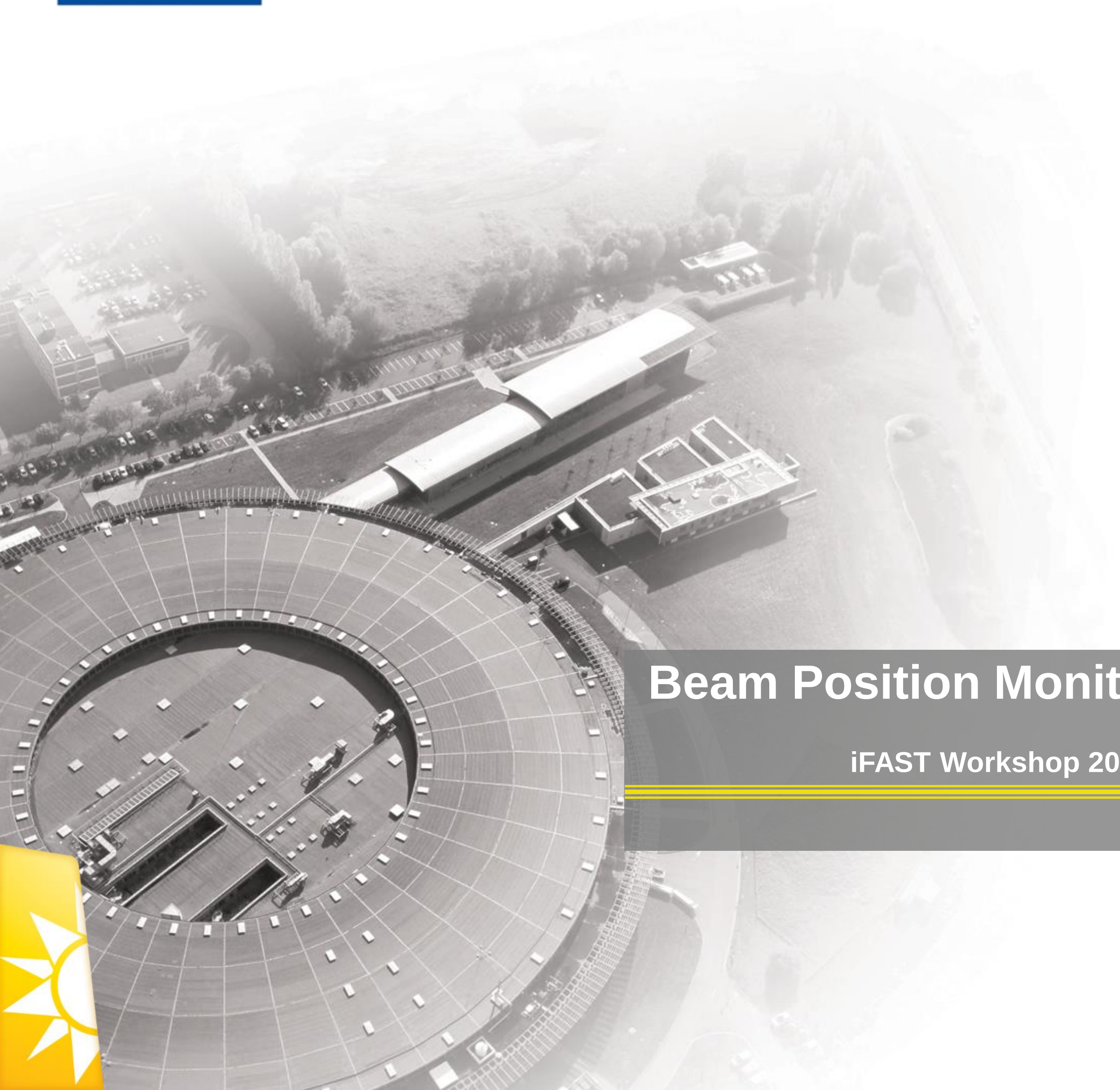


Beam Position Monitors and Orbit Feedback for Low Emittance Rings

Nicolas HUBERT, M. El Ajjouri, R. Broucquart

iFAST Workshop 2022: Beam Diagnostics and Dynamics in Ultra-Low Emittance Rings

- Stability requirements

Beam stability requirements at source points		3rd gen.	Low Em. Rings
Short Term	Position and Angle Stability (with respect to beam size and divergence)	10%	2-3%
	Minimum beam size (H/V) RMS	~200µm/~10µm	~5 to 10 µm both planes
	Position and Angle Stability (µm/µrad) RMS	~1 µm/µrad	~100 nm/nrad
	Range	0.01 Hz to ~1 kHz	0.01 Hz to ~1 kHz
Long Term	1 day	1 µm RMS	~ 500 nm RMS
	1 week	?	~ 1 µm RMS

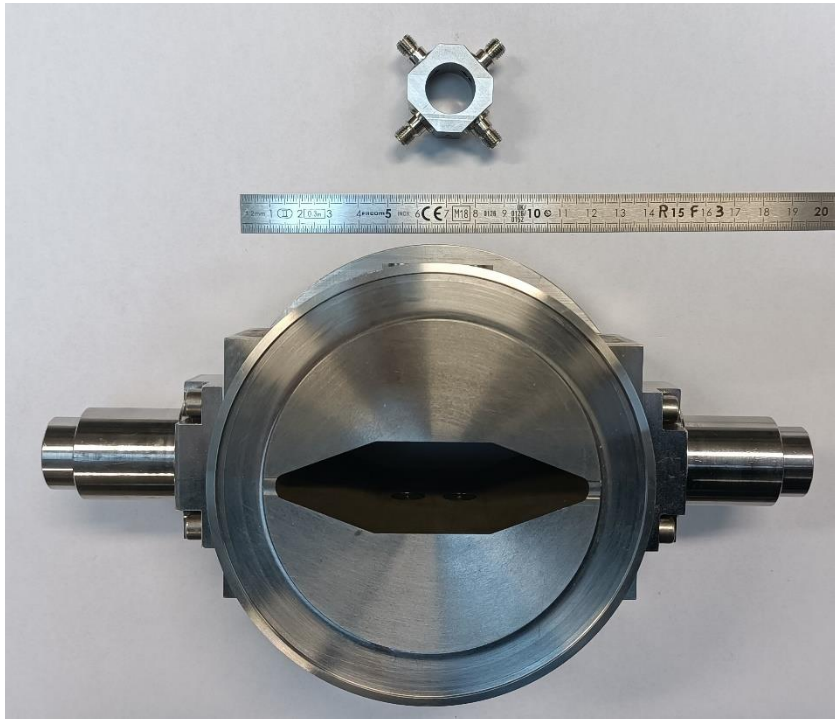
- Beam Position Monitor specifications

Type	Data	Spec.	Conditions
Resolution	Fast acquisition (~100 kHz, DC-2kHz bandwidth)	50 nm rms	Nominal current / Nominal filling pattern
	Turn by Turn	1 µm rms	
		100 µm rms	0.1-1 mA in 1 quarter (commissioning)
	Slow Acquisition (~10 Hz)	1 µm rms	
Beam Current Dependence	-	10 µm	From 0.1 mA – to nominal current
Absolute accuracy	-	< 500 µm	Before BBA
		< 5 µm	After BBA
Long term Stability	-	500 nm rms	Day drift
		1 µm rms	Week drift

Beam Position Monitors

- Usual guidelines for BPM design:
  - Maximize the linear region.
  - Maximize the amplitude of collected signal (for resolution)
  - Minimization of the BPM impedance (impedance budget)

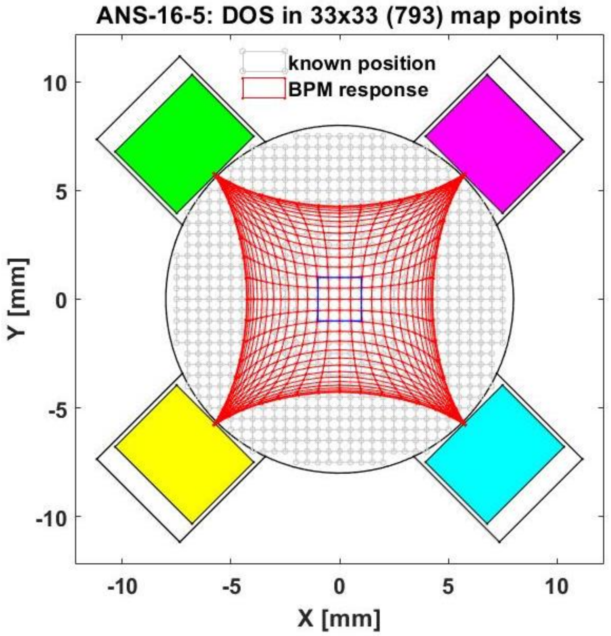
- Low emittance ring new constraints:
  - Improved stability:
    - Minimize the heat load on the BPM (SR, beam coupling)
    - Minimize mechanical stress from vacuum chamber
  - Drastic size reduction: from massive blocks to ‘key rings’
    - Miniaturizing the button and its housing with tightest mechanical tolerances
    - Mechanical integration constraints

