Beam Position Monitor:
Detector Principle, Hardware and Electronics

Outline:

- Signal generation → transfer impedance
- Consideration for capacitive shoe box BPM
- Consideration for capacitive button BPM
- Other BPM principles: stripline → traveling wave,
  inductive → wall current, cavity → resonator for dipole mode
- Electronics for position evaluation
- Some examples for position evaluation and other applications
- Summary

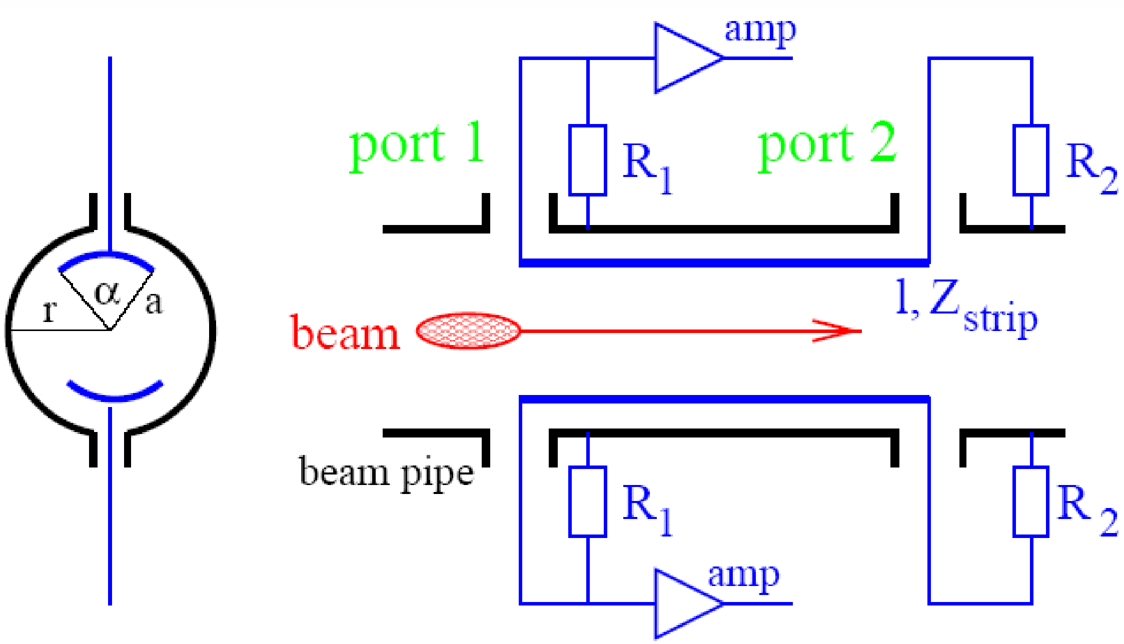
Stripline BPM: General Idea

For short bunches, the ***capacitive*** button deforms the signal

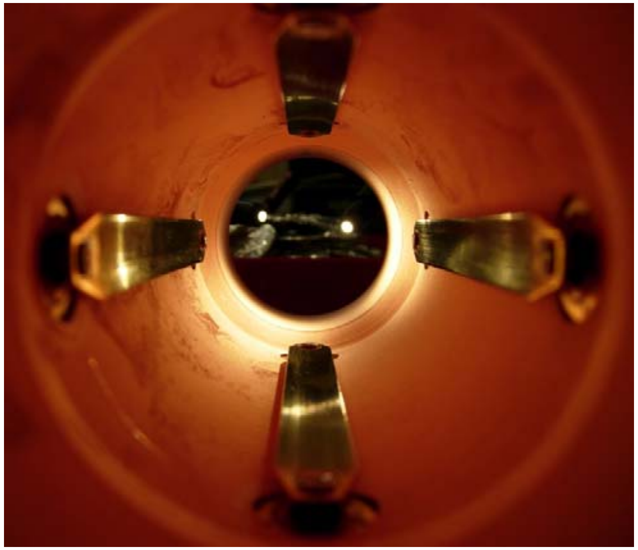
→ Relativistic beam $\beta \approx 1$ ⇒ field of bunches nearly TEM wave

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strips

→ Assumption: Bunch shorter than BPM, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$.



LHC stripline BPM, l=12 cm



From C. Boccard, CERN

Stripline BPM: General Idea

For relativistic beam with β≈1 and short bunches:

→ Bunch's Electro-magnetic field induces a **traveling pulse** at the strip

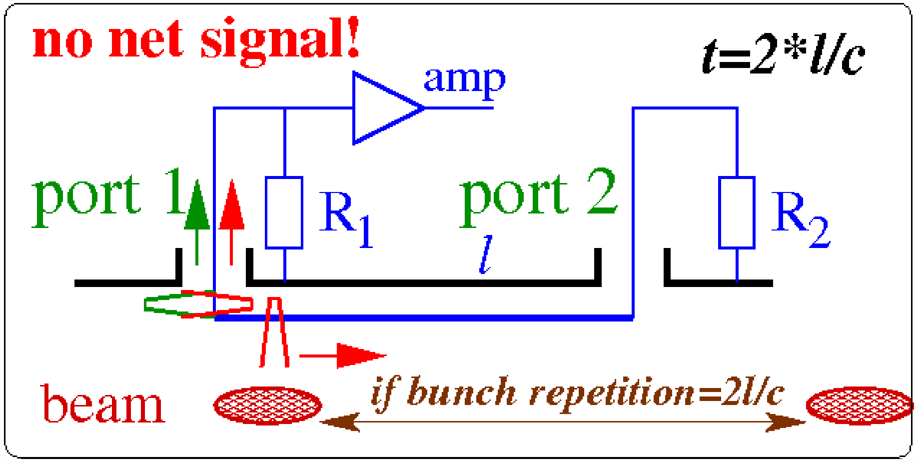
→ ***Assumption:*** $l_{bunch} << l$, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$

Signal treatment at upstream port 1:

t=0: Beam induced charges at **port 1**:
→ half to R_1, half toward **port 2**

t=l/c: Beam induced charges at **port 2**:
→ half to R_2, ***but*** due to different sign, it cancels with the signal from **port 1**
→ half signal reflected

t=2·l/c: reflected signal reaches **port 1**



$$\Rightarrow U_1(t) = \frac{1}{2}\cdot\frac{\alpha}{2\pi}\cdot Z_{strip}\left(I_{beam}(t) - I_{beam}(t-2l/c)\right)$$

If beam repetition time equals 2·l/c: reflected preceding port 2 signal cancels the new one:
→ no net signal at **port 1**

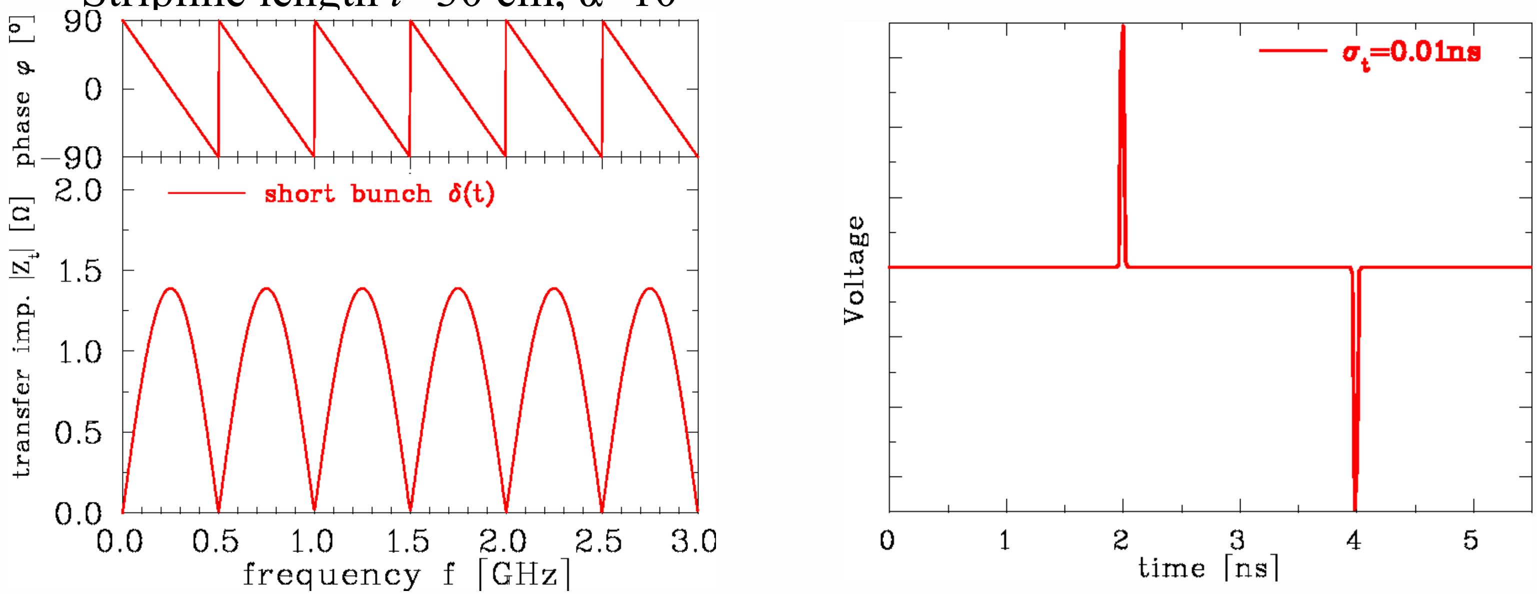
Signal at downstream port 2: Beam induced charges cancels with traveling charge from port 1
⇒ Signal depends direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel ⇒ minima in Z_t

For short bunches $I_{beam}(t) \rightarrow Ne \cdot \delta(t)$: $Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \sin(\omega l / c) \cdot e^{i(\pi/2 - \omega l / c)}$

Stripline length l=30 cm, $\alpha=10^0$



- Z_t show maximum at $l=c/4f=\lambda/4$ i.e. 'quarter wave coupler' for bunch train
  ⇒ l has to be matched to v_{beam}
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. For first lope: $f_{low}=1/2 \cdot f_{center}$, $f_{high}=3/2 \cdot f_{center}$ i.e. bandwidth $\approx 1/2 \cdot f_{center}$
- Precise matching at feed-through required t o preserve 50 Ω matching.

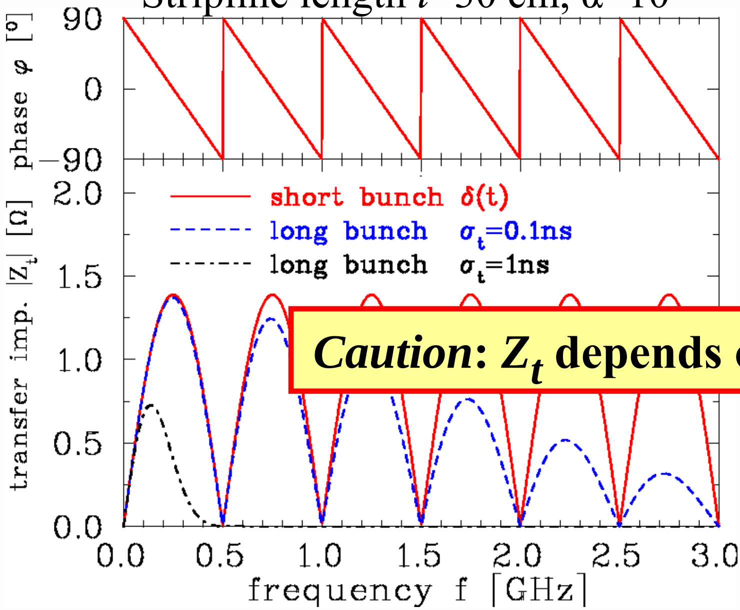
Stripline BPM: Finite Bunch Length

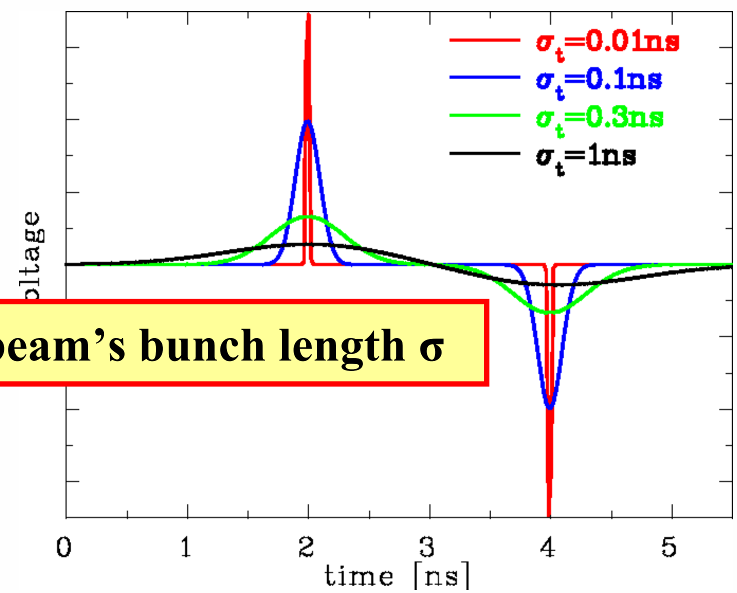
The signal at port 1 for a finite bunch of length σ: $I_{beam}(t) = I_0 \cdot e^{-t^2/2\sigma^2}$

$$\Rightarrow Z_t(\omega) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot e^{-\omega^2\sigma^2/2} \cdot \sin(\omega l/c) \cdot e^{i(\pi/2-\omega l/c)}$$

$$\Rightarrow \text{in time domain}: U_{im}(t) = Z_{strip} \cdot \frac{\alpha}{2\pi} \cdot \left(e^{-(t+l/c)^2/2\sigma^2} - e^{-(t-l/c)^2/2\sigma^2}\right) \cdot I_0$$

Stripline length l=30 cm, α=10^0





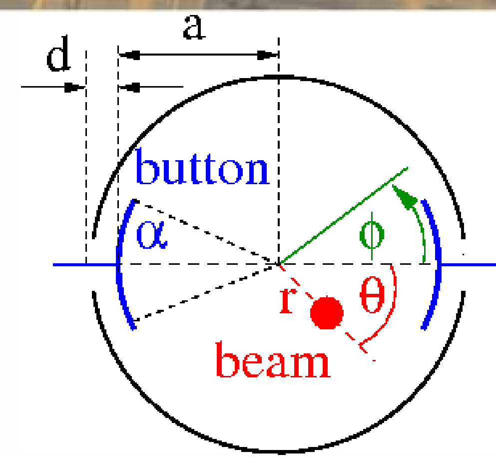
Caution: **Z_t depends on beam's bunch length σ**

- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $(\pm 3\sigma_t > l)$ destructive interference leads to signal damping

  Cure: length of stripline has to be matched to bunch length

2-dim Model for Stripline BPM

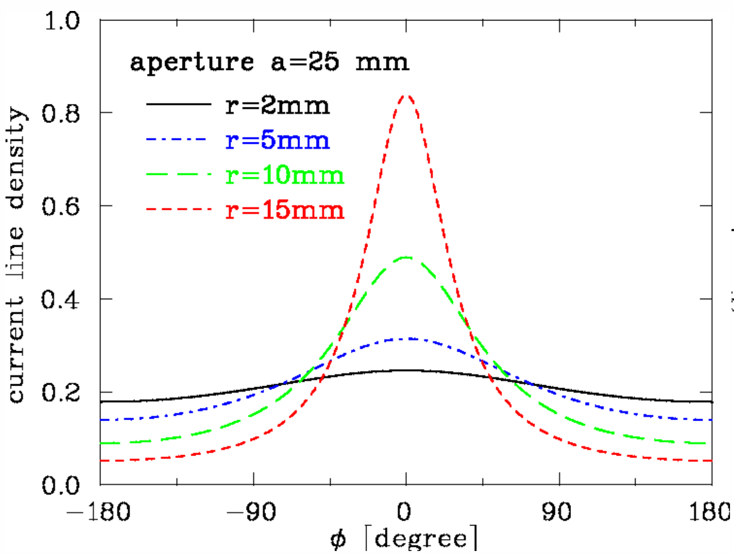
‘Proximity effect’: larger signal for closer plate

