OPERATIONAL EXPERIENCE WITH CW HIGH GRADIENT AND HIGH Q_L CRYOMODULES

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LINAC 2014, Geneva

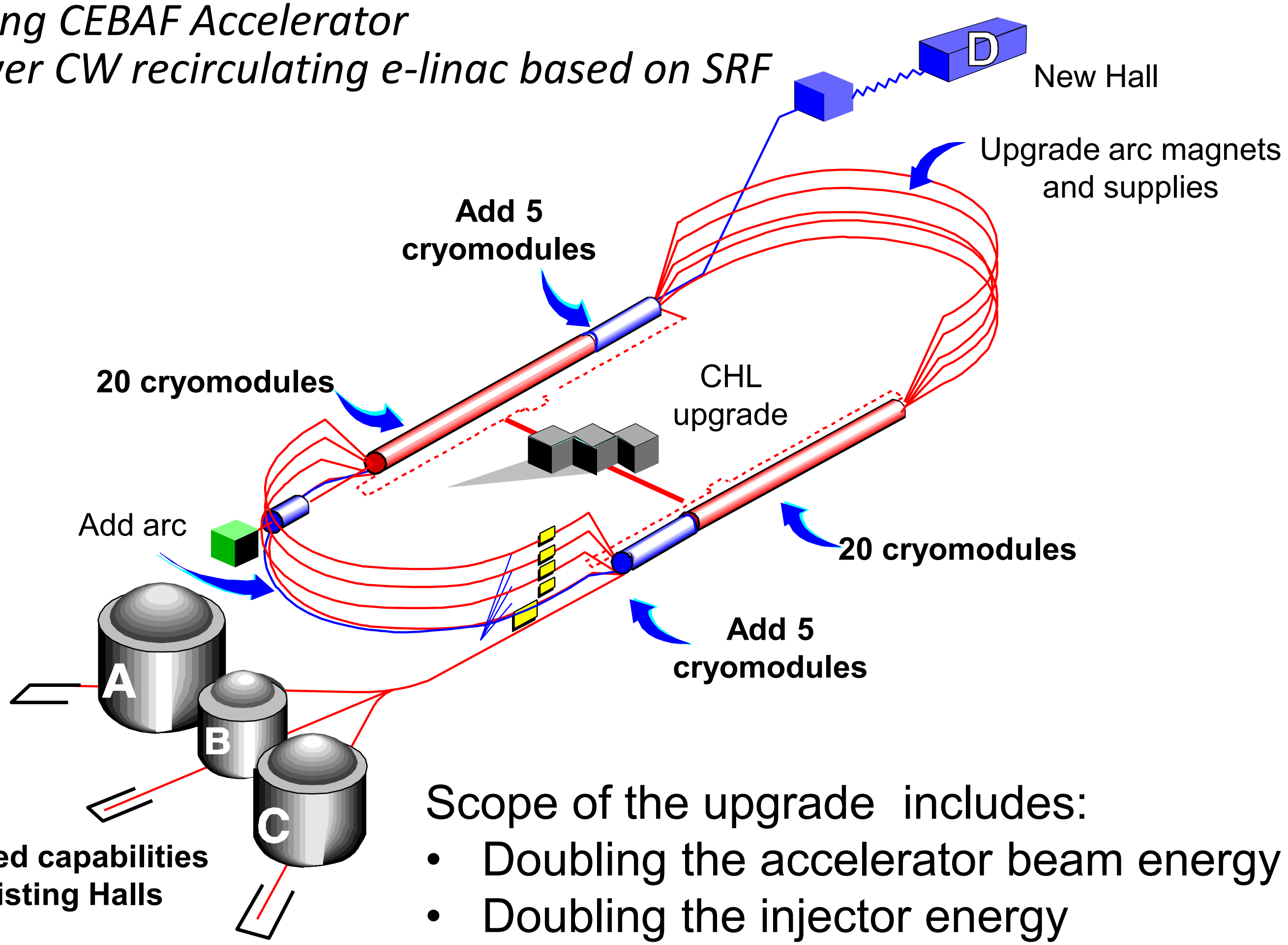
Outline

- **CEBAF Energy Upgrade**
- **C100 Cryomodules**
- **RF System**
- **RF & Cryomodule Commissioning**
- **Operational Experience**
- **Summary**

For the purposes of this talk I will qualify High Q_L as > 10^7 and gradients > 15 MV/m operating CW!

12 GeV Upgrade Project

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



Scope of the upgrade includes:

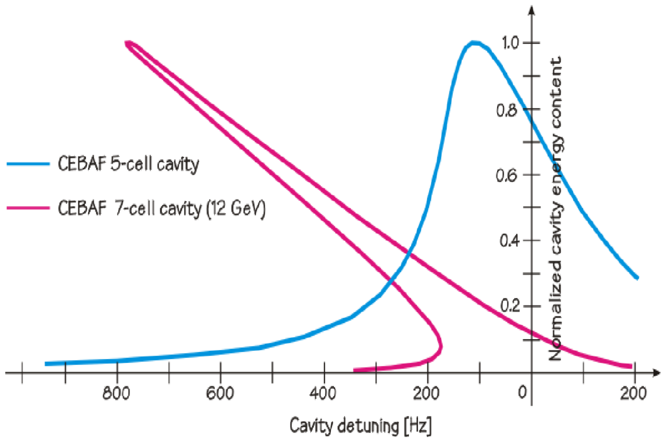
- Doubling the accelerator beam energy
- Doubling the injector energy
- New Hall and beam-lines
- Upgrades to existing Experimental Halls

