Microphonics analysis of ERL cryomodule

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Outline

- Introduction
- Microphonics in the MLC
- Microphonics compensations
- Summary

Introduction

What is detuning?

- Detuning is a shift in the resonant frequency of a cavity.
- Since we drive at a constant frequency, detuning reduces the field which can be sustained with a given value of forward RF power.

How to measure/calculate?

- Detuning δf is calculated with,

$$\delta f = \frac{f_{drive}}{2Q_L} \tan\phi_t \ , \qquad Q_L = \left(\frac{1}{Q_0} + \frac{1}{Q_{ext}}\right)^{-1}$$

- The LLRF system measures the tuning angle ϕ_t which is the phase difference between forward power and the field probe signal.

Sources?

- Lorentz Force Detuning (LFD); cavity field depend
- Microphonics Detuning; noise/vibrations comes from external, cavity field independent

Lorentz Force Detuning

Radiation pressure due to the electro-magnetic field inside the cavity exerts fc on the cavity walls deforming the cavity.

$$P_s = \frac{1}{4}\left(\mu\left|\vec{H}\right|^2 - \varepsilon_0\left|\vec{E}\right|^2\right)$$

$$\boxed{\Delta f_0 = (f_0)_2 - (f_0)_1 = -KE_{acc}{}^2}$$

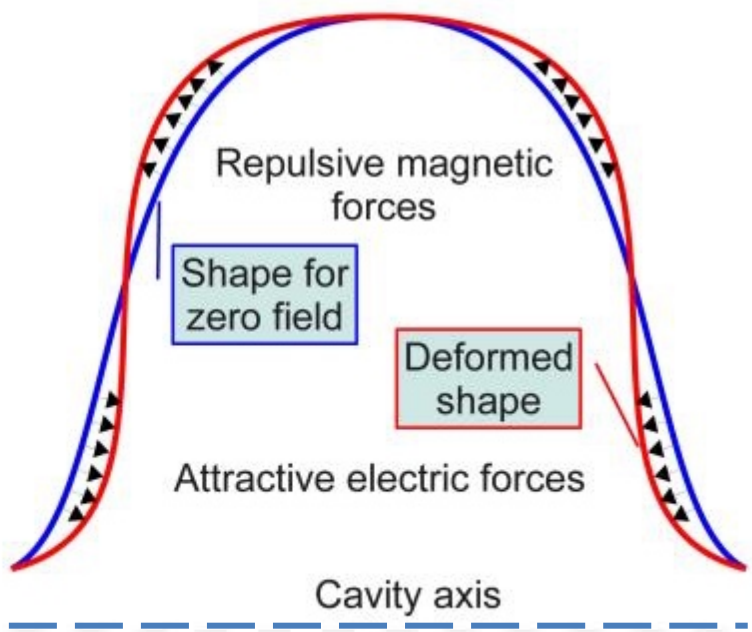

Image from Linear Collider Collaboration website

Effects:

1. The resonant frequency of the cavity is a function of field. Hence, if we tune the cavity say at 6 MV, it will be out of tune at low fields and the system won't be able to turn on. One way to turn on is to ramp up the field slowly in steps while manually tuning the cavity, but this is impractical. Hence detuning compensation using the piezo-actuator based fast tuner becomes necessary.

2. Non-linear behavior of the resonance curve.

High Q_L and Microphonics detuning

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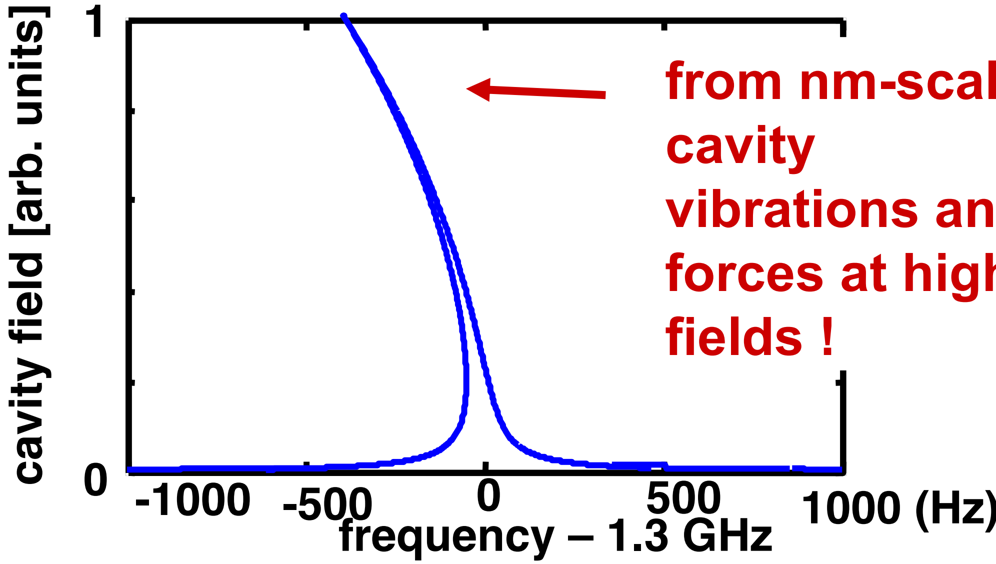
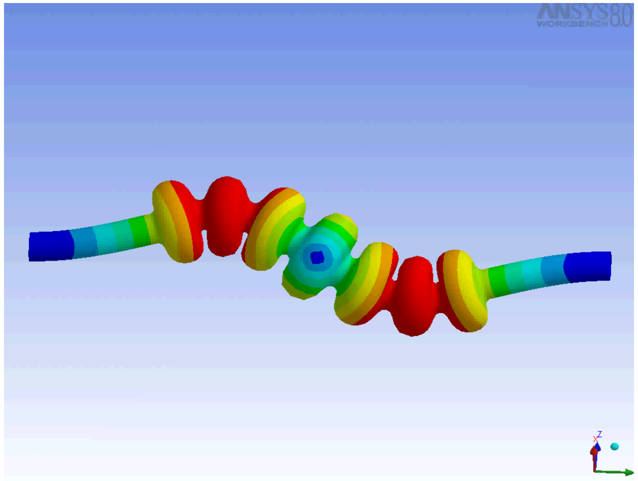
Narrow cavity resonance curve!

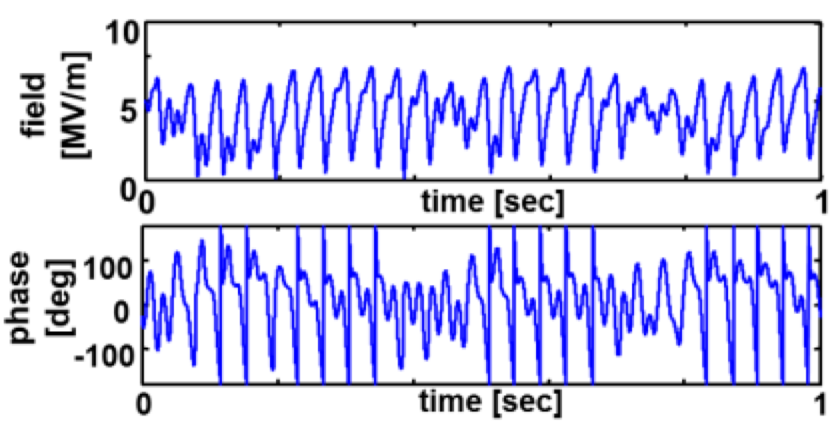


from nm-scale cavity vibrations and forces at high fields !

nm scale vibrations

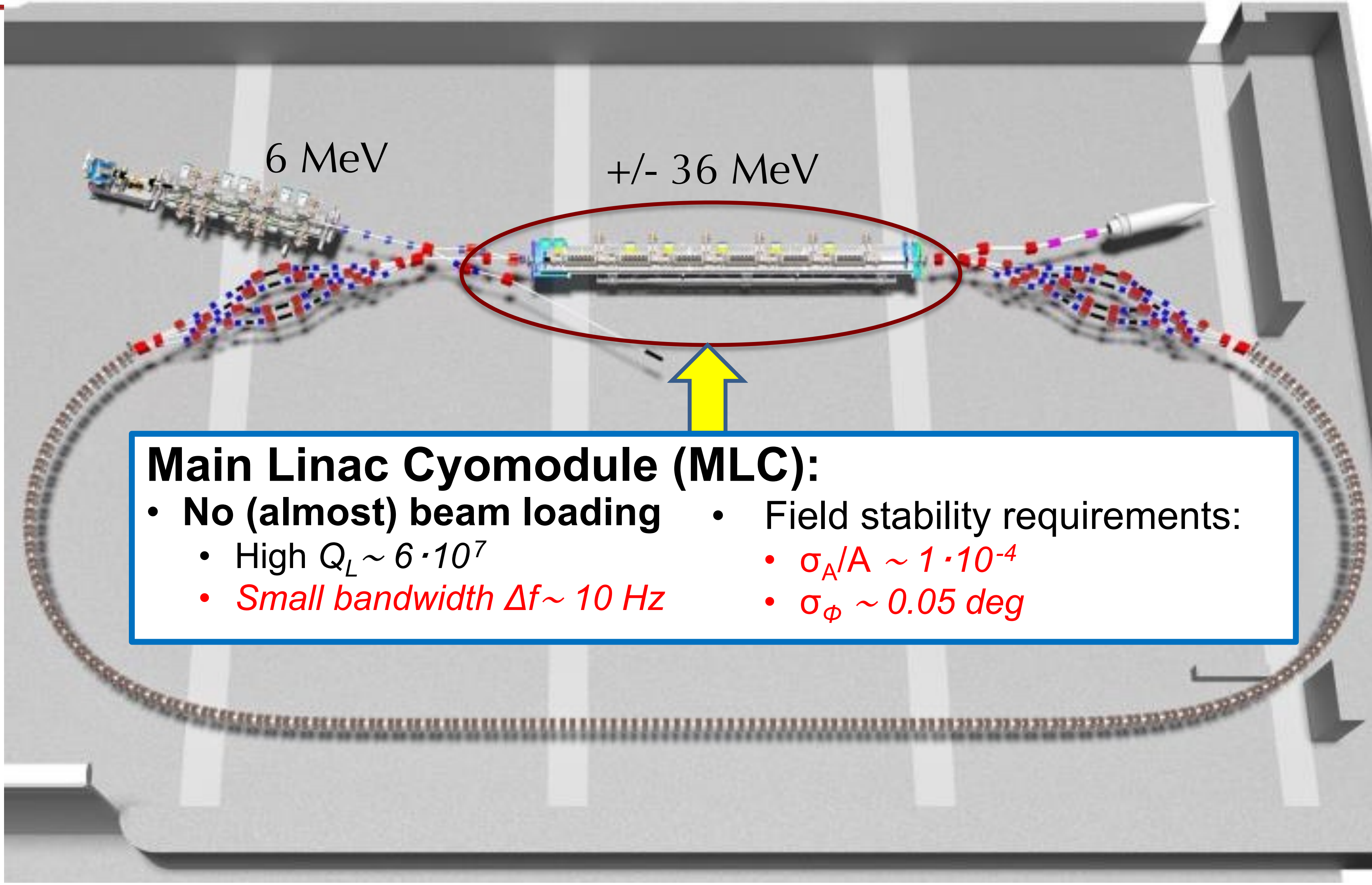


Without feedback:



Cavity field control and frequency stabilization becomes very critical!

