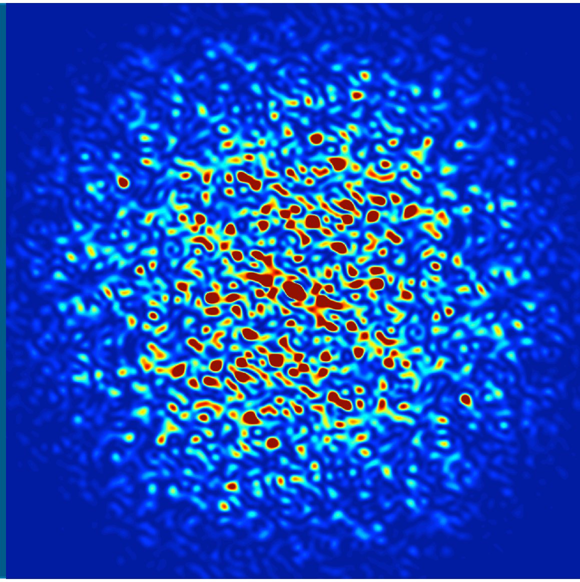
Experience with Rf at high beam Current at PEP-II



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EIC Accelerator Workshop
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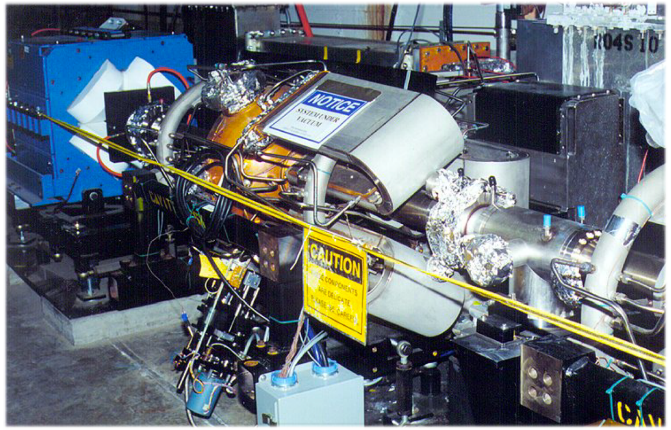
PEP-II Rf System Design



