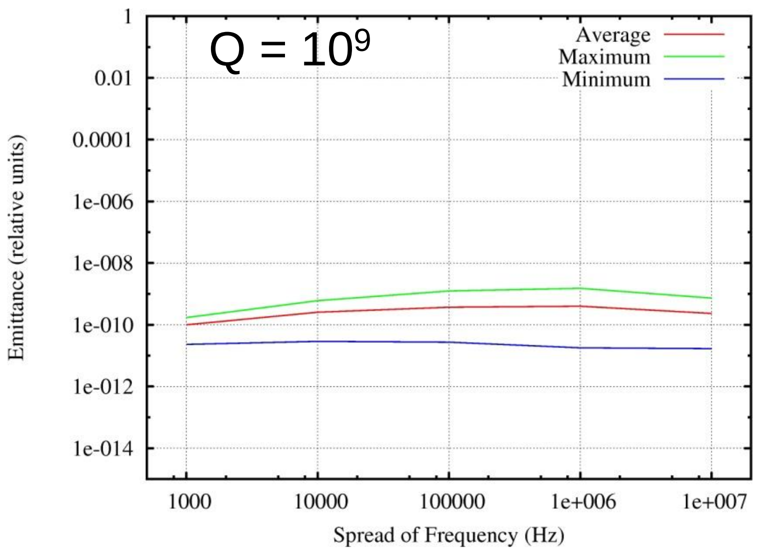


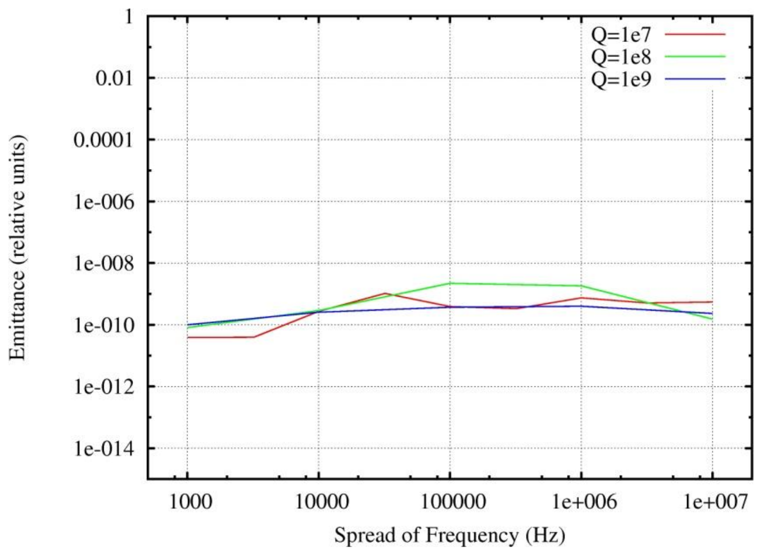


“Realistic” linac. Transverse emittance dilution vs. Δf.