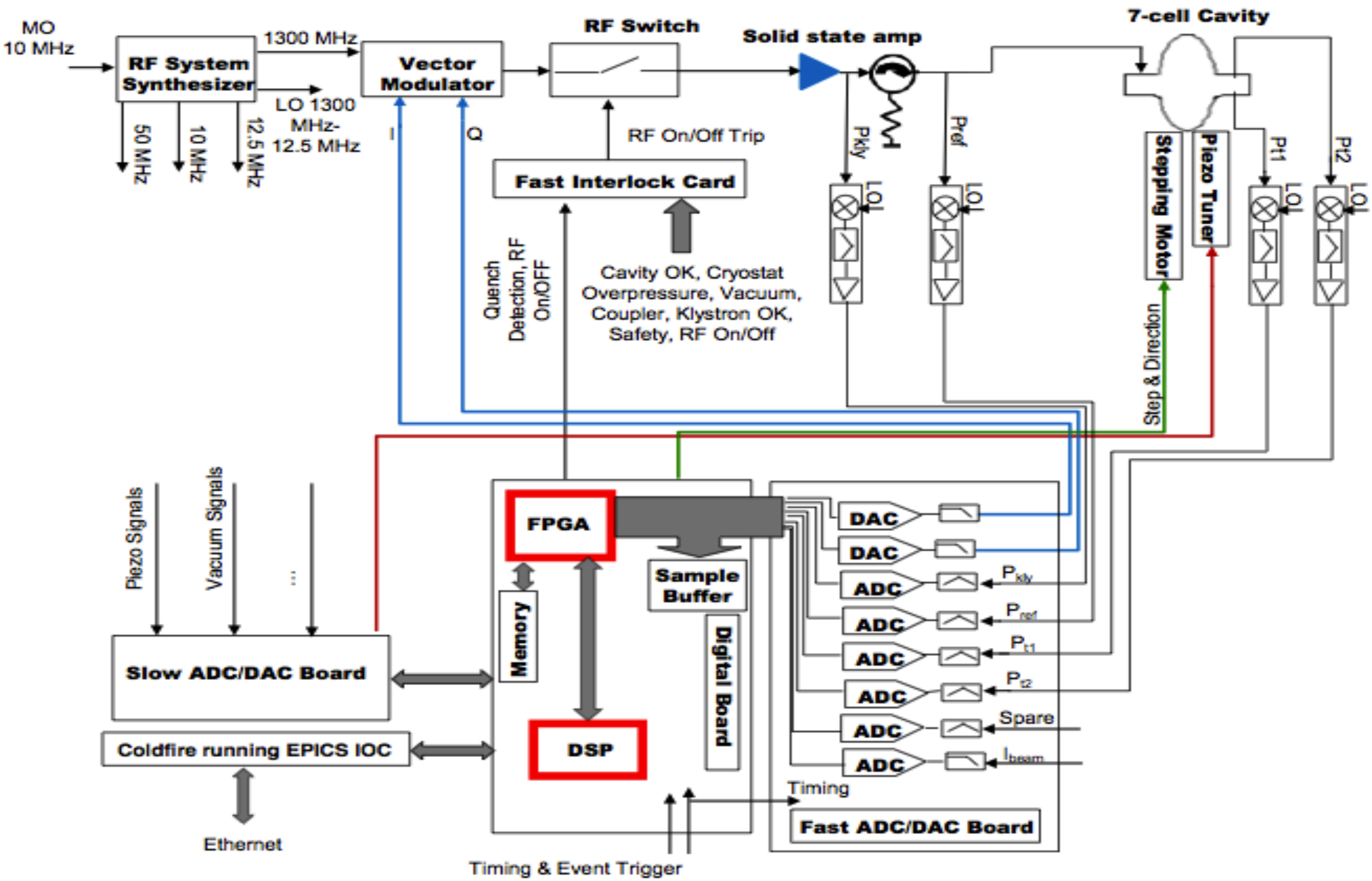
MLC for CBETA ring



Main Linac Cyomodule (MLC):

- **No (almost) beam loading**
  - High $Q_L \sim 6 \cdot 10^7$
  - *Small bandwidth $\Delta f \sim 10$ Hz*
- Field stability requirements:
  - $\sigma_A/A \sim 1 \cdot 10^{-4}$
  - $\sigma_\Phi \sim 0.05$ *deg*

Main Linac LLRF



Block diagram of the MLC LLRF system for a 7-cell cavity.

Cornell LLRF tests

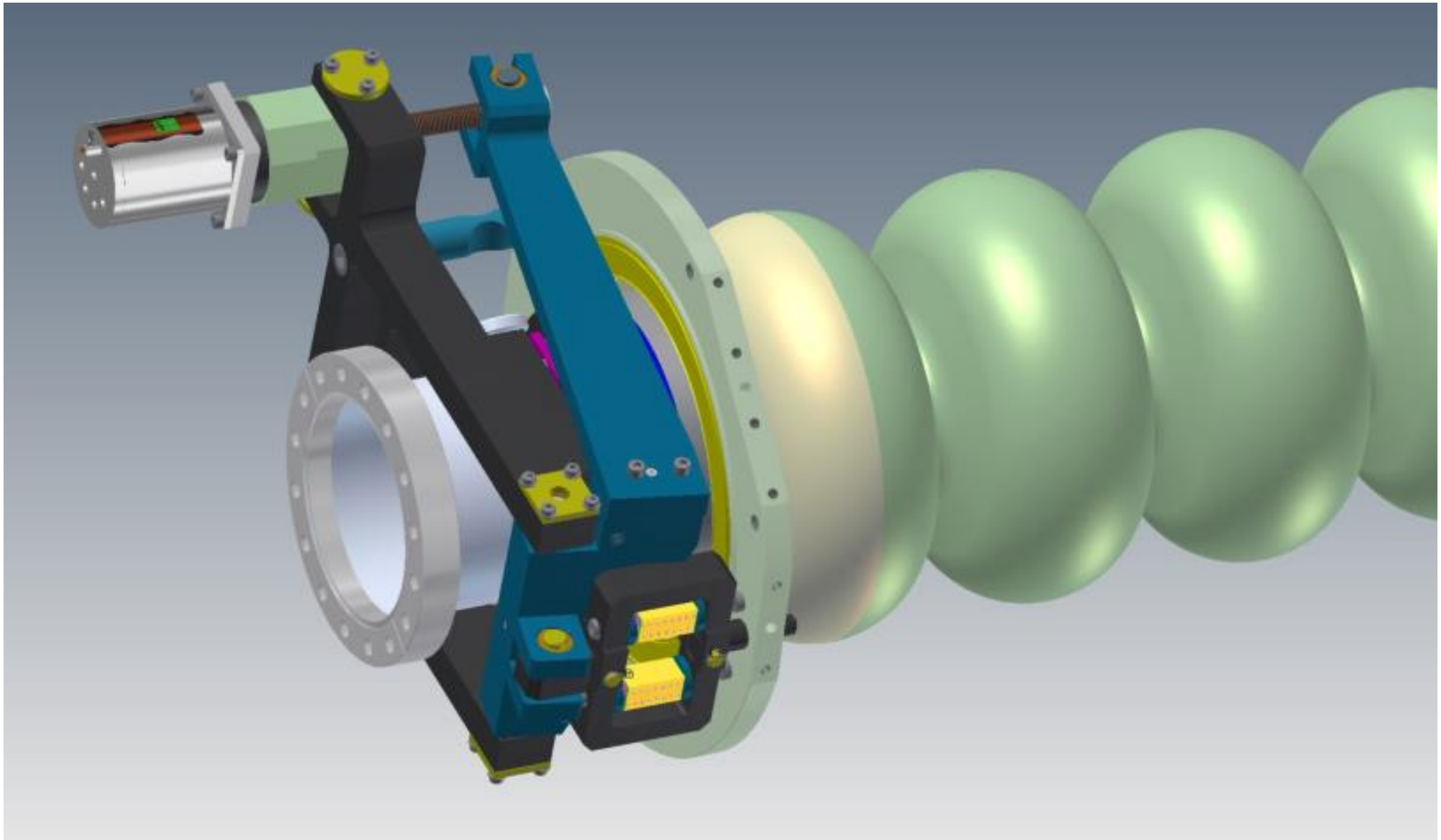
Facility	Conditions	Field stability
Requirements on CBETA	Q_L ~ $6x10^7$ (10 Hz half bandwidth)	σ_A/A ~ $1x10^{-4}$ σ_Φ~ 0.05deg
1.5GHz ERL cavity at Jlab	Q_L up to $1.2x10^8$ (6 Hz half bandwidth) 5 mA energy recovered beam	σ_A/A ~ $1x10^{-4}$ σ_Φ~ 0.02deg
1.3GHz 9-cell cavity at HoBiCaT at HZB	Q_L up to $2x10^8$ (3 Hz bandwidth) Peak microphonics: ~ 30 Hz)	$\sigma_A/A < 1x10^{-4}$ σ_Φ~ 0.01deg
1.3GHz 7-cell cavity at HTC* at Cornell	Q_L ~ $5x10^7$ (13 Hz half bandwidth) Peak microphonics: ~40 Hz 5 kW solid state RF amp	σ_A/A ~ $6.5x10^{-5}$ σ_Φ~ 0.01 deg

*Cornell Horizontal Test Cryomodule

- Cornell digital LLRF system for CBETA tested extensively with a wide range of parameters. Field stability meets and exceeds CBETA specifications.

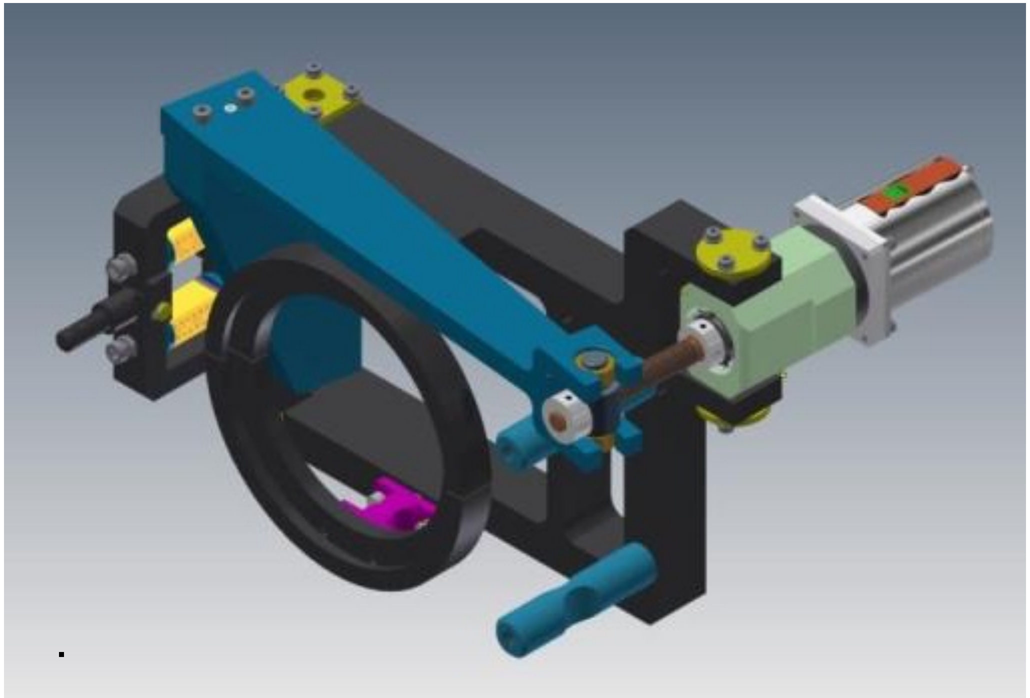
- All digital components and control codes on hand.
- LLRF optimization for MLC is in progress now.