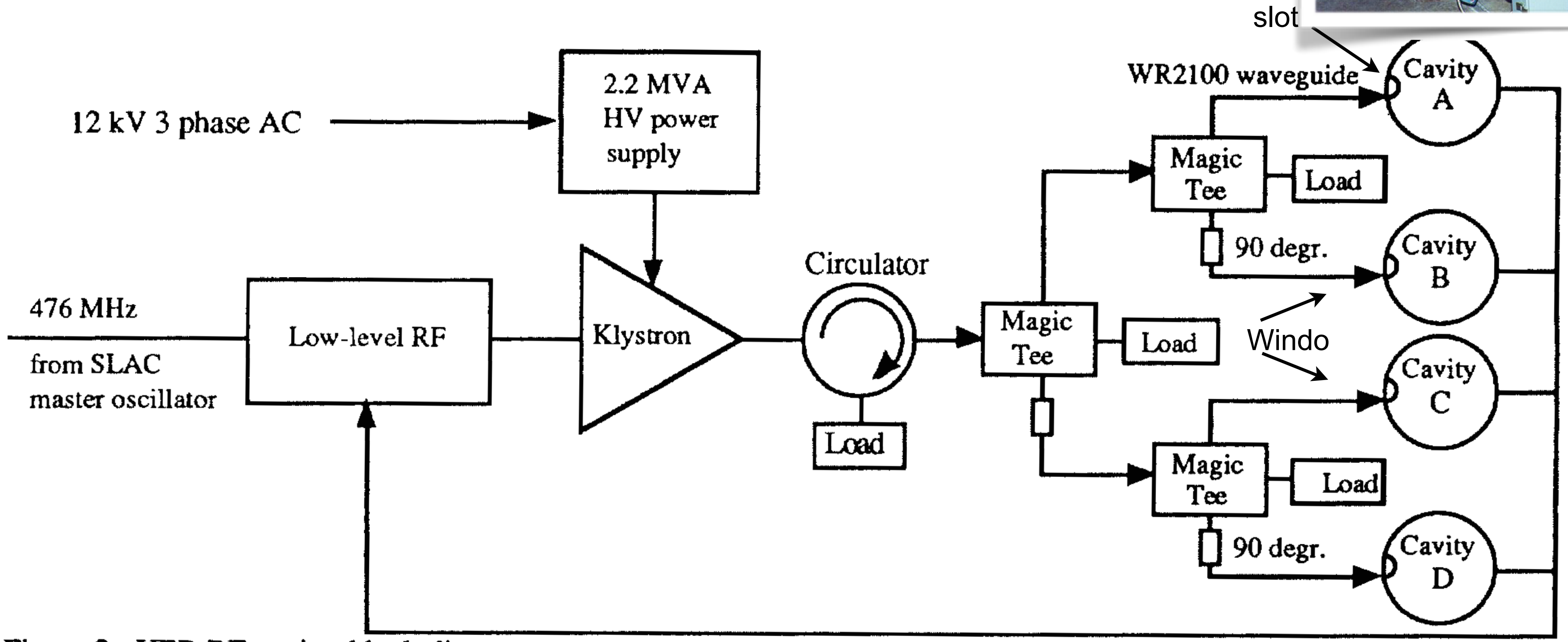


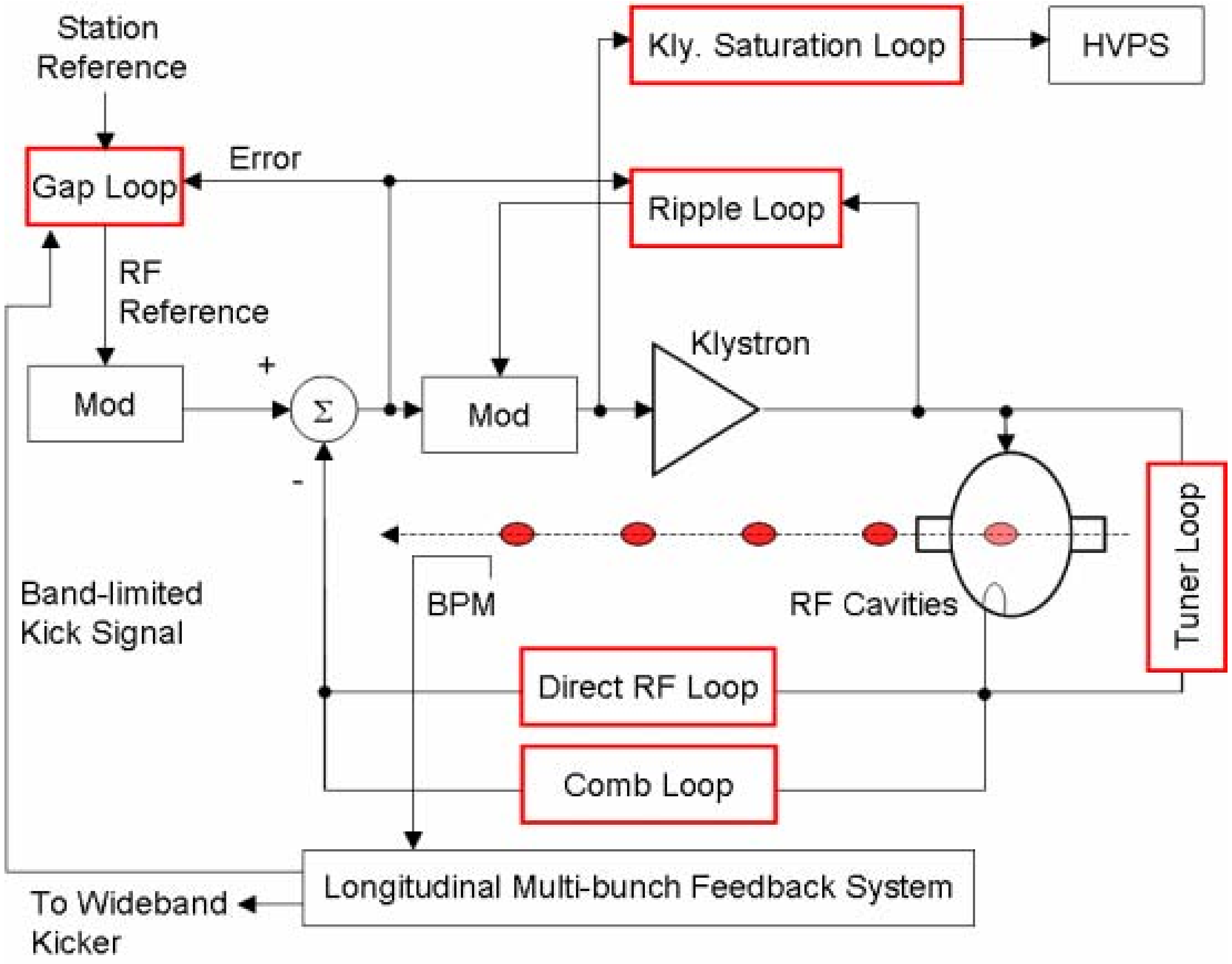
Figure 2. HER RF station block diagram

PEP-II Rf Parameters

Parameter	Symbol	Unit	HER	LER
Beam energy	E	GeV	9	3.1
Beam current (max achieved)	I	A	2	3.2
harmonic number	h	--	1792	1792
ion-clearing gap		% of bunches	5 ≈> 1	5 ≈> 1
Rf Voltage	Vrf	MV	16	6
Rf Frequency	frf	MHz	476	476
Total # cavities in ring			28	8
# cavities/klystron			4 & 2	2
cavity coupling factor	ß		3.6	3.6

Rf Station

- Digitally controlled analog LLRF system
  - comb filter is digital
- Baseband processing in the analog chain
- Rf voltage regulated using HV (no mod-anode)
- Piston tuners run by stepper motors.
- Input for phase control by LFB system (low-frequency kicker)



Why are fast & Comb-filter feedbacks needed?

- Cavity detuning for match to klystron:

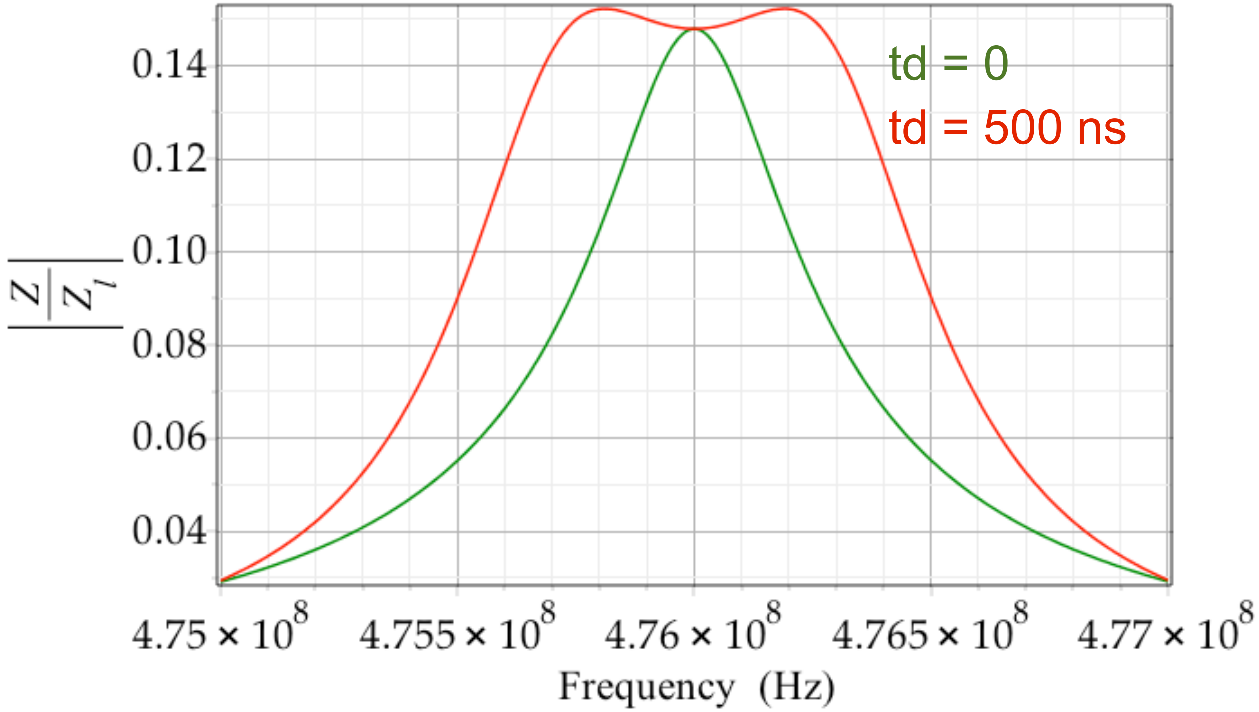
$$\omega_D = \frac{\omega_r I_0}{V_c} \frac{R}{Q}$$

