HZB BESSY II Light Source

Review of BPM Drift Compensation Schemes

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Helmholtz-Zentrum Berlin

IBIC 2022, Krakow, 12-15 Sep 2022

Nobody likes drift!

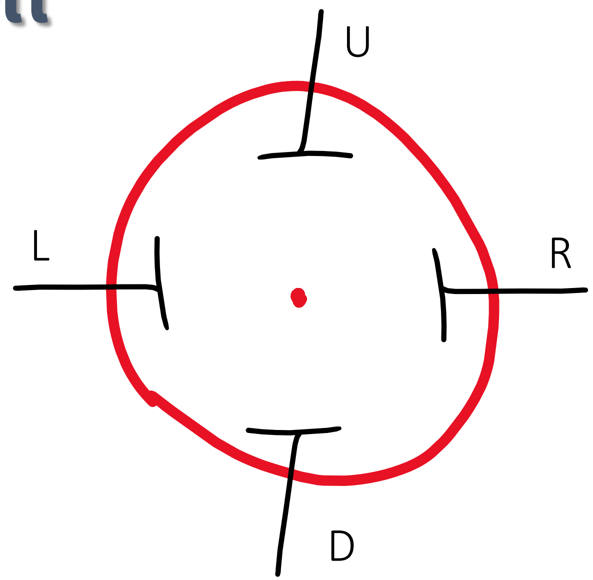
Overview

- Introduction to Beam Position Measurements and drift
- Sources of drift in processing channels
- Methods of drift compensation
- Summary

Acknoledgements

ALS	Greg Portmann
APS-U	Weixing Cheng
DESY/PETRA IV	Gero Kube
Diamond	Michael Abbott, Laurence Stant
Elettra	Gabriele Brajnik, Raffaele De Monte
NSLS-II	Guimei Wang, Danny Padrazo
PSI/SLS	Boris Keil
SIRIUS	Daniel de Oliveira Tavares, Sergio Rodrigo Marques
Soleil	Nicolas Hubert
SPRing-8	Mitsuhiro Masaki

Beam Position Measurement in a Nut Shell



- Pickups are antennas to the beam
- Position is proportional to Δ/Σ

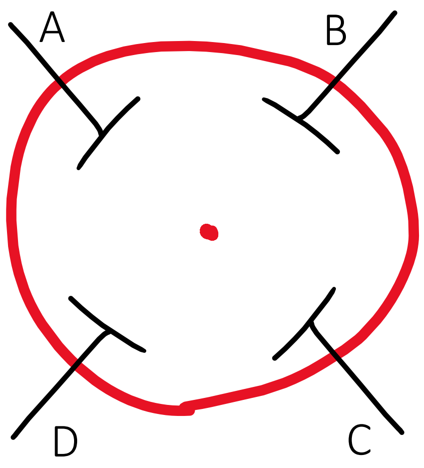
$$Y = K_Y \frac{V_U - V_D}{V_U + V_D} \quad \text{or} \quad Y = K_Y \frac{V_A + V_B - V_C - V_D}{V_A + V_B + V_C + V_D}$$

- Signal challenges:
  - Short repetive pulses <<1ns
  - High intensities >>10V
  - Intensities vary by factor >10,000 or >80dB
- High precision position demanded:

$$K_{X,Y} = 10\text{mm}, \sigma_{X,Y} < 100\text{nm}$$

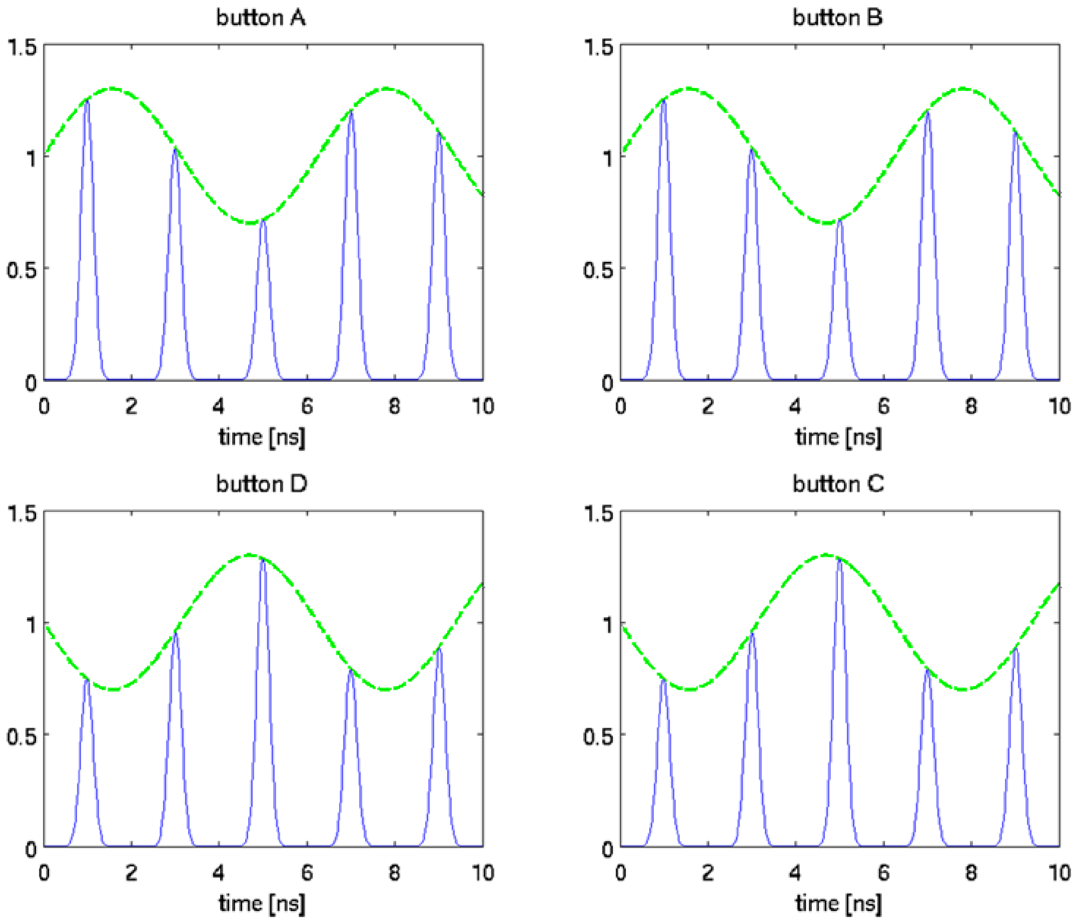
$$\rightarrow \frac{\sigma_V}{V} = \frac{2\sigma_{X,Y}}{K_{X,Y}} < 20\text{ppm}$$

or 0.00017 dB!



Communication Engineer‘s View of BPM Signals

- Signals are amplitude modulated by position and charge
- Carrier is a pulse comb from passing bunches
- Beam **movement is differential AM** an opposite buttons
- Pulse **amplitude is common AM**
  - Removed by Δ/Σ
- BPMs observe the **minute differences on the large pulses**

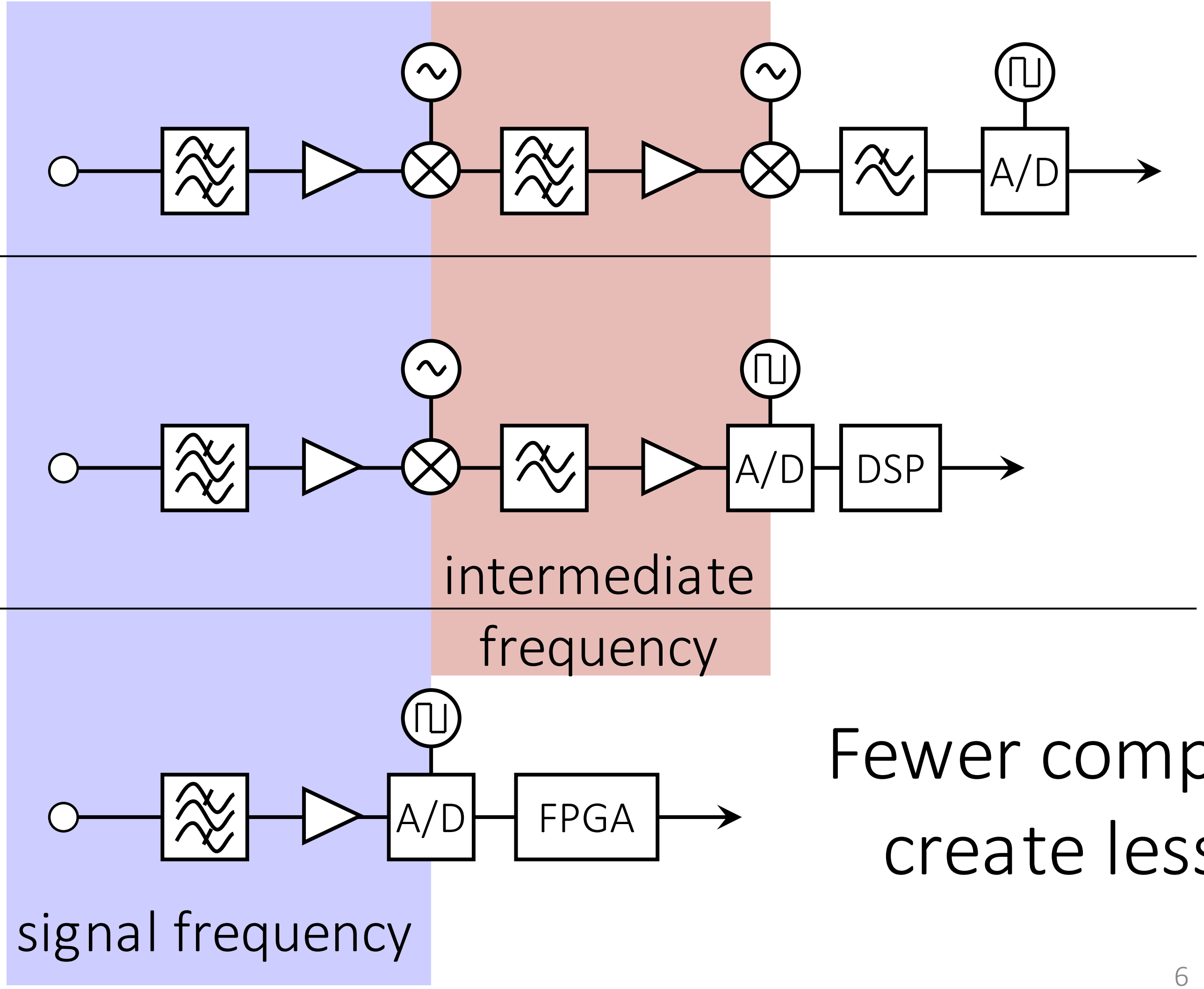


BPM processing channel evolution

analogue BPM
heterodyne receiver

1st gen digital
A/D in baseband
DSP reconfigurable

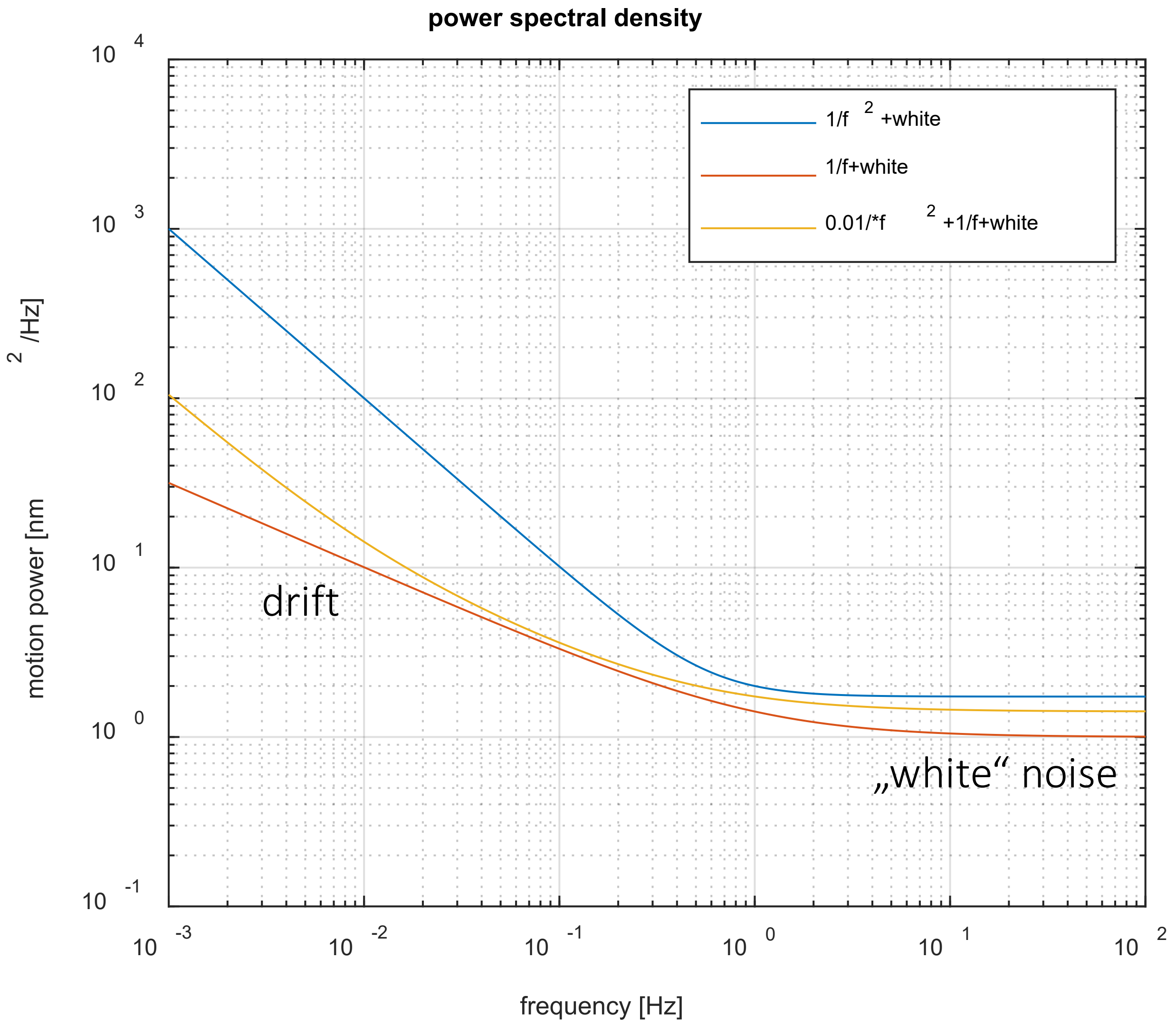
2nd gen digital
undersampling A/D
flexibility and
complexity in FPGA



Fewer components create less drift

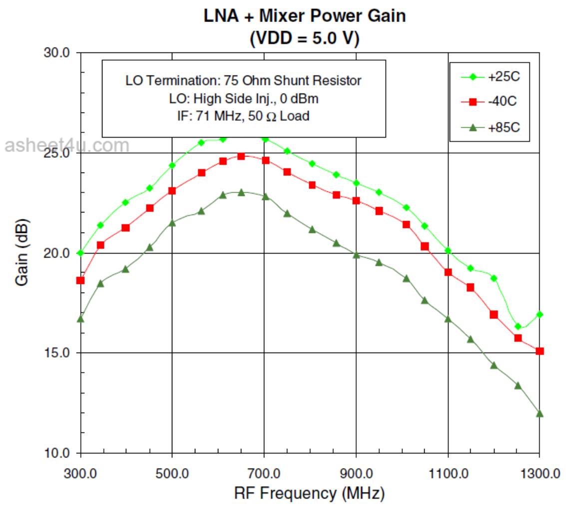
What is Drift?

