Orbit Stabilisation

L. Bobb

Diamond-II: challenges and novel solutions for upgrading the national synchrotron light facility

Rutherford Appleton Laboratory

19th January 2024

Challenges for Beam Diagnostics

Diamond-II presents **new challenges for diagnostics and feedbacks**, particularly for the delivery of **beam stability and emittance measurement**.

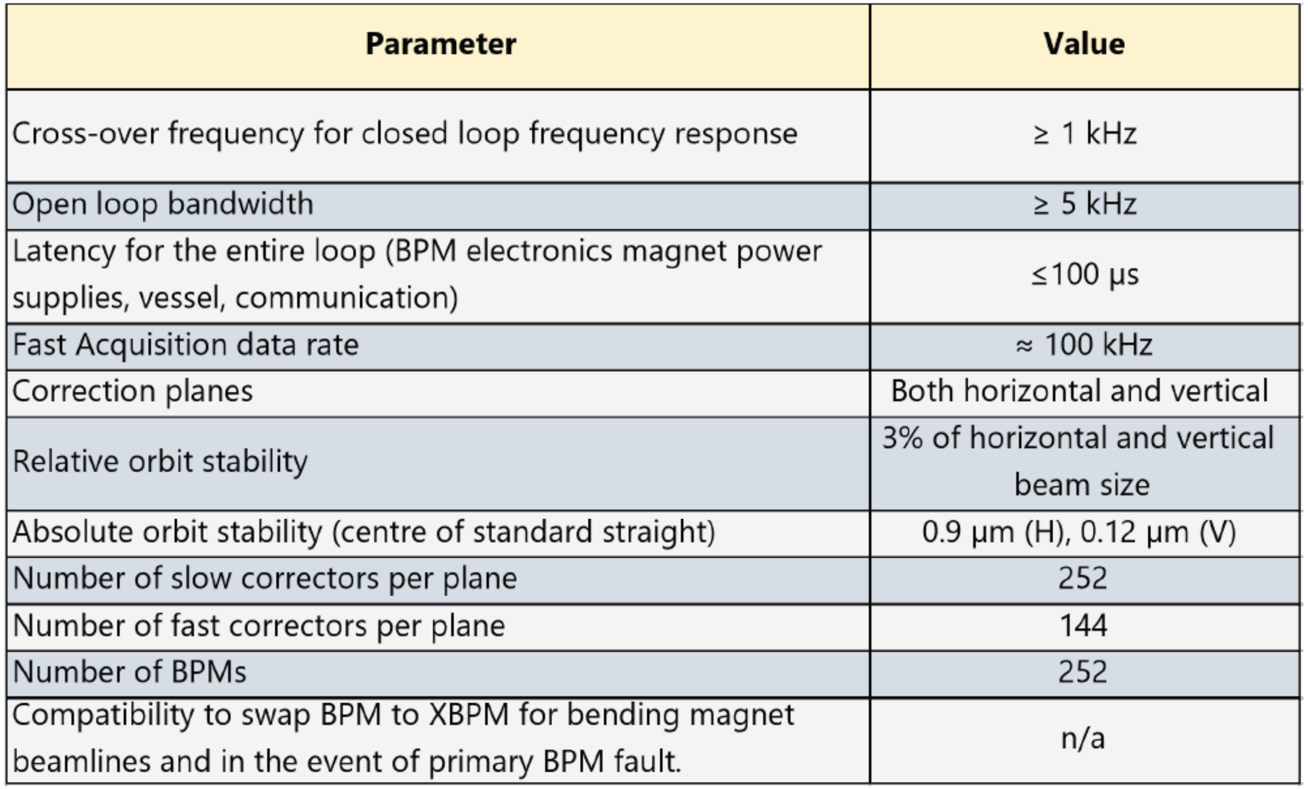
Parameter	Diamond	Diamond-II
Emittance H/V	2700 pm rad / 8 pm rad	160 pm rad / 8 pm rad
Beam size at sourcepoint H/V (standard straight)	123 µm / 3.5 µm	30 µm / 4 µm
Beam Position Monitor (BPM) block aperture H/V	80 mm / 22 mm	20 mm round 24 mm keyhole 26 mm round
Number of BPMs	175	252
Relative orbit stability (short term)	10% of H/V size up to 100 Hz	3% of H/V size up to 1000 Hz
Absolute orbit stability (short term) H/V (centre of standard straight)	12 µm / 0.35 µm	0.9 µm / 0.12 µm

Diamond-II Technical Design Report, 2022

diamond

Orbit Stability Requirements

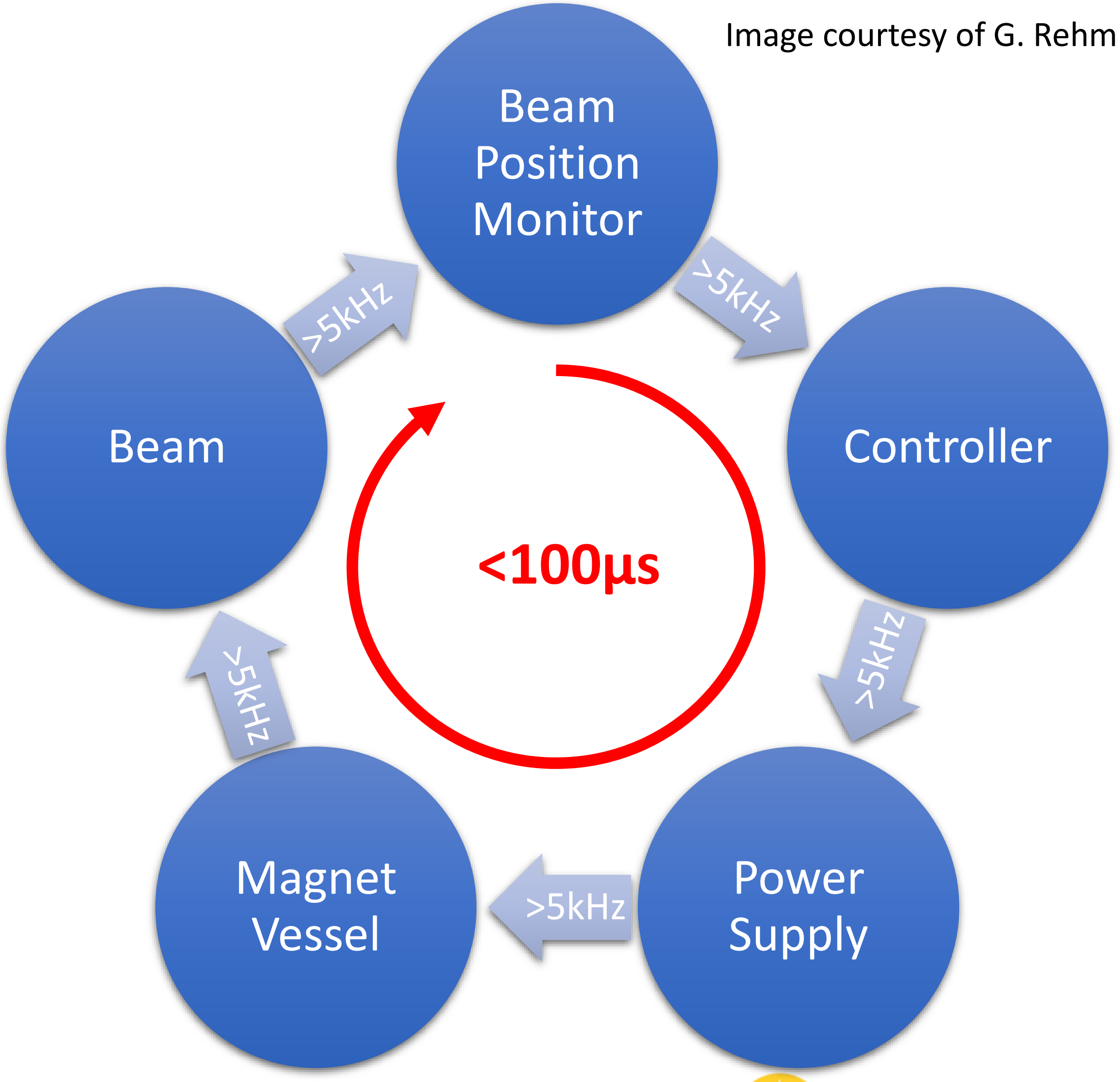
Table 2.11.9: Specification for Fast Orbit Feedback (FOFB).



