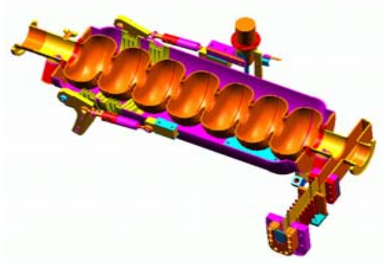
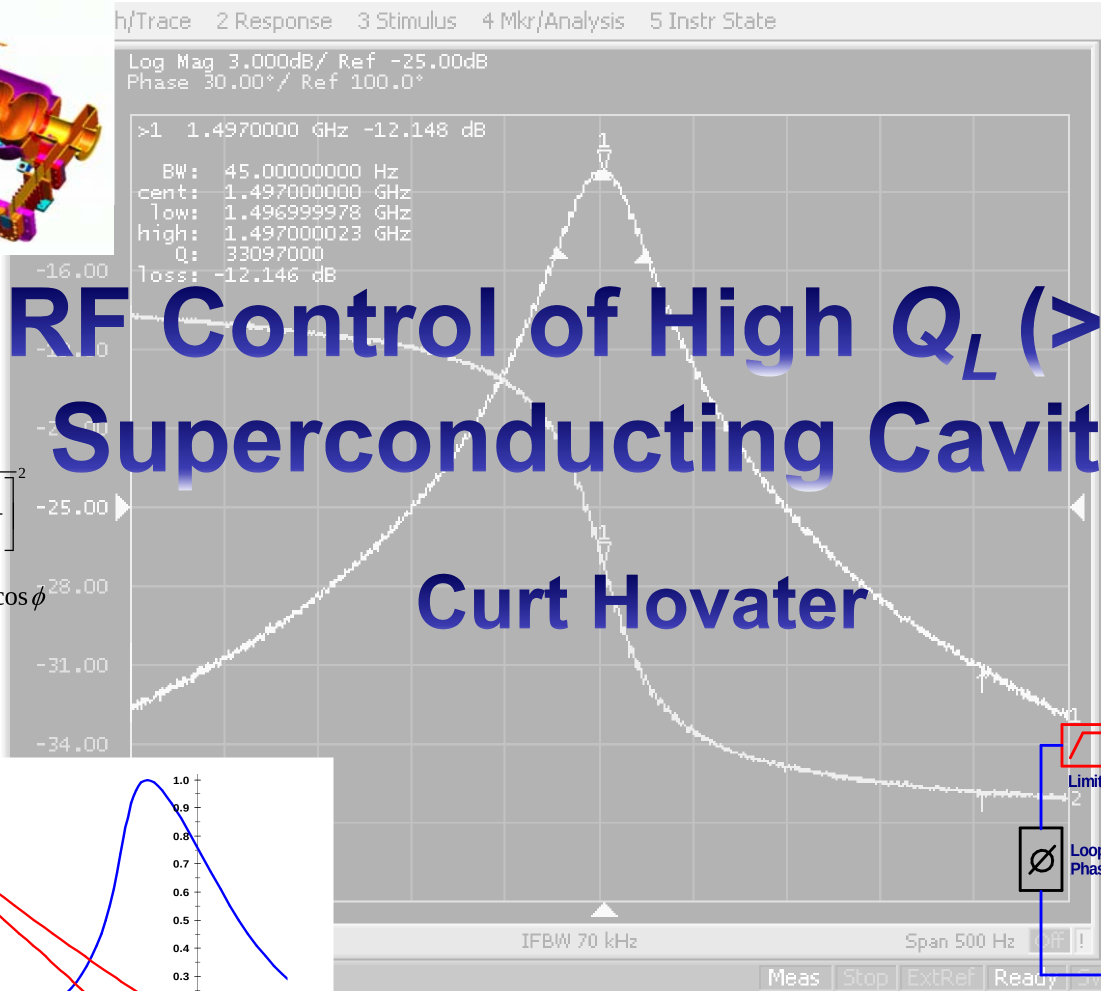
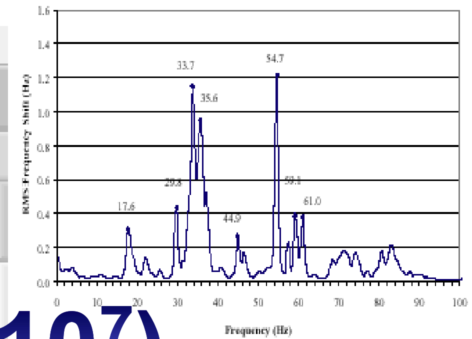
RF Control of High Q_L ($>10^7$) Superconducting Cavities

Curt Hovater

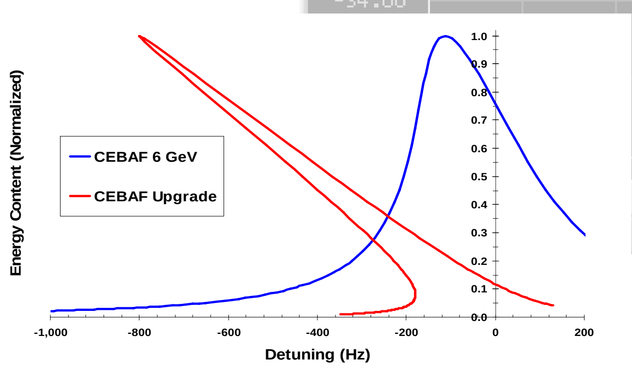


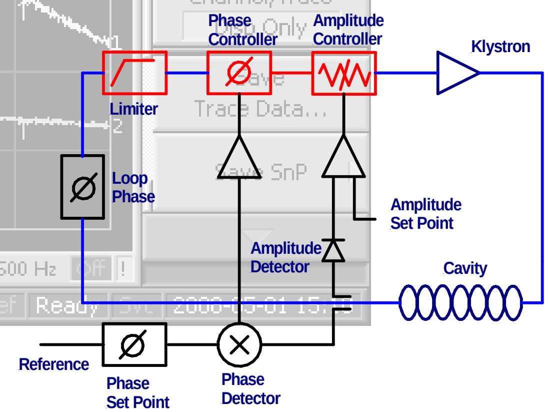




$$\beta_{opt} = \sqrt{(b+1)^2 + \left[\frac{2\delta f}{\Delta f_o}\right]^2}$$

$$\text{where} \quad b = \frac{I_o (R/Q) Q_o}{V} \cos\phi$$





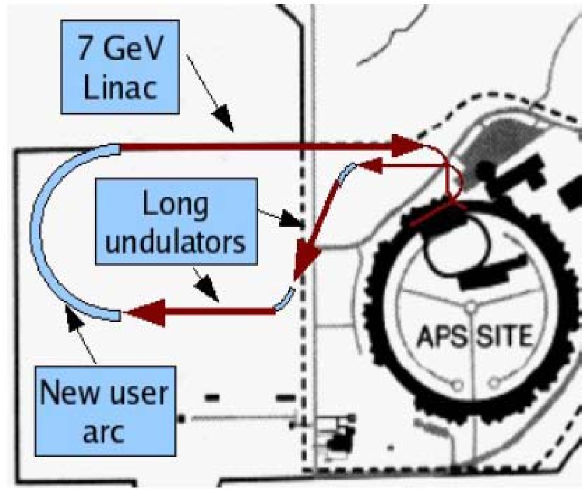
Scope/Agenda

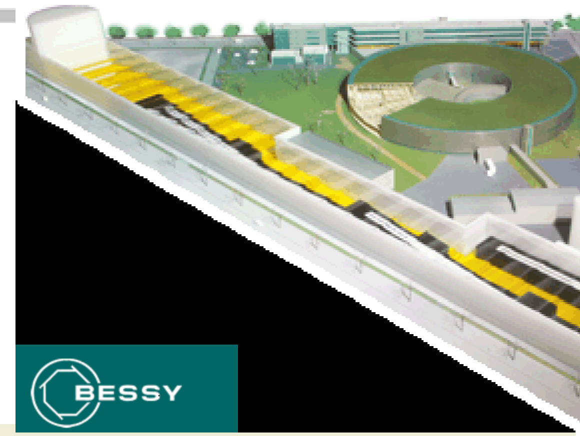
High Q_L (> 10^7) CW Superconducting Accelerating cavities supporting ERLs, Light sources or Nuclear Physics

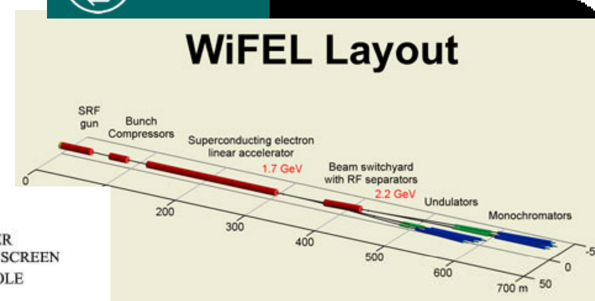
- Introduction
- Q_L Optimization
- Cavity Field Perturbations
- Cavity Control Algorithms
- RF Control Hardware & Design
- Resonance Control
- Summary