High Gradient & Q_L Challenges

Fundamental frequency f_0	1497 MHz
Accelerating gradient E_{acc}	> 20 MV/m
Input coupler Q_{ext}	3.2×10^7
Active length	0.7 m
r/Q	1300 Ω/m
Tunning sensitivity	0.3 Hz/nm
Pressure sensitivity	420 Hz/torr
Lorenz force coefficient K_L	~2 Hz/(MV/m)^2

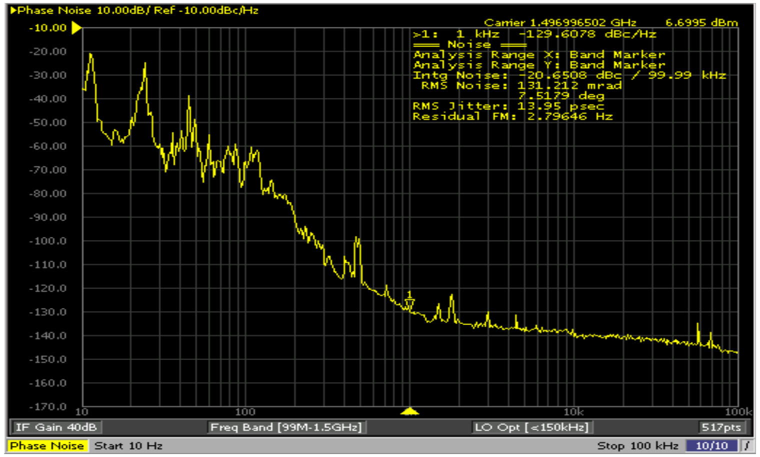
Seven Cell Cavity

Field startup



Lorentz Detuning

Field stability (microphonics)



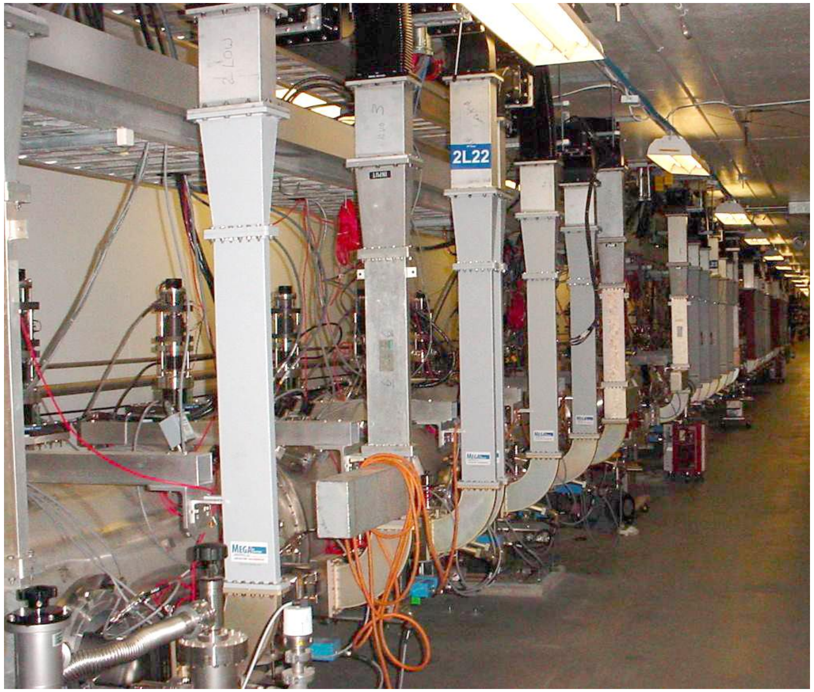
Phase Noise Plot

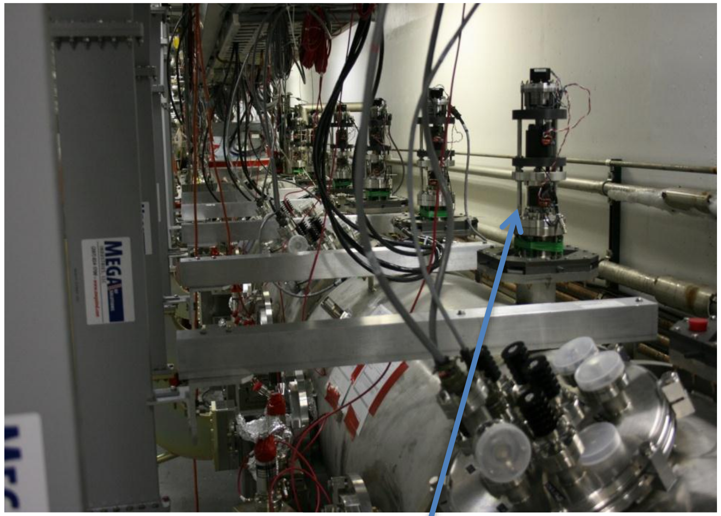
C100 Cryomodule

Each cryomodule contains a string of **eight 7-cell low-loss SRF 1497 MHz cavities**

