The ATF Damping Ring Beam Position Monitor System
– Status Report 2011 –

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Agenda

- Short review of the ATF damping ring BPMs
- Recent maintenance and R&D activities
- TBT BPM and machine studies
- Preliminary narrowband results
- Summary and Outlook

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,…
  - 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 BPM read-out system, tailored to ATF needs and requirements

Recent Activities

- October 2009
  - Prepare installation of the new BPM read-out system
    - Cables for LO, DC, CAN-bus signal distribution in the tunnel, grounding,…
    - Install analog downconverters in the tunnel
    - Install 4 VME crates, with each 24 digitizers, CPU & timing module.
- May 2010
  - First beam commissioning of the new BPM read-out system
    - 95 out-of 96 BPMs
    - Major firm- and software changes
- October 2010
  - Many firm- and software modifications, go to 33 samples per turn
  - First beam studies
- February 2011
  - More on software, e.g. last turn capability, crate sync, ping-pong CAL
  - Fixing a few hardware defects, rearranging tunnel hardware, etc.
  - Beam studies, also some follow up remote shifts

ATF DR BPM Hardware

Analog downconverter (located in the tunnel)

CAN-bus controls, IF filter, remote diagnostics, etc.

RF, DC & CAN-bus distribution. Grounding of tunnel hardware.

In-house VME digitizer

8-ch. ,125 MSPS ADC (serial outputs), Cylcone III FPGA, PLL-locked CLK distribution

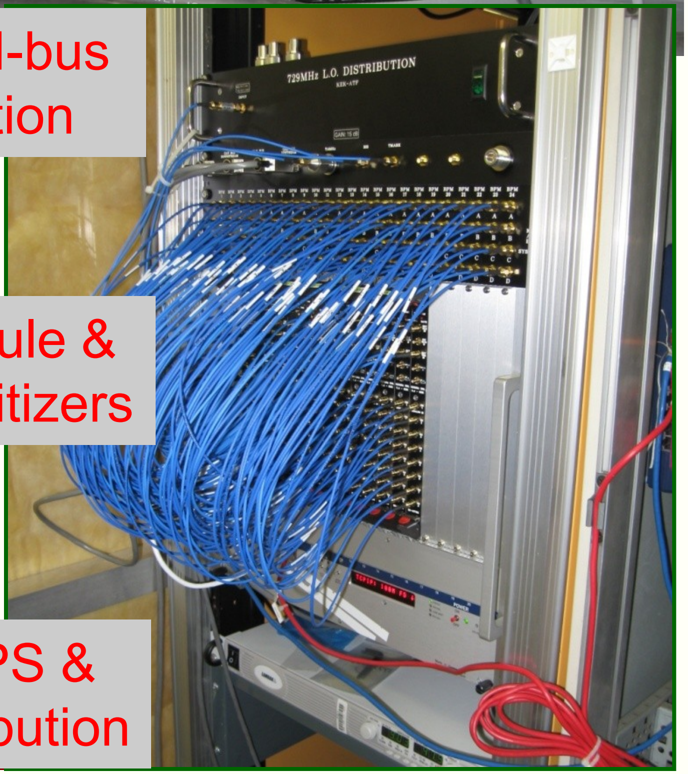
Able to measure Injection TBT, narrowband orbit, narrowband CAL orbit, and last turn on every injection

Downmix & Calibration

LO & CAN-bus Distribution

Timing Module & Custom Digitizers

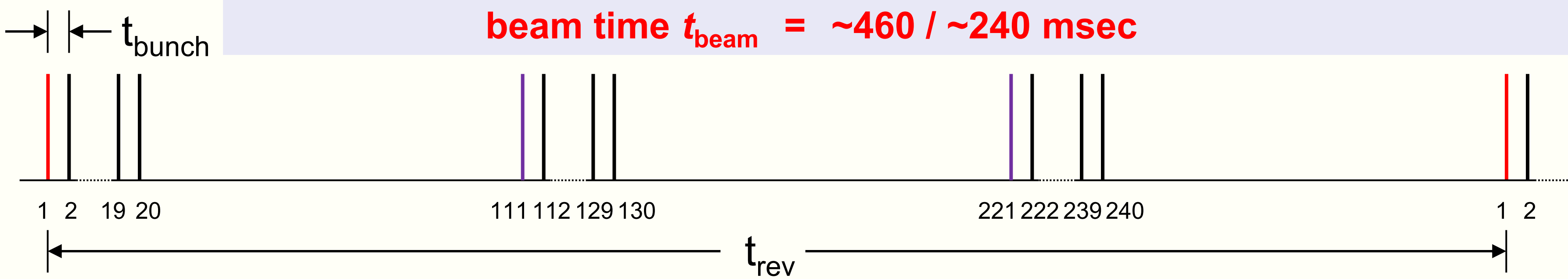
DC PS & Distribution



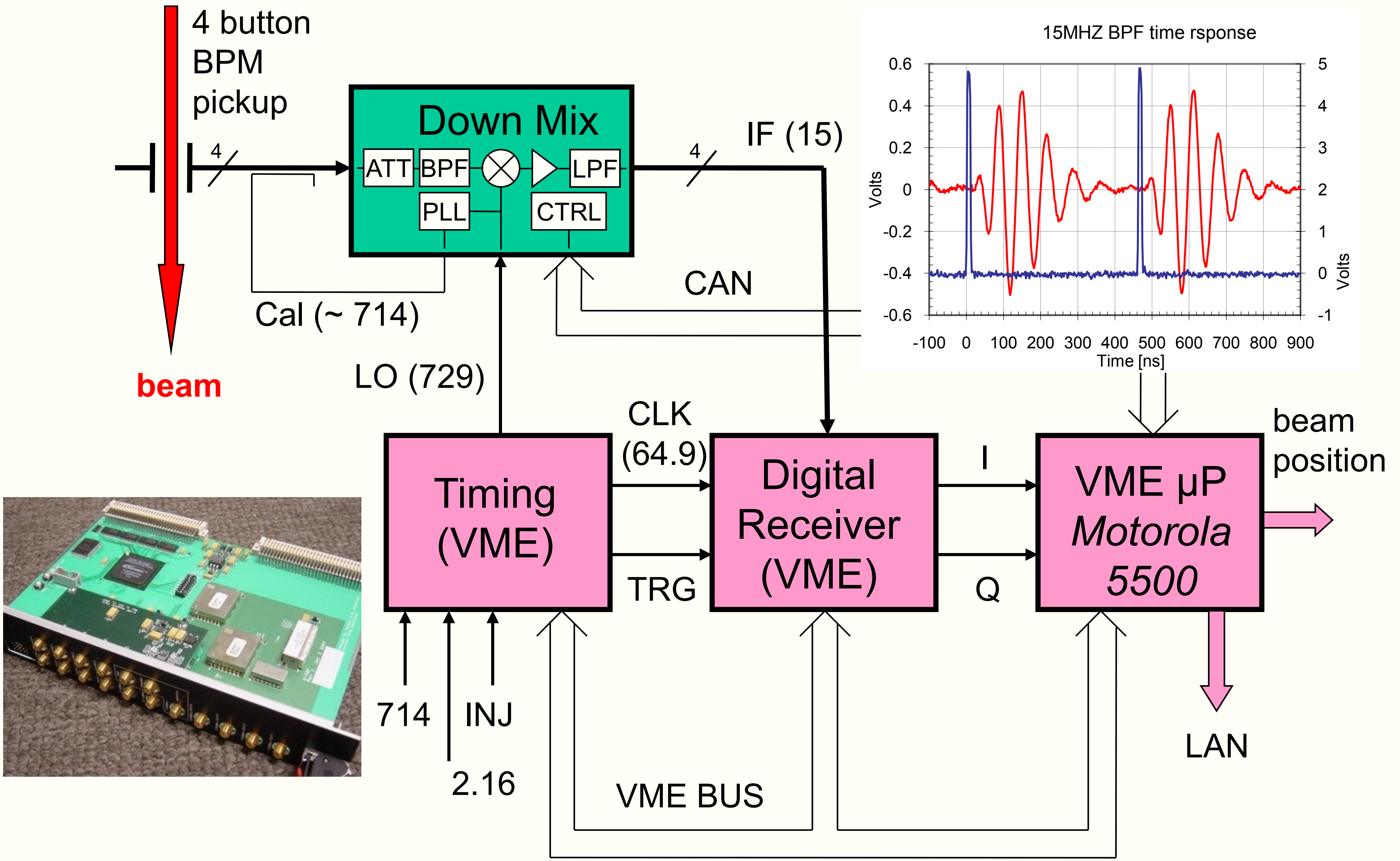
The ATF Damping Ring

Machine and Beam Parameters

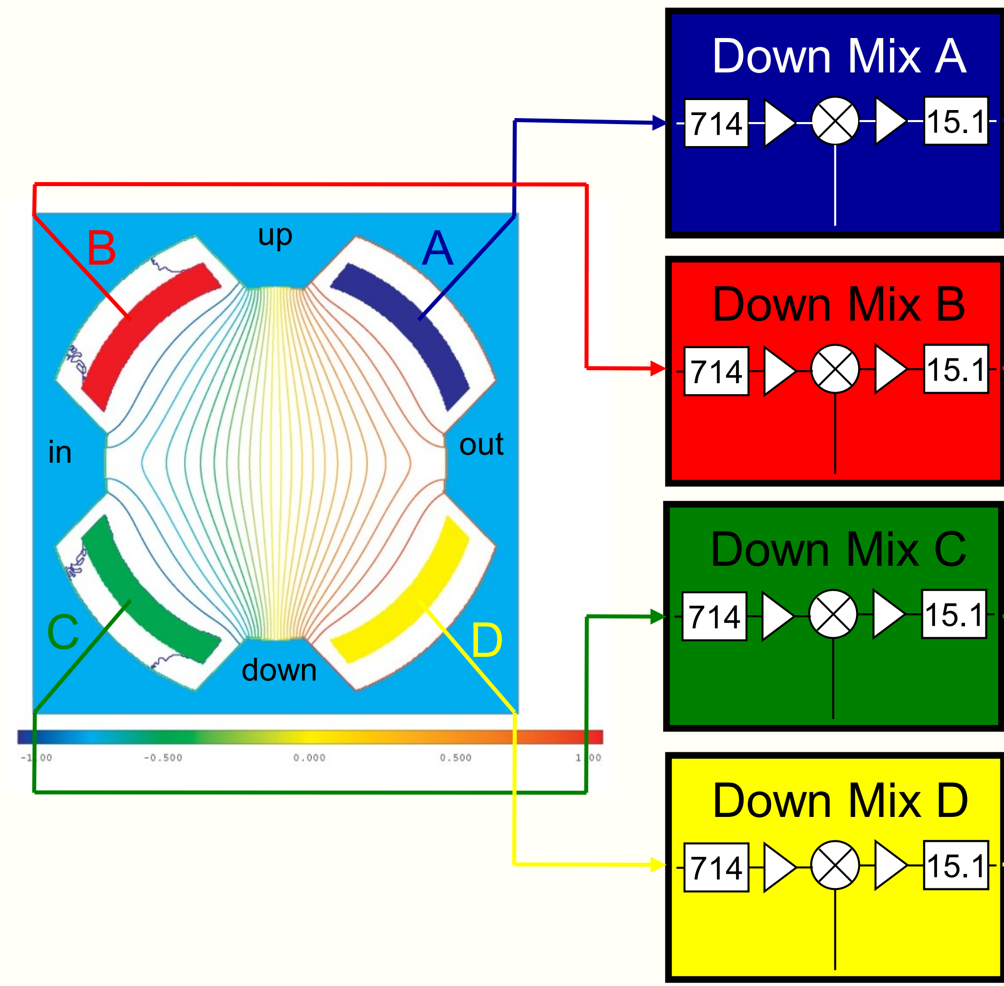
beam energy E	=	1.28 GeV
beam intensity, single bunch	≈	~1.6 nC ≡ 10^{10} e^- (≡ I_{bunch} ≈ 3.46 mA)
beam intensity, multibunch (20)	≈	~22.4 nC ≡ 20 x0.7 10^{10} e^- (≡ I_{beam} ≈ 48.5 mA)
accelerating frequency f_{RF}	=	714 MHz
revolution frequency f_{rev}	**=**	**f_{RF} / 330 = 2.1636 MHz (≡ t_{rev} = 462.18 nsec)**
bunch spacing t_{bunch}	=	t_{RF} / 2 = 2.8011 nsec
batch spacing t_{batch}	=	t_{rev} / 3 = 154.06 nsec
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 /3.12 Hz (≡ t_{rep} = 640 / 320 msec)**
beam time t_{beam}	**=**	**~460 / ~240 msec**



BPM Hardware Overview



Beam Position Signal Processing



Digital signal processing:

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

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

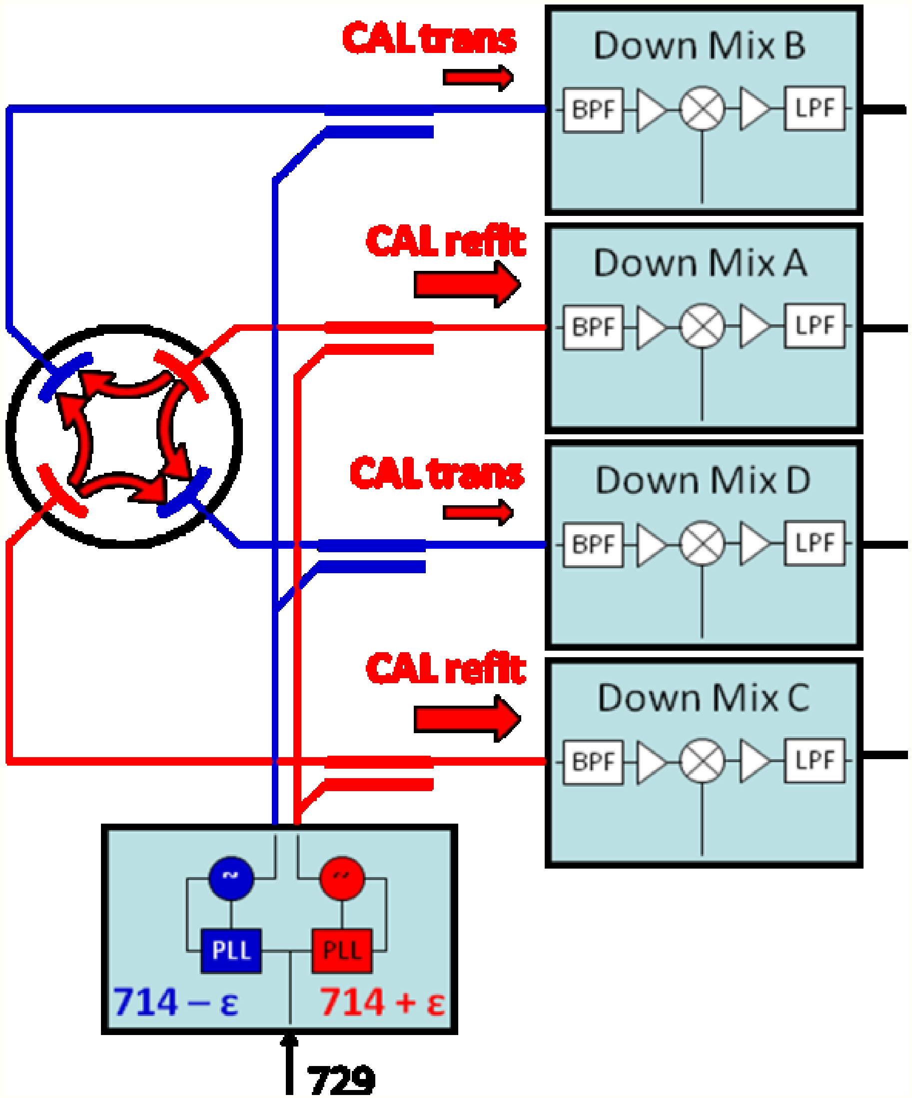
1D polynomial fit:

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

(we now use a 7th order 2D fit)

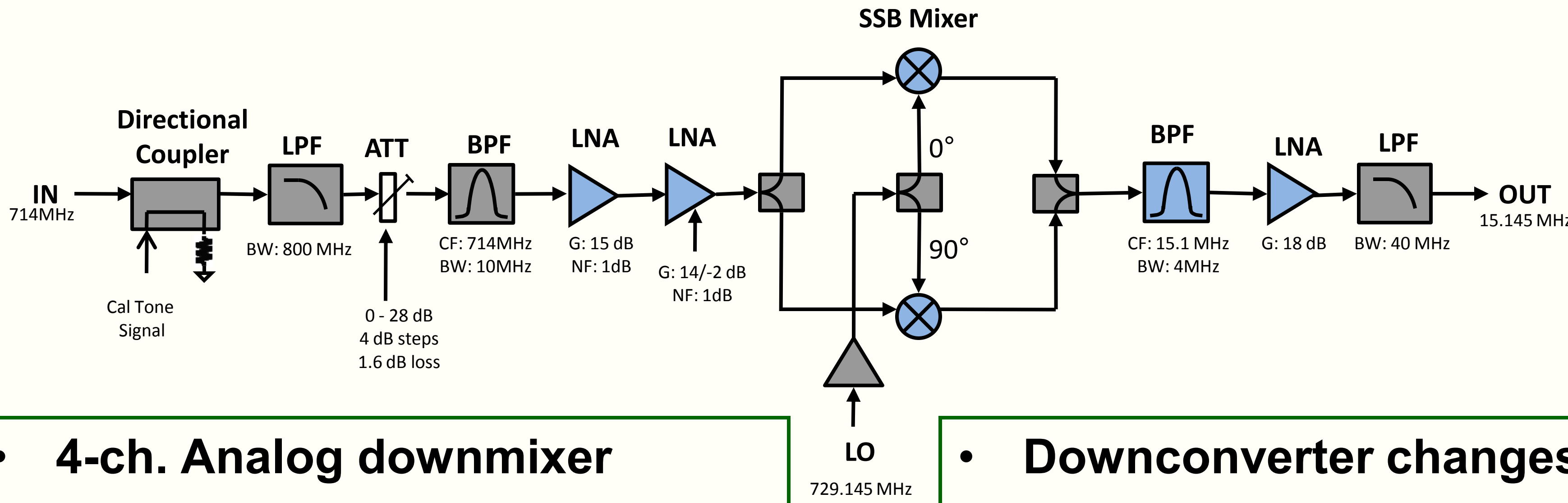
0.1 dB gain error ≡ 27 μm offset error !

Calibration Schema



- May Use two calibration tones of different frequency:
  - 714 + ε MHz
  - 714 – ε MHz
  - Can use reflected and thru BPM cal signal.
  - In passband of the downconverter in NB mode.
  - Separate digital NB receiver.
  - Works in presence of beam!
- Two separate tones may be not the best idea!?
  - Slightly different signal levels: Correction errors!
- Resolution for ATF
  - "Ping-Pong" CAL schema

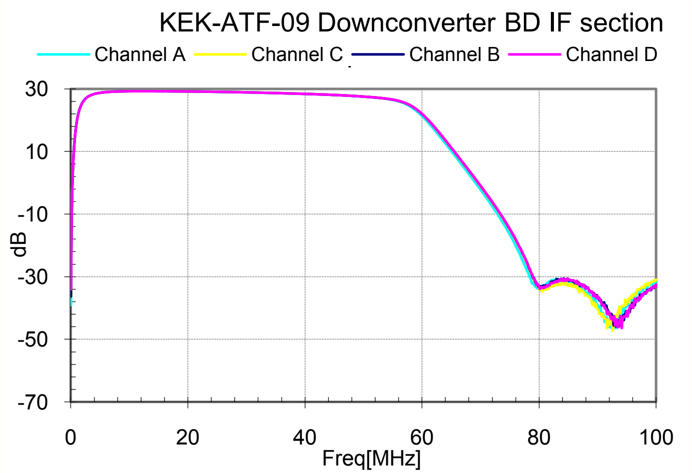
Analog Signal Processing

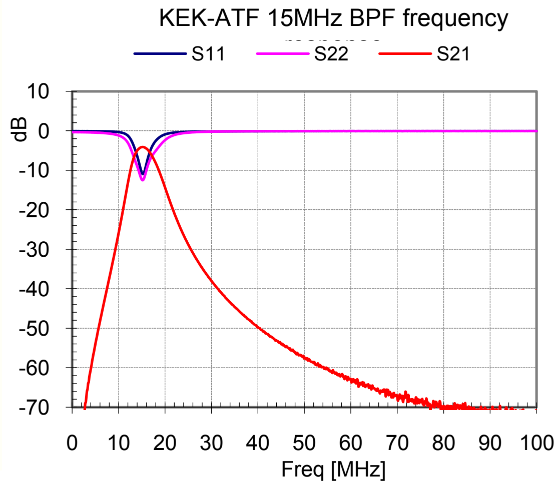


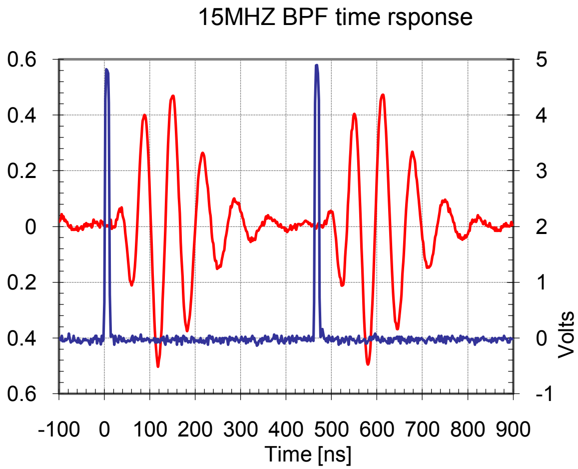
- 4-ch. Analog downmixer
  - IN: 714, LO: 729.1, IF: 15.1 MHz
  - CAN-bus controlled gain, attenuator & cal system
  - Gain switchable, low-noise, high IP3 input gain stage
  - Image rejection (SSB) mixer
  - ~30 dB gain, ultralinear IF stage

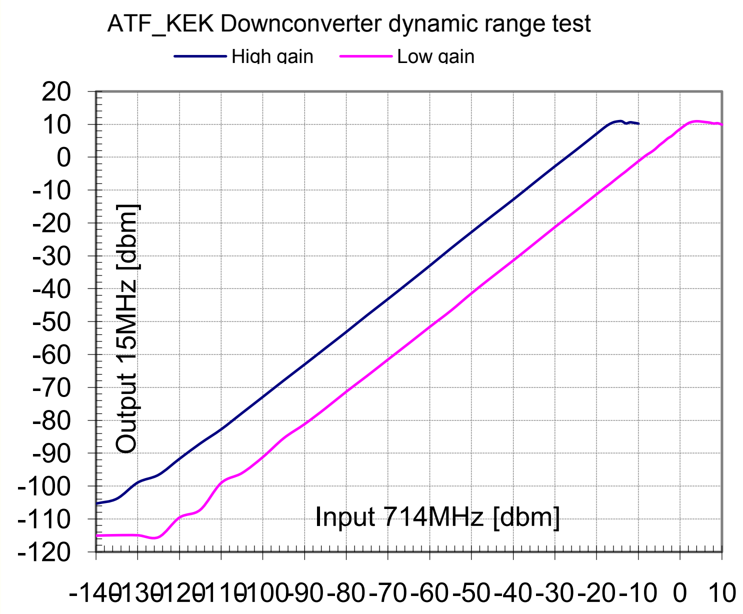
- Downconverter changes
  - Change the gain distribution (RF+, IF-)
  - Change mixers (+17 dBm -> +13 dBm)
  - Change response of the IF section BPF

Analog Downmixer



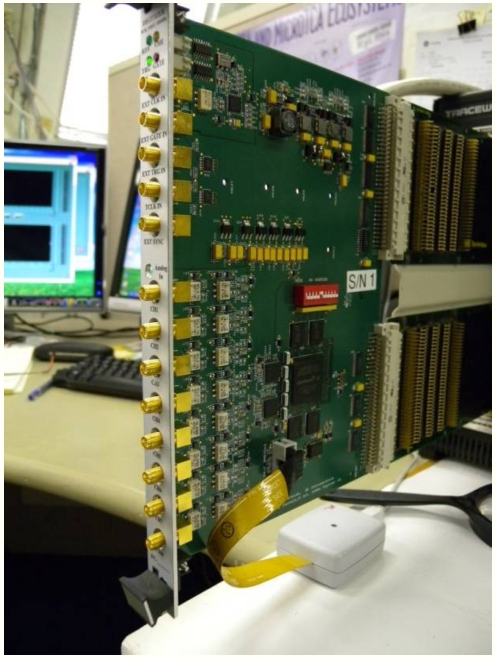


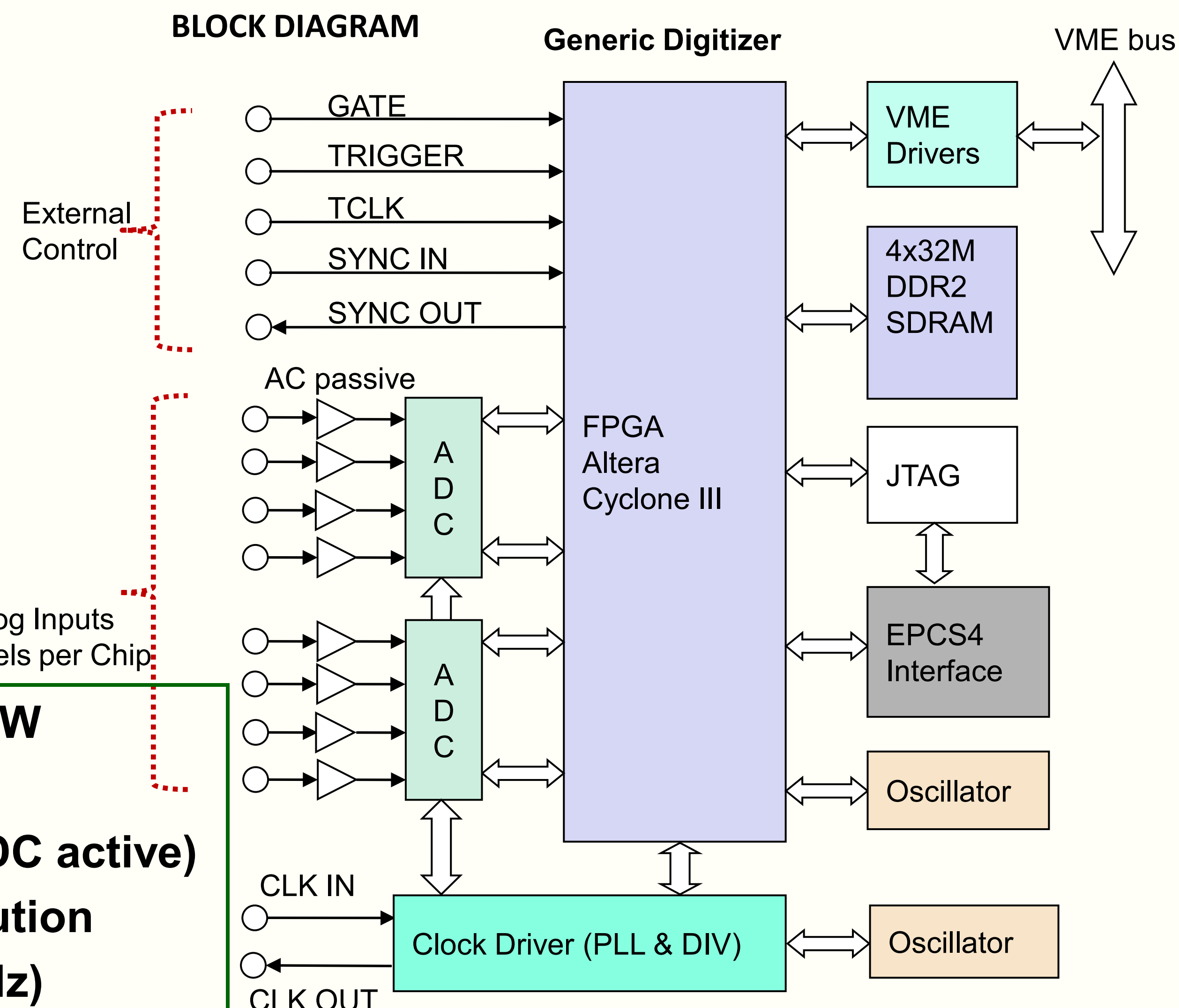




- **Modified IF section**
  - **Low-noise gain stage**
  - **15.1±1.5 MHz BPF, ~400 ns ring-time**
- **Improved NF & dynamic range**
  - **NF = 17 dB**
  - **>90 dB dynamic range**

