Cornell ERL CM Performance

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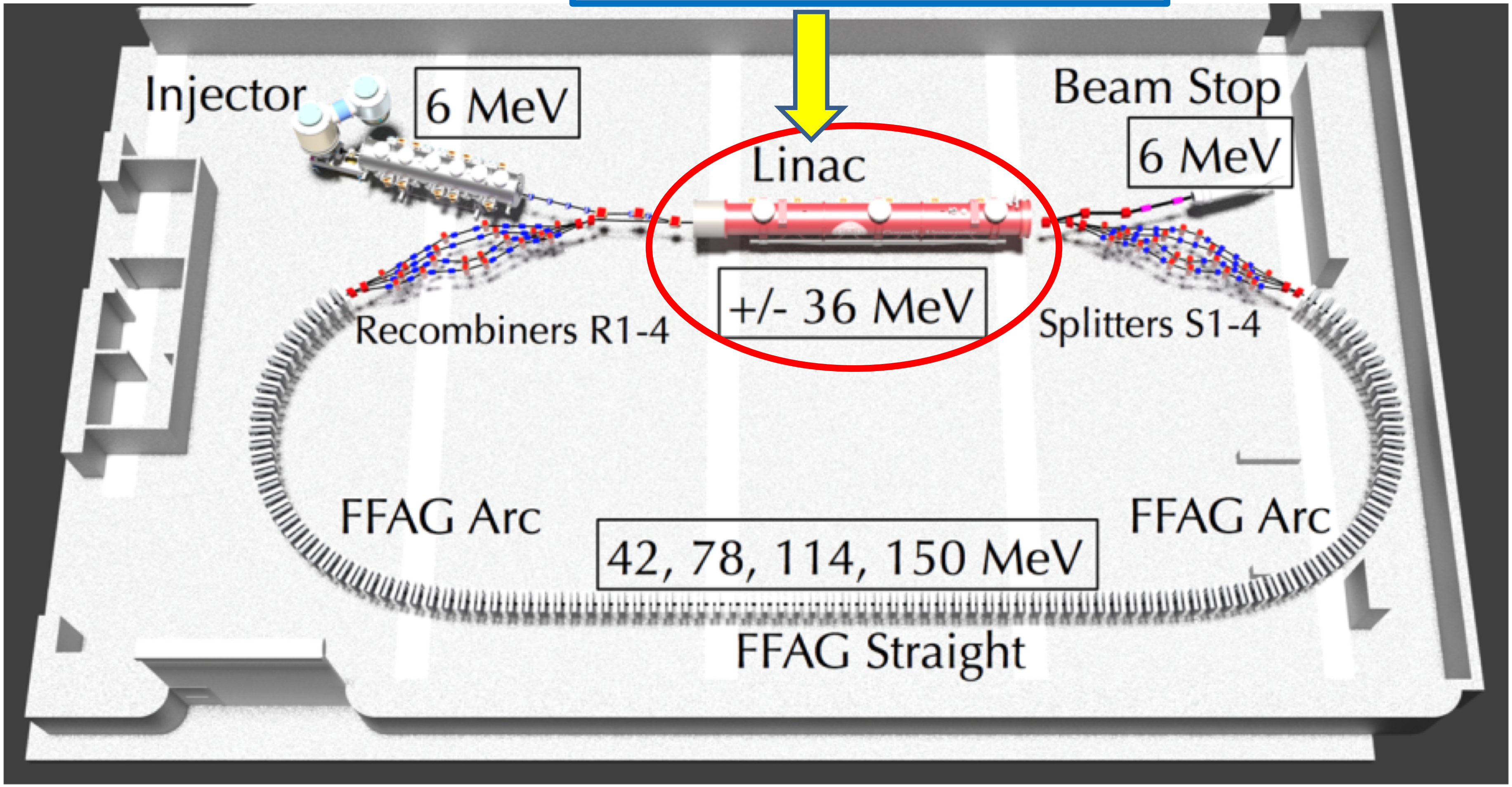
Outline

- Introduction
- Initial commissioning
- Beam through test
- Summary

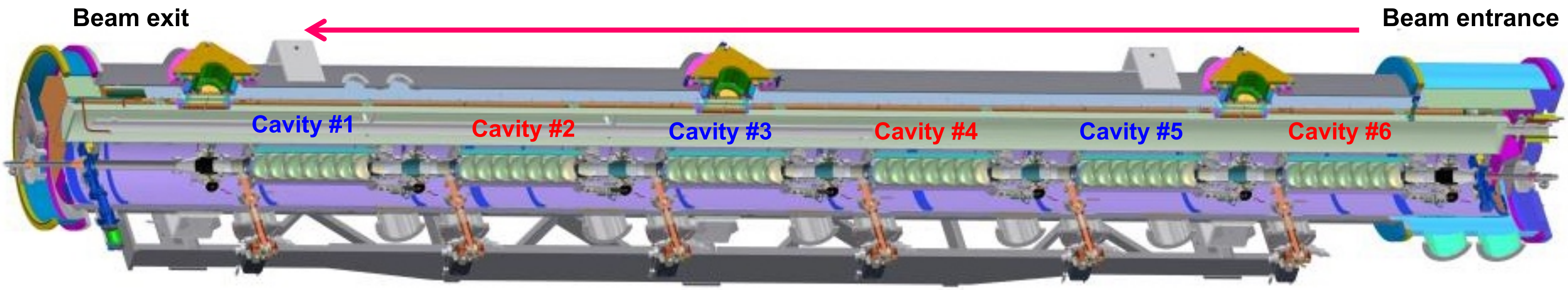
Introduction

CBETA
CORNELL-BNL ERL TEST ACCELERATOR

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

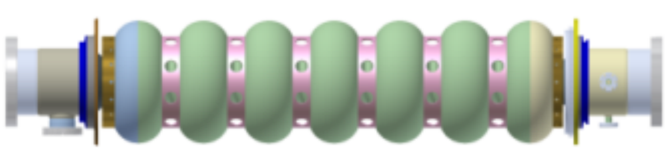


MLC design

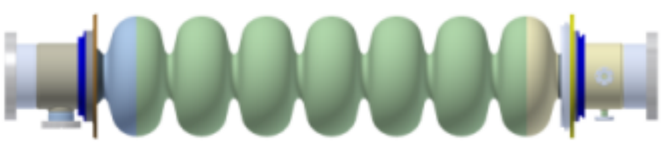


- Number of 7-cell cavities 6
- Acceleration gradient 16.2 MV/m
- R/Q 774 Ohm
- Qext 6.5×10^7
- Total 2K / 5K / 80K loads: 76W / 70W / 1500W
- Number of HOM loads 7
- HOM power per cavity 200 W
- Couplers per cavity 1
- RF powere per cavity 10 kW max.
- Amplitude/phase stability 10^{-4} / 0.05˚ (rms)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

Stiffened Cavity

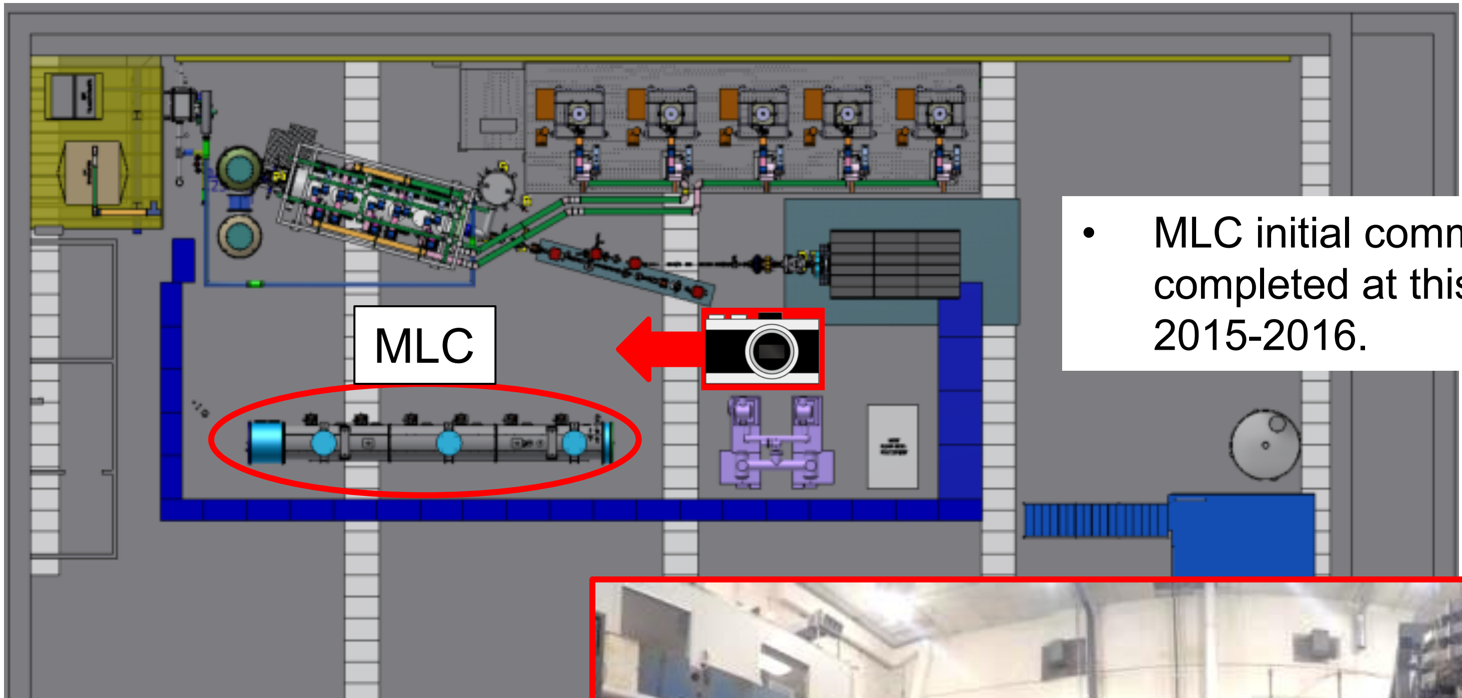


Un-stiffened Cavity



Cavity RF surface preparations:
bulk BCP, 650C outgassing, final BCP, 120C bake, HF rinse

MLC initial commissioning



- MLC initial commissioning was completed at this layout location in 2015-2016.

L0E layout 2016 summer
Wilson lab, Cornell

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!!

