BPM System Design

Invited tutorial at IBIC 2015, Melbourne
Hermann Schmickler, CERN

With most slides from:
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David Rubin (Cornell), M.Tejima (KEK)
Outline

• Principle, Applications of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals
• Electronics
• Synchronization, accelerator timing
• From precision to accuracy
• Outlook

• Not covered: Simulation Tools, Managerial Considerations
Introduction

- The particle beam induces an electrical signal in two opposing electrodes. The induced signals depend
  - on the beam intensity
  - on the proximity of the beam to the sensors
- Intuitively the term: “difference over sum” should measure the beam position...how well we will see later
- One of the principle problems is that the requested observable (beam position) is measured as the difference of two large numbers....We will see what impact this has on the measurement resolution/accuracy/precision
- Some smart people build monitors, which give the difference by the nature of the monitor...cavity BPMs.
  Those we will treat separately. In general they are limited to applications in linear accelerators due to their high coupling impedance.
Application of BPMs

- On bunched beam
- Trajectory Measurement: Measure beam positions during one revolution/passage through transfer line
- Closed Orbit Measurement (CO): Average over “many” trajectories
- Time resolution: from long averages of CO up to turn by turn trajectories, turn by turn trajectories even bunch by bunch ➞ depending on bunch length even observation of bunch shape
- Derived quantities:
  - tune, chromaticity, coupling (using excited betatron oscillations plus observation with a single BPM)
  - $\beta$-function and phase advance around the ring (using excited betatron oscillations plus observation with all BPMs), dispersion, injection matching…
- Usage in real time feedbacks (on CO, multibunch stability)
- Sensitivity down to nA beams (pC)
Accuracy, Precision, Resolution

- Very often confused in day-to-day language
- Accuracy: also called trueness of measurement
- Precision: indicates how well one can reproduce measurements
- Resolution: smallest possible difference in successive measurements

<table>
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<tr>
<th></th>
<th>Accurate</th>
<th>Inaccurate (systematic error)</th>
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</thead>
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| Precise           | ![Target](image1)
| Improise (reproducibility error) | ![Target](image2) |

Ex: BPM: Mechanical and electrical offsets, gain factors influence the accuracy, various noise sources or timing jitter influence the precision, quantization in the ADC can limit the resolution.
Functional Specification (FS)

- Make sure you have this (in writing) before you start developing.
  Initiative normally comes from the Instrument responsible, FS has to be written by future users of instrument.

- FS needs to contain
  - beam parameters,
  - modes of operation,
  - required accuracy, precision, resolution
  - expected frequency of usage (i.e. wire scanners)
  - specifications for control software and data analysis tools

- Leads to an Engineering Specification (ES) produced by instrument specialist.

- ES and FS represent a “contract” between producer and user.

Outline

• Principle, Applications of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals: capacitive sensors
• Electronics
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**General Idea: Detection of Wall Charges**

The image current at the vacuum wall is monitored on a high frequency basis i.e. the ac-part given by the bunched beam.

For relativistic velocities, the electric field is mainly transversal: \( E_{\perp,\text{lab}}(t) = \gamma \cdot E_{\perp,\text{rest}}(t) \)

Beam Position Monitor **BPM** equals Pick-Up **PU**
Principle of Signal Generation of capacitive BPMs

Animation by Rhodri Jones (CERN)

Same behavior as top plate

P. Forck et al., DITANET School March 2011

Beam Position Monitors
The wall current is monitored by a plate or ring inserted in the beam pipe:

The image current $I_{im}$ at the plate is given by the beam current and geometry:

$$I_{im}(t) = \frac{dQ_{im}(t)}{dt} = \frac{A}{2\pi a} \cdot \frac{dQ_{beam}(t)}{dt} = \frac{A}{2\pi} \cdot \frac{1}{\beta c} \cdot \frac{dI_{beam}(t)}{dt} = \frac{A}{2\pi} \cdot \frac{1}{\beta c} \cdot i\omega I_{beam}(\omega)$$

Using a relation for Fourier transformation: $I_{beam} = I_0 e^{i\omega t} \Rightarrow dI_{beam}/dt = i\omega I_{beam}$.
Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

\[ U_{im}(\omega) = Z_t(\omega) \cdot I_{beam}(\omega) \]

\[ |Z_t| = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{\omega / \omega_{cut}}{\sqrt{1 + \omega^2 / \omega_{cut}^2}} \]

\[ \varphi = \arctan(\omega_{cut} / \omega) \]

Parameter for shoe-box BPM:

\( C = 100 \text{pF}, \ l = 10 \text{cm}, \ \beta = 50\% \)

\( f_{cut} = \frac{\omega}{2\pi} = (2\pi RC)^{-1} \)

for \( R = 50 \ \Omega \Rightarrow f_{cut} = 32 \ \text{MHz} \)

for \( R = 1 \ \text{M}\Omega \Rightarrow f_{cut} = 1.6 \ \text{kHz} \)
Depending on the frequency range and termination the signal looks different:

- **High frequency range $\omega \gg \omega_{\text{cut}}$**: 
  
  $Z_t \propto \frac{i \omega/\omega_{\text{cut}}}{1 + i \omega/\omega_{\text{cut}}} \rightarrow 1 \Rightarrow U_{im}(t) = \frac{1}{C} \cdot \frac{1}{\beta c} \cdot \frac{A}{2\pi} \cdot I_{\text{beam}}(t)$

  ⇒ **direct image** of the bunch. Signal strength $Z_t \propto A/C$ i.e. nearly independent on length

Example from synchrotron BPM with 50 $\Omega$ termination (reality at p-synchrotron: $\sigma >> 1$ ns):
Signal Shape for capacitive BPMs: differentiated ↔ proportional

Depending on the frequency range and termination the signal looks different:

- **High frequency range** \( \omega >> \omega_{cut} \):
  \[
  Z_t \propto \frac{i \omega / \omega_{cut}}{1 + i \omega / \omega_{cut}} \to 1 \Rightarrow U_{im}(t) = \frac{1}{C} \cdot \frac{1}{\beta c \cdot 2\pi a} \cdot A \cdot I_{beam}(t)
  \]
  ⇒ direct image of the bunch. Signal strength \( Z_t \sim A/C \) i.e. nearly independent on length

