Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

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

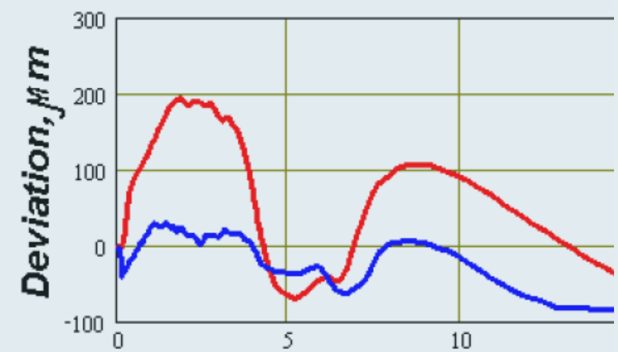
Motivation

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*



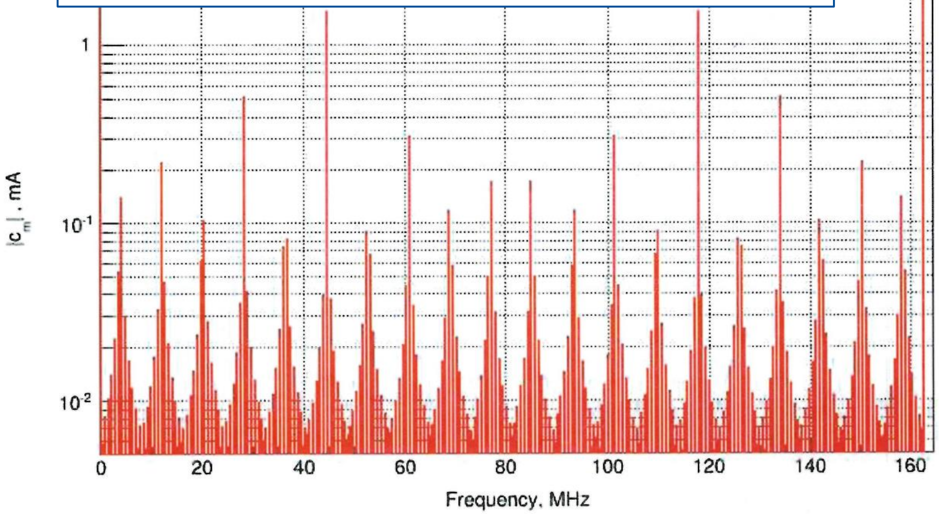
- HOMs parameters deviate from nominal values due to cavity imperfections.
- Coherent HOM excitation is essentially the probabilistic problem!
- Finding HOMs spread is essential for the probability estimation