MLC initial commissioning

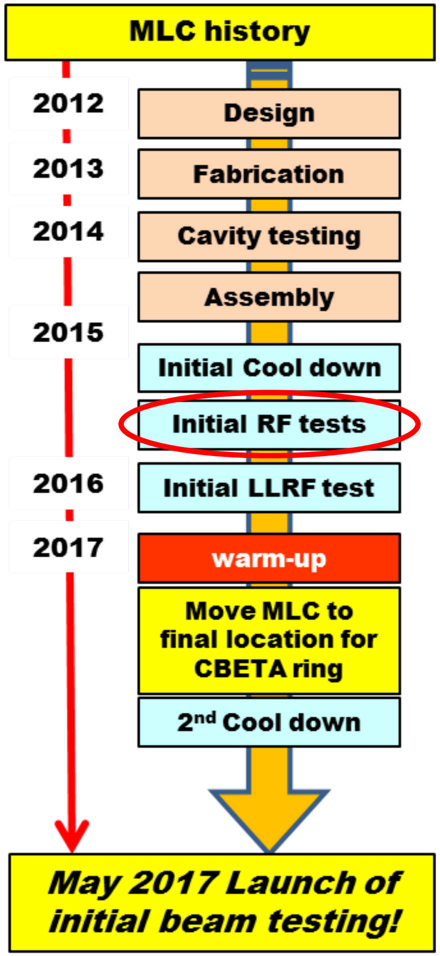
MLC history

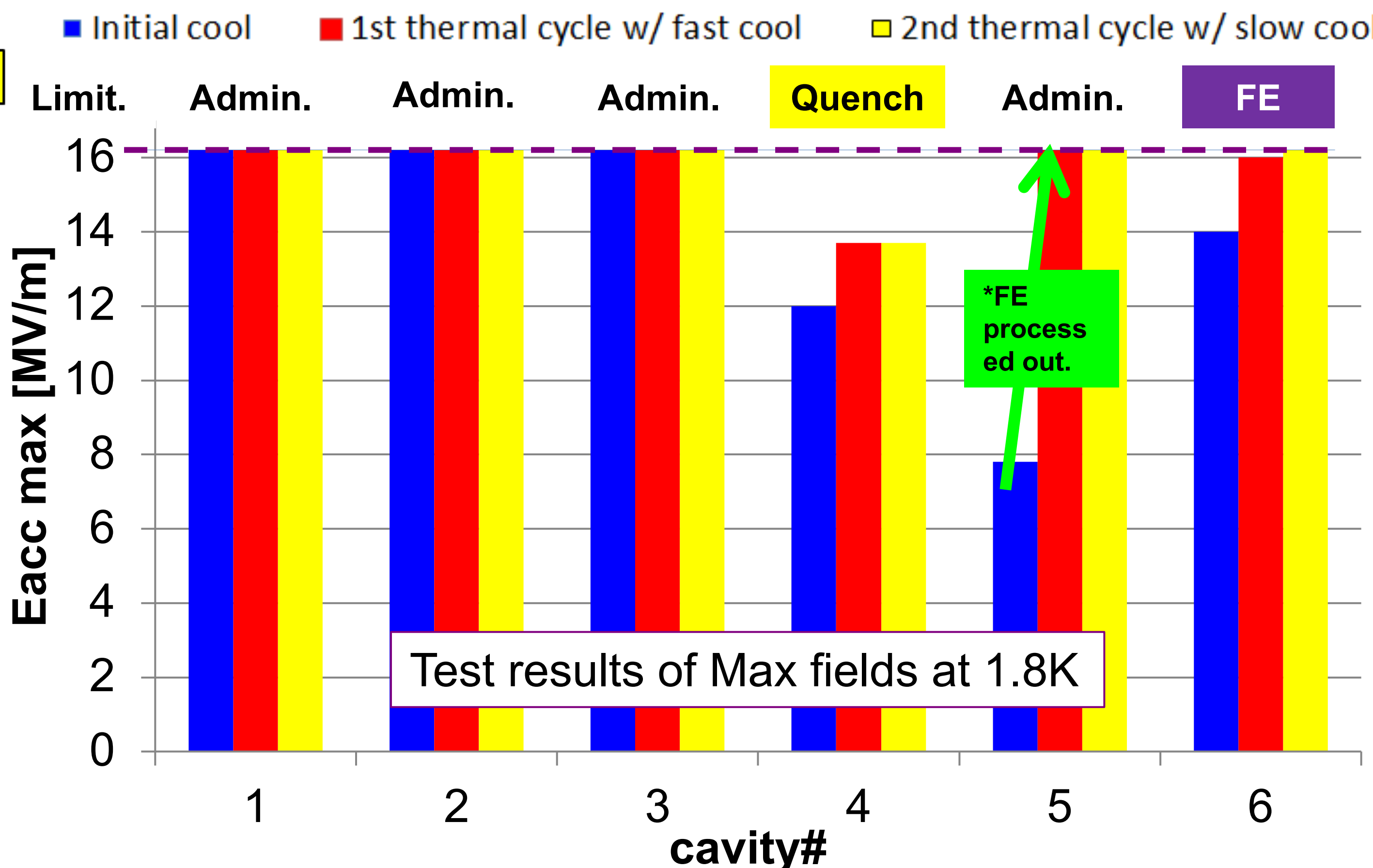
- 2012 — Design
- 2013 — Fabrication
- 2014 — Cavity testing
- Assembly
- 2015 — Initial Cool down
- Initial RF tests
- 2016 — Initial LLRF test
- 2017 — warm-up
- Move MLC to final location for CBETA ring
- 2^{nd} Cool down

May 2017 Launch of initial beam testing!

What we learned/done during the initial commissioning?

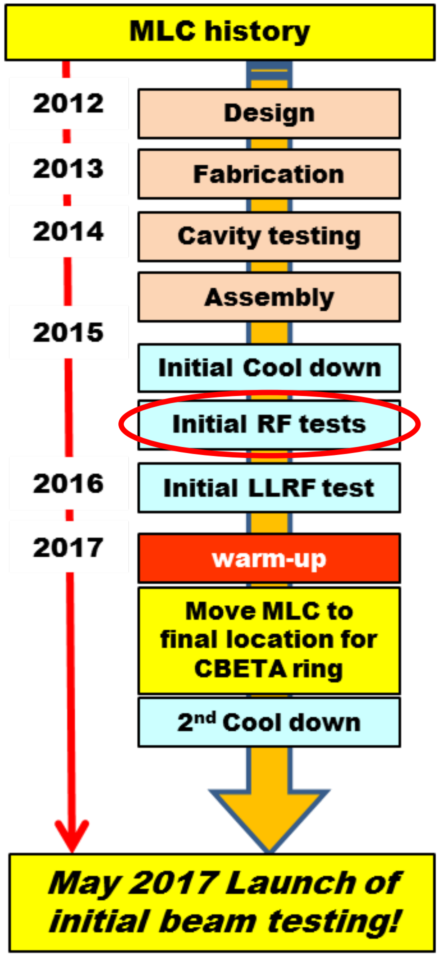
MLC initial RF test; cavity gradient

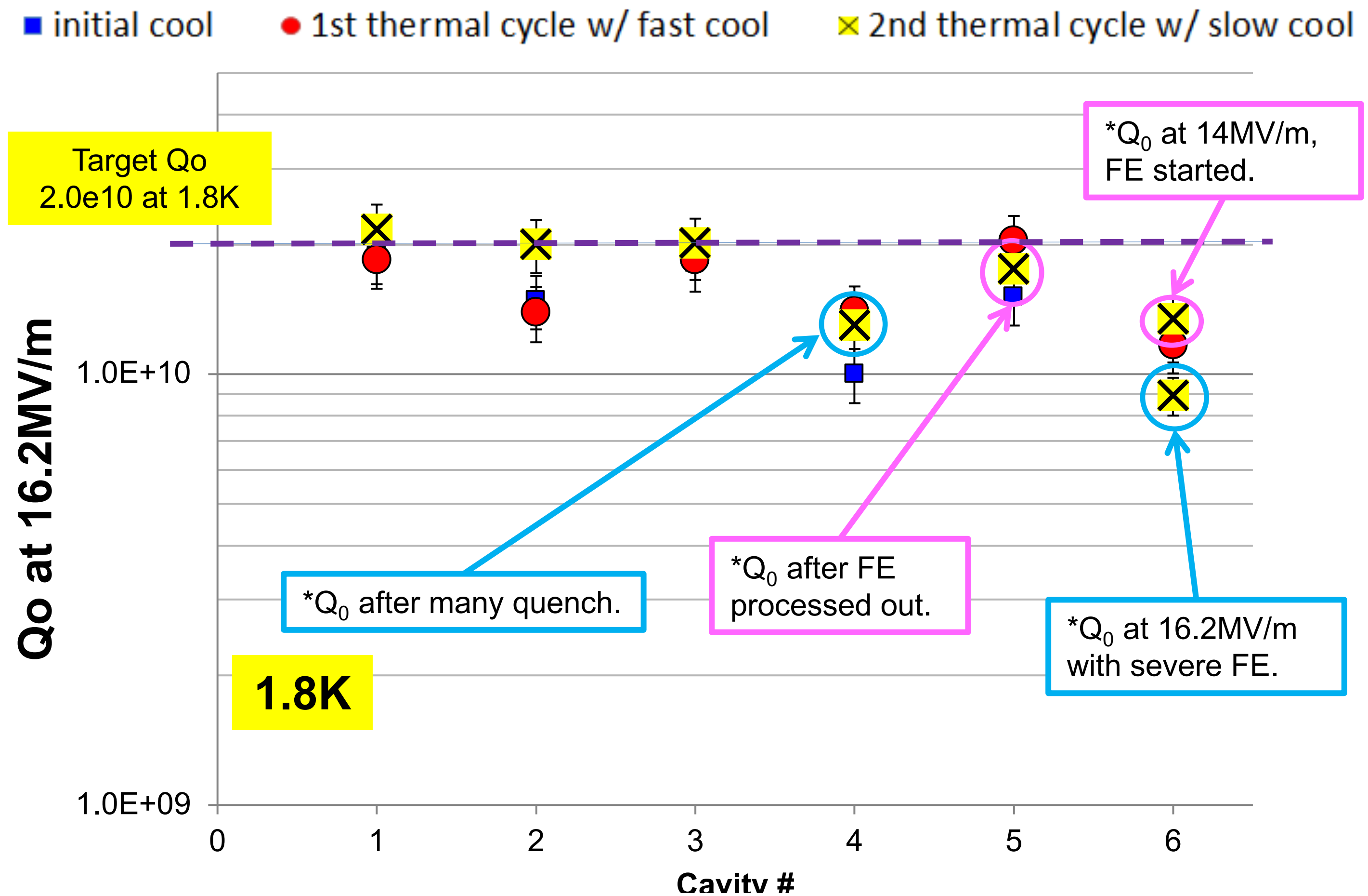




- 5 of 6 cavities had achieved MLC design gradient of 16.2MV/m at 1.8K.
- Cavity#4 is limited by quench so far, no detectable radiation during test.
- **The MLC can provide 76MeV per ERL turn, which significantly exceeds the CBETA requirement of 36MeV per ERL turn.**

