BPM System Design

Invited tutorial at IBIC 2015, Melbourne

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With most slides from:

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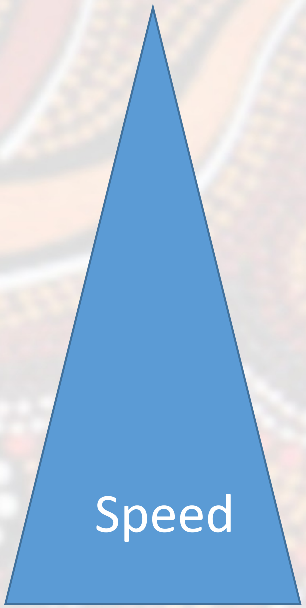
David Rubin (Cornell), M.Tejima (KEK)

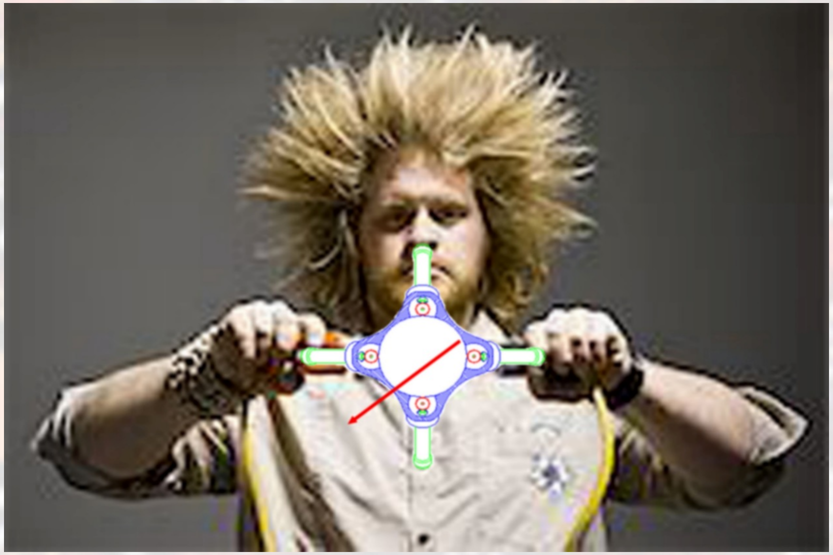
Outline

- Principle, Applications of BPMs
- Functional Specifications (FS)
- Sensors + Sensor Signals
- Electronics
- Synchronization, accelerator timing
- From precision to accuracy
- Outlook
- Not covered: Simulation Tools, Managerial Considerations



Introduction

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

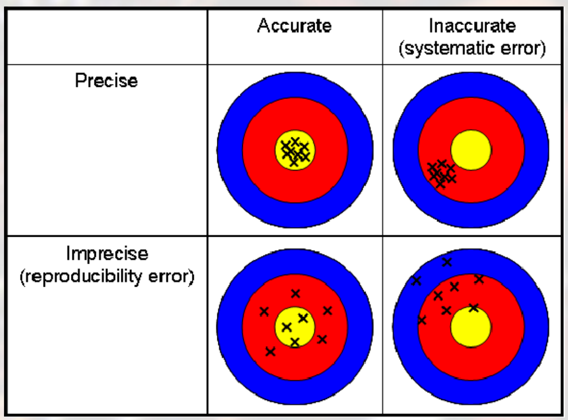


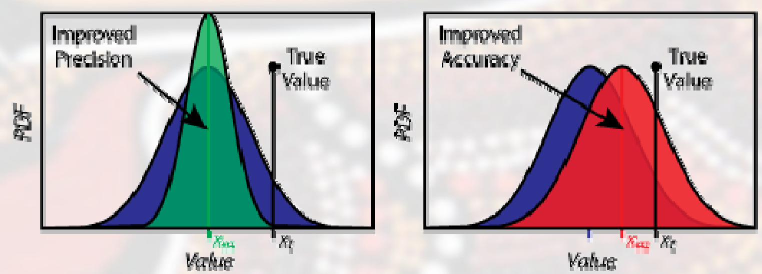
Application of BPMs

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

Accuracy, Precision, Resolution

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





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

Functional Specification (FS)

- Make sure you have this (in writing) before you start developing.
  Initiative normally comes from the Instrument responsible, FS has to be written by future users of instrument.
- FS needs to contain
  - beam parameters,
  - modes of operation,
  - required accuracy, precision, resolution
  - expected frequency of usage (i.e. wire scanners)
  - specifications for control software and data analysis tools
- Leads to an Engineering Specification (ES) produced by instrument specialist.
- ES and FS represent a “contract” between producer and user.
- Examples: http://sl-div-bi.web.cern.ch/sl-div-bi/LHC/ParamAndLayouts/Doc/FuncSpec.htm

Outline

- Principle, Applications of BPMs
- Functional Specifications (FS)
- Sensors + Sensor Signals: capacitive sensors
- Electronics
- Synchronization, accelerator timing
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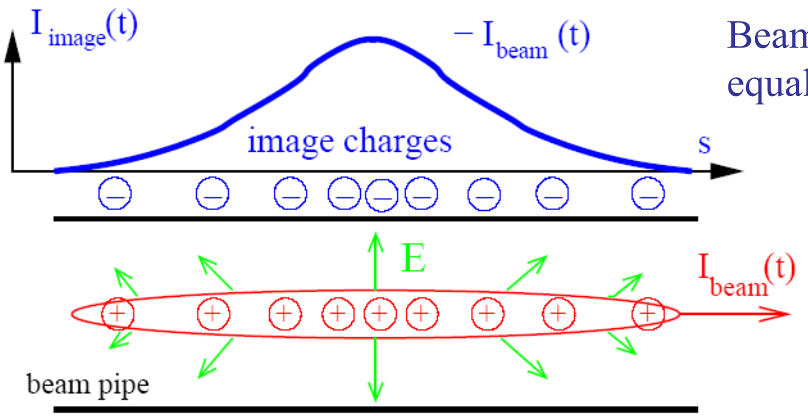
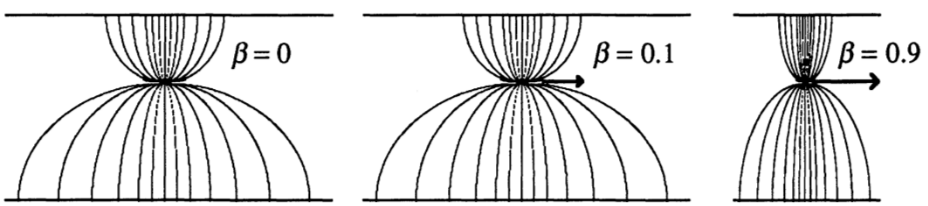
The image current at the vacuum wall is monitored on a high frequency basis
i.e. the ac-part given by the bunched beam.

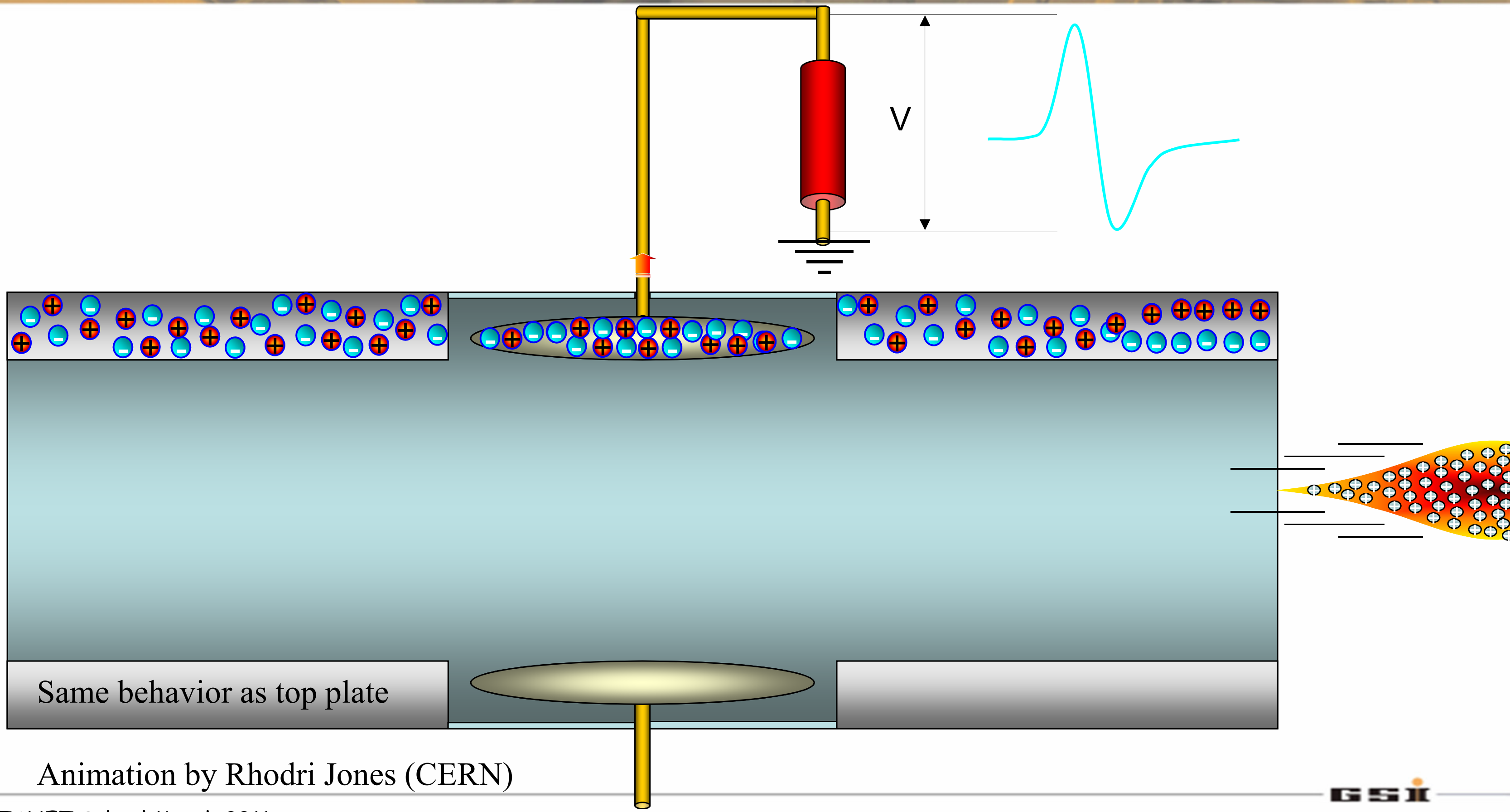


Beam Position Monitor **BPM** equals Pick-Up **PU**

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

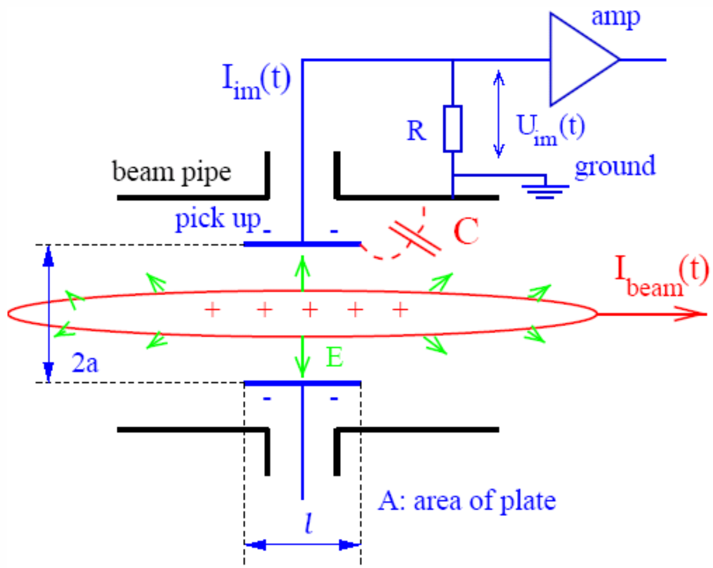


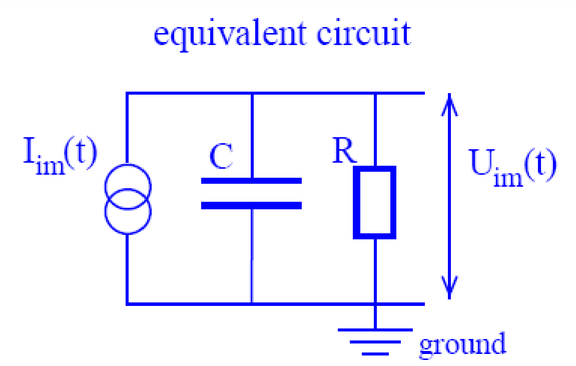
Principle of Signal Generation of capacitive BPMs



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:

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

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

The high-pass characteristic for typical synchrotron BPM:

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

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

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

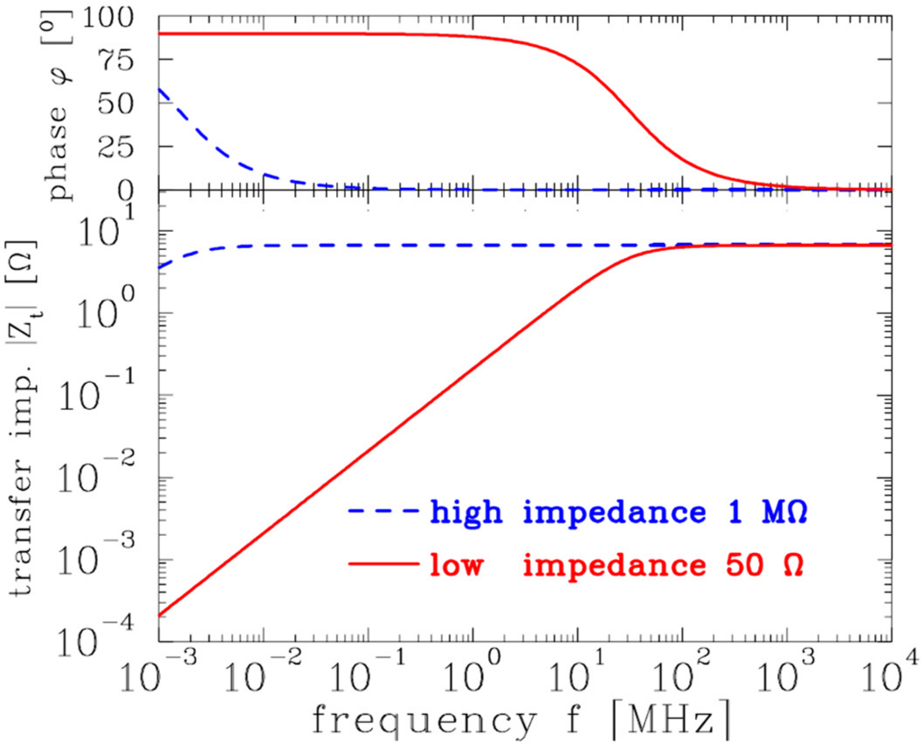
Parameter for shoe-box BPM:

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



Signal Shape for capacitive BPMs: differentiated ↔ proportional

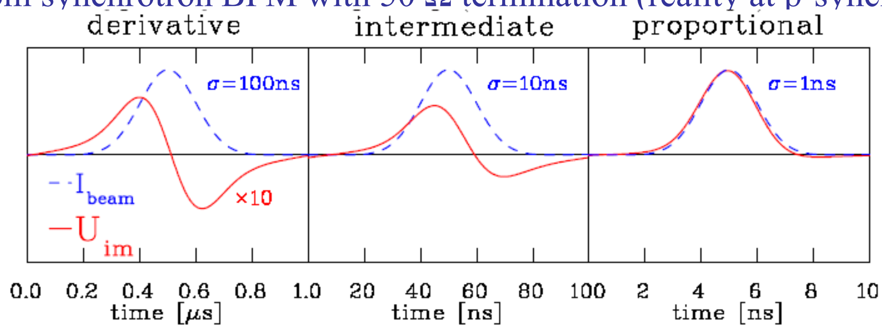
Depending on the frequency range ***and*** termination the signal looks different:

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

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

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

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



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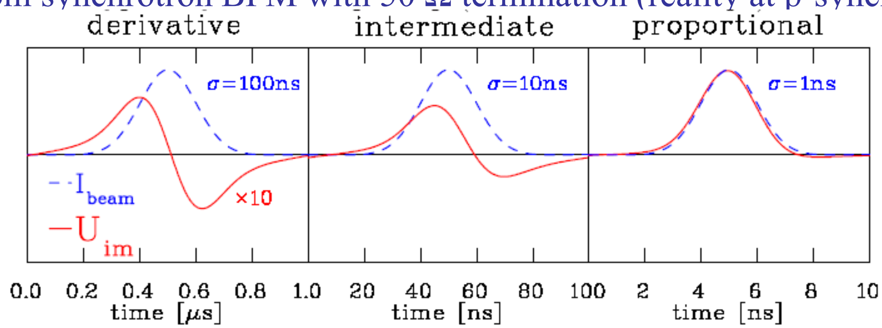
$\Rightarrow$ **direct image** of the bunch. Signal strength $\boldsymbol{Z_t \propto A/C}$ i.e. nearly independent on length

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

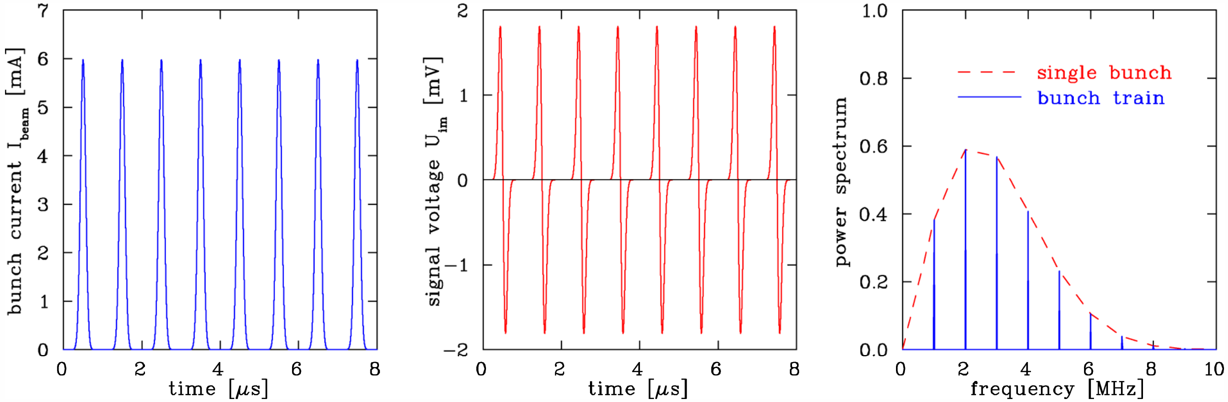
$$Z_t \propto \frac{i\omega/\omega_{cut}}{1+\cancel{i\omega/\omega_{cut}}} \rightarrow i\frac{\omega}{\omega_{cut}} \quad \Rightarrow \quad U_{im}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot i\omega I_{beam}(t) = R\cdot\frac{A}{\beta c\cdot 2\pi a}\cdot\frac{dI_{beam}}{dt}$$

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

Example from synchrotron BPM with 50 Ω termination (reality at p-synchrotron : $\boldsymbol{\sigma}$>>1 ns):



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



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

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

C=100pF, l=10cm, β=50%, σ_t=100 ns

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

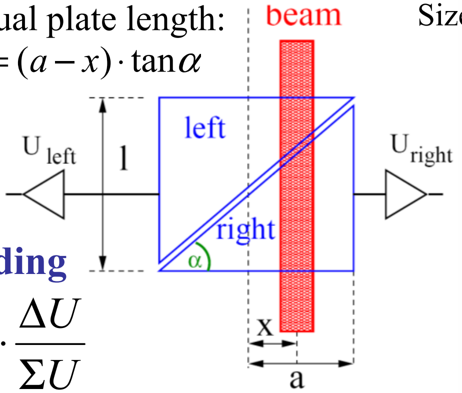
Remark: 1 MHz< f_{rf} <10MHz $\Rightarrow$ Bandwidth ≈100MHz = $10 \cdot f_{rf}$ for broadband observation.

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

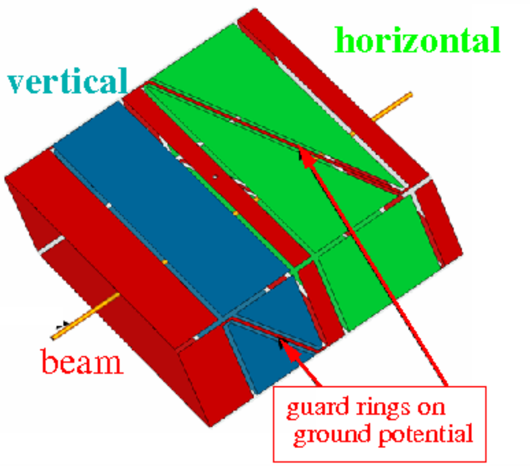
Signal is proportional to actual plate length:

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

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

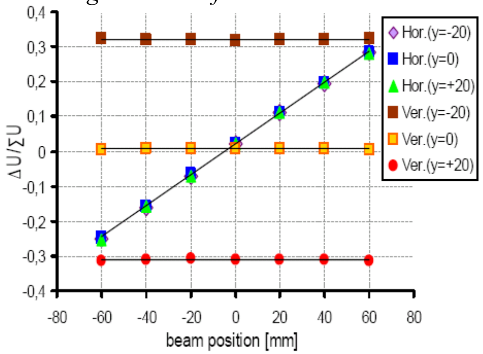


Size: 200x70 mm^2



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 for Proton or Ion Synchrotron

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

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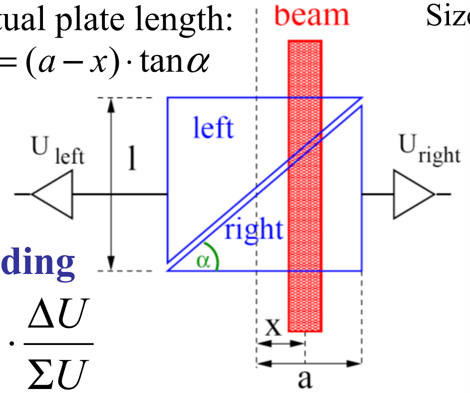

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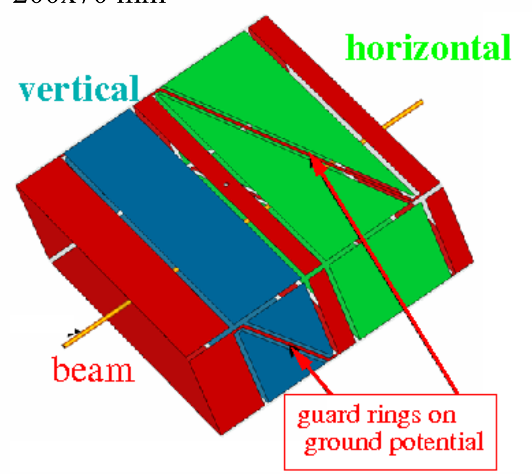

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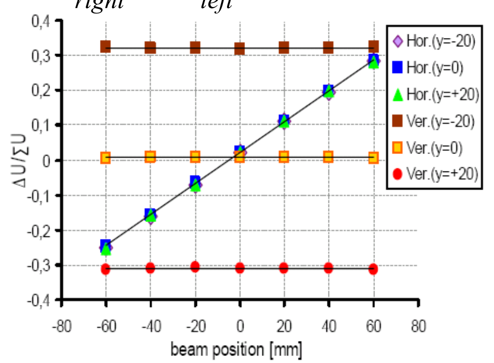
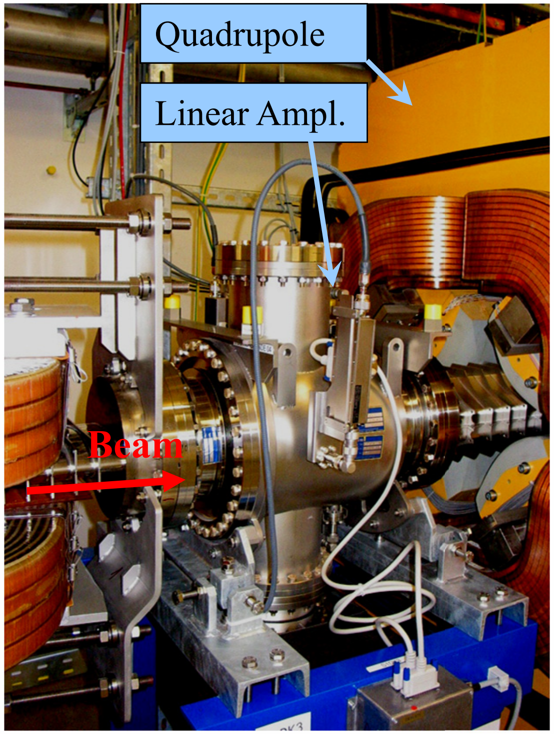


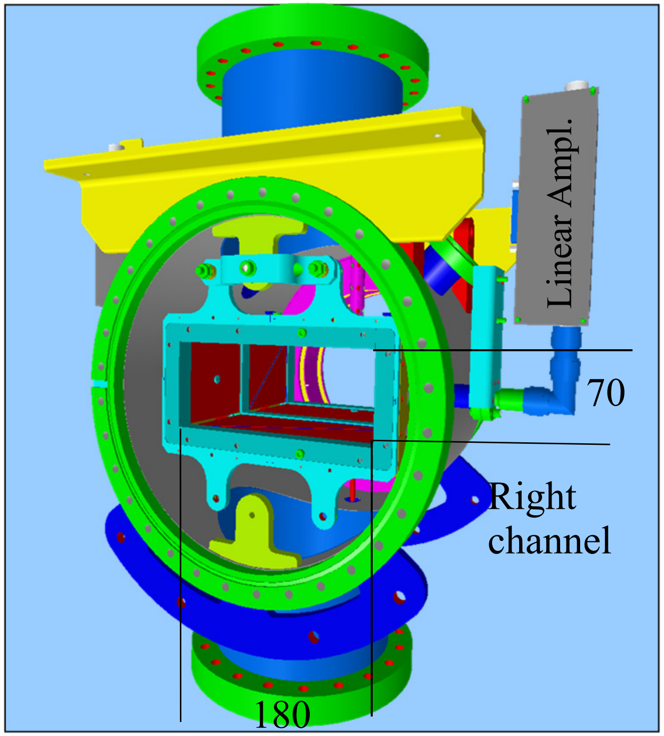
Shoe-box BPM:

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

Disadvantage: Large size, complex mechanics
high capacitance

Technical realization 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.





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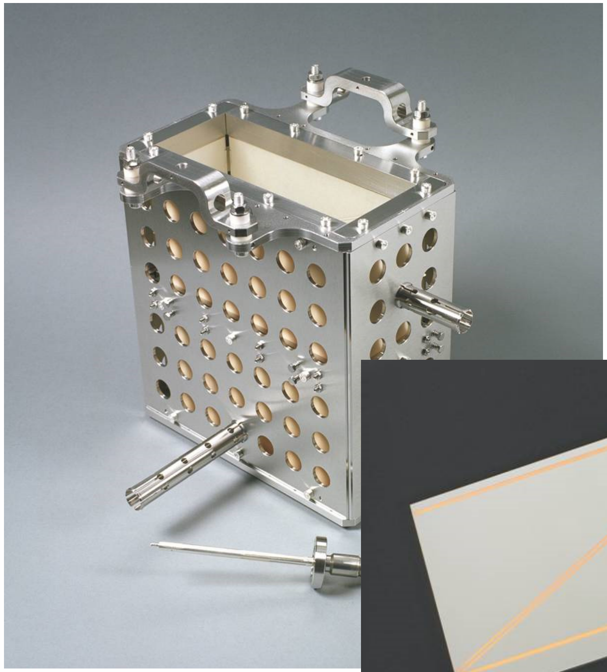
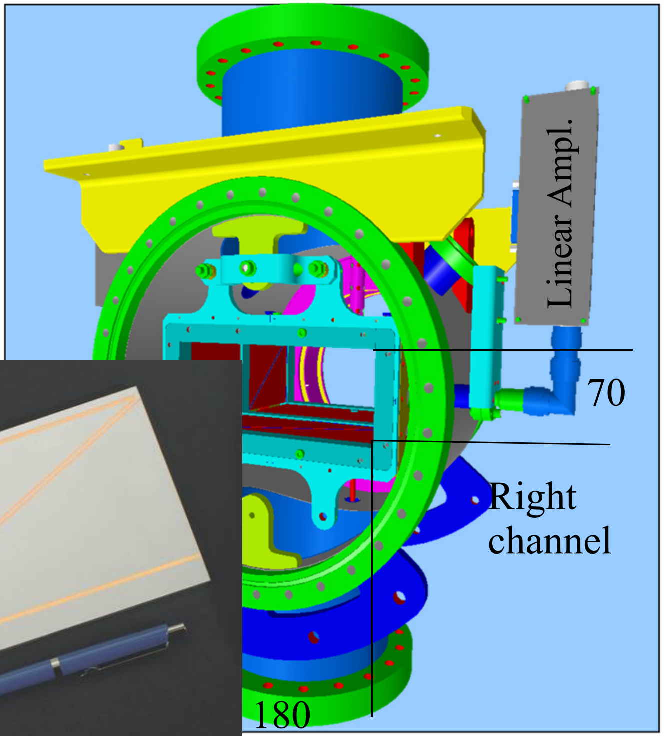
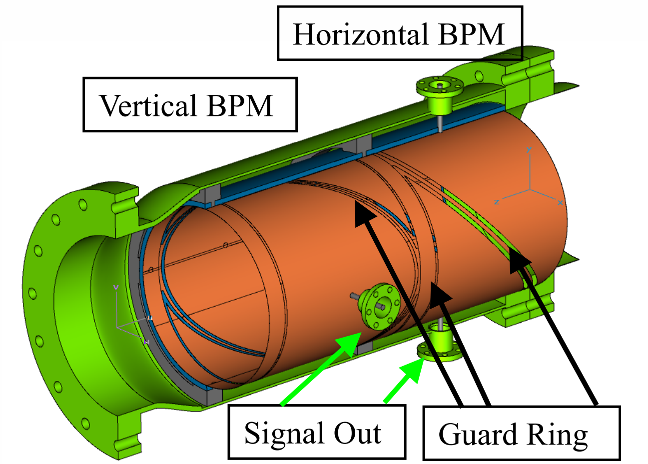




Round type: cut cylinder

Same properties as shoe-box:



Other realization: Full metal plates

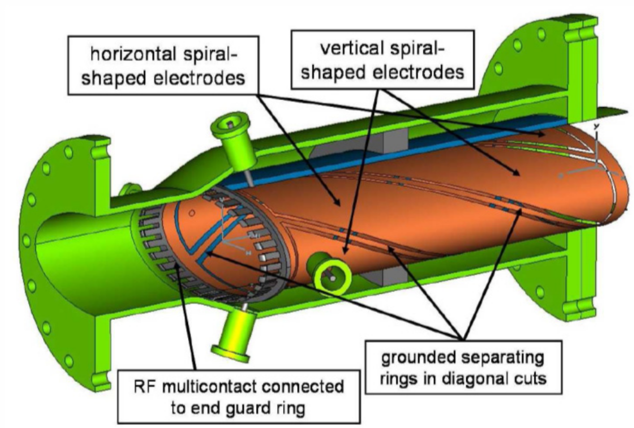
→ No guard rings required

→ but mechanical alignment more difficult

Wound strips:

Same distance from beam and capacitance for all plates

But horizontal-vertical coupling.



Button BPM Realization

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

→ 50 Ω signal path to prevent reflections

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

Button BPM Realization

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

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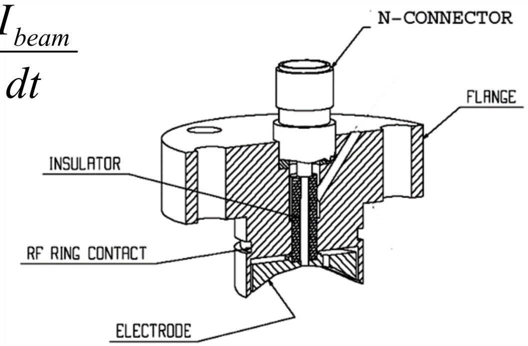
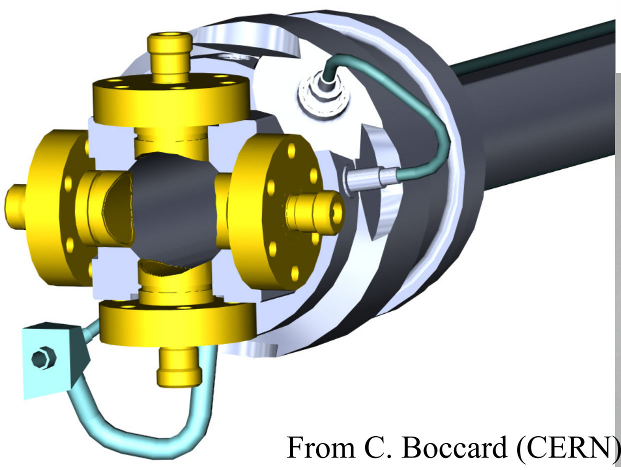
Button BPM with 50 Ω $\Rightarrow$ $$U_{im}(t) \approx R \cdot \frac{A}{\beta c \cdot 2\pi a} \cdot \frac{dI_{beam}}{dt}$$

Example: LHC-type inside cryostat:

$\varnothing$24 mm, half aperture $\boldsymbol{a}$ =25 mm, $\boldsymbol{C}$ =8 pF

$\Rightarrow \boldsymbol{f_{cut}}$= 400 MHz, $\boldsymbol{Z_t}$ = 1.3 Ω above f_{cut}





From C. Boccard (CERN)

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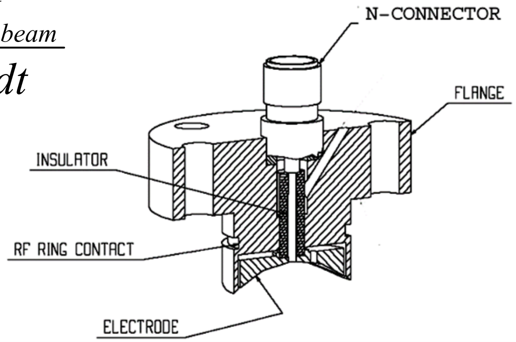

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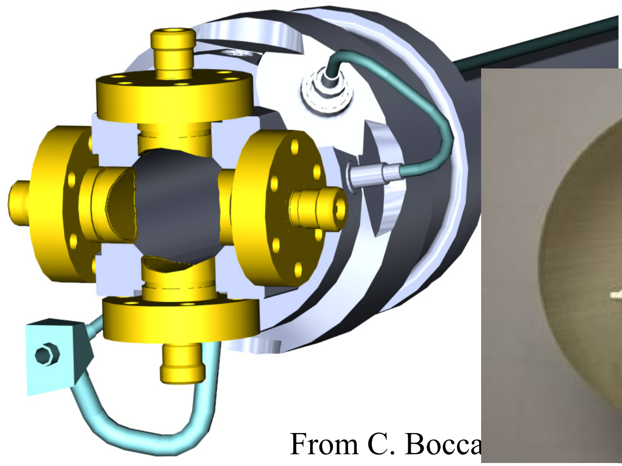
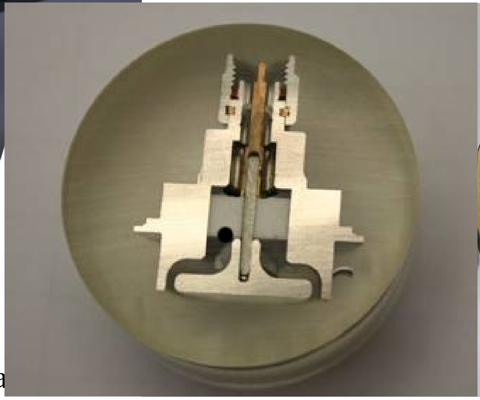
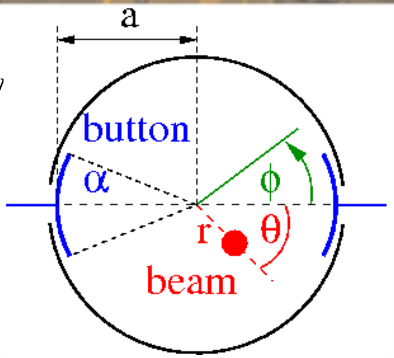


From C. Bocca

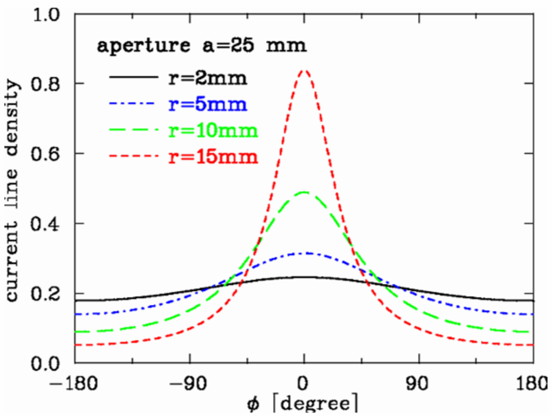


'Proximity effect': larger signal for closer plate

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



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



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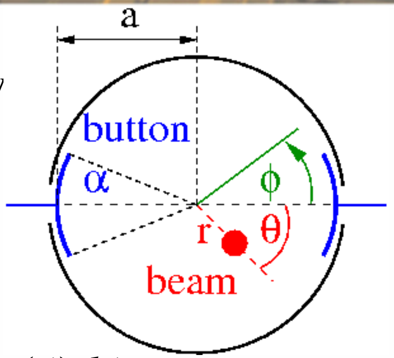