- **Low frequency range** \( \omega << \omega_{cut} \):
  \[
  Z_t \propto \frac{i \omega / \omega_{cut}}{1 + i \omega / \omega_{cut}} \to i \frac{\omega}{\omega_{cut}} \Rightarrow U_{im}(t) = R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot i \omega I_{beam}(t) = R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}
  \]
  ⇒ derivative of bunch, single strength \( Z_t \sim A \), i.e. (nearly) independent on \( C \)

Example from synchrotron BPM with 50 \( \Omega \) termination (reality at p-synchrotron: \( \sigma>>1 \) ns):
Calculation of Signal Shape: Bunch Train

Train of bunches with R=50 Ω termination ⇒ $f \ll f_{cut}$:

Calculation: $I_{beam}(t) \xrightarrow{\text{FFT}} I_{beam}(\omega) \rightarrow U_{im}(\omega) = Z_{tot}(\omega) \cdot I_{beam}(\omega) \xrightarrow{\text{invFFT}} U_{im}(t)$

Parameter: $R=50$ Ω ⇒ $f_{cut}=32$ MHz, all buckets filled

- Fourier spectrum is composed of lines separated by acceleration $f_{rf}$
- Envelope given by single bunch Fourier transformation
- Differenciated bunch shape due to $f_{cut} >> f_{rf}$

Remark: 1 MHz < $f_{rf}$ < 10 MHz ⇒ Bandwidth ≈100 MHz = 10$f_{rf}$ for broadband observation.
Shoe-box BPM for Proton or Ion Synchrotron

Frequency range: 1 MHz \(< f_{rf} < 10 \text{ MHz} \implies \text{bunch-length} \gg \text{BPM length.}

Signal is proportional to actual plate length:
\[ l_{\text{right}} = (a + x) \cdot \tan \alpha, \quad l_{\text{left}} = (a - x) \cdot \tan \alpha \]

\[ \Rightarrow x = a \cdot \frac{l_{\text{right}} - l_{\text{left}}}{l_{\text{right}} + l_{\text{left}}} \]

In ideal case: linear reading
\[ x = a \cdot \frac{U_{\text{right}} - U_{\text{left}}}{U_{\text{right}} + U_{\text{left}}} \equiv a \cdot \frac{\Delta U}{\Sigma U} \]

Size: 200x70 mm\(^2\)
Shoe-box BPM for Proton or Ion Synchrotron

Frequency range: $1 \text{ MHz} < f_{rf} < 10 \text{ MHz} \Rightarrow \text{bunch-length} \gg \text{BPM length.}$

Signal is proportional to actual plate length:

$l_{\text{right}} = (a + x) \cdot \tan \alpha, \quad l_{\text{left}} = (a - x) \cdot \tan \alpha$

$\Rightarrow \quad x = a \cdot \frac{l_{\text{right}} - l_{\text{left}}}{l_{\text{right}} + l_{\text{left}}}$

In ideal case: linear reading

$x = a \cdot \frac{U_{\text{right}} - U_{\text{left}}}{U_{\text{right}} + U_{\text{left}}} \equiv a \cdot \frac{\Delta U}{\Sigma U}$

Shoe-box BPM:

**Advantage:** Very linear, low frequency dependence
- i.e. position sensitivity $S$ is constant

**Disadvantage:** Large size, complex mechanics
- high capacitance

Size: $200 \times 70 \text{ mm}^2$

![Diagram of Shoe-box BPM with beam and guard rings on ground potential]
Technical Realization of Shoe-Box BPM

Technical realization at HIT synchrotron of 46 m length for 7 MeV/u → 440 MeV/u BPM clearance: 180x70 mm², standard beam pipe diameter: 200 mm.
Technical realization at HIT synchrotron of 46 m length for 7 MeV/u → 440 MeV/u
BPM clearance: 180x70 mm², standard beam pipe diameter: 200 mm.
**Other Types of diagonal-cut BPM**

**Round type: cut cylinder**

Same properties as shoe-box:

- Horizontal BPM
- Vertical BPM
- Signal Out
- Guard Ring

**Wound strips:**

Same distance from beam and capacitance for all plates
But horizontal-vertical coupling.

**Other realization: Full metal plates**

→ No guard rings required
→ but mechanical alignment more difficult
Button BPM Realization

LINACs, e⁻-synchrotrons: $100 \text{ MHz} < f_{rf} < 3 \text{ GHz} \rightarrow$ bunch length $\approx$ BPM length

$\rightarrow 50 \, \Omega$ signal path to prevent reflections

Button BPM with $50 \, \Omega \Rightarrow U_{im}(t) \approx R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$
Button BPM Realization

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Button BPM with $50 \ \Omega \ \Rightarrow \ \ U_{im}(t) \approx R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$

Example: LHC-type inside cryostat:
$\varnothing 24 \text{ mm},$ half aperture $a = 25 \text{ mm}, \ C = 8 \text{ pF}$

$\Rightarrow f_{cut} = 400 \text{ MHz}, \ Z_t = 1.3 \Omega \ \text{above } f_{cut}$

From C. Boccard (CERN)
Button BPM Realization

LINACs, e−-synchrotrons: $100 \text{ MHz} < f_{\text{rf}} < 3 \text{ GHz} \rightarrow \text{bunch length} \approx \text{BPM length} \rightarrow 50 \ \Omega \text{signal path to prevent reflections}$

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From C. Boccard (CERN)
‘Proximity effect’: larger signal for closer plate

Ideal 2-dim model: Cylindrical pipe → image current density via ‘image charge method’ for ‘pencil’ beam:

\[ j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left( \frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right) \]
2-dim Model for Button BPM

‘Proximity effect’: larger signal for closer plate

**Ideal 2-dim model:** Cylindrical pipe $\rightarrow$ image current density via ‘image charge method’ for ‘pencil’ beam:

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

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

![Graph showing current line density and signal versus angle and real beam position](image_url)
**Ideal 2-dim model**: Non-linear behavior and hor-vert coupling:

Sensitivity: \( x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U} \) with \( S \) [%/mm] or [dB/mm]

For this example: center part \( S = 7.4\% / \text{mm} \Leftrightarrow k = 1/S = 14 \text{mm} \)

The measurement of \( U \) delivers: \( x = \frac{1}{S_x} \cdot \frac{\Delta U}{\Sigma U} \) \( \rightarrow \) here \( S_x = S_x(x, y) \) i.e. non-linear.

