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STATISTICAL ANALYSIS OF THE EIGENMODE SPECTRUM IN THE SRF CAVITIES WITH MECHANICAL IMPERFECTIONS

A. Lunin, T. Khabiboulline, N. Solyak, A. Sukhanov, V. Yakovlev

ICAP'18, Key West, USA

20-24 October, 2018

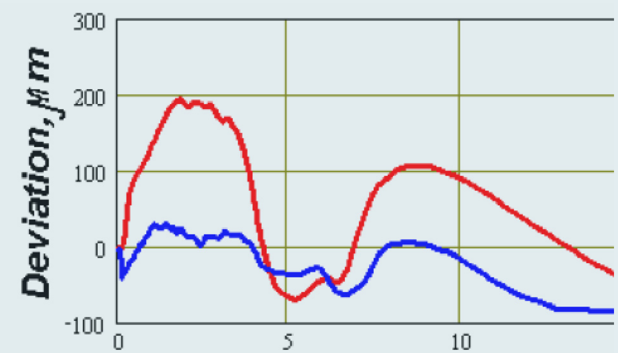
Motivation

HOMSC2014, A. Sukhanov et., all

- SRF cavities are very good resonance systems with multiple eigenmodes (HOMs) with very low losses (high Q-factors)
- Beam of charged particles interacts with HOMs in SRF cavities
  - Single bunch interaction
    - incoherent losses and wake fields
  - CW beam may have beam harmonics close to HOM frequencies
    - resonance excitation of HOMs
    - at exact resonance beam power loss may be high
      - for monopole modes: $P_{loss} = I_n^2 (R/Q)_m Q_L$
  - For a single cavity analysis of non-propagating modes is sufficient

?

3.9 GHz cavity profile deviation*

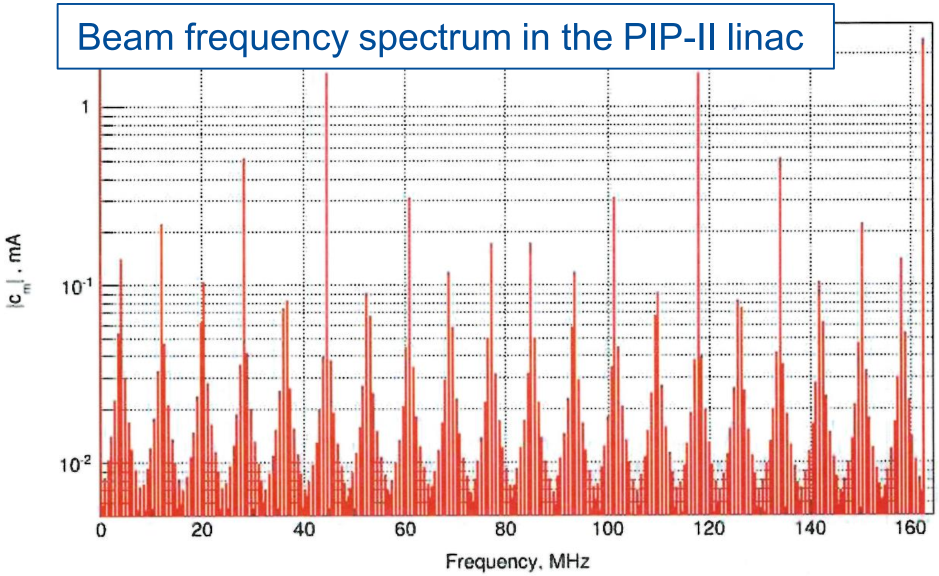


- HOMs parameters deviate from nominal values due to cavity imperfections.
- Coherent HOM excitation is essentially the probabilistic problem!
- Finding HOMs spread is essential for the probability estimation

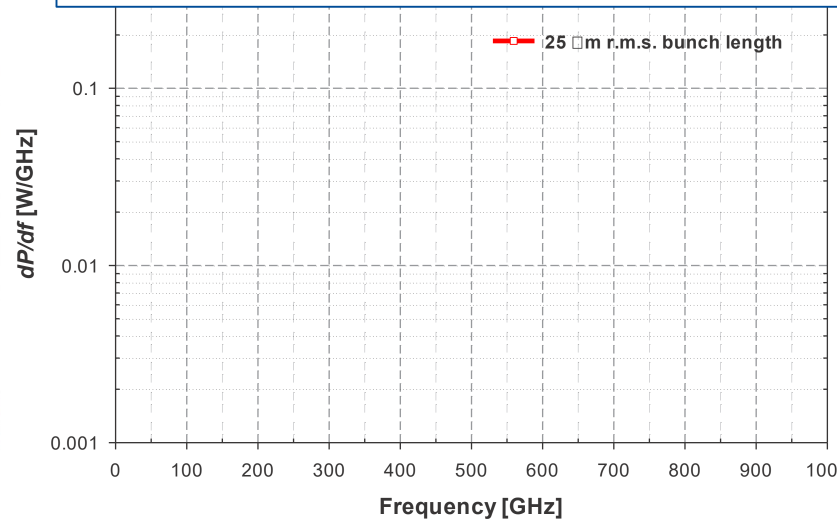
* **N. Solyak *et al.*, TPAB014,, *in Proc. PAC 2003***

