CEBAF Upgrade: Cryomodule Performance and Lessons Learned

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Outline

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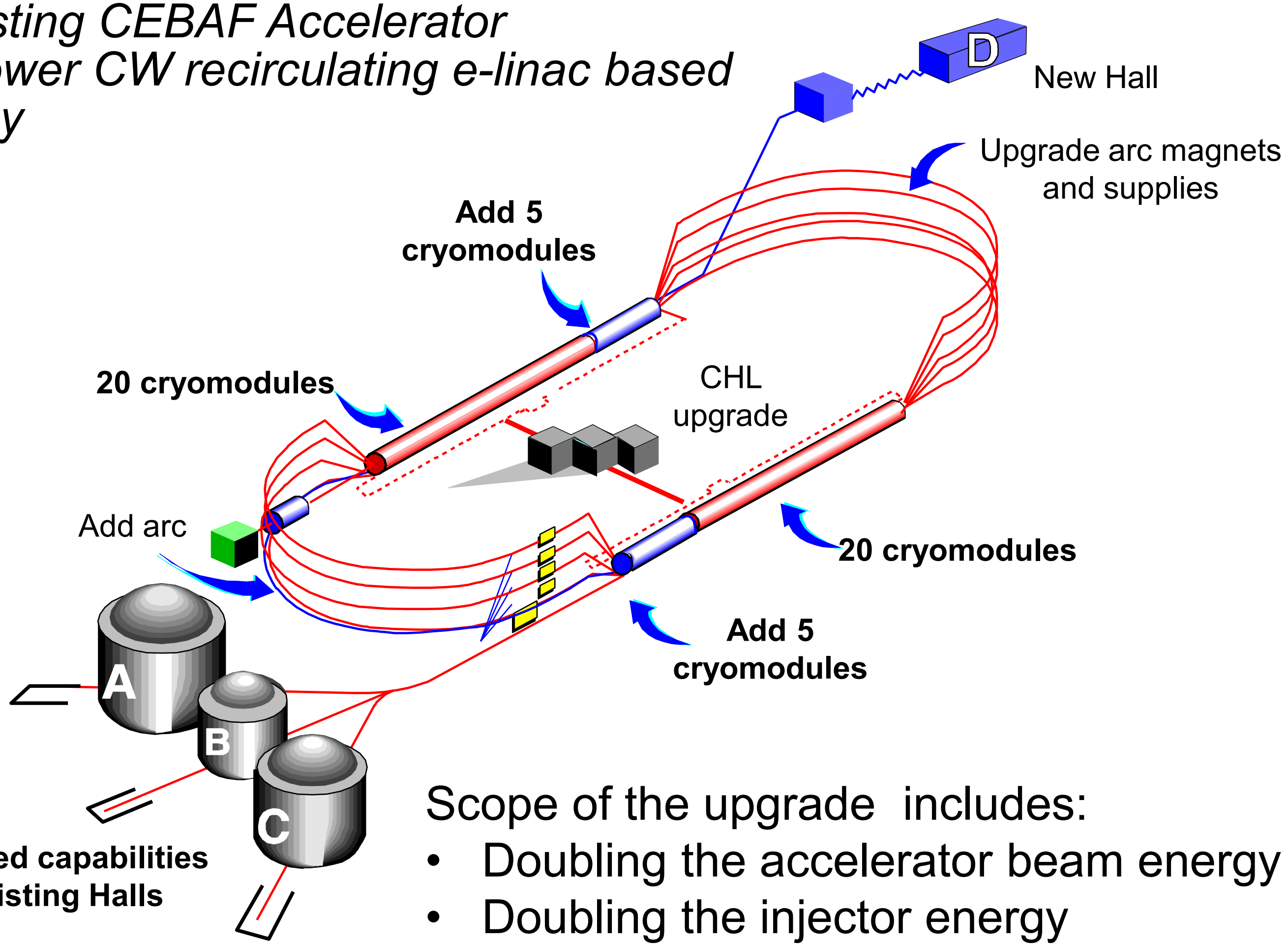
- C100 Cryomodule Status
- C100 Overview
  - Cavity
  - Cryomodule
- Cavity / Cryomodule Performance
- Operational Challenges
- Lessons Learned
- Summary & Acknowledgements

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

C100 Cryomodule Status

The C100 Cryomodule Project which began in 2009 is nearing its end.
Nine of the Ten Installed C100 Cryomodules have been Successfully Commissioned:
Average Max Operating Gradient = 19.6 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 = 110 MV (Design goal = 108 MV)

Two of these Cryomodules have been Operated with Beam
One has Successfully Operated at 108 MV with full beam loading of 465 μA

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)

- 2K Primary Circuit and 50K Shield Circuit via L-shaped end-cans
- Waveguide Coupler Assembly
  - Two Warm Windows
  - Guard Vacuum to Protect Cavity Vacuum
  - No helium to vacuum joints
- Scissor-jack tuner with easily accessible warm drive components
  - Provision for Piezo-electric component for fast control

Cryomodule Testing

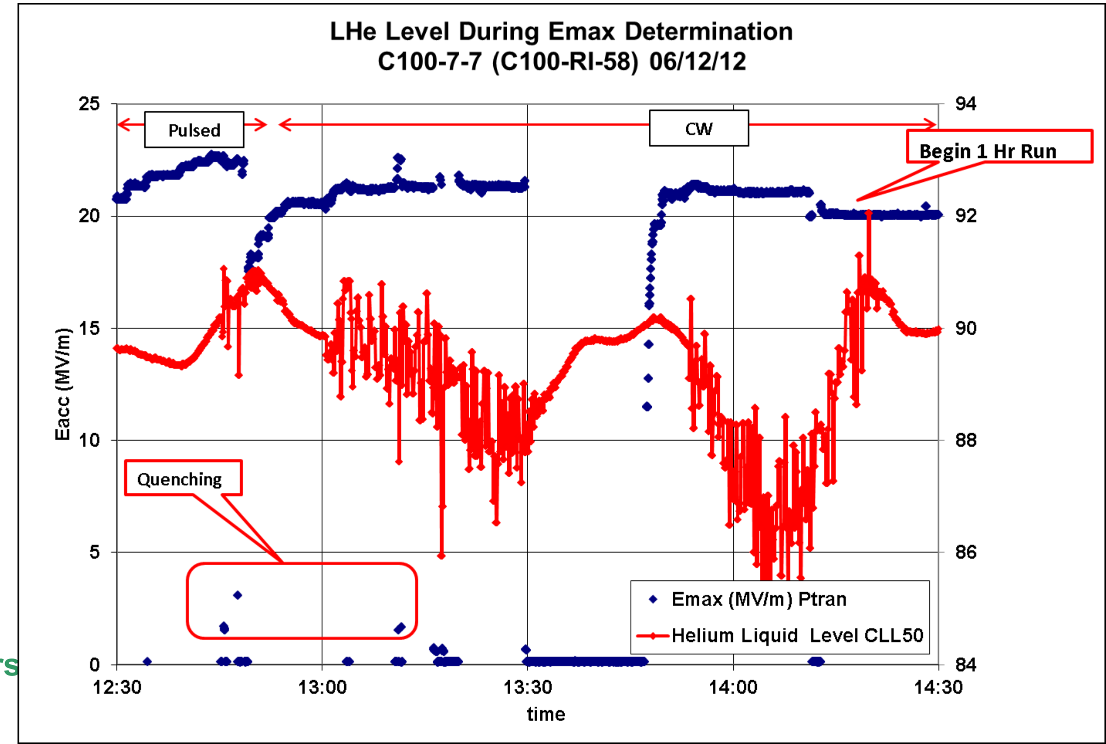
- Prior to Installation, all Cryomodules undergo a more comprehensive set of Acceptance tests in the Cryomodule Test Facility
- Acceptance tests are meant to uncover any major problems before delivery to the linac.
- Also include tuner qualification, Static Lorentz and Pressure Sensitivity Measurements

