Non-invasive Beam Diagnostics of High- and Low-Intensity Beams

Wolfgang Hillert

Physics Institute of Bonn University

- Electrostatic Pick-Ups: 4-Button-BPM
- RF Cavities: $I$ and $\Delta x$ Measurement of Low-Intensity Beams
- SYLI Monitors: High- and Low-Intensity Applications
- Streak Cameras: transverse and longitudinal Imaging with ps-Res.
Where is the beam?
Where is the beam?
The most simplest way:
Pick-Ups
Relativistic case: Electric & magnetic fields become transverse to the direction of motion (TEM).
Measuring Beam Position – The Principle
Electrostatic Monitor – The Principle
Electrostatic Monitor – Beam Response

\[ f_L = \frac{1}{2 \pi R C} \]

Caspers Jones Microwave sensors  GeMIC 2011
Electrostatic Pick-Up Buttons

- $\lambda_w(s)$
- $I_e$
- $Z_c$
- $U$
- $C$
- $R$
- $a$
- $E_t$
- $\lambda(s)$
- $s$
- $r$
- $2\sigma_s = 6 \text{ cm}$
- $\lambda_{HF} = 60 \text{ cm}$

Diagram showing a schematic of an electrostatic system with labels for different components and parameters.

Voltage vs. Time graph showing a wave form.

Electrode and Kammer labeled in the diagram.

Querschnitt (cross-section) and other components labeled.
4-Button BPM

Intensity $\leftrightarrow$ $\Sigma$-Signal:

$$\Sigma = U_1 + U_2 + U_3 + U_4$$

Position $\leftrightarrow$ $\Delta$-Signal:

$$q_x := \frac{\Delta x}{\Sigma} = \frac{U_1 - U_2 - U_3 + U_4}{U_1 + U_2 + U_3 + U_4}$$

$$q_y := \frac{\Delta y}{\Sigma} = \frac{U_1 + U_2 - U_3 - U_4}{U_1 + U_2 + U_3 + U_4}$$

$$u = k_u \cdot q_u$$
Signal Quality

- Quotient $q_x = \frac{\Delta x}{\Sigma}$
- Quotient $q_y = \frac{\Delta y}{\Sigma}$
- Summe $\Sigma$
- Skew $S$
BPM Electronics

BPM-Monitor

Details der analogen Signalverarbeitung

32 BPM’s in ELSA
Relative Genauigkeit: \( \Delta x/x = \mu m \)
Achievable Resolution

\[ \Delta f = 500 \text{Hz} \]
Beam Based Alignment

Calibration of the BPM offset:

Position of the misaligned Quadrupole

$\Delta n [1/m]$ vs. $\psi/(2\pi)$ [rad]

$\Delta y_i / \mu m$ vs. $y_m / \text{mm}$
Electron Stretcher Accelerator (ELSA)
Closed Orbit von ELSA

horizontale Ebene
Δf: -609.6 Hz
x_{max}: 2.799 mm
x_{rms}: 1.322 mm

vertikale Ebene
y_{max}: 1.508 mm
y_{rms}: 0.689 mm

Legende
- F- Quadrupol
- D- Quadrupol
- Dipol

Komponenten
- BPMs
- Korrekturen

Korrektur
- Orbitkorrektur

Einstellungen
- SYLI
- GDH

Bereich
- ±2 mm
- ±5 mm
- ±10 mm
- ±20 mm

I: 2.8 mA
E: 1.9 GeV
t: 0.000 h
Measurement on the Ramp

vertical beam position / mm in stretcher during ramp $E_{\text{inj}} = 1.200$ GeV, $E_{\text{extr}} = 2.350$ GeV

$\dot{B} = 1.2$ Tesla/s

$\Delta z_{\text{rms}} \leq 80$ µm
Cavities
How to increase U?
What happens when a Beam passes a Resonator?

... e.g. accelerating cavities:
Eigenmodes of a Pill-Box Resonator

We are interested in longitudinal electric fields!

