FP 420 BPM Workshop

Signal Processing for BPMs

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Comparison among signals processing for BPM

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Introduction

Signal analysis

Design parameters

System families

System descriptions

Introduction

- Very large evolution since early days
- Processing choice depends on machine parameters
- No unique solution
- Wide range of signal processing:
  - Individual
  - Multiplexed (MPX)
  - Difference-over-Sum (Δ / Σ)
  - Normalization (Phase & Time)

Signal analysis

- Beam current

$$I_b = [Q_b * N_b]/t_{rev}$$

Q_b = charge/bunch, N_b = number of bunches, t_{rev} = revolution period

- I_b or Q_b ?
  - $I_b \Rightarrow$ measurements over several revolution cycles
  - $Q_b \Rightarrow$ measurements on individual bunches
- Induced signal

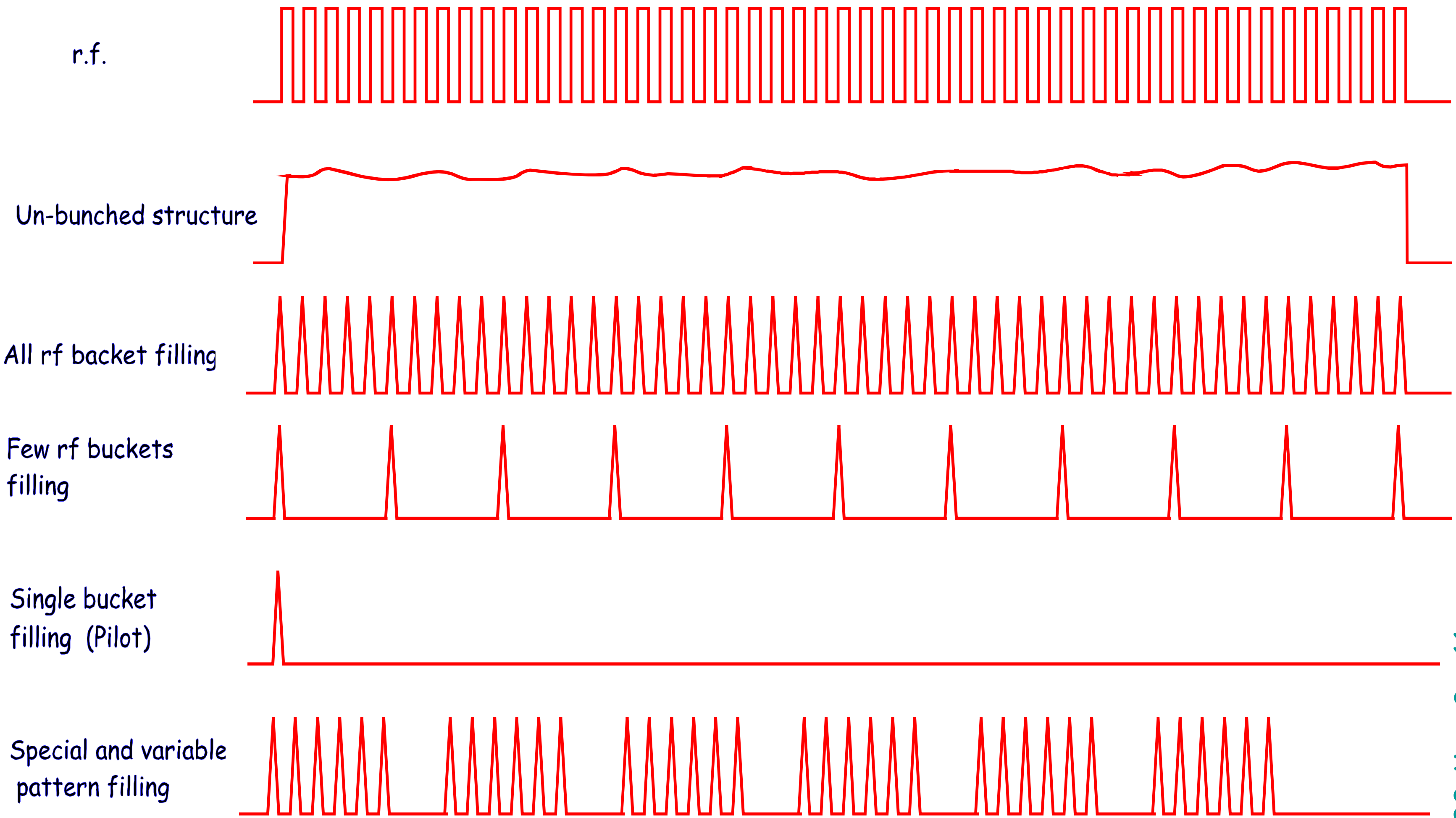
  $V(t) = Z_t * I_b(t)$

  Z_t is the PU's transfer impedance
- Bunch shape: (longitudinal charge density)
  - Gaussian for leptons, $(\text{Cosine})^2$ for protons
- Bunching factor:
  - BF = (Bunching period)/(Bunch width$_{fwhm}$)

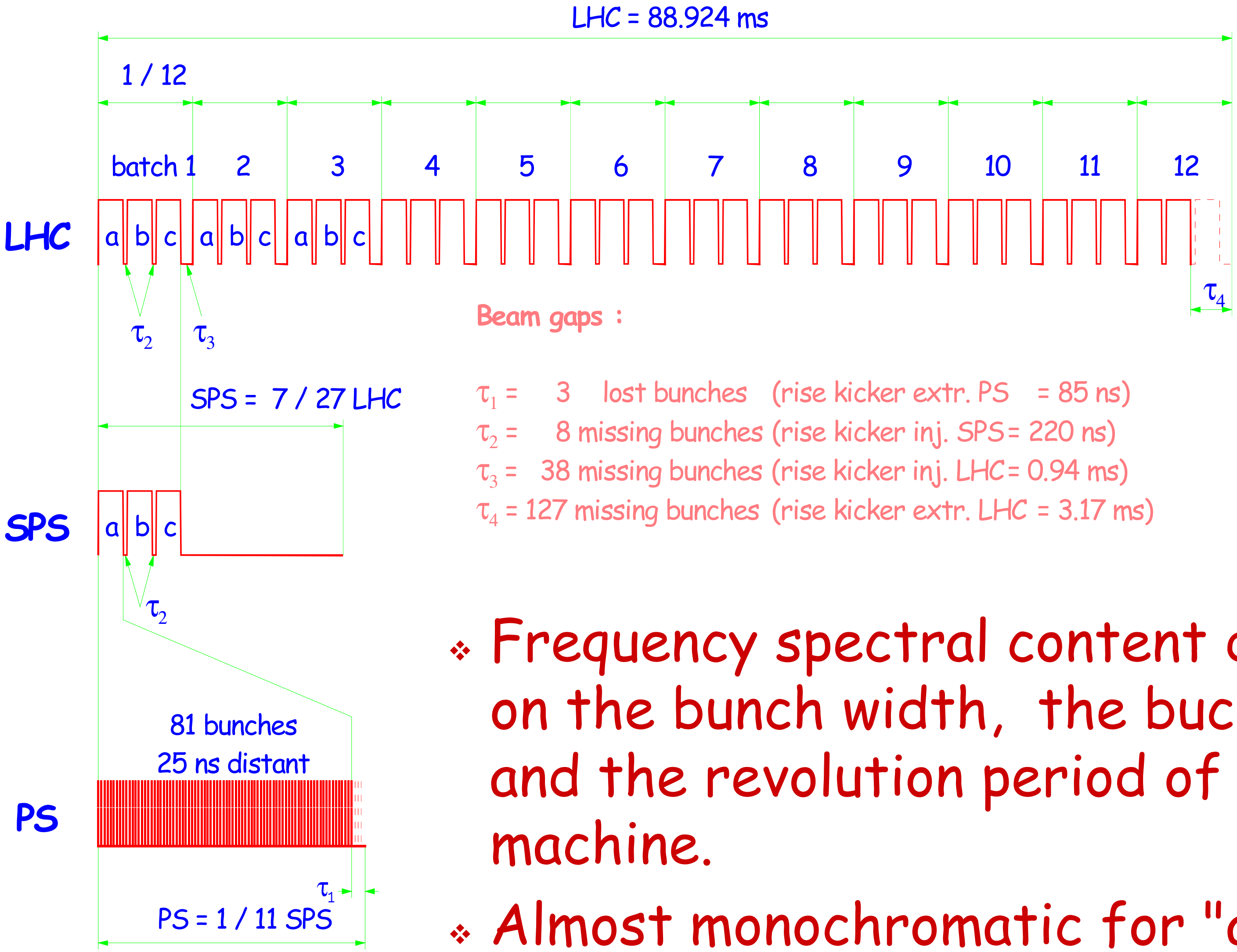
Beam structure (rf bucket filling)

- Un-bunched beam
  - Un-structure beam. No rf (Protons & Heavy Ions machines). Very difficult to be treated.
- All
  - Beam bunches in all rf bucket. Optimized for maximum I_b (SPS) The easiest to be treated. Almost monochromatic freq.spectrum
- Few
  - Beam bunches in few rf bucket with longitudinal symmetry. The highest bunch density (LEP).
- Variable
  - Particular structure (no longitudinal symmetry); it includes single bunch filling and single passage (transfer lines)

Beam structures



Beam structures (Special)



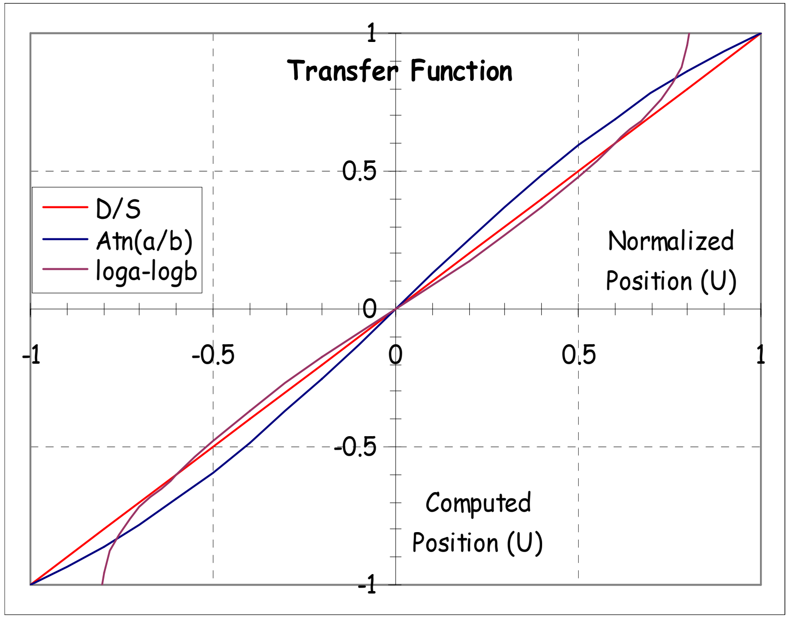
Beam gaps :

τ_1 = 3 lost bunches (rise kicker extr. PS = 85 ns)
τ_2 = 8 missing bunches (rise kicker inj. SPS = 220 ns)
τ_3 = 38 missing bunches (rise kicker inj. LHC = 0.94 ms)
τ_4 = 127 missing bunches (rise kicker extr. LHC = 3.17 ms)

- Frequency spectral content depends on the bunch width, the bucket filling and the revolution period of the machine.
- Almost monochromatic for "all bucket filling"
- Harmonics at frequencies = rf/N for "f... [text cut off]

Signal processing methods

- The <u>beam position</u> is uniquely related to the <u>amplitude ratio</u> of the induced signals on opposite electrodes.
- Processing methods for position calculation:
  - Difference over Sum (Δ/Σ)
    - *Analog and Digital process*
  - Amplitude to phase/ time
    - *Passive analog process*
  - Log-ratio (logA-logB)
    - *Active analog process*

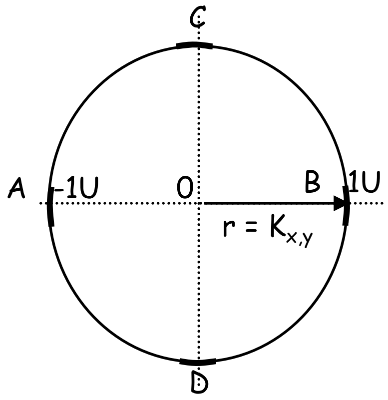


Reference parameter

$$Position = K_{x,y} * (A-B)/(A+B) = K_{x,y} * N_p$$

$K_{x,y}$ = scaling factor; A, B = induced signals; N_p = Normalized Position

N_p is dimensionless and varies between ±1U passing through 0 for a centered beam. 1U is the "Normalized half aperture" N_a



- The "<u>Normalized half aperture</u>" should be the reference parameter when specifying a processing system.
  - This will make possible comparisons among systems

Parameters: Accuracy

- The ability to minimize the beam position errors
- Error sources:
  - mechanic, magnetic and electronics causes
- The offset for a centered beam should be minimized
  - Beam based alignment techniques
- Electronics error sources:
  - Impedance mismatching on interconnecting cables
  - Electromagnetic interference and noise on the input stage
  - Non-linearity and beam intensity dependence
  - Channels gain differences and calibration errors
  - Digitizer granularity