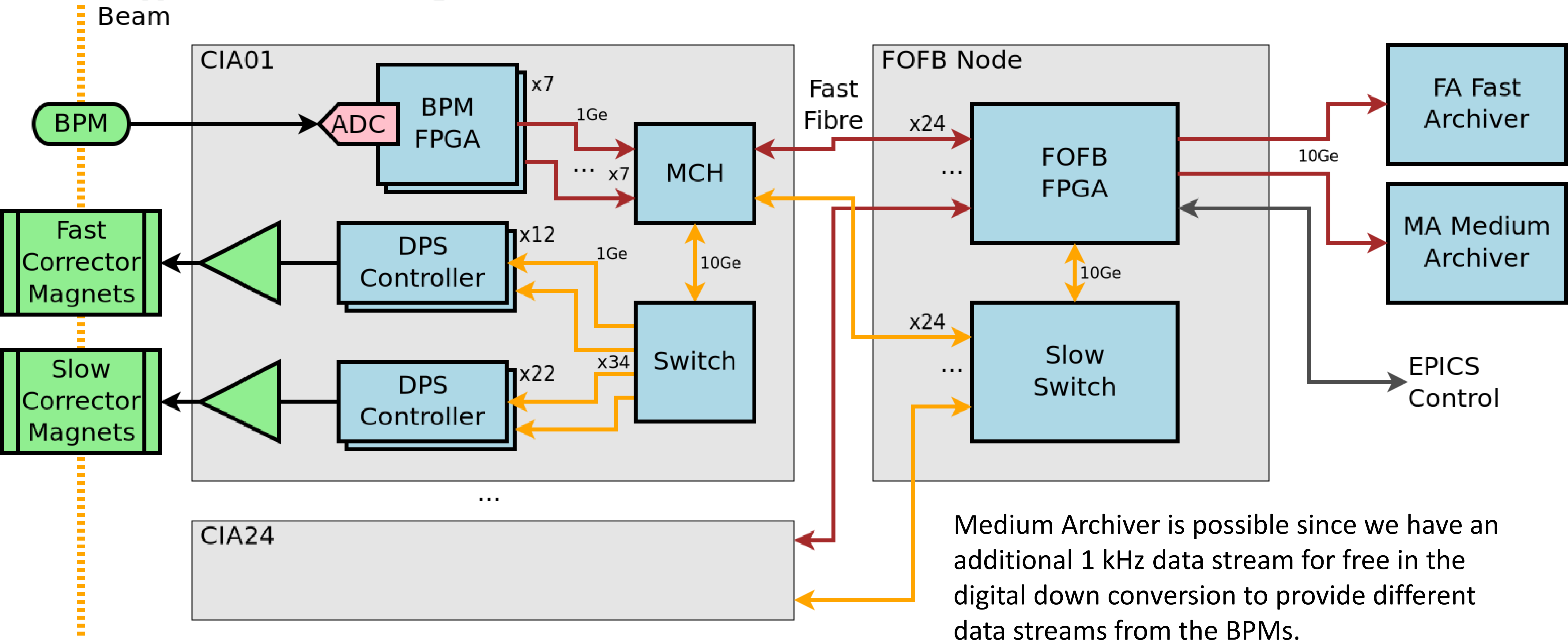
Parameter	Value
Cross-over frequency for closed loop frequency response	≥ 1 kHz
Open loop bandwidth	≥ 5 kHz
Latency for the entire loop (BPM electronics magnet power supplies, vessel, communication)	≤100 µs
Fast Acquisition data rate	≈ 100 kHz
Correction planes	Both horizontal and vertical
Relative orbit stability	3% of horizontal and vertical beam size
Absolute orbit stability (centre of standard straight)	0.9 µm (H), 0.12 µm (V)
Number of slow correctors per plane	252
Number of fast correctors per plane	144
Number of BPMs	252
Compatibility to swap BPM to XBPM for bending magnet beamlines and in the event of primary BPM fault.	n/a

Diamond-II Technical Design Report, 2022

Image courtesy of G. Rehm



Fast Orbit Feedback Architecture



Medium Archiver is possible since we have an additional 1 kHz data stream for free in the digital down conversion to provide different data streams from the BPMs.

Fast Orbit Feedback Central Node

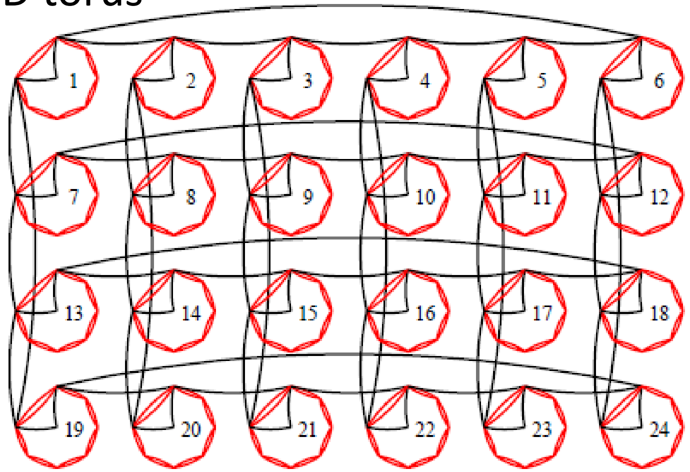
- FOFB 2D torus is currently implemented on Diamond with a total latency of 600 µs, crossover frequency (-3dB) of approx. 100 Hz i.e. closed loop bandwidth, open loop bandwidth of 600 Hz and uses a 10 kHz sample data rate from the BPMs.

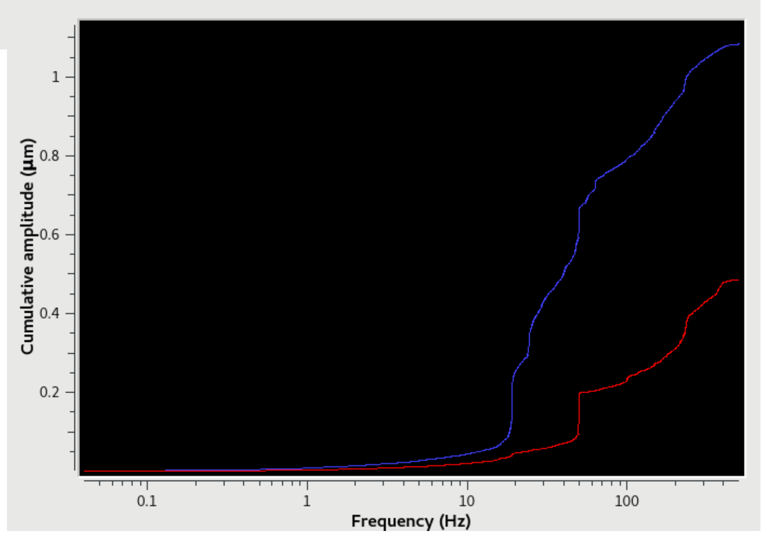
- To reach 100 µs latency a more direct architecture is required where all processing is done via a centralised node i.e. star topology.

- Alongside the existing 2D torus topology, we have implemented a star network with central node for Diamond-II R&D to enable testing the on the existing storage ring.

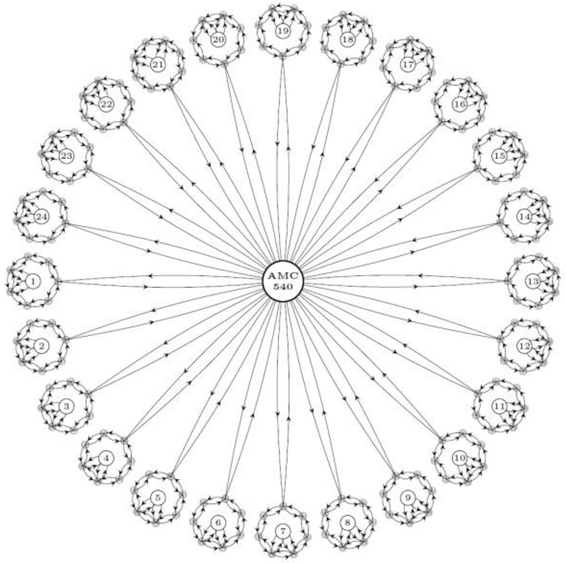
- Due to additional patches required to implement the star topology on the existing storage ring, it is expected that running the Diamond FOFB control algorithm on the star topology has similar performance to that of the 2d torus. However it enables us to test and gather experience of hardware and operation in this new architecture.