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



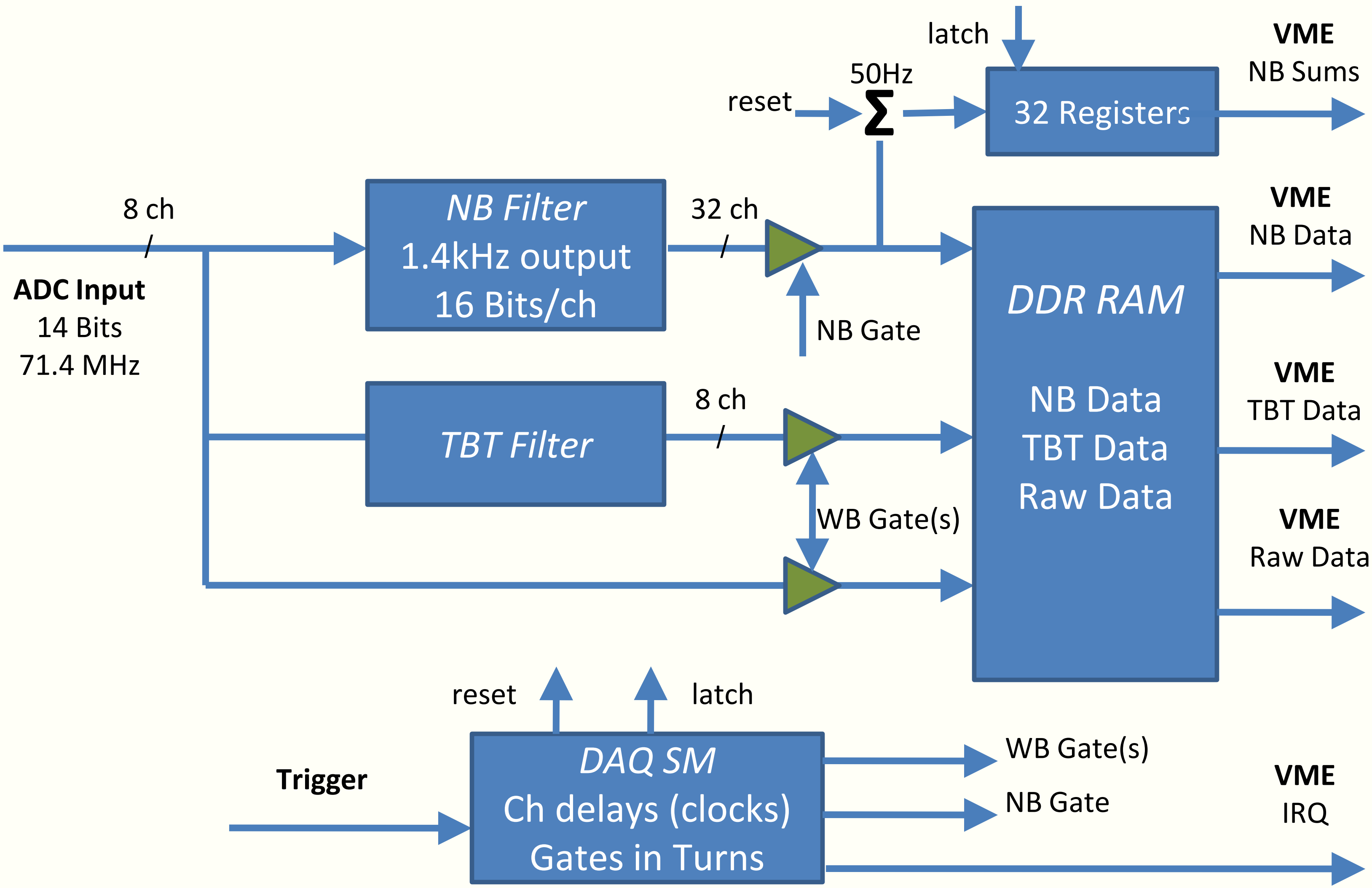


- **125 MSPS, 500 MHz BW**
- **4-ch serial ADC chips**
- **8-ch, AC passive (or DC active)**
- **PLL/VCO CLK distribution**
- **SNR > 72 dB (@50 MHz)**

Digital Signal Processing

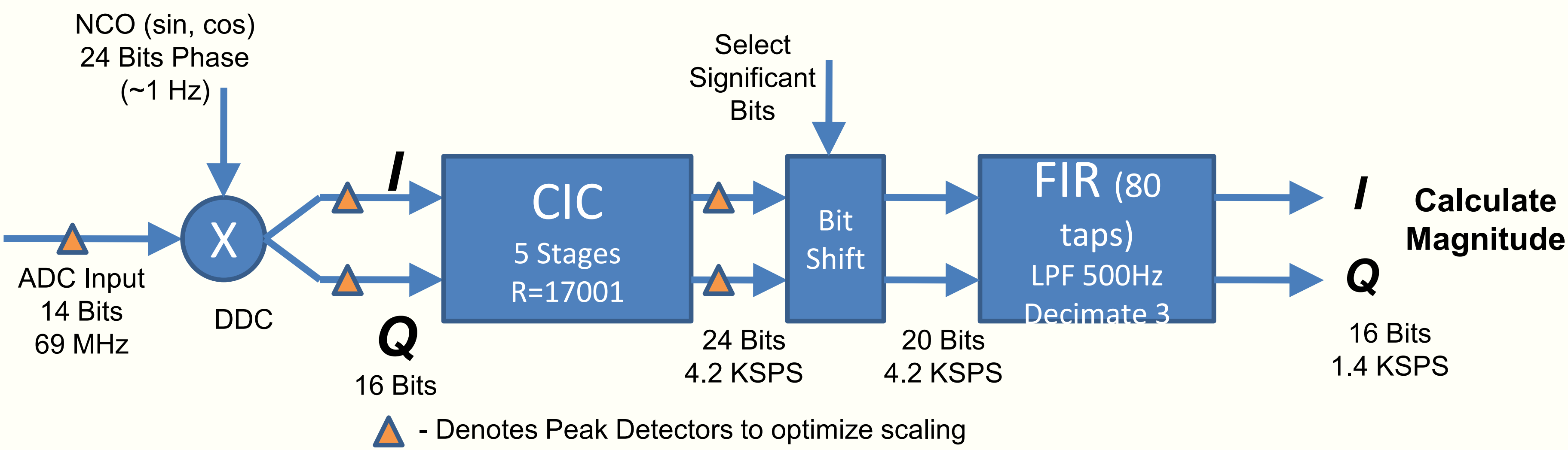
- **No Modes** - on external trigger processes data in parallel
  - TBT Filter
    - provide magnitude per turn for position & intensity
  - Narrowband processing (Filter & Decimate)
    - Provide magnitude of I,Q for position & intensity
    - Store array of I,Q per channel for readback
  - Raw ADC data to RAM
    - diagnostic readback
  - 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 pulls IRQ when data is ready

FPGA Block Diagram



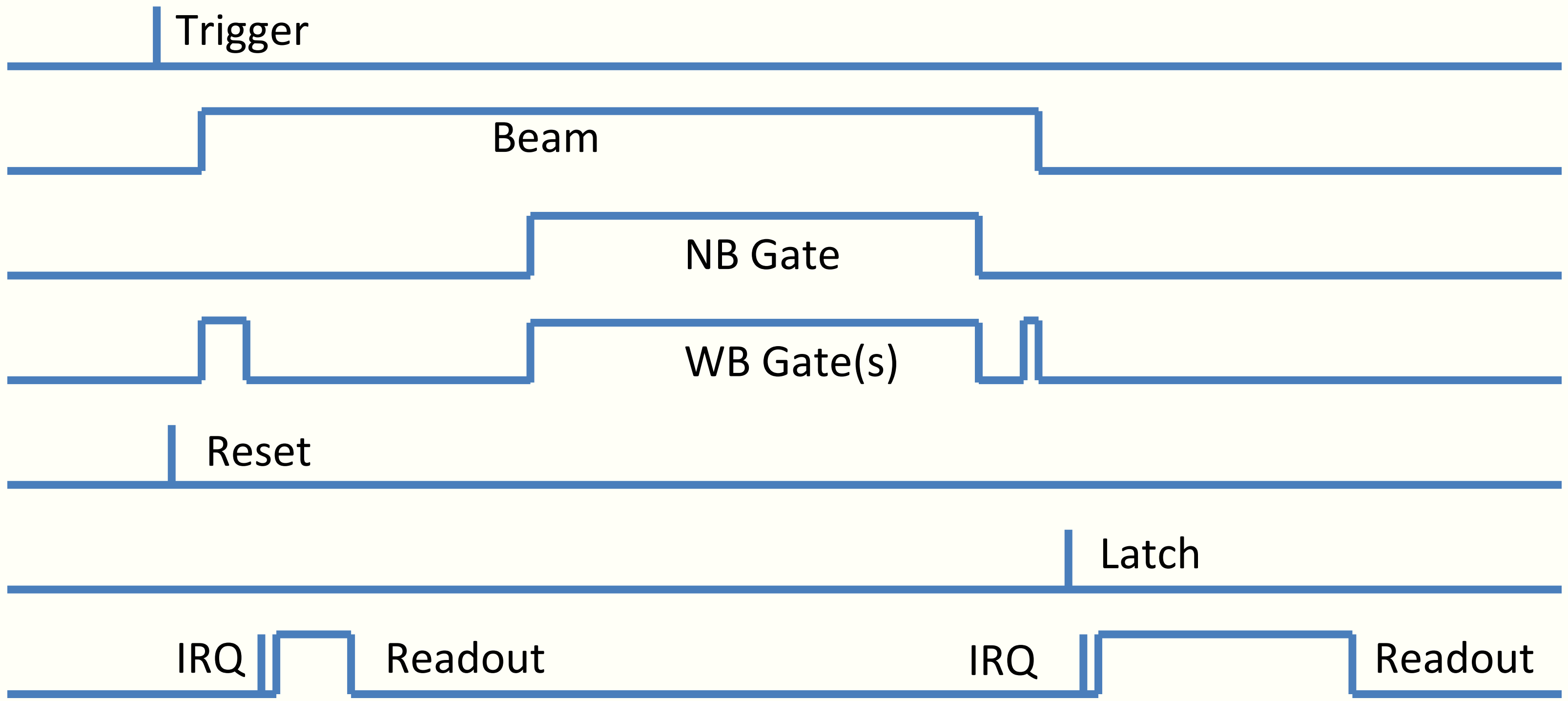
Narrowband Signal Processing

- **Process 8 ADC channels in parallel up to FIR filter**
  - **Digitally Downconvert each channel into *I,Q* then filter I,Q independently**
  - **CIC Filters operating in parallel at 71.4MHz**
    - **Decimate by 17KSPS to 4.2KSPS output rate**
  - **1 Serial FIR Filter processes all 32 CIC Filter outputs**
    - **80 tap FIR (400 Hz BW, 500 Hz Stop, -100 db stopband) -> 1KHz effective BW**
    - **Decimate by 3 to 1.4 KSPS output rate -> ability to easily filter 50Hz**
  - **Calculate Magnitude from *I,Q* at 1.4KHz**
    - **Both Magnitude and I,Q are written to RAM**
    - **Also able to write I,Q output from CIC to RAM upon request**



System Timing Cartoon

- **Trigger before beam injection (injection rep rate is ~1.5 Hz)**
  - **Beam in machine for ~1e6 turns (~450 msec)**
  - **Bunch RF is 714MHz with h=330, ADC clock 71.4MHz -> 33 ADC samples/turn**
  - **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***



Recent BPM Setup & Maintenance

- **Hardware related:**
  - Exchanged & relocated defect analog downconverter at BPM #31
  - Wired BPM #59 as "reference" BPM:
    - Four-way split of "A"-button signal into the electronics.
  - Installed new VME digitizer firmware
    - Detection of first & last turn
    - Improvements on signal offsets, etc.
  - Temporary switched analog downconverter to low-gain operation
    - False interpretation of spectrum analyzer saturation effects!
- **Software related**
  - Installation and troubleshooting of the new software.
  - Implemented new scaling polynomials for BPM 20 & 21.
  - Adjusted the timing for all BPMs (TBT and raw data).
  - Adjustment of the NCO frequencies (NB operation)
    - Beam NCO frequency offset: 25 Hz
    - CAL NCO frequency offset: 50 Hz

