RF CONTROLS EXPERIENCE WITH THE JLAB IR UPGRADE FEL

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(DISTRIBUTION STATE A)

Outline

- **Mathematical Background**
  - Beam loading effects.
  - Effects of Tuning
  - Examples of beam transients
- **System Hardware**
  - LLRF Modules
- **Operational examples**
  - Pulsed beam
  - Saturated controls
  - Buncher Cavity
- **Summary**

General Equation for RF Power and Phase

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}\left\{\left(E + I_0 R_C \cos\psi_B\right)^2 + \left(E\tan\psi + I_0 R_C \sin\psi_B\right)^2\right\}$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \frac{\delta f}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B}\right)$$

where

P_{Kly}	= klystron power {W)
V_C	= cavity accelerating voltage {V}
R_C	= $(r/Q)Q_L$ {W/m} = Coupling impedence
L	= Cavity accelerating length (m)
b	= cavity coupling
tan*y*	= Tangent of cavity detuning angle $= -2Q_L \frac{\delta f}{f_o}$
ψ_{Kly}	= phase of the RF drive voltage
I_R	= **resultant** beam current
f_R	= **resultant** phase of beam with respect to accelerating RF field
Q_L	= Loaded-Q of the Cavity
δf	= frequency difference between cavity frequency, f_0, and the Generator Frequency

Effects of Tuning and Beam Loading

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}(E)^2 \qquad \psi_{Kly} = 0$$

Cavity Tuned

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}\left\{E^2 + \left(2Q_L \frac{\delta f}{f_0} E\right)^2\right\} \qquad \psi_{Kly} = 2Q_L \frac{\delta f}{f_0}$$

Detuned Cavity

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}\left\{(E + I_0 R_C \cos\psi_B)^2 + \left(2Q_L \frac{\delta f}{f_0} E + I_0 R_C \sin\psi_B\right)^2\right\}$$

$$\psi_{Kly} = \arctan\left(\frac{2Q_L \dfrac{\delta f}{f_0} E + I_0 R_C \sin\psi_B}{E + I_0 R_C \cos\psi_B}\right)$$

Detuned Cavity With Beam loading

Effects of Tuning and Off Crest CW Beam Loading

- On beam turn on the forward power increases the phase shifts and microphonics effects are multiplied

- The tuner operates with a goal of making ψ_{Kly} *equal to zero by s*hifting the frequency by δf_S which compensates for the $I_0 R_C \sin\psi_B$ term.

- Thus $\psi_{Kly} \rightarrow 0$ and P_{Kly} is minimized to:

$$P_{Kly} = \frac{(\beta+1)L}{4\beta R_C}\left\{ \left(E + I_0 R_C \cos\psi_B\right)^2 + \left(2Q_L \frac{\delta f_M}{f_0} E + \cancelto{0}{\boxed{2Q_L \frac{\delta f_S}{f_0} E + I_0 R_C \sin\psi_B}}\right)^2 \right\}$$

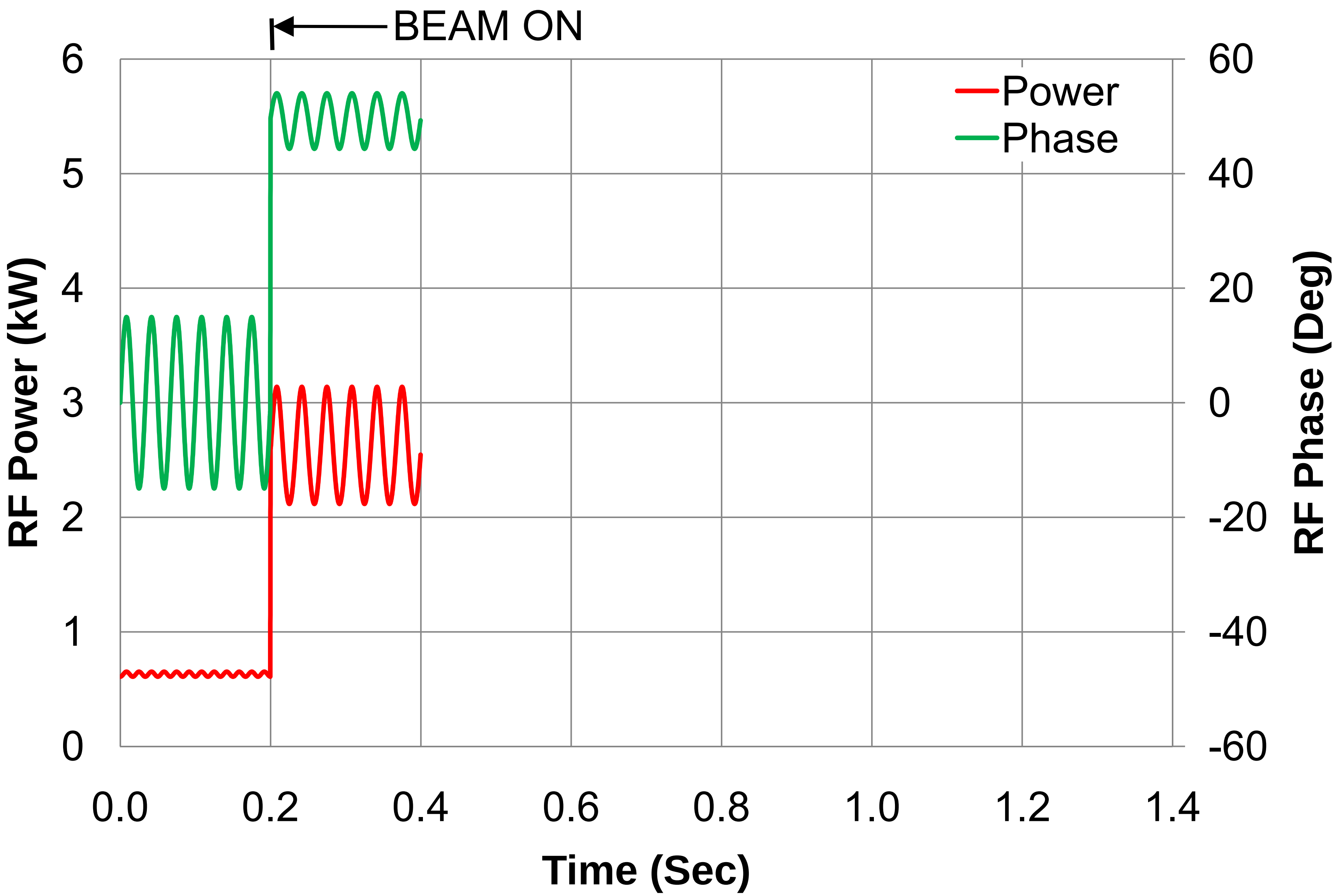
Where δf_M is the frequency shifts due to microphonics