- High frequencies, white **noise**, constant spectral noise density
- Low frequencies, spectral noise **density is funtion of frequency**
- Drift is often related to outside influences: temperature, humidity, pressure, supply voltage, EMI, …
- Power spectral density plots are **good way to diagnose drift**
- Data must be properly **decimated**
- Dropping samples aliases spectra



Drift with Temperature in Electronic Components

- Analogue components change with temperature
- Differences in behaviour or temperature lead to channel deviations



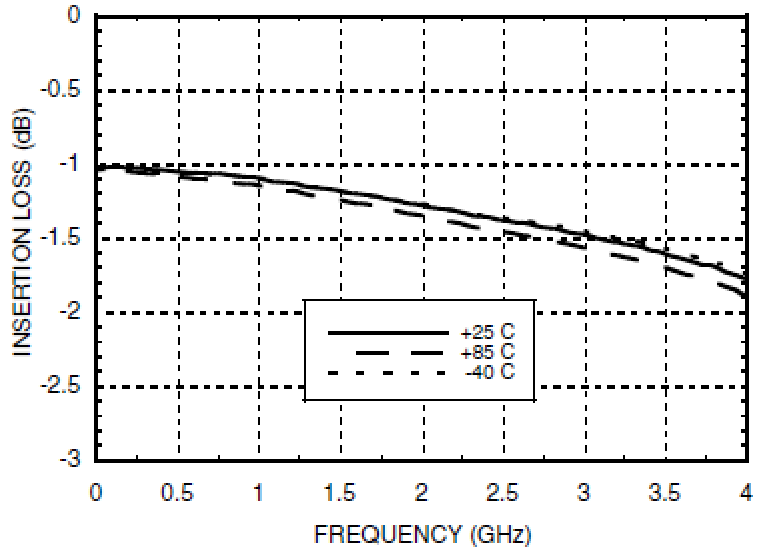
LTC2107

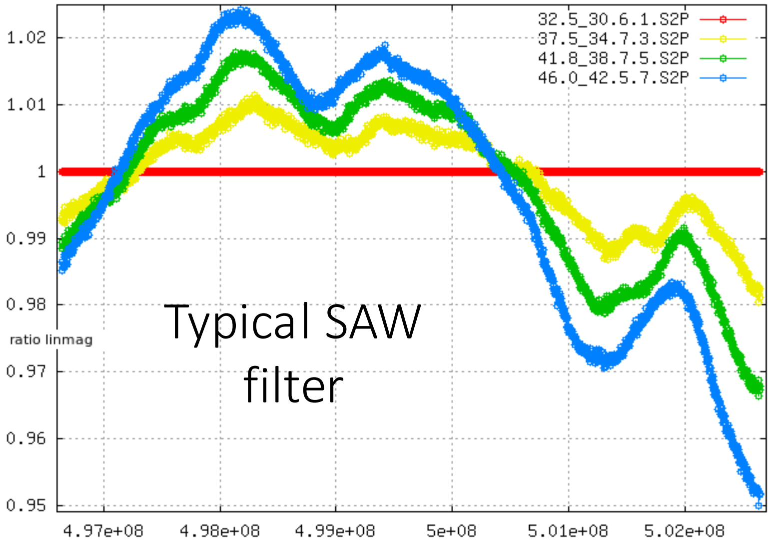
CONVERTER CHARACTERISTICS The ● denotes the specifications which apply over the full operating temperature range, otherwise specifications are at $T_A = 25°C$. (Note 5)

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
Resolution (No Missing Codes)		●	16			Bits
Integral Linearity Error	Differential Analog Input (Note 6)	●	–4.5	±1.6	4.5	LSB
Differential Linearity Error	Differential Analog Input		–1	±0.4	1.0	LSB
Offset Error	(Note 7)	●	–5	–0.5	5	mV
Gain Error	Internal Reference, PGA = 0 External Reference, PGA = 0	 ●	 –0.85	±1.5 –0.2	 0.85	%FS %FS
Offset Drift				–20		µV/°C
Full-Scale Drift	Internal Reference, PGA = 0 External Reference, PGA = 0			110 70		ppm/°C ppm/°C

Programmable precision attn

Insertion Loss

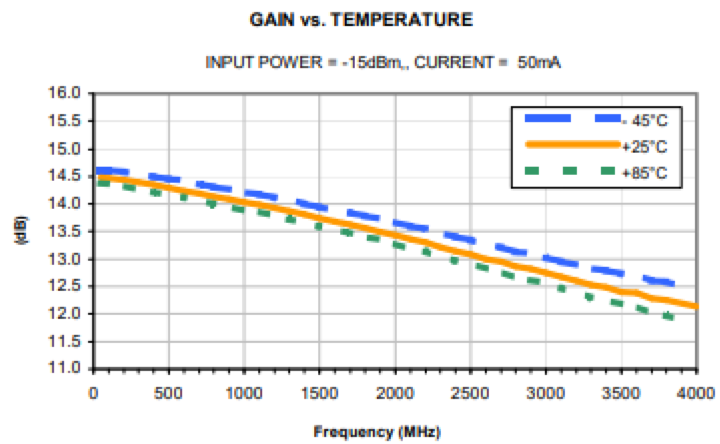




Typical SAW filter

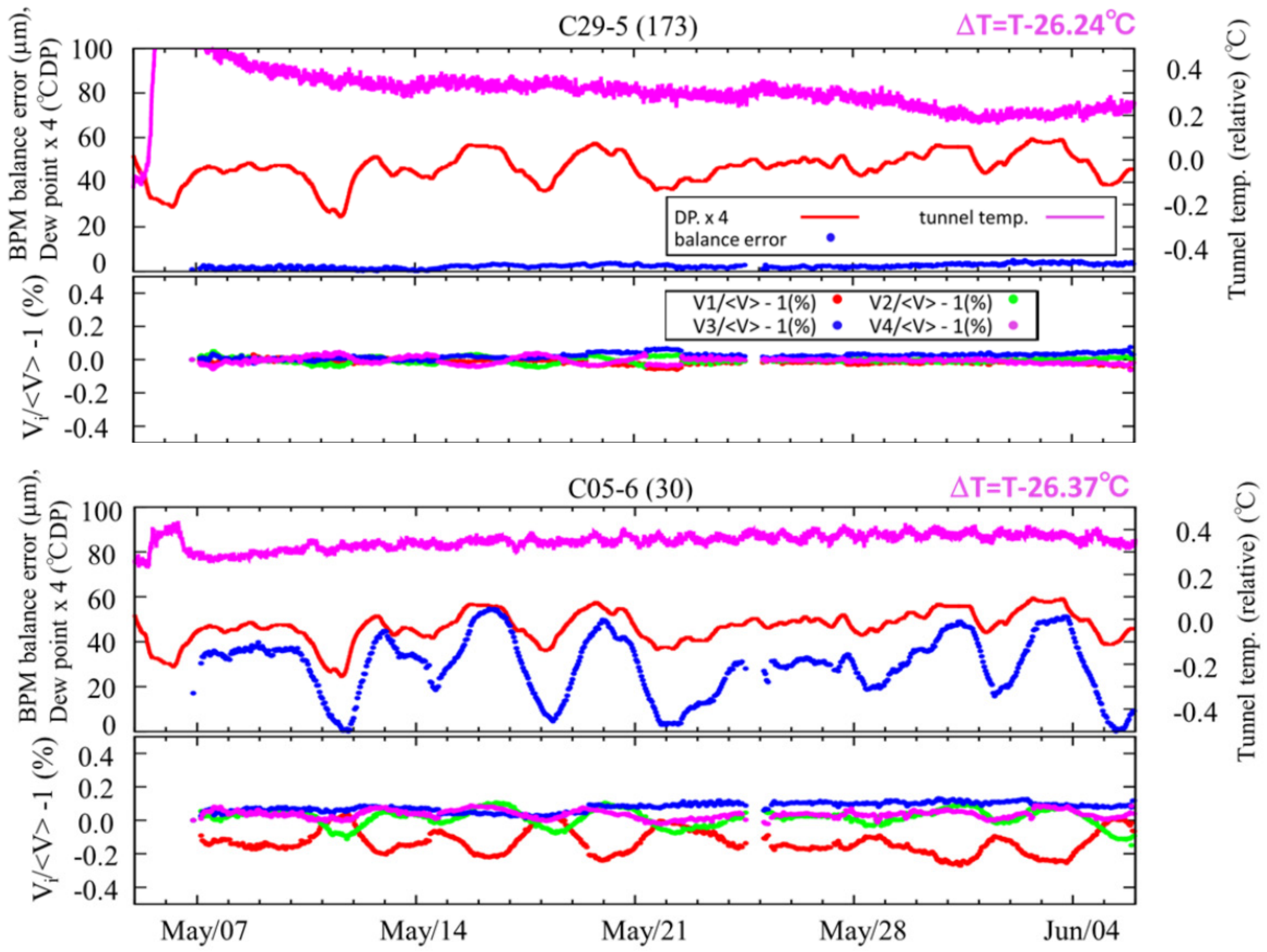
MMIC Amplifier

Typical Performance Curves



HZB BESSY II Light Source

SPring-8: Deviations between 3-Button calculated Positions



Stable BPM :
All four „positions“ don‘t deviate

BPM with daily changes:
Some of four „positions“ deviate
in correlation with due point (RH)

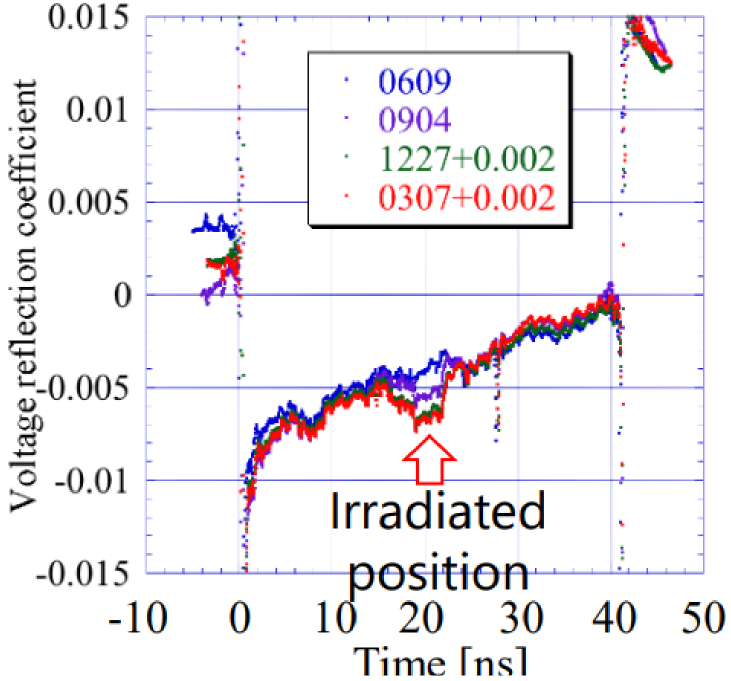
IBIC2015-TUPB020

Humidity Impact in Cables

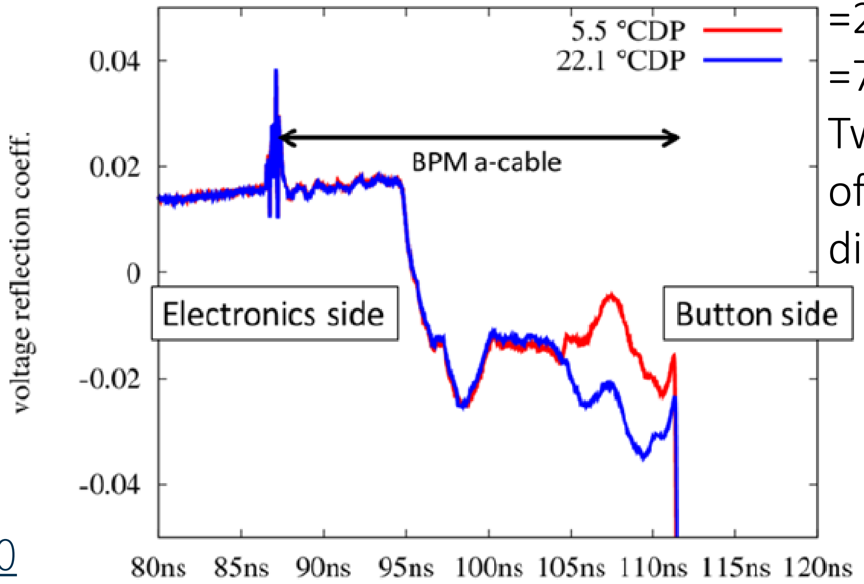
- Typical 20-30m cables have 5-10dB attenuation at signal frequency
- Transit time changes standing waves
- Variation gave been observed on (radiation damaged) cables
- Connected to relative humidity
- Observation possible by:
  - TDR or time domain transposed VNA
  - Balance error between 3-button positions
- **Cables need to be included in the channel stabilisation as well!**

S04272 flexible cable
(current SPring-8 BPM)

Similar to LMR-240
PE-foam dielectric



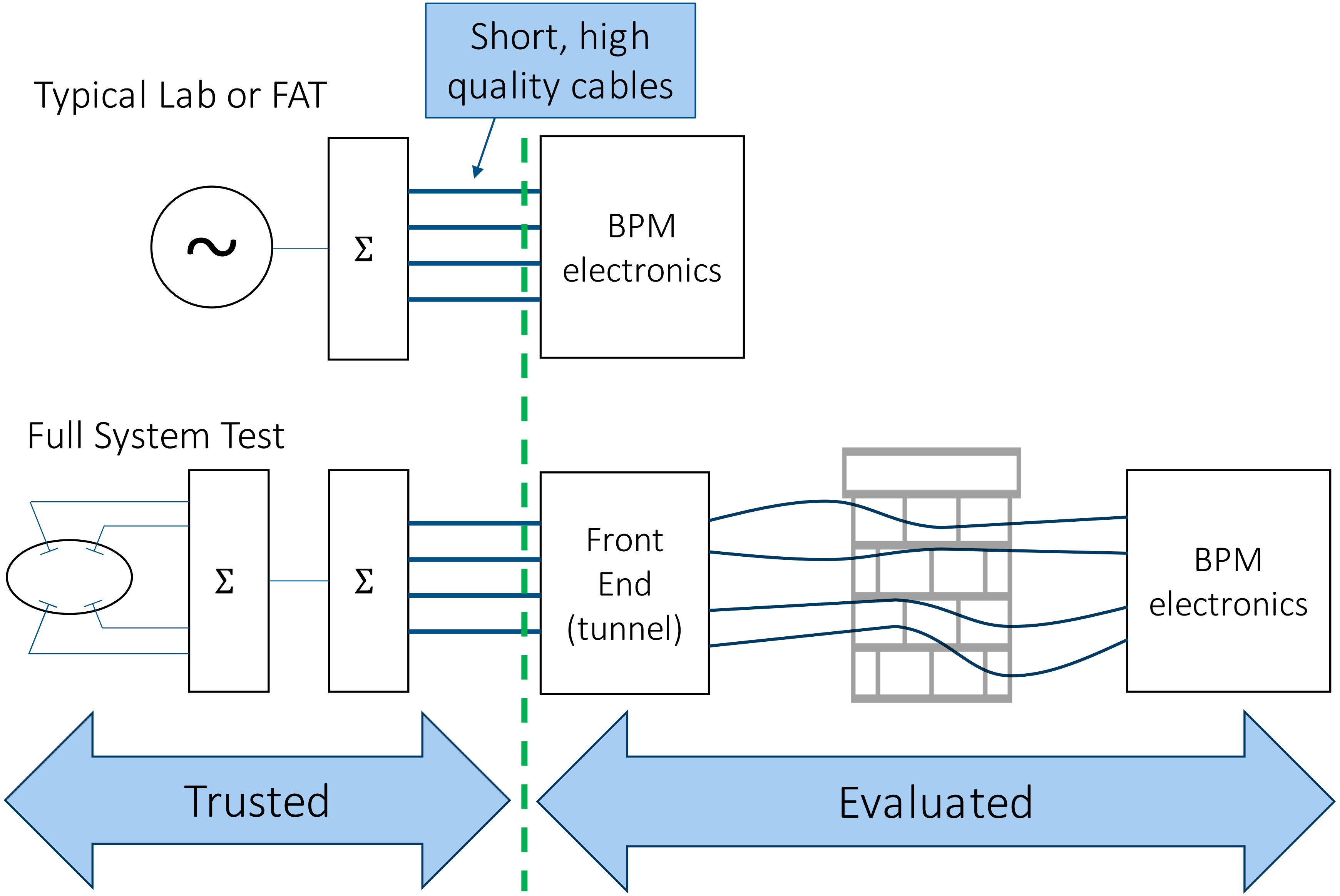
Measurement of same cable over several months



