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High Gradient Performance in Fermilab ILC Cryomodule

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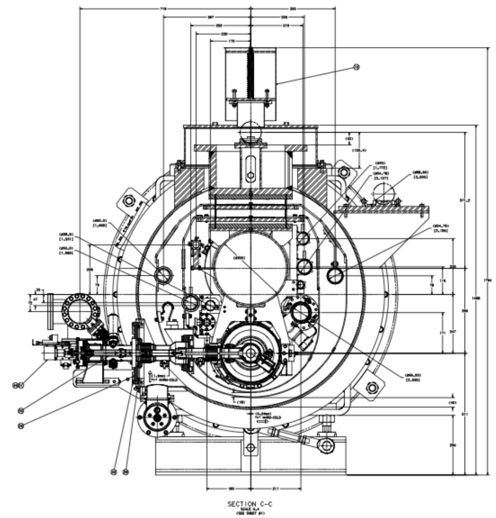
13-18 September 2015

Outline

- Introduction
- Peak performance
- Single cavity results
- Unit results
- Current Situation/Plans
- Summary

Introduction

- CM-2 is
  - Type 3+ TESLA/ILC type Cryomodule
  - 8 cavities (1.3 GHz) built by industry
  - Vertical testing at Jefferson lab
  - Horizontal tests at Fermilab (good to 35 MV/m)
  - Cryomodule assembled at Fermilab
  - First US-built ILC type cryomodule intended to achieve the average gradient specification of 31.5 MV/m in all 8 cavities
  - Designed for pulsed operation
- Main accelerating device for the *Fermilab Accelerator Science & Technology* (FAST) facility, formerly known as ILCTA and most recently ASTA
- Expect beam tests in FY16



Introduction

- ILC TDR:

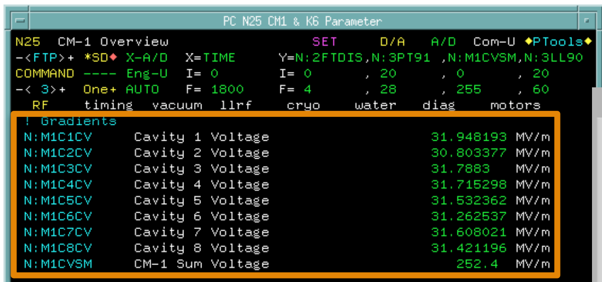
Four critical R&D topics were identified [12,13] by the ILC Program Advisory Committee and were adopted as the technical goals for the TDP. They are summarised in Table 2.1. (The notation *S0-S2* refers to the shorthand for the individual goals set at the beginning of the TDP). The goals include high-gradient operation in individual cavities (S0), assembly of a string of cavities in a cryomodule (S1), the test of a cryomodule with beam acceleration (S2), and to increase the involvement of industries in this development so that eventually major parts of the production can be carried out in industry.

Table 2.1
The main goals and timeline for SCRF R&D established at the beginning of the Technical Design Phase

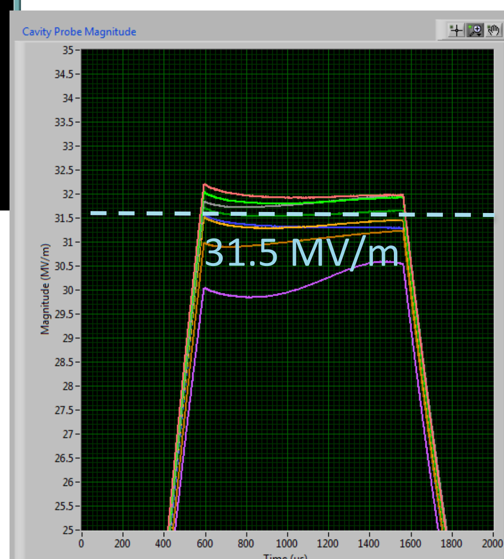
Year	2007	2008	2009	2010	2011	2012
S0: Cavity gradient at 35 MV/m in vertical test	→ yield 50%			→ yield 90%		
S1: Cavity string at average gradient of 31.5 MV/m in cryomodule		Global effort for string assembly and test				
S2: System test with beam acceleration including high- and low-level RF		FLASH at DESY, ASTA/NML at FNAL, STF2 at KEK				
Industrialisation: Study and preparation for industrial production of SCRF cavities and cryomodules			Production technology R&D			