Parameters: Resolution

- Important in colliding machines for luminosity
- Minimum position difference that can be resolved
  - Single shot:
    - *Stdev of individual measurements referred to the normalized aperture*
  - Averaged:
    - *as above but integrated over several revolutions*
- Limiting factors:
  - At low level, it depends on the input noise and the BW
  - For large signals, on the ADC resolution and the time jitter
- State of art resolutions :
  - Single shot: < 0.02% of N_a (few micron)
  - Averaged : < 20 ppm of N_a (sub-micron)

Parameters: Stability

- The measurement's uncertainty will affect the global resolution of system.
  - ✧The position measurements should be independent of the beam intensity, the bunch shaping and the rate.
  - ✧They should be stable vs. temperature and time, at least during the time interval between two calibrations
- <u>Stability versus input signal</u>
  - ✧Stdev from a series of digitized positions measured over the whole dynamic range.
- <u>Position temperature coefficient</u>
  - ✧Slope of the position drift versus temperature
- <u>Long term position stability</u>
  - ✧Stdev of a series of digitized positions versus time

Parameters: Sensitivity & Dynamic

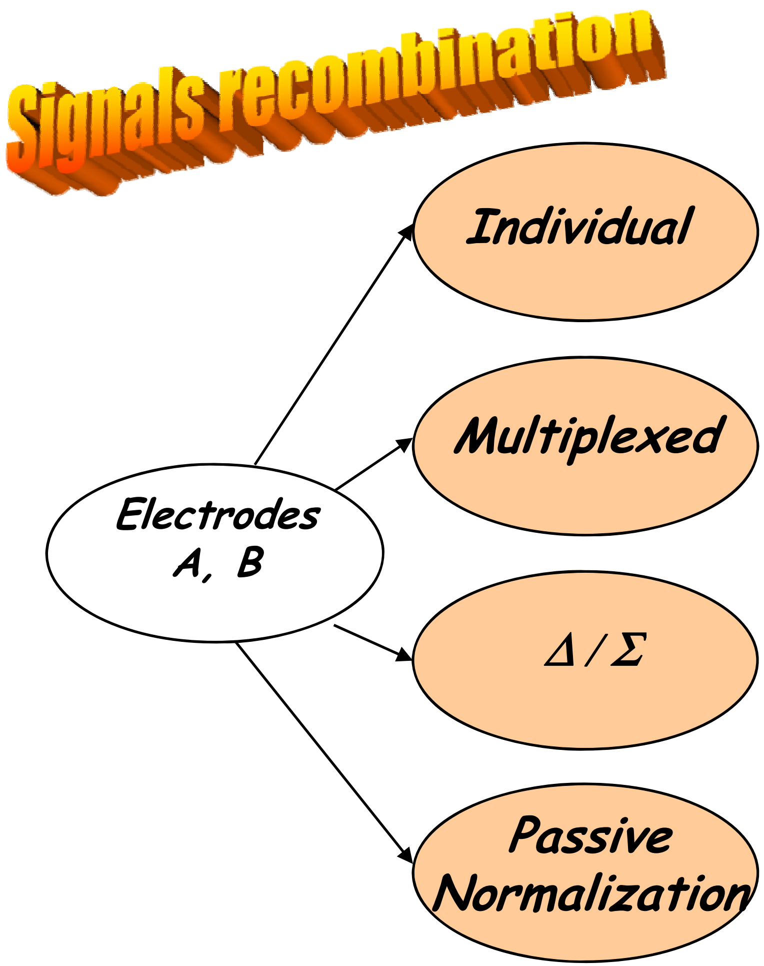
- Sensitivity:
  - The minimum input level at which a beam position measurement still fulfills the accuracy specifications (> 10^7 p/b)
- Dynamic
  - It determines the capability of the system to absorb very different beam intensities conditions
  - It's defined as the difference, expressed in dB, between the maximum input level before a large non-linearity on the output signal appears (saturation) and the minimum input level at which a pre-defined signal to noise ratio (S/N) is reached
    - *Processors using a discrimination level will not be limited by the S/N ratio, the lower limit being determined by the discriminator's threshold.*

Parameters: Acquisition time

- The time required for the signal processor to store a full set of data into the memory
  - *The importance of this parameter is related to the capability of resolving individual bunches and the absolute resolution of the processor*

- Several elements contribute to build-up this time:
  - The LP and BP filters
  - The switching and acquisition time (MPX processors)
  - The PLL's time to synchronize (synchronous detector)
  - The AGC's set-up time (constant sum)
  - The S&H circuit and the ADC's conversion time

Processing system families



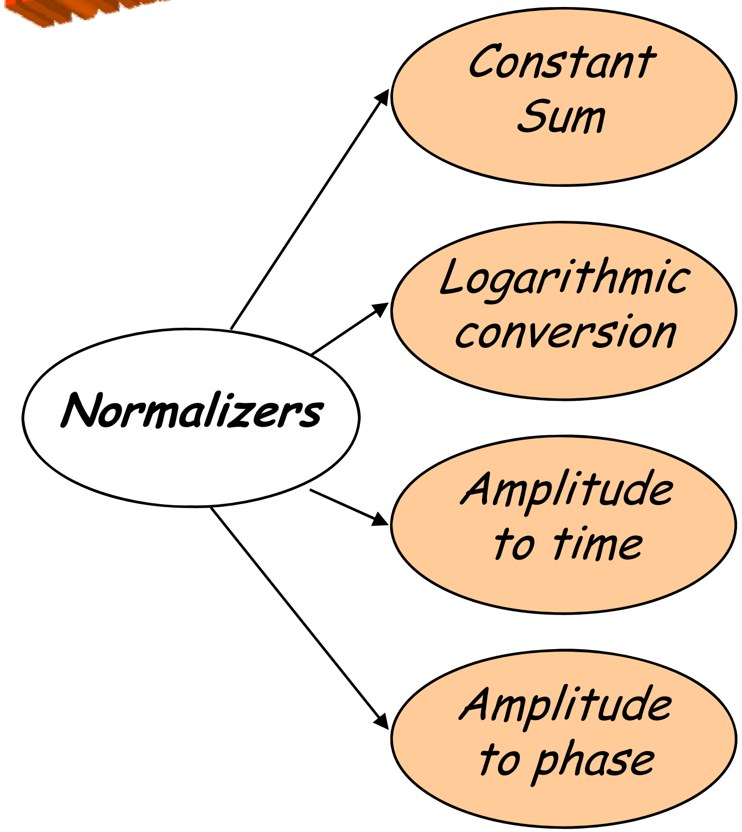
	Advantages	Weakness
Individual	*Large Bandwidth*	*Limited dynamic*
Multiplexed	*Long term stability*	*No turn by turn*
Δ / Σ	*Center stability*	*Gain switching*
Passive Normalization	*Amplitude independent*	*No intensity information*

Processing system families

Normalization Process

No intensity information

Reduced N°of digitizing bit



Advantages	Weakness
* *Long term stability*	*Gain matching*

Active process

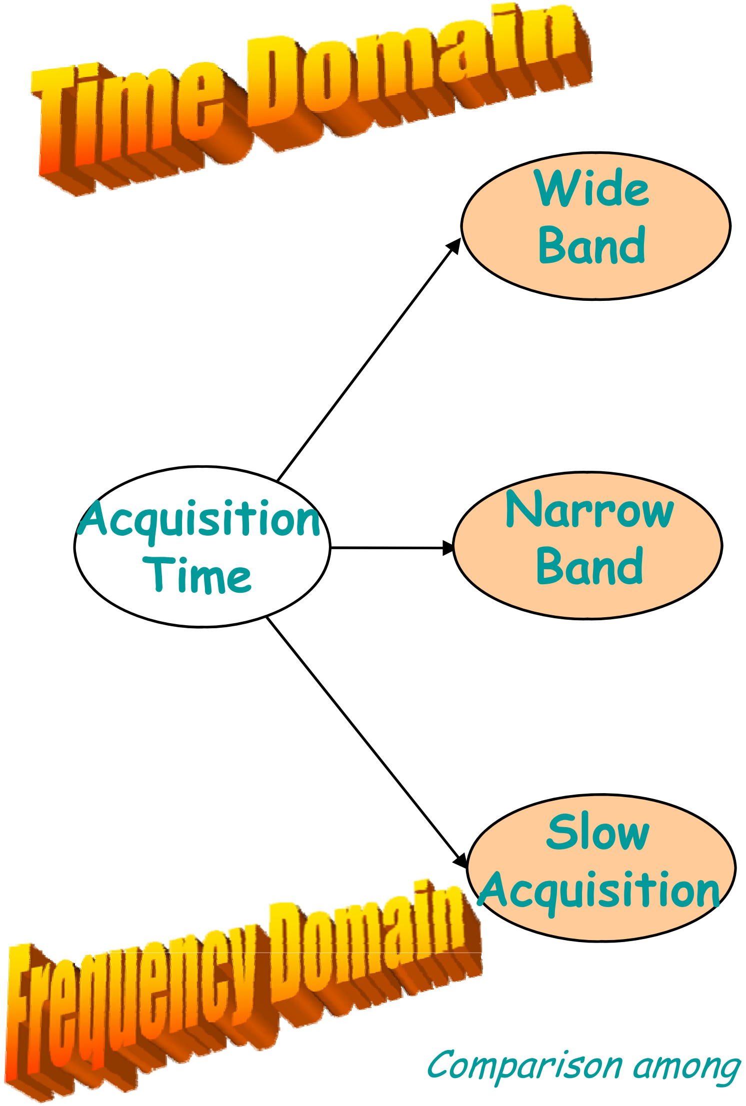
Advantages	Weakness
* *Large dynamic*	*Limited linearity*

Advantages	Weakness
* *Large Bandwidth*	*Time matching*

Passive process

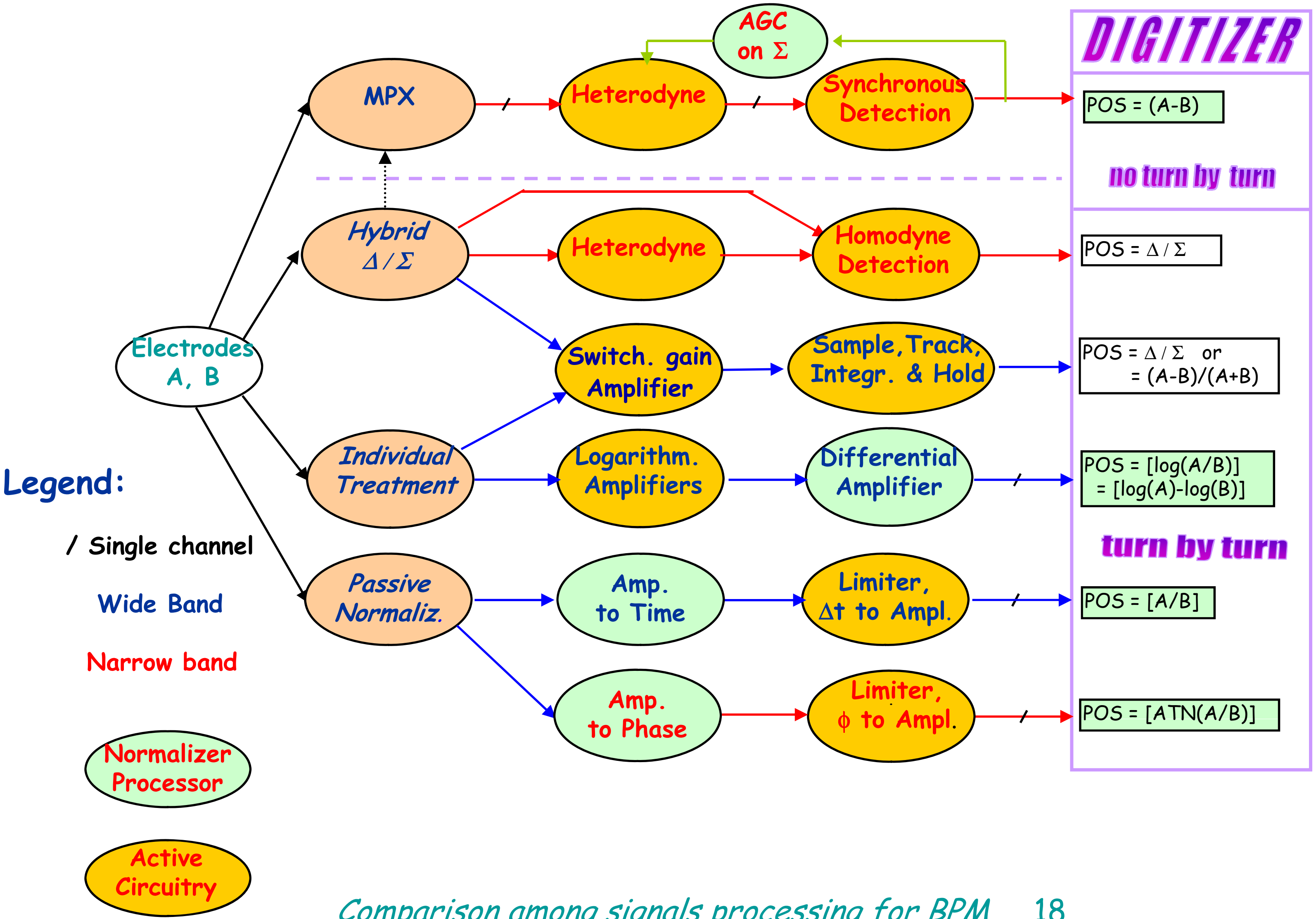
Advantages	Weakness
* *Simplicity*	*Phase matching*

