CEBAF Upgrade Experience

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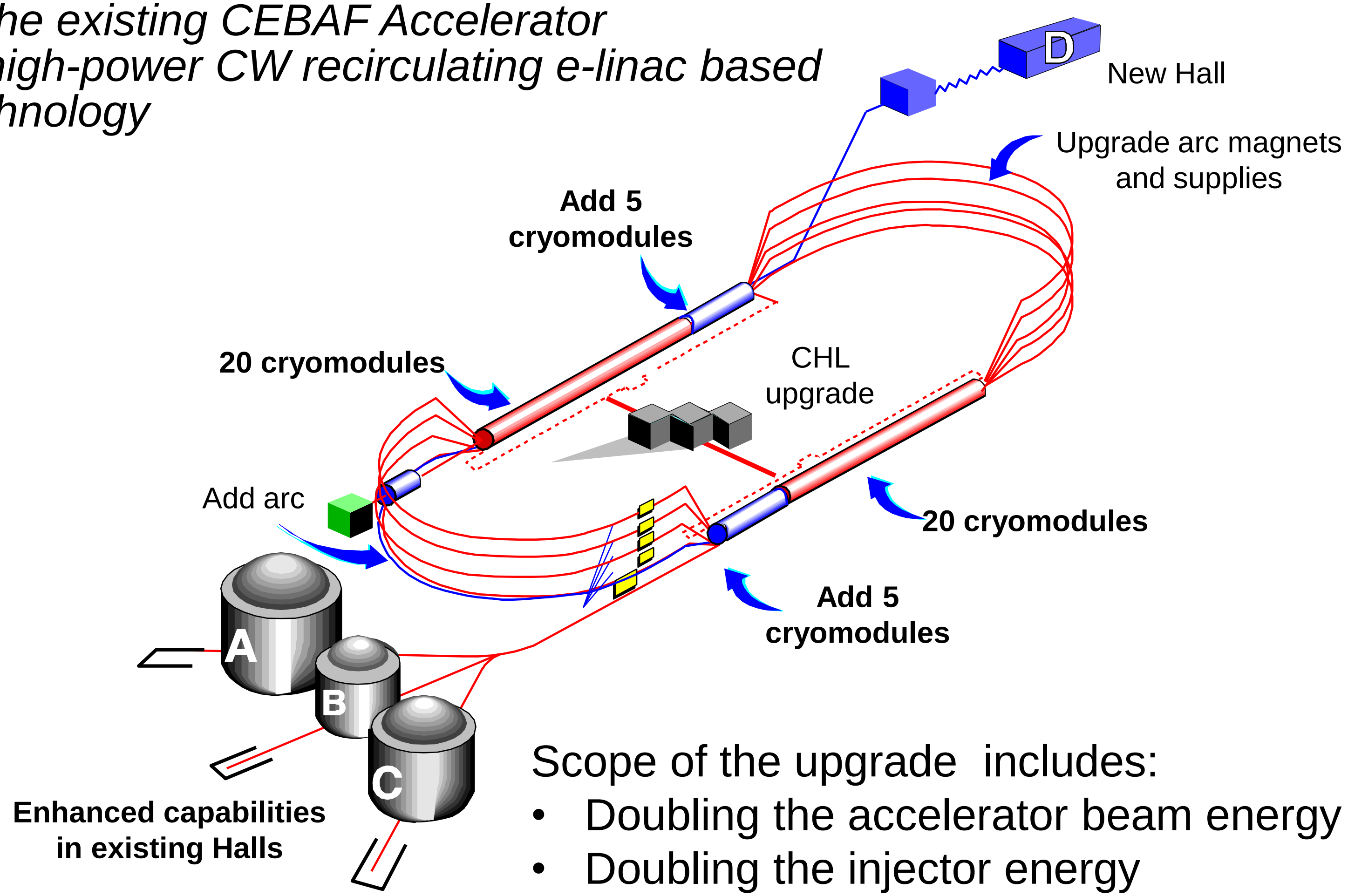
Outline

- 12 GeV and C100 Quick Overview
- C100 Cryomodule Status
- Accelerator Program Status
- VTA / Cryomodule Testing Comparison
- Operational Challenges
- Final Thoughts & Acknowledgements
- Extra stuff
  - Performance Over Time
  - Moving Cryomodules
- Working Groups
  - Helium processing
  - JLAB Test Facilities

12 GeV Upgrade

Built upon the existing CEBAF Accelerator
First large high-power CW recirculating e-linac based on SRF technology



Scope of the upgrade includes:

- Doubling the accelerator beam energy
- Doubling the injector energy
- New Hall and beam-lines
- Upgrades to existing Experimental Halls

Cavity

Cavities must deliver an Average Maximum Operating gradient of **19.2 MV/m** with average **Q_0 of 7.2E9 at 2.07 K**

96% exceeded requirement

Each cryomodule contains a string of **eight 7-cell low-loss SRF 1497 MHz cavities**
Each Cavity undergoes an rigorous qualification process

- 160 µM BCP
- 600 C Bake 24 hours – Hydrogen removal- Eliminates Q_0 disease
- 30 µM Electropolish – Reduce Q_0 Slope
- Multiple High Pressure Rinses
- 120 C Bake for 24 hours
- Vertical Test at 2.07 K
- Cavity String assembled in a Class 10 Clean room

Cryomodule

- Magnetic Shielding
  - 2K Shield CryoPerm@
  - Room Temp shielding mu-metal
- Thermal Shielding.
  - Multi Layer Insulation
  - Insulating Vacuum (1E-07 torr)

- Waveguide Coupler Assembly
  - Two Warm Windows
- Scissor-jack tuner with easily accessible warm drive components
  - Provision for Piezo-electric component for fast control

R100 - Rebuilt version of an earlier upgrade model - “Renascence”
Rebuilt with new in-house C100 cavities to mimic C100 design as closely as possible
Installed in the CEBAF Injector

C100 Cryomodule Status

The C100 Cryomodule Project which began in 2009 is complete

All of the Installed C100 Cryomodules and the R100 Cryomodule have been Successfully Commissioned:

Average Max Operating Gradient = 20.4 MV/m (Design goal = 19.2 MV/m)

Average Q_0 at 19.2 MV/m = 8.1E9 (Design goal = 7.2E9)

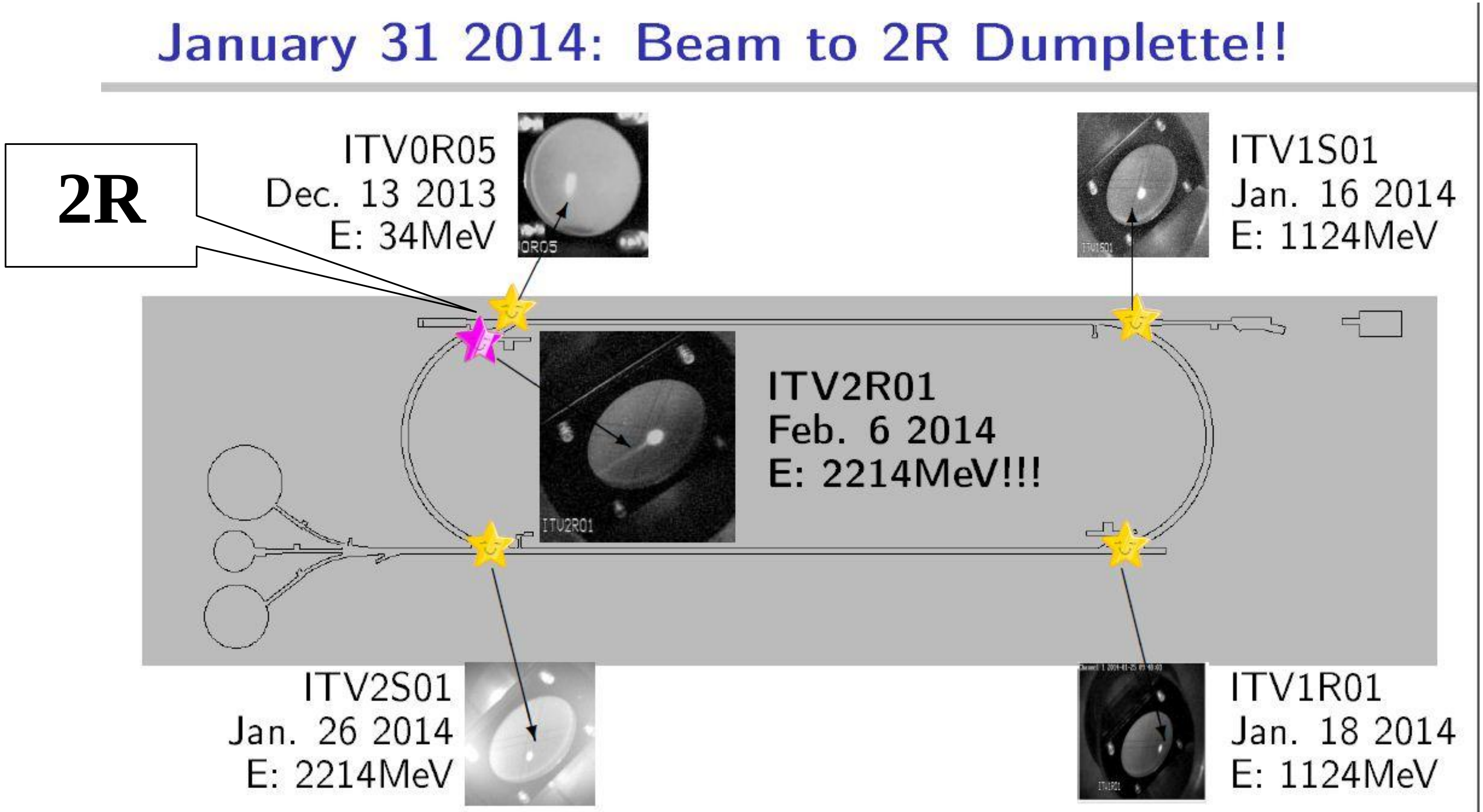
Average Energy Gain = 113 MV (Design goal = 108 MV)

