BPM Signal Processing using Time-Multiplexed Electrode Signals

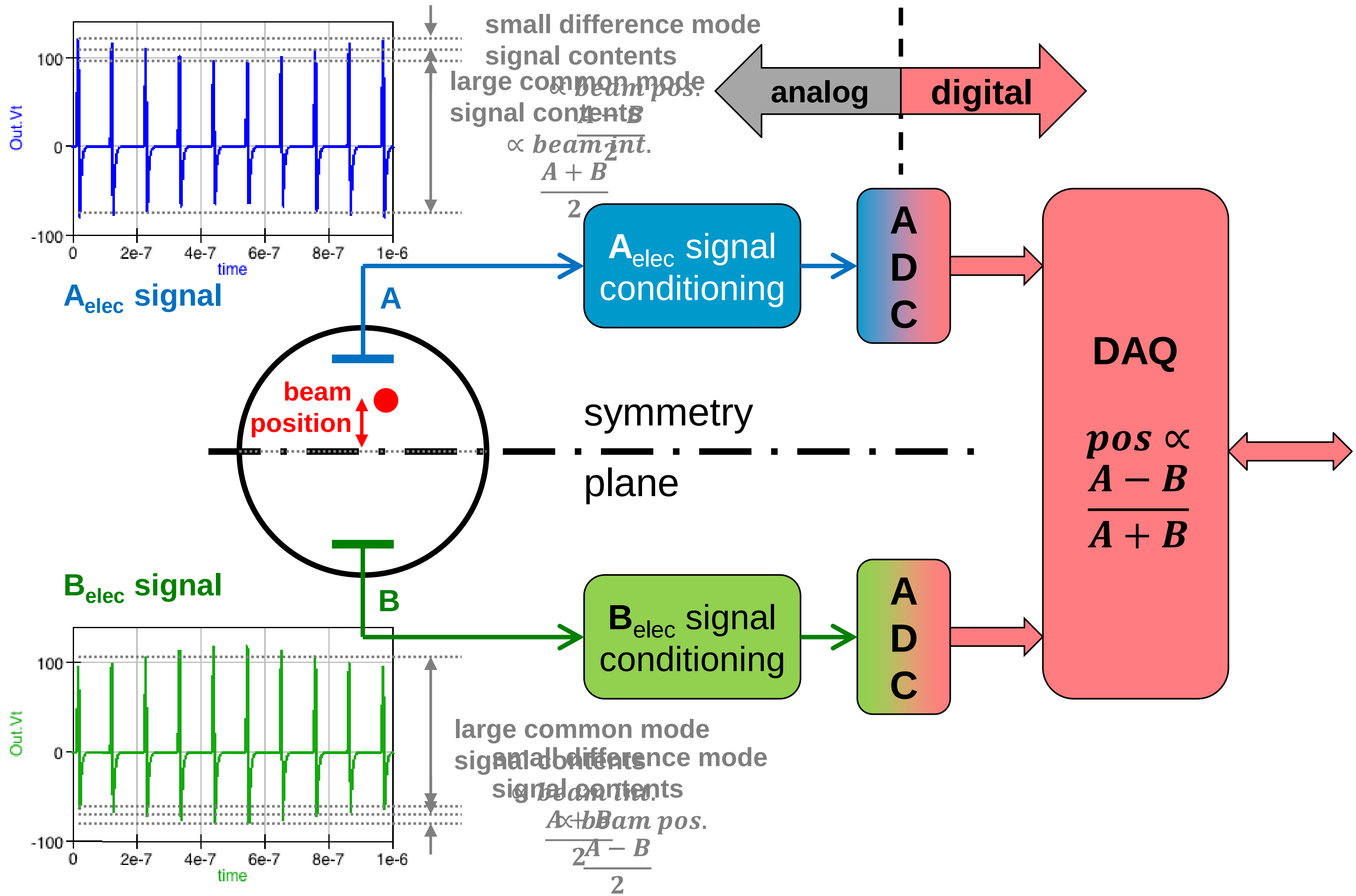
M. Wendt

CERN

Outline

- **Introduction to the Beam Position Measurement**
  - **Symmetry in beam position monitoring**
  - **Calibration methods to ensure a high measurement stability**
  - **Single channel heterodyne receiver**
- **BPM electronics utilizing time-multiplexed electrode signals**
  - **DESY: BPM electronics at HERA-e and FLASH**
    - Design principle introduced by *R. Neumann*
  - **CERN: LHC interlock BPM R&D**
    - Based on the thesis activities of *Oskar Bjorkquist,* and with help of *Irene Degl'Innocenti* and *Jan Posipil*

Introduction: A typical BPM setup



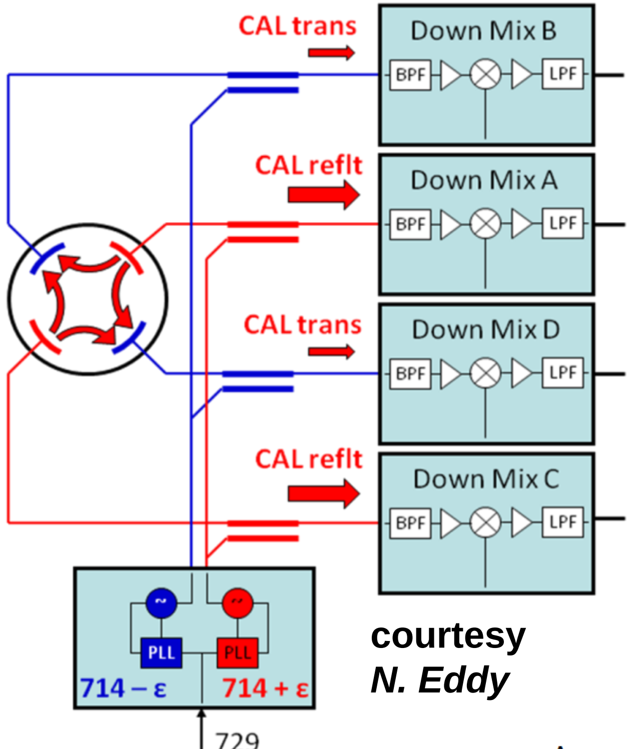
Beam Position Measurement

- **BPMs are based on a symmetric measurement setup**
  - **Detect the beam asymmetry, i.e. the beam position,**
    - by a perfect symmetric arrangement of 2 identical read-out channels
    - to suppress the common mode
    - to simplify the normalization to the beam intensity
    - Beam position signals: An AM signal with the bunch response as carrier
- **Asymmetries in the BPM read-out system channels**
  - **Will result in an (electronic) offset of the reported beam position**
    - can be tolerated and calibrated if the asymmetric effect does not change over time
    - Is often linked to tolerances of RF / analog electronic components, RF cables and connectors, etc.
      - Can also be design choices, e.g. different BPM electrodes or asymmetric arrangement, different gains to electronically center a permanent large beam offset
- **Time varying asymmetries result in uncontrollable position offsets, and are a major limitation of the BPM performance!**
  - **Caused by a variety of effects in the analog and RF signal processing, e.g. ambient temperature, humidity, aging and radiation effects of components**
  - **Also external EM-fields (pulsed RF, kicker signals), or uncontrolled grounding can break the symmetry**

Example: Aging of RF components

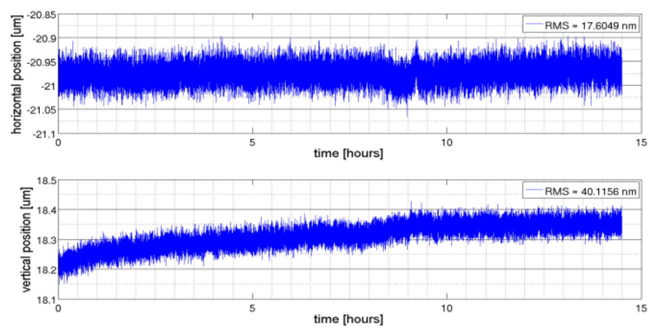
RF connectors and coaxial cables also undergo aging effects!

Online Calibration Methods

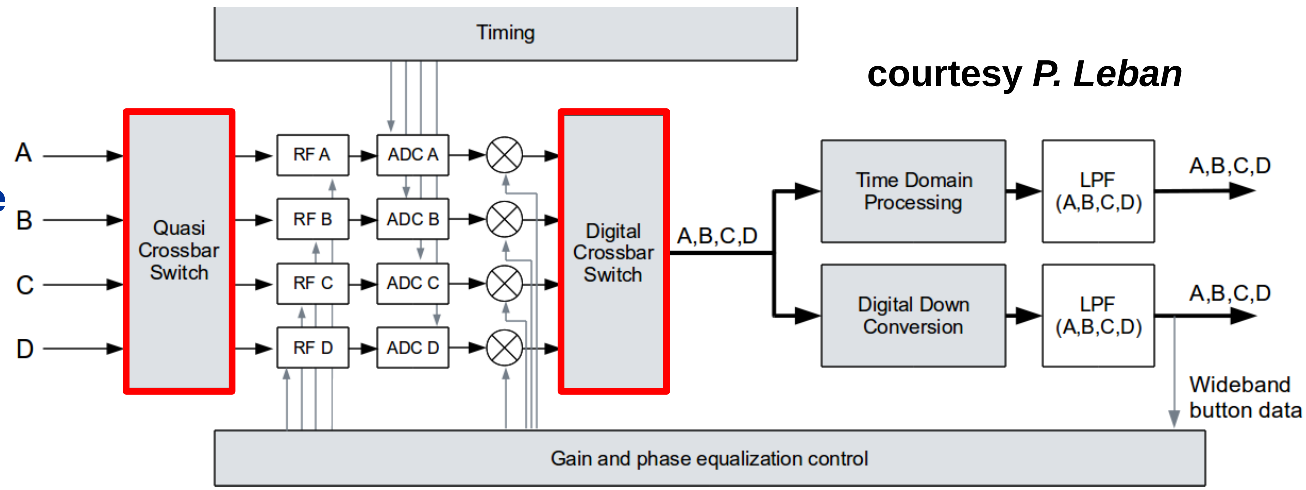


courtesy *N. Eddy*

- **Crossbar switching technique**
  - **e.g. used for the *Libera* BPMs from *Instrumentation Technology***
  - **<100 nm stability over 14 hours**
  - **No position measurement during switching transition**



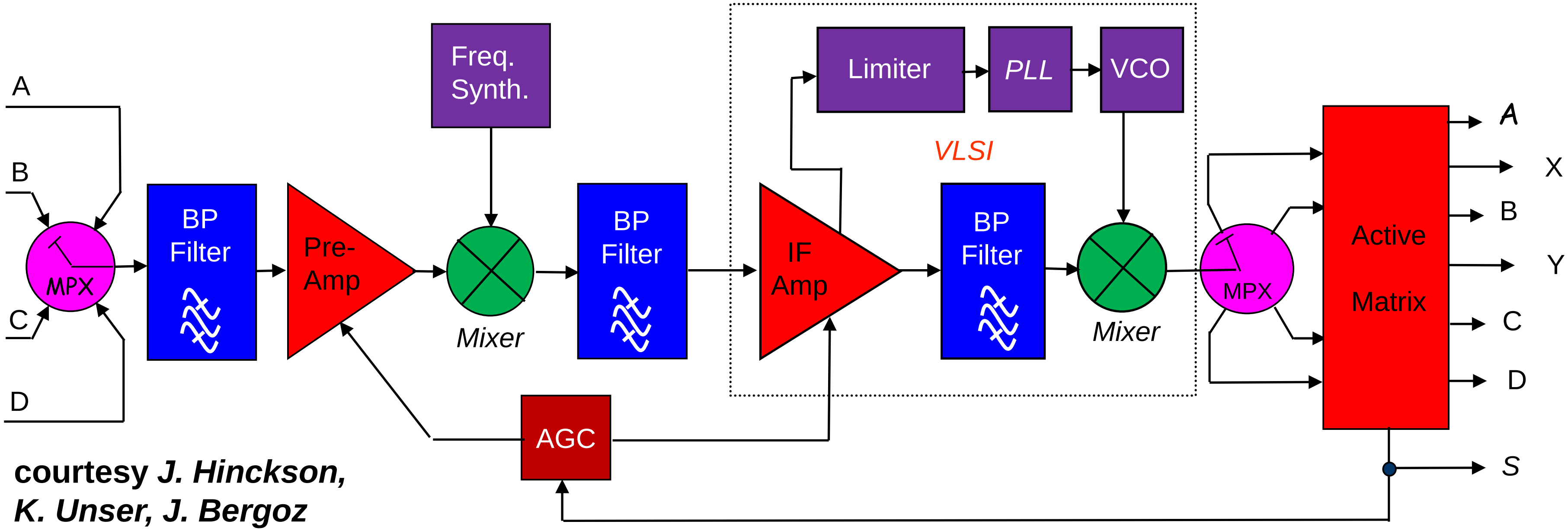
- **Online calibration methods**
  - **require a few stable, high performance "reference" components, like**
    - analog switches
    - RF couplers & connectors
    - transmission-lines
  - **Adds complexity to the BPM system**



courtesy *P. Leban*

- **Calibration tone technique**
  - **only applicable in narrowband operation**
  - **Requires a separate detector channel**