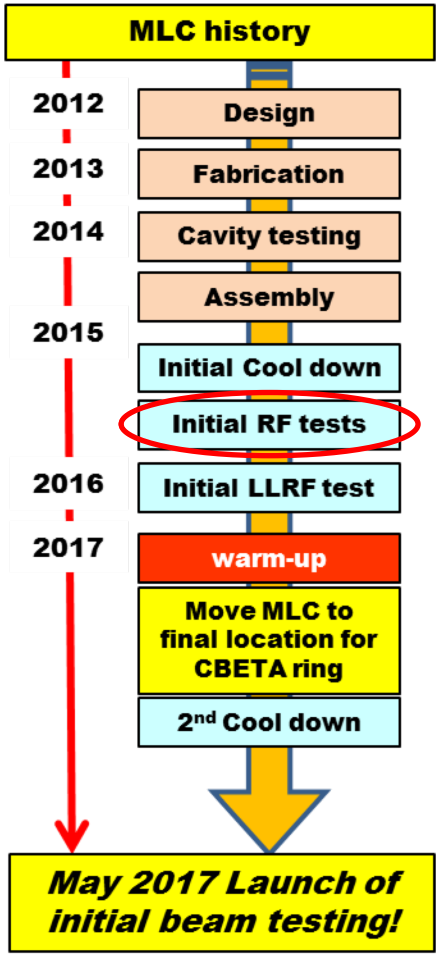
MLC initial RF test; Q_0 at 1.8K

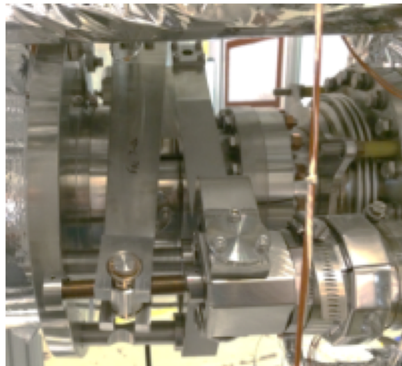




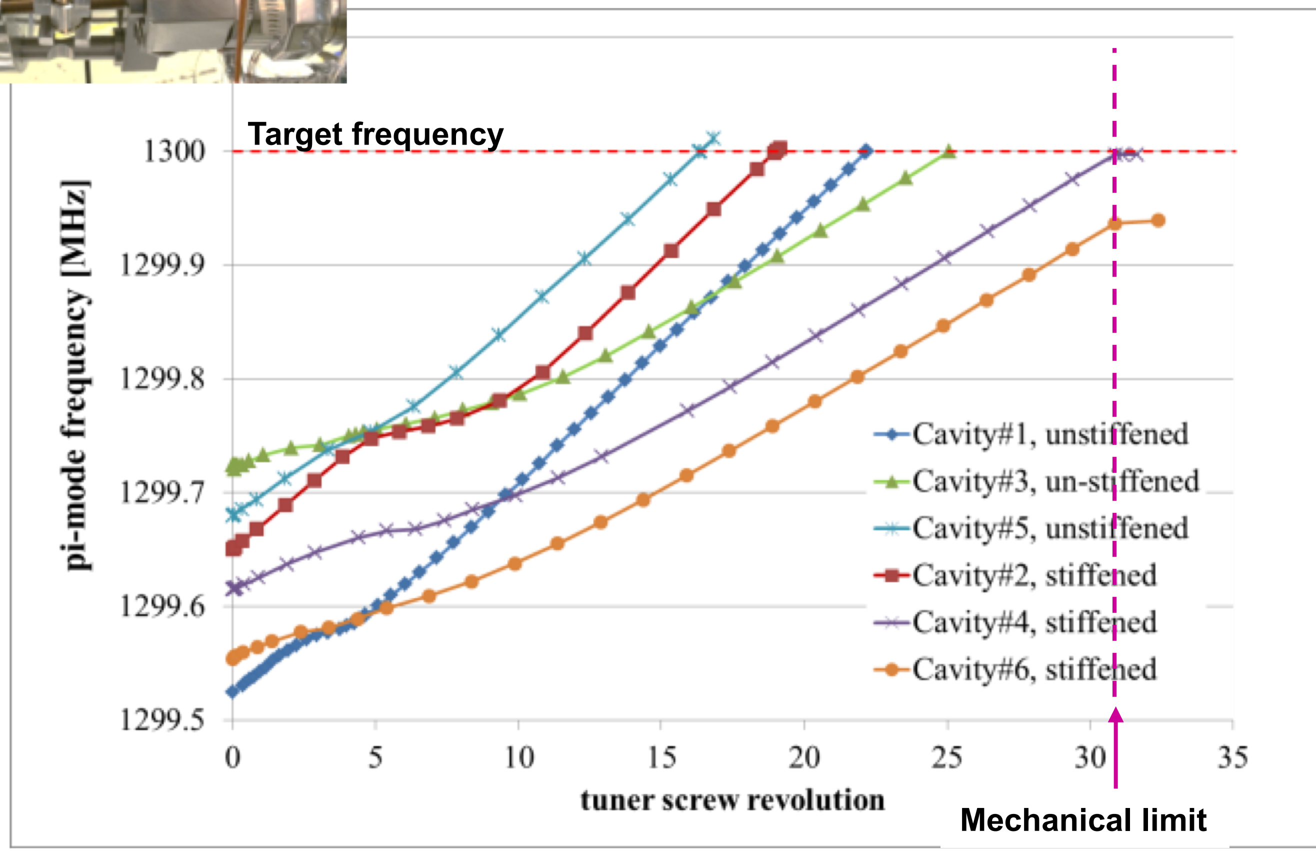
The benefits of slow cool down shows smaller spatial temperature gradient in horizontal direction ($dT_{horizontal}$) could suppress the thermal-currents in horizontal test which resulted in high Q_0 of cavities in the MLC.

MLC slow tuner test

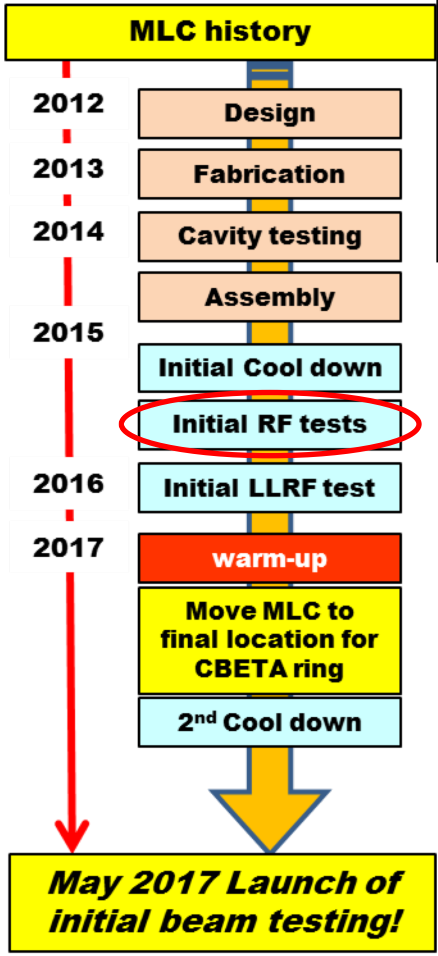


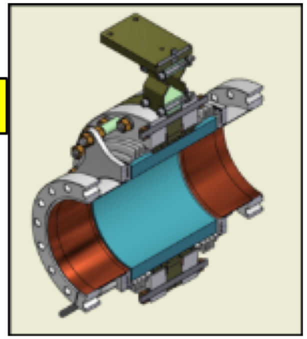


CBETA will have to run somewhat below 1.3GHz since some of the MLC cavities can not be tuned that far.

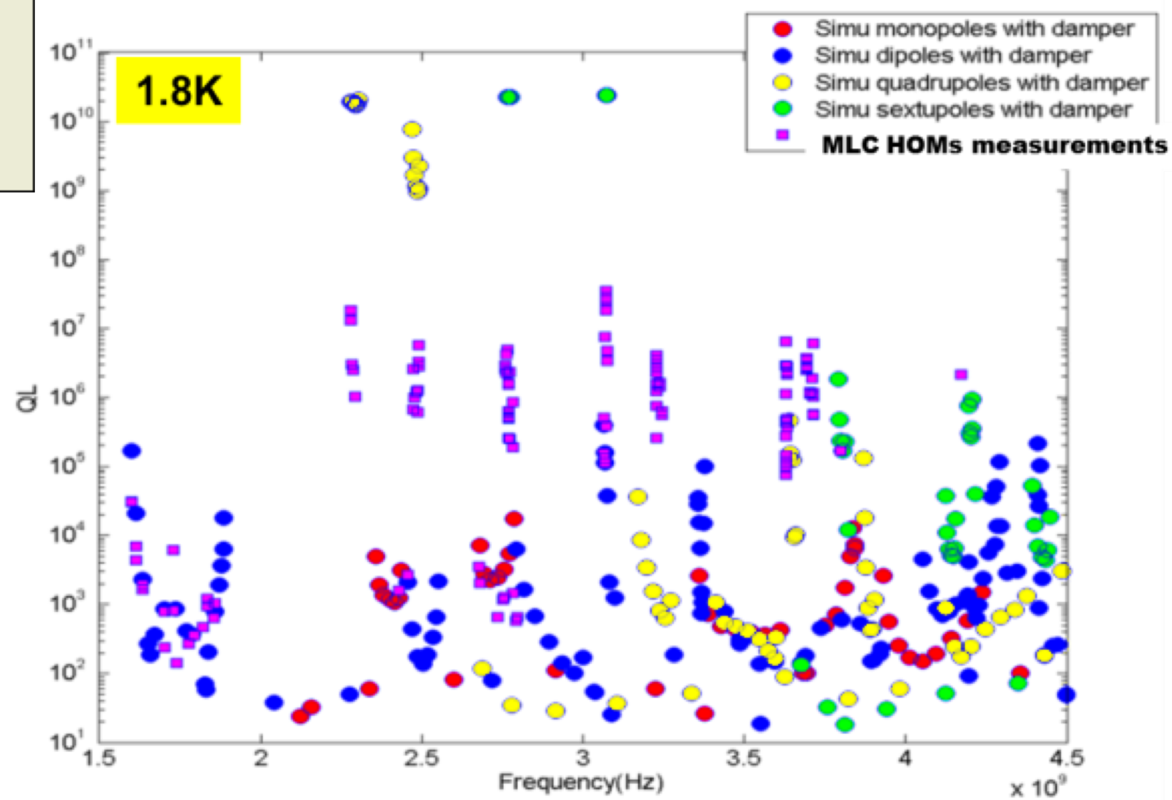


MLC HOM scan and analysis



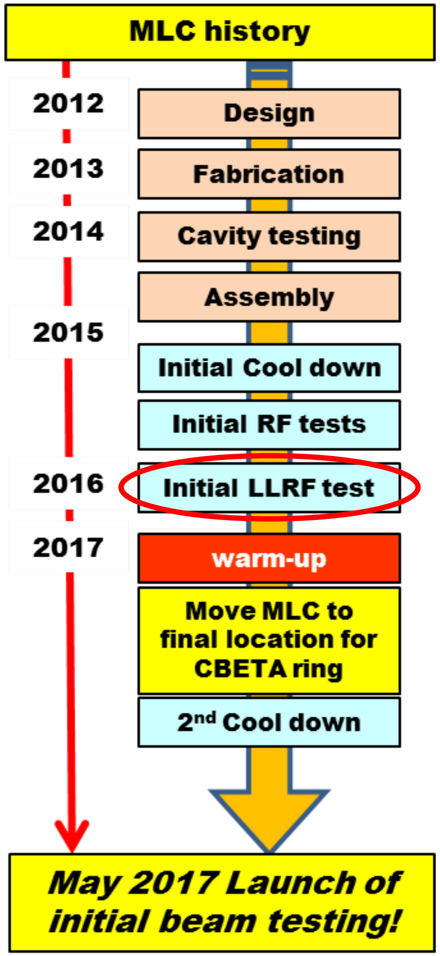


Dipole HOMs on MLC were strongly damped below Q~10^4.
Consistent with HTC and simulation results.

