High-efficiency, High-current Optimized Main-linac ERL Cryomodule

Fumio Furuta
Cornell University

Outline

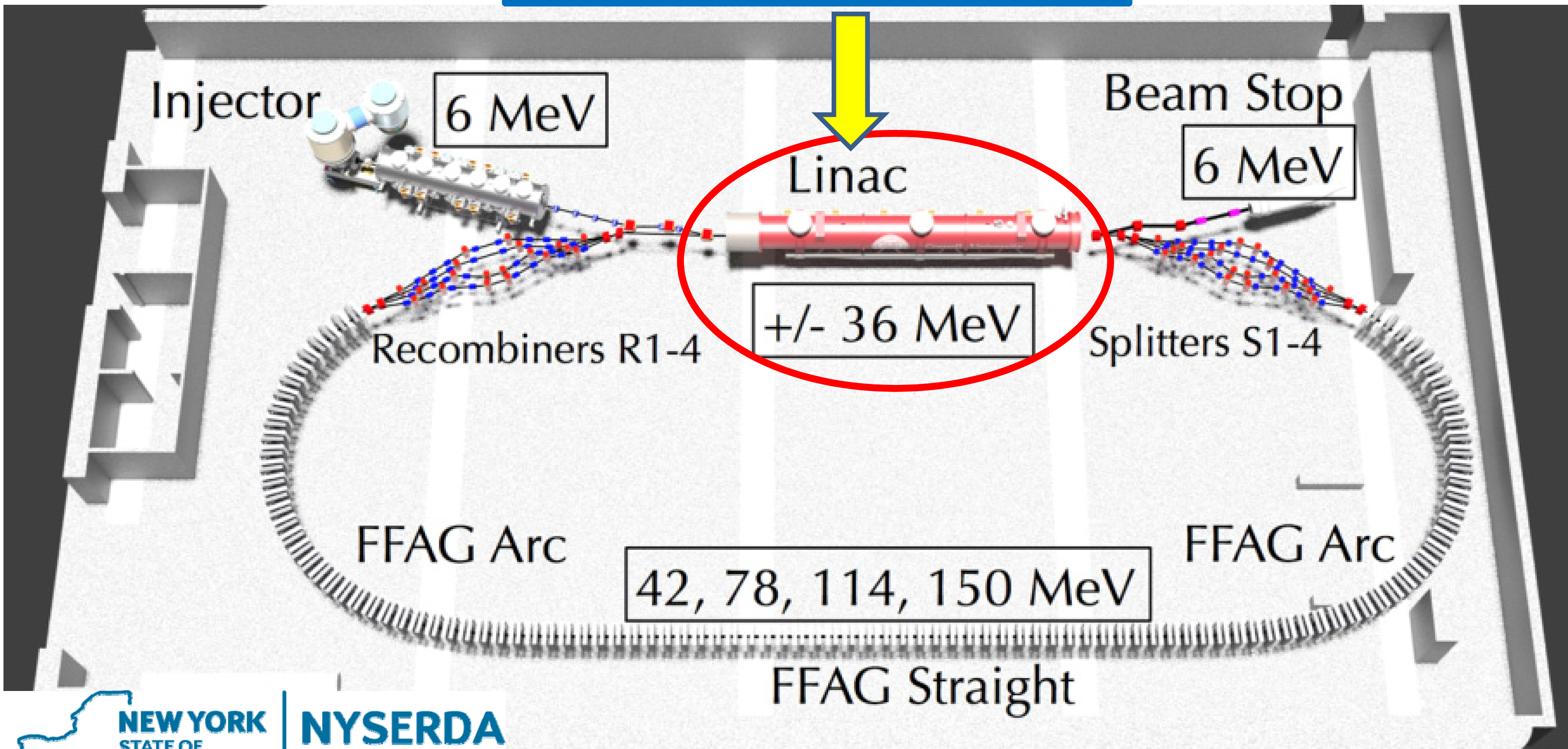
- Introduction
- Initial commissioning
- Microphonics in the MLC and compensations
- Beam acceleration test
- Summary

Introduction

CBETA
CORNELL BNL ERL TEST ACCELERATOR

Main Linac Cryomodule (MLC):
- **No (almost) beam loading**
  - High $Q_L \sim 6 \cdot 10^7$
  - *Small bandwidth Δf~ 10 Hz*

BROOKHAVEN NATIONAL LABORATORY



NEW YORK STATE OF OPPORTUNITY. NYSERDA Supported

FFAG: Fixed Field Alternating Gradient

MLC Design

The MLC in L0E at Wilson lab, Cornell, WG on cavity #6

MLC Design

Design goals

- **High cavity quality factor Q_0** (2×10^{10} at 16.2MV/m, 1.8K), and **a high loaded-Q** design of ~6×10^{7} (~10Hz half bandwidth).
- **High current (100mA average current);**
  The suppression of high order modes (HOMs) excited by beam in cavities is essential!!
- **Operate in CW at 1.3GHz with 2ps bunch length, normalized emittance 0.3mm-mrad,**

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MLC Parameters

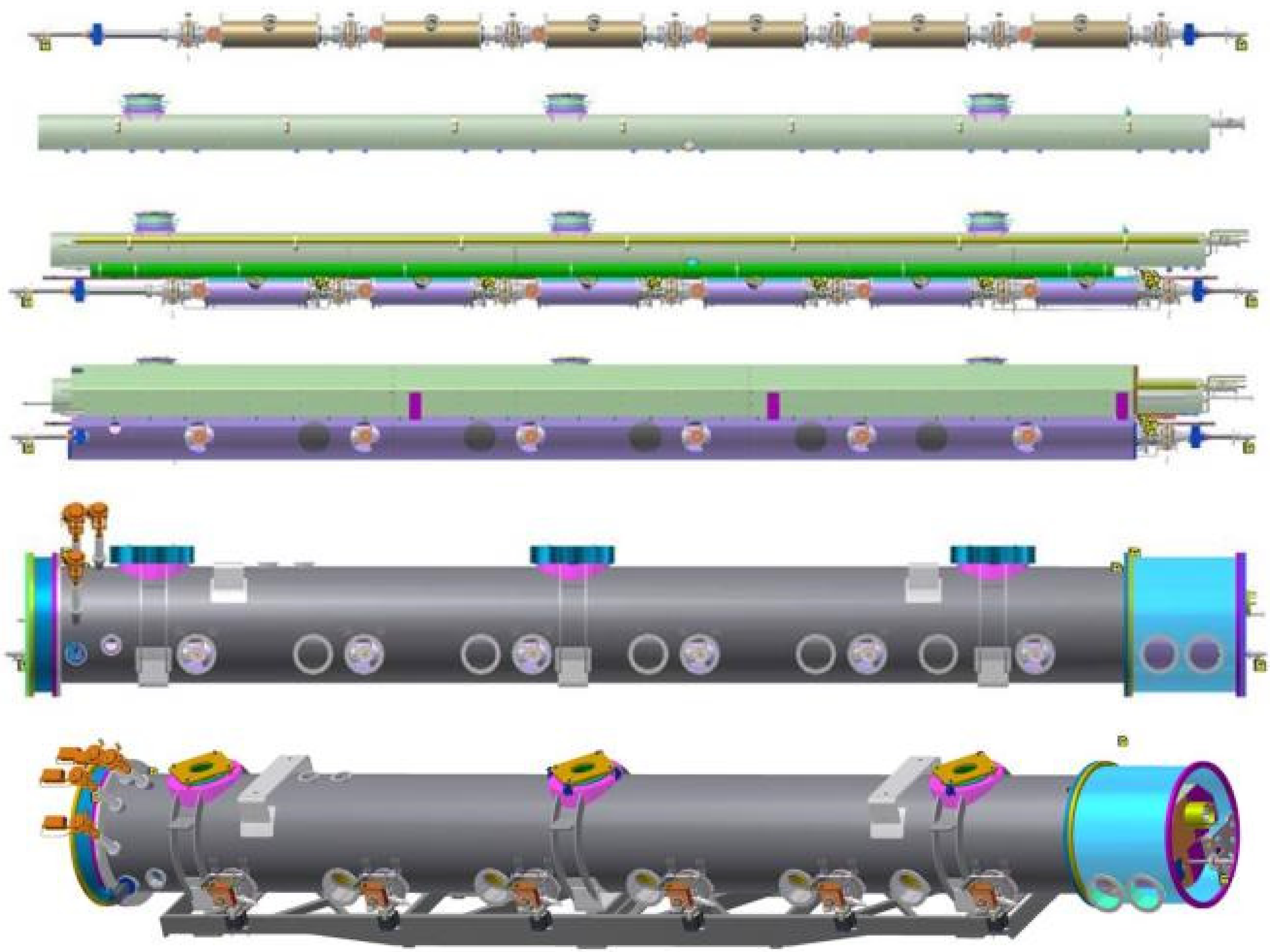
Number of 7-cell cavities	**6**	**Number of HOM loads**	**7**
Acceleration gradient	**16.2 MV/m**	**HOM power per cavity**	**200 W**
R/Q	**774 Ohm**	**Couplers per cavity**	**1**
Q_{ext}	**6.5×10^7**	**RF power per cavity**	**10 kW max.**
Total 2K / 5K / 80K loads:	**76W / 70W / 1500W**	**Amplitude/phase stability**	**10^{-4} / 0.05° (rms)**
		Module length	**9.8 m**

MLC Works

MLC history

- 2012 — **Design**
- 2013 — **Fabrication**
- 2014 — **Cavity testing**
- **Assembly**
- 2015 — **Initial Cool down**
- **Initial RF tests**
- 2016 — **Initial LLRF test**
- 2017 — **warm-up**
- **Move MLC to final location for CBETA ring**
- **2nd Cool down**

May 2017 Launch of initial beam testing!



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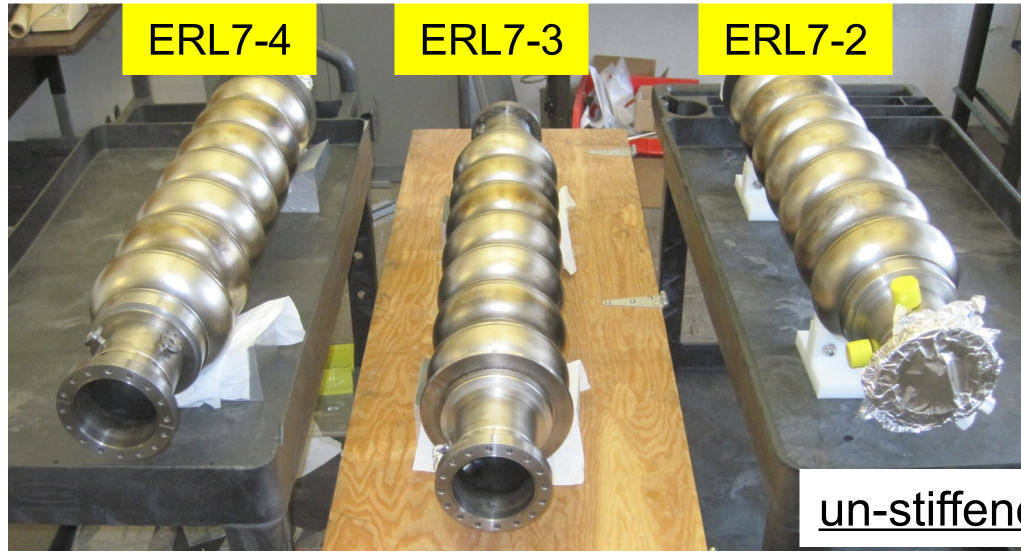

un-stiffened

ERL7-5

stiffened

Cavity surface preparations	
1) bulk BCP	4) 120C x 48hrs bake
2) 650C out-gassing	5) HF rinse
3) final BCP	

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Bare, w/ T-map

w/ He vessel

w/ additional mag. shield

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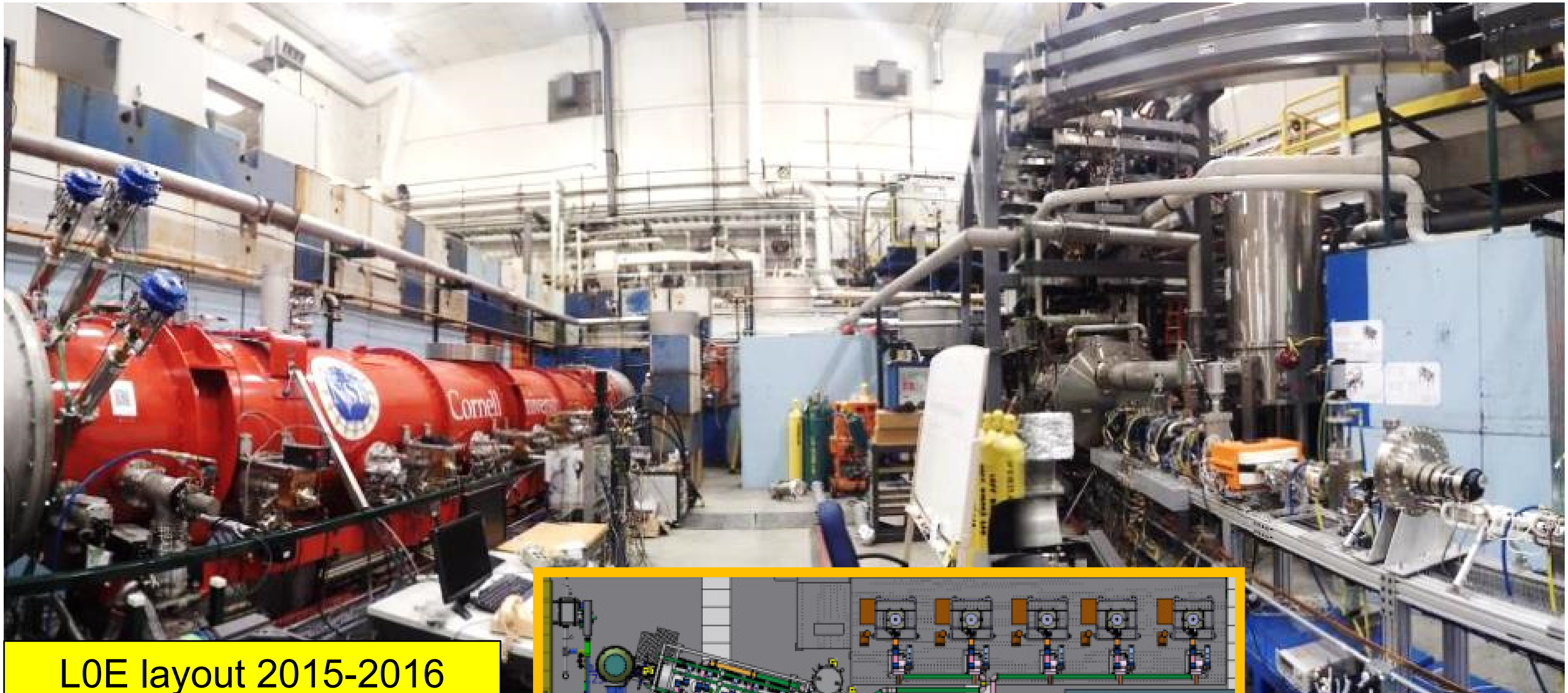
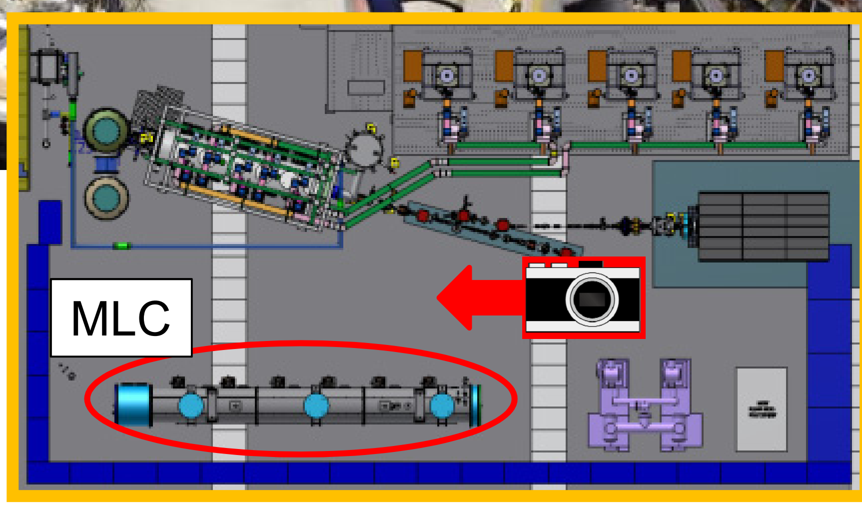
Initial commissioning

