Accelerator Laboratory: Introduction to Beam Diagnostics and Instrumentation

Gero Kube, Kay Wittenburg
DESY / MDI

- Introduction
- Beam Position Monitor
- Transverse Emittance / Beam Profile

37th ICFA Advanced Beam Dynamics Workshop, Frascati, Italy
Diagnostics and Instrumentation

**instrumentation**
- catchword for all technologies needed to produce primary measurements of beam parameters

**diagnostics**
- making use of these instruments in order to
  - operate the accelerators
    - orbit control
  - improve the accelerator performance
    - feedback, emittance preservation
  - deduce additional beam parameters or performance indicators of the machine by further data processing
    - chromaticity measurements, betatron matching, … (examples for circular accelerator)
  - detect equipment faults

**outline**
- emphasis on beam instrumentation

H. Schmickler, Introduction to Beam Diagnostics, CAS 2005
Beam Instrumentation for...

- **beam position**
  - orbit, lattice parameters, tune, chromaticity, feedback,…

- **beam intensity**
  - dc & bunch current, coasting beam, lifetime, efficiencies,…

- **beam profile**
  - longitudinal and transverse distributions, emittances,…

- **beam loss**
  - identify position of losses, prevent damage of components,…

- **beam energy**
  - mainly required by users,…

- **luminosity (collider)**
  - key parameter, collision optimization,…

and even more: charge states, mass numbers, timing…
Beam Monitors: Physical Processes

- **influence of particle electromagnetic field**
  - **non-propagating fields**, i.e. electro-magnetic influence of moving charge on environment
    - → beam transformers, pick-ups, …
  - **propagating fields**, i.e. emission of photons
    - → synchrotron radiation monitors, (OTR), …

**particle electromagnetic field**

- relativistic contraction characterized by Lorentz factor $1/\gamma$

- electric field lines in LAB frame

- proton: [image]
- electron: [image]
Beam Monitors: Physical Processes

- non-propagating field

\[ \text{Observer} \]

\[ \rho = 40 \text{ mm} \]

- propagating field
  (synchrotron radiation)

\[ \text{E}_{\text{kin}} = 20 \text{ GeV} \]
\[ \rho = 370 \text{ m} \]
Beam Monitors: Physical Processes

**Coulomb interaction of charged particle penetrating matter**

→ viewing screens, residual gas monitors, …

![Graph showing electron energy loss](image)

**Bethe Bloch Equation** („low-energy approximation“)

- **constants:**
  - $N_A$: Avogadro number
  - $m_e$, $r_e$: electron rest mass, classical electron radius
  - $c$: speed of light

- **target material properties:**
  - $\rho$: material density
  - $AT$, $ZT$: atomic mass, nuclear charge
  - $I$: mean excitation energy

- **particle properties:**
  - $Z_p$: charge
  - $\beta$: velocity, with $\beta = \frac{p}{Me}$, where $p$ is the proton momentum [GeV/c]

**Electrons: Bremsstrahlung**

![Diagram showing Bremsstrahlung](image)
**Beam Monitors: Physical Processes**

- **nuclear or elementary particle physics interactions**
  - beam loss monitors, luminosity monitors...

**electrons**
- simple (point) objects
- interaction cross sections into final states can be calculated precisely

**hadrons**
- constituent nature (collection of quarks and gluons)
- interaction cross sections not precisely calculable

- **interaction of particles with photon beams**
  - laser wire scanners, Compton polarimeters, ...

**electrons:** Compton scattering

**hadrons:** laser photo neutralization (H- beam)

applied for high power H- beam profile diagnostics
Signal Processing

- **system approach**

  ![Diagram of a signal processing system](image)

  **Input** $x(t)$ → **System Response** $h(t)$ → **Output** $y(t)$

  **time domain**

  **frequency domain**

- **monitors probing (non-propagating) el.magn. field**

  - **input**: beam current spectrum $I(\omega)$

  - **system response**: monitor impedance $Z(\omega)$

  - **output**: voltage $U(\omega)$

- **design task**

  proper impedance matching to maximize monitor output → sensitivity

- **monitor input**

  - radiation spectrum
  - secondary particles
  -...