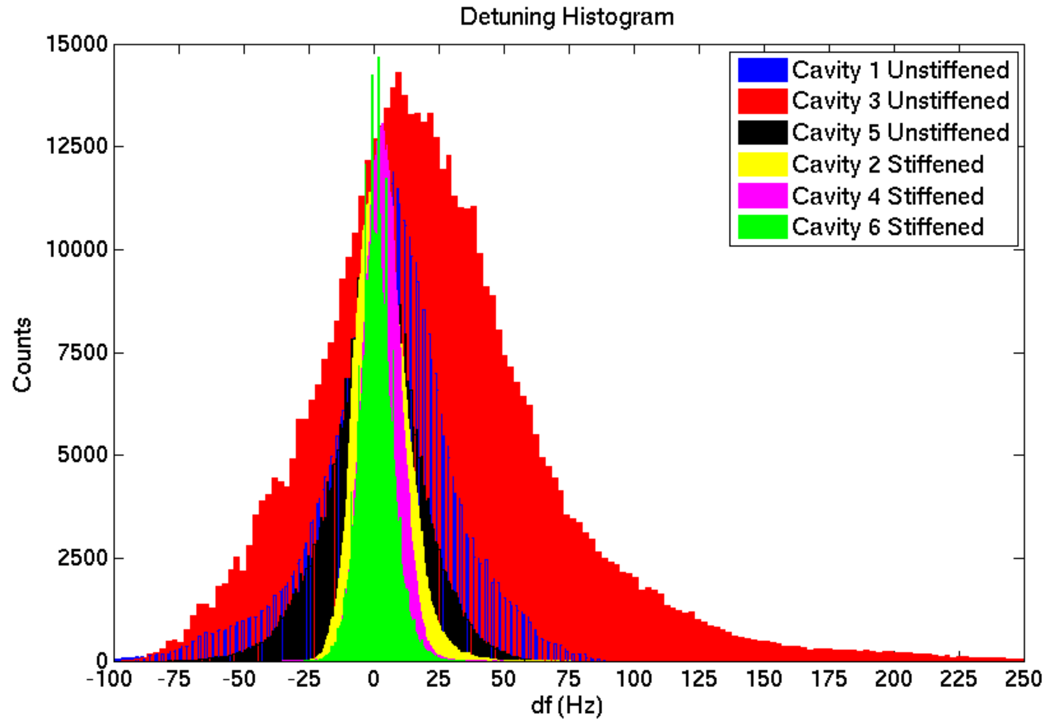


HTC results were:
HOM heating: currents are limited to < 40mA in CBETA
BBU no HOM limits BBU to below 100mA in one turn

Initial LLRF tests

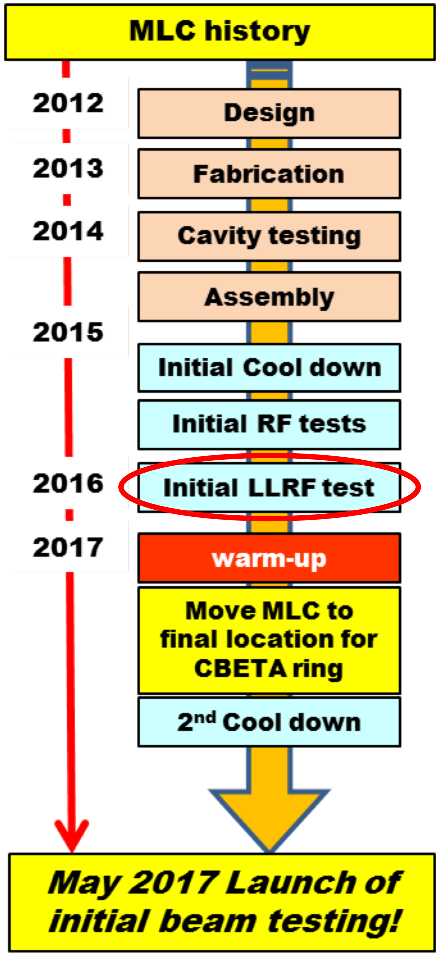


Detuning measurements in the initial MLC location



- 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.

Mechanical vibration sources



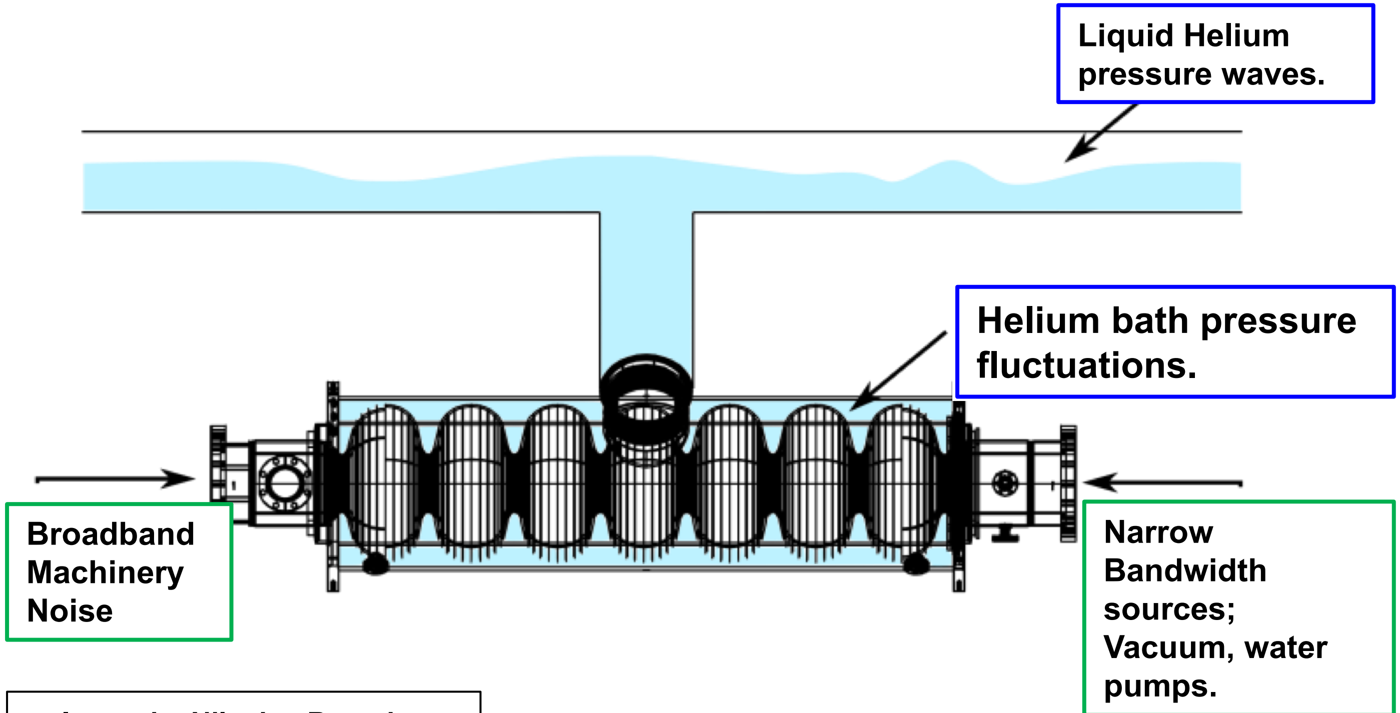
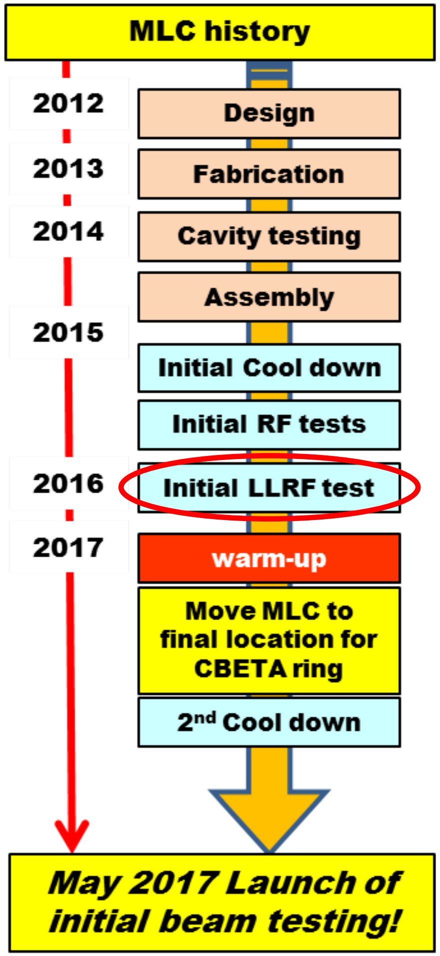


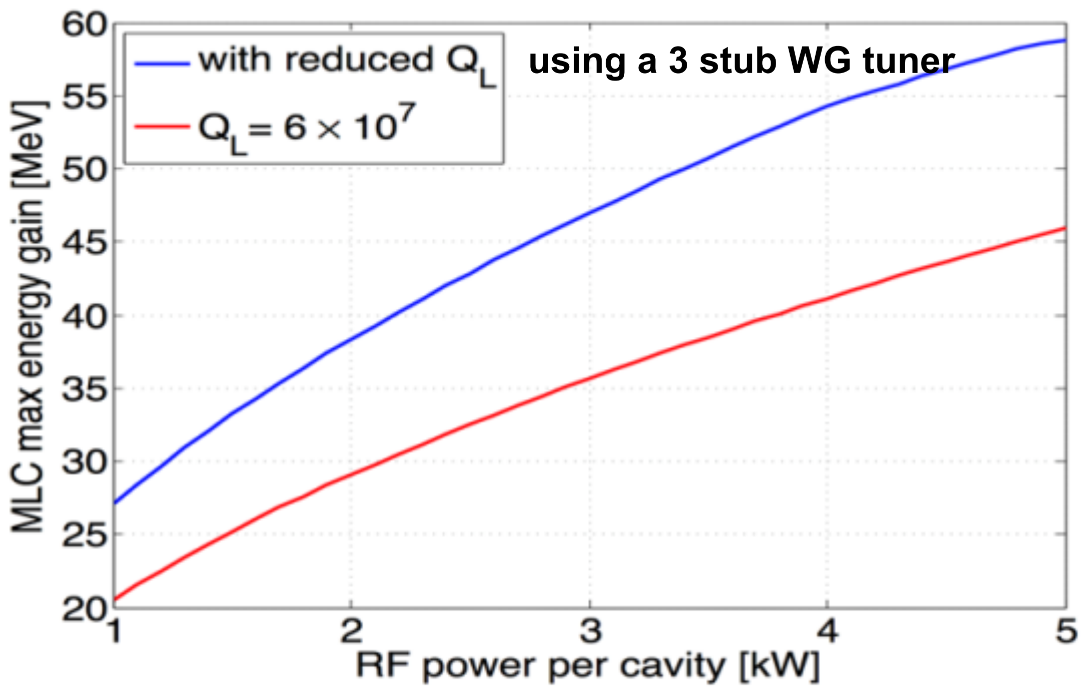
Image by Nilanjan Banerjee
(Graduate Student)

- 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.