Well known from waveguides:

Classification of modes:
- TM or E (transverse magnetic)
- TE or H (transverse electric)

Important boundary conditions:
- vanishing $H_{\perp}$ at the conducting walls
- vanishing $E_{\parallel}$ at the conducting walls
Solutions of the Diff. Equations

Bessel Functions:
- replace sin and cos for cylindrical sym.
- not much liked
- index is linked to azimuthal symmetry

**TE$_{mnp}$-Modes:** \[ H_z = H_{mn} \cdot J_m(k_cr) \cdot \cos(m\phi) \cdot \sin(p\pi/l \cdot z) \cdot e^{i\omega_{mnp}t} \]

**TM$_{mnp}$-Modes:** \[ E_z = E_{mn} \cdot J_m(k_nr) \cdot \cos(m\phi) \cdot \cos(p\pi/l \cdot z) \cdot e^{i\omega_{mnp}t} \]

For the resonant frequencies one has: \[ \omega_{mnp} = c \cdot \sqrt{(j_{mn}/a)^2 + (p\pi/l)^2} \]
Most important Eigenmodes

\textbf{TM}_{010} \textit{mode}

\( \hat{E}(\vec{r}) \) \hspace{1cm} \( \hat{H}(\vec{r}) \)
Most important Eigenmodes

$E(\vec{r})$  $H(\vec{r})$

$TM_{110}$ mode
A simple Equivalent Circuit

Voltages: \(-U_C = U_R = U_L\)

Currents: \(I_C + I_{\text{ext}} = I_R + I_L\)
\[
I_C = \dot{Q}_C = C \cdot \dot{U}_C
\]
\[
I_R = U_R / R
\]
\[
I_L = U_L / L
\]

\[
\hat{U} = \frac{R \cdot \hat{I}_{\text{ext}}}{1 + iQ \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)} \bigg|_{\omega = \omega_0} = R_S \cdot \hat{I}_{\text{ext}}
\]

Quality Factor

\[
\tan \varphi = Q \left( \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega} \right)
\]

Shunt Impedance
Coupling

- Coupling to the magnetic field (loop coupling)
- Coupling to the electric field (pin coupling)
- Direct coupling out of a waveguide (hole coupling)
Improving the Precision for Next Generation Accelerators

- Standard BPMs give intensity signals which need to be subtracted to obtain a difference which is then proportional to position
  - Difficult to do electronically without some of the intensity information leaking through
    - When looking for small differences this leakage can dominate the measurement
    - Typically 40-80dB (100 to 10000 in V) rejection ⇒ tens micron resolution for typical apertures

- Solution – cavity BPMs allowing sub micron resolution
  - Design the detector to collect only the difference signal
  - Dipole Mode $TM_{11}$ proportional to position & shifted in frequency with respect to monopole mode

![Frequency Domain Diagram](image)

Courtesy of D. Lipka, DESY, Hamburg

$U \sim Q$, $U \sim Q_r$, $U \sim Q$
Cavity BPMs

- BPM resolution typically limited by problem of taking a difference between large numbers (2 opposing electrodes)

- Cavity BPMs have different frequency response for fundamental and difference mode
  - Aids in fundamental rejection
  - Can give sub-micron resolution.

  **BUT:**
  - Damping time quite high due to intrinsic high Q $>>1000$
  - Poor time resolution (~100ns)
Today’s State of the Art BPMs

- Obtain signal using waveguides that only couple to dipole mode
  - Further suppression of monopole mode

Prototype BPM for ILC Final Focus
- Required resolution of 2nm (yes nano!) in a 6×12mm diameter beam pipe
- Achieved World Record (so far!) resolution of 8.7nm at ATF2 (KEK, Japan)
Signal Strength (cw Operation)

Signal power coupled out of a resonant cavity:

\[
P_{\text{sig}} = \frac{R_S \cdot I^2 \cdot B^2}{\text{"Ohm's law"}} \cdot \frac{\kappa}{(1 + \kappa)^2} \cdot \frac{1}{1 + 4Q^2 \cdot \left(\Delta \omega / \omega_0\right)^2}
\]

Shunt impedance:

\[
R_S(r, \varphi) = \frac{1}{2P_{\text{loss}}} \left| \int_0^L E_z(r, \varphi, z) \cdot e^{i(\omega_0 z/c + \phi_0)} \cdot dz \right|^2
\]

Electric fields:

\[
E_z(r, \varphi, t) = \hat{E} \cdot J_0\left(\frac{j_{01}}{R}\right) \cdot e^{i\omega_0 t}
\]

\[
E_z(r, \varphi, t) = \hat{E} \cdot J_1\left(\frac{j_{11}}{R}\right) \cdot \cos(\varphi) \cdot e^{i\omega_0 t}
\]

Bunch Factor \( B \):
**Bead-Pull Measurement**

Bead Constant:
\[ \alpha_s = \frac{1}{2} (\varepsilon - \varepsilon_0) V_s \]

\[ \omega_0 = \frac{1}{\sqrt{LC}} \quad \rightarrow \quad \hat{E}(z) = \sqrt{2 \cdot \frac{W}{\alpha_s} \cdot \frac{\Delta \omega(z)}{\omega_0}} \]
**Intensity Resonator**

