Beam Instrumentation, Controls, Feedback and Operation Aspects

(Main Classification 6)

IPAC 2026 Student Programme 2026

Peter Forck

Gesellschaft für Schwerionenforschung (GSI), p.forck@gsi.de

Demands on Beam Diagnostics and Control

Beam diagnostics is the ’sensory organs’ for a real beam in a real environment.

Beam control is the active influence on beam parameters by a person or machine.

Different demands lead to different installations:

- **Quick, non-destructive measurements leading to a single number or simple plots**

  Used as a check for online information.; reliable technology is required

  Example: Beam position (=center-of-mass) by Beam Position Monitor BPM

- **Complex instruments for severe malfunctions, accelerator commissioning & development**

  The instrumentation might be destructive and complex

  Example: Emittance determination, tune etc. measurement

General usage of beam instrumentation:

- Monitoring of beam parameters for operation, beam alignment & accel. development
- Instruments for automatic, active beam control mostly by a feedback system

  Example: Closed orbit feedback at synchrotrons using position measurement by BPMs

Demands on Beam Diagnostics

Beam diagnostics is the ’sensory organs’ for a real beam in a real environment.

Beam control is the active influence on beam parameters by a person or machine.

Non-invasive (= ’non-intercepting’ or ‘non-destructive’) methods are preferred:

- The beam is not influenced ⇒ ***at transfer line***: the **same** beam at several locations
  ⇒ ***at synchrotron***: properties of the stored beam are monitored
- The instrument is not destroyed due to high beam power

Instruments could be different for:

- Transfer lines with single passage ↔ synchrotrons with multi-passages
- Electrons are mostly relativistic ↔ protons are at the beginning non-relativistic

Remark:

Most instrumentation is installed outside of rf-cavities to prevent for signal disturbance

Outline of the Tutorial

Part 1 of the lecture on Beam Position Monitors:

- Beam position monitors for bunched beams
- Position measurements and feedback system
- Measurement of tune, chromaticity etc.

Part 2 of the lecture on transverse and longitudinal diagnostics:

- Profile measurement methods
- Transverse emittance measure, incl. tomography
- Measurement of longitudinal parameters

Measurements with BPMs

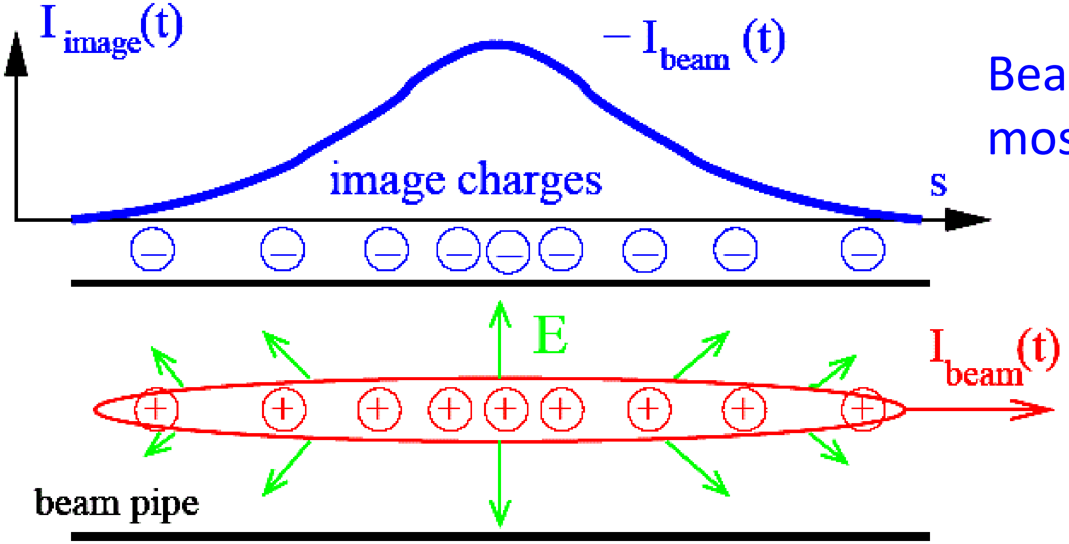
Outline for BPM measurements:

- **Signal generation and basic usage:**

  transfer impedance, button BPM
- **Electronics basics**
- **Cavity BPM at FELs**
- **Trajectory measurement, close orbit feedback**
- **Tune and lattice function measurement**

Pick-Ups for bunched Beams

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



Beam Position Monitor **BPM** is the most frequently used instrument!

Relativistic transformation of an electric field:

$$E_{\perp,lab}(t_{lab}) = \gamma \cdot E_{\perp,rest}(t_{rest})$$

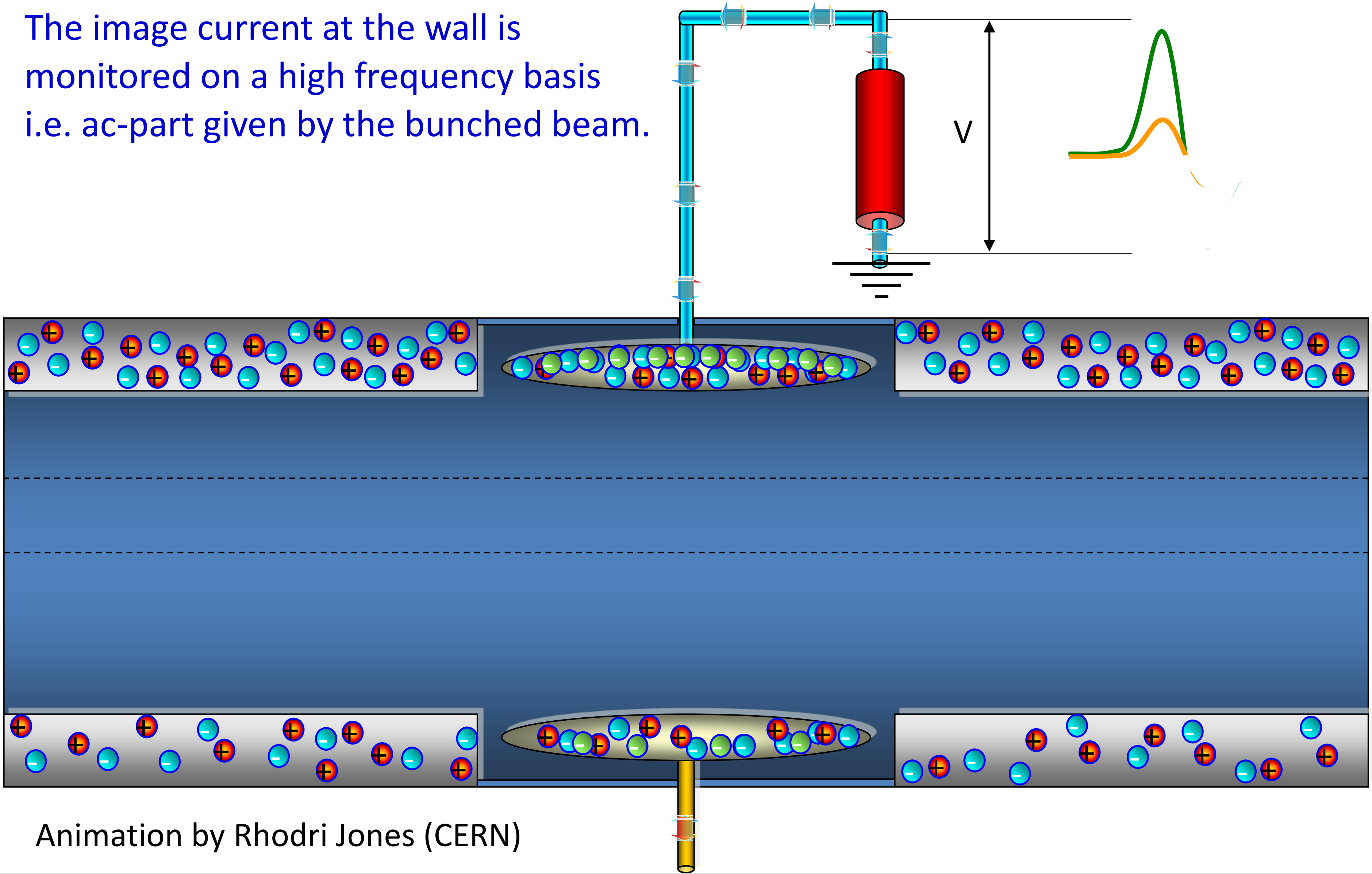
A Beam Position Monitor is an non-destructive device for bunched beams.
It delivers information about the transverse center of the beam:

- ***Trajectory:*** Position of an individual bunch within a transfer line or synchrotron
- ***Closed orbit***: Central orbit averaged over a period much longer than a betatron oscillation
- ***Single bunch position:*** Determination of parameters like tune, chromaticity, β-function

Remarks: - BPMs have a low cut-off frequency ⇔ dc-beam can’t be monitored
- The abbreviation **BPM** and pick-up **PU** are synonyms

Principle of Signal Generation of a BPMs: off-center Beam

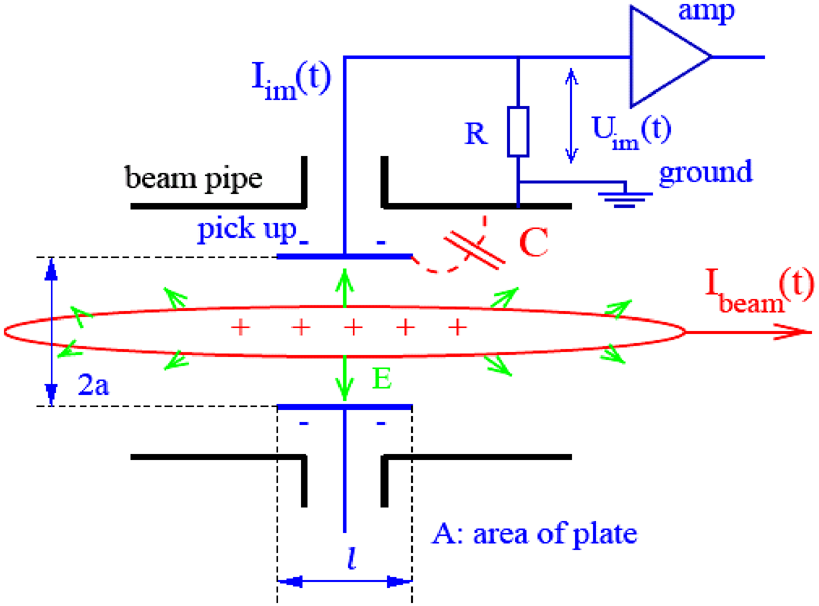
The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.

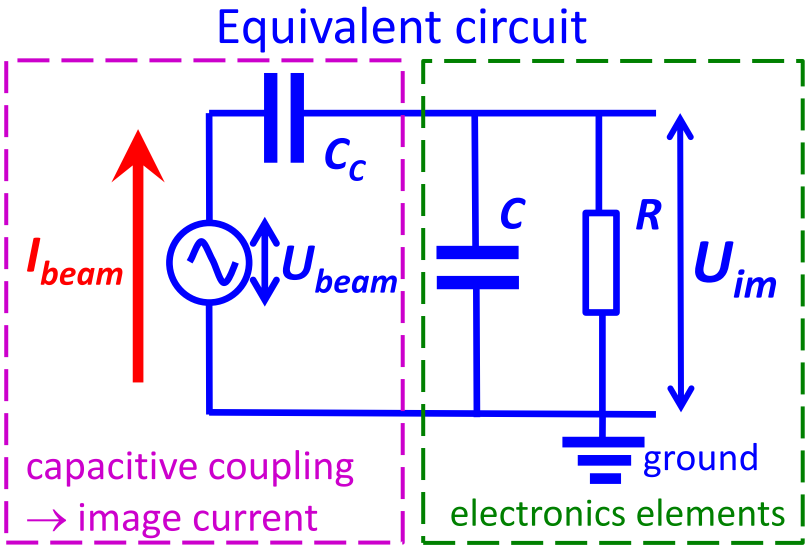


Animation by Rhodri Jones (CERN)

Model for Signal Treatment of capacitive BPMs

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





At a resistor ***R*** the voltage U_{im} from the image current is measured.

Goal: Connection from beam current to signal strength by transfer impedance $Z_t(\omega)$

in frequency domain: $U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega) \cdot I_{beam}(\omega)$

Result:

$$Z_t(\omega) = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1+i\omega RC} \quad \in \mathbb{C} \quad \text{i.e. complex function}$$

geometry

stray capacitance

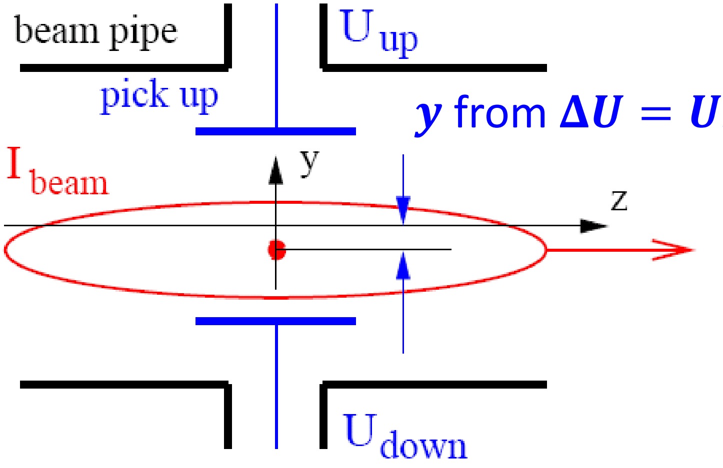
frequency response

Principle of Position Determination by a BPM

The difference voltage between plates gives the beam's center-of-mass
→**most frequent application**

$$y = \frac{1}{S_y(\omega)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} \equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y}$$

$$x = \frac{1}{S_x(\omega)} \cdot \frac{U_{right} - U_{left}}{U_{right} + U_{left}}$$



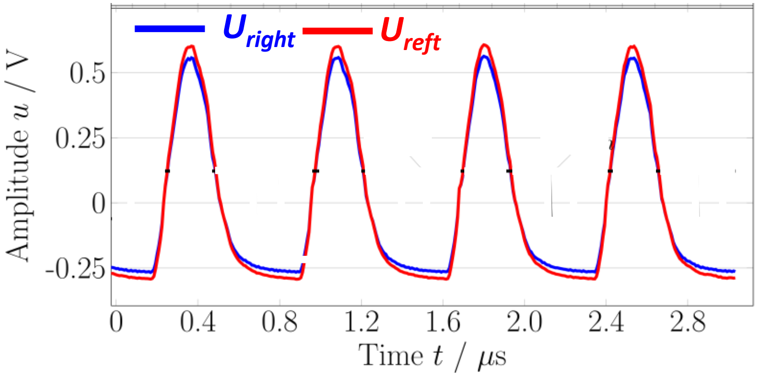
$\boldsymbol{y}$ from $\boldsymbol{\Delta U = U_{up} - U_{down}}$

$\boldsymbol{S(\omega, x)}$ is called **position sensitivity;** sometimes the inverse is used $k(\omega, x) = 1/S(\omega, x)$
$\boldsymbol{S}$ is a geometry dependent, non-linear function,
Units: S=[%/mm], sometimes S=[dB/mm] or k=[mm].

Typical desired position resolution:
$\Delta x \approx 0.1 \ldots 0.3 \cdot \sigma_x$ of beam width

It is at least: $\boldsymbol{\Delta U \ll \frac{1}{10} \Sigma U}$

Example: One turn = 4 bunches @ 35 MeV/u



2-dim Model for a Button BPM

'Proximity effect': larger signal for closer plate

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

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

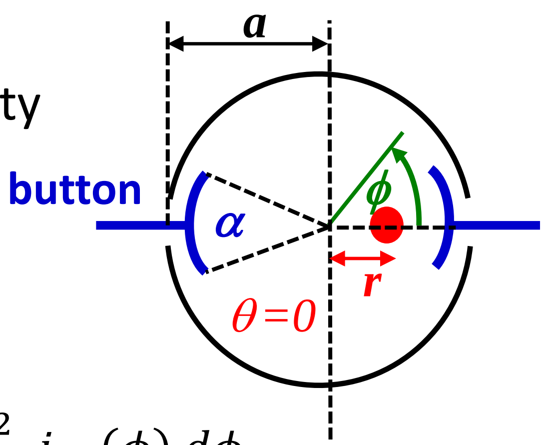
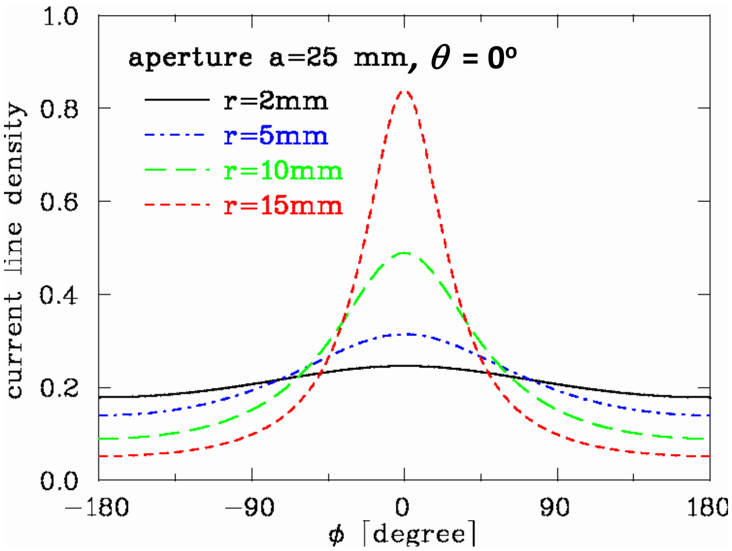
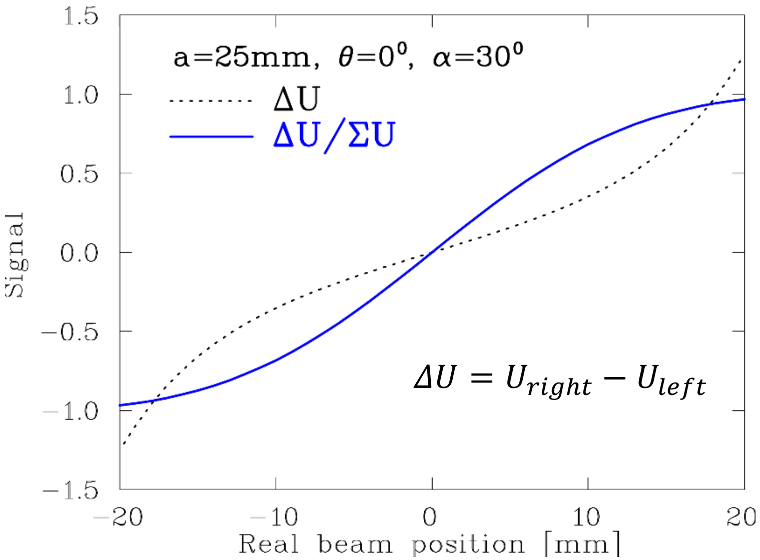


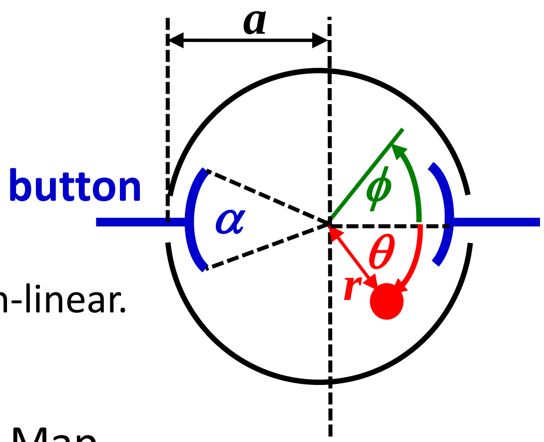
Image current: Integration over finite button size: $I_{im} = a \cdot \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi)\, d\phi$





2-dim Model for a Button BPM

Ideal 2-dim model: Non-linear behavior and hor-vert coupling:



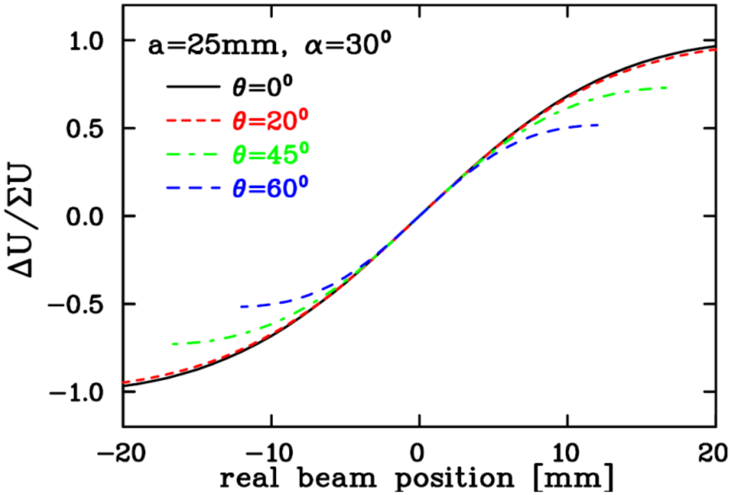
Sensitivity $\boldsymbol{S}$ converts signal to position $x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U}$

with S = [%/mm] or [dB/mm]

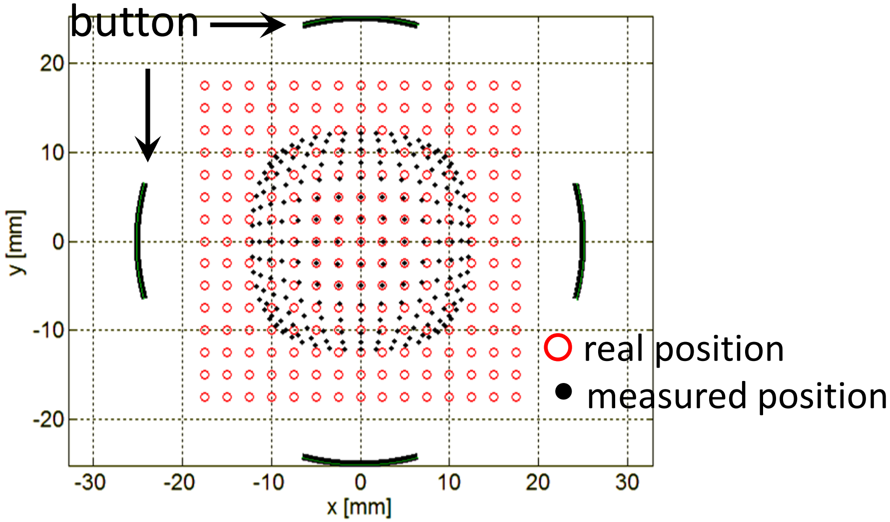
i.e. $\boldsymbol{S}$ is the derivative of the curve $S_x = \frac{\partial(\frac{\Delta U}{\Sigma U})}{\partial x}$, here $S_x = S_x(x,y)$ i.e. non-linear.