- 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

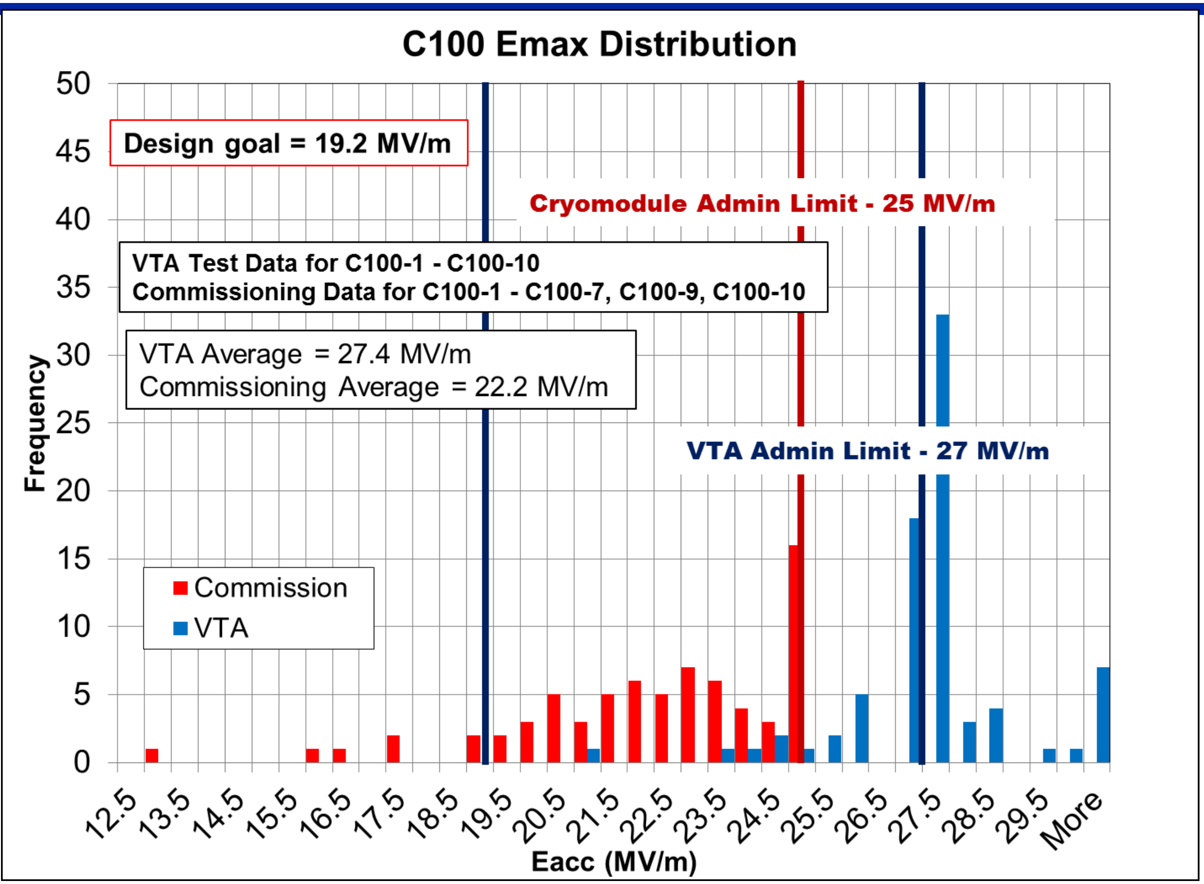
Emax Determination

- Calibrate the Gradient
- Increase Gradient in small steps
  - Find the limit – Pulsed RF
  - Check the limit –CW RF (Emax)
- One Hour run to test for stable operation (Emaxop)
  - 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:
Cavity Quench
High Heat Load
Admin Limit = 25 MV/m
~~Vacuum Degradation~~
~~Waveguide Arcs~~
~~RF Window Temperature~~



Emax - VTA / Commissioning



Preliminary accounting for gradient reductions:

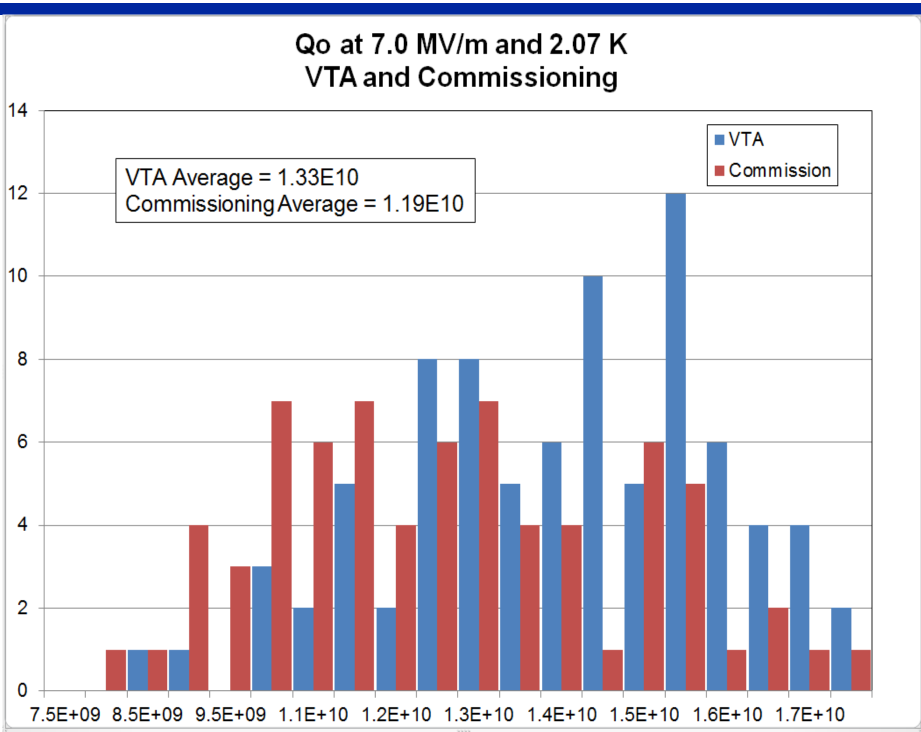
- Capping VTA Admin limit to 25 MV/m reduces VTA average to 24.9 MV/m
- Cryostat riser limits (50 – 60W per cavity) account for reductions in 21% of the cavities.
- Assembly / Testing “events” account for reductions in ~5% of the cavities