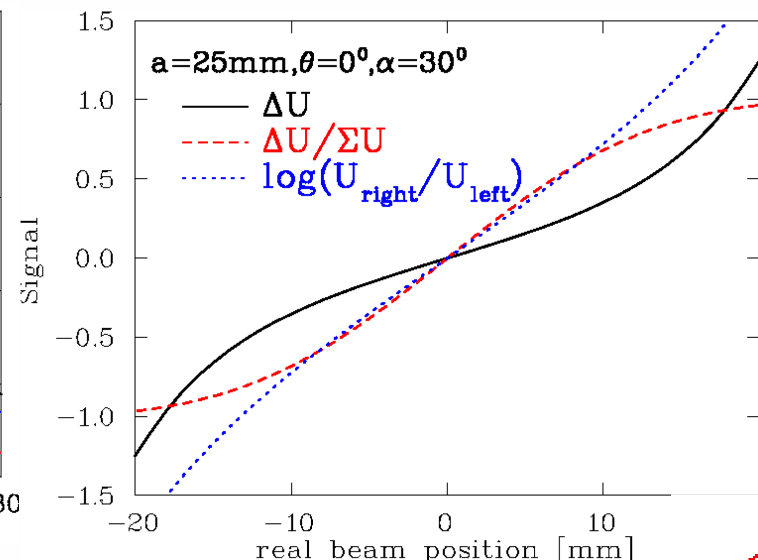


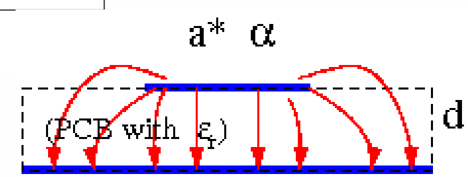
2-dim case: Cylindrical pipe → image current density:

$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

Image current of finite BPM size: $I_{im} = \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$





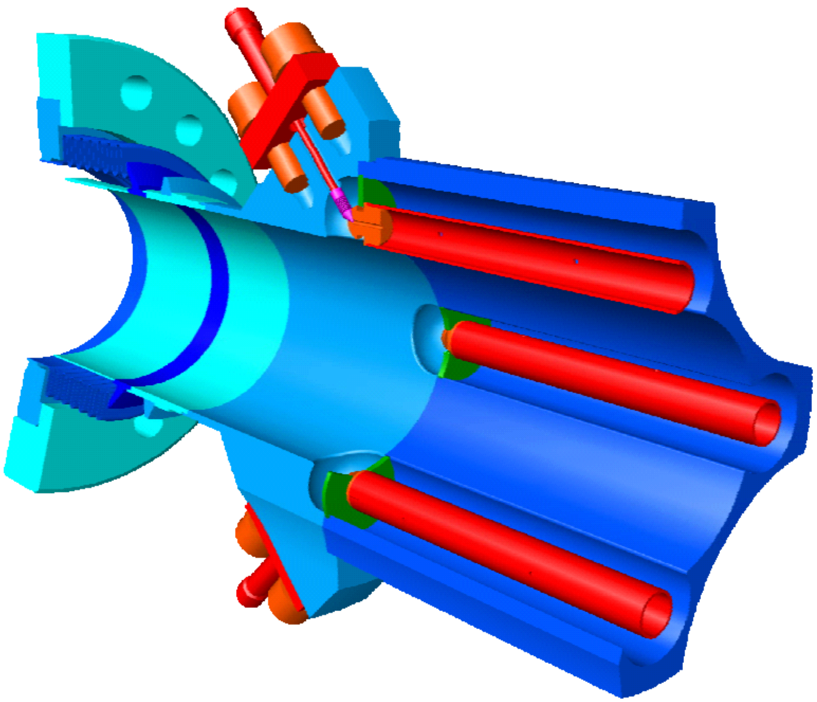


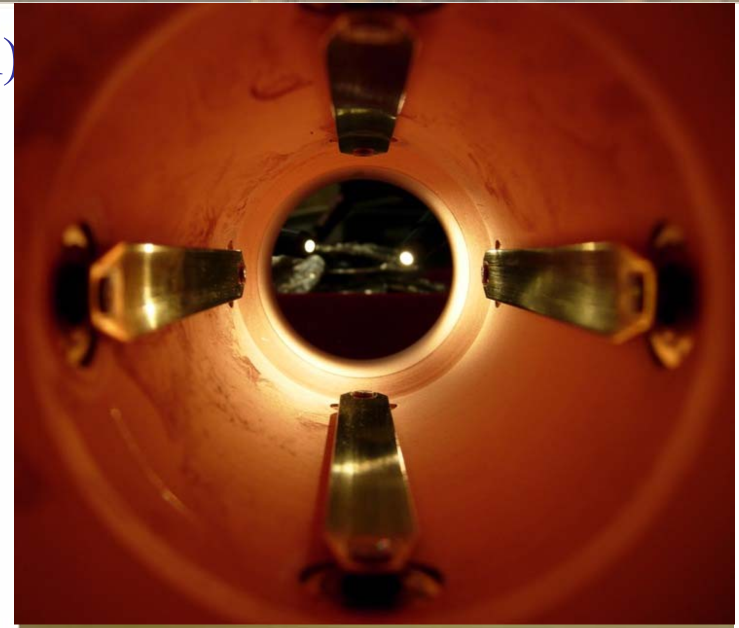
Impedance Z_{strip}=50Ω:

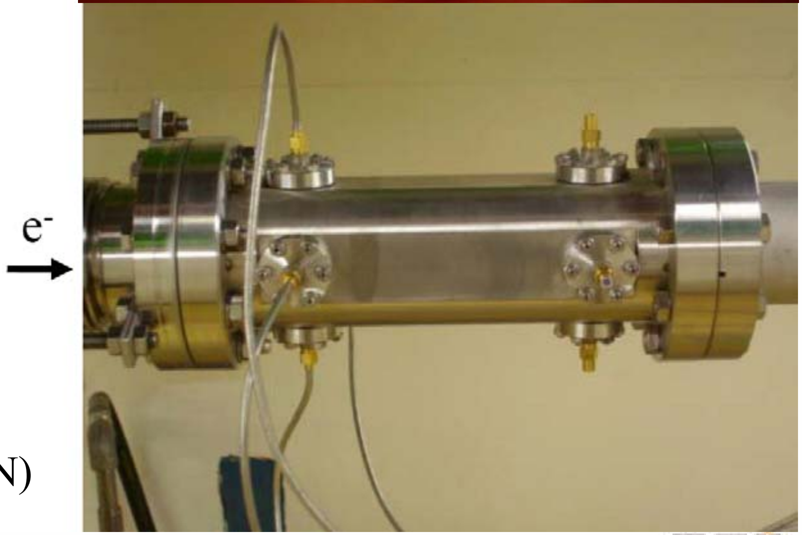
Comparable formula as for PCB micro-strip →dependence on d and α

Realization of Stripline BPM

20 cm stripline BPM at TTF2 (chamber ∅34mm)
And 12 cm LHC type:





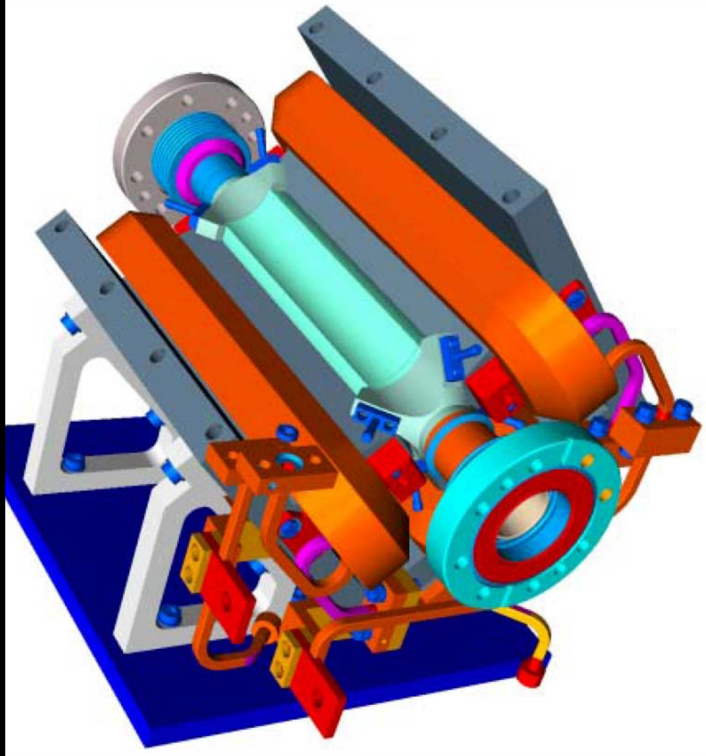


From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

Comparison: Stripline and Button BPM (simplified)

	Stripline	Button
Idea	traveling wave	electro-static
Requirement	Careful $Z_{strip}=50\Omega$ matching	
Signal quality	Less deformation of bunch signal	Deformation by finite size and capacitance
Bandwidth	Broadband, but minima	Highpass, but $f_{cut}<1$ GHz
Signal strength	Large Large longitudinal and transverse coverage possible	Small Size <∅3cm, to prevent signal deformation
Mechanics	Complex	Simple
Installation	Inside quadrupole possible ⇒improving accuracy	Compact insertion
Directivity	**YES**	No

TTF2 BPM inside quadrupole



From . S. Wilkins,
D. Nölle (DESY)

Broadband observation of bunches can be performed with a resistive Wall Current Monitor

Principle: Ceramic gap bridged with n=10…100 resistors of R=10…100 Ω

Voltage drop for $R_{tot}=1/n\cdot R$=1…10 Ω measured

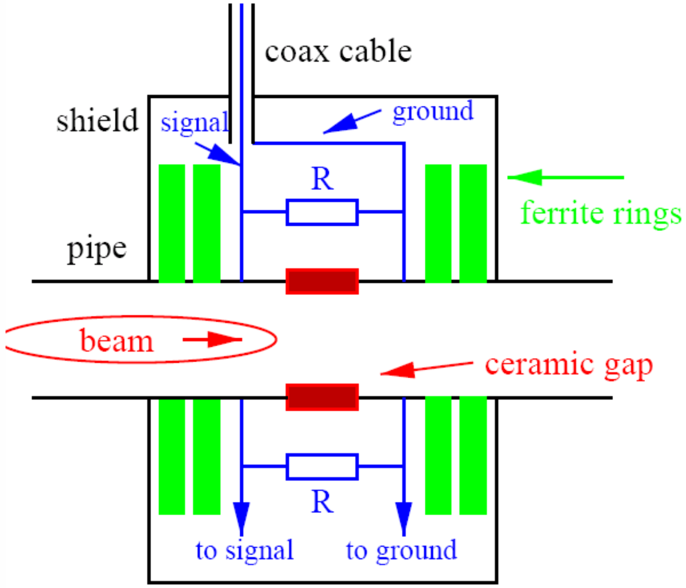
Ferrit rings with high L

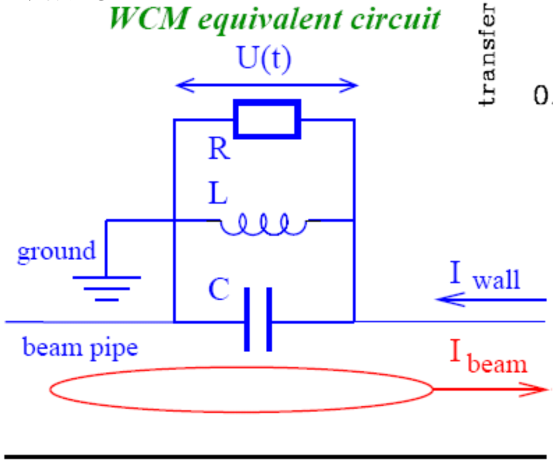
→forces low frequency components through R

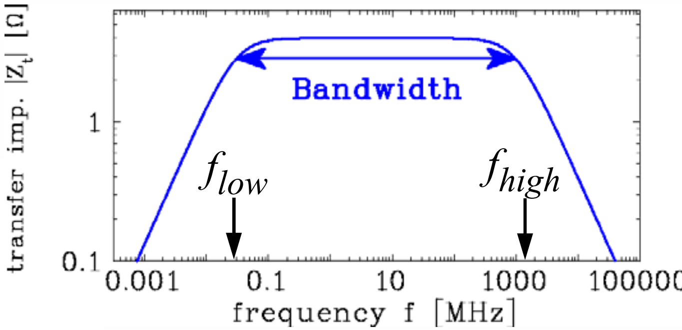
Bandwidth: typically $f_{low}=R/(2\pi L)\approx$10 kHz

$f_{high}=1/(2\pi R_{tot}C)\approx$1 GHz

Application: Broadband bunch observation



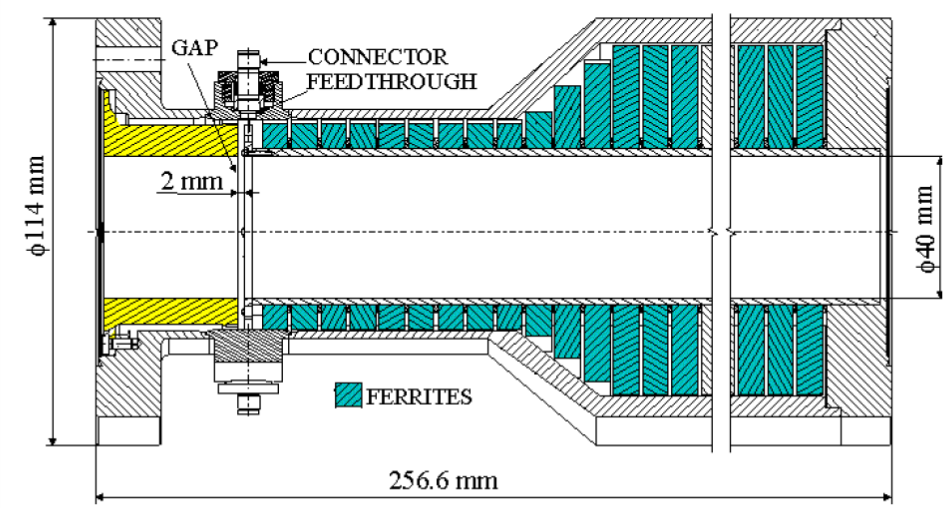


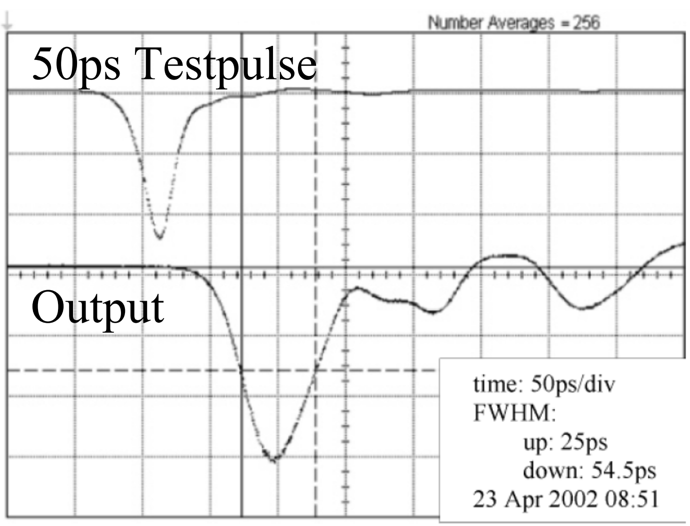


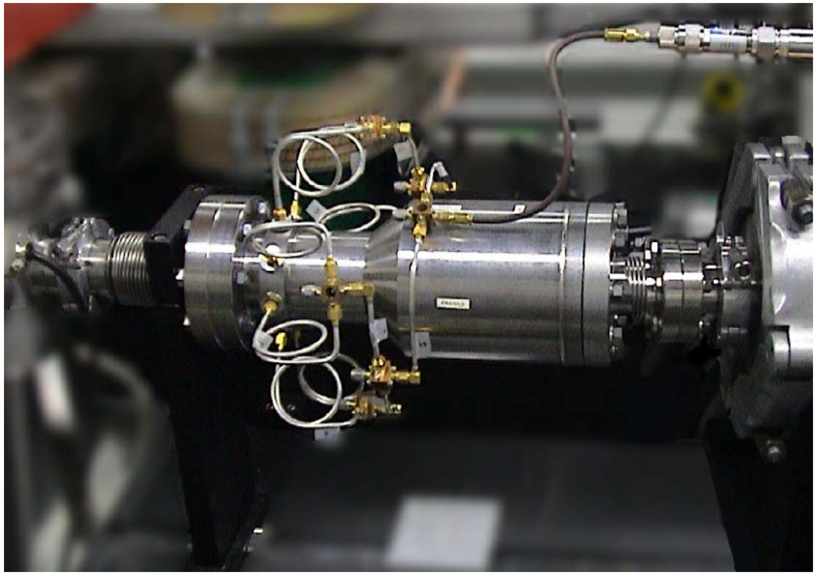
$$\frac{1}{Z_t}=\frac{1}{R_{tot}}+\frac{1}{i\omega L}+i\omega C$$