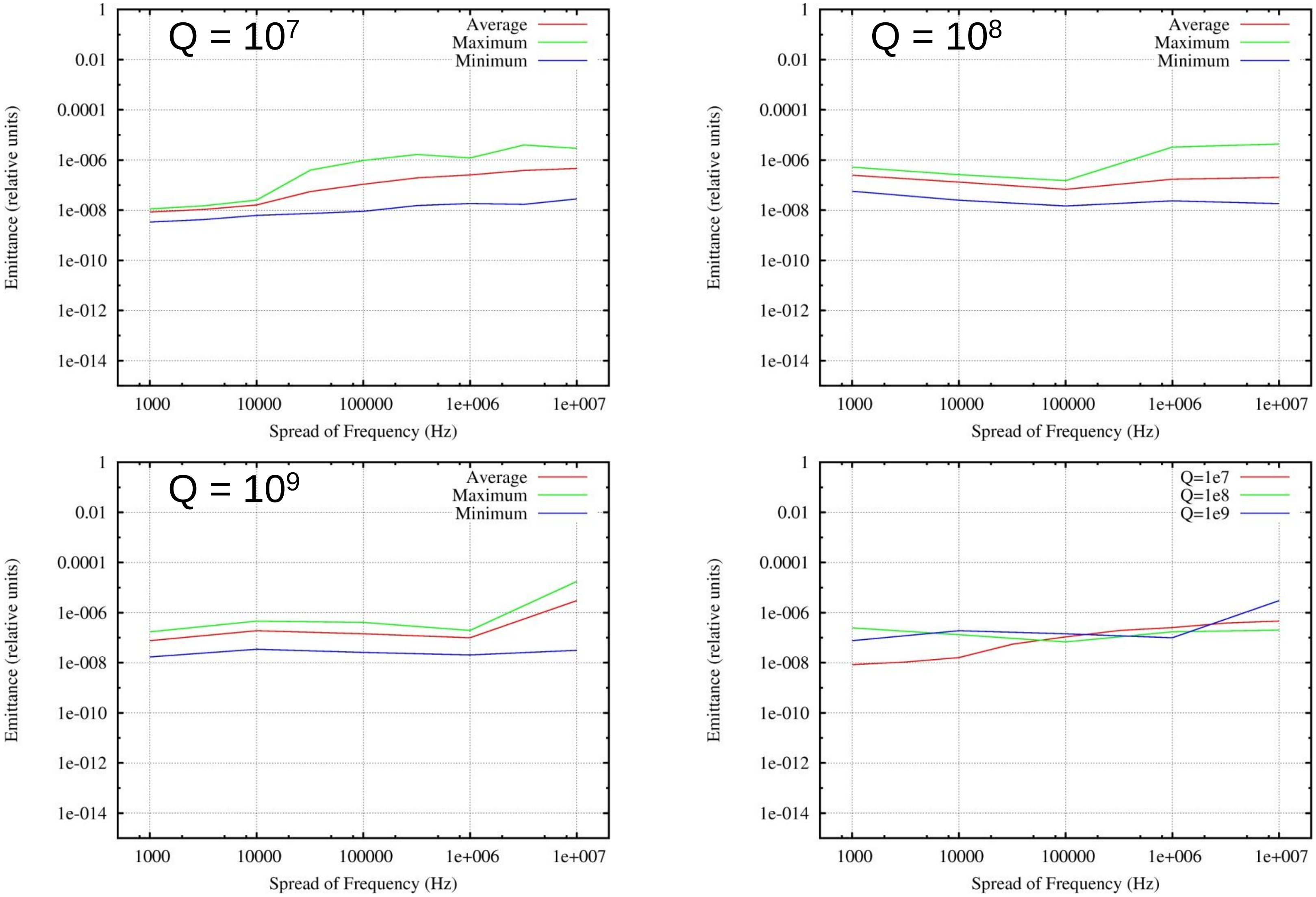






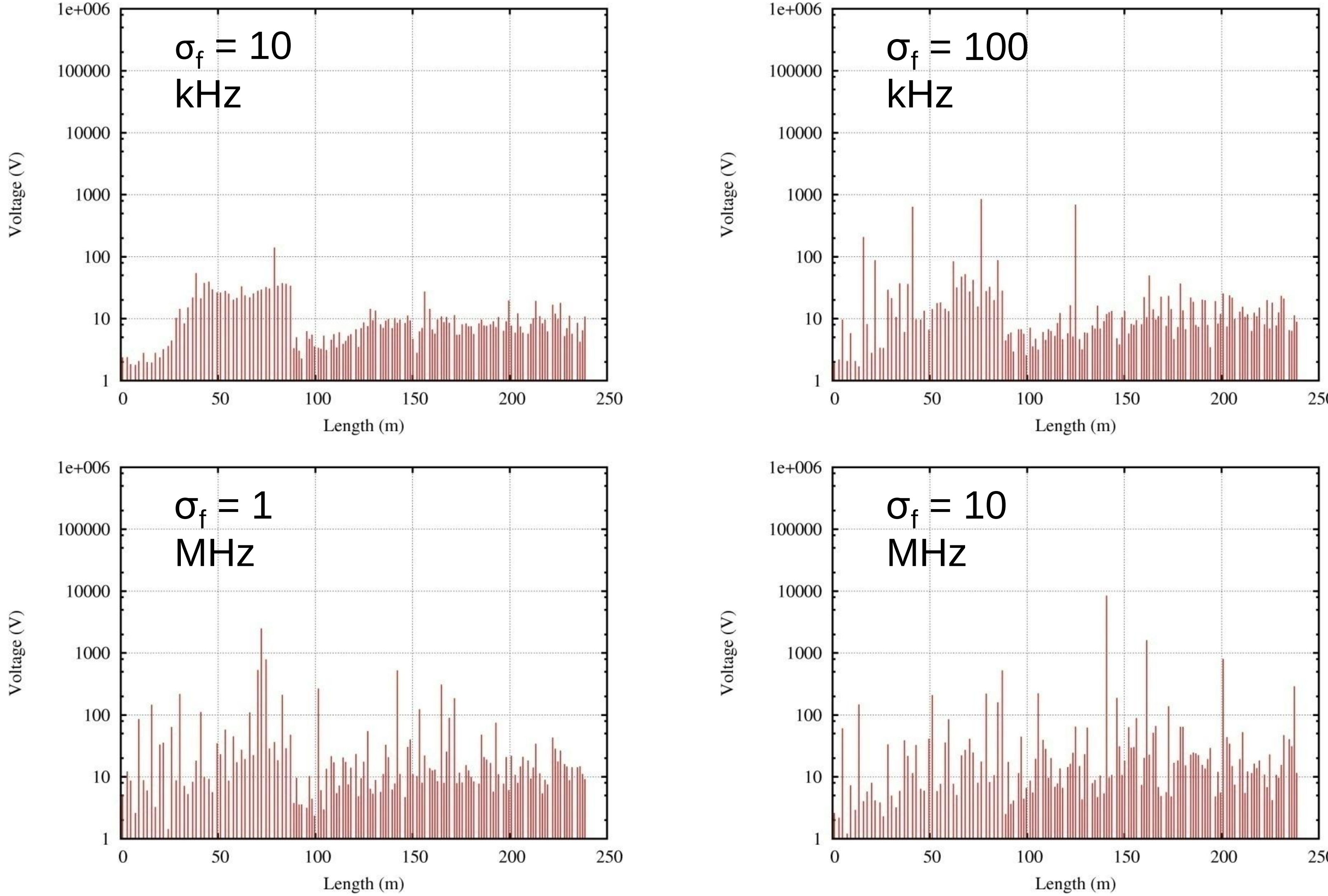
No noticeable effect.

Klystron-type longitudinal instability*,
longitudinal emittance dilution caused by monopole HOMs



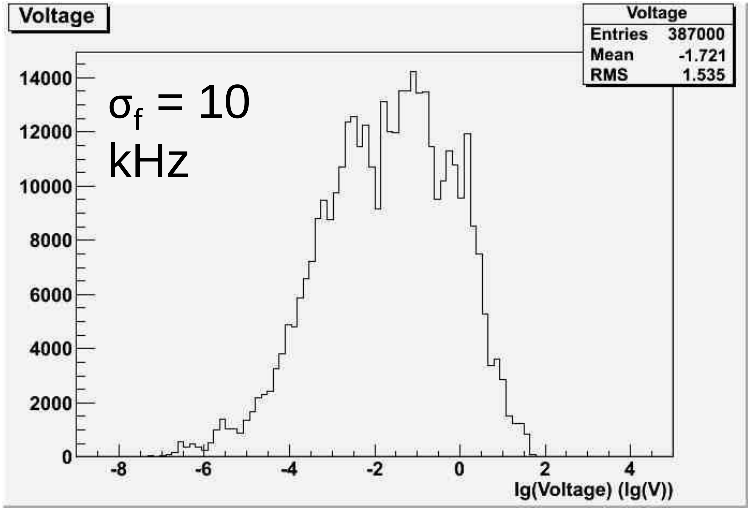
