Trends in High Precision, High Stability BPM Systems

Manfred Wendt

CERN

This presentation was assembled with a lot of help of the beam instrumentation community!

Contents

- Introduction
- BPM System Overview
- Button BPMs
- Electronics & Signal Processing
- BPM Performance & Beam Studies
- BPMs & Feedback Systems
- Long Term Stability Issues
- Summary

This is a personal selection of material on this BPM topic, based on recent conference and workshop presentations.
Thanks to all my friendly colleagues providing their help!

Introduction

- **A low emittance beam in a ring accelerator requires**
  - **Selection of the optimal lattice, e.g. multi bend achromat (MBA)**
  - **Magnets with minimum non-linearities (higher order multipoles)**
  - **Precision alignment of all accelerator components**
  - **Control of the beam trajectory along a "golden orbit"**
    - Along the center of the quadrupole fields
    - Correction of unwanted coupling, chromaticity and dispersion effects
- **The beam position monitors (BPM) deliver**
  - **Turn-by-turn beam orbit (wideband operation)**
    - Measurement time: some hundred ns … tens of us (circumference)
    - Bunch-by-bunch BPMs only for fast transverse feedback
  - **High resolution beam orbit (narrowband operation)**
    - Measurement time: ms range, typically synchronized with the AC mains frequency (n/50Hz or n/60Hz)
  - **BPM data for the fast (kHz) orbit feedback**
    - Low latency of the BPM signal processing

Beam Stability Requirements & Goals

Upcoming Projects

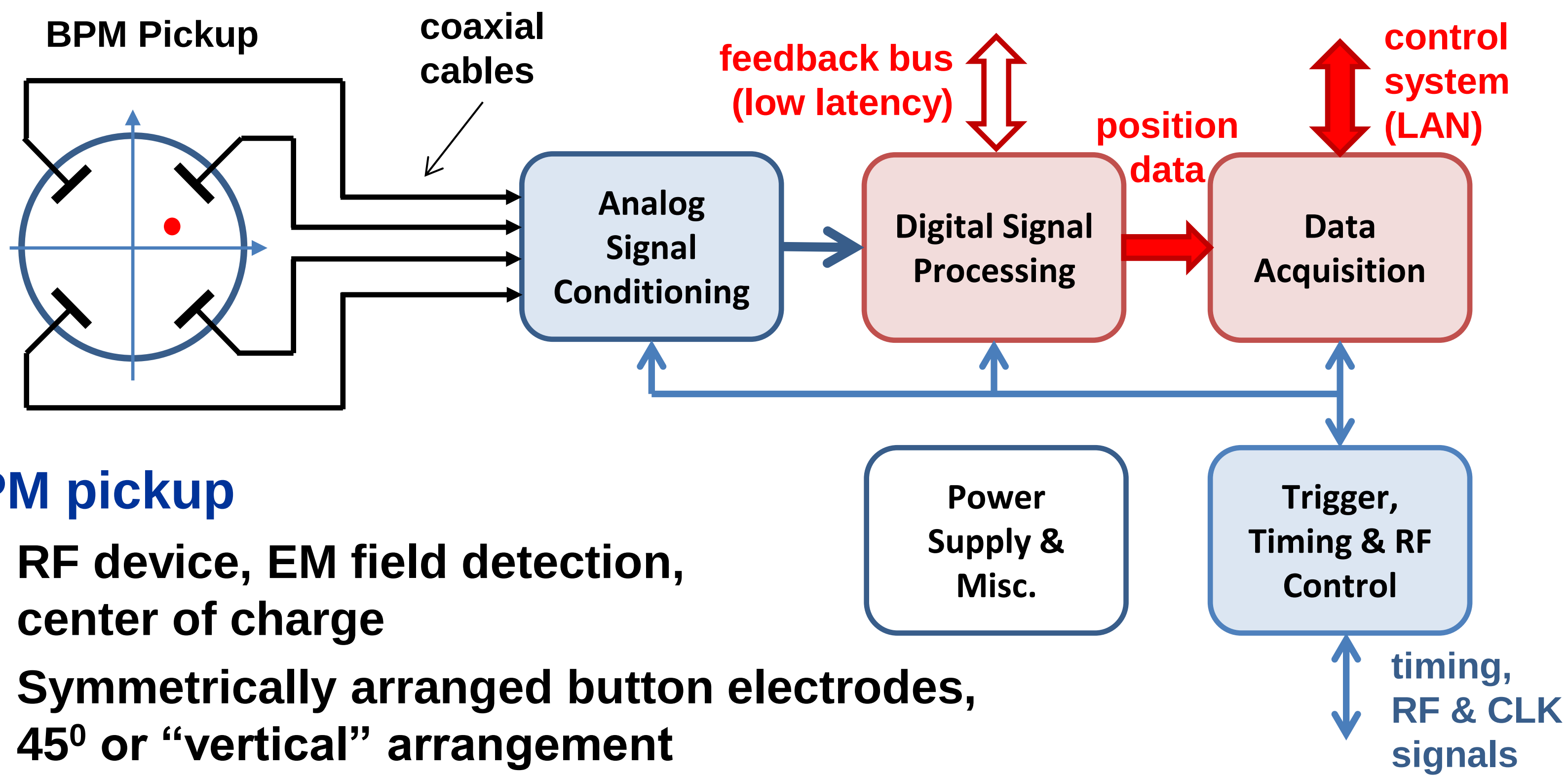
Facility	Stability (µm, RMS)	Bandwidth
Cornell ERL	0.3	1 kHz
LCLS-II FEL	<1.0	60 Hz
E-XFEL	3.0	>1 kHz
SwissFEL	<1.0	50 Hz
APS upgrade	0.4 / 0.8	200 Hz / 1 kHz

APS upgrade

courtesy *G. Decker*

		RMS Motion (0.1-200 Hz)		Long term (1 week, RMS)	
Horizontal	Now	5.0 µm	0.85 µrad	7.0 µm	1.4 µrad
	Upgrade	3.0 µm	0.53 µrad	5.0 µm	1.0 µrad
Vertical	Now	1.6 µm	0.80 µrad	5.0 µm	2.5 µrad
	Upgrade	0.42 µm	0.22 µrad	1.0 µm	0.5 µrad

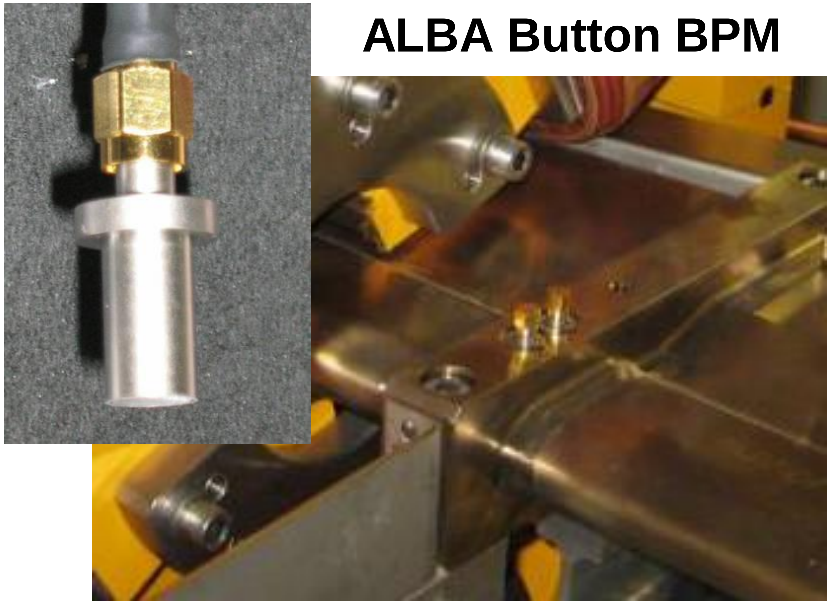
Typical BPM Hardware

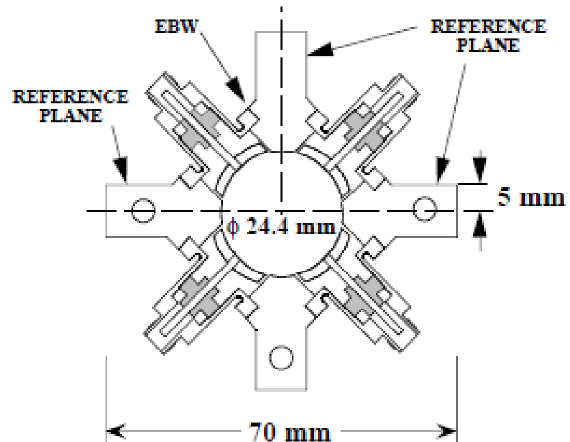


- **BPM pickup**
  - RF device, EM field detection, center of charge
  - Symmetrically arranged button electrodes, 45^0 or “vertical” arrangement
- **Read-out electronics**
  - Analog signal conditioning
  - Signal sampling (ADC)
  - Digital signal processing
  - Data acquisition and control system interface
  - Trigger, CLK & timing signals

Button BPM Pickup

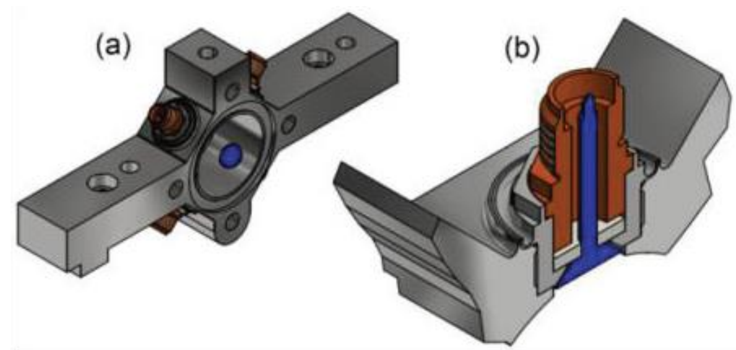
ALBA Button BPM





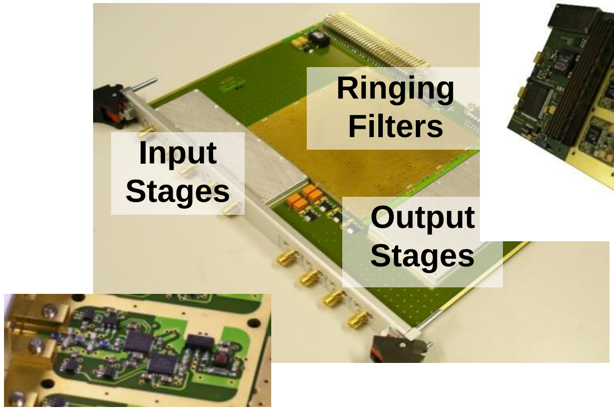
ATF Button BPM (KEK)

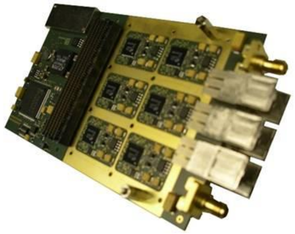
NSLS-II Button BPM (BNL)

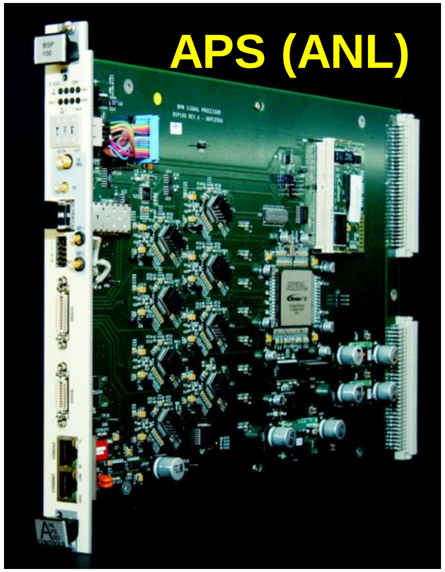


SIRIUS Button BPM (LNLS)

BPM Read-out Electronics



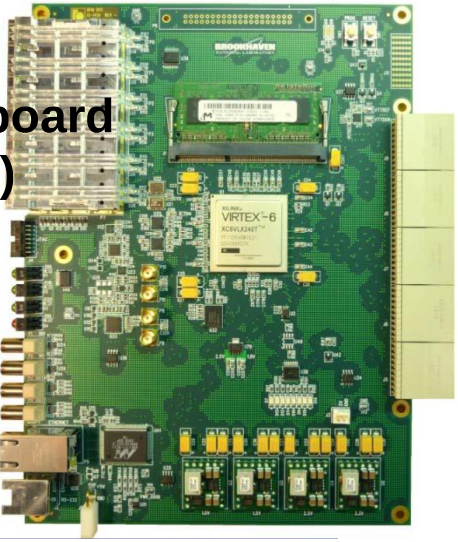




Modular BPM electronics for SLS (PSI)

Commercial BPM electronics
(Instrumentation-Technology)

Digital BPM board
NSLS-II (BNL)



Do we understand the Button BPM?

