

# Operational Experience with Superconducting RF Systems at Fermilab

Elvin Harms  
ASD Seminar  
20 August 2012

# Talking Points

- Introduction/Background
- Fermilab history/situation
- 3.9 GHz
- NML/ASTA
- Current activities
- Lessons learned/Perspectives
- Concluding Remarks

*Although a relatively recent entrant in the SRF field, Fermilab has made significant strides in building the necessary infrastructure and bringing SRF systems into operation. The speaker will share his experiences and perspective touching specifically on the 3.9 GHz system built at Fermilab and now in operation at FLASH/DESY as well as with ILC-style cryomodules being tested at the NML/Advanced Superconducting Test Accelerator facility.*

# Introduction / Background

- 33 years at Fermilab
  - MCR
  - Antiproton source (+ E760/835)
  - Collider
  - LHC/LARP
  - SRF
- Associated experience
  - CERN
  - DESY/FLASH
  - INFN/LASA



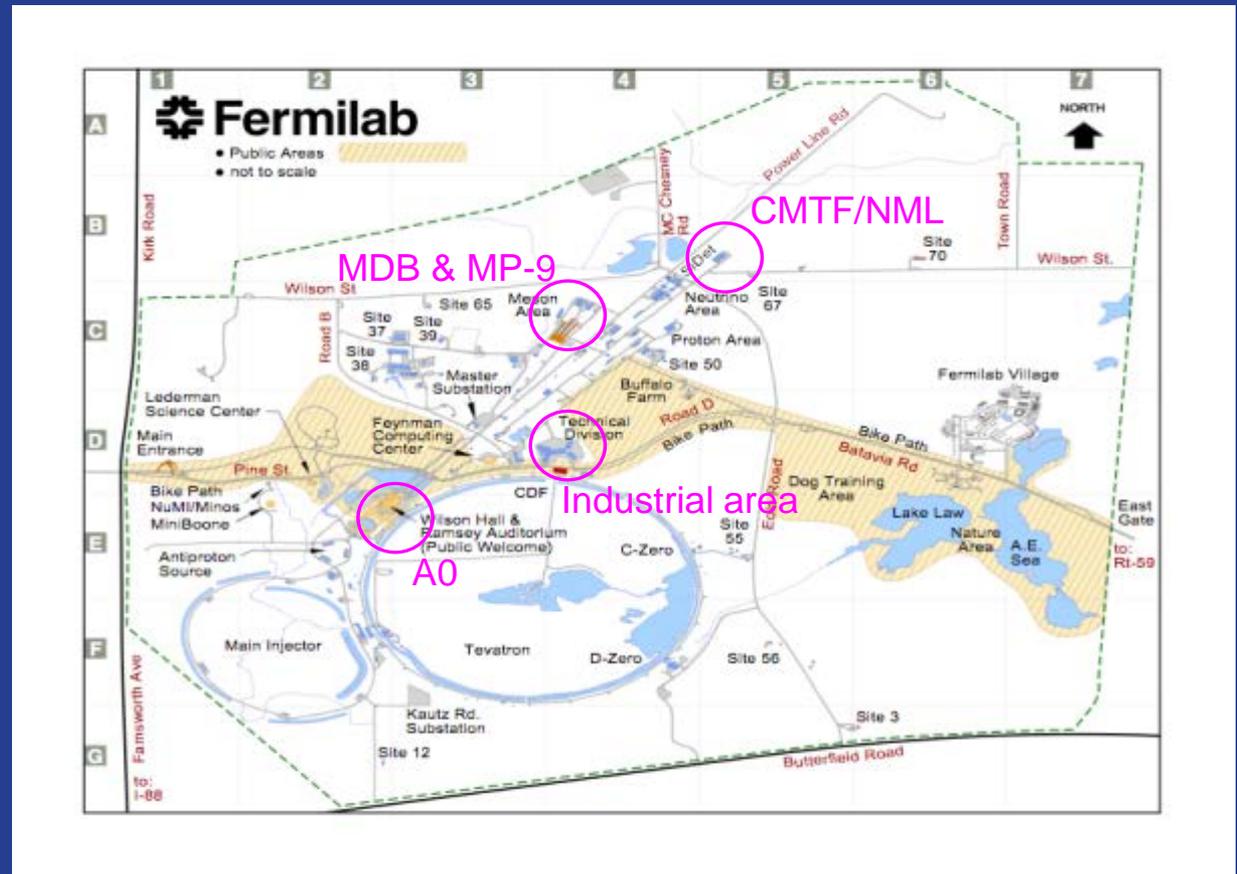
# Introduction

- Fermilab has a growing capability in operating SRF facilities
  - Cavity R&D Test facilities
  - Beam-based facilities
  - Cavity processing & cryomodule assembly
  - Expertise with sub-systems necessary for reliably operating SRF facilities



# SRF Facilities at Fermilab

- ⑩ A0 Photoinjector
  - CC1
  - 5-cell deflecting cavity
  - CKM
  - Vertical Test stand
- ⑩ Capture Cavity 2
  - MDB then NML
- ⑩ 3.9 GHz/Cryomodule
  - 1 swap
  - HTS
- ⑩ NML/ASTA/CMTF
- ⑩ TD
  - VTS
  - MP-9
  - ICB
  - IB4/



Collaborations: Argonne, Cornell, DESY, LASA/INFN, Jefferson Lab, LBNL/NGLS, India, China, UK, TTC

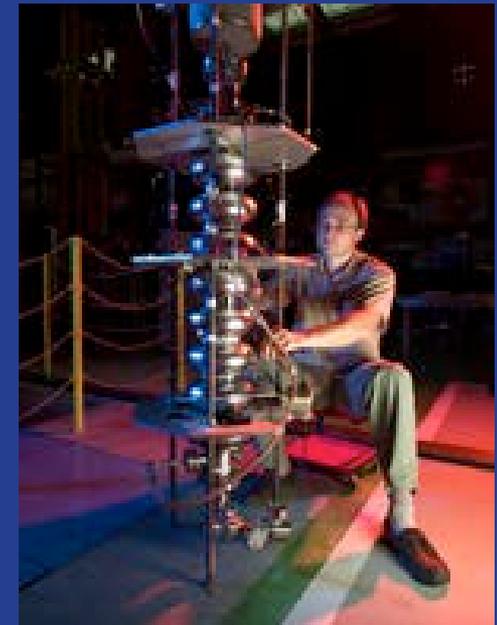
# A0 - Birthplace of SRF Activities

- Photoinjector
  - Gun
  - ‘Capture Cavity 1’ - superconducting 9-cell cavity
  - In operation from 1992 until October 2011
  - Routine, almost ‘turn key’ operation
  - User line for novel beam dynamics studies
- North cave
  - Deflecting mode cavity R&D for CKM, ILC, etc.
  - Test bed for 3.9 GHz effort
  - Single cell R&D
- 3.9 GHz Coupler Conditioning stand



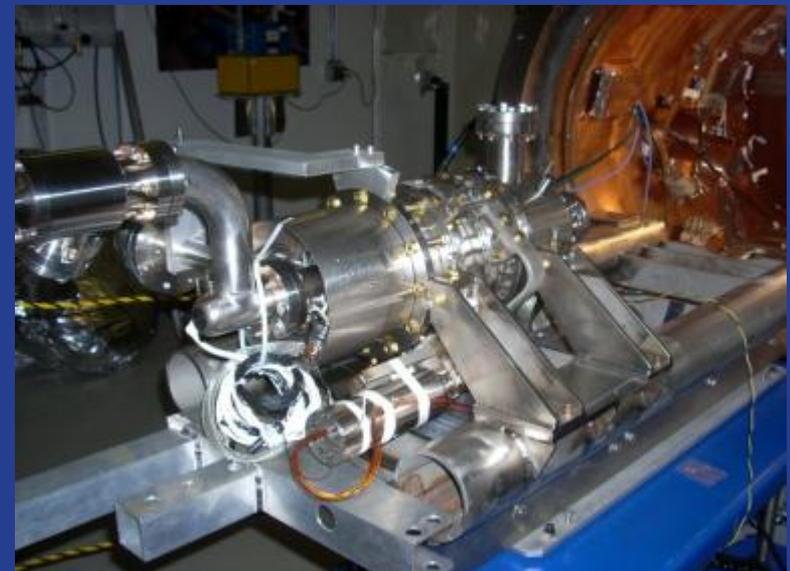
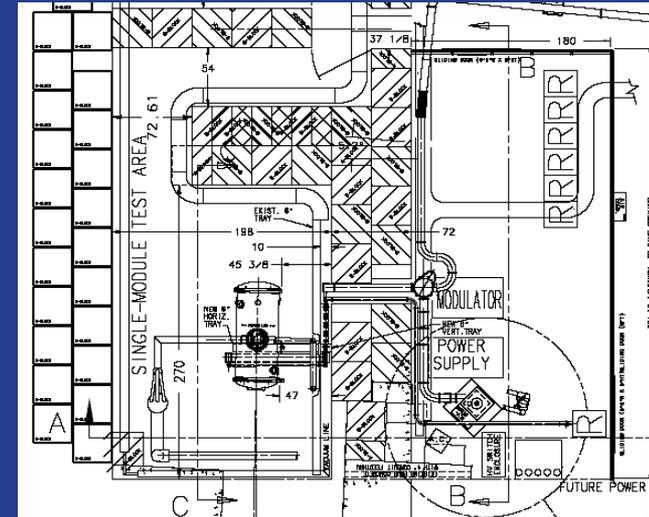
# IB1 - Vertical Test Stand

- Sized for testing 1.3 GHz 9-cell cavities+
- 206 tests to date, 70+ tests per year maximum throughput
- Expansion of two more test stands in progress
  - VTS-2: on-line in September
  - VTS-3: 2013
- Maximum throughput ~250 tests/year



# MDB

- Horizontal Test Stand
  - Single dressed 1.3 GHz and 3.9 GHz cavities
  - In operation since August 2007
  - 16+ cavities tested - several more than once
  - 300 kW RF system @ 1.3 GHz
  - 80 kW RF system @ 3.9 GHz
  - Cryogenics
    - 3 parallel Tevatron refrigerators
    - 625 Watts each @ 4.5K
    - 1.8K operation w/ pump @ 10g/s
  - LLRF, interlock system, Vacuum, etc.
  - ~ 1 cavity test/month
  - All ACC39 cavities
  - S-1 Global
  - CM-2
- HINS/Single Spoke Resonator R&D

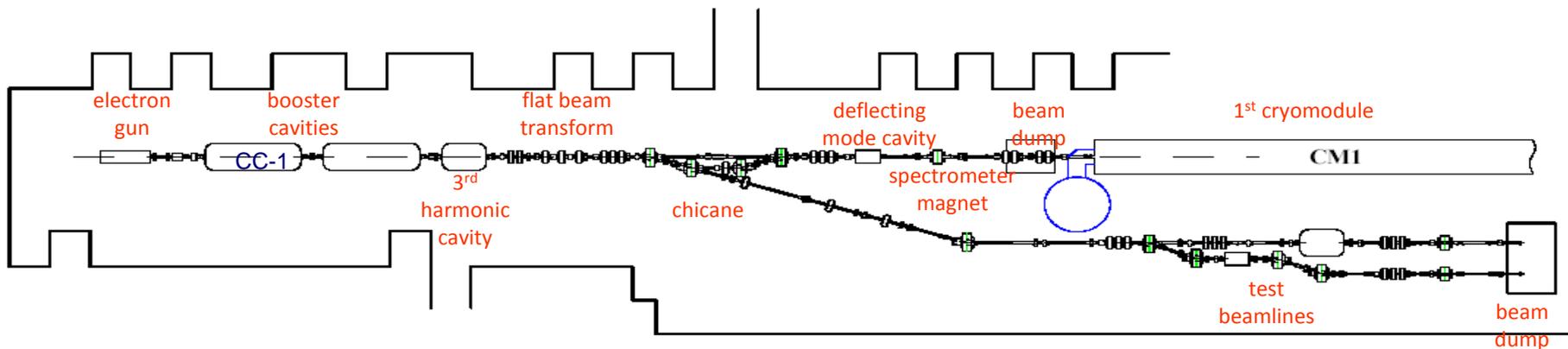


# NML/CM-1/ASTA/PXIE

- First ILC-style cryomodule in the U.S. brought into operation here
- Future e- beam facility: Advanced Superconducting Test Accelerator (ASTA)
- 2 SRF systems in operation
  - CC-2
  - CM-1
- Cryo system commissioned in 2009
- CM-1 cooldown: November 2010
- RF system for CM-1: early 2011
- Complete Cryomodule powered: June 2011
- In (routine) operation since
- CM-1 run ended March 2012
  - Swap cryomodules
- RFCA002 (CM-2) later this CY
  - first Fermilab-built ILC (TTF) style cryomodule