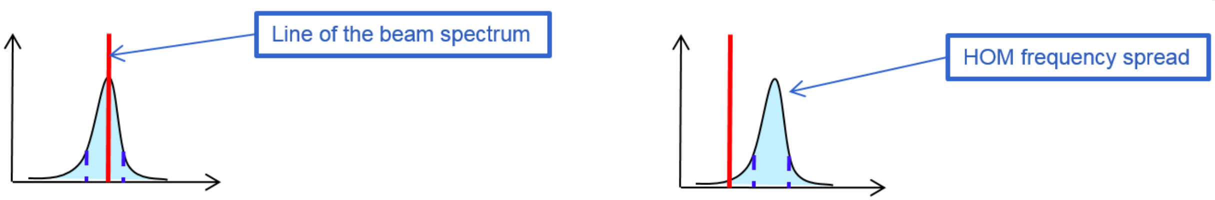
Coherent HOM Excitation

Beam frequency spectrum in the PIP-II linac



Wake power spectrum in the 1.3 GHz LCLS-II CM





$$\langle P \rangle_{max} = \frac{(R_{\parallel}/Q)\omega_0 q_0^2}{4 t_b}\left(\frac{e^{\alpha}+1}{e^{\alpha}-1}\right)$$

$\alpha = t_b/\tau$ — t_b is the bunch spacing

$\tau = 2Q_L/\omega_0$ is the HOM signal decay time

- High bunches rep. rate & peak beam current might result in large cryogenic losses and beam emittance dilution

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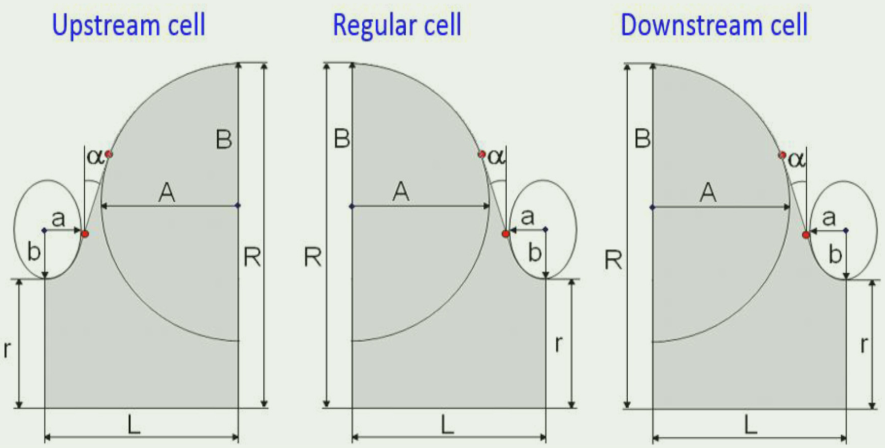
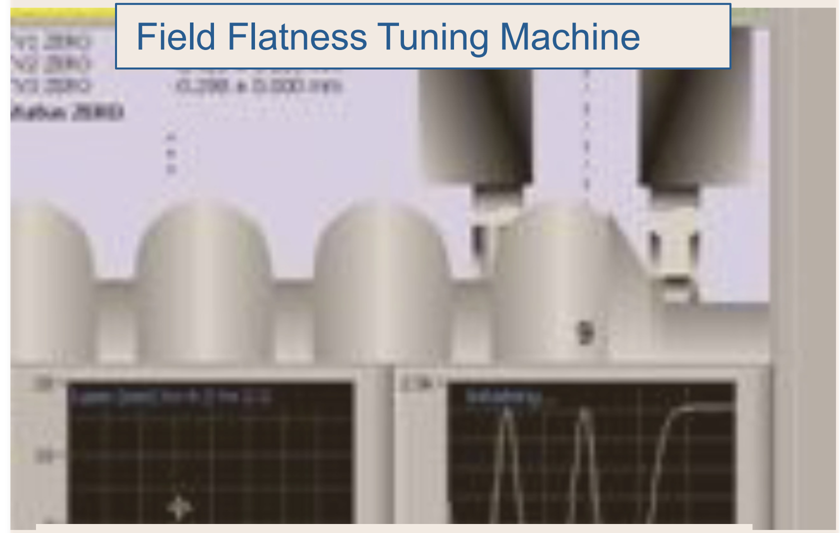
Random Cavity Generation

