A Prototype RF Comb Filter Feedback for the Fermilab Main Injector

Tim Berenc[#]

Fermilab LLRF Team: Brian Chase, Paul Joireman, Philip Varghese, Julien Branlard, Uros Mavric

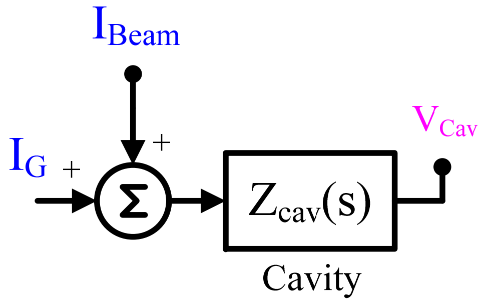
[#]work performed at Fermilab, presently at Argonne National Laboratory, APS

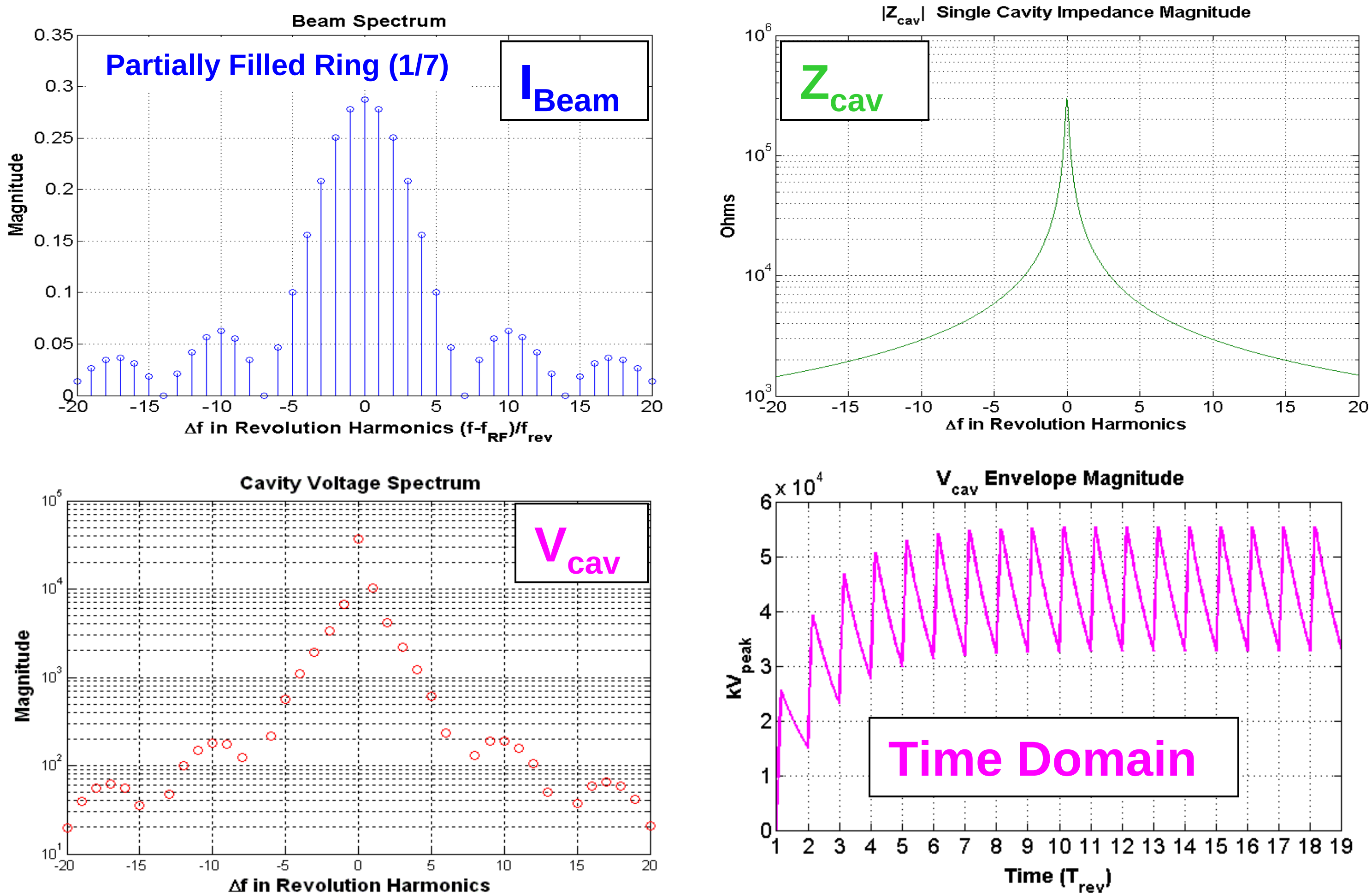
Fermilab Accelerator Complex

~Main Injector Evolution:

- 1999: MI ready for HEP, designed for 3E13 protons per cycle, conventional RF amp & phase control
- 2001: Direct RF FB development begins in preparation for slip-stacking
- 2003: Feed-Forward compensation added
- 2004-2005: Slip-stacking (S.S.) for pBar production becomes operational (~3.3E13 intensity)
  Solid State Driver upgrade, Mid-Level RF true Global amplitude and phase control added
- 2005-Present: Multi-batch slip-stacking development for Neutrino Program (design goal ~4.5 E13)
- 2007: MI record 4.6E13 accelerated to 120GeV, 4E13 delivered to NuMI during multi-batch S.S. studies
  Comb Filter Feedback development begins
- Future: 8E13 to 1.4E14

The Basics:

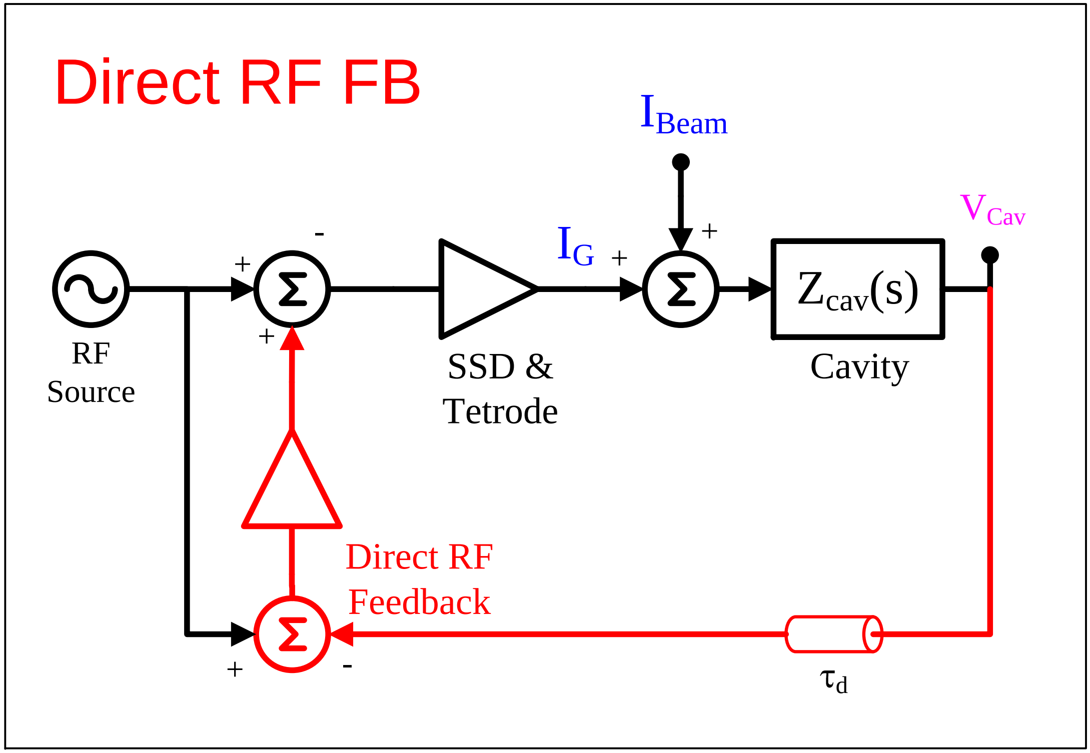

I_Beam
I_G
+
+
Σ
Z_cav(s)
V_Cav
Cavity


Beam Spectrum
Partially Filled Ring (1/7)
I_Beam
Magnitude
Δf in Revolution Harmonics (f-f_RF)/f_rev
|Z_cav| Single Cavity Impedance Magnitude
Z_cav
Ohms
Δf in Revolution Harmonics
Cavity Voltage Spectrum
V_cav
Magnitude
Δf in Revolution Harmonics
V_cav Envelope Magnitude
x 10^4
kV_peak
Time Domain
Time (T_rev)

Add Direct Feedback:

Offers Disturbance Rejection:

$$Z_{eff}(s) = \frac{Z(s)}{1 + e^{-s\tau_d} \dfrac{\beta}{R_s} e^{j\phi_{offset}} \cdot Z(s)}$$



Unavoidable delay:

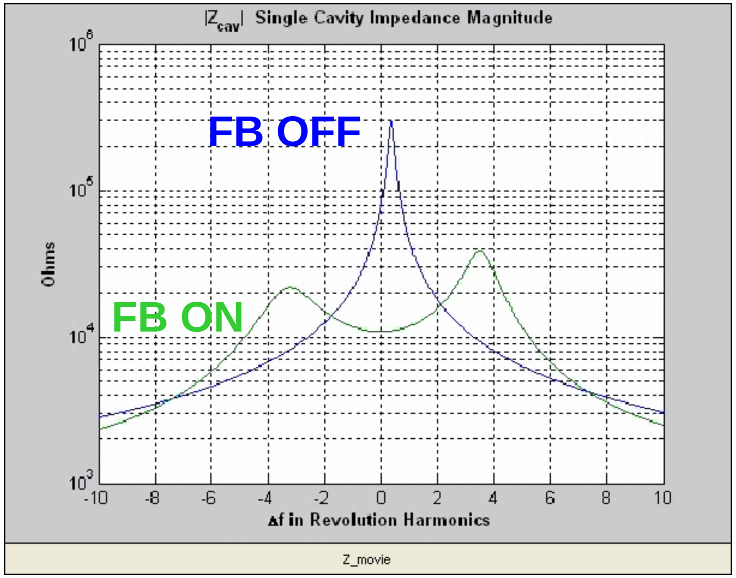
- limits gain (stability)

Loop Gain for 45deg phase margin:

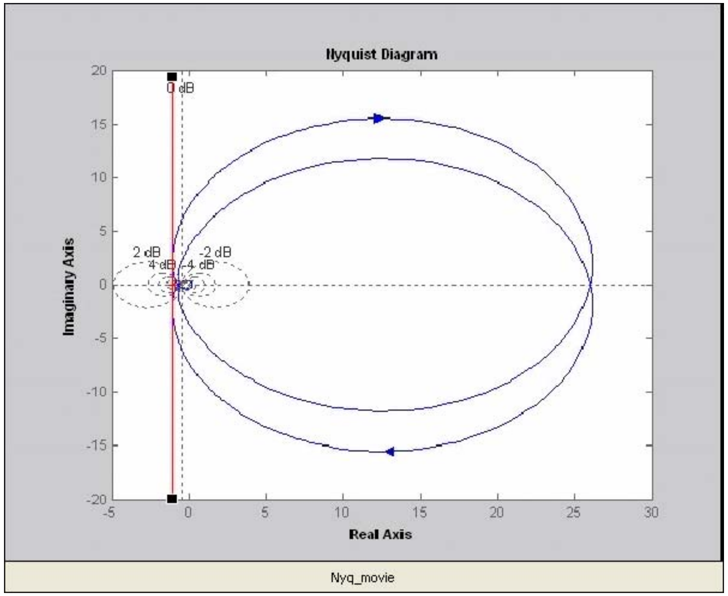
$$\beta_{\max} \approx \frac{1}{4}\frac{Q}{f_o\,\tau_{FBdelay}}$$

- increases impedance away from fundamental

Effective Impedance

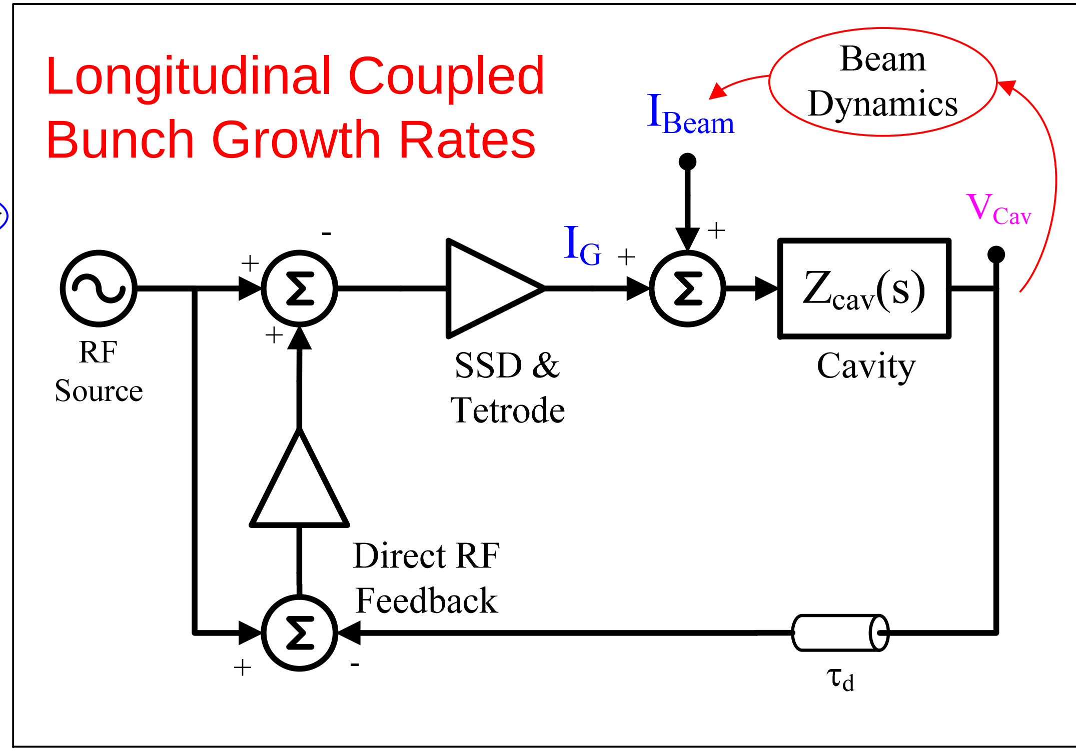


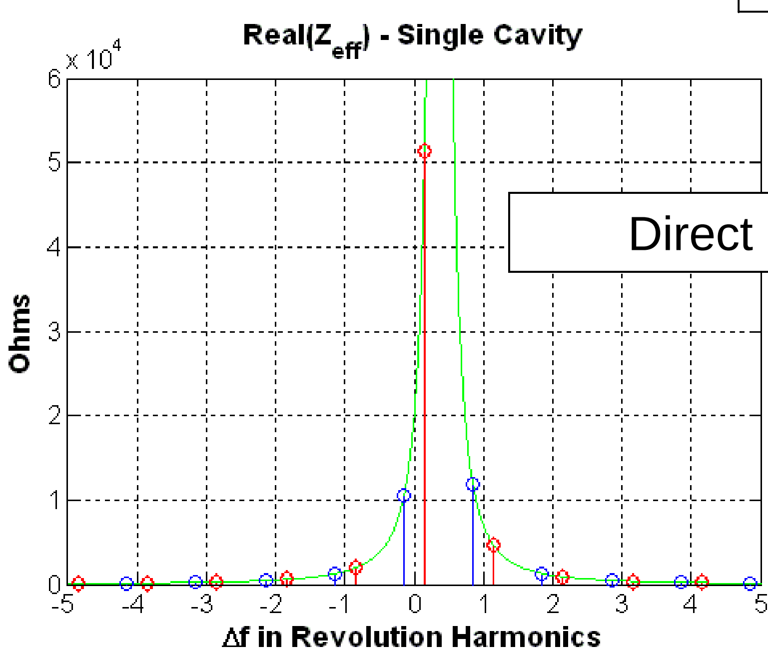
Nyquist Plot (Stability)



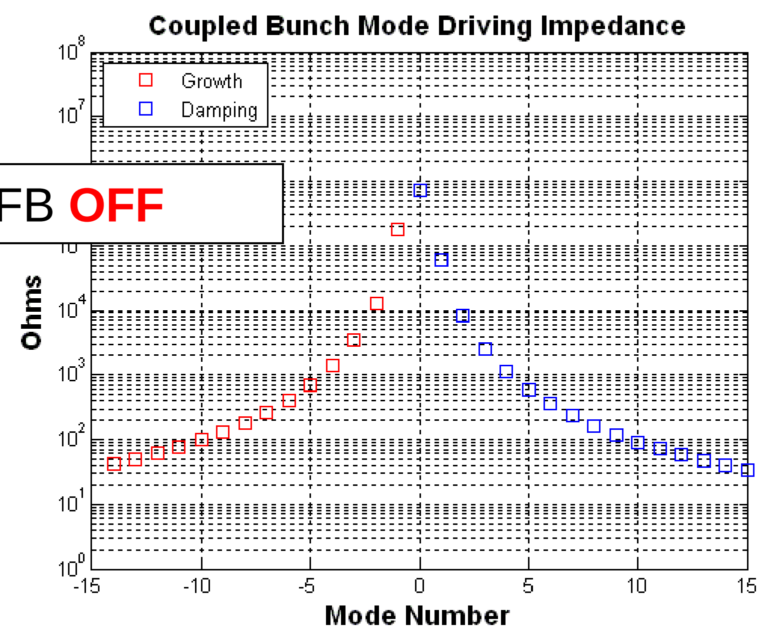
Growth Rate of dipole mode with coupled bunch mode number **n**:

$$\propto \eta_{slip} \cdot \mathrm{Re}\{\underbrace{Z_{eff}(f_{RF}+n\,f_{rev}+f_s)}_{Z_{eff}^{upper}} - \underbrace{Z_{eff}(f_{RF}-n\,f_{rev}-f_s)}_{Z_{eff}^{lower}}\}$$





Direct RF FB **OFF**



Growth Rate of dipole mode with coupled bunch mode number **n**:

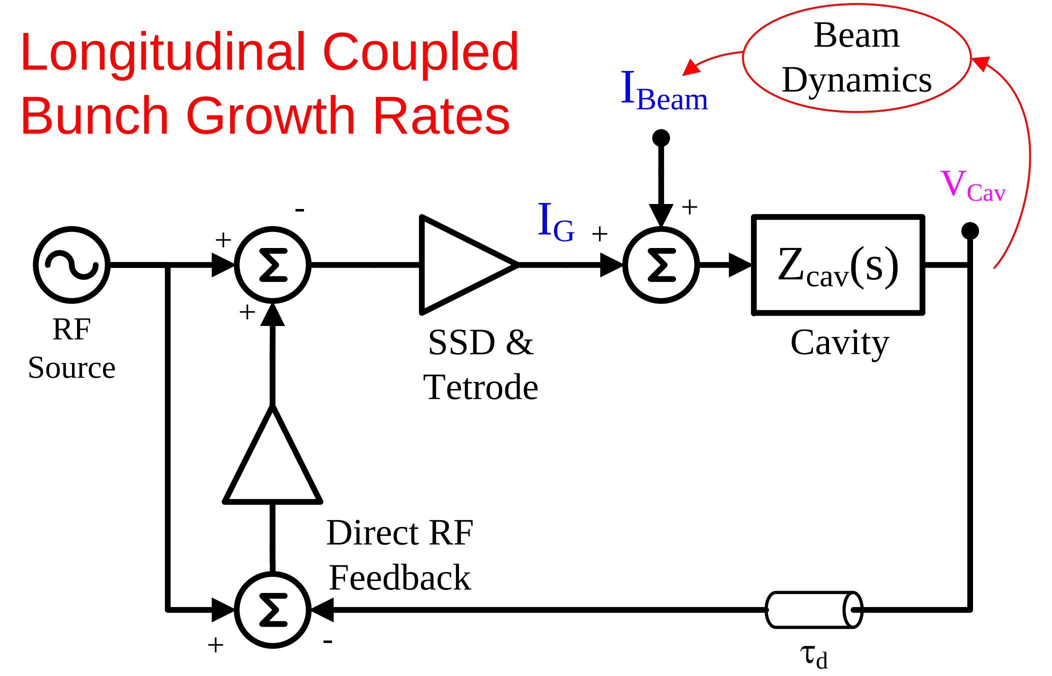
$$\propto \eta_{slip} \cdot \mathrm{Re}\{Z_{eff}(f_{RF} + n f_{rev} + f_s) - Z_{eff}(f_{RF} - n f_{rev} - f_s)\}$$

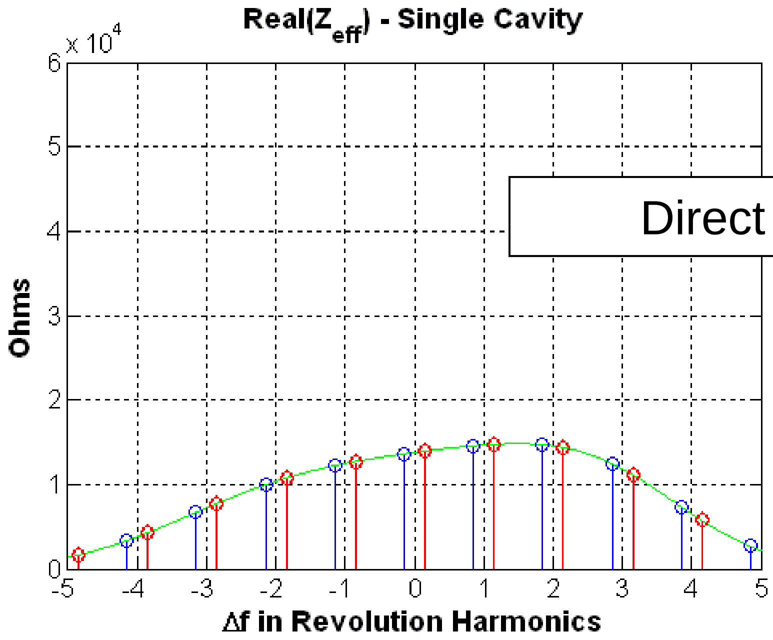
$$Z_{eff}^{upper} \qquad Z_{eff}^{lower}$$

Function of:

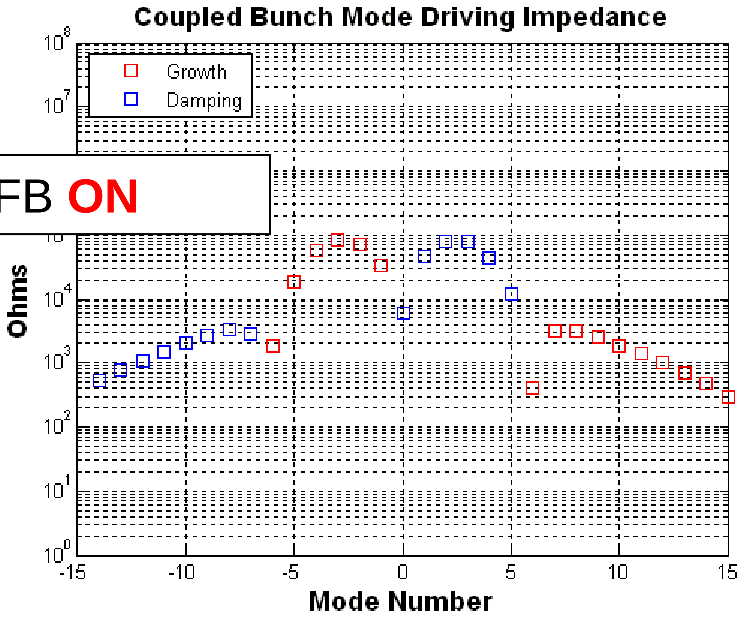
- FB Gain
- Cavity Detuning
- Synchrotron Tune ($Q_s = f_s / f_{rev}$)
- Fill Pattern

Longitudinal Coupled Bunch Growth Rates





Direct RF FB **ON**



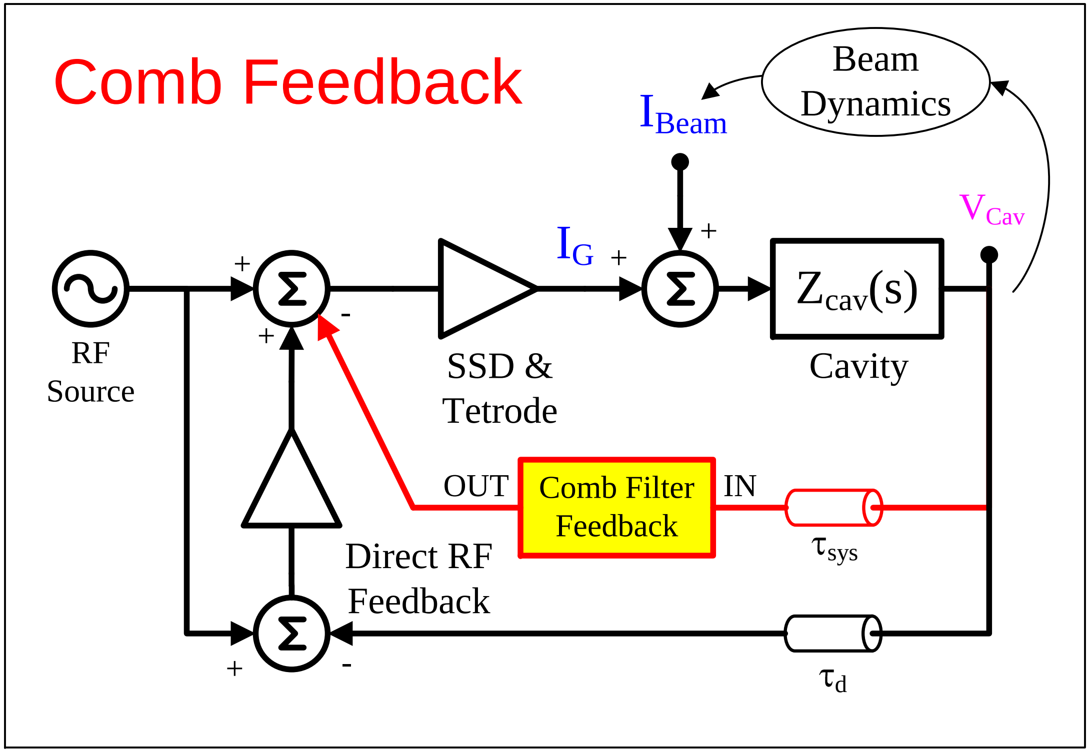
Single Peak Comb Filter Feedback:

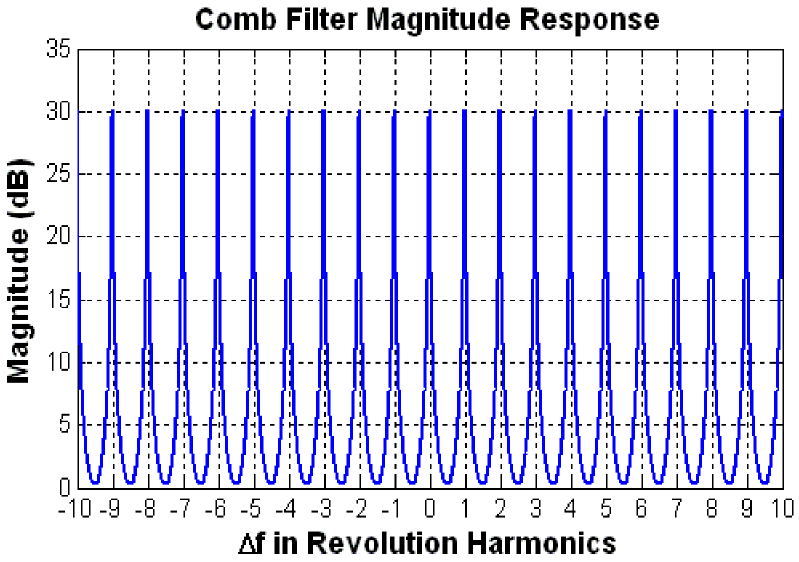
$$H(s) = \frac{G}{1 - K e^{-sT_{rev}}} \cdot e^{-sT_{rev}}$$

