Results from Cryomodule-1 at NML

Elvin Harms
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U.S. DEPARTMENT OF ENERGY

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Fermilab

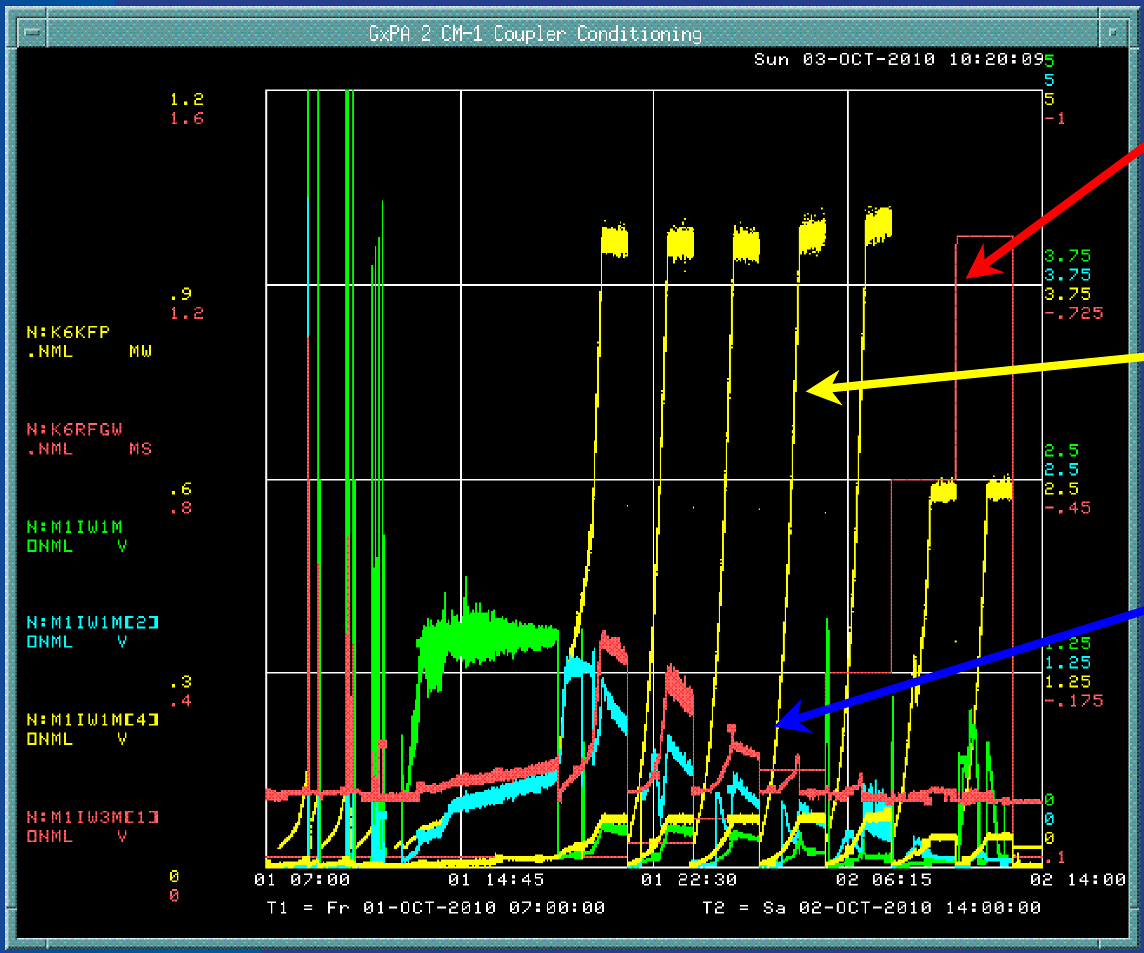
Introduction / What is CM1?

- Cryomodule 1, also dubbed 'S-1 Local'
- TTF Type III+ 8-cavity cryomodule
  - First one in the U.S.
- Provided to Fermilab by DESY as a 'kit'
  - Assembly by Fermilab, DESY, INFN-Milano
  - In exchange for 3.9 GHz cryomodule
    - Now in routine operation at DESY/FLASH
- Assembly at Fermilab
- Now installed at the refurbished New Muon Lab experimental hall

Recent Milestones

- Significant Progress has been made in making CM1 operational in the past 2 years
  - 22 January 2010: Cryomodule moved into final position and aligned
  - 23 February 2010: Warm side of input couplers under vacuum
  - March - May: Cryogenic piping connections
  - 11 June 2010: permission to initiate RF commissioning and warm coupler conditioning
  - June - July: RF/Klystron commissioning
  - 2 August 2010: Warm coupler conditioning begins, one cavity at a time, beginning with Cavity 8/S33
  - 16 August 2010: Cavity 8 conditioning complete (14 days)
  - 26 August 2010: Cavity 7/Z91 conditioning complete (10 days)
  - 2 September 2010: Cavity 6/Z98 conditioning complete (8 days)
  - 17 September 2010: Cavity 5/Z107 conditioning complete (15 days)
  - 22 September 2010: Cavity 4/Z106 conditioning complete (6 days)
  - 27 September 2010: Cavity 3/AC73 conditioning complete (6 days)
  - 30 September 2010: Cavity 2/AC75 conditioning complete (4 days)
  - 3 October 2010: Cavity 1/Z89 conditioning complete (4 days)

Warm Coupler Conditioning



Pulse Width
(20 μs - 1.2 ms)

Input power
(up to 1 MW)

Field Emission probe and PMT Response
(0-5 volts)

Cavity #1 (Z89)

Recent Milestones (2)

- 12 November 2010: Insulating vacuum space leak tight and pumped down
- 23 February 2010: Warm side of Couplers under vacuum
- 17 November 2010: Cool down begins
- 19 November 2010: Cool down to 4.5 Kelvin complete
- 22 November 2010: At 2 Kelvin
- 10 December 2010: Permission to initiate cold RF operation
- 13 December 2010: Cold coupler conditioning and Performance evaluation begins, one cavity at a time, first RF into CM-1 at Fermilab
- beginning with #1
- 17 December 2010 - 26 January 2011: Cavity 1/Z89 (days)
- 28 January 2011 - 7 March 2011: Cavity 8/S33 (days)
- 7 - 16 March 2011: Cavity 2/AC75 (10 days)
- 18 - 22 March 2011: Cavity 1/Z89 *reprise* (days)
- 26 March - 4 April 2011: Cavity 3/AC73 (9 days)
- 20 April - 19 May 2011: Cavity 4/Z106 (days)
- 20 - 25 May: Cavity 5/Z107 (6 days)

Recent Milestones (3)

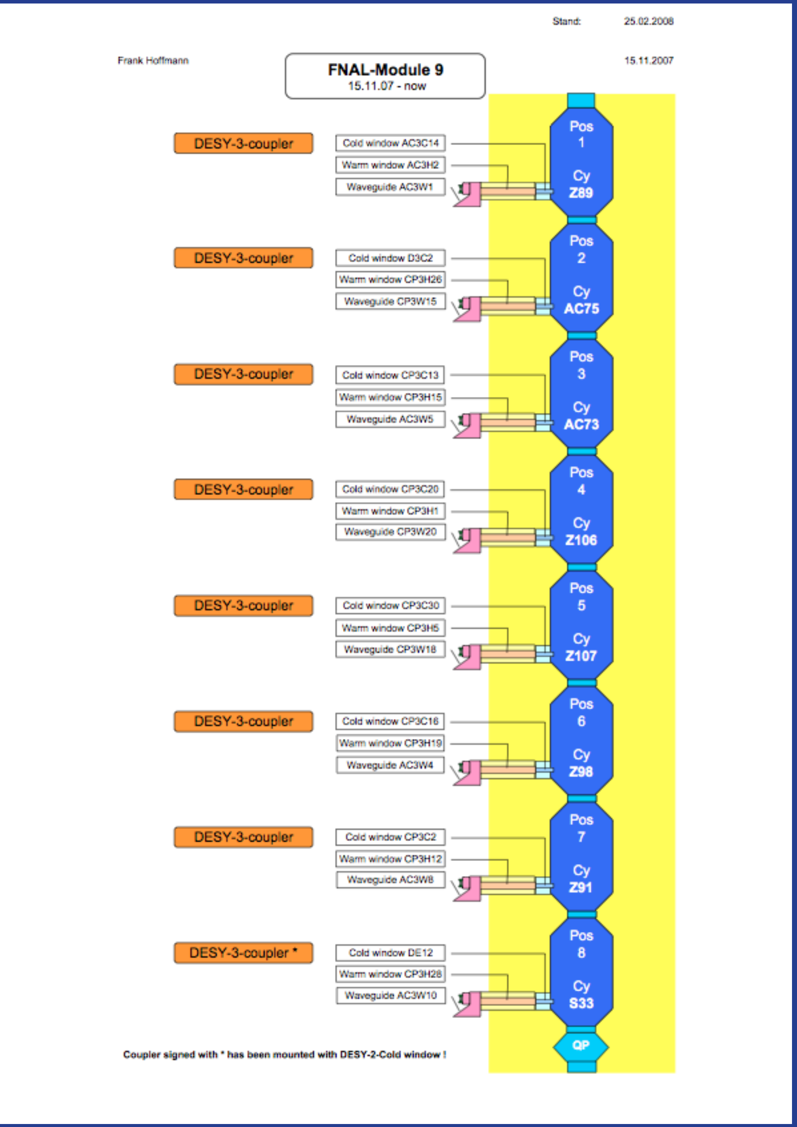
- 3 - 8 June: Cavity 6/Z98 (6 days)
- 9 - 11 June: Cavity 7/Z91 (3 days)
- 6 July: CM-1 Module powered
- 14 July - 5 August: LLRF calibration; single cavity re-evaluation
- 15 - 30 August - Single Cavity evaluation at 5 HZ (one cavity on resonance at a time)
- End of CY11: Expected end of CM-1 operation

