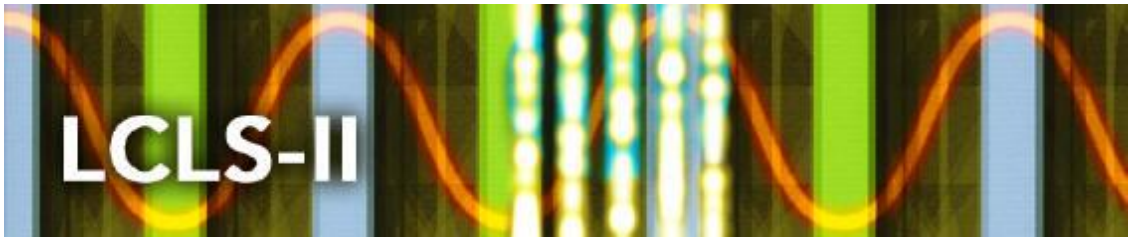

Status of HOMs Spectra Measurements in 1.3 GHz Cavities for LCLS-II

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(on behalf of TD/SRF Group, Fermilab)

LCWS2018 International Workshop on Future Linear Colliders

22-26 October 2018

U.S. DEPARTMENT OF ENERGY
Office of Science

Outline

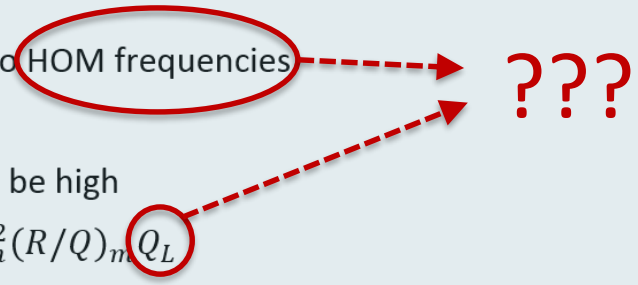
- Overview of the LCLS-II 1.3 GHz Cryomodule (CM) assembly
- CM RF quality control (RF/QC) procedure at Fermilab
- Measurement of HOM spectra at CM Test Facility (CMTF)
- HOMs data processing
- Operating passband statistics
- Dipole HOMs statistics
- Monopole HOMs statistics
- Cavity vendors performance
- Summary

Motivation

HOMSC2014, A. Sukhanov et., all

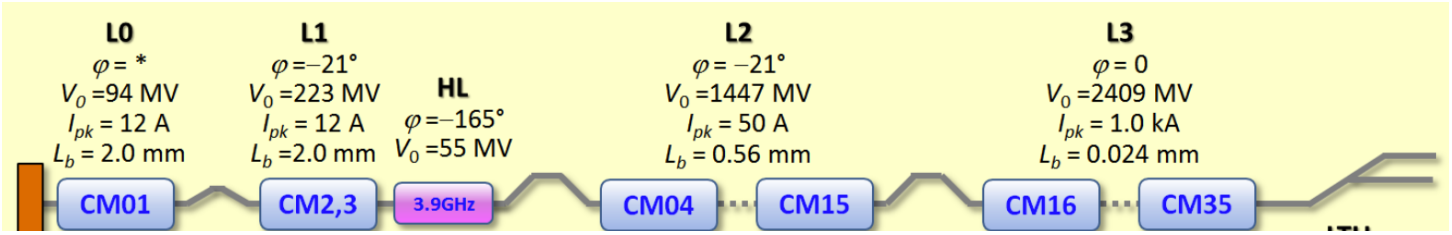
Motivation

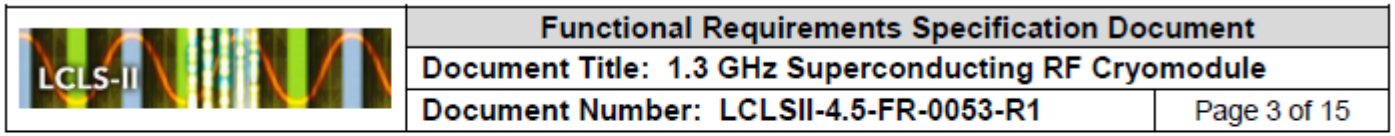
- SRF cavities are very good resonance systems with multiple eigenmodes (HOMs) with very low losses (high Q-factors)
- Beam of charged particles interacts with HOMs in SRF cavities
  - Single bunch interaction
    - incoherent losses and wake fields
  - CW beam may have beam harmonics close to HOM frequencies
    - 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



- Measurement of actual HOMs parameters @2K insures a reliable model of resonant HOMs excitation in the LCLS-II linac
- HOMs statistics allows to estimate and to compare a consistency of cavities mechanical tolerances for different vendors

LCLS-II Linac





1 Introduction

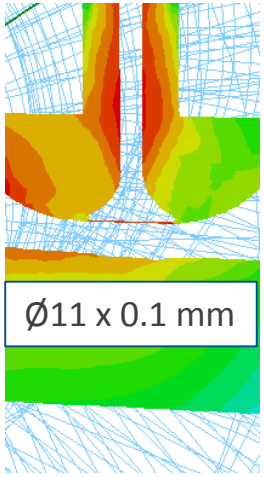
Fermilab and Jefferson Lab are collaborating with SLAC on their LCLS-II upgrade project by supplying SRF design and fabrication expertise [1]. The accelerating structures will utilize

- 4 GeV CW SRF Linac: 35 (+5) 1.3 GHz CMs , 50/50 by JLab & Fermilab
- Single 1.3 GHz CM: eight 9-cell TESLA-type cavities (280 cavities in linac)
- CW Beam: 0.1-0.3 nC bunch charge, 1 MHz rep. rate, 0.3 mA (max) average beam current
- HOM damped Q-value: ≤ 10^6 for HOMs with high R/Q

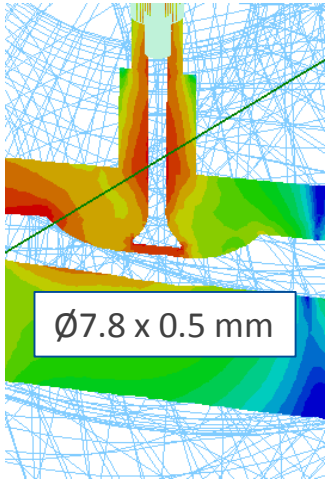
1.3 GHz LCLS-II Cavity Coupler Ports Changes

