Experience with *Echotek* Digital Receivers for High Performance Beam Position Measurements

– ATF Damping Ring BPM Upgrade –

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Fermilab

for the ATF DR BPM Upgrade Collaboration

ATF DR BPM Collaboration

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SLAC
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- Justin May
- Janice Nelson
- Andrei Seryi
- Tonee Smith
- Mark Woodley

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- Nathan Eddy
- Eliana Gianfelice
- Bill Haynes
- Peter Prieto
- Dennis Nicklaus
- Ron Rechenmacher
- Duane Voy
- Manfred Wendt

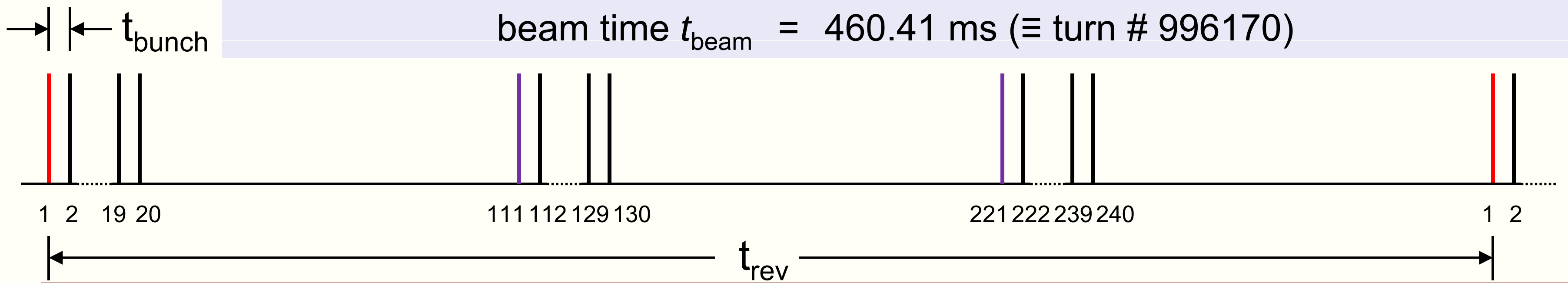
…and many others!

Motivation

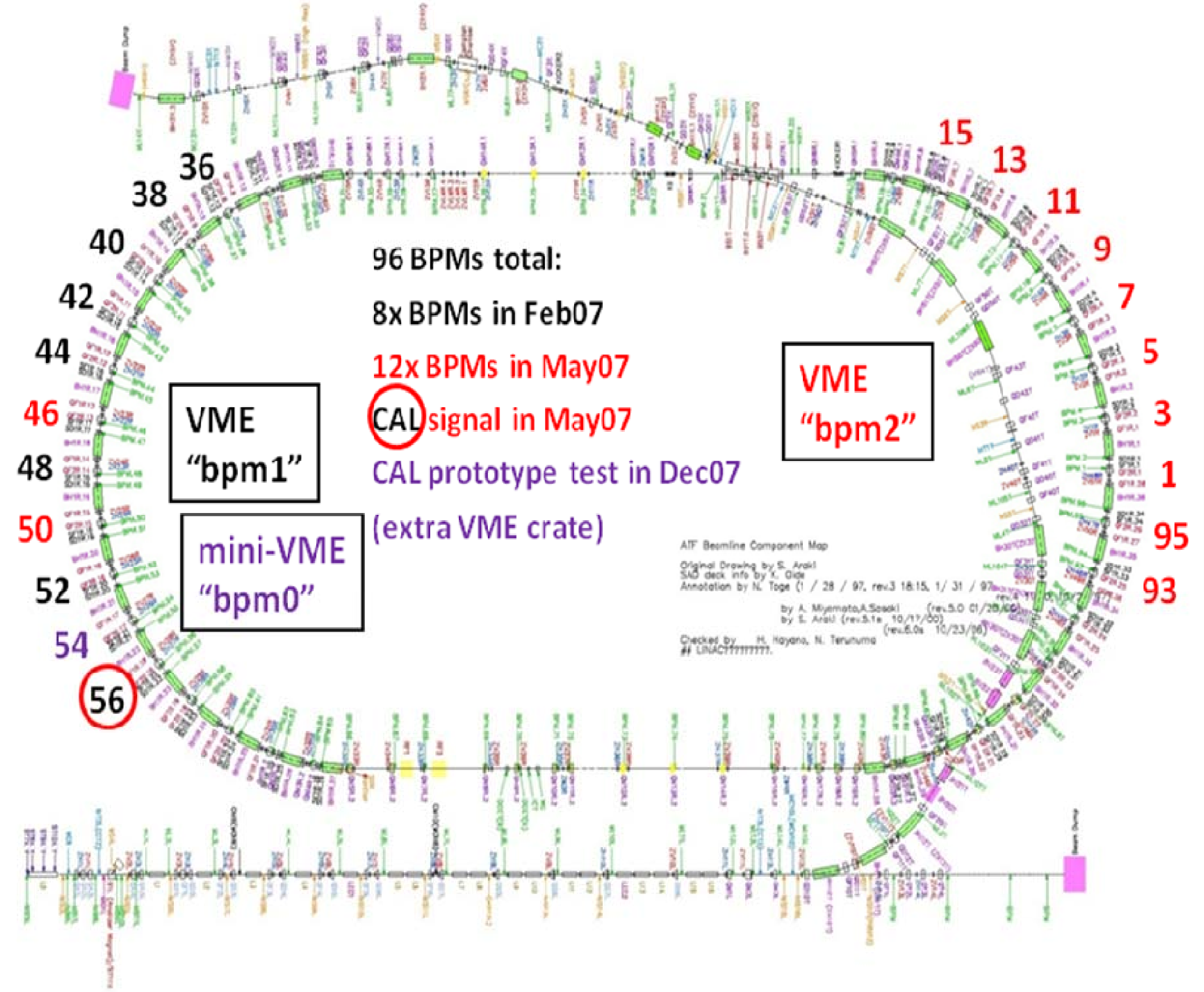
- **ILC damping ring R&D at KEK's Accelerator Test Facility (ATF):**
  - **Investigation of the beam damping process (damping wiggler, minimization of the damping time, etc.)**
  - **Goal: generation and extraction of a low emittance beam (ε_{vert} < 2 pm) at the nominal ILC bunch charge**
- **A major 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)**

The ATF Damping Ring

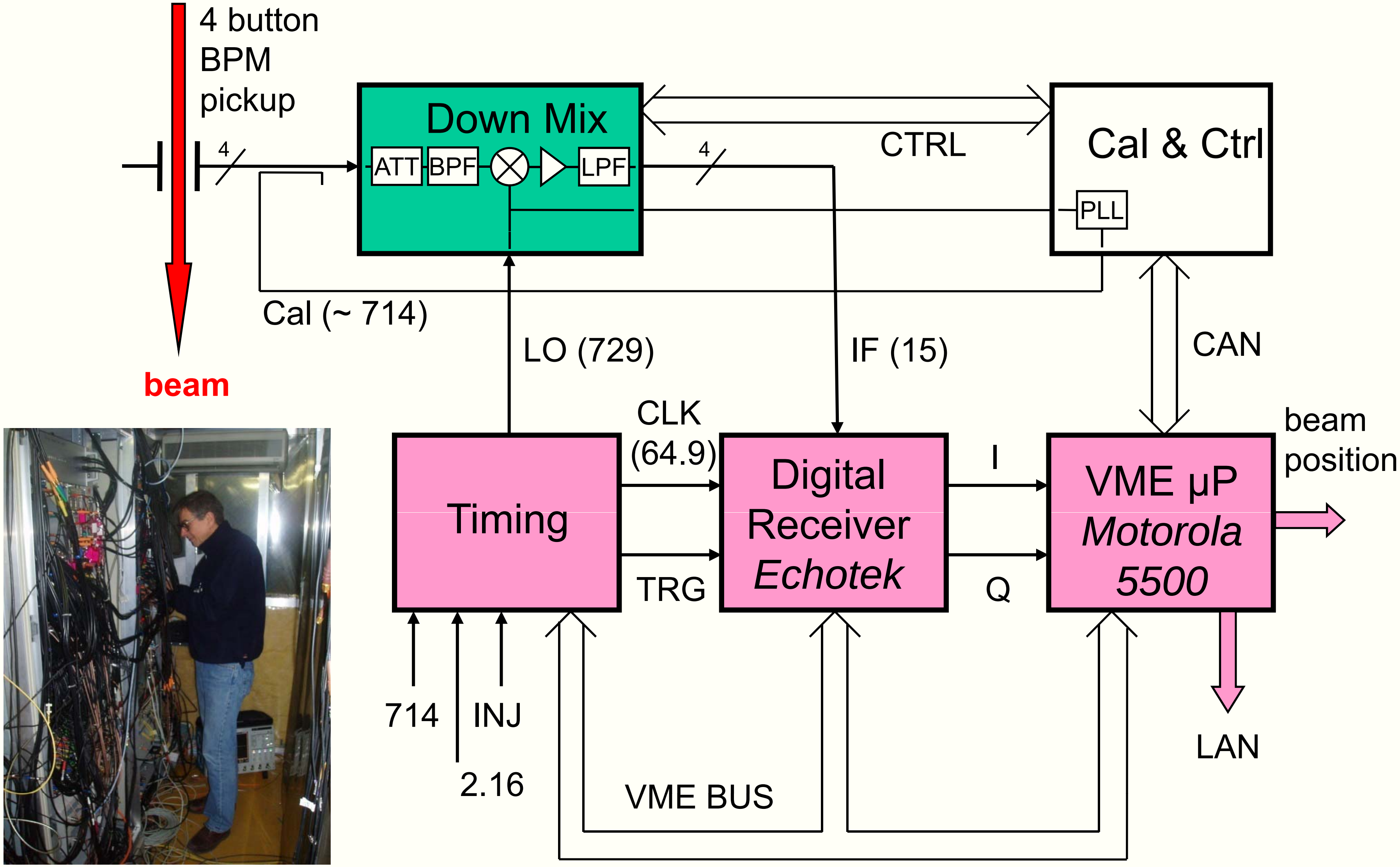
Machine and Beam Parameters		
beam energy E	=	1.28 GeV
beam intensity, single bunch	≈	~1.6 nC ≡ 10^{10} e^- (≡ I_{bunch} ≈ 3.46 mA)
beam intensity, multibunch (20)	≈	~22.4 nC ≡ 20 x0.7 10^{10} e^- (≡ I_{beam} ≈ 48.5 mA)
accelerating frequency f_{RF}	=	714 MHz
revolution frequency f_{rev}	=	f_{RF} / 330 = 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)