=24% RH
=70% RH
Two measurments of same cable at different humidity

IBIC2016-TUPG06, IBIC2015-TUPB020

Evolution of Drift Evaluation Methodology



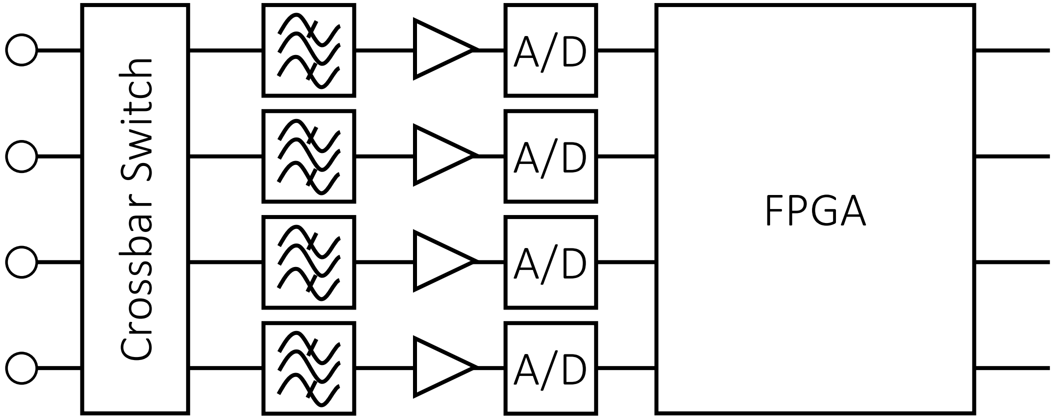
Pros	Cons
• Easier for R&D • Controlled soure • Controlled environment	• CW or AM only, no pulses • Cables not evaluated

Pros	Cons
• Requires existing synchrotron • Uses typical signals	• Environment can only be monitored

Two Ideas of Drift Compensation

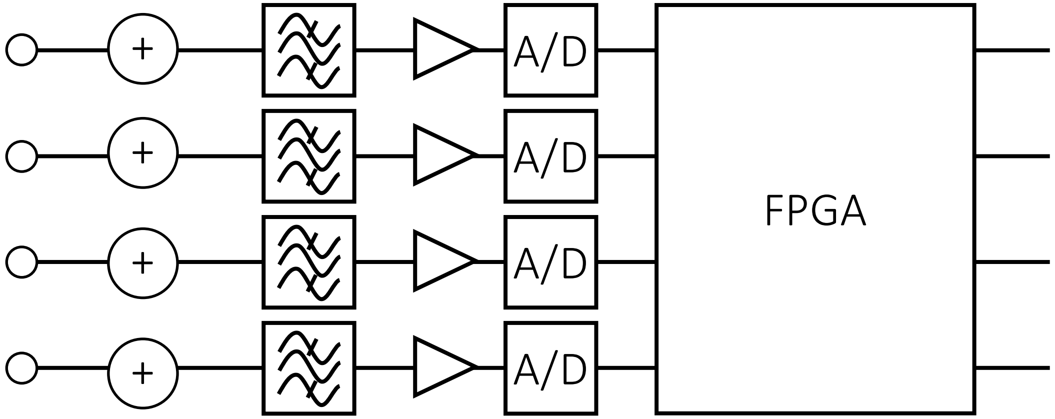
Switching:

- Transport inputs through different processing chains sequentially
- Un-swap and take average in FPGA
- Will generate disturbances through switching



Pilot Tone:

- Add additional signal at slightly different frequency
- Remove gains determined from PT from signals in FPGA
- Added signal needs to be removed from further processing



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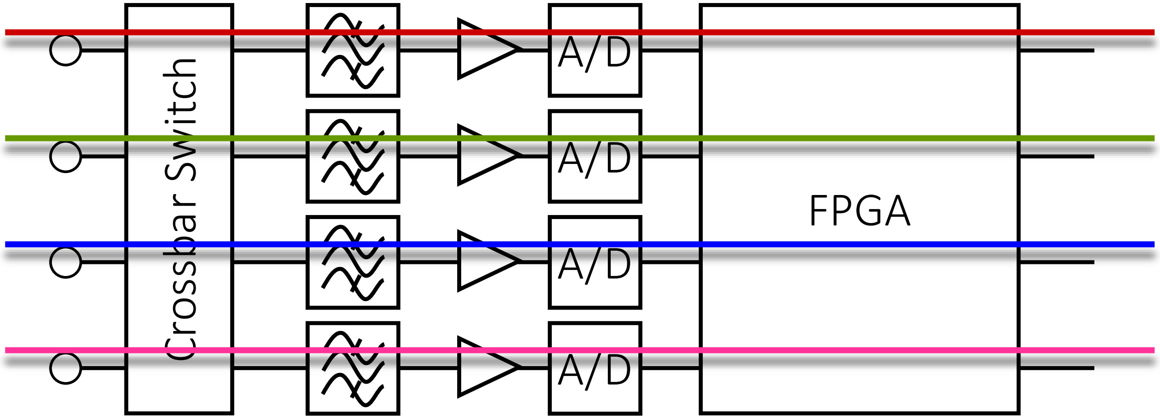

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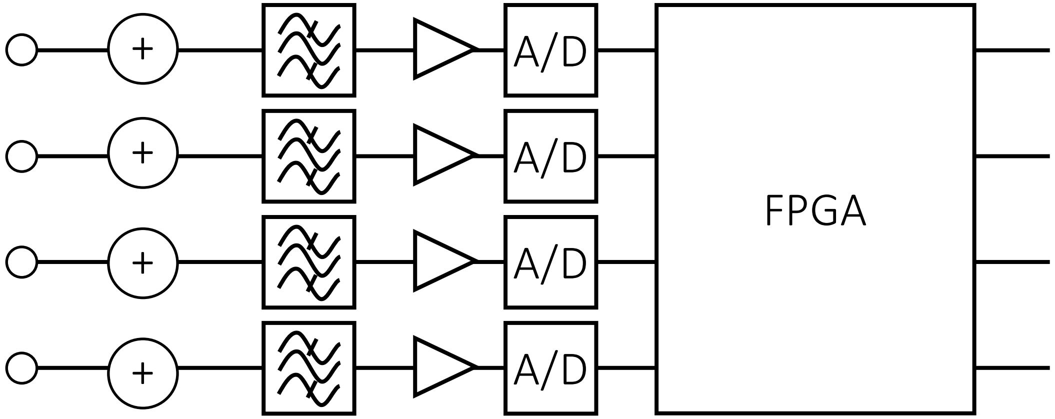

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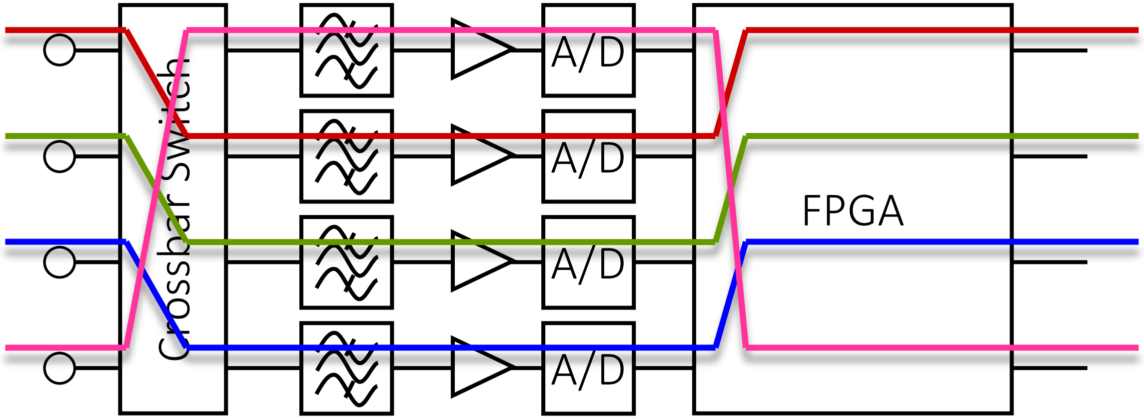

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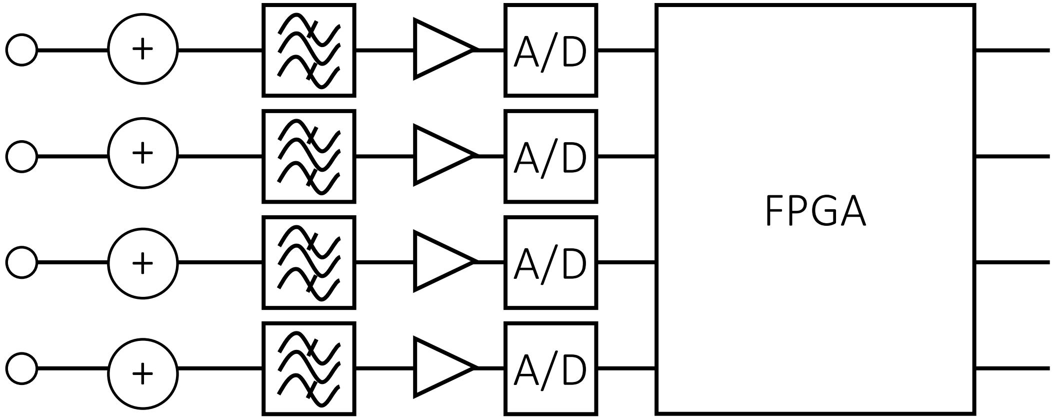

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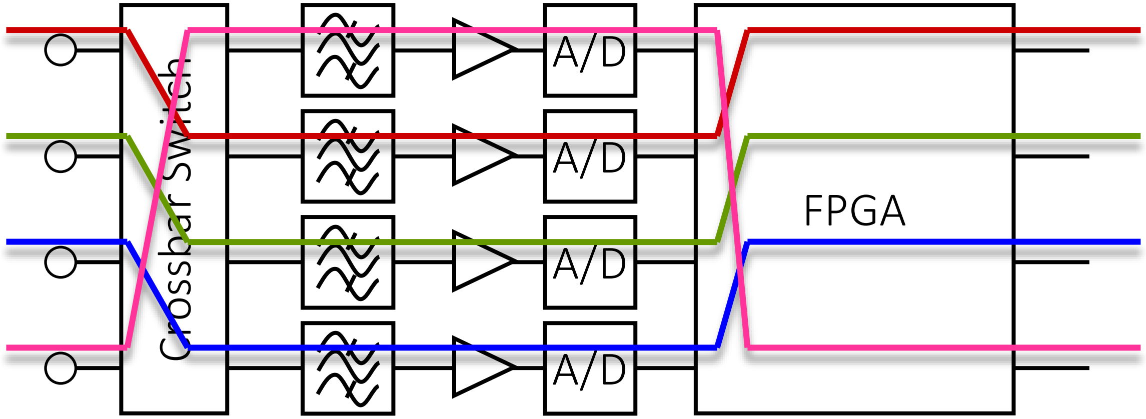

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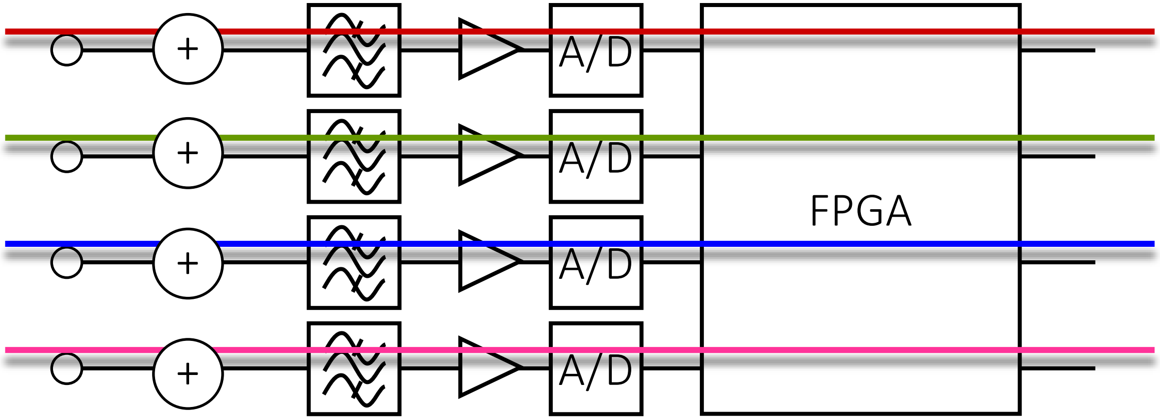

