Upgrading Front-End XBPMs for Diamond-II

Claire Houghton
Diamond Light Source
IBIC 2026

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- Front-End XBPM Principles
- Diamond-II Upgrade
- Diamond-II Feedbacks using XBPMs
- Optimising for Beam Sensitivity

Diamond Light Source

UK national synchrotron science facility | 3rd-generation storage ring, upgrading to Diamond-II

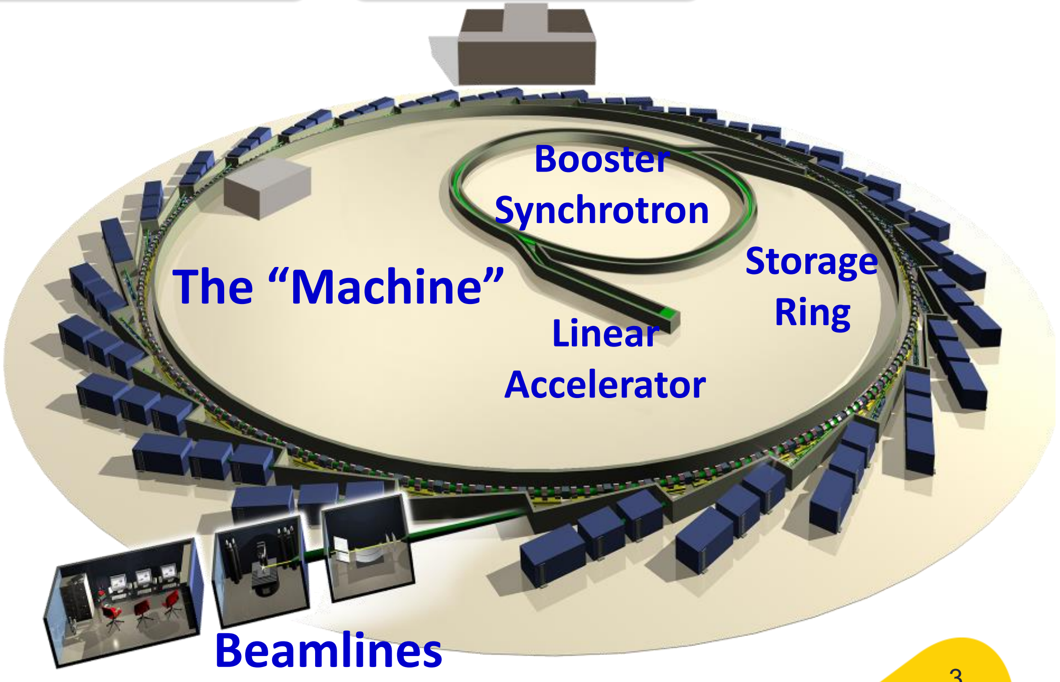
3rd generation synchrotron light source generating **very intense X-ray, infrared and ultraviolet beams** for experiments across life, physical and environmental sciences.

- Electrons are accelerated by a linac and booster, then stored at 3 GeV in the storage ring.
- Bending magnets and insertion devices produce synchrotron radiation, delivered to beamlines.
- 33 operating beamlines.
- Diamond-II will replace the machine with a 4th-generation source for brighter, more coherent light.

Key machine parameters

Current Diamond storage ring [1]

3 GeV electron beam energy	**561 m** circumference	**300 mA** maximum current
3100 pm rad horizontal emittance	**8 pm rad** vertical emittance	**17 ps** average bunch length

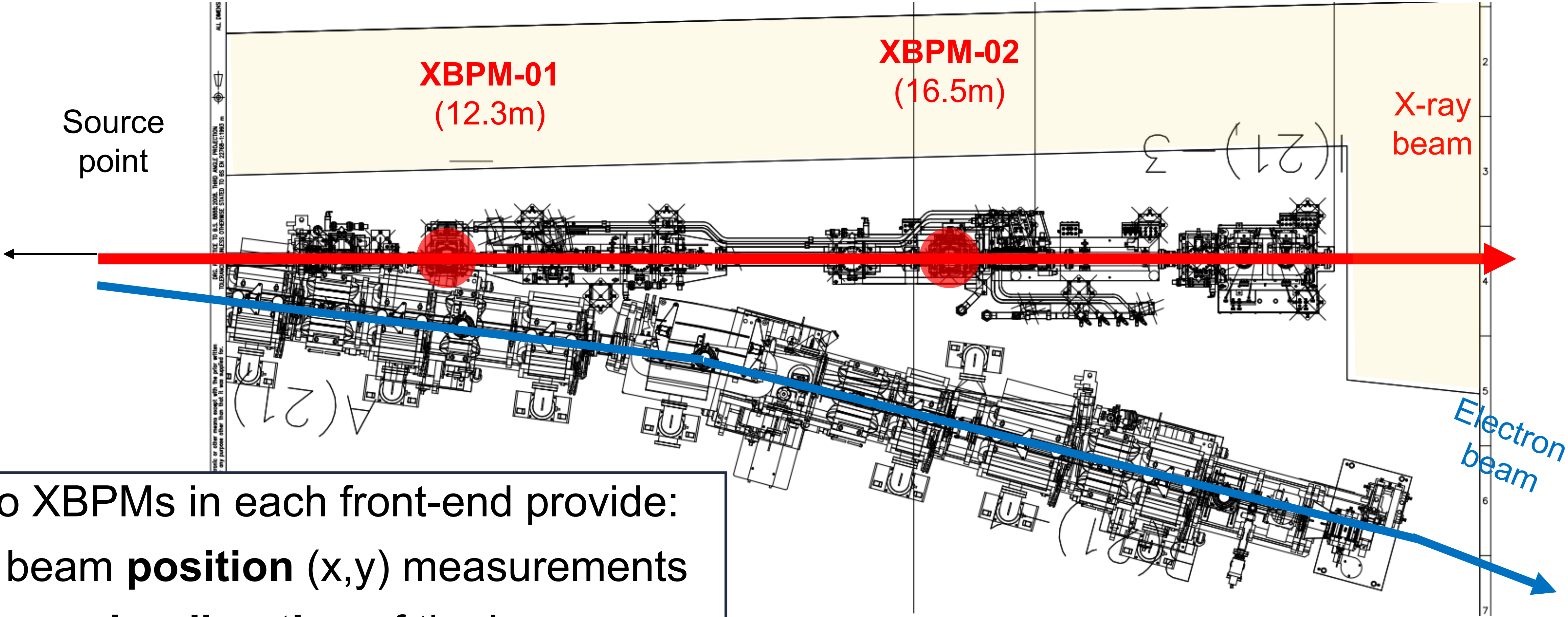


[1] Diamond-II TDR: https://www.diamond.ac.uk/Diamond-II.html

Front End XBPM Principles

Front End Diagnostics

- **X-ray Beam Position Monitors** (XBPMs) are the **first diagnostic** for the user photon beam.