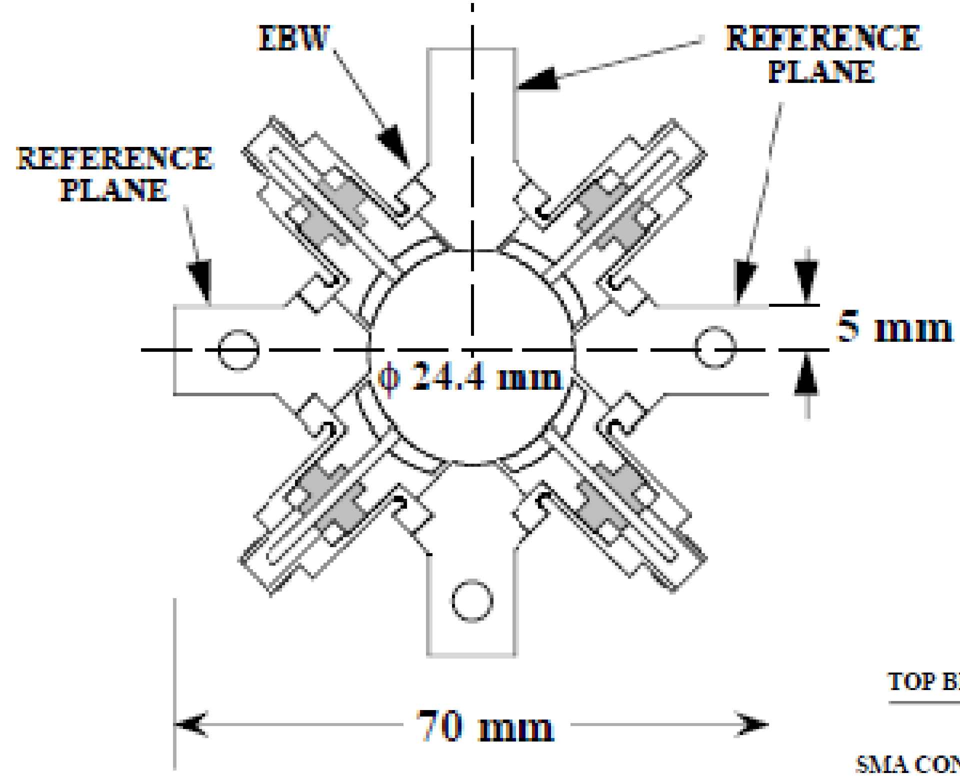
The ATF Damping Ring

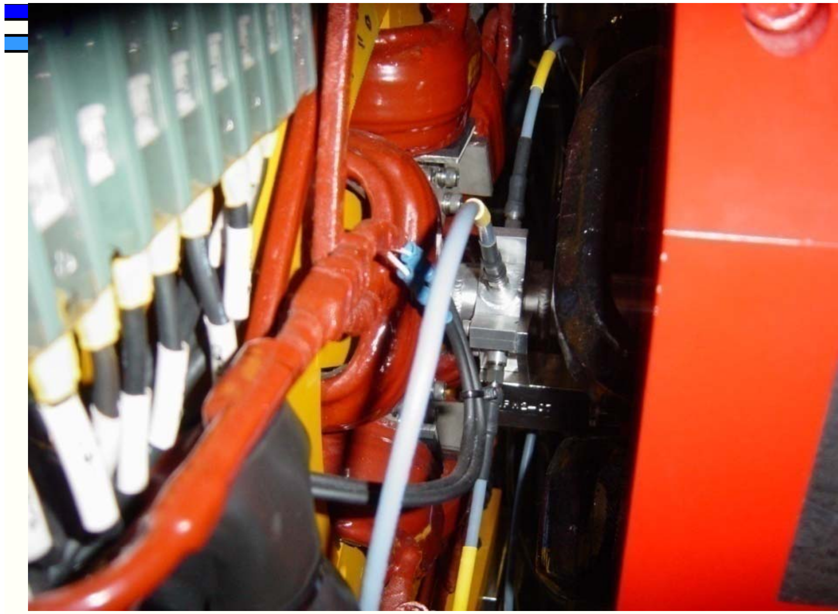


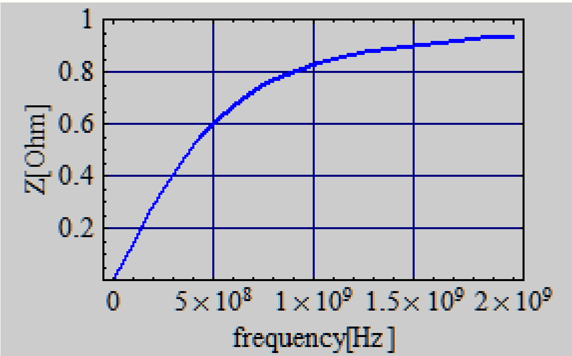
BPM Hardware Overview



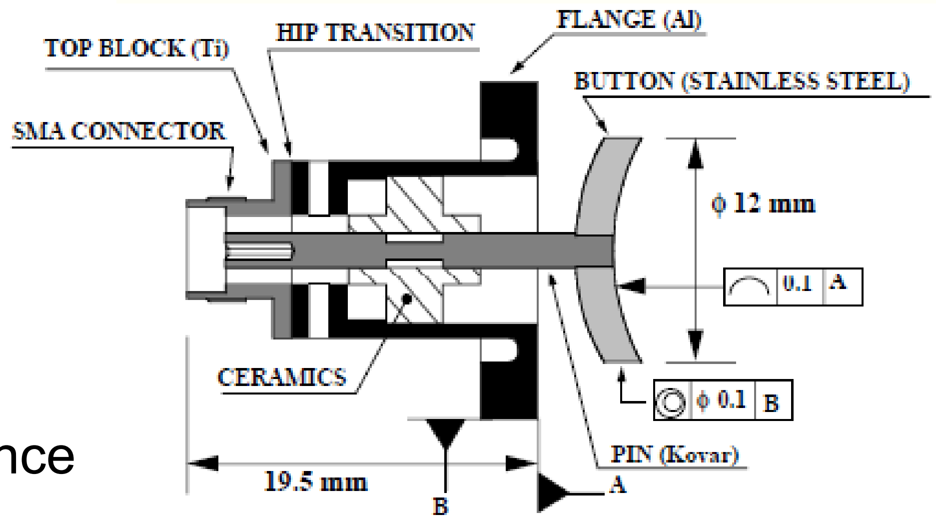
Button-style BPM Pickup



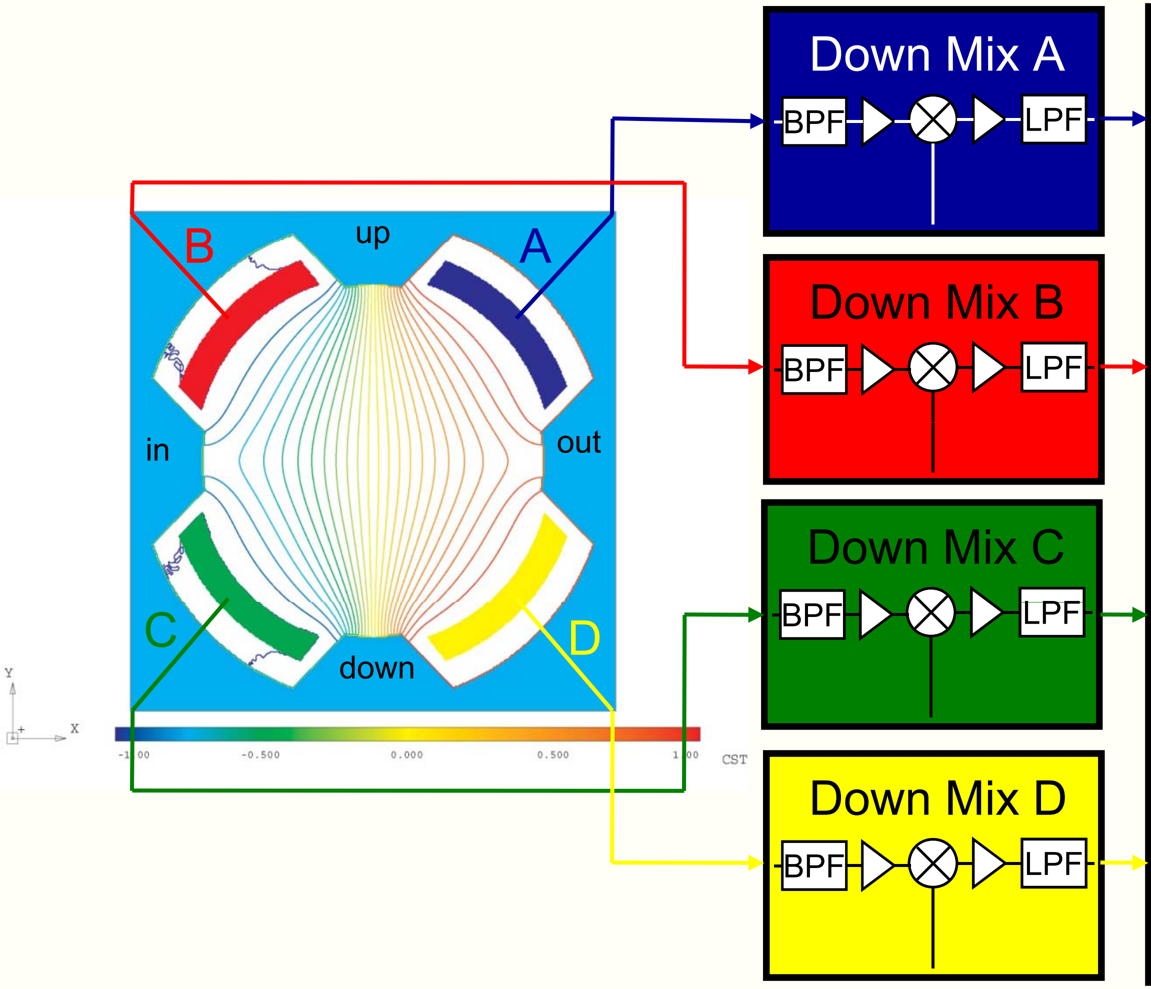




Button:
transfer
impedance



Beam Position Signal Processing



"Echotek" digital signal processing:

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

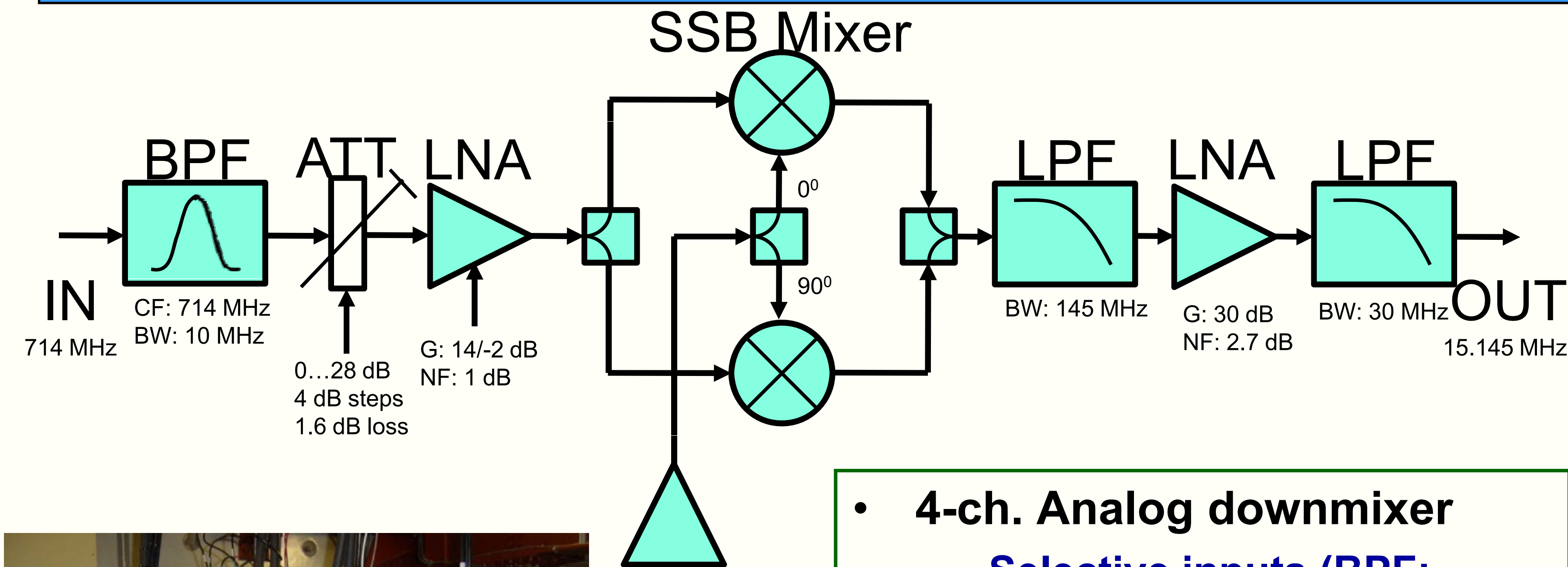
$$\phi_V = \frac{(A+B)-(C+D)}{A+B+C+D}$$

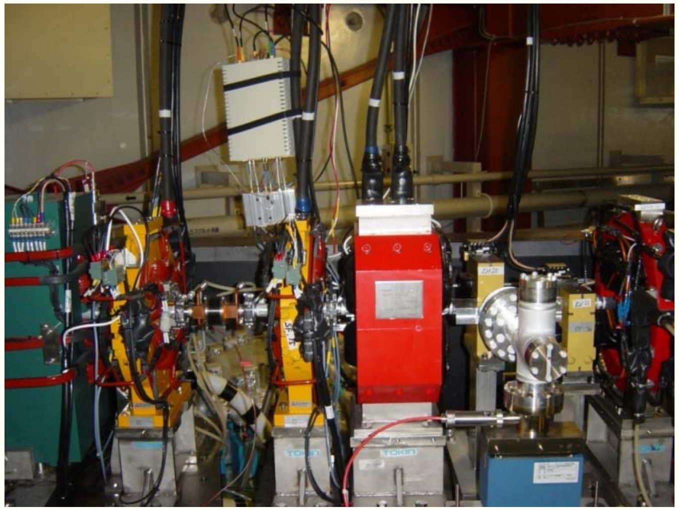
1D polynomial fit:

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

0.1 dB gain error ≡ 27 μm offset error !

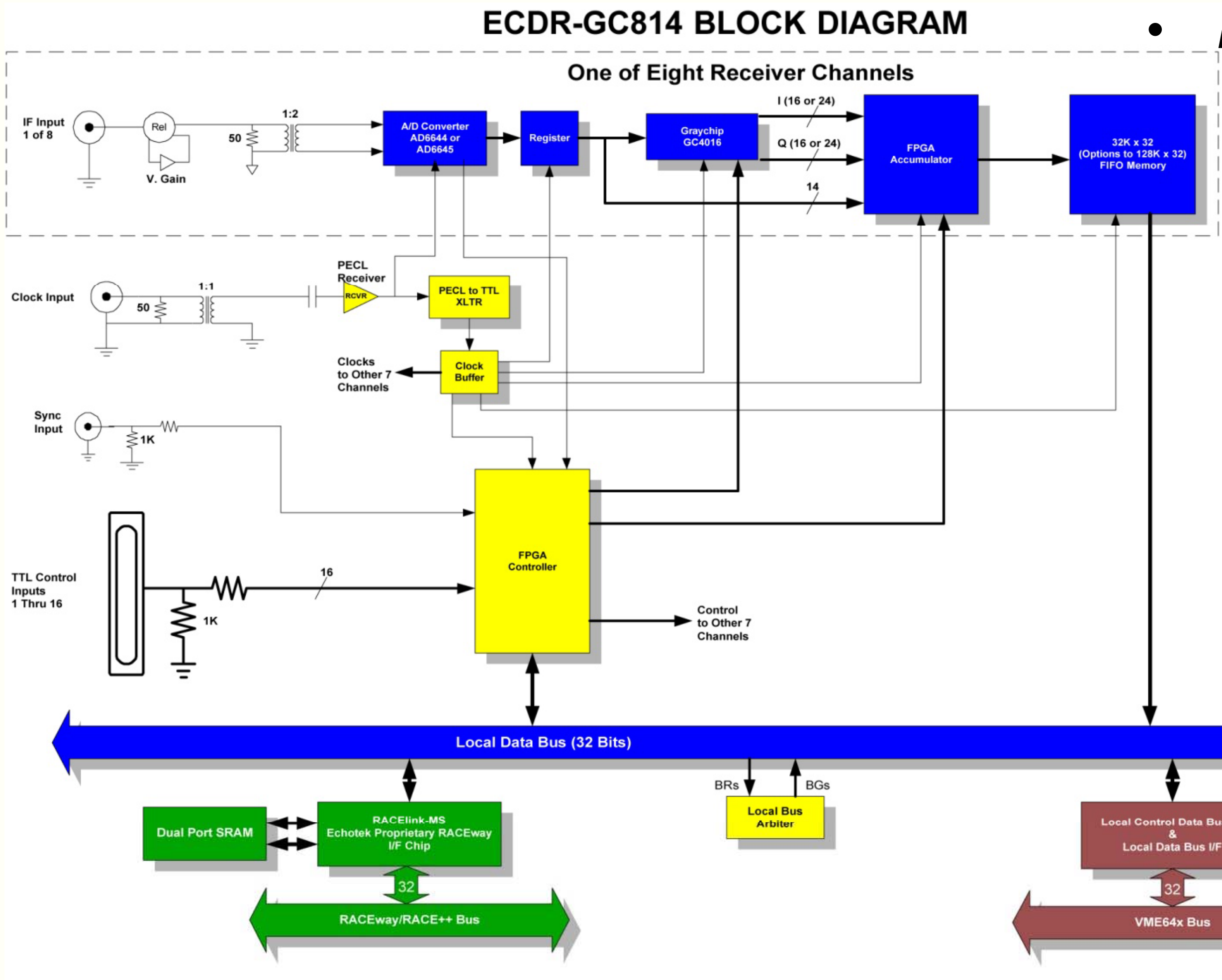
Analog Signal Processing



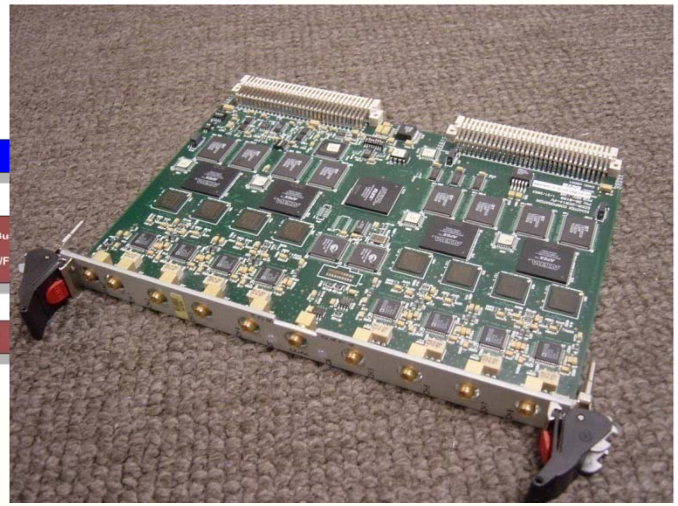


- **4-ch. Analog downmixer**
  - **Selective inputs (BPF: 714±5 MHz, ~100 ns ring-time)**
  - **Gain switchable, low-noise, high IP3 input gain stage**
  - **Image rejection (SSB) mixer**
  - **15.1 MHz high gain, ultralinear IF stage**