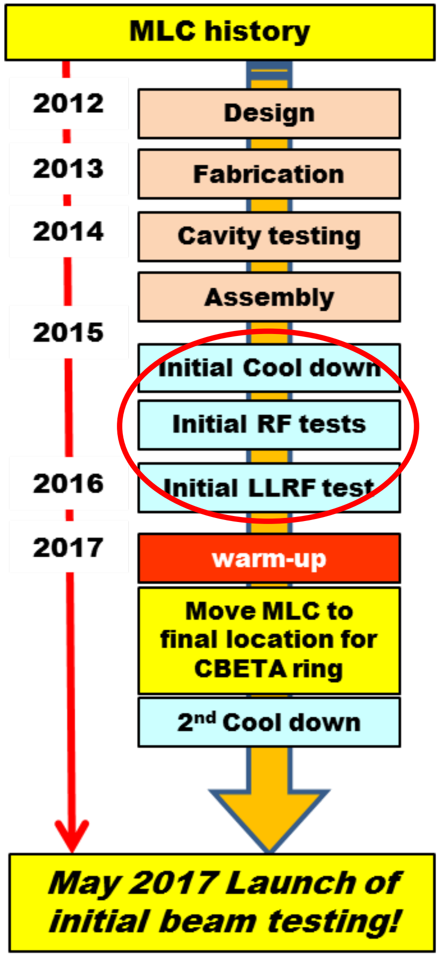


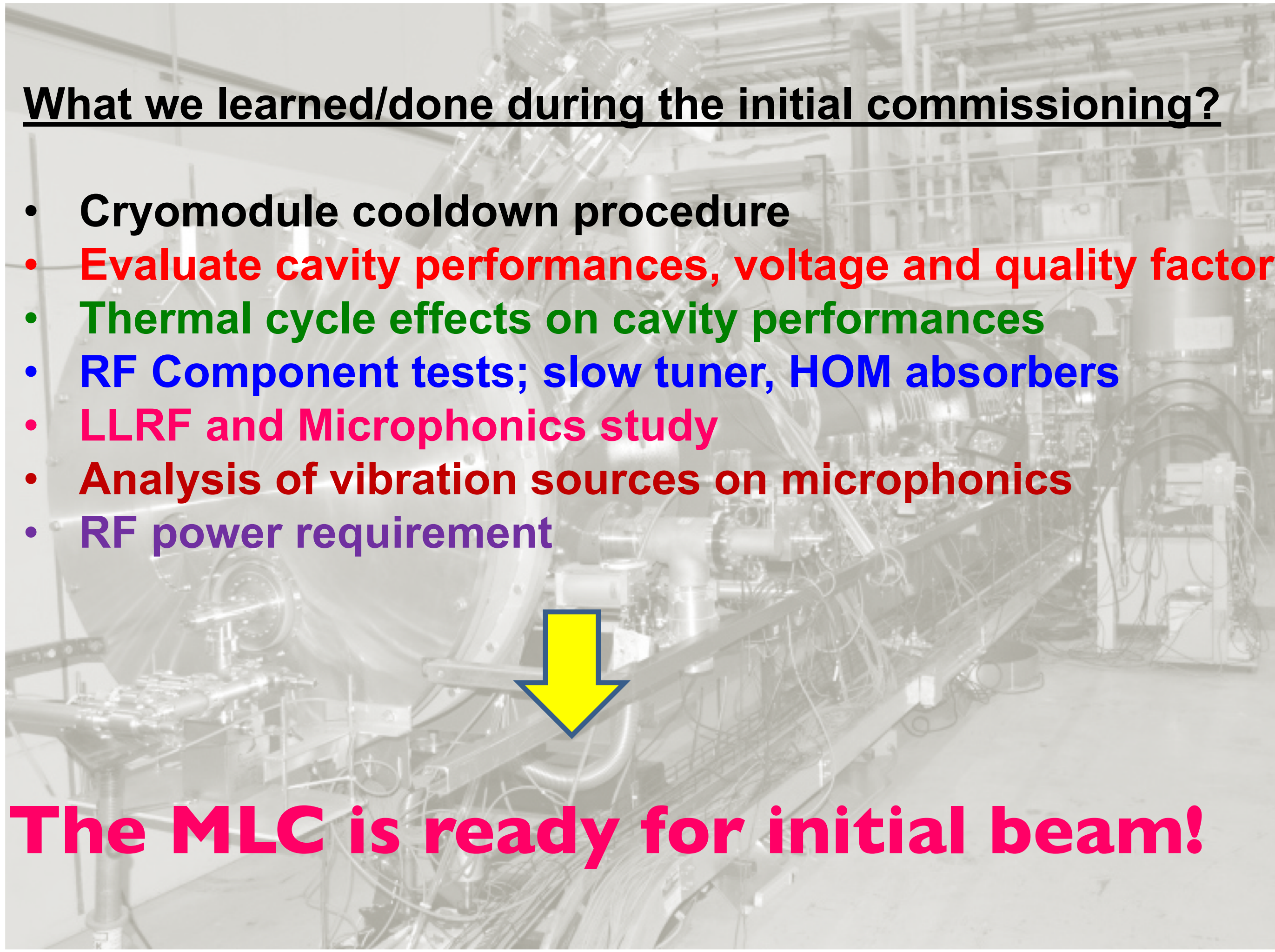
Based on these calculations and making allowance for the higher microphonics levels of the un-stiffened cavities,

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

were selected to be ordered.

