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

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Experiments on HOM Spectrum Manipulation in a ILC 1.3 GHz Cavity

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Project X

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Motivation:

- HOM couplers are an expensive and complicated part of SC acceleration structure (problems – manufacturing, multipactoring, additional hardware – cables, feed-through, connectors, loads, etc);

- SNS SC linac experience show that HOM couplers 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;

But

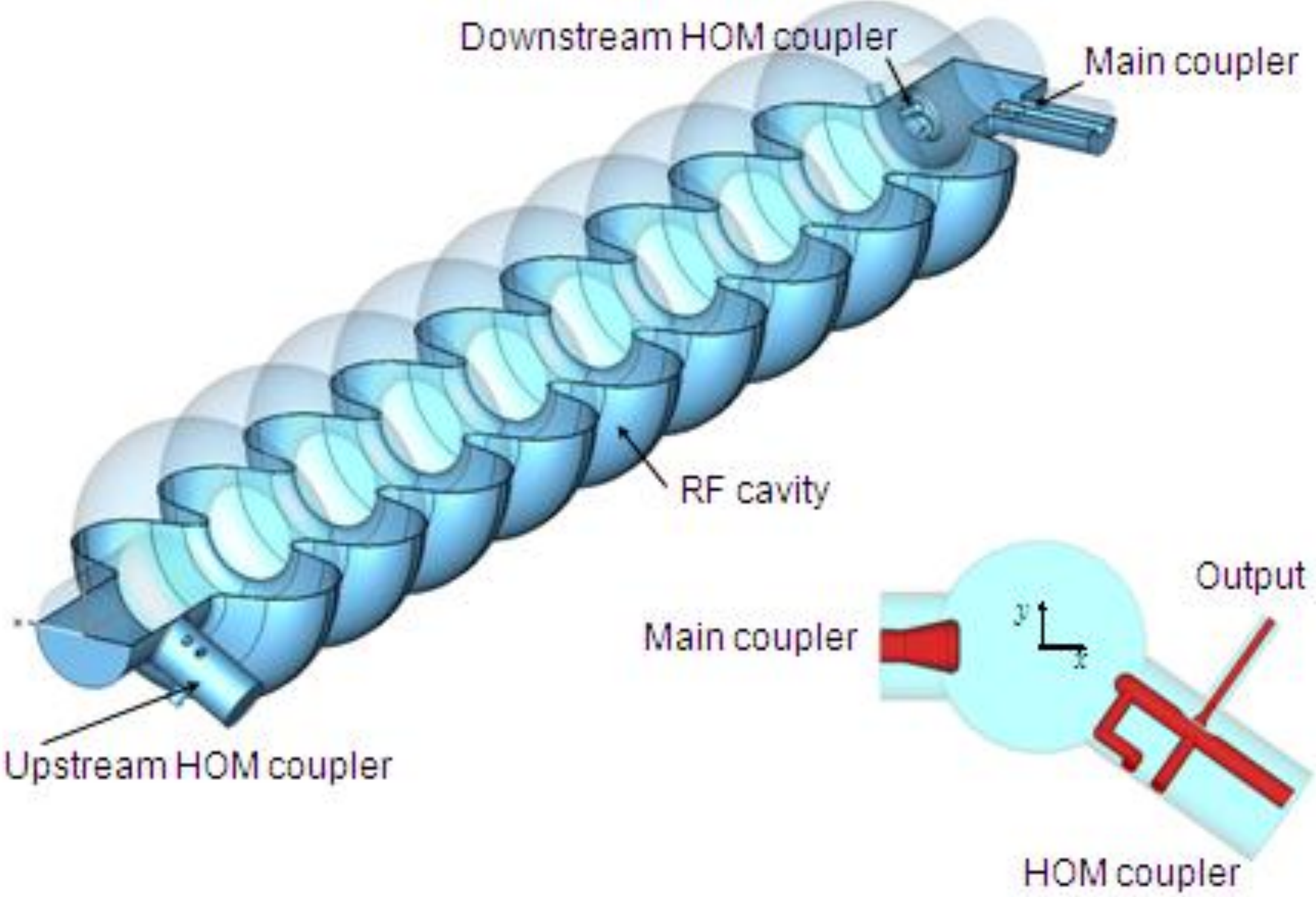
- What to do if the HOM has resonance frequency close to frequency of the beam spectrum line? When and how it is serious?

- 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.

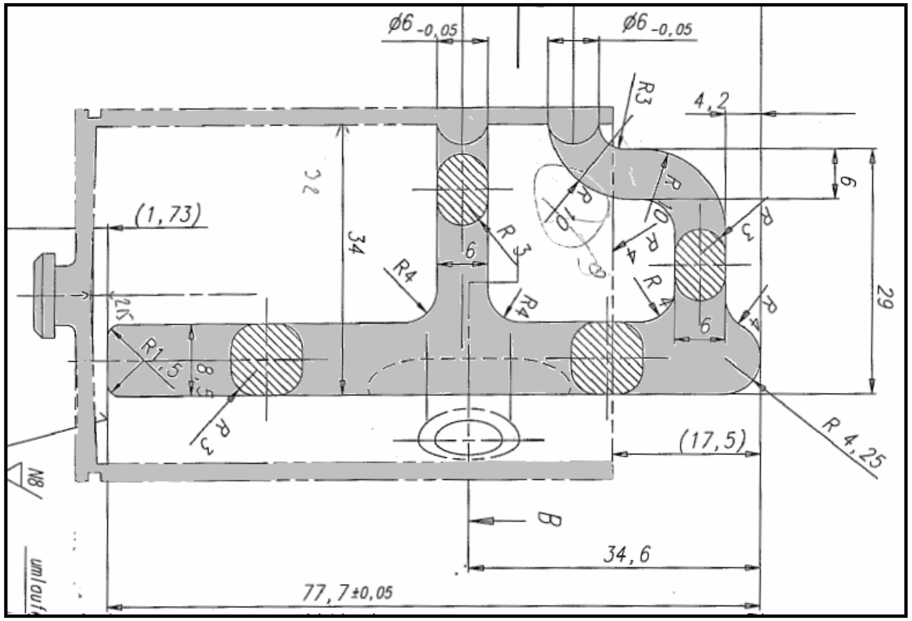
- From other side, in ILC HOM dampers are necessary. All 1.3 GHz ILC cavities are equipped by HOM couplers, that work successfully in FLASH at DESY.

