OVERVIEW OF RECENT TRENDS AND DEVELOPMENTS FOR BPM SYSTEMS

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Assembled with great help of the colleagues from the beam instrumentation community!

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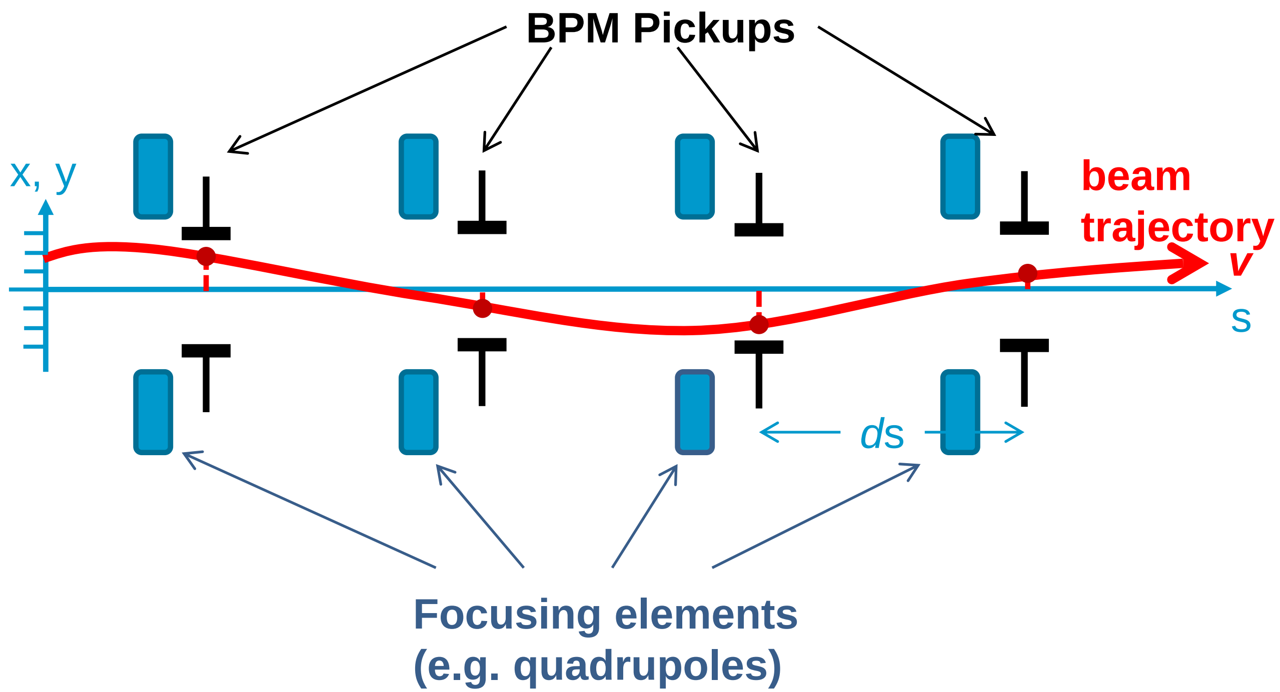
Introduction: Beam Trajectory

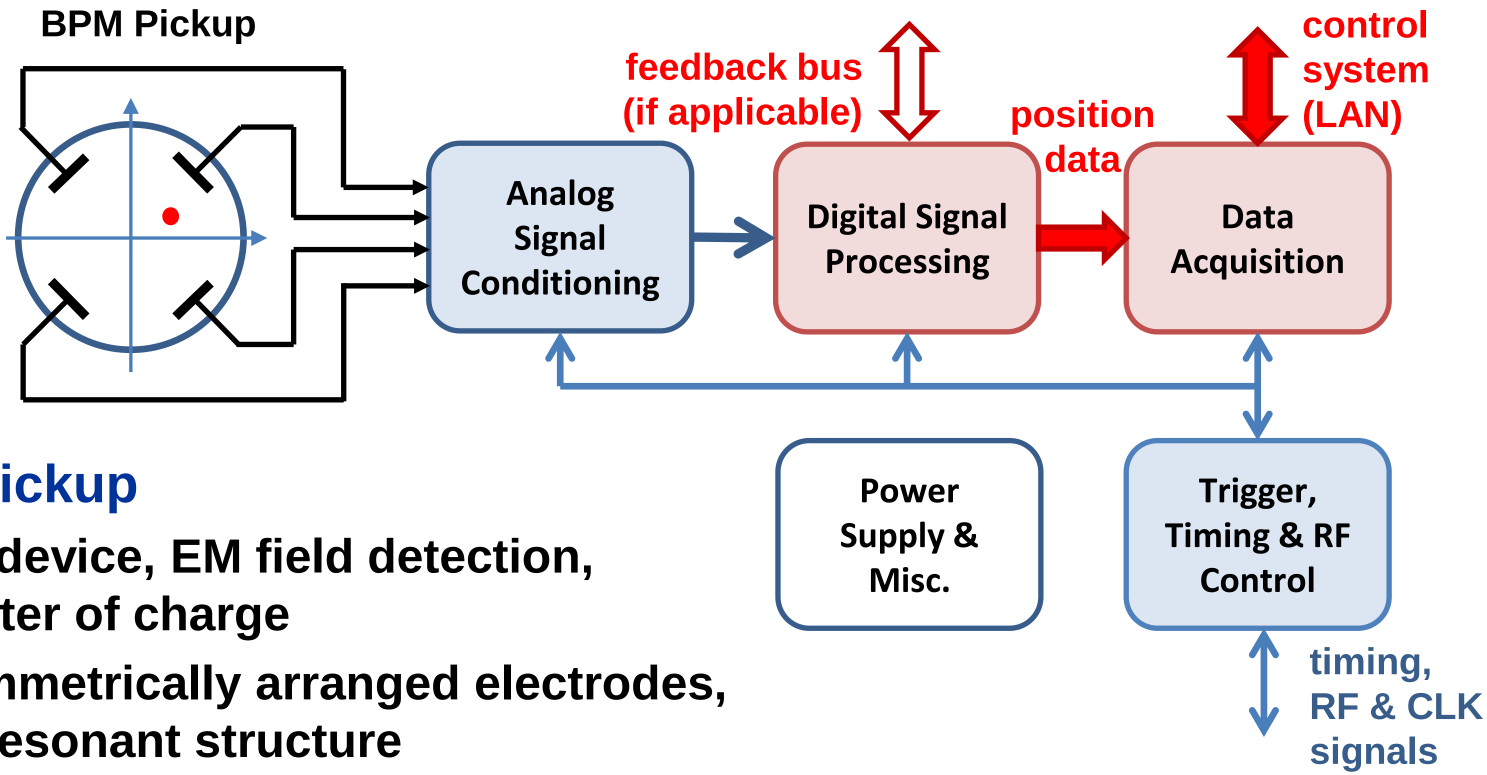


- **Primary task: A BPM system measures the beam trajectory**

$$u(s) = A\sqrt{\beta}\sin(Q\varphi + \delta)$$

  - $u = (x, y)$ **the horizontal / vertical beam position.**
  - **Measurement of *x, y* at discrete locations *s***
  - **Measurement of the beam angle *x', y'* between two BPMs**
    - **…if non optical elements are present.**

BPM Building Blocks

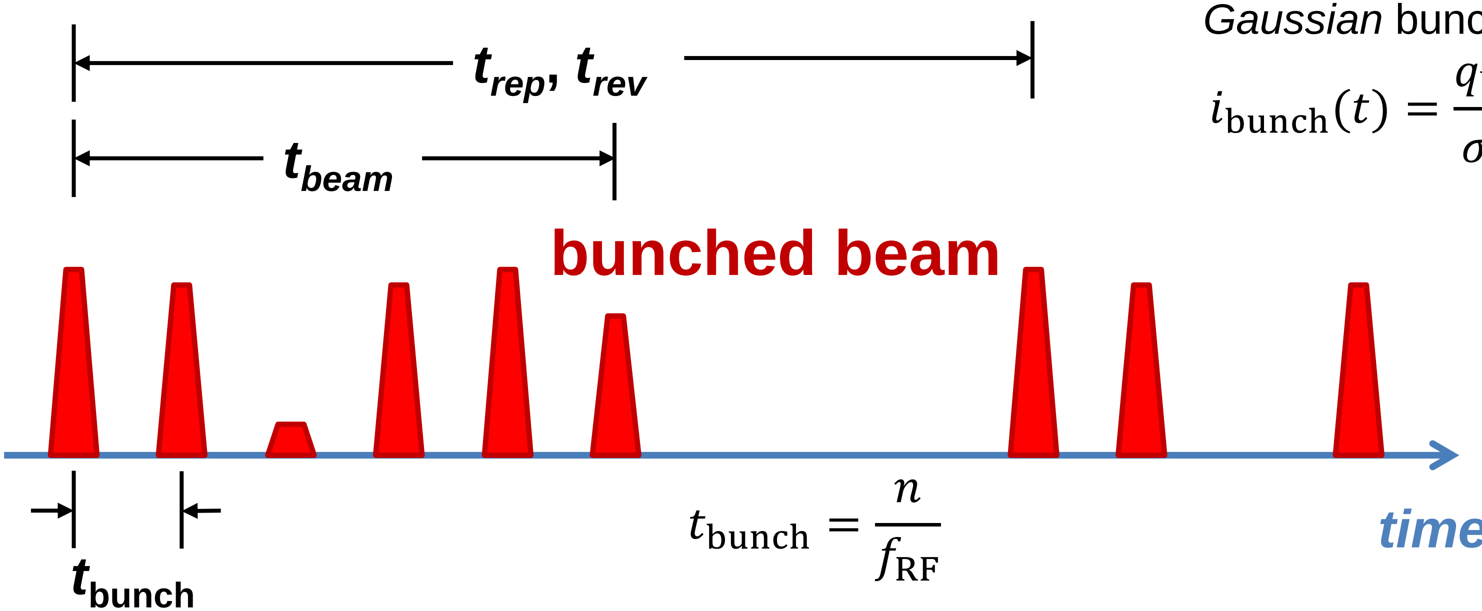


- **BPM pickup**
  - RF device, EM field detection, center of charge
  - Symmetrically arranged electrodes, or resonant structure
- **Read-out electronics**
  - Analog signal conditioning
  - Signal sampling (ADC)
  - Digital signal processing
  - Data acquisition and control system interface
  - Trigger,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

Beam Structure

Gaussian bunch:

$$i_{\mathrm{bunch}}(t) = \frac{q_{\mathrm{bunch}}}{\sigma\sqrt{2\pi}}\, e^{-\frac{t^2}{2\sigma^2}}$$