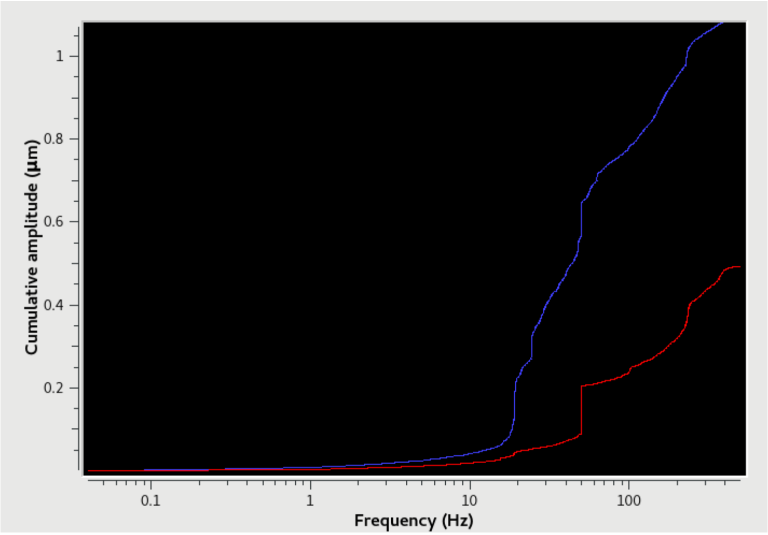
2D torus





Star





Latency Considerations

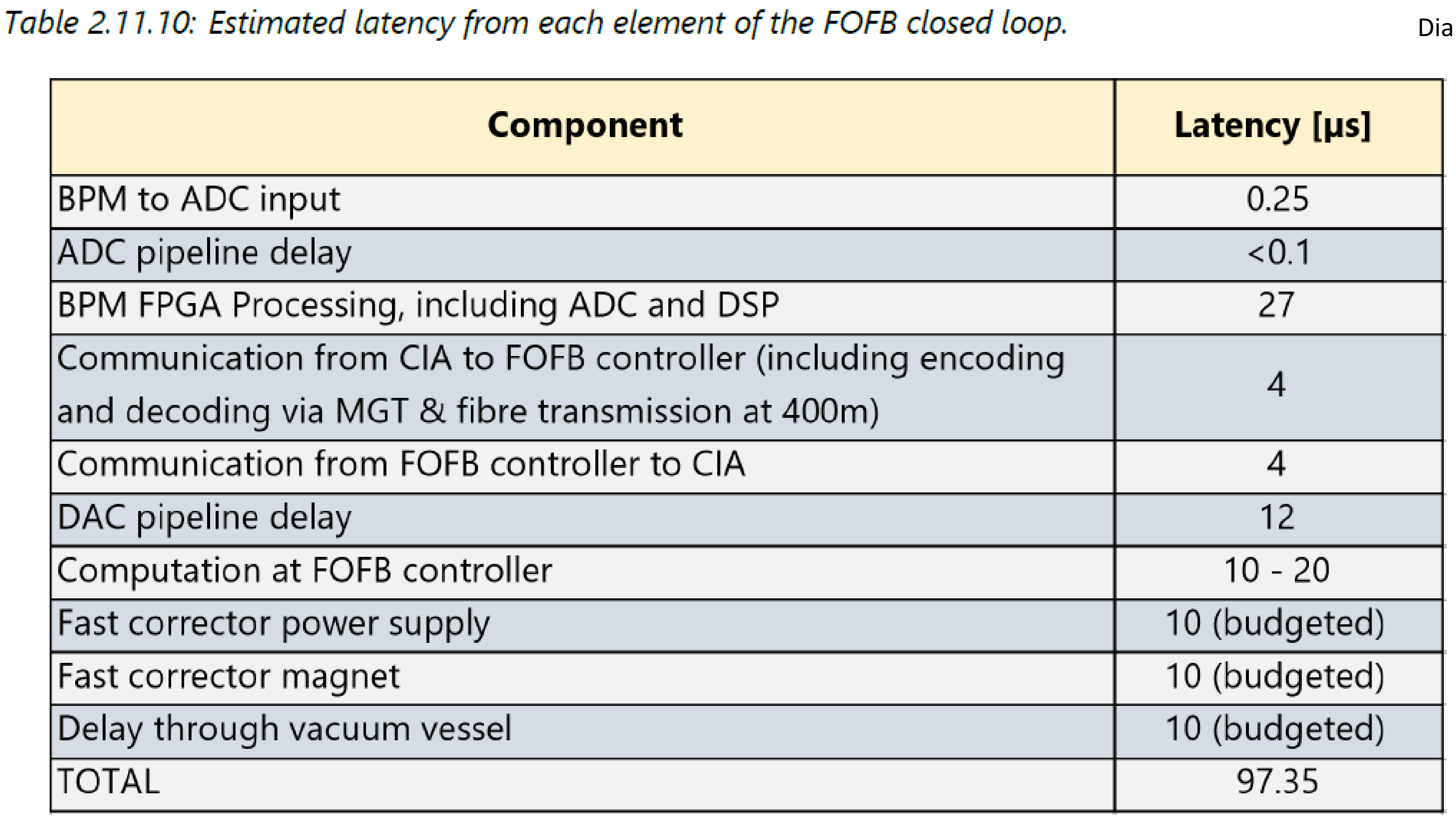


Table 2.11.10: Estimated latency from each element of the FOFB closed loop.

Diamond-II TDR, 2022

Component	**Latency [μs]**
BPM to ADC input	0.25
ADC pipeline delay	<0.1
BPM FPGA Processing, including ADC and DSP	27
Communication from CIA to FOFB controller (including encoding and decoding via MGT & fibre transmission at 400m)	4
Communication from FOFB controller to CIA	4
DAC pipeline delay	12
Computation at FOFB controller	10 - 20
Fast corrector power supply	10 (budgeted)
Fast corrector magnet	10 (budgeted)
Delay through vacuum vessel	10 (budgeted)
TOTAL	97.35

FOFB Controller Algorithm

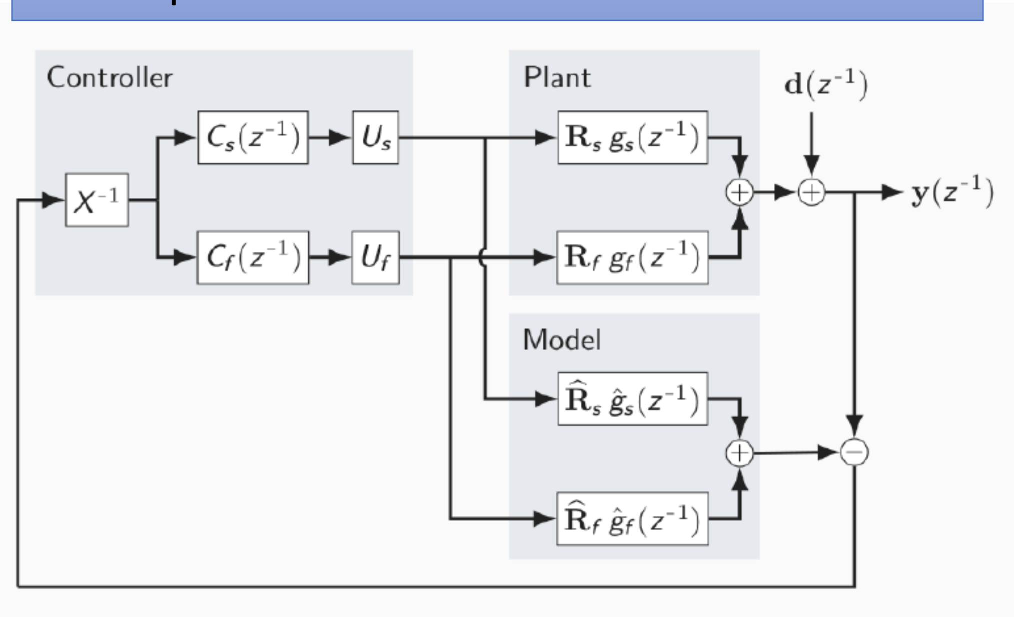
Control algorithm is based on the Internal Model Controller (IMC) with Regularised Response Matrix as currently used at Diamond, with two key changes:

1. The **feedback update rate has been increased from 10 kHz to 100 kHz**. This has little theoretical impact to the FOFB algorithm but has a large impact on the development of the controller, BPMs, and corrector magnets.
2. There are now corrector magnets operating at two different rates: ”**fast correctors**” with a 3 dB roll-off at around 8 kHz, and ”**slow correctors**” with a roll-off at 100-300 Hz.

Label	Description
Plant	**synchrotron** which takes corrector magnet inputs, applies slow and fast corrector dynamics followed by the orbit response matrices $R_{s,f}$.
y	**resulting beam motion measured by BPMs** with a noise and disturbance component denoted *d*
Model	**the internal model** which is used to predict the expected response from the system.

From the bottom right of the figure, the difference in measured and expected beam position is propagated to the Controller which calculates the required corrector magnet settings via decomposition and inversion of the orbit response matrix using Generalised Singular Value Decomposition*.