  - for PEP-II HER $R/Q \approx 120\ \Omega$, $V_c \approx 700$ kV, I_0=2 A: $\omega_D/(2\pi)$ > 160 kHz (negative), > 136 kHz.
  - Robinson unstable once revolution frequency is crossed.
  - (not crossing the rev. harmonic is no guarantee for stability, though!)
- Make V_c larger and/or R/Q smaller to avoid this?
  - impractical for r/t cavities, to much power dissipation (KEKB ARES comes close, though)
  - s/c cavities in principle can do this.

- Use rf feedback to suppress impedances.

Feedback Parameters

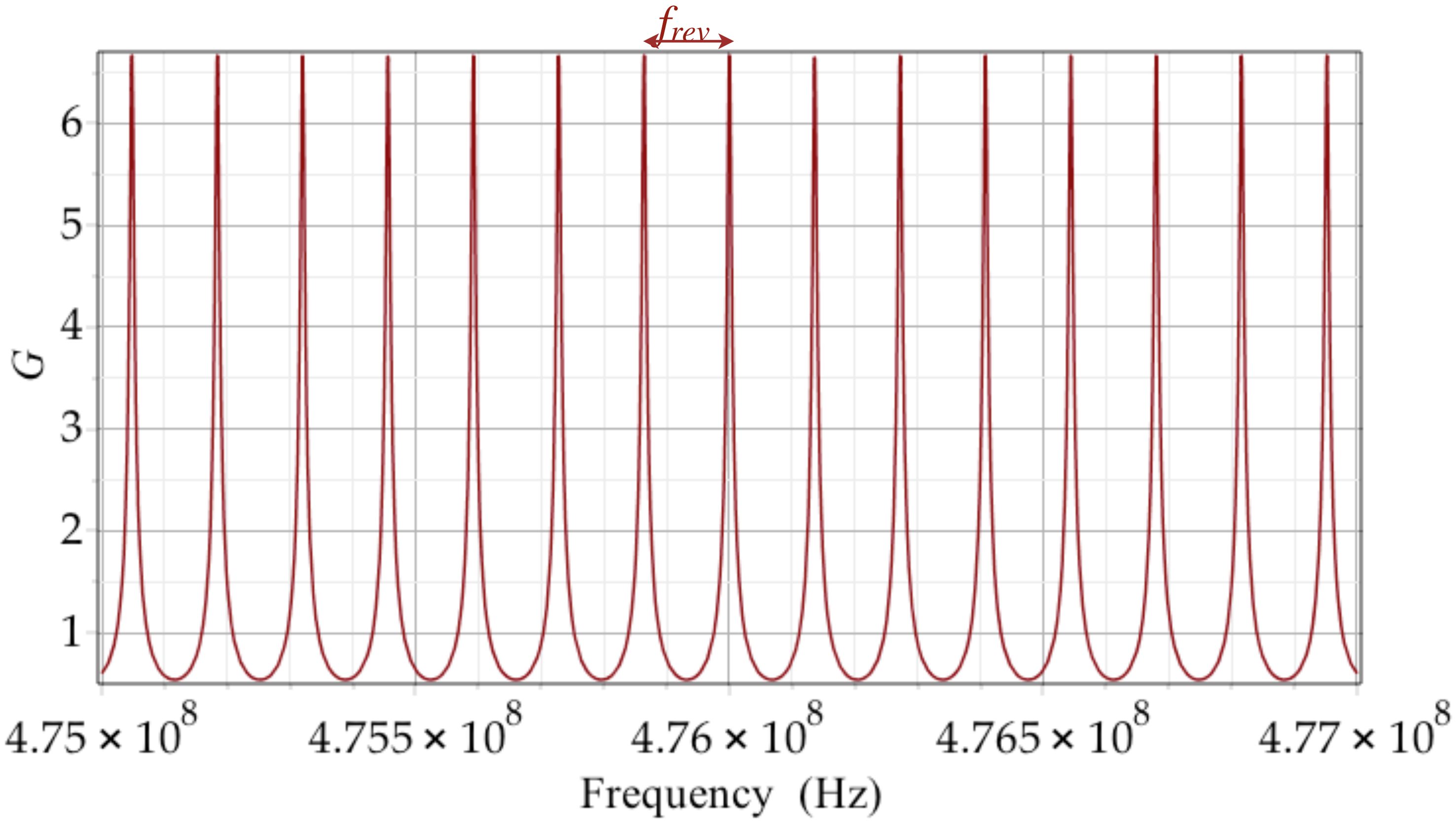
- Gain for direct loop is limited by group delay (≈ 17 dB in PEP-II case)
- small group delay is difficult