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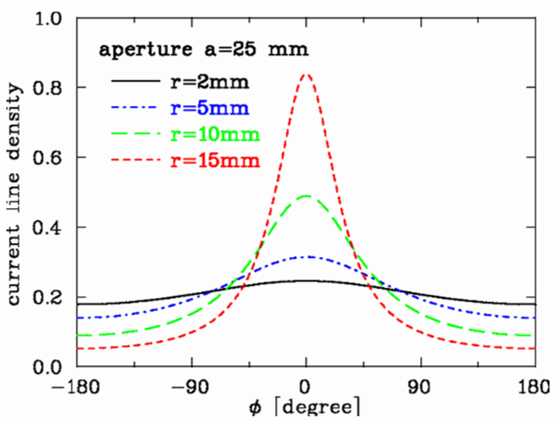
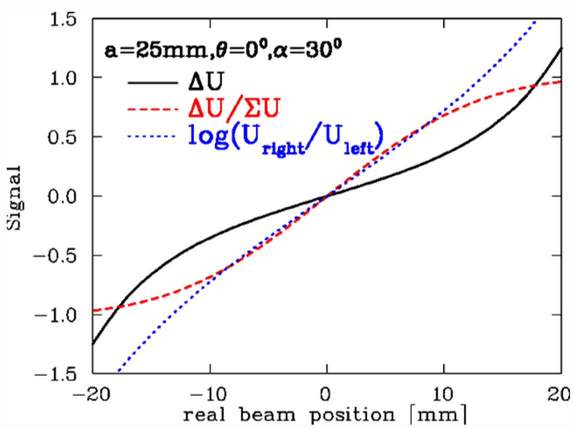
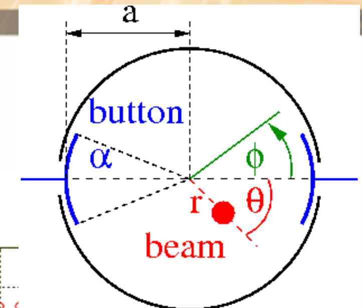
Image current: Integration of finite BPM size: $I_{im} = a \cdot \int_{-\alpha/2}^{\alpha/2} j_{im}(\phi) d\phi$





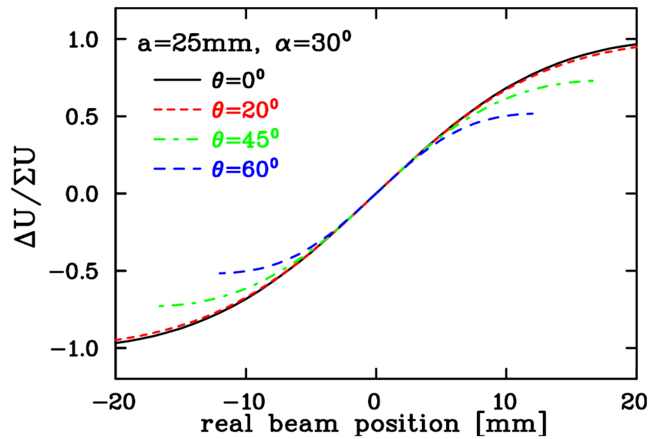
2-dim Model for Button BPM

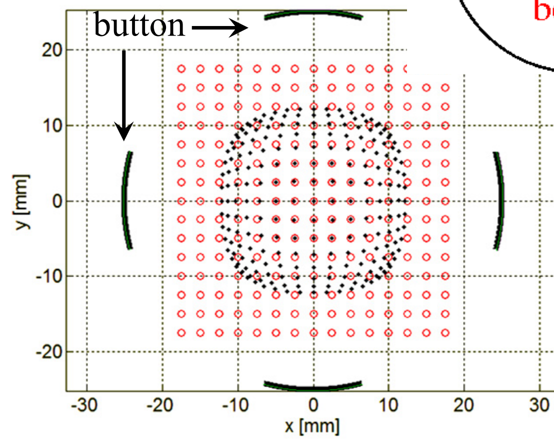


Ideal 2-dim model: Non-linear behavior and hor-vert coupling:

Sensitivity: $x = 1/S \cdot \Delta U / \Sigma U$ with S [%/mm] or [dB/mm]

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

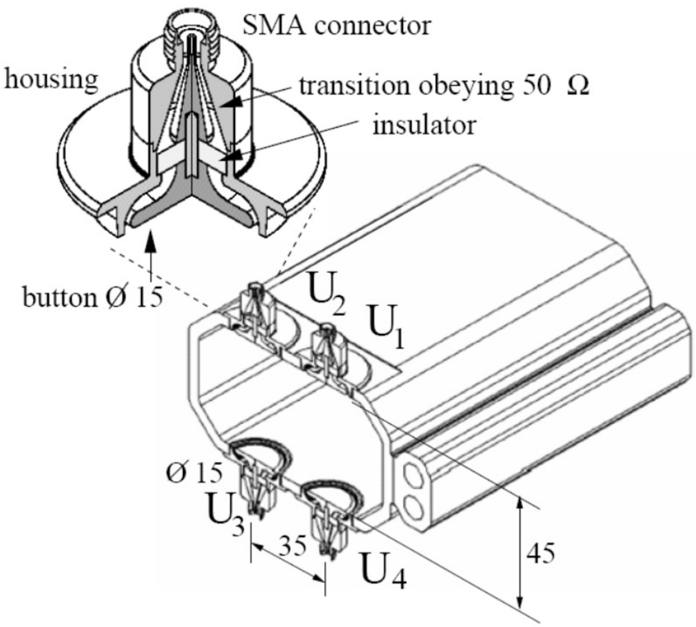


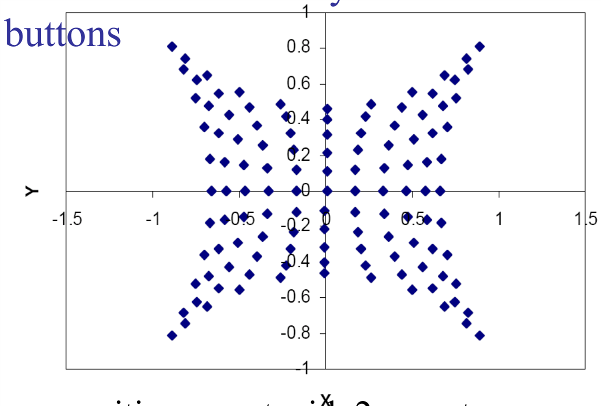


The measurement of U delivers: $x = \frac{1}{S_x} \cdot \frac{\Delta U}{\Sigma U}$ → here $\boldsymbol{S_x = S_x(x, y)}$ i.e. non-linear.

In addition, frequency dependence can be calculated by analytic model or numerically.

Due to synchrotron radiation, the button insulation might be destroyed
$\Rightarrow$buttons only in vertical plane possible $\Rightarrow$ increased non-linearity
Optimization: horizontal distance and size of buttons





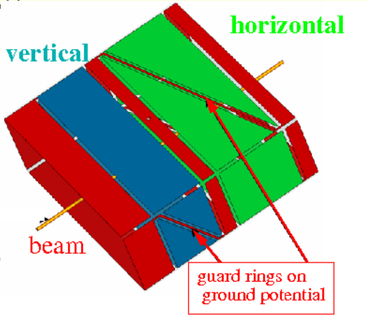
- Beam position swept with 2 mm steps
- Non-linear sensitivity and hor.-vert. coupling
- At center S_x = 8.5%/mm in this case

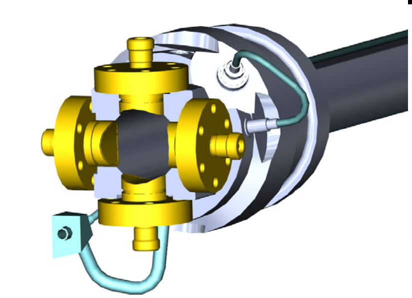
$$\text{horizontal}: x = \frac{1}{S_x} \cdot \frac{(U_1+U_4)-(U_2+U_3)}{U_1+U_2+U_3+U_4}$$

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

From S. Varnasseri, SESAME, DIPAC 2005

	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





Outline

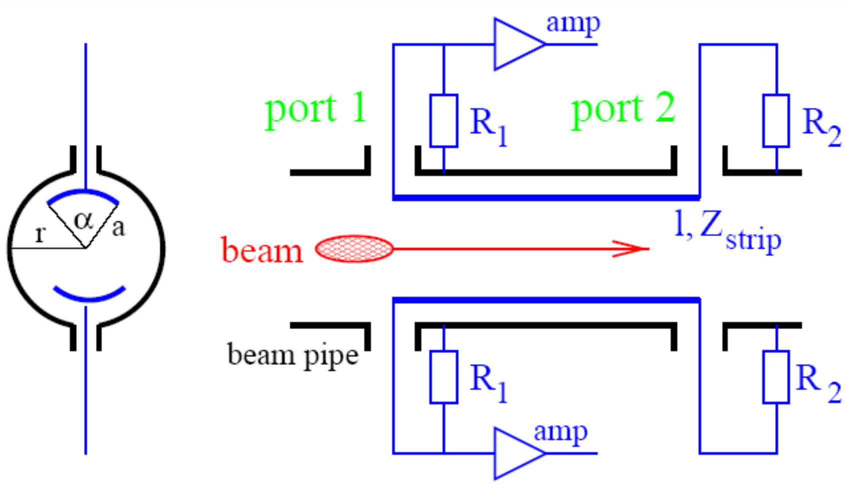
- Principle, Applications of BPMs
- Functional Specifications (FS)
- Sensors + Sensor Signals: stripline BPMs
- Electronics
- Synchronization, accelerator timing
- From precision to accuracy
- Outlook

For short bunches, the ***capacitive*** button deforms the signal

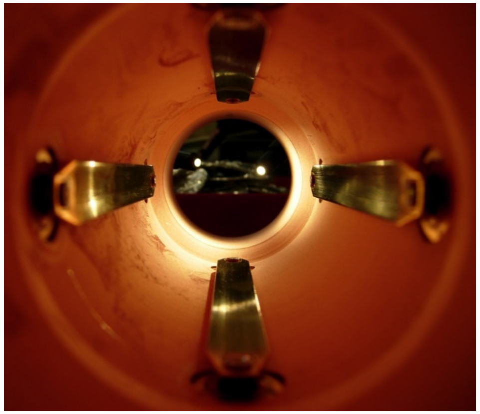
→ Relativistic beam ***β≈1*** ⇒ field of bunches nearly TEM wave

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strips

→ Assumption: Bunch shorter than BPM, $Z_{strip}=R_1=R_2=50\ \Omega$ and $v_{beam}=c_{strip}$.



LHC stripline BPM, *l*=12 cm



From C. Boccard, CERN

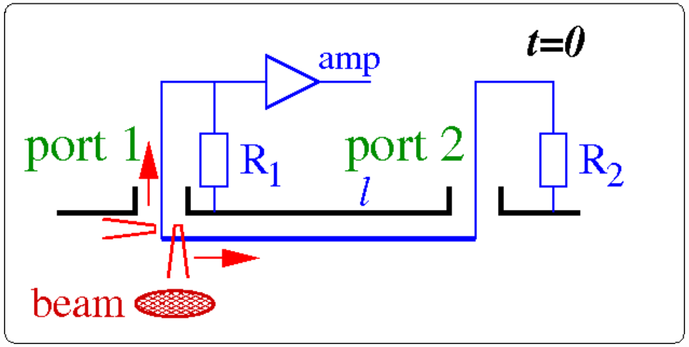
For relativistic beam with $\beta \approx 1$ and short bunches:

→ Bunch's electro-magnetic field induces a **traveling pulse** at the strip

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

Signal treatment at upstream port 1:

t=0: Beam induced charges at **port 1**:
→ half to R_1, half toward **port 2**



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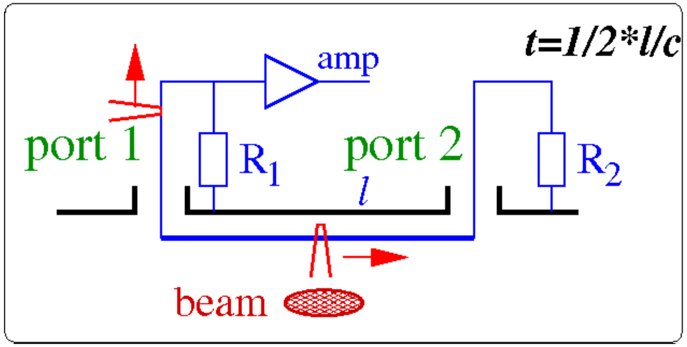

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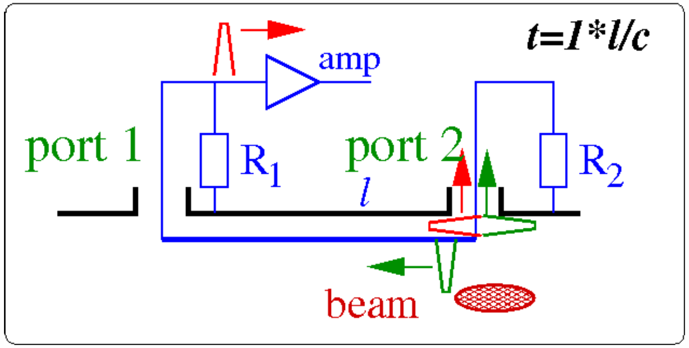
t=l/c: Beam induced charges at **port 2**:
→ half to R_2, ***but*** due to different sign, it cancels with the signal from **port 1**
→ half signal reflected



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

⇒ Signal depends on direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

Stripline BPM: General Idea

For relativistic beam with ***β≈1*** and short bunches:

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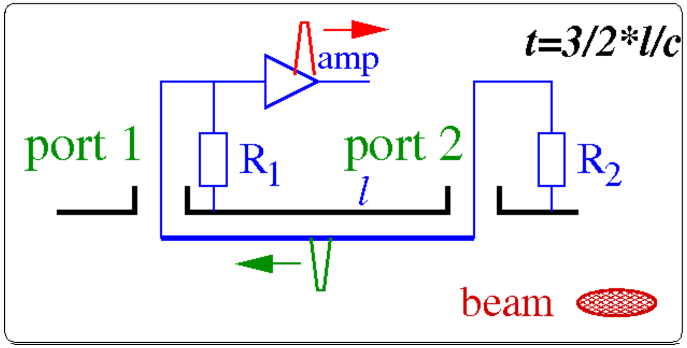
t=2·l/c: reflected signal reaches **port 1**



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

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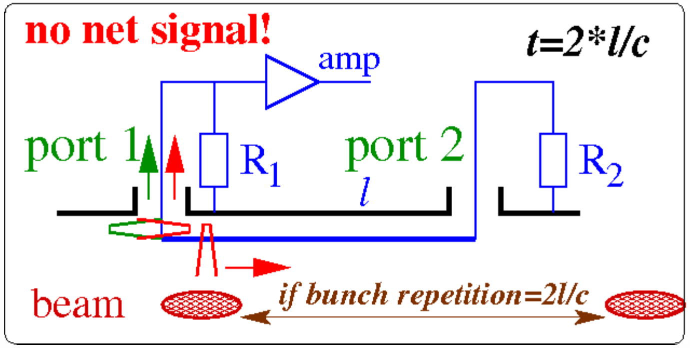


$$\Rightarrow U_1(t) = \frac{1}{2} \cdot \frac{\alpha}{2\pi} \cdot Z_{strip} \left(I_{beam}(t) - I_{beam}(t - 2l/c) \right)$$

If beam repetition time equals 2·l/c: reflected preceding port 2 signal cancels the new one:
→ no net signal at **port 1**

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

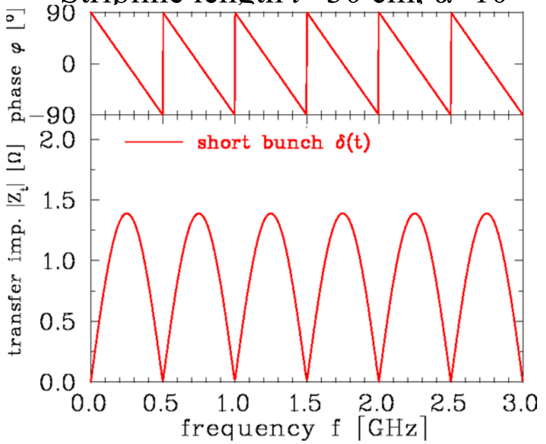
⇒ Signal depends on direction ⇔ directional coupler: e.g. can distinguish between e^- and e^+ in collider

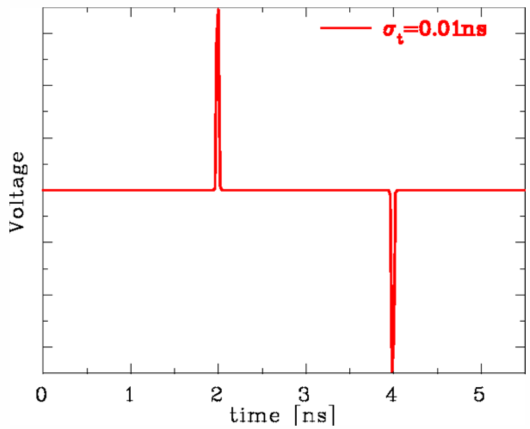
Stripline BPM: Transfer Impedance

The signal from port 1 and the reflection from port 2 can cancel ⇒ minima in Z_t.

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

Stripline length l=30 cm, $\alpha=10^0$





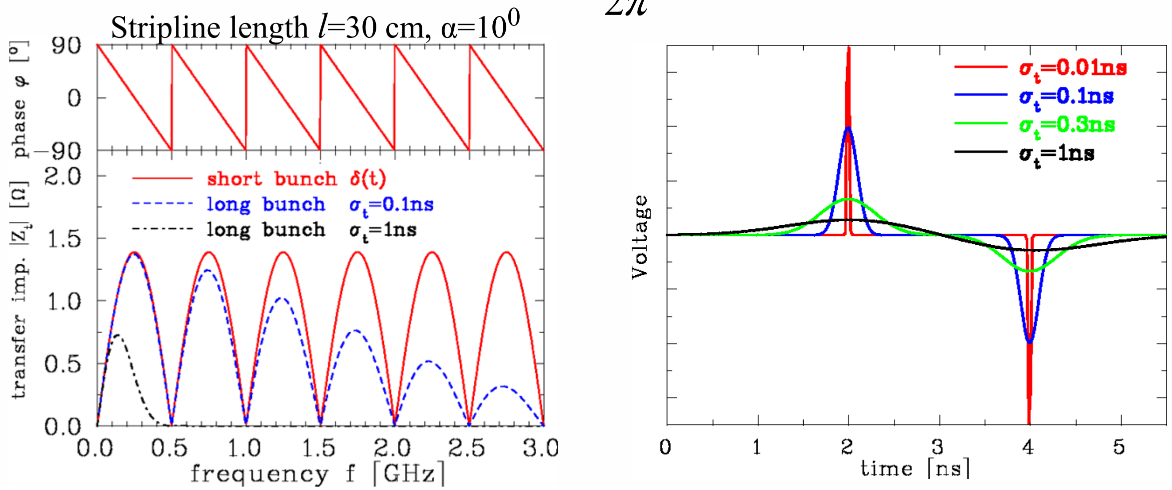
- Z_t show maximum at $l=c/4f=\lambda/4$ i.e. 'quarter wave coupler' for bunch train
  ⇒ l has to be matched to v_{beam}
- No signal for $l=c/2f=\lambda/2$ i.e. destructive interference with **subsequent** bunch
- Around maximum of $|Z_t|$: phase shift $\varphi=0$ i.e. direct image of bunch
- $f_{center}=1/4 \cdot c/l \cdot (2n-1)$. For first lope: $f_{low}=1/2 \cdot f_{center}$, $f_{high}=3/2 \cdot f_{center}$ i.e. bandwidth $\approx 1/2 \cdot f_{center}$
- Precise matching at feed-through required t o preserve 50 Ω matching.

Stripline BPM: Finite Bunch Length

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

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

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



- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long $(\pm 3\sigma_t > l)$ destructive interference leads to signal damping

  Cure: length of stripline has to be matched to bunch length

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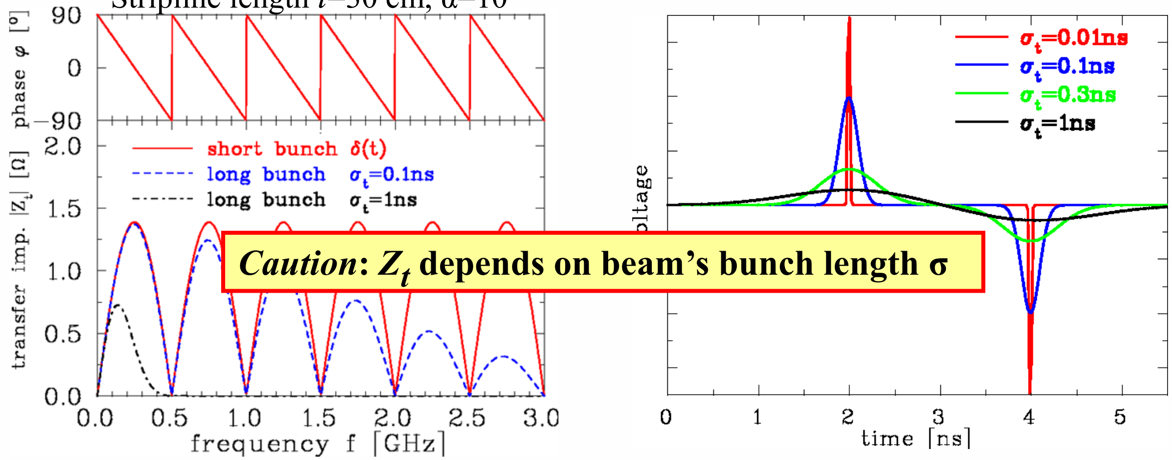
Stripline length l=30 cm, α=10^0

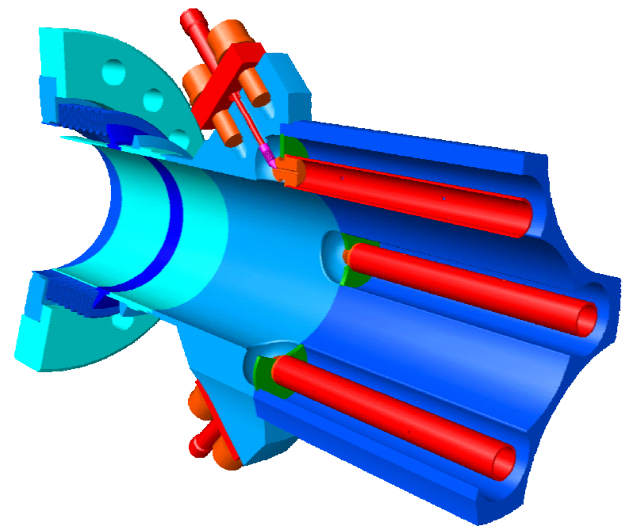


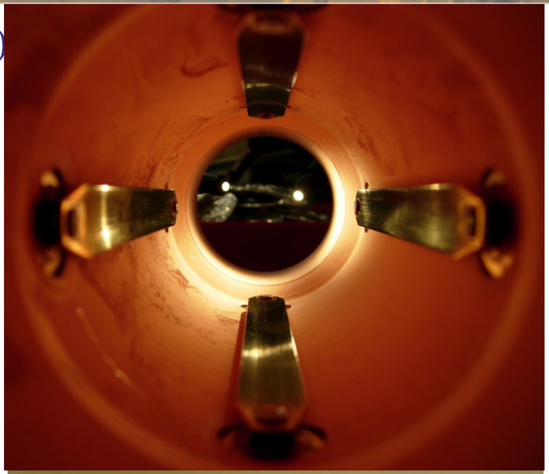
***Caution*: Z_t depends on beam's bunch length σ**

- $Z_t(\omega)$ decreases for higher frequencies
- If total bunch is too long ($\pm 3\sigma_t > l$) destructive interference leads to signal damping

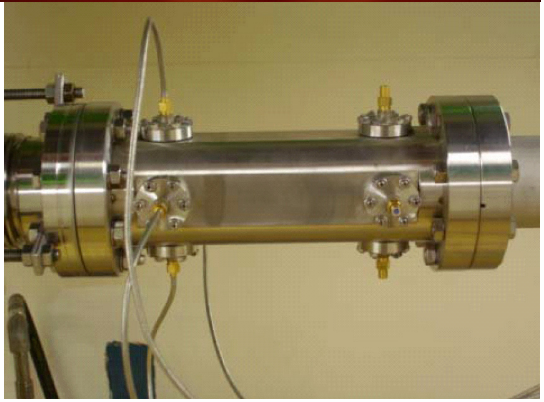
  Cure: length of stripline has to be matched to bunch length

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





e⁻ →



From . S. Wilkins, D. Nölle (DESY), C. Boccard (CERN)

Outline

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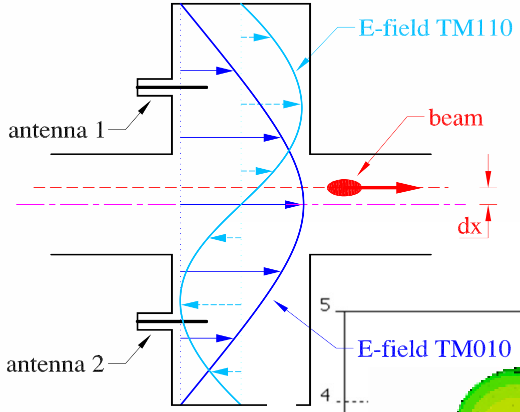
High resolution on t < 1 µs time scale can be achieved by excitation of a dipole mode:

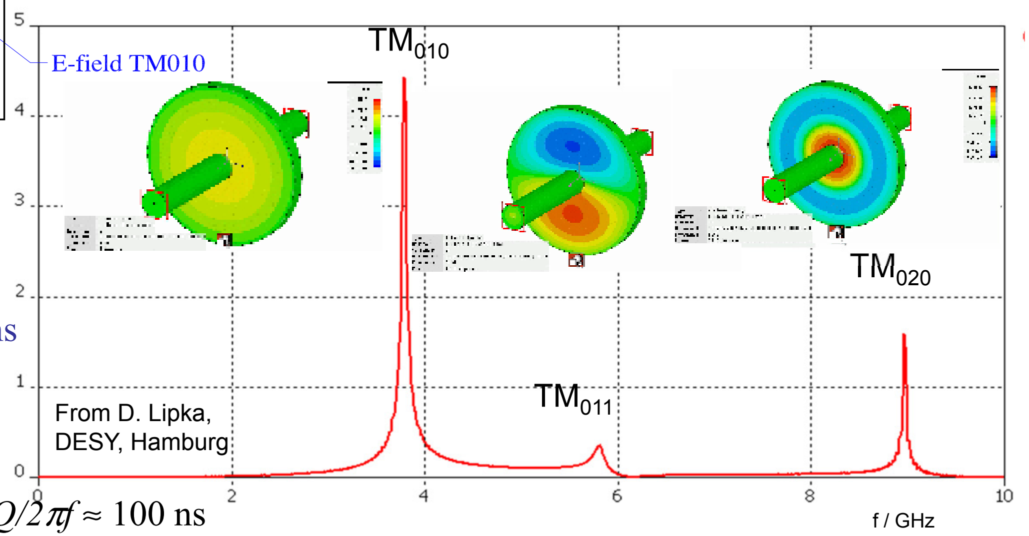


For pill box the resonator modes given by geometry:

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

⇒ Detection of dipole mode amplitude

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

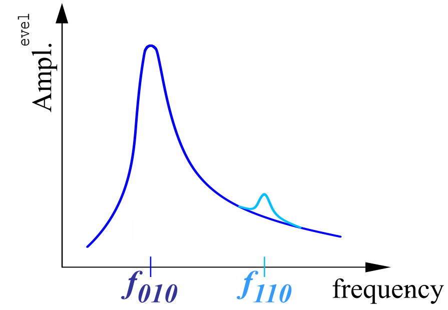


Basic consideration for detection of Eigen-frequency amplitudes:

Dipole mode f_{110} separated from monopole mode

but to finite quality factor $Q \Rightarrow \Delta f = f/Q$

- Frequency $f_{110} \approx 1 \ldots 10$ GHz
- Waveguide house the antennas (task: suppression of TM_{010} mode signal)



FNAL realization:

Cavity: ∅ 113 mm

Gap 15 mm

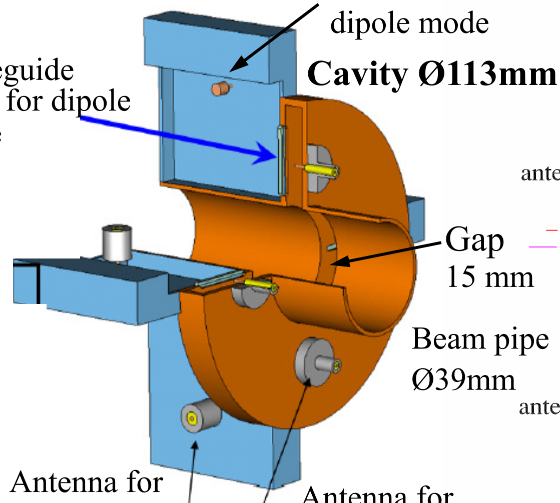
Mono. f_{010}=1.1GHz

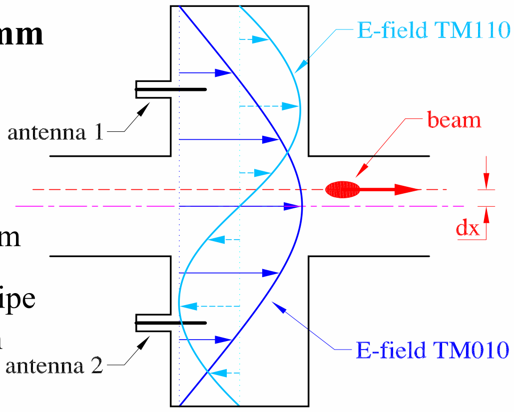
Dipole. f_{110}=1.5GHz

$Q_{load} \approx 600$

With comparable BPM

⇒0.1 µm resolution within 1 µs





From M. Wendt (FNAL)

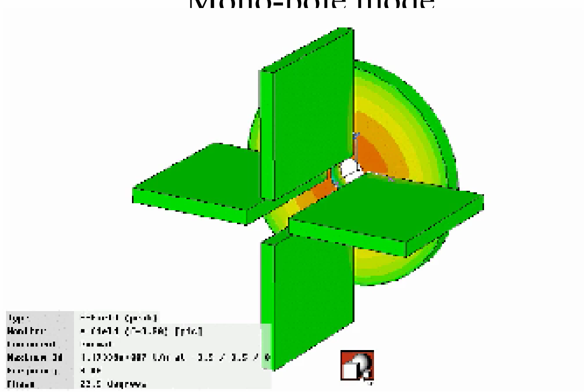
Courtesy of D. Lipka & Y. Honda

Cavity BPM: Suppression of monopole Mode

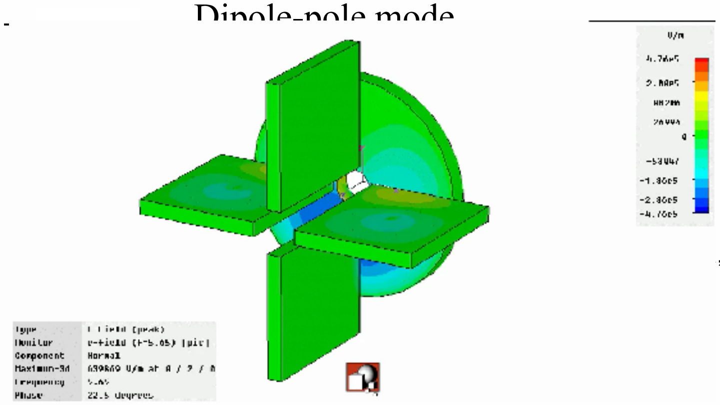
Suppression of mono-pole mode: waveguide that couple only to dipole-mode

due to $f_{mono} < f_{cut} < f_{dipole}$

Mono-pole mode



Dipole-pole mode



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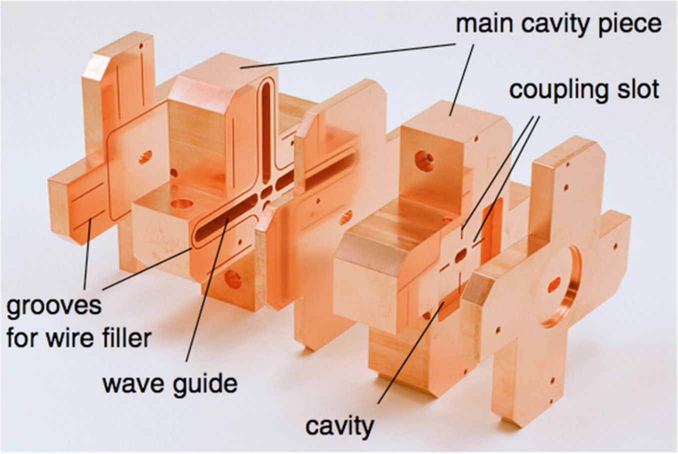
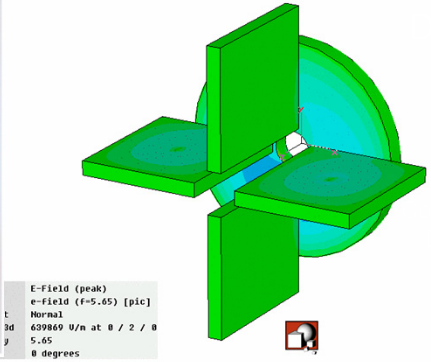


Courtesy of D. Lipka and Y. Honda

Dipole-pole mode



Courtesy of D. Lipka, DESY, Hamburg

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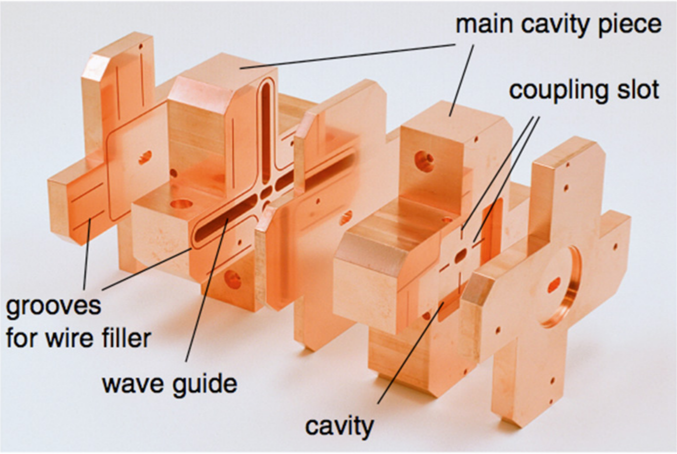

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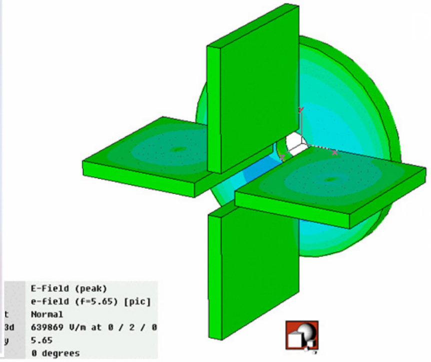

Courtesy of D. Lipka,
DESY, Hamburg

Prototype BPM for ILC Final Focus:

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

Comparison of BPM Types (simplified)

Type	Usage	Precaution	Advantage	Disadvantage
Shoe-box	p-Synch.	Long bunches f_{rf}< 10 MHz	Very linear No x-y coupling Sensitive For broad beams	Complex mechanics Capacitive coupling between plates
Button	p-Linacs, all e^- acc.	f_{rf}> 10 MHz	Simple mechanics	Non-linear, x-y coupling Possible signal deformation
Stipline	colliders p-Linacs all e^- acc.	best for $\beta\approx 1$, short bunches	Directivity 'Clean' signal Large signal	Complex 50 Ω matching Complex mechanics
Cavity	e^- Linacs (e.g. FEL)	Short bunches Special appl.	Very sensitive	Very complex, high frequency

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

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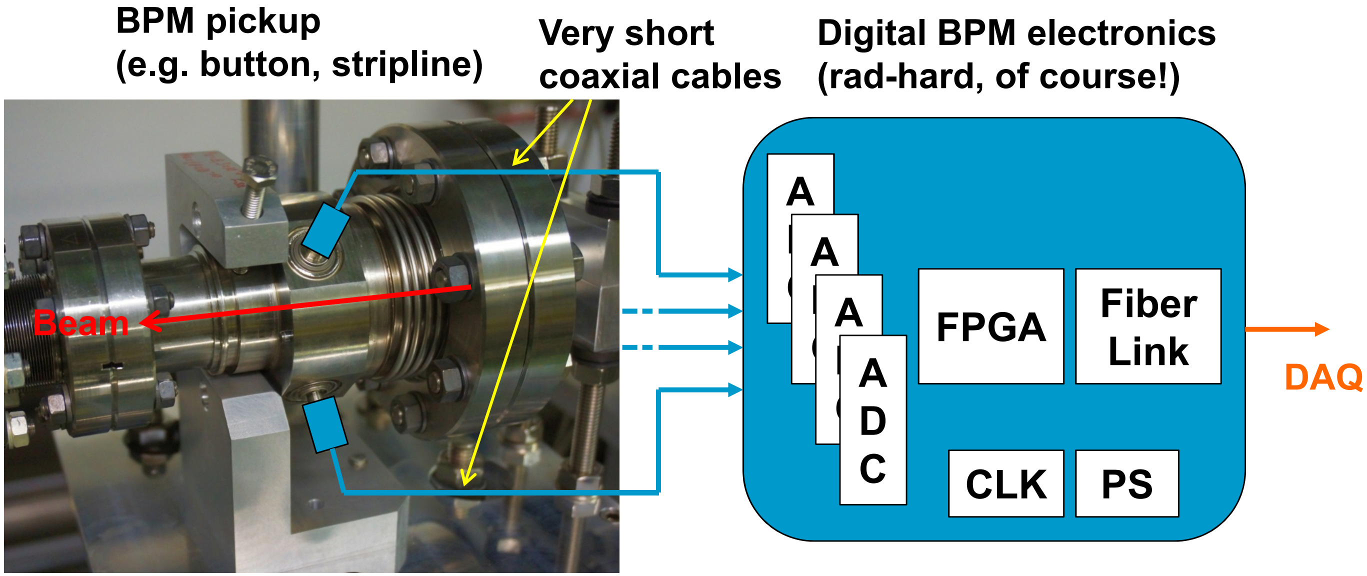
The Ideal BPM Read-out Electronics!?