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

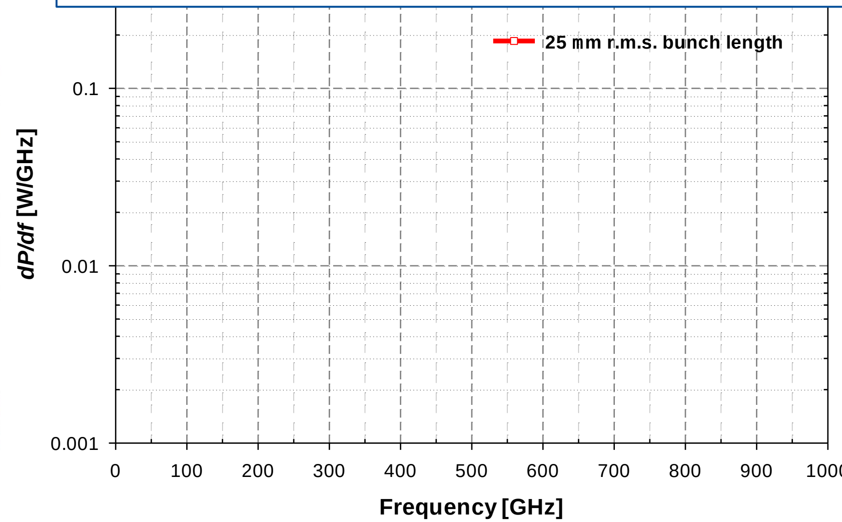
Fermilab

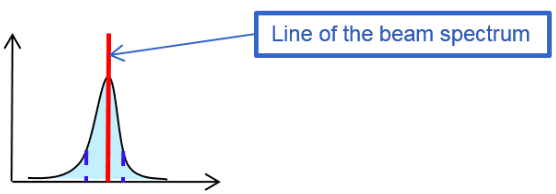
Coherent HOM Excitation

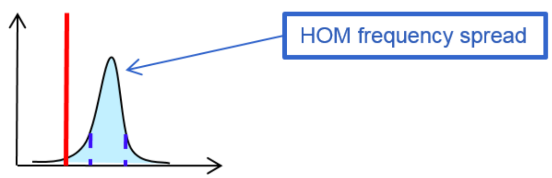
Beam frequency spectrum in the PIP-II linac



Wake power spectrum in the 1.3 GHz LCLS-II CM







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

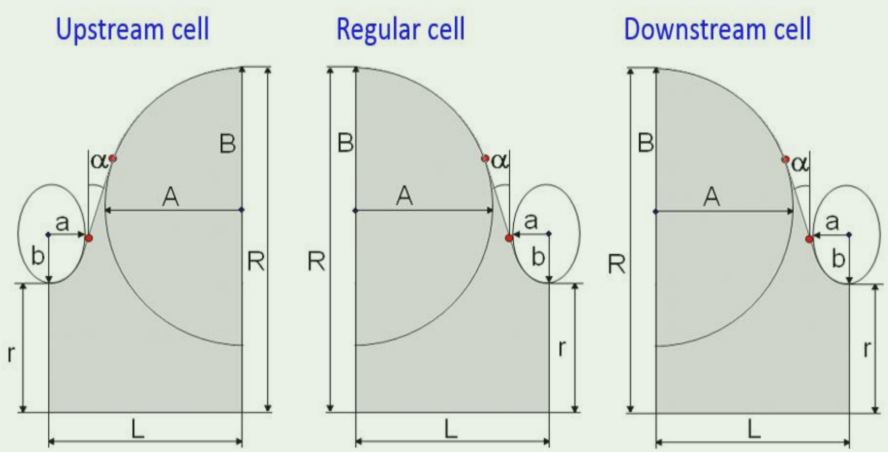
$\alpha = t_b/\tau$ — t_b is the bunch spacing