Cavity Parameters Randomization



$$P_n^i = P_n^{nom} + |\Delta_{tol}|[2Rnd(1) - 1]$$

Field Flatness Tuning Machine



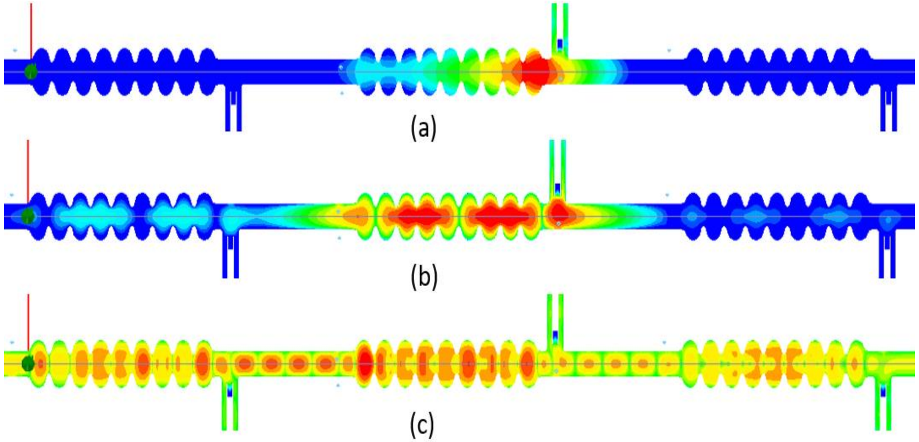
$$\Delta L^i \frac{\partial f}{\partial L^i} = -\sum_{n=1}^{N} \left[\Delta P_n^i \frac{\partial f}{\partial P_n^i}\right]$$

Δ_{tol} - cavity mechanical tolerance (~ 100..250 μm)

$\partial f/\partial L^i$ and $\partial f/\partial P^i{}_n$ - frequency-dependent sensitivities of the ***i***th half-cell parameters

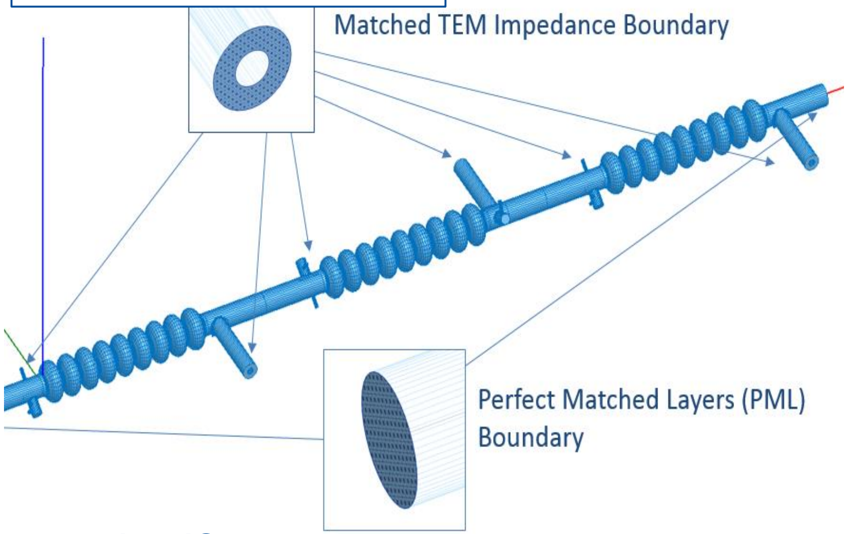
- We can randomize cavity parameters and keep the field flatness!
- Assumptions:
  a) parameter sensitivities are independent, b) tolerances are uncorrelated

Eigenmode Analysis Setup



Trapped modes in the infinite chain of random SRF cavities: a) - High-Q, b) – Medium-Q, c) – Low-Q