Dual Rate IMC using Generalised Singular Value Decomposition

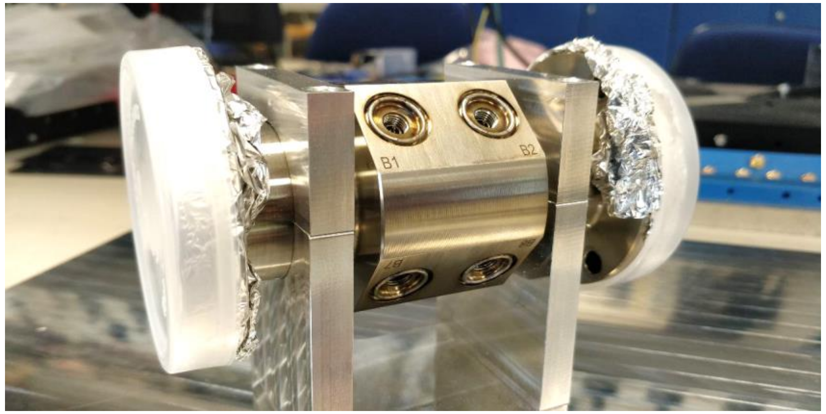


*I. Kempf *et al.*, *Proc. IEEE Conf. Decis.Contr. (CDC)*, Jeju Island, Republic of Korea, Dec. 2020, pp. 3431–3436. https://doi.org/10.48550/arXiv.2009.00345

BPM Main Requirements

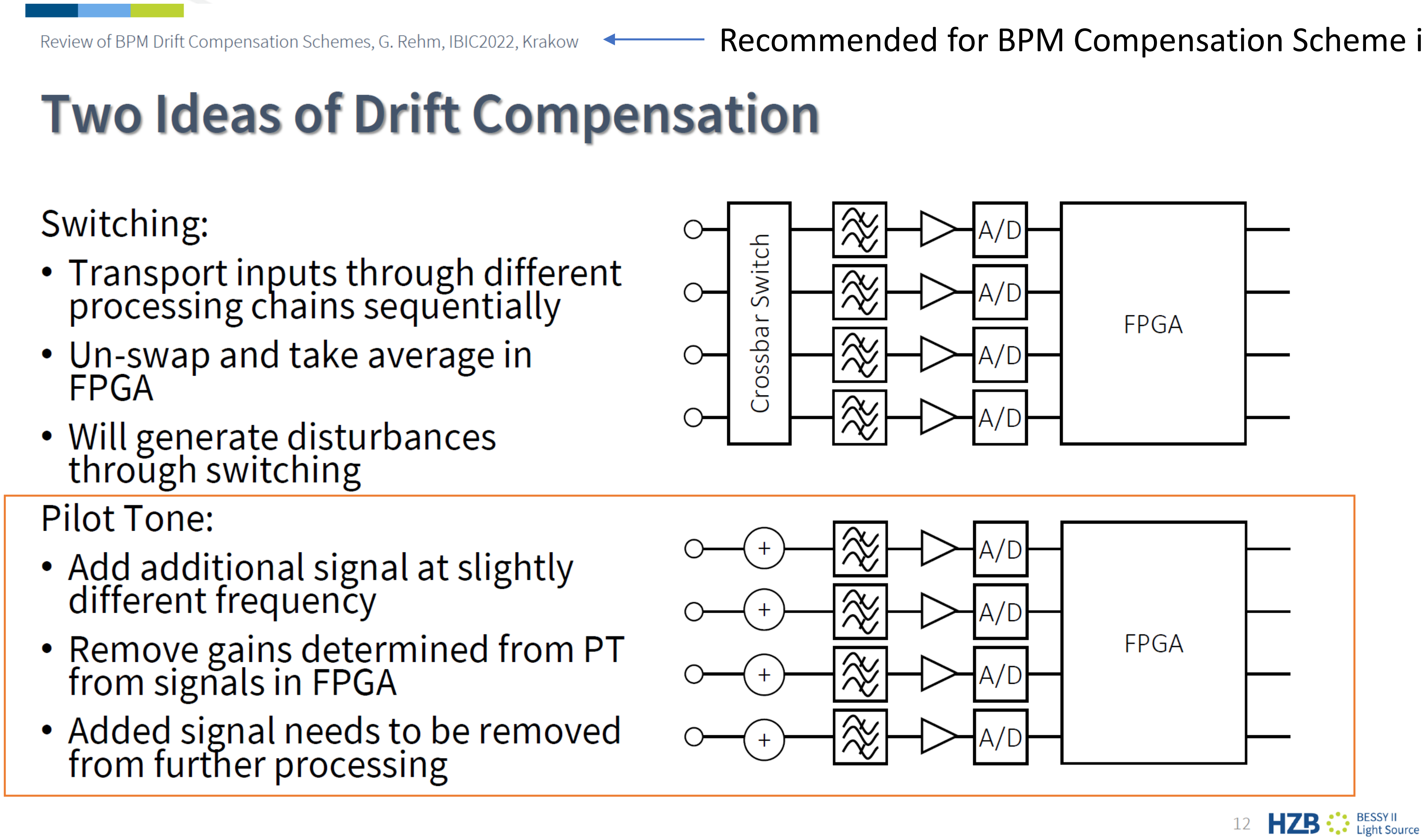
- 252 Storage Ring EBPMs (11/12 per cell):
  - 96 Primary EBPMs:
    - For beam alignment through IDs
    - Located in straights on dedicated thermally stable pillars
  - 162 Standard/Arc EBPMs:
    - For beam alignment through magnets.
    - Mounted directly to the girder.
- Injector EBPMs replaced after Diamond-II.

- Short-term motion (<1 second):
  - Commissioning (0.3 mA): <130 nm/√Hz
  - User beam (300 mA): <2 nm/√Hz
- Long-term motion (<1 wk): <1 μm/√Hz
- Data rate increase from 10 to 100 kHz.



L. T. Stant et al., “Diamond-II Electron Beam Position Monitor Development”, in Proc. IBIC'22, Kraków, Poland, Sep. 2022, pp. 168-172. doi:10.18429/JACoW-IBIC2022-MO3C2

BPM Compensation Schemes



Review of BPM Drift Compensation Schemes, G. Rehm, IBIC2022, Krakow

Recommended for BPM Compensation Scheme info

Two Ideas of Drift Compensation

Switching:

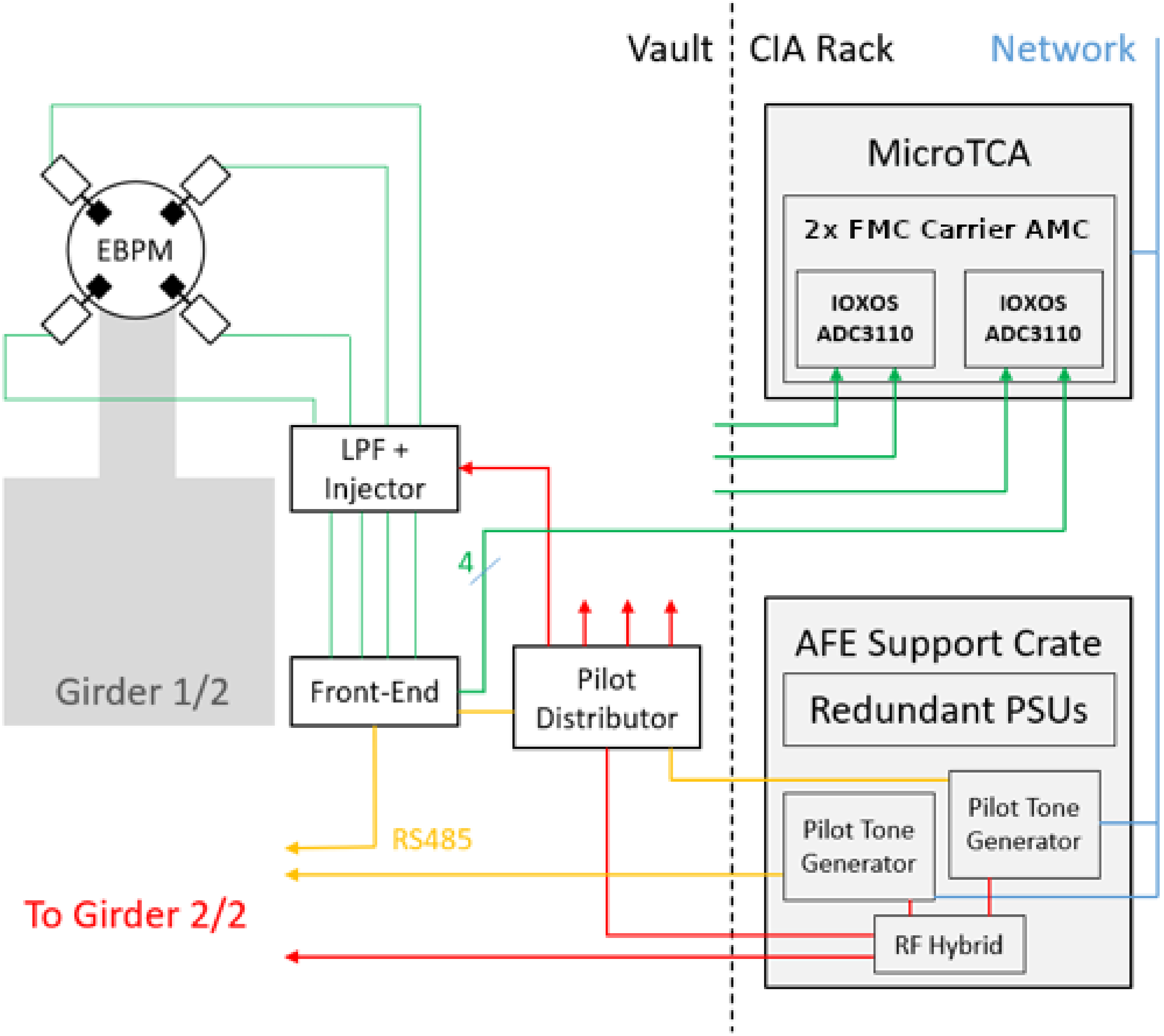
- Transport inputs through different processing chains sequentially
- Un-swap and take average in FPGA
- Will generate disturbances through switching