CAL Tone Correction

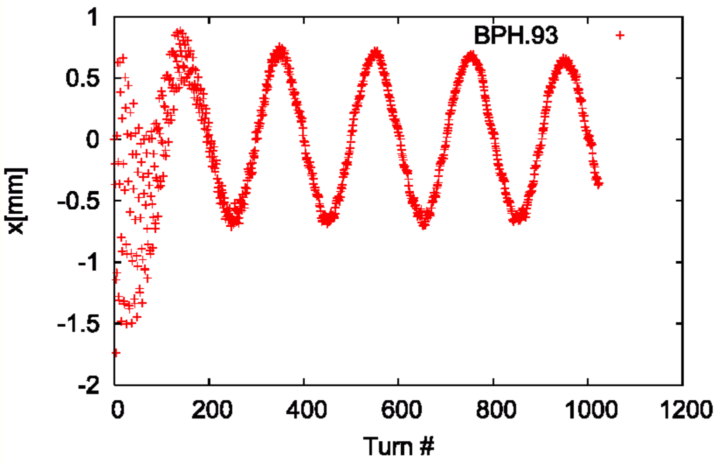
- **Narrow-band closed orbit data is provided with and without calibration tone correction**
  - **A CAL tone with ~400 kHz offset corrects for slow gain drifts of individual channels.**
  - **In 1.56 Hz operation we integrate 160 msec NB beam and CAL data (224 points).**
  - **The "ping-pong" CAL tone switches between A&C and B&D.**
  - **The CAL signals are averaged: 16+16 cycle running average.**
- **Test of calibrated / uncalibrated NB beam position of BPM #59:**

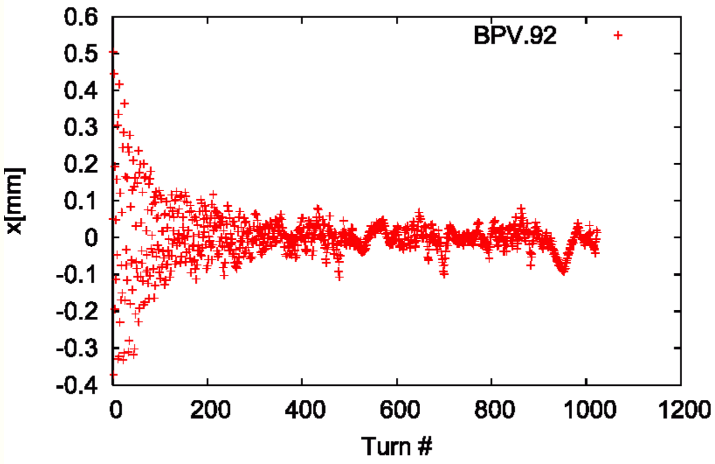
BPM 59 narrow-band beam position (µm)		CAL	no CAL
0dB	horizontal	-90	210
	vertical	250	-145
1 dB (CH.A)	horizontal	-90	-55
	vertical	250	120

BPM Data Collection

- **Took "snapshot" BPM data, for several 100 machine cycles:**
  - Collect first 1024 turns TBT BPM data at injection: the 1st turn is "empty", the following 1023 turns have data
  - Collect NB closed orbit data averaged over 160 msec, starting from turn #500,000, with / without CAL tone correction.
  - Collect last 64 turns TBT BPM data at ejection: the last 48 turns are "empty".
- **Collected TBT BPM data at turn #500,000**
  - Pinger set to 6200 V (hor.), 5800 V (vert.)
  - Took measurements on dispersion orbits ($\Delta RF = -10, +2$ kHz).
  - Also took measurements with tunes set close to the sum resonance: 0.25 (hor.) and 0.65 (vert.).
    - Did not found a reasonable result in x-y coupling. Random BPM tilts of 1 degree RMS would cause similar results.

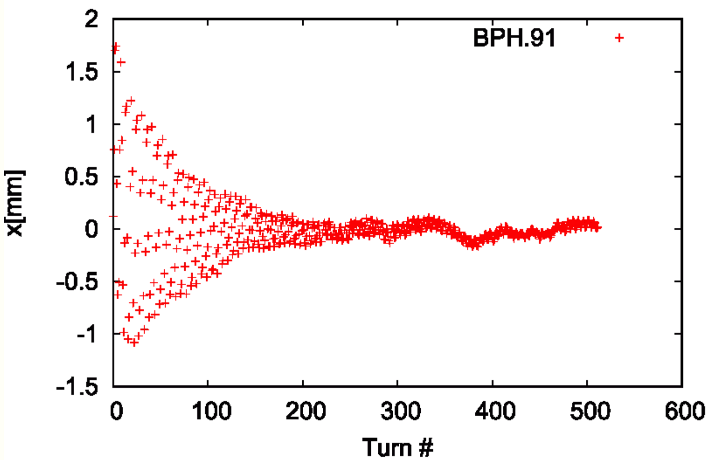
Typical TBT Injection Data



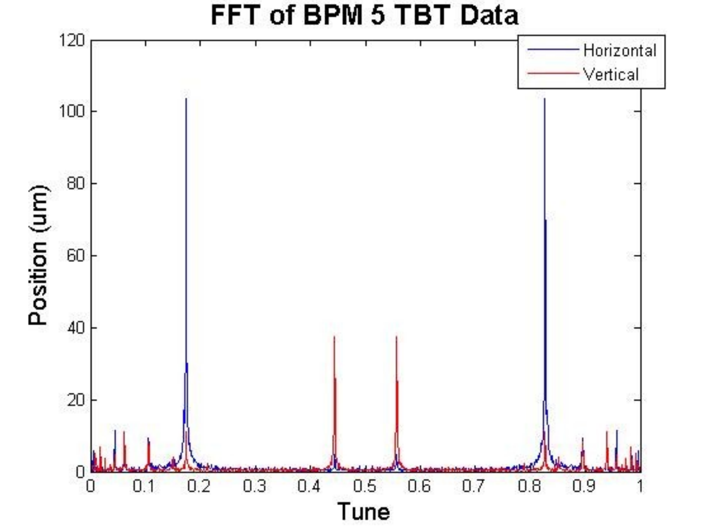


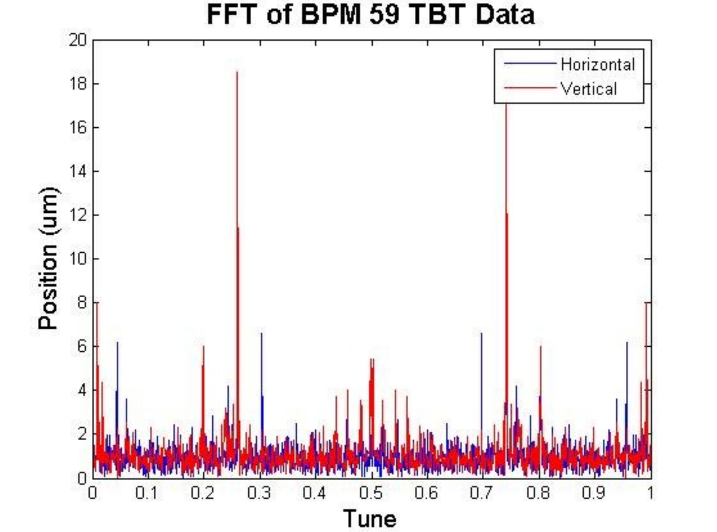
- **Injection shows large, un-damped synchrotron oscillations (hor.)**
  - **Betatron oscillations damp quickly within a few 100 turns**

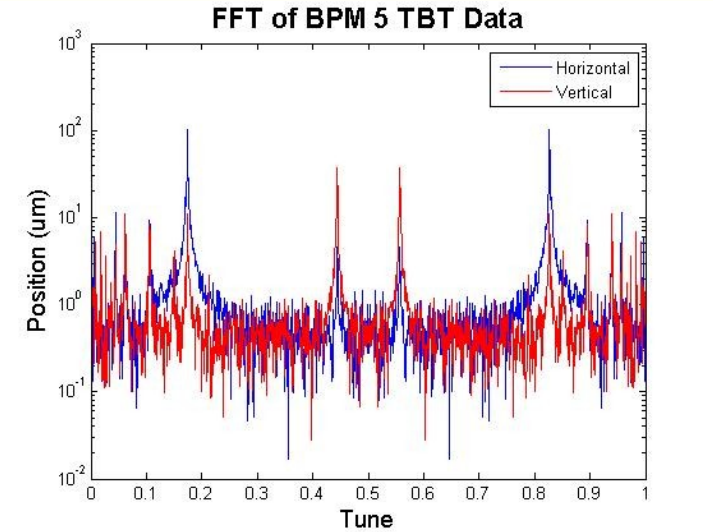
- **The synchrotron oscillation is fitted and subtracted**