Calculation of Transient and Tuning Effects

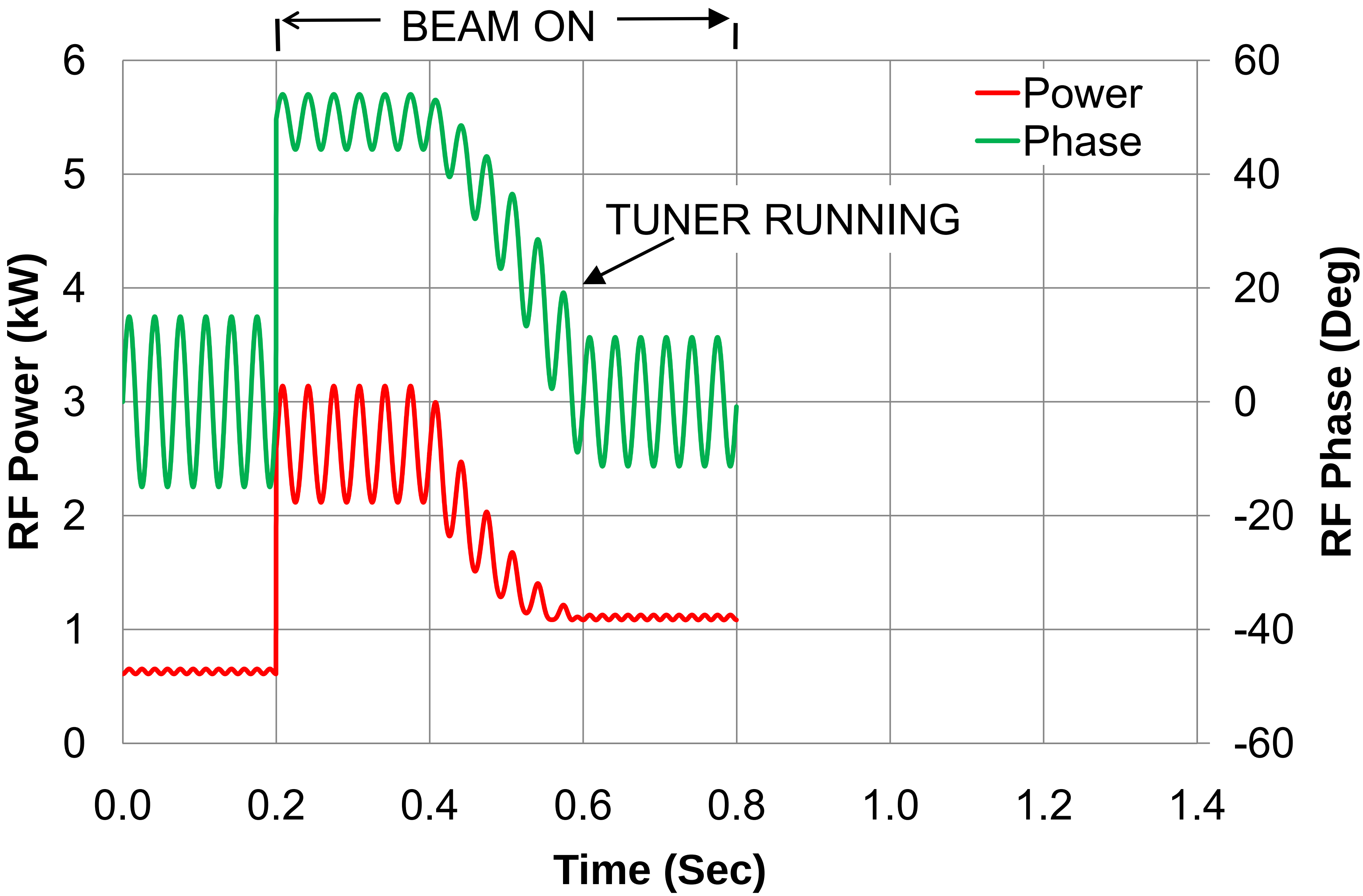
- I_{BEAM} = 10 mA, first pass at -10º, second pass at 166º
- Resultant beam, I_0 = 0.7 mA at ψ_B= 78º
- E = 8 MV/m, *(r/Q)* = 960 Ω/m, *L* = 0.7 m,
- "Simulated" microphonics of $\pm$10 Hz
- Once the beam comes on the tuner operates zeroing out the measured phase such that.