# NML/ASTA

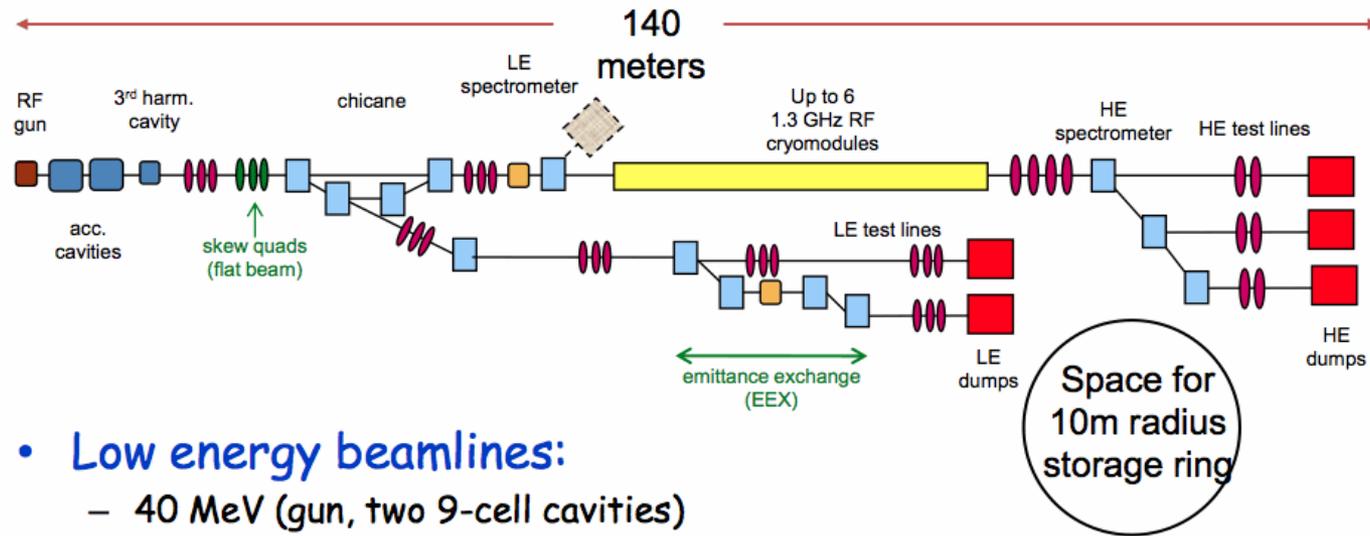


## 40-MeV Injector - *begin beam operation in 2012*

- 1.5 cell, 1.3 GHz electron gun with Cs<sub>2</sub>Te photocathode; identical to DESY/PITZ design
- Two 9-cell 1.3 GHz superconducting booster cavities (one currently installed, one from A0PI)
- Superconducting 3.9 GHz cavity (eventually) for bunch linearization
- Three skew quadrupoles for flat beam transformation
- Chicane for bunch compression ( $R_{56} = 0.198$ )
- 3.9 GHz, normal conducting deflecting mode cavity for longitudinal beam diagnostics (from A0PI)
- Vertical spectrometer dipole deflects beam  $22.5^\circ$  to dumps for beam energy measurement
- Test beamlines will be configured to suit experiments; example shown here is for emittance exchange
- **-40 MeV beam energy**

# NML/ASTA

## Schematic layout of NML beamlines



- **Low energy beamlines:**
  - 40 MeV (gun, two 9-cell cavities)
- **High energy beamlines:**
  - 810 MeV (3 cryomodules);
  - 1075 MeV (4 cryomodules);
  - 1500 MeV (6 cryomodules with radiation shielding considerations ),
- **Space for a 10 m storage ring**



# CMTF

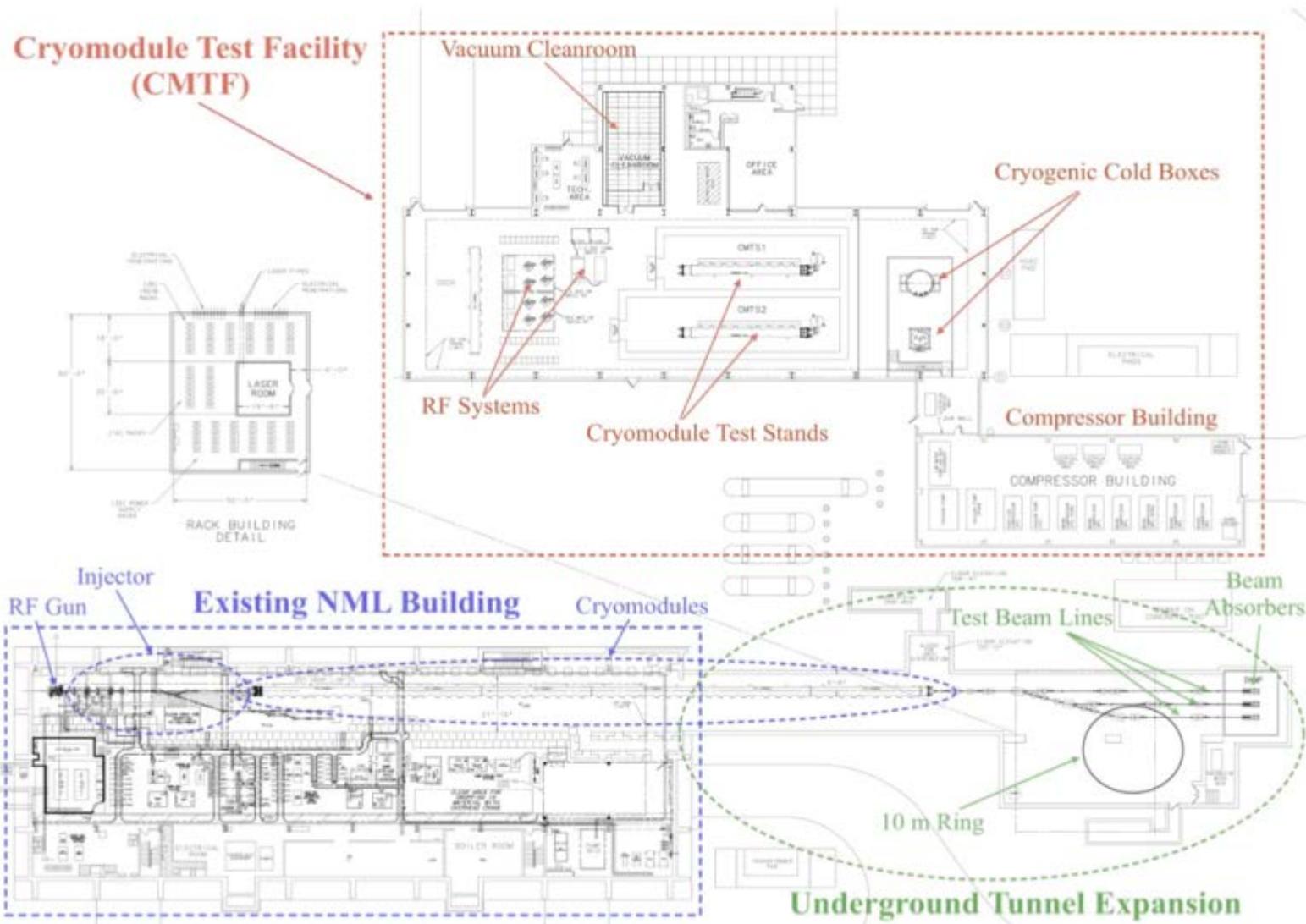
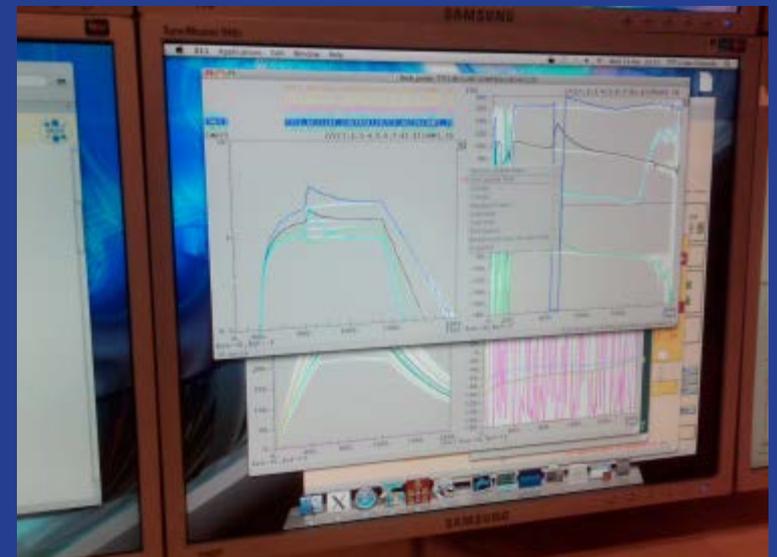
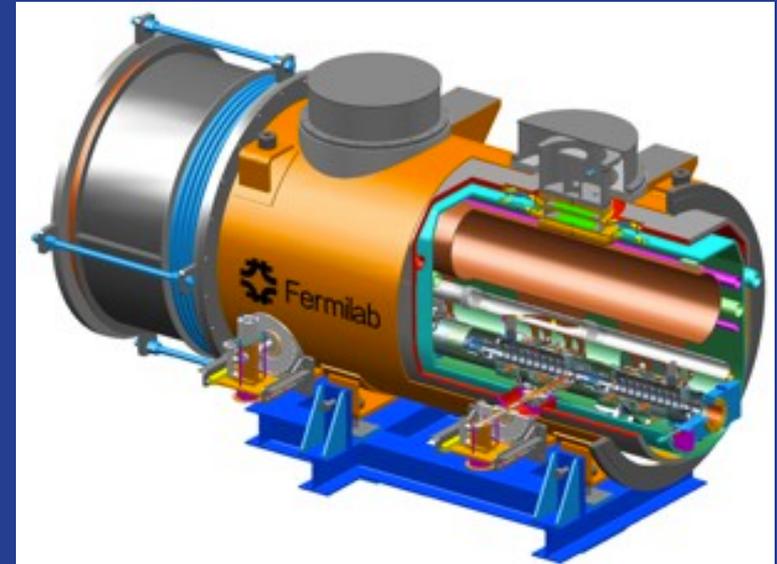


Figure 1: Overall layout of the new SRF Accelerator Test Facility at FNAL.

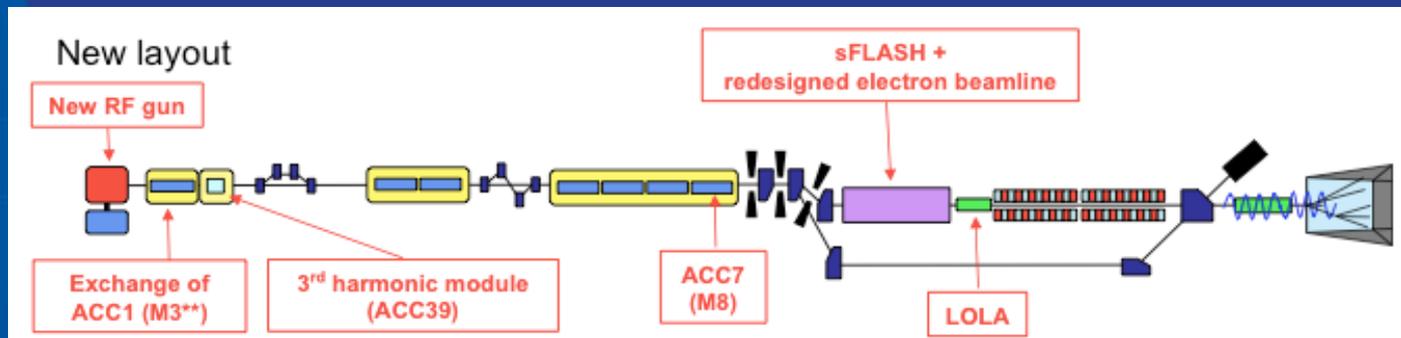
# 3.9 GHz/ACC39

- Fermilab's deliverable in return for Cryomodule 1
- 4-cavity cryomodule - deflecting mode
- Tesla design
- First real SRF design, fabrication, test, and assembly work
  - Cavities (w/Jlab)
  - Horizontal Test Stand
  - Coupler Conditioning
  - MP-9clean room and cold mass assembly
  - Pressure vessel certification, ORC
  - Overseas and overland Transport
- Issues
  - HOM's – not a simple scale-down
  - Titanium welding
  - HOM coupler feedthroughs
  - HTS commissioning
- Results
  - First 3.9 GHz system
  - Successful installation and commissioning in FLASH
  - Routine operation since April 2010
  - Basis for future systems (XFEL, NGLS)



# The 3.9 cavity module: What is it/What does it do?

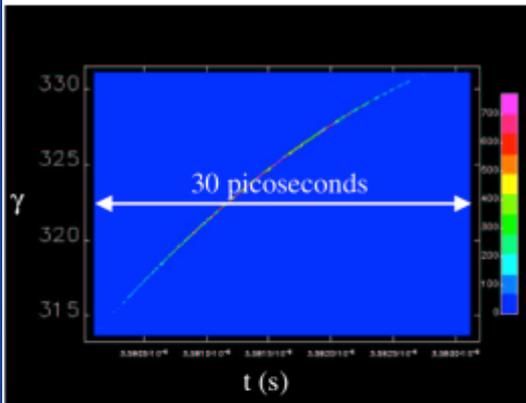
- The 3.9 GHz module, ACC39, is installed in the DESY FLASH injector just after the 1.3GHz ACC1 (first) cryomodule.
- It is used in conjunction with ACC1 in order to linearize the bunch energy vs. time over the bunch length.
- This in turn makes “bunch compression” to very short bunches with high peak currents more efficient, ~~or~~ a more controlled longer bunch charge distribution.
- The SASE FEL operation is more efficient and stable making seeded operation (sFlash) possible.
- It is an important proof of principle not only for FLASH and XFEL but also for accelerator-photon physics, not to mention a learning experience.
- The control of the phase and amplitude of the 1.3-3.9 module pair is very important.