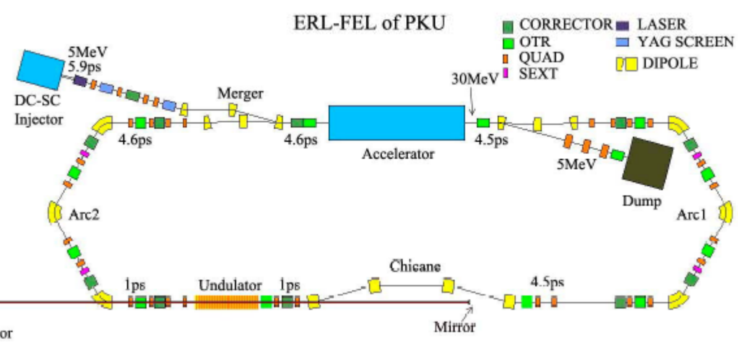
Proposed Accelerators

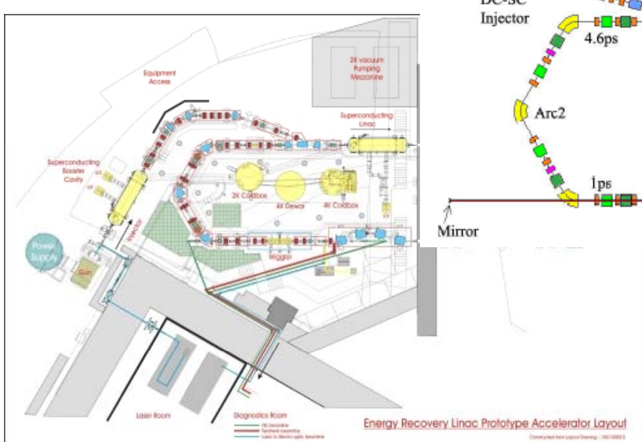
- Cornell
- Argonne
- Wisconsin
- JLAB Upgrade
- Daresbury
- FRIB
- BESSY
- Peking U.
- ….More….

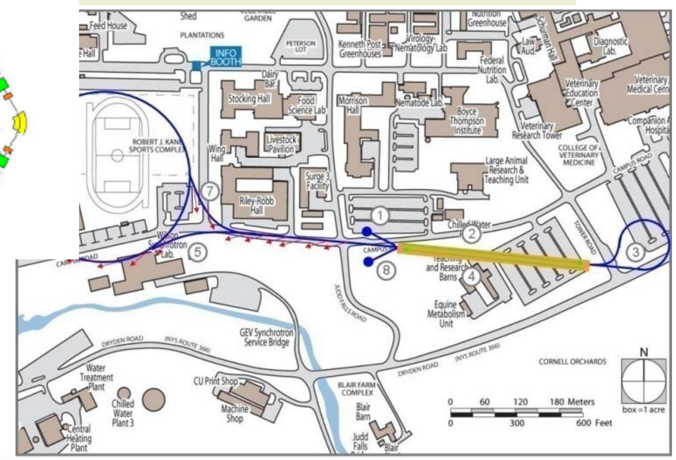












RF Control Challenges/Starting Points

- **Required Field Control to meet accelerator performance:**
  - **Proton/ion Accelerators: 0.5^{o} and 0.5%**
  - **Nuclear Physics Accelerators: 0.1^{o} and 0.05%**
  - **Light Source: 0.05^{o} and 0.01%**

- **Loaded *Q* Optimized for beam loading:**
  - **Nuclear Physics < 1 mA,**
  - **Light Sources > 1 mA**

- **Microphonics & Lorentz Detuning: Determined by cavity/cryomodule design and background environment.**

- **Master Oscillator/Timing/Synchronization: Determined by application (light sources < 100 fs!).**

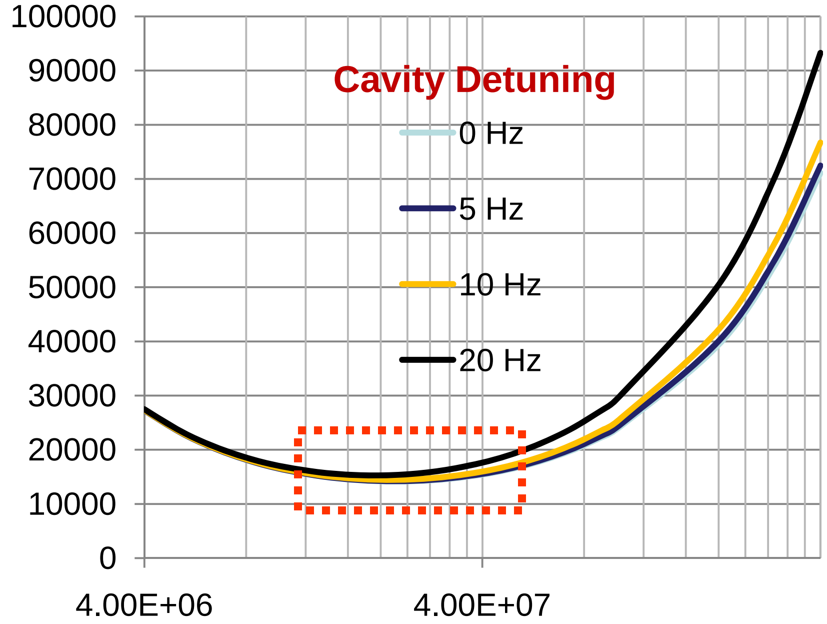
- **Accelerator Specific: Operational, Reliability/Maintainability Access etc.**

Q_L Optimization for Minimum Power

Depending on the application (injector/LINAC or ERL) the cavity Q_L must be optimized for minimum power.

