Direct (Under) Sampling vs. Analog Downconversion for BPM Electronics

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CERN

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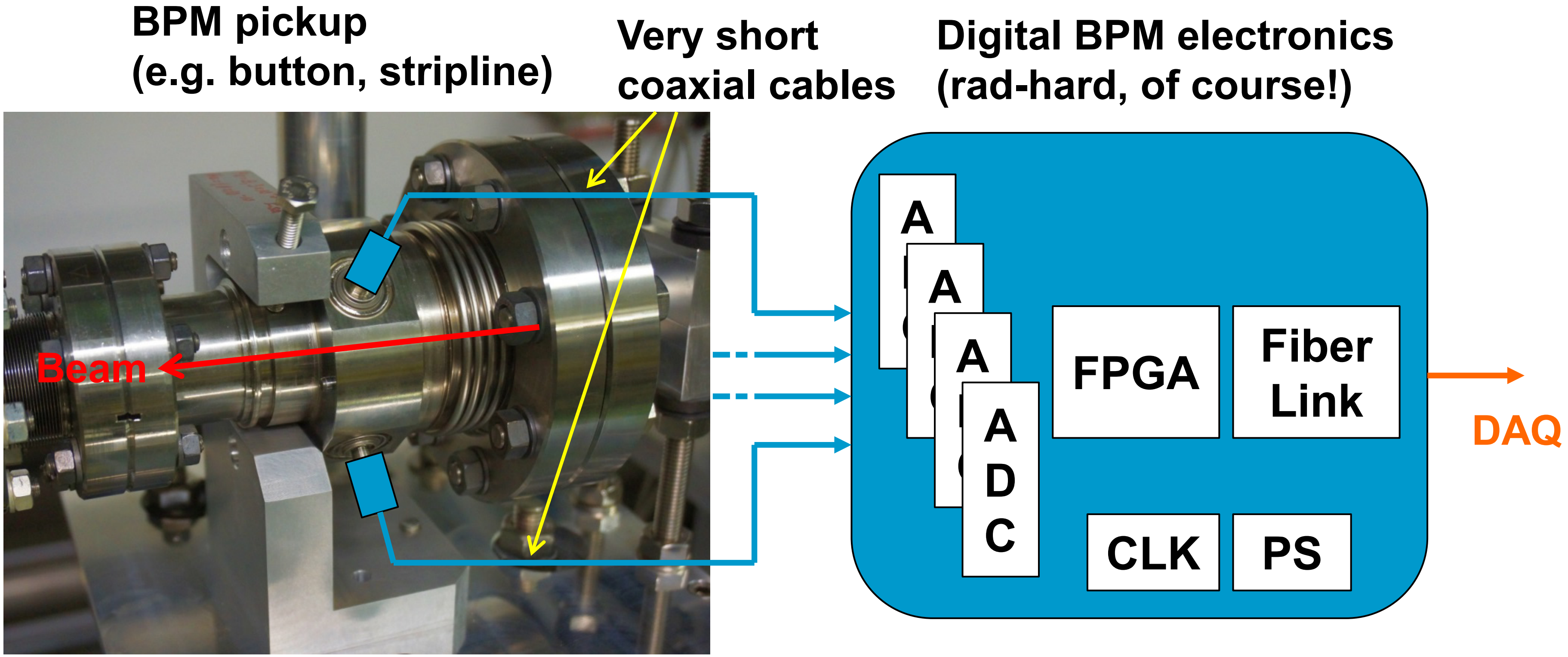
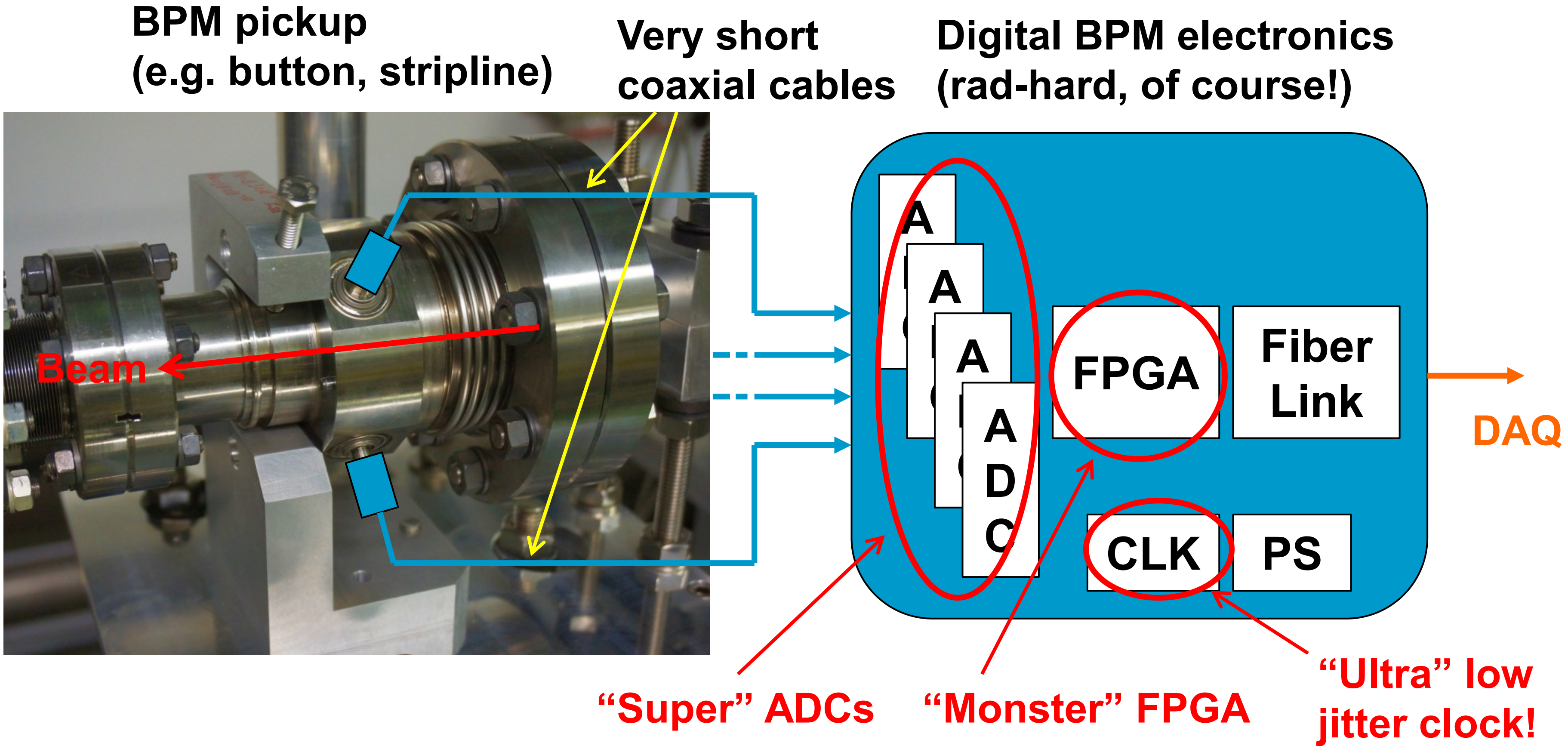
Contents

The Ideal BPM Read-out Electronics!?



The Ideal BPM Read-out Electronics!?



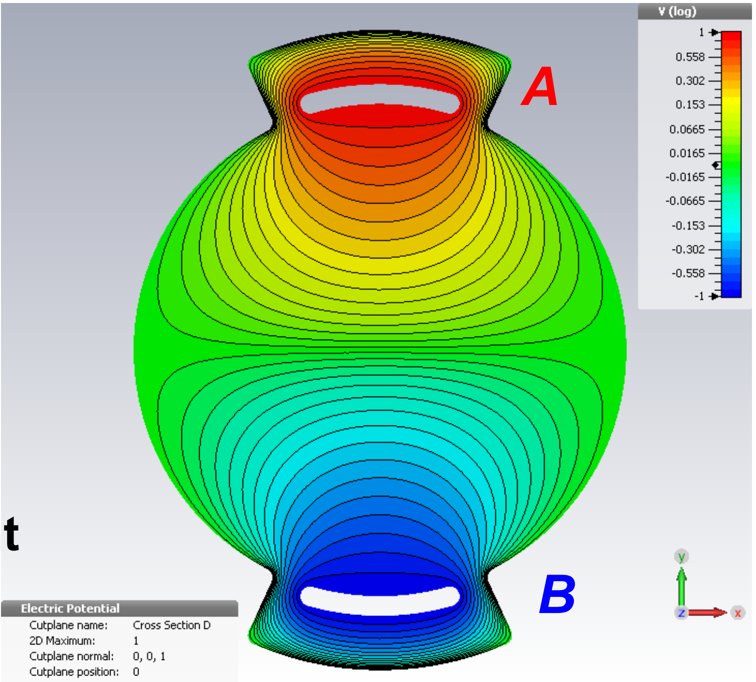
- **Time multiplexing of the BPM electrode signals:**
  - Interleaving BPM electrode signals by different cable delays
  - Requires only a single read-out channel!

BPM Pickup

- The BPM pickup detects the beam positions by means of:
  - identifying asymmetries of the signal amplitudes from symmetrically arranged electrodes *A* & *B*: broadband pickups, e.g. buttons, striplines
    $$\text{norm. beam position} \propto \frac{A-B}{A+B}$$
  - Detecting dipole-like eigenmodes of a beam excited, passive resonator:
    narrowband pickups, e.g. cavity BPM
- BPM electrode transfer impedance:

$$V_{elec}(x,y,\omega)=s(\boxed{x,y},\omega)\,Z(\omega)\,I_{beam}(\omega)$$

  - The beam displacement or sensitivity function *s(x,y)* is frequency independent for broadband pickups



Electric Potential
Cutplane name: Cross Section D
2D Maximum: 1
Cutplane normal: 0, 0, 1
Cutplane position: 0

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- **The BPM pickup detects the beam positions by means of:**
  - **identifying asymmetries of the signal amplitudes from symmetrically arranged electrodes *A* & *B*:** $\text{norm. beam position} \propto \frac{A-B}{A+B}$ **broadband pickups, e.g. buttons, striplines**
  - **Detecting dipole-like eigenmodes of a beam excited, passive resonator:**
    narrowband pickups, e.g. cavity BPM
- **BPM electrode transfer impedance:**

$$V_{elec}(x,y,\omega)=s(x,y,\omega)Z(\omega)I_{beam}(\omega)$$

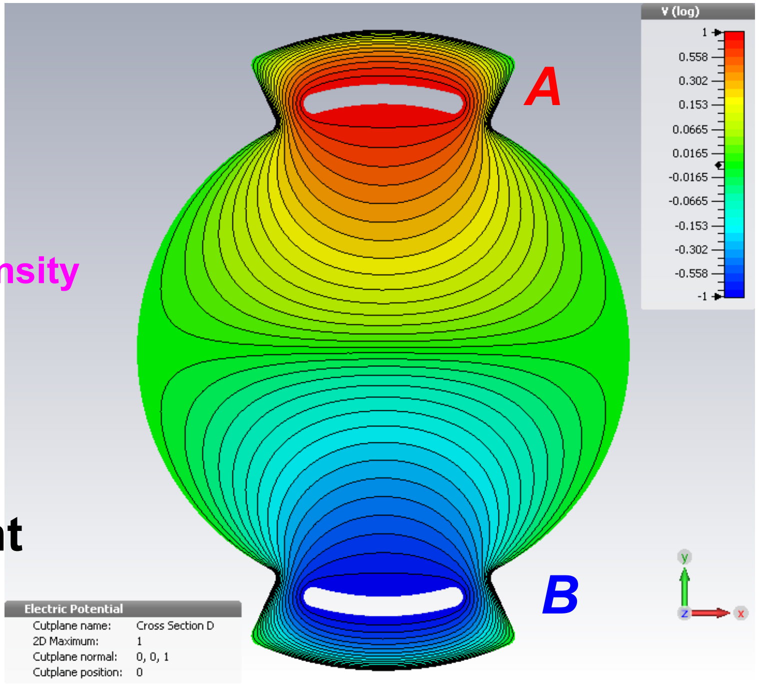
beam position

beam intensity

only for resonant pickups

Frequency depending coupling impedance of the BPM electrode

  - **The beam displacement or sensitivity function *s(x,y)* is frequency independent for broadband pickups**



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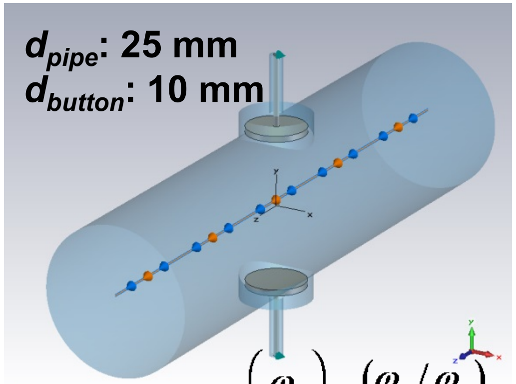
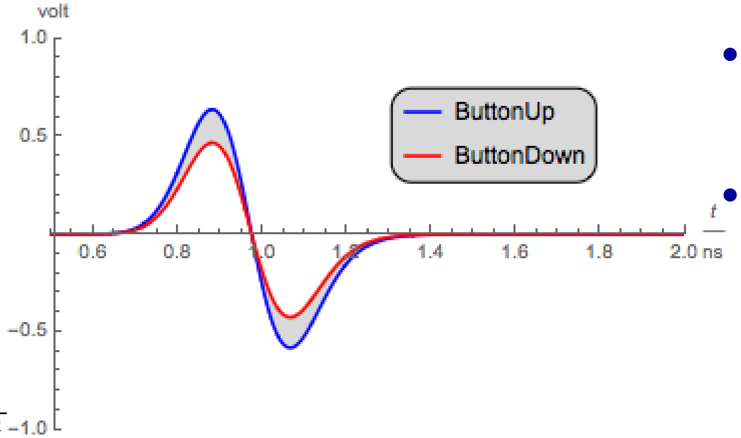
Broadband BPM Signals

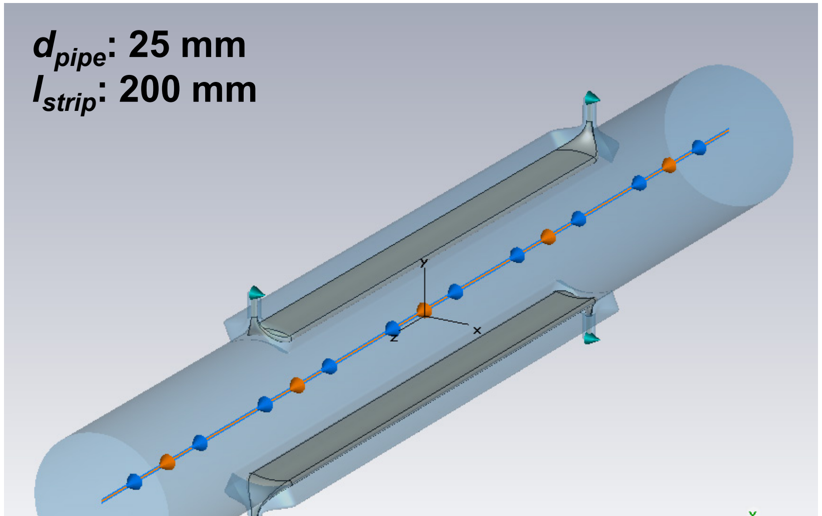


d_{pipe}: 25 mm
d_{button}: 10 mm

$$Z_{button}(\omega)=\phi R_{load}\left(\frac{\omega_1}{\omega_2}\right)\frac{(\omega_1/\omega_2)}{1+(\omega_1/\omega_2)^2}$$

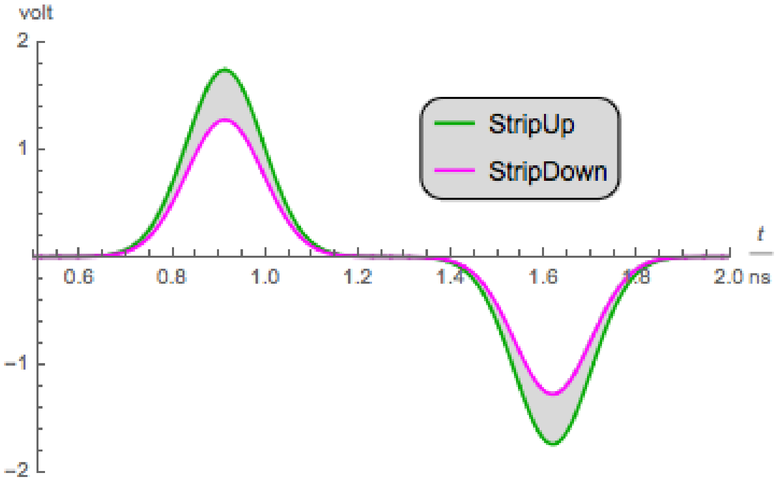


- **Gaussian bunch:**
  - **n=1E10, σ=25mm, $v=c_0$**
  - **vertical offset=1mm**
- **BPM sensitivity:**
  - **e.g.: 2.7 dB / mm**



d_{pipe}: 25 mm
l_{strip}: 200 mm

$$Z_{strip}(\omega)=i\phi Z_0 e^{-i\frac{\omega l_{strip}}{c_0}}\sin\left(\frac{\omega l_{strip}}{c_0}\right)$$



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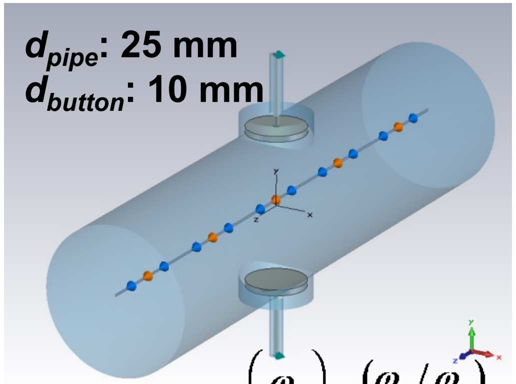

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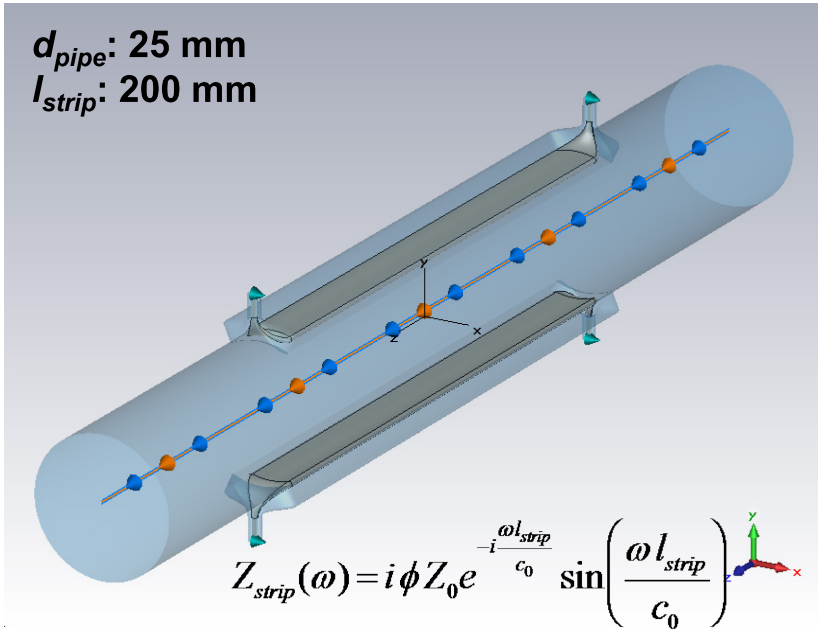

