Experimental Test of a Prototype System for Active Damping of the E-P Instability at the LANL PSR

C. Deibele

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Collaborators

- ORNL: S. Henderson (PI), S. Assadi, V. Danilov, C. Deibele, T. Hardek, M. Plum, C. Sibley
- LANL: R. Macek (PI), S. Breitzmann, D. Gilpatrick, R. McCrady, J. Power, L. Rybarcyk, T. Spickermann, T. Zaugg
- LBL: J. Byrd
- Indiana University: S.Y. Lee
- University of Wisconsin Madison: M. Schulte, S. Mamidi, A. Polisetti, Z. Xie

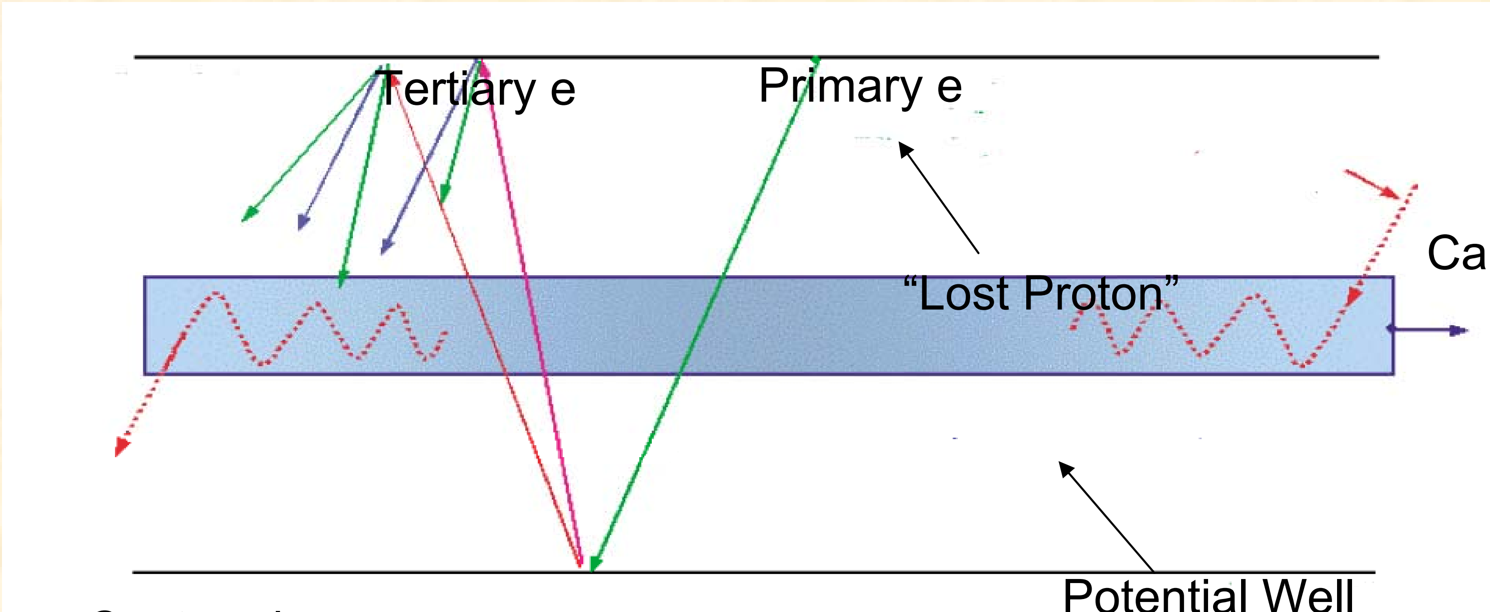
Additional References

- **MOPAS050 Active Damping of the e-p Instability at the LANL PSR - McCrady et. al.**
- **MOPAS080 A Digital Ring Transverse Feedback Low-Level RF Control System – Polisetti et. al.**

Background

- PSR (Proton Storage Ring) has a well-studied e-p instability. This instability is broadband – on the order of 100 MHz in bandwidth!
- The SNS and PSR rings are similar, so a study of PSR instability is important for the upgrade of SNS.
- Test was limited in bandwidth (50-250 MHz) and 7 uC/pulse to stay within the bandwidth of the power amplifiers.
- Deployed two used amplifiers from ENI 1-400 MHz, 100 Watt CW.
- Designed and built 4 LLRF chassis.
- We conducted a proof of principle experiment shows broadband feedback works for e-p instability in a long bunch machine.

Electron Cloud

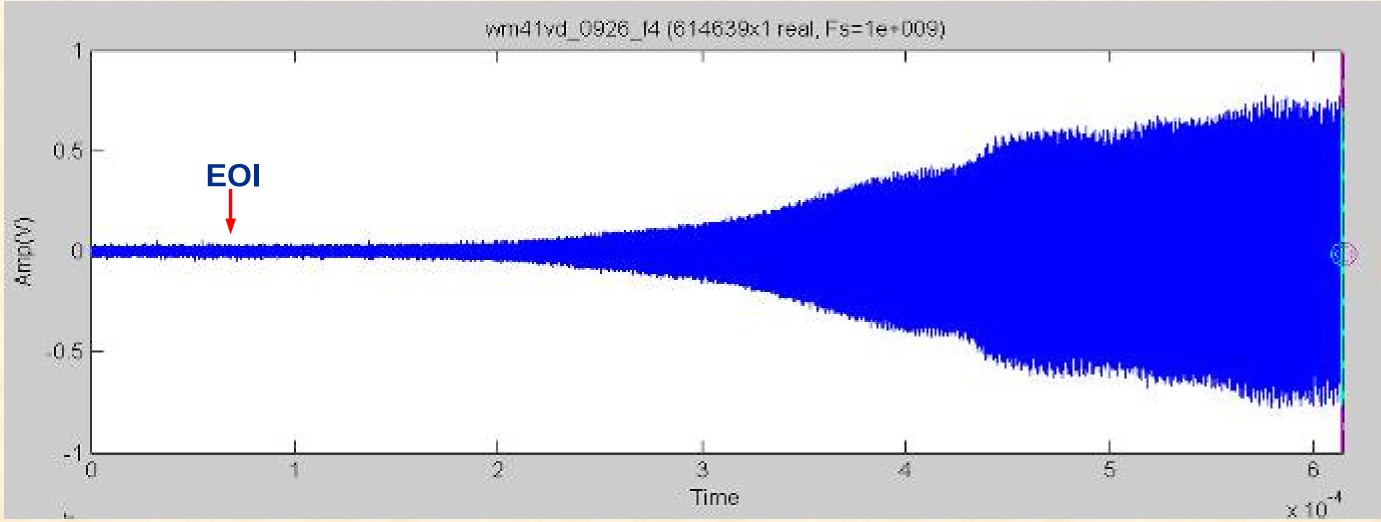


Cartoon By Pivi

- Captured e sits in potential well until bunch passes
- P losses cause primary e to be acc/dec by beam potential (net gain)
- Electrons survive the gap between beam passages -- net increase of electrons

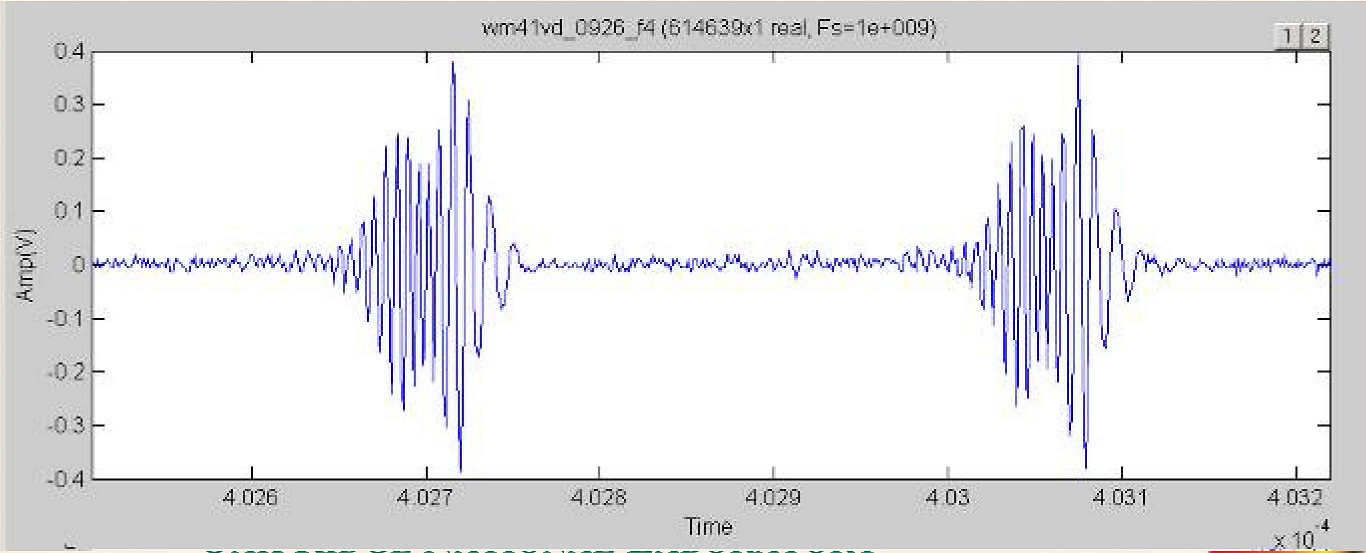
PSR Application
and
Physics Results

Vert. BPM Signal ~(yI)'



3 μC/pulse beam, 9/26/02

Expanded Signal (2 turns)



