Diamond-II: Diagnostics and Feedbacks

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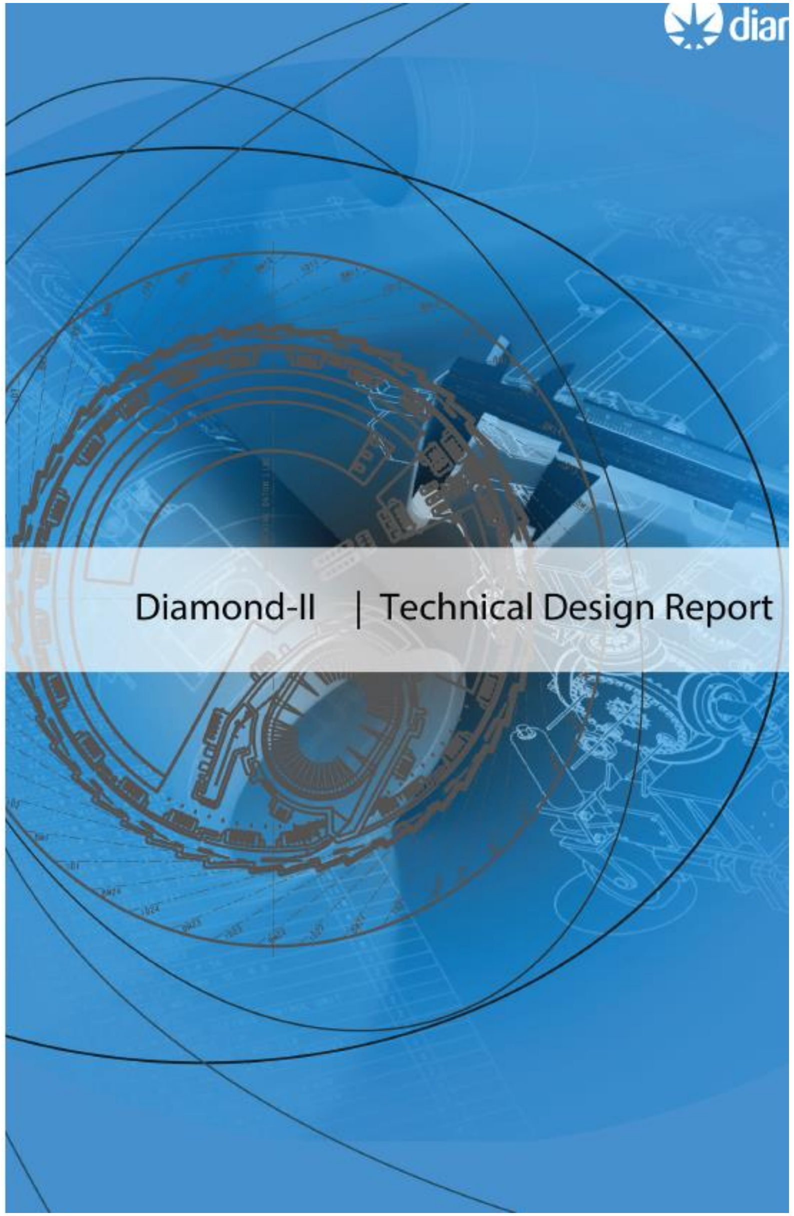
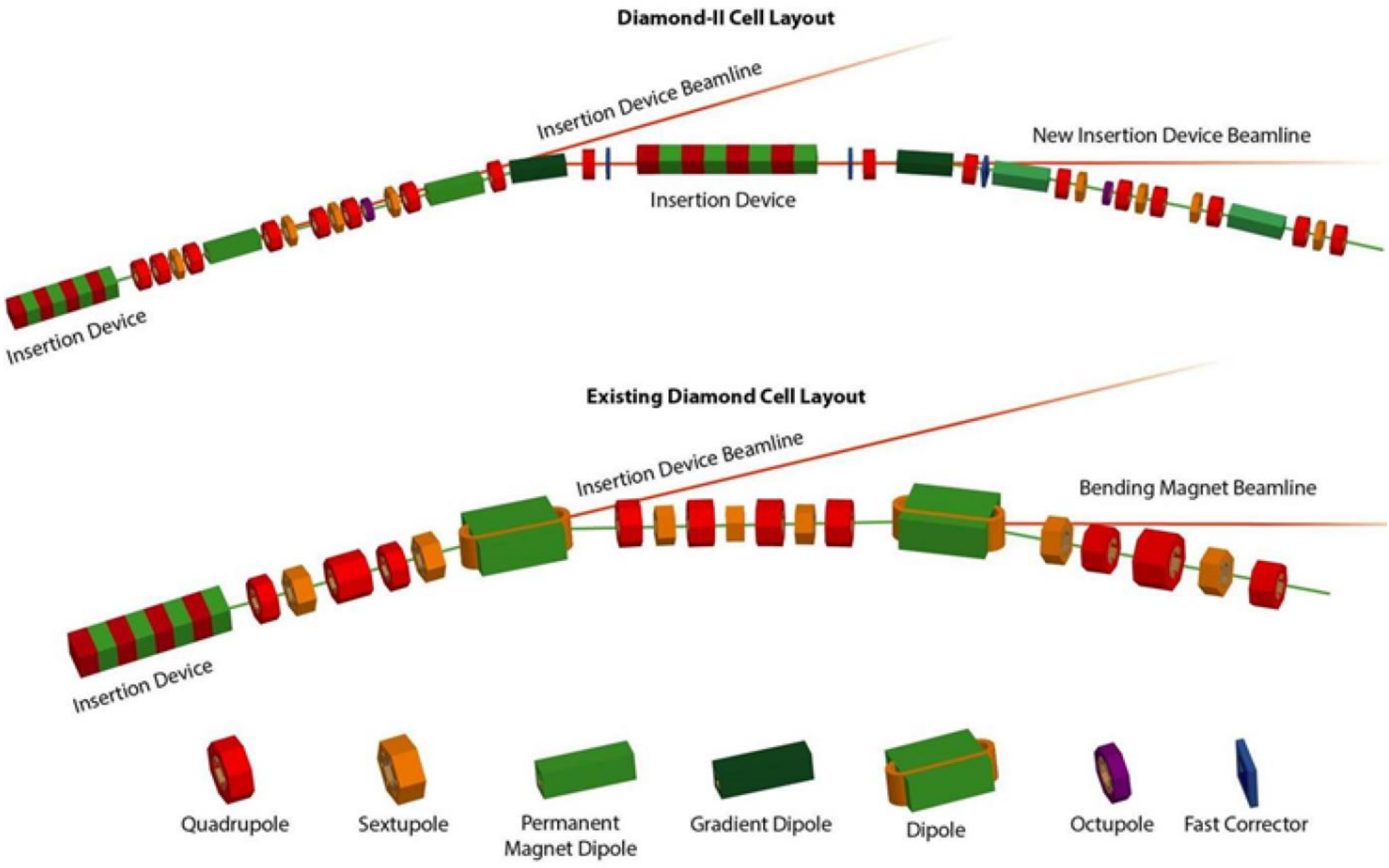
Contents

- Introduction to Diamond-II
- Challenges for beam diagnostics
- Diagnostics overview
- Electron beam position monitors
- Front-end X-ray beam position monitors
- Orbit stability and fast orbit feedback
- X-ray pinhole cameras
- Multibunch feedback
- Visible light extraction and diagnostics
- Injection stripline kickers
- Summary



Overview of Diamond-II

Diamond machine upgrade involves replacing the current Double Bend Achromat lattice structure with a **Multi Bend Achromat** in order **to reduce the emittance** of the electron beam and so **increase the brightness and coherence of the emitted synchrotron light**.



$$\varepsilon \propto \frac{E^2}{N_{bend}^3}$$

ε = Electron beam emittance

E = Number of bending magnets in each cell of the ring

N_{bend} = Electron beam energy

Dark period starts Dec 2027
Duration 18 months

Goals and Constraints

The **designs goals** for the Diamond-II Storage ring can be summarised as follows:

- **Equilibrium emittance** in-line with similar, state-of-the-art synchrotron radiation facilities worldwide.
- **Doubling of the number of straight sections to increase the capacity for beamlines** and maximise the scientific impact of the facility.
- Raise the electron beam energy from 3.0 GeV to **3.5 GeV to maximise the photon flux and brightness** above 10 keV.
- **Tuneable optics functions** in the insertion straights for future flexibility including possible increases in brightness.

There are also a number of **practical constraints** which must be met:

- **Existing ID beamline** source-points to **remain fixed**.
- **Minimum straight section lengths** matched to ID, RF and injection component requirements.
- **Minimum magnet separation** 75 mm (magnetic length).
- **Transparent injection** scheme with top-up mode of operation.
- **Lifetime and injection efficiency** sufficient to remain **compatible with existing shielding** and safety requirements.
- Maintain **high availability and high reliability**.

Comparison of Main Parameters

Parameter	Units	Diamond (no IDs)	Diamond (with IDs)	Diamond-II (no IDs)	Diamond-II (with IDs)
Energy	GeV	3.0	3.0	3.5	3.5
Beam current	mA	300	300	300	300
Beam lifetime	h	~ 10	~ 10	7.0	7.5
Circumference	m	561.571	561.571	560.561	560.561
Harmonic number		936	936	934	934
RF frequency	MHz	499.654	499.654	499.511	499.511
Total bending angle	deg.	360	360	388.8	388.8
Emittance (horizontal, natural)	pm rad	2729	3100	163	120
Emittance (vertical)	pm rad	8	8	8	8
Energy spread (rms)	%	0.096	0.107	0.095	0.109
Energy loss per turn	MeV	1.01	1.52	0.72	1.68
Momentum compaction factor	10^{-4}	1.57	1.56	1.042	1.041
Natural bunch length (rms)	ps	11.4	11.0	12.5	11.7
Average bunch length (rms)	ps	17	17	49	48