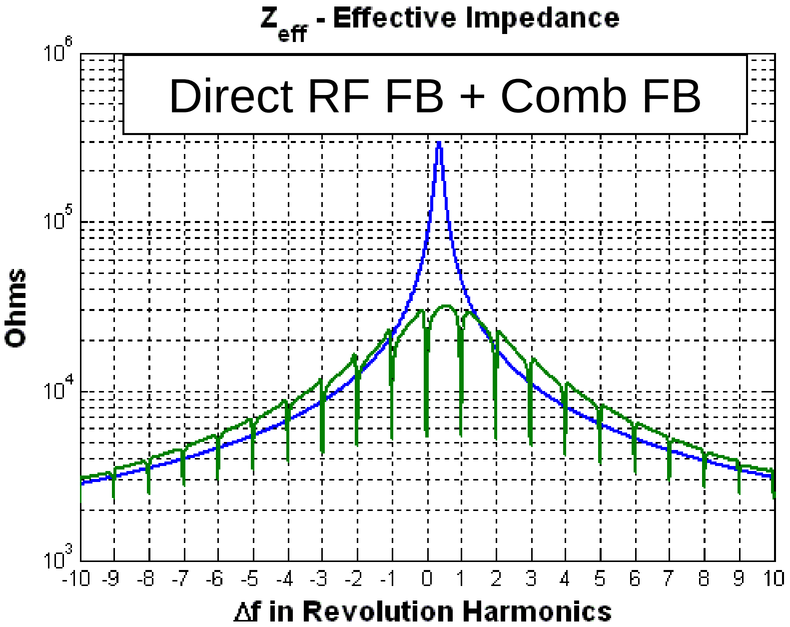
- Pioneered by Boussard (CERN)
- Provides loop gain at revolution harmonics
  - Reduces periodic beam loading
  - For low Q_s reduces growth rates
- Total Delay ~ 1 turn for loop stability

$$e^{-j2\pi f T_{rev}} = 1 \;\forall\; f : f = m \cdot f_{rev}$$

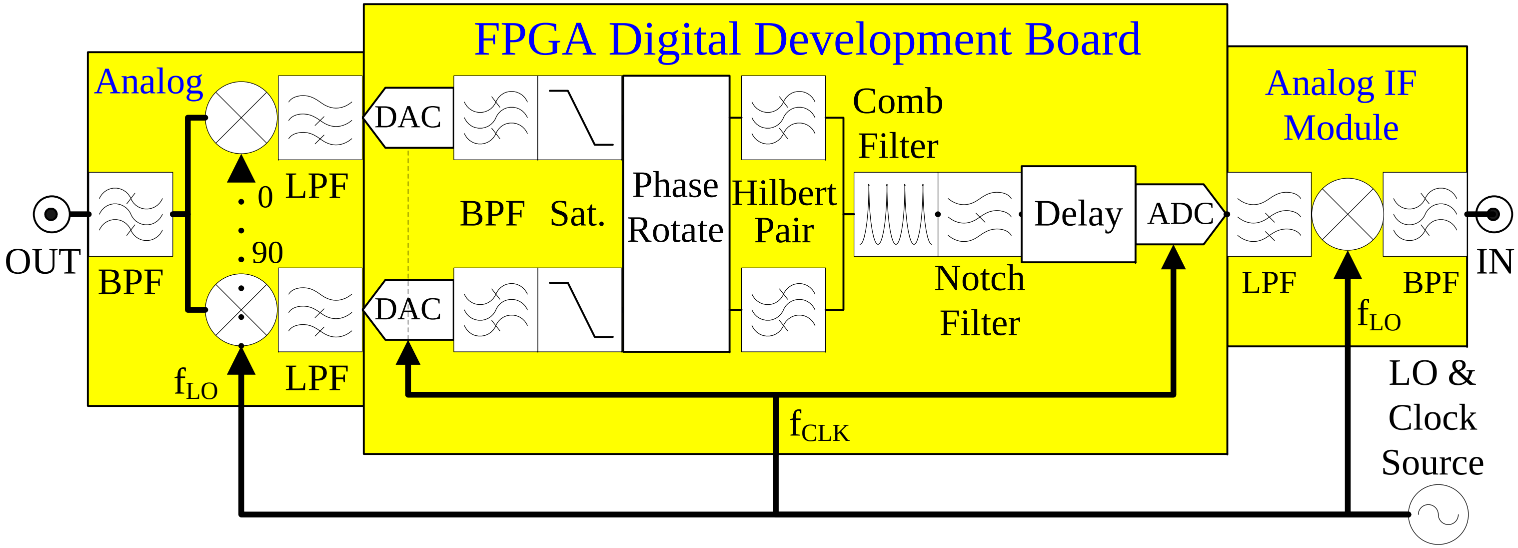
~ 180° feedback at rev harmonics





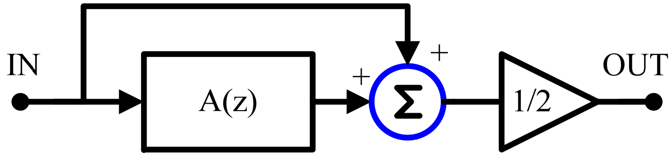


Comb Filter Architecture

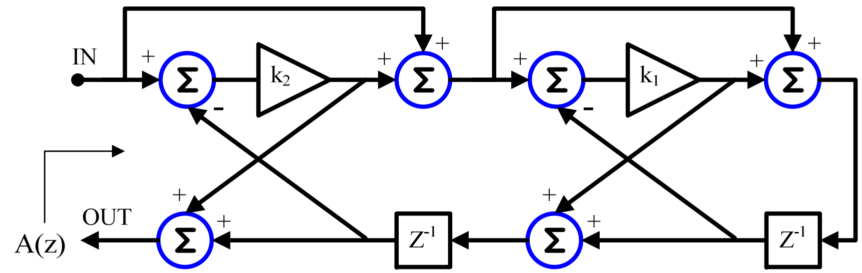


- IF Processing
  - Requires 2x the bandwidth as baseband processing, but only 1 ADC
  - Eliminates need for quadrature down-conversion
  - Allows for asymmetric filtering (upper/lower sidebands don't overlap as in baseband)
- Delay: to realize near 1 turn delay
- Notch Filter: eliminates fundamental
  - Minimizes impact on existing fundamental loop (Direct RF)
  - No need to generate a reference signal (difficult in swept RF system)
- Single Peak Comb Filter:
  - Fermilab MI max Q_s=~0.01, thus offers reduction of beam loading & growth rates
- Hilbert Pair (Quadrature Splitter):
  - Allows Phase Rotation
  - Provides quadrature output signals for single sideband up-conversion

Notch Filter Detail



$$N(z) = \frac{1}{2}\left[1 + A(z)\right]$$



[Ref]: Regalia et al., "**The Digital All-Pass Filter: A Versatile Signal Processing Building Block**" Proceedings of the IEEE, Vol. 76, No.1, Jan. 1988.

$$A(z) = \frac{k_2 + k_1(1+k_2)z^{-1} + z^{-2}}{1 + k_1(1+k_2)z^{-1} + k_2 z^{-2}}$$

$$k_1 = -\cos\left(2\pi \frac{f_{notch}}{f_{CLK}}\right)$$ Controls Notch frequency

$$k_2 = \frac{1 - \tan\left(\pi \frac{BW_{notch}}{f_{CLK}}\right)}{1 + \tan\left(\pi \frac{BW_{notch}}{f_{CLK}}\right)}$$ Controls Bandwidth

- natural choice in binary:

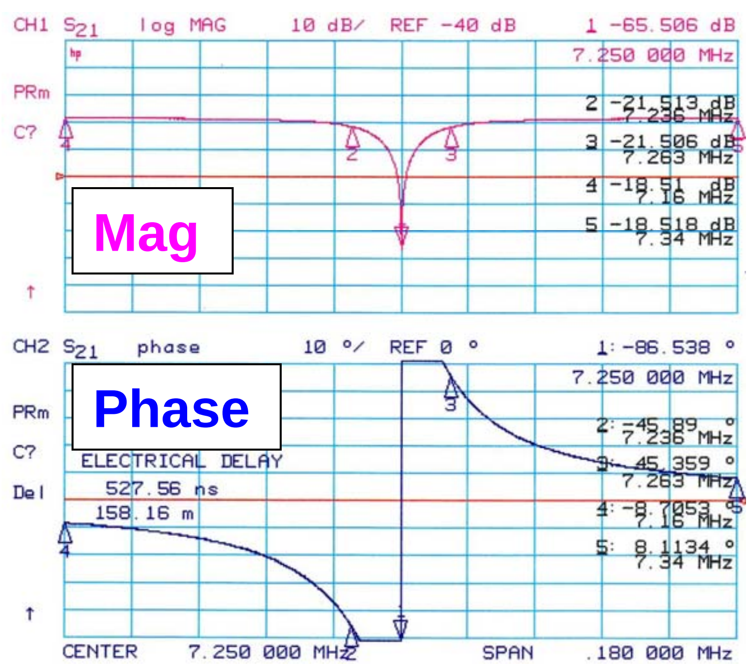
$$k_1 = -1/2 \;\Rightarrow\; f_{notch} / f_{CLK} = 1/6$$