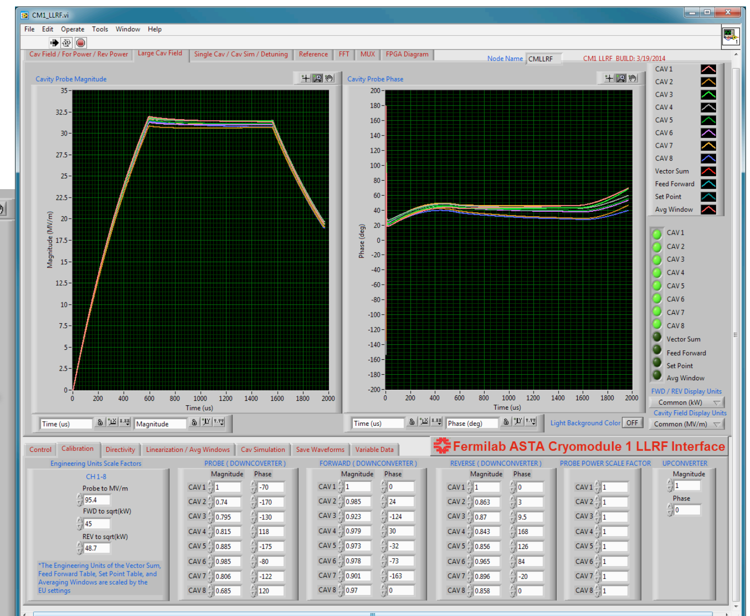
Peak Performance

- CM-2 achieved an average cavity gradient of 31.5 MV/m on 3 October 2014 with all 8 cavities powered simultaneously
- 1.6 millisecond pulse width, 5 Hz repetition rate
- Lorentz Force Detuning Compensation (LFDC) on and ‘adapting’
- Peak accelerating voltage = 252 MV



Snapshot of peak cavity gradients





CM2 Amplitude (MV/m, left) & Phase (right)

How did we get here?

	Activity Name	Duration (Days)	Start Date	Finish Date
1	Cryomodule installation	8.00	4/10/13	4/19/13
2	Warm coupler conditioning	22.00	5/9/13	6/7/13
3	Interconnects and Leak Check	132.00	4/22/13	10/22/13
4	Cooldown	14.00	10/23/13	11/11/13
5	Cavity #1 Characterization	57.00	11/13/13	1/30/14
6	Cavity #2 Characterization	11.00	1/31/14	2/14/14
7	Cavity #3 Characterization	7.00	2/24/14	3/4/14
8	Cavity #4 Characterization	5.00	3/4/14	3/10/14
9	Cavity #5 Characterization	7.00	3/18/14	3/26/14
10	Cavity #6 Characterization	5.00	3/28/14	4/3/14
11	Cavity #7 Characterization	3.00	4/4/14	4/8/14
12	Cavity #8 Characterization	11.00	5/23/14	6/6/14
13	Revisit Cavities 1, 6	10.00	7/1/14	7/14/14
14	Cavity 1 - 7 Unit test	23.00	7/25/14	8/26/14
15	Cavity 8 coupler vacuum	11.00	8/26/14	9/9/14
16	8 cavity unit test	89.00	9/9/14	1/9/15
17	Room temperature warm-up, repairs	63.00	1/13/15	4/9/15
18	Re-commissioning	46.00	4/9/15	6/11/15
19	Current tests	10.00	8/5/15	8/18/15

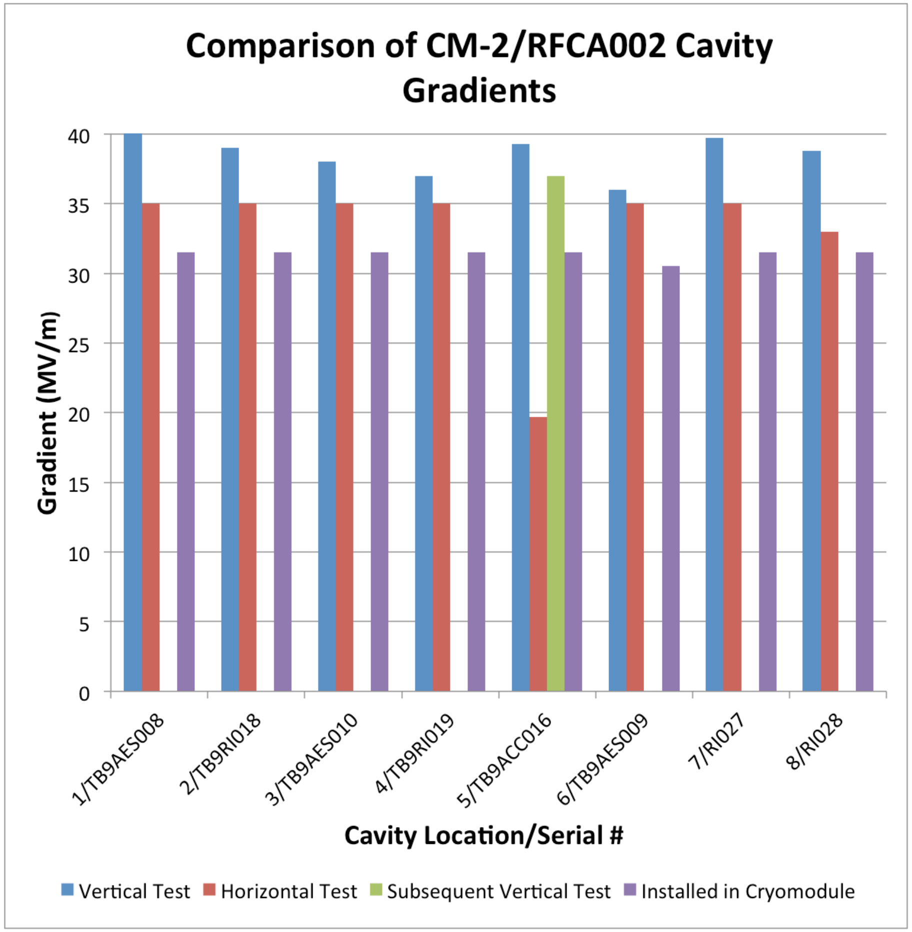
- Cryomodule installed in NML/ASTA/FAST – April 2013,
- Warm coupler conditioning (one cavity at a time) – 9 May to 18 June 2013
- Cooldown – 23 October to 11 November 2013
- Cold operation/single cavity characterization (13 November 2013 – 14 July 2014)
  – 57 days for first cavity
  – as fast as 6 days thereafter
  – 2 do-overs (1, 6)
- 7-cavity unit test (25 July - 26 August 2014)
- Complete unit, 8 cavities, test (9 September 2014– 10 January 2015)
- Warm-up to room temperature and coupler 8 repair (13 January 2015 – 9 April 2015)