For this example: central part S=7.4%/mm ⇔ $k = 1/S = 14$ mm

Horizontal plane



Position Map



Button BPM Realization

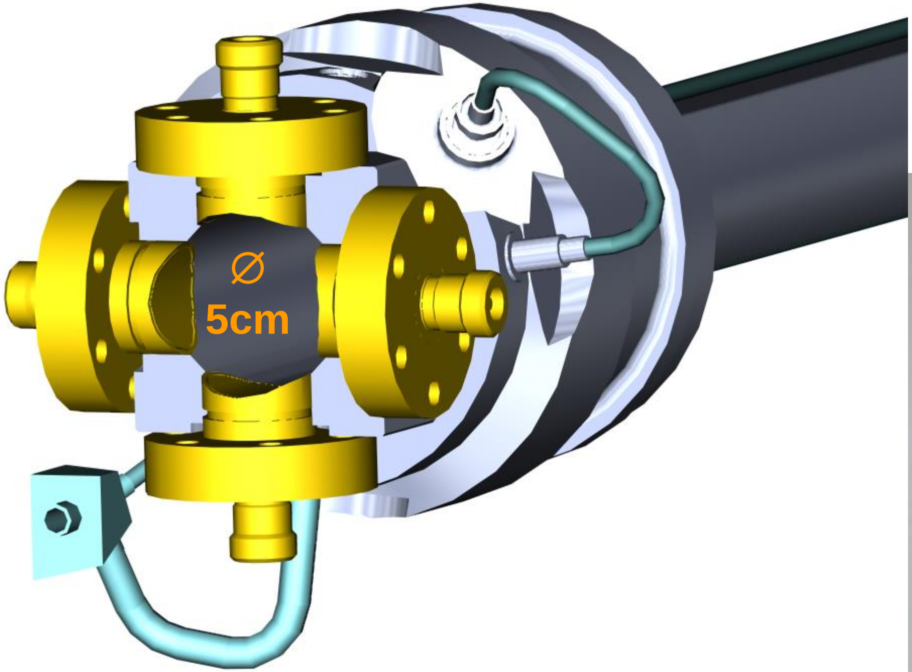
LINACs, e$^-$-synchrotrons: 100 MHz < f_{rf} < 3 GHz → bunch length ≈ BPM length

→ 50 Ω signal path to prevent reflections

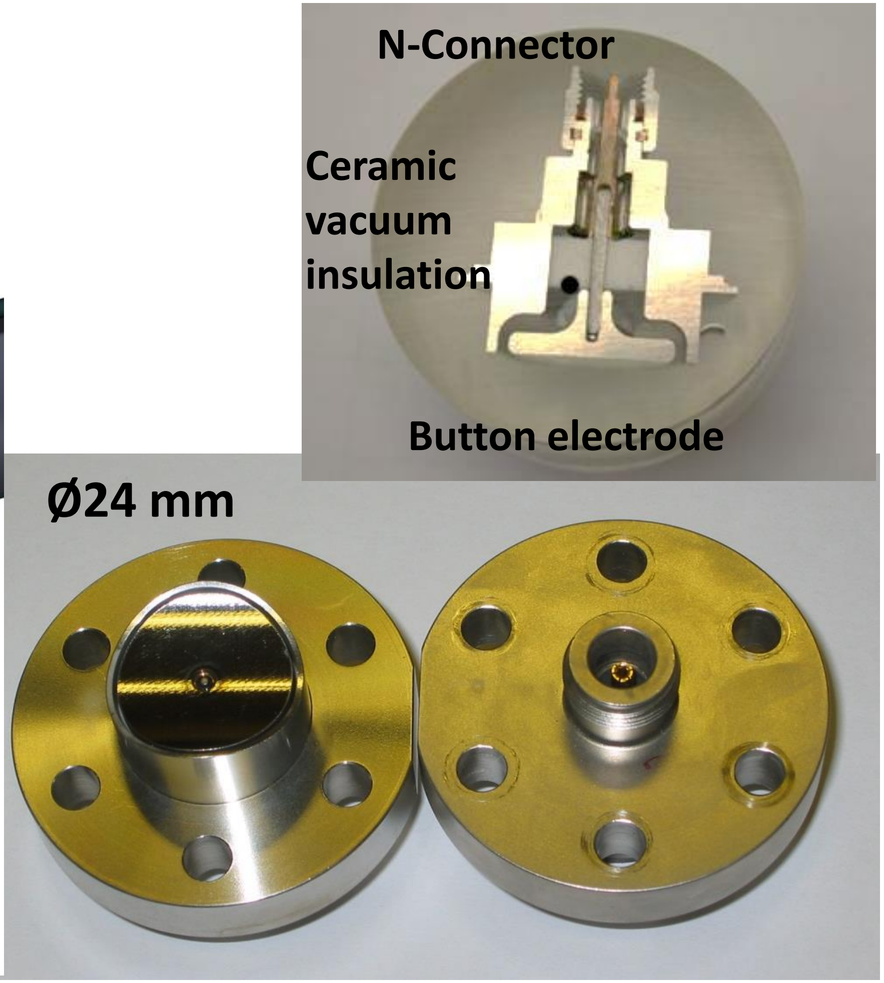
Example: LHC-type inside cryostat:

∅24 mm, half aperture a = 25 mm, C = 8 pF

⇒ f_{cut}= 400 MHz, Z_t = 1.3 Ω above f_{cut}



Courtesy C. Boccard (CERN)

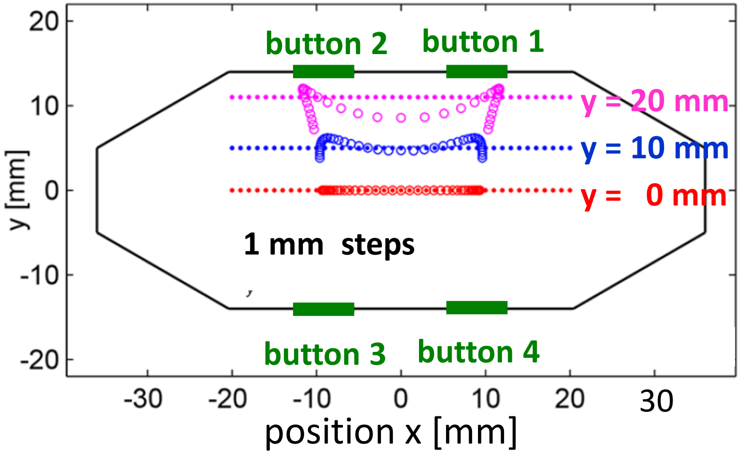


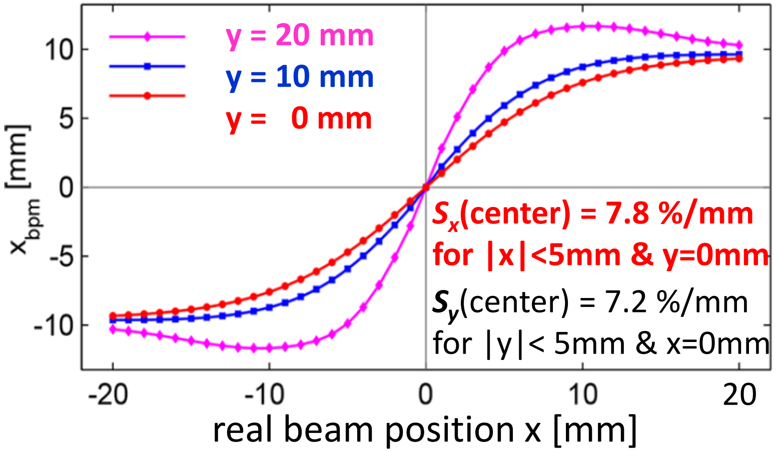
Simulations for Button BPM at Synchrotron Light Sources

Example: Simulation for ALBA light source for 72 x 28 mm^2 chamber

Horizontal: $x \propto \frac{1}{S_x}(left - right) \Leftrightarrow x = \frac{1}{S_x} \cdot \frac{(U_2+U_3)-(U_1+U_4)}{U_1+U_2+U_3+U_4}$

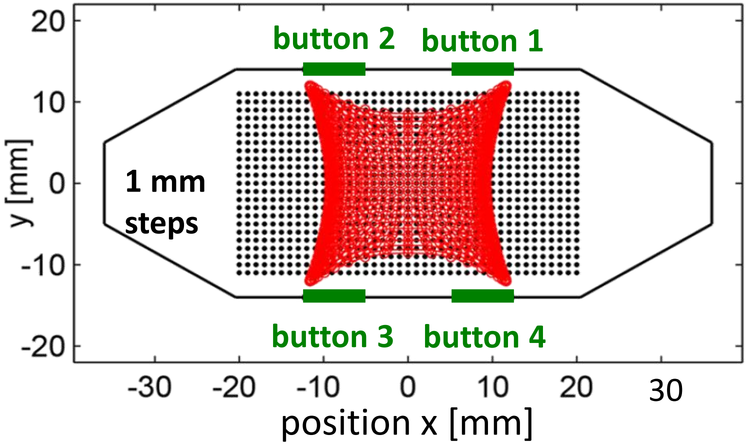
Vertical: $y \propto \frac{1}{S_y}(top - bottom) \Leftrightarrow y = \frac{1}{S_y} \cdot \frac{(U_1+U_2)-(U_3+U_4)}{U_1+U_2+U_3+U_4}$

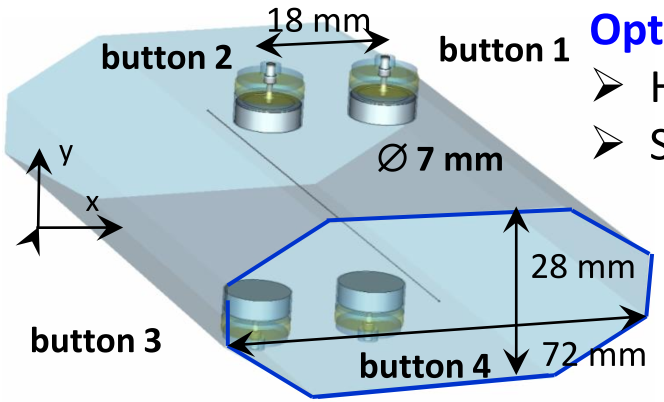




S_x(center) = 7.8 %/mm for |x|<5mm & y=0mm

S_y(center) = 7.2 %/mm for |y|< 5mm & x=0mm





Optimization:

- ➢ Horizontal distance
- ➢ Size of buttons

A.A. Nosych et al., IBIC'14

Result: - Non-linearity and ***xy***-coupling occur in dependence of button size and position

- Can be corrected by polynomial interpolation for beams much smaller than chamber

Measurement with BPMs

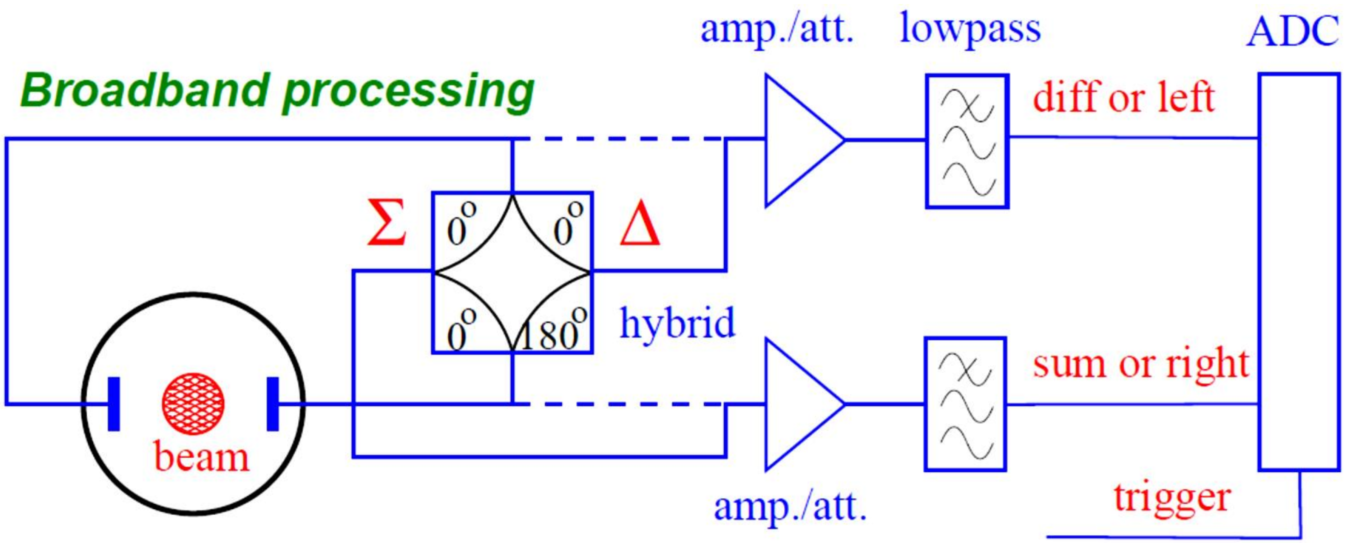
Outline for BPM measurements:

- Signal generation and basic usage:

  transfer impedance, button BPM
- Electronics basics:

  schemes for signal processing
- Cavity BPM at FELs
- Trajectory measurement, close orbit feedback
- Tune and lattice function measurement

Broadband Signal Processing



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

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

Disadvantage: Resolution down to ≈ 100 µm for large aperture, i.e. ≈ 0.1% of aperture,

resolution is worse than narrowband processing, see below

Challenge: Precise analog electronics with very low drift of amplification

General Noise Consideration

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$

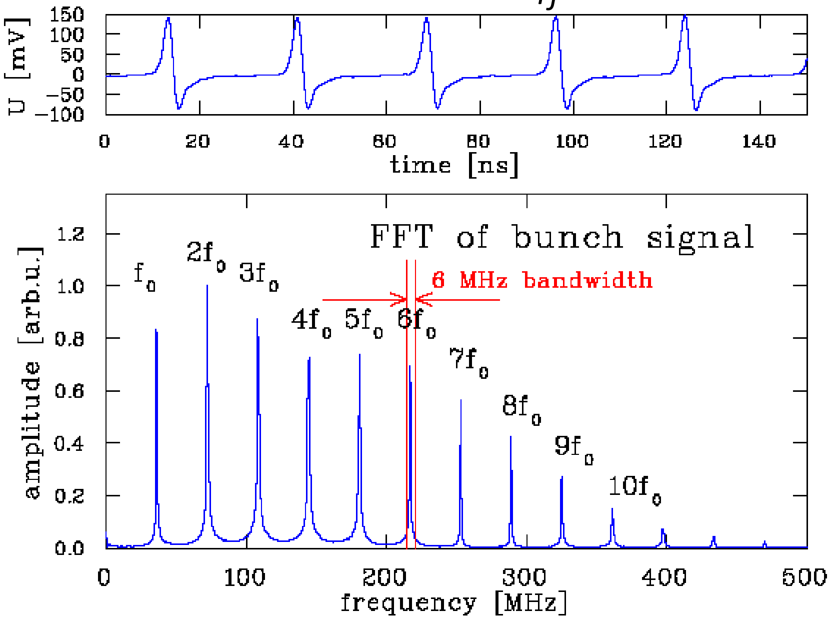
2. Thermal noise voltage given by: $U_{noise}(R, \Delta f) = \sqrt{4k_B \cdot T \cdot R \cdot \Delta f}$

Signal-to-noise $\boldsymbol{\Delta U_{im}/U_{noise}}$ is influenced by:

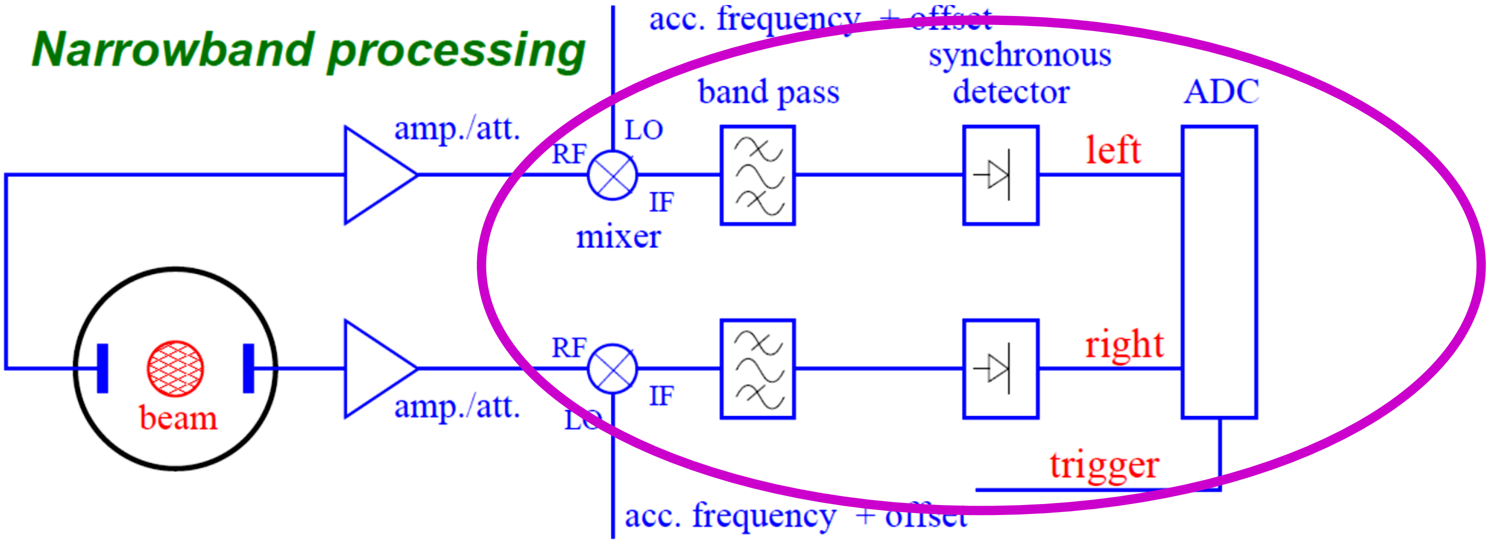
- ➢ Input signal amplitude
- ➢ Thermal noise from amplifiers etc.
- ➢ Bandwidth $\boldsymbol{\Delta f}$

⇒ Restriction of frequency width as the power is concentrated at harmonics $\boldsymbol{n \cdot f_{rf}}$

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



Narrowband Processing for improved Signal-to-Noise



Narrowband processing, analog correspondence heterodyne receiver (AM-radio, spectrum analyzer)

- Attenuator/amplifier
- Mixing with accelerating frequency $\boldsymbol{f_{LO}}$

  $\Rightarrow$ IF-output: signal with difference frequency $\boldsymbol{f_{IF} = f_{LO} - f_{RF}}$
- Bandpass filter of the mixed signal Rectifier: synchronous detector
- ADC: digitalization → followed calculation of $\boldsymbol{\Delta U / \Sigma U}$

Digital correspondence:
I/Q de-modulation
As today's technology

Advantage: Spatial resolution about 100 time better than broadband processing

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

Measurement with BPMs

Outline for BPM measurements:

- Signal generation and basic usage:

  transfer impedance, button BPM
- Electronics basics:

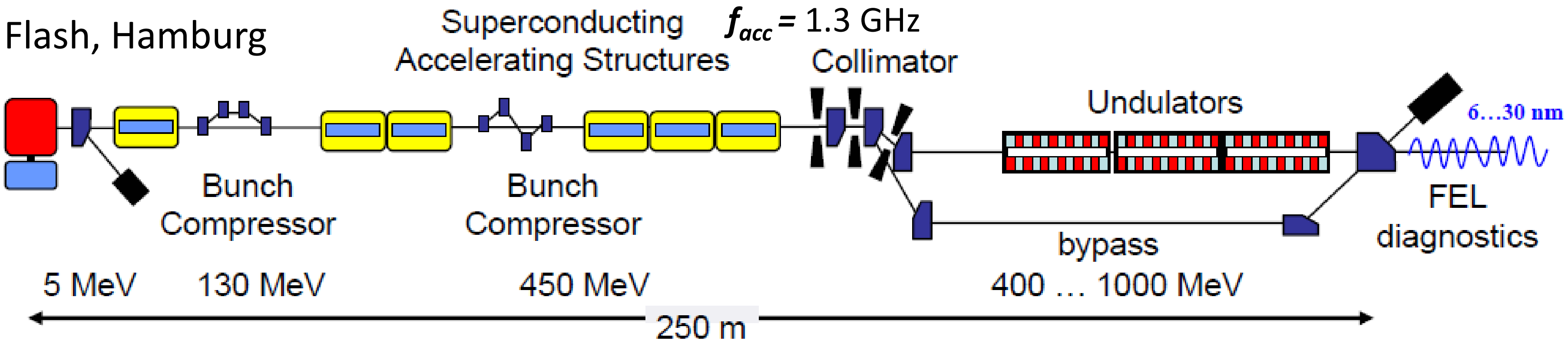
  Schemes for signal processing
- **Cavity BPM at FELs:**

  information storage for short pulses
- **Trajectory measurement, close orbit feedback**
- **Tune and lattice function measurement**

4th Generation Light Sources & Beam Delivery

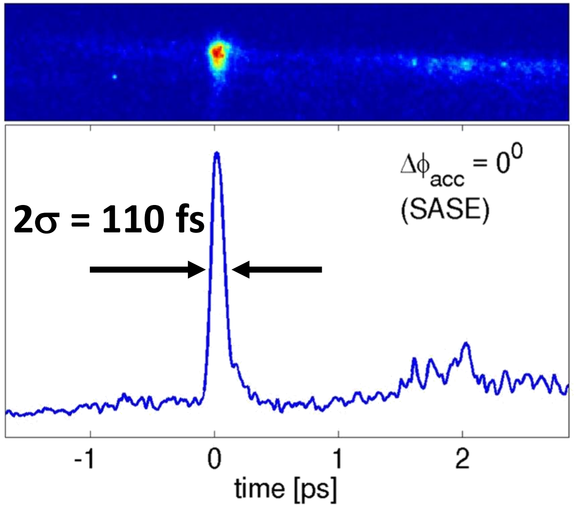
LINAC-based Light Sources:

$E_{electron} \approx 1 \ldots 18$ GeV, **coherent** light from undulator, $E_\gamma < 1000$ keV, temporally short pulse



Goal: **Short** bunches with **high** number of particles
→ short, intense laser pulses for electron generation
Requirement: Position stability ⇒ resolution < 1 μm

Single bunch duration < 100 fs:

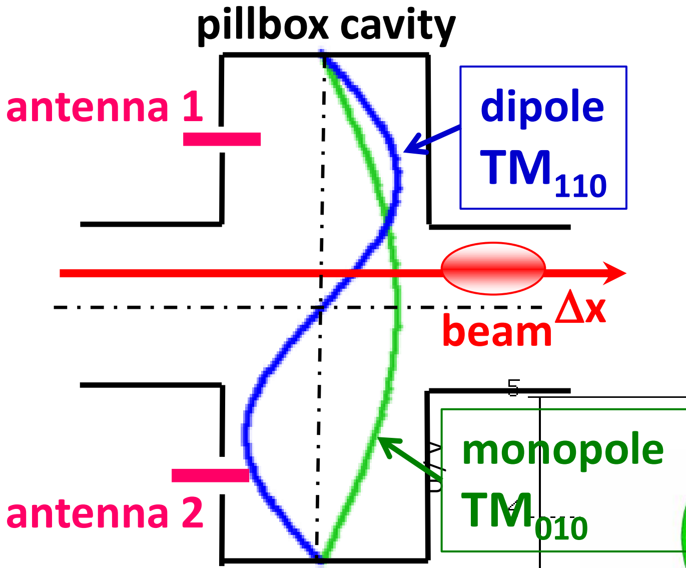


B. Steffen et al, DIPAC 2009, B. Steffen et al., Phys. Rev. AB 12, 032802 (2009)

Cavity BPM for FEL-LINACs: Principle

High resolution on ***t* <<** 1 µs time scale can be achieved by excitation of a dipole mode

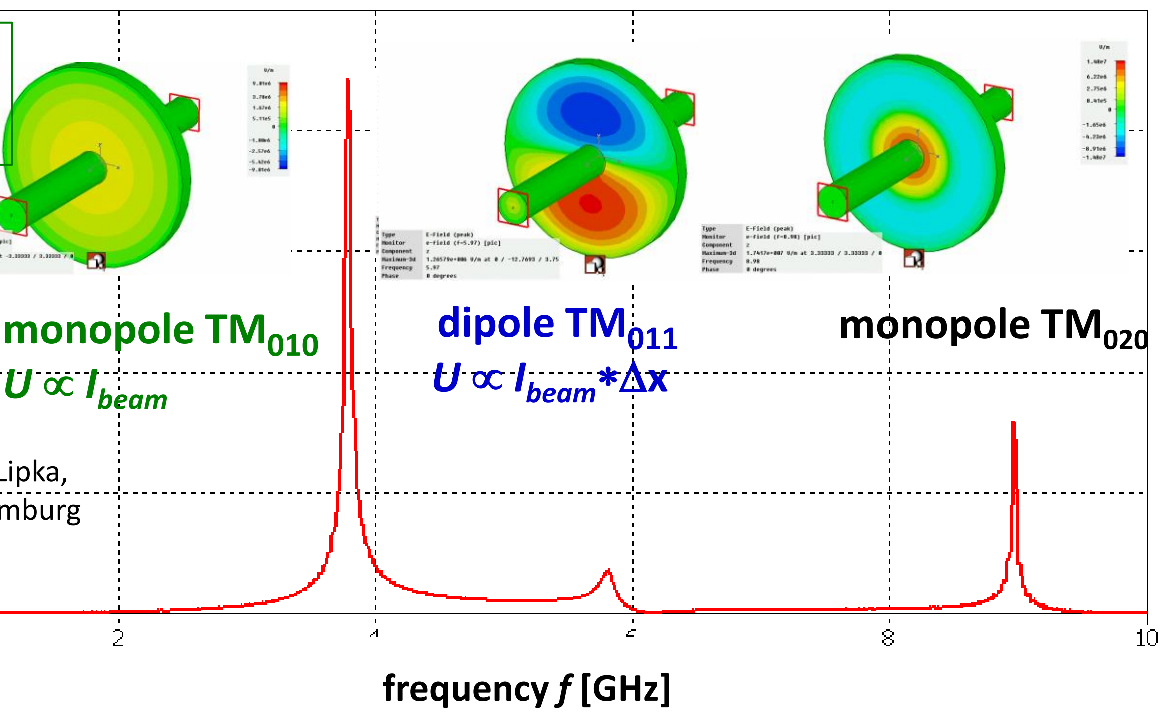
Depictive statement: ‘The position information is stored due to cavity mode excitation’



For pill box the resonator modes given by geometry:

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

⇒ Detection of dipole mode amplitude



From D. Lipka, DESY, Hamburg

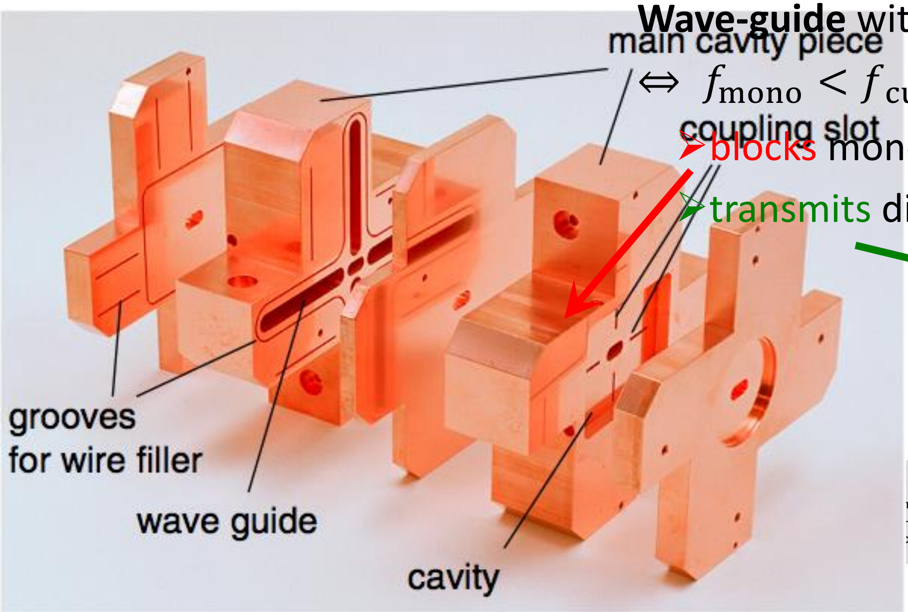
‘δ-excitation’ followed by oscillation with $Q \approx 1000$ and $\tau = 2Q/2\pi f \approx 100$ ns

⇒ **‘0.1 µm resolution within 100 ns‘**

Cavity BPM: Suppression of monopole Mode

Suppression of mono-pole mode: waveguide only for dipole-mode transmission

Example: $f_{dipole,hori}$ = 5.7 GHz, $f_{dipole,vert}$ = 6.4 GHz

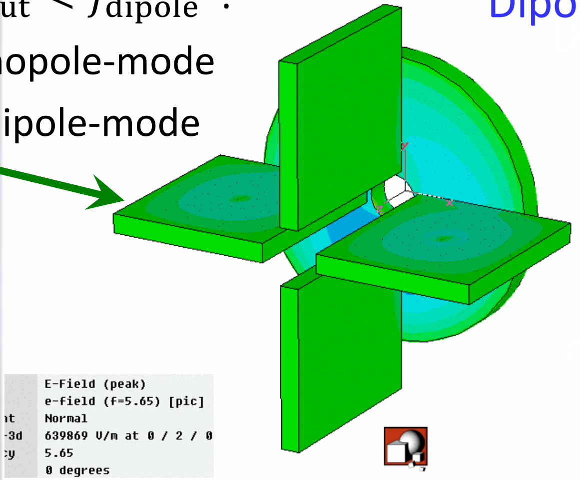


Wave-guide with cut-off frequency f_{cut}

⇔ $f_{\text{mono}} < f_{\text{cut}} < f_{\text{dipole}}$:

- blocks monopole-mode
- transmits dipole-mode

Dipole mode



```
E-Field (peak)
e-Field (f=5.65) [pic]
Normal
639869 V/m at 0 / 2 / 0
5.65
0 degrees
```

Courtesy of D. Lipka, DESY, Hamburg

Prototype BPM for ILC Final Focus:

Achieved **resolution** (i.e. 3 BPM relative) of 8.7 nm in a 6 × 12 mm beam pipe at ATF2 (KEK, Japan)

Remark: Separated, smaller cavity for monopole mode to have **same** frequency for normalization

Courtesy of D. Lipka and Y. Honda et al., Phys. Rev. Accel. Beams 11, 062801 (2008)

Measurement with BPMs

Outline for BPM measurements:

- Signal generation and basic usage:

  transfer impedance, button BPM
- Electronics basics:

  Schemes for signal processing
- Cavity BPM at FELs

  information storage for short pulses
- Trajectory measurement, close orbit feedback:

  Beam stabilization methods via real-time control
- Tune and lattice function measurement

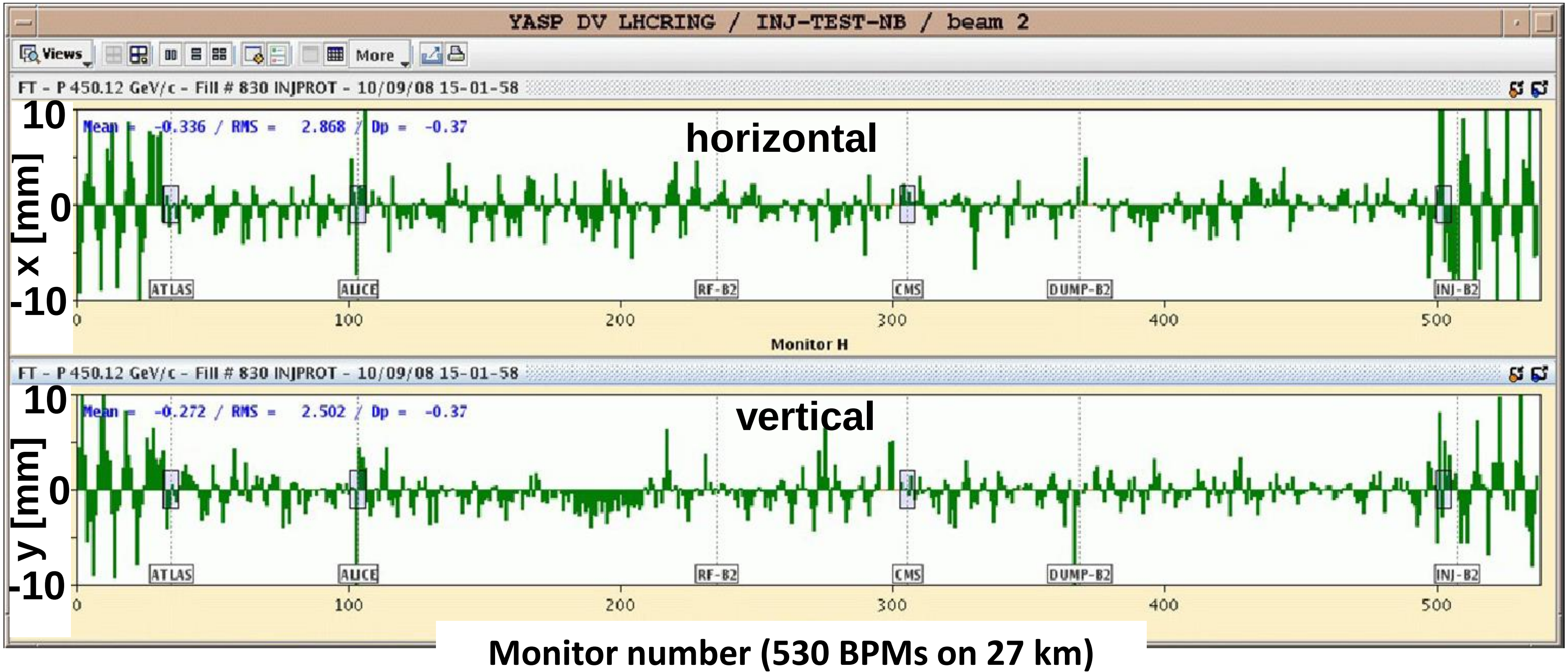
Trajectory Measurement with BPMs

Trajectory:

The position delivered by an **individual bunch** within a transfer line or a synchrotron.

Main task: Control of matching (center and angle), first-turn diagnostics

Example: LHC injection 10/09/08 i.e. first day of operation !



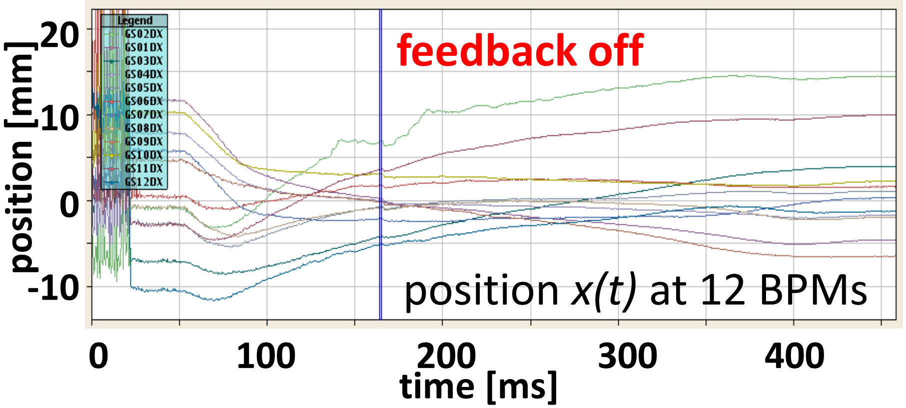
Courtesy R. Jones (CERN)

Tune values at LHC: $Q_h = 64.3$, $Q_v = 59.3$

Close Orbit Measurement with BPMs

Orbit measurement:

Example: 12 beam positions at GSI-SIS during ramping from E_{kin} =8.6 to 500 MeV/u for Ar^{18+}



feedback off

position *x(t)* at 12 BPMs

Closed orbit:

Beam position averaged over many turns

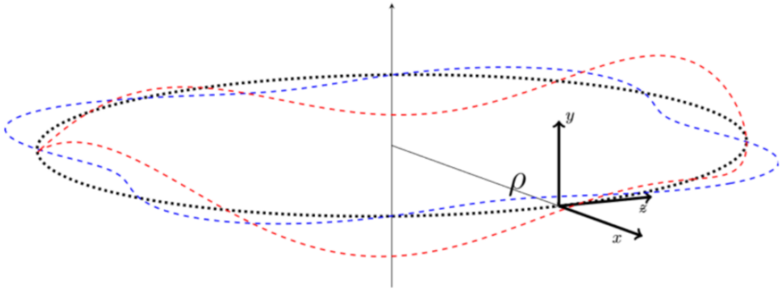
(i.e. betatron oscillations).

The result is the basic tool for alignment & stabilization

Position resolution Δx :

Required resol. Δx depends on beam size σ_x:

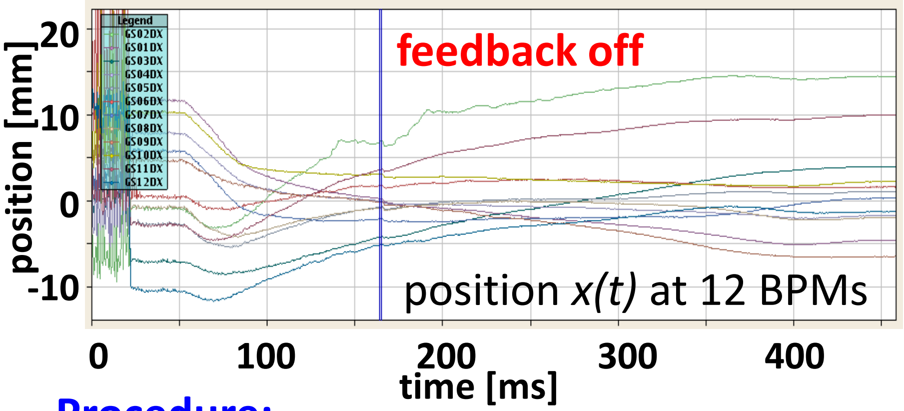
Role of thumb: $\Delta x \approx (0.1 \ldots 0.3) \cdot \sigma_x$

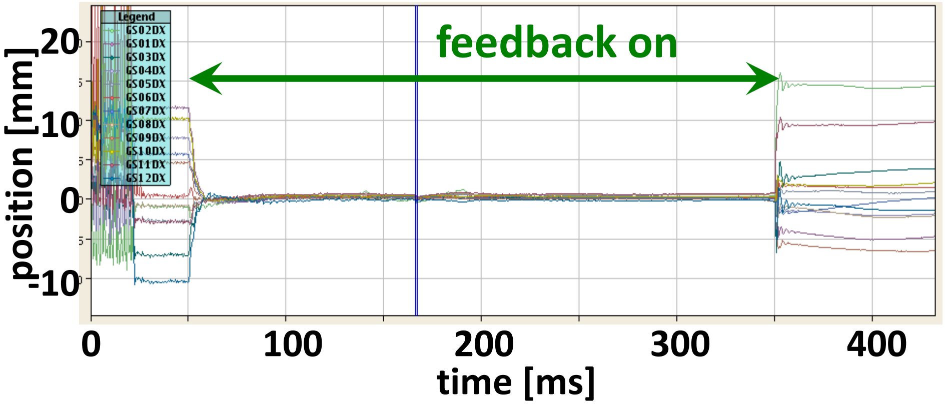


Close Orbit Feedback: Results

Orbit feedback:

Example: 12 beam positions at GSI-SIS during ramping from E_{kin} =8.6 to 500 MeV/u for Ar^{18+}





Procedure:

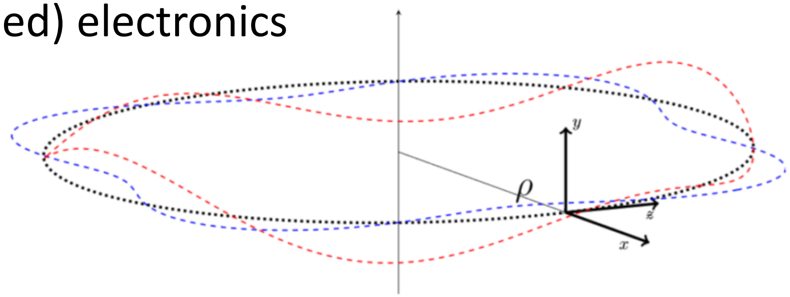
1. Position digitalization of all 12 BPMs

2. Calculation of corrector setting on fast (FPGA-based) electronics

3. Submission to corrector magnets

4. New position measurement

⇒ regulation time down to 10 ms



Rule of thumb:

Movement related to tune i.e. ‘natural oscillations by periodic focusing’

To determine the ‘sine-like’ oscillation 4 BPMs per oscillation are required

⇒ 4 BPMs per tune value (but detailed investigation required to determine the # of BPMs)

Closed Orbit Feedback: Typical Noise Sources

Beam movement:

Short term (min to 10 ms):

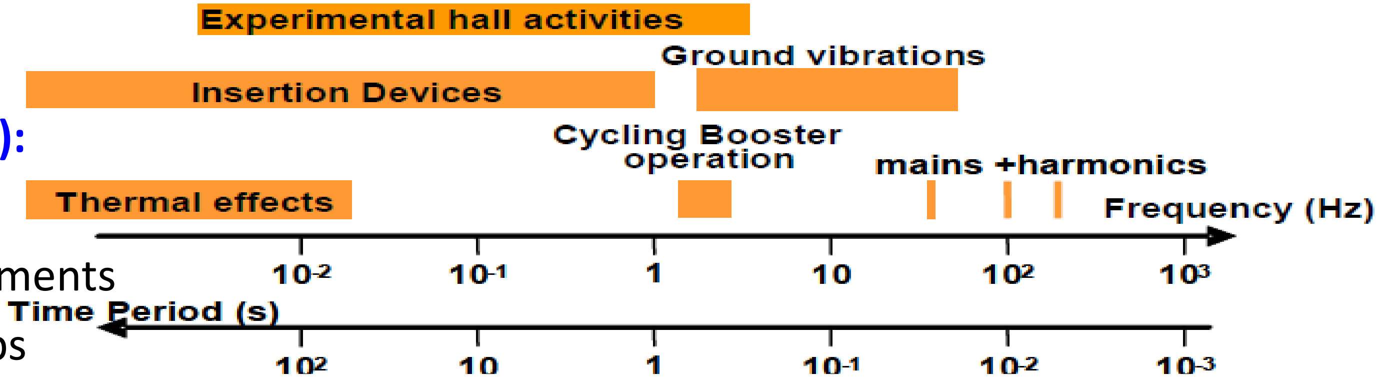
- Traffic
- Machine (crane) movements
- Water & vacuum pumps
- 50 Hz main power net

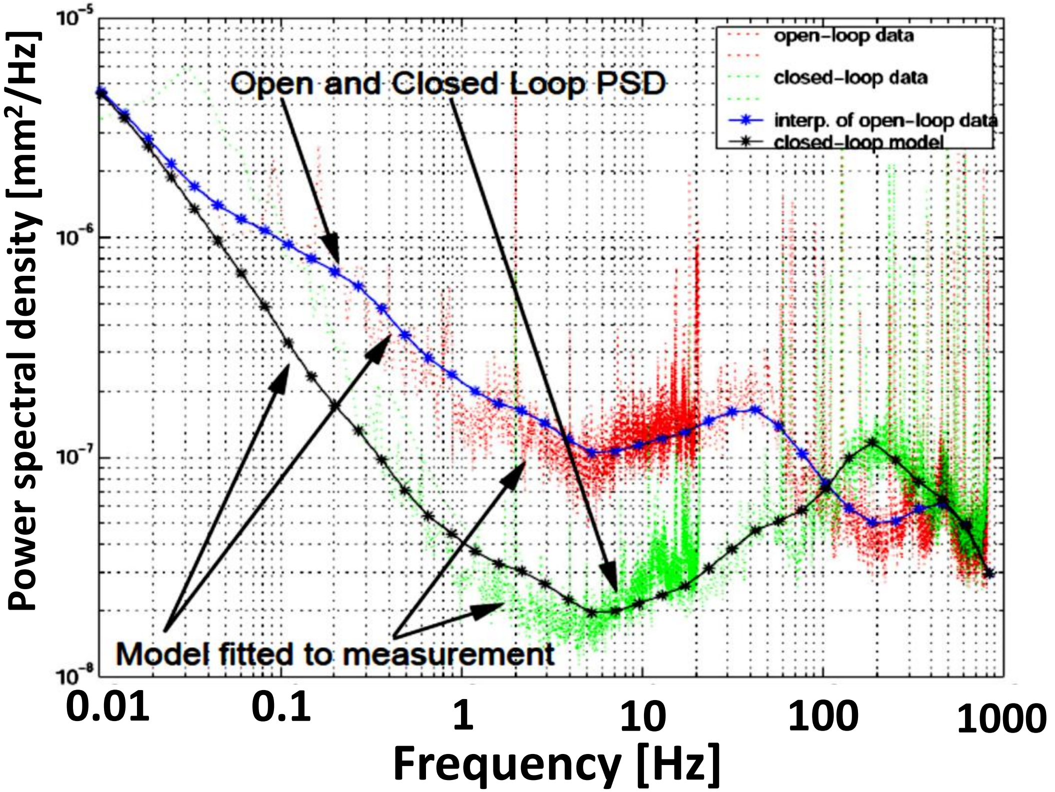
Medium term (day to min):

- Movement of chambers due to heating by radiation
- Day-night variation
- Tide, moon cycle

Long term (> days):

- Ground settlement
- Seasons, temperature variation



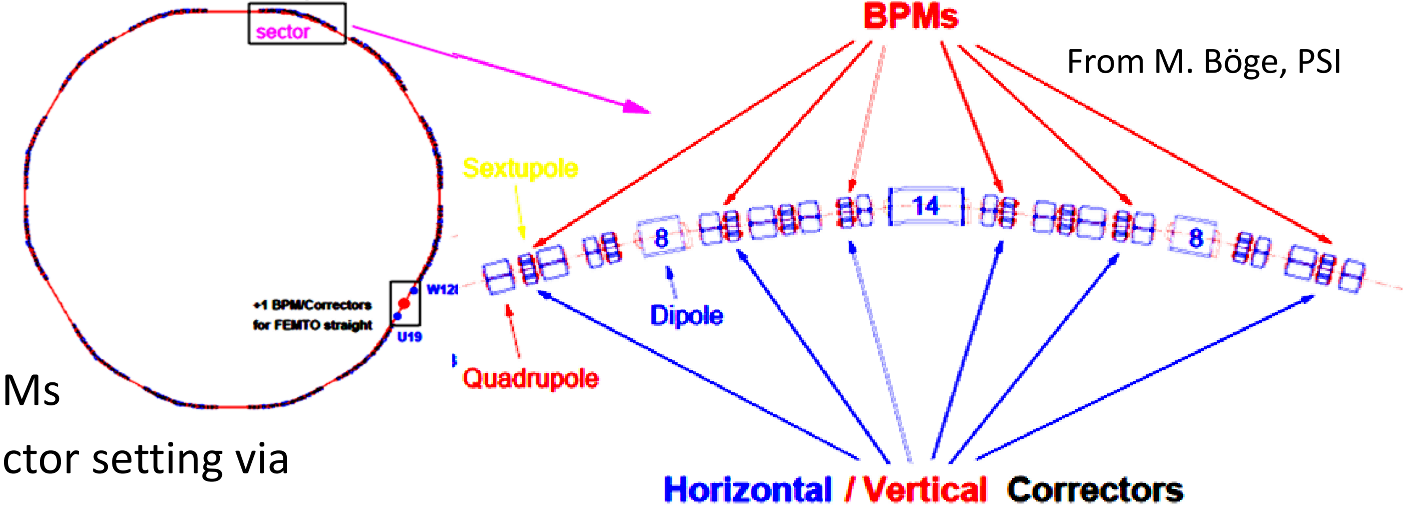


Courtesy M. Böge (PSI) CAS 2008, N. Hubert (Soleil) DIAPC 2009

Close Orbit Feedback: BPMs and magnetic Corrector Hardware

Orbit feedback: Synchrotron light source → spatial stability of light beam

Example: SLS-Synchrotron at Villigen, Switzerland



From M. Böge, PSI

Feedback loop:

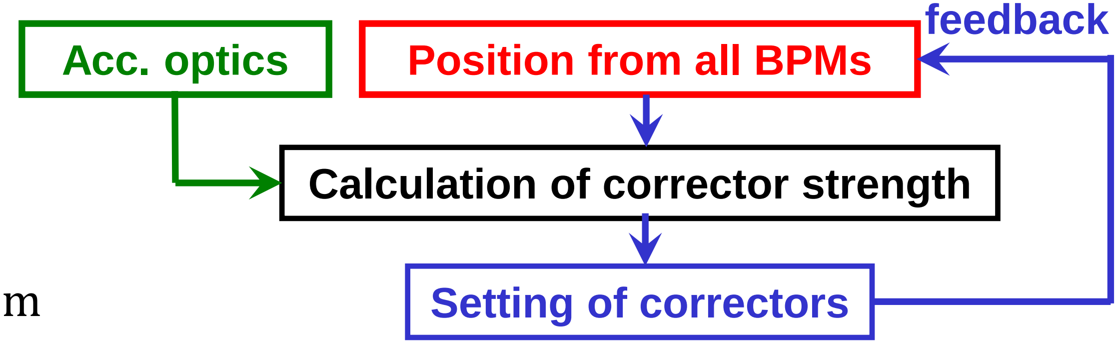
1. Position from all BPMs

2. Calculation of corrector setting via Orbit Response Matrix

3. Change of magnet setting

1.' New positon measurement .....

⇒ regulation time down to 10 ms



Acc. optics

Position from all BPMs

Calculation of corrector strength

Setting of correctors

Uncorrected orbit: typ. $\langle x \rangle_{rms} \approx 1\ \mathrm{mm}$

Corrected orbit: typ. $\langle x \rangle_{rms} \approx 1\ \mu\mathrm{m}$ up to ≈ 100 Hz bandwidth!