All of the Cryomodules have been Operated with Beam

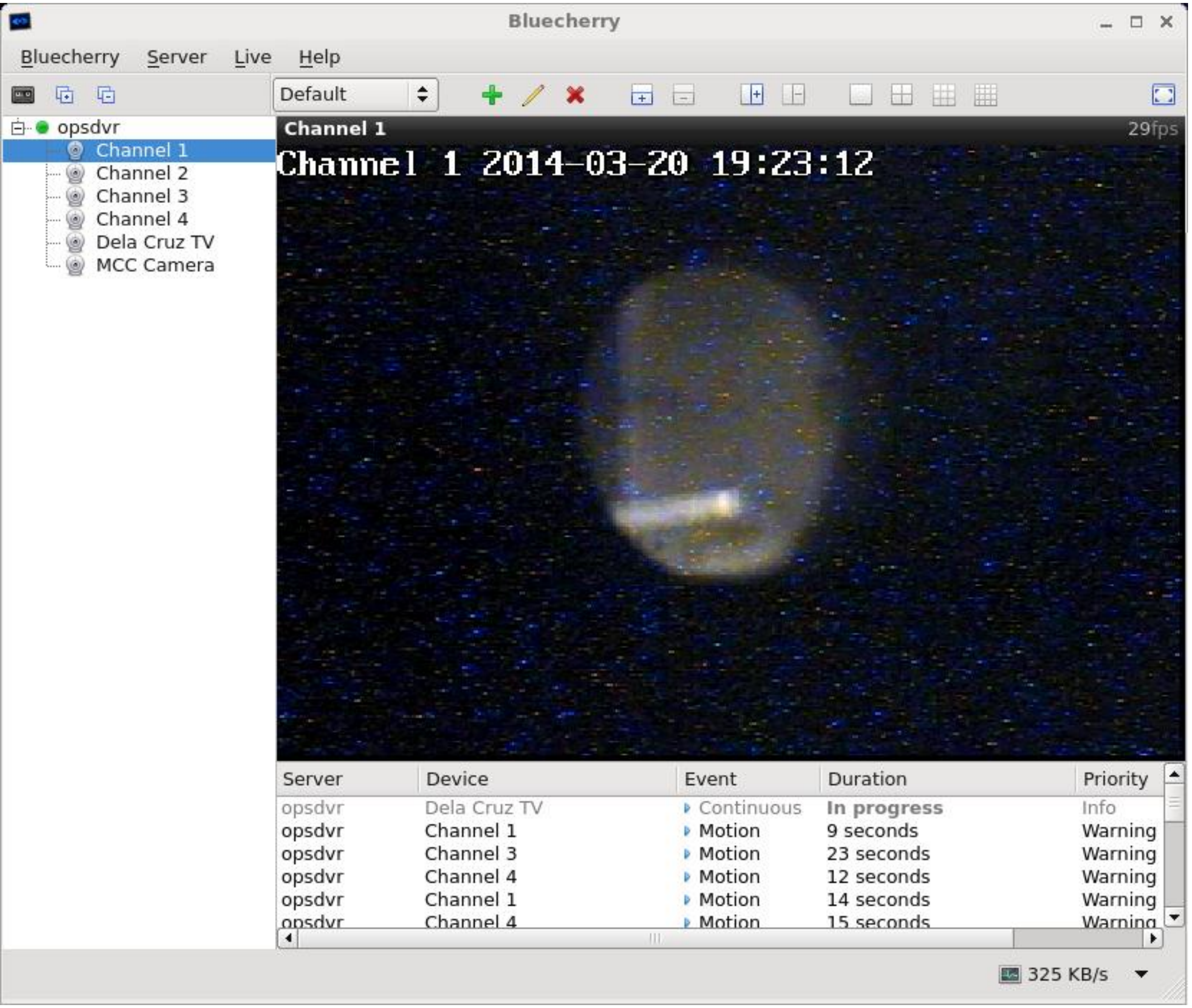
One has Successfully Operated at 108 MV with full beam loading of 465 μA

All have been operated with low current beam at an average 97 MV

Accelerator Status



Accelerator Status



Three pass beam delivered to Hall A dump for the first time on 3/20/14

Vertical Test Area

- Each cavity is subjected to RF qualification in the VTA.
- Cooled to 2.07K in a dewar
- Low Power RF testing includes:
  - Passband measurement
  - HOM Survey
- High Power Measurement includes:
  - Maximum Gradient Determination
  - Qo vs. Eacc
  - Qo vs. T at 20 MV/m

Cryomodule Testing

Acceptance Testing

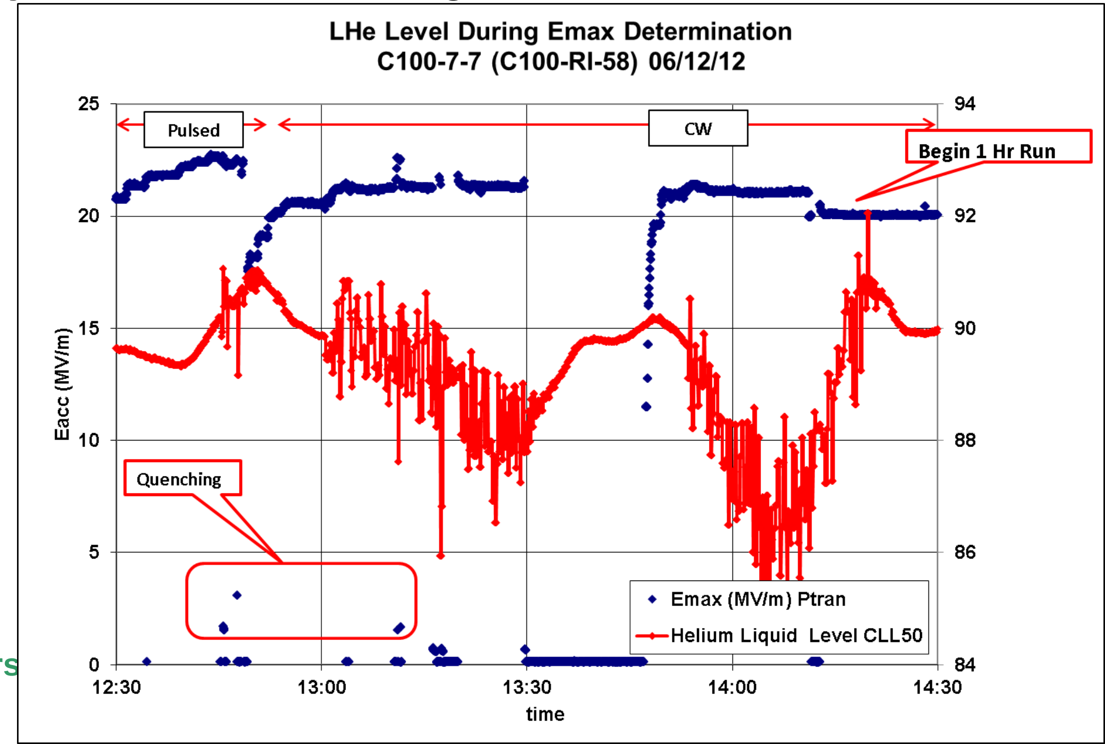
- Prior to Installation, all Cryomodules undergo a more comprehensive set of Acceptance tests in the Cryomodule Test Facility
- Acceptance tests are meant to uncover any major problems before delivery to the linac.
- Also include tuner qualification, Static Lorentz and Pressure Sensitivity Measurements

Commissioning

- Each cryomodule Commissioned after installation
  - Focused on determining stable operating gradients
  - Accomplished through a combination of
    - Maximum Gradient Determination
    - Field Emission Measurements
    - Q_0 / RF Heat Load Measurement
    - Microphonics

Emax Determination

- Calibrate the Gradient
- Increase Gradient in small steps
  - Find the limit using Pulsed RF
  - Check the limit –CW RF (Emax - Maximum Achievable Gradient)
  - Verify that cavity is not heat load limited
- One Hour run to test for stable operation (Emaxop - Maximum Stable Gradient)
  - On average, Emaxop < Emax by ~ 1 MV/m
- Later on after Heat Loads are Determined, final maximum gradient is set by ~ 29 W Dynamic Heat Load per cavity / 232 W for the string