- **Broadband pickup transfer impedance:**

$$V_{elec}(x,y,\omega) = s(x.y)\,Z(\omega)\,I_{beam}(\omega)$$

- **High-pass characteristic:**
  - **with:**

$$Z(\omega) = \phi\, R_{load} \left(\frac{\omega_1}{\omega_2}\right)\left(\frac{j\omega/\omega_1}{1+j\omega/\omega_1}\right)$$

load impedance, e.g. 50 Ω — *high-pass*

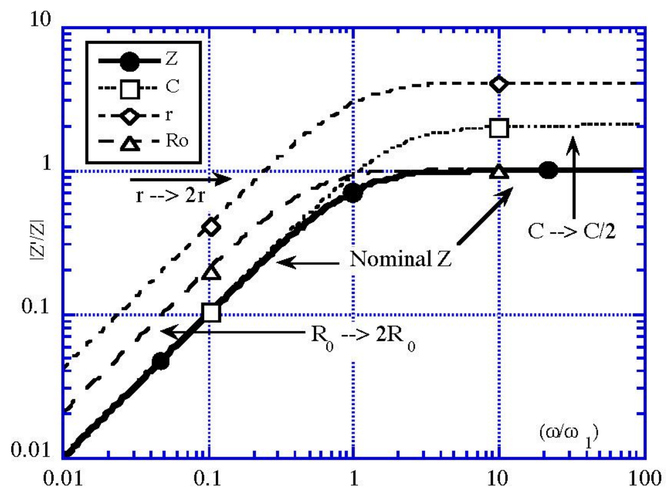
1 / electrode traversal time

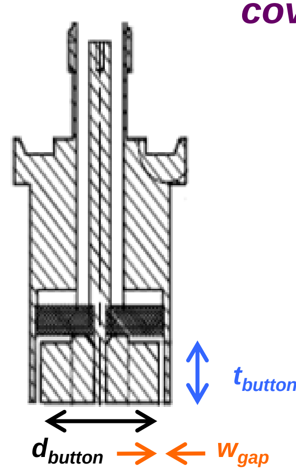
$$\omega_1 = \frac{1}{R_{load}\,C_{button}} \qquad \omega_2 = \frac{c_0}{2\,r_{button}} \qquad \phi = \frac{r_{button}}{4 r_{pipe}}$$

time constant — *coverage factor*

button capacitance

$$C_{button} \approx \frac{2\pi\varepsilon_0}{\ln\left(\frac{r_{button}+w_{gap}}{r_{button}}\right)}\,t_{button}$$





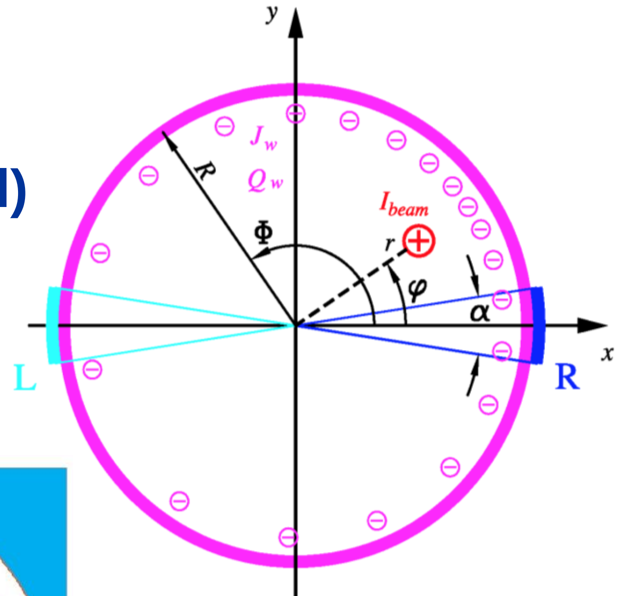
Increase	Effect
d_{button} (larger area & C_{button})	Higher signal level Lower resolution
t_{button} (larger volume)	Lower wake impedance Lower resolution, higher weight
w_{gap} (more trapped modes)	Higher resolution Higher wake impedance

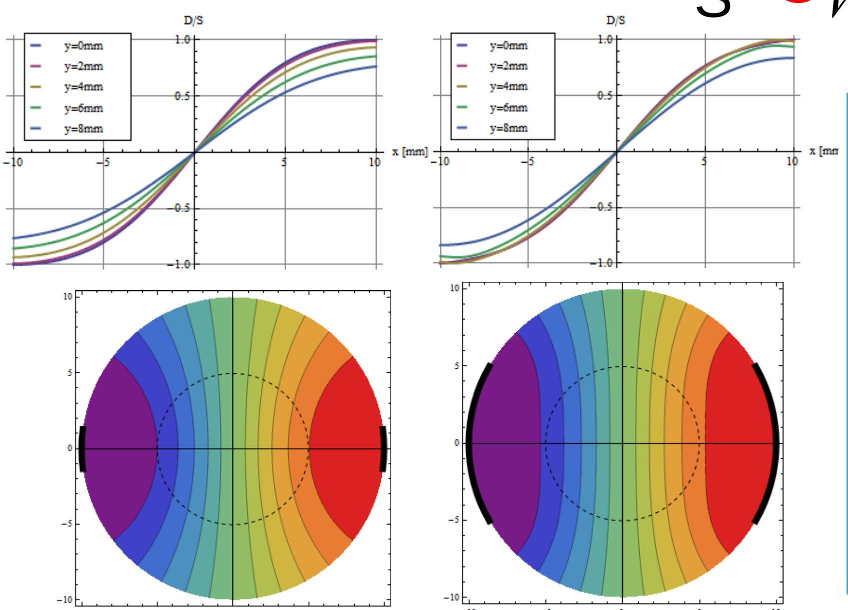
Correction of Pickup Non-Linearities (1)

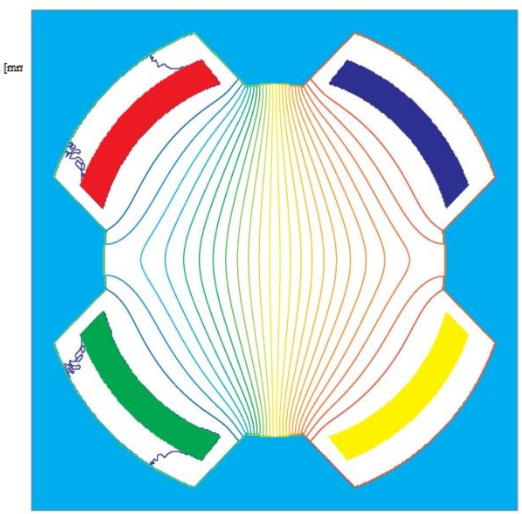
- **Position characteristics follows the image-current model**

$$V_{elec}(x,y,w) = s(x.y)\, Z(w)\, I_{beam}(w)$$

- **Two opposite electrodes (here: horizontal) process the**
  - **beam position** $= \dfrac{D}{S} = k\dfrac{V_r - V_L}{V_R + V_L}$ or $k\dfrac{V_R}{V_L}$



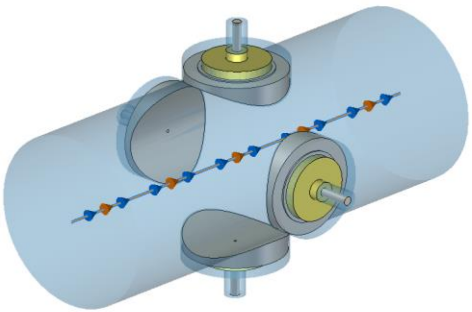




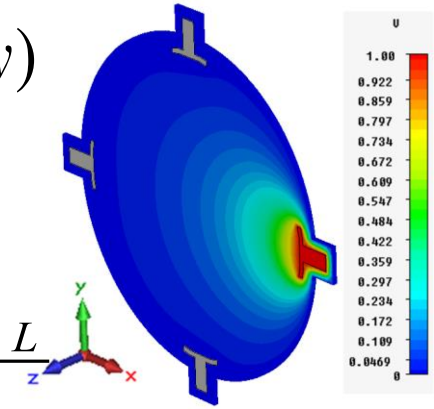
k is a 2D calibration polynomial, with k_{00} being the BPM offset. V_{elec} is given as digital data, e.g. ADC counts.

Correction of Pickup Non-Linearities (2)

- **Arbitrary shaped button BPM**
  - **Numerical analysis in 3D (bunch excitation, wakefield solver), or in 2D (e-static Laplace equation, Green's reciprocity theorem)**

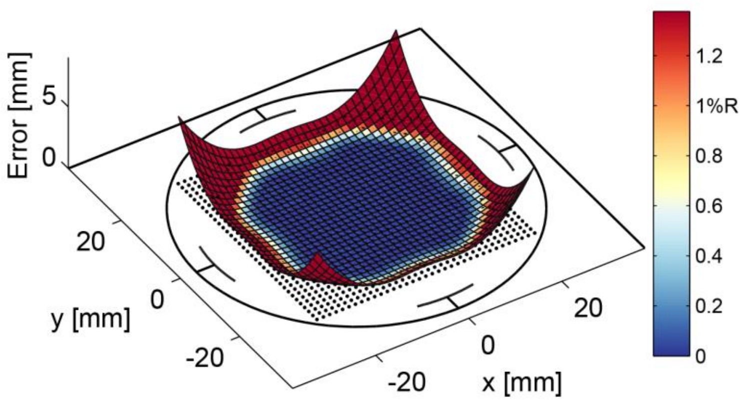


$$\nabla_{\perp}^{2}\Phi_{elec} = 0 \quad \rightarrow \quad \Phi_{elec}(x,y)$$



- Symmetric expansion of Φ_{elec} gives the scalar potential for the horizontal or vertical beam position, e.g.

$$F_x(x,y) = \frac{F_R - F_L}{F_R + F_L}$$



- **Calibration and non-linear correction can be achieved by**
  - **Lookup table for f^{-1} Φ, 1D or (better, includes cross-terms) 2D polynomial fit of f^{-1} Φ**

Remaining calibration errors for an LHC BPM, after applying a 7th order 2D polynomial fit for 60% of the aperture