Rule of thumb: 4 BPMs per tune value (to determine the 'sine-like' betatron oscillation)

Close Orbit Feedback: Mathematical Treatment

Linear beam optics lead to Orbit Response Matrix ORM:

Kick angle $\boldsymbol{\theta_j}$ of single steerer $\boldsymbol{j}$ transferres to an offset $\boldsymbol{x_i}$ at BPM $\boldsymbol{i}$:

$$\boldsymbol{x_i} = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi Q}\cos\left(\pi Q - \left|\mu_i - \mu_j\right|\right) * \boldsymbol{\theta_j} \equiv \boldsymbol{R_{ij}} * \boldsymbol{\theta_j}$$

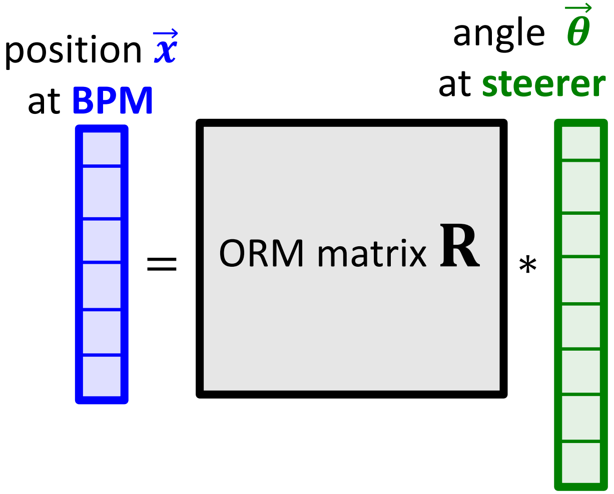
(Q transverse tune, $\left|\mu_i - \mu_j\right|$ phase advance, β_i, β_j: beta functions)

For all steerers $\boldsymbol{j} = 1 \ldots M$ and all BPMs $\boldsymbol{i} = 1 \ldots N$ the

Orbit **R**esponse **M**atrix $\mathbf{R}$ is defined as: $\vec{x} = \mathbf{R} * \vec{\theta}$

The matrix elements must be measured beforehand by

changing each steerer and observing the position at each BPM

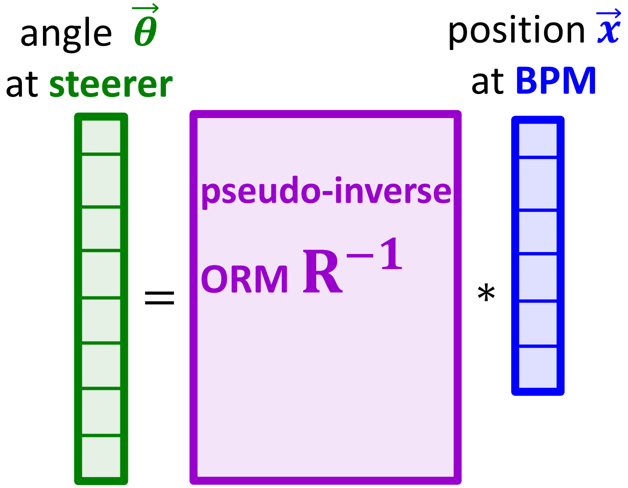


Closed orbit feedback:

1. Measurement of the position $\boldsymbol{x_i}$ at **all** BPMs,
2. Determine offset to respect to set value
3. Calculation of new steerer kick $\boldsymbol{\theta_j}$ for correction

⇒ determination of pseudo-inverse ORM $\vec{\boldsymbol{\theta}} = \mathbf{R}^{-1} * \vec{\boldsymbol{x}}$

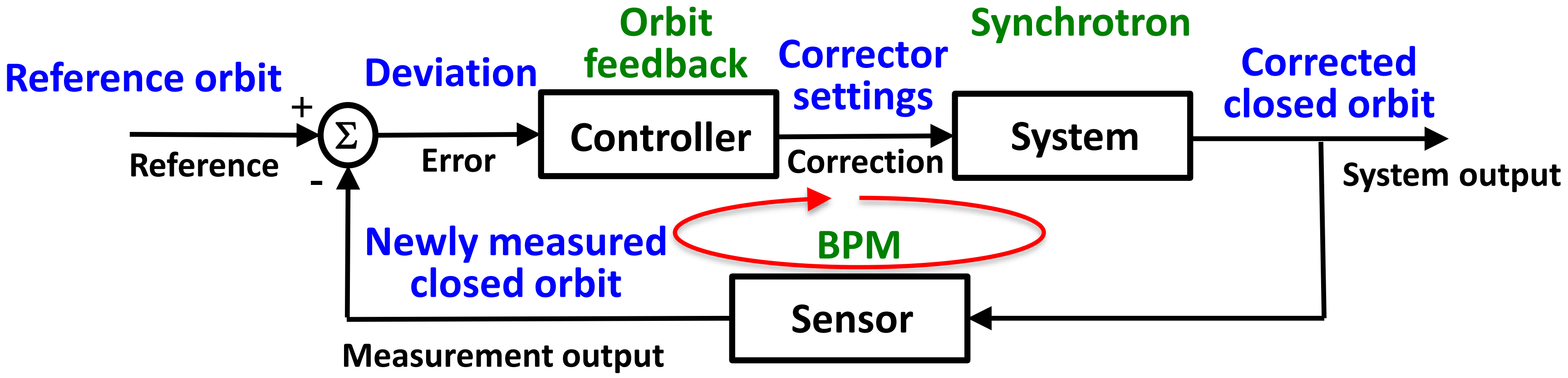
frequently used method: **S**ingular **V**alue **D**ecomposition



Close Orbit Feedback: Controller Principle

A feedback is modelled by Control Theory!

Visualization for a control loop:



Mathematical description for multi-input multi-output (MIMO) system:

- **Synchrotron optics:** Orbit Response Matrix
- **System reaction:** Model for power supplies, beam dynamics, tune spread etc.
- **BPM:** Accuracy and noise

Using Laplace Transformation and frequency domain visualization for dynamic behavior

Courtesy Guenther Rehm (BESSY), IBIC 2019 & CAS 2026

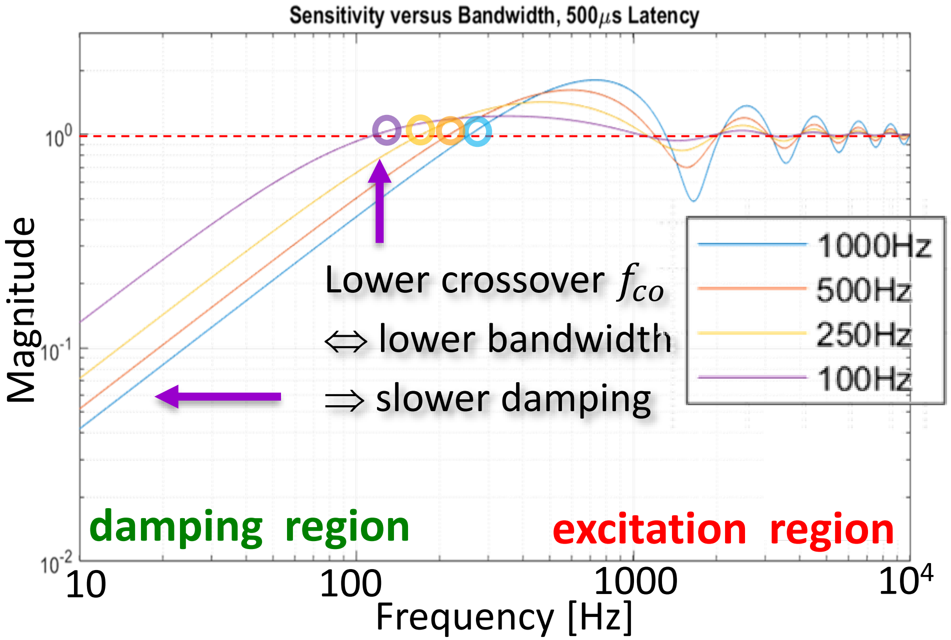
Close Orbit Feedback: System Bandwidth

Reaction depends on bandwidth and latency:

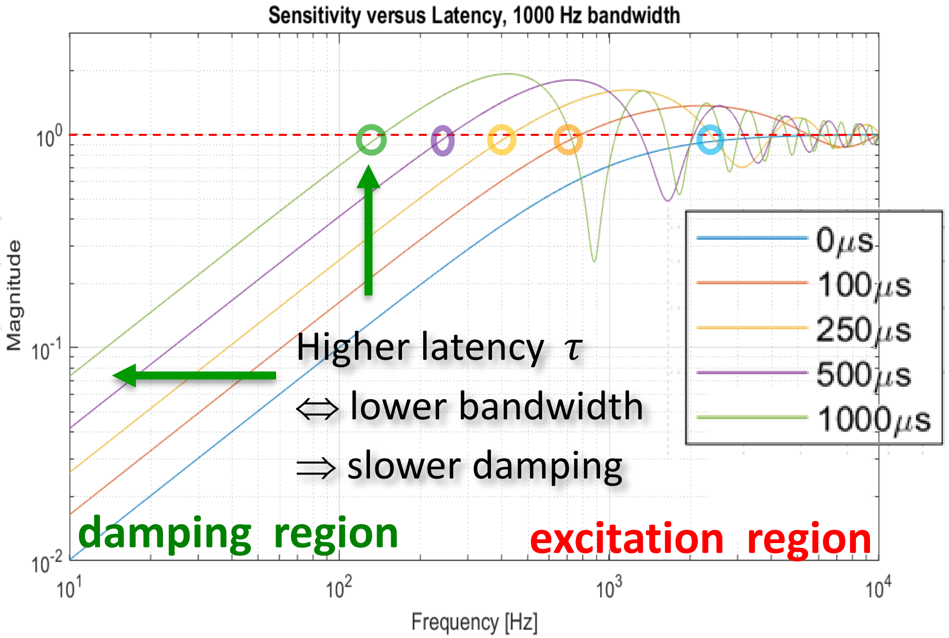
Performance measure by cross over frequency f_{co} and latency τ:

- Beam ***damping*** **below** f_{co} by anti-phase correction of disturbance
- Beam ***excitation*** **above** f_{co} by in-phase excitation with respect to disturbance

Large bandwidth required to enable fast damping



Lower crossover f_{co}
⇔ lower bandwidth
⇒ slower damping



Higher latency τ
⇔ lower bandwidth
⇒ slower damping

Slow feedback: time step of orbit correction much lower than system delay

Fast feedback: time step of orbit correction comparable to system delay

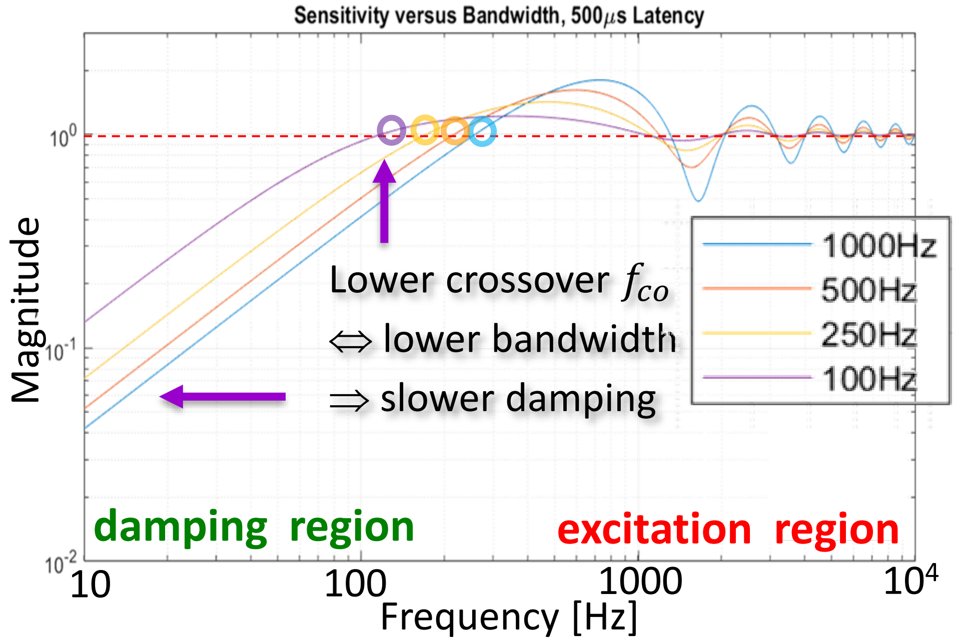
Courtesy Guenther Rehm (BESSY), IBIC 2019 & CAS 2026

Close Orbit Feedback: Actual Challenges

Actual challenges (mainly for 4th generation light sources):

- ➢ Measurement accuracy for BPMs
- ➢ High bandwidth regulation
- ➢ High bandwidth power supplies
- ➢ Model inclusion of alignment errors
- ⇒ Technical improvements

- ➢ Magnets with non-linear field contributions
- ➢ Space charge and impedance contributions
- ⇒ Linear approx. by ORM might be insufficient
- ⇒ Proposal of Machine Learning for non-linear problems

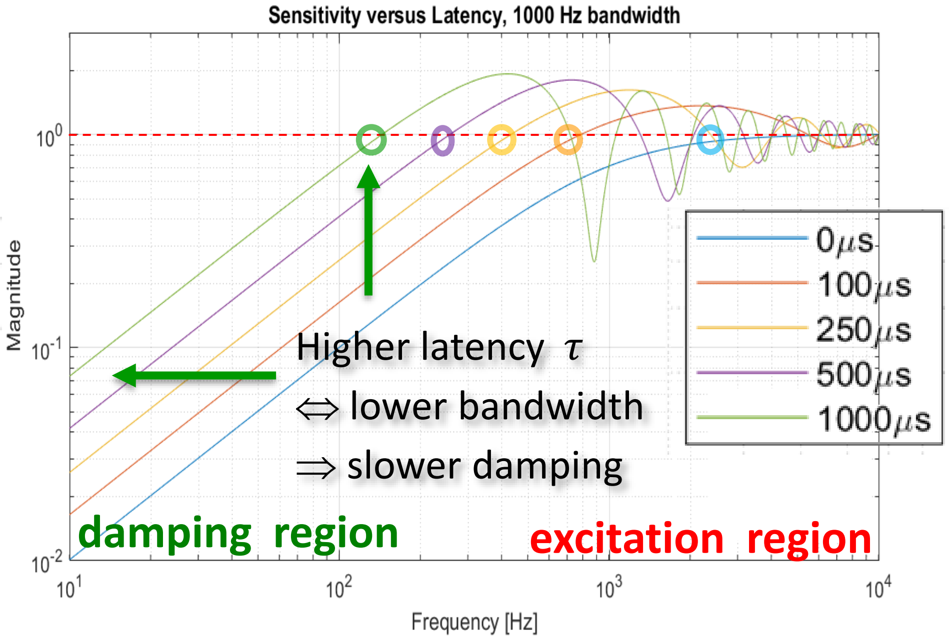

Sensitivity versus Bandwidth, 500μs Latency

Lower crossover f_{co}

⇔ lower bandwidth

⇒ slower damping

damping region **excitation region**


Sensitivity versus Latency, 1000 Hz bandwidth

Higher latency τ

⇔ lower bandwidth

⇒ slower damping

damping region **excitation region**

Slow feedback: time step of orbit correction much lower than system delay

Fast feedback: time step of orbit correction comparable to system delay

Courtesy Guenther Rehm (BESSY), IBIC 2019 & CAS 2026

Measurement with BPMs

Outline for BPM measurements:

- Signal generation and basic usage:

  transfer impedance, button BPM
- Electronics basics:

  Schemes for signal processing
- Cavity BPM at FELs

  information storage for short pulses
- Trajectory measurement, close orbit feedback:

  beam stabilization methods via real-time control
- Tune and lattice function measurement

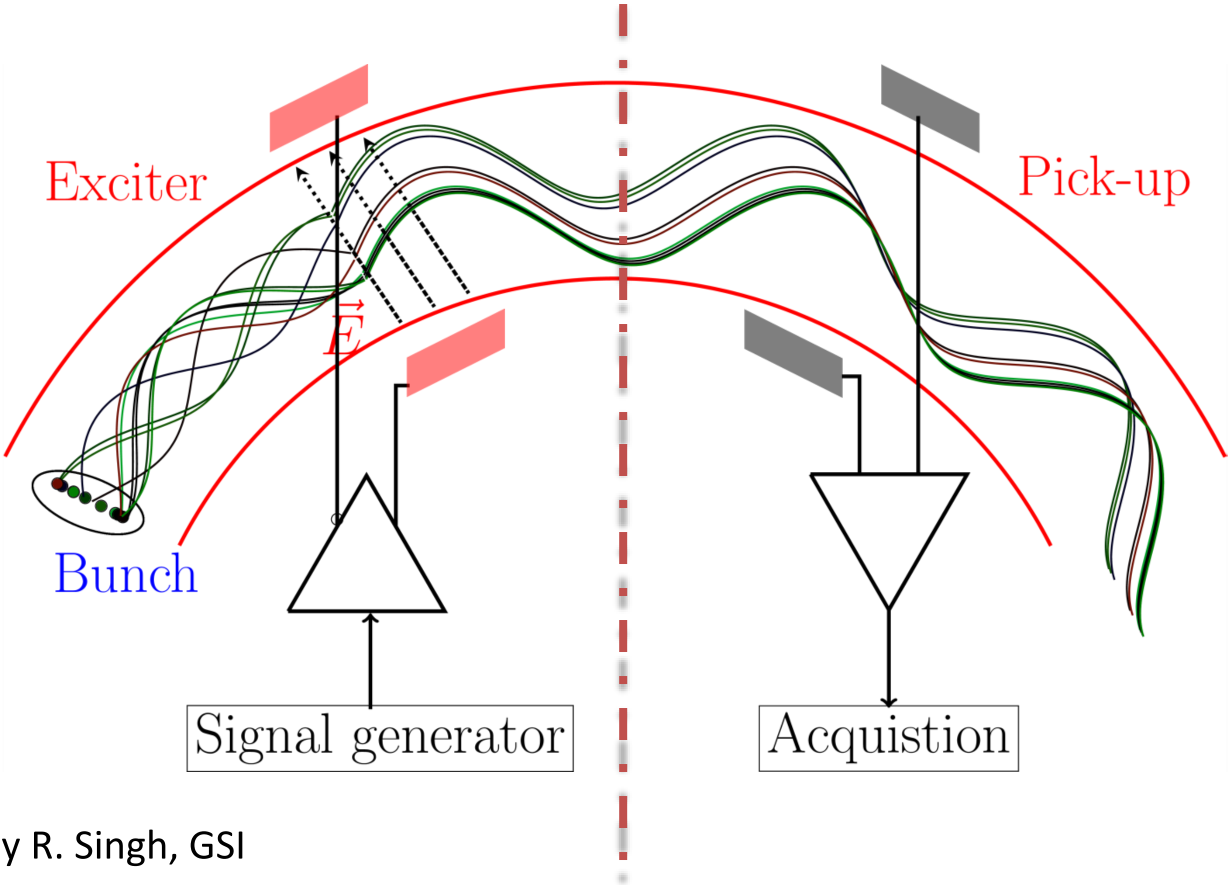
Tune Measurement: General Considerations

Coherent excitations are required for the detection by a BPM

Beam particle's ***in-coherent*** motion ⇒ center-of-mass stays constant

Excitation of **all** particles by rf ⇒ ***coherent*** motion

⇒ center-of-mass variation turn-by-turn i.e. center acts as **one** macro-particle



Graphics by R. Singh, GSI

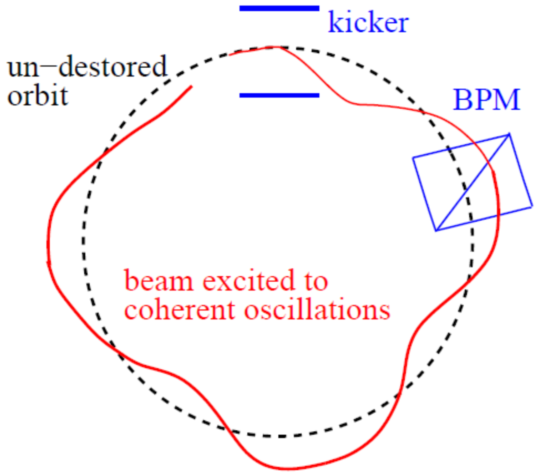
Tune Measurement: The Kick-Method in Time Domain

The beam is excited to **coherent** betatron oscillation:

→ Beam position measured each revolution ('turn-by-turn')

→ Fourier Trans. gives non-integer tune ***q***.

Short kick compared to revolution.



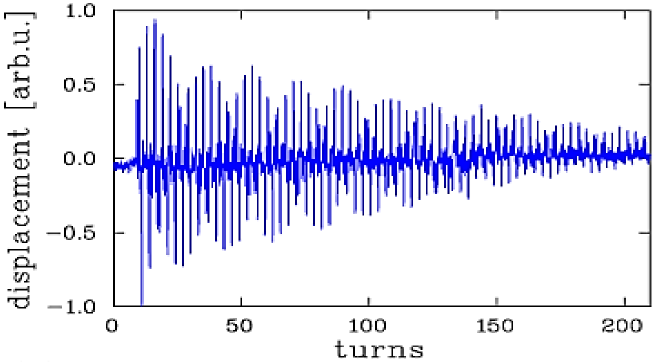
The de-coherence time limits the **resolution**:

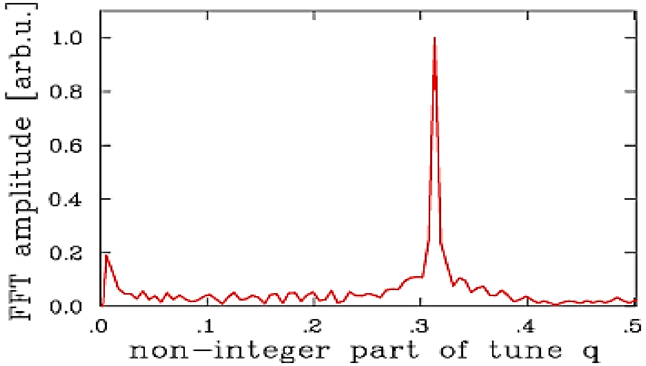
N non-zero samples

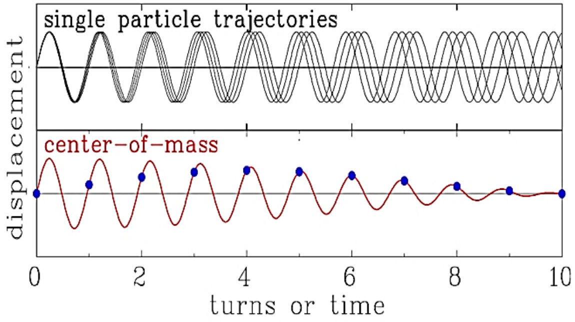
⇒ General limit of discrete FFT: $\Delta q > \frac{1}{2N}$

Here: ***N*** = 200 turn ⇒ **Δ*q*** > 0.003

(tune spreads can be **Δ*q*** ≈ 0.001!)





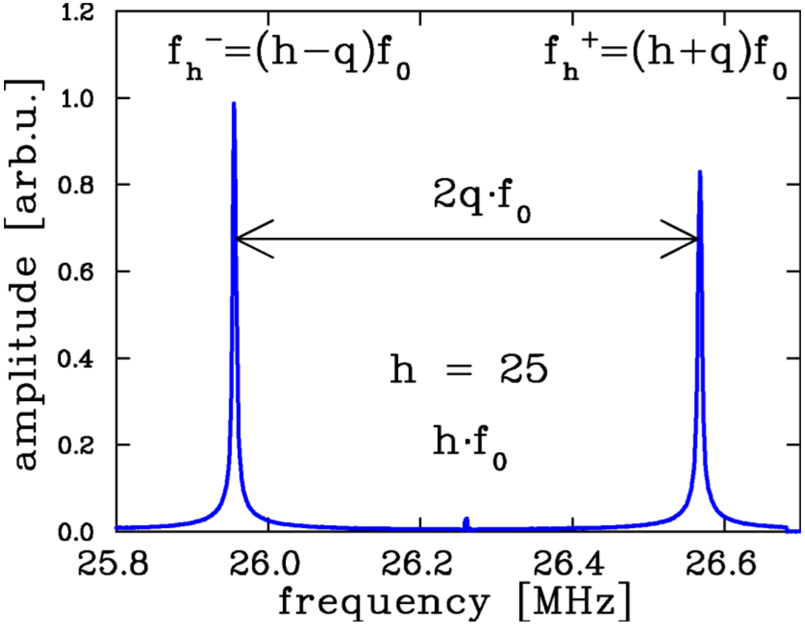


Decay is caused by de-phasing, **not** by decreasing single particle amplitude.

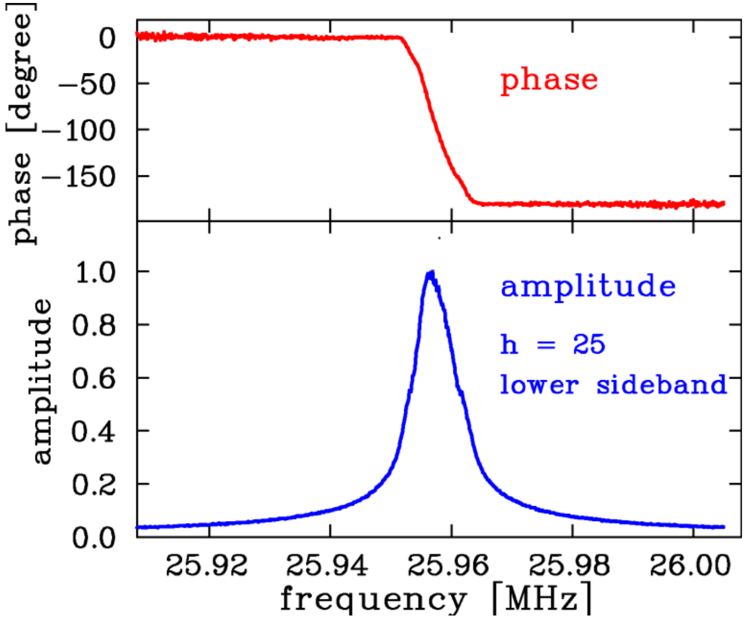
Tune Measurement: Frequency Chirp Measurement

Principle: Slowly scan of the excitation frequency → beam acts as driven oscillator!
(sometimes refer to as **B**eam **T**ransfer **F**unction **BTF** or frequency **chirp** measurement)

SIS-synchrotron: A wide scan with both sidebands at h=25th-harmonics:



A detailed scan for the ***lower*** *sideband → beam acts like a driven oscillator:*



From the position of the sidebands ***q*** = 0.306 is determined.