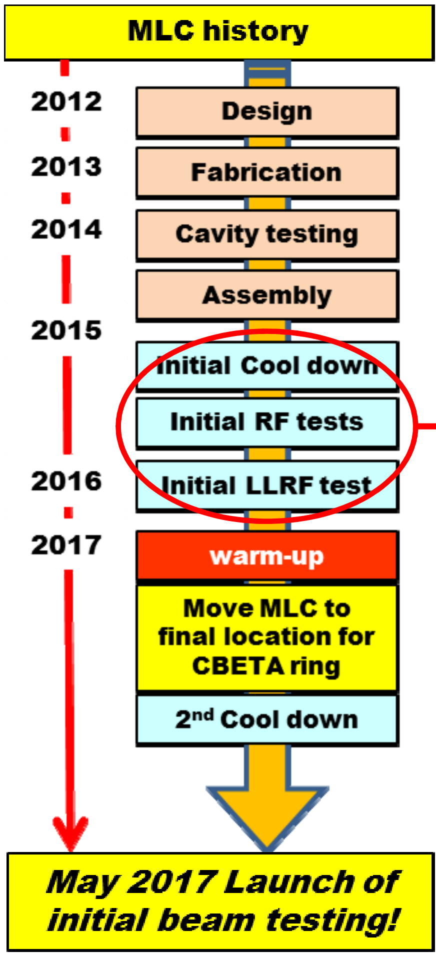
L0E Layout



L0E layout 2015-2016
Wilson lab, Cornell

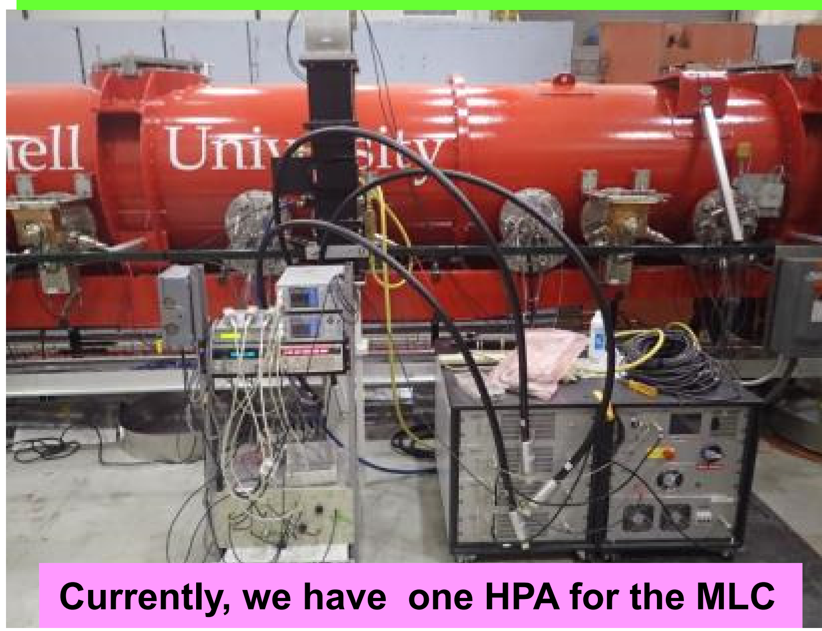


Initial MLC test/commissioning



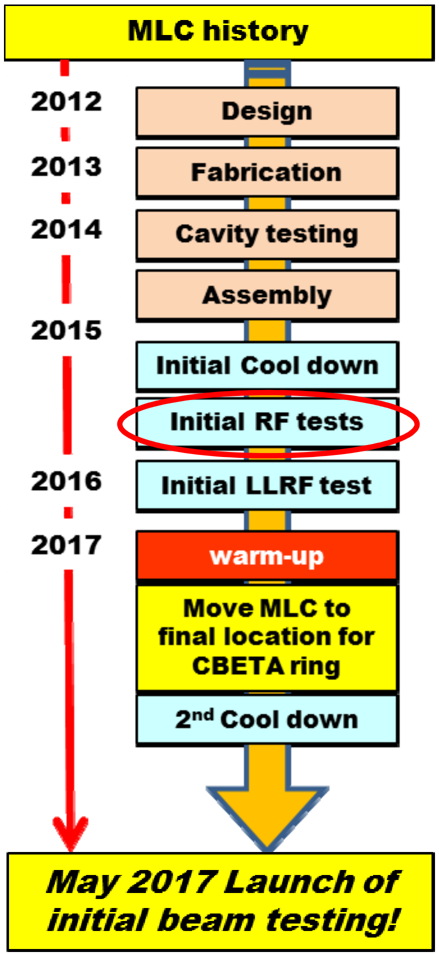
- Initial cool down
- Cavity test at 1.8K
- Thermal cycles
- Slow tuner test
- HOM scan
- LLRF and microphonics study

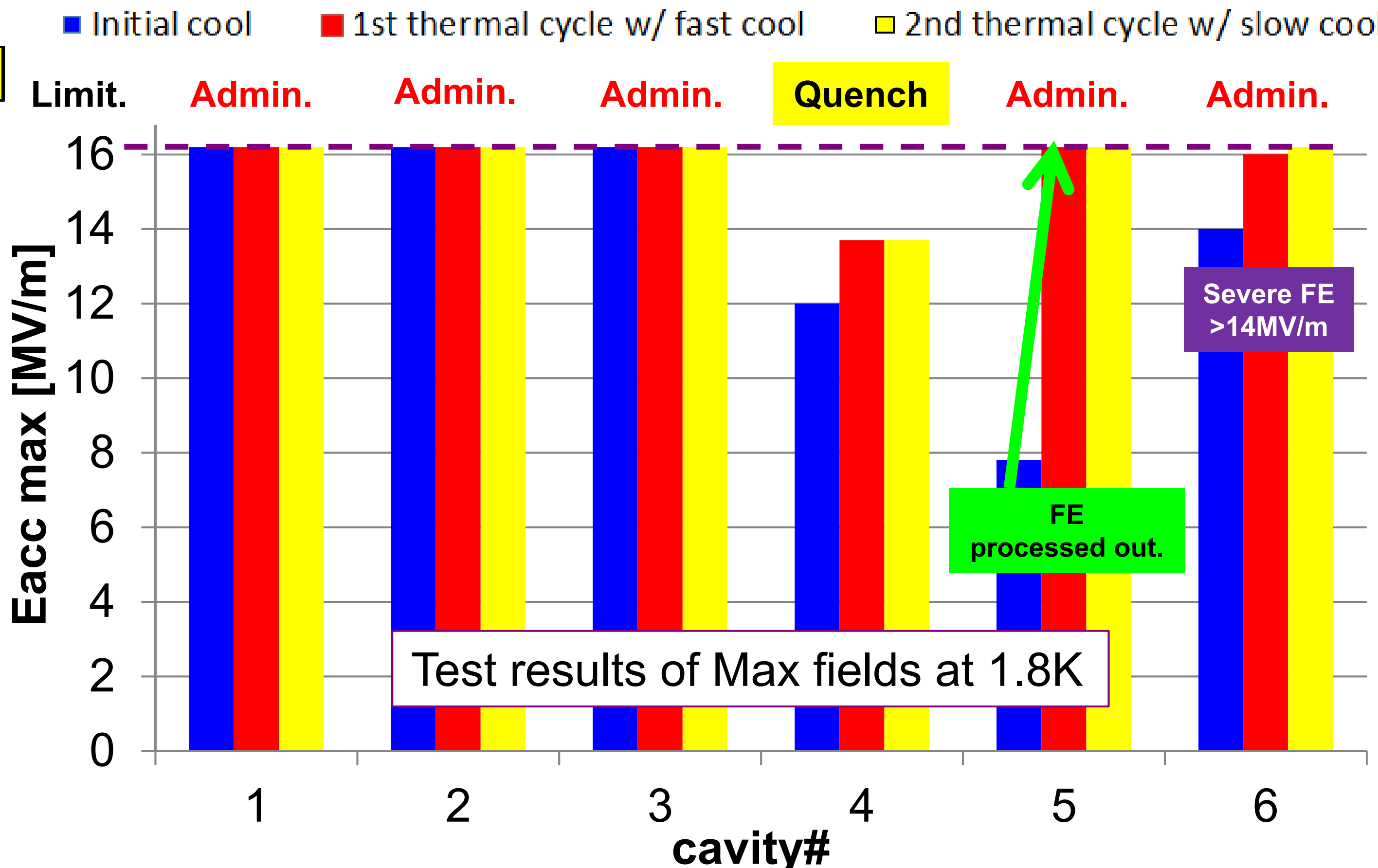
What we learned/done during the initial commissioning?



Currently, we have one HPA for the MLC

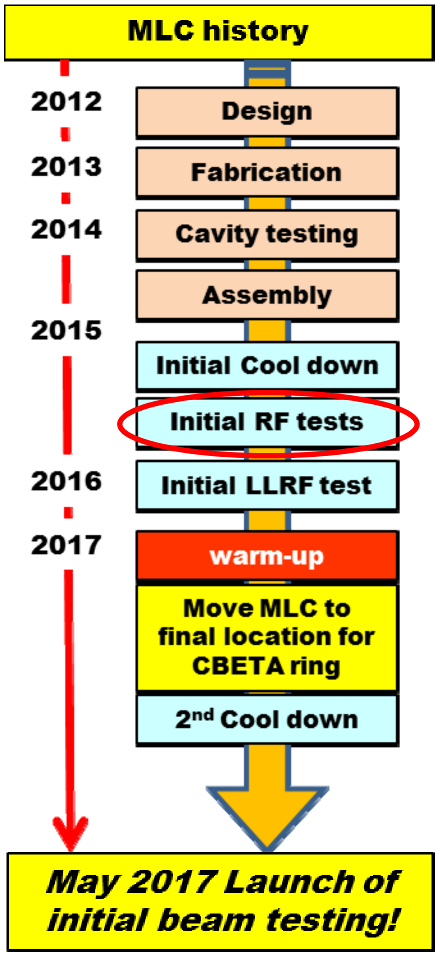
MLC initial RF test; Cavity field

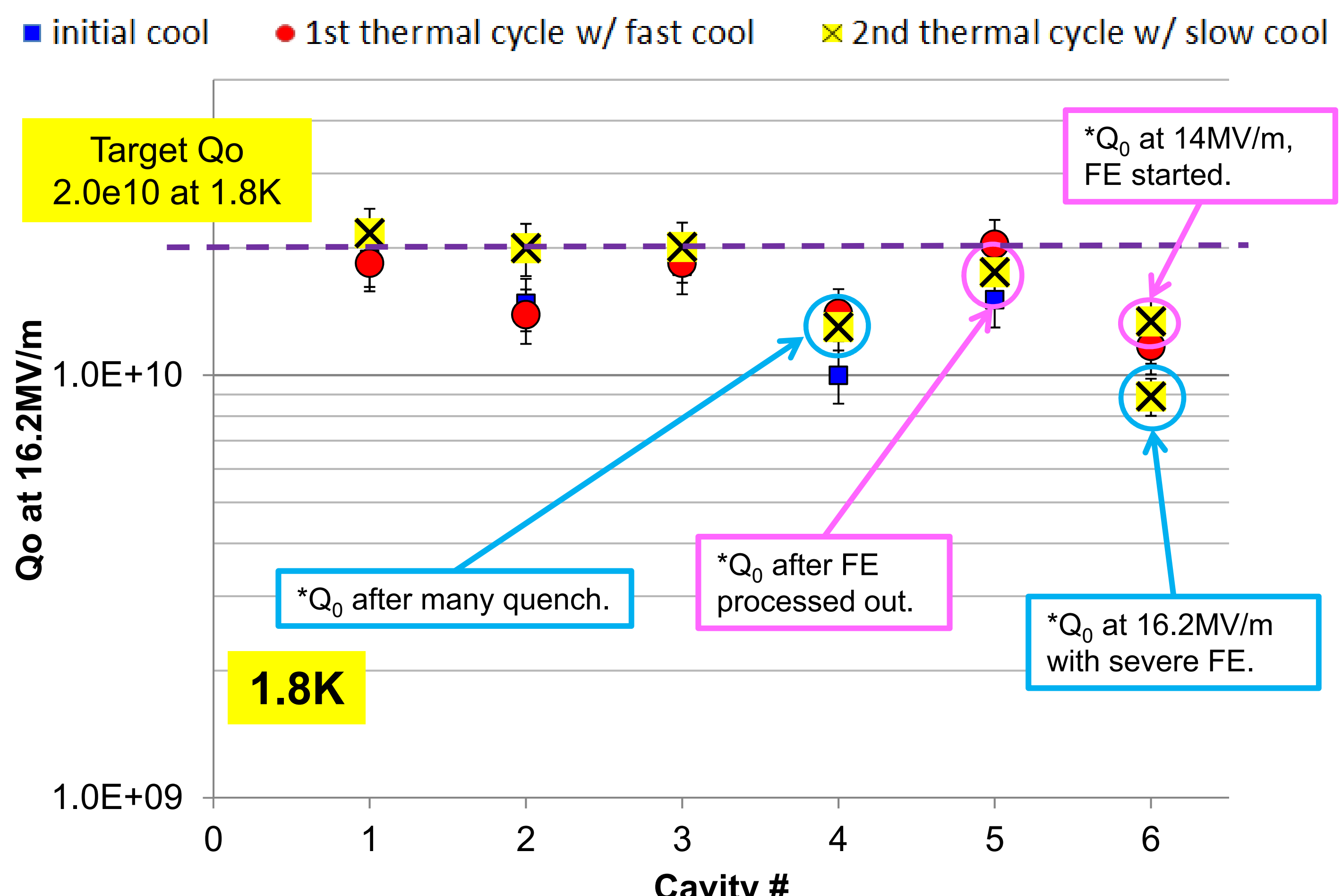




- 5 of 6 cavities had achieved MLC design gradient of 16.2MV/m at 1.8K.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- **The MLC can provide 76MeV per ERL turn, which significantly exceeds the CBETA requirement of 36MeV per ERL turn.**