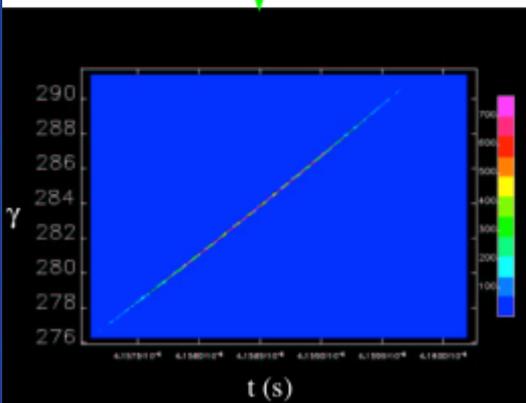
# Bunch Compression with 3.9 GHz Module

After acceleration w/o

after acceleration in a TESLA module

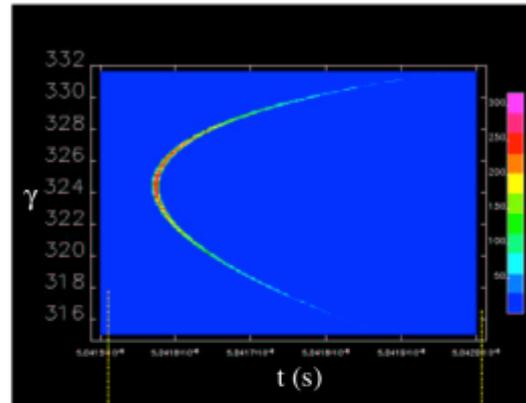


through 3.9 GHz acc. section

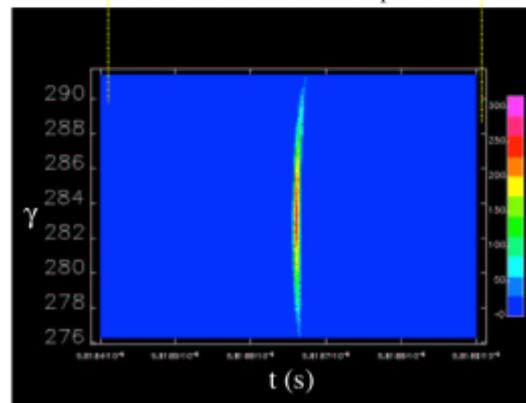


After compression w/o

downstream of bunch compressor

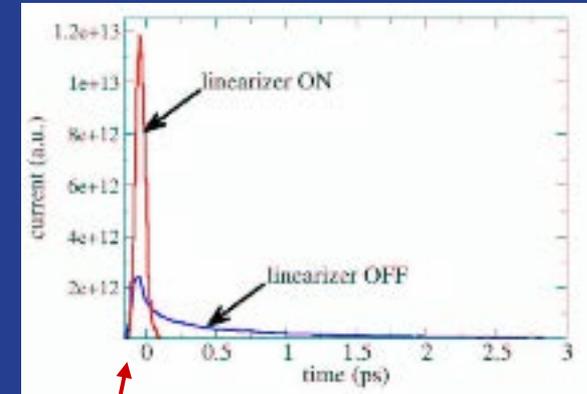


5 picoseconds  
downstream of bunch compressor



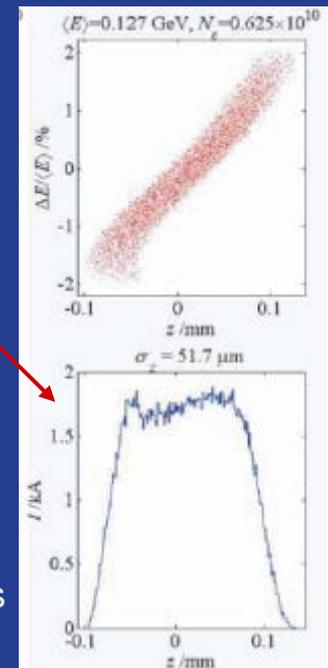
With 3rd harmonic

From P Plot



Short bunch

Flat bunch  
~250 fs  $\sigma$



From M Dohlus et al

# Parameters

Parameter List for the 3.9 GHz Cavities W. - D. Moeller, 14.08.02

Type of structure	standing wave
Accelerating mode	$\pi$ -mode
Voltage	20 MV
Accelerating gradient, $E_{acc}$	14 MV/m
Phase	-179°
Cell to cell coupling	3.97 %
Stored energy	1.2 J
Frequency	3.9 GHz
cavity	9 - cell
$R/Q$ [ $=U^2/(\omega W)$ ]	375 Ohm [750 Ohm]
$E_{peak}/E_{acc}$	2.26
$B_{peak}/E_{acc}$	4.86 mT/ (MV/m)
$B_{peak}$ @ $E_{acc} = 14$ MV/m	68 mT
Tuning range	3900 $\pm$ 1 MHz
$\Delta f/\Delta L$	2.39 MHz/mm
Lorenz force detuning constant $K_{L,or}$	6 Hz/(MV/m)
Number of cavities	4 (+2 spares)
Beam current	9 mA
$Q_{ext}$	13.0 x 10 <sup>3</sup>
Total Energy	20 MeV
Bandwith	4.1 kHz
Forward power	11.5 kW
Coupler power (per coupler)	45 kW
BBU limit for HOM, $Q_{ext}$	< 1.0 x 10 <sup>3</sup>
Active length of 9 cells	345.96 mm
2 x taper in beam pipe	0
2 x length of beam pipe (for power- and HOM- couplers)	159.94 mm
Cavity overall length	505.9 mm
Bellow length	102 mm
Total length needed (end flange to end flange)	2329.70 mm

# Cavity Design, Fabrication, Preparation

- Basic design was a 1/3 size modified version of a TTF style 1.3 GHz cavity.
- 8 cavities initially fabricated
  - 2 prototypes
  - 6 'production'
- Fabrication was a collaborative exercise with JLab & DESY
- E-beam welding done...
  - locally at Sciaky (Cavities 1-2, 7-8 plus Helium vessels)
  - at JLab (Cavities 3-6, repair on 2, 6).
- Cavity prep – including ultrasonic cleaning, BCP, 800° C bake, HPR, dressing into Helium vessel, etc. all carried out at Fermilab or overseen by FNAL staff
  - BCP carried out at Argonne by Fermilab staff (G-150)



# ACC39 Highlights

- 2002 TESLA Facility Phase 2 Report with 3.9 GHz module for bunch compression (TESLA-FEL 2002-01)
- 2002-3 Cavity design documents (TESLA-FEL 2002-05, 2003-01/FNAL TM 2210)
- 2005 DESY-FNAL MOU on 3.9 module
- 2006, 03-06 C1,C2 failures, Multipacting & HOM wall thickness
- 2006, 08 **C3 fabrication finished** – first production cavity
- 2007, 05 **C3 good vertical test** after HOM formteils cut, 24MV/m
- 2007, 10 C5 vertical tests with HOM feed-throughs complete 19MV/m
- 2008, 02-09 C5 in horizontal test stand (HTS)
- 2008, 04 **C5 achieved 22.5MV/m in HTS**
- 2008, 12 C7 last cavity of four removed from HTS
- 2009, 01 String assembled in MP9 Cleanroom
- 2009, 02 Cold mass to ICB
- 2009, 04 **Module finished** and shipped to DESY
- 2009, 09 ACC39 installed in CMTB
- 2010, 04 ACC39 operational in FLASH

# Cavity Pedigrees



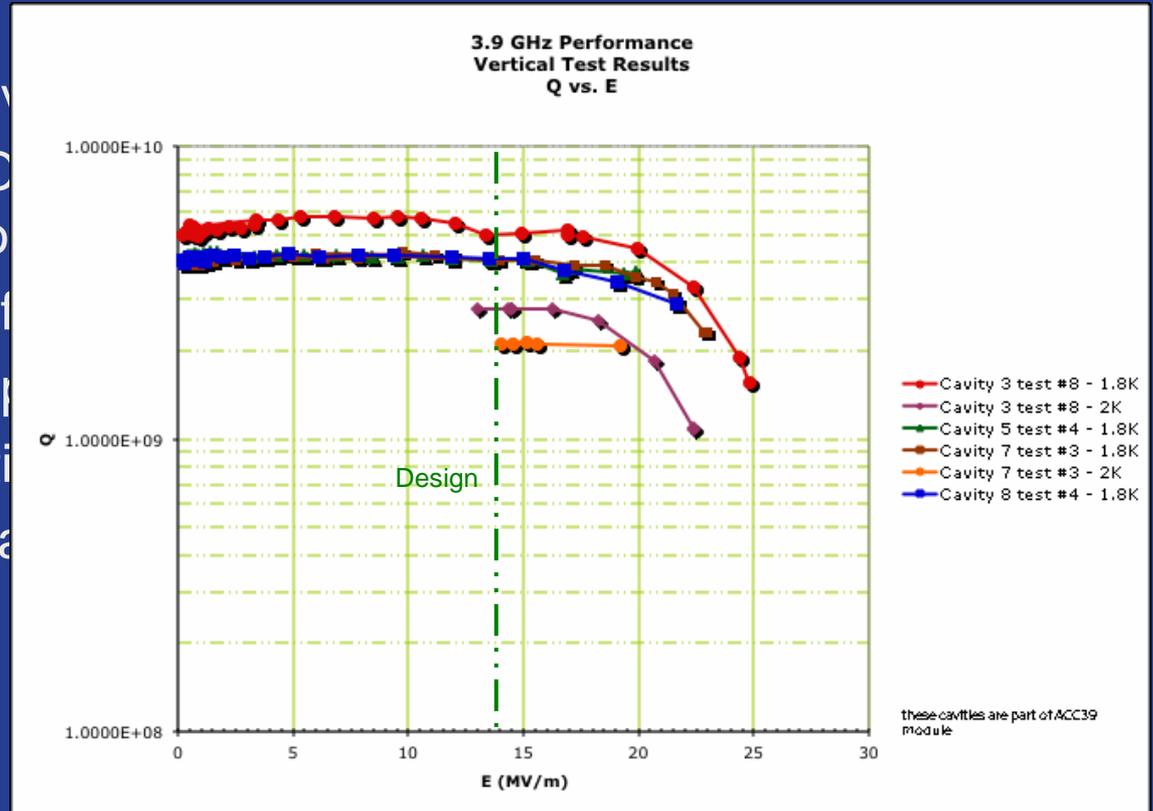
Cavity	Assembled by	Completion date	Test results and status
#1: 2-leg HOM	Fermilab	January 2006	Never tested: HOM membrane break during cleaning - Used as horizontal test prototype
#2: 2-leg HOM	Fermilab	February 2006	- Best vertical test: 12 MV/m limited by HOM heating - Fractured Formteils - Repair attempted
#3: 2-leg trimmed HOM	Fermilab JLab	August 2006	- Best Vertical test: <b>24.5 MV/m</b> , achieved after HOM trimming - Horizontal testing: <b>22.5 MV/m</b> limited by quench - <b>Part of final string assembly</b>
#4: 2-leg trimmed HOM	Fermilab JLab	March 2007	- Best Vertical test: <b>23 MV/m</b> - Horizontal testing: 18 MV/m limited by quench
#5: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: <b>24 MV/m</b> - Welded into Helium vessel - Horizontal testing: <b>22.5 MV/m</b> limited by quench - <b>Part of final string assembly</b>
#6: 2-leg trimmed HOM	Fermilab JLab	May 2007	- Best Vertical test: <b>22 MV/m</b> - Faulty welds repaired - Awaiting final vertical test with HOM feedthroughs
#7 single-post HOM	Fermilab JLab DESY	November 2007	- Best Vertical test: <b>24.5 MV/m</b> - Welded into Helium Vessel - Horizontal testing: <b>26.3 MV/m</b> limited by quench - <b>Part of final string assembly</b>
#8 single- post HOM	Fermilab DESY	October 2007	- Vertical test: <b>24 MV/m</b> - Horizontal testing: <b>24 MV/m</b> limited by quench - <b>Part of final string assembly</b>

# Vertical Testing/Results

- All Cavities went through at least 4 vertical tests (at A0 – Photoinjector and SRF R&D facility), including



- Bare cavity
- With HC ready for
- Some at
- Some up
- Production
- More than

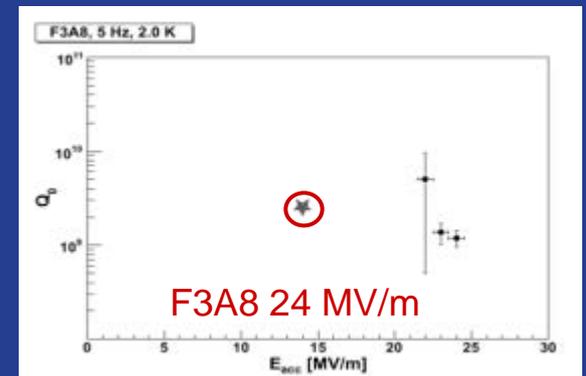
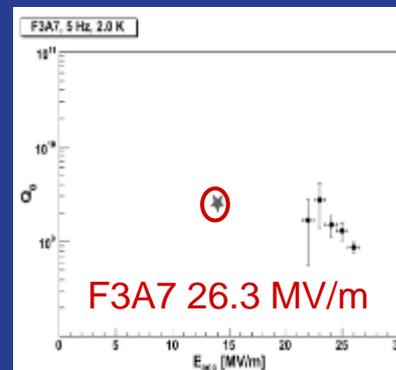
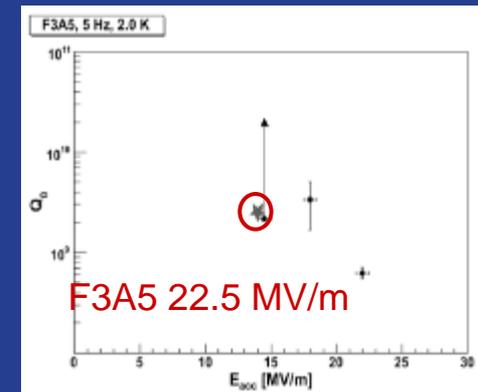
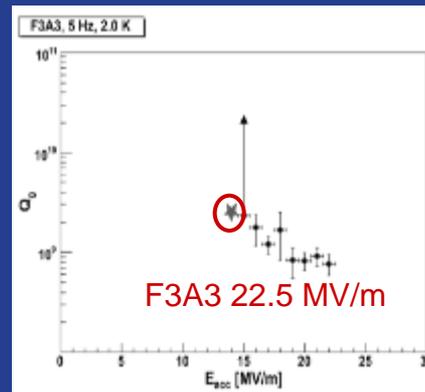


# Horizontal Testing/Results

- ACC39 cavities all tested at Horizontal Test Stand (HTS)
  - HTS commissioning largely carried out with 3.9 GHz cavities (#5)
  - ~ 1 month/test including installation, cooldown, and removal



Design Gradient  
14MV/m



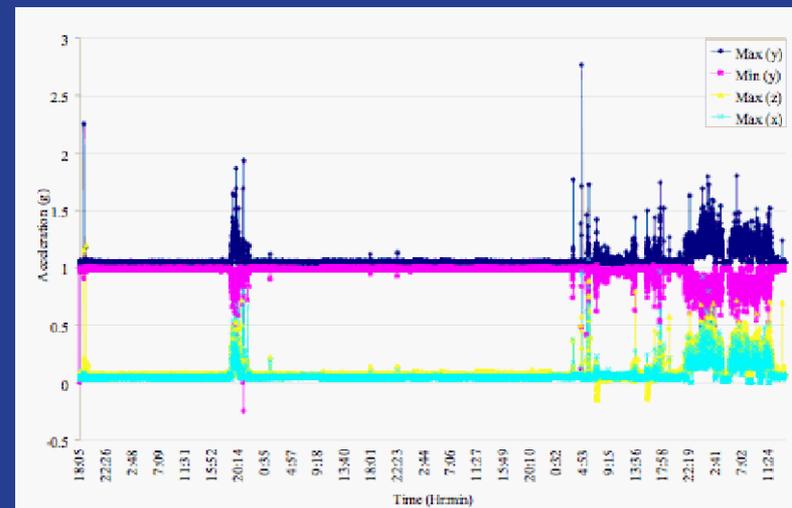
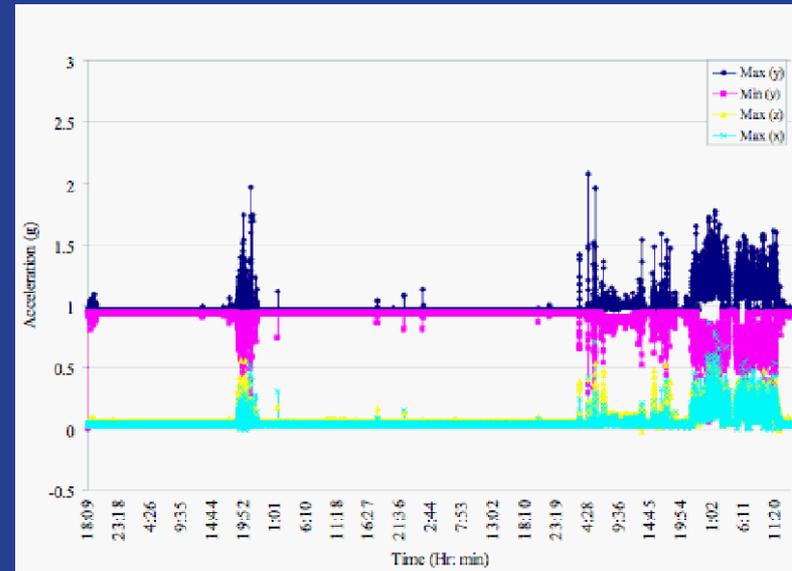
# Transport to DESY

- Completed module departed Fermilab on 24 April 2009
- Delivered to DESY four days later.
- Transport was accomplished
  - Via truck from Fermilab to Chicago O' Hare airport
  - Air cargo transport to Paris - Charles de Gaulle airport
  - Overland transport via truck from Paris to Hamburg
- All critical transfer points were witnessed by Fermilab and DESY personnel once the module arrived in Europe.