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

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

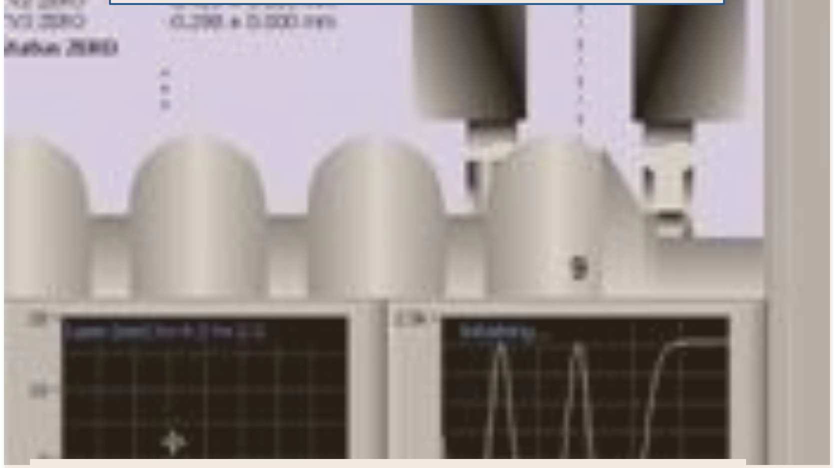
Random Cavity Generation

Cavity Parameters Randomization



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

Field Flatness Tuning Machine



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

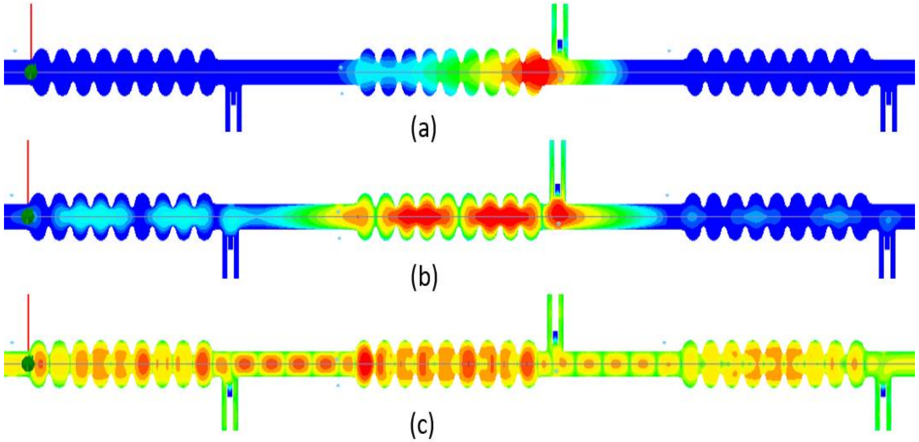
Δ_{tol} - cavity mechanical tolerance (~ 100..250 µm)

$\partial f/\partial L^i$ 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:

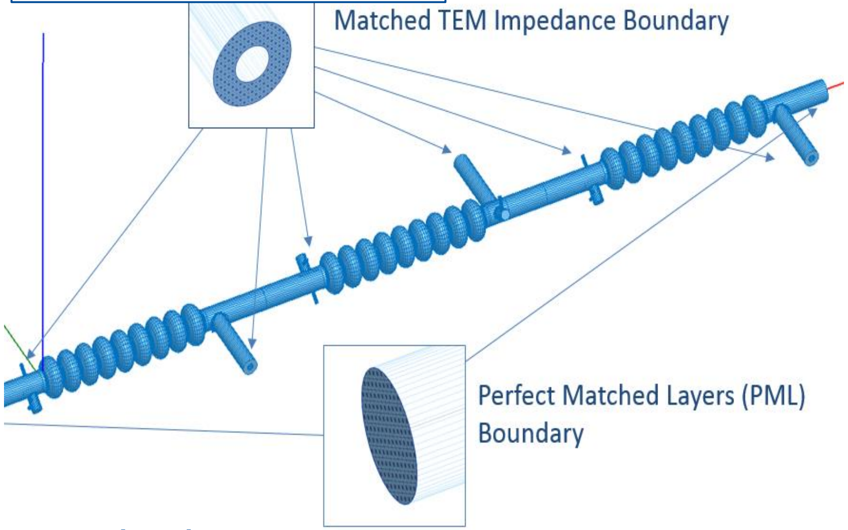
  a) parameter sensitivities are independent, b) tolerances are uncorrelated