HOM antenna

ILC

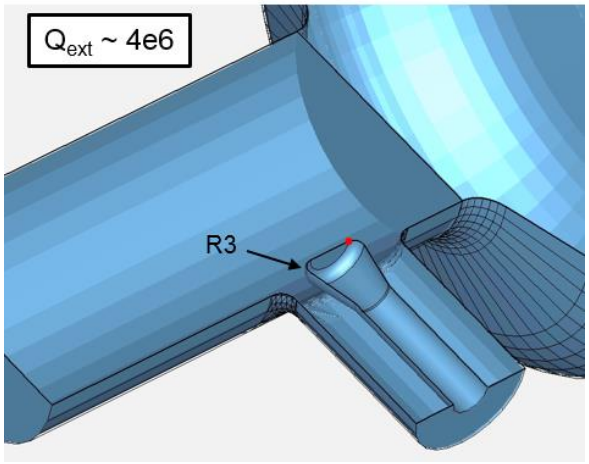


LCLS-II

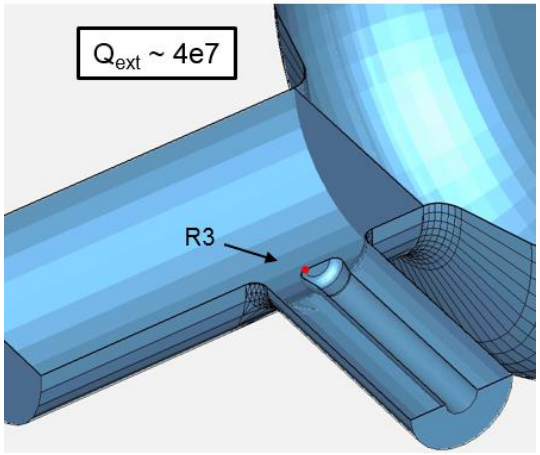


FPC antenna

Original antenna **ILC, XFEL**



Antenna tip cut by 8.5 mm **LCLS-II**



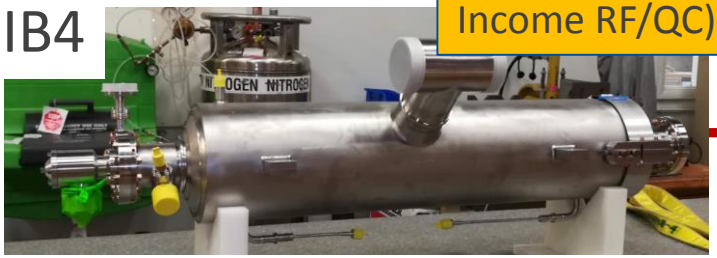
Changes to accommodate CW operation:

- Smaller size of HOM antenna tip and larger the f-part gap for minimization of local RF losses
- Weaker FPC coupling (~ by one order) for matching with beam current and lowering input RF power

CM assembly RF/QC at Fermilab

receiving

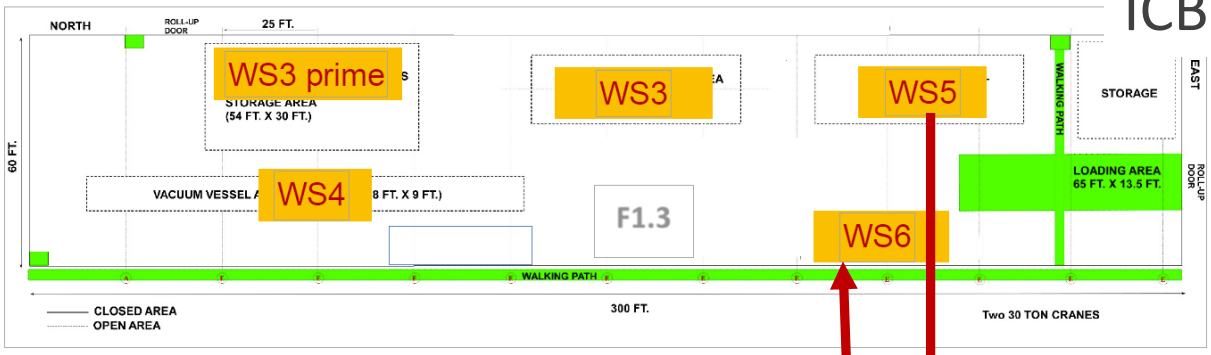
IB4



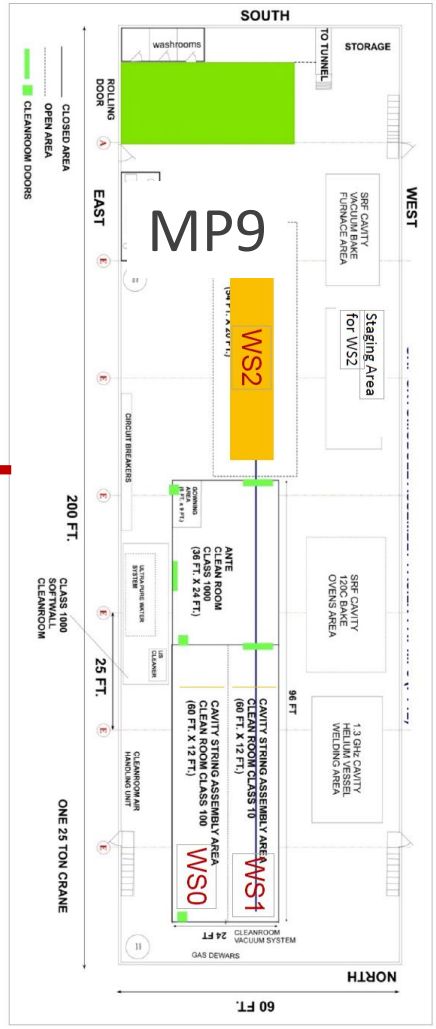
Income RF/QC)

IB1 (VTS)