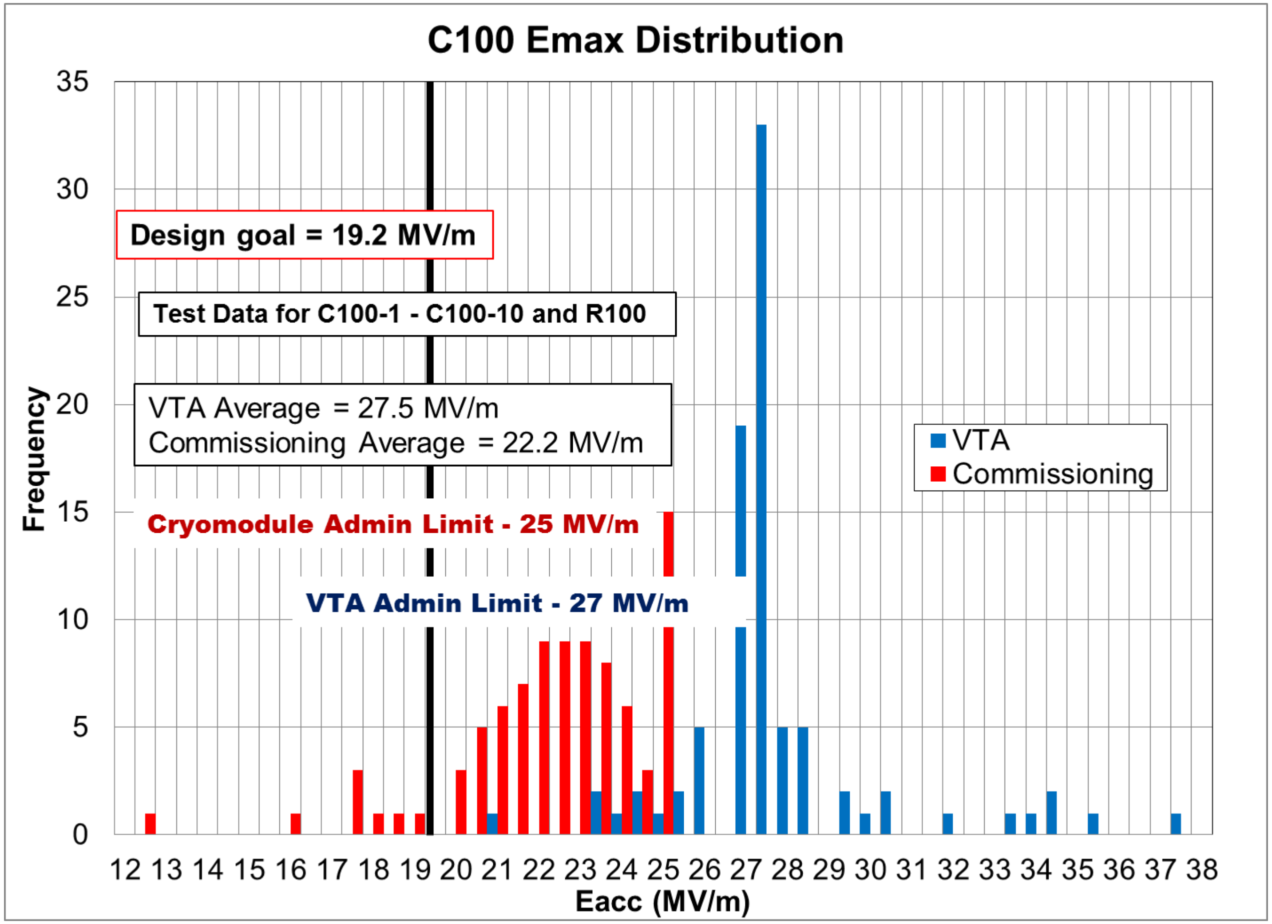


Gradient Limitations

- **Potential Gradient Limitations:**
- **Cavity Quench**
- **High Heat Load**
- **Admin Limit = 25 MV/m**
- **Vacuum Degradation**
- **Waveguide Arcs**
- **RF Window Temperature**

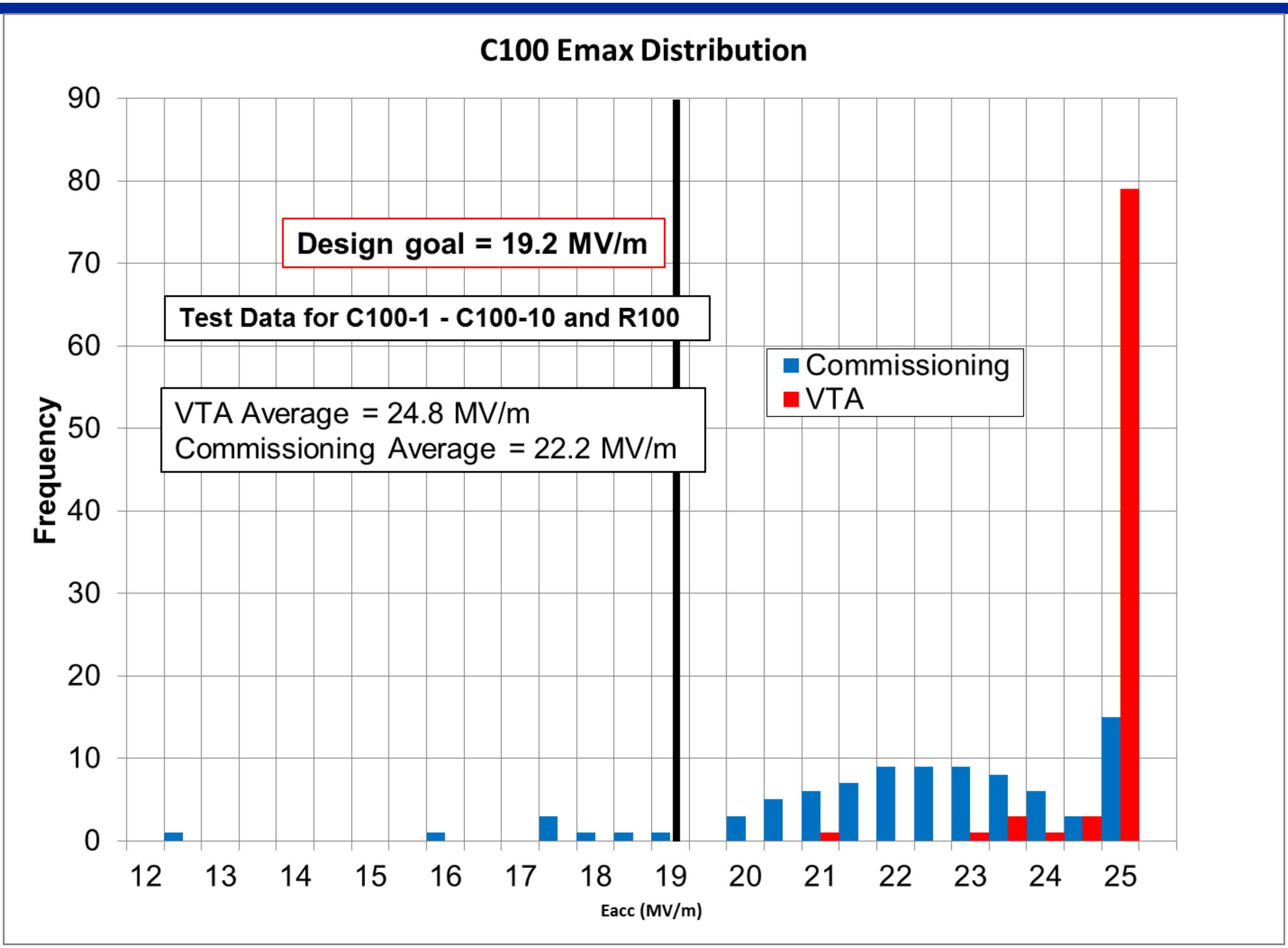
- **Admin Limit to protect cavity from high field quenches that lead to new field emitters / performance degradation.**
- **Anything above 25 MV/m is outside the installed RF power and control range**
- **All installed cavities limited by either quench, heat load or admin limit.**

Emax - VTA / Commissioning



- Differing Administrative Limits (VTA 27 MV/m / Cryomodule 25 MV/m)
- Cryostat riser limits (~50 – 60W per cavity) – some dependence on Temp, position
- Assembly / Testing “events” account for reductions in ~5% of the cavities