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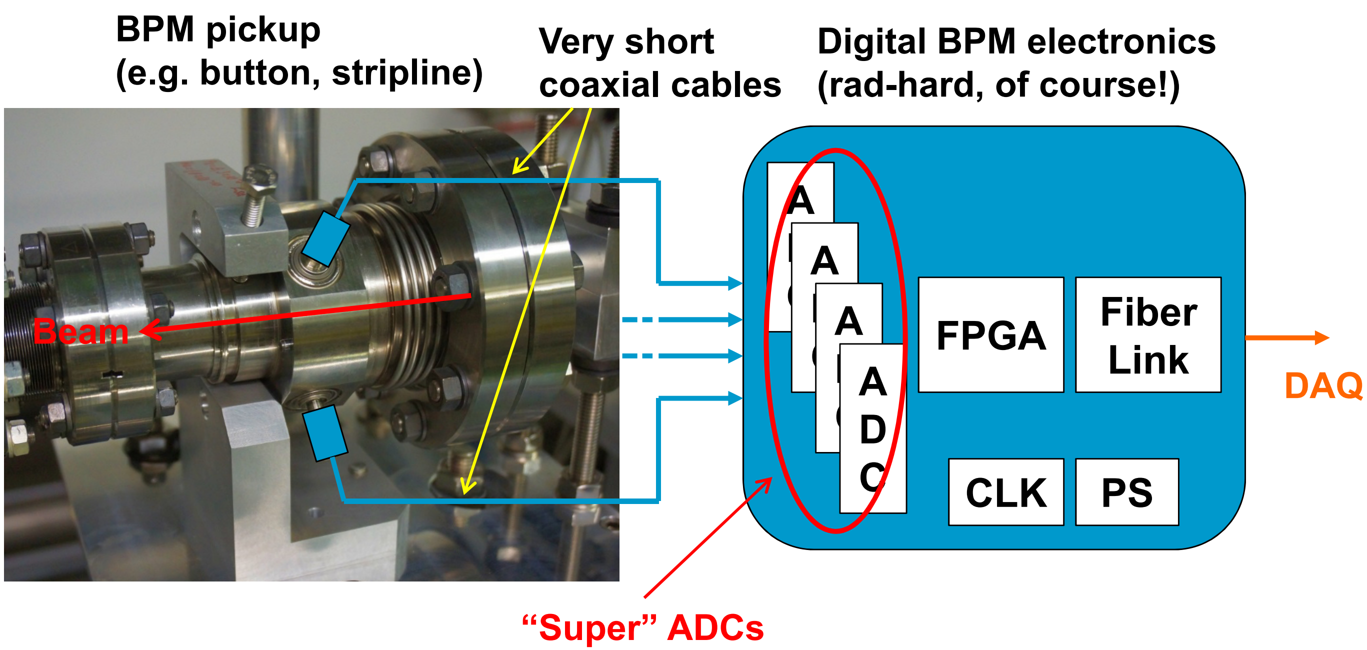

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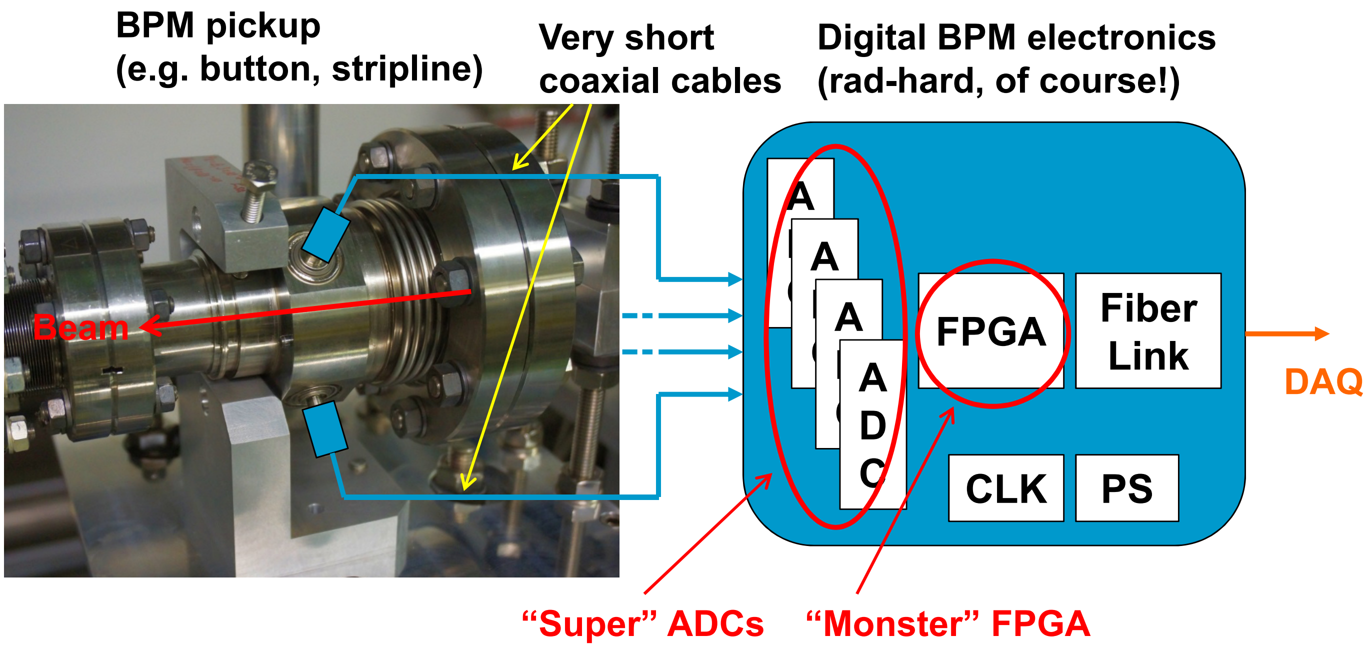

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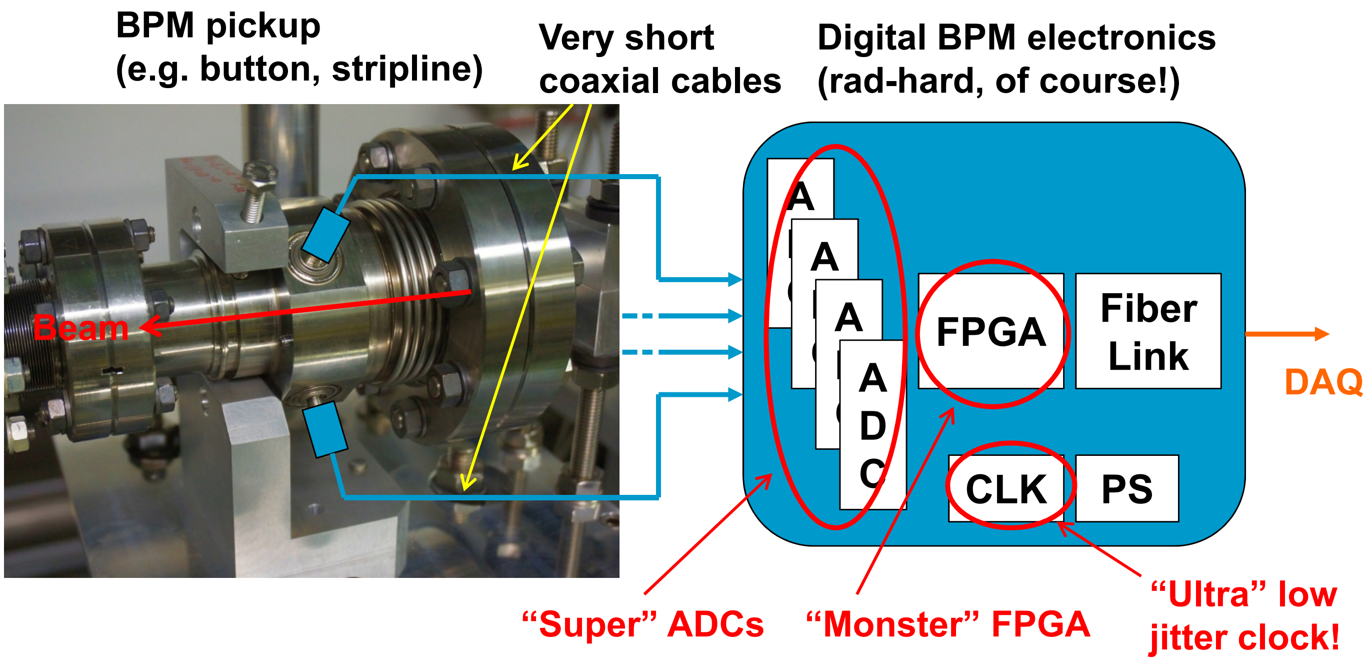

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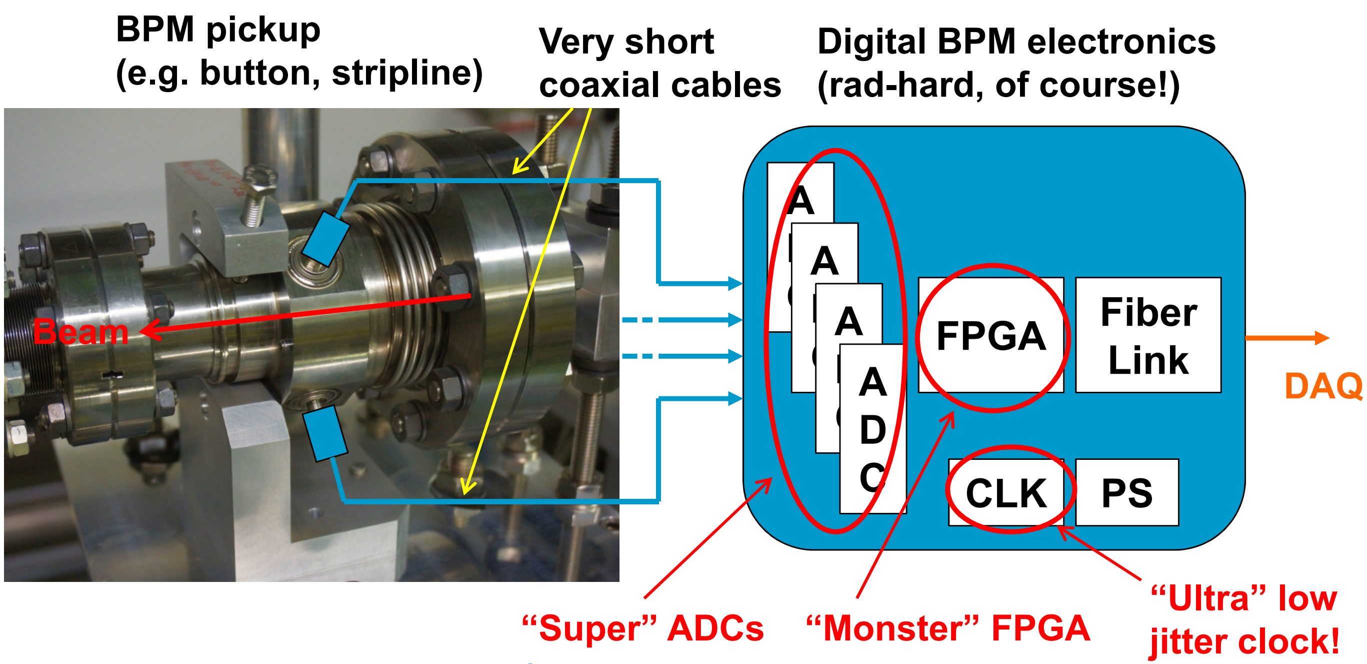
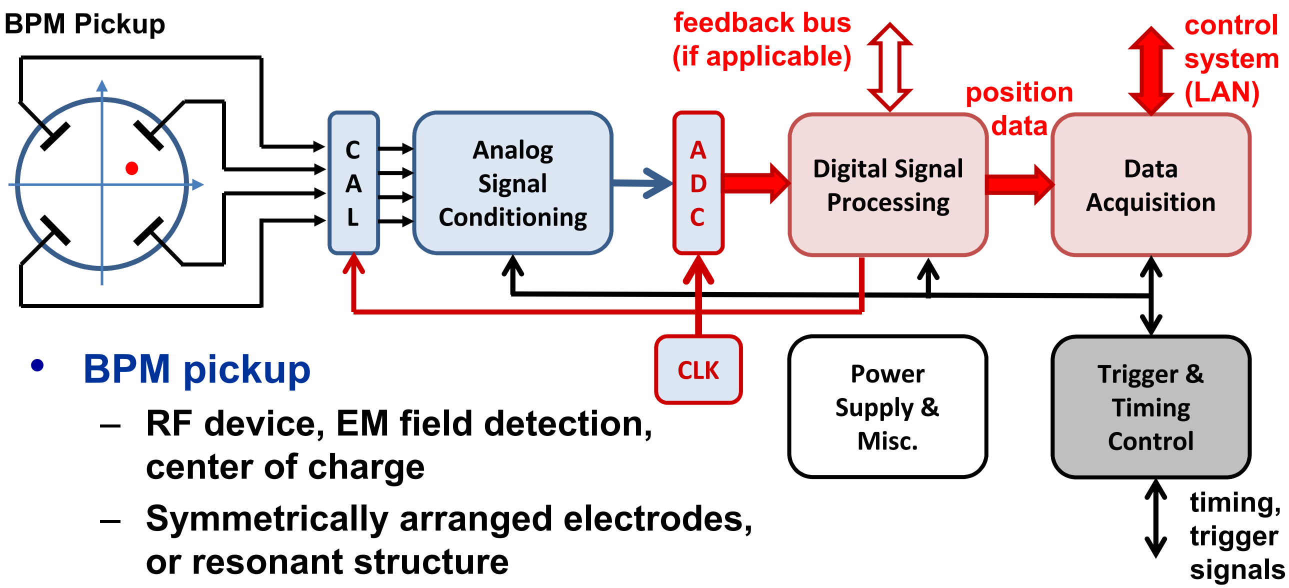


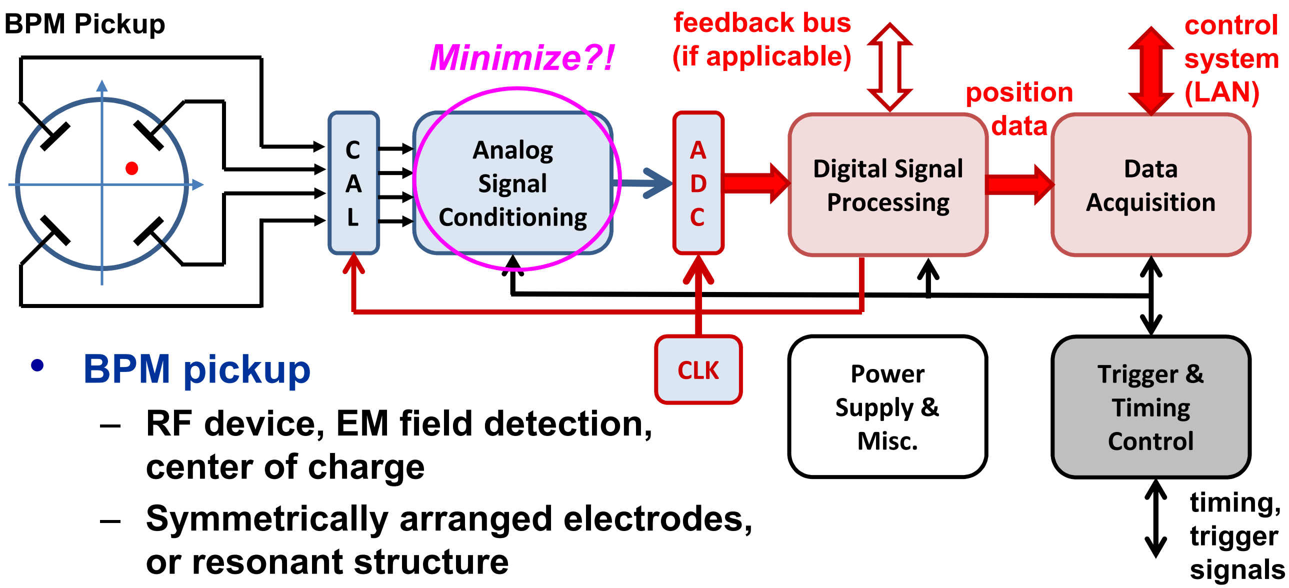
- Time multiplexing of the BPM electrode signals:
  – Interleaving BPM electrode signals by different cable delays
  – Requires only a single read-out channel!

BPM Building Blocks



- **BPM pickup**
  - RF device, EM field detection, center of charge
  - Symmetrically arranged electrodes, or resonant structure
- **Read-out electronics**
  - Analog signal conditioning
  - Signal sampling (ADC)
  - Digital signal processing
  - Data acquisition and control system interface
  - Trigger, CLK & timing signals
  - Provides calibration signals or other drift compensation methods

BPM Building Blocks



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Signal Processing & Normalization

- Extract the beam position information from the electrode signals: Normalization
  - Analog using Δ-Σ or 90^0-hybrids, followed by filters, amplifiers mixers and other elements, or logarithmic amplifiers.
  - Digital, performing the math on individual digitized electrode signals.
- Decimation / processing of broadband signals
  - BPM data often is not required on a bunch-by-bunch basis
    - Exception: Fast feedback processors
    - Default: Turn-by-turn and "narrowband" beam positions
  - Filters, amplifiers, mixers and demodulators in analog and digital to decimate broadband signals to the necessary level.
- Other aspects
  - Generate calibration / test signals
  - Correct for non-linearities of the beam position response of the BPM
  - Synchronization of turn-by-turn data
  - Optimization on the BPM system level to minimize cable expenses.
  - BPM signals keep other very useful information other than that based on the beam displacement, e.g.
    - Beam intensity, beam phase (timing)

For the “Oldies”: Analog Signal Processing Options

courtesy *G. Vismara (BIW 2001)*

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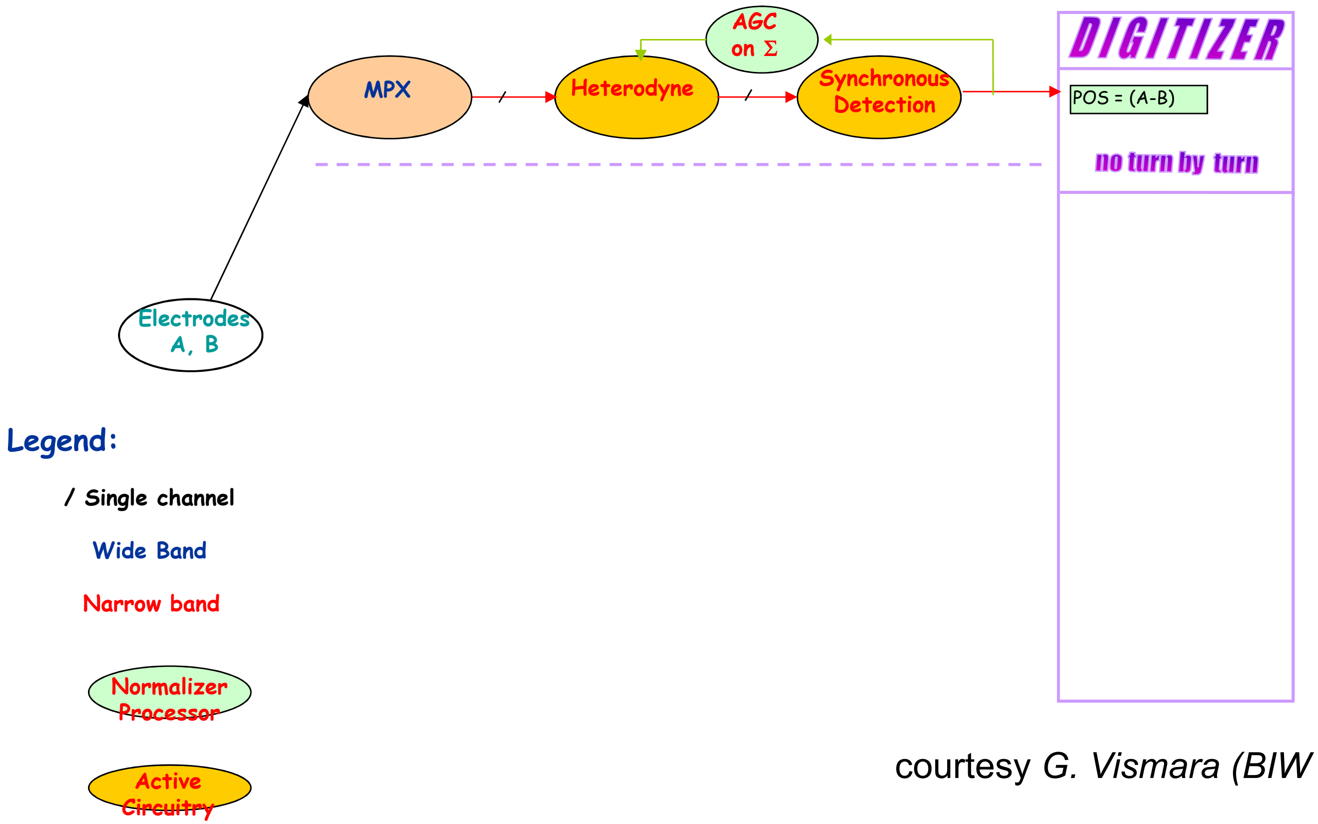

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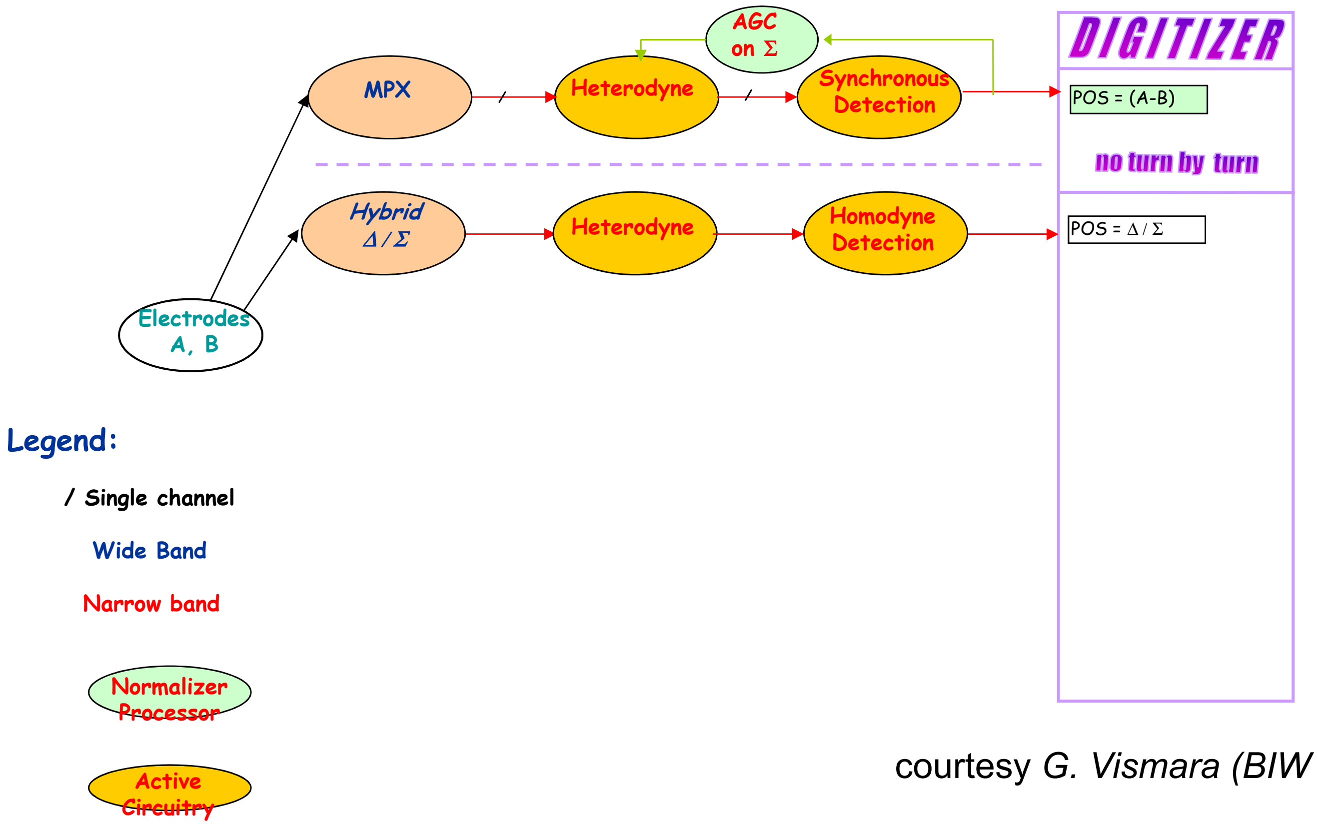

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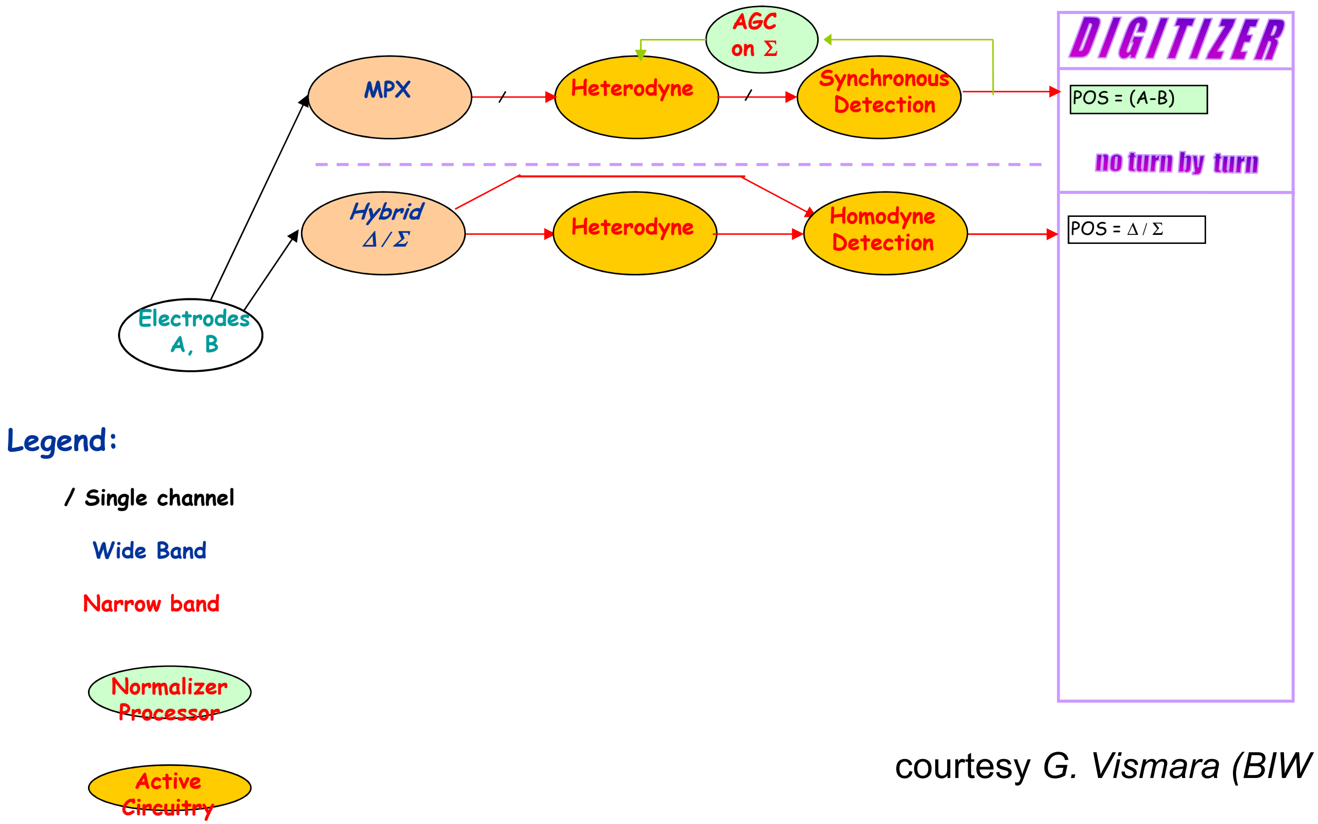

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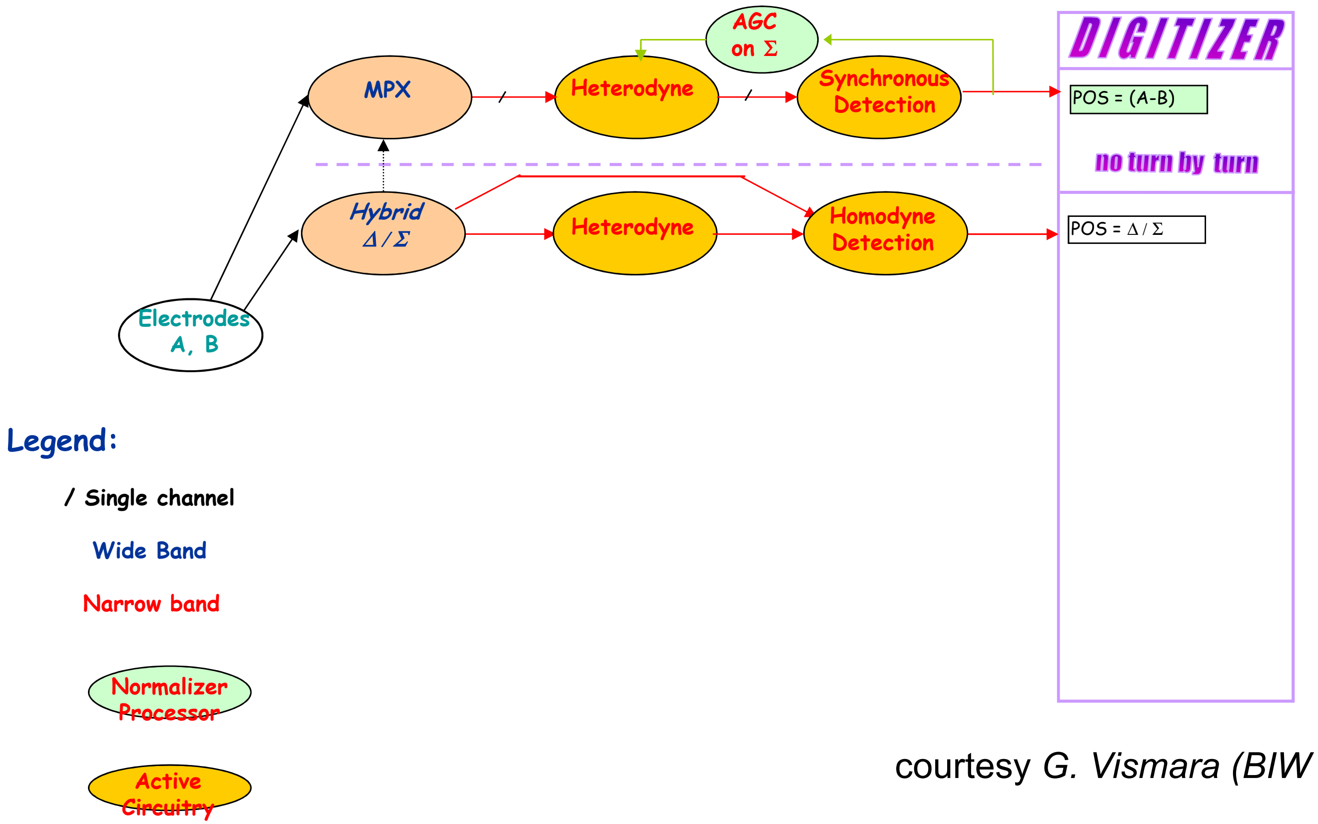
For the “Oldies”: Analog Signal Processing Options



courtesy *G. Vismara (BIW 2001)*

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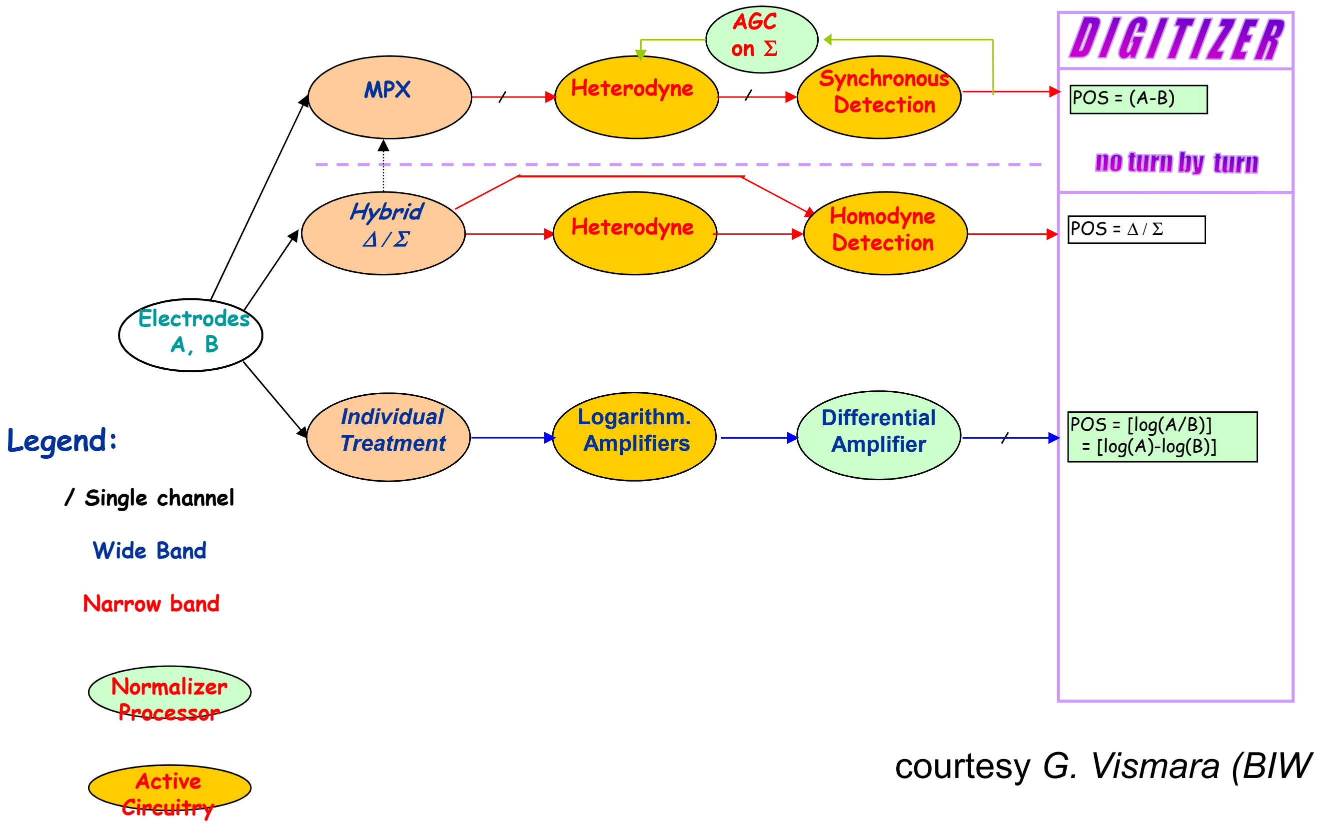

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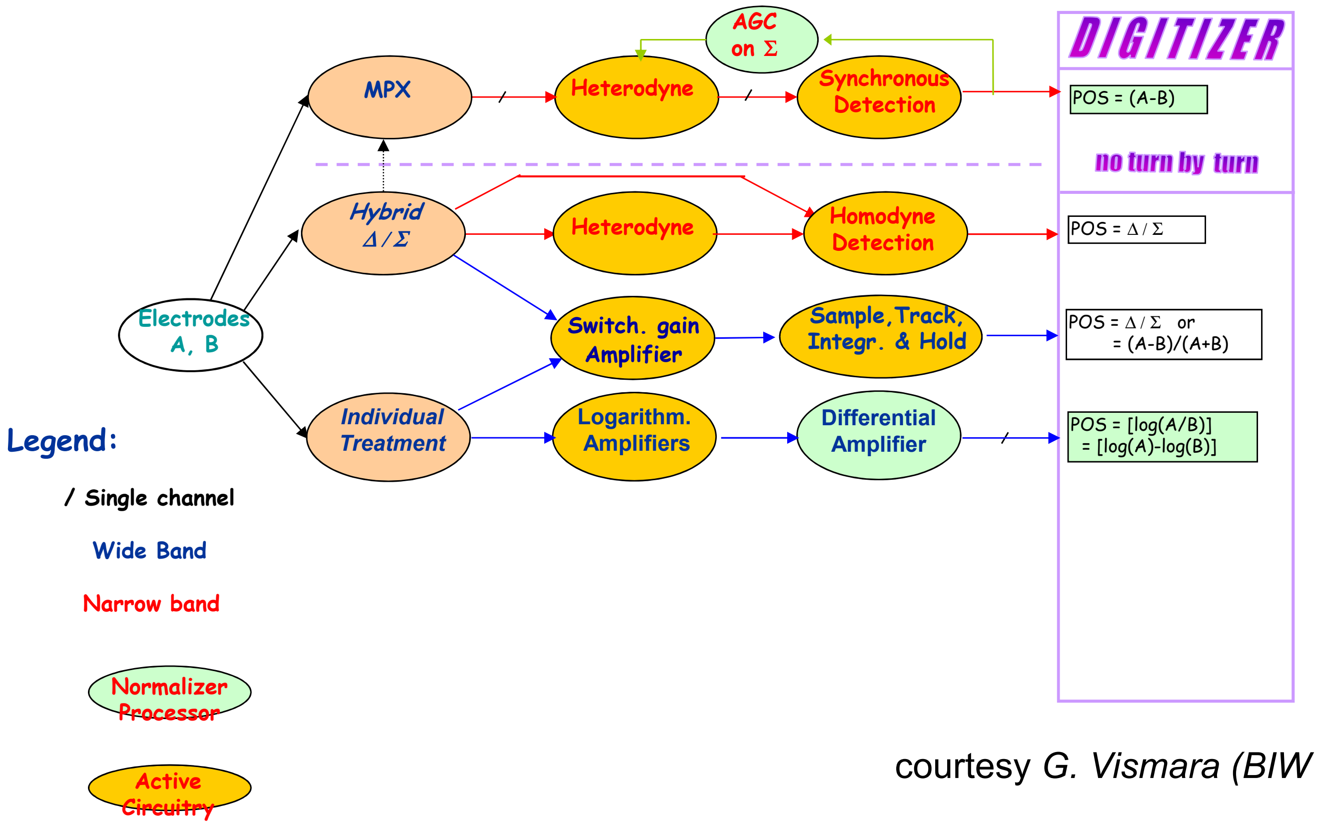