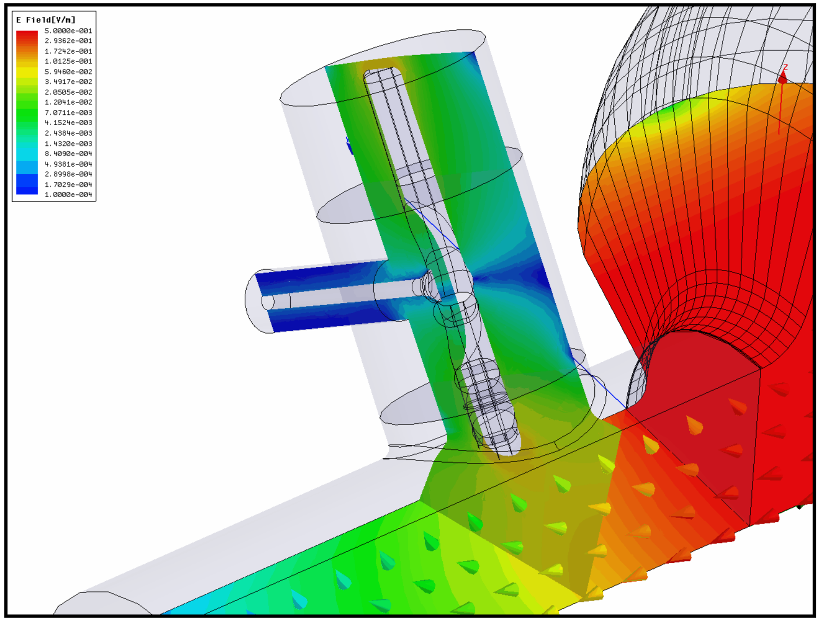
- In the case of future upgrade Project X couplers may become necessary.

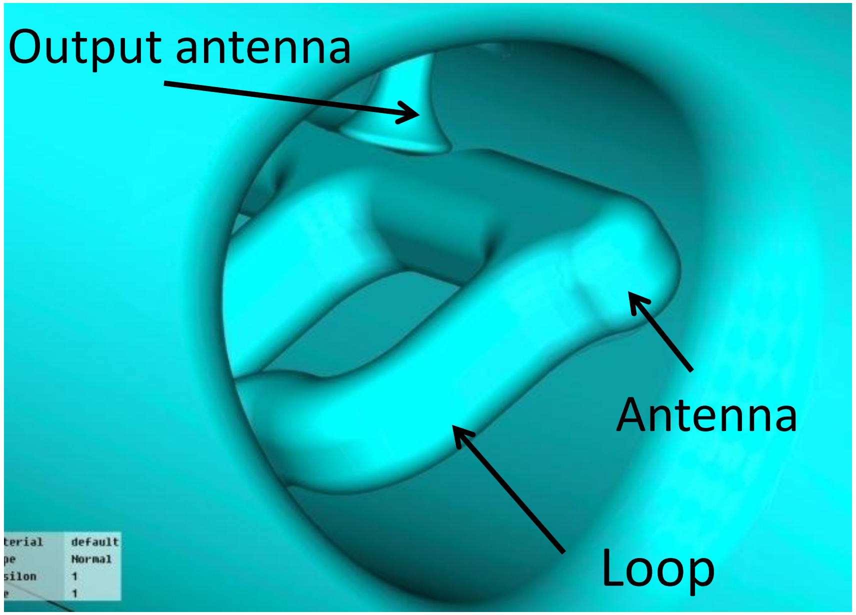
ILC RF cavity with the HOM and input couplers:



ILC-type HOM coupler







ILC (TESLA) HOM coupler 3D object.

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:

J. Sekutowicz, private communications.

Effect of the HOMs in the Project X linac:

- ➢Resonance excitation;
- ➢Collective effects.

❖Resonance excitation, monopole modes.

Monopole modes should not increase the beam longitudinal emittance 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

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

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*

$$\boxed{\delta f \gg 70\ \text{Hz}}$$

- *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 $Q_{loaded} \ll 1.8e7$.

❖Project X: Resonance excitation, dipole modes.

- ➢Dipole modes should not increase the beam transverse emittance (normalized emittance is 2.5e-7 m).
- ➢Transverse kick caused by the HOM is:

$$U_{kick} \approx \frac{f}{4\delta f}\left(\frac{x_0}{k}\right)\tilde{I}(R/Q)_1, \quad \delta f/f \gg 1/Q \qquad (k=2\pi/\lambda)$$

- ➢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,

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

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.

What to do if the HOM has resonance frequency close to one of the frequency of the beam spectrum line? Can we move it away.

- 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 tests were made with the 1.3 GHz, 9-cell ILC cavities **at 2 K**.

- The operating mode frequency was detuned by $\Delta F=90$ kHz, and then was tuned back with the accuracy of <20Hz.

