Optics Measurement Techniques for Transfer Line & Beam Instrumentation

CAS for Beam Injection, Extraction and Transfer Line
Erice, 16th and 17th of March 2017

Peter Forck

Gesellschaft für Schwerionenforschnung (GSI) and University Frankfurt

3rd part of this lecture covers:

- Pick-ups so called **B**eam **P**osition **M**onitors for position measurement
  Application: trajectory & closed orbit determination
- Longitudinal parameter (bunch length and momentum spread) measurement
  Application: longitudinal matching

Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies
- Capacitive *shoe-box* BPM for low frequencies
- Electronics for position evaluation
- BPMs for measurement
- Summary

Usage of BPMs

A *B*eam *P*osition *M*onitor is an non-destructive device for bunched beams

It has a low cut-off frequency i.e. dc-beam behavior can not be monitored
The abbreviation BPM and pick-up PU are synonyms

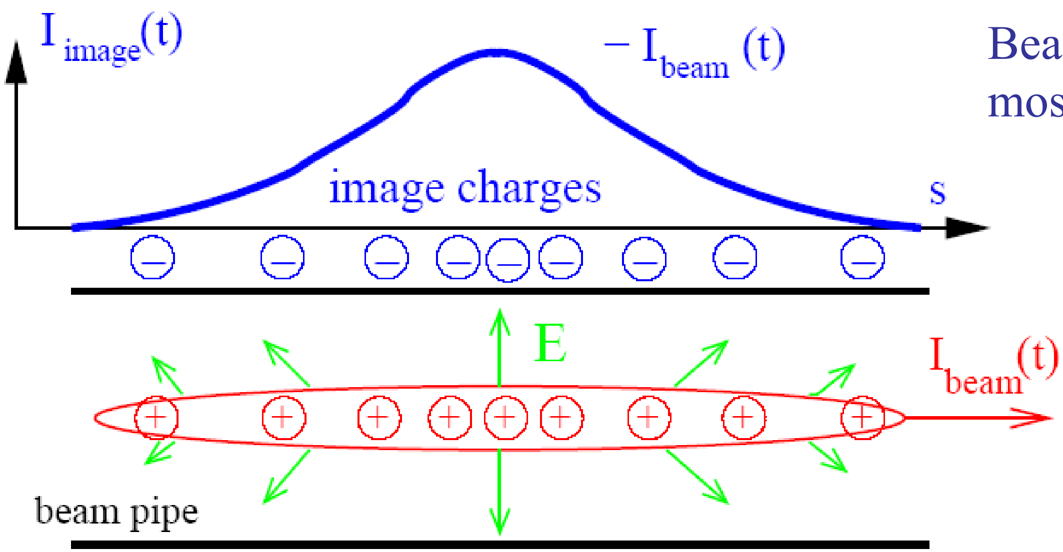
1. It delivers information about the transverse center of the beam

- ***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

2. Information on longitudinal bunch behavior (→ see next chapter)

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.



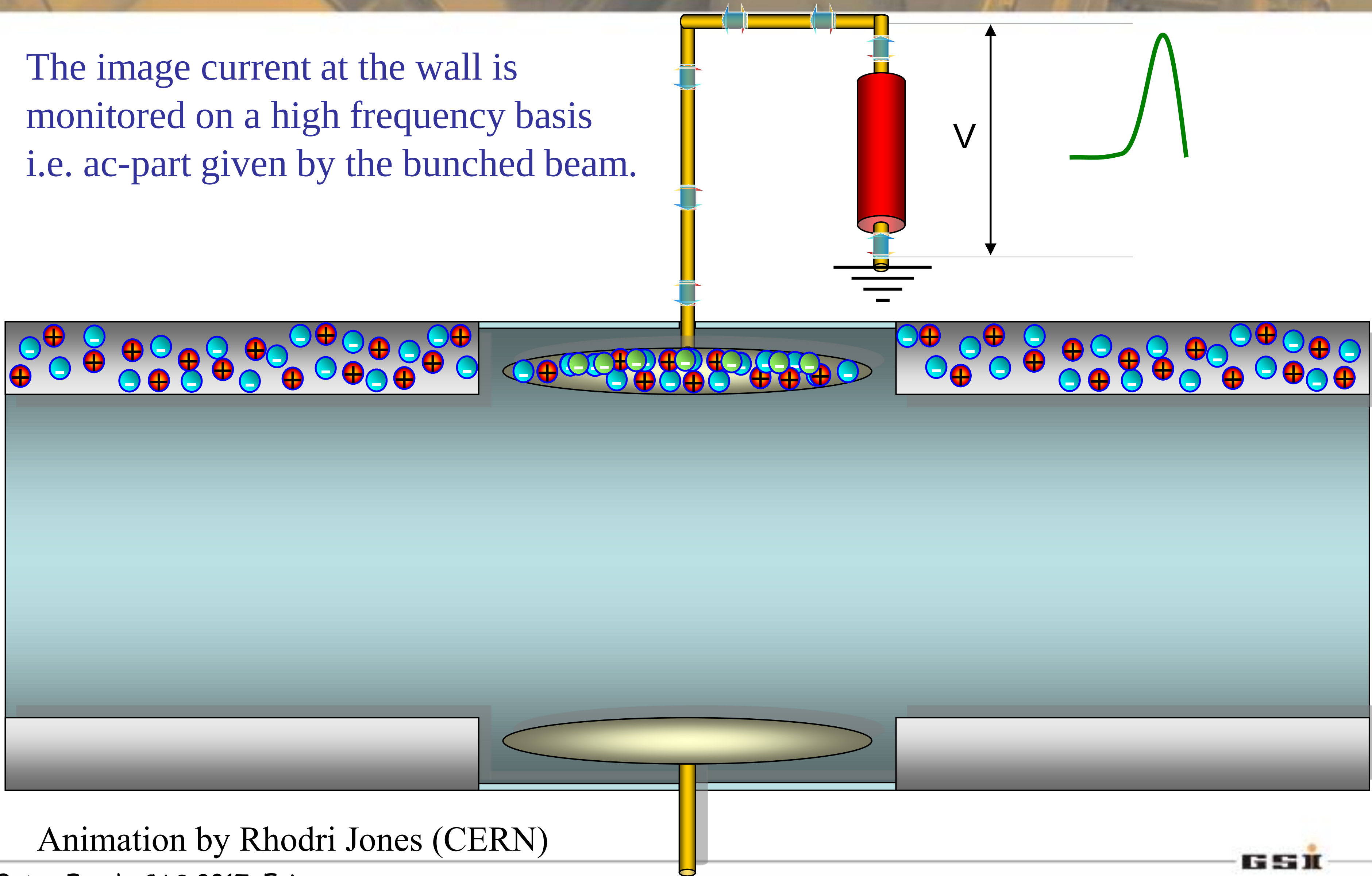
Beam Position Monitor **BPM** is the most frequently used instrument!

For relativistic velocities, the electric field is transversal:

$$E_{\perp,lab}(t) = \gamma \cdot E_{\perp,rest}(t')$$

Principle of Signal Generation of a BPMs, centered Beam

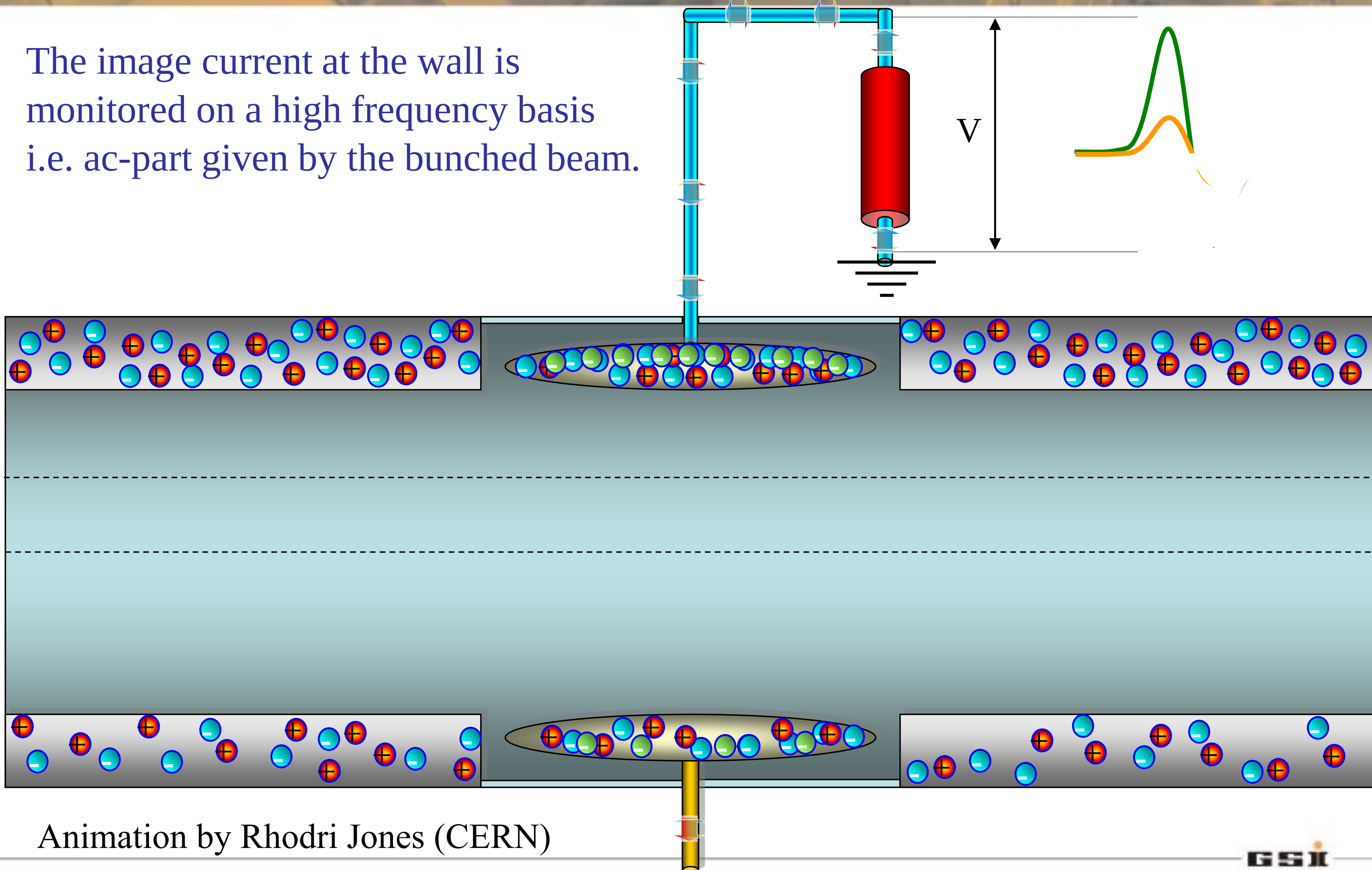
The image current at the wall is monitored on a high frequency basis i.e. ac-part given by the bunched beam.



Animation by Rhodri Jones (CERN)

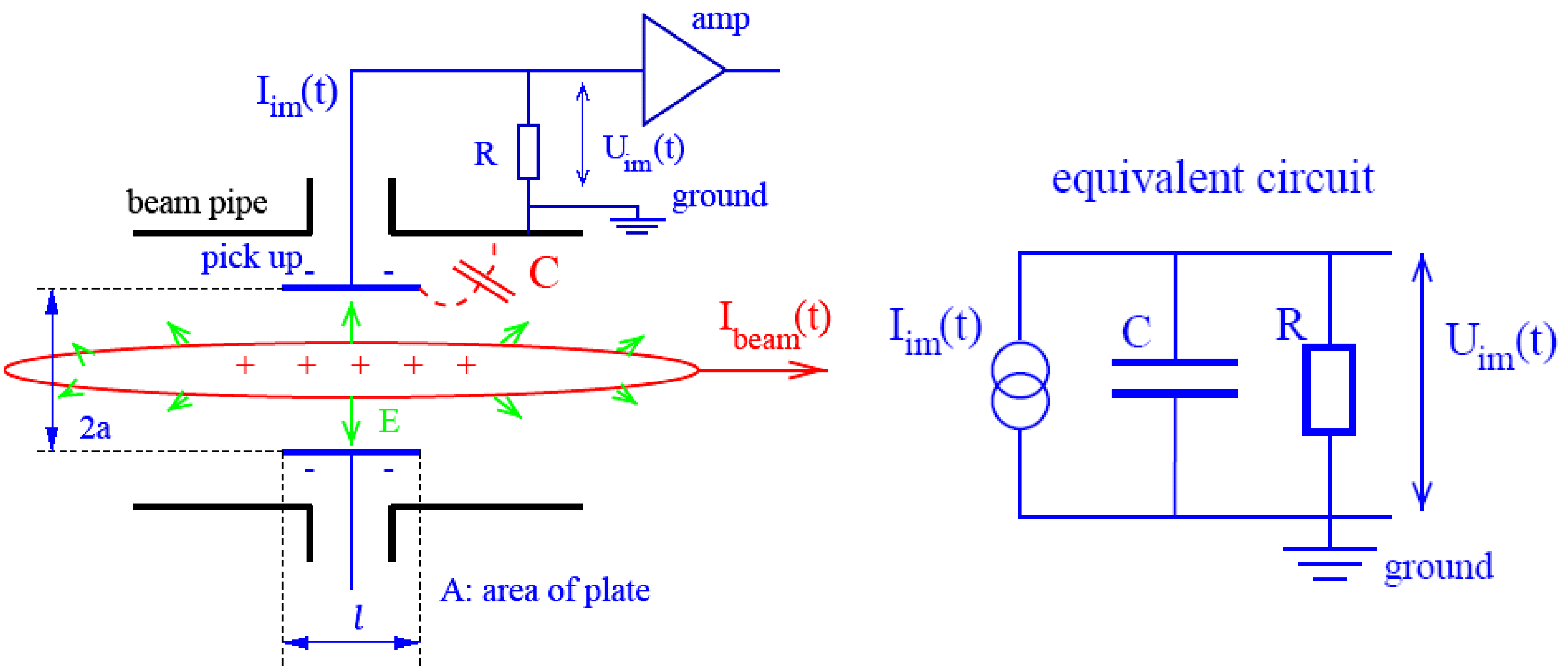
Principle of Signal Generation of a BPMs, off-center Beam

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)

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



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

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

Using a relation for Fourier transformation: $I_{beam} = I_0 e^{-i\omega t} \Rightarrow dI_{beam}/dt = -i\omega I_{beam}$.

Transfer Impedance for a capacitive BPM

At a resistor $\boldsymbol{R}$ the voltage $\boldsymbol{U_{im}}$ from the image current is measured.
The transfer impedance $\boldsymbol{Z_t}$ is the ratio between voltage $\boldsymbol{U_{im}}$ and beam current $\boldsymbol{I_{beam}}$
in ***frequency domain***: $\boldsymbol{U_{im}(\omega) = R \cdot I_{im}(\omega) = Z_t(\omega, \beta) \cdot I_{beam}(\omega)}$.

Capacitive BPM:

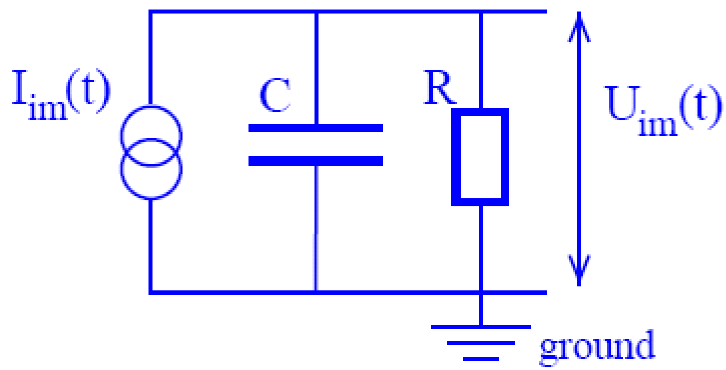
- The pick-up capacitance $\boldsymbol{C}$:
  plate ↔ vacuum-pipe and cable.
- The amplifier with input resistor $\boldsymbol{R}$.
- The beam is a high-impedance current source:

$$U_{im} = \frac{R}{1+i\omega RC} \cdot I_{im}$$

$$= \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{i\omega RC}{1+i\omega RC} \cdot I_{beam}$$

$$\equiv Z_t(\omega, \beta) \cdot I_{beam}$$

equivalent circuit



$$\frac{1}{Z} = \frac{1}{R} + i\omega C \Leftrightarrow Z = \frac{R}{1+i\omega RC}$$

This is a high-pass characteristic with $\boldsymbol{\omega_{cut} = 1/RC}$**:**

Amplitude: $|Z_t(\omega)| = \frac{A}{2\pi a} \cdot \frac{1}{\beta c} \cdot \frac{1}{C} \cdot \frac{\omega / \omega_{cut}}{\sqrt{1+\omega^2/\omega^2_{cut}}}$ **Phase:** $\varphi(\omega) = \arctan(\omega_{cut}/\omega)$

Example of Transfer Impedance for Proton Synchrotron

The high-pass characteristic for typical synchrotron BPM:

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

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

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

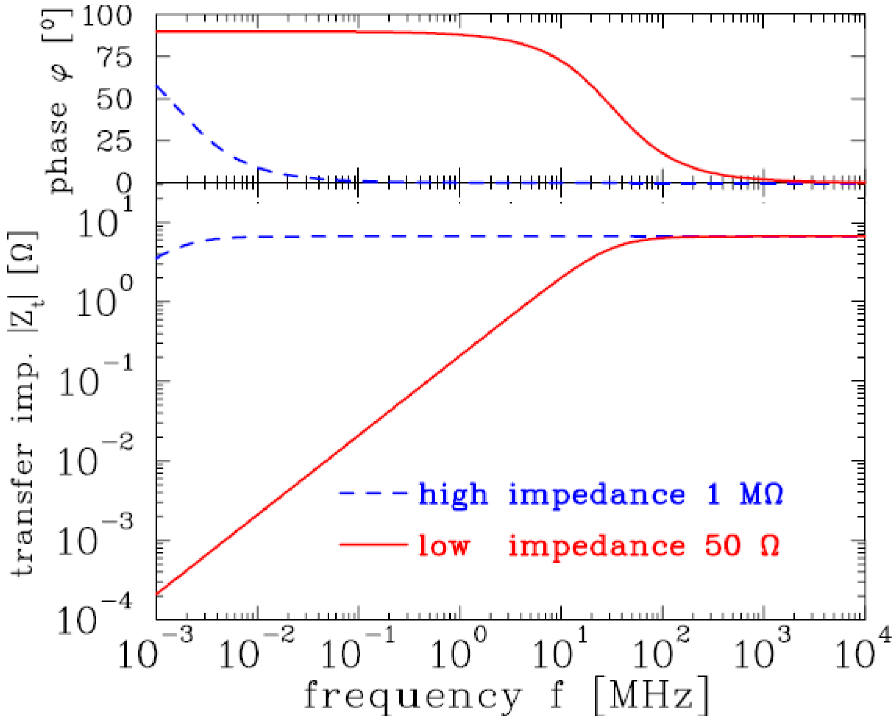
Parameter for shoe-box BPM:

C=100pF, l=10cm, β=50%

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

for R=50 Ω ⇒ f_{cut}= 32 MHz

for R=1 MΩ ⇒ f_{cut}= 1.6 kHz



Large signal strength for long bunches → **high impedance**

Smooth signal transmission important for short bunches → **50 Ω**

Remark: No signal is transferred from dc-beams e.g.

- de-bunched beam inside a synchrotron
- for slow extraction through a transfer line

Signal Shape for capacitive BPMs: differentiated ↔ proportional

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

- ***High frequency range $\omega >> \omega_{cut}$:***

$$Z_t \propto \frac{i\omega/\omega_{cut}}{1+i\omega/\omega_{cut}} \rightarrow 1 \Rightarrow U_{im}(t) = \frac{1}{C}\cdot\frac{1}{\beta c}\cdot\frac{A}{2\pi a}\cdot I_{beam}(t)$$

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

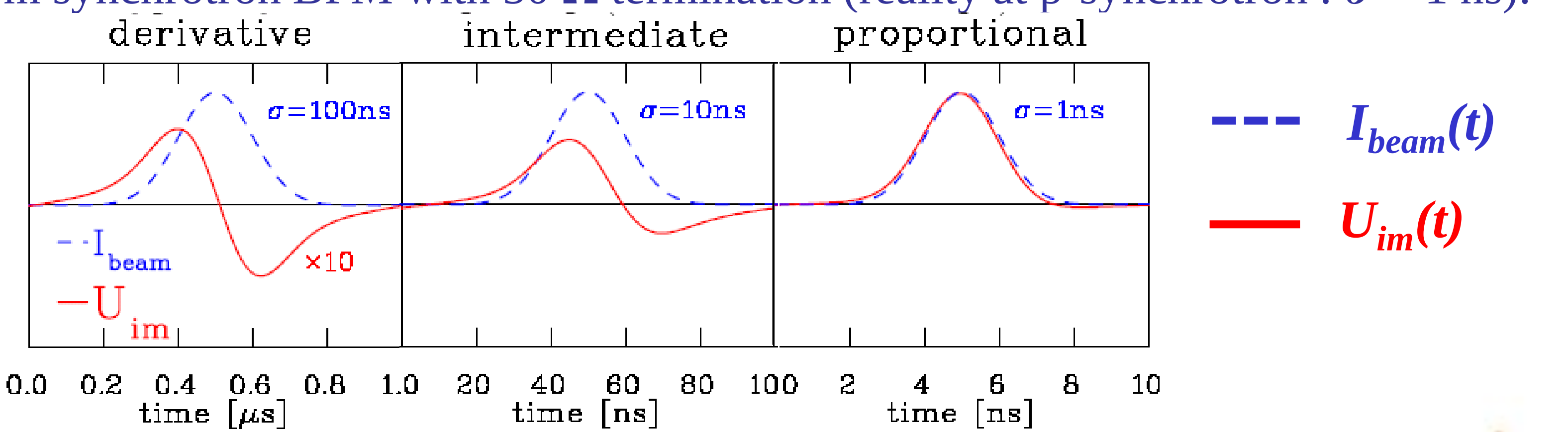
- ***Low frequency range $\omega << \omega_{cut}$:***

$$Z_t \propto \frac{i\omega/\omega_{cut}}{1+i\omega/\omega_{cut}} \rightarrow i\frac{\omega}{\omega_{cut}} \Rightarrow U_{im}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot i\omega I_{beam}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot\frac{dI_{beam}}{dt}$$

$\Rightarrow$ **derivative** of bunch, single strength $Z_t \propto A$, i.e. (nearly) independent on C

- ***Intermediate frequency range $\omega \approx \omega_{cut}$:*** Calculation using Fourier transformation

Example from synchrotron BPM with 50 Ω termination (reality at p-synchrotron : σ>>1 ns):



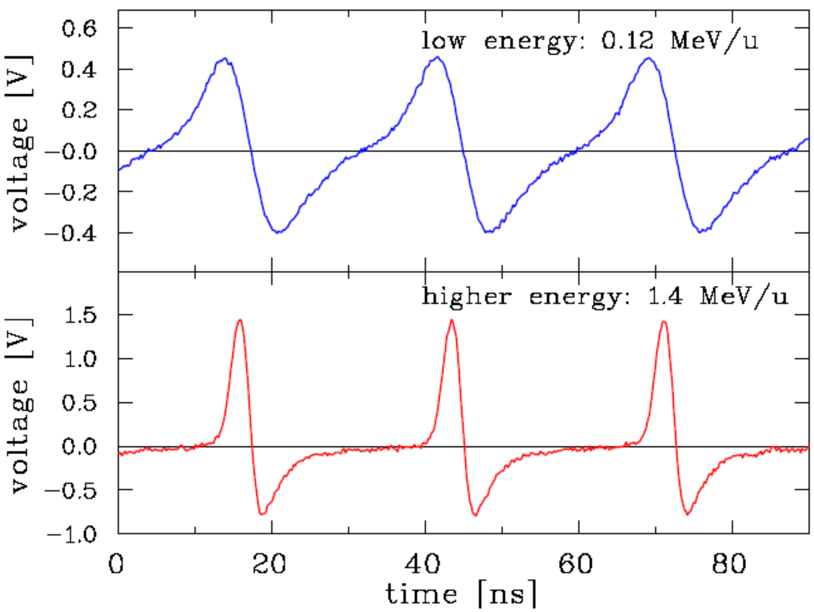
Proton LINAC, e$^-$-LINAC&synchrotron:

100 MHz < f_{rf} < 1 GHz typically

R=50 Ω processing to reach bandwidth

C≈5 pF ⇒ $f_{cut} = 1/(2\pi RC) \approx$ 700 MHz

Example: 36 MHz GSI ion LINAC



Proton synchrotron:

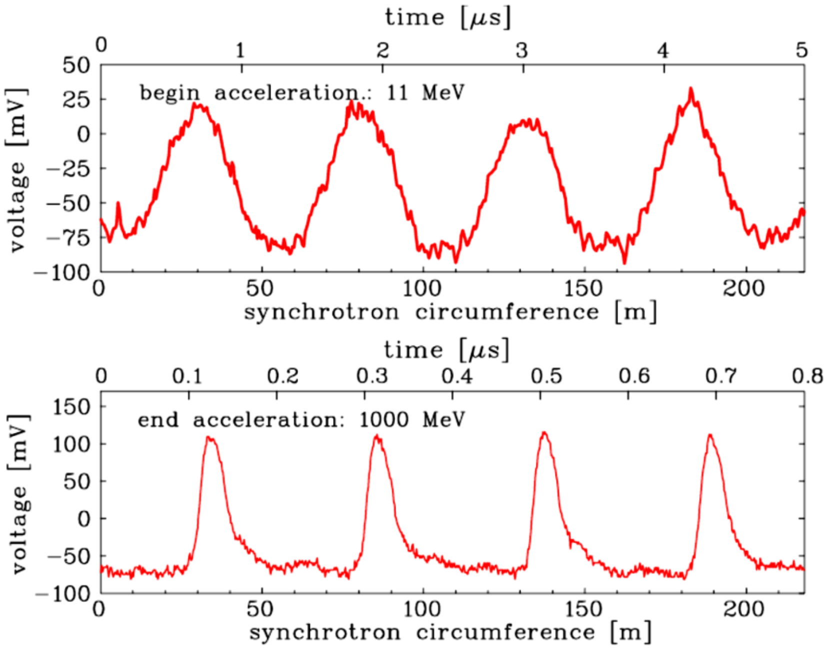
1 MHz < f_{rf} < 30 MHz typically

R=1 MΩ for large signal i.e. large Z_t

C≈100 pF ⇒ $f_{cut} = 1/(2\pi RC) \approx$10 kHz

Example: non-relativistic GSI synchrotron

f_{rf} : 0.8 MHz → 5 MHz



Remark: During acceleration the bunching-factor is decreased due to 'adiabatic damping'.