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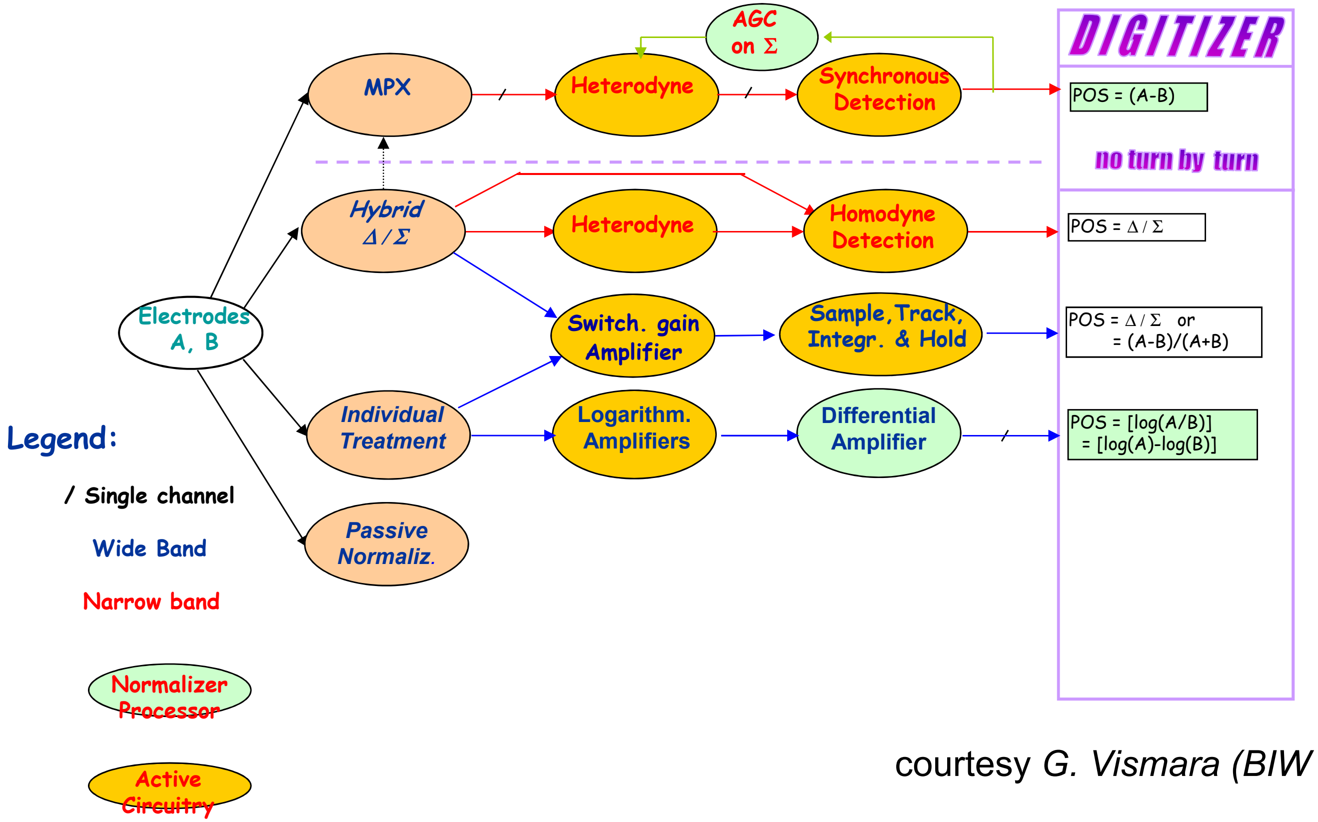

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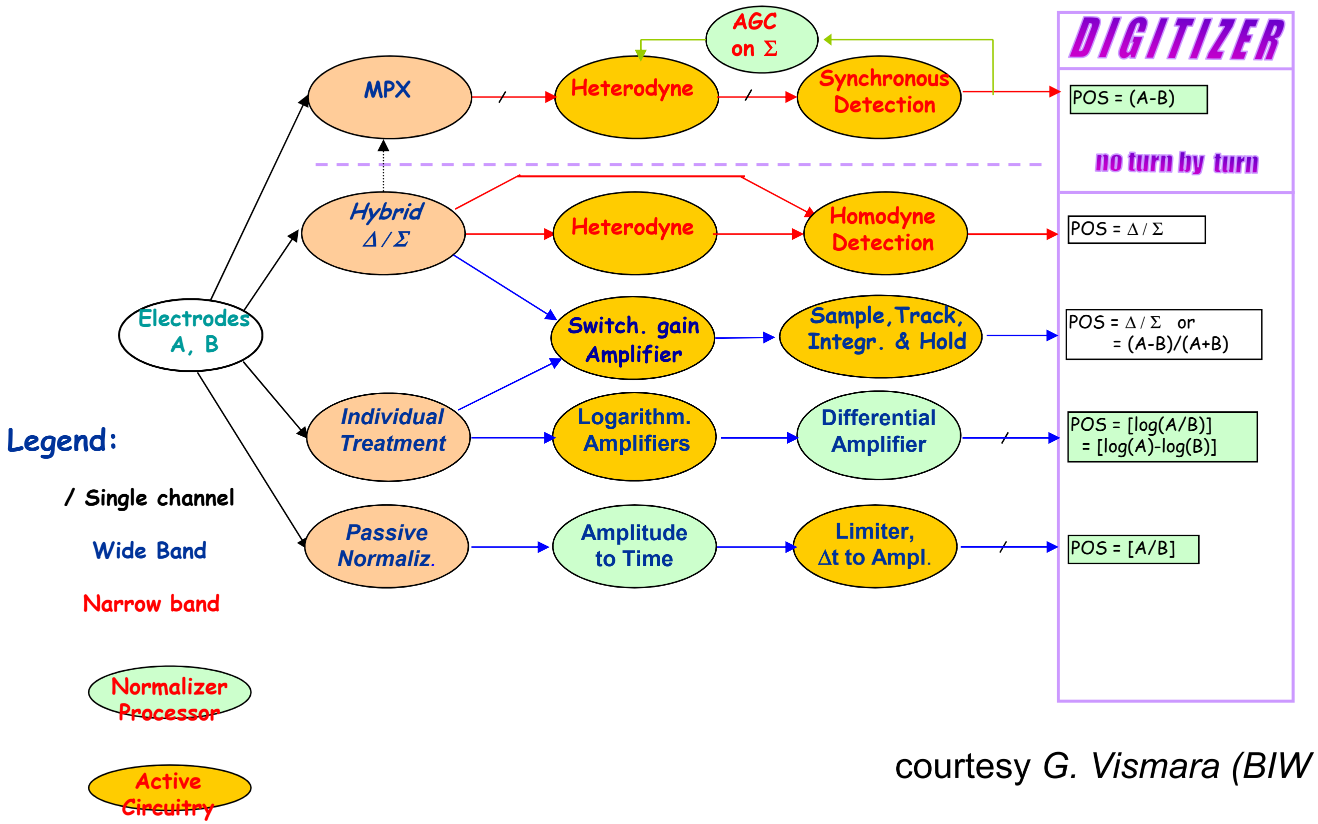

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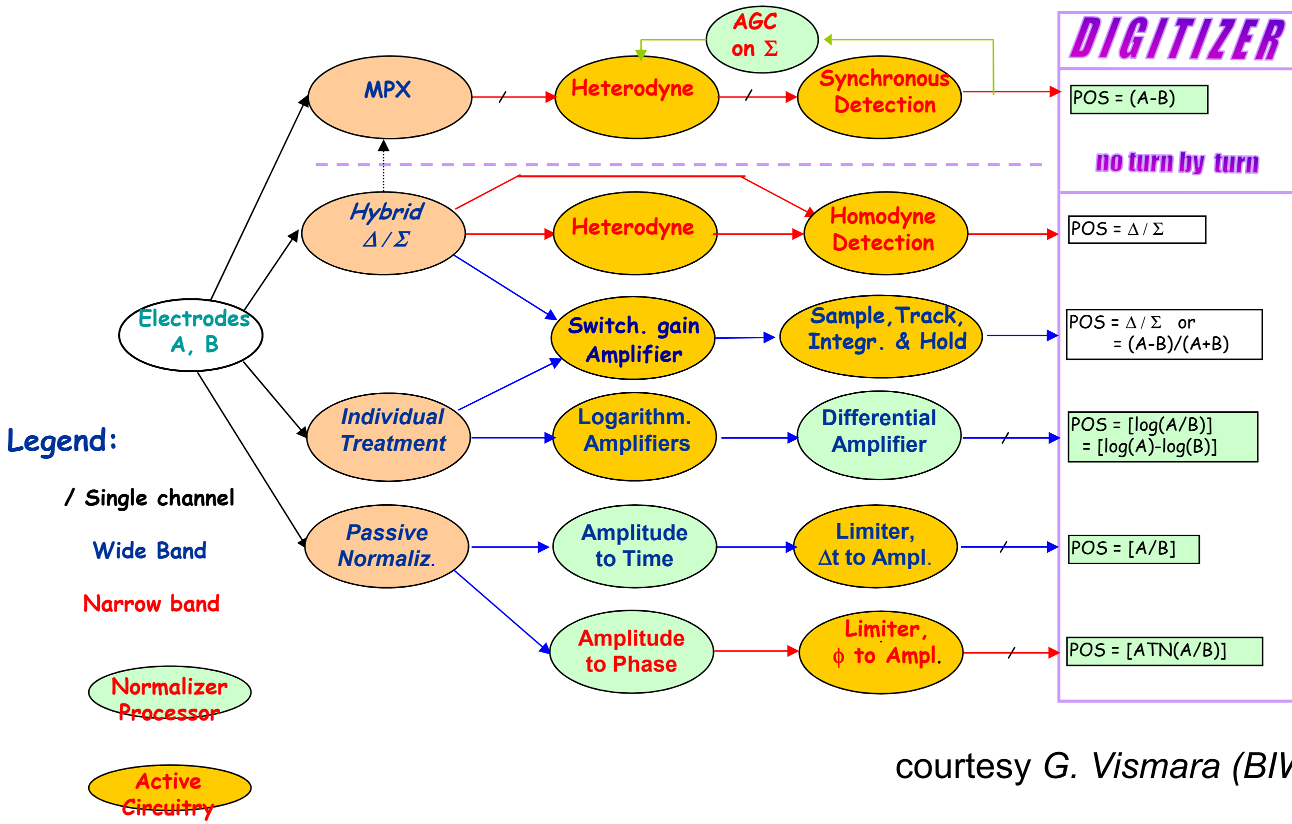

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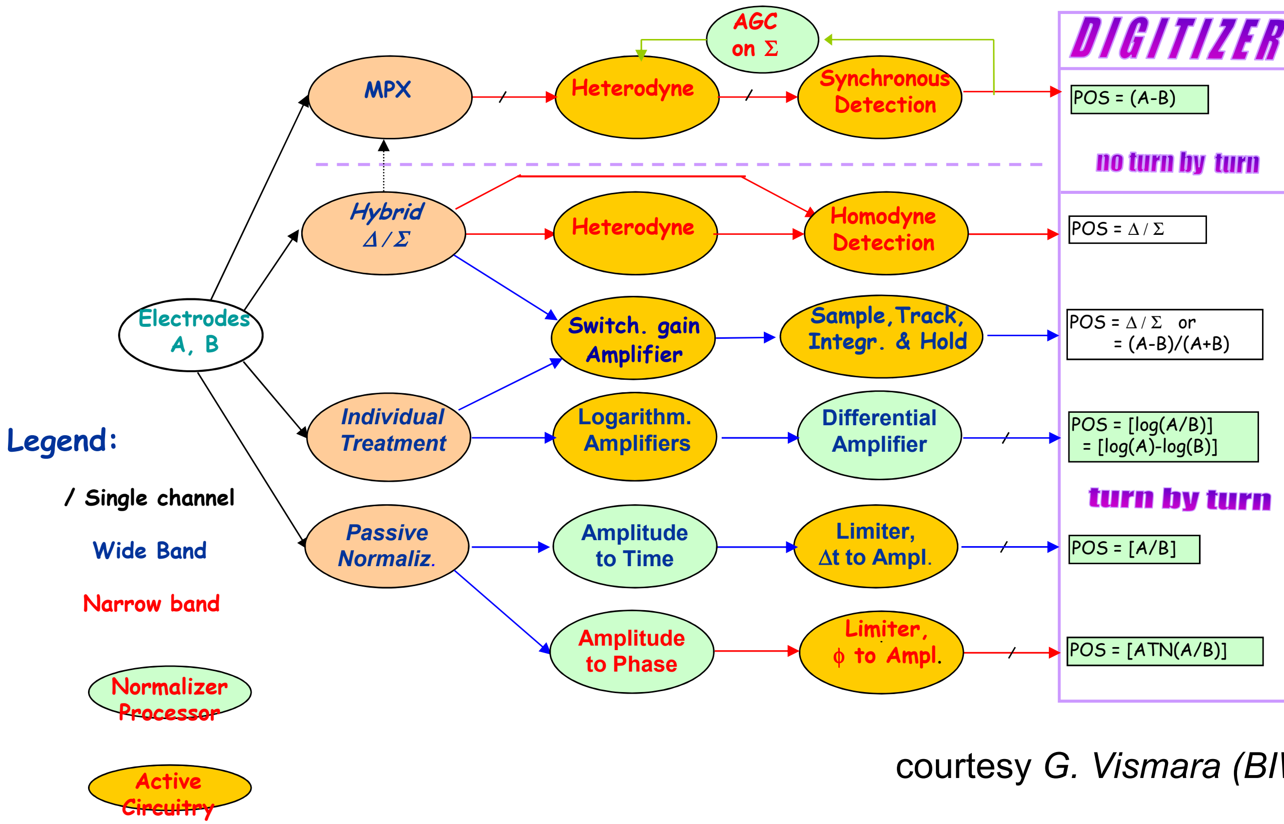
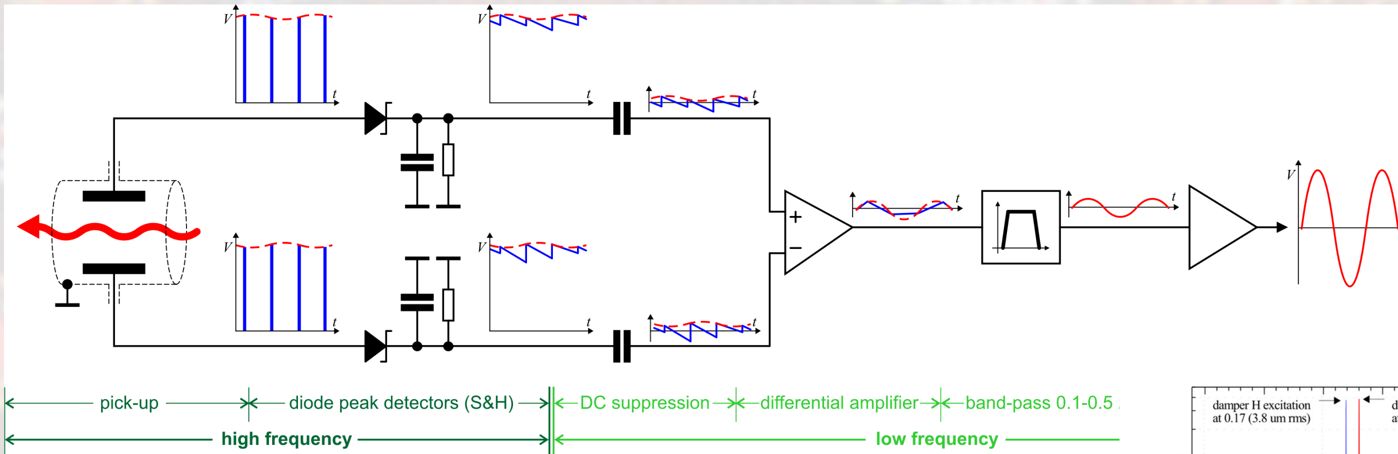
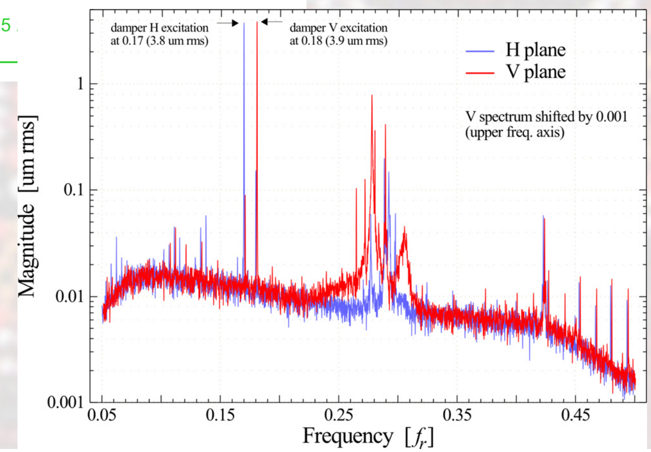


courtesy *G. Vismara (BIW 2001)*

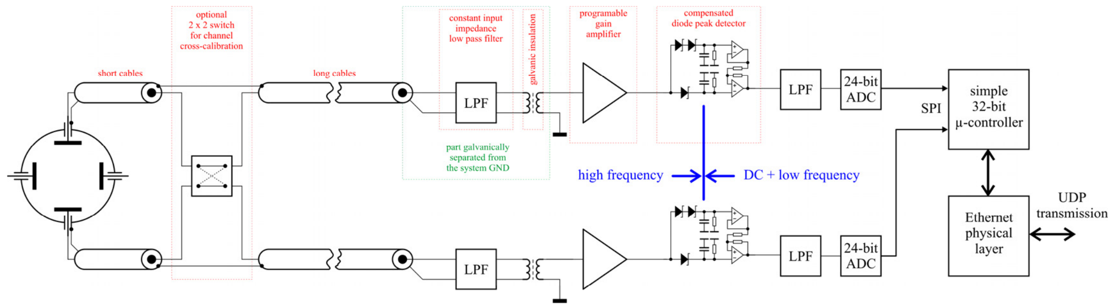
New member of analog orbit measurements:

- Further development of “BBQ”-tune measurement system (M.Gasior, CERN)





Compensated Diode Detector for BOM



Diode ORbit (DOR) Measurement

2 channels shown for one pick-up plane,
one 19" 1U unit accommodates 8 channels

courtesy *M. Gasior*

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

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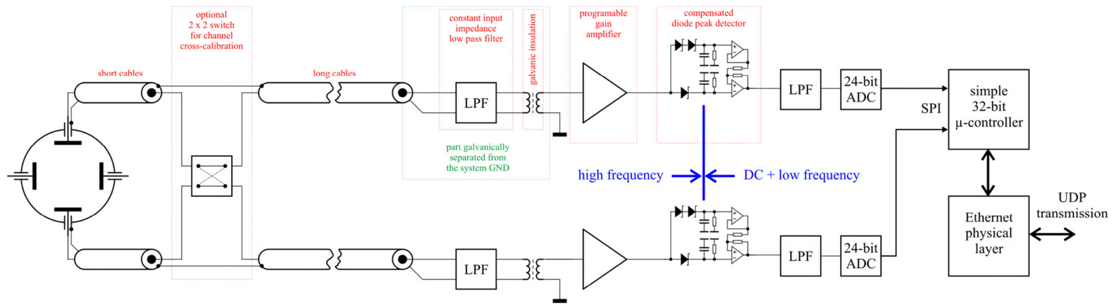

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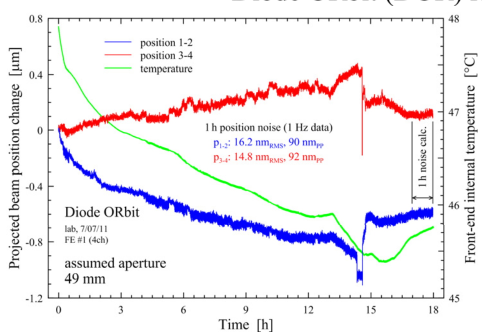
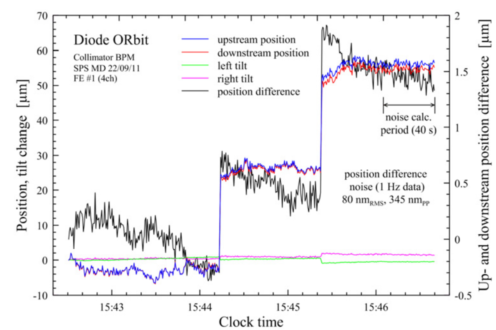


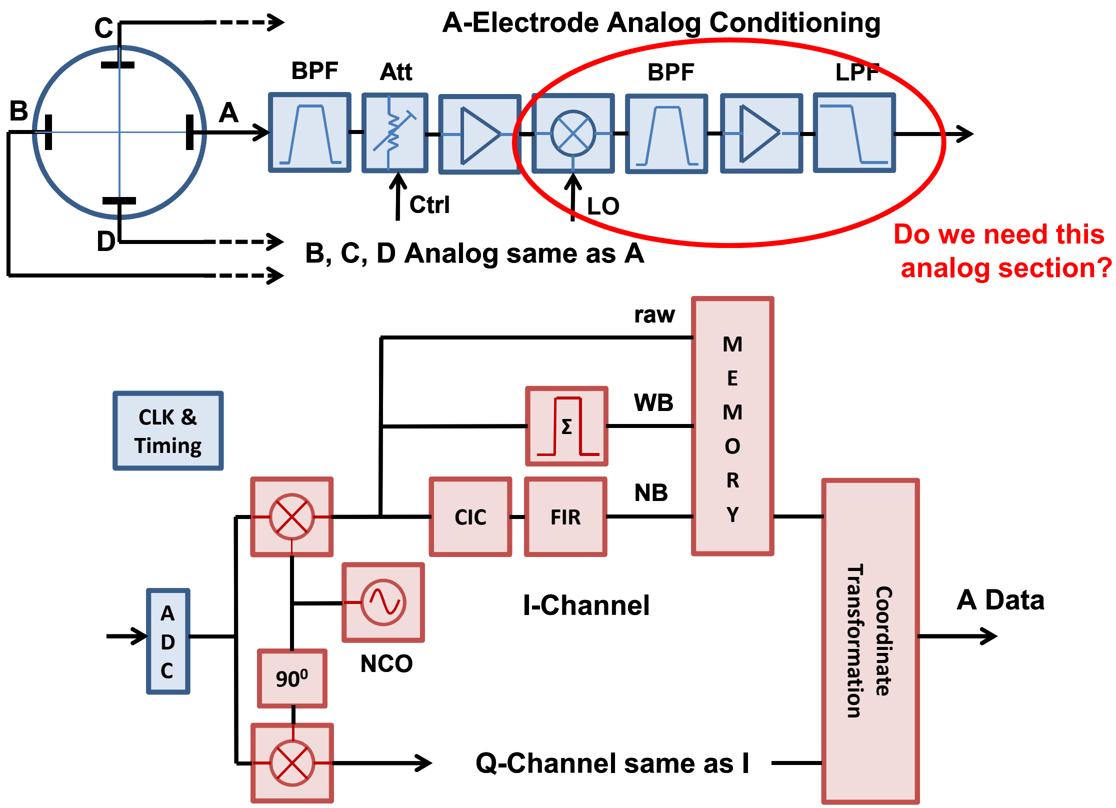


- Sub-micrometre resolution can be achieved with relatively simple hardware and signals from any position pick-up.
- To be used for the future LHC collimators with embedded BPMs.

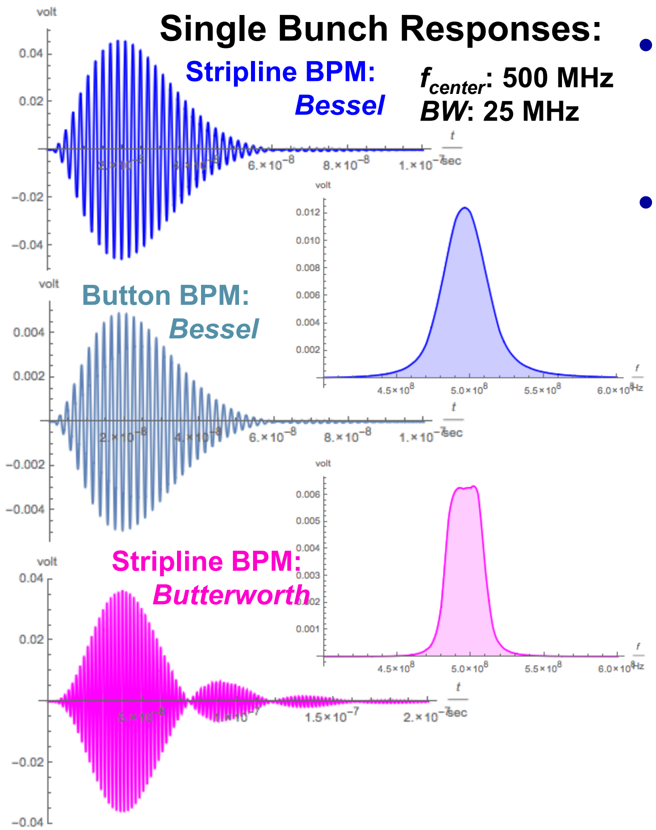
Digital BPM Signal Processing

- **Why digital signal processing?**
  - Better reproducibility of the beam position measurement
    - Robust to environmental conditions, e.g. temperature, humidity, (radiation?)
    - No slow aging and/or drift effects of components
    - Deterministic, no noise or statistical effects on the position information
  - Flexibility
    - Modification of FPGA firmware, control registers or DAQ software to adapt to different beam conditions or operation requirements
  - Performance
    - Often better performance, e.g. higher resolution and stability compared to analog solutions
    - No analog equivalent of digital filters and signal processing elements.
- **BUT: Digital is not automatically better than analog!**
  - Latency of pipeline ADCs (FB applications)
  - Quantization and CLK jitter effects, dynamic range & bandwidth limits
  - Digital BPM solutions tend to be much more complex than some analog signal processing BPM systems
    - Manpower, costs, development time

BPM Read-out Electronics

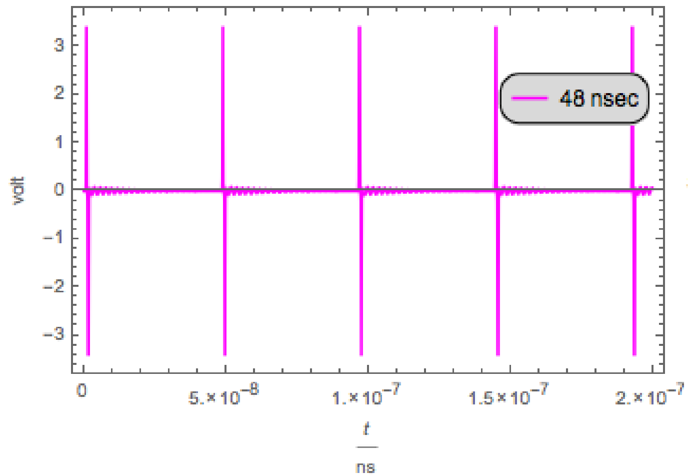


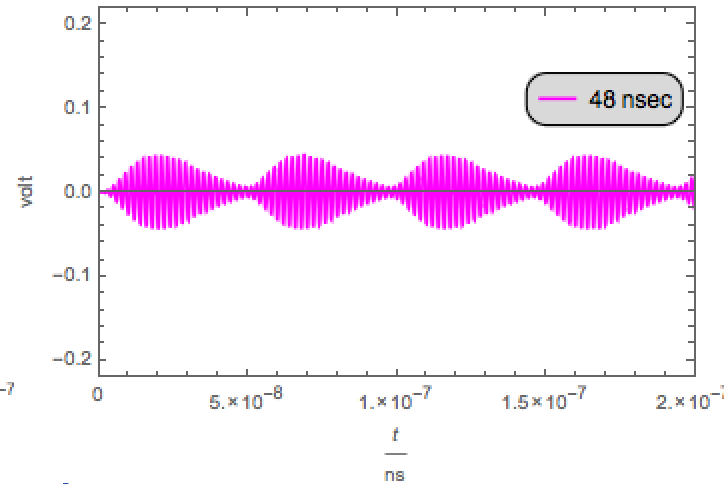
“Ringing” Bandpass-Filter (BPF)



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

“Ringing” BPF & Multi-Bunches





- **Bunch spacing < BPF ringing time:**
  - **Superposition of single bunch BPF responses**
  - **More continuous “ringing”, smearing of SB responses**
- **Bunch spacing < BPF rise time**
  - **Constructive signal pile-up effect**
    - ➢ **Output signal level increases linear with decreasing bunch spacing**

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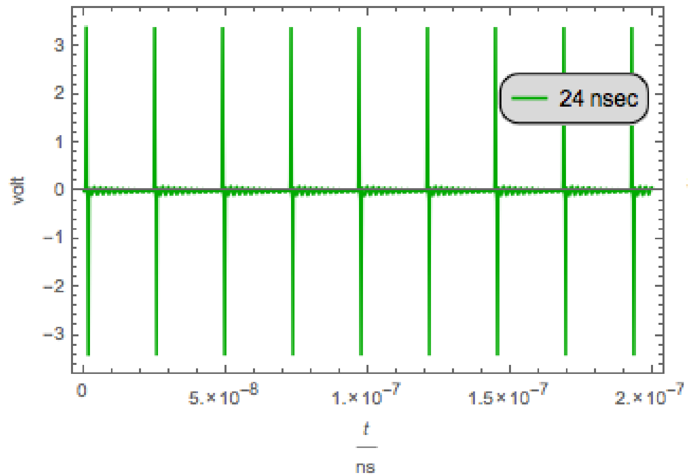

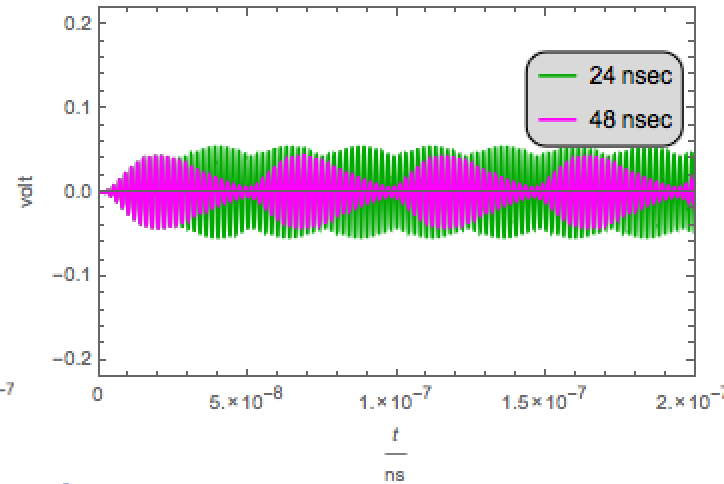

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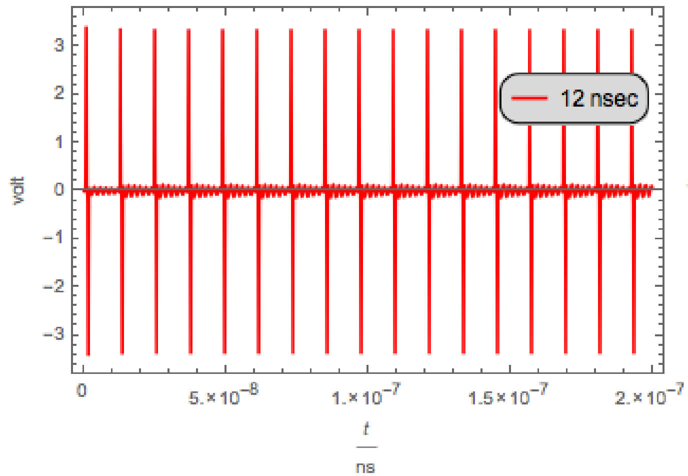

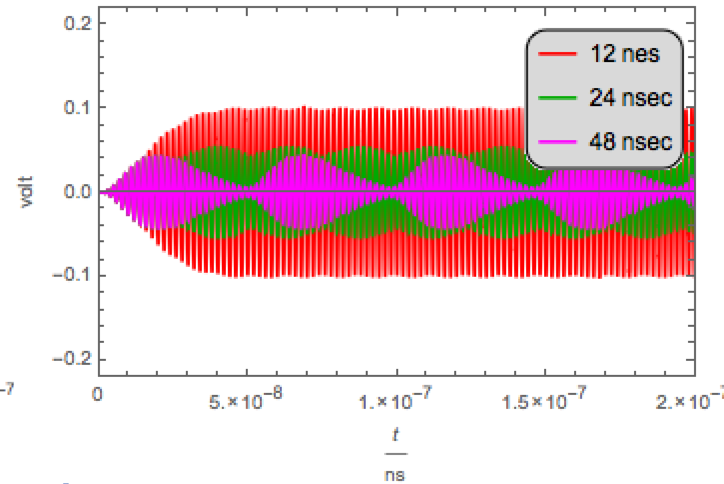

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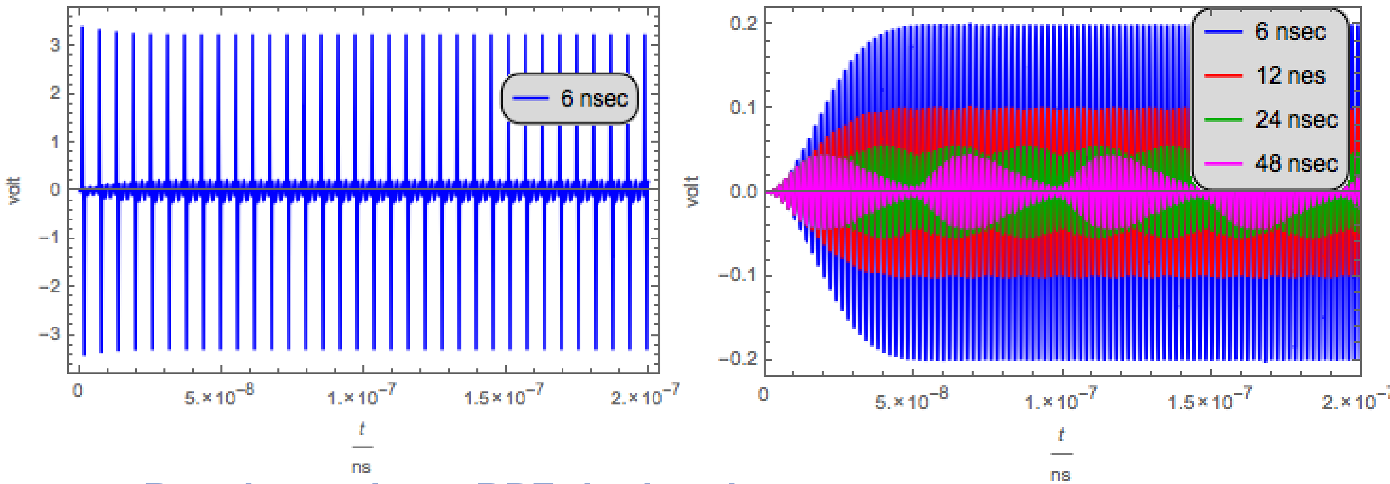

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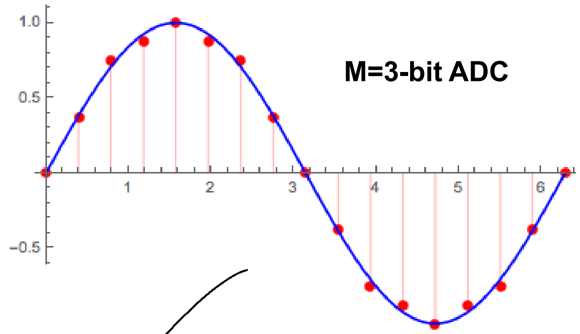
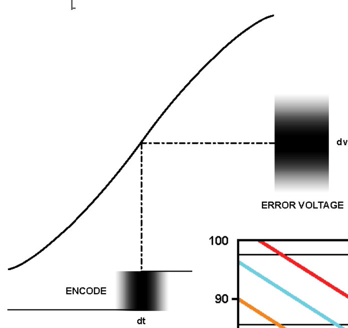
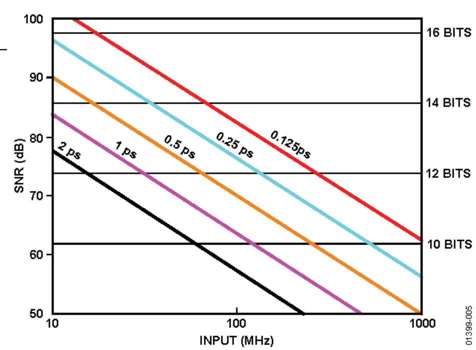
Analog Digital Converter