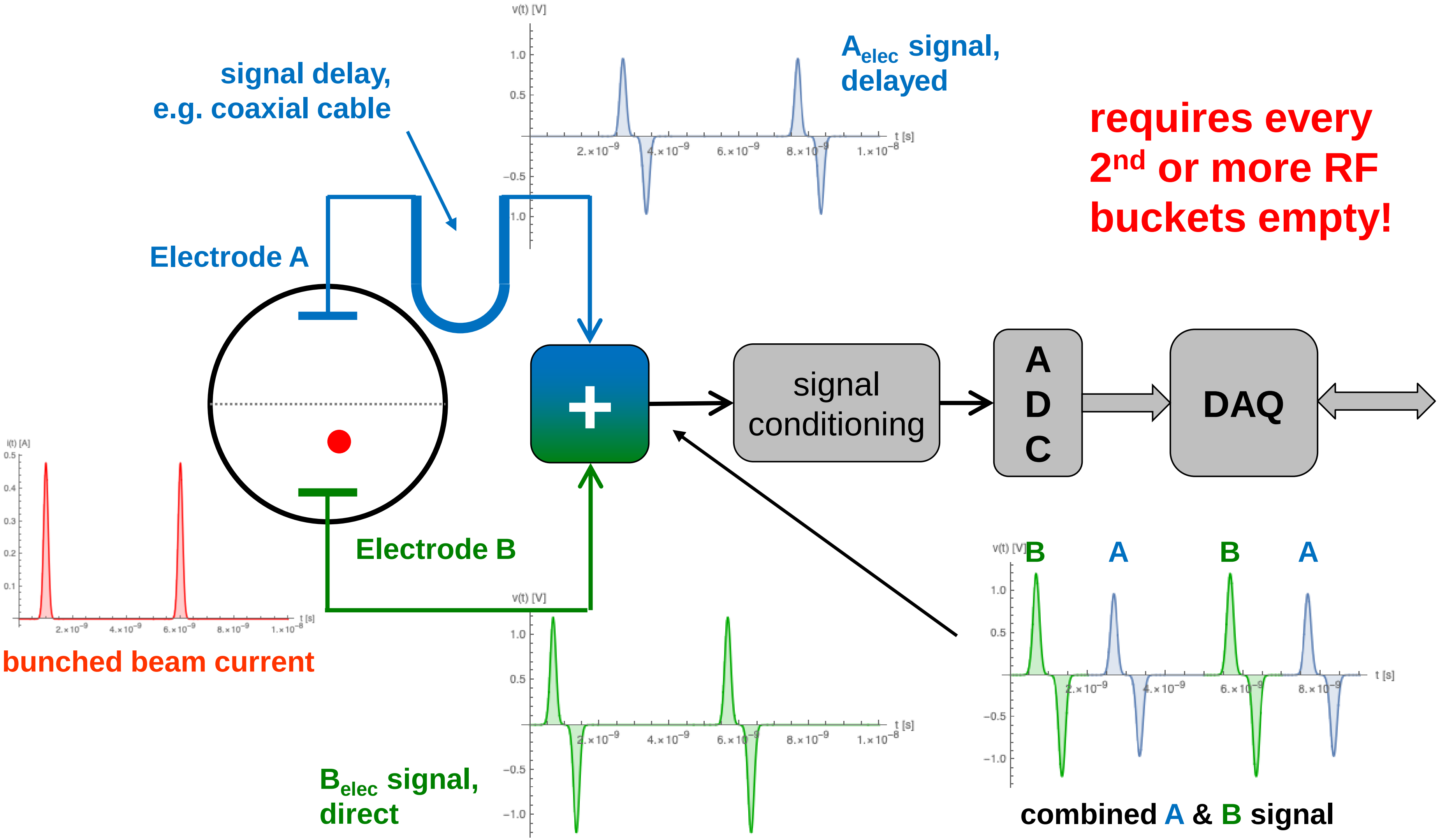
Single channel BPM: MPX Receiver



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

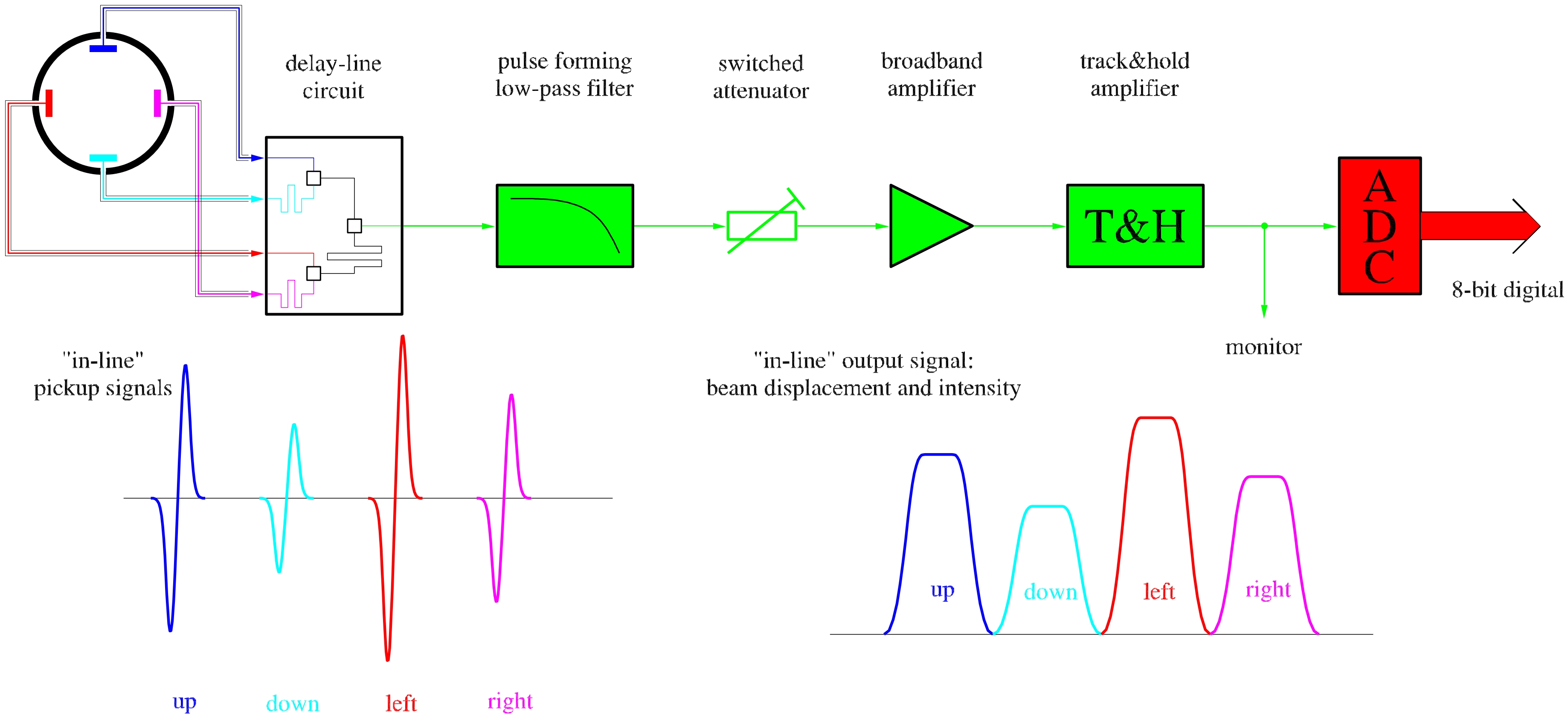
- **Narrowband RF heterodyne receiver with multiplexed inputs:**
  - **Downmix, demodulate and normalize the BPM signals**
    - Classical RF radio-receiver technology applied to process BPM signals
    - Supplies the individual BPM electrode signals and the hor./ vert. position signals
  - **Single channel signal processing with T&H at the analog outputs**
    - Improves the stability due to drift of electronics components

Time-multiplexed BPM signals



requires every 2nd or more RF buckets empty!

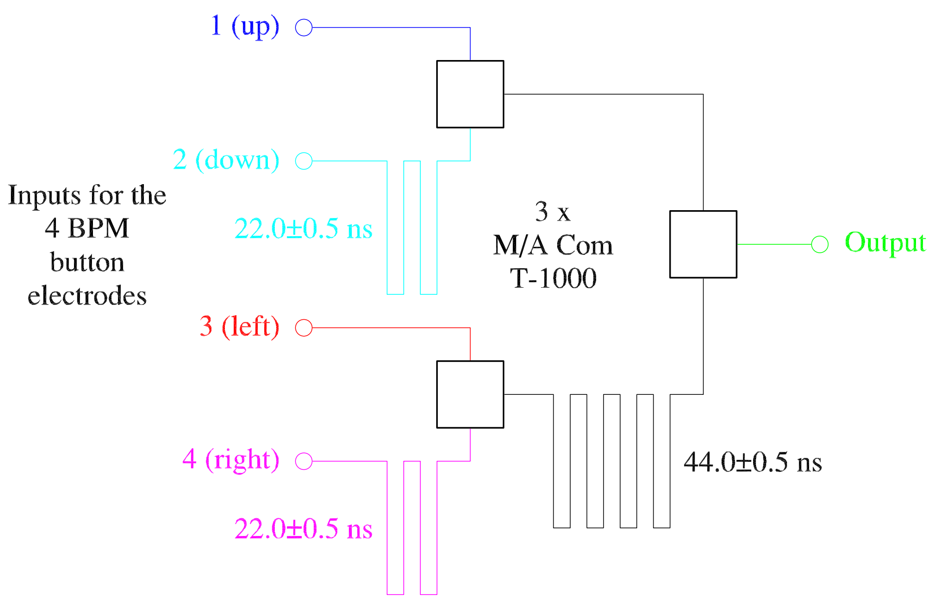
DESYs early MPX BPM System

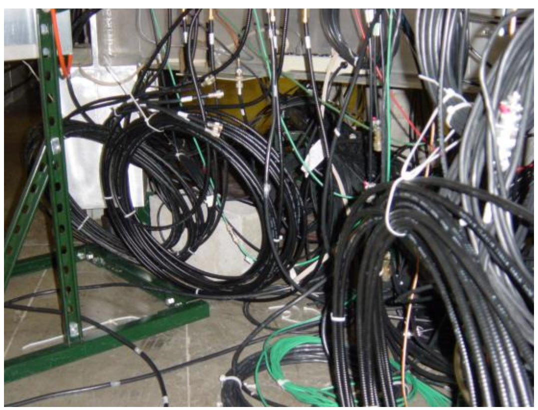


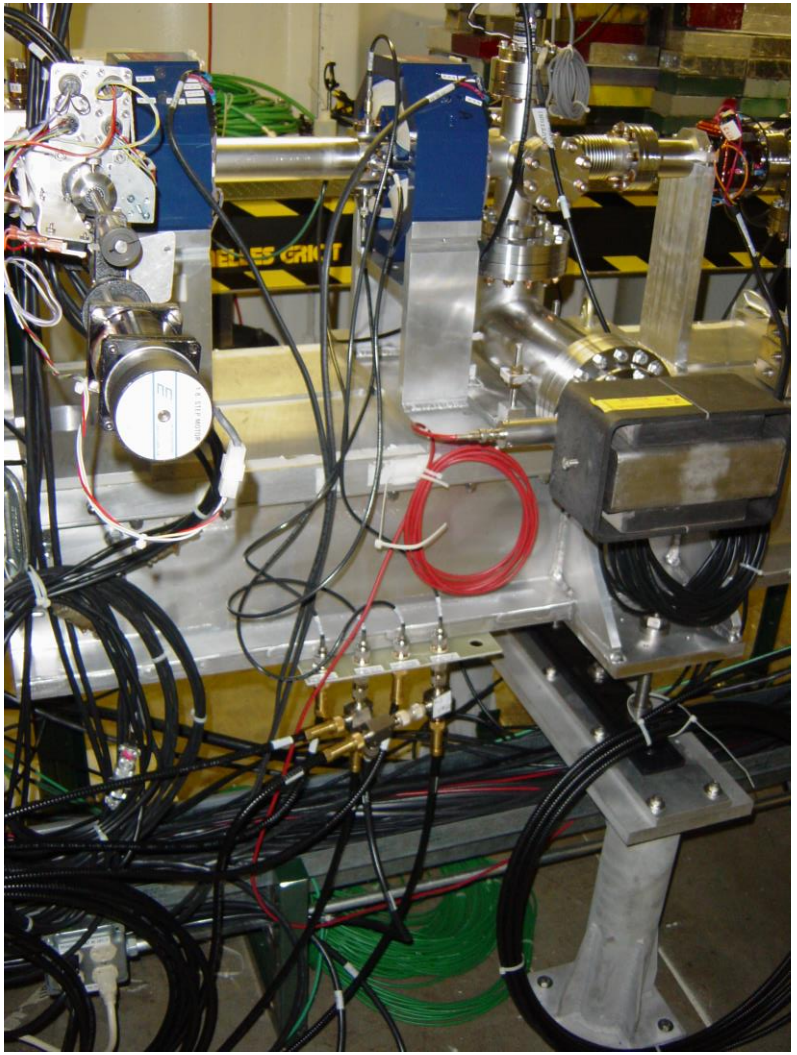
- **Developed and operated at the DESY HERA electron ring**
  - **Every 48th 2 ns bucket filled (96 ns bunch-to-bunch distance)**
- **“Exported” to the Fermilab A0-Photoinjector test facility linac**