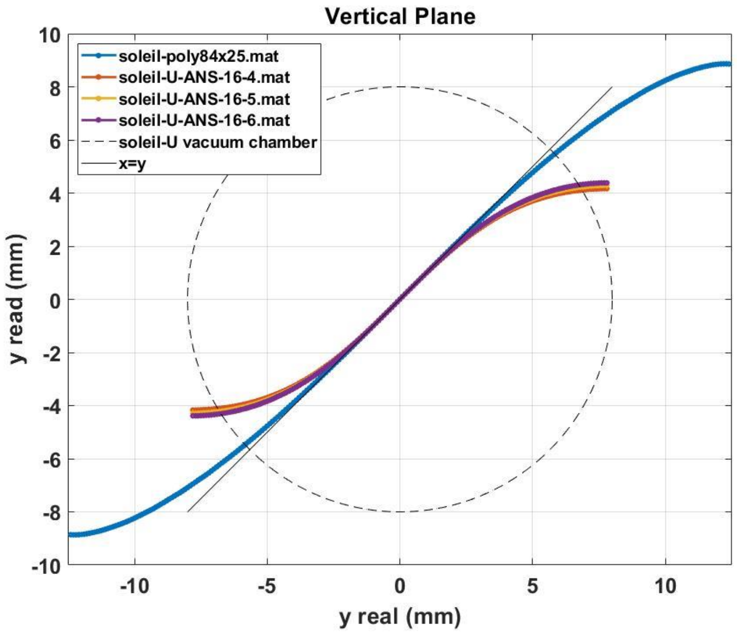


BPM prototypes for SOLEIL (bottom) and SOLEIL-Upgrade (top)

Beam Position Monitors

- Button design:
  - Linearity:
    - Smaller beam pipe, smaller linear region.
    - Different available reconstruction methods (polynomial, Newton inversion) for studies at large amplitudes.



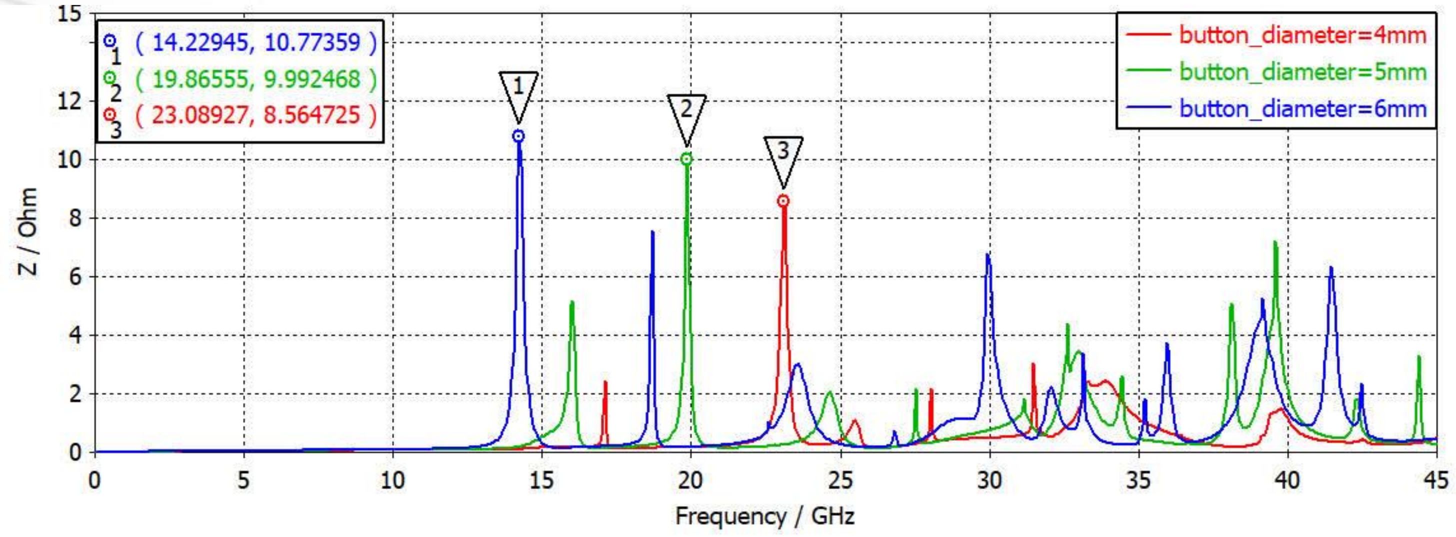


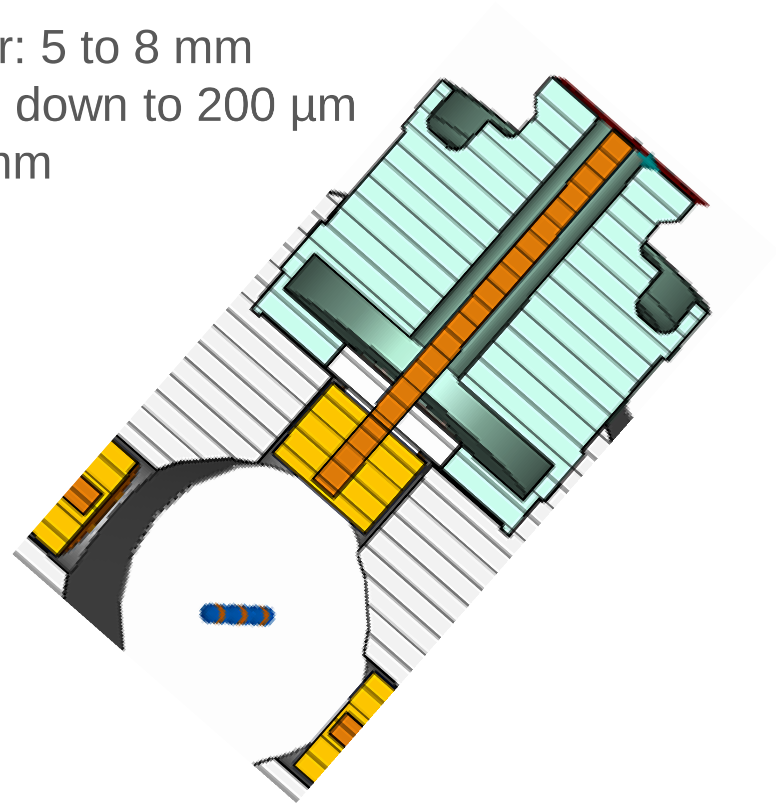
Delta over Sum response Φ16 mm BPM. Linear region is +-2 mm. *BPMLab simulation [1].*

Beam Position Monitors

- Button design: impedance optimization
  - Minimize BPM budget in the machine impedance
  - Minimize heat load on the button and the BPM block.

- What helps?
  - Small button diameter: 5 to 8 mm
  - Thin gap: trying to go down to 200 µm
  - Thick button: 3 to 5 mm





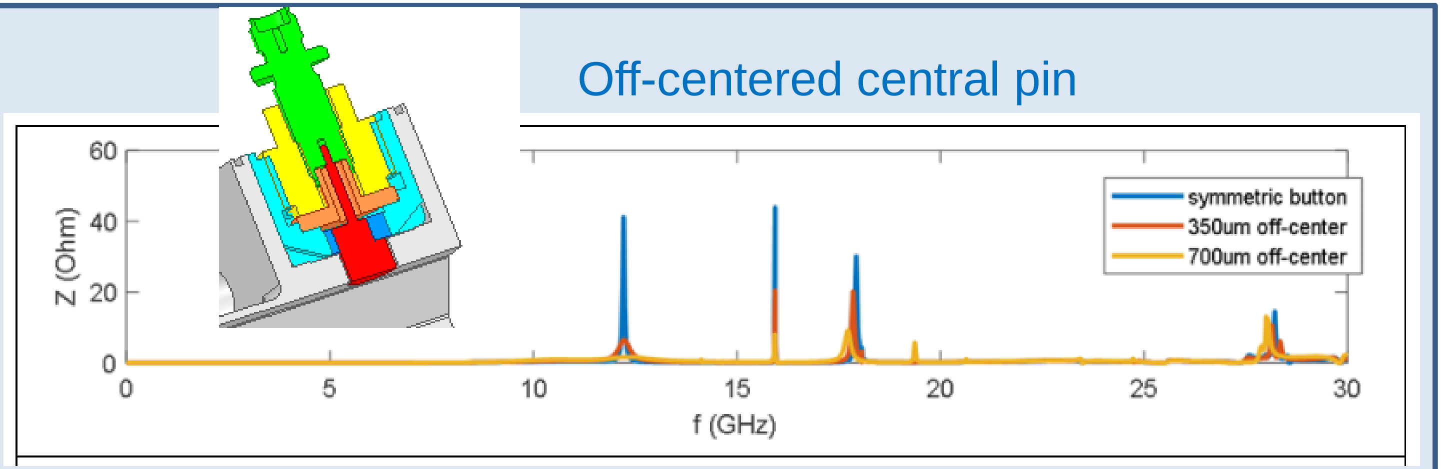
Longitudinal impedance (real part) vs. button diameter. SOLEIL simulations. *M. El-Ajjouri, IBIC2021 [2]*

Beam Position Monitors

- Button design: impedance optimization
  - Minimize BPM budget in the machine impedance.
  - Minimize heat load on the button and the BPM block.

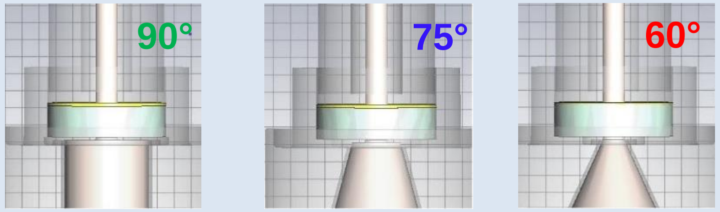
- What helps? -> Some tricks!