Pilot Tone:

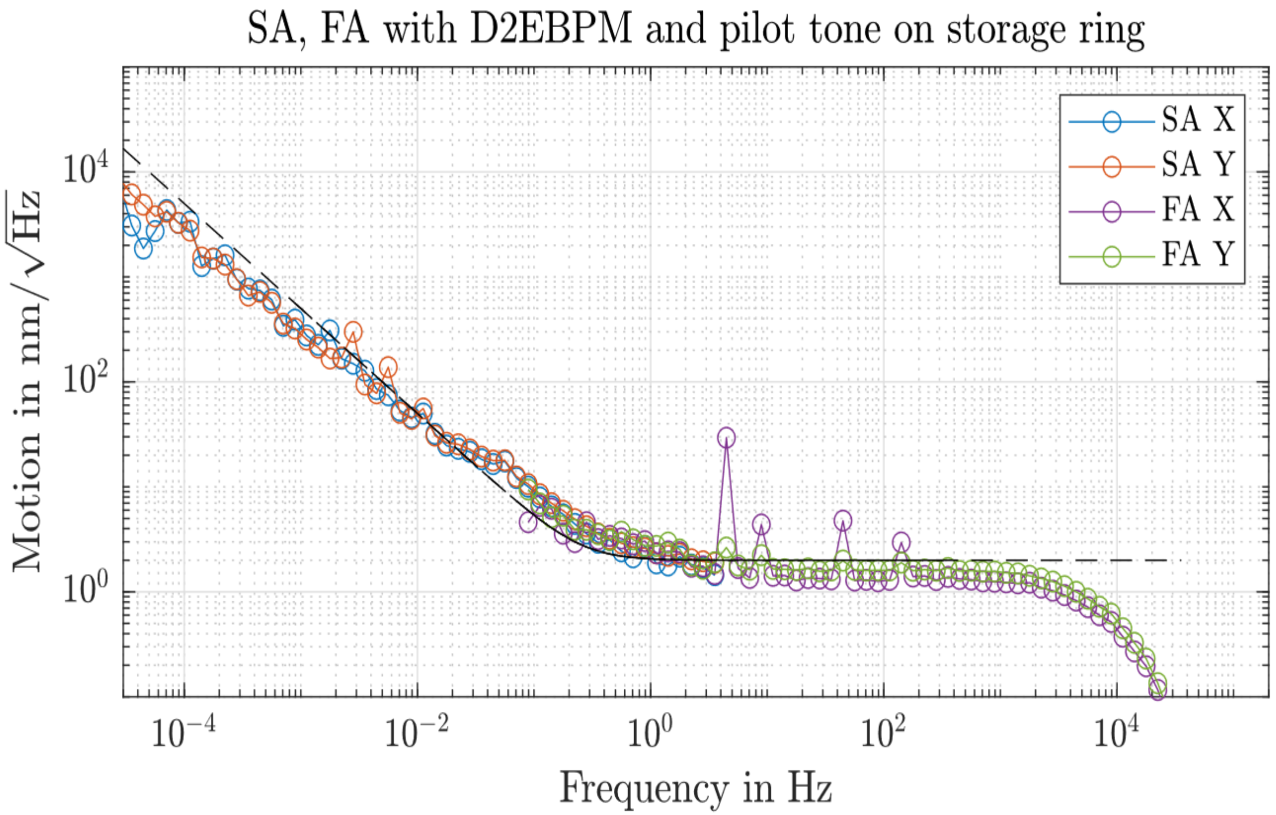
- Add additional signal at slightly different frequency
- Remove gains determined from PT from signals in FPGA
- Added signal needs to be removed from further processing

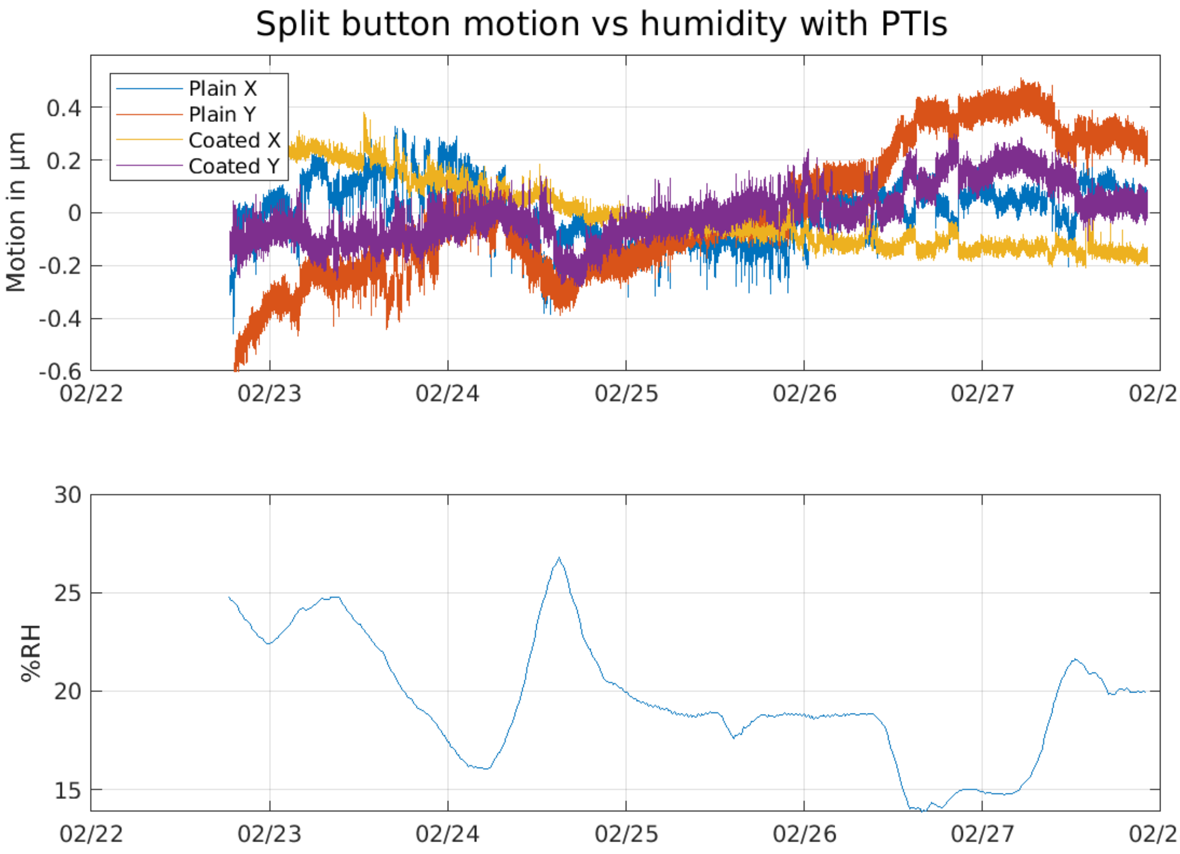
Beam Position Monitor Architecture

Image courtesy of L. Stant



BPM Performance (April'23)