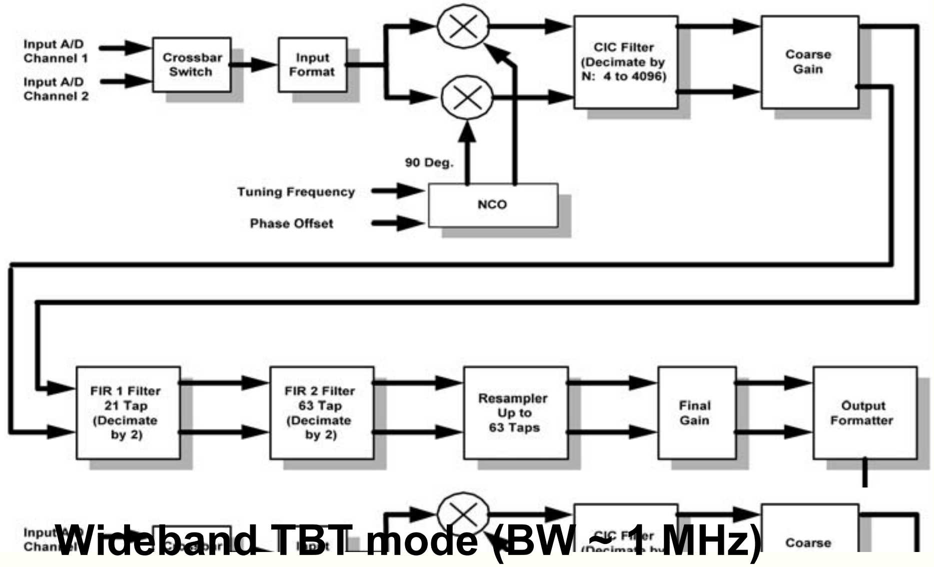
Digital Signal Processing



- *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

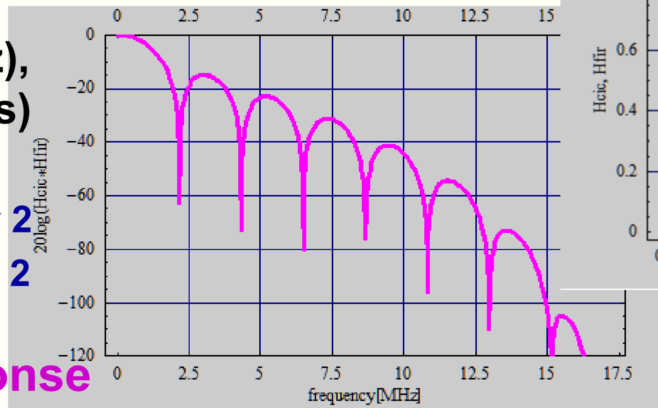


Digital Signal Processing (cont.)

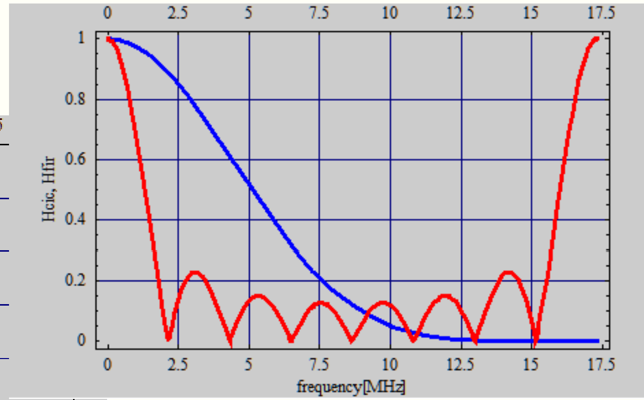


- *Graychip* digital downconverter
  - 4 independent channels per ADC
  - NCO set to f_{IF} = 15.145 MHz (downconvert to DC baseband)
  - ADC clock set to 32 samples per revoltion: $f_{CLK} = 32 \times f_{rev}$ = 69.2 MHz
  - Decimation and filtering for wide- and narrowband mode using CIC and FIR digital 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 ~ 1 kHz), 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



WB mode magnitude response

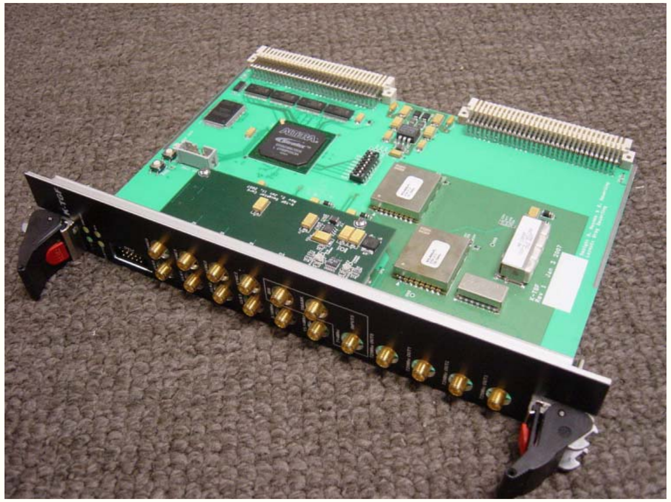


WB CIC response

WB FIR response

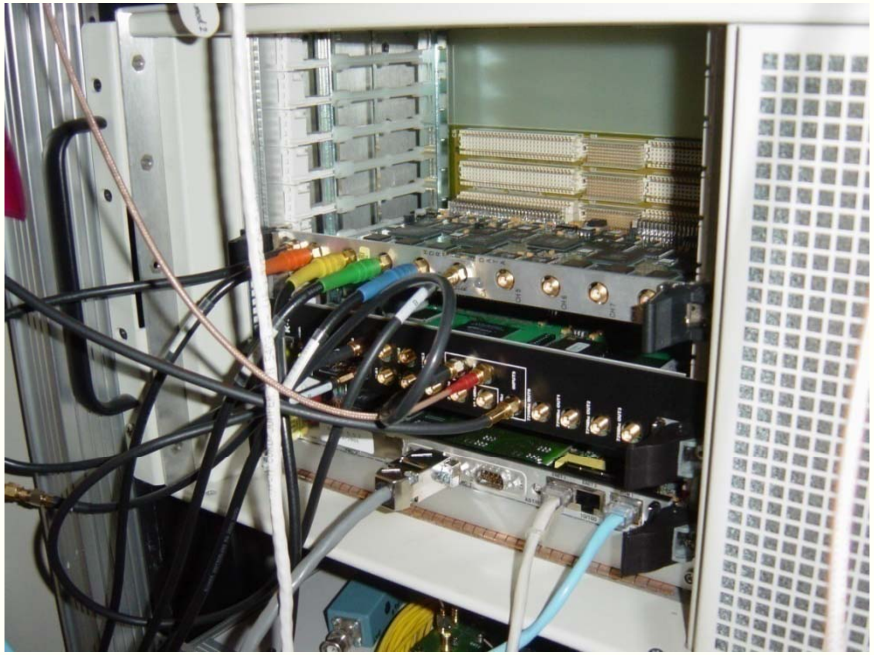
Other Hardware

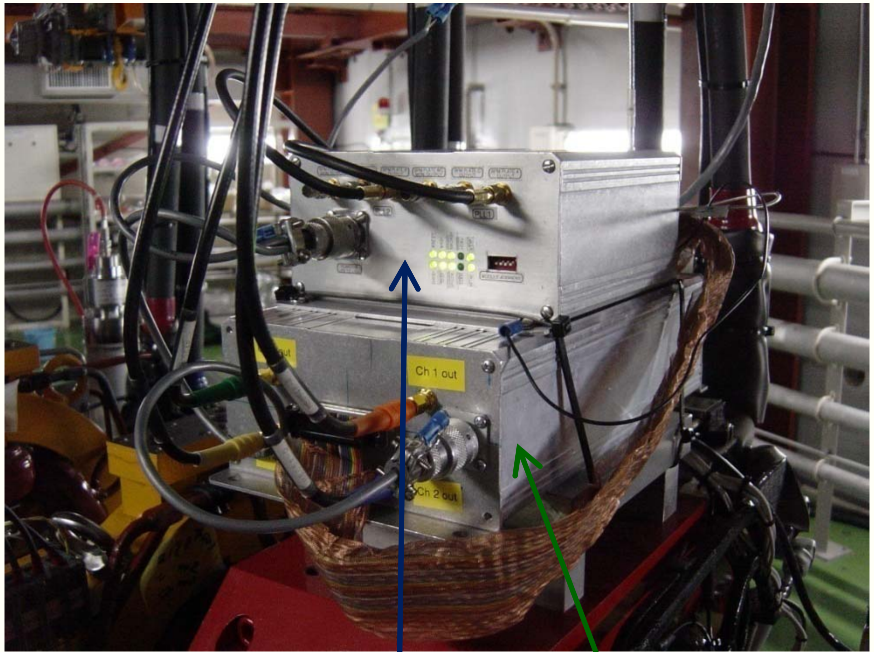
- **VME Timing module:**
  - $f_{CLK} = f_{RF}$*32/330 = 69.236 MHz clock signals (4x)
  - t_{rev} = 462.2 ns turn marker signals (4x), 0…115 double-buckets (2.8 ns) delayable
  - To f_{RF} phase-locked f_{LO} = 729.145 MHz
  - Auxiliary f_{rev} and f_{IF} signals



- ***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} ≈ 714 MHz (*Analog Devices* ADF4153)
  - In-passband, through button-BPM, or reflected signal calibration
  - 2nd and 3rd *Graychip* channels for CAL signal downconversion
  - CAN-bus remote control functions (attenuation, temperature, etc.)