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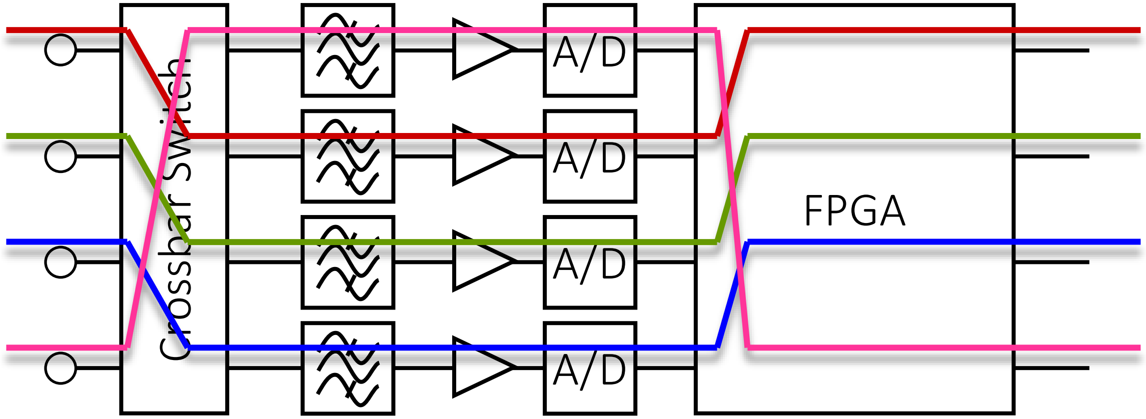
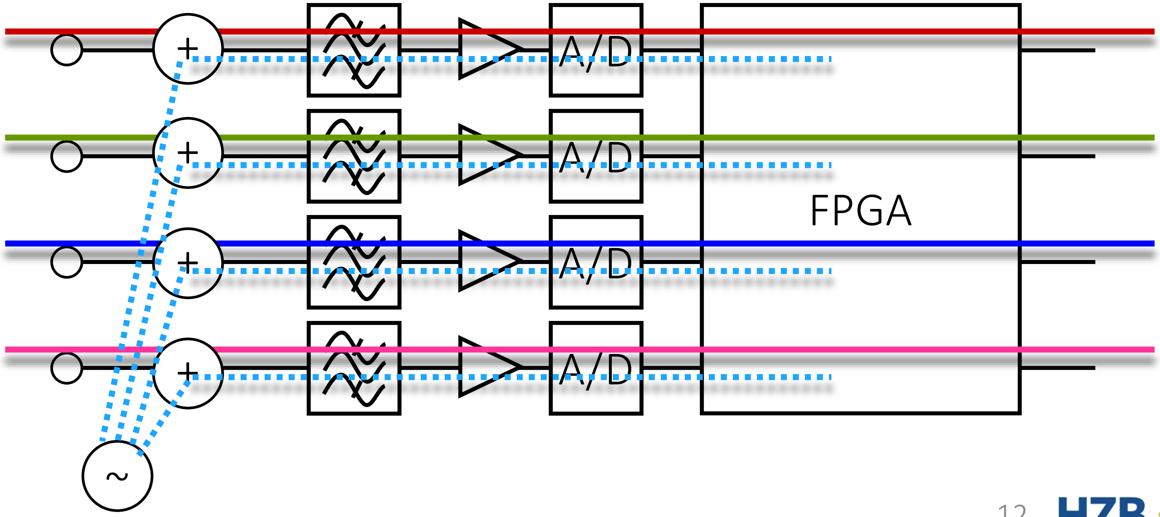
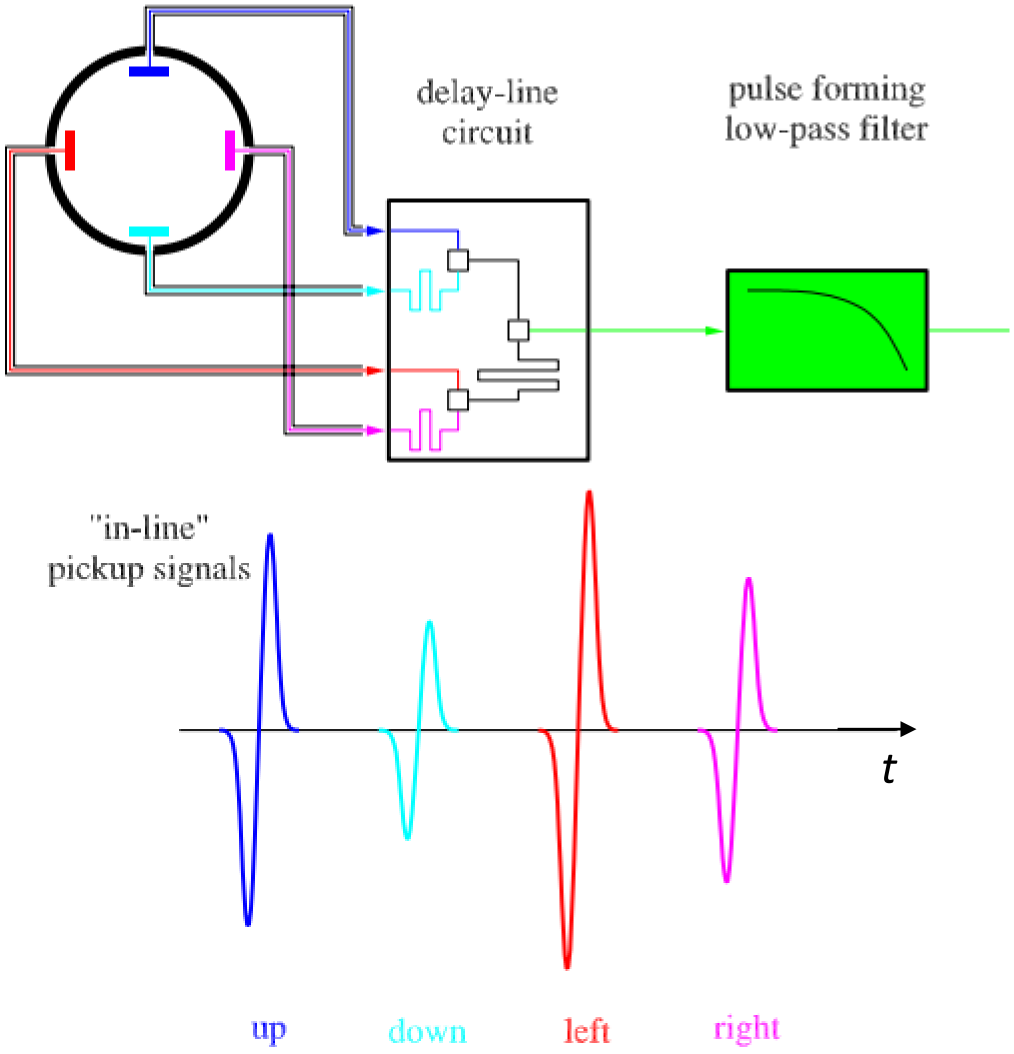




Time multiplexed processing

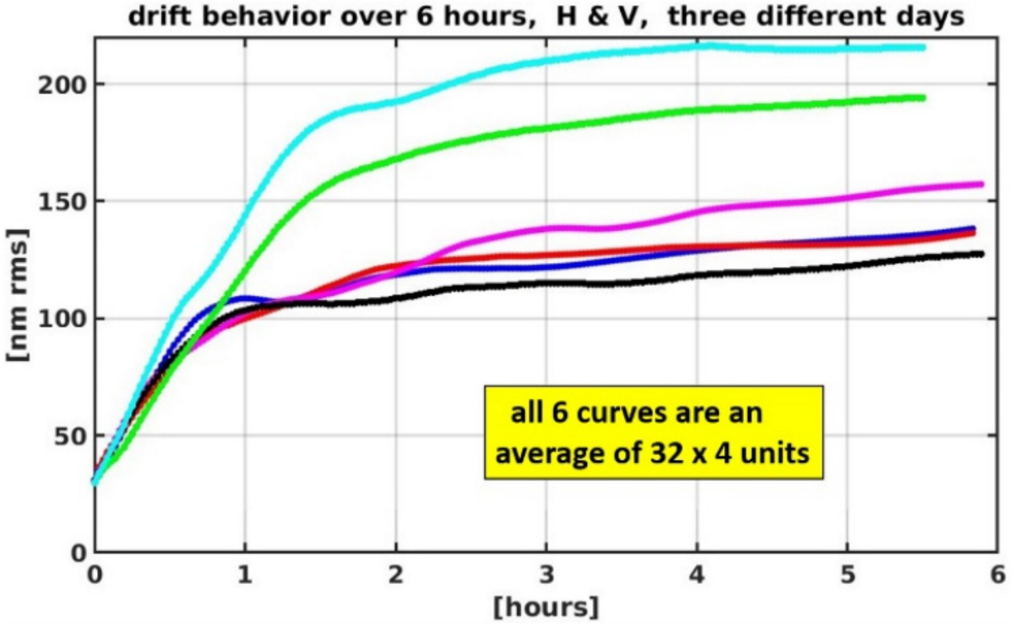
- Relies on signal combiners with good amplitude balance, low reflections
- **Bunch spacing >> single pulse duration**
- Single sampler to resolve pulses
  - Challenging for light sources (2ns bunch spacing)
- Works well on linear machines or with large bunch spacing
  - Used at DESY HERA-e
  - In use at DESY FLASH

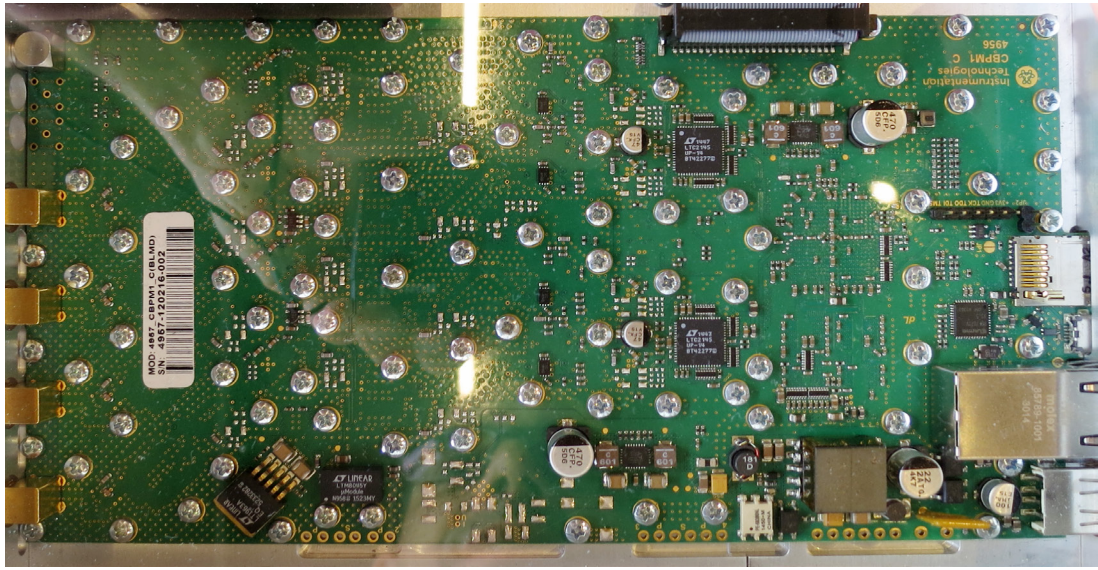


M. Wendt ARIES JOINT WS, ALBA 2018, IBIC2014-TUPF08, IPAC2018-WEPAF048

ESRF-EBS: 4 Channel Receiver

- New BPM co-developed with industry
- 1st gen for booster, 2nd gen to complement ERSF-EBS
- Tight connection of **whole PCB to large heatsink**
- Performance tested on large set (32 installations of 4 BPMs)
- Fed by splitters from individual branched button signals
- Assessed by looking at **deviations in sets of four**, then taking average
- **200nm pk-pk in 6h**, ($K_{X,Y} = 10\text{mm}$)
- 2000nm/°C observed on longer records

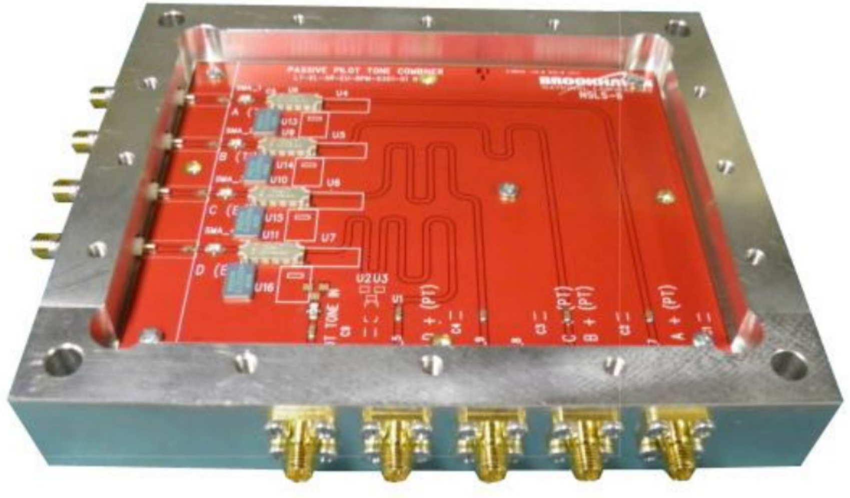


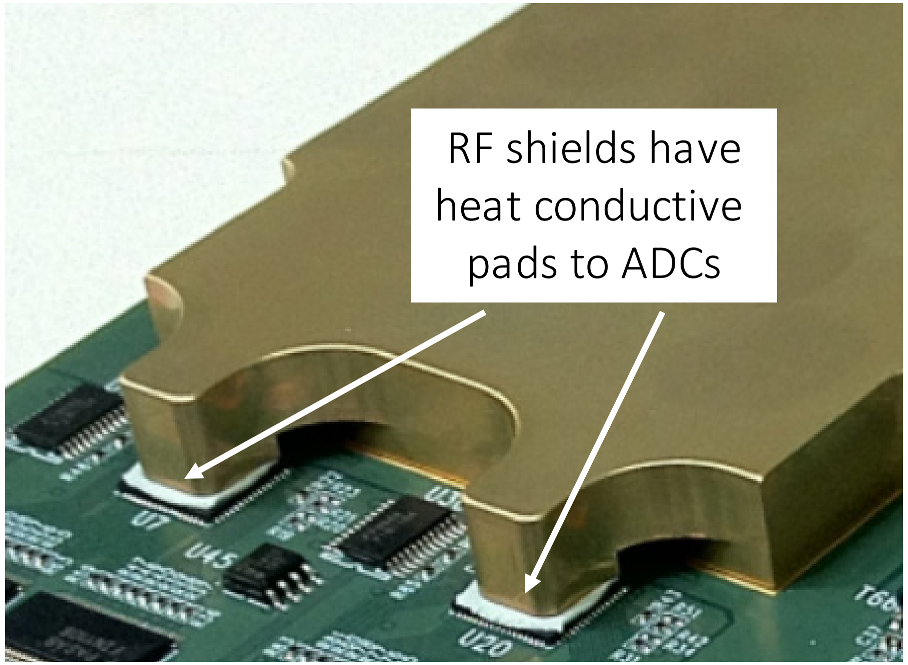


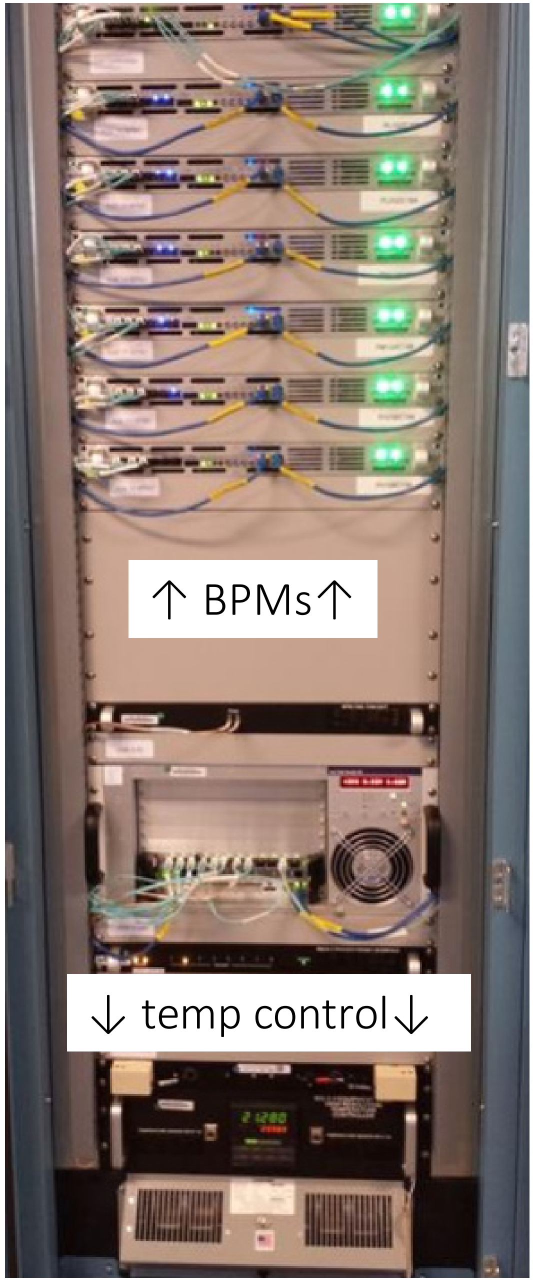
IBIC2018-TUPB02

NSLS-II: Original 4 Channel Receiver

- Rack **actively stabilised** to within **0.1°C RMS**, 1°C pk-pk
- Critical components coupled with pads to heat sink
- **Pilot tone for system commisioning**, no online correction
- 200nm pk-pk in 8h achieved ($K_{X,Y} = 3.4\text{–}14.3\text{mm}$)