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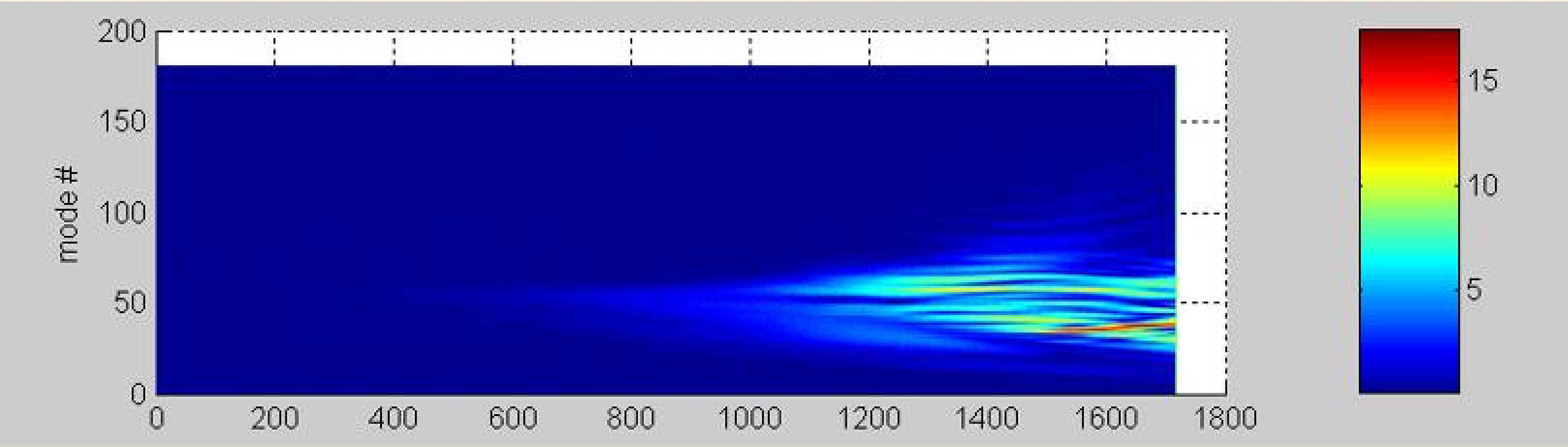
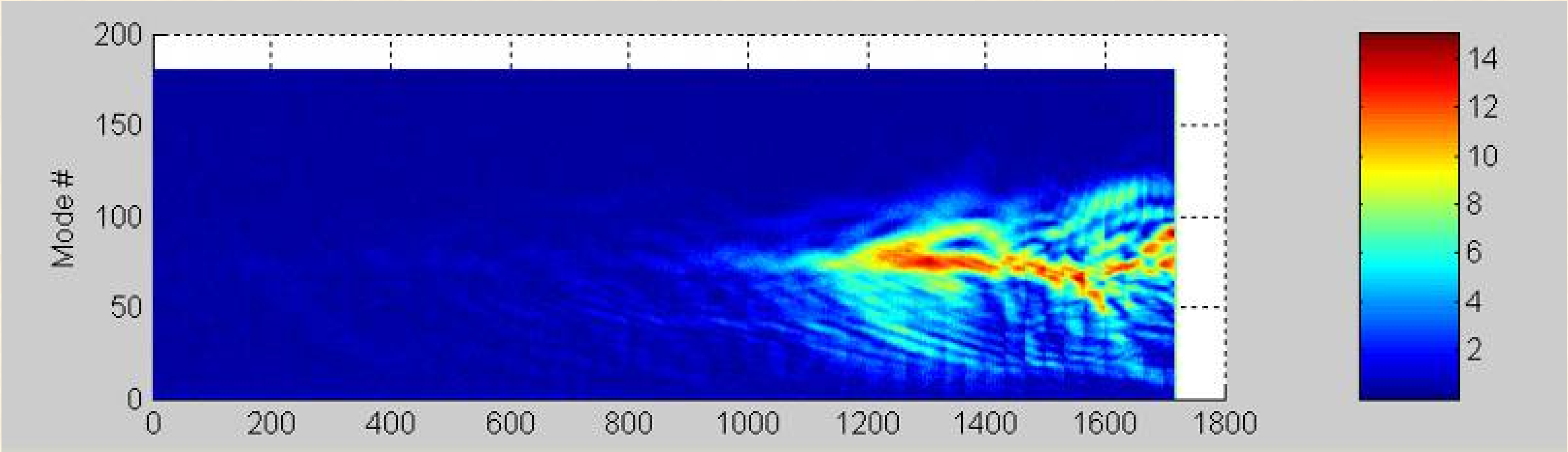
Frequency spectra vs Turn # for two intensities

3 μC/pulse



8 μC/pulse



Turn # →

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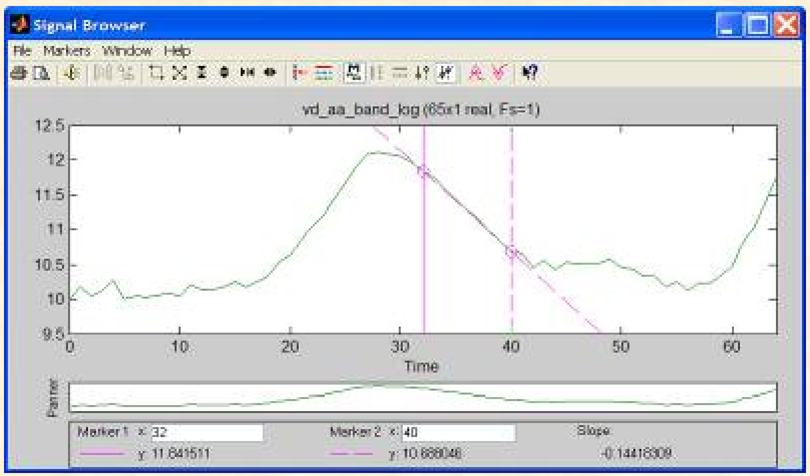
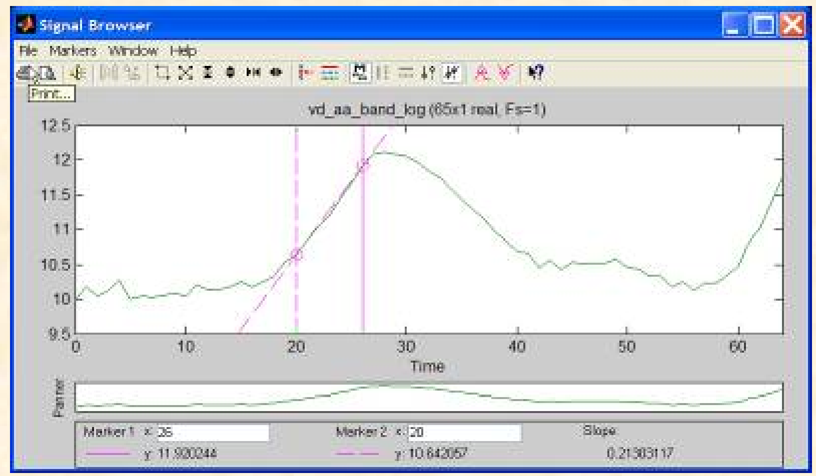
Grow/Damp with Comb Filter – 7 uC/pulse

Grow/Damp experiment not possible without comb filter





Damp rate=-0.01442 $usecs^{-1}$

Growth rate=0.0213 $usec^{-1}$

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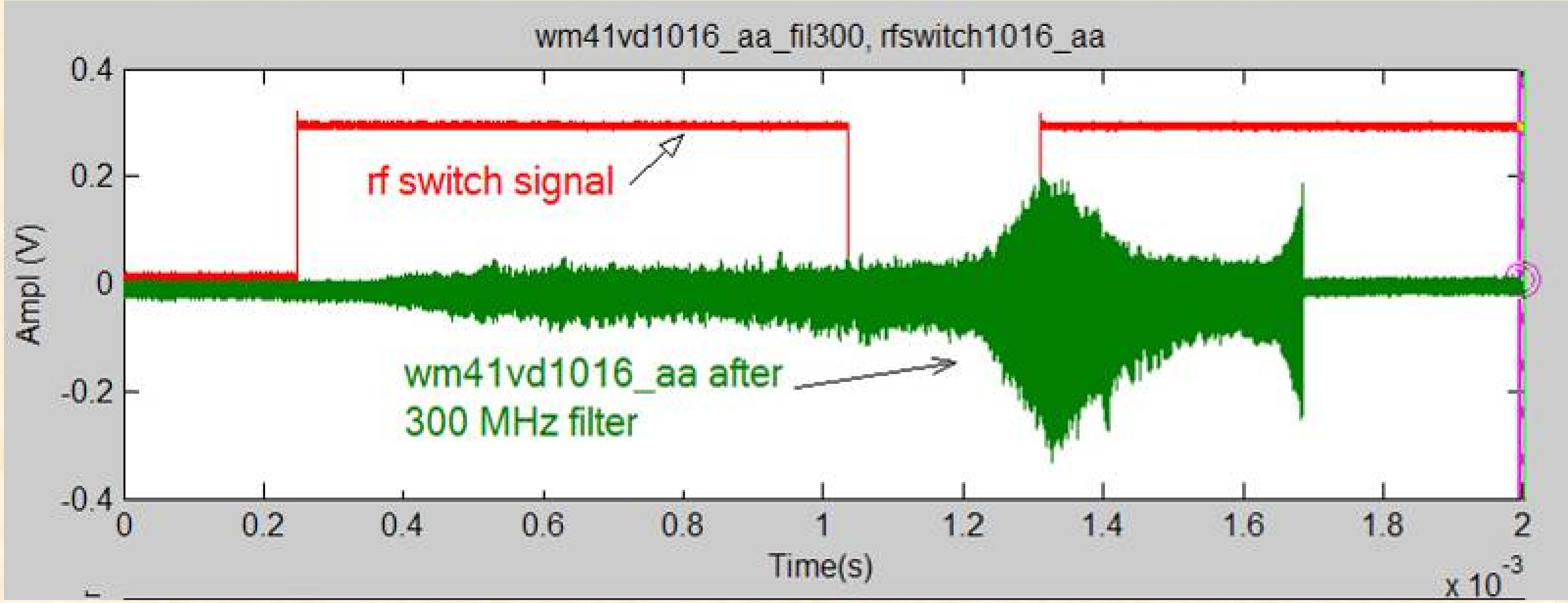
SNS SPALLATION NEUTRON SOURCE

- Data below taken during run with one 2-turn comb filter, buncher at 7203 V (part way between thresholds with damper on and off)
- Beam intensity 7.2 μC/pulse, stored for extra 400 μs.



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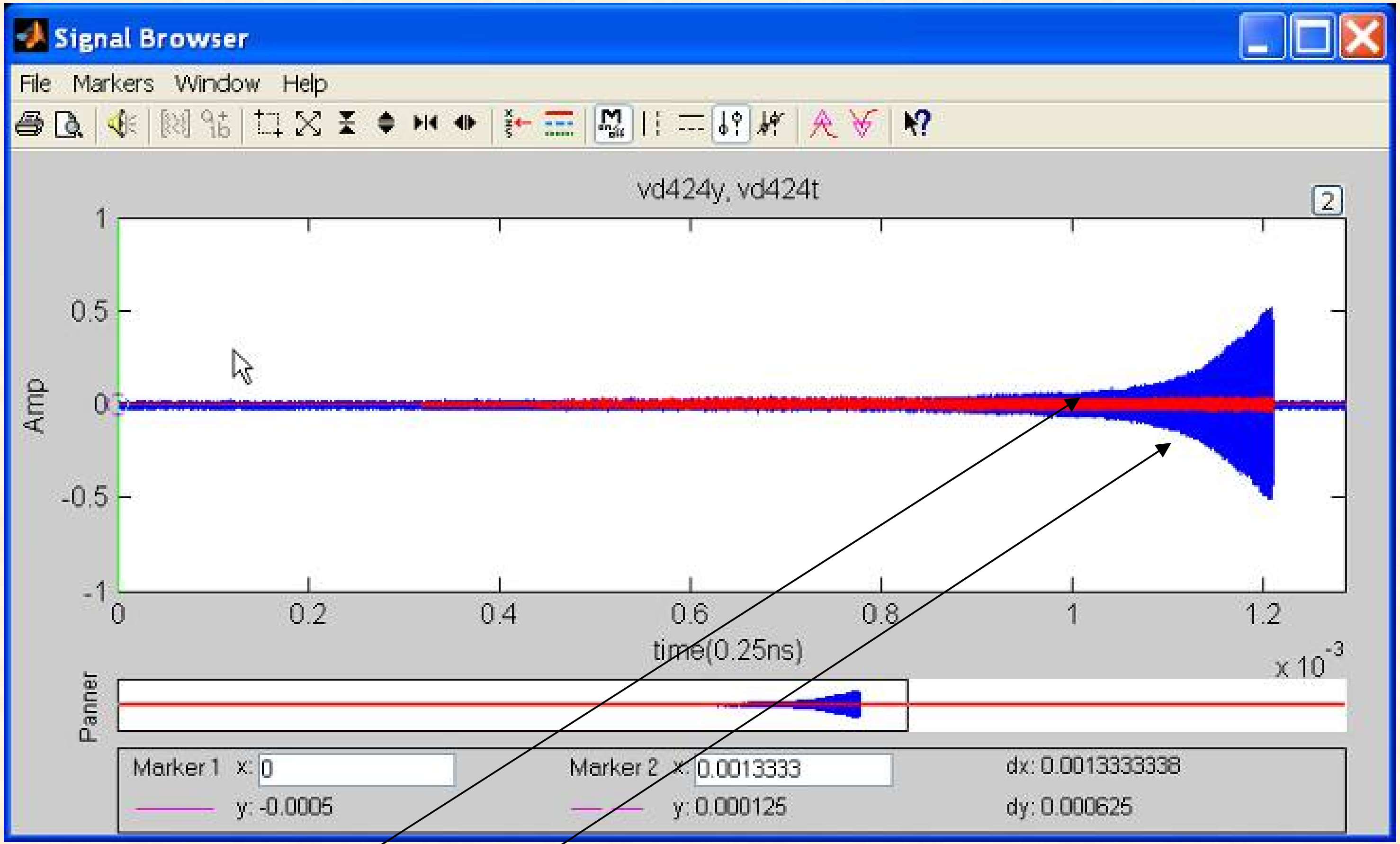
Vertical Difference