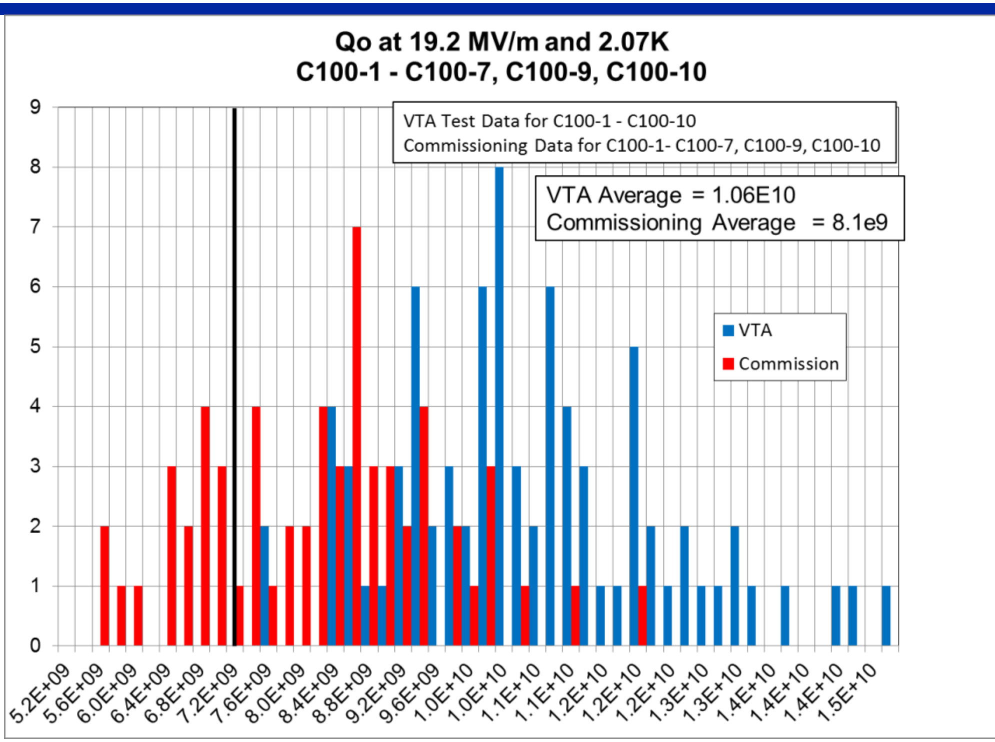
Q_0 Measurement

- **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



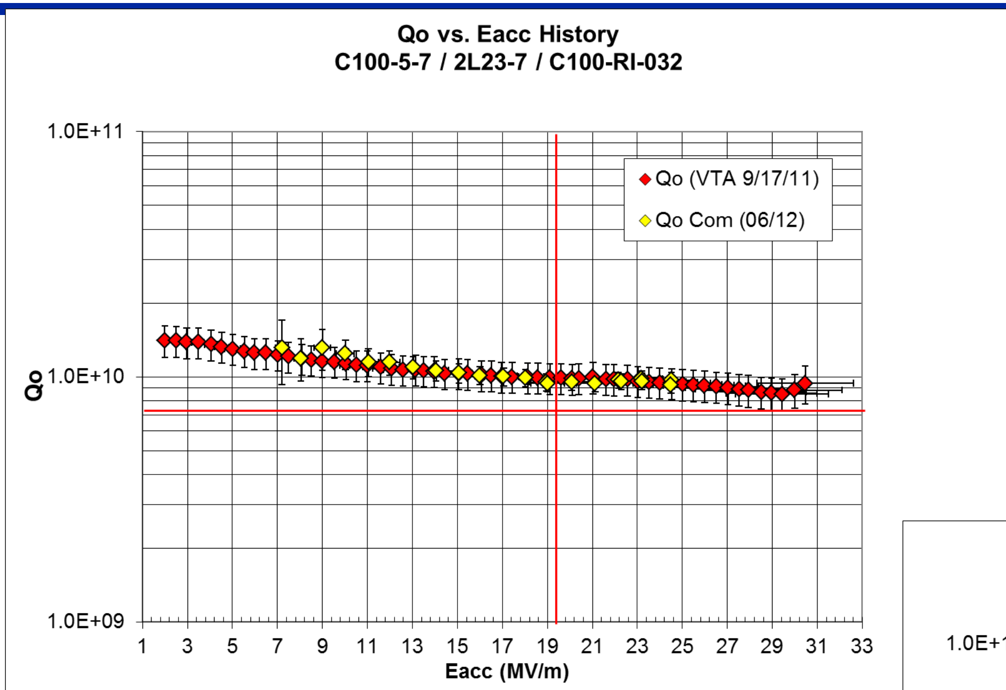


- Small divergence at lower gradients

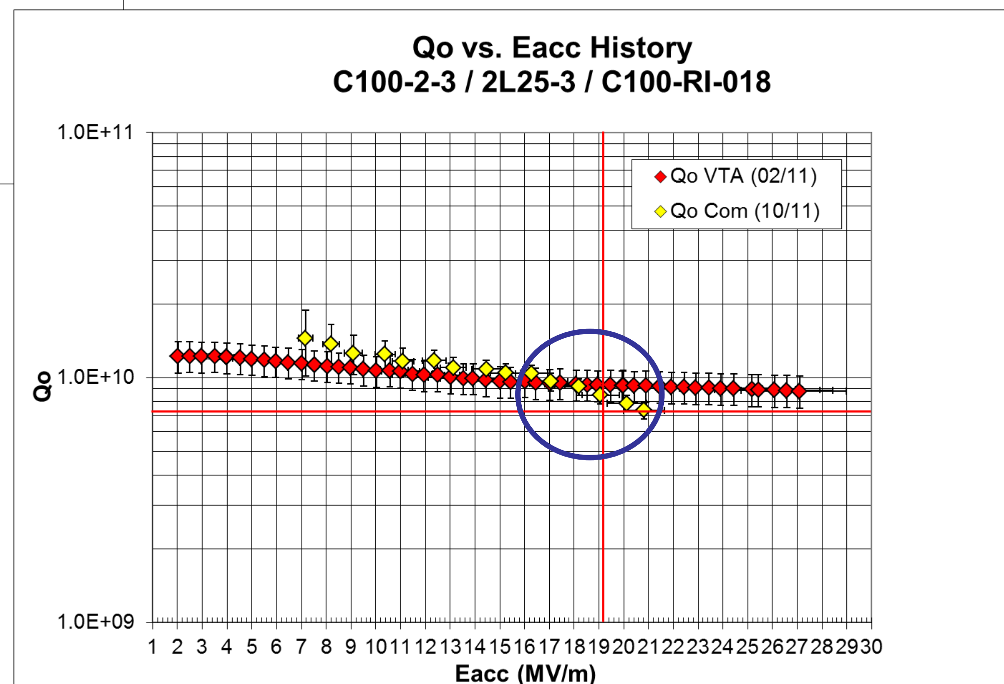
Divergence at higher gradients

- 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



Energy Gain

Q_0 measurements are used to set the final maximum operating gradient.
Average for the Final maximum operating gradient – **19.6 MV/m**
Dynamic heat load ≤ 29 W per cavity / 232 W for the string.
These gradients are used for the final commissioning step:
Extended runs at these energies:

Not yet optimized

	Commission (MV)	W /Beam (MV)
C100-1	104.3	94.5*
C100-2	109.6	108
C100-3	118.4	
C100-4	105.8	
C100-5	109.9	
C100-6	108.2	
C100-7	108.4	
C100-8		
C100-9	113.7	
C100-10	109.8	