IDs = Insertion Devices

Challenges for Beam Diagnostics

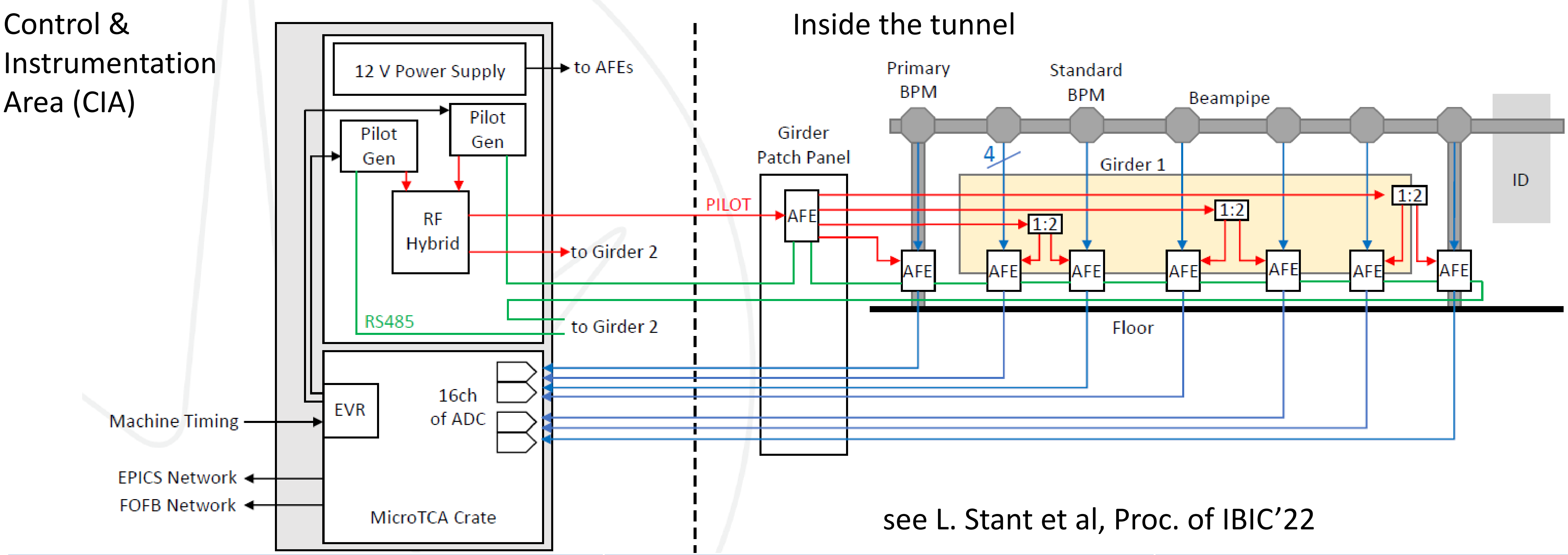
Diamond-II presents **new challenges for diagnostics and feedbacks**, particularly for the delivery of **beam stability and emittance measurement**.

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
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

Diagnostics Overview: Storage Ring

Diagnostic	Beam Parameter	Quantity	Location
BPMs	Position	252 + extras in chicanes	5/6 per girder incl. primary BPMs
BLDs + BLMs	Losses	1x BLM, 4x BLD	Injection straight
		1x BLM, 4x BLD per cell = 96 BLDs	End of each straight; Downstream of dipole on each girder
DCCT (Bergoz NPCT)	Current	1	K09 diagnostics straight
OTR/YAG screens	Transverse profile	2	Injection straight
Stripline kickers	Multibunch feedback	2	K09 diagnostics straight
Longitudinal cavity		1	
Extra BPM buttons		1x double BPM block	
Pinhole cameras	Emittance + energy spread	2	I01 (D1 dipole);K01 (D4 dipole)
Visible light extraction mirror	Visible SR to diagnostics optical cabin	1	Dipole 3, upstream of K02 straight
Time Correlated Single Photon Counting System	Fill pattern + bunch purity	2	Visible SR + X-rays (parasitic to pinhole camera)
Streak camera	Bunch length	1	B01 optical cabin using visible SR
Front-end tungsten blade XBPM	X-ray beam position	2-3 per beamline	-

Electron Beam Position Monitor Overview

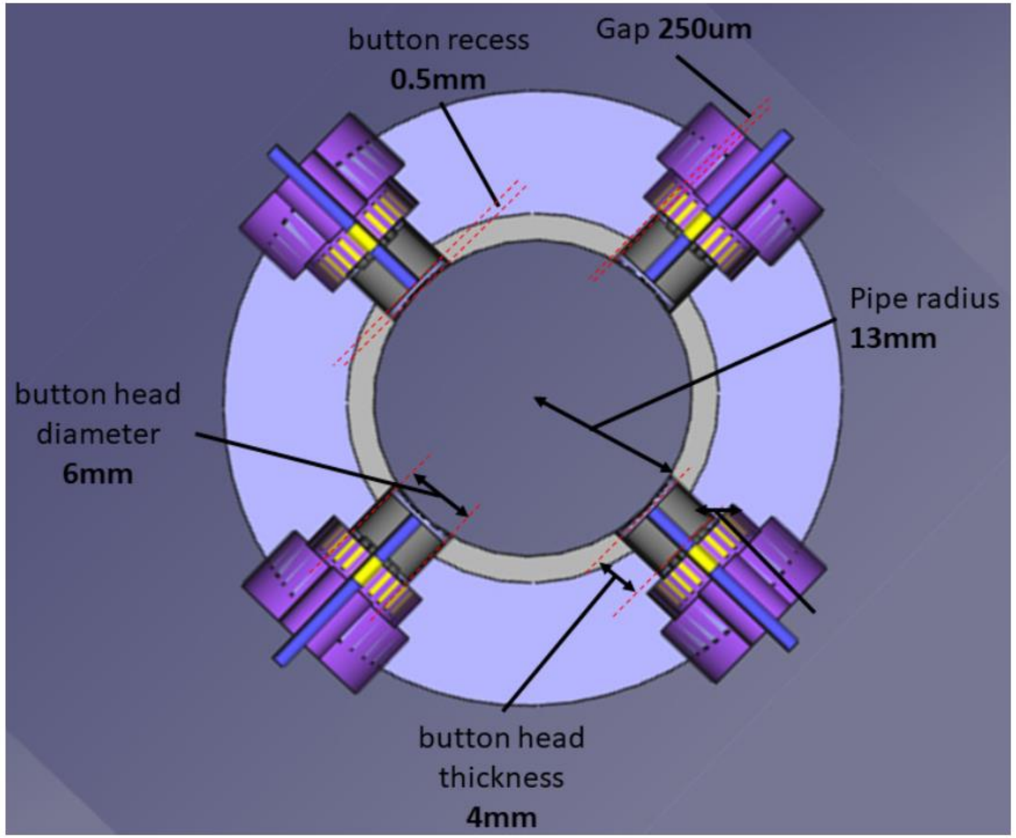


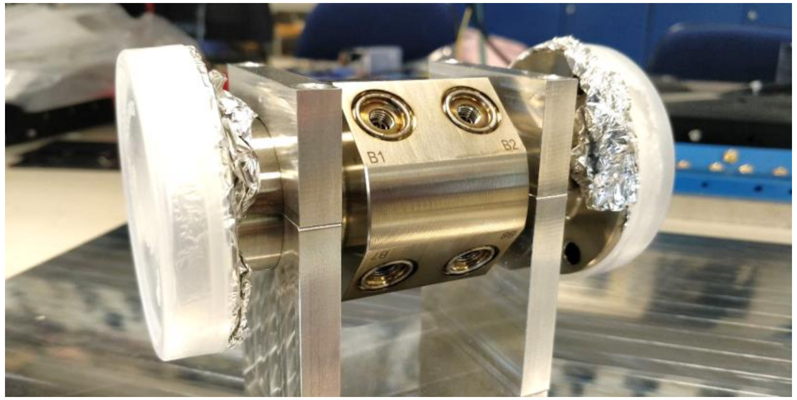
see L. Stant et al, Proc. of IBIC'22

	Commissioning	Operation
Short term uncertainty (period < 1 s)	< 130 nm/√Hz RMS (resolution < 500 µm ADC, < 100 µm TbT)	< 2 nm/√Hz RMS (resolution < 0.2 µm FA)
Long term uncertainty (1 s < period < 1 week)	N/A	< 1 µm pk-pk
Beam current dependence (0.3 mA to 300 mA)	N/A	< 10 µm pk-pk
Geometric factor, k	7.3 mm	7.3 mm

BPM Buttons

Button Parameter	Value
Diameter	6 mm
Thickness	4 mm
Gap	250 µm
Capacitance	2.78 pF
Additional details	316L casing, Molybdenum button





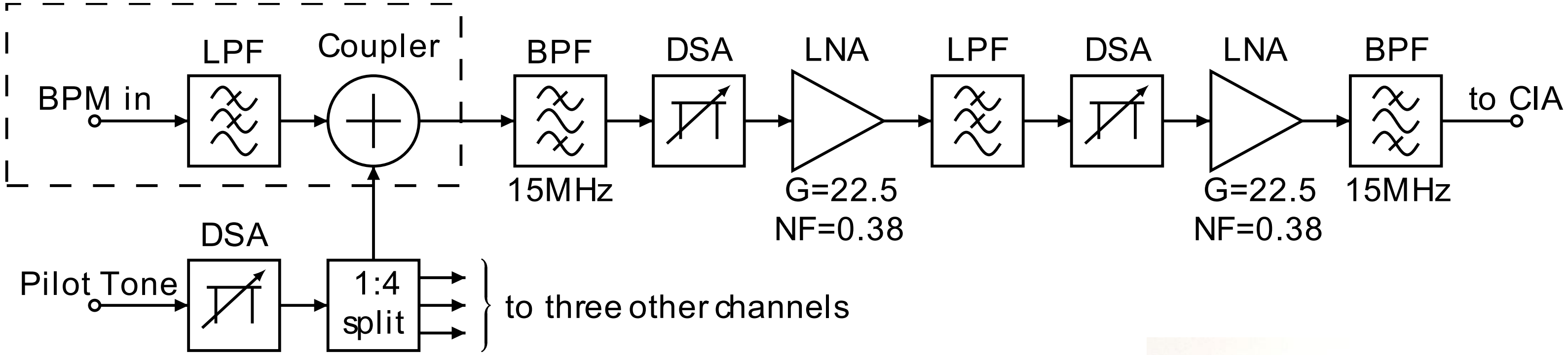
Buttons are orientated at 45 deg. and shadowed to avoid synchrotron radiation.

Prototyping ceramic and glass sealing technologies.