Performance Evaluation Steps

- Each cavity was singly connected to the output of the klystron to determine its performance.
- A prescribed series of measurements were made following the 'DESY recipe' test sequence at the Cryo Module Test Bench (CMTB)
  - RF Cable Calibration
  - Technical Sensor/Interlock Check
  - RF/Waveguide Check
  - Warm Coupler Conditioning (off resonance)
  - Cooldown to 2K
  - Frequency spectra measurements
  - Cavity Tuning to 1.300 GHz via motorized slow tuner
  - Q_L adjust to 3 E6
  - LLRF calibrations
  - Cold Coupler Conditioning (on resonance)
  - Performance Evaluation including
    - Maximum gradient
    - Dynamic Heat Load (Q_0 vs. E_{ACC})
    - Dark Current and X-rays vs. E_{ACC}
- Once all cavities were tested, the waveguide distribution system was installed and VTO's adjusted based on preliminary E_{Acc} determinations.
- Ultimately all 8 cavities are powered simultaneously by the 5 MW Klystron.
- Further evaluation
- Carry out Study Plan

Cavity Performance Summary

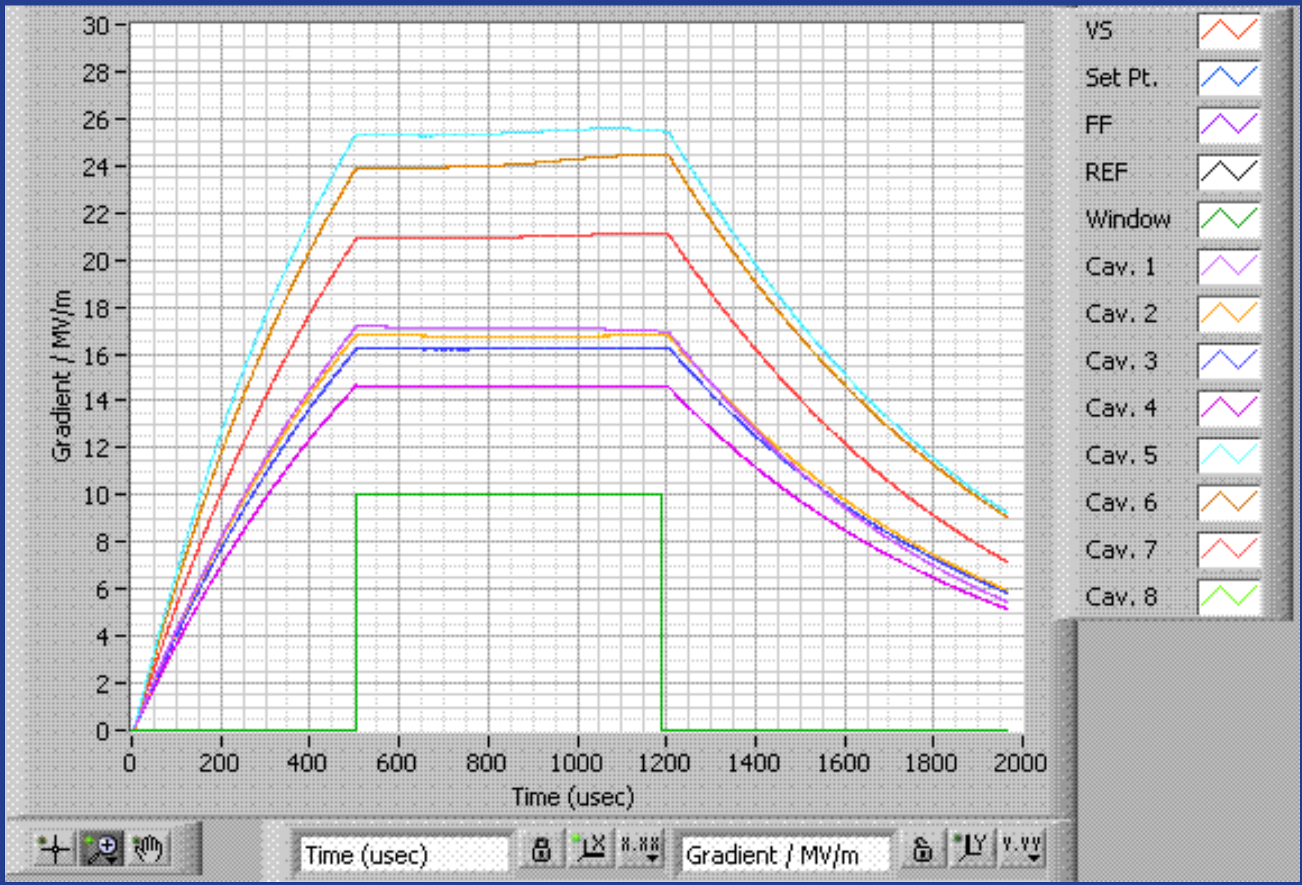
Cavity	Peak E_{acc} (MV/m)	Estimated maximum Q_0 (E09)	Limitation/Comments
1/Z89	20.2	11	'soft' quench/heat load
2/AC75	22.5	12	Quench
3/AC73	23.2	0.43	'soft' quench/heat load
4/Z106	24*	2.3	*RF-limited
5/Z107	28.2	39	Quench
6/Z98	24.5	5.1	Quench
7/Z91	22.3	4.7	'soft' quench/heat load
8/S33	25	18	Resonant frequency at 1300.240 MHz; tuner motor malfunction



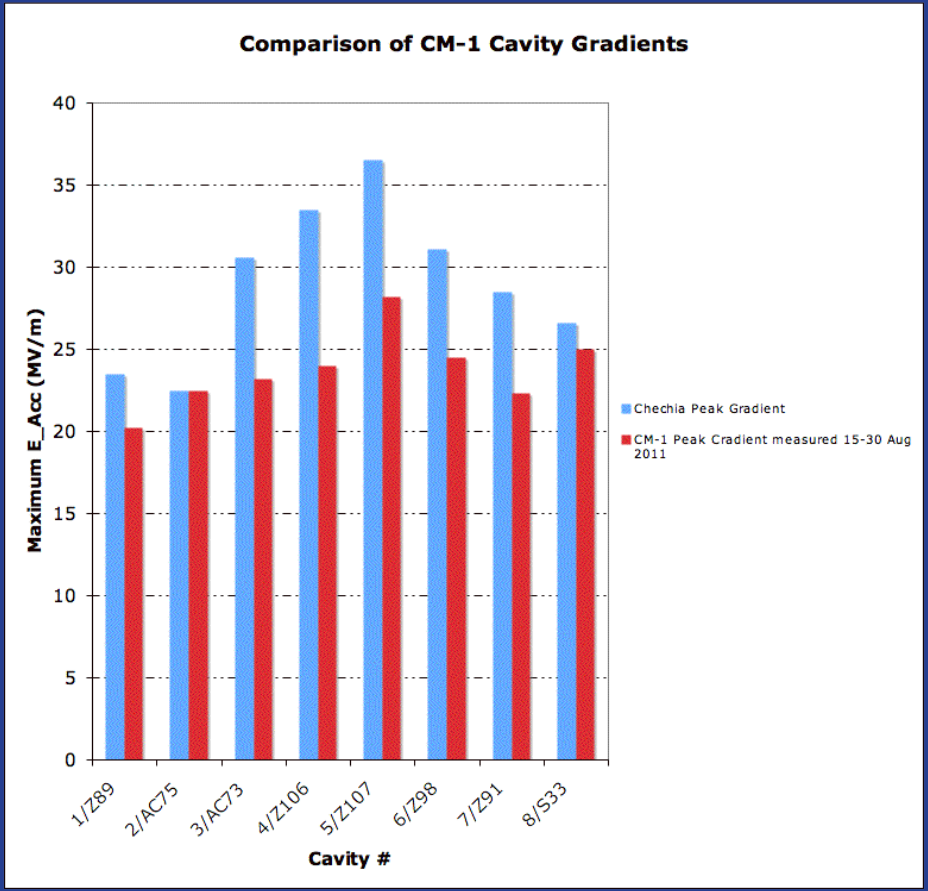
Details in 2nd Talk

Cavity Performance Summary

- Cryomodule evaluation focusing on
  - Final calibration values
  - Re-check individual cavity peak performance and limitation
- Lorentz Force Detuning Comp.
- Low Level RF
- Routine operation at 5 Hz.