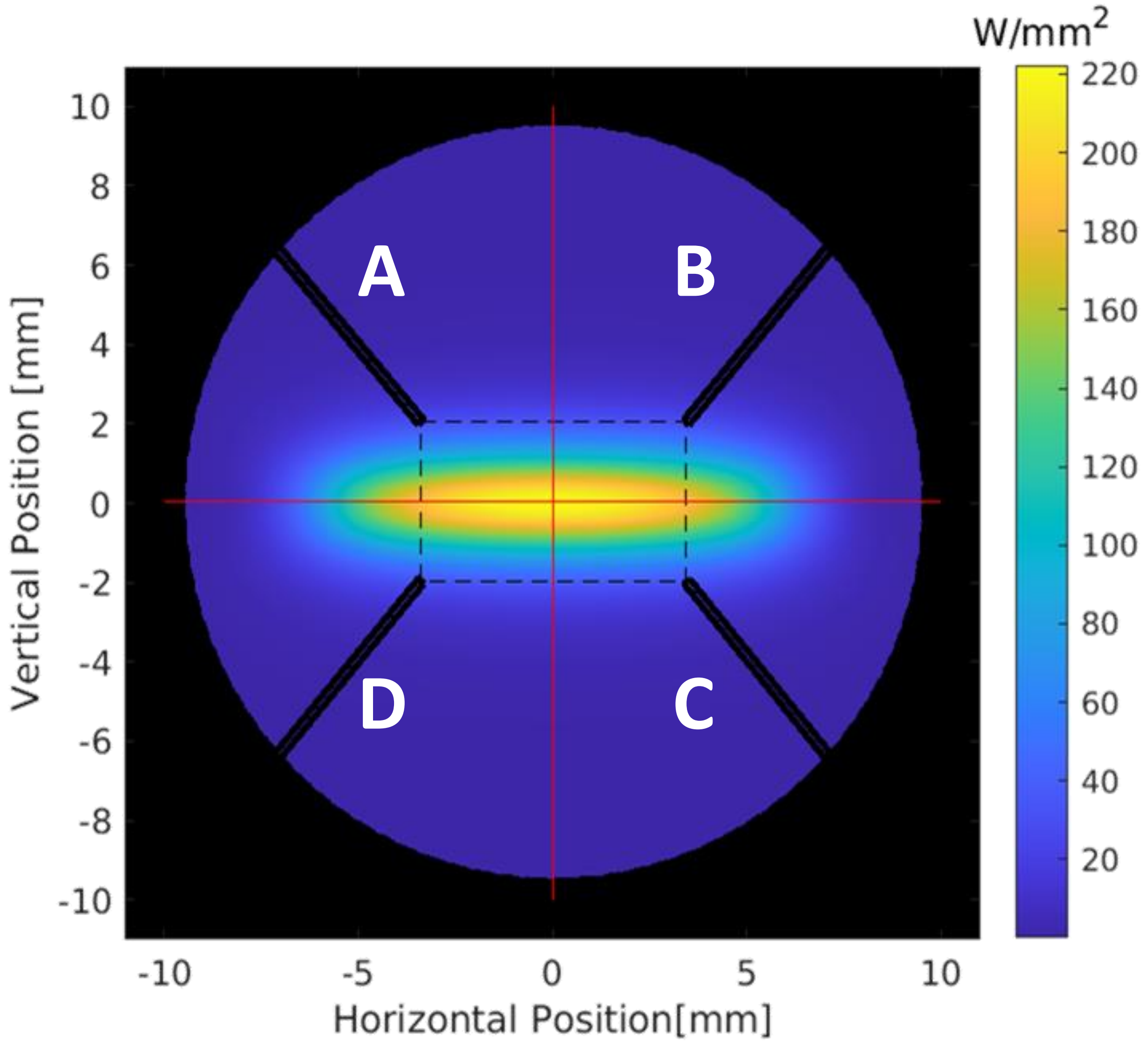


Two XBPMs in each front-end provide:

1. beam **position** (x,y) measurements
2. **angular direction** of the beam

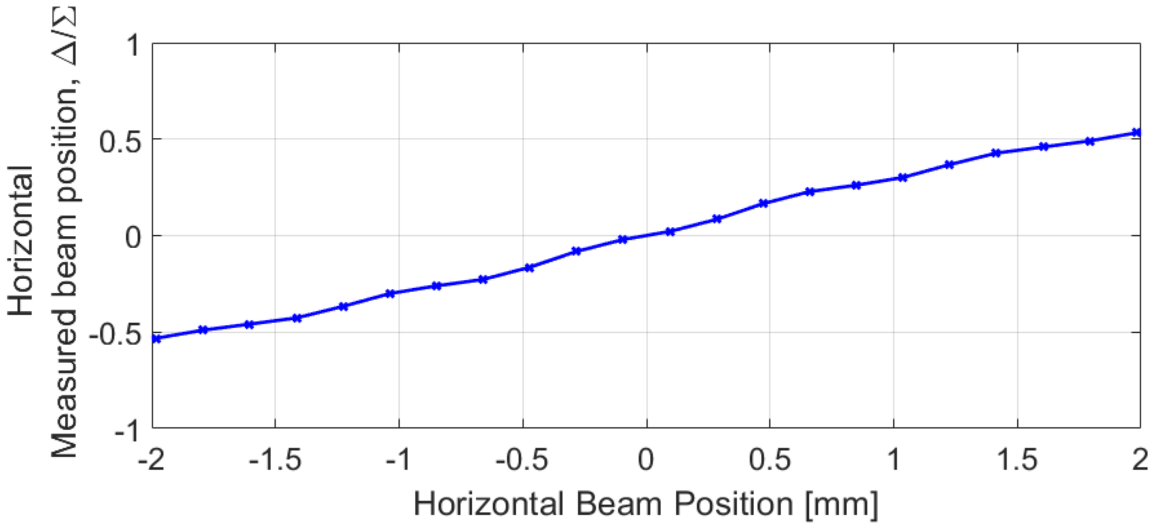
XBPM Principles

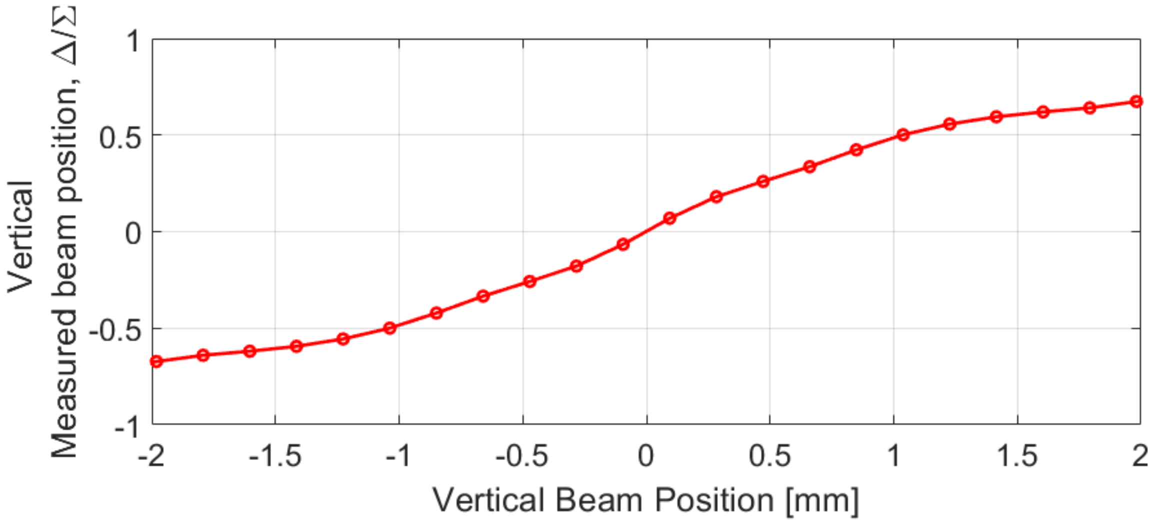
- **Four tungsten vanes** or blades which intercept **edges of the X-ray beam**
- A photocurrent is generated through the **photoelectric effect**.
- **Difference over sum** (Δ/Σ) calculation gives beam position.
- $$X = K_x \frac{[(A+D)-(B+C)]}{(A+B+C+D)} = K_x \frac{\Delta}{\Sigma}$$
  $$Y = K_y \frac{[(A+B)-(C+D)]}{(A+B+C+D)} = K_y \frac{\Delta}{\Sigma}$$
- $K_{x,y}$ is an ID gap dependent scale factor



Calculating Scale Factor $K_{x,y}$

- The **scale factor *K* converts** the **relative positions** of the four tungsten blades into an **absolute measurement** in millimetres.
- It is calculated from a known beam position difference and the **measured difference-over-sum value**.
- *K* equals the reciprocal of the curve's gradient where the stepper motor crosses zero.
- A **steeper gradient means greater sensitivity** in beam position measurement.
- Consistency between K_x and K_y means similar sensitivity in both axes.