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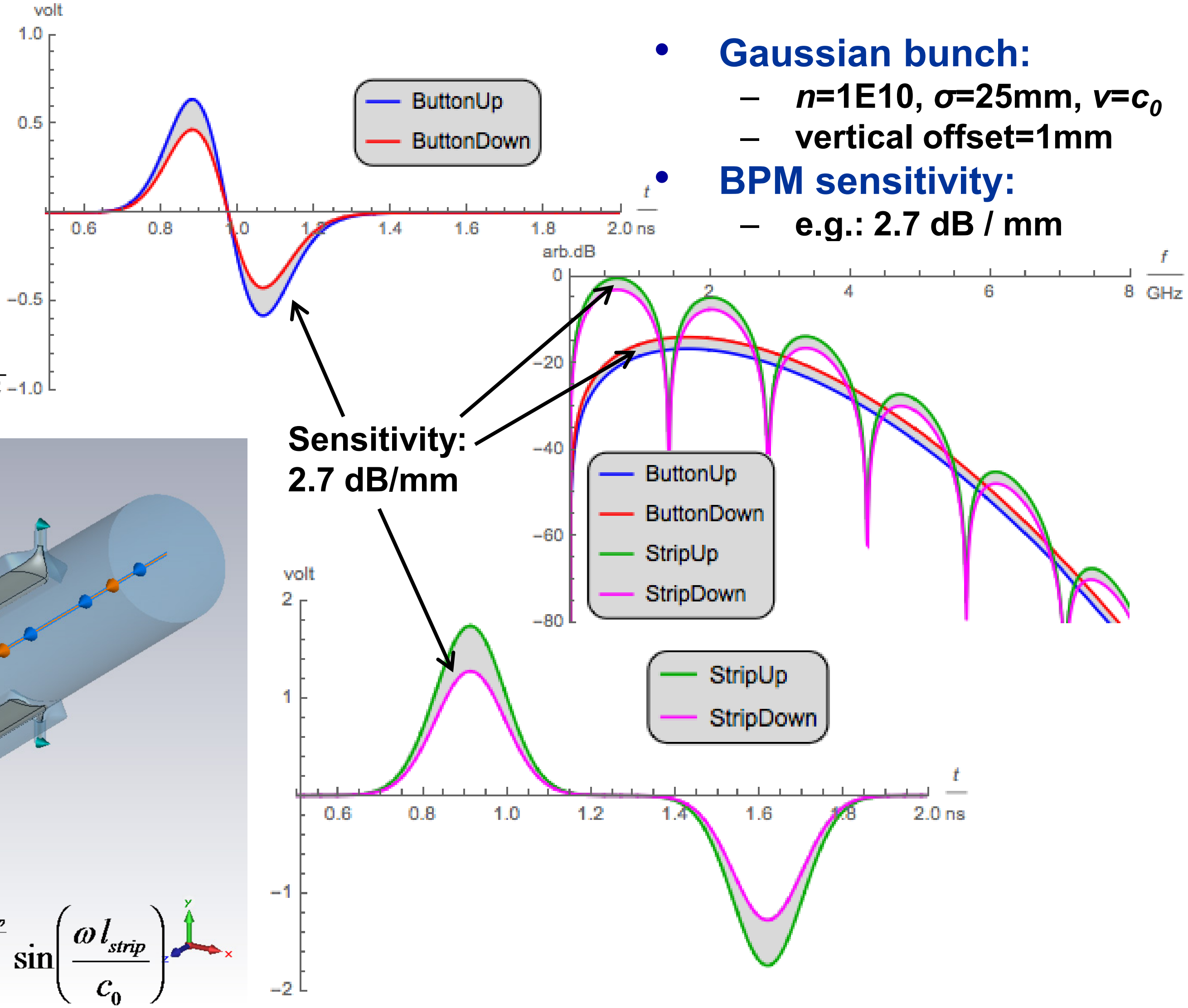

Sensitivity:
2.7 dB/mm

- **Gaussian bunch:**
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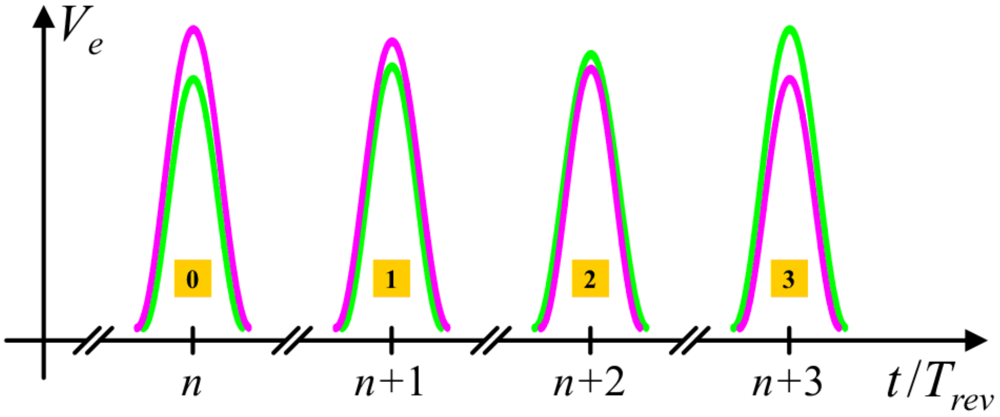
- **BPM sensitivity:**
  - **e.g.: 2.7 dB / mm**

BPM Signals (cont.)

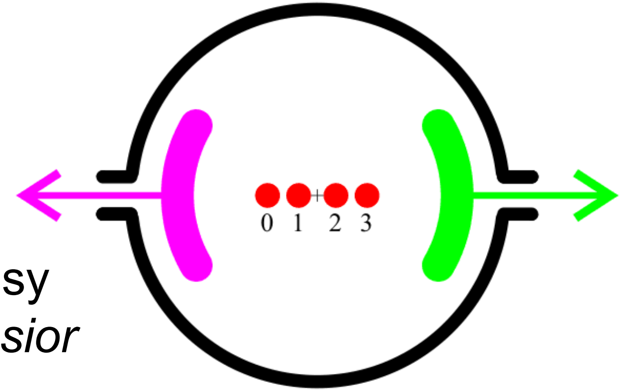
- **Raw broadband BPM bunch signals are short in time**
  - **Single bunch response *nsec* or sub-*nsec* pulse signals**
  - **The beam position information is amplitude modulated (AM) on the large (common mode) beam intensity signal!**
- **In ring accelerators, the beam position varies on a turn-by-turn basis, the signal spectrum is related to important machine parameters**
  - **Dipole moment spectrum of a single bunch: (simplistic case)**

courtesy *R. Siemann*

$$Z(\omega)I_{beam}(\omega)=D(\omega)=\omega_{rev}A_0Q\sum_{n=-\infty}^{+\infty}\delta\left[\omega-\left(n\omega_{rev}+\overset{\text{betatron frequency}}{\boxed{\omega_\beta}}\right)\right]\exp\left[-\frac{\left(\omega-\omega_\beta-\omega_\xi\right)^2\sigma_\tau^2}{2}\right]$$

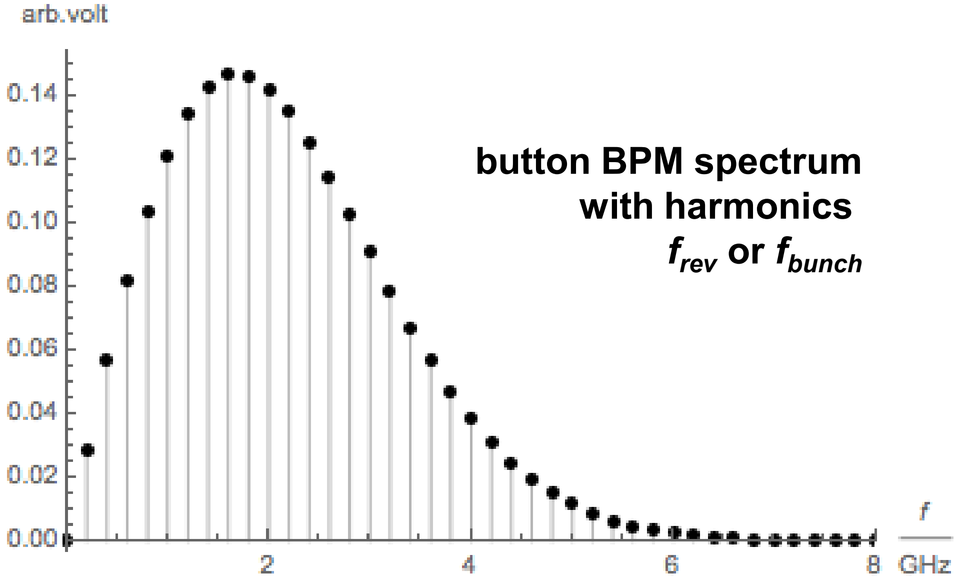


courtesy *M. Gasior*



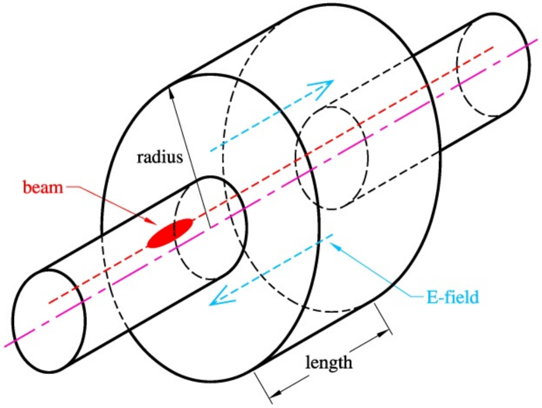
BPM Signals (cont.)

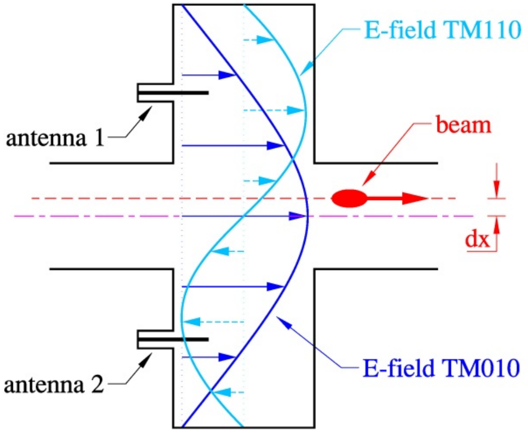
- The beam formatting defines the signal spectrum
  - E.g. f_{rev} , f_{bunch} in circular or linear accelerators

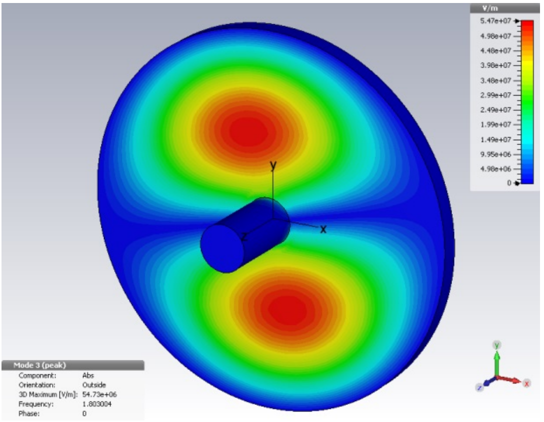


- The position information of broadband BPMs in frequency independent!
  - The broad spectral response of the BPM can be band limited without compromising the position detection!

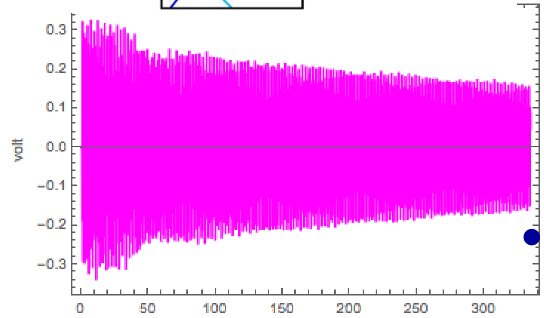
Resonant BPM Pickups

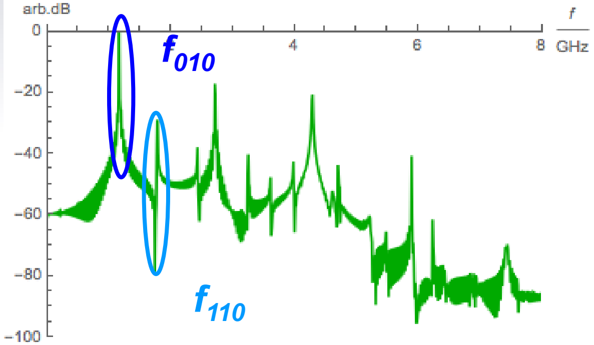






d_{pipe}: 25 mm
d_{cav}: 200 mm
l_{cav}: 10 mm





- "Pill-box" has eigenmodes at:

$$f_{mnp} = \frac{1}{2\pi\sqrt{\mu_0\varepsilon_0}}\sqrt{\left(\frac{j_{mn}}{R}\right)^2 + \left(\frac{p\pi}{l}\right)^2}$$

- Beam couples to:

$$E_z = C J_1\left(\frac{j_{11} r}{R}\right) e^{i\omega t}\cos\varphi$$

dipole (TM_{110}) and monopole (TM_{010}) & other modes

- Common mode (TM_{010}) frequency discrimination

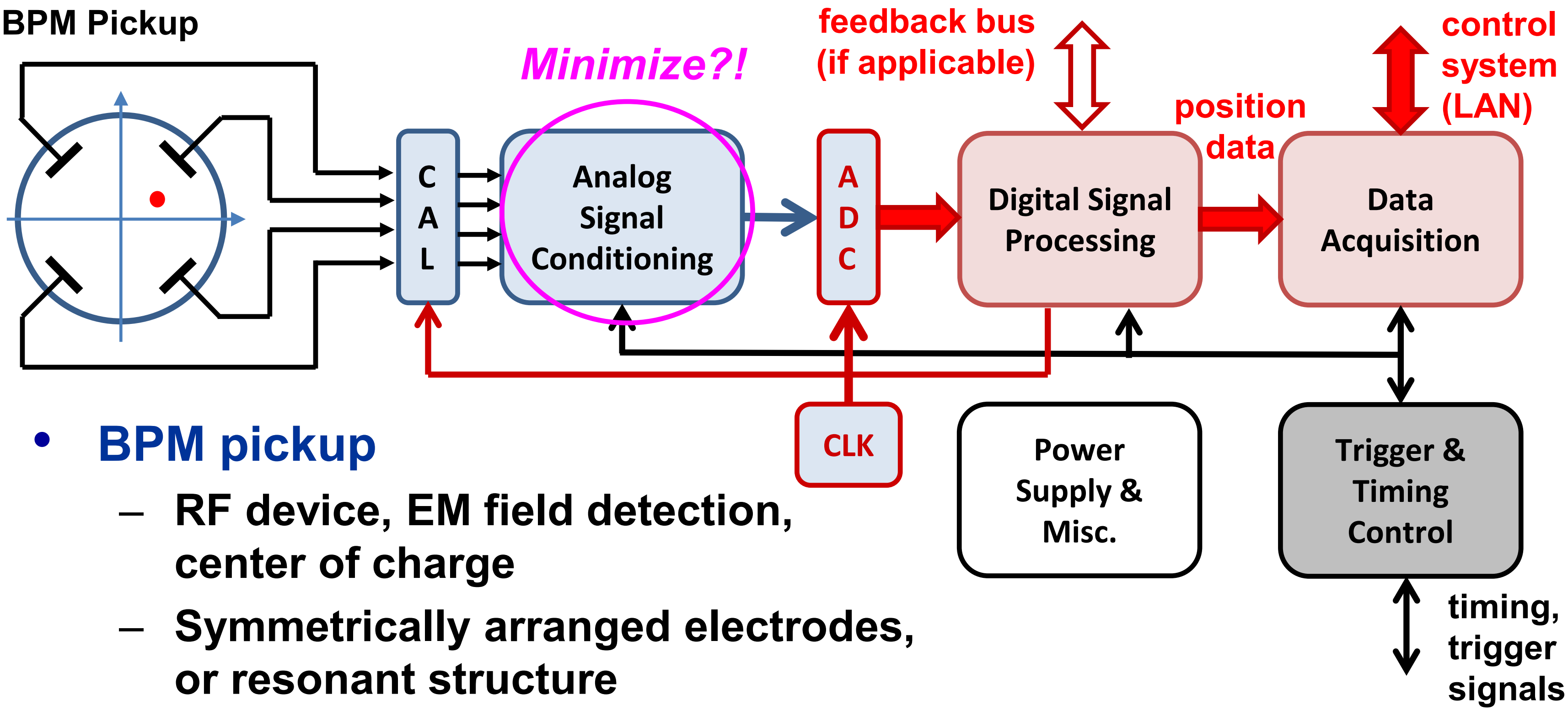
Decaying RF signal response

  - Position signal: TM_{110}
    - ➢ Requires normalization
  - Intensity signal: TM_{010}

Signal Processing & Normalization

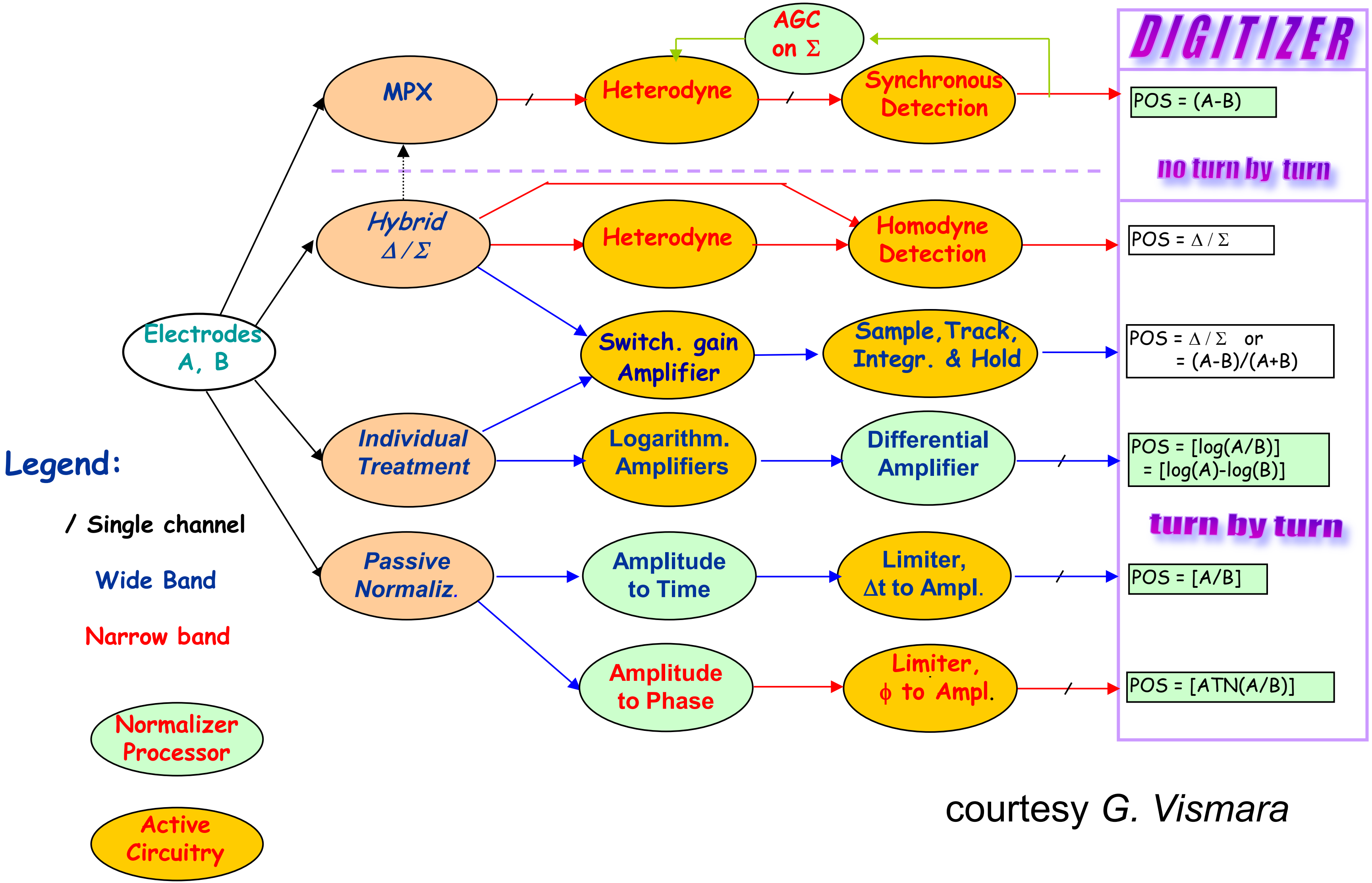
- Extract the beam position information from the electrode signals: Normalization
  - Analog using Δ-Σ or 90^0-hybrids, followed by filters, amplifiers mixers and other elements, or logarithmic amplifiers.
  - Digital, performing the math on individual digitized electrode signals.
- Decimation / processing 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)

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

Analog Signal Processing Options



DIGITIZER

Electrodes A, B

MPX → Heterodyne → Synchronous Detection → POS = (A-B)

AGC on Σ

no turn by turn

Hybrid Δ / Σ → Heterodyne → Homodyne Detection → POS = Δ / Σ

Switch. gain Amplifier → Sample, Track, Integr. & Hold → POS = Δ / Σ or = (A-B)/(A+B)

Individual Treatment → Logarithm. Amplifiers → Differential Amplifier → POS = [log(A/B)] = [log(A)-log(B)]

turn by turn

Passive Normaliz. → Amplitude to Time → Limiter, Δt to Ampl. → POS = [A/B]

Amplitude to Phase → Limiter, ϕ to Ampl. → POS = [ATN(A/B)]

Legend:

/ Single channel

Wide Band

Narrow band

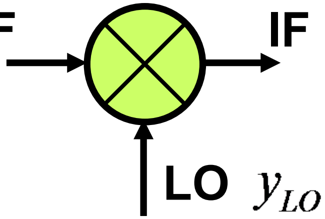
Normalizer Processor

Active Circuitry

courtesy *G. Vismara*

The RF Mixer as Downconverter

$y_{RF}(t)=A_{RF}\sin(\omega_{RF}t+\varphi_{RF})$



$y_{IF}(t)=y_{RF}(t)\,y_{LO}(t)$

$y_{LO}(t)=A_{LO}\sin(\omega_{LO}t+\varphi_{LO})$

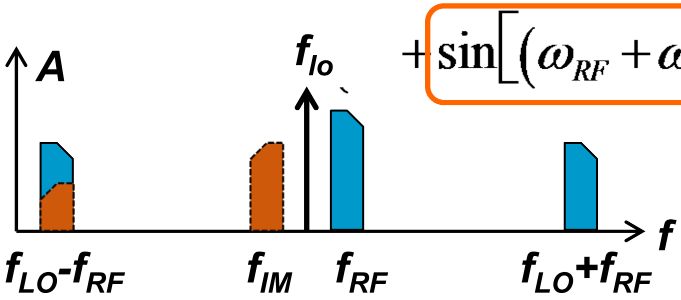
- **Ideal mixer:** $f_{IF}=f_{RF}\pm f_{LO}$

$$y_{IF}(t)=\frac{1}{2}A_{LO}A_{RF}\left\{\boxed{\sin\left[(\omega_{RF}-\omega_{LO})t+(\varphi_{RF}-\varphi_{LO})\right]}\right.$$

upper sideband

$$\left.+\boxed{\sin\left[(\omega_{RF}+\omega_{LO})t+(\varphi_{RF}+\varphi_{LO})\right]}\right\}$$