Note: $f_{notch} = f_{IF}$

- Choose k_2 to minimize phase at 1st revolution harmonics:

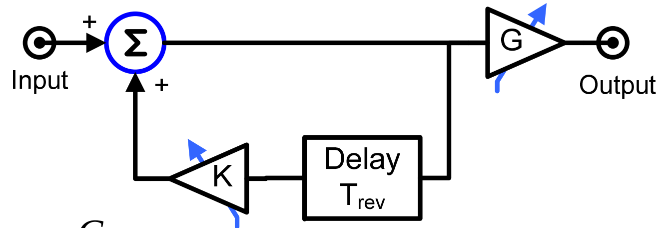
$$k_2 = 255/256$$

- be sure to understand internal node word lengths needed



$f_{IF}-f_{rev}$ $f_{notch}=f_{RF}-f_{LO}$ $f_{IF}+f_{rev}$

Comb Filter Detail



$$H(z) = \frac{G}{1 - K z^{-\frac{f_{CLK}}{f_{rev}}}}$$

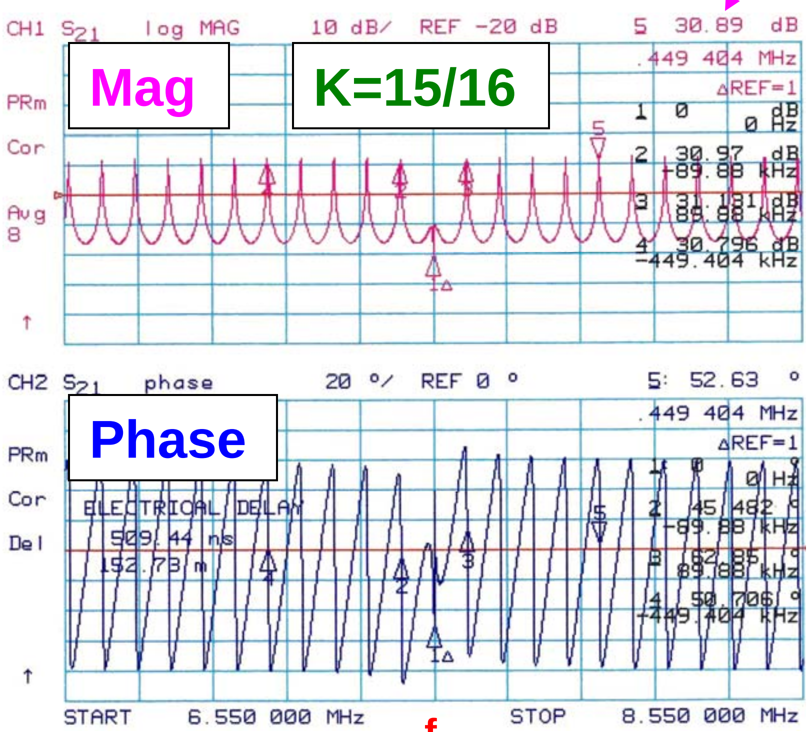
want an integer delay: $f_{CLK} = P \cdot f_{rev}$

- MI harmonic number : h=588 $f_{RF} = h\, f_{rev}$
- From Notch k_1 : $f_{CLK} = 6\ f_{IF} = 6\left[f_{RF} - f_{LO}\right]$
- Solution : $f_{CLK} = f_{LO} = \frac{6}{7} f_{RF} = 504\ f_{rev}$

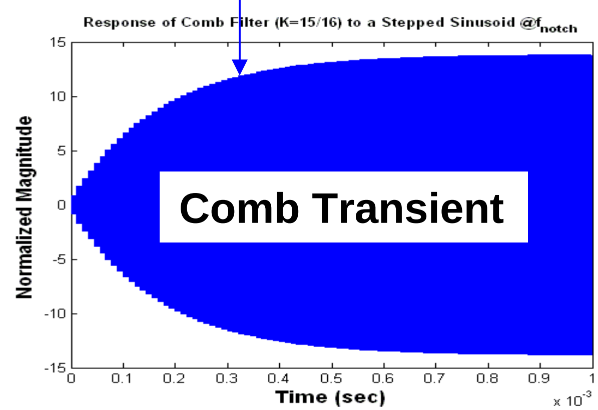
!! fortunately h=588 (multiple of 7) !!

Comb K - controls peak to valley ratio **AND** response time

Notch + Comb Freq. Response

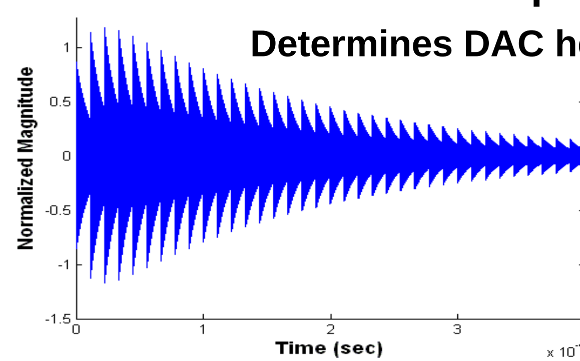


f_{IF}



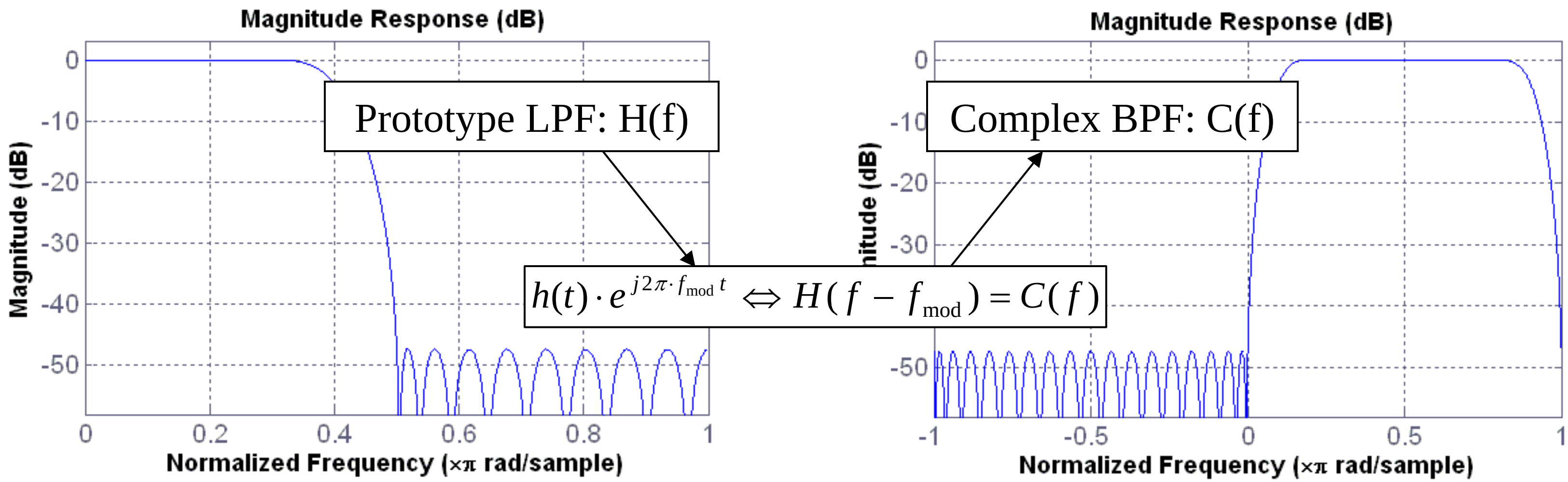
Notch + Comb Transient Response

Determines DAC headroom

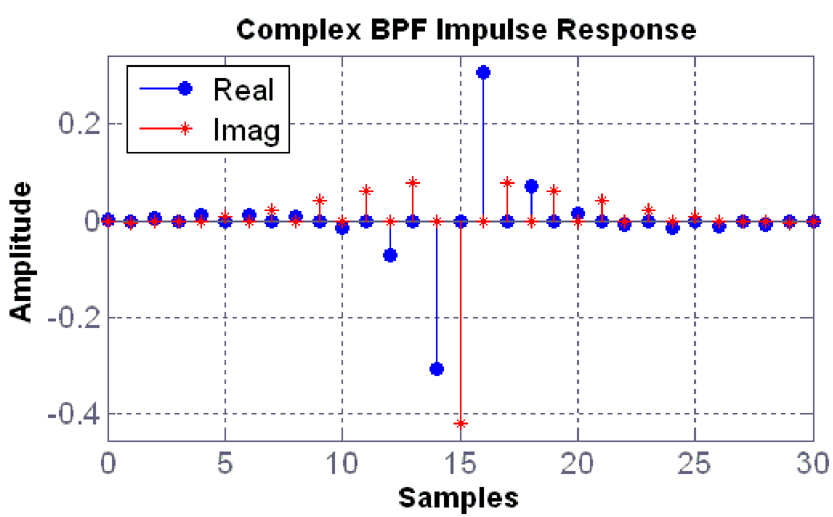


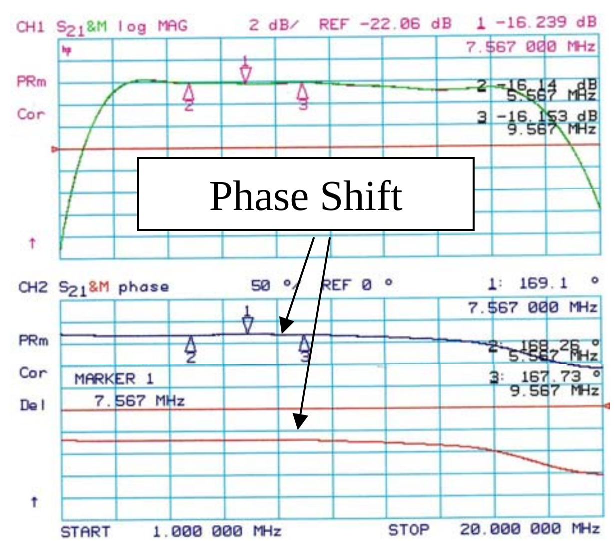
Hilbert Pair (Digital Quadrature Splitter)

[Ref]: R. Lyons, "**Understanding Digital Signal Processing**"



Analytic signal: $x_a(t) = \cos(\omega_o t) + j\cdot\sin(\omega_o t) \Leftrightarrow \delta(\omega - \omega_o)$ **Note: = 0 @ neg freq.**
If C(-f) = 0 for f in passband, the real and imaginary parts of C(f) are in quadrature. Thus one can form a **"quadrature splitter"** by taking the real and imaginary parts of C(f) as two separate filters.