Within bandwidth: $Z_t \cong R_{tot}$

Large bandwidth WCM for short bunch longitudinal observation at CLIC



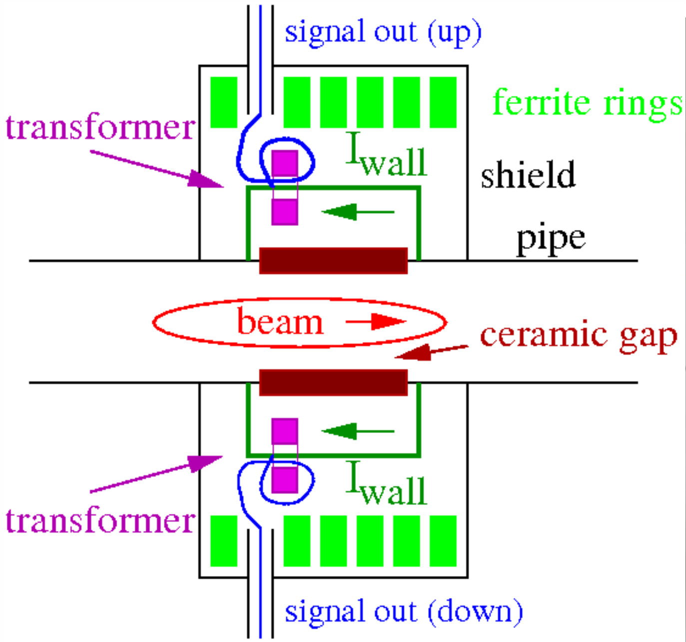


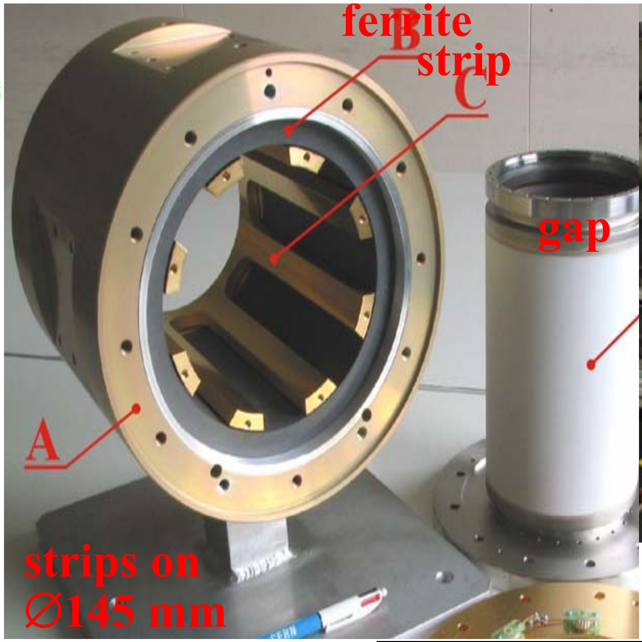


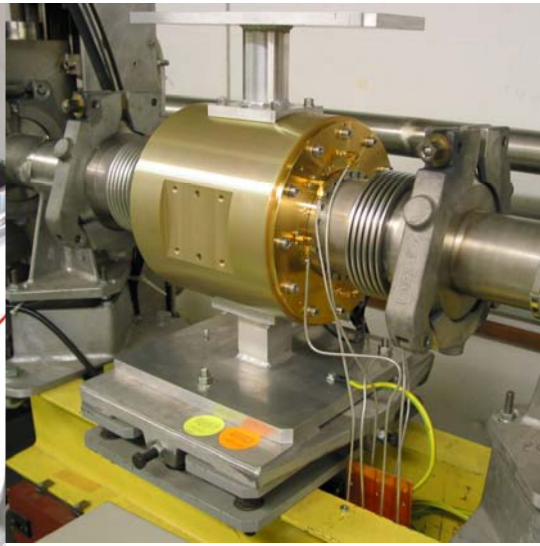
Parameter: f_{low} =250 kHz
f_{high}= 10 GHz
n=8 with R=50 Ω
gap length 2 mm
Z_t=4 Ω
insertion length 256 mm

From P. Odier (CERN) DIPAC 03&05

The wall current is passed through strips and is determined be transformers.







From M.Gasior (CERN), DIPAC 2003 & 2005

Example: CERN **CTF3** and LINAC2 device

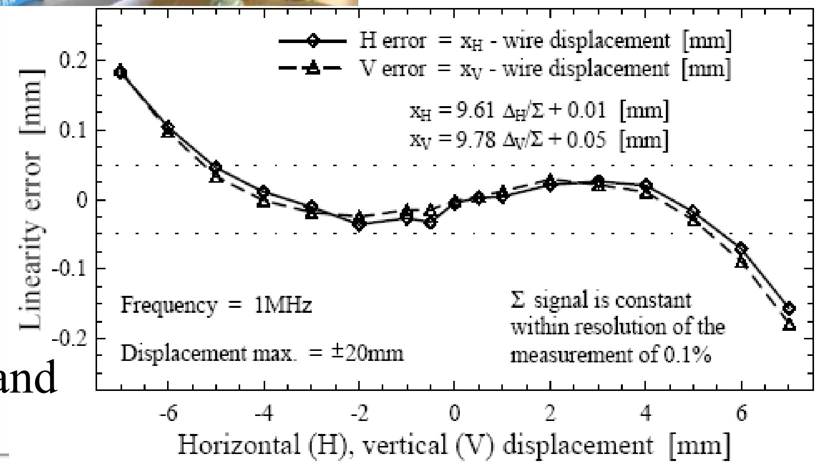
Parameters: 8 strips on ∅50 mm

for CFT3 Bandwidth: 300 kHz to 250 MHz

Transfer impedance: Z_t=10 Ω

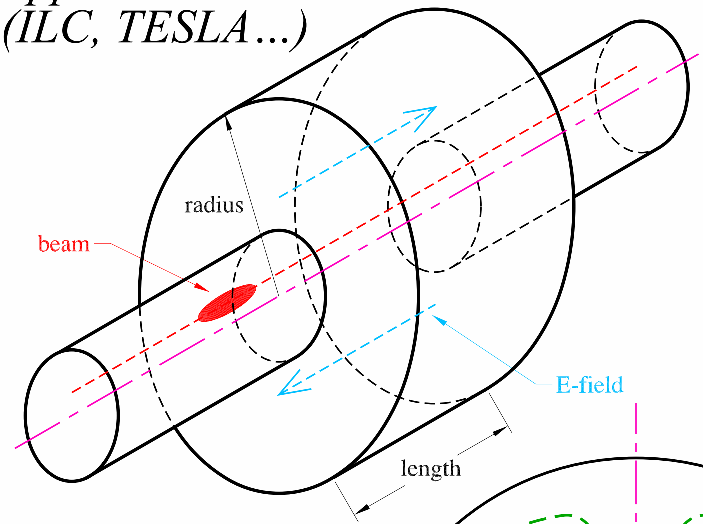
Sensitivity: k=10 mm (central part)

Advantage: Everything outside vacuum, broadband



High resolution on μs time scale can be achieved by excitation of a dipole mode:

Application: small e⁻ beams (ILC, TESLA…)

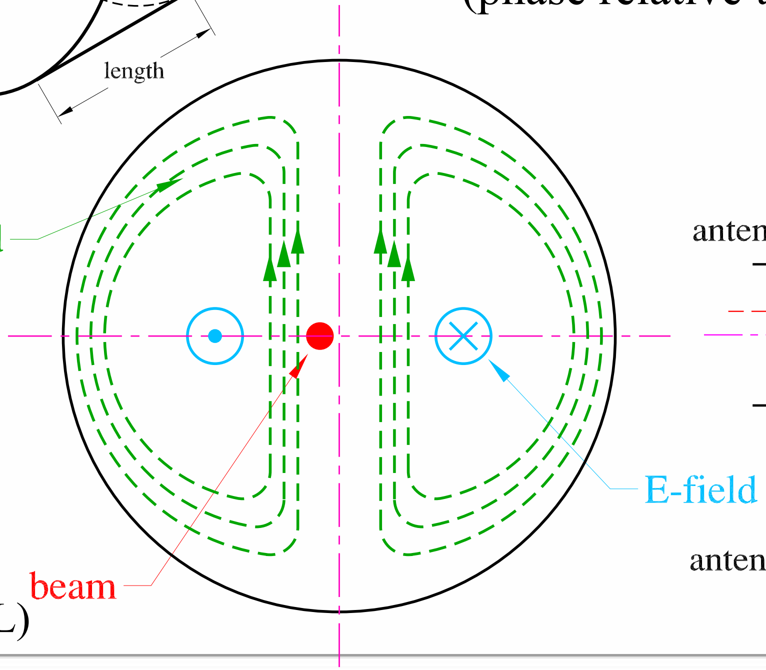


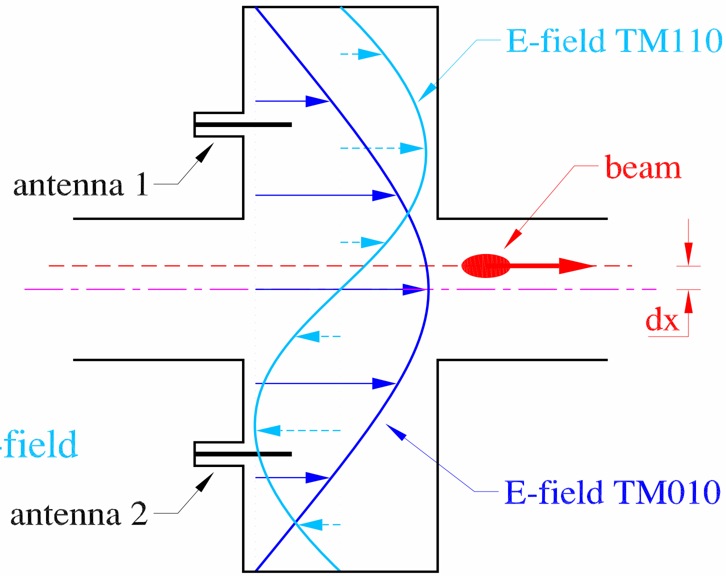
For pill box the resonator modes given by geometry:

- monopole TM_{010} with f_{010}
  → maximum at beam center ⇒ strong excitation
- Dipole mode TM_{011} with f_{011}
  → minimum at center ⇒ excitation by beam offset

⇒ Detection of dipole mode amplitude

(phase relative to monopole gives sign of displacement)



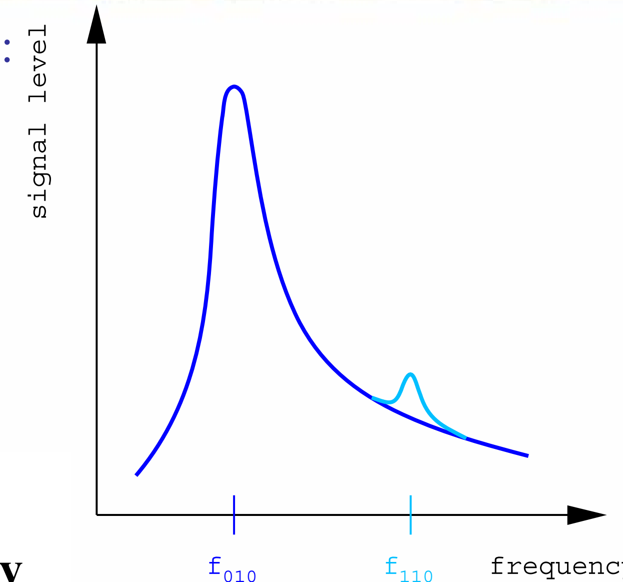


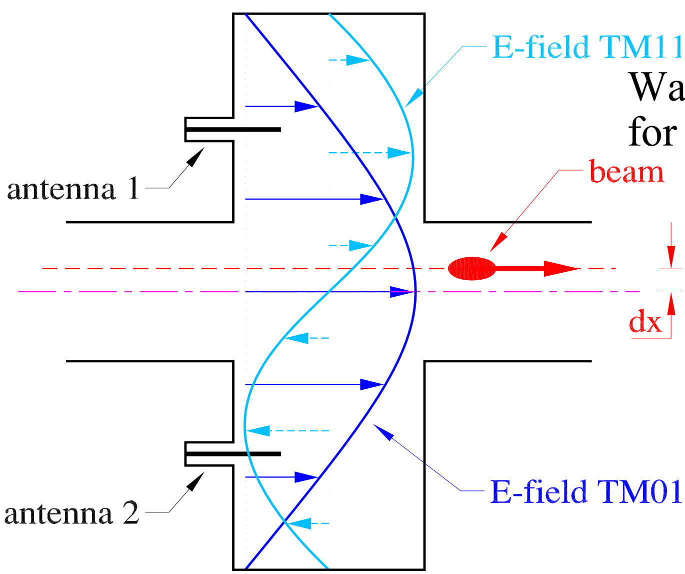
From
M. Wendt (FNAL)

Cavity BPM

Basic consideration for detection of eigen-frequency amplitudes:

- Monopole mode f_{010} should differ from f_{rf}
- Dipole mode f_{110} separated from monopole mode
  due to finite quality factor $Q \Rightarrow \Delta f = f/Q$
- Waveguide house the antennas
  (task: suppression of TM_{010} mode signal)
- Frequency range $f_{110} \approx 1 \ldots 10$ G





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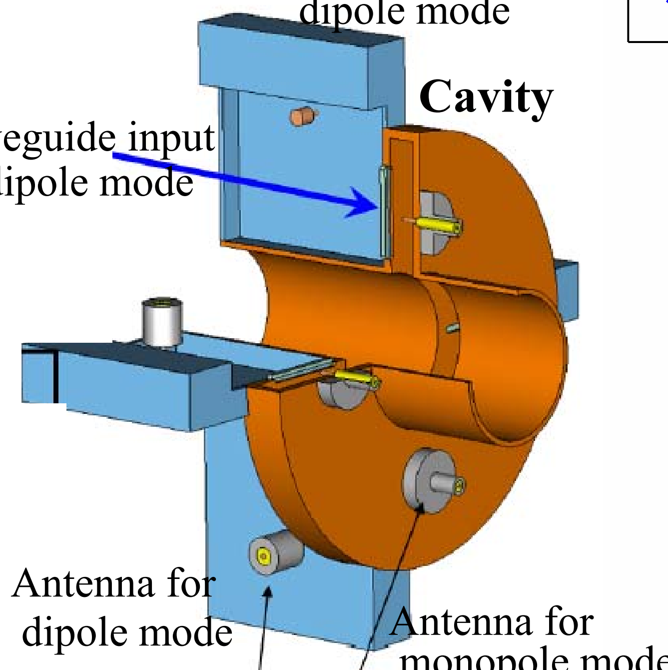

FNAL BPM develop.