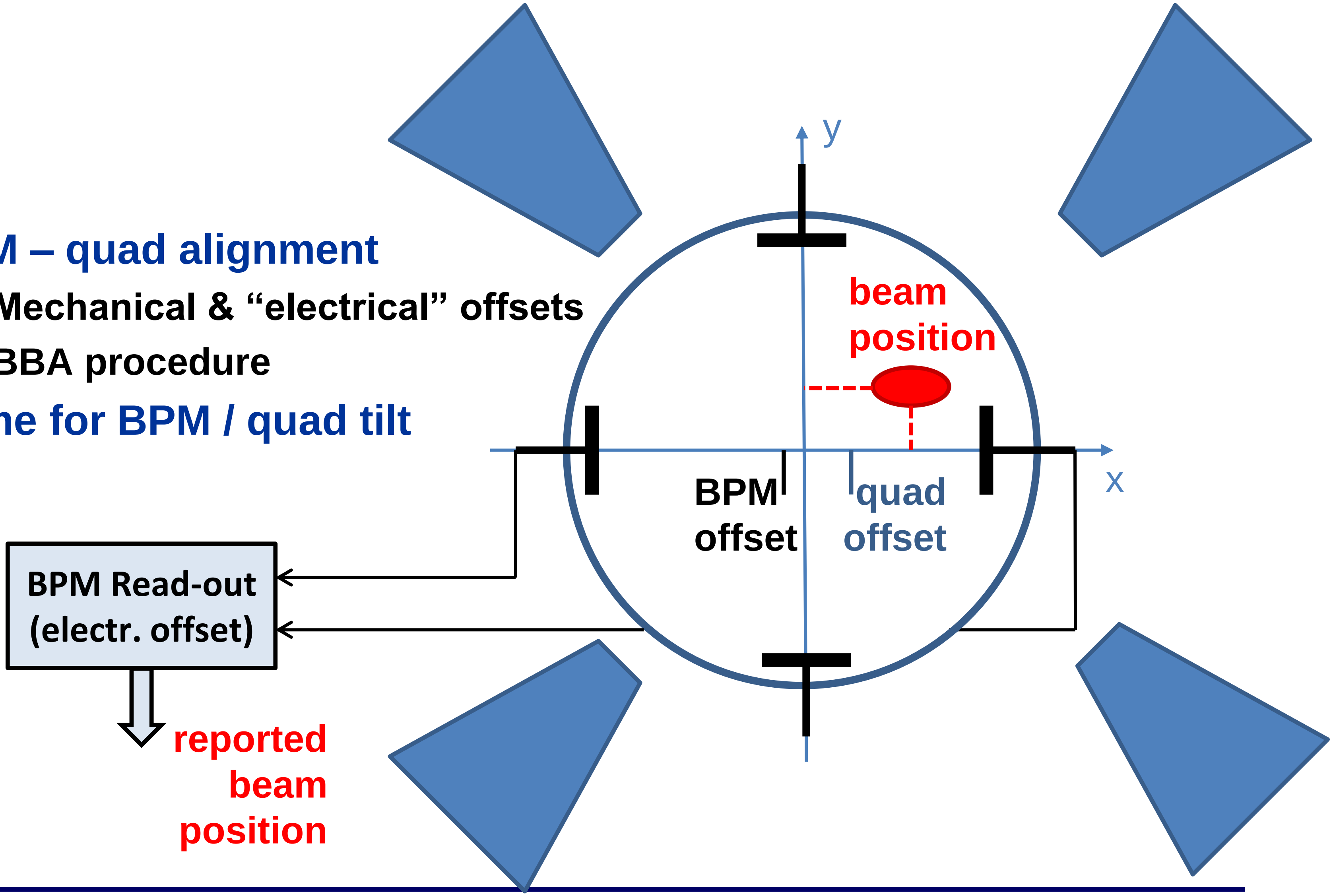
- t_{beam} **repeats with**
  - t_{rep} **in linacs and transport-lines**
  - t_{rev} **in circular accelerators**
- **Bunch intensities may vary**
  - **Shot to shot, within** t_{beam}
  - **"Missing" bunches**
- **Adapt BPM integration time**
  - **Single / multi-bunch**
  - **TBT, multiturn, narrowband, etc.**
- **Operation conditions may change**
  - **Particle species (e^-, e^+, p, $\bar{p}$, H^-,…)**
  - **RF gymnastics, multiple beams,…**

BPM Characteristics & Applications

- Measurement / integration time
- Position resolution
  – Resolve a orbit difference (depends on the measurement time).
- Linearity and accuracy
  – Absolute error of the reported beam position
  – BPM offset (zero-order correction coefficient), BPM tilt
- x-y coupling
- Dynamic range
  – Beam intensity independence (saturation / noise floor).
- Reproducibility and long term stability
  – Reference “golden” orbit
- Variety of applications beyond beam orbit measurements
  – Injection oscillations, betatron & synchrotron tunes, dispersion & beam energy, x-y coupling, beam optics, magnet alignment and errors, non-linear field effects, etc.
  – Machine commissioning (intensity), beam phase and TOF

BPM Offset & Tilt

- **BPM – quad alignment**
  - **Mechanical & "electrical" offsets**
  - **BBA procedure**
- **Same for BPM / quad tilt**



BPM Pickup

- **Simplistic characterization for beams with $v \approx c_0$**
  - **Broadband pickup** $V_{\mathrm{elec}}(x,y,\omega) = s(\boldsymbol{x},\boldsymbol{y})\, Z(\omega)\, I_{\mathrm{beam}}(\omega)$
  - **Resonant pickup** $V_{\Delta}(x,y,\omega) = s(\boldsymbol{x},\boldsymbol{y},\omega)\, Z(\omega)\, I_{\mathrm{beam}}(\omega)$
  - **RF or microwave device**
  - **Part of the accelerator vacuum system (UHV certified)**
  - **Operation in cryogenic and ultra-clean environment**
- **Broadband pickup**
  - **Button (electrostatic), stripline (electromagnetic), inductive wire loop (magnetic), based on symmetric electrode arrangement.**
  - **Same position sensitivity characteristics** $s(x,y)$ **(image current model)**
  - **Different transfer impedance** $Z(\omega)$ ***(literature)***
  - **Strong common mode signal component** I_{beam}
- **Resonant pickup (symmetric cavity or coaxial resonators)**
  - **Beam excited dipole (*Δ*) eigenmode with a shunt impedance** $Z(\omega)$
  - **Frequency discrimination of the common mode by** $s(x,y,\omega)$

Broadband PU: Image Current Model

- **Laplace problem solved for circular and elliptical cross-section**
  - **Image current density**
    (cylindrical coordinates, *ρ=r/R*)

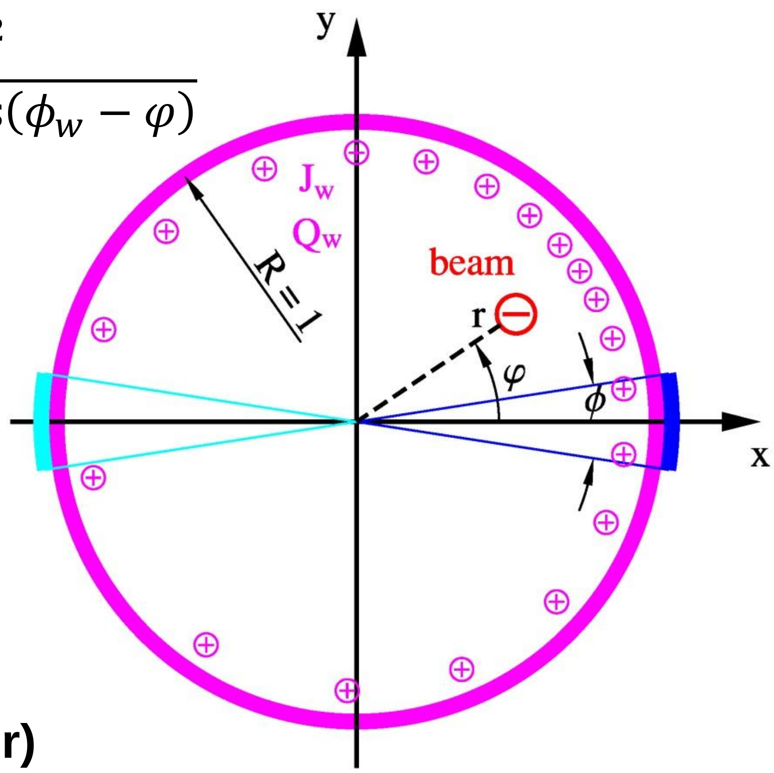
$$J_w(R=1,\phi_w) = -\frac{I_{beam}}{2\pi}\frac{1-\rho^2}{1+\rho^2-2\rho\cos(\phi_w-\varphi)}$$

  - **Electrode beam position sensitivity**

$$s(\rho,\varphi) = \phi + 4\sum_{n=1}^{\infty}\frac{\rho^n}{n}\cos(n\varphi)\sin\left(\frac{n\phi}{2}\right)$$

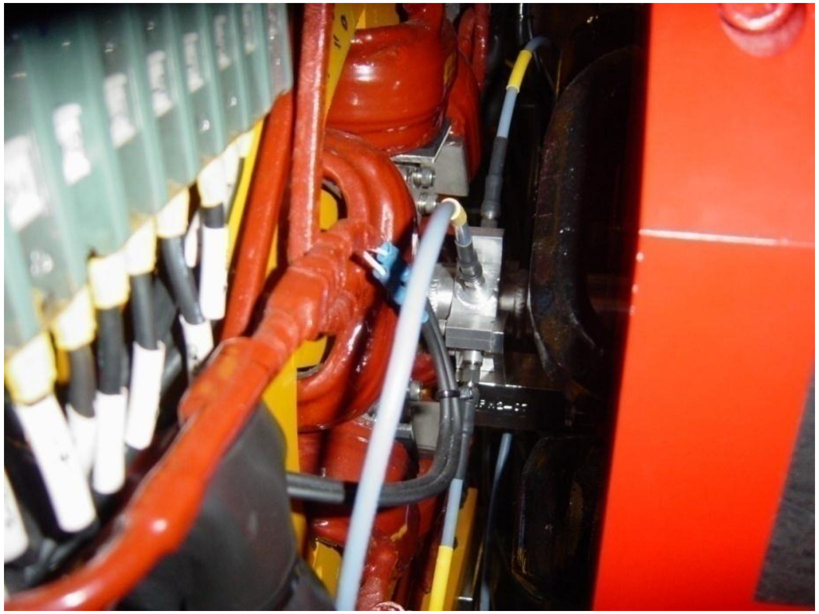
  - **Two symmetric arranged electrodes**

$$\text{pos.} = f\left(\frac{A-B}{A+B}\right) \text{ or } = f\left(20\log_{10}\left(\frac{A}{B}\right)\right)$$



- **Example:**
  - R = 25 mm, ϕ = 30^0
    -> sensitivity: 2.75 dB/mm (near center)

Button BPM

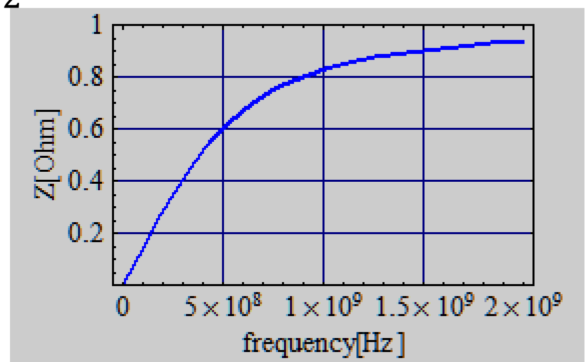


- **Commercial UHV RF button feedthroughs, made to specs**
  - **RF properties (numerical simulation)**
  - **Environmental requirements**
- **Compact construction**
- **Installation, tolerances, cabling**
- **Other button load impedance, than $R_0 = 50\ \Omega$?**

$$Z_{\text{button}}(\omega) = \phi\, R_0 \left(\frac{\omega_1}{\omega_2}\right) \frac{(\omega_1/\omega_2)}{1 + (\omega/\omega_1)^2}$$

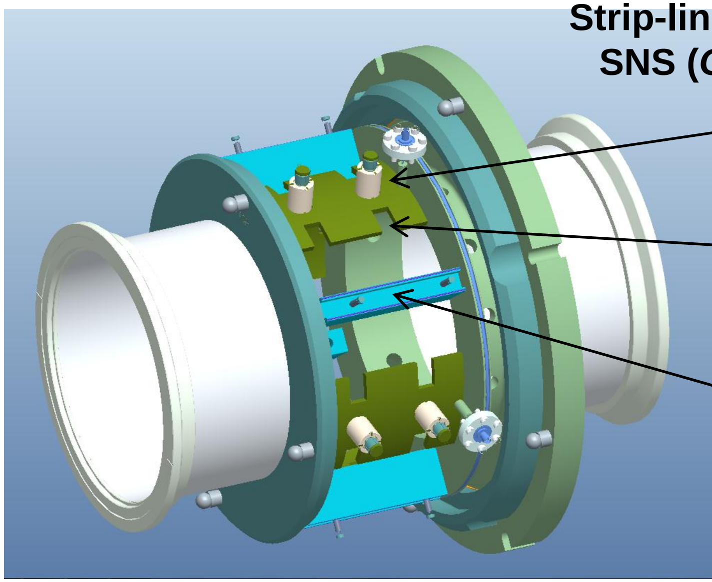
$$\omega_1 = \frac{1}{R_0\, C_{\text{button}}} \qquad \omega_2 = \frac{v_{\text{beam}}}{2\, r_{\text{button}}}$$

$$\phi = \frac{r_{\text{button}}}{4\, R_{\text{pipe}}}$$



Strip-line / Transmission-line BPMs

Strip-line BPM
SNS (*ORN*)



