The ATF Damping Ring Beam Position Monitor System

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for the ATF Damping Ring BPM Team

Agenda

- Motivation & "History"
- The ATF Damping Ring
- BPM Upgrade Hardware
- Results of Beam Studies
- Summary

Motivation

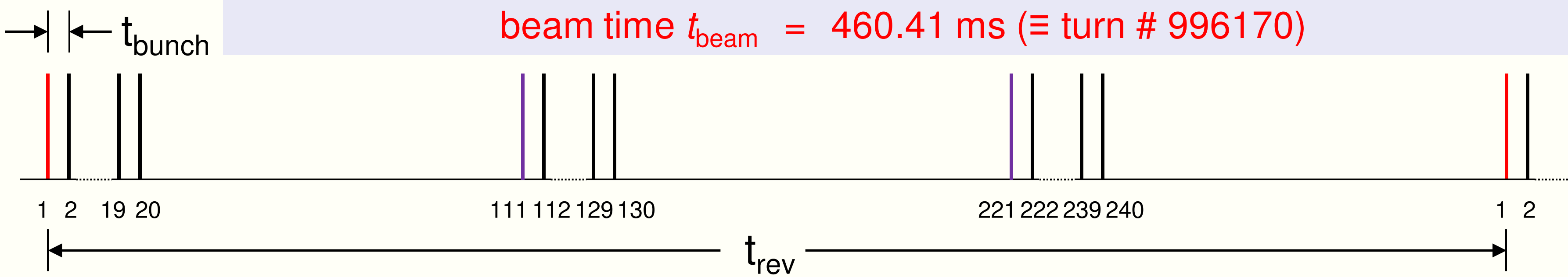
- ILC damping ring R&D at KEK's Accelerator Test Facility (ATF):
  - Investigation of the beam damping process (damping wiggler, minimization of the damping time, etc.)
  - Goal: generation and extraction of a reproducible low emittance beam (ε_{vert} < 2 pm-rad) at the nominal ILC bunch charge
- A major tool for low emittance corrections: a high resolution BPM system
  - Optimization of the closed-orbit, beam-based alignment (BBA) studies to investigate BPM offsets and calibration.
  - Correction of non-linear field effects, i.e. coupling, chromaticity,…
  - (Fast) global orbit feedback(?)
  - Necessary: a state-or-the-art BPM system, utilizing
    - a broadband turn-by-turn mode (< 10 μm resolution)
    - a narrowband mode with high resolution (~ 100 nm range)
- ATF BPM read-out system upgrade
  - Button BPMs and signal cabling remains unchanged
  - New flexible BPM read-out system, tailored to ATF needs and requirements

Some ATF BPM "History" Notes

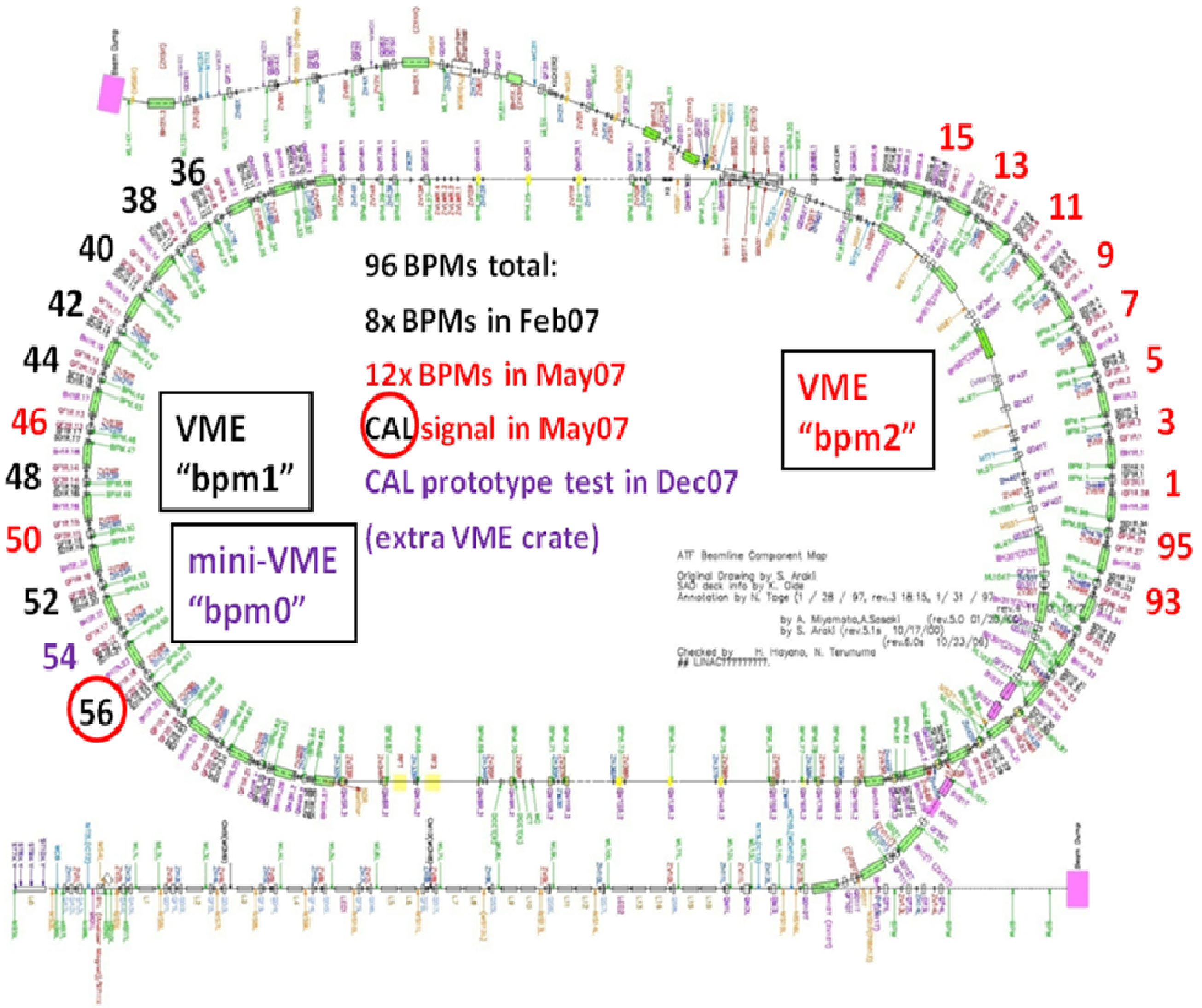
- ATF Damping Ring Beam Position Monitor System
  - Button style BPM pickup stations
  - Original read-out electronics:
    Analog signal processing, no TBT, intensity dependence
- 2006: M. Ross & SLAC team
  - Analog downconverter & digital receiver (*Echotek*) read-out system, prototype achieves 1-2 µm resolution
- 2007/8: KEK/SLAC/Fermilab collaboration
  - Beam tests of 20 BPMs in both arcs, equipped with new read-out system
  - EPICS & LabVIEW software
  - Achieved <10 µm resolution in TBT, ~200 nm in narrowband mode
  - First test of an integrated automatic calibration system
- 2009: KEK/Fermilab
  - Improvements on the analog downconverter
    - CAN-bus controls, IF filter, remote diagnostics, etc.
  - Switch to in-house VME digitizer (as of LHC delays: no Tevatron BPM *Echotek*'s)
    - 8-ch. ,125 MSPS ADC (serial outputs), Cylcone III FPGA, PLL-locked CLK distribution
  - New RF, DC & CAN-bus distribution. Grounding of tunnel hardware.

The ATF Damping Ring

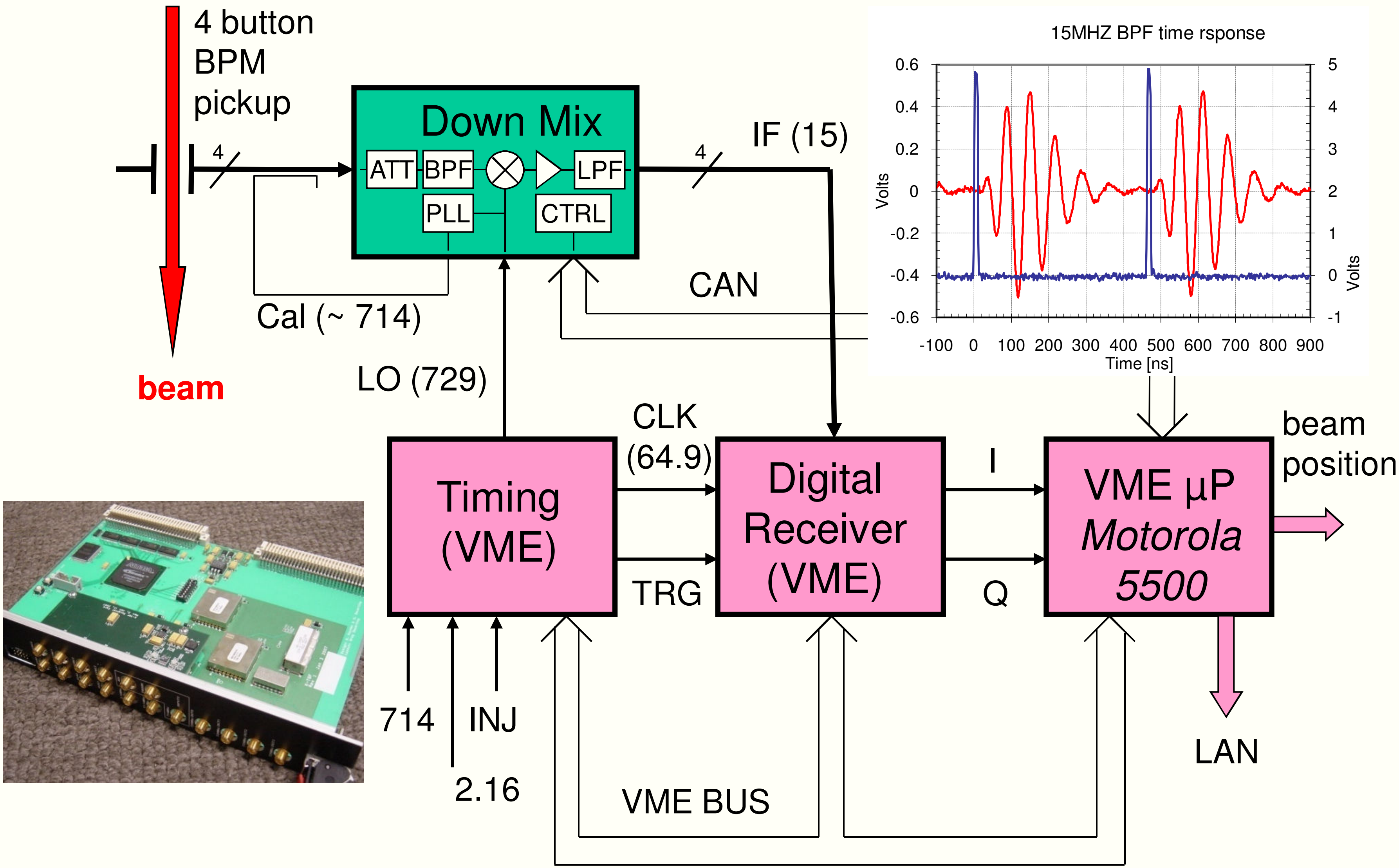
Machine and Beam Parameters		
beam energy E	=	1.28 GeV
beam intensity, single bunch	≈	~1.6 nC ≡ 10^{10} e^- (≡ I_{bunch} ≈ 3.46 mA)
beam intensity, multibunch (20)	≈	~22.4 nC ≡ 20 x0.7 10^{10} e^- (≡ I_{beam} ≈ 48.5 mA)
accelerating frequency f_{RF}	=	714 MHz
revolution frequency f_{rev}	**=**	**f_{RF} / 330 = 2.1636 MHz (≡ t_{rev} = 462.18 ns)**
bunch spacing t_{bunch}	=	t_{RF} / 2 = 2.8011 ns
batch spacing t_{batch}	=	t_{rev} / 3 = 154.06 ns
horizontal betatron tune	≈	15.204 (≡ f_h ≈ 441 kHz)
vertical betatron tune	≈	8.462 (≡ f_v ≈ 1000 kHz)
synchrotron tune	≈	0.0045 (≡ f_s ≈ 9.7 kHz)
repetition frequency f_{rep}	=	1.56 Hz (≡ t_{rep} = 640 ms)
beam time t_{beam}	=	460.41 ms (≡ turn # 996170)