<table>
<thead>
<tr>
<th>Größe</th>
<th>Zeichen</th>
<th>Simulation</th>
<th>Messwert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonanzfrequenz</td>
<td>$\nu_0$</td>
<td>(1,499 010 ± 0,000 010) Ghz</td>
<td></td>
</tr>
<tr>
<td>Koppelfaktor</td>
<td>$\kappa$</td>
<td>1,069 ± 0,013</td>
<td></td>
</tr>
<tr>
<td>Leerlaufgüte</td>
<td>$Q_0$</td>
<td>18 913</td>
<td>17 540 ± 130</td>
</tr>
<tr>
<td>Shuntimpedanz</td>
<td>$R_s^L$</td>
<td>4,00</td>
<td>(2,94 ± 0,22) MΩ</td>
</tr>
</tbody>
</table>
Signal Quality

\[ P_{\text{noise}} = 4 k_B T \cdot \Delta f \]

\[ P_{\text{noise}} = 1.7 \cdot 10^{-20} \text{ W/Hz} \cdot \Delta f \]
Position Cavities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td>$\text{TM}_{110}$</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>242 mm</td>
</tr>
<tr>
<td>Inner length</td>
<td>52 mm</td>
</tr>
<tr>
<td>Opening diameter</td>
<td>34 mm</td>
</tr>
<tr>
<td>Resonant frequency $\nu_0$</td>
<td>1,499010 GHz</td>
</tr>
<tr>
<td>Shunt impedance $R_s/\Delta x^2$ (CST)</td>
<td>411 Ω/mm²</td>
</tr>
<tr>
<td>Unloaded quality factor $Q_0$</td>
<td>11090</td>
</tr>
<tr>
<td>Coupling factor $\kappa$</td>
<td>0.89</td>
</tr>
</tbody>
</table>
$I_B = 800 \text{ pA}$
$I_B = 600 \text{ pA}$
$I_B = 400 \text{ pA}$
$I_B = 200 \text{ pA}$

$P_{\text{noise}} = 4k_B T \cdot \Delta f$

$P_{\text{noise}} = 1.7 \cdot 10^{-20} \text{ W/Hz} \cdot \Delta f$
Signal Processing

- 1 MHz to 102.4 kHz frequency range
- >100 dB dynamic reserve
- 5 ppm/°C stability
- 0.01 degree phase resolution
- Time constants from 10 µs to 30 ks (up to 24 dB/oct rolloff)
- Auto-gain, -phase, -reserve and -offset
- Synthesized reference source
- GPIB and RS-232 interfaces
Signal Processing
Signal Processing

> 100 dB Isolation!!!
Electronic Modules

(a) Oszillator-Modul.
(b) Referenz-Modul.
(c) Verstärker-Modul.
Results
**Results**

**Achievable resolution:**

\[
\Delta P = \lambda \cdot \left( x_1^2 - x_0^2 \right)
\]

\[
\Delta x = \frac{\Delta P}{\lambda \left( 2x_0 + \Delta x \right)} \approx \frac{0.014 \text{ mm}^2}{2x_0 + \Delta x}
\]

\( (I = 250\text{pA}, \ \tau = 30\text{ms}) \)
And what about beam quality?
And what about beam quality?
Synchrotron Radiation

Hertz Dipole:

$$P = \frac{e^2}{12\pi \varepsilon_0 c^3} \cdot \omega^4 d^2$$

Curved Orbit:

$$P = \frac{e^2 c}{6 \pi \varepsilon_0} \cdot \frac{\gamma^4}{R^2}$$

Can this be used to take “pictures” of the beam?
Principle of Imaging

2D image of the revolving bunch!
→ Access to the transverse intensity distributions!
Aberrations

Curved Orbit:

$$\Delta x_k = \frac{R}{\cos \Theta_h} - R \approx \frac{1}{2} R \Theta_h^2 \approx \sigma_k$$

Emission Length:

$$\tan \Theta_2 = \frac{\Delta x_s}{d}, \quad \sin \Theta_1 = \frac{d}{2R}$$

$$\Delta x_s \approx 2R\Theta_1\Theta_2 \approx 4\sigma_s$$

horz.: $$\Theta_1 = \Theta_2 \approx \frac{b}{2L}$$
Aberrations

Diffraction:

\[ \delta \approx 0.183 \cdot \frac{2\lambda}{b}, \quad M = \frac{L'}{L}, \quad \Theta \approx \frac{b}{2L} \]

\[ \sigma_b = \frac{L'}{M} \tan \delta \approx 0.183 \cdot \frac{2L\lambda}{b} \approx 0.183 \frac{\lambda}{\Theta} \]