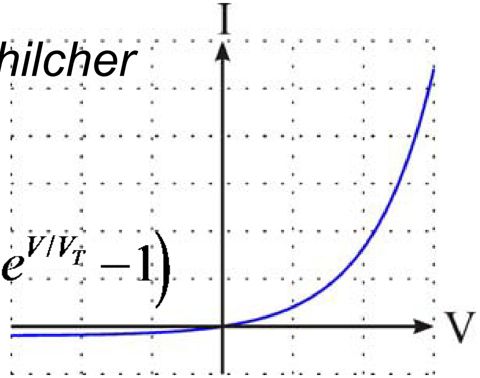
lower sideband



- **Frequency conversion**
  - $f_{RF} > f_{LO}$: heterodyne receiver
  - $f_{RF} = f_{LO}$: homodyne, demodulator
- **Real mixer:** $f_{IF}=mf_{RF}\pm nf_{LO}$
  - Image frequency: $f_{IM}=f_{LO}-f_{IF}$

I=f(V) **of a *Schottky* diode**

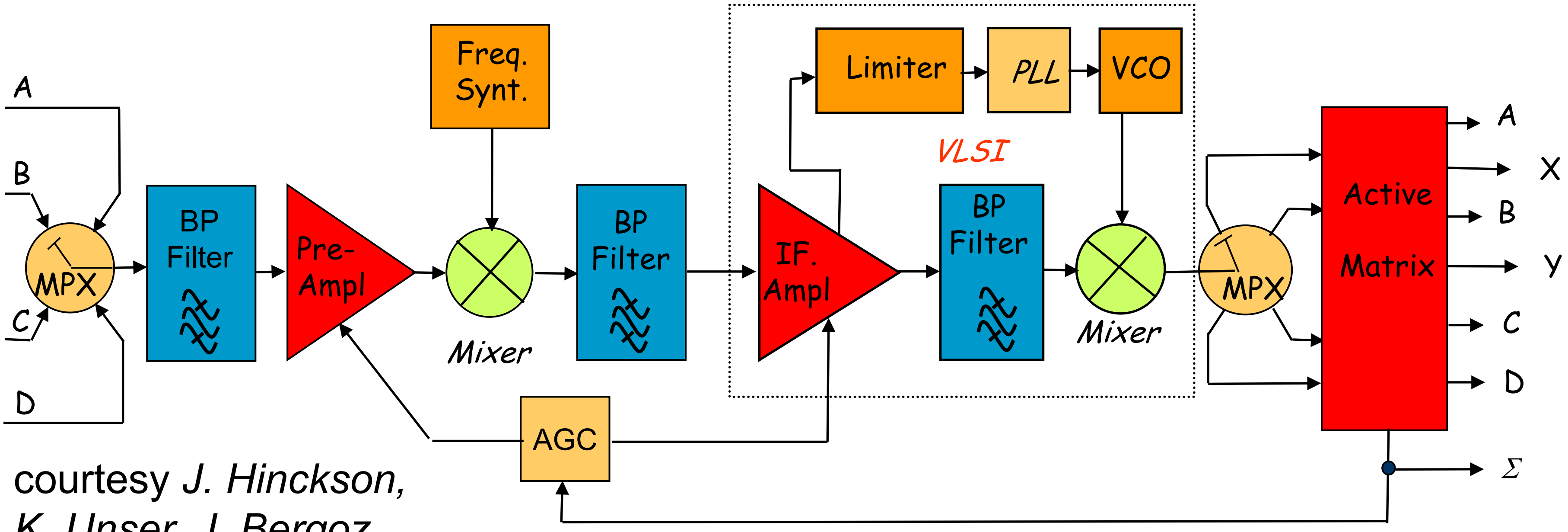
courtesy *T. Schilcher*



$$I=I_0\left(e^{V/V_T}-1\right)$$

$$\Delta I=I_0e^{V/V_T}\left(\frac{\Delta V}{V_T}+\frac{1}{2}\left(\frac{\Delta V}{V_T}\right)^2+\frac{1}{6}\left(\frac{\Delta V}{V_T}\right)^3+\cdots\right)$$

Example: MPX Heterodyne Receiver



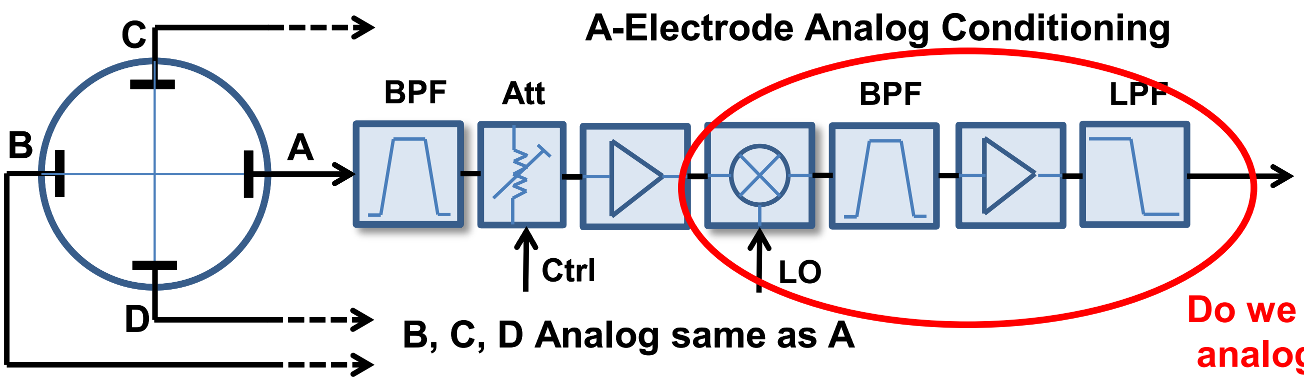
courtesy *J. Hinckson, K. Unser, J. Bergoz*

- **Analog BPM signal processing schemas typically:**
  - **Normalize and demodulate (downconversion to baseband) the BPM signals BEFORE digitalization.**
  - **Substantially reduces the performance requirements for the ADC**
    - **Resolution, dynamic range, bandwidth, sampling rate**

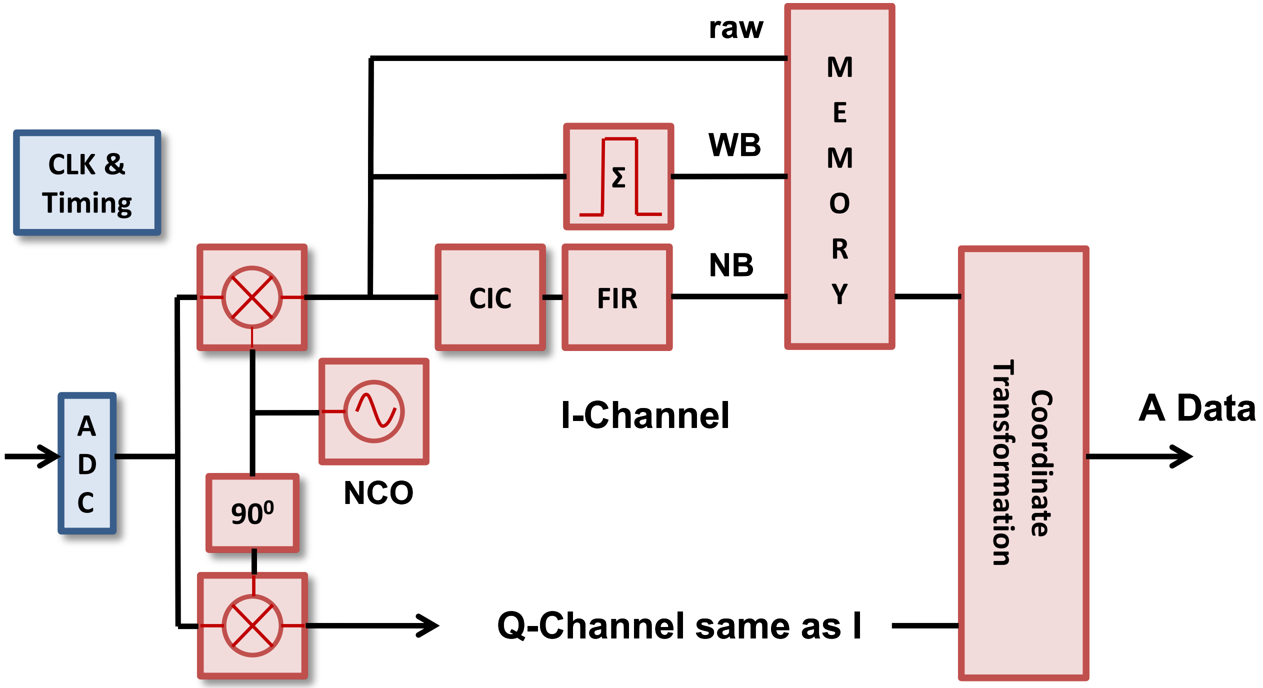
Digital BPM Signal Processing

- **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**

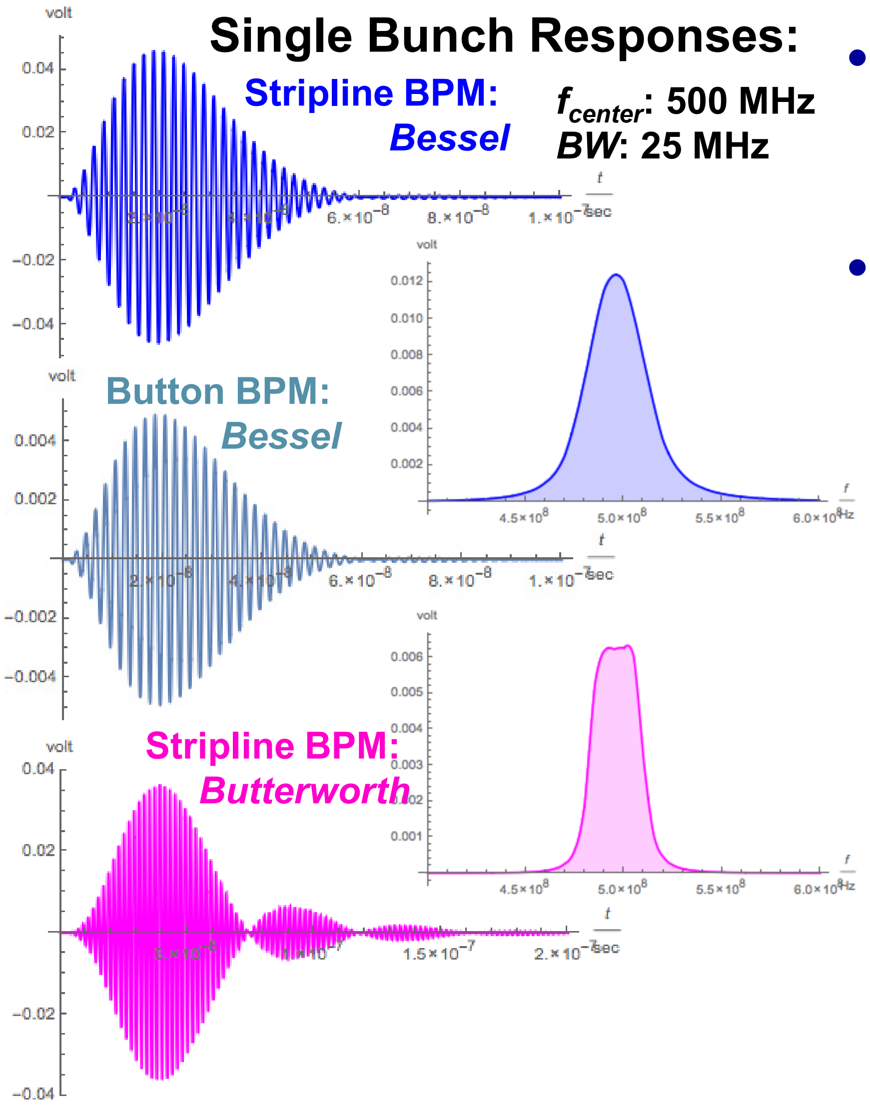
BPM Read-out Electronics



Do we need this analog section?



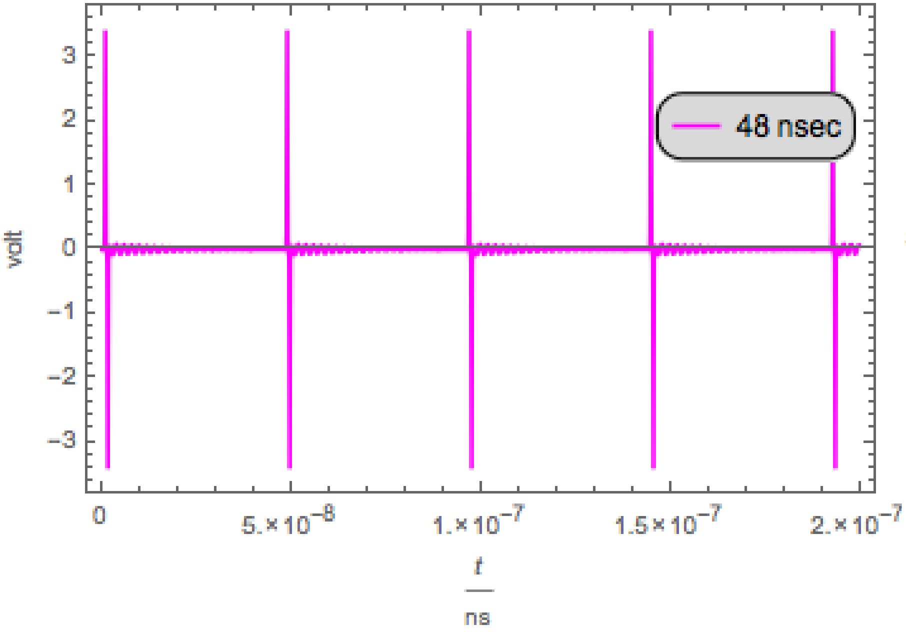
"Ringing" Bandpass-Filter (BPF)

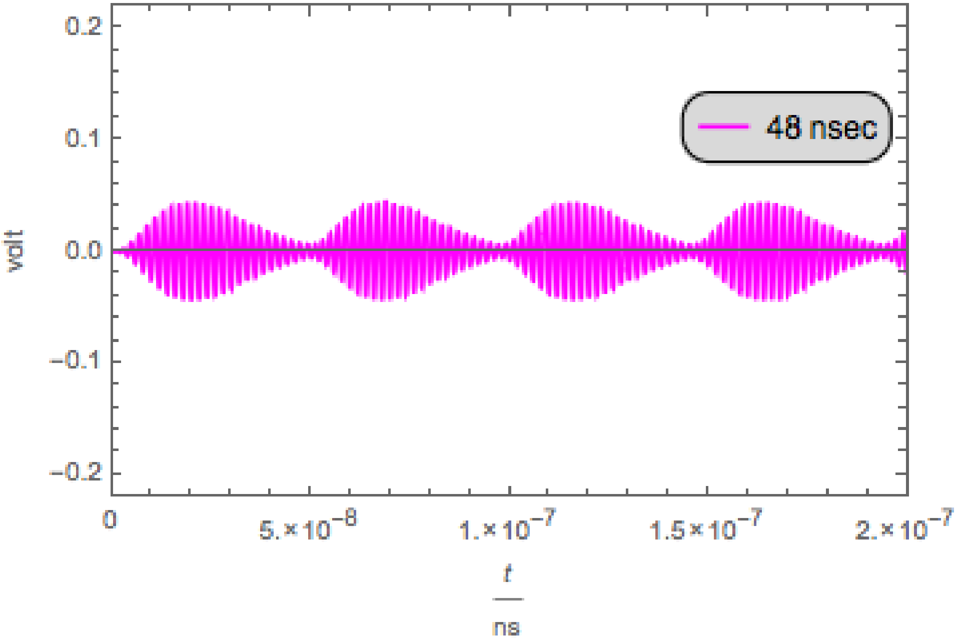


Single Bunch Responses:

- 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

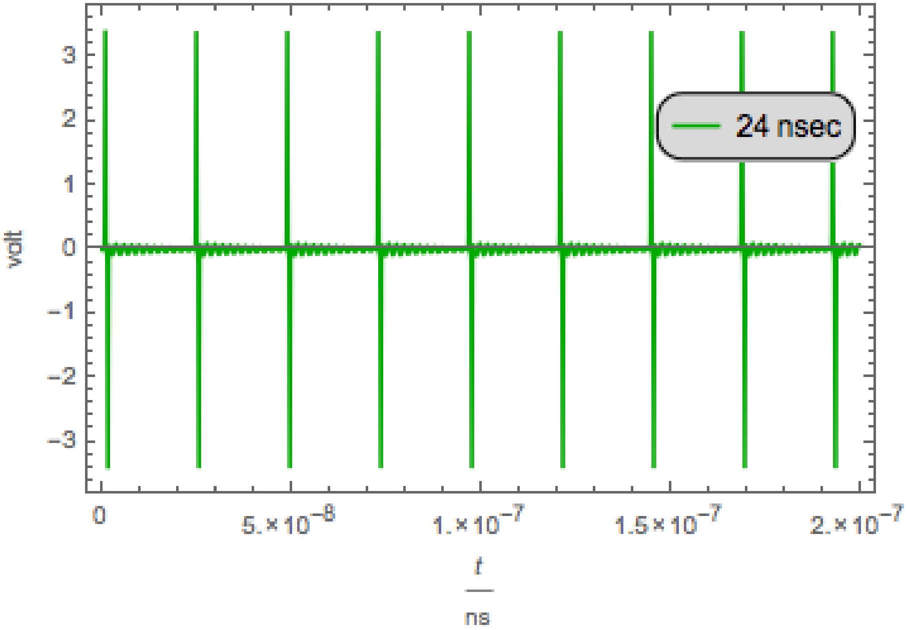
“Ringing” BPF & Multi-Bunches

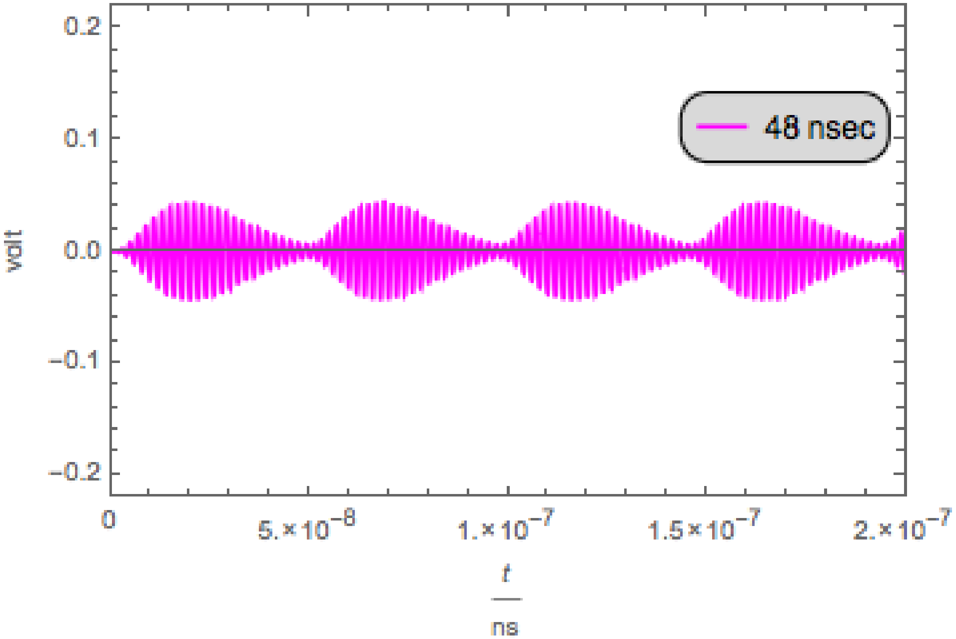




- **Bunch spacing < BPF ringing time:**
  - **Superposition of single bunch BPF responses**
  - **More continuous “ringing”, smearing of SB responses**
- **Bunch spacing < BPF rise time**
  - **Constructive signal pile-up effect**
    - ➢ **Output signal level increases linear with decreasing bunch spacing**