Beam Loaded Cavity

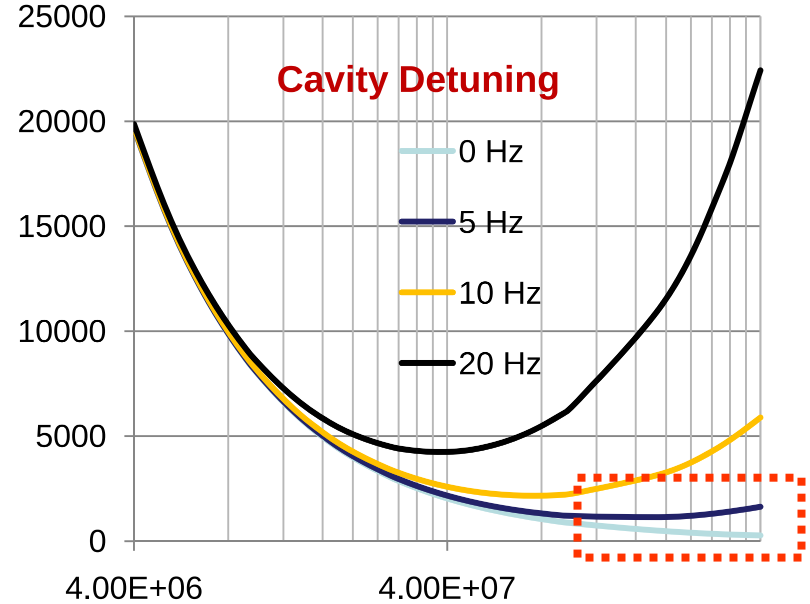
$$Q_{Lopt} \cong V / I_O (R / Q)$$



I = 1 mA

Lightly-non beam loaded Cavity

$$Q_{Lopt} \cong f_o / 2\delta f$$

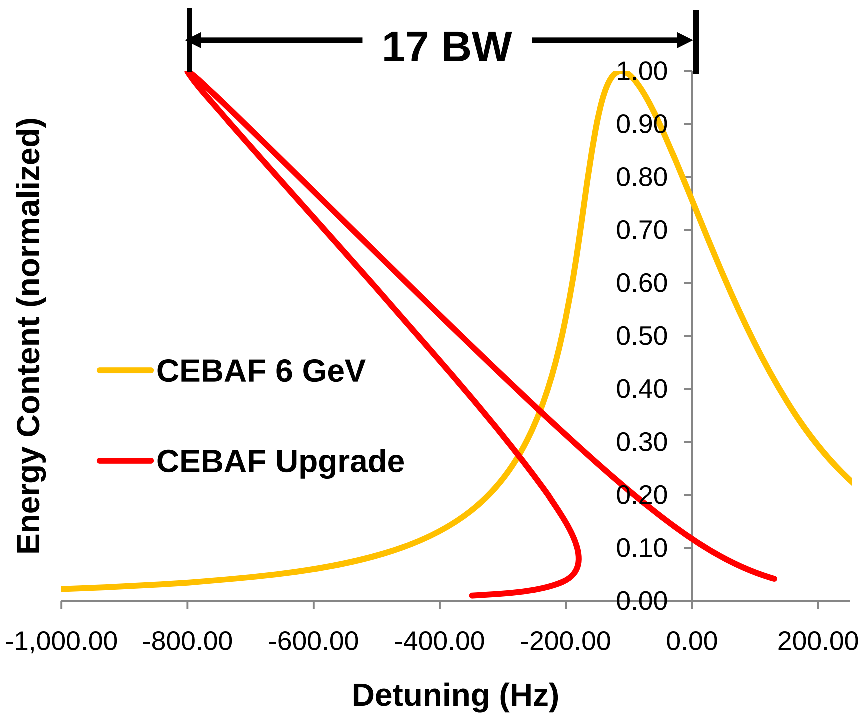


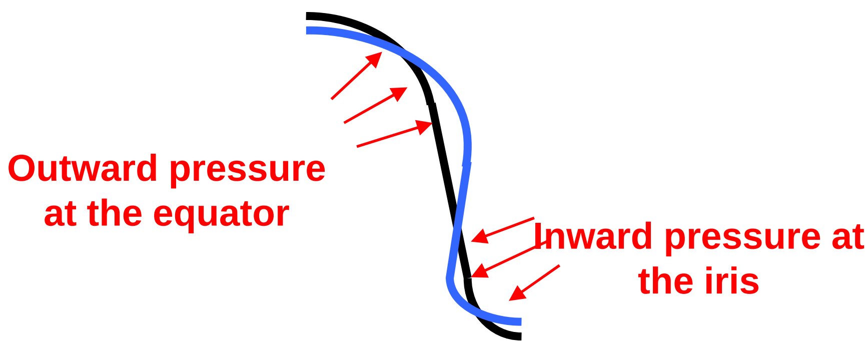
I = 10 μA

Lorentz Detuning

- RF power produces radiation pressures : $P = (\mu_0 H^2 - \varepsilon_0 E^2)/4$

- Pressure deformations produce a frequency shift : $\Delta f = K_L E^2_{acc}$

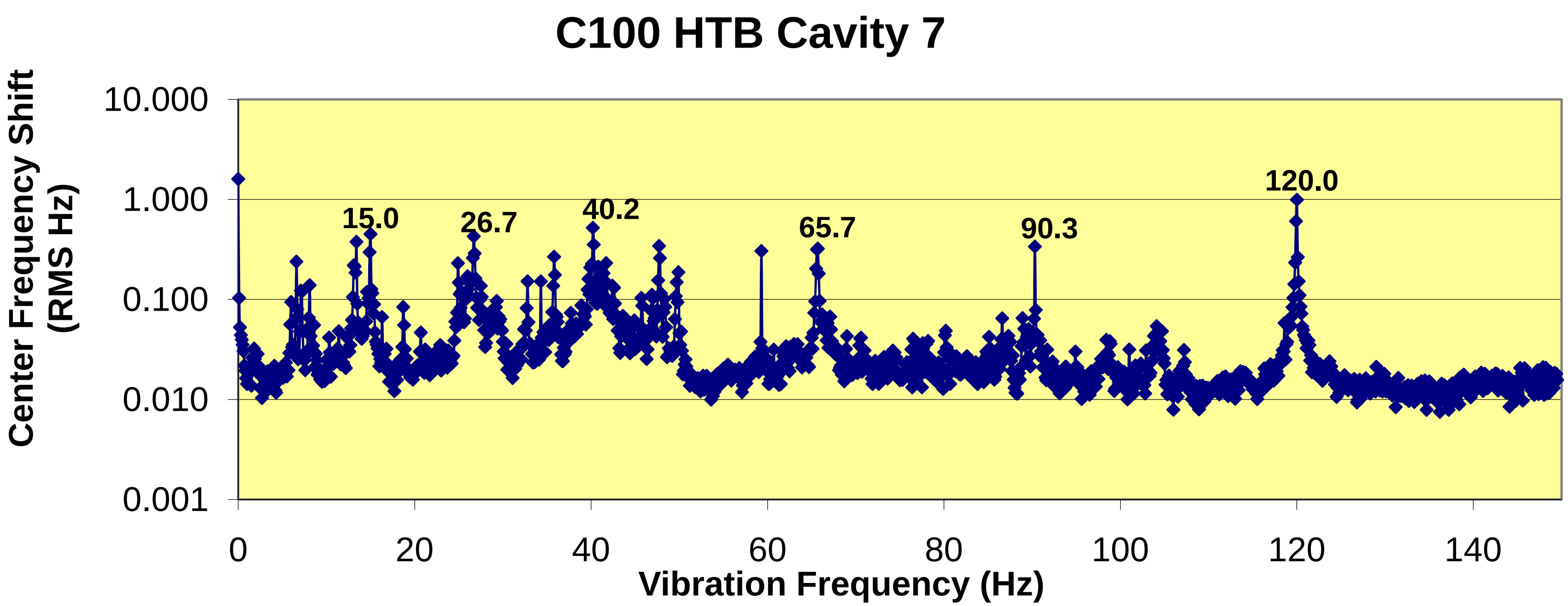




The Quadratic relationship with Gradient becomes an issue at the high gradients (15+ MV/m) needed for new accelerators

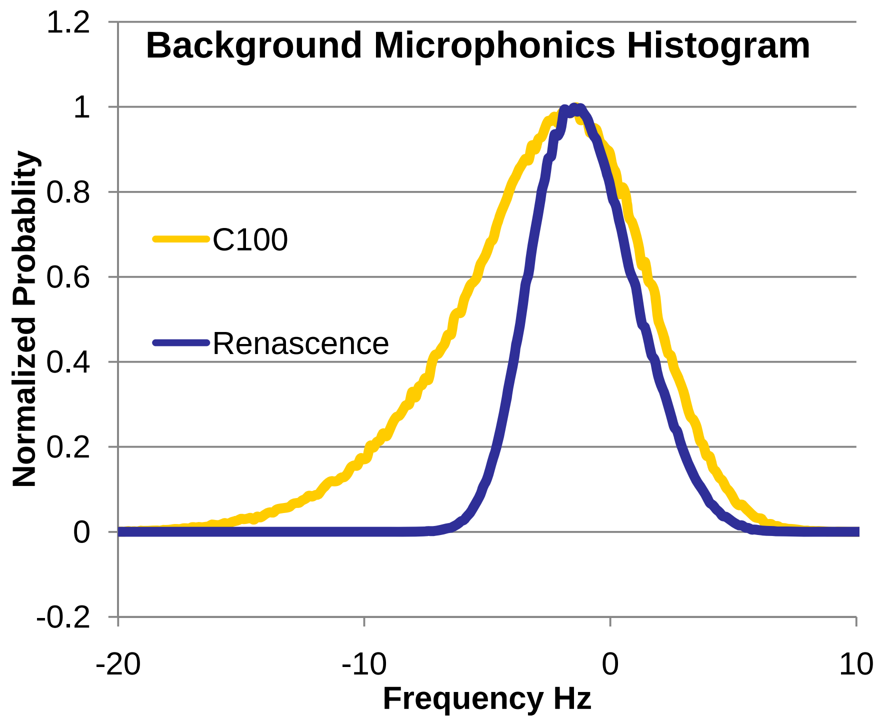
Cavity Microphonics

- **Determines the *<u>Feedback Gain</u>* needed for control.**
- **Determines the Q_L and the klystron power for lightly loaded cavities**



Cavity Microphonics Cont.

Microphonic Detuning*	C100	Renascence stiffened	What If ??
RMS (Hz)	3.65	1.98	0.83
6σ(Hz)	21.9	11.9	5.0



*Data Taken in Same Environment

Microphonic Impact on cavity power operating at 20 MV/m (100 mA of beam)

- C100 = 5.3 kW
- REN = 3.3 kW
- ??? = 2.0 kW

Potential for cost reduction

- Utility
- Power amplifier

Can we reduce microphonics even more?