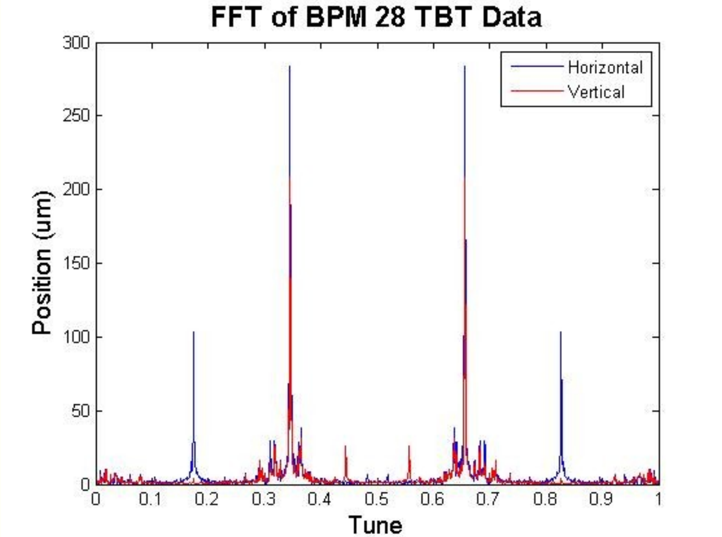


Typical TBT FFT Plots

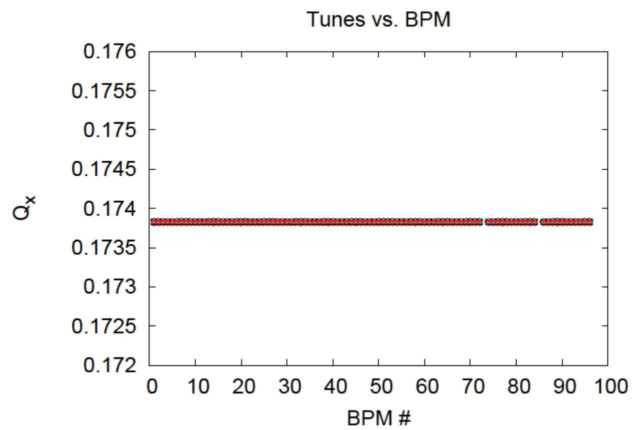




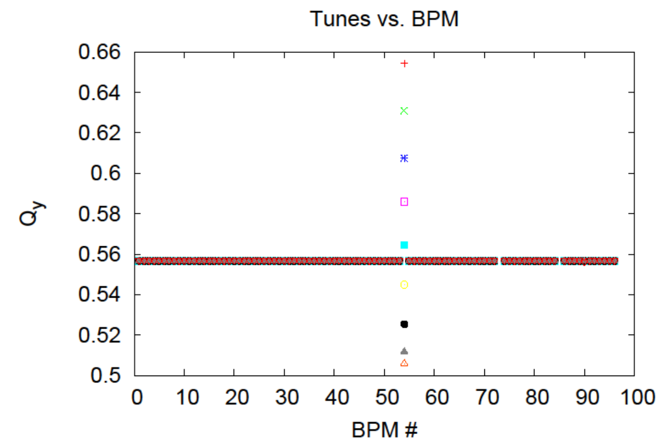


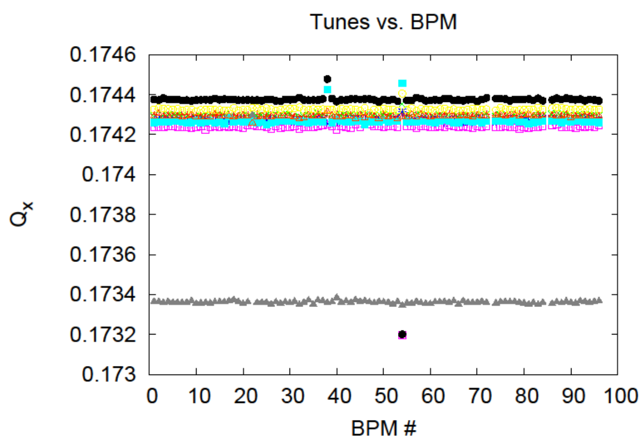


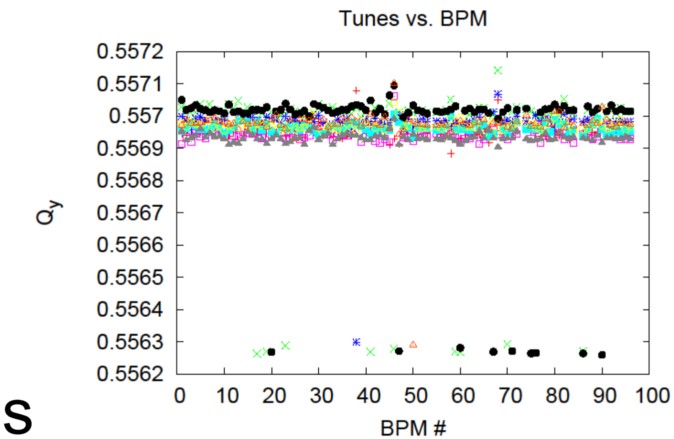
Shot-to-shot TBT Tunes



FFT only







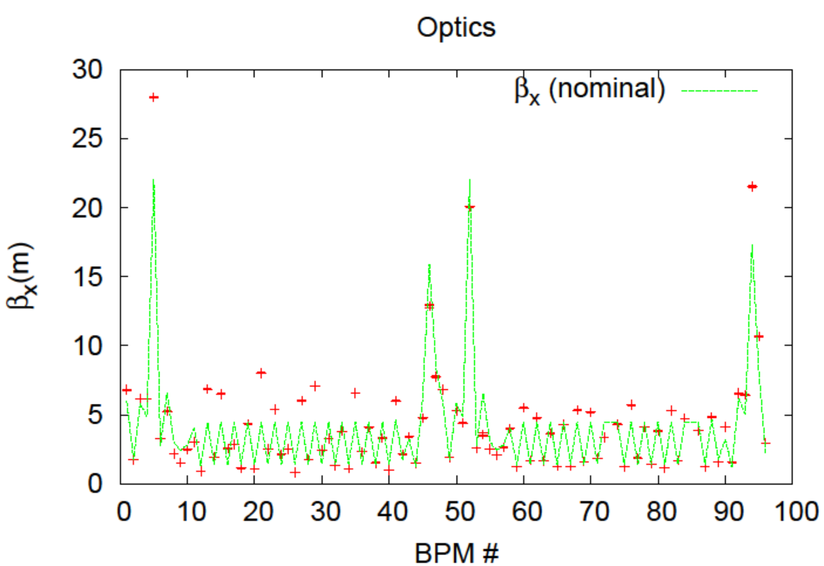
FFT plus

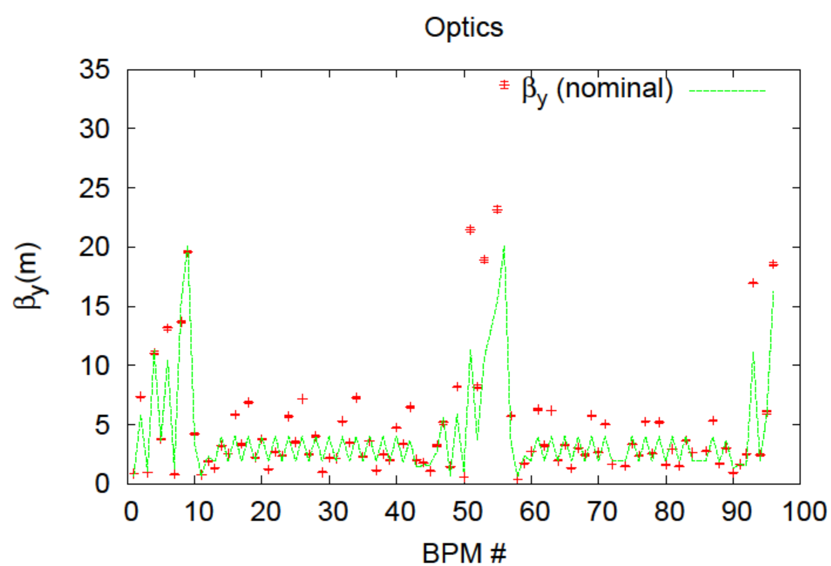
continuous FT around the peak

- **BPM #28 data has a strong noise source**

TBT Damping Ring Optics

- **Test DR optics with pinged TBT data, average over five data sets.**
  - **Excluded are BPMs 46 and 72.**
  - **Vertical kick is weak due to unfortunate kicker location.**
  - **BPM numbers are shifted to the kicker location, i.e. +26**
  - **Horizontal measurements shows different agreement with theoretical optics for the two arcs.**
    - **Seems the agreement is better in the 2nd arc?!**

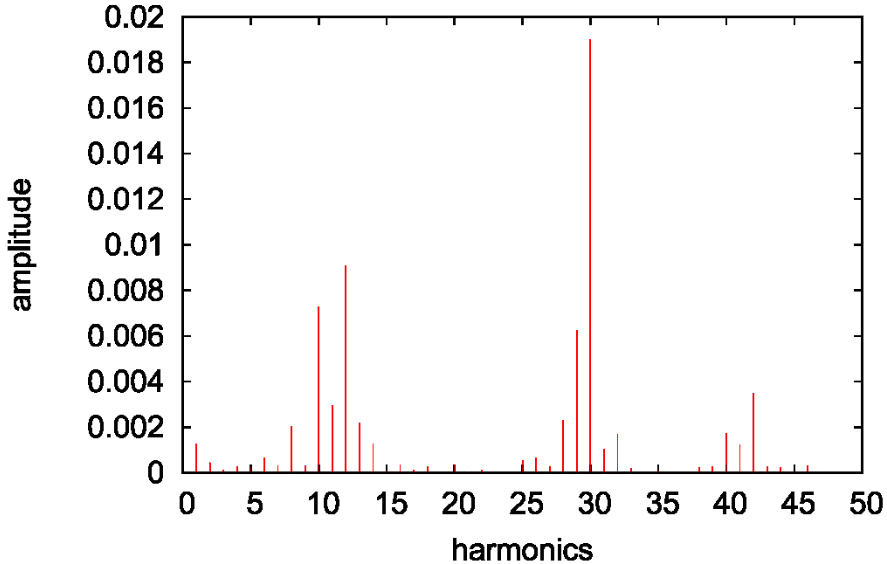




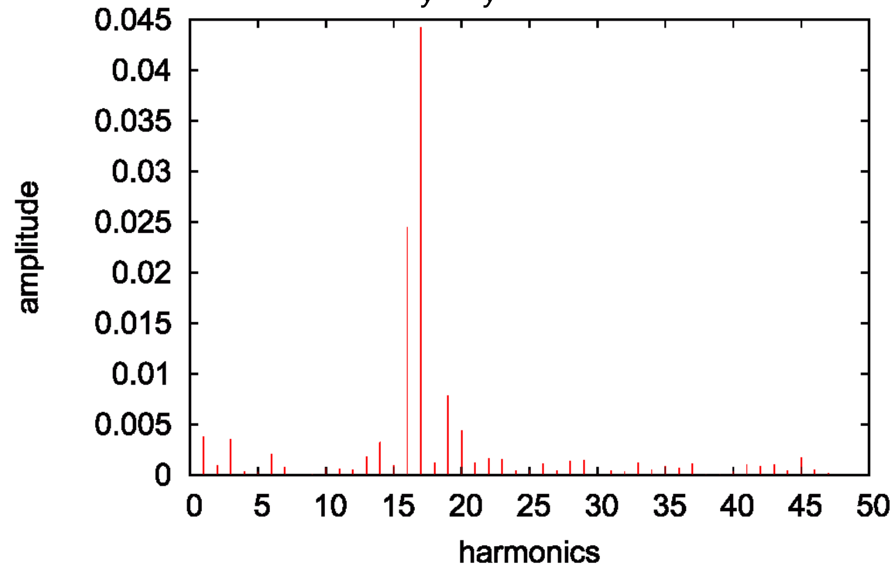
TBT Damping Ring Optics (cont.)

- **Pinged data shows β-beating wrt. to nominal optics**
  - $\Delta\beta_x / \beta_x = 29\ \%$
  - $\Delta\beta_y / \beta_y = 44\ \%$
  - **The *Fourier* analysis verifies this result**
    - $\Delta\beta / \beta \sim 1/\sin(2\pi Q)$, i.e. peaks at $2Q$

$\Delta\beta_x / \beta_x$ spectrum

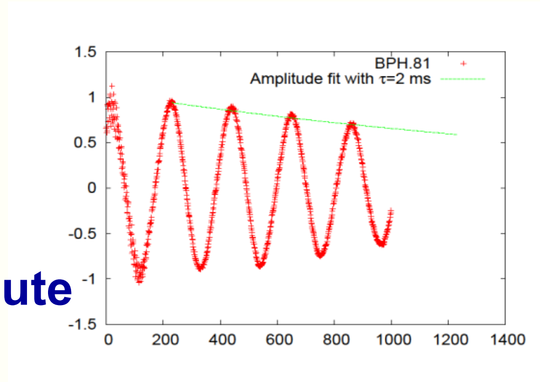


$\Delta\beta_y / \beta_y$ spectrum

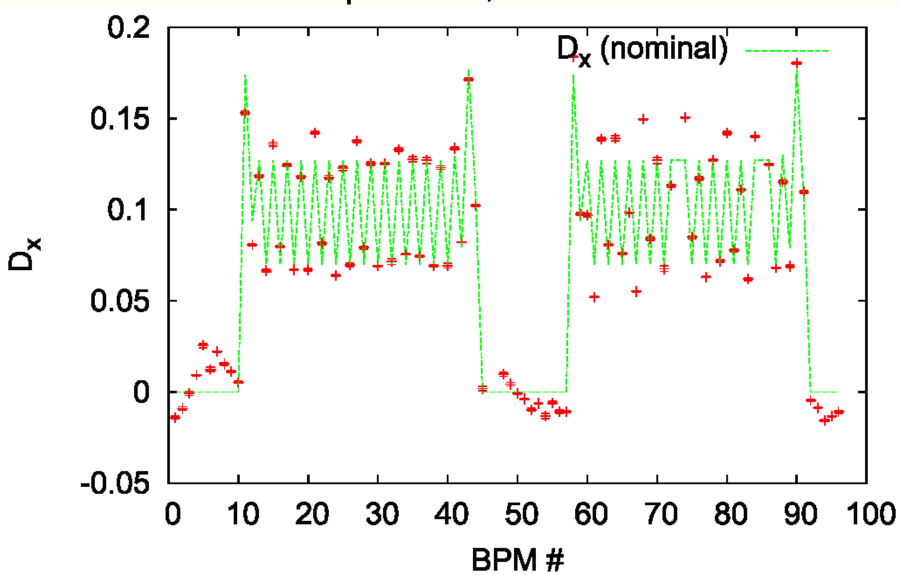


TBT Inj.: Dispersion Measurement

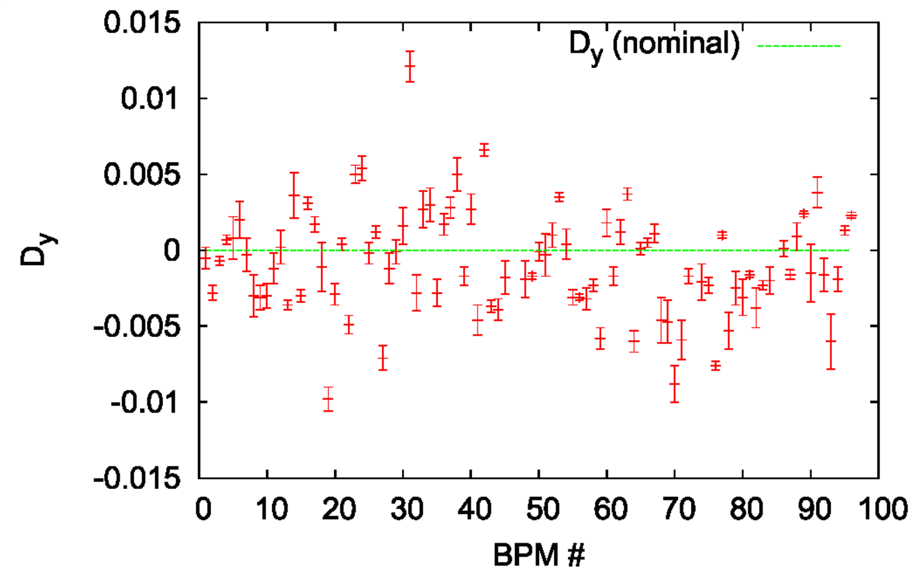
- **Use TBT data to fit the dispersion functions**
  - Use nominal D_x to find the amplitude A and phase φ, which best fits x_TBT.
    - For this we can use all BPMs
  - The values found for A And φ are used to compute the actual D, which best fit each BPM *TBT*.