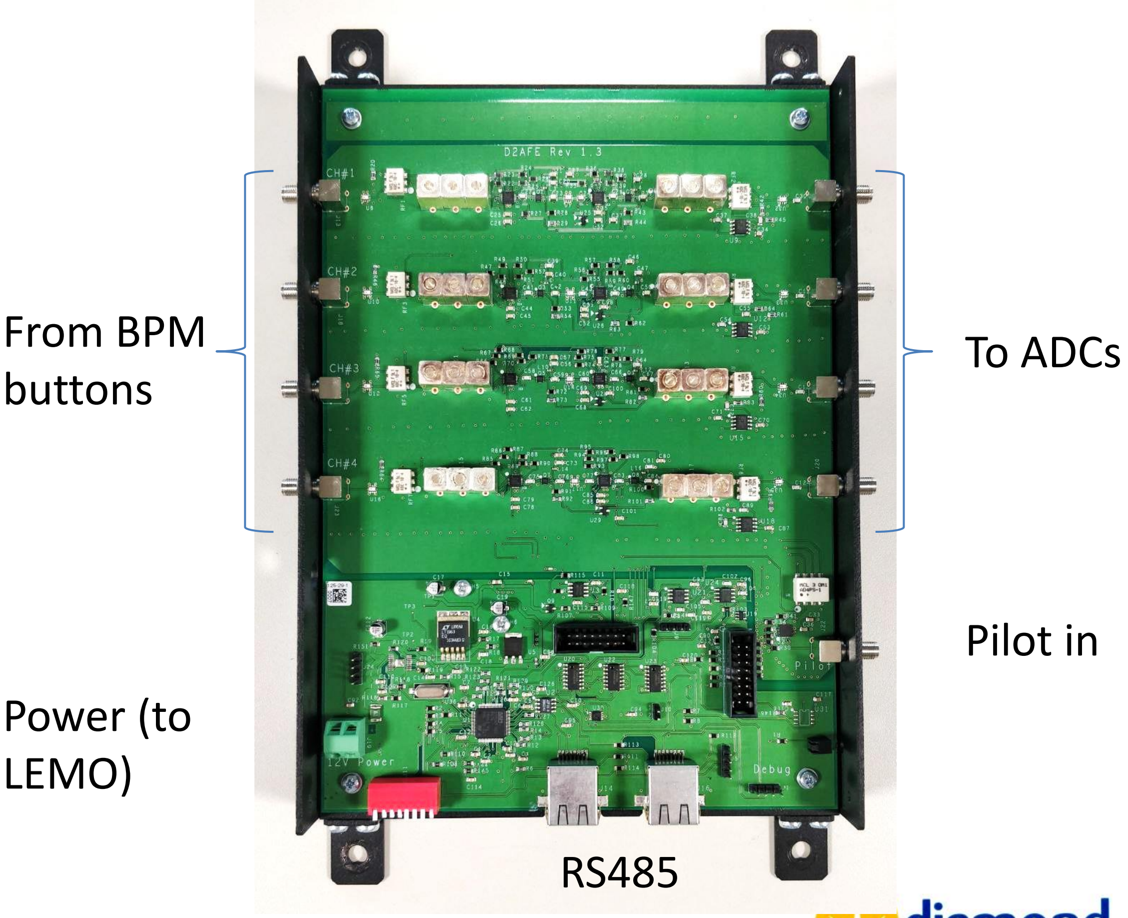
Boundary Element Method is used to calculate the 2D electric field distribution.

Gdfidl simulations estimate 3D electromagnetic interactions to provide the longitudinal wake loss factor and impedance.

BPM Pilot Tone Analogue Front-End

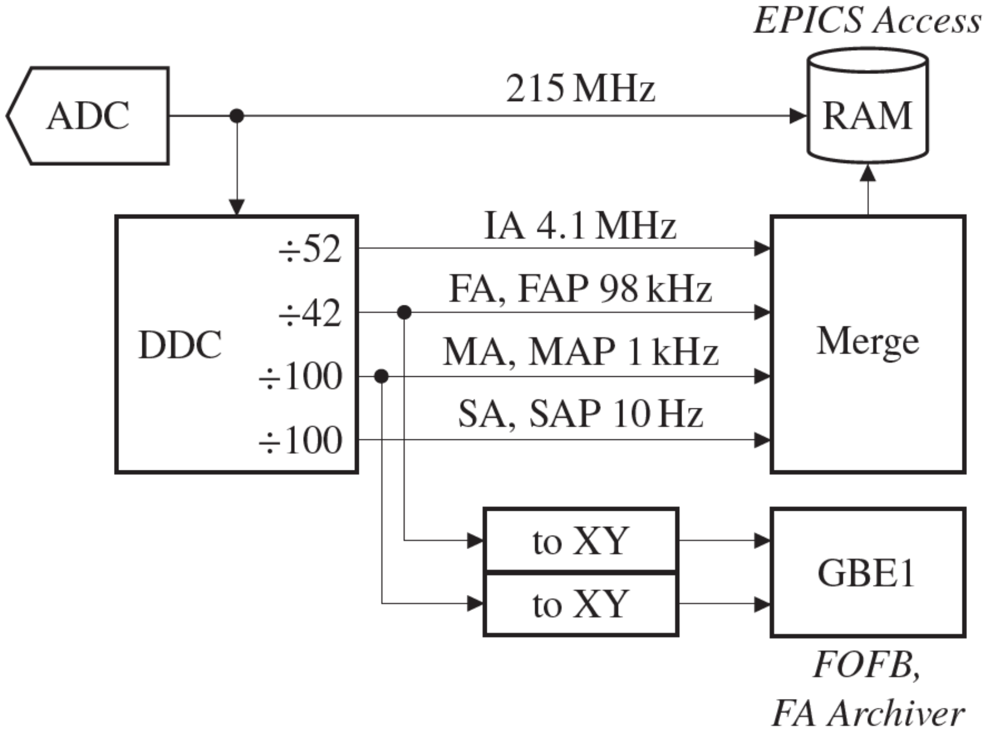


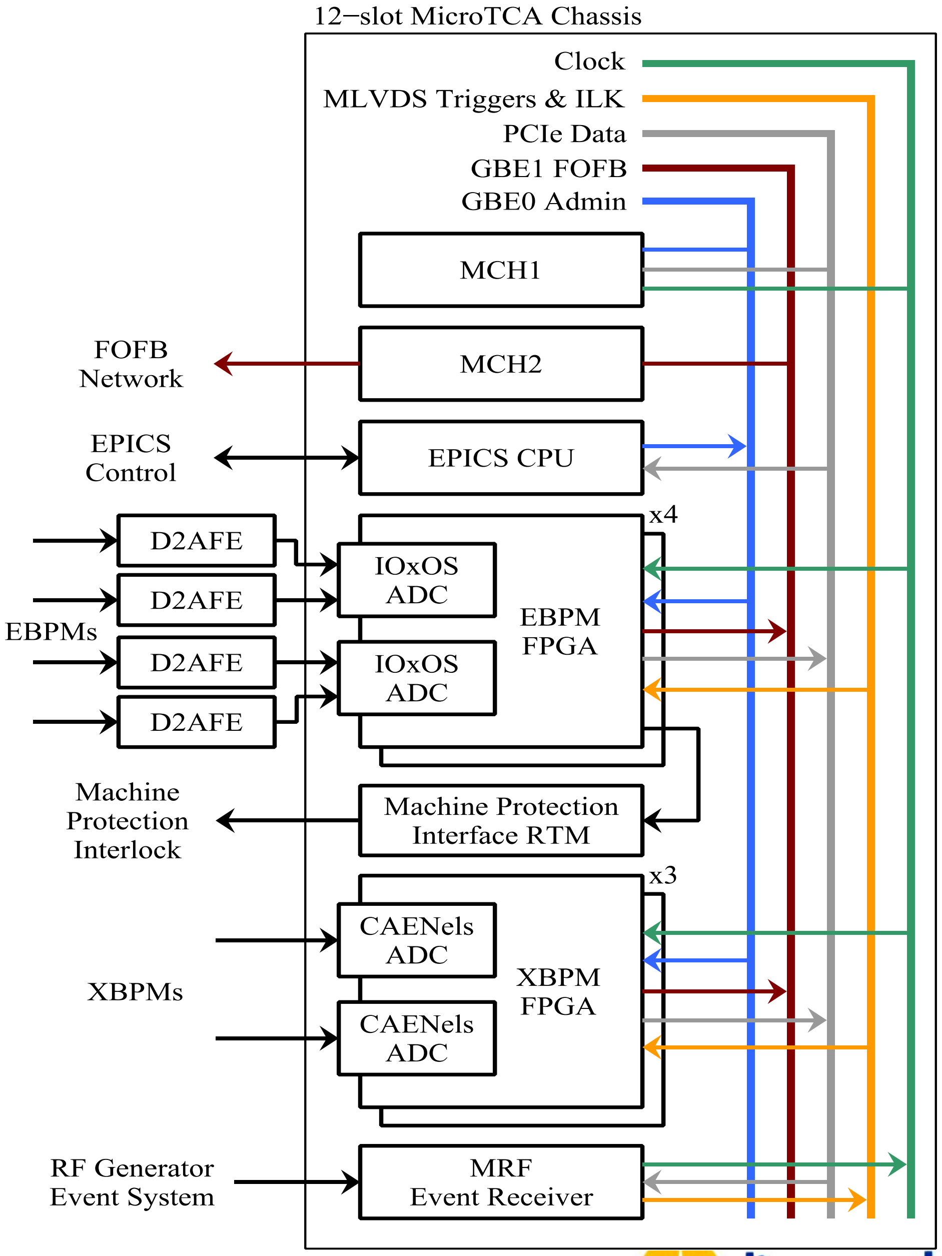
- **Pilot tone compensation scheme** to reduce front-end and cabling perturbations to the BPM button signal
  - **enables commissioning BPMs without beam**
- **Located in the tunnel** to improve cable drift
- Four channels of filtering, amplification and switchable attenuation.
- External pilot tone splitter and coupling.
- Helical filters (cheaper, tunable)
- STM32 ARM microcontroller with RS485 communication and firmware updates.
- Linear regulators fed from remote dual-redundant 12 V switched-mode supplies.