RF System Modeling and Control Algorithms

Modeling

- CW accelerators can use simple proportional & integral feedback.
- Very good models exist of:

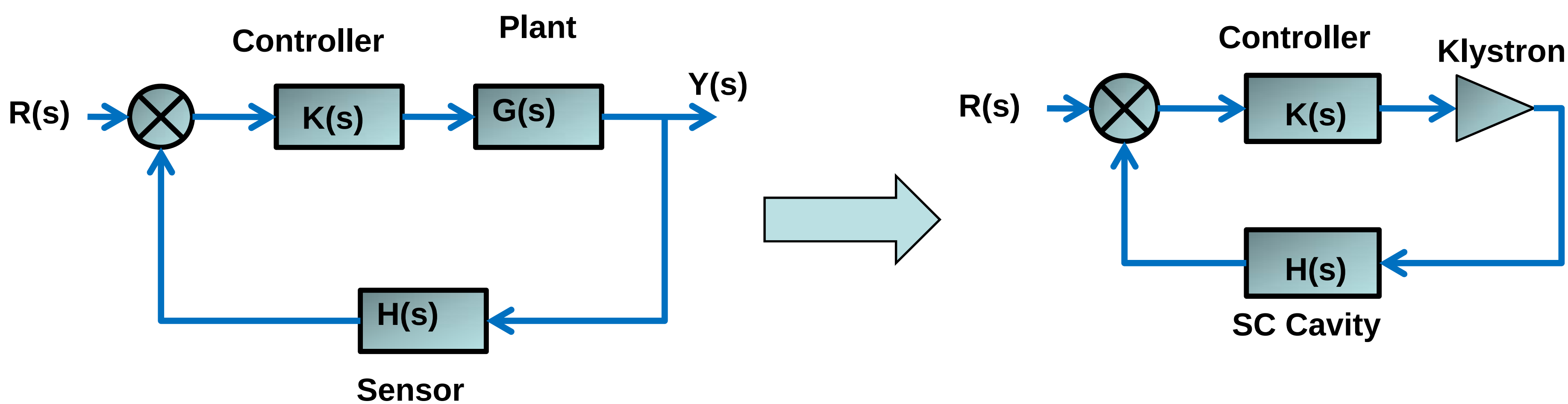
  Cavity: beam loading, detuning, Lorentz effects

  Klystron : saturation

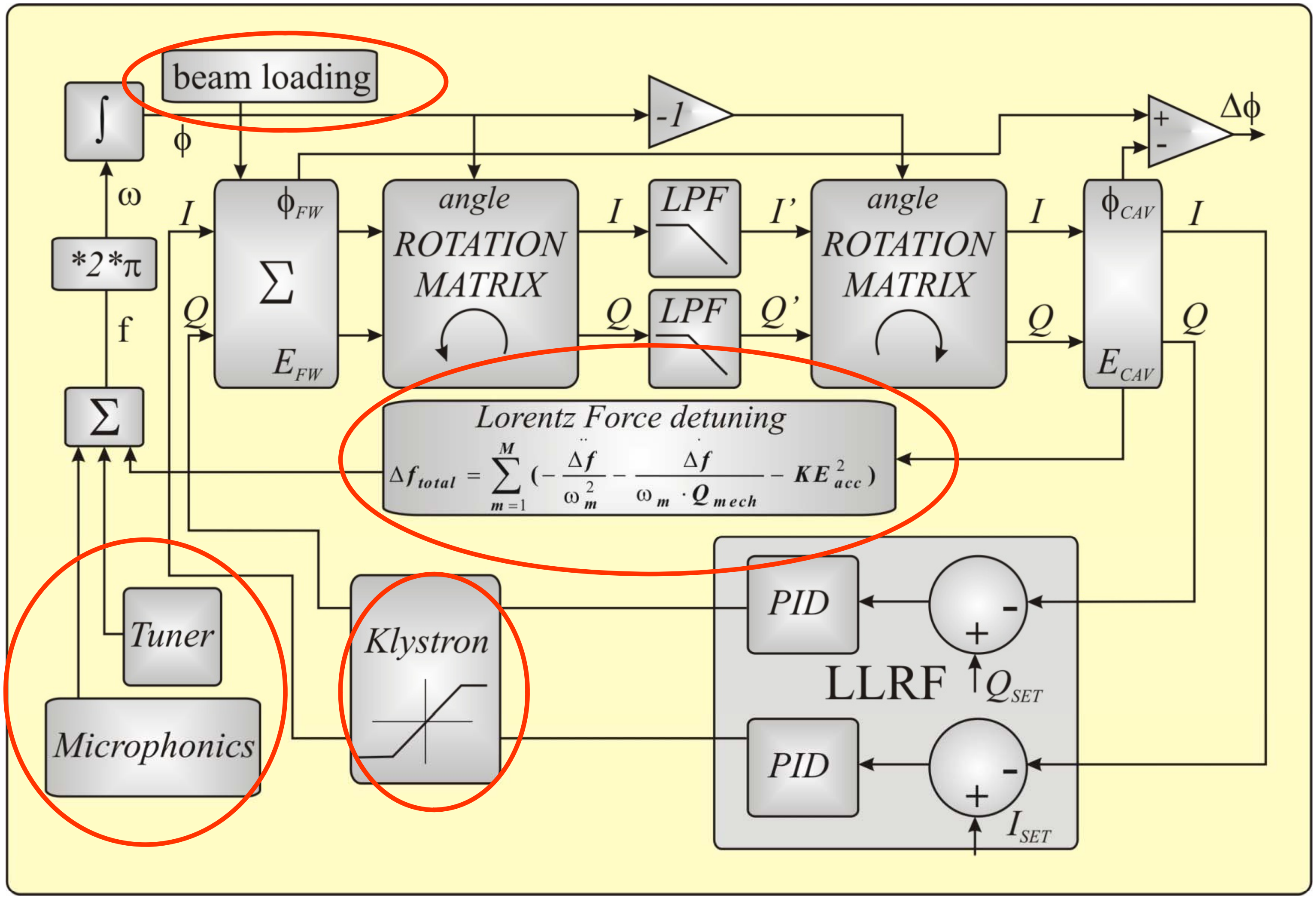
  After modeling, more often than not, the control algorithm is a PID loop!

Algorithms

- Generator Driven Resonator (GDR)
- Self Excited Loop (SEL)



Block Diagram of the JLAB Cavity Control Model

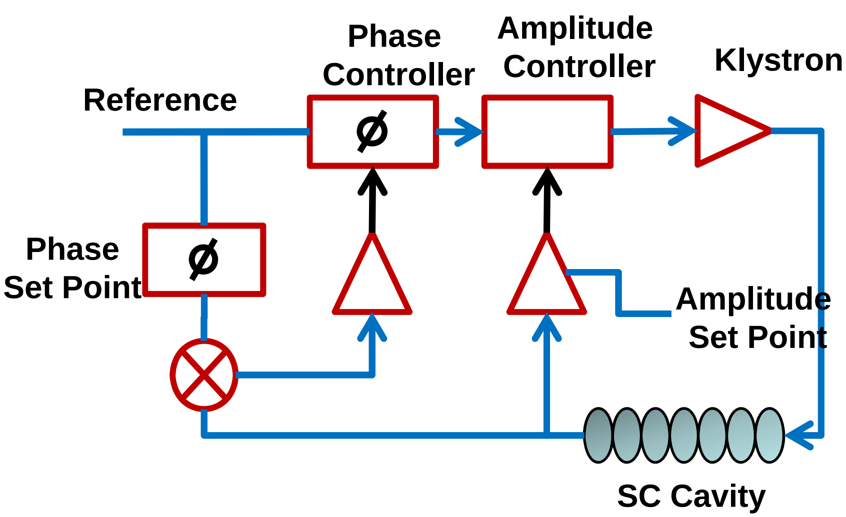


Courtesy of T. Plawski

Generator Driven Resonator vs. Self Excited Loop

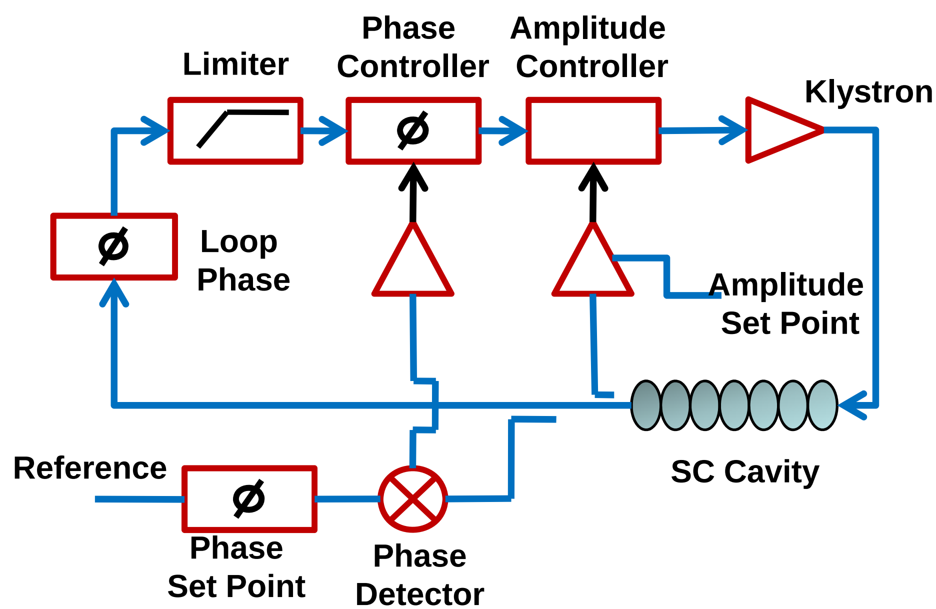
GDR

- **Advantages**
  - Where fast/deterministic lock up times are critical
- **Disadvantages**
  - High Q machines with high microphonic content and large Lorentz detuning could go unstable