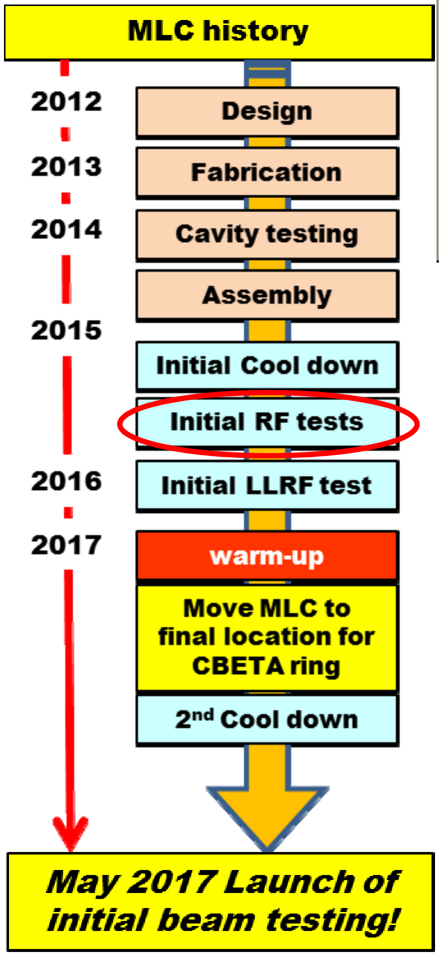
MLC initial RF test; Q_0 at 1.8K

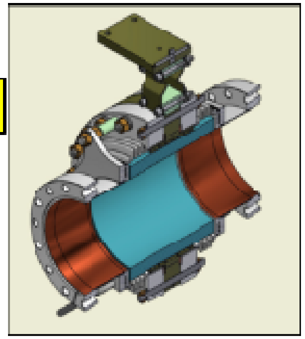


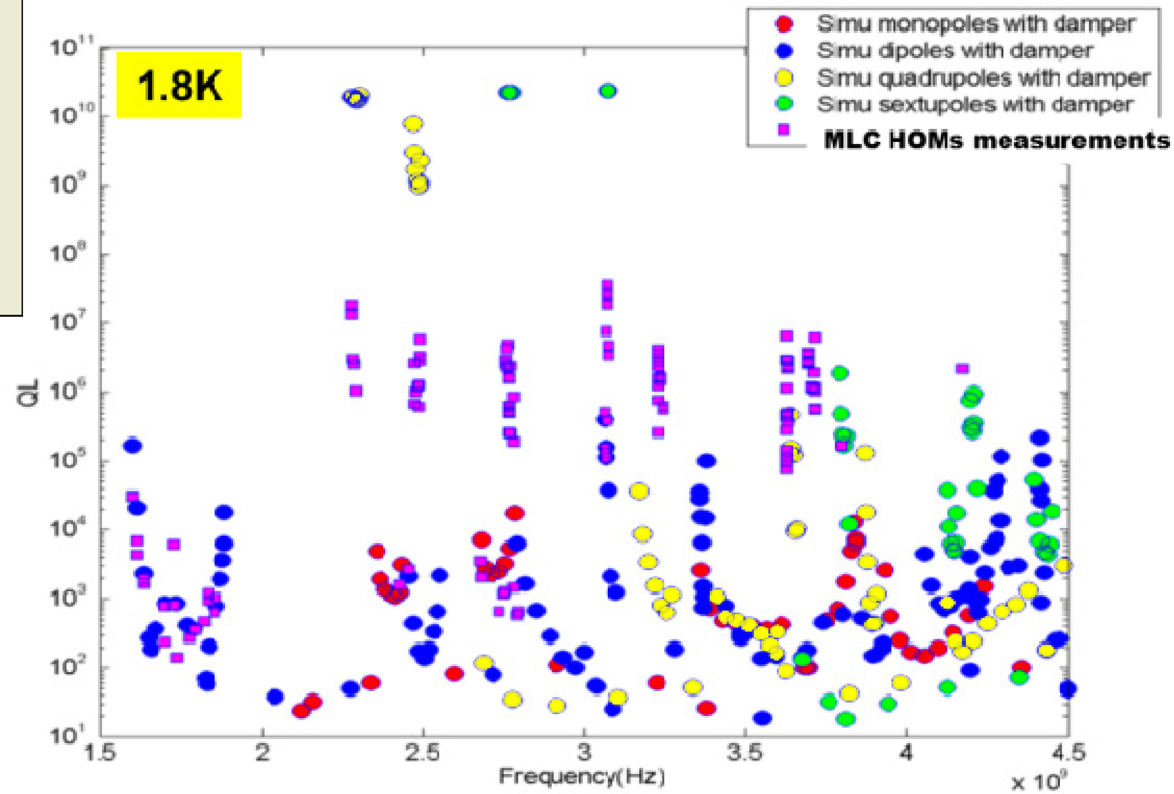


A slow cool down with a small spatial temperature gradient (ΔT) gave the highest Q_0 for the MLC cavities. The benefit of slow cool down with smaller ΔT on the MLC is likely due to a suppression of thermal-currents and their induced magnetic fields.

MLC HOM scan and analysis

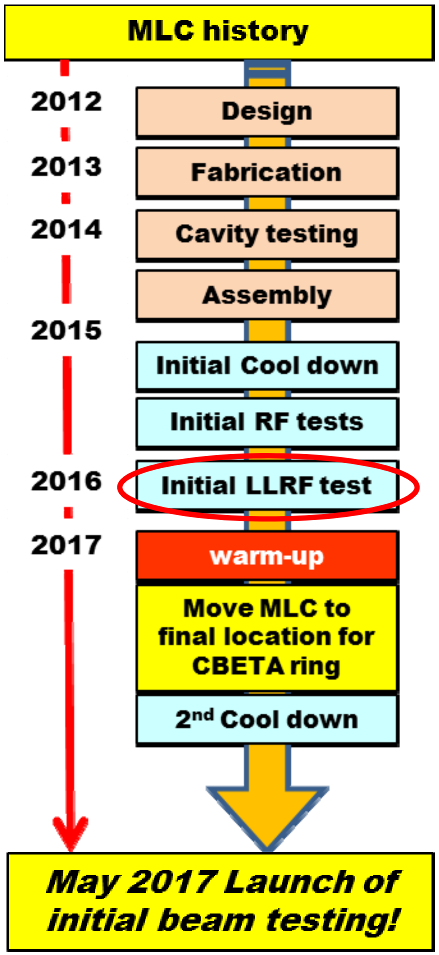


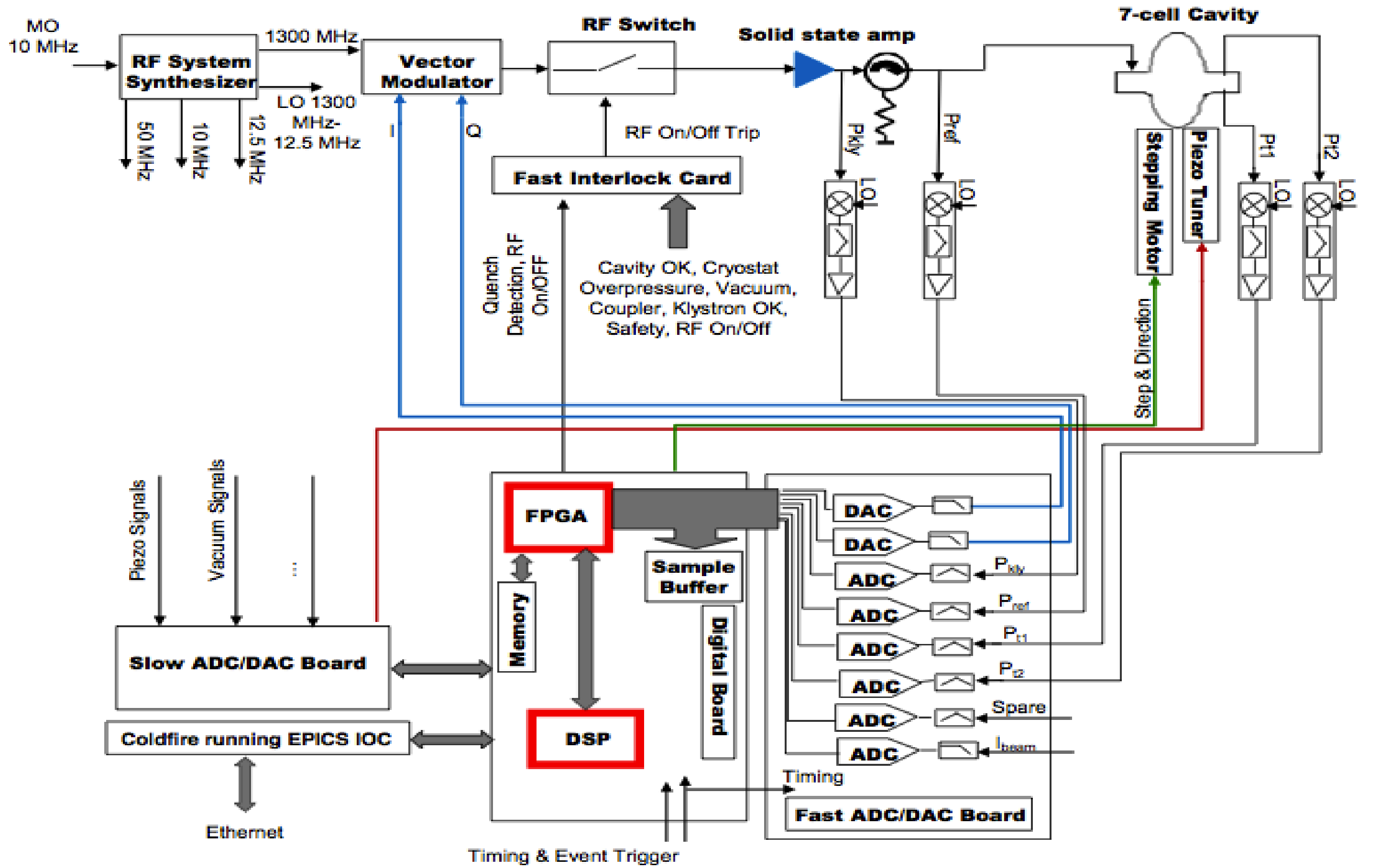




- Dipole HOMs on MLC were strongly damped below Q~10^4. Consistent with HTC and simulation results.
- NO HOM limits BBU to below 100mA in one turn.

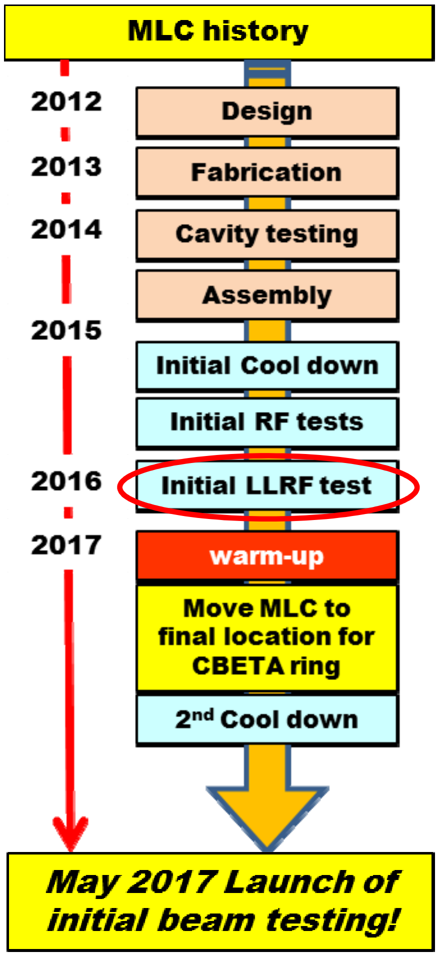
LLRF and Microphonics

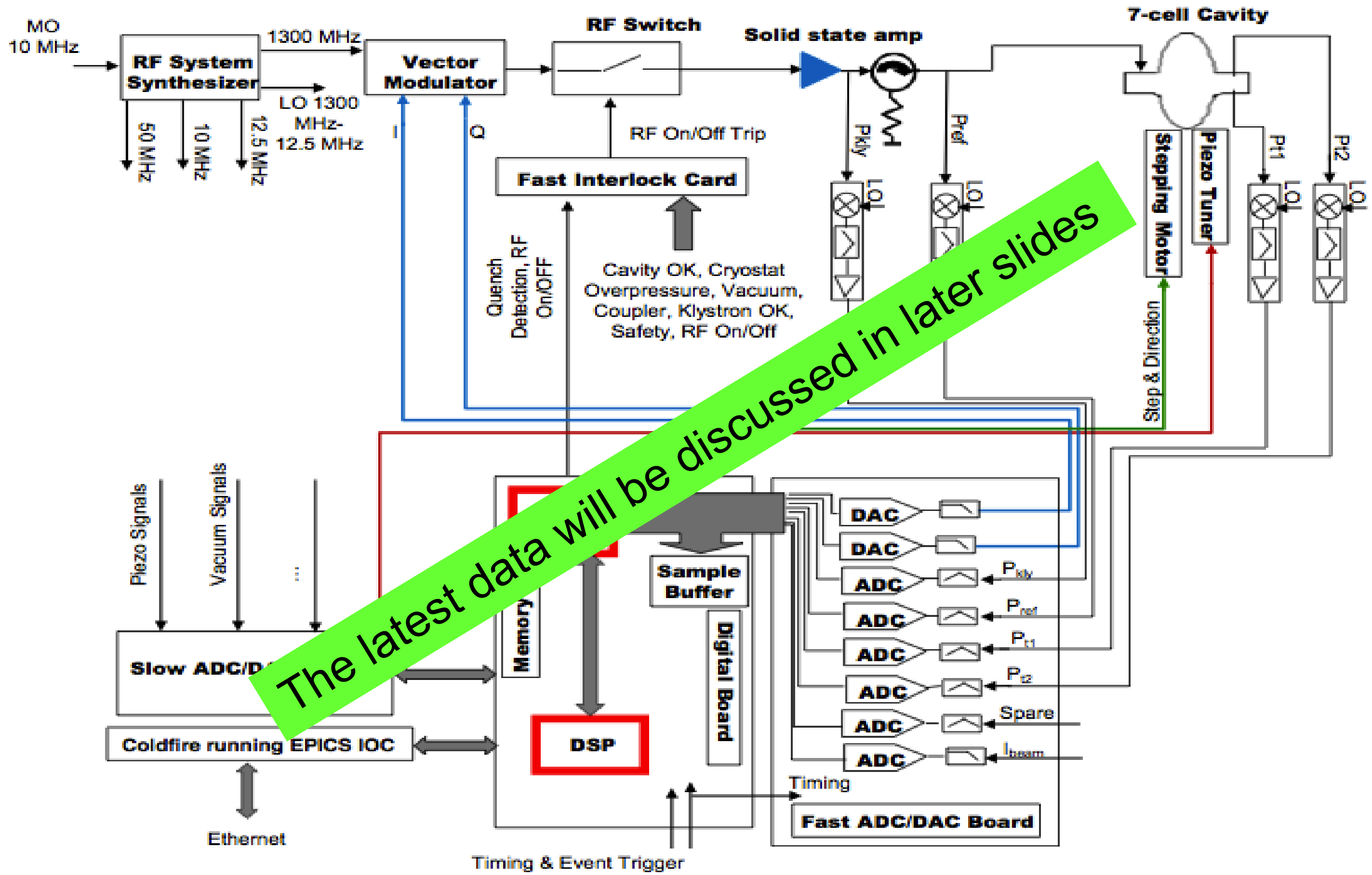




Block diagram of the MLC LLRF system for a 7-cell cavity.