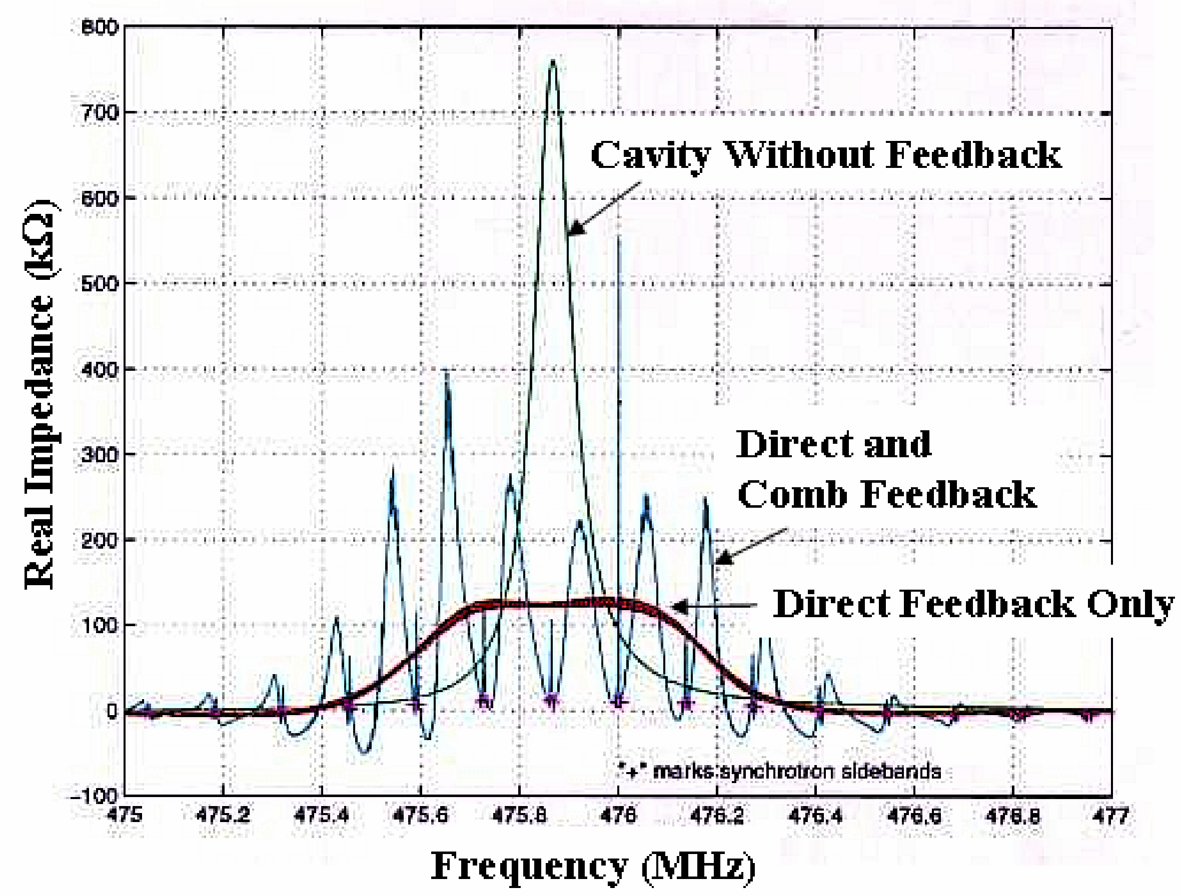
  - PEP-II klystrons spec'd for 150 ns (c/f 600 ns, APS klystrons (352 MHz, 1.1 MW))
  - direct loop electronics ≤ 100 ns
  - rf and cable runs

Comb Filter

- Comb filter loop to make up the rest
  - the trick is to get the correct phase at each synchrotron harmonic, phase flip in between
  - in practice, we used a double comb peaked at ν_s sidebands (avoid amplifying rev. harmonics)
  - can get another 20…30 dB



Combined effect



"Woofer"

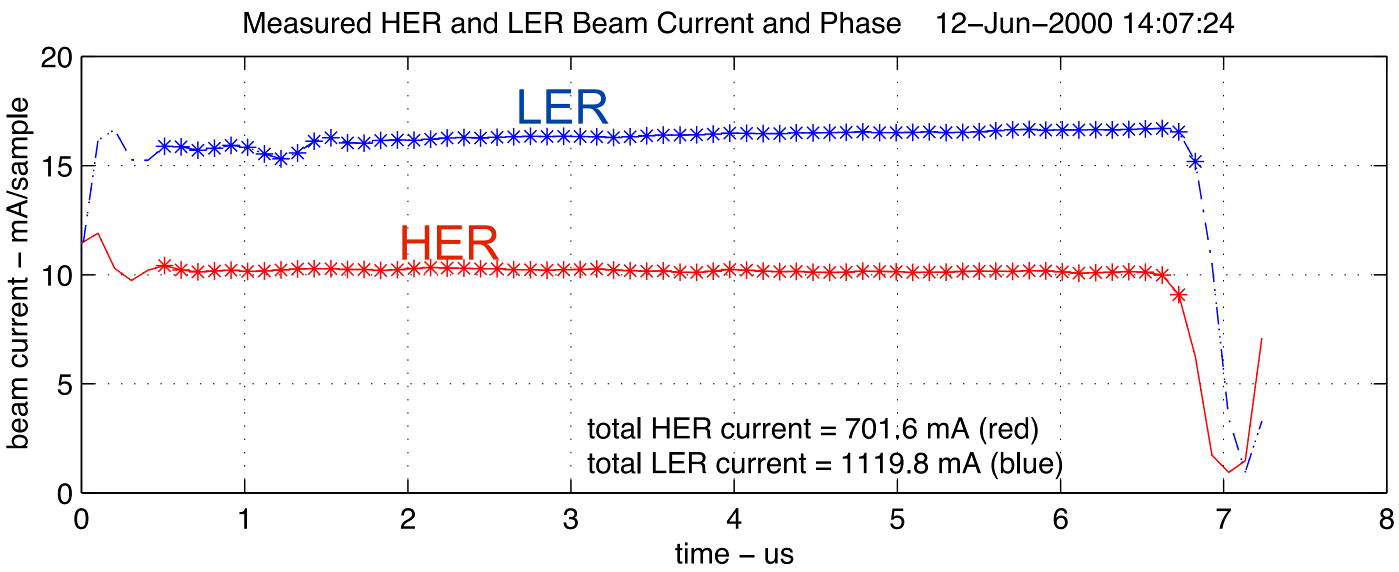
- Direct & comb filter were not sufficient for low-lying, negative modes at higher beam currents (≥ 1 A or so)

- Use a direct link from the LFB system into the rf system, adjusting the rf phase
  - ≈ 1 MHz bandwidth (up to maybe mode ±6)

- in principle can reduce effect of rf noise (mode 0) as well
  - in practice, better to fix at the source (klystron), maybe using ripple compensation.