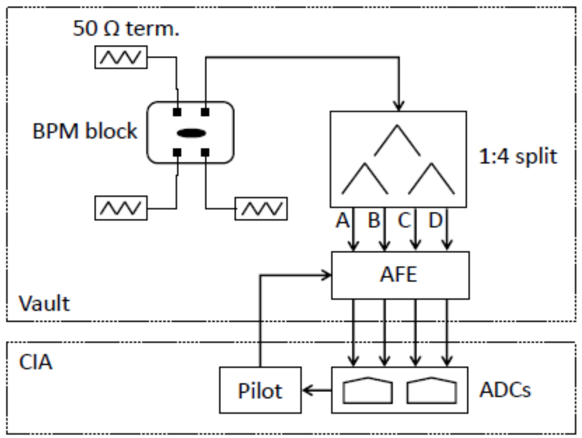
BPM Digitisation and Processing

Data Stream	Used for
Intermediate Acquisition (IA)	Converted to turn-by-turn data
Fast Acquisition (FA)	Fast orbit feedback (FOFB) and fast archiver
Medium Acquisition (MA)	Additional archiver/fault detection
Slow Acquisition (SA)	Live EPICS data



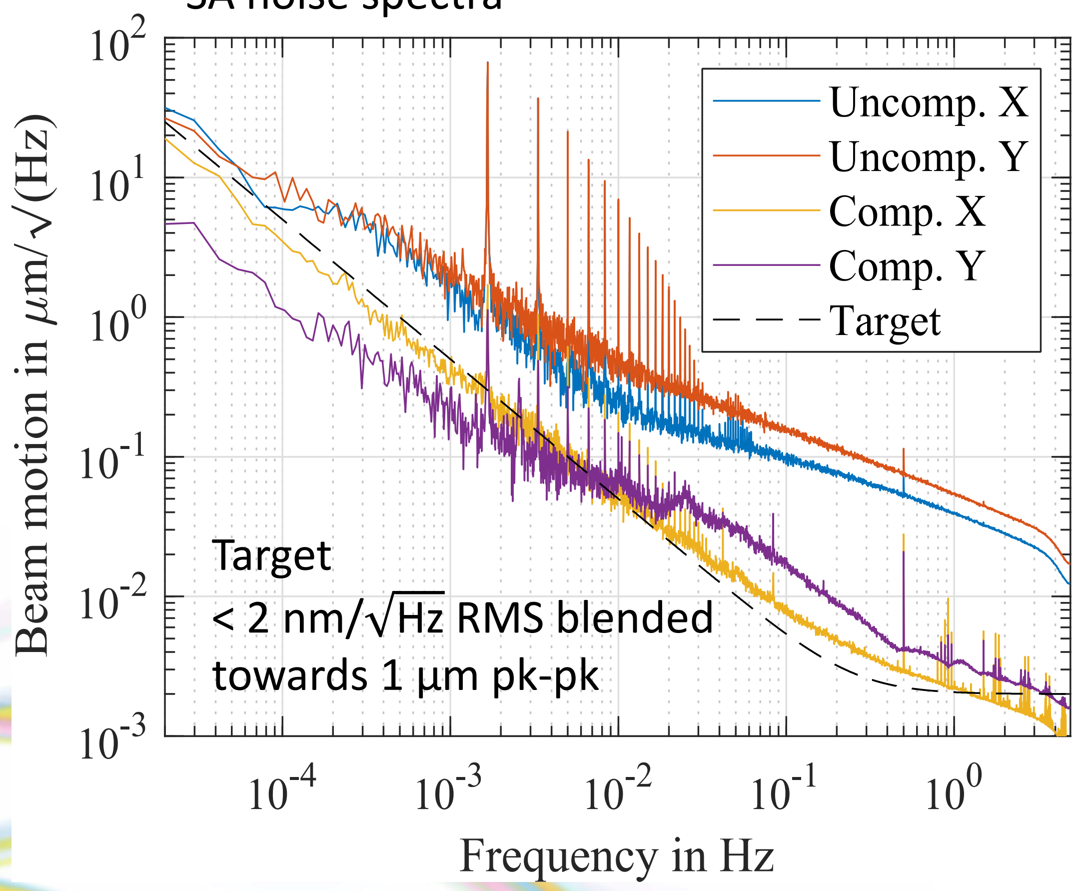


BPM System Measurements

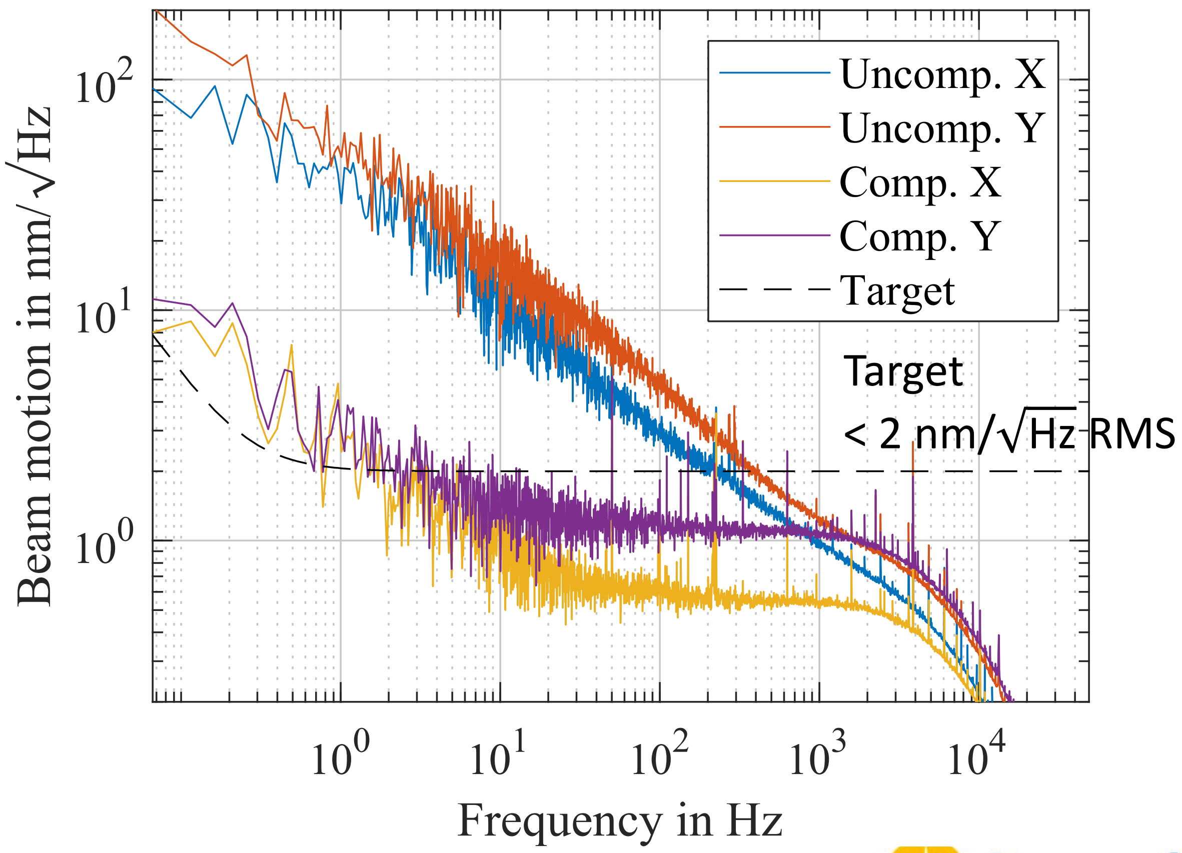


- Demonstrates efficacy of pilot-compensation.
- Line at 1.67 mHz and its decaying harmonics are caused by the 10 minute top-up, and are reduced by increasing the attenuation in the D2AFE to improve the linearity.
- Line at 0.5 Hz is the flash rate of a status LED on the AFE modulating the power supply, shows high sensitivity!