Dispersion, horizontal



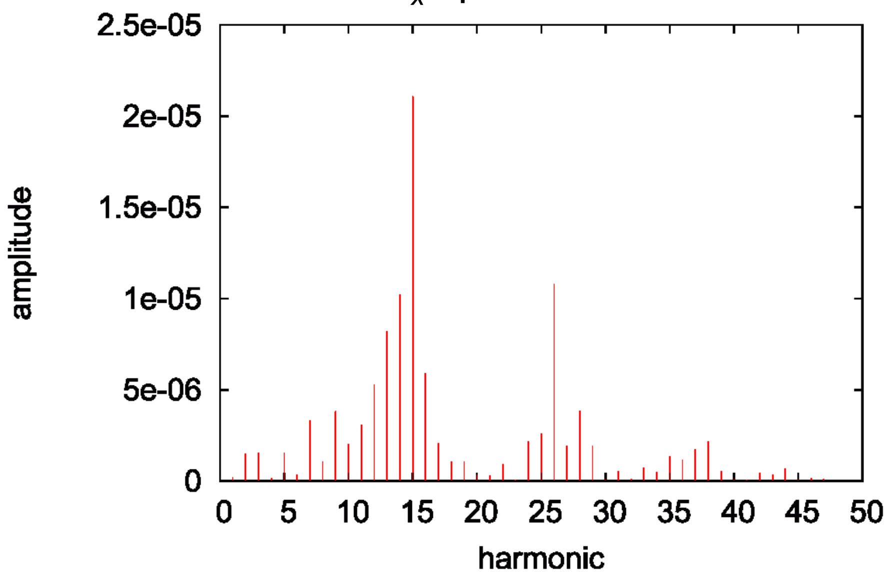
Dispersion, vertical



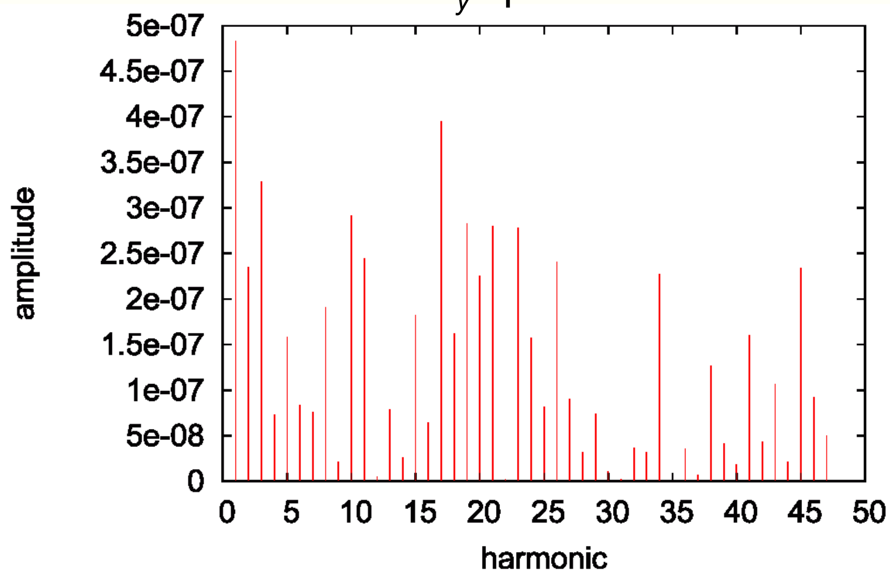
Dispersion Measurement (cont.)

- **Fourier analysis of the dispersion $\Delta D(s) = D_{meas}(s) - D_{theo}(s)$**
  - **Peaks as expected at h = 15 (Q_h = 15.18)**
    - **The actual dispersion depends on the orbit (beam offsets in the quads -> dipole)**
    - **Dispersion peaks at the main orbit harmonic, i.e. the betatron tune, as the closed orbit is proportional to the dipole error fields 1/sin(πQ).**
  - **No peak observed in the vertical plane around h = 8.**

ΔD_x spectrum



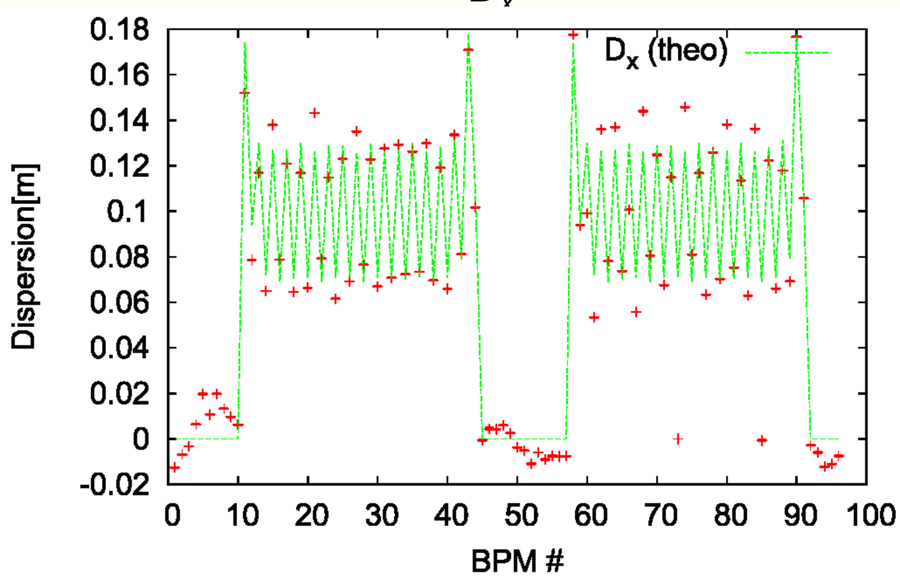
ΔD_y spectrum



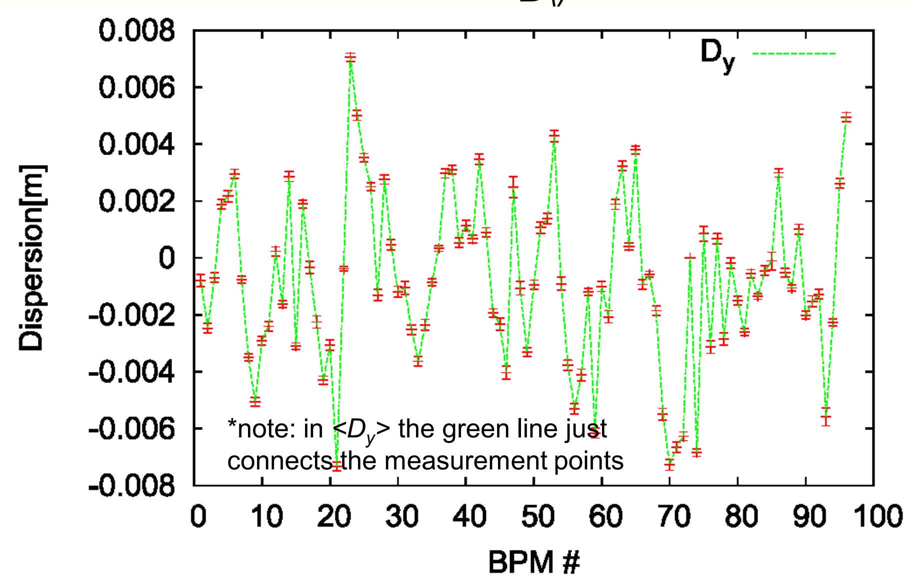
Dispersion Measurement (RF)

- **Dispersion measurement using a frequency shift**
  - **Perform closed orbit measurements with Δf = -10 kHz**
    - **Reference orbit: average 50 data sets**
      RF shifted orbit: average 15 data sets
    - **Particle are now on the dispersion orbit *D dp/p*, with *dp/p* □ *df/f***

<D_x>

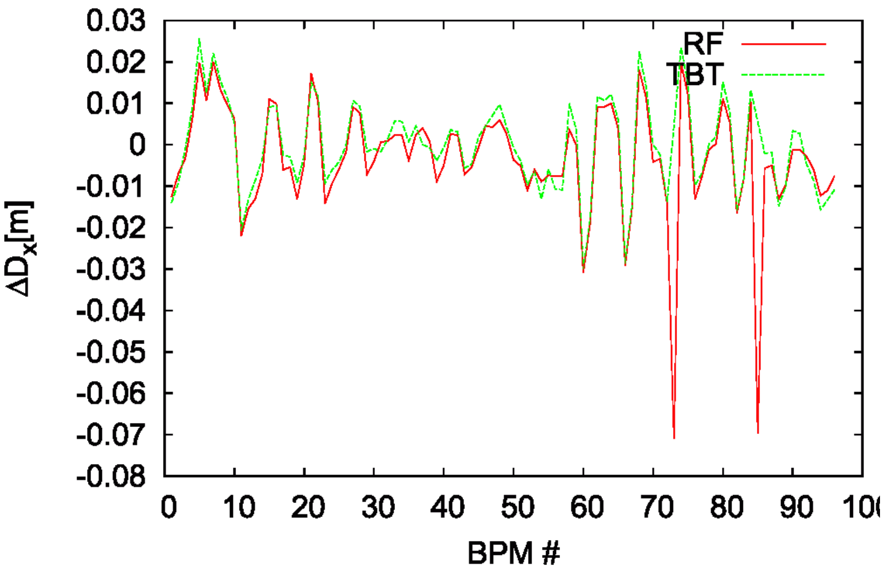


<D_y>*

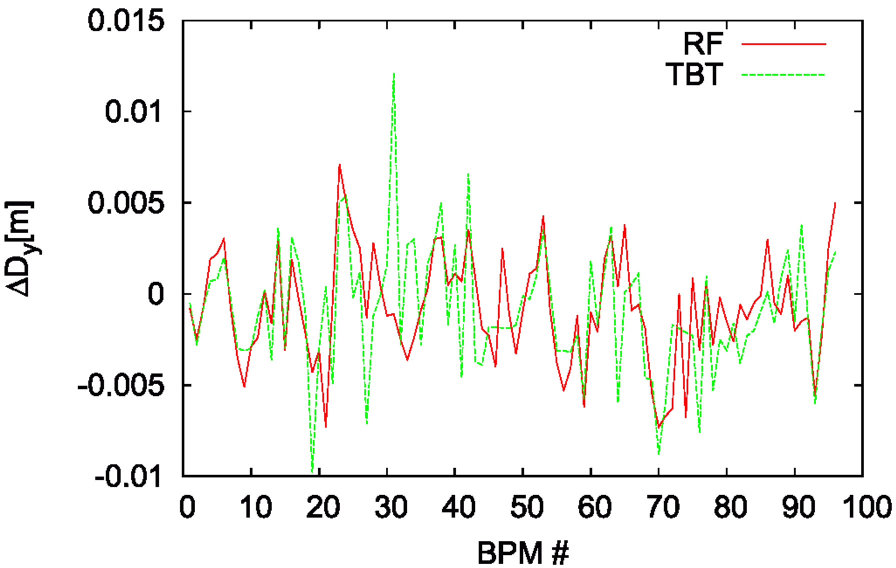


- Compare RF and TBT inj. dispersion measurements
  - Good agreement in the horizontal plane
    - BPMs 73 (#47) and 85 (#59) where disabled (large “errors”)
  - Still fair agreement in the vertical plane, having only little dispersion perturbation.

ΔD_x



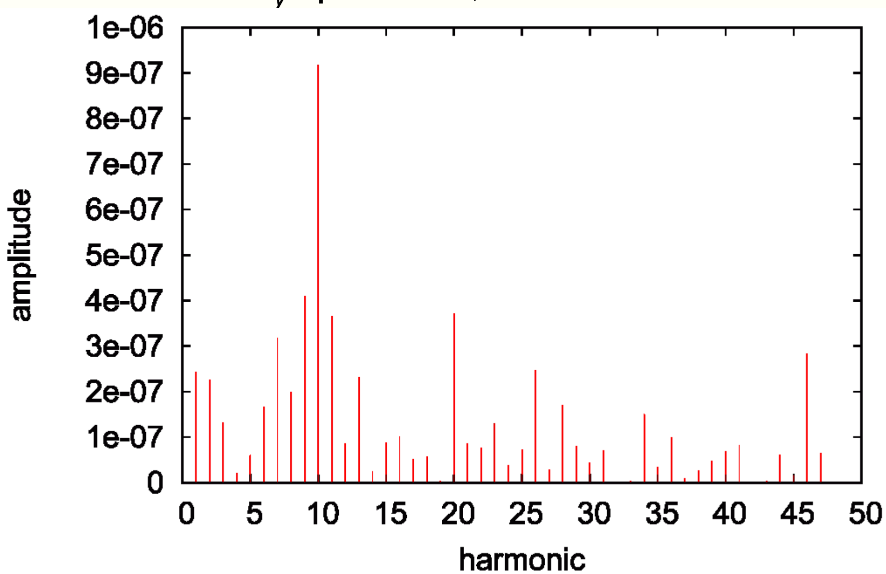
ΔD_y



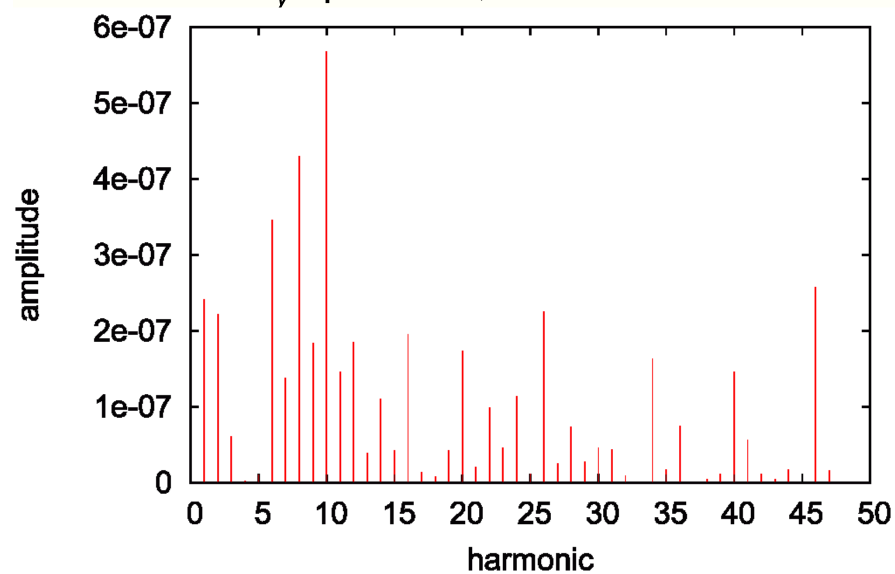
Dispersion Analysis (cont.)