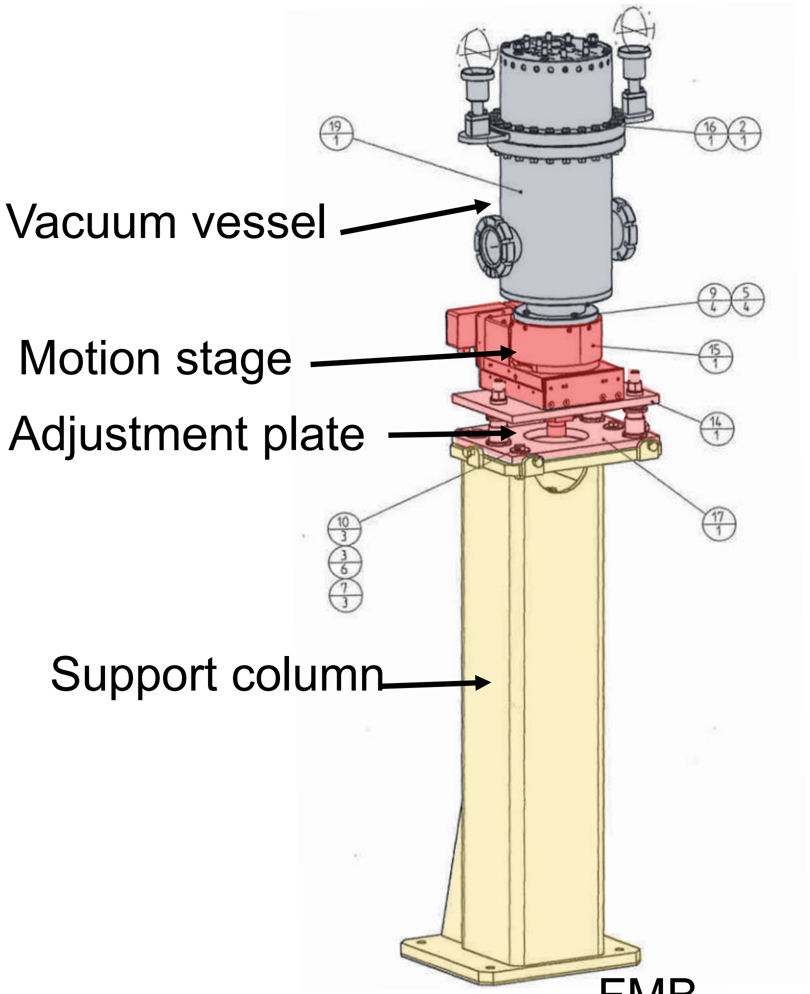


XBPM Assembly

The XBPM assembly can be split into 3 parts

1. The **total XBPM assembly** (including stepper motor, stand and vessel)

XBPM Assembly



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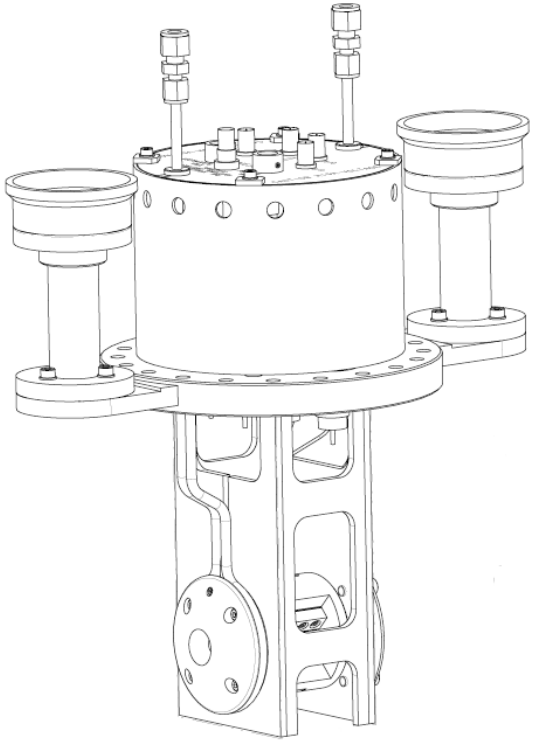
XBPM Assembly

The XBPM assembly can be split into 3 parts

1. The **total XBPM assembly** (including stepper motor, stand and vessel)

2. The **insert flange**, which sits inside the vessel

Insert Flange



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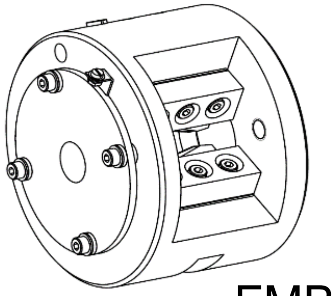
Blade Holder



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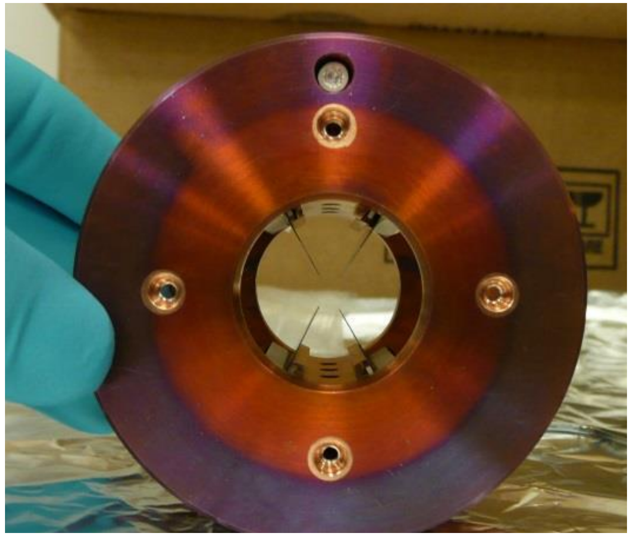
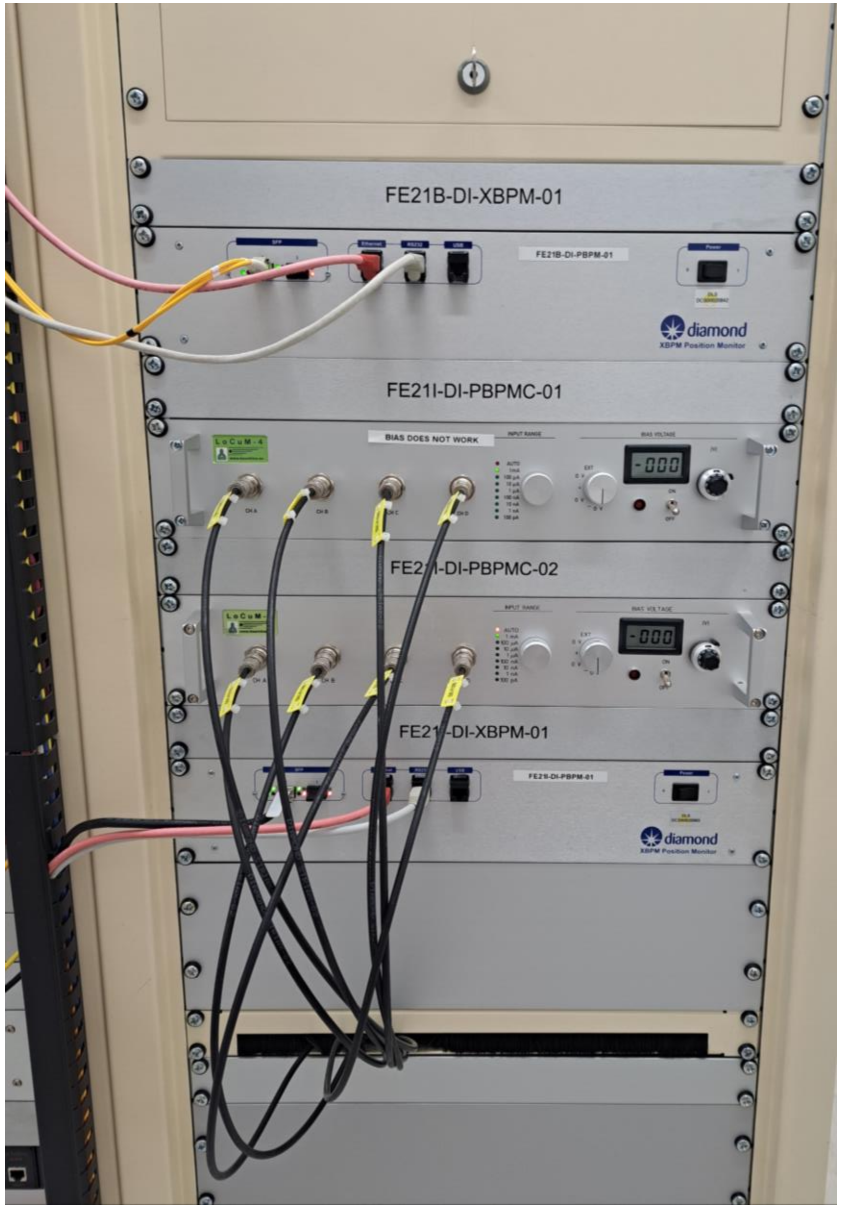


