Measuring the Unloaded Quality Factor (Q_0) of Superconducting RF Cavities

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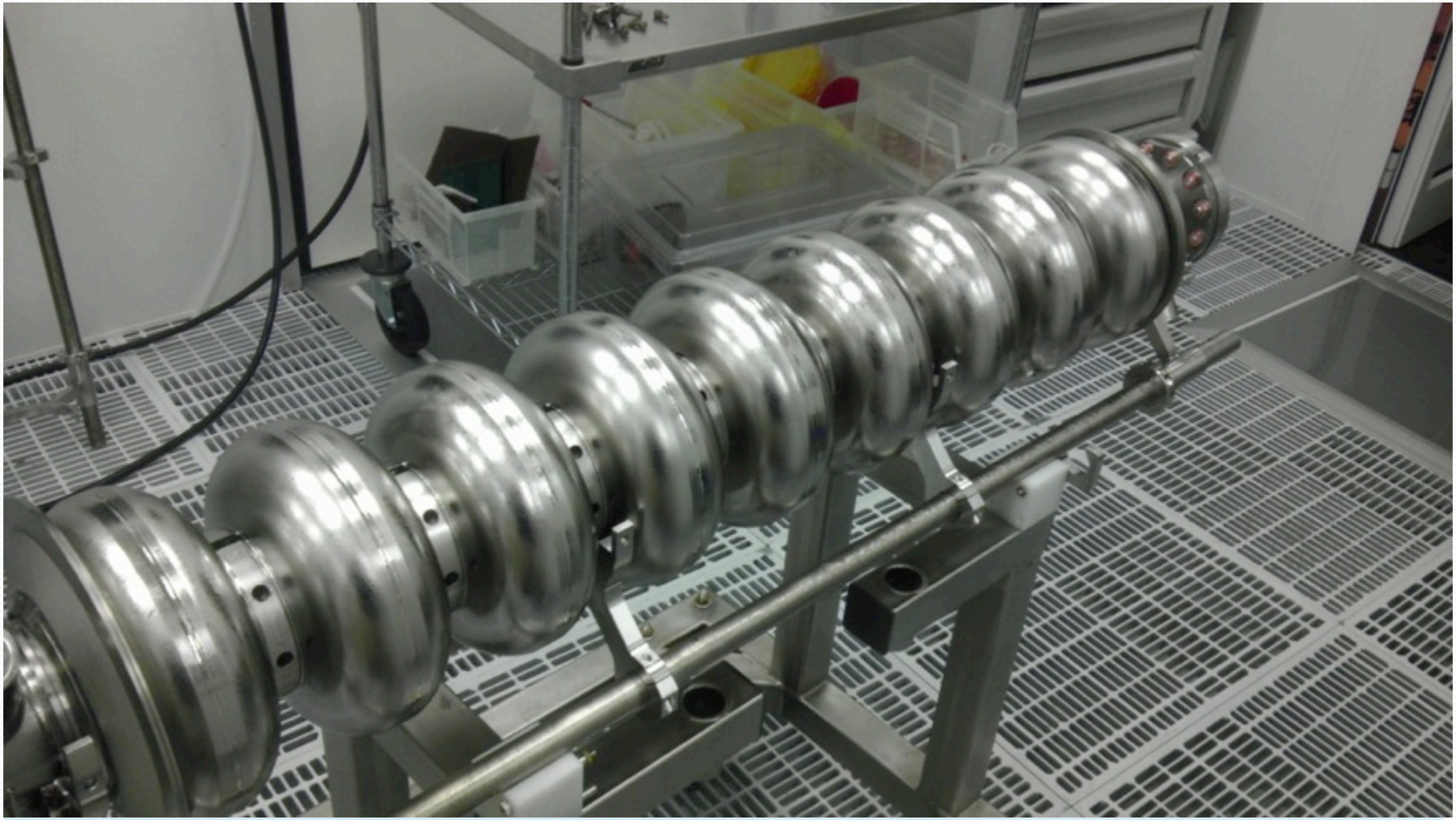
The Performance of SRF Cavity

- The response of the cavity to RF power input
- The unloaded quality factor (Q_0) of the cavity
  - As a function of the peak electric field
- Accelerating field E (peak gradients ~40 MV/m)
- The total behavior of all cavities in the cryomodule

NML/Cryomodule 1 (CM-1)