Achievable Resolution:

- horizontal: \[ \sigma_{\text{hor}} = \sqrt{\sigma_k^2 + \sigma_s^2 + \sigma_b^2} = \sqrt{\frac{R^2 \Theta_h^2}{2} + \frac{0.183^2 \cdot \lambda^2}{\Theta_h^2}} \]
- vertical: \[ \sigma_{\text{ver}} = \sqrt{\sigma_s^2 + \sigma_b^2} = \sqrt{\frac{R^2 \Theta_h^2}{4} + \frac{0.183^2 \cdot \lambda^2}{\Theta_v^2}} \]
Achievable Resolution

Messingrad zum Einstellen der Blendenposition

Blendenpaar
\[ I = 0.003 \text{ Lux} \quad @ \quad F = 1.4 \]
Digital Image Processing
Imaging @ 100 pA:
Transport via Fibre Optics
\[ N_e \approx 10^5 \text{ e}^- \]
First SYLI-Monitor @ ELSA

- differential pumping, vacuum < $10^{-8}$ mbar !!
- water-cooled mirror of optical quality !!
The Mirror Problem

Abbildung 8.13: Simulierte Temperaturverteilung mit den Programmen Solid Works (links) und ADINA (rechts)[15].
The Mirror Problem
The UV Monitor

\[ E = 1.2 \text{ GeV} \]

\[ \sigma_x = 0.98 \text{ mm} \]

\[ \sigma_z = 0.31 \text{ mm} \]

\[ f_1 = 1000 \text{ mm} \]
Streaks
Streak Camera

Time resolved measurement of intensity (distributions)
System set-up:
The M7 Photon Beamline

- Primary reflecting mirror
- Streak camera Hamamatsu C10910
- Beam shaping optics
Dual Axis Sweep Operation

Single $e^-$ bunches at 1.2 GeV beam energy
Dual Axis Sweep Operation

9 bunch train revolutions over 195 $\mu$s
Vertical oscillations due to ion effects
Dual Axis Sweep Operation

9 bunch train revolutions over 195 \( \mu s \)
Vertical oscillations due to ion effects

What about horizontal dynamics?
The streak operation reduces beam information to one transverse plane.
The streak operation reduces beam information to one transverse plane.

For simultaneous observation two beam images are required.
Optical Imaging Beamline

\[ M = \frac{f_1}{g_1 - f_1} \cdot \frac{f_3}{f_2} \]

Variable image magnification with lens pair \( f_3 \) & \( f_2 \)
Optical Imaging Beamline

\[ M = \frac{f_1}{g_1 - f_1} \cdot \frac{f_3}{f_2} \]

- Variable image magnification with lens pair $f_3$ & $f_2$
- Horizontal and vertical beam image projection
Optical Imaging Beamline

\[ M = \frac{f_1 \cdot f_3}{g_1 - f_1 \cdot f_2} \]

- Variable image magnification with lens pair \( f_3 \) & \( f_2 \)
- Horizontal and vertical beam image projection simultaneously
Optical Imaging Beamline

\[ M = \frac{f_1}{g_1} \cdot \frac{f_3}{f_2} \]

- Variable image magnification with lens pair \( f_3 & f_2 \)
- Horizontal and vertical beam image projection \textit{simultaneously}
- Variable path length allows photon TOF adjustment \((0 - 300 \text{ ps})\)
The Injection Process

a) Focus mode
a) Focus mode

b) Injection bunch train, turn 1
The Injection Process

a) Focus mode
b) Injection bunch train, turn 1
c) Betatron oscillations, 4 turns
The Injection Process

a) Focus mode
b) Injection bunch train, turn 1
c) Betatron oscillations, 4 turns
d) $\approx 300$ turns of injected beam
Single Bunch Resolution

Damped & stable beam

For high SNR, image averaging becomes necessary
Single Bunch Resolution

For high SNR, image averaging becomes necessary

Jitter $> 100$ ps is unavoidable for very slow streaks!
Single Bunch Resolution

- Damped & stable beam
- Very slow streak
- TOF difference
- Streak 1, Streak 2, Streak 3
- Trigger jitter of several ps

- For high SNR, image averaging becomes necessary
- Jitter > 100 ps is unavoidable for very slow streaks
- Better synchronization is given by “synchroscan mode”
Single Bunch Resolution - Synchroscan