Emax - VTA / Commissioning

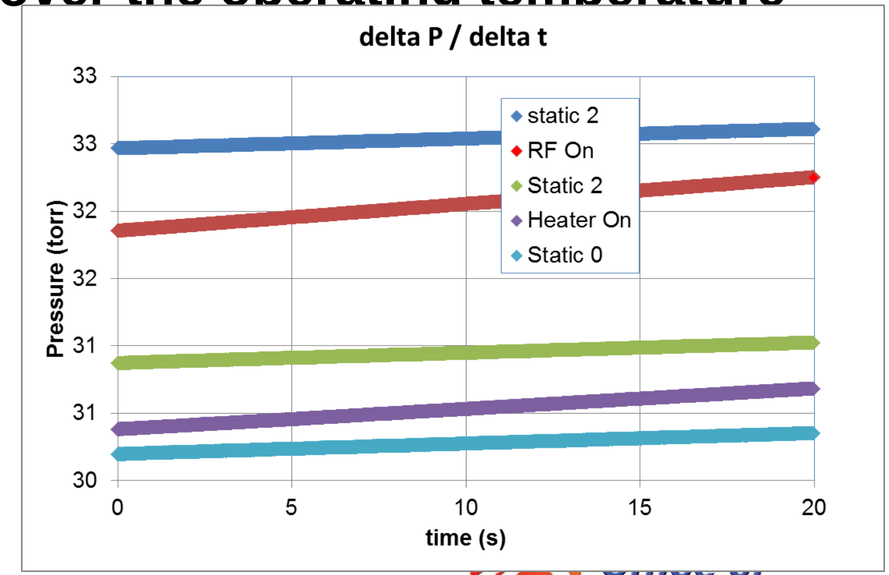


VTA data Adjusted to Cryomodule admin limit
And 50 W RF heat load limit

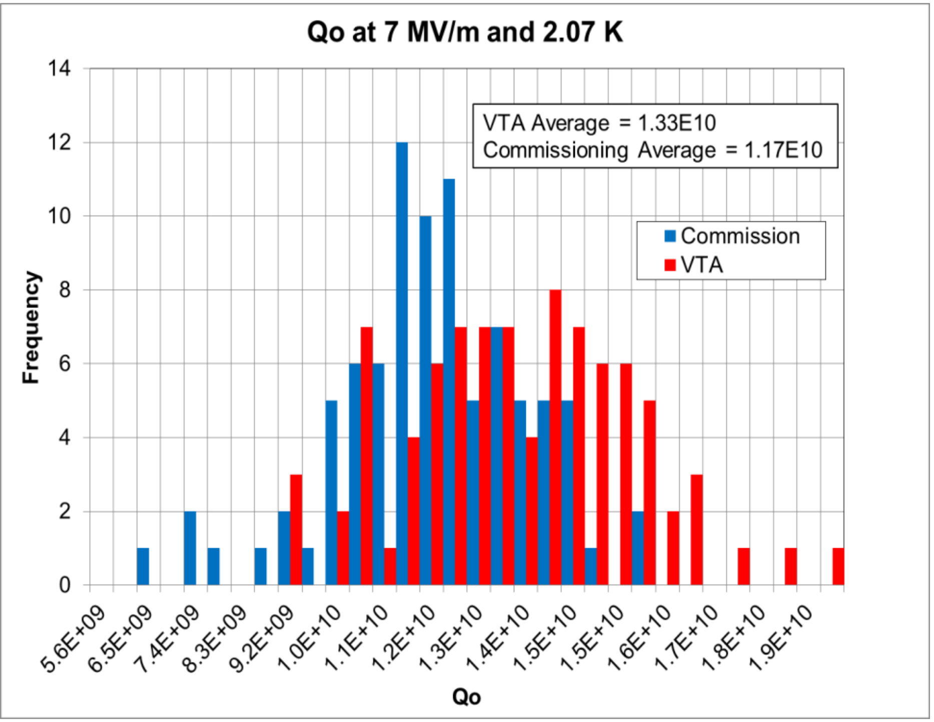
Q_0 Measurement

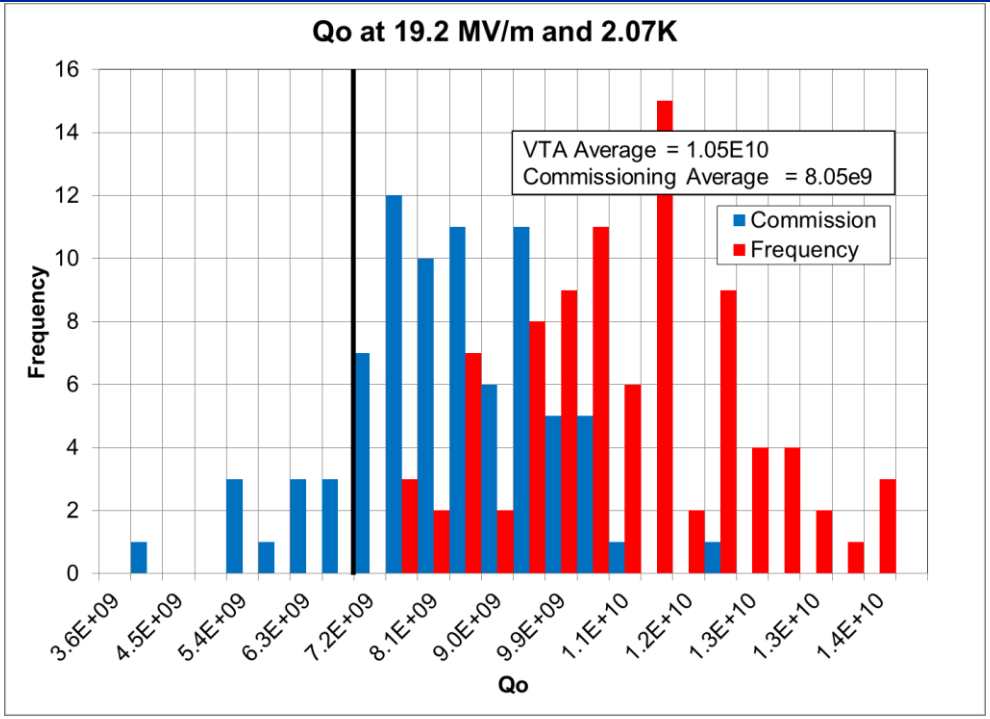
- Calorimetric Method
  - Isolate the cryomodule from refrigerator
    - Close JT and RT valves
  - Perform a series of measurements of ΔP /Δt
    1. No input heat (other than static)
    2. Known heat load from heater
    3. RF on at desired gradient
  - ΔP /Δt linear with heat load over the operating temperature range

$$Heat_{RF} = Pwr_{Htr} \frac{\Delta P_{RF} - \Delta P_{static}}{\Delta P_{htr} - \Delta P_{static}}$$



Q_0 – VTA / Commissioning



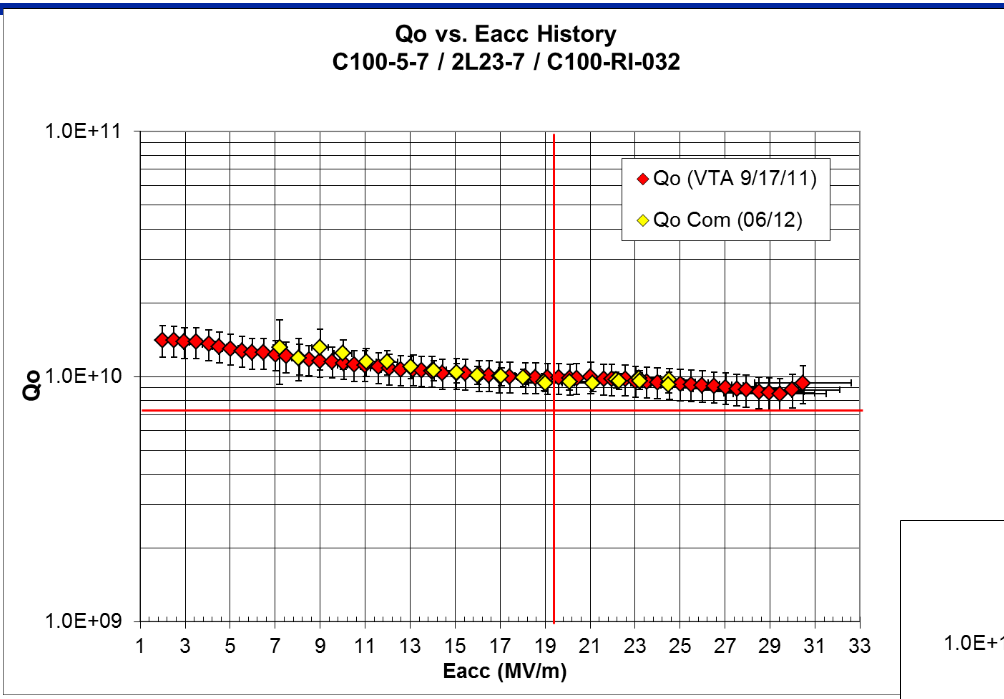


- Small divergence at lower gradients

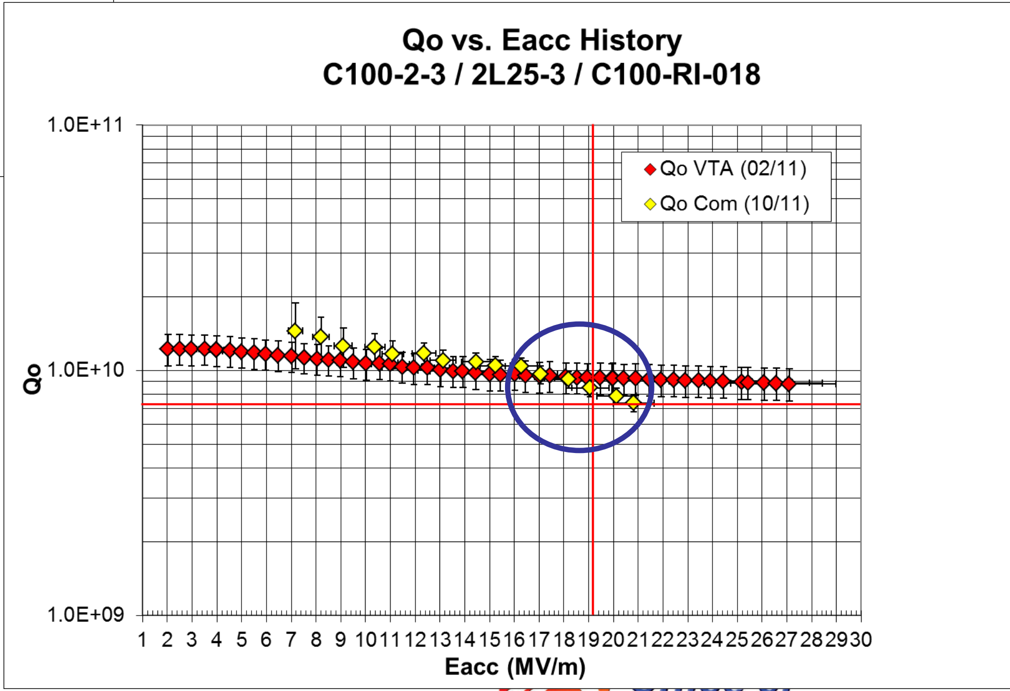
Divergence at higher gradients

- Higher field emission
- Small heat load contributions from power couplers / HOM couplers (1-2 W)