Cavity: ∅ 113 mm

Gap length 15 mm

Mono. f_{010}=1.12 GHz

Dipole. f_{110}=1.47 GHz

$Q_{load} \approx 600$

With comparable BPM

⇒0.1 µm resolution within 1 µs

Comparison of BPM Types (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Shoe-box	p-Synch.	Long bunches f_{rf}<10 MHz	Very linear No x-y coupling Sensitive For broad beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	f_{rf}>10 MHz	Simple mechanics	Non-linear, x-y coupling Possible signal deformation
Stipline	colliders p-Linacs all e^- acc.	best for β≈1, short bunches	Directivity 'Clean' signals Large Signal	Complex 50 Ω matching Complex mechanics
Ind. WCM	all	non	Broadband	Complex, long insertion
Cavity	e^- Linacs (e.g. FEL)	Short bunches Special appl.	Very sensitive	Very complex, high frequency

Remark: Other types are also some time used, e.g. inductive antenna based, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.

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Detector Principle, Hardware and Electronics

Outline:

- *Signal generation $\rightarrow$ transfer impedance*
- *Consideration for capacitive shoe box BPM*
- *Consideration for capacitive button BPM*
- *Other BPM principles: stripline $\rightarrow$ traveling wave, inductive $\rightarrow$ wall current, cavity $\rightarrow$ resonator for dipole mode*
- ***Electronics for position evaluation***
  Noise consideration, broadband and narrowband analog processing, digital processing
- ***Some examples for position evaluation and other applications***
- ***Summary***

Characteristics for Position Measurement

Sensitivity: Factor between position calculation and signal quantity (Δ/Σ, $\log U_1/U_2$ etc)

Accuracy: Ability for position reading relative to a mechanical fix-point ('absolute position')

- influenced by mechanical tolerances and alignment accuracy
- for cryogenic installations: reproducibility after cryogenic cycles
- by electronics: e.g. amplifier drifts, electronic interference, ADC granularity

Resolution: Ability to determine small displacement variation ('relative position')

- typically: ***single bunch***: 10^{-3} of aperture $\approx$ 100 µm

  averaged: 10^{-5} of aperture $\approx$1 µm, with dedicated methods $\approx$0.1 µm
- in most case much better than accuracy!
- electronics has to match the requirements e.g. bandwidth, ADC granularity…

Bandwidth: Frequency range available for measurement

- has to be chosen with respect to required resolution via analog or digital filtering

Signal-to-noise: Ratio of wanted signal to unwanted background

- influenced by thermal and circuit noise, electronic interference
- can be matched by bandwidth limitation

Dynamic range: Range of beam currents the system has to respond

- position reading should not depend on input amplitude

Signal sensitivity = detection threshold: minimum beam current for measurement

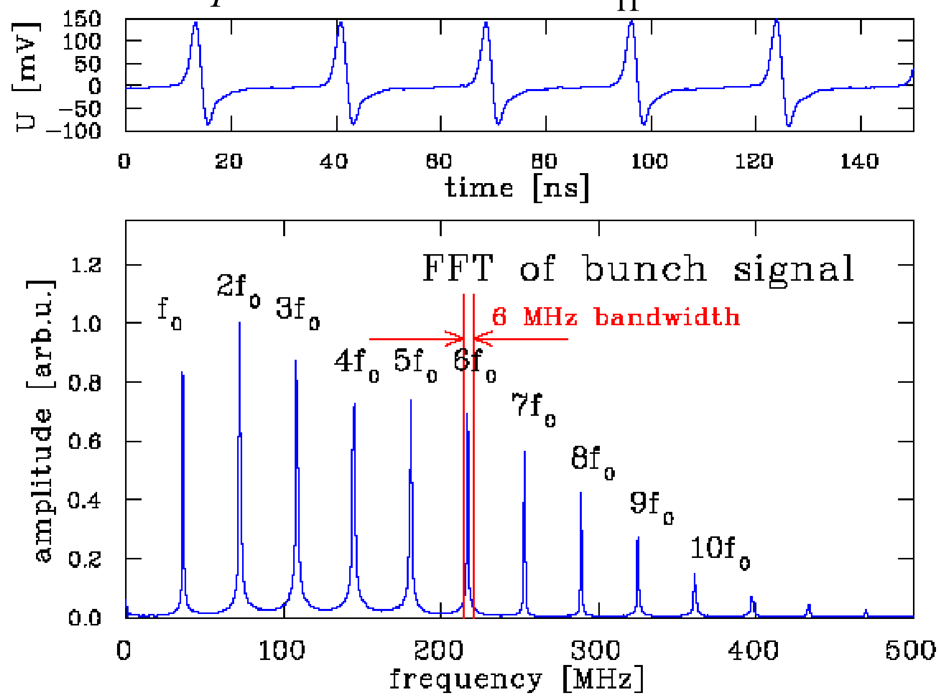
General: Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Position information from voltage difference: $x \propto k \cdot U_{\Delta}$
3. Thermal noise voltage given by: $U_{eff}(R, \Delta f) = \sqrt{4 k_B \cdot T \cdot R \cdot \Delta f}$

⇒ Signal-to-noise U_{im}/U_{eff} is influenced by:

- Input signal amplitude
  → large or matched Z_t
- Thermal noise at R=50Ω for T=300K
  (for shoe box R=1kΩ …1MΩ)
- Bandwidth Δf
  ⇒ Restriction of frequency width because the power is concentrated on the harmonics of f_{rf}

Example: GSI-LINAC with f_{rf}=36 MHz

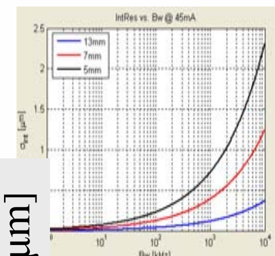


Remark: Additional contribution by non-perfect electronics typically a factor 2
Pick-up by electro-magnetic interference can contribute ⇒ good shielding required

Example for Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Thermal noise voltage given by: $U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$
3. Signal-to-noise ratio has to be calculated and expressed in spatial resolution σ

Example for button BPM resolution at ALBA: **Estimation takes *only* thermal noise into account**:



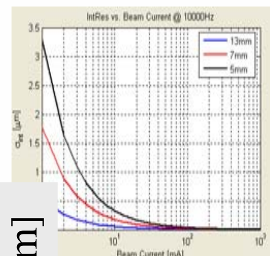
Resolution σ [µm]

Bandwidth [Hz]

∅ button

⇒ $\sigma \propto \sqrt{\Delta f}$

⇒ Lower σ for large ∅button



Resolution σ [µm]

Beam Current [mA]

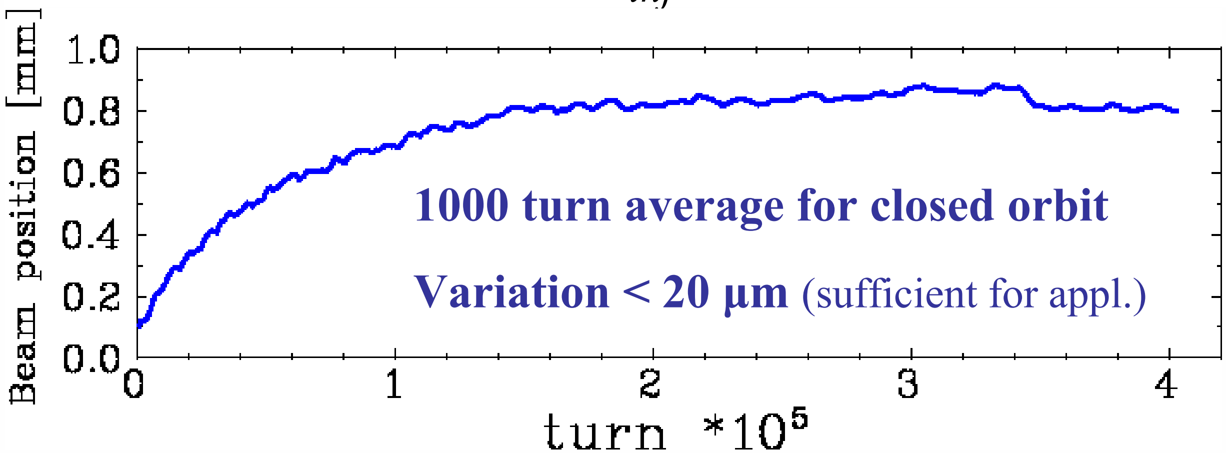
⇒ σ deceases with current

⇒ Lower σ for large ∅button

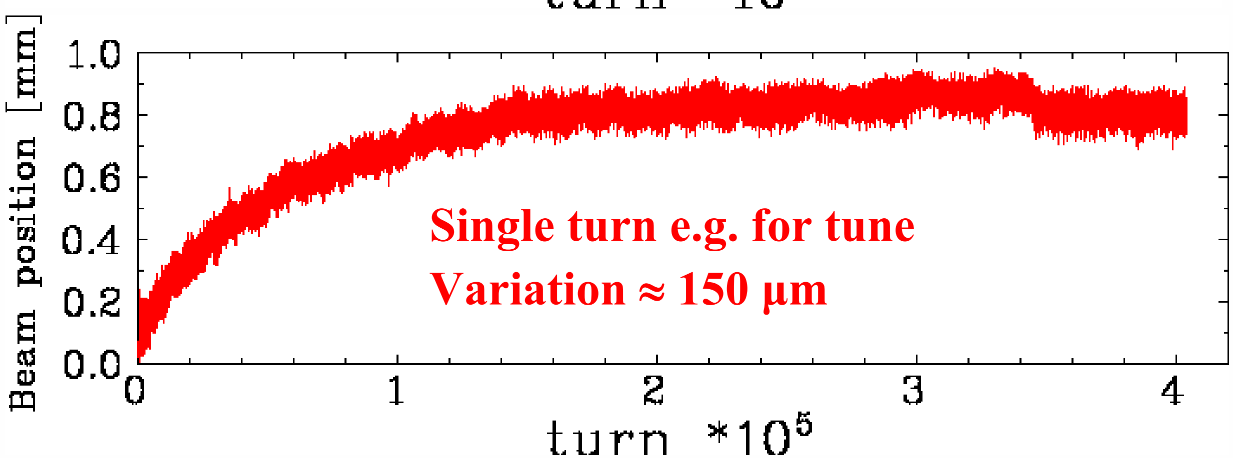
From A. Olmos (ALBA) DIPAC 2007

Comparison: Filtered Signal ↔ Single Turn

Example GSI Synchr.: U^{73+}, E_{inj}=11.5 MeV/u→ 250 MeV/u within 0.5 s, 10^9 ions



- Position resolution < 20 µm (BPM half aperture a=40 mm)
- average over 1000 turns corresponding to ≈0.3 ms or ≈1 kHz bandwidth

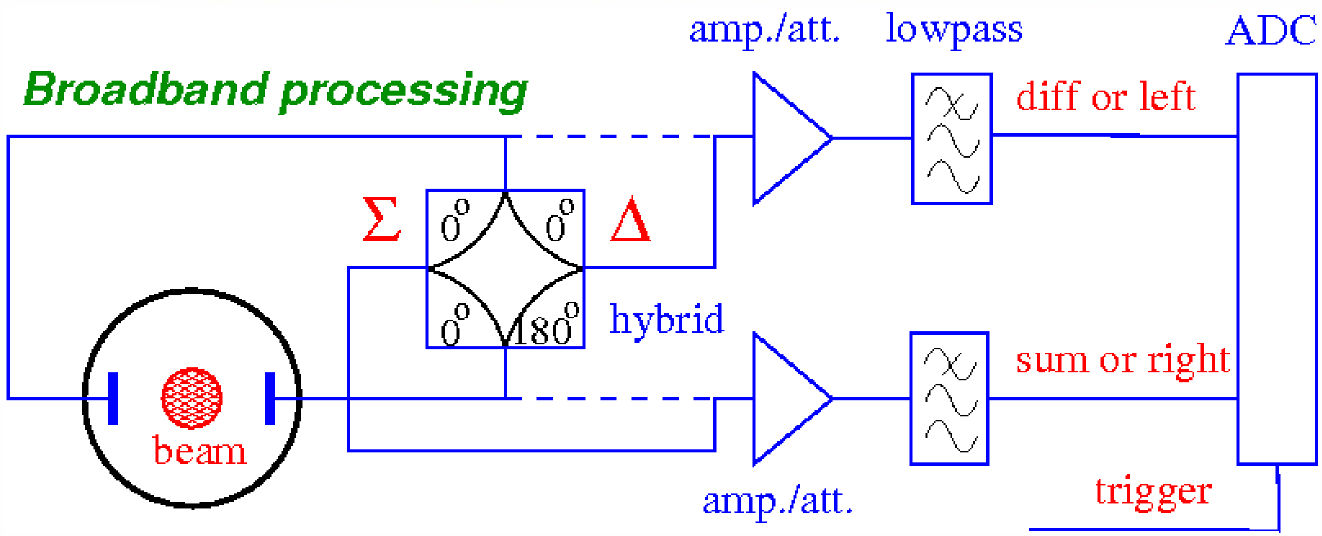


- Turn-by-turn data have much larger variation

However: not only noise contributes but additionally **beam movement** by betatron oscillation

⇒ broadband processing i.e. turn-by-turn readout for tune determination

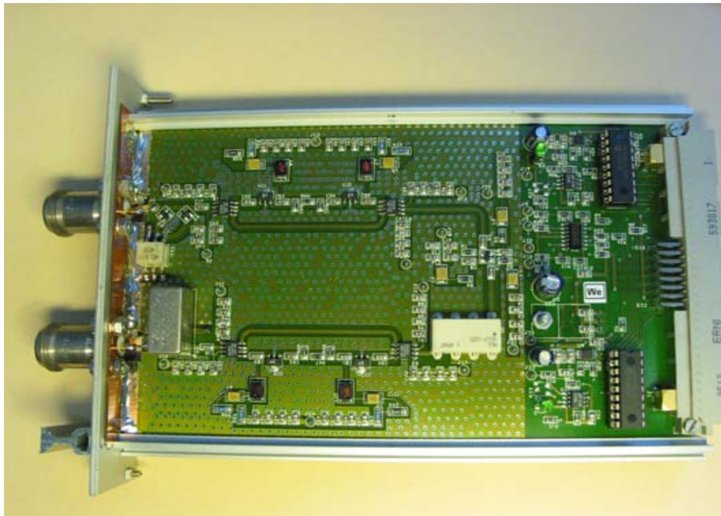
General Idea: Broadband Processing

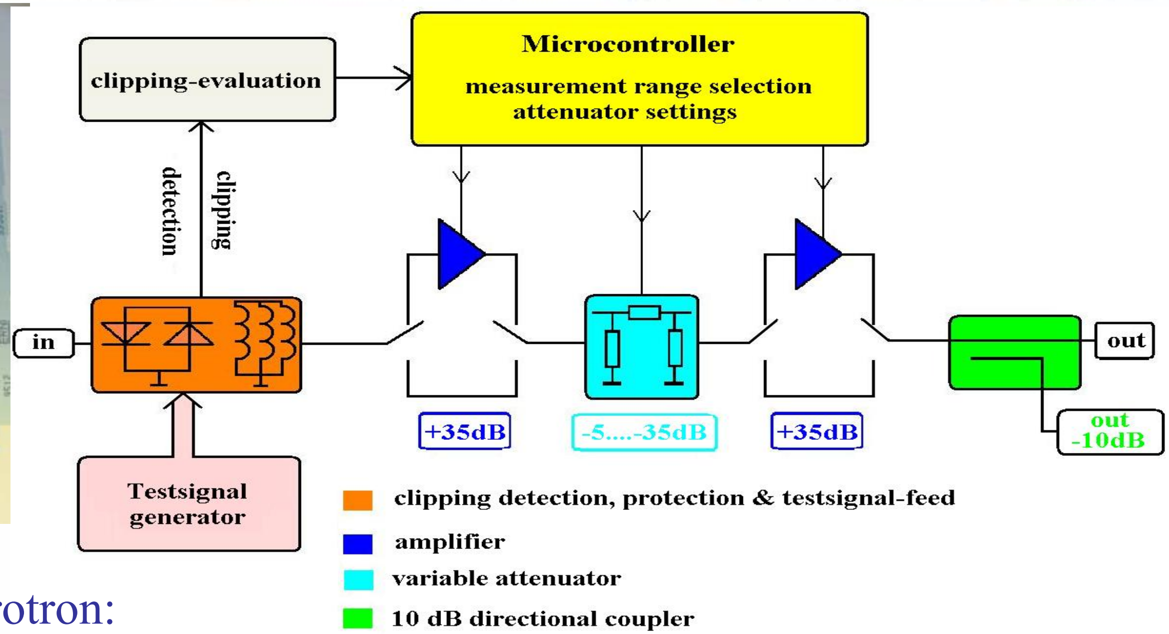


- Hybrid or transformer close to beam pipe for analog U_Δ & U_Σ generation or U_{left} & U_{right}
- Attenuator/amplifier
- Filter to get the wanted harmonics and to suppress stray signals
- ADC: digitalization of U_Δ /U_Σ or calculation from U_{left} & U_{right}

Advantage: Bunch-by-bunch possible, versatile post-processing possible

Disadvantage: Resolution down to ≈ 100 μm for shoe box type , i.e. ≈0.1% of aperture, resolution is worse than narrowband processing.