ANSYS HFSS Model

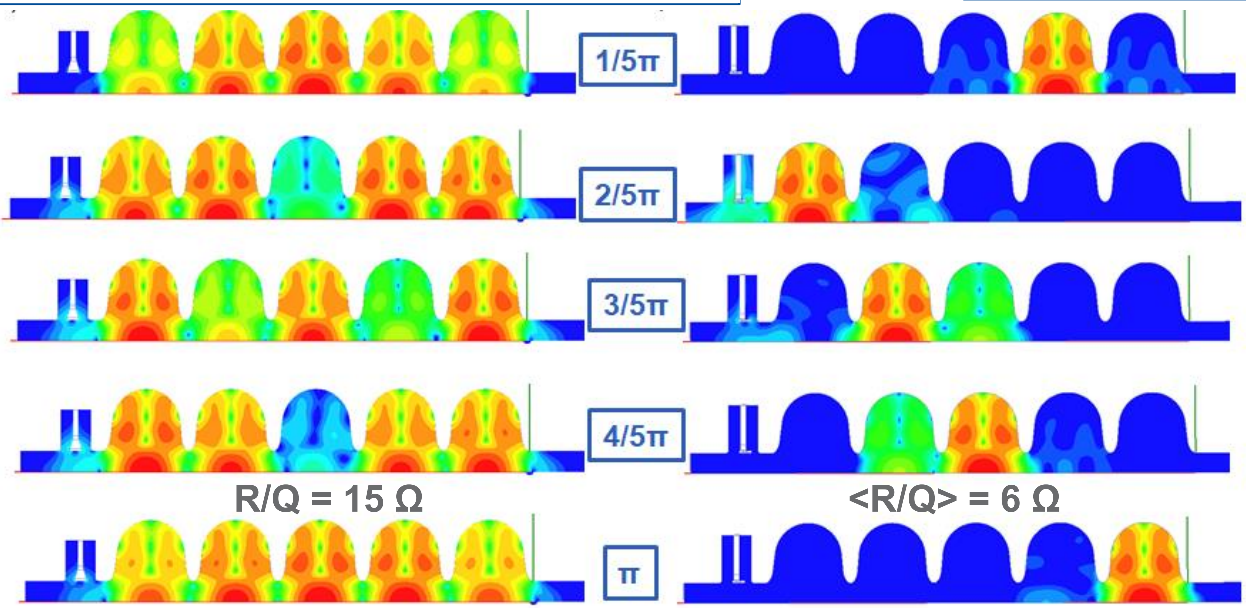


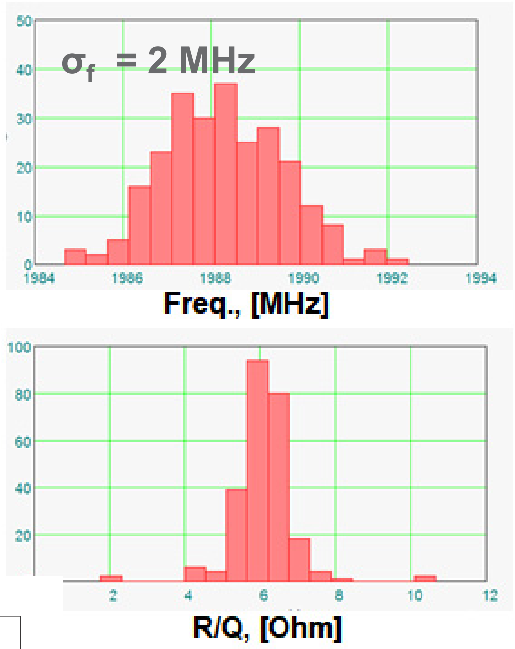
- What is a minimum number of SRF cavities is required?
  - 1 cavity for HOMs below the beam pipe cut off frequency (TE11, TM01..)
  - 3 cavities is the optimum choice for HOMs above the cut off frequency
  - >3 cavities give a little or no impact to the overall result.
- Boundary conditions:
  - TEM impedance (377 Ω) on all coaxial ports
  - PML on open beam pipe
- Secondary values (important for the HOMs sorting):
  - local stored energy in each cavity and adjacent beam pipes
  - longitudinal and transverse R/Q-s
  - partial external quality factors for all coupler ports

Stochastic HOM Analysis (HE 650 MHz PIP-II Cavity*)

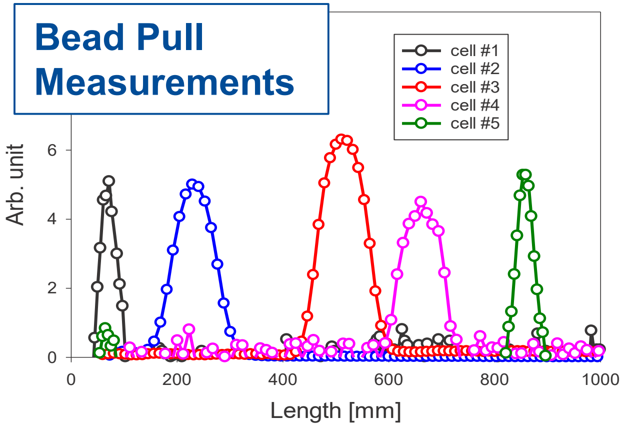
Ideal Cavity: 5th Mon Band $f_\pi - f_0 \approx 40$ kHz