Principle of Position Determination by a BPM

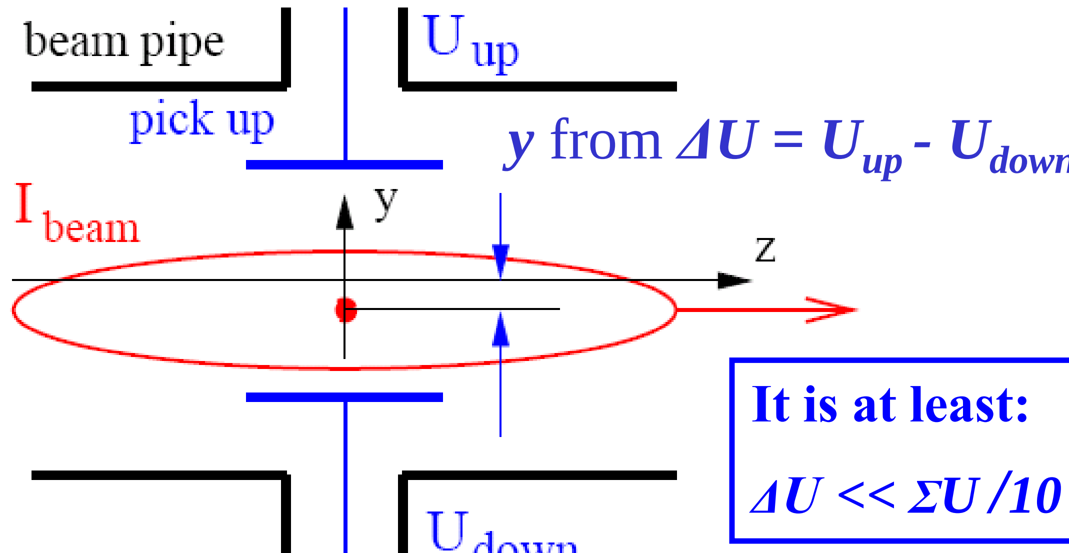
The difference voltage between plates gives the beam's center-of-mass
→**most frequent application**

'Proximity' effect leads to different voltages at the plates:

$$y = \frac{1}{S_y(\omega)} \cdot \frac{U_{up} - U_{down}}{U_{up} + U_{down}} + \delta_y(\omega)$$

$$\equiv \frac{1}{S_y} \cdot \frac{\Delta U_y}{\Sigma U_y} + \delta_y$$

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



It is at least:

$\Delta U << \Sigma U / 10$

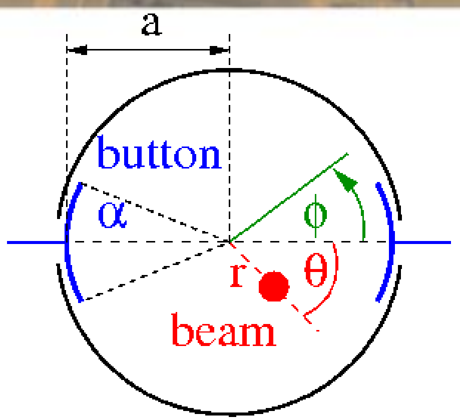
S(ω,x) is called **position sensitivity,** sometimes the inverse is used ***k(ω,x)=1/S(ω,x)***
S is a geometry dependent, non-linear function, which have to be optimized
Units: ***S***=[%/mm] and sometimes ***S***=[dB/mm] or ***k***=[mm].

Outline:

- ➢ Signal generation $\rightarrow$ transfer impedance
- ➢ Capacitive ***button*** BPM for high frequencies

  used at most proton LINACs and electron accelerators
- ➢ Capacitive *shoe-box* BPM for low frequencies
- ➢ Electronics for position evaluation
- ➢ BPMs for measurement of closed orbit, tune and further lattice functions
- ➢ Summary

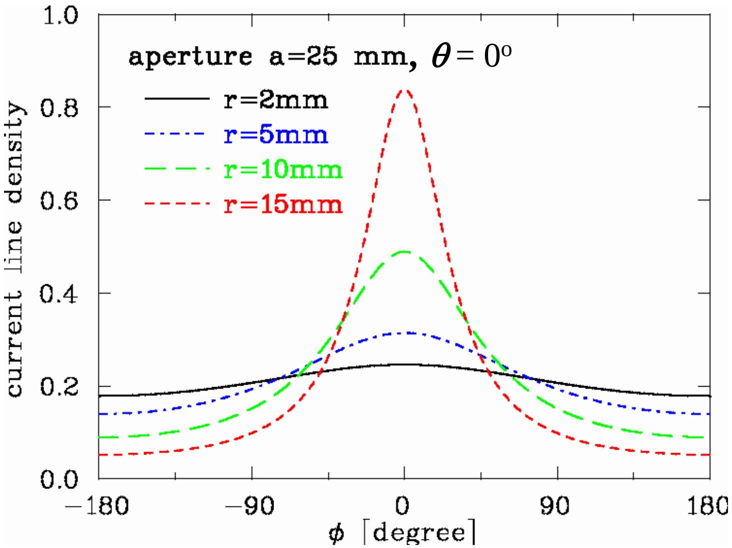
'Proximity effect': larger signal for closer plate

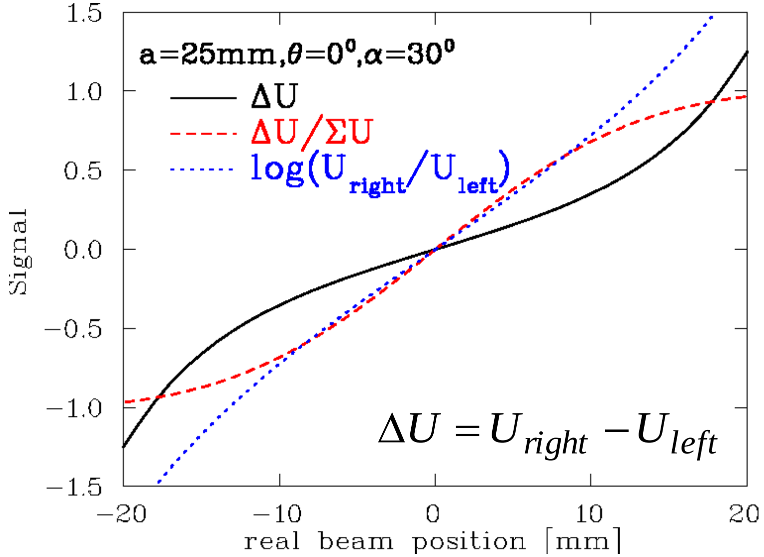


Ideal 2-dim model: Cylindrical pipe → image current density via 'image charge method' for 'pensile' beam:

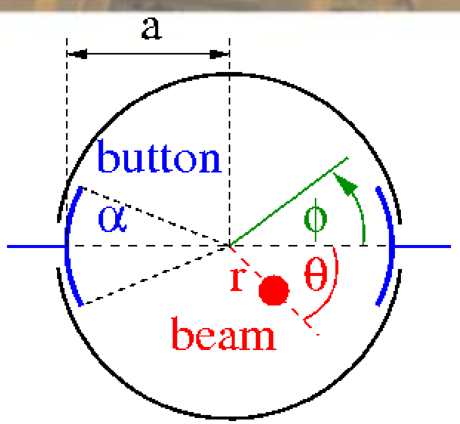
$$j_{im}(\phi) = \frac{I_{beam}}{2\pi a} \cdot \left(\frac{a^2 - r^2}{a^2 + r^2 - 2ar \cdot \cos(\phi - \theta)} \right)$$

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





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



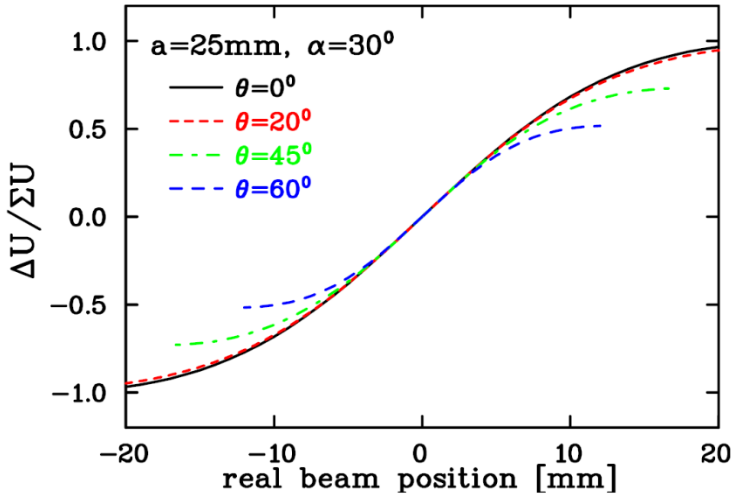
Sensitivity $\boldsymbol{S}$ is converts signal to position $x = \frac{1}{S} \cdot \frac{\Delta U}{\Sigma U}$

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

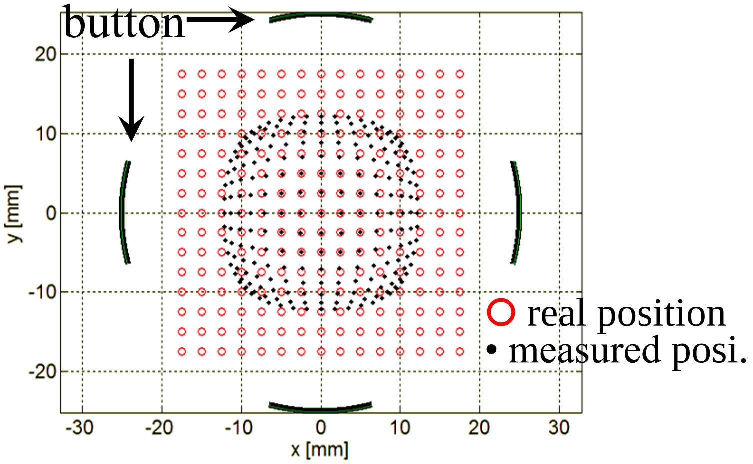
i.e. $\boldsymbol{S}$ is the derivative of the curve $S_x = \frac{\partial(\frac{\Delta U}{\Sigma U})}{\partial x}$, here $S_x = S_x(x, y)$ i.e. non-linear.

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

Horizontal plane:



'Position Map':



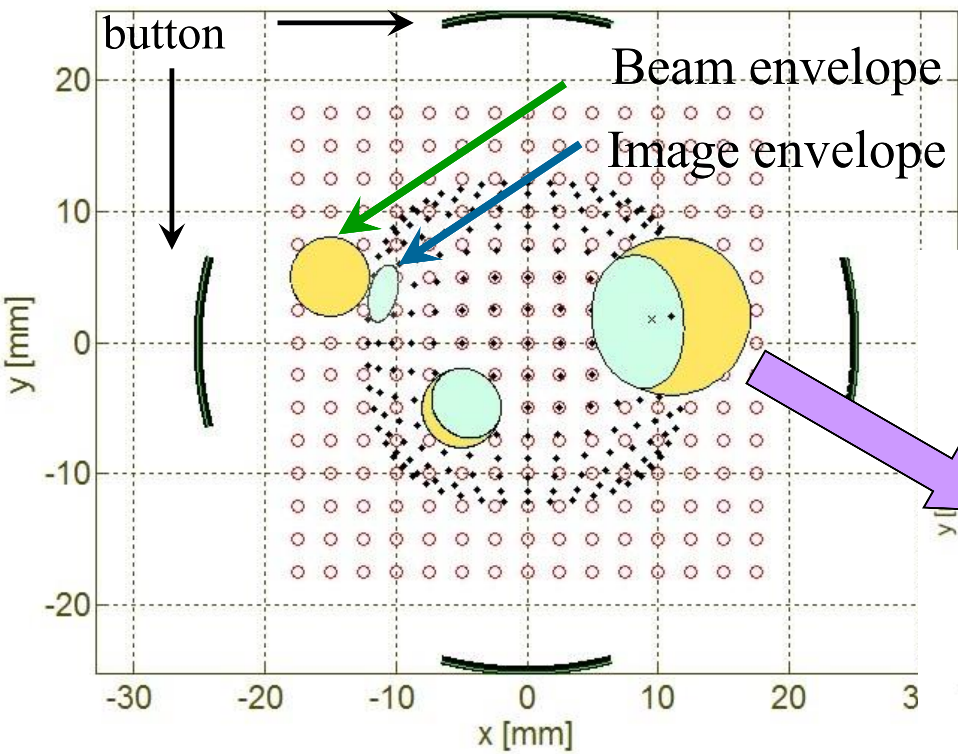
Ideal 2-dim model:

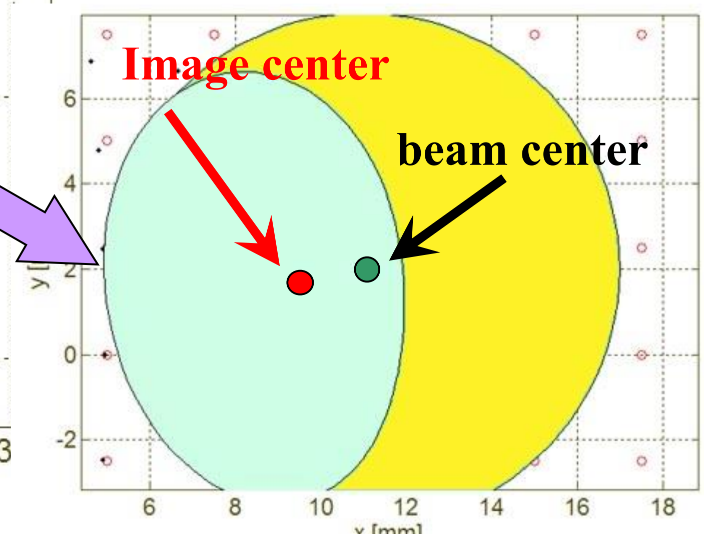
Due to the non-linearity, the beam size enters in the position reading.

Finite beam size:

- ➢Calculation of signal response at different location
- ➢'Averaging' of image position

⇒ Cannot be corrected !





Remark: For most LINACs: Linearity is less important, because beam has to be centered

Position correction as feed-forward for next macro-pulse.

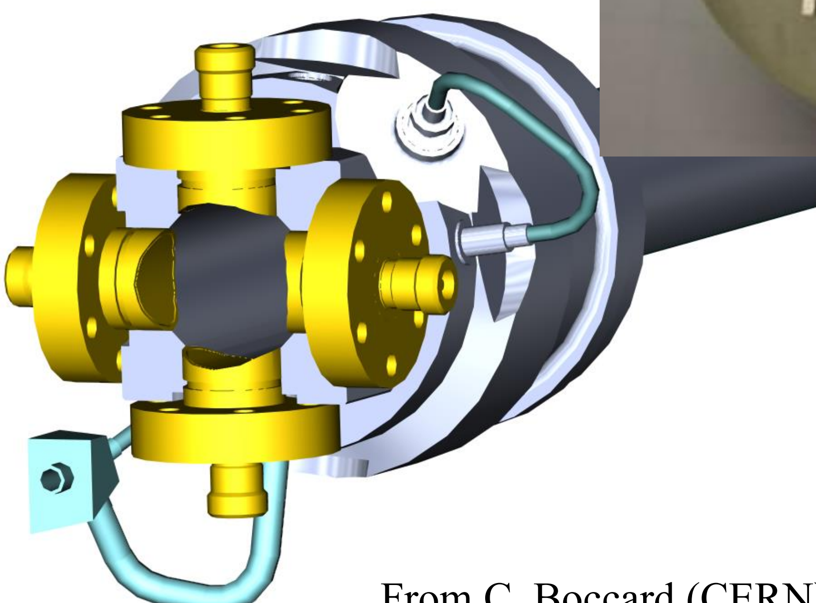
LINACs, e$^-$-synchrotrons: 100 MHz < f_{rf} < 3 GHz → bunch length ≈ BPM length

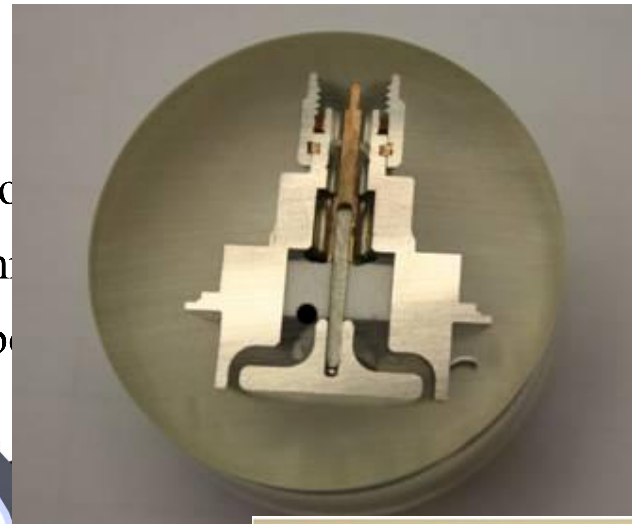
→ 50 Ω signal path to prevent reflections

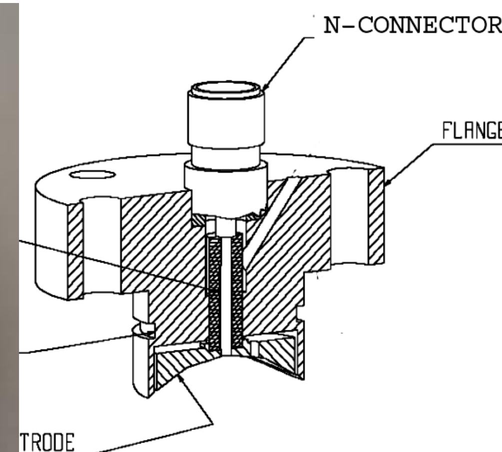
Example: LHC-type inside cryo

∅24 mm, half aperture a=25 m

⇒ f_{cut}=400 MHz, Z_t = 1.3 Ω ab



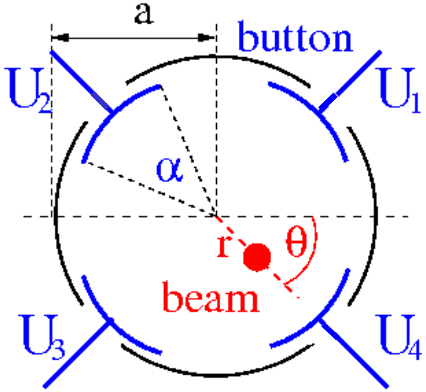




From C. Boccard (CERN)

The button BPM can be rotated by 45^0 to avoid exposure by synchrotron light:

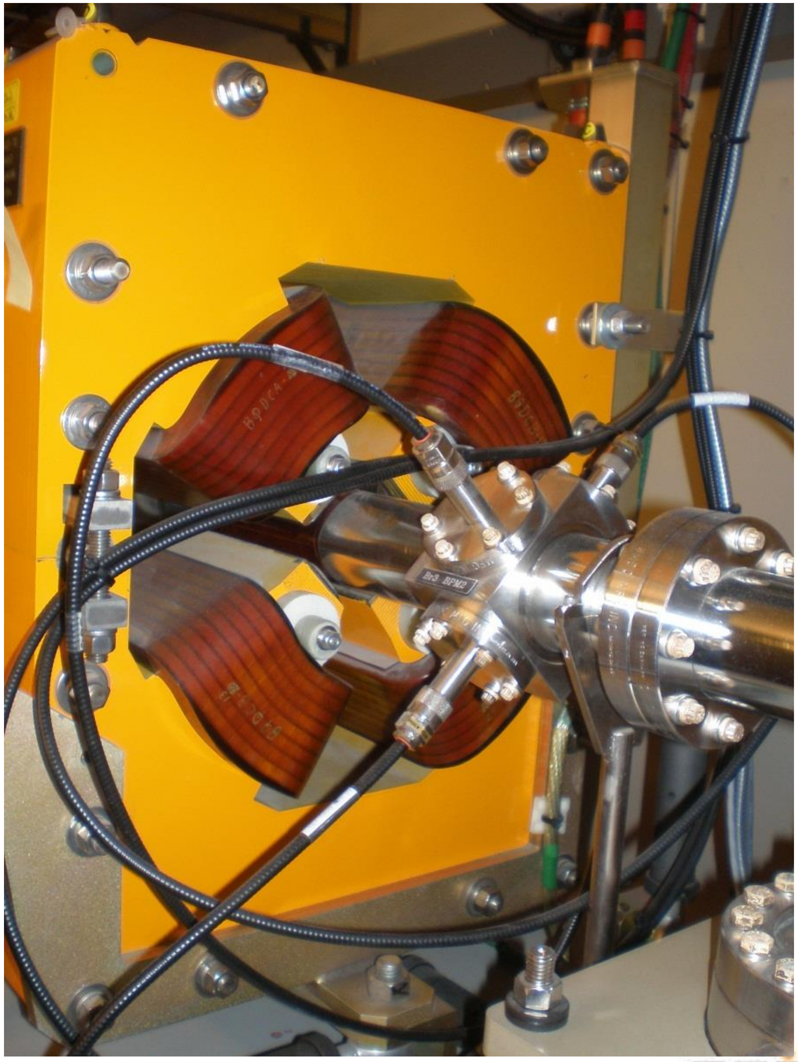
Frequently used at boosters for light sources



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

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

Example: Booster of ALS, Berkeley



Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies

  used at most proton LINACs and electron accelerators
- Capacitive ***shoe-box*** BPM for low frequencies

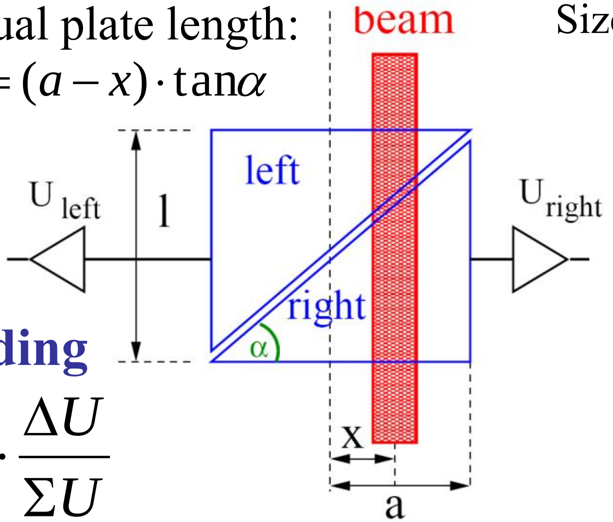
  used at most proton synchrotrons due to linear position reading
- Electronics for position evaluation
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