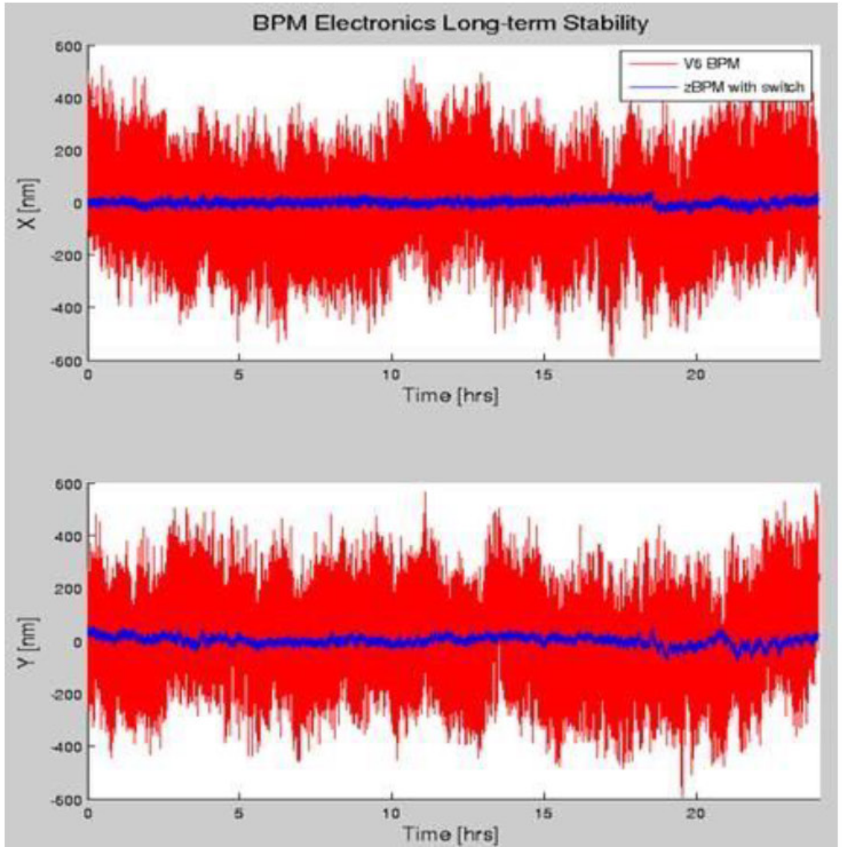


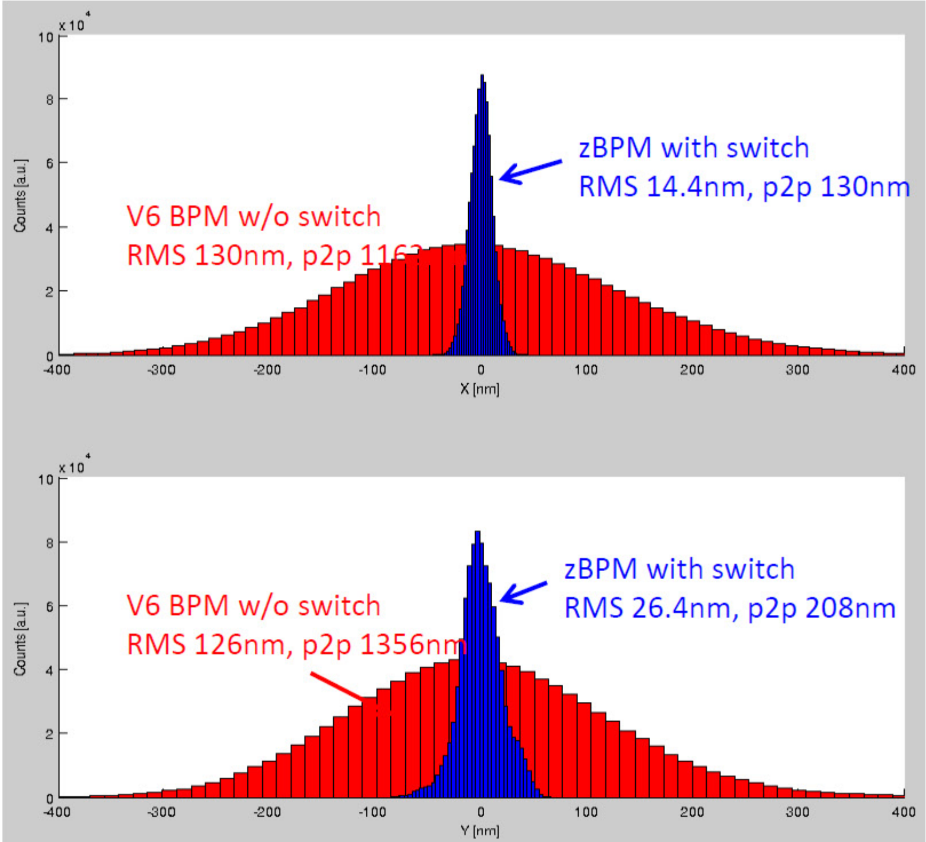


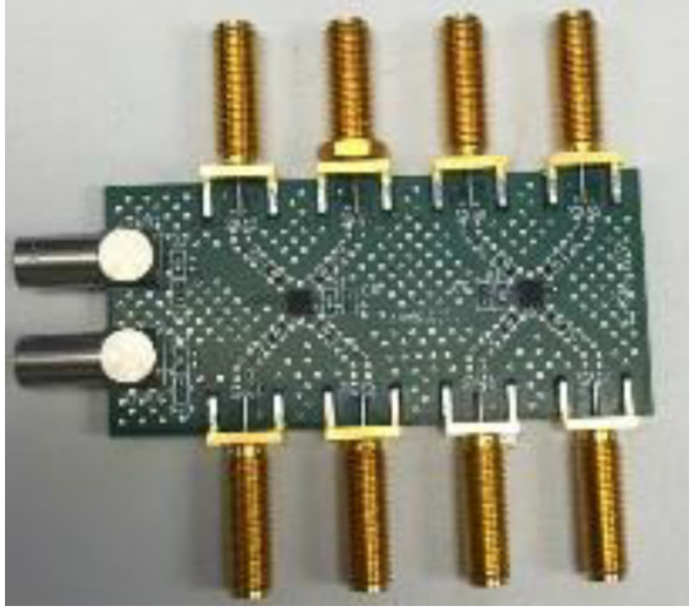
D. Padrazo ARIES JOINT WS, ALBA 2018, BIW12-MOPG027, IBIC2014-WECYB2

NSLS-II: Experiments with switching

- Tests with 2 external switches accross diagonals
- excellent results in 24h, full integration required



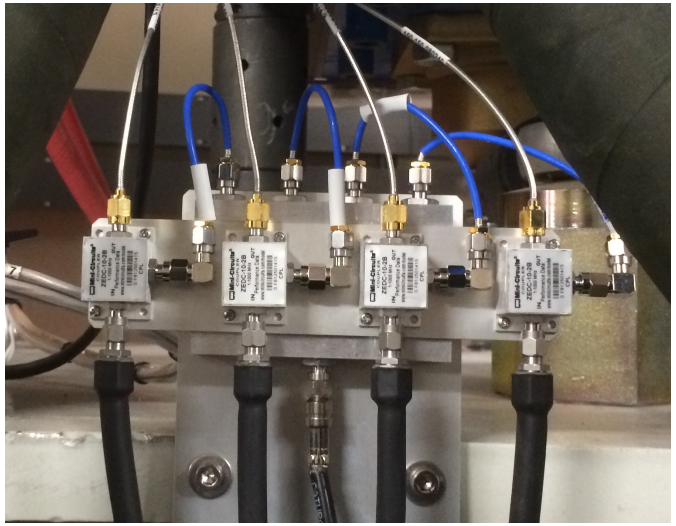




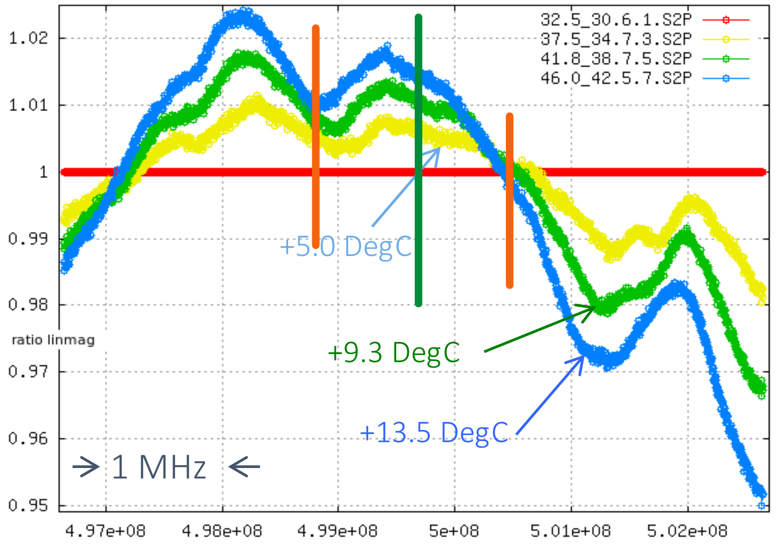
D. Padrazo ARIES JOINT WS, ALBA 2018, BIW12-MOPG027, IBIC2014-WECYB2

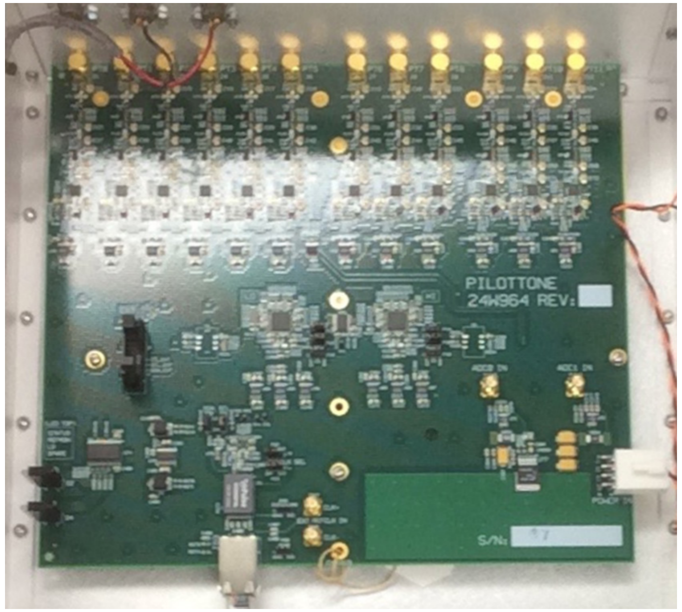
BPM Upgrade at ALS

- BPMs upgraded in 2018/2019
- Variant of NSLS-II BPM with changed analogue FE
    - **Ceramic filter** replaces SAW filter
    - **PCB thermally connected** to case
    - Many smaller changes
- Pilot tone injection built from **connectorised** power divider and directional couplers in the tunnel
- Pilot tone generated outside tunnel, **phase locked** to RF frequency
- **Two pilot tones** above and below signal to interpolate channel gain
- **Three DDCs** per channel!