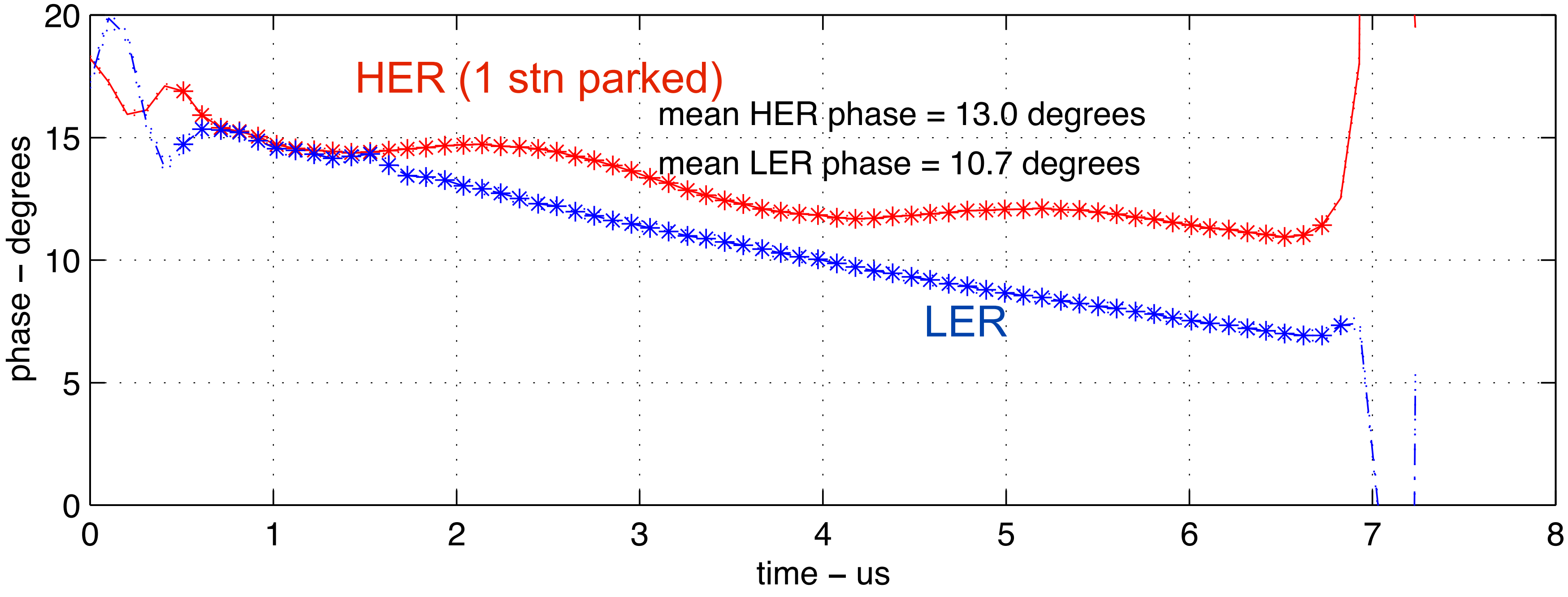
Gap transients

- Never(!) enough klystron power to compensate transients from gaps in beam
  - pre-compensate rf reference so LLRF would not try to compensate; adjusting to beam conditions.
  - operationally, we could increase beam current by reducing gap length (5% ≈> 1%).
  - slightly larger detuning than optimal gives the transient 1st-order behavior.
- Schemes like guard bunches to compensate gaps cause beam-beam issues in colliders.
  - either too much beam-beam
  - or (if non-colliding) too little
  - short lifetime, high background



Parked Cavities

- Occasionally one is forced to run with some stations off.
  - tune rf cavities *in pairs* to ± 2.5 revolution harmonics to minimize impedance
  - pairwise detuning cancels the imaginary(?) part of the (uncontrolled) impedance.