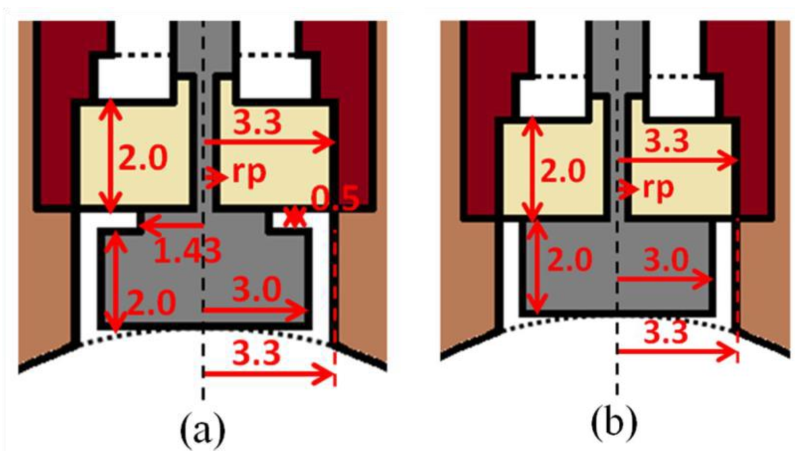
BPM Wake-Potential & Impedance

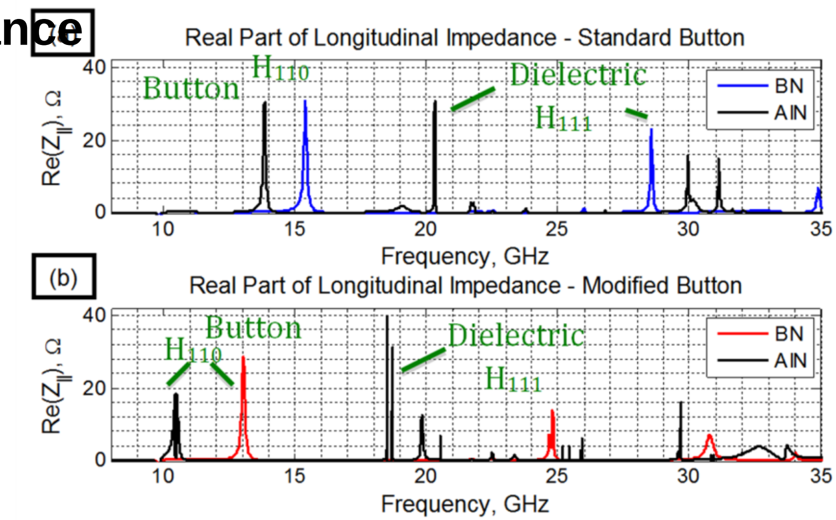
- **The longitudinal coupling impedance of the button pickup is based on the transfer impedance and scales with r_{button}^4**
  - **The slot between button and pipe acts as resonator, thus gives additional impedance effects, also contributes at low frequencies:**

$$Z_l(\omega) = f\left(\frac{\omega_1}{\omega_2}\right) Z(\omega)$$

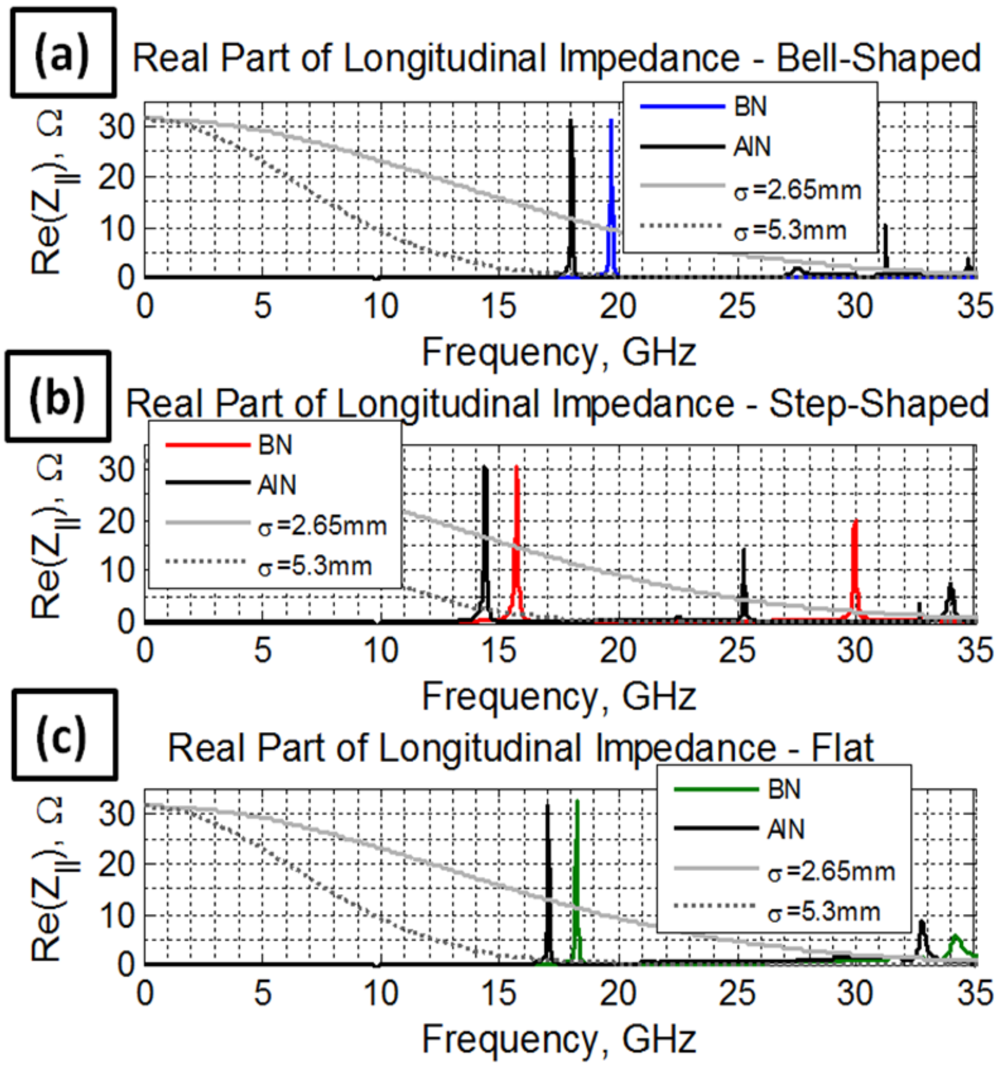
  - **Thickness and shape of the button have significant influence on the coupling impedance**

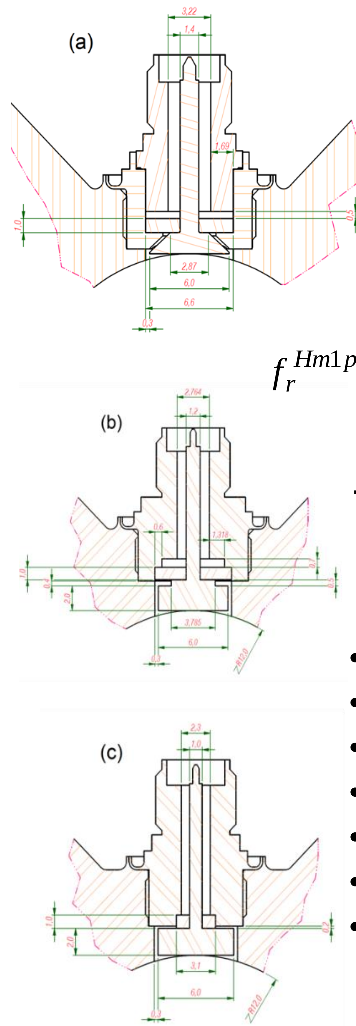
$$Z_{1gap}(\omega) \approx j\left(\frac{Z_0\,\omega\,(r_{button}+w_{gap})^3}{8\,c_0\,r_{pipe}^2\left\{\ln\left[32(r_{button}+w_{gap})/w_{gap}\right]-2\right\}}\right)$$





Coupling Impedance Studies for Sirius





Trapped H-modes in the insulator dielectric

$$f_r^{Hm1p} = \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{2\pi} \sqrt{\left(\frac{2m}{r_p + r_h}\right)^2 + \left(\frac{\pi p}{t_c}\right)^2}$$

Trapped H-modes in the button

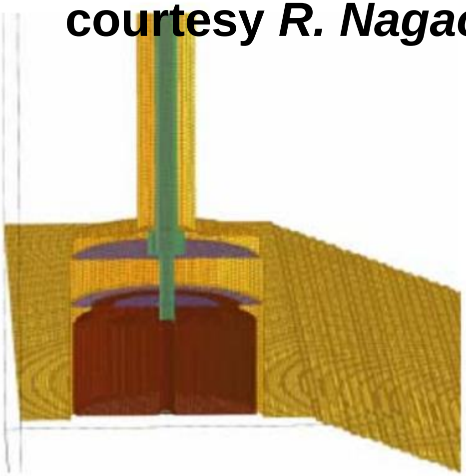
$$f_c^{Hm1} = \frac{c}{\pi} \frac{m}{r_b + r_h}$$

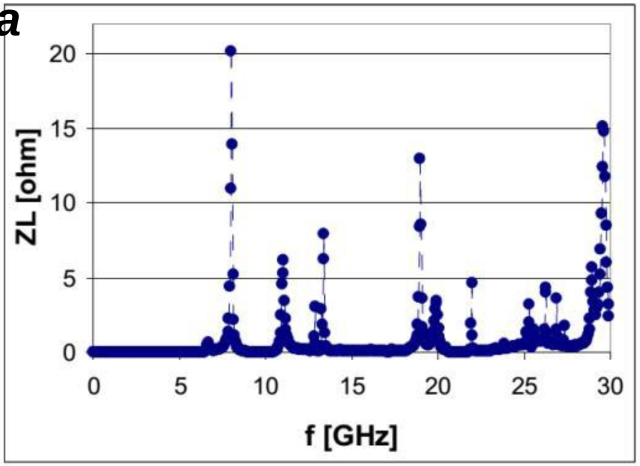
- ε_r: dielectric permittivity
- m: azimuthal index and
- p: longitudinal mode number
- r_p: insulator pin radius
- r_h: housing radius
- r_b: button radius
- t_c: ceramics thickness