BPM #54: Downconverter & CAL Proto

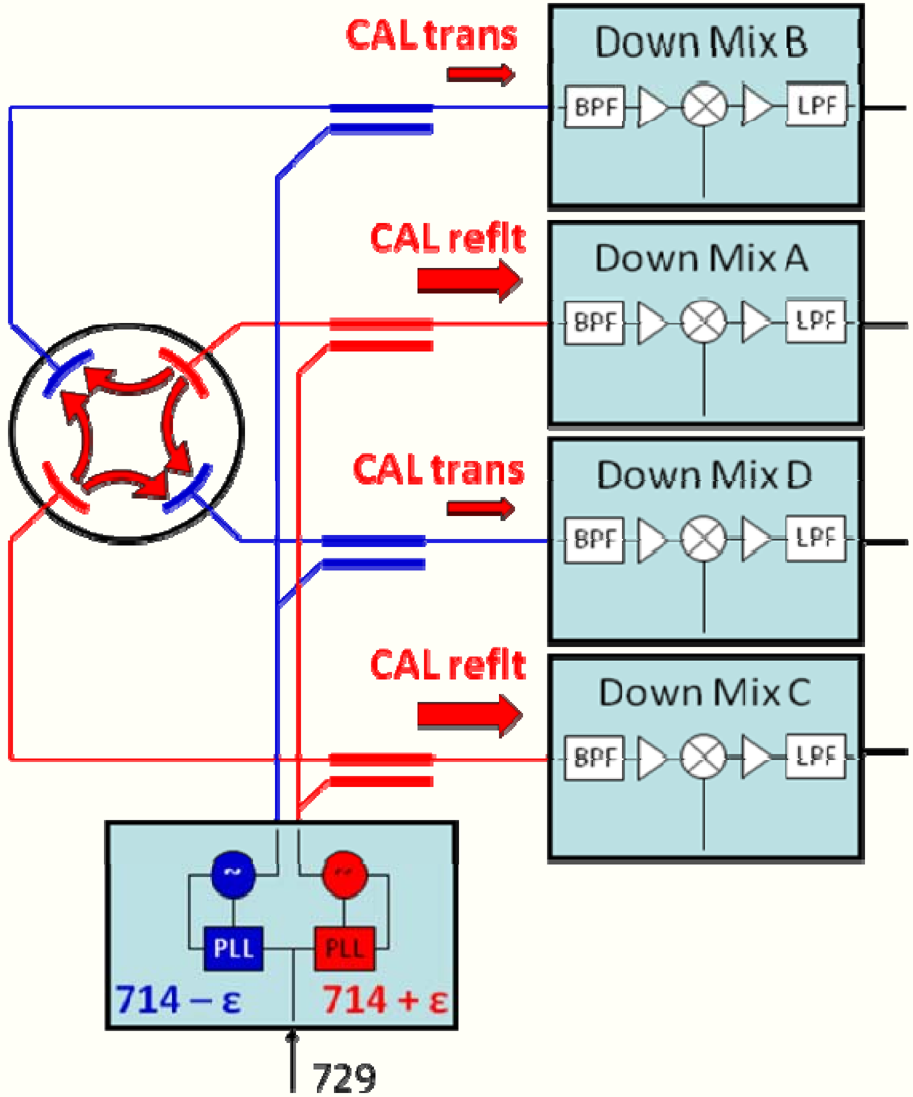




- Mini VME crate accommodating:
  - *Motorola* 5500 CPU
  - PMC CAN bus interface *ECAN-2*
  - Timing module TGF
  - *Echotek* digital receiver module

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

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
  - Using separate *Graychip* channels

Calibration Details

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

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

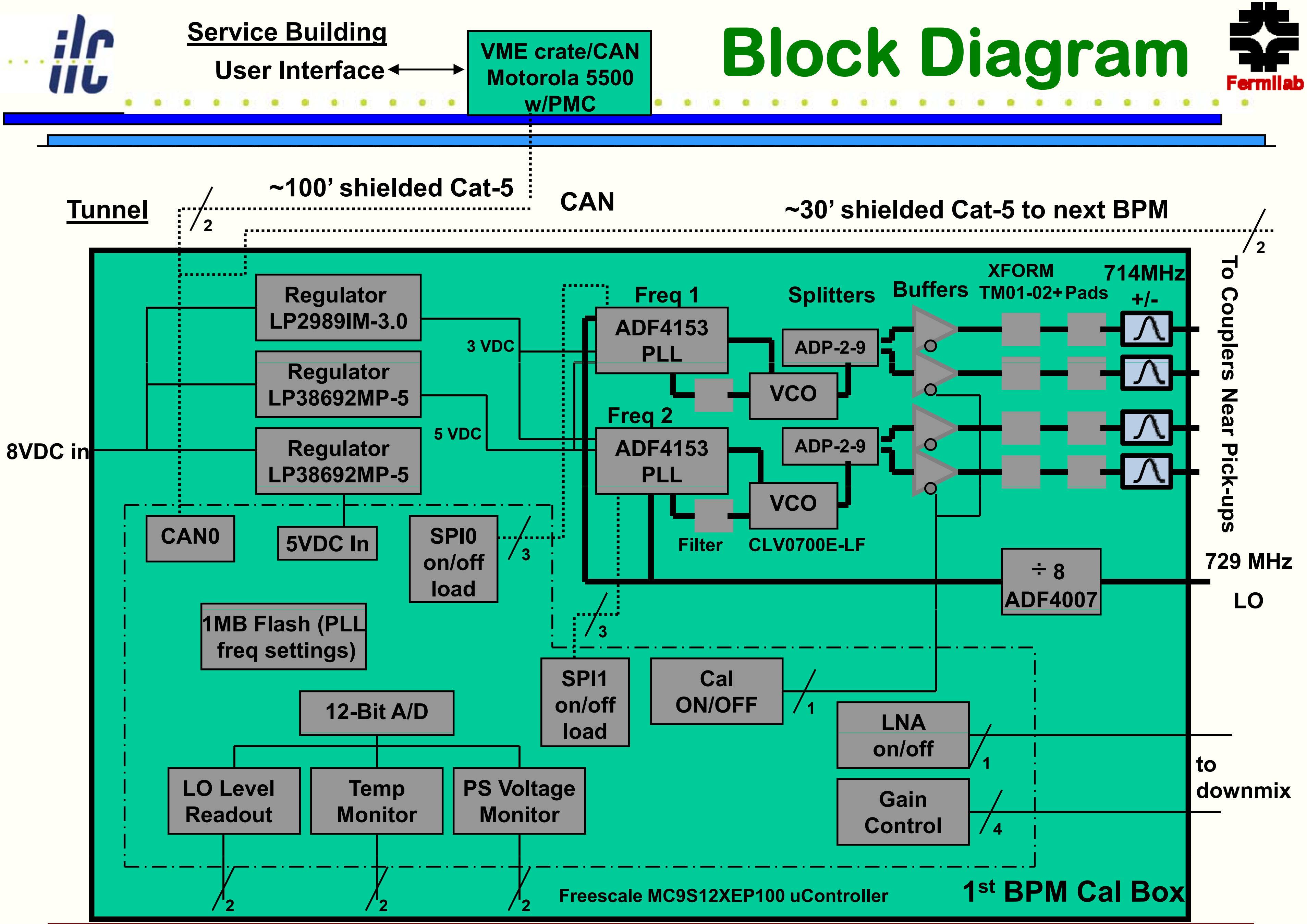
$$C_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4C_{CAL}} \qquad D_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4D_{CAL}}$$

  - **Corrected beam positions:**

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

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

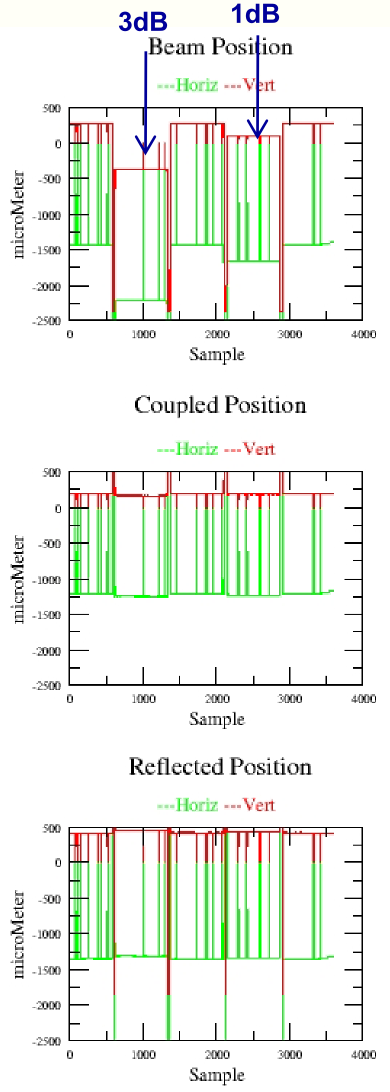
Block Diagram



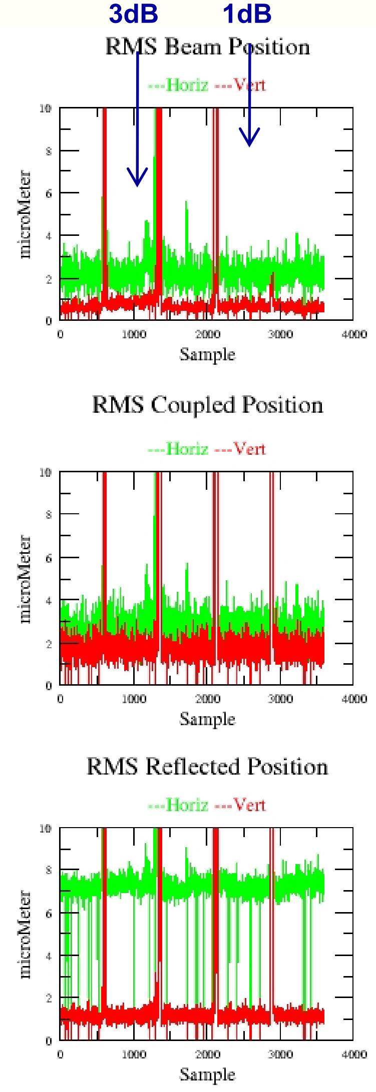
CAL Hardware Key Components

- *PMC-ECAN-2* Bus controller
  - Commercial PMC CAN bus controller
  - VxWorks PPC driver support
- *Freescale MC9S12XEP100* 16-bit µContoller
  - Serial interface support (CAN, I^2C, RS485, etc.)
  - 8/10/12-bit ADC's (2x16 ch.), timers, I/O, etc.
  - Up to 1M flash, 64k RAM, 4k EEPROM
- *Analog Devices AD4153* fractional PLL
  - Successfully tested the calibration generation during the last run (729 MHz locking, 714 ± ε MHz CAL signals).
  - Selectable frequency, on/off switch, acceptable phase noise and spurious harmonics.