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

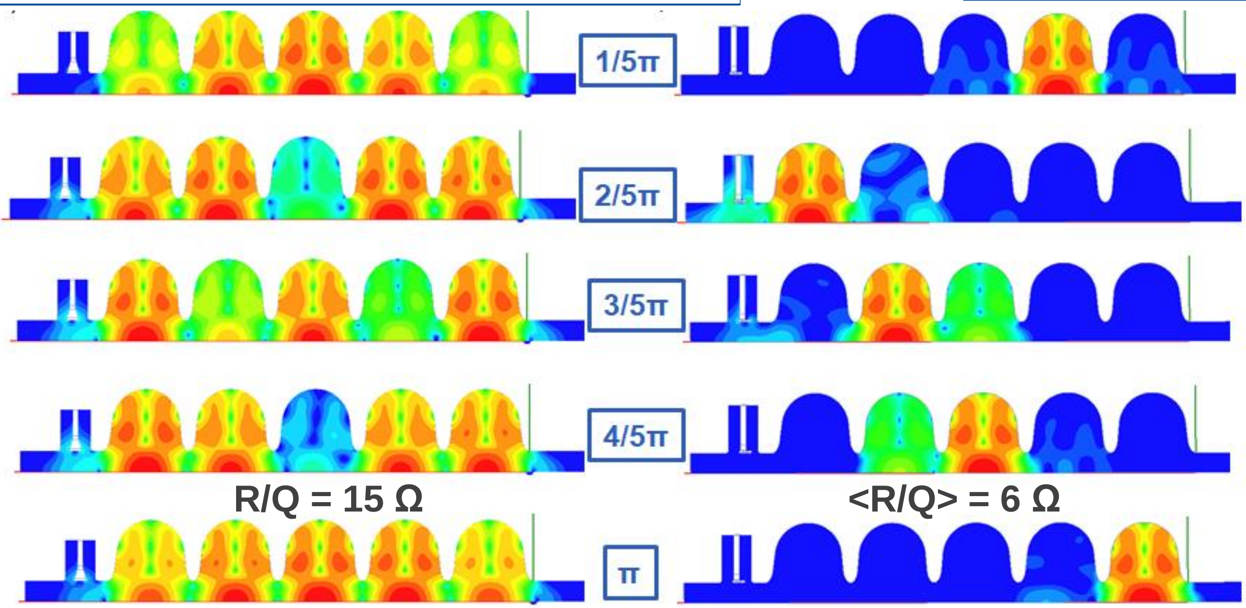


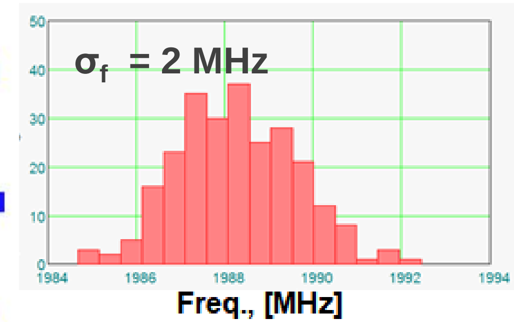
- What is a minimum number of SRF cavities is required?
  - 1 cavity for HOMs below the beam pipe cut off frequency (TE11, TM01..)
  - 3 cavities is the optimum choice for HOMs above the cut off frequency
  - >3 cavities give a little or no impact to the overall result.
- Boundary conditions:
  - TEM 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

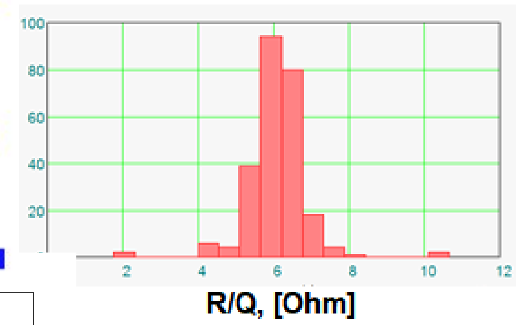
Stochastic HOM Analysis (HE 650 MHz PIP-II Cavity*)