J. Tuckmantel, "Do we need HOM dampers on superconducting cavities in proton linacs?", HOM Workshop, CERN, July 2009

Cavity voltage distribution for different HOM frequency spread

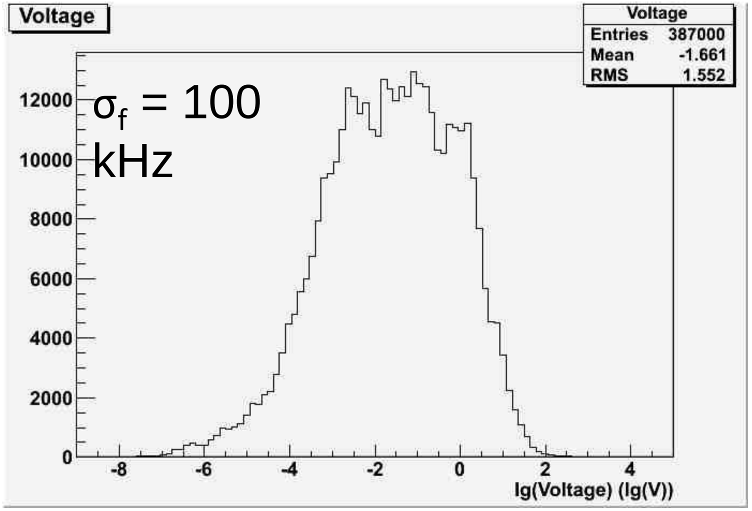


No noticeable effect.