DESY MPX BPM Electronics @ FNAL

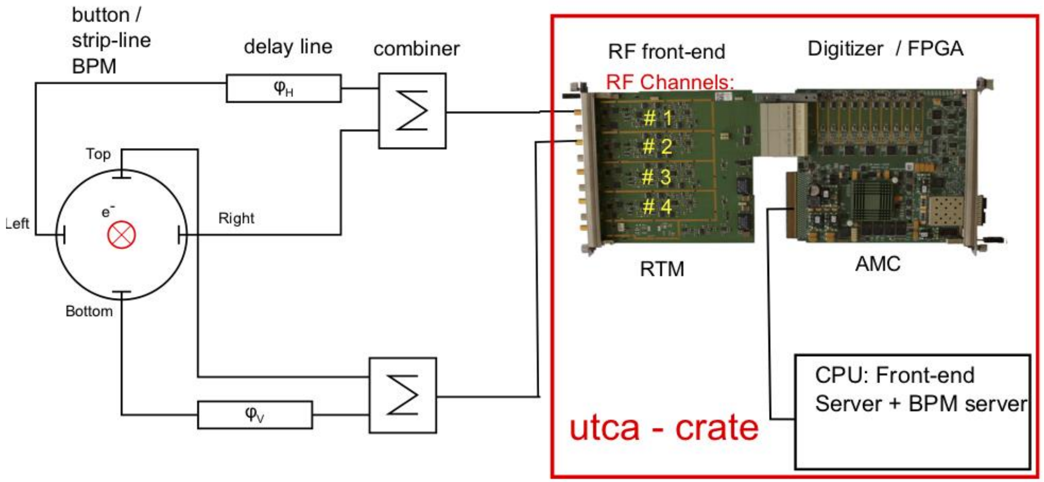
Delay Line Unit

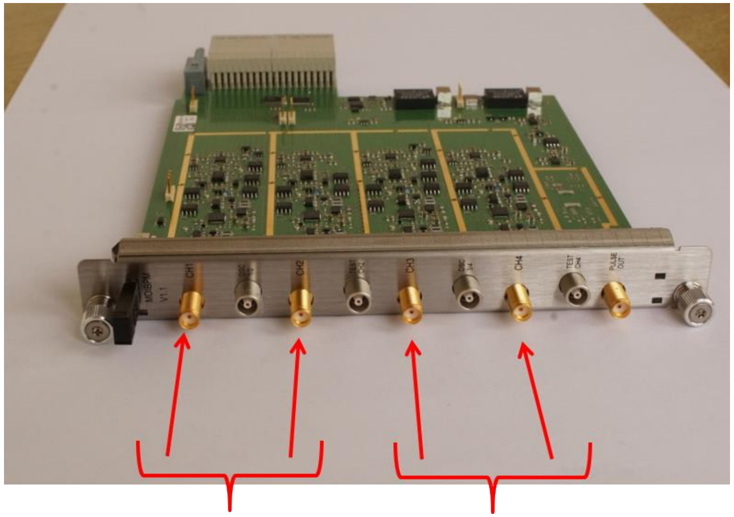






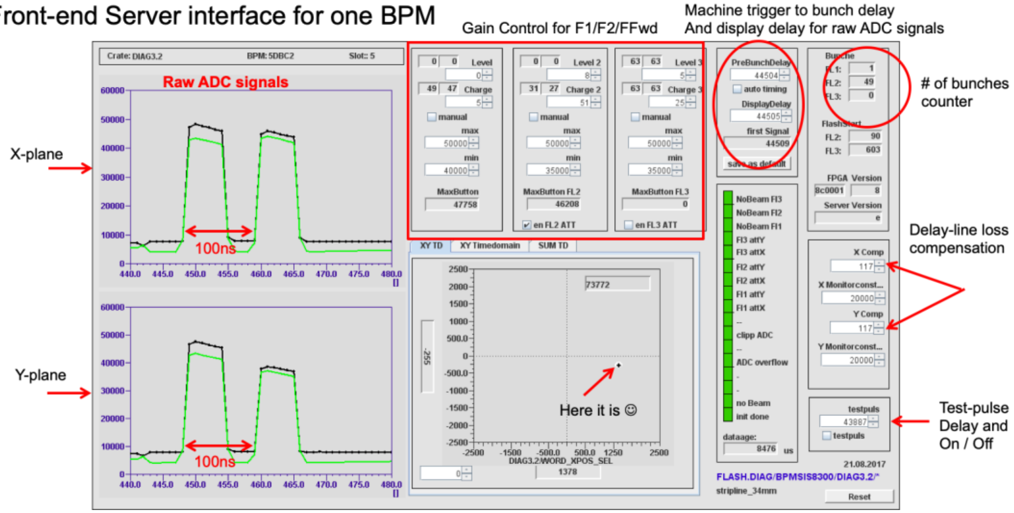
DESY FLASH MPX BPM System

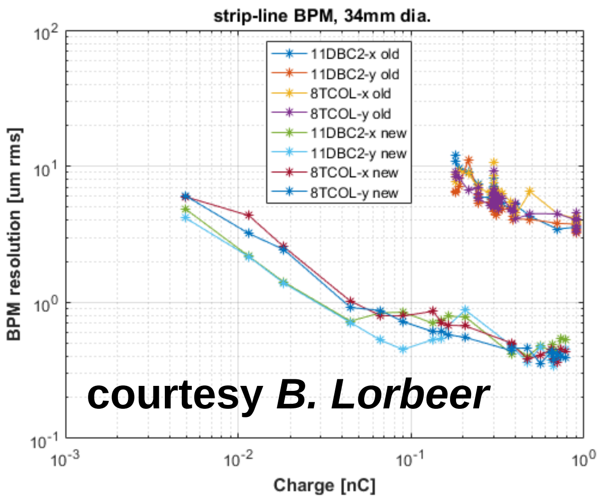




Two BPMs are connected to one RTM

Front-end Server interface for one BPM

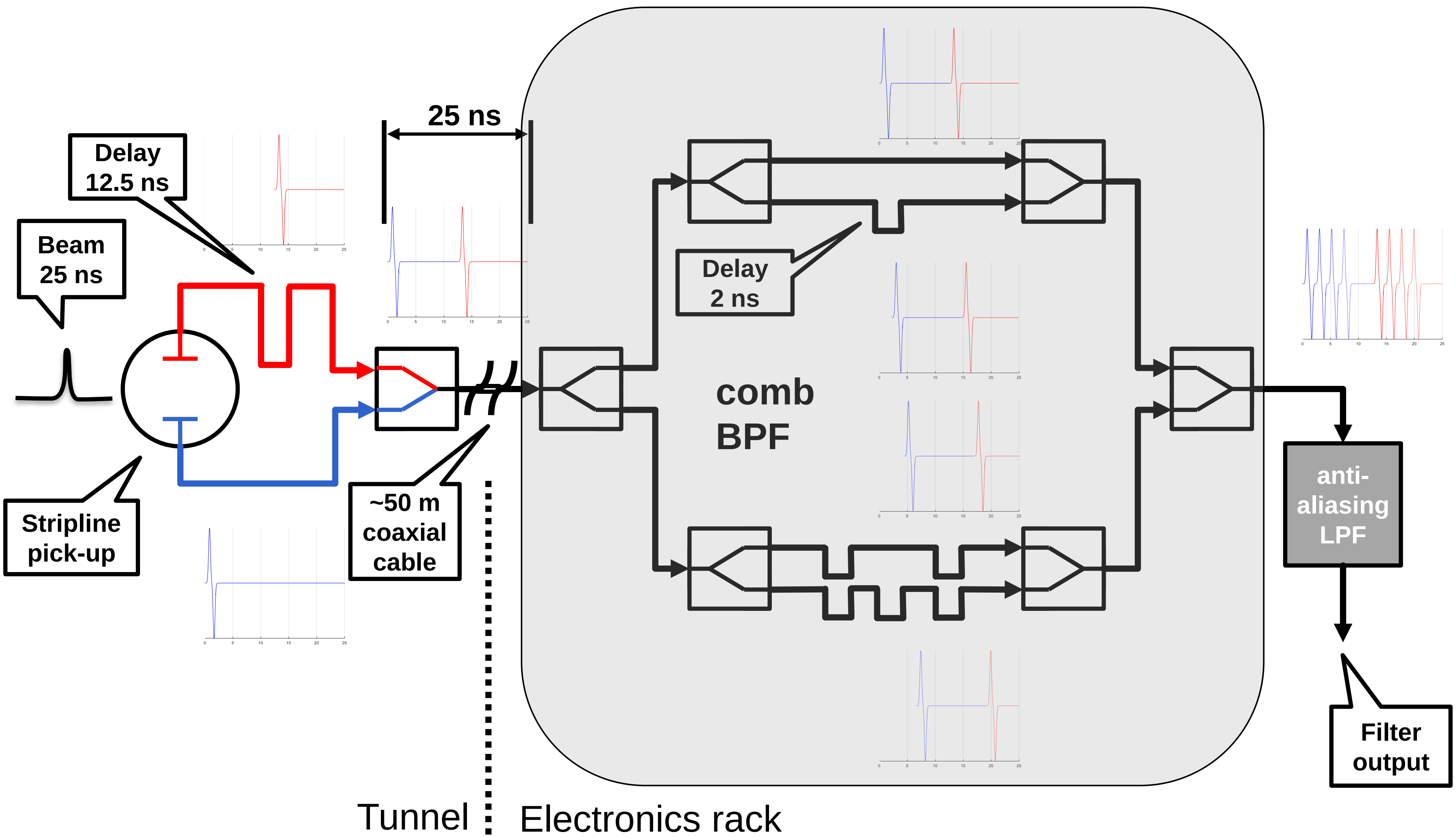




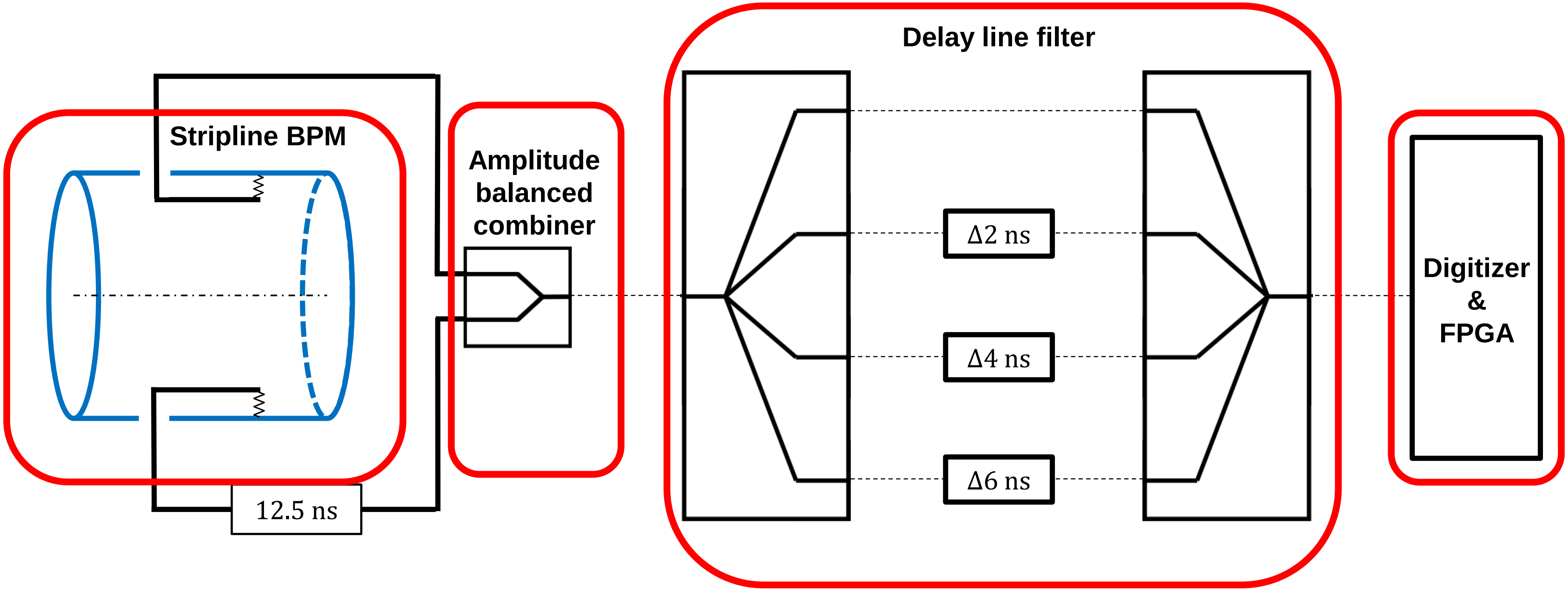
DESY MPX BPM Electronics

- **100 ns delay-line signal combination (2 electrodes)**
  - **80 m long 3/8” high quality coaxial cables**
- **40 dB RF pre-amplifier to cover 15 pC single-bunch operation**
  - **NF = 3.3 dB, 600 MHz BW**
  - **Resolution <10 µm for single bunch operation >10 pC**
- **Analog electronics based on µTCA RTM**
  - **600 MHz BW (-3 dB) & double-peak detector**
    - ➢ V_{RF} peak min = 5 mV
  - **Gain switching (RF step attenuator)**
  - **4 input channels and test pulse generators**
- **Commercial µTCA digitizer *Struck SIS8300***
  - **10-ch, 125MS/s, 16-bit**
  - **External RF synchronous 108 MHz clock**
- **Unfortunately: No long-term drift analysis data available, …yet.**
  - **However, this BPM technology is routinely and successfully used for beam energy calibration, which is cross calibrated to the photon energy of the FLASH FEL.**

CERN LHC Interlock BPM R&D

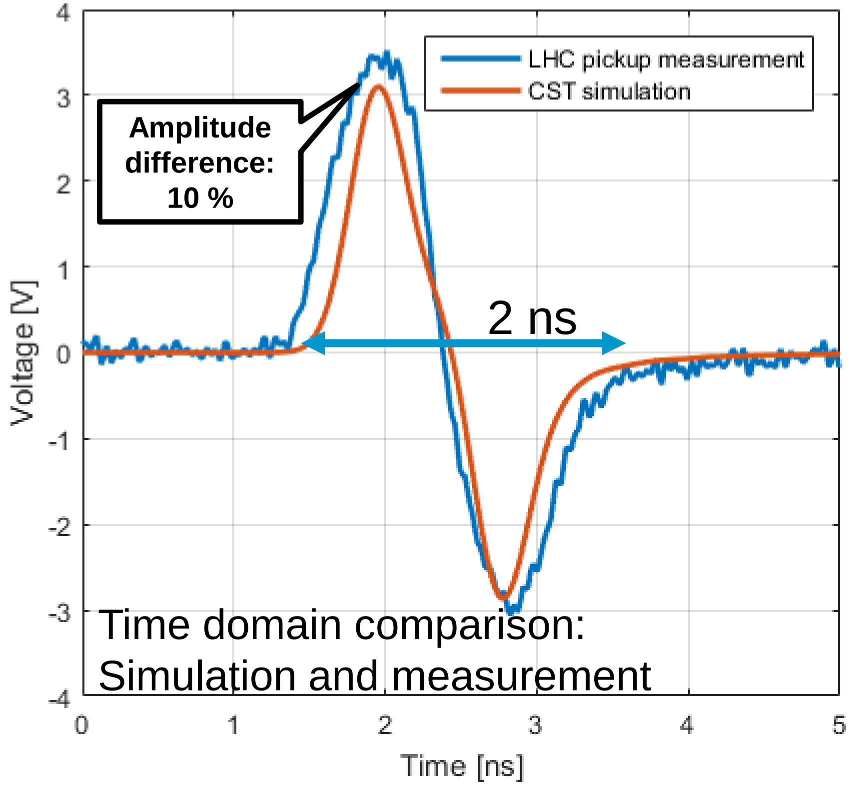


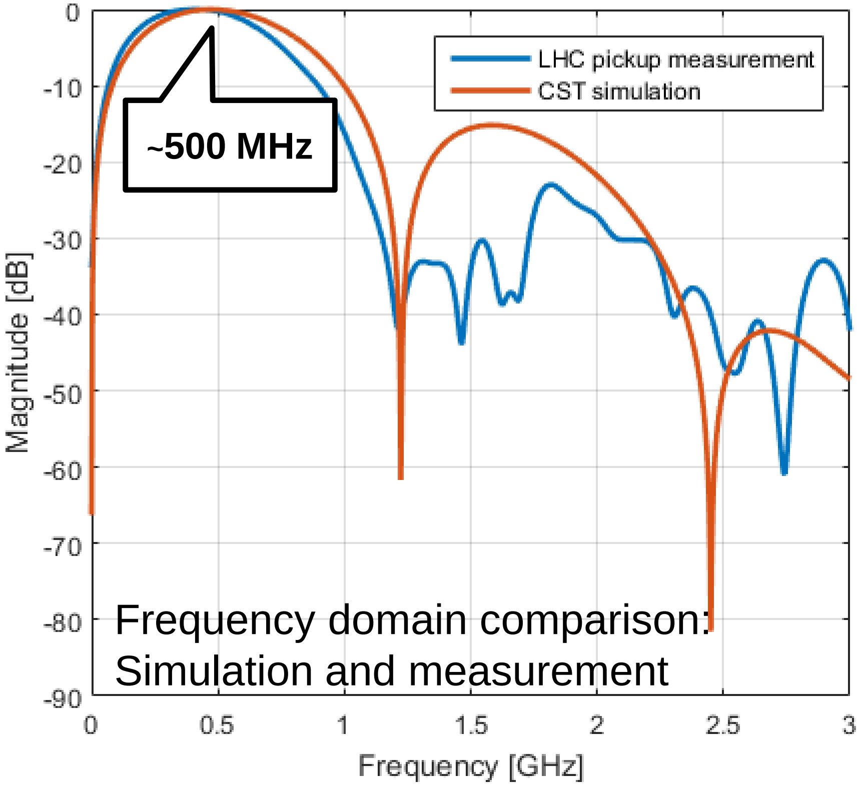
LHC Interlock BPM: Key Elements



- **Stripline BPM**
  - **2 vertical and 2 horizontal, 120 mm long electrodes**
- **High isolation, balanced high-power signal combiner**
- **4-stage delay-line based, comb (FIR) band-pass filter**
- **ADC digitizer and digital signal processing**