# Transport to DESY - 2

- The choice and placement of diagnostics to monitor shock and vibration during transport done with deliberation.
- Acceleration of the cryomodule during all phases of transport was maintained at or below 1.2 g in all planes – well within the specified criteria.
- Cavity string was shipped under vacuum; instrumentation was installed during cold mass assembly to allow one to monitor the vacuum pressure prior to, during, and after shipment.
  - $4.8 \times 10^{-4}$  Torr prior to departure (two weeks after active pumping was ceased)
  - $7.7 \times 10^{-4}$  Torr upon arrival in Paris and thereafter

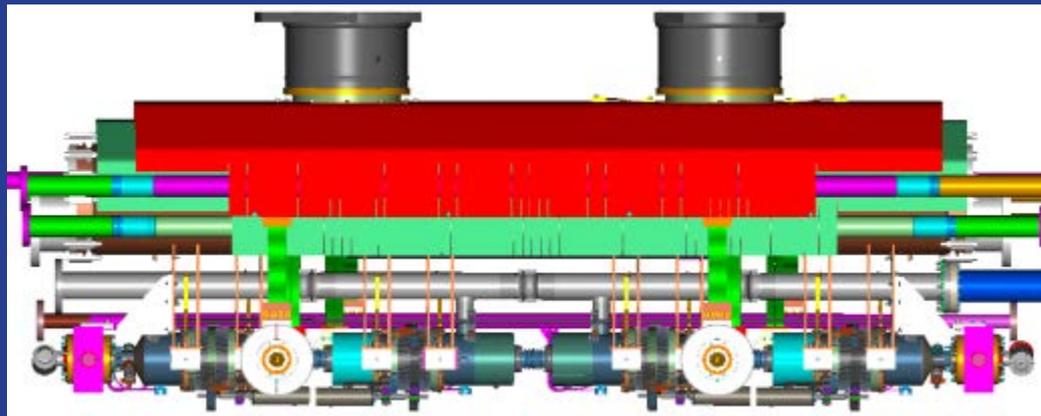


# Checkout & Preparation for Testing at DESY

- Post-transport checkout to verify
  - vacuum leak tightness
  - Alignment - no significant misalignment of the cavity string occurred during transport.
- Misalignment of some needle bearings necessitated the partial disassembly of the module.
- Longitudinal realignment of the cavity string  $\sim 4\text{mm}$  upstream of its initial location with respect to the fixed support post.

upstream

downstream

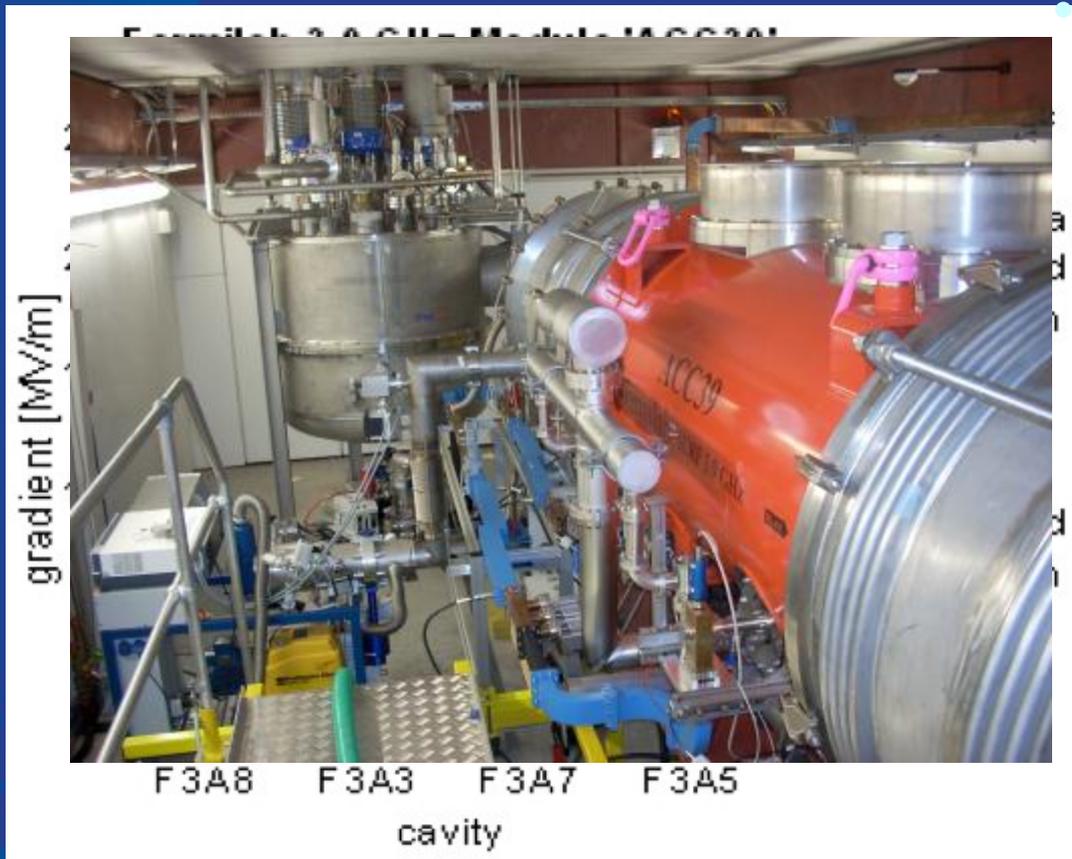


String shifted by 4.0 mm upstream

# Checkout & Preparation for Testing at DESY - 2

- Faulty thermometry splices were similarly discovered and corrected.
- Warm ends of the input couplers installed and verified leak tightness once the re-alignment was completed.
- External electrical connections to internal instrumentation and tuner motors operated and verified.
- Two checks of the string alignment and the cavities relative to each other. Deviation found to be within specification as compared to Fermilab exit data.
  - Cavity targets as a group - maximum difference 0.16mm
  - Relative to cold mass - maximum difference 0.28mm
  - Measurement accuracy ~0.15mm
  - Gate valve motion ~0.7 mm.
- Frequency spectrum and HOM notch frequencies measured and compared with Fermilab exit data - ok.

# Cumulative Test Results

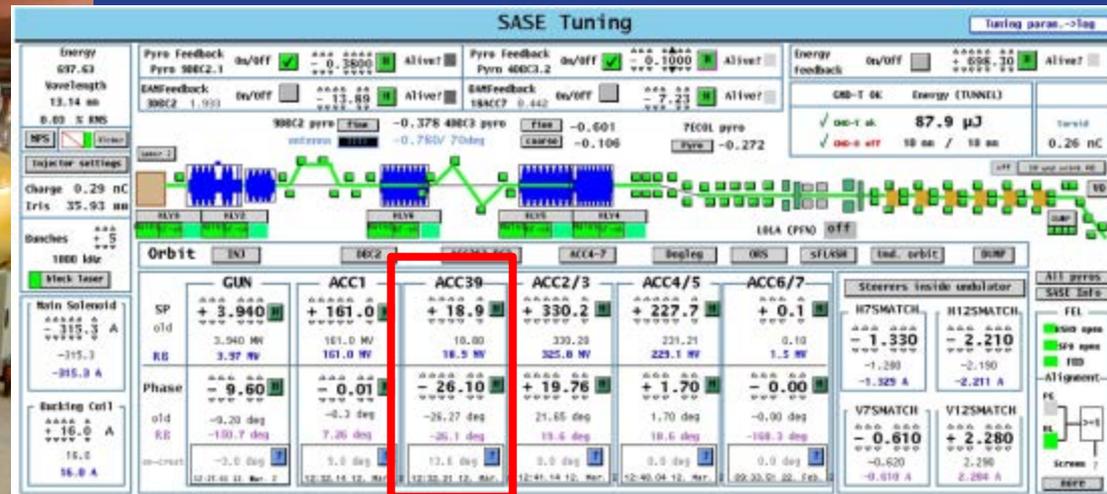


Entire cryomodule was tested for the first time at DESY in their CryoModule Test Bench (CMTB) prior to installation in FLASH

- (mostly) Successful assembly
- Successful transatlantic shipment
- Some rework at DESY

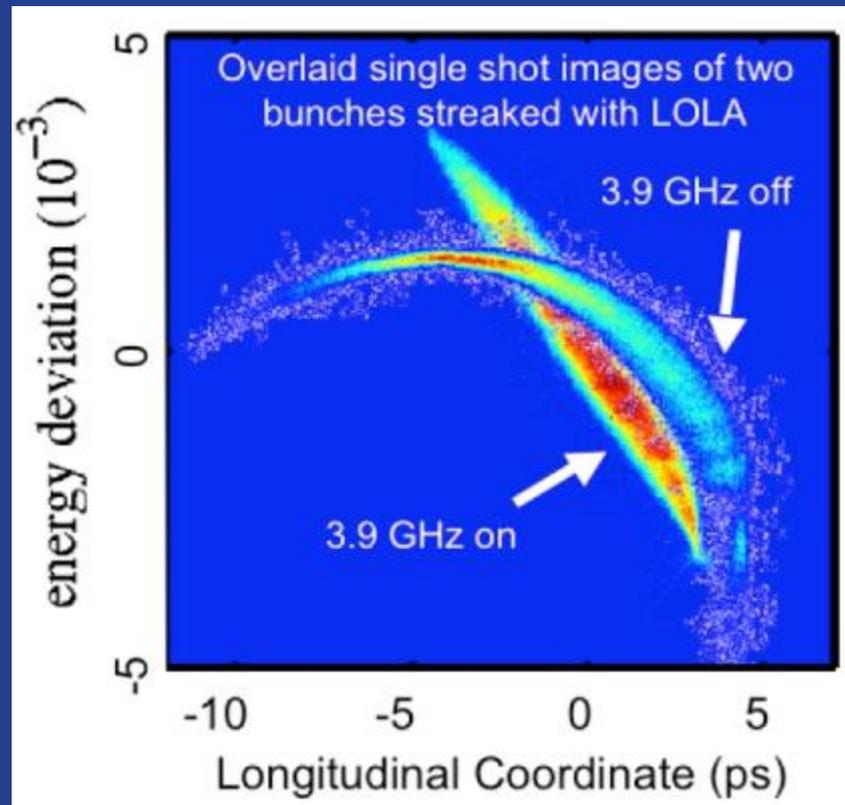
# ACC39 Performance

- ACC39 routinely operates at 18.9 to 19.7 MV/m
- Peak Capability is 22 MV/m
  - Limitation set by thermal interlocks – concern about compromising HOM's on Cavities 3 & 5 (trimmed 2-post style)



# ACC39 Performance

- Set up for lasing has gone from expert tune up (shifts) to nearly immediate after turn-on



# Operation in FLASH

The screenshot shows a web browser window displaying a news article from the DESY website. The article is titled "Record wavelength at FLASH - First lasing below 4.5 nanometres at DESY's free-electron laser" and is dated Hamburg, 2010/06/15. The main text states: "For the first time, FLASH produced laser light with a wavelength of 4.45 nanometres; thus, DESY's free-electron laser for soft X-ray light considerably beat its previous record of 6.5 nanometres. At the same time, the peak intensity of single light pulses nearly doubled, with 0.3 millijoule. Prior to this, there was a five-month machine upgrade, above all with a significant improvement of the superconducting linear accelerator and the installation of a seeding experiment together with the University of Hamburg." A graph shows a sharp peak in the spectrum of the record laser pulse at a wavelength of 4.45 nanometres. The article also mentions that the linear accelerator was operated at 1.207 GeV and the 3.9-GHz module shapes the electron bunches in a way that the intensity of the laser light is higher than ever before. A quote at the bottom of the article reads: "This success is also an important milestone for the European XFEL on the way to the observation of movements that only take femtoseconds. The accelerator module recently built-in at FLASH is a prototype for the XFEL accelerator, and the properties of the 3.9-GHz module too are decisive for operating the XFEL injector. The third FLASH user period is to start end of August." The website header includes the DESY logo and navigation links for accelerators, photon science, and particle physics.

“Moreover, a special 3.9-GHz module was installed to improve the quality of the accelerated electron bunches. The first tests during the current commissioning showed excellent results: the linear accelerator was operated at 1.207 GeV and the 3.9-GHz module shapes the electron bunches in a way that the intensity of the laser light is higher than ever before.”