$$\delta f_S = -\frac{f_0 I_0 R_C \sin \psi_B}{2E(Q_L)}$$

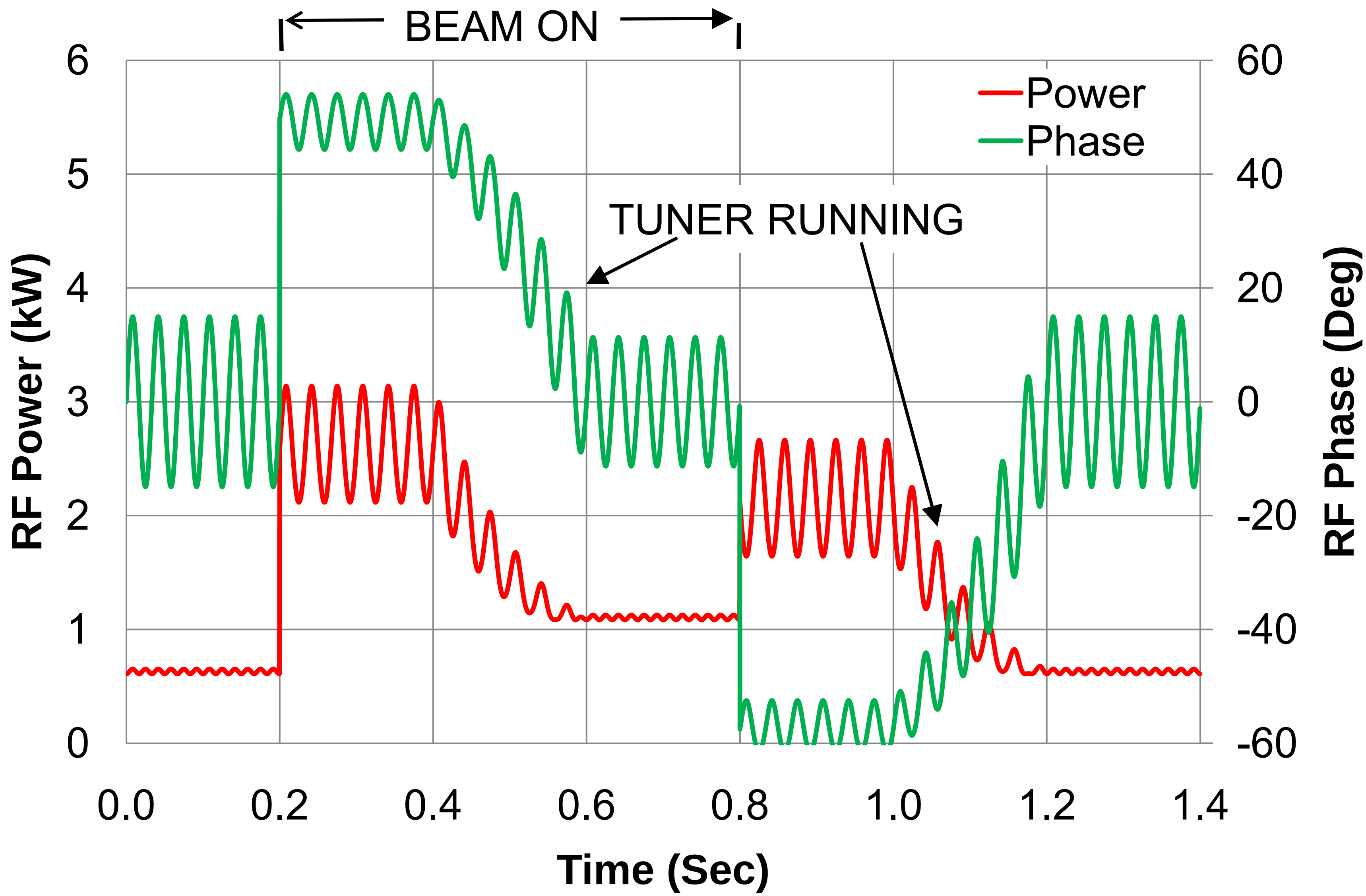
Beam Off to Beam On



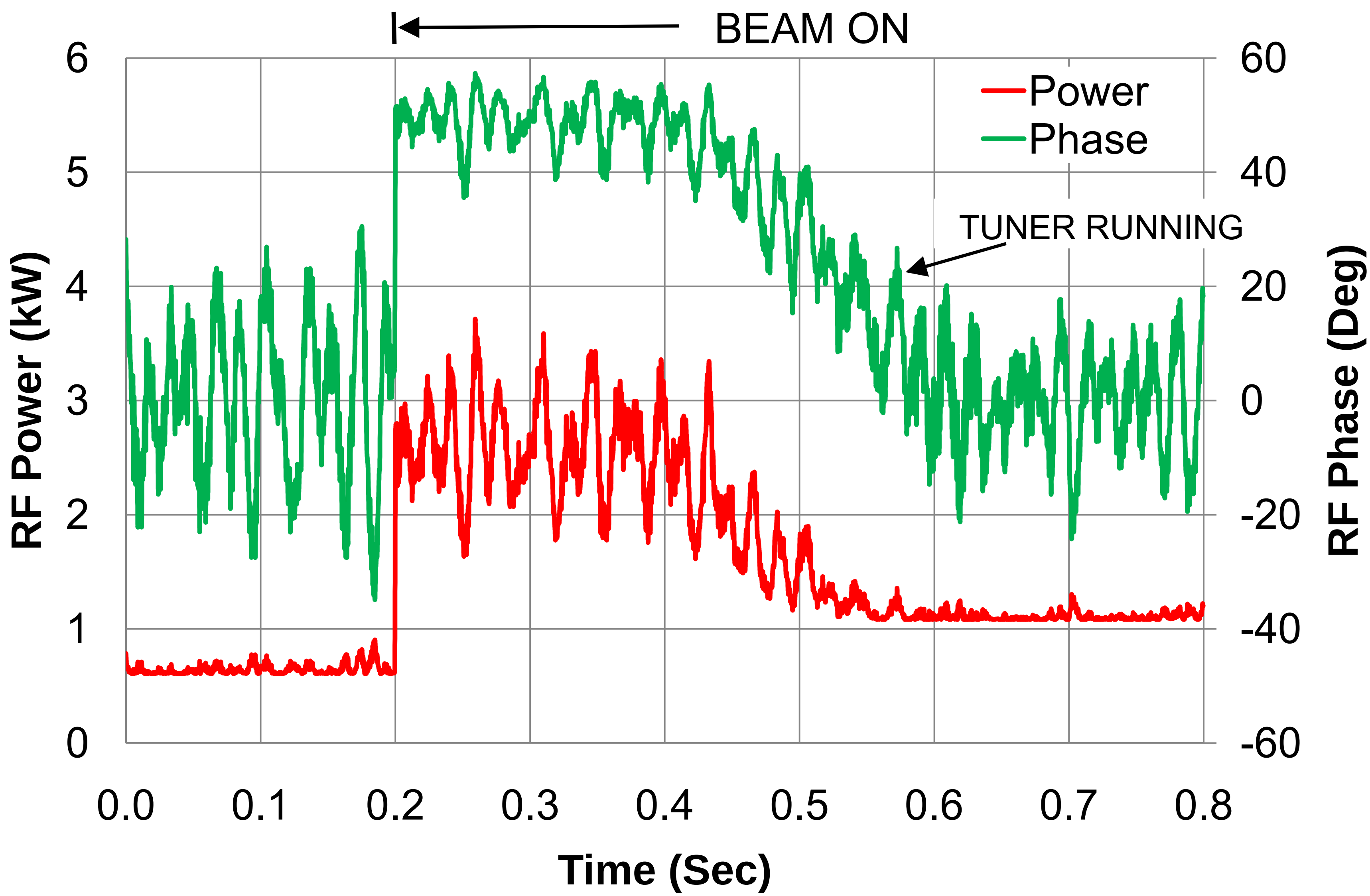
Tuner Compensates Zeroing Out the Phase Error