Single cavity results

- Once cold, each cavity individually powered to determine performance characteristics
  - Tune cavity to resonance
  - Map out and set Q_L
  - System calibrations, calculate gradient, k
  - On-resonance conditioning
  - Determine peak performance (gradient, limitation)
  - Final (high power) LLRF calibration
  - Lorentz Force Detuning Compensation set-up
  - Document dark current, x-rays vs. gradient
  - Dynamic Heat Load measurements (Q_0)

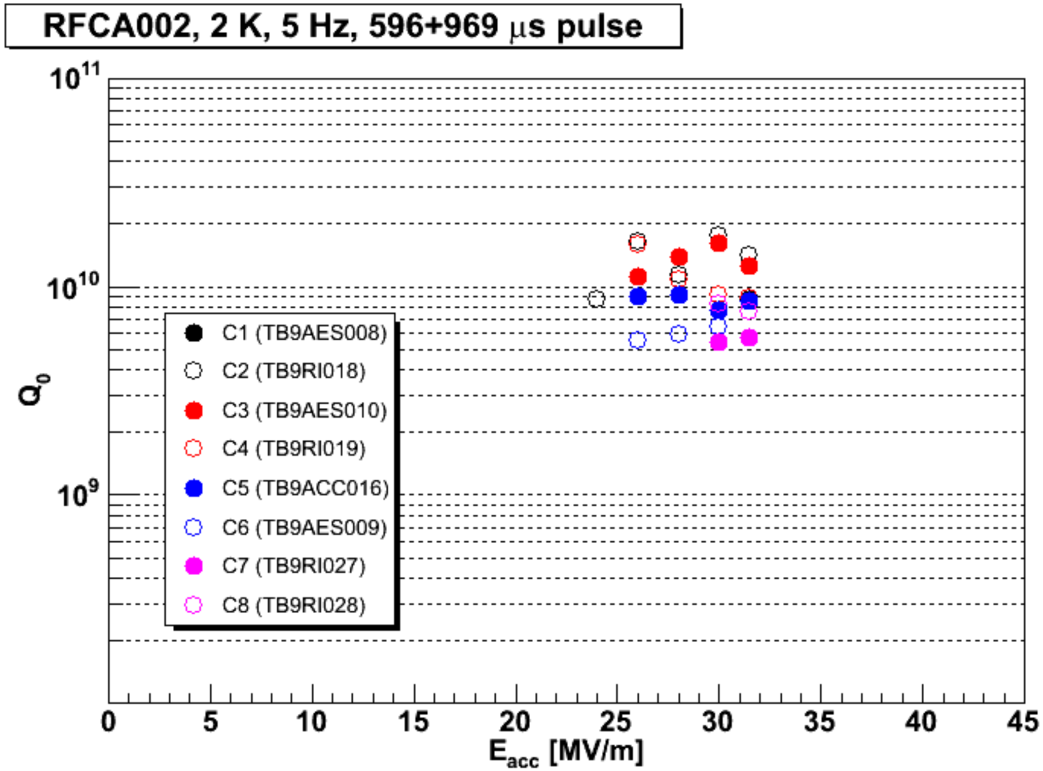
Single cavity results

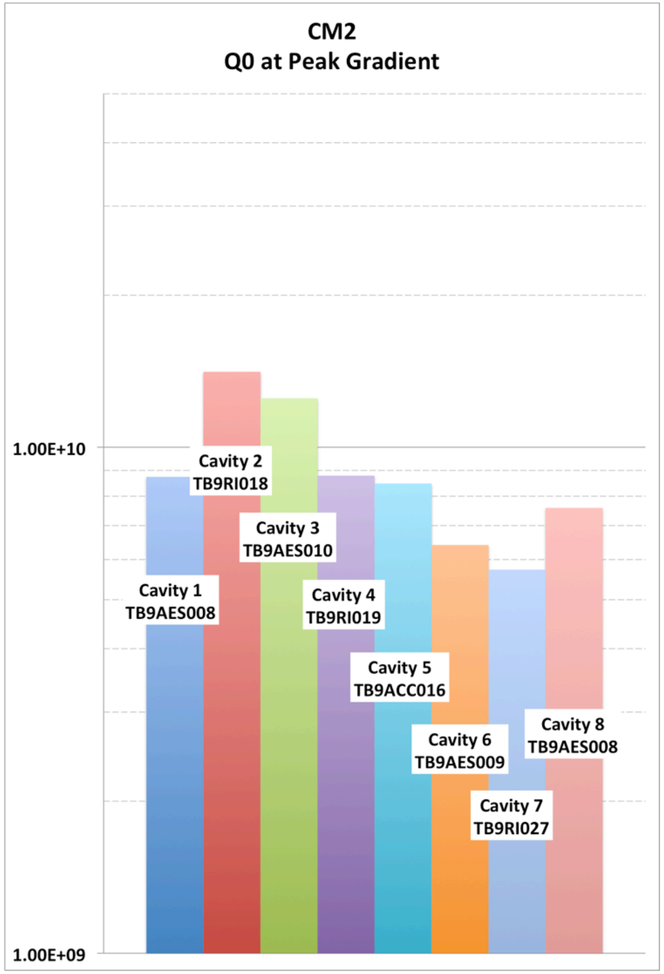
- Operating conditions
  - 2 Kelvin (23 Torr)
  - Pulsed operation
  - 1.6 ms pulse
    - 590 μs fill + 969 μs flattop
  - 5 Hz repetition rate
  - Q_L set to 3.5 E6, variable coupling
  - LFDC active
- Results
  - 7/8 cavities achieve 31.5 MV/m (administrative limit)
  - Cavity #6 quenches at 30.5 MV/m



Complete summary by Andy Hocker et al at IPAC 14 – WEPRI051: http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/wepri051.pdf