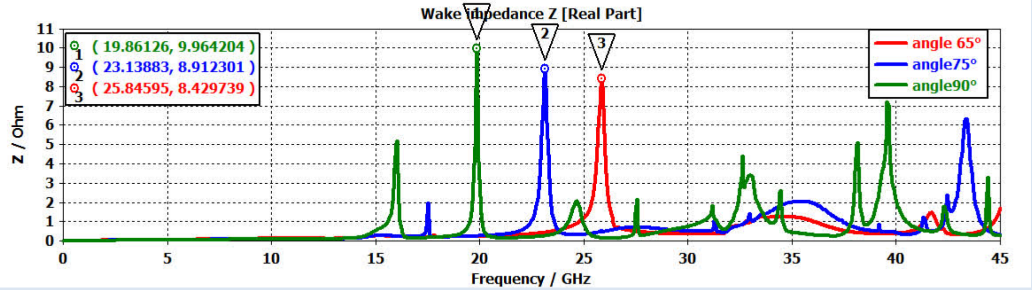
Off-centered central pin



Longitudinal impedance vs. central pin eccentricity at SLS. *SLS-II TDR [3]*

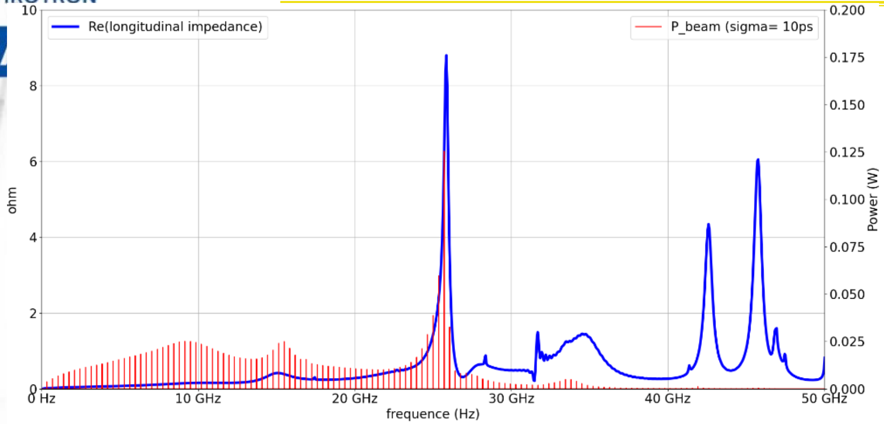
Conical button



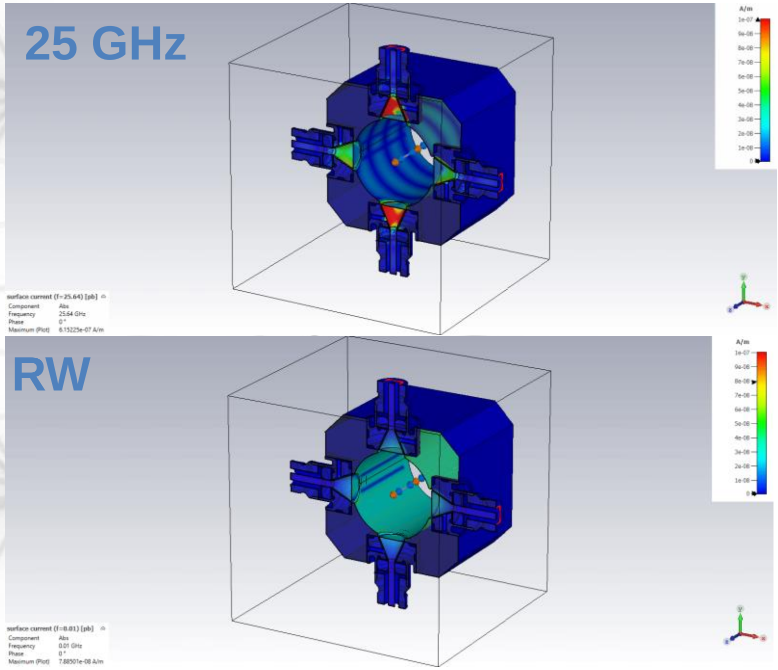


Longitudinal impedance vs. button angle. SOLEIL simulations [2] following SIRIUS design [4].

Beam Position Monitors



Real part of the long. Impedance (blue) and loss map (red) for a 10 ps rms bunch length (SOLEIL case)



Beam induced surface current at 25 GHz (top) and at low frequency (bottom). SOLEIL CST simulation.

- BPM design: choice of the materials
  - Button heat load mitigation
    - Buttons heated by the trapped modes
    - Button Conductivity >>Body conductivity to maximize the dissipated power on the body. *I. Pinayev, PAC 2009 [5]*

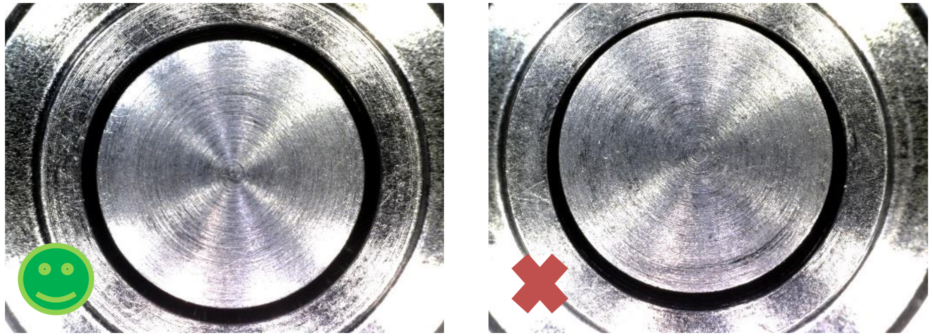
Button Body	**Mo**	**316L**
Mo	50%	74 %
Cu	64%	85%
316L	26%	50%

Part of the trapped mode power deposition that goes on the button in function of the button and body material

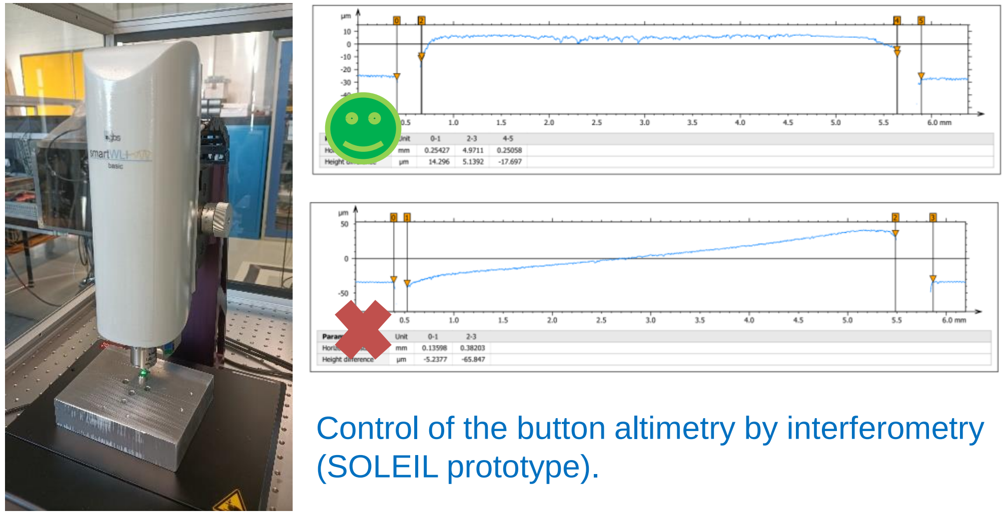
  - BPM heat load mitigation
    - Resistive wall is minimized for high conductivity materials.

Beam Position Monitors

- Button manufacturing:
  - Miniaturization: take care to the mechanical tolerances and accuracy
    - -> tightest tolerances
    - -> smaller pieces, adjustments are more complex
    - -> Metrology with optical devices
  - Button gap and concentricity are the main concern:
    - Absolute error
    - Frequency/amplitude of the trapped modes
    - Button sensitivity (due to capacitance error)
  - Button sorting before welding
  - BPM measurement before installation
    - Lambertson method for the electrical offset *B. Roche, DEELS 2019 [6]*



Control of the button gap (200µm) and concentricity with a microscope (SOLEIL prototype).



Control of the button altimetry by interferometry (SOLEIL prototype).