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

C100 Cryomodule





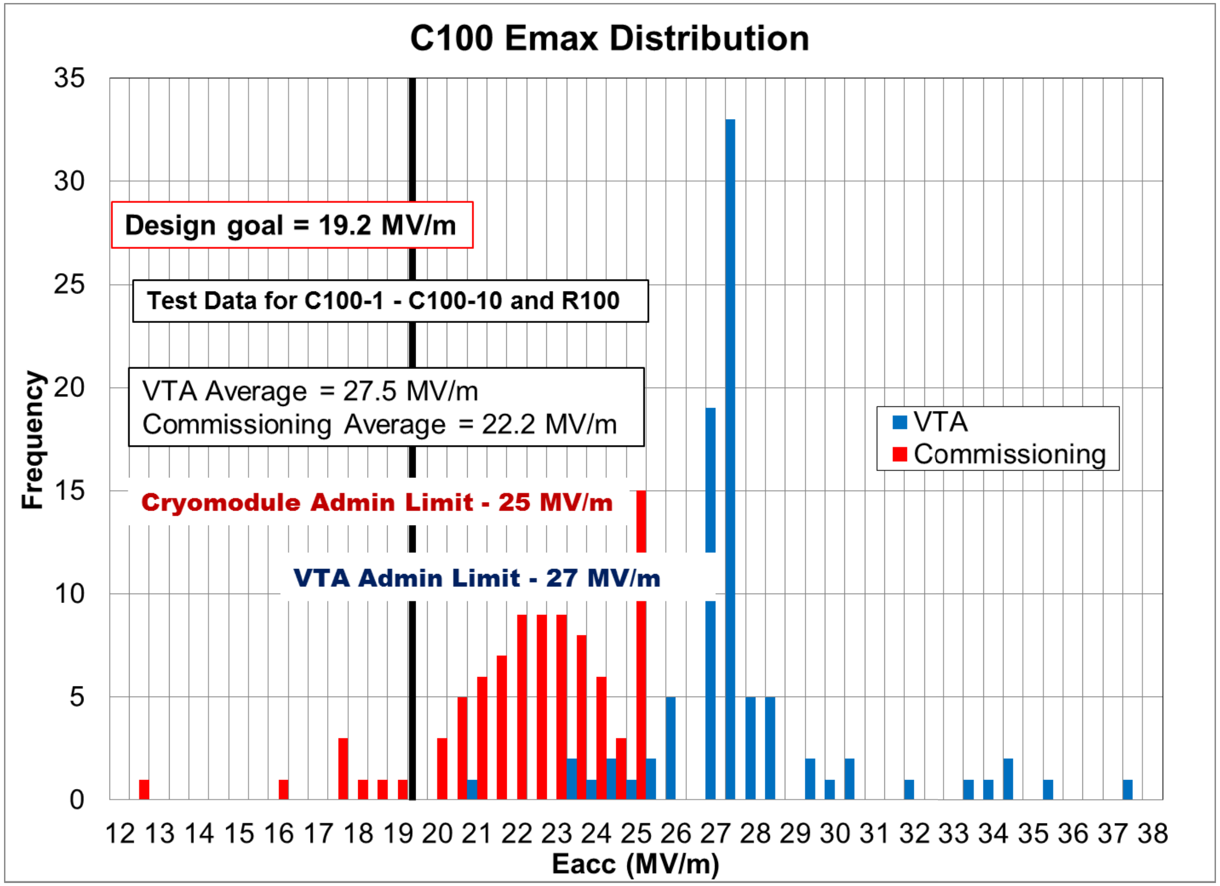
- 2K Primary Circuit and 50K Shield Circuit via L-shaped end-cans
- Waveguide Coupler Assembly
  - Two Warm Windows
  - Guard Vacuum to Protect Cavity Vacuum
  - No helium to vacuum joints
- Scissor-jack tuner with easily accessible warm drive components
  - Provision for Piezo-electric component for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



Accounting for gradient reductions:

- Differing Administrative Limits (VTA 27 MV/m / Cryomodule 25 MV/m)
- Cryostat riser limits (50 – 60W per cavity)
- Assembly / Testing "events" account for reductions in ~5% of the cavities

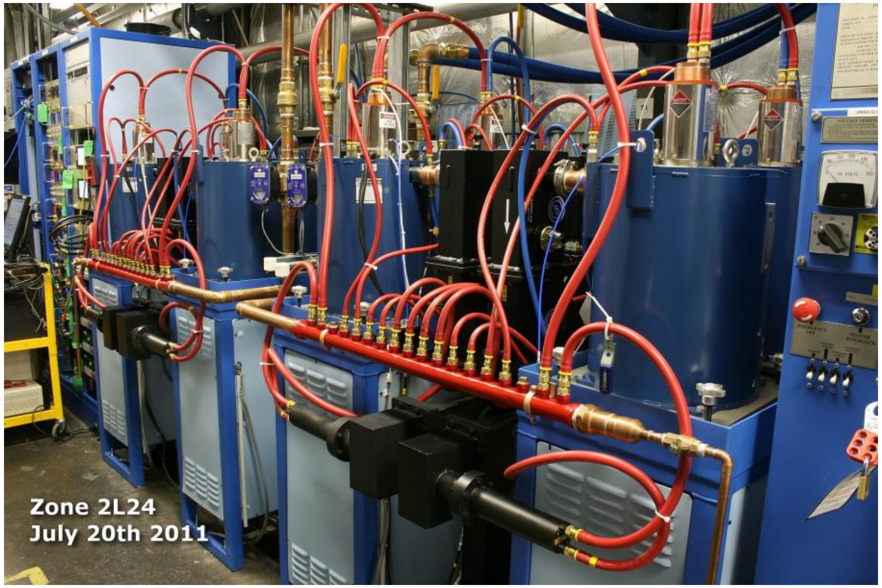
Results – C100

Average for the Final maximum operating gradient – **20.4 MV/m**
Dynamic heat load ≤ **35 W** per cavity / **240 W** for the string.
Static Heat Load ~**18 W**
Average Energy Gain = **113 MV / 108 MV**