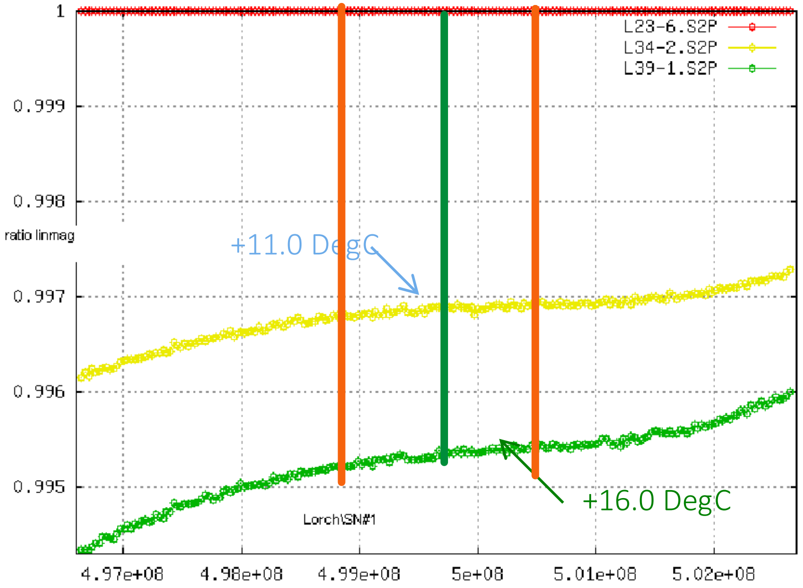


NSLS-II BPM Channel with SAW Filters



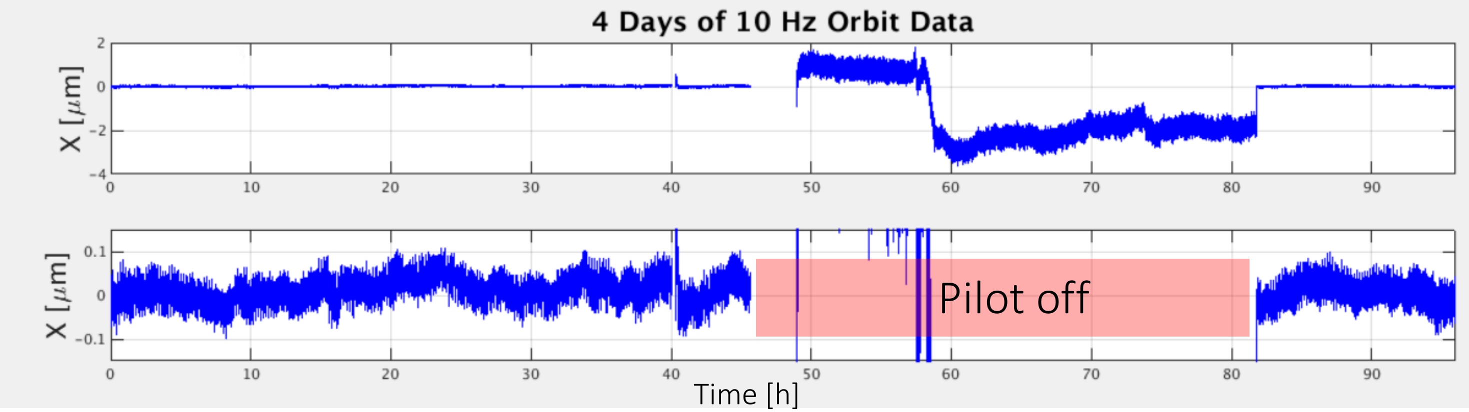


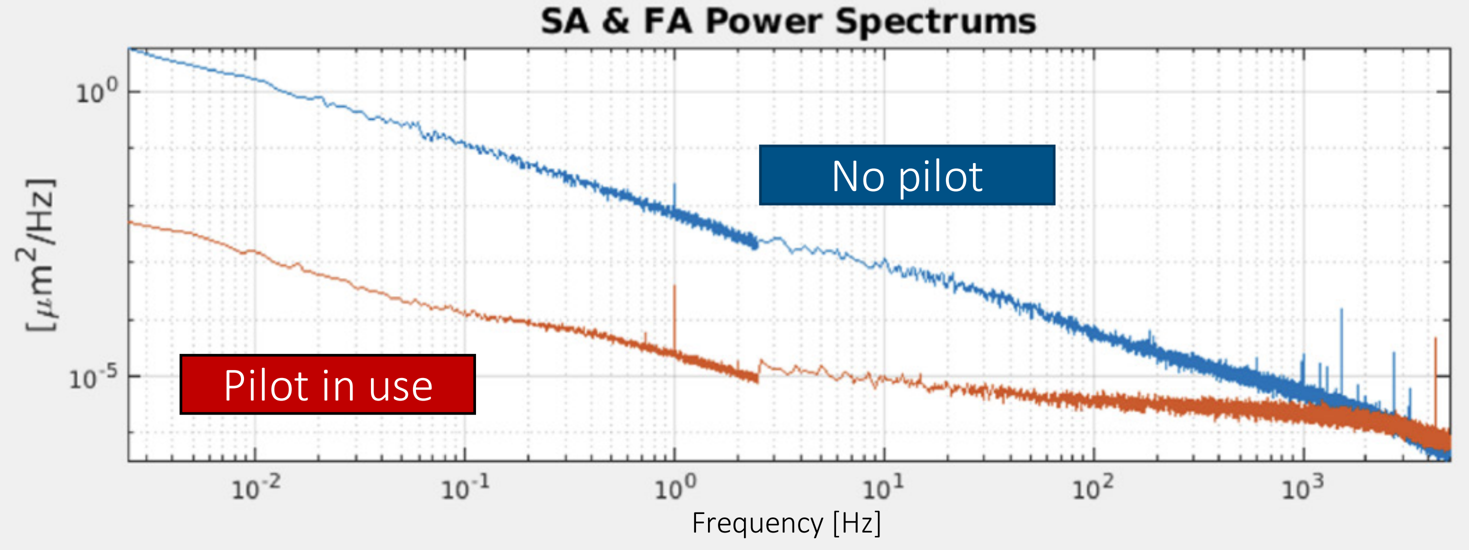
Ceramic Filter Temperature Test



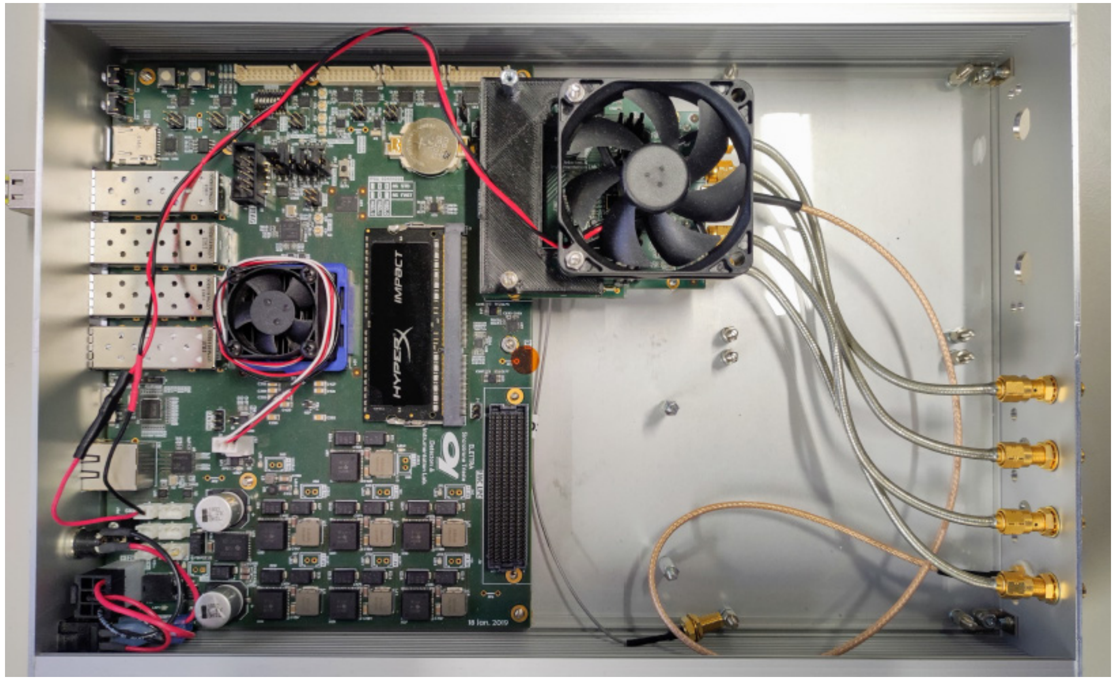
ALS BPM results

- With pilot tone 200nm pk-pk in 4 days ($K_{X,Y} = 16\text{mm}$)
- Noise improvement by pilot seen up to 1 kHz
- Phase locked pilot tone @±11/19 f_{rev} easily removed by averaging 19 turns
- Pilot tone needs to be switched off for TbT data!

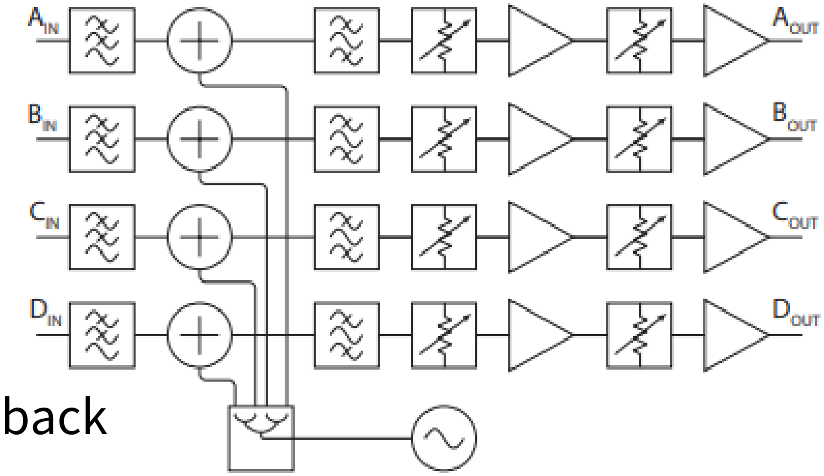




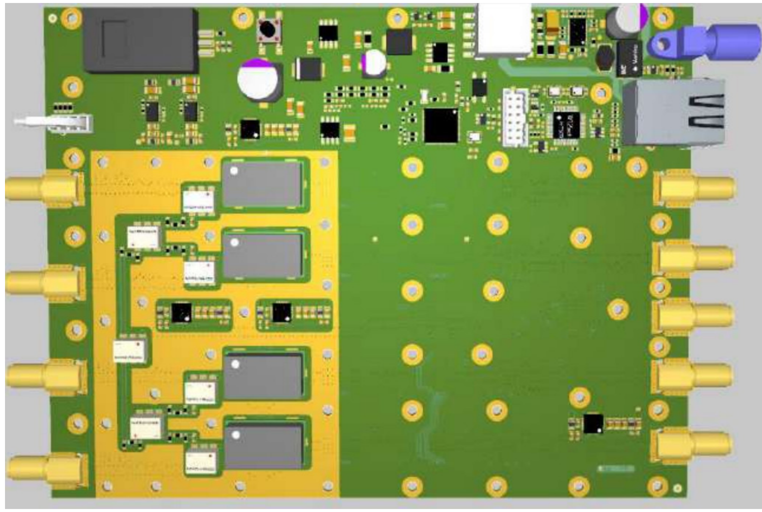
BPM upgrade for Elettra 2.0



- Inhouse development of whole system
- Distribution and injection with system of **2-way power splitters**
- Amplification, filtering, switchable attenuation, radiation sensor in the FE
- **Selectable filters SAW and LC**
- On board pilot tone generation or external feed in
- Power/Comms through **PoE/GBE**
- Fibre optic to notify FPGA of gain changes
- Digitiser has no BPM specific components (potential re-use)
- **Variable rate up to TbT** to orbit feedback
- Contract to industrialise and produce FE and digitiser for Elettra 2.0



concept

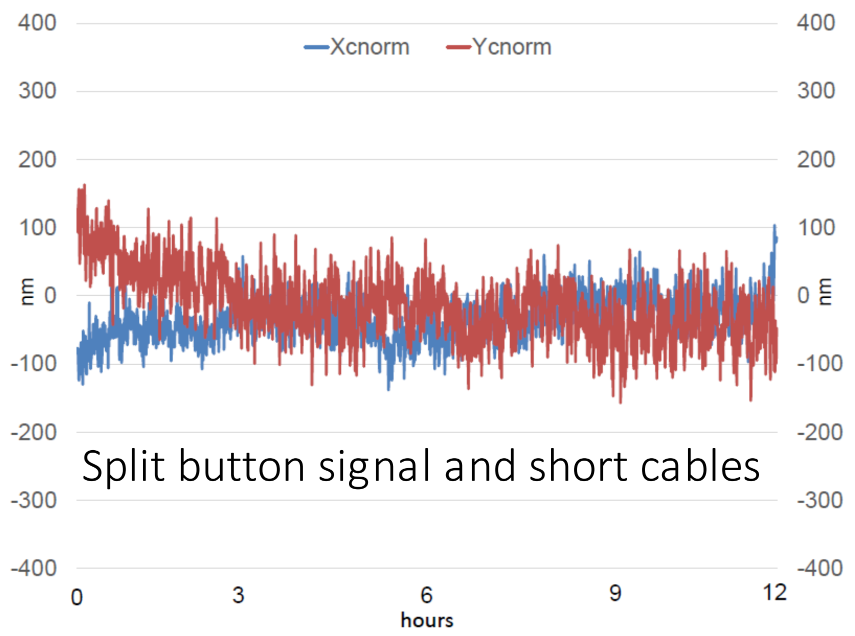


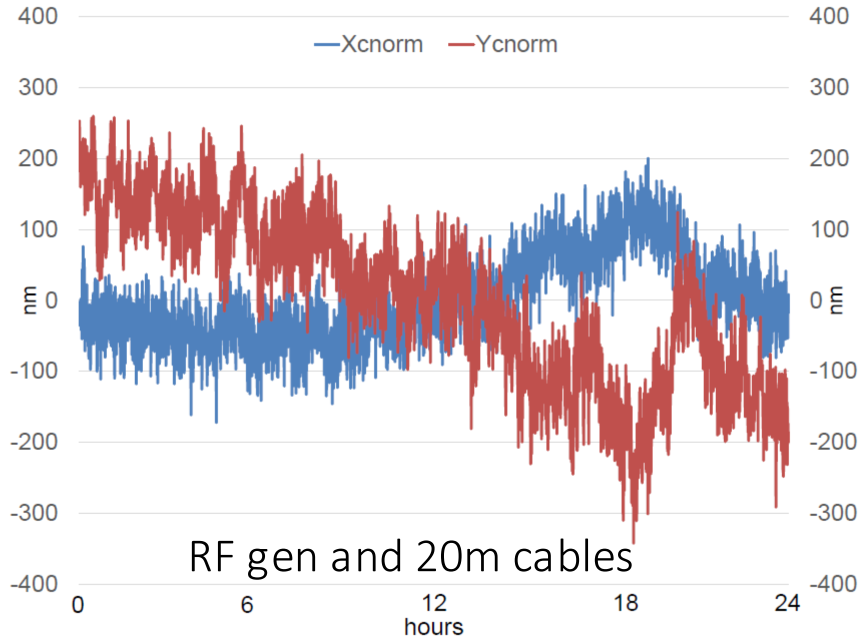
final, industrialised PCB

This conf: MOP13, MOP14 IBIC2021-MOPP16 IBIC2018-TUPB13

Elettra 2.0 BPM results

- FAT of FE with modified Libera Spark (added pilot tone processing)
- Influence of temperature and humidity extensively tested using climatic chambers
- Impact of beam current and fill pattern changes tested using beam
- First test of final FE show excellent performance ~200nm pk-pk in 12h
- Earliers test with prototype showed 700nm pk-pk in 3 days ($K_{X,Y} = 20\text{mm}$)

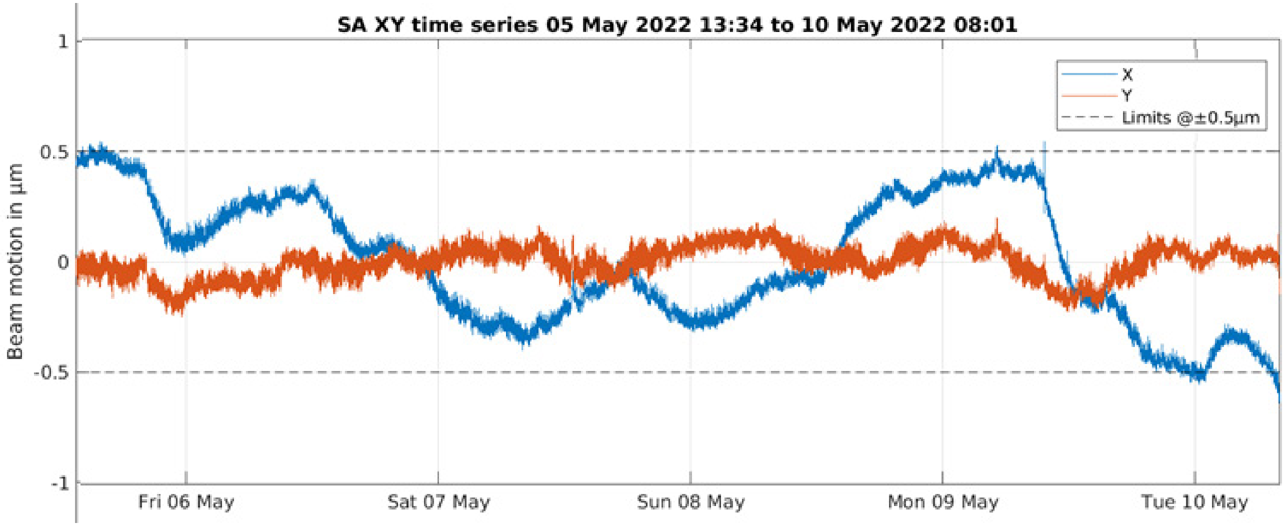


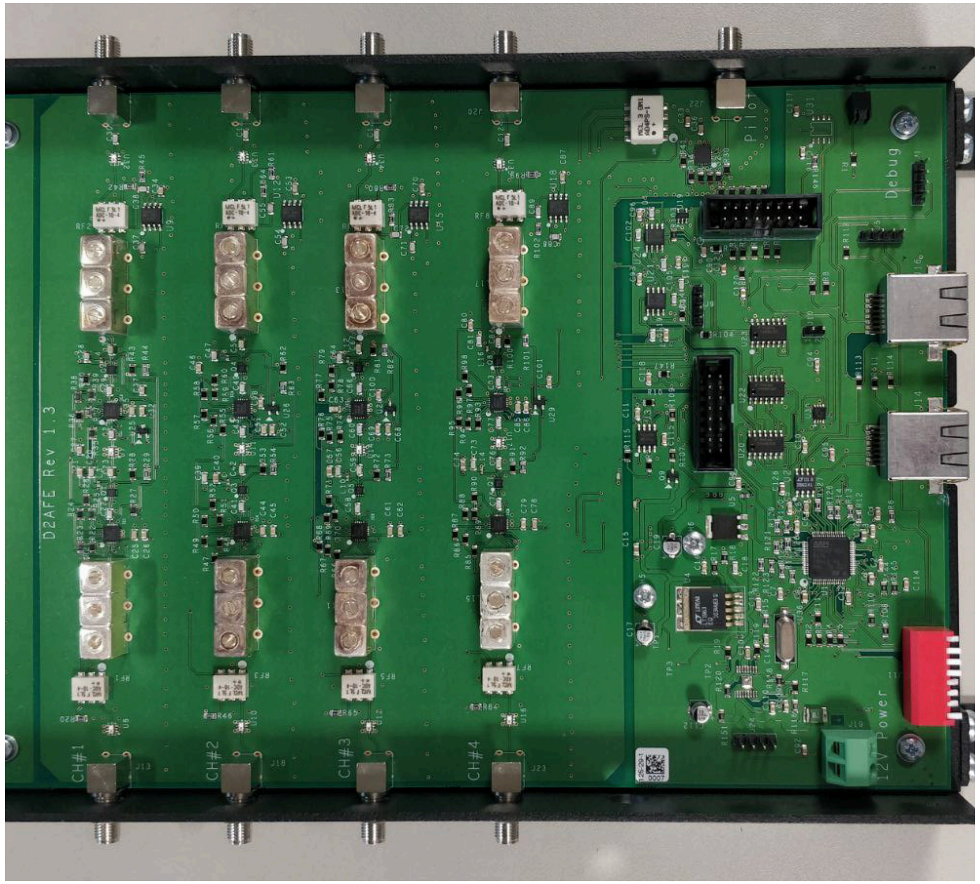


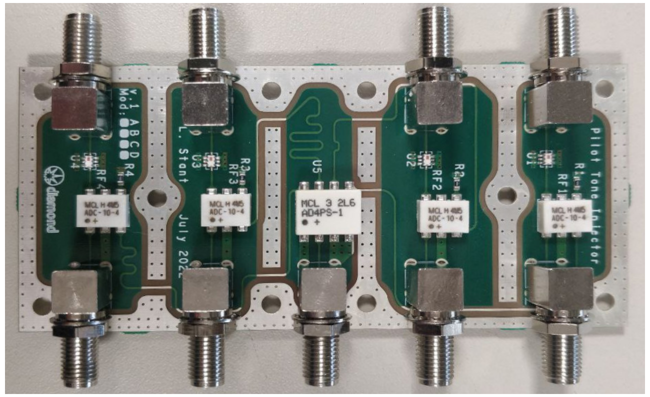
This conf: MOP13, MOP14 IBIC2018-TUPB13 IPAC2019-WEPGW072