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

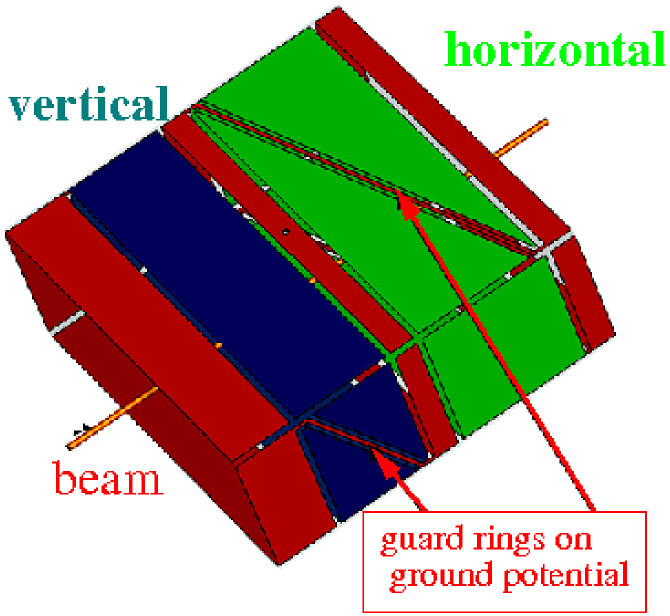
Signal is proportional to actual plate length:

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

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

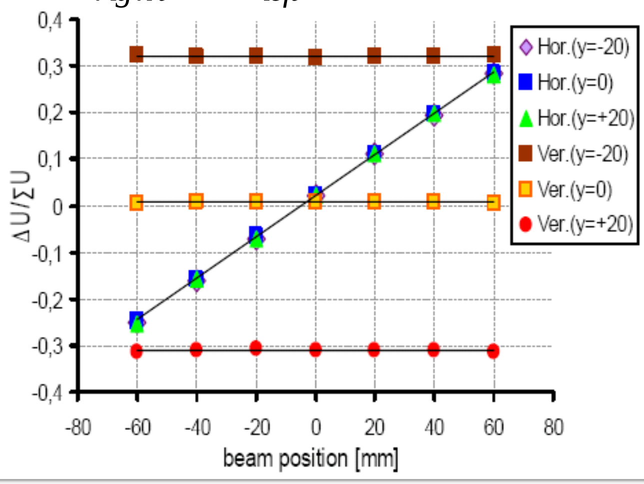


Size: 200x70 mm^2



In ideal case: linear reading

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



Shoe-box BPM:

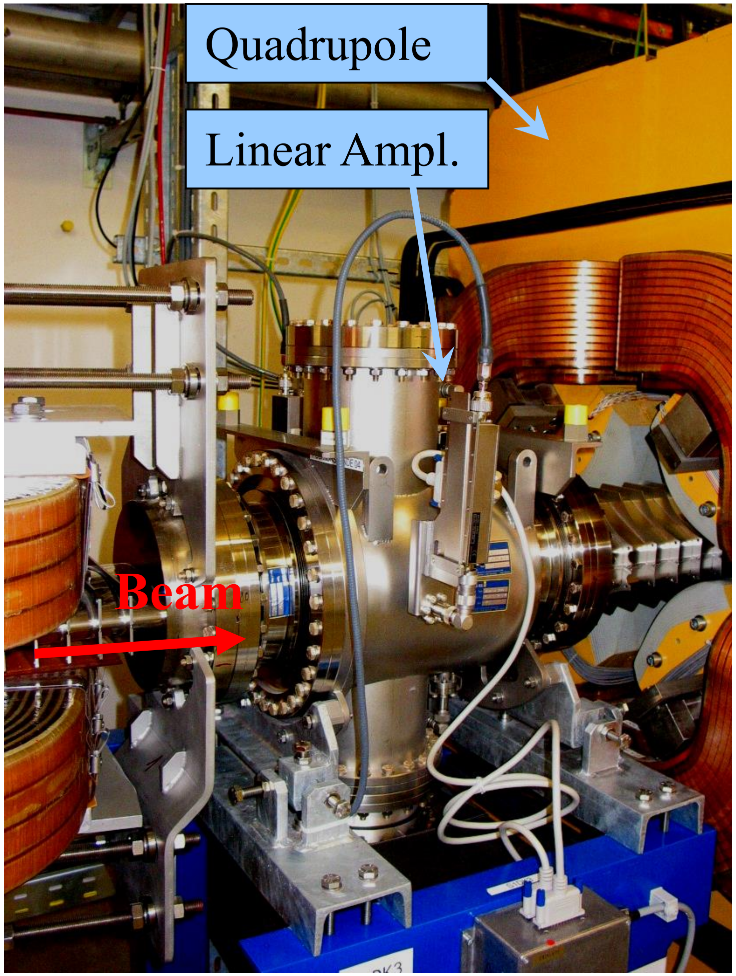
Advantage: Very linear, low frequency dependence i.e. position sensitivity S is constant

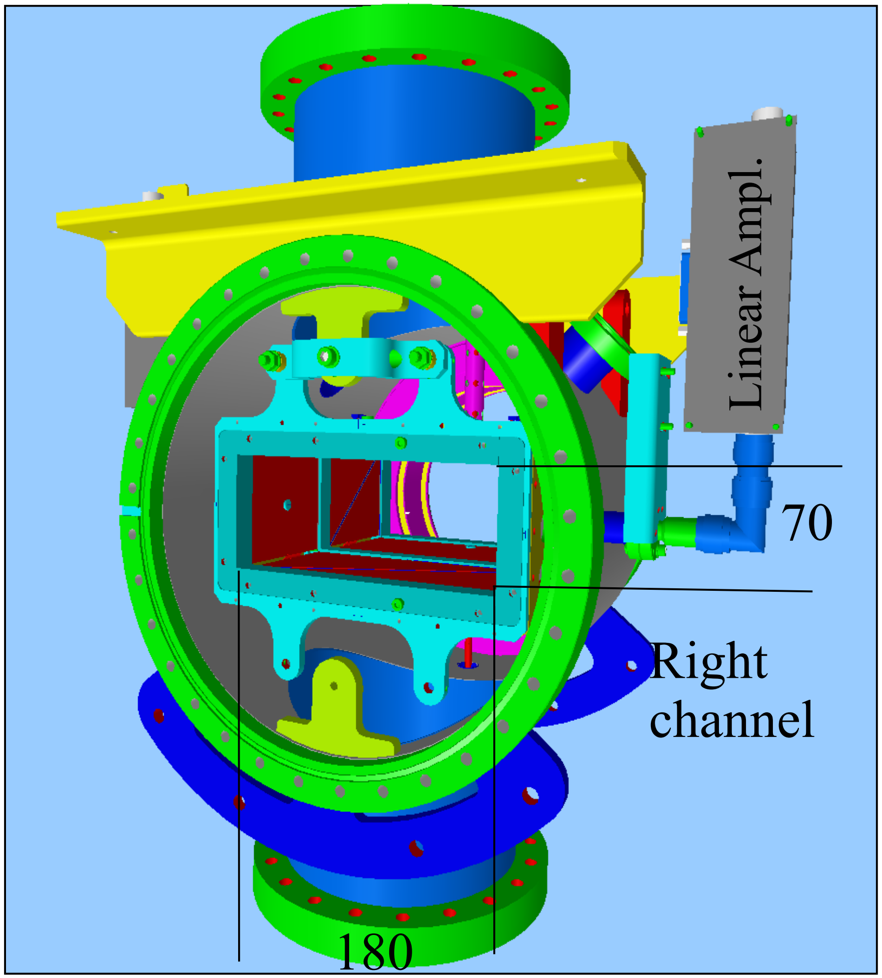
Disadvantage: Large size, complex mechanics high capacitance

Technical Realization of a Shoe-Box BPM

Technical realization at HIT synchrotron of 46 m length for 7 MeV/u$\rightarrow$ 440 MeV/u

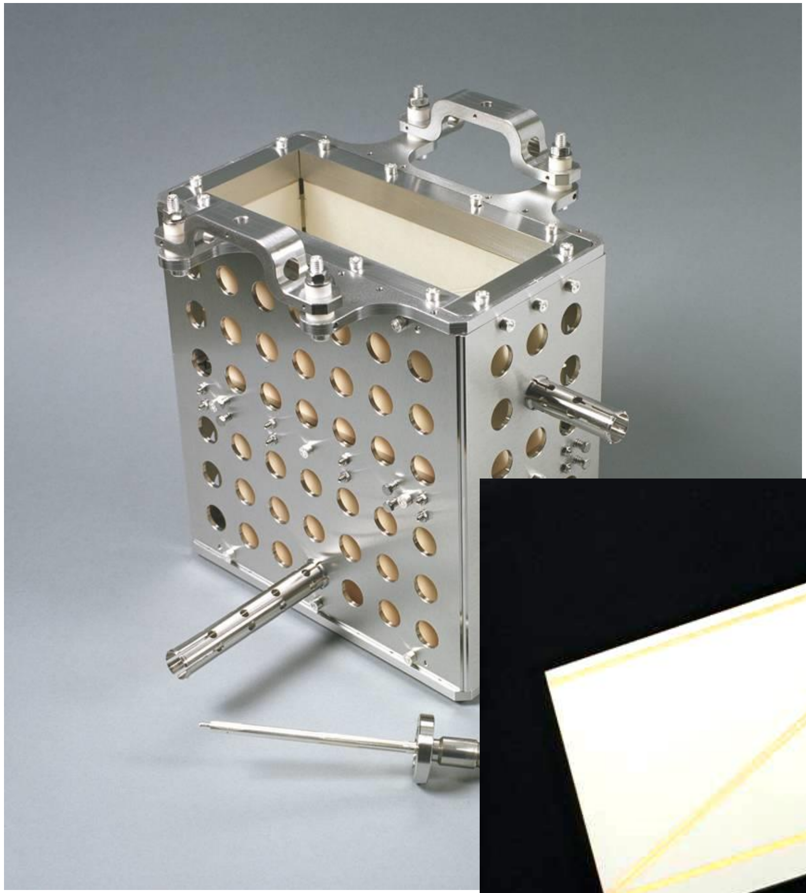
BPM clearance: 180x70 mm^2, standard beam pipe diameter: 200 mm.

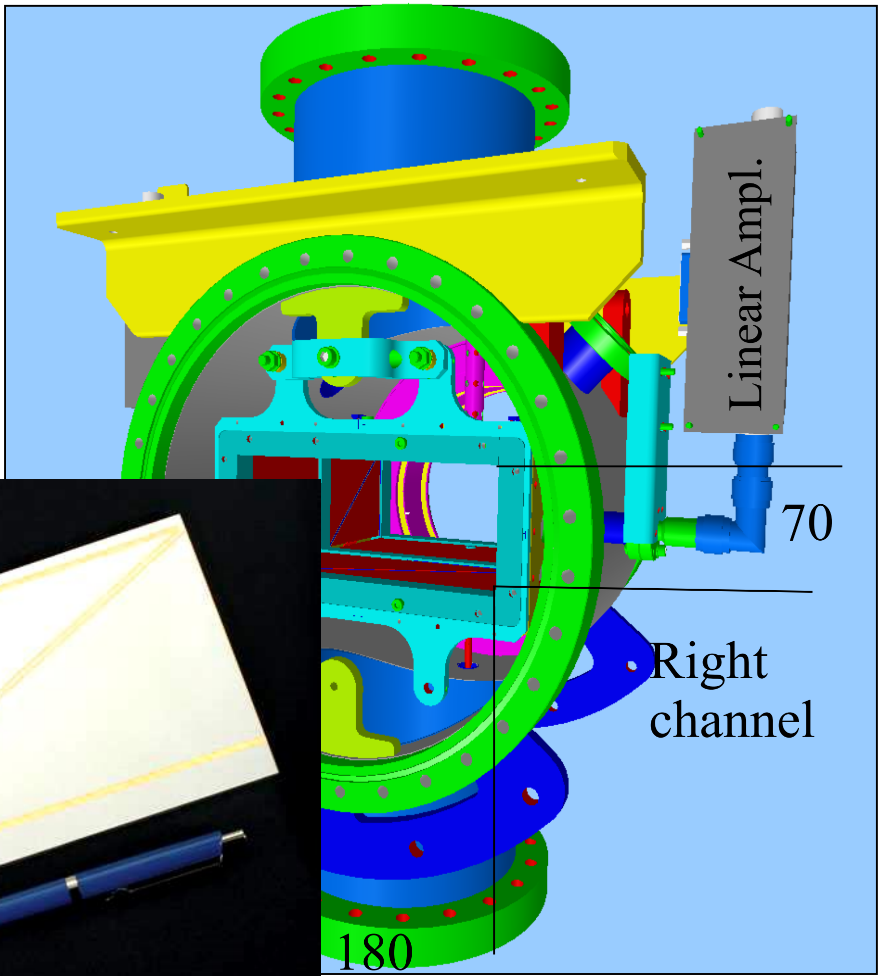




Technical realization at HIT synchrotron of 46 m length for 7 MeV/u→ 440 MeV/u

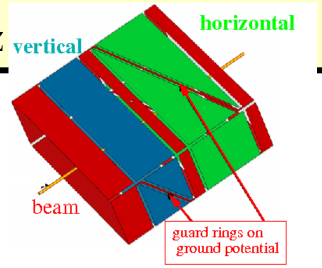
BPM clearance: 180x70 mm^2, standard beam pipe diameter: 200 mm.

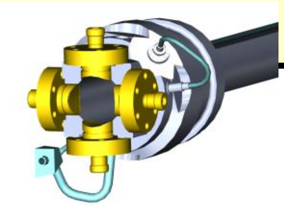




Comparison Shoe-Box and Button BPM

	Shoe-Box BPM	Button BPM
Precaution	Bunches longer than BPM	Bunch length comparable to BPM
BPM length (typical)	10 to 20 cm length per plane	∅1 to 5 cm per button
Shape	Rectangular or cut cylinder	Orthogonal or planar orientation
Bandwidth (typical)	0.1 to 100 MHz	100 MHz to 5 GHz
Coupling	1 MΩ or ≈1 kΩ (transformer)	50 Ω
Cutoff frequency (typical)	0.01… 10 MHz (C=30…100pF)	0.3… 1 GHz (C=2…10pF)
Linearity	Very good, no x-y coupling	Non-linear, x-y coupling
Sensitivity	Good, care: plate cross talk	Good, care: signal matching
Usage	At proton synchrotrons, f_{rf} < 10 MHz	All electron acc., proton Linacs, f_{rf} > 100 MHz



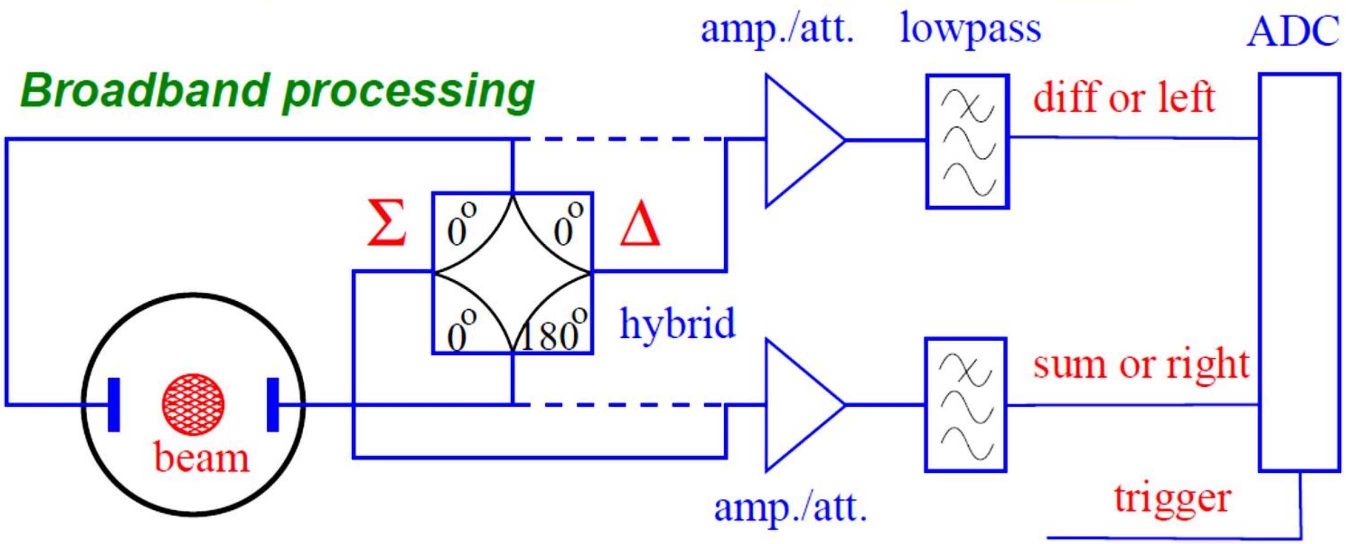


Remark: Other types are also some time used: e.g. wall current monitors, inductive antenna, BPMs with external resonator, cavity BPM, slotted wave-guides for stochastic cooling etc.

Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies
  used at most proton LINACs and electron accelerators
- Capacitive *shoe-box* BPM for low frequencies
  used at most proton synchrotrons due to linear **position reading**
- Electronics for position evaluation
  analog signal conditioning to achieve small signal processing
- BPMs for measurement of closed orbit, tune and further lattice functions
- Summary

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 $\longrightarrow$ followed by calculation of of $\Delta U / \Sigma U$

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

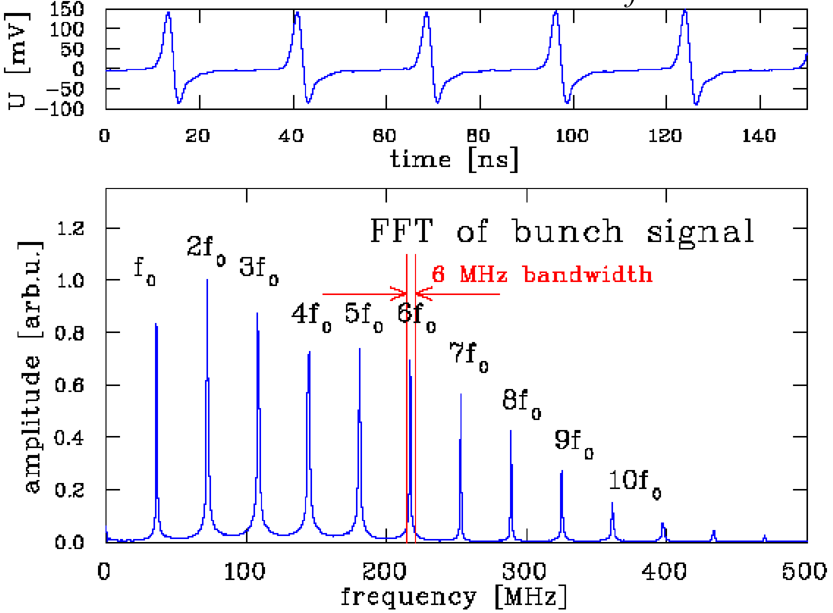
Disadvantage: Resolution down to ≈ 100 µm for shoe box type , i.e. ≈0.1% of aperture, resolution is worse than narrowband processing, see below

1. Signal voltage given by: $U_{im}(f) = Z_t(f) \cdot I_{beam}(f)$
2. Position information from voltage difference: $x = 1/S \cdot \Delta U / \Sigma U$
3. Thermal noise voltage given by: $U_{noise}(R, \Delta f) = \sqrt{4 k_B \cdot T \cdot R \cdot \Delta f}$

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

- Input signal amplitude
- Thermal noise at R=50 Ω for T=300 K
  (for shoe box R = 1 kΩ …1 MΩ)
- Bandwidth Δf
  $\Rightarrow$ Restriction of frequency width because the power is concentrated on the harmonics of f_{rf}

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

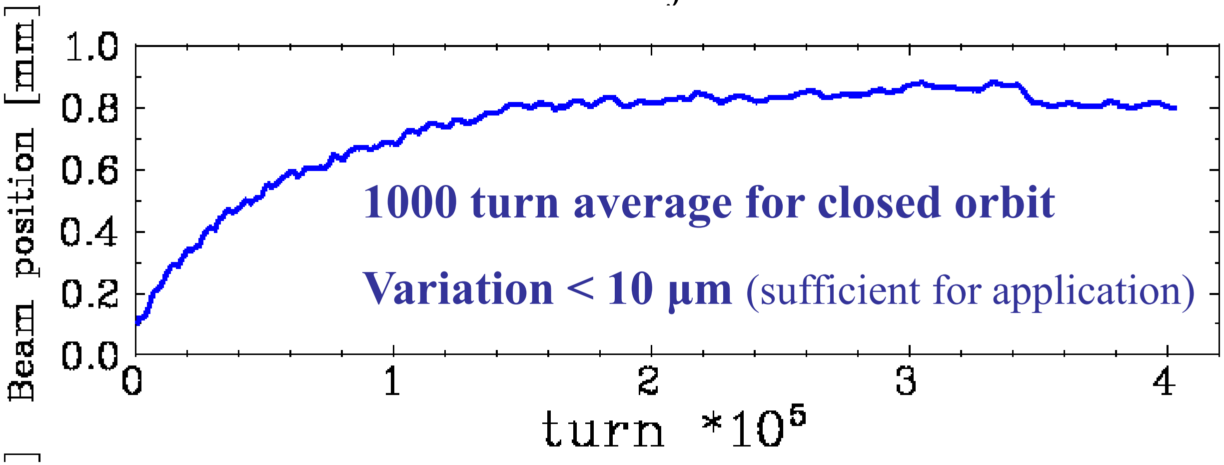


Remark:

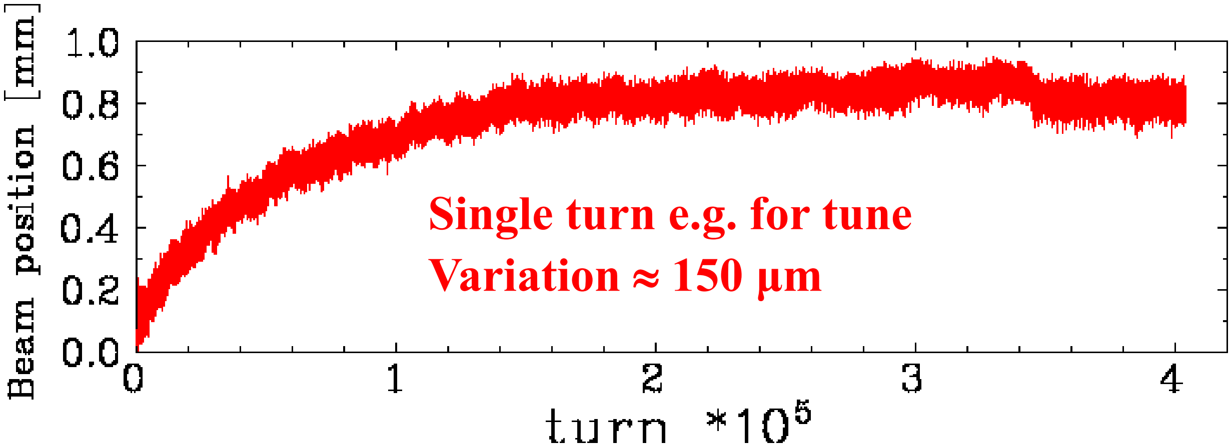
- Bandwidth restriction only meaningful for many bunches e.g. at LINAC or stored beam
- Additional contribution by non-perfect electronics, typically a factor ≈ 3

Comparison: Filtered Signal ↔ Single Turn

Example: GSI Synchr.: U^{73+}, E_{inj}=11.5 MeV/u→ 250 MeV/u within 0.5 s, 10^9 ions

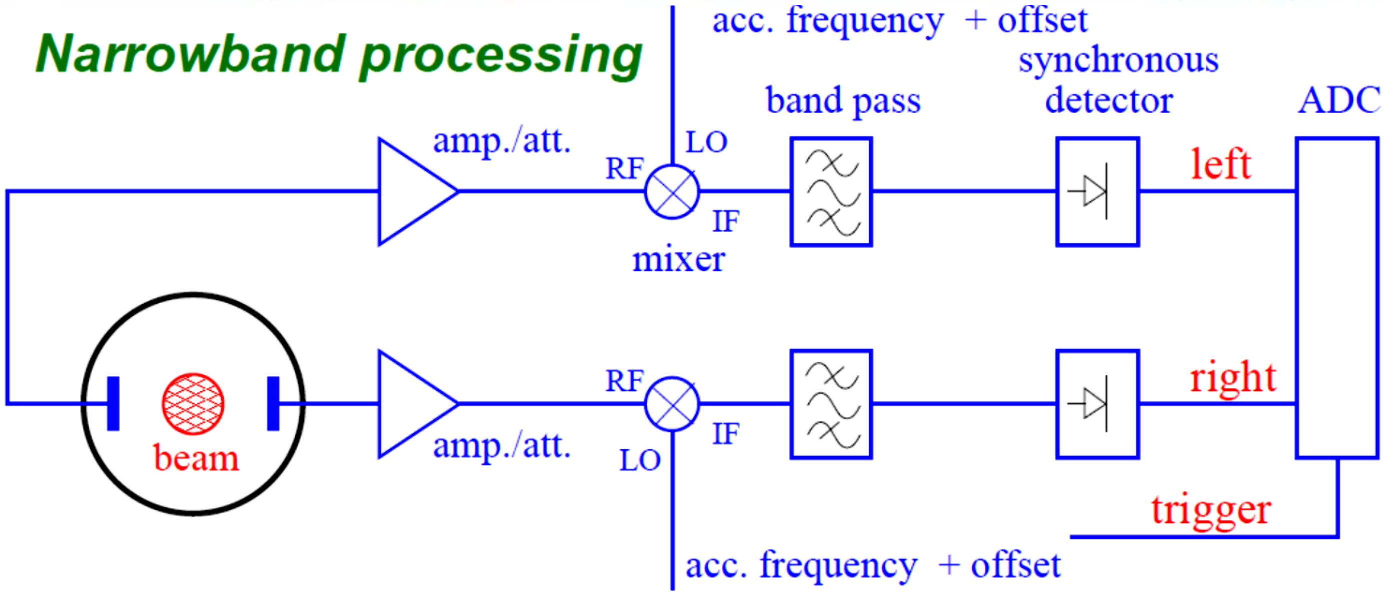


- Position resolution < 30 µm (BPM half aperture *a*=90 mm)
- average over 1000 turns corresponding to ≈1 ms or ≈1 kHz bandwidth



- Turn-by-turn data have much larger variation

However: not only noise contributes but additionally **beam movement** by betatron oscillation
⇒ broadband processing i.e. turn-by-turn readout for tune determination.