Single cavity results – DHL/Q_0

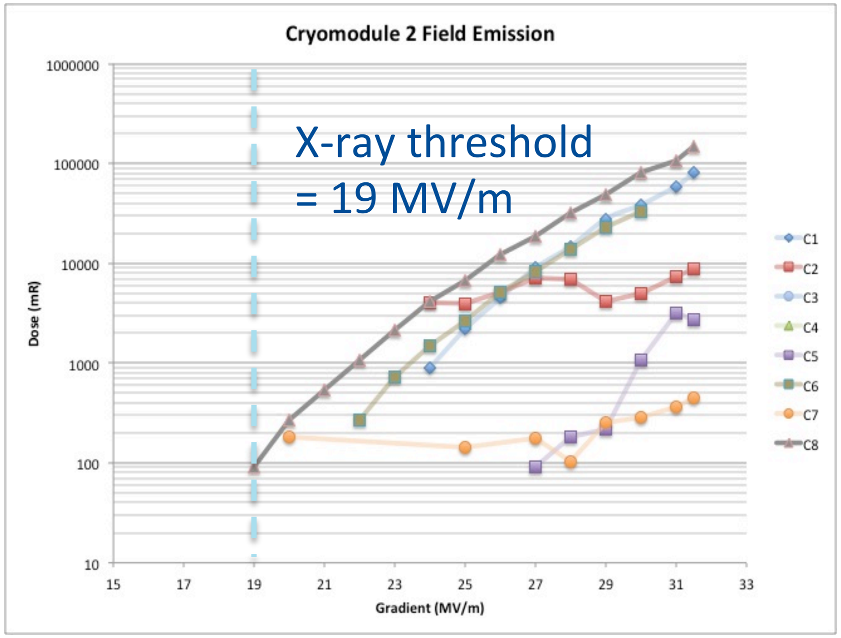


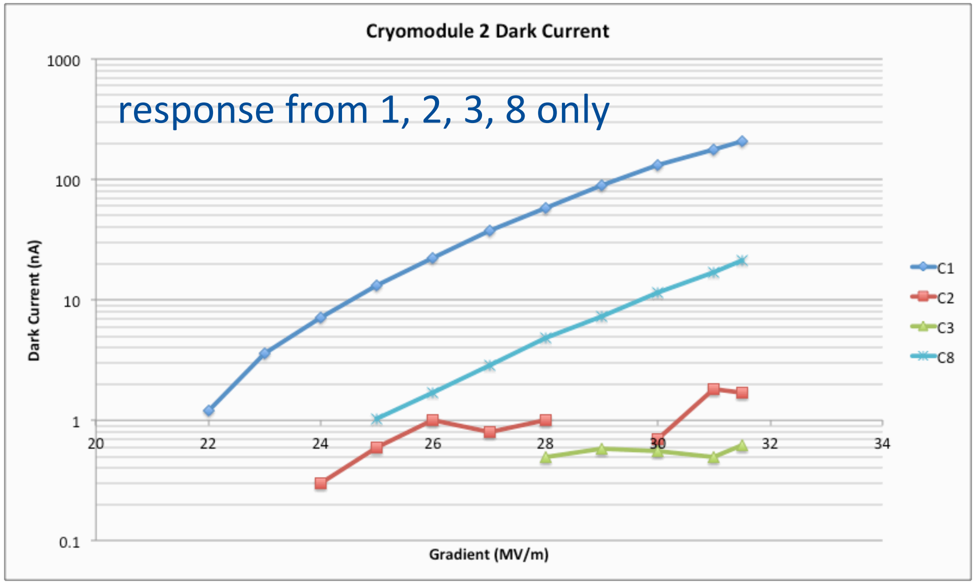


Q_0 vs. gradient

courtesy of Andy Hocker

Single cavity – field emission, dark current





Field Emission measured by 'chipmunk' placed below cavity under test

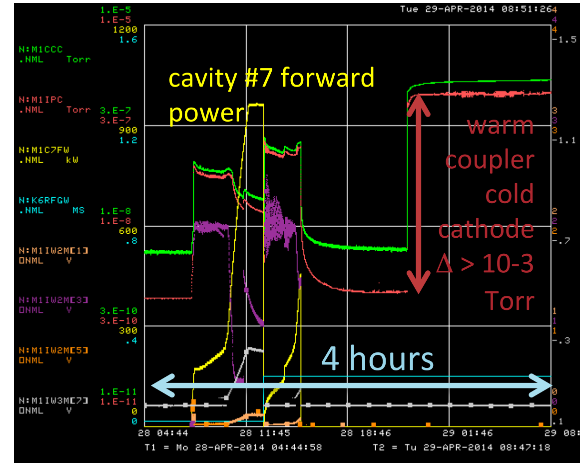
Dark current measured by Faraday cups at end end of cryomodule

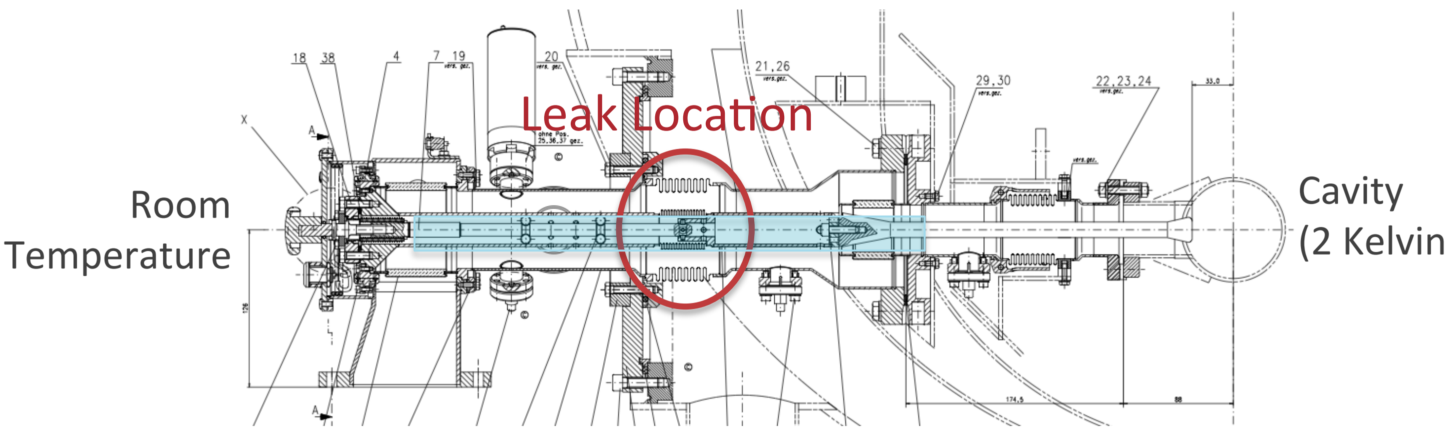
Unit results

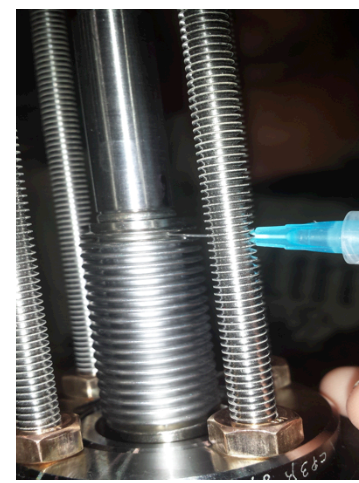
- Warm coupler vacuum issues with cavity #8 (more later) prompted initial unit test powering only 1-7 initially
- Leak checking, nitrogen purge, luck? finally allowed full unit operation
- 5 days of coupler conditioning was required before high power testing was possible – cavity 8 vacuum and warm window field emission
- Peak gradient limited by cavity #6 (hard) quench (30.5 – 31 MV/m)