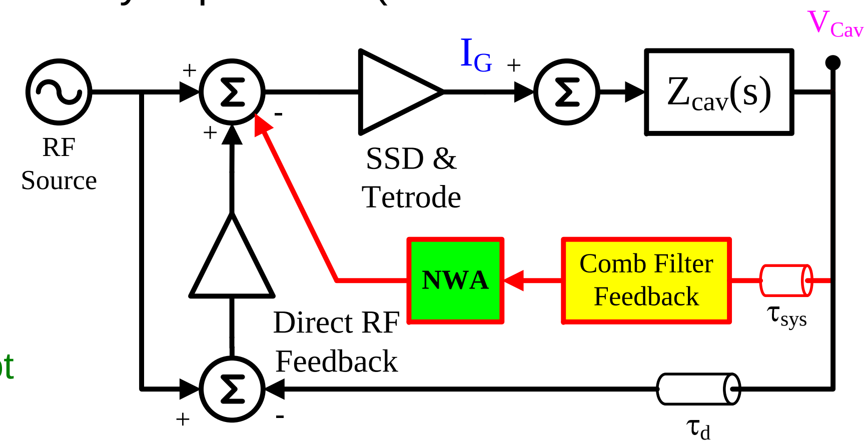


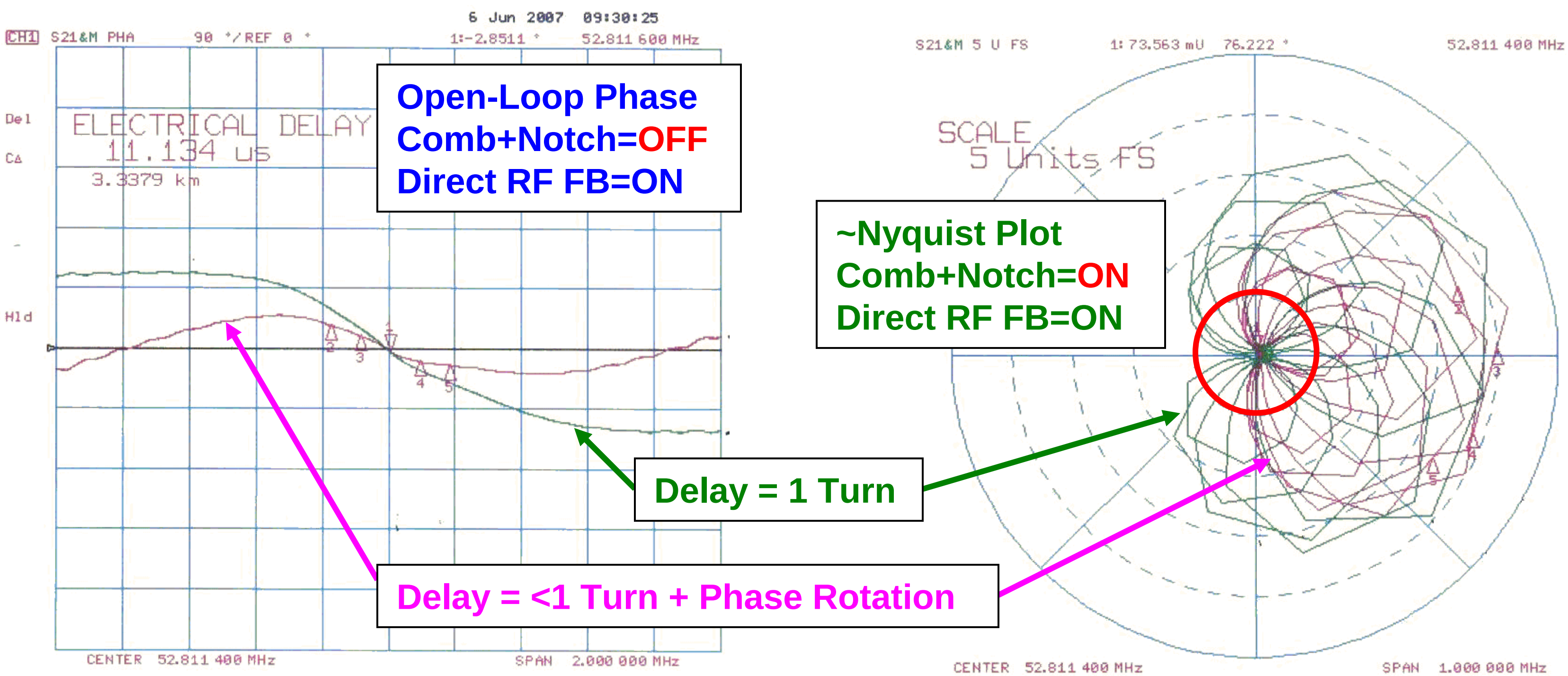


Simplified Phase Equalization = <1Turn Delay + Phase Rotation

- Phase (not group delay!) Equalization is important for comb loop stability
- Largest deviation from linear phase is from cavity impedance (as seen outside Direct RF FB)

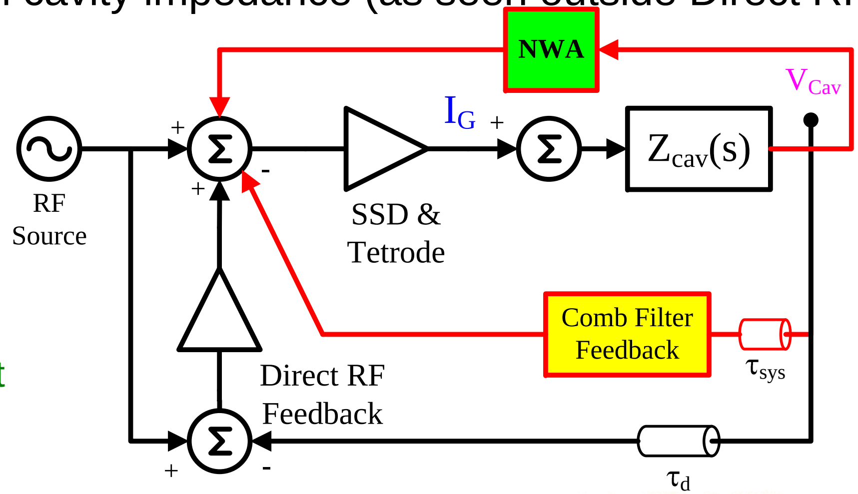
- Open Comb Loop & insert **NWA**
- Deactivate Notch & Comb
- Set NWA delay to T_{rev} and Phase Offset=180°
  - Thus 0deg becomes ref. for all rev. harmonics
- Adjust (1) Integer Delay & (2) Phase Offset to minimize phase across the loop bandwidth
- Turn On Notch & Comb – measure Nyquist Plot
- Measure Effective Impedance