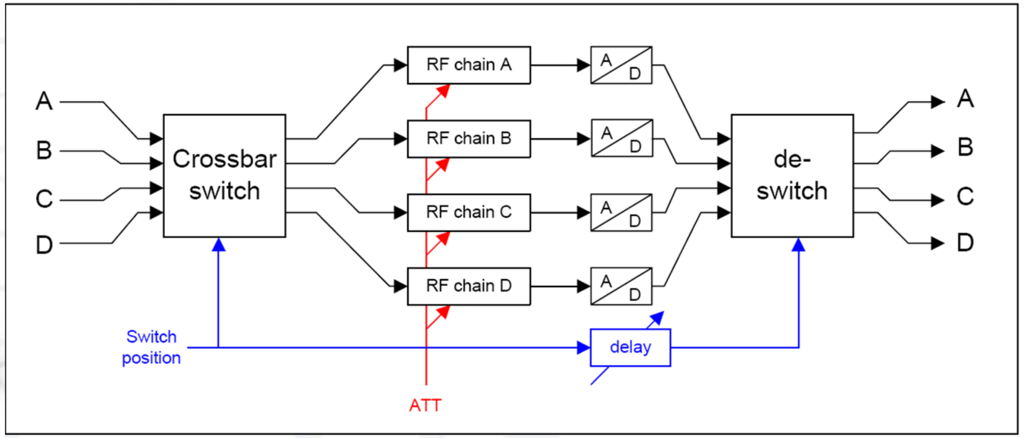
Beam Position Monitors

- BPM Mechanical Stability:
  - For a usual air regulation at +-0.1°, low thermal expansion supports are mandatory to reach the stability specifications.
  - BPMs = fixed points of the vacuum chamber with bellows to isolate the BPM from vacuum chamber mechanical stress.
  - Upstream taper to keep the BPM in the shadow of the synchrotron radiation
  - Achromat BPMs may have relaxed stability specifications:
    - High density/ lack of space for bellows
    - Invar has non-zero magnetic permeability

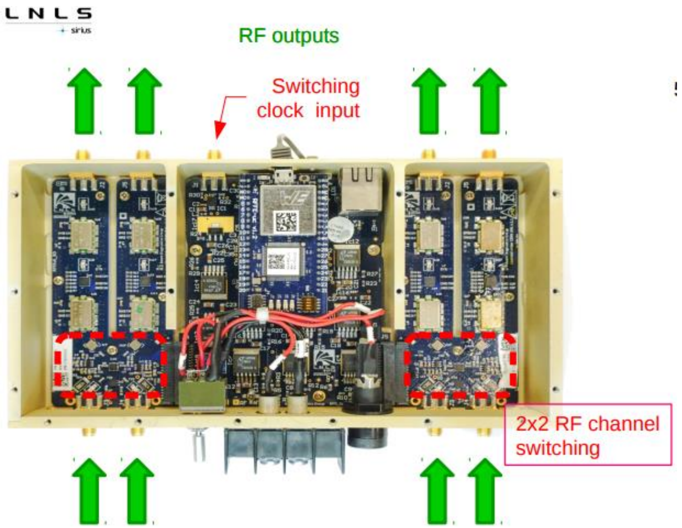
    Provided that:
    - Source points on bending magnet are nevertheless stabilized
      - Addition of the XBPMs in the orbit feedback loop
    - Correctors are in sufficient numbers to stabilize the source point positions independently from the achromat ones.

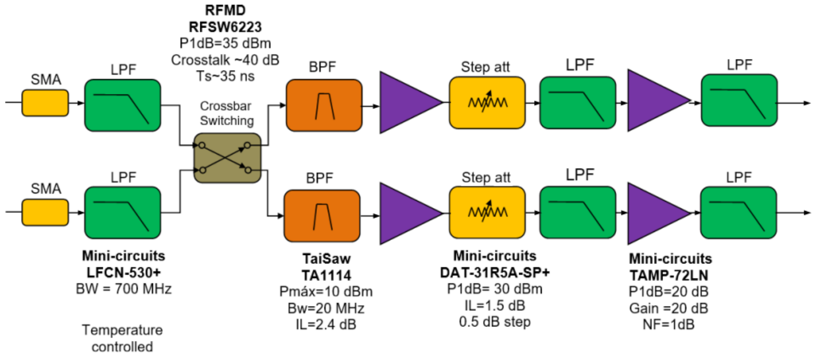
	Linear thermal expansion coefficient ($x10^6$ K^{-1})	Drift for T=+-0.1 °C (considering 1.2m support)
Steel	12	2.9 µm
Invar	1.2	0.3 µm
Granit	5	1.2 µm

- Current BPM electronics:
  - Largely dominated by digital processing with (fast) switching mechanism to compensate drifts of their analog frontend :



Libera commercial module: 4x4 channel multiplexing [7].

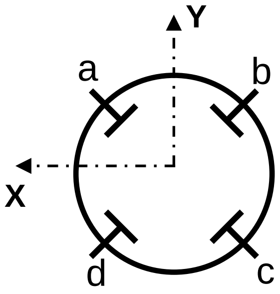




SIRIUS BPM RFFE: 2x2 channel multiplexing.
D. Tavares, Next Gen. Beam Pos. Acq. and Feedback Systems Workshop (ARIES) 2018 [8].

Beam Position Monitors Electronics

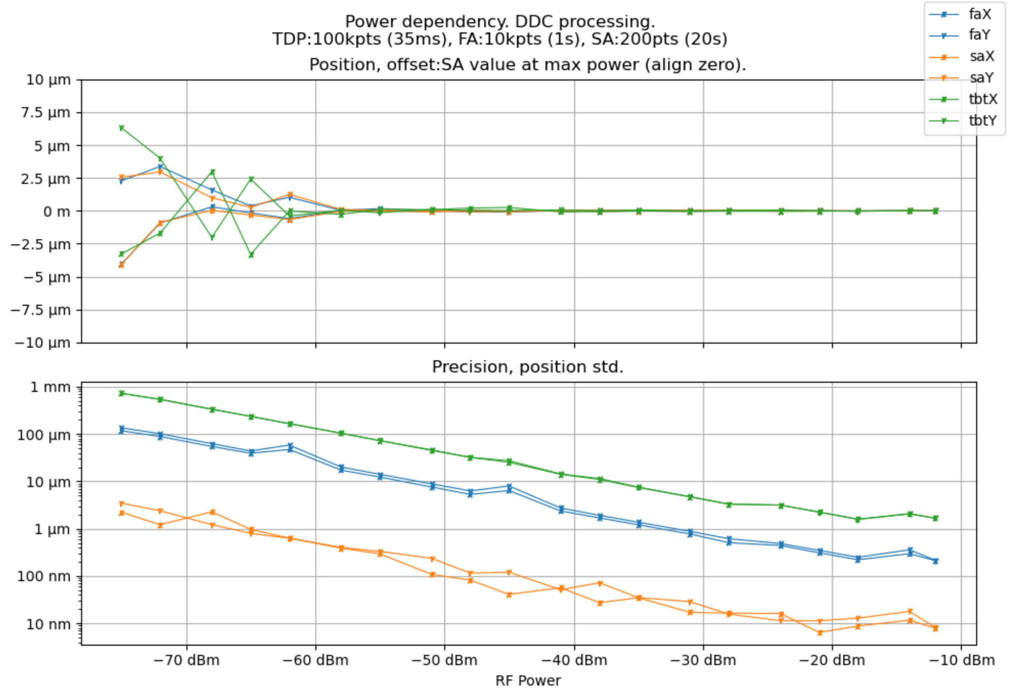
- How to meet new specifications?
  - Beam current dependence: OK
  - Resolution: already almost achieved (with the help of smaller geometric factors)



$$X = K_x\left(\frac{Va+Vd-Vb-Vc}{Va+Vb+Vc+Vd}\right)$$

$$Y = K_y\left(\frac{Va+Vb-Vc-Vd}{Va+Vb+Vc+Vd}\right)$$

	K_x/K_y
SOLEIL	11.4 mm
SOLEIL-U	~6 mm



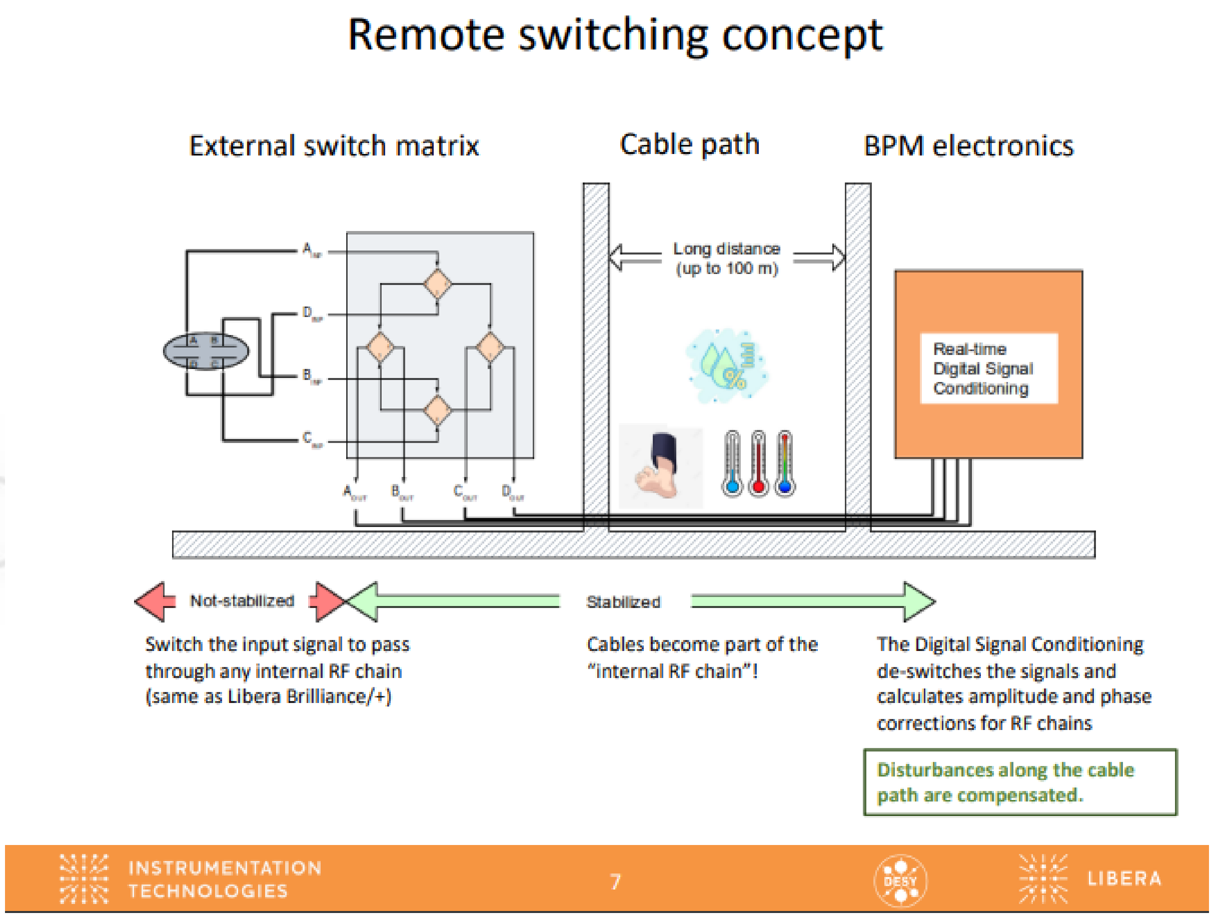
BCD and resolution lab measurement on a Libera Brilliance + BPM electronics for a 25% simulated filling pattern and a geometric factor of 11.4 mm (SOLEIL).