This success is also an important milestone for the European XFEL on the way to the observation of movements that only take femtoseconds. The accelerator module recently built-in at FLASH is a prototype for the XFEL accelerator, and the properties of the 3.9-GHz module too are decisive for operating the XFEL injector. The third FLASH user period is to start end of August.

# Spare Cavities



- One new 'modern' style cavity fabricated and vertically tested – F3A9
  - Single-post HOM F-piece
  - $>20$  MV/m with no field emission, good  $Q_0$
  - ready for dressing and HTS
- Two production cavities rebuilt with new ends/single post HOM's
  - Cracked HOM F-pieces prompted re-work
  - Vertical tests
    - First cavity achieved 14.4 MV/m limited by field emission (similar to LASA result)
    - Ready to re-test – next week?

# Lessons Learned (and applied)

- New infrastructure built and commissioned
  - Commissioning in parallel with qualifying components
- HOM redesign
  - Not simply a scaled version
  - Modeling and prototyping important
  - Robust design is the end result
- HOM coupler antennae
  - Prototyping and testing is vital before placing order
- Engineering Notes (Director Exceptions)
- Operational Readiness Clearance (ORC)
- Welding certification
  - Especially Helium vessels
- 'New' technologies explored and applied

# Lessons Learned - 2

- This effort proved to be far more than merely a scaled version of a 1.3 GHz TESLA module.
- Prototyping is vital, mock-ups were very helpful
- Do not assume vendor competence; regular visits are important
  - even to partner labs
- Do not order all parts at once. Order a subset, evaluate, then complete order.
- Develop a test plan, include flexibility and contingency
  - Single tests are insufficient
  - System calibration is a must
  - If test are done across labs, consider cross-calibration
  - 20% variation in results
- Infrastructure development
- Encourage reviews (within reason)

# Why Do It & What Has It Done for Fermilab?

- The 3.9 effort is part of an ongoing collaboration with DESY
- In this collaboration DESY has advised Fermilab on many of the aspects of SRF development and has supplied design and assembly information.
- DESY provided for Fermilab a 8 cavity module at 1.3 GHz. This Module was installed and operated in the NML facility – **successful** operation recently ended.
- The 3.9 GHz module has been/will be a learning experience for FNAL in all aspects of beta 1 SRF cavity and module design through commissioning
- Successful completion has clearly shown Fermilab's growing competence and abilities in SRF technology
- We have learned and benefited for our experiences and “Lessons Learned”
- We are applying and sharing this capability

# How?

- Consult with LASA, Milano on design and fabrication of 3.9 GHz cavities for XFEL
  - ongoing collaboration
  - participate in tests later this month
- Prototype 3.9 GHz Input couplers for European XFEL assembled, inspected, and conditioned here (only 3.9 GHz coupler test stand in existence)
- In negotiation for HTS testing dressed cavities (only one 3.9 GHz capable test stand in existence)
- Investigating a 3.9 GHz module for NML – in discussion with an industrial partner
- NGLS design includes a 3<sup>rd</sup> Harmonic system

## 3.9 GHz Summary

- Fermilab has successfully designed and built the only 3.9 GHz multi-cavity cryomodule now in existence
- ACC39 is now in routine operation at DESY/FLASH
- Cavity performance well exceeded specifications
- Performance is consistent with cavity tests
- Cavity & Cryomodule work were valuable learning experiences for SRF development here
- Acknowledged leader in this niche area – our expertise is sought
- Unique infrastructure developed – could support possible future collaborations
- Investigating future application at NML/ASTA



# 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
- Assembly at Fermilab
- Installed and operated at the refurbished New Muon Lab experimental hall until March 2012



# Achievements

- All couplers conditioned in the warm
- Cooldown from room temperature to 2 K in  $< 1$  week
- Cold coupler conditioning and cavity performance determined – one cavity at a time
- Installation of waveguide distribution and complete cryomodule operated
- All subsystems commissioned (and improved)
  - Esp. LLRF & LFDC
- 9ms pulse test for P-X
- Thermal cycle
- Warm-up & Removal
- *26 months from installation to removal*

# Test Plan/Performance Evaluation Steps

- Each cavity singly connected to the output of the klystron to determine its performance.
- A prescribed series of measurements are 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.  $E_{ACC}$
- Waveguide Distribution system installation
- Full cryomodule powering and evaluation
- Ad hoc measurements as deemed necessary

# Milestones

- Steps towards making CM1 operational
  - 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)

## 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
- . 28 January 2011 - 7 March 2011: Cavity 8/S33
- . 7 - 16 March 2011: Cavity 2/AC75
- . 18 - 22 March 2011: Cavity 1/Z89 *reprise*
- . 26 March - 4 April 2011: Cavity 3/AC73
- . 20 April - 19 May 2011: Cavity 4/Z106
- . 20 - 25 May 2011: Cavity 5/Z107
- . 3 – 9 June 2011: Cavity 6/Z98
- . 9 – 11 June 2011: Cavity 7/Z91

# Milestones - 3

- 6 July 2011: Initiate full module operation
- 22 September – 5 October 2011: Klystron High Voltage power supply repair
- 7 December 2011 – 3 January 2012: long pulse (9ms) tests
- 4 January – 9 February 2012: thermal cycling and IN2 leak repair
- 2 March 2012: CM-1 operation ends
- 26 April 2012: CM-1 leaves NML, CM-2 delivered
- 26 June 2012: CM-2 returned to ICB after 2-phase leak found

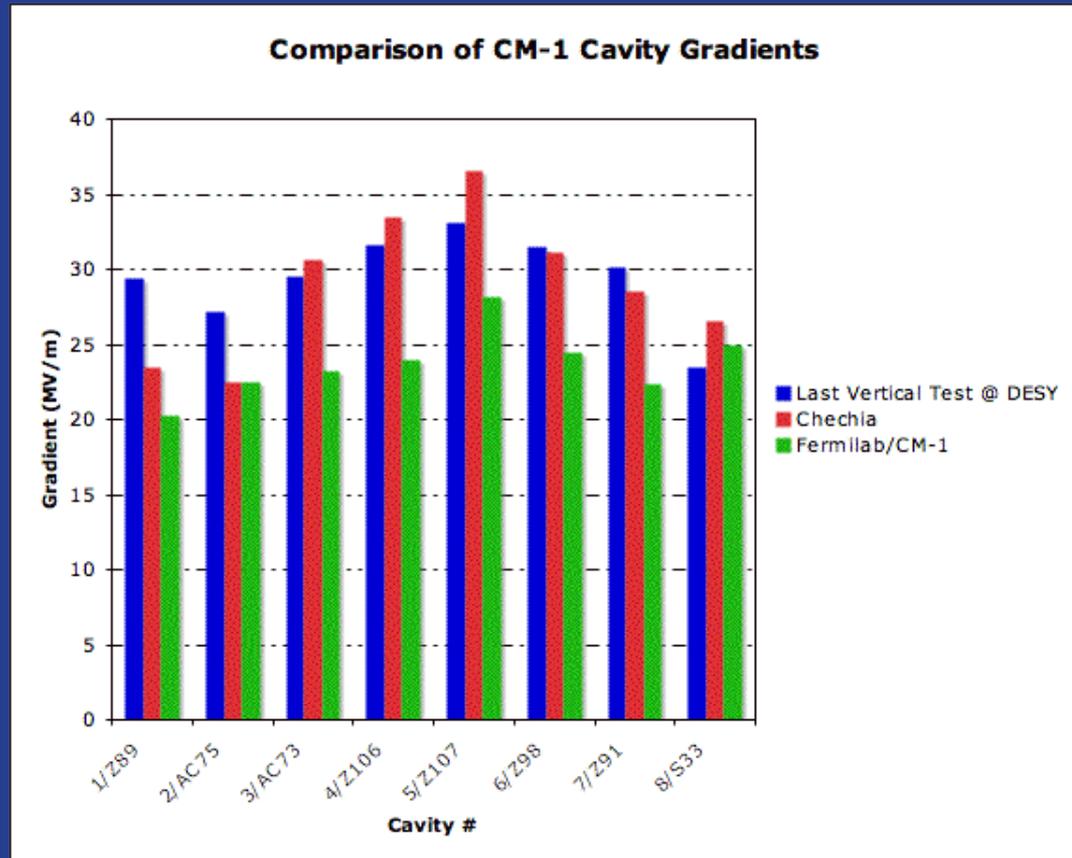
# Cavity Performance Summary

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



# Cavity Performance – Peak Gradient

- After final signal calibrations completed
- Cavity Peak Gradients
  - All cavities on resonance
  - One cavity on resonance at a time
- ILC-like operating conditions
  - 580  $\mu$ s fill
  - 620  $\mu$ s flattop
  - 5 Hz

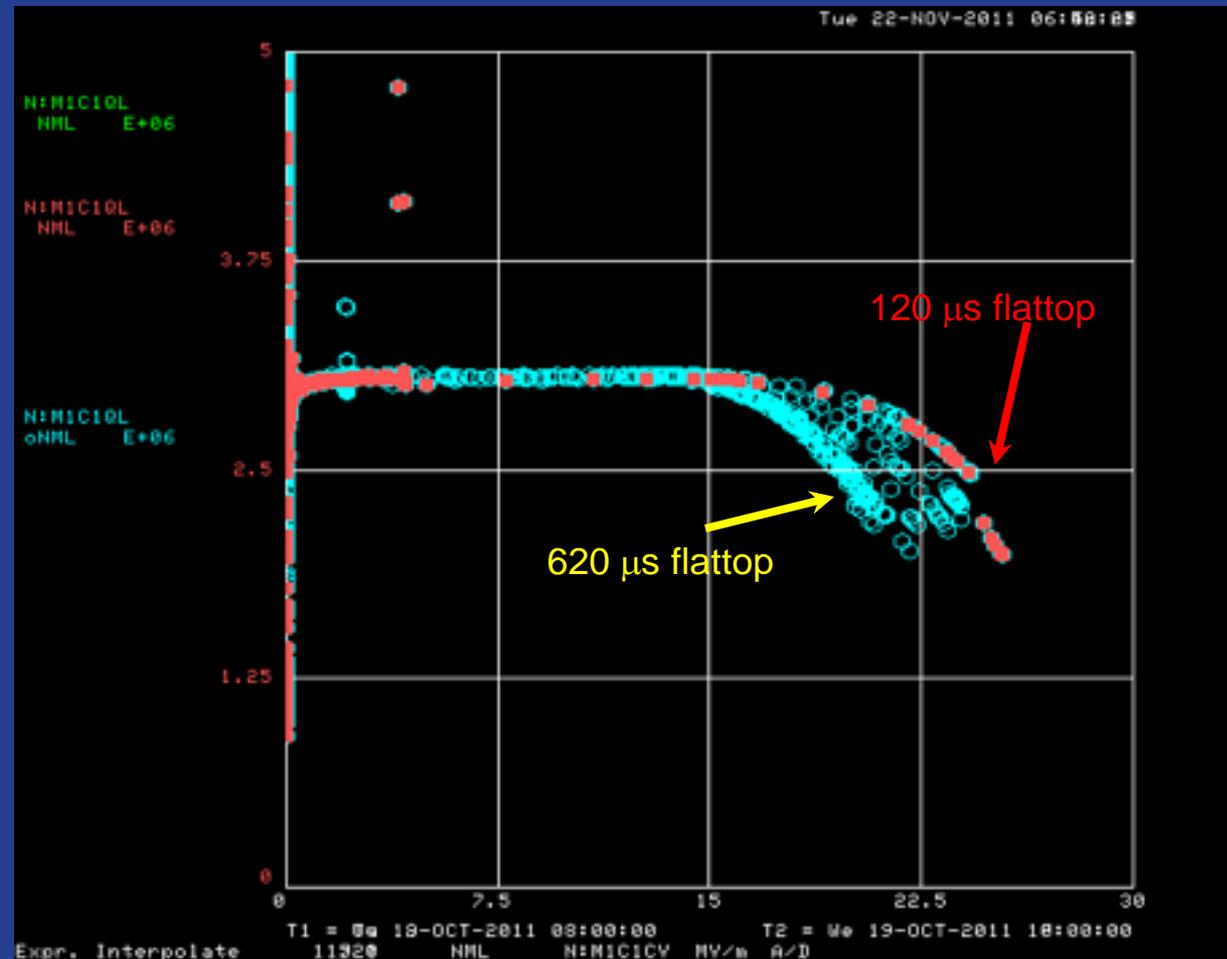


	1	2	3	4	5	6	7	8	Mean
CM-1 Peak Gradient	20.2	22.5	23.2	24*	28.2	24.5	22.3	25	<b>23.7</b>
Ratio compared to Chechia	0.860	1.00	0.758	0.716	0.773	0.788	0.782	0.940	<b>0.827</b>