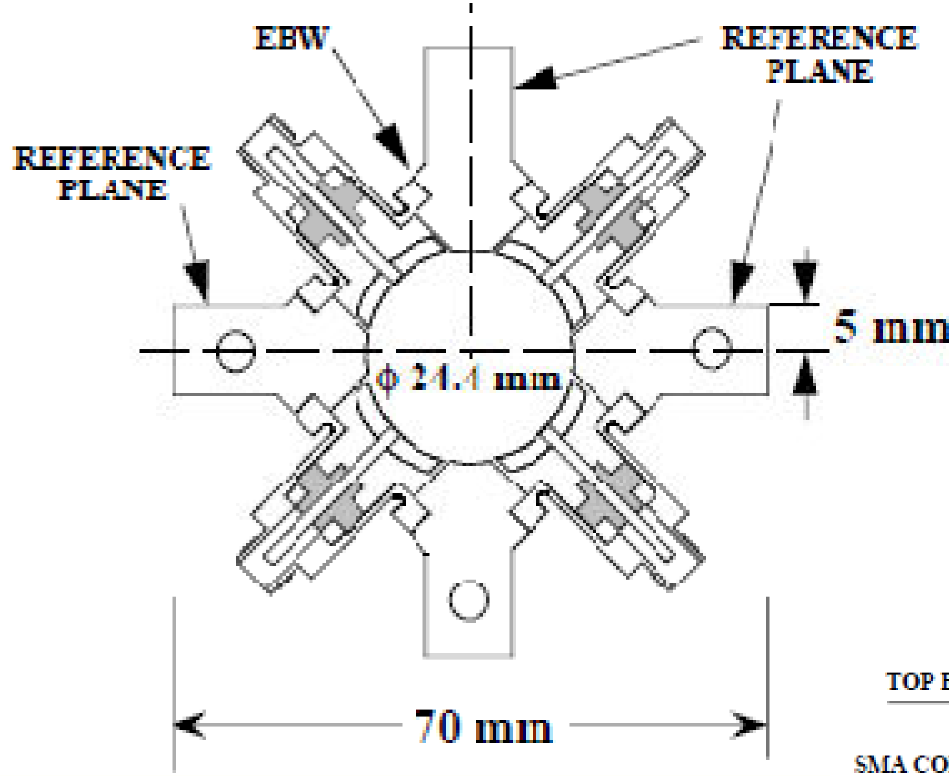
The ATF Damping Ring

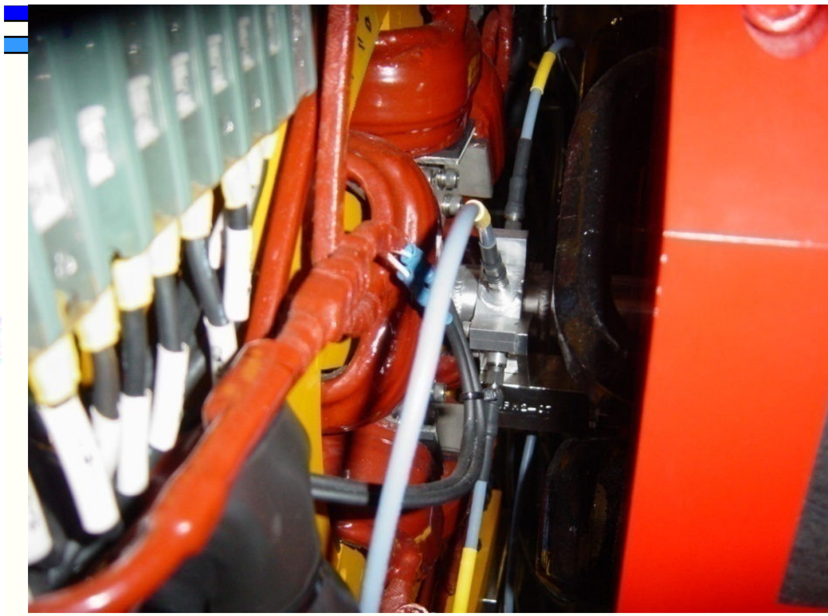


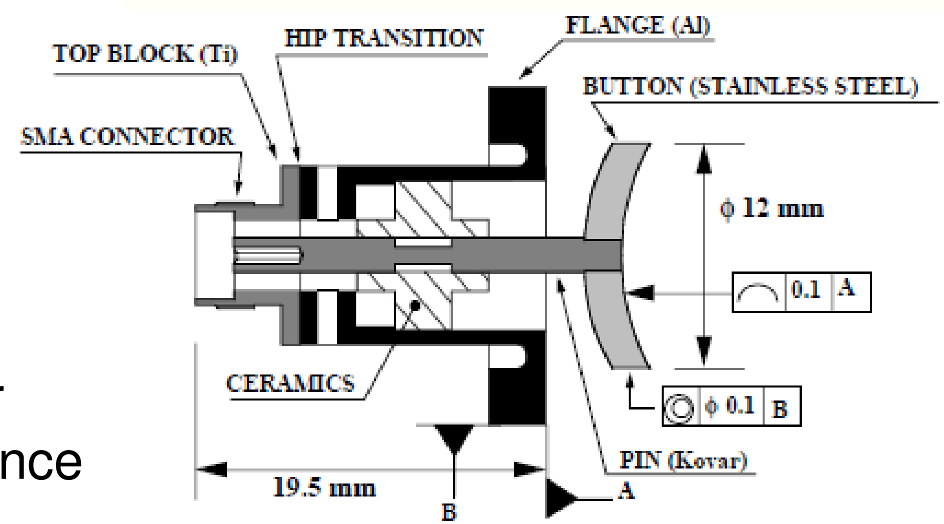
BPM Hardware Overview

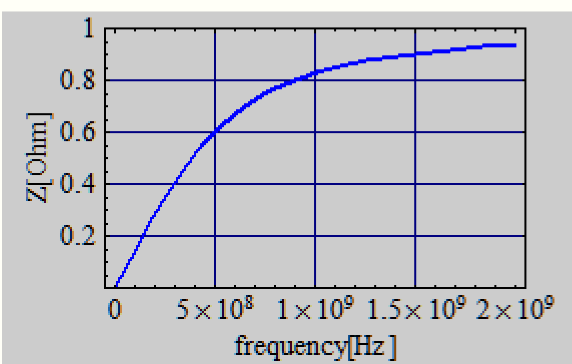


Button-style BPM Pickup



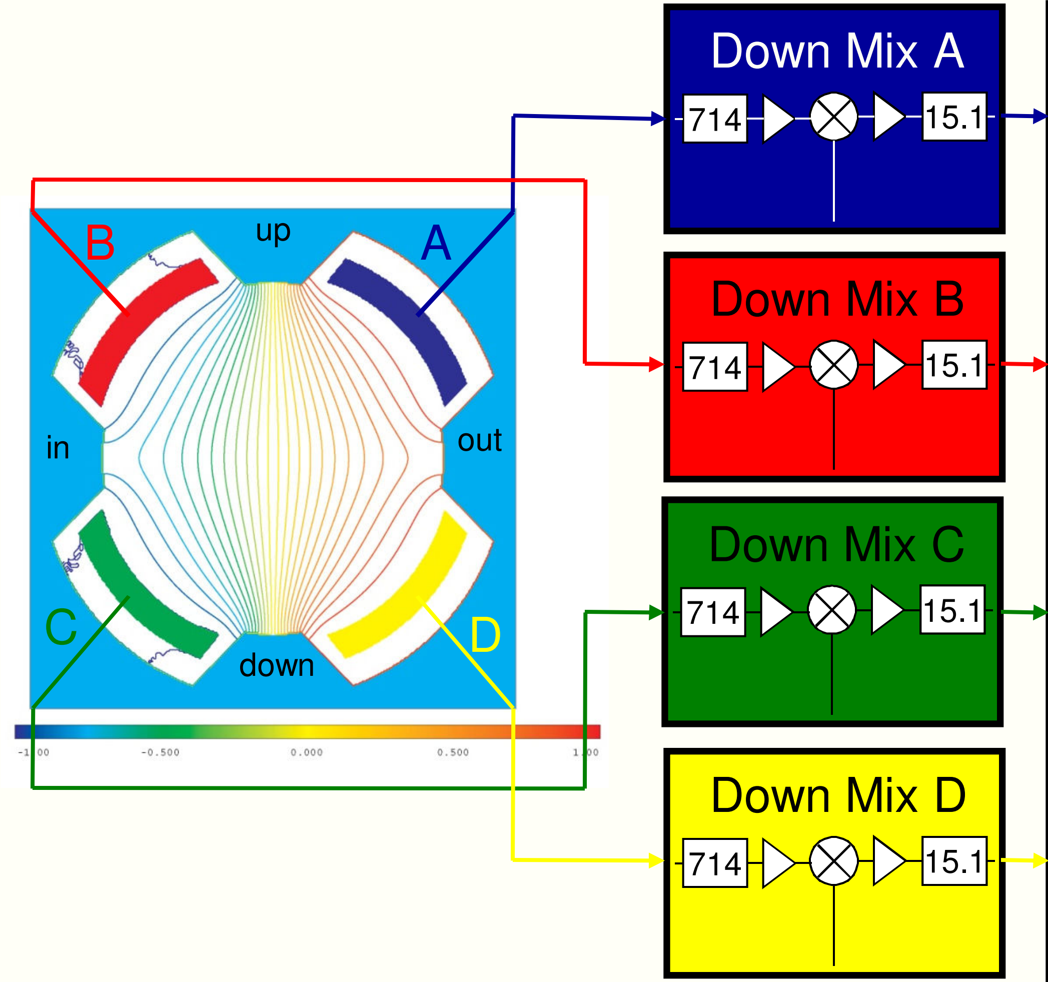






Button: transfer impedance

Beam Position Signal Processing



"Echotek" digital signal processing:

$$\phi_H = \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$\phi_V = \frac{(A+B)-(C+D)}{A+B+C+D}$$

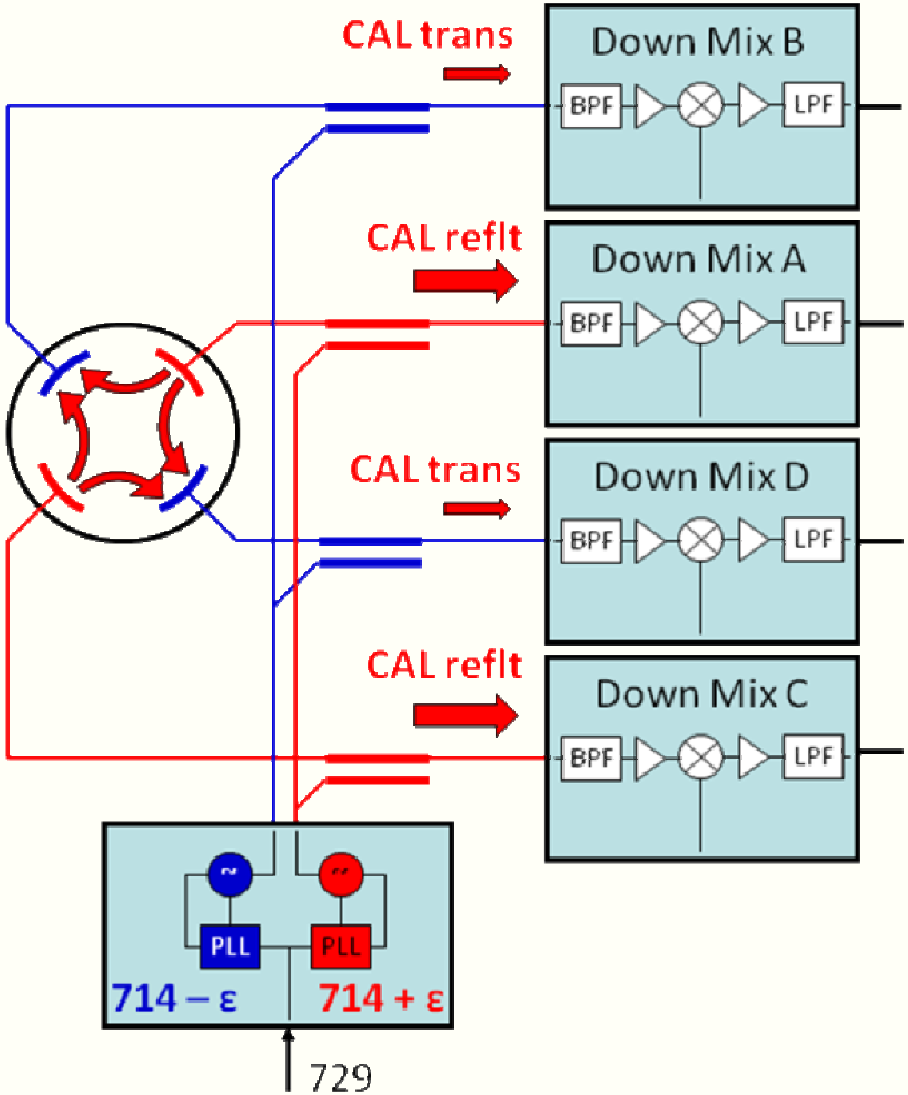
1D polynomial fit:

(2D fit is prepared)

$$Pos[mm] = 9.35\phi + 1.00\phi^3 + 7.79\phi^5$$

0.1 dB gain error ≡ 27 µm offset error !

Calibration Schema



- 2 calibration tones:
  - 714 + ε MHz
  - 714 – ε MHz
  - In passband of the downconverter
  - Coupled through the button BPM
  - Alternative: Reflected CAL signal
- On-line calibration
  - In presents of beam signals
  - Available only in narrowband mode
  - Need separate downconverter channels

Analog Downmixer (prototype)