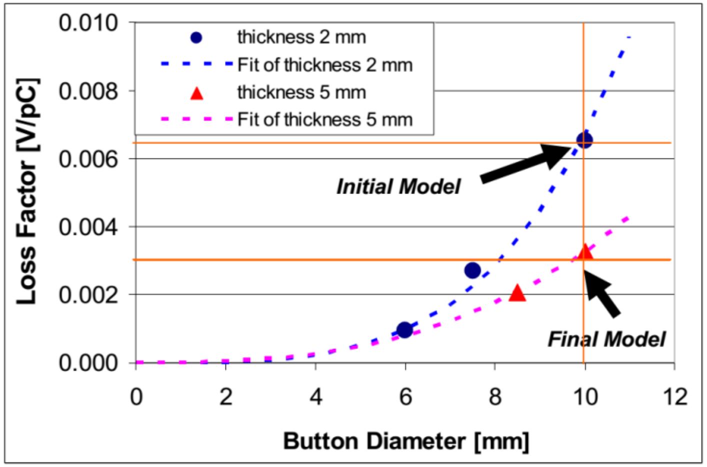
courtesy *H. Duarte*

BPM Coupling Impedance Issues at SOLEIL

courtesy *R. Nagaoka*

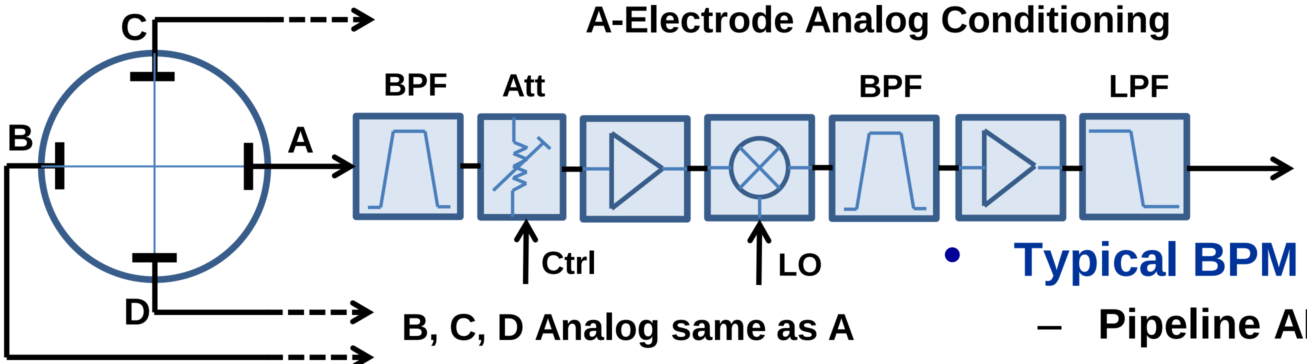




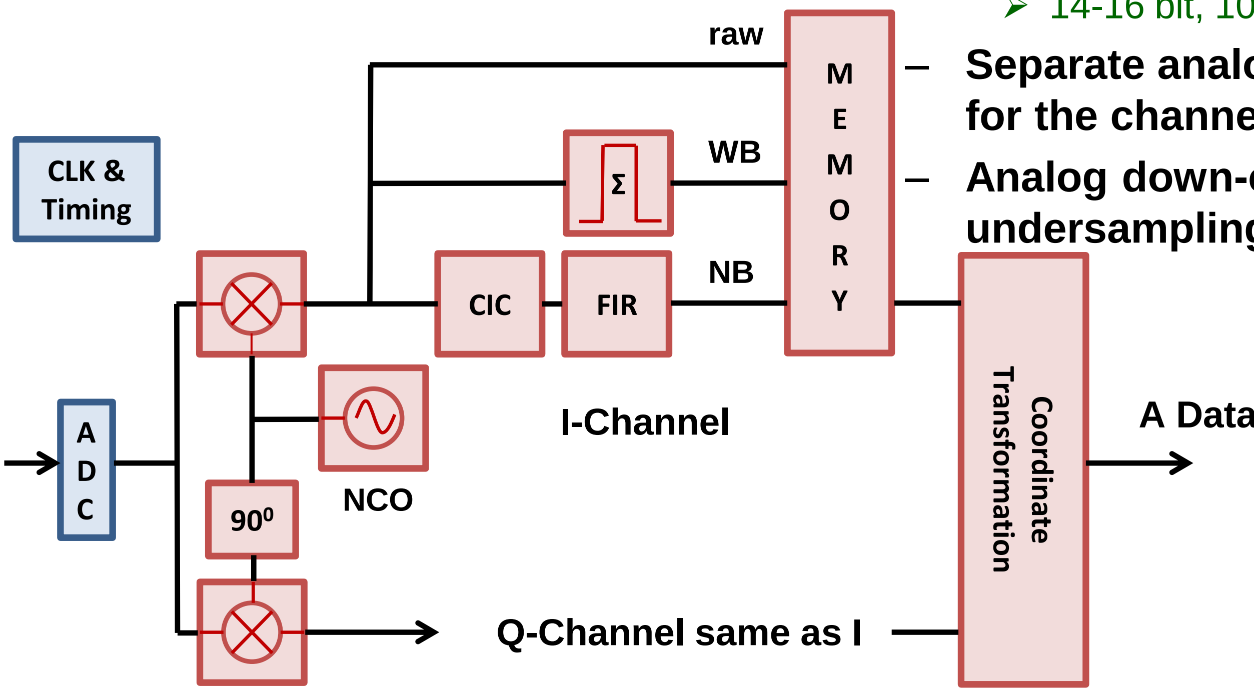


- **At SOLEIL impedance minimization is of crucial importance**
  - **The machine becomes more sensitive to collective effects as lower beam emittances are achieved.**
  - **Critical: Short range / high frequency wakes, beam induced heating**
  - **The BPMs account for ~30 % of the total impedance budget!**
- **BPM pickup modifications helped to reduce k_{loss} by a factor of 2**
  - **Trapped mode: Increased t_{button} in favor decreasing r_{button}**
- **How many BPM pickups should a low emittance ring have?!**

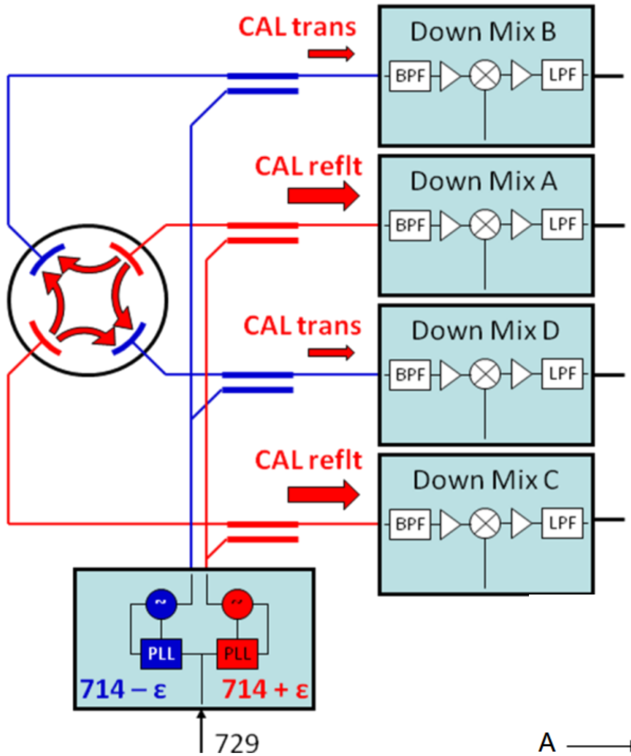
BPM Signal Processing



- **Typical BPM read-out scheme**
  - Pipeline ADC & FPGA
    - 14-16 bit, 100-300 MSPS, >70 dB S/N
  - Separate analog signal processing for the channels
  - Analog down-converter if undersampling is not applicable.



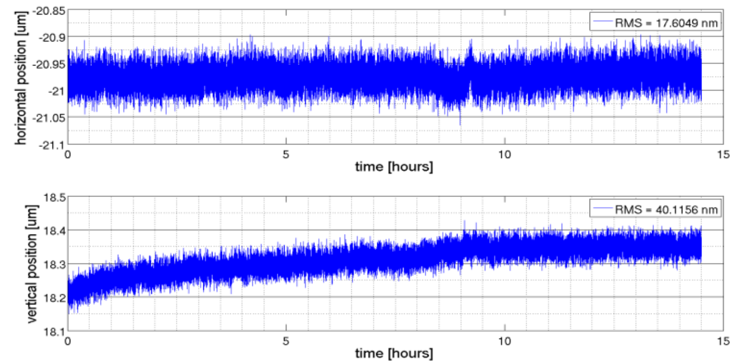
Long-Term Drift Compensation

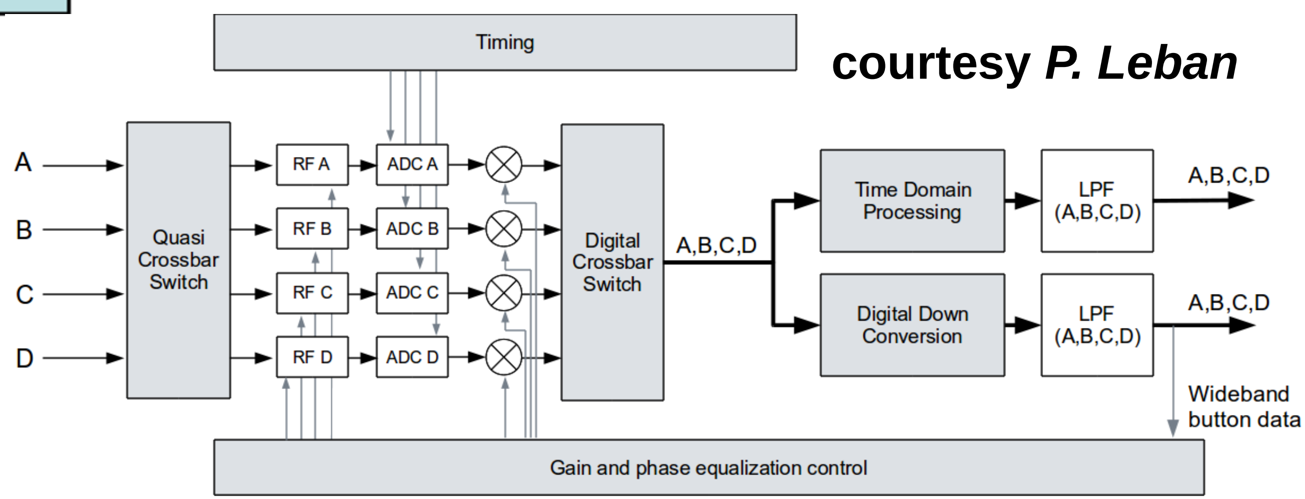


courtesy *N. Eddy*

- **Calibration tone technique (only in narrowband operation)**
  ATF (KEK)

- ***Libera*** **crossbar switching technique**
  - **<100 nm stability over 14 hours**

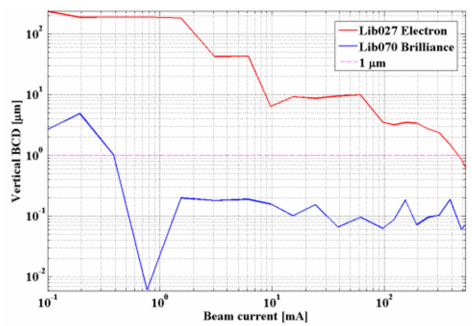


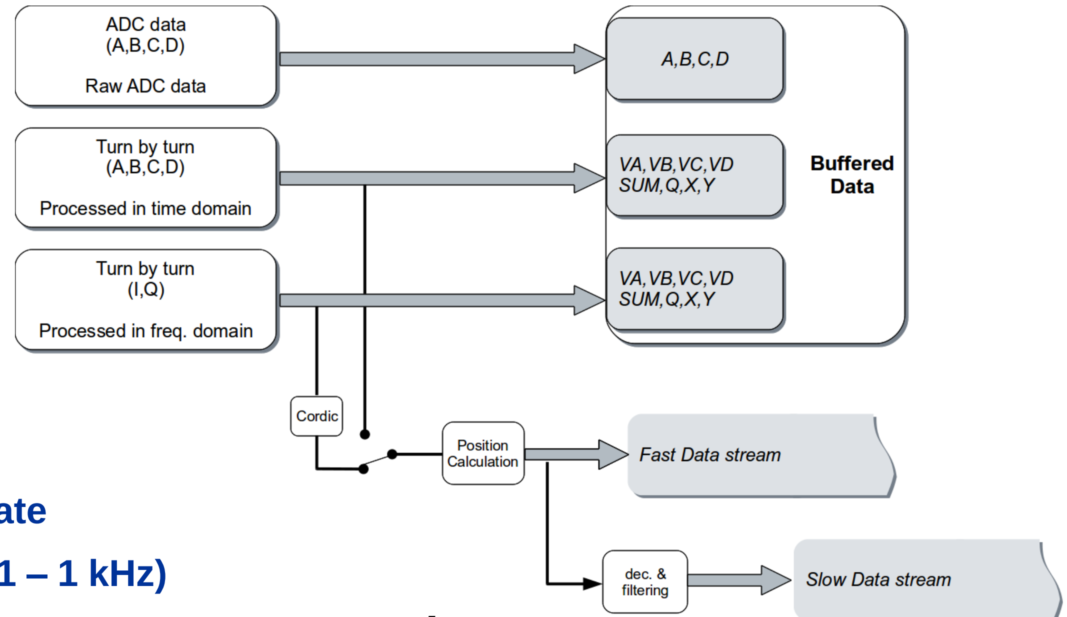


courtesy *P. Leban*

Signal Processing & Performance

Beam Current Dependence



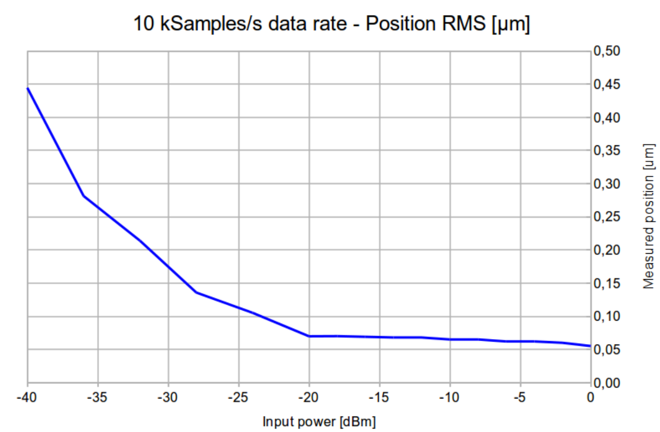


Libera Brilliance +

Electron beam position measurements

- **< 0.5 µm RMS at turn-by-turn data rate**
- **40 nm RMS at 10 kS/s data rate (0.01 – 1 kHz)**
- **10 nm RMS for slow monitoring**
- **sub-micron longterm stability**
- **Temperature drift < 200 nm / °C**
- **Full Fast Orbit Feedback implementation with magnet output**
- **Fast Interlock detection (< 100 µs)**
- **Clean turn to turn measurement using Time-Domain Processing**