# 'Soft Quench' investigation: Vary Flattop Length

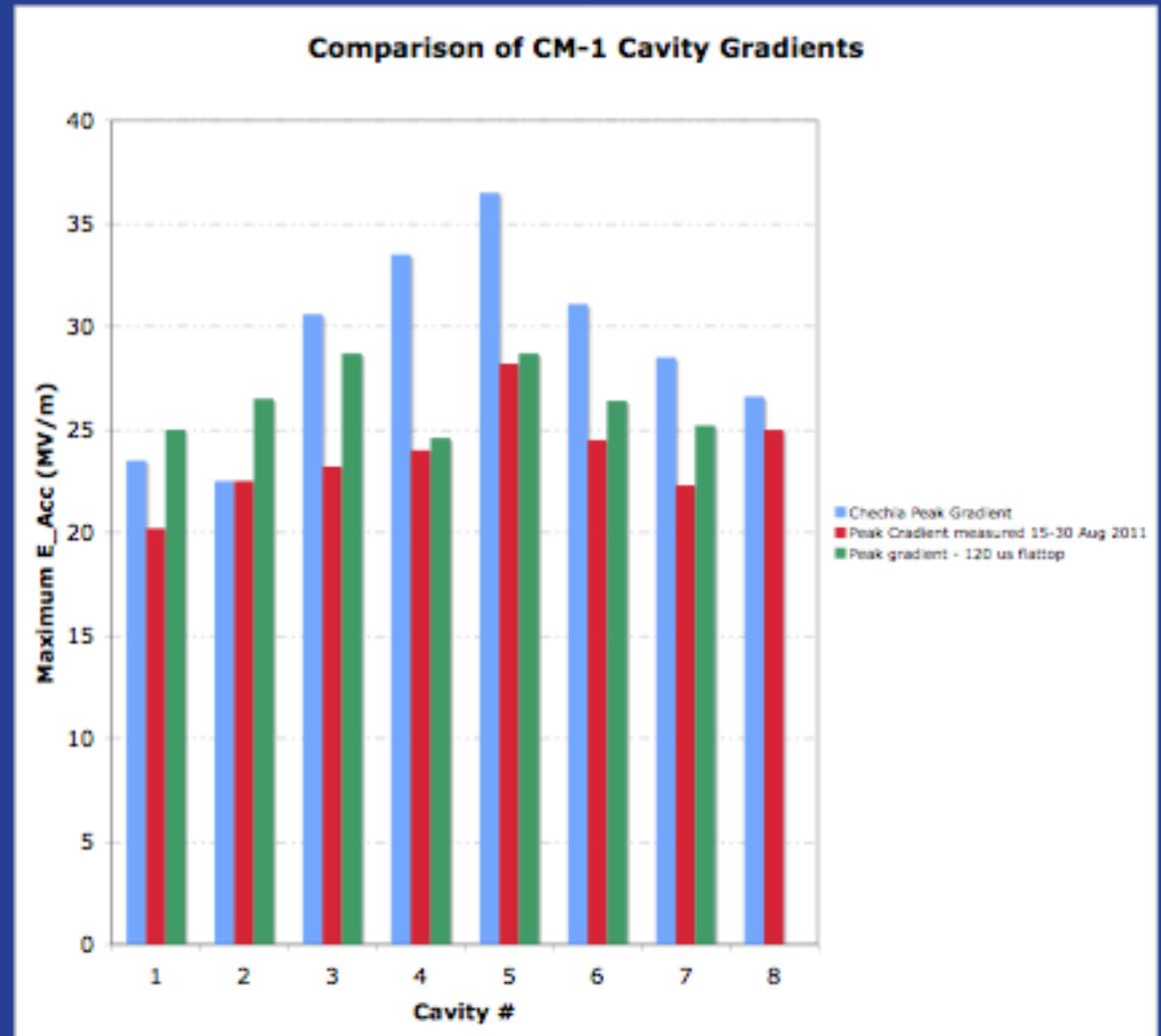
- Cavity #1

- Variation of  $Q_L$  and peak gradient with flattop length
- 100  $\mu$ s increments in flattop length
- Onset of  $Q_L$  drop from 14 - 17 MV/m
- Peak gradient increased from 21 to 25 MV/m

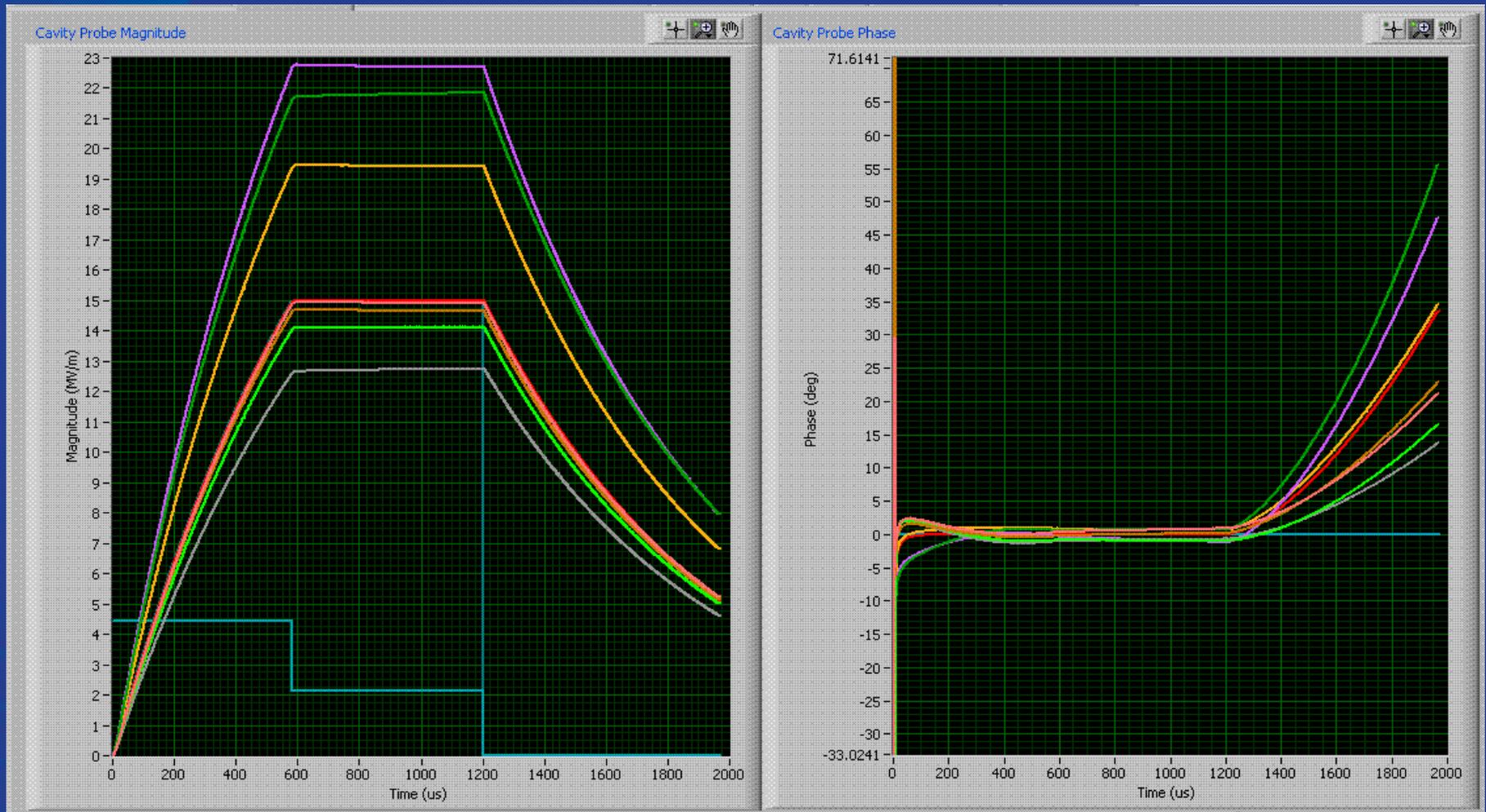


# Vary Flattop Length

- Peak gradients all increased (green compared to red)
- No clear indication of increased HOM heating on suspect cavities
- Quench limit generally inversely proportional to flattop length
- Some cavities limited by available RF power



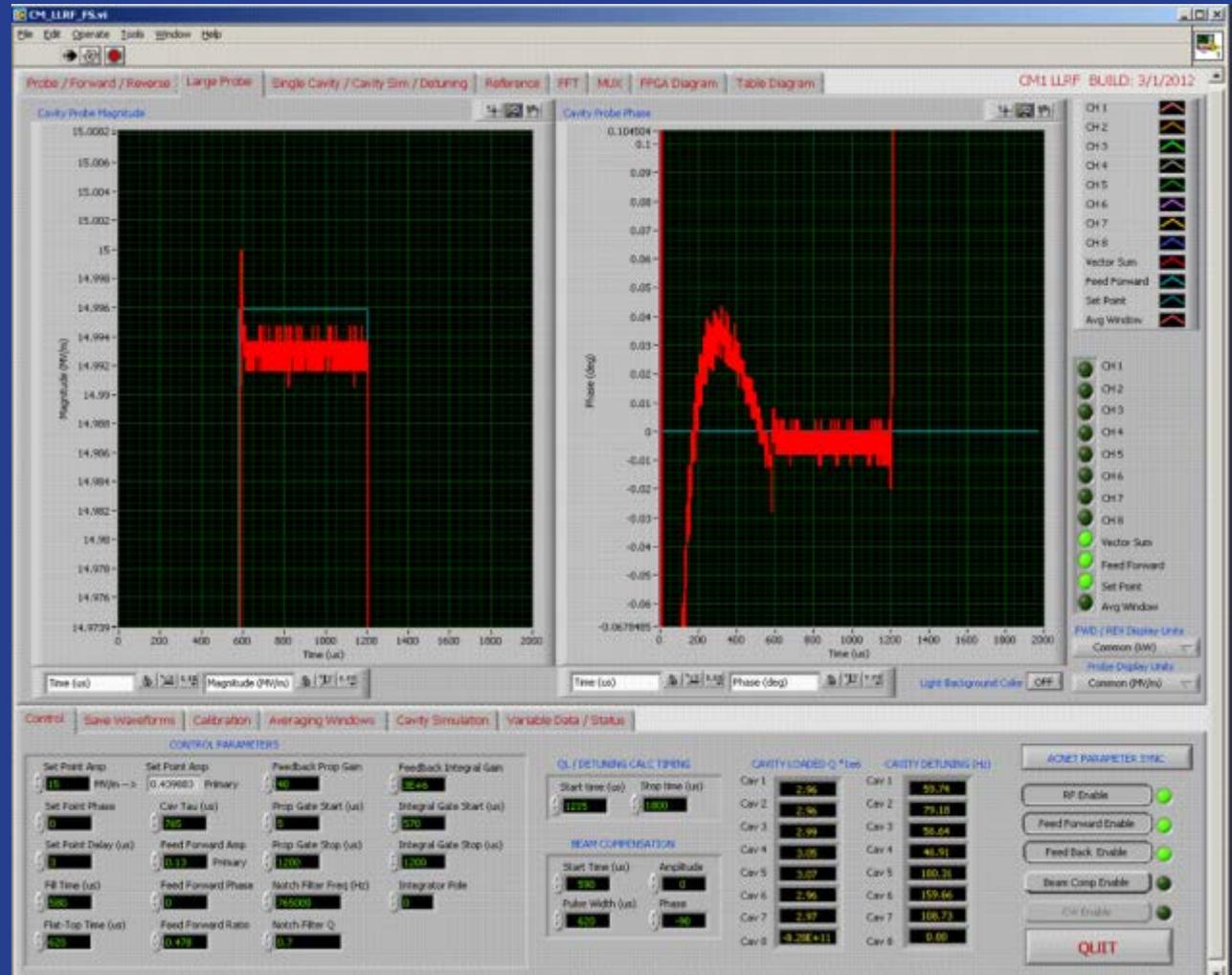
# LLRF System Performance



**LLRF Feedback ON, LFDC ON**

# LLRF System Measurements

- Pulse to Pulse Vector Sum regulation with RF feedback ON and piezo ON.
- 50 Pulses
- Pulse to Pulse RMS magnitude error (%) in loop =  $6e-3\%$
- Pulse to Pulse RMS Phase error (deg) in loop =  $5.0e-3$



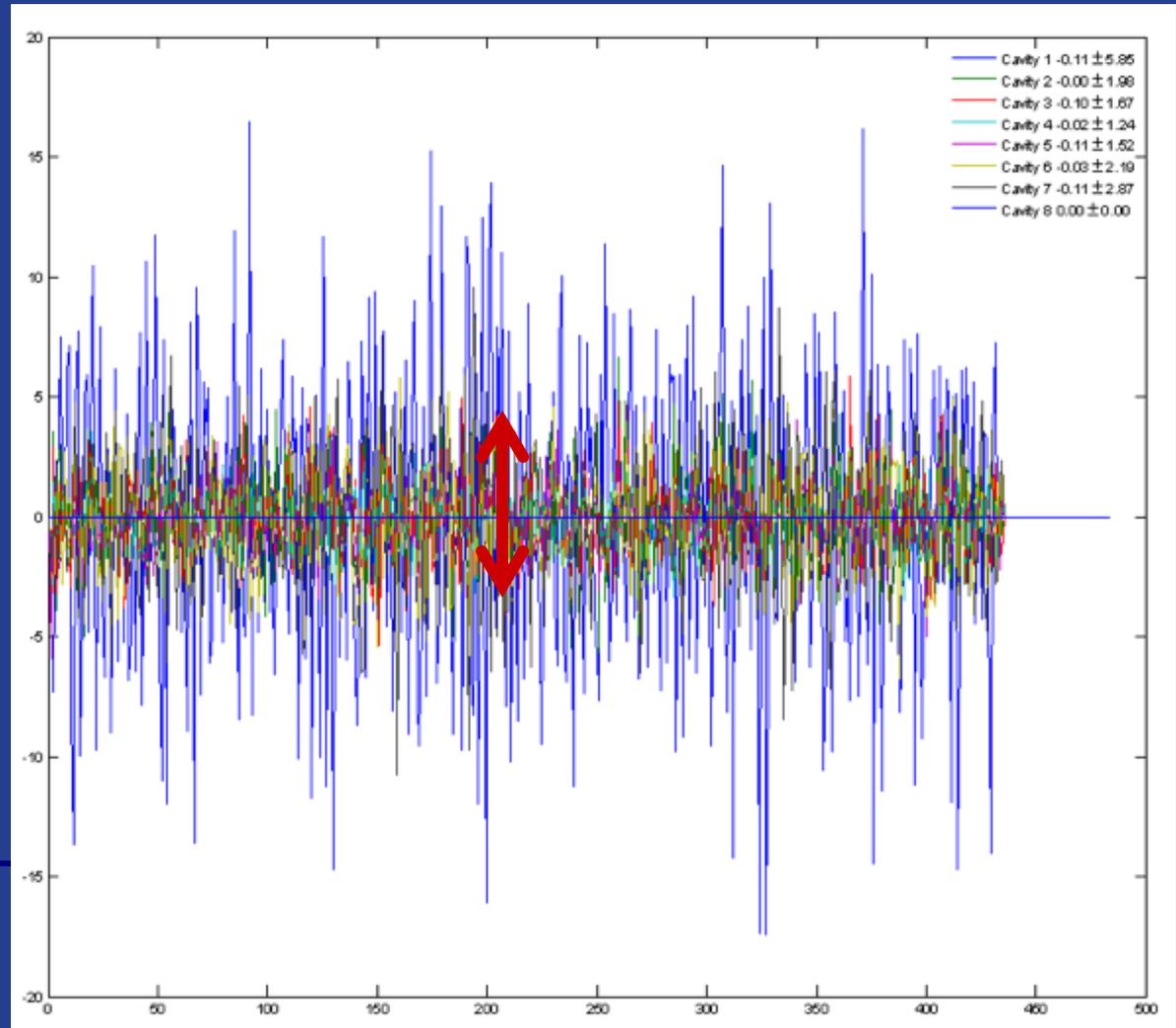
# LLRF System Measurements - 2

## RF Distribution phase measurements

Cavity	Forward Phase	Transmitted Phase	$\Delta$
1	0	0	0
2	-6.5	-6	-0.5
3	-2	-8	6
4	0	5	-5
5	-12	-12	0
6	-6	-4	-2
7	0	16	-16