Cryomodule



The Unloaded Quality Factor

- Wall currents dissipate energy
  - Even a superconductor has a small resistance
- Q_0 represents how efficiently the input power is being used
  - Q0 of SRF: 10^5 times more than room temperature (copper) cavity
- Q_0 for a given dynamic heat load Pc:

$$Q_0 = \frac{< E_{acc}^2 > L_{cav}^2}{(R/Q) < P_c >}$$

- Cavity length=1.038m, R/Q=1036
- Cavity Resonant Frequency, f_0 = 1300 MHz
- Full pulse into cavity
  - Fill time: 500μs
  - Flattop (pulse length): 700 μs
  - Decay time $\tau_L = Q_L/\omega$

    Q_L *is the loaded Q,* ω *is the angular excited frequency*
  - Pulse repetition rate: 5Hz

CM-1 Dynamic Heat Load Measurement

- Measure the cryomodule heat load at discrete power levels
  - Run without power input to measure the static heat load (baseline)
  - Stay at each power level (gradient) for ~1 hour (2 hours at some levels)
  - 1st day with LLRF feed back off; 2nd day with LLRF feed back on
- RF power generated by a klystron is carried into the cavity via a waveguide and then a coupler

Gradient (E)

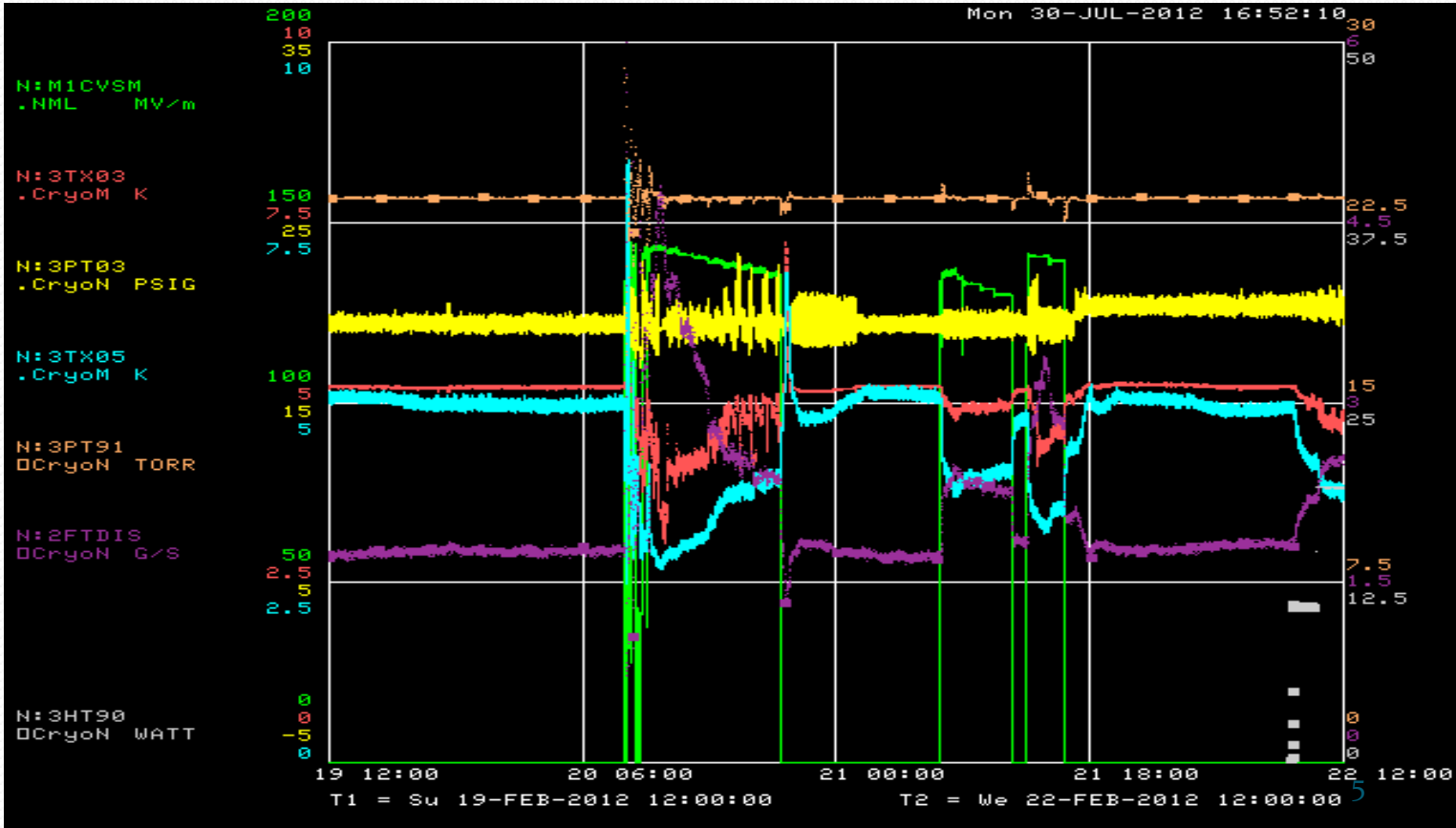