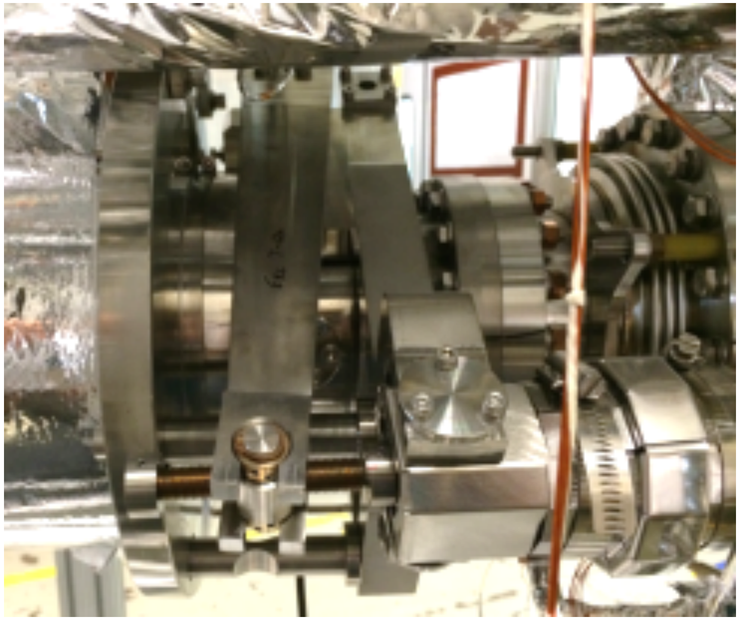
MLC cavity tuner



MLC Cavity Tuner Mounted on an Un-stiffened Cavity Helium Vessel

Mechanical slow tuner

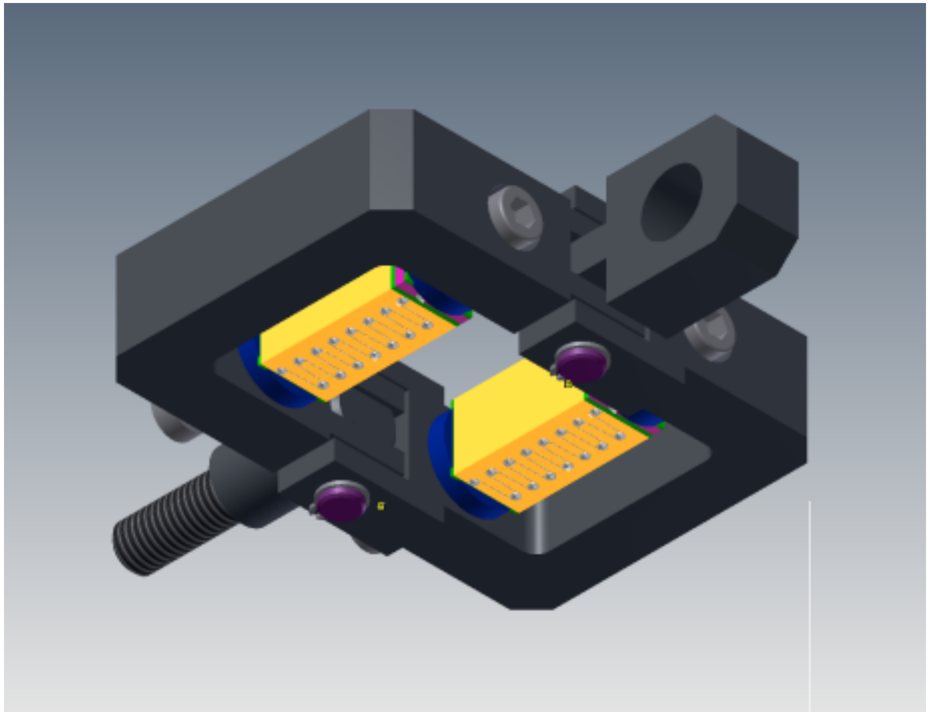




Mechanical slow tuner

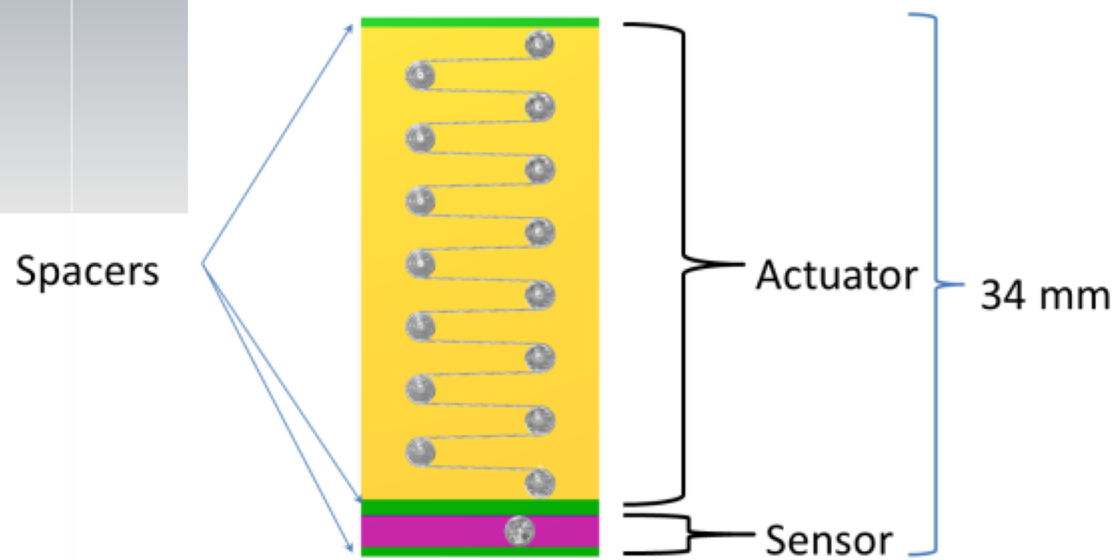
- Tuning range; ~400KHz
- Step motor drive current; 1A
- 200K steps per tuner screw revolution
- Max available revolution ~33

Piezo subassembly/ Piezo stacks



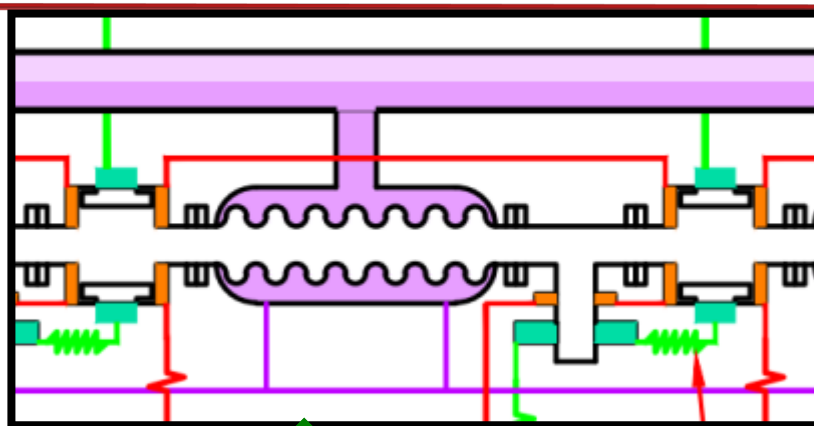
Piezoelectric fast tuner

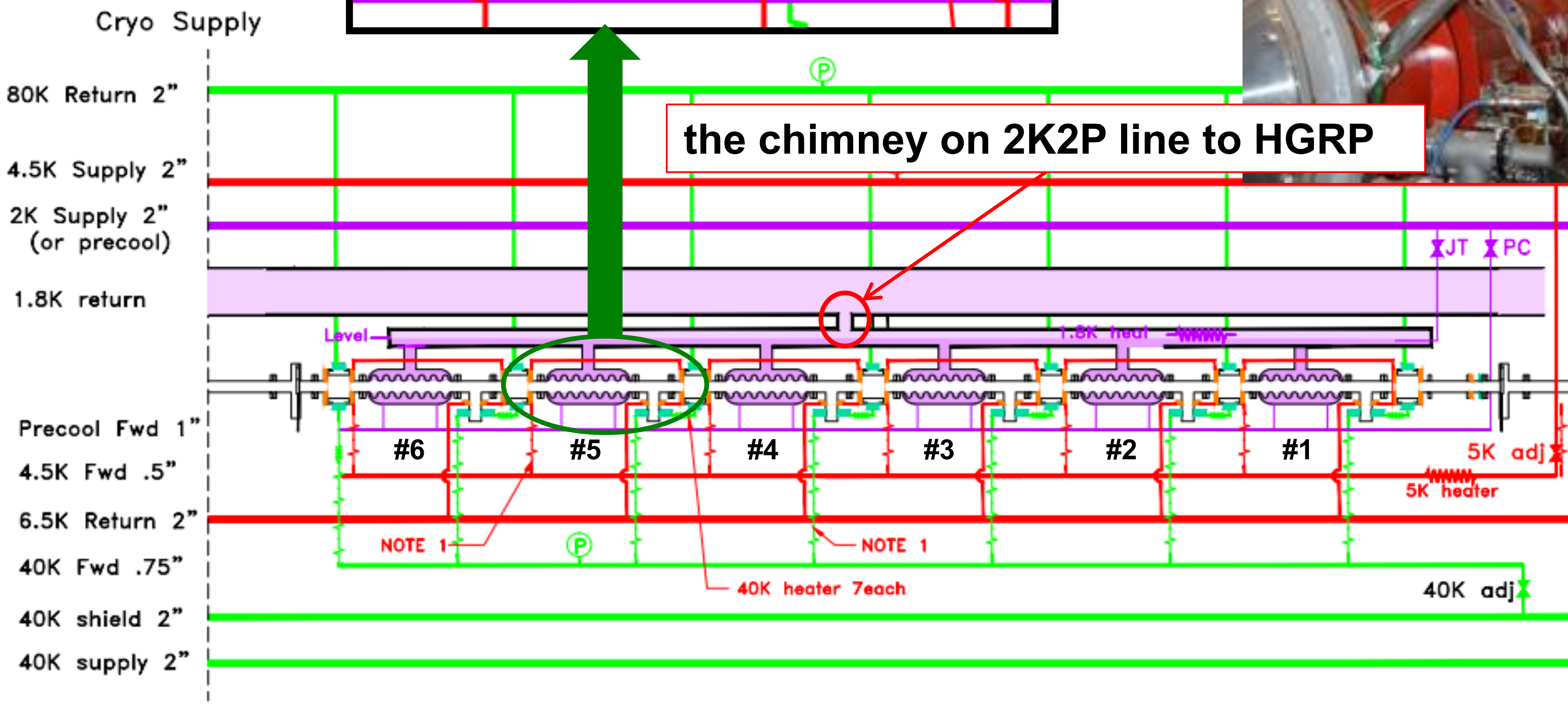
- input voltage; 0~150V
- tuning range; > 2kHz
- piezoelectric sensors attached to the fast tuners pick up vibrations in the cavity walls.