Cavity with Errors





Bead Pull Measurements

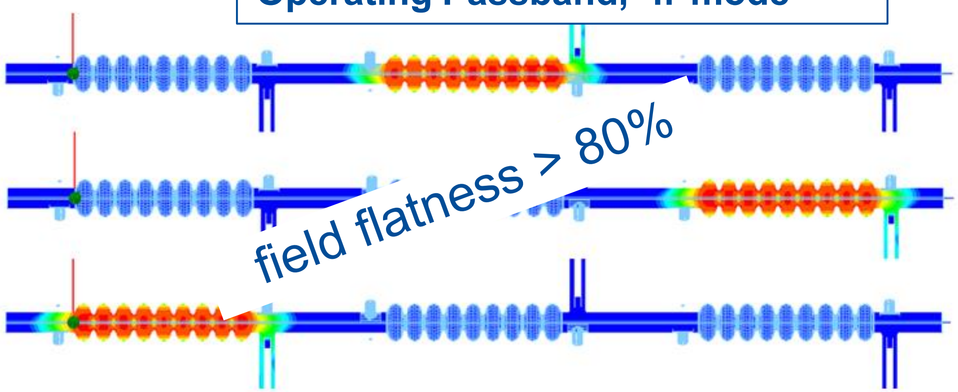


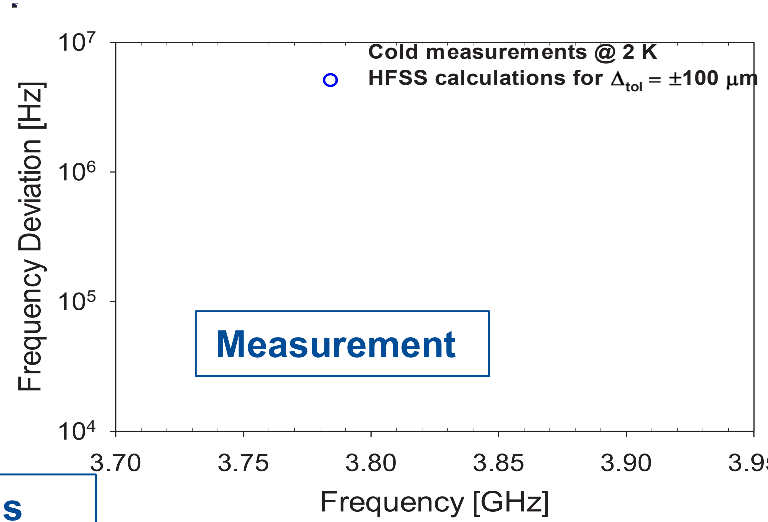
Geometrical imperfections might significantly change the HOM parameters!

* A. Sukhanov *et al.*, *Nucl. Instr. Methods Phys. Res.*, Sect. A 734,, (2014)

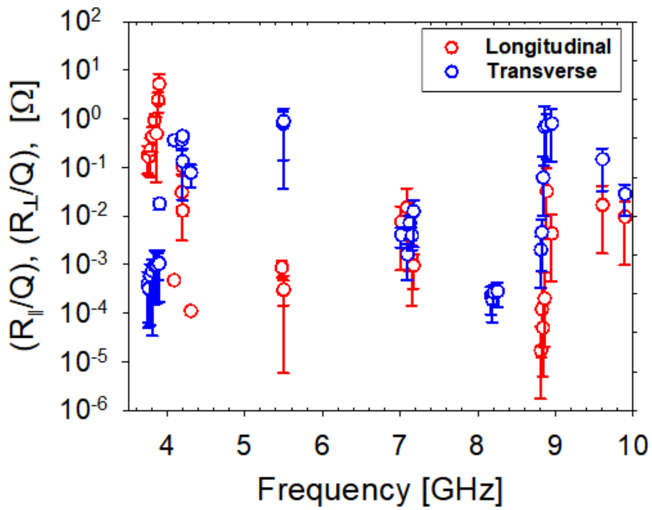
Stochastic HOM Analysis (3.9 GHz LCLS-II Cavity*)