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

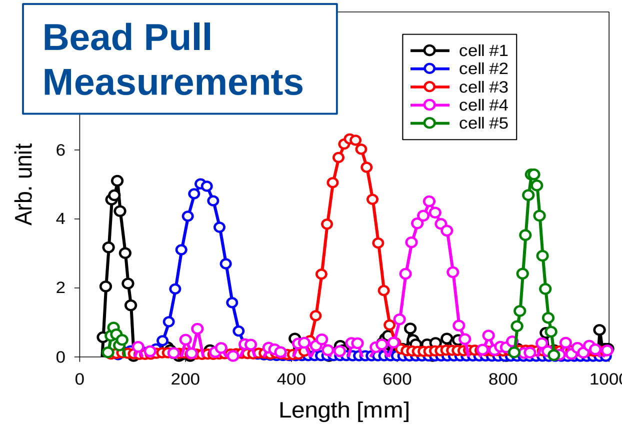
Cavity with Errors







Bead Pull Measurements

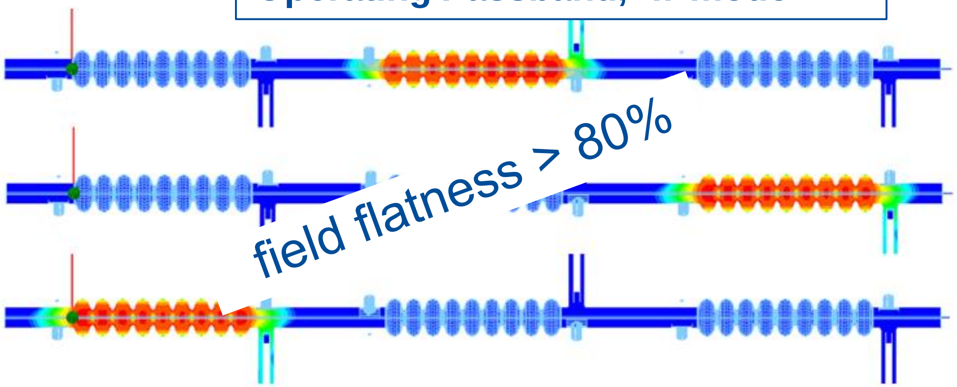


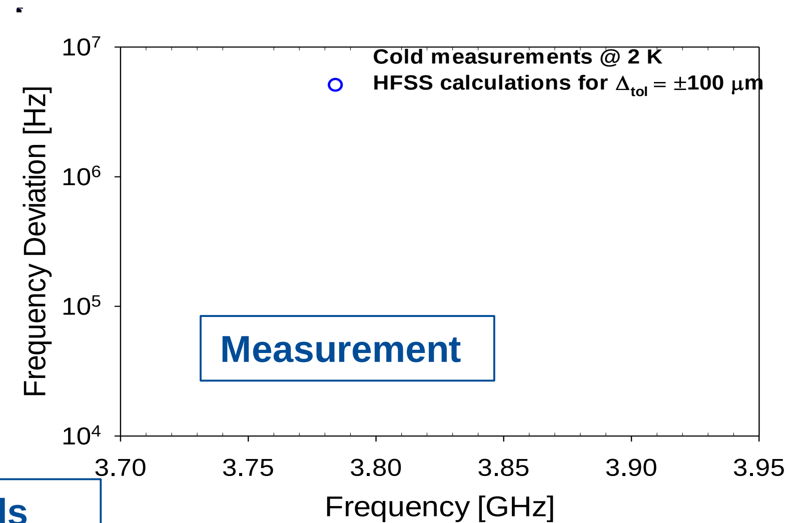
Geometrical imperfections might significantly change the HOM parameters!

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

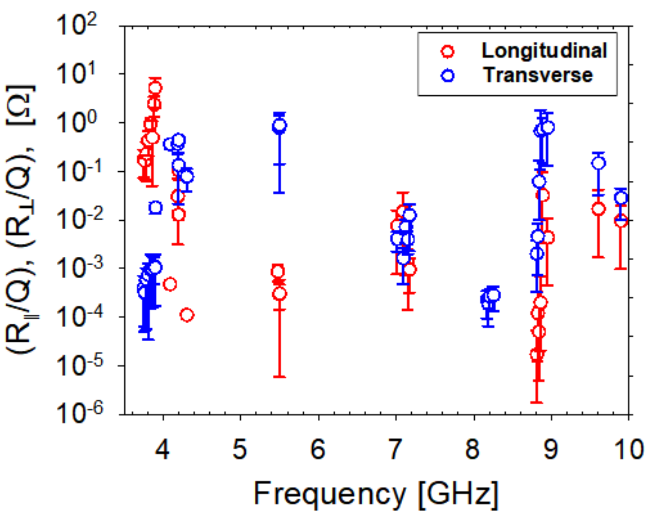
Stochastic HOM Analysis (3.9 GHz LCLS-II Cavity*)