Processing system families

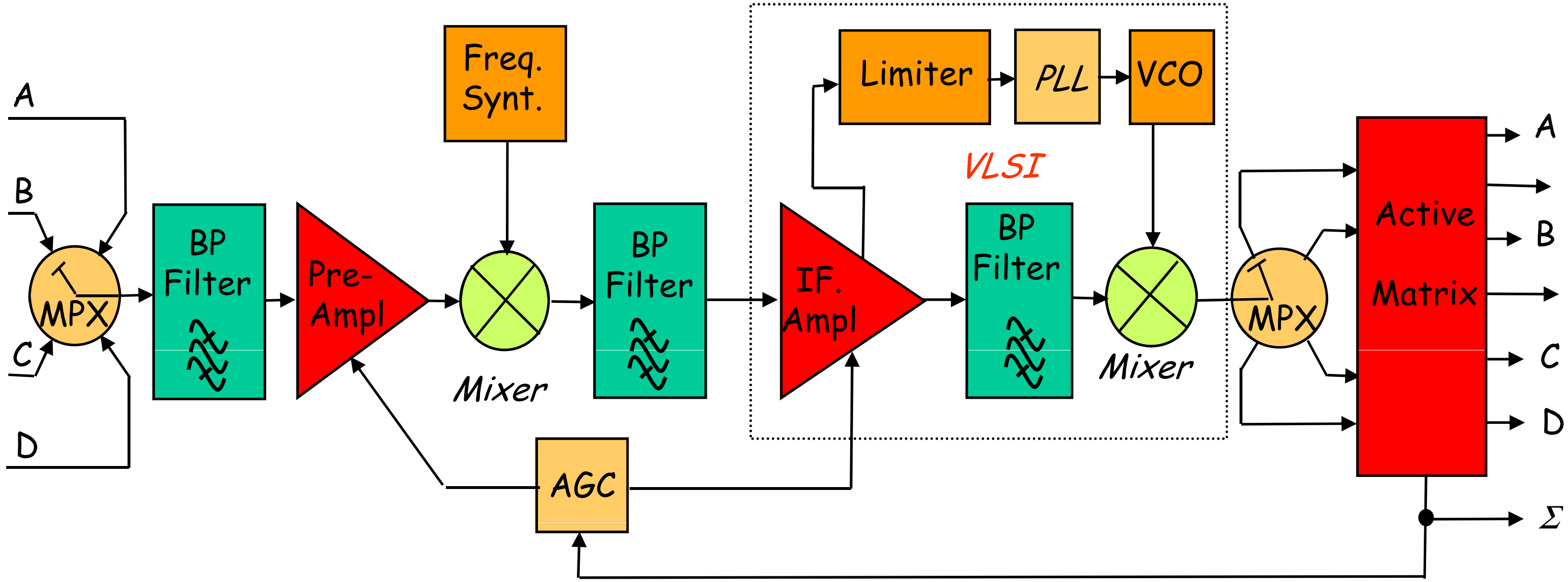


	Definition	Types
Wide Band	* *Individual bunches separated by >10 ns* to single	*- Track & Hold* *- Log amplifiers* *- Amp to Time Normalizer*
Narrow Band	* *Turn-by-turn or individual bunches separated by >100 ns*	*- Heterodyne* *- Amplitude to Phase normalizer*
Slow Acquisition	* *Non consecutive turns measurements*	*- MPX*

Processing system families



MPX schematics



MPX description

- Conceived for closed orbit of stable stored beams
  - The input signals are sequentially multiplexed into a single receiver
  - Multi-stage configuration of GaAs **switches** (Channels isolation >50 dB)
  - A **BP filter** selects the largest line of the spectrum
  - **Pre-amplifier** with ***AGC***. Large input dynamic (>80 dB) and gain control (>50 dB) Noise Figure difficult to optimize.
  - **Active mixer**, driven by a frequency synthesizer, down convert to standard IF
  - **IF amplifier** with ***AGC*** and **synchronous detection,** by comparing the phase of a sample of carrier signal with a reference signal via a VCO in a phase lock loop (VLSI)
  - **BP filter** to suppress side-bands (100 kHz > BW< 1MHz).
  - **De-multiplexer, Track & Hold and active matrix** produce 7 signals (A, B, C, D, Sum, X, Y) store theirs values in four analog memories

MPX performances

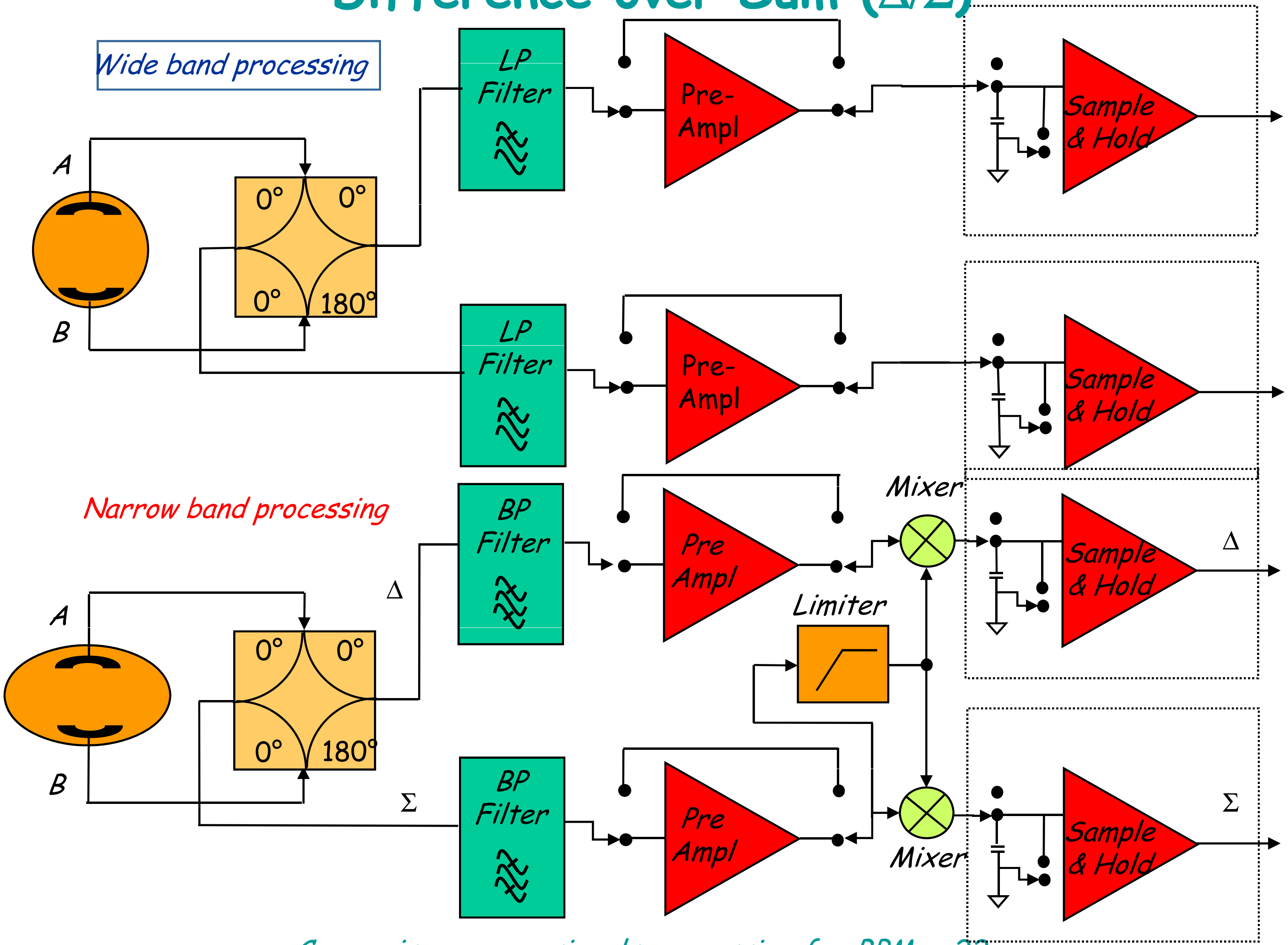
Advantages

- *Reduced number of channels (x4)*
- *Identical gain for all the channels*
- *No need for gain selection (AGC)*
- *Large dynamic range (>80dB)*
- *Excellent position stability*
- *No temperature dependence and components aging.*
- *Reduced N° of bits at equivalent resolution (Normalization)*

Limitations

- *Stable beam during the scanning*
- *No turn by turn acquisition*
- *Slow acquisition rate (MPX)*
- *Reduced Noise Figure (front end matching & MPX insertion losses, AGC pre-ampli.)*
- *Reduced linearity, for non-linear PU's since the Σ is not constant*
- *Large engineering*
- *No intensity information (AGC)*

Difference over Sum (Δ/Σ)



Difference over Sum (Δ/Σ) description

- The Δ and Σ signals are obtained from a passive four port 180° hybrid
  - **Wide-band**
  - It offers wide-band response (from kHz to GHz over >3 decades), very large dynamic only limited by the electronics, isolation among ports (>30 dB)
  - Programmable gain amplifiers (Ga As switches) and track or peak & hold circuits
  - Wide bunches may be directly digitized by FADC (>1 GS/s)
  - A & B signals can be treated separately by suppressing the 180° hybrid
- **Narrow-band**
- **BP filters** are used to select the largest line in the spectrum.
- **Programmable gain amplifiers** and **homodyne detector** (a fraction of Σ signal is limited and used as local oscillator).
- **Track & Hold** and an externally triggered ADCs, digitize the Δ and Σ signals

Difference over Sum (Δ / Σ) performances

Advantages

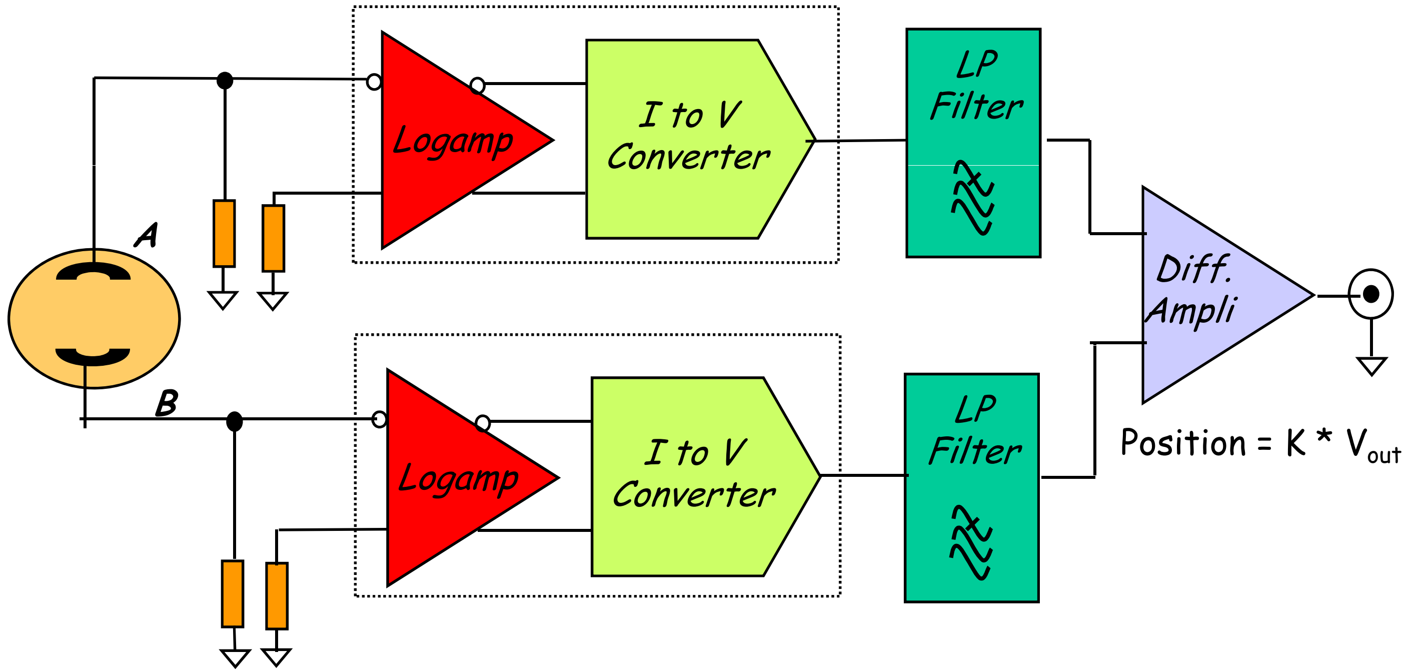
- *[W.B.] & {N.B.}*

- *The central position independent on input intensity.*
- *Intensity measurement available*
- *Excellent Noise Figure*
- *[Wide band allows measurements on multiple bunches (Δt <20 ns)]*
- *{ Large dynamic > 90 dB}*

Limitations

- *Programmable gain amplifiers*
- *Multiple calibration coefficients*
- *The absolute position is f(gain)*
- *{Tight phase matching(Δ, Σ) at all the gains required by the synchronous detection (±5°) }*
- *{ Pedestal error on Σ }*