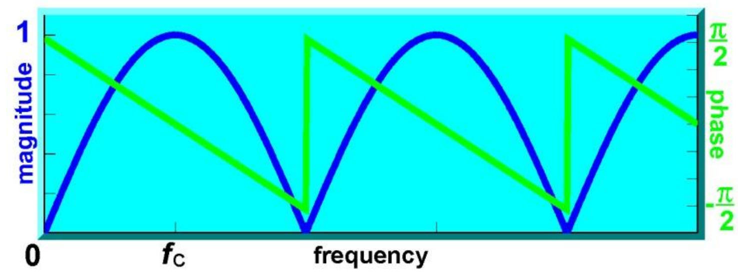
Ceramic posts hold the electrode

Impedance Match at the post

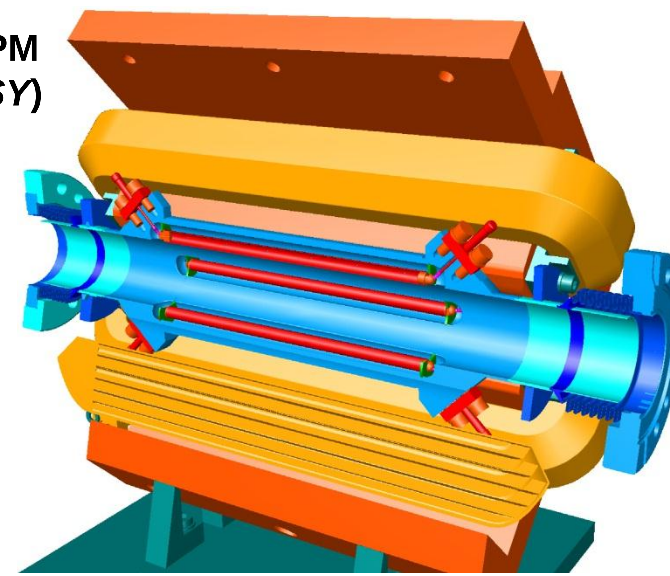
Inner-shielding bar reduces electrode to electrode coupling

$$Z_{\text{strip}}(\omega) = i\, Z_0 e^{-i\frac{\omega\, l_{\text{strip}}}{c_0}} \sin\left(\frac{\omega\, l_{\text{strip}}}{c_0}\right)$$

$$f_{center} = \frac{c_0}{4\, l_{\text{strip}}}(2n-1)$$

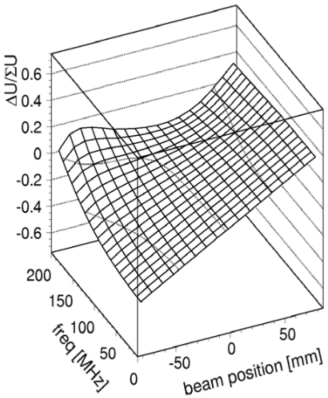


Strip-line BPM
FLASH (*DESY*)

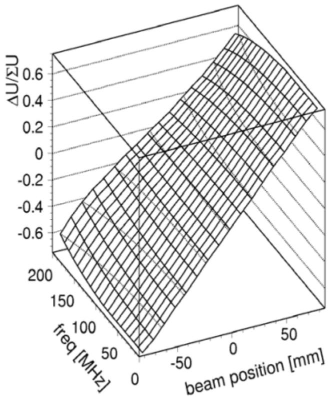


- **Impedance-matched *λ*/4 transmission-line coupler antennas**
  - **Beam directivity (directional coupler)**
  - **Downstream port terminated or shortened**
  - **Matched to bunch frequency $f_{\text{center}} \approx f_{\text{bunch}}$**

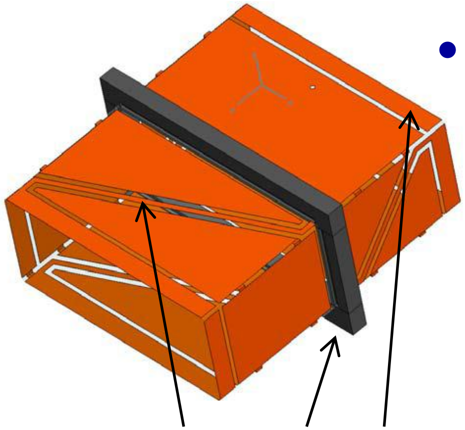
Numerical Analysis & Optimization



without

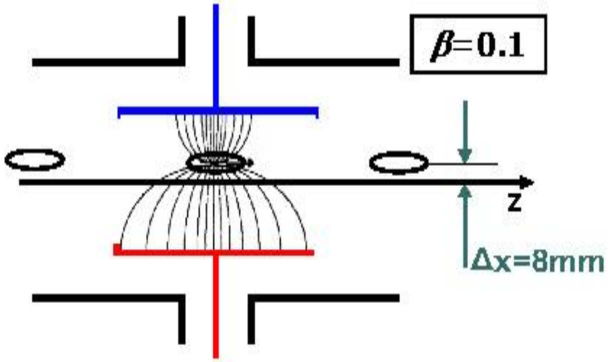


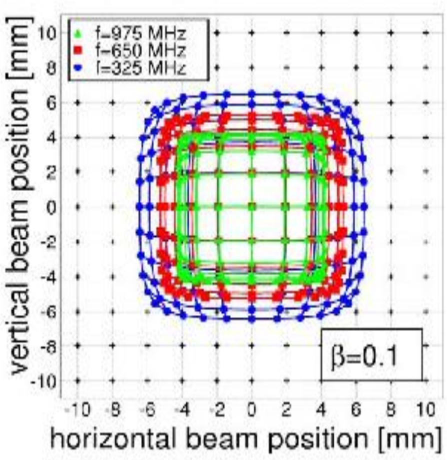
with



ground guards & separations

- **Split-plane ("shoe-box") BPM**
  - **Improved sensitivity and reduced cross-talk**
  - **Improved linearity**

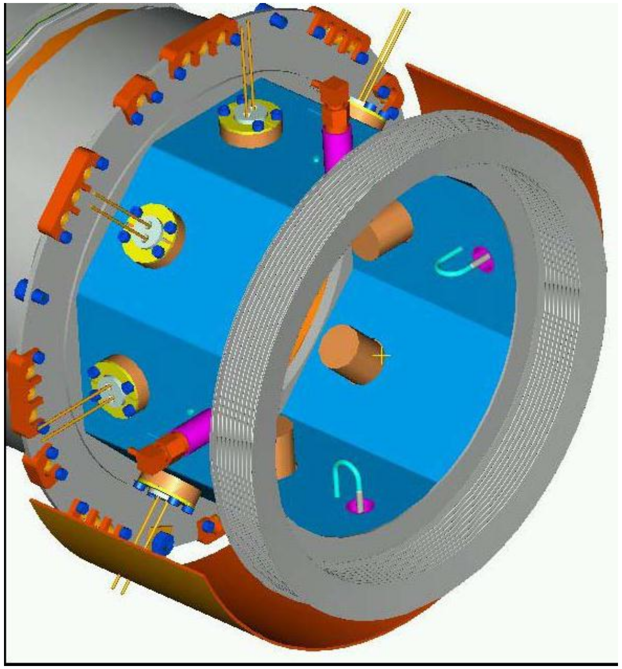




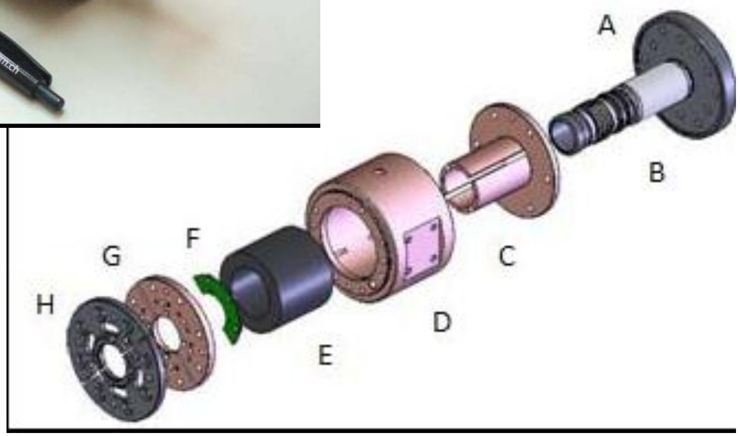
- **Low β beam velocity effects (button BPM)**
  - **Reduced sensitivity**
  - **Frequency dependent**

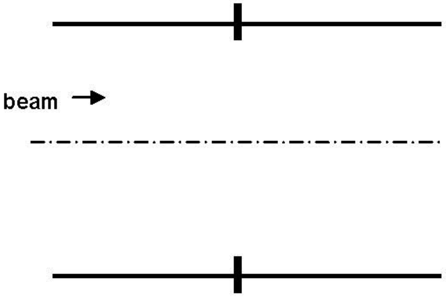
P. Kowina **(DIPAC'09)**

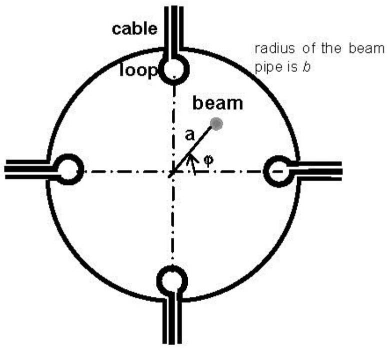
Examples of Inductive BPMs



- **Simple loop antenna (DESY)**
  - **In-"air" (N_2) application near the beam dump**
- **Ferrite-loaded strip design (CERN)**
  - **100 nm resolution, BW: 0.1…30 MHz**

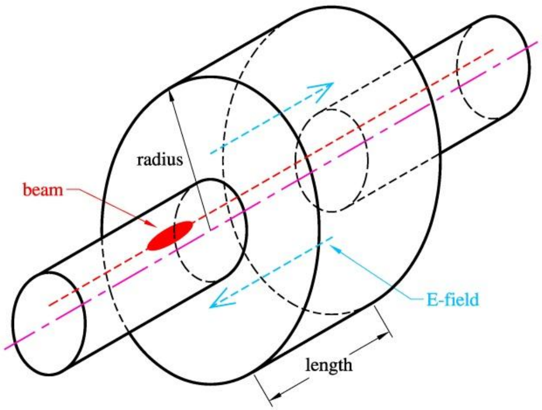


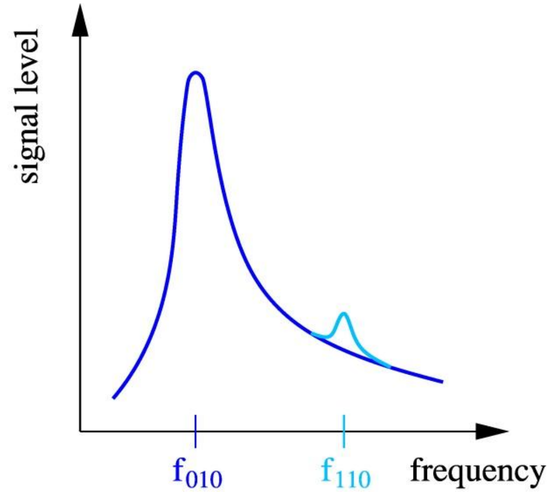


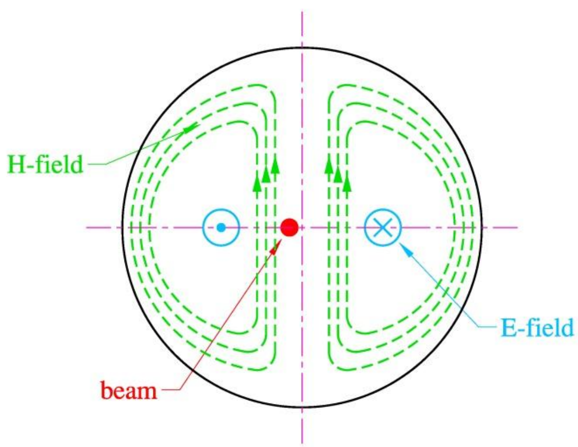


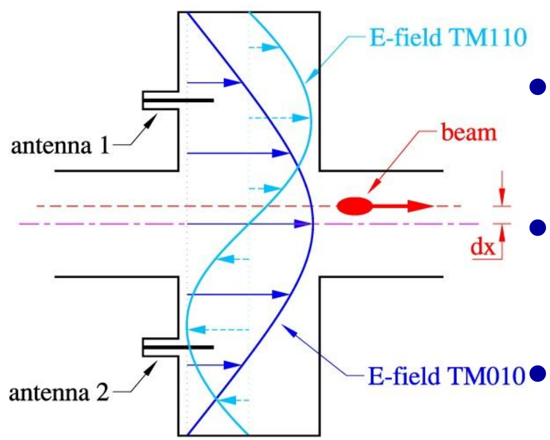
- **Deflection angle measurement idea (China)**

Resonant BPM Pickups









- **"Pill-box" has eigenmodes at:**

$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0 \varepsilon_0}} \sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