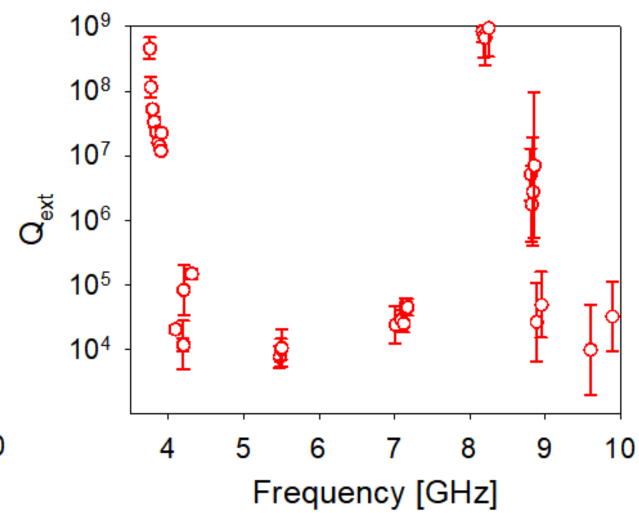
Operating Passband, π-mode





HOM Parameters Spreads



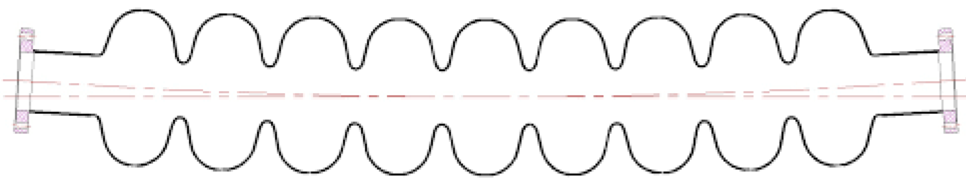


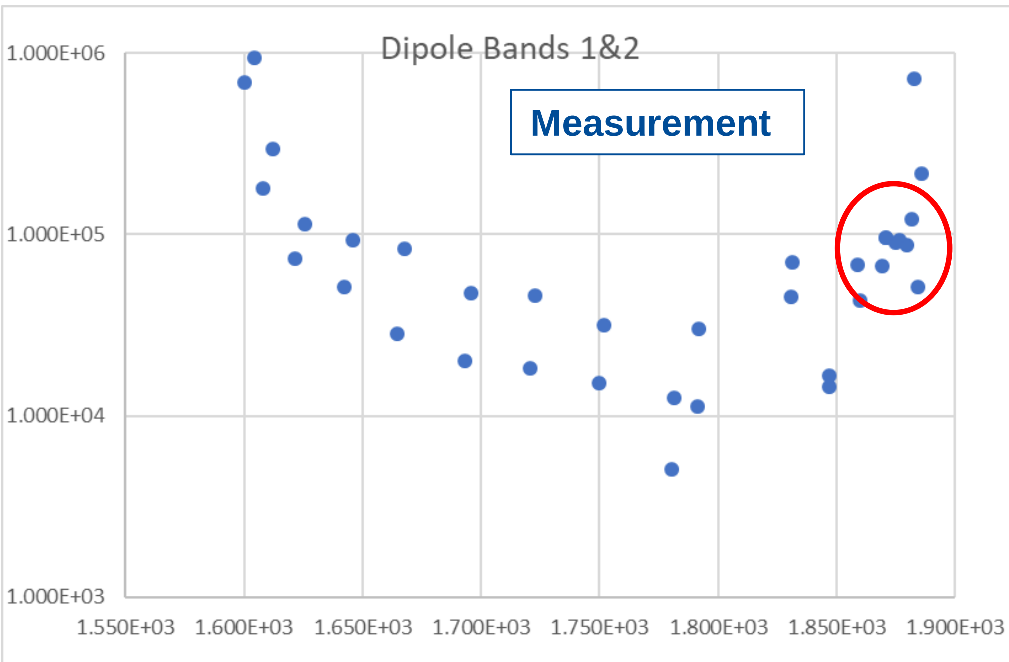
* A. Lunin *et al.*, Phys. Rev. ST AB, 21, 022001 (2018)

Fermilab

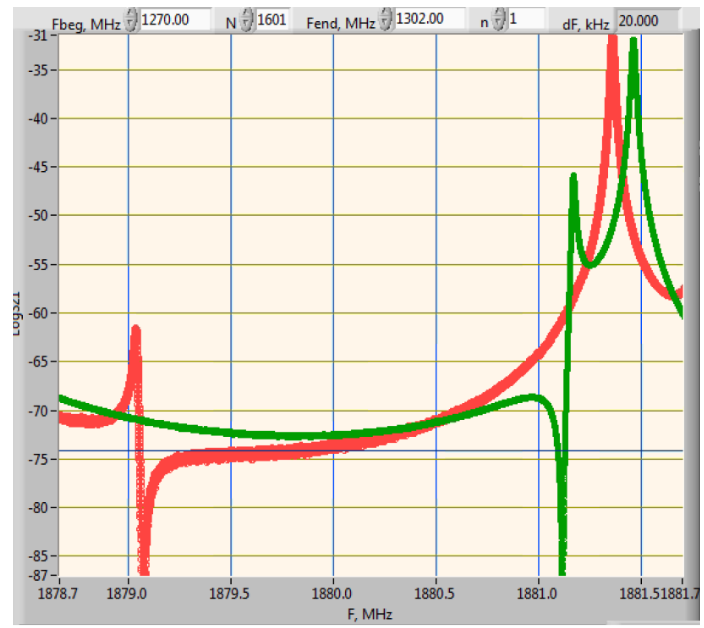
Stochastic HOM Analysis (1.3 GHz LCLS-II Cavity)