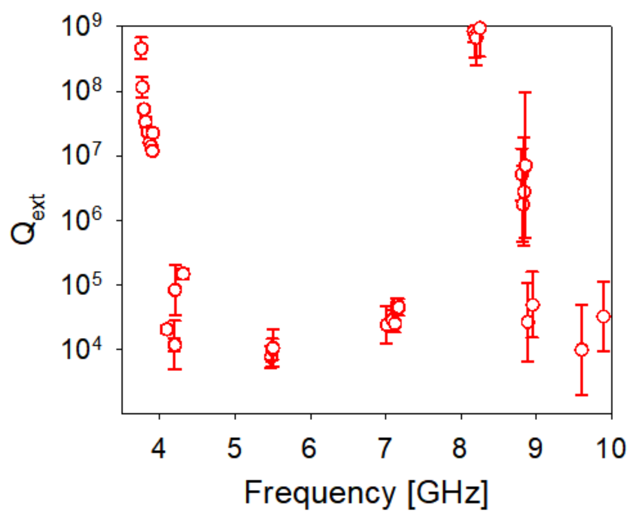
Operating Passband, π-mode





HOM Parameters Spreads

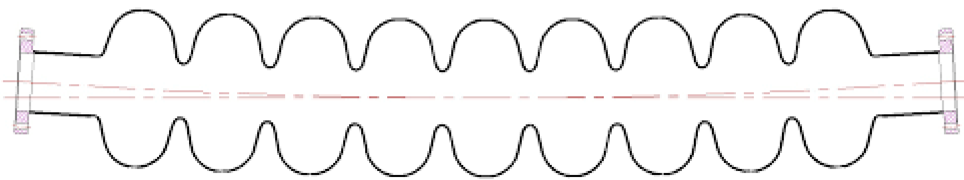


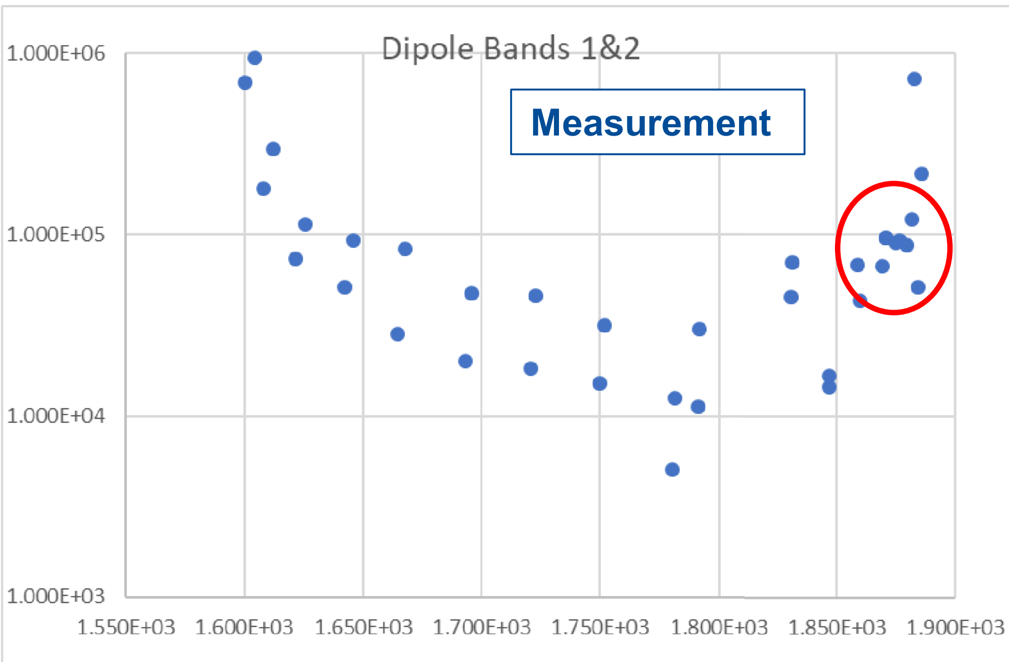


* A. Lunin *et al.*, Phys. Rev. ST AB, 21, 022001 (2018)

Stochastic HOM Analysis (1.3 GHz LCLS-II Cavity)

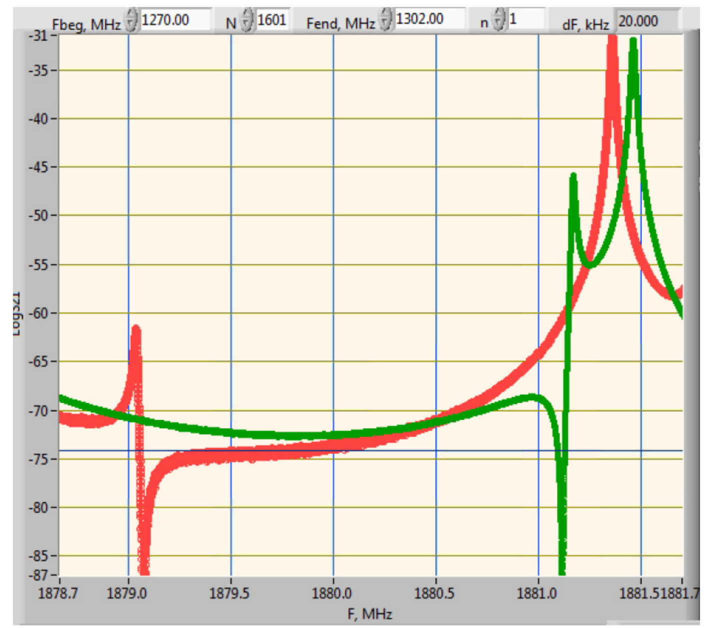
Cavity “Banana shape”