Logarithmic amplifier schematics

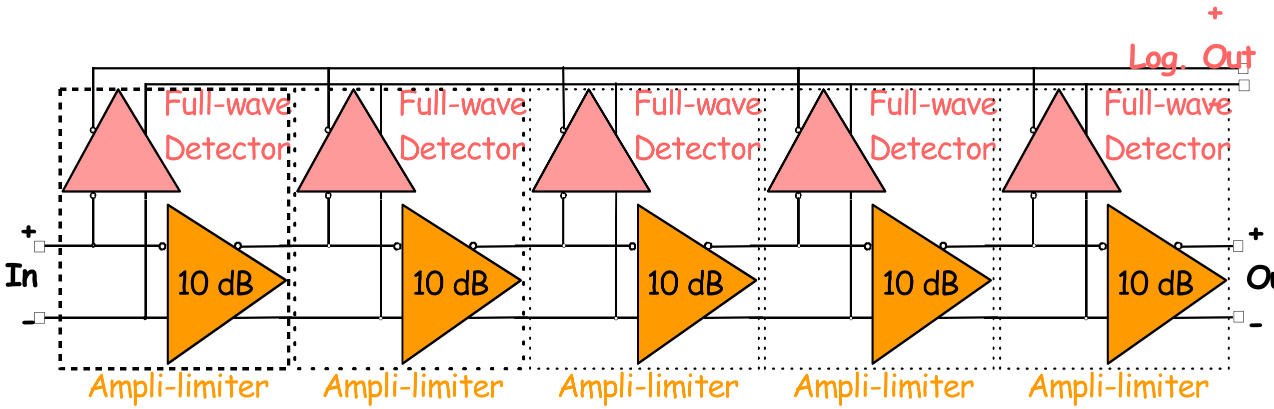


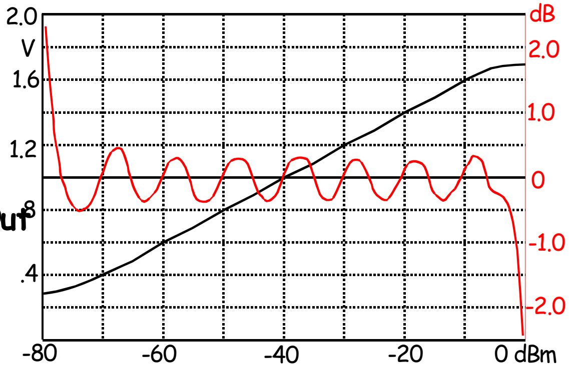
- *Each signal is compressed by a logarithmic amplifier, filtered and applied to a differential amplifier.*
- *The position response is*

$$Pos. \equiv [log(A/B)] = [log(A)-log(B)] \equiv (V_{out})$$

where V_{out} is the voltage difference between the log-amplifiers outputs

Logarithmic amplifier description





- *New generation circuits use several cascaded limiting amplifiers, with fix gain and wide bandwidth. Full wave rms detectors are applied among each stage and by summing theirs output signals, a good approximation to a logarithmic transfer function is obtained. Typical parameters are:*
- *Input dynamic range :* *>90* *dB*
- *Input noise:* *< 1.5* *nV/√Hz*
- *Non conformance lin.:* *<± 0.3* *dB*
- *Limiter Bandwidth:* *D.C. to >2* *GHz*
- *Video Bandwidth:* *D.C. to 30* *MHz*

Logarithmic amplifiers performances

Advantages

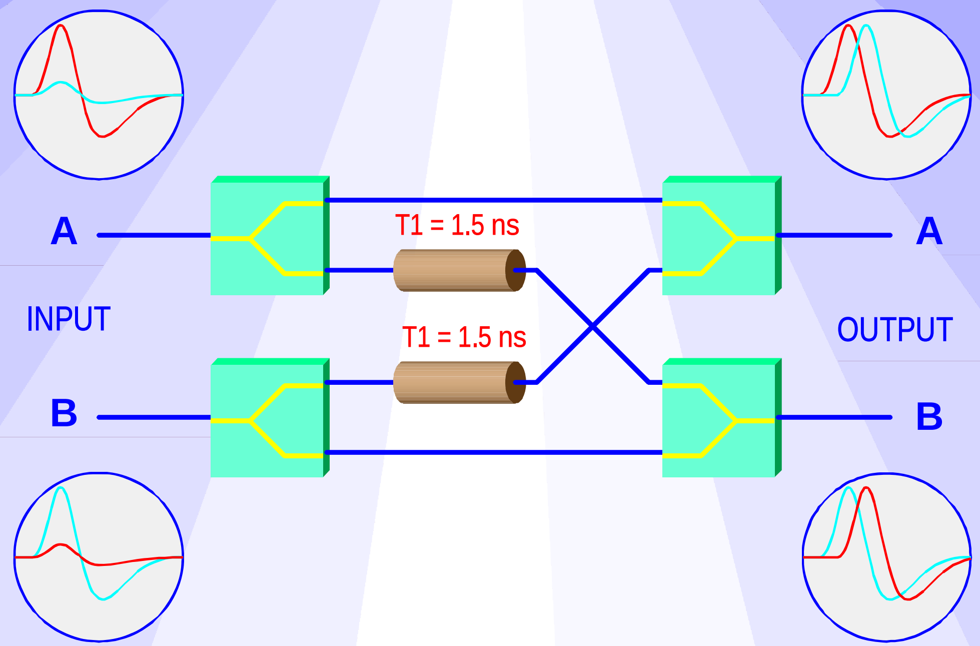
- *Possible applications in the time and frequency domain (NB & WB)*
- *Very large dynamic range (>90 dB) without gain adjustment*
- *Wide input bandwidth*
- *No bunch shape dependency*
- *Simultaneous digitization of individual + and - charges*
- *Auto-triggering capability*
- *Simple engineering*

Limitations

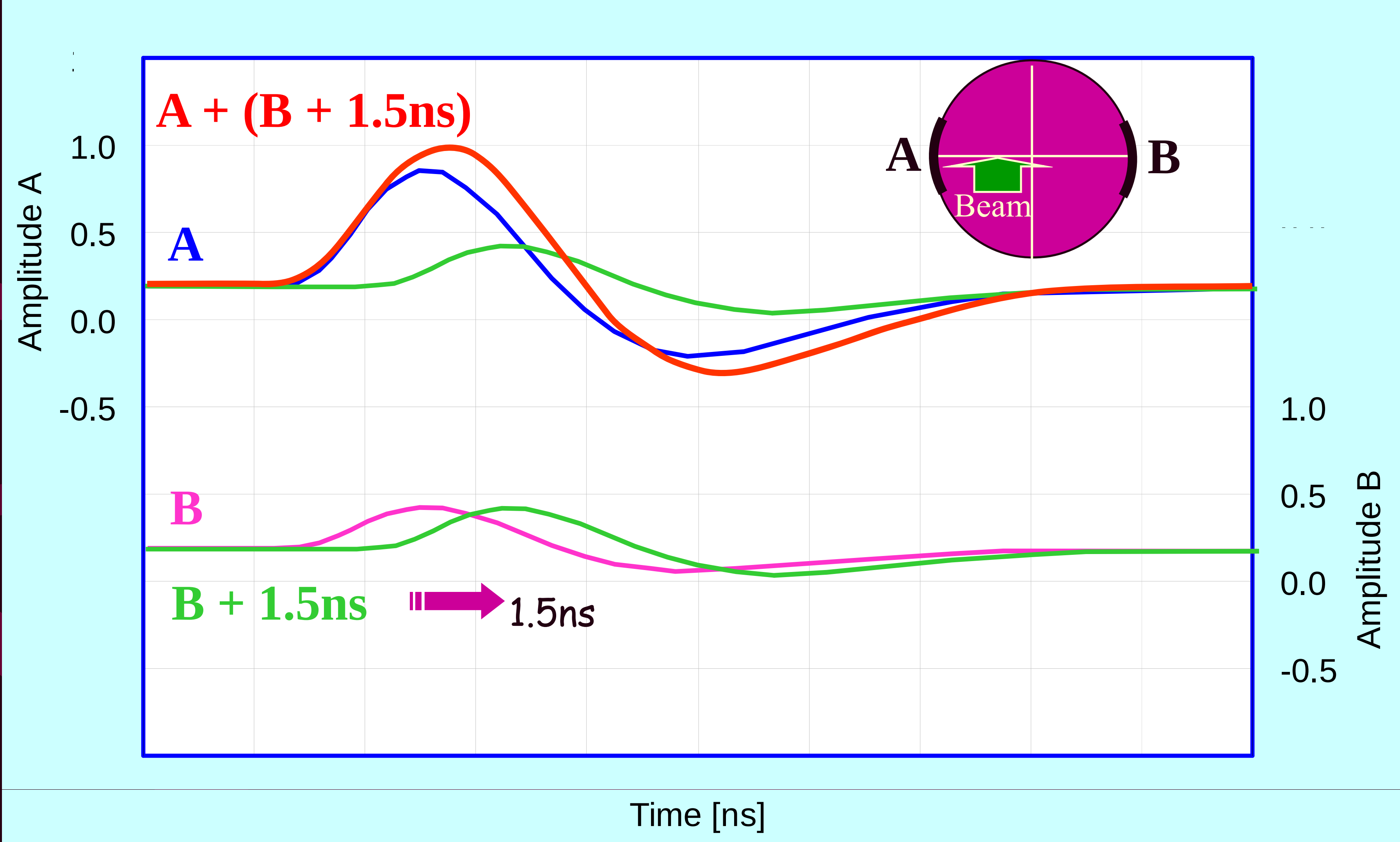
- *State of art performances are not simultaneously available*
- *Poor position stability vs.. input level, for particular conditions*
- *Limited linearity (few % of the normalized aperture)*
- *Limited long term stability*
- *Temperature dependence*

The Front-End Electronics

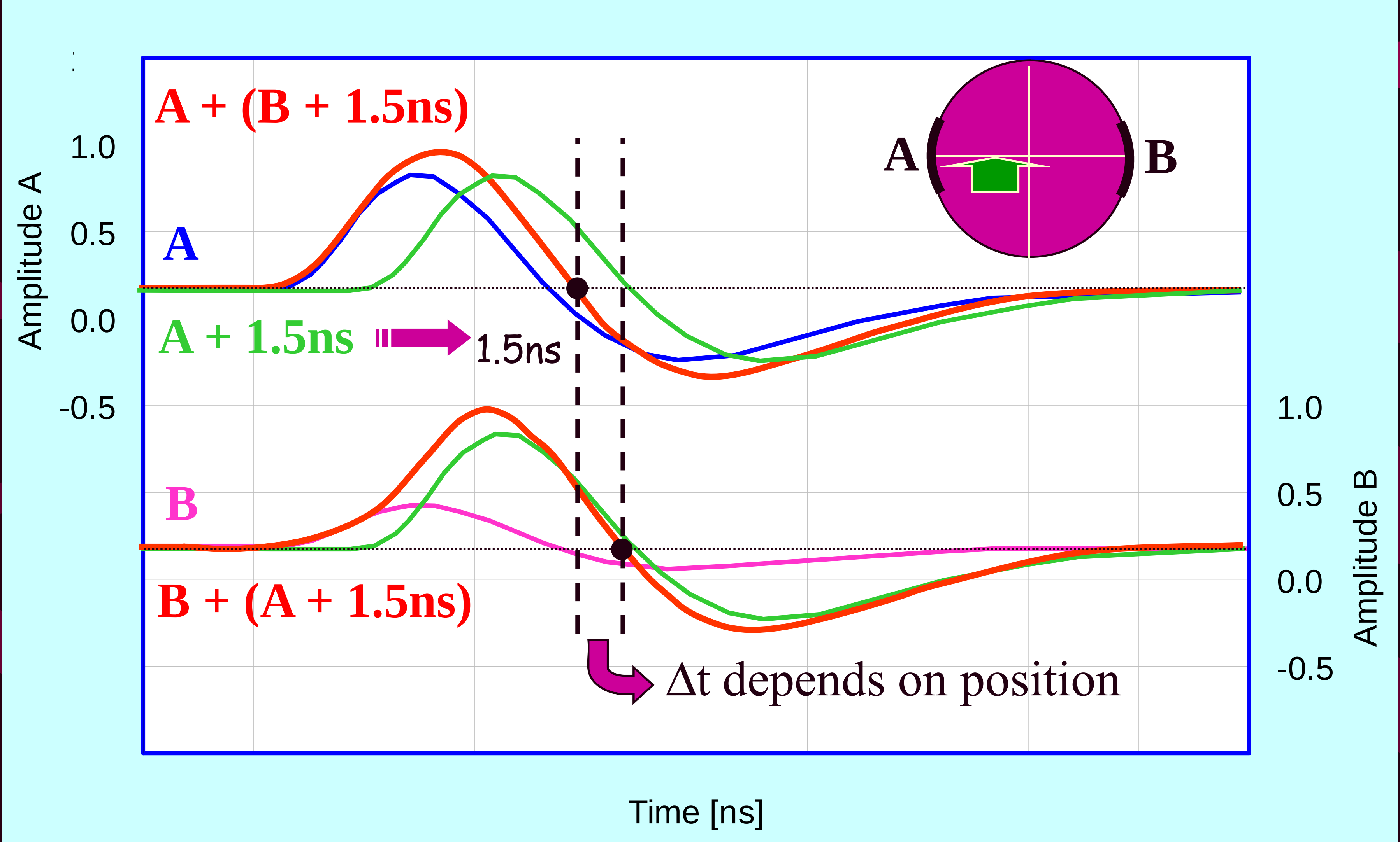
WIDE BAND TIME NORMALISER PRINCIPLE (WBTN)