Advantage: High resolution, possibility of tune feedback by phase detection

Disadvantage: Long sweep time (up to several seconds).

Alternative: Excitation by band-limited noise with beam ‘picks’ the correct frequency

Chromaticity Measurement from Closed Orbit Data

Chromaticity ξ: Change of tune for off-momentum particle $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$

Two step measurement procedure:

1. Change of momentum ***p*** by detuned rf-frequency $\frac{\Delta p}{p} = \eta^{-1} \cdot \frac{\Delta f_{acc}}{f_{acc}}$

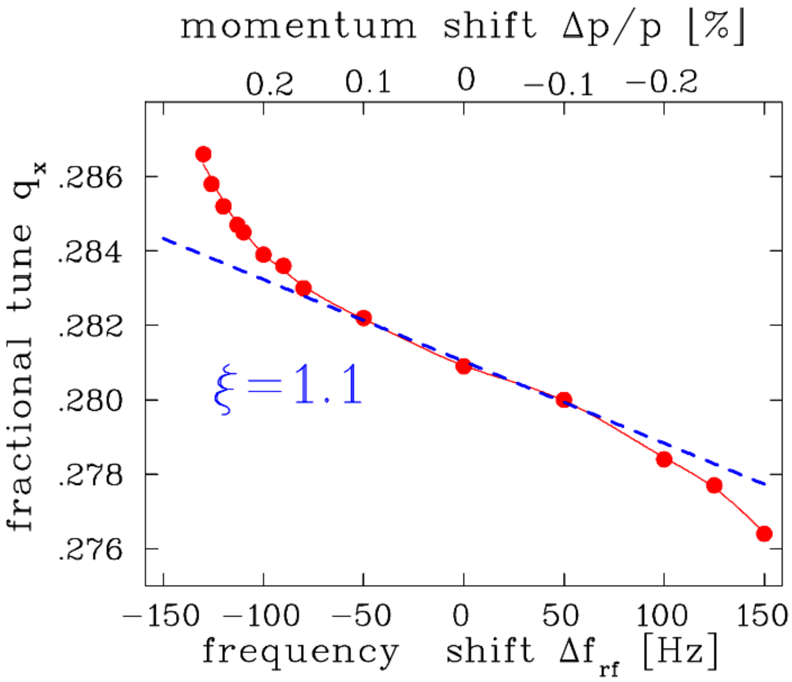
2. Excitation of coherent betatron oscillations
   and tune measurement

(kick-method, BTF, noise excitation):

Plot of ***ΔQ/Q*** as a function of ***Δp/p***

⇒ slope is dispersion ***ξ***.

Example: Measurement at LEP:



From M Minty, F. Zimmermann,
Measurement and Control of charged Particle Beam,
Springer Verlag 2003

Actual Challenges for BPMs

Actual challenges for BPMs and COFB:

→ ***Position resolution requirement at 4th generation circular light sources : about 1 µm (!)***

- **Low drift analog and digital electronics**

  Solution keywords: Pilot tone or channel multiplexing
- **Fast signal processing providing high bandwidth & low latency**

  Solution keywords: Parallel signal processing on powerful FPGAs
- **Improved accelerator model**

  Solution keywords: Machine Learning to include non-linearities

Actual challenges for tune etc. measurement:

- **Low excitation strength**

  Solution keywords: Phase-sensitive tracking (PLL-tracking)
- **Possible tune & chromaticity feedback**

  Solution keywords: Under development

Related talks at IPAC'26 within MC6:

- Laura Torino (ALBA), *Overview of the beam position monitors development for the next generation light sources*

Measurement of Beam Profile

Outline for profile measurements:

- **Scintillation screens:**

  emission of light, universal usage, limited dynamic range

- **Optical Transition Radiation:**

  light emission due to crossing material boundary, mainly for relativistic beams

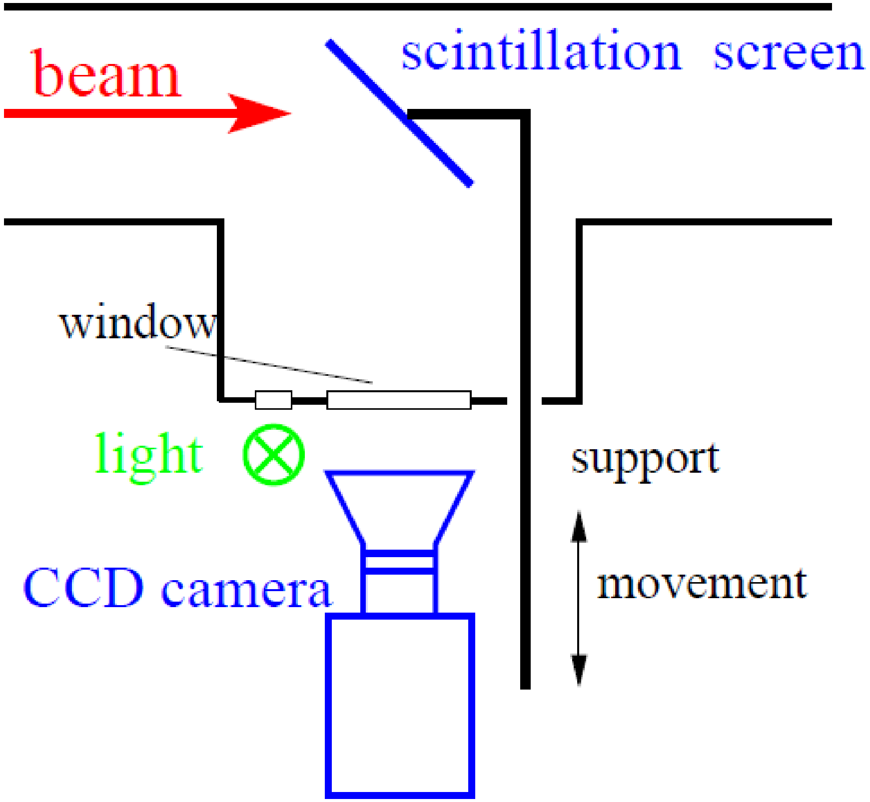
- **Ionization Profile Monitor and Beam Induced Fluorescence**

- **Synchrotron Light Monitors**

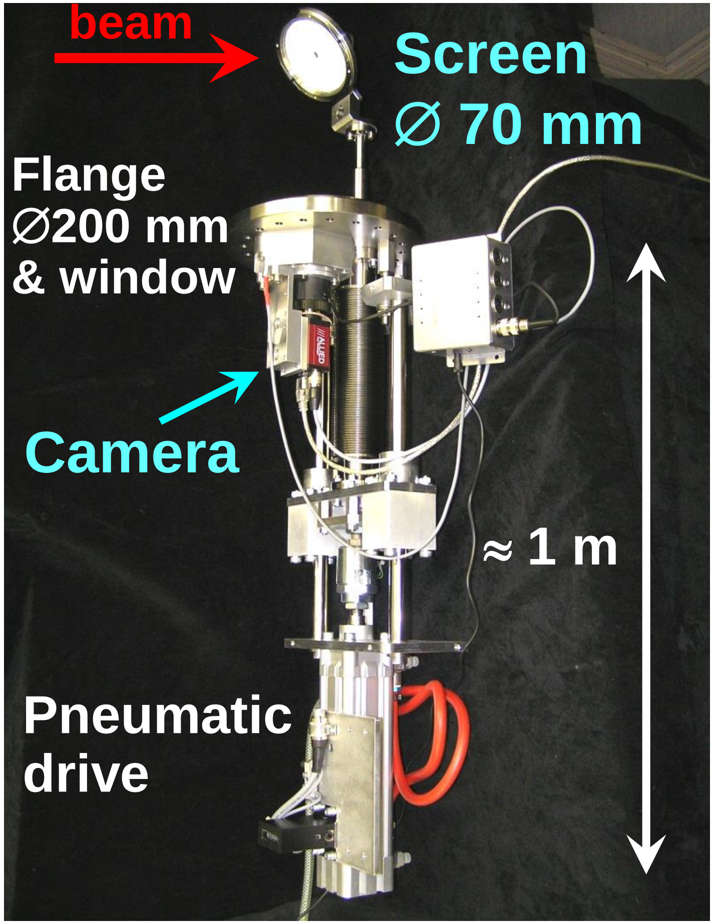
Scintillation Screen

Scintillation: Particle's energy loss in matter causes emission of light

→ the most direct way of profile observation as used from the early days on!



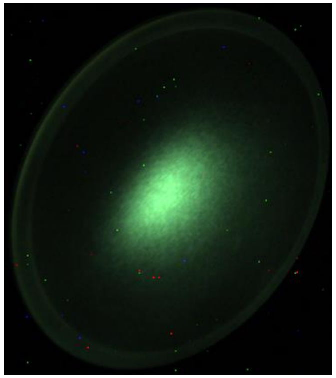
Pneumatic drive with Ø70 mm screen:



Light output from various Scintillating Screens

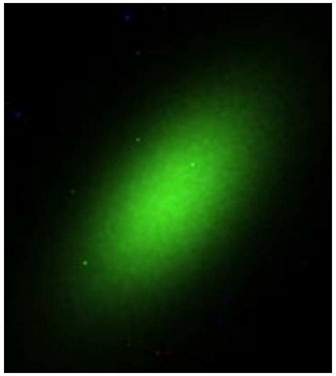
Example: *Color CCD camera: Images at different particle intensities determined for U at 300 MeV/u*

Alumina: Al_2O_3

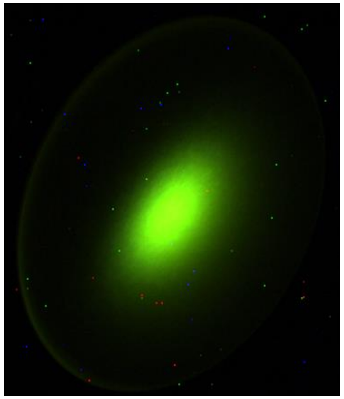


CsI:Tl

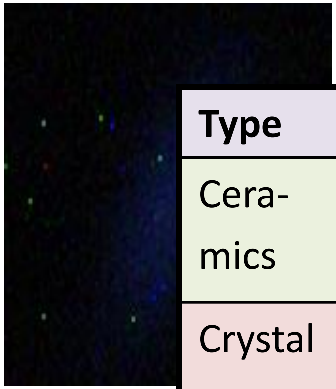
Chromox: Al_2O_3:Cr



P43



YAG:Ce



Qu

- ➢ Very different light yield i.e. phot
- ➢ Different wavelength of emitted

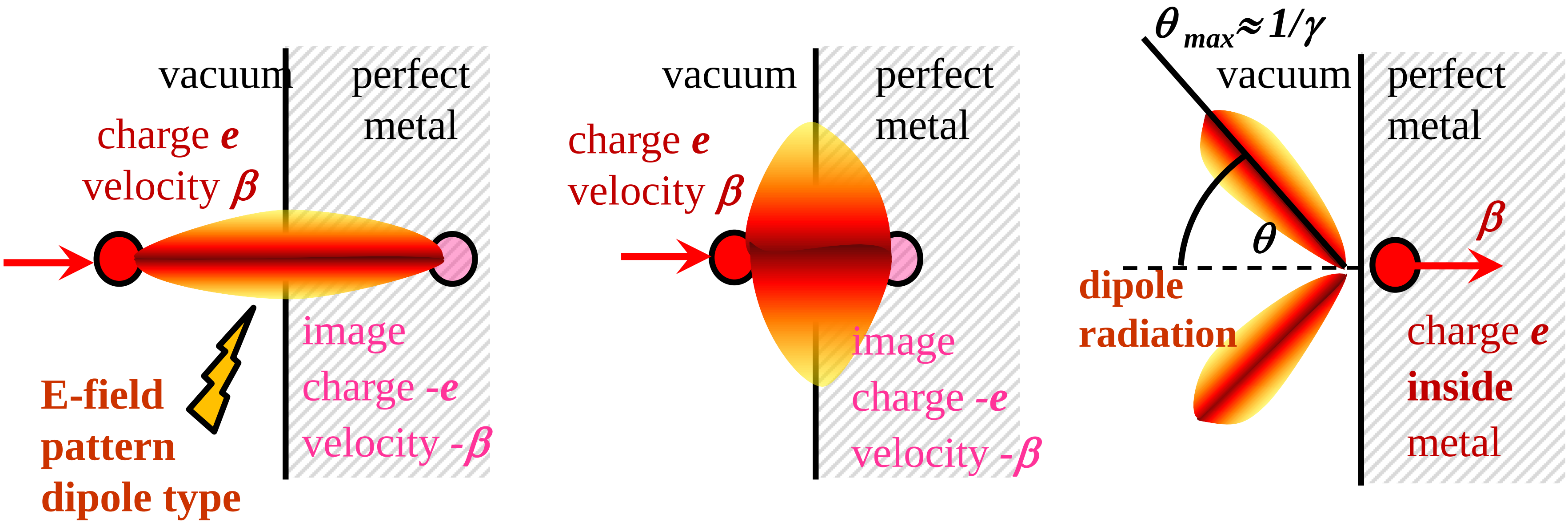
Type	Name	Material	Activ.	Max. λ	Decay
Cera-mics	Chromox	Al_2O_3	Cr	700nm	≈ 10ms
	Alumina	Al_2O_3	Non	380nm	≈ 10ns
Crystal	YAG:Ce	$Y_3Al_5O_{12}$	Ce	550nm	200ns
	LYSO	$Lu_{1.8}Y_{.2}SiO_5$	Ce	420nm	40ns
Powder of gains Ø≈10μm on glass	P43	Gd_2O_3S	Tb	545nm	1ms
	P46	$Y_3Al_5O_{12}$	Ce	530nm	300ns
	P47	Y_2SiO_5	Ce&Tb	400nm	100ns

Optical Transition Radiation: Depictive Description

Optical Transition Radiation OTR for a single charge *e*:

Assuming a charge ***e*** approaches an ideal conducting boundary e.g. metal foil:

- Image charge is created by electric field with dipole type field pattern
- Field distribution depends on velocity β and Lorentz factor γ due to relativistic trans. field increase
- Penetration of charge through surface within ***t*** < 10 fs: sudden change of source distribution
- Emission of radiation with dipole characteristic



Physics: sudden change charge distribution rearrangement of sources ⇔ radiation

Other physical interpretation: Impedance mismatch at boundary leads to radiation

Technical Realization of Optical Transition Radiation OTR

OTR is emitted by charged particle passage through a material boundary.

Photon distribution:

within a solid angle $\boldsymbol{d\Omega}$ and

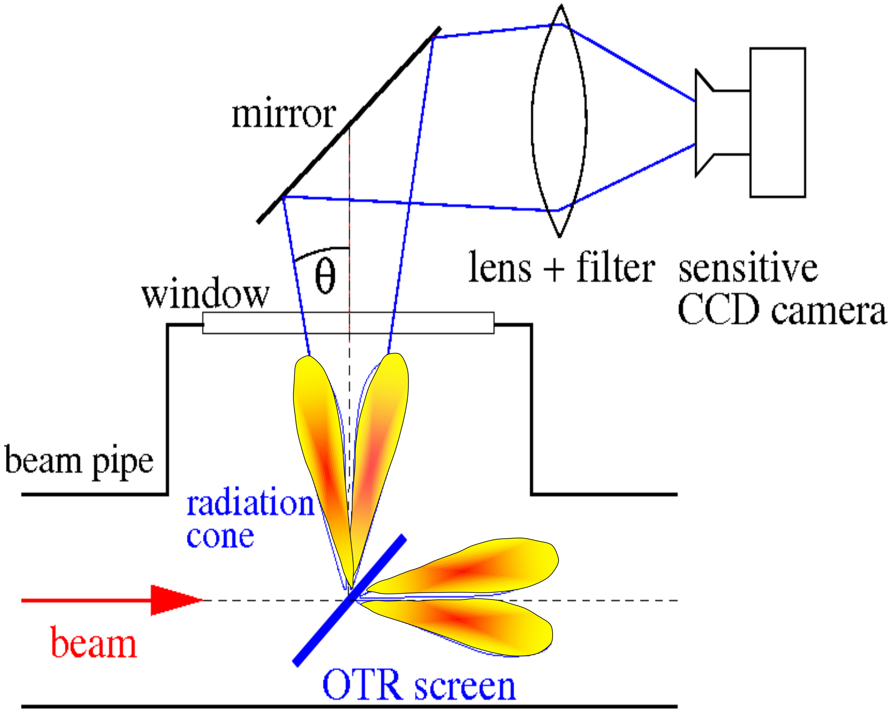
Wavelength interval λ_{begin} to λ_{end}

$$\frac{dN_{photon}}{d\Omega} = N_{beam} \cdot \frac{2e^2\beta^2}{\pi c} \cdot \log\left(\frac{\lambda_{begin}}{\lambda_{end}}\right) \cdot \frac{\theta^2}{\left(\gamma^{-2}+\theta^2\right)^2}$$

- Detection: Optical 400 nm < λ < 800 nm
- Larger signal for relativistic beam $\gamma \gg 1$
- Low divergence for $\gamma \gg 1 \Rightarrow$ large signal

$\Rightarrow$ **Well suited for e⁻ beams**

$\Rightarrow$ **p-beam used for $E_{kin} \gtrsim 10$ GeV $\Leftrightarrow \gamma \gtrsim 10$**



- Insertion of thin Al-foil under 45°
- Observation of low light by CCD.

Measurement of Beam Profile

Outline:

- Scintillation screens:

  emission of light, universal usage, limited dynamic range
- Optical Transition Radiation:

  light emission due to crossing material boundary, mainly for relativistic beams
- Ionization Profile Monitor and Beam Induced Fluorescence:

  secondary particle detection from interaction beam-residual gas
- Synchrotron Light Monitors

Interaction between Residual Gas and the Beams

Physics: Energy loss of ions in gas ***dE/dx***

⇒ Profile determination from residual gas

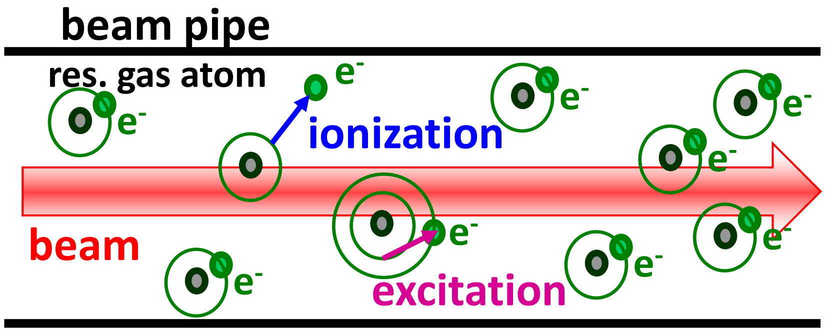
- **Ionization:**

  in average roughly ≈ 100 eV/ionization

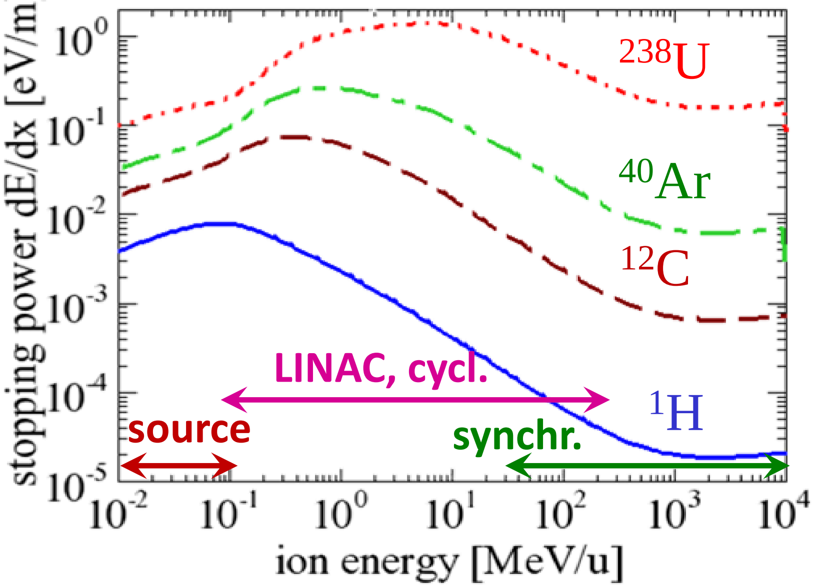
- **Excitation** followed by photon emission:

in average roughly ≈ 300 eV/event e.g. N_2

However, depends strongly on gas molecule



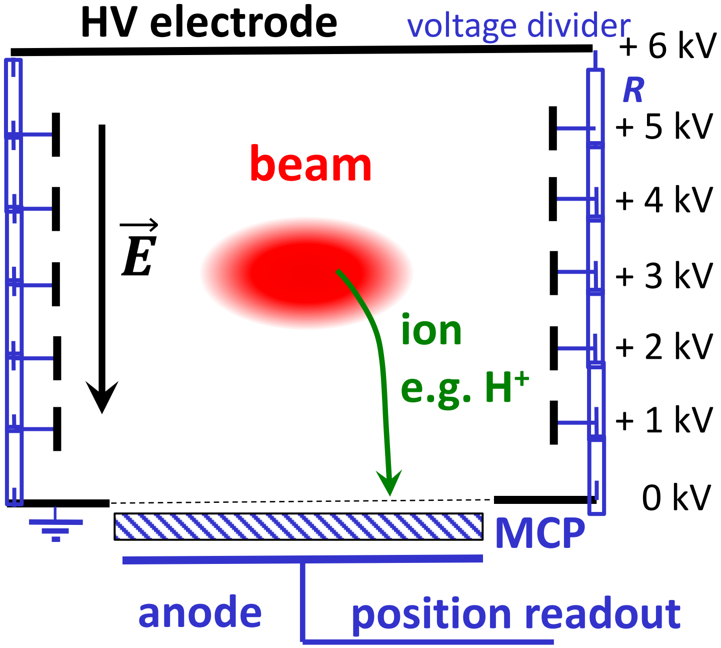
Energy loss in $p = 10^{-7}$ mbar N_2 by SRIM



Ionization Profile Monitor at GSI Synchrotron

Non-destructive device for proton synchrotron:

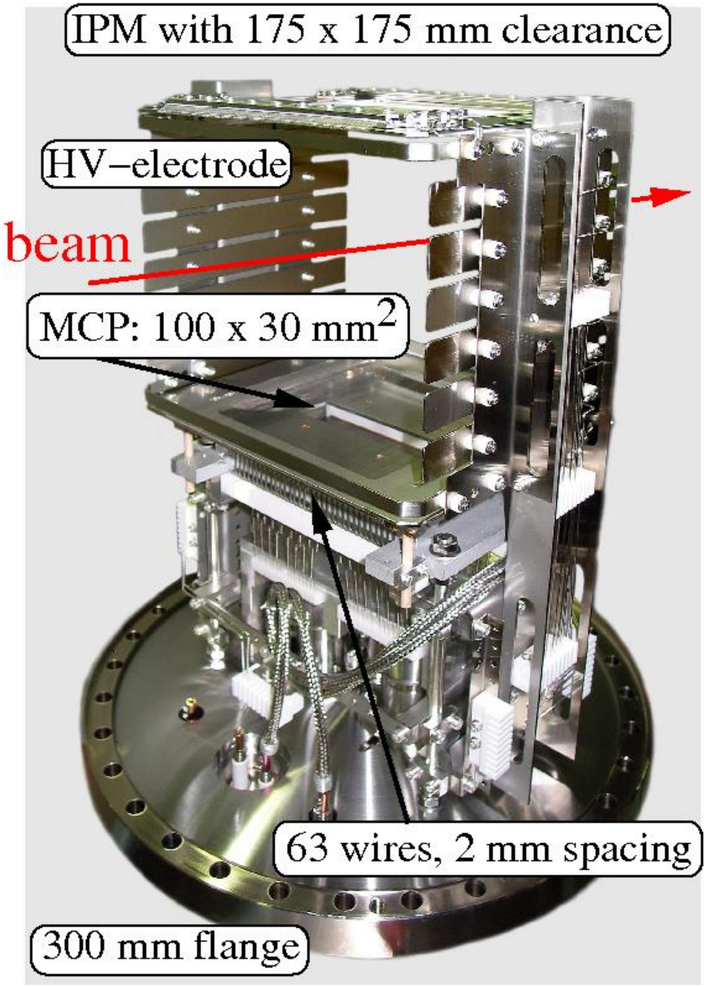
- Beam ionizes the residual gas by electronic stopping
- Gas ions or e$^-$ accelerated by E -field ≈1 kV/cm
- Spatial resolved single particle detection