Microphonics

- **Design allows for 25 Hz Peak Detuning**

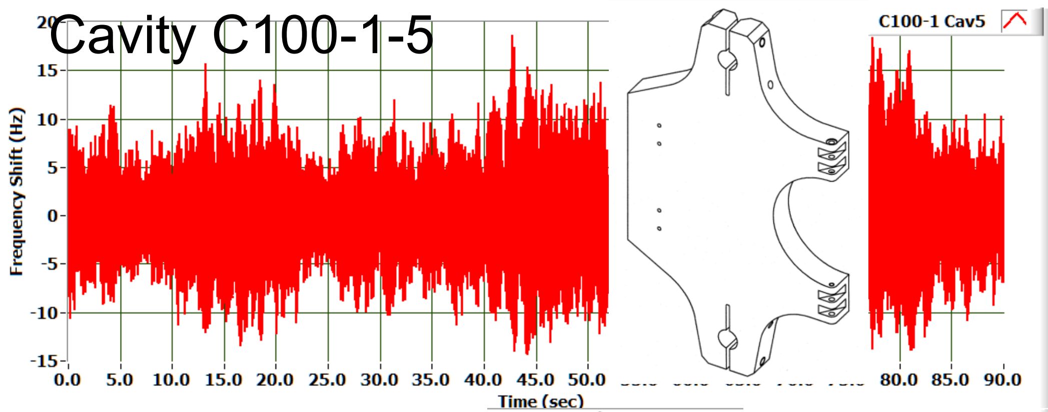
- Actual peak detuning **(21 Hz)** was higher than expected in first cryomodules
- A detailed vibration study was initiating which led to the following design change.

- A minor change to the **tuner pivot** plate substantially improved the microphonics for the CEBAF C100 Cryomodules.

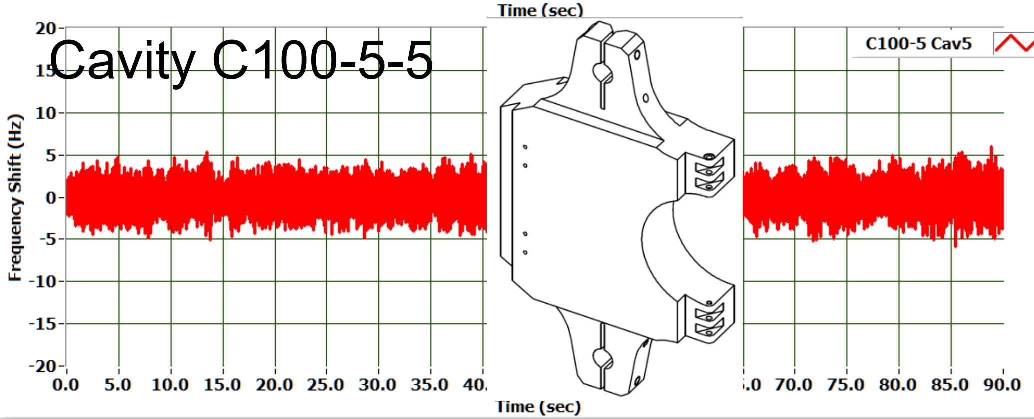
- While both designs meet the overall system requirements the improved design has a larger RF power margin

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

Cavity C100-1-5



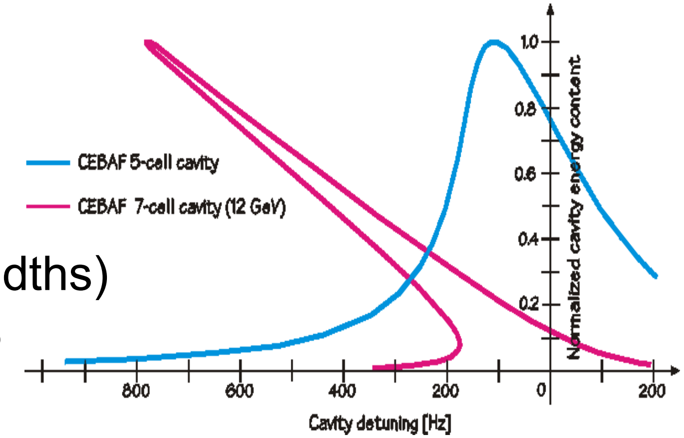
Cavity C100-5-5



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%



Cavity Fraticide
- 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

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**

Lessons Learned

- The effect of the cryomodule environment on performance must be considered when designing a cavity specification.
- Cryostat design may place limits on performance that are not readily apparent during vertical tests.
- The best quality control will not prevent all potential performance losses such as increases in field emission.

Finally…

- Cryomodule Commissioning will be complete in a few weeks.
- CEBAF will begin beam operations again in November.
- The C100's will deliver an additional ~550 MV per linac