ICB



shipping

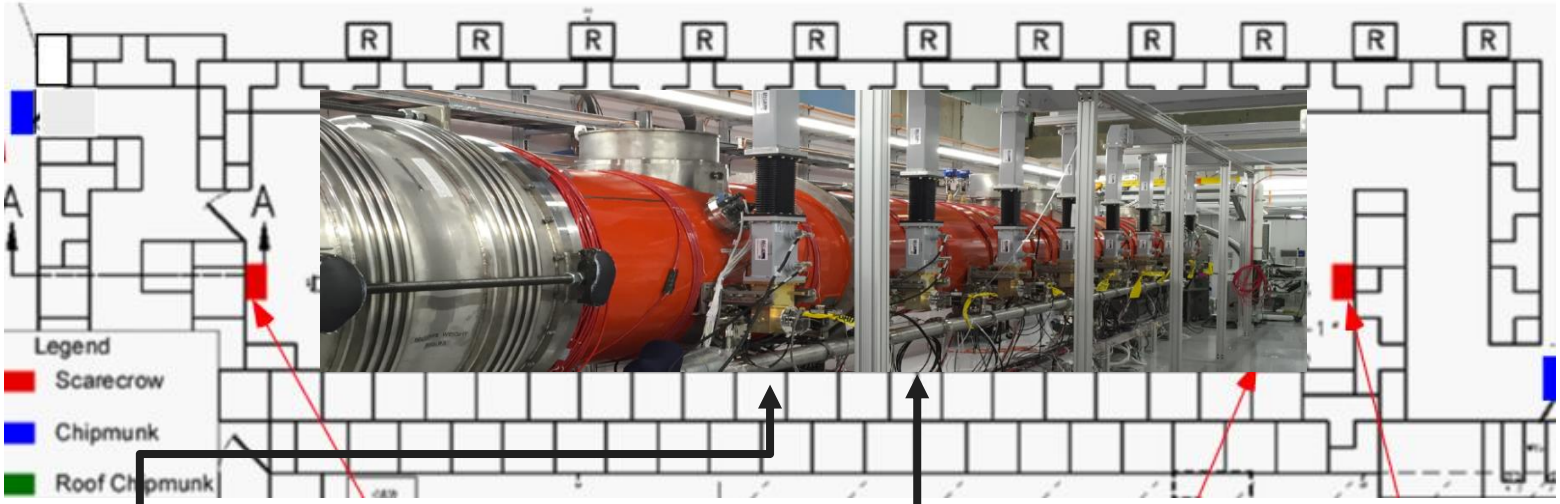


CMTF

Cavity RF/QC:

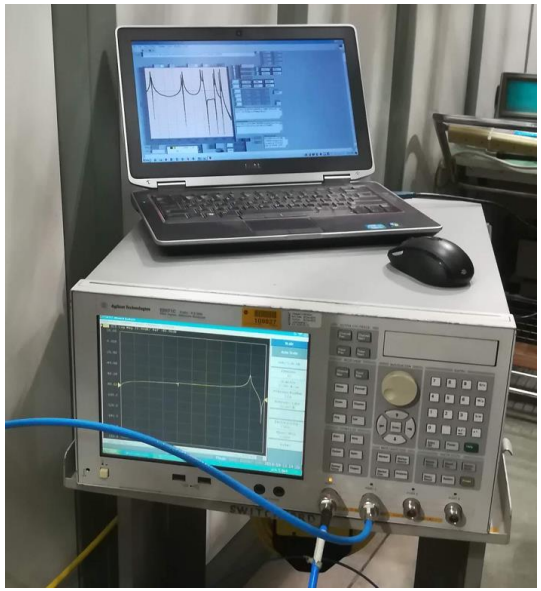
- RT Spectra
- HOM Notch
- Cables Integrity
- 2K Spectra
- FPC tune-up

Cryomodule Cold Test @CMTF

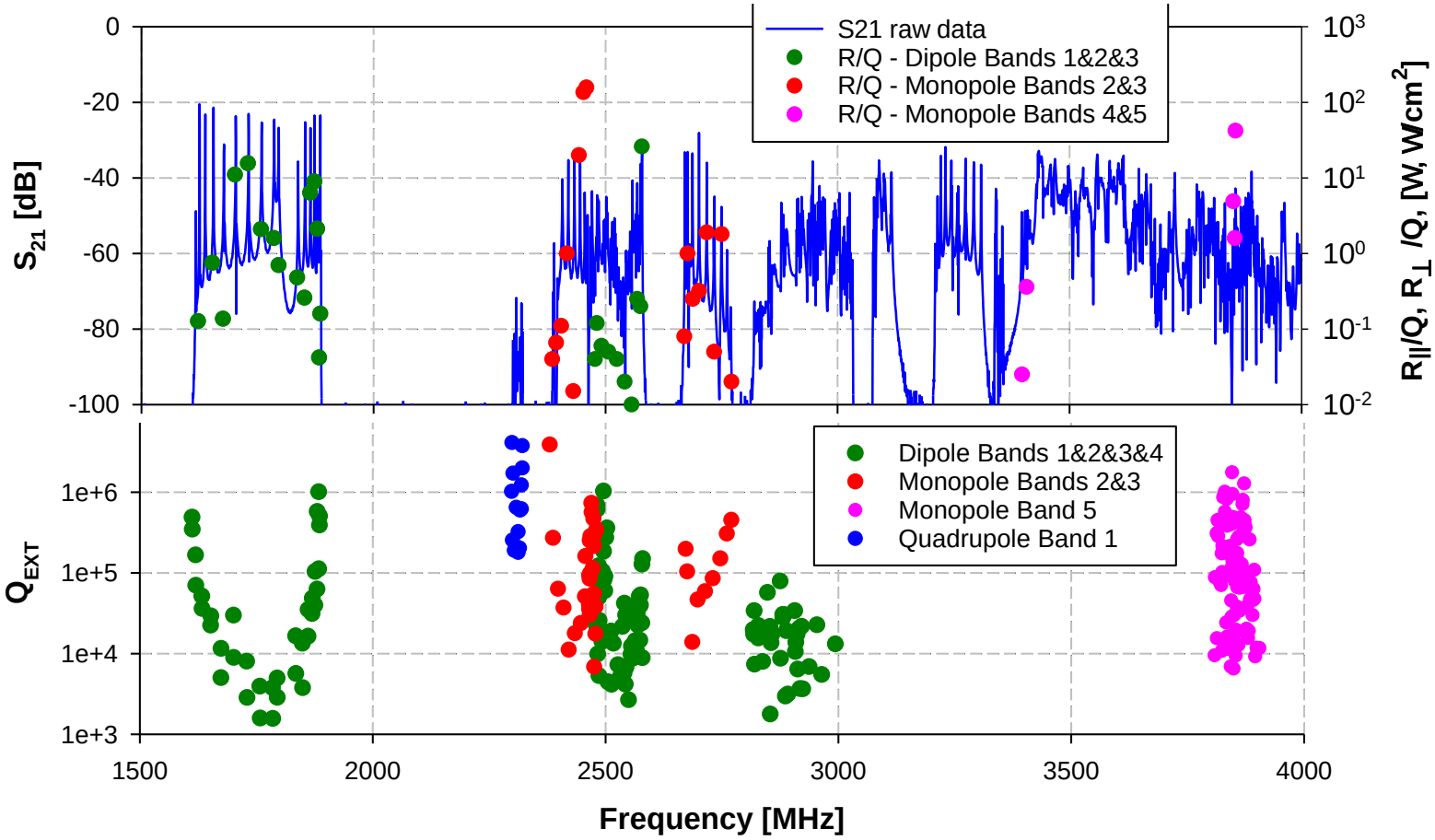


HOMs 2K Spectra Measurements

- Cables: 20m ⅜” Heliax, ~3dB loss
- HOM1 to HOM2 S21 signal
- Agilent E5071C NWA, <4.5GHz
- LabVIEW data acquisition
- Frequency sub-ranges: 5
- Step: 0.25 .. 2 kHz
- Max Qext: 5E6