MLC cooling schematic

1.8K
5K
80K

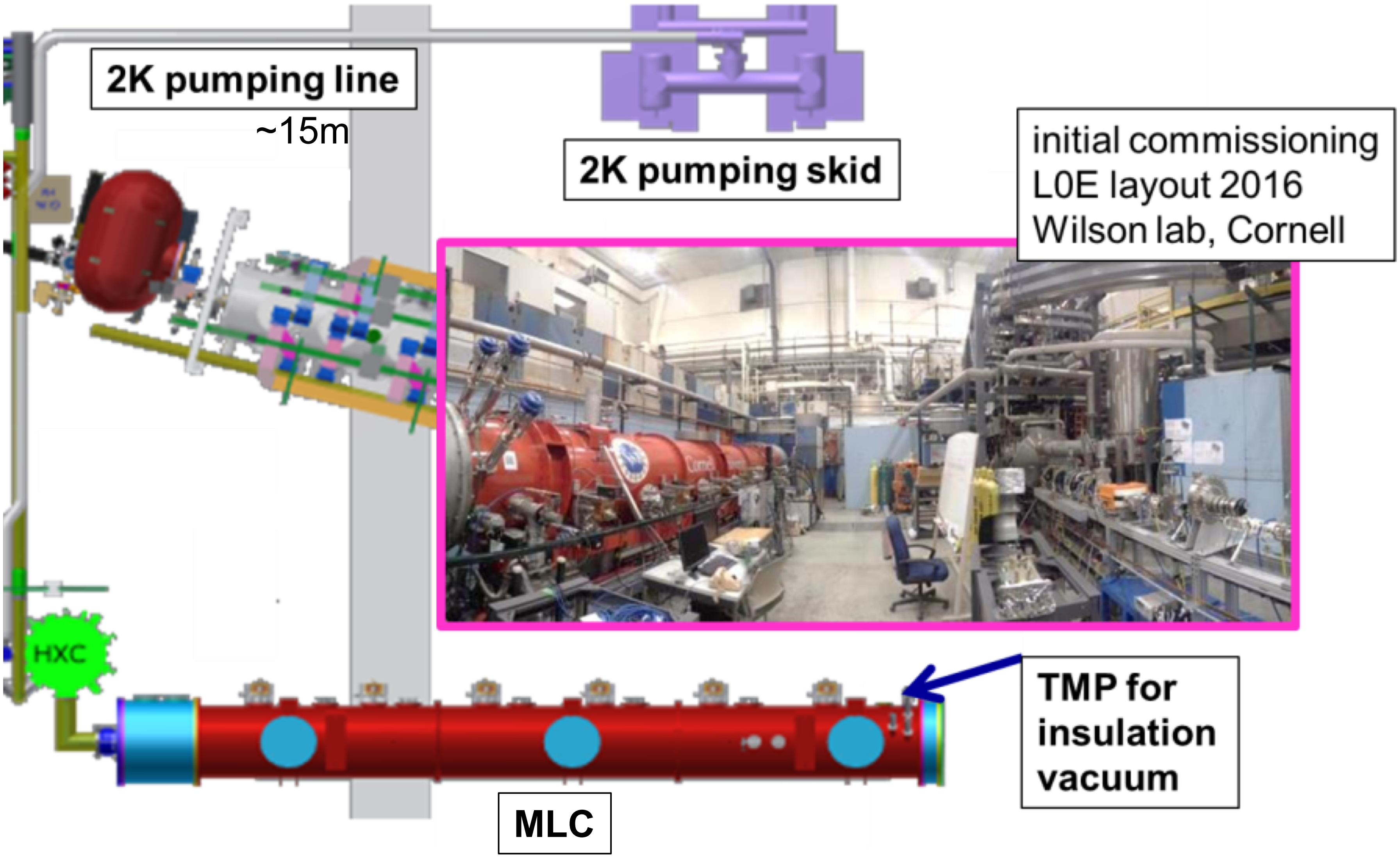




Lesson1

Microphonics in the MLC

Initial cryogenic layout of MLC



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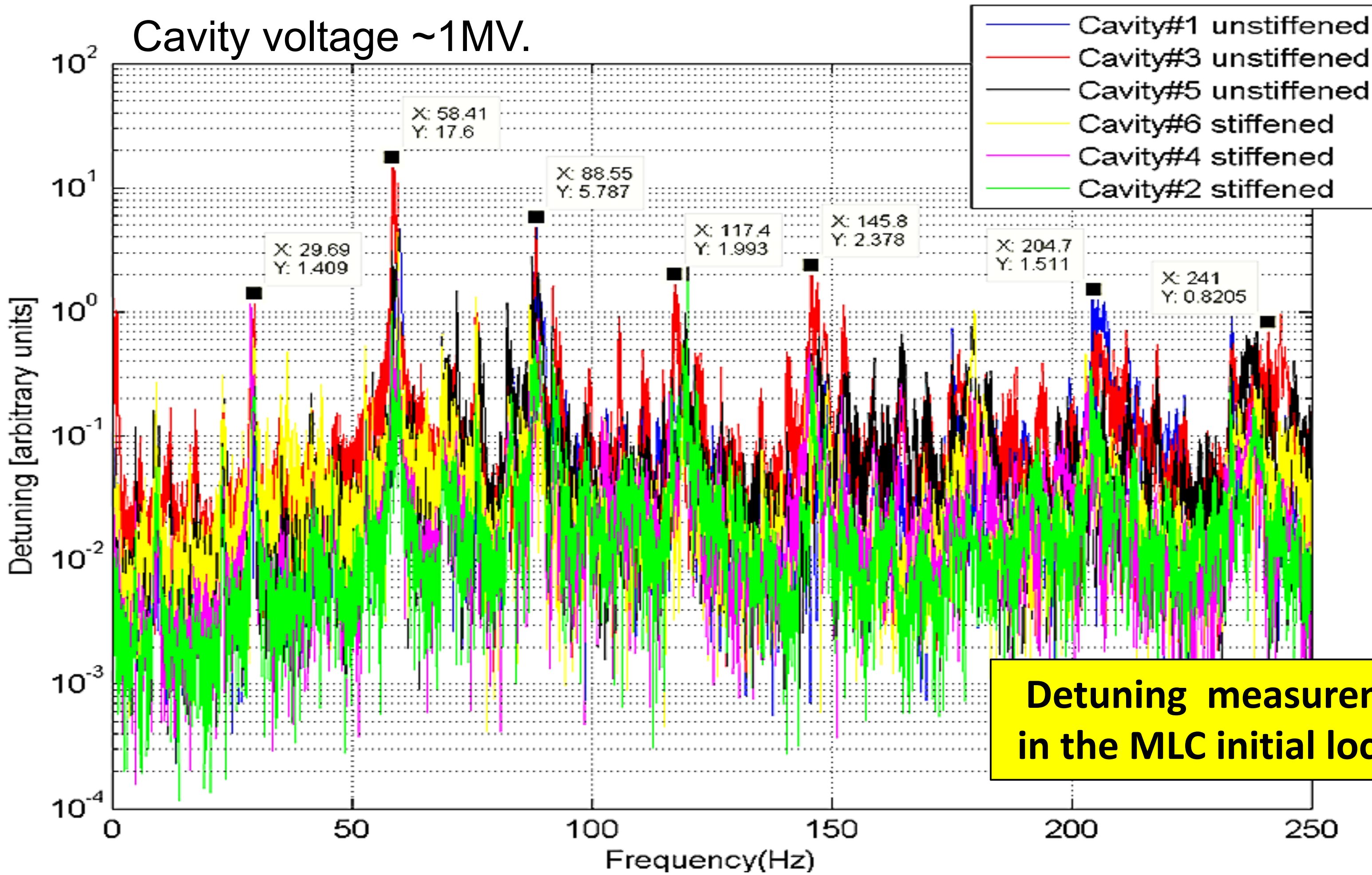
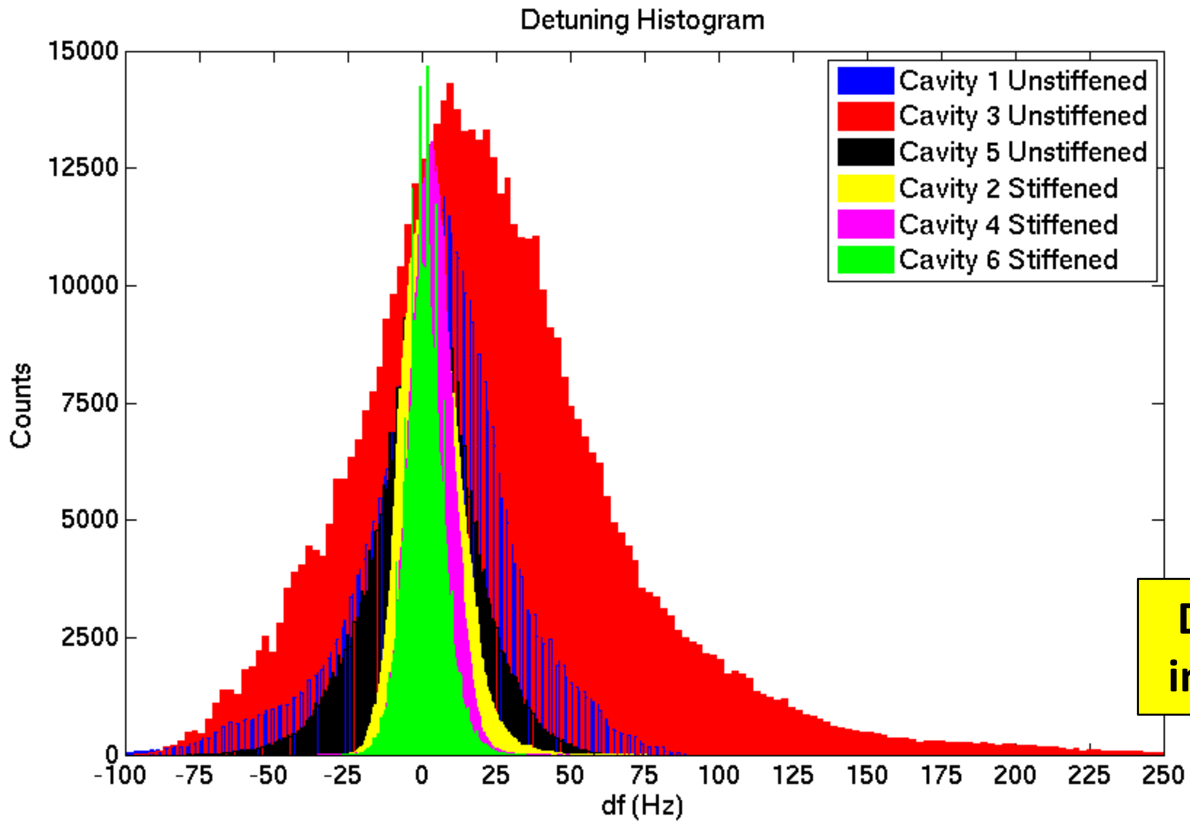
Microphonics in the MLC



Detuning measurements in the MLC initial location

The spectrum of mechanical resonant : 30Hz, 60Hz, 90Hz, etc.

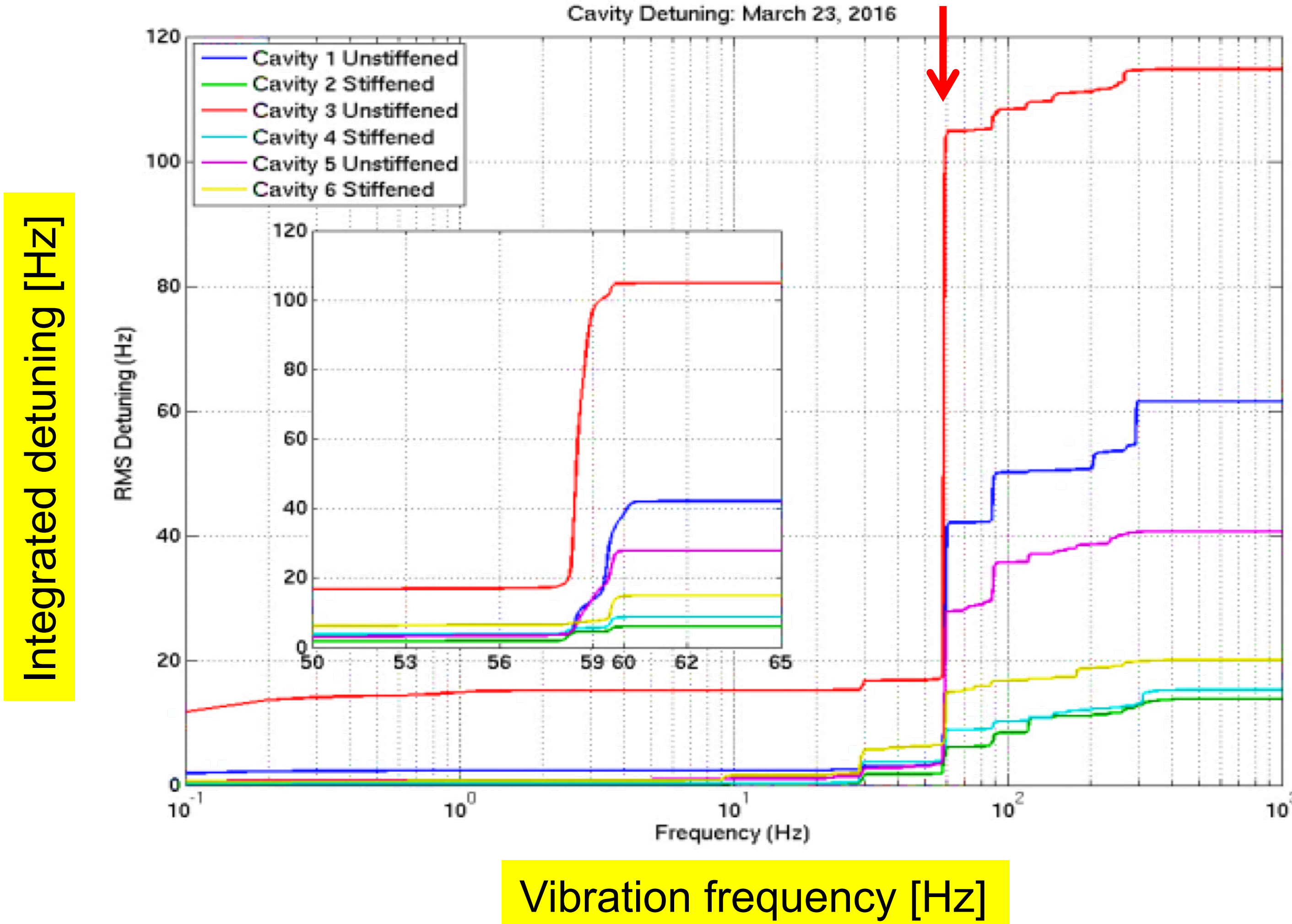
Peak Detuning



Detuning measurements in the MLC initial location

- **Average peak detuning of stiffened cavity: ~40Hz, un-stiffened cavity: ~100Hz, during the initial test, <u>but no optimisations or no fast tuner compensations at the moment.</u>**
- **Detuning has been measured again at final MLC location.**
- **LLRF optimizations and microphonics compensations with piezoelectric fast tuner is in progress.**

Integrated detuning



- **the vibration peak of ~60Hz seemed to make high gain on detuning on un-stiffened cavities.**