In addition, frequency dependence can be calculated by analytic model or numerically.
Due to synchrotron radiation, the button insulation might be destroyed
⇒ buttons only in vertical plane possible ⇒ increased non-linearity
Optimization: horizontal distance and size of buttons

- Beam position swept with 2 mm steps
- Non-linear sensitivity and hor.-vert. coupling
- At center $S_x = 8.5\% / \text{mm}$ in this case

$$\text{horizontal: } x = \frac{1}{S_x} \cdot \frac{(U_1 + U_4) - (U_2 + U_3)}{U_1 + U_2 + U_3 + U_4}$$

$$\text{vertical: } y = \frac{1}{S_y} \cdot \frac{(U_1 + U_2) - (U_3 + U_4)}{U_1 + U_2 + U_3 + U_4}$$

From S. Varnasseri, SESAME, DIPAC 2005
## Comparison Shoe-Box and Button BPM

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<th>Button BPM</th>
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<td><strong>Linearity</strong></td>
<td>Very good, no x-y coupling</td>
<td>Non-linear, x-y coupling</td>
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<td><strong>Sensitivity</strong></td>
<td>Good, care: plate cross talk</td>
<td>Good, care: signal matching</td>
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<td><strong>Usage</strong></td>
<td>At proton synchrotrons, $f_{\text{rf}} &lt; 10$ MHz</td>
<td>All electron acc., proton Linacs, $f_{\text{rf}} &gt; 100$ MHz</td>
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Stripline BPM: General Idea

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**
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Stripline BPM: General Idea

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

$\rightarrow$ Bunch’s electro-magnetic field induces a **traveling pulse** at the strip

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

**Signal treatment at upstream port 1:**

$t=0$: Beam induced charges at **port 1**:

$\rightarrow$ half to $R_1$, half toward **port 2**

$t=l/c$: Beam induced charges at **port 2**:

$\rightarrow$ half to $R_2$, **but** due to different sign, it cancels with the signal from **port 1**

$\rightarrow$ half signal reflected

**Signal at downstream port 2:** Beam induced charges cancels with traveling charge from port 1

$\Rightarrow$ Signal depends on direction $\leftrightarrow$ directional coupler: e.g. can distinguish between $e^-$ and $e^+$ in collider
**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:** $l_{bunch} << l$, $Z_{strip} = R_1 = R_2 = 50 \, \Omega$ 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

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

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

**Signal at downstream port 2:** Beam induced charges cancels with traveling charge from port 1

⇒ Signal depends on direction ⇔ directional coupler: e.g. can distinguish between $e^-$ and $e^+$ in collider
**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**:
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→ half signal reflected

$t=2l/c$: 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·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 on direction $\Leftrightarrow$ 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 \( \Rightarrow \) minima in \( Z_t \).

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

- \( Z_t \) 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 \( \phi = 0 \) 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.

P. Forck et al., DITANET School March 2011
Stripline BPM: Finite Bunch Length

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

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

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

- $Z_t(\omega)$ 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

Stripline length $l=30$ cm, $\alpha=10^0$
The signal at port 1 for a finite bunch of length $\sigma$:

$$I_{\text{beam}}(t) = I_0 \cdot e^{-t^2/2\sigma^2}$$

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

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

Caution: $Z_t$ depends on beam’s bunch length $\sigma$

1. $Z_t(\omega)$ decreases for higher frequencies
2. 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
Realization of Stripline BPM

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

From S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)
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Cavity BPM: Principle

High resolution on $t < 1 \mu s$ time scale can be achieved by excitation of a dipole mode:

- For pill box the resonator modes given by geometry:
  - monopole $TM_{010}$ with $f_{010}$
    - maximum at beam center $\Rightarrow$ strong excitation
  - Dipole mode $TM_{011}$ with $f_{011}$
    - minimum at center $\Rightarrow$ excitation by beam offset
    - Detection of dipole mode amplitude

Application:
small e' beams
and short pulses < ns
(ILC, X-FEL...)‘δ-excitation’
$\Rightarrow$ oscillation with $Q \approx 1000$ and $\tau = 2Q/2\pi f \approx 100$ ns

From D. Lipka, DESY, Hamburg
Cavity BPM: Example of Realization

Basic consideration for detection of Eigen-frequency amplitudes:
- Dipole mode $f_{110}$ separated from monopole mode
  - but to finite quality factor $Q \Rightarrow \Delta f = f/Q$
- Frequency $f_{110} \approx 1…10\ GHz$
- Waveguide house the antennas
  - (task: suppression of TM_{010} mode signal)

FNAL realization:
- Cavity: $\varnothing\ 113\ mm$
- Gap $15\ mm$
- Mono. $f_{010} = 1.1\ GHz$
- Dipole. $f_{110} = 1.5\ GHz$
- $Q_{load} \approx 600$
- With comparable BPM
  - $\Rightarrow 0.1\ \mu m\ resolution\ within\ 1\ \mu s$

From M. Wendt (FNAL)
Cavity BPM: Suppression of monopole Mode

Suppression of mono-pole mode: waveguide that couple only to dipole-mode due to $f_{\text{mono}} < f_{\text{cut}} < f_{\text{dipole}}$

Mono-pole mode

Dipole-pole mode
Suppression of mono-pole mode: waveguide that couple only to dipole-mode due to $f_{\text{mono}} < f_{\text{cut}} < f_{\text{dipole}}$
Suppression of mono-pole mode: waveguide that couple only to dipole-mode due to $f_{\text{mono}} < f_{\text{cut}} < f_{\text{dipole}}$

**Prototype BPM for ILC Final Focus:**

- Required resolution of 5 nm (yes nano!) in a 6×12 mm diameter beam pipe
- Achieved world record resolution of 8.7 nm ±0.28(stat)± 0.35(sys) nm at ATF2 (KEK, Japan).