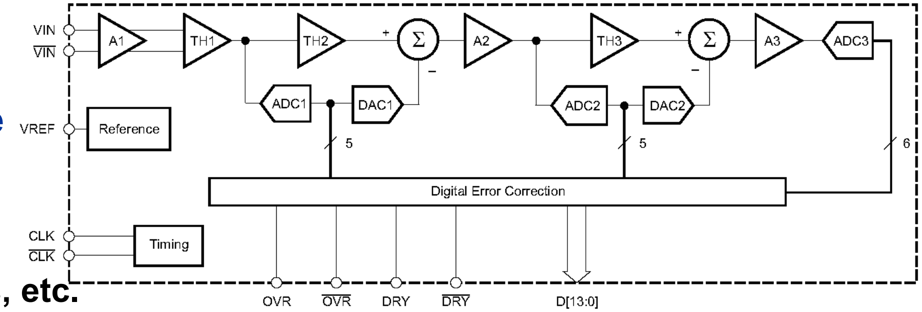
- **Quantization of the continuous input waveform at equidistant spaced time samples**
  - **Digital data is discrete in amplitude and time**
- **LSB voltage (resolution)** $Q = \frac{V_{FSR}}{2^M}$
  - **E.g. 61 µV (14-bit), 15 µV (16-bit) @ 1 volt V_{FSR}**
- **Quantization error (dynamic range)**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

ADC Technology

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

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

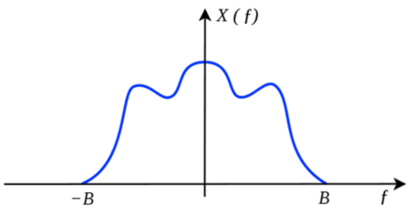
- **Dual Channel**
  - **I-Q sampling with separate ADCs**
- **Pipeline architecture**
  - **Continuous CLK**
  - **Data latency**
- **A-D mixed designs**
  - **Mixers, gain, filters, etc.**



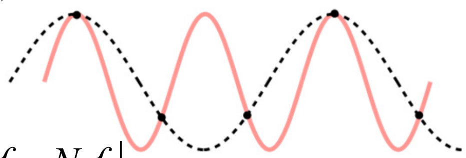
Sampling Theory

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

$$f_s \geq 2 f_{\max}$$



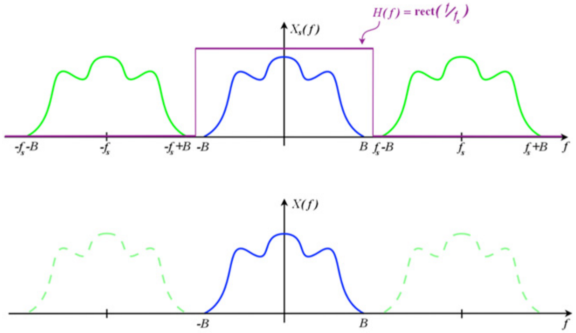
$$x(t)=\sum_{n=-\infty}^{+\infty} x_n \frac{\sin \pi(2 f_{\max} t-n)}{\pi(2 f_{\max} t-n)}=\sum_{n=-\infty}^{+\infty} x_n \operatorname{sinc} \frac{t-nT}{T}$$

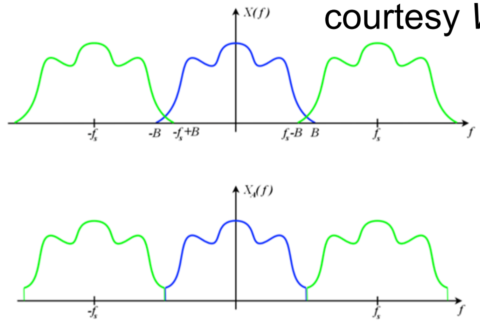


- **Aliasing of a sampled sin-function**
  - **Samples can be interpreted by**

$$f_{alias}(N)=\left|f-N f_s\right|$$

courtesy *Wikipedia*





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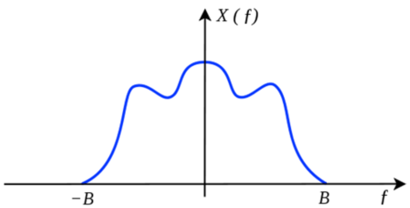
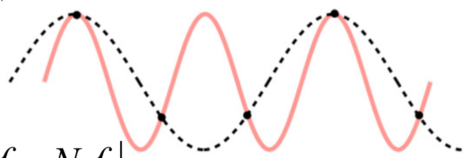


$$x(t) = \sum_{n=-\infty}^{+\infty} x_n \frac{\sin \pi (2 f_{\max} t - n)}{\pi (2 f_{\max} t - n)} = \sum_{n=-\infty}^{+\infty} x_n \operatorname{sinc} \frac{t - nT}{T}$$



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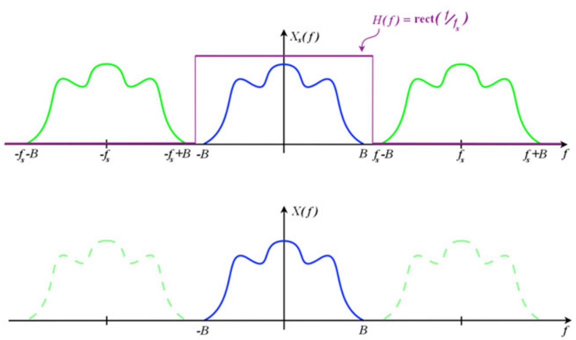
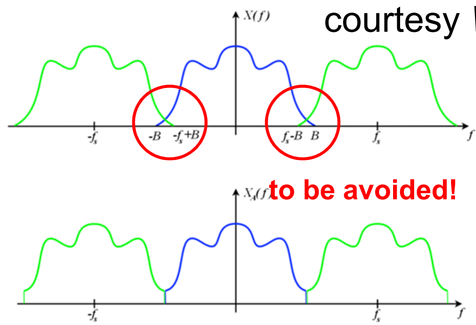
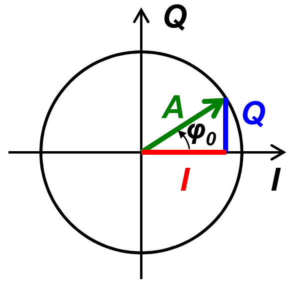




I-Q Sampling



$$y(t) = I \sin \omega t + Q \cos \omega t$$

$$I = A \cos \varphi_0 \qquad A = \sqrt{I^2 + Q^2}$$

$$Q = A \sin \varphi_0 \qquad \varphi_0 = \arctan\left(\frac{Q}{I}\right)$$

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

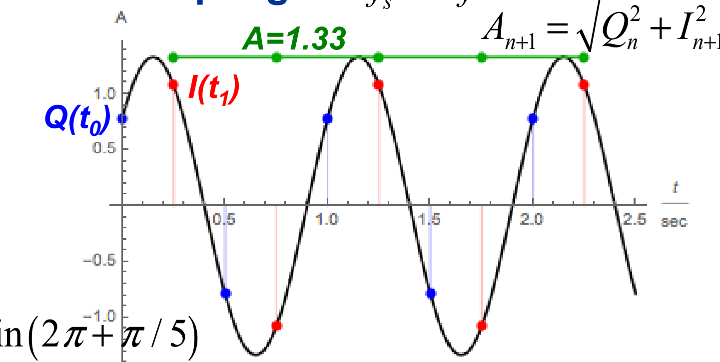
$$y(t) = A \sin(\omega t + \varphi_0)$$

$$y(t) = \underbrace{A \cos \varphi_0}_{=:I} \sin \omega t + \underbrace{A \sin \varphi_0}_{=:Q} \cos \omega t$$

I: in-phase component   **Q: quadrature-phase component**

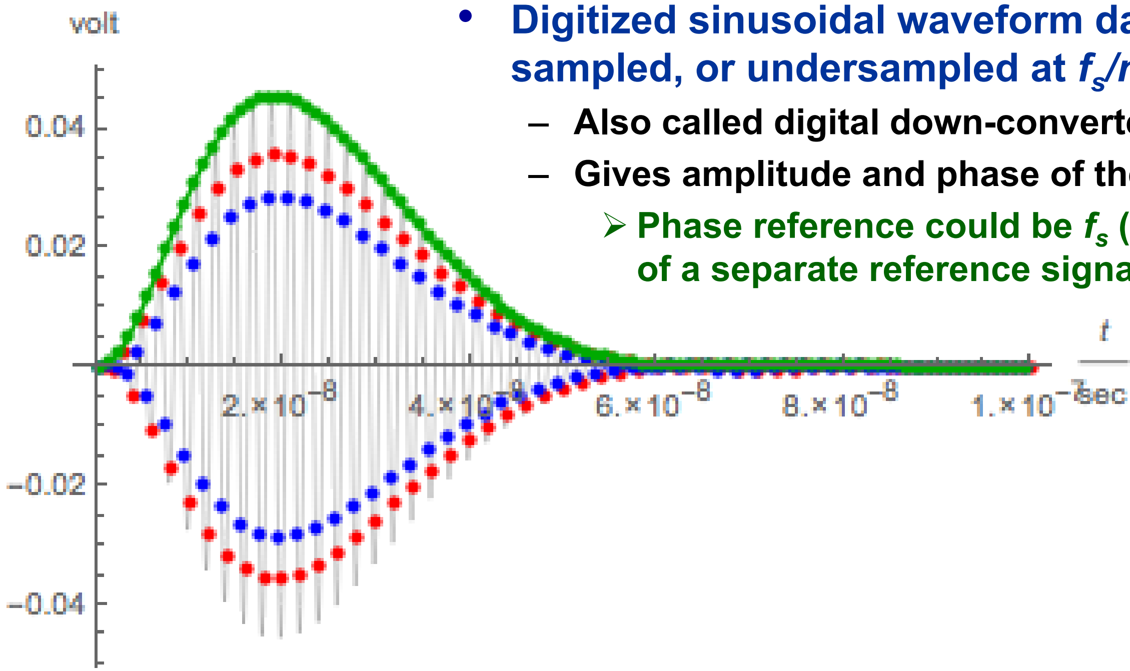
- **I-Q sampling at:** $f_s = 4f$

$$A_{n+1} = \sqrt{Q_n^2 + I_{n+1}^2}$$



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

I-Q Demodulation of BPM Signals

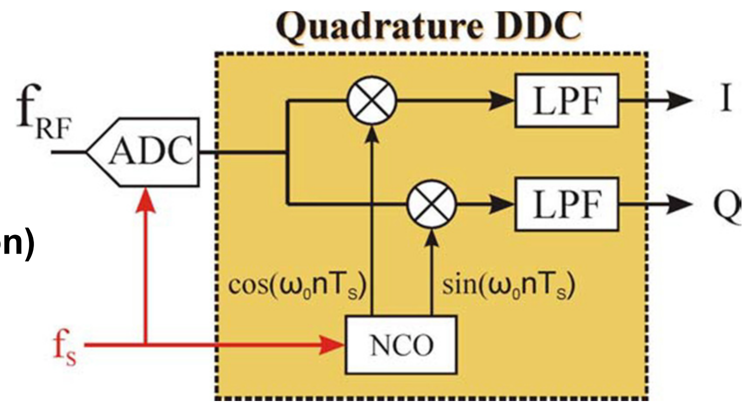


n=2

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

Digital Down-Converter

- **Goals**
  - Convert the band limited RF-signal to baseband (demodulation)
  - Data reduction (decimation)
- **DDC Building blocks:**
  - ADC
    - ➢ Single fast ADC (oversampling)
  - Local oscillator
    - ➢ Numerically controlled oscillator (NCO) based on a direct digital frequency synthesizer (DDS)
  - Digital mixers ("ideal" multipliers)
  - Decimating low pass (anti alias) filters
    - ➢ Filtering and data decimation.
    - ➢ Implemented as CIC and/or FIR filters



courtesy *T. Schilcher*

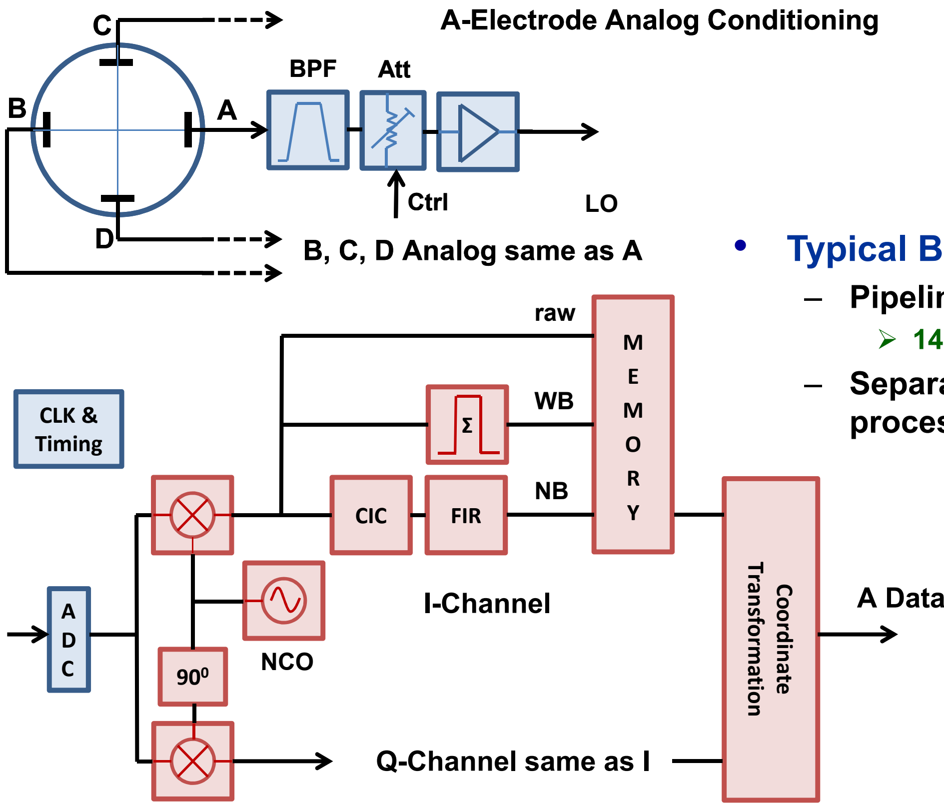
Signal/Noise & Theoretical Resolution Limit

- **Minimum noise voltage at the 1st gain stage:** $$v_{noise} = \sqrt{4 k_B T R \Delta f}$$
  - **With the stripline BPM and Bessel BPF example:** **R = 50 Ω, Δf = 25 MHz ➔ v_{noise} = 4.55 µV (-93.83 dBm)**
- **Signal-to-noise ratio:** $$S/N = \frac{\Delta v}{v_{noise}}$$
  - **Where Δv is the change of the voltage signal at the 1st gain stage due to the change of the beam position (Δx, Δy).**
  - **Consider a signal level v ≈ 22.3 mV (-20 dBm)**
    - **Bessel BPF output signal of the stripline BPM example**
  - **22.3 mV / 4.55 µV ≈ 4900 (73.8 dB) would be the required dynamic range to resolve the theoretical resolution limit of the BPM**
    - **Under the given beam conditions, e.g. n=1e10, σ=25mm, single bunch, etc.**
    - **The equivalent BPM resolution limit would be: Δx=Δy=0.66µm (assuming a sensitivity of ~2.7dB/mm)**

S/N & BPM Resolution (cont.)

- **Factors which reduce the S/N**
  - **Insertion losses of cables, connectors, filters, couplers, etc.**
    - ➢ **Typically sum to 3…6 dB**
  - **Noise figure of the 1st amplifier, typically 1…2 dB**
  - **The usable S/N needs to be >0 dB,**
    e.g. 2.3 dB is sometimes used as lowest limit. (*HP* SA definition)
  - **For the given example the single bunch / single turn resolution limit reduces by ~10 dB (~3x): 2…3 µm**
- **Factors to improve the BPM resolution**
  - **Increase the signal level**
    - ➢ **Increase BPM electrode-to-beam coupling, e.g. larger electrodes**
    - ➢ **Higher beam intensity**
  - **Increase the measurement time, apply statistics**
    - ➢ **Reduce the filter bandwidth (S/N improves with $1/\sqrt{BW}$)**
    - ➢ **Increase the number of samples (S/N improves with $\sqrt{n}$)**

BPM Read-out Electronics



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

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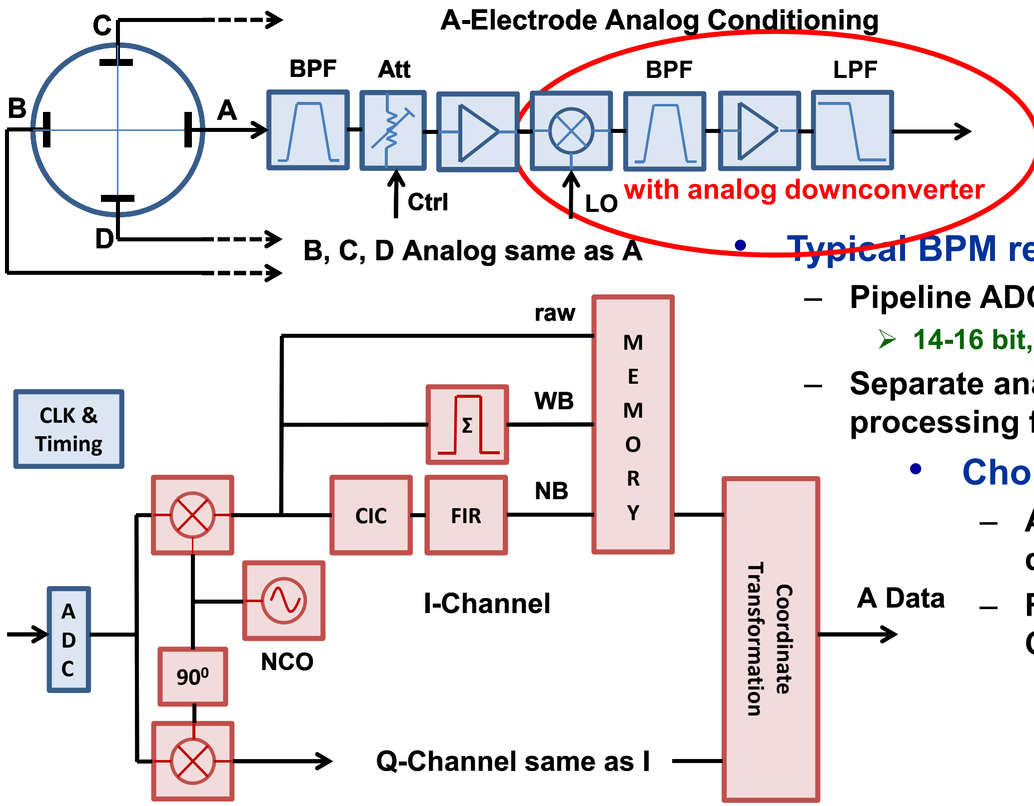

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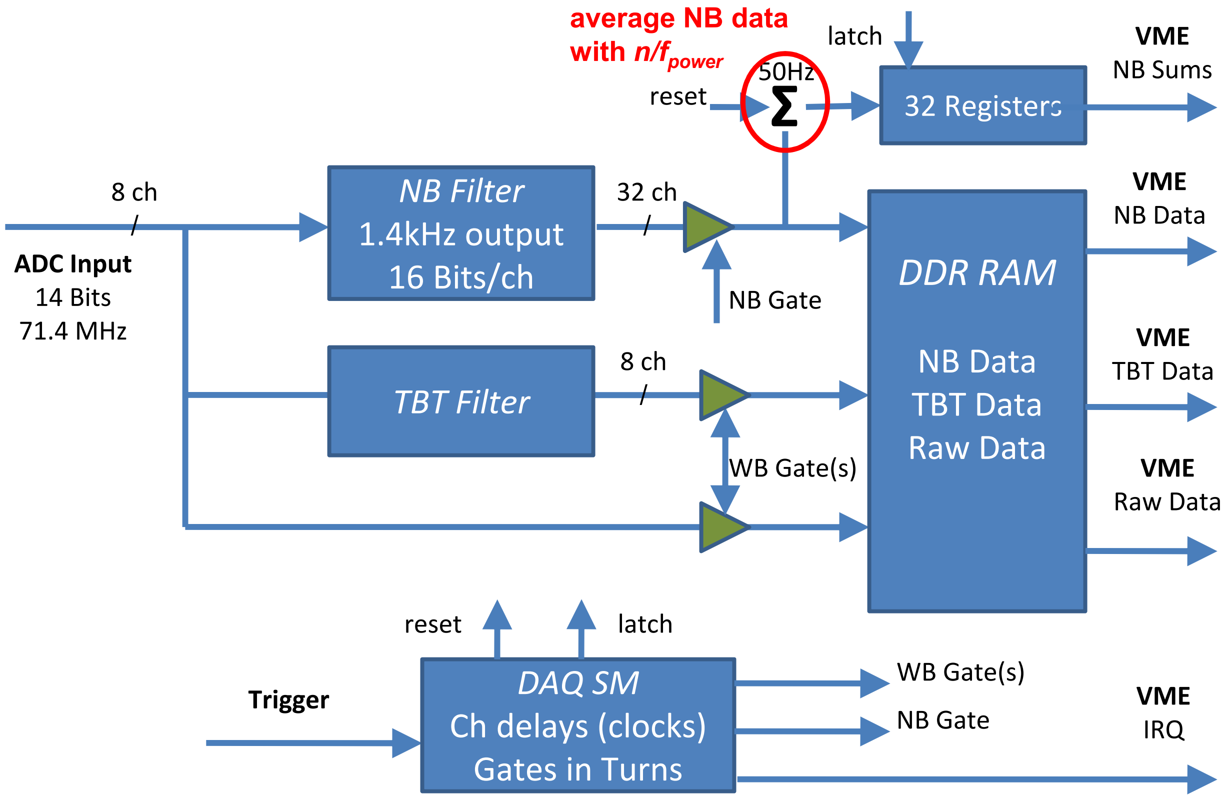
  - Pipeline ADC & FPGA
    - 14-16 bit, >300 MSPS, ~70 dB S/N
  - Separate analog signal processing for the channels
    - **Choices:**
      - Analog downconverter?!
      - RF locked (sync) CLK & LO signals?!
        - No I-Q required

Analog Downconverter vs. Direct Digital Under-Sampling

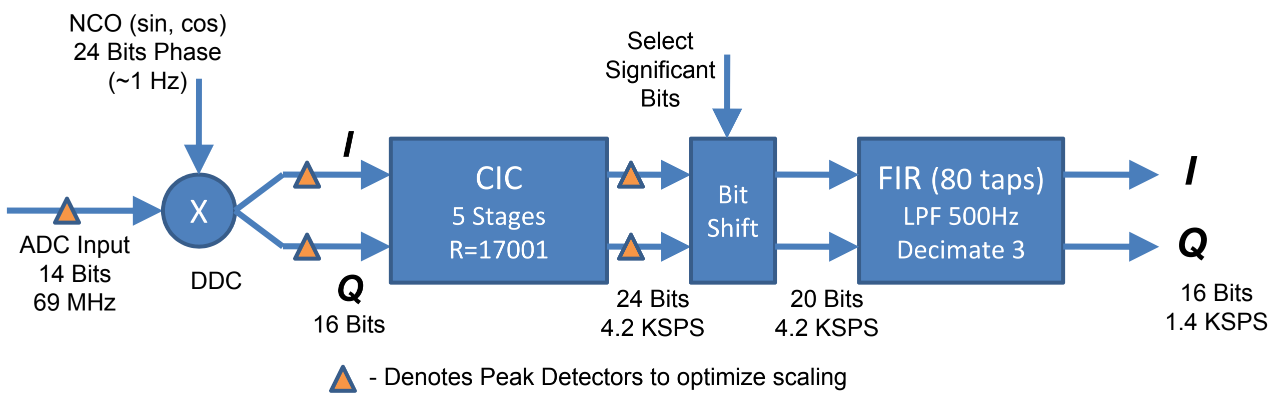
- ADC dynamic range is limited to ~70 dB
  - Not sufficient for most BPM applications
  - Need for analog signal attenuator / gain stages
    - ➢ Requires calibration signal to avoid "electronic offsets"
- Analog downconverter
  - \+ Certainly necessary for the conditioning of cavity BPM signals
  - \+ Allows sampling in the 1st Nyquist passband (no undersampling)
  - \+ Relaxes input RF filter requirements
  - \+ Relaxed ADC and CLK requirements
  - \+ May relax cable requirements and improve S/N
    - ➢ Analog hardware installation near the BPM pickup
    - ➢ Transfer analog IF signals out of the tunnel
  - – Additional analog hardware required
  - – Generates additional image frequencies
    - ➢ Consider image rejection analog mixer!

Example: ATF DR BPM Signal Processing



ATF BPM Narrowband Signal Processing

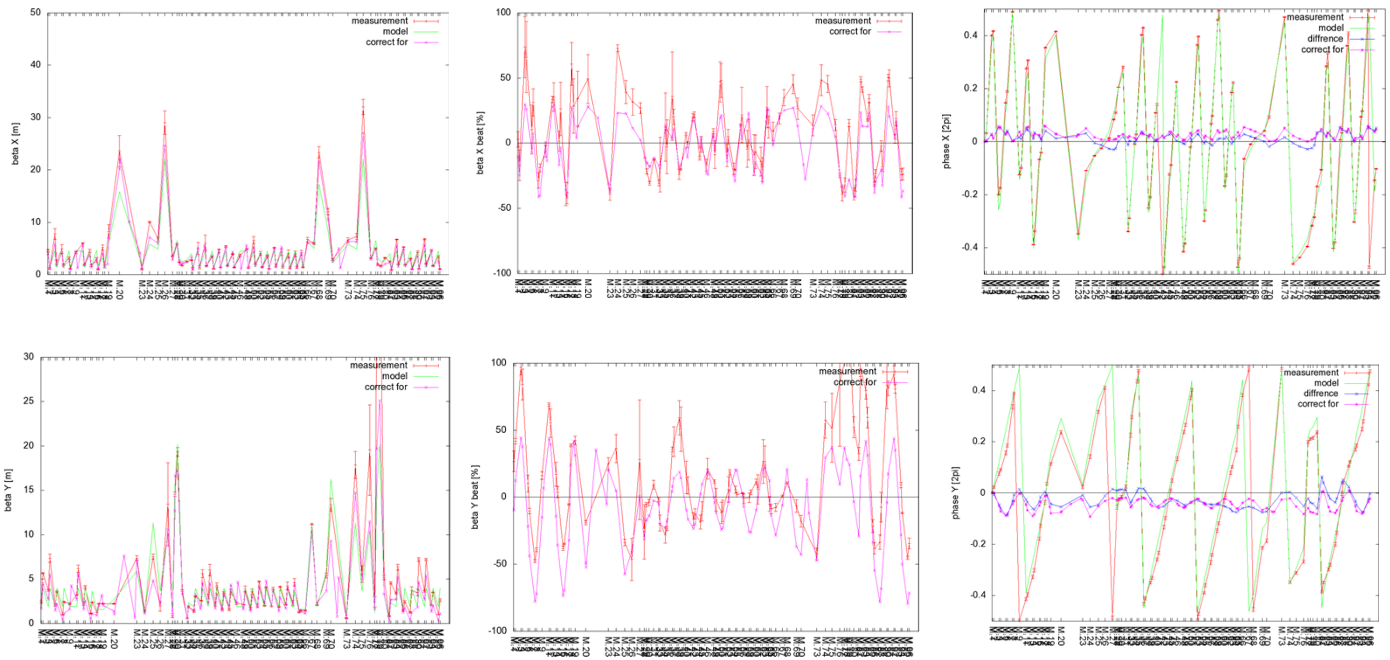
- **Process 8 ADC channels in parallel up to FIR filter**
  - **Digitally downconvert each channel into *I,Q* then filter I,Q independently**
  - **CIC Filters operating in parallel at 71.4MHz**
    - **Decimate by 17KSPS to 4.2KSPS output rate**
  - **1 Serial FIR Filter processes all 32 CIC Filter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



ATF DR Turn-by-Turn Beam Studies

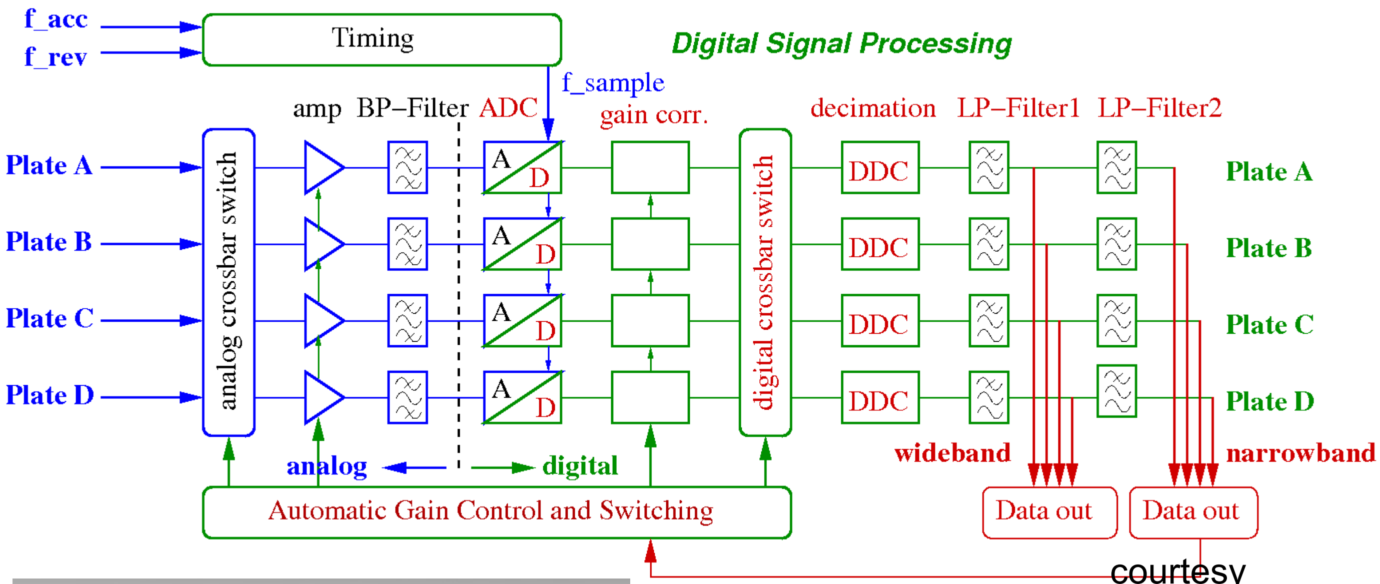
- **Beam optics studies with 96 BPMs in the ATF damping ring**

β function measurement **β beating measurement** **ϕ measurement**



courtesy *Y. Renier*

Libera BPM Electronics

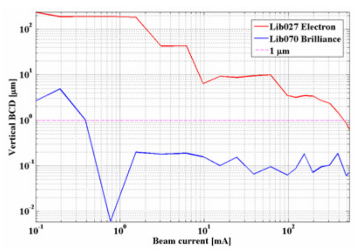


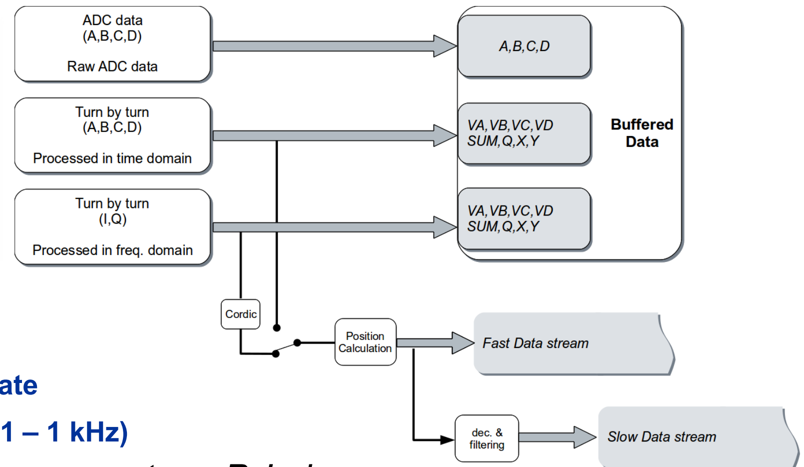
courtesy *Instrumentation Technologies*

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

Libera BPM Performance

Beam Current Dependence



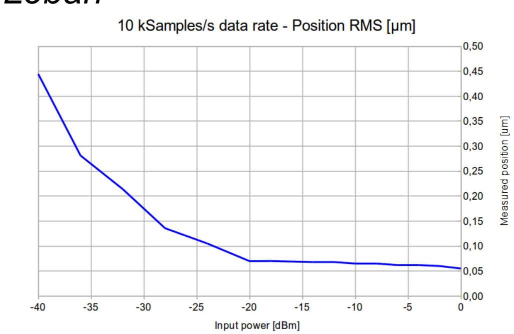


Libera Brilliance +

Electron beam position measurements

- **< 0.5 µm RMS at turn-by-turn data rate**
- **40 nm RMS at 10 kS/s data rate (0.01 – 1 kHz)**
- **10 nm RMS for slow monitoring**
- **sub-micron longterm stability**
- **Temperature drift < 200 nm / °C**
- **Full Fast Orbit Feedback implementation with magnet output**
- **Fast Interlock detection (< 100 µs)**
- **Clean turn to turn measurement using Time-Domain Processing**

courtesy *P. Leban*



Outline

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

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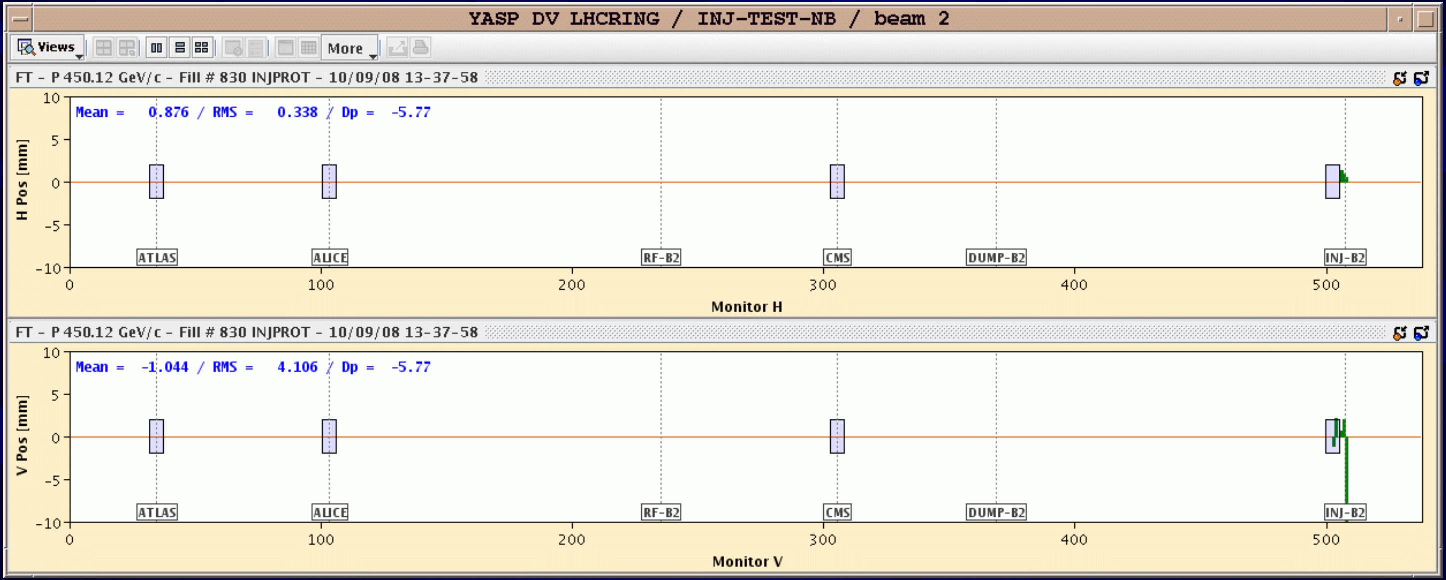