Stripline BPM Bunch Signals

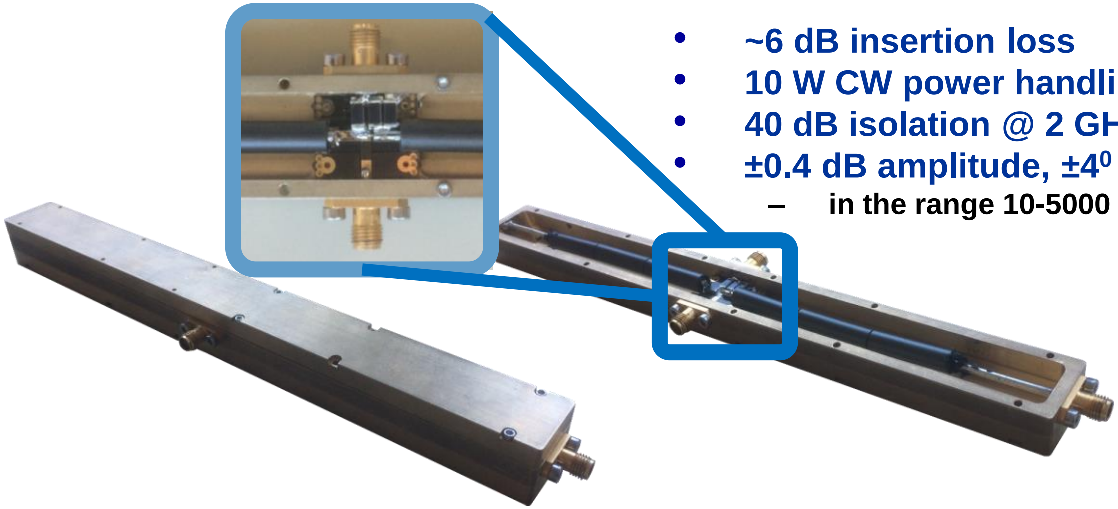


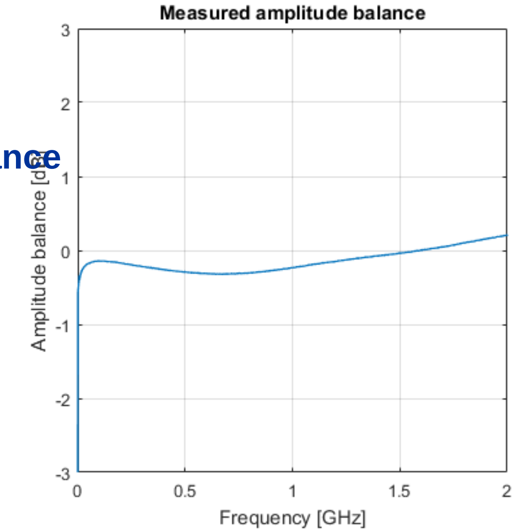


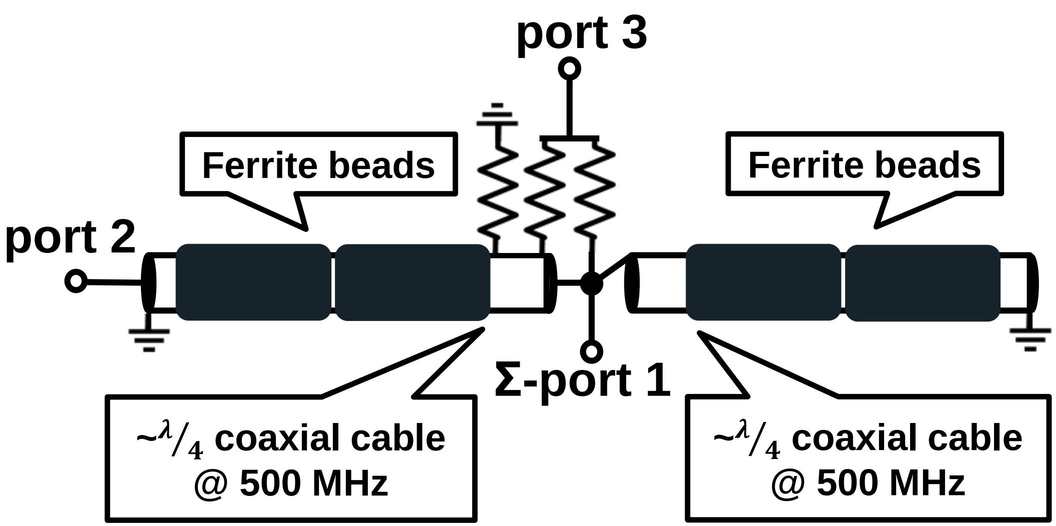
- ***CST*** **wakefield simulation and oscilloscope measurement**
  - **1.35e11 protons per bunch**
  - **Measurement captured after ~70 m ½" Heliax cable**
    - Oscilloscope *LeCroy Waverunner SDA 18000* (60 GS/s, 18 GHz BW)

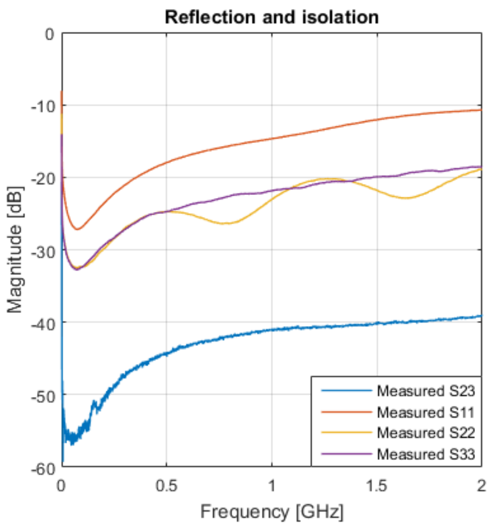
Amplitude-balanced Power Combiner

- ~6 dB insertion loss
- 10 W CW power handling
- 40 dB isolation @ 2 GHz
- ±0.4 dB amplitude, ±4⁰ phase balance
  - in the range 10-5000 MHz



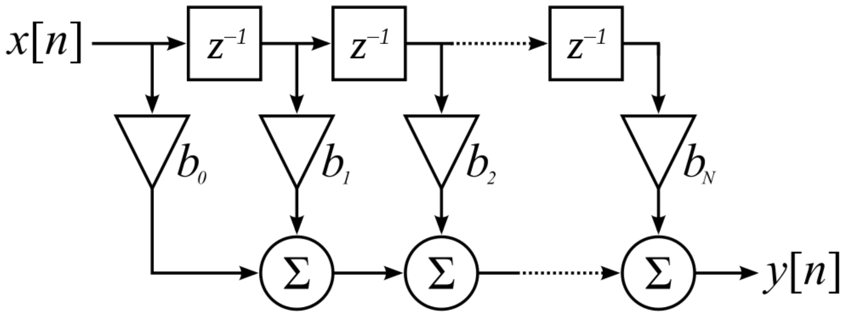




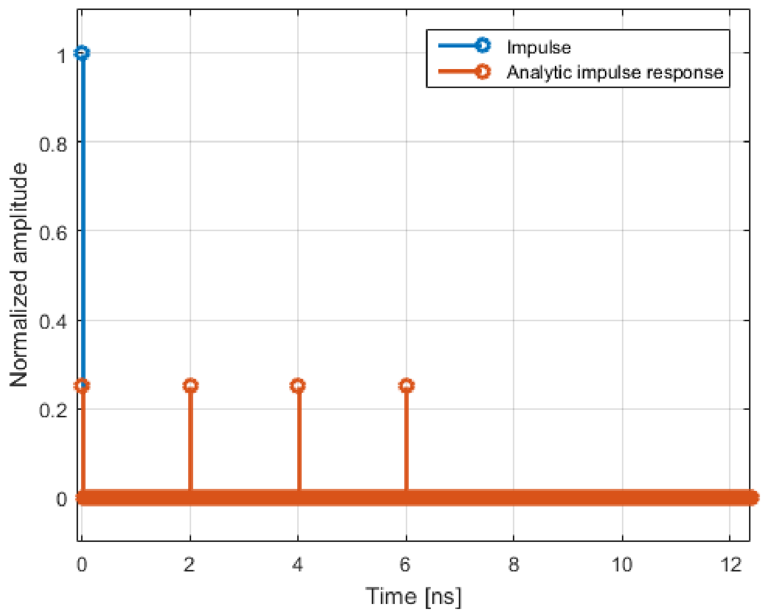


RF FIR Filter Theory

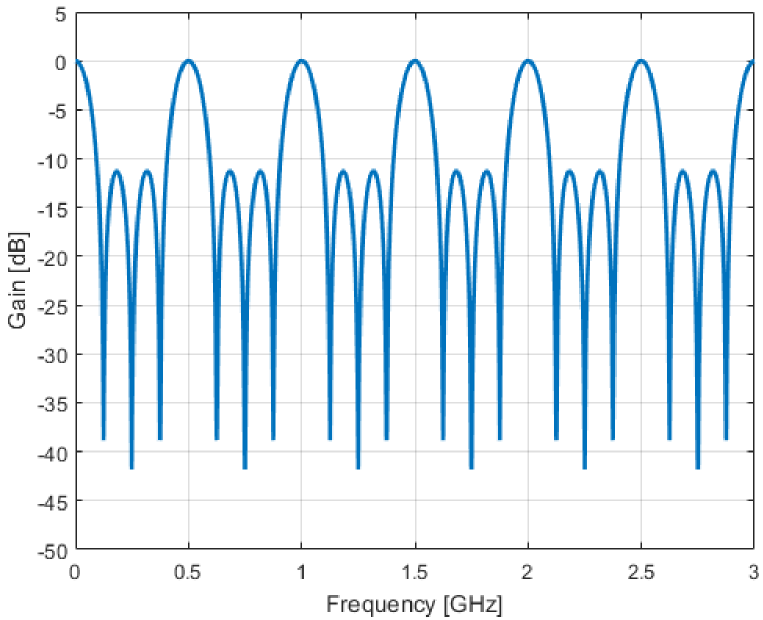
- **4x 2 ns delays:**
  - **maxima at: n x 500 MHz**