Beam Position Monitors Electronics

- How to meet new specifications?
  - Beam current dependence: OK
  - Resolution: already almost achieved (with the help of smaller geometric factors)
  - Improve the long-term stability to reach 0.5 µm / day, 1 µm / week:
    - Cable stability vs temp. or humidity

Beam Position Monitors Electronics

- Drift compensation mechanism: Switching
  - Move switching in the tunnel, close to the BPM



Remote switching concept for the PETRA-IV BPM electronics.
P. Leban, MicroTCA Workshop 2021 [9]

Beam Position Monitors Electronics

- Drift compensation mechanism: Switching
  - Drawbacks: spikes at switching frequency and sub-harmonics

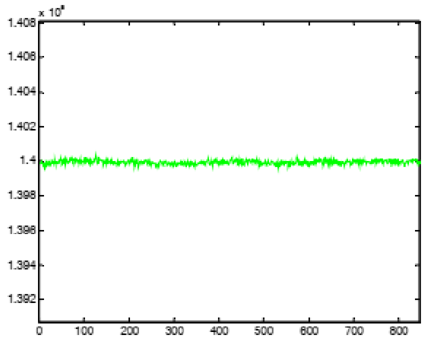


Figure 19: TBT data, one channel. Acquisition with Switches Stopped

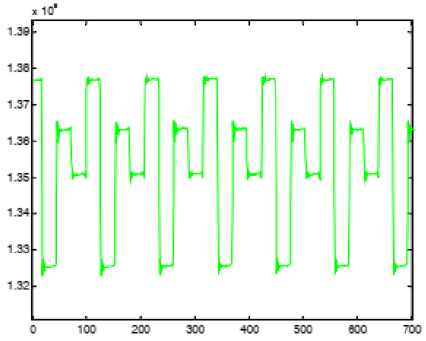


Figure 20: TBT data, one channel. Acquisition only with Switching Enabled. The Transitions between Four Switch Positions are Visible.

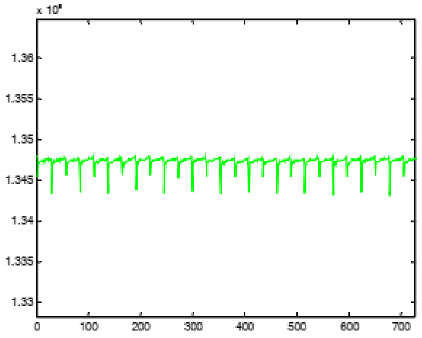
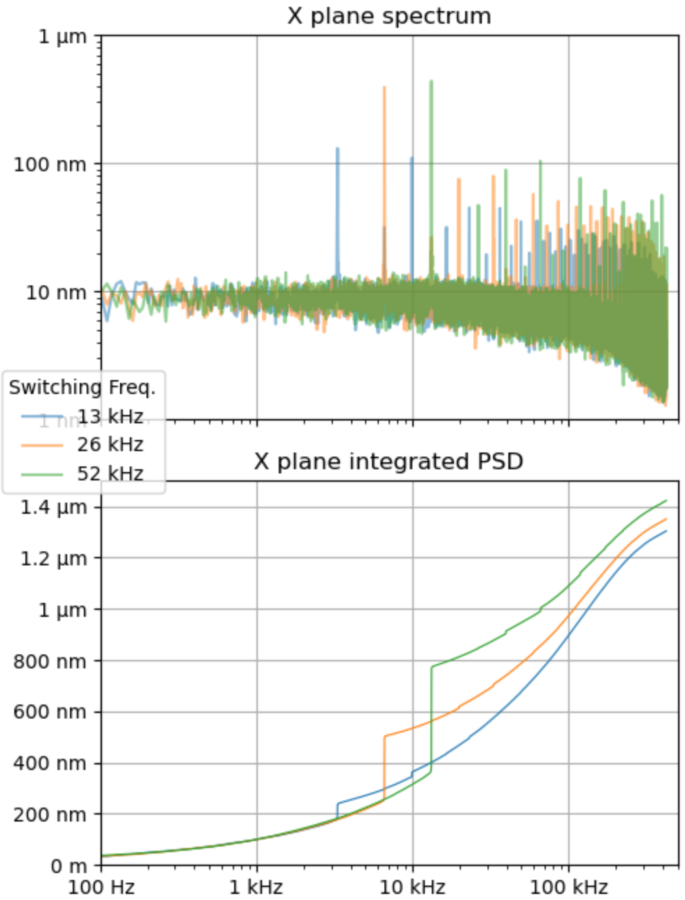


Figure 21: TBT Data, one channel. Switching Enabled with both Amplitude and Phase Compensation

Effect of the switching on turn-by-turn data. *Libera user manual, Instrumentation Technologies [7]*

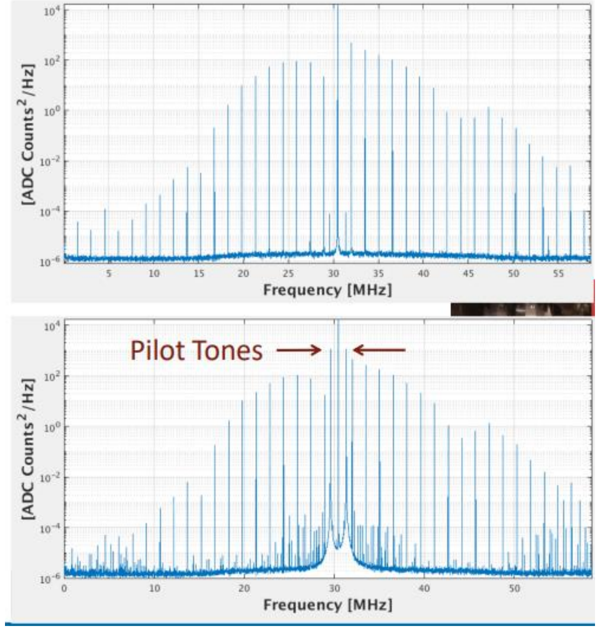


Turn by turn power spectral density for different switching frequencies. *SOLEIL test*

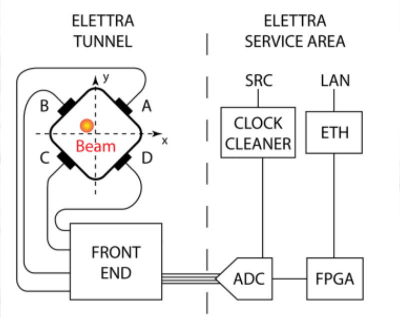
  - To be pushed above the fast correction data bandwidth: increase of the switching frequency
  - Switching to be stopped for turn-by-turn measurements typ. during machine physics studies

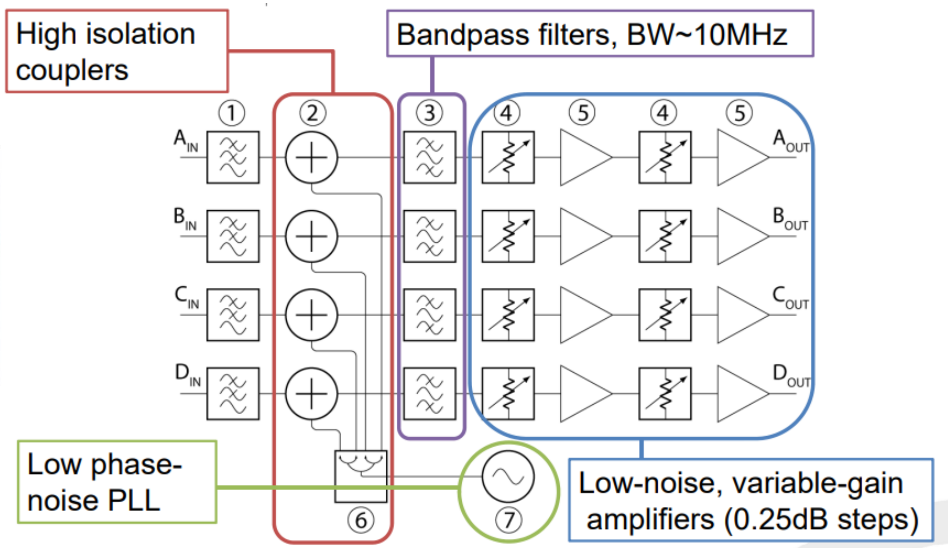
Beam Position Monitors Electronics

- Drift compensation mechanism: Pilot Tone
  - Mix the BPM signal with one (or two) tone close to the RF frequency.
  - Correct the RF signal with the tone drift assuming they 'see' the same perturbation.