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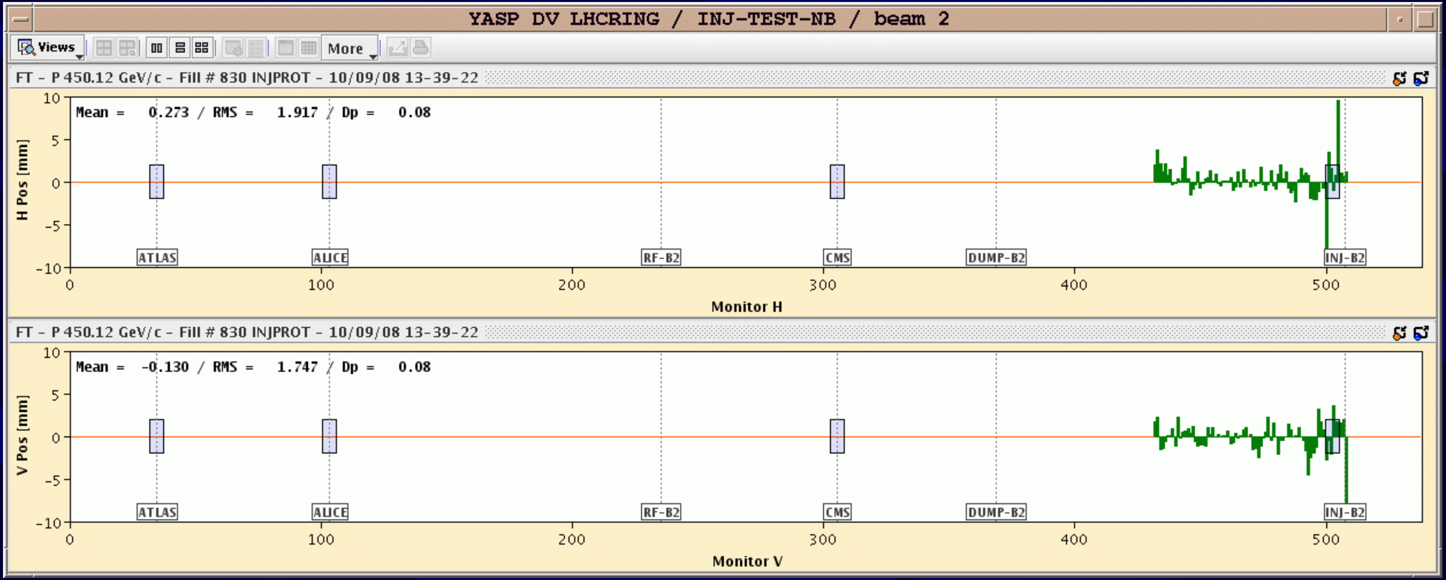

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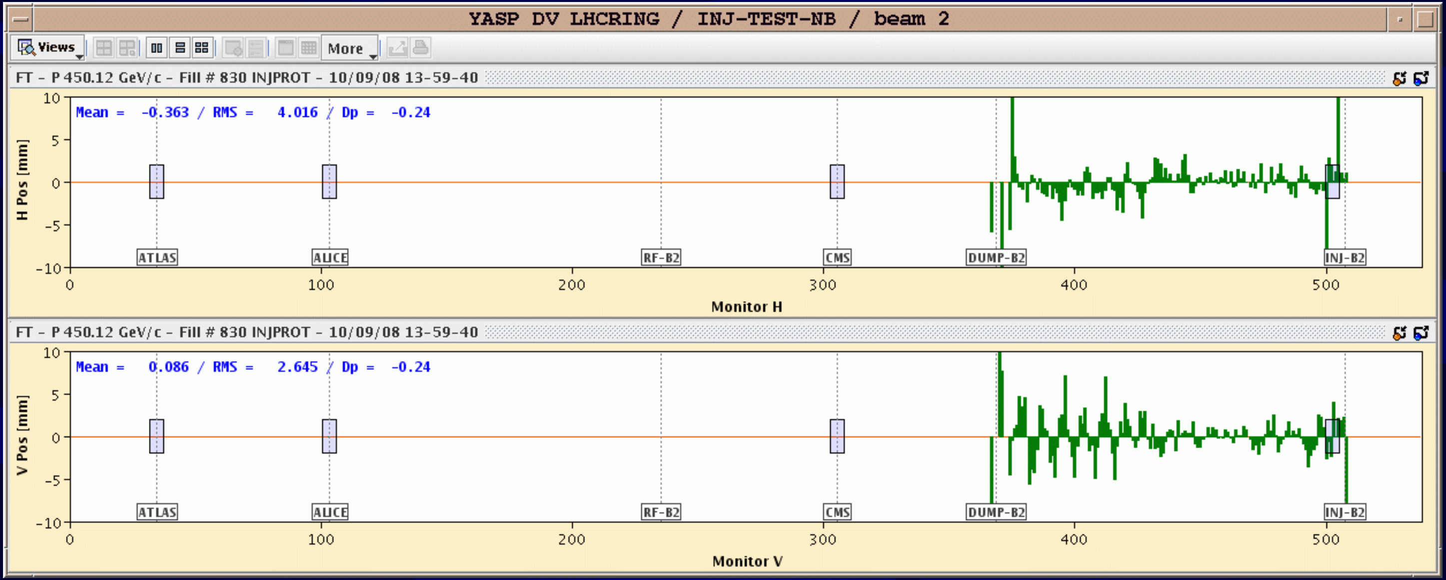

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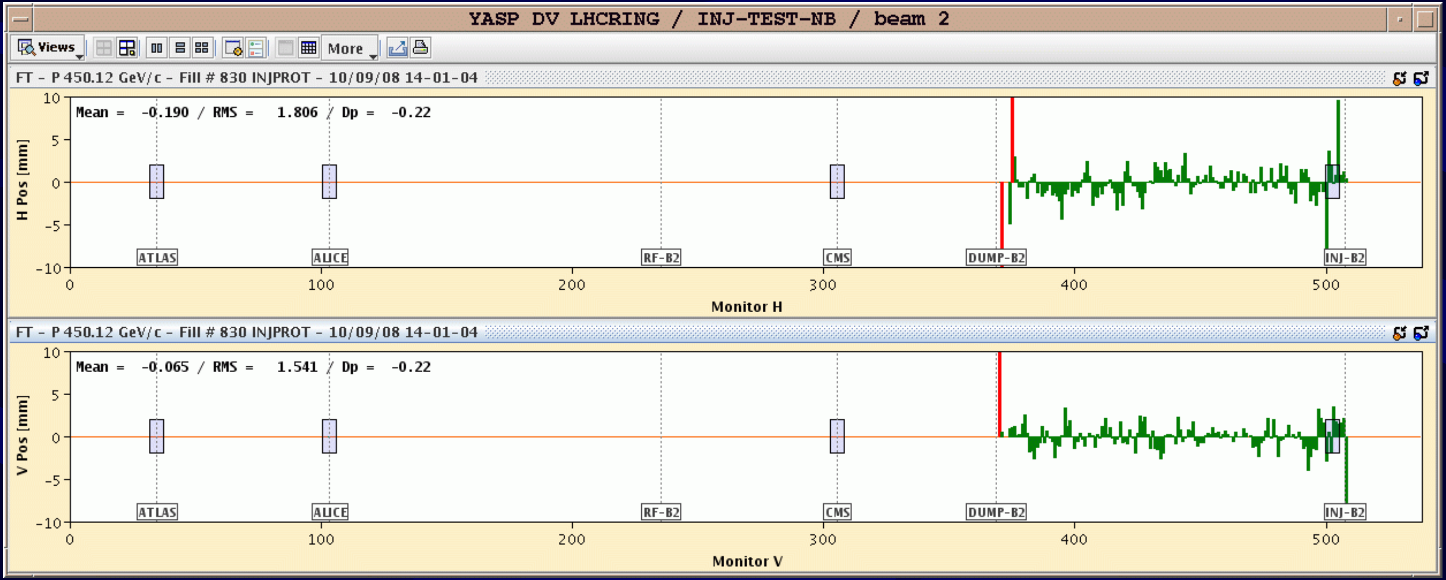

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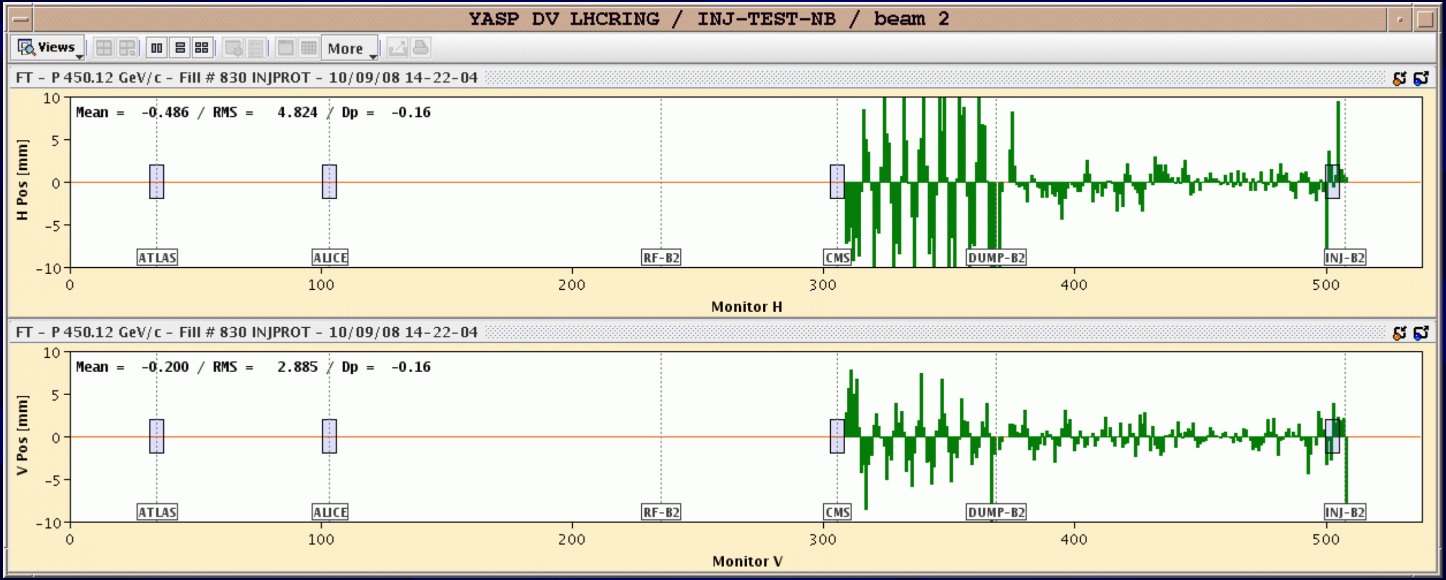

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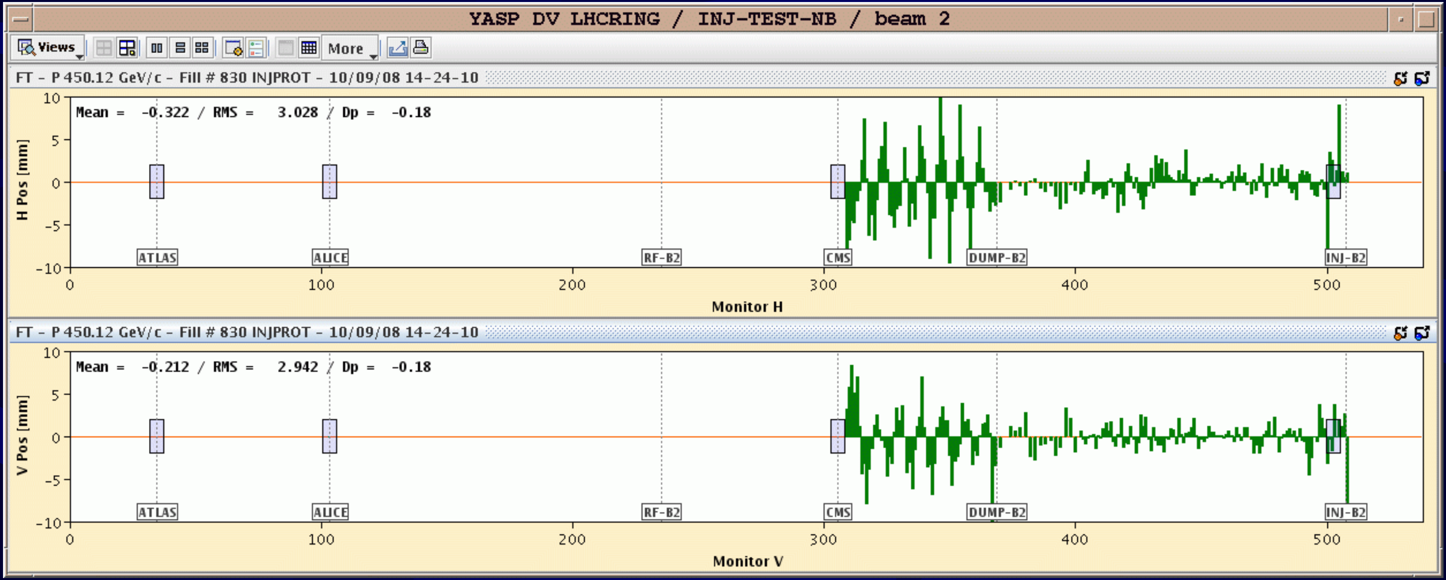

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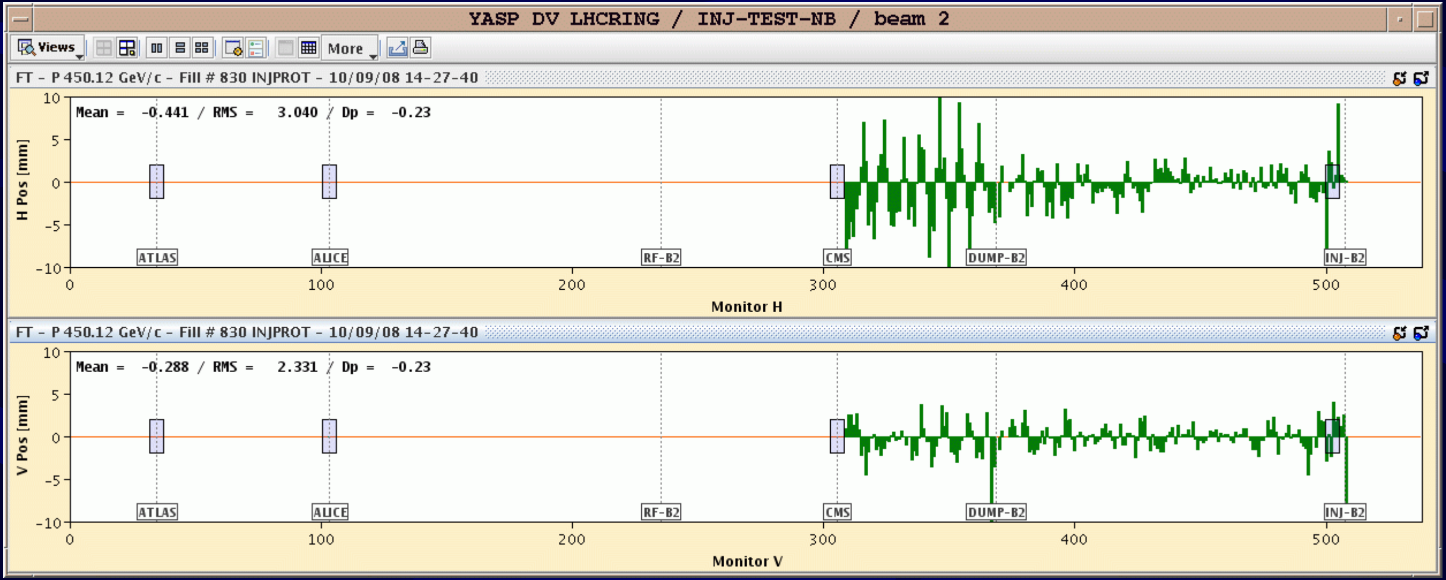

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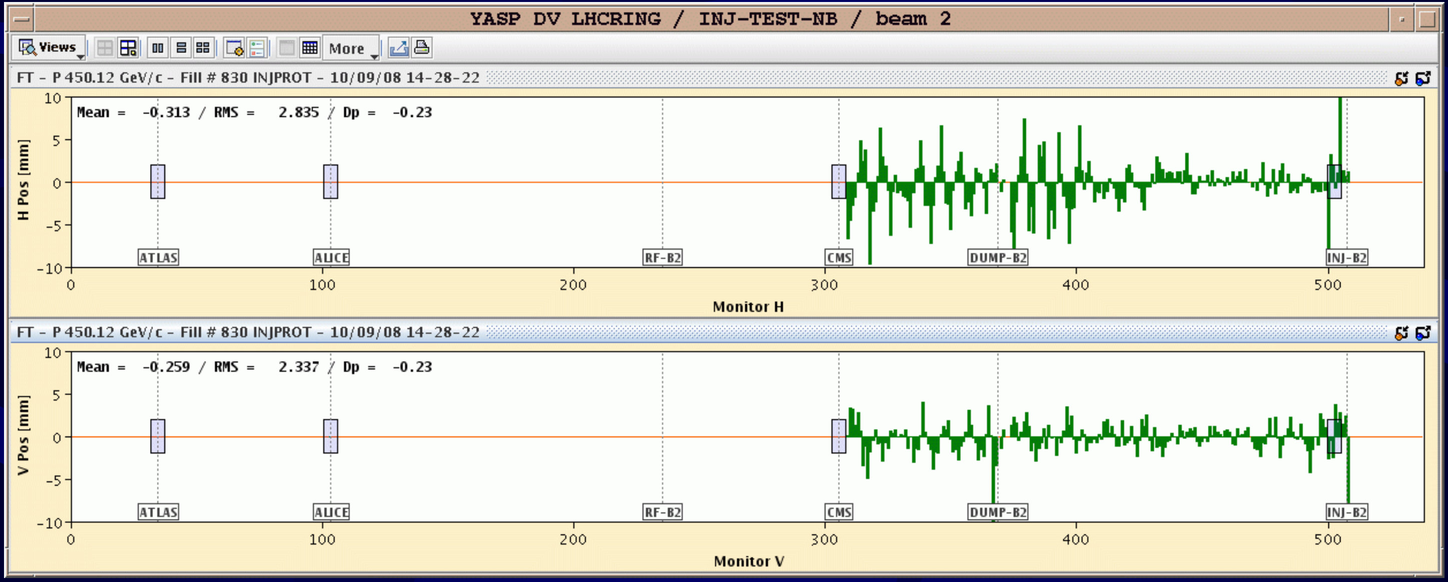

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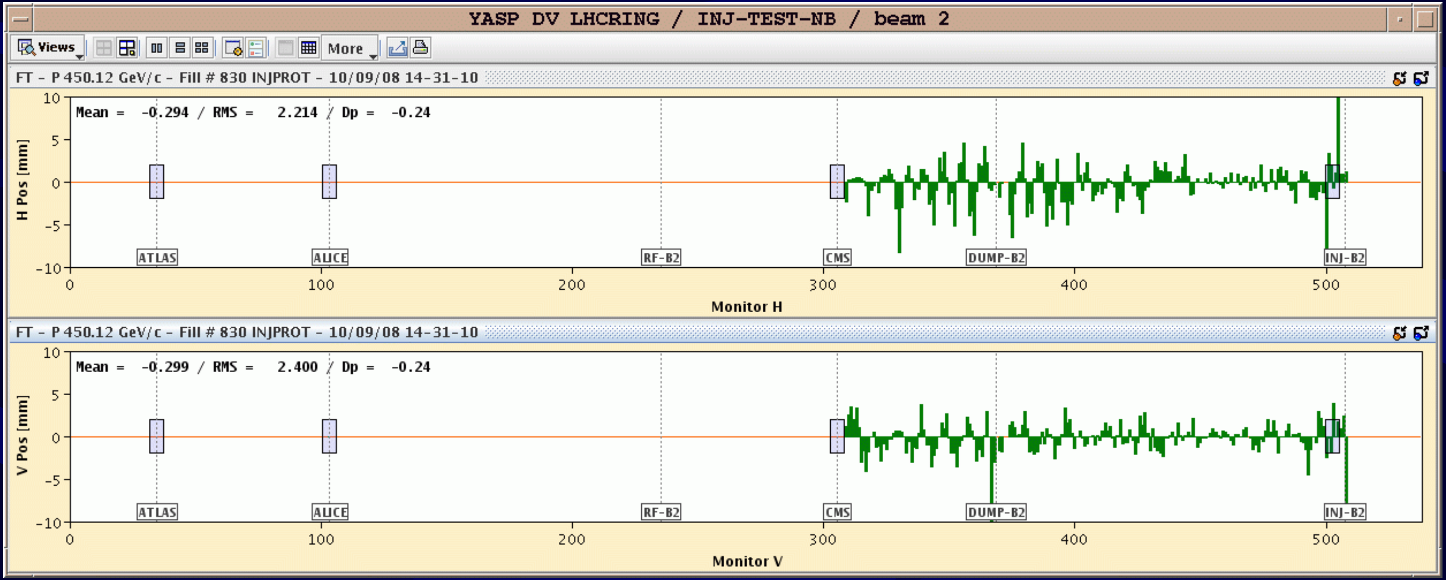

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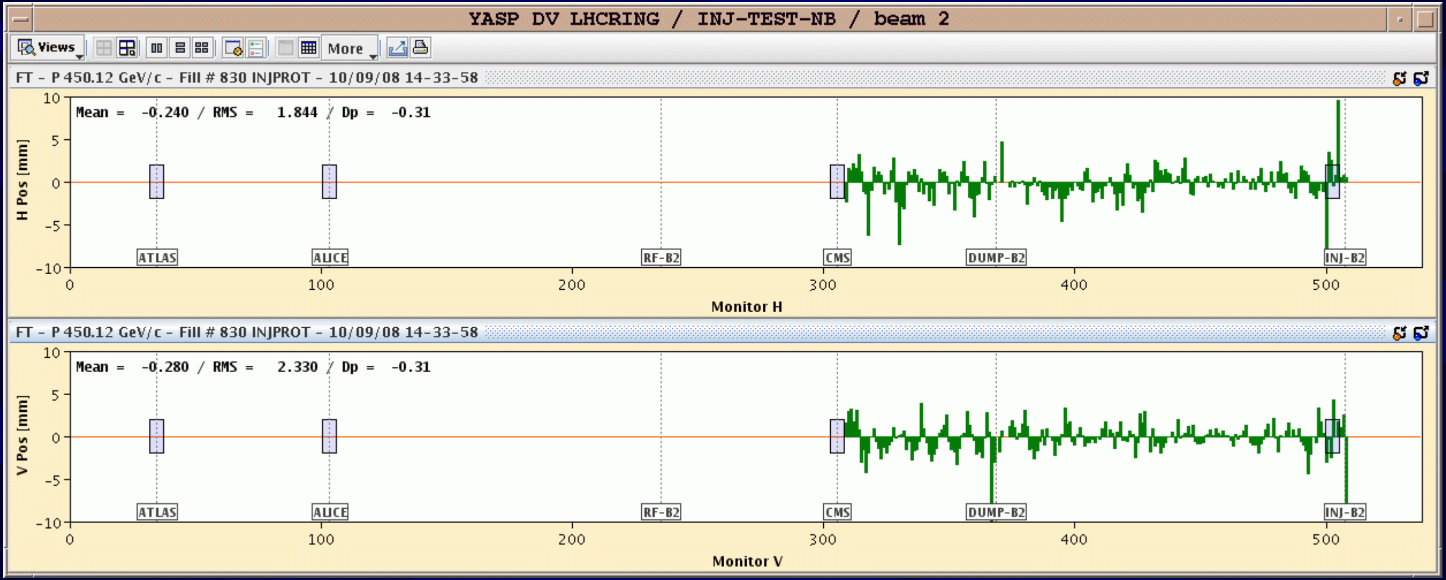

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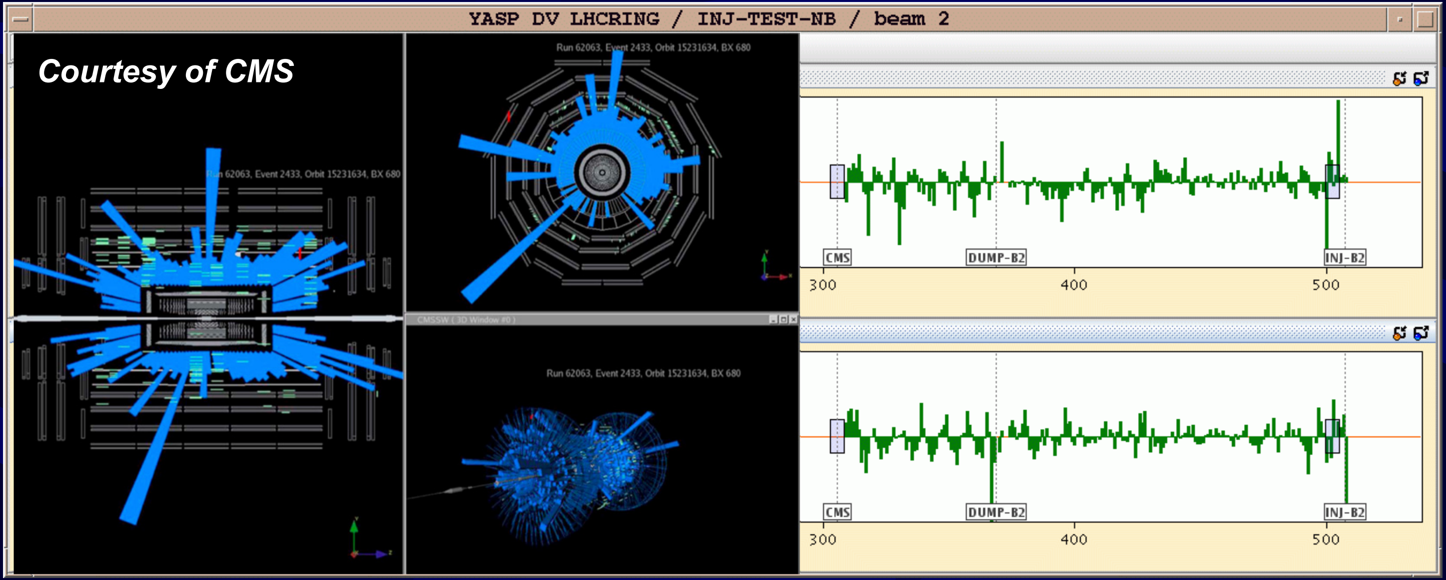

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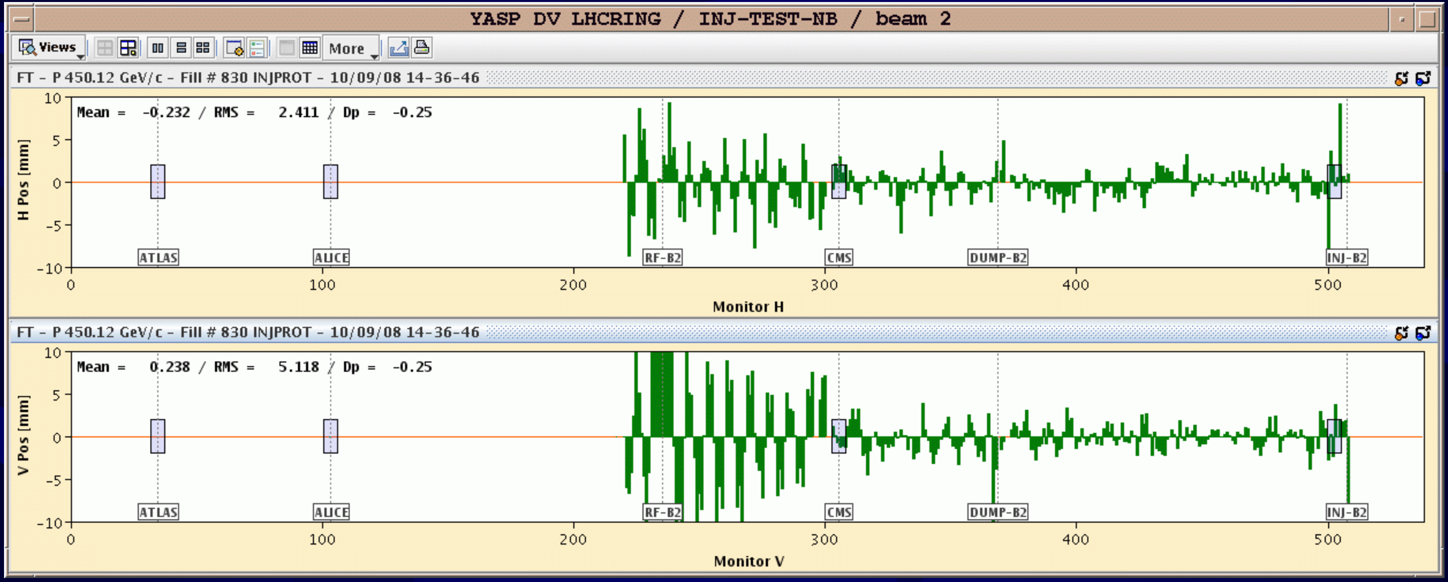

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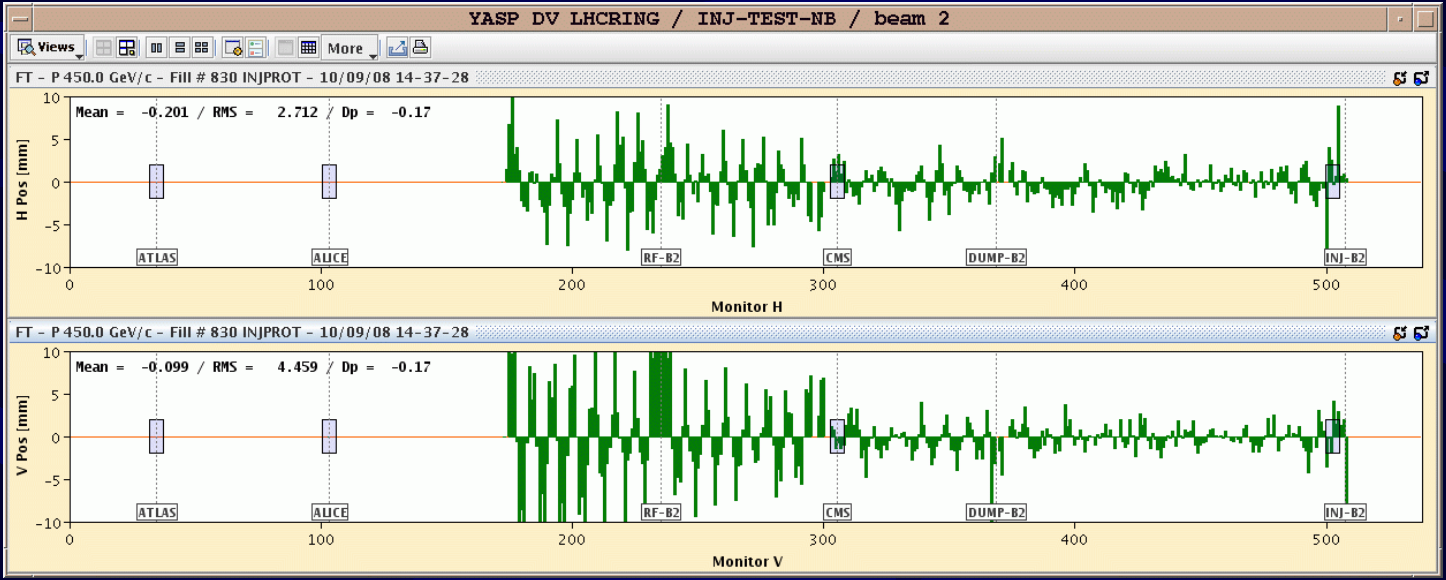

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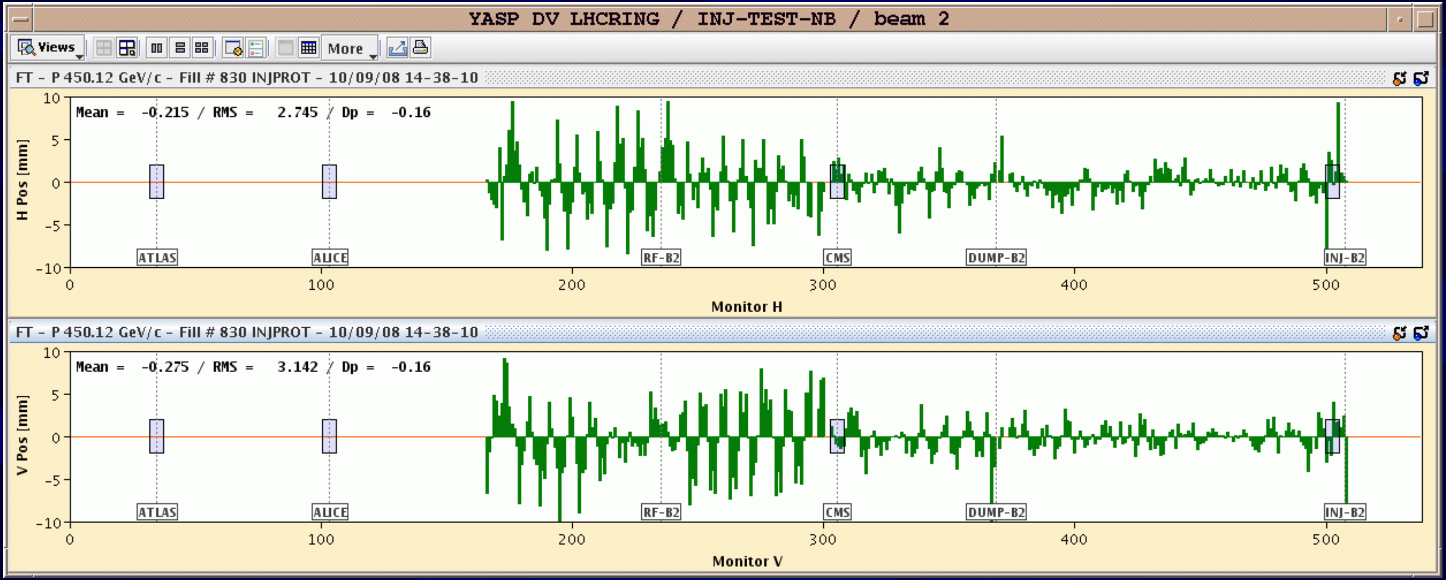

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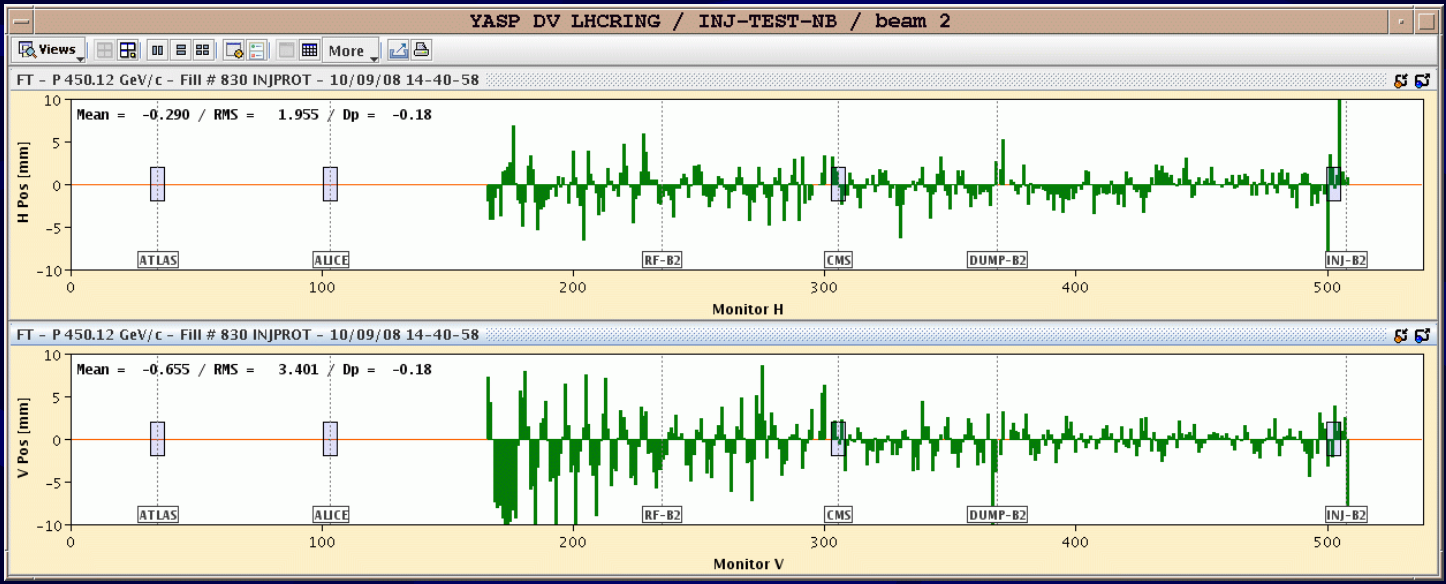

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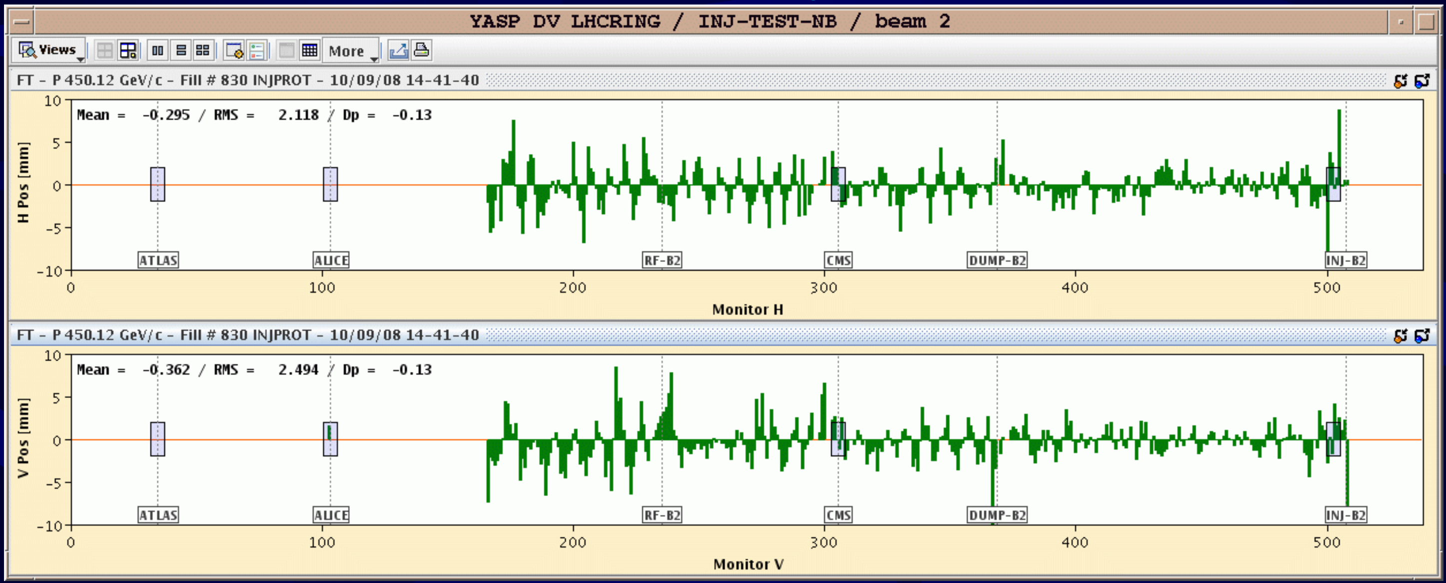