LLRF and Microphonics





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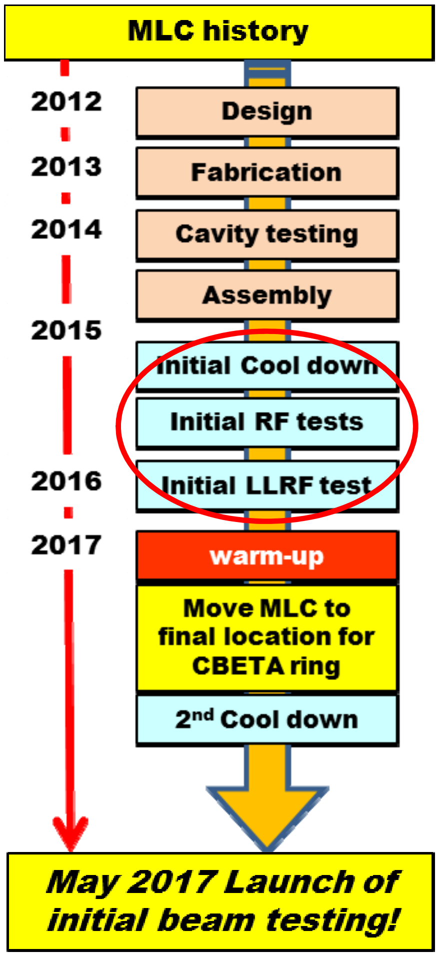
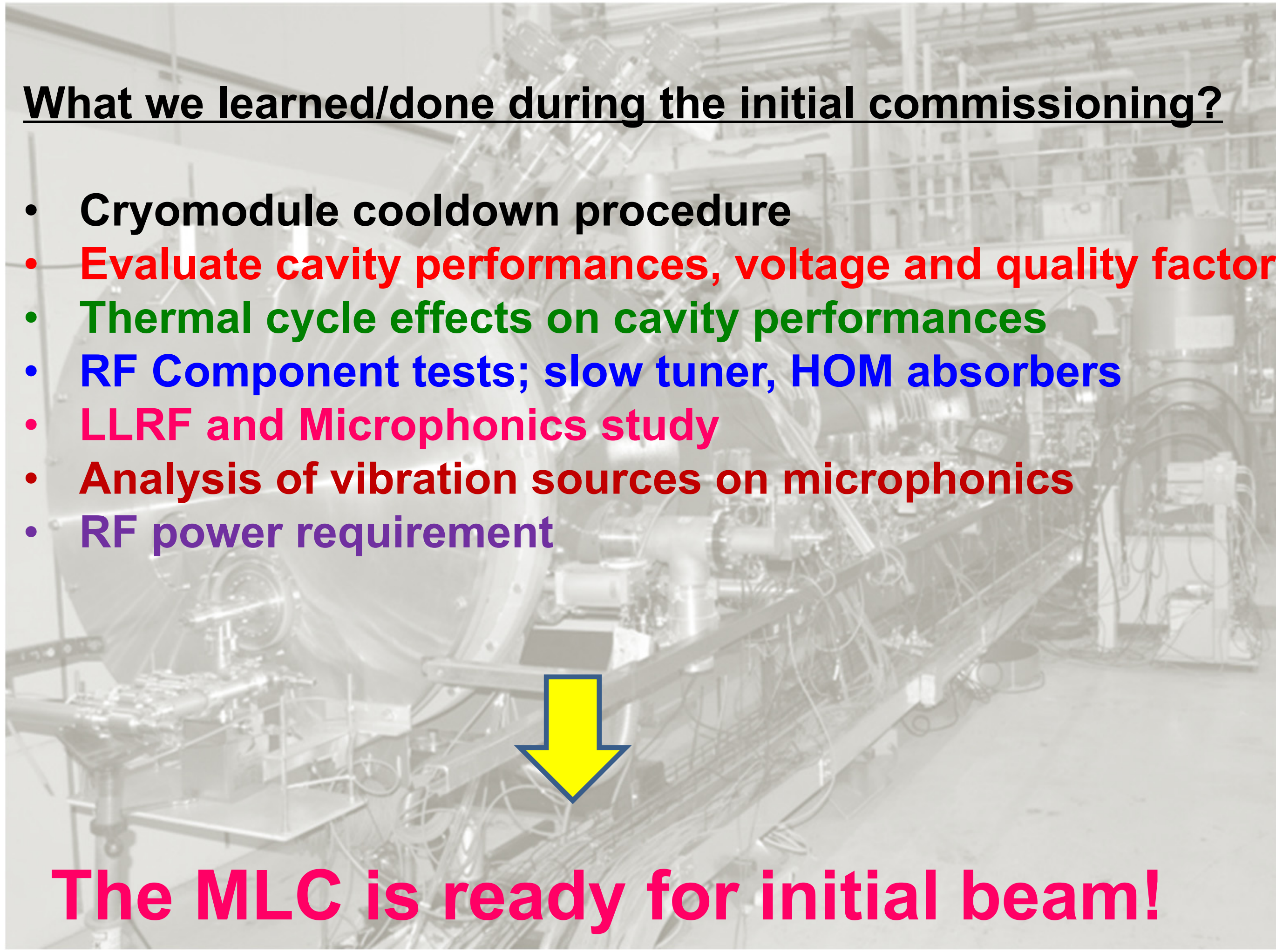
MLC is,,,





What we learned/done during the initial commissioning?

- Cryomodule cooldown procedure
- Evaluate cavity performances, voltage and quality factor
- Thermal cycle effects on cavity performances
- RF Component tests; slow tuner, HOM absorbers
- LLRF and Microphonics study
- Analysis of vibration sources on microphonics
- RF power requirement

The MLC is ready for initial beam!

MLC moving on Feb. 8th 2017

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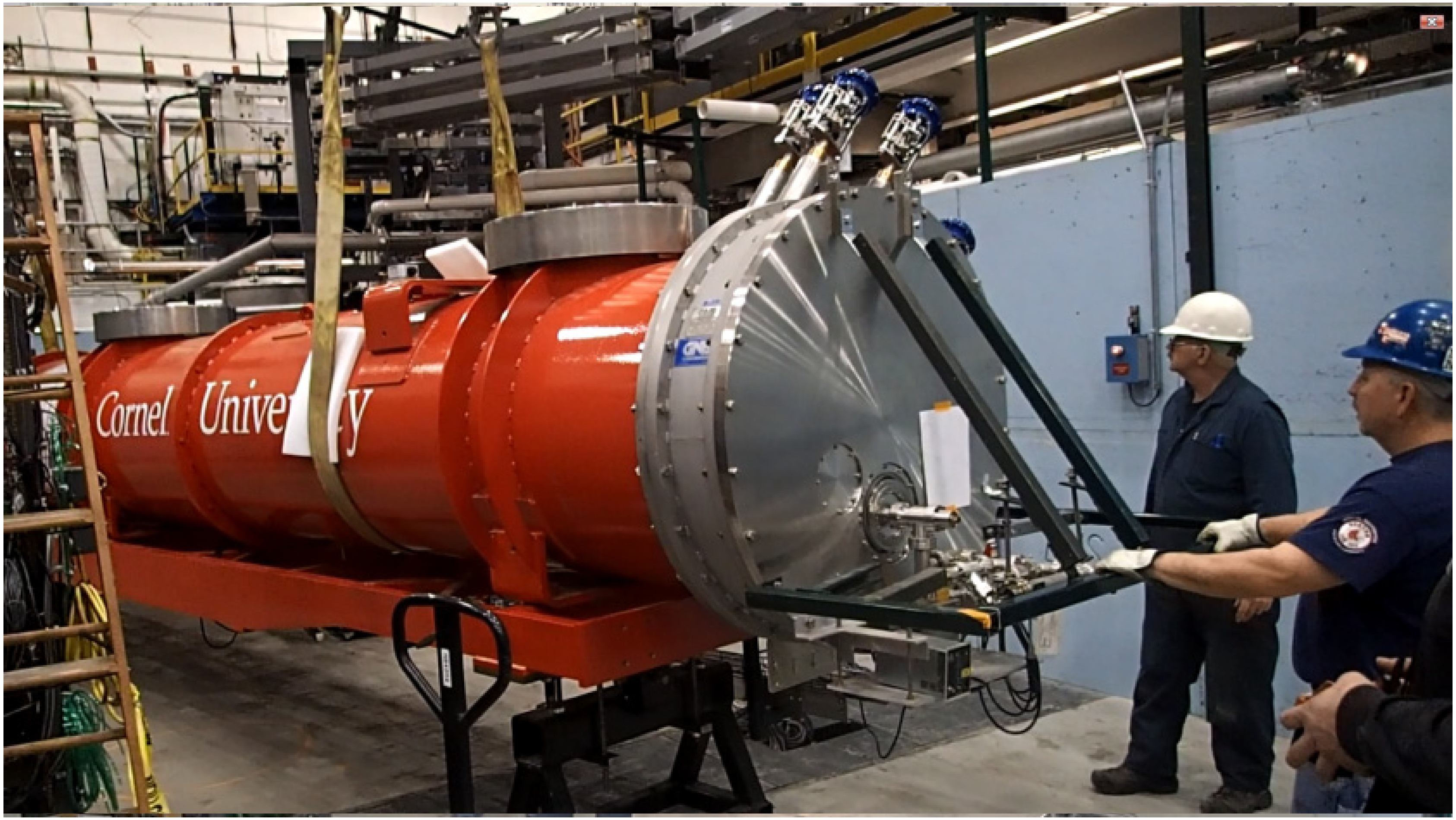

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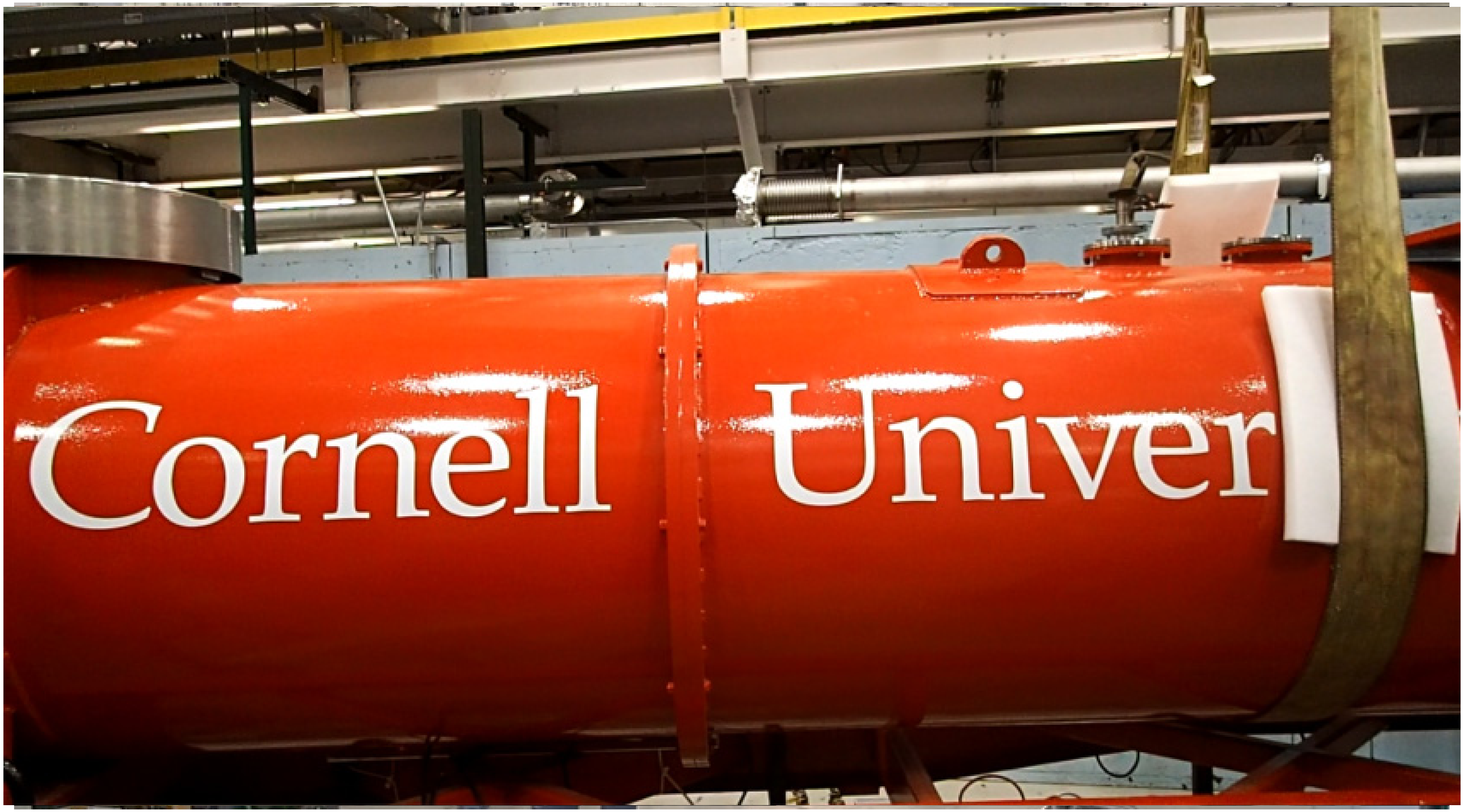

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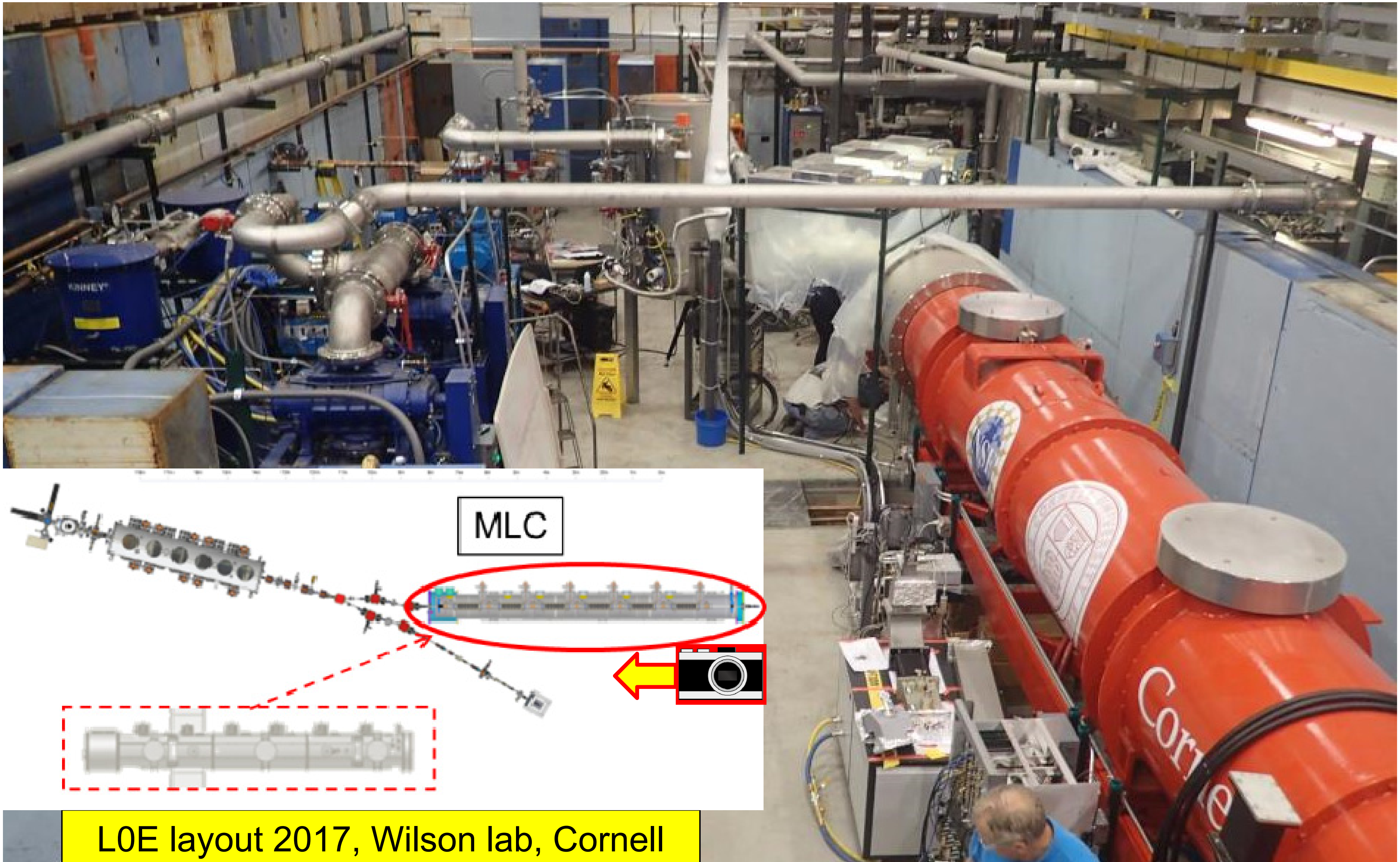
MLC moving on Feb. 8th 2017