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.
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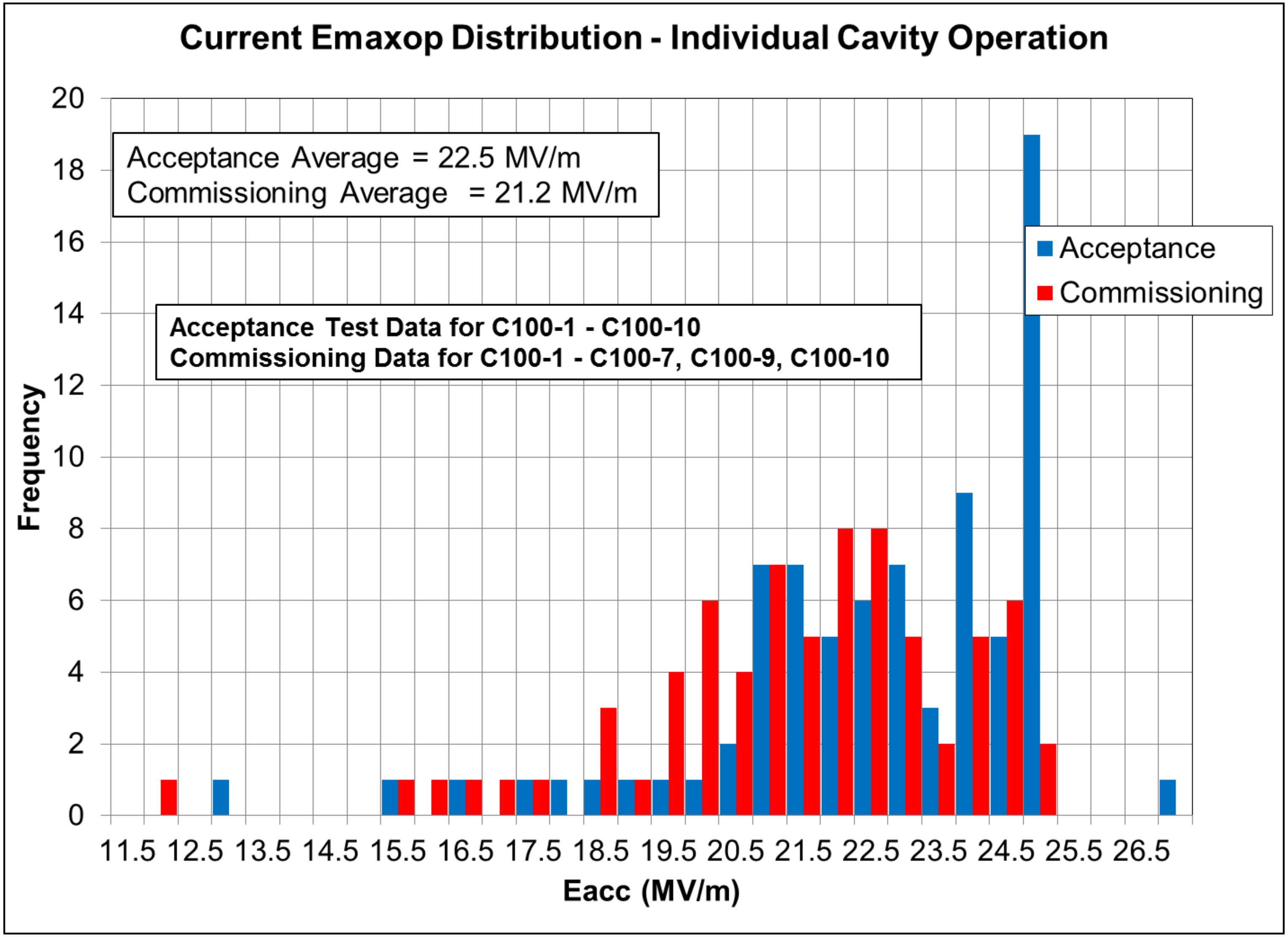
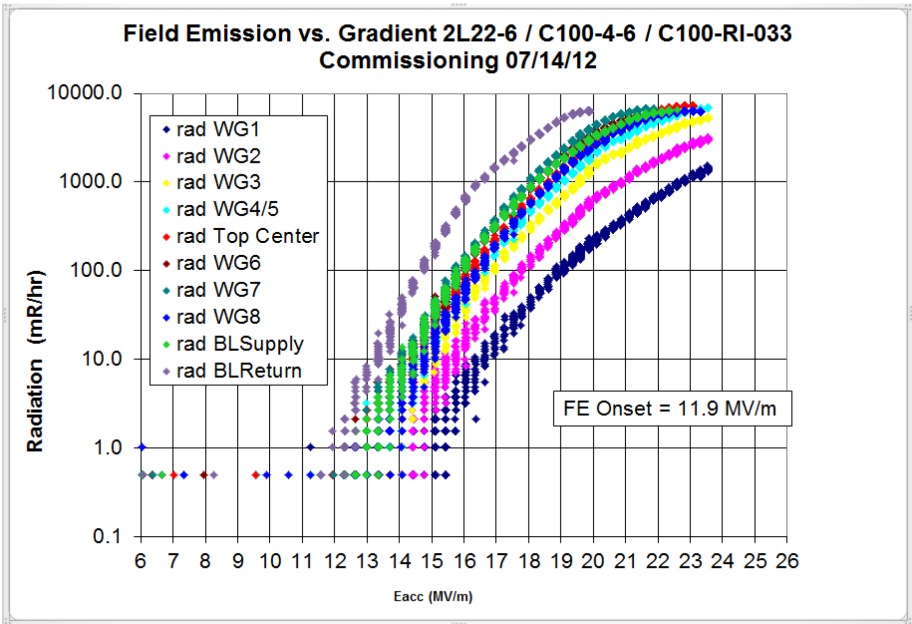
- C. Hovater *et al*, “Commissioning and Operation of the CEBAF 12 GeV upgrade Cryomodules”, IPAC 2012, New Orleans LA.
- C. Hovater *et al*, “Status of the CEBAF Energy Upgrade RF Control System”, LINAC 2010, Tsukuba, Japan

Appendix



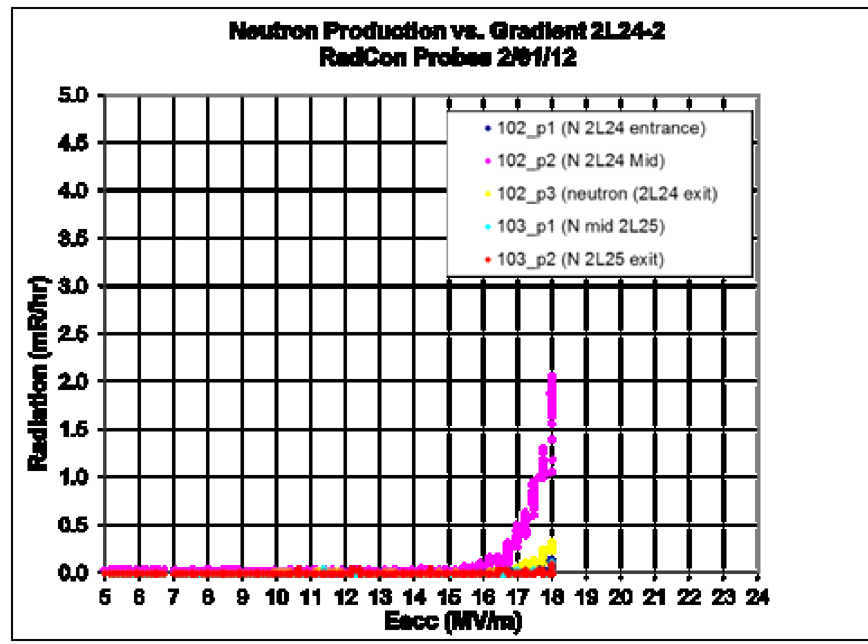
Current Emaxop Distribution - Individual Cavity Operation
Acceptance Average = 22.5 MV/m
Commissioning Average = 21.2 MV/m
Acceptance Test Data for C100-1 - C100-10
Commissioning Data for C100-1 - C100-7, C100-9, C100-10
Acceptance
Commissioning
Frequency
20
18
16
14
12
10
8
6
4
2
0
11.5 12.5 13.5 14.5 15.5 16.5 17.5 18.5 19.5 20.5 21.5 22.5 23.5 24.5 25.5 26.5
Eacc (MV/m)