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

- Attenuator/amplifier
- Mixing with accelerating frequency $f_{rf} \Rightarrow$ signal with sum and difference frequency
- Bandpass filter of the mixed signal (e.g at 10.7 MHz)
- Rectifier: synchronous detector
- ADC: digitalization $\longrightarrow$ followed calculation of $\Delta U/\Sigma U$

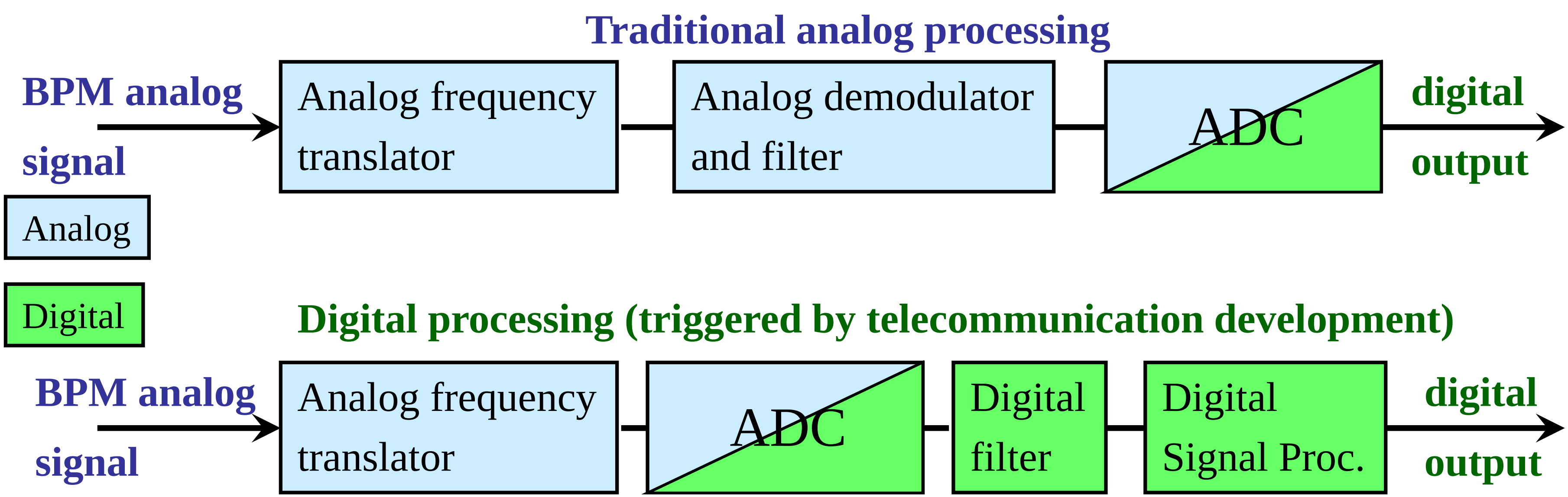
Advantage: spatial resolution about 100 time better than broadband processing

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

For non-relativistic p-synchrotron: $\rightarrow$ variable f_{rf} leads via mixing to constant intermediate freq.

Analog versus Digital Signal Processing

Modern instrumentation uses **digital** techniques with extended functionality.



Digital receiver as modern successor of super heterodyne receiver

- Basic functionality is preserved but implementation is very different
- Digital transition just after the amplifier & filter or mixing unit
- Signal conditioning (filter, decimation, averaging) on FPGA

Advantage of DSP: Versatile operation, flexible adoption without hardware modification

Disadvantage of DSP: **non**, good engineering skill requires for development, expensive

Comparison of BPM Readout Electronics (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Broadband	p-sychr.	Long bunches	Bunch structure signal Post-processing possible **Required for transfer lines with few bunches**	Resolution limited by noise
Narrowband	all synchr.	Stable beams >100 rf-periods	High resolution	No turn-by-turn Complex electronics
Digital Signal Processing	all	Several bunches ADC 125 MS/s	Very flexible High resolution **Trendsetting technology for future demands**	Limited time resolution by ADC $\rightarrow$ undersampling complex and expensive

Outline:

- Signal generation → transfer impedance
- Capacitive *button* BPM for high frequencies

  used at most proton LINACs and electron accelerators
- Capacitive *shoe-box* BPM for low frequencies

  used at most proton synchrotrons due to linear position reading
- Electronics for position evaluation

  analog signal conditioning to achieve small signal processing
- BPMs for measurement of closed orbit, tune and further lattice functions

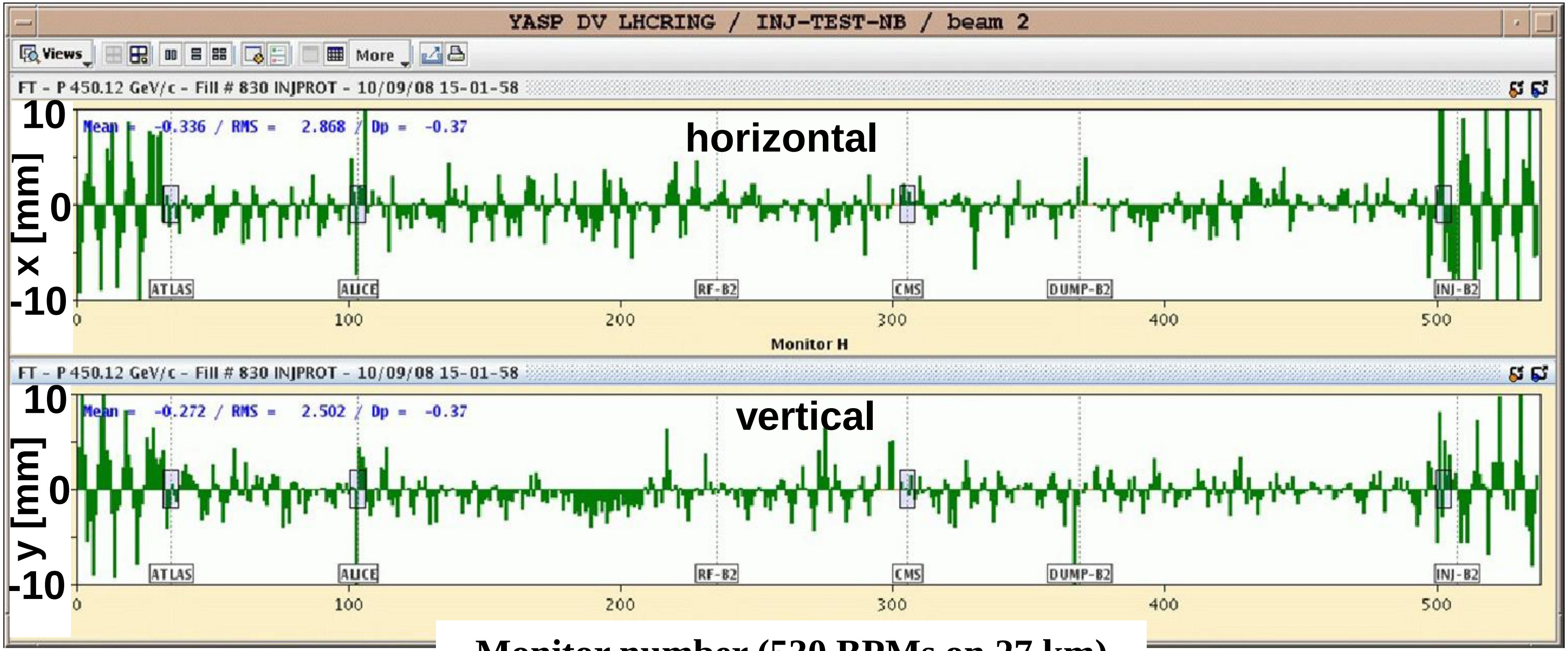
  frequent application of BPMs
- Summary

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 !

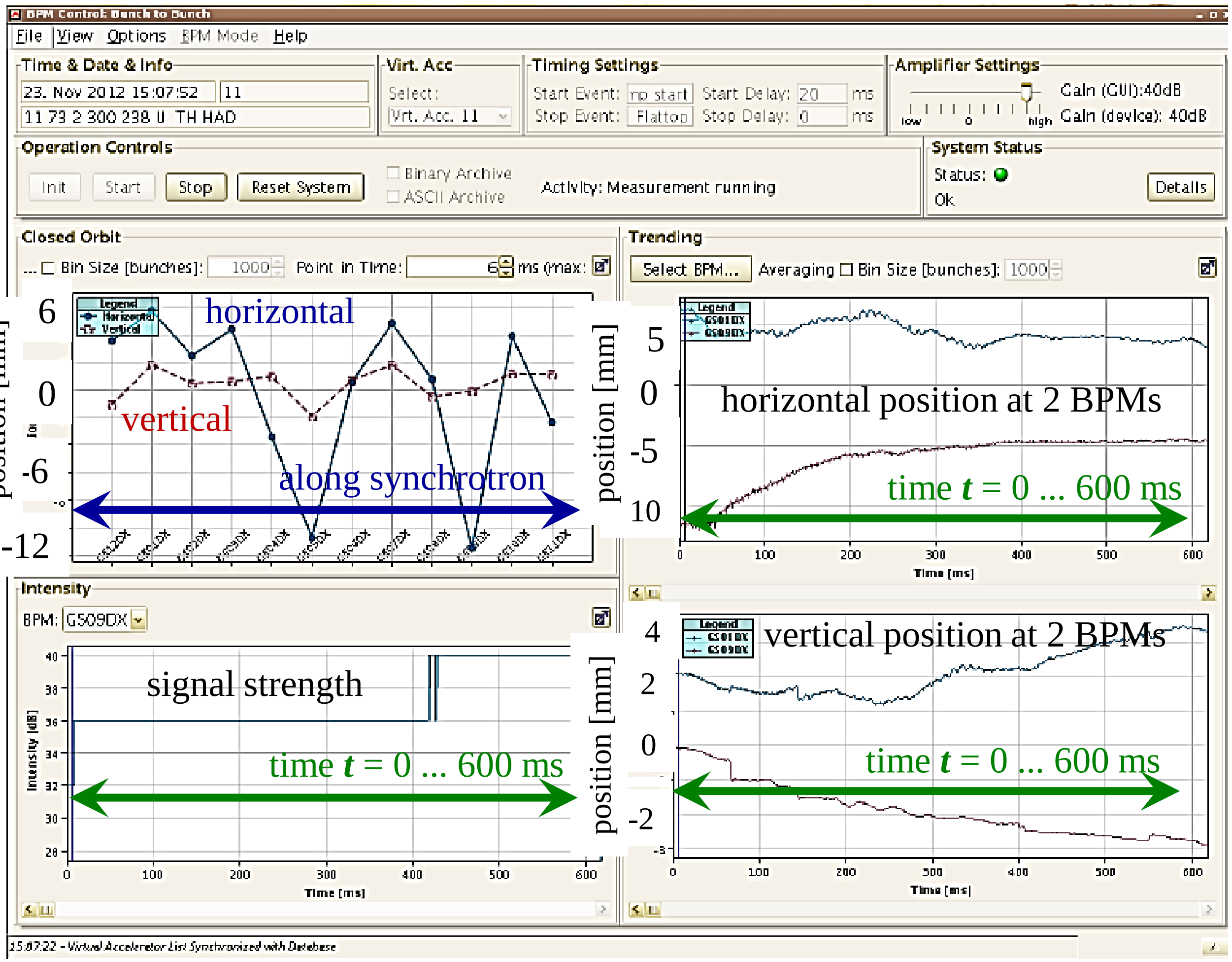


Monitor number (530 BPMs on 27 km)

From R. Jones (CERN)

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

Single bunch position averaged over 1000 bunches → closed orbit with ms time steps.
It differs from ideal orbit by misalignments of the beam or components.
Example: GSI-synchrotron at two BPM locations, 1000 turn average during acceleration:



Closed orbit:
Beam position averaged over many turns (i.e. betatron oscillations).
The result is the basic tool for alignment & stabilzation

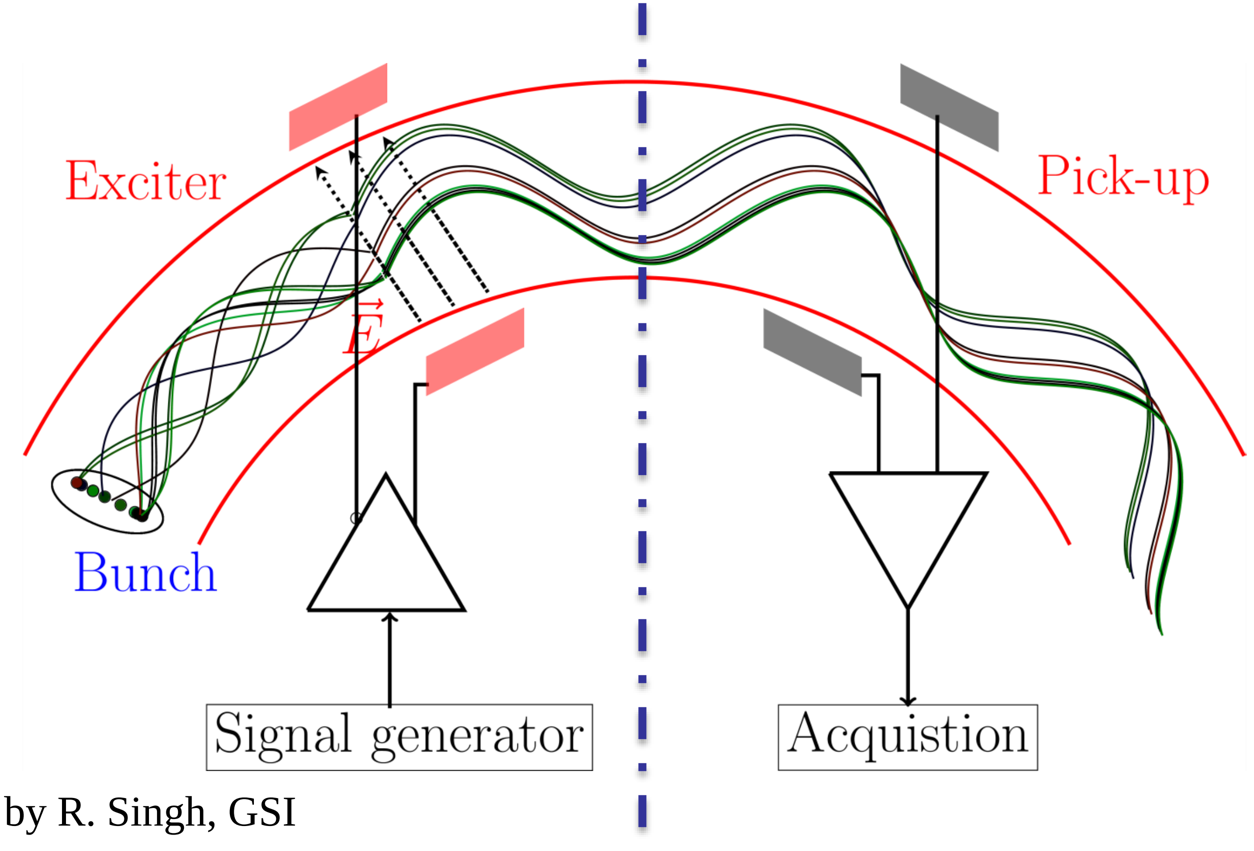
Remark as a role of thumb:
Number of BPMs within a synchrotron: $N_{BPM} \approx 4 \cdot Q$
Relation BPMs ↔ tune due to close orbit stabilization feedback
(justification outside of the scope of this lecture)

Coherent excitations are required for the detection by a BPM

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

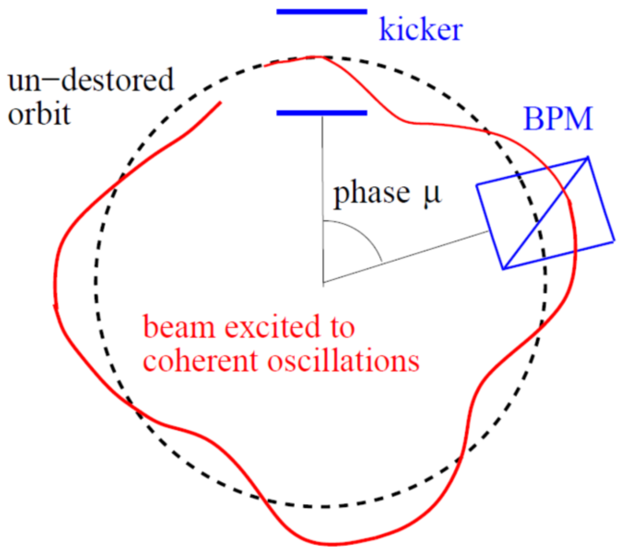
Excitation of **all** particles by rf ⇒ ***coherent*** motion

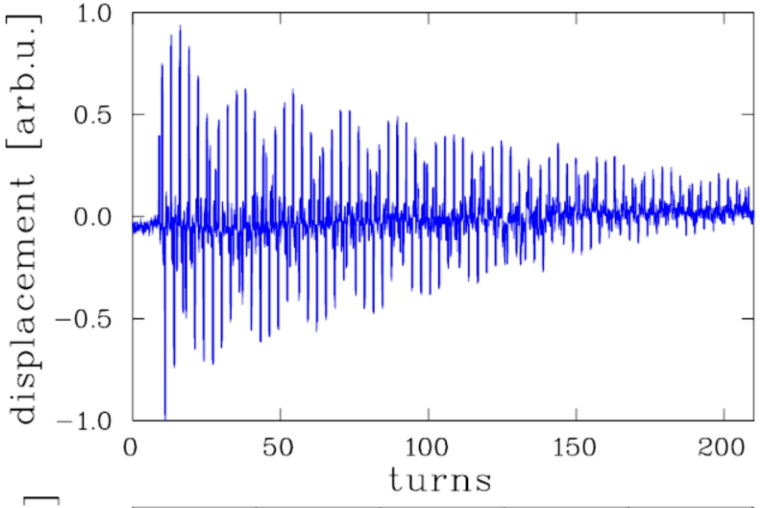
⇒ center-of-mass variation turn-by-turn

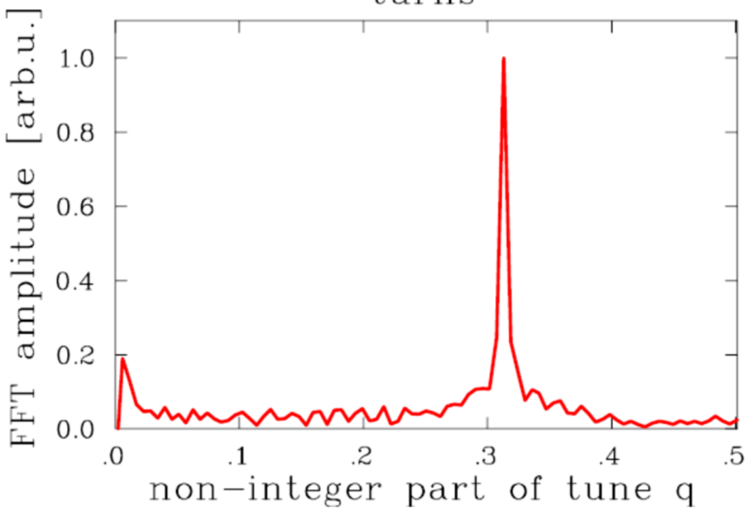


Graphics by R. Singh, GSI

The beam is excited to coherent betatron oscillation
→ the beam position measured each revolution ('turn-by-turn')
→ Fourier Trans. gives the non-integer tune ***q***.
Short kick compared to revolution.





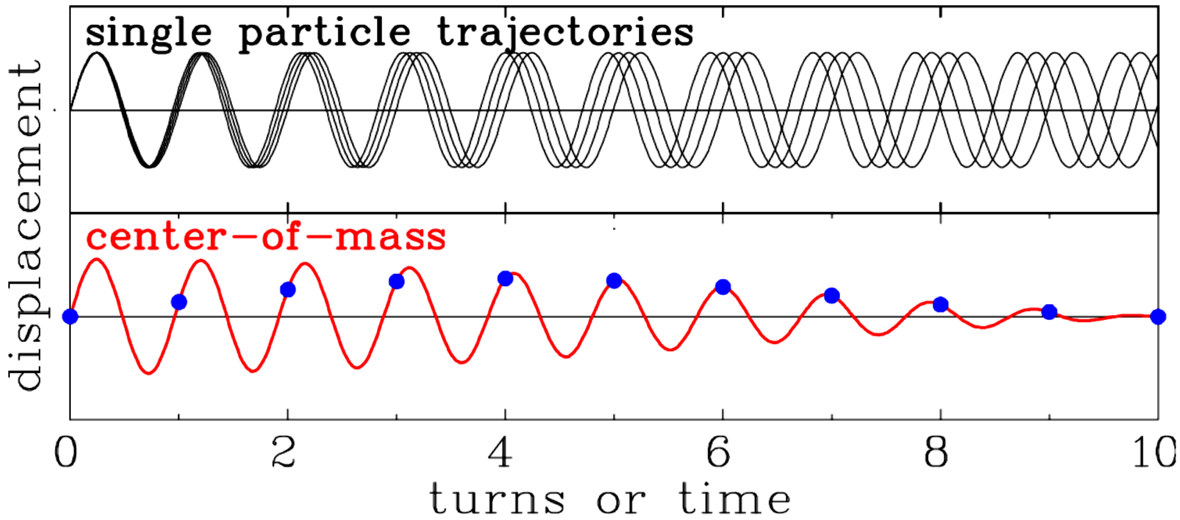


The de-coherence time limits the **resolution**:
N non-zero samples
⇒ General limit of discrete FFT: $\Delta q > \frac{1}{2N}$

N = 200 turn ⇒ Δq > 0.003 as resolution
(tune spreads are typically $\Delta q \approx 0.001$!)

Tune Measurement: De-Coherence Time

The particles are excited to betatron oscillations, but due to the spread in the betatron frequency, they getting out of phase ('Landau damping'):



Scheme of the individual trajectories of four particles after a kick (top) and the resulting ***coherent*** signal as measured by a pick-up (bottom).

$\Rightarrow$ Kick excitation leads to limited resolution

Remark: The tune spread is much lower for a real machine.