T in

P in

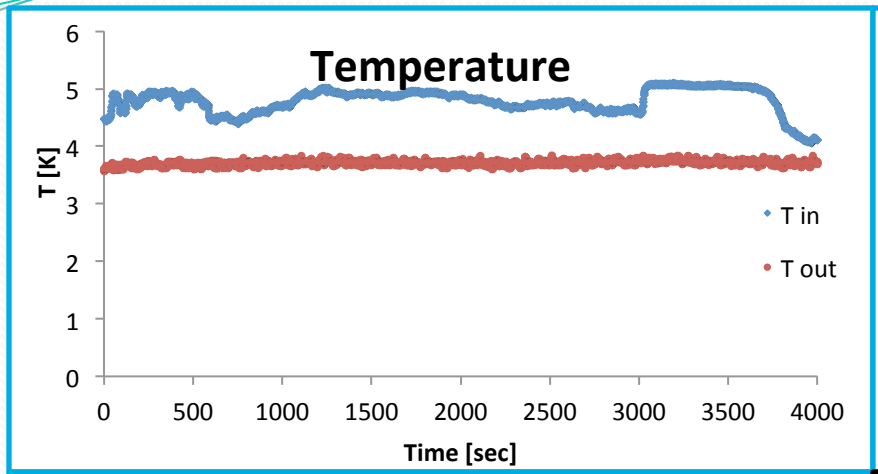
T out

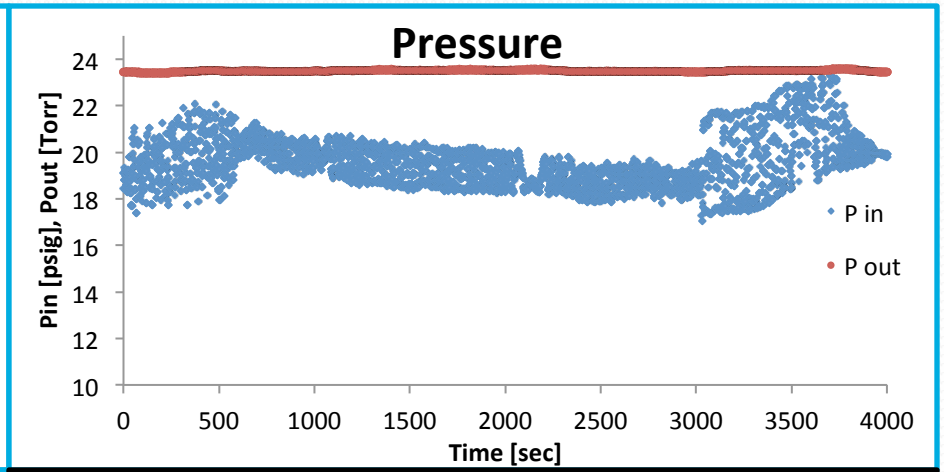
P out

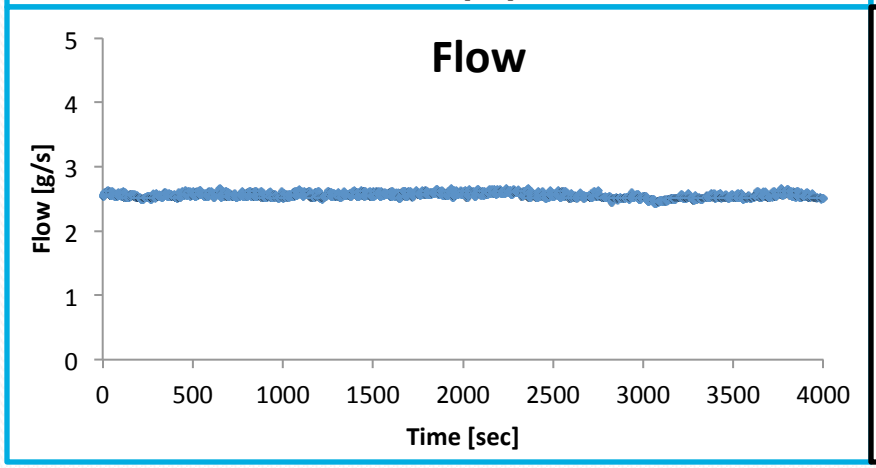
Helium mass flow

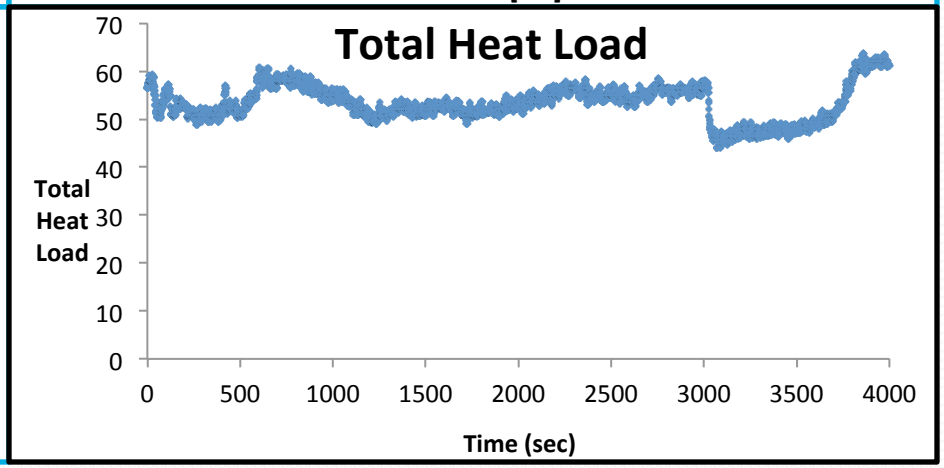


Data for Discrete Power Levels







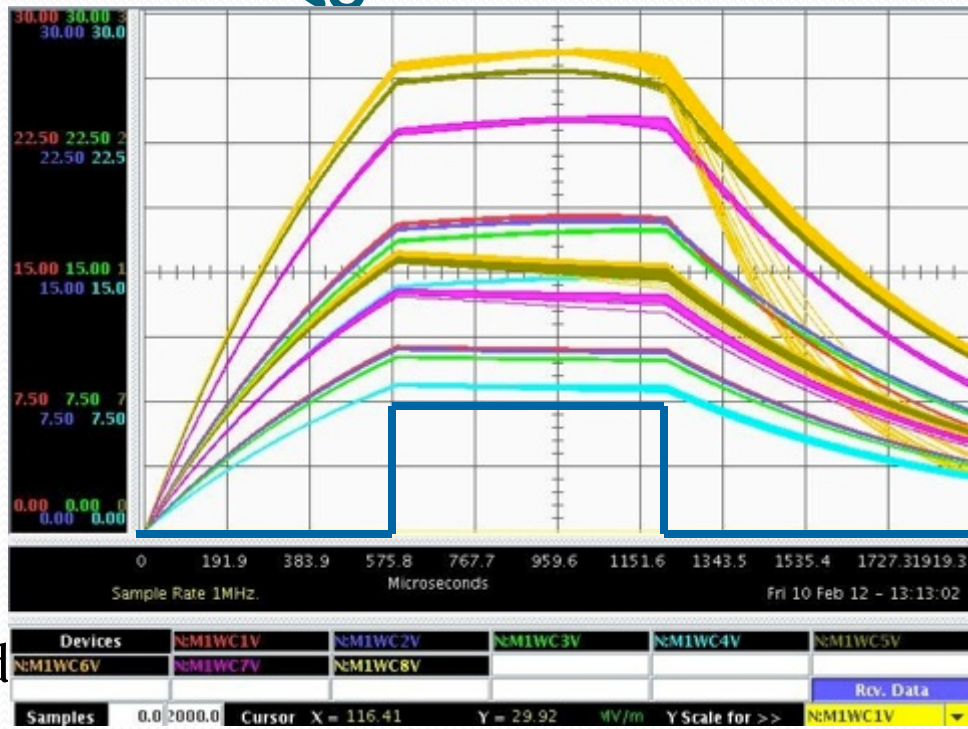


- HEPAK is used to calculate the heat based on the temperature and Pressure
- The calculated heat and the helium mass flow determine the total heat load, the static heat load is subtracted to get **the dynamic heat load *Pc*** at a specific power level