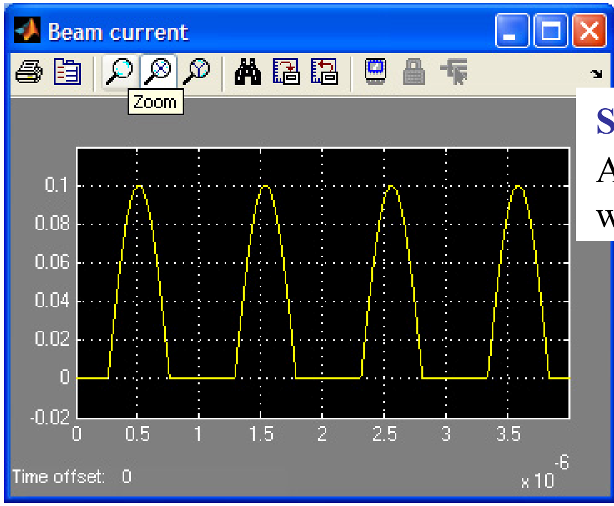


Example: pre-amp from GSI-synchrotron:

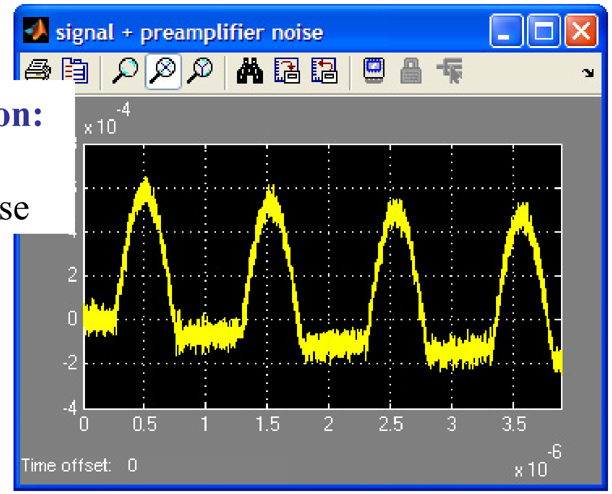
Shoe box BPM → matching 2:12 transformer R_{prim}=1.8kΩ→ ≈3 m cable → amplifier

- Requirement: Dynamic range from $1x10^8$ to $4x10^{13}$ charges per bunch
  ⇒ 120dB dynamic range of signal amplitude
- Switchable 35dB amplifier stages, bandwidth 0.2 to 100 MHz.
- Variable PIN-diode attenuator -5dB…-35dB.
- Test generator input for control of constant gain and temperature drift calibration
- Common mode gain matching better than 0.1dB each BPM-plate pair for large accuracy

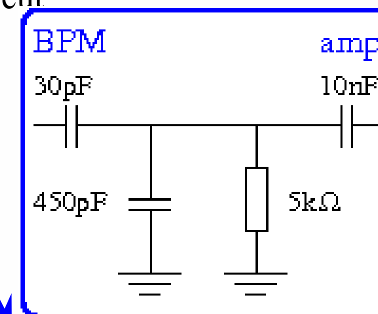
Goal of lowpass filter: restriction of bandwidth to the required resolution for the bunches

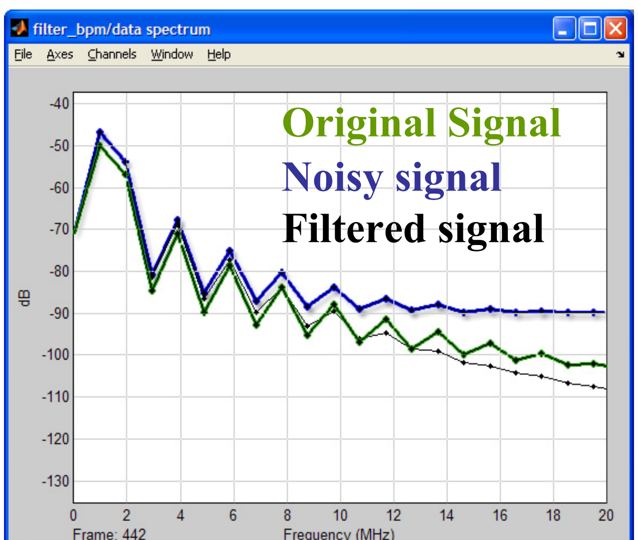


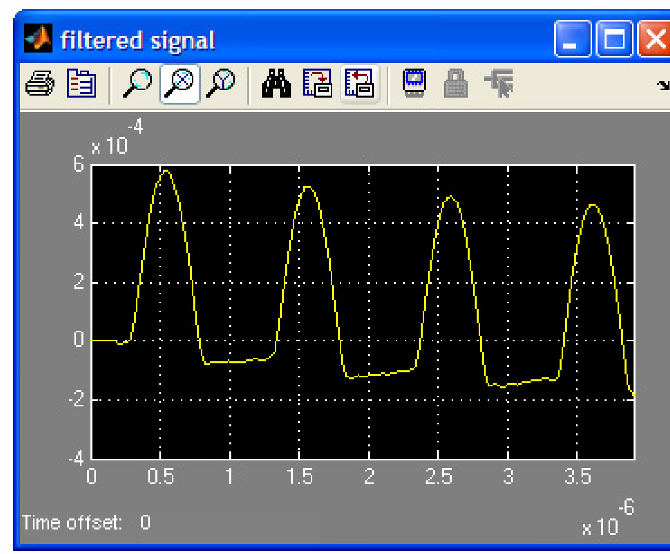
Simulation:
Adding white noise



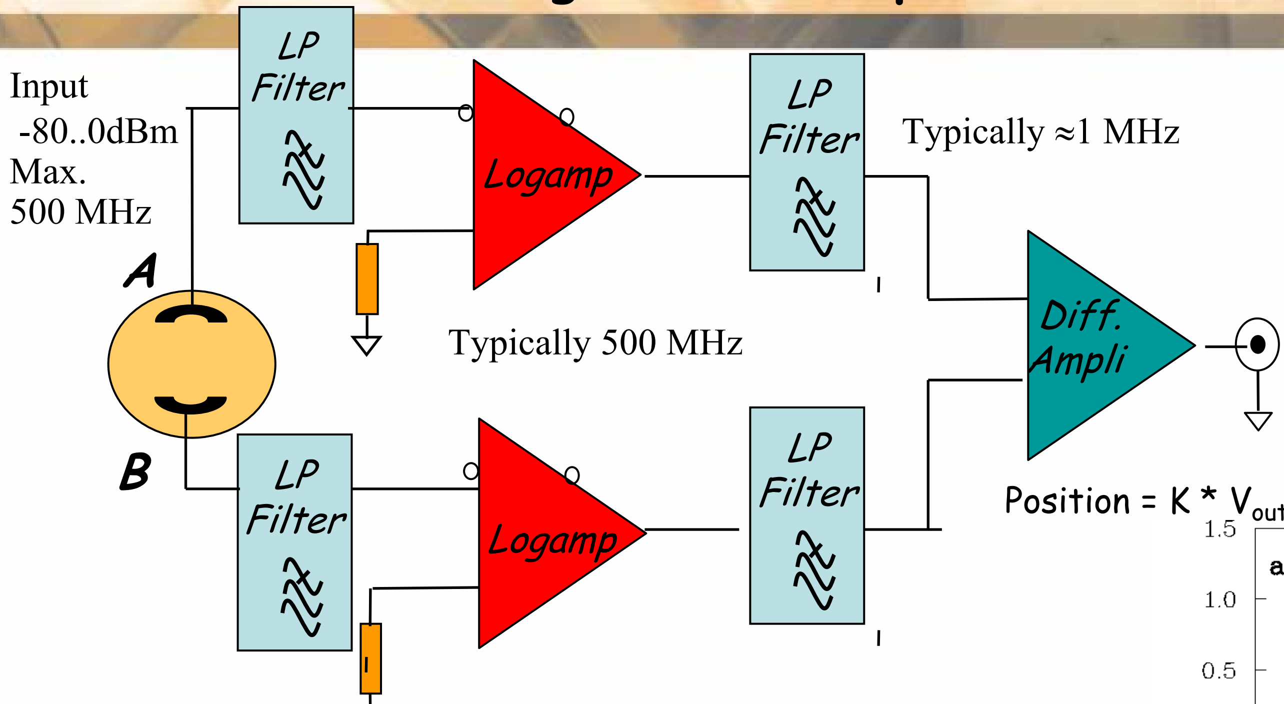
Lowpass Filter:
Besselfilter of 3rd order
f_{cut}= 10 MHz

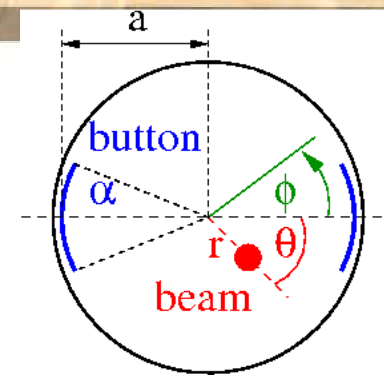


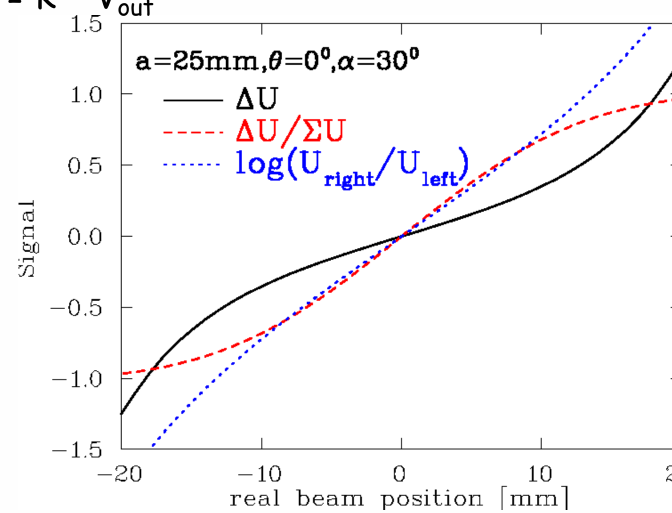




Logarithmic Amplifier Schematics







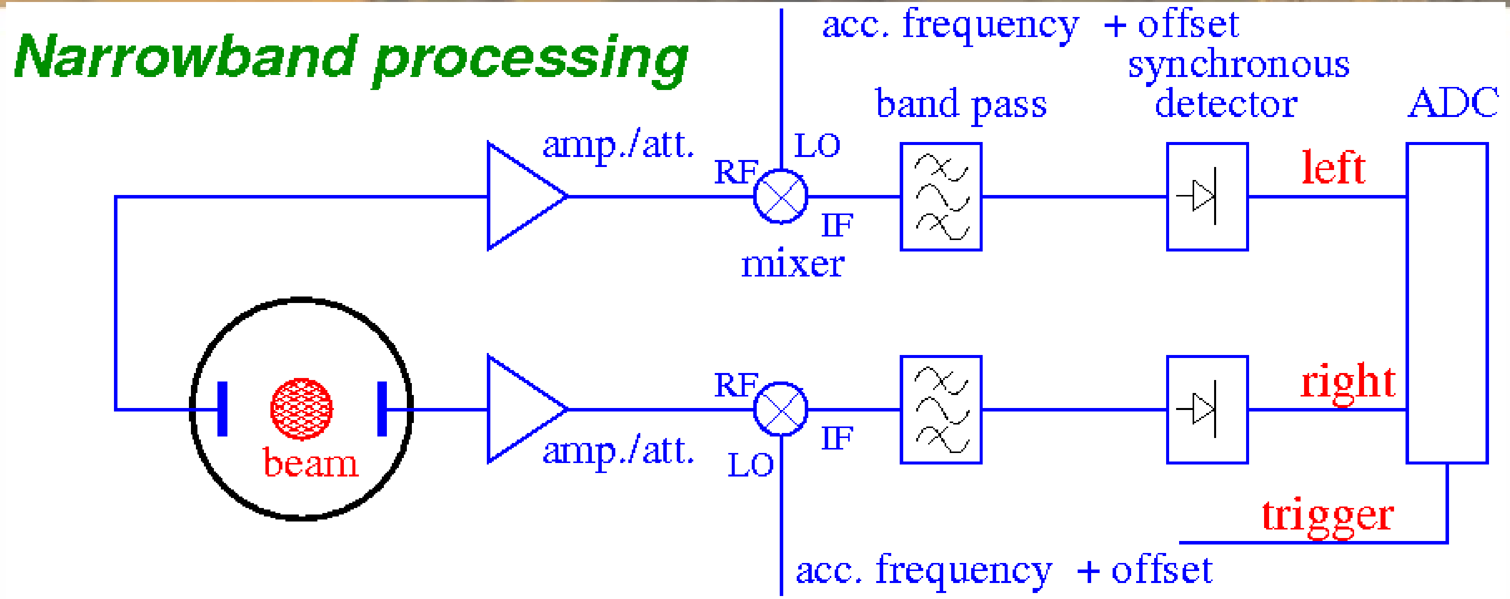
- Signal is 'compressed' by a logarithmic amplifier, filtered and applied to a differential amplifier.
- Typical video bandwidth ≈1MHz
- Position: $x = k\cdot[log(A/B)] \equiv k\cdot[log(A)\text{-}log(B)] = k\cdot V_{out}$

Advantage: Improved linearity for button, broadband robust electronics, large ≈90 dB dynamics range without gain switching

Disadvantage: limited linearity and accuracy, possible temperature dependence

Log-amp card ready for BPM use is commercially available!