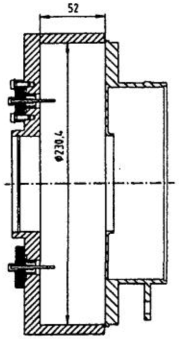
- **Beam couples to:**

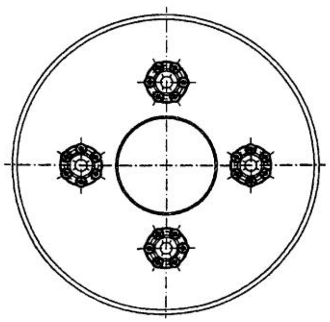
$$E_z = C\, J_1\left(\frac{j_{11} r}{R}\right) e^{i\omega t} \cos\varphi$$

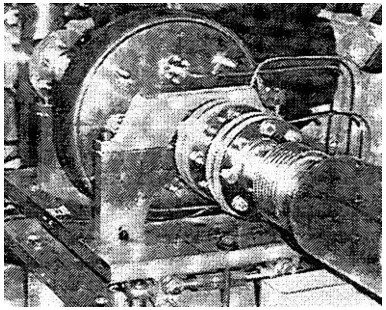
dipole (TM_{110}) and monopole (TM_{010}) & other modes

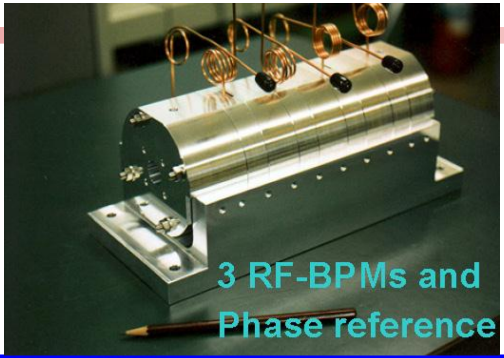
- **Common mode (TM_{010}) frequency discrimination**
- **Mode polarization**
  - **x-y cross-talk**
- **Normalization (intensity) & phase reference**

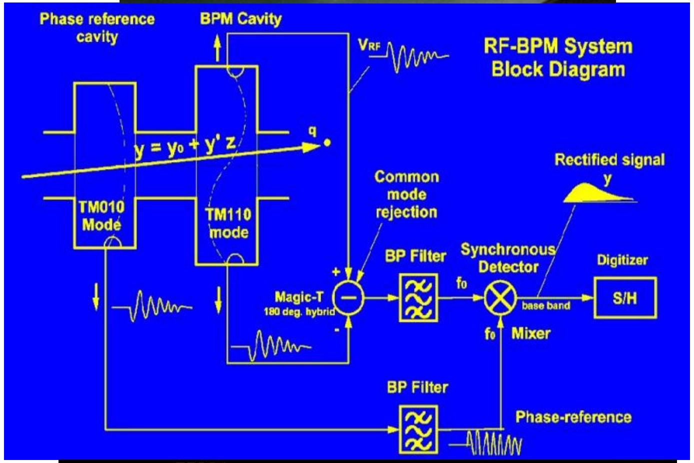
Early Cavity BPMs (mid ‘90)

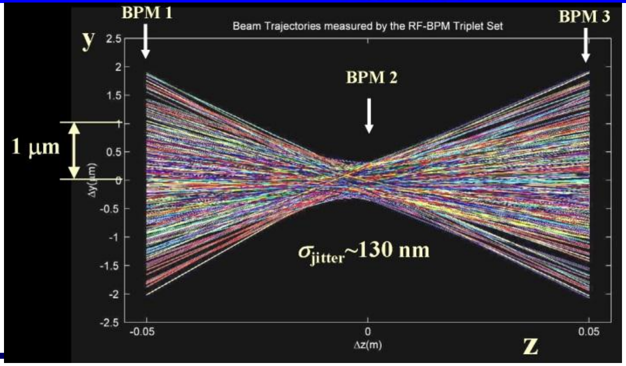






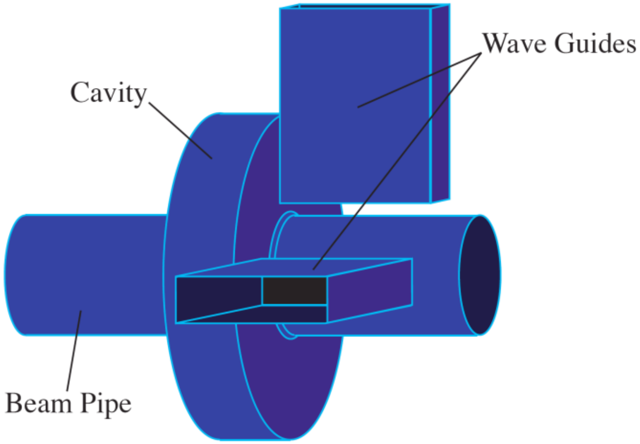




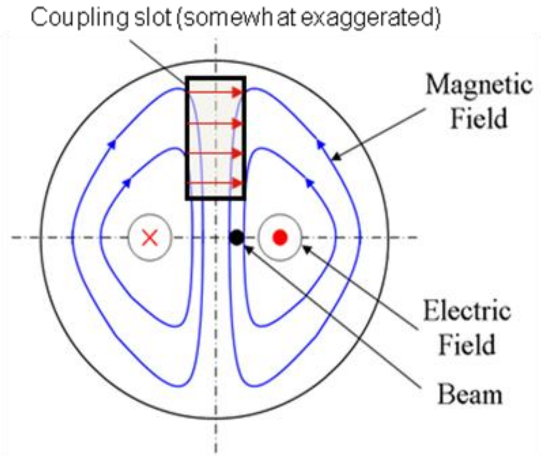


- **Cold L-Band cavity BPM (DESY)**
  - **Operates in TTF/FLASH cryomodules**
- **High resolution C-Band cavity BPM system (SLAC-FFTB)**
  - **3 cavity BPMs & reference cavity**
  - **Correlated beam jitter subtracted: -> 25 nm BPM resolution!**

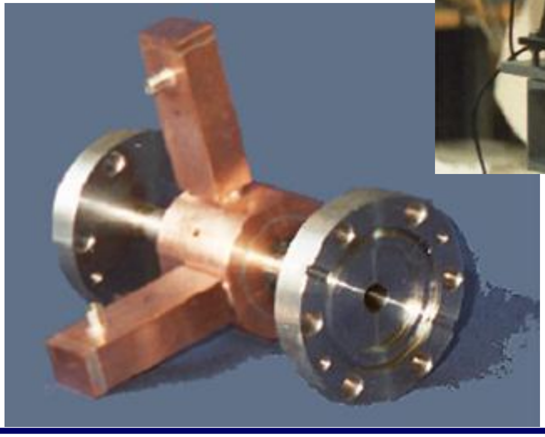
Common-Mode Free Cavity BPM

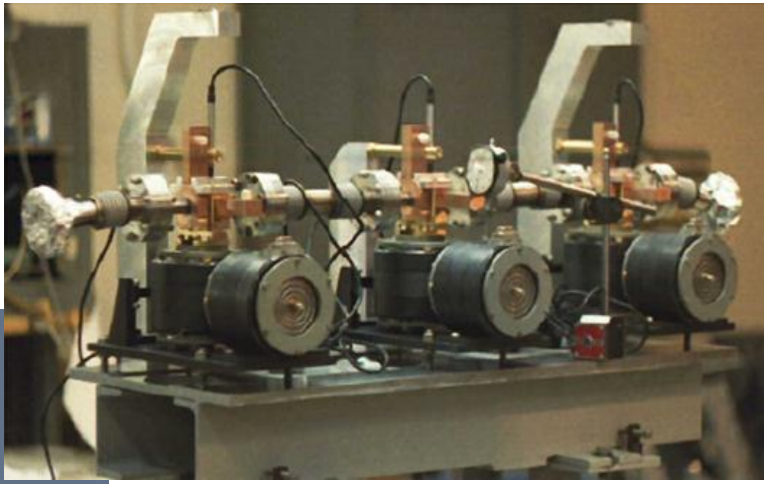


- **Add slot-coupled waveguide TE01-mode high-pass filter** $f_{010} < f_{10} = \frac{1}{2a\sqrt{\varepsilon\mu}} < f_{110}$ **between cavity and coaxial output port.**
  - **Finite Q of TM_{010} still leaks into TM_{110}!**



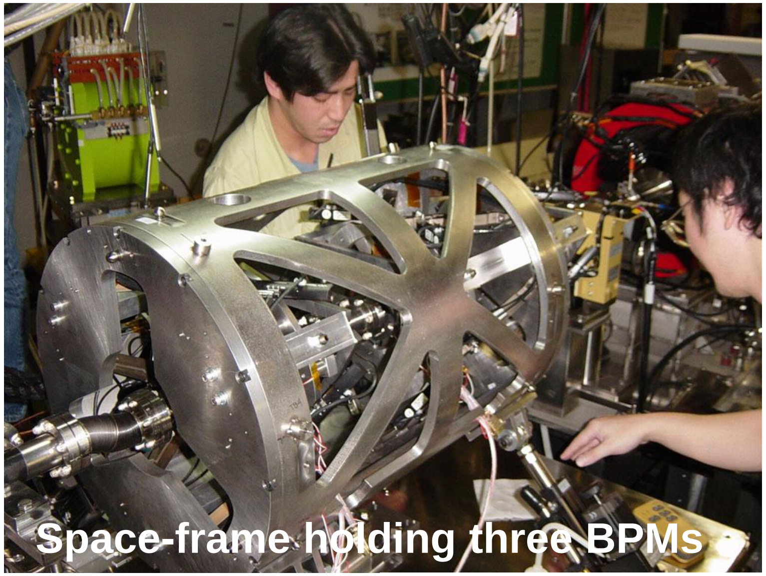
VLEPP 14 GHz Cavity BPM





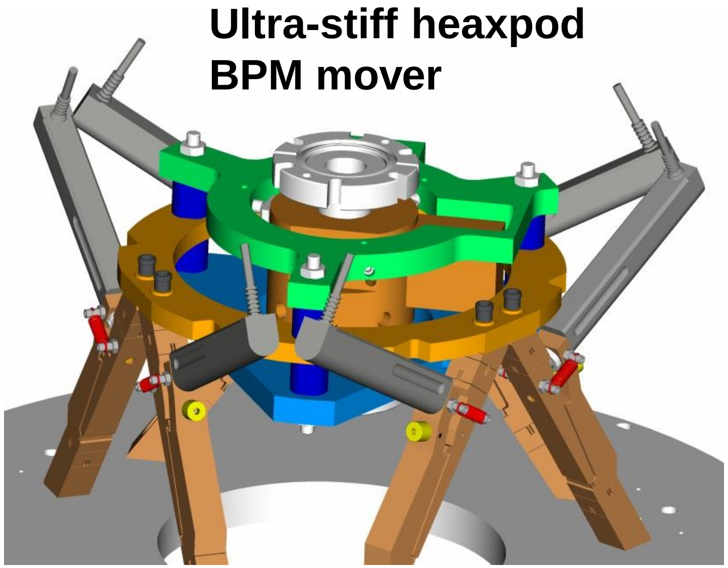
Setup of three VLEPP cavity BPMs for ATF (1997)