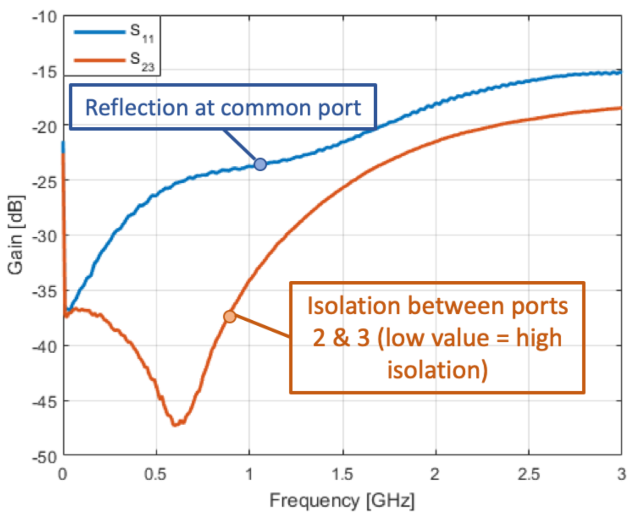
Ideal filter impulse response

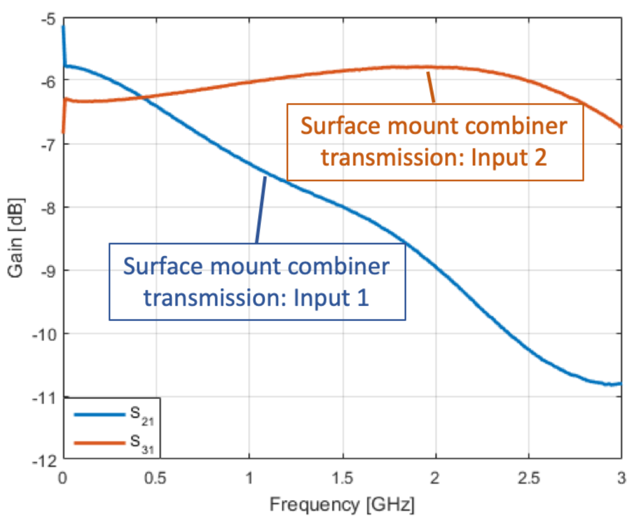


Ideal filter transfer function

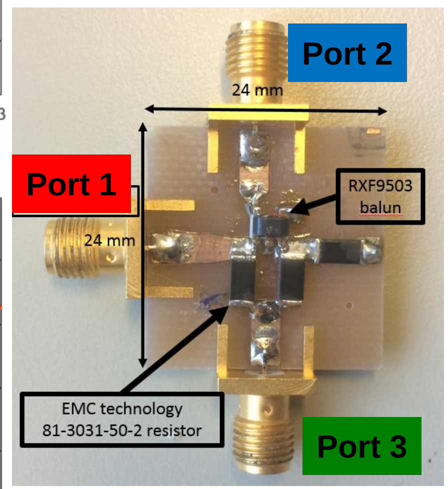


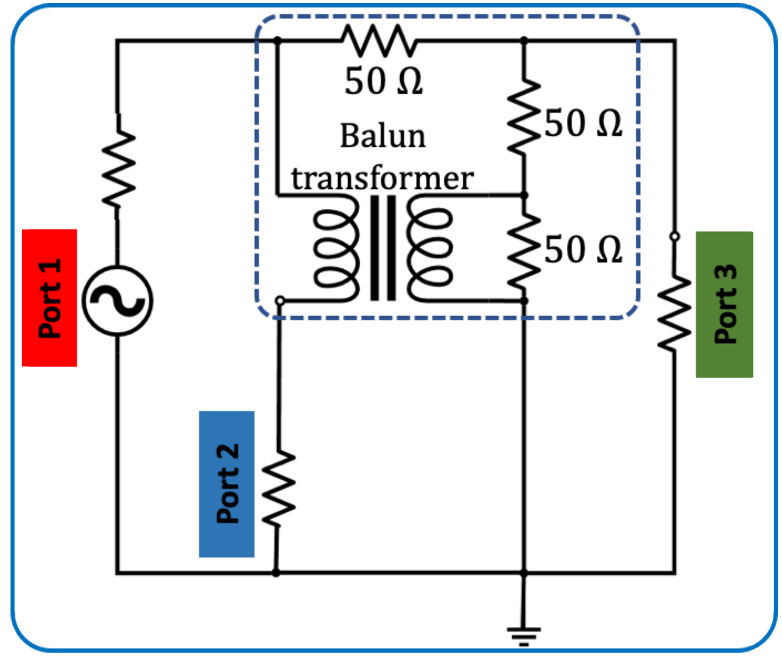
High Isolation Power Combiner

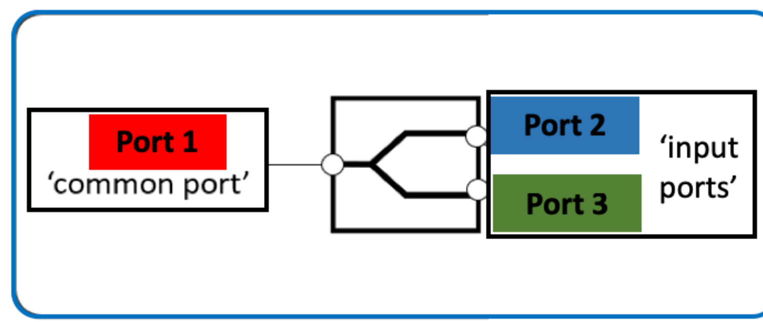




Prototype design

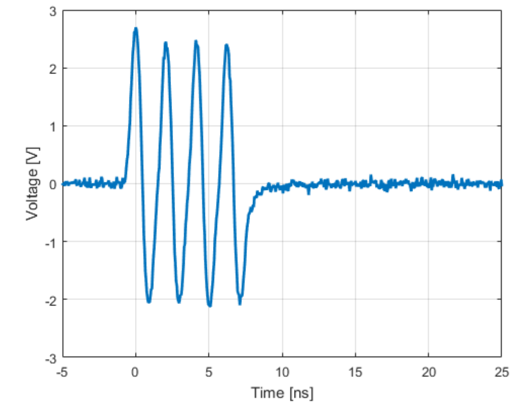






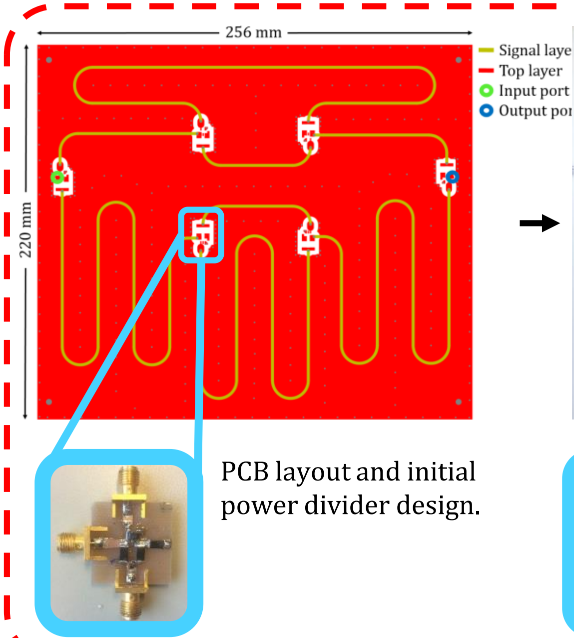
Stripline PCB Comb BPF

- **1.35e11 proton bunch via ~70 m long coaxial cable**
  - **Acquired at 60 GS/s with 18 GHz BW**

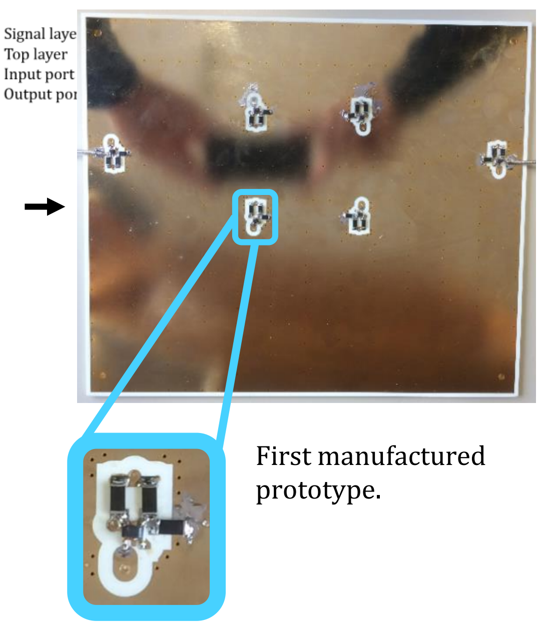


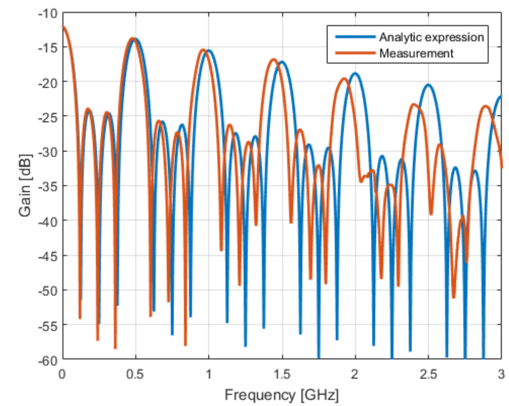
LHC beam measurement of PCB filter at 1.35e11 bunch intensity.

- **Stripline PCB prototype**
  - **Center frequency off by ~5 %**
  - **Substrate: *Rogers RO4360G2* (ε_r = 6.15)**



PCB layout and initial power divider design.

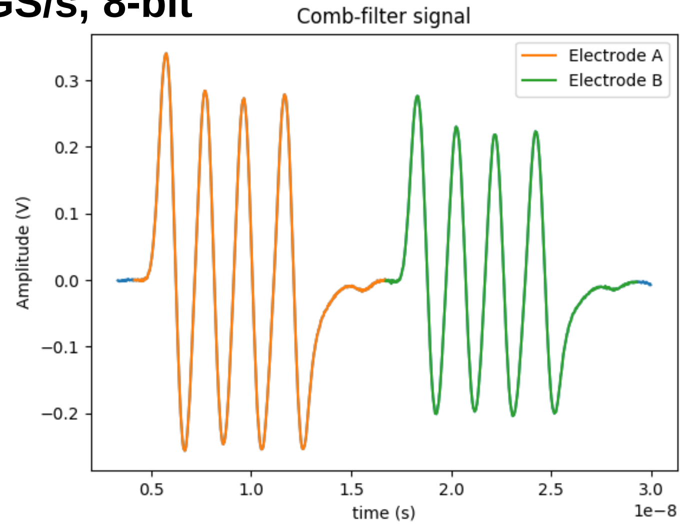

First manufactured prototype.

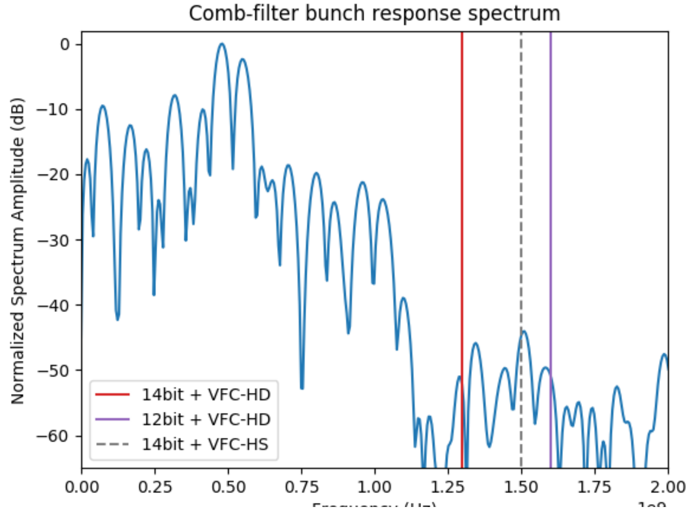


Frequency response of PCB filter.