“Ringing” BPF & Multi-Bunches





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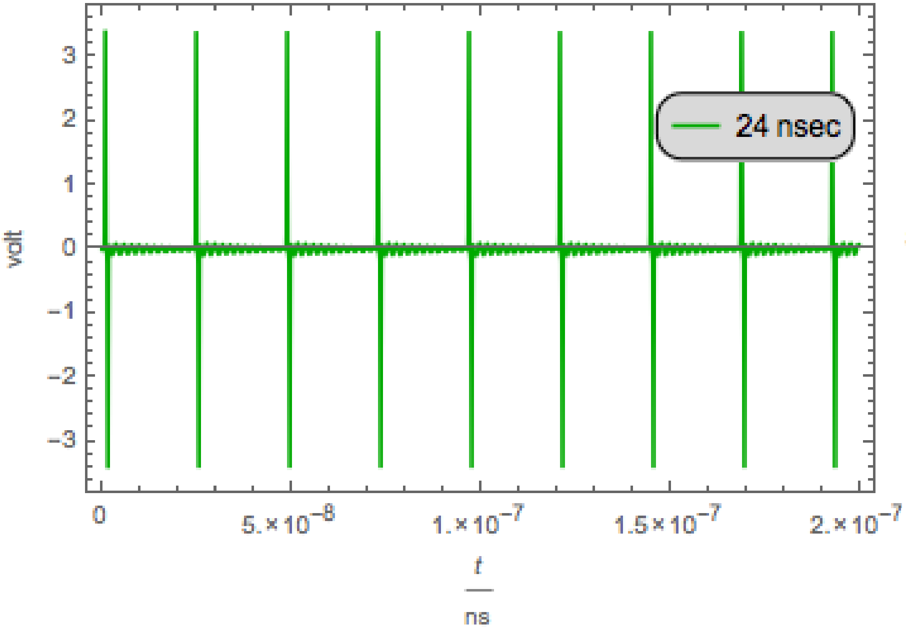

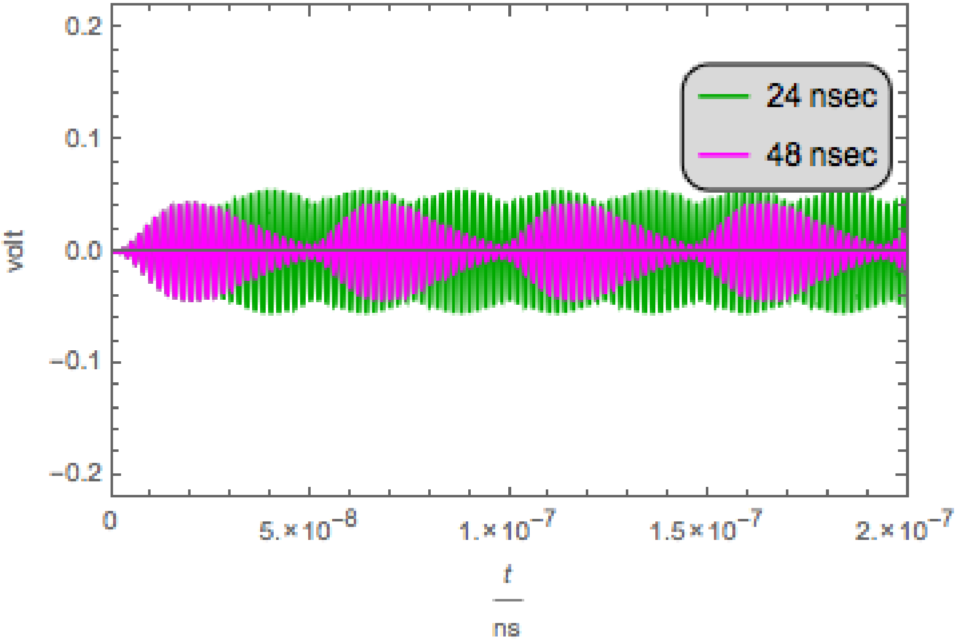

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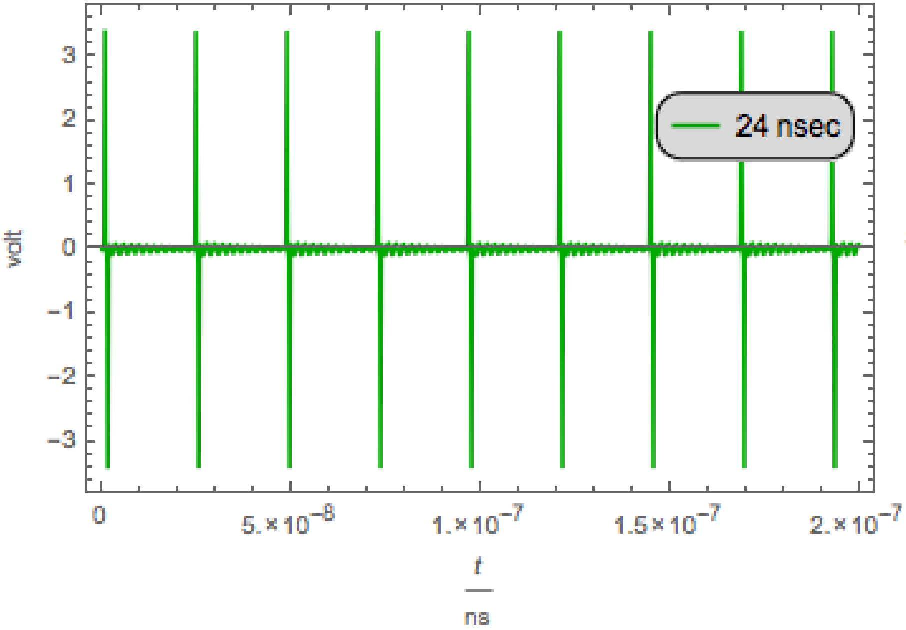

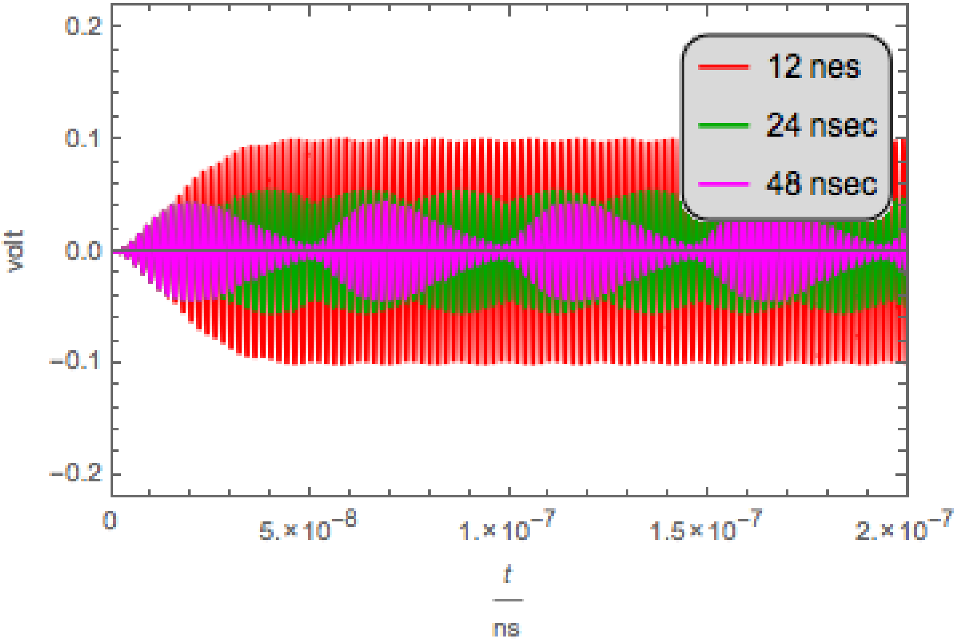

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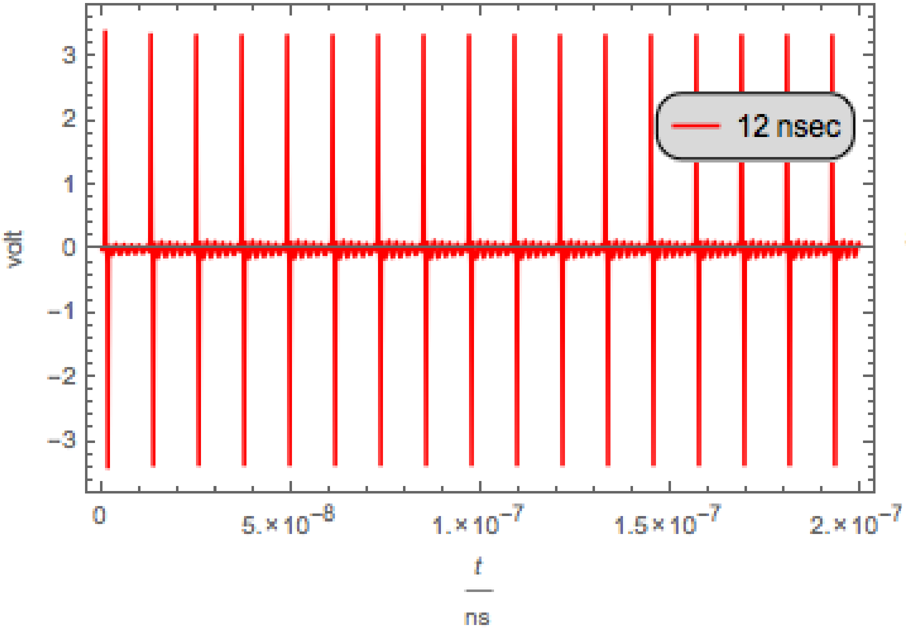

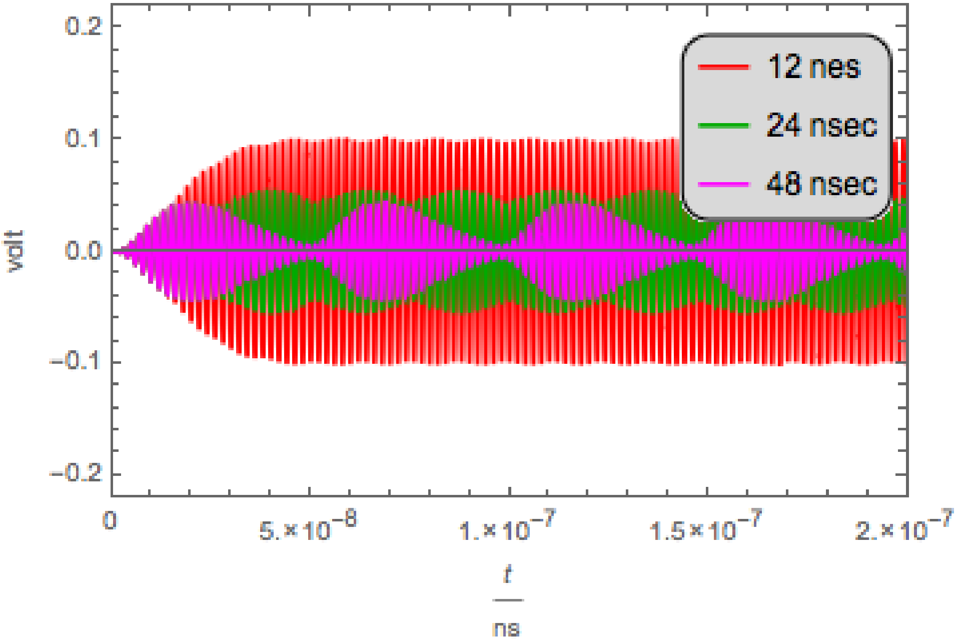

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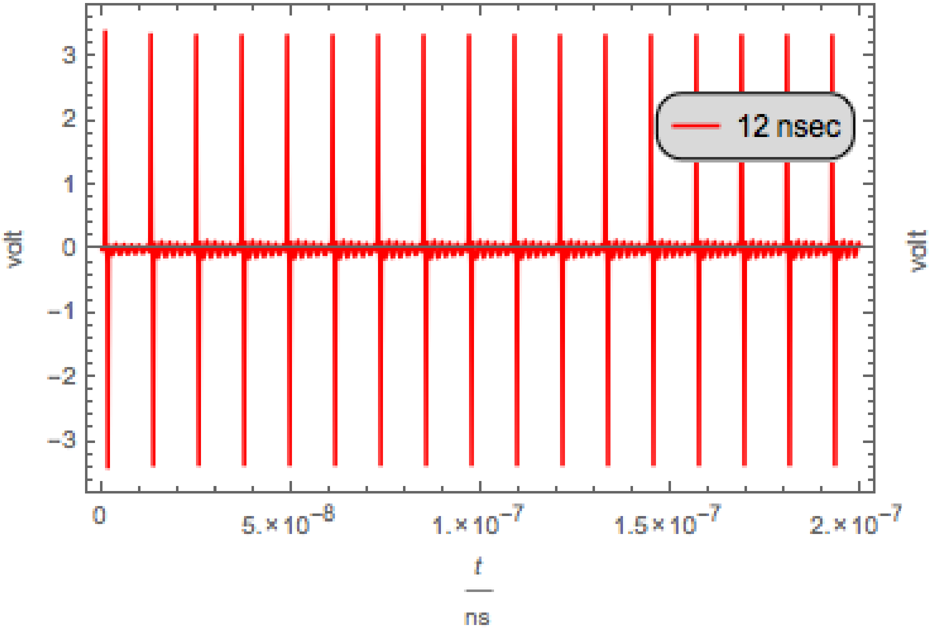

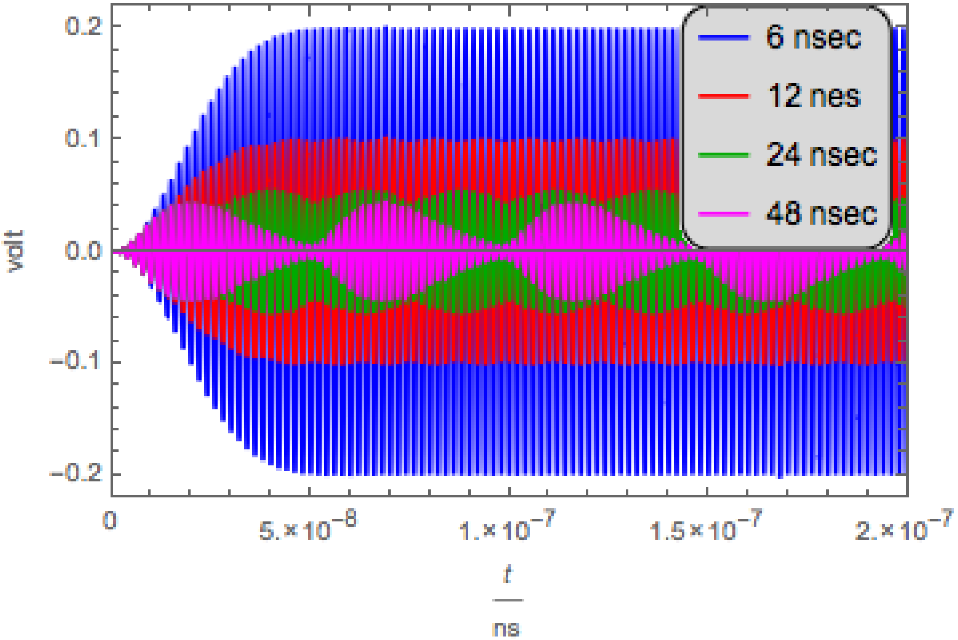

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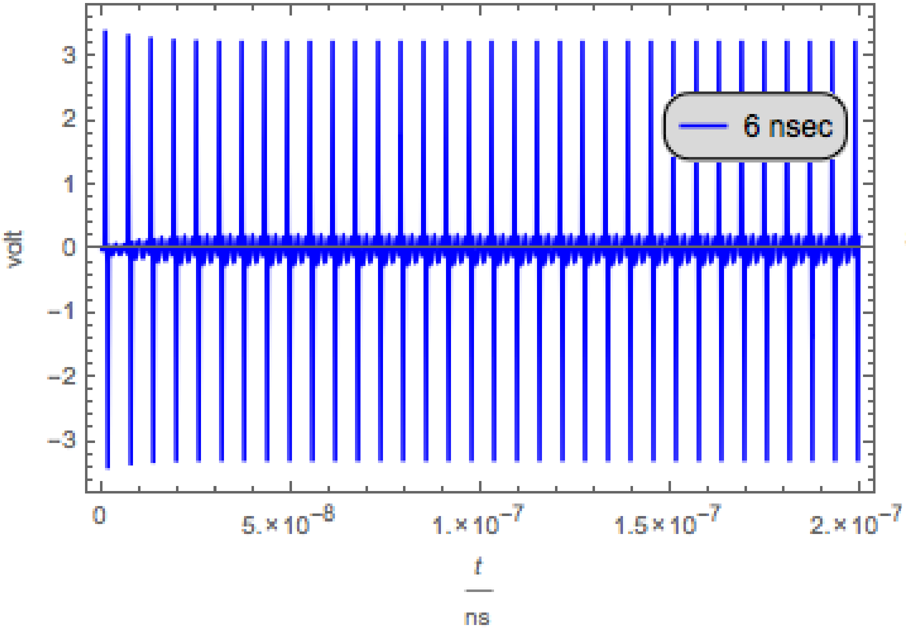
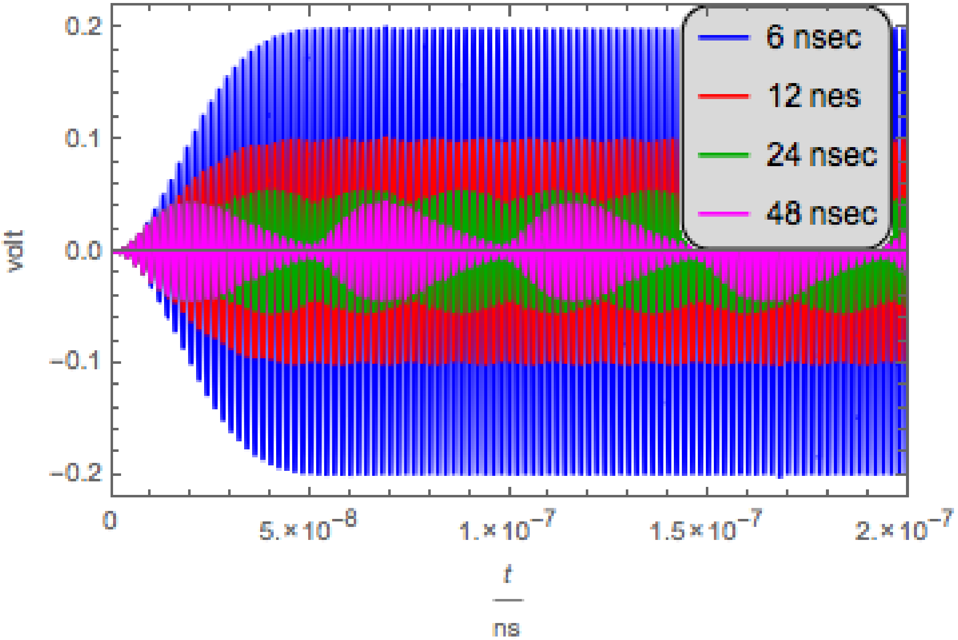
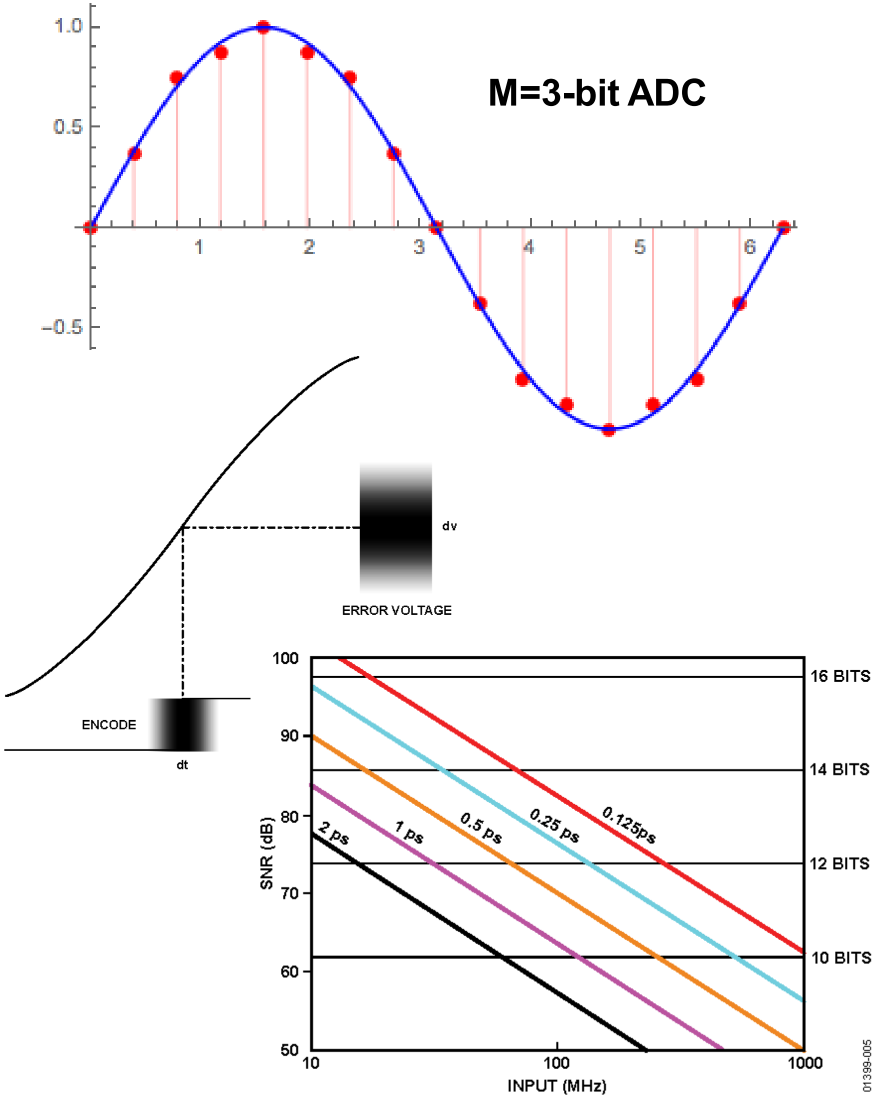
“Ringing” BPF & Multi-Bunches