nanoBeam Studies at ATF

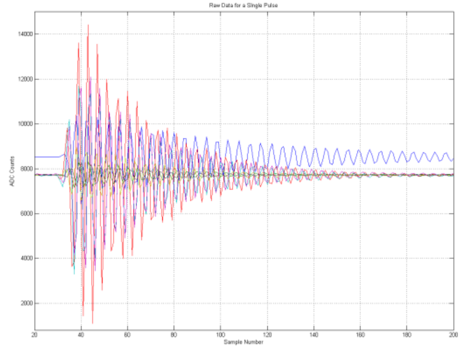


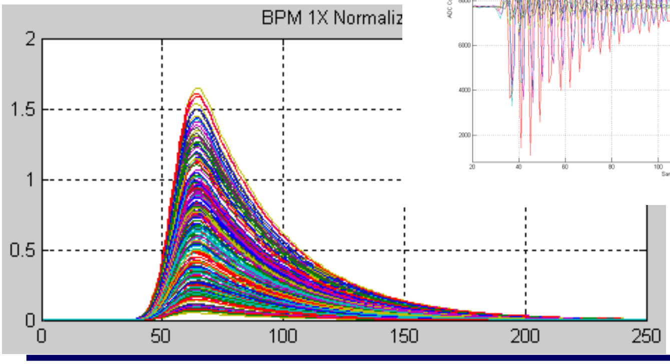
Space-frame holding three BPMs

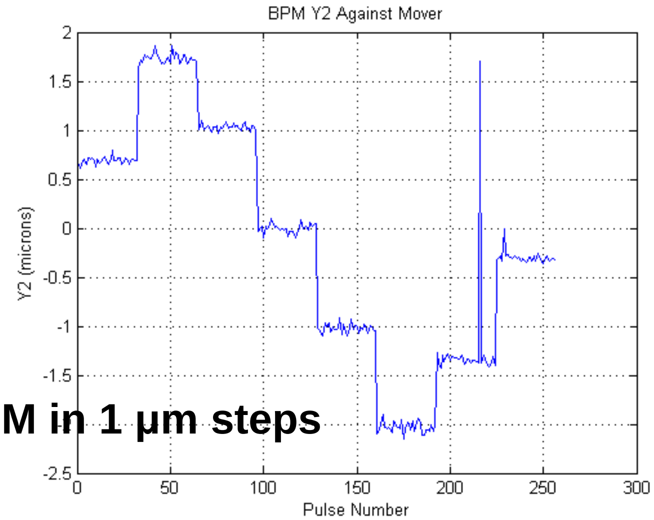
Ultra-stiff heaxpod BPM mover



Raw & demodulated single bunch signals

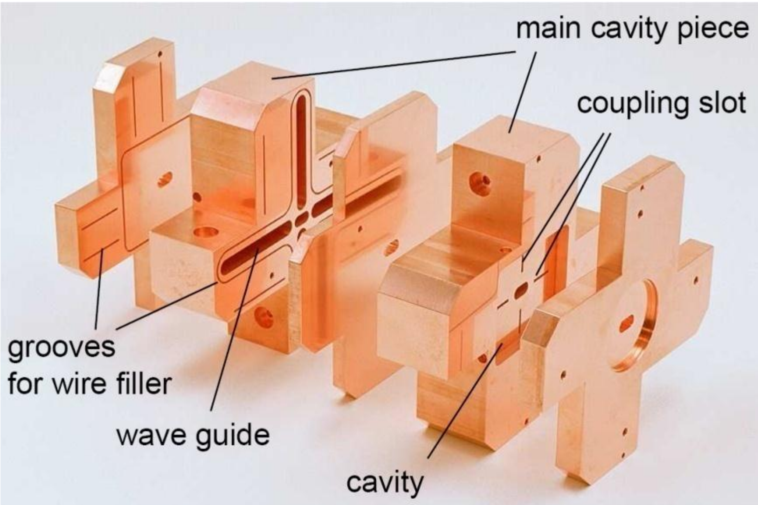


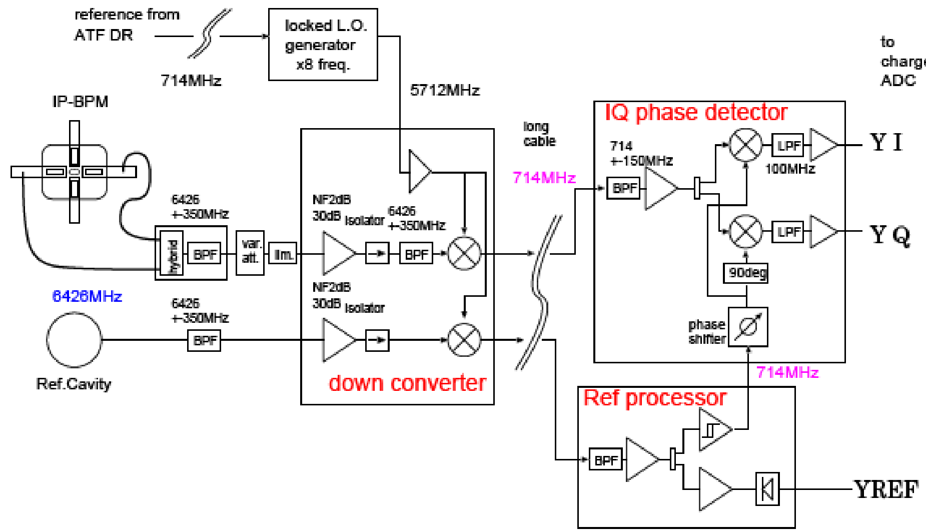




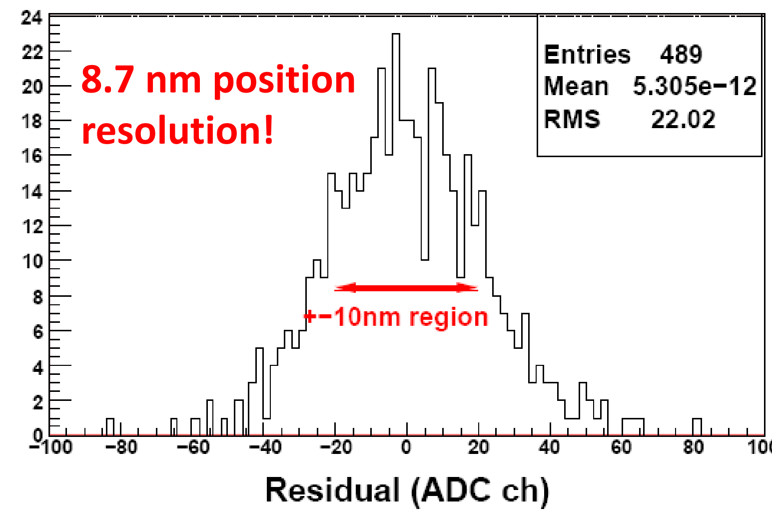
Move BPM in 1 µm steps

BPM Resolution Record!



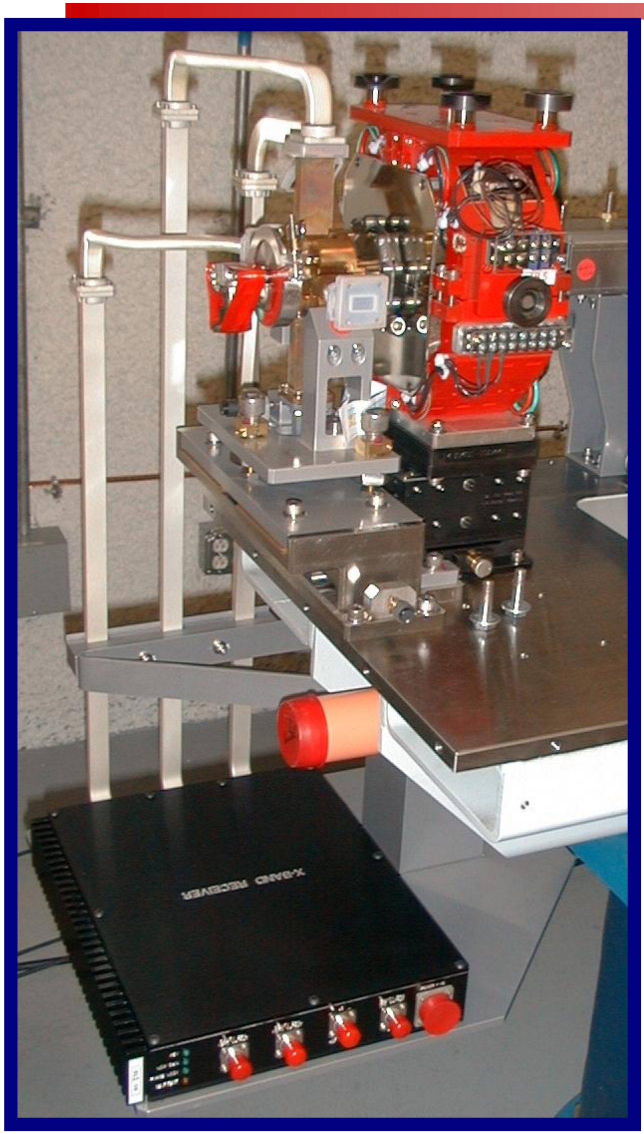


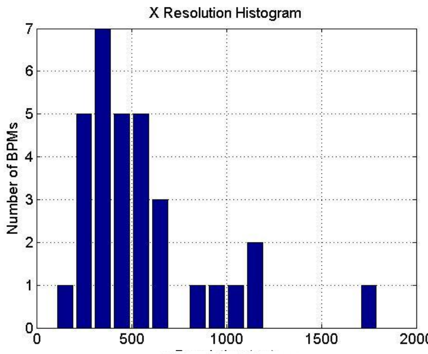
- **C-Band ILC IP-BPM (KEK)**
  - **Narrow gap to be insensitive to the beam angle**
  - **Small aperture (beam tube) for high sensitivity.**
  - **x-y frequency separation (rectangular cavities).**
  - **Double stage homodyne down-converter**

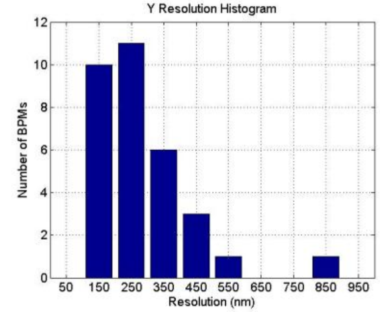


port	*f* (GHz)	*β*	Q_0	Q_{ext}
X	5.712	1.4	5300	3901
Y	6.426	2	4900	2442

LCLS Cavity BPM System







- **32 BPMs (ANL / SLAC)**
  - **X-Band (11.4 GHz),**
    WG directly coupled to receiver (40 MHz).
- **Typical resolution (median)**
  - **$\sigma_x \approx 440$ nm, a few BPMs >1 µm**
  - **$\sigma_y \approx 230$ nm, no BPM >1 µm**
- **Why the difference?!**
  - **Offset? Jitter? Energy variation?**

ATF2 Cavity BPM System

S-Band BPMs (movers)

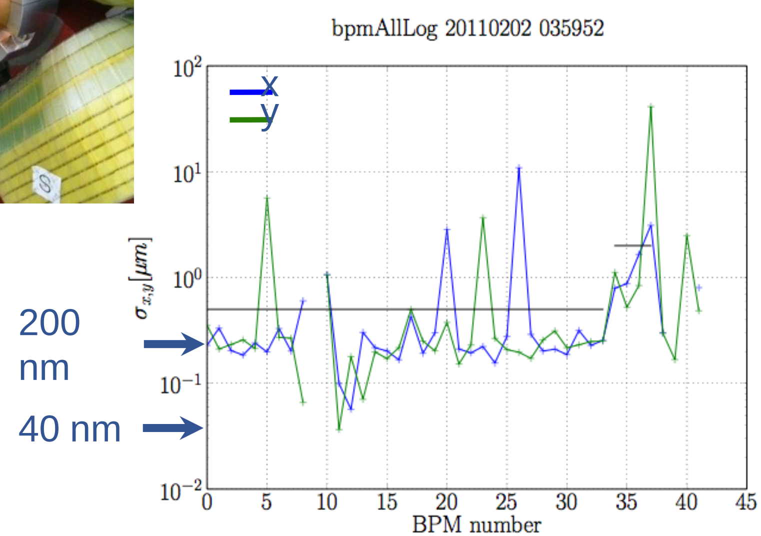
C-Band BPMs (movers)