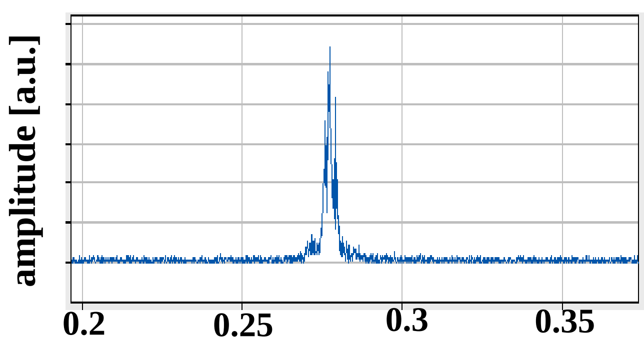
Instead of a sine wave, noise with adequate bandwidth can be applied

→ beam picks out its resonance frequency:

- broadband excitation with white noise of ≈ 10 kHz bandwidth
- turn-by-turn position measurement
- Fourier transformation of the recorded data

⇒ Continues monitoring with low disturbance

vertical tune at fixed time ≈ 15ms

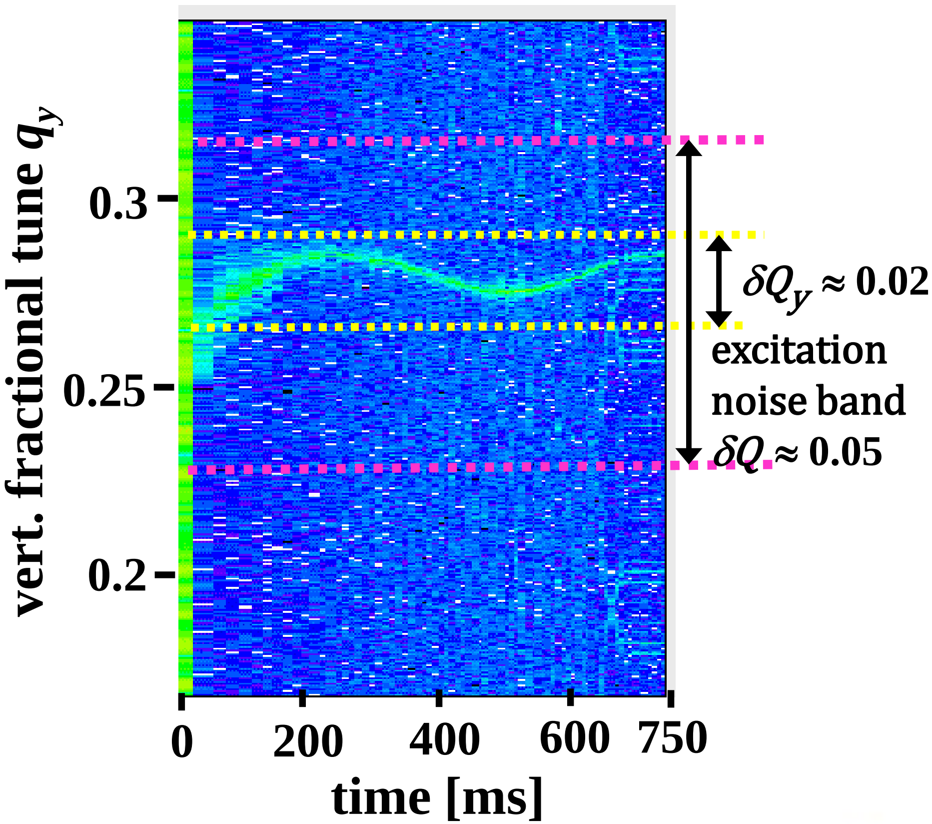


Advantage:

Fast scan with good time resolution

Example: Vertical tune within 4096 turn duration ≃ 15 ms at GSI synchrotron 11 → 300 MeV/u in 0.7 s

vertical tune versus time



Goal of a transfer line: Acceptance at input → transport with low loss → matching to output

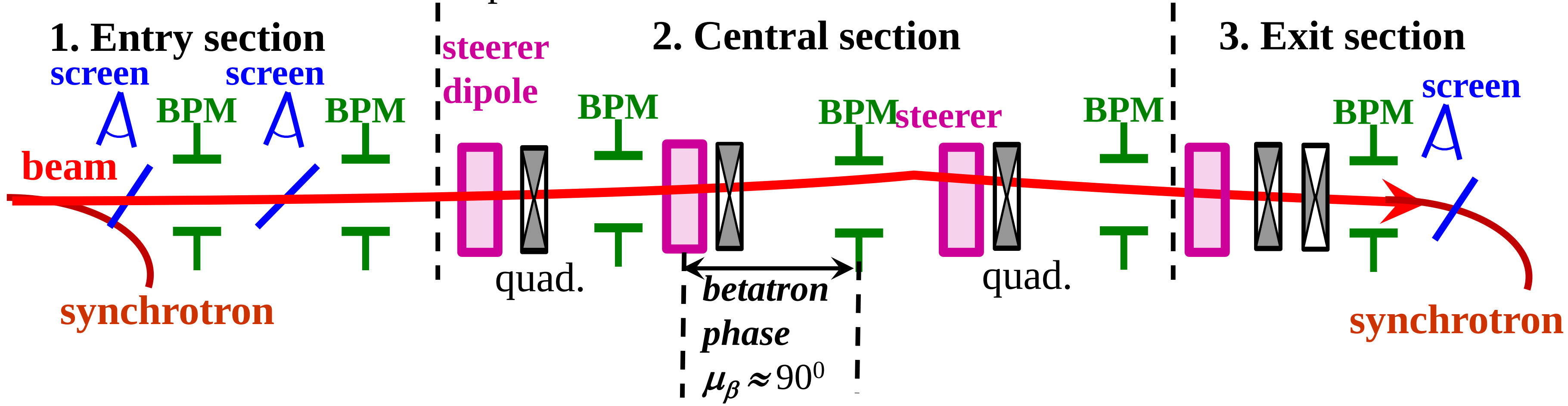
Instruments in transfer lines:

Current: transformer (bunched beam) or IC etc. (slow extraction)

Position: BPM (bunched beam)

Position and profile: SEM-Grid, scintillation screen, OTR screen (relativistic beam $\gamma > 100$)

Beam loss for transmission optimization: BLM



1. Entry section: position and angle e.g. by two BPMs, beam size by e.g. screen

2. Central section (often FODO cell): BPM or screen, comparison to optics calculation, best setting for orbit correction: steerer for active control → $\mu_\beta \approx 90^0$ betatron phase advance to BPM i.e. angle ***x'@steerer*** is transformed to offset ***x @BPM***

3. Exit section: Matching to next part via steerer and quadrupole duplet or triplet

Summary Pick-Ups for bunched Beams

The electric field is monitored for bunched beams using rf-technologies ('frequency domain'). Beside transfromers they are the most often used instruments!

Differentiated or proportional signal: rf-bandwidth ↔ beam parameters

Proton synchrotron: 1 to 100 MHz, mostly 1 MΩ → proportional shape

LINAC, e−-synchrotron: 0.1 to 3 GHz, 50 Ω → differentiated shape

Important quantity: transfer impedance $Z_t(\omega, \beta)$.

Types of capacitive pick-ups:

Shoe-box (p-synch.), button (p-LINAC, e−-LINAC and synch.)

Position reading: difference signal of four pick-up plates (BPM):

- Non-intercepting reading of center-of-mass → online measurement and control
  Synchrotron: slow reading → closed orbit, ***fast bunch-by-bunch***→ trajectory
- ***Synchrotron:*** Excitation of ***coherent*** betatron oscillations delivers tune q etc. .
- ***Transfer line:*** Position reading and matching conditions

Remark: BPMs have high pass characteristic ⇒ no signal for dc-beam e.g. slow extraction.

Measurement of longitudinal parameter:

- Proton LINAC: Determination of mean energy & longitudinal emittance
- Longitudinal injection matching and Schottky noise analysis
- Bunch length measurement for relativistic beams
- Summary

Longitudinal ↔ transverse correspondences:

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

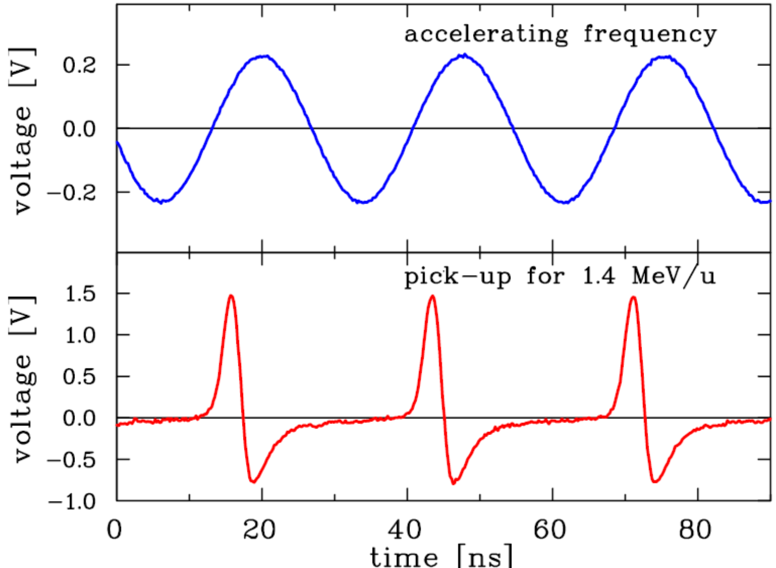
The ***bunch position*** is given relative to the accelerating rf.

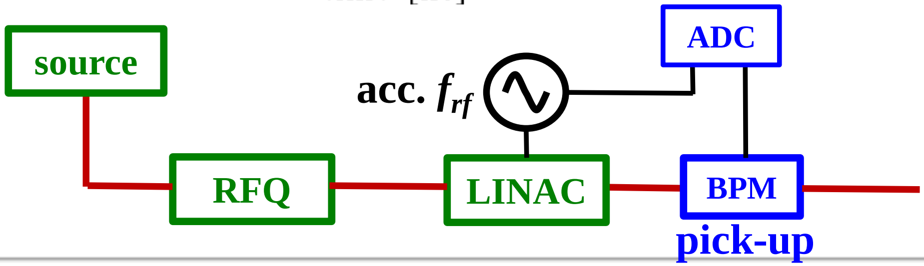
e.g. φ_{ref}=-30^o inside a rf cavity

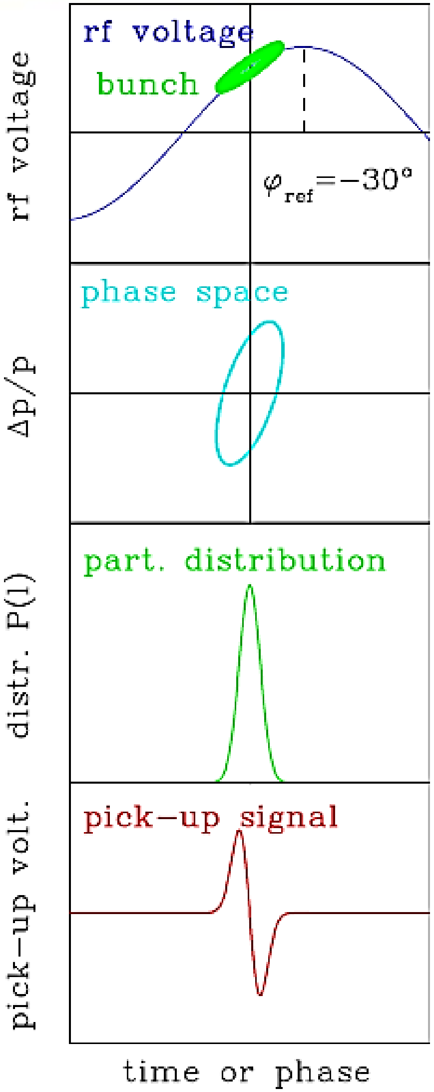
must be well aligned for optimal acceleration

Transverse correspondence: Beam position

Example: Pick-up signal and 36 MHz rf at GSI-LINAC:





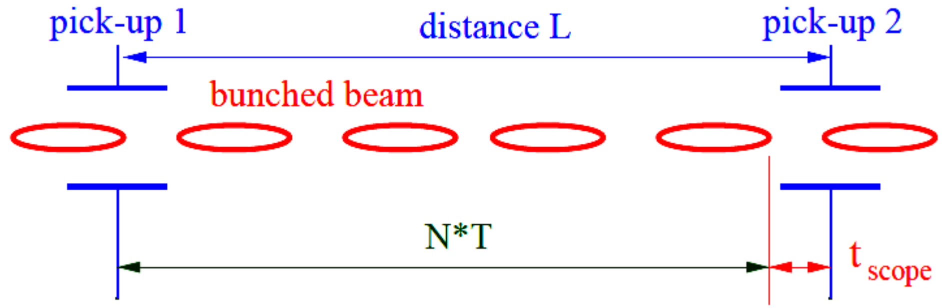


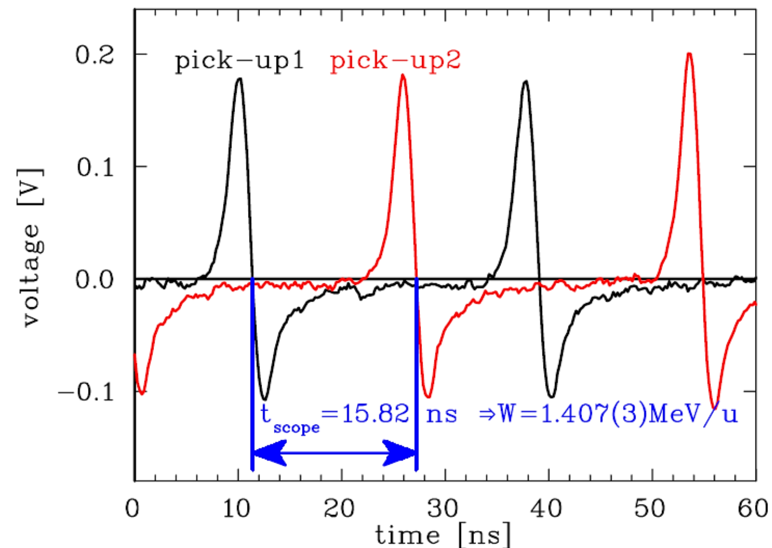
The energy delivered by a LINAC is sensitive to the mechanics, rf-phase and amplitude.

For non-relativistic energies at proton LINACs time-of-flight (TOF) with two pick-ups is used:

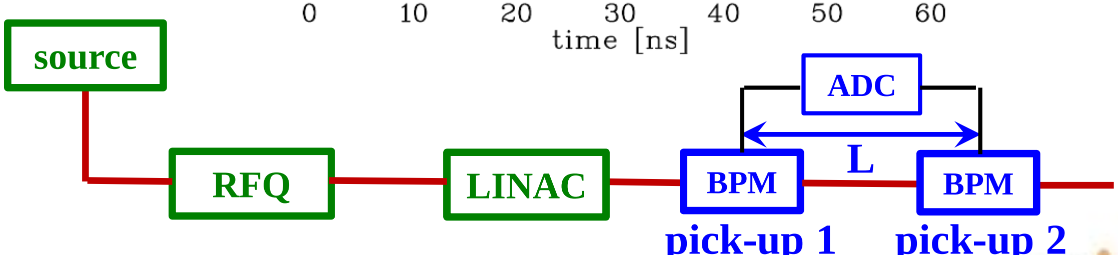
$$\beta c = \frac{L}{NT + t_{scope}}$$

$\rightarrow$ the velocity $\boldsymbol{\beta}$ is measured.





Example: Time-of-flight signal from two pick-ups at 1.4 MeV/u:
The reading is t_{scope}= 15.82(5) ns with
f_{rf} = 36.136MHz $\Leftrightarrow$ T = 27.673ns
L = 1.629(1) m and N = 3
$\Rightarrow \beta = 0.05497(7)$
$\Leftrightarrow$ W=1.407(3) MeV/u
The accuracy is typically 0.1 %
i.e. comparable to ΔW/W



The particle trajectory is described with the 6-dim vector $\vec{x}^{\,t} = \left(x, x', y, y', l, \delta\right)$

For linear beam behavior the 6x6 transport matrix R is used:

Transformation from location $\boldsymbol{s_0}$ to $\boldsymbol{s_1}$ is:

Single particle:

$$\vec{x}(s_1) = \mathrm{R} \cdot \vec{x}(s_0)$$

$$\vec{x}(s_1) = \begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & \dots & \dots & \dots & \dots \\ R_{31} & \dots & R_{33} & R_{34} & \dots & \dots \\ R_{41} & \dots & R_{43} & R_{44} & \dots & \dots \\ R_{51} & \dots & \dots & \dots & R_{55} & R_{56} \\ R_{61} & \dots & \dots & \dots & R_{65} & R_{66} \end{pmatrix} \cdot \begin{pmatrix} x \\ x' \\ y \\ y' \\ l \\ \delta \end{pmatrix}$$

Envelope i.e. emittance defined by beam matrix:

$$\sigma(s_1) = \mathrm{R} \cdot \sigma(s_0) \cdot \mathrm{R}^T$$

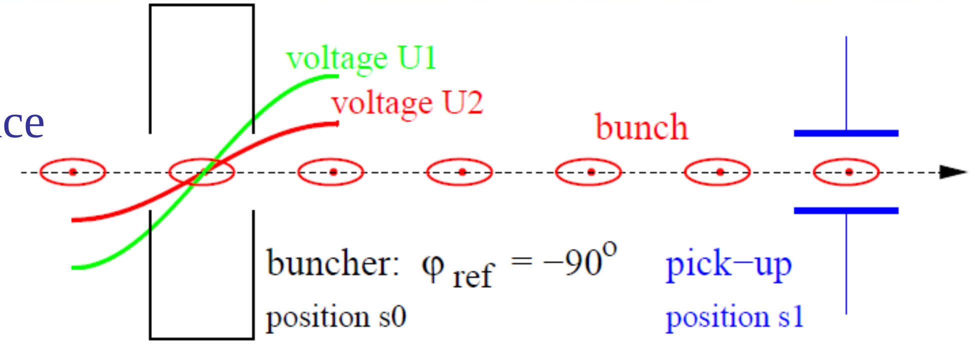
R separates in 3 matrices only **if** the transverse and longitudinal planes do **not** couple,
e.g. no dispersion $\boldsymbol{D = -R_{16} = 0}$

The longitudinal beam matrix $\boldsymbol{\sigma}$ is **then** a 2 x 2 matrix

with bunch length $l_{rms} = \sqrt{\sigma_{55}}$ & momentum spread $\frac{\Delta p}{p} = \delta_{rms} = \sqrt{\sigma_{66}}$

Longitudinal focusing:

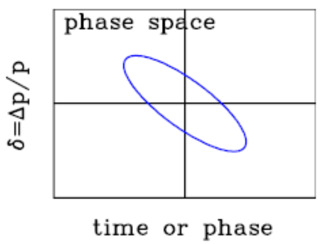
Variation of the bunch shape by a rf-buncher
$\rightarrow$ components 5 and 6 from 6-dim phase-space
Transversal corres.: Quadrupole variation

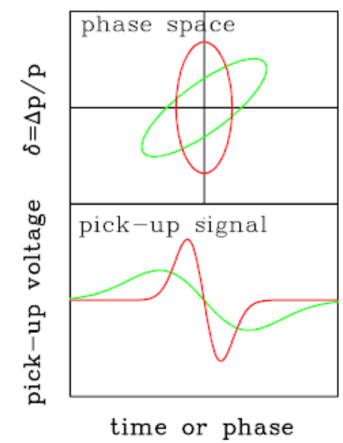


- Transfer matrix of buncher & drift:

$$R_{buncher} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}, \quad R_{drift} = \begin{pmatrix} 1 & L/\gamma^2 \\ 0 & 1 \end{pmatrix}$$

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





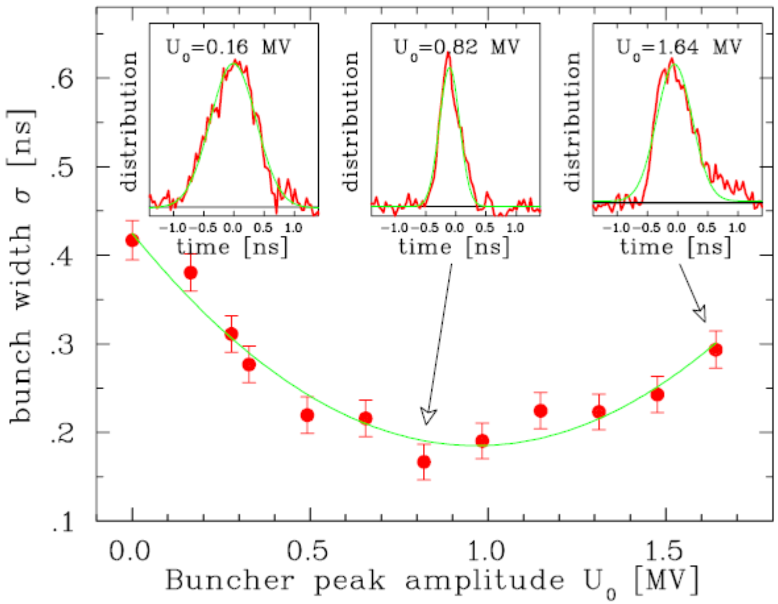
- Variation of buncher amplitude ***U***
  $\Rightarrow$ different bunch width at s_1:
  beam matrix $\Delta t^2_{rms} = \sigma_{55}(1, f)$
- System of redundant linear equations for $\sigma_{ij}(1)$ using **σ(1)=R·σ(0)·R^T**:

$$\begin{aligned} \sigma_{55}(1, f_1) &= R_{55}^2(f_1)\cdot\sigma_{55}(0) + 2R_{55}(f_1)R_{56}(f_1)\cdot\sigma_{56}(0) + R_{56}^2(f_1)\cdot\sigma_{66}(0) && \text{focusing } f_1 \\ &\vdots \\ \sigma_{55}(1, f_n) &= R_{55}^2(f_n)\cdot\sigma_{55}(0) + 2R_{55}(f_n)R_{56}(f_n)\cdot\sigma_{56}(0) + R_{56}^2(f_n)\cdot\sigma_{66}(0) && \text{focusing } f_n \end{aligned}$$

Result of a longitudinal Emittance Measurement

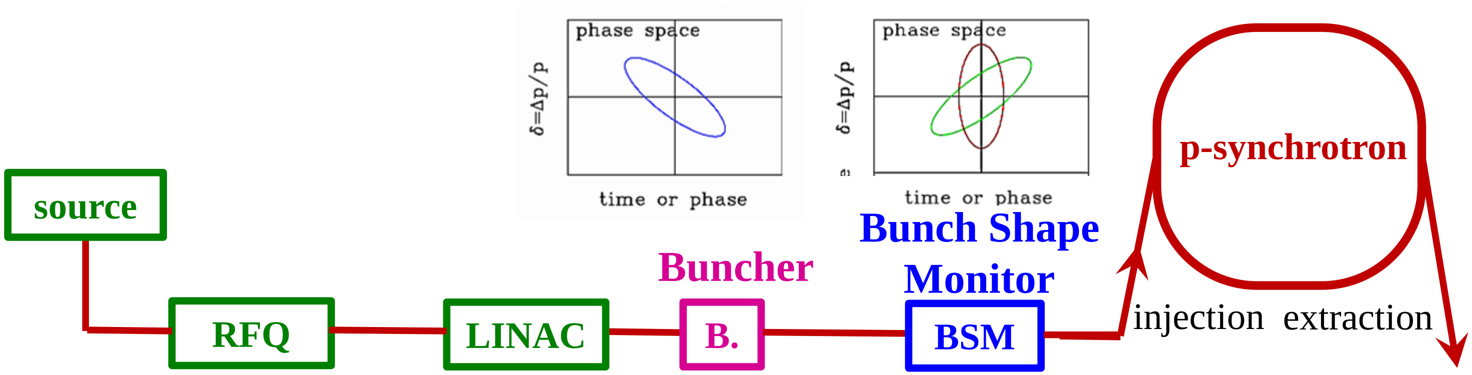
Example GSI LINAC: Voltage variation at buncher for 11.4 MeV/u Ni^{14+} beam, 31 m drift:

- The structure of short bunches can be determined with special monitor
- This example: The resolution is better than 50 ps or 2° for 108 MHz
- Typical bunch length at proton LINACs: $\sigma_{bunch} \approx$ 10 to 300 ps
- Determination of longitudinal emittance possible



Application for synchrotron injection:

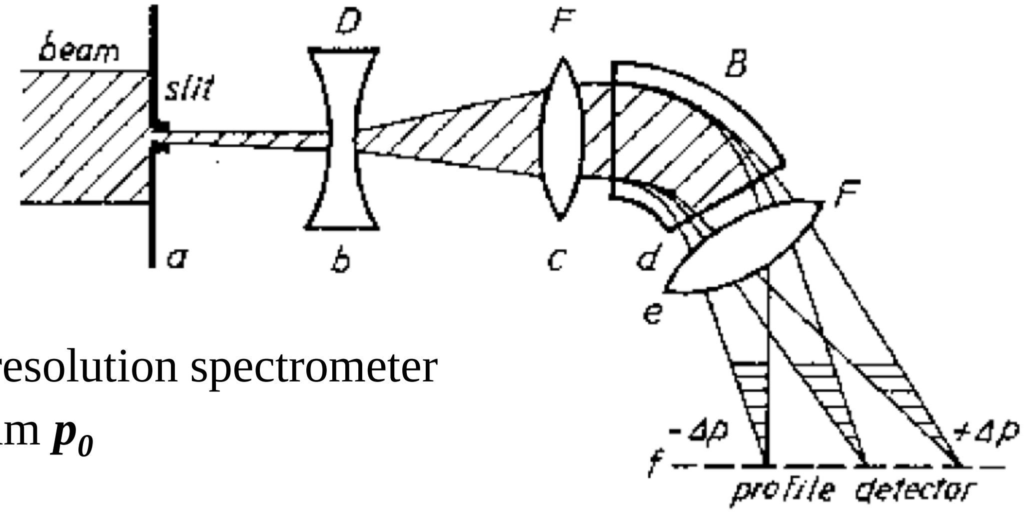
Shaping of longitudinal phase space by buncher
i.e. long bunches ⇔ low momentum spread
to match to the synchrotron long acceptance



Measurement of Energy Spread by magnetic Spectrometer

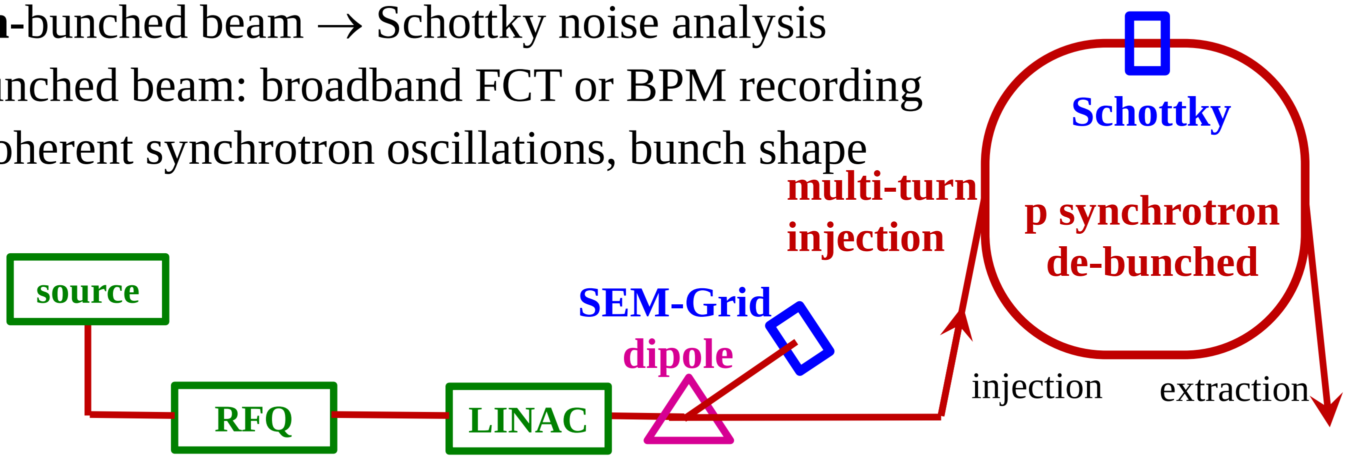
Transfer line: The mom. spread $\delta = \Delta p/p$ can be determined by a magnetic spectrometer: via dispersion, the momentum is shifted to a spatial distance.