- Determine final signal calibrations
- Cavity Peak Gradients
  - All cavities on resonance
  - One cavity on resonance at a time

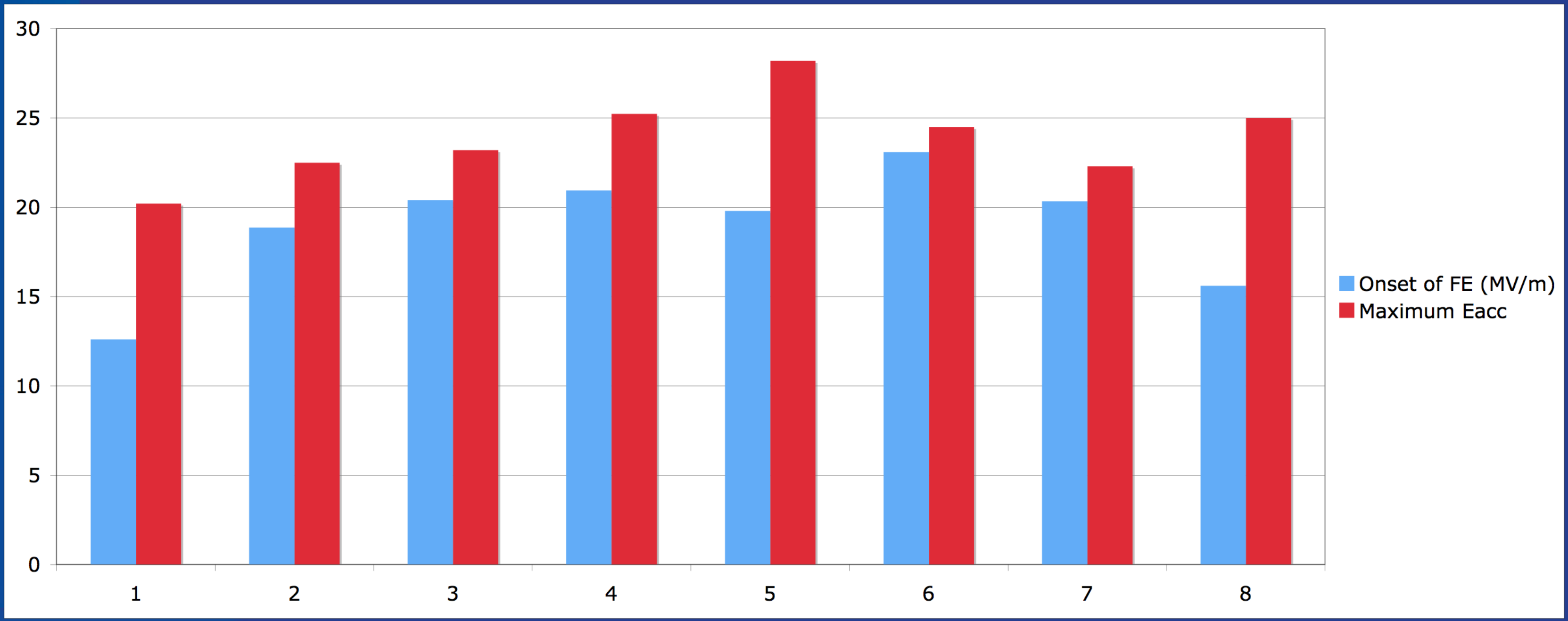


	1	2	3	4	5	6	7	8	Mean
CM-1 Peak Gradient	20.2	22.5	23.2	24*	28.2	24.5	22.3	25	23.7
Ratio compared to Chechia	0.860	1.00	0.758	0.716	0.773	0.788	0.782	0.940	0.827

Cryomodule Performance - Field Emission

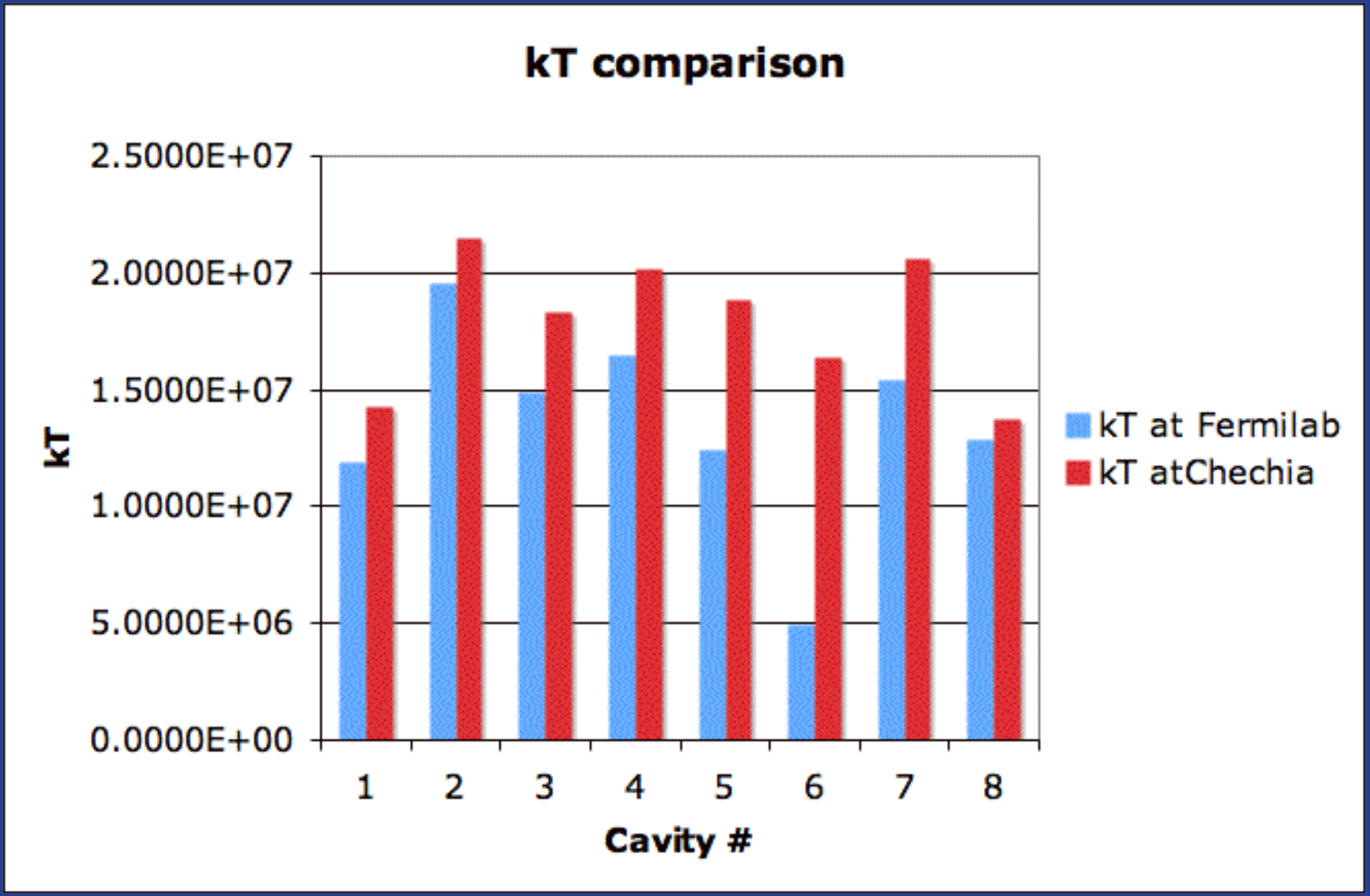
Cavity	Onset of Field Emission (MV/m)	Peak Field Emission (mR)	Maximum E_{Acc}	Ratio Onset/Peak	Detector with Peak Response	Location
1	12.6	30	20.2	62.4%	3241	middle
2	18.86	130	22.5	83.8%	3241	middle
3	20.4	105	23.2	87.9%8	3227	upstream
4	20.94	120	25.2	3%	3241	middle
5	19.8	125	28.2	70.2%	3241	middle
6	23.08	104	24.5	94.2%	3241	middle
7	20.34	103	22.3	91.2%	3227	upstream
8	15.6	213	25	62.4%	3241	middle

Installation of localized dosimetry planned in the near future.