FB ON, FB OFF 3 μC/pulse, buncher 5.0 kV

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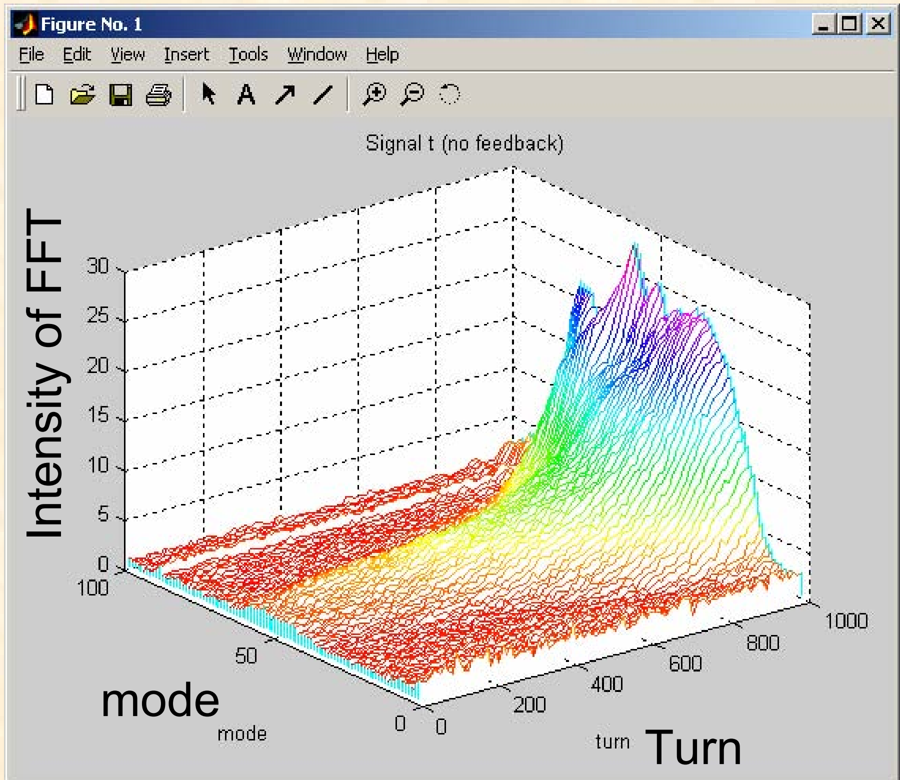
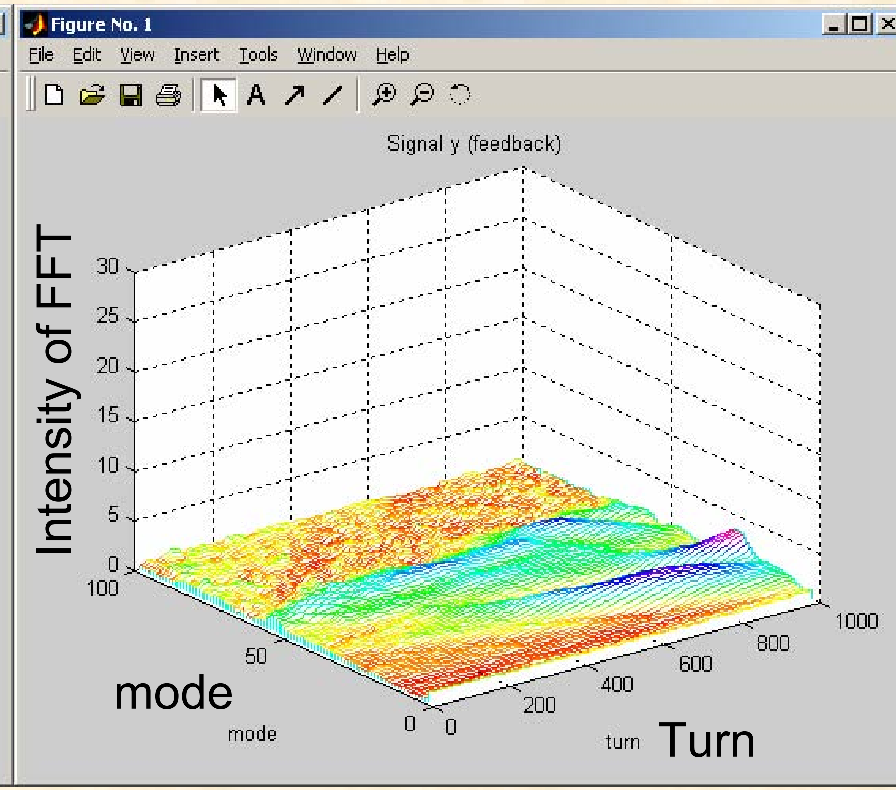