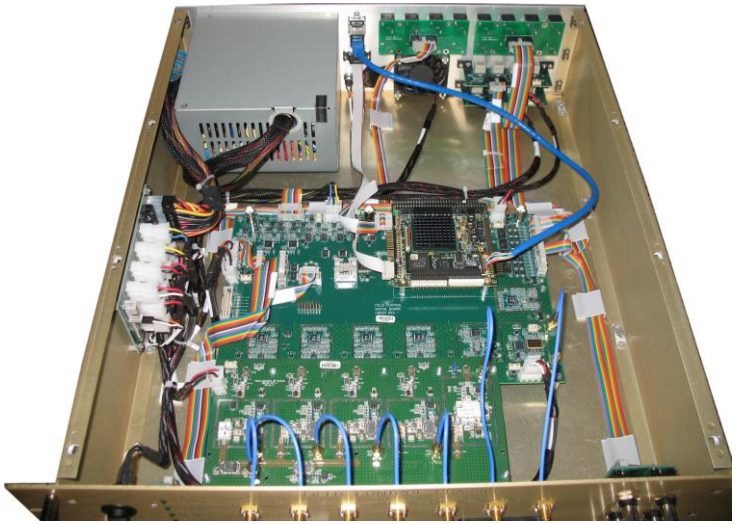
	Commission (MV)	W / Beam correction (MV)
C100-1	110	104
C100-2	120	122*
C100-3	124	108
C100-4	105	93*
C100-5	110	121
C100-6	113	111
C100-7	113	103
C100-8	109	110
C100-9	117	105
C100-10	116	104
R100	116	106

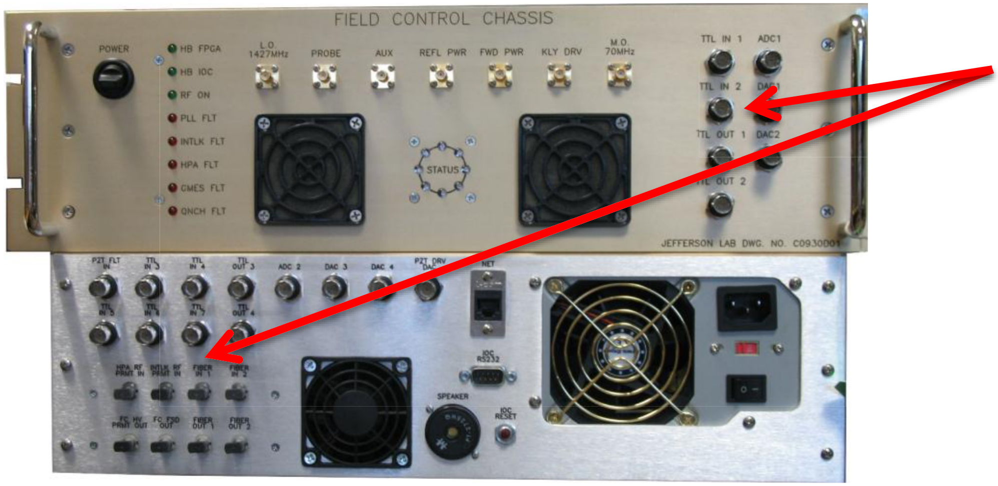
RF System: Power

- Each system powers eight 13 kW klystrons
- Resonant mode switcher design (15-20 KHz)
- 4 separate supplies. Each feeds 2 klystrons
  - Minimizes klystrons taken offline due to power supply failure
  - Controlled as a "unit"
- Each adjustable to -15kV
- 15 A total



RF System: LLRF





- **Features**
  - 4 Receivers, 1 Transmitter
  - Altera/Cyclone FPGA
  - Network Attached Design
  - EPICs IOC on board (PC104)
  - Digital card can mate with multiple RF front ends
  - Numerous I/O: analog and digital
  - Uses commercial PC power supply

RF System: LLRF

LLRF Racks

- Field Control
- HPA Control
- Cryomodule Interlocks
- Stepper Control
- Piezo Amplifier
- Solenoid Power Supply

	Requirement	Measured
Amplitude RMS error	4.5×10^{-4}	2.8×10^{-4}
Phase RMS error	0.5°	0.08°

Cavity field stability requirements and average measured values.