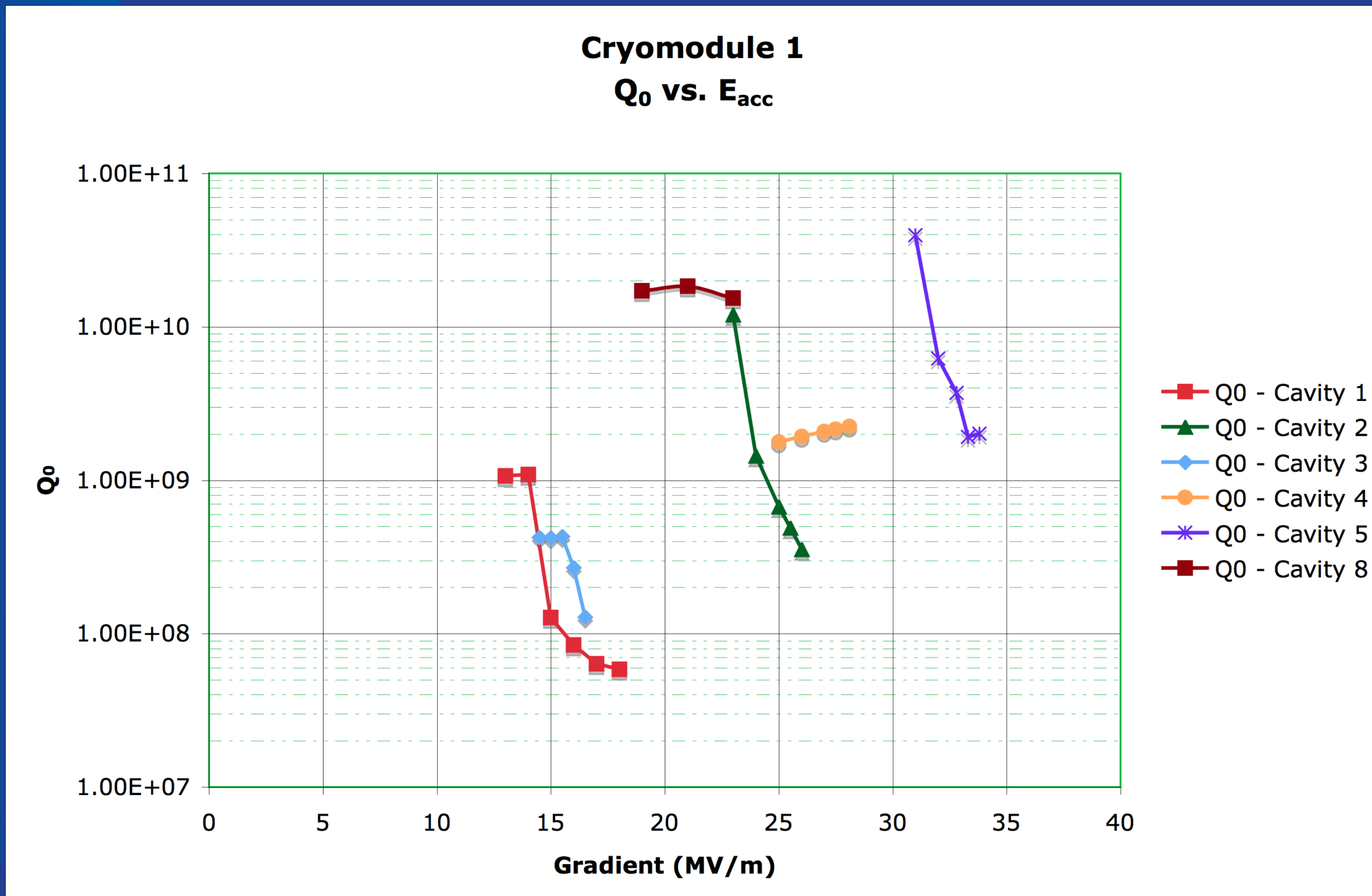


Cryomodule Performance - k_T

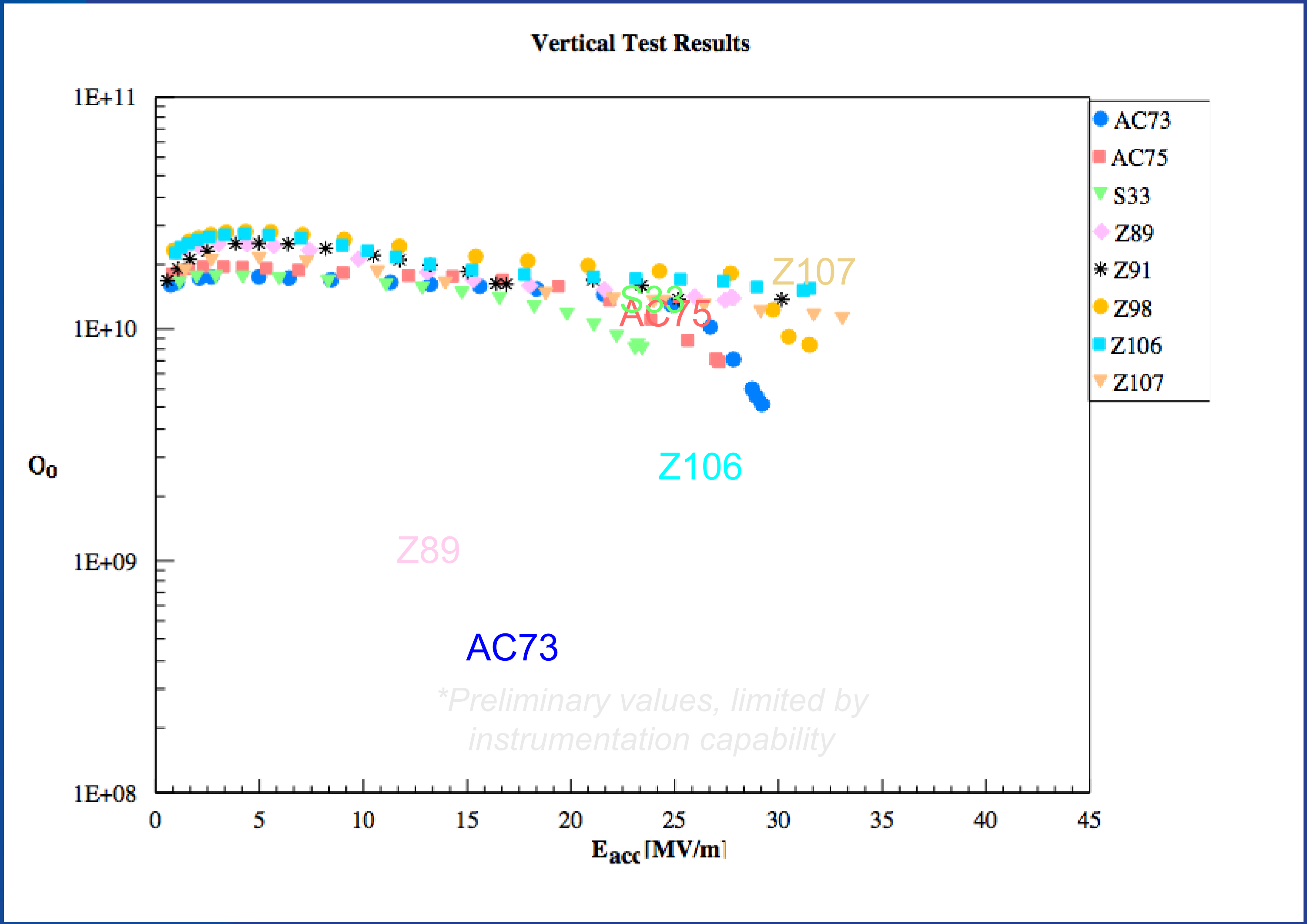
- Uncertainty estimated to be <10%



Q_0 vs E for Cavities Tested to Date

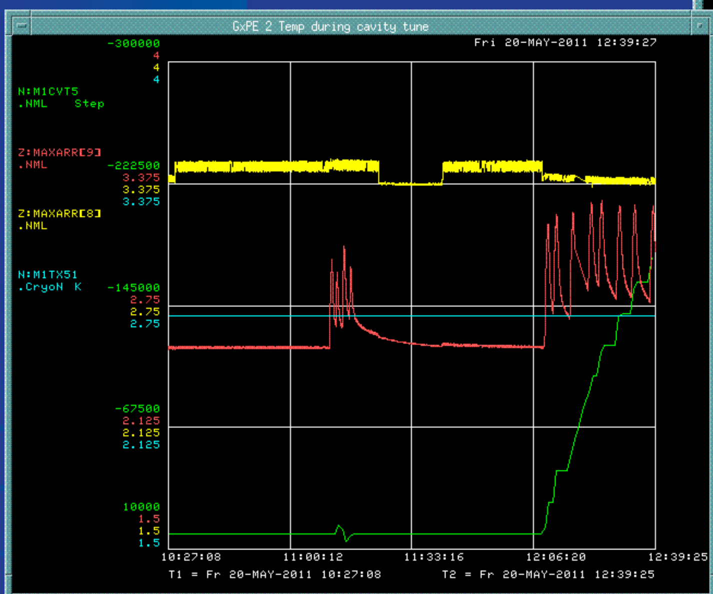


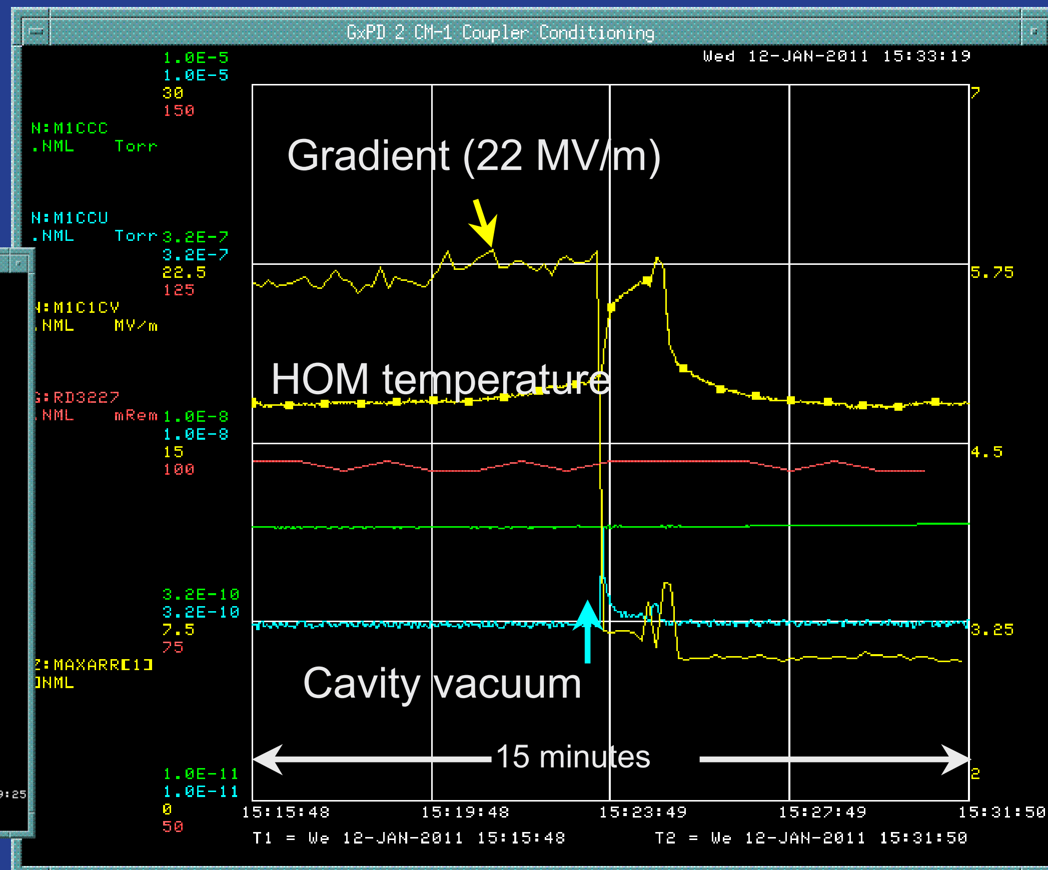
Results to Date



Subsystem Performance - Thermometry

- System has yet to be fully exploited
- Interfaced to ACNET
- Ongoing improvements

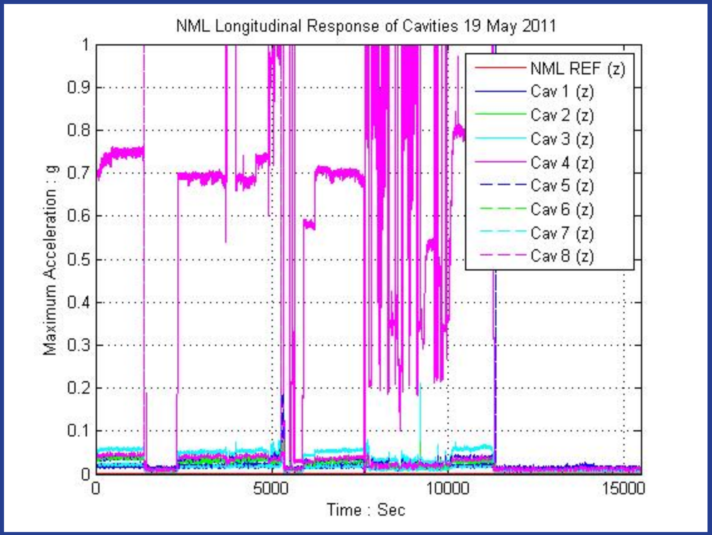