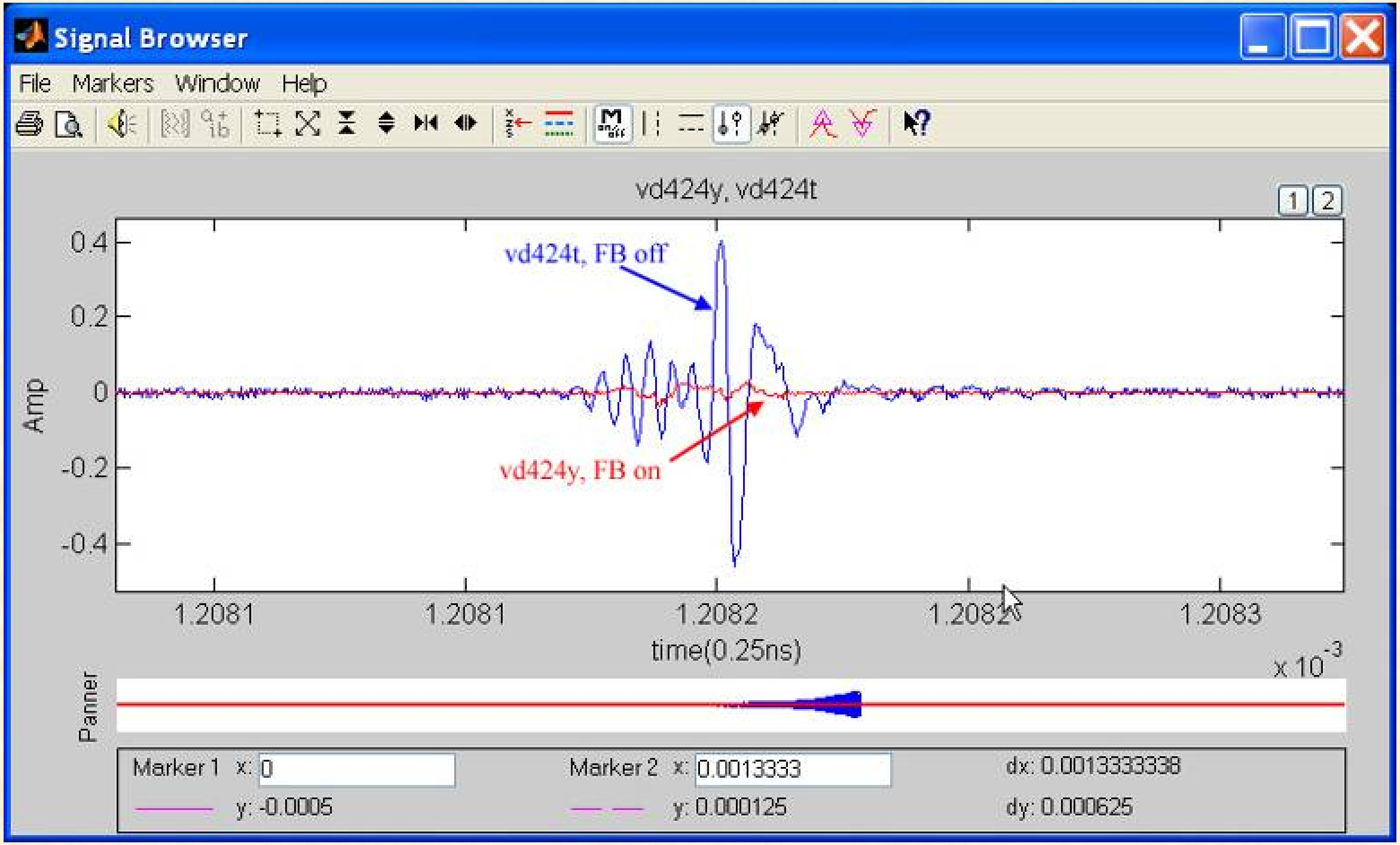
Feedback Off



Feedback On

S. Breitzmann

Vertical Difference



Vertical difference for one turn near end of store

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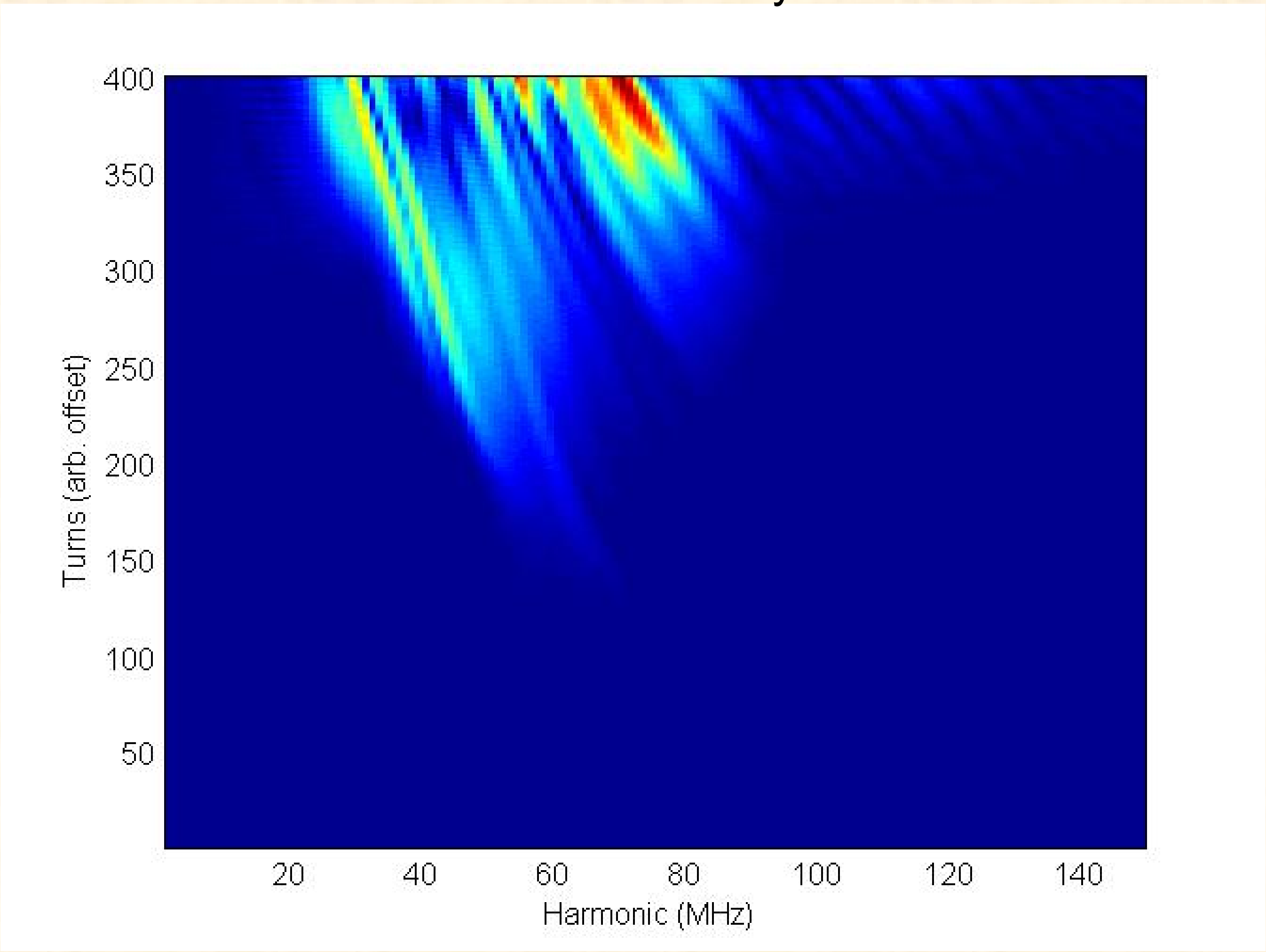
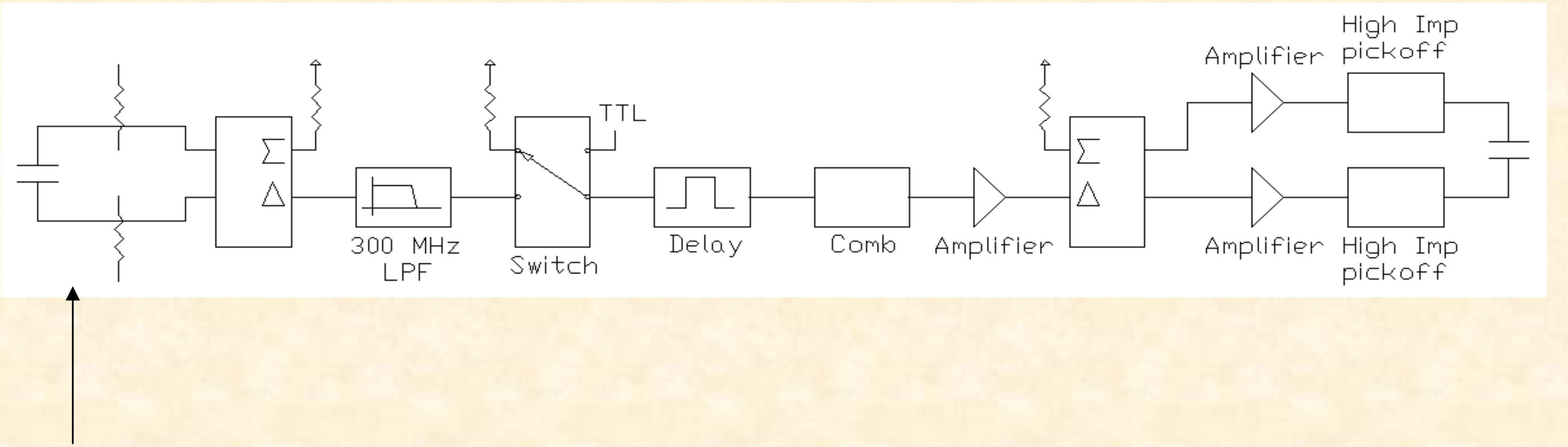
SNS Instability



S. Cousineau

Analog Hardware Design

Block Diagram

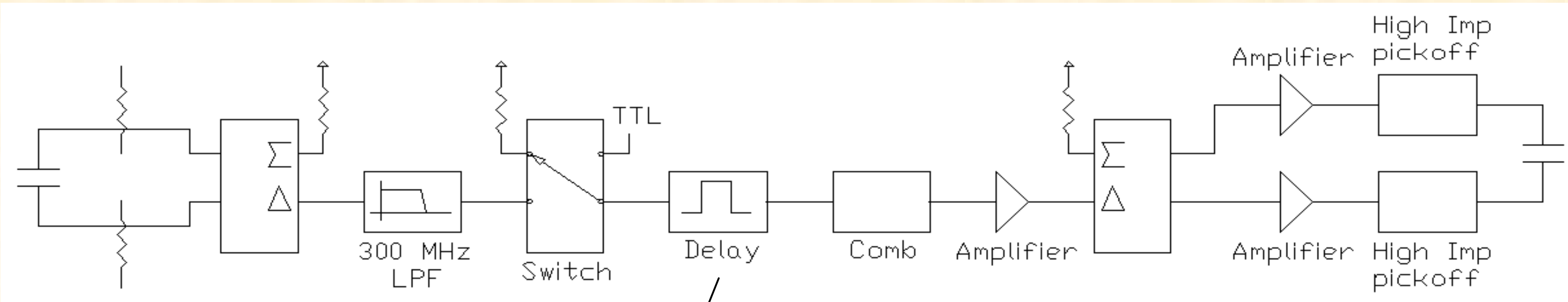


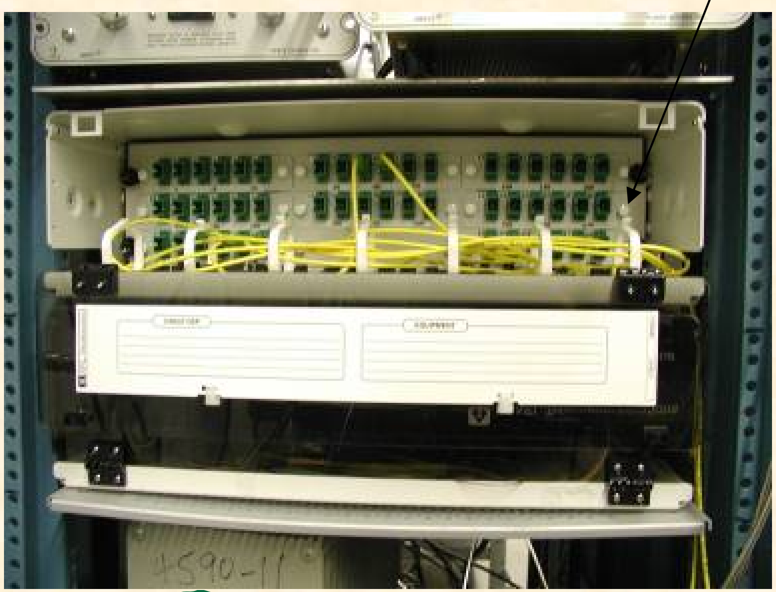
pickup

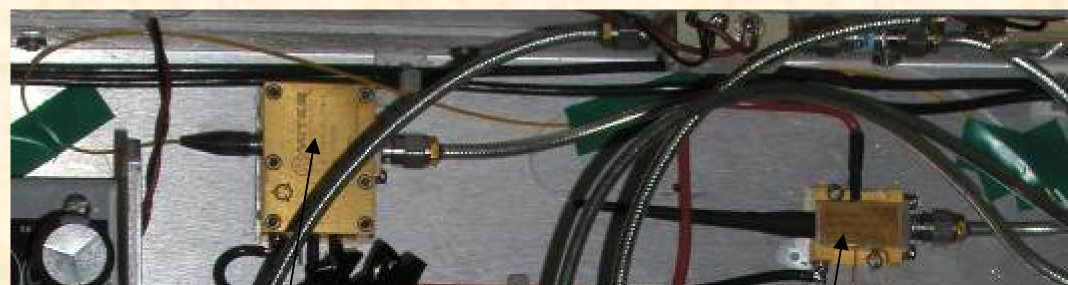
kicker

- Delay line is adjustable for differing configurations
- 4 different comb filters for single and dual turn.
- High impedance pickoff measures signals from the amplifiers

Optical Delay Chassis







Transmitter

Receiver

ENI Amplifier Measurement

- Uses 2 ENI amplifiers – 100 Watts 1-400 MHz
- The output of each ENI goes through a High-Z pickoff to measure output signals and to loads.

180

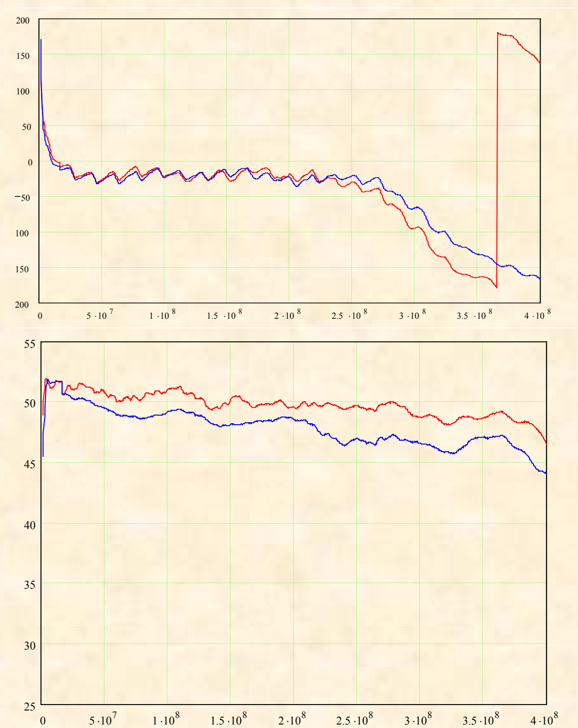
Phase (deg) 0

-180

50

Gain (dB) 40

30



100 200 300 400 MHz

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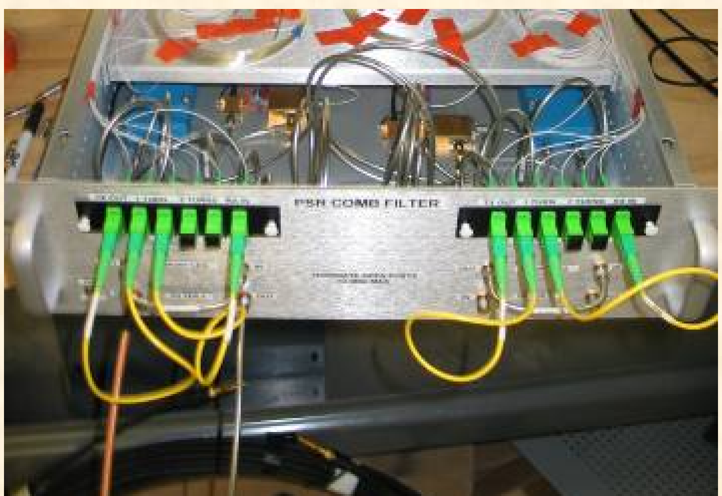
Comb Filters

- Uses 2 Miteq Fiber transmitters/receivers

- An option to use a single turn or two turn notch spacing is available

- Fine tuning available via ARRA trombones



Long leg tuned to notch spacing accurate to better than 3 psec on average across the band.