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Beam Position Monitor
(BPM)
### Beam Position Monitors

#### short version of E-XFEL BPM specification

<table>
<thead>
<tr>
<th>Type</th>
<th>Number</th>
<th>Beam Pipe Length</th>
<th>Beam Type</th>
<th>Single Bunch Resolution (RMS)</th>
<th>Train Averaged Resolution (RMS)</th>
<th>Optimum Resolution Range</th>
<th>Relaxation Crosstalk Range</th>
<th>x/y Crosstalk Tolerance (RMS)</th>
<th>Bunch to Bunch Crosstalk Tolerance (RMS)</th>
<th>Trans. Alignment Tolerance (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard BPM</td>
<td>219</td>
<td>mm</td>
<td>mm</td>
<td>Button</td>
<td>50 µm</td>
<td>± 3.0 mm</td>
<td>± 10 %</td>
<td>10 µm</td>
<td>10 µm</td>
<td>200 µm</td>
</tr>
<tr>
<td>Cold BPM</td>
<td>102</td>
<td>78 mm</td>
<td>170 mm</td>
<td>Button/Re-entrant Cavity</td>
<td>50 µm</td>
<td>± 3.0 mm</td>
<td>± 10 %</td>
<td>10 µm</td>
<td>300 µm</td>
<td></td>
</tr>
<tr>
<td>Cavity BPM Beam Transfer Line</td>
<td>12</td>
<td>40.5 mm</td>
<td>255 mm</td>
<td>Cavity</td>
<td>10 µm</td>
<td>± 1.0 mm</td>
<td>± 2 %</td>
<td>1 µm</td>
<td>1 µm</td>
<td>200 µm</td>
</tr>
<tr>
<td>Cavity BPM Undulator IBFB</td>
<td>117</td>
<td>10 mm</td>
<td>100 mm</td>
<td>Cavity</td>
<td>1 µm</td>
<td>± 0.5 mm</td>
<td>± 2 %</td>
<td>1 µm</td>
<td>0.1 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>200 mm</td>
<td>255 mm</td>
<td>Cavity</td>
<td>1 µm</td>
<td>± 1.0 mm</td>
<td>± 2 %</td>
<td>1 µm</td>
<td>0.1 µm</td>
<td>200 µm</td>
</tr>
</tbody>
</table>

specification charge range: 0.1 – 1 nC

different BPM types to meet different requirements

courtesy: D.Nölle (DESY)
**Beam Position Monitor**

- **most common: capacitive pickups**
  - signal generation via beam electric field
  - popular design: **button-type pickup**
    - simple, cheap, ...
    - moderate resolution

- **operation principle**
  - electric field induces image charge on pick-up
    - pick-up mounted isolated inside vacuum chamber
    - amount of induced charge depends on distance between beam and pick-up

- **button pickup: high pass characteristics**

*not well suited for long bunches*
- especially: low energy hadron beams, i.e. heavy ion beams
- small coupling between pickup and bunch

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P. Forck, “Lecture Notes on Beam Instrumentation and Diagnostics”, JUAS 2011

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BPM Signal Generation

- Induced charge on BPM button: $Q_{\text{ind}}(t)$
- BPM button, Ø2a
- E-bunch
- Chamber geometry
- Beam charge & bunch length

- Image charge
- Button voltage
- Signal behind cable

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BPM Signal Calculation

Beam Instrumentation System Simulator (B.I.S.S.)
- calculation from BPM signals in time- and frequency domain
- study influence of various parameters
BPM Signals

observation (1): signals are short with small modulation
- single bunch response → nsec or sub-nsec pulse signals
- beam position information → amplitude modulated on large (common mode) beam intensity signal!