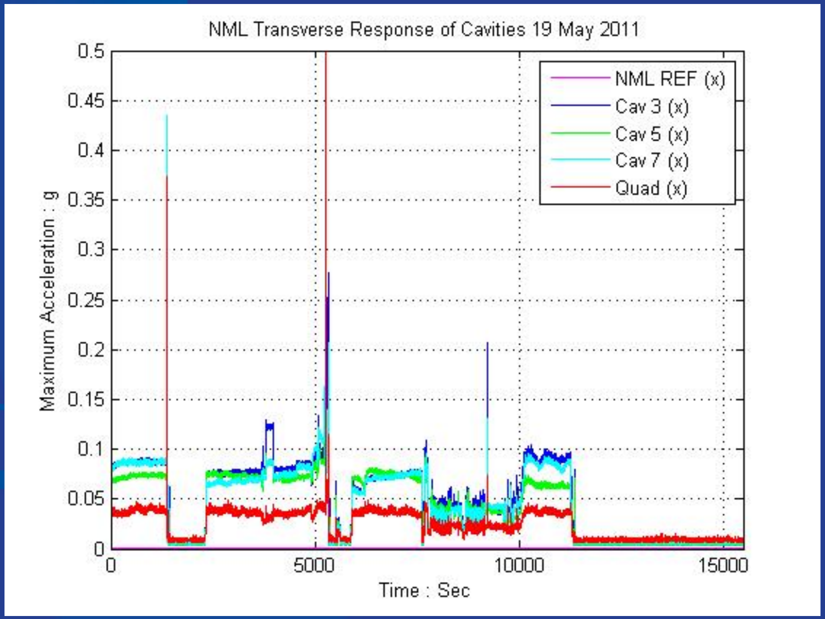
Fast Thermometry response during a possible quench in Cavity 1

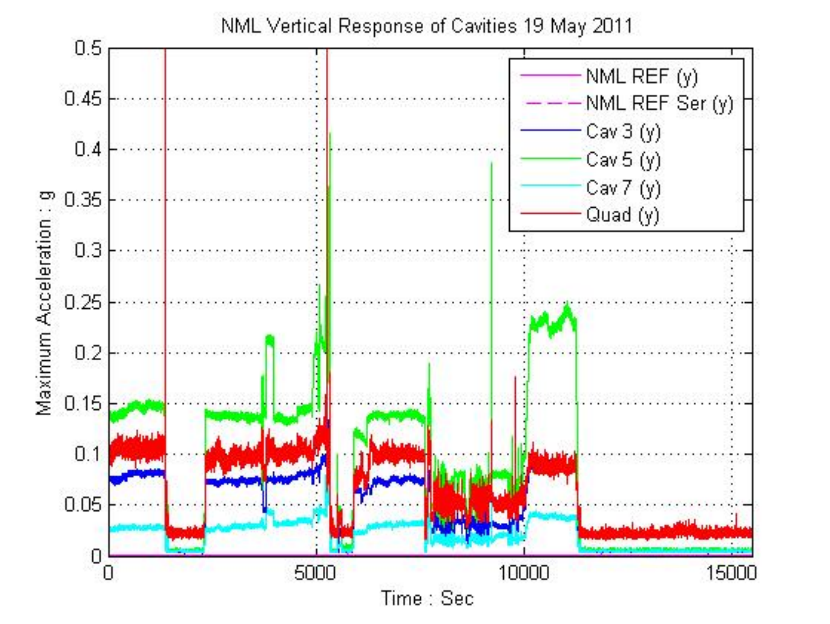
Subsystem Performance - Microphonics

- System evolving
- Interfaced to ACNET
- Ongoing improvements



Cavity 4 Operation

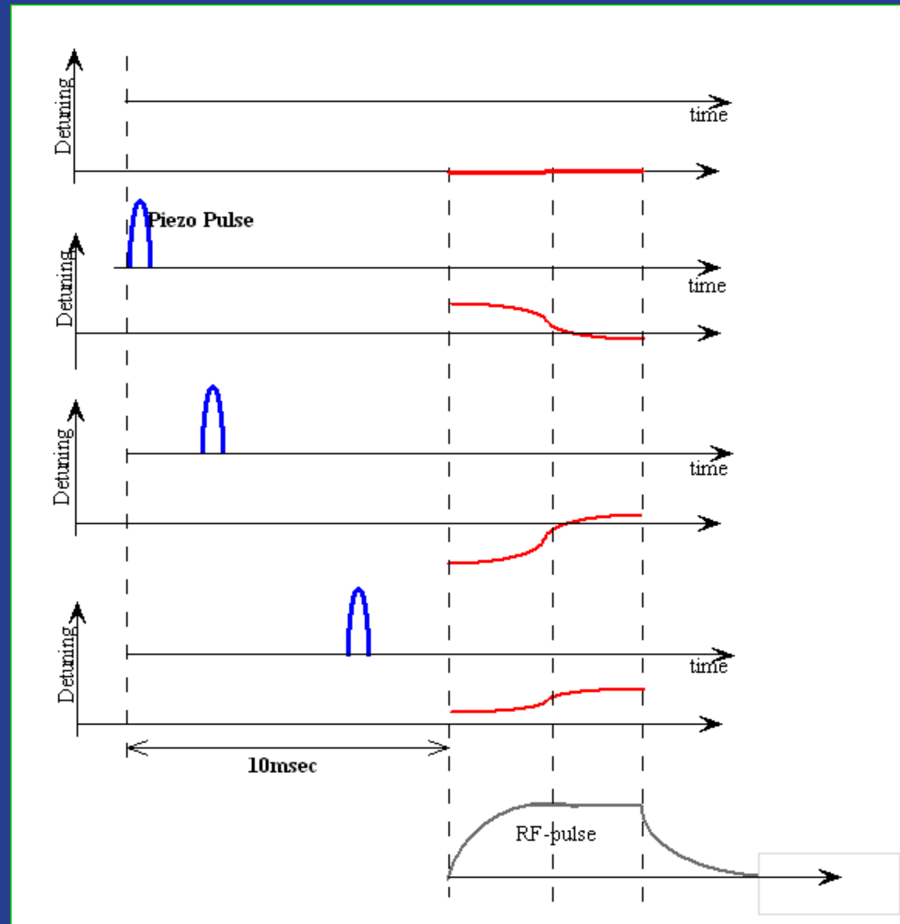




Adaptive Least Square LFD Algorithm

The response of the cavity frequency to the piezo impulse (TF) can be easily measured when cavity operated in CW-mode.