MLC moving on Feb. 8th 2017

MLC at its final location, 2017



Microphonics in the MLC

and compensations

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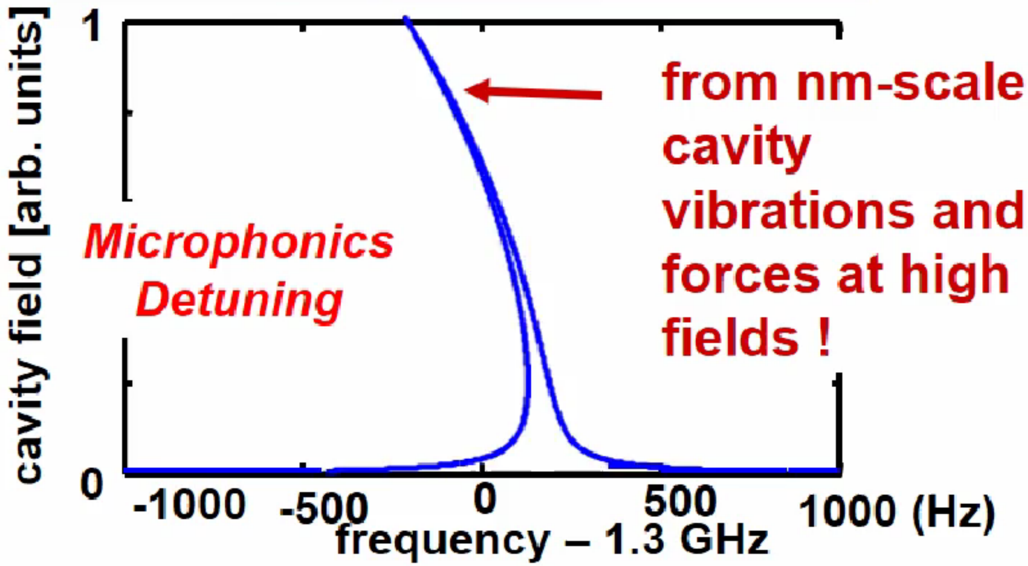
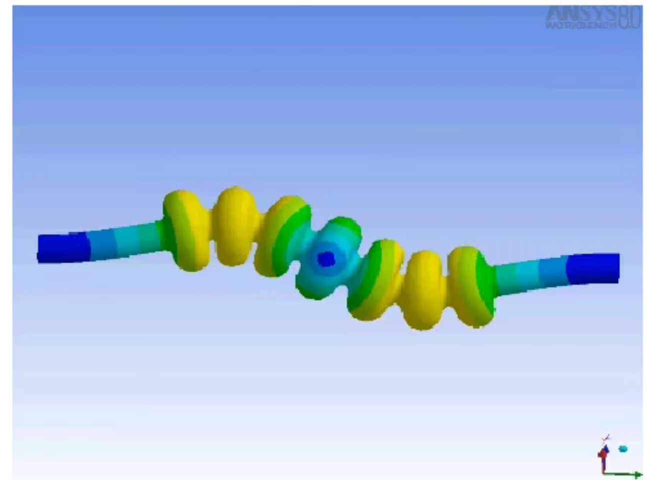
High Q_L and Microphonics

Microphonics (mechanical cavity vibration) is one of the major sources of **frequency perturbation (detuning)** and **field perturbation** of SRF cavities.

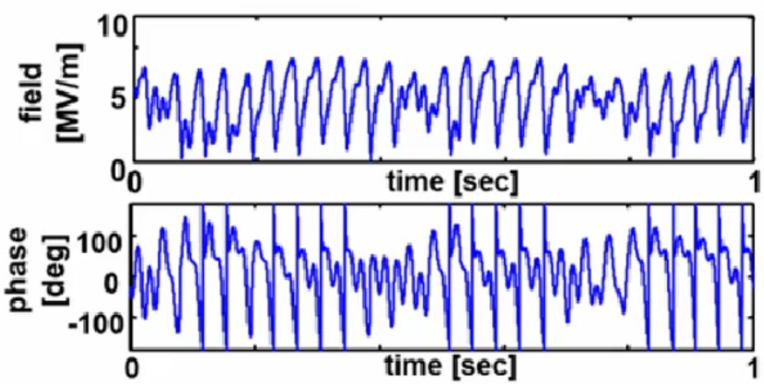
Narrow cavity resonance curve!



nm scale vibrations



Without feedback:



Cavity field control and frequency stabilization becomes very critical!

Lorentz Force Detuning

Another source of detuning, cavity field depend

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

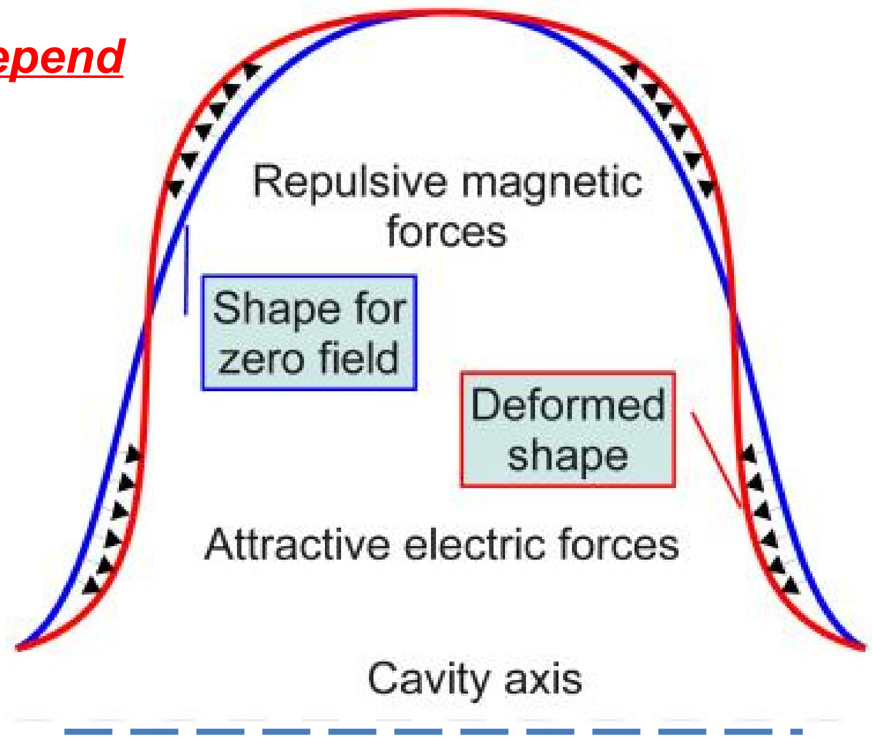


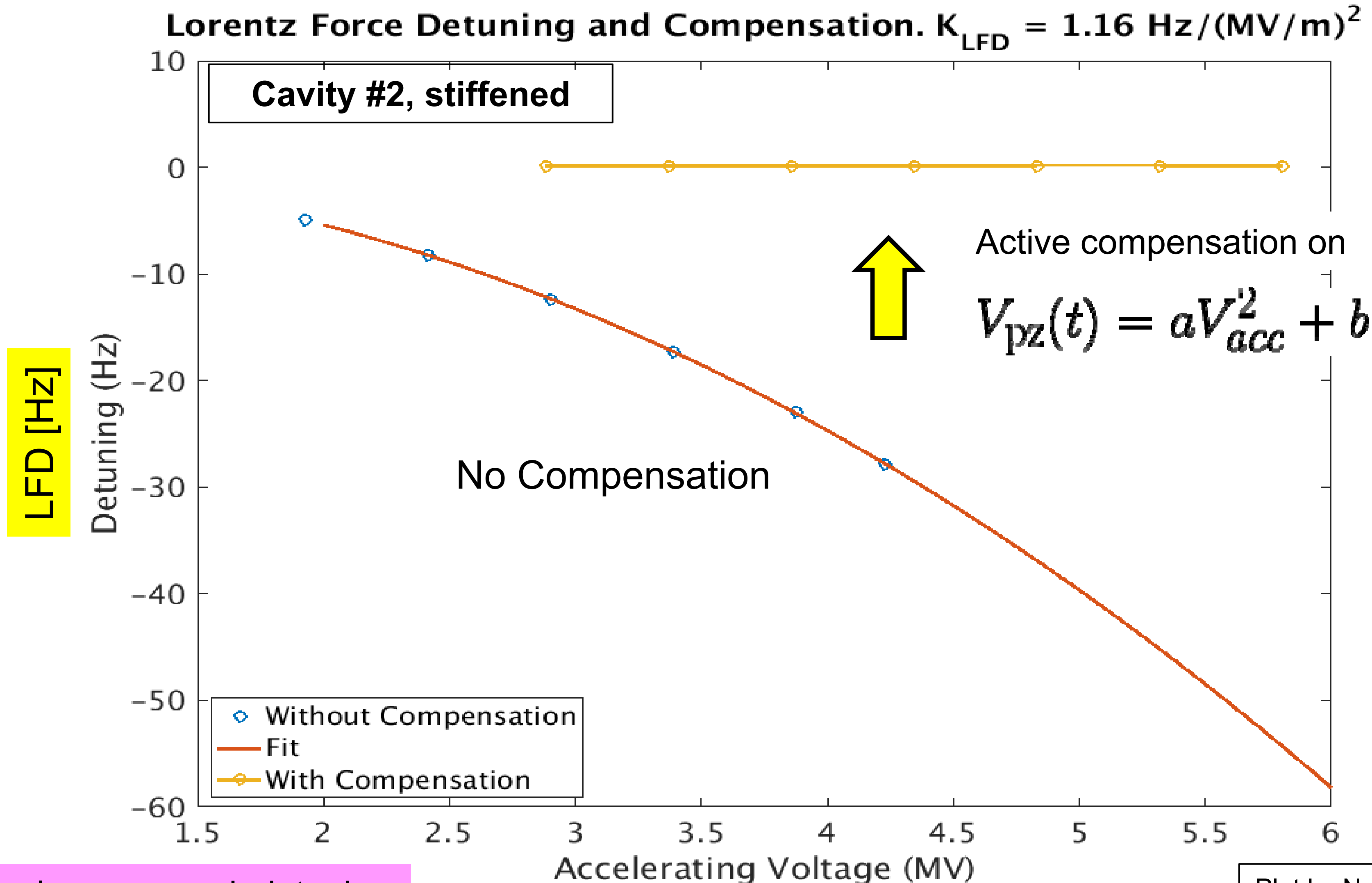
Image from Linear Collider Collaboration website

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

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

Courtesy of Nilanjan Banerjee
nb522@cornell.edu

LFD measurements/compensation

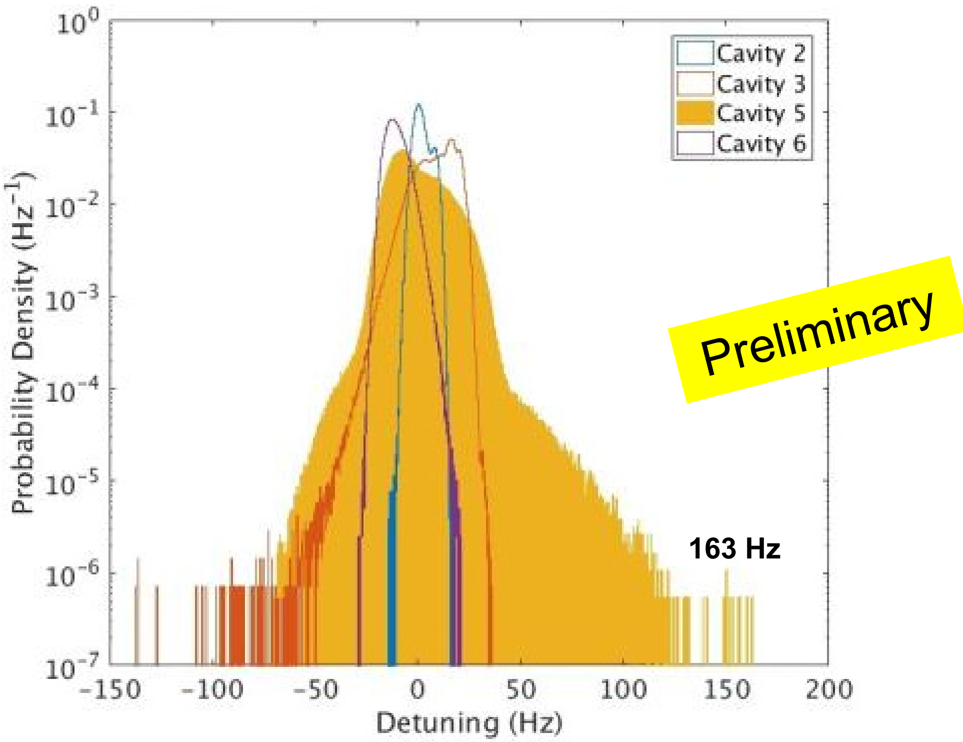


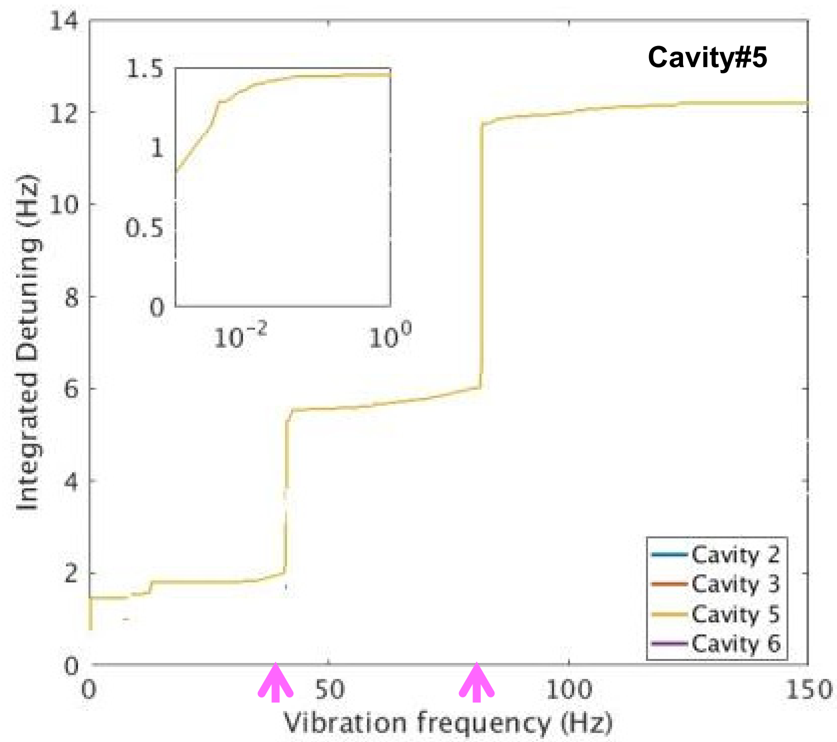
*values are peak detuning in Hz, not rms

Plot by N. Banerjee
nb522@cornell.edu

Microphonics Detuning Meas.