_Courtesy of D. Lipka and Y. Honda_
### Comparison of BPM Types (simplified)

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<td>p-Synch.</td>
<td>Long bunches $f_{rf} &lt; 10$ MHz</td>
<td>Very linear, No x-y coupling, Sensitive, For broad beams</td>
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</tr>
<tr>
<td><strong>Button</strong></td>
<td>p-Linacs, all e⁻ acc.</td>
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<td>Non-linear, x-y coupling, Possible signal deformation</td>
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<td>colliders p-Linacs, all e⁻ acc.</td>
<td>best for $\beta \approx 1$, short bunches</td>
<td>Directivity, ‘Clean’ signal, Large signal</td>
<td>Complex 50 Ω matching, Complex mechanics</td>
</tr>
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<td>e⁻ Linacs (e.g. FEL)</td>
<td>Short bunches Special appl.</td>
<td>Very sensitive</td>
<td>Very complex, high frequency</td>
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### Comparison of BPM Types (simplified)

<table>
<thead>
<tr>
<th>Type</th>
<th>Usage</th>
<th>Precaution</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
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**Remark:** Other types are also some time used, e.g. wall current, inductive antenna, BPMs with external resonator, slotted wave-guides for stochastic cooling etc.
Outline

• Principle, Applications of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals: capacitive sensors
  • Electronics
• Synchronization, accelerator timing
• From precision to accuracy
• Outlook
The Ideal BPM Read-out Electronics!?

BPM pickup (e.g. button, stripline)

Very short coaxial cables

Digital BPM electronics (rad-hard, of course!)

Beam

DAQ
The Ideal BPM Read-out Electronics!? 

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Very short coaxial cables  
Digital BPM electronics (rad-hard, of course!)

“Super” ADCs
The Ideal BPM Read-out Electronics!?  

- **BPM pickup** (e.g. button, stripline)  
- **Very short coaxial cables**  
- **Digital BPM electronics** (rad-hard, of course!)  
- **“Super” ADCs**  
- **“Monster” FPGA**  

**Diagram components:**  
- Beam  
- ADC  
- FPGA  
- Fiber Link  
- CLK  
- PS  
- DAQ
The Ideal BPM Read-out Electronics!? 

BPM pickup (e.g. button, stripline) 

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Digital BPM electronics (rad-hard, of course!) 

“Super” ADCs 

“Monster” FPGA 

“Ultra” low jitter clock! 

Beam 

FPGA 

Fiber Link 

CLK 

PS 

DAQ
The Ideal BPM Read-out Electronics!? 

- Time multiplexing of the BPM electrode signals:
  - Interleaving BPM electrode signals by different cable delays
  - Requires only a single read-out channel!

- BPM pickup (e.g. button, stripline)
- Very short coaxial cables
- Digital BPM electronics (rad-hard, of course!)
- "Super" ADCs
- "Monster" FPGA
- "Ultra" low jitter clock!
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
  - Provides calibration signals or other drift compensation methods
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  - Digital signal processing
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  - Trigger, CLK & timing signals
  - Provides calibration signals or other drift compensation methods
Signal Processing & Normalization

• Extract the beam position information from the electrode signals:
  Normalization
  – Analog using $\Delta\Sigma$ or $90^\circ$-hybrids, followed by filters, amplifiers mixers and other elements, or logarithmic amplifiers.
  – Digital, performing the math on individual digitized electrode signals.

• Decimation / processing of broadband signals
  – BPM data often is not required on a bunch-by-bunch basis
    ➢ Exception: Fast feedback processors
    ➢ Default: Turn-by-turn and “narrowband” beam positions
  – Filters, amplifiers, mixers and demodulators in analog and digital to decimate broadband signals to the necessary level.

• Other aspects
  – Generate calibration / test signals
  – Correct for non-linearities of the beam position response of the BPM
  – Synchronization of turn-by-turn data
  – Optimization on the BPM system level to minimize cable expenses.
  – BPM signals keep other very useful information other than that based on the beam displacement, e.g.
    ➢ Beam intensity, beam phase (timing)
For the “Oldies”: Analog Signal Processing Options
courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:

/ Single channel
Wide Band
Narrow Band

Electrodes A, B

Normalizer Processor

Active Circuitry

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry

AGC on Σ

POS = (A-B)

no turn by turn
courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:

- / Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry

Heterodyne

MPX

Hybrid $\Delta/\Sigma$

Synchronous Detection

AGC on $\Sigma$

Electrodes A, B

POS = $(A-B)$

POS = $\Delta/\Sigma$

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For the “Oldies”: Analog Signal Processing Options

Legend:

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Normalizer
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Heterodyne
Synchronous Detection
POS = (A-B)
no turn by turn

Hybrid Δ/Σ
Heterodyne
Homodyne Detection
POS = Δ/Σ

MPX

Electrodes A, B
courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry

POS = (A - B)

Synchronous Detection

AGC on Σ

Hybrid Δ/Σ

Electrodes A, B

Individual Treatment

Logarithm. Amplifiers

Differential Amplifier

Heterodyne

Homodyne Detection

Δ / Σ

Differential Amplifier

Δ / Σ

Heterodyne

Synchronous Detection

AGC on Σ

POS = log(A/B) = log(A) - log(B)

DIGITIZER

no turn by turn

POS = Δ / Σ

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
- Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry

Heterodyne Detection

AGC on Σ

POS = (A-B)

Synchronous Detection

POS = Δ / Σ

Electrodes A, B

Hybrid Δ / Σ

Switch, gain Amplifier

Sample, Track, Integr. & Hold

Logarithm. Amplifiers

Individual Treatment

Differential Amplifier

POS = log(A/B) = log(A) - log(B)

Differential Amplifier

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:

/ Single channel
Wide Band
Narrow band

Normalizer Processor
Active Circuitry

Heterodyne
Hybrid $\Delta / \Sigma$
Individual Treatment
Passive Normaliz.
Logarithm. Amplifiers
Differential Amplifier
Sample, Track, Integr. & Hold
Switch, gain Amplifier
AGC on $\Sigma$
Synchronous Detection
Heterodyne Detection
POS = $\Delta / \Sigma$
or $\Delta / \Sigma = (A-B)/(A+B)$
POS = $\log(A/B)] = [\log(A)-\log(B)]$