Identify the vibration sources

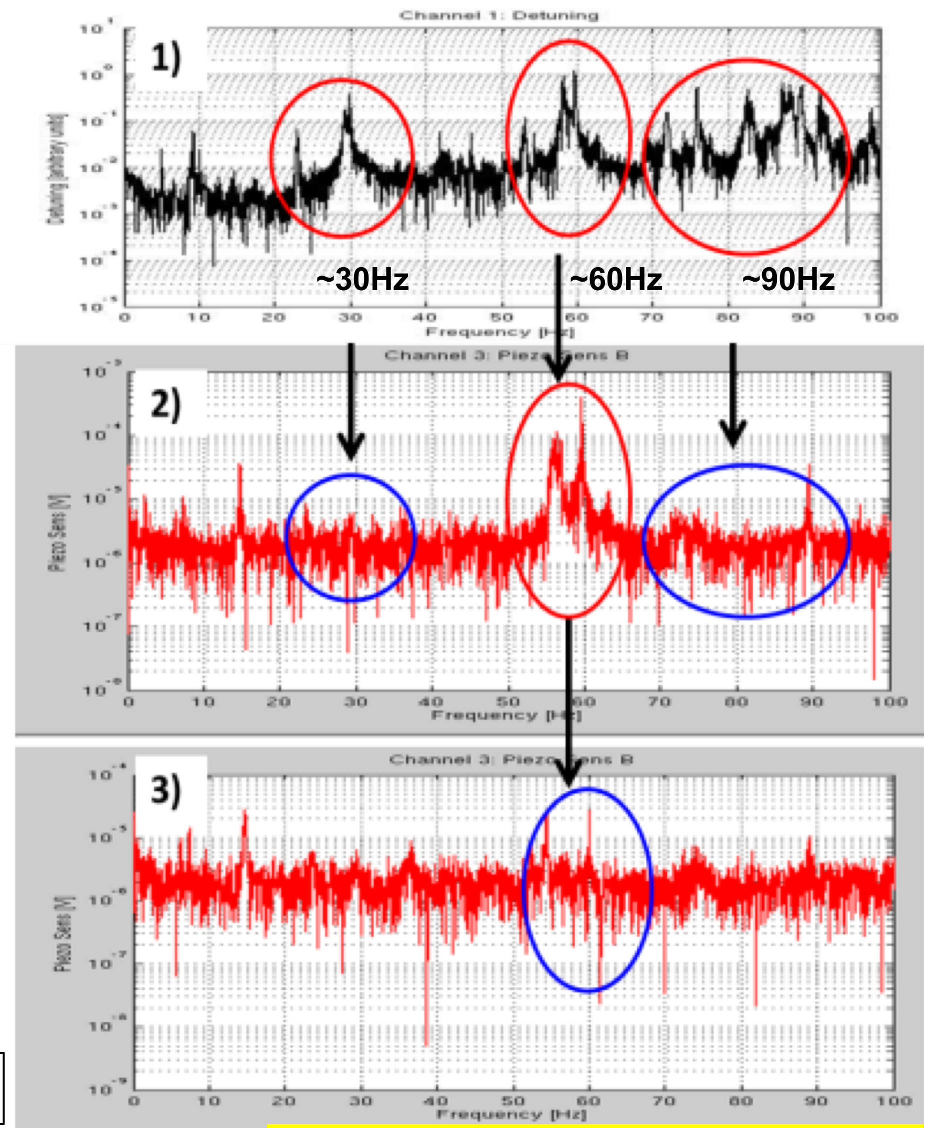
1) Pump Skid ON
80K flow was 7.5 g/s (high flow)
5K flow was 1.8 g/s

2) Pump skid Off
80K flow was 2.425 g/s (low flow)
5K flow was 1.6 g/s
Insulation vacuum turbo pumps ON valve Open.

measurements were done by directly measuring the voltage on the piezo B sensor

3) Pump skid Off
80K flow was 2.425 g/s(low flow)
5K flow was 1.6 g/s
Insulation vacuum turbo pumps off, valve Close.

measurements were done by directly measuring the voltage on the piezo B sensor



Measured with Cavity#2 (stiffened)

Mechanical vibration sources

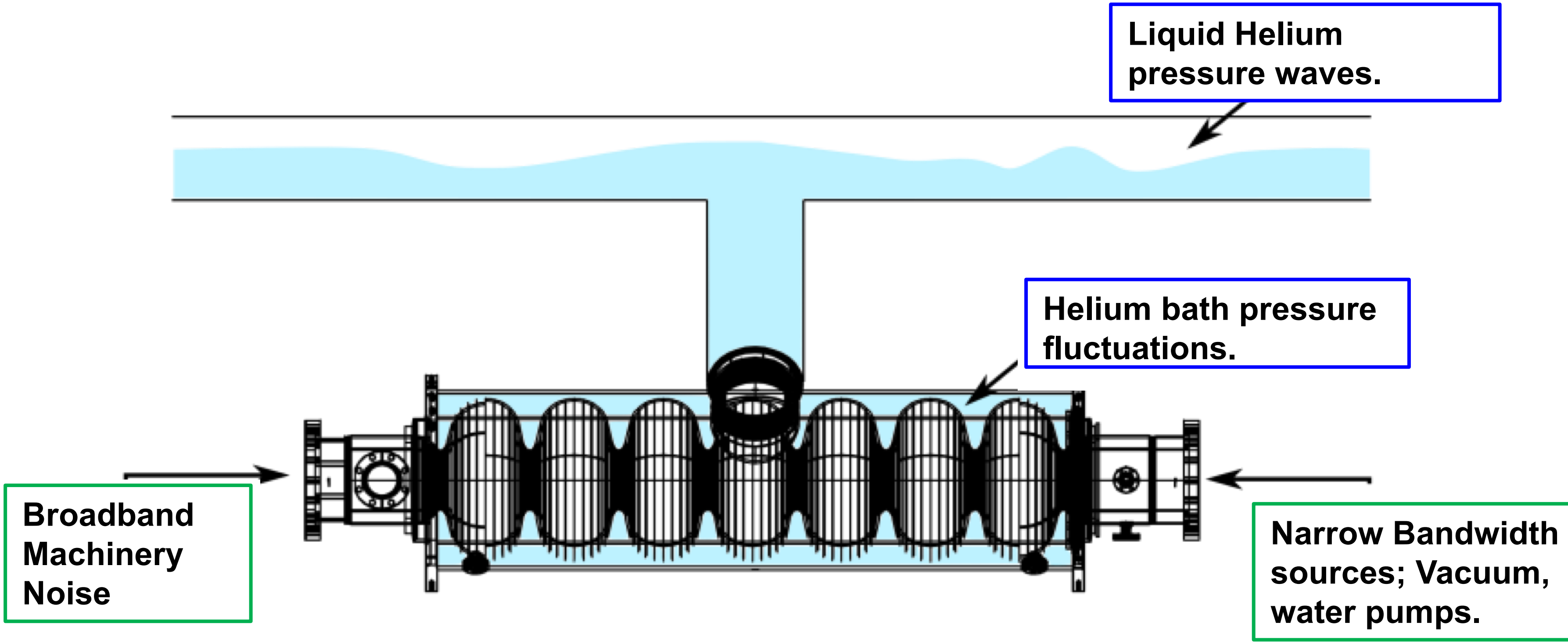
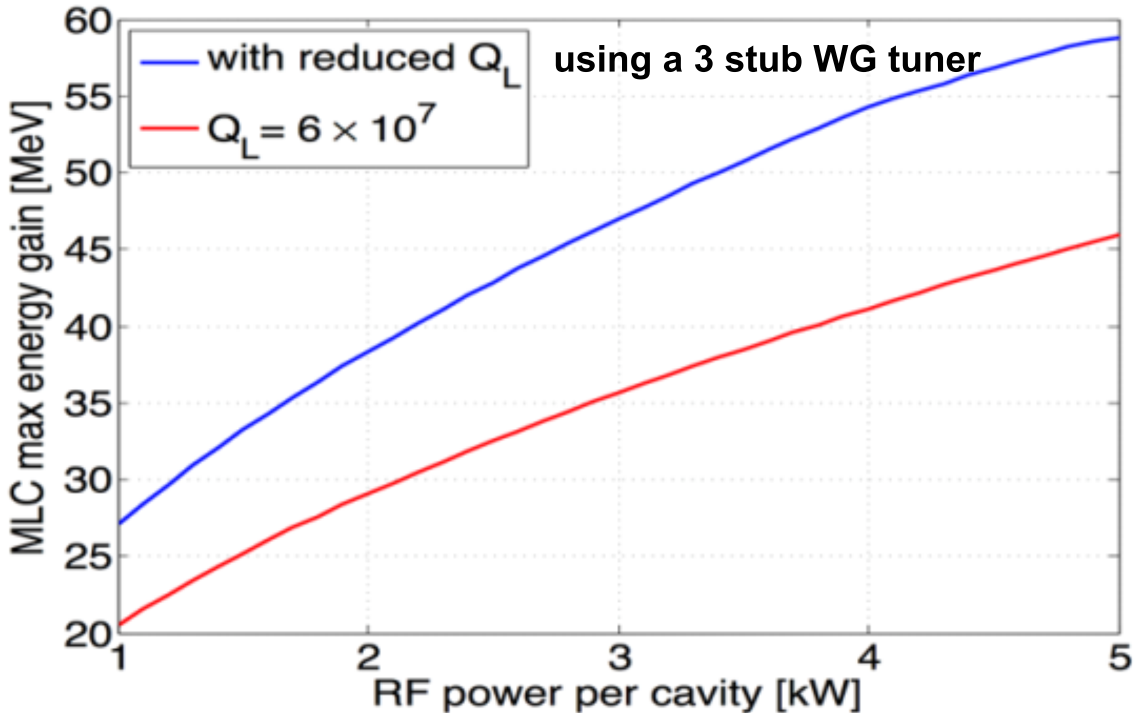


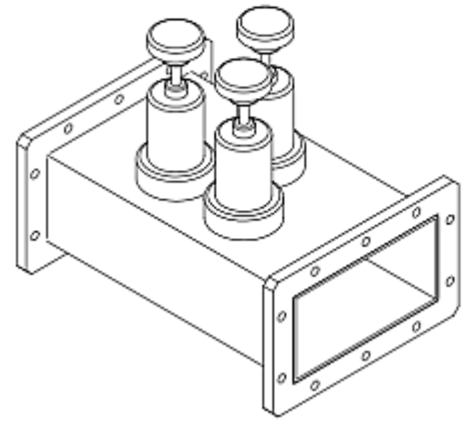
Image by Nilanjan Banerjee (Graduate Student)

- Preliminary identification and isolation of vibration sources were done in the initial MLC location.
- Optimization on the MLC cooling scheme and compensation of microphonics with piezoelectric fast tuner are in progress during initial MLC beam through test.

RF power requirements

Calculation of the maximum energy gain of the MLC with the measured initial microphonics levels.





Q_L could be reduced to ~2×10^7 using a 3 stub waveguide tuner to increase the maximum possible energy gain or reduce the required peak power.