An appropriate optic must b e chosen to separate the transverse and longitudinal parameters



However, a synchrotron is a very high resolution spectrometer
Goal: Measurement of central momentum p_0
and momentum spread $\Delta p / p_0$

- **un**-bunched beam → Schottky noise analysis
- bunched beam: broadband FCT or BPM recording
  coherent synchrotron oscillations, bunch shape



Outline:

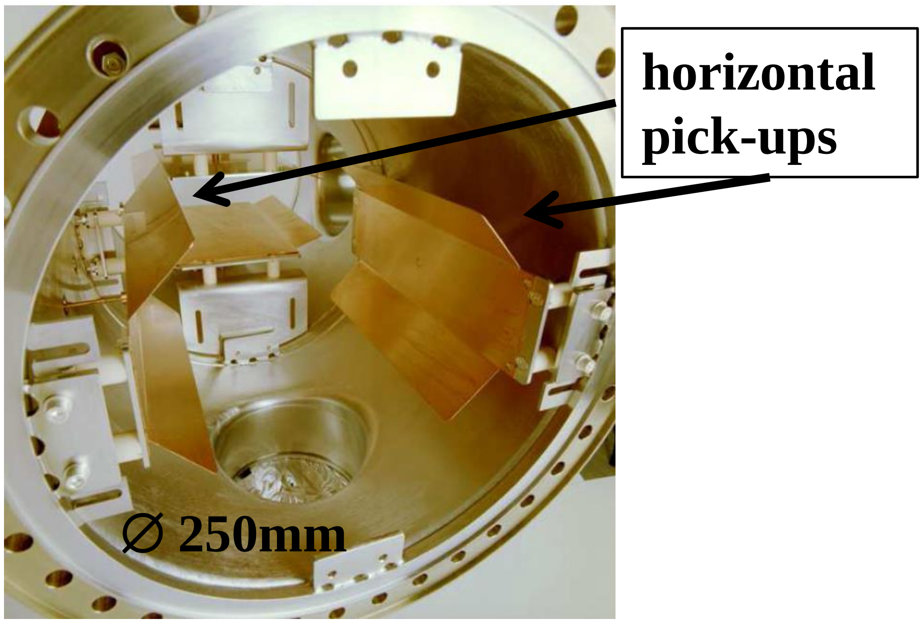
- Proton LINAC: Determination of mean energy & longitudinal emittance used for alignment of cavities phase and amplitude
- **Longitudinal injection matching and Schottky noise analysis**

  Signal generation by repetitive particle passage

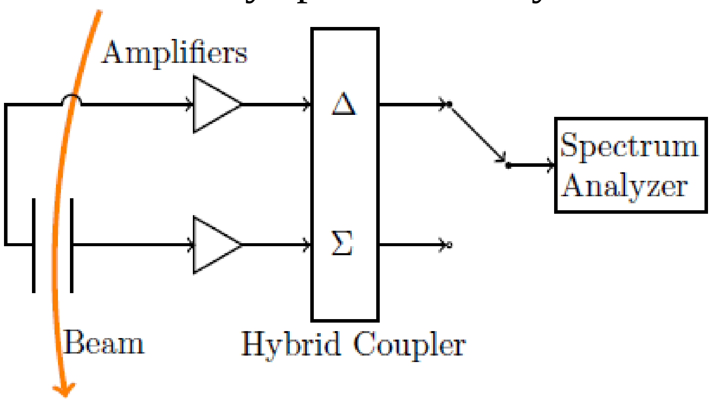
  Used at Hadron synchrotrons for momentum spread analysis for Multi-turn inj.
- Bunch length measurement for relativistic beams
- Summary

Schottky noise analysis is based on the power spectrum
for consecutive passage of the **same** finite number of ions

Schottky pick-up at GSI synchrotron



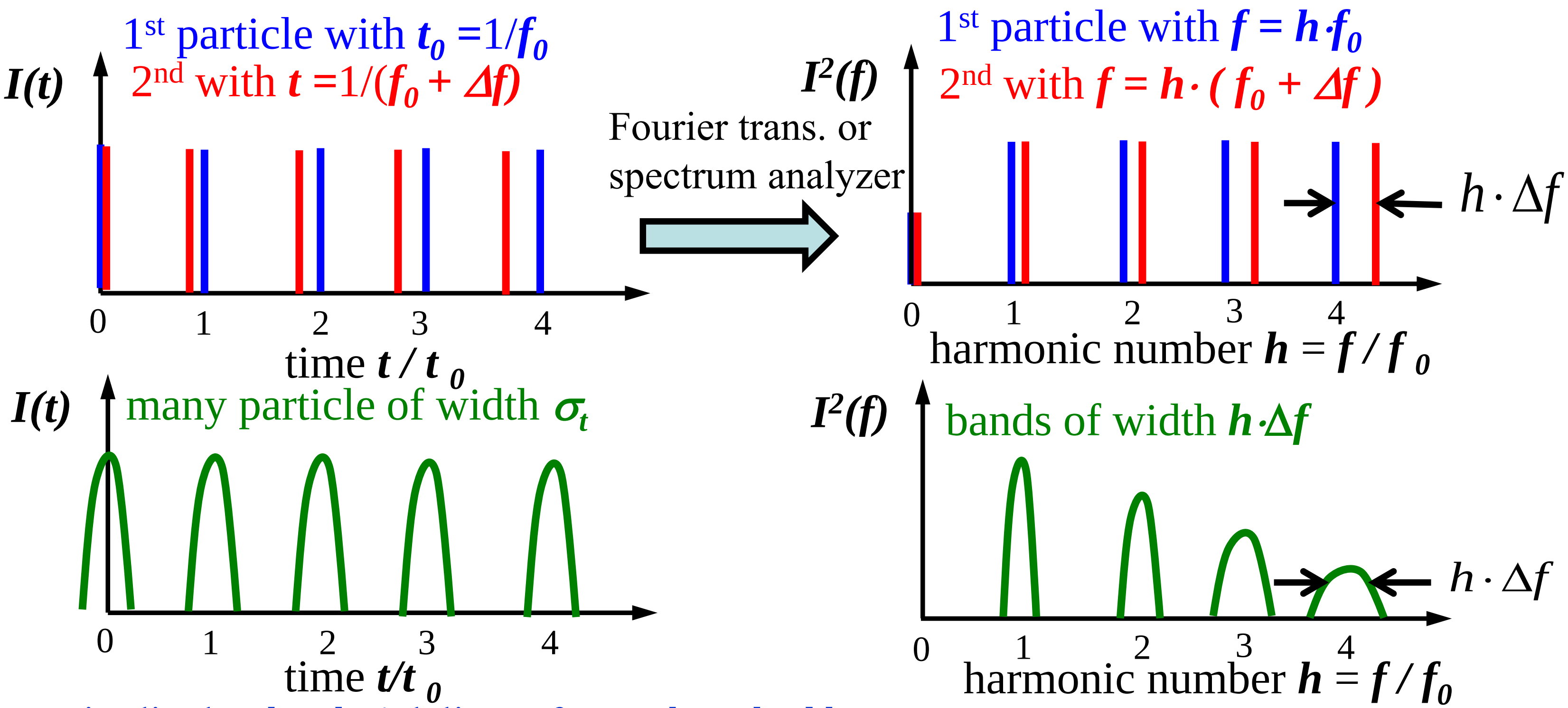
Analog signal processing chain:
- Sensitive broadband amplifier
- Hybrid for sum or difference
- Evaluation by spectrum analyzer



'Longitudinal Schottky' delivers for **un**-bunched beams
- mean revolution frequency ⇒ mean momentum
- momentum spread via

$$\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{f_h} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h f_0}$$

Schottky noise analysis is based on the power spectrum
for consecutive passage of the **same** finite number of ions



'Longitudinal Schottky' delivers for **un**-bunched beams

- mean revolution frequency $\Rightarrow$ mean momentum
- momentum spread via

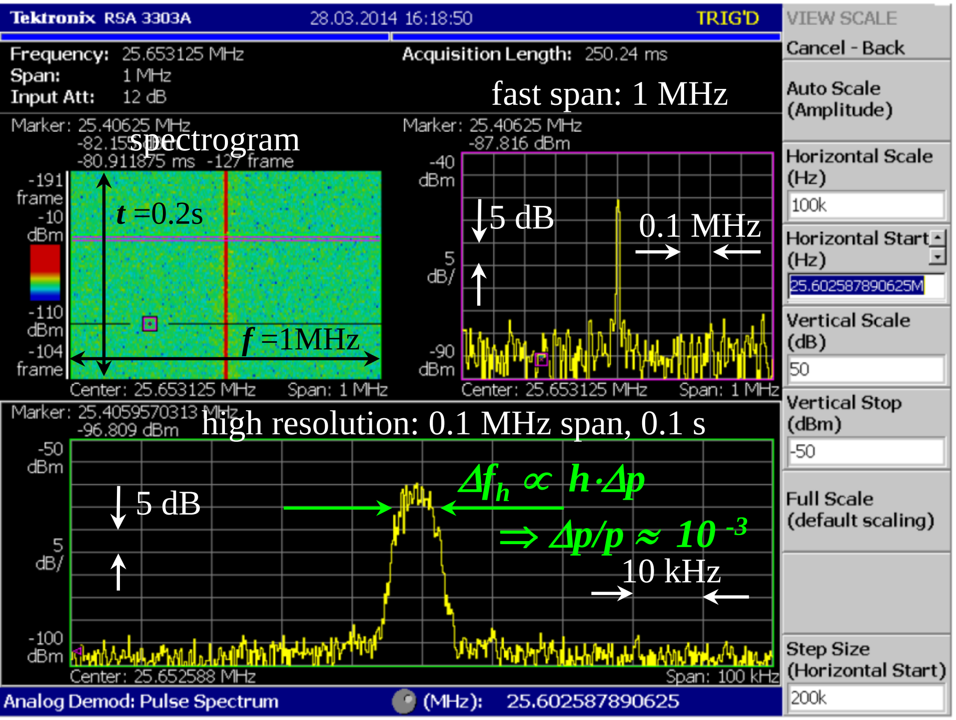
$$\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{f_h} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h f_0}$$

Schottky bands feature:

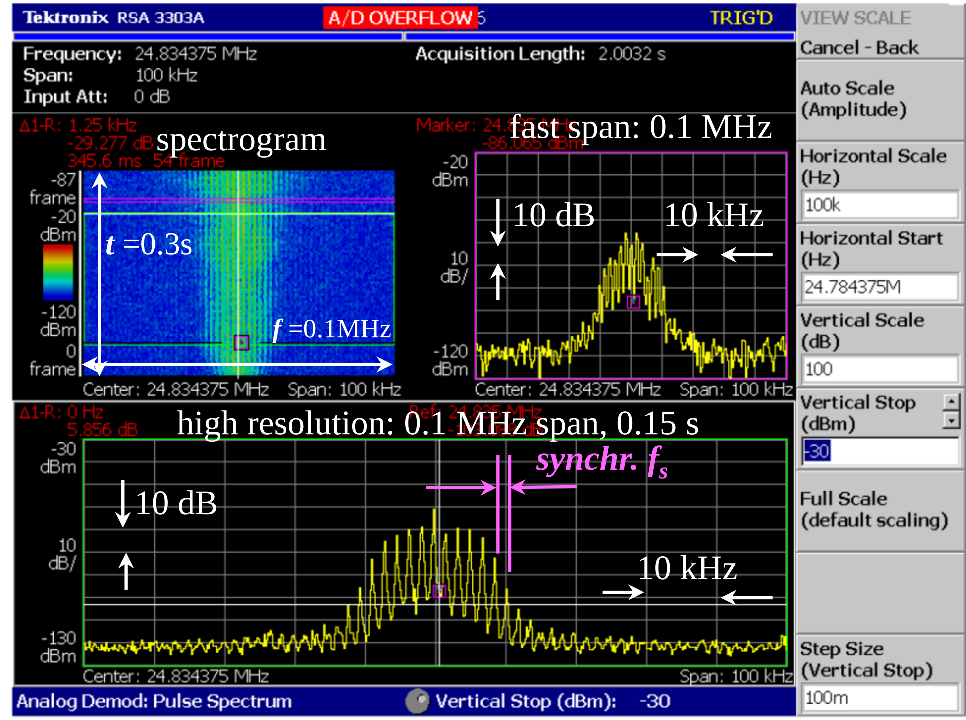
- constant power within each band
- width scales with harmonics ***h***

Longitudinal Schottky Noise Analysis

Example: **Coasting** beam at GSI synchr.



Example: **Bunched** beam at GSI synchr.



Frequent application for coasting beam:

- Injection: matching i.e. f_{center} stable at begin of ramp
- Injection: momentum spread via $\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h\, f_0}$
  as influenced by re-buncher at LINAC
- Extraction: Momentum spread

Application for bunched beam:

- Measurement of synchrotron frequency
- Coarse spectra: Observation during acceleration
- Longitudinal mismatch diagnostics

Remark: Less useful as for coasting beam

Longitudinal Schottky for Momentum Spread $\Delta p/p_0$ Analysis

Momentum spread $\Delta\, p/p_0$ measurement after multi-turn injection & de-bunching of t < 1ms duration to stay within momentum acceptance during acceleration

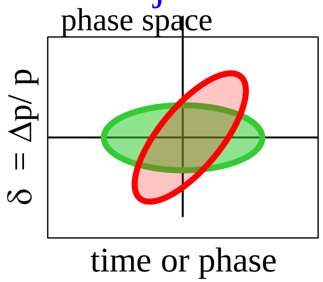
Method: Variation of buncher voltage

i.e. sheering in phase space

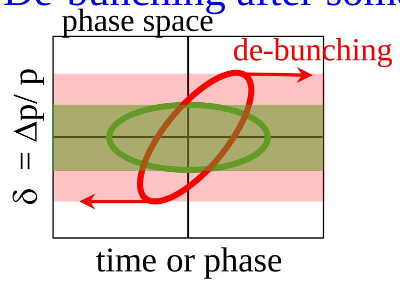
→ minimizing of momentum spread $\Delta\, p/p_0$

→ $\Delta\, p/p_0$ preserves after de-bunching

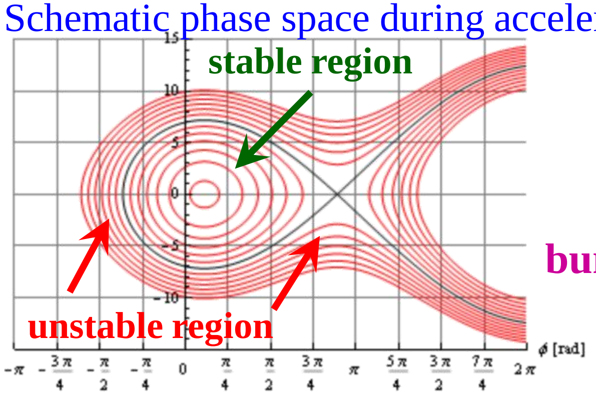
At injection:

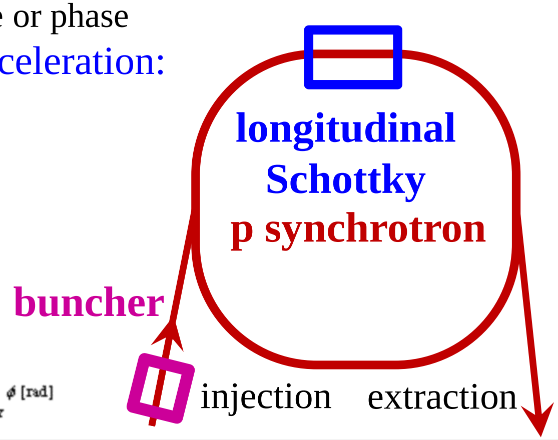


De-bunching after some ms:



Schematic phase space during acceleration:





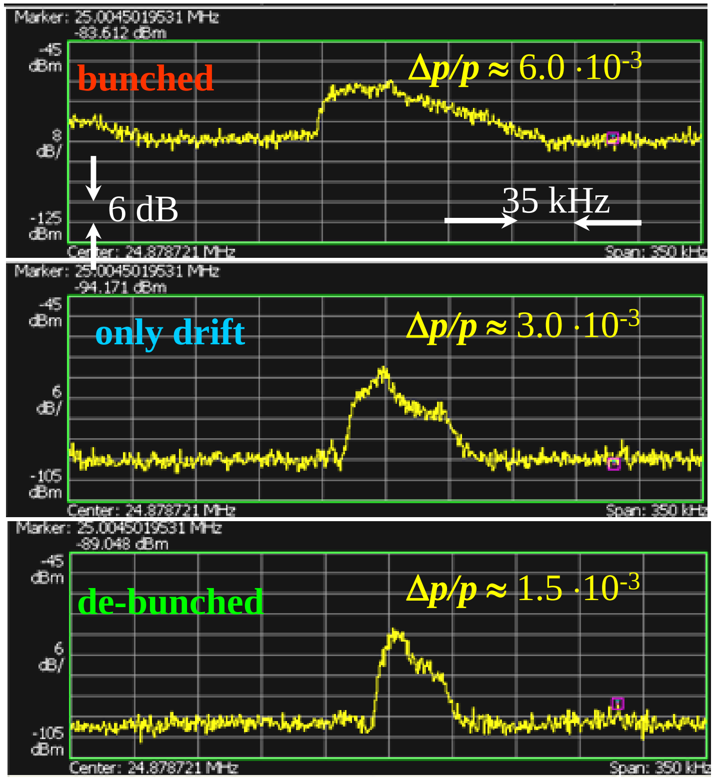
Example: 10^{10} U^{28+} at 11.4 MeV/u

injection plateau 150 ms, η = 0.94

Longitudinal Schottky at harmonics h = 117

Momentum spread variation:

$\Delta p/p \approx (1.5... 6.0) \cdot 10^{-3}$

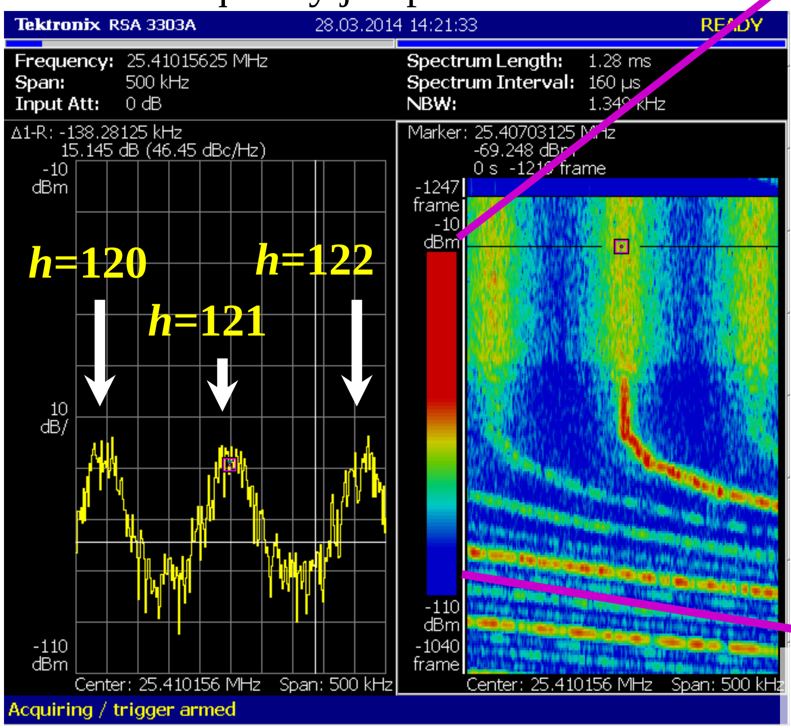


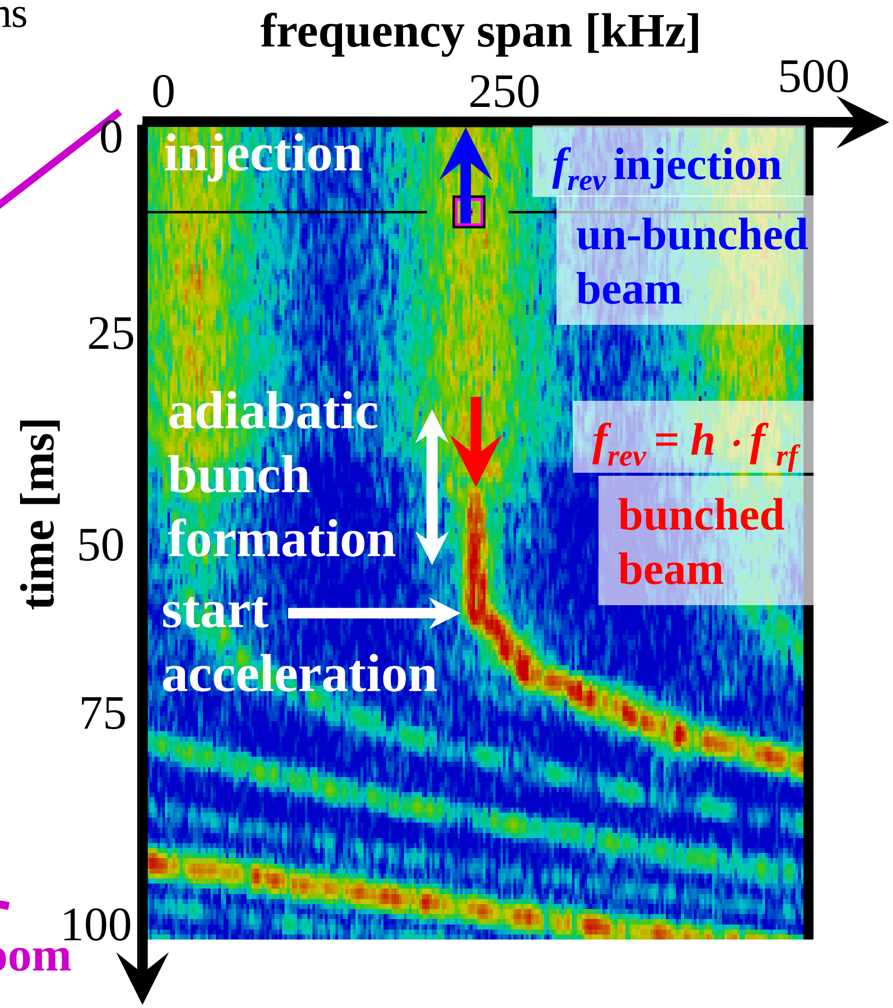
Injection Mismatch: Longitudinal Schottky Noise Analysis

Example for longitudinal Schottky spectrum to check proper acceleration frequency:

- Injection energy given by LINAC settings, here 11.4 MeV/u, β = 15..5 %
- multi-turn injection & de-bunching within ≈ ms
- adiabatic bunch formation & acceleration
- Measurement of revolution frequency f_{rev}
- Alignment of acc. f_{rf} to have $f_{rev} = h \cdot f_{rf}$

i.e. no frequency jump !