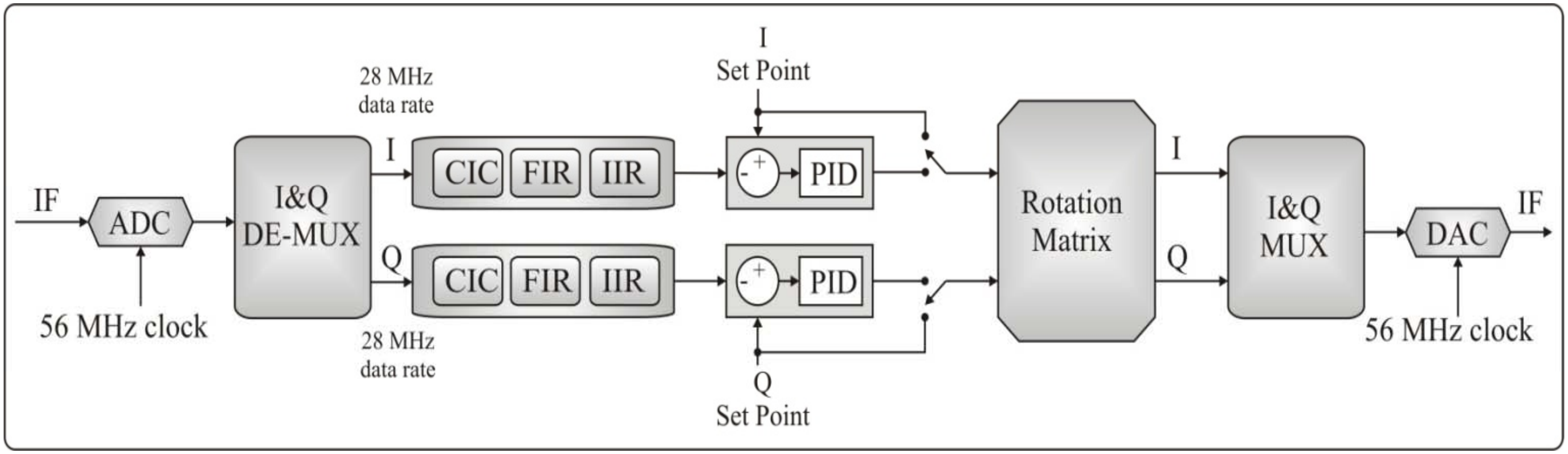


SEL

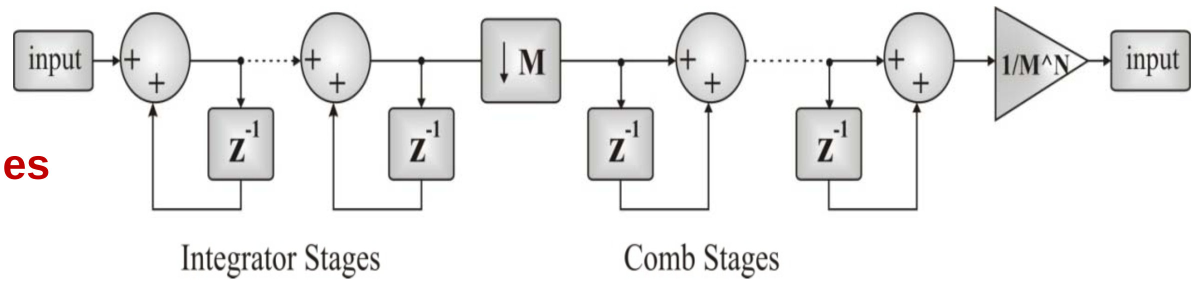
- **Advantages**
  - High Q_L Cavities
  - Systems with large Lorentz detuning
- **Disadvantages**
  - Slow lock up time



Control Algorithms: GDR

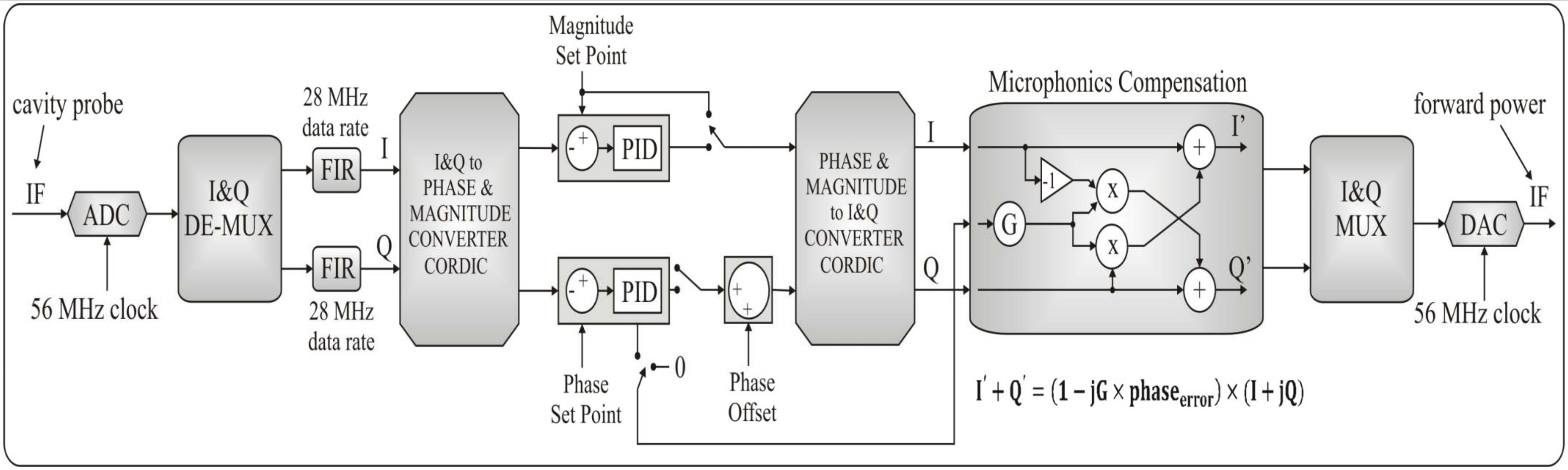


- IF direct I&Q sampling
- Digital filtering
- PID controller for I and Q values
- Rotation matrix
- Single DAC generating IF signal



N-stage cascaded integrator-comb (CIC) filter (decimator)

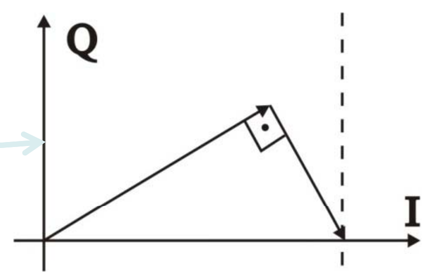
Control Algorithms: SEL



- IF direct I&Q sampling
- digital filtering
- I&Q to Phase&Magnitude - COordinate Rotation DIgital Computer (CORDIC)
- SEL mode
- Microphonics Compensation
- single DAC generating IF signal

$$[x', y'] = [x, y] \cdot \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

$$x_{i+1} = K_i \left[x_i - y_i \cdot d_i \cdot 2^{-i} \right]$$
$$y_{i+1} = K_i \left[y_i + x_i \cdot d_i \cdot 2^{-i} \right]$$