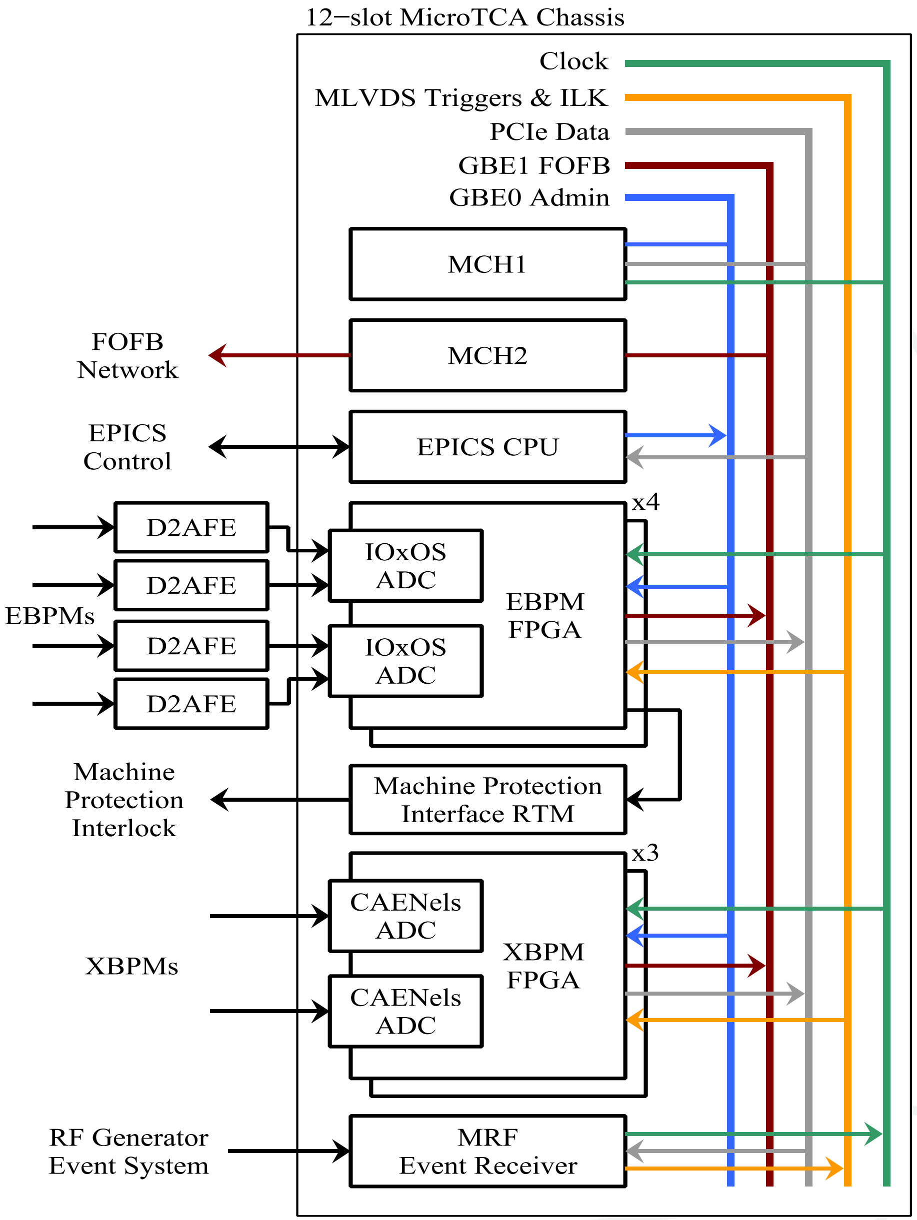




Spikes at 50 Hz and harmonics are due to pilot tone injector being outside of enclosure (was not available) so it is picking up external noise.

Testing conformal coating of pilot tone injector boards to improve longterm stability.

BPM Digitisation and Processing - MicroTCA

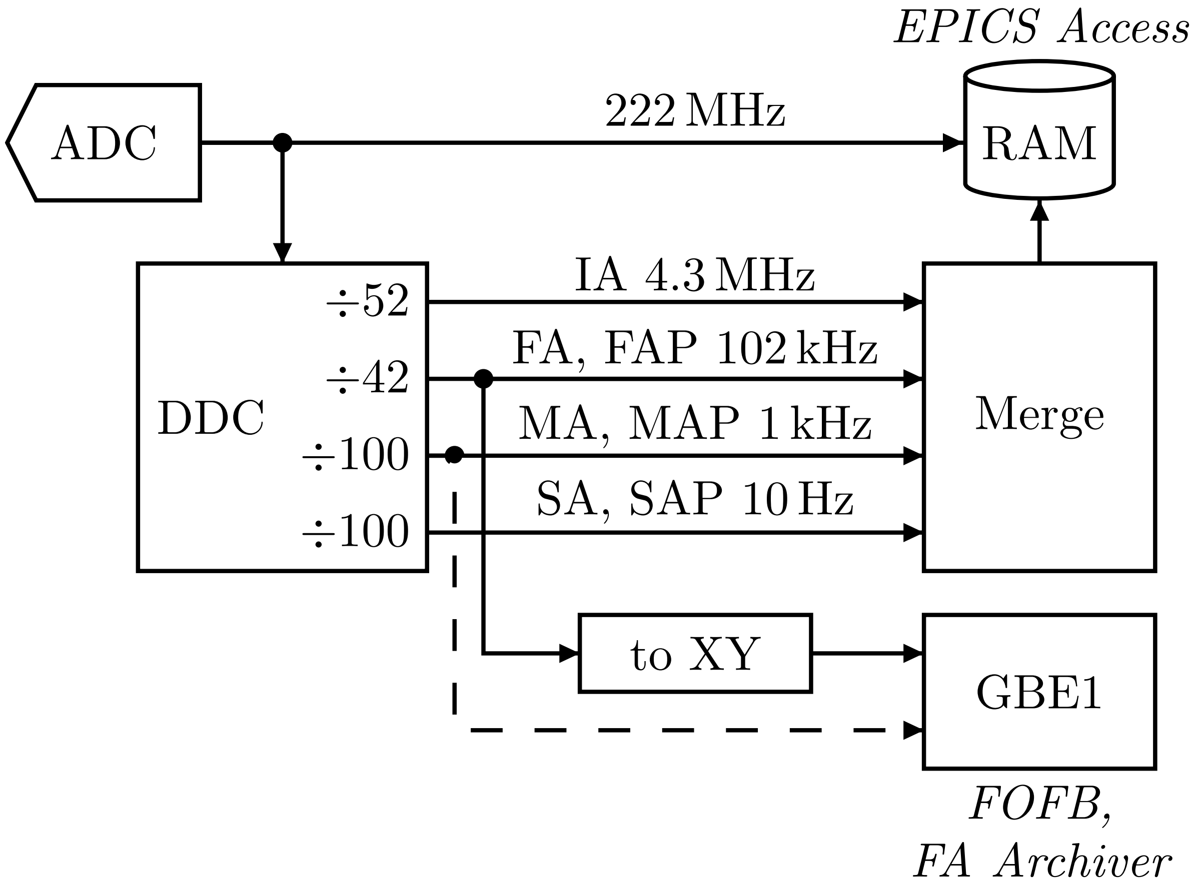


- A single 12-slot crate handles an entire cell of EBPM and XBPM diagnostics.
- Four EBPM dual-FMC carrier cards.
- Each FMC has an 8-ch 16-bit 250 Msps ADC.
- Up to three XBPM dual FMC carrier cards.
- Dual MCH: One for PCIe, one for FOFB GbE.
- Event receiver card, CPU card.
- Machine protection from custom RTM.

BPM Data Streams

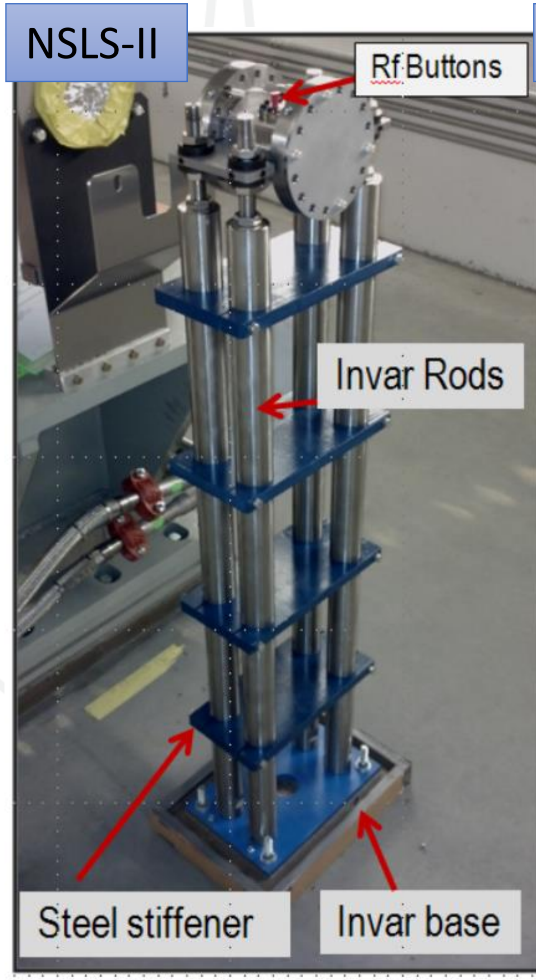
- 222 Msps ADC streamed to RAM.