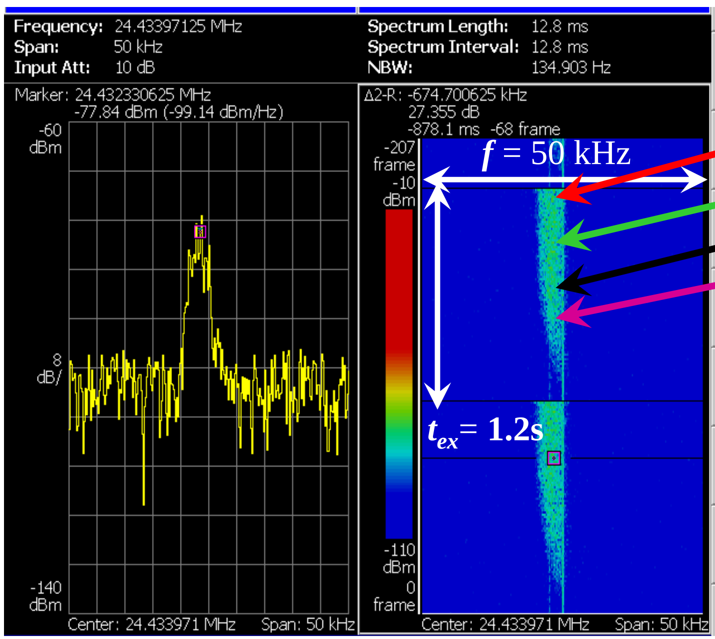
Momentum Variation during Quadrupole-driven Extraction

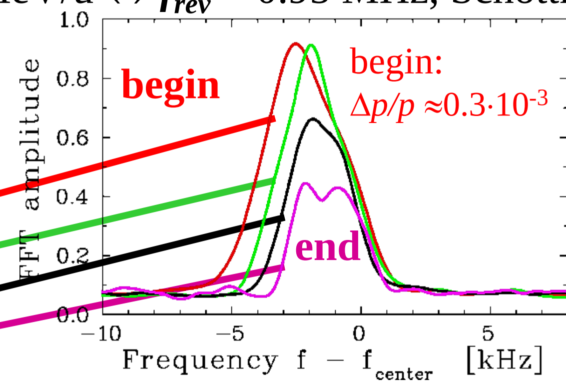
Example for longitudinal Schottky spectrum to visualize slow extraction:

- Momentum spread before extraction here $\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h\, f_0} = 0.3 \cdot 10^{-3}$ (1σ)
- Chromaticity (here ξ=-1.5) i.e. coupling tune $\leftrightarrow$ momentum spread : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$
- Slow extraction by quadrupole variation i.e. momentum dependent extraction

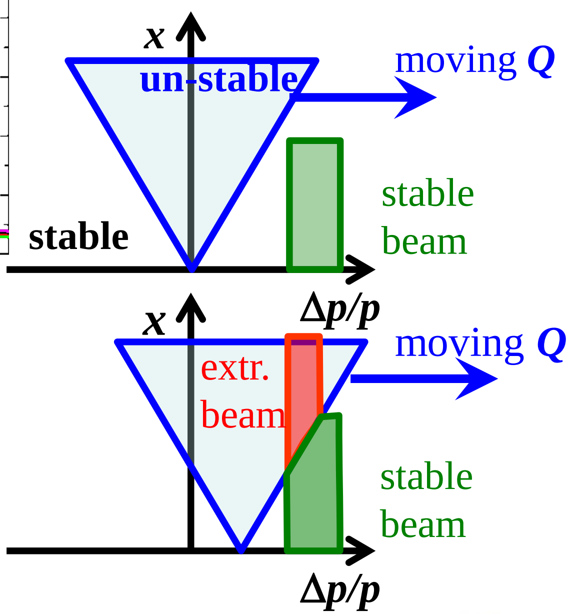
$\Rightarrow$ Lower momentum ions extracted first & variation of extraction angle at dispersive section in transfer

Beam parameter: GSI-synch. C^{6+} at 300 MeV/u $\Leftrightarrow$ f_{rev} = 0.95 MHz, Schottky for h =26, Δf = 1.6 kHz (1σ)

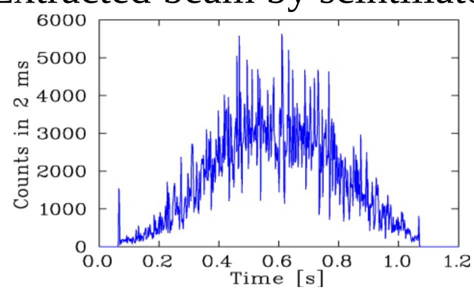




Steinbach diagram:



Extracted beam by scintillator:

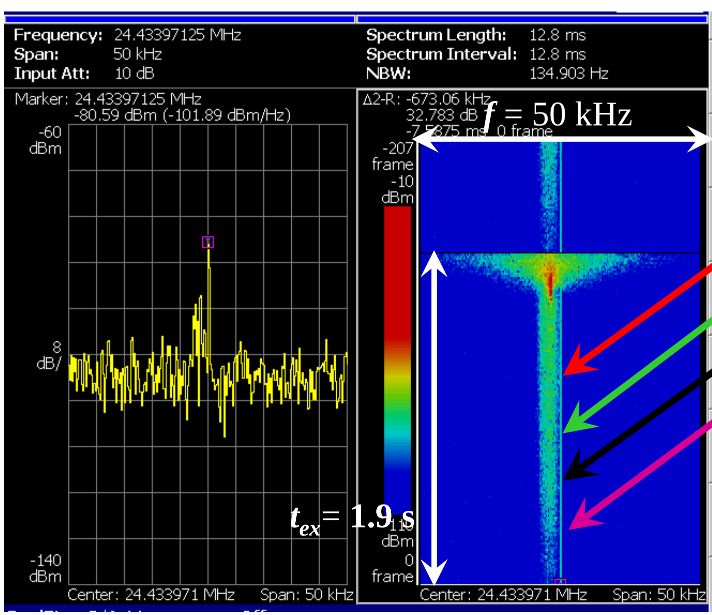


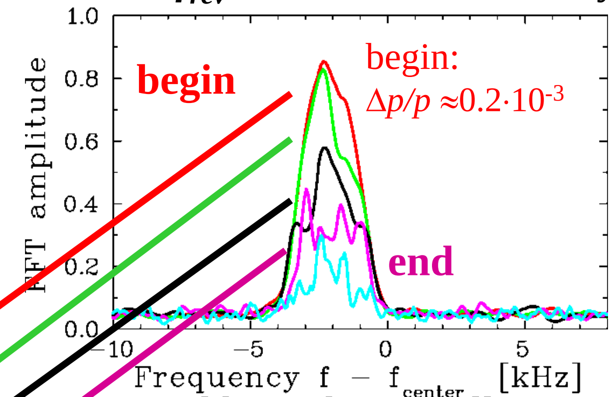
Example for longitudinal Schottky spectrum to visualize slow extraction:

- Momentum spread before extraction here $\frac{\Delta p}{p_0} = -\frac{1}{\eta} \cdot \frac{\Delta f_h}{h\, f_0} = 0.2 \cdot 10^{-3}$ (1σ)
- Chromaticity (here ξ=-1.5) i.e. coupling tune ↔ momentum spread : $\frac{\Delta Q}{Q} = \xi \cdot \frac{\Delta p}{p}$
- Slow extraction by knock-out extraction i.e. only trans. amplitude growth ⇒ **no** momentum dependent

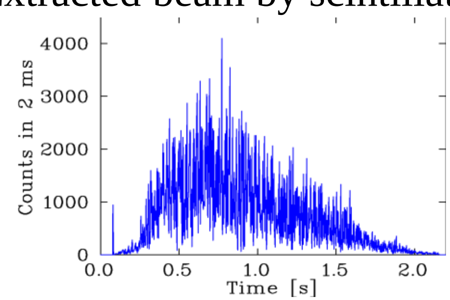
⇒ Lower momentum ions extracted first & variation of extraction angle at dispersive section in transfer

Beam parameter: GSI-synch. C^{6+} at 300 MeV/u ⇔ f_{rev} = 0.95 MHz, Schottky for h =26, Δf = 1.0 kHz (1σ)

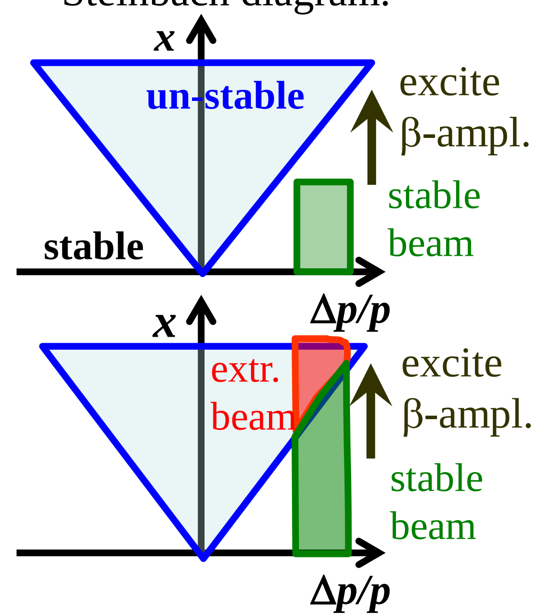




Extracted beam by scintillator:



Steinbach diagram:



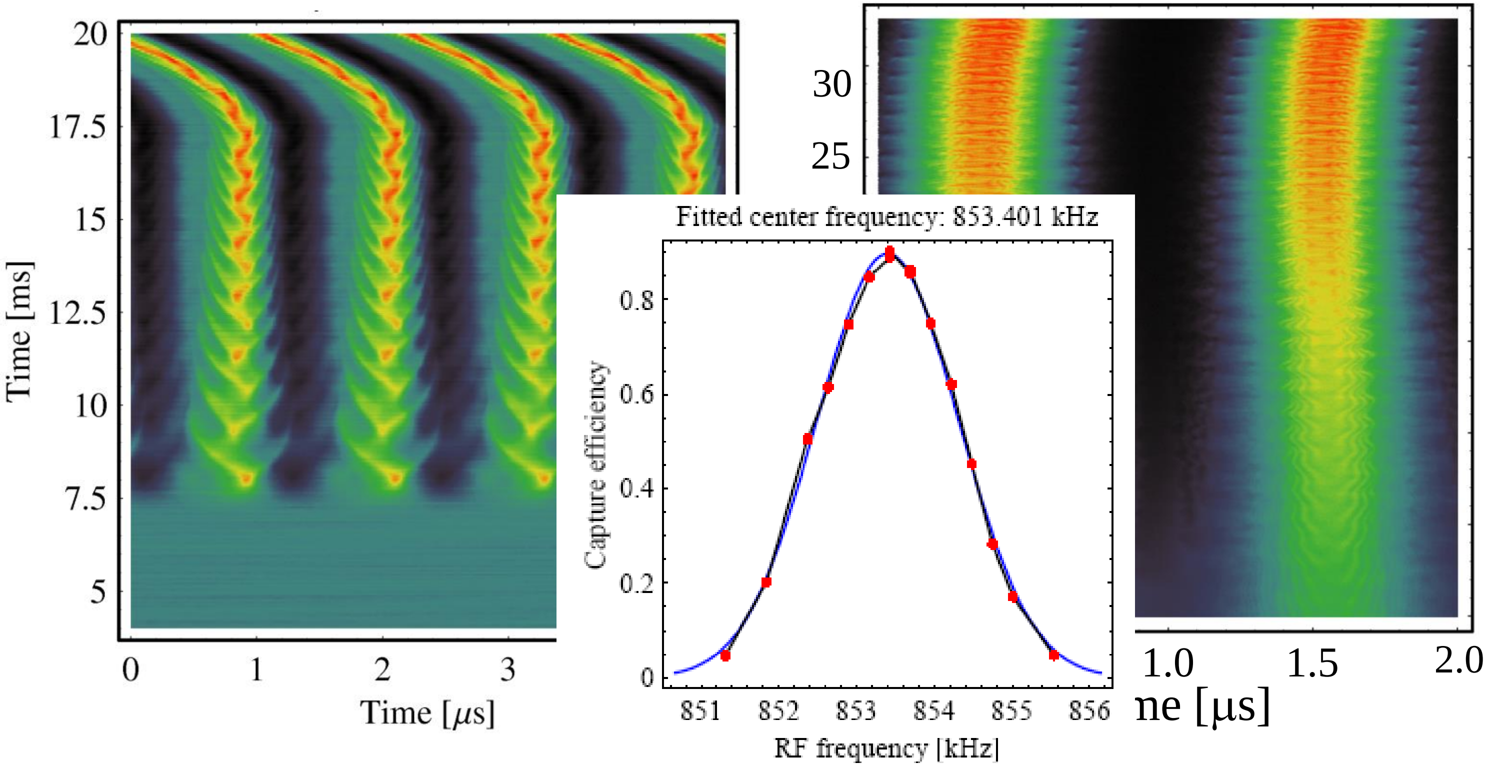
Broadband longitudinal Bunch Shape Observation by FCT

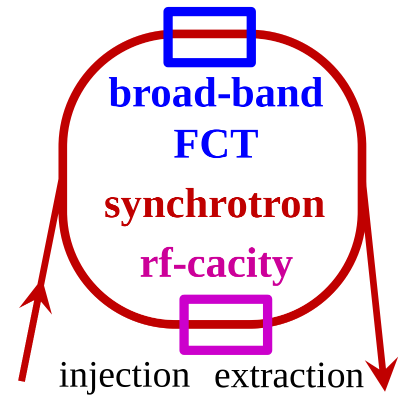
Example: After multi-turn injection, the **bunch formation** is critical to avoid coherent synchrotron oscillations → emittance enlargement

Observation by a FCT or BPM sum signal in broad-band mode and adaption of f_{rf}

f_{rf} shift by 0.2% of nominal value ⇒ Coherent oscillation

Matched f_{rf} ⇒ no oscillation





Same type of alignment required for transfer between synchrotrons

Required accuracy here: Δf_{rf} = 1 kHz or $\Delta f_{rf} / f_{rf}$ = 0.1%

Courtesy H. Damerau, CERN

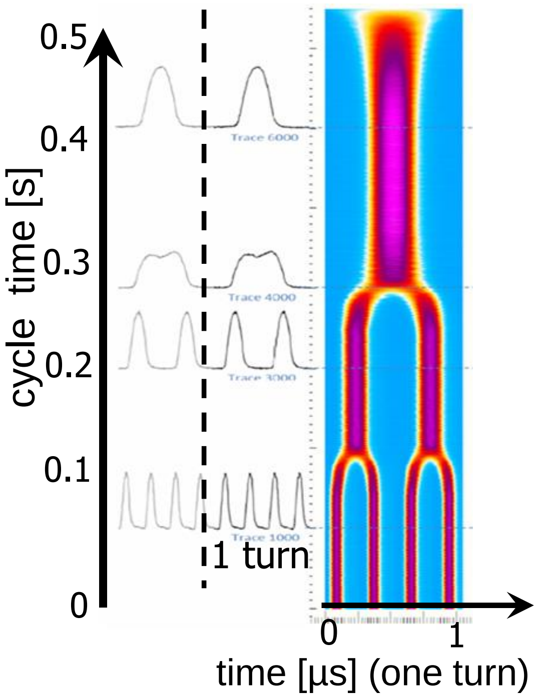
Longitudinal Bunch Diagnostics inside Synchrotron using FCT

Acceleration and bunch 'gymnastics' are performed **inside** synchrotrons
$\Rightarrow$ different beam parameter for fast, single turn extraction

Measurement within synchrotron because bunch shape is constant during transport in most cases

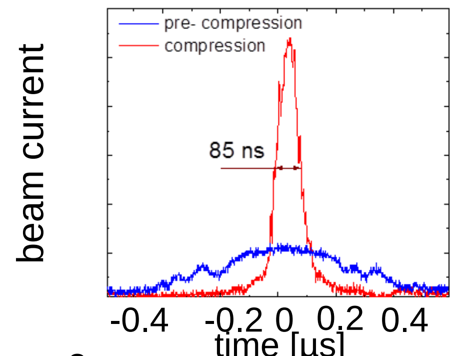
Example: Transfer line L=100m, β=1, $\frac{\Delta p}{p} = 2 \cdot 10^{-3} \rightarrow \Delta t = \frac{\Delta p}{p} \cdot t_{drift} = \frac{\Delta p}{p} \cdot \frac{L}{\beta c} = 0.7 \text{ ns} \ll \sigma_{bunch}$

Example: Bunch merging at upper flattop using 2 cavities at GSI synchrotron
Beam: 10^9 U^{73+} at 600 MeV/u, FCT

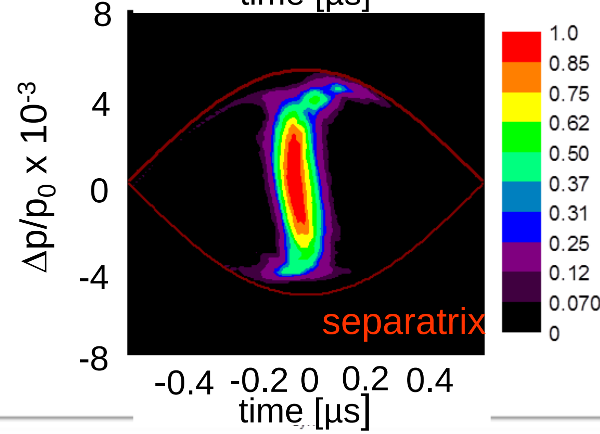


Courtesy H. Klingbeil, U. Hartel, et al. GSI

Example: Bunch shape for 'bunch compression' prior to extr.
Beam: U^{73+} at 300 MeV/u at GSI synchrotron



After acceleration before & after bunch compression



Tomographic reconstruction of longitudinal phase space depicted for min. bunch width

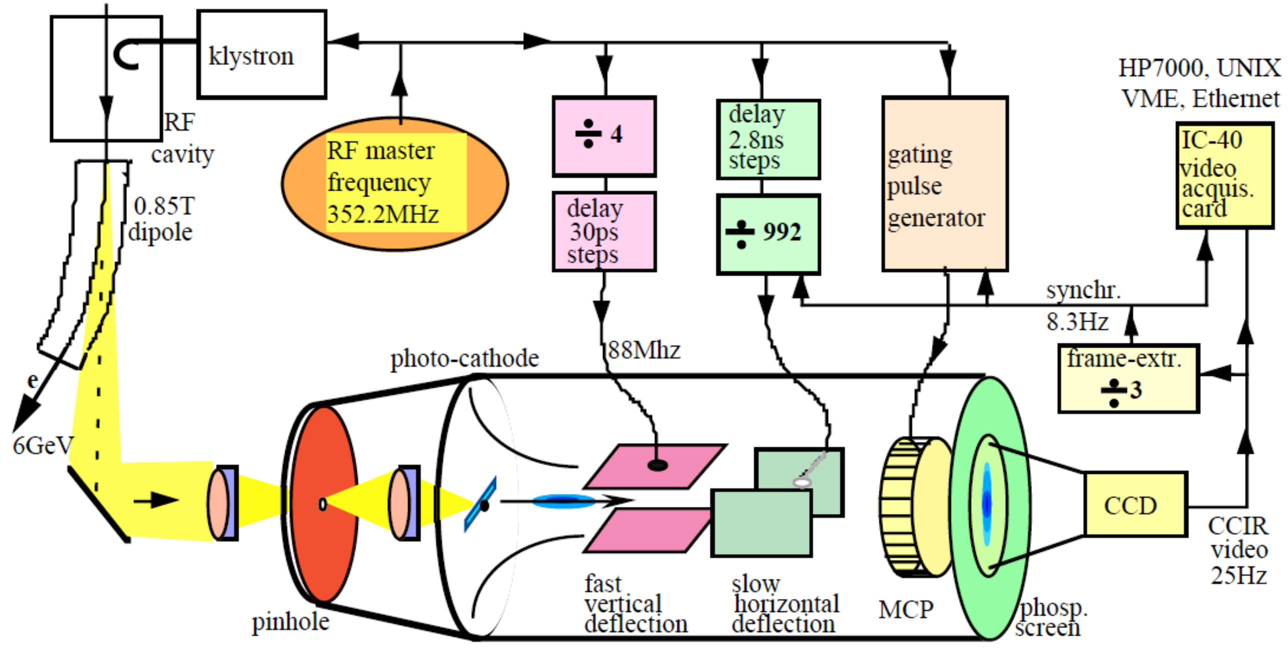
Courtesy O. Chroniy, GSI

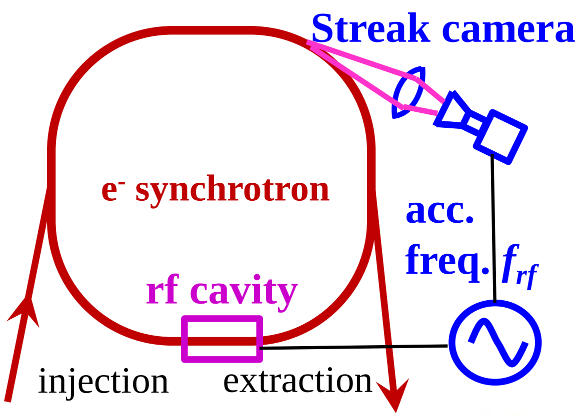
Outline:

- Proton LINAC: Determination of mean energy & longitudinal emittance
  used for alignment of cavities phase and amplitude
- Longitudinal injection matching and Schottky noise analysis
  Signal generation by repetitive particle passage
  Used at Hadron synchrotrons for momentum spread analysis for Multi-turn inj.
- **Bunch length measurement for relativistic beams**
  Synchrotron light monitor used together with streak camera for long. matching
- Summary

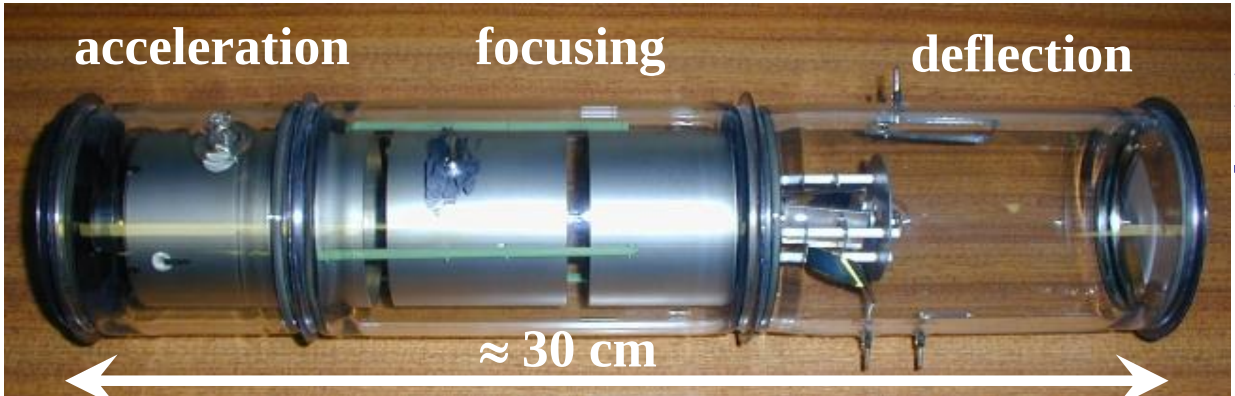
Electron bunches are too short (σ_t < 300 ps) to be covered by the bandwidth of pick-ups (f < 1 GHz ⇔ t_{rise} >300 ps) for structure determination.