- **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

Analog Digital Converter



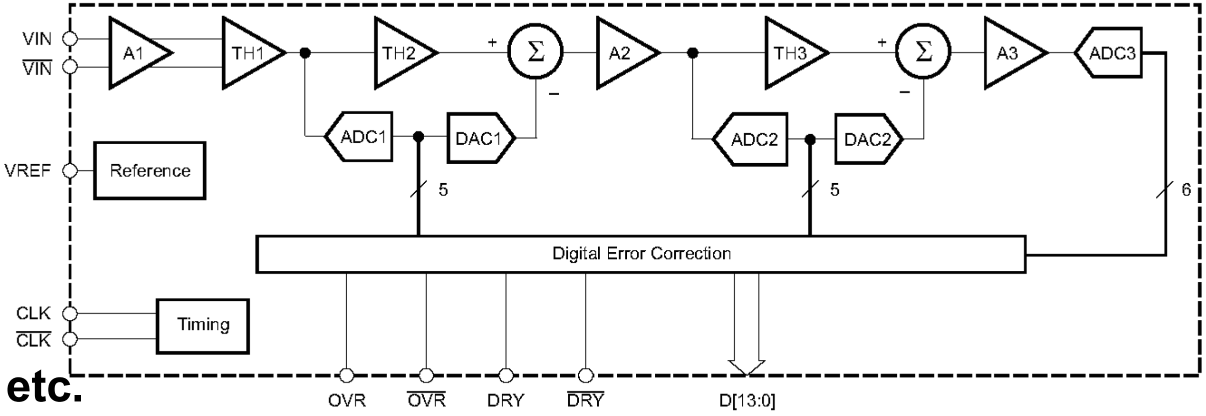
- Quantization of the continuous input waveform at equidistant spaced time samples
  - Digital data is discrete in amplitude and time
- LSB voltage (resolution) $Q = \frac{V_{FSR}}{2^M}$
  - E.g. 61 µV (14-bit), 15 µV (16-bit) @ 1 volt V_{FSR}
- Quantization error (dynamic range) $SQNR = 20 \log_{10}(2^M)$
  - 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

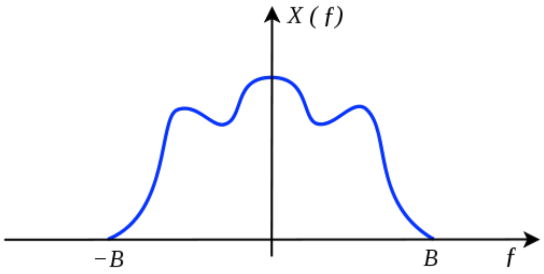
* has an analog I-Q mixer integrated, 0.7 GHz < f_{in}< 4 GHz

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

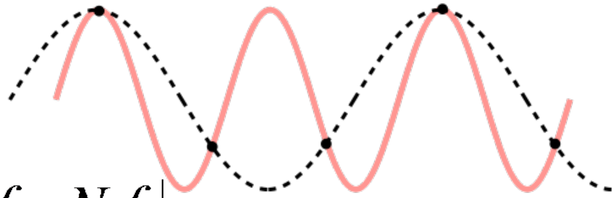


Sampling Theory

- **A band limited signal *x(t)* with *B*=f_{max} can be reconstructed if** $$f_s \geq 2 f_{\max}$$
  - **Nyquist-Shannon theorem**
  - **The exact reconstruction of *x(t)* by $x_n = x(nT)$:**

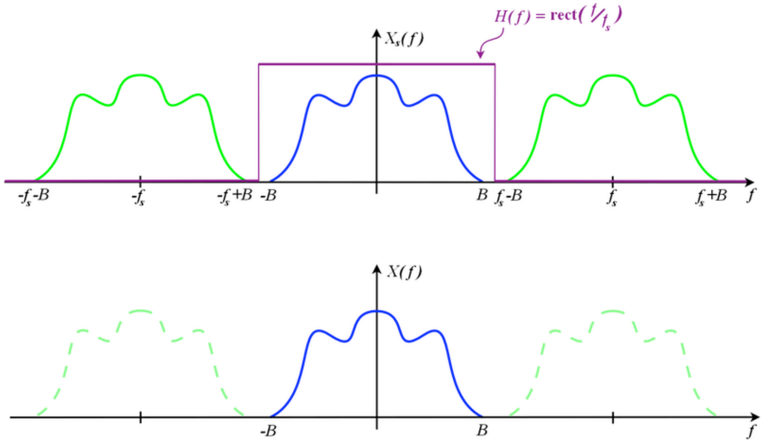


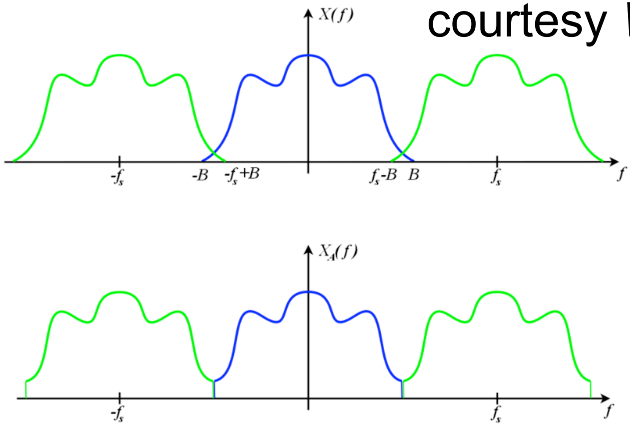
$$x(t) = \sum_{n=-\infty}^{+\infty} x_n \frac{\sin \pi(2 f_{\max} t - n)}{\pi(2 f_{\max} t - n)} = \sum_{n=-\infty}^{+\infty} x_n \operatorname{sinc} \frac{t - nT}{T}$$



- **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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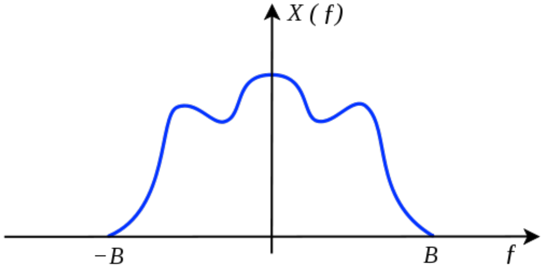

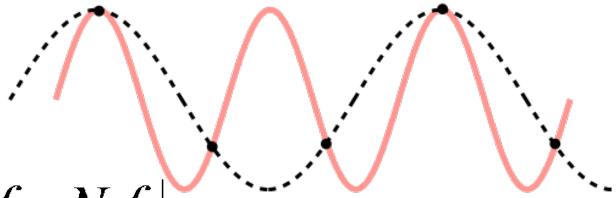

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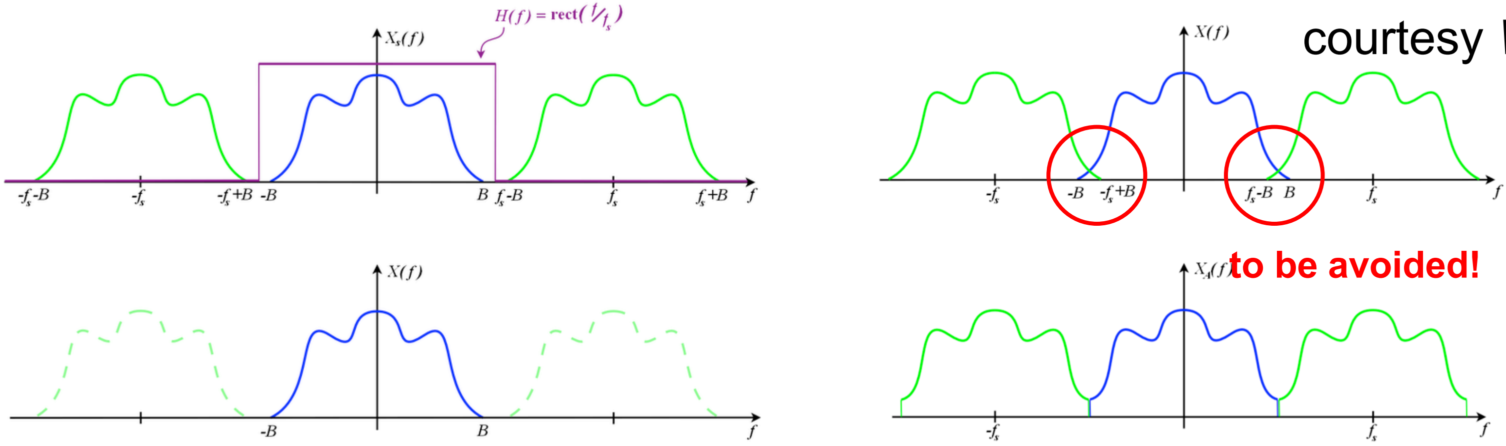


courtesy *Wikipedia*

to be avoided!

Bandpass or Undersampling

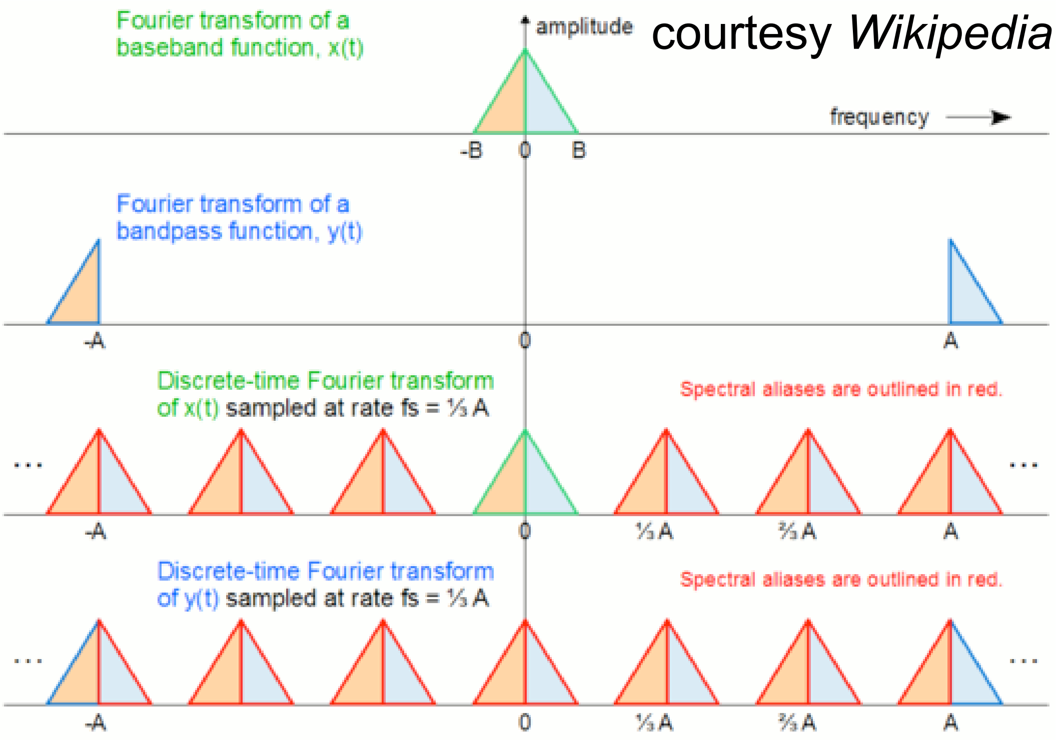
- **A bandpass signal $f_{lo}=A$, $f_{hi}=A+B$ is down-converted to baseband**
  - **The sampling frequency has to satisfy:**

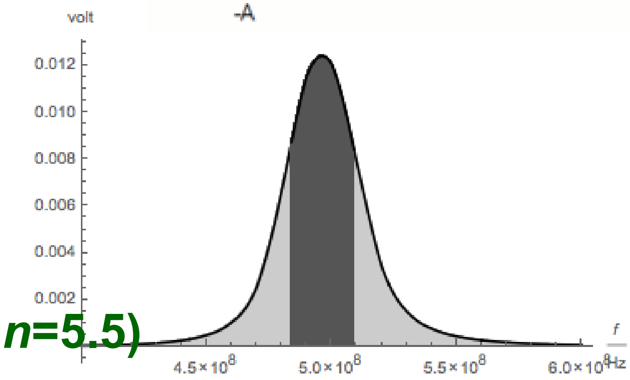
$$\frac{2f_{hi}}{n} \le f_s \le \frac{2f_{lo}}{n-1}$$

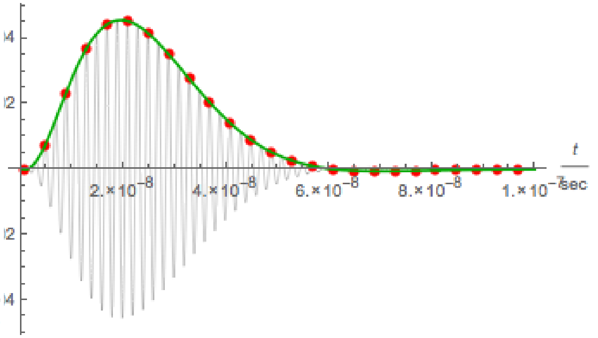
$$\text{with: } 1 \le n \le \left|\frac{f_{hi}}{f_{hi}-f_{lo}}\right|$$

- **Digital down-conversion (DDC) of BPM signals**
  - **BPM -> BPF (Bessel)**
    - **f_{center}: ~500 MHz** **BW (3 dB): 25 MHz**
    - **T=4 ns, f_s=200 MHz (f_{hi}/f_{lo}=550/450 MHz, n=5.5)**

courtesy *Wikipedia*







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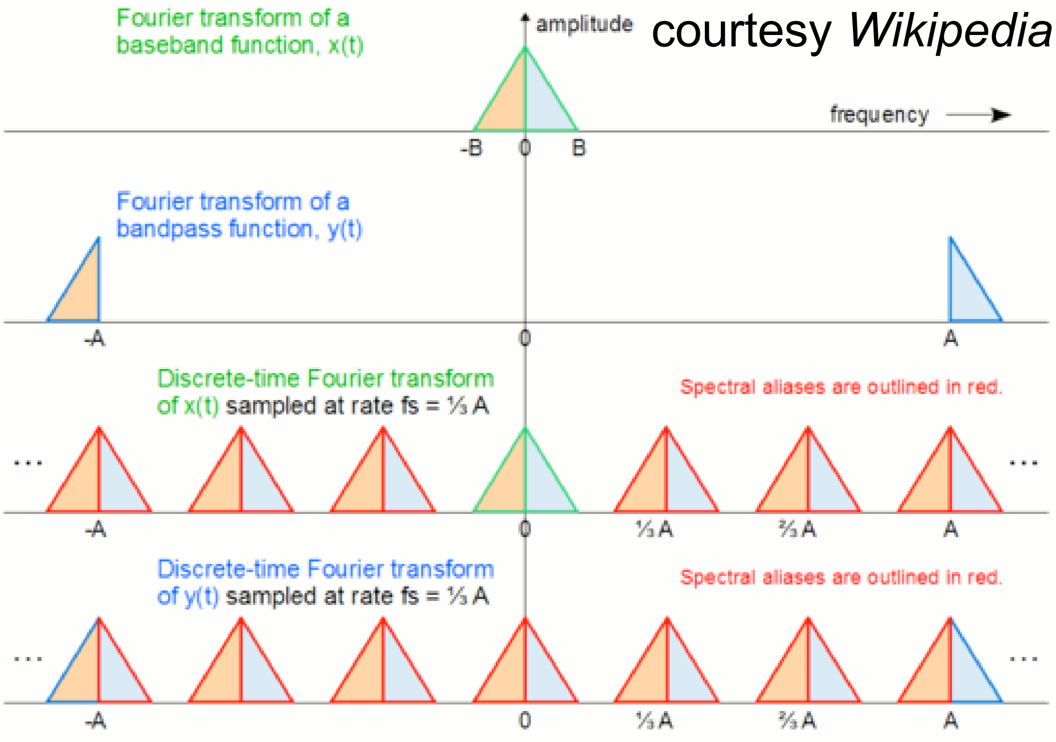
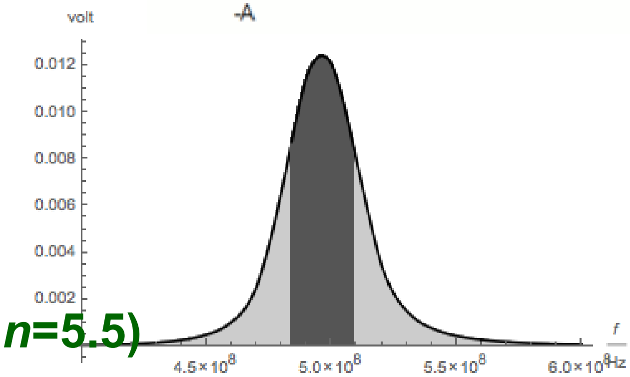
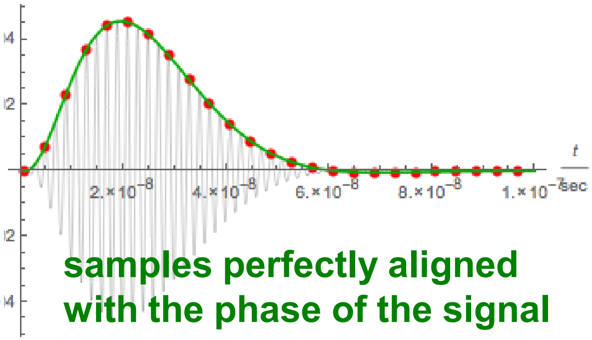


courtesy *Wikipedia*





samples perfectly aligned with the phase of the signal

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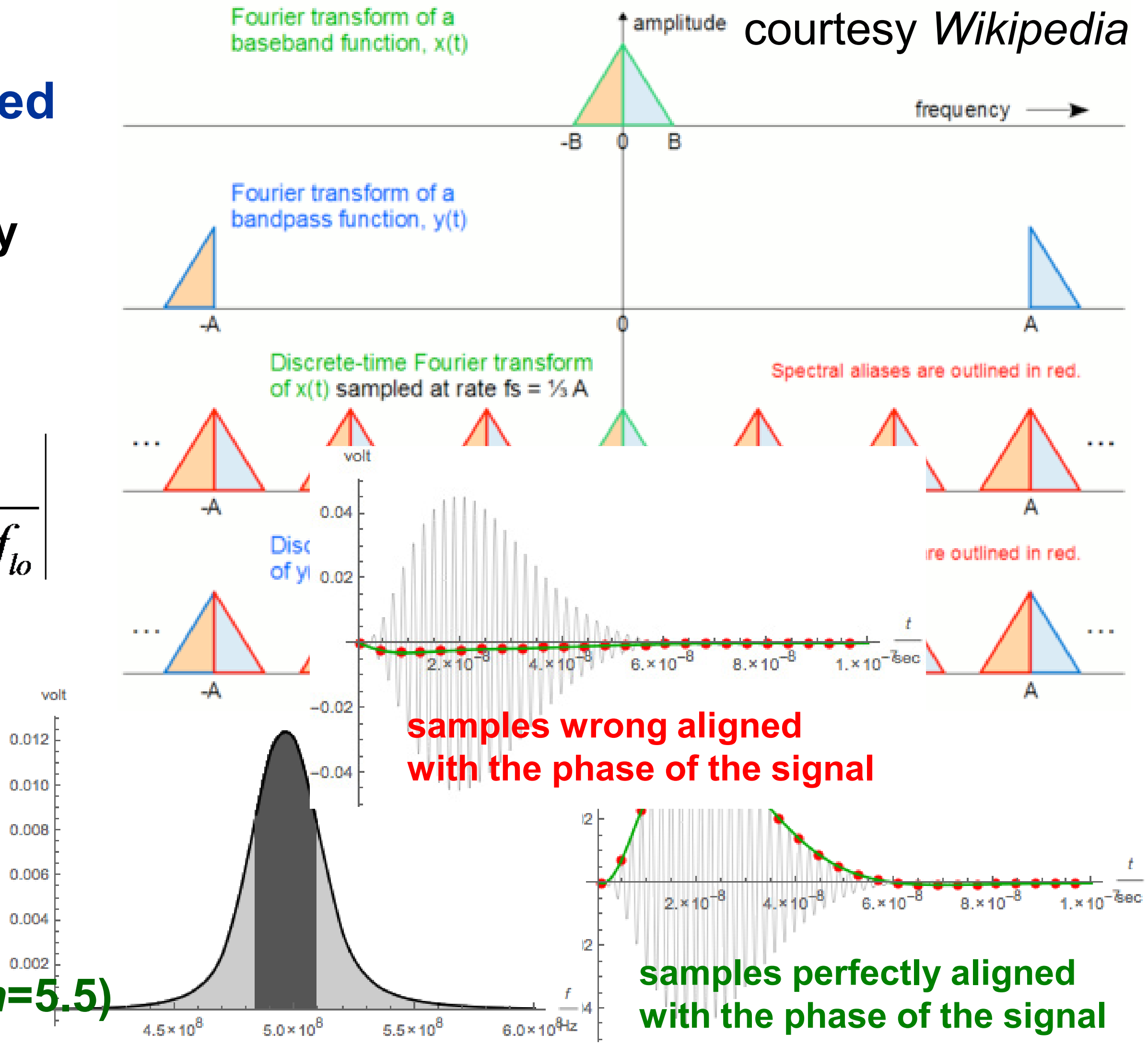
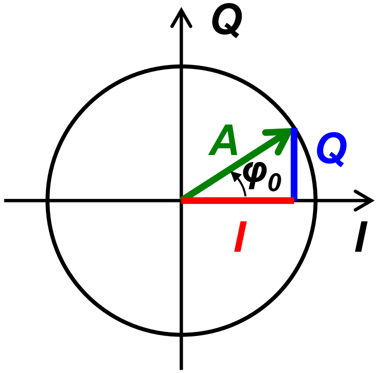
courtesy *Wikipedia*



samples wrong aligned with the phase of the signal

samples perfectly aligned with the phase of the signal

I-Q Sampling



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

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

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

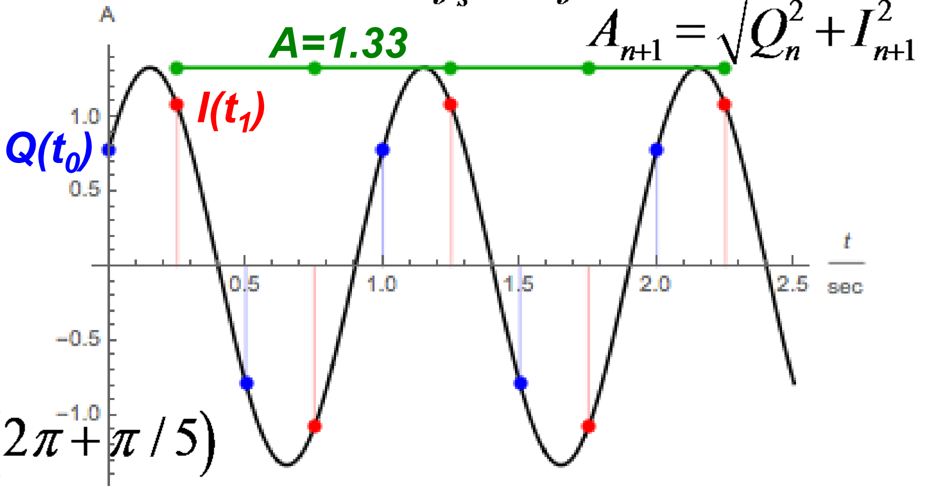
I: in-phase component **Q: quadrature-phase component**