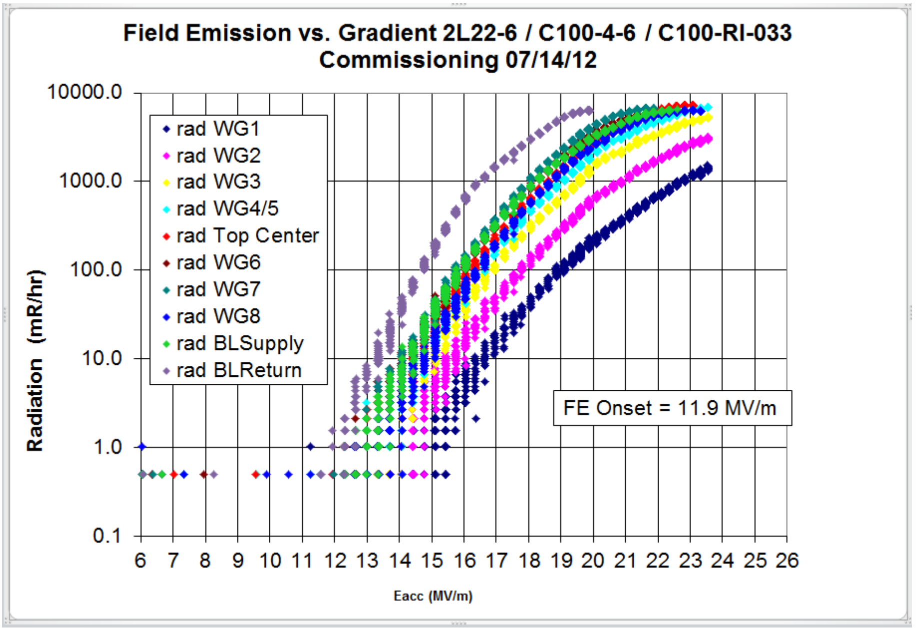
Q_0 Examples



Qo reduction due to increased field emission since VTA

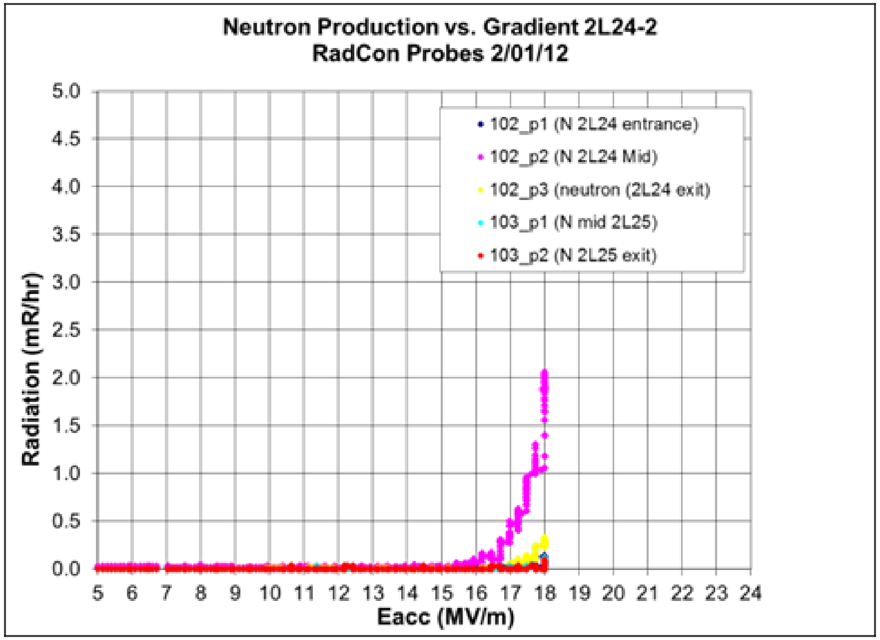


Field Emission

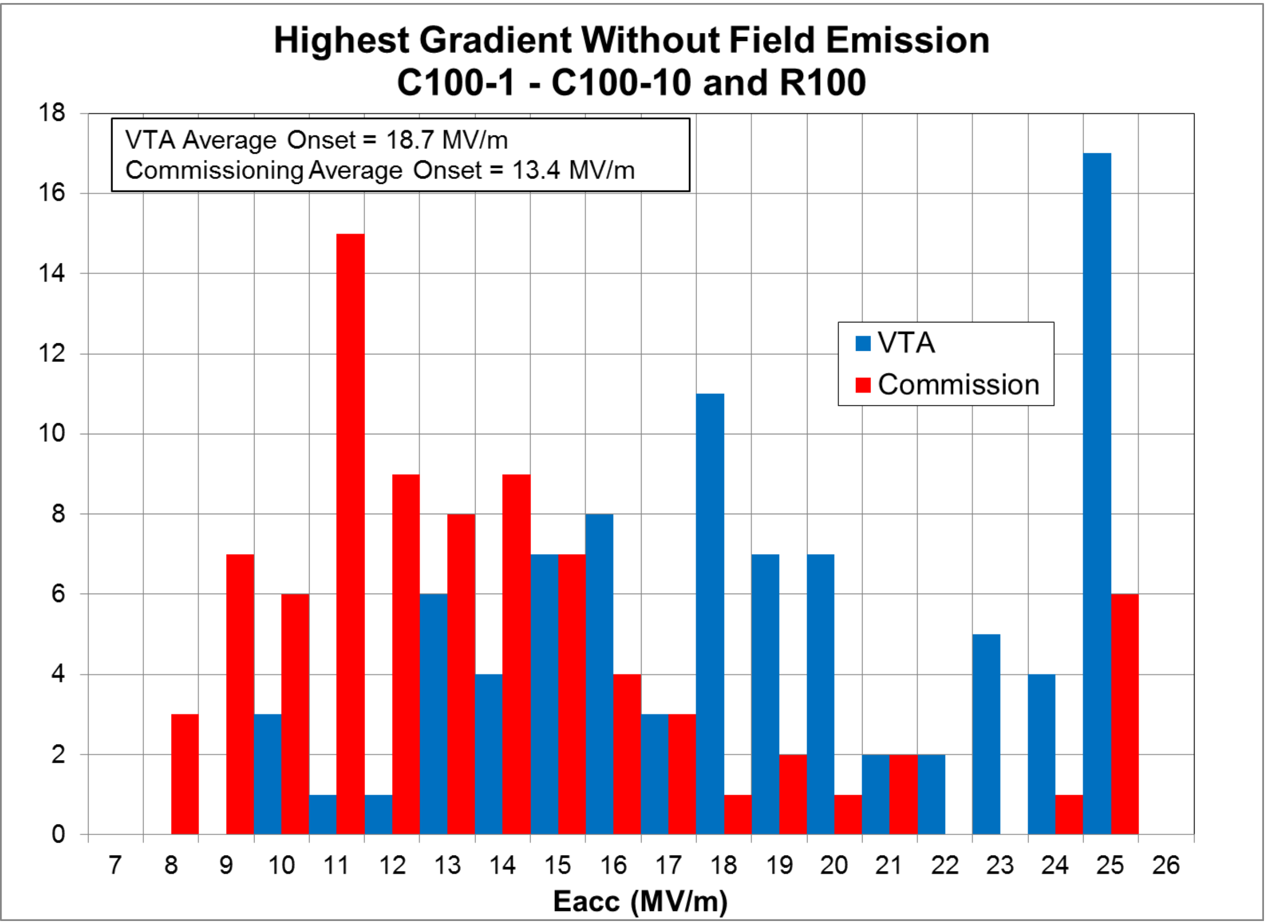


X-Rays measured with a set of ten Geiger-Mueller tubes arrayed around the cryomodule

Neutron Production measured with ion chambers.
Not routinely measured but noted on first two cryomodules.

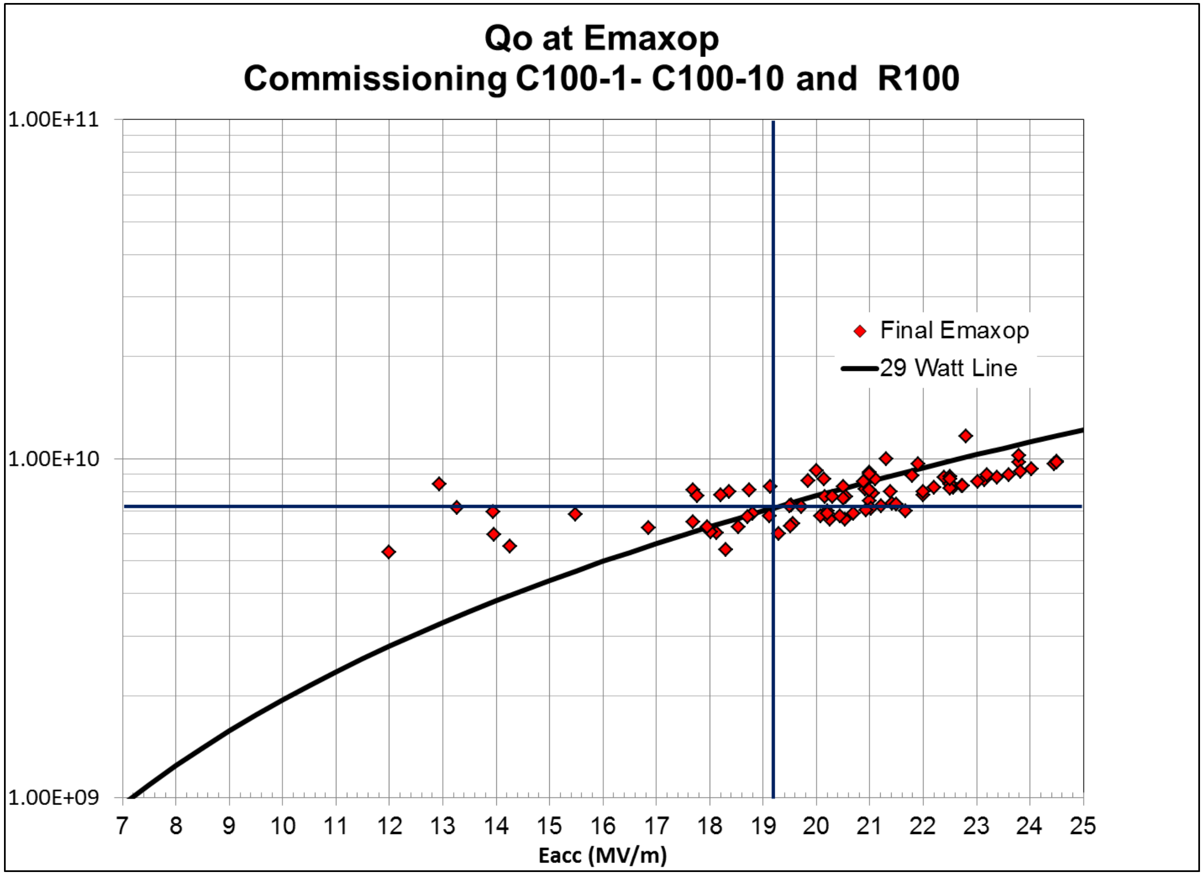


Field emission



Potential for beamline contamination during assembly process
Creation of new field emitters during testing

Qo at Emaxop



Using Qo data we calculate a final set of maximum gradients

Optimized by cryomodule
Individual cavity dynamic heat load <= 35 W (stay below He vessel riser limits)
Total dynamic heat load <= 240 W (dynamic portion of 300 W budget)

Energy Gain

Q_0 measurements are used to set the final maximum operating gradient.
Average for the Final maximum operating gradient – **20.4 MV/m**
Dynamic heat load ≤ 30 W per cavity / 240 W for the string.
These gradients are used for the final commissioning step: One hour run of all eight cavities

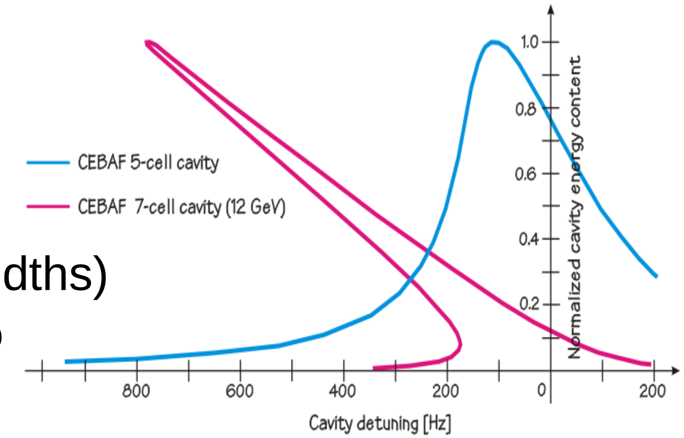
	Commission (MV)	W / Beam 2012 (MV)	W/ Beam 2014 (MV) (low current)
C100-1	104	94.5*	94
C100-2	120	108	99
C100-3	124		99
C100-4	105		90
C100-5	110		100
C100-6	113		102
C100-7	113		104
C100-8	109		100
C100-9	117		101
C100-10	116		87
R100	116		89

Optimization is still required

Operational Challenges

1st two C100's operated with beam for six months ending May 2012
In May 2012, C100-2 operated for extended run at 108 MV / 465 uA

Challenges:
- Microphonics (peak detuning 21 Hz)
- High Pressure Sensitivity (350 Hz / torr)
- High Lorentz detuning (~ 2 Hz / $(MV/m)^2$
- 800 Hz detuning from RF Off to 20 MV/m (~50 bandwidths)
- Mechanical coupling between adjacent cavities – 10%