- **Hypothesis: Random BPM tilt errors**
  - **Would generate small vertical offsets, even if $D_y = 0$**
    - **Is compatible with white D_y spectrum on page 32 (right plot).**
  - **Re-compute the vertical dispersion subtracting the D_x contribution due to the *BPM* tilt (*tilt* = D_y/D_x < 5 degrees)**
    - **Enhances *h* = 8 and damps *h* = 10 in the D_y spectrum**

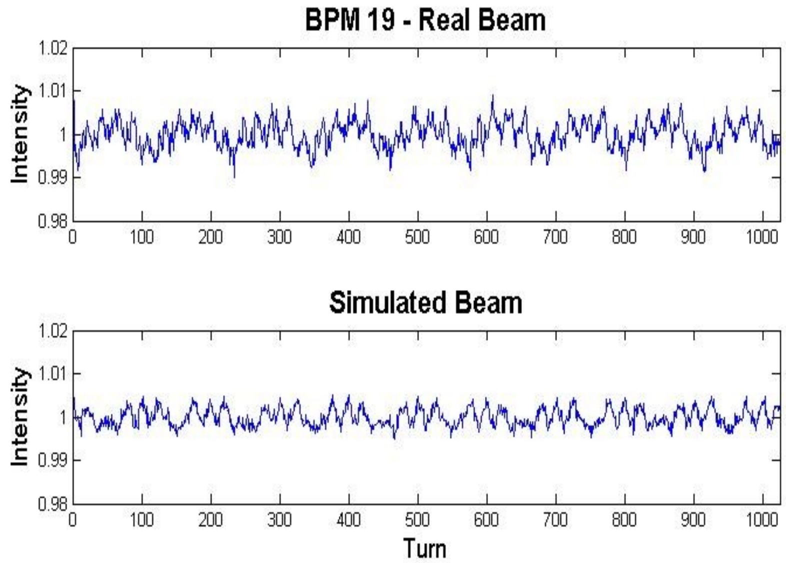
ΔD_y spectrum, no tilt correction

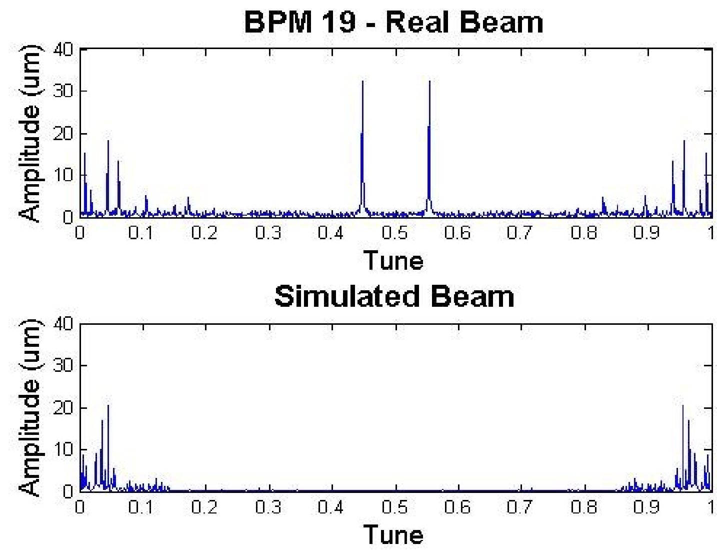


ΔD_y spectrum, with tilt correction

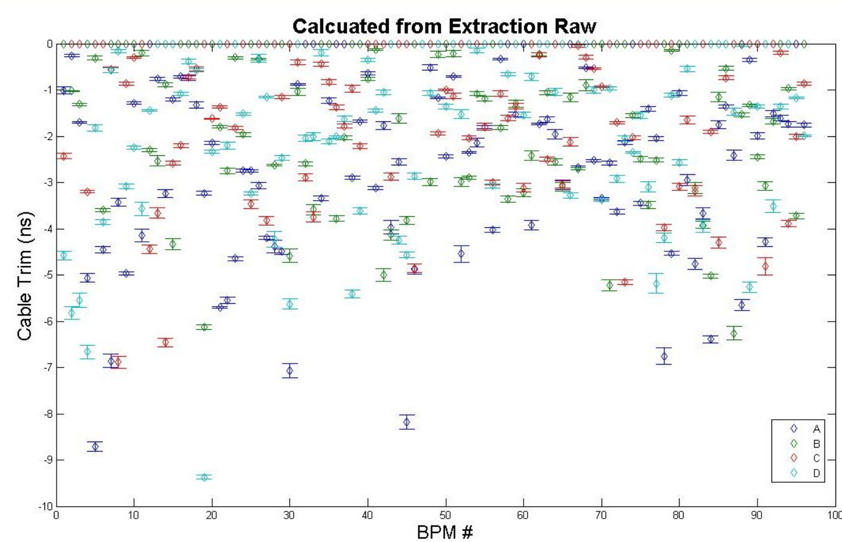


TBT Phase Analysis



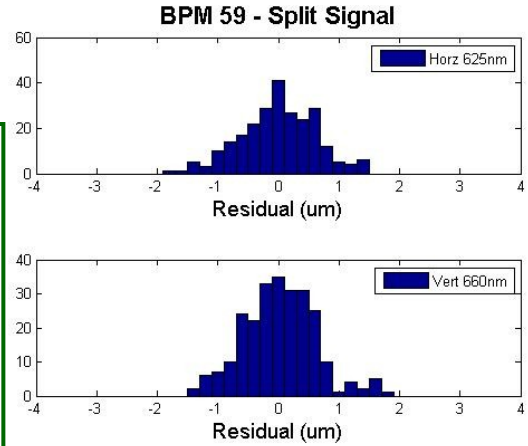


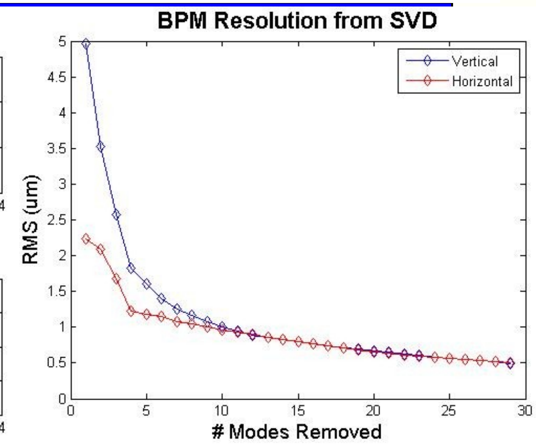
- **Beam phase motion (synchrotron oscillation) results in an error on each button magnitude**
- **This effect can be seen on the intensity (button sum)**
- **In the ideal case where each channel is sampled at the same phase, this would not affect the position**
- **Simulated beam signals with expected synchrotron oscillation (200 turn period)**
- **We can minimize the channel to channel sampling phase via cable trims**

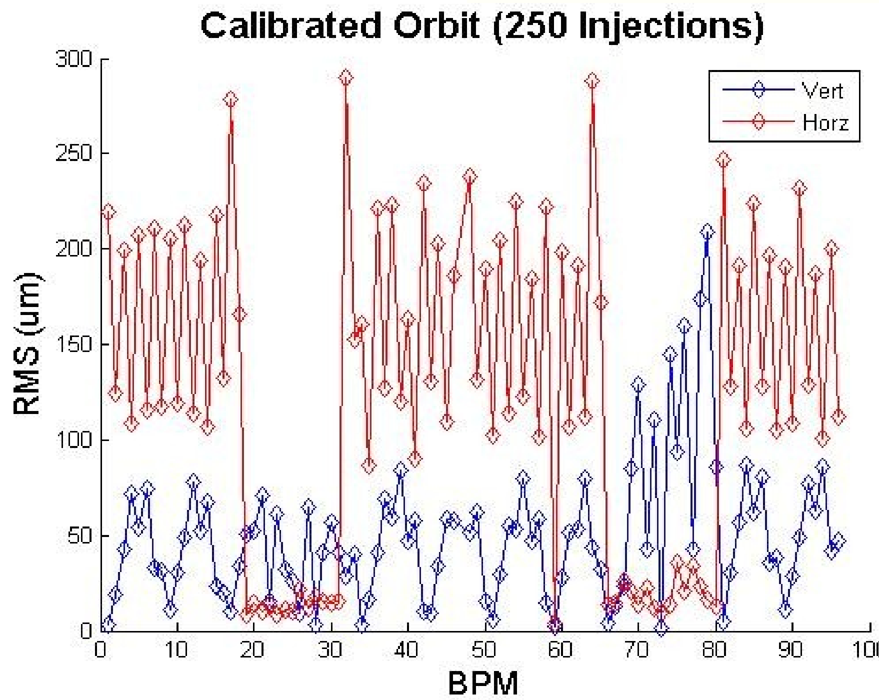


Narrowband Results (preliminary)

- 250 Orbit measurements made over an 8 hour shift
- Resolution estimated with split signal BPM and by SVD technique
  - 0.650 µm with split signal
  - 1.25 µm (6 SVD modes)
  - 0.660 µm (20 SVD modes)
- Measurements where performed in low gain
- Need more investigations!







Summary and Outlook

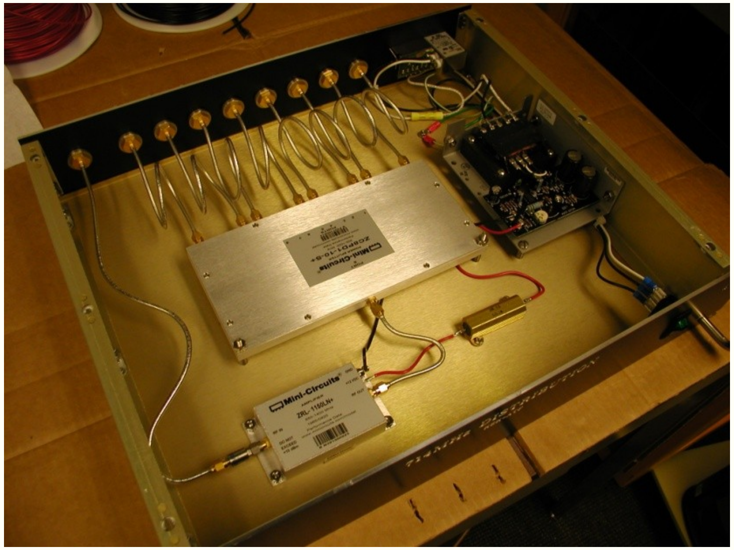
- The ATF damping ring BPMs are made operational
  - Report 1024 TBTs at injection, 64 TBTs at extraction, and high resolution NB data, all at the same machine cycle
    - No problems in 1.56 Hz operation, 3.12 Hz operation needs to be tweaked.
    - Crate synchronization, last turn data, time stamping, etc. are OK!
    - Automated search for first and last turn in the FPGA.
    - Automatic gain correction on NB data.
  - Provide additional operation modes for dedicated studies.
    - Flexible combination of raw, TBT and NB data
- Need more beam studies and some improvements
  - Phase match of tunnel-to-rack cables
  - BBA mandatory for further machine studies
    - BPM-quad offsets and tilts!
  - Need control system tools and GUIs

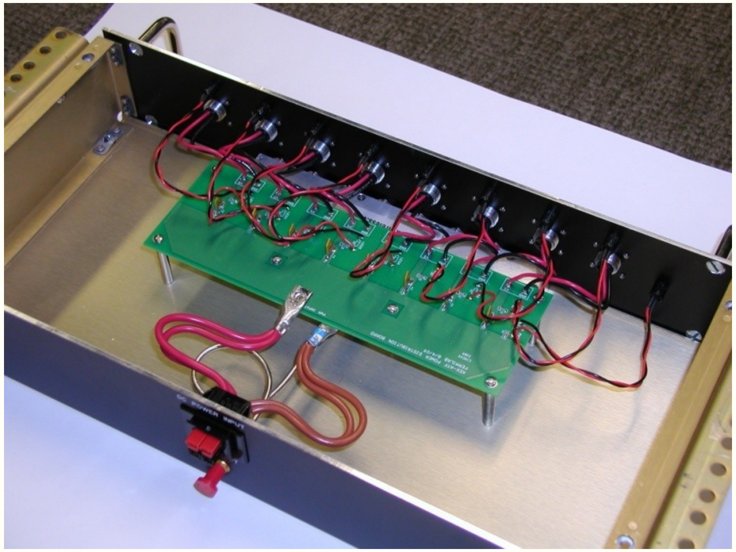
Thanks for Listening!

THANKS!