Digitalizer
no turn by turn
POS = $(A-B)$
POS = $\Delta / \Sigma$

Electrodes A, B

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
/ Single channel
Wide Band
Narrow band
Normalizer Processor
Active Circuitry

DIGITIZER

no turn by turn

POS = (A-B)

POS = \Delta / \Sigma

POS = (A-B)/(A+B)

POS = \log(A/B)

POS = [A/B]

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer
- Processor
- Active Circuitry

Heterodyne
- Synchronous Detection
  - POS = (A-B)

Hybrid Δ/Σ
- Heterodyne
- Homodyne Detection
  - POS = Δ / Σ
  - POS = (A-B)/(A+B)

Individual Treatment
- Switch, gain Amplifier
  - Sample, Track, Integr. & Hold
- Logarithm. Amplifiers
- Differential Amplifier
  - Limiter, Δt to Ampl.
  - Limiter, φ to Ampl.
  - POS = [log(A/B)]
  - POS = [ATN(A/B)]

Passive Normaliz.
- Amplitude to Time
- Amplitude to Phase

Electrodes A, B

DIGITIZER

no turn by turn

courtesy G. Vismara (BIW 2001)
For the “Oldies”: Analog Signal Processing Options

Legend:
- / Single channel
- Wide Band
- Narrow band
- Normalizer Processor
- Active Circuitry
- AGC on Σ

**DIGITIZER**

- **no turn by turn**
  - POS = (A-B)

- **turn by turn**
  - POS = Δ/Σ or
  - POS = (A-B)/(A+B)
  - POS = [log(A/B)]
  - POS = [log(A)-log(B)]
  - POS = [A/B]
  - POS = [ATN(A/B)]

Courtesy G. Vismara (BIW 2001)
New member of analog orbit measurements:

- Further development of “BBQ”-tune measurement system (M. Gasior, CERN)
Compensated Diode Detector for BOM

- Sub-micrometre resolution can be achieved with relatively simple hardware and signals from any position pick-up.
- To be used for the future LHC collimators with embedded BPMs.
Compensated Diode Detector for BOM

- Sub-micrometre resolution can be achieved with relatively simple hardware and signals from any position pick-up.
- To be used for the future LHC collimators with embedded BPMs.
Digital BPM Signal Processing

• Why digital signal processing?
  – Better reproducibility of the beam position measurement
    ➢ Robust to environmental conditions, e.g. temperature, humidity, (radiation?)
    ➢ No slow aging and/or drift effects of components
    ➢ Deterministic, no noise or statistical effects on the position information
  – Flexibility
    ➢ Modification of FPGA firmware, control registers or DAQ software to adapt to different beam conditions or operation requirements
  – Performance
    ➢ Often better performance, e.g. higher resolution and stability compared to analog solutions
    ➢ No analog equivalent of digital filters and signal processing elements.

• BUT: Digital is not automatically better than analog!
  – Latency of pipeline ADCs (FB applications)
  – Quantization and CLK jitter effects, dynamic range & bandwidth limits
  – Digital BPM solutions tend to be much more complex than some analog signal processing BPM systems
    ➢ Manpower, costs, development time
BPM Read-out Electronics

Do we need this analog section?
“Ringing” Bandpass-Filter (BPF)

- BPM electrode signal energy is highly time compressed
  - Most of the time: “0 volt”!
- A “ringing” bandpass filter “stretches” the signal
  - Passive RF BPF
    - Matched pairs!
    - $f_{center}$ matched to $f_{rev}$ or $f_{bunch}$
    - Quasi sinusoidal waveform
  - Reduces output signal level
    - Narrow BW: longer ringing, lower signal level
  - Linear group delay designs
    - Minimize envelope ringing
    - Bessel, Gaussian, time domain designs
“Ringing” BPF & Multi-Bunches

• Bunch spacing < BPF ringing time:
  – Superposition of single bunch BPF responses
  – More continuous “ringing”, smearing of SB responses

• Bunch spacing < BPF rise time
  – Constructive signal pile-up effect
    ➢ Output signal level increases linear with decreasing bunch spacing
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    - Output signal level increases linear with decreasing bunch spacing
Analog Digital Converter

- Quantization of the continuous input waveform at equidistant spaced time samples
  - Digital data is discrete in amplitude and time
- LSB voltage (resolution) $Q = \frac{V_{FSR}}{2^M}$
  - E.g. 61 $\mu$V (14-bit), 15 $\mu$V (16-bit) @ 1 volt $V_{FSR}$
- Quantization error (dynamic range) $SQNR = 20 \log_{10}(2^M)$
  - E.g. 84 dB (14-bit), 96 dB (16 bit)
- SNR limit due to aperture jitter $SNR = -20 \log_{10}(2\pi f t_a)$
  - E.g. 62 dB@500 MHz, 0.25 psec (equivalent to EOB=10.3)
ADC Technology

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>Res. [bit]</th>
<th>Ch.</th>
<th>Power [W]</th>
<th>$f_s$ (max) [MSPS]</th>
<th>BW [MHz]</th>
<th>SNR @ $f_{in}$ [dB @ MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD</td>
<td>AD9652</td>
<td>16</td>
<td>2</td>
<td>2.2</td>
<td>310</td>
<td>485</td>
<td>72 @ 170</td>
</tr>
<tr>
<td>AD</td>
<td>AD9680</td>
<td>14</td>
<td>2</td>
<td>3.3</td>
<td>1000</td>
<td>2000</td>
<td>67 @ 170</td>
</tr>
<tr>
<td>LT</td>
<td>LTM9013*</td>
<td>14</td>
<td>2</td>
<td>2.6</td>
<td>310</td>
<td>300*</td>
<td>62 @ 150</td>
</tr>
<tr>
<td>TI</td>
<td>ADC16DX370</td>
<td>16</td>
<td>2</td>
<td>1.8</td>
<td>370</td>
<td>800</td>
<td>69 @ 150</td>
</tr>
<tr>
<td>TI</td>
<td>ADS5474-SP</td>
<td>14</td>
<td>1</td>
<td>2.5</td>
<td>400</td>
<td>1280</td>
<td>70 @ 230</td>
</tr>
</tbody>
</table>