BPM ADC Spectrum w/ and w/o pilot tone at ALS. *G. Portman, IBIC 2020 [11]*

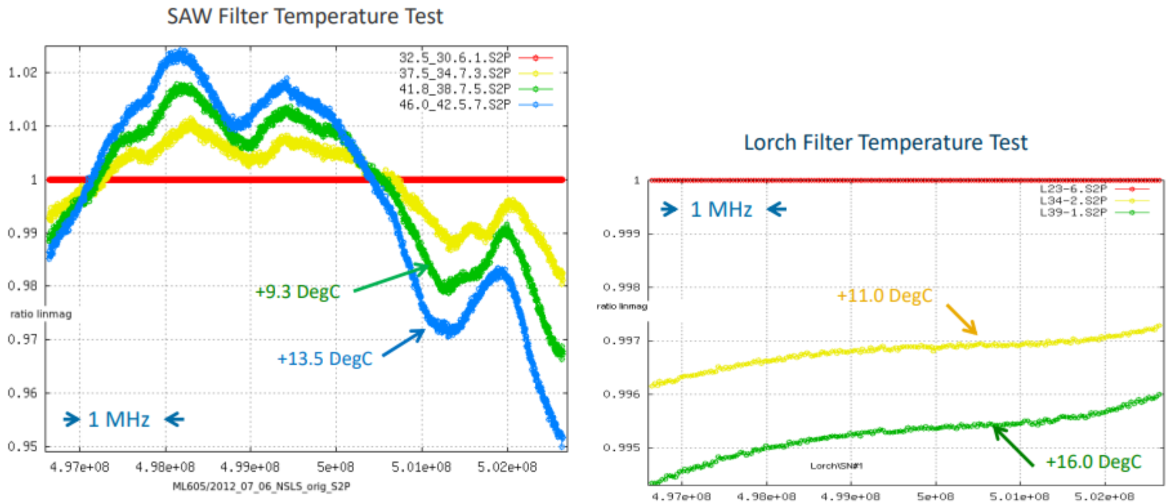




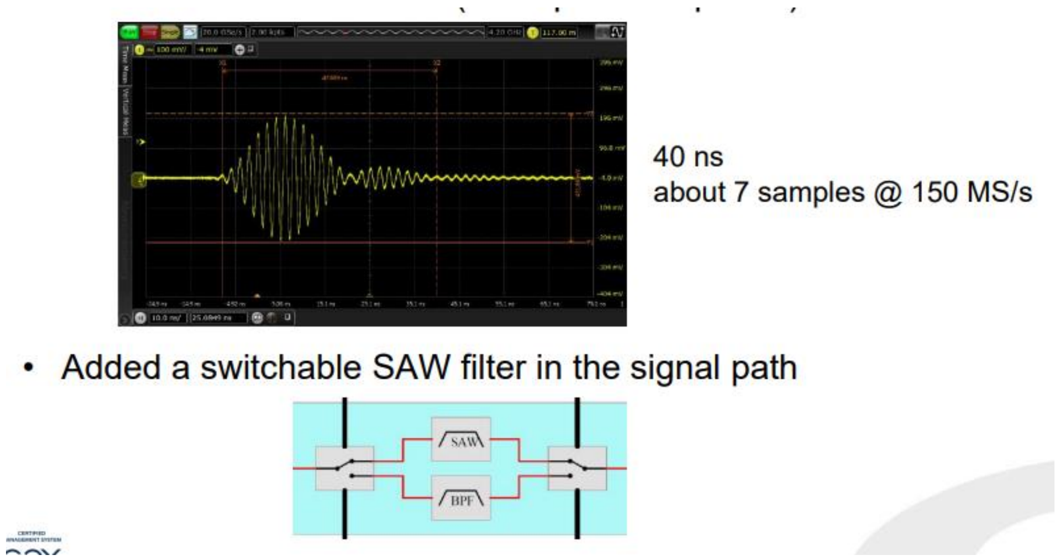
Pilot Tone front-end developed at Elettra. *G. Brajnik, IBIC 2018 [10]*

Beam Position Monitors Electronics

- Drift compensation mechanism: Pilot Tone
  - Band pass filter
    - Usual narrow SAW bandpass filter have a strong temperature dependence.
    - Replaced by larger (flat response) bandpass filter
    - Degraded resolution for single bunch operation (short pulse response)
    - Switchable SAW filter for single operation but without compensation



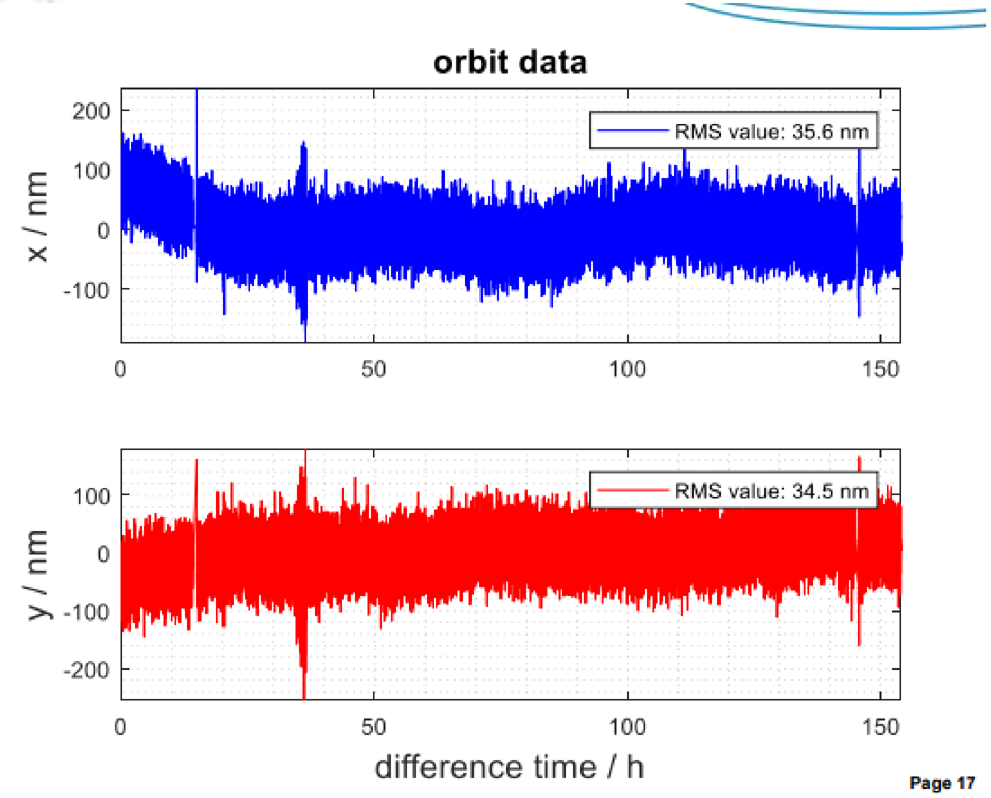
Bandpass filter temperature dependance. *G. Portman, IBIC 2020 [11]*



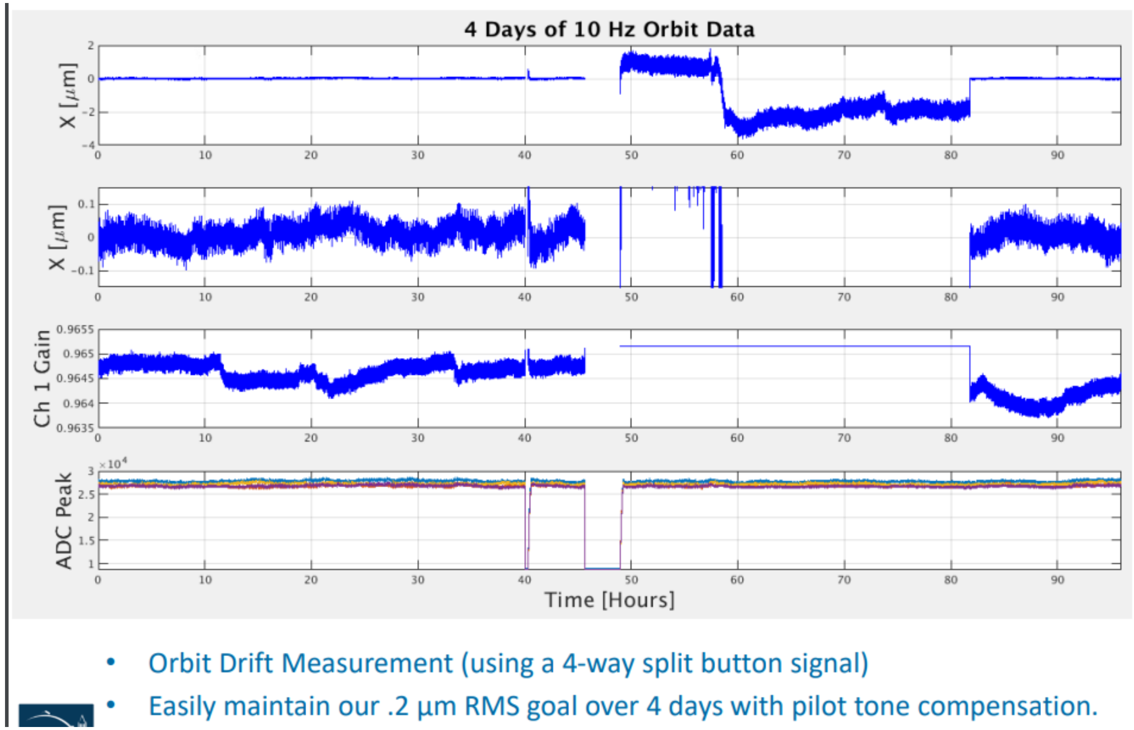
G. Brajnik, Libera Workshop 2021 [12]