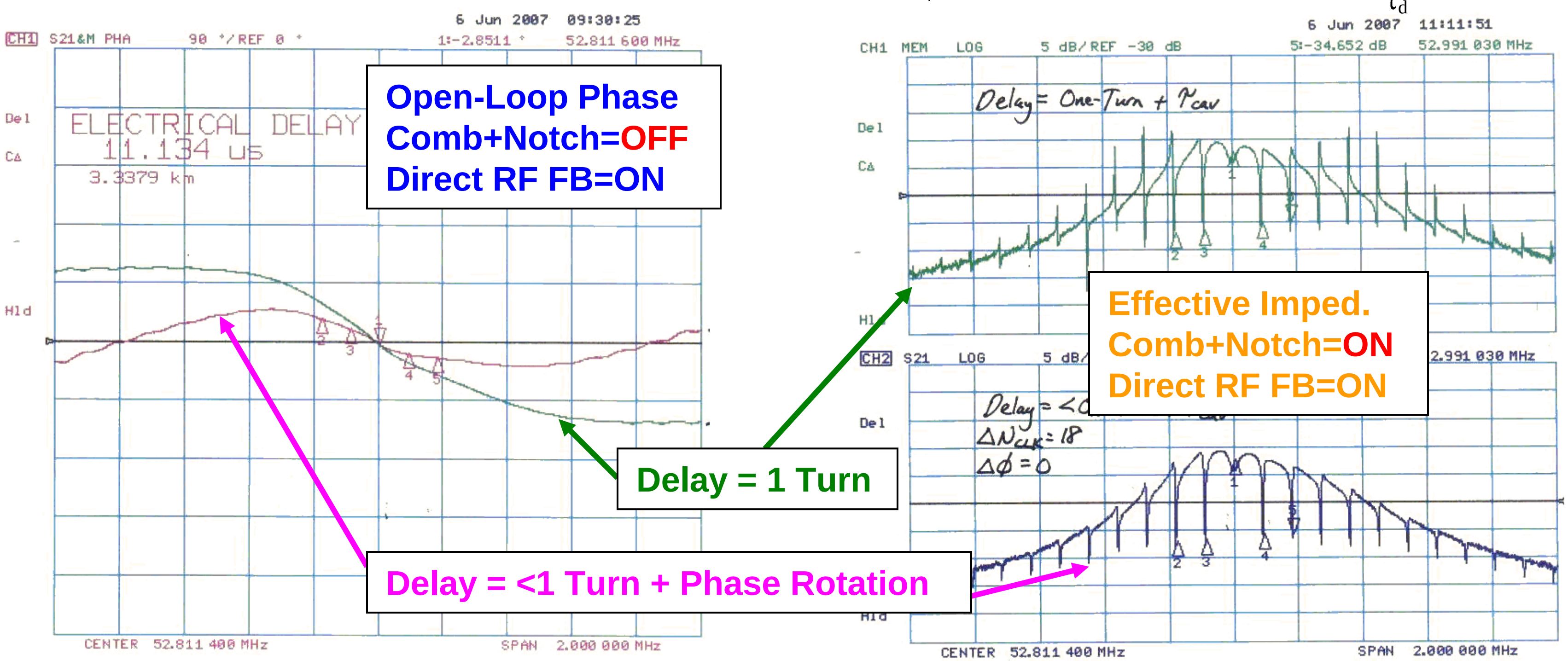


Simplified Phase Equalization = <1Turn Delay + Phase Rotation

- Phase (not group delay!) Equalization is important for comb loop stability
- Largest deviation from linear phase is from cavity impedance (as seen outside Direct RF FB)



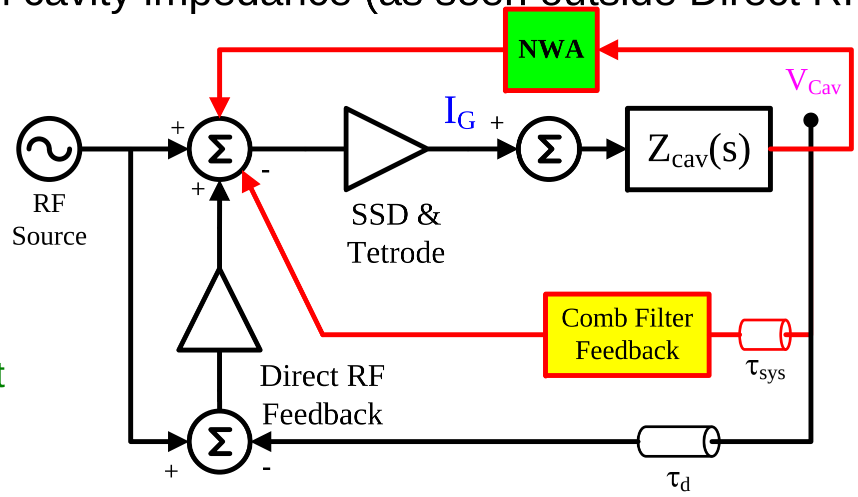
- Open Comb Loop & insert **NWA**
- Deactivate Notch & Comb
- Set NWA delay to T_{rev} and Phase Offset=180°
  - Thus 0deg becomes ref. for all rev. harmonics
- Adjust (1) Integer Delay & (2) Phase Offset to minimize phase across the loop bandwidth
- Turn On Notch & Comb – measure Nyquist Plot
- Measure Effective Impedance

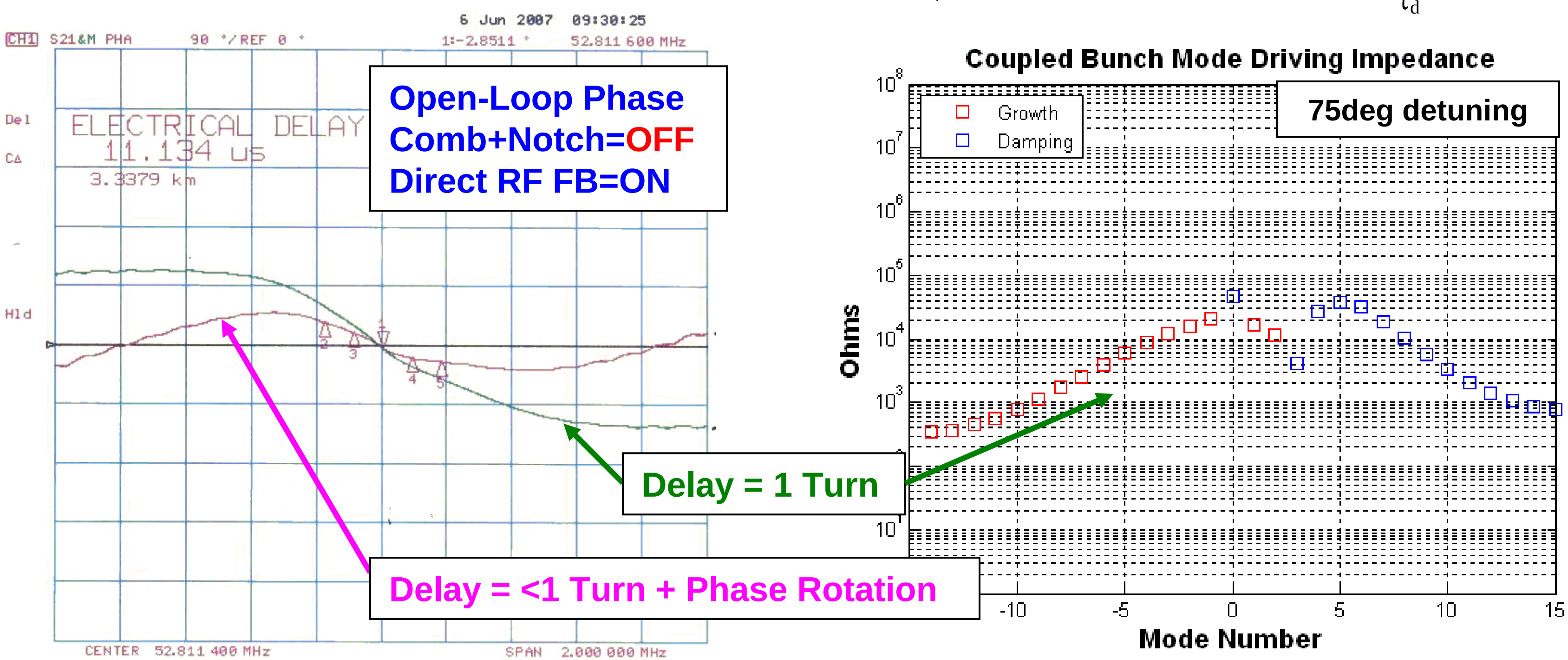


Simplified Phase Equalization = <1Turn Delay + Phase Rotation

- Phase (not group delay!) Equalization is important for comb loop stability
- Largest deviation from linear phase is from cavity impedance (as seen outside Direct RF FB)

- Open Comb Loop & insert **NWA**
- Deactivate Notch & Comb
- Set NWA delay to T_{rev} and Phase Offset=180°
  - Thus 0deg becomes ref. for all rev. harmonics
- Adjust (1) Integer Delay & (2) Phase Offset to minimize phase across the loop bandwidth
- Turn On Notch & Comb – measure Nyquist Plot
- Measure Effective Impedance