Cavity #8 – warm coupler vacuum

- Spontaneous vacuum event
  - 5×10^{-9} to 1.4×10^{-6} Torr in a matter of minutes w/ no power being applied
  - warm side of #8
  - eventual room temperature warm-up
  - successful repair and cool-down
  - post mortem identifies very localized leak on a bellows convolution







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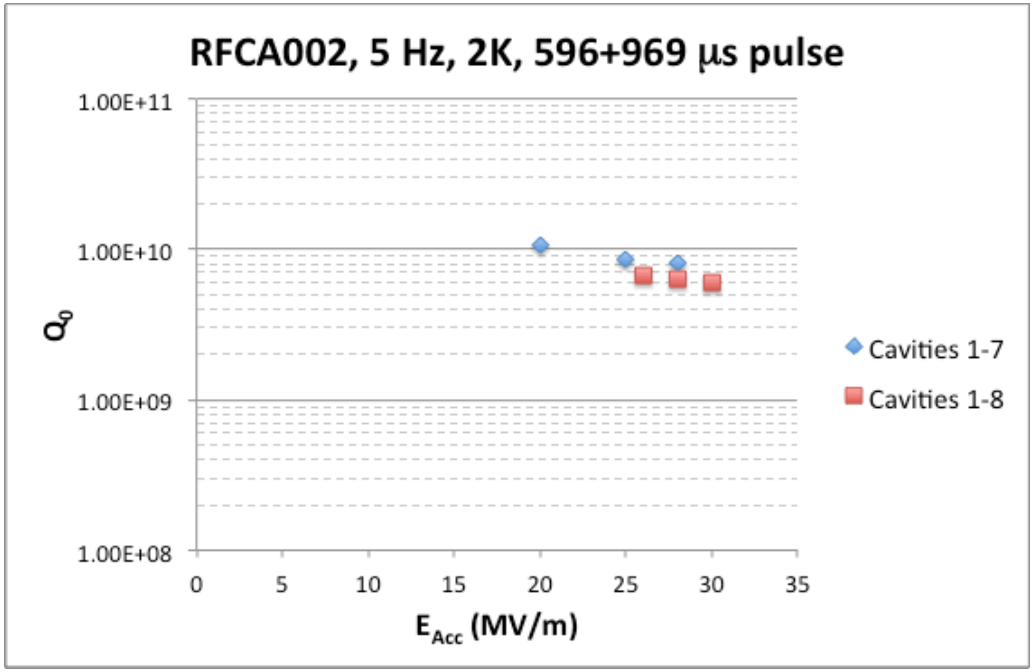
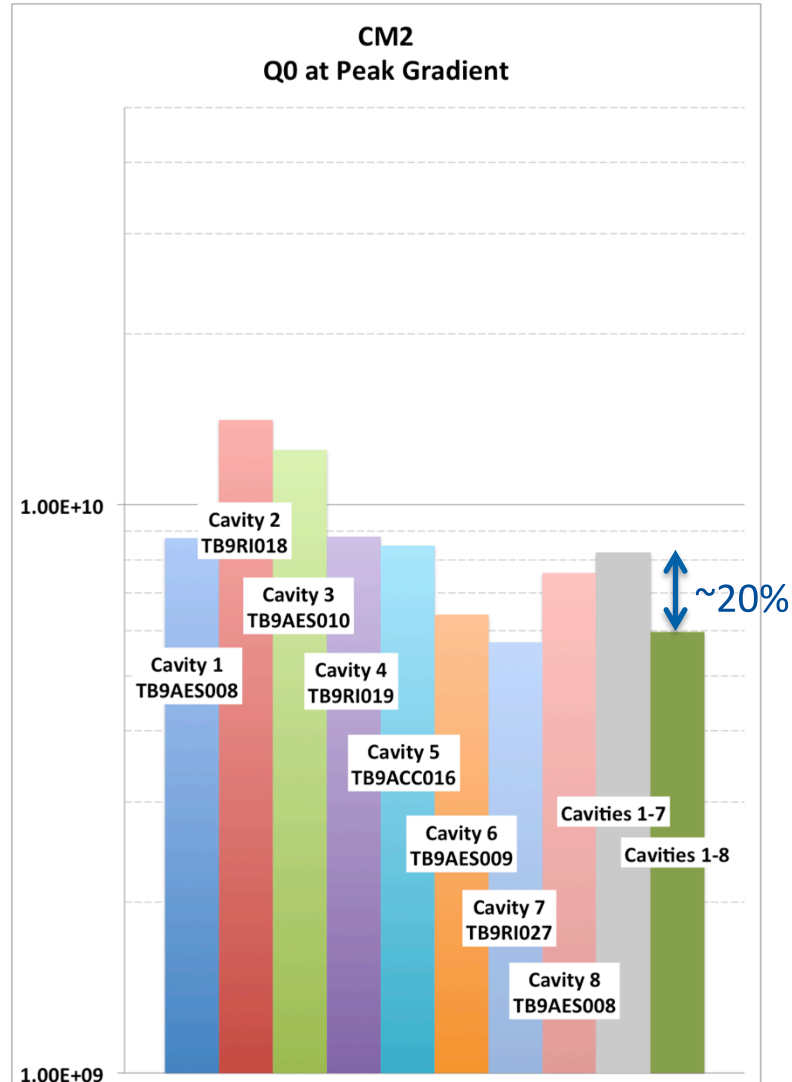
Unit results – DHL/Q_0