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

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

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

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

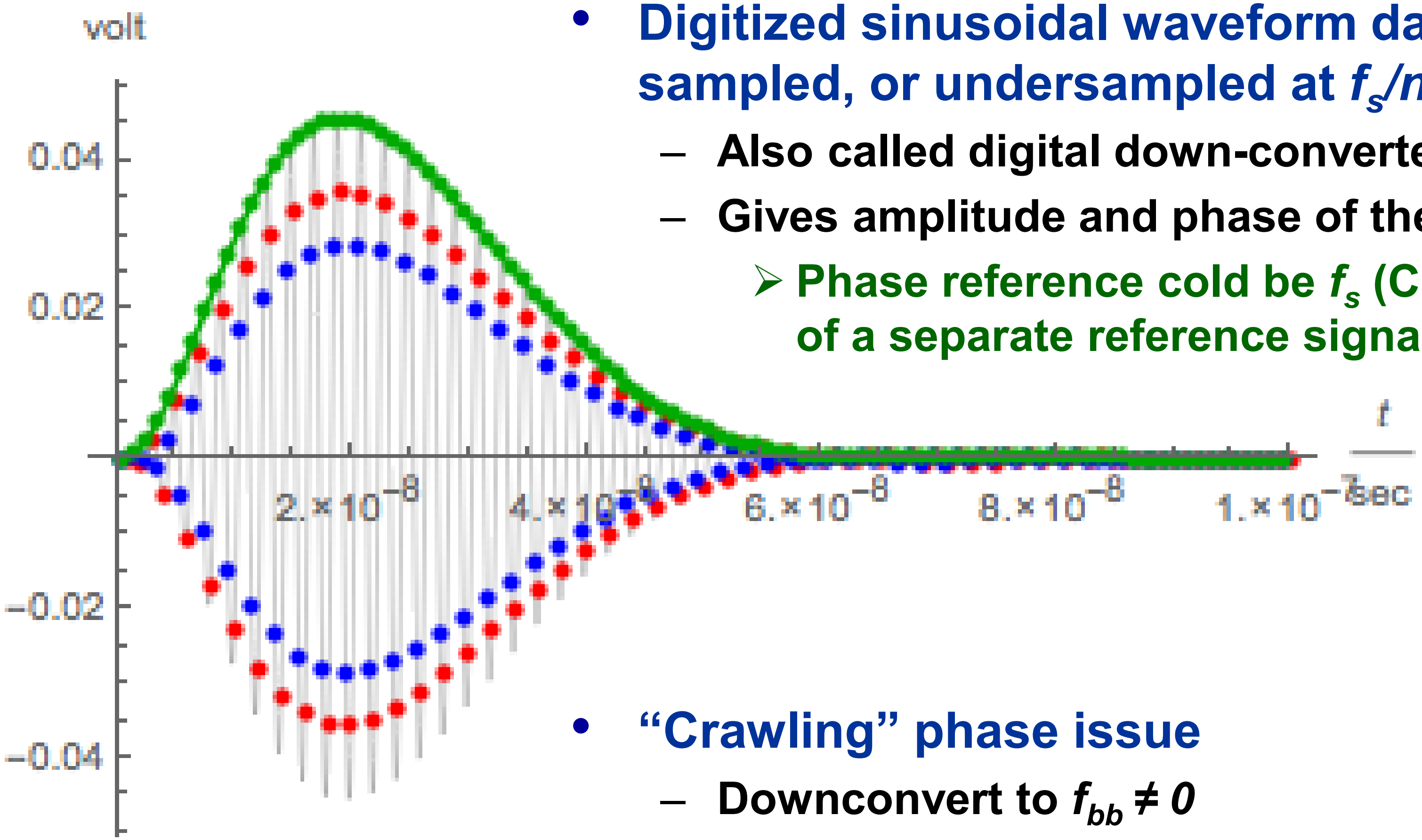


$$A_{n+1} = \sqrt{Q_n^2 + I_{n+1}^2}$$

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

I-Q Demodulation of BPM Signals

- 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 cold be f_s (CLK), of a separate reference signal

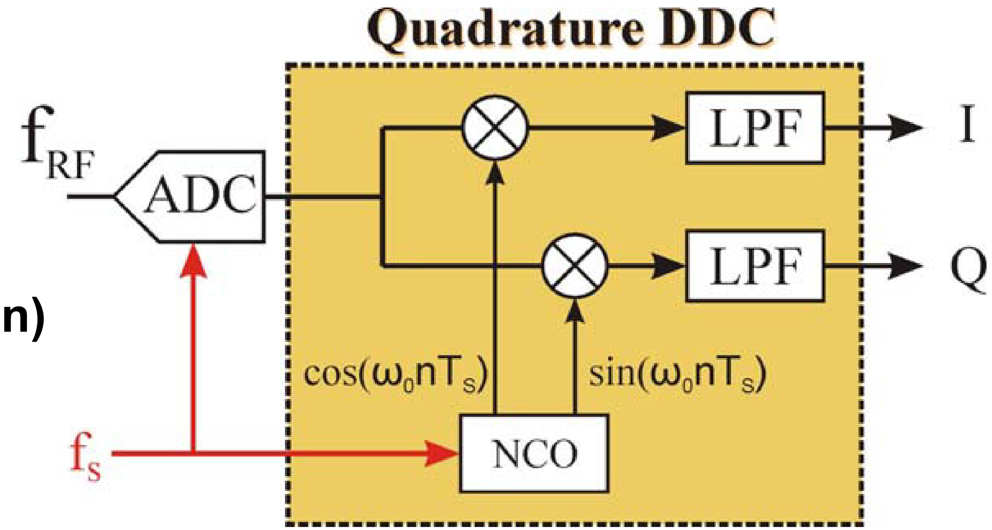


n=2

- "Crawling" phase issue
  - Downconvert to $f_{bb} \neq 0$
  - For TbT BPM measurements ensure $f_{bb}=i\ f_{rev}$

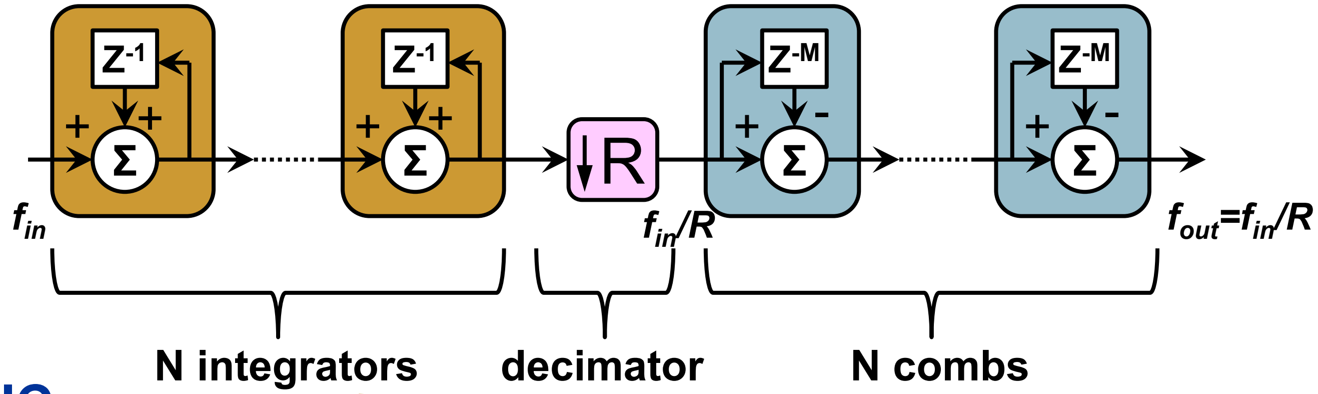
Digital Down-Converter

- **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*

Cascaded Integrator Comb Filter (CIC)



- **Decimating CIC**
  - **Boxcar filter (anti aliasing)**
    - non-recursive
      moving average filter
  - **Decimator**
    - Data rate reduction
  - **Comb filter**
    - Recursive running-sum
- **Economical implementation**
  - **No multiplier, minimum storage requirements**

$$H(z) = H_I^N(z)\,H_C^N(z)$$
$$= \frac{1}{\left(1 - z^{-1}\right)^N}\left(1 - z^{-RM}\right)^N$$
$$= \left(\sum_{k=0}^{RM-1} z^{-k}\right)^N$$

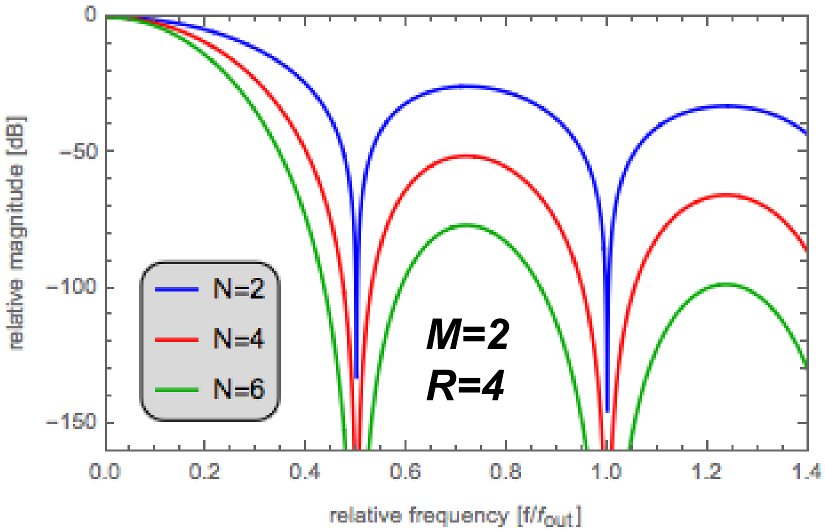
FIR filter (stable)

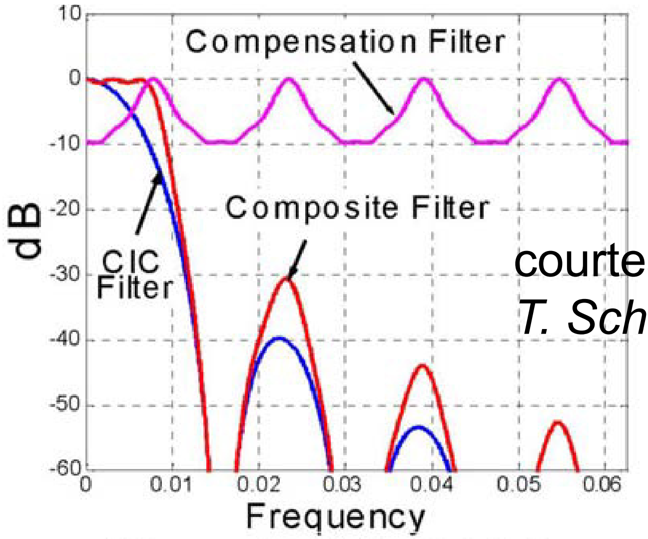
CIC Filter (cont.)

- CIC frequency response

$$H(f)=\left(\frac{\sin \pi M \dfrac{f}{f_{out}}}{\sin \dfrac{\pi}{R}\dfrac{f}{f_{out}}}\right)^N$$

  - With respect to the output frequency: $f_{out}=\dfrac{f_{in}}{R}$
  - *M:* differential delay, determines the location of the zeros: $f_0 = k\dfrac{f_{out}}{M}$
  - *N*: number of CIC stages
  - *R*: decimation ratio
    - ➢ Has little influence on the filter response
- CIC plus FIR compensation filter
  - Compensate CIC passband drop

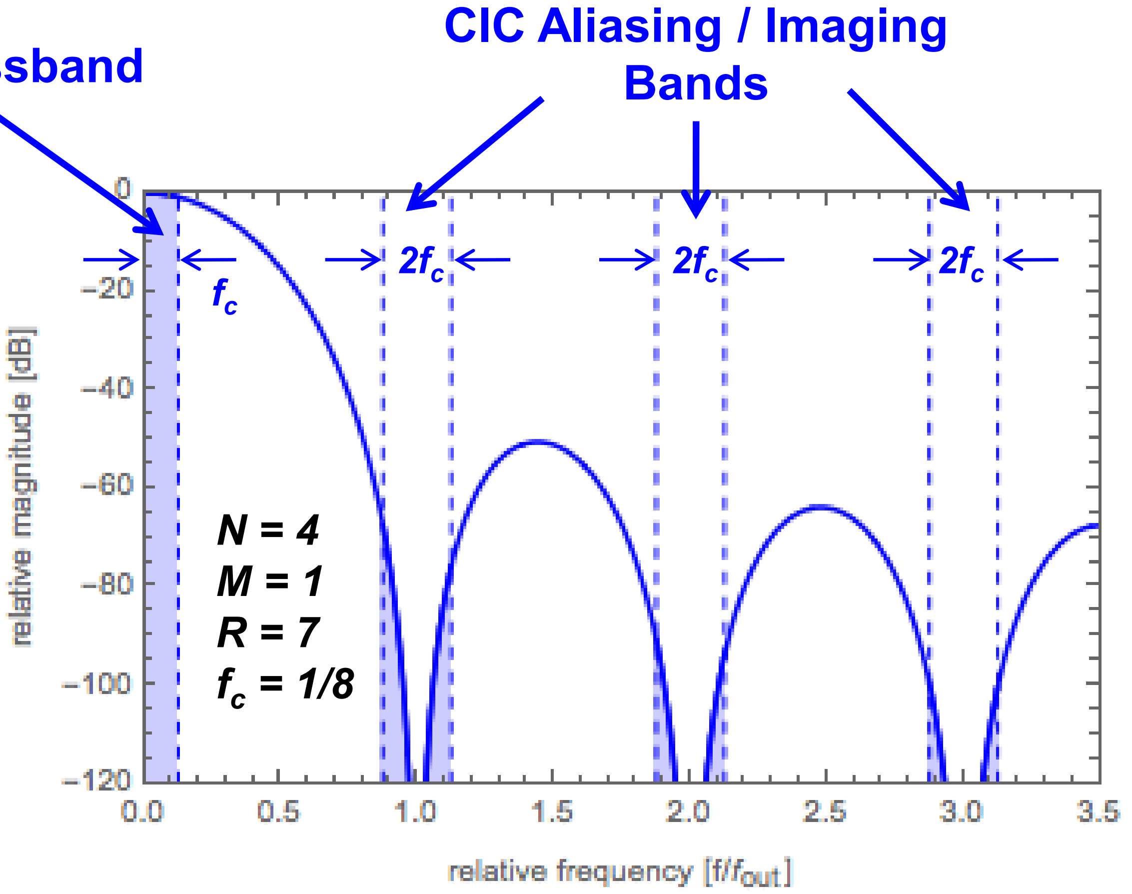




CIC compensation filter for M = 3, R = 64.