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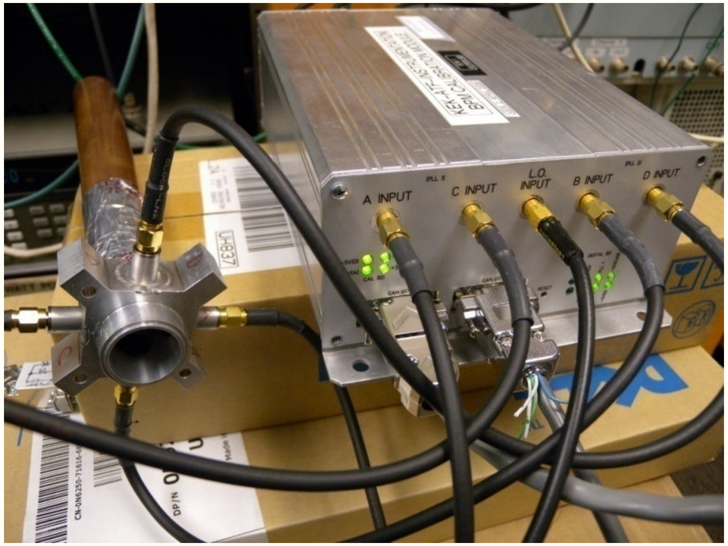
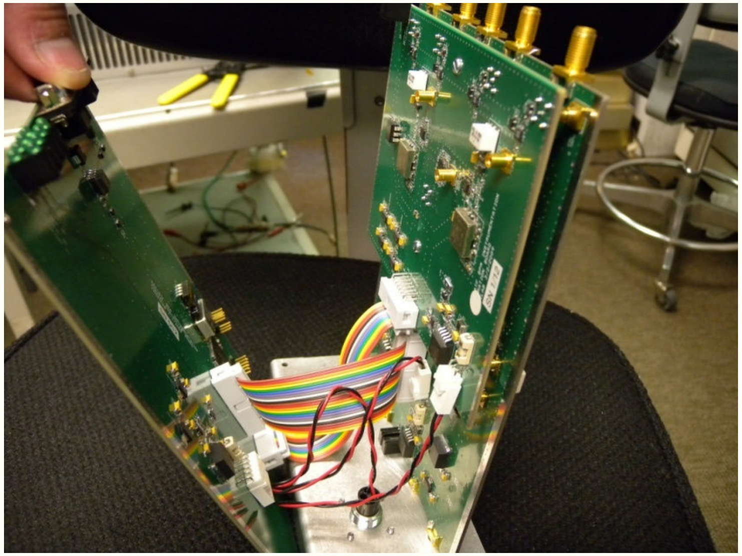
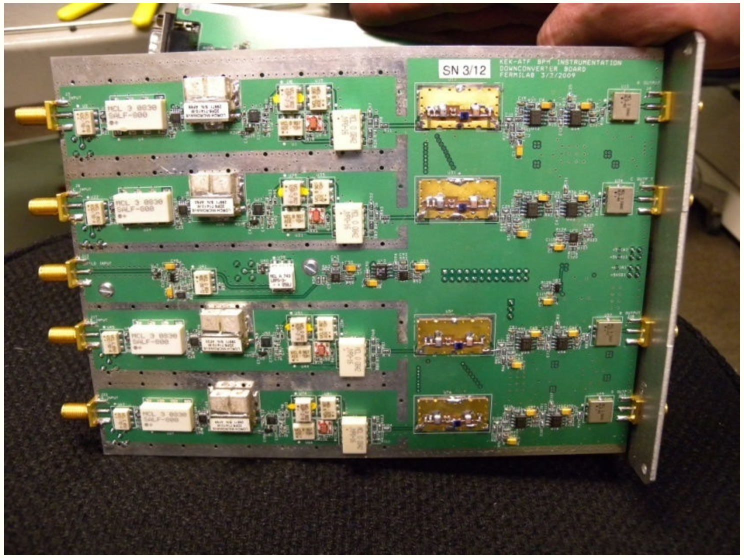
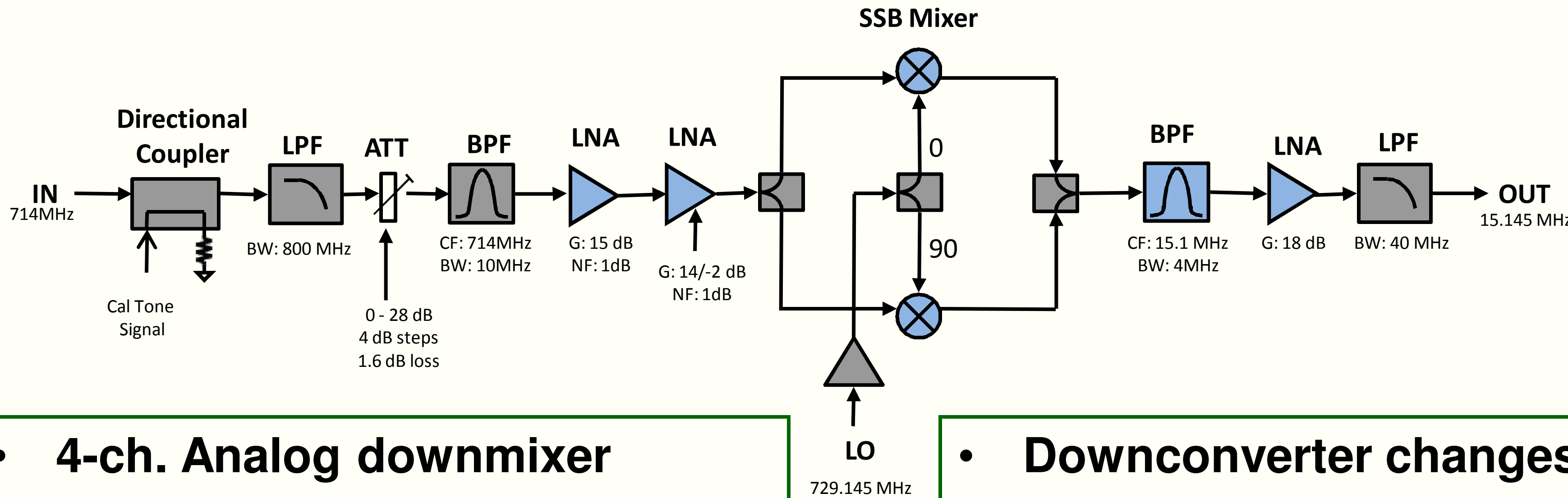






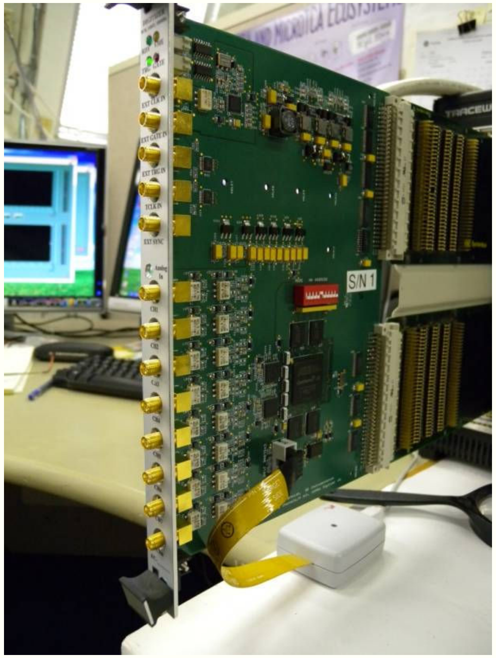
Analog Signal Processing

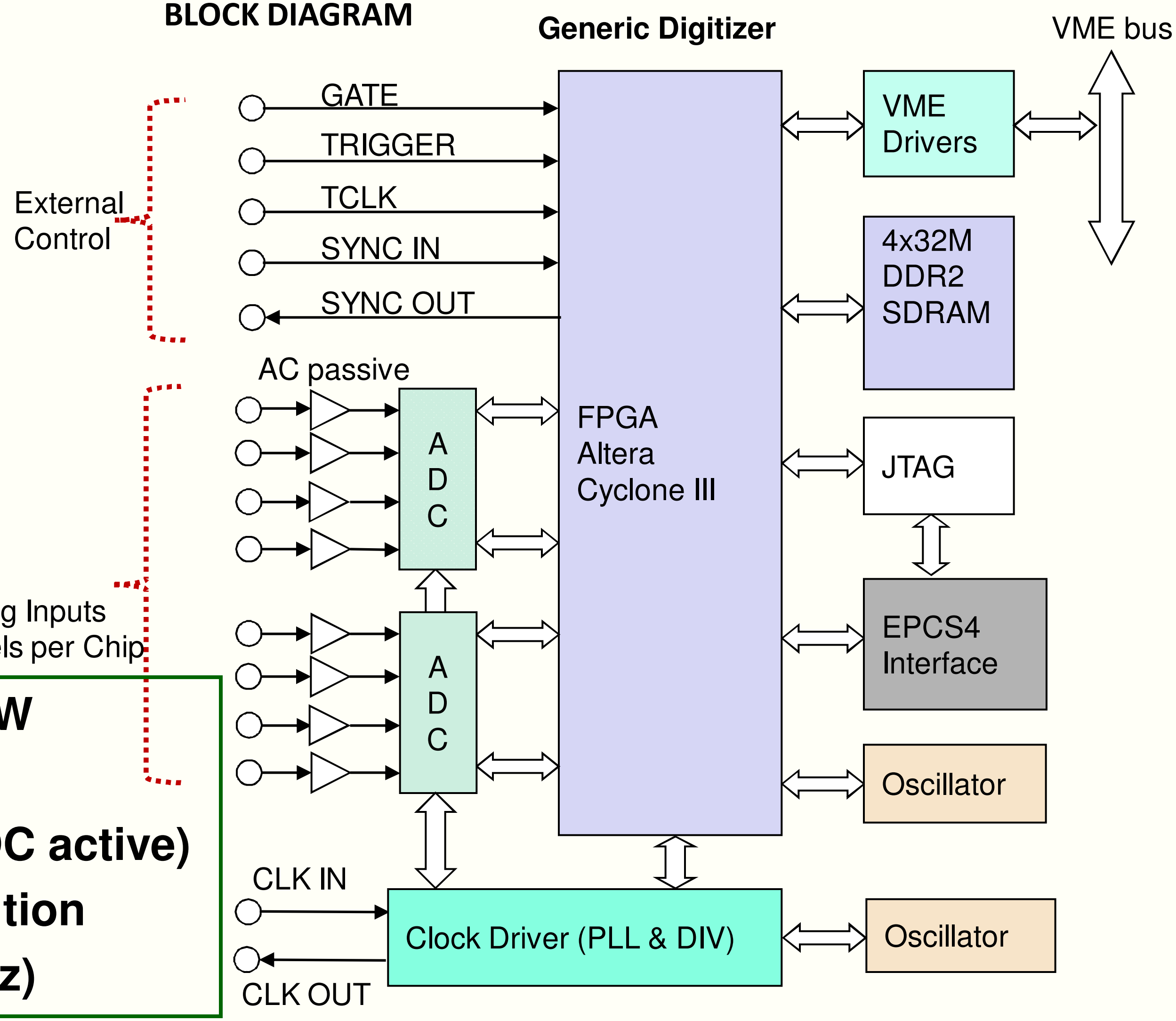


- **4-ch. Analog downmixer**
  - IN: 714, LO: 729.1, IF: 15.1 MHz
  - CAN-bus controlled gain, attenuator & cal system
  - Gain switchable, low-noise, high IP3 input gain stage
  - Image rejection (SSB) mixer
  - ~30 dB gain, ultralinear IF stage

- **Downconverter changes**
  - Change the gain distribution (RF+, IF-)
  - Change mixers (+17 dBm -> +13 dBm)
  - Change response of the IF section BPF

8-Ch,14-bit, 125 MS/s VME Digitizer



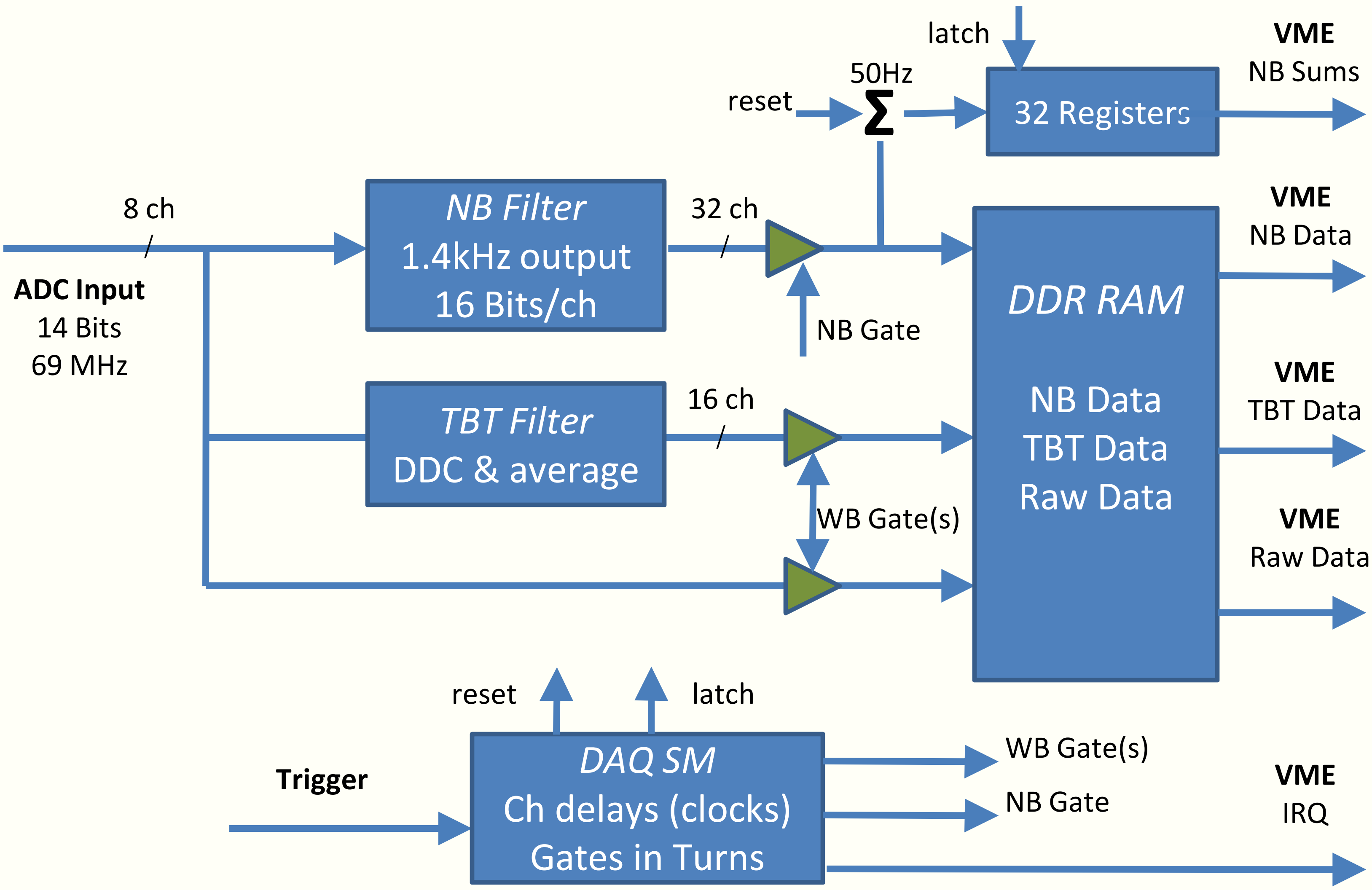


- **125 MSPS, 500 MHz BW**
- **4-ch serial ADC chips**
- **8-ch, AC passive (or DC active)**
- **PLL/VCO CLK distribution**
- **SNR > 72 dB (@50 MHz)**

Digital Signal Processing

- **No Modes - one external trigger processes data**
  - **Raw data to RAM**
    - **TBT readback & process (DDC & average) -> I,Q per turn**
    - **diagnostic readback**
  - **Narrowband processing (Filter & Decimate)**
    - **Store array of I,Q per channel for readback**
    - **Provide single sum I,Q per channel over n*50 Hz**
  - **Programmable trigger delay per channel (adc samples)**
- **Any data type (NB, TBT, Raw) can be readback after each trigger**
  - **All data will be read out as I,Q pairs**
  - **Caveat: The CAL tone has to be disabled for TBT data**
  - **Each board will pull IRQs when data is ready**