courtesy *P. Leban*

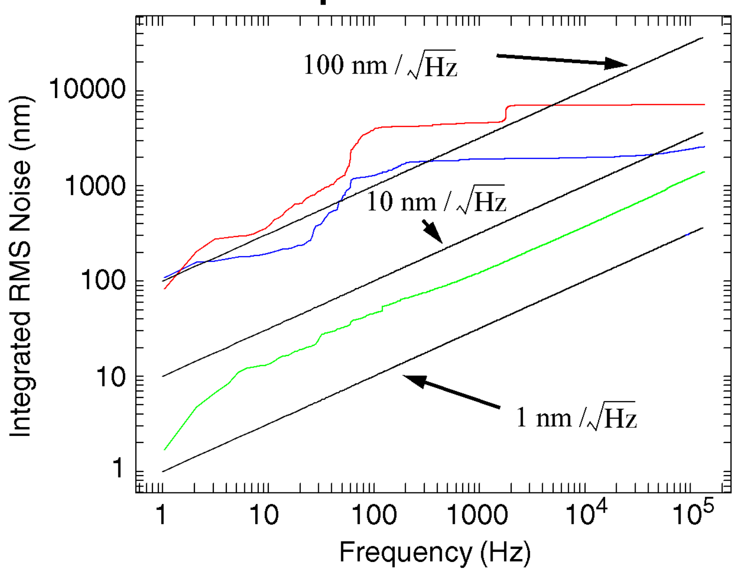


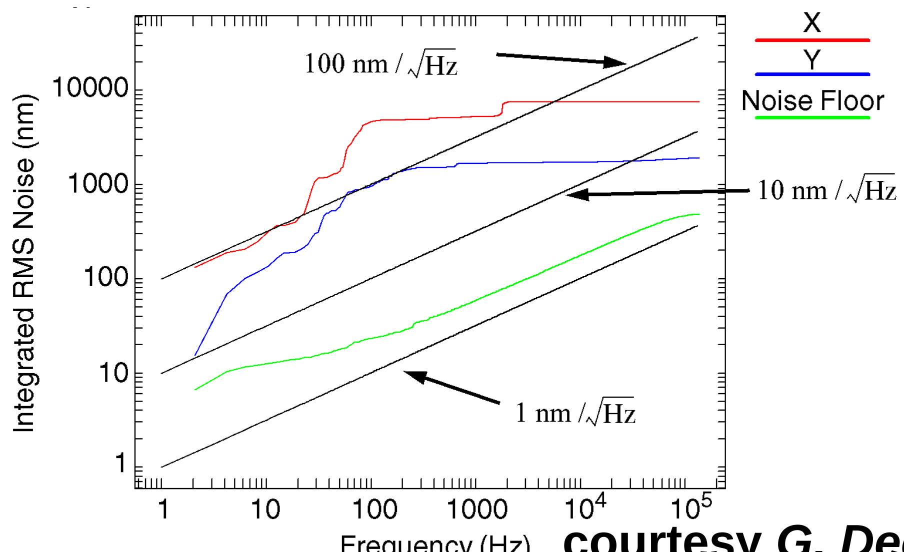
Home-brew vs. Commercial Performance

Libera Brilliance
(@APS *ANL*)

BSP-100 module
(APS *ANL*)

Square root of the forward-integrated power spectral density

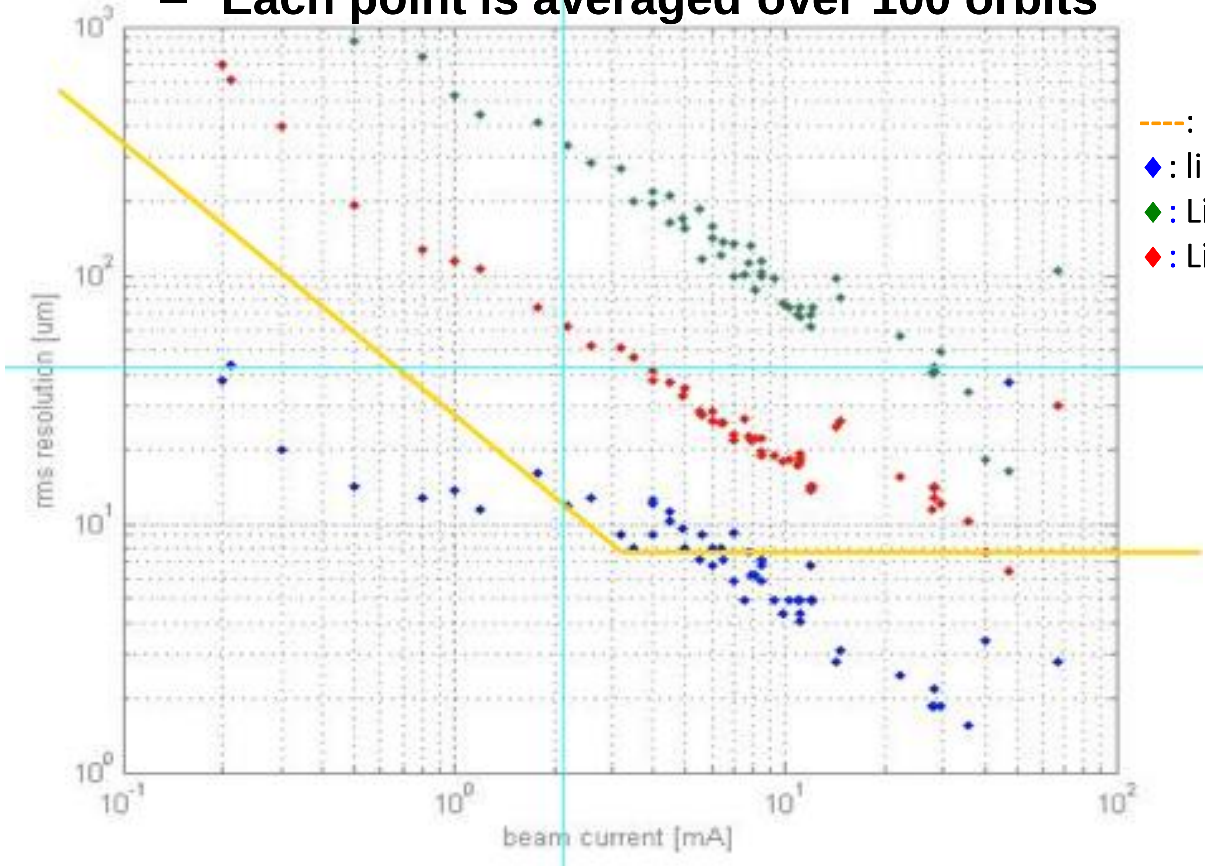




courtesy *G. Decker*

BPM Resolution vs. Beam Current

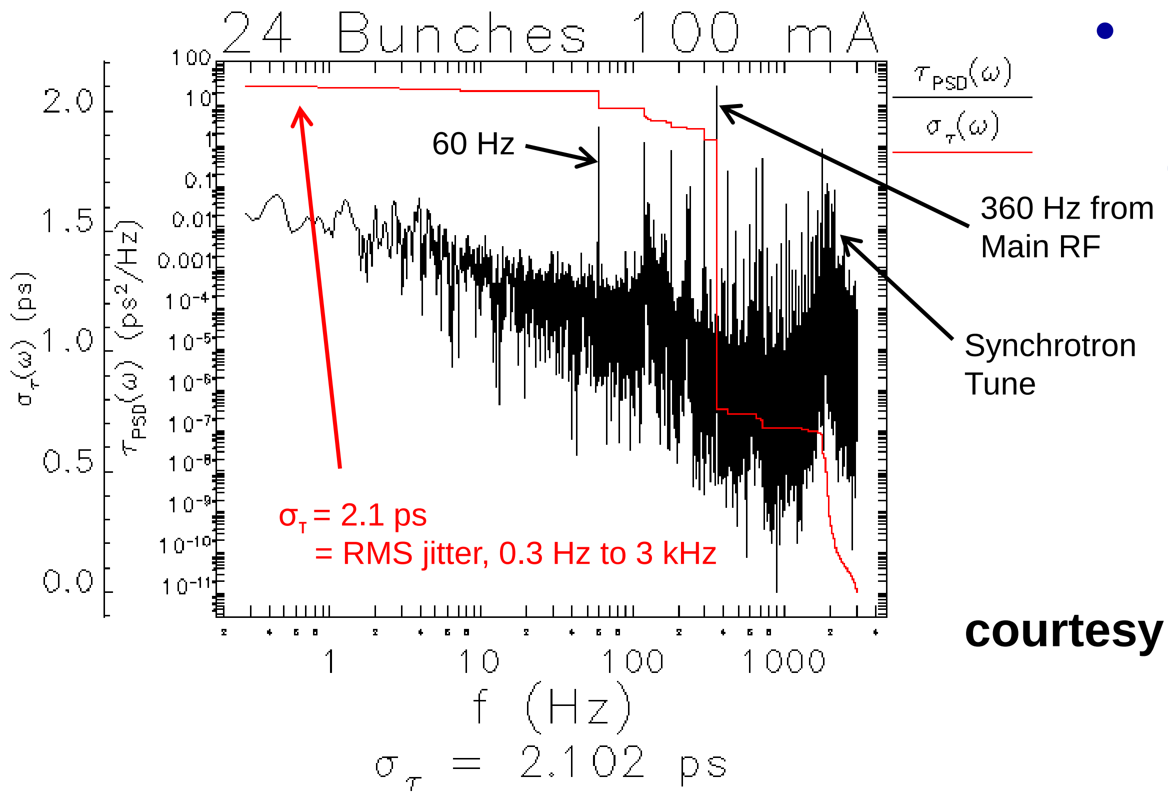
- **Observed at DAΦNE (INFN-LNF)**
  - ***Libera*** **(digital) and** ***Bergoz*** **(analog) BPM read-out electronics**
    - This study was made some years ago, not with the actual *Libera* technology
  - **Each point is averaged over 100 orbits**



----: Bergoz system resolution
♦: libera slow acquisition mode
♦: Libera turn by turn mode
♦: Libera turn by turn mode (decimated)

courtesy *C. Milardi*

Bunch Arrival Time / Beam Phase



- **Beam arrival time jitter power spectral density (APS)**
  - $\sigma_\tau(\omega)$ = Square Root of reverse-integrated power spectral density
  - Note: the RMS bunch length for 24-singlets fill pattern is 34 ps.