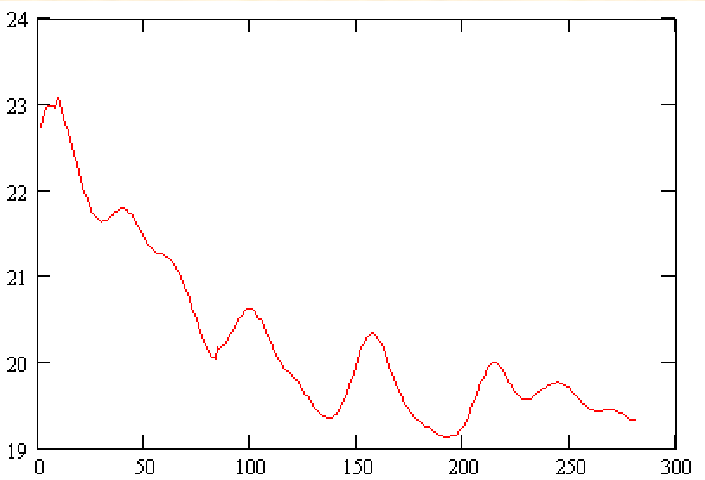
Notch Depths of Filter #1 and Filter #2

Filter #1

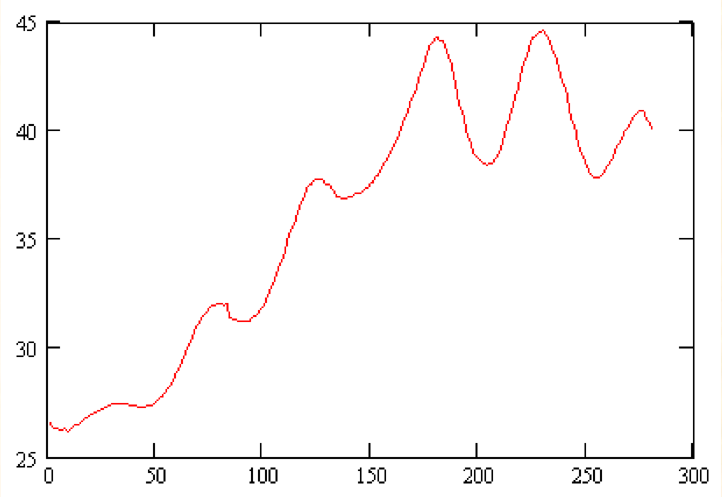
Filter #2

2 Turn

dB

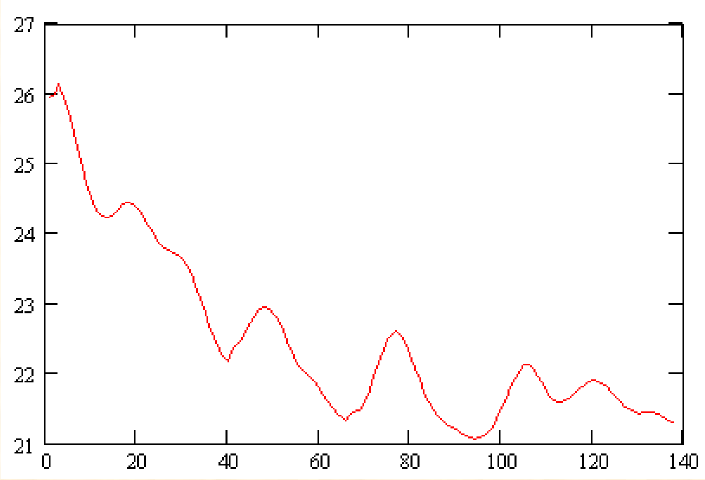


dB

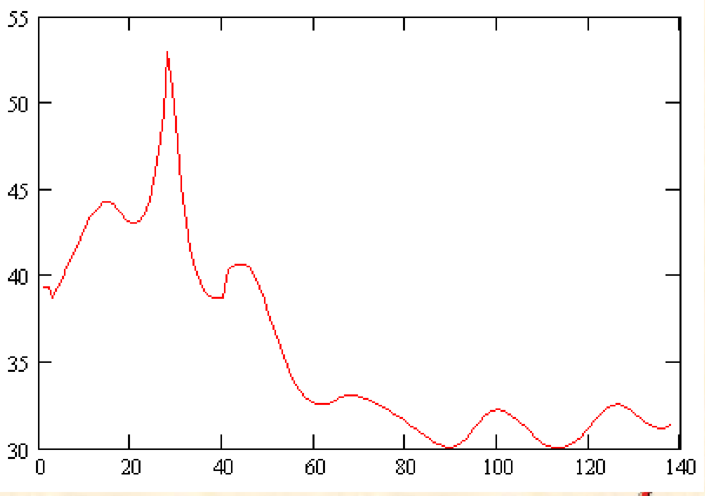


1 Turn

dB



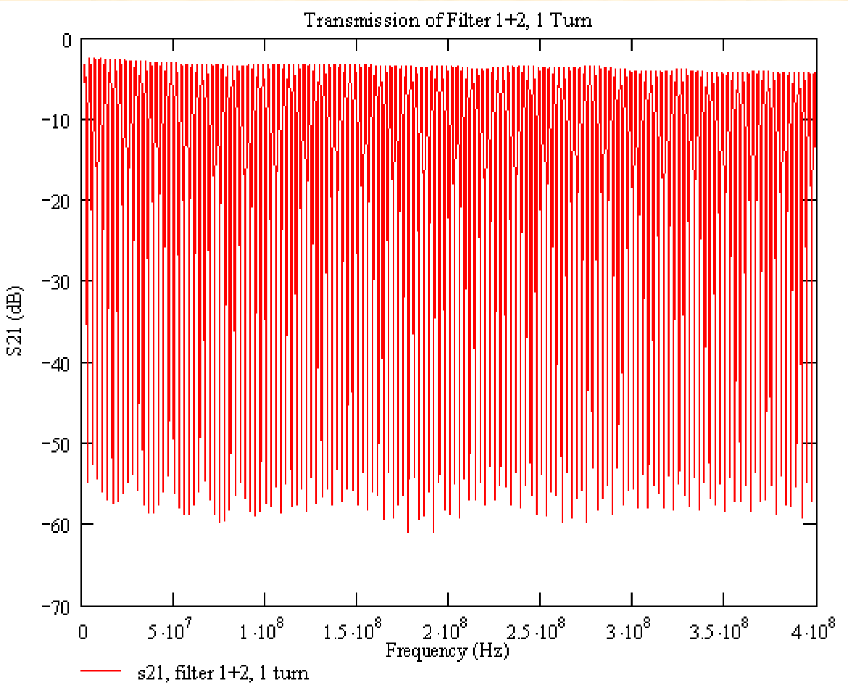
dB



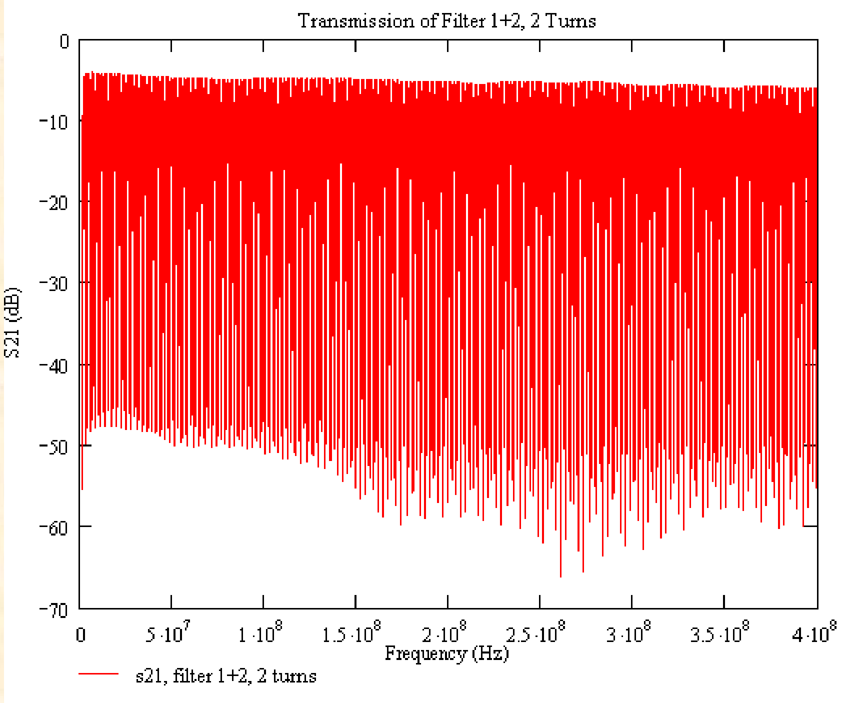
Notch #

Notch #

Measured VNWA Notch Depths of Filter #1 and Filter #2 in Series



1 Turn



2 Turn

Signal lines from electrodes

Main LLRF chassis

High Z pickoff

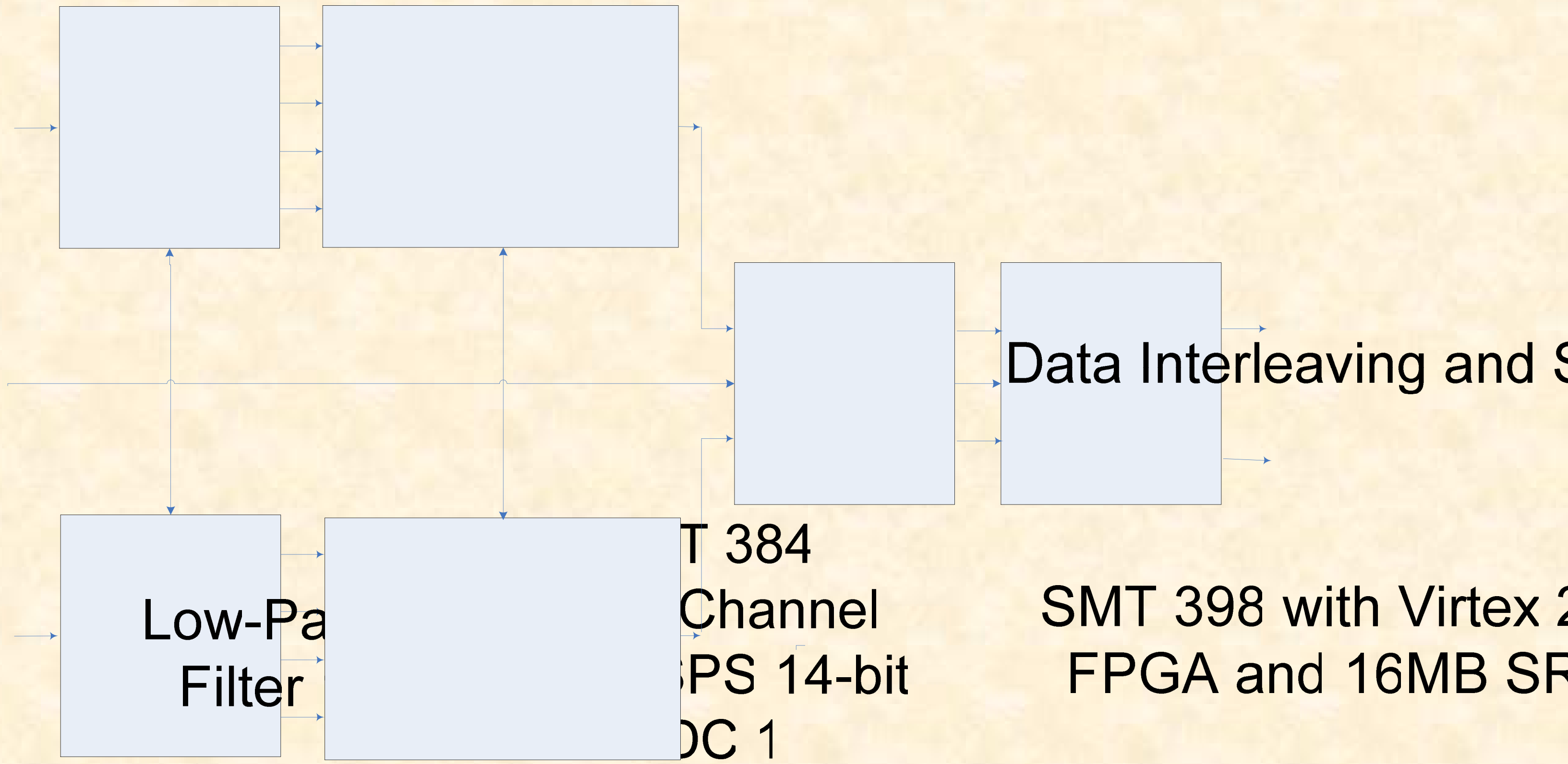
LLRF pre-amplifiers

Fiber Delay Line

Comb Filters

Binary Adjustable Delay

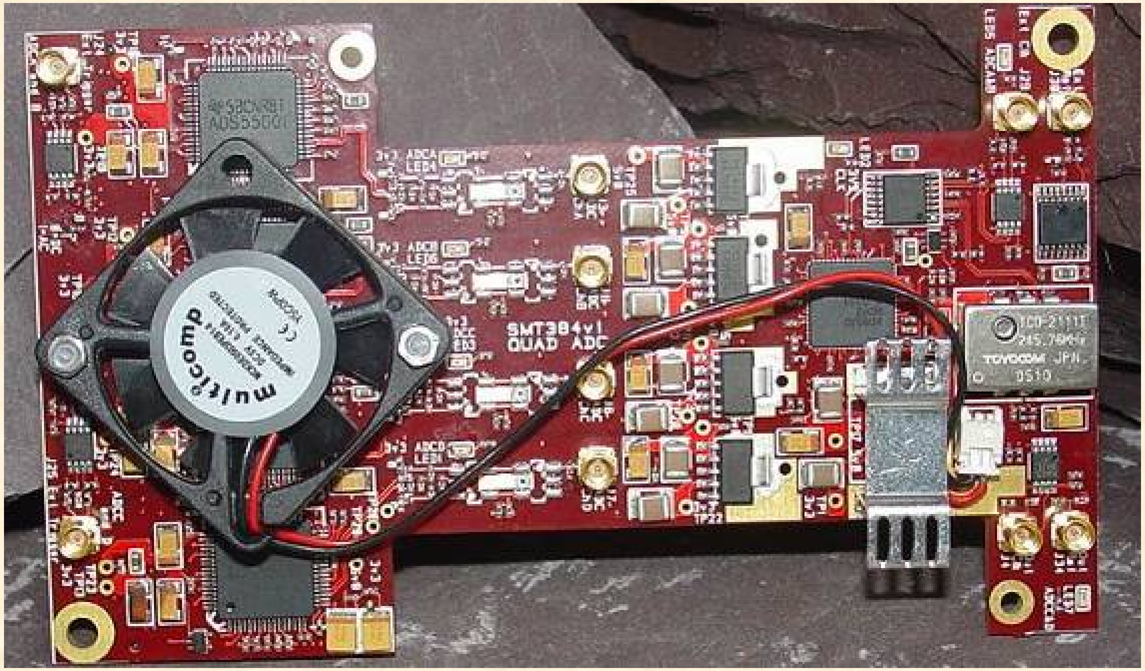
Digital Subsystem Implementation



- **The digital subsystem includes synchronized ADCs, FPGAs, and DACs**

Analog-to-Digital Converters

- **Two parallel SMT384 ADC Modules**
  - **Quad-channel, 125 MSPS, 14-bit ADC (11.3 ENOB)**