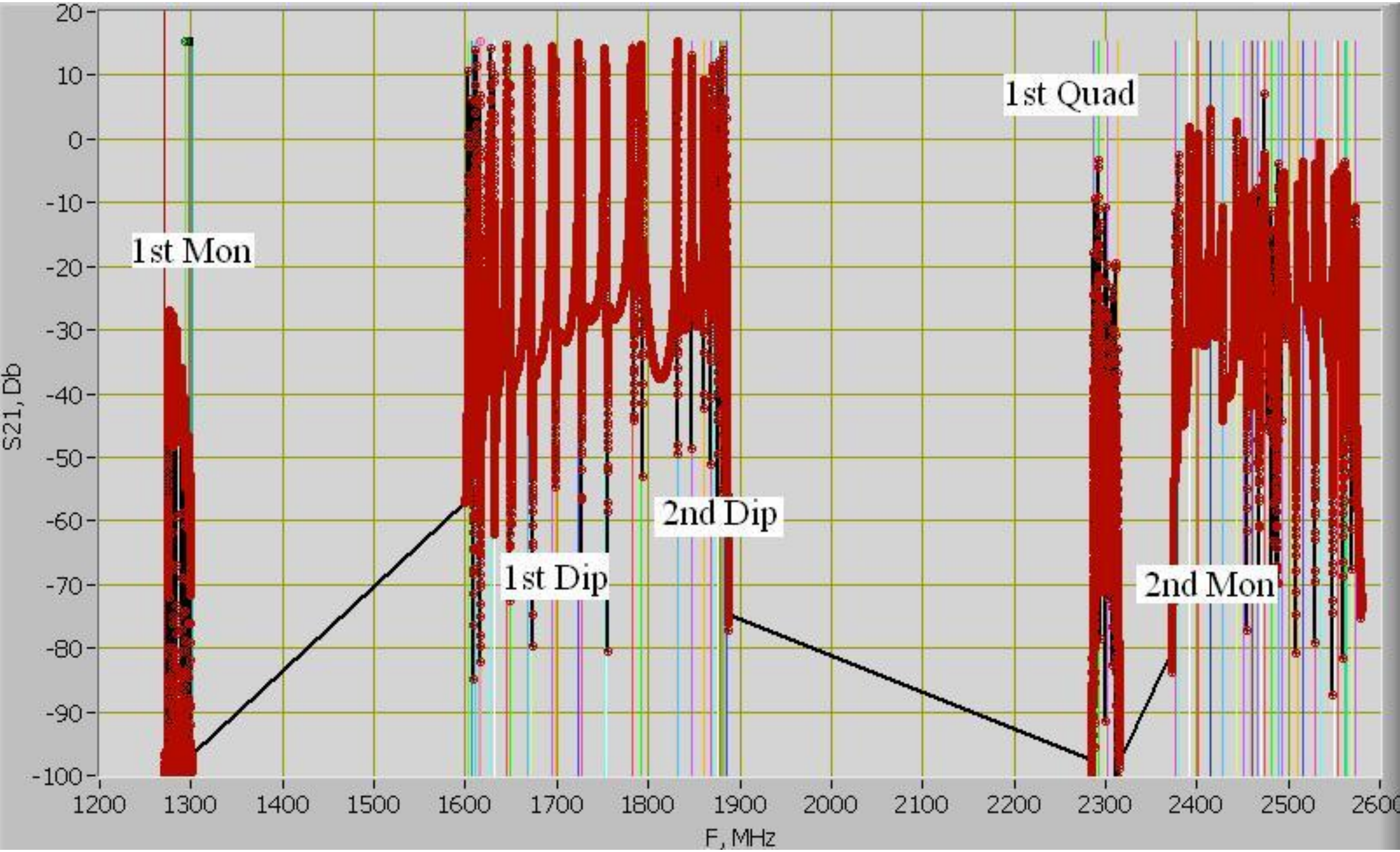
- The frequencies of HOMs moved after this procedure by $\delta F=100\text{-}500$ Hz because of small residual deformation of the cavity or/and cavity helium vessel support.

Table 1. Cavity TB9AES009 in HTS, 5/10/2010. Cavity was detuned by +90 kHz and tuned back.

F, MHz	ΔF, kHz	δF, Hz	Pass-band	Q
1300	90	0	1Monopole	3e6
1600.093	-218	360	1Dipole	5.1e5
1604.536	-215	240	1Dipole	6.7e5
1607.951	-214	360	1Dipole	1.5e5
1612.189	-210	360	1Dipole	1.5e5
1621.344	-211	240	1Dipole	9.1e4
1625.458	-208	370	1Dipole	1.3e5
1830.836	-185	370	2Dipople	2.5e4
1859.882	-36	120	2Dipople	2.6e4
2298.807	-278	480	1Quadrupole	6.5e6
2299.346	-278	490	1Quadrupole	7.1e6
2372.333	-224	490	2Monopole	3.5e5
2377.333	-221	490	2Monopole	6.8e4
2383.575	-213	240	2Monopole	2.1e5
2399.289	-210	490	2Monopole	3.7e4

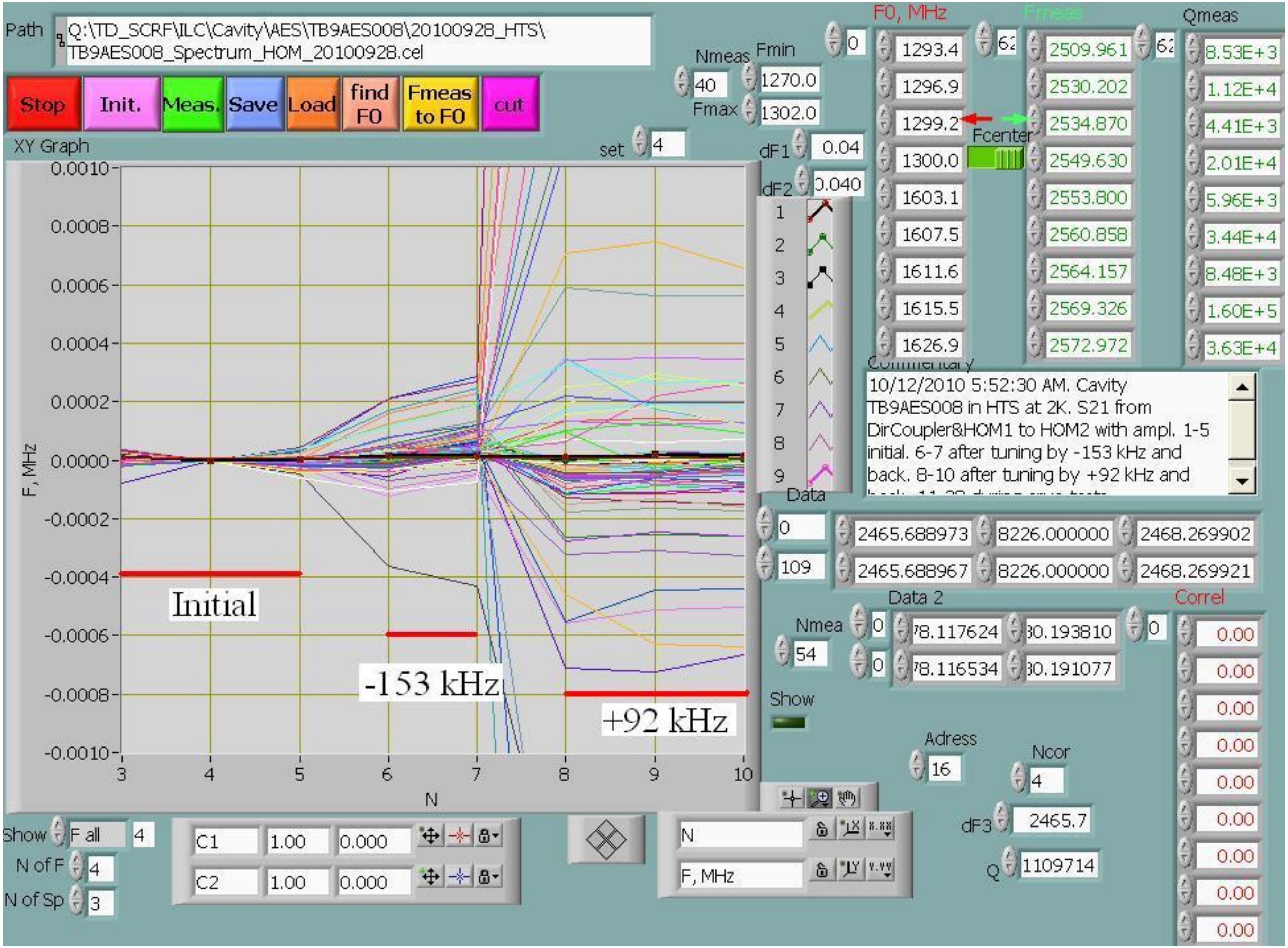
Step1. S21 measurements.