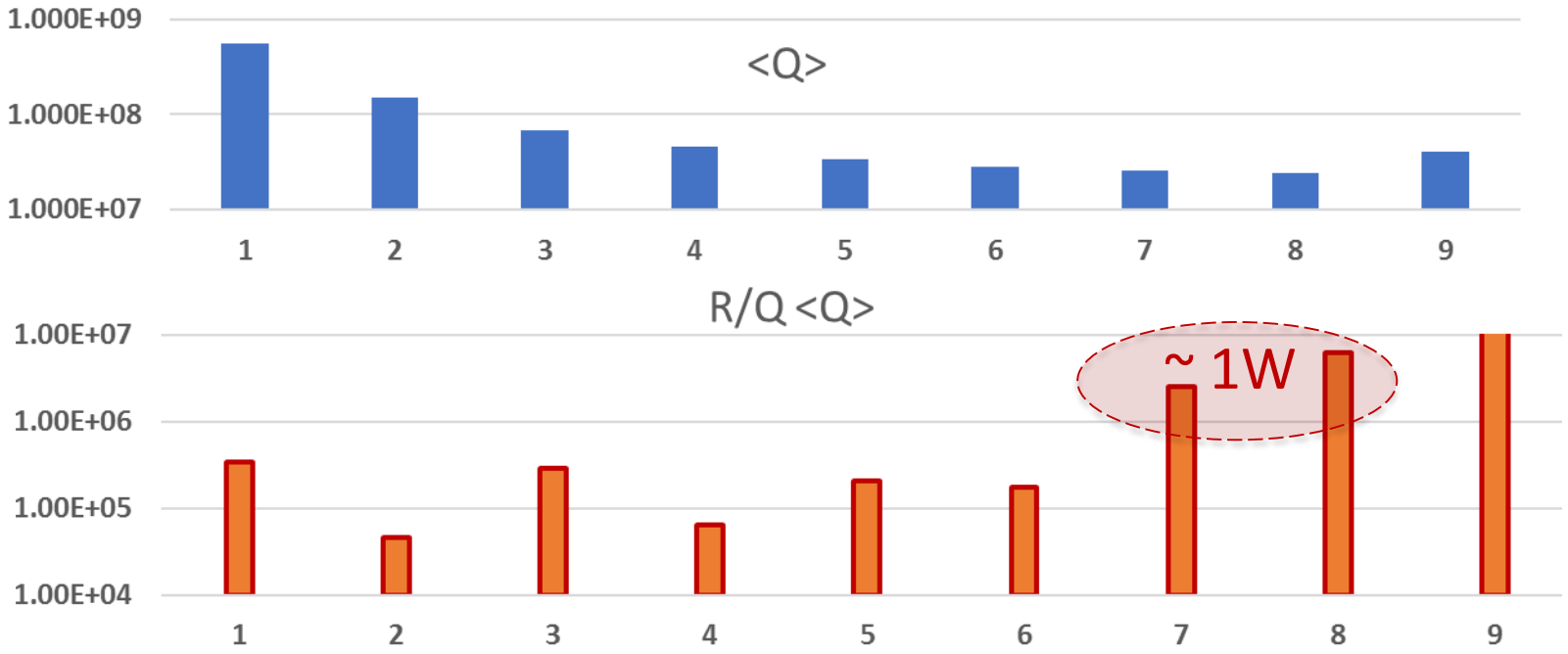


HOMs 2K Spectra @CMTF



- High risk HOMs: Dipole bands 1&2&3, Monopole band 2&5
- Dipole #3 and Monopole #5 bands interferes with other HOMs (difficult to sort out)
- Logged CM HOMs data: Dipole bands 1&2 and Monopole band 2