MLC is,,,





<u>What we learned/done during the initial commissioning?</u>

- 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

L0E before/after

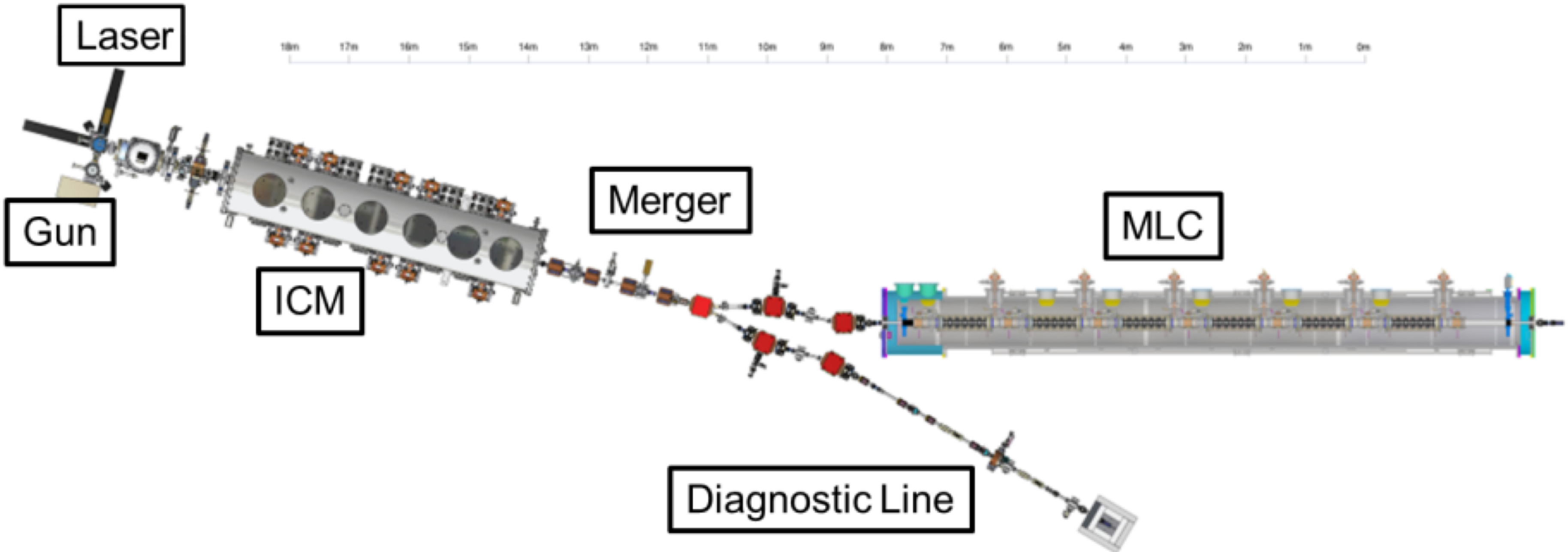
MLC at initial test location

As of Jan 20^{th} 2017

MLC was moved into its final location on Feb. 8^{th} 2017

As of Apr. 20^{th} 2017

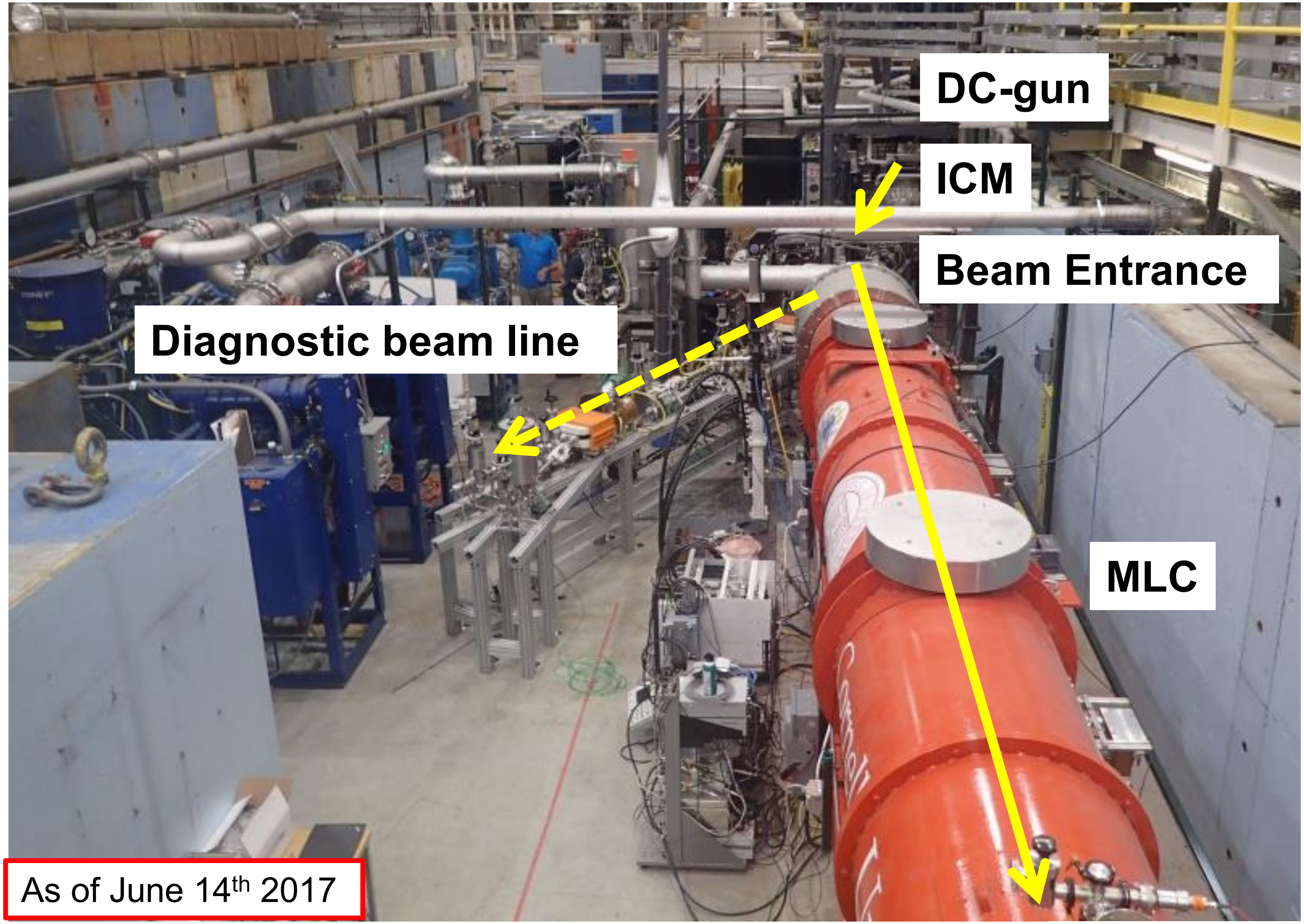
MLC beam through test



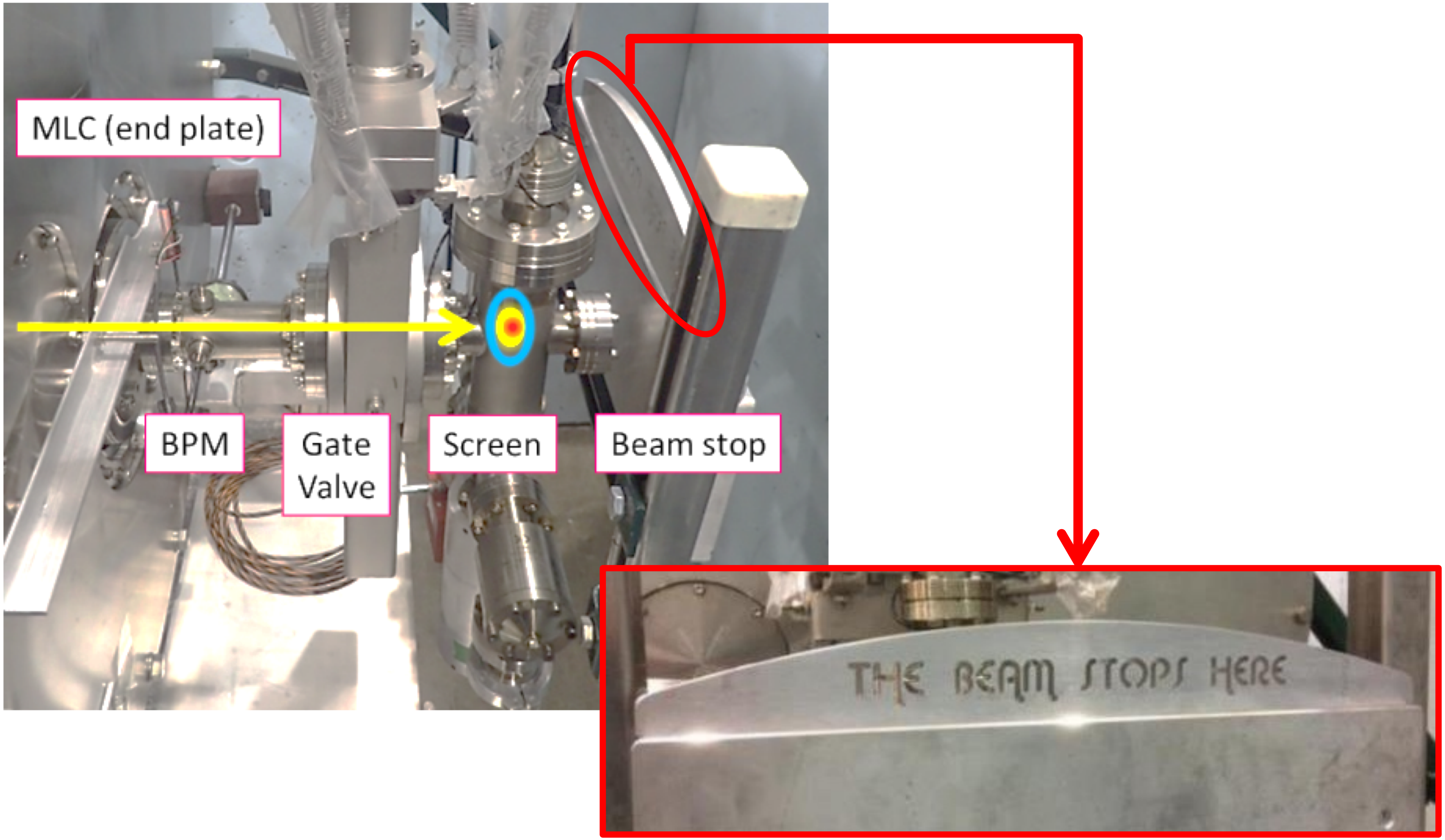
Initial beam test layout

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.

Accelerate beam through the MLC



Beam stop assembly

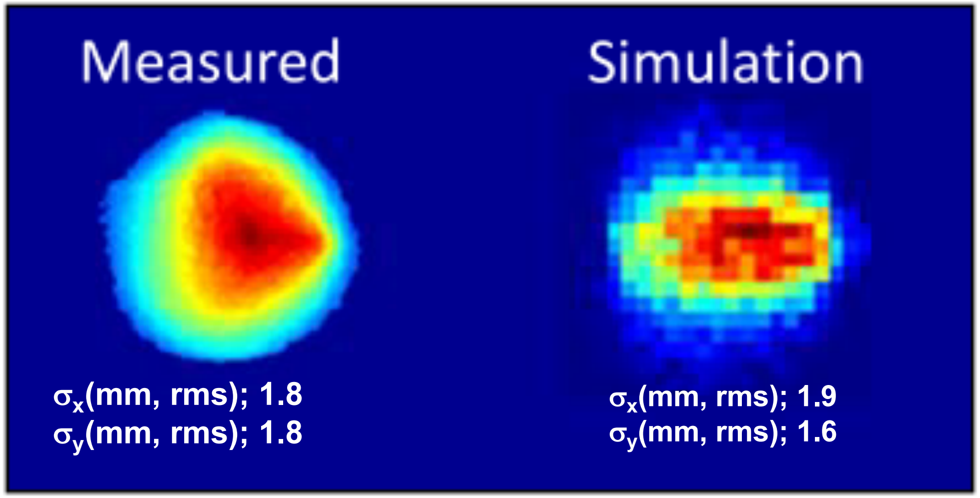


Beam through the MLC

First beam through the MLC on May 4th, 2017

Machine setting
- 300kV gun
- Frequency; 1.3GHz
- 6MeV from ICM
- 15nA (3pC x 50MHz x 0.01%)
- MLC RF turned Off

The primary result…



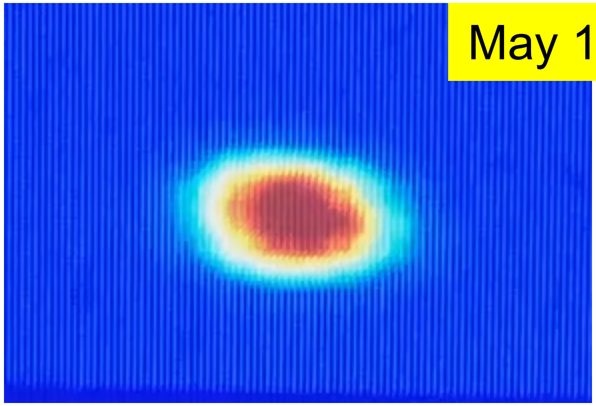
" ,, After opening gate valve, required about 30 seconds to steer through the MLC,, "

Beam operation, images, by Adam Bartnik

Acceleration test; MLC cavity#5

9MeV beam through the MLC, limited by microphonics

Machine setting
- 300kV gun
- Frequecny; 1.3GHz
- 6MeV from ICM
- 3MeV from MLC cavity#5 (un-stiffened)



May 10th

Scrn shot image

- Cavity#5 was tested first, but limited by microphonics and LFD.
- Preliminary detuning measurement was done.
- Microphonics study, LLRF optimization have been continued.
- we will revisit cavity#5 later.