Since it is often not convenient to connect a pulsed cavity to CW source we developed alternative technique to measure this response (TF) when cavity operated in RF-pulse mode.



Piezo/cavity excited be sequence of small (several volts) narrow (1-2ms) pulses at various delay.

The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning.

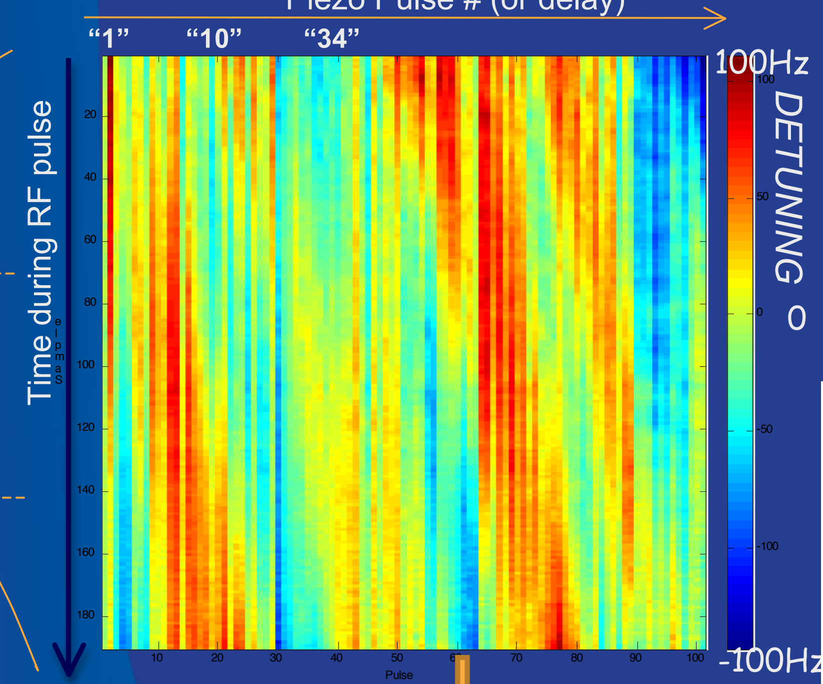
[Response Matrix]

Details of Adaptive LS LFD Algorithm at :

"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation". Fermilab Preprint –TM-2476-TD. And at PAC2011.

Adaptive LS LFD Algorithm

Response Matrix

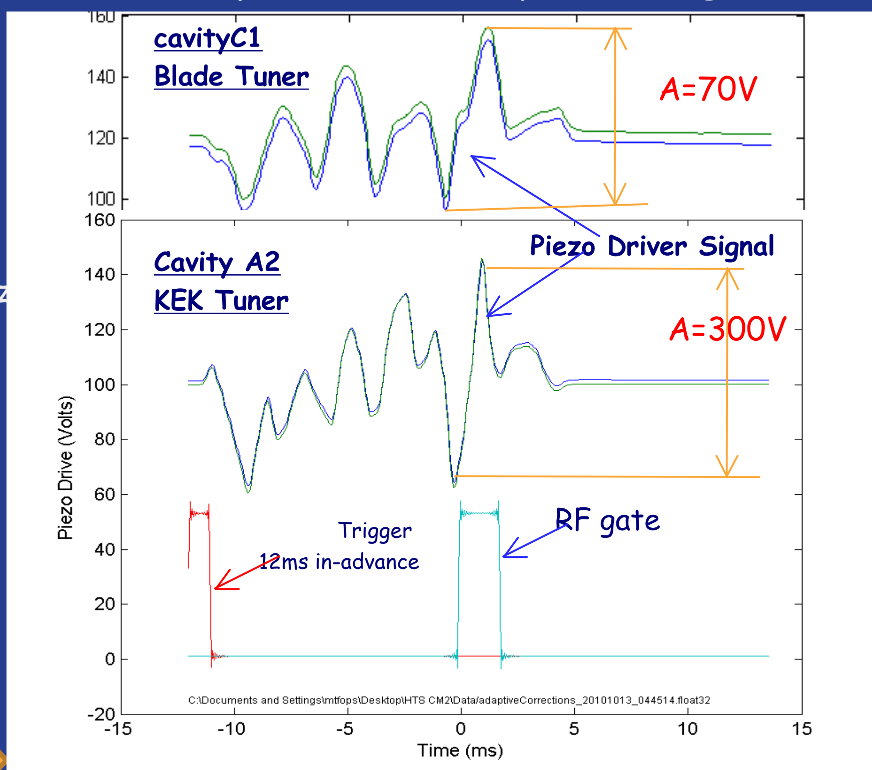


Invert the response matrix and determine combination of pulses needed to cancel out the LFD using LS

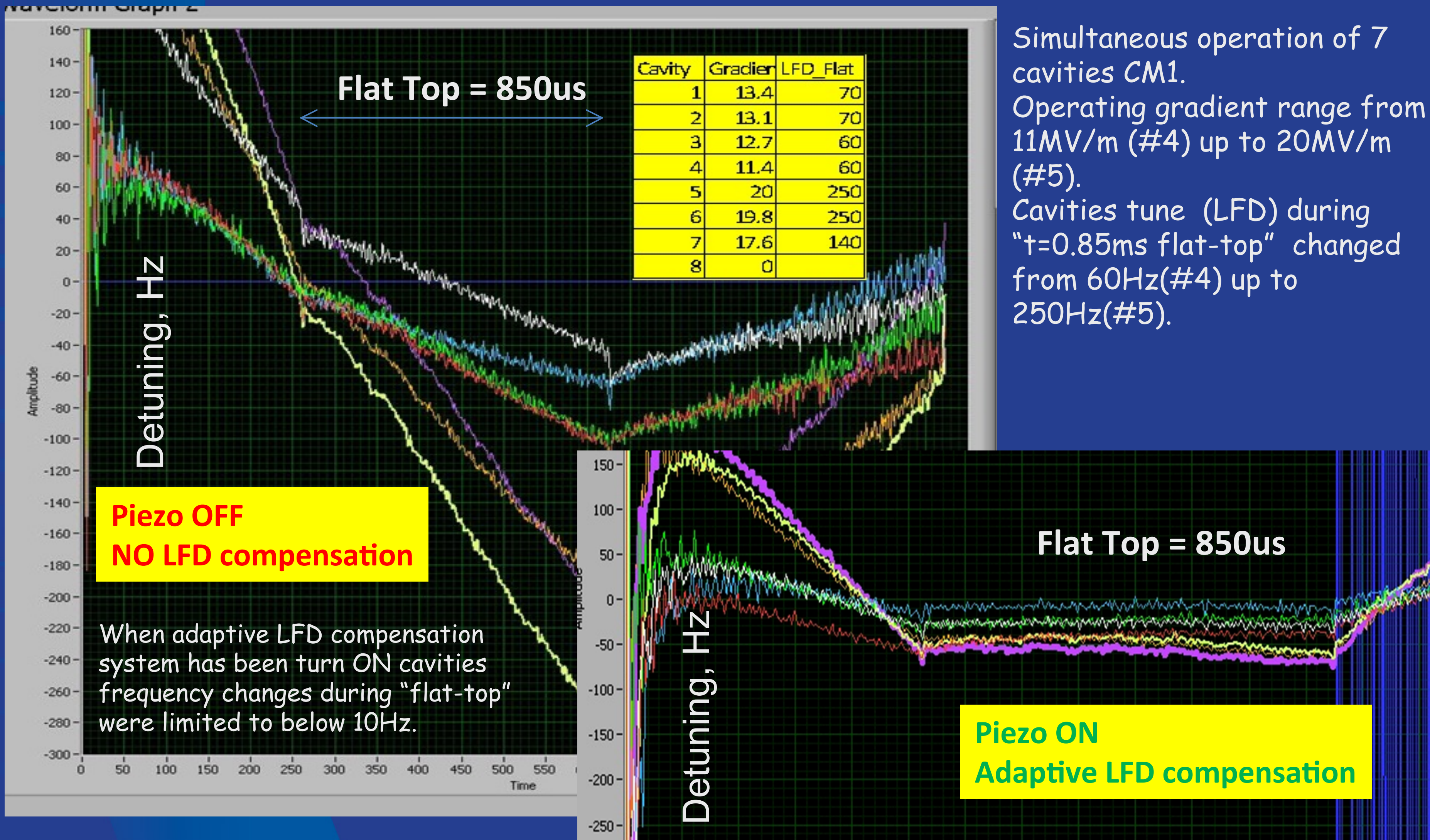
Any part of RF pulse could selected for Compensation: "Fill+FlatTop" only "FlatTop"