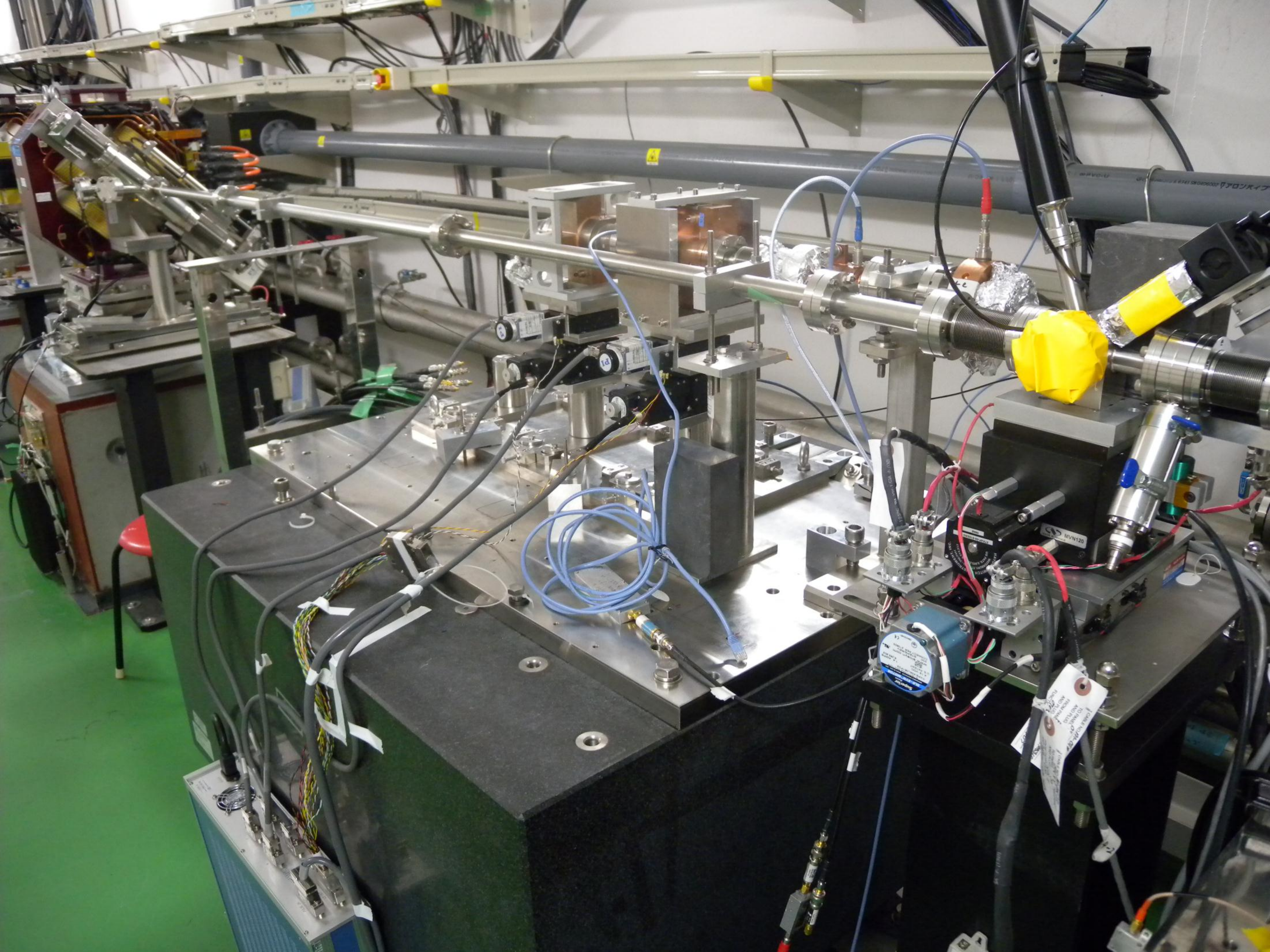
BPM test area (low-Q, high-Q, tilt)

strip-line / cavity BPMs (rigid)

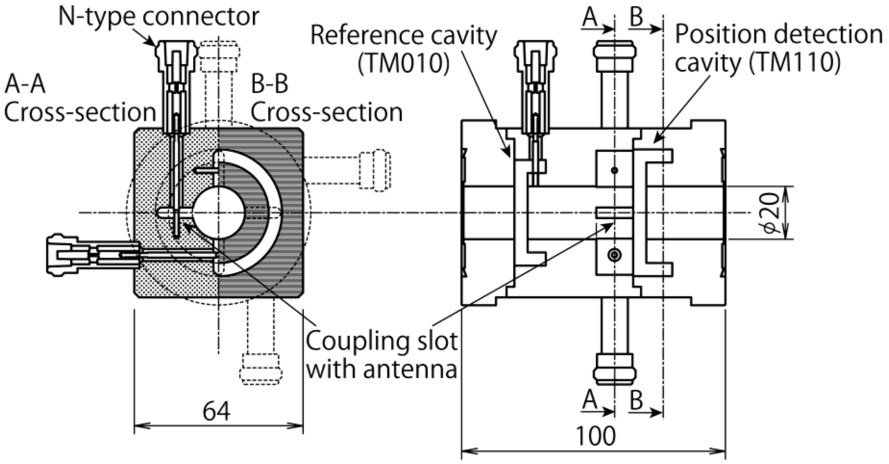
IP region 4 BPMs

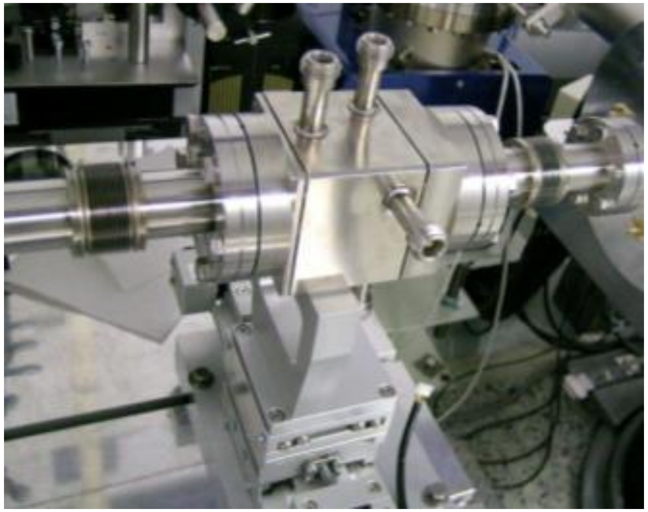
- **ATF2 cavity BPM system**
  - ~40 cavity BPMs
  - 3 designs, C- & S-Band
  - BPMs mounted on quads
- **Signal processing**
  - Single-stage analog down-converter
  - Digitalization and demodulation
- **Objectives**
  - Resolution: <500 nm
  - Precision: <1 %
  - Stability: weeks



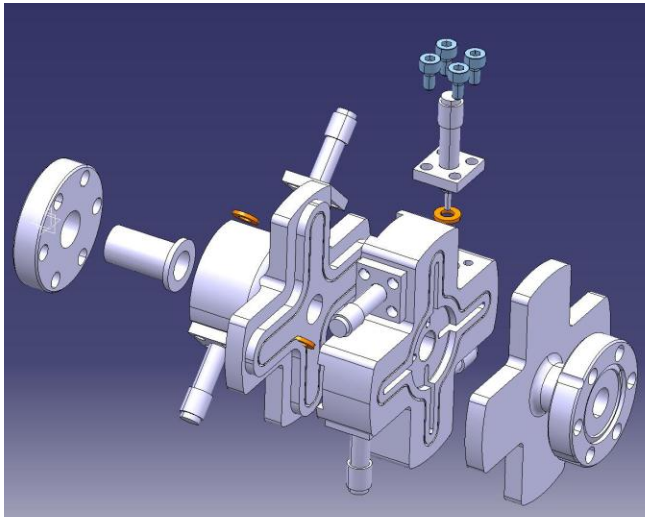

MVN120

Low-Q Cavity BPMs



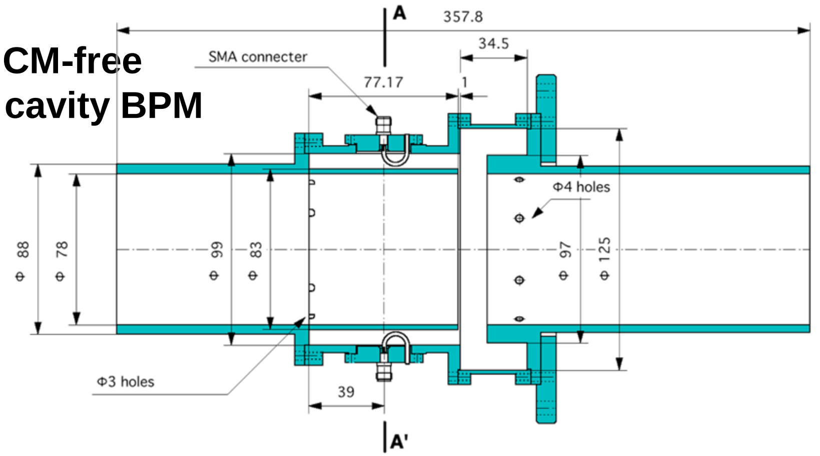


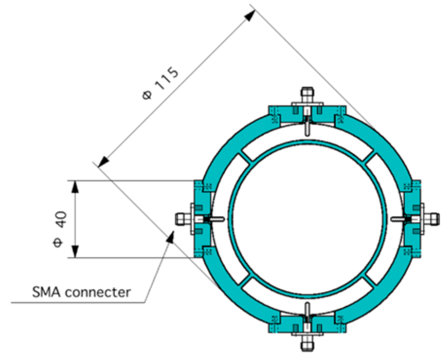
- **Compromise between spatial and temporal resolution**
  - **C-Band, $Q_l \approx 50$, magnetic coupled coaxial port (SPring-8)**
    - ➢ **~200 nm resolution (test beam)**
    - ➢ **~30 psec TOF resolution (reference cavity)**
  - **X-Band design study, $Q_l \approx 250$ (CLIC-CTF)**
    - ➢ **<50 nm resolution (anticipated)**
    - ➢ **<50 nsec integration time**
    - ➢ **8 mm beam pipe diameter!**



Strip-line / Coaxial Resonator BPMs

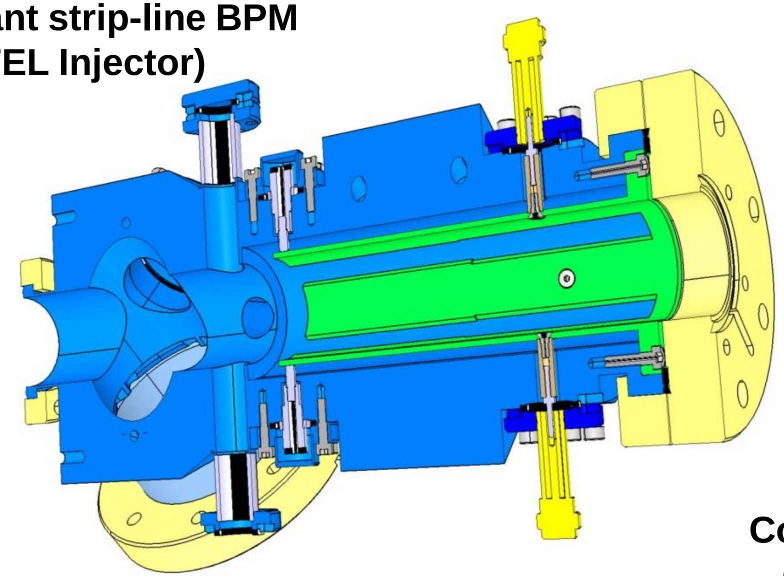
Cold, WG-loaded, CM-free L-Band re-entrant cavity BPM (ILC, *KEK*)

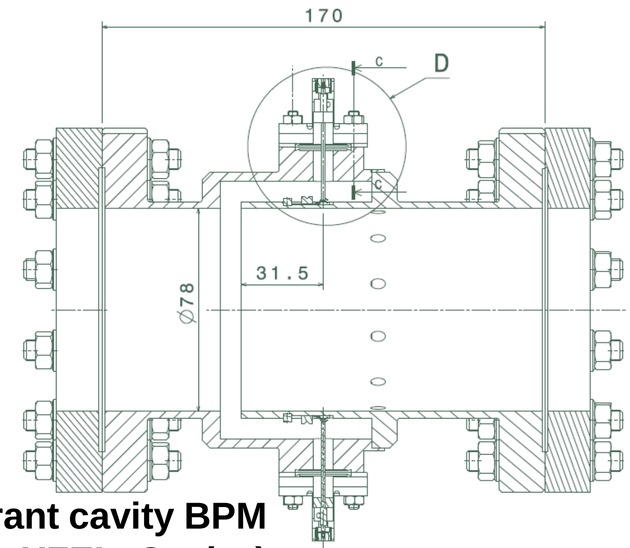




A - A' cross section

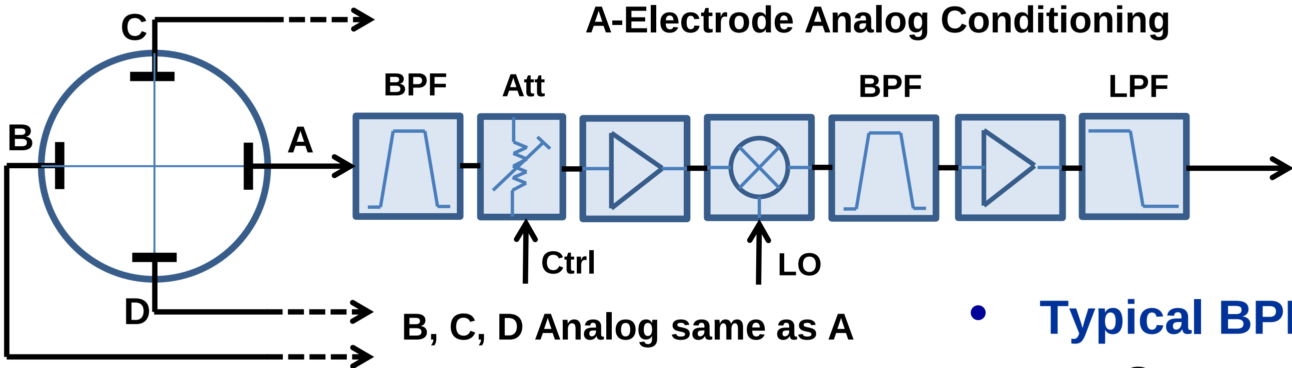
Resonant strip-line BPM (PSI-XFEL Injector)