Mechanical Tuner Modification

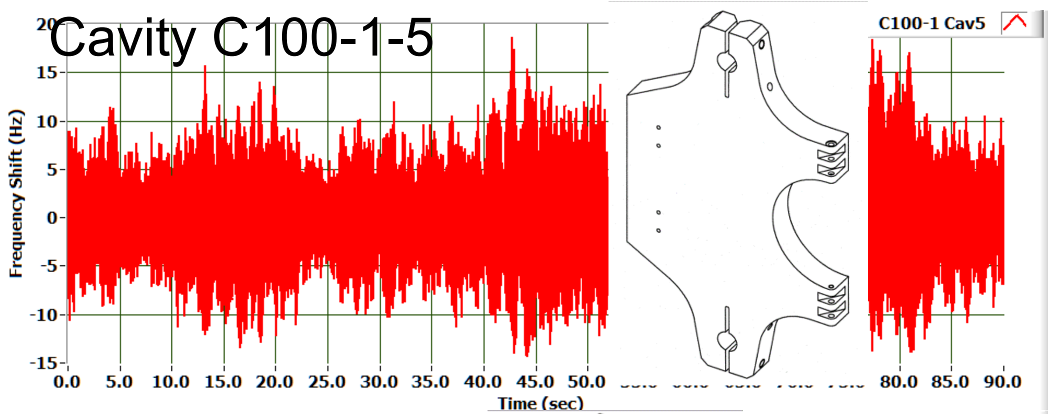
- Design allows for 25 Hz Peak Detuning

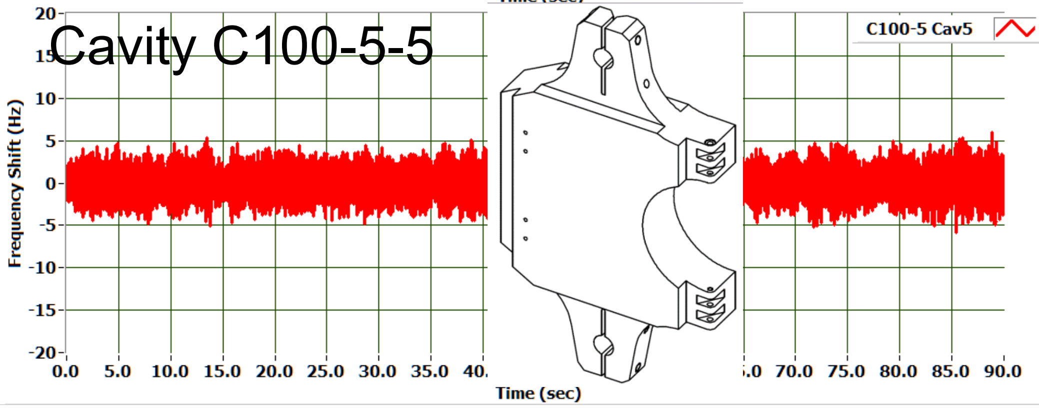
- Actual peak detuning **(21 Hz)** was higher than expected in first cryomodule (R100)
- A detailed vibration study was initiating which led to the following design change.

- 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 results in a larger RF power margin

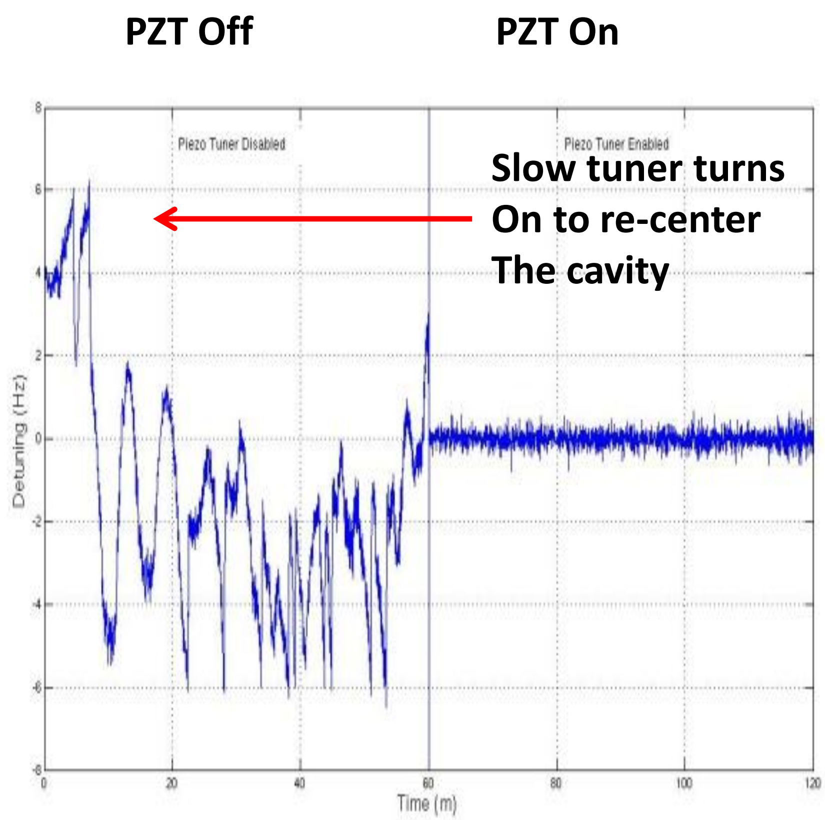
Microphonic Detuning*	C100-1	C100-4
RMS (Hz)	2.985	1.524
6σ(Hz)	17.91	9.14





Piezo Tuners

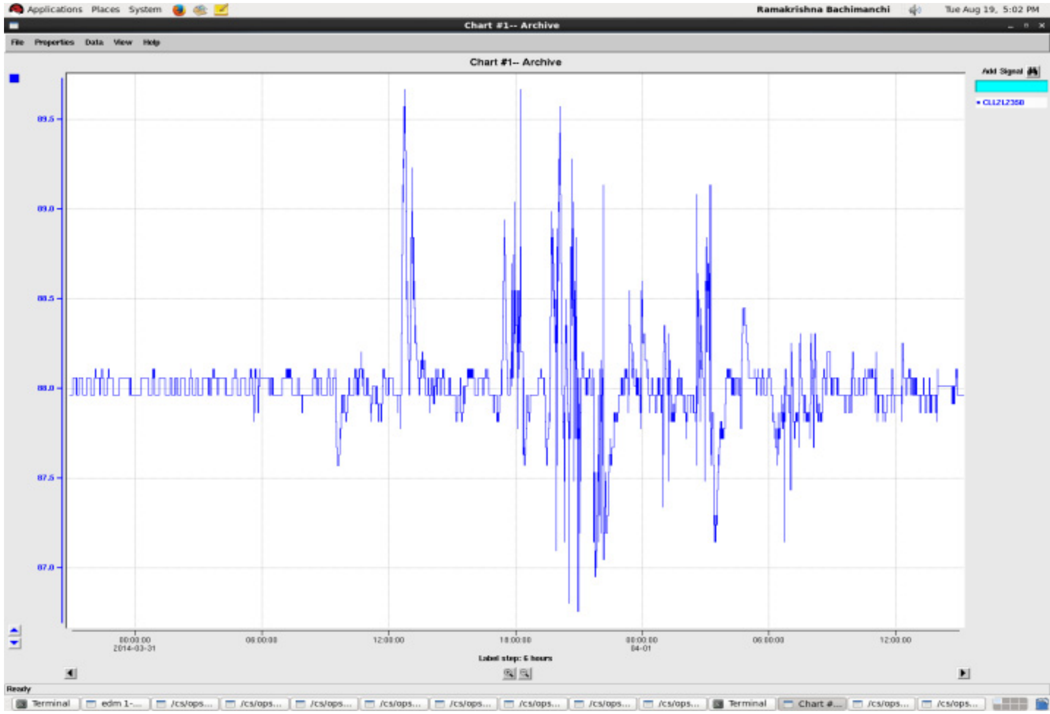
- C100 cavity operating at ~ 15 MV/m with the PZT off and then on.
- Slow tuner was on in the background.
- PI regulator.
- Substantial improvement for slow detuning (helium pressure drift or slow microphonics).
- PZT phase control ~ 2° .
- PZT system oscillated above 2 Hz control bandwidth.