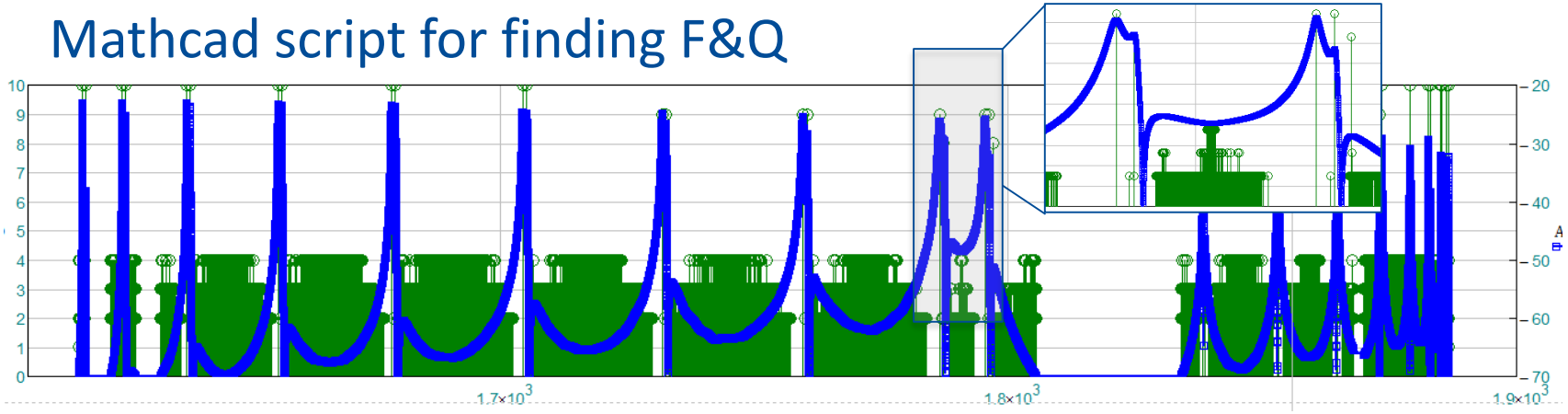
Operating Passband 2K Spectrum



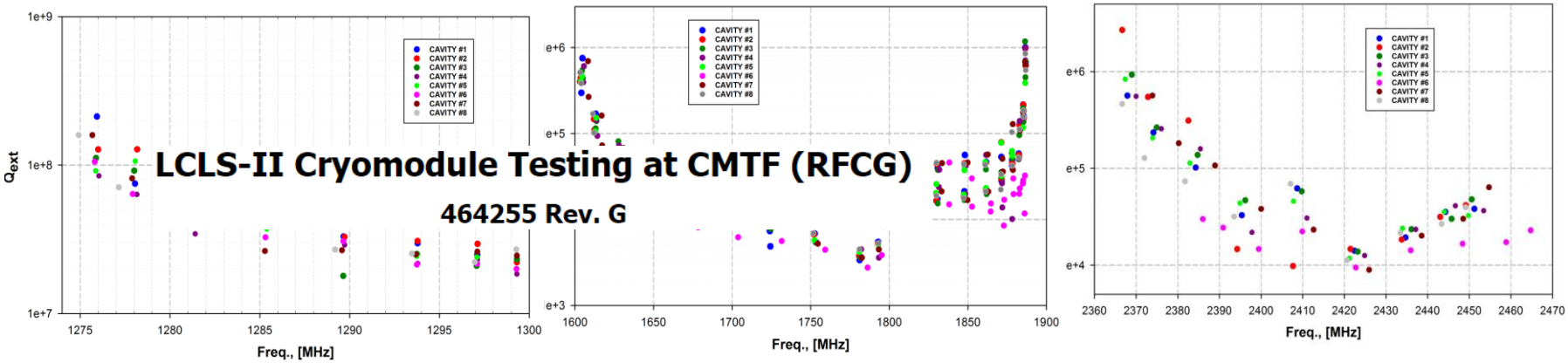
- Operating band monopole modes may generate up to 1 W power, if in resonance with the harmonic frequencies of 0.3 mA average beam current
- High Q-value (up to 10^9): difficult to locate and measure
- Slow S21 data acquisition: BW <20 Hz
- We take data for 3 cavities in the CM (left, right and middle)

HOMs Data Processing

Mathcad script for finding F&Q

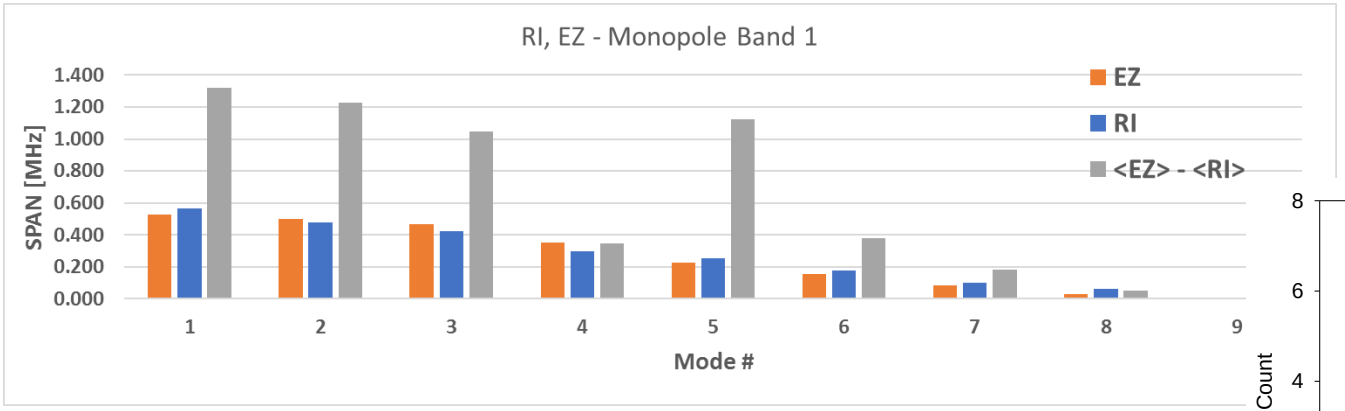


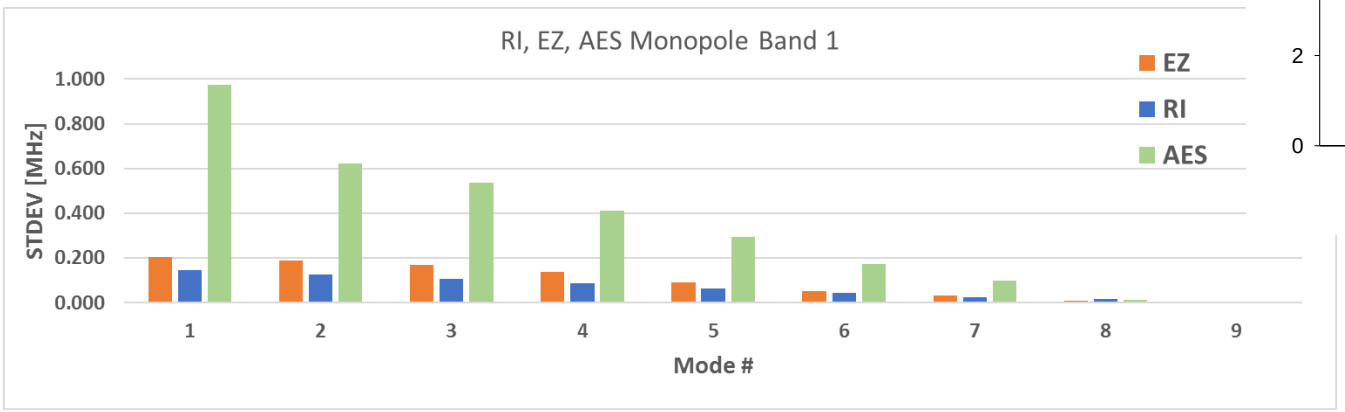
Sorted HOMs data

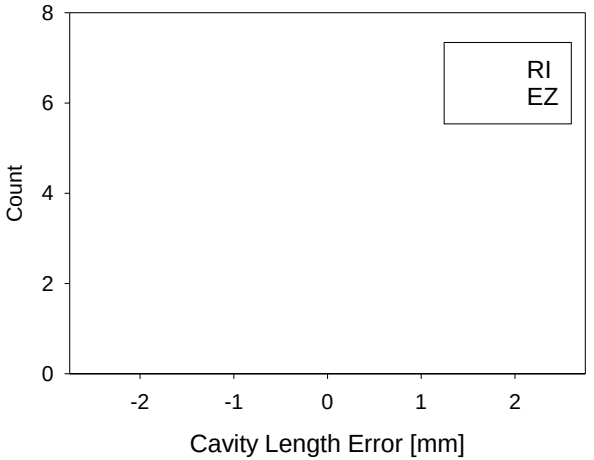


- Data filtering issues: noise, spurious peaks, bands overlapping
- Final sorted HOMs data are attached to each CM traveler

Statistics: Operating Passband Frequencies







- Cavity Vendors: pCM01 – 8 by AES, 9 production CMs – 50 by RI & 22 by EZ (Zanon)
- AES cavities were procured for the ILC prototyping and passed many clean&tune steps
- There is a large systematic frequency span between RI & EZ spectra (dies error, e/b welding ?)
- The average length of RI's cavities is ~1.5 mm shorter than the EZ's after field flatness tuning