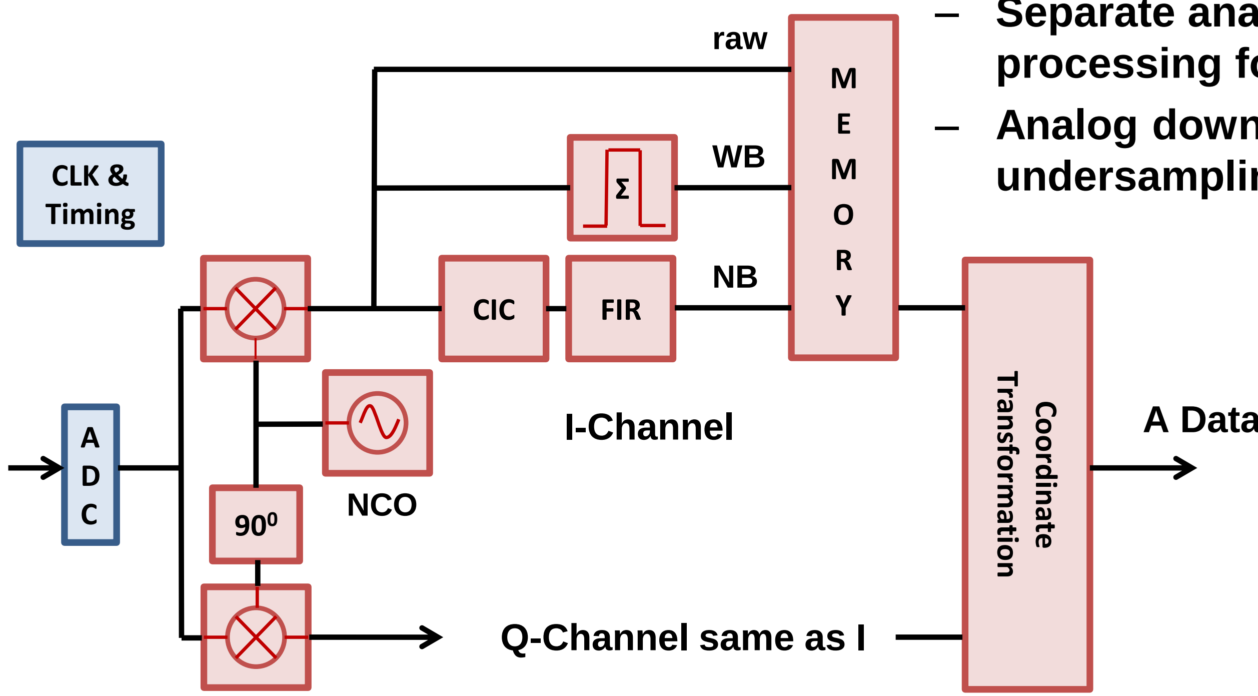


Cold re-entrant cavity BPM (European-XFEL, *Saclay*)

Read-out Electronics

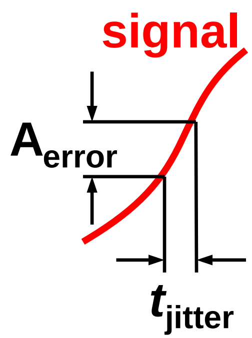


- **Typical BPM read-out scheme**
  - Separate analog signal processing for the channels
  - Analog down-converter if undersampling is not applicable.



Some Remarks

- **Analog down-converter / signal conditioning**
  - **Defines the TD waveform / frequency band to be digitized.**
  - **May need to be located close to the BPM pickup (e.g. pickup input frequencies in the microwave range)**
  - **Analog down-conversion vs. undersampling!?**
    - **CLK jitter requirements**
  - **Linearity / dynamic range extension (attenuator / gain switching)**
  - **May need calibration & gain correction system**

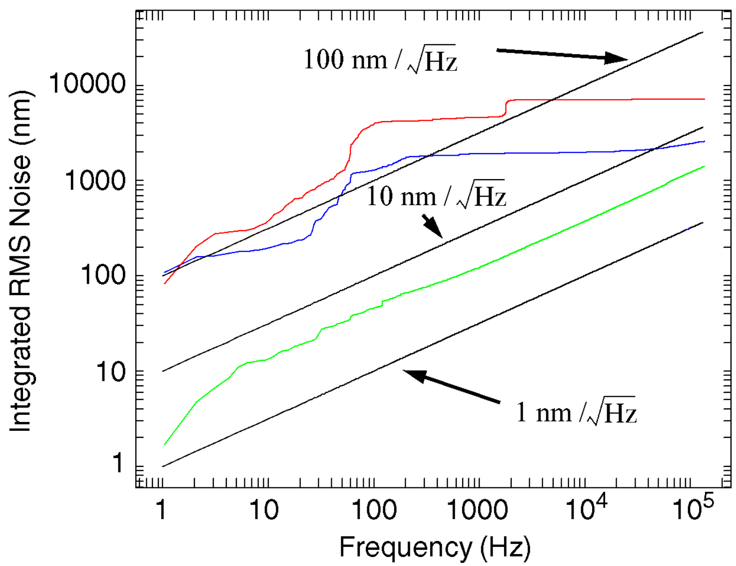


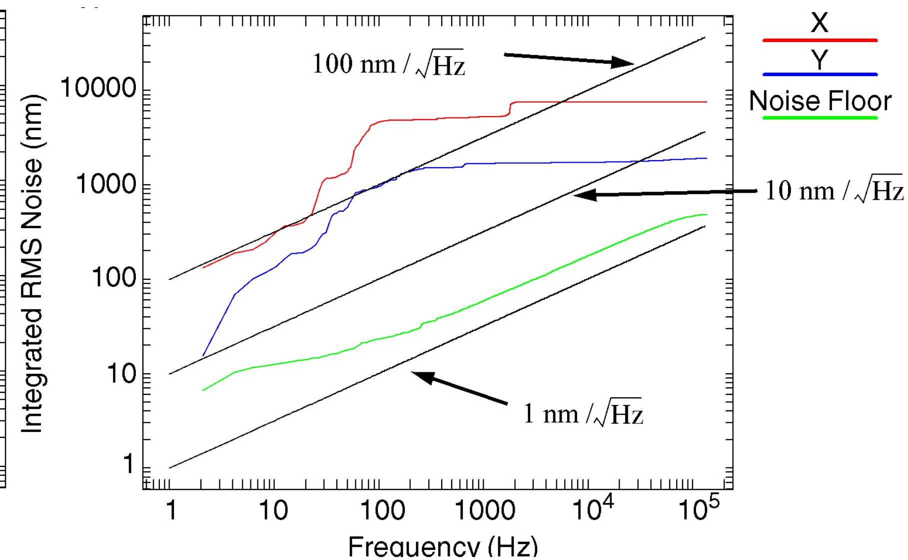
- **Digital signal processing**
  - **FPGA vs. CPU processing**
  - **I-Q is only required if ADC CLK is not phase locked to f_{RF}**
  - **Down-conversion to base-band, low frequency but not DC**
    - **Crawling phase**
  - **Coordinate transformation $\sqrt{I^2+Q^2}$ vs. rotation to I'?!**
- **Key elements: Dynamic range (linearity) & statistics (sample-rate)!**

Typical Performance

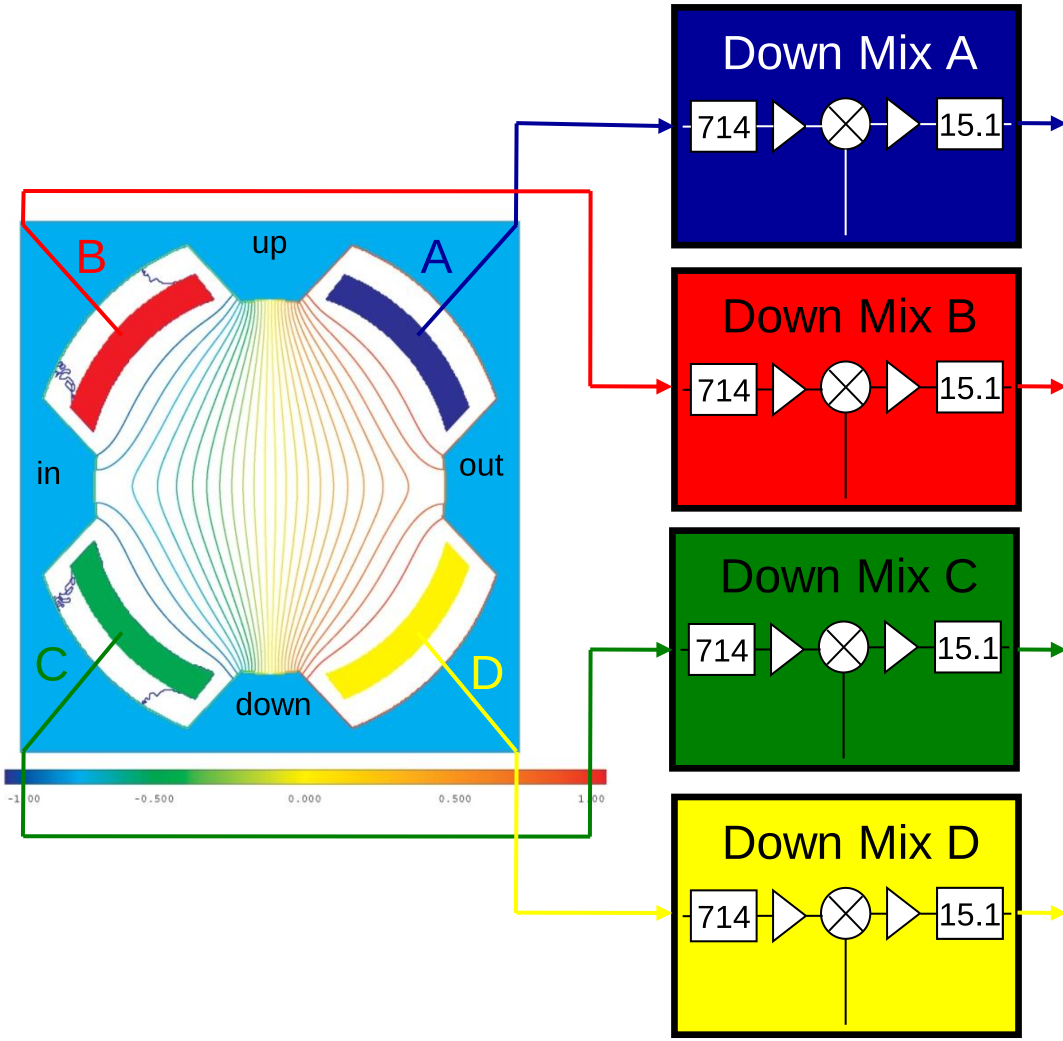
BSP-100 module
(APS *ANL*)

Libera Brilliance
(@APS *ANL*)





BPM Electronics Scheme (ATF DR)



Digital signal processing:

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

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

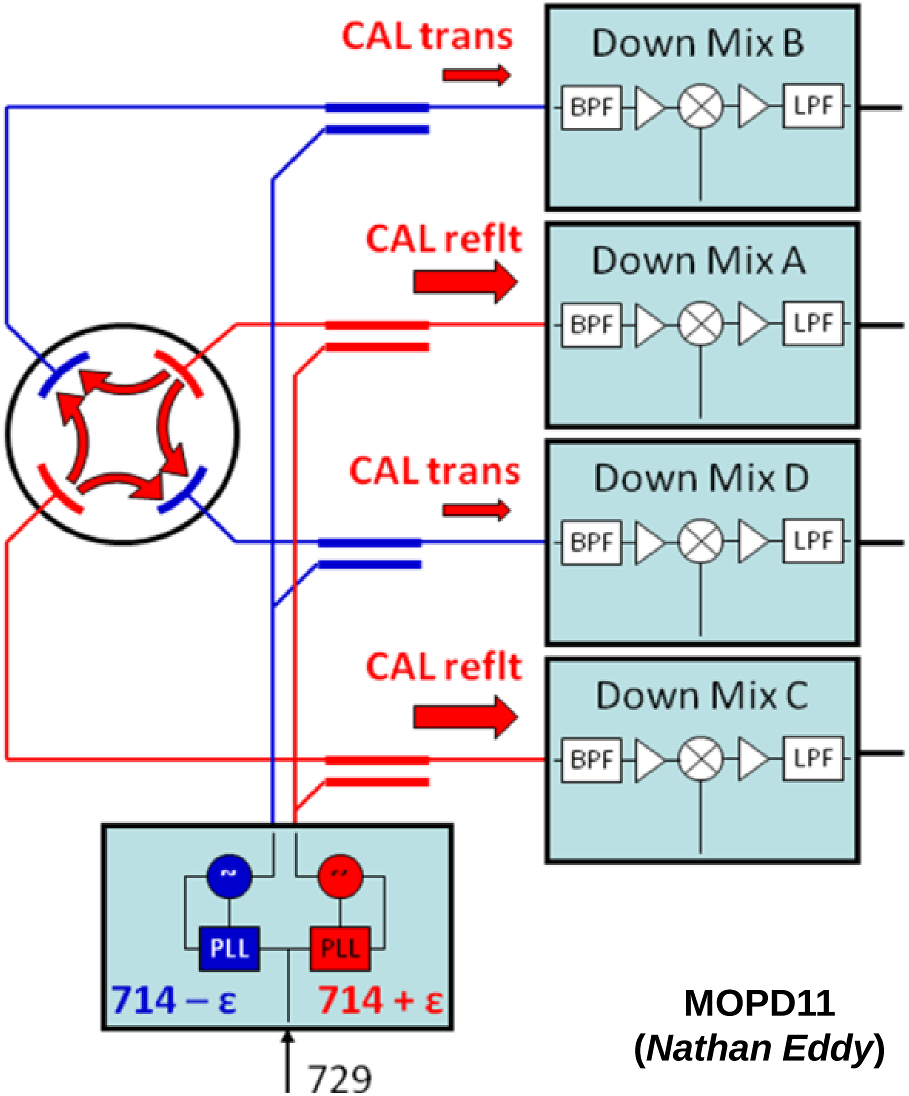
1D polynomial fit:

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

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

0.1 dB gain error ≡
27 µm offset error !

Automatic Gain Correction (ATF DR BPMs)



MOPD11
(*Nathan Eddy*)

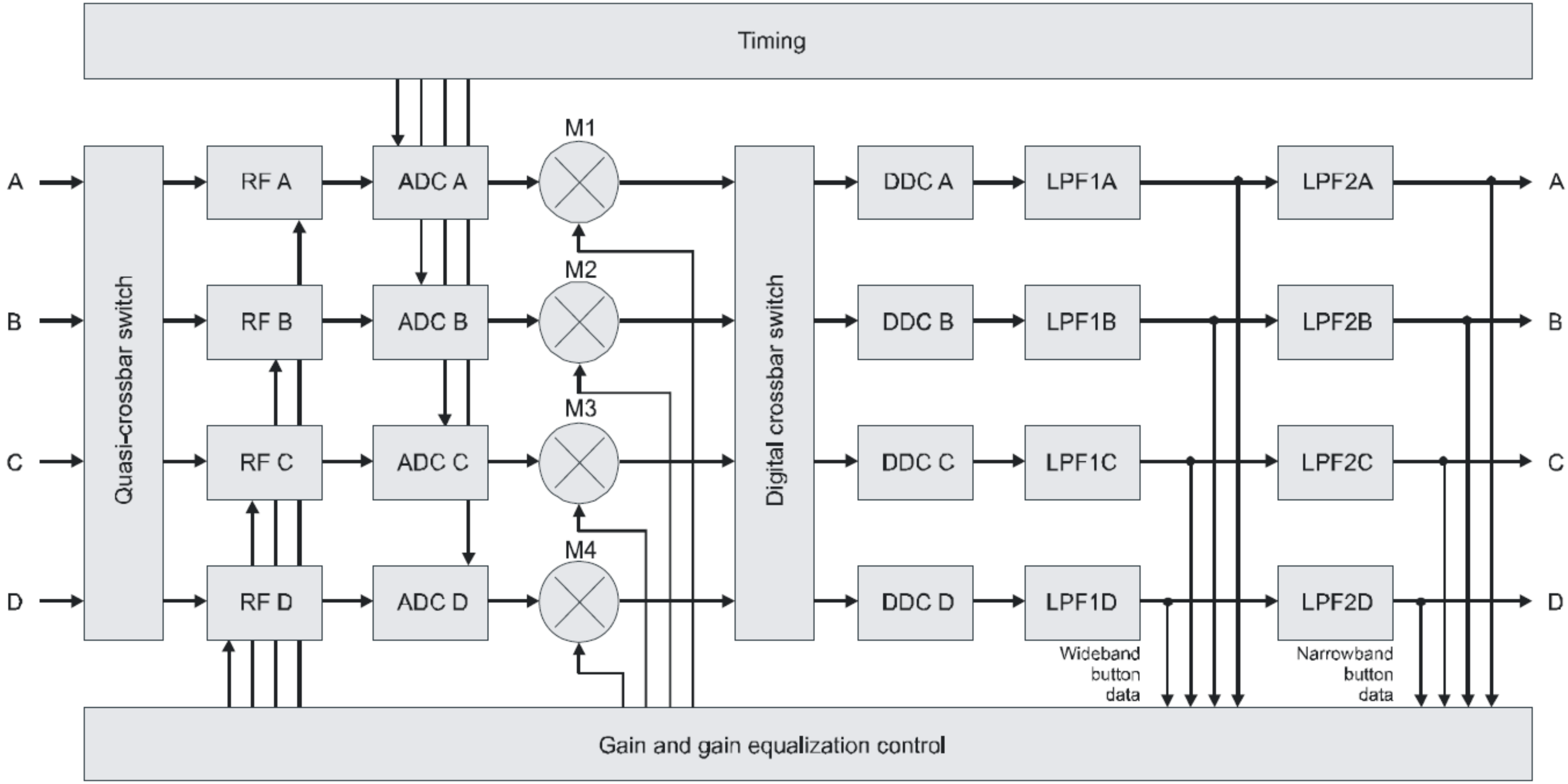
- **Use calibration tone(s)**
  - **714+ε MHz, 714-ε MHz**
  - **Reflected and/or thru BPM calibration signal**
  - **Inside analog pass-band**
  - **Separate DDC in NB mode**
  - **Error & correction signals:**

$$X_{\mathrm{Err}} = \frac{A_{\mathrm{CAL}} + B_{\mathrm{CAL}} + C_{\mathrm{CAL}} + D_{\mathrm{CAL}}}{4\, X_{\mathrm{CAL}}}$$

$$X_{\mathrm{Corr}} = X_{\mathrm{raw}}\, X_{\mathrm{Err}} \qquad X{:}\, A, B, C, D$$

- **Advice:**
  - **Two calibration tones is not a good idea!**
    (use “ping-pong” calibration workaround)

Libera Crossbar Switch CAL Scheme



Schematics of crossbar switch based BPM electronics from Istrumentation Technologies.
Pat. No.: US2004/0222778 A1

Summary & Final Remarks

- **A lot of BPM R&D activities worldwide, labs & industry**
  - **Pickups & feedthroughs, electronics, etc.**
- **Trent towards high resolution resonant BPMs, e.g. cavity BPMs**
  - **In favor of higher, microwave frequencies**
  - **Demands in precision mechanics, tolerances, EM simulations (also higher costs)**
- **Trent to digital signal processing, plus some analog electronics with integrated calibration / drift correction scheme.**
  - **Complex processing / math in the digital domain.**
  - **Very flexible by FPGA re-programming, however labor intensive!**
- **Many open points and issues to be further discussed!**
- **This short overview could only give a glimpse**
  - **Missing: Beam phase / TOF monitoring, BPM as beam intensity monitor, tilt (angle), wake-potential, invasive (screens) & optical BPMs.**
  - **Our large, world-wide distributed community needs events like this to exchange information and experience!**

THANKS!

REFERENCES

[1] B. Banerjee, et.al., “Fermilab Main Injector Beam Position Monitor Upgrade,” BIW’06, Batavia, IL, USA, May 2006, AIP Conf. Proc. **868** (2006), pp. 540-548.

[2] R. Brinkmann and M. Boege, “Beam-Based Alignment and Polarization Optimization in the HERA Electron Ring,” EPAC’94, London, UK, June/July 1994, pp. 938-940.

[3] C. E. Adolphsen, et.al., “Beam-Based Alignment Technique for the SLC Linac,” PAC’89, Chicago, IL, USA, March 1989, Proc. of IEEE (1998), SLAC-PUB-4902

[4] M. Boege, et.al., “The Swiss Light Source A “Test-Bed” for Damping Ring Optimization,” IPAC’10, Kyoto, Japan, May 2010, WEPE091, pp. 3560-62 (2010).

[5] A. Hofmann, “Beam Diagnostics and Applications,” BIW’98, Stanford, CA, USA, May 1998, AIP Conf. Proc. **451** (1998), pp. 3-22.

[6] J. Cuperus, “Monitoring of Particle Beams at High Frequencies,” CERN, Geneva, Switzerland, November 1976, CERN/PS/LIN 76-7.

[7] K. Satoh, “New Beam Position Monitor by detecting Wall Currents,” Rev. Sci. Instr. **4** (1979), p. 450.

[8] R. C. Shafer, “Characteristics of Directional Coupler Beam Position Monitors,” PAC’85, Vancouver, BC, Canada, May 1985, IEEE Trans. Nucl. Sci. **32** (1985), pp. 1933-37.

[9] N. Baboi, et.al., “Magnetic Coupled Beam Position Monitor for the FLASH Dump Line,” BIW’10, Santa Fe, NM, USA, May 2010, TUPSM039, pp. 214-217 (2010).

[18] S. Smith, et.al., “LCLS Cavity Beam Position Monitors,” DIPAC’09, Basel, Switzerland, May 2009, TUOC03, pp. 285-287 (2009).

[19] R. Lorenz, “Cavity Beam Position Monitors,” BIW’98, Stanford, CA, USA, May 1998, AIP Conf. Proc. **451** (1998), pp. 53-73.

[20] D. Lipka, et.al., “Cavity BPM Designs, Related Electronics and Measured Performances,” DIPAC’09, Basel, Switzerland, May 2009, MOPD07, pp. 280-284 (2009).

[21] V. Sargsyan, “Cavity Beam Position Monitor for the TESLA Cryomodule – Cross-Talk Minimization,” Ph. D. thesis, Technical University Berlin, Germany (2003).

[22] T. Slaton, et.al., “Development of Nanometer Resolution C-Band Radio Frequency Beam Position Monitors in the Final Focus Test Beam,” SLAC-PUB-7921, August 1998

[23] V. Balakin, et.al., “Experimental Results form a Microwave Cavity Beam Position Monitor,” PAC’99, New York, NY, USA, March/April 1999, IEEE Proc. (1999), pp. 461-464.

[24] T. Nakamura, et.al., “High Resolution Cavity BPM for ILC Final Focus System (IP-BPM),” LCWS/ILC 2007, Hamburg, Germany, May/June 2007, arXiv:0709.2254v1, eConf C0705302.

[25] H. Maesaka, et.al., “Development of the RF Cavity BPM of XFEL/Spring-8,” DIPAC’09, Basel, Switzerland, May 2009, MOPD07, pp. 56-58 (2009).

[26] D. Lipka, et.al., “Orthogonal Coupling in Cavity BPM with Slots,” DIPAC’09, Basel, Switzerland, May 2009, MOPD07, pp. 44-46 (2009).

[27] H. Schmickler, et.al., “Submicron Mulit-Bunch BPM for CLIC,” IPAC’10, Kyoto, Japan, May 2010