- Downconverted with 70 MHz IF and then downsampled into streams:
  - 4.3 MHz intermediate acquisition
  - 102 kHz fast acquisition (+ pilot) *Used for FOFB and fast archiver*
  - 1 kHz medium acquisition (+ pilot) *Used as a new archiver source*
  - 10 Hz slow acquisition (+ pilot)

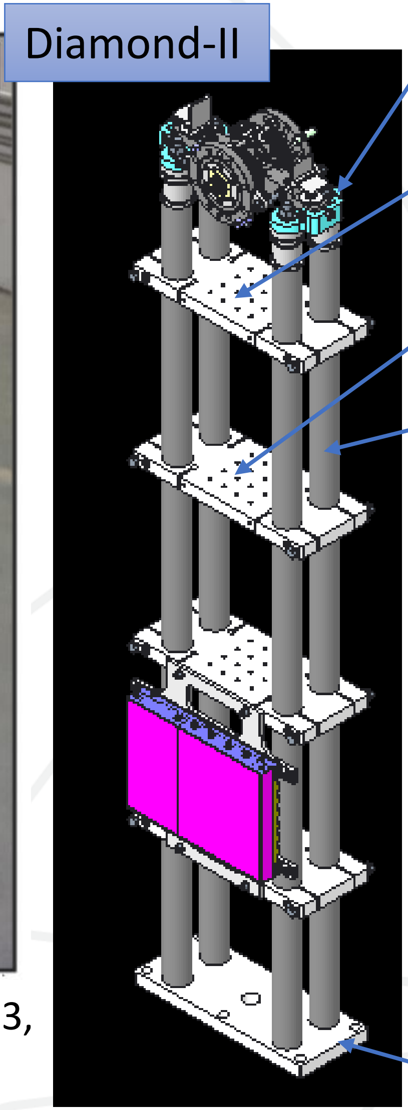


Primary BPM Support

Given the motivation of a low CTE material, Diamond-II design is based on NSLS-II



O. Singh et al., Proc. of IBIC2013, Oxford, UK, 2013 (TUBL1)



Adjusters

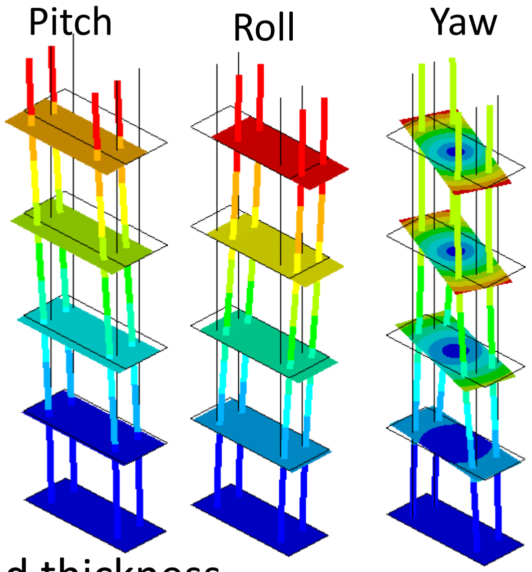
Space and mounting reserved for tuned mass damper option

Stiffener plates (st.st. or Al)

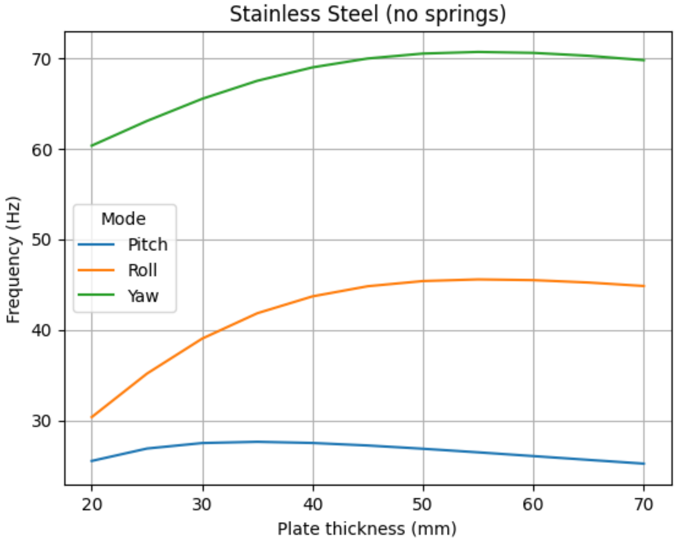
Column (Invar 36)

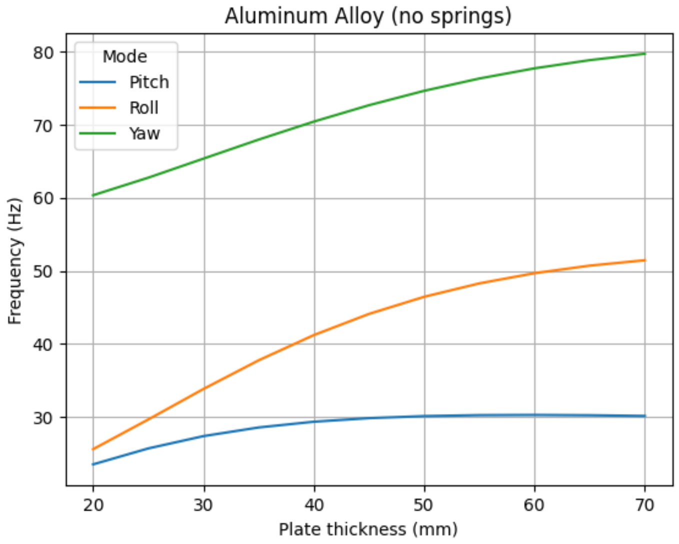
Invar baseplate

Courtesy of D. Crivelli



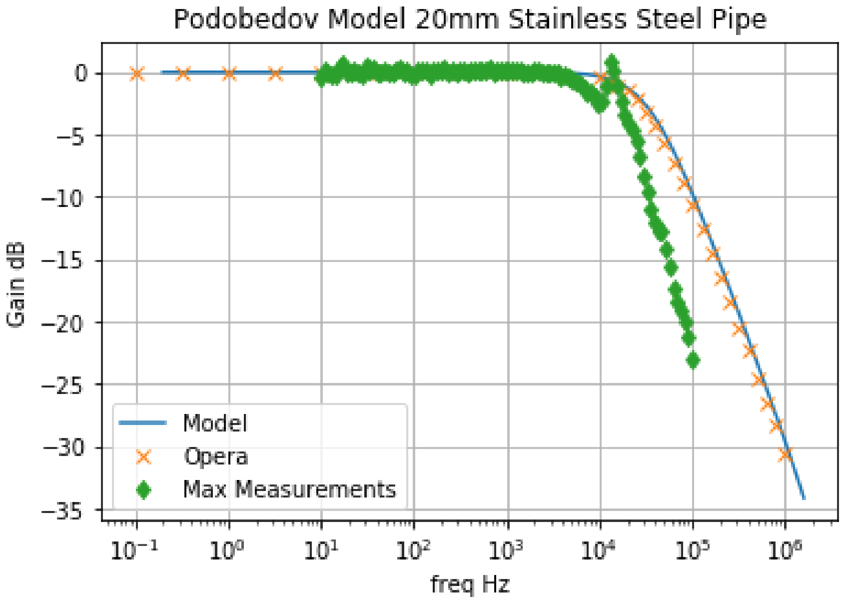
Studies to choose plate material and thickness