Plots by N. Banerjee (Graduate student)





- **The data sets shown are taken without any active compensations.**
- **Max detuning in cavity #5 (un-stiffened) is 163 Hz in the measured dataset which caused by the opening of a valve in the 5K pre-cool line. We will revisit cavity #5 later, and resolve this by cryo optimization.**
- **Major contributions at 40 Hz and 80 Hz are probably driven by 5K Helium gas flow.**

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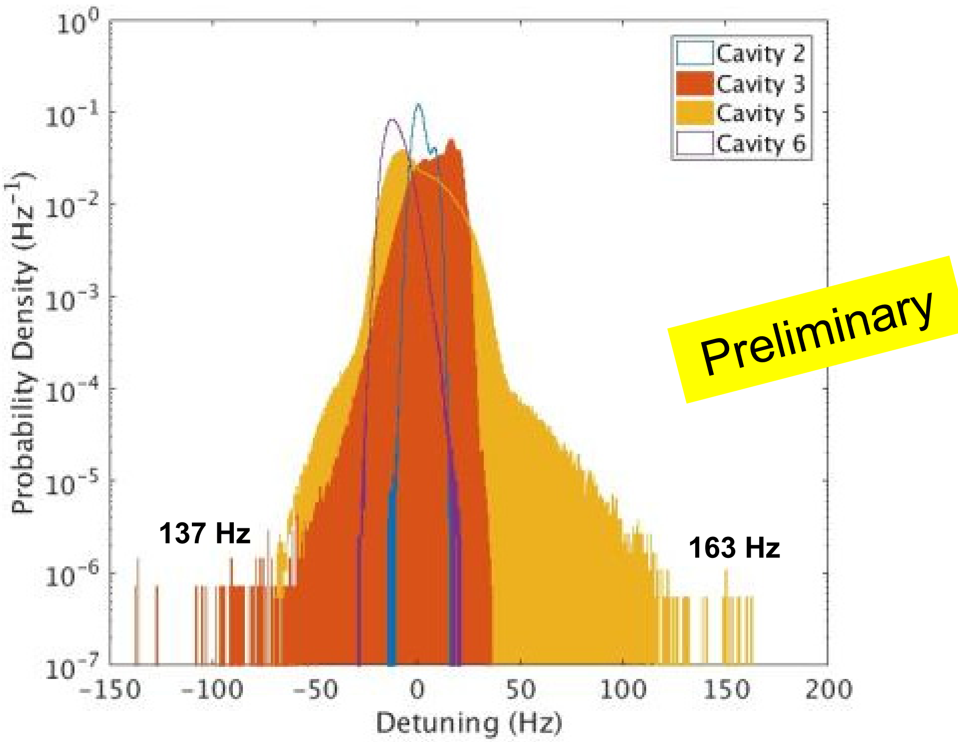

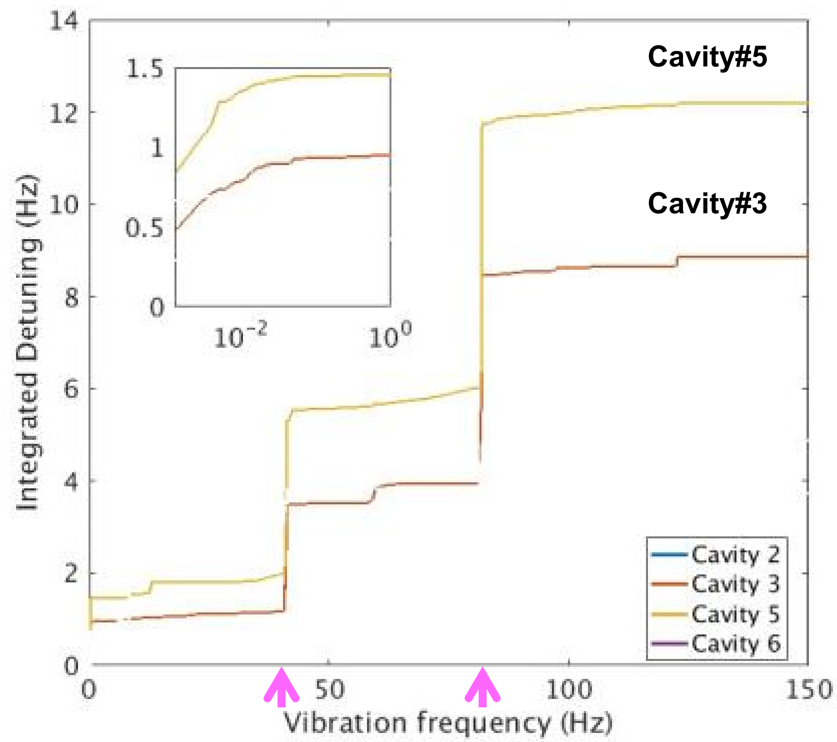

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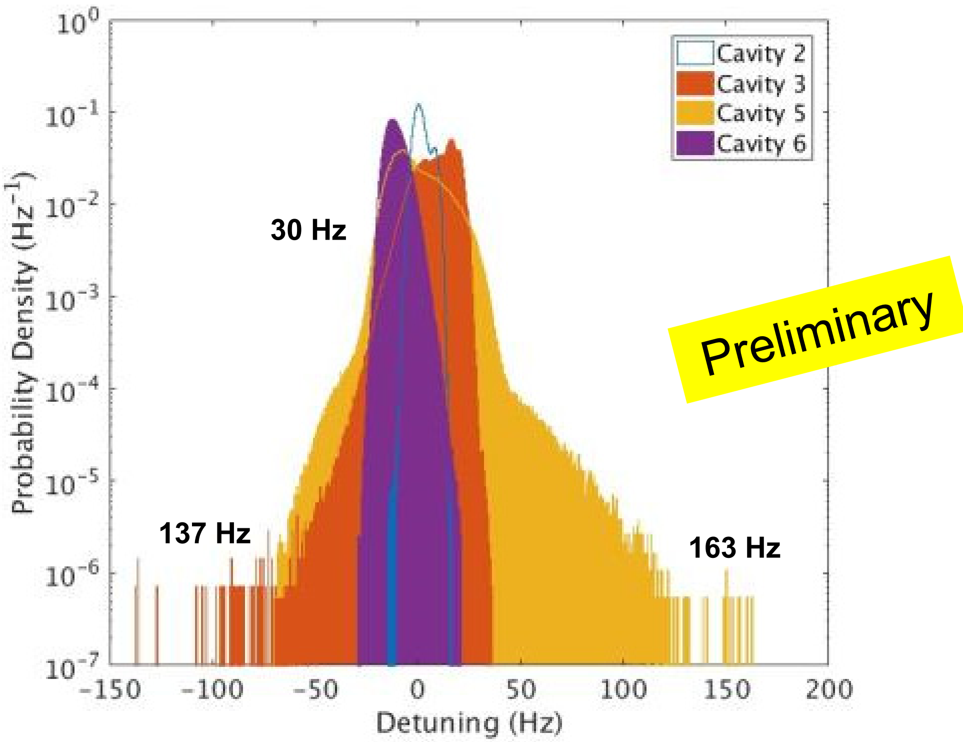

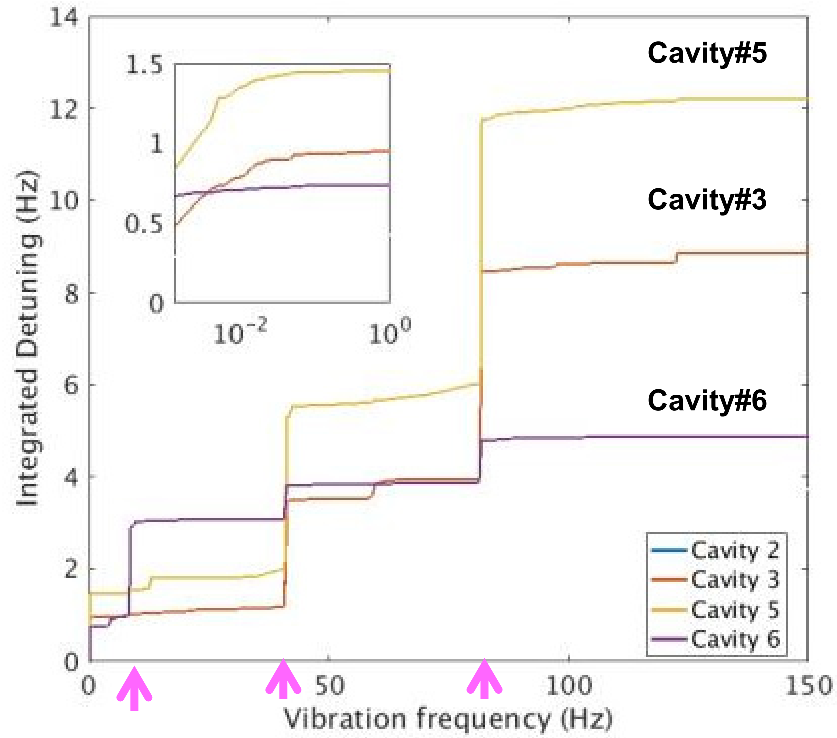

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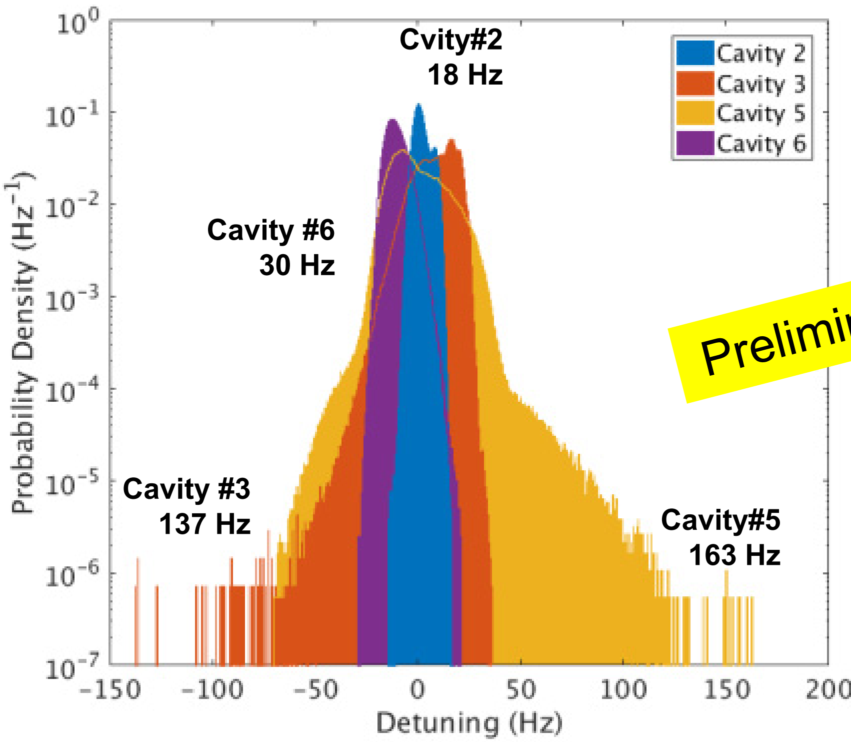

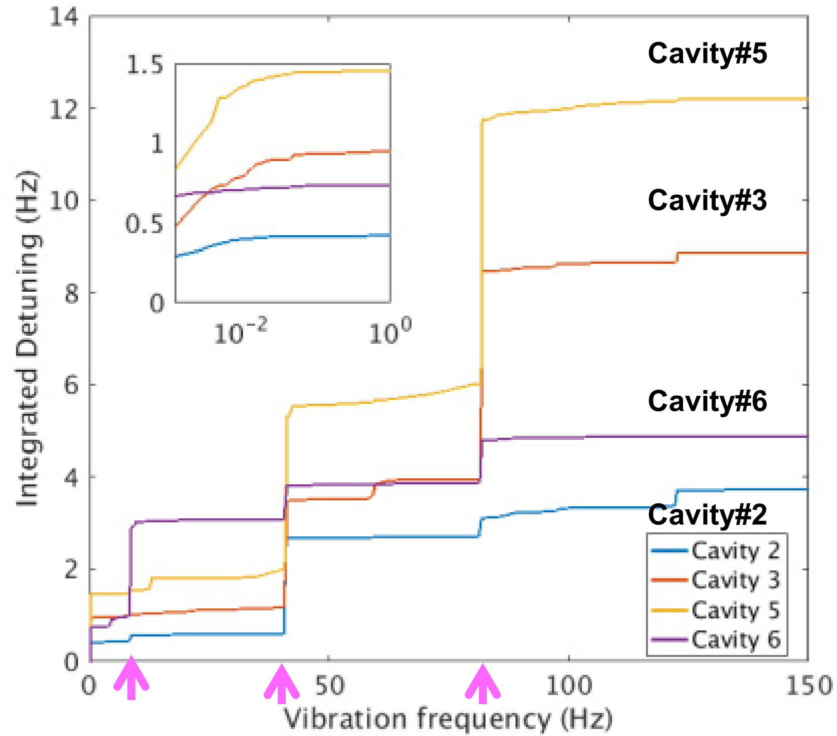

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Microphonics Sources

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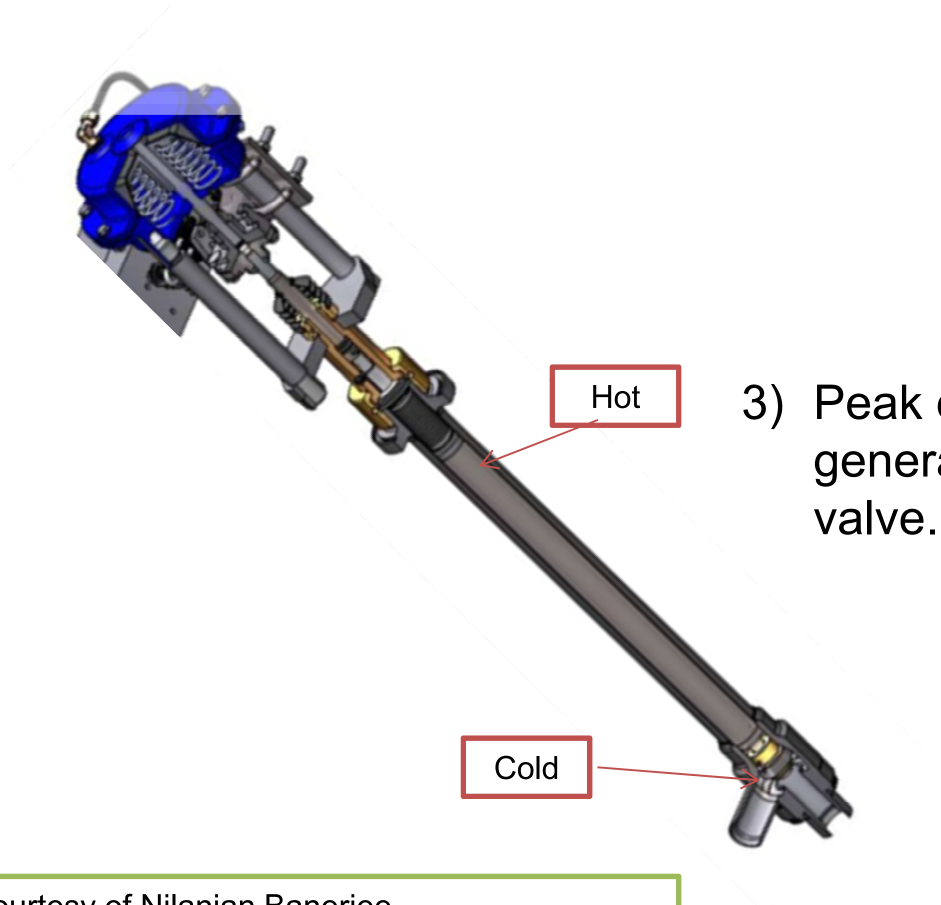
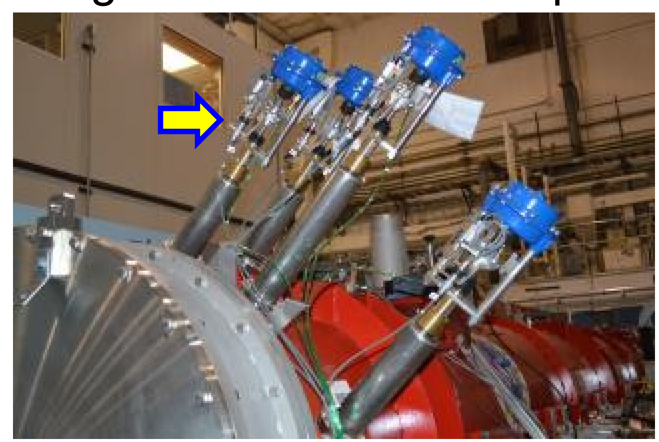


Courtesy of Nilanjan Banerjee
Valve image from Warren Schappert, FNAL

2) 8 Hz is generated from the blower.

3) Peak events are caused by small bubbles generated during the actuation of the pre-cool valve.