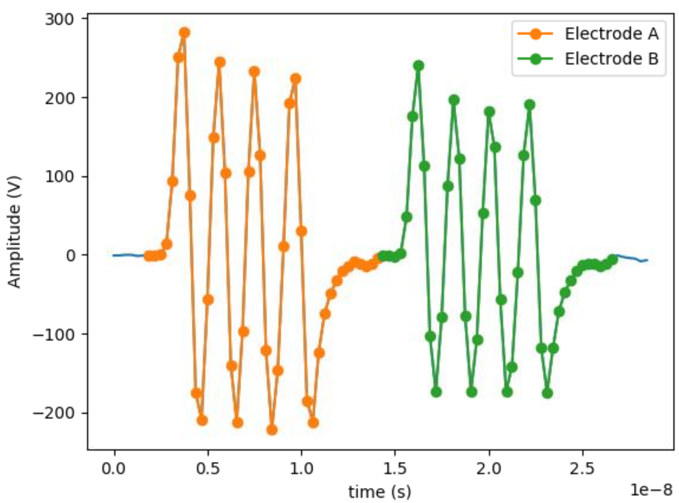
Beam Measurements

60 GS/s, 8-bit

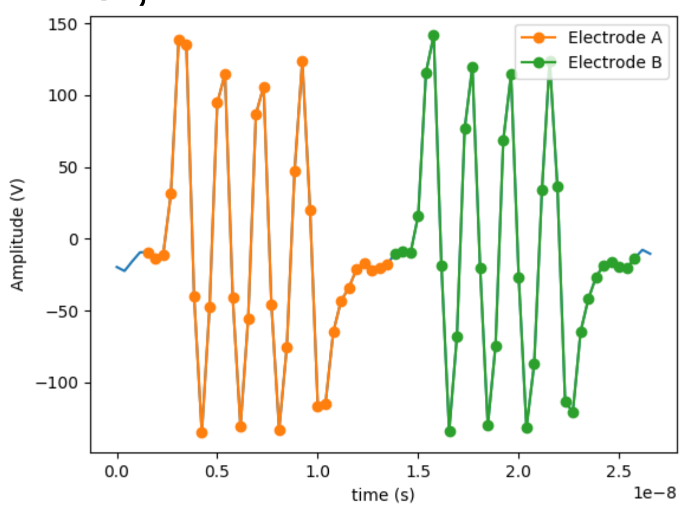




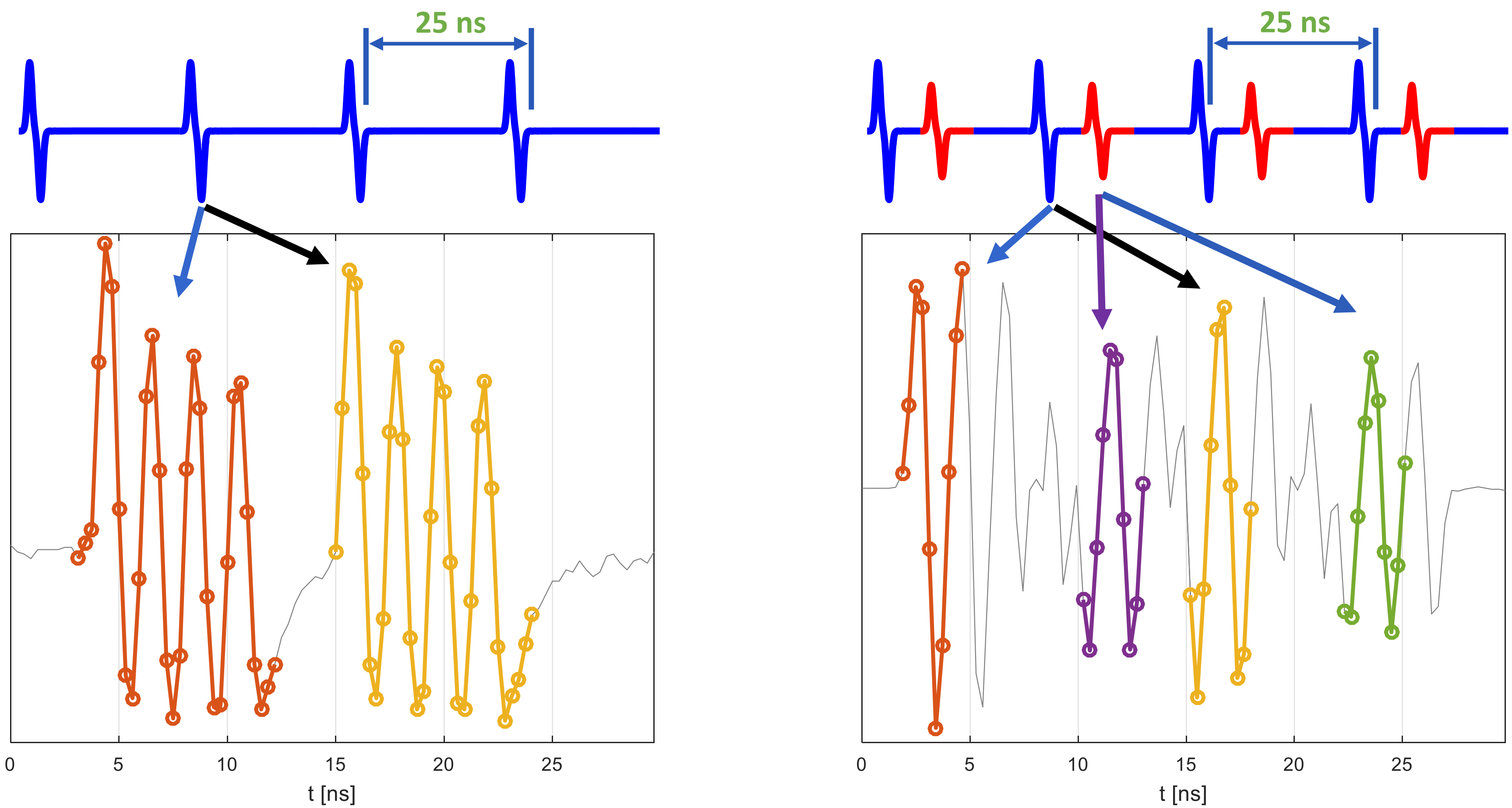
3.2 GS/s, 12-bit



2.6 GS/s, 14-bit

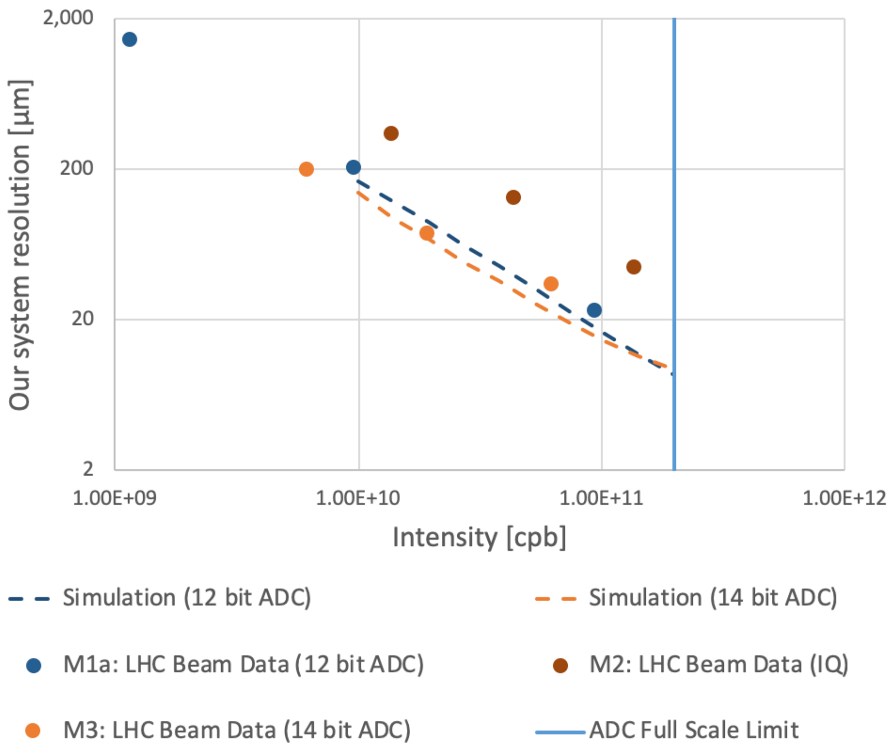


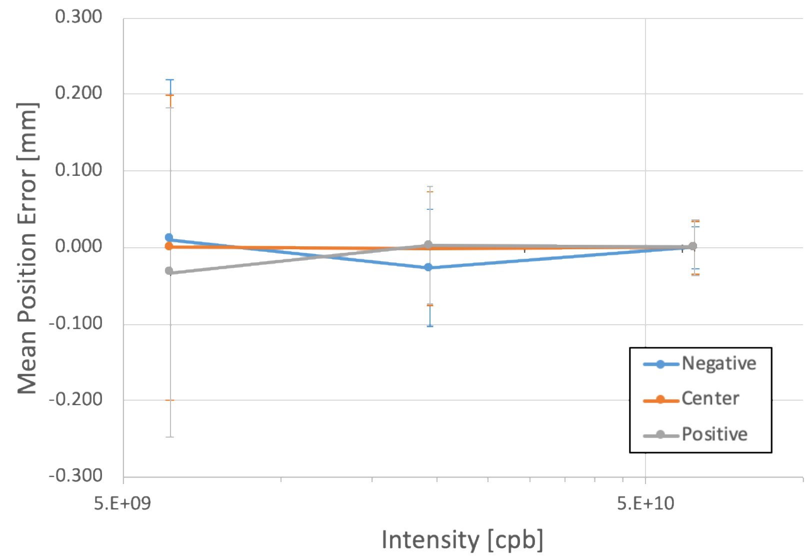
LHC Doublet Bunches (Simulation)



Single bunch (measured) Doublet bunch (simulated)

Estimated Performance





- **Meets the LHC interlock BPM resolution requirement**
  - **<500 µm RMS bunch-by-bunch for a range of 5e9…2e11 ppb w/o gain switching!**
  - **including a beam displacement range of ±7.5 mm**
- **Keeps the reported mean value beam position over the entire bunch intensity range**
- **Operates also with 5+20 ns doublet bunches**
  - **at a reduced performance**

Summary

- **Single channel, time-multiplexed BPM electronics can be an alternative to a multi-channel BPM read-out technique**
  - **Requires empty RF buckets**
- **Time MPX BPM technologies are based on**
  - **Precise, stable time delays utilizing high quality coaxial cables and power combiners**
  - **Low-pass integration or comb-style FIR band-pass filters in connection with track&hold circuits, peak detectors, or fast digitizers**
- **Time MPX BPMs performance is successfully demonstrated in ring and linear accelerators**
  - **DESY HERA-e, Fermilab A0-Photoinjector, DESY FLASH**
  - **In future: CERN LHC interlock BPMs**
- **Long term drift stability could not yet be quantified: TBD!**
  - **However, the concept omits the needs of online calibration or channel switching schemas, thus appears to be more simple and straightforward.**

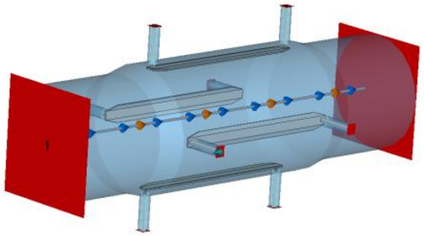
Backup Slides…

Thank you!

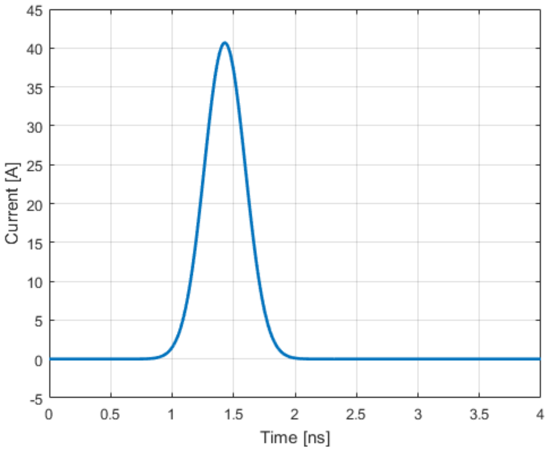
Stripline electrodes: Characteristics

- **Coupled signal is dependent on geometry of electrode**
- **One can say that a certain impulse response $z_T(t)$ relates the beam current $i_b(t)$ to the pickup voltage $v_{pu}(t)$ in the time domain through convolution:**

$$v_{pu}(t) = \int_{-\infty}^{t} i_b(\tau) z_T(t-\tau)\,\mathrm{d}\tau$$

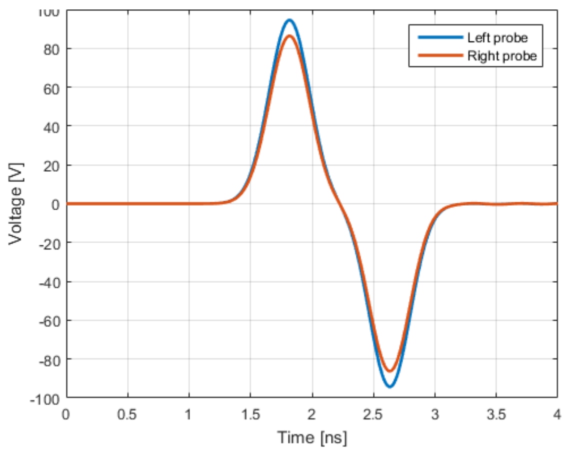


Beam current



z_T

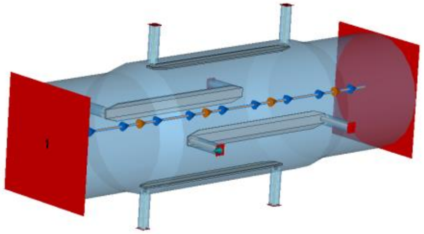
Electrode voltage

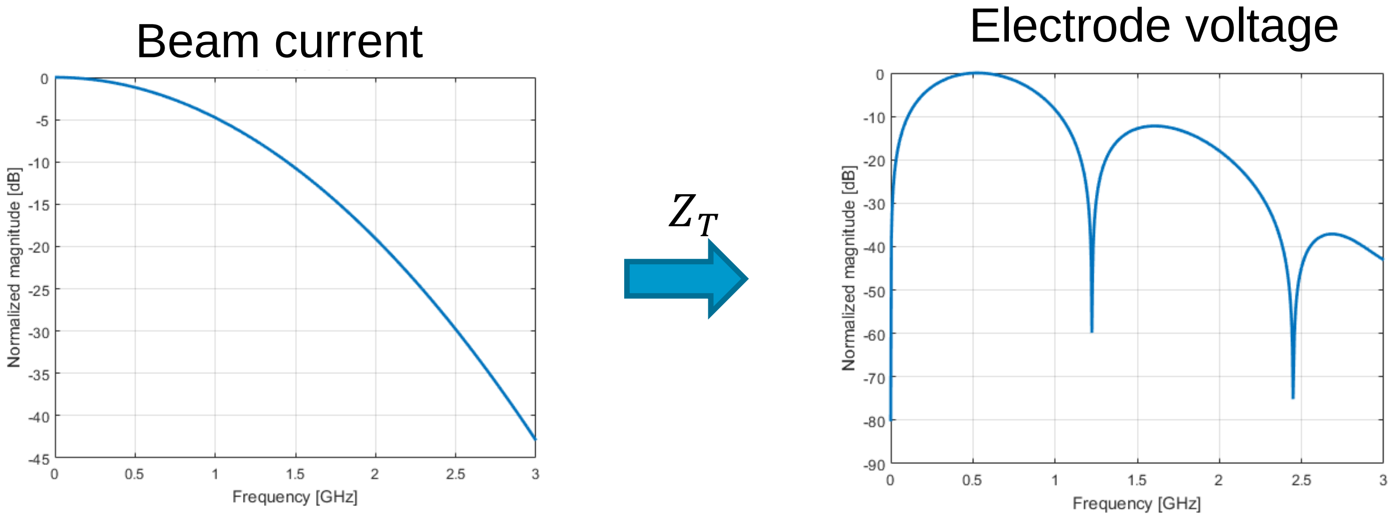


Stripline electrodes: Characteristics

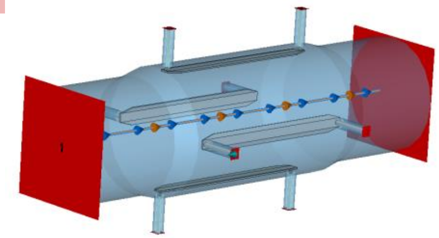
- … And in the frequency domain, a certain transfer impedance $Z_T(\omega)$ relates the beam current and the pickup voltage through multiplication (ohms law):

$$V_{\mathrm{pu}}(\omega) = Z_T(\omega) I_b(\omega)$$

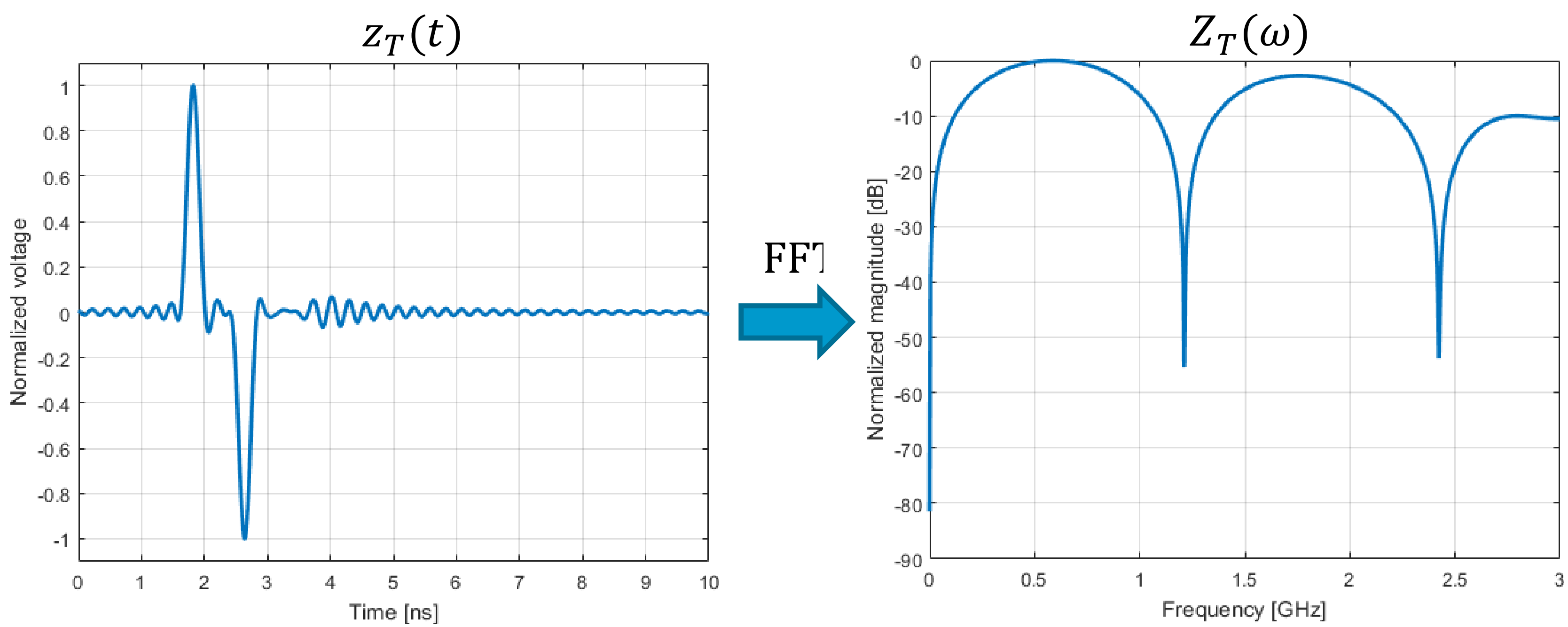




Stripline electrodes: Characteristics

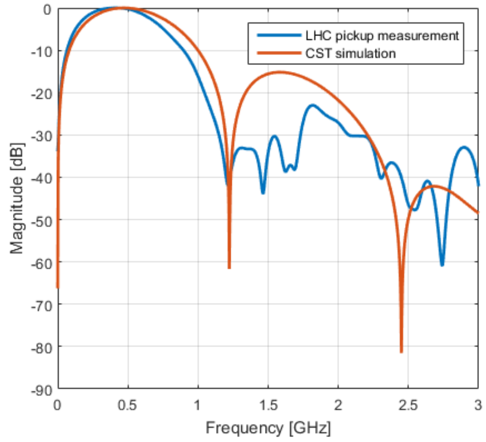


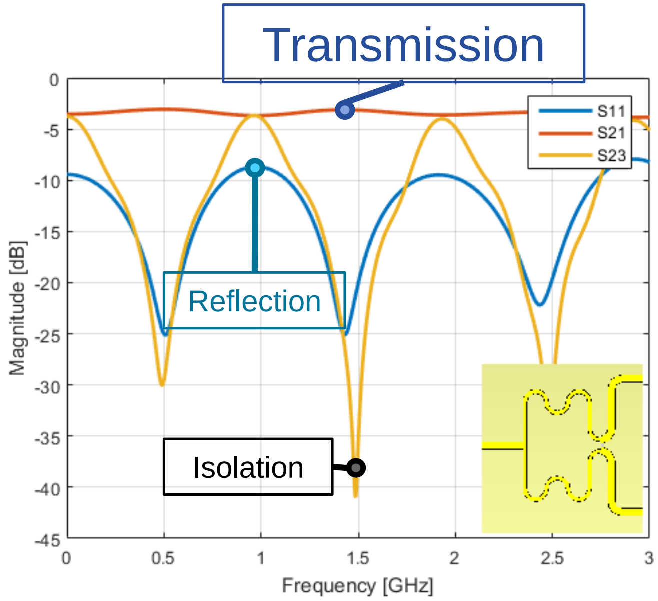
- **Given the beam current and the electrode voltage signal, the transfer impedance can be calculated:**