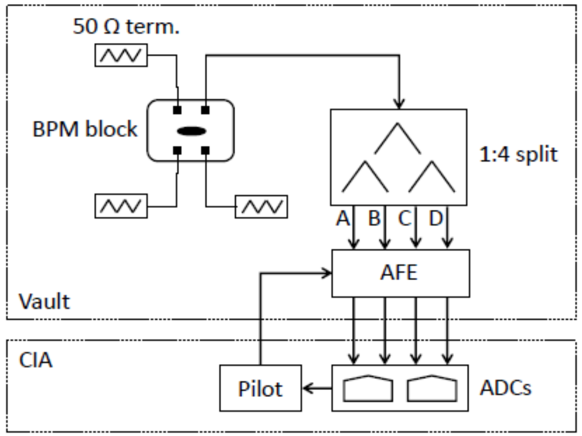
SA noise spectra



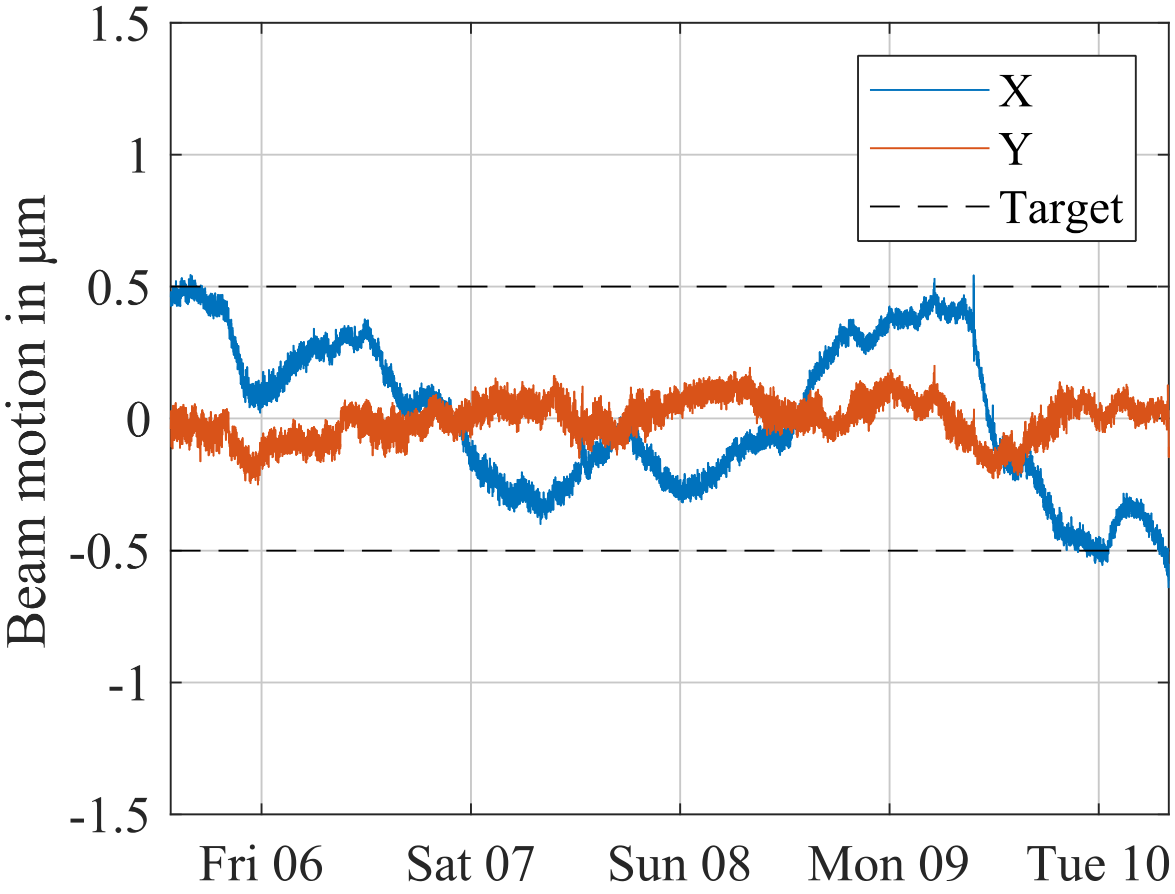
FA noise spectra

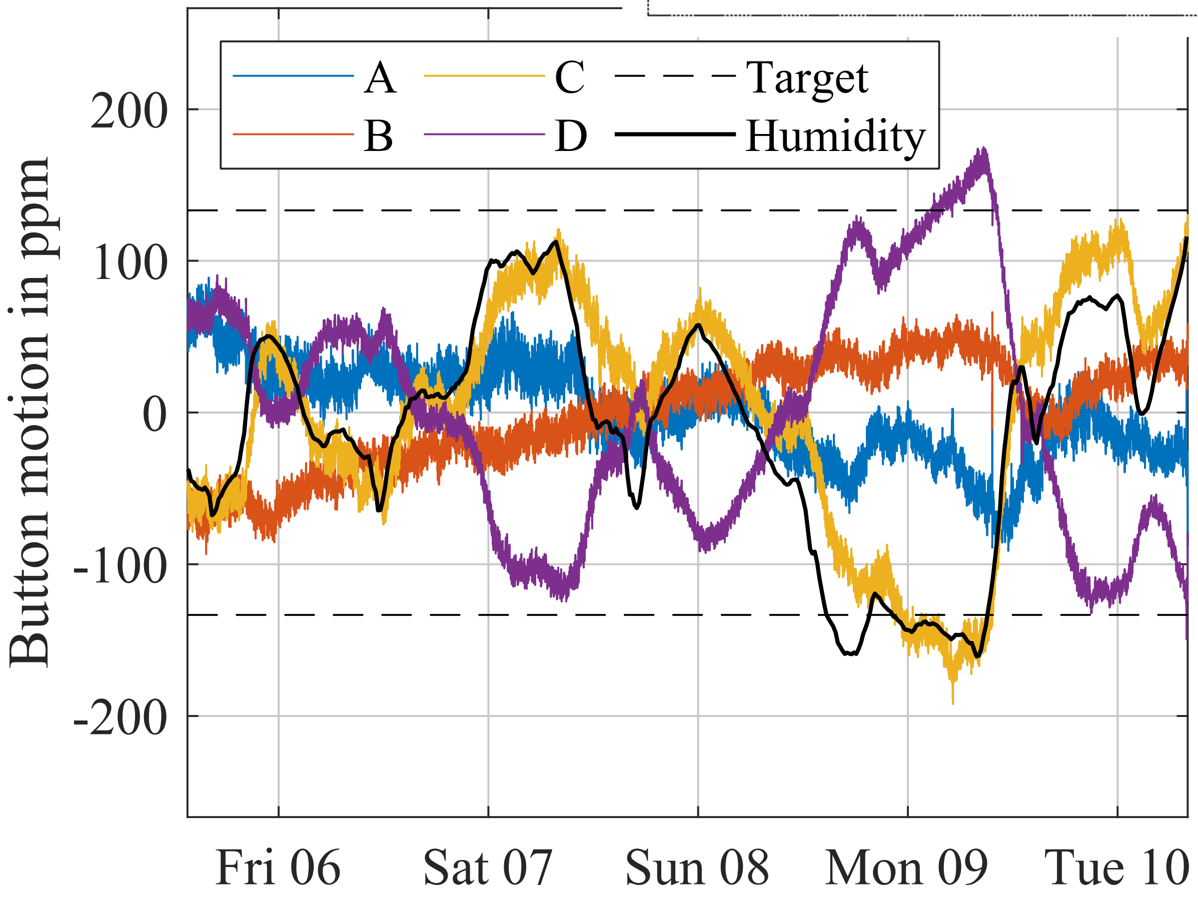


BPM System Measurements



- Performance of the Y signal is satisfactory, the X signal is drifting significantly, at times exceeding the target.
- Explained by correlation of channels C and D with humidity
- Investigations underway to answer if this comes from the AFE (under test) or the 1:4 splitter (used for testing)





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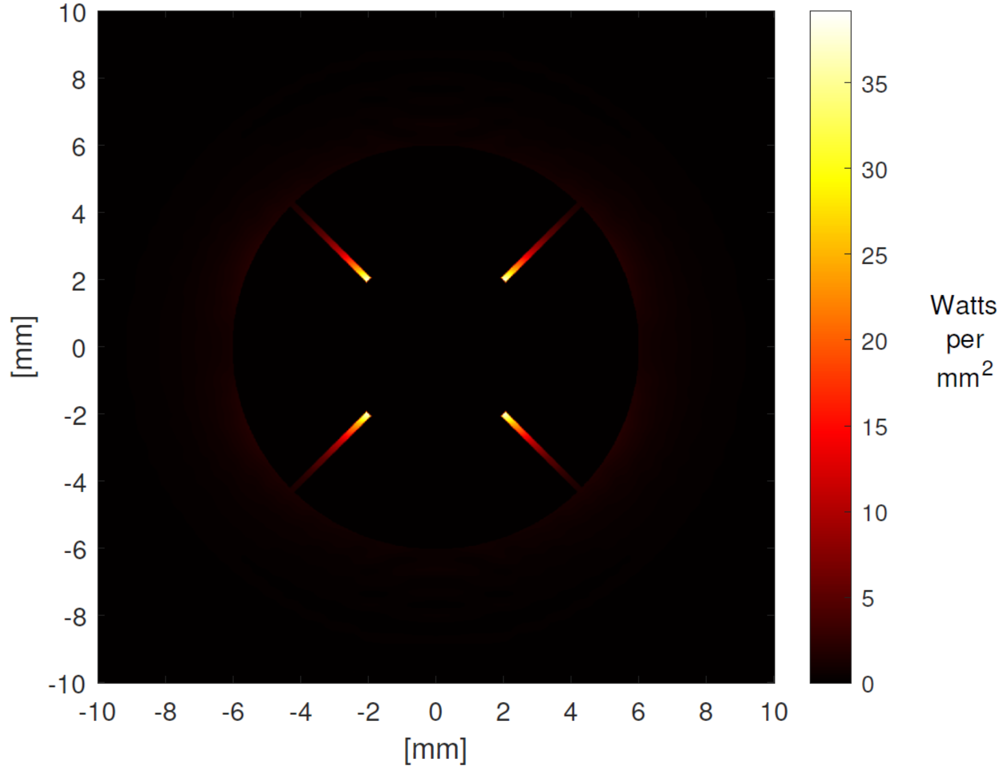
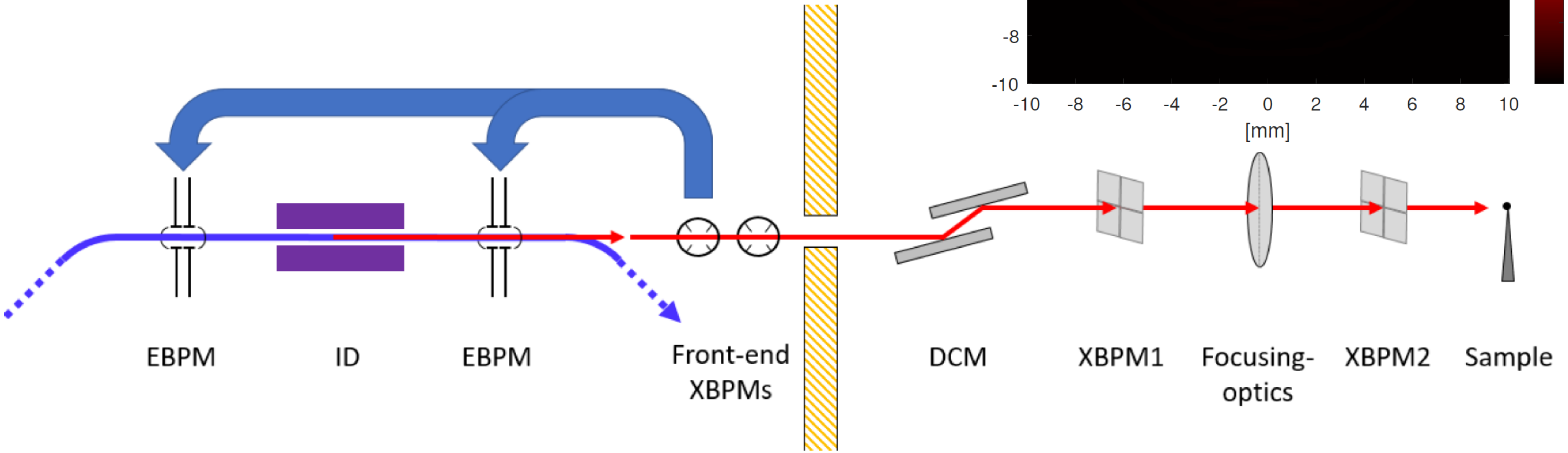
Front-end X-ray Beam Position Monitors

- FE XBPMs measure **position and angle** of the synchrotron radiation
- Located in the beamline front-end
- Principle: Photoelectric effect on tungsten vanes in synchrotron radiation beam path
- Complementary diagnostic to electron BPMs
- Will be incorporated into orbit feedback
  → holistic view of beam stability





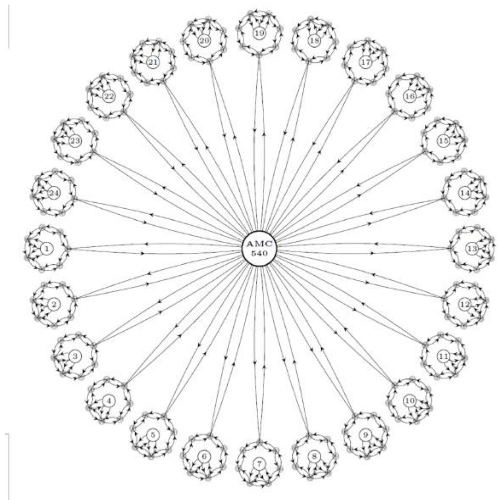
Orbit Stability Considerations

Sources of disturbance:

- Temperature and humidity variation in the tunnel
- Ground motion
- On-girder vibration (BPMs, water-cooling, magnets)
- Noise from power supplies
- RF noise gives rise to an energy oscillation which translates into horizontal motion through the dispersion.