Acceleration test; MLC cavity#2

12MeV beam through the MLC on May 15th, 2017

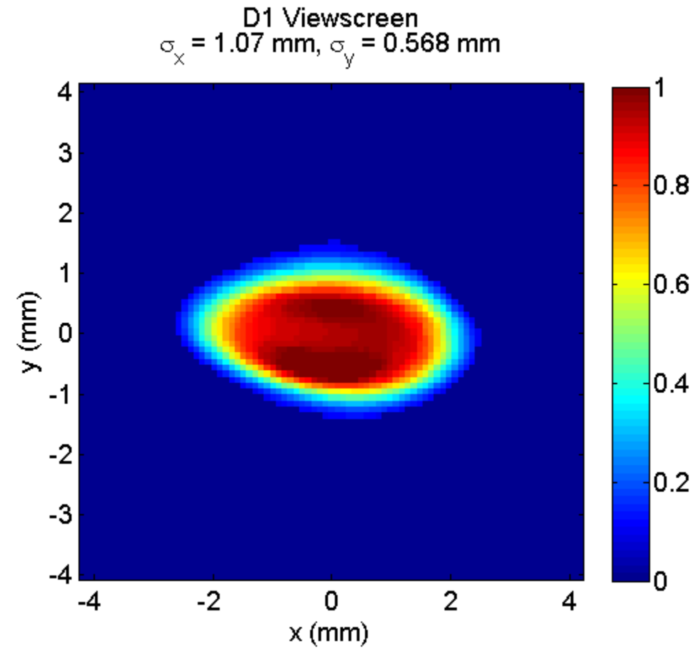
Machine setting

- 300kV gun
- Frequecny; 1.3GHz
- 6MeV from ICM
- 6MeV from MLC cavity#2 (stiffened)

Preliminary

- Field amplitude/phase stability measured
  Amplitude: 0.02%, rms
  Phase: 0.5 degrees, rms
  (note: did not try to optimize, just measure)

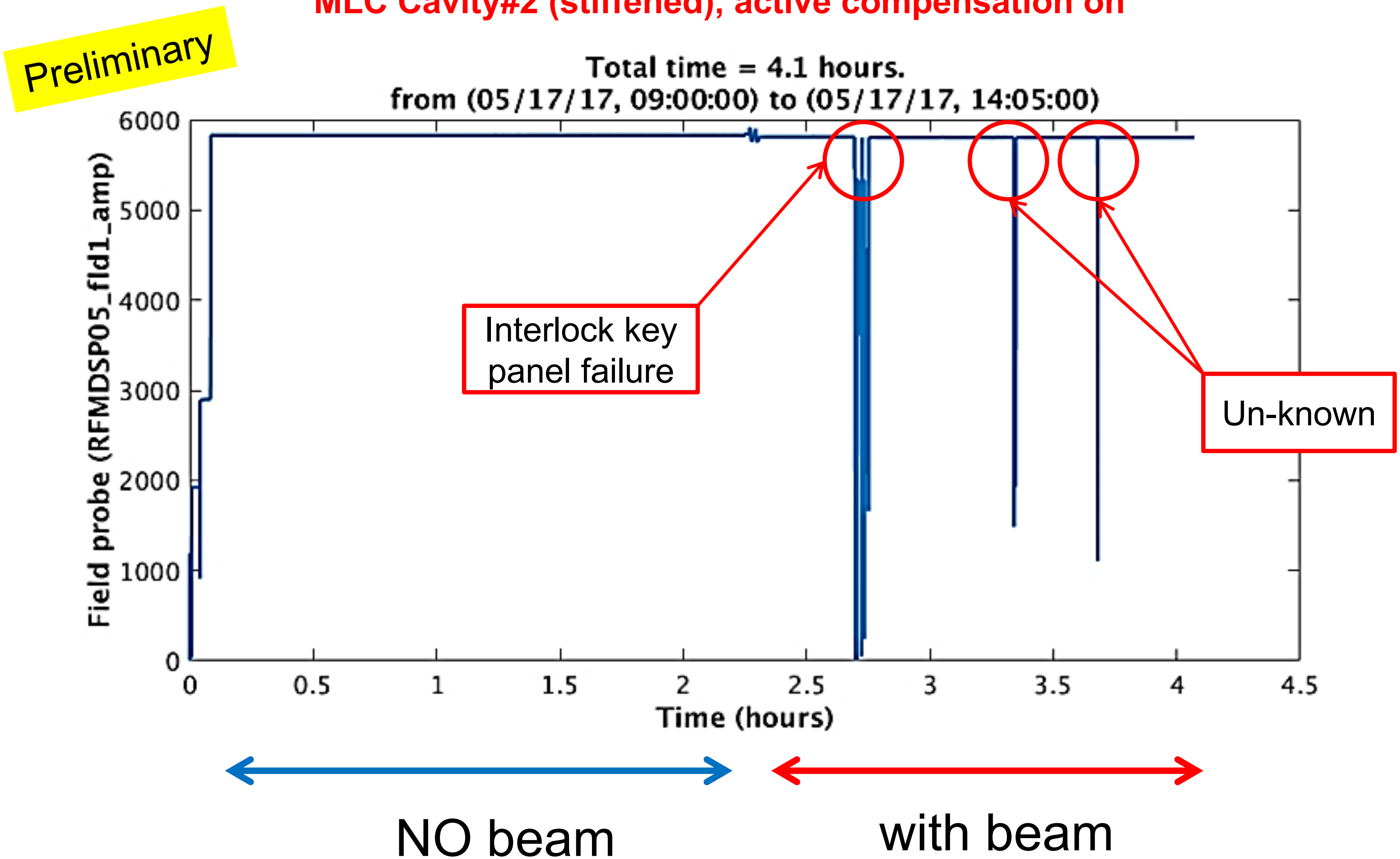
First 12 MeV beam



- LFD compensation has been implemented and tested.
- Preliminary detuning measurement was done.

Long term stability

MLC Cavity#2 (stiffened), active compensation on



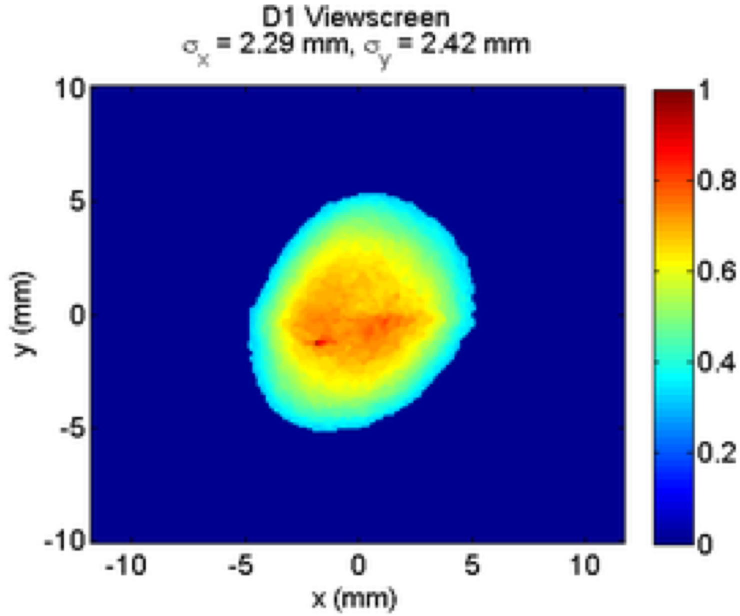
Acceleration test; MLC cavity#6

12MeV beam through the MLC on June 15th, 2017

Machine setting

- 300kV gun
- Frequency; 1.299925GHz, due to the tuning range of MLC cavity #6
- Run ICM with ICM cavity#2 turned off, due to the incompatible tuning ranges of ICM cavity #2 and MLC cavity #6.

- 6MeV from ICM (cavity#1, #3, #4, and #5)
- 6MeV from MLC cavity#6 (stiffened)
- LFD compensation has been implemented and tested.
- Preliminary detuning measurement was done.



An ELOG entry of MLC cavity#6

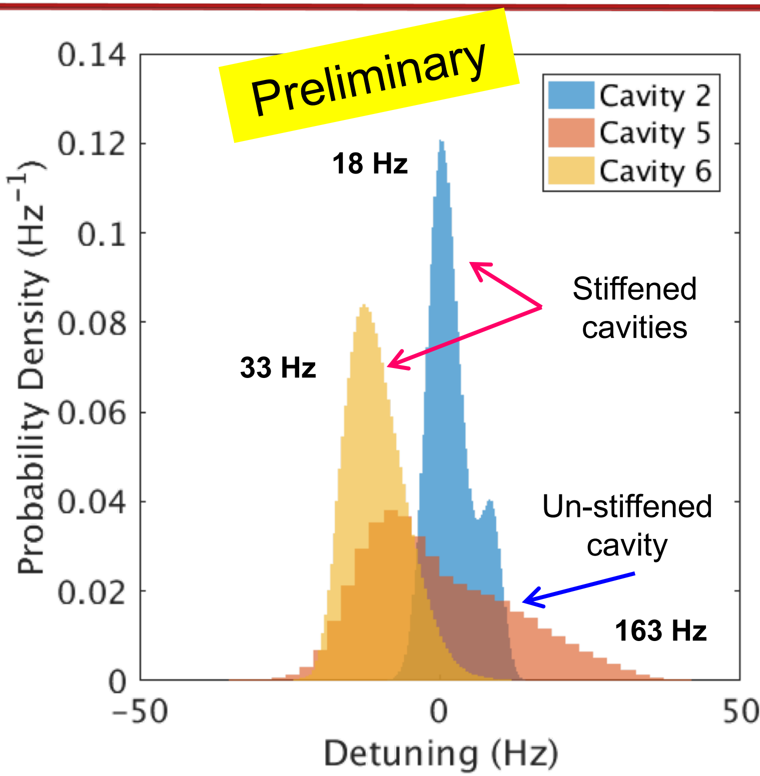
This is the final planned 12 MeV beam test involving the MLC for this operation period.

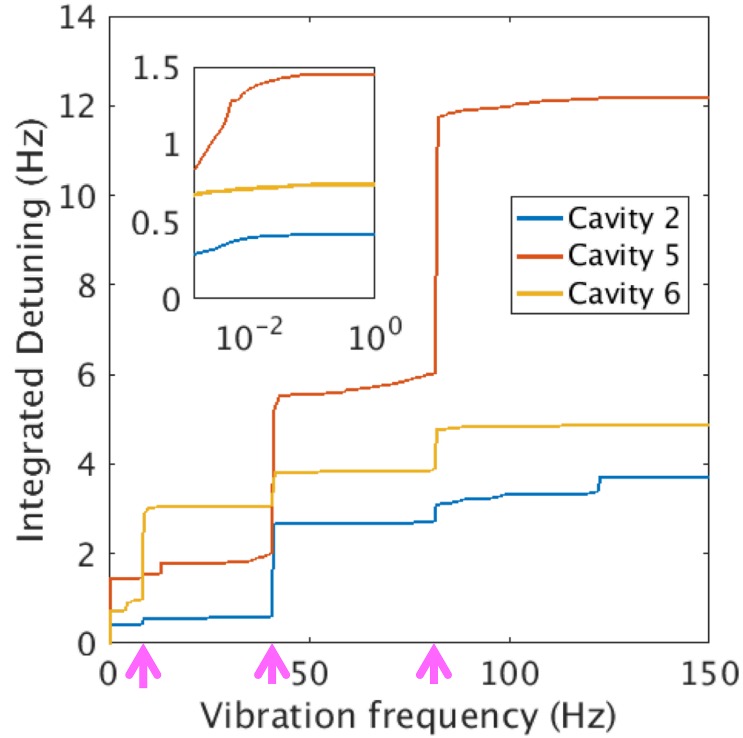
This test establishes that all the various accelerator components can operate at the lower master clock frequency ,,,,

After this, any further tests of the MLC will be performed without beam. we will switch to 6 MeV beam operation in the newly constructed diagnostic line, or operation through the MLC without any MLC acceleration.

By Adam Bartnik, ELOG entry on 2017-06-15

Microphonics detuning meas.