Digital SEL Tests

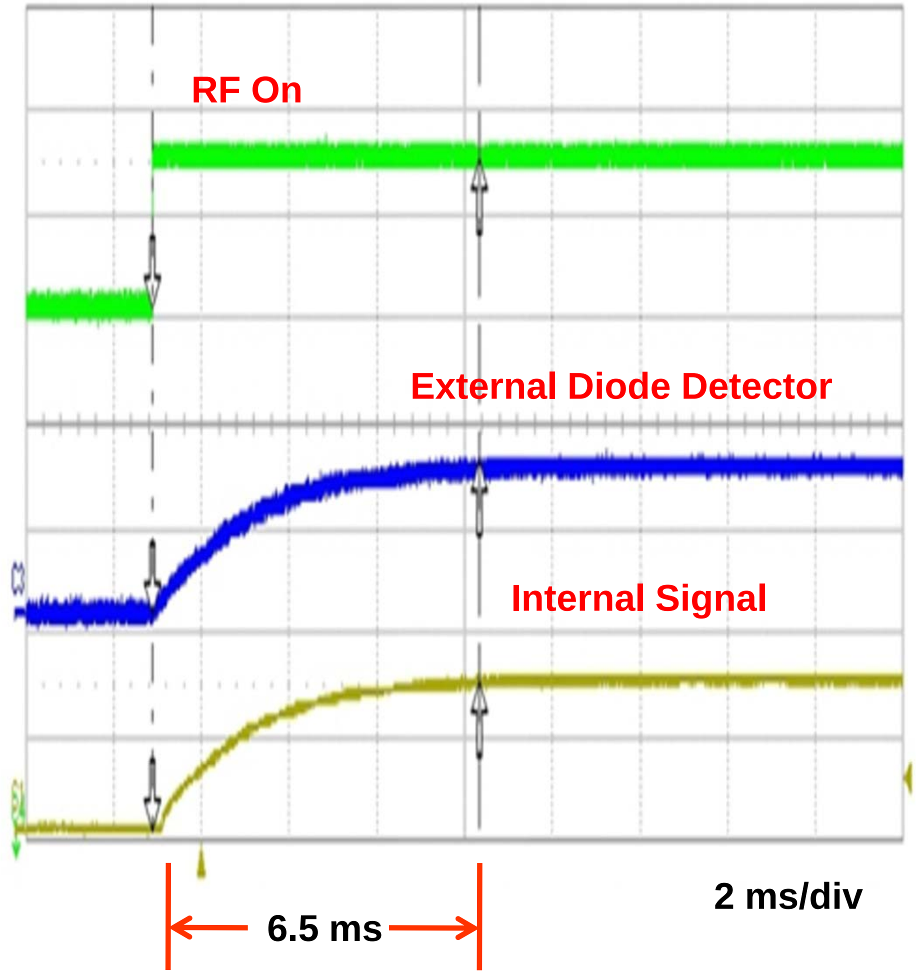
SEL mode

- Detuned the cavity by +/- 50 kHz and RF system tracked it.
- RF turn on of the detuned cavity system works perfect, no excessive power needed!

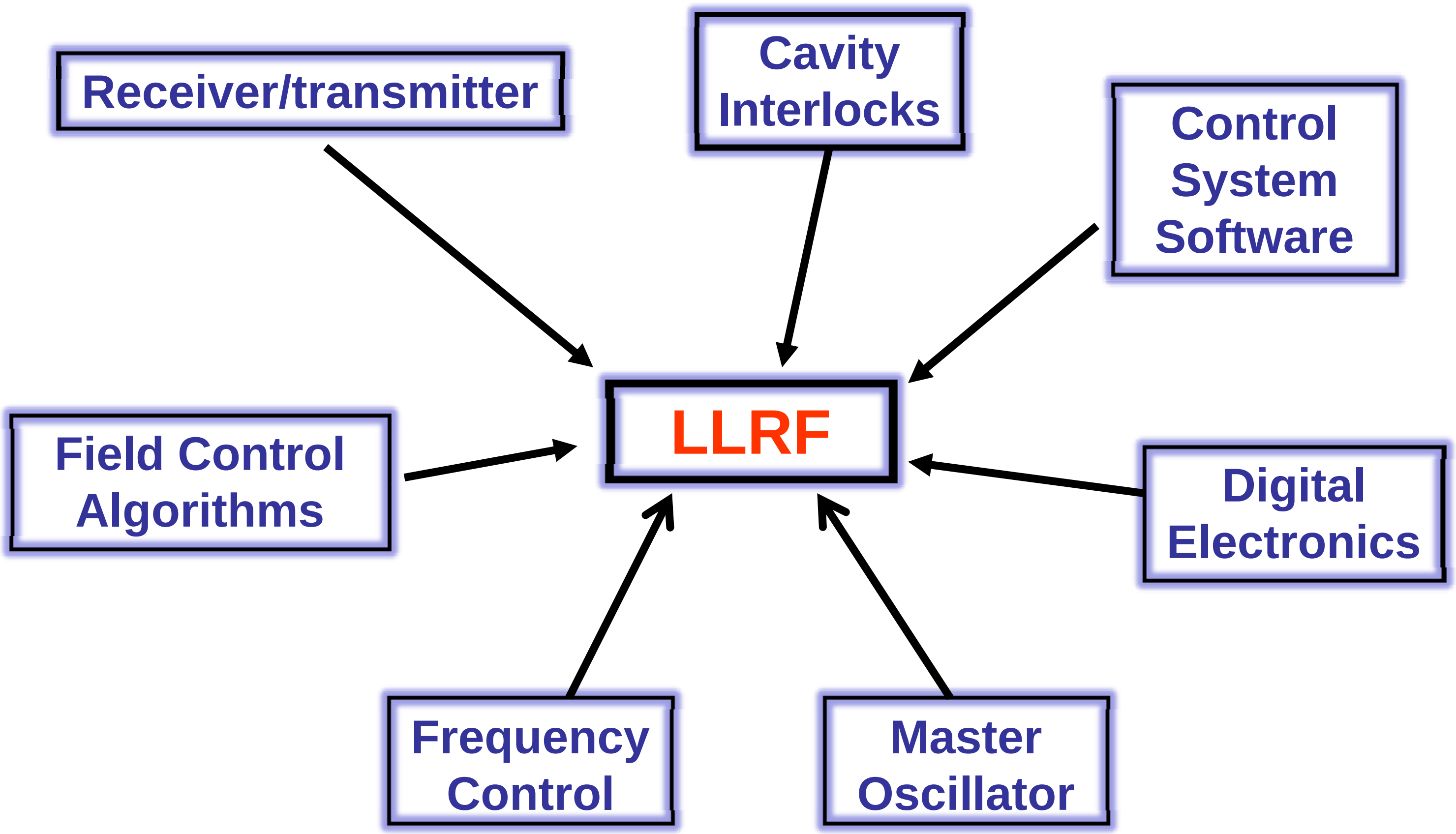
Microphonics compensation

- Phase regulation: phase noise dropped from 1.2 deg RMS down to 140 mdeg RMS
- AM noise when compensator is ON is around 0.2 % . (w/o amplitude feedback)

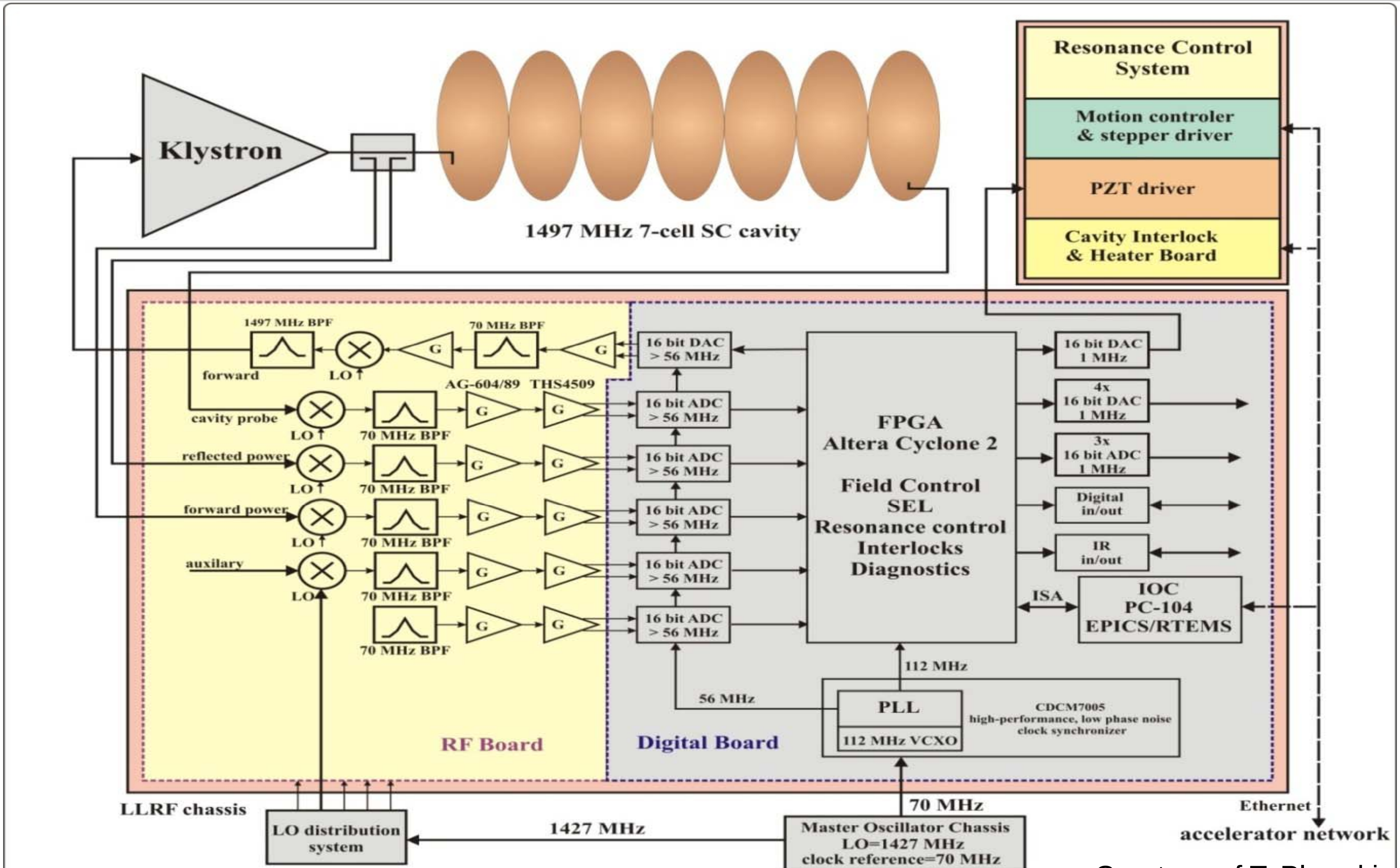
0 to 20 MV/m in 6.5 ms!