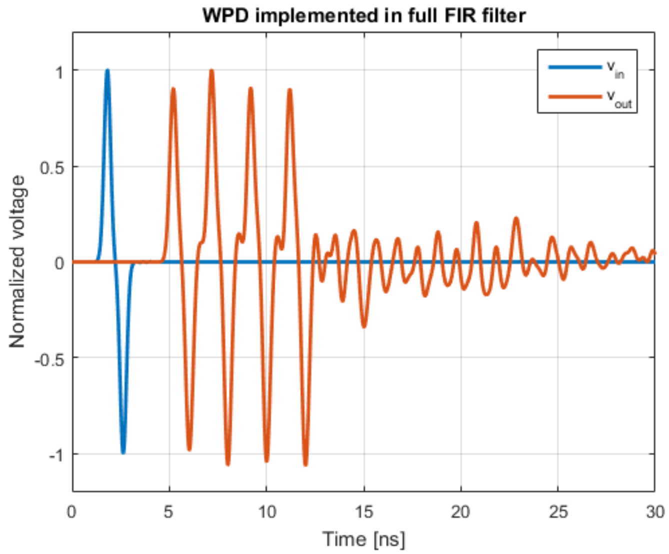


Wilkinson power divider

- **'Typical' choice of high isolation power divider**
  + Cheap and simple to manufacture
  - Poor bandwidth

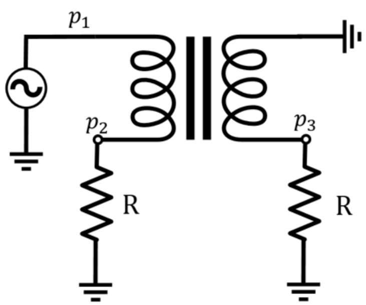


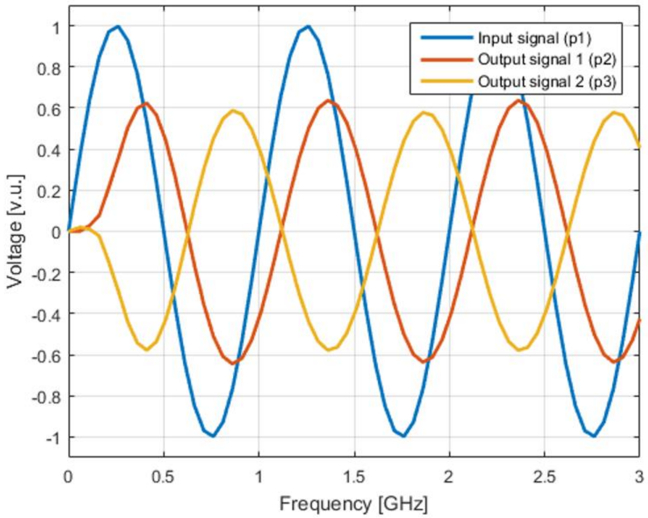




High isolation power combiner: How does the isolation work?

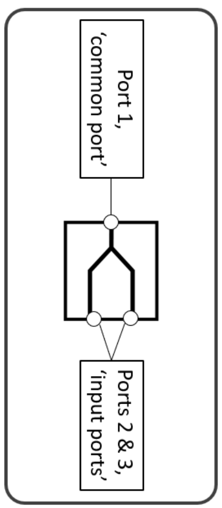
- **A Balun is a 1:1 transformer**
  - **Signal amplitudes on primary and secondary are equal**
- **Primary and secondary signals are 180^0 out of phase**
  - **Bal-Un: Balanced-Unbalanced transformer**

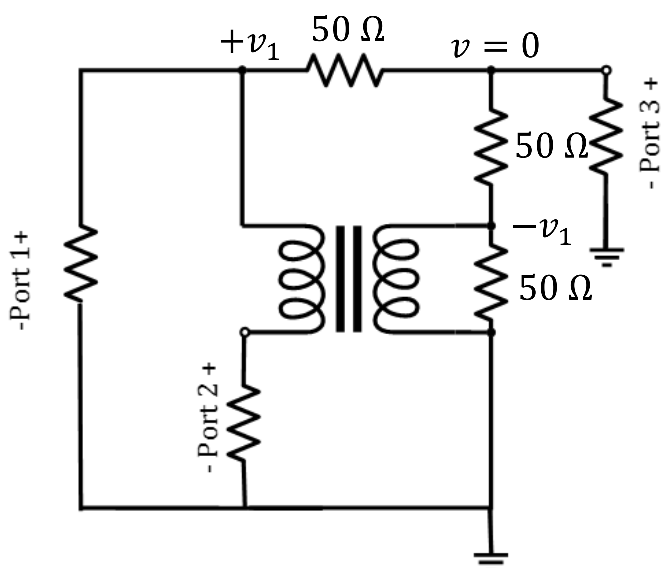


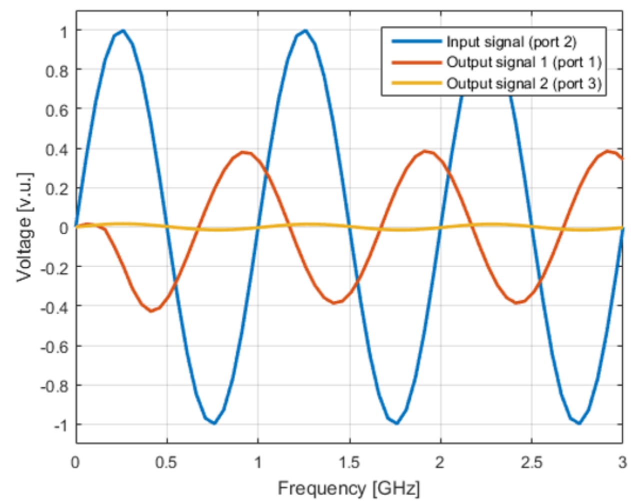


High isolation power combiner: How does the isolation work?

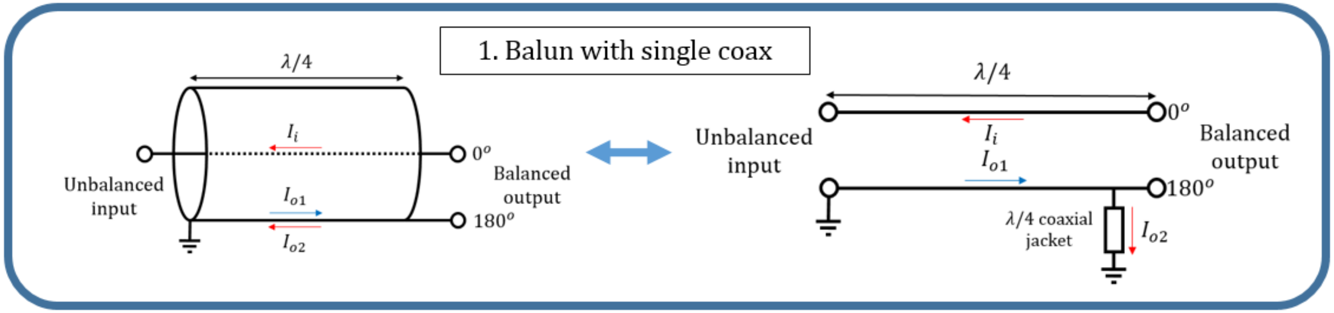
- **Example: Assume the input signal at port 2**
  - **All resistors are 50 Ohm**
- **The 180^0 phase shift of the balun forces the node at port 3 to receive zero voltage**
  - **port 2-3 isolation**

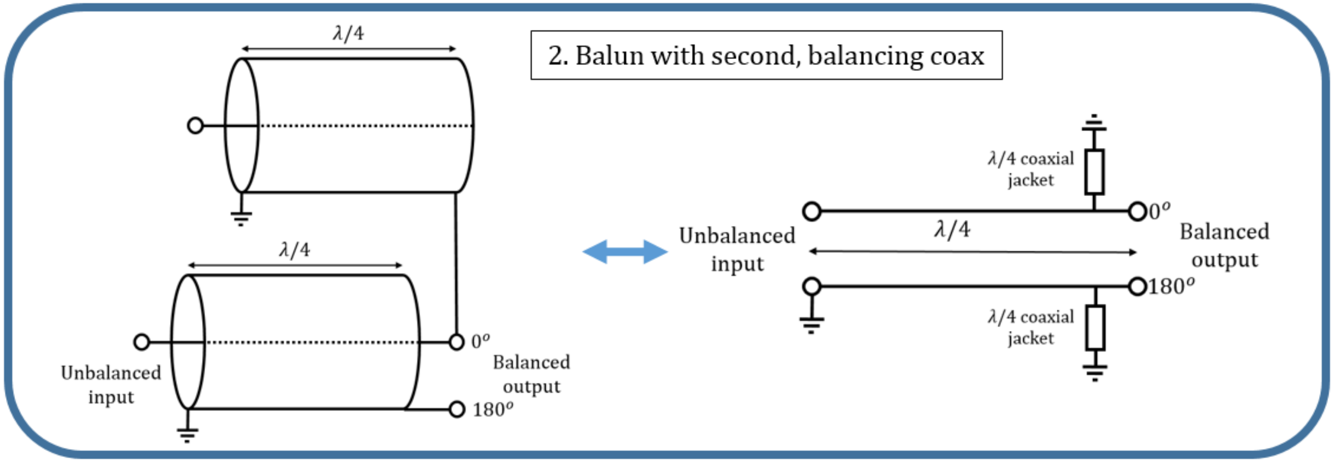


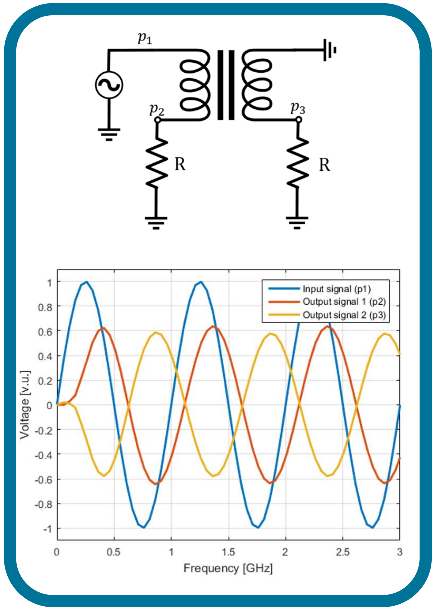




Amplitude balanced power combiner: Coaxial balun design

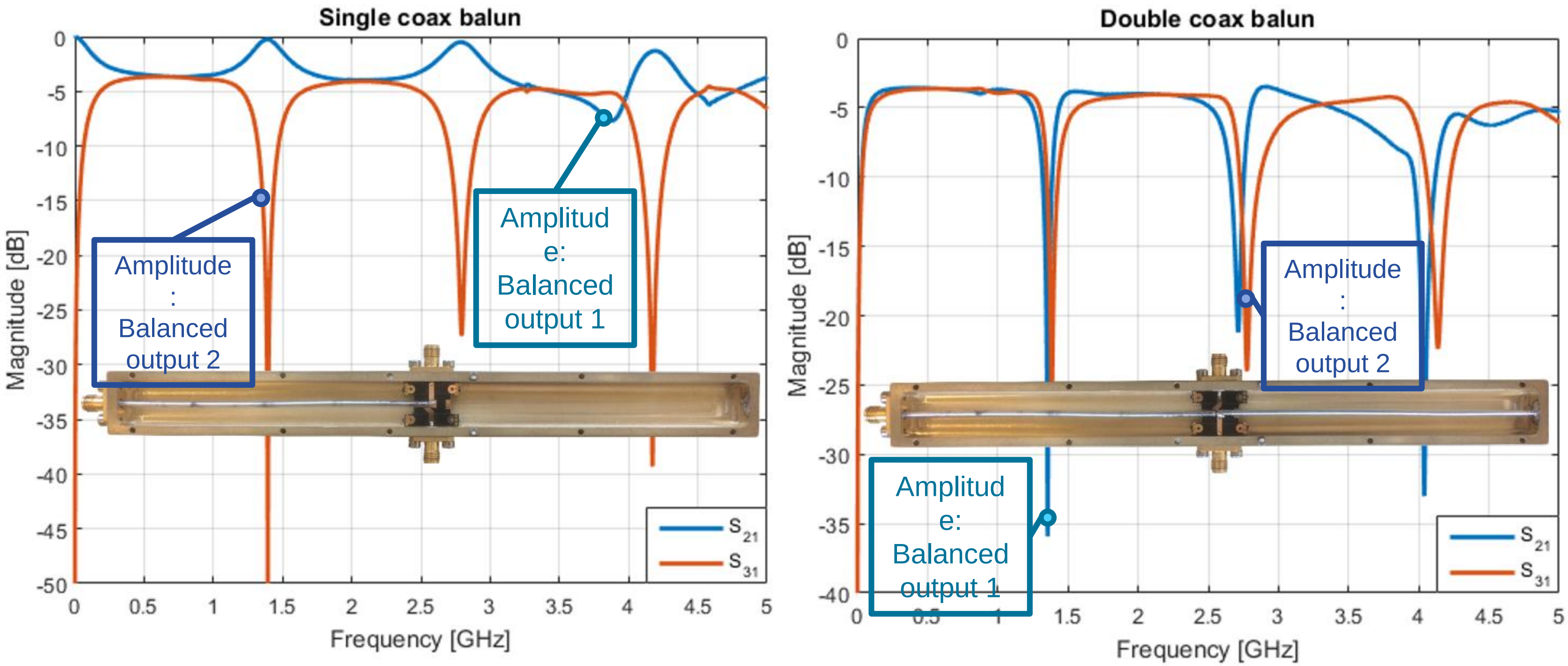






Amplitude balanced power combiner: Balun design

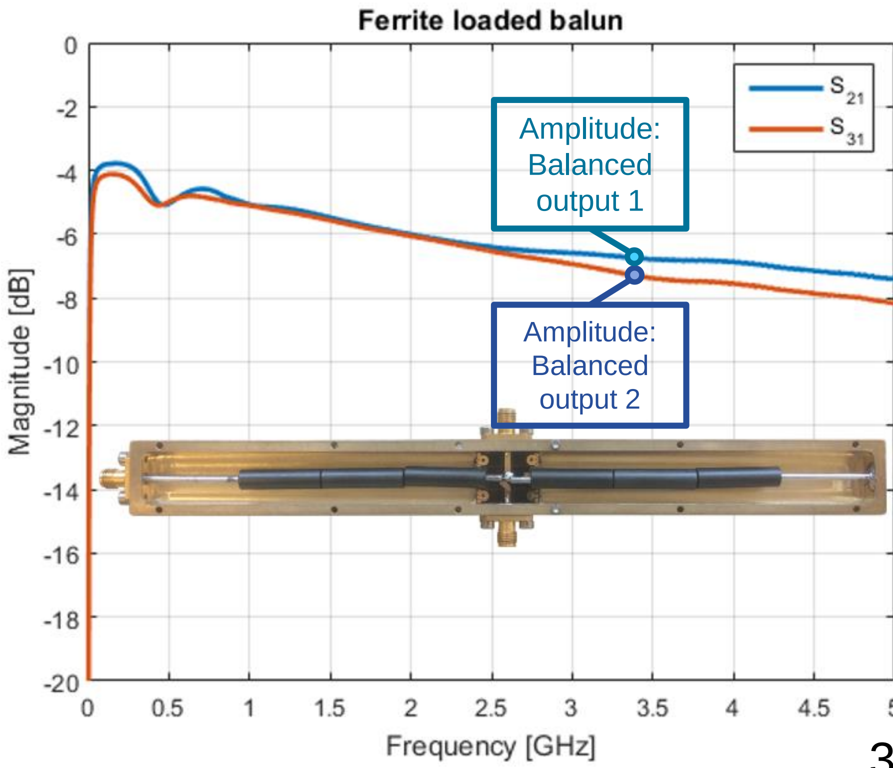
- Second coax balances amplitudes, but balanced outputs are still frequency dependent