Field Emission

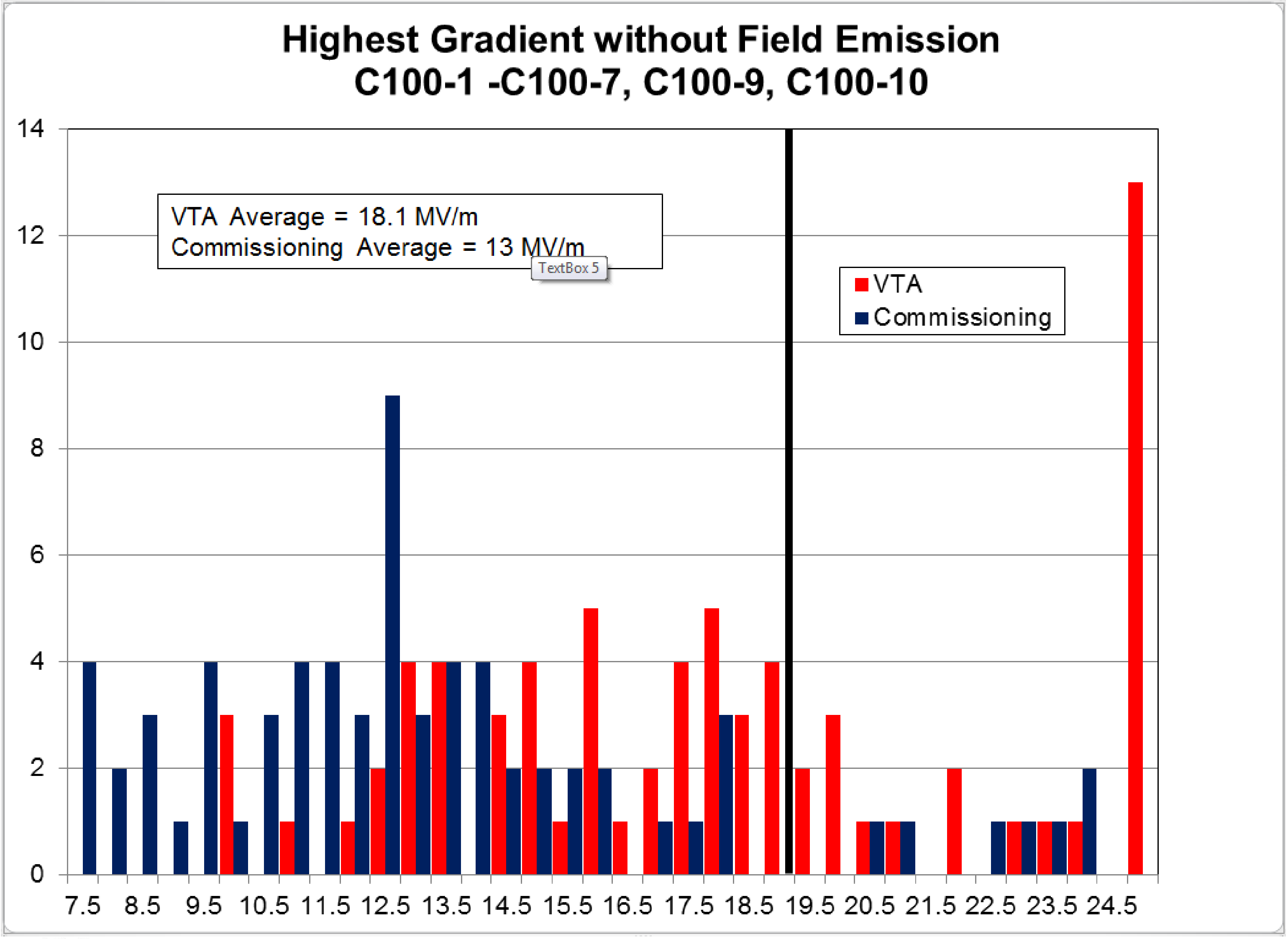


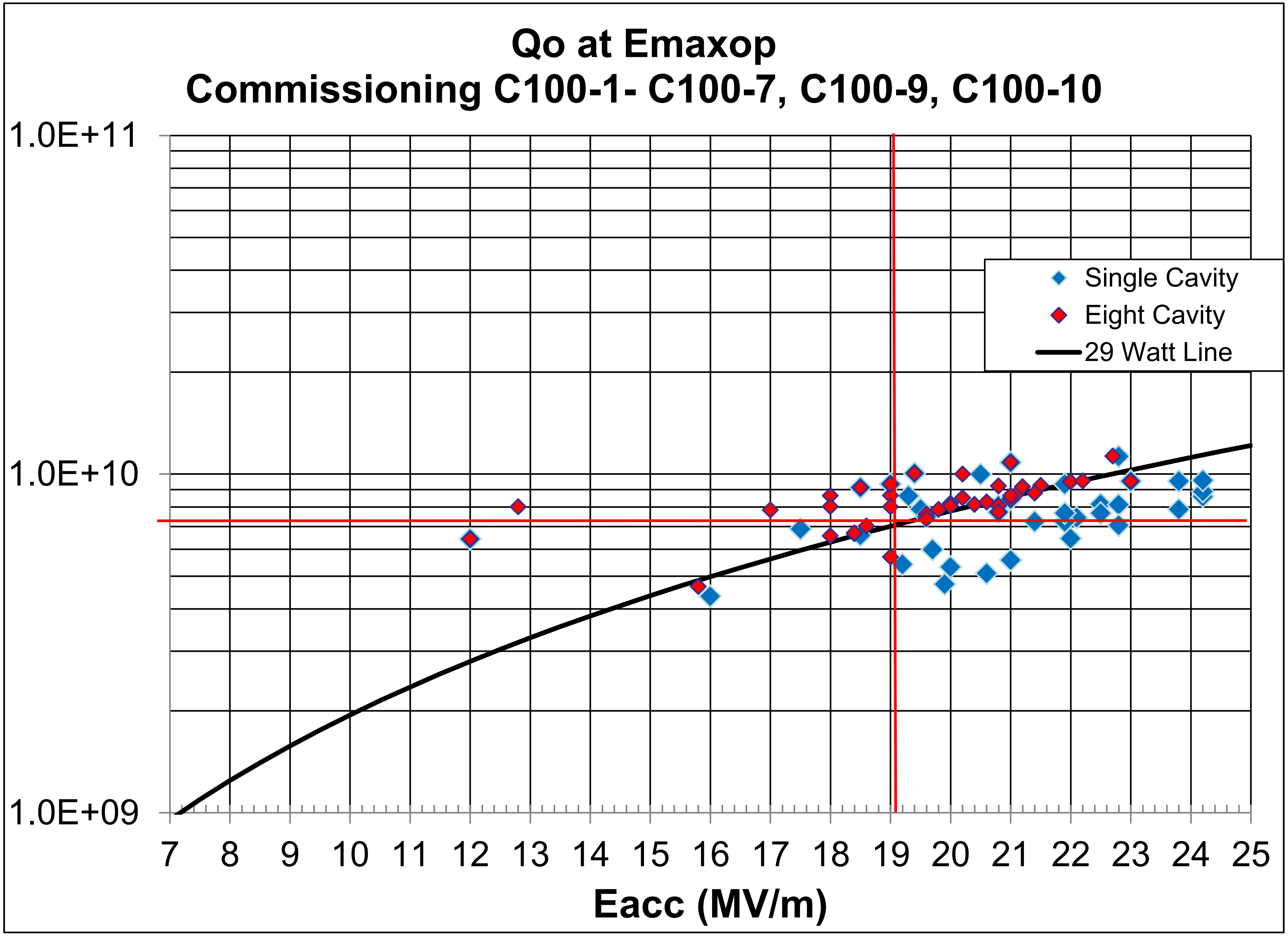
X-Rays measured with a set of ten Geiger-Mueller tubes arrayed around the cryomodule