FPGA Block Diagram



System Timing Cartoon

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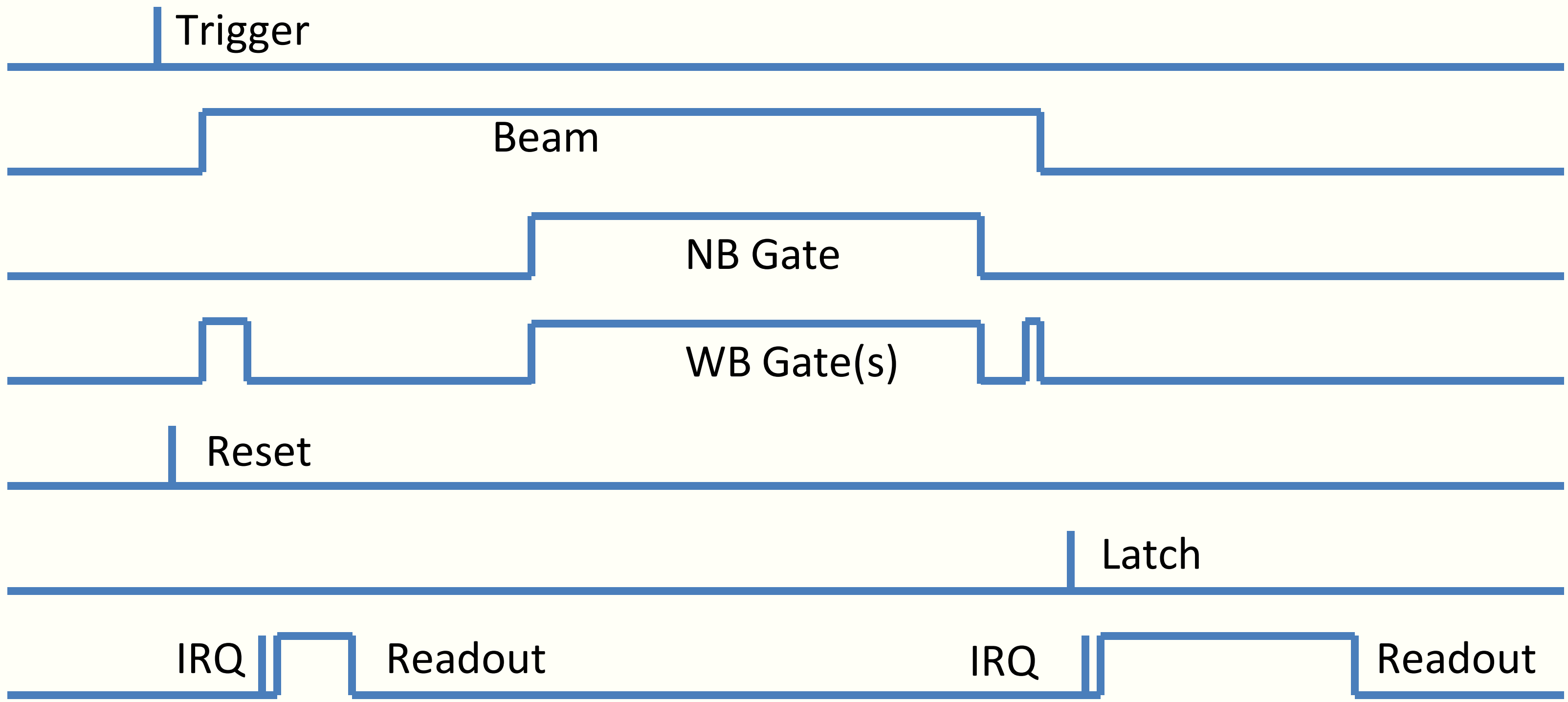
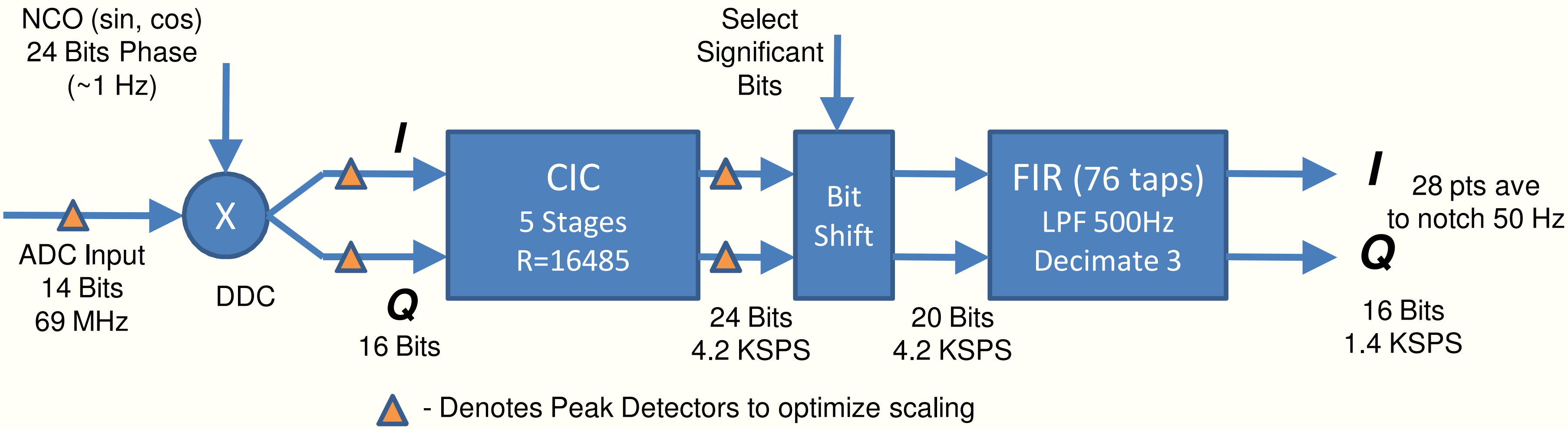
- **Trigger before beam injection (injection rep rate is ~1.5 Hz)**
  - **Beam in machine for ~1e6 turns (~450 msec)**
  - **Each machine turn is 462.18 nsec -> 32 ADC clocks**
  - **Gates specified in turns (need to account for filter delay/decimation for NB)**
  - **Data in boards is overwritten on each trigger**
  - **Note for WB readback (diagnostic and some TBT data) it will be necessary to halt the system to readback all data over the network - *these are special study modes***



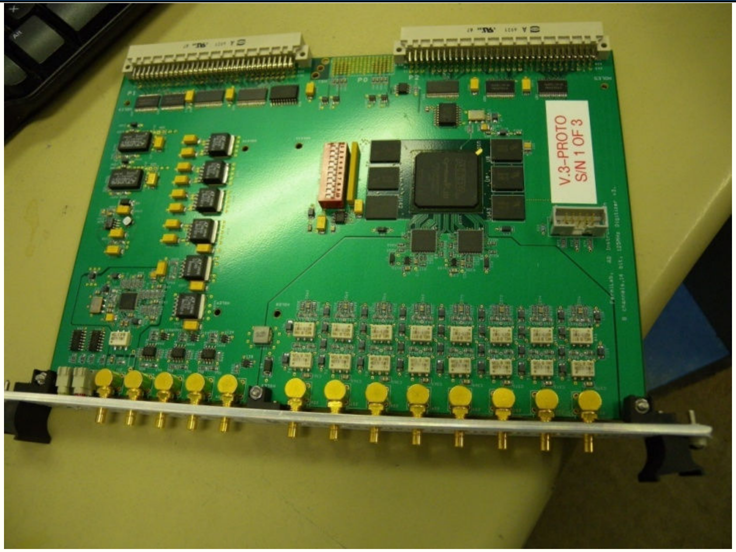
Narrowband Signal Processing

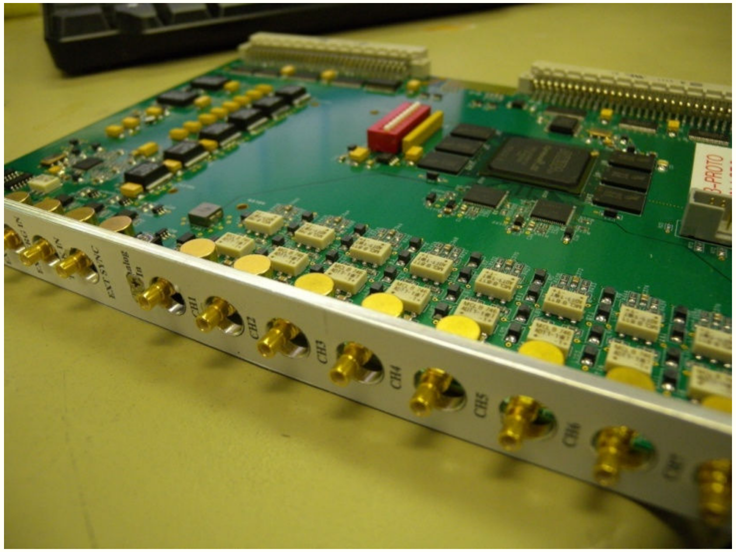
- **Design footprint for 8 ADC channels**
  - **2 NCOs for beam and cal frequencies -> 16 DDCs**
  - **32 CIC Filters operating at 69 MHz**
    - **5 stage CIC uses 13 k LEs and <1% of RAM**
  - **1 Serial FIR Filter will process all 32 CIC Filter outputs**
    - **76 tap FIR (400 Hz BW, 500 Hz Stop, -120 db stopband)**
    - **Decimate by 3 to 1.4 KSPS output**

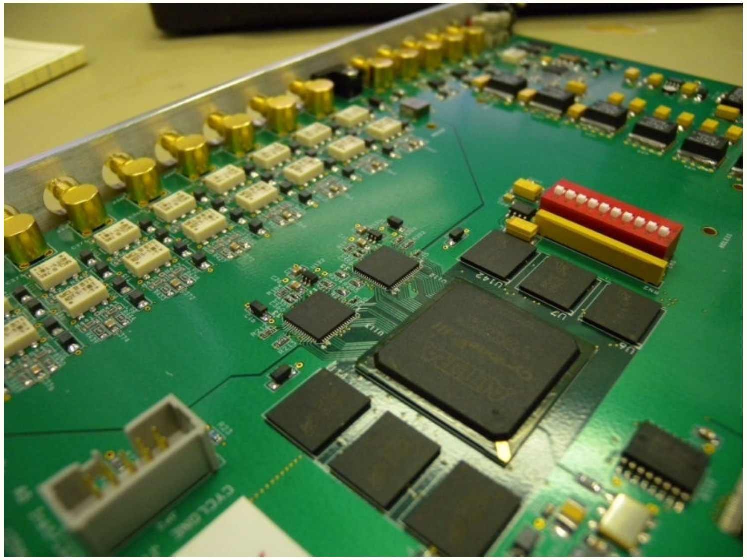
- **General Design Considerations**
  - **For 256 pts get 183 msec data points**
    - ***I,Q* will be read out and magnitude/position calculations done in the VME CPU**
    - **Raw I,Q Data is stored in DDR Ram and may be readback for detailed orbit analysis**
  - **Provide average in realtime for single *I,Q* readback**
    - **Average a multiple of 28 to remove 50Hz**