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



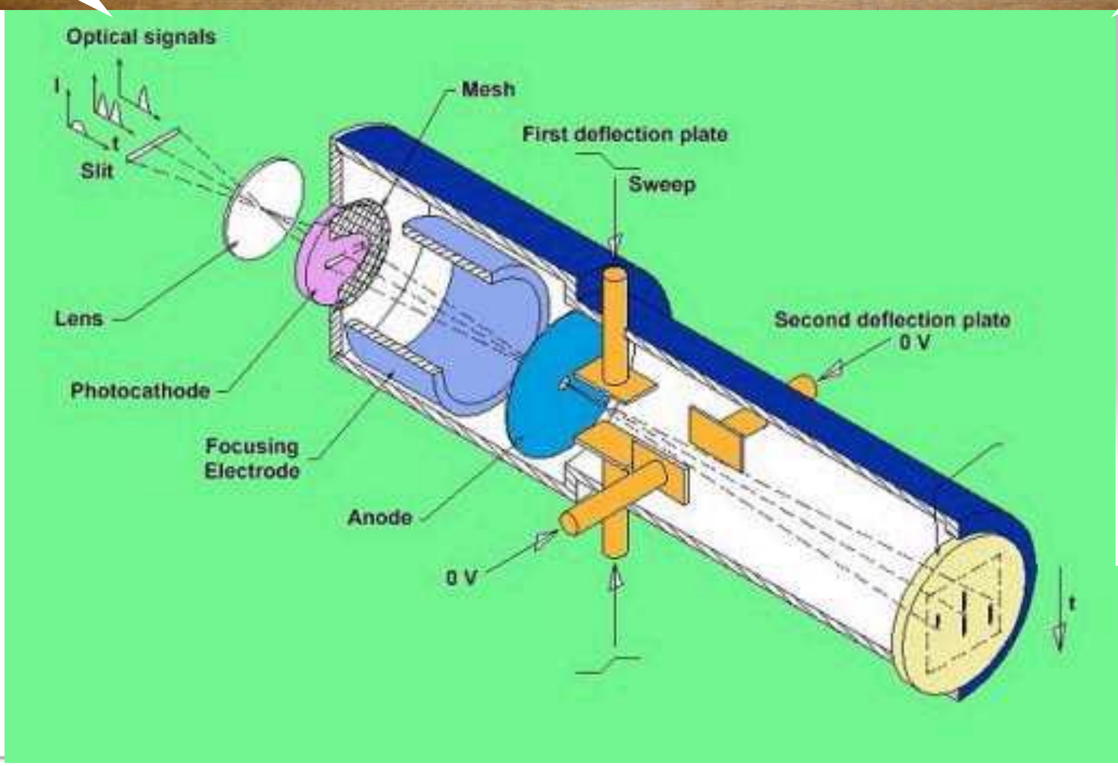


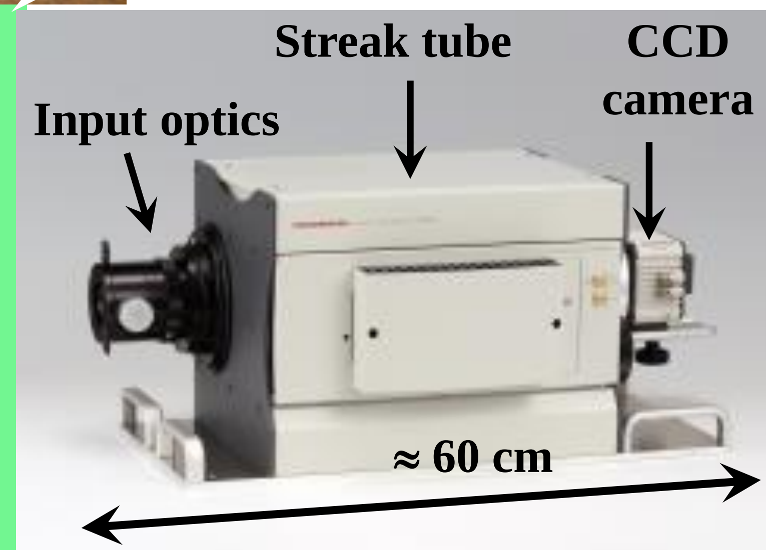
Technical Realization of Streak Camera

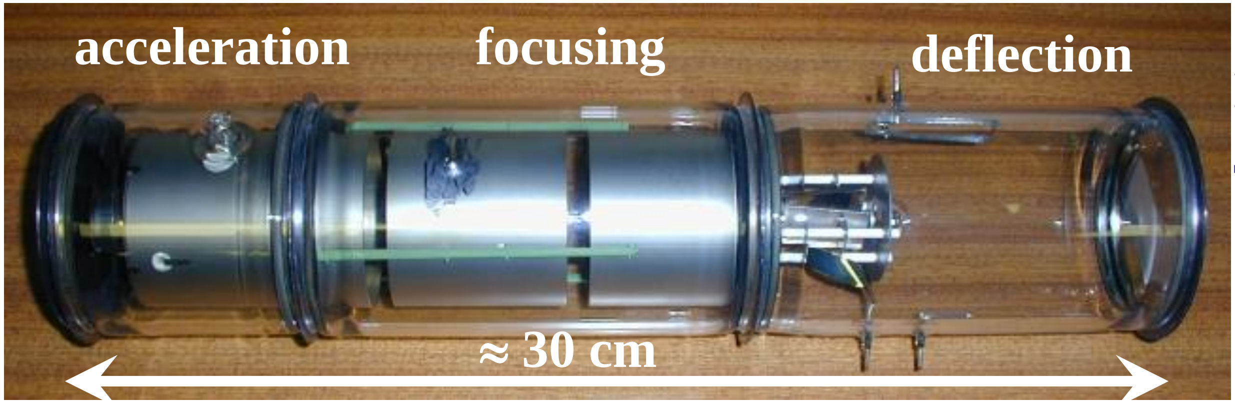


Hardware of a streak camera

Time resolution down to 0.5 ps:

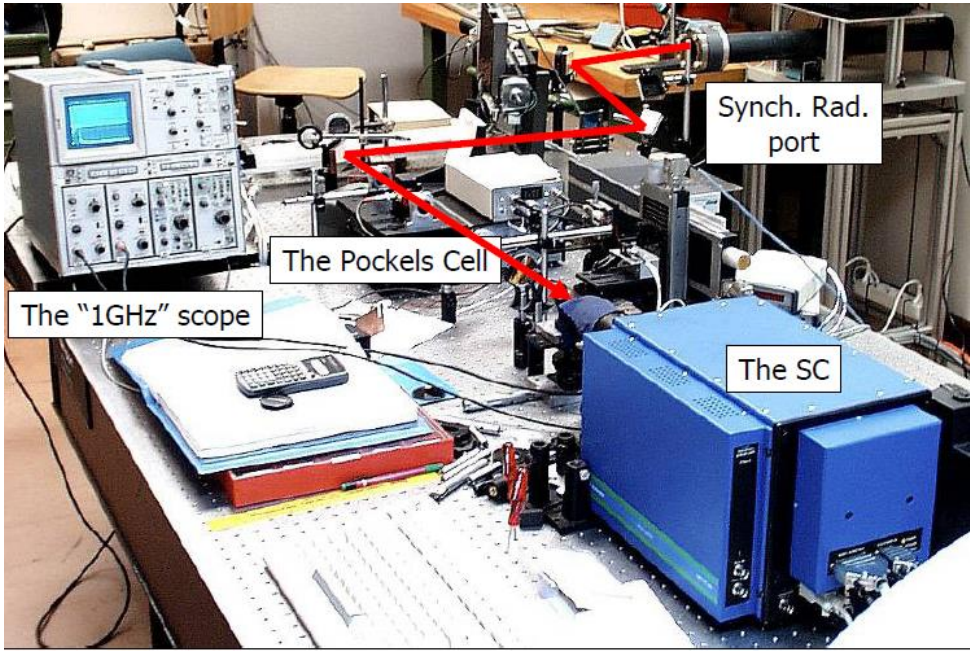




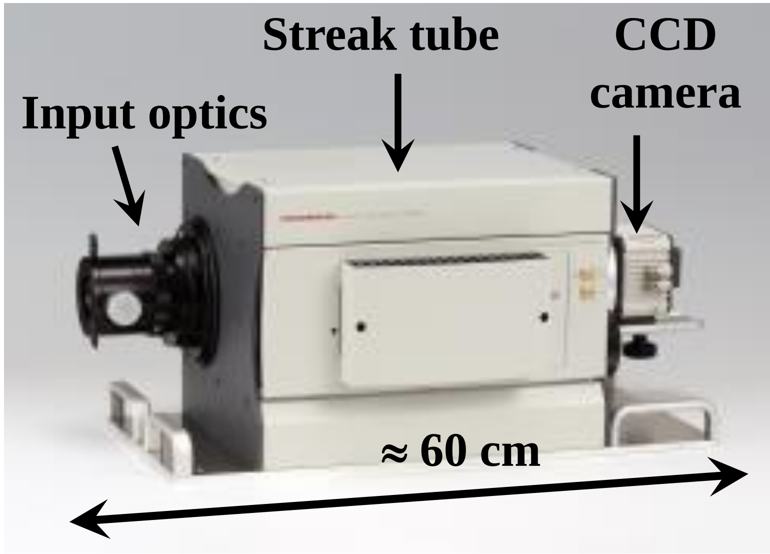


Hardware of a streak camera

Time resolution down to 0.5 ps:



The Streak Camera setup at ELETTRA, Trieste, Italy



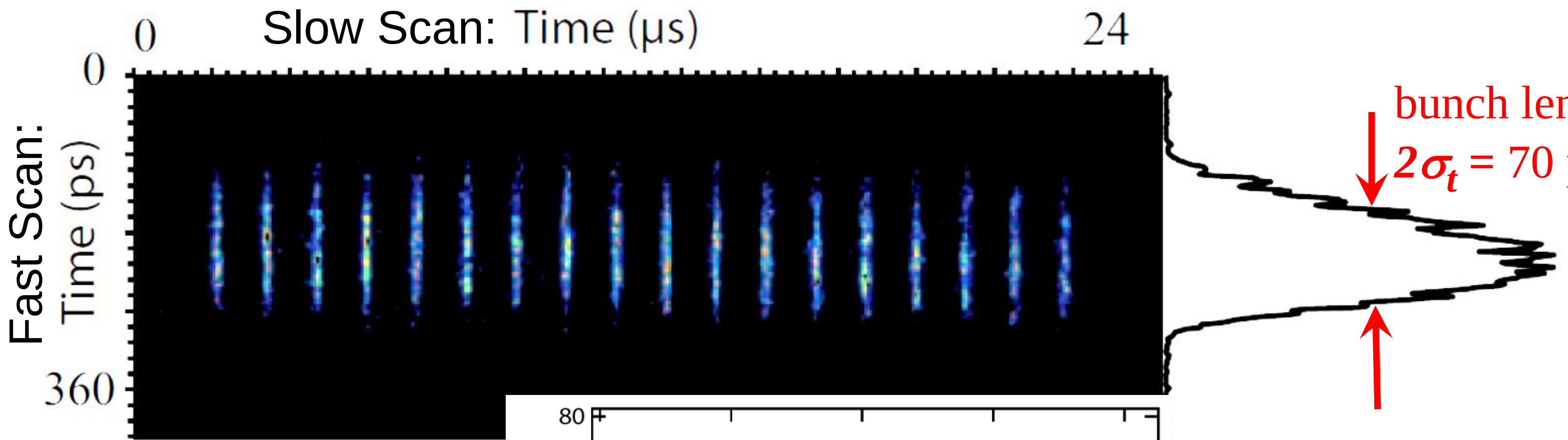
Results of Bunch Length Measurement by a Streak Camera

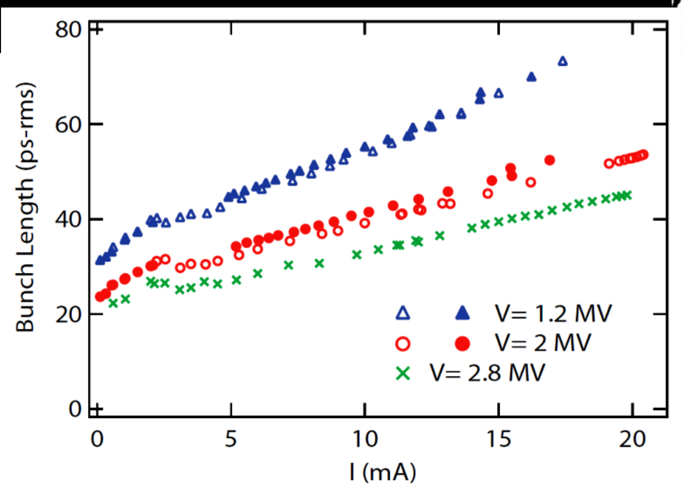
The streak camera delivers a fast scan in vertical direction (here 360 ps full scale)

and a slower scan in horizontal direction (24 μs).

Example: Bunch length at the synchrotron light source SOLEIL for U_{rf} = 2 MV

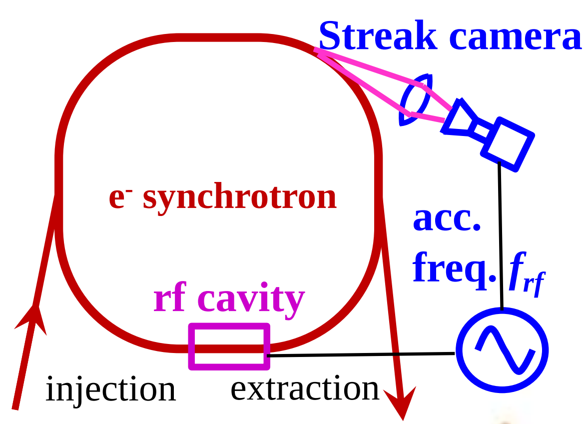
for slow direction 24 μs and scaling for fast scan 360 ps: measure σ_t = 35 ps.





Short bunches are desired by the users

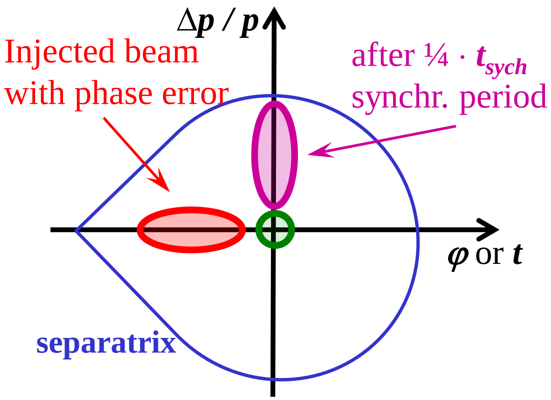
Example: Bunch length σ_t as a function of stored current (i.e. space charge de-focusing) at SOLEIL



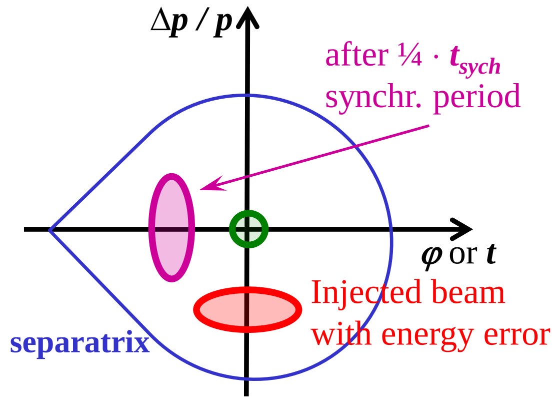
Courtesy of M. Labat et al., DIPAC'07

Injection Mismatch at ALS Electron Ring

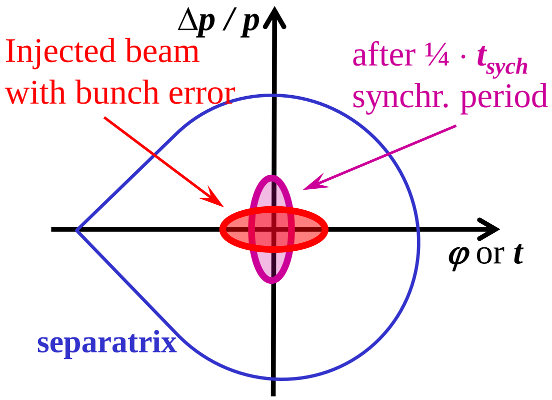
Injection mismatch in phase:



Injection mismatch in phase & energy:



Mismatch in bunch length:

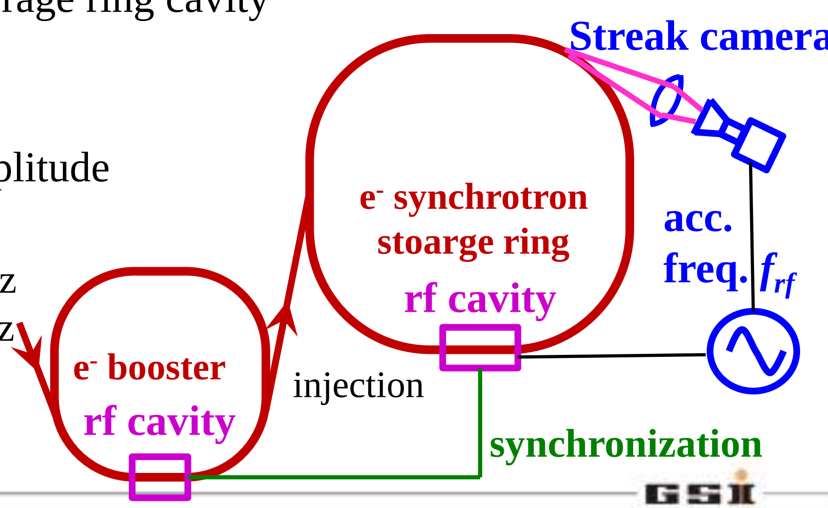


Caused by:
Phase error between
booster cavity ↔ storage ring cavity
Cure:
Adjustment of
cavity phase synchronization
& timing for kicking

Caused by:
Phase & frequency error between
booster cavity ↔ storage ring cavity
Cure:
Adjustment of
cavity phase and amplitude

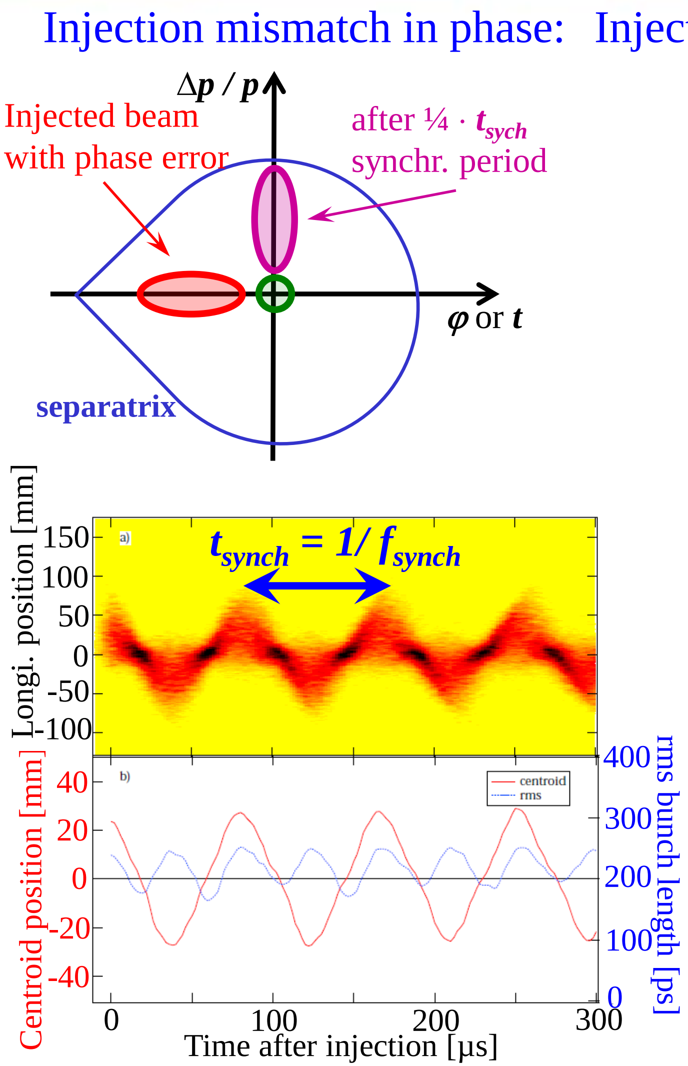
Caused by:
combined errors

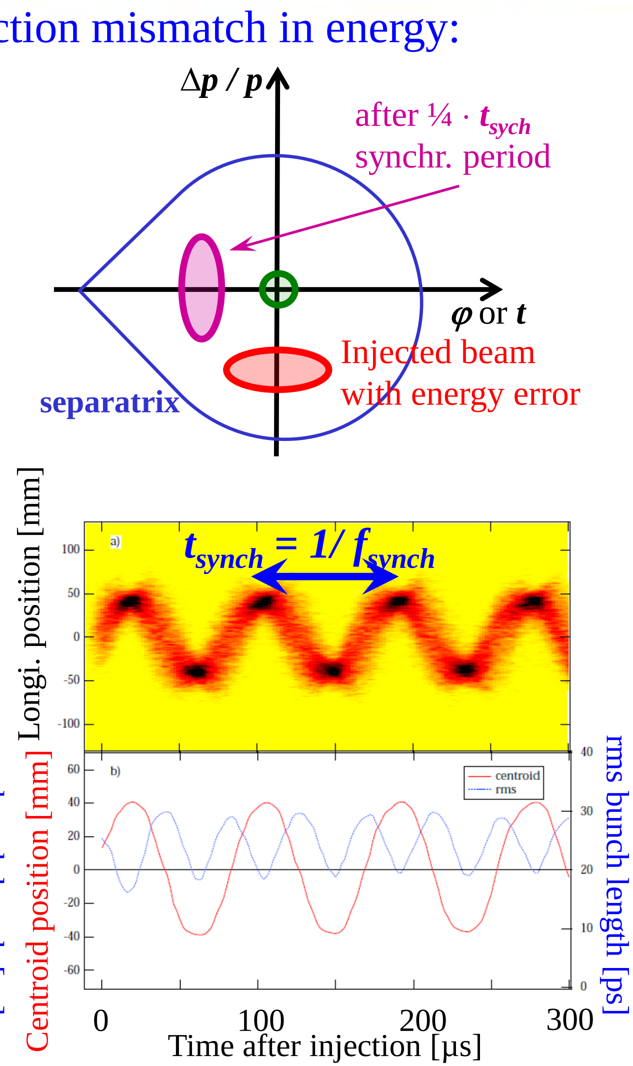
ALS (Berkeley): E_{in} = 1.5 GeV
f_{rf} = 499.7 MHz
f_{synch} = 11.4 kHz

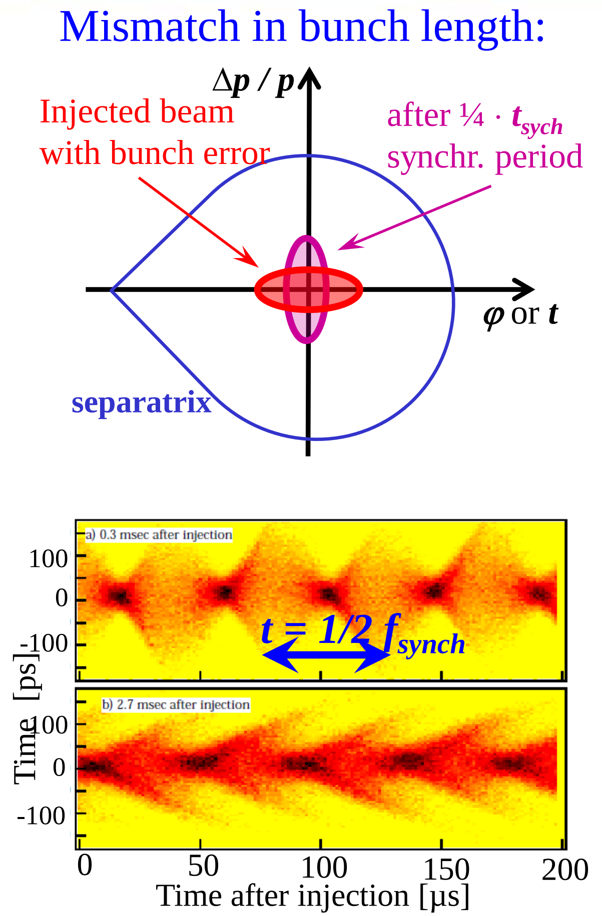


Courtesy of J.M. Bryd et al., PAC'99
& http://escholarship.org/uc/item/8k6677nw

Injection Mismatch at ALS Electron Ring observed by Streak Camera







Courtesy of J.M. Bryd et al., PAC'99 and http://escholarship.org/uc/item/8k6677nw

Summary of longitudinal Measurements

Devices for bunch length and momentum spread measurements:

Broadband pick-ups:
- position relative to rf, mean energy
- emittance at synchrotron via tomography

  requirement: bunches longer than pick-up or $\beta \approx c$

Injection matching:
- for **de**-bunched beam: momentum spread via long. Schottky Spectra
- for bunched beam: broadband observation of synch. oscillations

Streak cameras:
- time resolved monitoring of synchrotron radiation

  $\rightarrow$ for relativistic e^--beams, t_{bunch} < 1 ns, injection matching

  reason: too short bunches for rf electronics.

Thank you very much for your attention!

General Reading on Beam Instrumentation

- D. Brandt (Ed.), *Beam Diagnostics for Accelerators*, Proc. CERN Accelerator School CAS, Dourdan, CERN-2009-005, 2009.
- Proceedings of several CERN Acc. Schools (introduction & advanced level, special topics).
- V. Smaluk, *Particle Beam Diagnostics for Accelerators: Instruments and Methods*, VDM Verlag Dr. Müller, Saarbrücken 2009.
- P. Strehl, *Beam Instrumentation and Diagnostics*, Springer-Verlag, Berlin 2006.
- M.G. Minty and F. Zimmermann, *Measurement and Control of Charged Particle Beams*, Springer-Verlag, Berlin 2003.
- S-I. Kurokawa, S.Y. Lee, E. Perevedentev, S. Turner (Eds.), *Proceeding of the School on Beam Measurement*, Proceedings Montreux, World Scientific Singapore (1999).
- P. Forck, *Lecture Notes on Beam Instrumentation and Diagnostics*, JUAS School, JUAS Indico web-site.
- Contributions to conferences, in particular to **I**nternational **B**eam **I**nstrumentation **C**onference IBIC.