  - **Data interleaving on FPGAs provides a single 500 MSPS, 14-bit data stream per channel**



* *Figure from Sundance DSP, Inc.*

Data Interleaving and Storage FPGAs

- **Two parallel SMT 398 FPGA Modules**
  - **Contain Xilinx Virtex-II Pro FPGA**
  - **Store up to 8M 16-bit samples per channel**
  - **Interleave data for further processing**

* *Figure from Sundance DSP, Inc.*

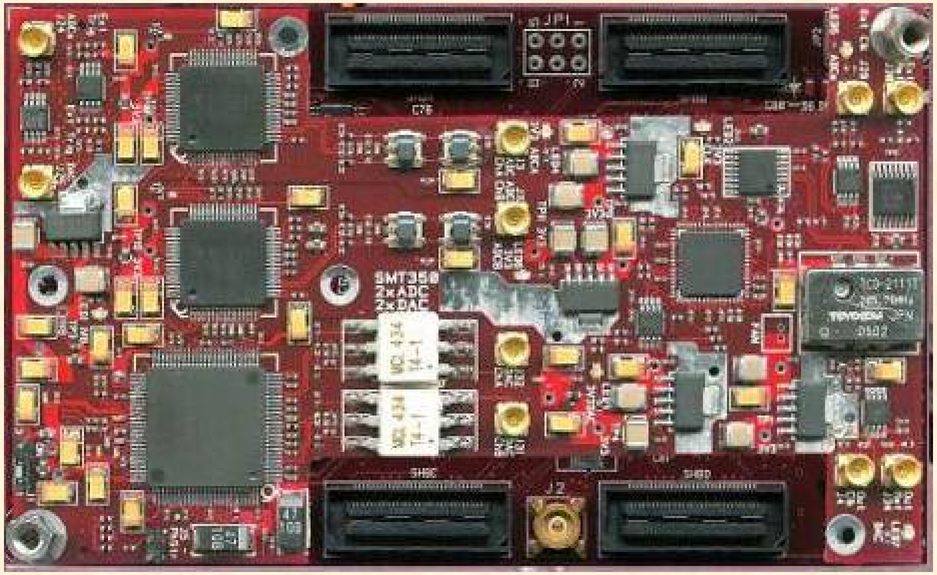
Data Processing FPGA

- **SMT 368 FPGA Module**
  - **Contains Virtex-4 FPGA (500 MHz)**
  - **Stores up to 4M 16-bit samples**
  - **Processes digital data and sends outputs to DAC**

* *Figure from Sundance DSP, Inc.*

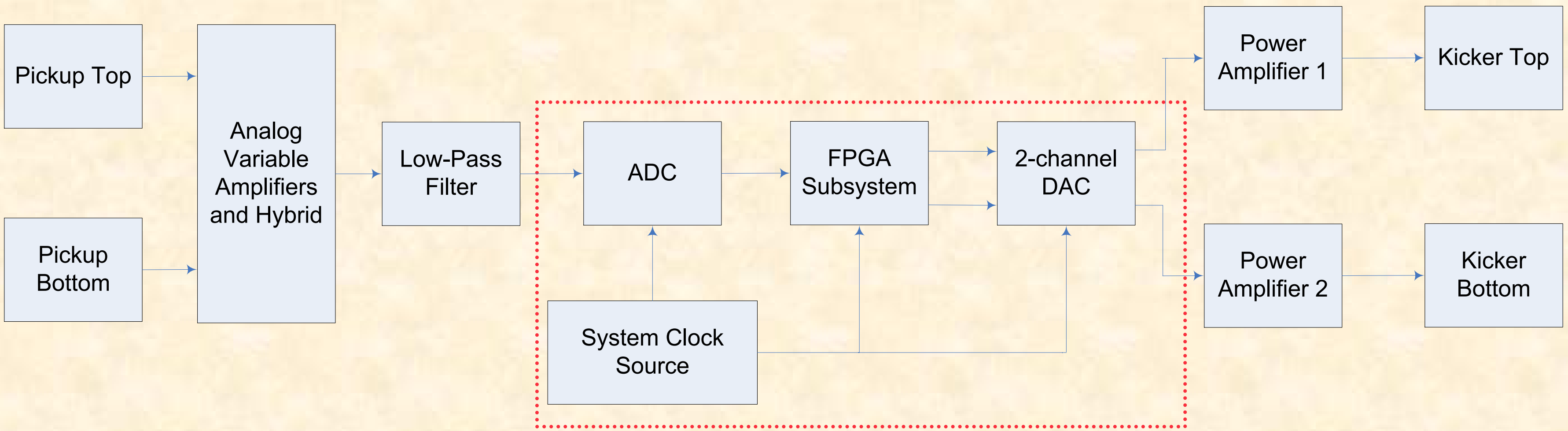
Digital-to-Analog Converters

- **SMT 350 DAC Module**
  - **SMT350 Dual-Channel 500 MSPS, 16-bit DAC**
  - **Accepts data at 125 MSPS and interpolates by 4**
  - **Later upgrade to a true 500 MSPS, 14-bit DAC**
  - **Outputs sent to power amplifiers**