General Idea: Narrowband Processing



Narrowband processing equals heterodyne receiver (e.g. at AM-radios or spectrum analyzer)

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with sum and difference frequency
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digital calculation of $\Delta U/\Sigma U$

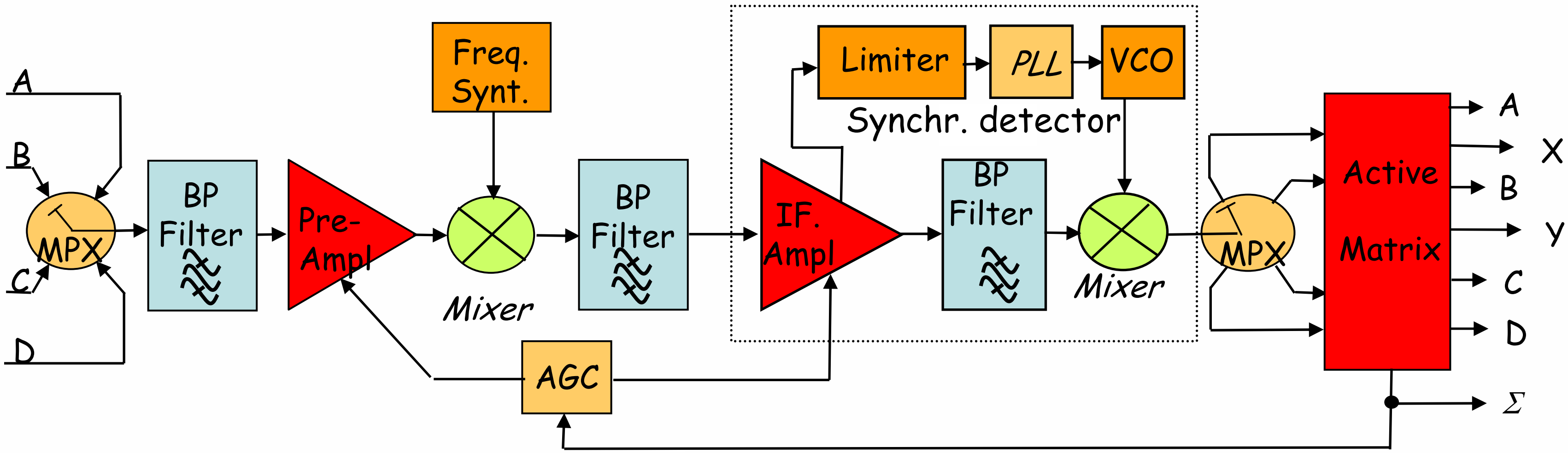
Advantage: spatial resolution about 100 time better than broadband processing.

Disadvantage: No turn-by-turn diagnosis, due to mixing = 'long averaging time'

For non-relativistic p-synchrotron → variable f_{rf} leads via mixing to constant intermediate freq.

Narrowband Processing with Multiplexing

Dedicated analog electronics for narrowband processing on one card (commercially available):



Idea: narrowband processing, all buttons at same path ⇒ multiplexing of single electronics chain

Multiplexing within ≈1ms: ⇒ only one button is processed ⇒ minimal drifts contribution

Processing chain: Buttons → multiplexer → filter → linear amplifier with fine gain steps
→ mixing with f_{rf} → narrow intermediate frequency filter BW 0.1 ….1 MHz
→ synchronous detector for rectification → de-multiplexer → slow and precise ADC

Advantage: High accuracy, high resolution, high dynamic range by automated gain control AGC

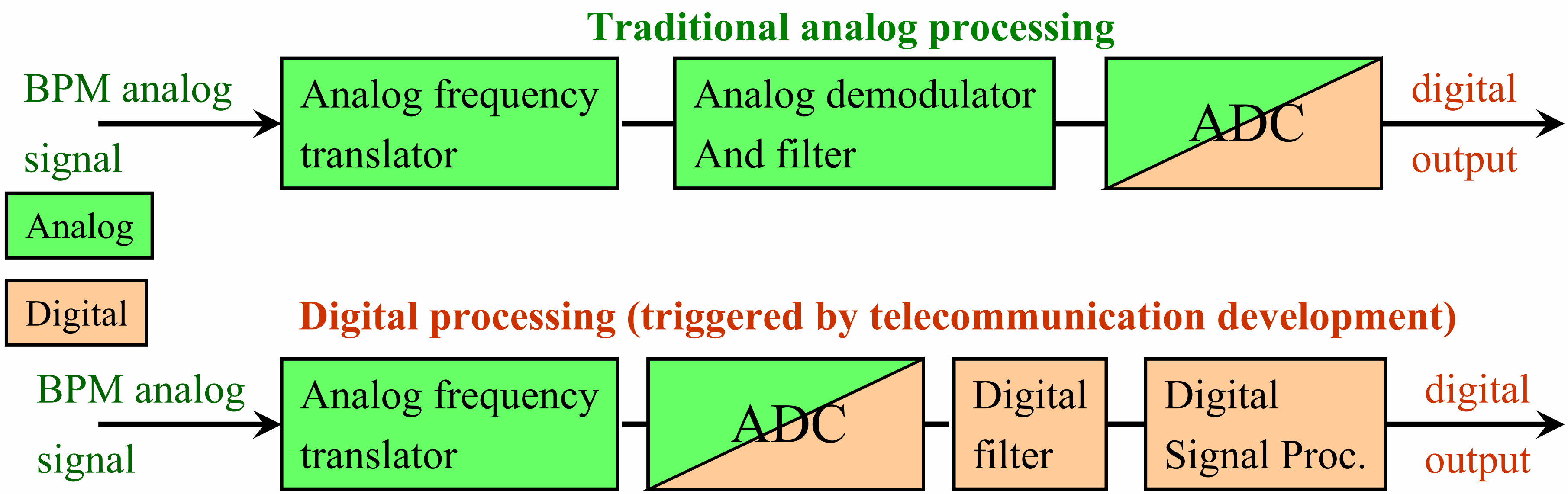
Disadvantage: Multiplexing ⇒ only for stable beams >> 10 ms, narrowband ⇒ no turn-by-turn

Remark: 'Stable' beam e.g. at synch. light source, but not at accelerating synchrotrons!

P From G. Vismara, CERN, DIPAC 1999

Analog versus Digital Signal Processing

Modern instrumentation uses **digital** techniques with extended functionality.



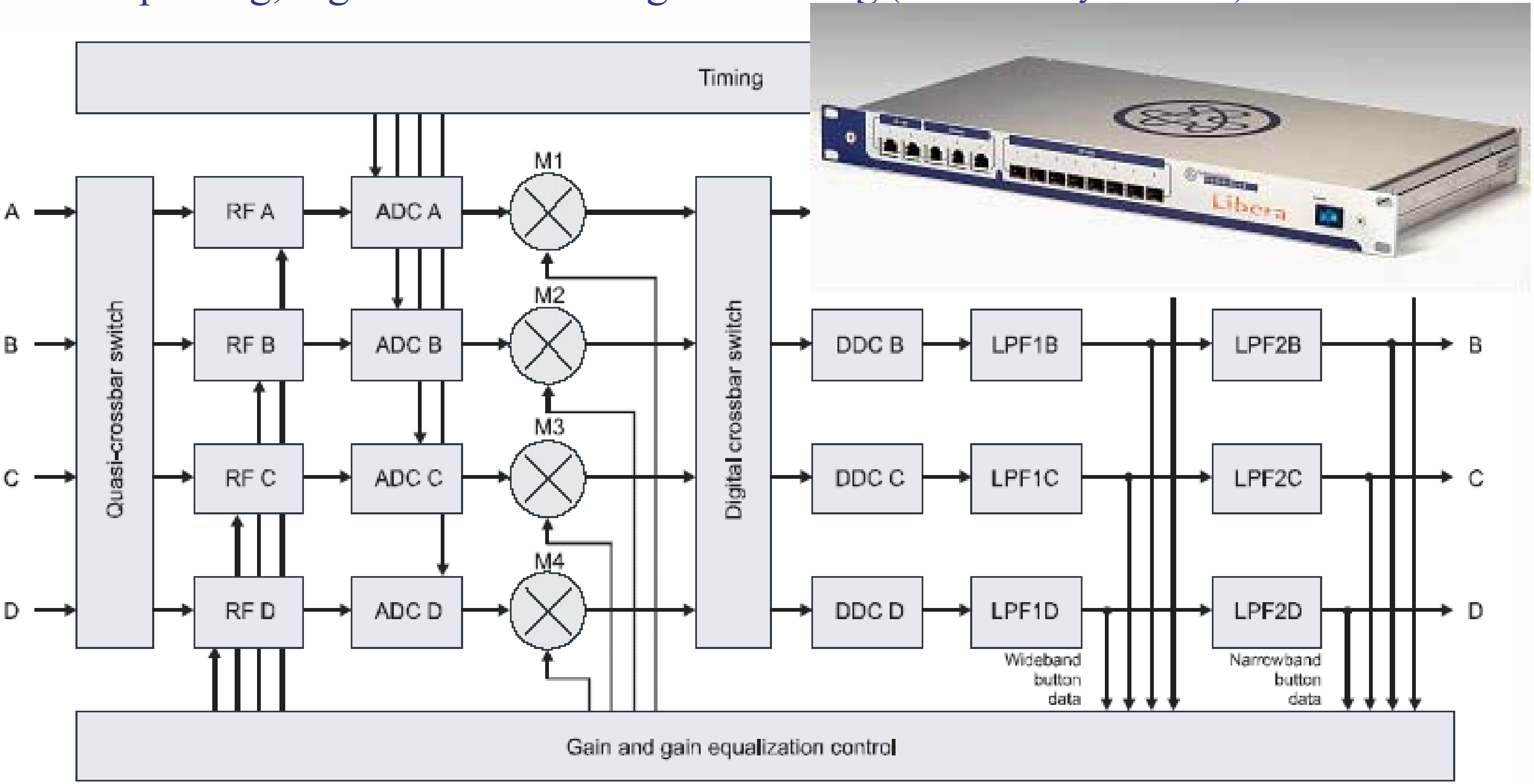
Digital receiver as modern successor of heterodyne receiver

- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier&filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

Advantage of DSP: Stable operation, flexible adoption without hardware modification

Disadvantage of DSP: non, good engineering skill requires for development, expensive

Multiplexing, digitalization and digital filtering (commercially available):

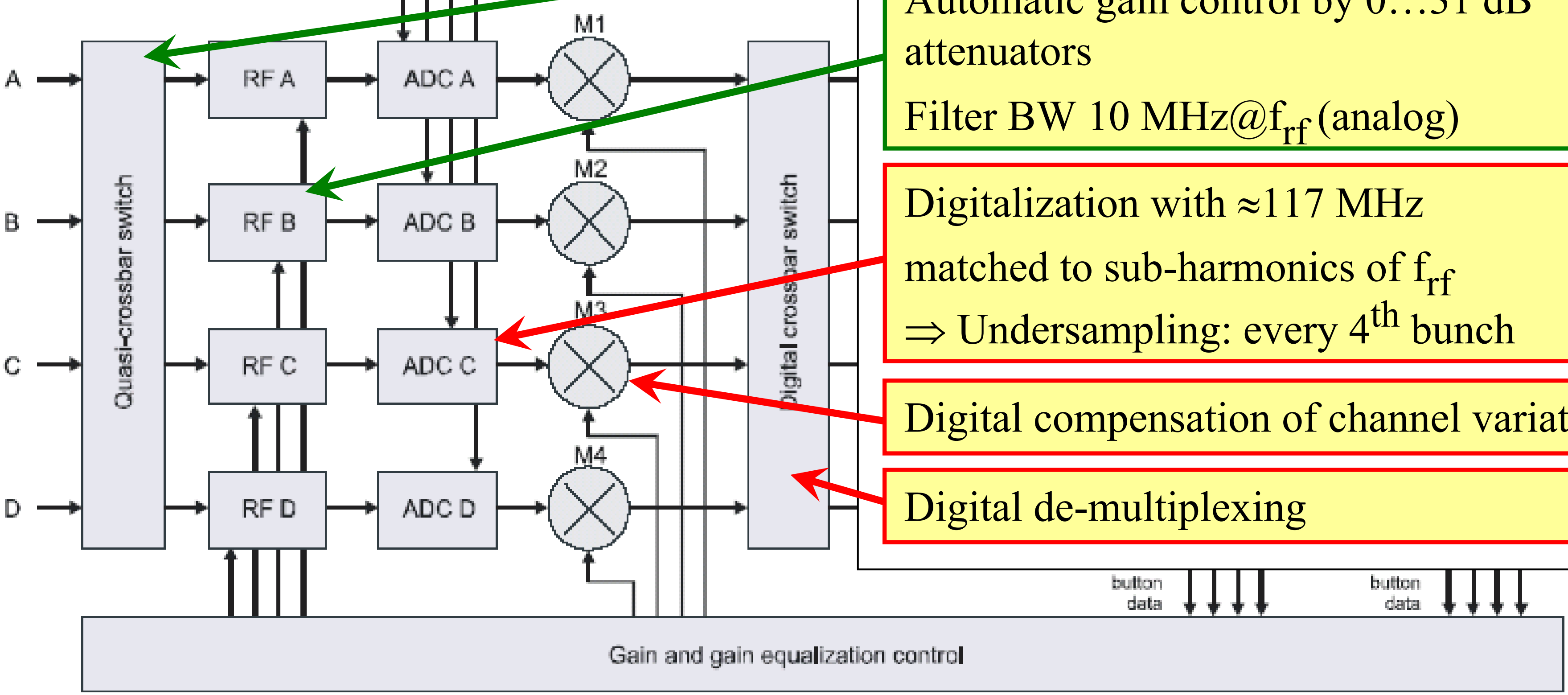


From I-Tech LIBERA Specification

LIBERA Digital BPM Readout: Analog Part and Digitalization

Timing for Synchrotron Light Source:

f_{rf}=352 or 500 MHz, revolution $f_{rev}\approx$1 MHz



Crossbar multiplexing of **all** channels at ≈13 kHz (analog)

Automatic gain control by 0…31 dB attenuators

Filter BW 10 MHz@f_{rf} (analog)

Digitalization with ≈117 MHz matched to sub-harmonics of f_{rf}

⇒ Undersampling: every 4th bunch

Digital compensation of channel variation

Digital de-multiplexing

From I-Tech LIBERA Specification

LIBERA Digital BPM Readout: Digital Signal Processing

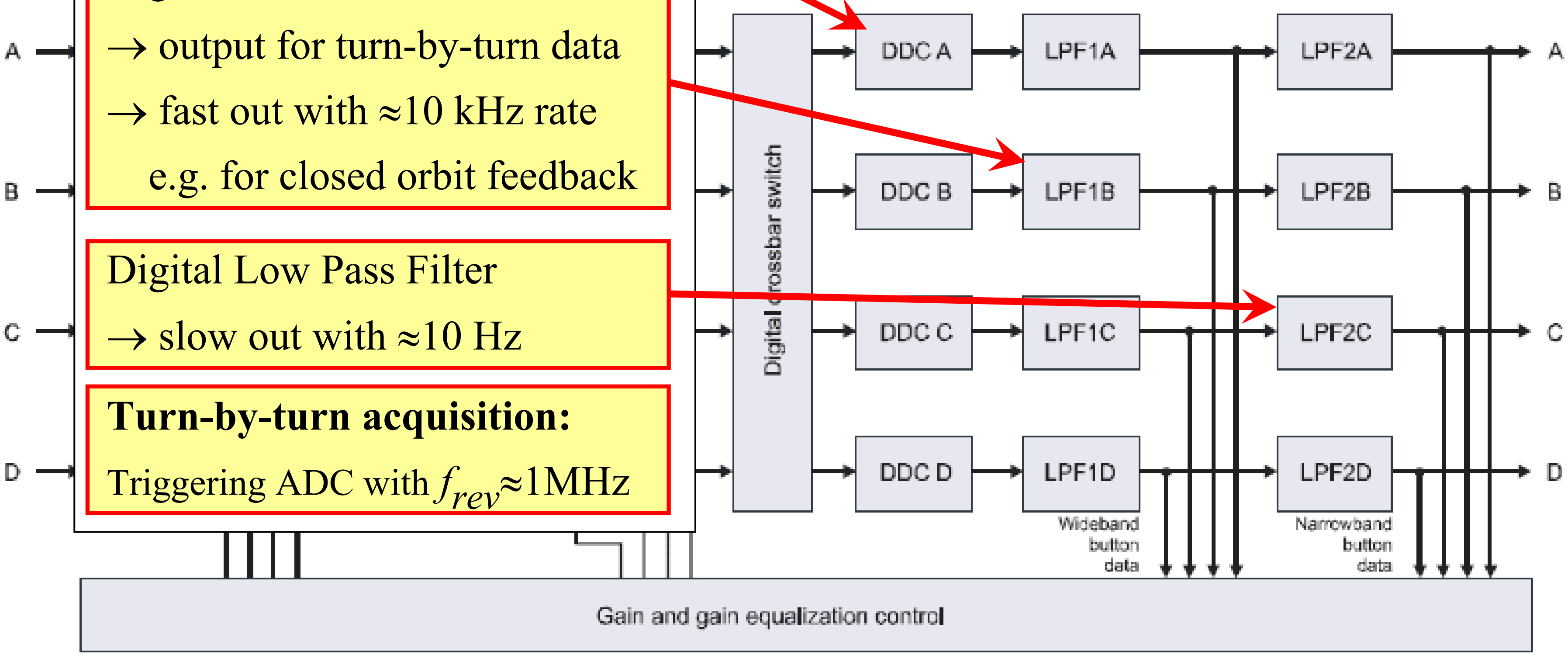
Digital Down Conversion for data reduction