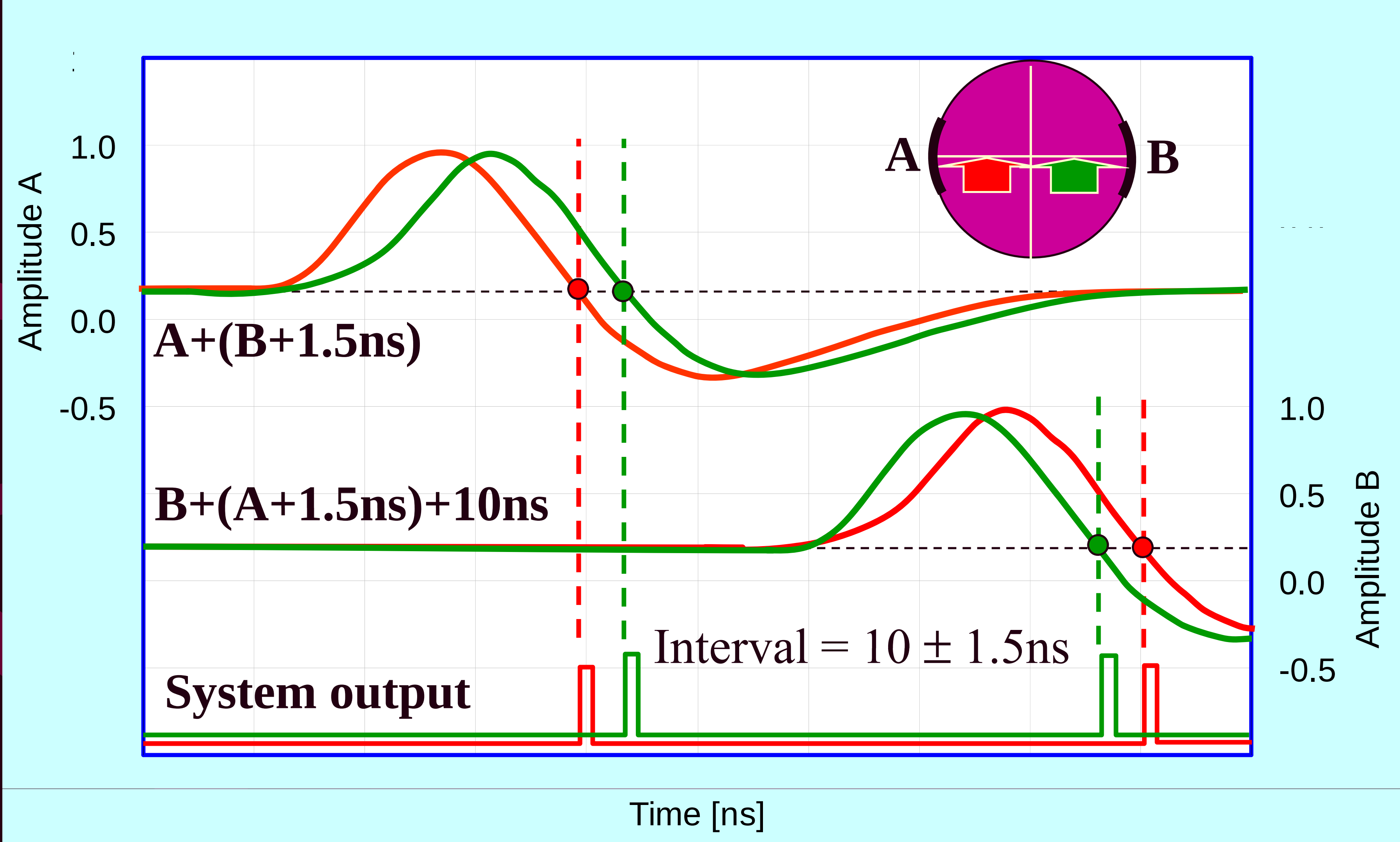
The Wide Band Time Normaliser



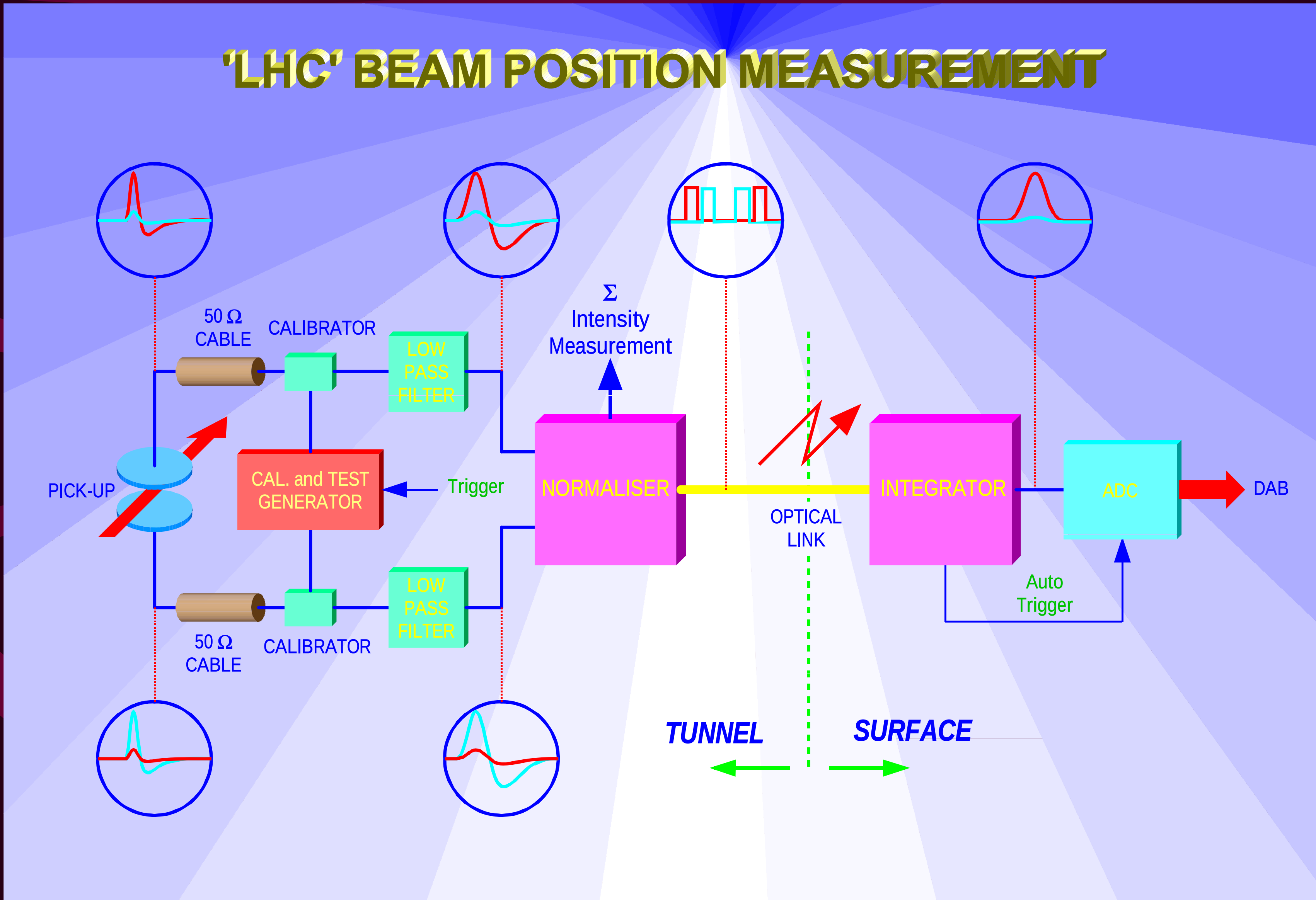
The Wide Band Time Normaliser



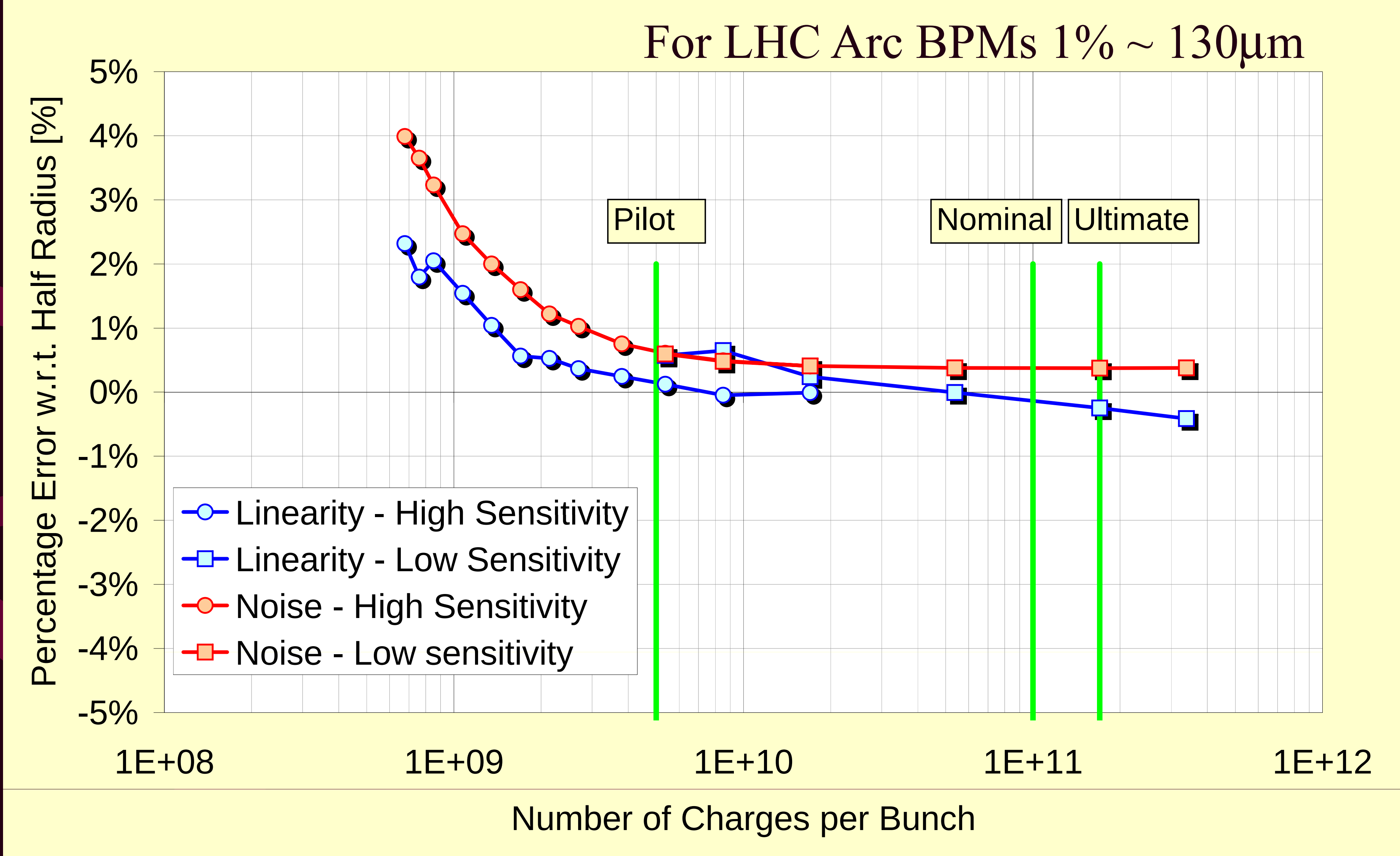
The Wide Band Time Normaliser



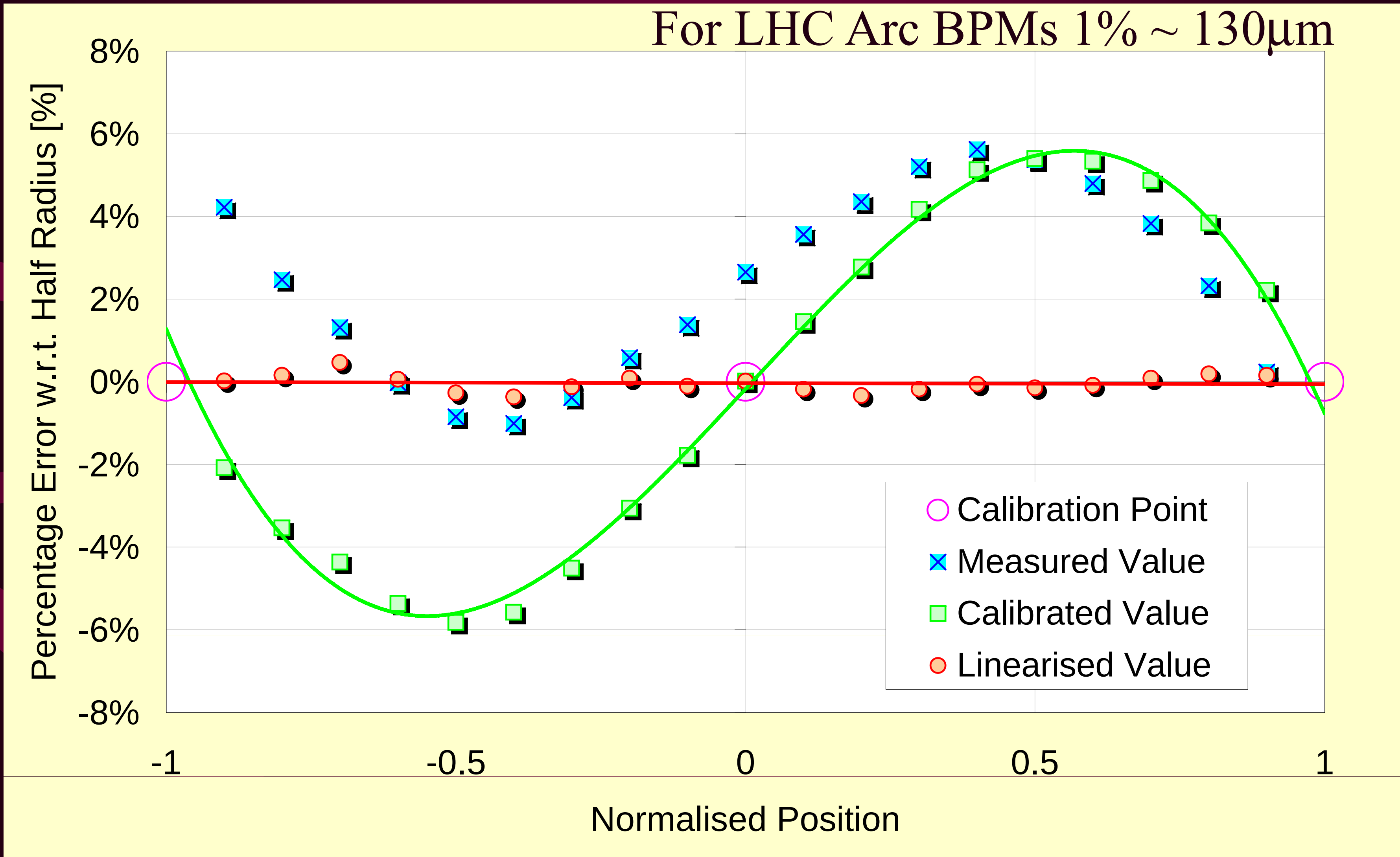
The Wide Band Time Normaliser



WBTN - Linearity v Intensity



WBTN - Linearity v Position



Accuracy and Resolution

Bunch Type		Pilot Bunch		Bunches of Nominal Intensity		
Mode of Operation		**Trajectory** (single shot)	**Orbit** (224 turn average)	**Trajectory** (single shot, single bunch)	**Trajectory** (single shot, average of all bunches)	**Orbit** (average of all bunches over 224 turns)
ELECTRONICS	**Resolution (rms)**	200µm	20µm	50µm	5µm	5µm
ELECTRONICS	**Accuracy (rms)**	150µm				
MECHANICAL	**Alignment Error (rms)**	200µm				
MECHANICAL	**Residual after k-modulation (rms)**	<50µm				

Accuracy + Alignment Error: $3\sigma = \pm 750\mu m$ $\Rightarrow$ 20% of 4mm Closed Orbit 'budget' (Spec = $\pm 500\mu m$)

Amplitude to Time Normalizer performances

Advantages

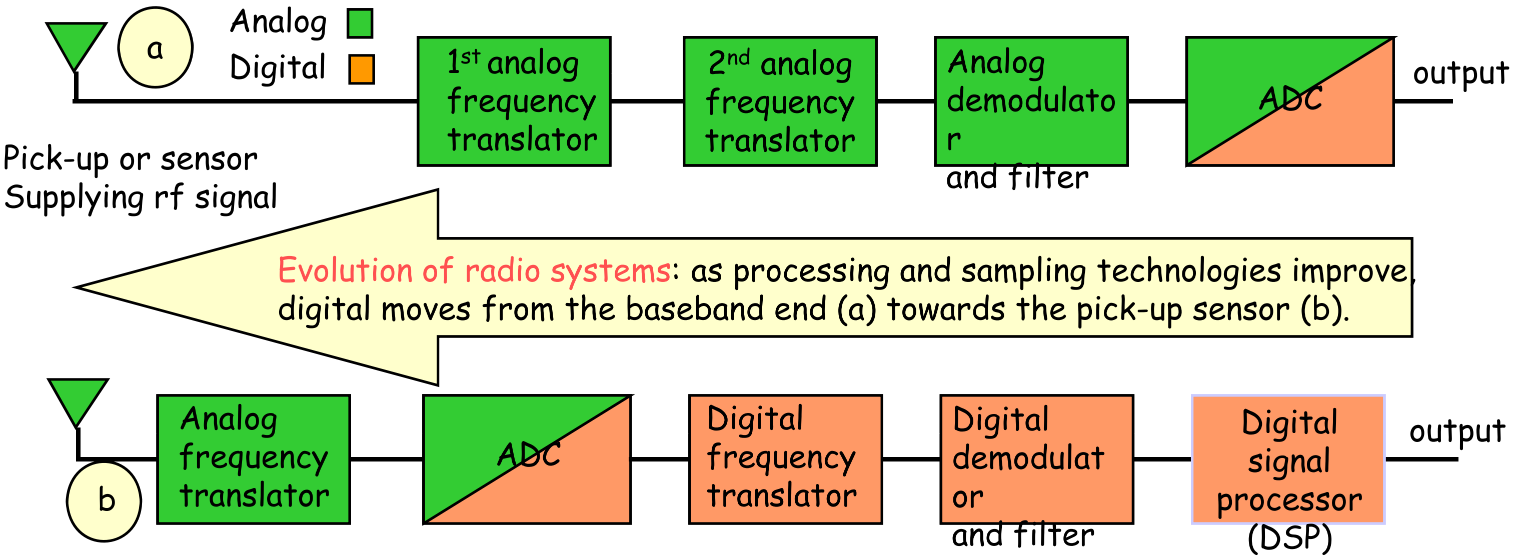
- *Reduced number of channels (x2)*
- *No need for gain selection*
- *Input dynamic > 50 dB*
- *Signal dynamic independent on the number of bunches*
- *~10 dB compression of the position dynamic (recombination)*
- *Acquisition rate > 40 MS/s*
- *Auto-trigger*
- *Reduced N° of bits at equivalent resolution (Normalization)*

Limitations

- *Mainly reserved to bunched beams*
- *Tight time adjustment*
- *Propagation delay stability and switching time uncertainty are the limiting performance factors*
- *No Intensity information*

Remark: A specifically designed monolithic Ga-As chip will allow for a large speed breakthrough

