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
For short bunches, the capacitive button deforms the signal

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

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

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

From C. Boccard, CERN
**Stripline BPM: General Idea**

For relativistic beam with $\beta \approx 1$ and short bunches:

- Bunch’s Electro-magnetic field induces a **traveling pulse** at the strip
- **Assumption:** $l_{\text{bunch}} < l$, $Z_{\text{strip}} = R_1 = R_2 = 50\ \Omega$ and $v_{\text{beam}} = c_{\text{strip}}$

**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

$t=2\cdot l/c$: reflected signal reaches port 1

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

*If beam repetition time equals $2\cdot l/c$: 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 $\leftrightarrow$ directional coupler: e.g. can distinguish between $e^-$ and $e^+$ in collider
The signal from port 1 and the reflection from port 2 can cancel \( \Rightarrow \) minima in \( Z_t \).

For short bunches \( I_{beam}(t) \rightarrow Ne \cdot \delta(t) \):

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

- \( Z_t \) show maximum at \( l=c/4f=\lambda/4 \) i.e. ‘quarter wave coupler’ for bunch train
  \( \Rightarrow l \) 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 to preserve 50 \( \Omega \) matching.
The signal at port 1 for a finite bunch of length $\sigma$:  
\[ I_{\text{beam}}(t) = I_0 \cdot e^{-t^2/2\sigma^2} \]

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

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

- $Z_t(\omega)$ 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

*Caution: $Z_t$ depends on beam’s bunch length $\sigma$*
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 \( Z_{\text{strip}} = 50\Omega \):

Comparable formula as for PCB micro-strip → dependence on \( d \) and \( \alpha \)
Realization of Stripline BPM

20 cm stripline BPM at TTF2 (chamber Ø34mm)
And 12 cm LHC type:

From S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)
<table>
<thead>
<tr>
<th></th>
<th>Stripline</th>
<th>Button</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Idea</strong></td>
<td>traveling wave</td>
<td>electro-static</td>
</tr>
<tr>
<td><strong>Requirement</strong></td>
<td>Careful $Z_{\text{strip}} = 50 \Omega$ matching</td>
<td></td>
</tr>
<tr>
<td><strong>Signal quality</strong></td>
<td>Less deformation of bunch signal</td>
<td>Deformation by finite size and capacitance</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>Broadband, but minima</td>
<td>Highpass, but $f_{\text{cut}} &lt; 1 \text{ GHz}$</td>
</tr>
<tr>
<td><strong>Signal strength</strong></td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td></td>
<td>Large longitudinal and transverse coverage possible</td>
<td>Size &lt; $\varnothing 3 \text{ cm}$, to prevent signal deformation</td>
</tr>
<tr>
<td><strong>Mechanics</strong></td>
<td>Complex</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Installation</strong></td>
<td>Inside quadrupole possible</td>
<td>Compact insertion</td>
</tr>
<tr>
<td></td>
<td>$\Rightarrow$ improving accuracy</td>
<td></td>
</tr>
<tr>
<td><strong>Directivity</strong></td>
<td>YES</td>
<td>No</td>
</tr>
</tbody>
</table>

From S. Wilkins, D. Nölle (DESY)
Resistive Wall Current Monitor

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

**Principle:** Ceramic gap bridged with $n=10...100$ resistors of $R=10...100\ \Omega$

- Voltage drop for $R_{tot}=1/n\cdot R=1...10\ \Omega$ measured
- Ferrite rings with high $L$
  - $\rightarrow$ forces low frequency components through $R$

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

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

**Application:** Broadband bunch observation

![WCM equivalent circuit](image)

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

Within bandwidth: $Z_t \approx R_{tot}$
Realization of Wall Current Monitor

Large bandwidth WCM for short bunch longitudinal observation at CLIC

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

From P. Odier (CERN) DIPAC 03&05
Inductive Wall Current Monitor

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

Example: CERN CTF3 and LINAC2 device

Parameters: 8 strips on $\varnothing$50 mm

for CFT3 Bandwidth: 300 kHz to 250 MHz
Transfer impedance: $Z_t = 10 \, \Omega$
Sensitivity: $k = 10 \, \text{mm} \text{ (central part)}$