Measurement

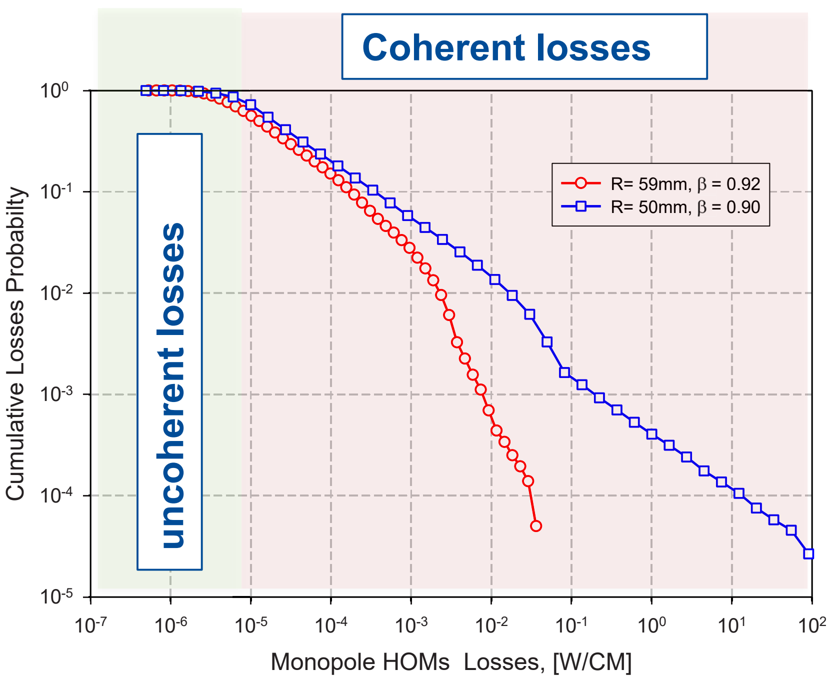
Dipole Modes Splitting

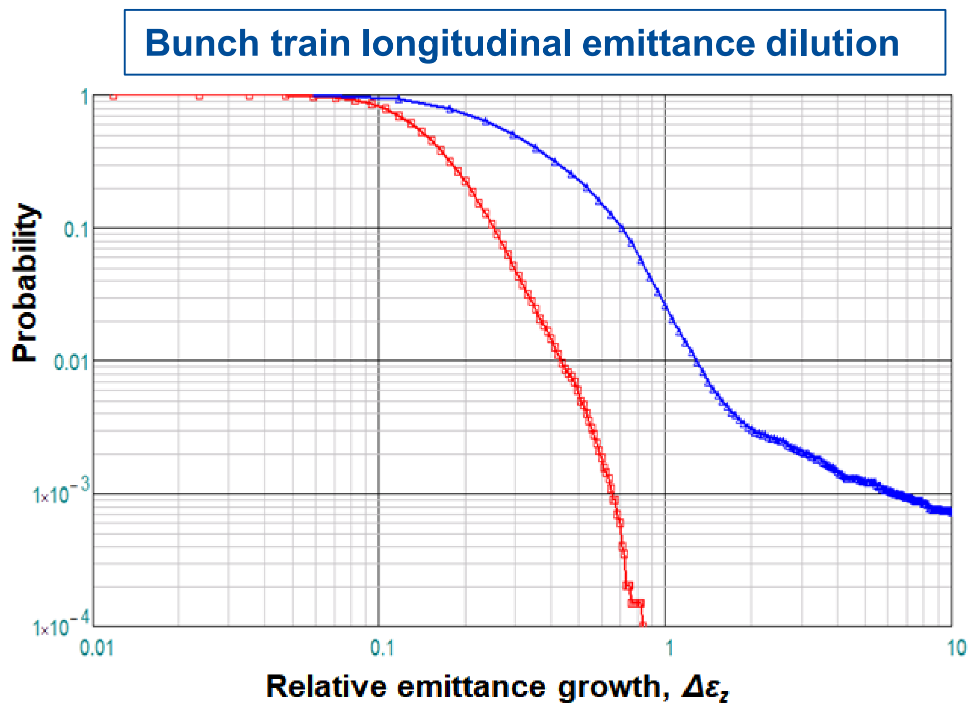


Geometrical imperfections might significantly change the HOM parameters!