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

RF device, EM field detection, center of charge symmetrically arranged electrodes or resonant structure

trigger, CLK & timing signals provides calibration signals or other drift compensation methods
timing, trigger signals

courtesy: M. Wendt (CERN)
BPM Signals

observation (2): nonlinearities

- synchrotron radiation emission
  → pickups mounted **out of orbit plane**
- vacuum chamber not rotational symmetric
  → $\varepsilon_{\text{hor}} \gg \varepsilon_{\text{vert}}$ (SR emission in hor. plane)
  → injection oscillations due to off-axis injection (allows intensity accumulation)

especially BPMs for circular e-accelerators

courtesy: A. Delfs (DESY)

Position Map

Pump channel

button pickup (cut)

PETRA-III BPM close to ID

correction of strong non-linearities in beam position required
Position Reconstruction

**two common monitor geometries**
- difference in position reconstruction

**linac-type**

\[
x = \frac{P_1 - P_3}{K}\]

\[
y = \frac{P_2 - P_4}{K}\]

**storage ring-type**

\[
x = \frac{(P_1 + P_4) - (P_2 + P_3)}{K}\]

\[
y = \frac{(P_1 + P_2) - (P_3 + P_4)}{K}\]

**position information**
- requires knowledge of monitor constant \(K_x, K_y\)
- rule of thumb (circular duct)

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Monitor Constant Calculation

- arbitrary geometries
  - no simple rule of thumb calculation

strategy for calculation
- start with position raster for point beam
- for each beam position \((x_0, y_0)\)
  - calculate induced charge onto buttons
    - e.g. via boundary element method:
  - build position map
    - for each \((x_0, y_0)\) assign \(\Delta x, y / \Sigma\) values

- sensitivity: slope at origin

plot values along \((x, y)\)-axes

monitor constant: \(K_{x,y} = S_{x,y}\)
**Narrowband Signals: Cavity BPM**

**Linac: high resolution BPM for short bunches and single pulses**
- **requirement:** increase in BPM signal strength
- **standard BPMs:** intensity signals which have to be subtracted to obtain position information
  - difficult to do electronically without some of the intensity information leaking through

**cavity BPM: collect directly position information**
- bunch excites several resonating modes while passing a pillbox-like cavity
  - short bunches deliver wide spectrum of frequencies
- monopole mode $TM_{01}(0)$: beam intensity
  - maximum at center
  - strong excitation
- dipole mode $TM_{11}(0)$: beam position
  - minimum at center
  - excitation by beam offset
  - slightly shifted in frequency wrt. monopole mode

**task: antenna design to couple out dipole mode**
- **amplitude:** position information $\rightarrow$ only absolute value!
- **phase** (wrt. monopole mode): sign information $\rightarrow$ simultaneous measurement required!

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Cavity BPM

cavity frequency spectrum

- **q**: beam charge, **r**: beam offset
- **problem**: monopole mode (TM01) leakage into dipole mode (TM11)
  → suppression of monopole mode required

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**Cavity BPM**

**suppression of monopole mode**

- dipole mode (TM11) signal coupled out via waveguide
  → choose outcoupling at position of large TM11 electric field amplitude
- design waveguide with cutoff frequency above \( f_{01} \) (monopole mode) resonance

**influence of outcoupling waveguide**

- Monopole Mode
- Dipole Mode

**narrow-band electronics for signal processing**

→ B. Keil, Proc. DIPAC’09, Basel (Switzerland) 2009, TUOC01, p.275
→ D. Lipka, Proc. DIPAC’09, Basel (Switzerland) 2009, TUOC02, p.260

*EDIT 2015, Frascati (Italy), 23./27.October 2015*

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# Comparison of BPM Types

<table>
<thead>
<tr>
<th>BPM Type</th>
<th>Application</th>
<th>Precaution</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoe-Box</td>
<td>p-synchrotrons, heavy-ion</td>
<td>long bunches, fRF &lt; 10 MHz</td>
<td>very linear, no x-y coupling, sensitive for broad beams</td>
<td>complex mechanics, capacitive coupling between plates</td>
</tr>
<tr>
<td></td>
<td>accelerators</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Button</td>
<td>p-linacs, all e-accelerators</td>
<td>fRF &gt; 10 MHz</td>
<td>simple mechanics</td>
<td>non-linear, x-y coupling, possible signal deformation</td>
</tr>
<tr>
<td>Stripline</td>
<td>colliders, p-linacs, all e-accelerators</td>
<td>best for β ≈ 1 short bunches</td>
<td>directivity, „clean“ signal, large signal</td>
<td>complex 50 Ω matching, complex mechanics</td>
</tr>
<tr>
<td>Cavity</td>
<td>e-linacs (e.g. FELs), short bunches, special applic.</td>
<td>very sensitive</td>
<td>high frequency</td>
<td>very complex</td>
</tr>
</tbody>
</table>