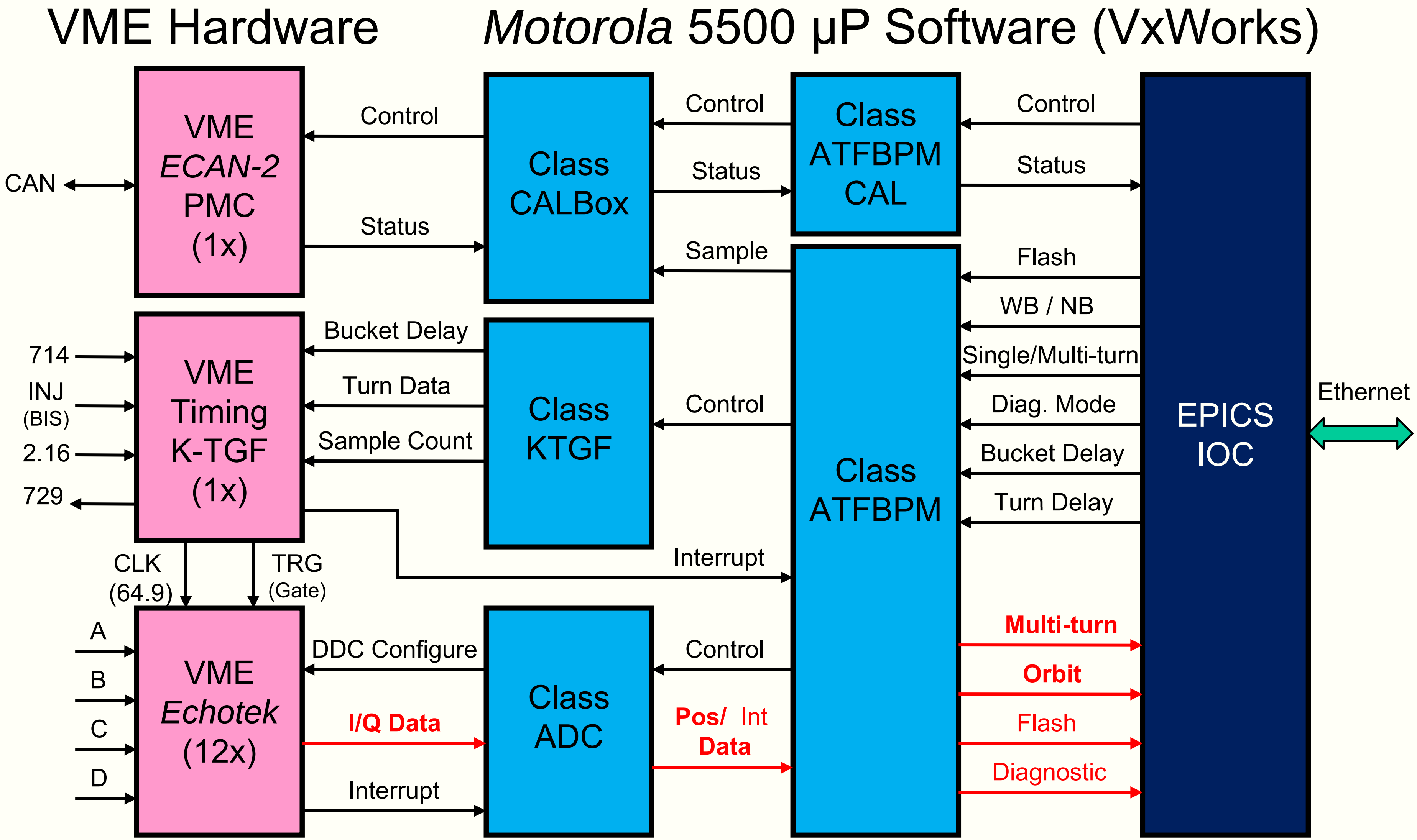
CAL System: Dec07 Test



- 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

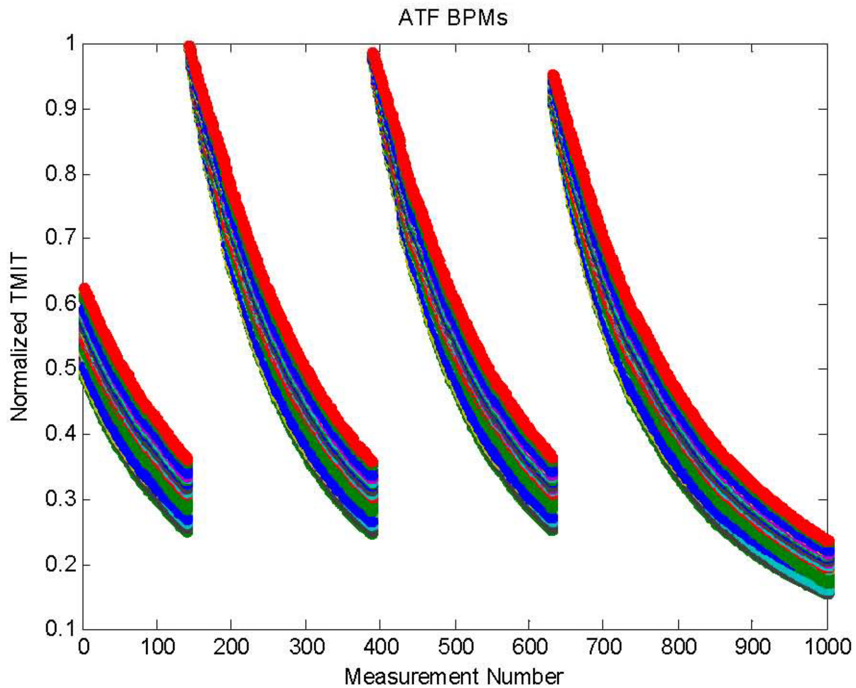


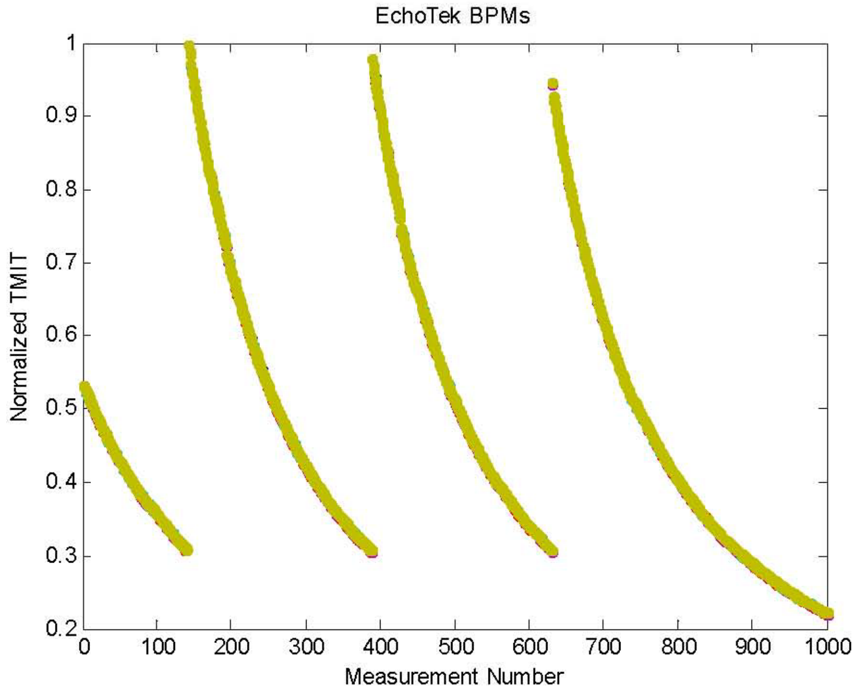
EPICS Data Acquisition

	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

Scrubbing Mode, Intensities
070518

Normalized Intensities

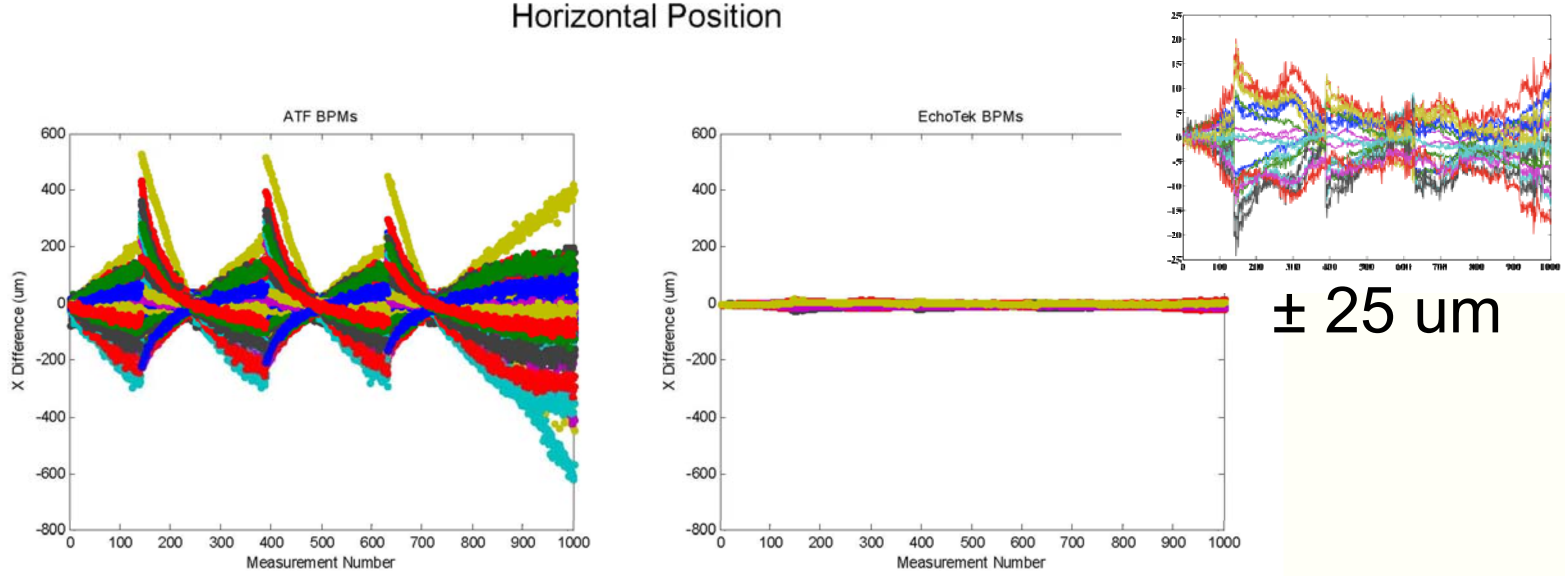




Scrubbing Mode, Positions

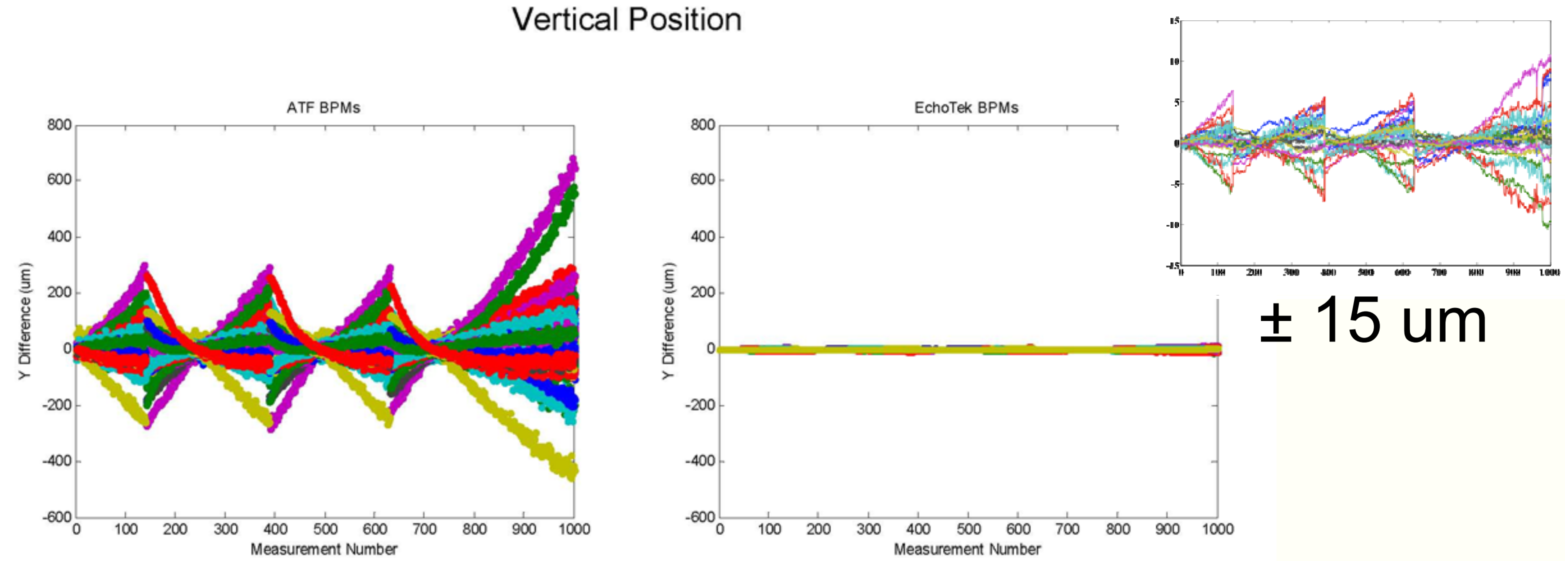
070518