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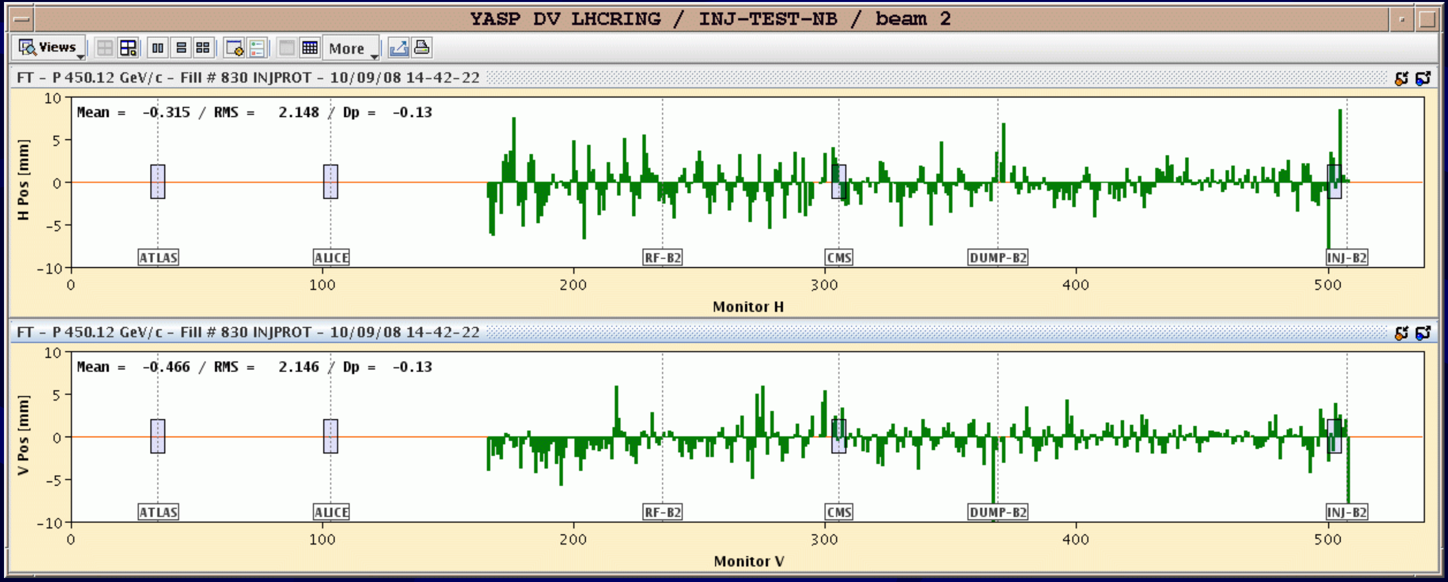

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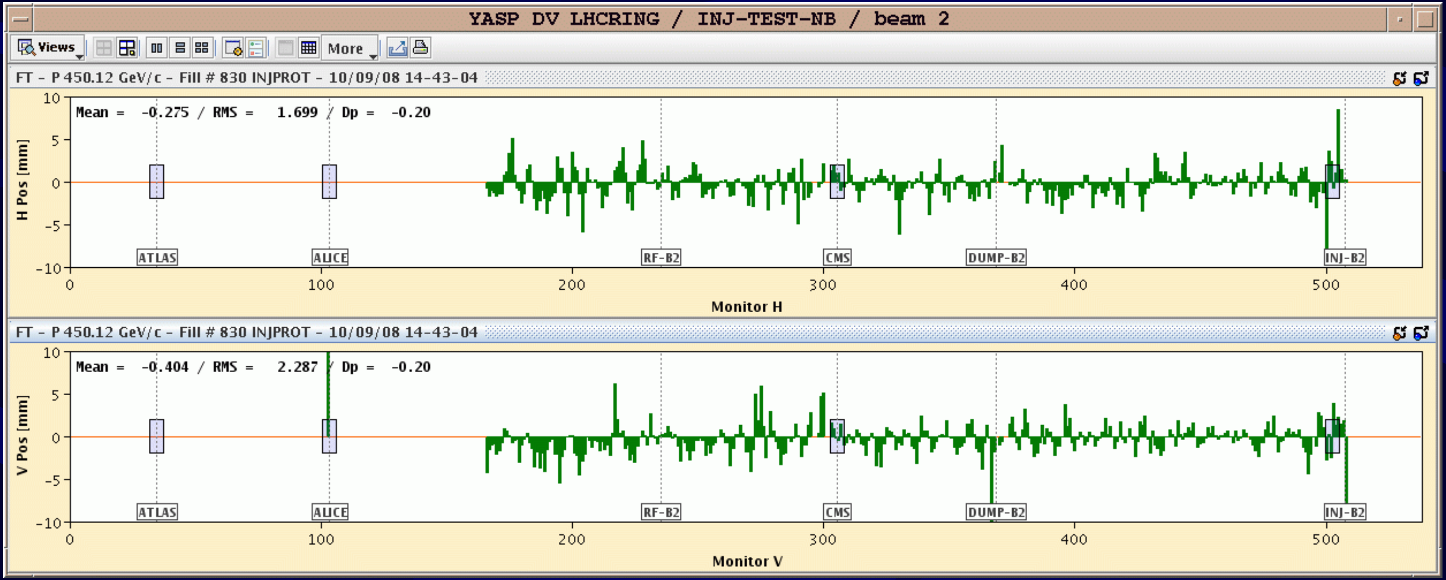

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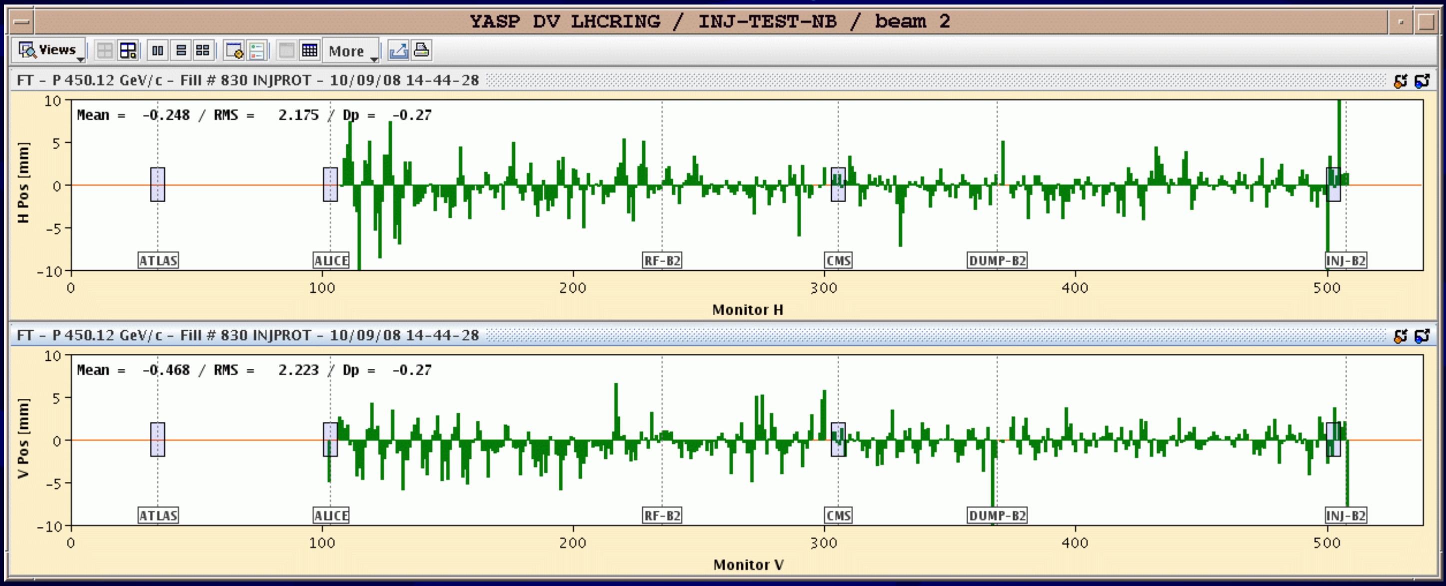

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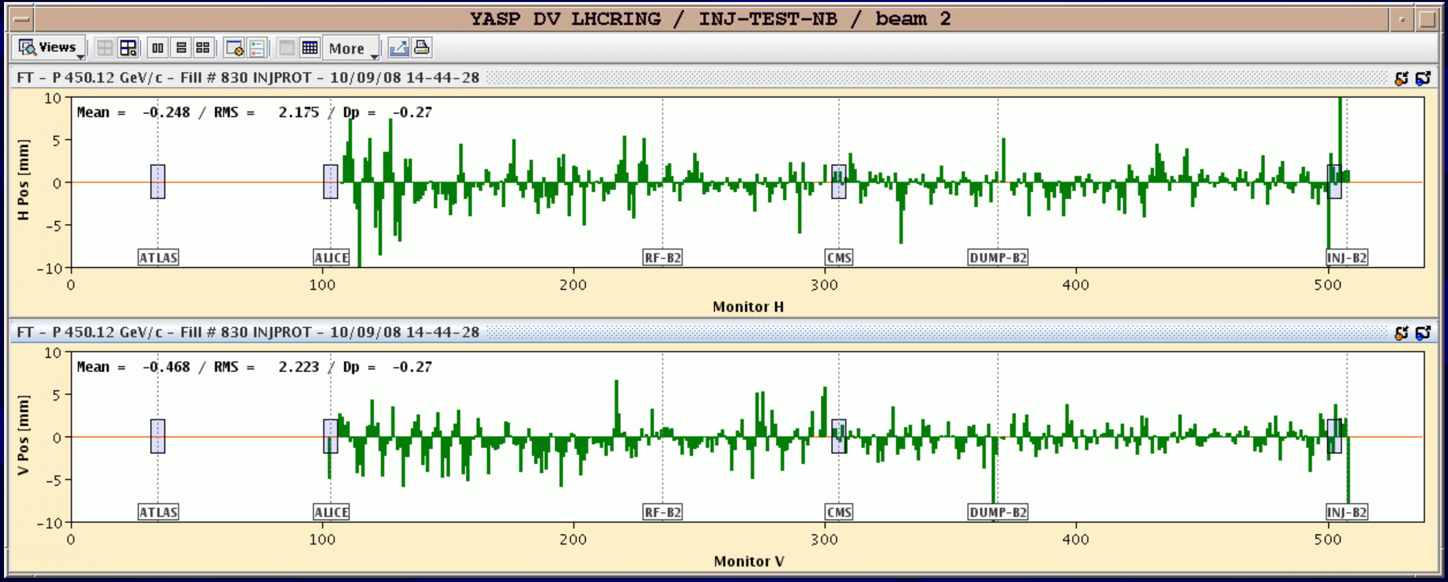

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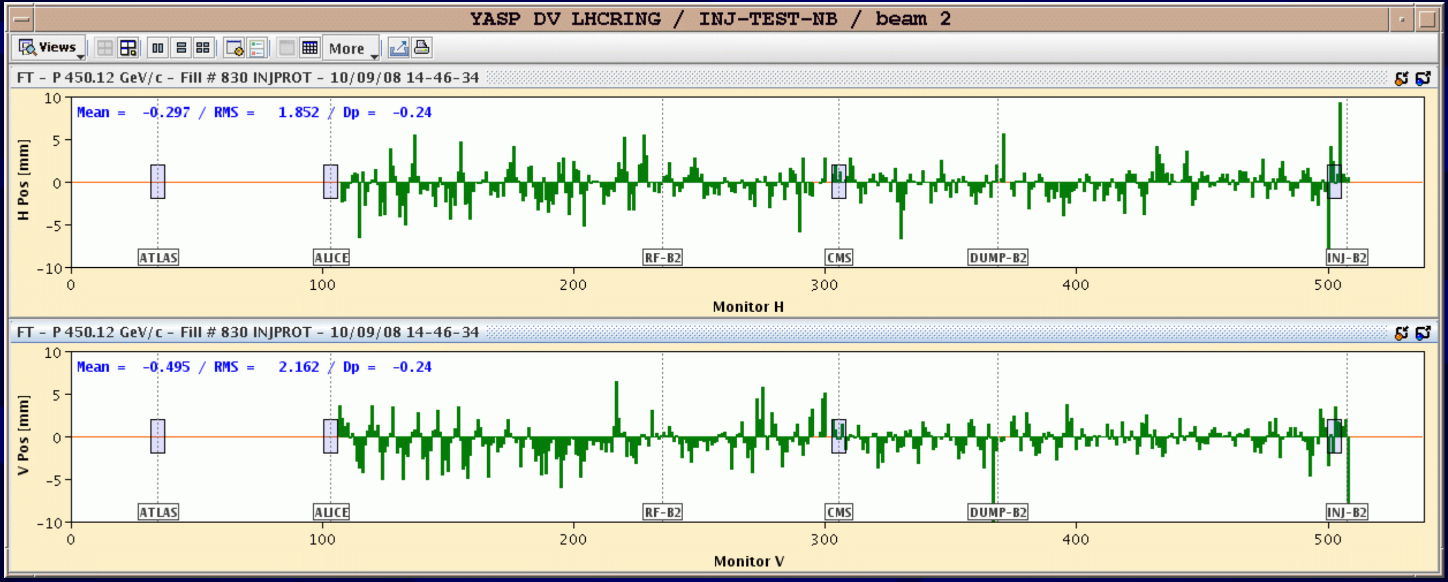

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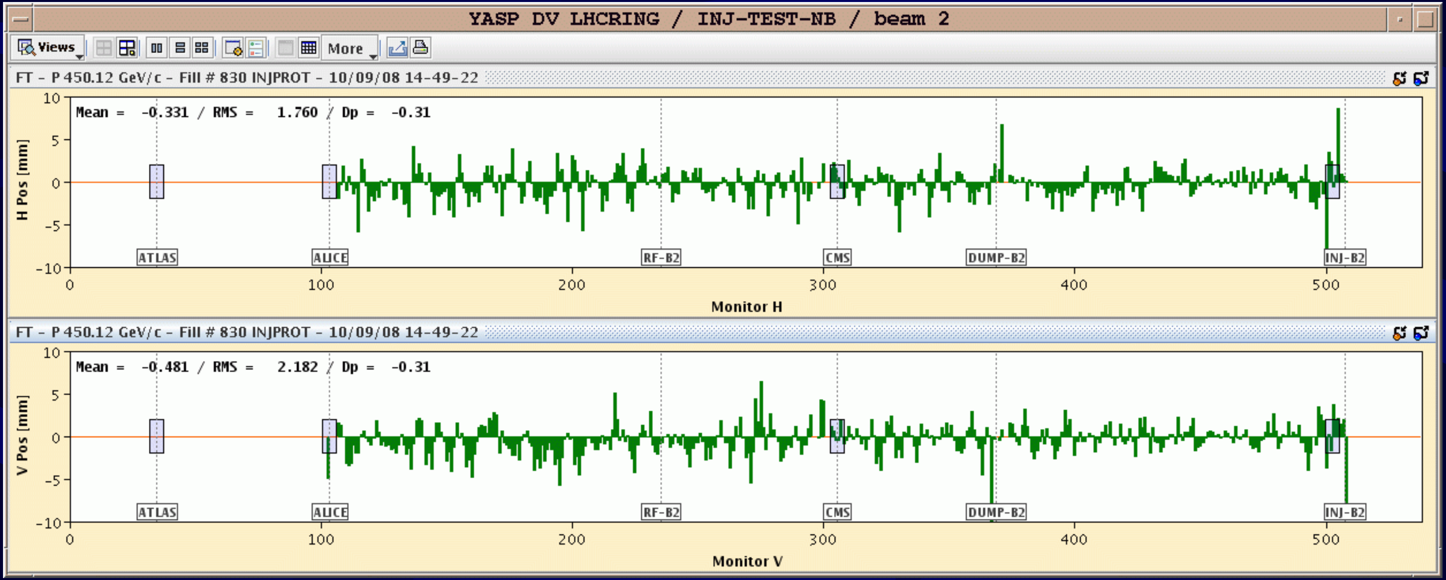

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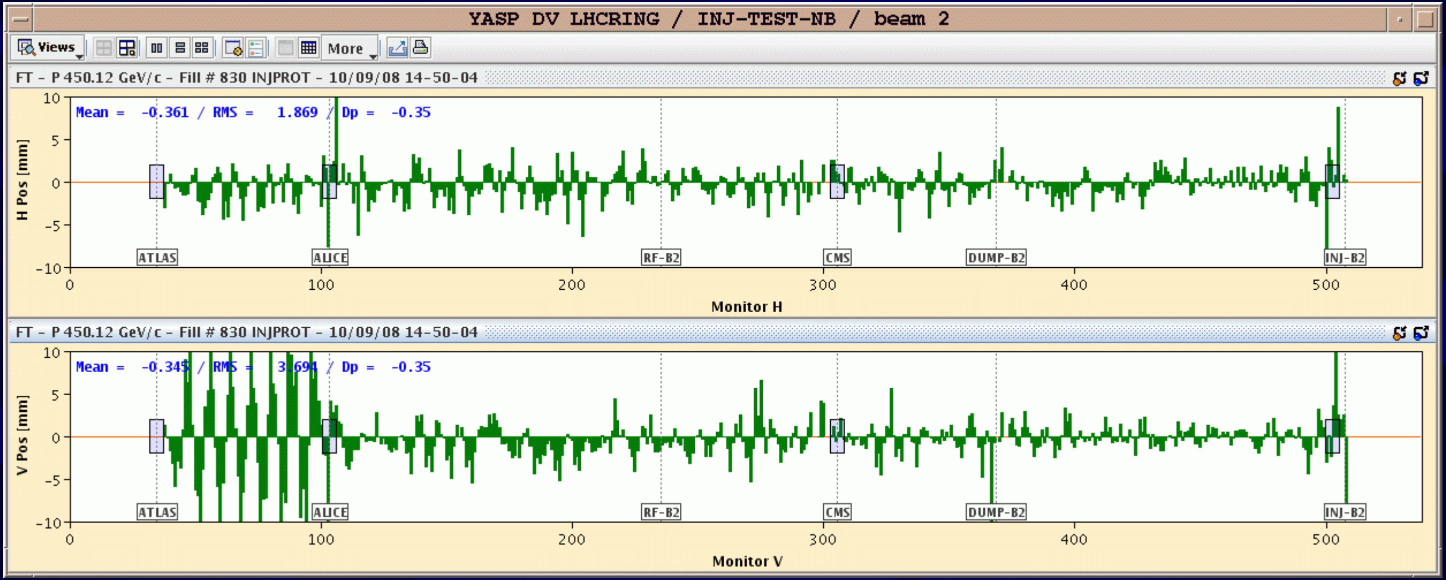

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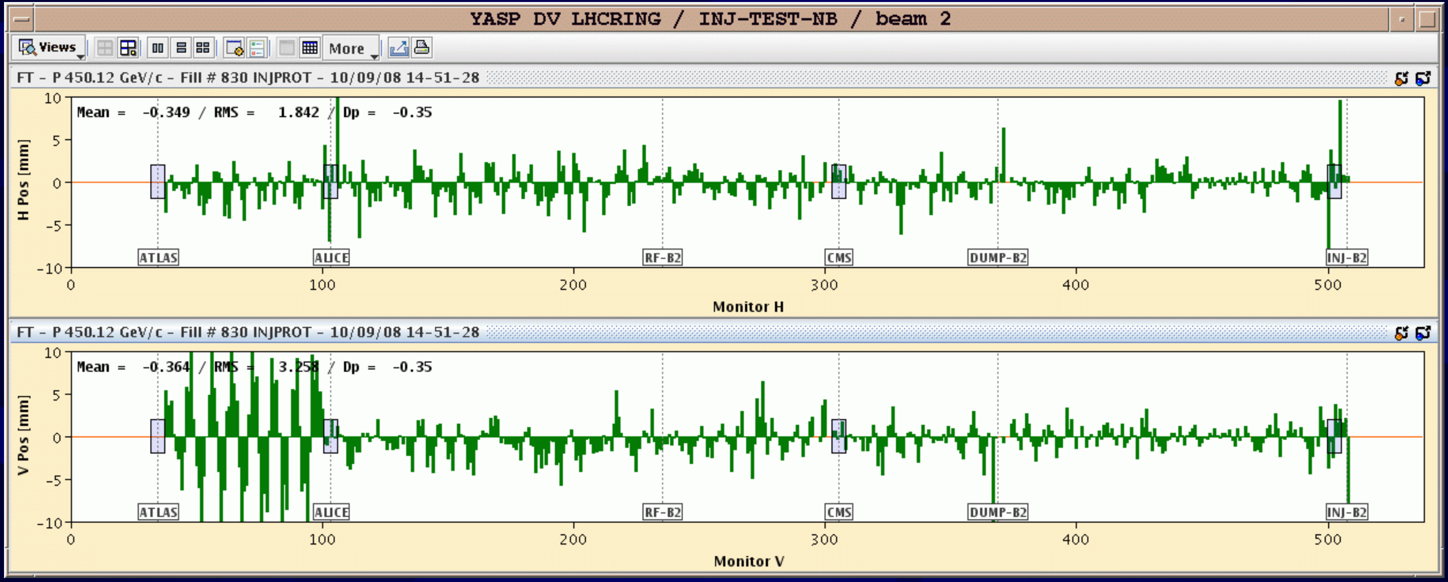

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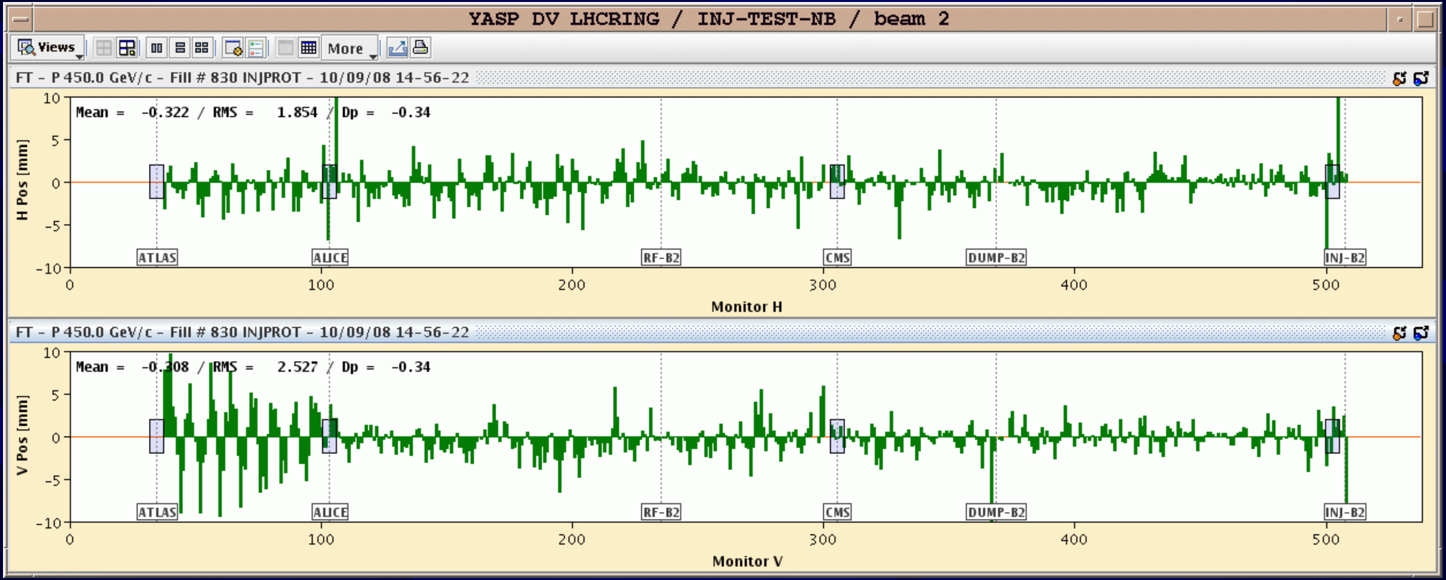

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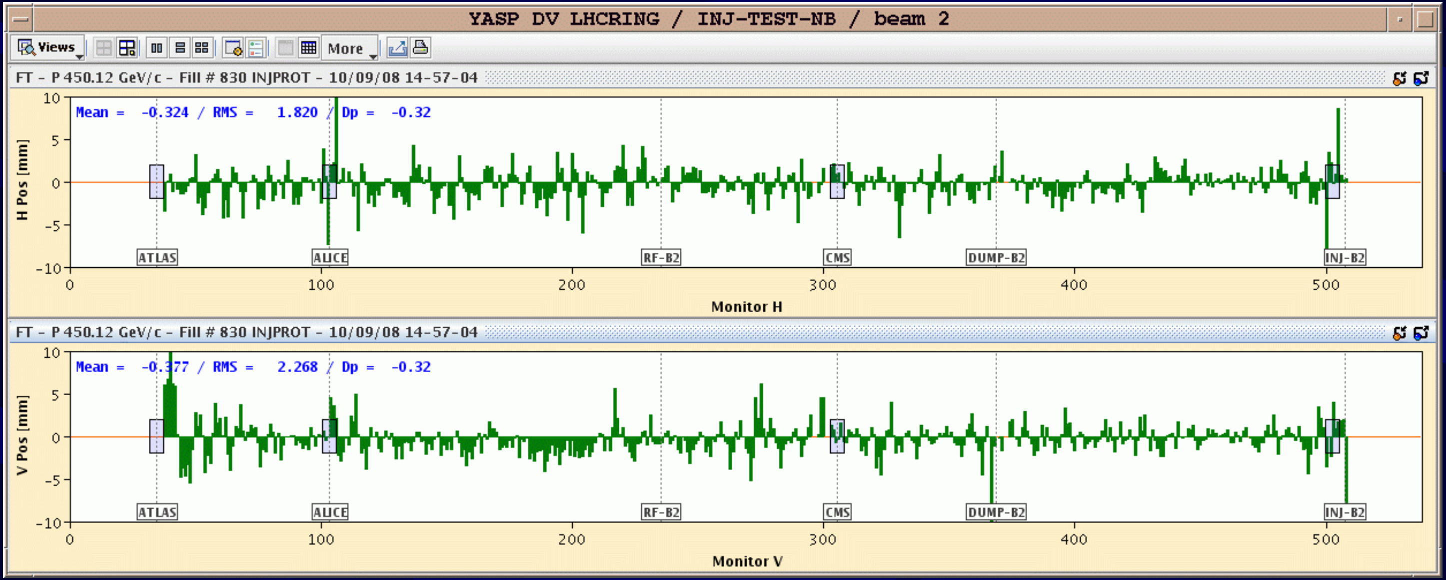

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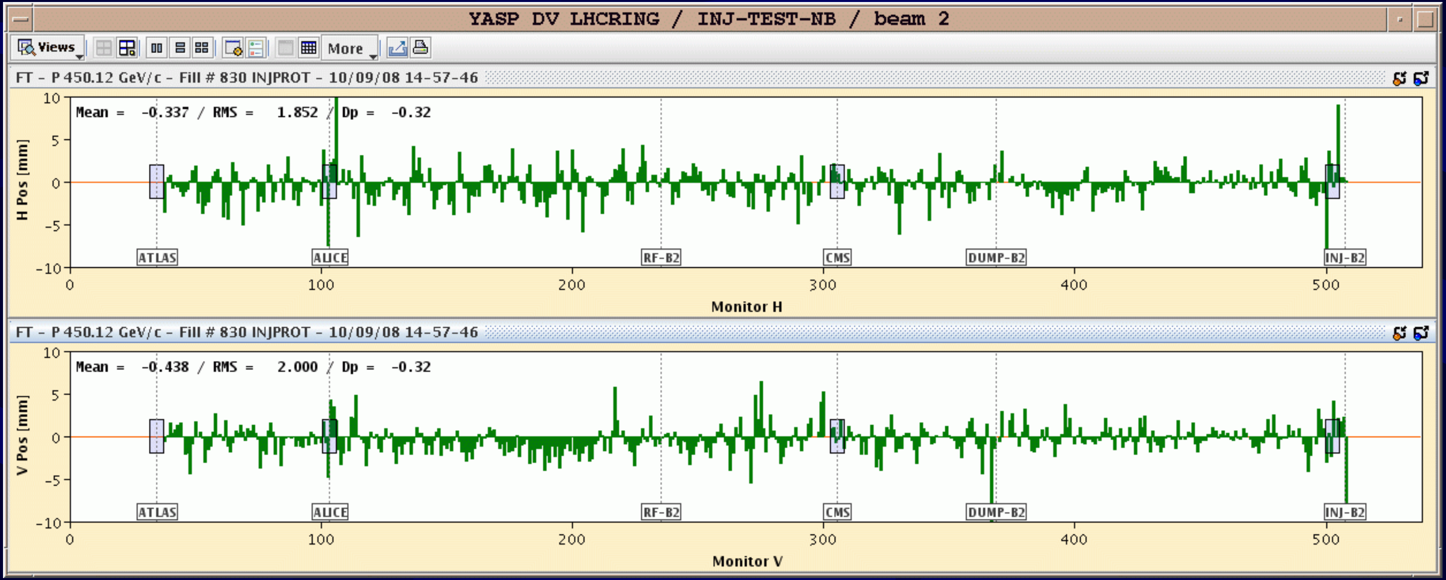

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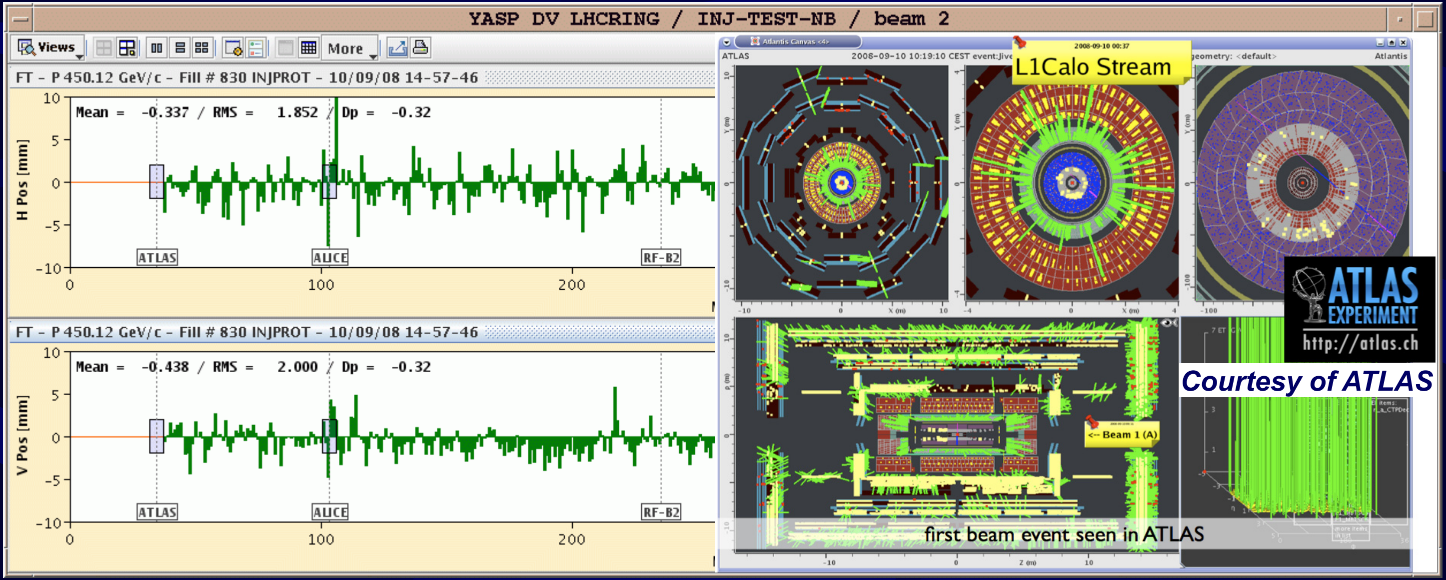

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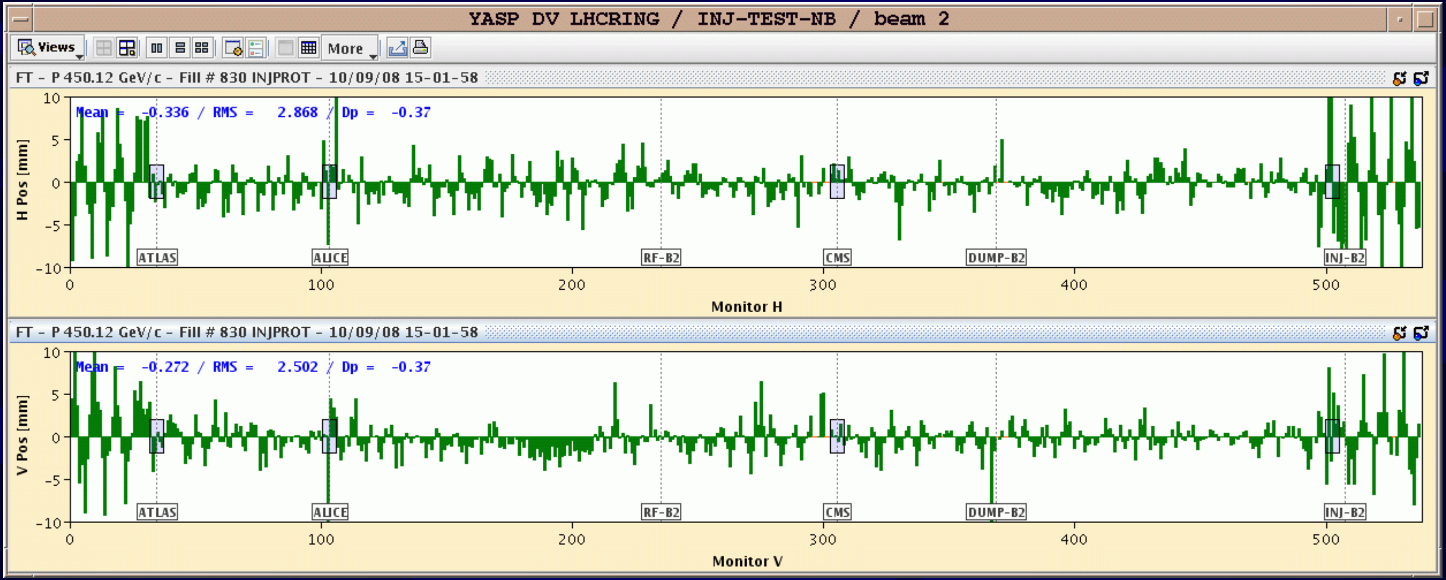

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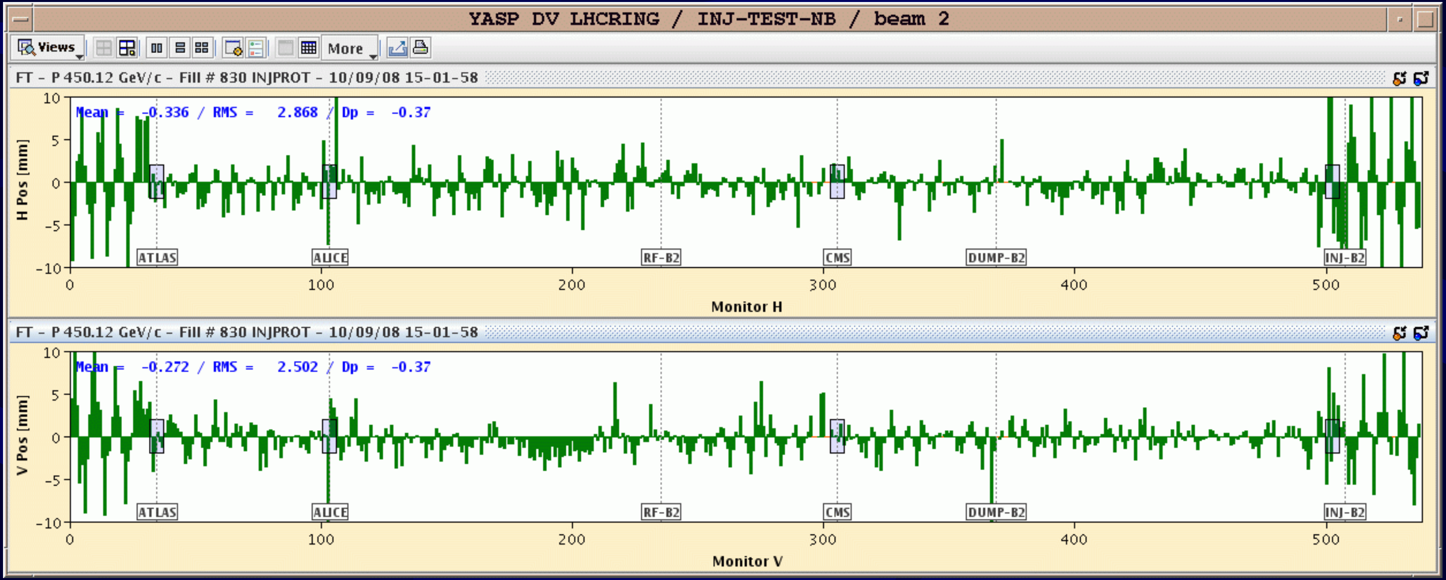
Beam 2 threading