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Forck, "Lecture Notes on Beam Instrumentation and Diagnostics", JUAS 2011

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EDIT 2015, Frascati (Italy), 23./27.October 2015
two-photon exchange in lepton scattering

- compare e+p and e-p elastic scattering

R. Milner et al., „The OLYMPUS experiment“, Nucl. Instrum. Methods A741 (2014) 1
OLYMPUS Target Chamber BPMs

**target chamber BPMs:**

- Round: Ø 60.325 mm  button diameter 10.8 mm

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**Monitor Profile**

**Position Map**

**Sensitivity**

- Horizontal: $k_x = 21.412486$ mm
- Vertical: $k_y = 21.412486$ mm

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**Monitor Profile**

**Position Map**

**Sensitivity**

- Monitor constant $k = 15.1183$ mm

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Monitor Constant Measurement

BPM test stand

U. Schneekloth et al., Proc. IBIC 2014, Monterey (Ca), USA, (2014) 324

- **test stand**
  - vertical scanning device
  - 2 precision movers (micro screws) on top
  - wire antenna (Ø 0.2mm) centered in BPMs, stretched by weight, damped movement

- **electrical input signal**
  - 500 MHz cw signal induced on wire
  - electrical wire length: \( \frac{3}{4} \lambda \) of 500 MHz (standing wave)
  - essential: solid ground connections

- **signal readout**
BPM Test Stand

- wire antenna

- RF generator
- power amplifier
- weight
- nylon chord
- solder tag

3rd ICFP Advanced Beam Dynamics Workshop, Frascati (Italy), 23./27. October 2015
Tasks: BPMs

- **calculate BPM signals using B.I.S.S**
  - get a first impression about BPM signal forms
    - chamber geometry influence
    - non-linearities
    - output impedance

- **calculate monitor constants for OLYMPUS BPMs**
  - use rule-of-thumb formulae for both geometries
    - compare with simulation results

- **measure OLYMPUS BPM monitor constants** (both geometries)
  - define electrical center of both BPM bodies (origin)
  - perform 1-dim. scan along one axis
    - max. wire position: ± 15 mm (!!!)
  - measure signal amplitudes from each button
  - calculate Δ/Σ from measured signals
  - plot Δ/Σ versus wire position and compare with simulation results
  - determine monitor constant from slope at origin

(measure 2-dim. position map)
Transverse Phase Space: Beam Size and Emittance
Accelerator Key Parameters

**light source:** spectral brilliance

- measure for phase space density of photon flux
- user requirement: high brightness
  → lot of monochromatic photons on sample
- connection to machine parameters

**collider:** luminosity

- measure for the collider performance
- relativistic invariant proportionality factor between cross section $\sigma$ (property of interaction) and number of interactions per second
- user requirement: high luminosity
  → lot of interactions in reaction channel
- connection to machine parameters

**requirements**

- design of small emittance machine
  → proper choice of magnet lattice
- preserve small emittance
  → question of stability
  → require active feedback systems / careful design considerations

for two identical beams with emittances $\varepsilon_x = \varepsilon_z = \varepsilon$
Transverse Emittance

- **projection of phase space volume**
  - separate horizontal, vertical and longitudinal plane

- **accelerator key parameter**
  - defines luminosity / brilliance

- **linear forces**
  - any particle moves on an ellipse in phase space \((x,x')\)
  - ellipse rotates in magnets and shears along drifts
  - but area is preserved: **emittance**

- **transformation along accelerator**
  - knowledge of the magnet structure (beam optics)
  - transformation from initial \((i)\) to final \((f)\) location

  - single particle transformation
  - transformation of optical functions

\(\alpha, \beta, \gamma, \varepsilon: \text{Courant-Snyder or Twiss parameters}\)
**Transverse Emittance Ellipse**