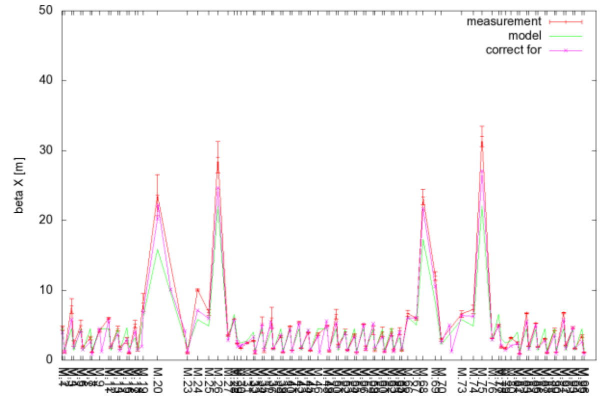
courtesy *G. Decker*

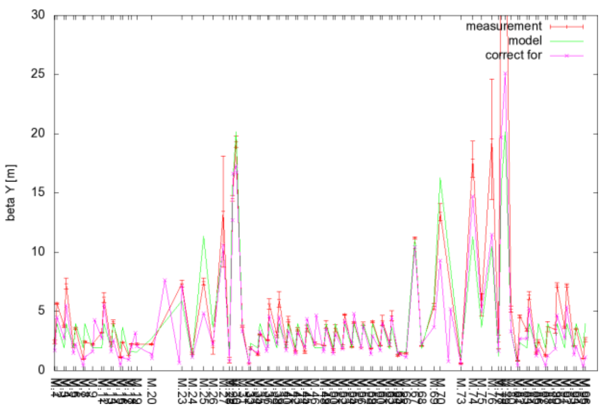
- **Using the phase information allows to measure the beam arrival time**
  - **J. Seebek (SLAC) reports 100 fs resolution with his digital read-out system at SPAER (it has 1.4 μm single turn resolution)!**

ATF DR Turn-by-Turn Beam Studies

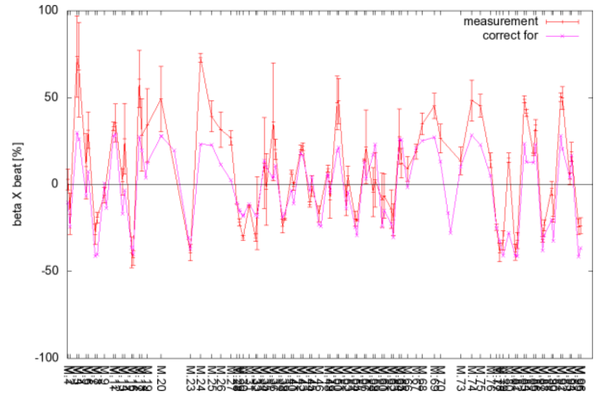
- **Beam optics studies with 96 BPMs in the ATF damping ring**