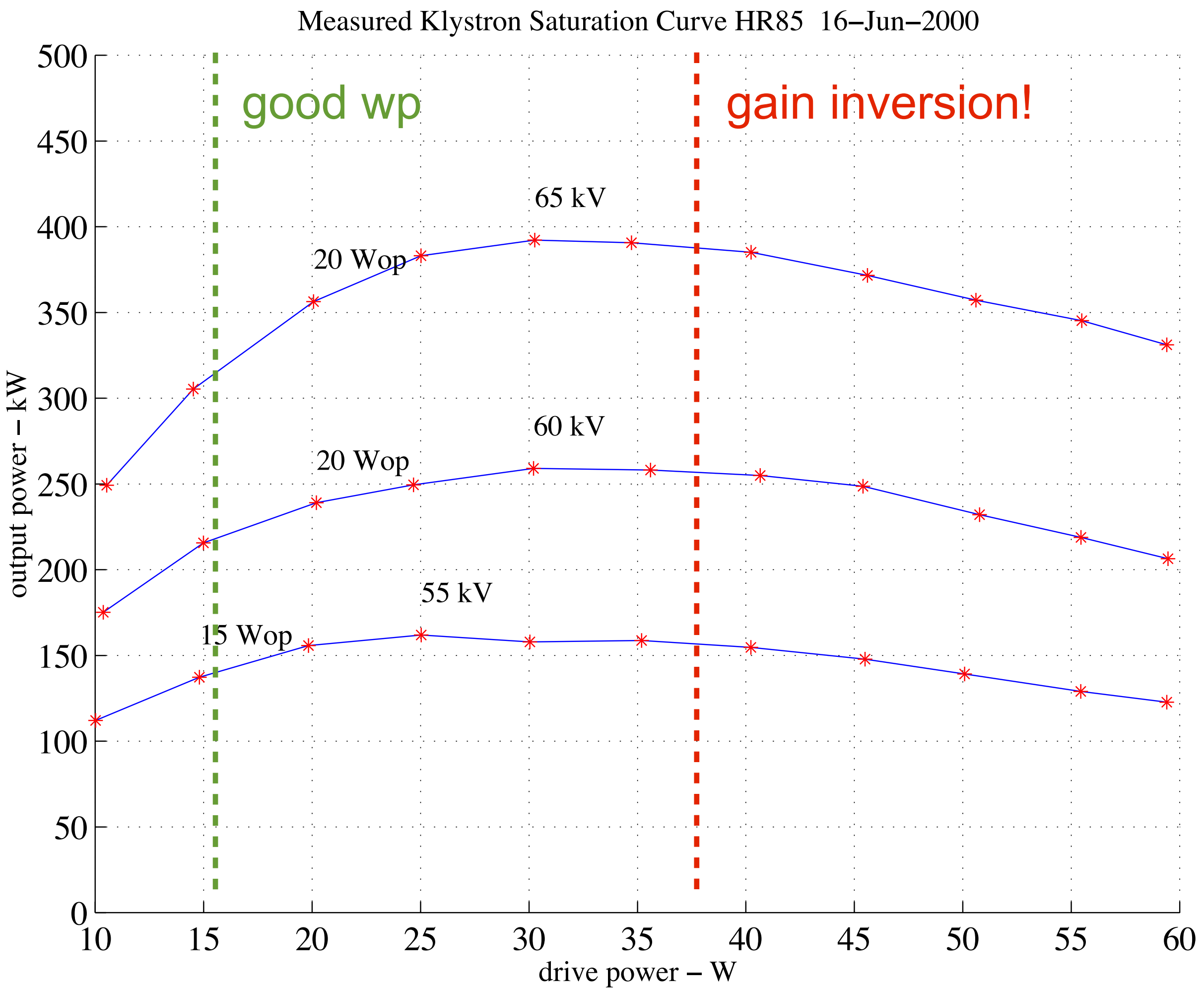
Practical Experience

- The strong feedback loops are very sensitive to transients.
  - due to high loop gain, transients tend to cause relatively quick changes of rf voltage -> reflected power -> station trip
- Ramping a station up initially very slow
  - Turn rf on with no feedback & moderate rf voltage
  - ramp up loop gains (very slowly to avoid trips)
  - raise gap voltage slowly to control transients.
  - It turned out much faster to run the stations up with loops set at no-beam settings.
- ac ripple a significant limit on performance
  - gain of klystron varies -> loop gain varies -> cannot operate too close to the limit
  - needs to be taken care of at the LLRF level
  - solid-state rf power amplifiers do not have this issue.

Dynamics of Analog Circuitry

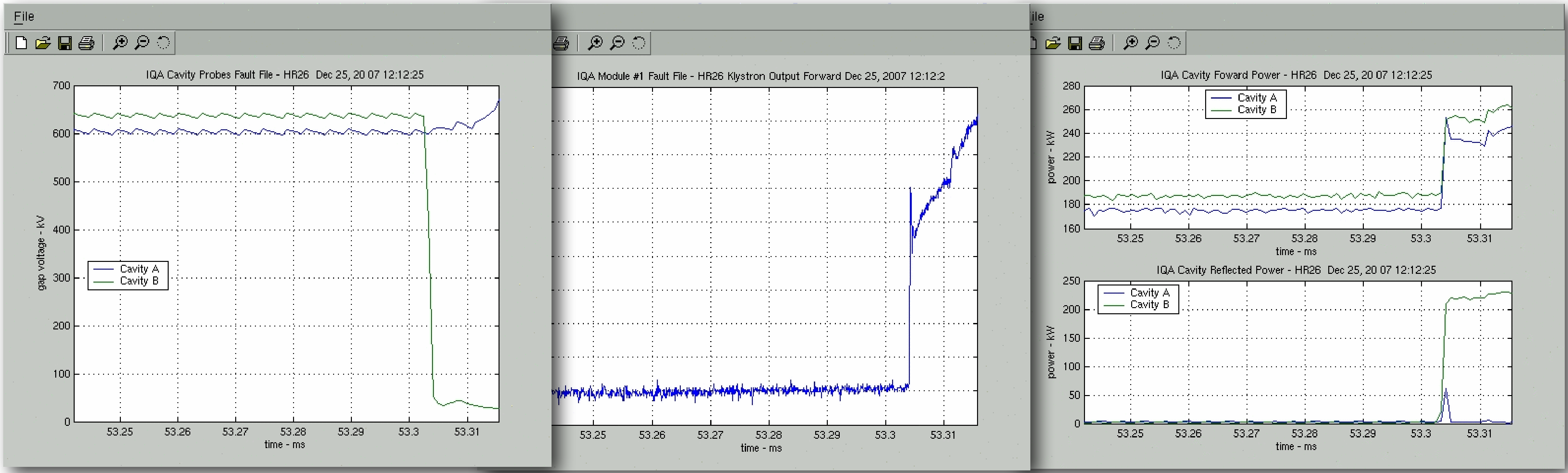
- Any noise or transient can cause klystron saturation: game over!