BPM availability ~ 99%



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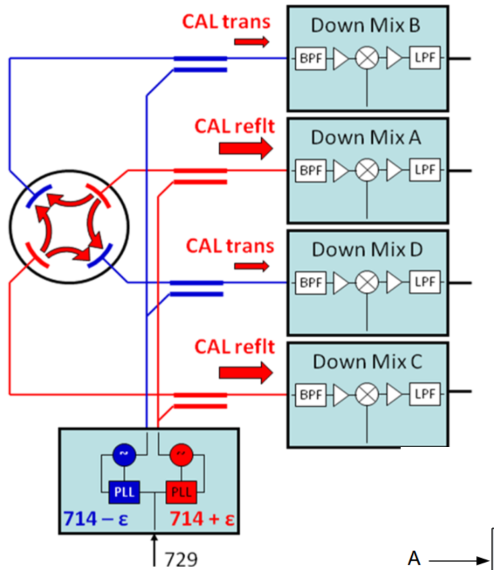
- Sensors + Sensor Signals: capacitive sensors
- Electronics
- Synchronization, accelerator timing
- From precision to accuracy
- Outlook

From Precision to Accuracy

- BPM sensor:
  - matching of sensor pairs
  - mechanical pre-alignment to nearest quadrupole magnetic axis (~100 um); further refinement of offsets with k-modulation of quadrupole
  - linearization of response by post-processing based on characterization of BPM response on a measurement bench
  - thermal stabilization of BPM body (= one of the reasons for top-up injection)
- BPM electronics (prior to beam)
  - measurement of insertion losses and phase errors of whole RF signal path
  - calculation/measurement of coupling impedance to beam
  - measurement of gain factors of each acquisition chain
- Various setups in order to inject calibration tones as close to the sensor as possible
  -> button systems: inject in one button + capacitive coupling to 2 adjacent buttons
  -> stripline couplers: use 2nd unused port for calibration tone injection
  -> use coupling transformers in RF-frontend
- Thermal stabilization of (analog) readout electronics
- Crossbar switches in the RF front-end: Periodically reassign input signals to the different acquisition chains. Deduce gain factors from signal changes

→ show a few examples (also taken from this conference):

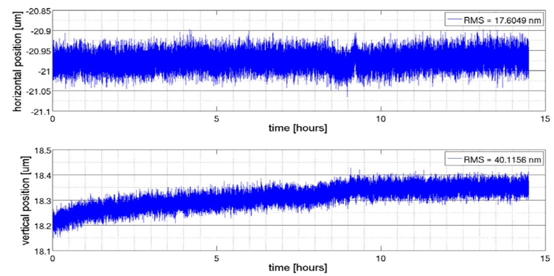
LONG-TERM DRIFT COMPENSATION (AS USED IN MANY LIGHTSOURCES)

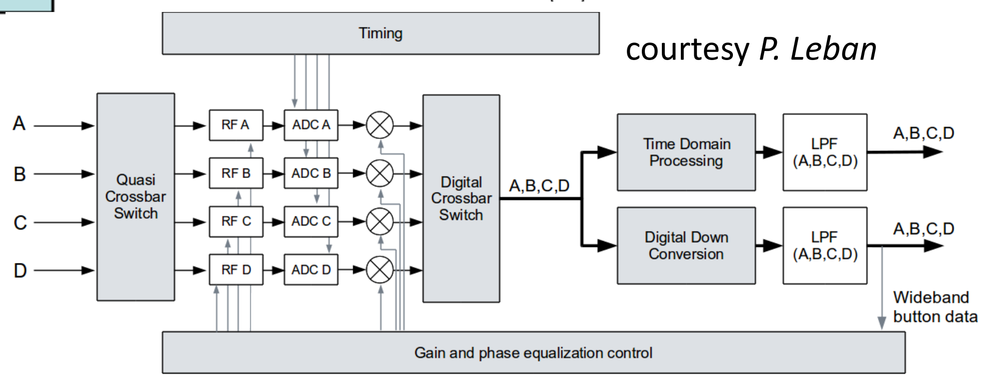


courtesy *N. Eddy*

- **Calibration tone technique (only in narrowband operation)**
  ATF (KEK)

- *Libera* crossbar switching technique
  - <100 nm stability over 14 hours



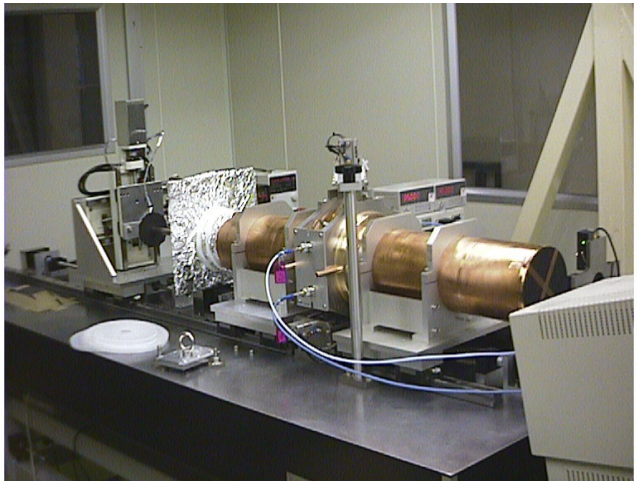


courtesy *P. Leban*

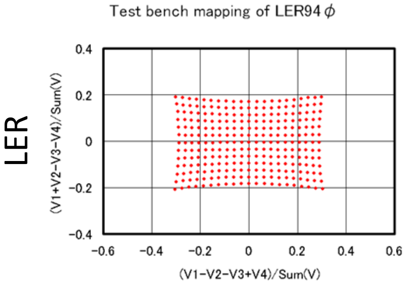
STEP 1, Mapping of BPM head

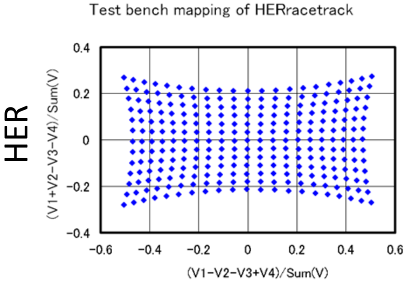
All BPMs were mapped at a test bench with a movable antenna .

Test bench for the mapping



result for mapping

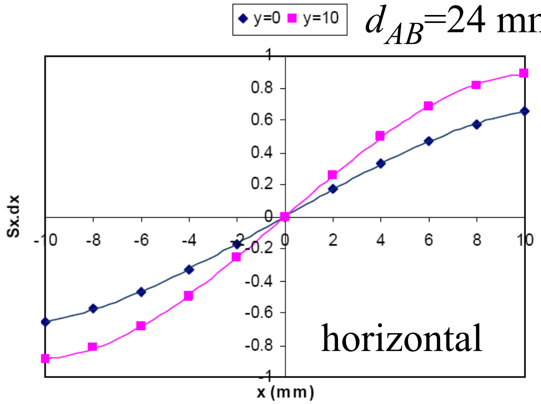




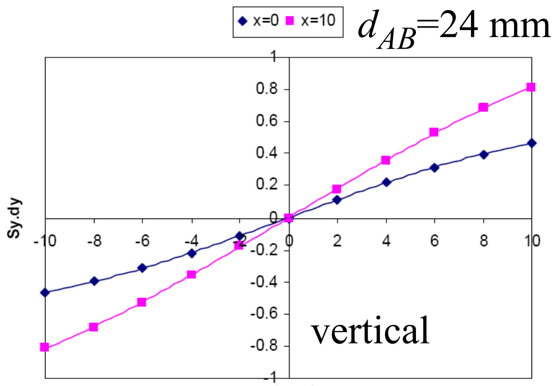
Button BPM at Synchrotron Light Sources

2-dim electro-static simulation:

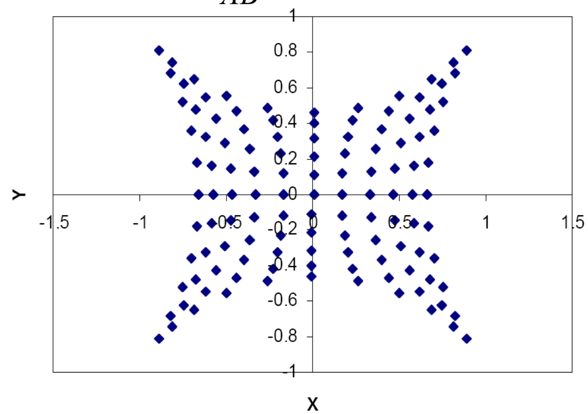
d_{AB}=24 mm



d_{AB}=24 mm

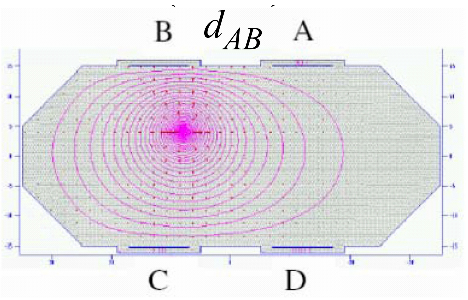


d_{AB}=24 mm



Result:

- Hori. S_x= 8.5%/mm
- Vert. S_y = 5.6%/mm
- x&y dependent polynomial fit possible



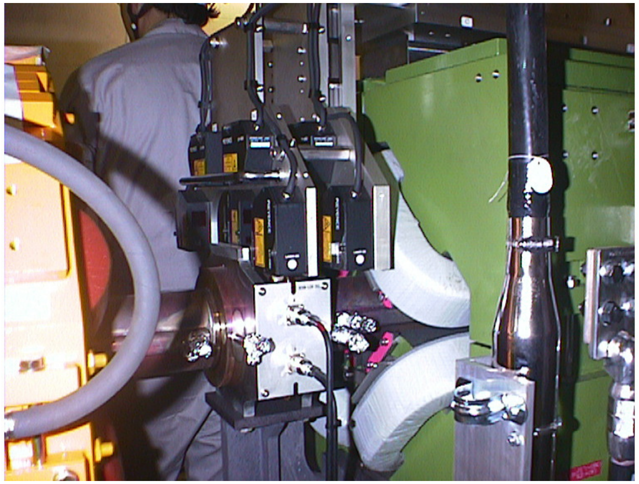
Beam position swept with 2 mm steps

From S. Varnasseri, SESAME, DIPAC 2005

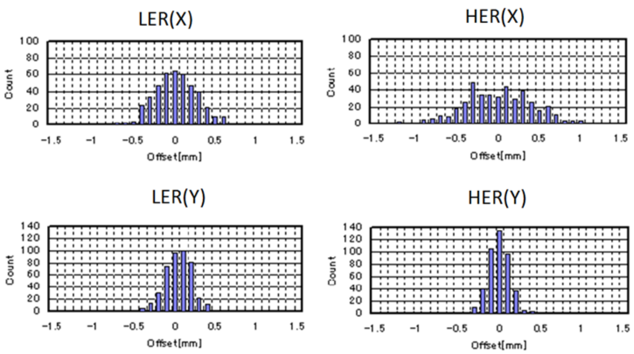
STEP 2, Alignment of BPM heads against to the Q-magnets

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

Photograph of Measurement tool



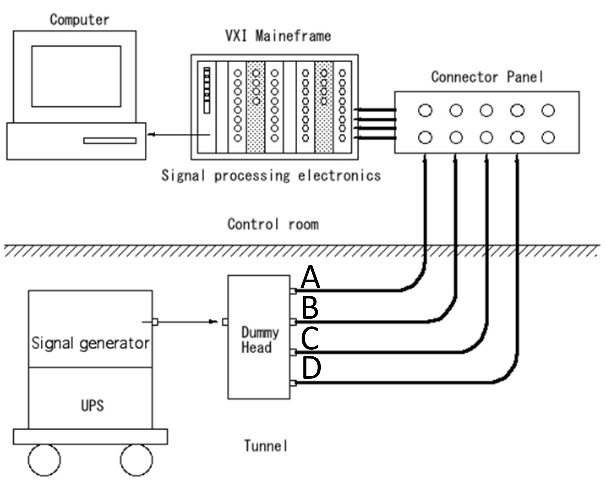
Results of alignment of BPM heads against to the reference plane of the Q-Magnets



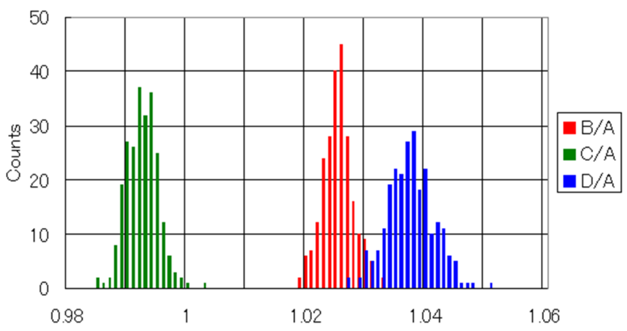
STEP-3, Gain calibration of the electronics

Attenuation of cable, switch, electronics, etc.

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



Results for ration between output signal B,C and D against to A in all electronics



Output signals: A, B, C, D

Beam based calibration

Beam Based Alignment

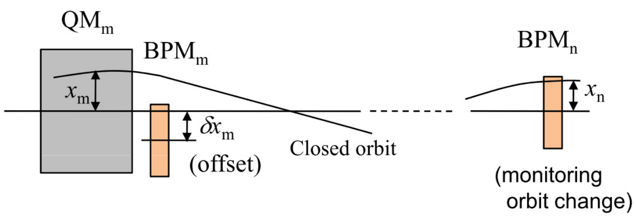
- Measurement of the offset of BPM to the field center of the adjacent Q-magnet using the beam.

Beam Based Gain Calibration

- Calibration of the gain imbalance among four outputs of a BPM using the beam.

Beam based alignment(BBA)
- Principle -

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

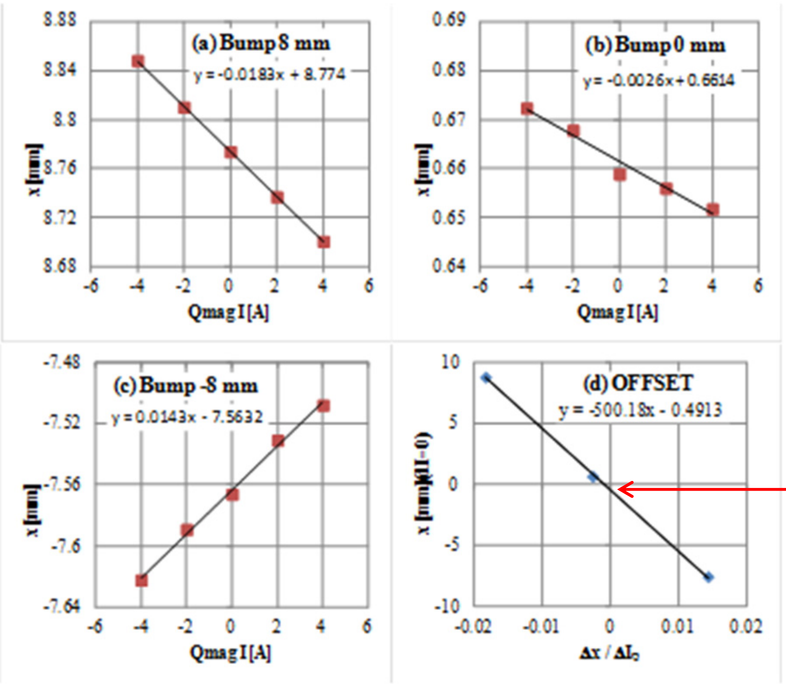


$$\Delta x_n = -a_{nm}(x_m - \delta x_m)\Delta K_m$$

$$a_{nm} = \frac{\sqrt{\beta_n \beta_m}}{2\sin \pi\nu}\cos(\pi\nu - |\phi_n - \phi_m|)$$

$\Delta Xm = 0$ then δxm offset

Actual procedure for BBA



Bump orbits: -8, 0, 8[mm]

I_Q : -4, -2, 0, 2, 4 [A]

-current of correction coil

from figure (a),(b),(c),

$\Delta x/\Delta I_Q$ and $x\ (I_Q=0)$,

where $x=x_m$

$\Delta x / \Delta I_Q = 0$

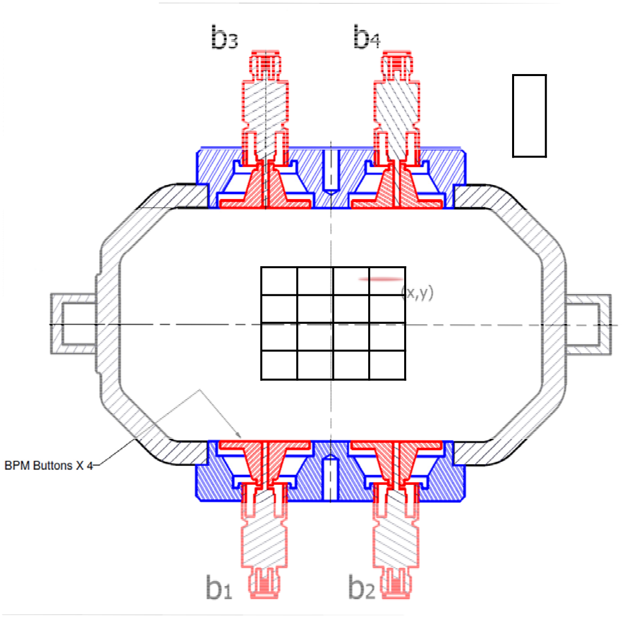
Offset

$X=0.4913$[mm]

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

Gain mapping

Slides provided by: D. Rubin, Cornell University
8-September 2015



Button to button gain errors

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

Characterization of BPM Gain Errors

Signal at each button depends on bunch current (*k*) and position (*x,y*)

$$B_1 = kf(x,y)$$

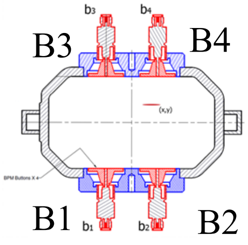
$$B_1 \approx k\left(f(0,0) + \frac{\partial f}{\partial x}x + \frac{\partial f}{\partial y}y + \frac{1}{2}\frac{\partial^2 f}{\partial x^2}x^2 + \frac{1}{2}\frac{\partial^2 f}{\partial y^2}y^2 + \frac{\partial^2 f}{\partial x \partial y}xy + \ldots\right)$$

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

Signals on the four buttons are related by symmetry

$$B_2 = kf(-x,y)$$
$$B_3 = kf(x,-y)$$
$$B_4 = kf(-x,y)$$

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



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

$$B(+--+) = \frac{c}{k}B(+-+-)B(++--)$$

Gain mapping with turn by turn data

A single beam passage gives a measurement of intensity at each of four button electrodes

$$B_{j=1,4}$$

N beam passages gives

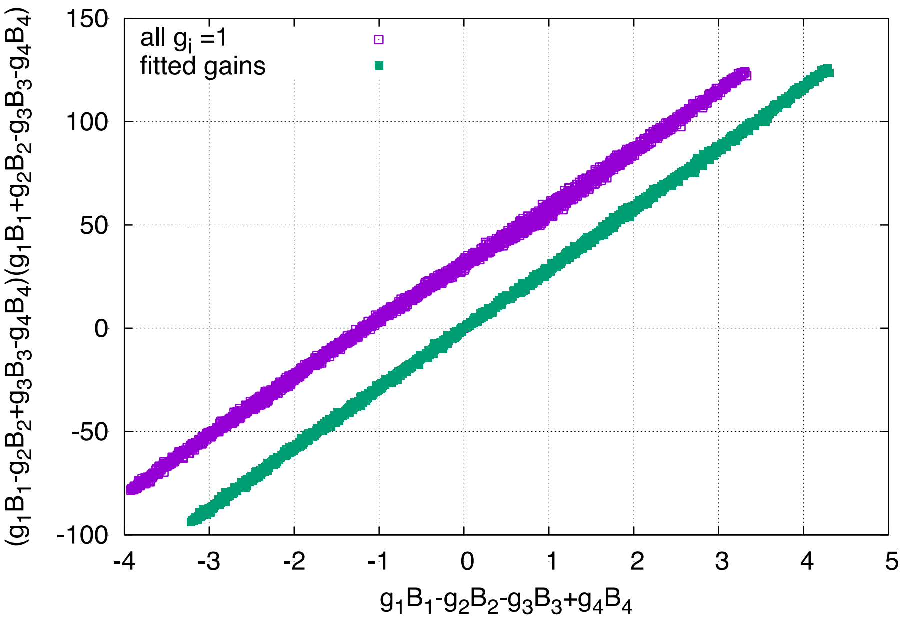
$$B_{j=1,4}^{i=1,N}$$

The gains are the set of g_j that minimize

$$\chi^2 = \sum_i^N \Big[(g_1B_1^i - g_2B_2^i - g_3B_3^i + g_4B_4^i)$$
$$-\frac{c}{I}(g_1B_1^i - g_2B_2^i + g_3B_3^i - g_4B_4^i)(g_1B_1^i + g_2B_2^i - g_3B_3^i - g_4B_4^i)\Big]^2$$

Turn by turn data

$$B(+--+) = \frac{c}{k} B(+-+-) B(++--)$$



1024 measurements

Fitted gains $g_{1\text{-}4} = (1.007, 1.016, 0.9434, 1.035)$

Outline

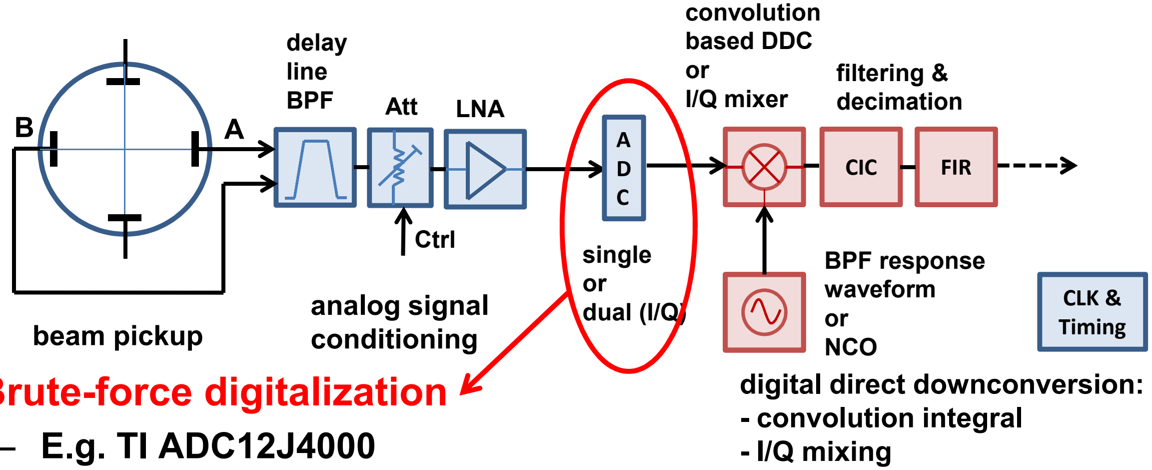
- Principle, Usage of BPMs
- Functional Specifications (FS)
- Sensors + Sensor Signals
- Electronics
- Synchronization, accelerator timing
- From precision to accuracy
- Outlook
  - new LHC orbit system for LHC-LS3 (2024)
  - Electro-optical BPMs → Intrabunch Measurements for <ns bunches

LHC BPM Timing Specs – 1st thoughts

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

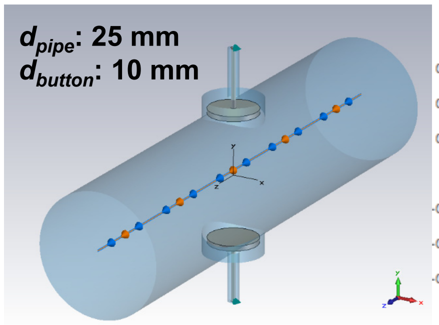
- **Relaxed external timing requirements:**
  - **RF bucket synchronous trigger signals in 2.5 ns increments**
    - **Jitter & drift effects <<1 ns**
    - **Needs to be supplied to each BPM DAQ electronics**
      - Of course separate trigger signals for B1 and B2

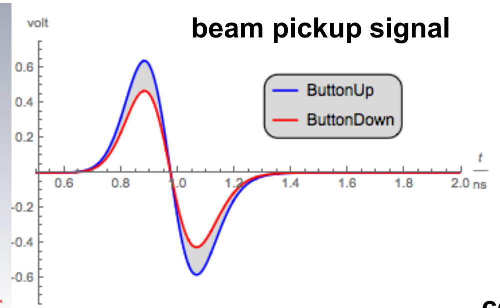
Conceptual Idea



- **Brute-force digitalization**
  - **E.g. TI ADC12J4000**
    - **12-bit, 4 GSPS, SFDR ≈ 67 dBFS, SINAD ≈ 55 dBFS (@350MHz)**
    - **Intergraded DDC, decimation by 4 or 8 (400MHz pass-band)**
      - SFDR ≈ 75 dBFS, SINAD ≈ 63 dBFS (@600MHz)
  - **Internal CLKs for ADC and FPGA**
  - **External 40 MHz trigger (2.5ns steps) for bunch tagging (memory)**
- **Single analog processing channel**
  - **Based on delay-line networks and band-pass filters**

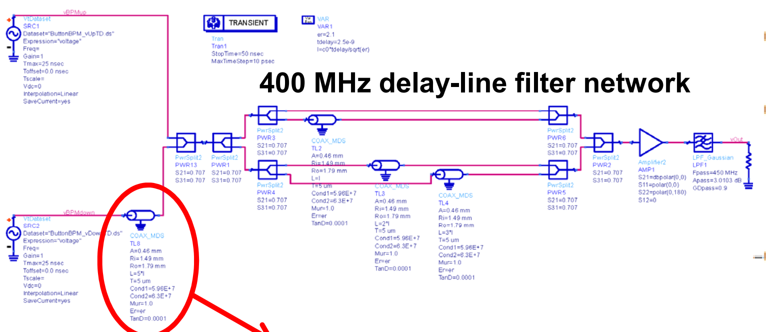
Analog Signals

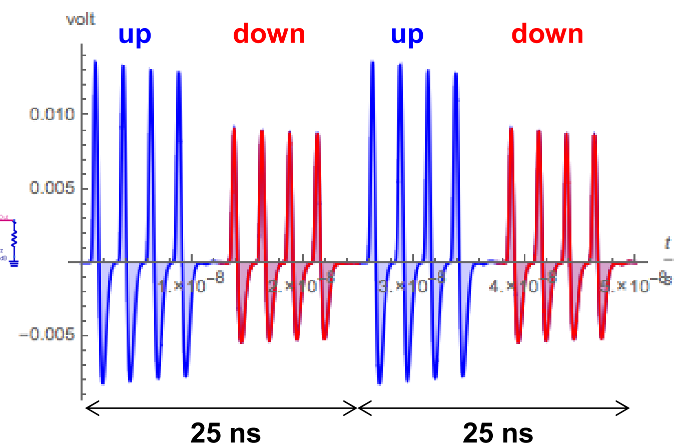




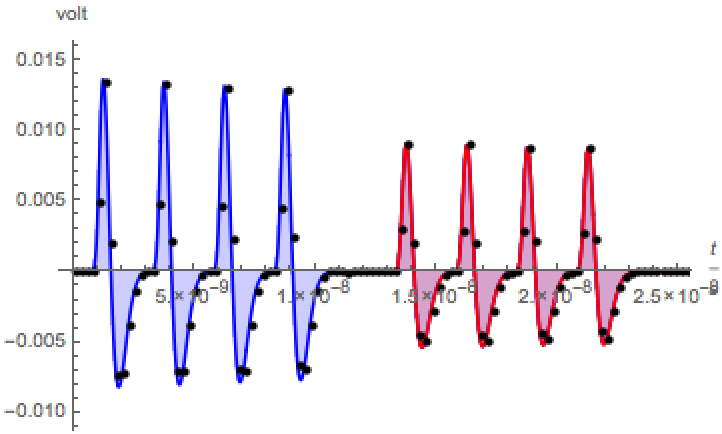
- **Gaussian bunch:**
  - n=1E10, σ=25mm, $v=c_0$
  - vertical offset=1mm
- **BPM sensitivity:**
  - e.g.: 2.7 dB / mm

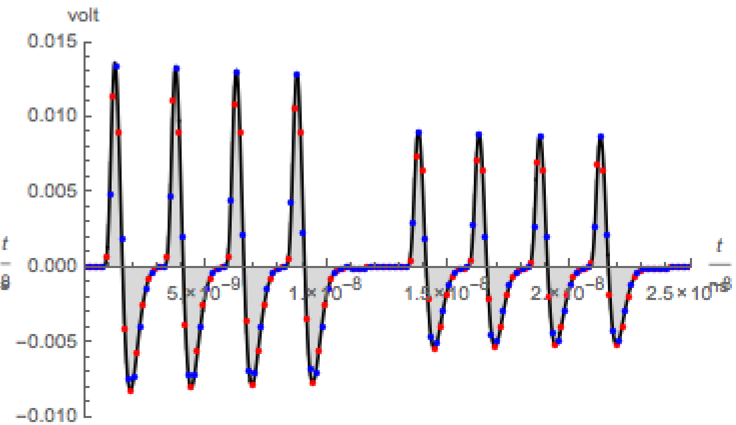
conditioned analog signal





Waveform Sampling Options





- **4 GSPS = 250 ps sample spacing**
  - **100 samples per 25 ns with single ADC**
    - **50 samples per electrode signal, but only 20…24 samples ≠ 0**
  - **200 samples per 25 ns with two interleaved ADC in I/Q operation**
- **Requires low CLK jitter within 25 ns time interval**
  - **E.g. t_a = 0.15 ps -> 68.5 dB@400 MHz (equivalent to EOB=11.1)**

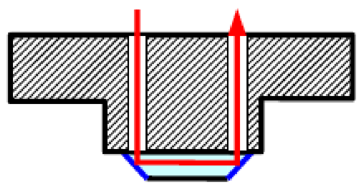
$$SNR = -20\log_{10}(2\pi f\, t_a)$$

Schematic of EO-BPM

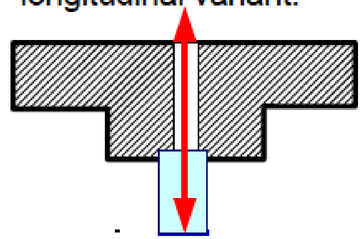
See also: S.Gibson (RHUL   this conference)

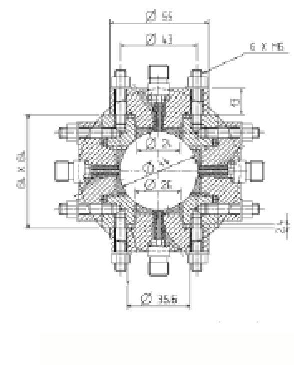
- All-Optical-BPM layout scheme, re-use conceptually LHC BPM design:
  - Keep the same body, keep external button form-factor

transverse variant:

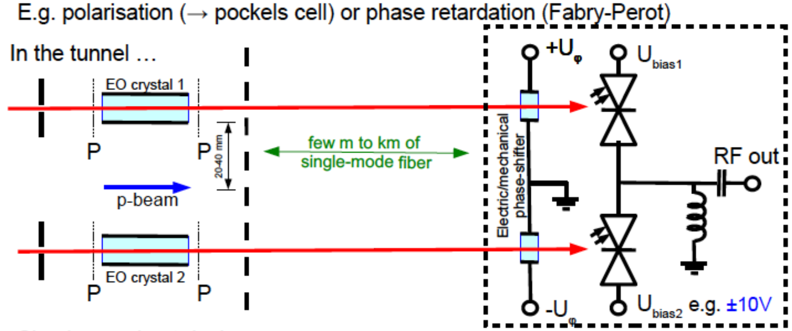


longitudinal variant:



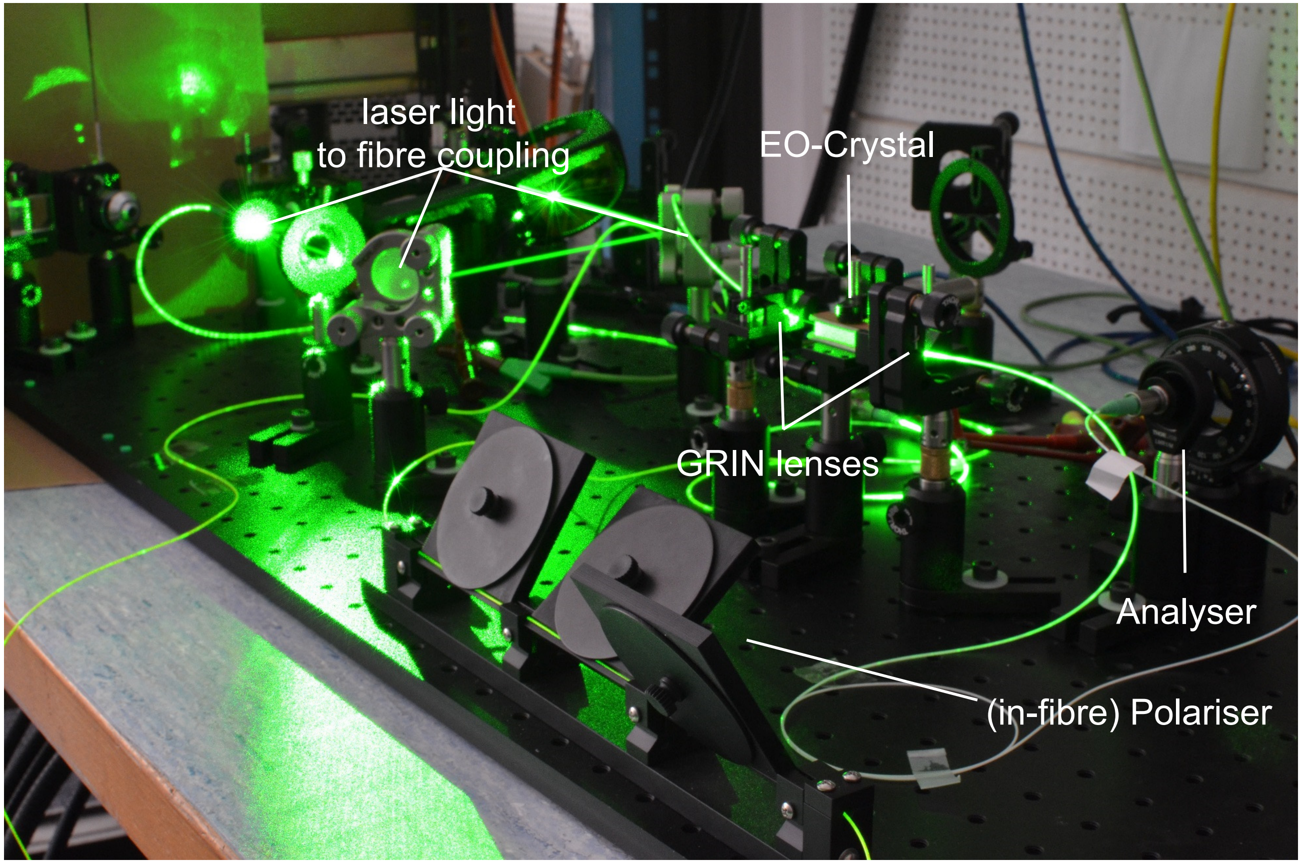


- E.g. polarisation (→ pockels cell) or phase retardation (Fabry-Perot)



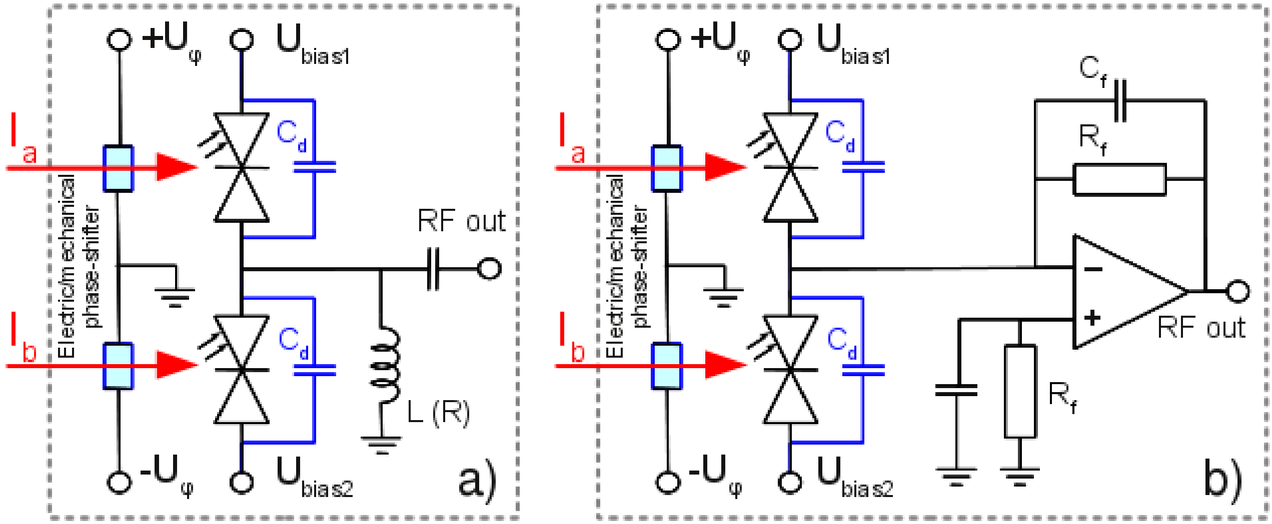
- Simple → robust design:

All optical BPM laser lab set-up



Possible Detection scheme

- Wide-Band Improvement on RF Hybrid Junction: (MSM)



- Sum Σ and Difference Δ signals are computed in electro-optical domain
  - Aim at 12+ GHz Bandwidth

Instead of a summary: Thank You for Your Patience