**propagation along accelerator**
- change of ellipse shape and orientation → area is preserved

**beam envelope:**
- minimum in envelope → minimum in $\beta$ → $\beta' = 0$ → $\alpha = 0$

**beam waist:**
- minimum in envelope → minimum in $\beta$ → $\beta' = 0$ → $\alpha = 0$
Emittance and Beam Matrix

Beam matrix

transformation of beam matrix

via Twiss parameters

statistical definition


εrms is measure of spread in phase space

root-mean-square (rms) of distribution

εrms useful definition for non-linear beams

→ usually restriction to certain range
  (c.f. 90% of particles instead of \([-\infty, +\infty]\))
Emittance Measurement: Principle

- Emittance: projected area of transverse phase space volume

- Not directly accessible for beam diagnostics

\[ F = \pi \varepsilon \]
\[ \sqrt{\varepsilon \gamma} \]
\[ -\alpha \sqrt{\frac{\varepsilon}{\gamma}} \]

- Measured quantity
  - Beam size
  - Beam divergence
  - Divergence measurements seldom in use → restriction to profile measurements

- Measurement schemes
  - Beam matrix based measurements → determination of beam matrix elements:
  - Mapping of phase space → restrict to (infinitesimal) element in space coordinate, convert angles \( x' \) in position

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Circular Accelerators

- **emittance diagnostics in circular accelerators**
  - circular accelerator: periodic with circumference \( L \)
    - one-turn transport matrix: \( R(s+L) = R(s) \)
  - Twiss parameters \( \alpha(s), \beta(s), \gamma(s) \) uniquely defined at each location in ring
  - measurement at one location in ring sufficient to determine \( \varepsilon \)
    - measured quantity: beam profile / angular distribution

- **classification**
  - imaging
    - beam size
  - interference
    - beam size
  - projection
    - beam divergence

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starting point: beam matrix

emittance determination
- measurement of 3 matrix elements $\Sigma_{11}, \Sigma_{12}, \Sigma_{22}$
- remember: beam matrix $\sigma$ depends on location, i.e. $\Sigma(s)$
  → determination of matrix elements at same location required

access to matrix elements
- profile monitor determines only
- other matrix elements can be inferred from beam profiles taken under various transport conditions
  → knowledge of transport matrix $R$ required

measurement of at least 3 profiles for 3 matrix elements
- measurement: profiles
- known: transport optics
- deduced: matrix elements

→ more than 3 profile measurements favourable, data subjected to least-square analysis

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Beam Dynamics
Workshop
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Beam Matrix based Measurements

„quadrupole scan“ method

- use of variable quadrupole strengths
  - change quadrupole settings and measure beam size in profile monitor located downstream

\[ Q \ (f = 1/K) \quad S \ (\text{drift space}) \]

\[ \Sigma_{11} \text{ depends quadratically on quadrupole field strength} \]

\[ R = SQ \]

G. Penco et al., Proc. EPAC’08, Genoa (Italy), p.1 23 6

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Beam Matrix based Measurements

"multi profile monitor" method

- fixed particle beam optics
  → measure beam sizes using multiple profile monitors at different locations

example:
emittance measurement
setup at FLASH injector (DESY)
courtesy: K. Honkavaara (DESY)

task
beam profile measurement
Storage Ring: Profile Measurement

**circular accelerator**
- only non- or minimum-invasive diagnostics → otherwise beam loss after few turns

**e-/e+ ring**
- working horse: synchrotron radiation
- problem: heat load @ extraction mirror

**hadron ring**
- **wire scanners**: scan of thin wire across the beam
- detect beam-wire interaction as function of wire position

**HERA e SyLi monitor**
- problem: heat load @ extraction mirror
- $T_{max} = 1200°C$

**residual gas monitor**:
- residual gas ionization / luminescence

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Linac or Transport Line: Profiles

**linear machine**
- single pass diagnostics → interaction with matter (care has to be taken)

**hadron accelerators**
- working horse: screen monitors
  → scintillating light spot intensity corresponds to beam profile
- wire harp
  → extension of wire scanner
courtesy: U. Raich (CERN)

**electron accelerators**
- screen monitors → lower resolution (?)
- working horse: OTR monitors
  → even potential for sub-micron beams