As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

Piezo Impulse Calculated by LS LFD algorithm



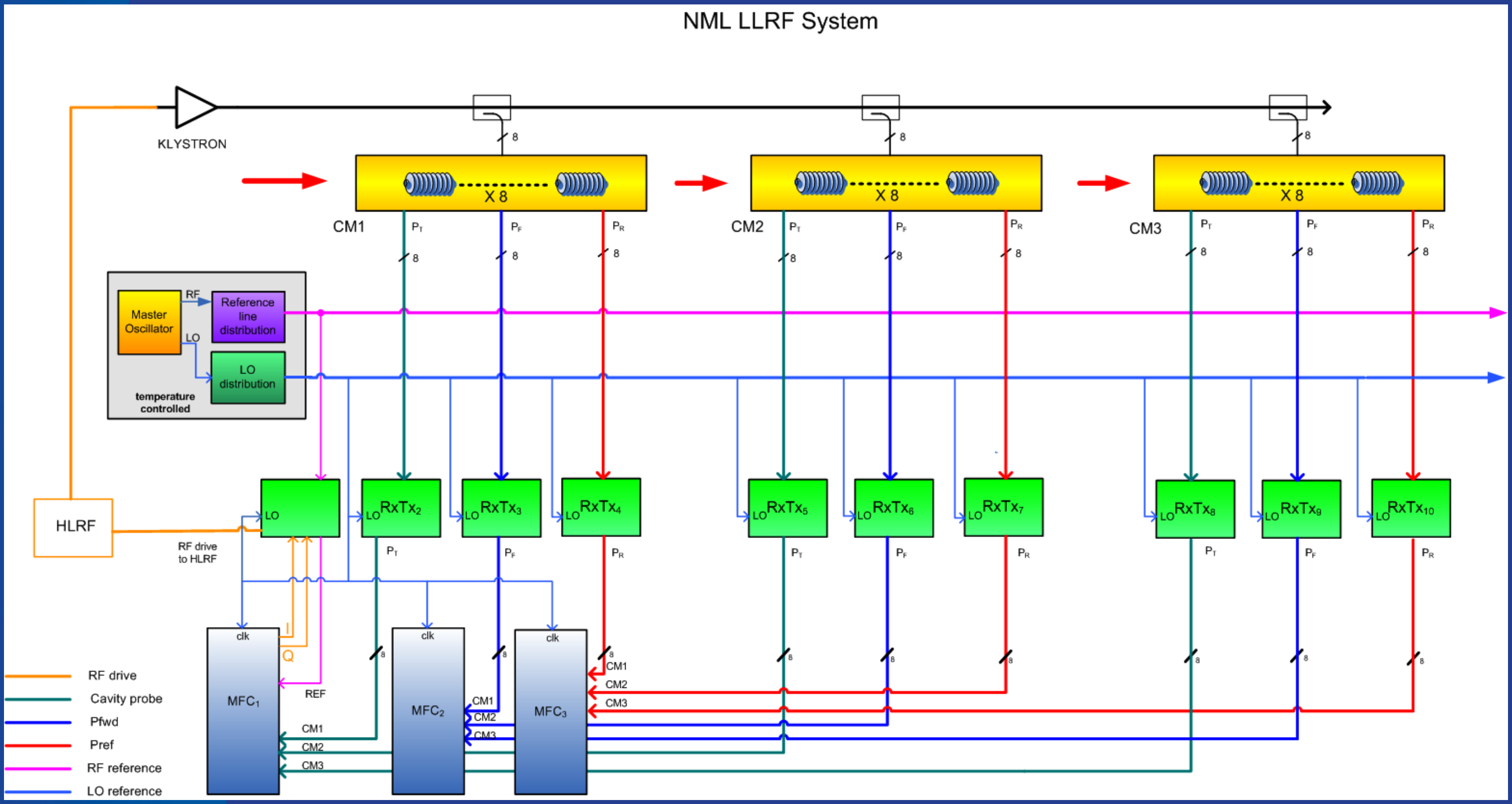
CM1- 8(7) Cavities LFD Compensation (LLRF in open loop operation)



Cavity	Gradien	LFD_Flat
1	13.4	70
2	13.1	70
3	12.7	60
4	11.4	60
5	20	250
6	19.8	250
7	17.6	140
8	0	

Simultaneous operation of 7 cavities CM1.
Operating gradient range from 11MV/m (#4) up to 20MV/m (#5).
Cavities tune (LFD) during “t=0.85ms flat-top” changed from 60Hz(#4) up to 250Hz(#5).

Low Level RF - Schematic Overview



Courtesy of Brian Chase, Philip Varghese, et al

Low Level RF - Installed Hardware

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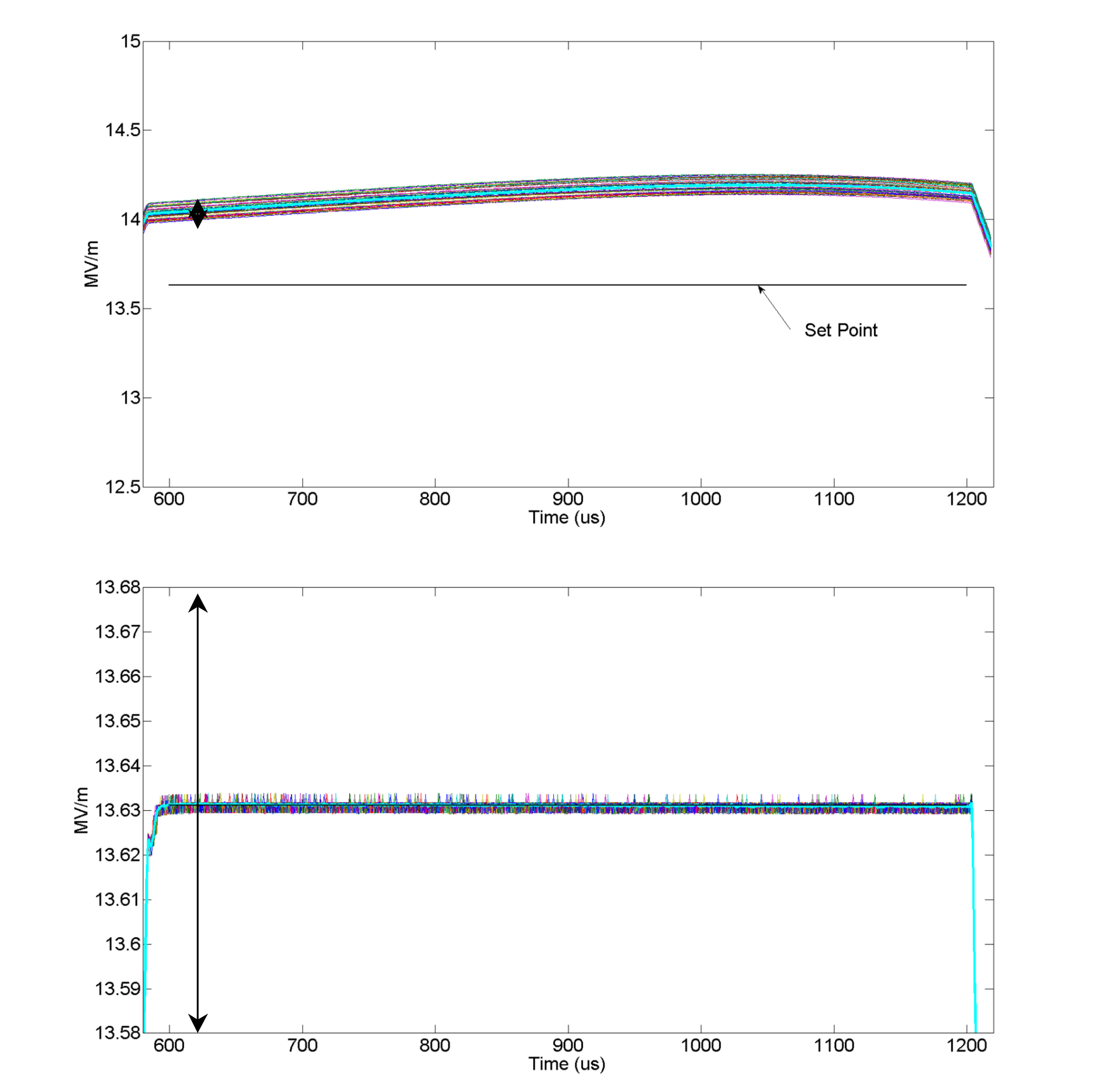
Low Level RF - Vector Sum Magnitude