Cavity Detuning (Hz) vs Time (s)

Cryomodule Heaters

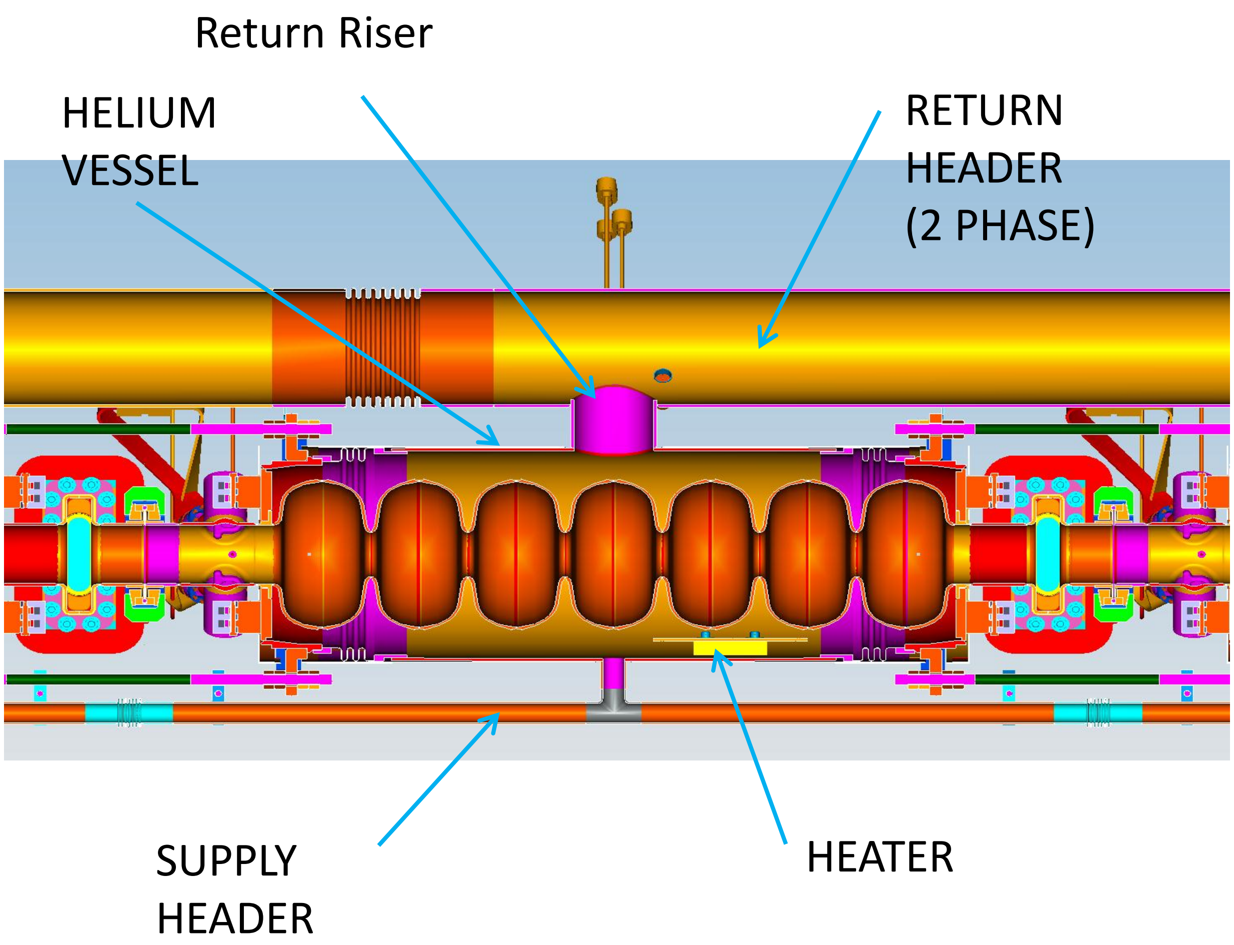
- Increased microphonics were observed when heaters were on.
- Out of the eight installed, only the even (4) cavity heaters were initially used.
- When an odd cavity would turn off, additional heat would be supplied to the even cavities to compensate .....
- The cryostat He riser then became a choke point as additional heat was applied.



He Liquid Level (%) in a cryomodule as heat was applied.