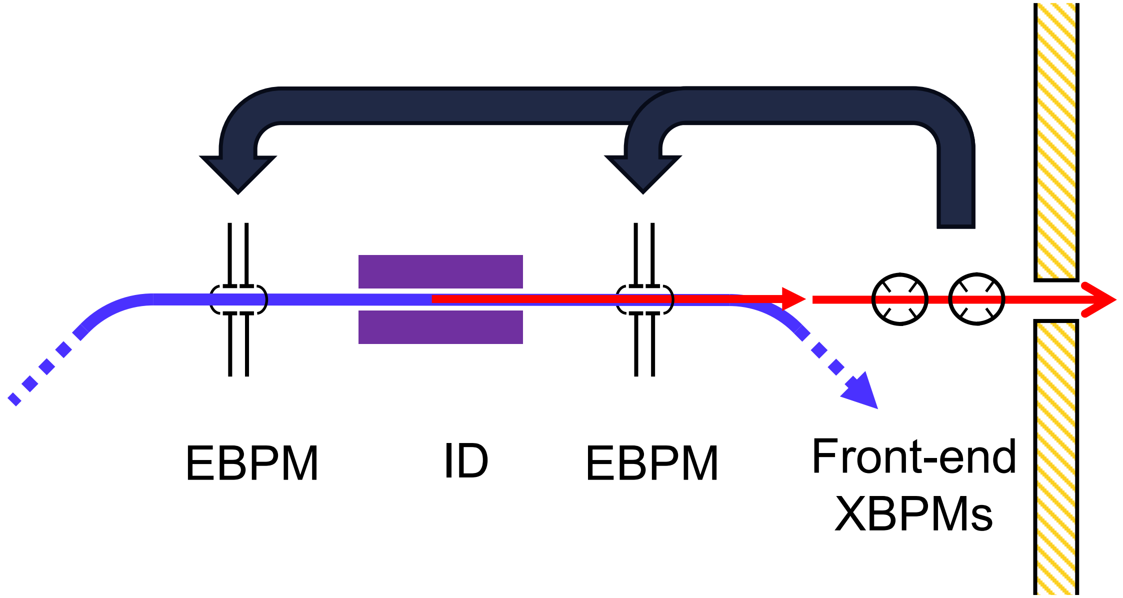
Diamond Front End XBPM Readout

- Signal currents from ID beamlines are **~100μA** on each blade.
- Triaxial cable is used to bring the signal from the XBPM into the Control Instrument Area (CIA).
- This **μA** output is amplified and **converted into a 0-10V** signal using a transimpedance amplifier, ENZ LoCuM-4.
- The 0-10V output from the LoCuM goes to an in-house digitiser, IsaPhoton, a 10 kHz **ADC**.



Diamond Front End XBPMs in Operation

- 37 XBPMs currently in operation (approx. 2 per beamline).
- All XBPMs purchased from FMB Berlin.
- Due to acquisition chain, synchronisation with Electron Beam Position Monitors (EBPMs) is challenging.
- Currently no integration into Fast Orbit Feedback.
- Slow (≈0.5 Hz) feedback to stabilise the **pointing angle** of the beam, **making changes to the electron beam** Golden Orbit.



Golden Orbit = **Desired trajectory** of the electron beam

Diamond-II Upgrade

Diamond Light Source: Diamond-II

UK national synchrotron science facility | 4th-generation storage ring

Diamond-II will replace the machine with a **4th-generation source** for brighter, more coherent light by:

- **Increasing electron beam energy**
- Upgrading Insertion Devices with high fields and shorter periods
- **Reducing emittance**

- 3 new 'flagship' beamlines + significant upgrades to many existing beamlines.
- Machine diagnostics must **measure nm-level beam motion** and feed back at kHz bandwidth.

[1]Diamond-II TDR: https://www.diamond.ac.uk/Diamond-II.html

Key machine parameters

Diamond-II storage ring[1]

3.5 GeV
Electron Beam Energy

300 mA
Maximum Current

36
Operating Beamlines

120 pm rad
Horizontal emittance

8 pm rad
Vertical emittance

7 ps
Average Bunch Length

Key diagnostic requirements

Orbit Stability
3% up to 1 kHz
Sub-micron source stability required in both planes.

FOFB Architecture
100 kHz loop
24 CIA endpoints feed a central controller; fast corrections are returned to the CIAs.

BPM Electronics
<2 nm/√Hz
Operation short-term uncertainty target <1 um pk-pk long-term.

Key dates

Dec 2027
Dark Period Start

18 months
Dark Period Length

Diamond-II: Impact on XBPMs

D-II Challenges	Diamond XBPM limitations	XBPM Upgrade
↑ brightness = ↑ **power of user X-ray beam**	**Max. power** on blade= 50 W	XBPM blade position **redesign** to cope with increase power
Changes to/new insertion devices, new **source points**	**Profile of beam changes**, blades not on edge of beam	XBPM blade position **redesign** optimising for each source
Fast orbit feedback increased operational importance	**Cannot integrate XBPMs** in fast feedbacks	Use the **same architecture** for EBPMs and XBPMs to allow for the inclusion of XBPMs in feedback
Demand for better **postmortems** to diagnose faults	**XBPMs not synchronised** with other diagnostics	Use the **same architecture** for EBPMs and XBPMs to allow synchronised measurement
Future proofing the next 20 years operation	**ENZ LoCuM-4 obsolete**	**Replace acquisition** hardware with FMCs
Time is limited during dark period	**-**	Upgrade as much as possible **before dark period**
Cost, **environmental** impact and **space** constraints	**-**	**Reuse** as much as possible of existing equipment

Diamond-II: XBPM Redesign

The XBPM assembly can be split into 3 parts

1. The **total XBPM assembly** (including stepper motor, stand and vessel)

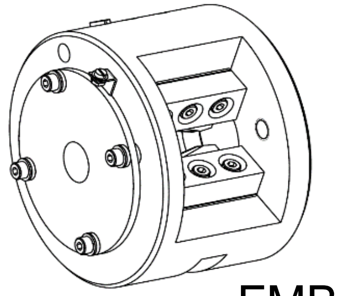
2. The **insert flange**, which sits inside the vessel

3. The **blade holder**

The **blade holder** only part which needs to be **adjusted for Diamond-II**.

However, swapping the blade holders at Diamond comes with **increased risk to vacuum recovery**.

Blade Holder



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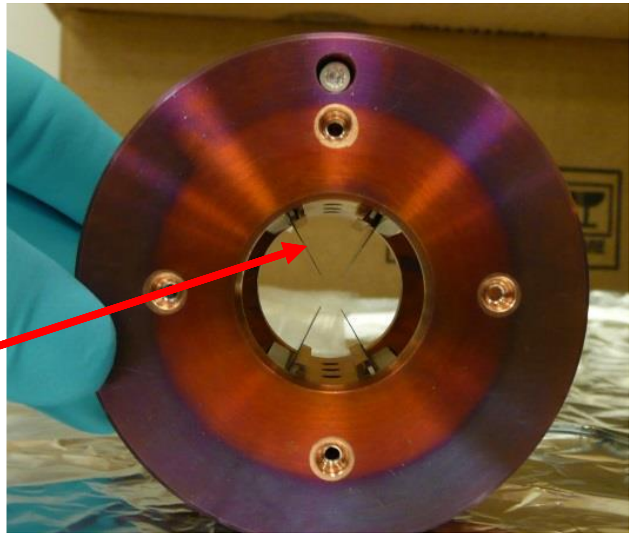