Based on these calculations and making allowance for the higher microphonics levels of the un-stiffened cavities,

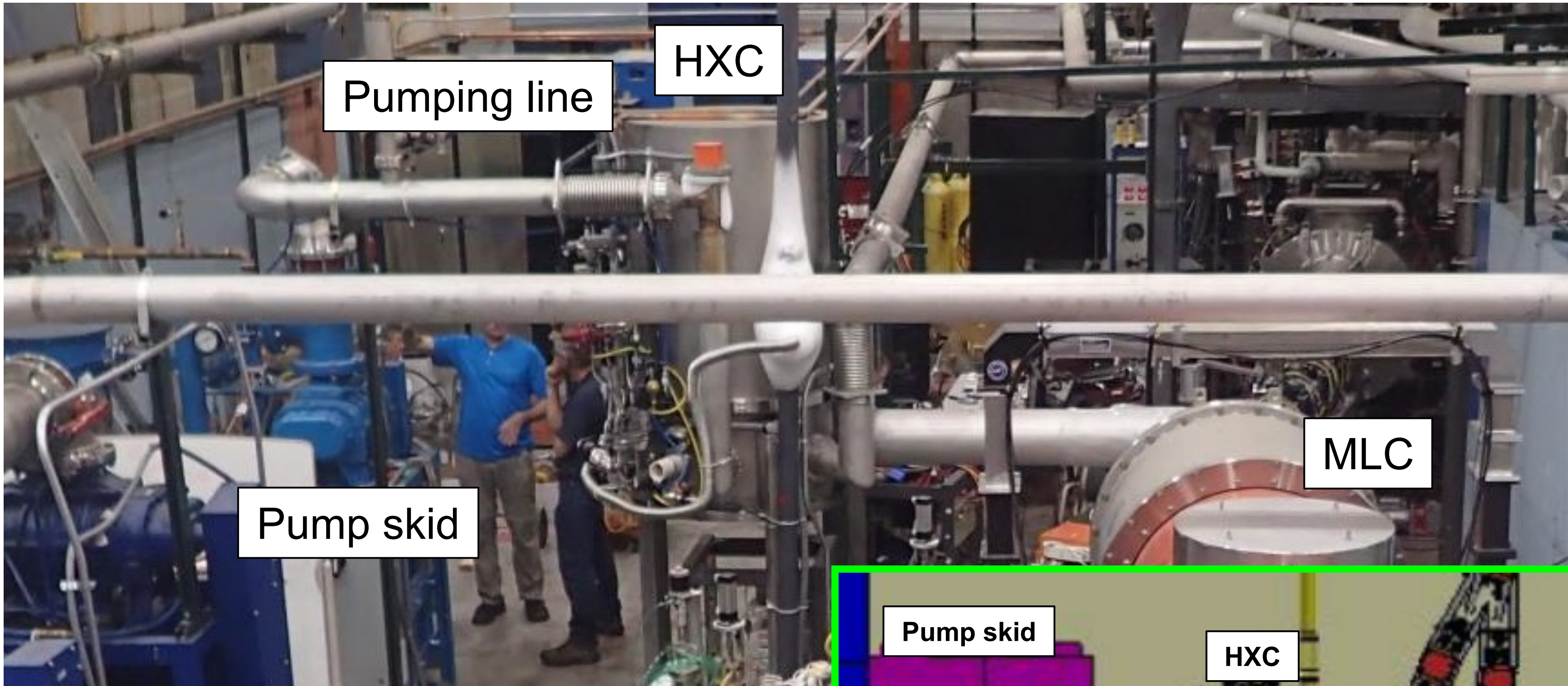
- **three 5kW solid state RF amplifiers (SSAs) for stiffened cavities**
- **three 10kW SSAs for the un-stiffened cavities**

were selected to be ordered.

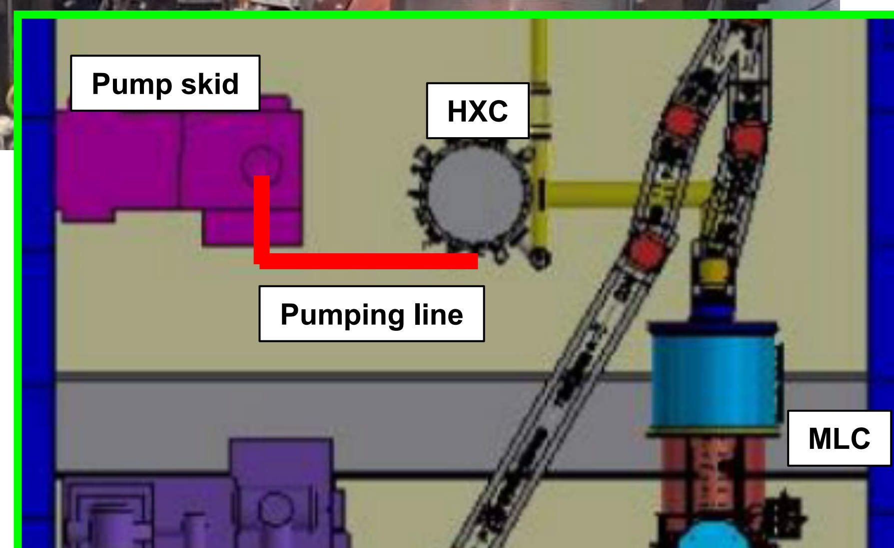
Lesson 2

Microphonics compensation

MLC at its final location, 2017



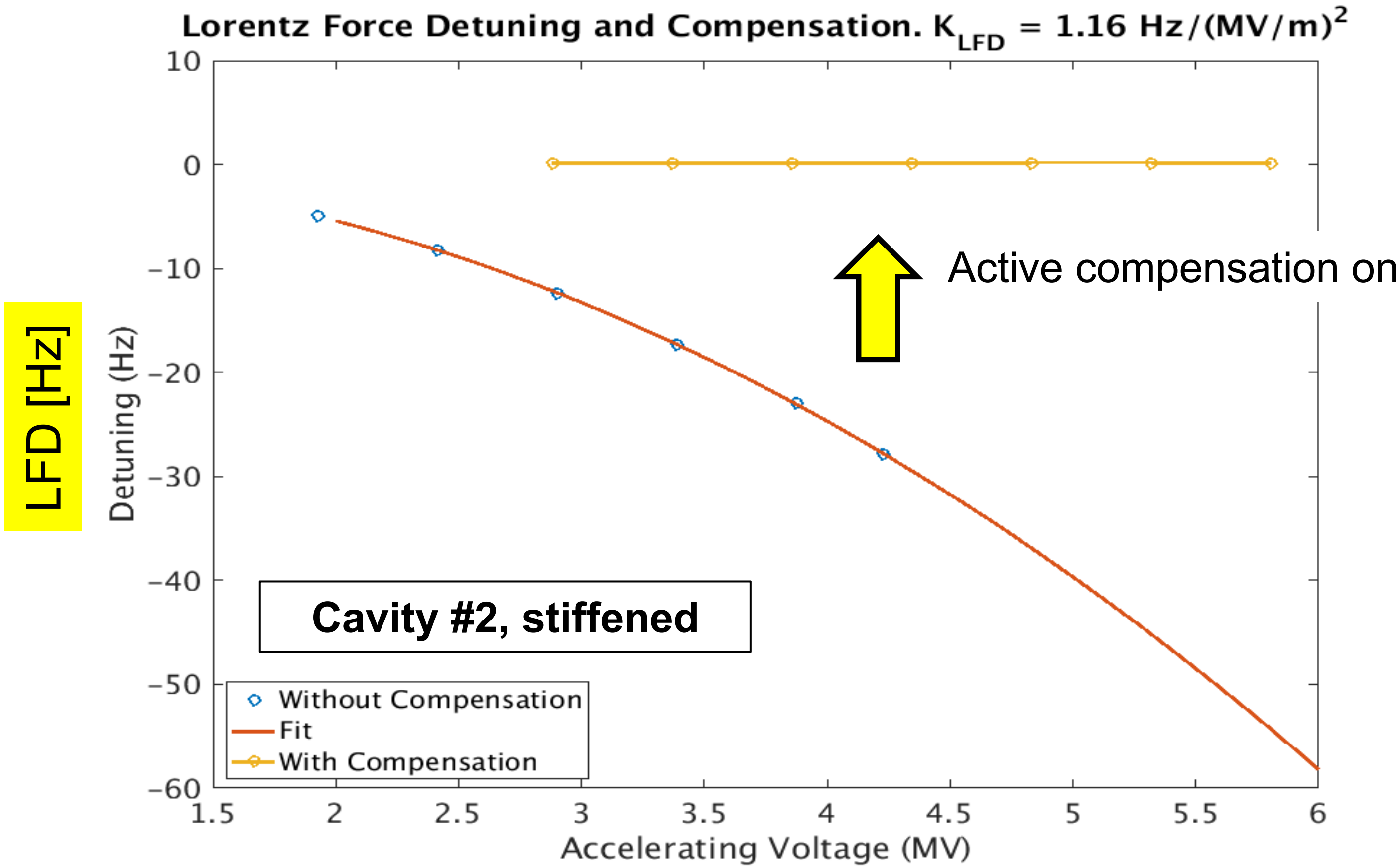
L0E layout 2017, Wilson lab, Cornell,



- MLC was moved to its final location on Feb. 2017.
- Beam accelerate test is in progress!!

LFD measurements/compensation

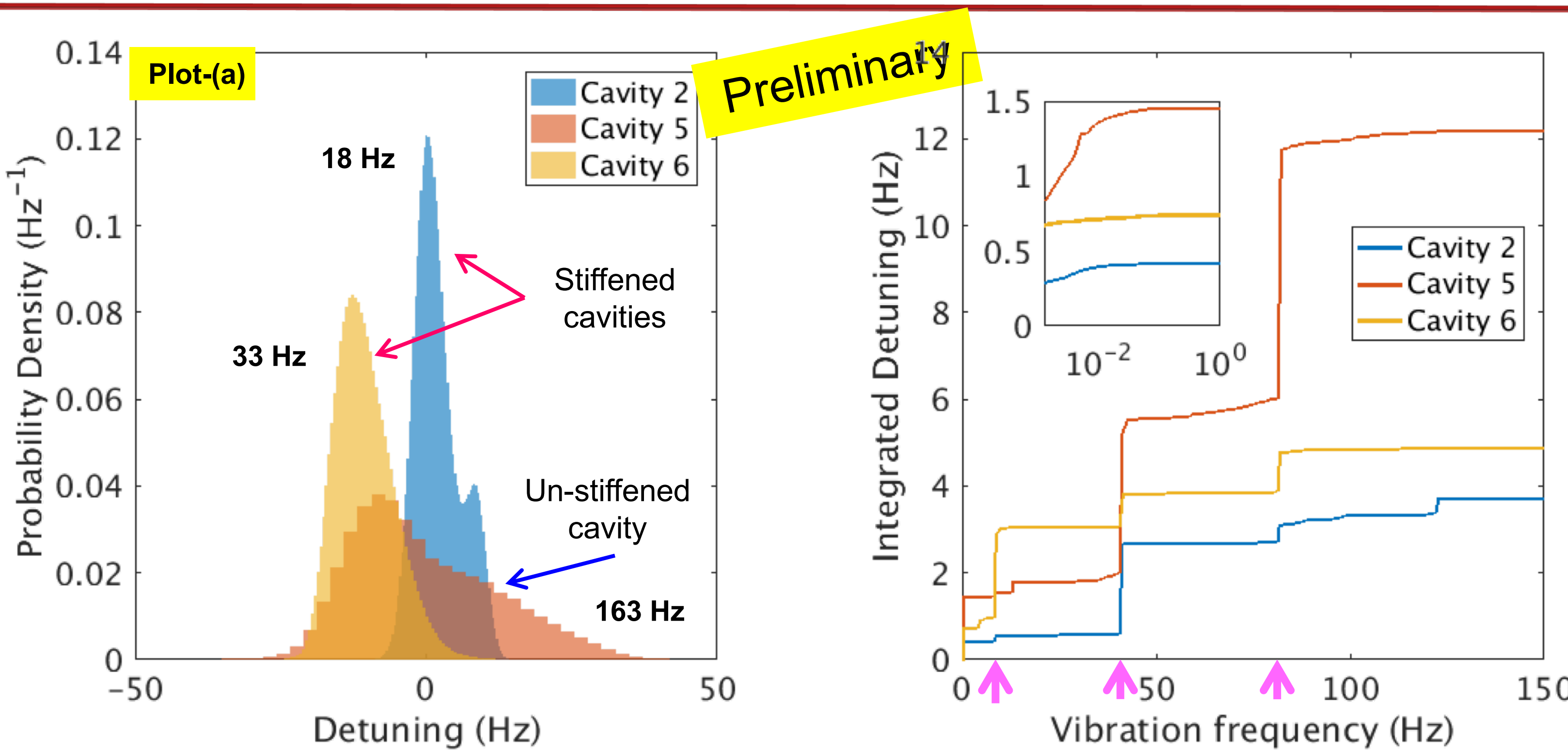
"Measured peak detuning w/o any compensation"
= "LFD (field depend)" + "microphonics detuning (const.) "



Cavity Half
Bandwidth
: 11.2 Hz

- Compensation $$V_{\rm pz}(t) = aV_{acc}^2 + b$$ works!

Microphonics detuning meas.