courtesy
T. Schilcher

CIC Aliasing – Imaging



courtesy
E. Hogenauer

- **CIC aliasing / imaging bands are around:** $(i - f_c) \le f \le (i + f_c)$

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:**

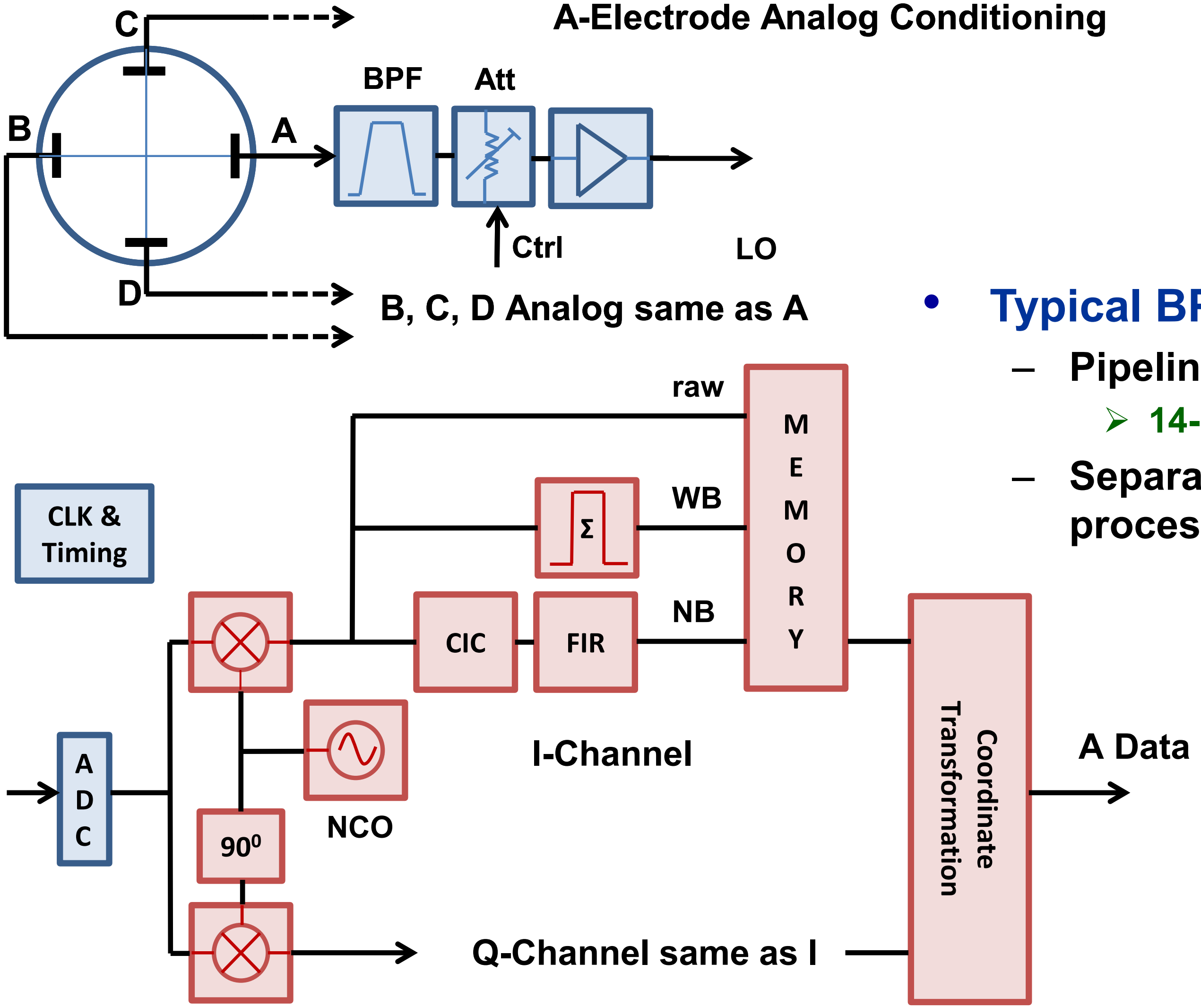
$$S / N = \frac{\Delta v}{v_{noise}}$$

  - **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/√BW)**
    - **Increase the number of samples (S/N improves with √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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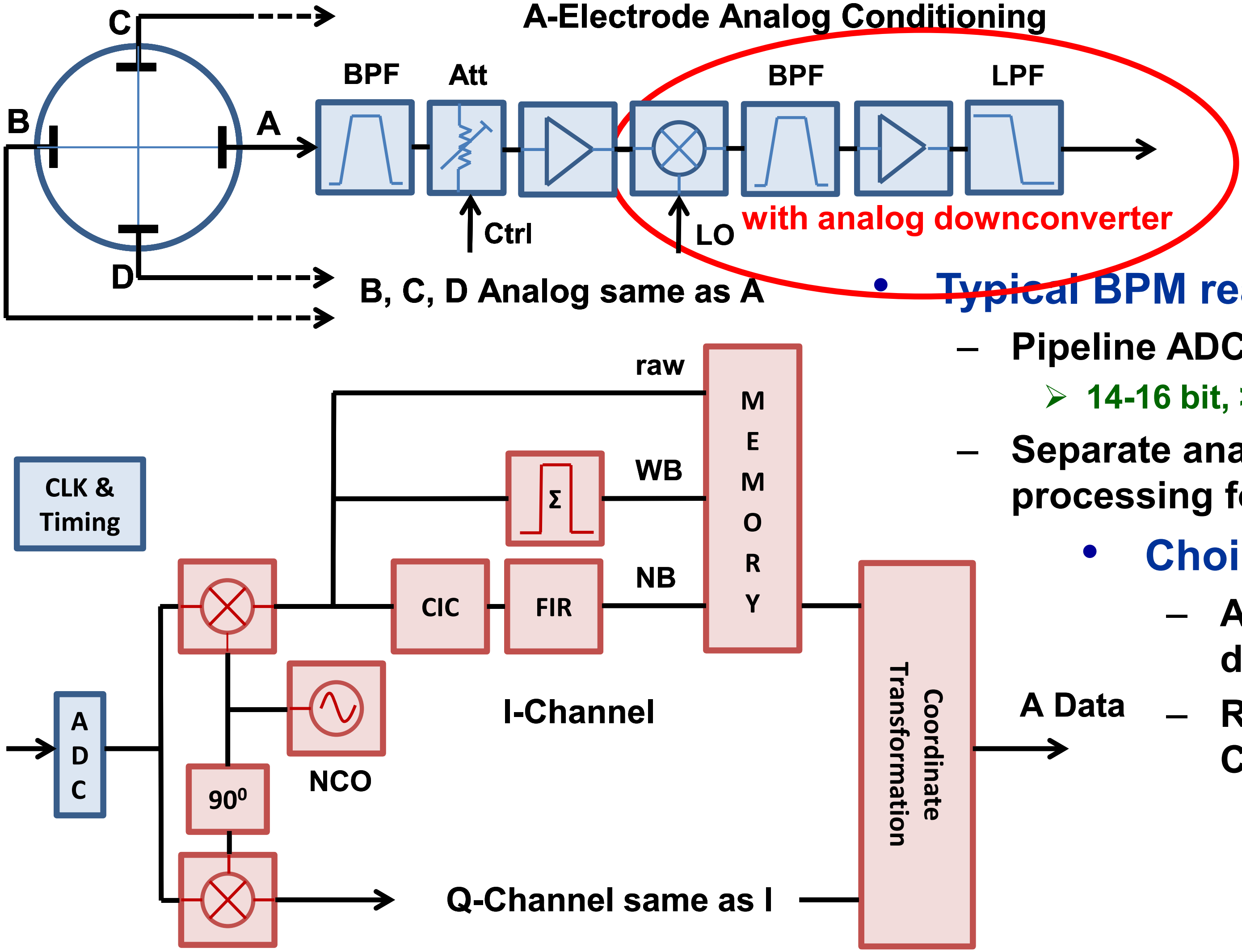
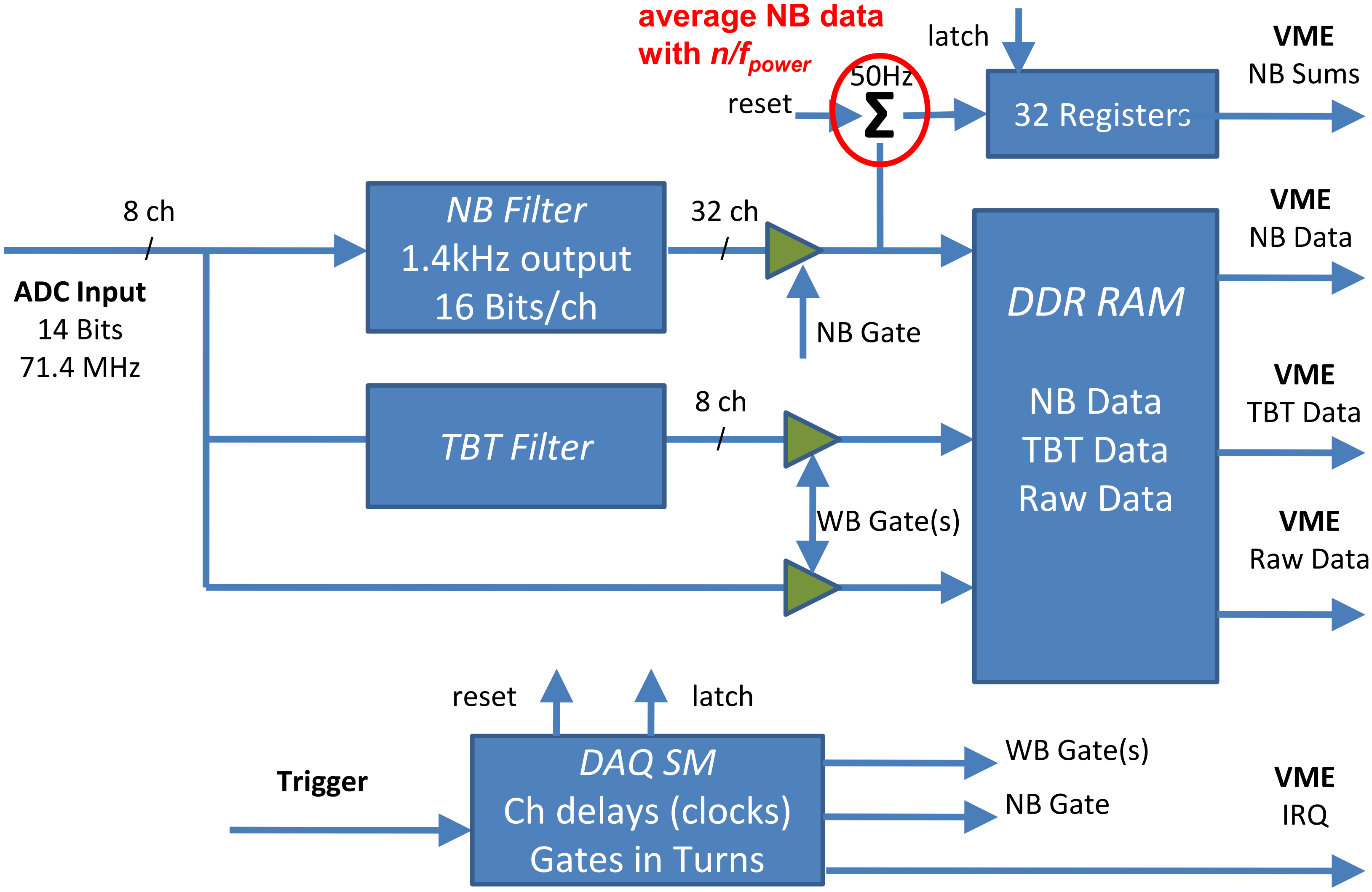


- **Typical BPM read-out scheme**
  - Pipeline ADC & FPGA
    - 14-16 bit, >300 MSPS, ~70 dB S/N
  - Separate analog signal processing for the channels
    - **Choices:**
      - Analog downconverter?!
      - RF locked (sync) CLK & LO signals?!
        - No I-Q required

Analog Downconverter vs. Direct Digital Under-Sampling

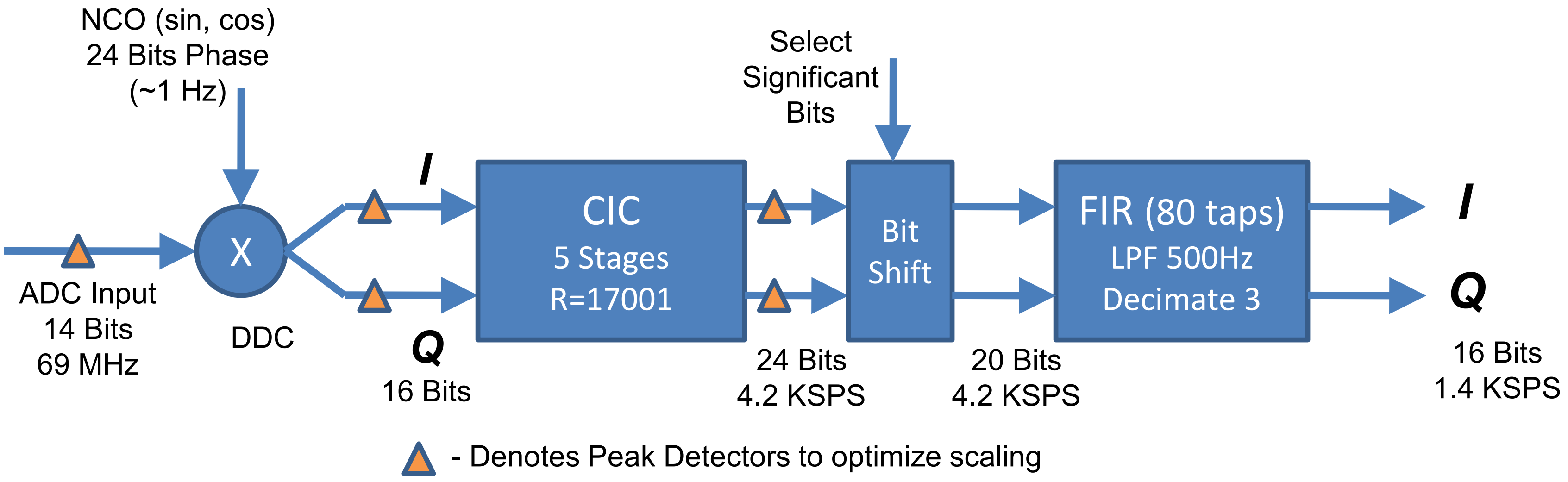
- ADC dynamic range is limited to ~70 dB
  - – Not sufficient for most BPM applications
  - – Need for analog signal attenuator / gain stages
    - ➢ Requires calibration signal to avoid "electronic offsets"
- Analog downconverter
  - + Certainly necessary for the conditioning of cavity BPM signals
  - + 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

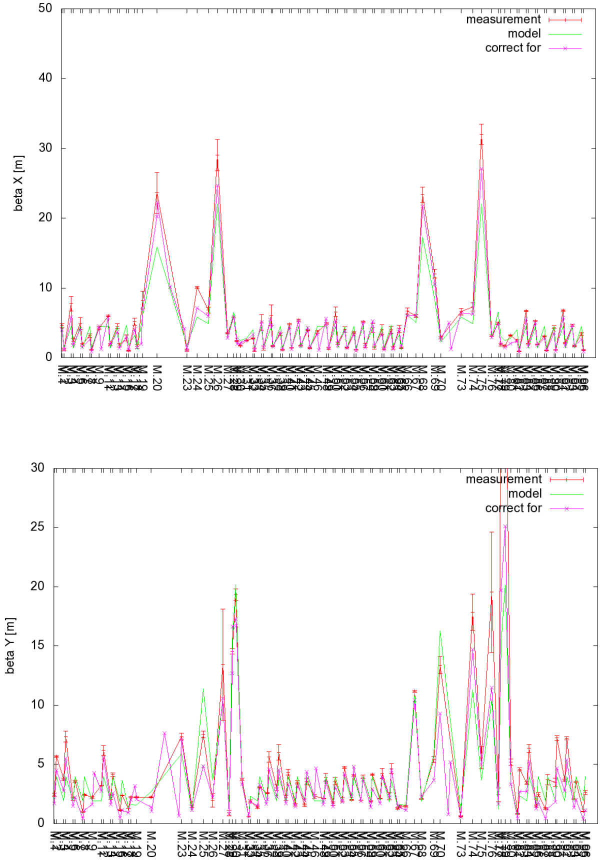
- **Process 8 ADC channels in parallel up to FIR filter**
  - **Digitally downconvert each channel into *I,Q* then filter I,Q independently**
  - **CIC Filters operating in parallel at 71.4MHz**
    - **Decimate by 17KSPS to 4.2KSPS output rate**
  - **1 Serial FIR Filter processes all 32 CIC Filter 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**