σ = 1.44 μm


G. Kube et al., Proc. IBIC 2015, Melbourne (Australia), TUPB012

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OTR Monitors

working horse: Transition Radiation
electromagnetic radiation emitted when a charged particle crosses boundary between two media with different optical properties

visible part: Optical Transition Radiation (OTR)
beam diagnostics: backward OTR
typical setup: image beam profile with optical system

radiation generation
→ virtual photon reflection at boundary
(perfect conductivity)

advantage: fast single shot measurement
linear response (neglect coherence !)
disadvantage: high charge densities may destroy radiator → limitation on bunch number

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OTR Monitors at FLASH

K. Honkavaara et al., Proc. PAC 2003, p.2476

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optical system

<table>
<thead>
<tr>
<th>magnification</th>
<th>f / mm</th>
<th>a / mm</th>
<th>b / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>0.382</td>
<td>200</td>
<td>724</td>
<td>276</td>
</tr>
<tr>
<td>0.25</td>
<td>160</td>
<td>800</td>
<td>200</td>
</tr>
</tbody>
</table>

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Example of Beam Images (matched)

1 bunch, 1 nC, Solenoid 277 A, ACC1 on-crest

Example of Beam Images (matched) courtesy: K. Honkavaara (DESY)

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**Screen Monitors**

**principle**

- radiator
  - scintillator / OTR screen
  - generation of light spot: intensity distribution reflects particle beam density (i.e. linear light generation mechanism)

- optical system / CCD
  - imaging / recording of light spot

- target mover
  - move screen in / out of particle beam

- illumination
  - check system performance

**screen monitor setup**

- radiator → Al2O3:Cr (Chromox) screen (thickness 1.0 mm / 0.5 mm / 0.3 mm)
- CCD → USB camera
- optics → CCTV lens

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Size Measurement: Resolution

fundamental resolution limit

- point observer detecting photons from point emitter
  → location of emission point?

high resolution:
(i) small $\lambda$
(ii) high NA

image of point source

point-like object

Airy pattern:
→ Point Spread Function

magnification $M$

resolution broadening: additional contributions

- depth of field
- radius of curvature
  → mainly for synchrotron radiation based diagnostics

http://www.astro.ljmu.ac.uk
Emittance Measurement Test Setup

- emittance of laser beam
  - “multi-profile monitor“ method
Emittance Measurement Test Setup

test setup

![Image of test setup with labeled components: Screen Monitor, moveable Lens, Laser, Aperture, Attenuator.]

calibration / resolution targets
  - check system performance of detector system

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Emittance Measurement Test Setup

readout: PHYTEC Vision Demo 2.2

- CCD control parameters
  - gain
  - exposure time

- histogram
  - control of 8 bit ADC

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Emittance Measurement Test Setup

analysis: ImageJ → freeware

image analysis
projections
access to data
basic fitting routines
Tasks: Emittance Diagnostics

- **estimate the image resolution for an optical synchrotron radiation profile monitor**
  - modern 3rd generation light source: \( E = 6 \text{ GeV}, \lambda_{\text{obs}} = 500 \text{ nm}, \sigma_y = 10 \mu\text{m} \)
    
    \( \rightarrow \) assume „self diffraction“, i.e. aperture limitation imposed by radiation angular distribution \((1/\gamma)\)

- **derive the single particle transport matrix for a drift space**
  - assume paraxial approximation
    
    \( \rightarrow \) \( \sin(x') \approx x' \)

- **calculate the evolution of the beam size after a drift space**
  - use the beam matrix transformation together with the transport matrix \( R \) for a drift space

- **investigate the performance of the CCD**
  - spatial calibration
    
    \( \rightarrow \) dot grid target \((0.5 \text{ mm spacing})\)
  - resolution
    
    \( \rightarrow \) Siemens star, USAF 1951 target

- **measure the emittance of the laser beam**
  - measure spot sizes for different distances of the lens
  - analyse the horizontal profiles as function of the lens position
  - calculate the laser beam emittance
    
    \( \rightarrow \) use the simplest way with only 2 values
  - (repeat with a different scintillator thickness)