Abbreviation: Ionization Profile Monitor **IPM** or

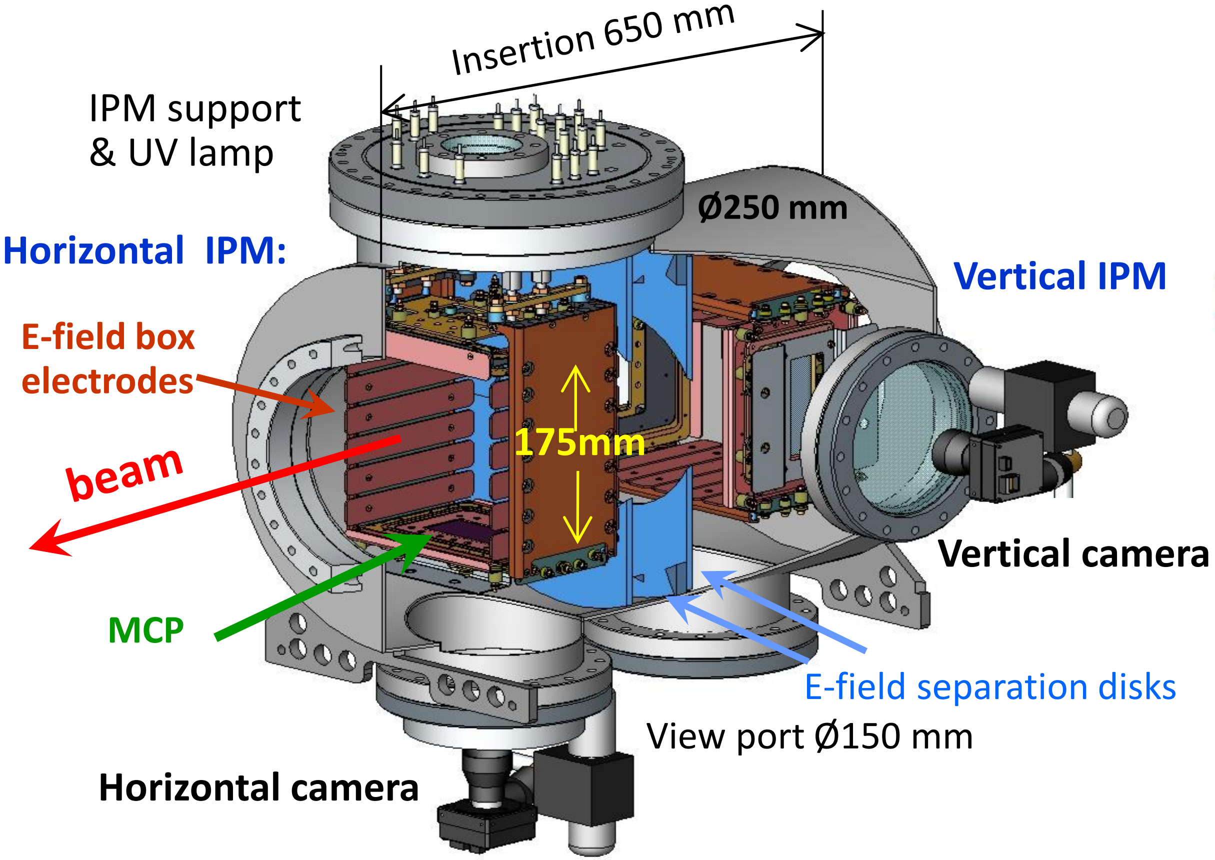
at CERN Beam Gas Ionization **BGI** Monitor

Realization at GSI synchrotron:
One monitor per plane

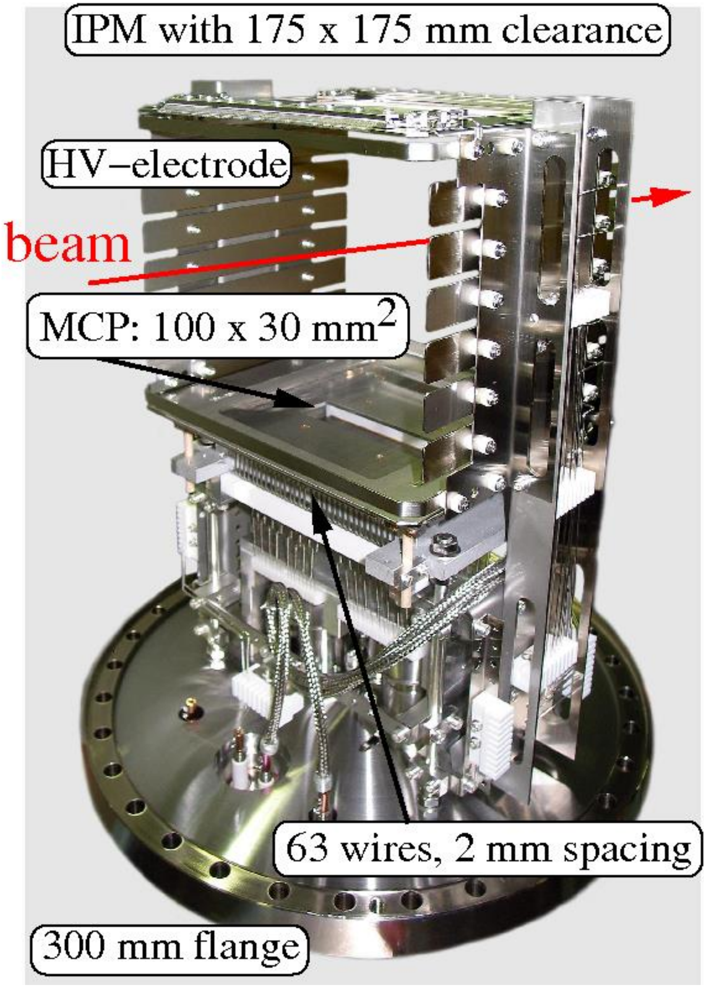


Ionization Profile Monitor Realization

The realization for the heavy ion storage ring ESR at GSI:



Realization at GSI synchrotron:
One monitor per plane



Beam Induced Fluorescence for intense Profiles

Large beam power → Non-intercepting method:

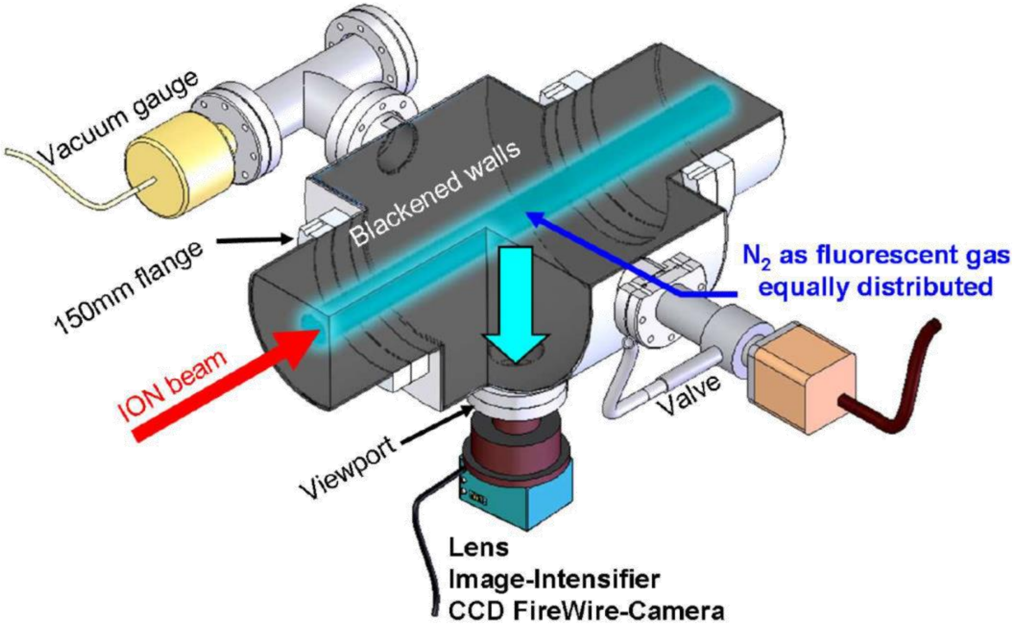
⇒ **B**eam **I**nduced **F**luorescence BIF

$N_2 + \text{Ion} \rightarrow (N_2^+)^* + \text{Ion} + e^- \rightarrow N_2^+ + \gamma + \text{Ion} + e^-$

With single photon detection scheme

390 nm < λ < 470 nm blue wavelength

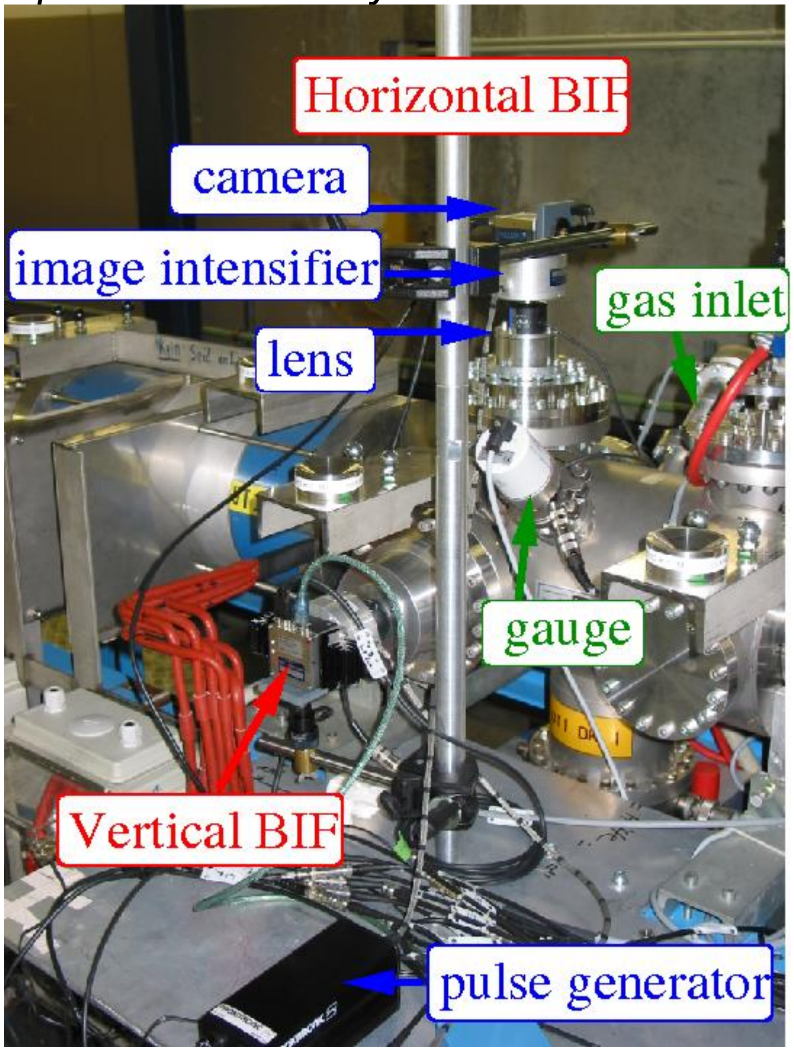
⇒ non-destructive, compact installation.



Fluorescence gas:

- Either from residual gas or extended gas bump
- Or intersecting gas jet

Example: Installation of hor&vert. BIF Monitor:



Measurement of Beam Profile

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- Scintillation screens:

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- Optical Transition Radiation:

  light emission due to crossing material boundary, mainly for relativistic beams
- Ionization Profile Monitor and Beam Induced Fluorescence:

  secondary particle detection from interaction beam-residual gas
- Synchrotron Light Monitors

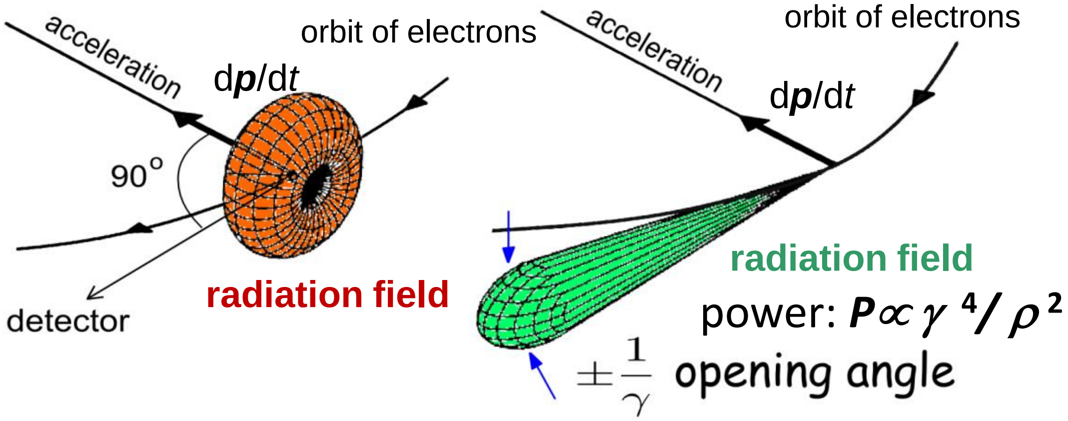
  standard for circular light sources, visible or X-ray range

Synchrotron Light Monitor

An electron bent (i.e. accelerated) by a dipole magnet emit synchrotron light.

This light is emitted
into a cone of
opening $2/\gamma$ in lab-frame.
$\Rightarrow$Well suited for rel. e^-
For protons:
Only for energies $E_{kin} > 100$ GeV

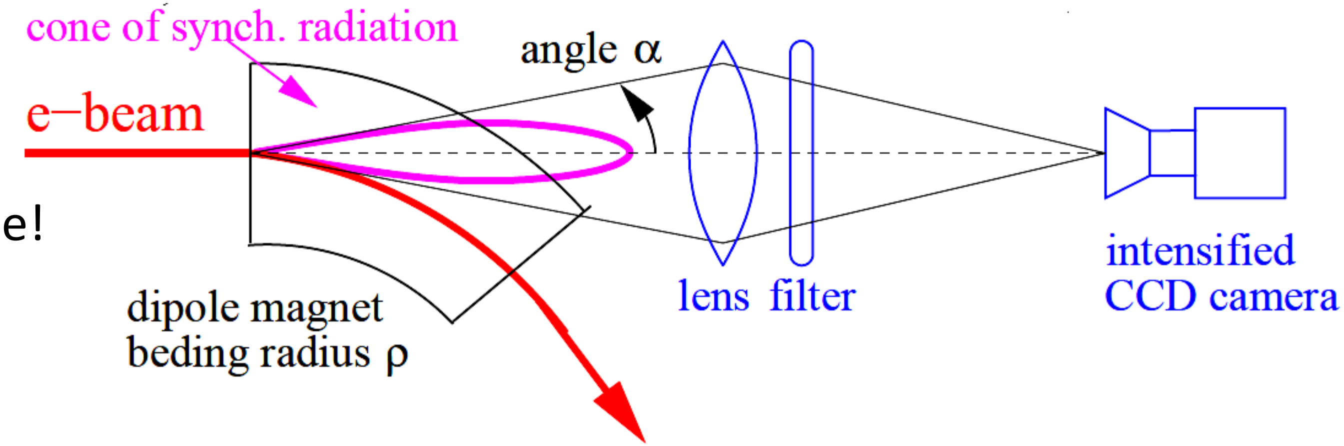
Rest frame of electron: **Laboratory frame:**



power: $P \propto \gamma^4/\rho^2$

$\pm\frac{1}{\gamma}$ opening angle

The light is focused to a camera



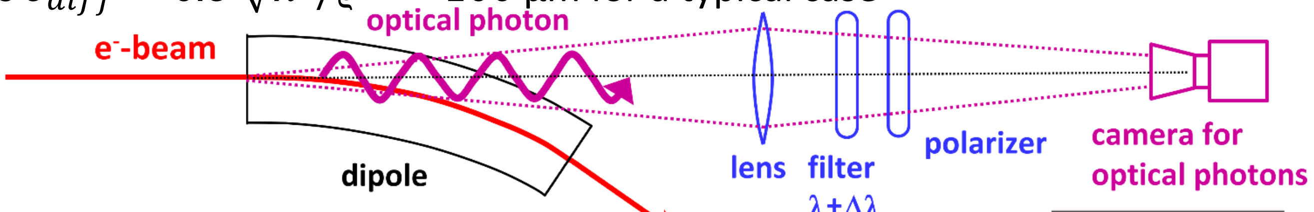
Advantage:

Signal anyhow available!

Synchrotron Light Monitor overcoming Diffraction Limit

Problem: The diffraction limit is $\sigma_{diff} \approx 0.6 \sqrt[3]{\lambda^2/\varrho} \approx 100\ \mu\text{m}$ for a typical case

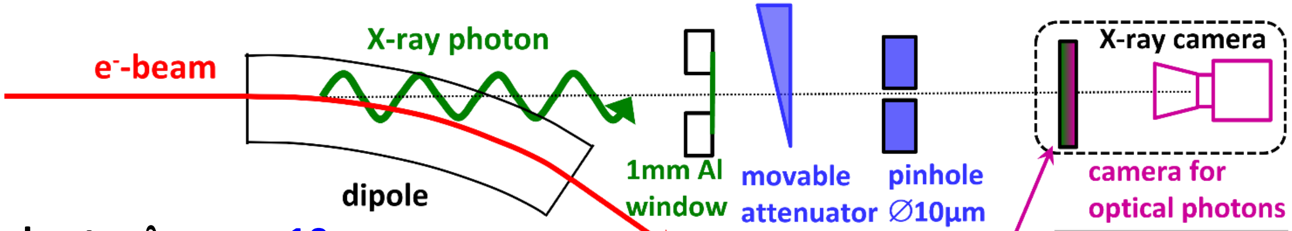
<u>**Optical imaging:**</u>
Spatial resolution
roughly ≈ 100 µm



Direct optical observation: $\sigma \approx 100\ \mu\text{m}$

→ **Relative simple installation, but** resolution insufficient for modern light sources

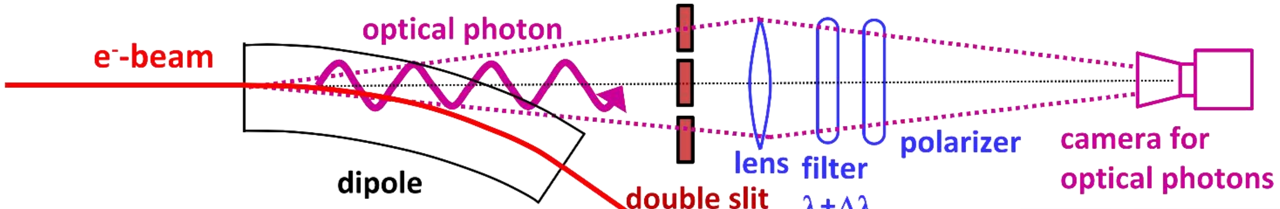
<u>**X-ray imaging:**</u>
Spatial resolution
roughly ≈ 10 µm

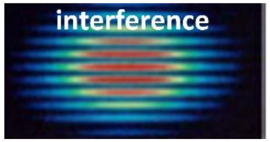


Direct X-ray observation with shorter λ : $\sigma \approx 10\ \mu\text{m}$

→ **Medium complex but expensive installation,**
installed at most synchr. light sources referred to as **pinhole camera**

<u>**Optical interference:**</u>
Spatial resolution
roughly ≈ 1 µm





Interference optical observation: $\sigma \approx 1\ \mu\text{m}$

→ **Complex installation,** seldom installed; basis: blurring of interference pattern

Actual Challenges for Profile Measurement

Actual challenges for profile measurement:

- **High resolution and dynamic range**

  Solution keywords: Material choice, complicated optical setup,
  sensitive electronics and/or optics

- **Non-invasive methods**

  Reason: high beam power at hadron acc., multi-location observation

  Solution keywords: Machine Learning based image reconstruction

Related talks at IPAC'26 within MC6:

- Renjun Yang (CSNS), *Achieve a record dynamic range of halo diagnostics with a novel fluorescence wire concept*
- Carsten Welsch (University of Liverpool), *Progress in Data-Driven Beam Diagnostics within LIV.INNO*

Measurement of transverse Emittance

Outline for transverse emittance diagnostics:

- Quadrupole strength variation and position measurement

  emittance from several profile measurement and beam optical calculation

Definition of Coordinates and basic Equations

The basic vector is 6 dimensional:

$$\vec{x} = \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix} = \begin{pmatrix} \text{hori. spatial deviation} \\ \text{horizontal divergence} \\ \text{vert. spatial deviation} \\ \text{vertical divergence} \\ \text{long. deviation} \\ \text{momentum deviation} \end{pmatrix} = \begin{pmatrix} [\mathrm{mm}] \\ [\mathrm{mrad}] \\ [\mathrm{mm}] \\ [\mathrm{mrad}] \\ [\mathrm{mm}] \\ [10^{-3}] \end{pmatrix}$$

The transformation of a single particle from a location s_0 to s_1 is given by the Transfer Matrix R: $\vec{x}(s_1) = \mathrm{R}(s) \cdot \vec{x}(s_0)$

The transformation of a the envelope from a location s_0 to s_1 is given by the Beam Matrix σ : $\Sigma(s_1) = \mathrm{R}(s) \cdot \Sigma(s_0) \cdot \mathrm{R}^{\mathrm{T}}(s)$

6-dim Beam Matrix with *decoupled* hor., vert. and long. plane:

$$\Sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & 0 & 0 & 0 & 0 \\ \sigma_{12} & \sigma_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_{33} & \sigma_{34} & 0 & 0 \\ 0 & 0 & \sigma_{34} & \sigma_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{55} & \sigma_{56} \\ 0 & 0 & 0 & 0 & \sigma_{56} & \sigma_{66} \end{pmatrix}$$

horizontal
vertical
longitudinal
hor.-long. coupling
→ 10 values

Horizontal beam matrix:

$$\sigma_{11} = \langle x^2 \rangle$$
$$\sigma_{12} = \langle x\, x' \rangle$$
$$\sigma_{22} = \langle x'^2 \rangle$$

Beam width for the three coordinates:

$$x_{rms} = \sqrt{\sigma_{11}}$$
$$y_{rms} = \sqrt{\sigma_{33}}$$
$$l_{rms} = \sqrt{\sigma_{55}}$$

Definition of Beam Matrix: 6-dim versus 2-dim Matrices

Generally, the beam matrix contains all 6-dim variances (i.e. correlations):

$$\boldsymbol{\Sigma}_x = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle \end{pmatrix}$$

$$\boldsymbol{\Sigma} = \begin{pmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle & \langle xl \rangle & \langle x\delta \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle & \langle x'l \rangle & \langle x'\delta \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle & \langle yl \rangle & \langle y\delta \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle & \langle y'l \rangle & \langle y'\delta \rangle \\ \langle lx \rangle & \langle lx' \rangle & \langle ly \rangle & \langle ly' \rangle & \langle ll \rangle & \langle l\delta \rangle \\ \langle \delta x \rangle & \langle \delta x' \rangle & \langle \delta y \rangle & \langle \delta y' \rangle & \langle \delta l \rangle & \langle \delta\delta \rangle \end{pmatrix}$$

$\boldsymbol{\Sigma}$ is symmetric matrix $\boldsymbol{\Sigma} = \boldsymbol{\Sigma}^{\mathrm{T}}$
due to $\langle xx' \rangle = \langle x'x \rangle$ etc.
$\Rightarrow \boldsymbol{\Sigma} \in \mathbb{R}^{6\mathrm{x}6}$ has 21 independent quantities **if** all directions are coupled.