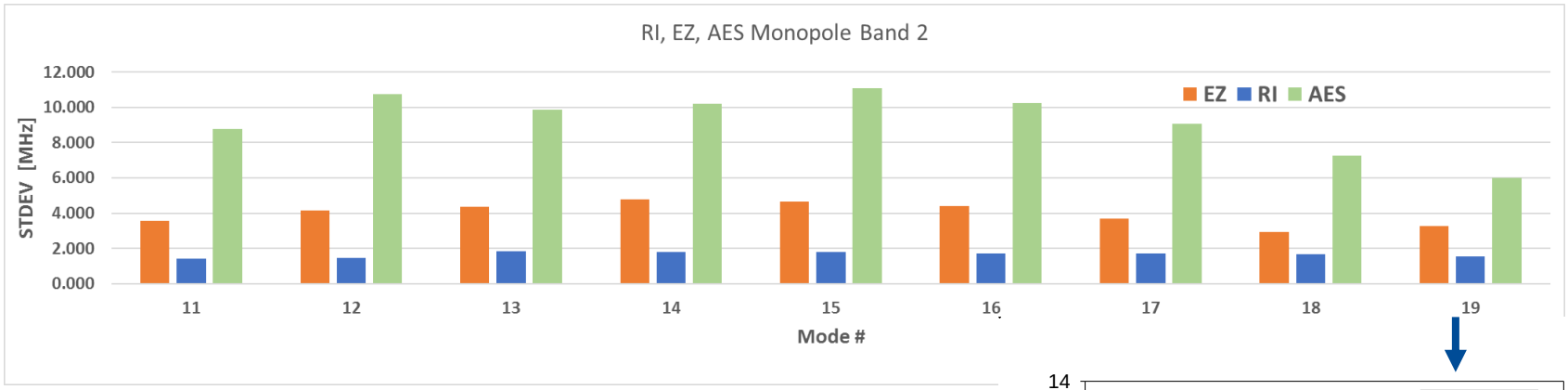
Statistics: Operating Passband Q-loaded

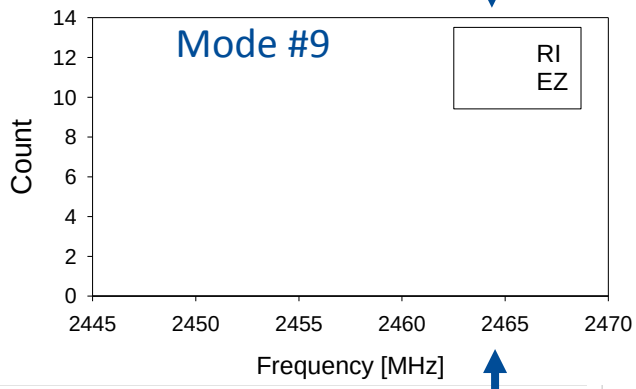
#	1	2	3	4	5	6	7	8	9
F [MHz]	1276.62	1278.67	1281.82	1285.73	1289.91	1293.87	1297.12	1299.25	1300.00
Q-loaded	6.71E+8	1.73E+8	8.13E+7	4.92E+7	3.45E+7	2.69E+7	2.27E+7	2.07E+7	4.0e+7

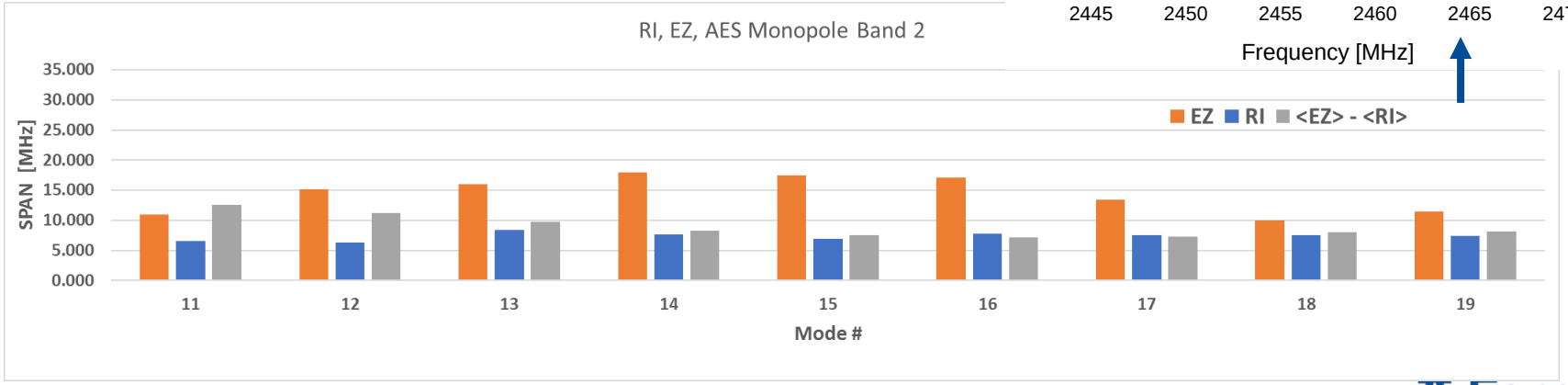
ANSYS HFSS

- Both RI and EZ spectra deviate from the spectrum of ideal cavity used in HFSS
- There is a good agreement of average Q values with HFSS simulations

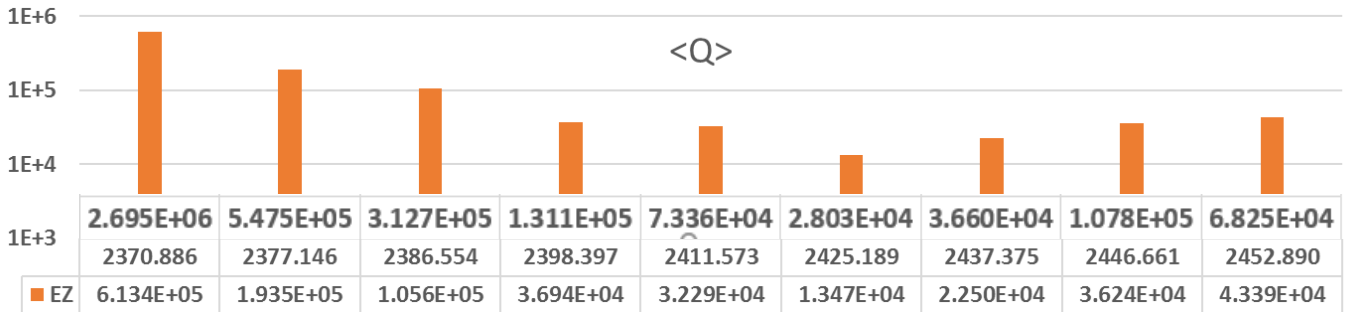
HOMs Statistics: Monopole Passband #2 Frequencies