Two ways to calculate Q_0

- For constant accelerating E-field

  $< E_{acc}^2 >= E^2 \times DF, DF \text{ is the RF duty factor}$



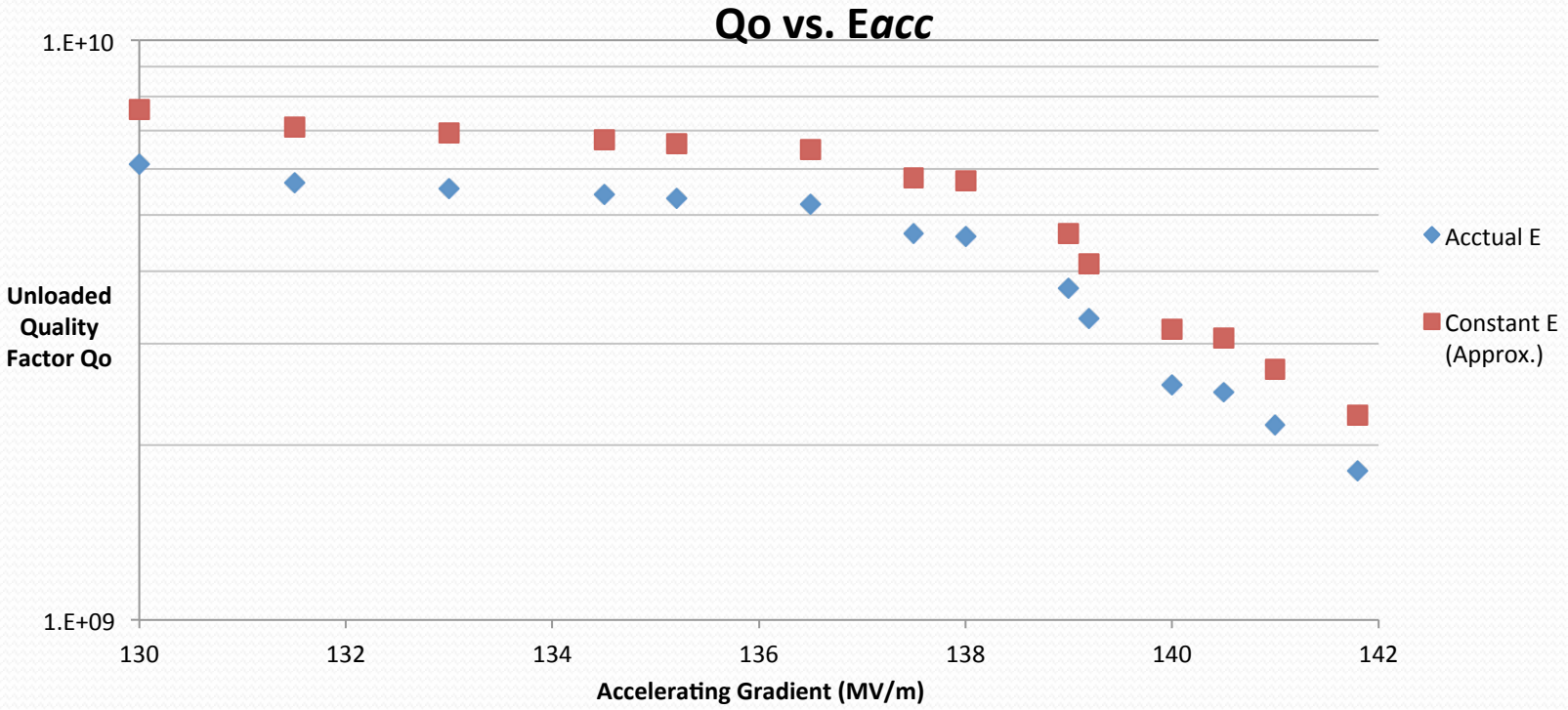
- For general (non-constant) E-field

$$< E_{acc}^2 >= \frac{E^2}{T}\left\{\frac{t_f + \tau_L\left[\left(1 - e^{-t_f/\tau_L}\right) - 4\left(1 - e^{-t_f/2\tau_L}\right)\right]}{\left(1 - e^{-t_f/2\tau_L}\right)^2} + \left(t_p - t_f\right) + \tau_L\right\}$$