± 700 um



± 25 um

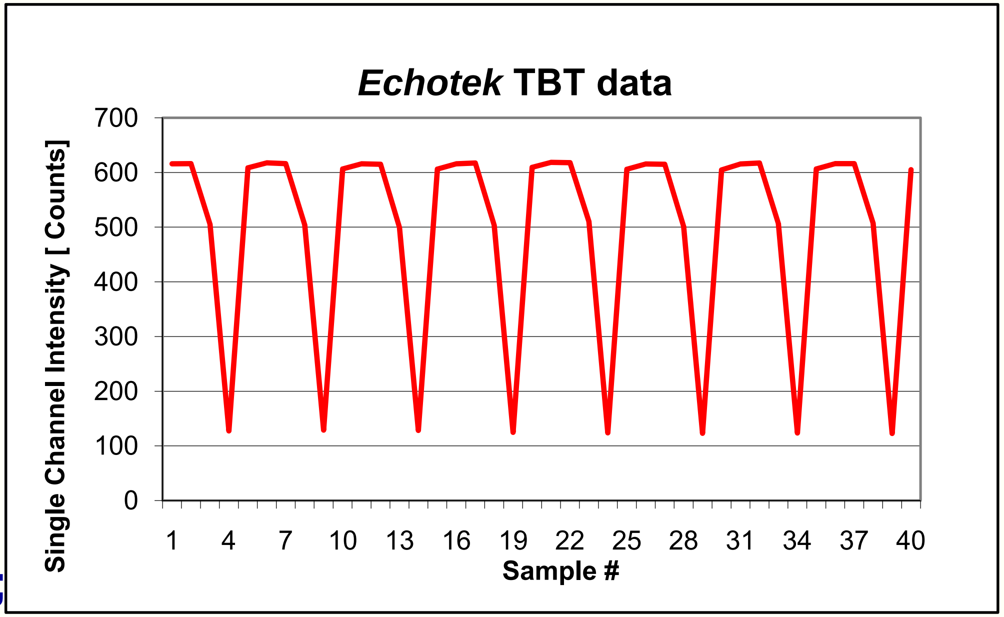
± 700 um



± 15 um

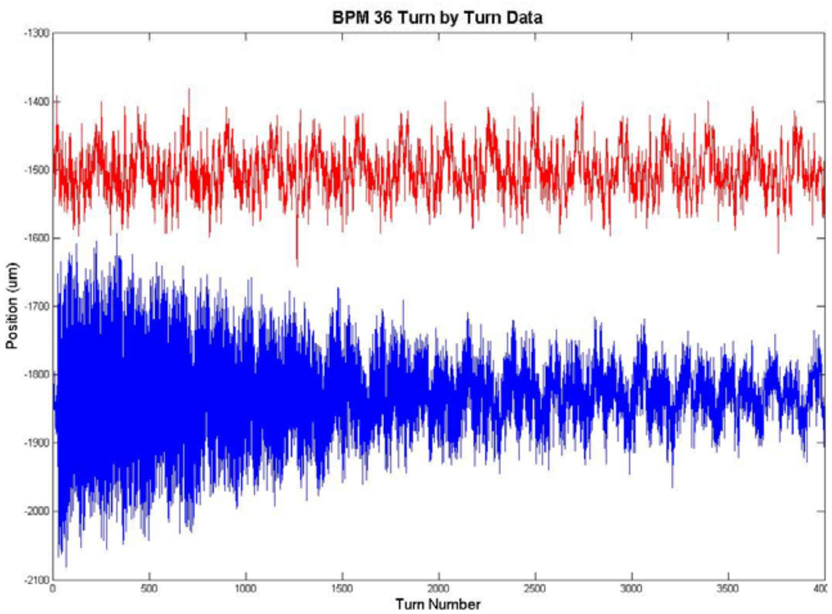
Wideband, TBT Mode Beam Tests

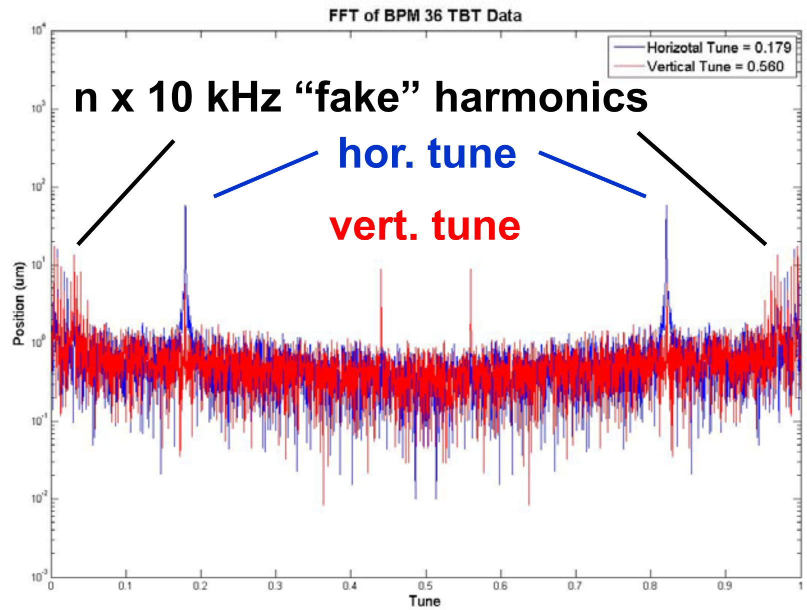
- Several "issues" had to be resolved:
  - CIC & FIR digital filter impulse responses to resolve true turn-by-turn data (no "smearing")
  - Timing issues, e.g. channel-to-channel, as well as between BPMs and "houses" (VME crates); and of course the usual "seam" problem.