* has an analog I-Q mixer integrated, 0.7 GHz < $f_{in}$ < 4 GHz

- **Dual Channel**
  - I-Q sampling with separate ADCs
- **Pipeline architecture**
  - Continuous CLK
  - Data latency
- **A-D mixed designs**
  - Mixers, gain, filters, etc.
Sampling Theory

• A band limited signal $x(t)$ with $B=f_{\text{max}}$ can be reconstructed if
  – Nyquist-Shannon theorem
  – The exact reconstruction of $x(t)$ by $x_n = x(nT)$:

$$x(t) = \sum_{n=-\infty}^{+\infty} x_n \frac{\sin \pi(2f_{\text{max}}t-n)}{\pi(2f_{\text{max}}t-n)} = \sum_{n=-\infty}^{+\infty} x_n \frac{\sin t-nT}{T}$$

• Aliasing of a sampled sin-function
  – Samples can be interpreted by

$$f_{\text{alias}}(N) = |f - Nf_s|$$

courtesy Wikipedia
Sampling Theory

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- Aliasing of a sampled sin-function
  - Samples can be interpreted by
    $$f_{\text{alias}}(N) = |f - Nf_s|$$

[f_s \geq 2f_{\text{max}}]

courtesy Wikipedia

to be avoided!
I-Q Sampling

- Vector representation of sinusoidal signals:
  - Phasor rotating counter-clockwise (pos. freq.)

\[
y(t) = A \sin(\omega t + \varphi_0) \\
y(t) = A \cos \varphi_0 \sin \omega t + A \sin \varphi_0 \cos \omega t
\]

\[
I: \text{ in-phase component} \\
Q: \text{ quadrature-phase component}
\]

- I-Q sampling at: \( f_s = 4 f \)

\[
y(t) = 1.33 \sin(2\pi + \pi / 5)
\]

\[
A_{n+1} = \sqrt{Q_n^2 + I_{n+1}^2}
\]
I-Q Demodulation of BPM Signals

- Digitized sinusoidal waveform data is sampled, or undersampled at \( f_s/n = 4f_{in} \)
  - Also called digital down-converter (DDC)
  - Gives amplitude and phase of the input signal
    - Phase reference could be \( f_s \) (CLK), of a separate reference signal
Digital Down-Converter

- **Goals**
  - Convert the band limited RF-signal to baseband (demodulation)
  - Data reduction (decimation)

- **DDC Building blocks:**
  - ADC
    - Single fast ADC (oversampling)
  - Local oscillator
    - Numerically controlled oscillator (NCO) based on a direct digital frequency synthesizer (DDS)
  - Digital mixers (“ideal” multipliers)
  - Decimating low pass (anti alias) filters
    - Filtering and data decimation.
    - Implemented as CIC and/or FIR filters
Signal/Noise &
Theoretical Resolution Limit

- Minimum noise voltage at the 1st gain stage:
  - With the stripline BPM and Bessel BPF example:
    \[ R = 50 \, \Omega, \, \Delta f = 25 \, MHz \Rightarrow v_{\text{noise}} = 4.55 \, \mu V \, (-93.83 \, \text{dBm}) \]

- Signal-to-noise ratio:
  - Where \( \Delta v \) is the change of the voltage signal at the 1st gain stage due to the change of the beam position (\( \Delta x, \Delta y \)).
  - Consider a signal level \( v \approx 22.3 \, \text{mV} \, (-20 \, \text{dBm}) \)
    - Bessel BPF output signal of the stripline BPM example
    - \( 22.3 \, \text{mV} / 4.55 \, \mu V \approx 4900 \, (73.8 \, \text{dB}) \) would be the required dynamic range to resolve the theoretical resolution limit of the BPM
  - Under the given beam conditions, e.g. \( n=1e10, \, \sigma=25\text{mm}, \) single bunch, etc.
  - The equivalent BPM resolution limit would be: \( \Delta x=\Delta y=0.66\mu m \)
    (assuming a sensitivity of \( \sim 2.7\text{dB/mm} \))
**S/N & BPM Resolution (cont.)**

- **Factors which reduce the S/N**
  - Insertion losses of cables, connectors, filters, couplers, etc.
    - Typically sum to 3…6 dB
  - Noise figure of the 1st amplifier, typically 1…2 dB
  - The usable S/N needs to be >0 dB, e.g. 2.3 dB is sometimes used as lowest limit. (*HP SA definition*)
  - For the given example the single bunch / single turn resolution limit reduces by ~10 dB (~3x): 2…3 μm

- **Factors to improve the BPM resolution**
  - Increase the signal level
    - Increase BPM electrode-to-beam coupling, e.g. larger electrodes
    - Higher beam intensity
  - Increase the measurement time, apply statistics
    - Reduce the filter bandwidth (S/N improves with $1/\sqrt{BW}$)
    - Increase the number of samples (S/N improves with $\sqrt{n}$)
BPM Read-out Electronics

- Typical BPM read-out scheme
  - Pipeline ADC & FPGA
    - 14-16 bit, >300 MSPS, ~70 dB S/N
  - Separate analog signal processing for the channels
BPM Read-out Electronics

- *Typical BPM read-out scheme*
  - Pipeline ADC & FPGA
    - 14-16 bit, >300 MSPS, ~70 dB S/N
  - Separate analog signal processing for the channels
- **Choices:**
  - Analog downconverter?!
  - RF locked (sync) CLK & LO signals?!
    - No I-Q required

---

[Diagram of BPM read-out electronics with labeled components: A-Electrode Analog Conditioning, BPF, Att, Ctrl, LO, BPF Att, B, C, D Analog same as A, Ctrl LO, CLK & Timing, ADC, NCO, 90°, I-Channel, Q-Channel same as I, Coordinate Transformation, A Data, with analog downconverter.]
Analog Downconverter vs. Direct Digital Under-Sampling

• ADC dynamic range is limited to ~70 dB
  – Not sufficient for most BPM applications
  – Need for analog signal attenuator / gain stages
    ➢ Requires calibration signal to avoid “electronic offsets”

• Analog downconverter
  + Certainly necessary for the conditioning of cavity BPM signals
  + Allows sampling in the 1st Nyquist passband
    (no undersampling)
  + Relaxes input RF filter requirements
  + Relaxed ADC and CLK requirements
  + May relax cable requirements and improve S/N
    ➢ Analog hardware installation near the BPM pickup
    ➢ Transfer analog IF signals out of the tunnel
  – Additional analog hardware required
  – Generates additional image frequencies
    ➢ Consider image rejection analog mixer!
Example: ATF DR BPM Signal Processing