Cryomodule Heaters

- **Quick solution was to power all eight resistive heaters.**
- **This allowed the load to be distributed more evenly in cryomodule.**
- **Ultimately we intend to control the heaters individually.**



Coupled Cavities

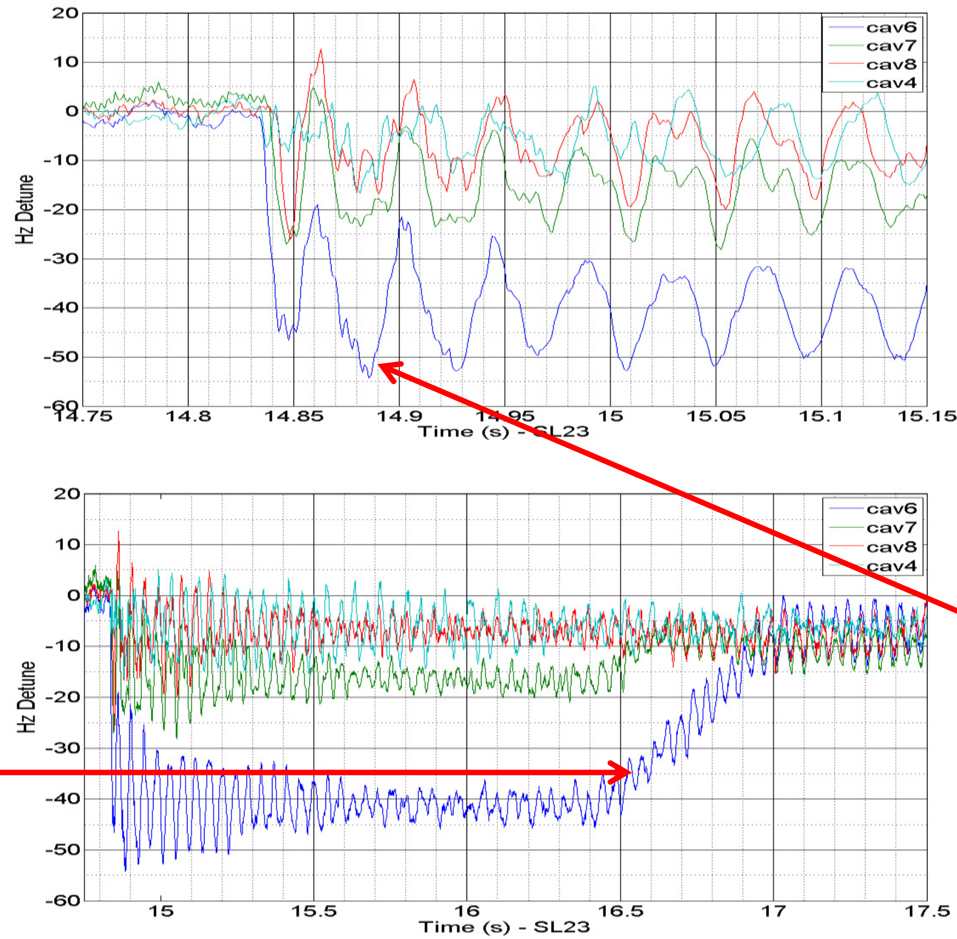
C100-4 Cavities 4, 6, 7, 8 responding to an applied PZT step voltage change from 4 to 3 volts in cavity 5

Cavity 5 PZT moved 460 Hz

Cavity Gradients 10 MV/m Locked in GDR Mode

Klystron had the overhead to keep cavities locked

Stepper Motor kicks in to tune cavity 6

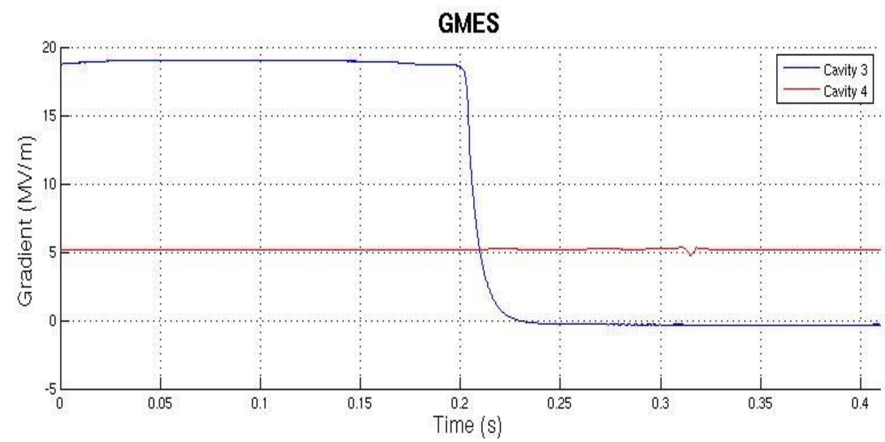


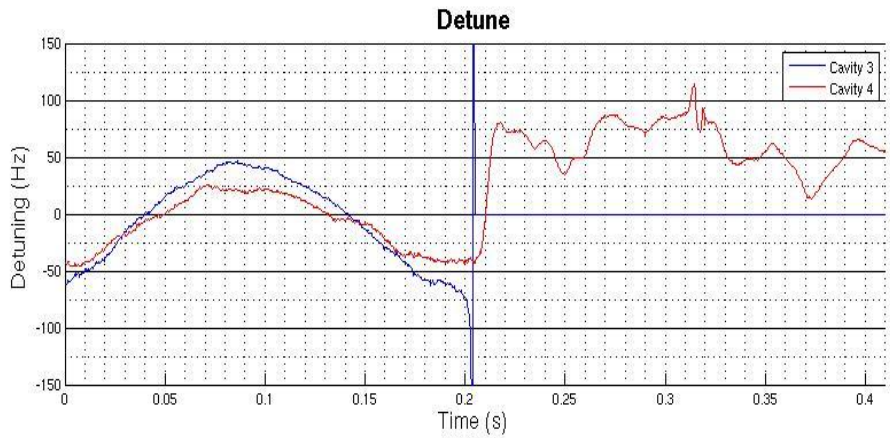
Adjacent Cavity coupling is ~ 10% between 1-4 and 5-8 cavities

Cavities 4 and 5 have a "quasi" mechanical support between them.