Digital Low Pass Filter
→ output for turn-by-turn data
→ fast out with ≈10 kHz rate
e.g. for closed orbit feedback

Digital Low Pass Filter
→ slow out with ≈10 Hz

Turn-by-turn acquisition:
Triggering ADC with $f_{rev} \approx 1$MHz

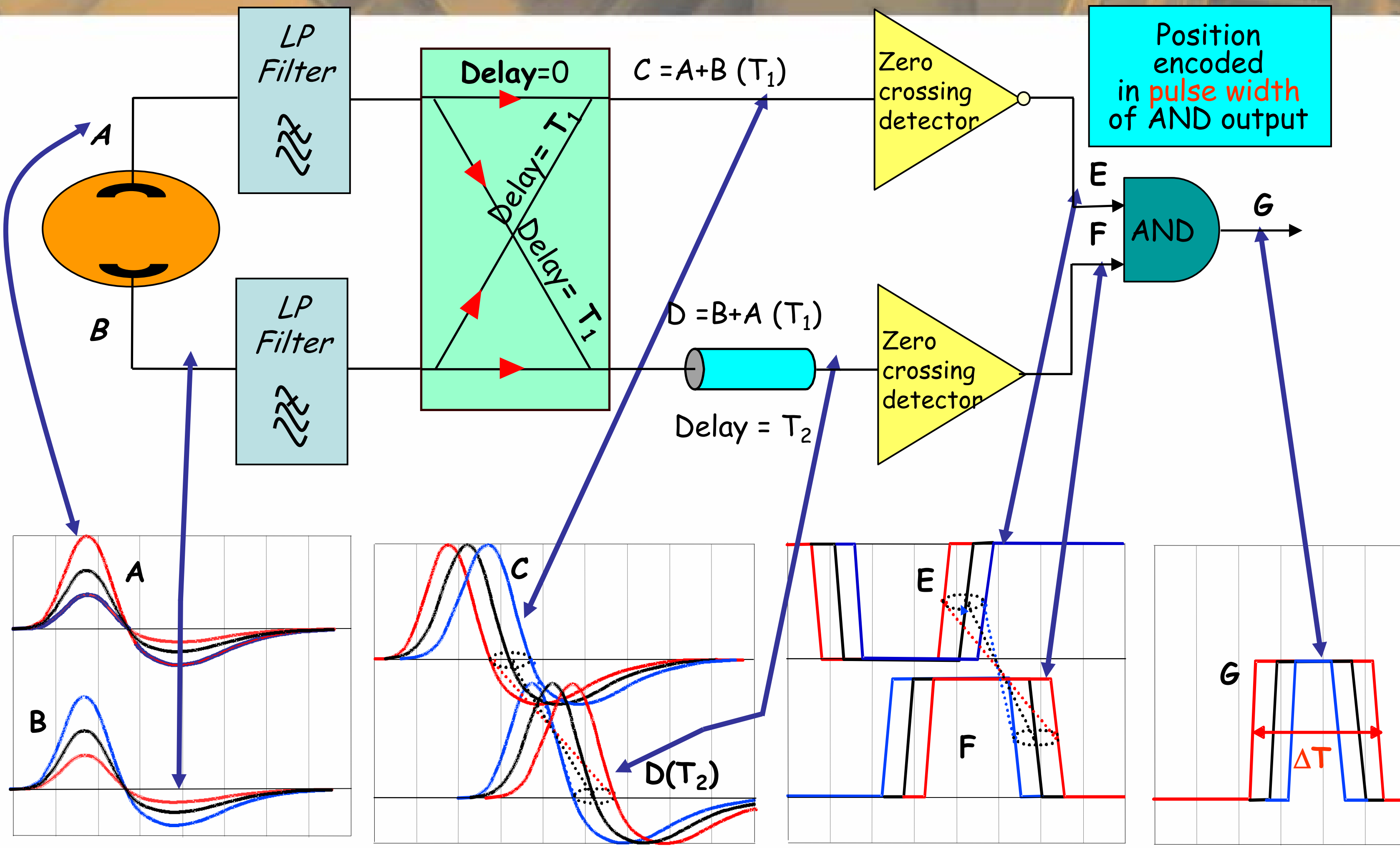
Timing for Synchrotron Light Source:
f_{rf}=352 or 500 MHz, revolution $f_{rev} \approx 1$ MHz



Remark: For p-synchrotrons direct 'baseband' digitalization with 125 MS/s due to f_{rf}<10 MHz

From I-Tech LIBERA Specification

Amplitude-to-Time Normalizer Schematics



Remark: Design for LHC with f_{rf}=40 MHz and ≈900 locations
Partly comparable to traditional AM/PM modulation

From G. Vismara, CERN, DIPAC 1999

Amplitude-to-Time Normalizer Description

General functionality for Amplitude-to-time Normalizer:

- Bipolar signals A, B are split into two branches
- One branch is delayed by T_1
- The delayed signal of A is added to the direct branch of B and vice versa
- The zero crossing time depends on the signals ratio and varies in opposite directions for two branches; it can vary up to a maximum of T_1
- Zero-crossing detector converts to time $\rightarrow$ start of logical pulse $\Leftrightarrow$ zero crossing
- Delay of channel D by T_2
- AND produces time overlap of channel C and D
- Position information is given by $\Delta t = 2 * T_1 \, [(A - B)/(A + B)] + T_2$
- ***Requirement:*** Bunch separation $> T_1 + T_2$

Advantage: reduction of 2 channels and cables, high input dynamics, auto-trigger

Disadvantage: requires specialized and tightly time-adjusted electronics, no intensity signal

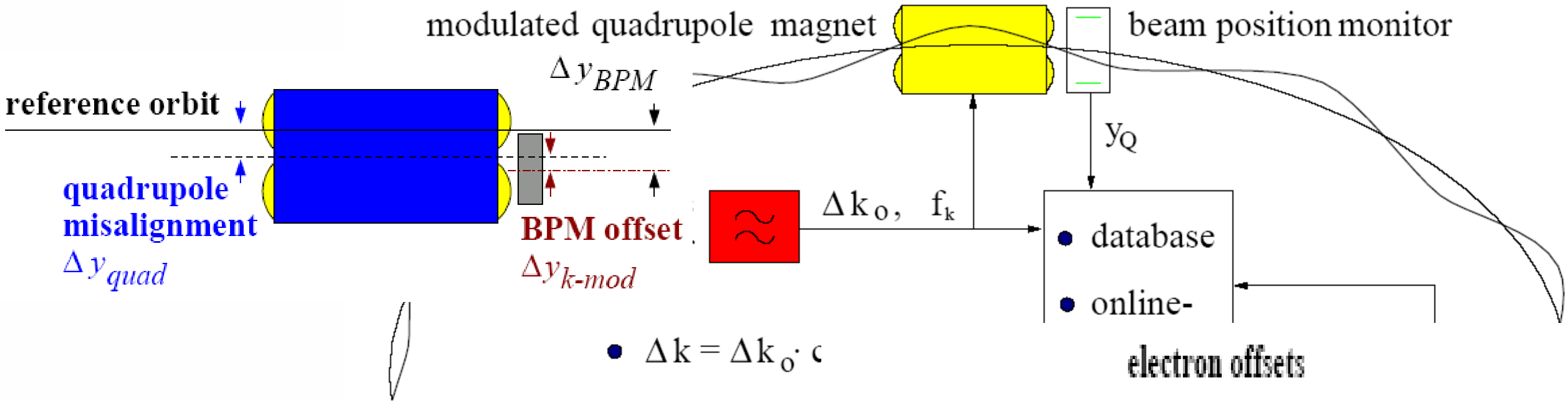
Remark:

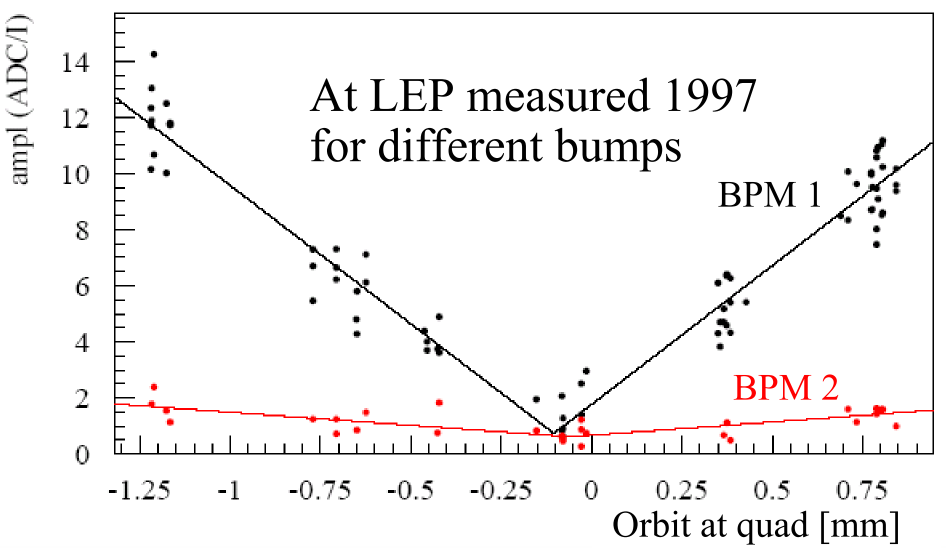
Comparison of BPM Readout Electronics (simplified)

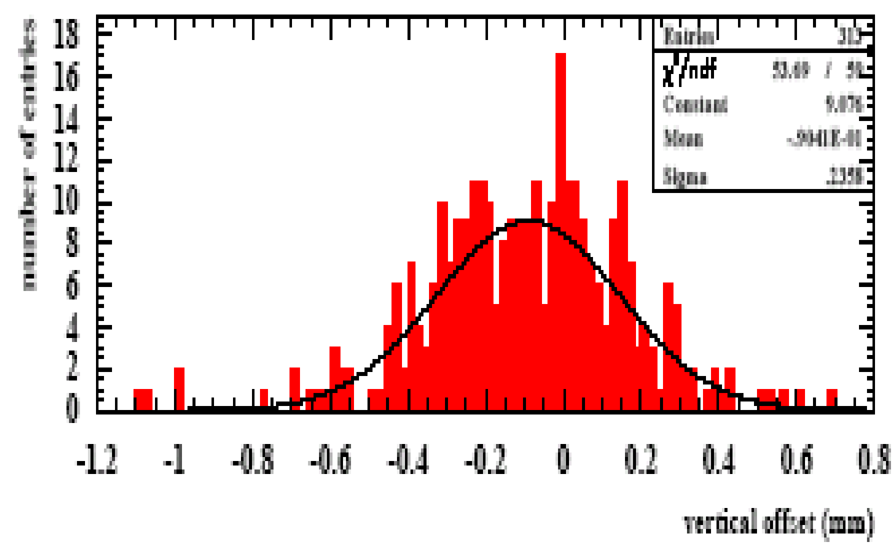
Type	Usage	Precaution	Advantage	Disadvantage
Broadband	p-sychr.	Long bunches	Bunch structure signal Post-processing possible Required for fast feedback	Resolution limited by noise
Log-amp	all	Bunch train >10μs	Robust electronics High dynamics Good for industrial appl.	No bunch-by-bunch Possible drifts (dc, Temp.) Medium accuracy
Narrowband	all synchr.	Stable beams >100 rf-periods	High resolution	No turn-by-turn Complex electronics
Narrowband +Multiplexing	all synchr.	Stable beams >10ms	Highest resolution	No turn-by-turn, complex Only for stable storage
Digital Signal Processing	all	Several bunches ADC 125 MS/s	Very flexible High resolution **Trendsetting technology for future demands**	Limited time resolution by ADC → undersampling (complex or expensive)
Ampl.-to-Time Normal. and AM→PM	(all)	Limited f_{rf} Low bunching factor	Only 2 channels High dynamics	Special electronics No intensity signal A bit exotic

The **accuracy** can be improved by 'k-modulation'

→alignment of the BPM with respect to the axis of the quadrupoles







Beam Position Monitor:
Detector Principle, Hardware and Electronics

Outline:

- *Signal generation $\rightarrow$ transfer impedance*
- *Consideration for capacitive shoe box BPM*
- *Consideration for capacitive button BPM*
- *Other BPM principles: stripline $\rightarrow$ traveling wave, inductive $\rightarrow$ wall current, cavity $\rightarrow$ resonator for dipole mode*
- *Electronics for position evaluation*
- ***Some examples for position evaluation and other applications closed orbit, tune, bunch capture, energy at LINAC***
- ***Summary***

Close Orbit Measurement

Detected position on a analog narrowband basis → closed orbit with ms time steps

Example from GSI-Synchrotron:

Detecting the bunch position on a turn-by-turn basis the tune can be determined:

Fourier transformation of position data

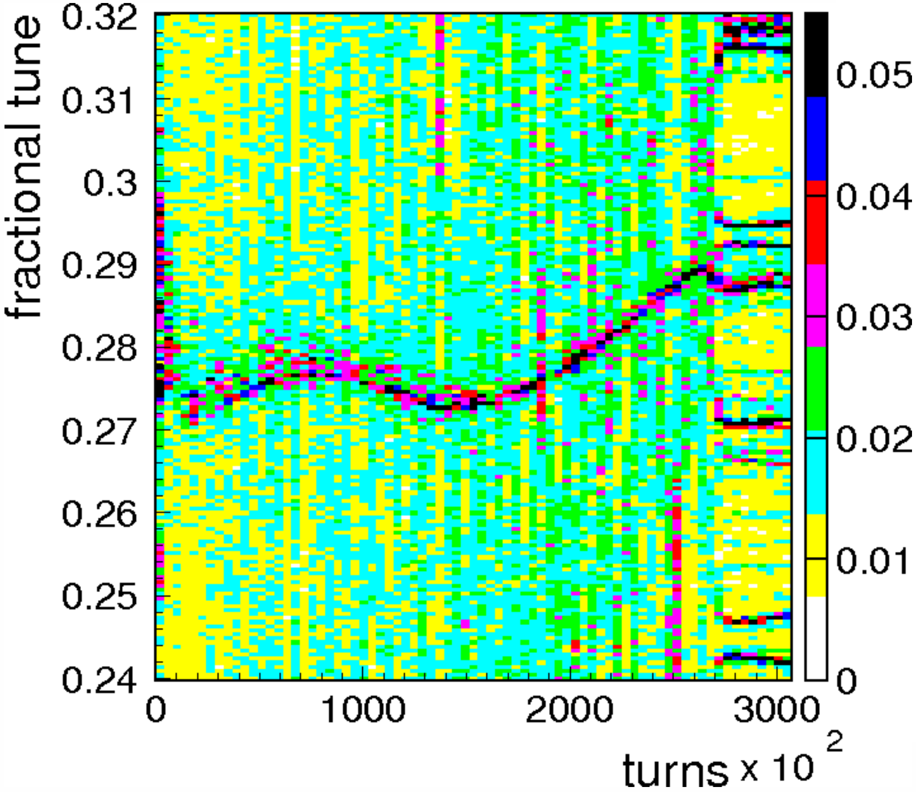
→ tune within 2000 turns corresponding ≈5 ms time resolution