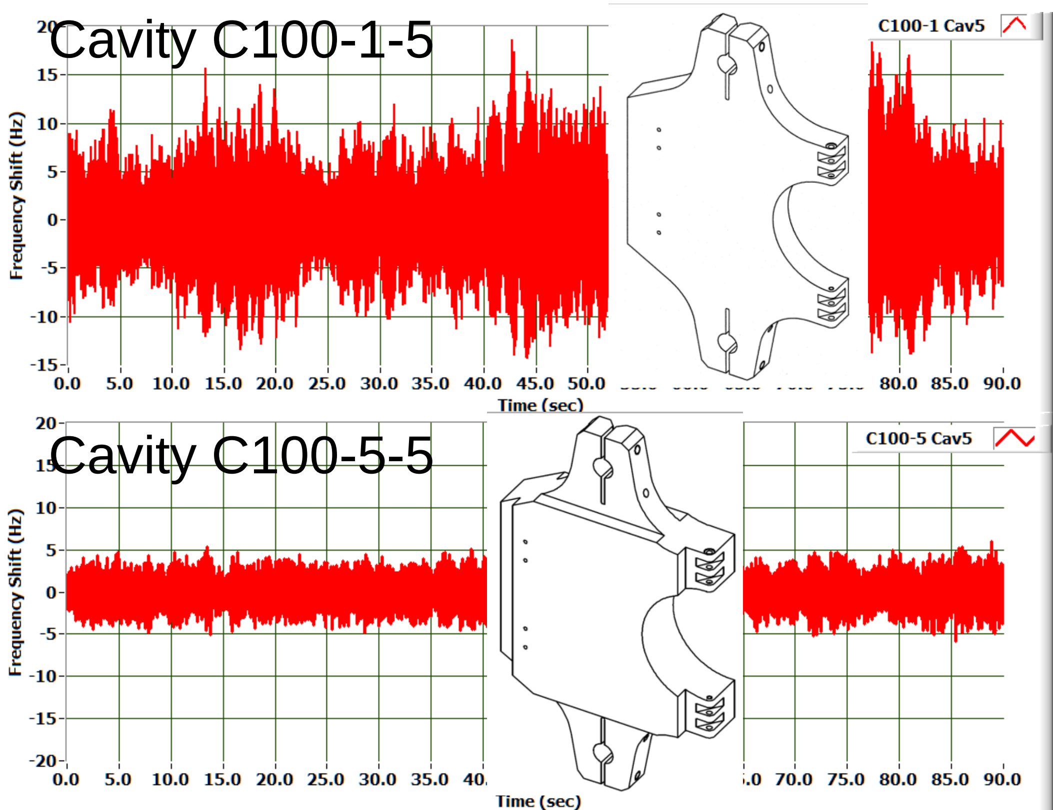


Solutions:
- Use of piezo tuner to compensate for pressure drift and slow microphonics
- Flexible field controls can switch to a self – excited loop mode to track detuning. This Mitigates "domino" effect
- **Tuner modification in newer cryomodules reduces detuning**

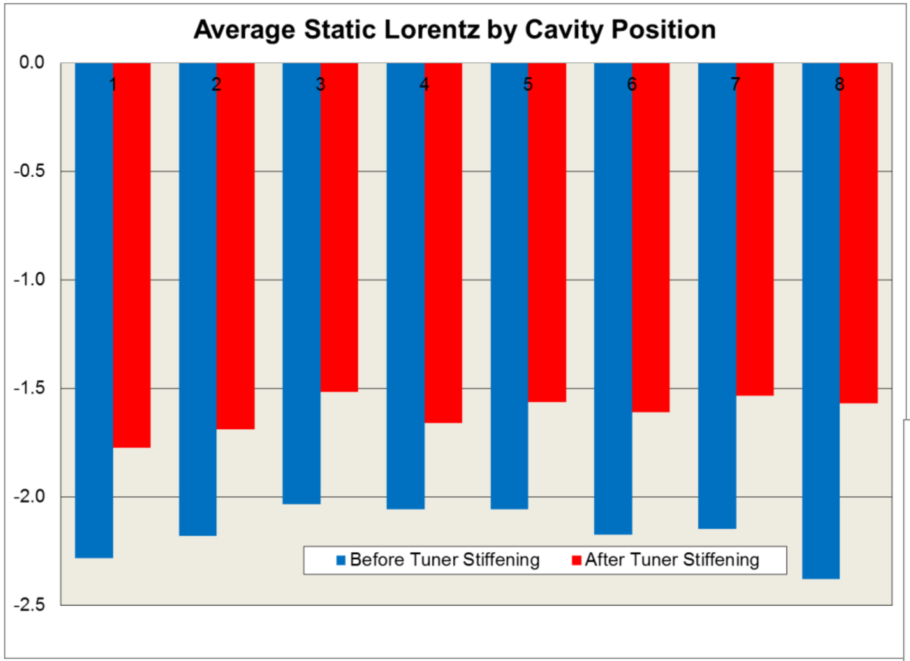
Microphonics

- **Design allows for 25 Hz Peak Detuning**
- Actual peak detuning **(21 Hz)** was higher than expected in first cryomodules
- A detailed vibration study was initiating which led to the following design change.
- A minor change to the **tuner pivot** plate substantially improved the microphonics for the CEBAF C100 Cryomodules.
- While both designs meet the overall system requirements the improved design has a larger RF power margin

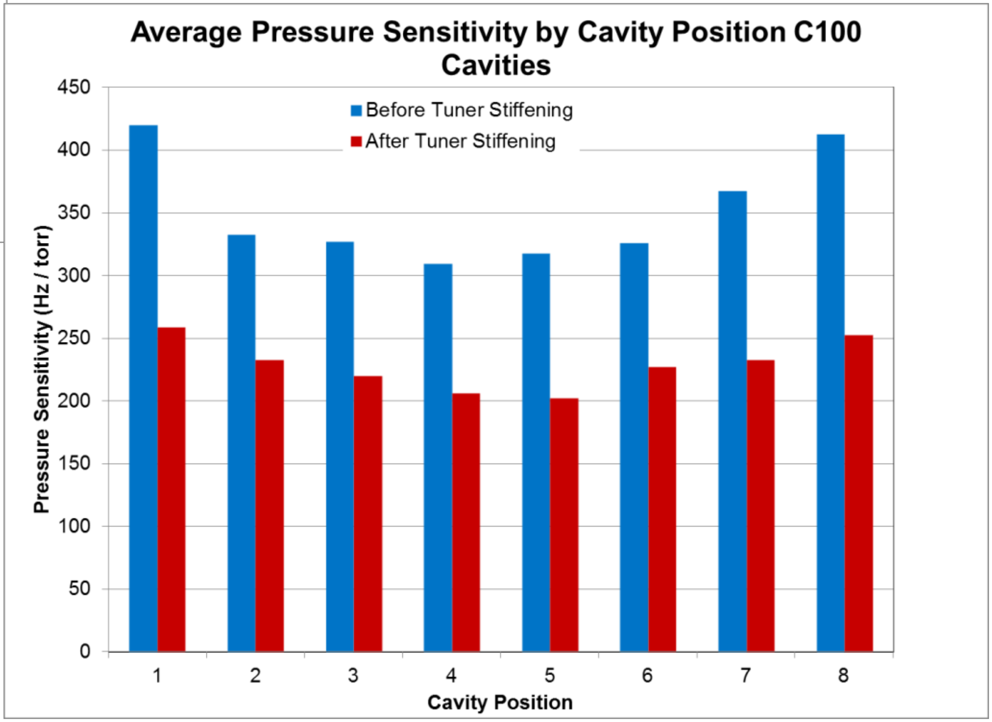
Microphonic Detuning*	C100-1	C100-4
RMS (Hz)	2.985	1.524
6σ(Hz)	17.91	9.14