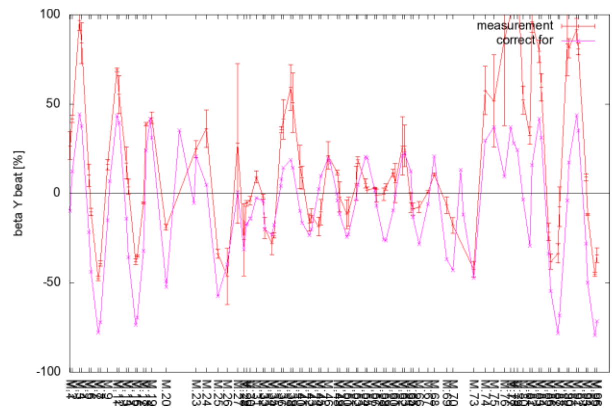
β function measurement



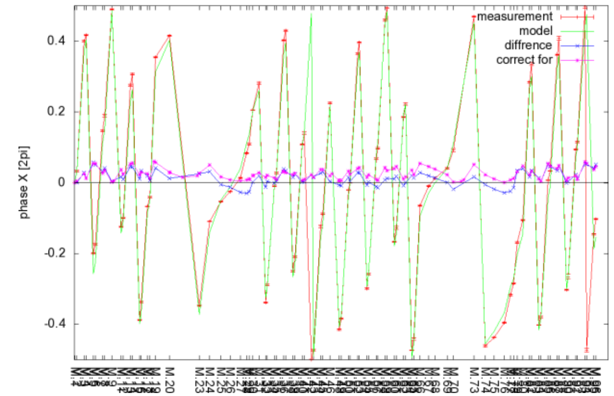


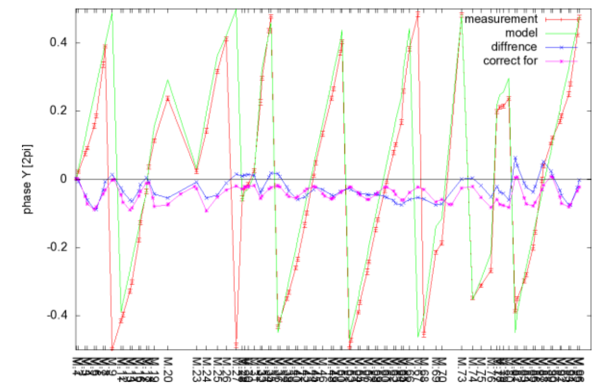
β beating measurement





ϕ measurement



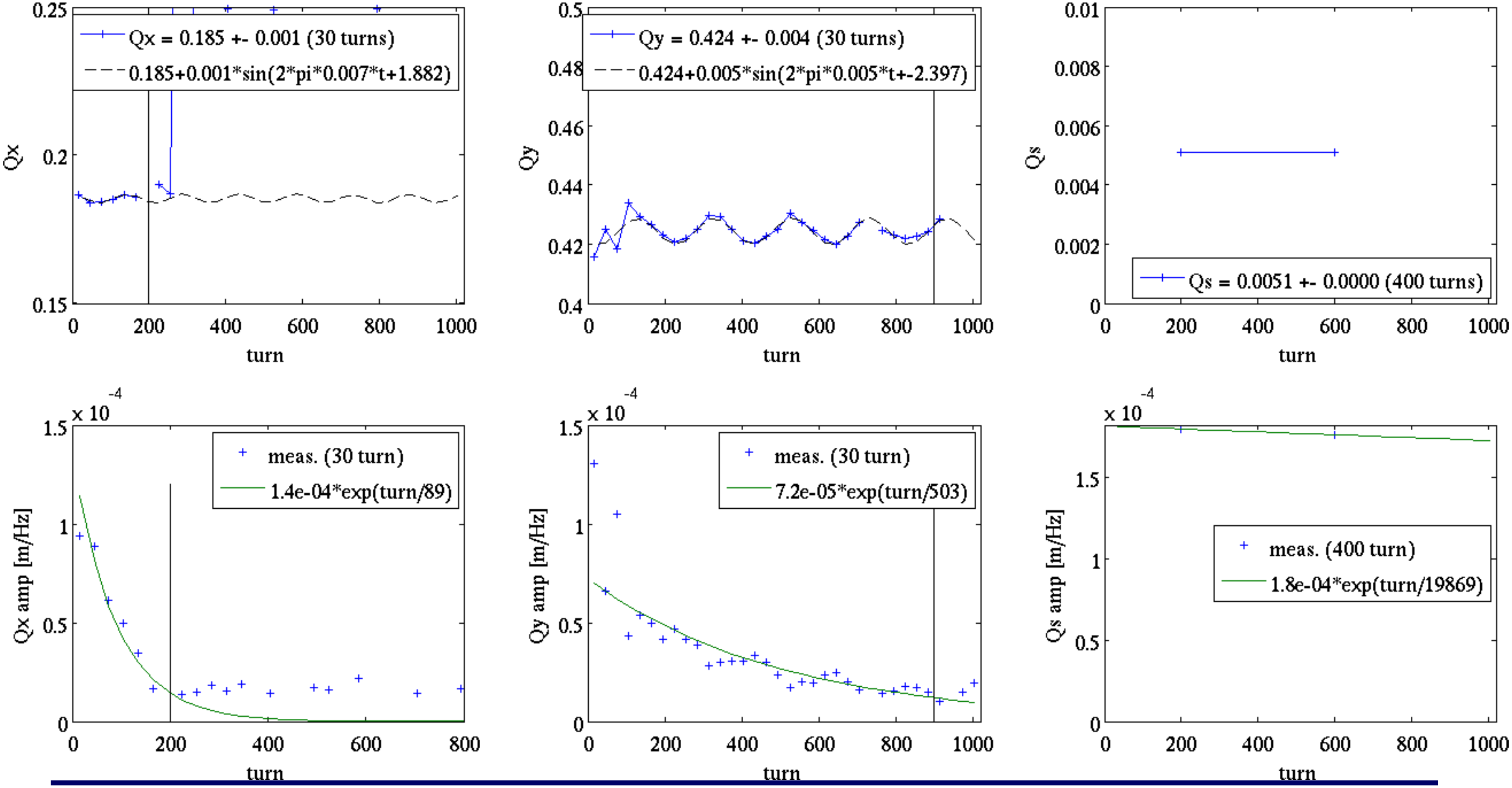


courtesy *Y. Renier*

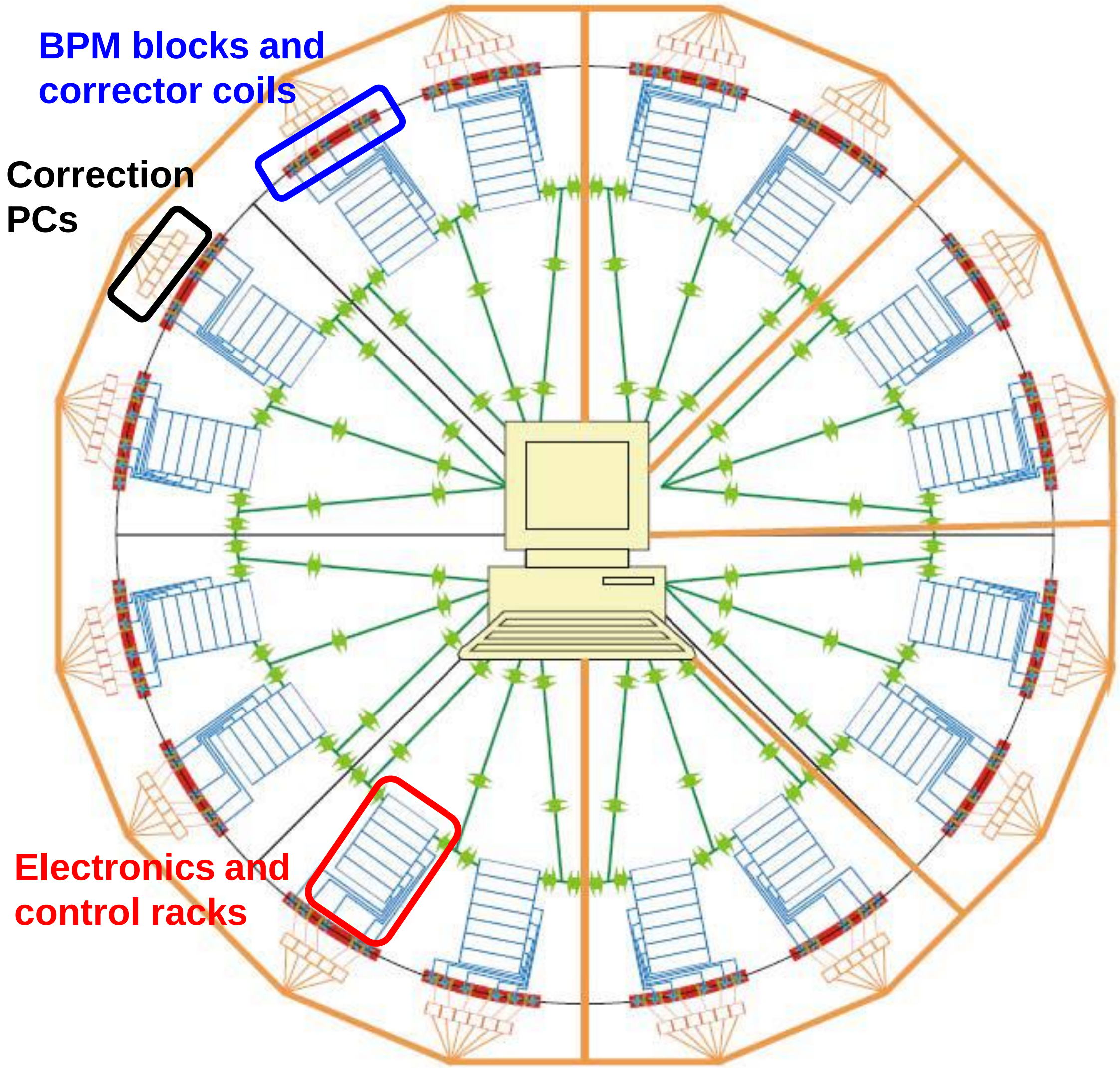
Combining BPMs Tune Measurements

- **Combining TbT BPM data allows tune measurements within a few 10 turns**

courtesy *Y. Renier*



ALBA Fast Orbit Feedback Layout

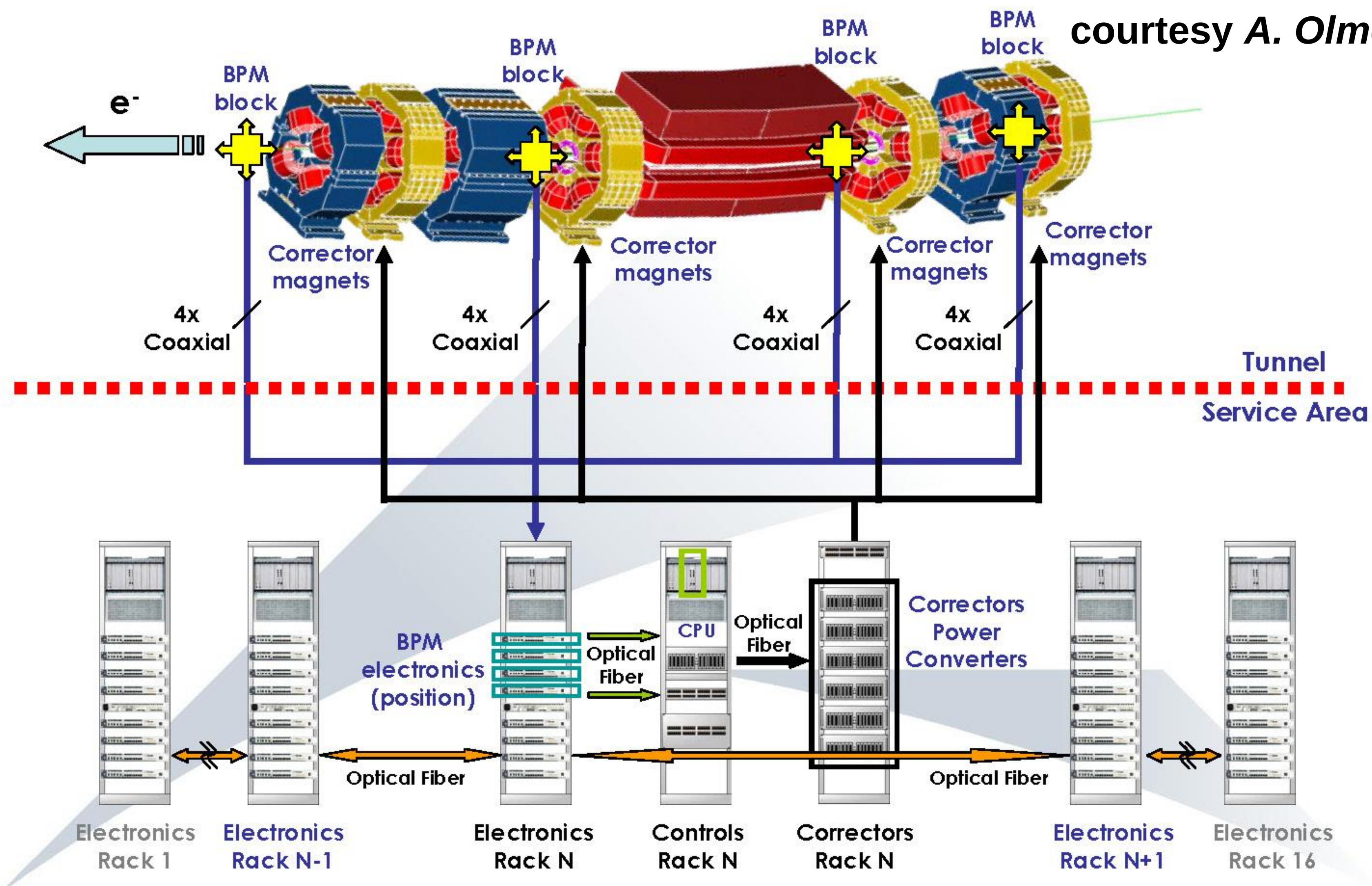


- **Equipment**
  - **120 BPM blocks**
  - **120 BPM electronics**
  - **16 correction CPUs**
  - **16 timing boards**
  - **16 clock splitters**
  - **176 correction PCs**
- **Cables**
  - **692 timing LEMO**
  - **960 coaxial RF**
  - **120 ethernet links**
  - **120 copper fast-TX**
  - **909 optical fibers**

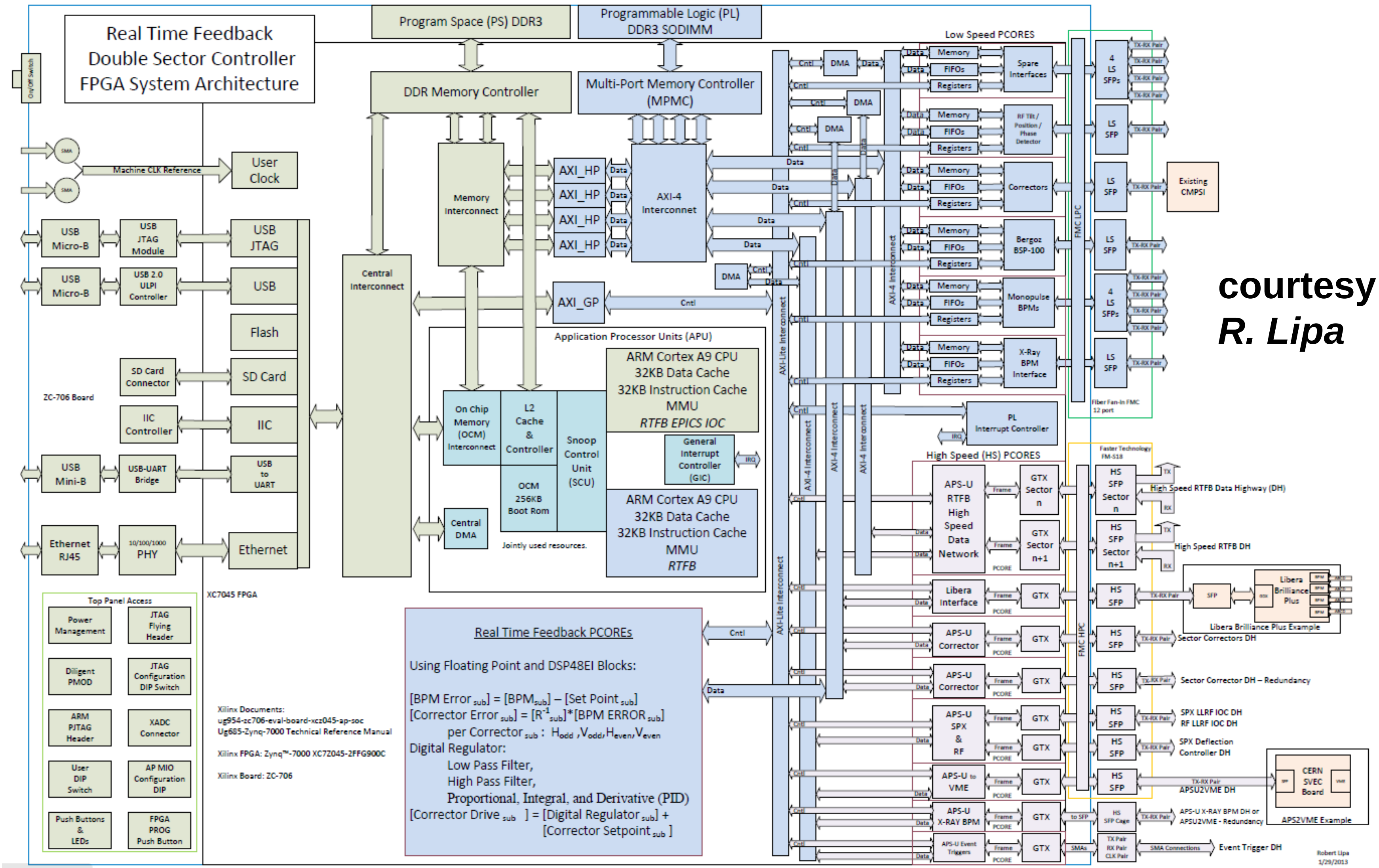
courtesy *A. Olmos*

Physical FOFB Layout (ALBA)

courtesy *A. Olmos*



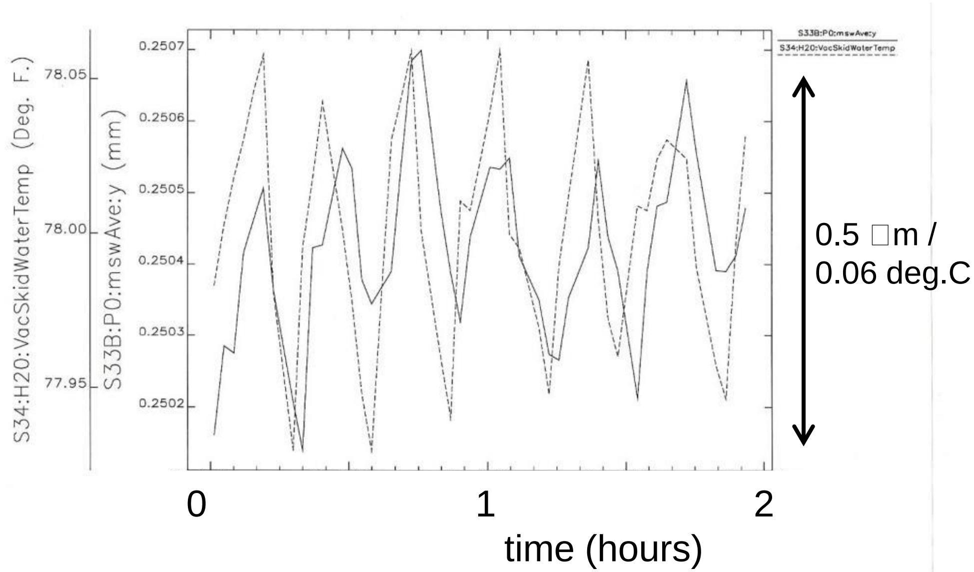
APS Fast Orbit FB FPGA System Architecture

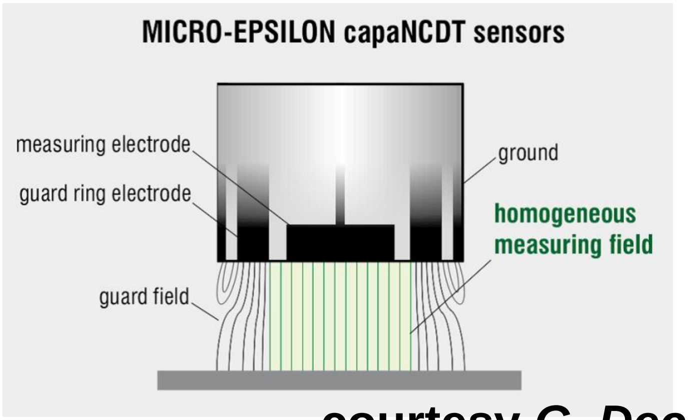


courtesy *R. Lipa*

Temperature Issues – APS (ANL)