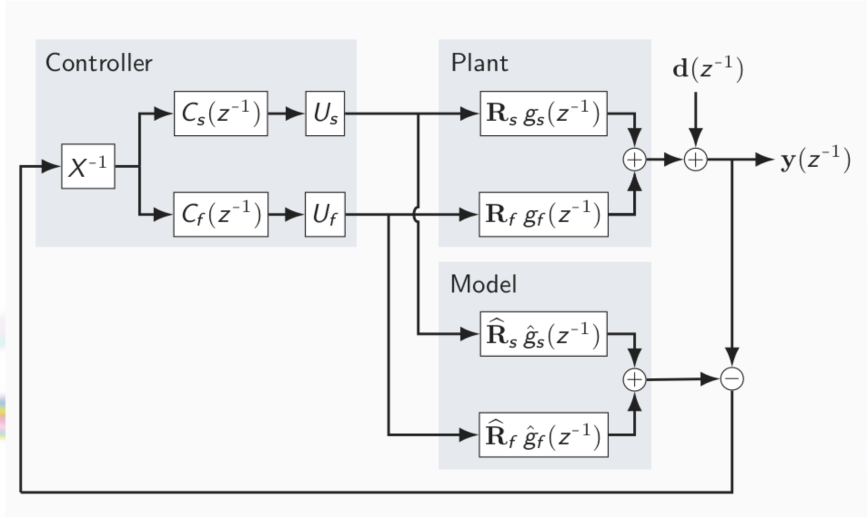
Fast Orbit Feedback Requirements	Value
Cross-over frequency for closed loop frequency response	≥ 1 kHz
Open loop bandwidth	≥ 5 kHz
Latency for the entire loop (BPM electronics, magnet power supplies, vessel, communication)	≤ 100 µs
Fast Acquisition data rate	≈ 100 kHz
Correction planes	Both horizontal 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)
Compatibility to swap EBPM to XBPM for bending magnet beamlines and in the event of primary BPM fault.	

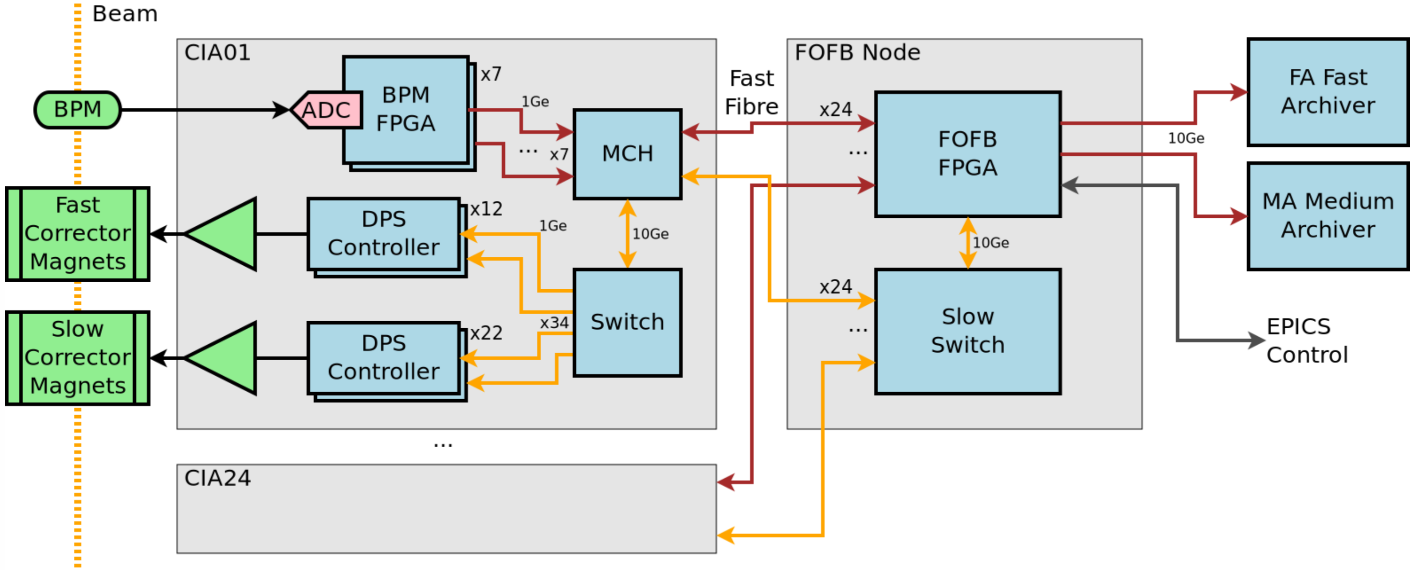
Fast Orbit Feedback



FOFB **control algorithm is based on the Internal Model Controller (IMC) with Regularised Response Matrix** as currently used in Diamond with two key changes:

- The **feedback update rate has been increased from 10 kHz to 100 kHz** which has a large impact on the development of the controller, BPMs, and corrector magnets. Also requires **centralised controller** for low latency.
- 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 around 300 Hz.





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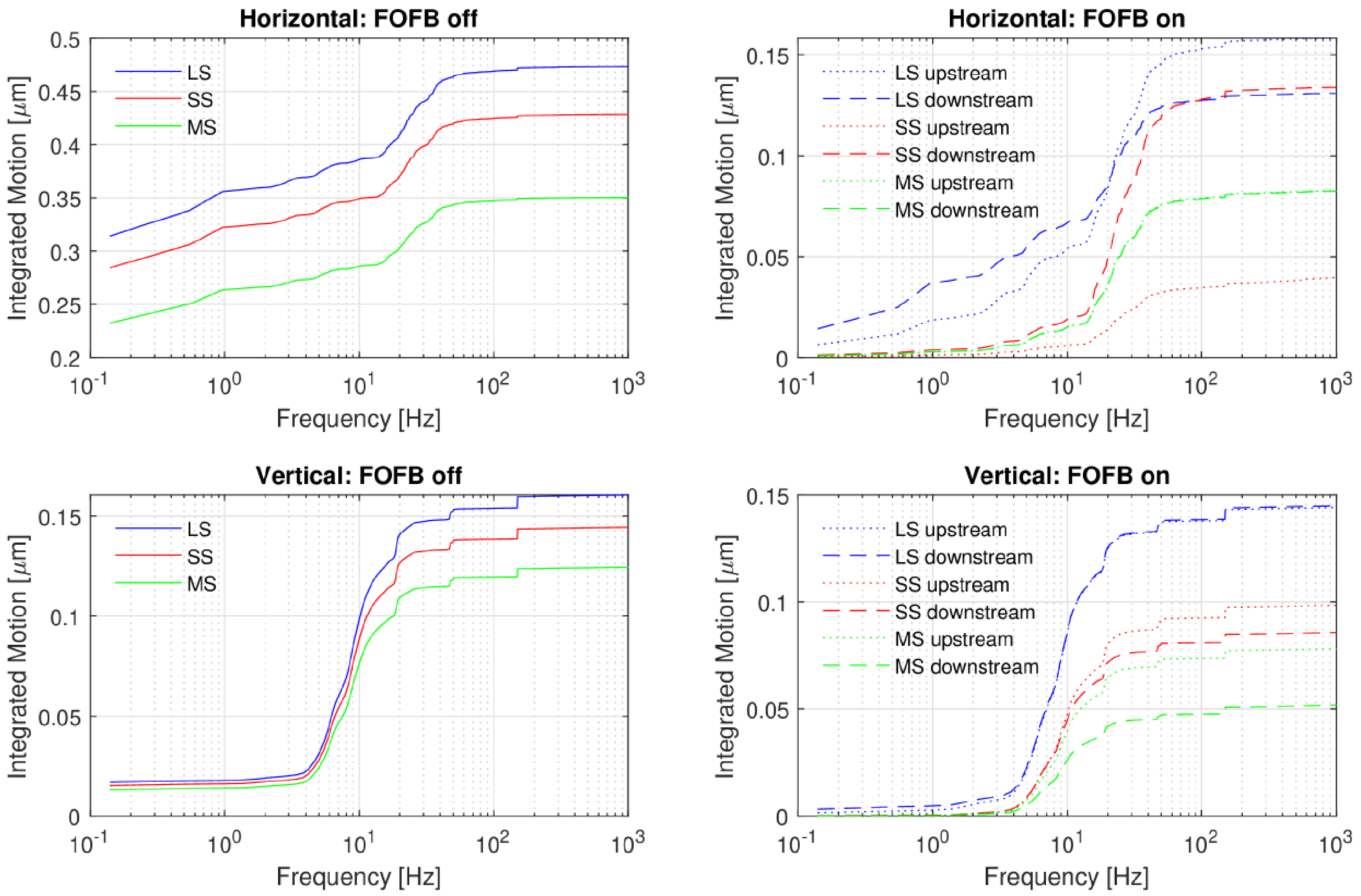
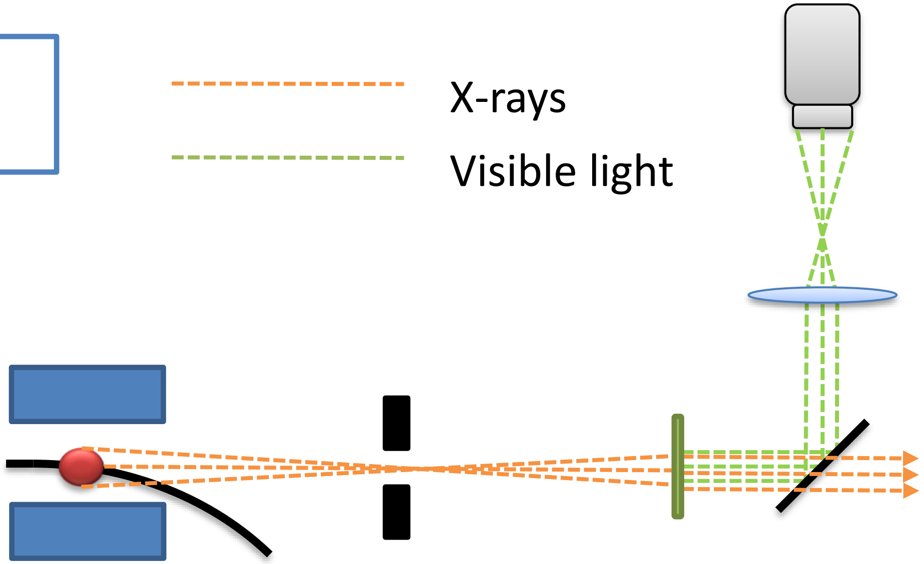
Fast Orbit Feedback at Primary BPMs



X-ray Pinhole Camera

Beam size measurement for **emittance feedback** and **energy spread** measurement, in addition to **human-friendly monitoring of the electron beam**.