Beam parameters at GSI Synchr.:

U^{73+} acc. 11 → 250 MeV/u

within 500 ms,

Noise excitation corresponding ΔQ=0.04 of power 1.5 W



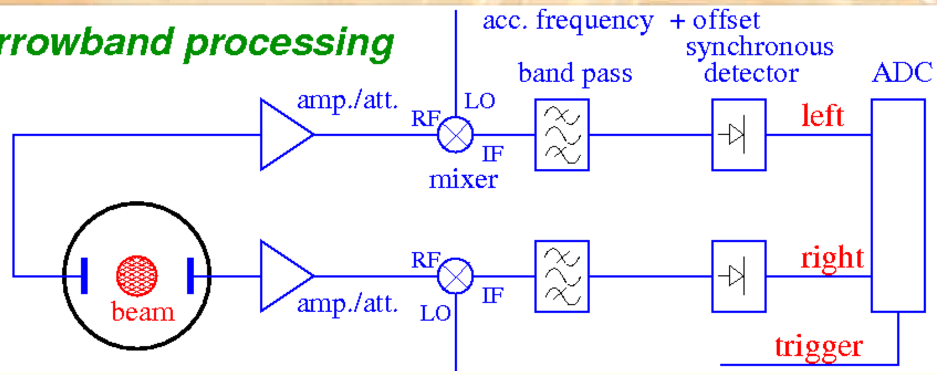
Form U. Rauch, GSI

The sensitivity of a BPM **Σ-signal** by **narrowband processing** is higher as for a dc-transformer (with ≈1 μA on 1 kHz bandwidth).

Sum-Signal after mixing with f_{rf}:

I_{beam}>10 nA on 1 kHz bandwidth

Narrowband processing



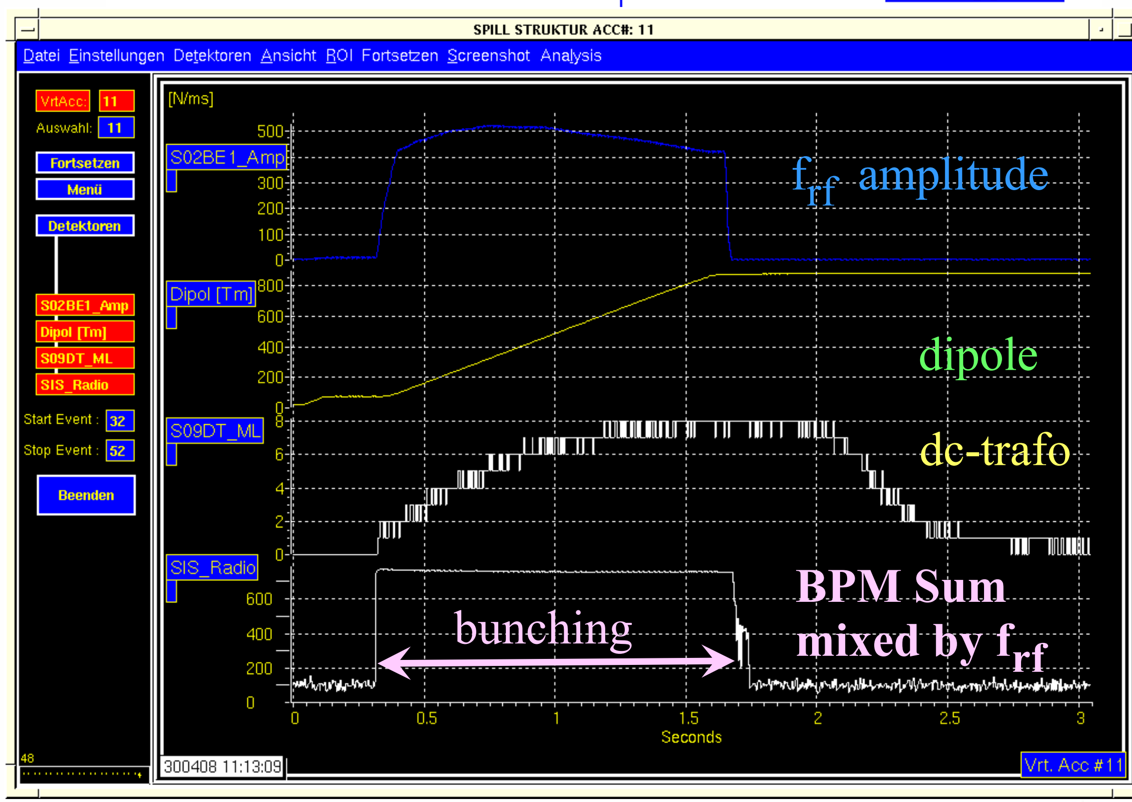
But:

- Only for bunched beams
- Only relative measurement:

→ Signal strength depend on bunch shape i.e. frequency component!

Beam parameter: U^{73+},

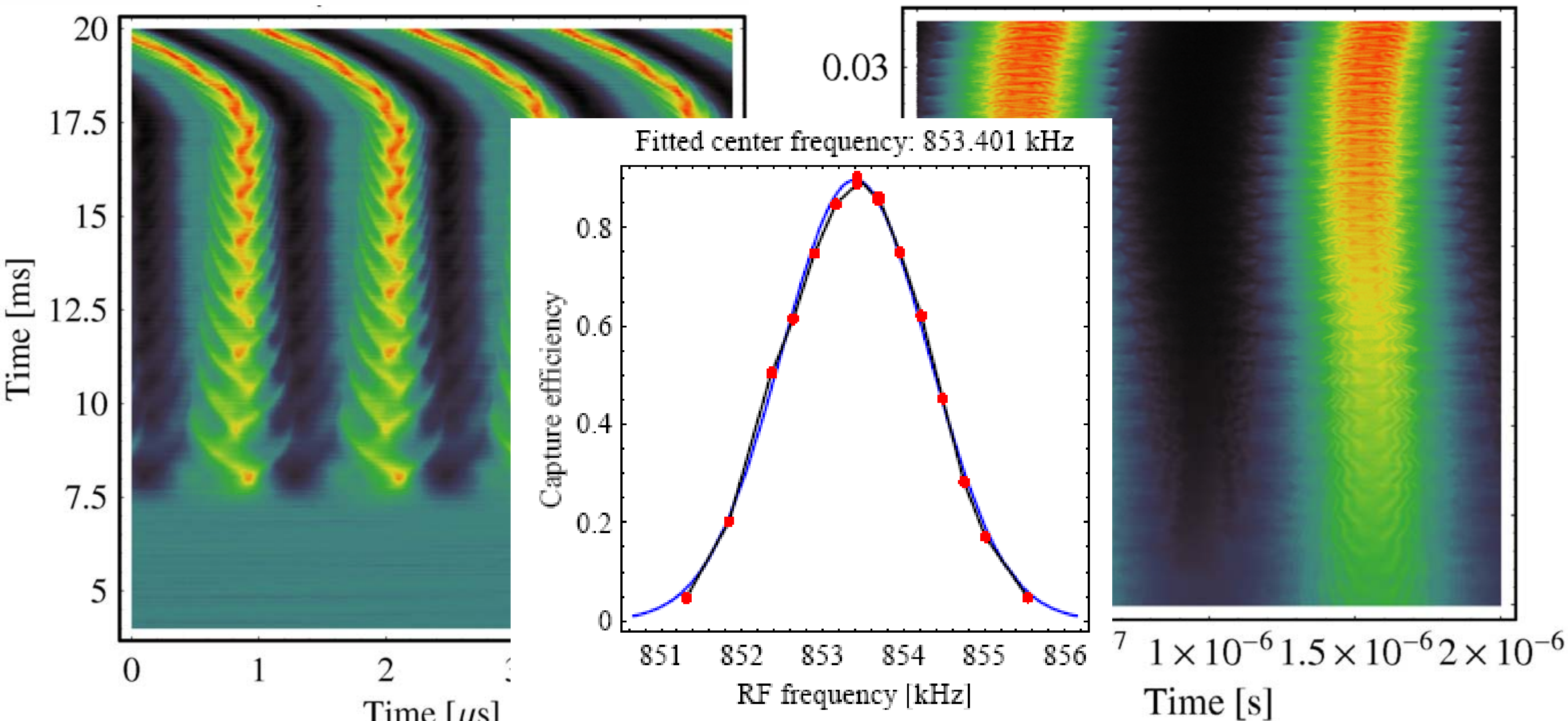
11 MeV/u →1 GeV/u



Example: After multi-turn injection, the **bunch formation** is critical to avoid coherent synchrotron oscillations → emittance enlargement

f_{rf} shift by 0.2% of nominal value
⇒ Coherent oscillation

Matched f_{rf} ⇒ no oscillation



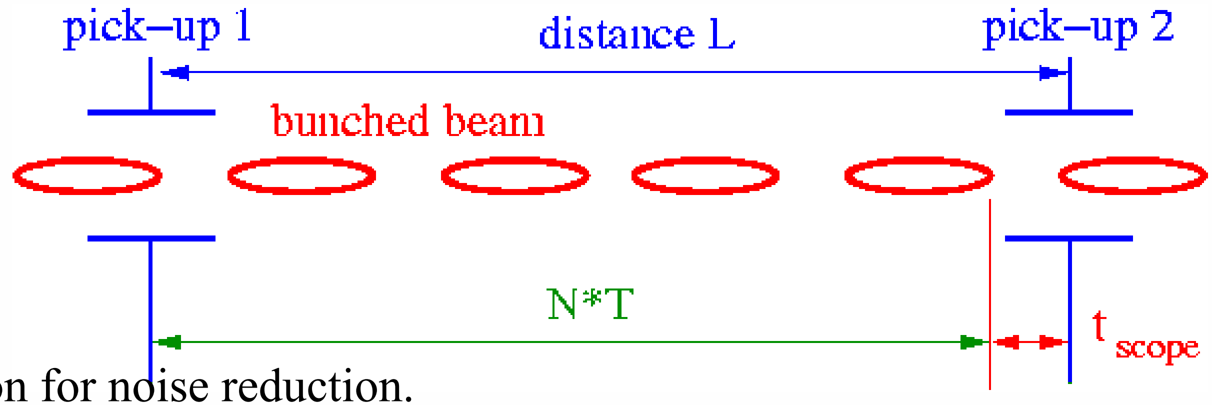
Required accurecy here: Δf_{rf}=1 kHz or or $\Delta f_{rf}/f_{rf}$=0.1%

Form H. Damerau, GSI

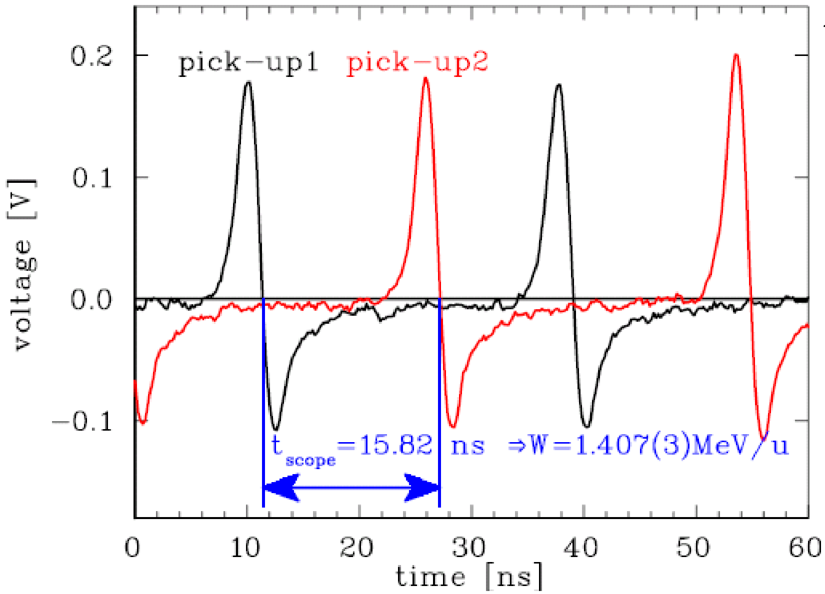
Important tool for rf-phase and amplitude alignment:

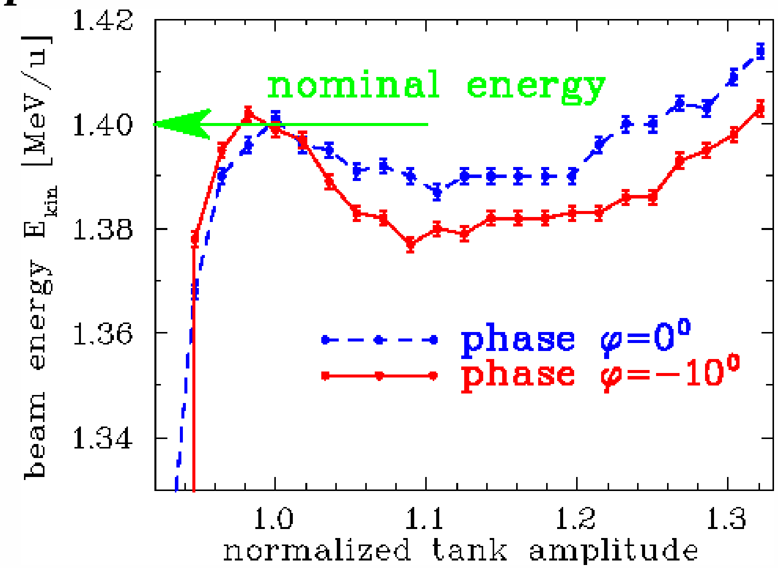
Time-of-flight measurement
with 100 ps resolution
(='phase measurement')

Modern system:
Digitalization
+ correlation function calculation for noise reduction.



Example: TOF for 1.4 MeV/u behind IH-LINAC





With BPMs the center in the transverse plane is determined for bunched beams.

Coupling beam → detector given by the transfer impedance $Z_t(\omega)$ signal estimation $I_{beam} \rightarrow U_{im}$

Different type of BPM:

Shoe box = linear cut: for p-synchrotrons with f_{rf}<10 MHz

Advantage: very linear. **Disadvantage:** complex mechanics

Button: Most frequently used at all accelerators, best for f_{rf}>10 MHz

Advantage: compact mechanics. **Disadvantage:** non-linear, low signal

Stripline: Taking traveling wave behavior into account, best for short bunches

Advantage: precise signal. **Disadvantage:** Complex mechanics for 50Ω, non-linear

Cavity BPM: dipole mode excitation → high resolution 1µm@1µs ↔ spatial application

Electronics used for BPMs:

Basics: Resolution in space ↔ resolution in time i.e. the bandwidth has to match the application

Broadband processing: Full information available, but lower resolution, for fast feedback

Log-amp: robust electronics, high dynamics, but less precise

Analog narrowband processing: high resolution, but not for fast beam variation

Digital processing: very flexible, but limited ADC speed, more complex