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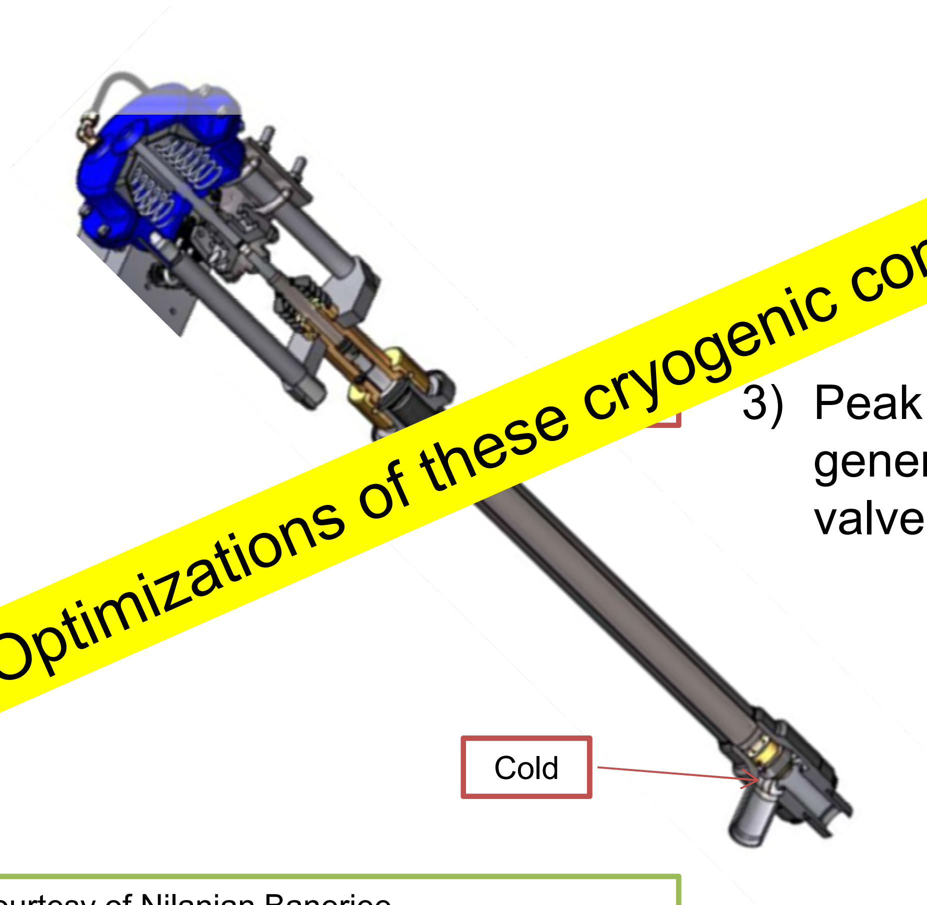

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Optimizations of these cryogenic components are in progress.

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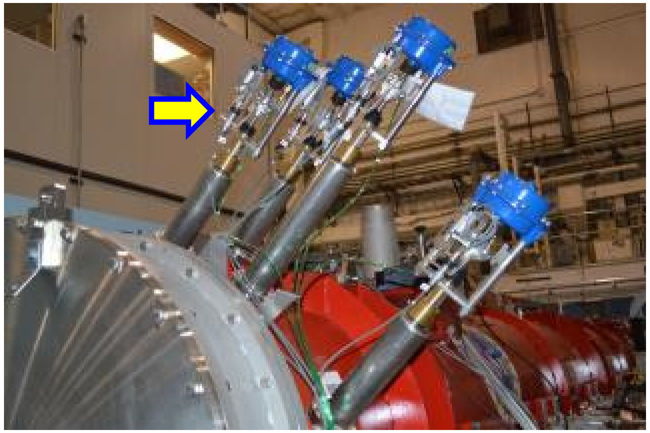

Courtesy of Nilanjan Banerjee
Valve image from Warren Schappert, FNAL

Microphonics compensations

❑ LFD Compensation

$$V_{pz}(t) = aV_{acc}^2 + b$$

❑ Proportional Integral Feedback Loop

- Currently only the integral term is used which automatically works as a low pass filter. The feedback loop is effective at sub Hz frequencies.
- If the field is increased slowly then it also compensates for LFD.

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

❑ Feedforward Algorithm

- Idea: Treat this as a real time least squares optimization problem.

  Actuator Signal: $$u_{pz}(t_n) = \sum_m I_{mn} \cos \omega_m t_n + Q_{mn} \sin \omega_m t_n$$

  Detuning:

$$\delta f_{comp}(t_n) = \delta f_{ext}(t_n) + \sum_m \alpha_m \{ I_{mn} \cos(\omega_m t_n - \phi_m) + Q_{mn} \sin(\omega_m t_n - \phi_m) \}$$

  Where, α_m and φ_m describe the transfer function from actuator to detuning at the frequency ω_m.
  Mean Square Detuning: $$F_n = E[\{\delta f_{comp}(t_n)\}^2] \sim \{\delta f_{comp}(t_n)\}^2$$

  Minimize the mean square detuning using a gradient descent algorithm.

$$I_{m,n+1} = I_{m,n} - \mu_m \delta f_{comp}(t_n) \cos(\omega_m t_n - \phi_m)$$
$$Q_{m,n+1} = Q_{m,n} - \mu_m \delta f_{comp}(t_n) \sin(\omega_m t_n - \phi_m)$$

$$\phi_{m,n+1} = \phi_{m,n} - \eta_m \delta f_{comp}(t_n) \{ I_{m,n+1} \sin(\omega_m t_n - \phi_m) - Q_{m,n+1} \cos(\omega_m t_n - \phi_m) \}$$

  ω_m and μ_m are fixed by the operator.

Courtesy of Nilanjan Banerjee

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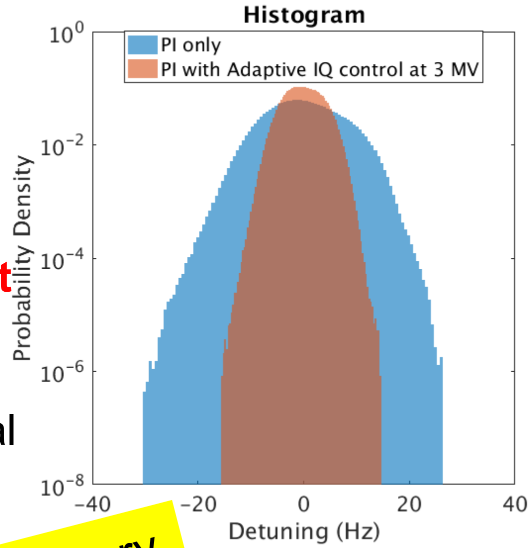
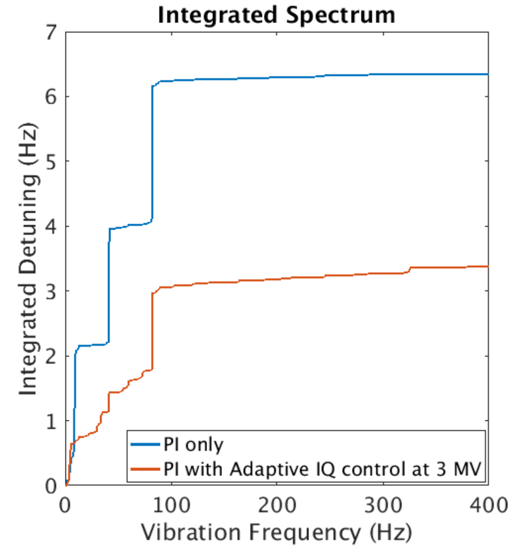
Compensations results

Cavity#6 (stiffened)

- The LMS algorithm was applied on three vibration frequencies of 8Hz, 40Hz and 80Hz.
- **Algorithm is stable and reduces peak detuning from 30Hz to 16Hz at 3MV.**
- Peak detuning ~30Hz at 7.5MV. New vibration peak at 325Hz (a mechanical resonance maybe) limited the effectiveness of compensation.





Preliminary

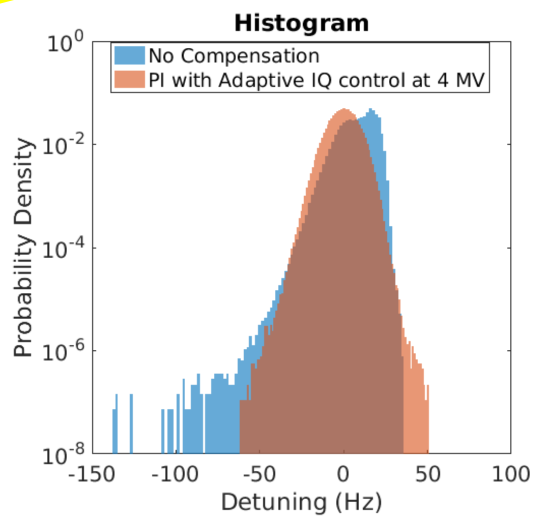
Cavity#3 (un-stiffened)

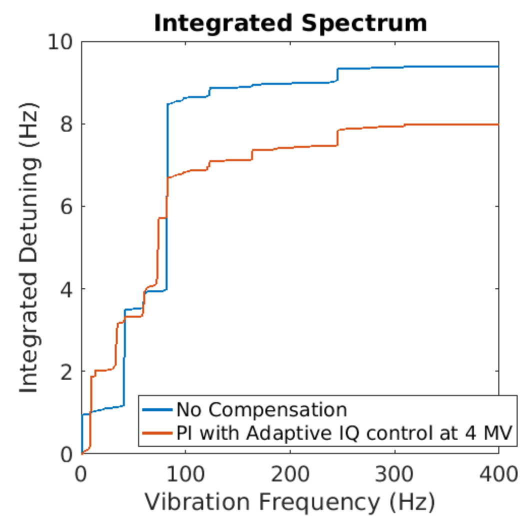
- **Peak detuning**

  without compensation:137Hz @1MV

  with compensation: 61Hz @4MV

- The modified algorithm introduces energy into many frequency components reducing it's effectiveness.

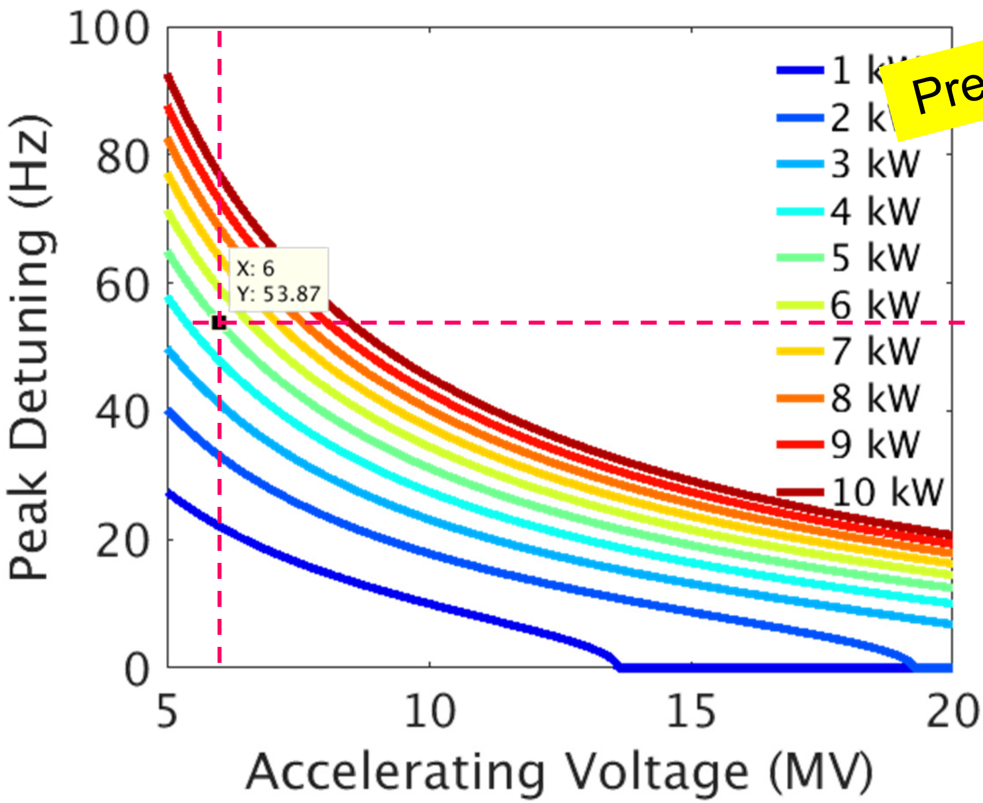




Plots by N. Banerjee

Peak Detuning vs. Cavity Voltage

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



	Peak detuning	**Achievable cavity voltage**
Stiffened cavity with 5kW SSA		
Cavity#2	18Hz	16MV
Cavity#6	*30Hz	10MV
Un-stiffened cavity with 10kW SSA		
Cavity#3	*61Hz	7MV
Cavity#5	163Hz	4MV

* Active compensation ON

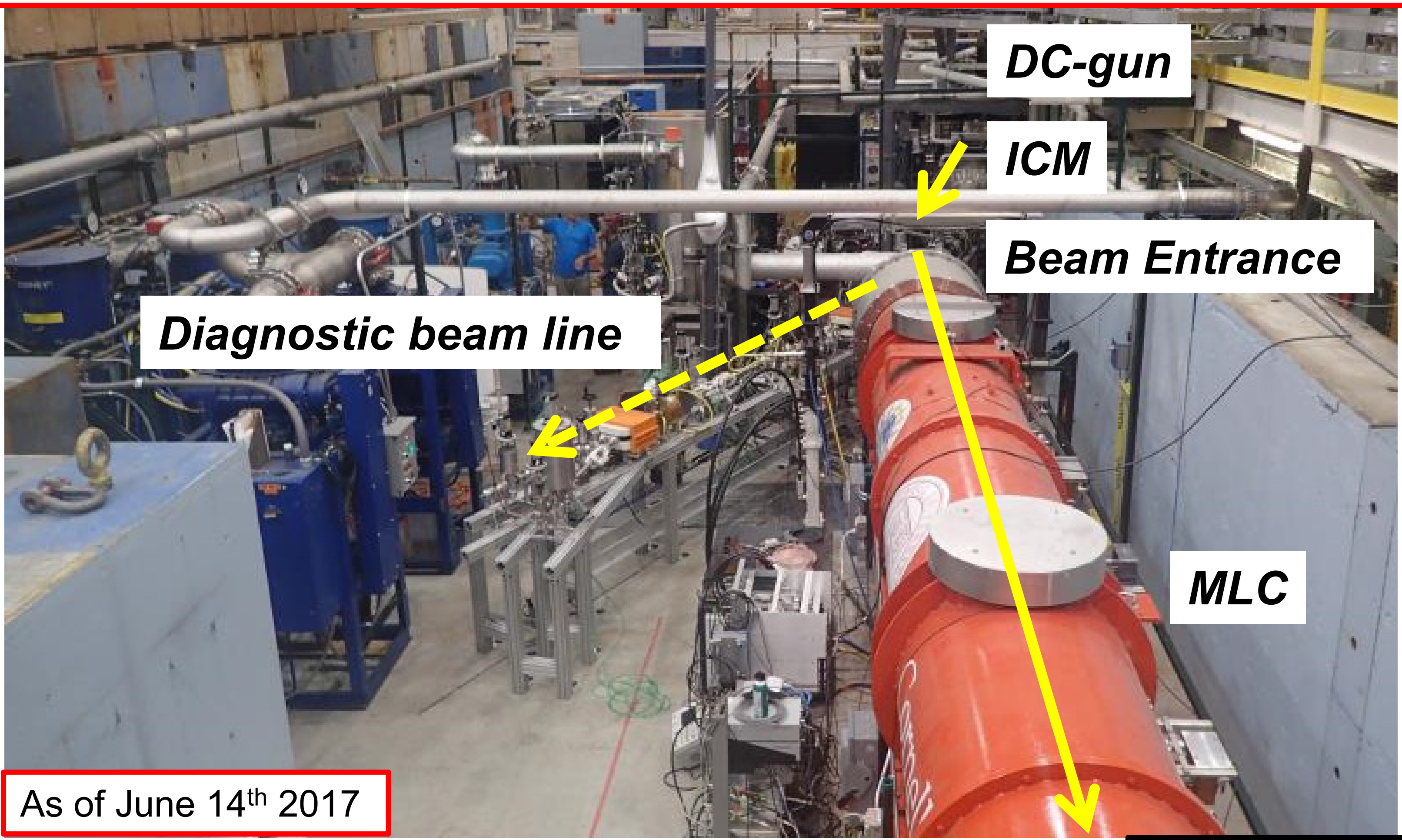
Plot by N. Banerjee

Microphonics compensation is necessary for;
- **Stable machine operation**
- **Enough overhead on RF power/energy gain**