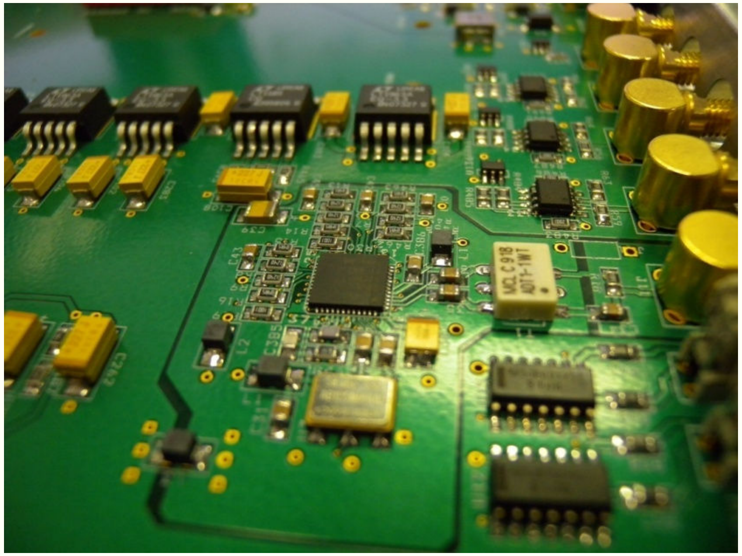


VME/VXS Digitizer

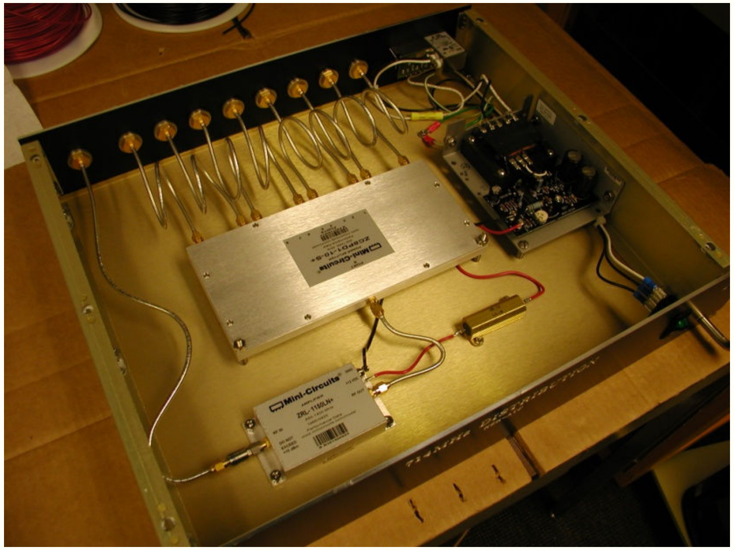


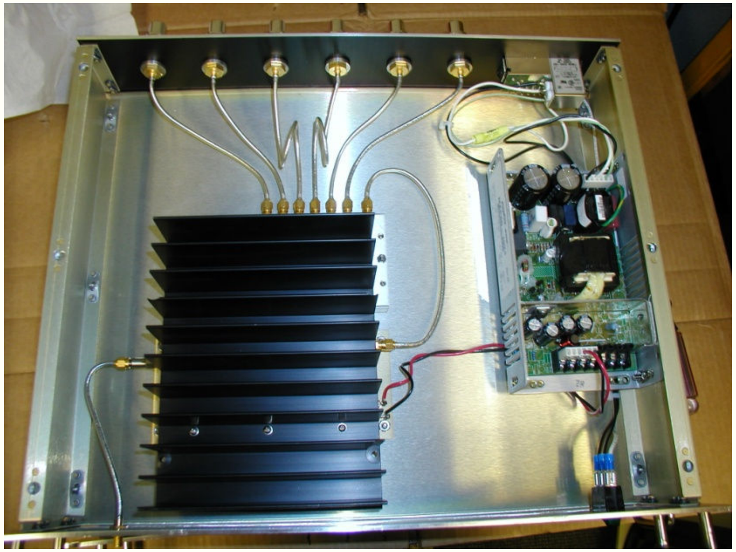


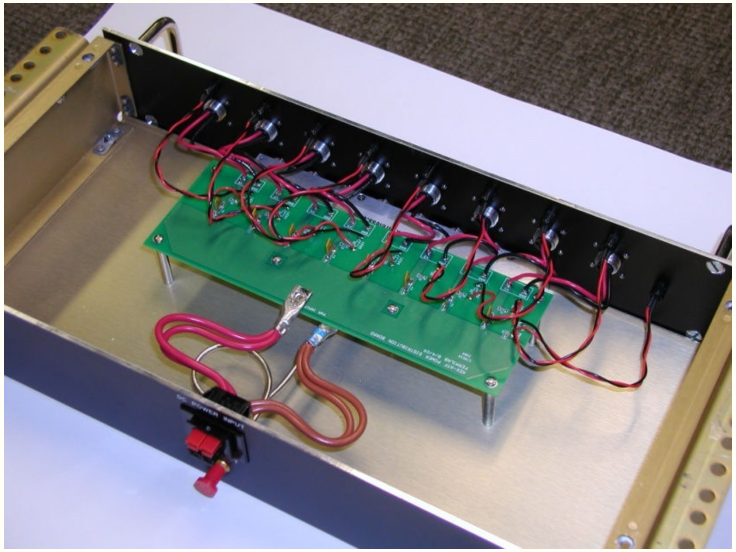




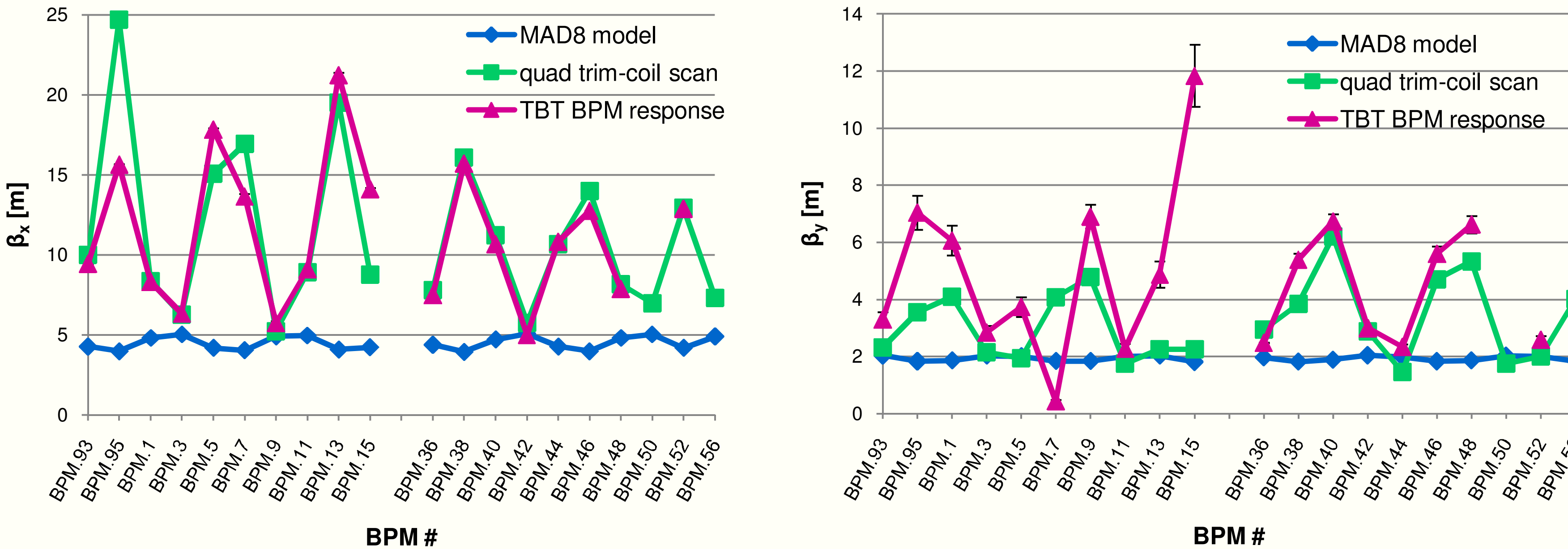
RF, LO & DC Distribution





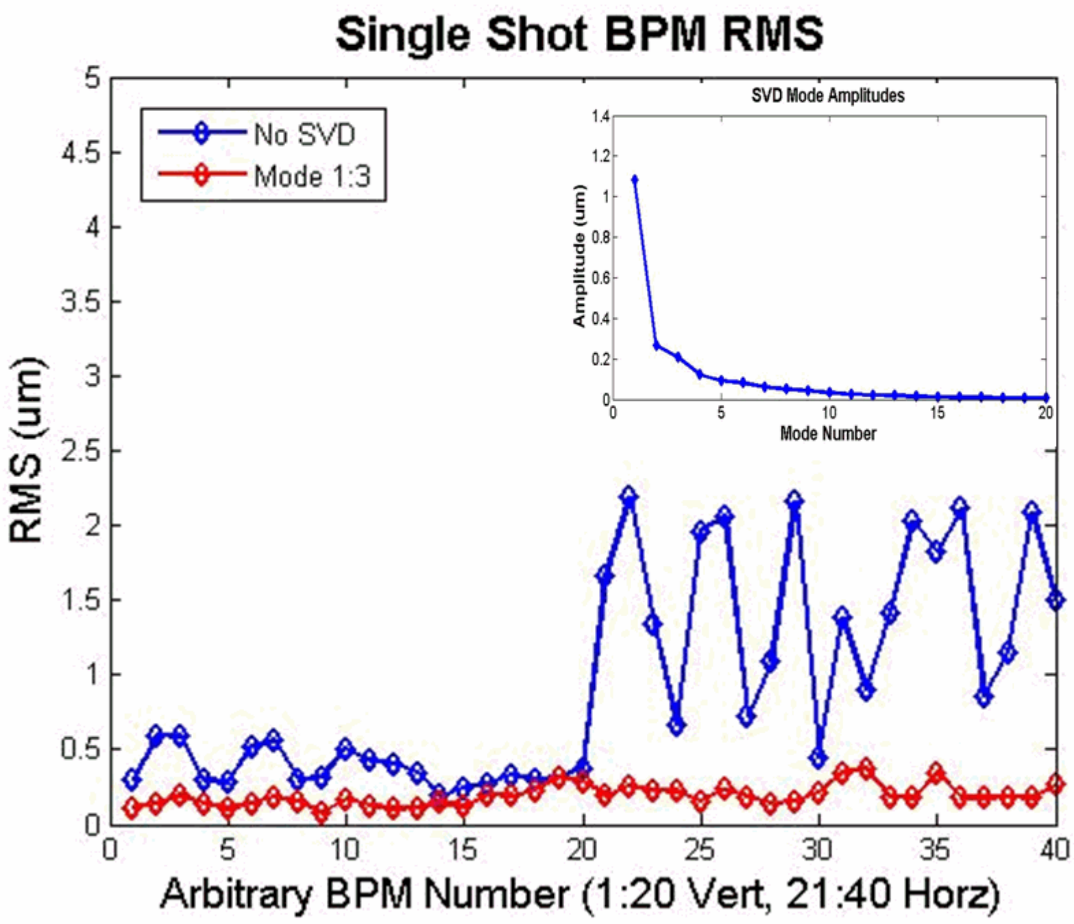


TBT: Measurements vs. Model



- **MAD8 model (M. Woodley, marginal differences wrt. Kuroda SAD model).**
- **Nearby quadrupole trim coil scan (May 2008).**
- **TBT Fourier analysis, amplitude by fit to beta measured through trim coil scan (April 2008).**

Narrowband Mode Resolution



- **Triggered at turn #500,000**
- **~200 ms position data per shot (1280 narrowband mode BPM measurements).**
- **126 tap box car filter to reject 50 Hz:**
  - **~ 800 nm resolution**
- **SVD analysis, removing modes with hor./ vert. correlation:**
  - **~200 nm resolution**

Summary

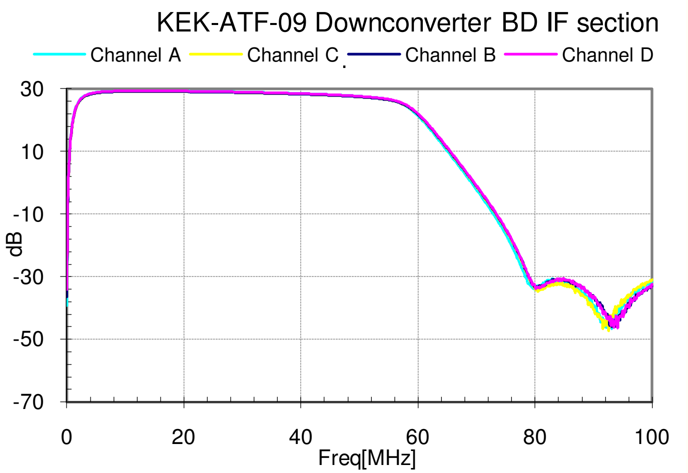
- **After 4 years of developments and beam studies the ATF damping ring BPM upgrade enters the final lap:**
  - **A tailored BPM system towards the specific needs of the ATF damping ring has been developed:**
    - **no DAC outputs, analog downconversion in the tunnel, digitalization in the 1st *Nyquist* passband, automatic calibration system, adaptable design (attenuators, mod. FPGA & EPICS codes)**
  - **The hardware design is frozen**
    - **Successful prototype testing of every system module completed.**
    - **All electronics hardware components are in house.**
    - **Assembly is underway,
followed by individual tests and an integrated system test.**
  - **Next Steps:**
    - **Installation and commissioning of the system (May 2010).**
    - **First beam studies with the new BPM system.**

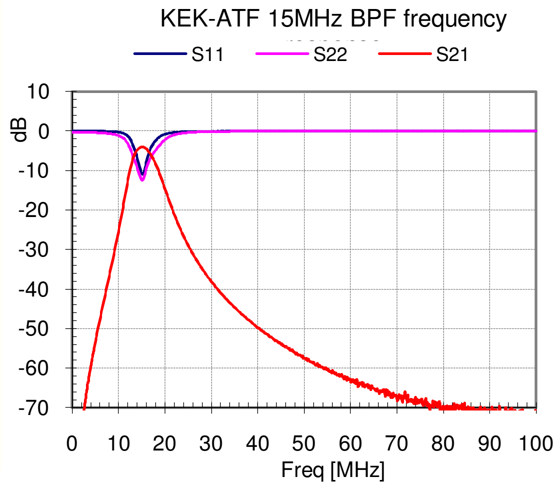
Backup

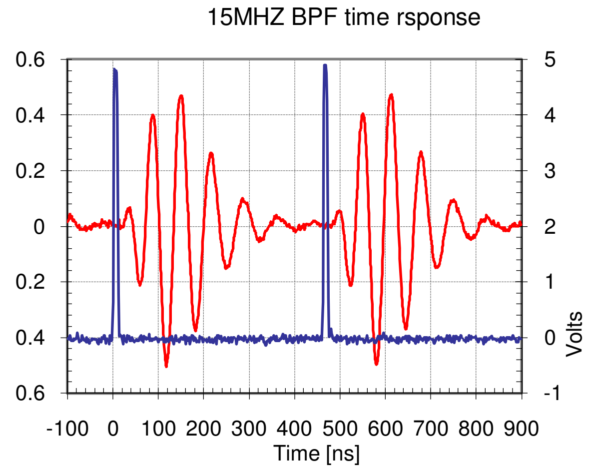
Overview of the BPM Upgrade

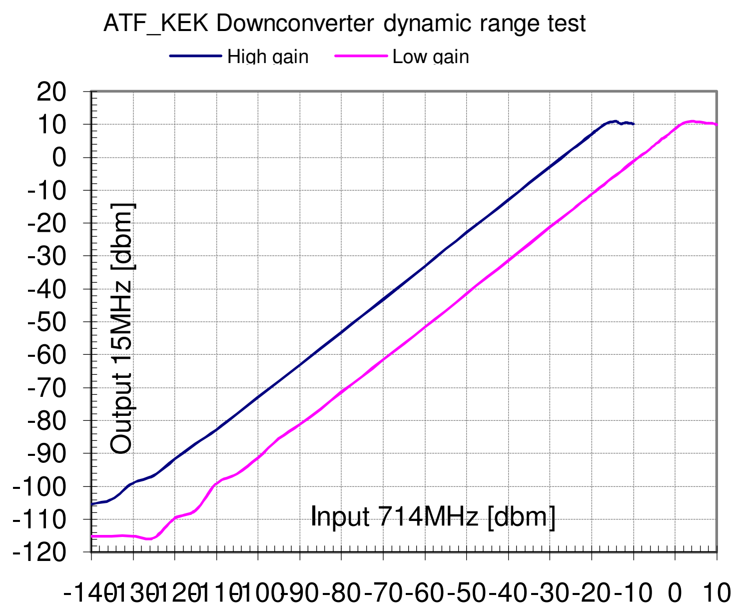
- New read-out hard-, firm- and software, BPM pickups (button-style) stay unchanged.
- R&D activities over the last couple of years on 20 BPMs in the arcs, utilizing mixed analog/digital signal processing
  - Test of different analog downconverters (w/o CAL)
  - Digital signal processing based on spare *Echotek* digital receivers.
- Final upgrade scenario (96 BPMs, plus spares)
  - 714-to-15.1 MHz analog downconverter with CAN-bus controlled calibration tone, located in the tunnel.
  - VME hard- & software, in 4 rack locations
    - 8-ch. 125 MSPS digitizer with an *Altera* Cyclone III FPGA
    - 12 ch. VME timing generator (Fermilab).
    - *Motorola* 5500 VME controller, with CAN-bus interface, running VxWorks & EPICS software
  - Auxiliary hardware, e.g. power supplies and distribution, LO-signal distribution, CAN-bus distribution, etc.