- Amplitude limiter helps
  - but the gain still drops



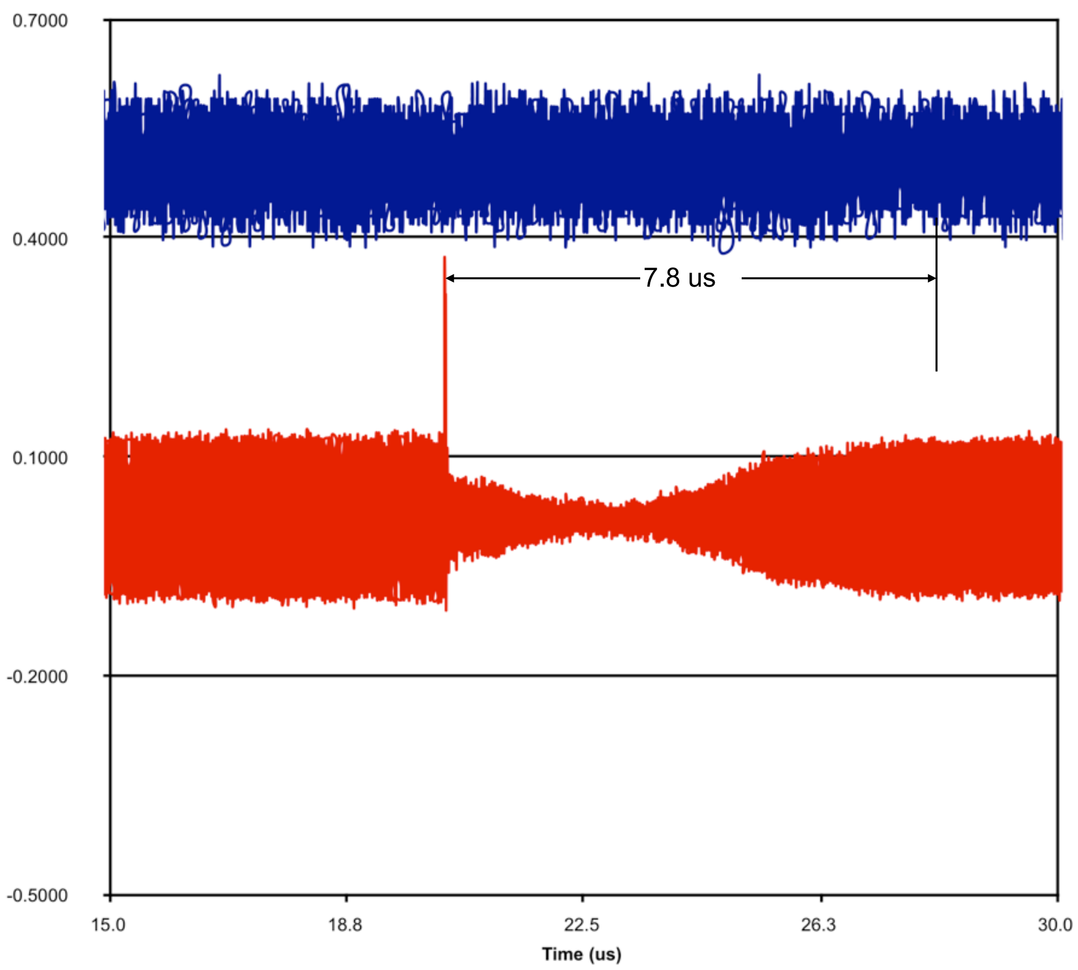
Trips from Transients

- Irregularities in the cavity probe signals initially a significant source of rf trips.
  - drop in probe signal *not* due to arc, causes large increase in klystron power to compensate
  - this leads to reflected power in other cavities -> trip.
  - reduced by masking short drop-outs.