Tungsten Blade

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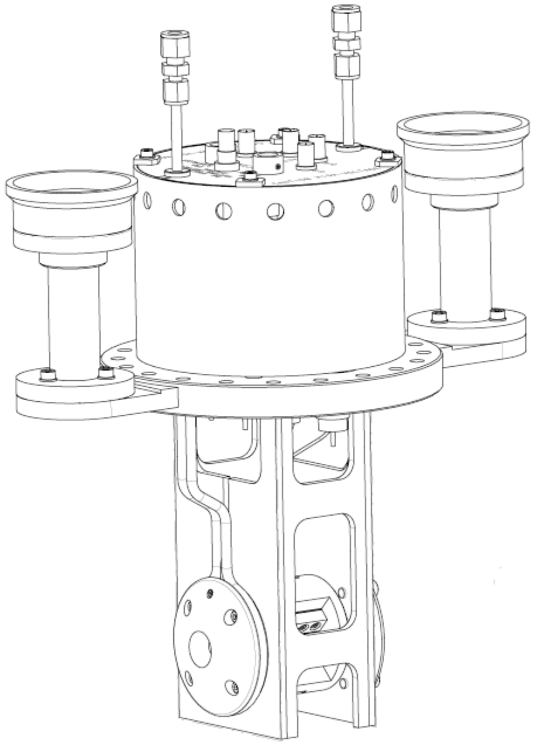
Insert Flange



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We plan to swap all existing insert flanges for Diamond-II

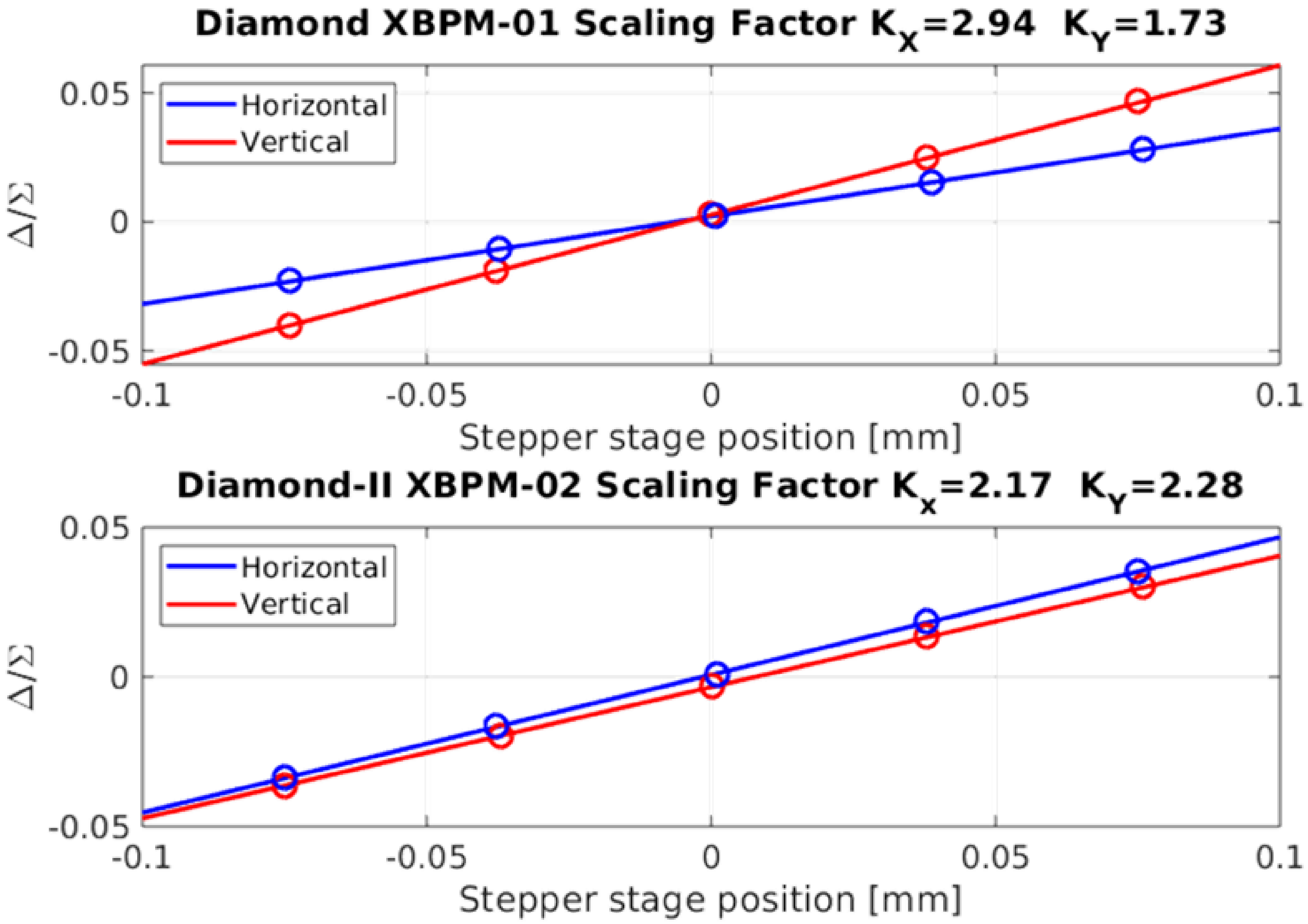
Diamond-II Upgrade Progress so far

1. Upgrade our existing ID front end XBPMs

2. Buy brand new XBPMs for new flagship / K beamlines

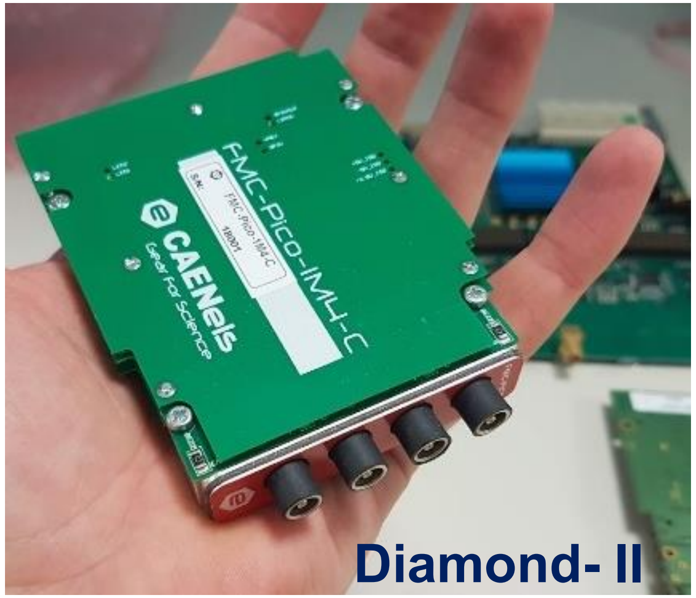
XBPM Comparison between Diamond & Diamond-II Design

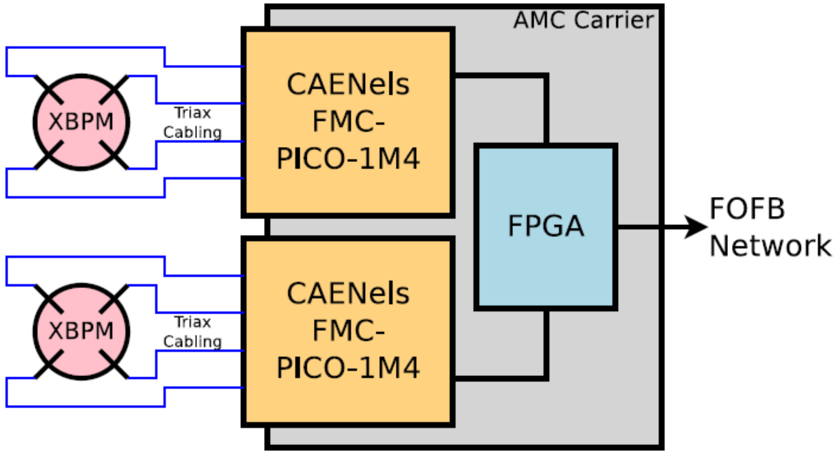
- Results from I02 (first insert swap)
- Moved stepper stage ±0.04 mm steps.
- Measured responses recorded on both XBPMs across both axes.
- Scaling factors for the new XBPMs are **more consistent**, with sensitivity more evenly **balanced between axes**.



Diamond-II Upgrade Path

- Replace LoCuM & IsaPhoton system with **single 4-channel FMC**.
- Measurement **rate of 100 kHz**.
- Compatible with Electron Beam Position Monitor (EBPM) IOxOS MTCA, **unified electronics architecture**.
- Beam position can be archived **synchronously with EBPM** measurements for postmortem investigations.
- Possibility for **inclusion in Fast Orbit Feeback** for bending magnet beamlines or as redundancy for EBPMs on ID beamlines.