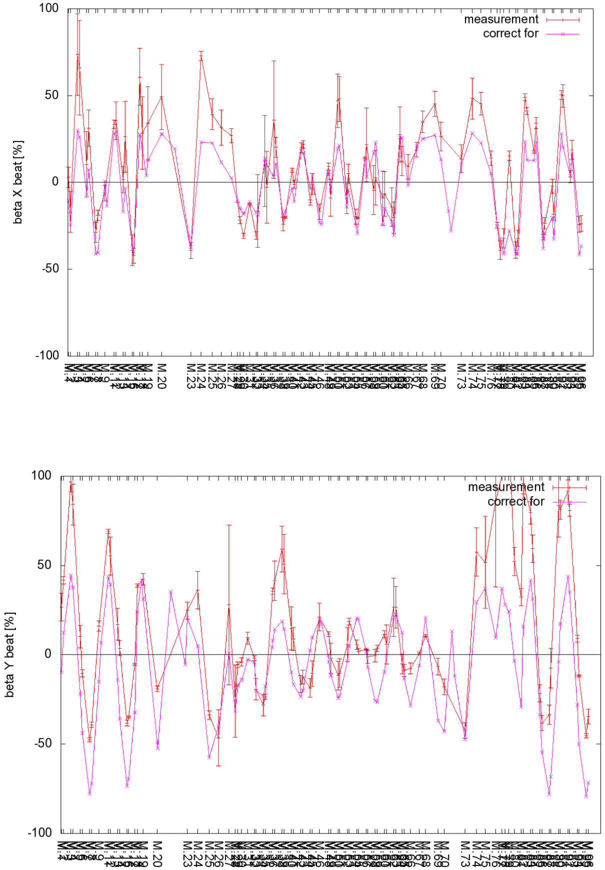
ATF DR Turn-by-Turn Beam Studies

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

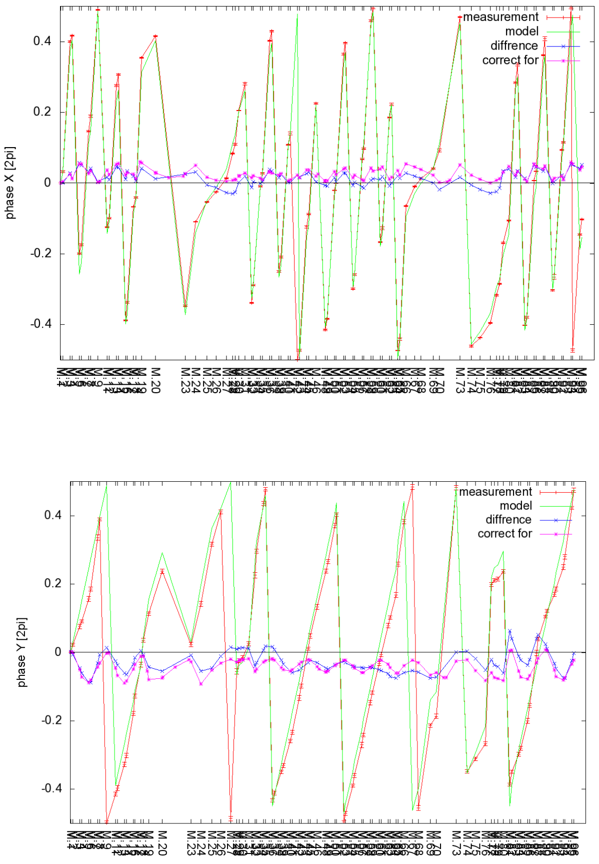
β function measurement



β beating measurement

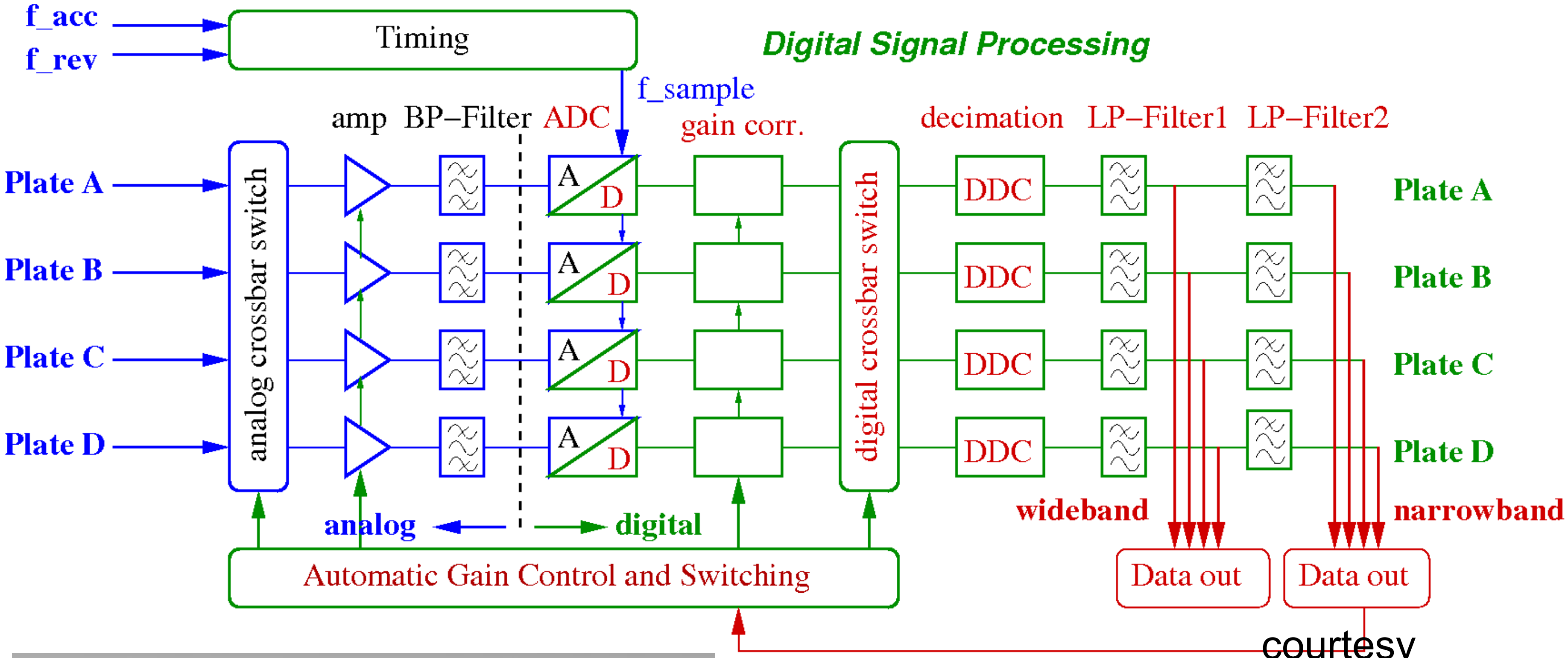


ϕ measurement



courtesy *Y. Renier*

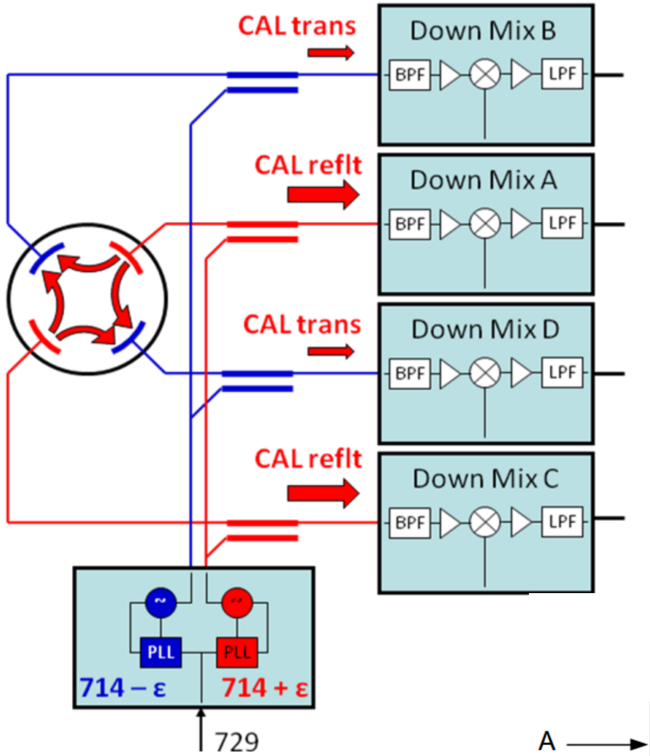
Libera BPM Electronics



courtesy *Instrumentation Technologies*

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

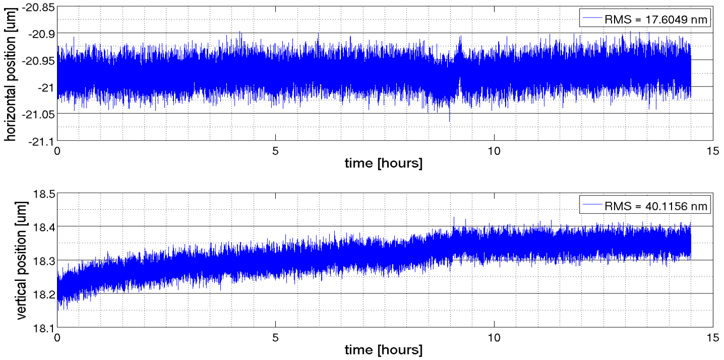
Long-Term Drift Compensation

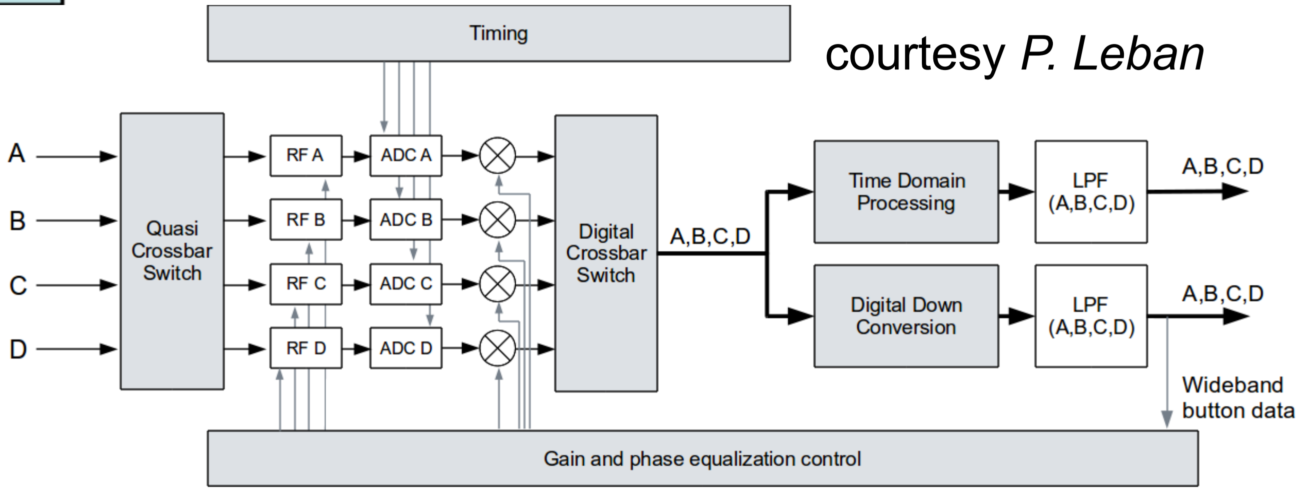


courtesy *N. Eddy*

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

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

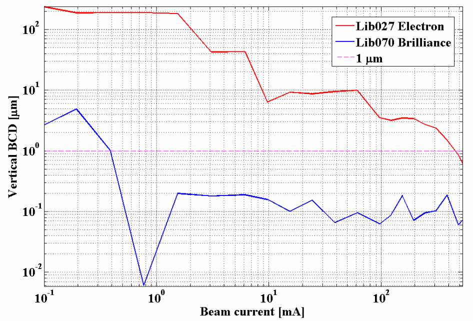


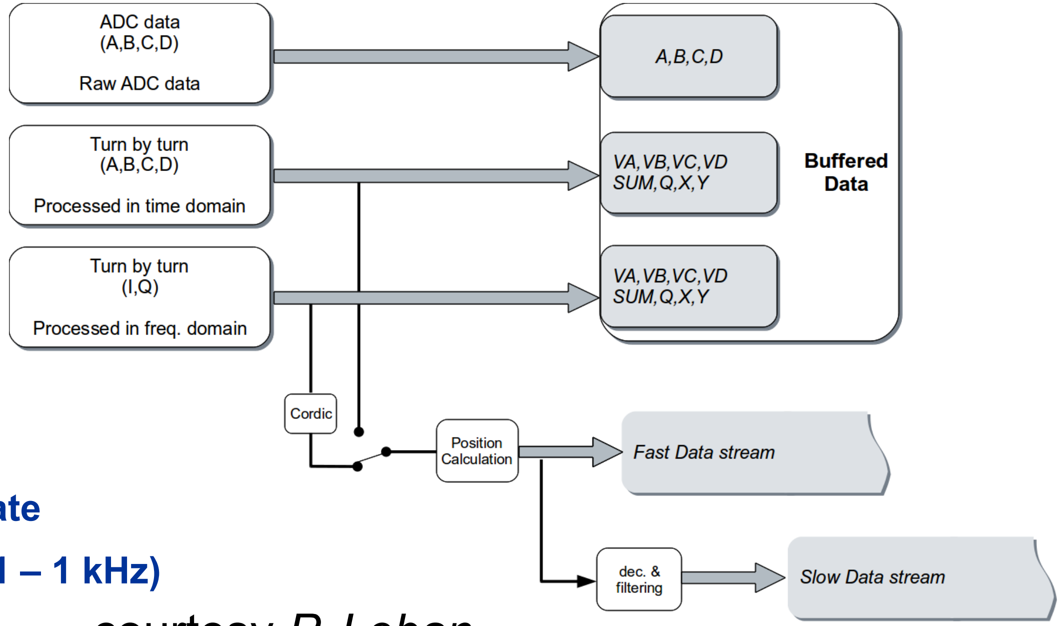


courtesy *P. Leban*

Libera BPM Performance

Beam Current Dependence





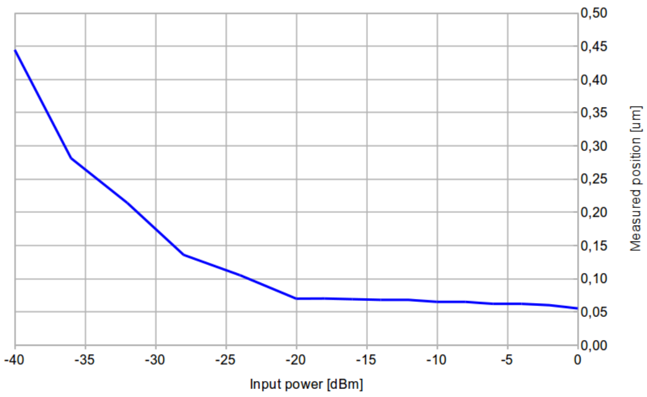
Libera Brilliance +

Electron beam position measurements

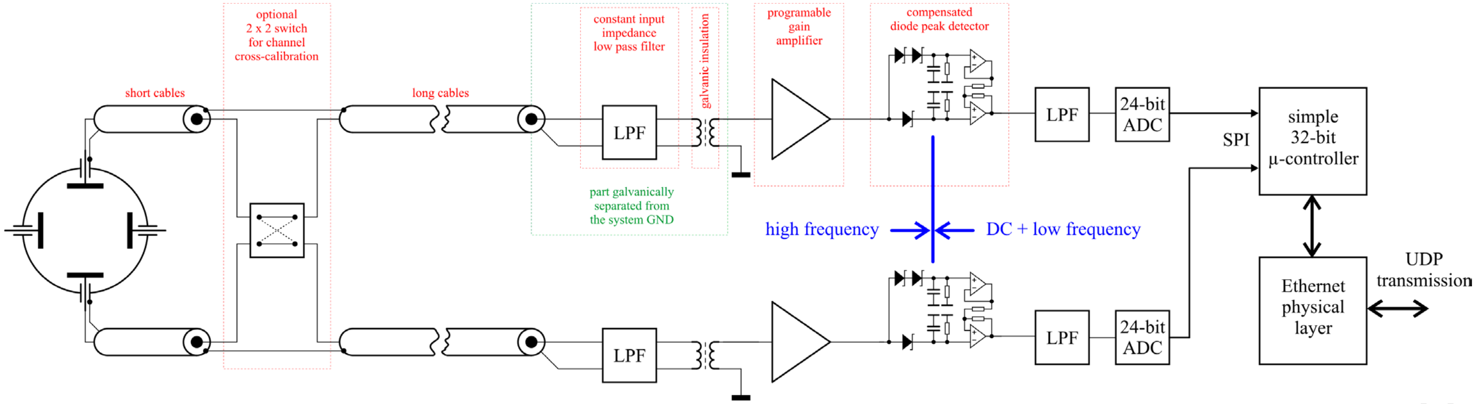
- **< 0.5 µm RMS at turn-by-turn data rate**
- **40 nm RMS at 10 kS/s data rate (0.01 – 1 kHz)**
- **10 nm RMS for slow monitoring**
- **sub-micron longterm stability**
- **Temperature drift < 200 nm / °C**
- **Full Fast Orbit Feedback implementation with magnet output**
- **Fast Interlock detection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

courtesy *P. Leban*

10 kSamples/s data rate - Position RMS [µm]



Compensated Diode Detector for BOM



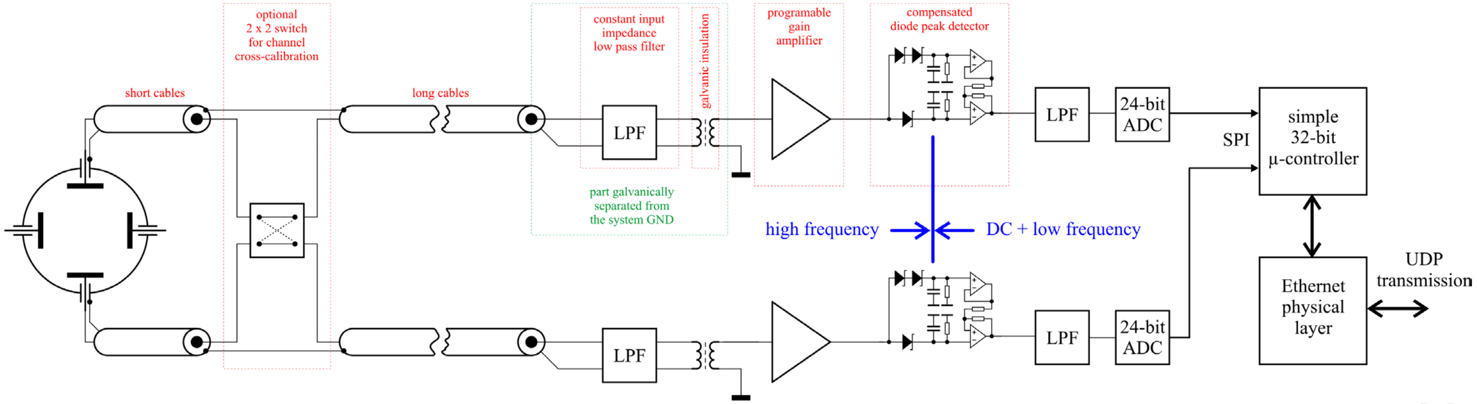
Diode ORbit (DOR) Measurement

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.**

Compensated Diode Detector for BOM



courtesy *M. Gasior*

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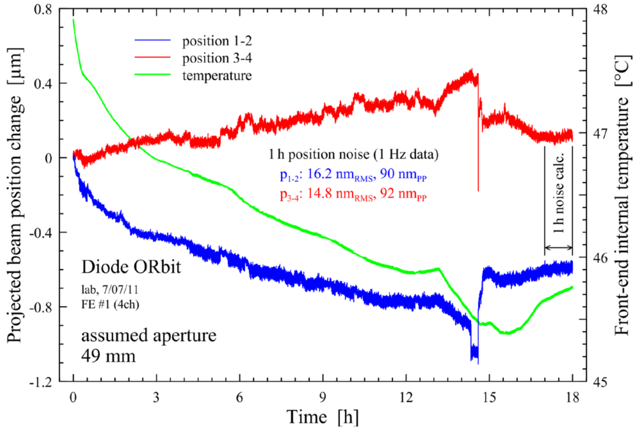

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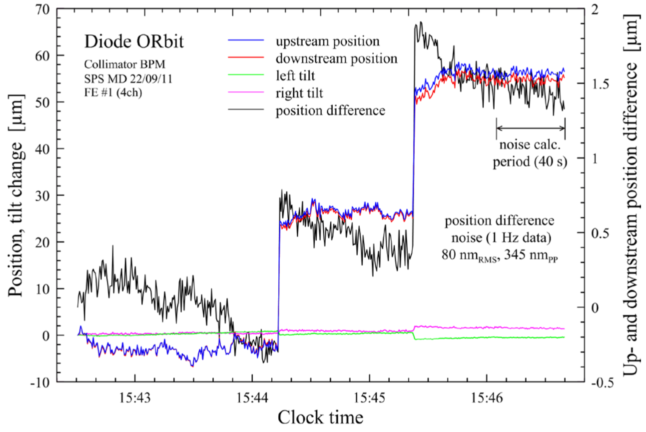


- **Sub-micrometre resolution can be achieved with relatively simple hardware and signals from any position pick-up.**
- **To be used for the future LHC collimators with embedded BPMs.**

Summary & Final Remarks

- Analog vs. digital
  - Both technologies require the same great engineering care and well thought through design efforts!
  - Digital signal processing has many advantages, however
    - Digital is not always and automatically better!
    - Digital often tends to be more complex and manpower consuming.
- The greater picture
  - Today, the BPM read-out technology is very advanced, and in most cases not the limiting factor of the BPM system performance.
    - Sub-μm resolution and stability
    - Self offset error correction techniques
    - Calibration of pickup non-linearities
  - Analog, RF and EM issues are still the dominating performance limits
    - Cables, connectors, RF & analog components, etc.
    - Wakefield and impedance effects of the BPM pickup!

Thanks!

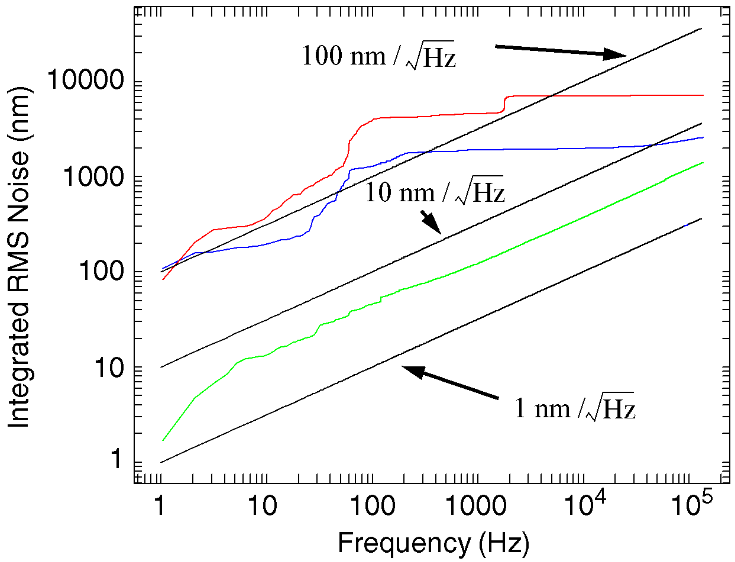
- **Further reading:**
  - *P. Forck*, et.al.: Beam Position Monitors (DITANET School 2011)
  - *E.B. Hogenauer*: An Economical Class of Digital Filters for Decimation and Interpotation (IEEE Trans. 1981)
  - *T. Schilcher*: Digital Signal Processing in RF Applications (CAS 2007)
  - *R.H. Siemann*: Spectral Analysis of Relativistic Bunched Beams (BIW 1996)
  - *G. Vismara*: Comparison Among Signals Processing for BPM (BIW 2000)
  - *M. Wendt*: Overview of Recent Trends and Developments for BPM Systems (DIPAC 2011)
  - *M. Wendt*: Trends in High Precision , High Stability BPMs (ALERT 2014)
  - Internet: Wikipedia, many articles from companies, etc.

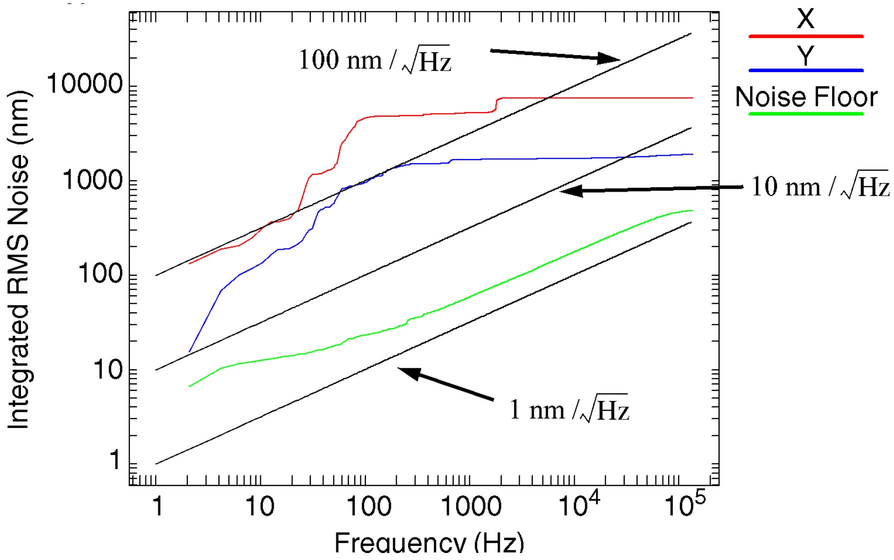
Typical Performance

courtesy
G. Decker

BSP-100 module
(APS *ANL*)

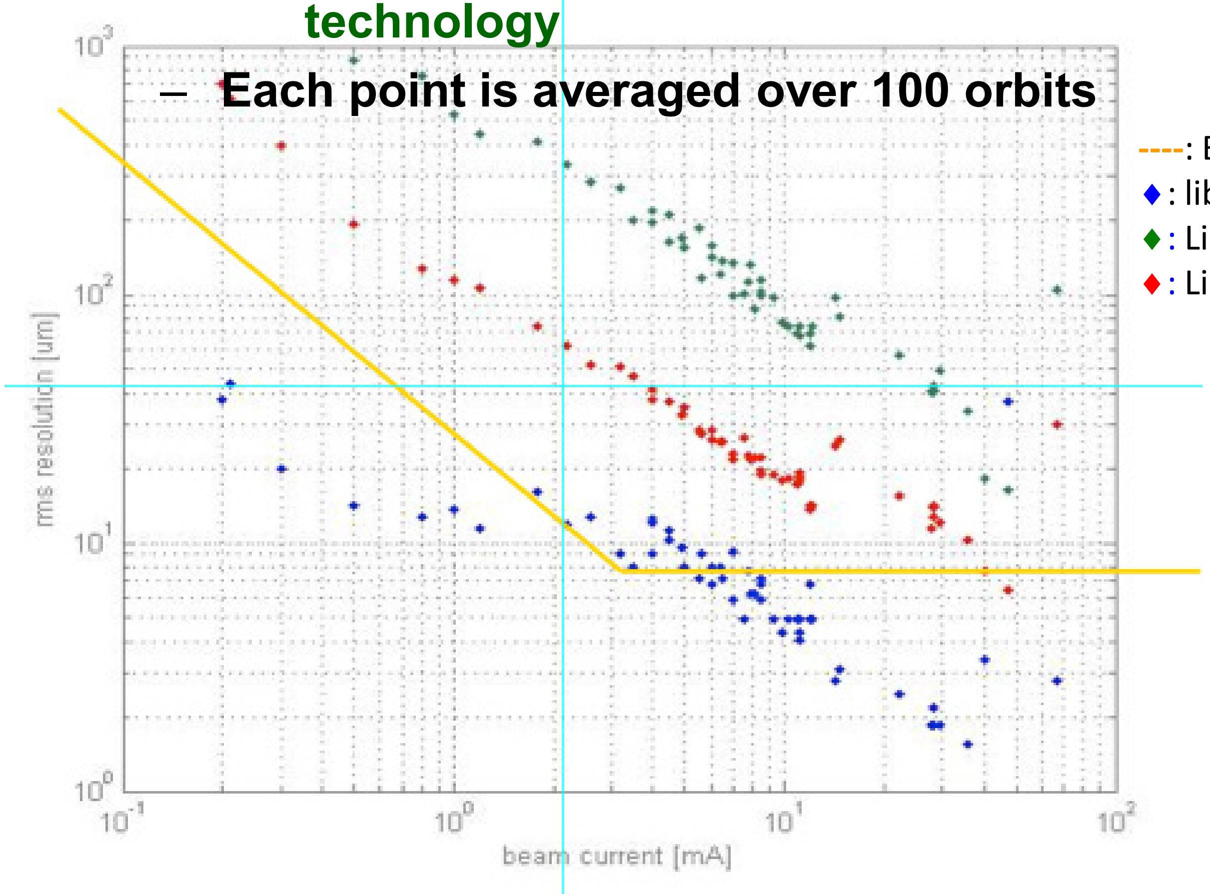
Libera Brilliance
(@APS *ANL*)





BPM Resolution vs. Beam Intensity

- **Observed at DAΦNE (INFN-LNF)**
  - ***Libera*** **(digital) and** ***Bergoz*** **(analog) BPM read-out electronics**
    - **This study was made some years ago, not with the actual *Libera* technology**
  - **Each point is averaged over 100 orbits**



----: Bergoz system resolution
♦ : libera slow acquisition mode
♦ : Libera turn by turn mode
♦ : Libera turn by turn mode (decimated)

courtesy *C. Milardi*