- For **linear** forces, the equation $\boldsymbol{\Sigma}(s_1) = \mathbf{R}(s) \cdot \boldsymbol{\Sigma}(s_0) \cdot \mathbf{R}^{\mathrm{T}}(s)$ is valid for **all** dimensions
- For **linear** forces, the **6-dim** emittance is preserved: $\varepsilon_{6d}^2 = \det \boldsymbol{\Sigma} = \mathrm{const.}$

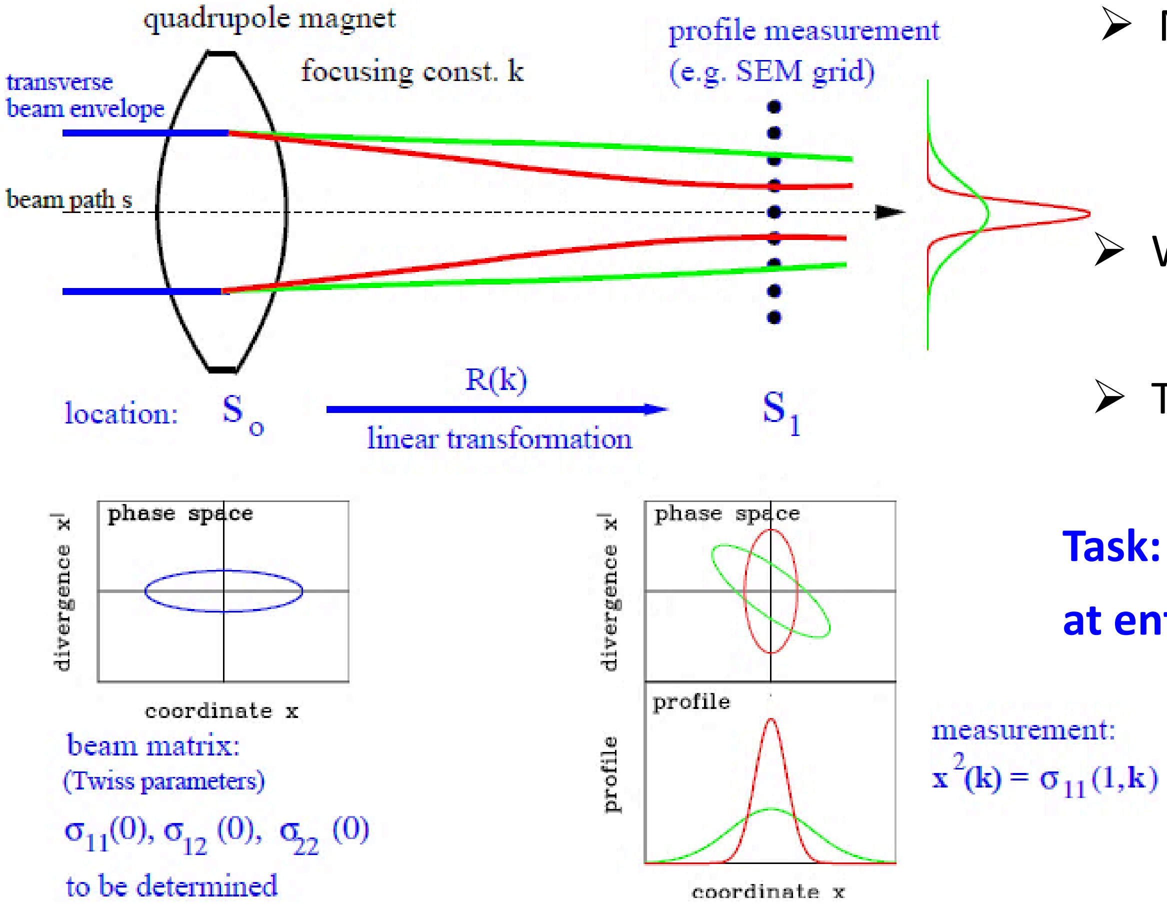
Remarks:

- A 2-dim matrix $\boldsymbol{\Sigma}_x \in \mathbb{R}^{2\mathrm{x}2}$ was used in textbooks providing simpler formulas
- **Non**-linear forces are e.g.:
  - Sextupole, octupole etc. i.e. higher-order magnetic fields
  - Non-linear contribution by longitudinal rf as it is a sine-wave
  - **Space charge forces for intense beams or cooled beams**
  - **Impedance contributions**

Emittance Measurement by Quadrupole Variation

From a profile determination, the emittance can be calculated via linear transformation, if a well known and constant distribution (e.g. Gaussian) is assumed.

The basis is beam matrix transformation $\boldsymbol{\sigma}\,(s_1) = \mathbf{R}(s_0 \to s_1) \cdot \boldsymbol{\sigma}(s_0) \cdot \mathbf{R}^{\mathrm{T}}(s_0 \to s_1)$



beam matrix:
(Twiss parameters)
$\sigma_{11}(0)$, $\sigma_{12}(0)$, $\sigma_{22}(0)$
to be determined

measurement:
$x^2(k) = \sigma_{11}(1,k)$

- Measurement of beam width

$$\boldsymbol{x^2_{max}} = \boldsymbol{\sigma_{11}(1,k)}$$

- With the drift matrix the transfer is

$$\mathbf{R}(k_i) = \mathbf{R}_{drift} \cdot \mathbf{R}_{focus}(k_i)$$

- Transformation of the beam matrix

$$\boldsymbol{\Sigma}(1,k_i) = \mathbf{R}(k_i) \cdot \boldsymbol{\Sigma}(0) \cdot \mathbf{R}^{\mathbf{T}}(k_i)$$

Task: Calculation of matrix $\sigma(\mathbf{0})$

at entrance s_0 i.e. all three elements

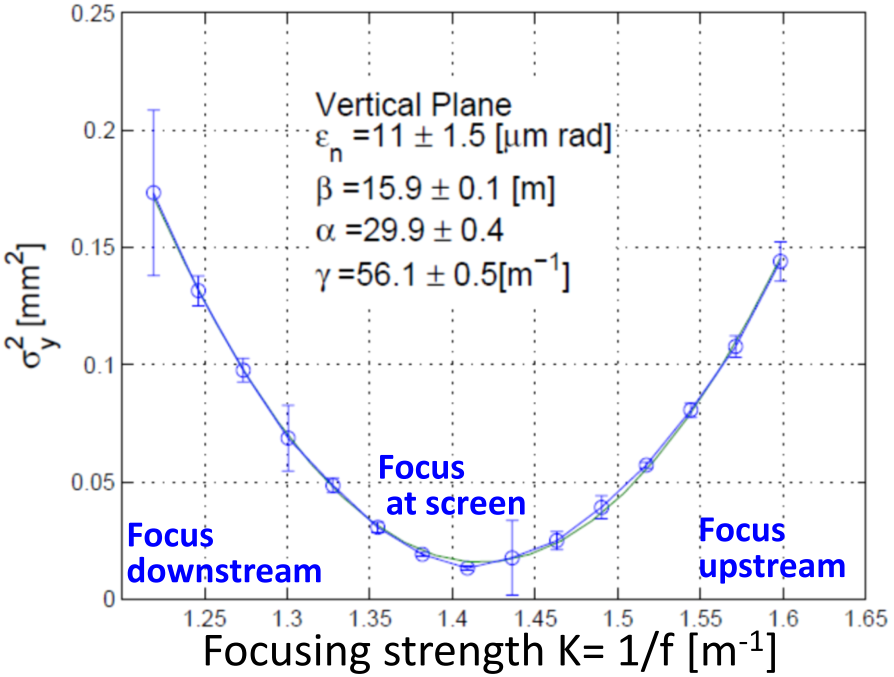
Measurement of transverse Emittance under ideal Conditions

Using the 'thin lens approximation' i.e. the quadrupole has a focal length of ***f***:

$$\mathbf{R}_{focus}(K) = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \equiv \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix} \quad \Rightarrow \quad \mathbf{R}(L,K) = \mathbf{R}_{drift}(L) \cdot \mathbf{R}_{focus}(K) = \begin{pmatrix} 1+LK & L \\ K & 1 \end{pmatrix}$$

Measurement of matrix-element $\boldsymbol{\sigma}_{\mathbf{11}}(s_1, K)$ from matrices $\boldsymbol{\sigma}(s_1,K_i) = \mathrm{R}(K_i) \cdot \boldsymbol{\sigma}(s_0) \cdot \mathrm{R}^{\mathrm{T}}(K_i)$

Example: Square of the beam width at ELETTRA 100 MeV e⁻ Linac, YAG:Ce screen:



Focus downstream

Focus at screen

Focus upstream

G. Penco (ELETTRA) et al., EPAC'08

For completeness: The relevant formulas

$$\begin{aligned}\boldsymbol{\sigma_{11}(1,K)} &= \boldsymbol{L^2\sigma_{11}(0)\cdot K^2} \\ &\quad \boldsymbol{+\,2\cdot(\ L\sigma_{11}(0)+L^2\sigma_{12}(0)\ )\cdot K} \\ &\quad \boldsymbol{+\,L^2\sigma_{22}(0)+\sigma_{11}(0)} \\ &\equiv \boldsymbol{a\cdot K^2 \ -\ 2ab\cdot K \ +\ ab^2 + c} \\ &= \boldsymbol{a\cdot(K-b)^2 + c}\end{aligned}$$

A fit delivers the beam matrix elements $\boldsymbol{\sigma_{ij}(s_0)}$

Assumptions:

- Well aligned beam, no steering
- 'Regular' phase space distribution
- No emittance blow-up due to space charge

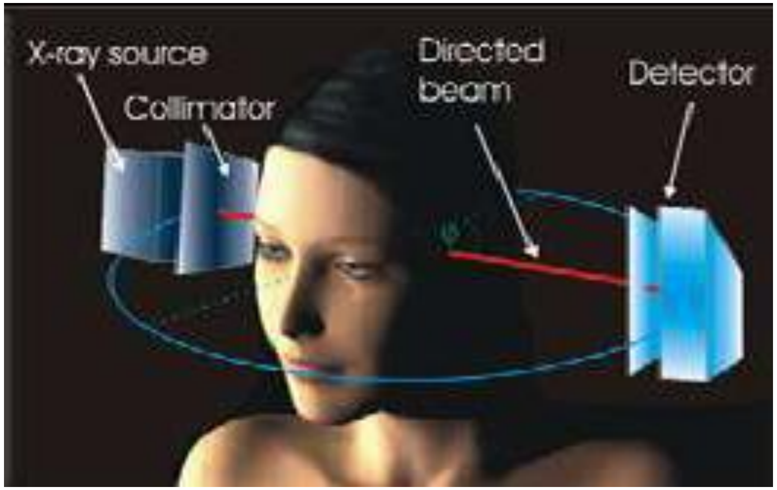
Improved methods:

Based on e.g. tomographic reconstruction

Tomographic Reconstruction

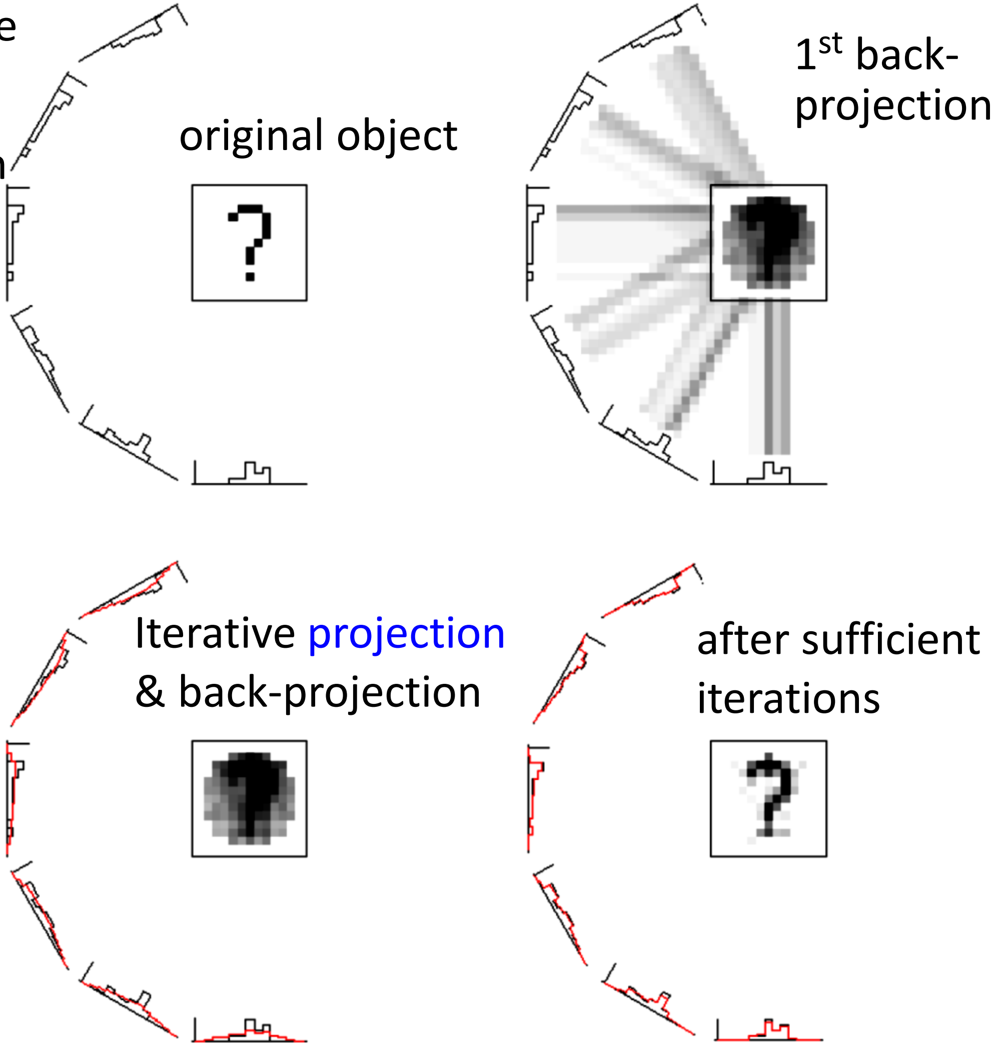
Tomography: Generation of a n-dim image from many lower-dim projections

Medical application: 2-dim reconstruction using sufficient 1-dim projections



Filtered back projection:

Iterative process by redistributing the 2-dim image and considering the differences to the previous iteration step.



Courtesy S. Hancock et al.

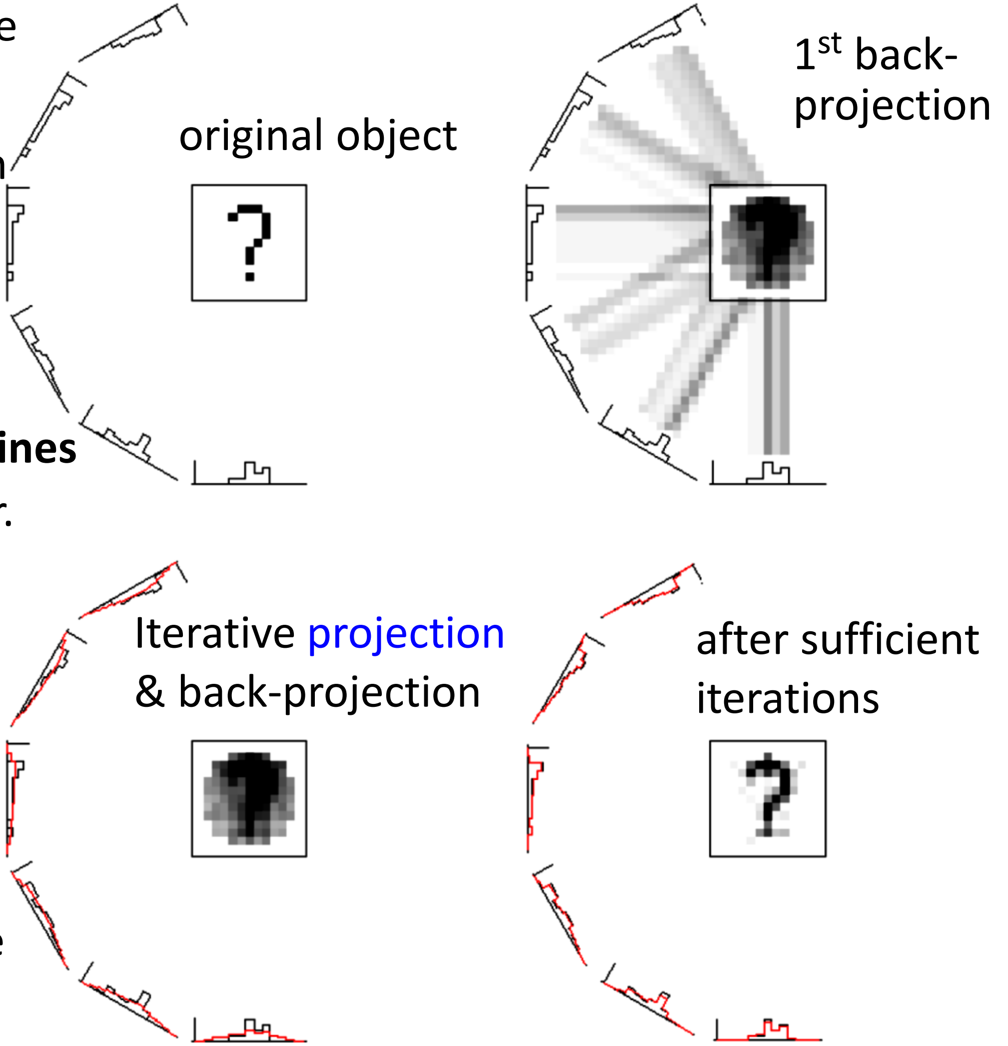
Tomographic Reconstruction

Tomography: Generation of a n-dim image from many lower-dim projections

Medical application: 2-dim reconstruction using sufficient 1-dim projections

Application at accelerators:

- **Transverse & longitudinal emittance reconstruction in transfer lines**
- Longitudinal bunch evolution in synchr.



Courtesy S. Hancock et al.

Most often used:

FBP: **F**iltered **B**ack-**P**rojection

ART: **A**lgebraic **R**econstruction **T**echnique

Other methods:

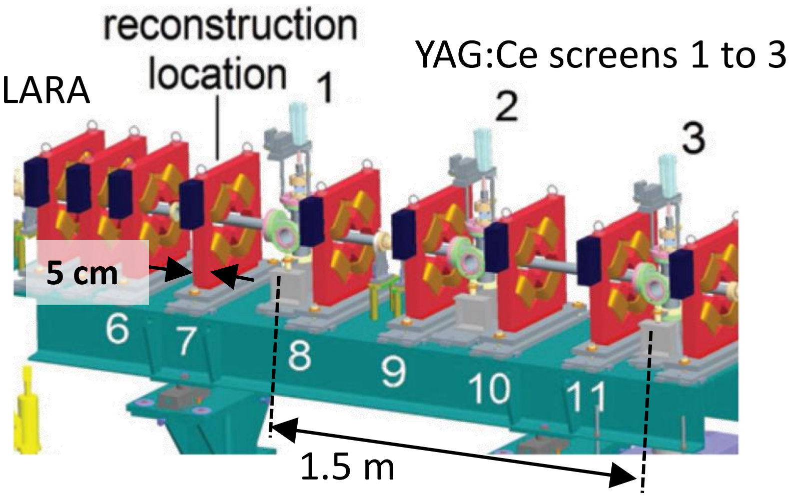
MENT: **M**aximum **E**ntropy

Image recognition by **Machine Learning**

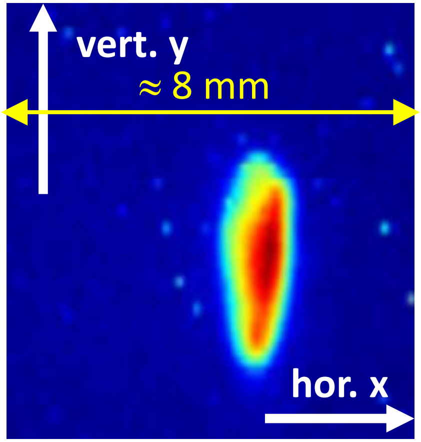
Exemplary Results of 2-dim Emittance Reconstruction

Experiments at ALICE dedicated transfer line Daresbury Laboratory (UK):

- Electron LINAC ALICE with $E_{kin} = 12$ MeV in the frame of EMMA FFAG (up to year 2016), then CLARA
- Dedicated line with typ. 60^0 betatron phase advance between Yag:Ce screens (0.75 m distance each)
- Several quadrupoles for flexible beam setting for versatile experiments

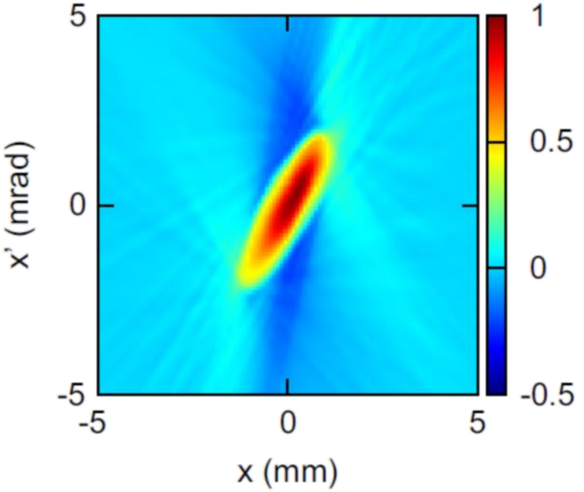


Typical 2-d trans. **profile** @ YAG:Ce#1



Typically 150 quad-setting Quad 7 (20^0… 170^0 betatron phase) & profile measurements screen 1 → **tomography by FBP**

Phase space at entrance of Quad 7 for low current (20 pC/bunch)



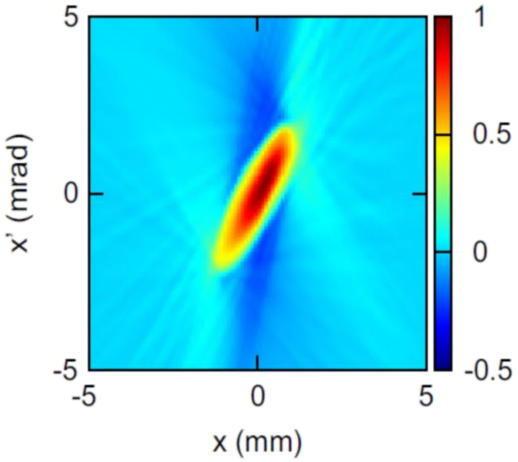
K.M. Hock, A. Wolski et al., NIM A 753, 38 (2014), M.G. Ibison et al., JINST 7, P04016 (2012), IPAC 2013

Exemplary Results of 2-dim Emittance Reconstruction

Experiments at ALICE dedicated transfer line Daresbury Laboratory (UK):

Beam current effect detected

Phase space in front of Quad 7
for low current **(20 pC/bunch)**

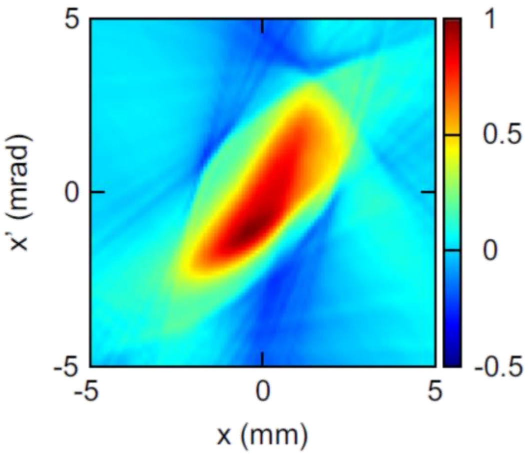


Scan of Quad 7 &
measure at screen 1

Increase of current

Related to
Space charge defocusing
upstream Quad 7

Phase space in front of Quad 7
for high current **(80 pC/bunch)**



Consistency check:

Comparison of measured beam profile and reconstructed profile at reconstruction location

Actual Challenges for Emittance Measurement

Actual challenges for emittance measurement:

- **High resolution and dynamic range**

  Solution keywords: Material choice, sensitive electronics and/or optics

- **Reconstruction algorithms**

  Solution keywords: Tomography with optimized ‘traditional’ methods,
  Machine Learning based image reconstruction

Related talks at IPAC’26 within MC6:

- Sarah Geffroy (Université Paris-Saclay, CNRS/IN2P3, IJCLab*),*
  Emittance measurement of the CERN antimatter beam for the GBAR experiment
- Mayu Wada (The University of Tokyo),
  Development of a new ultraslow muon beam diagnostic system for the J-PARC muon g-2/EDM experiment

Related talks at IPAC’26, MC6 on Machine Learning:

- Eito Iwai (RIKEN), *ML-driven automated tuning of SACLA XFEL: progress and future*
- Ysabella Kassandra Ong (INFN), *AI and machine learning techniques for LNL accelerators*
- Thorsten Hellert (LBNL),
  Bridging the Gap Between Control Systems and Natural Language: A Framework for Semantic Channel Finding
- Fuhao Ji (SLAC), *Intelligent scientific facility R&D: AI/ML developments at SLAC MeV-UED*

Measurement of longitudinal Parameters

Measurement of longitudinal parameter:

Bunch length measurement at

- **FEL-LINACs**
- **Circular synchrotron light facilities**

Longitudinal ↔ transverse correspondences:

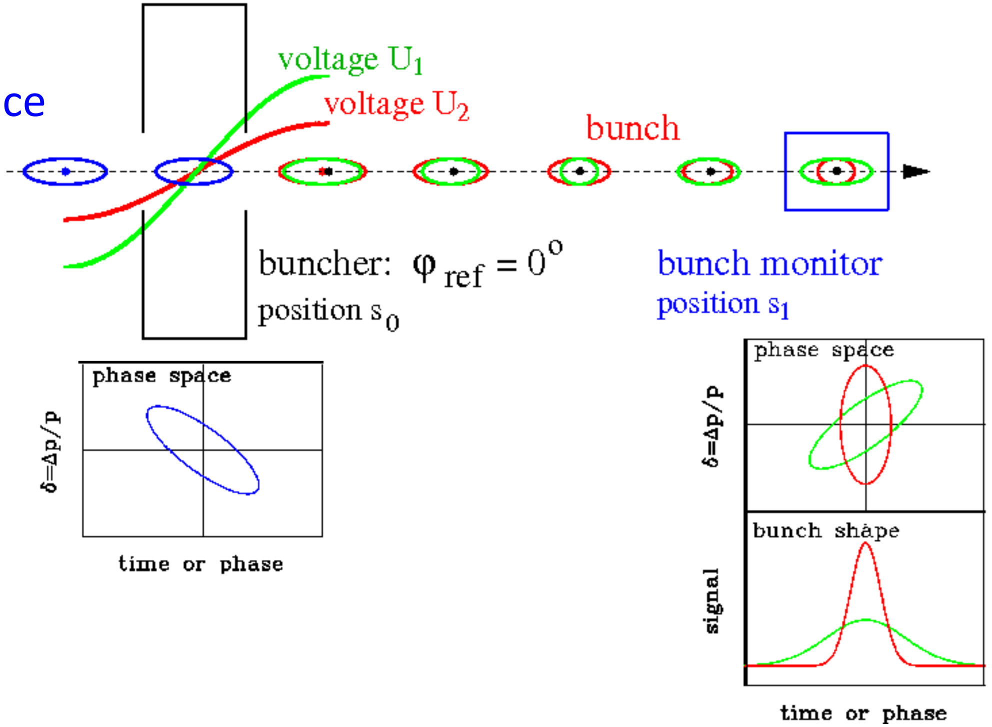
- position relative to rf ↔ transverse center-of-mass
- bunch structure in time ↔ transverse profile
- momentum or energy spread ↔ transverse divergence
- longitudinal emittance ↔ transverse emittance.