Cavity "Banana shape"





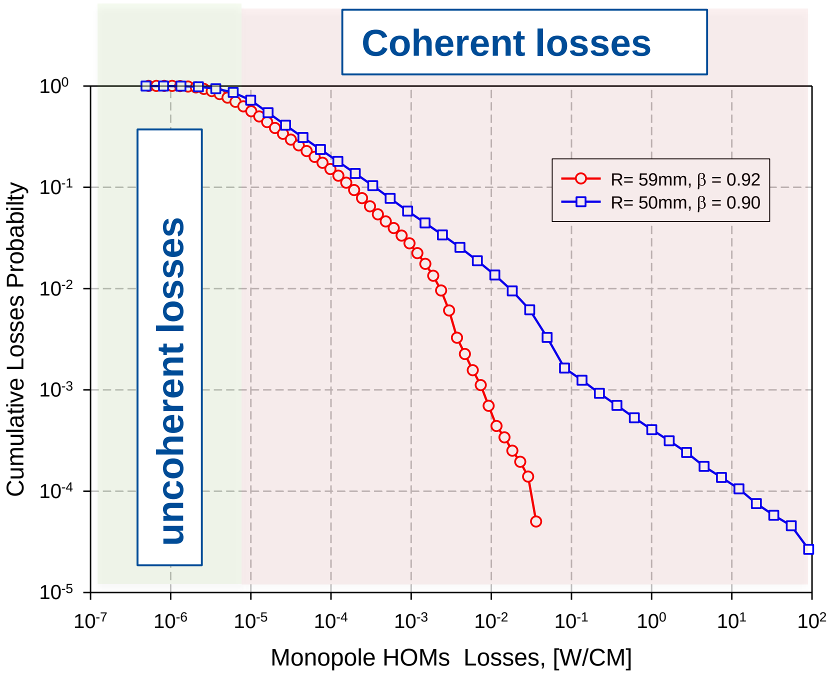
Dipole Modes Splitting

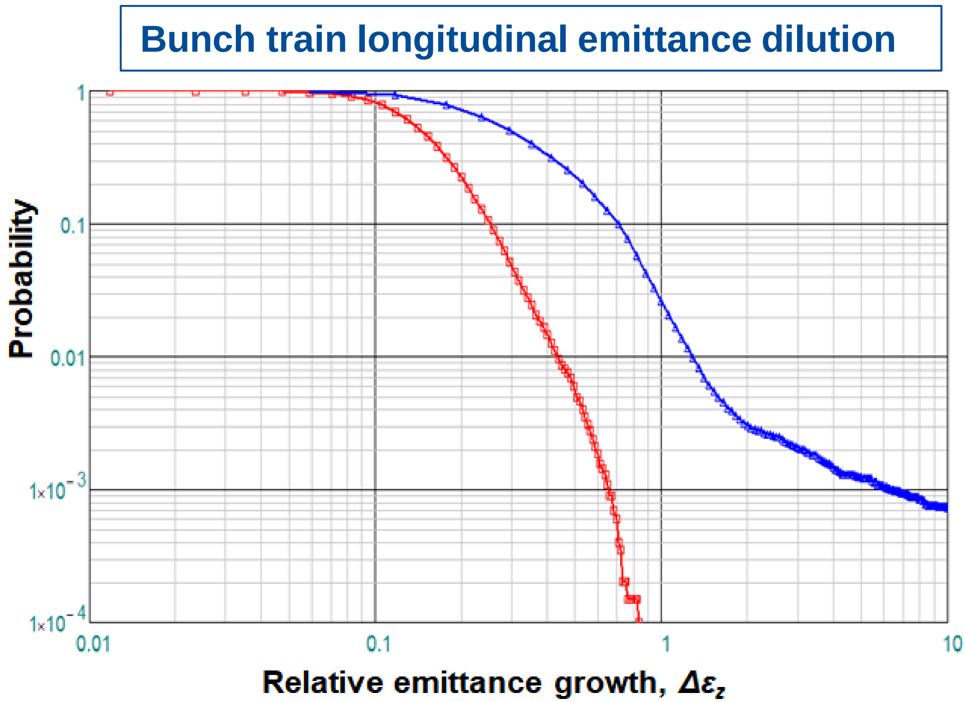


Geometrical imperfections might significantly change the HOM parameters!