RF Control Components

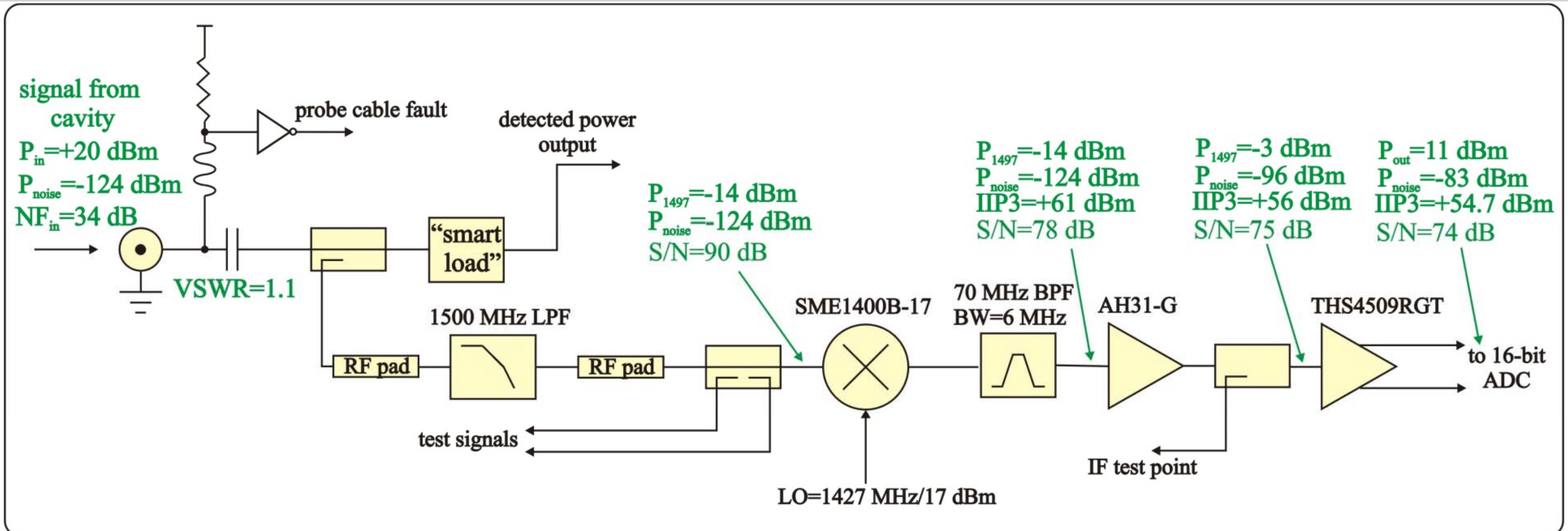


JLAB Upgrade RF Control System



Courtesy of T. Plawski

JLAB Upgrade RF Receiver



Parameter	Specification Value	Imposing Quantities
S/N	72 dB	0.1 degree resolution, 0.01% gradient accuracy
Receiver Bandwidth	8 MHz	Latency, S/N, temperature stability
Latency	100 ns	Control BW
Noise Figure (NF)	52 dB, BW = 100 kHz	S/N for phase resolution
Linearity	0.01% F.S.	Stability, accuracy
Dynamic Range	+54 dBm IIP3	Gradient range
Channel Isolation	67 dB	Phase, gradient resolution/accuracy
In-band intermodulation distortion (IMD)	67 dBc	THD

Field Control: Amplitude

- **Receiver S/N determines minimum residual amplitude control.**

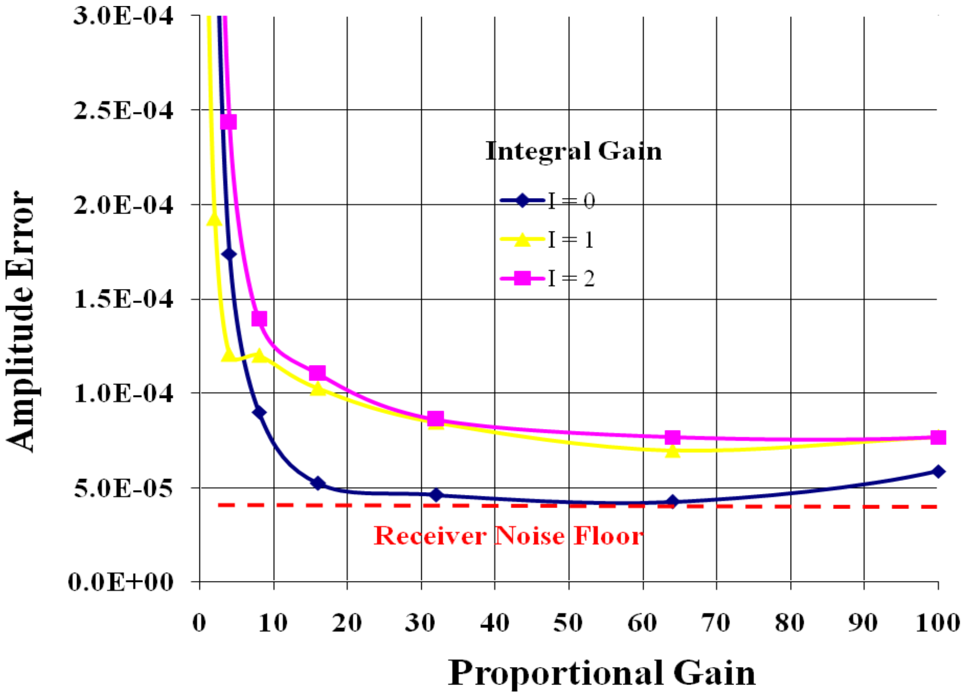
  Amplifiers

  Mixer

  ADC

- **Linear components needed for stability and accuracy over large dynamic range.**

It is possible to improve S/N, through process gain, but at the expense of control bandwidth and ultimately stability (latency).

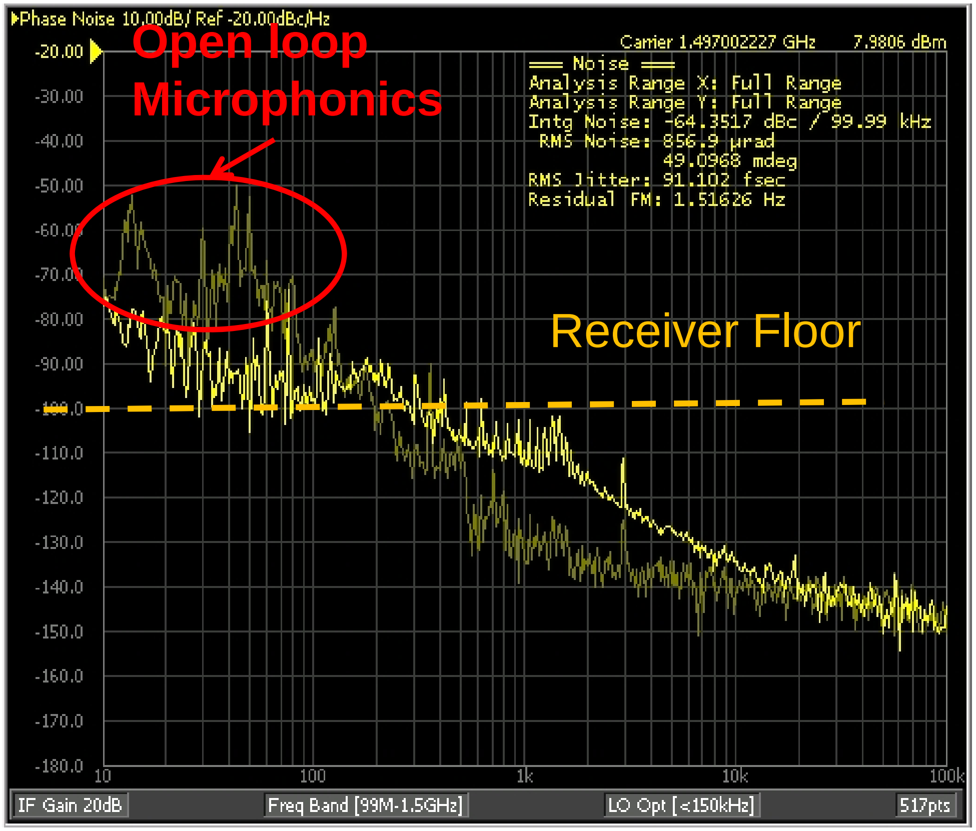


Measured amplitude error vs. proportional gain for a digital receiver (14 bit).
Over Sampling improved S/N from 74 dB to ~ 85 dB.