Step2. Resonance frequency calculations from step1 data.



ILC cavity TB9AES008

Step3. Resonance frequency and Q factor measurements.



Path: Q:\TD_SCRF\ILC\Cavity\AES\TB9AES008\20100928_HTS\TB9AES008_Spectrum_HOM_20100928.cel

Nmeas: 40

Fmin: 1270.0

Fmax: 1302.0

set: 4

dF1: 0.04

dF2:).040

F0, MHz (0)	Fmeas (62)	Qmeas (62)
1293.4	2509.961	8.53E+3
1296.9	2530.202	1.12E+4
1299.2	2534.870	4.41E+3
1300.0	2549.630	2.01E+4
1603.1	2553.800	5.96E+3
1607.5	2560.858	3.44E+4
1611.6	2564.157	8.48E+3
1615.5	2569.326	1.60E+5
1626.9	2572.972	3.63E+4

Commentary:
10/12/2010 5:52:30 AM. Cavity TB9AES008 in HTS at 2K. S21 from DirCoupler&HOM1 to HOM2 with ampl. 1-5 initial. 6-7 after tuning by -153 kHz and back. 8-10 after tuning by +92 kHz and

Data

0	2465.688973	8226.000000	2468.269902
109	2465.688967	8226.000000	2468.269921

Data 2

Nmea: 54

0	78.117624	30.193810
0	78.116534	30.191077

Correl (0):
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00
0.00

Adress: 16

Ncor: 4

dF3: 2465.7

Q: 1109714

Show: F all 4

N of F: 4

N of Sp: 3

C1	1.00	0.000
C2	1.00	0.000

N

F, MHz

Resonance frequency measurements accuracy.

1. Network Analyzer dynamic frequency error dF/F<1e-9 is small enough for this measurements.

2. Contribution o the noise of S21 measurements.

$$\delta F \approx 0.3\frac{F}{Q} * \frac{A_{noise}}{A}, \frac{A_{noise}}{A} < 0.001$$

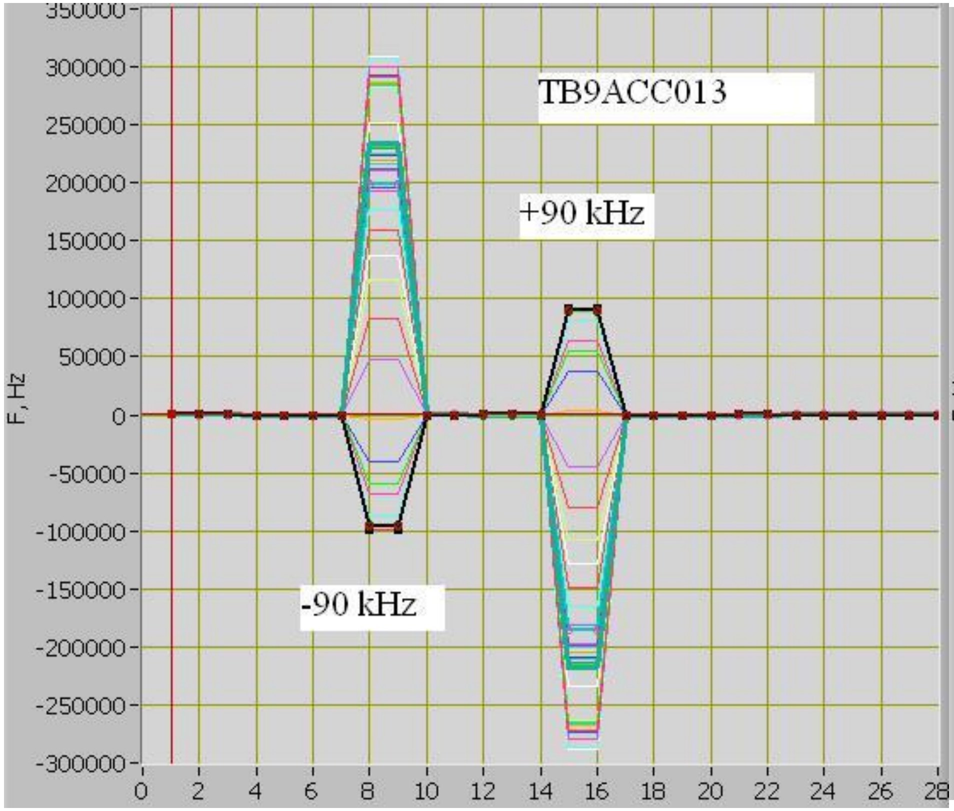
F, MHz	Q	A_{noise}/A	Pass-band	dF, Hz
1300.002	3e6	1e-2	1Monopole	1.3
1626.927	5.7e4	1e-4	1Dipole	0.9
2450.597	2.6e4	2e-4	2Monopole	5.7

3. Helium pressure stability.
At Operating temperature of 2K Helium pressure is P=23 Torr.
Mid term pressure fluctuations dP<0.1-0.2 Torr in HTS.
For operating mode (1300 MHz) dF/dP is 100 Hz/Torr. Which corresponds to 10-20 Hz of frequency fluctuations.