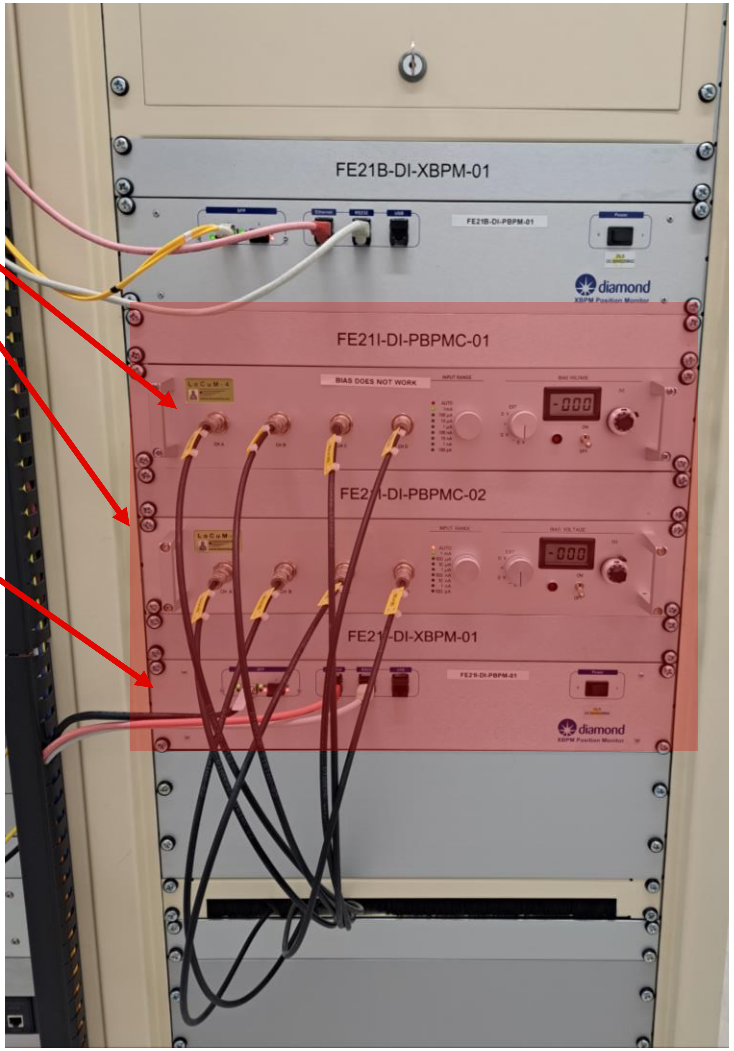


Comparison Diamond & Diamond-II Acquisition

Diamond (6U Space)

ENZ LoCuM

IsaPhoton



Upgrade

Diamond- II (<1U Space)

FMC

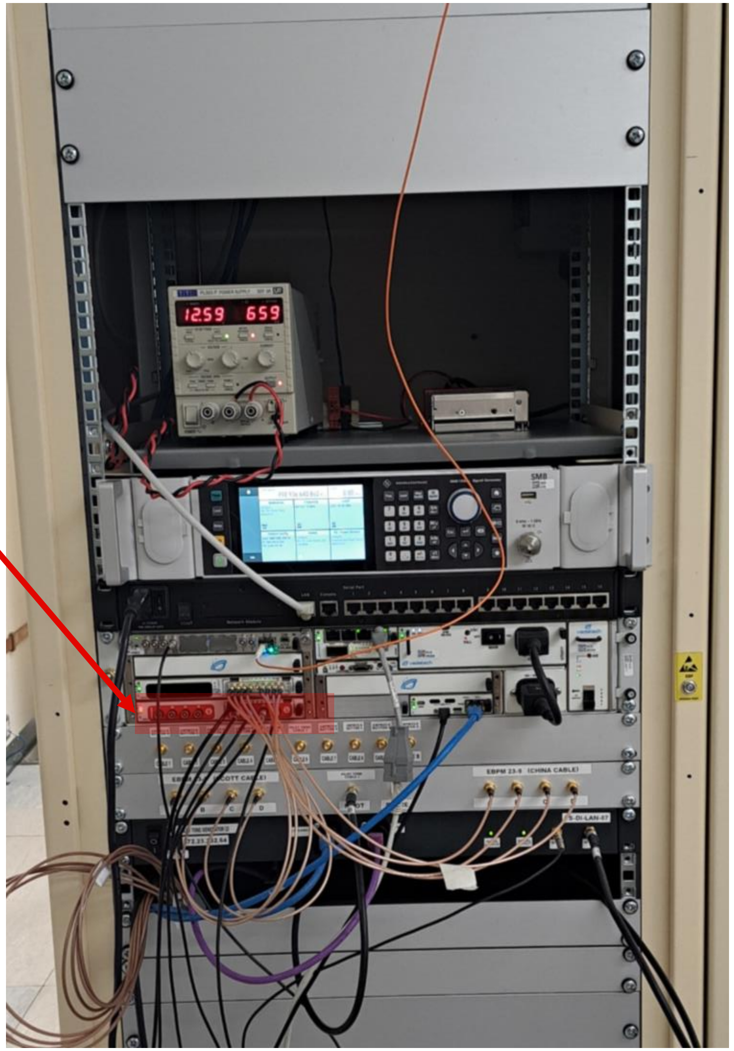
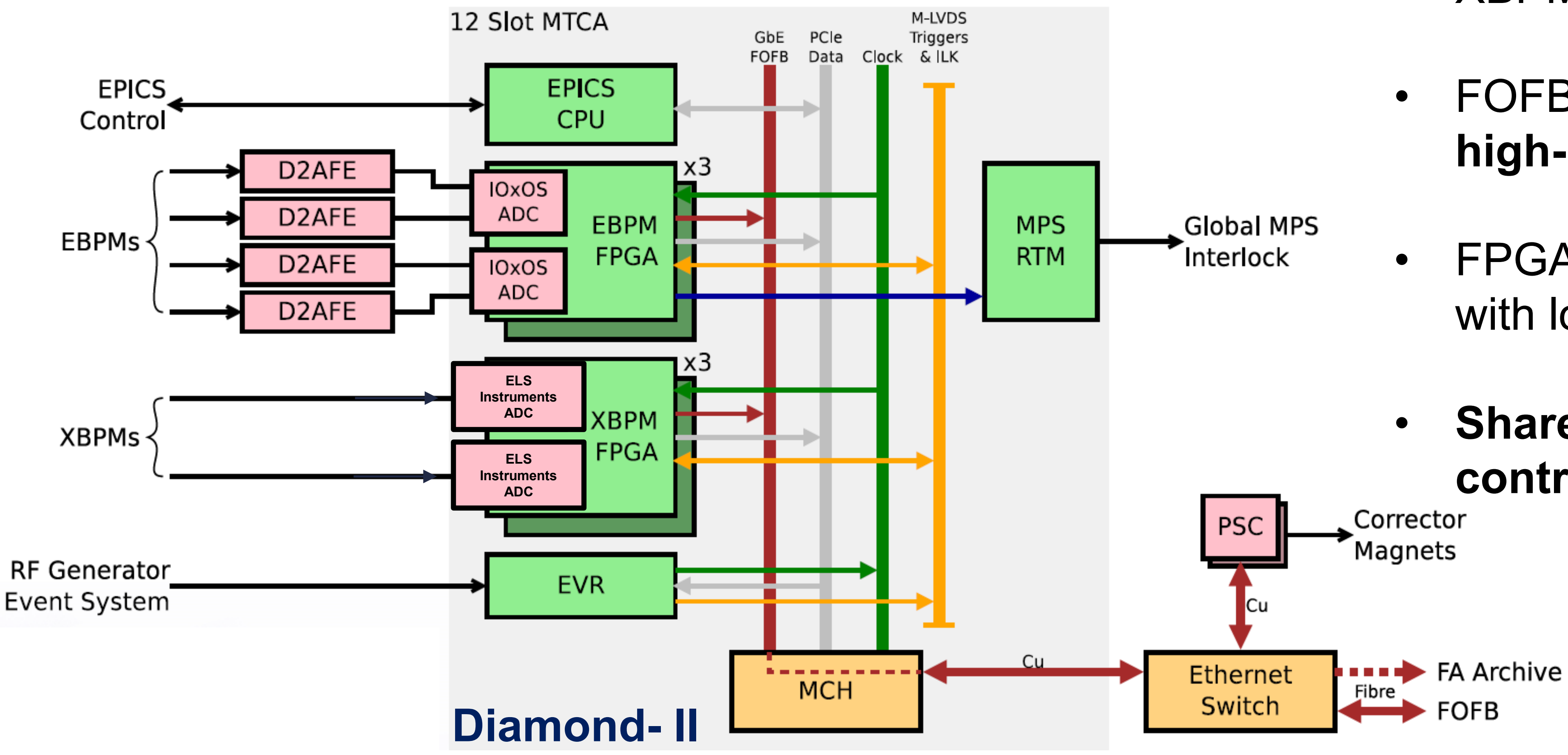


Image shows test rack.
Final rack will include 12 slot MTCA.