Ringing is the 21 Hz mechanical Mode

Cavity Fratricide





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

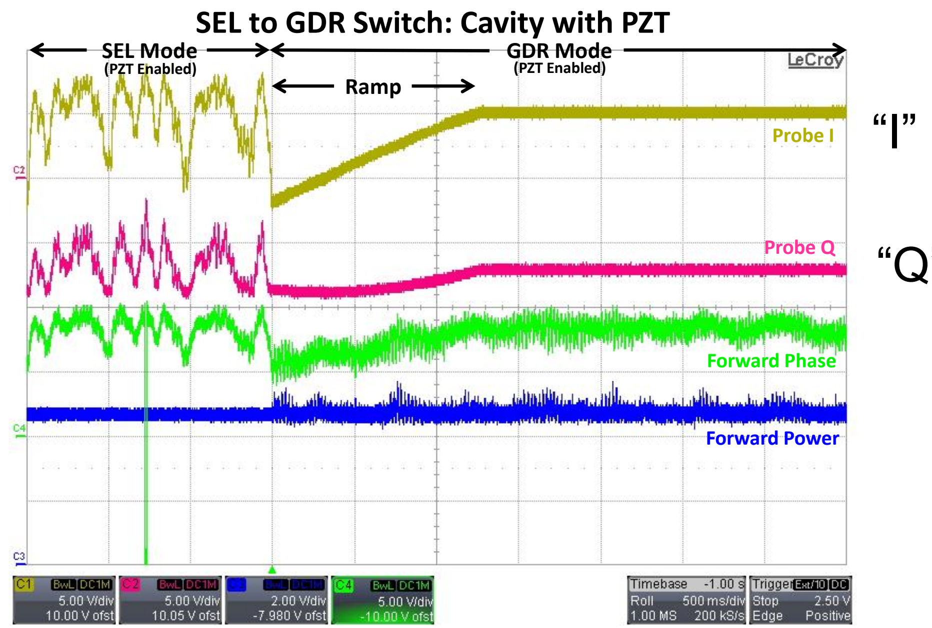
Adjacent cavity was operating at 5 MV/m so the klystron had the overhead to absorb the detuning.

Operability: Cavity Faults & Recovery

- **Cavity/Cryomodule: Fault, Mitigation and Recovery**
  - At 20 MV/m and K_L of 2 you are looking at a 800 Hz detuning when the cavity trips (~ 13 bandwidths).
  - Adjacent cavities will feel this and RF systems must react. Typically too fast for a PZT.
  - If we assume a cavity to cavity coupling of 10%, the RF system must have the power overhead to absorb a neighbor cavity faulting.
  - If not, it will set up a "domino" effect which will trip the entire cryomodule.
  - CEBAF C100 cavities have observed this at 20 MV/m and a K_L of 2.
  - One solution is to switch the adjacent cavities to SEL mode keeping gradient in the cavities. Then switch back to GDR mode when the faulted cavity is recovered.

Cavity/Cryomodule Turn On

- Uses a digital self-excited loop (SEL) that tracks the cavity frequency and quickly restores the cavity to its operational gradient.
- A firmware application then tunes the cavity and switches to Generator Driven Resonator (GDR) mode, locking the cavity to the reference.
- The procedure has evolved to the point that it is a “single button” automated turn on for the high gradient cryomodules.
- It takes ~ 40 seconds to recover a cavity ….we are working to reduce this time to around 10 seconds.



Transition from SEL to GDR

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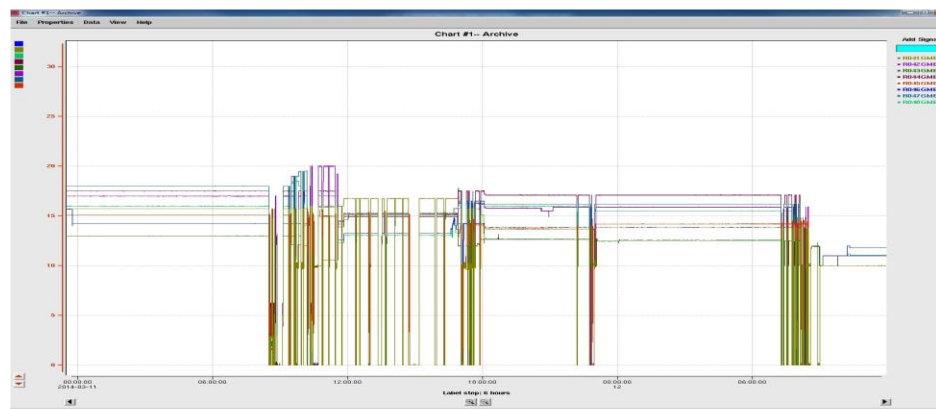
Cryomodule Operations and Construction

- The gradient “drops” in the graph show the cavities faulting during the day due to construction.
- RF Power could not compensate for the rapid detuning.



C100 Cavity Gradients

Summary

- **All 10 high gradient cryomodules have been commissioned and met performance goals.**
- **Most importantly our Nuclear physics brothers have been happy with the beam they have received.**
- **Future**
  - **Improve cryomodule turn-on time**
  - **Single heater control**
  - **Continue tests with Piezo tuners**
  - **Develop microphonic sensitive excavators!**

Thank You For Your Time

Special thanks to

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