Analog Downmixer









- **Modified IF section**
  - **Low-noise gain stage**
  - **15.1±1.5 MHz BPF, ~400 ns ring-time**
- **Improved NF & dynamic range**
  - **NF = 17 dB (?)**
  - **>90 dB dynamic range**

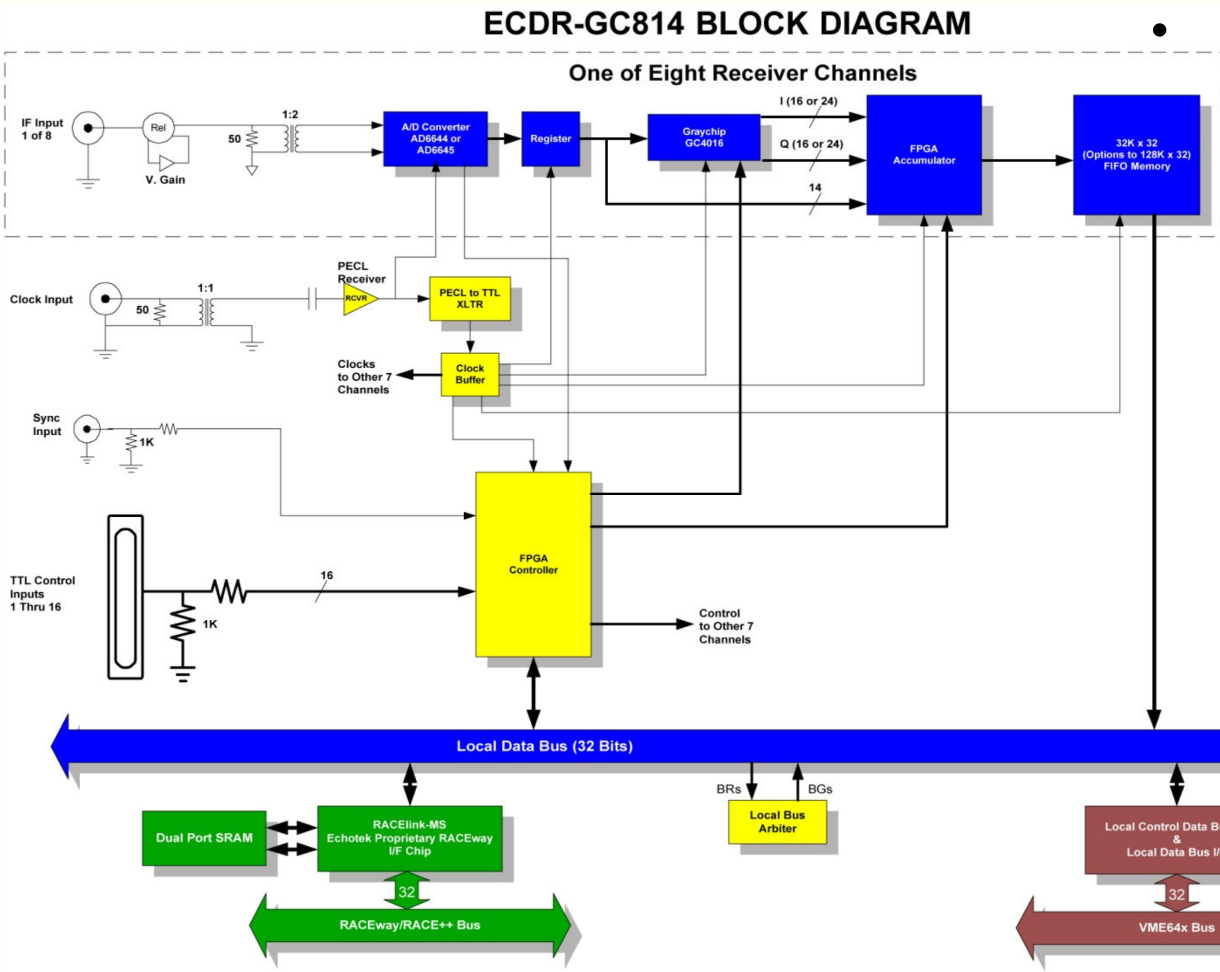
Memory Map

- Control Space
  - Channel delays (8)
    0 to 31 samples
  - Gate parameters (18)
    1 to ~1e6 turns
    - NB specified by start and stop turn
    - WB (8 gates) specified by start and stop turn
  - NCO frequencies (2), CIC shift (1)
    - Possibly FIR coefficients for NB
  - Specify TBT box filter –
    1st sample, number to average (2)
  - IRQ Level (1)
    - Multi-level IRQ handler
    - Data Ready/Overflows
  - Diagnostic Peak Detectors (to monitor saturation) each 32 bit register
    - Peak Detectors record max value at each stage for last injection (Reset & Latch from DAQ SM)

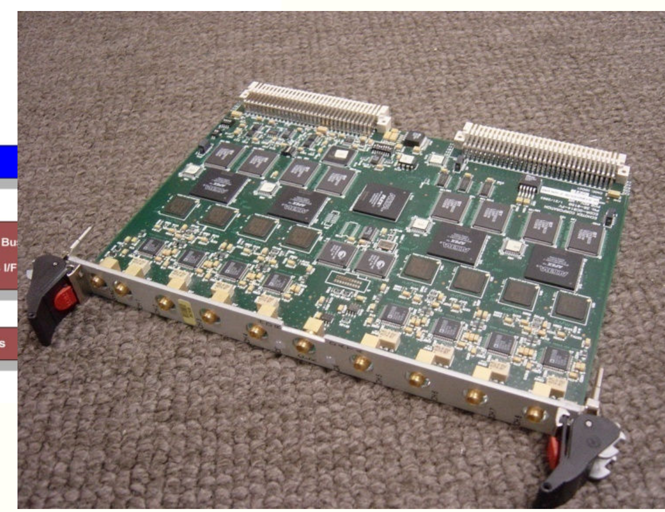
- Store SumI, SumQ for each I,Q channel in 32 contiguous registers
  - Sum will be a multiple of 50 Hz (28 pts out of NB)
  - Standard Narrowband readout

- DDR RAM
  - All Data from gates stored in RAM
  - Separate Banks for Narrowband, TBT, and RAW Data
    - Each Bank mapped to VME
    - Address offsets for each bank programmable
  - Channel data in each bank can be readback as contiguous data blocks
    - Facilitate readback of data from single bpm if requested (ie TBT data)

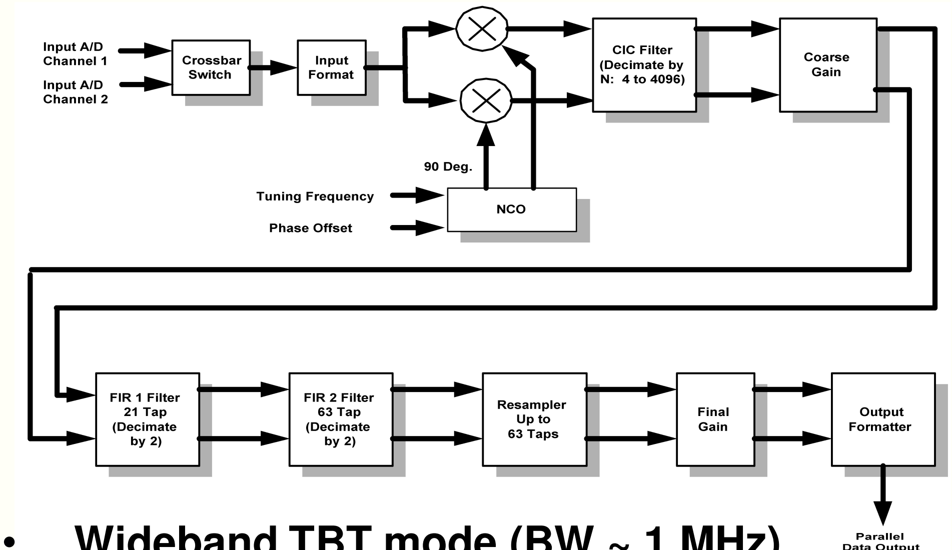
Digital Signal Processing



- *Echotek* digital receiver
  - 8-ch VME64x module
  - *Analog Devices* 14-bit 105 MS/s AD6645
  - Each ADC channel: *Texas Instruments* 4-ch GC4016 “*Graychip*” digital downconverter
  - 128 kWord FIFO

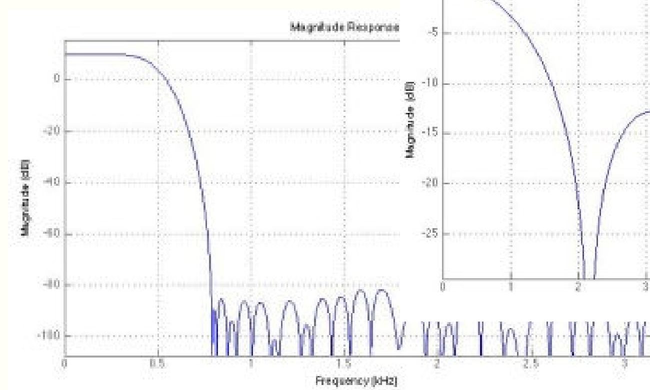


Digital Signal Processing (cont.)

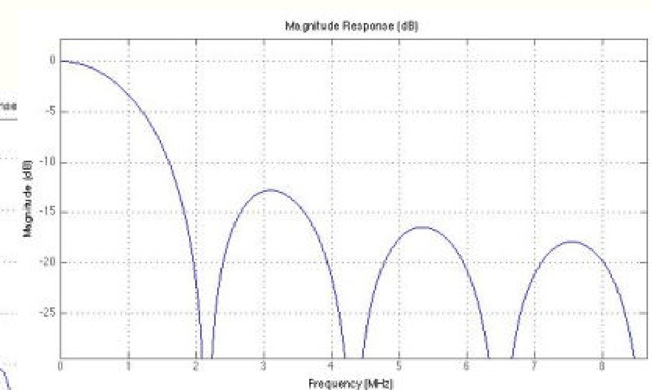


- *Graychip* digital downconverter
  - 4 independent channels per ADC
  - NCO set to f_{IF} = 15.145 MHz (downconvert to DC baseband)
  - ADC clock set to 32 samples per revoltion: $f_{CLK} = 32 \times f_{rev}$ = 69.2 MHz
  - Decimation and filtering for wide- and narrowband mode using CIC and FIR digital filters
  - Simultaneous DDC operation of beam and calibration signals!

- Wideband TBT mode (BW ~ 1 MHz)
  - 5 stage CIC: decimate by 4
  - CFIR: 7-tap boxcar, decimate by 2
  - PFIR 1-tap, no decimation
- Narrowband mode (BW ~ 500 Hz), t_{dec} = 158.7 µs, 1280 pt (~200 ms)
  - 5 stage CIC: decimate by 2746
  - CFIR: 21-tap RRC, decimate by 2
  - PFIR: 63-tap RRC, decimate by 2



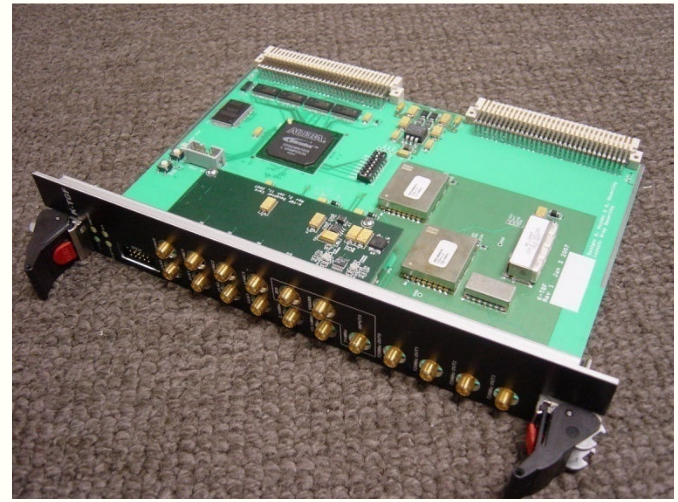
NB mode PFIR response



WB CFIR response

Other Hardware

- **VME Timing module:**
  - $f_{CLK} = f_{RF}$*32/330 = 69.236 MHz clock signals (4x)
  - t_{rev} = 462.2 ns turn marker signals (4x), 0…115 double-buckets (2.8 ns) delayable
  - To f_{RF} phase-locked f_{LO} = 729.145 MHz
  - Auxiliary f_{rev} and f_{IF} signals



- ***Motorola* 5500 VME CPU:**
  - Data collection and normalization
  - Box-car post-processing filter (20 ms)
  - Local diagnostic and control software
  - EPICS control interface
- **Calibration & remote control unit (prototype):**
  - To f_{RF} phase-locked $f_{CAL} \approx$ 714 MHz (*Analog Devices* ADF4153)
  - In-passband, through button-BPM, or reflected signal calibration
  - 2^{nd} and 3^{rd} *Graychip* channels for CAL signal downconversion
  - CAN-bus remote control functions (attenuation, gain, PLL freq., etc.)