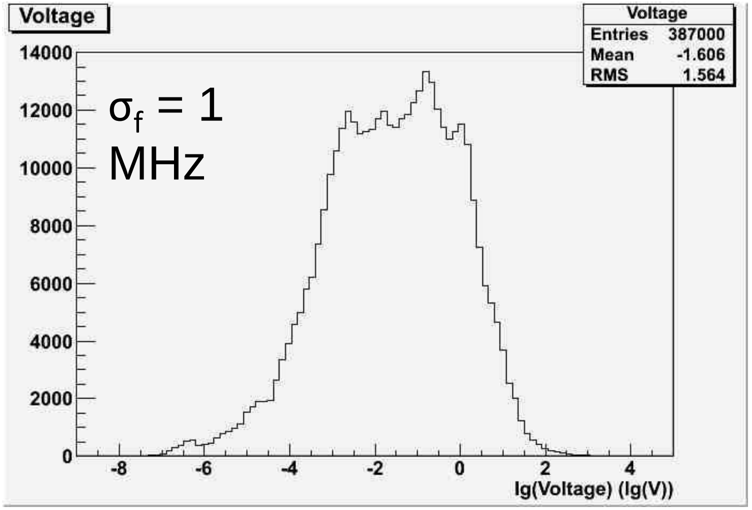
HOM Voltage



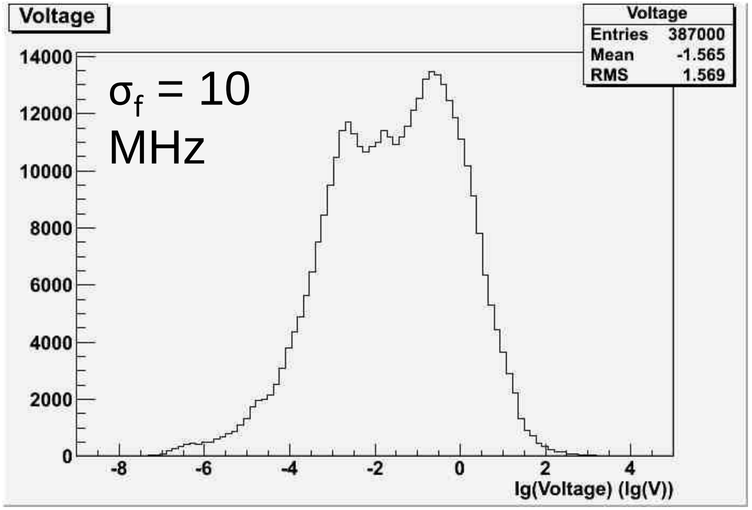
Voltage
Voltage
Entries 387000
Mean -1.721
RMS 1.535
σ_f = 10 kHz
lg(Voltage) (lg(V))



Voltage
Voltage
Entries 387000
Mean -1.661
RMS 1.552
σ_f = 100 kHz
lg(Voltage) (lg(V))



Voltage
Voltage
Entries 387000
Mean -1.606
RMS 1.564
σ_f = 1 MHz
lg(Voltage) (lg(V))



Voltage
Voltage
Entries 387000
Mean -1.565
RMS 1.569
σ_f = 10 MHz
lg(Voltage) (lg(V))

Summary.

To damp or not to damp?

- BBU in 650 MHz section should not be a problem;
- "Klystron-type" longitudinal instability does not look to be a problem as well.
- Resonance excitation of the dipole modes does not look to be an issue;
- Accidental resonance excitation of the 2d monopole band in beta=0.9 section may lead to longitudinal emittance dilution.

It may be mitigated by

- properly tuning of the cavities in order to remove the two "dangerous" HOMs from the beam spectrum line (> few hundred of Hz);
- tuning-detuning of the operating mode that leads to HOM frequency change caused by residual deformation (needs further tests).

However, further investigations are definitely necessary in order to make such a critical decision.