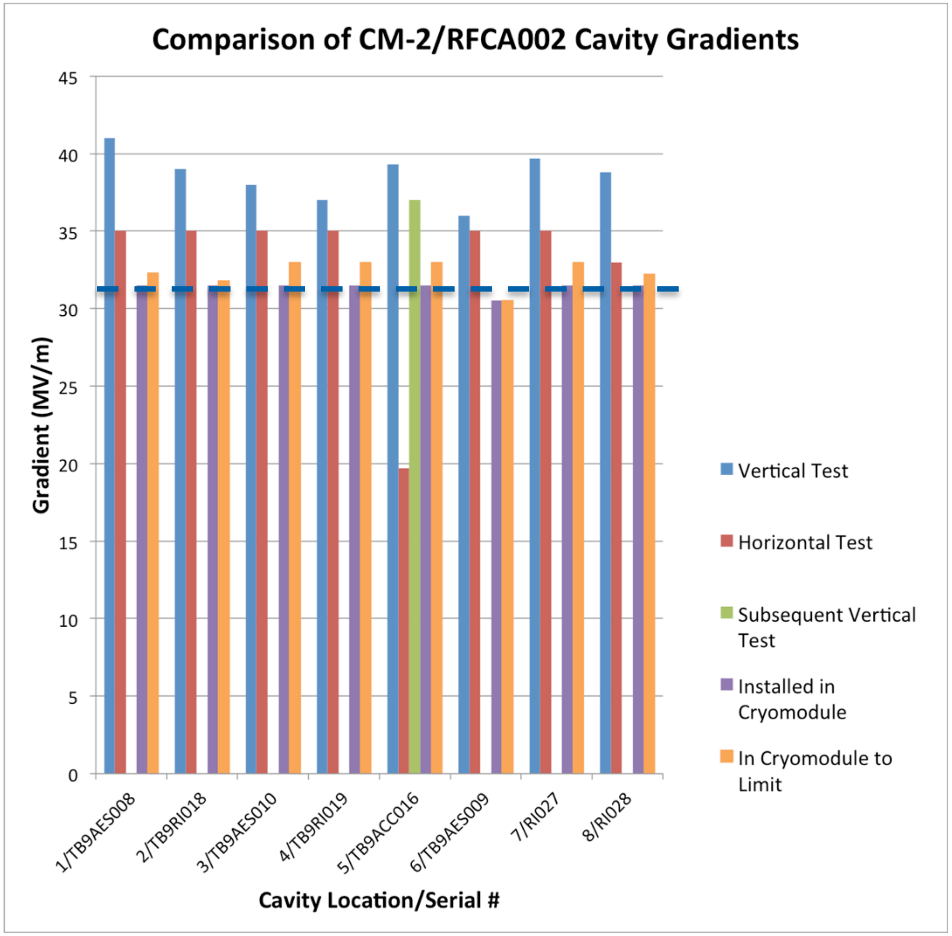




Q_0 for cavities powered together

courtesy of Andy Hocker

Absolute Peak Gradient Determination



Cavity	Peak Gradient (MV/m)	Limitation
1/TB9AES008	32.3	Quench
2/TB9RI018	31.8	Quench
3/TB9AES010	≥ 33	tbd
4/TB9RI019	≥ 33	tbd
5/TB9ACC016	≥ 33	tbd
6/TB9AES009	29.8	Quench
7/RI027	≥ 33	tbd
8/RI028	32.2	Quench

Peak CM-2 Cavity Gradients with all 8 powered at once:

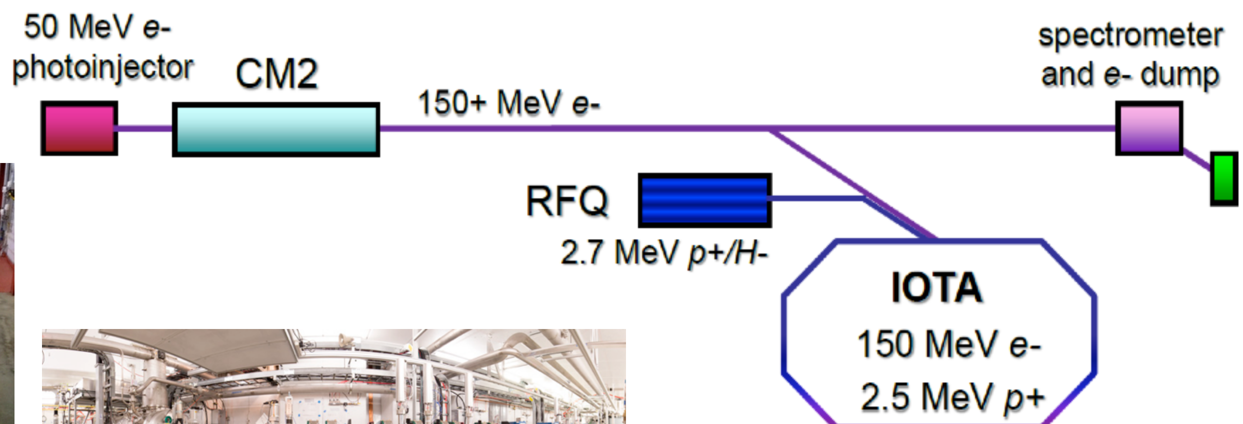
Sum = 258.1 MV, Average = 32.2 MV/m

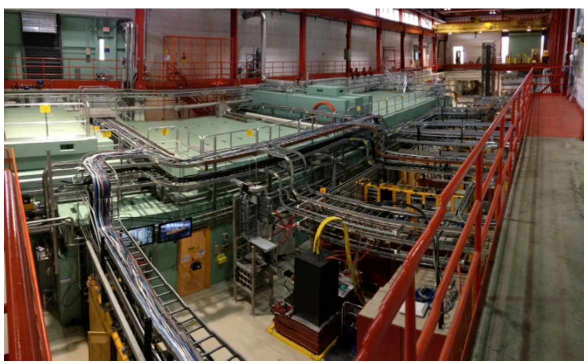
Current situation/Plans

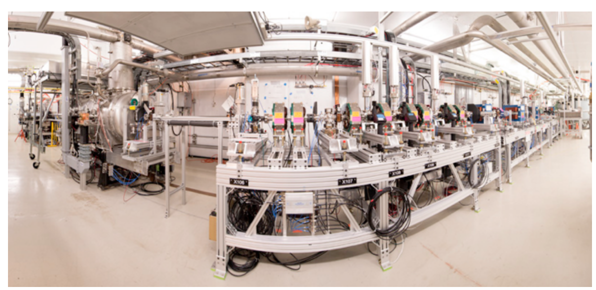
- Operate LLRF in closed loop
  - only limited work on this so far
  - closed loop operation has been demonstrated
- Ongoing LFDC investigation
- Finish peak gradient determinations
  - likely adjust waveguide distribution Variable Tap-Off's
- Dark current energy spectrum
- Commission Internal radiation detectors
- Magnet testing
- Long-term (reliability) testing
  - 3+ days continuous operation at moderate gradient (20 MV/m average)
  - Cavity #7 coupler temperature – thermal short?
- At room temperature now to integrate CC1 to FAST

Longer-term Plans

- CM-2 is installed within an accelerator enclosure containing a test electron accelerator, the Fermilab Accelerator Science & Technology (FAST) facility
  - Recently accelerated its first 20 MeV photoelectrons (TUPB014)
  - Connect the FAST injector to CM-2 to create a facility that can provide up to 300 MeV electrons for accelerator R&D – FY2016
  - Primary role as injector for IOTA - FY2017







Summary

- The primary goal of demonstrating that an ILC-type cryomodule of eight cavities can be operated at an average gradient of 31.5 MV/m with all cavities powered simultaneously has been achieved with CM-2, thus meeting the ILC S1 goal.
- This was accomplished with cavities processed in the U.S.
- Demonstrates that Fermilab has developed the infrastructure and expertise to produce high gradient cryomodules.
- Repair of the warm coupler vacuum has shown that the technical staff is able to address and successfully make in-situ repairs.
- CM-2 appears to be operationally capable of providing an accelerating voltage of up to 250 MeV.

Acknowledgements

- This is a team accomplishment
- Thank you and congratulations to our many international partners including commercial ones!

thank you for your attention