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

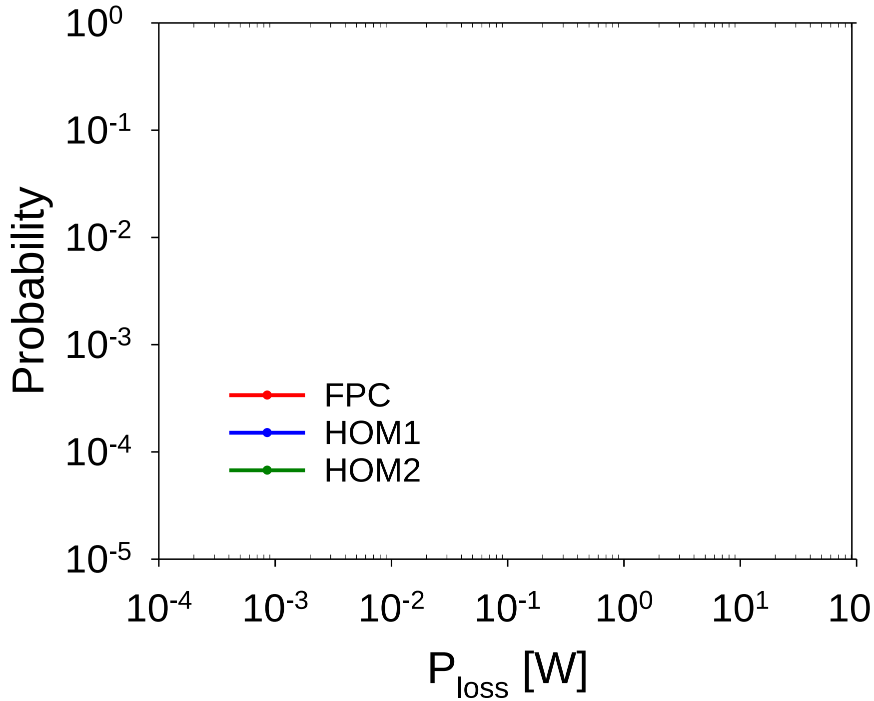




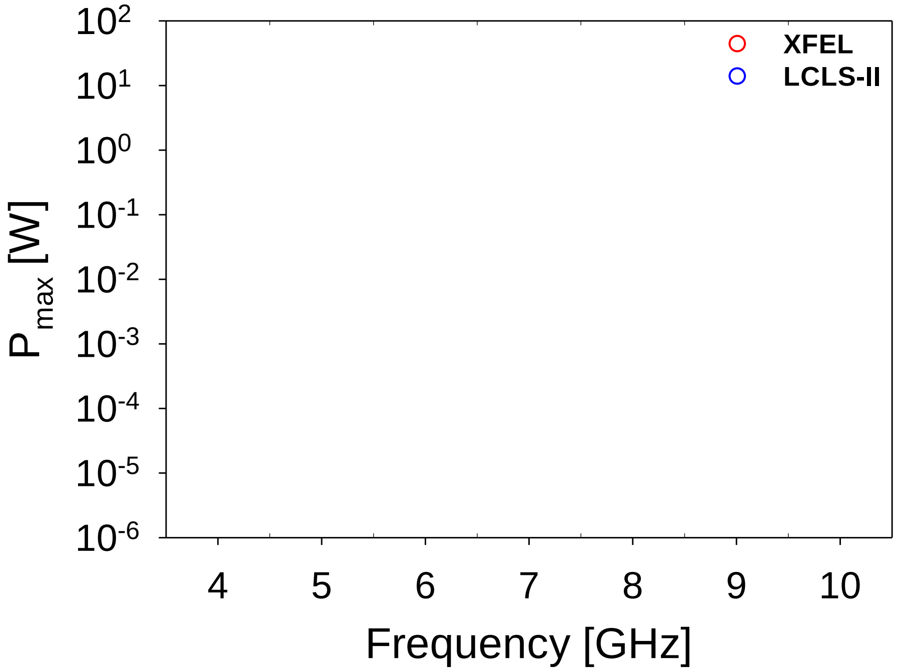
Comparison of two versions (beta 0.90 and 0.92) of HE 650 cavity for the PIP-II linac

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