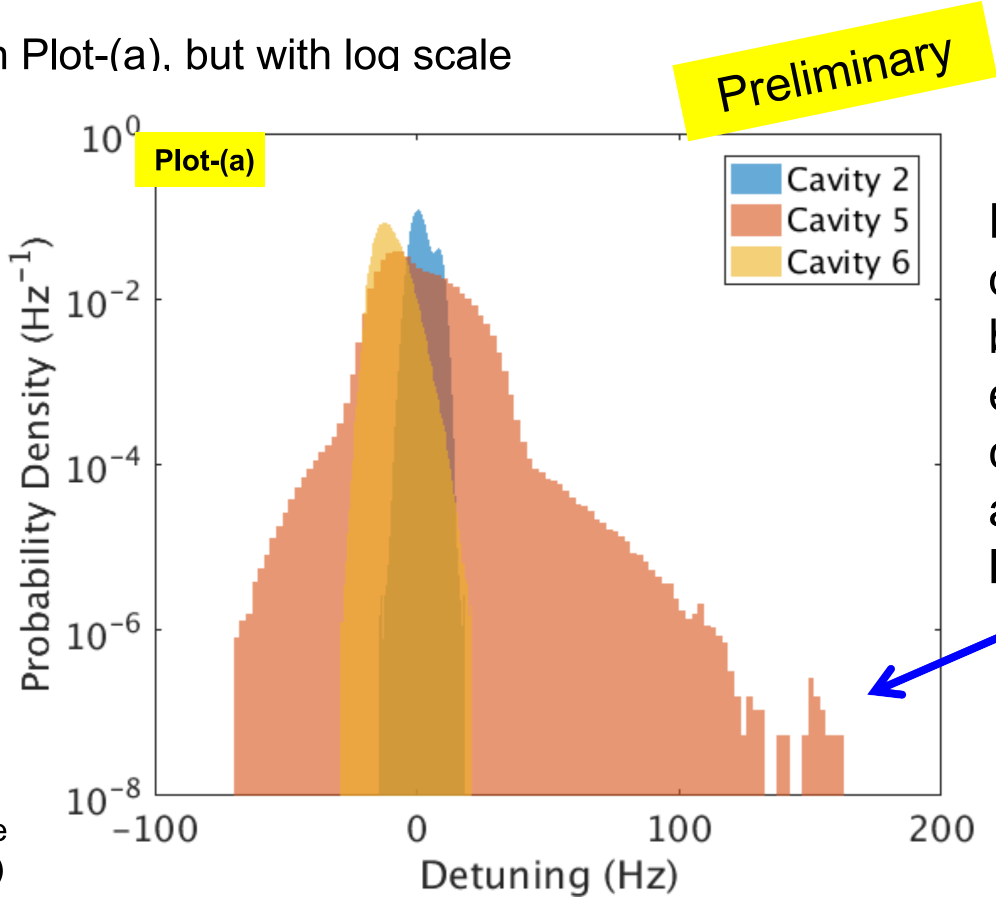
Plots by N. Banerjee (Graduate student)

- Max detuning in cavity #5 (un-stiffened) is 163 Hz in the measured dataset (but not seen clearly in plot(a) with linear scale, please see next slides with more notes).
- We will revisit cavity #5 later, and resolve this by cryo optimization.
- Cavity #2 (stiffened) is less sensitive to the valve.
- Major contributions at 40 Hz and 80 Hz, these are probably driven by 5K Helium gas flow.

- Cavity #6; There is a strong intermittent source of vibration around 8 Hz which is weak in other cavities.

Microphonics detuning meas.

Same plot with Plot-(a), but with log scale



High instantaneous detuning (163Hz) caused by intermittent pulses every few minutes, which caused by the opening of a valve in the 5K pre-cool line.

Plot by N. Banerjee (Graduate student)

- **Cryogenic valves will be static for beam running and helium liquid level will be regulated with a 2K 2-Phase heater.**
- **Will resolve this by cryo optimization.**

Microphonics compensation

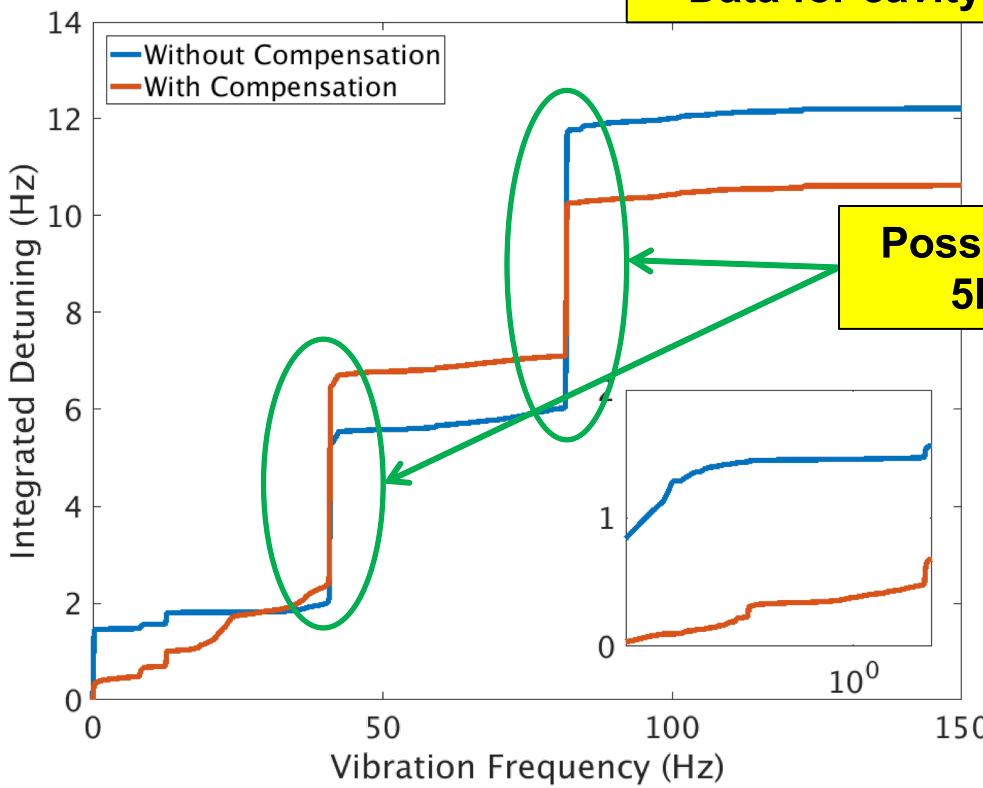
Low frequency compensation:

$$\boxed{u_{pz}(t) = K_P \delta f(t) + K_I \int_0^t \delta f(t') dt'}$$

Where, the detuning is passed through a low pass filter with cut-off at 30 Hz to enhance stability of the loop.

Data for cavity #5 (un-stiffened)

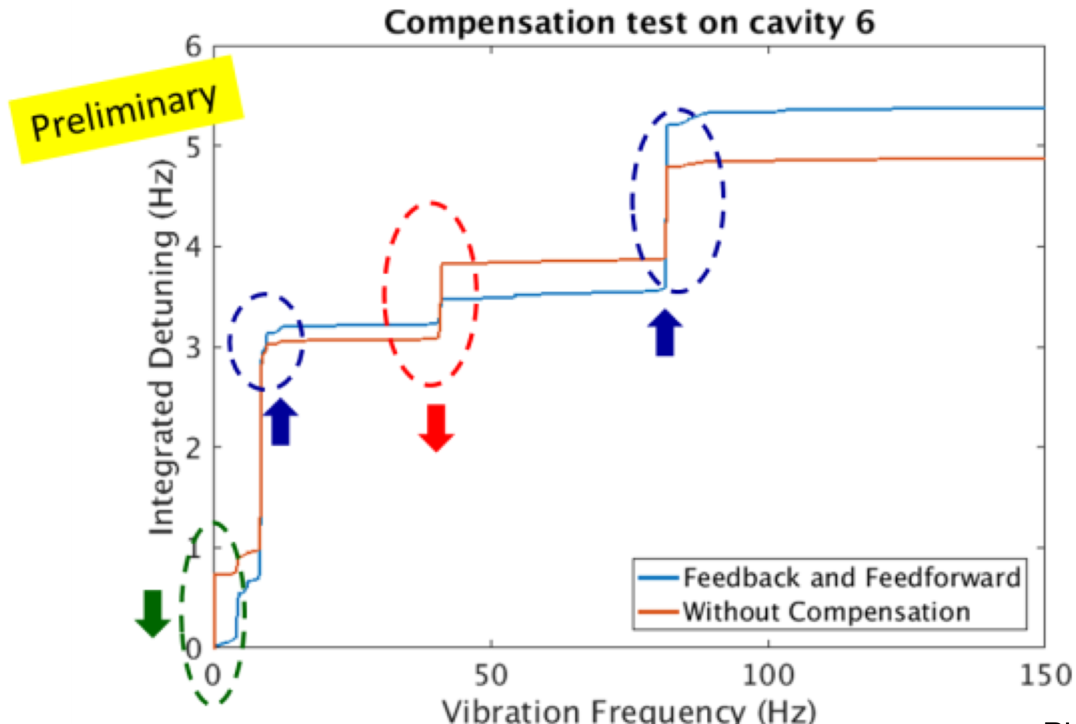
Preliminary



Possibly driven by 5K gas flow

Plots by N. Banerjee (Graduate student)

Feedforward compensation



The first attempt of microphonics feedforward compensation on cavity#6.

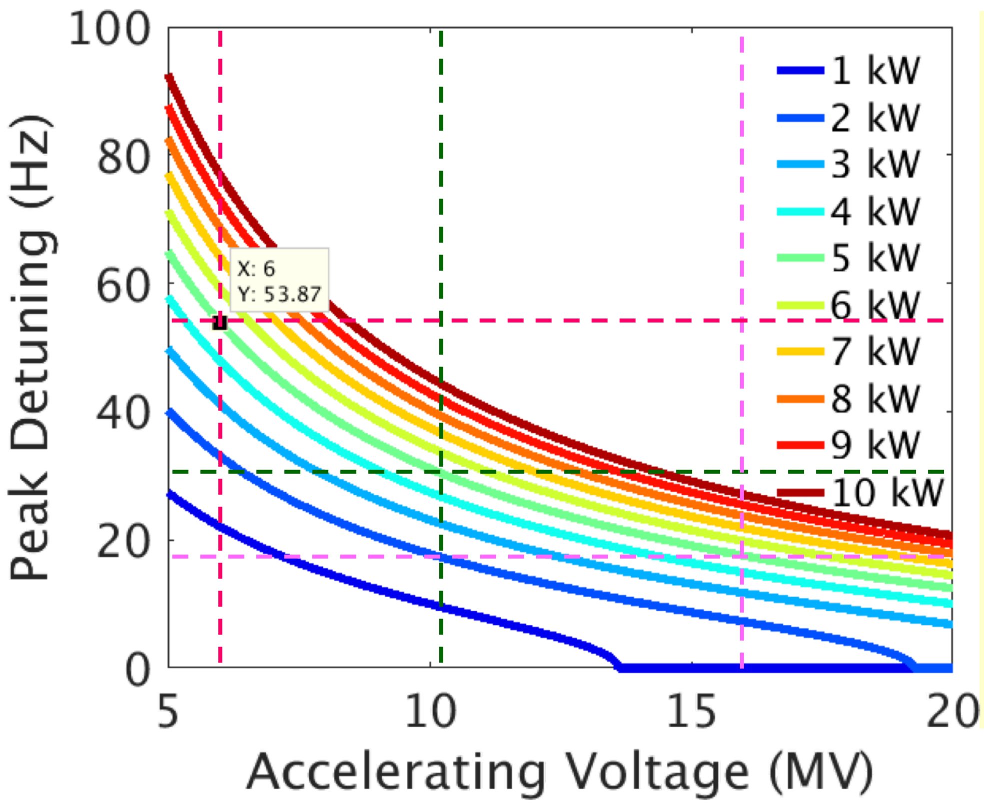
- Microphonics study/compensation is in progress,,,
- Need more run time to improve feedforward compensation.

Plot by N. Banerjee (Graduate student)

- **Feedforward signal is taken from an accelerometer mounted on the frame outside the MLC.**
- **Low frequency compensation (PI feedback loop) works as expected.**
- **Feedforward is stable and compensates for the 40 Hz vibration component while enhancing the 80 Hz component.**
- **Finally the cavity #6 reached 6MV without feedforward compensation, as expected.**

Detuning vs. Cavity Voltage

Calculations on Peak Detuning vs. Cavity Voltage for various RF input power



<u>With measured peak detuning,</u>

- Cavity #2(stiffened): 18 Hz
- Cavity #6(stiffened): 33 Hz
  - ➢ The plot predicts 5kW SSA could provide up to 16MV(cavity #2) or 10MV(cavity #6) <u>without compensation</u>.
- Cavity #5(un-stiffened): 163 Hz
  - ➢ The plot predicts 10kW SSA could provide up to 4MV <u>without compensation</u>.