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

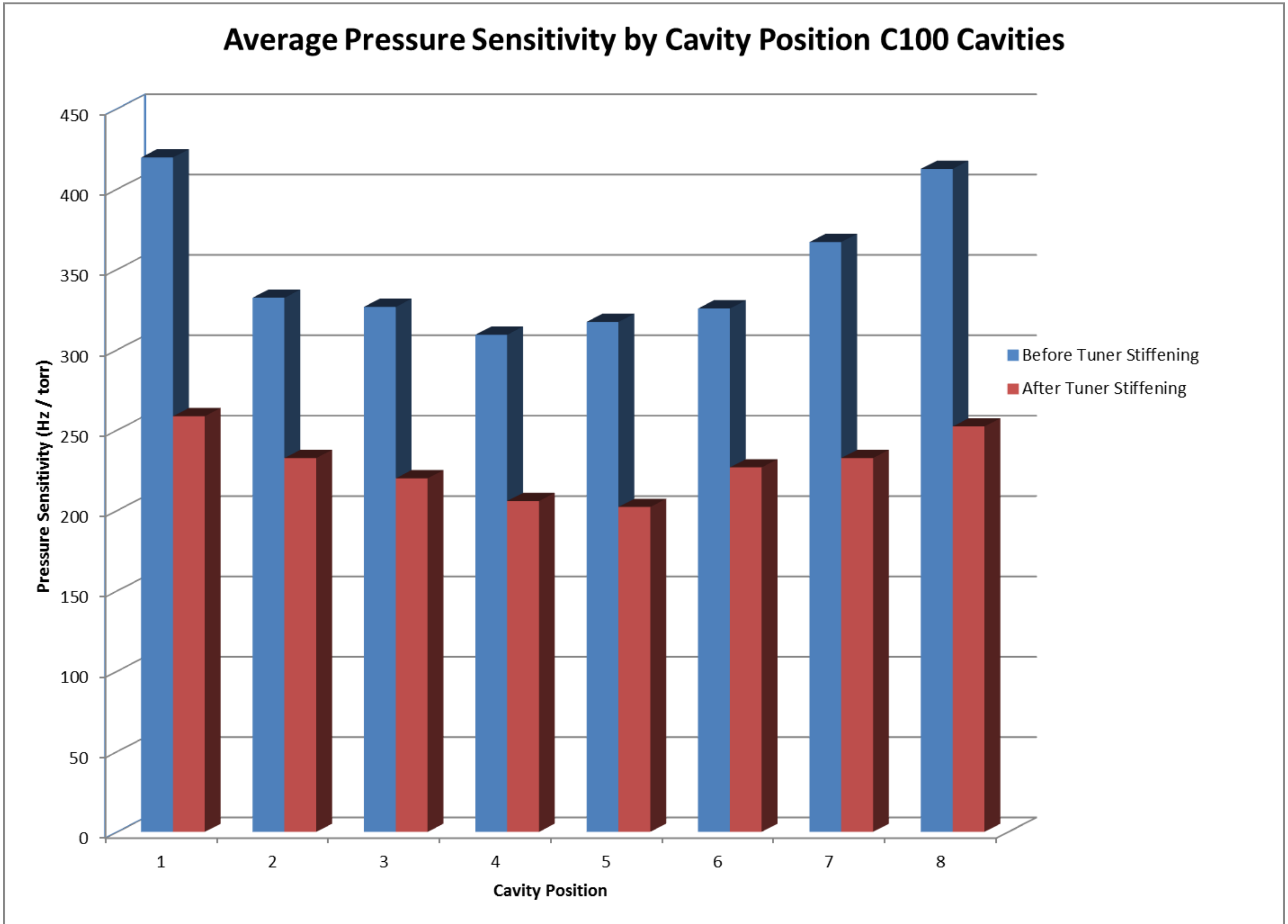


Field emission

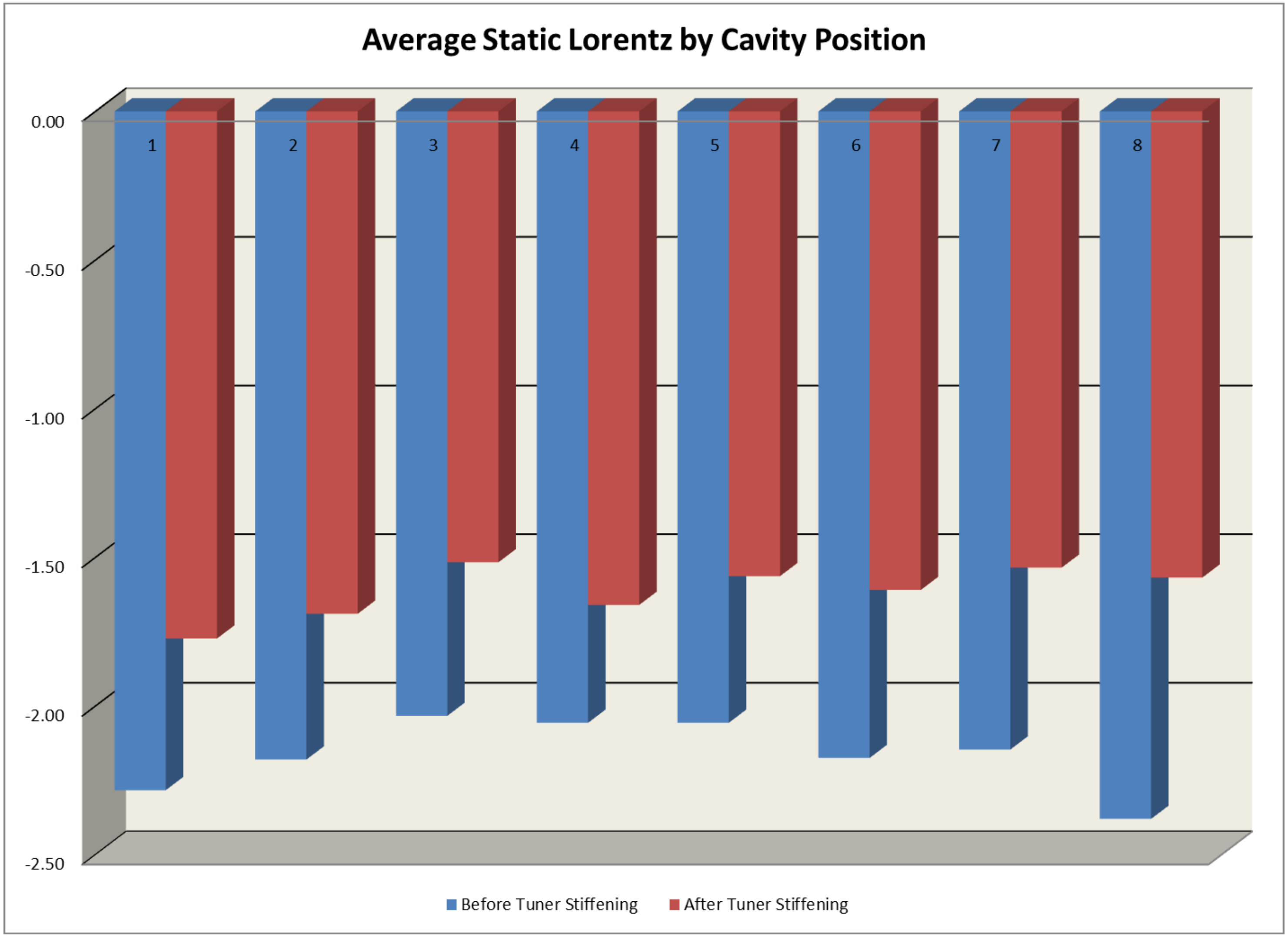




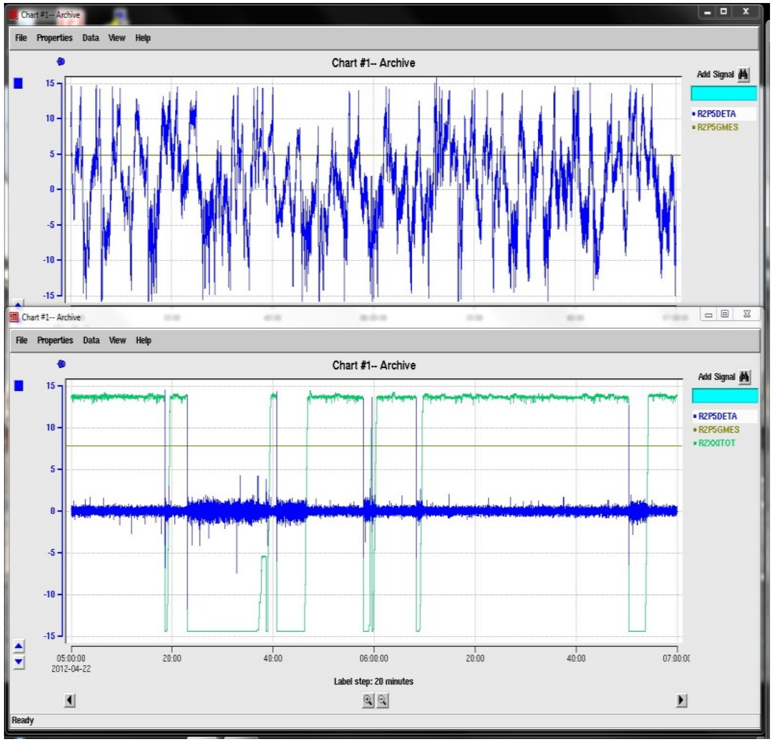
Qo at Emaxop
Commissioning C100-1- C100-7, C100-9, C100-10
1.0E+11
1.0E+10
1.0E+09
7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Eacc (MV/m)
Single Cavity
Eight Cavity
29 Watt Line

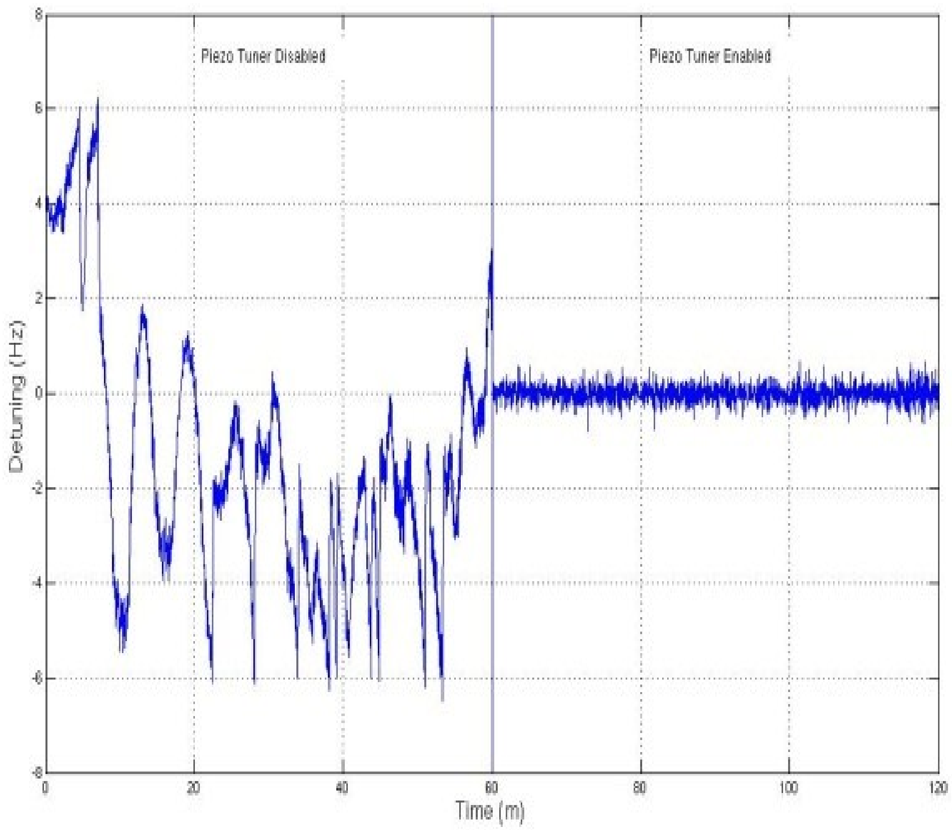


Average Pressure Sensitivity by Cavity Position C100 Cavities
Pressure Sensitivity (Hz / torr)
0
50
100
150
200
250
300
350
400
450
1
2
3
4
5
6
7
8
Cavity Position
Before Tuner Stiffening
After Tuner Stiffening


Average Static Lorentz by Cavity Position
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