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 TM₀₁₀ with \( f_{010} \) → maximum at beam center ⇒ strong excitation
- Dipole mode TM₀₁₁ with \( f_{011} \) → minimum at center ⇒ excitation by beam offset
⇒ Detection of dipole mode amplitude (phase relative to monopole gives sign of displacement)
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 $f_{110} \approx 1 \ldots 10 \text{ GHz}$

From M. Wendt (FNAL)

**Cavity BPM**

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Frequency range $f_{110} \approx 1 \ldots 10 \text{ GHz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap length $15 \text{ mm}$</td>
<td></td>
</tr>
<tr>
<td>Mono. $f_{010} = 1.12 \text{ GHz}$</td>
<td></td>
</tr>
<tr>
<td>Dipole $f_{110} = 1.47 \text{ GHz}$</td>
<td></td>
</tr>
<tr>
<td>$Q_{load} \approx 600$</td>
<td></td>
</tr>
<tr>
<td>With comparable BPM $\Rightarrow 0.1 \mu\text{m resolution within } 1 \mu\text{s}$</td>
<td></td>
</tr>
</tbody>
</table>

FNAL BPM develop.
### Comparison of BPM Types (simplified)

<table>
<thead>
<tr>
<th>Type</th>
<th>Usage</th>
<th>Precaution</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoe-box</strong></td>
<td>p-Synch.</td>
<td>Long bunches $f_{\text{rf}} &lt; 10$ MHz</td>
<td>Very linear</td>
<td>Complex mechanics</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No x-y coupling</td>
<td>Capacitive coupling between plates</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sensitive</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>For broad beams</td>
<td></td>
</tr>
<tr>
<td><strong>Button</strong></td>
<td>p-Linacs, all e- acc.</td>
<td>$f_{\text{rf}} &gt; 10$ MHz</td>
<td>Simple mechanics</td>
<td>Non-linear, x-y coupling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Possible signal deformation</td>
</tr>
<tr>
<td><strong>Stipline</strong></td>
<td>colliders p-Linacs, all e- acc.</td>
<td>best for $\beta \approx 1$, short bunches</td>
<td>Directivity 'Clean' signals</td>
<td>Complex 50 $\Omega$ matching</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>'Clean' signals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Large Signal</td>
<td></td>
</tr>
<tr>
<td><strong>Ind. WCM</strong></td>
<td>all</td>
<td>non</td>
<td>Broadband</td>
<td>Complex, long insertion</td>
</tr>
<tr>
<td><strong>Cavity</strong></td>
<td>e- Linacs (e.g. FEL)</td>
<td>Short bunches Special appl.</td>
<td>Very sensitive</td>
<td>Very complex, high frequency</td>
</tr>
</tbody>
</table>

**Remark:** Other types are also sometimes used, e.g. inductive antenna based, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.
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
  - 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, \( \log \frac{U_1}{U_2} \) 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 \( \approx 100 \, \mu m \)
- **averaged**: \( 10^{-5} \) of aperture \( \approx 1 \, \mu m \), with dedicated methods \( \approx 0.1 \, \mu m \)
- 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: \( U_{eff}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f} \)

⇒ Signal-to-noise \( \frac{U_{im}}{U_{eff}} \) is influenced by:

- Input signal amplitude
  → large or matched \( Z_t \)
- Thermal noise at \( R=50\Omega \) for \( T=300K \)
  (for shoe box \( R=1k\Omega \ldots 1M\Omega \))
- Bandwidth \( \Delta f \)
  ⇒ Restriction of frequency width
  because the power is concentrated on the harmonics of \( f_{rf} \)

Example: GSI-LINAC with \( f_{rf}=36\text{ MHz} \)

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 \( \sigma \)

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

\[ \sigma \propto \sqrt{\Delta f} \]
\[ \Rightarrow \text{Lower } \sigma \text{ for large } \varnothing \text{button} \]

\[ \Rightarrow \sigma \text{ decreases with current} \]
\[ \Rightarrow \text{Lower } \sigma \text{ for large } \varnothing \text{button} \]
**Example** GSI Synchr.: $^{73+}\text{U}$, $E_{\text{inj}}=11.5$ MeV/u $\rightarrow$ 250 MeV/u within 0.5 s, $10^9$ ions

- Position resolution $< 20 \mu$m (BPM half aperture $a=40$ mm)
- average over 1000 turns corresponding to $\approx$0.3 ms or $\approx$1 kHz bandwidth