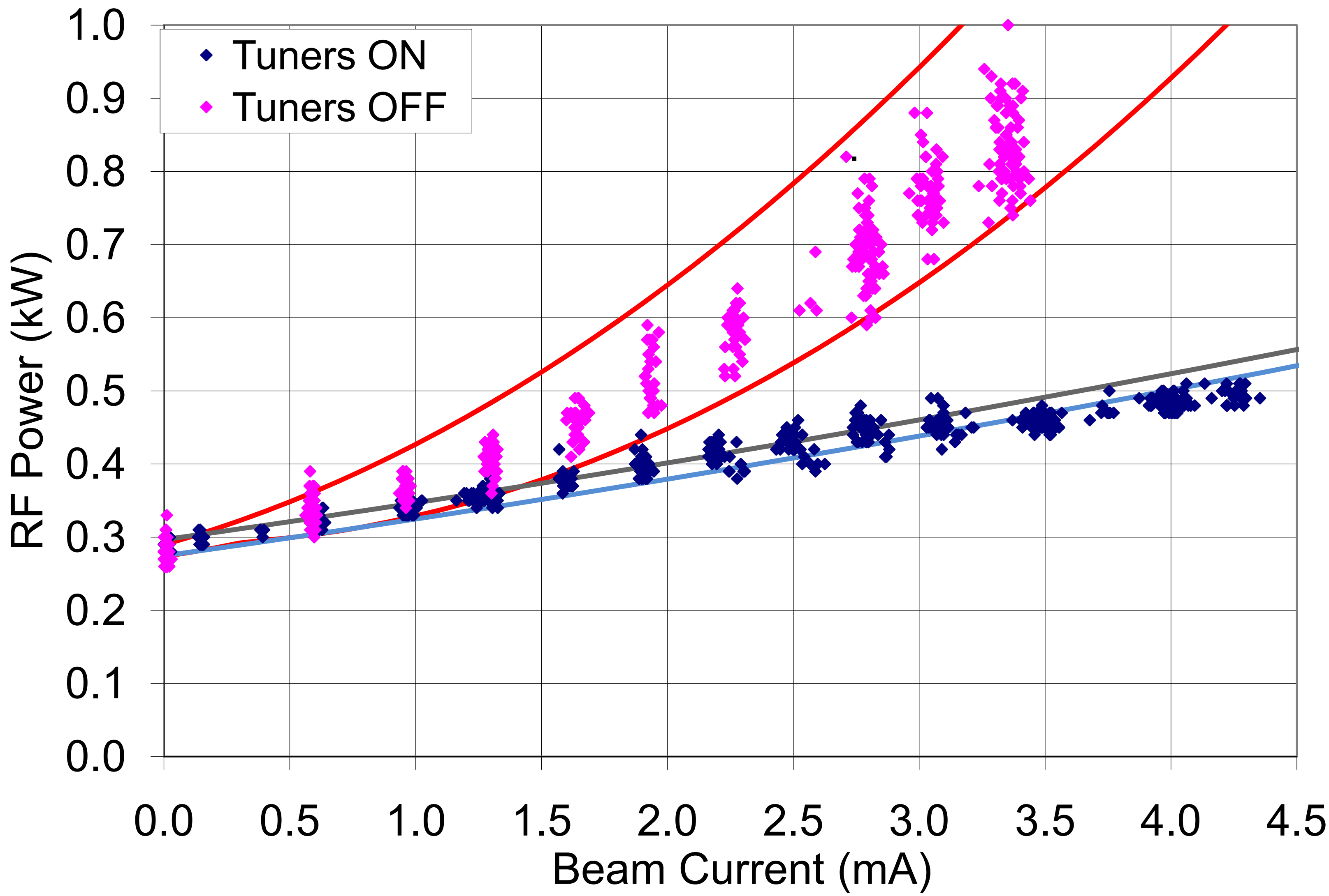
Beam Off and Tuner Operating Again



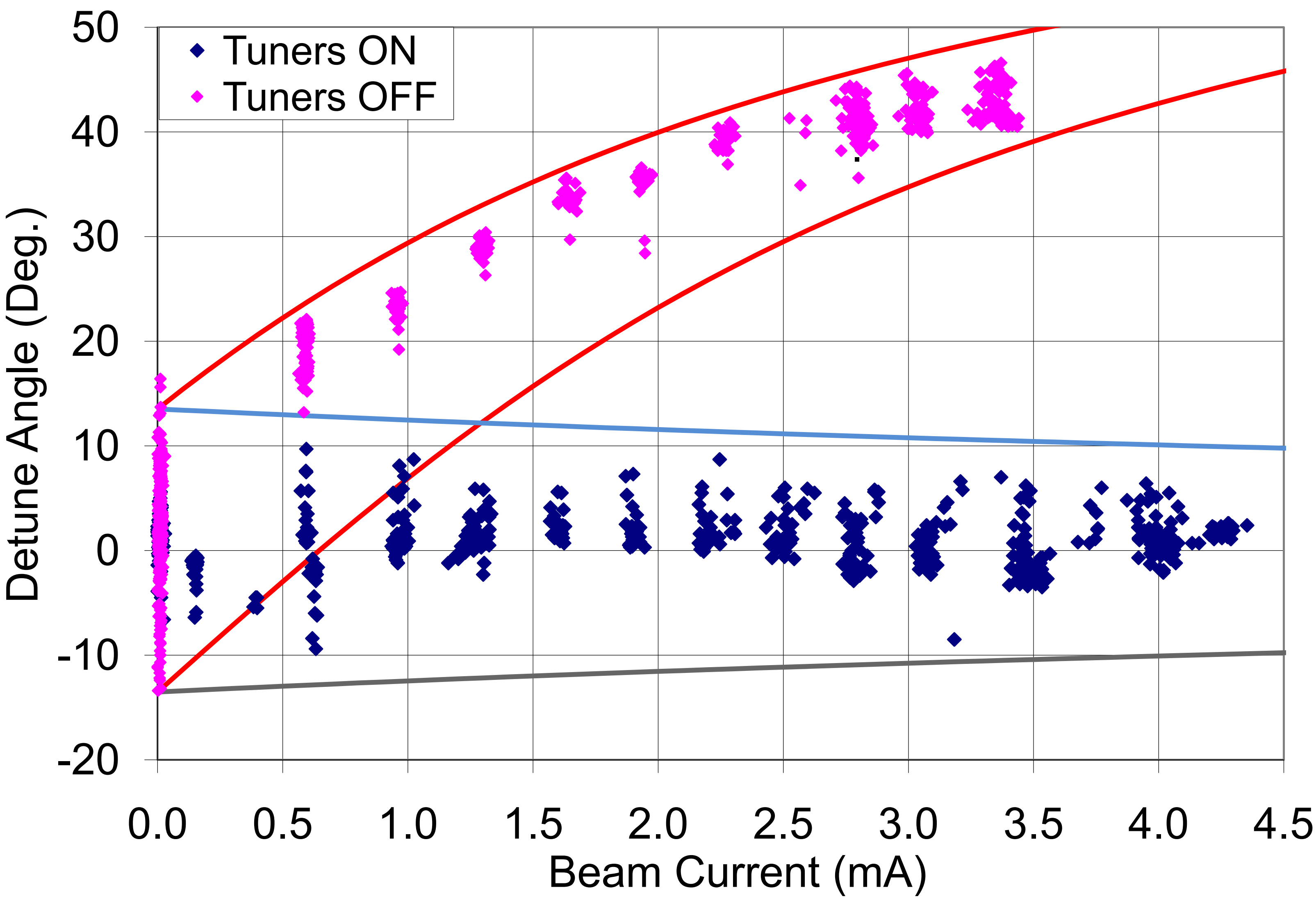
Beam On Transient With Real Microphonics