Diamond-II: new BPM

- In-house developed FE
- Injection of PT with PCB mounted couplers, filters, amps, attenuators
- Digitiser from COTS in MTCA
- Early beam test show 1000nm pk-pk in 4 days ($K_{X,Y} = 10\text{mm}$)
- Planned experiments with passive PT injection only



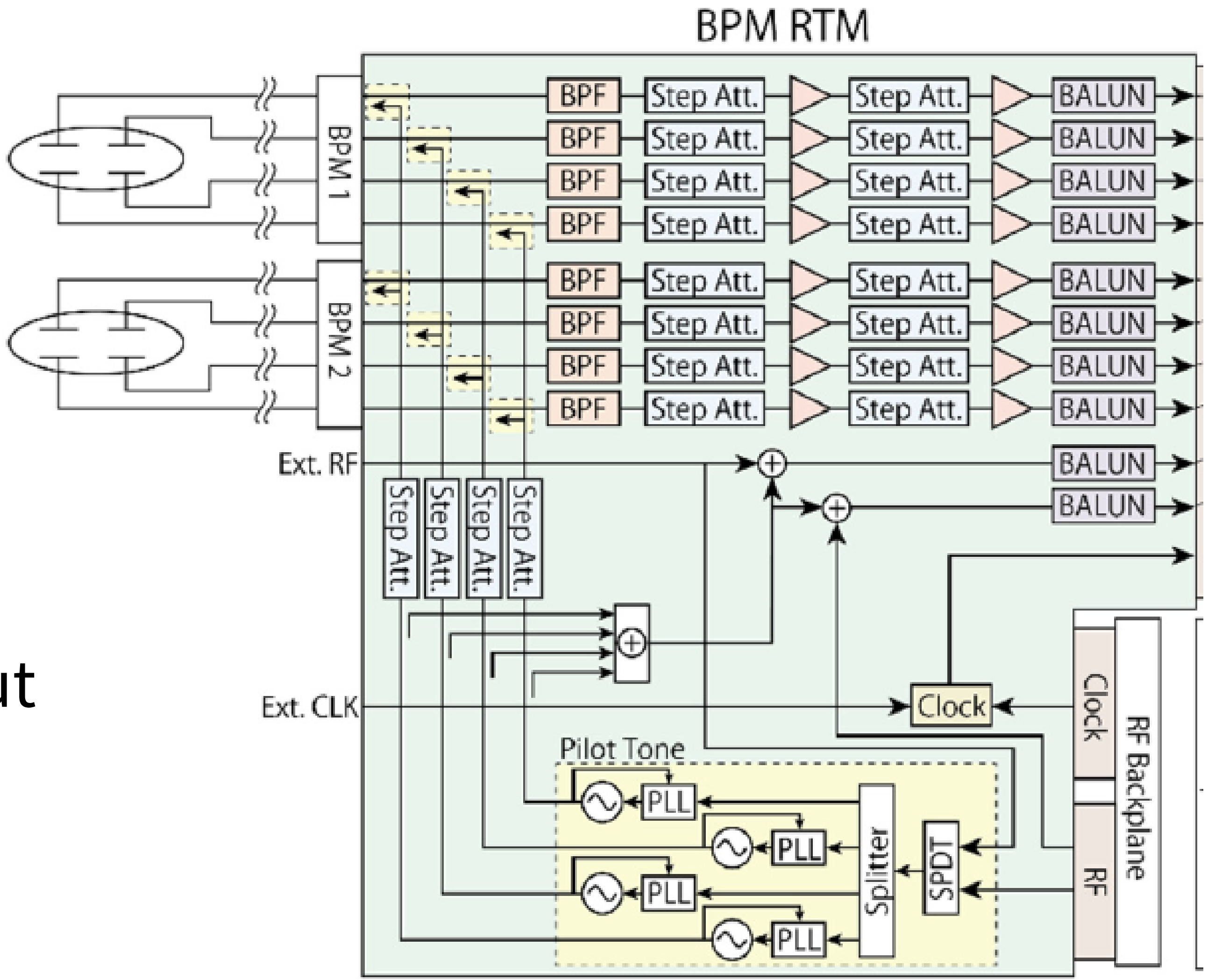




This conf: MO3C2

SPring-8: BPM Upgrade Plans

- New BPMs to include pilot tone injected from the BPM RTM
- PT with individual frequencies are coupled towards buttons and reflected there
- Very flexible scheme, cables and buttons can be monitored without beam
- Online calibration not yet demonstrated



IBIC2019-WEBO03

SIRIUS: Switching Diagonal Channels

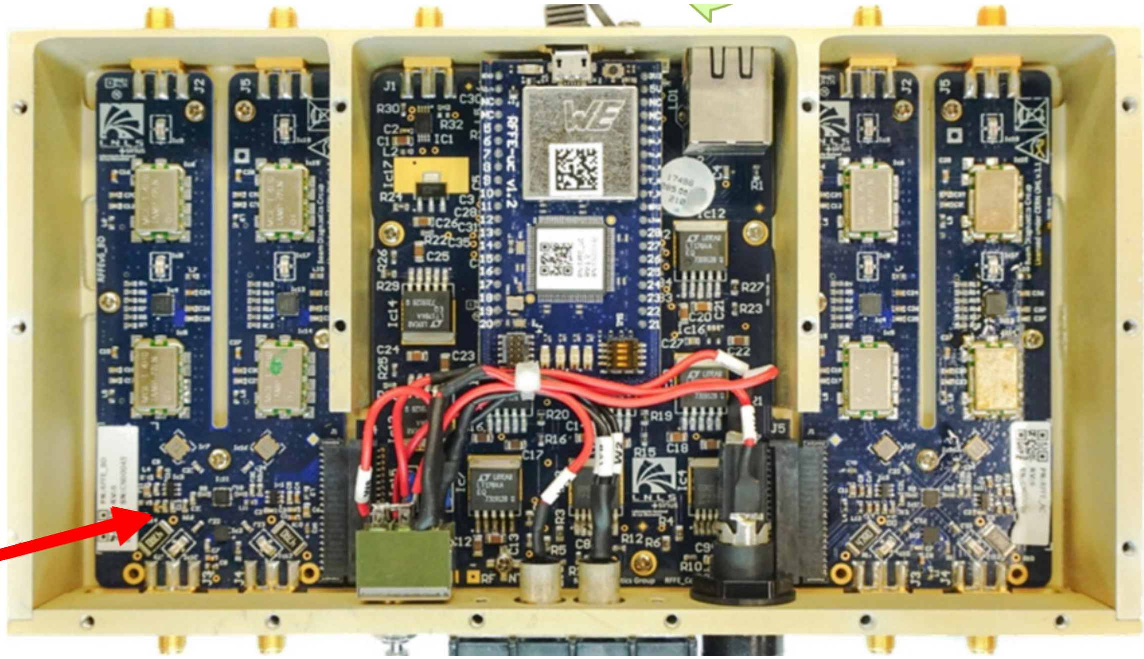
- Two 2x2 switches, simpler than 4x4 crossbar
- RF generator and splitters for signal
- Potential to relocate FE to tunnel

RFFE Modules

MicroTCA.4 crate

Ethernet switch

RFFE Modules

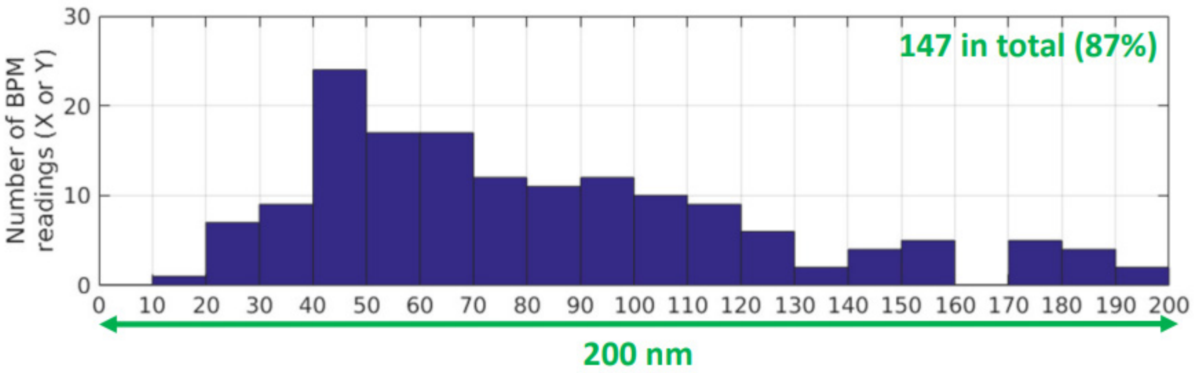


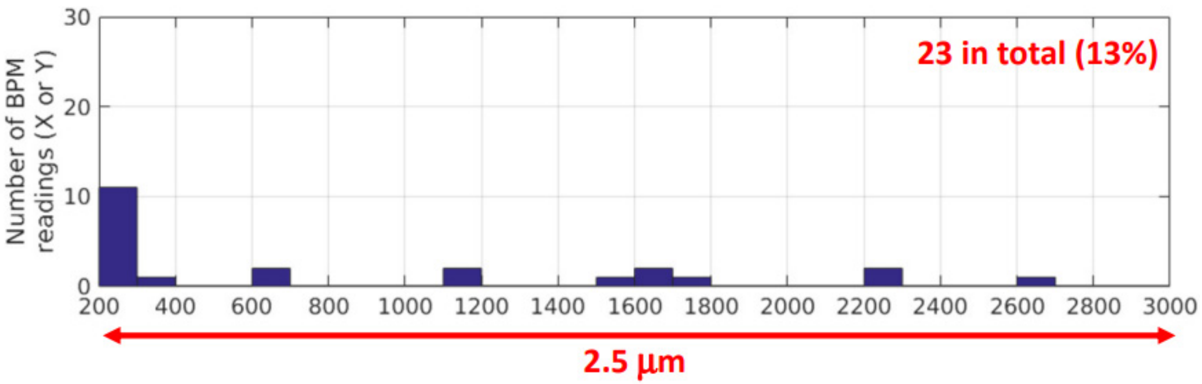
Switch

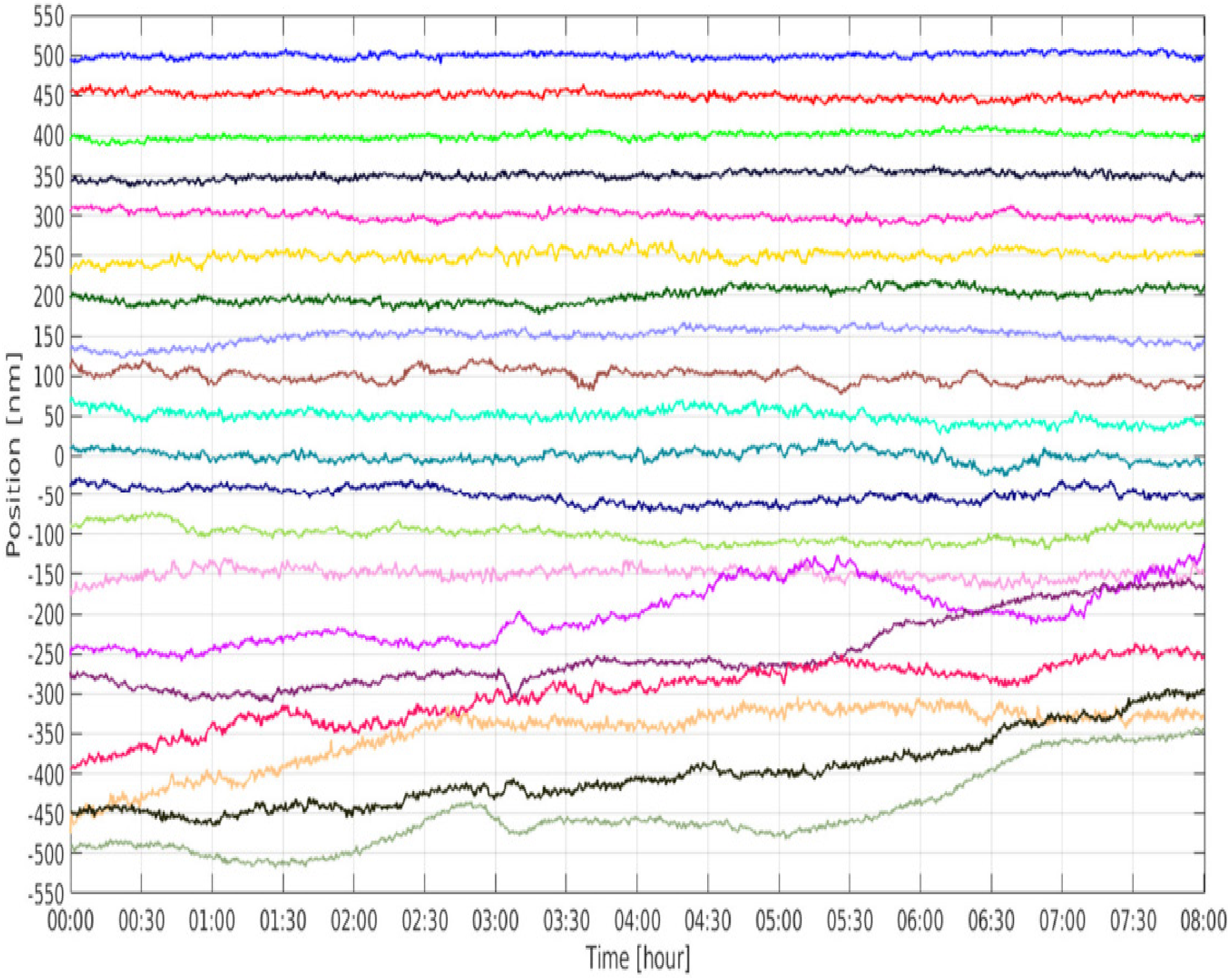
IBIC2018-TUOC03

SIRIUS BPM long term results

- Manufactured BPMs tested in racks
- Temp stabilised room (1°C pk-pk)
- Many with <200nm pk-pk in 8 h ($K_{X,Y} = 10\text{mm}$)