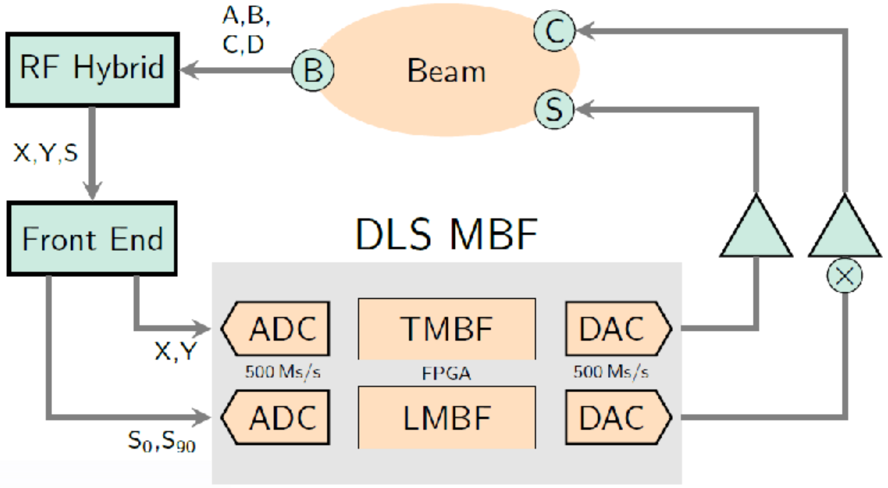


Parameter	D1	D4	Unit
Horizontal beam size	16.3	9.4	µm
Vertical beam size	12.6	10.5	µm
Source-to-scintillator magnification	4.9	4.2	-
Estimate minimum resolvable beam size at source point	7.1	7.6	µm
Peak photon energy after window	23		keV
Estimate horizontal emittance resolution	5		pm rad
Estimate vertical emittance resolution	0.2		pm rad

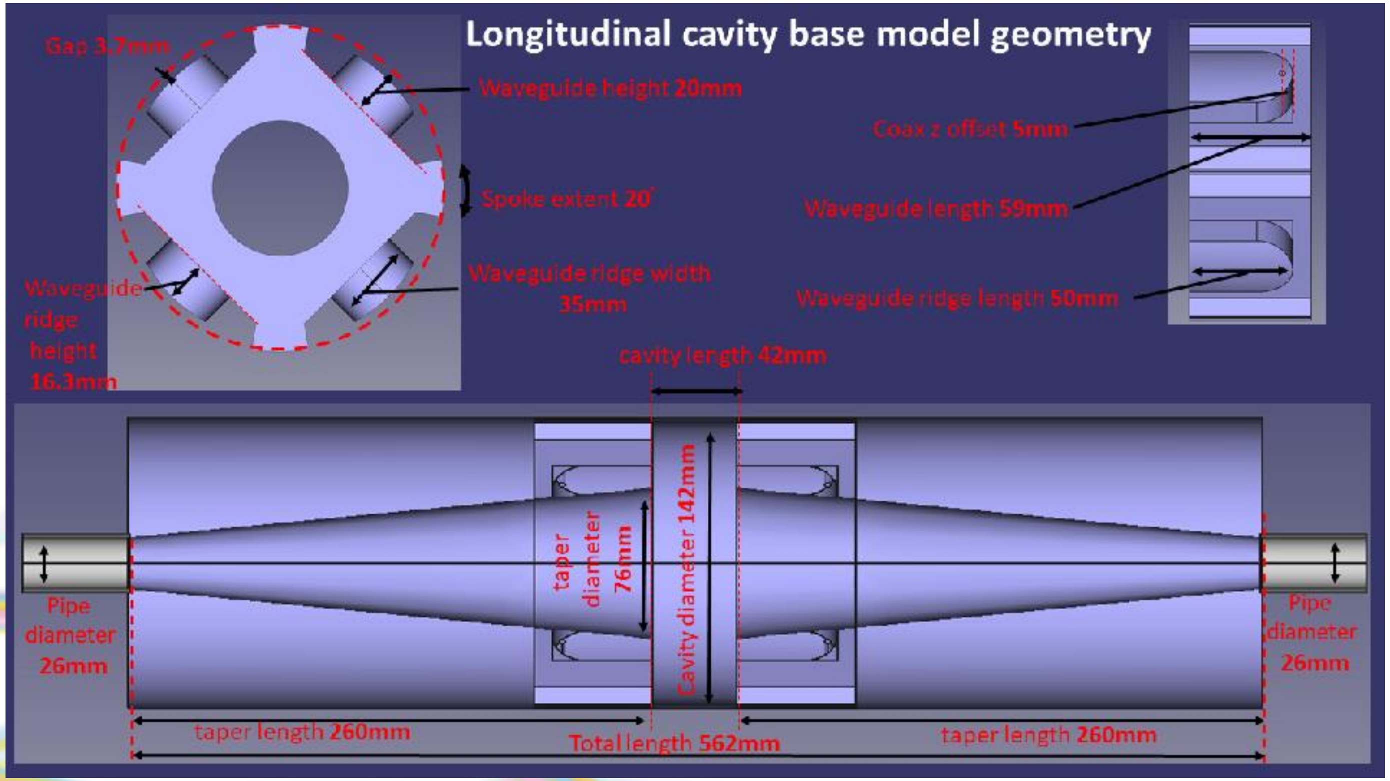
Emittance feedback provided by **betatron tune sideband excitation** using multibunch feedback system in both planes.

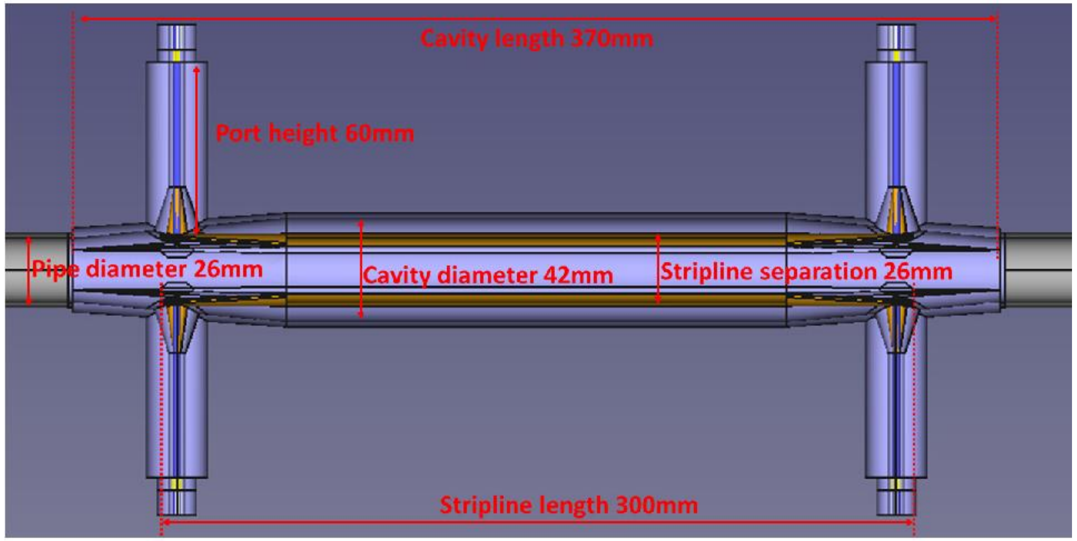
Multibunch Feedback

- Recycle existing MBF from Diamond
- Betatron **tune** measurement
- **Suppression of bunch-by-bunch** transverse and longitudinal **instabilities**
- **Excitation** for **emittance feedback and energy measurement** using resonant spin depolarisation



Ⓑ EBPM pickup; Ⓒ Longitudinal cavity; Ⓢ Transverse striplines.



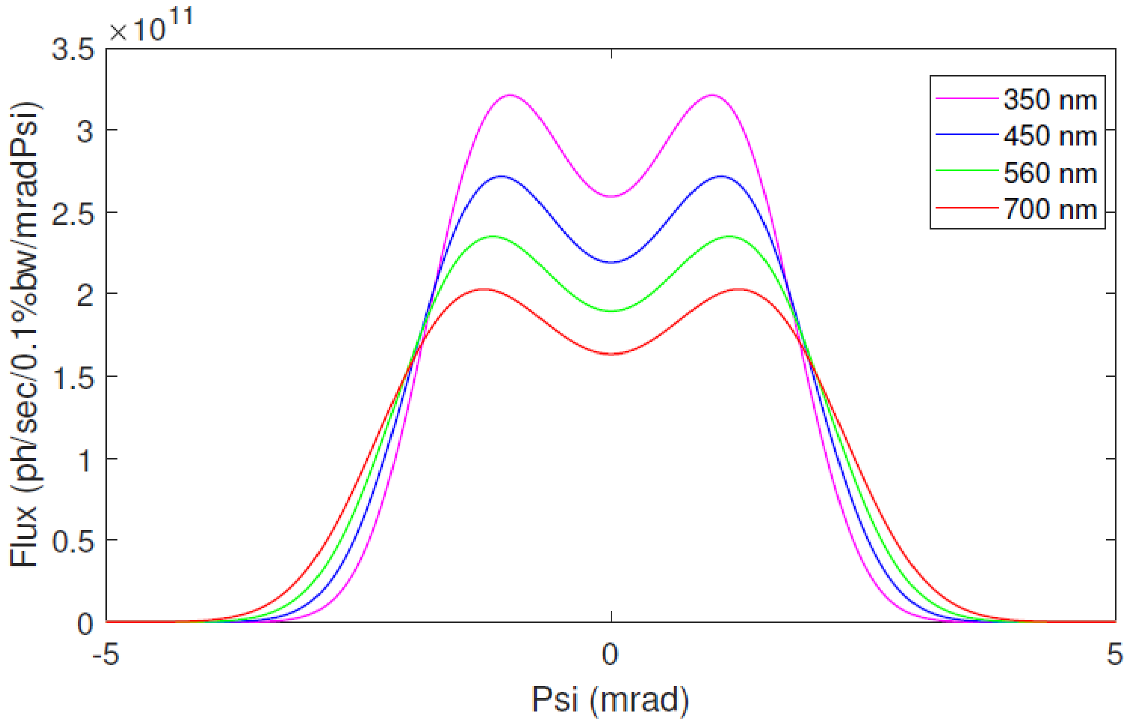


Visible Light Extraction and Diagnostics

Fill pattern and bunch purity measurements using Time Correlated Single Photon Counting System (TCSPCS) recycled from Diamond.
→ essential for Top-up
→ second TCSPCS detects X-ray synchrotron radiation and acts as a spare online fill pattern monitor

Bunch length measurement using **streak camera** recycled from Diamond.