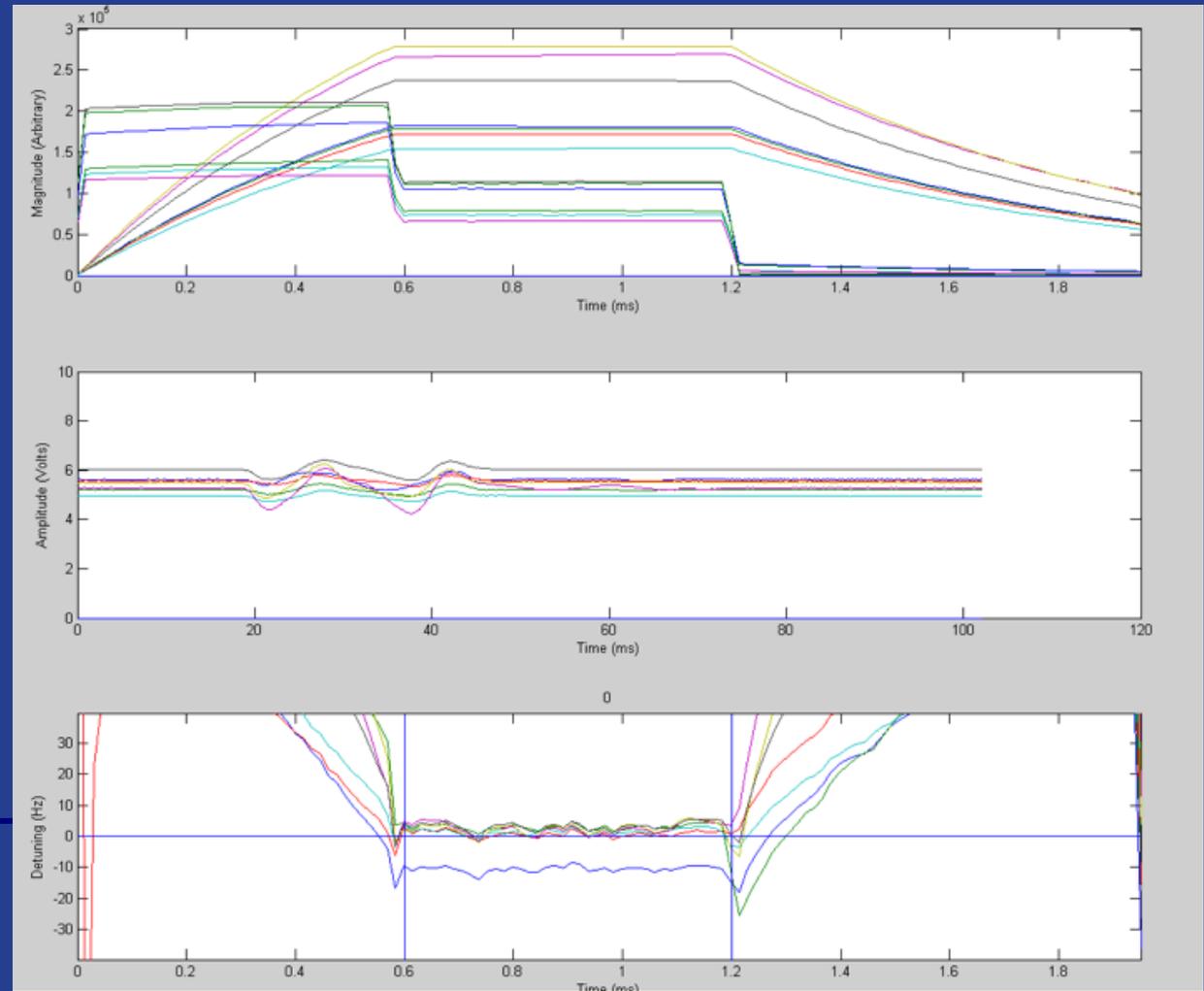
# LFDC Short-term Stability

- The number in the stability plot represent the mean and RMS pulse to pulse detuning over all of the pulses in the plot.



# LFDC Short-term Stability

- The second subplot of the screen-shot shows the piezo waveform while the third subplot show the detuning of the cavities

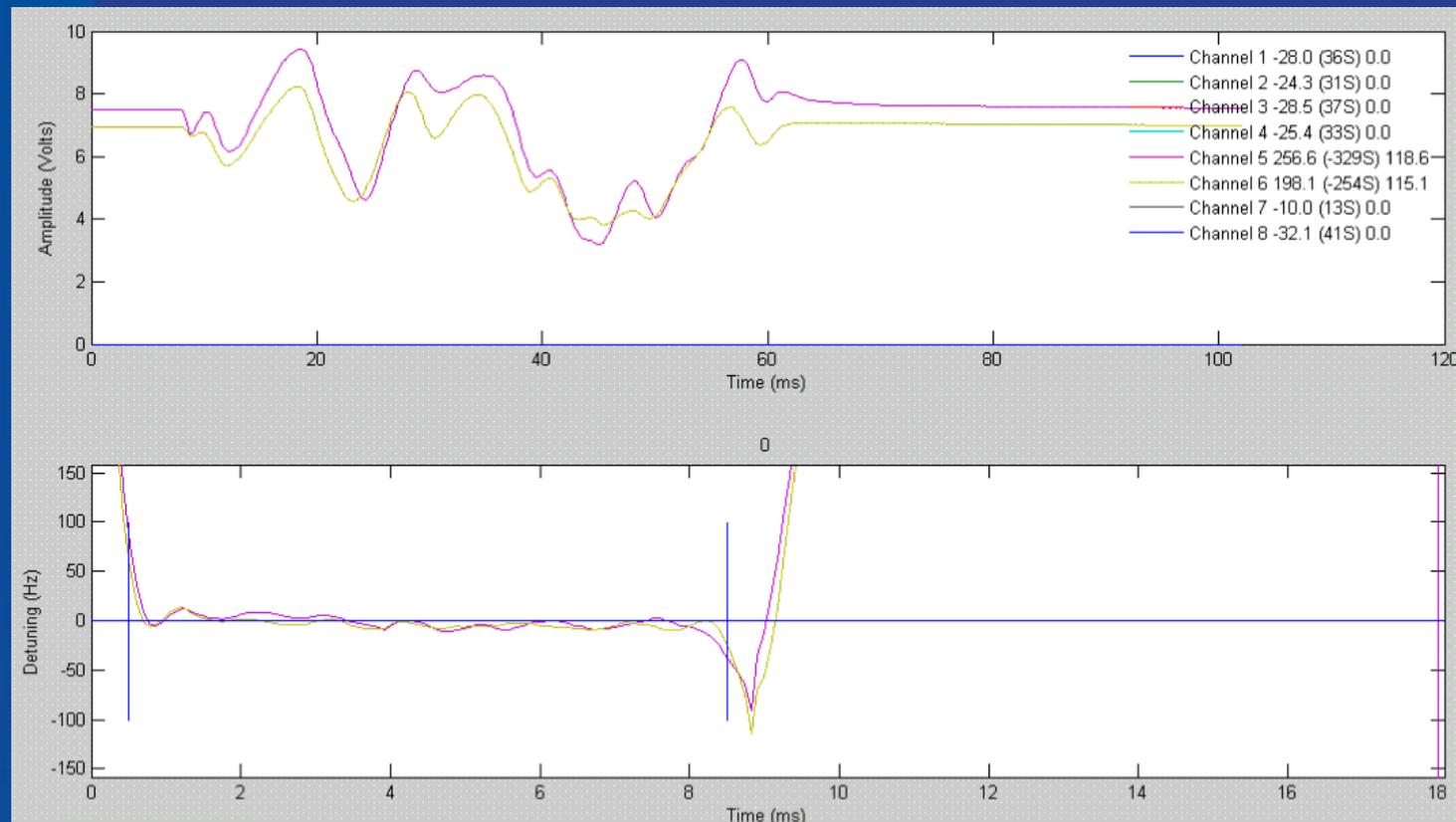


# Long Pulse Operation

- Operate the best performing cavity pair under conditions proposed for Project-X cryomodules and determine if preliminary operating parameters are reasonable
- Studies with set of variables in matrix:
  - **RF power limitations: 80 kW; 100 kW**, 120 kW per two cavities.
  - **External Q: 3 X 10<sup>6</sup>; 6 X 10<sup>6</sup>; 1 X 10<sup>7</sup>**
  - **Gradient: 15MV/m; 20 MV/m; 25 MV/m**
  - **9 ms** pulse width
- Achieved:
  - Demonstrated overall performance – proof of principle – good first pass test
  - Good LFD compensation at the nominal parameters: Q=1.e7 and 25 MV/m
  - LLRF feedback works; phase stability good to  $\pm 4^\circ$
  - Good reliability
- Limitations:
  - Power limitation for low Q case (Q~3.e6). Gradients are limited to < 20 MV/m.
  - System ‘very touchy’ under dynamic conditions – nearly constant attention required, especially when adjusting power

# Long Pulse - 2

- LFD compensation screen with voltages applied to piezo-tuners (cavity #5 and #6) and frequency detuning during 9 ms pulse (below)





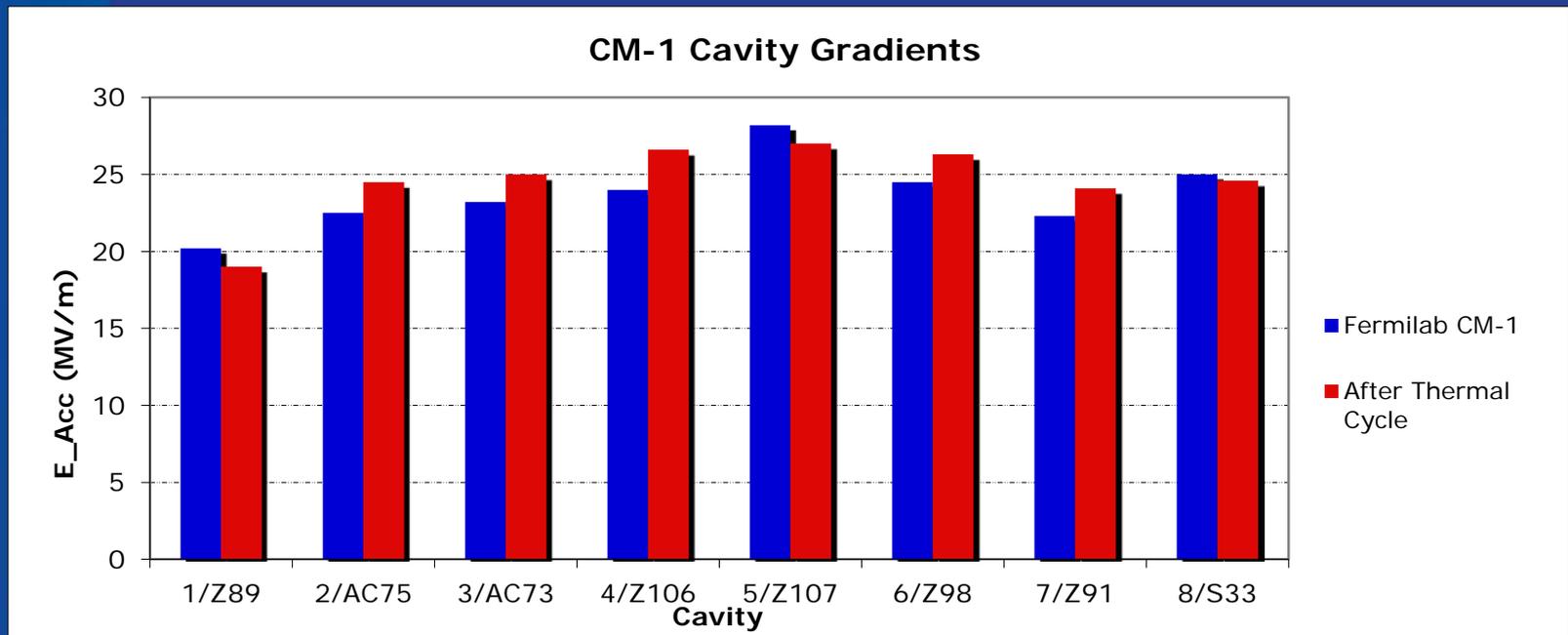
# Thermal Cycling

- Warm-up to Room temperature and then cool back down to determine effect on Cryomodule performance, especially lower performing cavities
  - 10 K/hour rate
  - 2-1/2 day – manned 2 shifts/day by cryogenics staff
  - Uneventful warm-up
  - IN<sub>2</sub> leak appeared as cooldown went below 150K
  - Sensors replaced with surface mount ones
  - Valuable experience in identifying and repairing such leaks
  - Subsequent cooldown revealed a helium to insulating vacuum leak – cause for concern, but not a showstopper