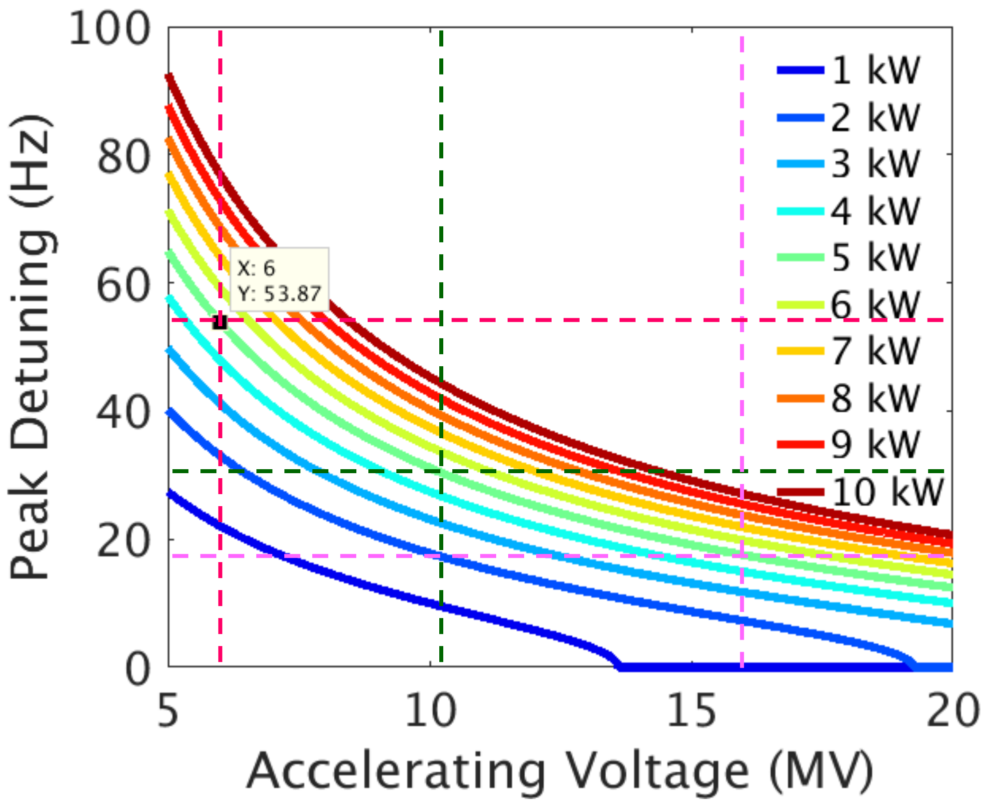
Plots by N. Banerjee (Graduate student)

- **Cavity #5 (un-stiffened); Events correspond to cycling of the Pre-cool valve. Cryogenic valves will be static for beam running and helium liquid level will be regulated with a 2K 2-Phase heater. 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.**

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Detuning vs. Cavity Voltage



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

th measured peak detuning,

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) without compensation.

Cavity #5(un-stiffened): 163 Hz

- ➢ The plot predicts 10kW SSA could provide up to 4MV without compensation.

Microphonics compensation is necessary for;

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

Plot by N. Banerjee (Graduate student)

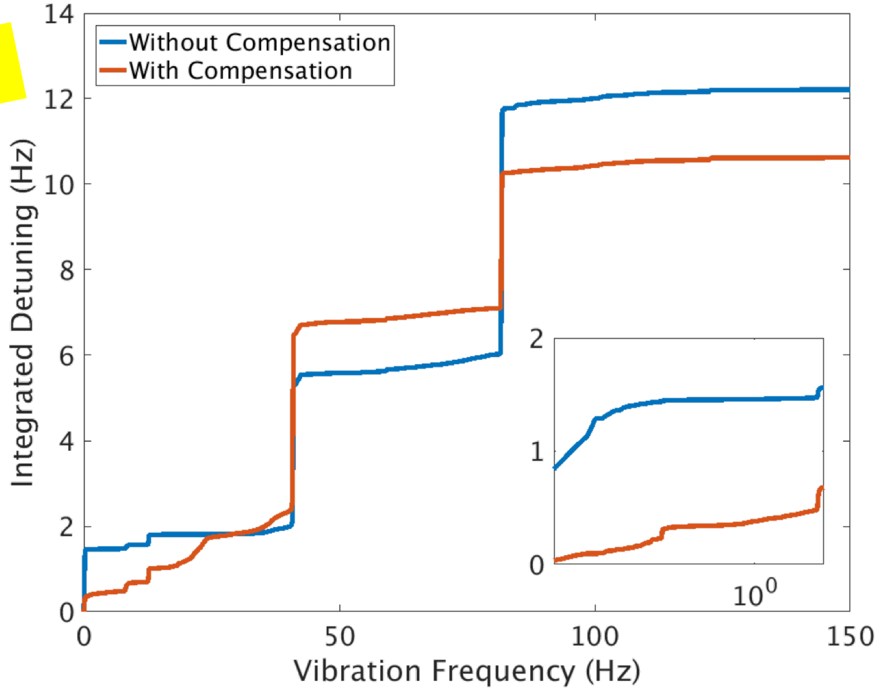
Microphonics compensation

Low frequency compensation:

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

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

Preliminary



Data for cavity #5 (un-stiffened)

Plots by N. Banerjee (Graduate student)

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 10th, revisit later**
Cavity#2, stiffened	**Yes (1.3GHz)**	**6MV**	**18Hz**	**Yes**	**12MeV Beam through on May 15th**
Cavity#6, stiffened	**Yes (1.299925GHz)**	**6MV**	**33Hz**	**Yes**	**12MeV Beam through on June 15th.**
Cavity#3, un-stiffened	**Detuning meas., microphonics study and compensations are planed**				
Cavity#1, un-stiffened					
Cavity#4, Stiffened					

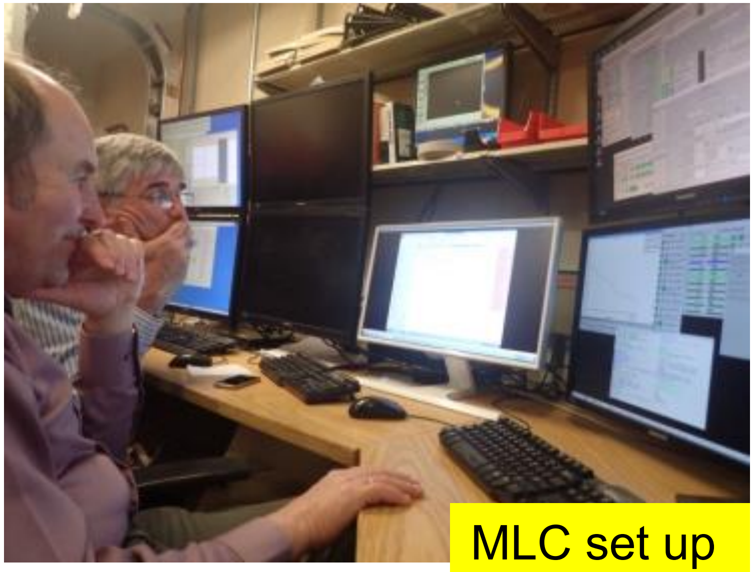
MLC plans

Year	Month	Items
2017	June	LLRF optimization microphonics study and compensation beam through MLC test
	July	NO RF test due to water shutdown 1ST SSA delivery will be the end of August
	August	
	September	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
	October	
	November	
	December	
2018	January	
	February	
	March	
	April	Fractional Arc Test

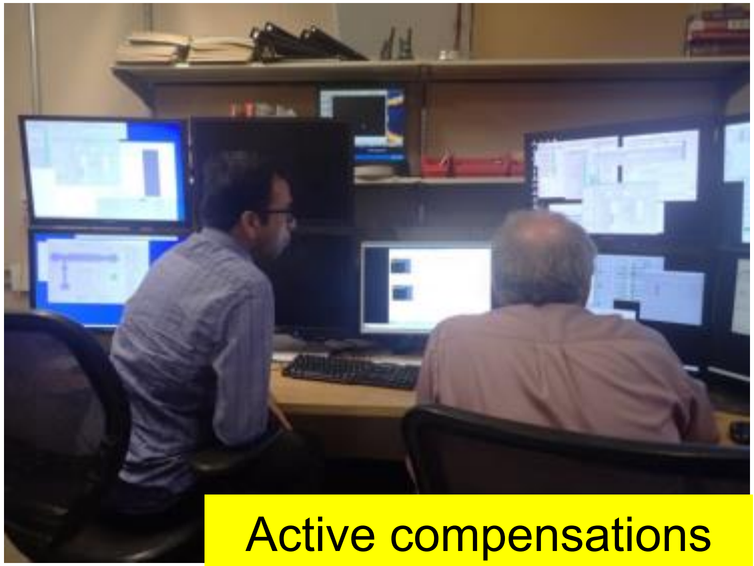
Summary

- Commissioning of the 7-cell cavities in the MLC had been done successfully, the cavities can provide an energy gain of up to 76MeV per ERL turn.
- The nominal energy gain of 36 MeV per pass for the CBETA project could be reached with the available RF power at the measured initial microphonics levels.
- The MLC was moved to its final location and cooled down to 1.8K again.
- 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.
- Microphonics meas./study/compensation has been performed on cavity#5, #2, and #6. Next microphonics study on MLC Cavity#3 (un-stiffened) will provide deeper perspective of the MLC operation for CBETA.
- The next milestone of the MLC is to demonstrate/confirm the MLC could regulate the 1st pass energy gain of 36MeV in total.

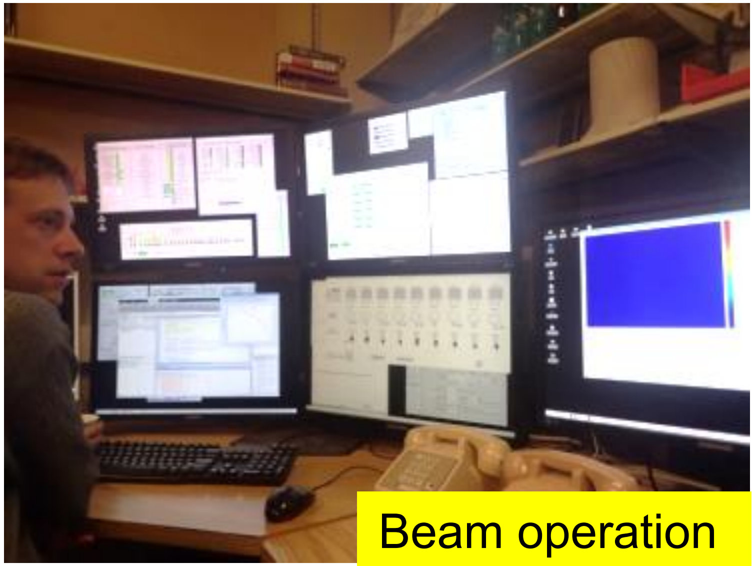
Thanks to the ERL team



MLC set up



Active compensations



Beam operation

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


THE TALK STOPS HERE