Resonant HOMs Excitation of the 650 MHz PIP-II cavity

- Statistical approach of resonant HOMs excitation:
  - sort out the middle cavity HOMs compendium
  - find means and spreads of F, R/Q, Q for each mode
  - generate 10^N cavities/cryomodules with random HOMs spectra
  - calculate probabilities of RF losses and emittance dilution

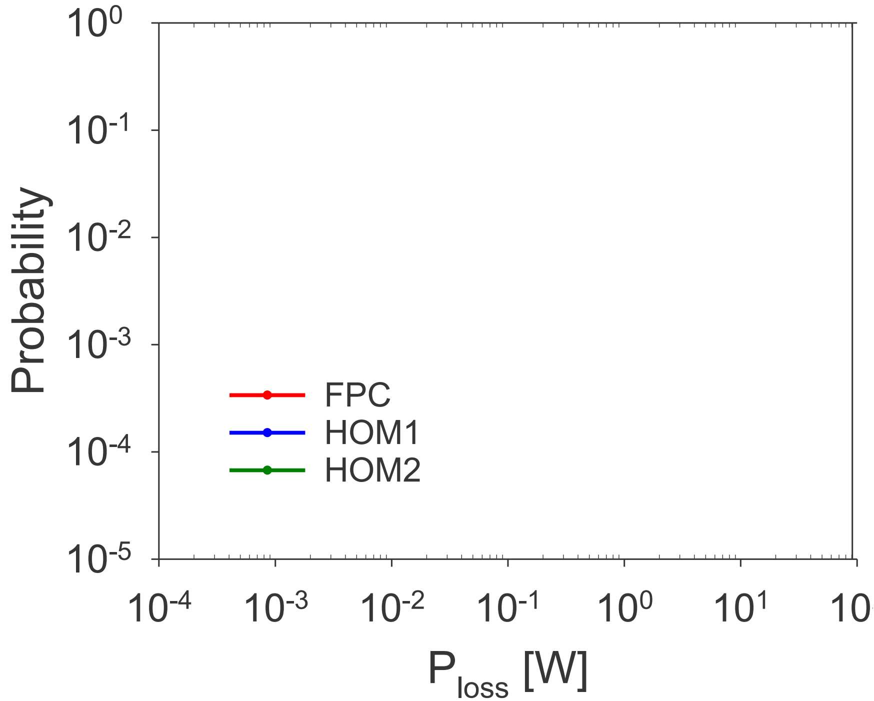




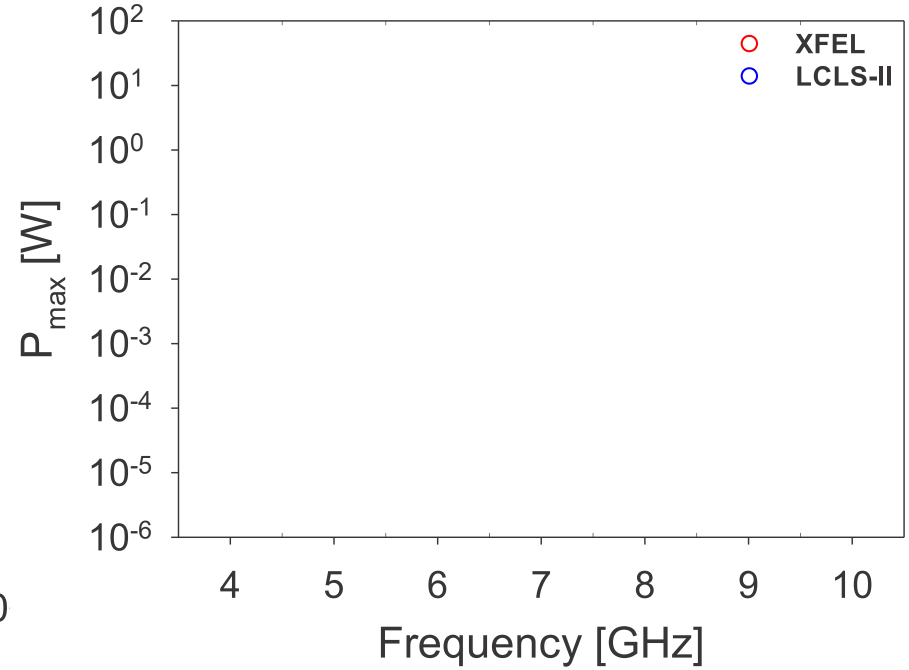
Comparison of two versions (beta 0.90 and 0.92) of HE 650 cavity for the PIP-II linac

Resonant HOMs Excitation of the 3.9 GHz LCLS-II cavity

Monopole HOMs losses per individual coupler ports



Comparison of XFEL and LSLS-II cavities



- Modified 3.9 GHz cavity is capable of efficiently damping the resonant excitation of HOMs spectrum by the continuous beam in the LCLS-II linac

Conclusions

- The statistical analysis of the eigenmode spectrum in SRF cavities is reliable tool for quantitative evaluation of the coherent HOM excitation by the beam with arbitrary time structure
- The outcome of HOM analysis resulted in critical decisions for the design of superconducting accelerating cavities:
  - optimized HE 650 MHz cavity design
  - modification of the 3.9 GHz cavity End Group
- Proposed technique can be easily adapted and used for other superconducting particle accelerators operating at high average beam current and high duty factor regimes