Microphonics compensation is necessary for;

- **Stable machine operation**
- **Enough overhead on RF power/energy gain**

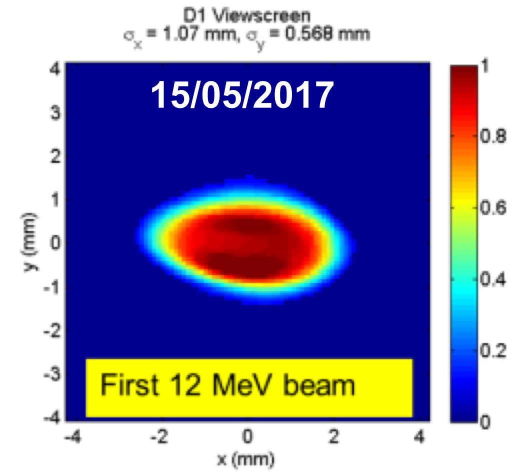
Plot by N. Banerjee (Graduate student)

Initial beam acceleration test

12MeV beam through the MLC

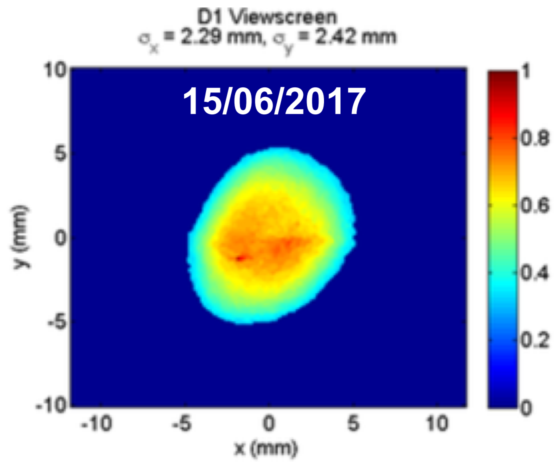
1) Machine setting

- Frequecny; 1.3GHz
- 6MeV from ICM
- 6MeV from MLC cavity#2 (stiffened)
- LFD compensation on.
- Peak detuning; 18Hz



2) Machine setting

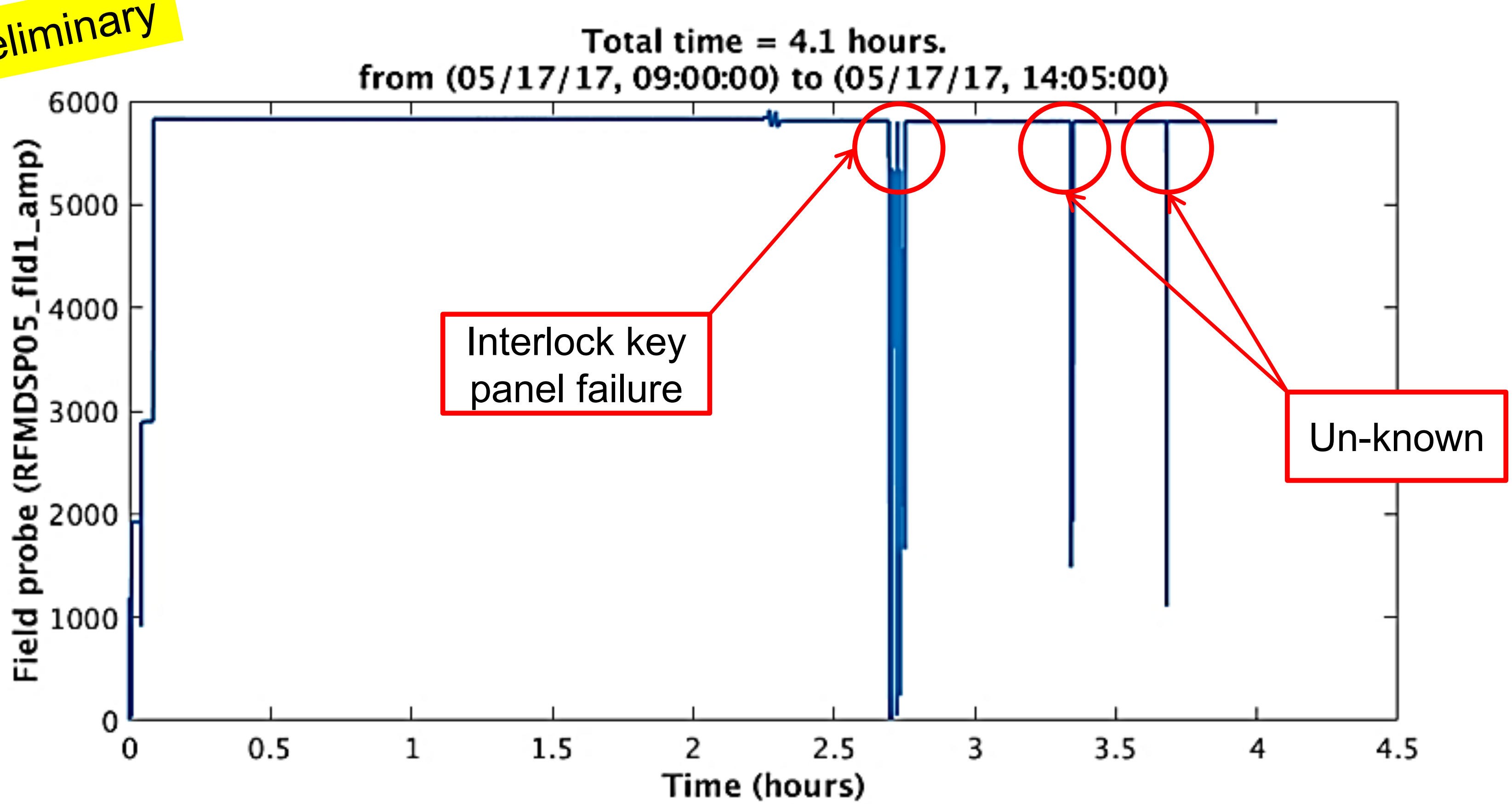
- Frequency; 1.299925GHz, due to the tuning range of MLC cavity #6
- 6MeV from ICM (cavity#1, #3, #4, and #5)
- 6MeV from MLC cavity#6 (stiffened)
- LFD compensation on.
- Peak detuning; 33Hz



Long term stability

MLC Cavity#2 (stiffened), active compensation on

Preliminary



NO beam

with beam

MLC cavities status

Preliminary

MLC cavity	Beam acceleration? (frequency)	Cavity Voltage	Max. Microphonics detuning	Active compensation	notes
Cavity#5, un-stiffened	Yes (1.3GHz)	3MV	163Hz	No	9MeV Beam through on May 10^{th}, revisit later
Cavity#2, stiffened	Yes (1.3GHz)	6MV	18Hz	Yes	12MeV Beam through on May 15^{th}
Cavity#6, stiffened	Yes (1.299925GHz)	6MV	33Hz	Yes	12MeV Beam through on June 15^{th}.
Cavity#3, un-stiffened	**Detuning meas., microphonics study and compensations are planed**				
Cavity#1, un-stiffened					
Cavity#4, Stiffened					

Summary

Key of the MLC operation

- Due to **the high Qext** for the MLC cavities, **detuning** is an important issue limiting the field sustained in the cavity. Especially in the **un-stiffened cavity**.
- Due to **the small bandwidth** of the MLC cavity, it is very sensitive to **Lorentz Force detuning**. LFD compensation has been implemented and tested in cavity #2 and #6.

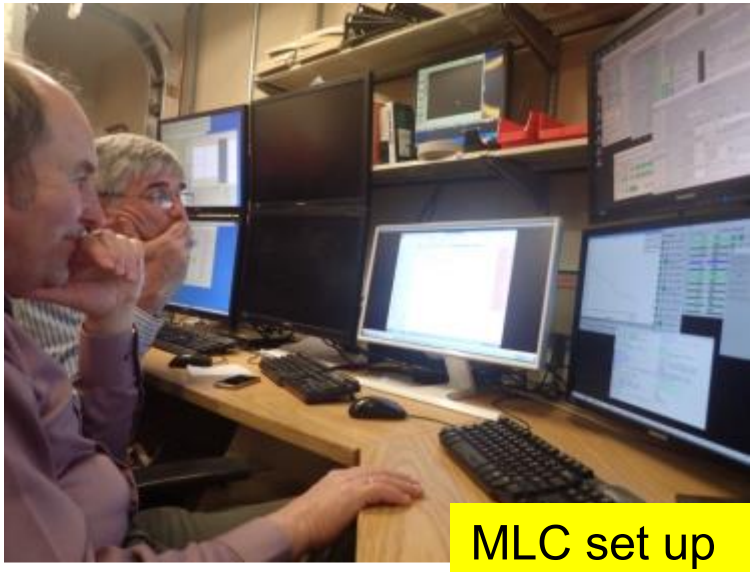
Microphonics Compensations

- **Low frequency microphonics** compensation has been implemented using a Proportional-Integral feedback loop which deals with pressure changes in the helium bath.
- **High frequency microphonics** compensation will be implemented to deal with vibrations more than 1 Hz. This will be done using adaptive feed-forward schemes.

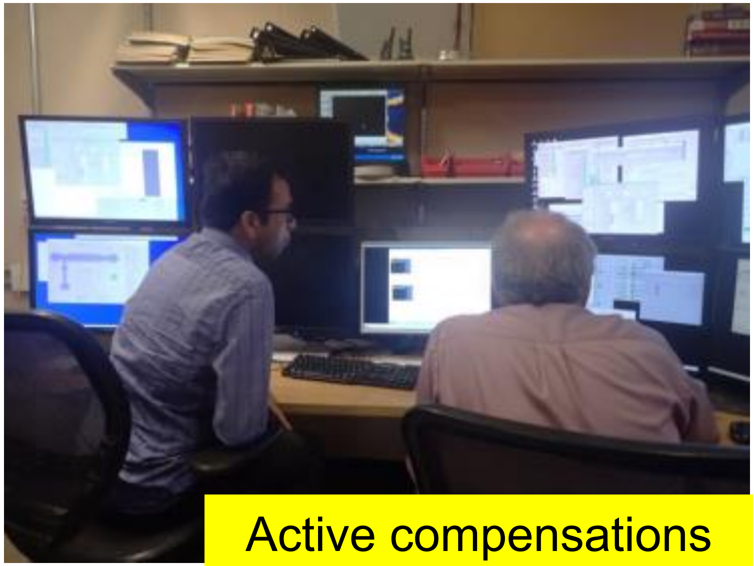
Future work

- Further **optimization of cryogenic control and LLRF control**, more microphonics measurements, and studies on **an active compensation with the piezoelectric fast tuner** are in progress.
- Confirm **the MLC could provide/regulate the 1st pass energy gain of 36MeV in total** is the next milestone of the MLC prior to Fractional Arc Test

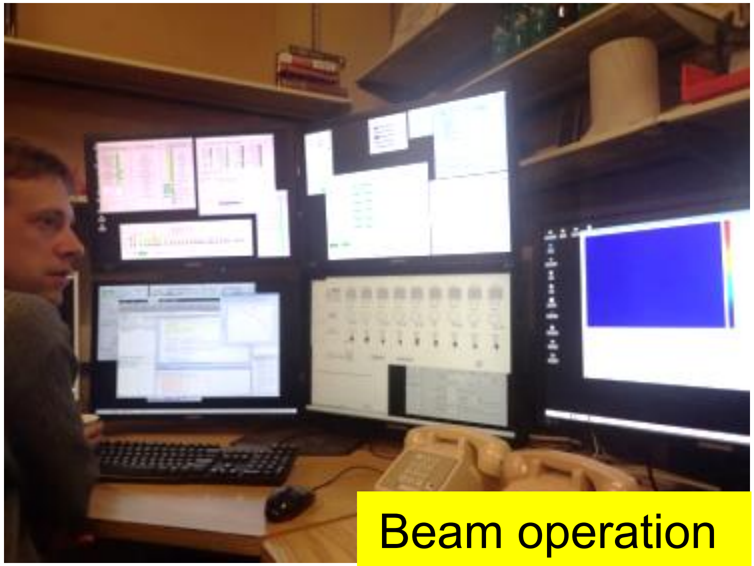
Thanks again to the ERL team



MLC set up



Active compensations



Beam operation

Special thanks to
Nilanjan Banerjee, Adam Bartnik,
John Dobbins, Peter Quigley,
and Vadim Veshcherevich.

Thank you for your attention!