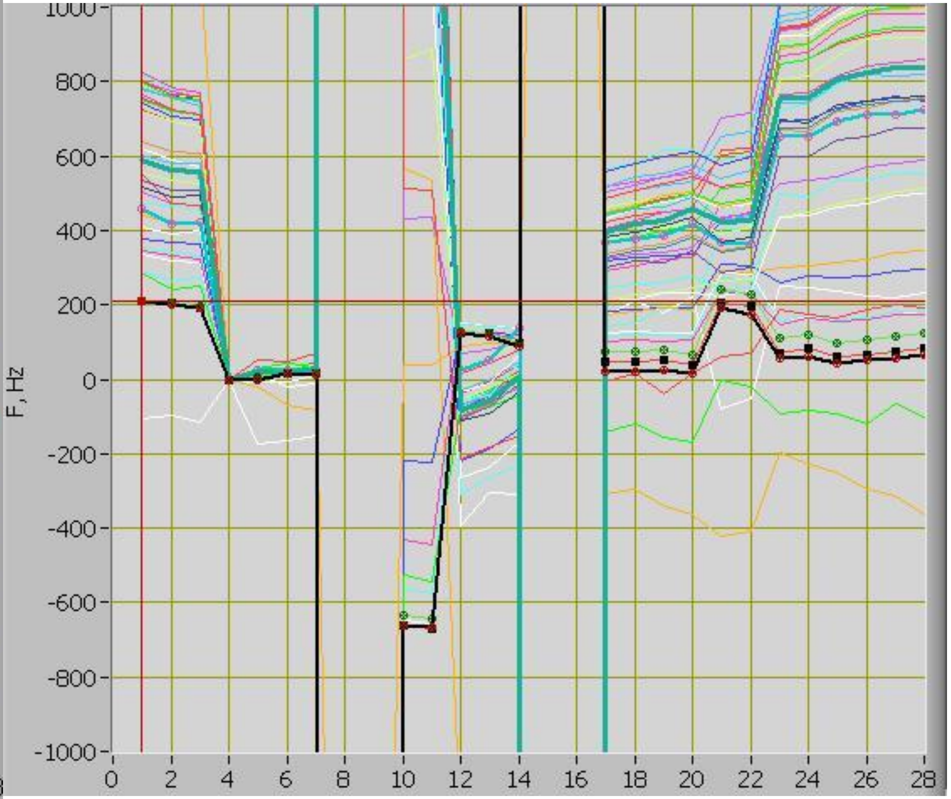
4. Operating mode resonance frequency tuning accuracy.
Blade Tuner with stepping motor change the frequency of the operating mode by 1.5 Hz per step.

Resonance frequency measurements accuracy mostly defined by Helium pressure stability.

Example of HOM spectrum manipulations of ILC cavity in Horizontal Test Station (HTS). We detune cavity frequency using Cavity Tuner and tune it back. Operating mode (p-mode of 1st monopole pass band, F=1.3 GHz) frequency returned back with accuracy of ~10 Hz. Frequency tuning range of the cavity tuner is more than ±300 kHz.