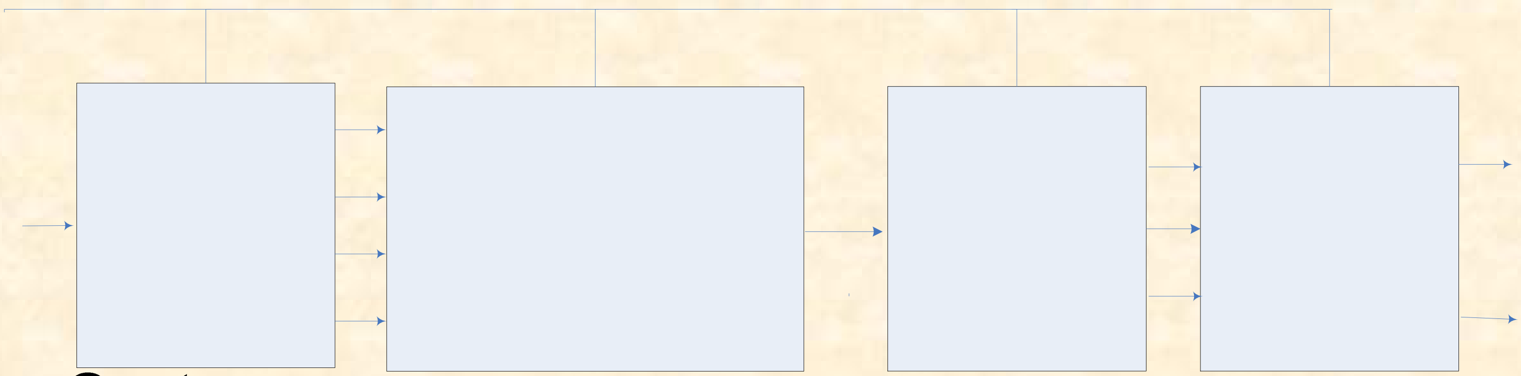
* *Figure from Sundance DSP, Inc.*

Mixed Signal System Realization



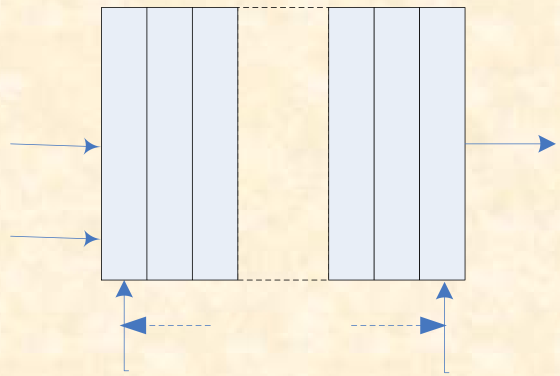
- **The offset multipliers and subtraction can be implemented using analog circuits**
  - **+ Reduces system complexity**
  - **+ May improve accuracy of voltage difference**
  - **– Introduces additional distortion from analog components**
  - **– Reduces available diagnostic information**

Mixed Signal System



- **Implementing the offset multipliers and subtraction using analog circuits**
  - **+ Eliminates one of the ADCs and one of the FPGAs modules**
  - **– Reduces available diagnostic information, since individual voltages are no longer available**

Programmable Delay Module



Progra

- **Programmable delay module controls the overall system delay:** $Delay = FIFO\ length \times Clock\ \ period$
- **Implemented using FIFO16 module**
- **Additional fine-tuning of the delay is required**

Gain Multiplier

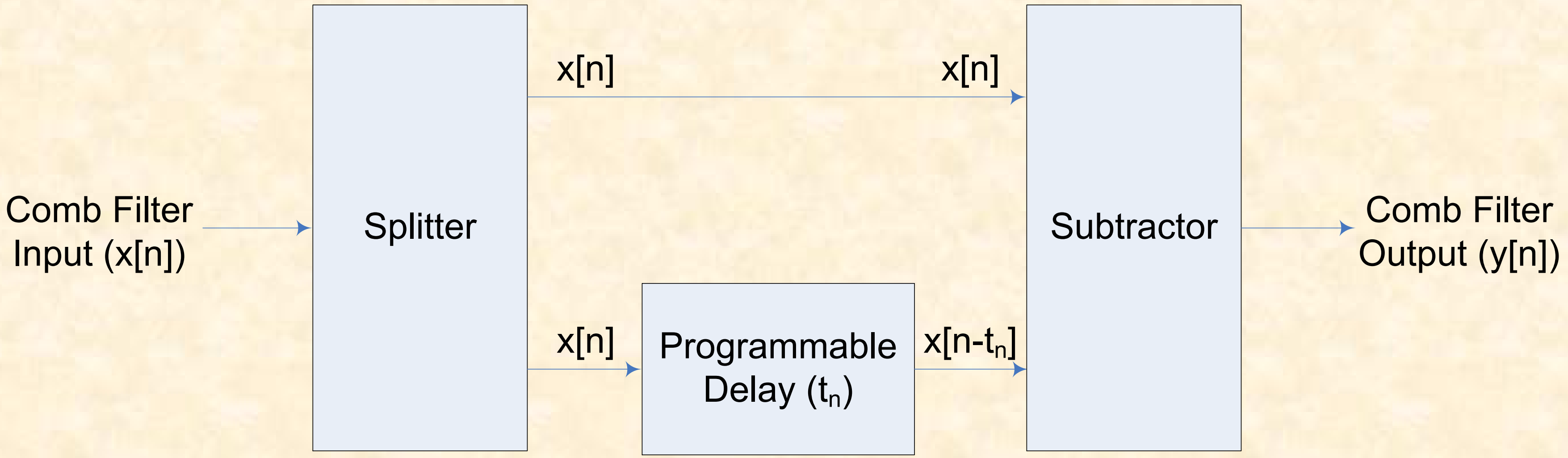
Output (V_{out})

Clock

Prog

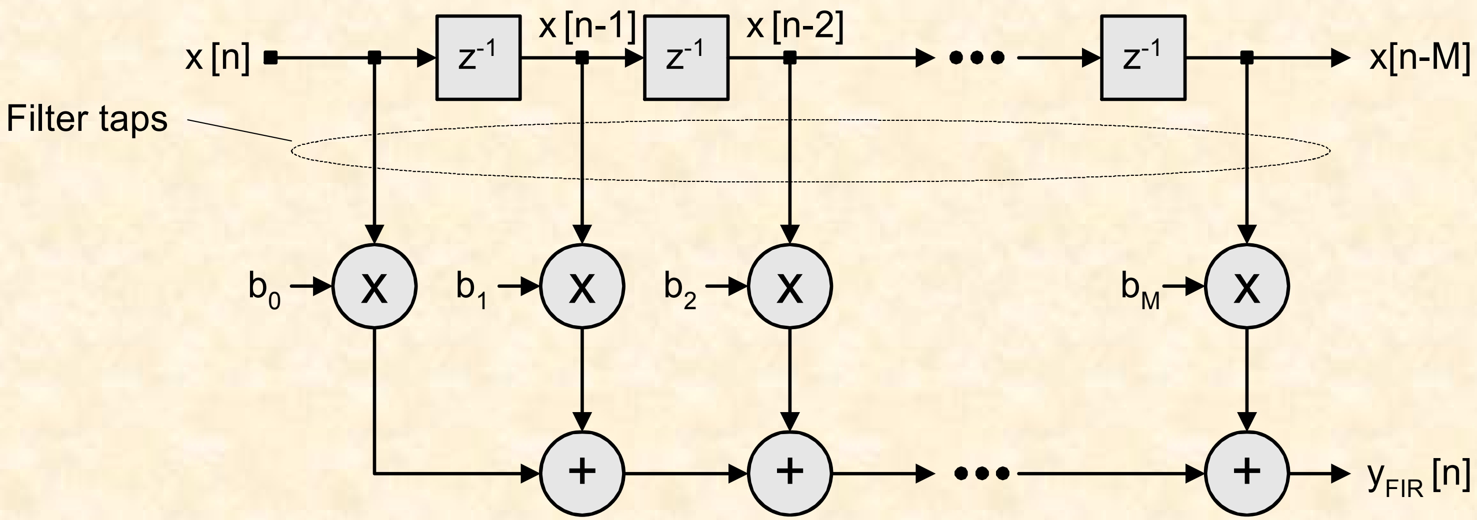
Dela

Comb Filters



- **The comb filters dampen the ring frequency harmonics to save power**
  - **Comb filter output:** $y[n] = x[n] - x[n - t_n]$
  - **Comb filter frequency response:** $Y(\omega) = X(\omega)[1 - e^{-i\omega t_n}]$
  - **t_n is set as a multiple of the ring frequency (≈ 1 μsec)**
- **Implemented using FIFO16 and DSP48 modules**

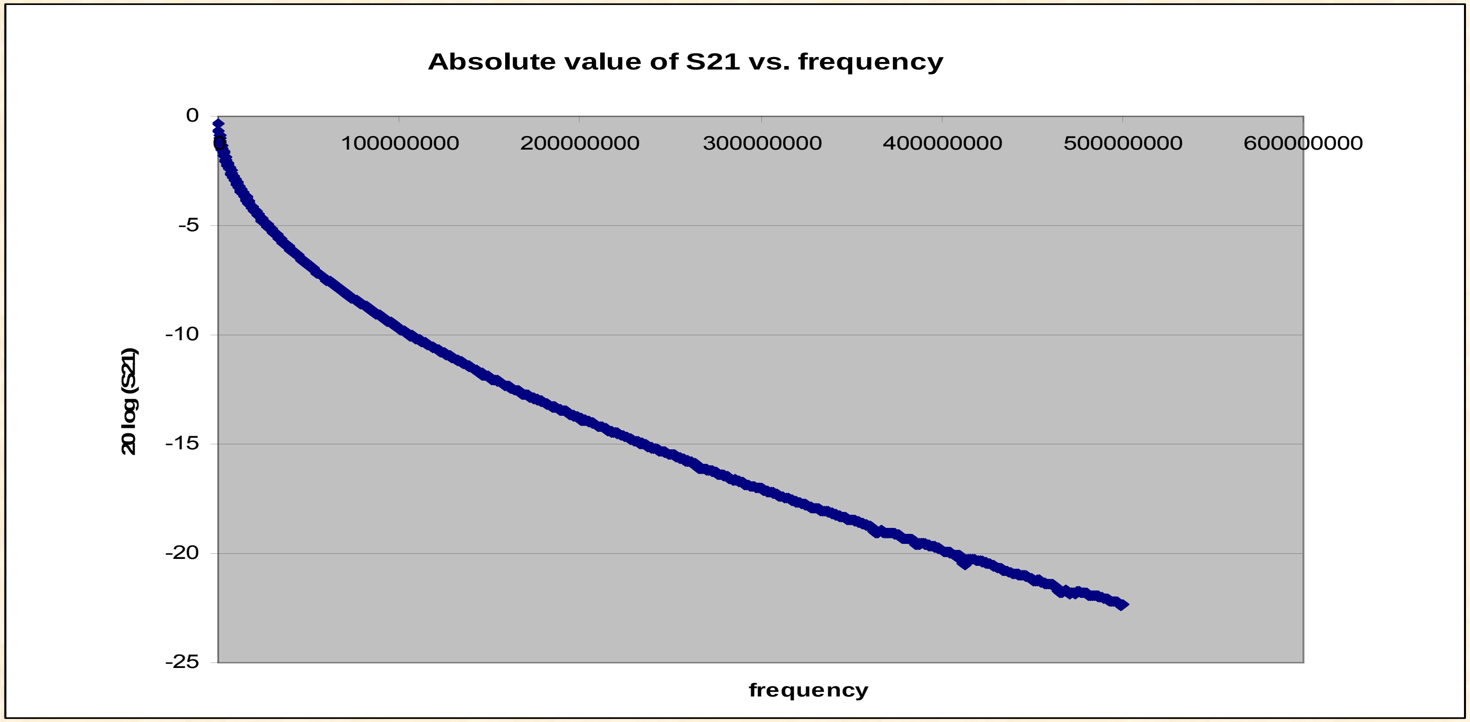
FIR Filters



- **The FIR filters compute:** $$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$
- **Serve as equalizers that correct for dispersion in analog components**
  - **Electrodes have non-uniform gain verses frequency**
  - **Amplifiers have phase dispersion**
  - **Analog hybrids, low-pass filters, and cables have magnitude and phase dispersion**