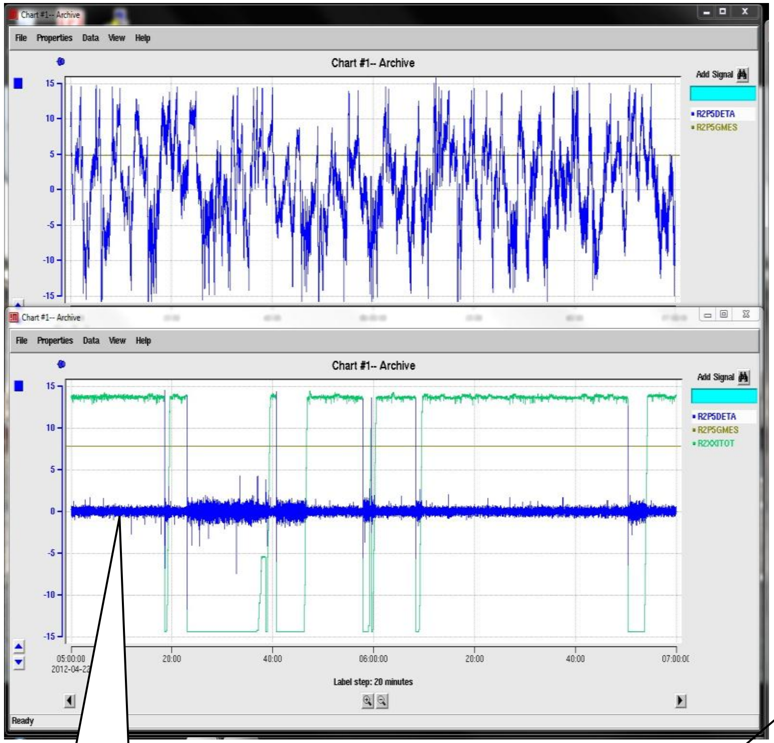
Tuner Improvements

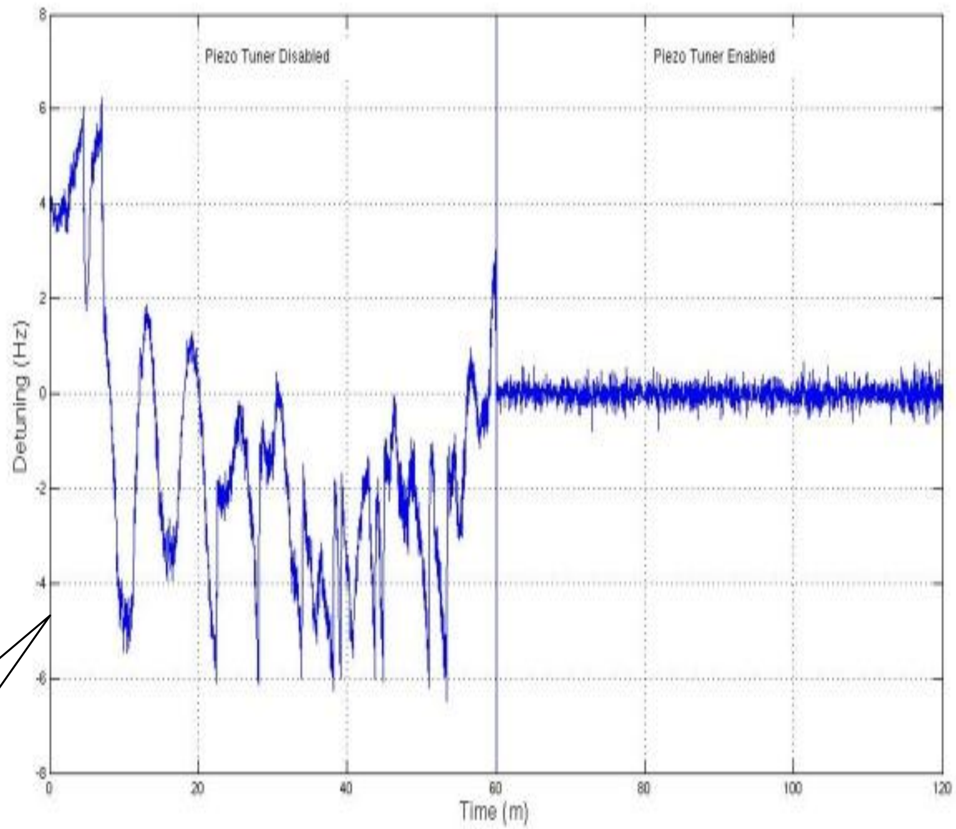


Tuner modification resulted in significant reduction in both the static Lorentz coefficient and in the pressure sensitivity



C100 PZT Control





Detune angle

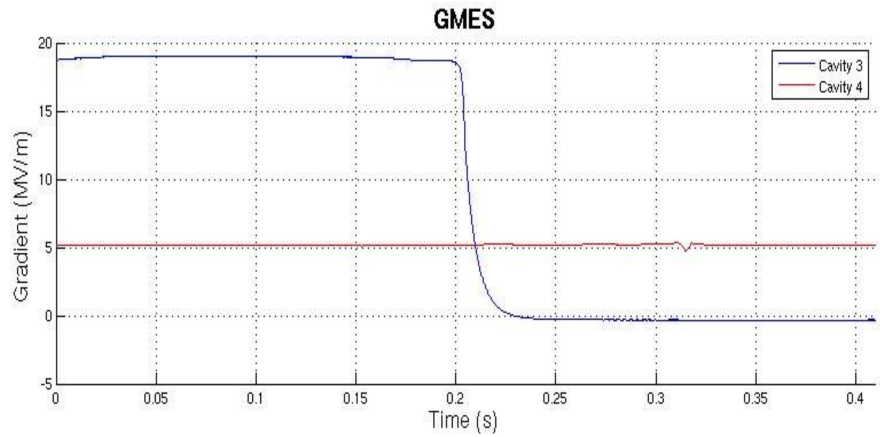
2 Hz / div

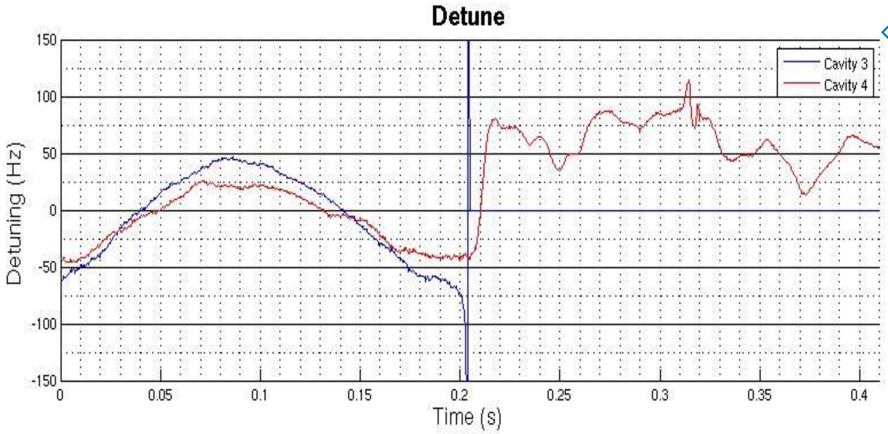
Piezo compensation bandwidth: 1 Hz
PI regulator
Wider bandwidth causes mechanical mode excitation/ instabilities
Substantial improvement for slow detuning (helium pressure drift or slow microphonics)

C100 PZT Controls

- Piezo tuners installed in the first four cryomodules
  - R100 and first three C100's (unmodified tuner)
  - Improvements made to the mechanical tuner have rendered piezo tuning unnecessary in the later cryomodules

Cavity Fratricide





Graph of gradient and detuning (Hz) as a cavity is faulting (blue)

Cavity Fratricide

- When one cavity trips - adjacent cavity can detune by ~80 Hz
- If klystron overhead is not high enough – adjacent cavity will trip
- “Domino” effect can trip entire string

Adjacent cavity was operating at 5 MV/m so the klystron had the overhead to absorb the detuning

Flexible digital field control can switch from GDR mode to a self excited loop mode allowing rf drive to track the detuning and stop the dominoes from falling.

Final Thoughts…

- C100 Cryomodule Commissioning is complete. It is expected that these cryomodules will exceed performance expectations.
- CEBAF has successfully delivered 2.2 GeV single pass beam and has begun multipass beam commissioning in Hall A.
- The C100's have delivered an average 98 MV with single pass, low current beam. Performance optimization is still needed.
- Expect to see a C100 gradient push in April
- Much work remains to be done