Beam Position Monitors Electronics

- Drift compensation mechanism: long term stability performance

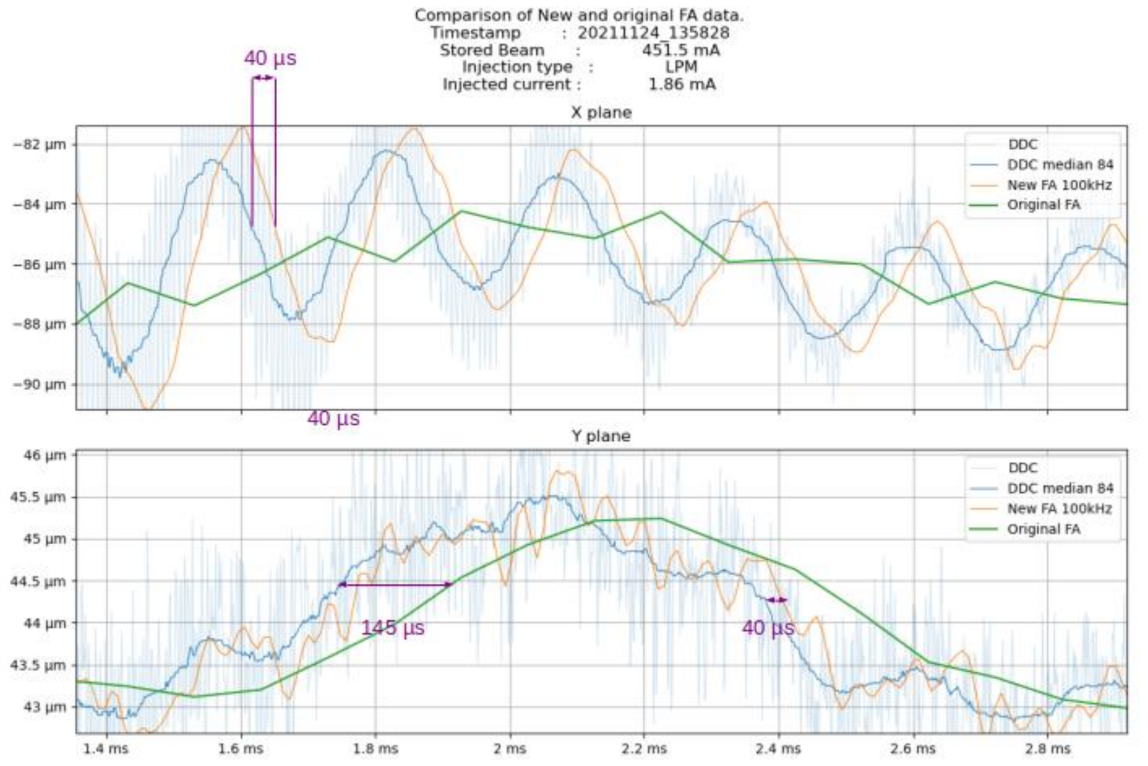


Long term stability measurement at PETRA III with remote switching. *G. Kube, Libera Workshop 2021 [13]*



Long term stability measurement at ALS with pilot tone. *G. Portman, IBIC 2020 [11]*

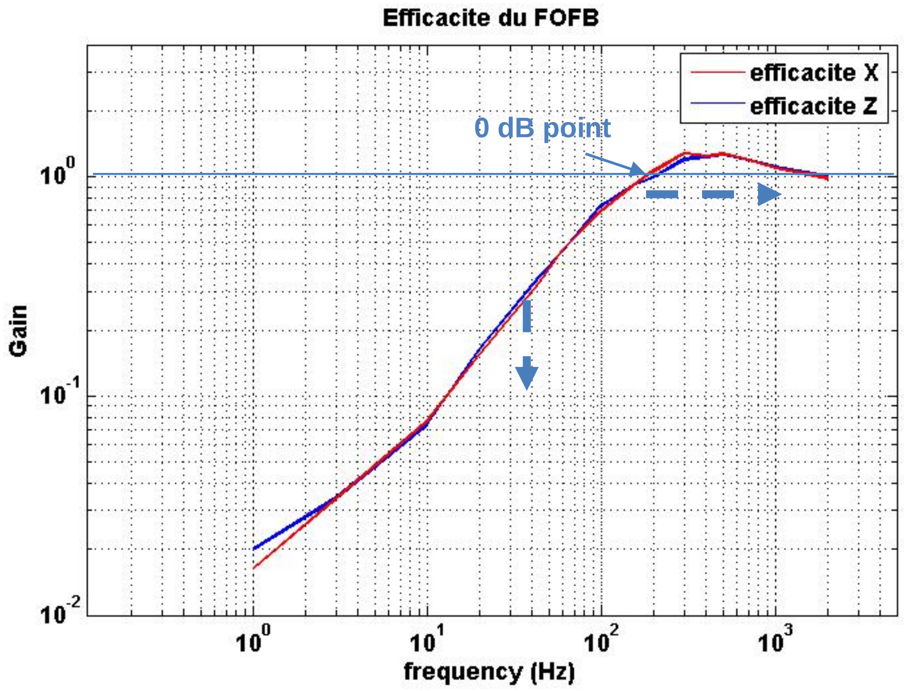
- Latency:
  - Reduce as much as possible the latency of the fast data (used for fast orbit correction):
    - Increase of the fast data sampling rate: from ~10 kHz up to ~100 kHz.
    - Take care at the digital filtering group delay



Numerical filtering of the TbT data by a 25 kHz butterworth filter compared with the current 2 kHz FIR filter . *SOLEIL simulation.*

Orbit Feedback System(s)

- Increase efficiency range of the orbit correction
  - Target: 0 dB point at ~1 kHz

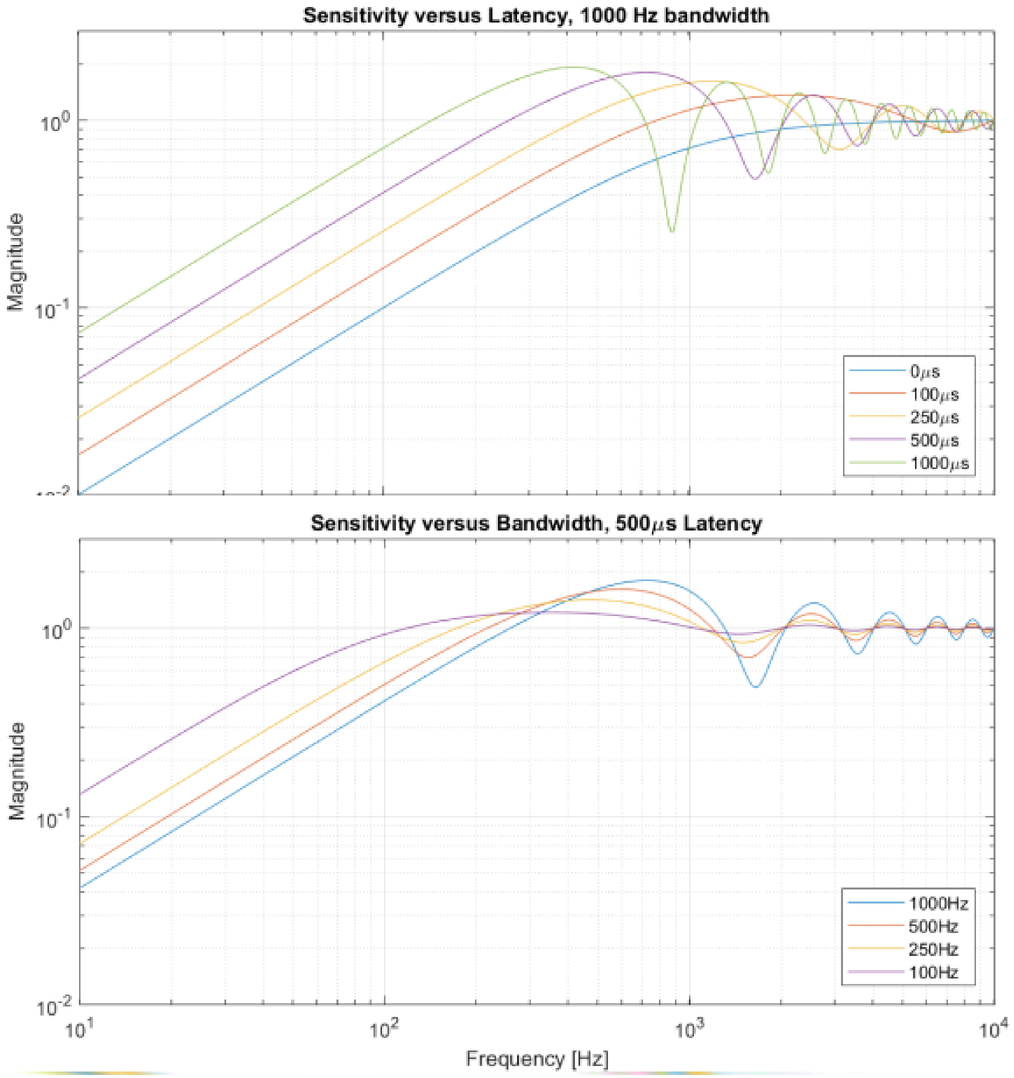


Orbit Feedback System(s)

- Increase efficiency range of the orbit correction
  - Target: 0 dB point at ~1 kHz
  - Minimize latencies:
    - It is generally considered that the latency should not exceed the tenth of the closed-loop 0dB point corresponding period.