Cable Magnitude Dispersion

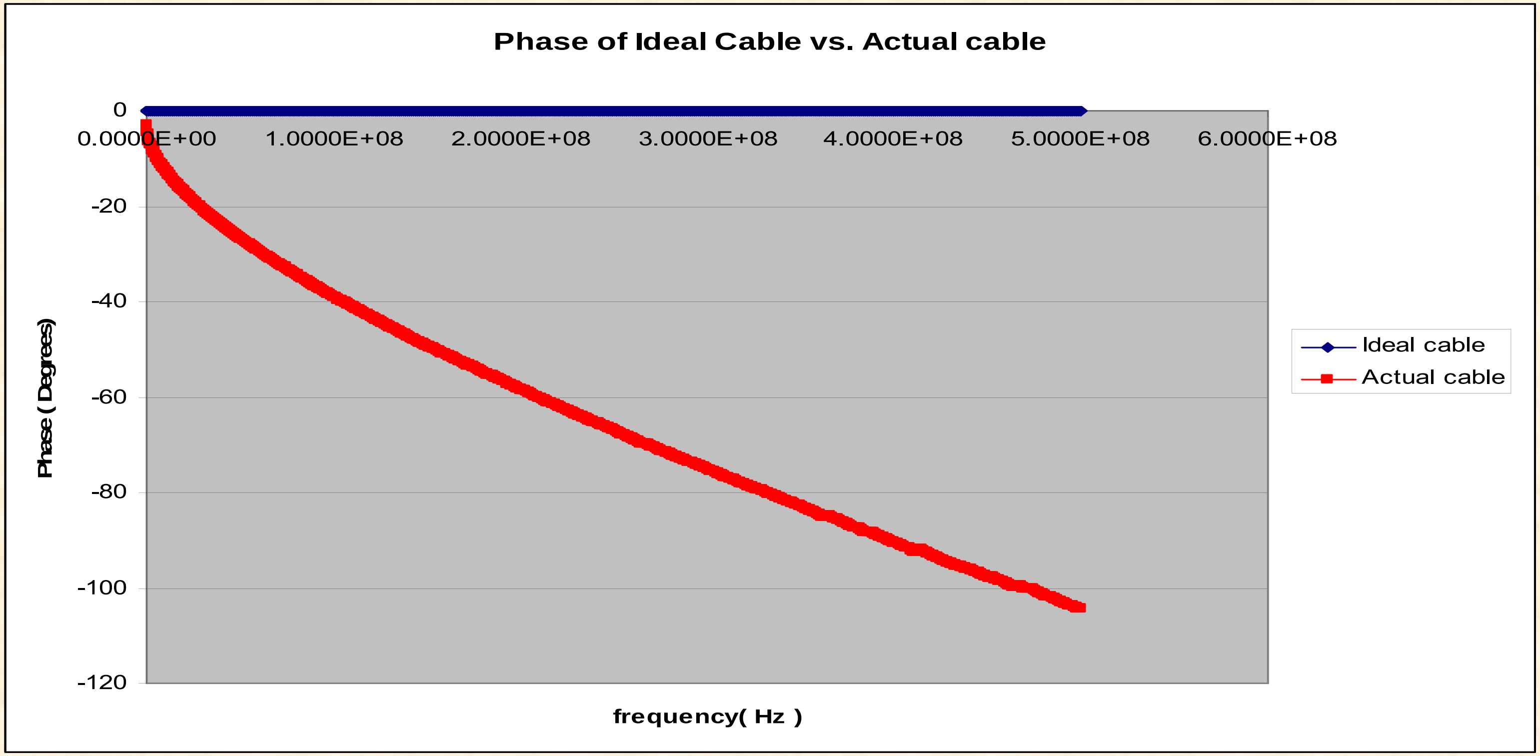
- **The cables have magnitude and phase dispersion due to copper and dielectric losses**



S_{21} characteristics of the measurement cable (in dB) vs. frequency

Cable Phase Dispersion

- **The cables have magnitude and phase dispersion due to copper and dielectric losses**

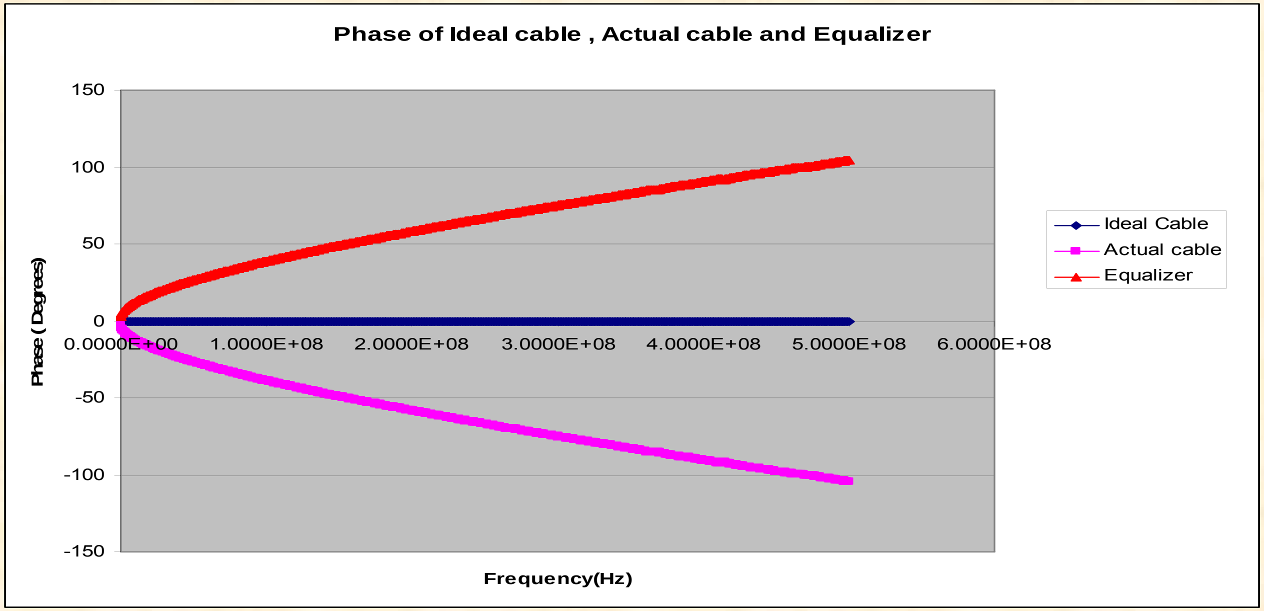


Phase Response of Ideal cable vs. Actual cable

Reducing Cable Dispersion

- **Find the frequency (S_{21}) characteristics of the cable using a vector network analyzer**
- **Determine the equalizer characteristics necessary to compensate for magnitude and phase dispersion**

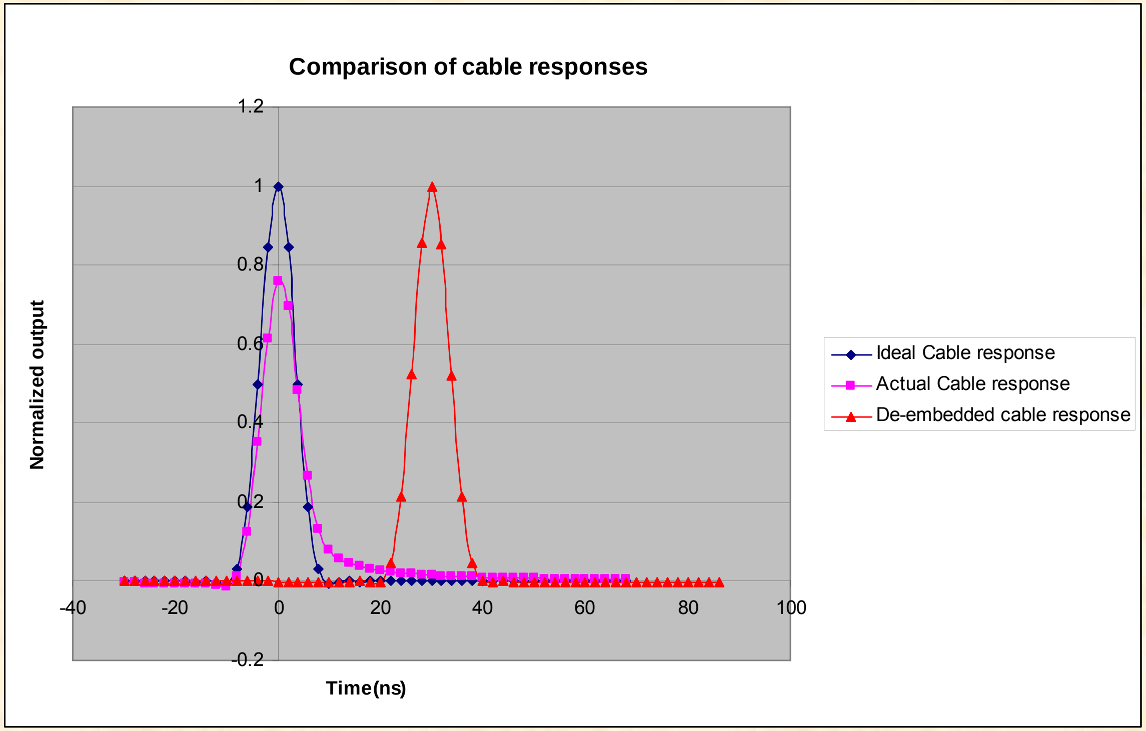
$$G(\omega) = \frac{H2(\omega)}{S_{21}(\omega) * e^{i\omega T_d}} \qquad H2(\omega) = \cos^4\left(\frac{\pi\omega}{2\omega_c}\right)$$



Phase response of ideal cable, actual cable and the equalizer versus frequency

Reducing Cable Dispersion

- Determine the number of taps and tap values for the equalizer
- Run the equalizer in series with the cable to reduce dispersion



Comparison of the time-domain responses of an ideal, actual, and de-embedded cable

Future Work

- **Optimize signal levels to stay out of compression**

- **Optimize signal levels to each hardware component**
  - **Amplifiers**
  - **Delay Line**
  - **Overall system gain**

- **Optimize growth rate/damp rate for production quality beams.**

- **Develop mixed signal (analog and digital) transverse feedback system.**

Conclusion

- **15-30% increase in threshold with feedback, depending on beam conditions**
- **Begin to see instability in the horizontal plane**
- **We were able to over-damp the beam after optimizing settings, and had to reduce power.**
- **Production runs show issues with hardware – compression and loop gain.**
- **E-P instability can be damped using wideband feedback.**
- **Damping varies with real part of signal. Dispersion makes us lose about 30% of our power**

Special Thanks

to the SNS team who went the extra mile to help pull it all the hardware together

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Syd Murray, Dan Newby, Jim Pogge,
Mary Rutherford, Madhan Sundaram, Theresa Toomey
and Andy Webster.