- **ADC Input**: 14 Bits, 71.4 MHz
- **NB Filter**: 1.4 kHz output, 16 Bits/ch
- **TBT Filter**: 8 ch
- **DAQ SM**: Ch delays (clocks), Gates in Turns
- **DDR RAM**: NB Data, TBT Data, Raw Data
- **32 Registers**: latch
- **NB Gate**: reset
- **WB Gate(s)**
- **VME**: NB Sums, NB Data, TBT Data, Raw Data
- **IRQ**: reset latch
- **Average NB data with n/f<sub>power</sub>**
ATF BPM Narrowband Signal Processing

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

- ADC Input
  - 14 Bits
  - 69 MHz

- NCO (sin, cos)
  - 24 Bits Phase (~1 Hz)

- DDC
  - NCO (sin, cos) 24 Bits Phase (~1 Hz)
  - ADC Input 14 Bits 69 MHz

- CIC
  - 5 Stages
  - R=17001

- Bit Shift
  - 24 Bits 4.2 KSPS
  - 20 Bits 4.2 KSPS

- FIR (80 taps)
  - LPF 500Hz
  - Decimate 3

- Select Significant Bits

- Both Magnitude and I,Q are written to RAM
- Also able to write I,Q output from CIC to RAM upon request

- Triangle symbol denotes Peak Detectors to optimize scaling
ATF DR Turn-by-Turn Beam Studies

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

\[ \beta \text{ function measurement} \]
\[ \beta \text{ beating measurement} \]
\[ \phi \text{ measurement} \]

-courtesy Y. Renier-
Libera BPM Electronics

- Analog & digital crossbar switch
  - Compensation of long term drift effects in the analog sections
Libera BPM Performance

- < 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
Outline

• Principle, Applications of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals: capacitive sensors
• Electronics
• Synchronization, accelerator timing
• From precision to accuracy
• Outlook
Beam Threading

- Threading the beam round the LHC ring (very first commissioning in 2008)
  → One beam at a time, one hour per beam.
  → Collimators were used to intercept the beam (1 bunch, $2 \times 10^9$ protons)
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_Courtesy of CMS_
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CAS 2011 H.Schmickler (CERN-BE-BI)
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**Beam 2 threading**

![Graph showing beam threading results](image_url)
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**Beam 2 threading**

*BPM availability ~ 99%*
Outline

• Principle, Applications of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals: capacitive sensors
• Electronics
• Synchronization, accelerator timing
• From precision to accuracy
• Outlook
From Precision to Accuracy

- **BPM sensor:**
  - matching of sensor pairs
  - mechanical pre-alignment to nearest quadrupole magnetic axis (~100 um); further refinement of offsets with k-modulation of quadrupole
  - linearization of response by post-processing based on characterization of BPM response on a measurement bench
  - thermal stabilization of BPM body (= one of the reasons for top-up injection)

- **BPM electronics (prior to beam)**
  - measurement of insertion losses and phase errors of whole RF signal path
  - calculation/measurement of coupling impedance to beam
  - measurement of gain factors of each acquisition chain

- **Various setups in order to inject calibration tones as close to the sensor as possible**
  - button systems: inject in one button + capacitive coupling to 2 adjacent buttons
  - stripline couplers: use 2nd unused port for calibration tone injection
  - use coupling transformers in RF-frontend

- **Thermal stabilization of (analog) readout electronics**

- **Crossbar switches in the RF front-end:** Periodically reassign input signals to the different acquisition chains. Deduce gain factors from signal changes

→ show a few examples (also taken from this conference):
LONG-TERM DRIFT COMPENSATION (AS USED IN MANY LIGHTSOURCES)

• Libera crossbar switching technique
  – <100 nm stability over 14 hours

• Calibration tone technique (only in narrowband operation)
  ATF (KEK)

courtesy N. Eddy
STEP 1, Mapping of BPM head

All BPMs were mapped at a test bench with a movable antenna.

Test bench for the mapping

result for mapping

Test bench mapping of LER (θ)

Test bench mapping of HER (θ)
Button BPM at Synchrotron Light Sources

2-dim electro-static simulation:

\[ d_{AB} = 24 \text{ mm} \]

Result:

- Hori. \( S_x = 8.5\% / \text{mm} \)
- Vert. \( S_y = 5.6\% / \text{mm} \)
- \( x \& y \) dependent polynomial fit possible

Beam position swept with 2 mm steps

From S. Varnasseri, SESAME, DIPAC 2005
STEP 2, Alignment of BPM heads against to the Q-magnets

Measurement of the mechanical offsets of the BPM heads to the Q-magnets.

**Photograph of Measurement tool**

**Results of alignment of BPM heads against to the reference plane of the Q-Magnets**
STEP-3, Gain calibration of the electronics
Attenuation of cable, switch, electronics, etc.

We measured the distribution of signal attenuation of all electronics. We used a dummy head instead of BPM heads.

Results for ratio between output signal B, C, and D against A in all electronics.

Output signals: A, B, C, D
Beam Based Alignment

• Measurement of the offset of BPM to the field center of the adjacent Q-magnet using the beam.