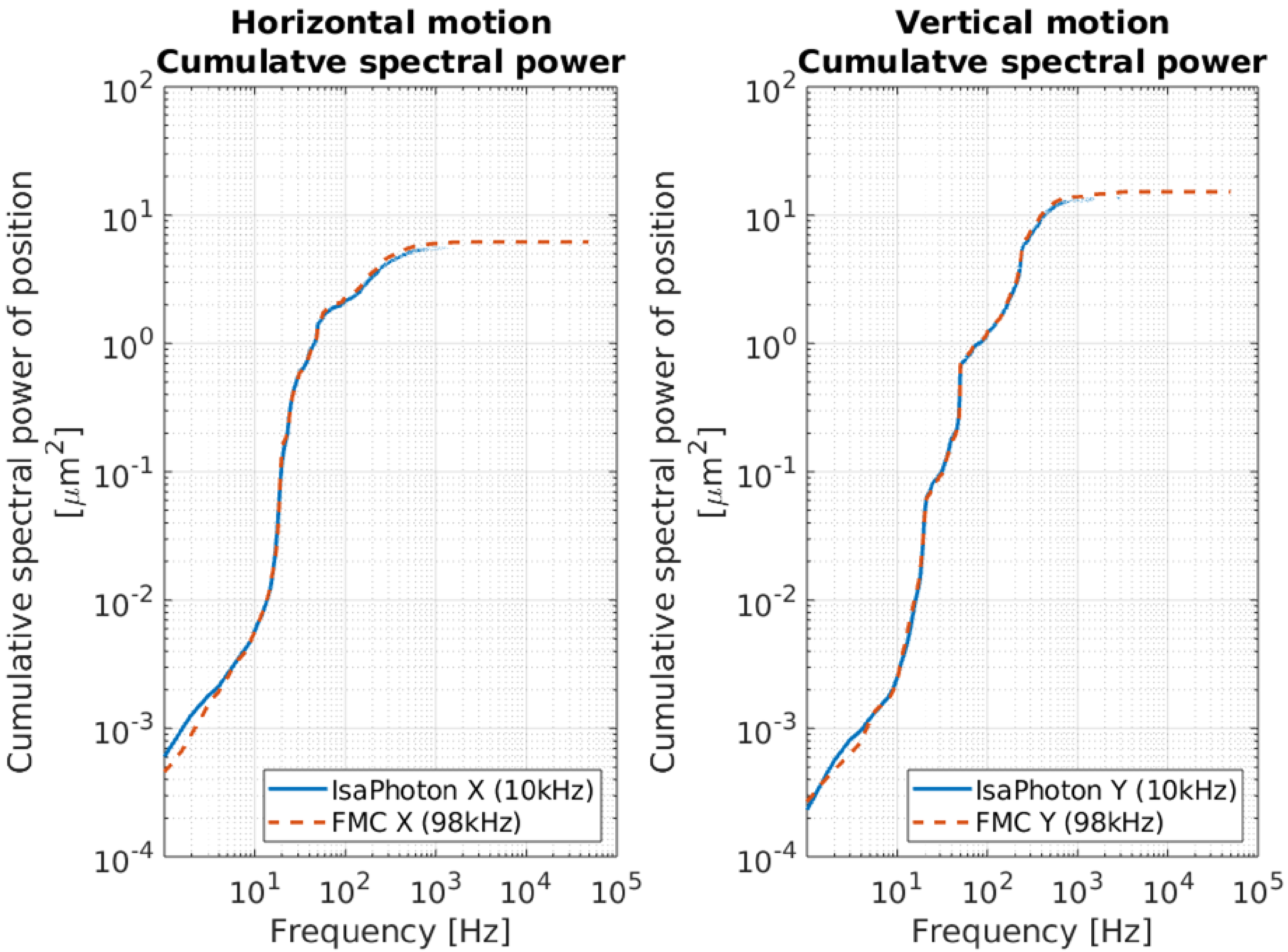
Common Architecture for EBPM & XBPMs



- **Common platform** for EBPM and XBPM systems
- FOFB-ready with **synchronised high-rate data** streams
- FPGA-based real-time processing with low
- **Shared timing, networking and control infrastructure**

Comparing Diamond and Diamond-II Readout

- **Real beam position data** from an I23 XBPM.
- **Comparison** of the existing LoCum-4 & IsaPhoton system and the planned D-II FMC.
- **Small differences** in spectra due to small **fluctuations in real beam movement** between datasets.
- **Higher frequency** information available with **FMC**.



Diamond-II Feedbacks using XBPMs

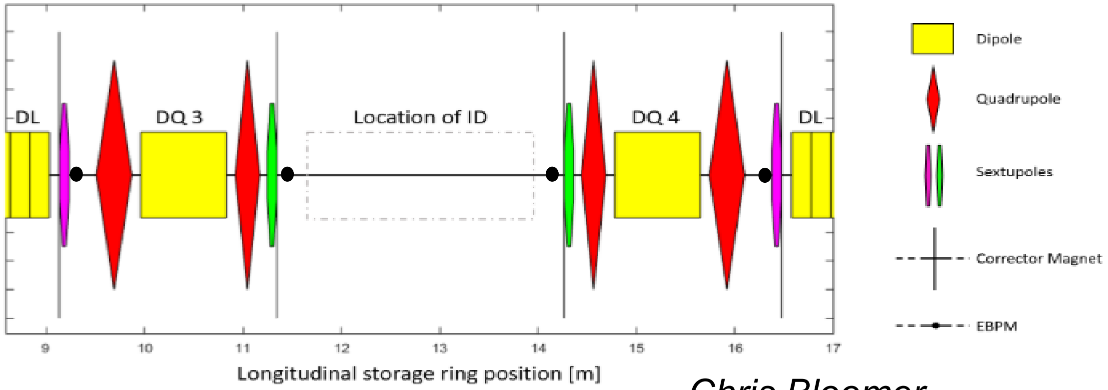
XBPM Feedbacks for Diamond-II

Slow Front-End Feedback

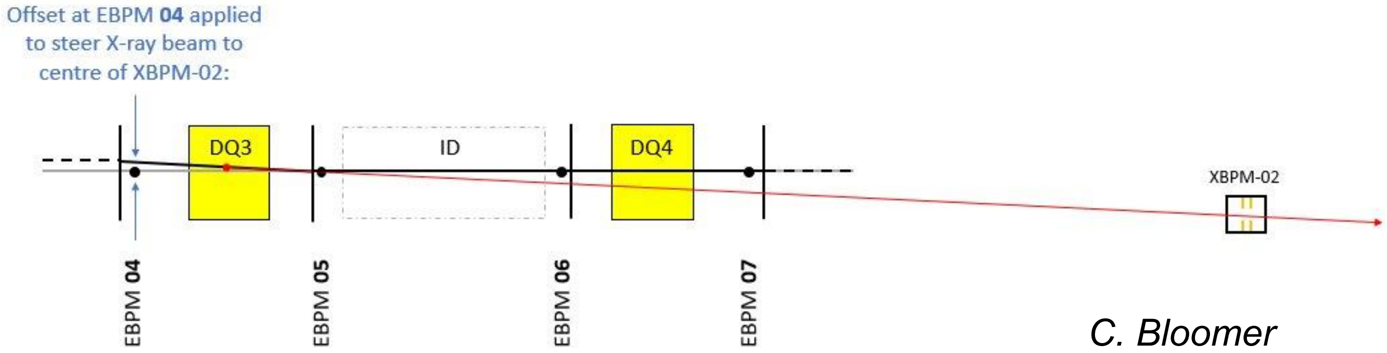
- Keep the slow (0.5 Hz) feedback, which keeps the pointing angle consistent for all beamlines
    - Requires that Insertion Device gaps are static due to scaling.