**Comparison: Filtered Signal ↔ Single Turn**

- Turn-by-turn data have much larger variation

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

$\Rightarrow$ broadband processing i.e. turn-by-turn readout for tune determination
General Idea: Broadband Processing

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

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

**Disadvantage:** Resolution down to $\approx 100 \, \mu\text{m}$ for shoe box type, i.e. $\approx 0.1\%$ of aperture, resolution is worse than narrowband processing.
**Example:** pre-amp from GSI-synchrotron:

Shoe box BPM → matching 2:12 transformer $R_{\text{prim}} = 1.8k\Omega$ → $\approx 3$ m cable → amplifier

- Requirement: Dynamic range from $1 \times 10^8$ to $4 \times 10^{13}$ 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
Noise Limitation by Lowpass Filtering

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

Simulation:
Adding white noise

Lowpass Filter:
Besselfilter of 3rd order
\[ f_{\text{cutoff}} = 10 \text{ MHz} \]

Simulation:
Adding white noise

Original Signal
Noisy signal
Filtered signal

Simulation:
Adding white noise

Beam Position Monitors: Principle and Realization
Signal is ‘compressed’ by a logarithmic amplifier, filtered and applied to a differential amplifier.

Typical video bandwidth ≈1MHz

Position: \( x = k \cdot [\log(A/B)] \equiv k \cdot [\log(A)-\log(B)] = k \cdot V_{out} \)

**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!

From G. Vismara, CERN, DIPAC 2000
General Idea: Narrowband Processing

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

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{\text{rf}} \Rightarrow$ 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 $\rightarrow$ variable $f_{\text{rf}}$ 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 ≈ 1 ms: ⇒ 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!
Modern instrumentation uses **digital** techniques with extended functionality.

### Traditional analog processing

BPM analog signal → Analog frequency translator → Analog demodulator And filter → ADC → digital output

### Digital processing (triggered by telecommunication development)

BPM analog signal → Analog frequency translator → ADC → Digital filter → Digital Signal Proc. → digital output

**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

Crossbar multiplexing of all channels at \( \approx 13 \text{ kHz} \) (analog)

Automatic gain control by 0…31 dB attenuators

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

Digitalization with \( \approx 117 \text{ MHz} \)

matched to sub-harmonics of \( f_{rf} \)

\( \Rightarrow \) Undersampling: every 4\textsuperscript{th} bunch

Digital compensation of channel variation

Digital de-multiplexing

Timing for Synchrotron Light Source:

\( f_{rf} = 352 \text{ or } 500 \text{ MHz}, \ f_{\text{rev}} \approx 1 \text{ MHz} \)
**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 $\approx 900$ 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 → start of logical pulse ⇔ 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)

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

The **accuracy** can be improved by ‘k-modulation’ → alignment of the BPM with respect to the axis of the quadrupoles

The accuracy can be improved by ‘k-modulation’ → alignment of the BPM with respect to the axis of the quadrupoles.

At LEP measured 1997 for different bumps

![Graph showing the relationship between BPM and orbit at quad in millimeters.](image)

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: closed orbit, tune, bunch capture, energy at LINAC
- Summary
Close Orbit Measurement

Detected position on a analog narrowband basis $\rightarrow$ 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 $\Delta Q=0.04$
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

**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 \(\rightarrow\) emittance enlargement

\[ f_{\text{rf}} \text{ shift by 0.2\% of nominal value} \]
\[ \Rightarrow \text{Coherent oscillation} \]

Matched \( f_{\text{rf}} \) \(\Rightarrow\) no oscillation

Required accuracy here: \( \Delta f_{\text{rf}} = 1 \text{ kHz} \) or \( \Delta f_{\text{rf}} / f_{\text{rf}} = 0.1\% \)

Form H. Damerau, GSI
BPM for Energy Determination

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
Summary

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 \( f_{rf} < 10 \text{ MHz} \)

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

**Button:** Most frequently used at all accelerators, best for \( f_{rf} > 10 \text{ MHz} \)

  - **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 \( 50\Omega \), non-linear

**Cavity BPM:** dipole mode excitation → high resolution 1\( \mu \text{m} \)@1\( \mu \text{s} \) ↔ 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