- Visible light **extraction is challenging due to** the **small beam pipe** diameters in 4th generation machines.
- In-vacuum full mirror with finger absorber at 45 deg. to the beam.
- Aim to **minimise optical path length** (to approx. 10 m) from source point to B01 optics lab to limit beam divergence and **maintain high quality wavefront.**
  - allowing future upgrade path for visible SR beam size monitors e.g. interferometers, pi-pol



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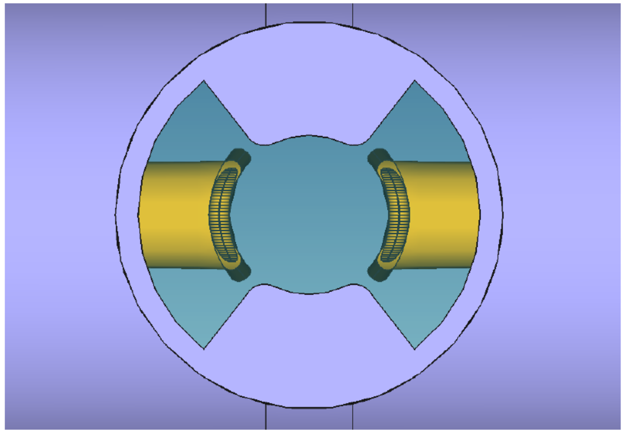
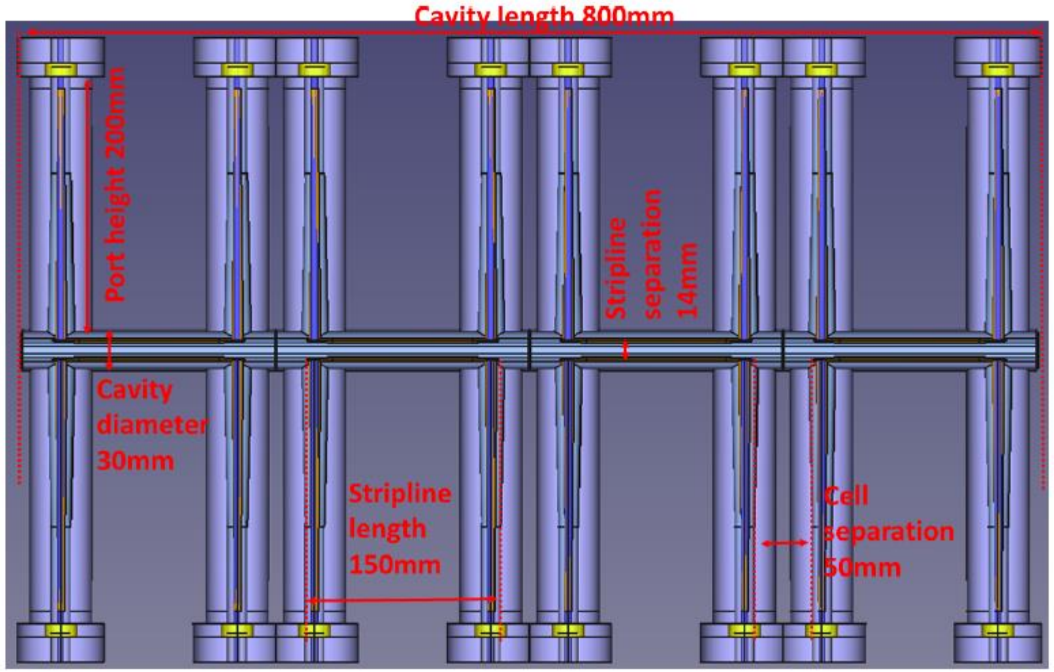
Injection Stripline Kickers

New development required for **transparent injection during top-up**

Stripline design lead by Diagnostics group due to familiarity with smaller scale MBF striplines.

Parameter	Value
Number required	4
Magnetic length	0.15 m
Full gap	14 mm
Rise time (5-95%)	≤ 1 ns
Fall time (5-95%)	≤ 1 ns
Pulse duration (flat stop, 95-95%)	> 1 ns
Total duration	≤ 3 ns
Peak voltage	± 11.8 to ± 21.0 kV





Summary

- Majority of diagnostics on the linac, booster and transfer lines will be retained.
- Main challenges in Diamond-II for beam instrumentation:
  - Beam stability
  - Emittance measurement
- Development of new BPMs using in-house AFE with MTCA digital signal processing and pilot tone compensation.
- Important that diagnostics are robust and reliable, with straight forward commissioning e.g. commissioning BPMs using pilot tone prior to beam.
- Future-proofing systems wherever possible and enabling potential upgrade paths.
- Essential to collaborate and discuss with other facilities undertaking similar upgrades.

Bibliography

[1] Guenther Rehm. Specification for Diamond-II Electron Beam Position Monitor Electronics. Technical report, Diamond Light Source, 2020.

[2] Robert E. Shafer. Beam position monitoring. pages 26–58, 2008.

[3] Uros Mavric. Innovative RF Design Unites Benefits of Multiplexed and Multi-Channel System. In AIP Conference Proceedings, volume 732, pages 373–378. AIP, 2004.

[4] T Fujita, S Sasaki, M Shoji, and T Takashima. A Problem in RF Switches of Multiplexing BPM System. In Proc. 7th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC'05). JACoW Publishing, 2005.

[5] G. Brajnik, S. Bassanese, G. Cautero, S. Cleva, and R. De Monte. Integration of a pilot-tone based bpm system within the global orbit feedback environment of elettra. In Proc. 7th Int. Beam Instrumentation Conf. (IBIC'18), pages 190–195. JACoW Publishing, Sep. 2018. https://doi.org/10.18429/JACoW-IBIC2018-TUOC01.

[6] A. Olmos, F. P´ erez, and G. Rehm. Matlab code for bpm button geometry computation. In Proc. 8th European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators (DIPAC'07), pages 186–188. JACoW Publishing, May 2007.

[7] F. Marcellini, M. Serio, and M. Zobov. DAFNE Broad-Band Button Electrodes. Technical report, INFN-LNF Accelerator Division, 1996.

[8] R. Bartolini, C. Abraham, M. Apollonio, C. P. Bailey, M. P. Cox, A. Day, R. T. Fielder, N. P. Hammond, M. T. Heron, R. Holdsworth, J. Kay, I. P. S. Martin, S. Mhaskar, A. Miller, T. Pulampong, G. Rehm, E. C. M. Rial, A. Rose, A. Shahveh, B. Singh, A. Thomson, and R. P. Walker. Double-double bend achromat cell upgrade at the Diamond Light Source: From design to commissioning. Physical Review Accelerators and Beams, 21(5):050701, May 2018.

[9] W. Bruns. Gdfidl: A finite difference program with reduced memory and cpu usage. In Proc. 17th Particle Accelerator Conf. (PAC'97), pages 2651–2653. JACoW Publishing, May 1997.

[10] Ryutaro Nagaoka and Karl L F Bane. Collective effects in a diffraction-limited storage~ring. Journal of Synchrotron Radiation, 21(5):937–960, sep 2014.

[11] A. F. D. Morgan and G. Rehm. Considerations and improved workflow for simulation of dissipated power from wake losses. In Proc. 4th Int. Beam Instrumentation Conf. (IBIC'15), pages 202–205. JACoW Publishing, Sep. 2015. https://doi.org/10.18429/JACoW-IBIC2015-MOPB065.

[12] Cyrille Thomas, Guenther Rehm, Ian Martin, and Riccardo Bartolini. X-ray pinhole camera resolution and emittance measurement. Physical Review Special Topics - Accelerators and Beams, 13(2):022805, feb 2010.

[13] C. Thomas, G. Rehm, and R. Bartolini. An X-ray pinhole camera with a range of defined apertures. Proc. of BIW, pages 116–118, 2012.

[14] L M Bobb, A F D Morgan, G Rehm, and Diamond Light Source. PERFORMANCE EVALUATION OF MOLYBDENUM BLADES IN AN X-RAY PINHOLE CAMERA. In Proc. of IBIC 2016, pages 795–798, Barcelona, Spain, 2016.

[15] I P S Martin, M G Abbott, M Apollonio, D Hickin, and R Bartolini. Operating the Diamond Storage Ring With Reduced Vertical Emittance. IPAC 2013 Proceedings, pages 1–3, 2013.

[16] B K Scheidt. MEASUREMENT OF VERTICAL EMITTANCE WITH A SYSTEM OF SIX -In-Air-X-Ray- PROJECTION MONITORS AT THE ESRF DETECTO : THE OPTICAL SYSTEM. In Proc. of DIPAC, pages 72–74, 2007.

[17] Manuel S´anchez del R´ıo and Roger J Dejus. XOP v2.4: recent developments of the x-ray optics software toolkit. In Manuel Sanchez del Rio and Oleg Chubar, editors, Advances in Computational Methods for X-Ray Optics II, volume 8141, pages 368–372. International Society for Optics and Photonics, SPIE, 2011.

[18] ESRF. ESRF-EBS Storage Ring Technical Report. Technical report, ESRF, 2018. 26

[19] L Bobb and G Rehm. Performance of a Reflective Microscope Objective in an X-ray Pinhole Camera. In Proc. 7th Int. Beam Instrumentation Conf. (IBIC'18), pages 477–481. JACoW Publishing, 2018.

[20] E W Becker, W Ehrfeld, P Hagmann, A Maner, and D M¨unchmeyer. Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process). Microelectronic Engineering, 4(1):35–56, 1986.

[21] M G Abbott and G Rehm. Tune Computation via Model Fitting to Swept Machine Response Measurement. In Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19), pages 490–494. JACoW Publishing, 2019.

[22] G Rehm, M G Abbott, and A F D Morgan. New Features and Measurements using the Upgraded Transverse Multibunch Feedback at Diamond. In Proc. 3rd Int. Beam Instrumentation Conf. (IBIC'14), pages 696–699. JACoW Publishing, 2014.

[23] Niki Vitoratou, Pavel Karataev, and Guenther Rehm. Continuous energy measurement of the electron beam in the storage ring of Diamond Light Source with resonant spin depolarization. Physical Review Accelerators and Beams, 22(12):122801, dec 2019.

[24] T Olsson. First Measurements of Pulse Picking by Resonant Excitation (PPRE) at the MAX IV 3 GeV Storage Ring. In Proc. 8th Int. Particle Accelerator Conf. (IPAC'17), pages 2750–2752. JACoW Publishing, may 2017.

[25] G Rehm, M G Abbott, and A F D Morgan. Measurements of Longitudinal Coupled Bunch Instabilities and Status of New Feedback System. In Proc. 5th Int. Beam Instrumentation Conf. (IBIC'16), pages 298–301. JACoW Publishing, 2016.

[26] L. Torino and K. B. Scheidt. New beam loss detector system for EBS-ESRF. Proceedings of the 7th International Beam Instrumentation Conference, IBIC 2018, 00:0–6, 2018.

[27] N Hubert, M El Ajjouri, and D P´edeau. New Beam Loss Monitor System at SOLEIL. In Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19), pages 118–121. JACoW Publishing, 2019.

[28] J W Flanagan and Others. Thermal Performance of Diamond SR Extraction Mirrors for SuperKEKB. In Proc. 8th Int. Beam Instrumentation Conf. (IBIC'19), pages 332–335. JACoW Publishing, 2019.

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