Digital receiver (basic)



- Digital receiver is a new approach of the heterodyne receiver
- The basic functionality is preserved but implemented differently
- Present situation allows to place the digital transition just after the IF amplifier

Digital Receiver performances

Advantages

- *Programmability*
- *Narrow and wide band processing*
- *Identical gain for all the channels due to possible permanent calibration*
- *Resolution may be improved by over-sampling techniques*
- *Excellent linearity (ADC)*
- *Large dynamic range (AGC)*
- *Reduced N° of bits at equivalent resolution (Normalization)*

Limitations

- *No single shot measurement*
- *No "plug and play" system*
- *Large engineering*
- *All problems related to a new un-experienced processing system*

- *The present advantages alone do not justify the man power investment, but I consider this technique as one of the most promising for the future*

Conclusions for FP 420 BPMs

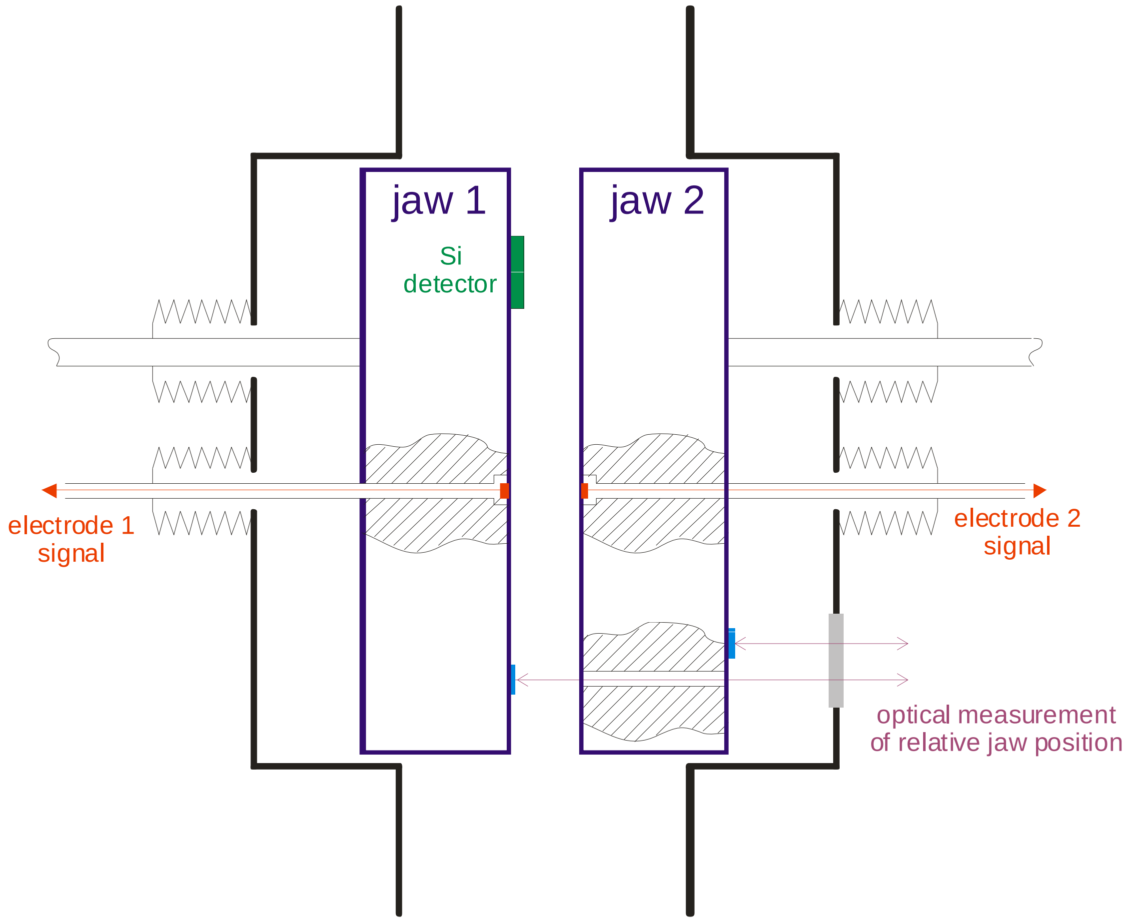
- No obvious solution to satisfy all FP 420 BPM requirements, especially
  - Required „normalized accuracy" in the order of 10 um / 100 mm, i.e. 10^{-4}
  - Bunch by bunch measurement

- Already „bunch by bunch" resolution in the order of 10^{-4} is difficult to achieve

- Propositions
  - Measurement with a single multiplexed channel for a few bunches
  - Something special, which employs specific features of the FP 420 BPM system

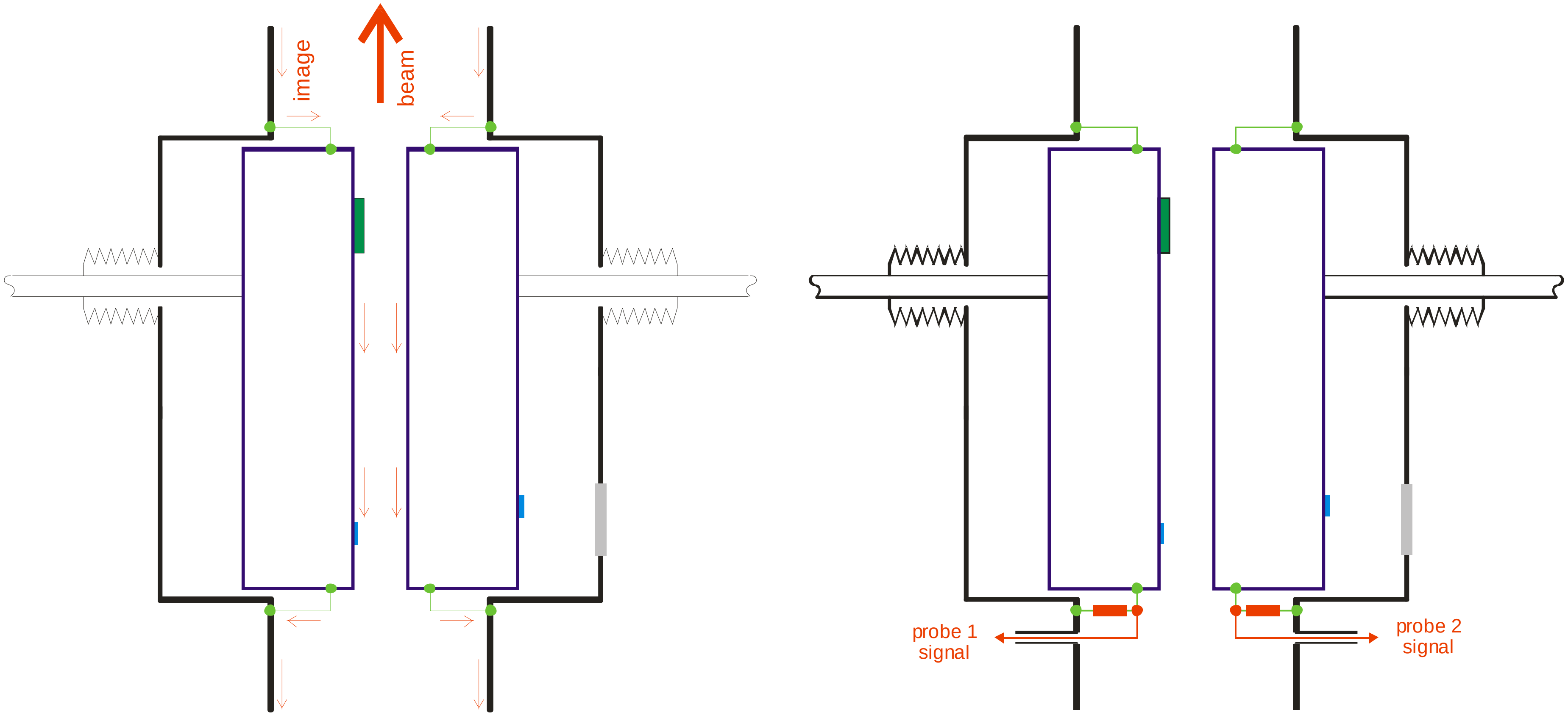
- What can help to relax the difficult requirements?
  - Required accuracy concerns relative distance beam – SI detector
  - Required measurement range is much smaller than the vacuum chamber diameter