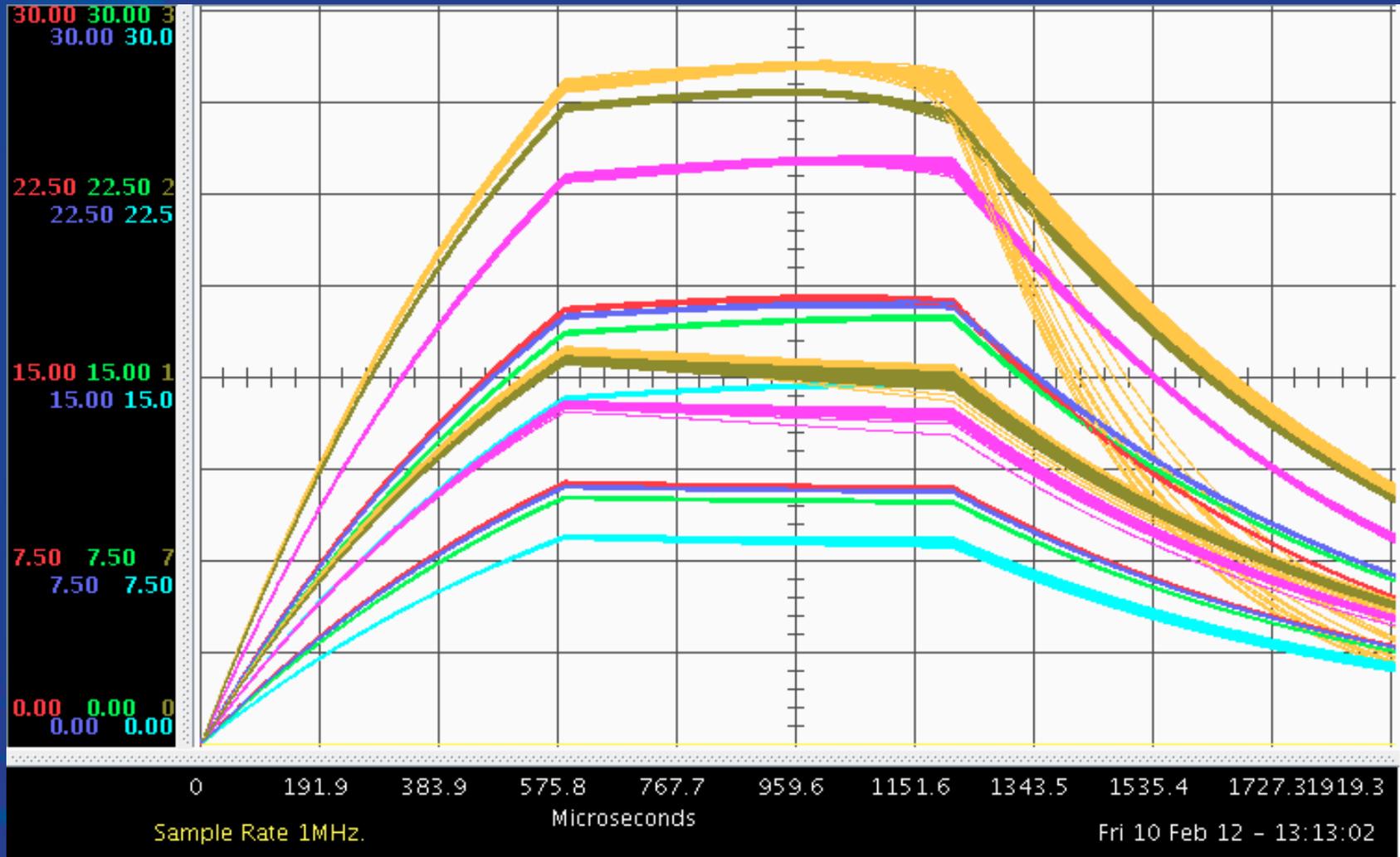


# Thermal Cycling - 2

- Resumption of operation on 8 February
  - Re-tune cavities to cold resonant frequency (they were de-tuned prior to warm-up)
  - Gently bring up power
    - 100  $\mu$ s, 500 $\mu$ s, 1.3 ms pulse widths
    - Bring up to full power at each pulse width in 20-30 minutes while observing FEP's, vacuum, etc.
  - Repeat cavity performance measurements - cryo instability, quench limit, FEP, etc. as before and compare
  - Overall modest improvement in performance



# Cavity Peak Performance

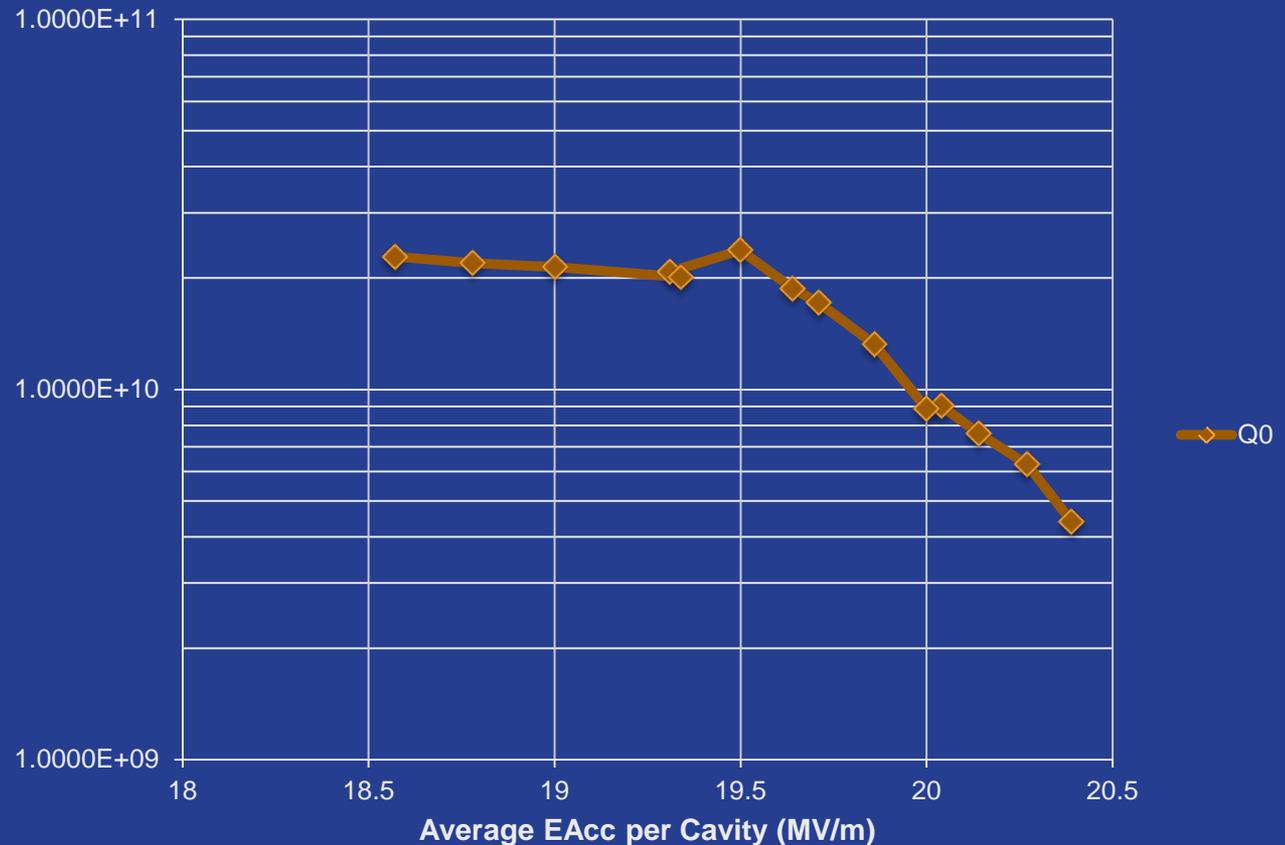


# Module Dynamic Heat Load Measurement

- Static Heat Load

- Total ~37 Watts
- CM-1 ~22 Watts
  - Consistent with measurements at DESY & S-1
- CC-2 ~15 Watts

Q0 vs EAcc for CM-1



# Post Mortem

- Based on operational experience, some inspection is needed at ICB or at MP-9 as string is disassembled:
  - Cryomodule and ends for helium leak
    - unsuccessful in situ search
  - Cavity #2 & #8 tuners
    - #8 is non functional after ~160k steps
    - #2 'sticks'
  - Thermal intercepts on Cavities 1, 3, 7, especially HOM cans
  - Piezo on #7 plus possibly others....
  - Cavity #4 coupler –  $Q_L$  behavior
  - Range of/specify range of  $Q_L$



# Post Mortem - 2

- Based on operational experience, some inspection is needed at ICB or as string is disassembled:
  - 'As found' check of cold mass
  - Some subset of the 'soft quench' cavities should be tested at the Horizontal Test Stand
    - 1/Z89, 3/AC73, 7/Z91
    - a recent cavity under test at HTS, RI021, is exhibiting similar behavior, further investigation is in progress
    - A not infrequent occurrence at DESY, results repeated at Chechia, but no resolution
    - Make  $\pi$ -mode measurements to try to understand offending cells, if any
    - Thermal instrumentation on beam pipe, HOM's?
  - Gunk in piping

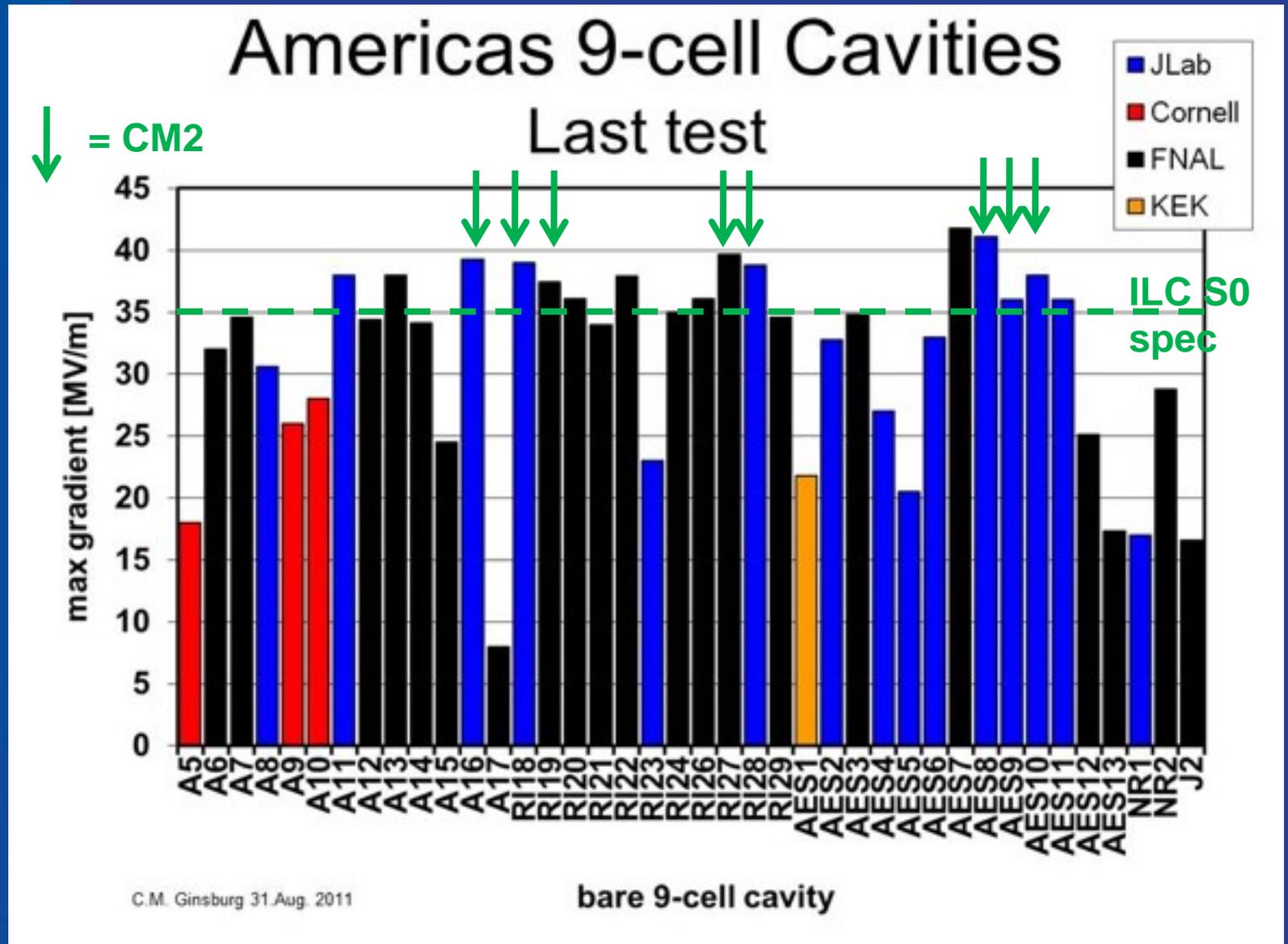


# RFCA002 (CM-2) is Next

- First ILC cryomodule to meet ILC performance spec?
- 2-phase leak found ~1 week before planned start of warm operation
  - 14 mm longitudinal movement at downstream end
  - Investigation in progress – leak cannot be replicated
  - Expect cryomodule return by year's end
- Test plan, including conservative test of peak gradients, prepared



# CM-2 - Vertical Results



# CM-1, 2 Summary & Conclusions

- First Operation of a Tesla Style Cryomodule an unqualified success
  - Even low performing cavities lead to new understandings
- A few issues
  - Tuner motor - Cavity 8
  - Cavities 1 & 3 Heat Load: other things to look at
  - Failed piezo
  - Small leaks
- Up to 144.5 MV/m total output
- Subsystems all commissioned and operational
  - Stable Cryogenics system
  - Evolving and flexible Controls
  - Growing involvement by more people
- Reliability generally good
  - 'Weak' systems identified and improvements planned
- 'Lessons learned' applied to RFCA002
- Operational review completed; experiences to be incorporated into future Cryomodules.
- List of things on CM-1 to post-mortem are identified
- Look forward to RFCA002 soon

# Operational Experience Impressions

- Subgroups have successfully operated separate facilities for some time
  - Test stands
  - Photoinjector
  - Clean rooms
  - Cryogenics
- Operation of ASTA is the culmination - for now
- New opportunities emerging/merging
  - Decommissioning of Photoinjector area
  - ASTA
  - IARC
  - etc.
- Only limited outside involvement in operating Fermilab's facilities
  - 2 visitors for CM-1 operation (both from DESY and invited)
  - Indian collaborators
- Photoinjector had a fairly regular stream of students and involvement from other institutions
  - Operation of ASTA should expand the possibilities
- Protons (hadron) vs. Electrons (leptons):
  - Immaterial in large measure - SRF is SRF

# Impressions - 2

- Demonstrated capabilities
  - Cryogenics
  - Cavity processing
  - High power RF systems
  - Low Level RF
  - (Adaptive) Lorentz Force Detuning Compensation
  - Controls
  - Testing/Operations
- Subtle(?) transition from student -> teacher
  - ACC39
  - CM-1 was a 'kit'
  - CM-2 is Fermilab-built
  - India & China collaborations
  - S-1 Global participation
  - Industrial engagement
  - Requests to share expertise – these are welcomed these days
  - But - still lots to learn...
- Collaboration

Thanks for your attention