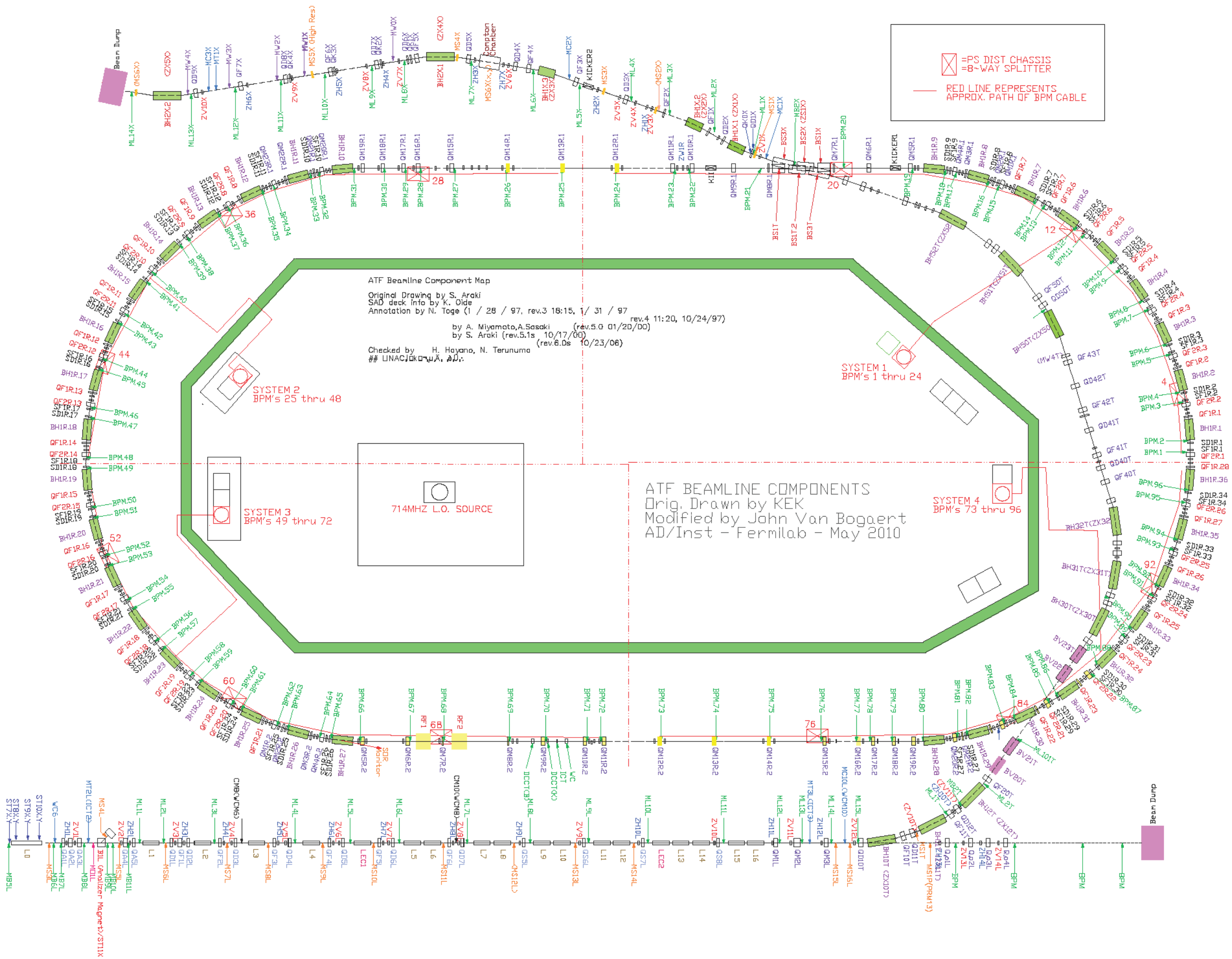
Backup

RF, LO & DC Distribution

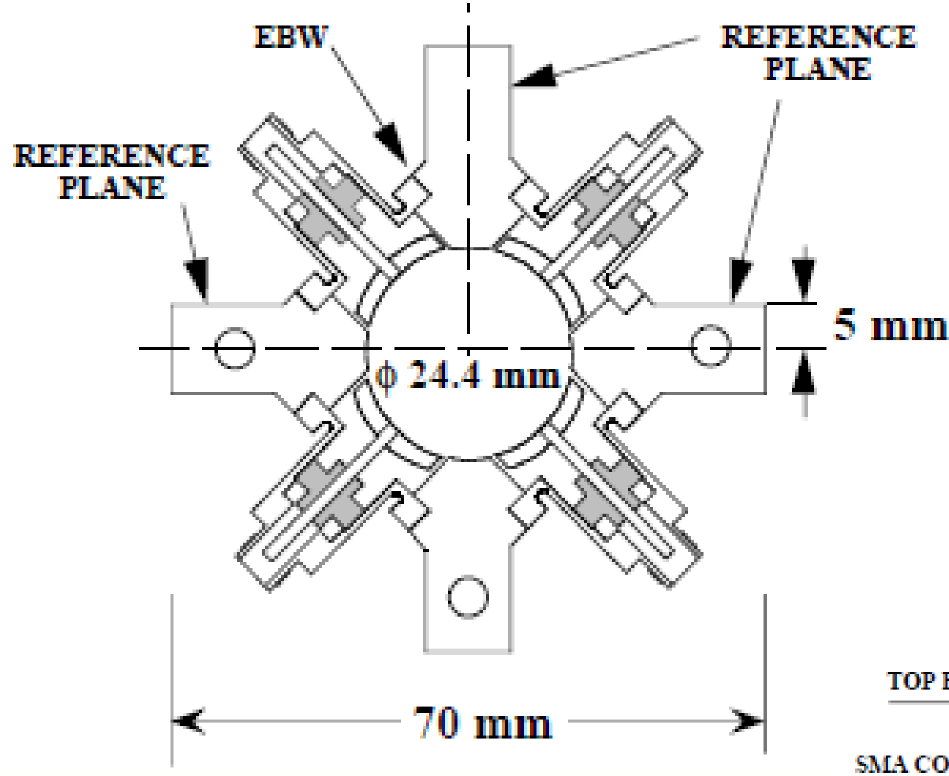


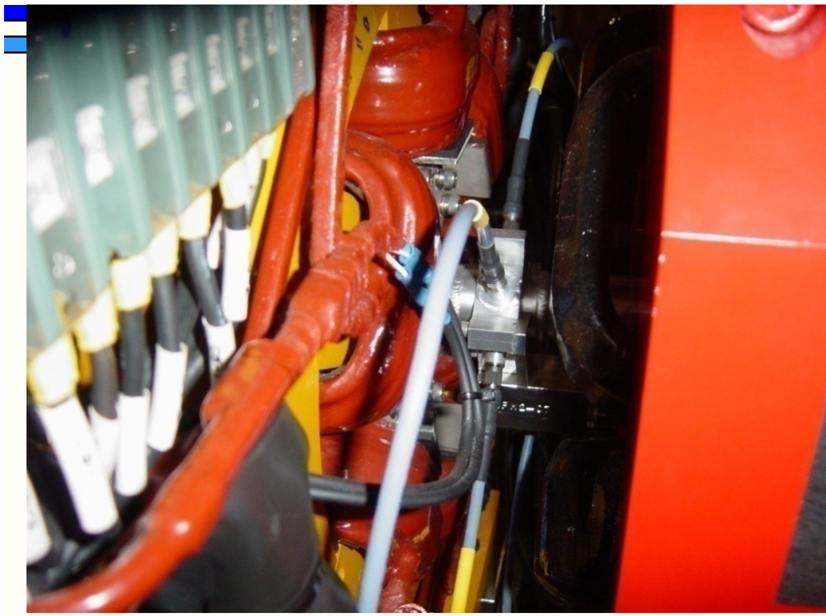


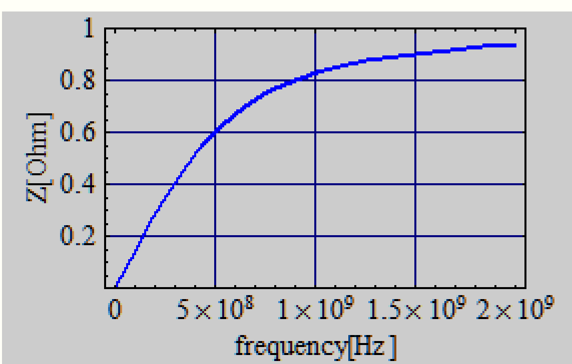
The ATF Damping Ring



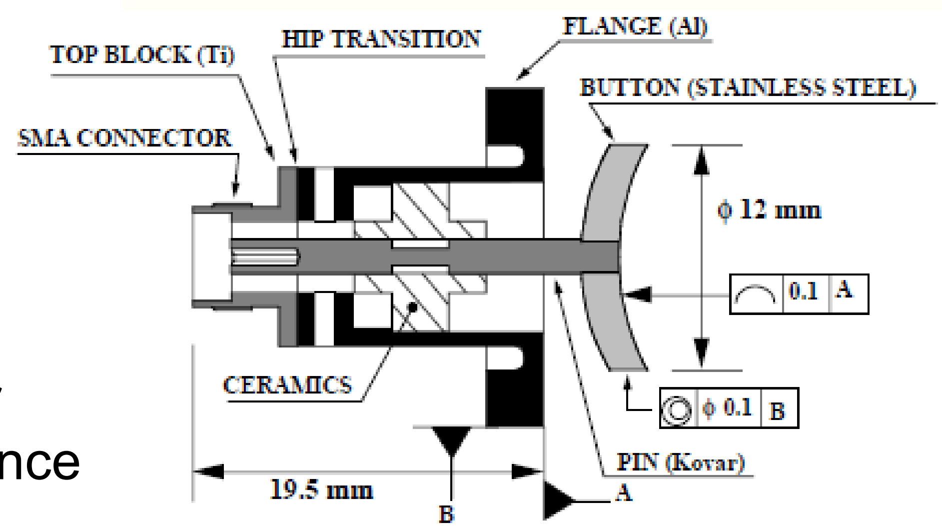
Button-style BPM Pickup







Button: transfer impedance



Calibration Details

- **Calibration in narrowband mode:**
  - **Calibration tone frequency: f_{CAL} = 713.6 MHz**
  - **Beam frequency: f_{beam} = 714.0 MHz**
- **Basic calibration procedure:**
  - **Correction values:**

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

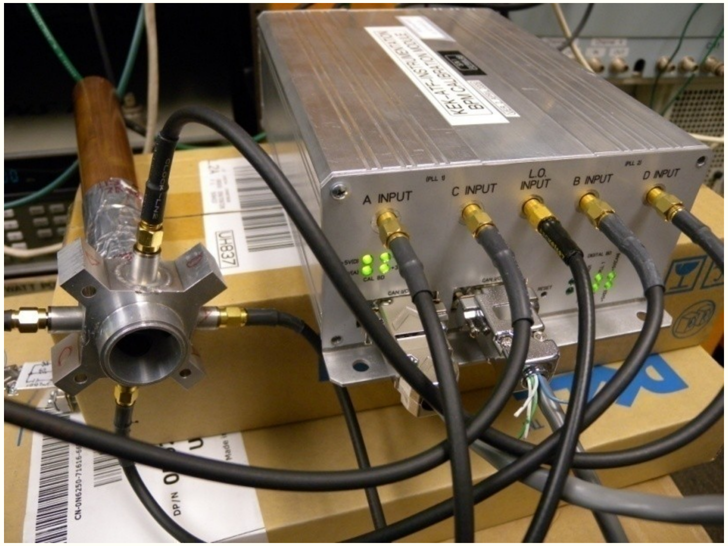
$$C_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4 C_{CAL}} \qquad D_{Corr} = \frac{A_{CAL} + B_{CAL} + C_{CAL} + D_{CAL}}{4 D_{CAL}}$$

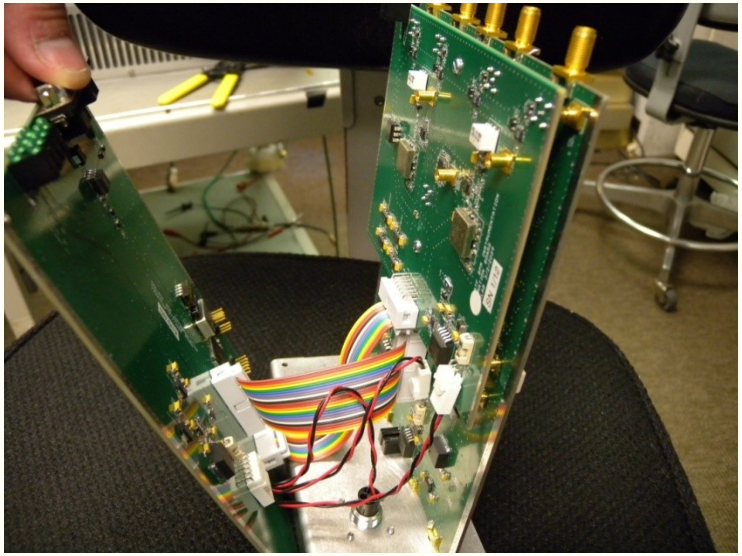
  - **Corrected beam positions:**

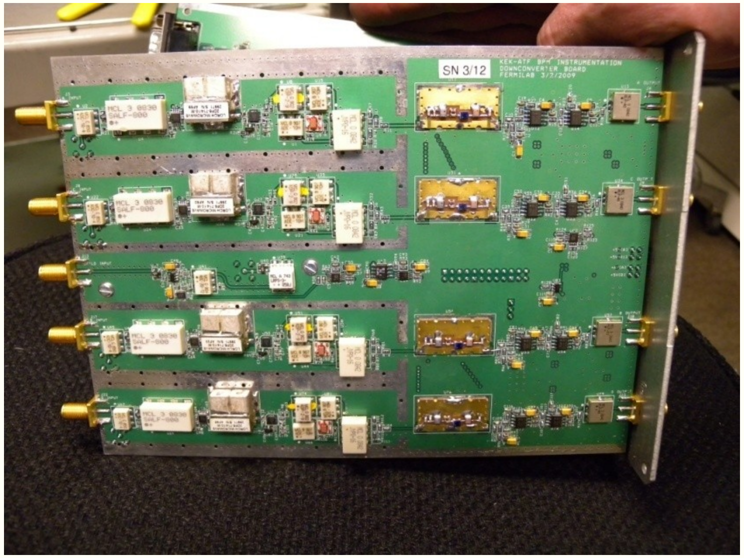
$$\phi_{Hcorr} = \frac{(A\,A_{Corr} + D\,D_{Corr}) - (B\,B_{Corr} + C\,C_{Corr})}{A\,A_{Corr} + B\,B_{Corr} + C\,C_{Corr} + D\,D_{Corr}}$$

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

Analog Downmixer (prototype)







Memory

- The board has six 16bit by 32Meg DDR2 memory chips
  - Provide a total of 384MBytes of storage with 96bit bus
  - Operating at 300MHz -> ~2GB/s of memory bandwidth
    - Need to account for setup & refresh time
- Able to write raw ADC data at 71.4MHz as well as processed data in parallel
  - The raw ADC data requires ~1GB/s of memory bandwidth
  - NB windows - store all processed and diagnostic data
  - WB windows – store processed TBT data and raw ADC data
- The current readout rate using A32D32 DMA transfers is ~10MB/s
  - It would take over 30 seconds to DMA out entire on board ram!
    - This is only used for diagnostic purposes
  - For the ATF operation, all physics data is readout in ~20ms
  - The readout can be further optimized if needed ~20MB/s is possible

Software Components