0 dB point at 1 kHz

-> latency must be below 100 µs

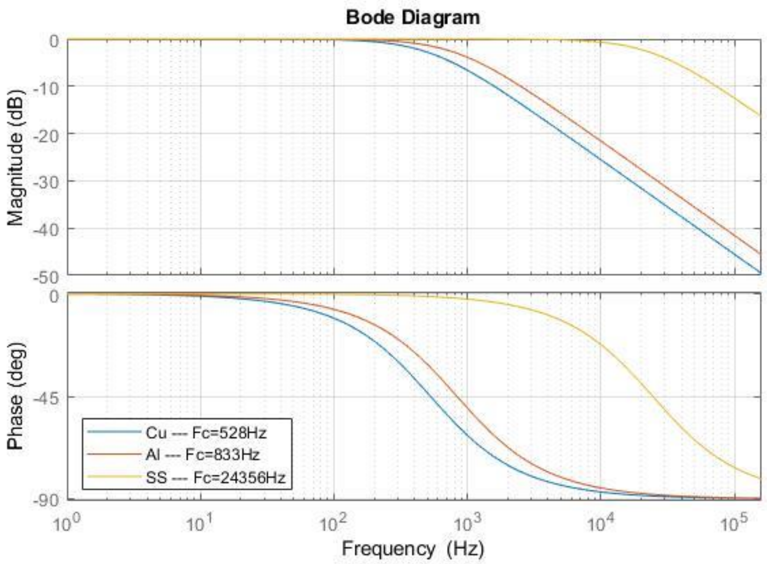


Influence of the latency and bandwidth on the feedback close loop response (with IMC controller).
G. Rehm, Low Emittance Workshop 2018 [14]

Orbit Feedback System(s)

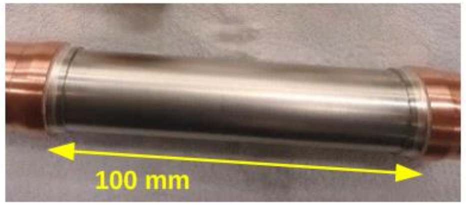
- Increase efficiency range of the orbit correction
  - Target: 0 dB point at ~1 kHz
  - Minimize latencies:
    - It is generally considered that the latency should not exceed the tenth of the closed-loop 0dB point corresponding period.

    0 dB point at 1 kHz
    -> latency must be below 100 µs
  - Increase subsystem bandwidth accordingly:
    - BPMs
    - Magnets+ power-supplies
    - Vacuum chamber: good analytic models for simple geometries: *Podobedov, PAC09 [15]*.



Gain and phase response of a 1 mm thick, 16 mm diameter circular vacuum chamber.

Material thickness to be considered for a cut-off frequency of 15 kHz (latency@1kHz < 10 µs) Case of a 16mm round vacuum chamber	
Copper	35 µm
Aluminium	55 µm
Stainless steel	1.5 mm



SIRIUS fast correctors vacuum chamber. The 0.3 mm SS circular geometry gives a cut-off frequency of 48 kHz [8]

Orbit Feedback System(s)

	Actual FOFB	Future FOFB (specifications)
Position Processing BPM FA filter	190 µs	~40 µs
Position data gathering	60 µs	5 µs
Correction Computation	6 µs	~2 µs
Correction data distribution	0 Already on site	5 µs
Communication to PSU	20 µs	5 µs
FOFB com + comp total	*86 µs*	*< 20 µs*
PSU controller latency	20 µs	*10 µs*
PSU + Self rise time (90%)	30 µs (for 2.5% excursion range)	*Target < 20 µs* (for 2.5% excursion range)
Eddy Currents in vacuum chamber	Unknown	*Target < 10 µs*
Total	~ 360 µs estimated, 400/500 µs observed	< 100 µs

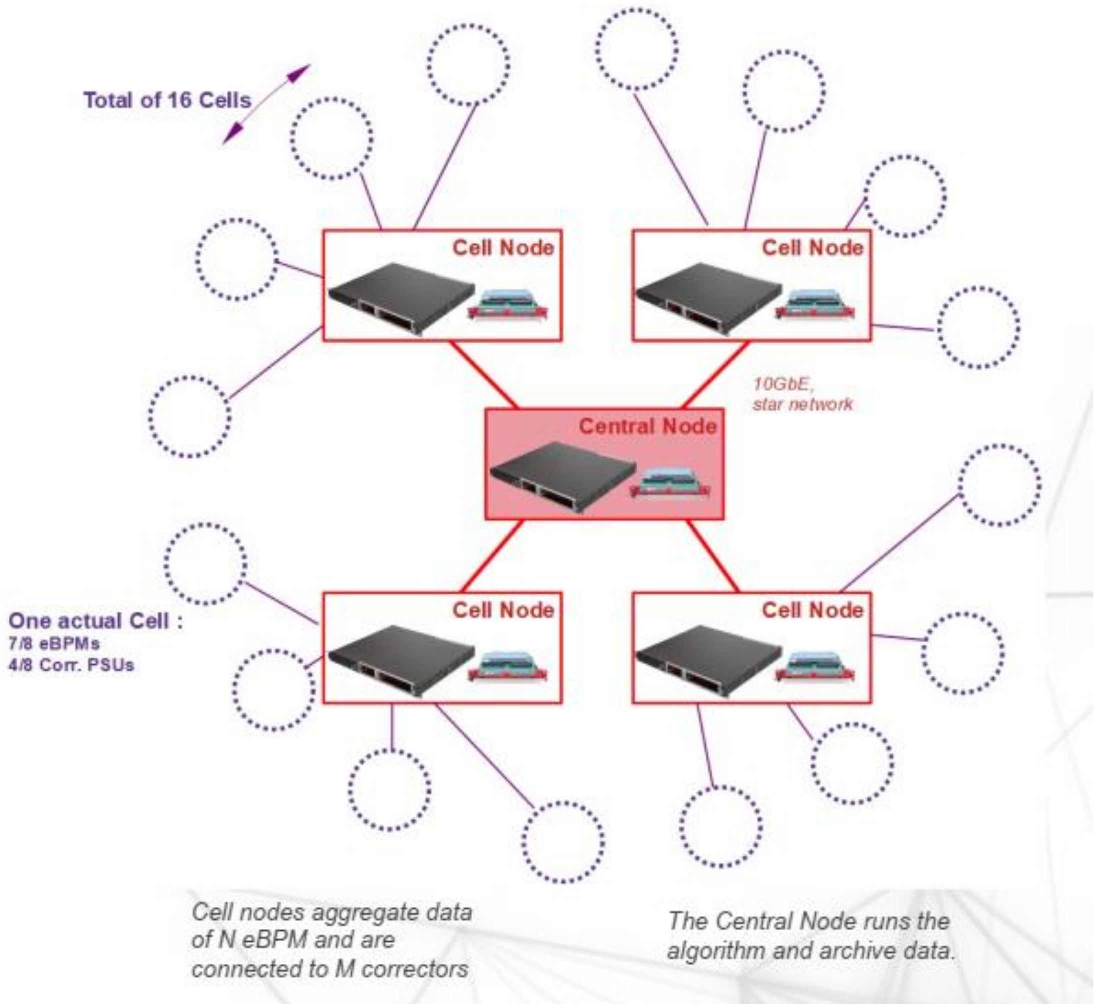
→ New eBPM

→ New FOFB network

Latencies contributions for the current and the future SOLEIL fast orbit feedback.

Orbit Feedback System(s)

- FOFB Network
  - From distributed to central architecture
  - Layered network:
    - Higher network:
      - Star network with a central node
      - Cell nodes aggregates the data
      - High data rate (10 Gbps)
    - Lower network:
      - Topology and data rate less critical
      - BPMs and correctors
  - Numerous high-density high-speed interfaces on the nodes
  - High speed interfaces on the power supplies



Foreseen topology for future SOLEIL FOFB.

Orbit Feedback System(s)

- Sets of correctors
  - Generally difficult to have a single set of correctors that combines strength and high bandwidth.
  - Correction efficient on a unified frequency range.
  - Possibility to have several loops at different update rates that interact between each other. *N. Hubert. DIPAC 2009 [16]*
- Centralized architecture:
  - Slow and fast loops runs on the same hardware.
  - Allows more complex controller schemes (mode control). *G. Rehm, Low Emittance Workshop 2018 [14]*
  - Easy integration of additional sensors (XBPMs, injection events, temperatures…).
  - Ease the control of fast AC machine parameters measurements (response matrix, BBA). *Z. Marti, IBIC 2021 [17]*

Conclusion

- BPM designs are driven by stability requirements:
  - Heat load mitigation
  - Stable supports
  - Compensation mechanism for slow drifts (including cables)
- Big effort put on FOFB efficiency:
  - High bandwidths
  - Shortest latencies
- This attention must not be limited to BPMs and feedback (see Friday presentations)
  - Eliminate the perturbations at the source!
- Open question:
  - Can the synchrotron frequency fall into the FOFB overshoot? Possible consequences to be studied….

Thank you for your attention….

References

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