Longitudinal Emittance by linear Transformation using a Buncher

Longitudinal focusing:

Variation of the bunch shape by a rf-buncher
→ components 5 and 6 from 6-dim phase-space

Transversal correspondence: Quadrupole variation



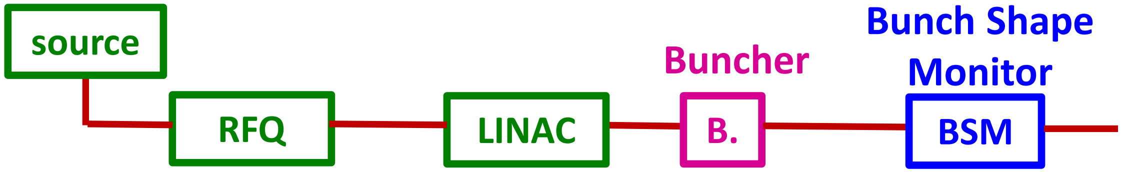
- Transfer matrix of buncher & drift:

$$R_{buncher} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

with focal length $\frac{1}{f} = \frac{2\pi f_{rf}}{Apv^2} \cdot U$

$$R_{drift} = \begin{pmatrix} 1 & L/\gamma^2 \\ 0 & 1 \end{pmatrix}$$

- Variation of buncher amplitude $\boldsymbol{U}$
  ⇒ different bunch width at monitor location


source

RFQ

LINAC

Buncher

B.

Bunch Shape Monitor

BSM

Bunch Length Measure by electro-optical spectral Decoding

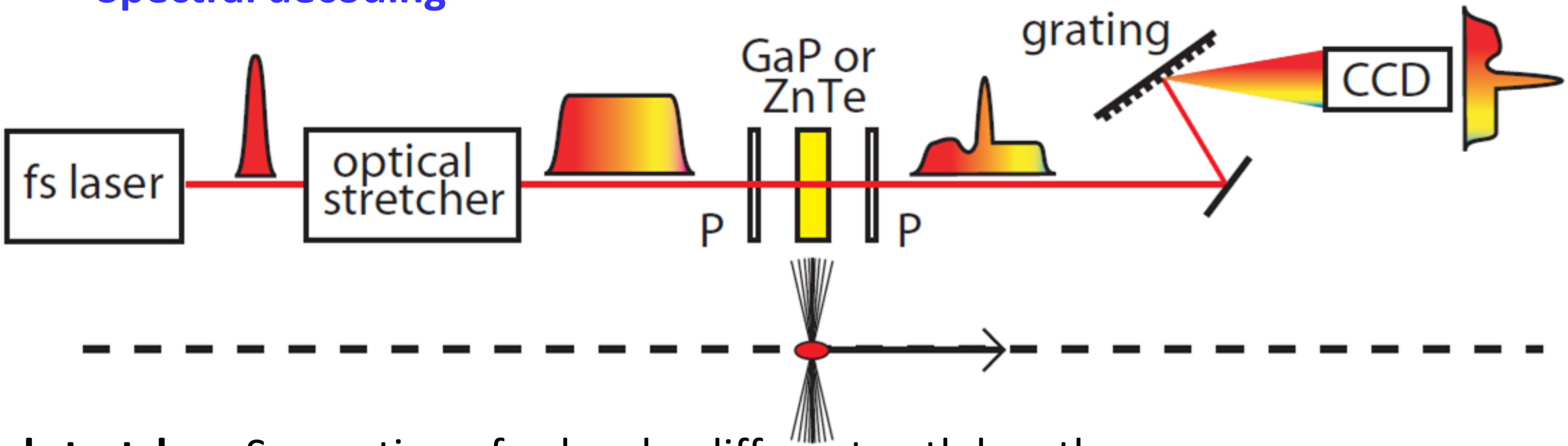
For Free Electron Lasers → bunch length below 1 ps is achieved

- Below the resolution of streak camera
- Short laser pulses with **$t \approx 10$ fs** and electro-optical modulator

Electro optical modulator: Birefringent, rotation angle depends on external electric field

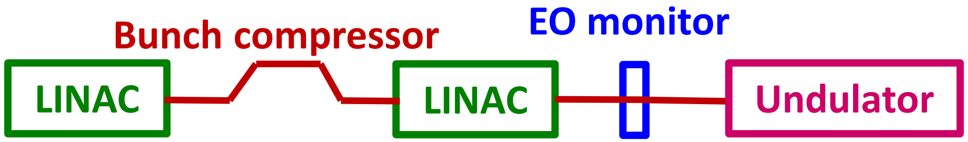
Relativistic bunch: transverse elecitc field $E_{\perp,lab} = \gamma E_{\perp,rest}$ carries the time information

Spectral decoding



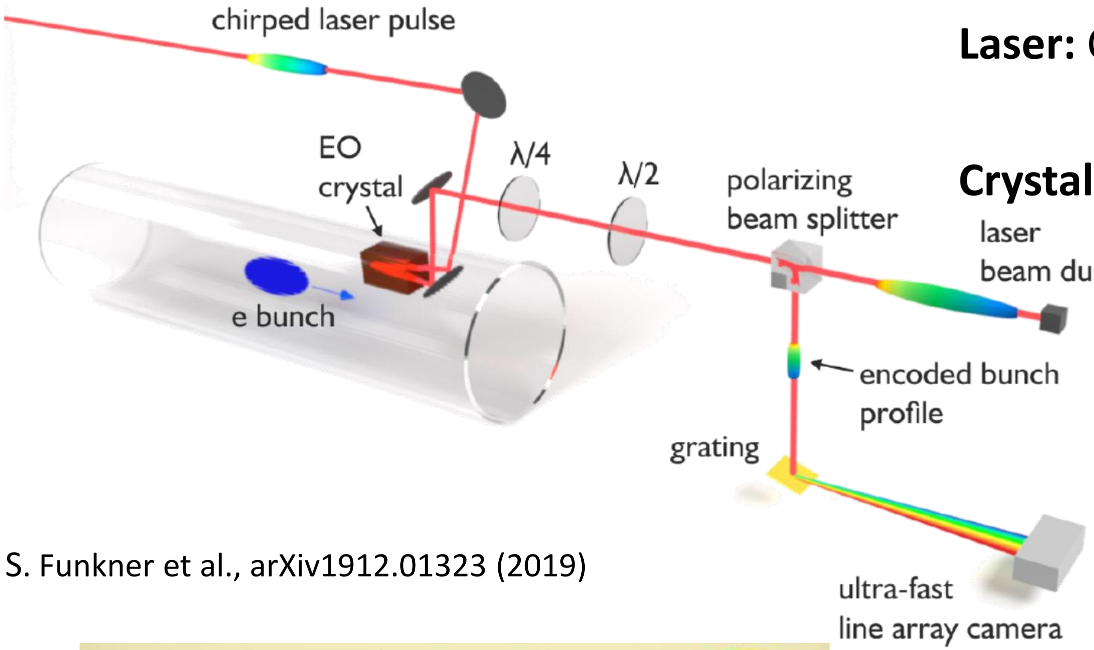
Optical stretcher: Separation of colors by different path length

⇒ different colors at different time ⇒ **single-shot observation**



Courtesy S.P.Jamison et al., EPAC 2006

Hardware of a spectral-decoded EOSD Scanning Setup



S. Funkner et al., arXiv1912.01323 (2019)

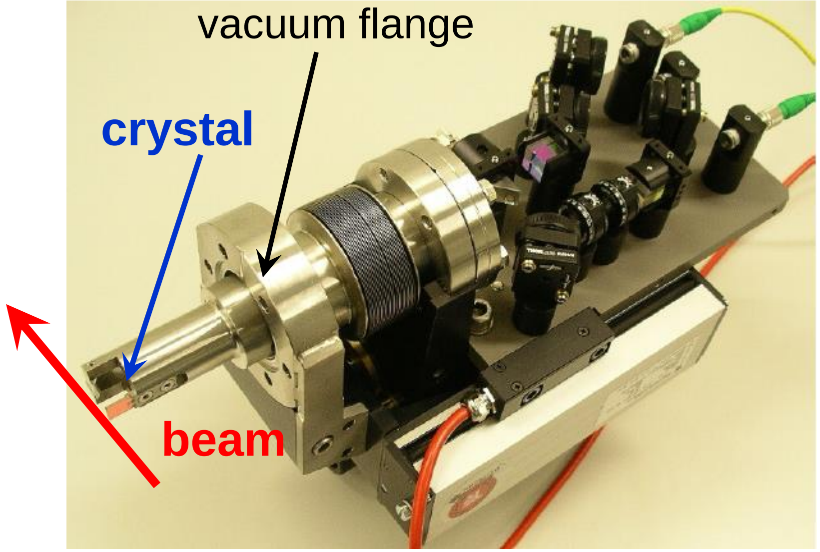
Laser: Commercial Ti:Sa or Yb-fibre,

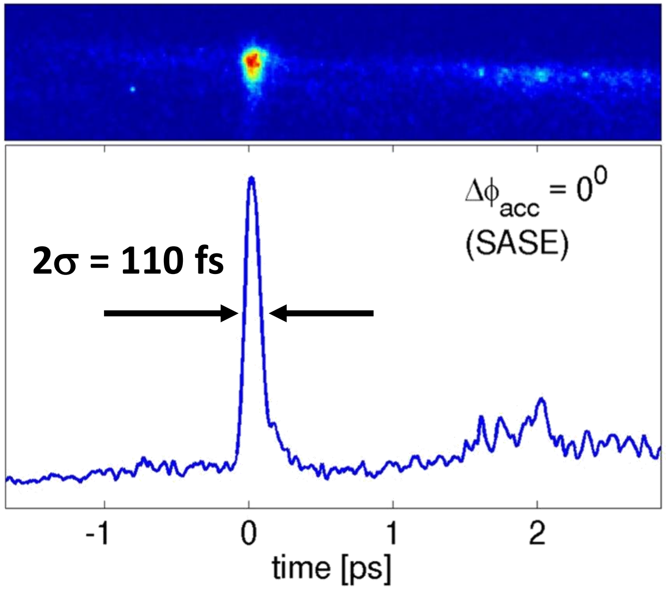
10 fs duration, near IR,

Crystal: GaP or ZnTe, 100 µm thickness

Example: Bunch length at FLASH

100 fs bunch duration = 30 µm length!



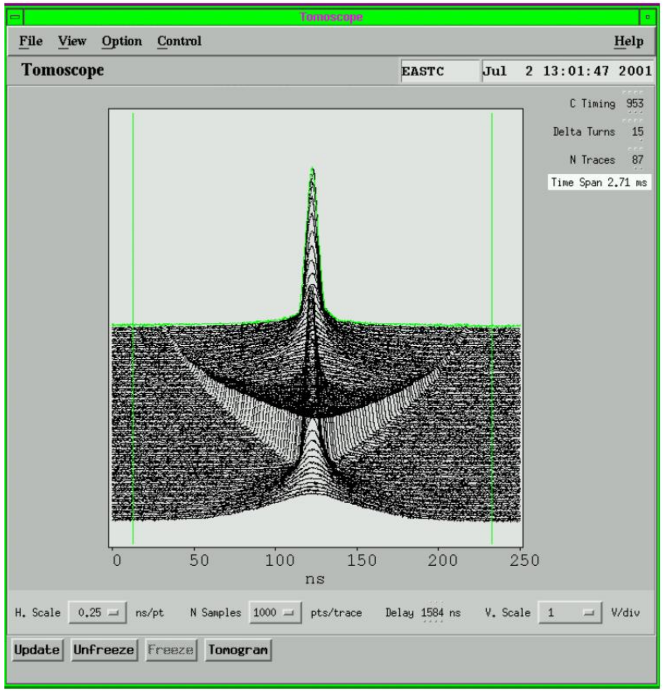


B. Steffen et al, DIPAC 2009

B. Steffen et al., Phys. Rev. AB 12, 032802 (2009)

Results of tomographic Reconstruction at a Synchrotron II

Bunches from 500 turns at CERN PS and phase space for time slice of shortest bunch, measured with a Wall Current Monitor WCM:



Tomoscope EASTC Jul 2 13:01:47 2001

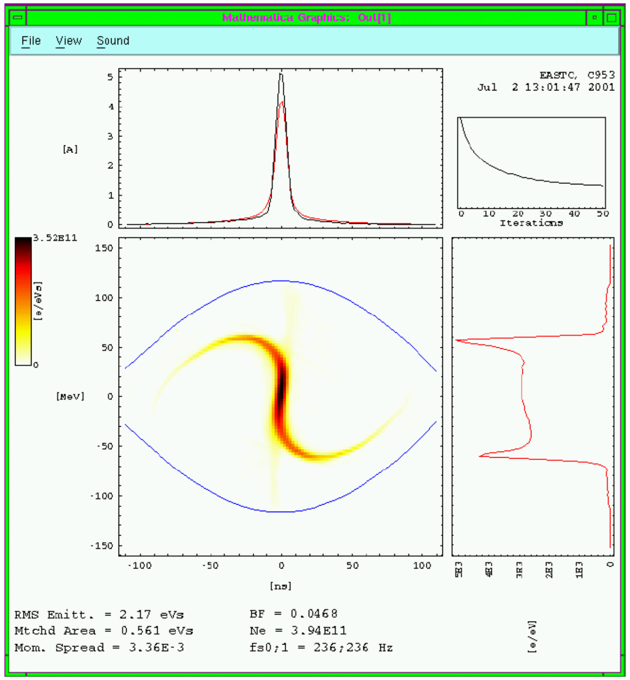
C Timing 953

Delta Turns 15

N Traces 87

Time Span 2.71 ms

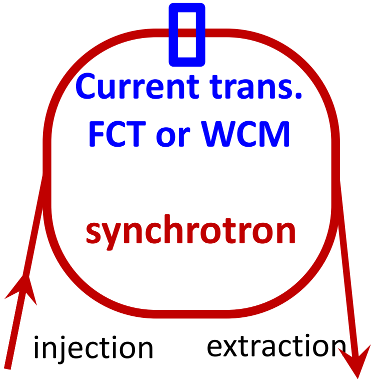
H. Scale 0.25 ns/pt N Samples 1000 pts/trace Delay 1584 ns V. Scale 1 V/div



EASTC, C953
Jul 2 13:01:47 2001

RMS Emitt. = 2.17 eVs
Mtchd Area = 0.561 eVs
Mom. Spread = 3.36E-3

BF = 0.0468
Ne = 3.94E11
fs0;1 = 236;236 Hz



Current trans.
FCT or WCM

synchrotron

injection extraction

Fast rise of rf-amplitude for 'bunch-rotation':

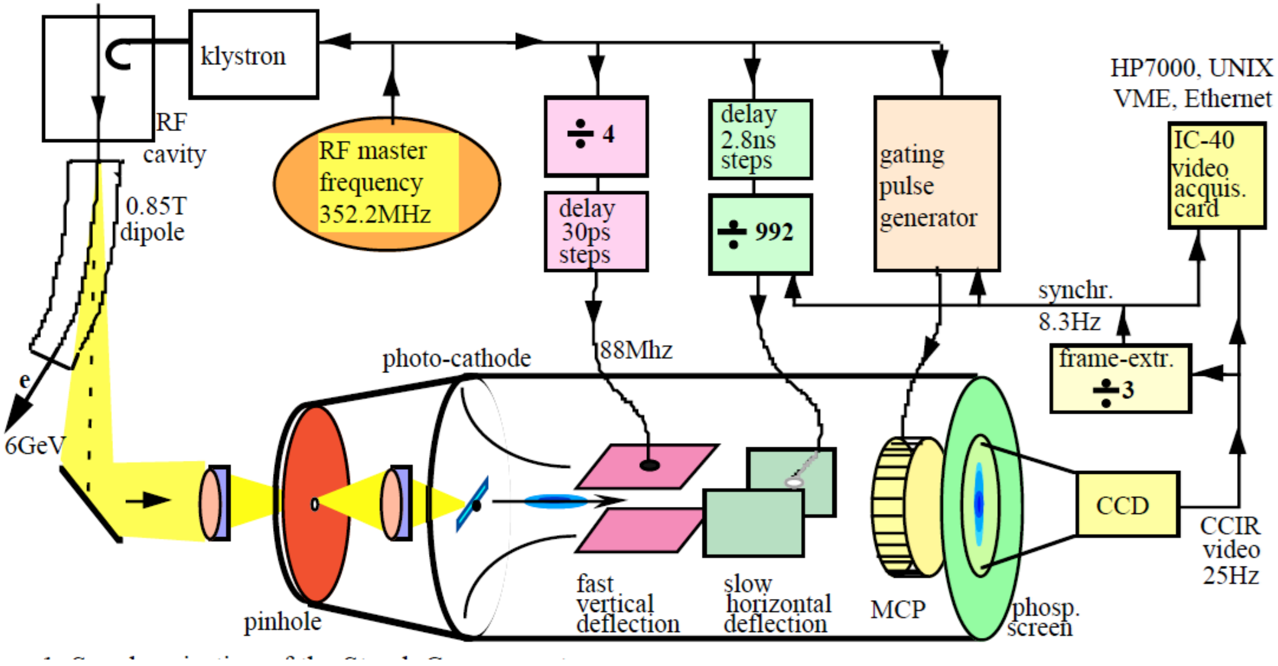
- Bunch is compressed in time
- Filamentation due to amplitude- dependent synchrotron frequency

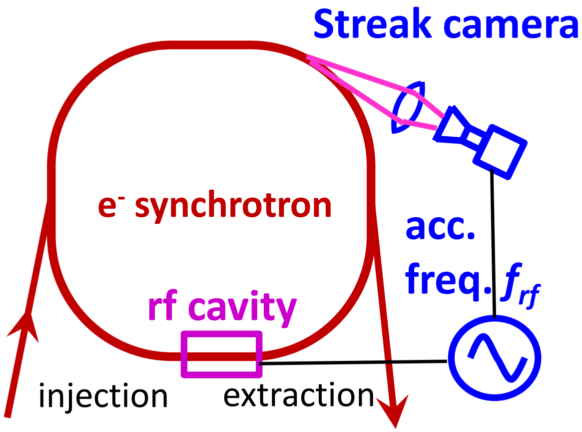
Bunch Length Measurement for relativistic Electrons

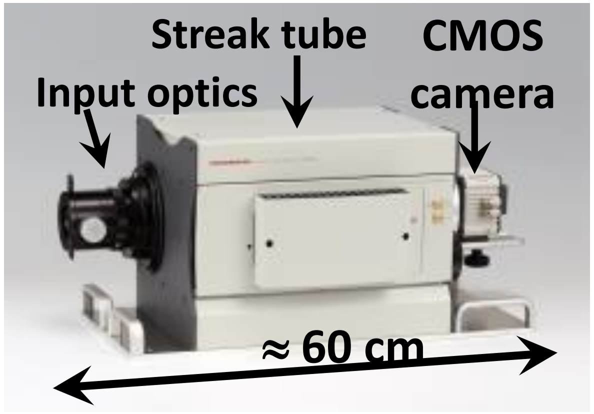
Electron bunches are too short (σ_t < 100 ps) to be covered by the bandwidth of pick-ups (f < 3 GHz ⇔ t_{rise} > 100 ps) for structure determination.

→ Time resolved observation of synchr. light with a streak camera: Resolution ≈ 1 ps.

Scheme of a streak camera





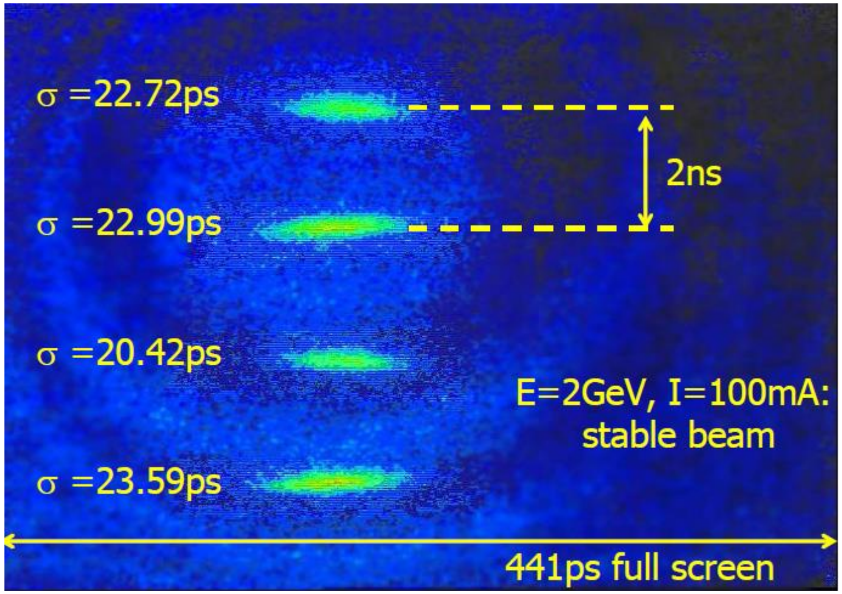


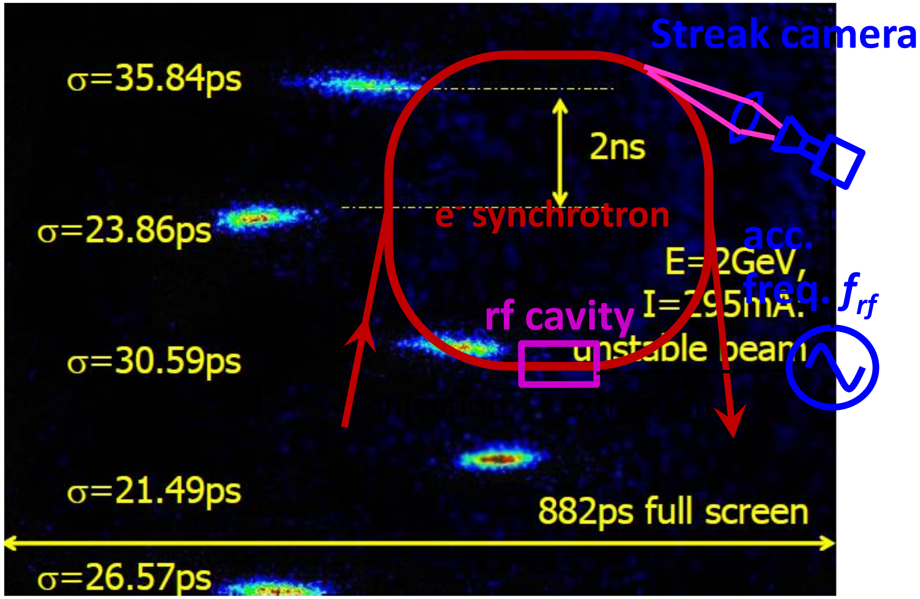
Bunch observation by Streak Camera

The streak camera delivers a fast scan in horizontal direction (here 441 ps full scale) and a slower scan in vertical direction (here 9 ns).

Example: Bunch shape oscillations at Elettra, Trieste, $f_{acc} = 500$ MHz :

→ Longitudinal mismatched injection leads to coherent synch. oscillations, coupled bunch motion





From M. Ferianis, CAS’07

Actual Challenges for Bunch Shape Measurements

Actual challenges for bunch shape measurement:

- **High resolution and dynamic range**

  Solution keywords: FEL-LINACs costly methods such as **T**ransverse **D**eflecting **C**avity

- **Reconstruction algorithms**

  Solution keywords: Tomography with optimized 'traditional' methods,
  Machine Learning based image reconstruction

- **For FELs: Synchronization of cavities and experiential trigger**

  Solution keywords: Electro-optical signal transmission, ultra-accurate electronics

Related talks at IPAC'26 within MC6:

- Frank Ludwig (DESY), *From femtosecond to attosecond RF field control*

Conclusion for Instrumentation and Control

Beam instrumentation is required to control the ‘real-world’ beam correctly

- **Beam Position Monitors:**

  Non-invasive, versatile application, sensor for feedback

- **Profile detectors:**

  Various detector types, non-invasive preferred

- **Emittance determination:**

  Reconstruction by beam optics and tomography, non-linear solutions e.g.by ML

- **Bunch length determination:**

  Various methods, partly complex or costly instruments, tomography

Thank you for your attention

Do you have questions or comments?