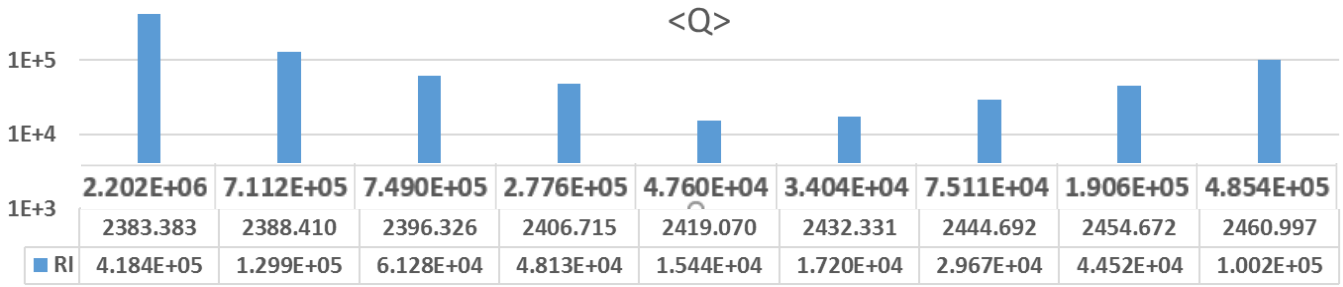


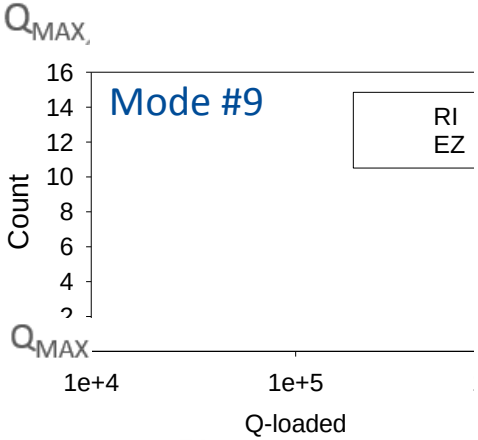


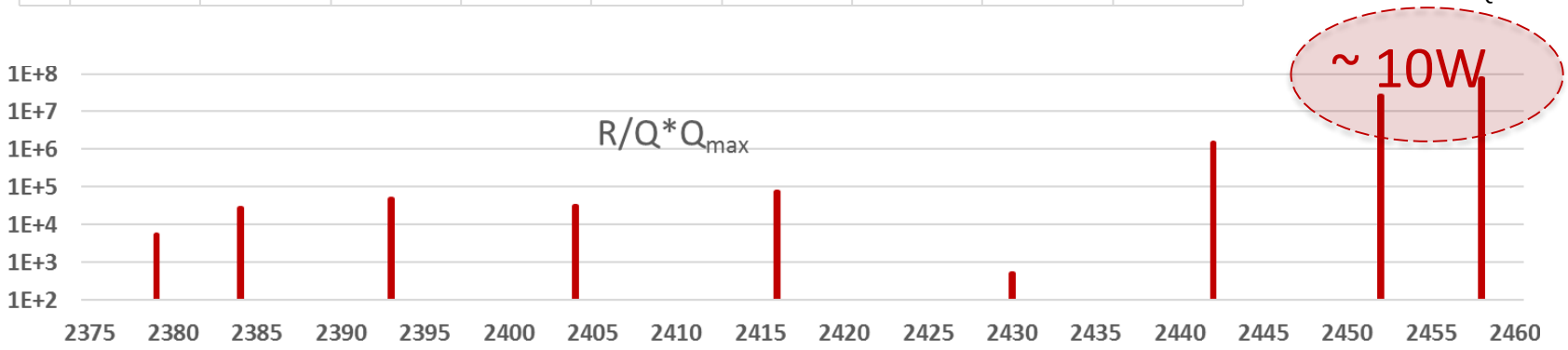


HOMs Statistics: Monopole Passband #2 Q-loaded



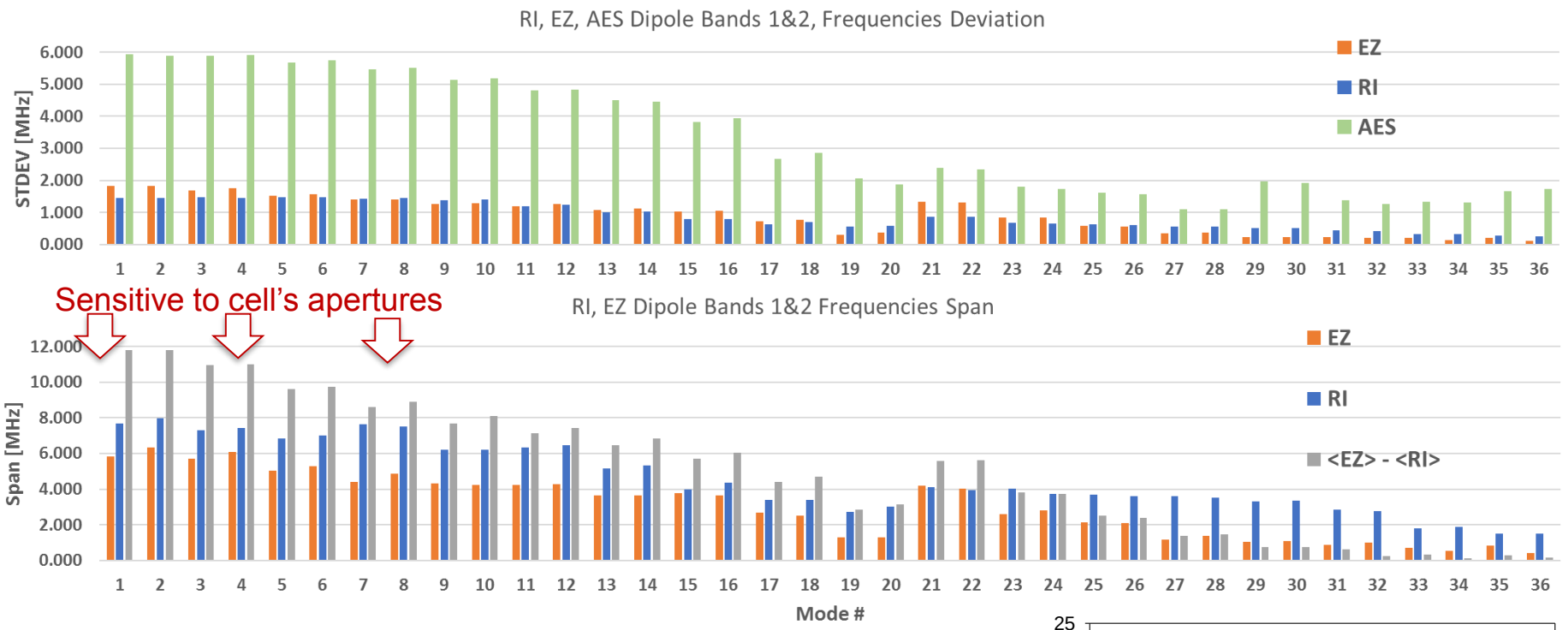




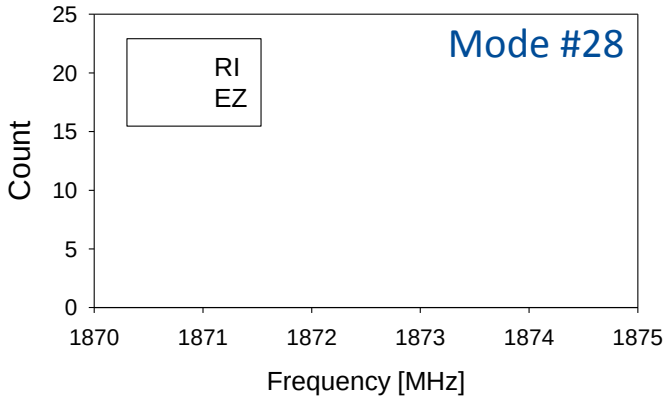


- 5 RI cavities have high Q-loaded of the M2_9 mode, EZ's are OK

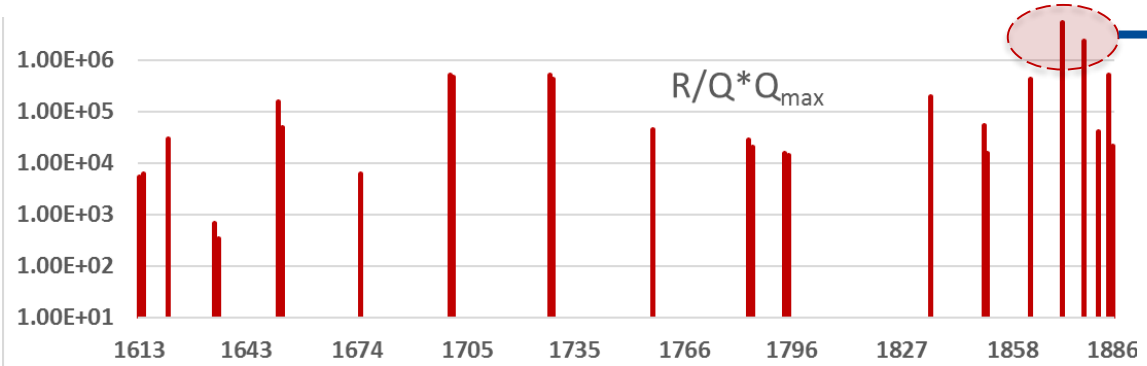
HOMs Statistics: Dipole Passband 1&2 Frequencies

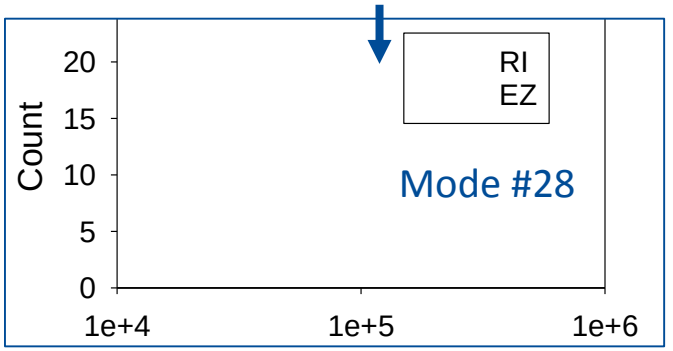


The triangle shape of RI and EZ dipole spectra frequencies span might indicate the difference of the dies aperture between vendors



HOMs Statistics: Dipole Passband 1&2 Q-loaded





Cavity Vendors Evaluation

HOMs frequencies [MHz]

Vendor	Monopole Operating Band		Dipole Bands 1&2		Monopole Band 2	
	rms	span	rms	span	rms	span
RI	<0.20	<0.6	<1.5	<8	<2	<9
EZ	<0.15	<0.5	<1.9	<6	<5	<18

Danger HOMs Q-loaded

Vendor	Mode 7/9 Operating Band		Mode #14 Dipole Bands		Mode #9 Monopole Band 2	
	rms	max	rms	max	rms	max
RI	2.5E7	3.0E7	4.6E4	6.0E5	1.0E5	4.9E5
EZ	2.4E7	3.1E7	3.8E4	7.8E4	4.3E4	6.8E4

Cavity Vendors Evaluation cont.

- HOMs frequencies
  - Both RI and EZ demonstrate similar HOMS frequencies r.m.s.
  - There are significant offsets between RI and EZ HOMs spectra, few time larger than frequencies rms for operating and dipole bands.
  - RI cavities are longer than EZ by about 2 mm
- HOMs Q-loaded
  - Both RI and EZ demonstrate similar Q-loaded for the operating band
  - Few RI cavities have significantly high Q-values of danger dipole and monopole HOMs
  - Maximum measured danger HOMs Q-loaded are about 2-3 times larger than ones predicted by simulation for the ideal cavity geometry.
  - Danger HOMs Q-values are below the LCLS-II requirements ($<10^6$)

Discussion

- Danger HOMs: 7/9 pi, dipole 2nd #14, monopole 2nd #9