An idea of a PU with reduced „working aperture”



- A „collimator arrangement” to reduce the PU „working aperture”
- If the jaw distance can be reduced to some 10 mm, then the „normalized accuracy” drops to 10^{-3}, which is much more reasonable
- One PU electrode on one unit with the Si detector, giving excellent relative positioning
- Jaw relative position measured with optical means
- Possible dynamic jaw positioning with respect to the beam
- Some know-how could be quickly transferred from the collimator people, especially if they could think about using a similar idea for the collimator system

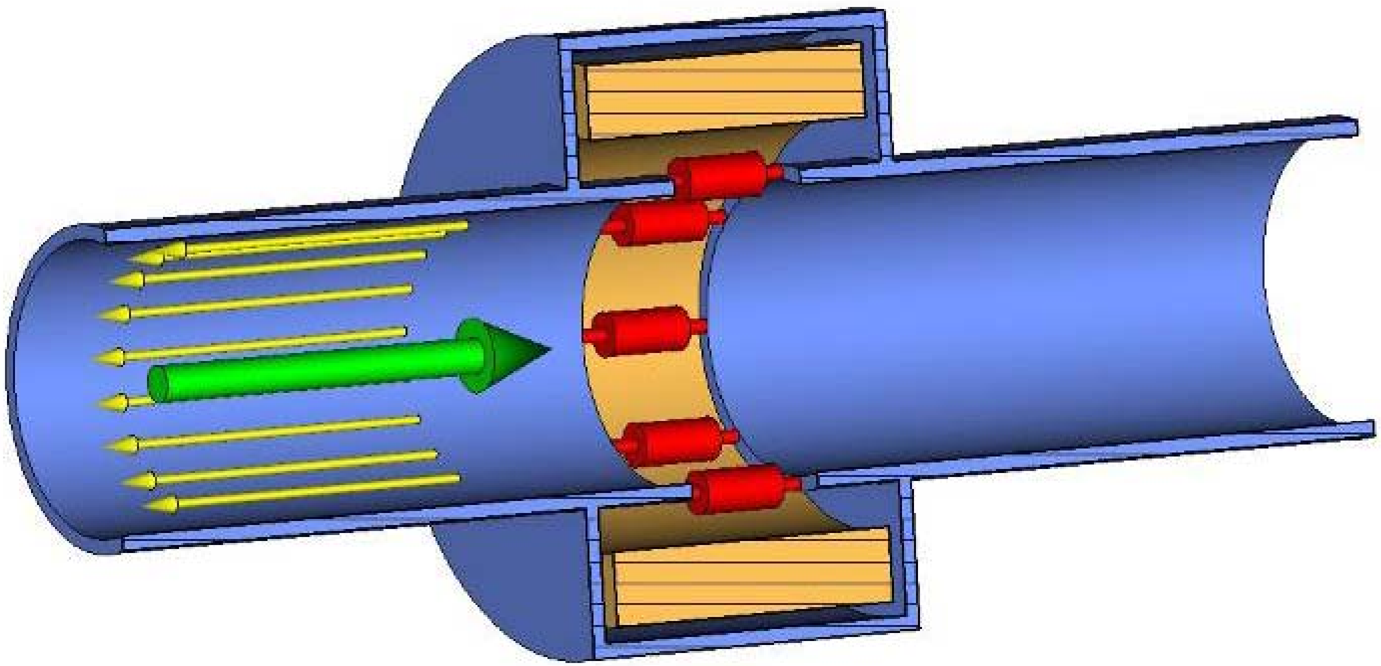
A version more robust for scattered particles



- This version may be also interesting for collimators, for symmetric jaw positioning with respect to the beam
- Signal quality not very demanding for simple signal equalization from both probes

Spare slides

Wall Current Monitor (WCM) principle

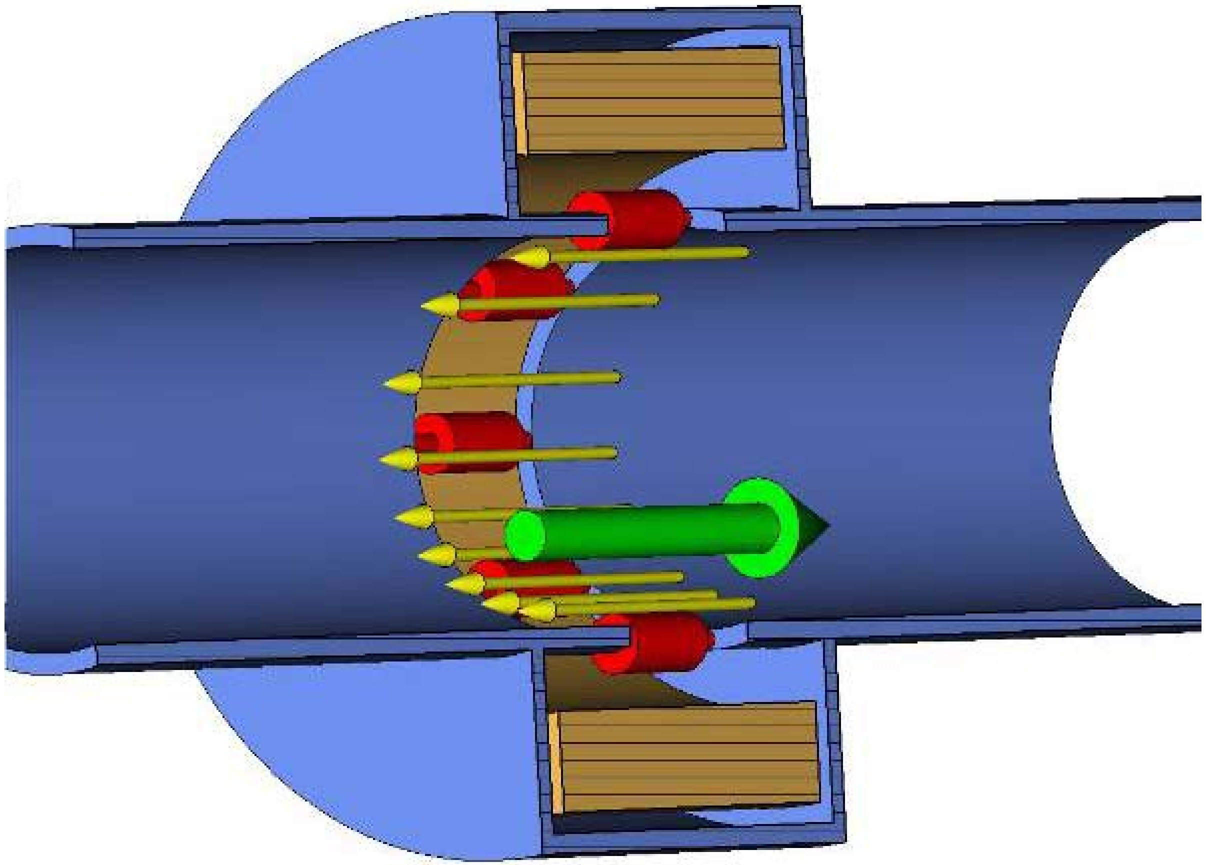


- The **BEAM** current is accompanied by its **IMAGE**
- A voltage proportional to the beam current develops on the **RESISTORS** in the beam pipe gap
- The gap must be closed by a box to avoid floating sections of the beam pipe
- The box is filled with the **FERRITE** to force the image current to go over the resistors
- The ferrite works up to a given frequency and lower frequency components flow over the box wall

WCM as a Beam Position Monitor

$$f_{L\Sigma} = \frac{R}{2\pi L_\Sigma}$$

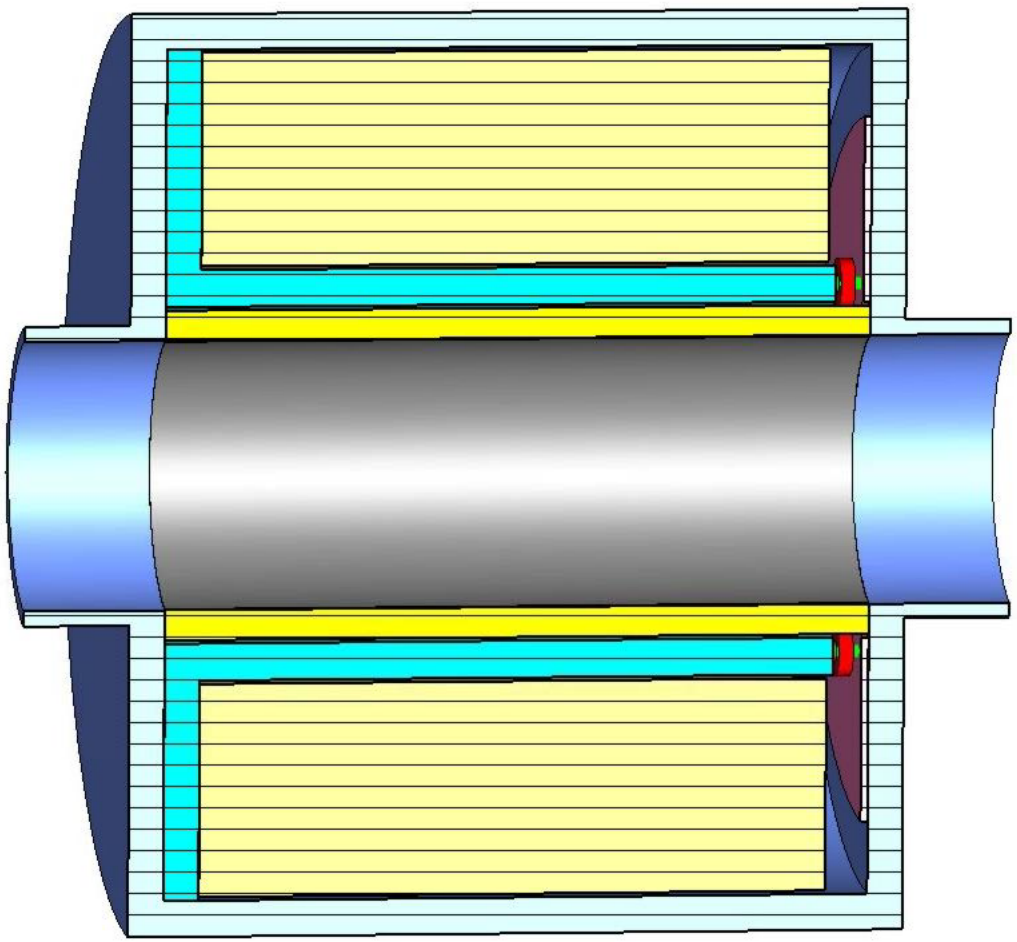
$$f_{L\Delta} = \frac{R}{2\pi L_\Delta}$$



- For a centered **BEAM** the **IMAGE** current is evenly distributed on the circumference
- The image current distribution on the circumference changes with the beam position
- Intensity signal (Σ) = resistor voltages summed
- Position dependent signal (Δ) = voltages from opposite resistors subtracted
- The Δ signal is also proportional to the intensity, so the position is calculated according to Δ/Σ
- Low cut-offs depend on the gap resistance and box wall (for Σ) and the pipe wall (for Δ) inductances