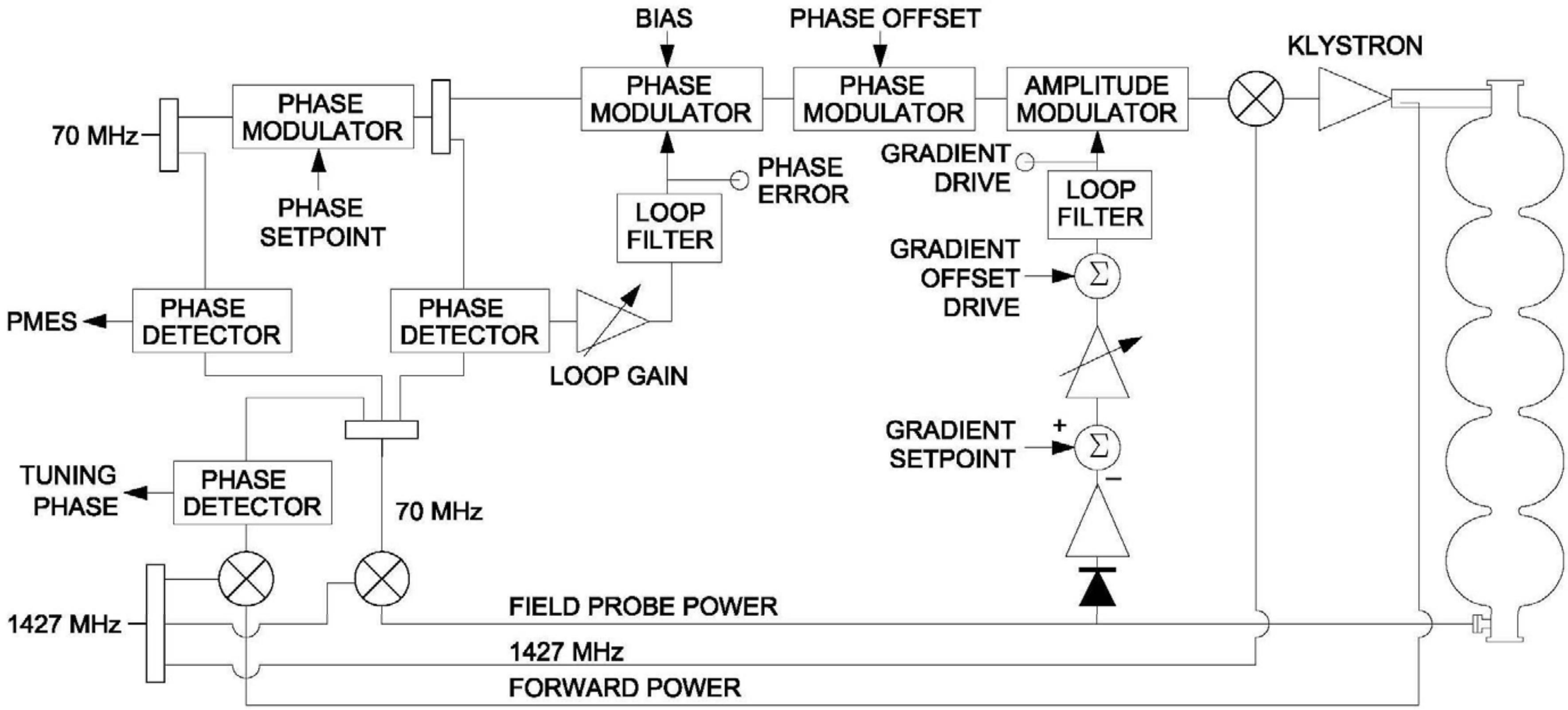
Predicted and Measured Forward power



Predicted and Measured Phase Shift



“Simple” Block Diagram of Control System



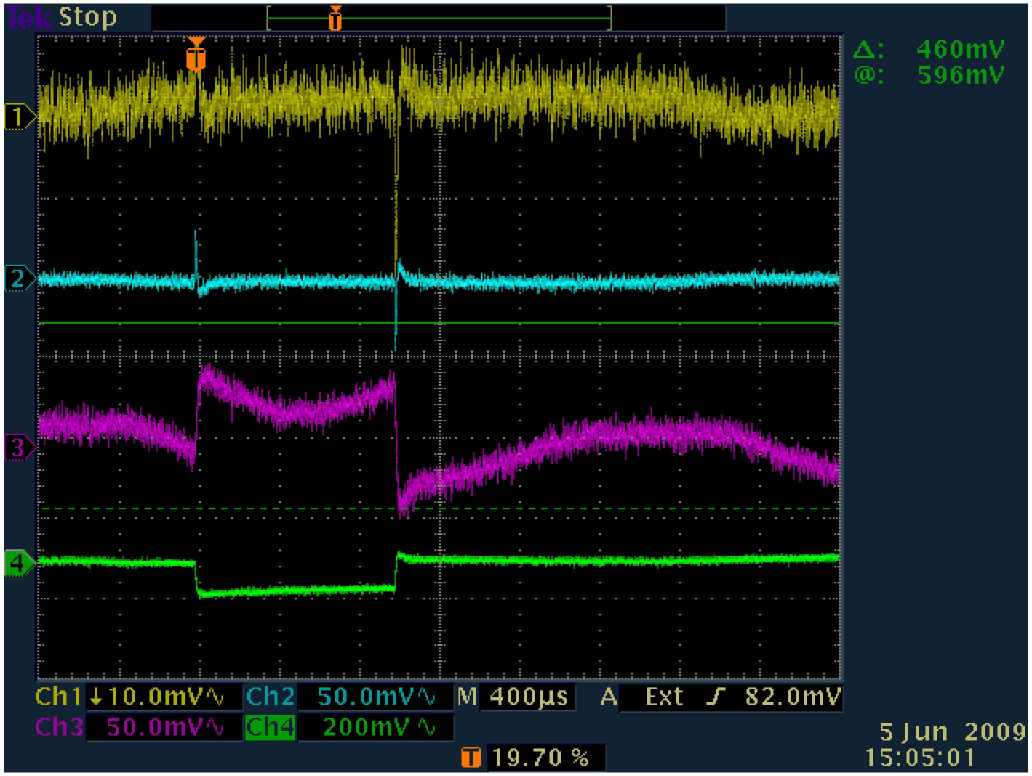
Control System Overview

- System down converts to 70 MHz
- Phase and amplitude control are done at 70 MHz.
- Software control of loop gains allows for on the fly changes during operations.
- Analog monitor ports, coupled with the FEL's analog monitoring system allows us to monitor the health of the control loops during CW and pulsed operations
- Bias control on phase shifter allows increased range at the price of loop gain.
- The design has 20 years of history and successful use at CEBAF.

Control System "Features"

- System designed in the early 90s for a CW machine.
- Proportional control, no integral term, no derivative term.
- No flexibility in control loop to increase the speed when driving the low bandwidth fundamental power couplers