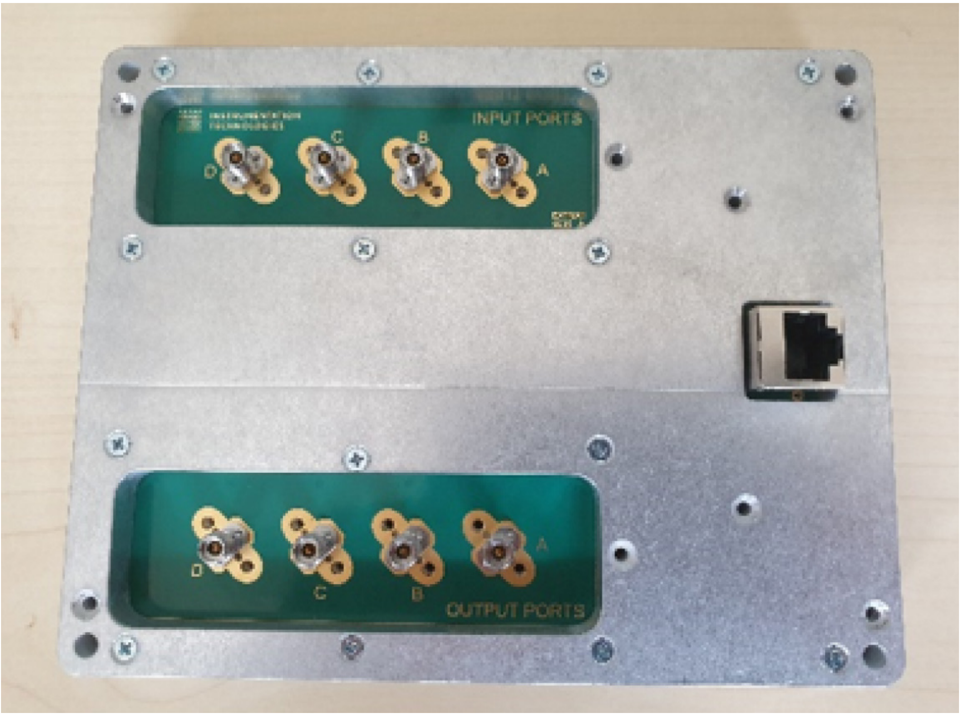


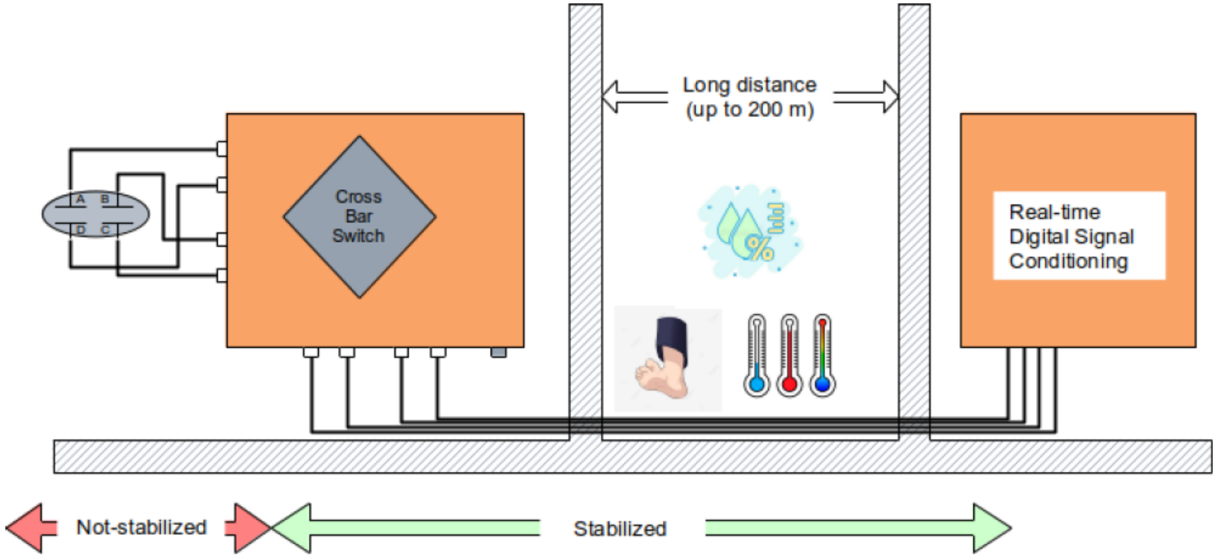


IBIC2018-TUOC03

DESY: BPMs for PETRA IV

- BPM cables run for 100-200m in uncontrolled climatic conditions
- Compared PT and switching schemes
- Idea: move crossbar-switch to tunnel, include cables in stabilisation
- Contract with industry to evaluate and advance idea

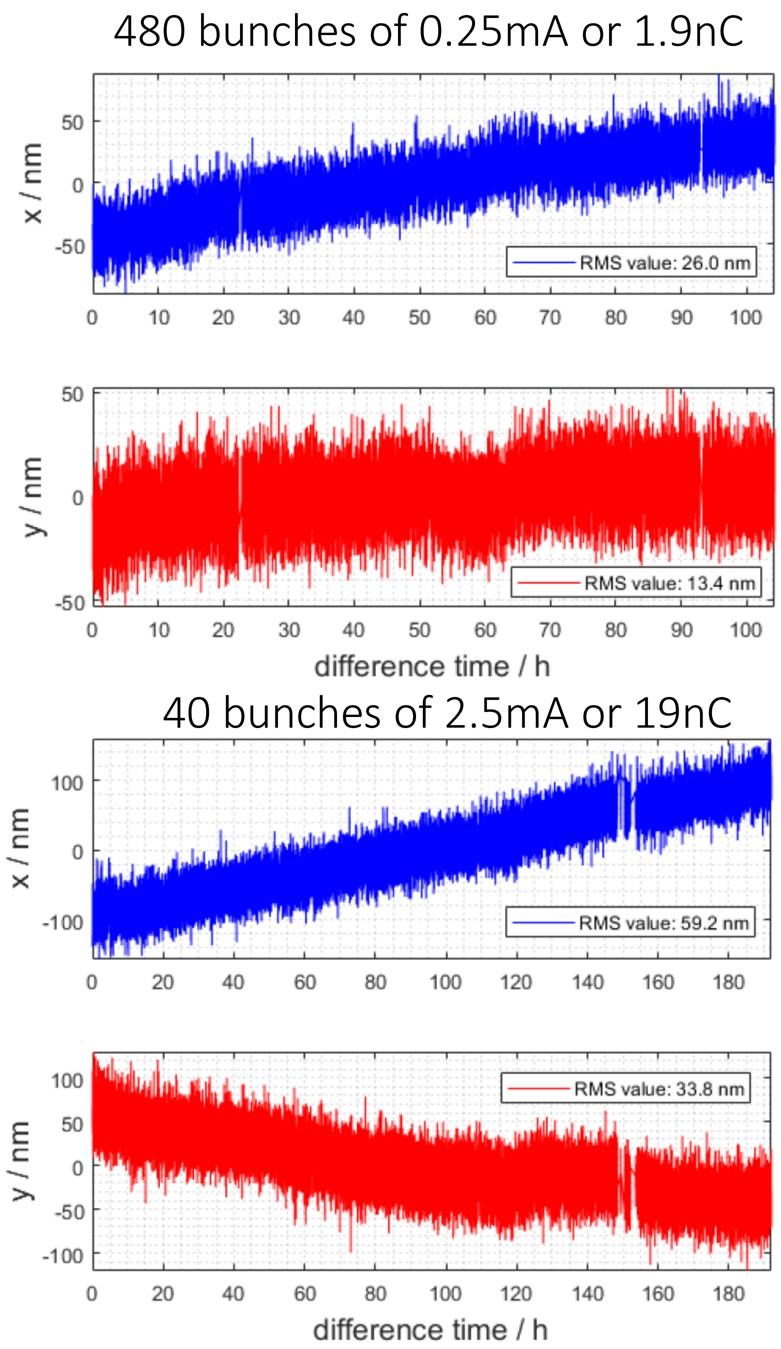




This conf: WEP08, WEP09, IBIC2021-MOPP30, IBIC2021-MOPP36

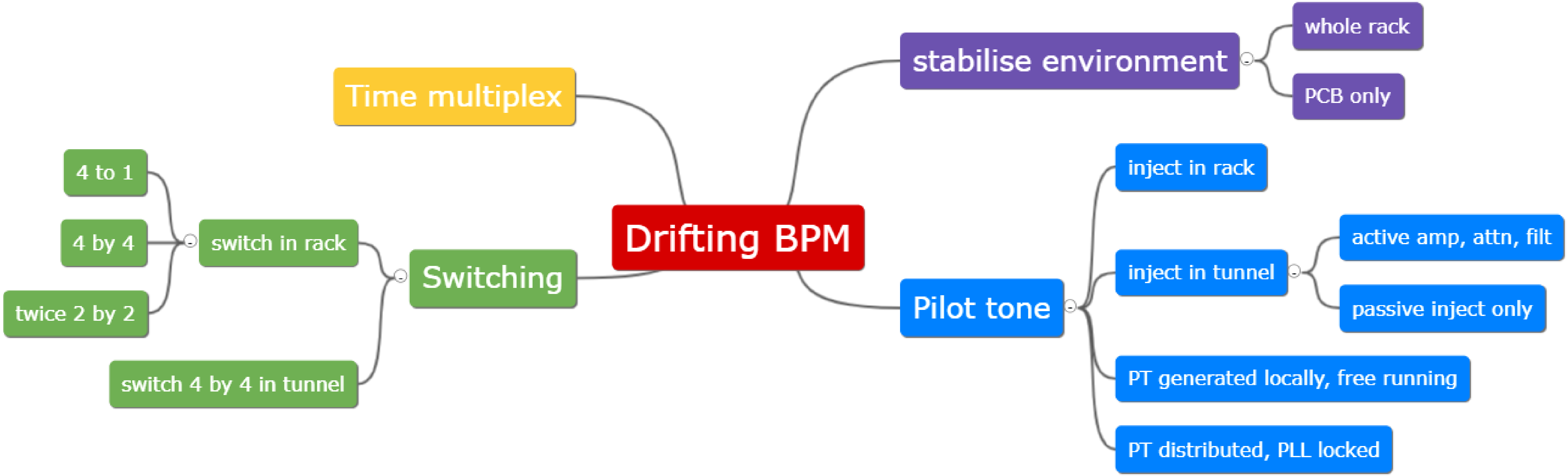
PETRA IV BPM Prototype Tests

- Beam tests in PETRA III
- Tested with two fill patterns
  - No obvious differences found
- Results likely influenced by temperature rising slowly (1.2°C in 8 days)
- 150nm pk-pk in 4 days
- 300nm pk-pk in 8 days ($K_{X,Y} = 10\text{mm}$)

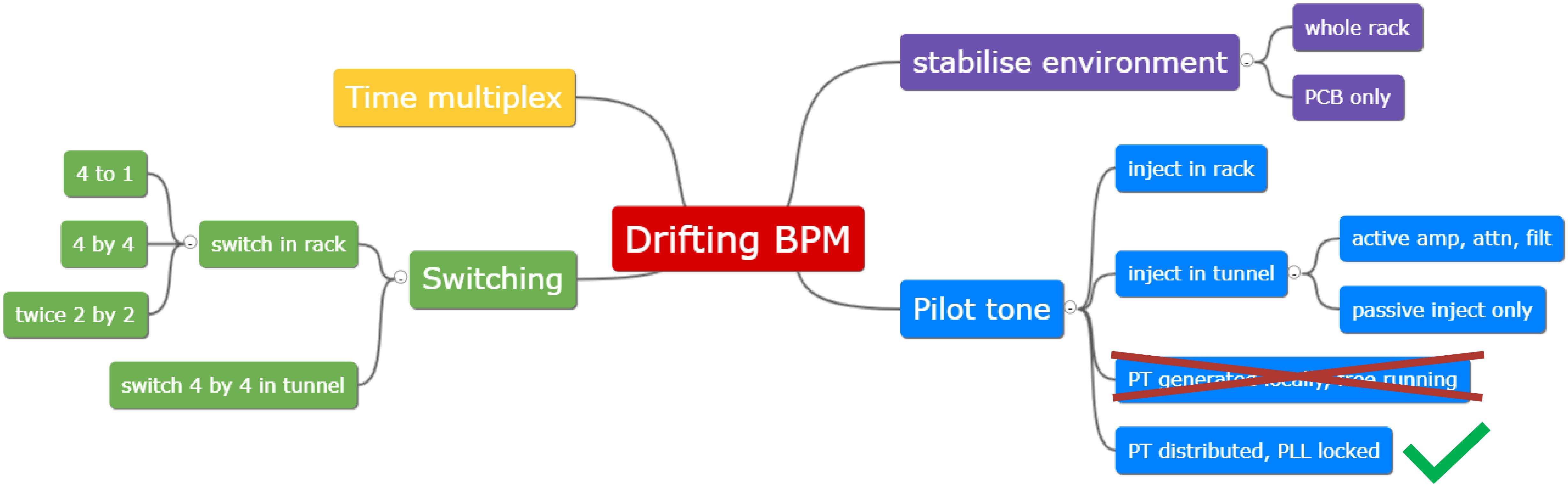


This conf: WEP08, WEP09

A Mindmap of Drift Compensations

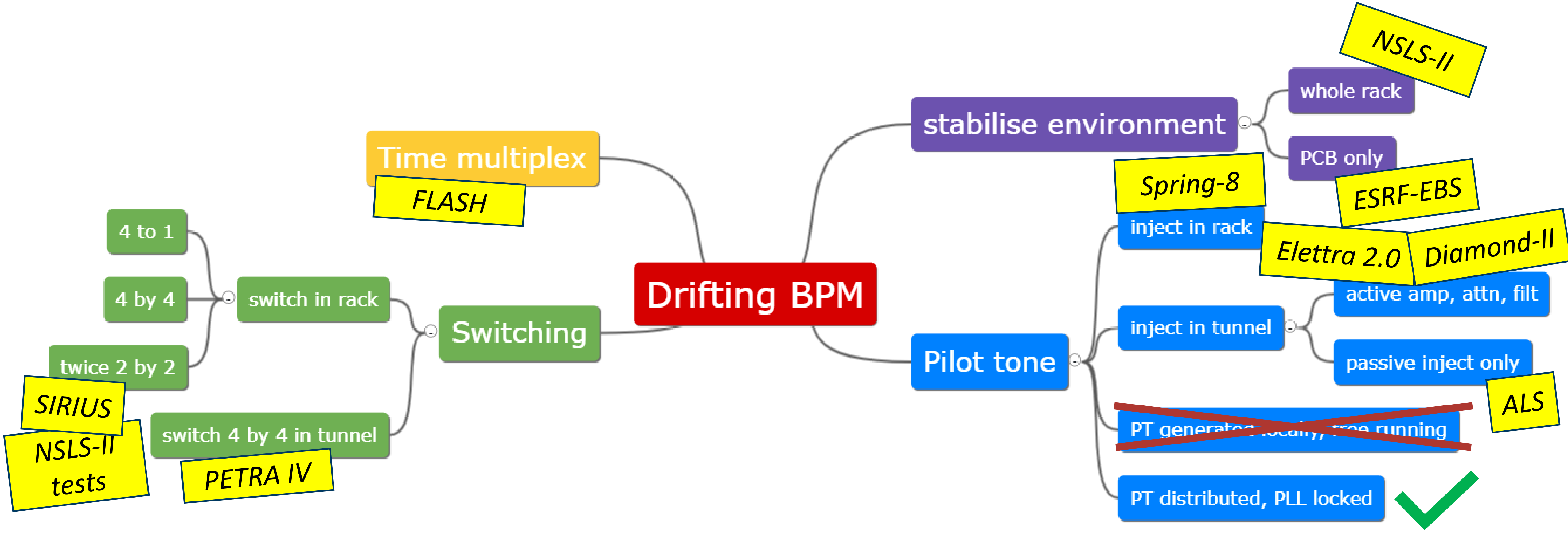


A Mindmap of Drift Compensations



HZB BESSY II Light Source

A Mindmap of Drift Compensations



Conclusions

- Inclusion of cables in stabilisation is required and demonstrated
- Results <1µm drift in 1 week demonstrated: PT and switching alike
- PT with 2 tones and passive injection provides best results so far
- PT beneficial for monitoring without beam
- Test of full production provides more reliable assessment
- Lesser drift values provide diminishing benefit
  - Buttons feedthrough or BPM block temperature varies with beam current
  - Physical block position not controlled to this level, steel expands 11ppm / °C
  - Floor position not certain on these scales
- Additional monitors (temperature, humidity, floor motion, photon beam, …) are beneficial in operation