Field Control: Phase

- Highly dependent on the reference (LO/IF) and subsequent board level clock
- Linear components needed to minimize AM to PM contributions
- ADC aperture jitter ~ 100 fs
- Some ADC linearity can be improved with near quadrature sampling

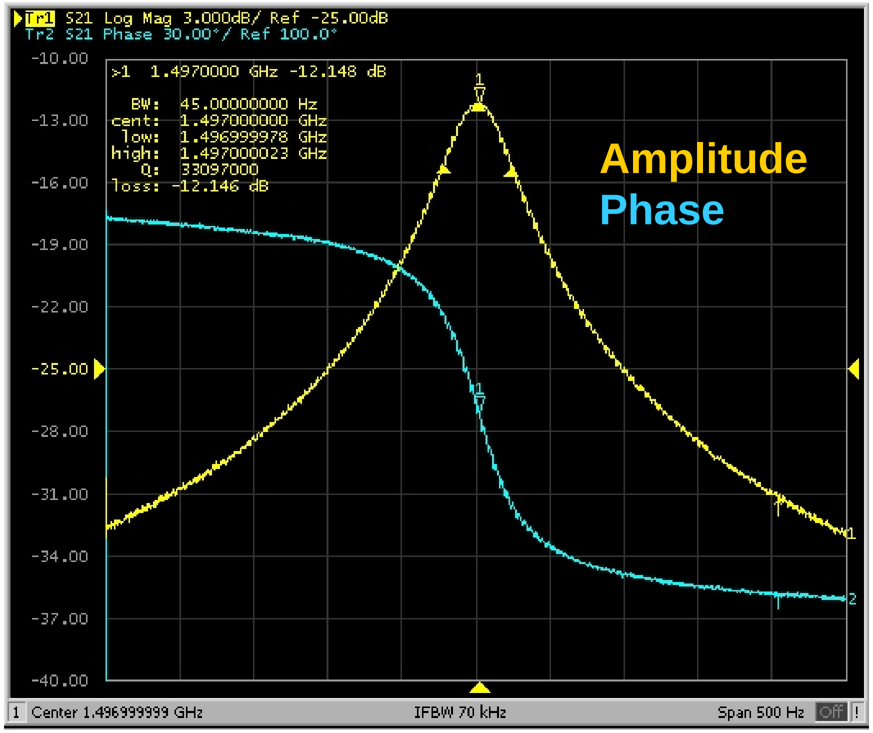
Jitter/drift budget from MO to the beam needs to be completed.



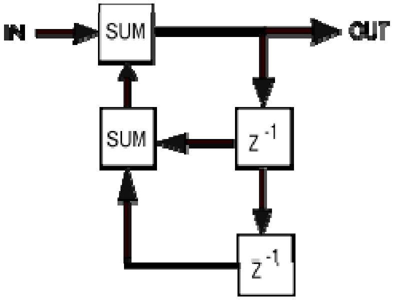
Phase Noise of Open and Closed Loop. Bright Yellow is Closed loop. RMS Phase Noise is 0.049º

Digital Signal Processing

- ADC to DAC Delay Estimate
- Simulation (both digital and model)
- Other Passband modes need to be filtered
- Klystron Linearization
- Tuner Controls
- Internal Cavity Interlocks (Quench)



Cavity Emulator using IIR Filter

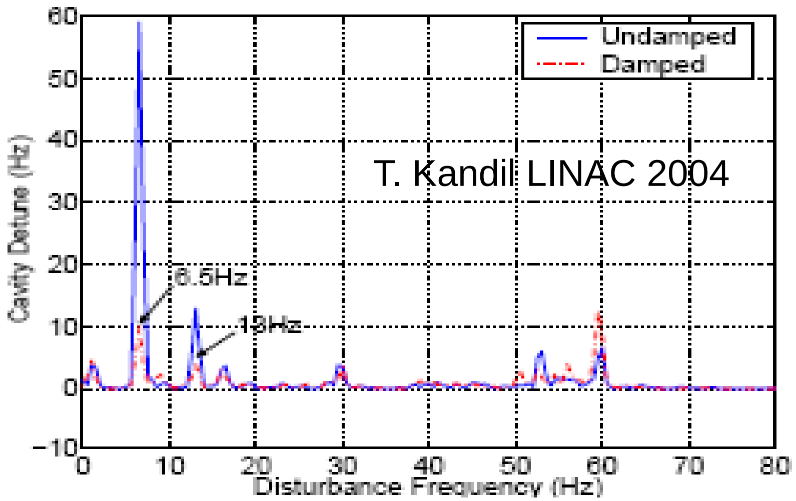


Cavity Resonance Control

Slow Tuner

Stepper Motor:

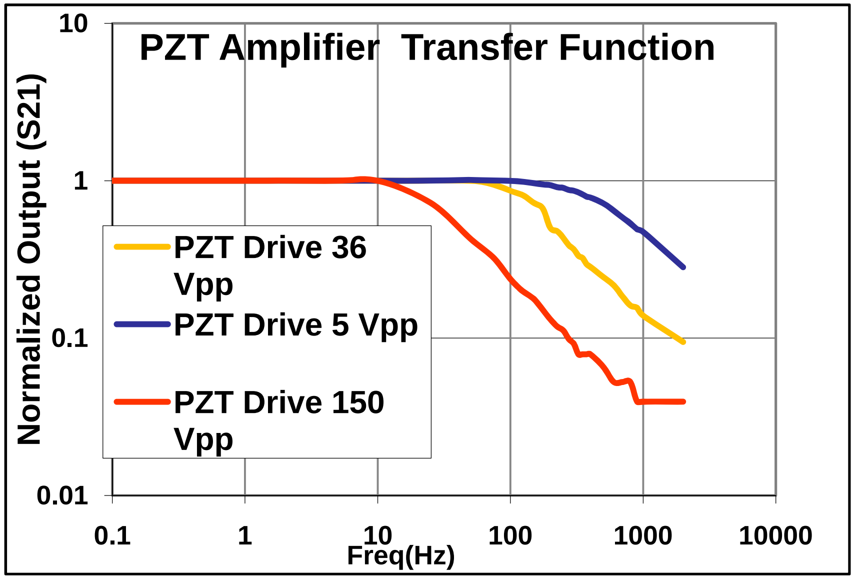
- Recover cavity from large excursions associated with down time activities or CHL trips.
- Keep Fast Tuner centered
- Control can be slow < 1 sec



Fast Tuner

Piezo-Electric Tuner (PZT):

- Large Industrial Base for Piezo and electronics
- Recover or compensate for Lorentz Detuning (Feed Forward or Feedback)
- Minimizes small changes in resonance do to He pressure.
- Control logic embedded in FPGA or fast DSP



Summary

Where we are

- **Field control requirements of 0.05° and .01%, phase and amplitude control can be met with modern electronics.**
- **Reconfigurable Digital Hardware has made development and operations easier.**

Challenges - Thoughts

- **Field control requirements beyond 0.05° and .01% control are pushing the limits of the receiver hardware.**

  Trade offs between process gain (increased latency) and loop gain need to be made to reach beyond these values.
- **ERL incomplete energy recovery has not been completely resolved from an RF Control perspective.**
- **Moving beyond the one amplifier/cavity control for cw proton/ion accelerators.**

Acknowledgement - References

The author wishes to thank Tomasz Plawski, John Musson, Trent Allison, Jean Delayen, Tom Powers and Brian Chase for many insightful discussions on the subject of RF control.

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