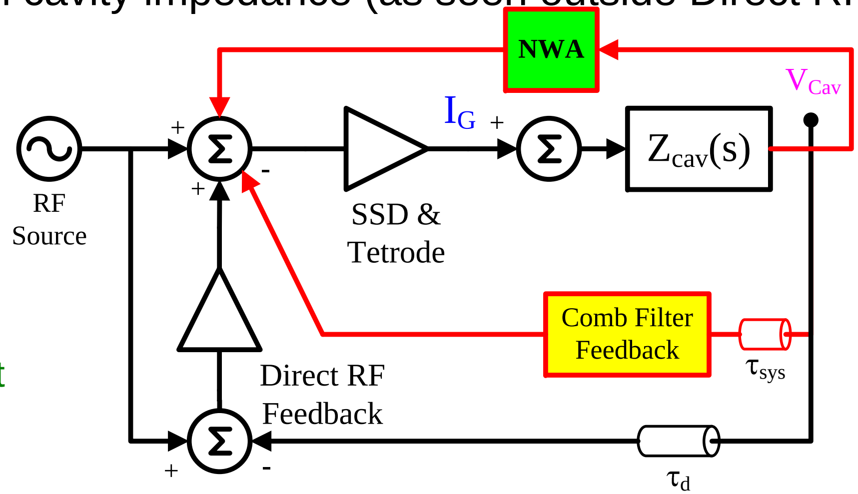


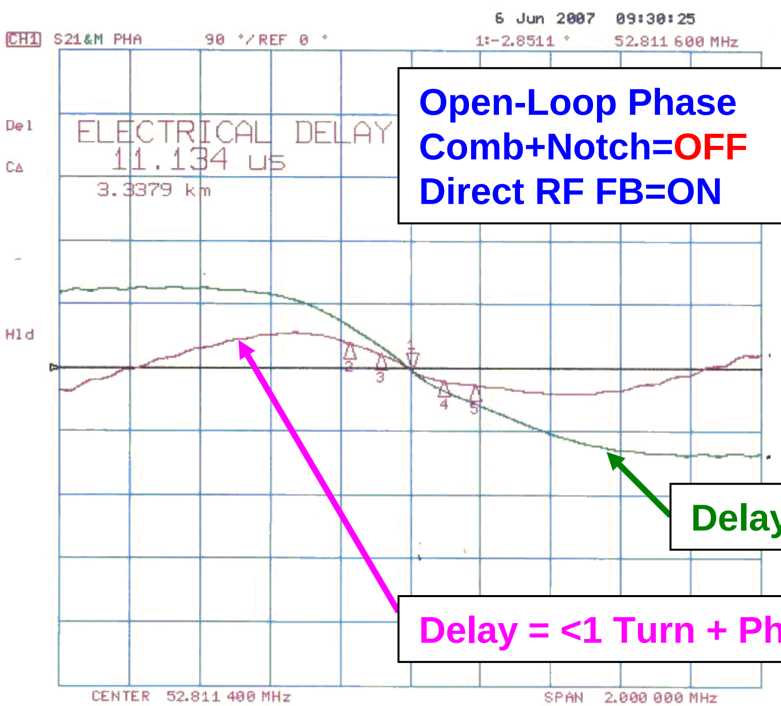


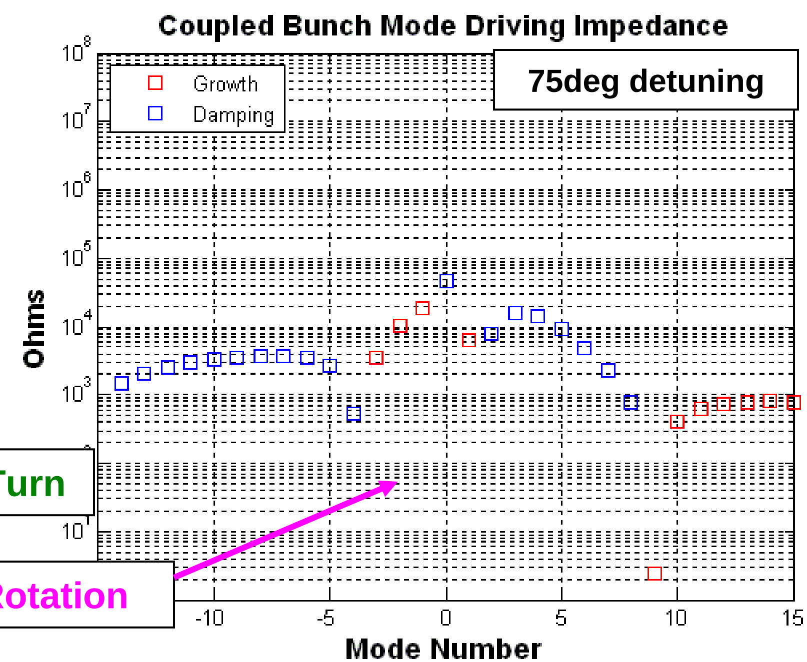
Simplified Phase Equalization = <1Turn Delay + Phase Rotation

- Phase (not group delay!) Equalization is important for comb loop stability
- Largest deviation from linear phase is from cavity impedance (as seen outside Direct RF FB)

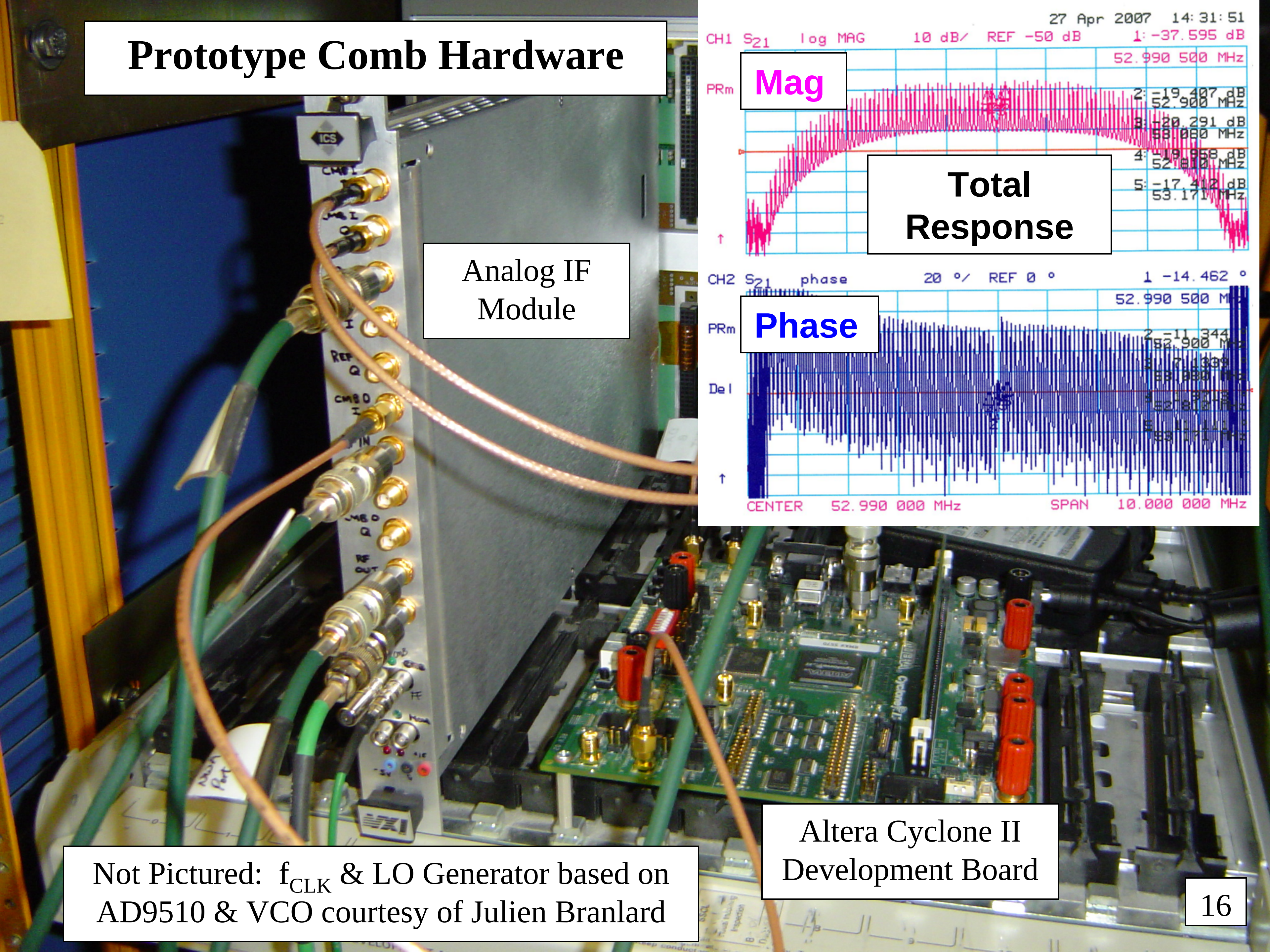
- Open Comb Loop & insert **NWA**
- Deactivate Notch & Comb
- Set NWA delay to T_{rev} and Phase Offset=180°
  - Thus 0deg becomes ref. for all rev. harmonics
- Adjust (1) Integer Delay & (2) Phase Offset to minimize phase across the loop bandwidth
- Turn On Notch & Comb – measure Nyquist Plot
- Measure Effective Impedance







Prototype Comb Hardware



Analog IF Module

Altera Cyclone II Development Board

Not Pictured: f_{CLK} & LO Generator based on AD9510 & VCO courtesy of Julien Branlard

Results With Beam – Single Station Test

Summary

- Comb Feedback
  - Complements (adds ~12dB) existing Feed-Forward beam loading compensation (total ~30dB)
  - Offers advantages of Feedback over Feed-Forward
  - Offers both longitudinal growth rate reduction due to low Q_s & periodic beam loading reduction
    - Growth rates still need to be measured with beam
- Combination of Comb+Notch & Direct RF FB for RF loop stability
  - Direct RF FB reduces impedance that comb loop sees and phase shifts due to cavity detuning
    - Fundamental reduction allows for higher comb loop gain since stability is determined by highest gain point
  - Notch Filter simplifies integration of comb FB into existing system & contributes to stability
  - Direct RF FB helps reduce impact of comb FB on RF turn-on transients
- Tips
  - Consult literature !
  - Understand HLRF system (i.e., system gain vs. parameter space, operating points) !
  - Use simulation tools ! (frequency & time domain, i.e., Matlab)
    - Freq. domain for impedance, stability, & growth rates (many different parameter configurations)
    - Time domain for understanding turn-on transients
- Future Work Needed
  - Phase rotation (equalizer) program for swept RF capability
  - Measure growth rates
  - Final design with LLRF designed FPGA board, interface, mass production

Acknowledgements

- Pioneers & Practitioners of Comb Feedback & their literature !
  - (CERN) Boussard, Lambert, Pedersen, Garoby, Blas, etc.
  - (SLAC) Corredoura, Sapozhnikov, Tighe, Teytelman, etc.
- Brian Chase (Fermilab) for design brain-storming sessions, guidance, and encouragement
- Fermilab LLRF team for LO & f_{CLK} generator, FPGA advice, and teamwork