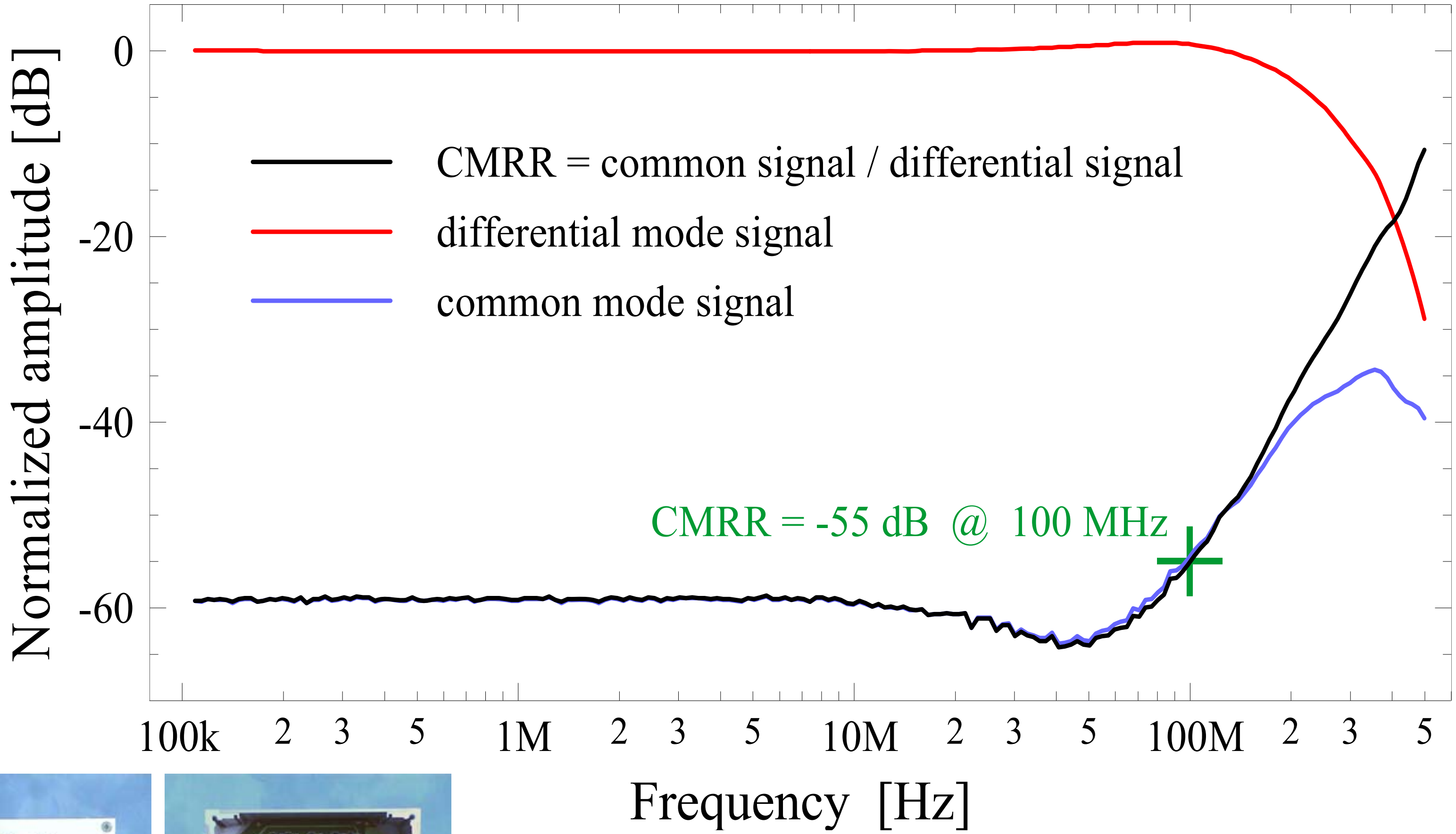
A new design: Inductive Pick-Up (IPU)

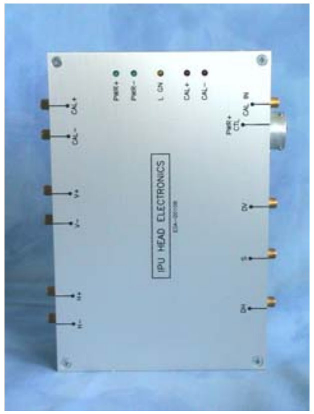
MORE INDUCTANCE   LESS RESISTANCE

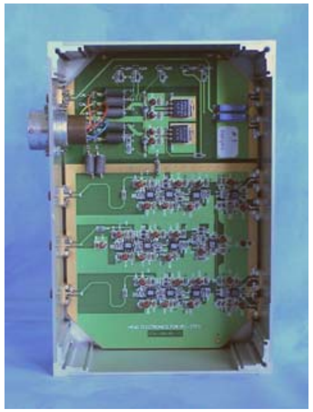


- An eight electrode “tight” design to avoid resonances in the GHz range
- The electrodes cover 75 % of the circumference
- The electrode internal diameter is only 9 mm larger then the vacuum chamber of 40 mm and it is occupied by the ceramic insertion (alumina)
- The transformers are as small as possible to gain high frequency cut-off with many turns
- The transformers are mounted on a PCB
- The connection between the electrodes and the cover is made by screws
- Electrode diameter step is occupied by the ceramic tube
- The tube is titanium coated on the inside

Active Hybrid Circuit – Performance

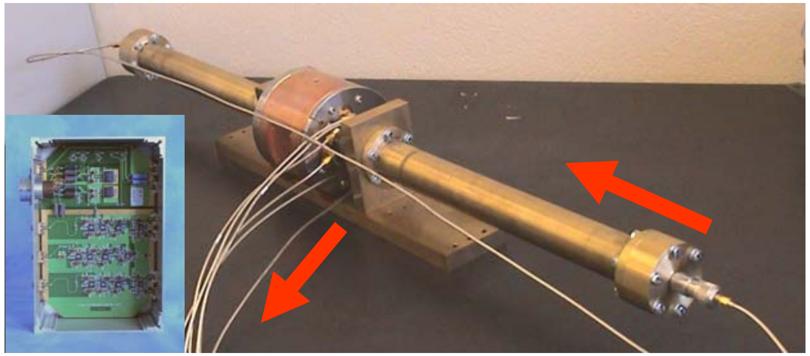




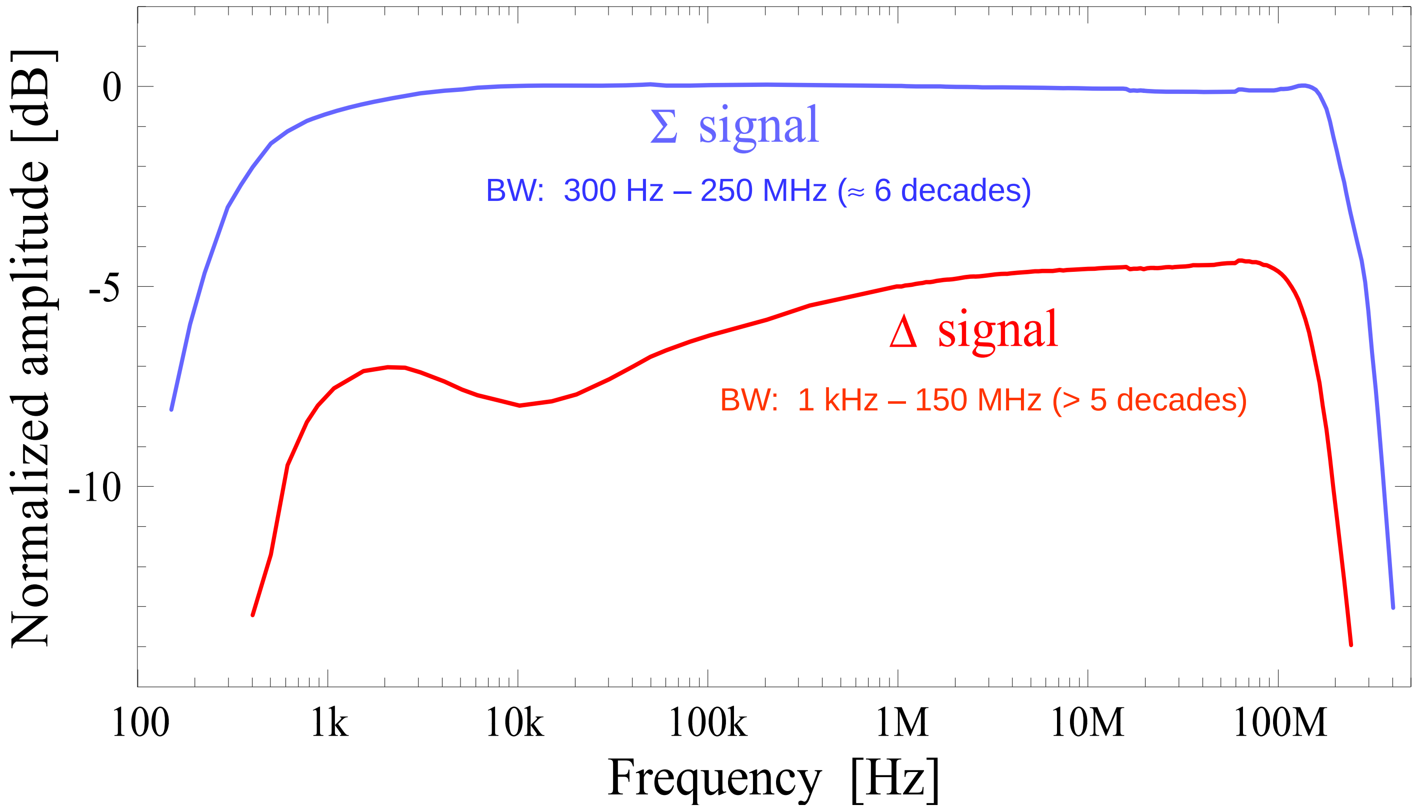


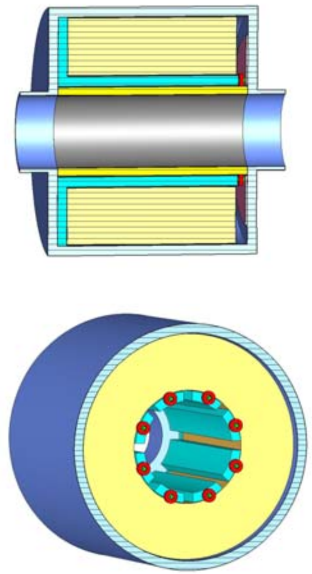
- The CMRR at 100 MHz is as high as 55 dB (datasheet 42 dB)
- The CMRR for frequencies below 10 MHz is limited by the measurement setup
- Δ signal high cut-off frequency about 200 MHz

IPU and AHC – Frequency Characteristics



- A wire method with a 50 Ω coaxial setup which the IPU is a part
- Σ signal – flat to 0.5 dB within 5 decades, almost 6 decades of 3 dB bandwidth (no compensation)
- Δ signal – 5 decades (four decades + one with an extra gain for low frequencies)

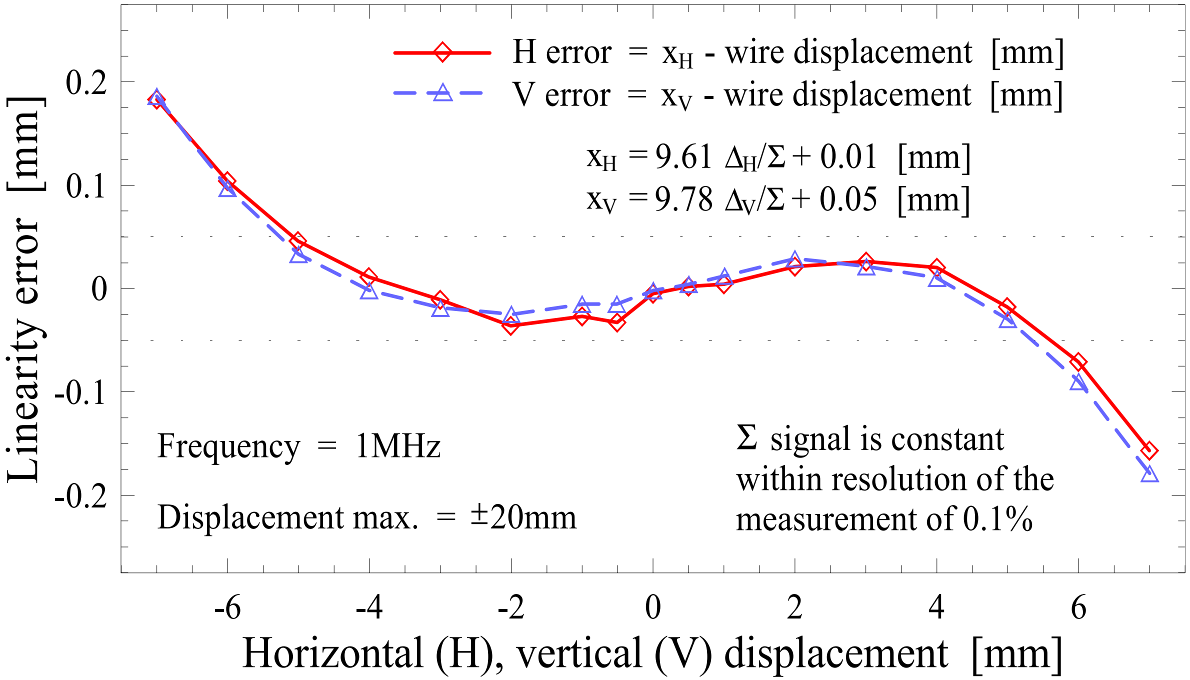




IPU and AHC – Displacement Characteristics

$$\text{horizontal position} = 9.61\frac{\Delta_H}{\Sigma} + 0.01 \ \text{[mm]}$$

$$\text{vertical position} = 9.78\frac{\Delta_V}{\Sigma} + 0.05 \ \text{[mm]}$$



A thin wire forming a coaxial line was displaced diagonally across the pick-up aperture.
The measurement was done with a network analyzer: signal was applied to the wire and hybrid signals were observed.