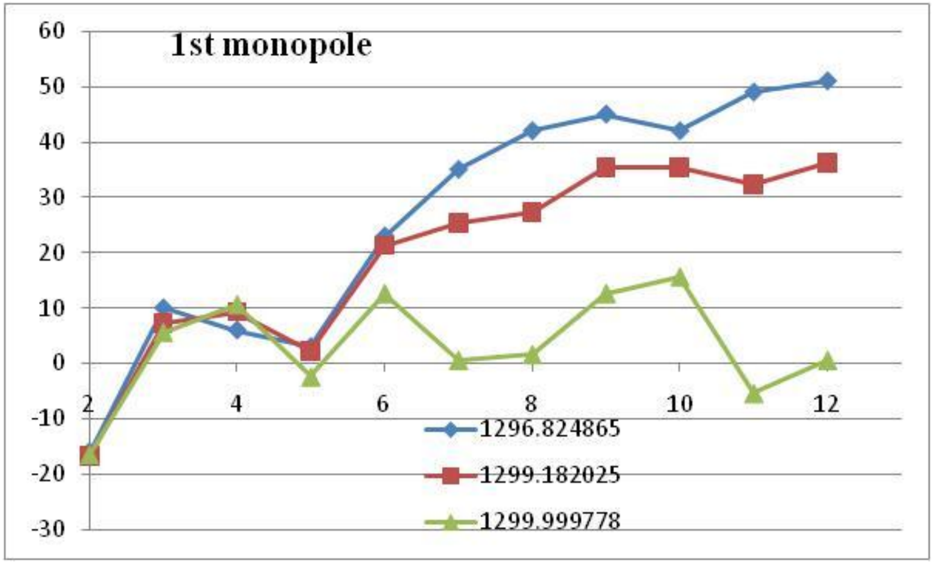


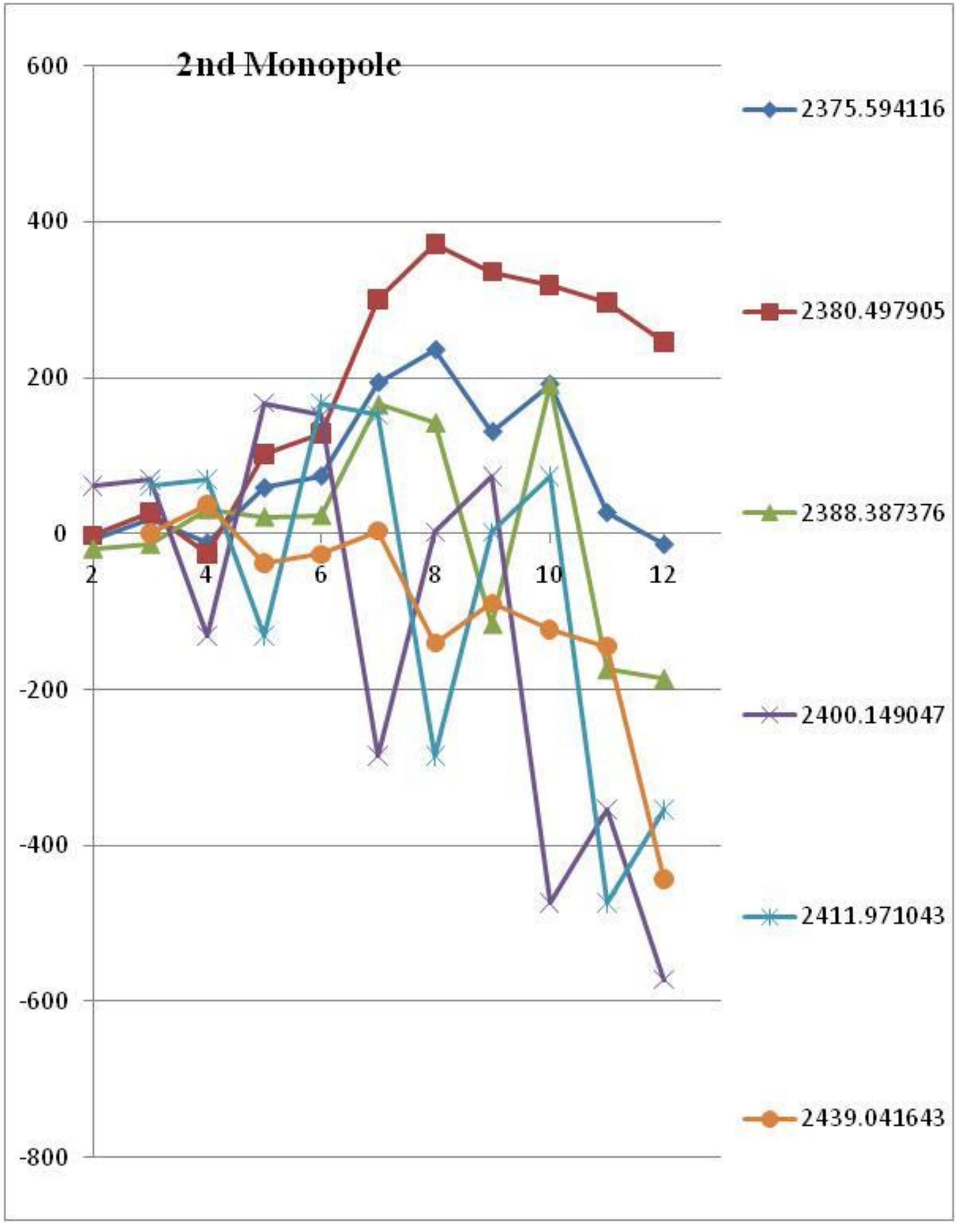
Frequency change during test for all modes, full scale

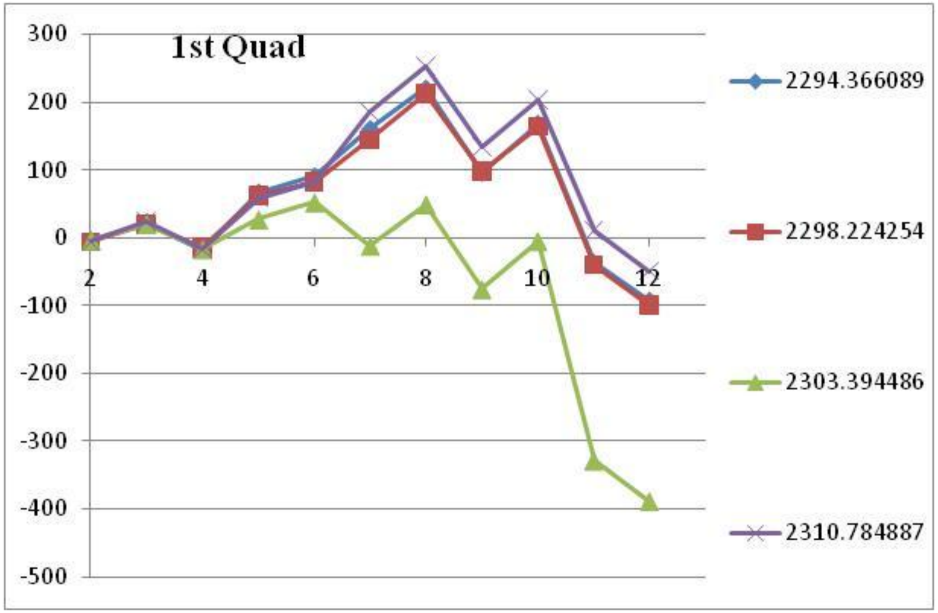


Zoomed to dF ±1000 Hz range.

8/19/2010 6:19:07 PM. TB9AES010 in HTS 2K.
1-4 reference. 5-6 +97 kHz, 7-8 -104 kHz, 9-10 a-100 kHz, 11-12 -200 and back.