t_f *is the fill time,* t_p *is the RF pulse length, and* $\tau_L = Q_L/\omega$

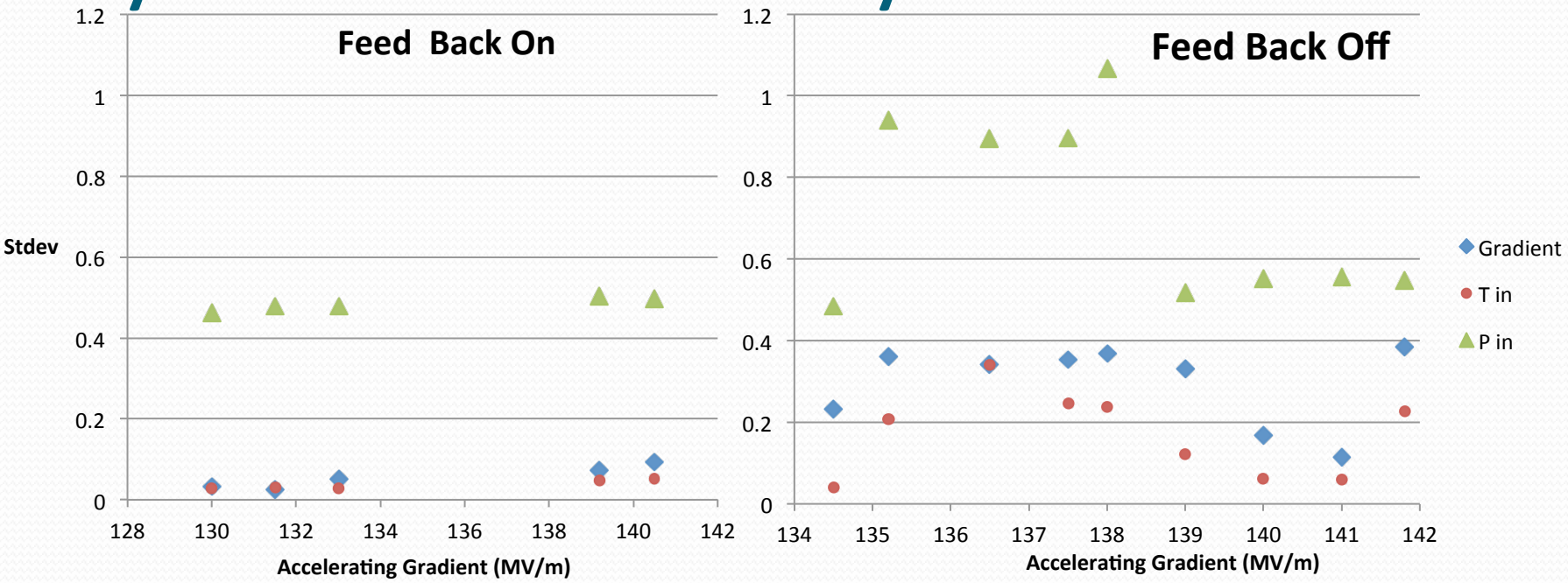
Q_L *is the loaded* Q, ω *is the angular excited frequency*

Q_o Versus E_{acc}



- The constant E approximation is valid
- Qo values based on actual E is preferred
  - Using real shape of E, yielding a conservative value
- The calculated Qo agree with the expectation scale ~ 10^{10}
- Qo drops at higher gradient as expected

Cryomodule Stability



- Better (more stable) performance with the LLRF feed back on
- The standard deviations of the Temperature and Gradient (E) in stable levels are about 10 times smaller than those in the unstable levels
- More difficult to maintain stability at higher gradient (feed back on)

Summary

- The data for the whole cryomodule (7 cavities active)
  - Measured Qo agree with the expectation range
  - The LLRF feed back is essential to achieve a stable system
- Single cavity analysis has been done and can be applied to any cavity in the cryomodule if necessary
- Create a GUI in MATLAB for data processing
  - Analyzing data is time-consuming
  - Using a GUI to calculate dynamic heat load

Thank you!

- Elvin Harms
- Lee Teng Undergraduate Internship
- Fermi Lab
- Accelerator Division Staff
- Intern program directors and mentors