- 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* ≡ *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**

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

$\Phi_z \equiv \mu_z - Q_z\theta$ (periodic phase function)

- **Twiss functions:**

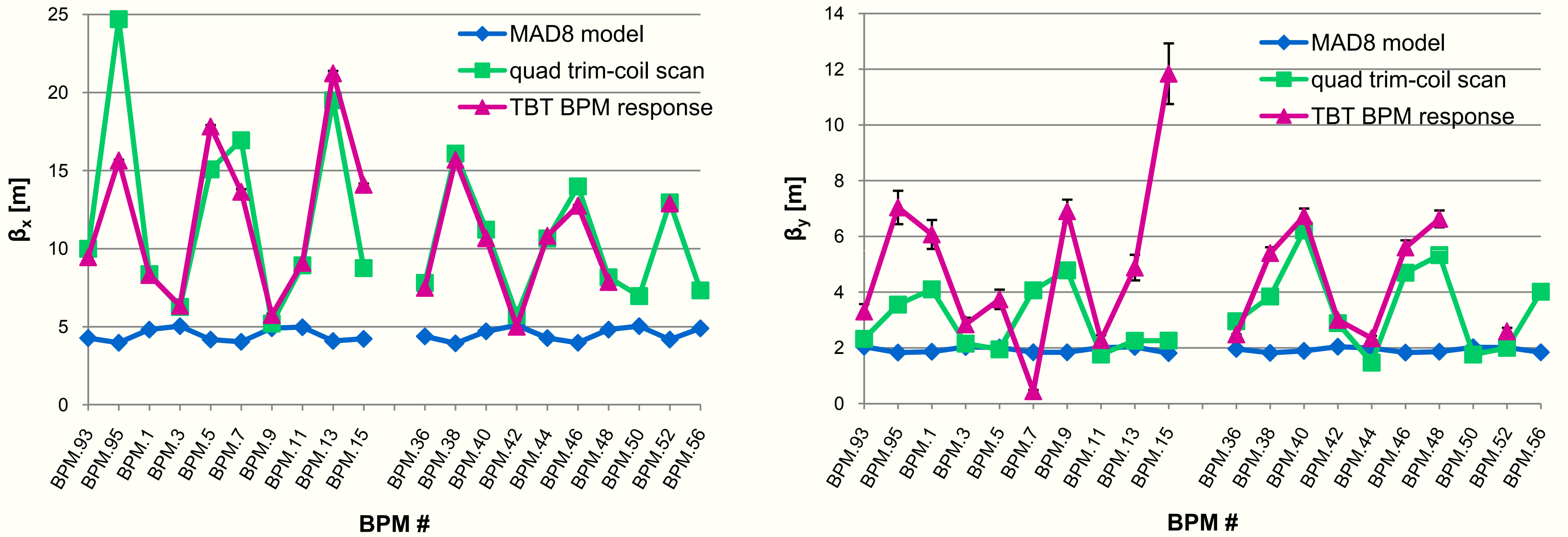
$$\beta_z^j = |Z_j(Q_z)|^2 / A_z^2 \qquad \mu_z^j = \arg(Z_j) - \delta_z$$

$Z_j(Q_z) \equiv$ *Fourier* component of z_j

- **Amplitude fit:**

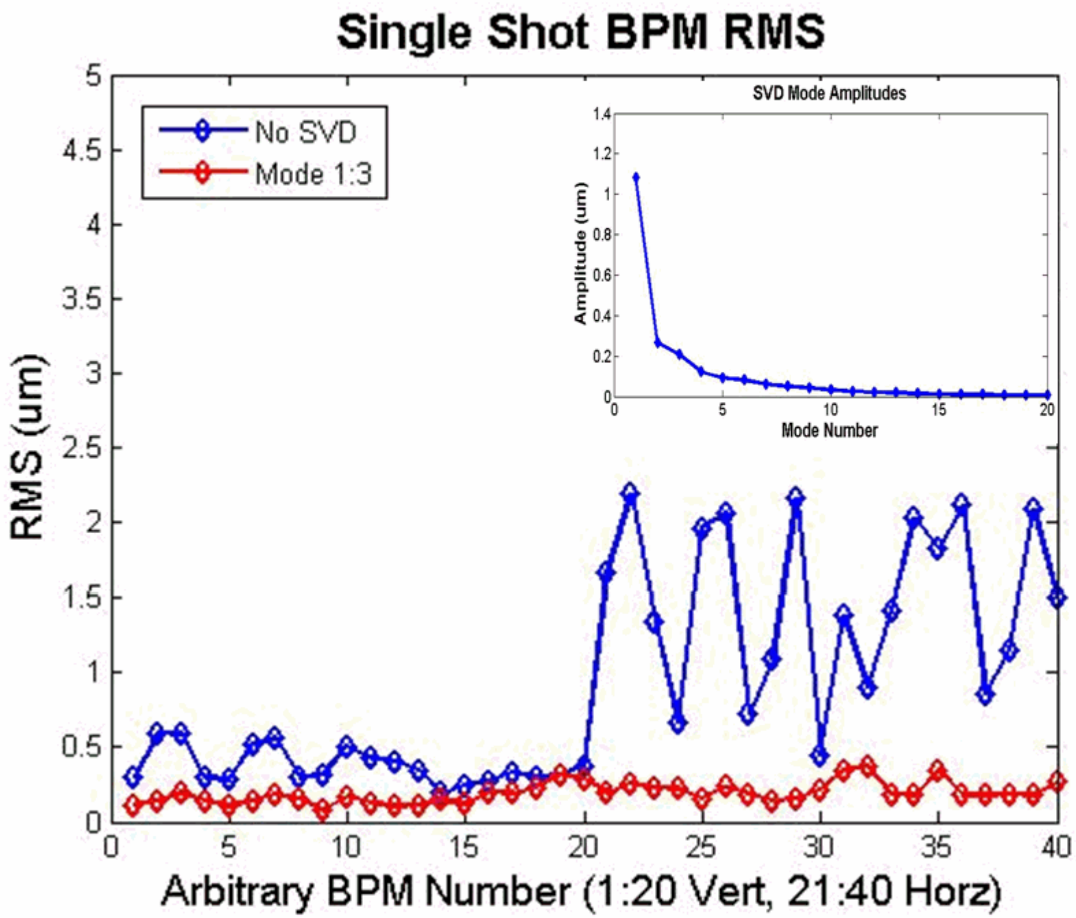
$$|A_z|^2 = \frac{\sum_j 1/\beta_z^{0\,j}}{\sum_j 1/|Z_j(Q_z)|^2}$$

Comparison: Measurements vs. Model



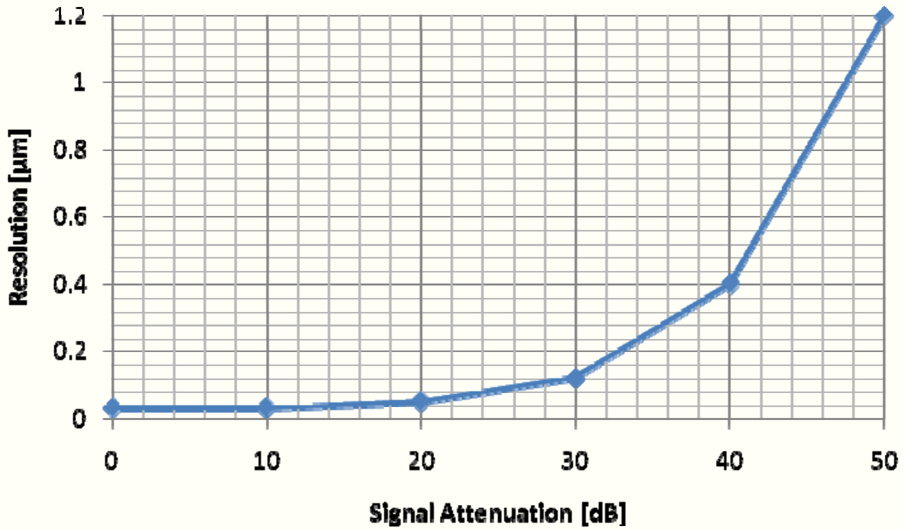
- **MAD8 model (M. Woodley, marginal differences wrt. Kuroda SAD model).**
- **Nearby quadrupole trim coil scan (May 2008).**
- **TBT Fourier analysis, amplitude by fit to beta measured through trim coil scan (April 2008).**

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

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)

Next Steps…!?

- Resolve known issues and defects
  - Two defect downmix units
  - EMI interference into downmix electronics
- Publish a revised plan to continue the BPM upgrade!
  - Integrated downmix-CAL prototype, simplified RF housing and cabling.
  - Proposal: Next upgrade step to a total 48 BPMs
  - Install only improved downmix & CAL hardware into the ATF tunnel.
  - Utilize spare *Echotek* digital receivers
    or new low-cost VME digitizers (Fermilab development)
    for DDC of the BPM signals.
  - Increase ADC clock rate (32 -> 40 samples / turns)
- Most soft-/firmware activities & beam studies:
  Remote operation!
- Still need to demonstrate the long term offset drift stabilization.