  - Shall we try to track dipole 3rd and monopole 5th passbands? How danger they are?
- HOMs spectra of RI and EZ vendors are significantly different
  - Is there an optimum solution how to put them in a linac? Randomly? Neighbor cavities of different vendors might reflect the HOM signal of propagating modes. Too late to change for the LCLS-II but we can think about for the ILC
- Control cavity production stabilities
  - HOMs spectra are a sensitive indicator of the cavity imperfections. Shall we ask vendors to perform HOMs 2K measurement at VTS/HTS and to sort out/reject “bad” cavities?
  - Can we estimate operating mode field flatness ?
- How we may use the accumulated HOMs data?
  - Coherent HOMs excitation might be an issue for the high-current or large scale machines (ILC). Using measured HOMs data for the beam dynamics analysis would secure our understanding of machine operation and ensure project reliability
  - Verification of numerical simulations results is a challenging question. Experimental HOMs data is a reliable source of the HOMs statistical parameters.
- What else …?

Conclusions

- Production of 1.3 GHz LCLS-II cryomodules is ongoing at Fermilab, 11 CMs passed the final cold test @CMTF facility
- RF/QC procedures are implemented through the CM assembly and testing
- HOMs signals acquisition procedure during the CM cold test is developed along with further data processing
- Both RI and EZ cavity vendors show similar results in terms of HOMs frequencies deviations
- Few RI cavities have a larger spread of HOMs Q-loaded
- Most of danger HOMs are identified and tracked
- Danger HOMs Q-values are below the LCLS-II specification ($<10^6$)

Acknowledgments

We would like to thank Elvin Harms and the CMTF team for their support and assistance during the 2K HOMs spectra measurements of LCLS-II cryomodules.