32

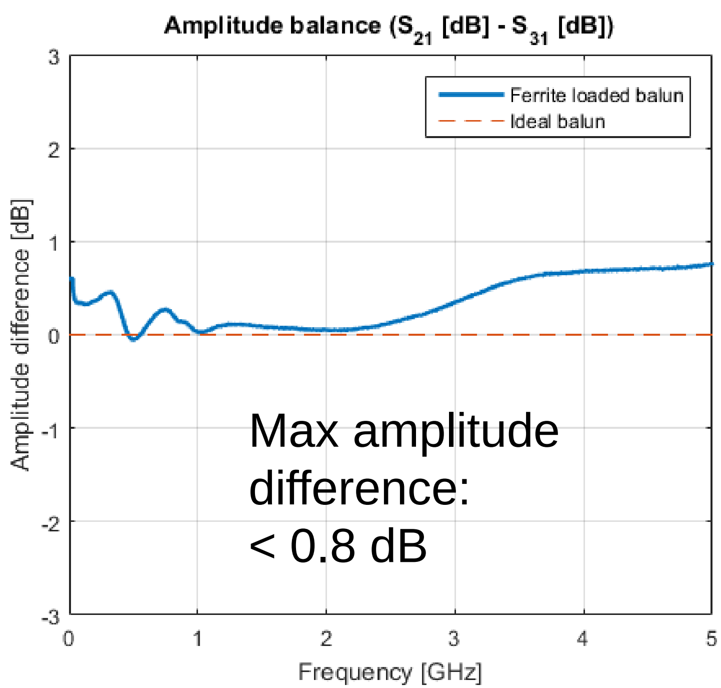
Amplitude balanced power combiner: Balun design

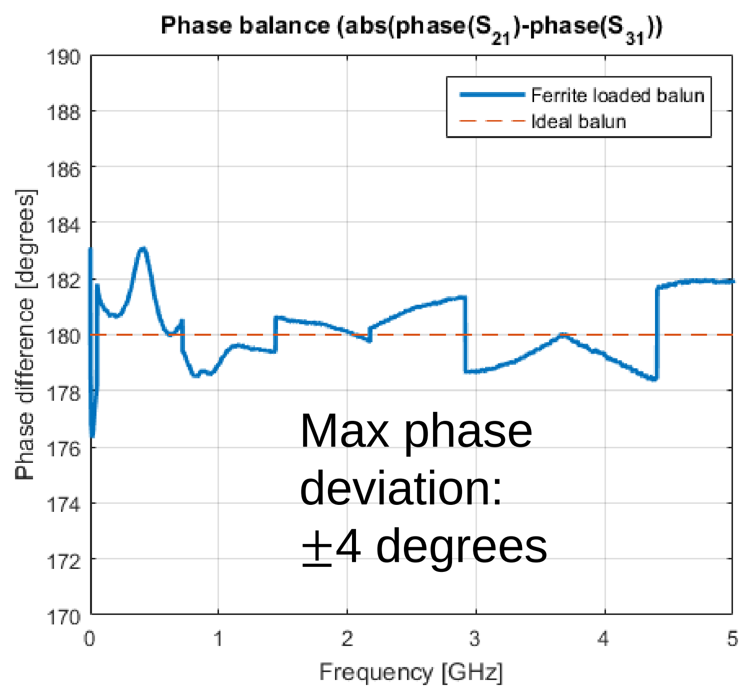
- Ferrite beads nearly remove frequency dependency



33

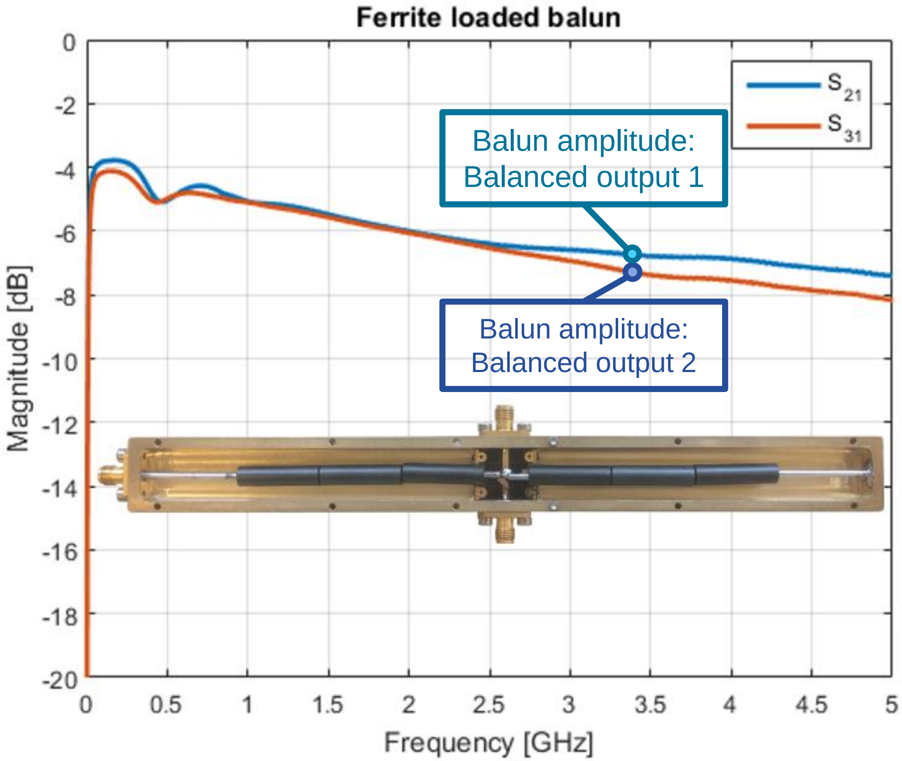
Amplitude balanced power combiner: Balun design





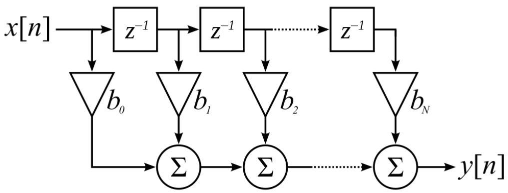
Amplitude balanced power combiner: Balun design

- Coaxial cable based balun
- Cables covered in ferrites to prevent currents from flowing on the outside of coaxial jacket
- Produces a very well performing amplitude balance over a large frequency range



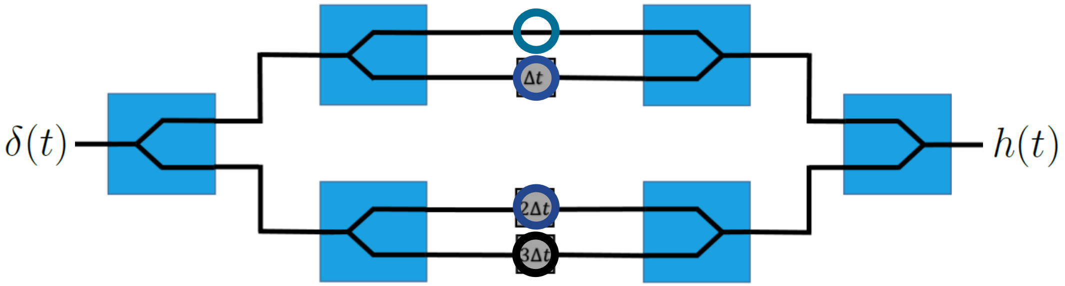
35

Delay line filter: Theory

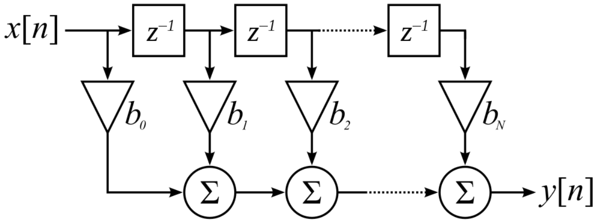


- **An ideal filter (no losses) can be modelled very easily using basic signal theory**

$$h(t) = \frac{1}{4}\left[\delta(t) + \delta(t - T_d) + \delta(t - 2T_d) + \delta(t - 3T_d)\right]$$



Filter theory



- **What is the frequency domain behavior?**

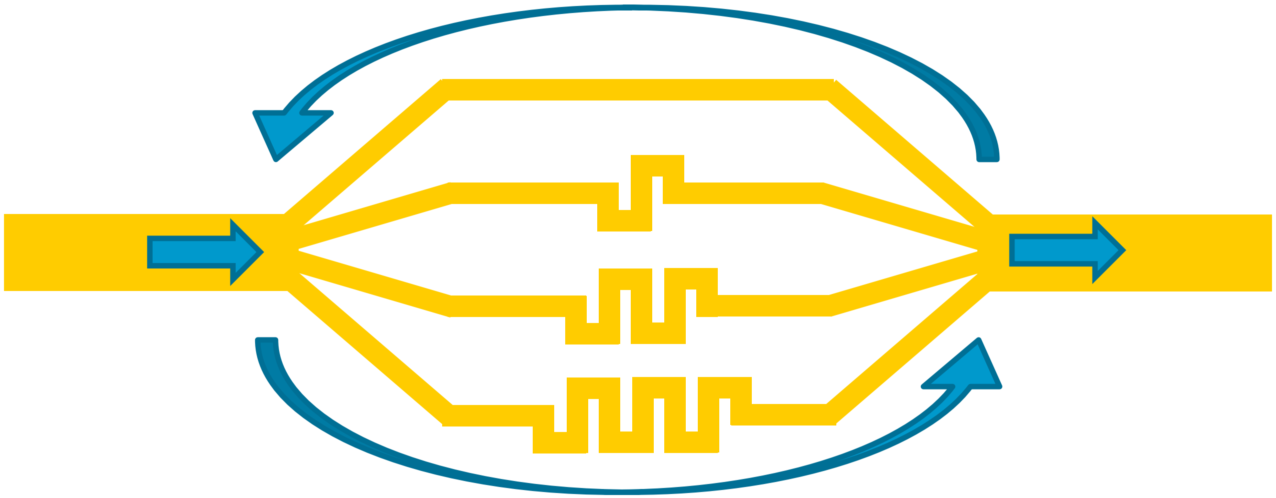
Impulse response: $h(t) = \frac{1}{4}\left[\delta(t) + \delta(t - T_d) + \delta(t - 2T_d) + \delta(t - 3T_d)\right]$

Standard transform pairs:
$$\begin{cases} x(t-T) \xrightarrow{\mathscr{F}} X(j\omega)\mathrm{e}^{-\mathrm{j}\omega T} \\ \delta(t) \xrightarrow{\mathscr{F}} 1 \end{cases}$$

Transfer function: $H(\omega) = \left(\frac{1}{4} + \frac{1}{4}\mathrm{e}^{-\mathrm{j}\omega T_d} + \frac{1}{4}\mathrm{e}^{-\mathrm{j}2\omega T_d} + \frac{1}{4}\mathrm{e}^{-\mathrm{j}3\omega T_d}\right)$

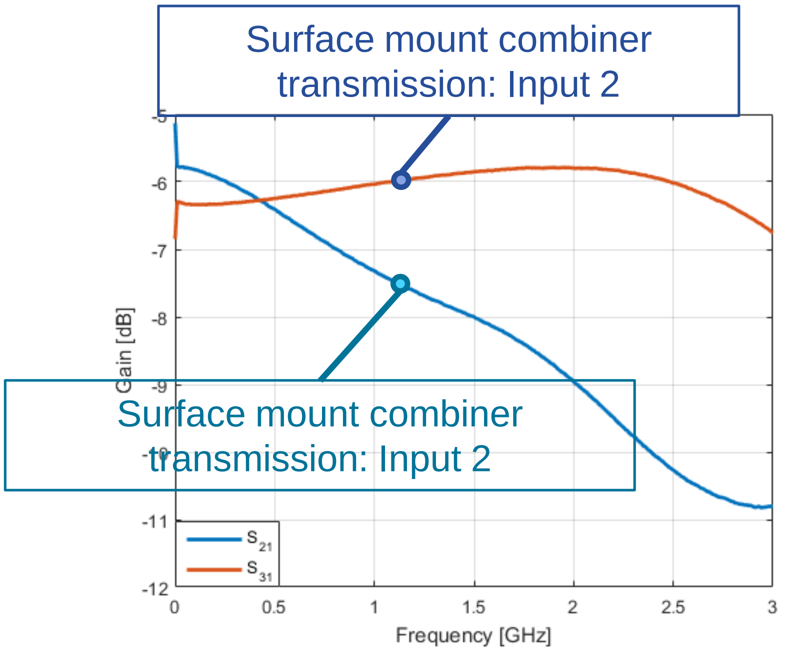
Surface mount power dividers/combiners: Why high isolation?

- Why can we not split and combine the signals directly on the transmission line?
  - No isolation causes filter to ring!



Amplitude balanced power combiner

- **The surface mount combiner is not well balanced for some frequencies**
- **This performance is effectively limited by performance of the balun transformer**
- **The other circuit is in principle the same as the surface mount version**
  - **uses a different type of a balun, based on distributed transmission-line elements**



Power combiners: Dissipation

- **Software developed specifically to estimate the power dissipation in a S-parameter network that is fed with a real stripline pickup signal**