- **Vacuum chamber water temperature correlates with BPM position read back**
  - **Impact on missed top-up shots**
- **BPM instrumented with *Keyence* laser tracker to measure BPM movement relative to APS air / water temperature**
- **Temperature regulation is at the level of 0.3-0.5^{0}C$_{pp}$ for air, and 0.06^{0}C$_{pp}$ for water (24 hours)**
- **Mechanical motion monitoring system proposed for APS upgrade**
  - **Using capacitive sensor technology**
  - **NCDT 6300 single channel system: 0.01 %FSO resolution in 8 kHz BW**

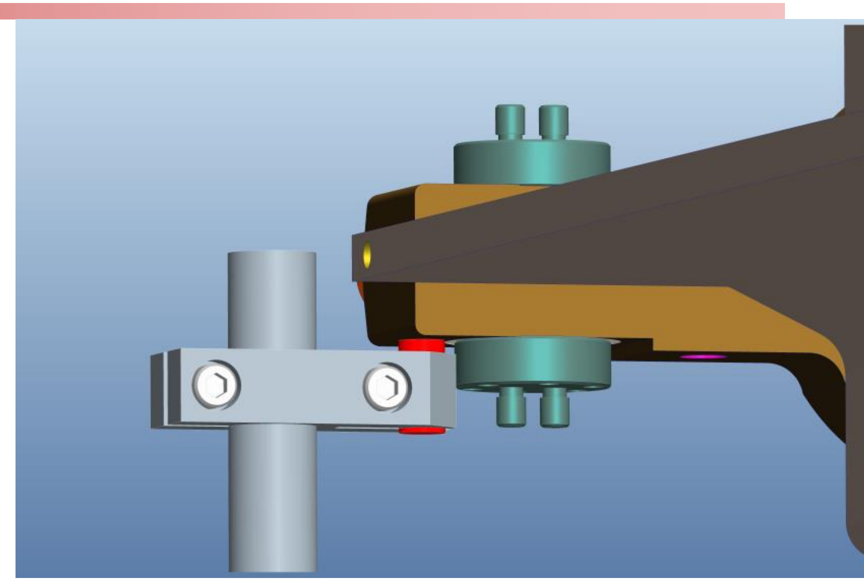


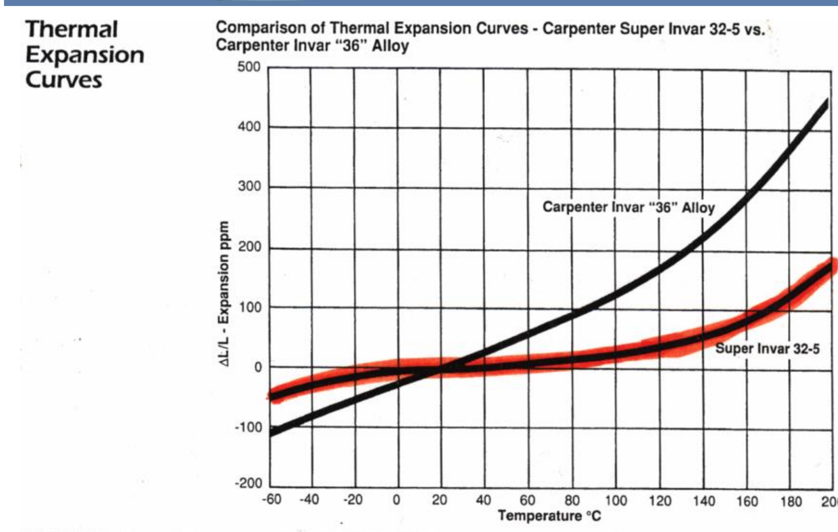


courtesy *G. Decker*

Super Invar Reference Stands

- Simple Invar stand was designed to evaluate capacitive detection of BPM
- Super Invar was used because of its very low thermal expansion (270 nm/C) for full length of support
- Standard Invar can provide a significant cost saving if requirements relaxed.

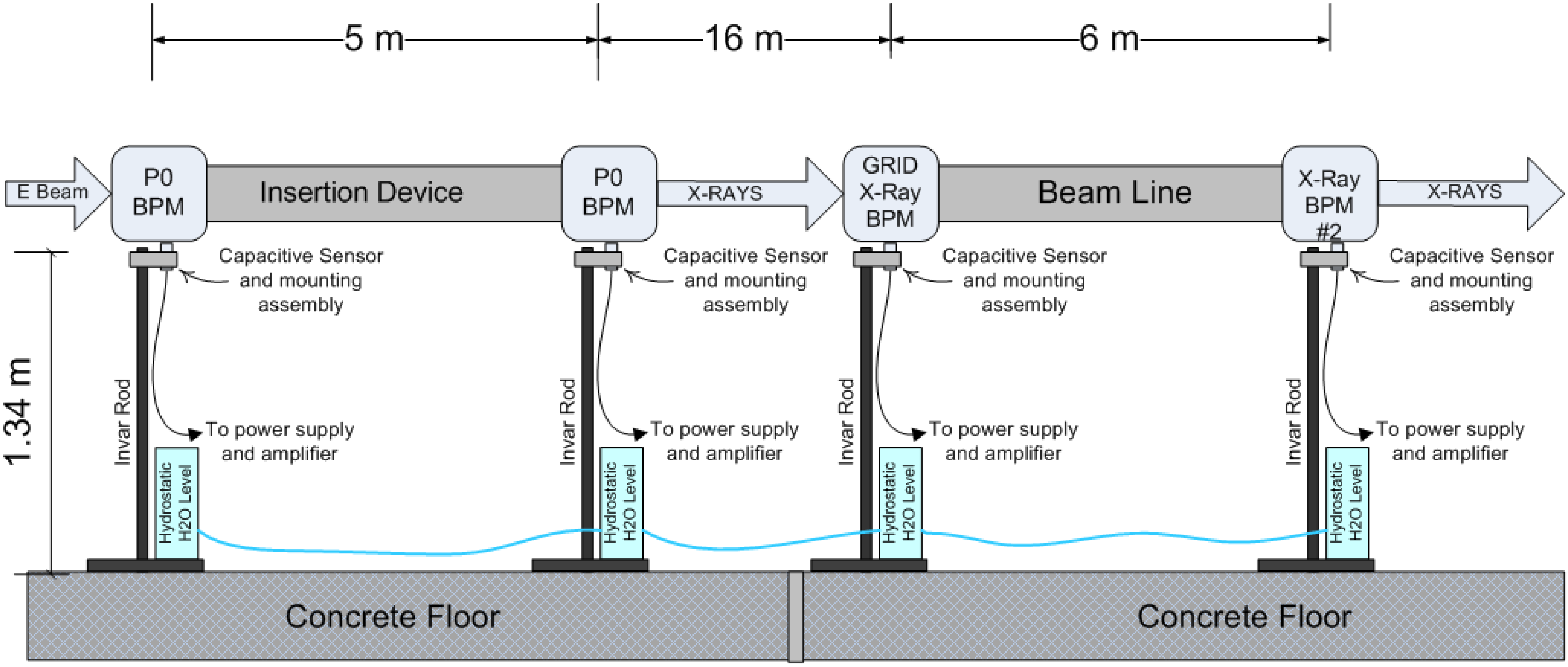




courtesy *G. Decker*

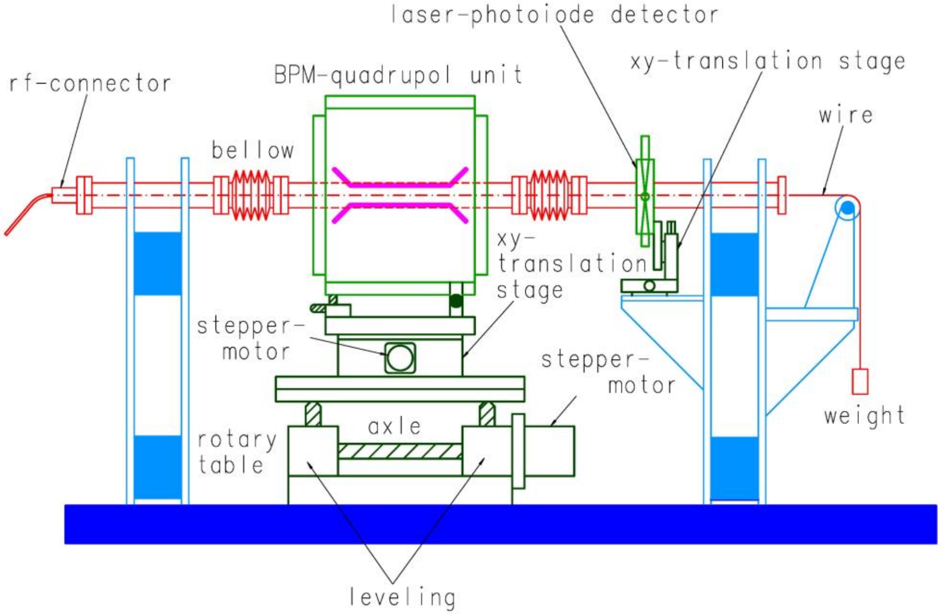
Mechanical Motion Sensor System (APS)

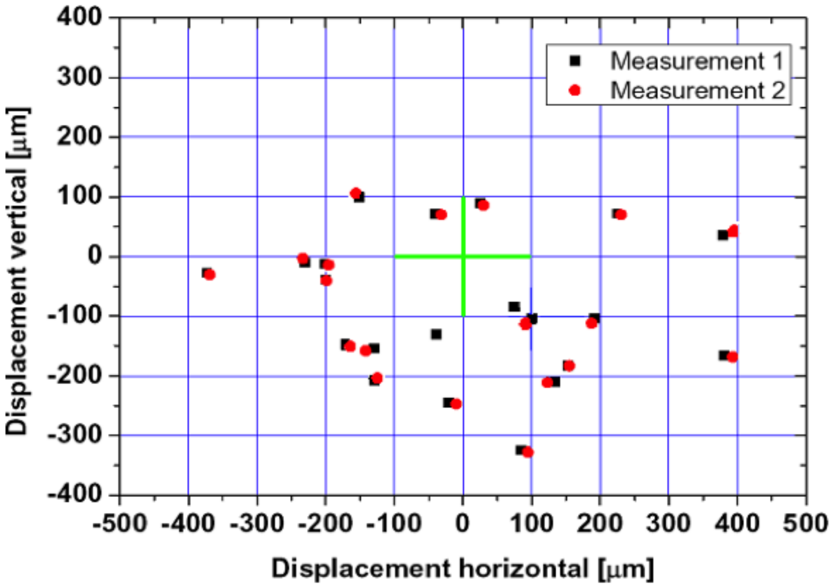
courtesy *G. Decker*



Stretched-Wire Quad-BPM Alignment

- **Alignment of the center of the quadrupole's magnetic field and the electrical center of the BPM pickup**
  - **Was performed in 2005 at FLASH (DESY) with 10-20 µm precision**





- **New initiative at CERN: PACMAN**
  - **Marie Curie Action on BPM alignment and stabilization issues!**

Summary & Remarks

- Today the read-out electronics are not the performance limitation
  - Some experts say, there is too much focus on the electronics, while e.g. BPM pickup issues tend to be neglected.
- Button pickups & mechanics are a critical part of the BPM system
  - Keeping the mechanics stable <1 μm is very difficult
  - Buttons can have a substantial impact on the impedance budget of the ring accelerator!
- FPGAs provide a huge, still untapped potential
  - Fast orbit FB systems benefit most from this technology, however, the systems are not simple.

THANK YOU!

…and thanks to the contribution from my beam instrumentation colleagues!