- Slower streak
- 125 MHz vertical sweep
- Linear horizontal sweep
- 8 ns
- 1.2 GeV, single shot

Bunch number (500 MHz spacing)
Synchronized to 500 MHz master clock

Every 4th bucket is displayed in each row (125 MHz)

Precise longitudinal measurements from 60 ns to 100 ms
Single Bunch Resolution - Synchroscan

- Synchronized to 500 MHz master clock
- Every 4\textsuperscript{th} bucket is displayed in each row (125 MHz)
- Precise longitudinal measurements from 60 ns to 100 ms
- Side & top view of single bunches
Bunch Length Measurements

Bunch length and beam energy
Bunch Length Measurements

Bunch length and beam energy

- Bunch length is dependent on energy spread
- Agreement with theoretical expectation
Longitudinal Beam Dynamics

Longitudinal particle oscillation around the acceleration phase $\psi_s$:

$\Delta \frac{p}{p} < 0$

$\Delta \frac{p}{p} = 0$

$\Delta \frac{p}{p} > 0$

Damping time at 1.2 GeV $\approx 30$ ms
Longitudinal Beam Dynamics

Longitudinal particle oscillation around the acceleration phase $\psi_s$:

$U_0$

$U_{acc}$

longitudinal oscillations due to dispersion

$\frac{\Delta p}{p} < 0$

$\frac{\Delta p}{p} = 0$

$\frac{\Delta p}{p} > 0$

$\triangleright$ Damping time at 1.2 GeV $\approx 30$ ms

$\triangleright$ The cavity phase jump causes coherent bunch oscillations
Longitudinal Beam Dynamics

Longitudinal particle oscillation around the acceleration phase $\psi_s$:

- Damping time at 1.2 GeV $\approx 30$ ms
- The cavity phase jump causes coherent bunch oscillations, decoherence and temporary change of charge distr.
Longitudinal Beam Dynamics

Longitudinal particle oscillation around the acceleration phase $\psi_s$:

- Damping time at 1.2 GeV $\approx 30$ ms
- The cavity phase jump causes coherent bunch oscillations, decoherence and temporary change of charge distr.
Longitudinal Beam Dynamics – Damping Times

![Synchroscan image]

Exponential fit to long. beam envelope

\[ \tau = 19.78 \text{ ms} \]
Longitudinal Beam Dynamics – Damping Times

Damping constant $\tau_s$ depends on energy
Damping constant $\tau_s$ depends on energy

More beam stability at higher energies due to faster damping
Longitudinal Beam Dynamics

Damping behavior in dependency of accelerating cavity temperature:

Wakefields within the cavity

Multibunch instability is driven by switching off the BBB feedback for 5 ms
Longitudinal Beam Dynamics

Damping behavior in dependency of accelerating cavity temperature:

- Wakefields within the cavity

- Multibunch instability is driven by switching off the BBB feedback for 5 ms
- Self-driving instability observed for certain cavity temperatures
Longitudinal Beam Dynamics

Damping behavior in dependency of accelerating cavity temperature:

Wakefields within the cavity

- Multibunch instability is driven by switching off the BBB feedback for 5 ms
- Self-driving instability observed for certain cavity temperatures
Longitudinal Beam Dynamics

Damping behavior in dependancy of accelerating cavity temperature:

Wakefields within the cavity

- Multibunch instability is driven by switching off the BBB feedback for 5 ms
- Self-driving instability observed for certain cavity temperatures
Longitudinal Beam Dynamics

Damping behavior in dependancy of accelerating cavity temperature:

Wakefields within the cavity

- Multibunch instability is driven by switching off the BBB feedback for 5 ms
- Self-driving instability observed for certain cavity temperatures
Conclusions: what should be remembered?

Measurement of Beam Intensity and Position:

- Electrostatic Pick-Ups ($I \geq 1\text{mA}$): standard device, $\mu$m precision
- RF Cavities (small $I$ down to pA): $\text{TM}_{01} / \text{TM}_{11}$, low bandwidth or ultra-high precision ($\text{nm!}$) in case of sufficient intensity

Measurement of Beam Profile:

- Synchrotron-Light Monitors: transv. imaging, resolution $>10\ \mu\text{m}$ typ. Intensity resolution depends on residual light, can go down to pA-regime
- Streak Camera (ps-resolution): enables longitudinal imaging full 3D-imaging of single bunches with beam splitter and dove prism!

Thank you for your attention!