- Nominal phase loop control range +/-45º
- 6/7 or 4/5 Pi mode filter hard wired on analog board.
- Designed for CW operations, which meant problems during high current pulsed operations.

Typical Control Transients Loaded Q = $1x10^5$

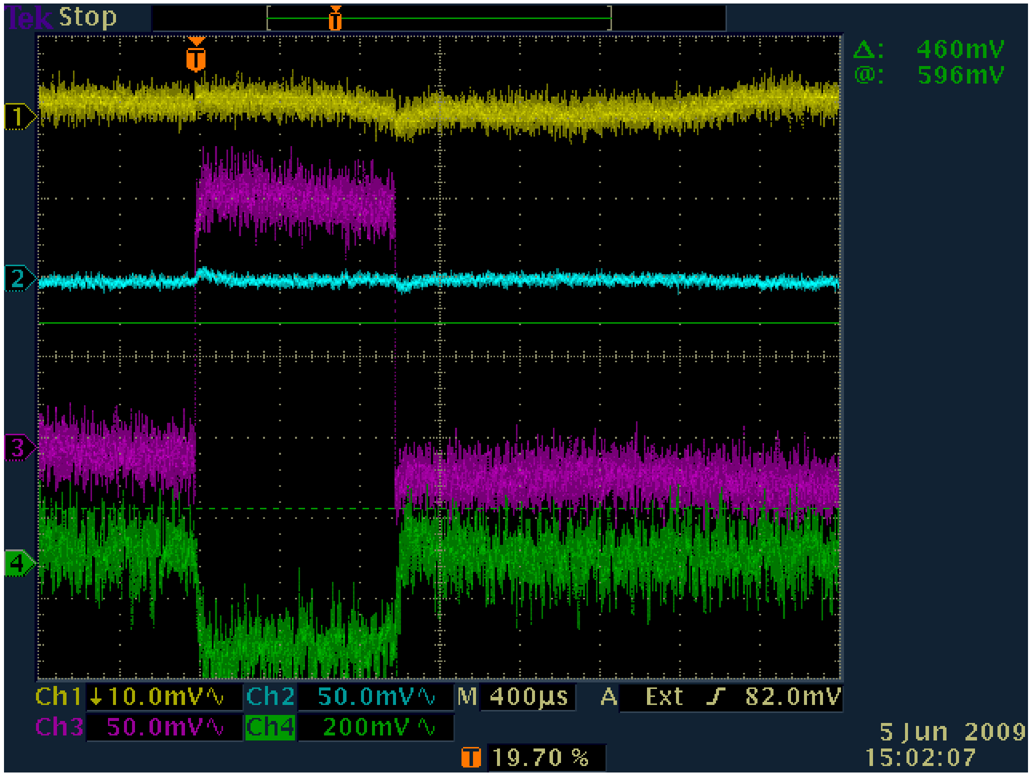


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 90°

- "Normal" beam loading in the buncher cavity where the beam is at the zero crossing.
- Note the fast rise time of the signals and the short transients on the measured phase signal

Typical Control Transients Loaded Q = $2x10^6$

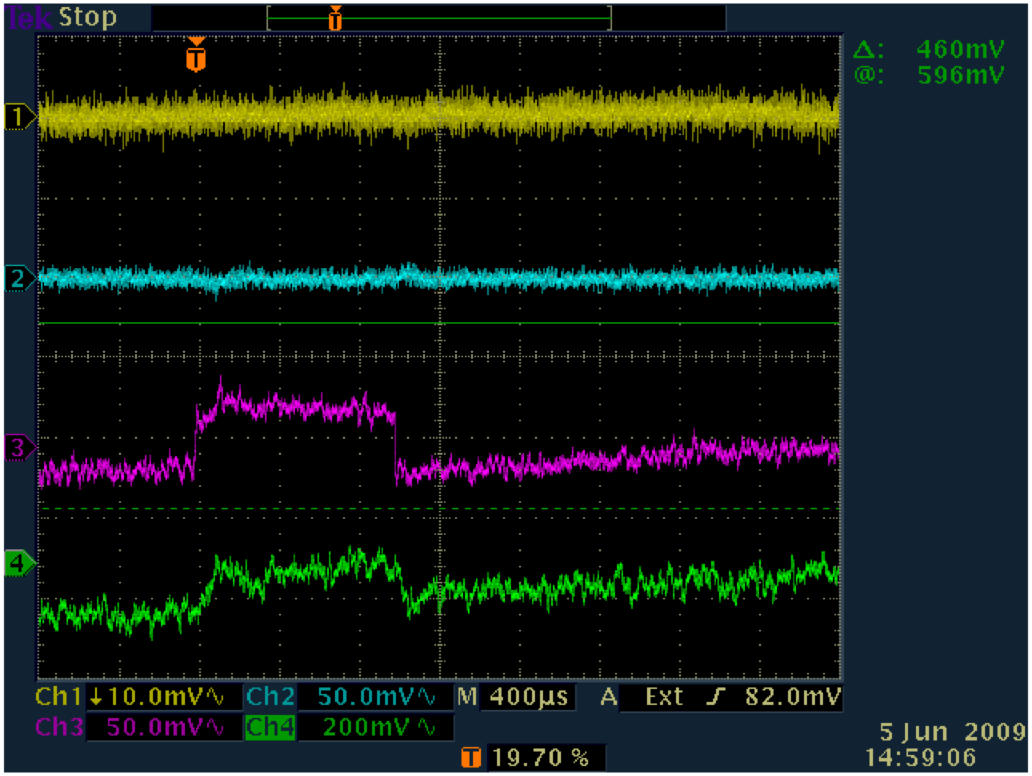


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Phase ≅ 0°

- "Normal" beam loading in the injector where the beam is near crest.
- Note the rise time of the signals and the fact that Gradient drive signal has a moderate transient.