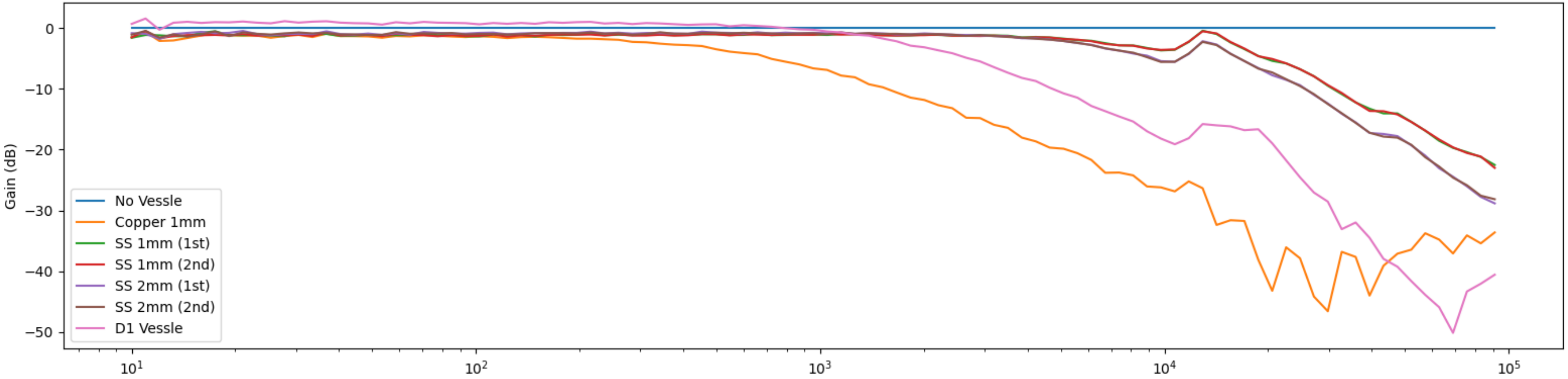


Vessel Considerations

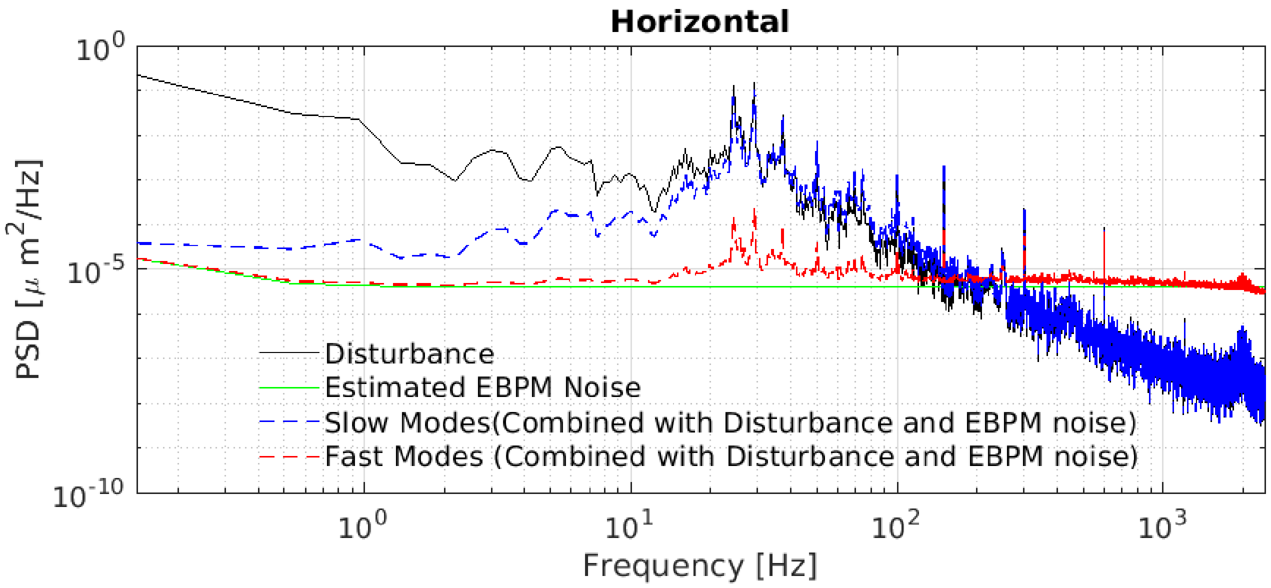
Courtesy of Max Simmonds, Colin Abraham, Alan Tipper

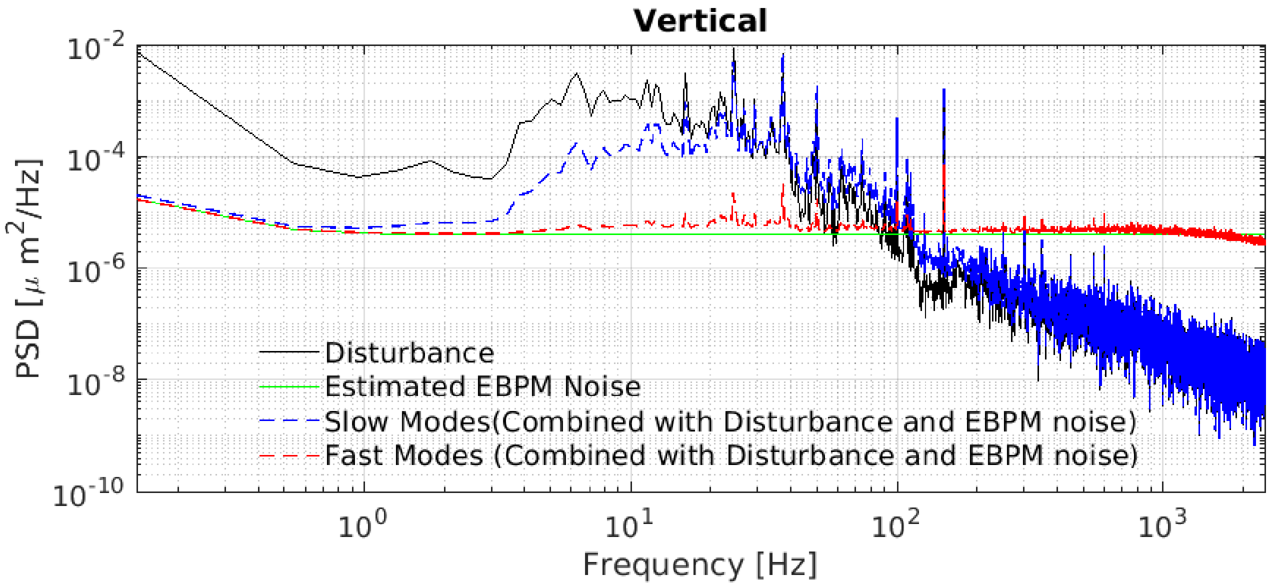


Initial measurements were performed in 2021 and compared against the Podobedov model and simplified Opera simulation.



Disturbance Model





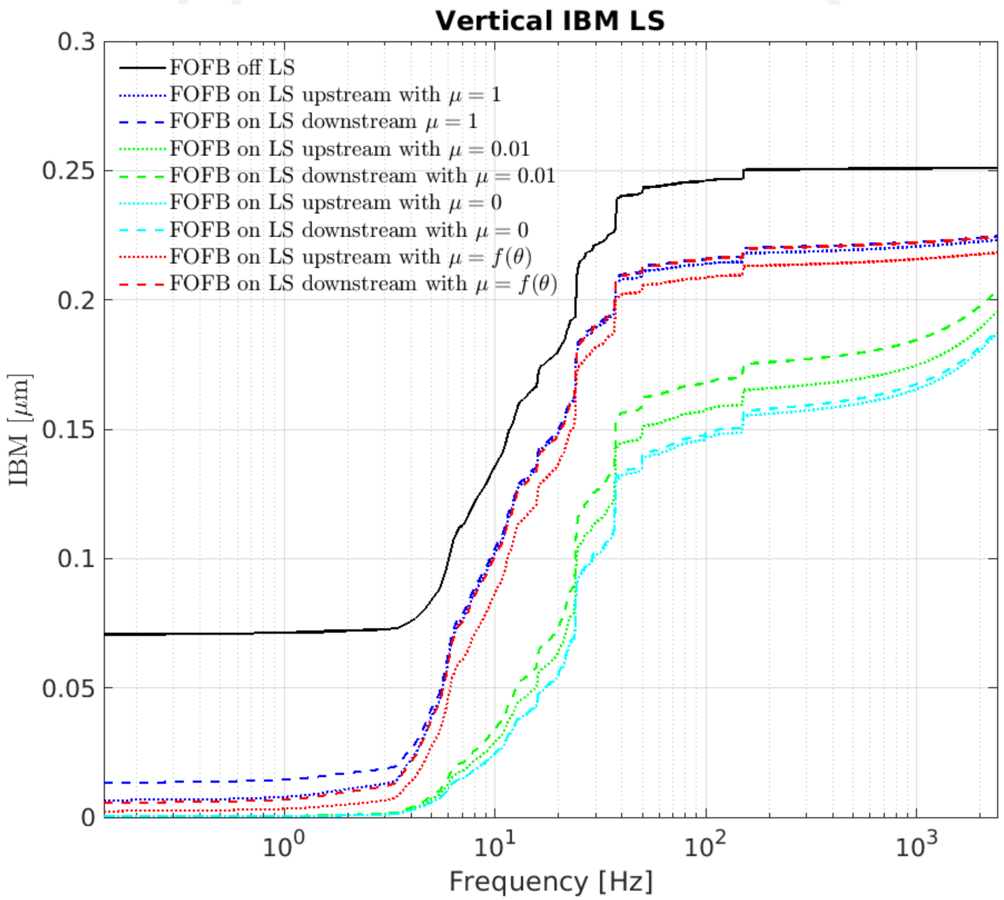
- Power spectral density of the expected beam displacement along standard straights (black).
- Power spectral density of the estimated EBPM noise (green).
- Resulting displacement when the closed-loop FOFB gain for slow and fast modes is applied (dashed lines).

<200 Hz disturbance dominates over the EBPM noise.
>200 Hz EBPM dominates over the disturbance.

→ Controller is designed to attenuate the disturbance only within the specified 1 kHz closed-loop bandwidth.

FOFB Performance

Integrated motion at primary BPMs of the Long Straight



Location	Plane	Target at BPM [µm]	FOFB off [µm]	FOFB on (average*) [µm]	
				From upper bound	From simulation
Long Straight	Horizontal	<1.20	0.72	0.29	0.27
	Vertical	<0.23	0.26	0.22	0.20
Standard Straight	Horizontal	<0.97	0.66	0.20	0.15
	Vertical	<0.18	0.53	0.15	0.13
Mid Straight	Horizontal	<0.90	0.23	0.19	0.15
	Vertical	<0.14	0.19	0.11	0.10

*Calculated average of the upstream and downstream primary BPMs in each straight. Results represent upper bound based on Power Spectral Density data i.e. “worst-case” scenario.

3% wrt beam size is satisfied in both planes. LS vertical is marginal, however we are exploring the use of the regularisation parameter against the gains on the slow and fast corrector magnets to optimise performance. Fast corrector demand analysis is on-going.

Acknowledgements

M. Abbott, C. Abraham, S. Banerjee, G. Christian, D. Crivelli, I. Kempf, I. Martin, A. Morgan, E. Perez Juarez, G. Rehm, A. Rose, M. Simmonds, L. Stant, A. Tipper, and P. Vivian.

Thank you for your attention!