Beam acceleration test

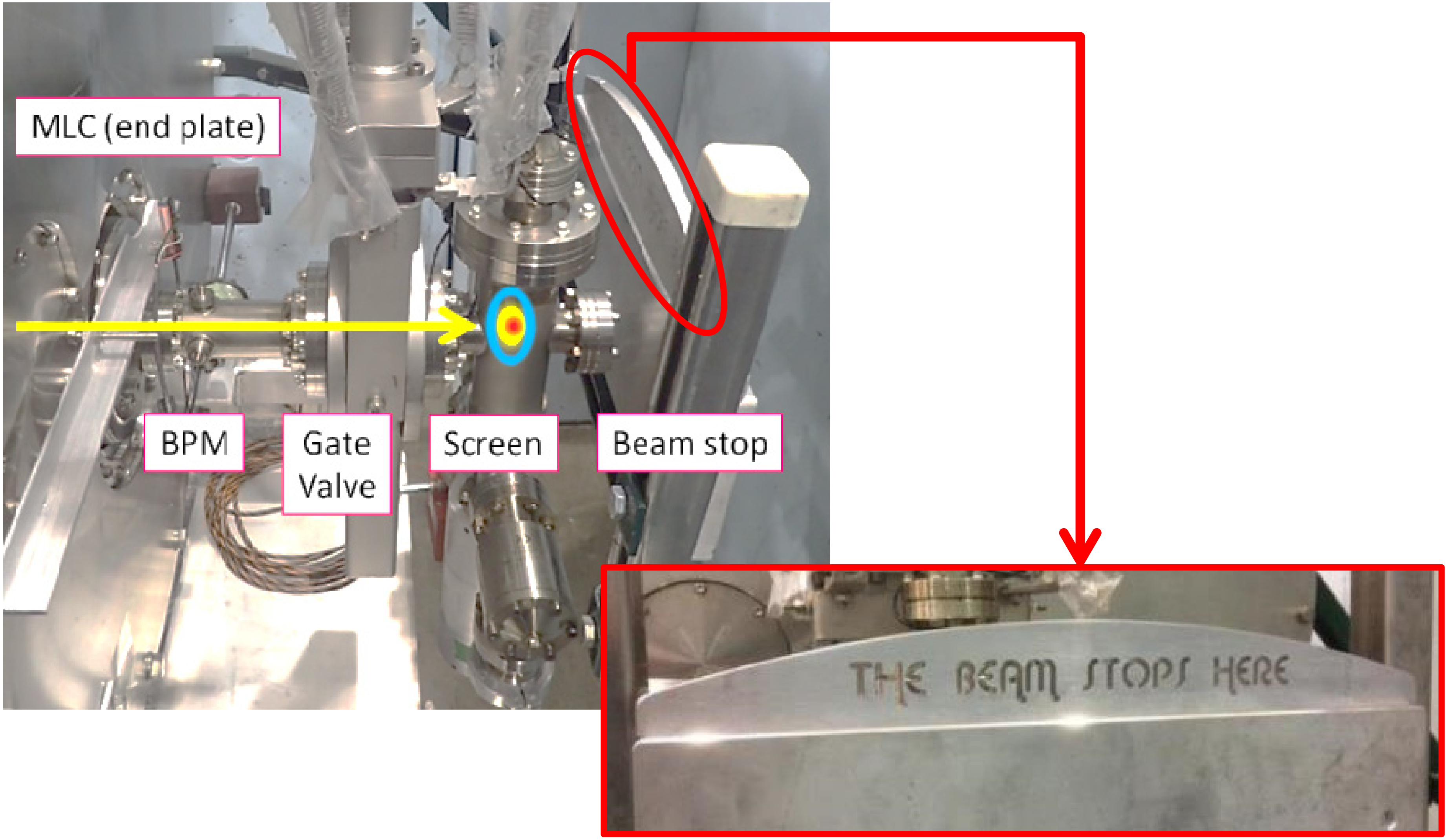
Accelerate Beam through the MLC

Cornell ERL high voltage DC gun and Injector Cryomodule (ICM) were connected to the MLC via the entry beam line; the beam stop assembly was also installed as the exit line.



As of June 14th 2017

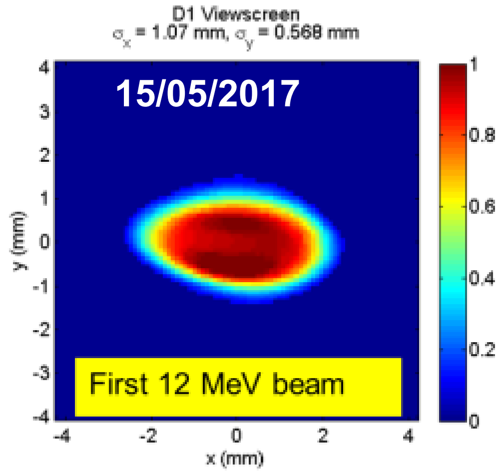
Beam stop assembly



12MeV beam through the MLC

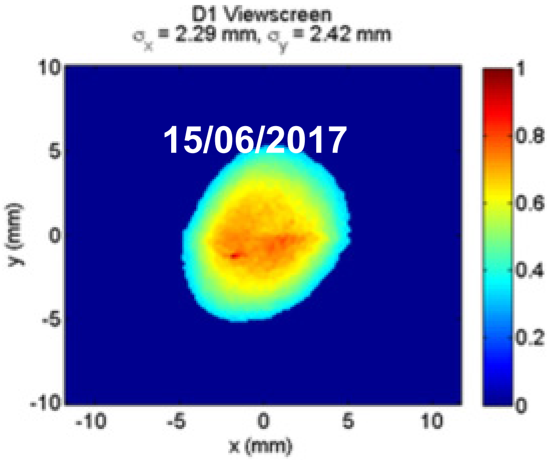
Beam acceleration with ICM + MLC Cavity#2

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

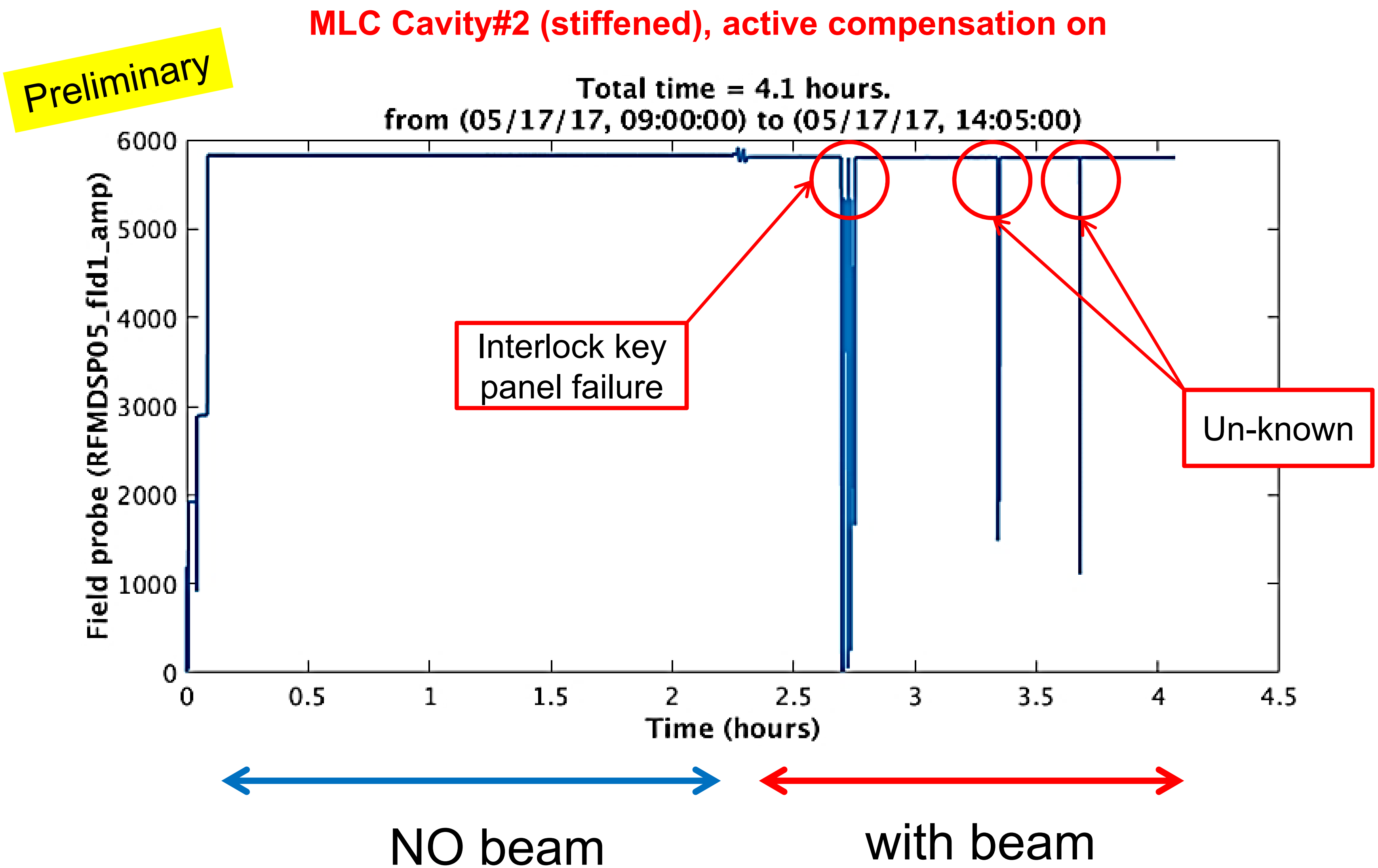


Beam acceleration with ICM + MLC Cavity#6

- Machine 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



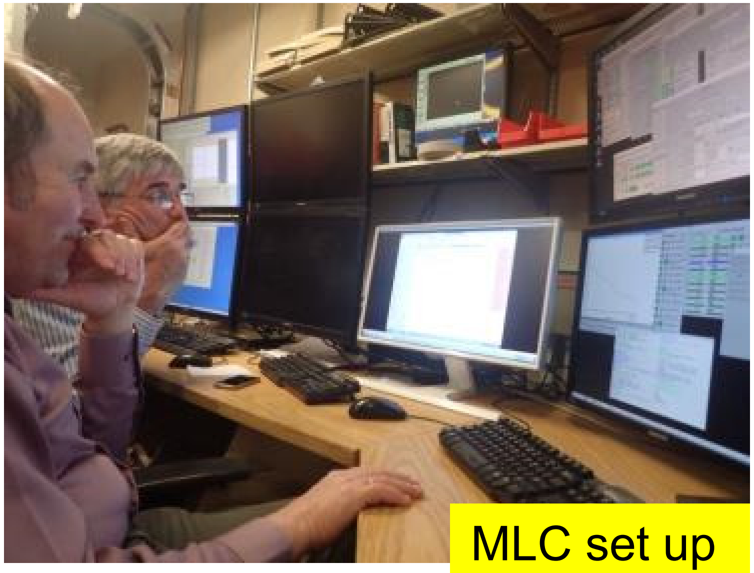
MLC plans

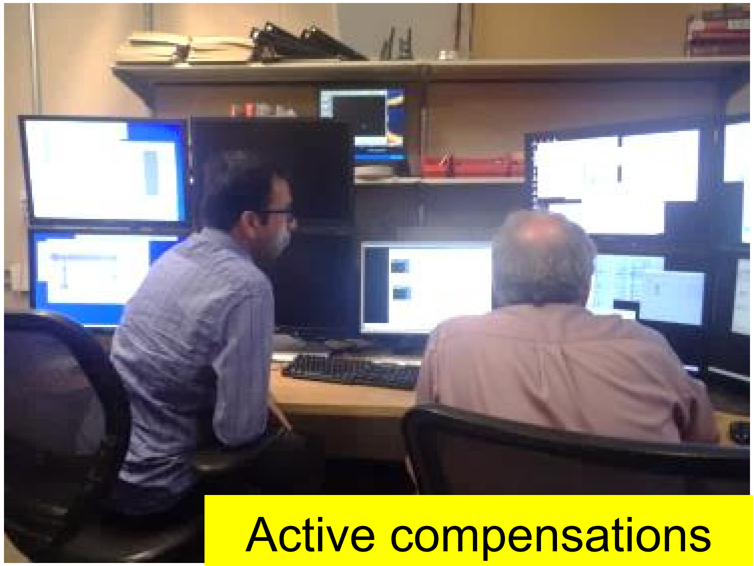
<table>
<tr><th>Year</th><th>Month</th><th>Items</th></tr>
<tr><td rowspan="7">2017</td><td>June</td><td>LLRF optimization
Microphonics study and compensation
Beam through MLC test</td></tr>
<tr><td>July</td><td rowspan="2">NO RF test due to water shutdown
Cryo. optimization
1ST SSA delivery will be the end of August</td></tr>
<tr><td>August</td></tr>
<tr><td>September</td><td rowspan="7">Microphonics study and compensation
SSA installation, initial commissioning with wave guide
All SSA will be delivered by the end of the year
Multi MLC cavity operation with SSAs
Revisit Q_0 vs. E_{acc}</td></tr>
<tr><td>October</td></tr>
<tr><td>November</td></tr>
<tr><td>December</td></tr>
<tr><td rowspan="4">2018</td><td>January</td></tr>
<tr><td>February</td></tr>
<tr><td>March</td></tr>
<tr><td>April</td><td>Fractional Arc Test (FAT)</td></tr>
</table>

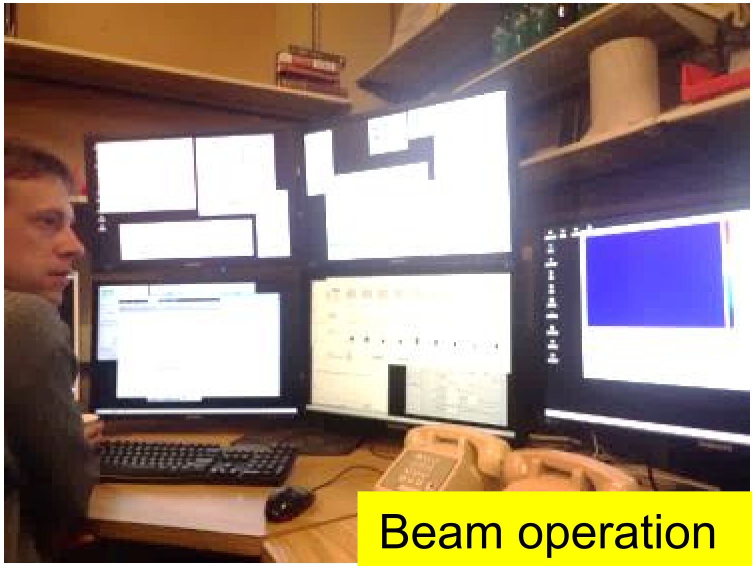
Summary

- The MLC, which is the first high current, high Q_0 linac module ever, has been comissioned sucessfully.
- The 7-cell cavities in the MLC can provide an energy gain of up to 76MeV per ERL turn.
- A new microphonics compensation algorithm has been implemented and is stable and more effective than a traditional feedforward algorithm.
- A beam with a total energy gain of 12MeV was transported through the MLC, including active detuning compensation using the piezoelectric tuner, reaching the defined goal for the initial CBETA beam test.
- The next milestone for the MLC is to confirm that it can reach the 1st pass total energy gain of 36MeV.

Thanks to the ERL team


MLC set up


Active compensations


Beam operation

Special thanks to
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Thank you for your attention!