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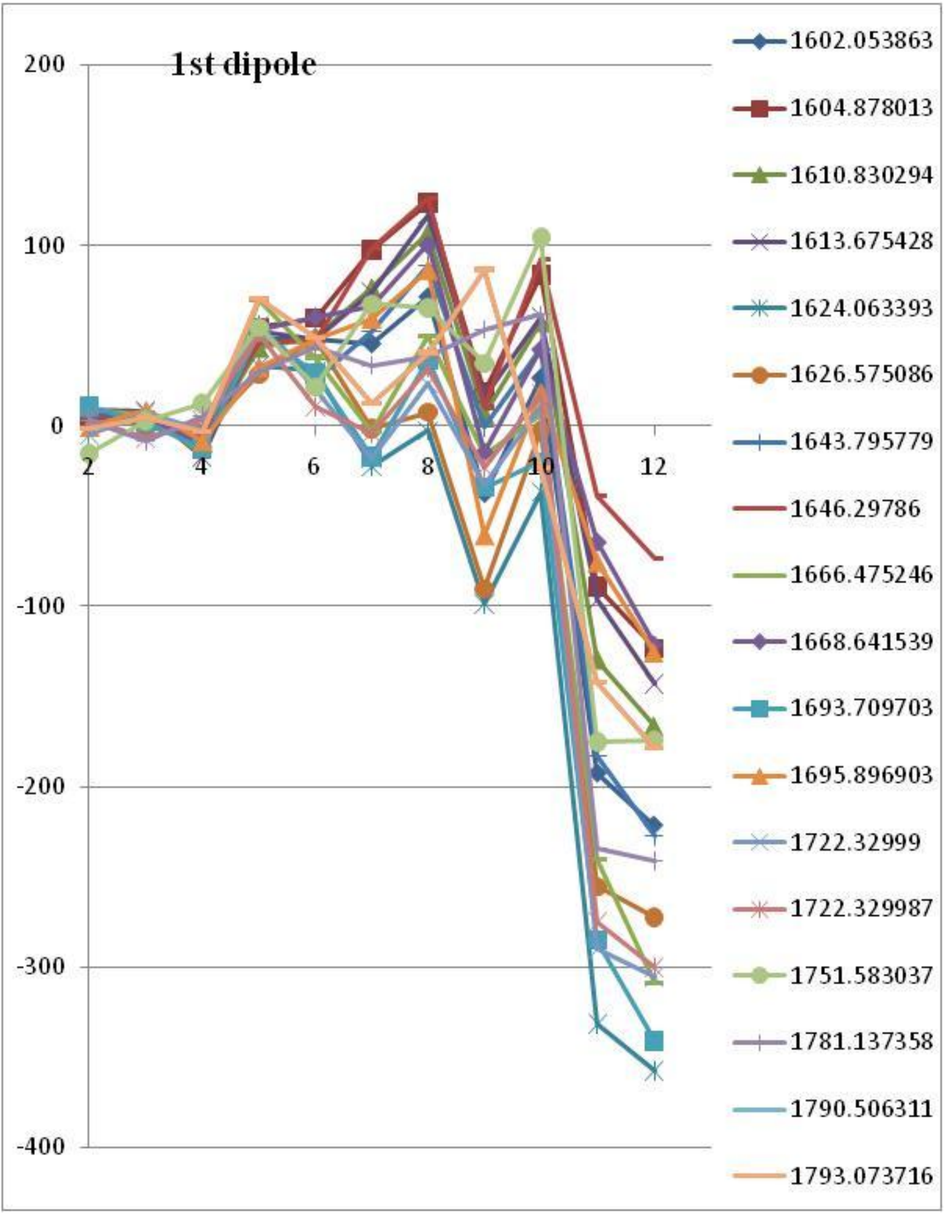
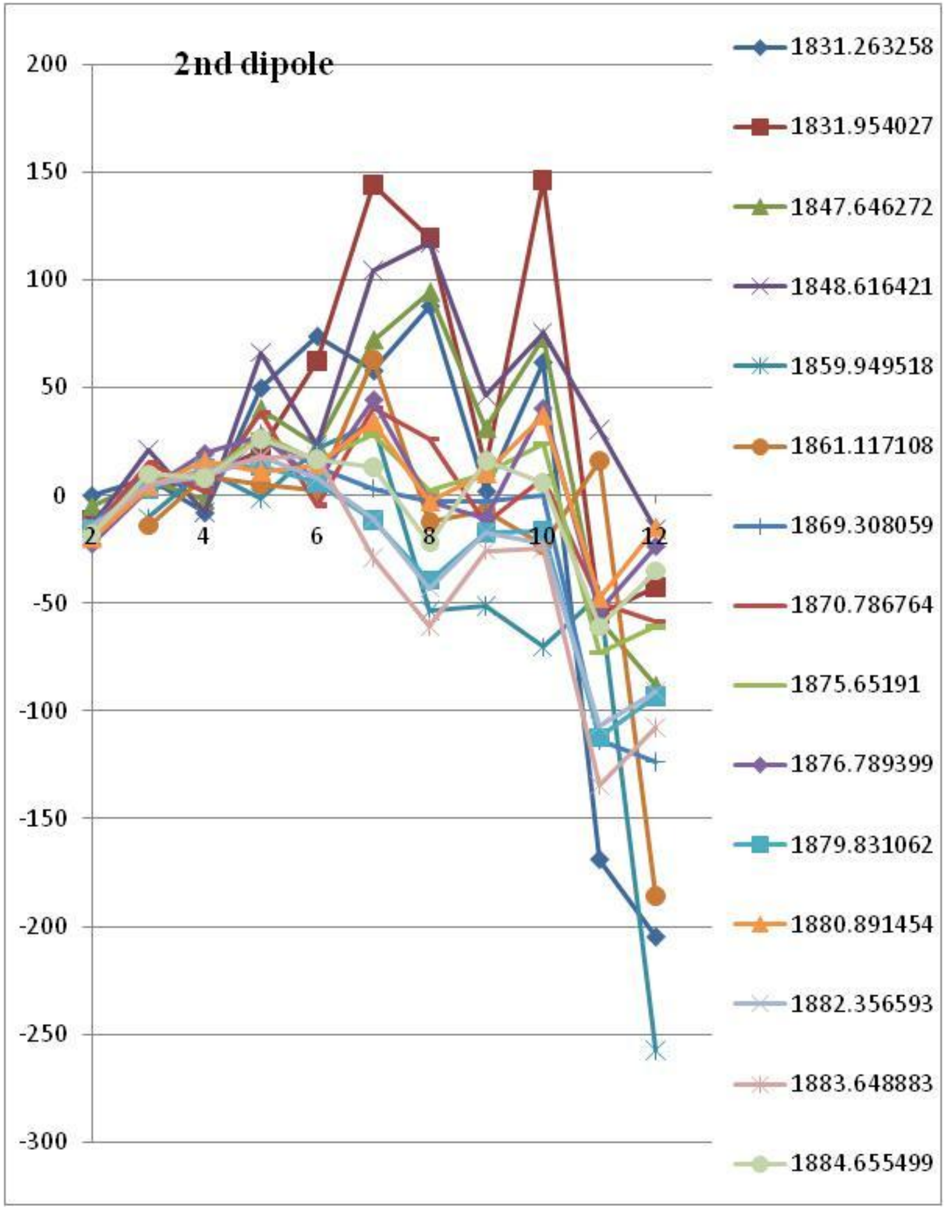
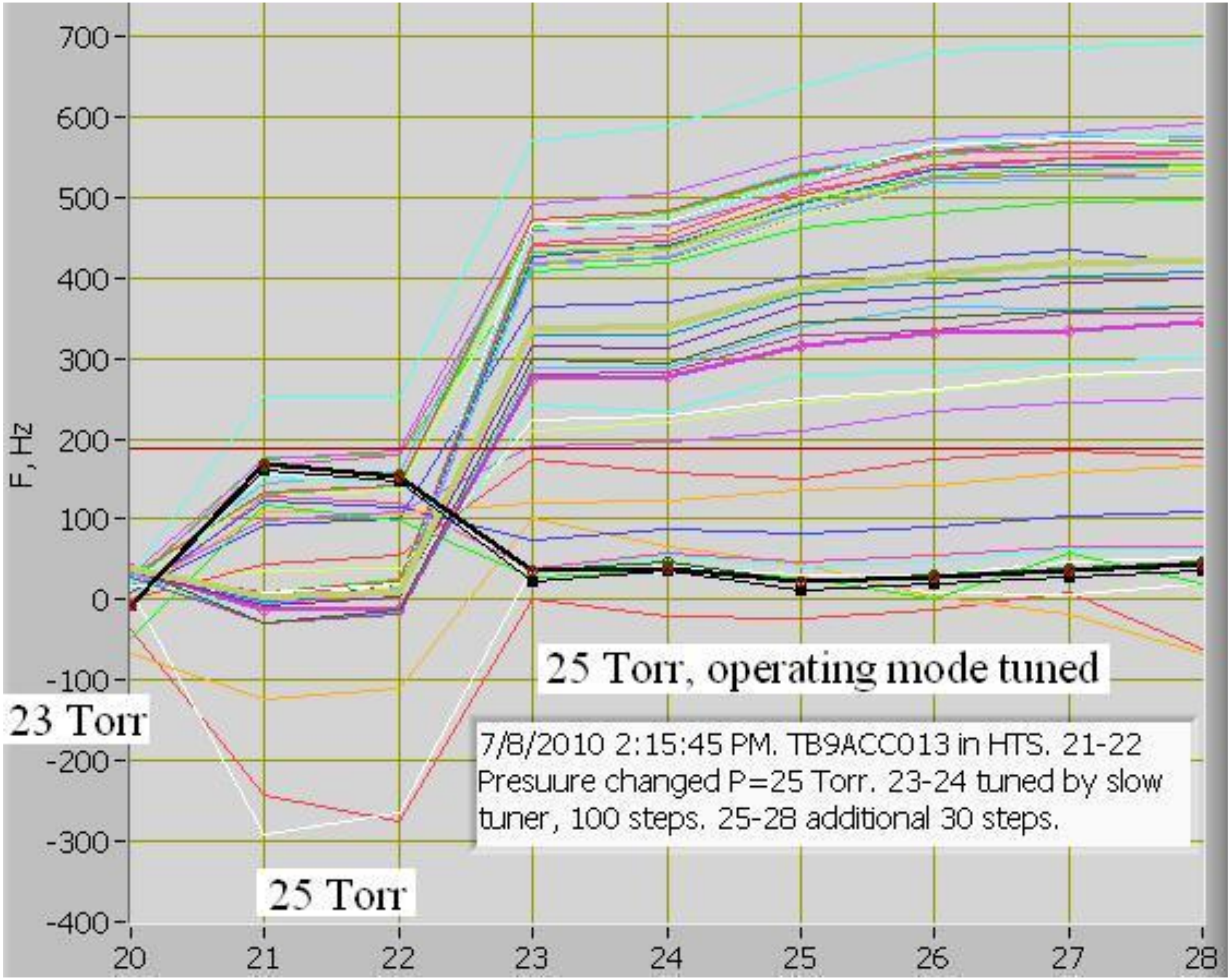