Acknowledgements

Acknowledgements

- C. H. Rode, "Jefferson Lab 12 GeV CEBAF Upgrade", AIP Conference Proceedings 1218 (2010).
- J. Delayen, “RF Parameters for the 12 GeV Upgrade Cryomodule”, Jefferson Lab Tech Note, JLAB-TN-05-044.
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- A. Burrill, K. Davis, C. Reece, A. Reilly, M. Stirbet, “SRF Cavity Performance Overview for the 12 GeV Upgrade”, IPAC 2012, New Orleans LA.
- A. Reilly, T. Bass, A. Burrill, K. Davis, F. Marhauser, C. E. Reece, M. Stirbet, “Preparation and Testing of the SRF Cavities for the CEBAF 12 GeV Upgrade”, SRF 2011, Chicago IL
- Drury *et al*, “Performance of the First C100 Cryomodules for the CEBAF Upgrade Project”, LINAC 2012, Tel Aviv, Israel.
- K. Davis, J. Matalevich, T. Powers, M. Wiseman, “Vibration Response Testing of the CEBAF 12 GeV Upgrade Cryomodules”, LINAC 2012, Tel Aviv, Israel.
- C. Hovater *et al*, “Commissioning and Operation of the CEBAF 12 GeV upgrade Cryomodules”, IPAC 2012, New Orleans LA.
- C. Hovater *et al*, “Status of the CEBAF Energy Upgrade RF Control System”, LINAC 2010, Tsukuba, Japan
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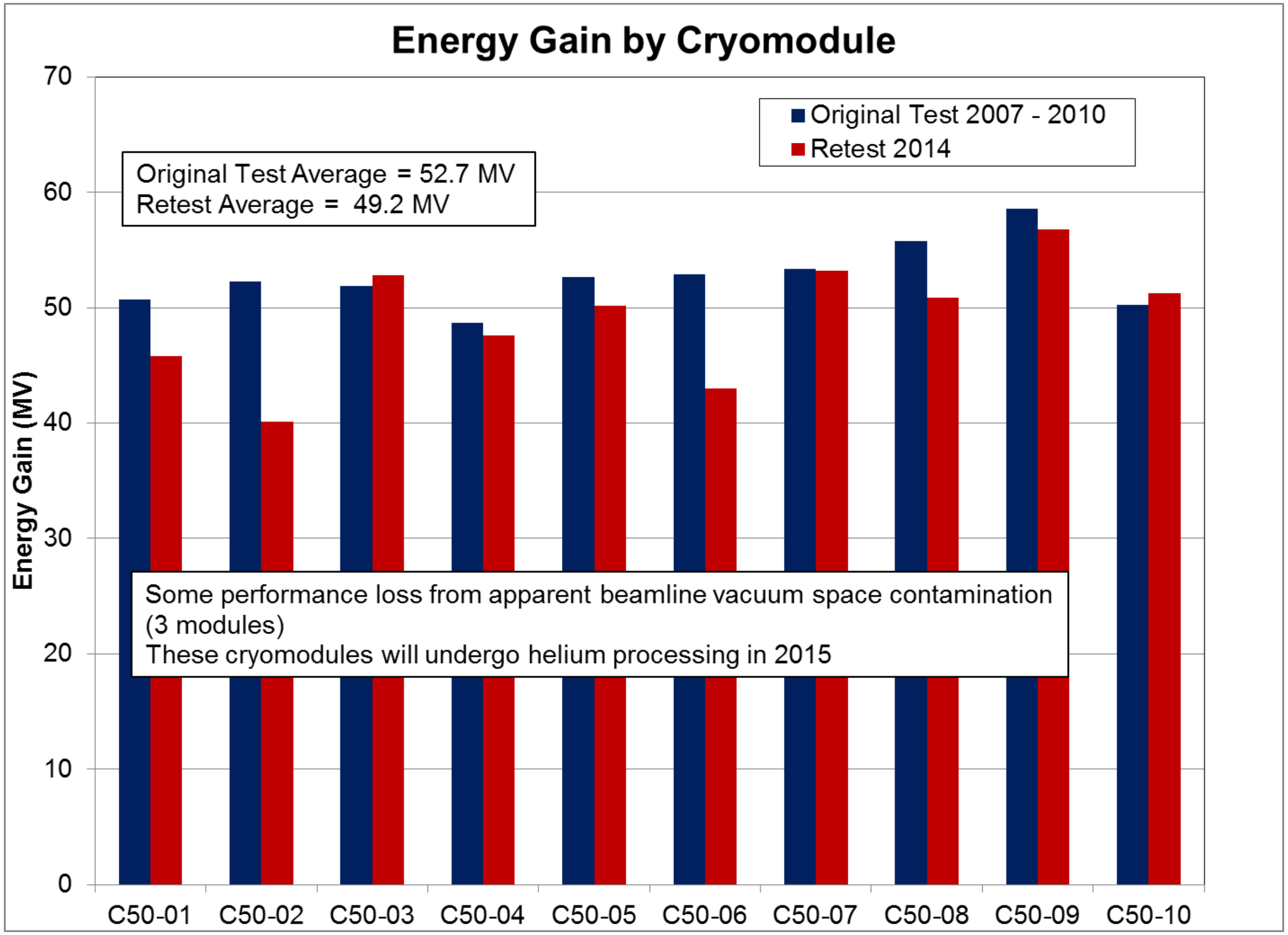
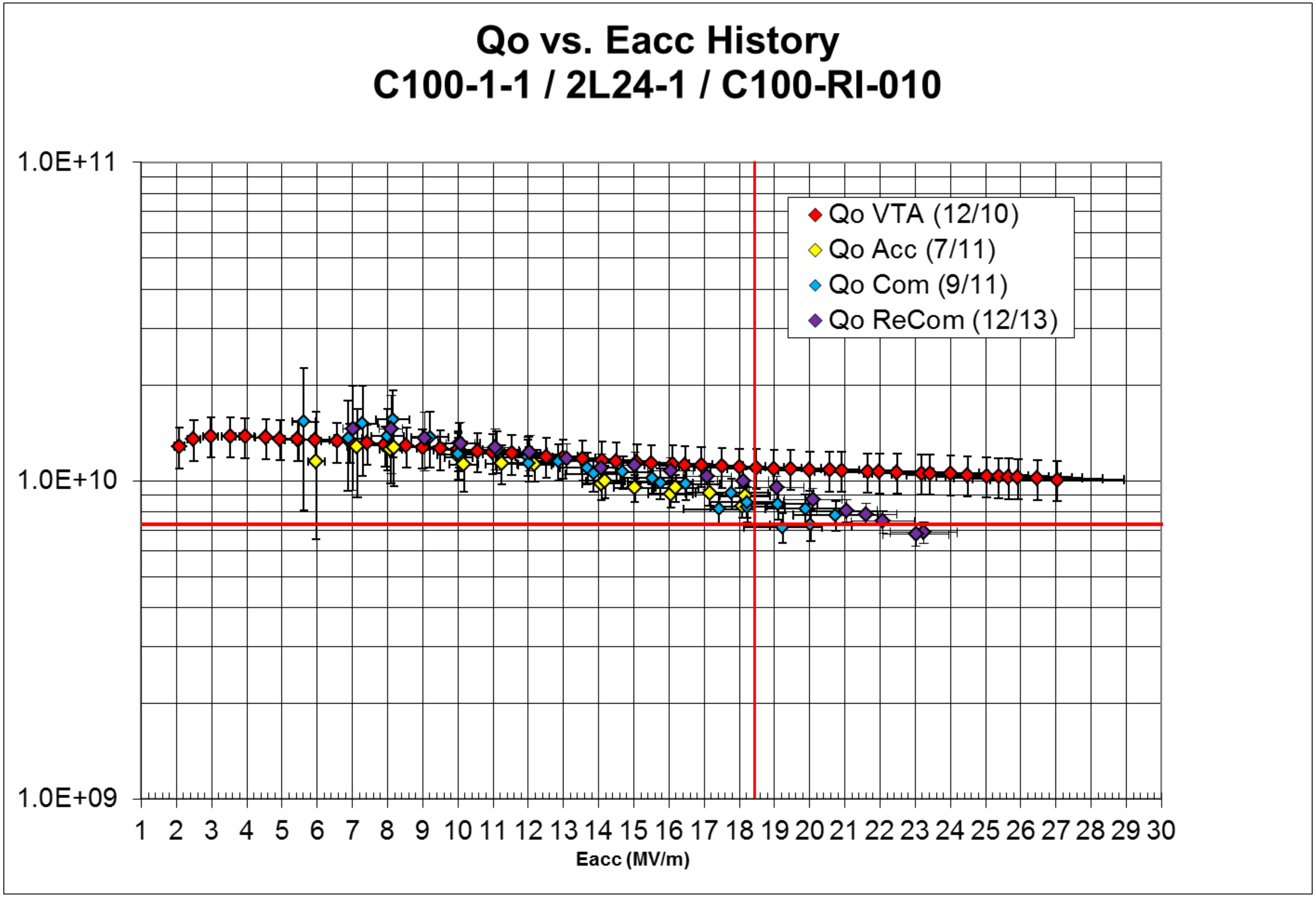
Appendix

C50 Performance over time



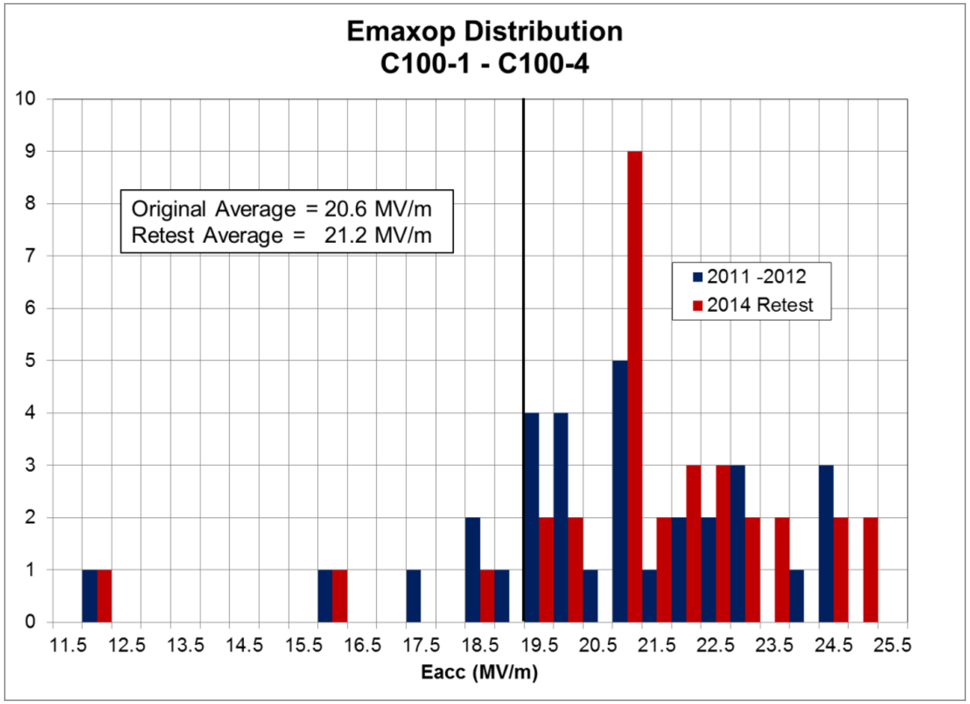
In parallel with various 12 GeV upgrade efforts,
All of the installed cryomodules were re-commissioned

C100 Performance over time

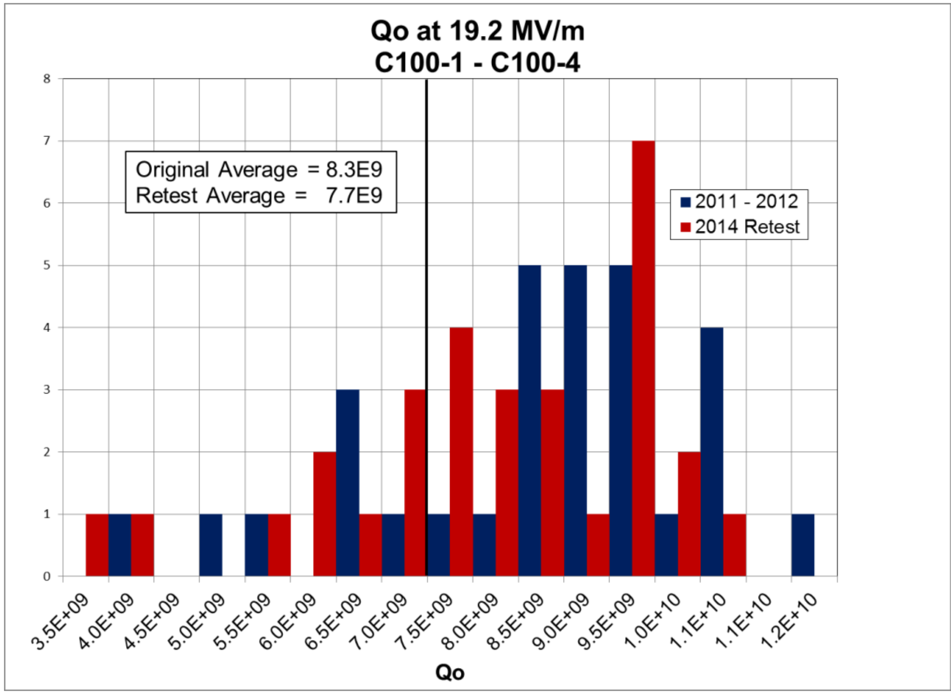


Typical Example

C100 Performance Over Time



Differences in gradient attributable to improvements in test method and / or measurement uncertainties.



Differences in Qo attributable to measurement uncertainty?
Difference of ~2W between the Averages.
Heat Load measurement good to ~1W

Cryomodule Replacement

- Original C20 cryomodules have been in service for 20+ years.
- Many have suffered from mechanical deterioration over time
  - Insulating and waveguide vacuum leaks
  - Broken tuners
- C50 Refurbishment program attempts to remove, refurbish and reinstall a cryomodule every 1-2 years.

Removing a Cryomodule

- Starts with a warm up to room temperature
- Beamline valves at either end must be leak checked
  - Radiation causes deterioration of seals
  - Frequently adjacent cryomodules must be warmed up depending on valve status
- Preparation for removal including warm up costs about 4 days of down time

Moving a cryomodule

Transporting: 6 technicians / 5 hours
Typical cost of removal and transport:
~ 2 person-weeks

Total Downtime
If spare available – two weeks
If not (dummy install) ~ 1 week