1
2
3
4
5
6
7
8
Before Tuner Stiffening
After Tuner Stiffening

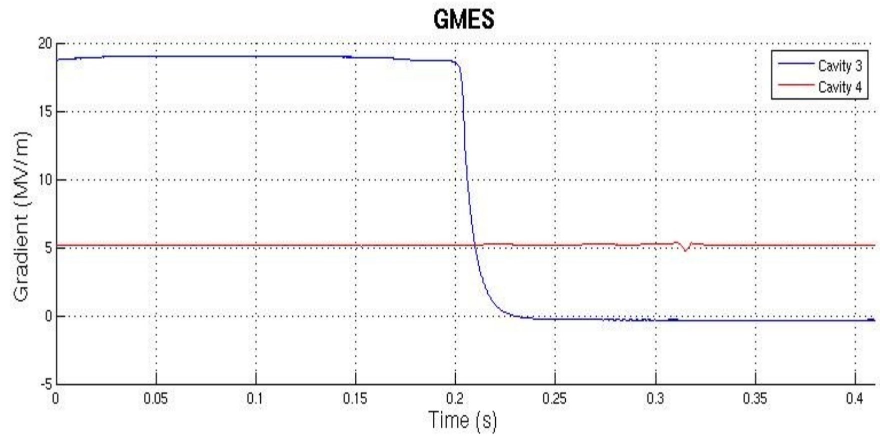
C100 PZT Control

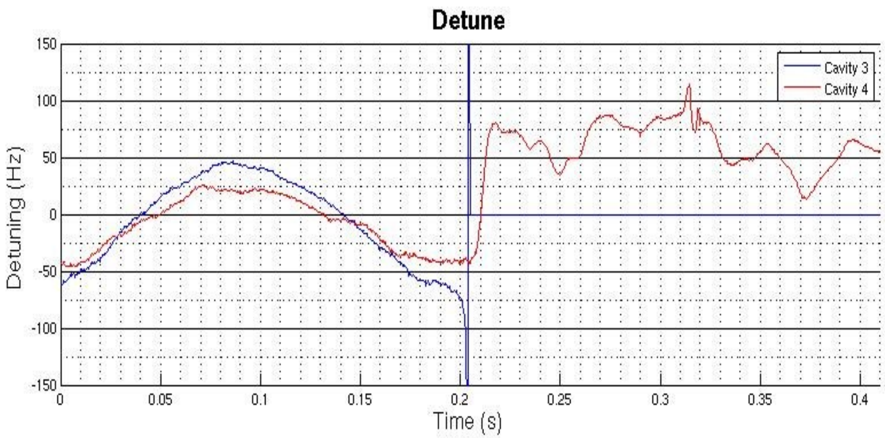




Piezo compensation bandwidth: 1 Hz
PI regulator
Wider bandwidth causes mechanical mode excitation/ instabilities
Substantial improvement for slow detuning (helium pressure drift or slow microphonics)

Cavity Fratricide





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

Cavity Fratricide occurs when one cavity faults (Arc, waveguide vacuum, quench etc.) and the Lorentz force detuning of the faulted cavity detunes the adjacent cavities resulting in the cavity faulting too.

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