HER 12-6 Aborts

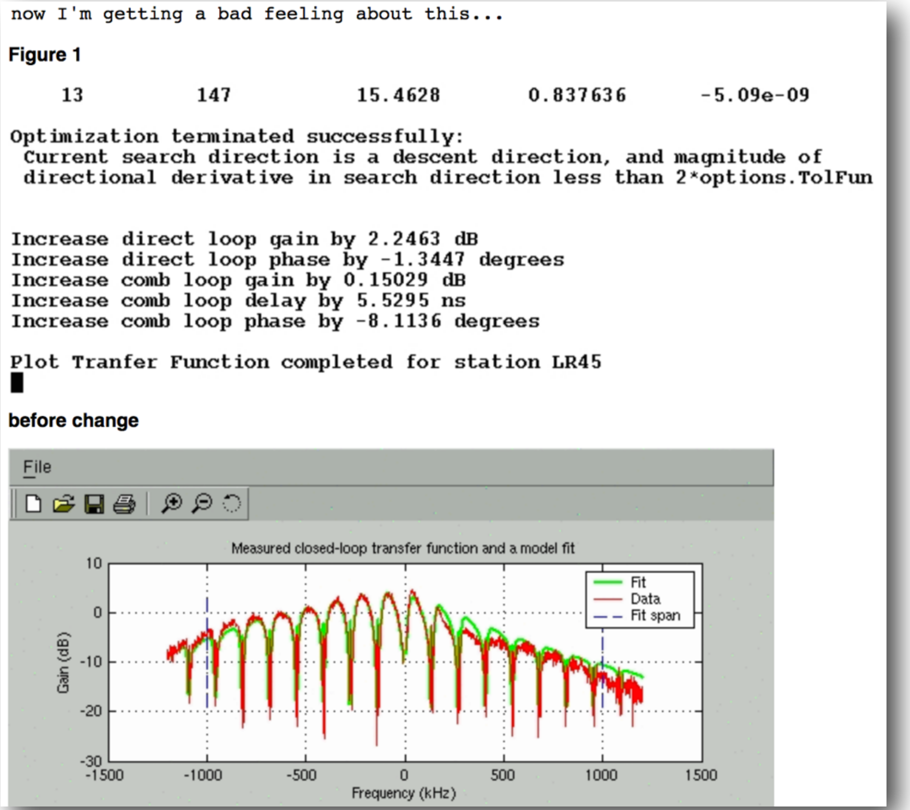
Probe signal masked in LLRF

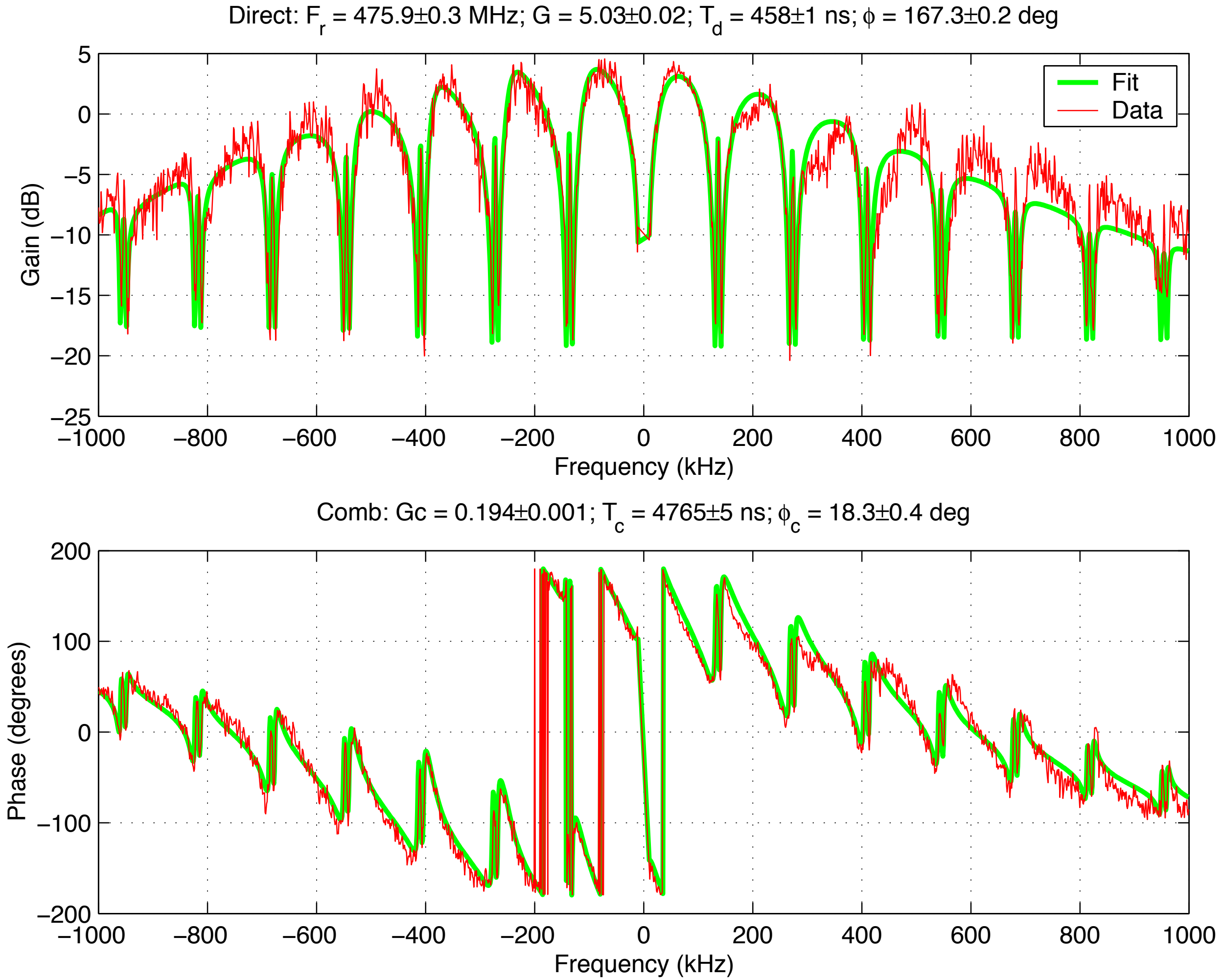


- Masked cavity A probe in the LLRF system on 7/22 to ignore such a fast change in signal.
- Station has not aborted on such a fault since.
- Signal is dropping out somewhere in the probe signal path and recovers within 10 μs – cavity probe, cable or coupler in LLRF rack.

Tuning of the LLRF System

- Online fit of linear model allows to optimize loop gains and phases:
  - iterative online procedure would setup loops





Modeling of the Rf Dynamic

- System modeled in MatLab/Simulink during PEP-II construction
  - Time-domain modeling code
  - Cavity model, klystron model including some nonlinearities, saturation

- Nowadays, *elegant* may be able to do similar modeling
  - rfmode element, beam-cavity interaction, feedback loops (direct & comb).
  - true multibunch modeling, parallelized version exists.
  - not presently in elegant: klystron model, saturation, gain variation

Some General Design Considerations

- Minimize the delays in the rf system (klystron, cabling, electronics)
  - can a fully digital system achieve minimal delay?
- Minimize the noise on the klystron output, phase-stabilize klystron
  - allows running closer to saturation
- Consider the effect of limited collector power on the output capability
- Gap transients will be a fact of life;
  - matching the transients of hadron and electron rings may be tricky
  - even if matched, large transients may limit achievable beam current
- Harden system against effects of transients
  - Redundant cavity probes may be important in reducing spurious trips.
  - Amplitude limiters (maybe with soft clipping)
  - Avoid overdriving mixers lest they produce phase rotations.

Conclusion

- Feed-back controlled rf worked, eventually worked well.
  - significant tuning effort
  - system remained sensitive to transient disturbances
- Optimal performance at PEP-II required
  - Suitable diagnostics in the LLRF system (network analyzer, fault-file history, modeling of beam-cavity interaction)
  - Operating the klystrons not too close to saturation (affects collector power)
  - Compensation of ps ripple for klystron amplifiers
  - Ability to ride through transients in the signals from the cavity
  - Detailed modeling in the design stage to anticipate performance
- Larger rings will be more challenging
  - detuning is stronger (relative to revolution frequency)
  - synchrotron frequency is lower (sidebands closer together)

Credits

- Design and operation of the PEP-II rf systems was enabled by many:
- Design: M. Allen, H. Schwarz, R. Rimmer, M. Neubauer, P. Corredoura, R. Tighe
- Operation, improvements (esp. LLRF): P. Corredoura, D. Teytelman, C. Rivetta, D. van Winkle, P. McIntosh, J. Judkins & many others
- Longitudinal feedback: D. Teytelman, J. Fox, S. Prabhakar, H. Hindi et al.

- F. Pedersen (CERN) laid the foundation for the LLRF system during a sabbatical at SLAC in 1992. The essence of the system architecture was defined in SLAC-R-400, p. 192 ff (1992).
- Several of the ideas were pioneered by D. Boussard at CERN in the 70s and 80s.
- Apologies to all I forgot. It’s been more than 10 years ago…

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