Cooling Helium pressure change is disturbing the HOM spectrum.



7/8/2010 2:15:45 PM. TB9ACC013 in HTS. 21-22 Presuure changed P=25 Torr. 23-24 tuned by slow tuner, 100 steps. 25-28 additional 30 steps.

7/8/2010 2:15:45 PM. Cavity TB9ACC013 in HTS. 20 at nominal Helium pressure of 23 Torr. Measurement number21-22 Helium pressure changed to P=25 Torr. 23-24 tuned by slow tuner, 100 steps. 25-28 additional 30 steps.

Summary

1. For Project-X linac monopole HOMs are more dangerous. To avoid longitudinal emittance grow dF>>70 Hz detuning is necessary. The probability that the cavity has the resonant frequency close enough to the beam spectrum line is ~1e-5 per cavity.
2. Increase of the beam transverse emittance caused by transverse HOMs does not look to be a problem. dF>>1 Hz detuning usually caused by regular microphonics.
3. Detuning the frequency of the HOM mode by several hundred Hz is possible without warming up of the cavity. Cavity frequency Tuner can be exercised in order to shift frequency of the problem mode.
4. HOM frequency detuning can be explained by a small residual deformation of the cavity and residual stresses on cavity support system which cause a little bending of the cavity.
5. Stretching of the cavity by Tuner at room temperature is possible if more detuning is necessary. Plastic deformation of the cavity can change HOM frequency spectrum by several kHz without significant distortion of the accelerating field distribution.
6. In the case of HOM couplers integration in Project-X cavity will be decided, dumping to Q<1e6 is enough for HOM Monopole modes.