Typical Control Transients Loaded Q = $5x10^6$

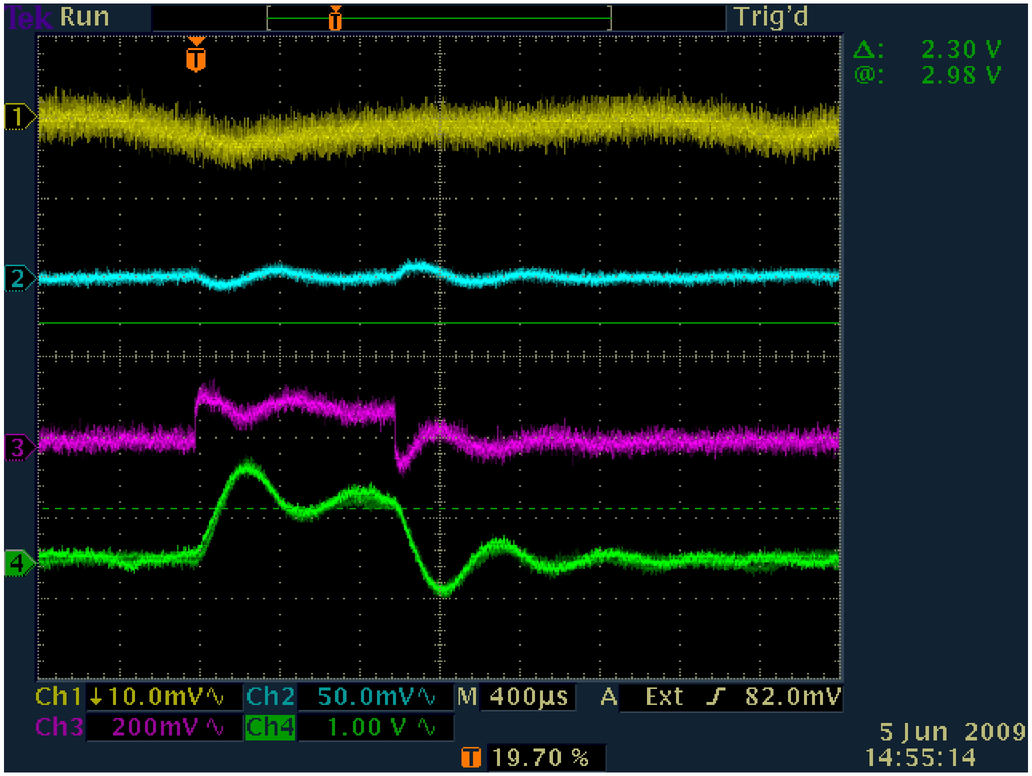


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Pass 1 Phase ≅ -10°
Pass 2 Phase ≅ 166°

- Beam loading on a moderate Loaded-Q cavity.
- Note the rise time of the signals and the fact that Phase drive signal has a fairly large transient.

Typical Control Transients Loaded Q = $2x10^7$

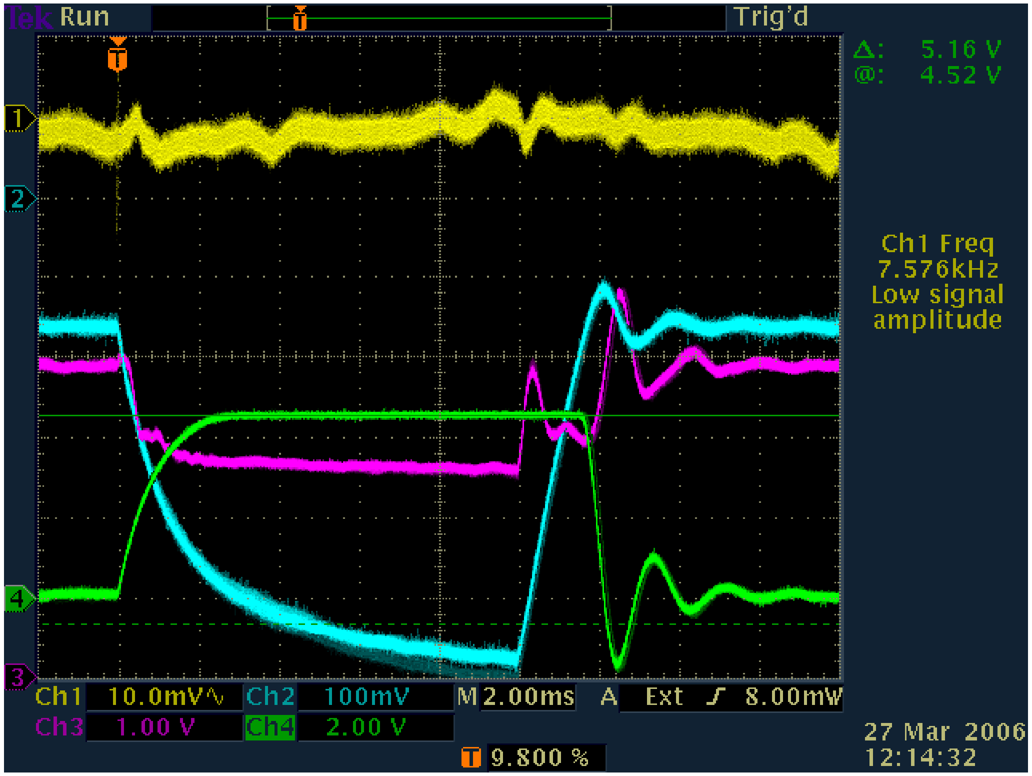


1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Pass 1 Phase ≅ -10°
Pass 2 Phase ≅ 166°

- Beam loading on a high Loaded-Q cavity.
- Note the rise time of the signals and the fact that Phase drive signal has a fairly large transient.