Calibration Details

- **Calibration tone frequencies:**
  - f_{CALx} = 713.6 MHz
  - f_{CALy} = 714.4 MHz
- **Calibration procedure:**
  - Correction values:

$$A_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4A_{CAL}} \qquad B_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4B_{CAL}}$$

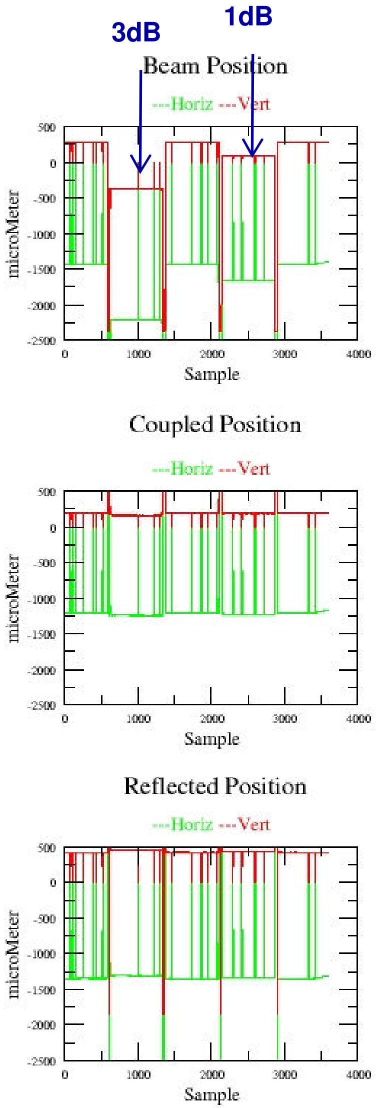
$$C_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4C_{CAL}} \qquad D_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4D_{CAL}}$$

  - Corrected beam positions:

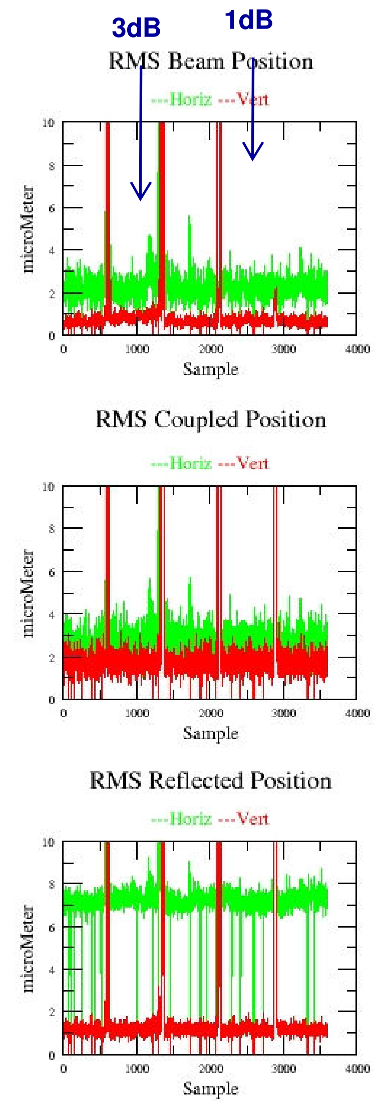
$$\phi_{Hcorr} = \frac{(A\,A_{Corr} + D\,D_{Corr}) - (B\,B_{Corr} + C\,C_{Corr})}{A\,A_{Corr} + B\,B_{Corr} + C\,C_{Corr} + D\,D_{Corr}}$$

$$\phi_{Vcorr} = \frac{(A\,A_{Corr} + B\,B_{Corr}) - (C\,C_{Corr} + C\,C_{Corr})}{A\,A_{Corr} + B\,B_{Corr} + C\,C_{Corr} + D\,D_{Corr}}$$

CAL System Test

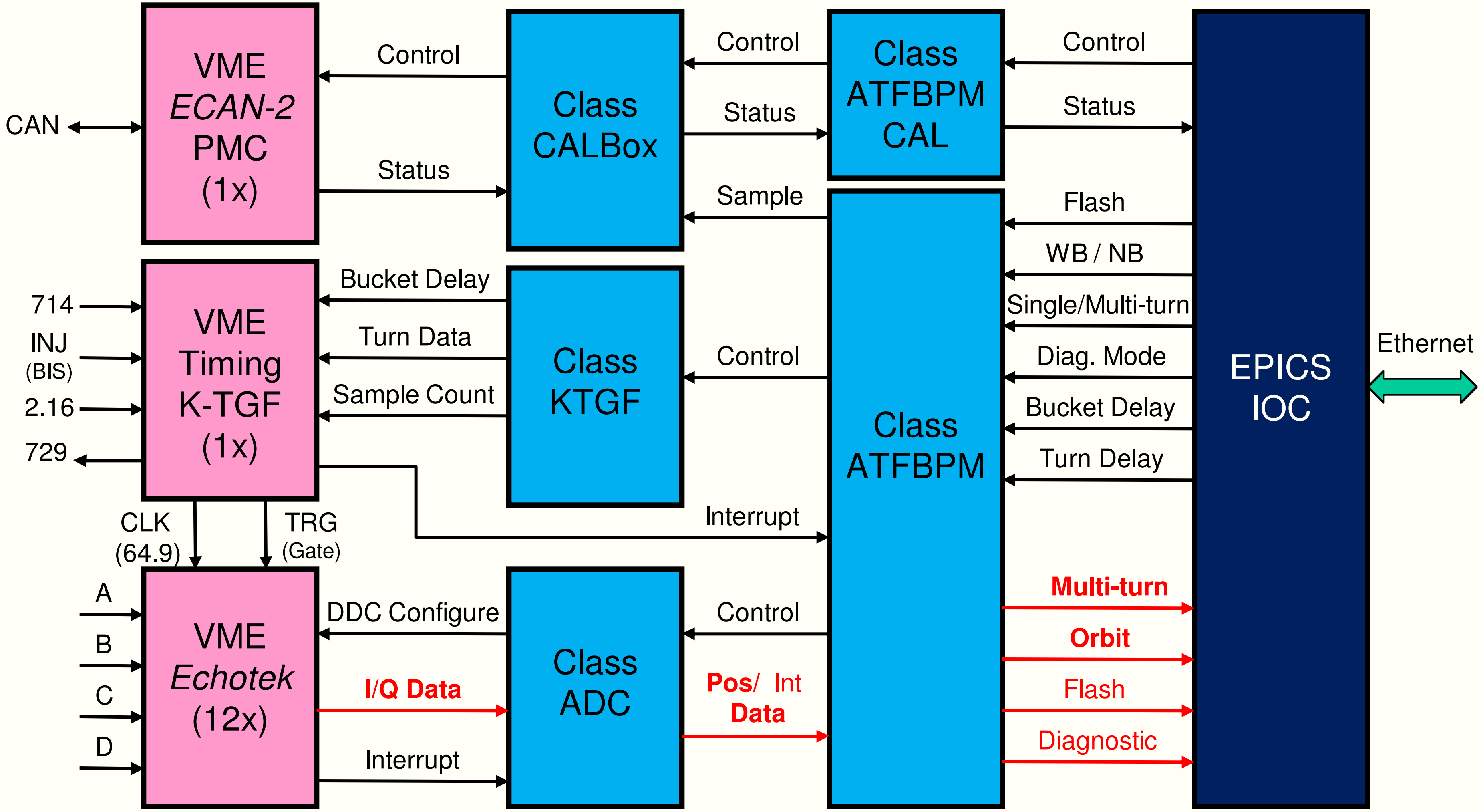


- Calibration on, datalogger on
- Comparing uncorrected, corrected (coupled-through), and corrected (reflected)
- Introduce large 3 & 1 dB gain errors.
- Automatic correction compensates the gain error almost completely!!
- Corrected beam position shows a slight increase of the RMS error (to be further studies!).



Software Components

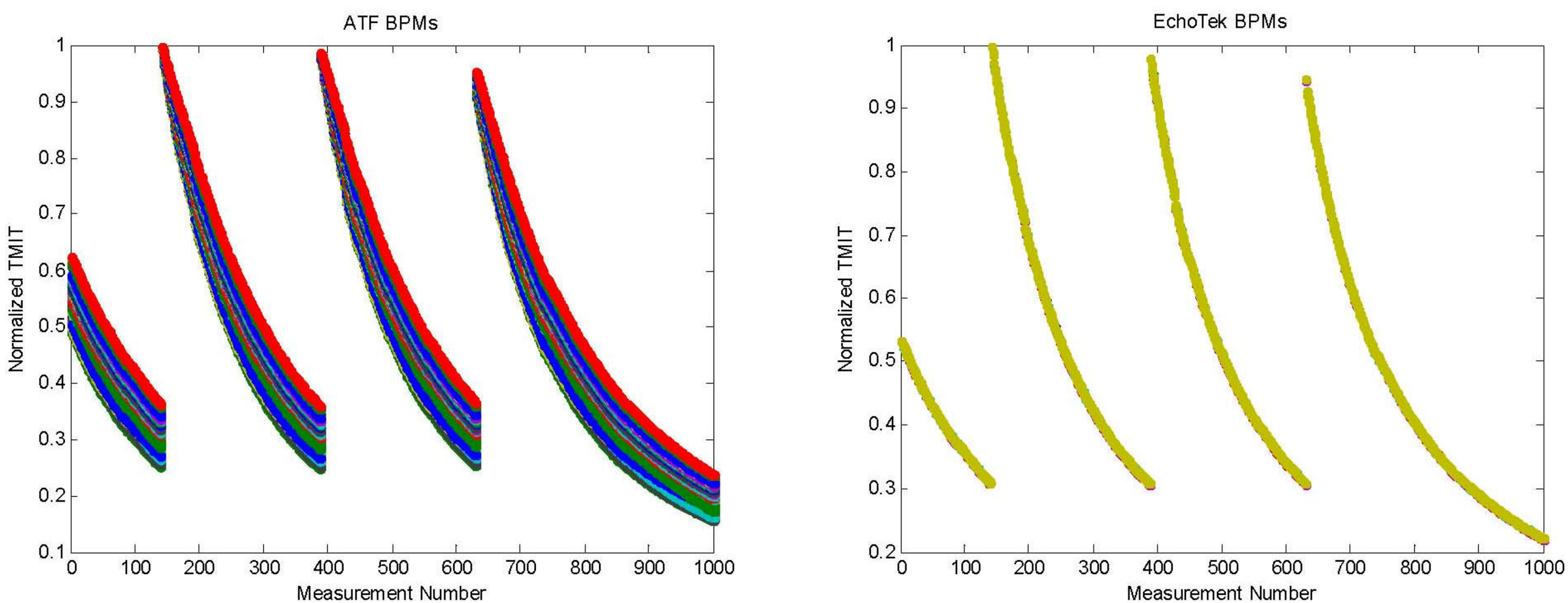
VME Hardware — *Motorola* 5500 µP Software (VxWorks)