Without Feedback

With Feedback



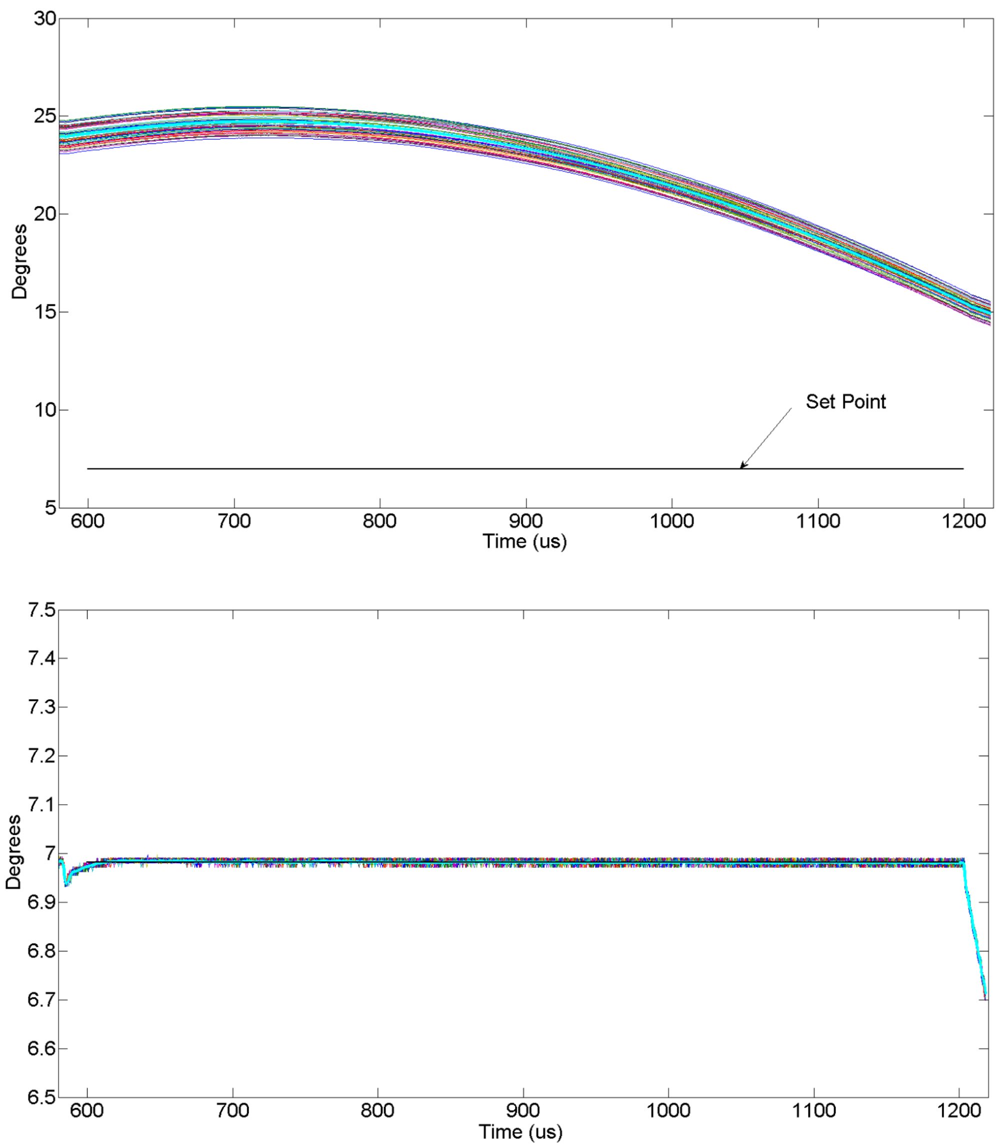
50-pulse overlay in flat-top region

Note: Amplitude Scale Smaller by x25

Low Level RF - Vector Sum Phase

Without Feedback

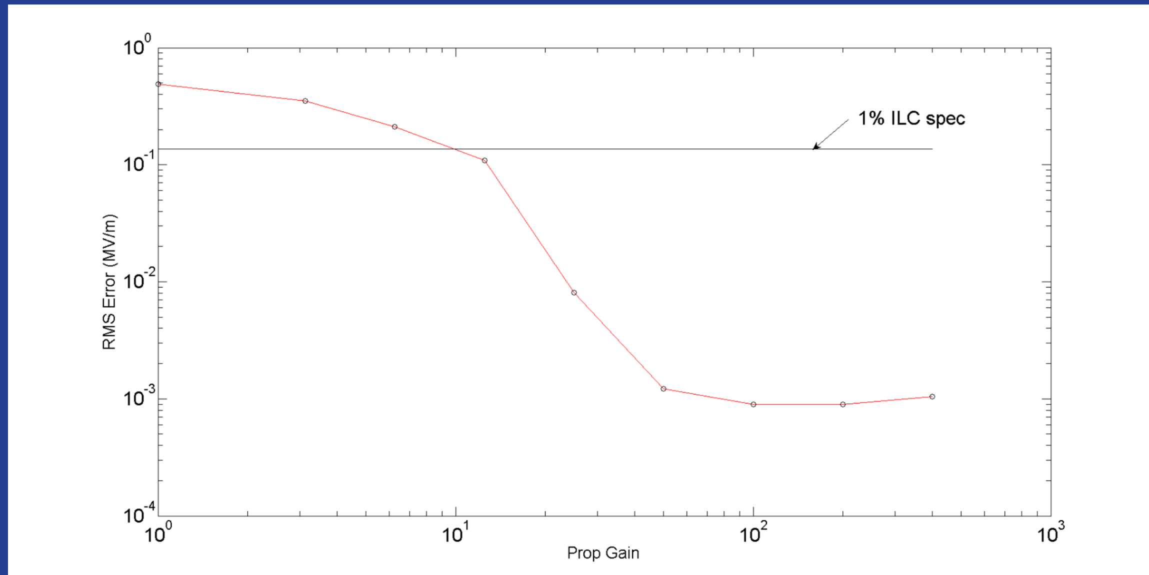
With Feedback



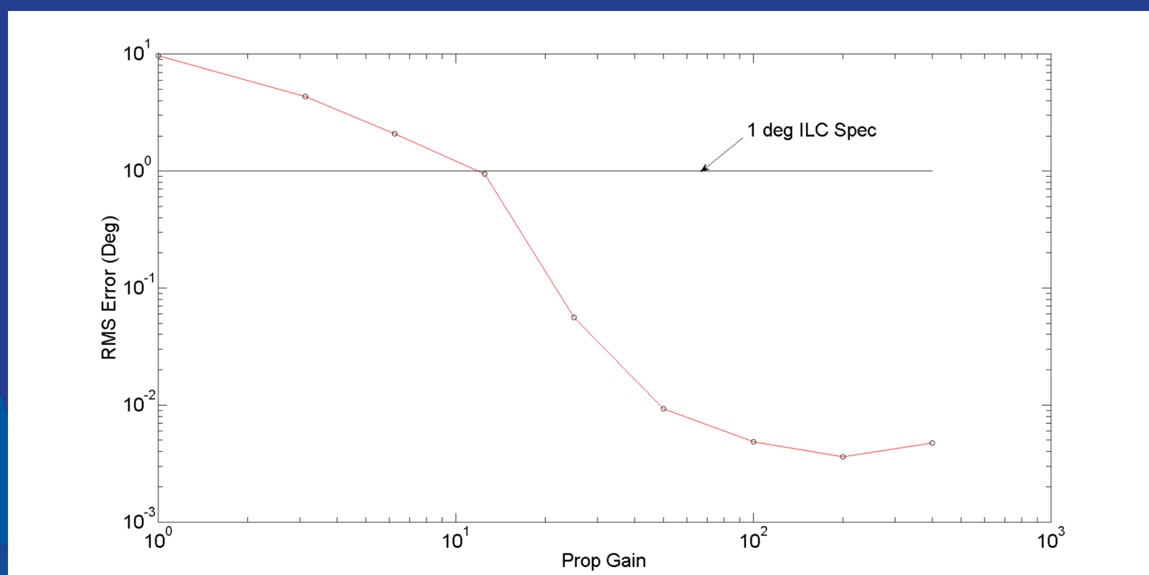
50-pulse overlay in flat-top region

Note: Phase Scale Smaller by x25

Low Level RF - RMS Error vs. Feedback Gain



Magnitude



Phase

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Module Test Plan

1) Signal calibrations verified (1/2 day) 0.5
2) Waveguide distribution system assembled to all cavities (2 weeks) 10.0
3) Adjust Variable Tap Off's (VTO's) based on cavity maximum gradient data (2 days) 2.0
4) Adjust phase shifters – minimize field emission, dark current?
5) Verify power to cavities as seen on directional couplers (1/2 day) 0.5
6) Set Q_L = 3 E6 for all cavities (1/2 day)
   a. LLRF system should be ready for real time Q_L measurements 0.5
7) Set cavities to as close to the same resonant frequency as possible (except #8) (1/2 day) 0.5
   a. LLRF should be ready for real time df measurements
8) Determine maximum achievable E_{ACC} (1 day) 1.0
9) Verify system LFDC/piezo system (6 months/3 weeks) 15 (parasitic)
10) Investigate Microphonics (parasitic)

Module Test Plan - 2

11)Determine LLRF regulation limits (3 days) 3

   a. Assess any potential issue with 8/9 pi modes (7-8 of them)
   b. Adjustable gain in LLRF controller to control 7 or 8 cavities
   c. FF operation
   d. Test phase and amplitude calibration scheme
   e. FB operation
   f. Test real time measurements (QI, detuning, control error, system noise)
   g. Evaluate controller performance and regulation limits

12)Measure dark current/x-rays levels and source(s) (mostly parasitic)

13)HOM signal investigation (mostly parasitic)

14) Investigate possible cross-talk between cavities: de-tune one cavity at a time to investigate response (2 days) 2

15) Cryo heat load (should be parasitic)

16) Life test – investigate stability over 100? Hours 5

   a. Stability / drift analysis (requires waveform DAQ storage system)

17) 9mA related studies (Carwardine et al, meeting next week) (tbd) 5

18)higher Q (1E7) /P-X studies resonance control, 2-cavity 8ms pulse demonstration 3

*48 days/5 = 9+ weeks

Not Just Cavity Testing

- Although the priority, CM-1 operation has competition for time:
  - NML is still a construction area
    - Tunnel extension
    - Electrical Upgrades
    - Water system
  - Gun window evaluation and conditioning (typically 1-2 days/week)
  - Photoinjector installation
  - Tours
  - Performance limitations
    - Insufficient LCW capacity and cooling
    - New skid to be brought on-line inJuly
- Strive to run as much as possible
  - Overnights and weekends when practical and testing program allows
  - Growing involvement by MCR crews/Staff increasing beginning in October

the Team

We also acknowledge and are indebted to all of our international and domestic colleagues