Uncontrolled Transient, Loaded Q = $2x10^7$



1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

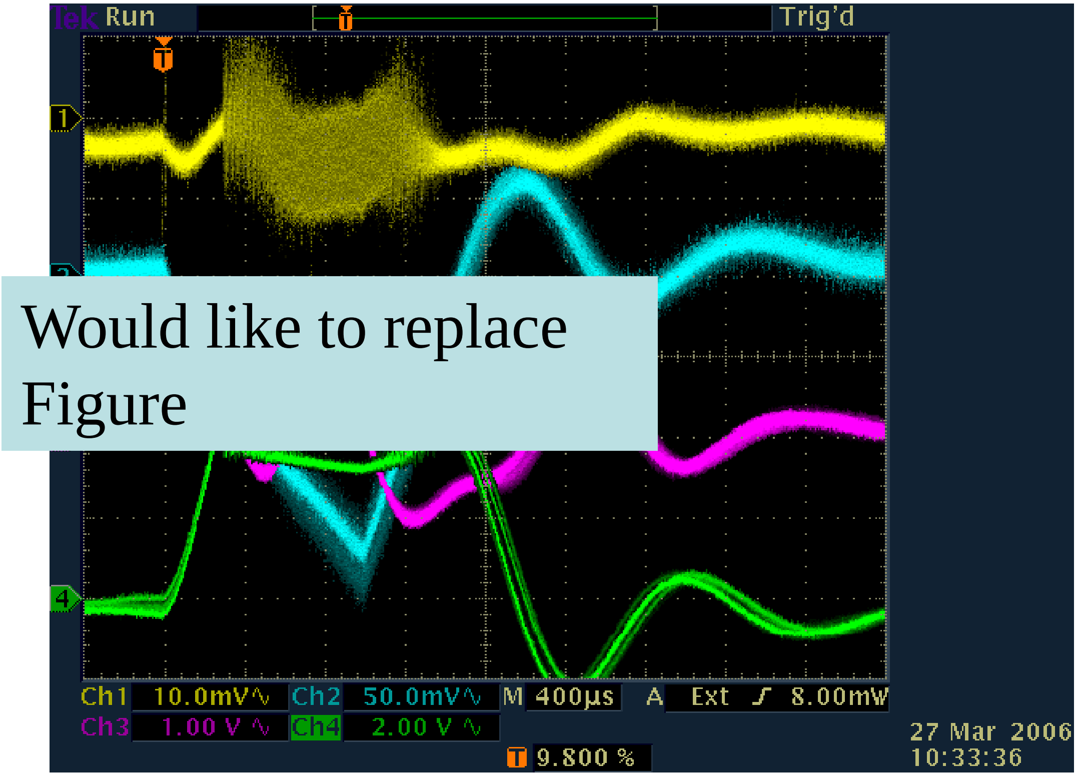
I_{BEAM} = 1's of mA
Pass 1 Phase ≅ -10°
Pass 2 Phase ≅ 166°

- Note the measured phase has a large transient.
- Note that the phase drive signal is saturated
- This was "fixed" by adjusting the phase modulator bias signal thus providing more range.

Pass Band Mode Filters

- Multicell cavities support a number of frequencies that are close to the fundamental frequency of the pi-mode.
- For the JLAB 5-cell cavity the closest mode is about 4 Mhz lower than the fundamental frequency.
- For the JLAB 7-cell cavity the closest mode is between 2 and 2.7 MHz lower than the fundamental.
- If the control system is not designed correctly this mode can be excited and an energy modulation is introduced on the beam.
- Although special filters were added to the low level RF system they were not always adequate to suppress these modes.
- Typically the 8/9 Pi mode on ILC cavities is 800 kHz below the Pi mode. Thus, it presents even more of a concern.

Example of 6/7 Pi Mode Oscillations



1 Measured gradient
2 Measured phase
3 Gradient drive
4 Phase drive

I_{BEAM} = 600 uA
Pass 1 Phase ≅ -10°
Pass 2 Phase ≅ 166°

- Beam loading on a high Loaded-Q cavity.
- In addition to poor phase regulation the 6/7-Pi mode is causing an oscillation in the system, which was remedied by lowering the broad band gain in the phase loop.

Phase Stability

- Everyone worries about phase stability and control in the system from tens of Hz out to the MHz range.
- One of the big problems is low frequency phase stability.
- Depending on setup parameters such as the drive laser pulse width, our injector really cares about phase drifts down to a few tenths of a degree.
- Careful master oscillator distribution design and implementation is critical.

Summary

- Cavities coupled with standard feedback control systems can be operated in an ERL successfully.
- Items of concern are:
  - High loaded-Q cavities (i.e. $\geq 10^7$) can present problems.
  - Beam transients that occur with incomplete energy recovery can present problems.
- It is important to be able to monitor intermediate signals within the system during beam operations.
- Modern control systems can be used to improve the feedback systems.

Some of the JLAB FEL Team

Photo taken Jan 16, 2007

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Backup Slides

Comment on Buncher Operations

- At first blush one would assume that running the beam at 90º would mean that no energy is transferred to the beam and the forward power does not change with the beam on or off.

- This is not the case.

$$P_{Kly} = \frac{(\beta+1)L}{4\beta\, R_C}\left\{\left(E + I_0 R_C \cancelto{0}{\cos\psi_B}\right)^2 + \left(E\tan\psi + I_0 R_C \cancelto{1}{\sin\psi_B}\right)^2\right\}$$

- Thus the following condition must be true for there to be no change in the forward power.

$$\psi = ArcTan\left(-\frac{f_0 I_0 R_C}{2Q_L E}\sin\psi_B\right)$$

Note on Initial Response Time

- In this and all of the SRF cavities that are shown the slow rise time in the gradient and phase drive is not due to the control system.
- The beam must extract enough stored energy to effect the cavity gradient or phase.
- 5 and 7 Cell CEBAF cavities at 10 MV/m has 35 J and 49 J of stored energy respectively.
- At 600 uA tune beam in the injector a 0.1% change in cavity gradient occurs after 23 us.
- At 600 uA tune beam in the high loaded-Q zone 3 cavities where there is energy recovery that time is 330 us.

Some Real Phase and Amplitude Data

- Machine operated with CW beam at various currents.
- First pass beam at -10º and the second pass beam at about 166º
- For one series of measurements the cavities were tuned in between each current set point and the mechanical tuners were disabled.
- The beam was turned on and the klystron phase and forward power measurements were recorded
- For the second series the tuners were allowed to operate and the data was taken once the cavities were tuned.