Scrubbing Mode, Intensities

070518

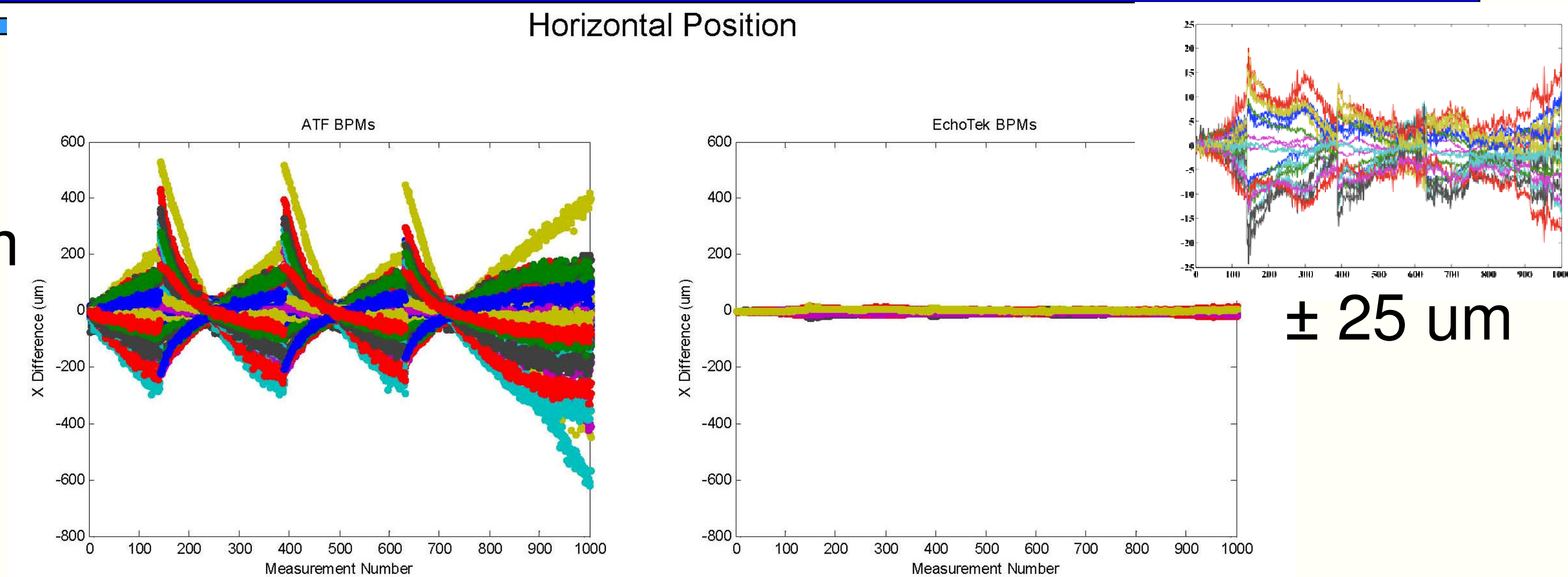
Normalized Intensities



Scrubbing Mode, Positions

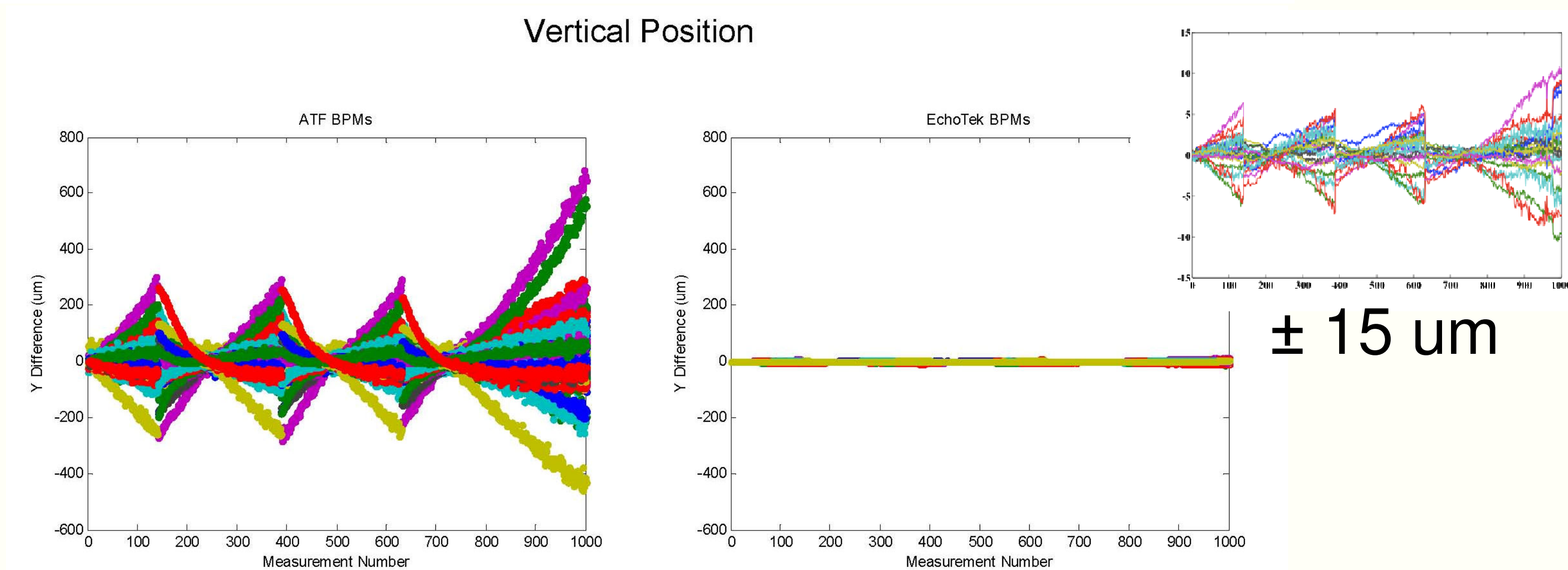
070518

± 700 um



± 25 um

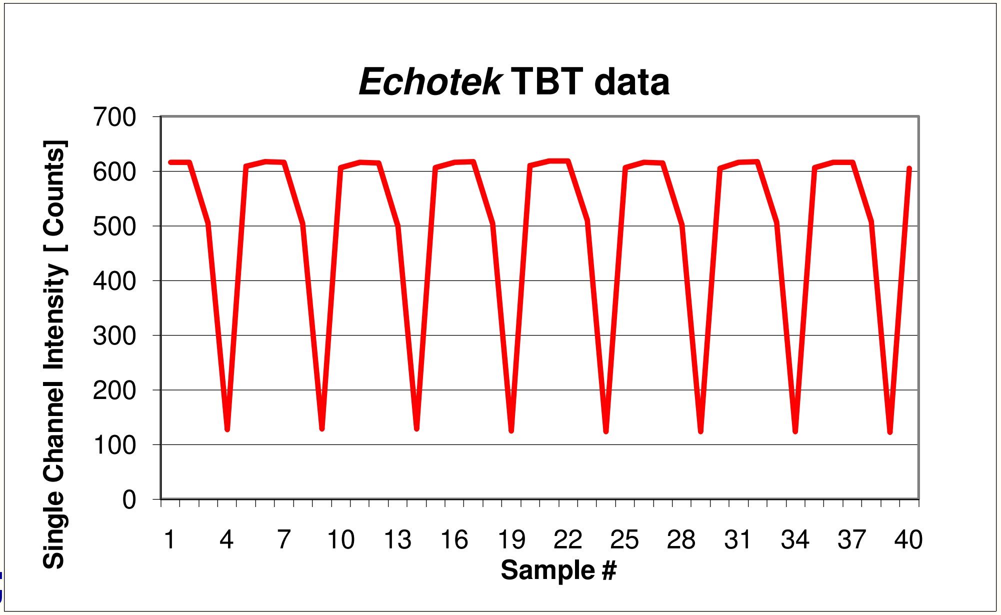
± 700 um



± 15 um

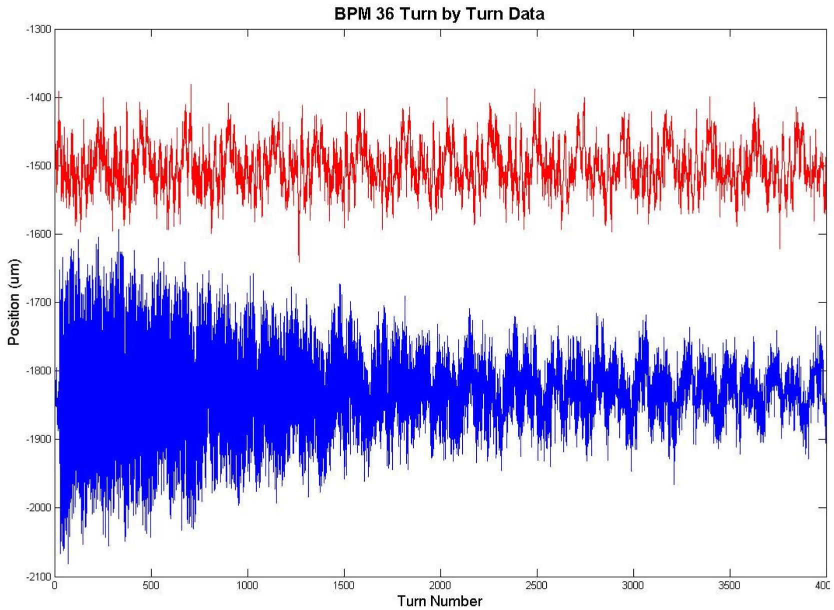
Wideband, TBT Mode Beam Tests

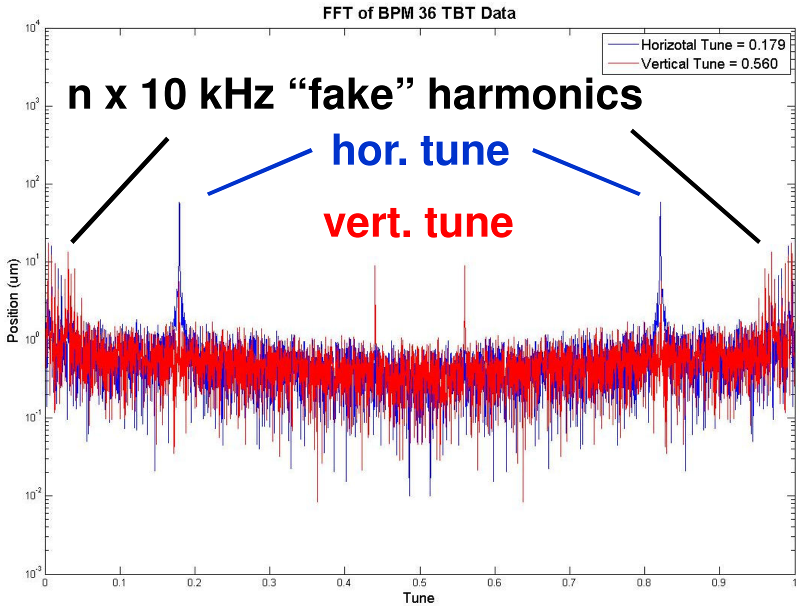
- **Several "issues" had to be resolved:**
  - **CIC & FIR digital filter impulse responses to resolve true turn-by-turn data (no "smearing")**
  - **Timing issues, e.g. channel-to-channel, as well as between BPMs and "houses" (VME crates); and of course the usual "seam" problem.**



- **In particular for the kicked beam TBT response tests:**
  - **Vertical beta at pinger is 0.5 m (12 times smaller than the horizontal one): we had to resort to injection oscillations -> lower resolution.**

Kicked Beam Tests (May 2007)





- Turn-by-Turn data BPM #36 (pinger: On)
- Identifying hor. and vert. tune lines (387 kHz, 1.212 MHz).
- Observed short time, broadband TBT resolution: few µm!
- Observation of "fake" harmonics at n x 10 kHz (not f_s), due to power supply EMI in the analog downconverter unit!

TBT Fourier Analysis

- **TBT data at the j^{th} BPM following a single kick in the *z*-plane ($z \equiv x, y$):**

$$z_n^j = \frac{1}{2}\sqrt{\beta_z^j}\, e^{i\Phi_z^j}\, A_z\, e^{iQ_z(\theta_j + 2\pi n)} + c.c.$$

  - **with**

$$n \equiv \text{turn number}, \qquad A_z = |A_z| e^{i\delta_z} \equiv \text{constant of motion}$$

$$\Phi_z \equiv \mu_z - Q_z\theta \quad \text{(periodic phase function)}$$

- **Twiss functions:**

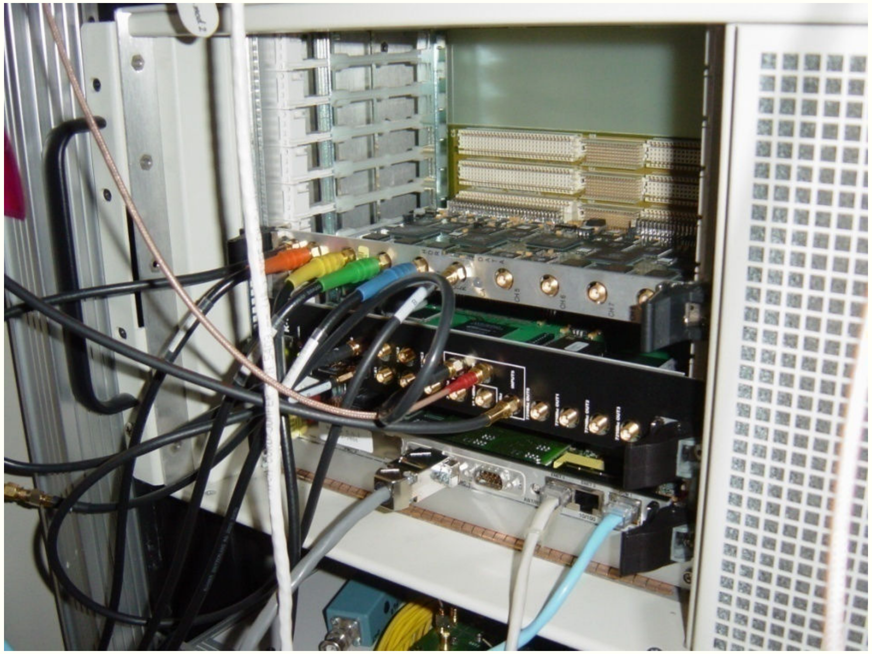
$$\beta_z^j = |Z_j(Q_z)|^2 / |A_z|^2 \qquad \mu_z^j = \arg(Z_j) - \delta_z$$

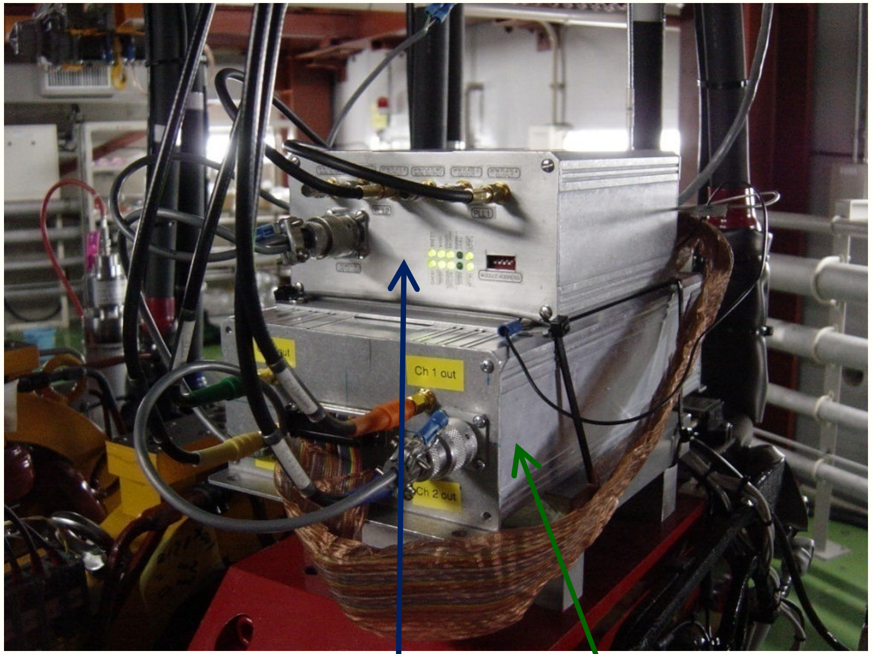
$$Z_j(Q_z) \equiv \textit{Fourier} \text{ component of } z_j$$

- **Amplitude fit:**

$$|A_z|^2 = \frac{\sum_j 1/\beta_z^{0j}}{\sum_j 1/|Z_j(Q_z)|^2}$$

Downconverter & CAL Proto





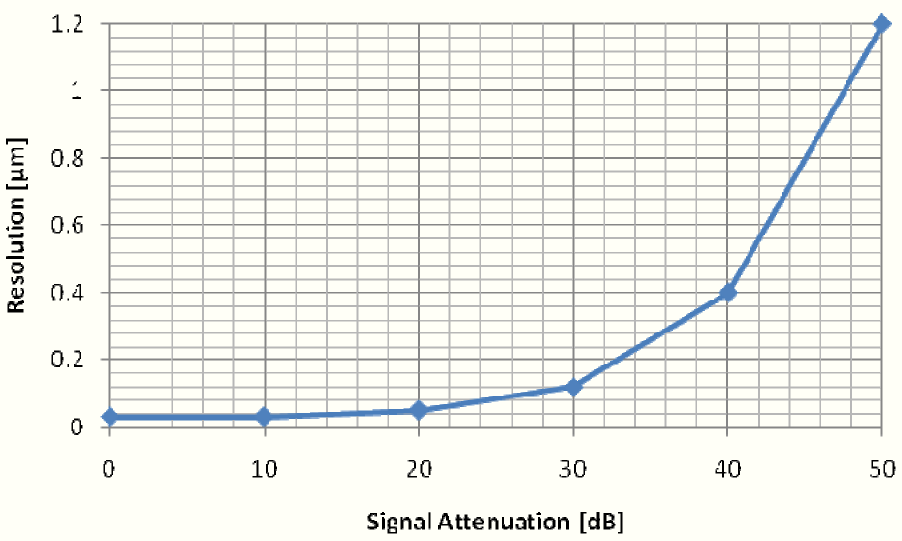
- Mini VME crate accommodating:
  - *Motorola* **5500 CPU**
  - **PMC CAN bus interface *ECAN-2***
  - **Timing module TGF**
  - ***Echotek* digital receiver module**

- BPM #54 prototype installation (temporary):
  - **CAN bus remote control & CAL signal PLL unit (Fermilab)**
  - **4 ch. Downconverter unit (SLAC)**

EPICS Data Acquisition

	Multi-turn	Orbit	Flash
Wide-Band	Samples: 4096 Samples/turn: 4 Turns: 1024 POSITION Intensity	Average Samples: 4096 Turns: 1024 POSITION (RMS & StdDev) Intensity (RMS & StdDev)	N^{th} Sample (1) POSITION Intensity
Narrow-Band	Samples: 1280 μsec/Sample: 158.73 Turns: 439600 POSITION Intensity	Average Samples: 126 (50 Hz Boxcar) Turns: 43273 POSITION (RMS & StdDev) Intensity (RMS & StdDev)	N^{th} Sample (1) POSITION Intensity

NB Mode Resolution Limit



Theoretical:

- **ADC SNR: 75 dB**
- **Process gain: 40.4 dB**
- **NF 1st gain stage: ~ 1 dB**
- **CAL tone level: -10 dBm**
- **Splitter attenuation: 6 dB**
- **Effective gain: ~ 100 dB**
- **BPM sensitivity: 240 µm/dB**
- **Calculated equivalent resolution: ~ 20 nm**

CAL tone resolution measurement on BPM #56: ~30 nm(!) equiv. resolution (no beam operation at ATF!, magnets off)