Beam Based Gain Calibration

• Calibration of the gain imbalance among four outputs of a BPM using the beam.
Beam based alignment (BBA) - Principle -

- BBA is searching for the beam orbit which is insensitive to the change of field strength in the quadrupole = magnetic axis of this quad.
- The measured beam position for this orbit corresponds to origin offset of the BPM.
- The offset gets introduced into correction tables for the BPM readings.

\[ \Delta X_m = 0 \quad \text{then} \quad \delta x_m \text{ offset} \]
Actual procedure for BBA

Bump orbits: -8, 0, 8 [mm]
I_Q: -4, -2, 0, 2, 4 [A]
- current of correction coil
from figure (a), (b), (c),
\( \Delta x / \Delta I_Q \) and \( x (I_Q=0) \),
where \( x = x_m \)

\[ \Delta x / \Delta I_Q = 0 \]
\[ X = 0.4913 \text{[mm]} \]

Alternative method (sinusoidal modulation of q-current at low frequencies) + synchronous detection of orbit variations at the modulation frequency....
Gain mapping

Button to button gain errors

Any difference in the effective button gains, electronic or physical, couple real horizontal dispersion into measured vertical dispersion (and the horizontal dispersion is large)

Slides provided by: D. Rubin, Cornell University
8-September 2015
Signal at each button depends on bunch current \( (k) \) and position \((x,y)\)

\[
B_1 = k f(x, y)
\]

\[
B_1 \approx k \left( f(0,0) + \frac{\partial f}{\partial x} x + \frac{\partial f}{\partial y} y + \frac{1}{2} \frac{\partial^2 f}{\partial x^2} x^2 + \frac{1}{2} \frac{\partial^2 f}{\partial y^2} y^2 + \frac{\partial^2 f}{\partial x \partial y} x y + \ldots \right)
\]

\[
B_1 \approx k (c_0 + c_1 x + c_2 y + c_3 x^2 + c_4 y^2 + c_5 xy)
\]

Signals on the four buttons are related by symmetry

\[
B_2 = k f(-x, y)
\]

\[
B_3 = k f(x, -y)
\]

\[
B_4 = k f(-x, y)
\]

Combining sums and differences we find the following relationship, good to second order

\[
B_1 - B_2 - B_3 + B_4 = \frac{1}{k} \left( \frac{c_5}{c_1 c_2} \right) (B_1 - B_2 + B_3 - B_4)(B_1 + B_2 - B_3 - B_4)
\]

\[
B(+-+-) = \frac{c}{k} B(+--+)(+---)
\]
A single beam passage gives a measurement of intensity at each of four button electrodes

\[ B_j = 1, 4 \]

N beam passages gives

\[ B^i = 1, N \]

\[ B_j = 1, 4 \]

The gains are the set of \( g_j \) that minimize

\[ \chi^2 = \sum_{i}^{N} \left[ (g_1 B_1^i - g_2 B_2^i - g_3 B_3^i + g_4 B_4^i) \right] \]

\[- \frac{c}{I} (g_1 B_1^i - g_2 B_2^i + g_3 B_3^i - g_4 B_4^i) (g_1 B_1^i + g_2 B_2^i - g_3 B_3^i - g_4 B_4^i) \]
\[ B(+ - - +) = \frac{c}{k} B(+ - + -)B(+ + --) \]

1024 measurements
Fitted gains \( g_{1-4} = (1.007, 1.016, 0.9434, 1.035) \)
Outline

• Principle, Usage of BPMs
• Functional Specifications (FS)
• Sensors + Sensor Signals
• Electronics
• Synchronization, accelerator timing
• From precision to accuracy
• Outlook
  - new LHC orbit system for LHC-LS3 (2024)
  - Electro-optical BPMs → Intrabunch Measurements for <ns bunches
LHC BPM Timing Specs – 1st thoughts

• Upgrade of the LHC BPM electronics (for HL-LHC):
  – Keep existing infrastructure
    ➢ Beam pickups, cables, fibers, VME system, etc.
  – Upgrade of analog, DAQ and trigger electronics
    ➢ Minimalistic analog front-end
      – Preferable time-multiplexed single channel for 2 BPM electrodes
    ➢ Digital direct downconversion (DDC) technique
      – Convolution integral or I/Q mixing?
    ➢ Internal ADC and FPGA clocks with ultra-low sub-ps jitter!
    ➢ External RF bucket tagging trigger!

• Relaxed external timing requirements:
  – RF bucket synchronous trigger signals in 2.5 ns increments
    ➢ Jitter & drift effects <<1 ns
    ➢ Needs to be supplied to each BPM DAQ electronics
      – Of course separate trigger signals for B1 and B2
Conceptual Idea

- **Brute-force digitalization**
  - E.g. TI ADC12J4000
    - 12-bit, 4 GSPS, SFDR \(\approx 67\ \text{dBFS}\), SINAD \(\approx 55\ \text{dBFS}\) (@350MHz)
    - Intergraded DDC, decimation by 4 or 8 (400MHz pass-band)
      - SFDR \(\approx 75\ \text{dBFS}\), SINAD \(\approx 63\ \text{dBFS}\) (@600MHz)
  - Internal CLKs for ADC and FPGA
  - External 40 MHz trigger (2.5ns steps) for bunch tagging (memory)

- **Single analog processing channel**
  - Based on delay-line networks and band-pass filters
Analog Signals

- Gaussian bunch:
  - $n=1\times10^8$, $\sigma=25\text{mm}$, $v=c_0$
  - vertical offset=$1\text{mm}$

- BPM sensitivity:
  - e.g.: 2.7 dB / mm

Beam pickup signal

Conditioned analog signal

400 MHz delay-line filter network

12.5 ns delay-line

$25\text{ns}$ $25\text{ns}$
Waveform Sampling Options

• 4 GSPS = 250 ps sample spacing
  – 100 samples per 25 ns with single ADC
    ➢ 50 samples per electrode signal, but only 20…24 samples ≠ 0
  – 200 samples per 25 ns with two interleaved ADC in I/Q operation

• Requires low CLK jitter within 25 ns time interval
  – E.g. \( t_a = 0.15 \text{ ps} \rightarrow 68.5 \text{ dB@400 MHz} \) (equivalent to EOB=11.1)

\[
\text{SNR} = -20 \log_{10}(2\pi f t_a)
\]
Schematic of EO-BPM

See also: S. Gibson (RHUL this conference)

- All-Optical-BPM layout scheme, re-use conceptually LHC BPM design:
  - Keep the same body, keep external button form-factor
  - Transverse variant:
  - Longitudinal variant:

- E.g. polarisation (→ pockels cell) or phase retardation (Fabry-Perot)
  - In the tunnel...
  - Simple → robust design:

- Few m to km of single-mode fiber
- RF out
All optical BPM laser lab set-up
Wide-Band Improvement on RF Hybrid Junction: (MSM)

- Possible Detection scheme

Sum $\Sigma$ and Difference $\Delta$ signals are computed in electro-optical domain
  - Aim at 12+ GHz Bandwidth
Instead of a summary: Thank You for Your Patience