Fast Orbit Feedback for Dipole Sourcepoints

- It is not possible to have EBPMs on either side of dipole sources for beamlines.
- XBPM-02 used to correct orbit in place of EBPM, XBPM-01 will monitor the beam position.



Chris Bloomer



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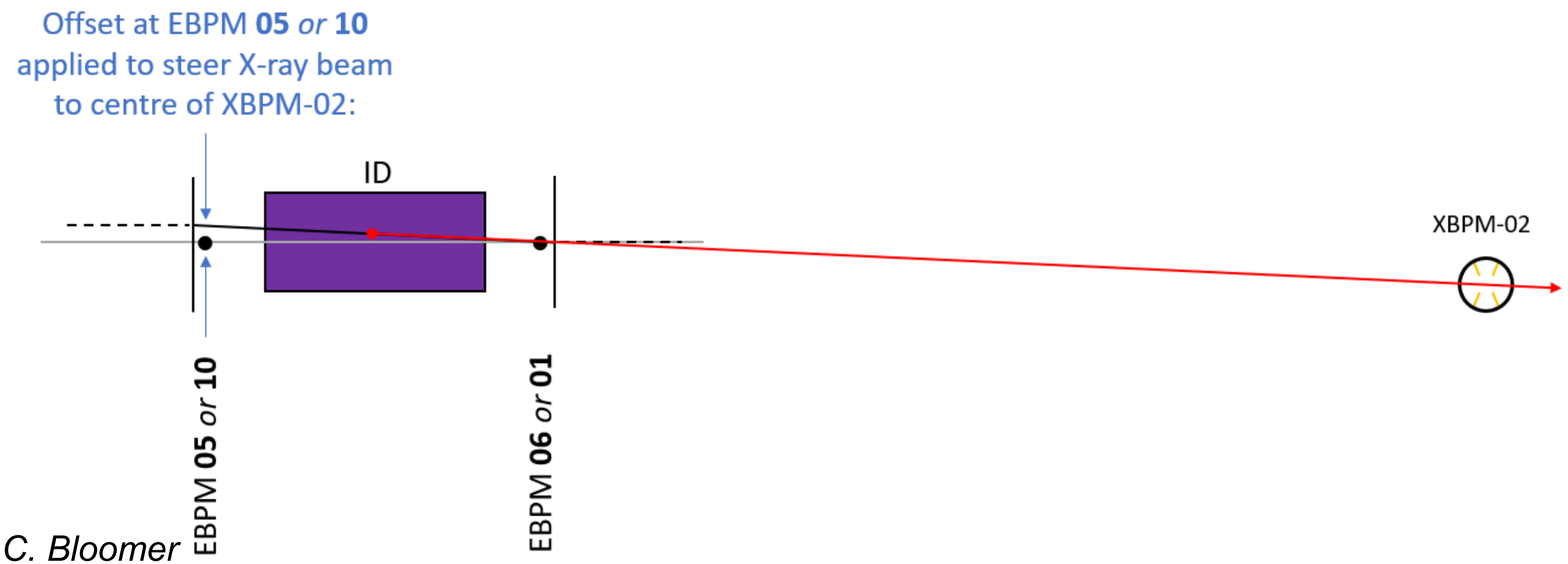
XBPM Feedbacks for Diamond-II

Fast Orbit Feedback for Insertion Device Sourcepoints

- **Stabilise** the **X-ray beam** from an **ID source point** in the event of a primary **EBPM failure.**
- Similar to dipole feedback, **utilising XBPM-02** to replace the failed EBPM.
- Corrects both **horizontal and vertical pointing angles**.



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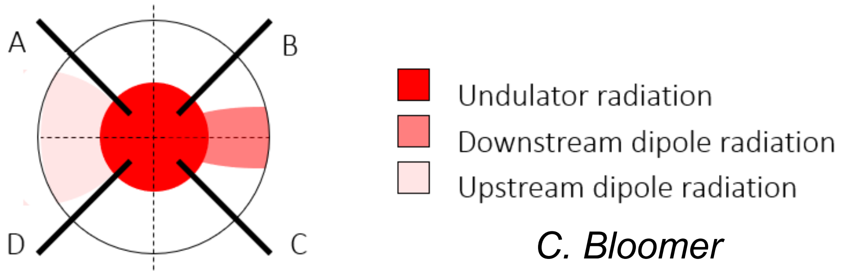
Challenges with XBPM Feedbacks for Diamond-II

Challenges	Requirements
Dipole magnets produce **"background" light skewing XBPM** measurements	Only run when **ID is closed** below some threshold
Scaling factor is **dependent on ID gap**	Need **live-updating scaling calibration** to account for ID gap changes; see Samuel Jackson poster WEP008.
XBPM-02 is behind front-end absorber	Feedback can **only** operate **when the front end is open**



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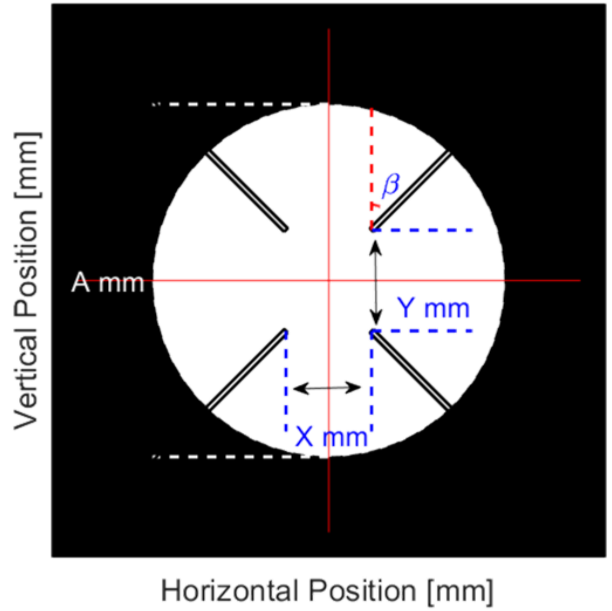
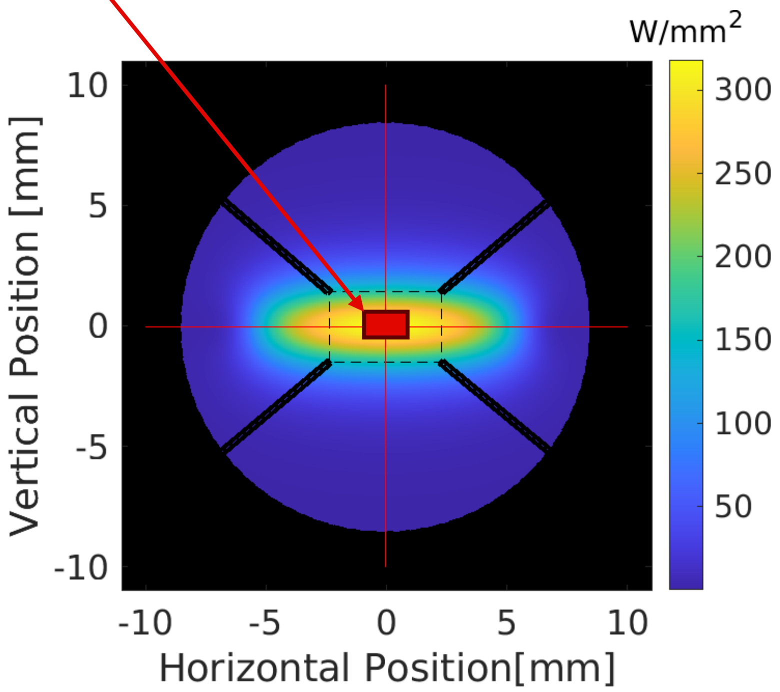
Optimising for Beam Sensitivity

XBPM Design Principles

- Tungsten XBPM blades are ideally positioned with their tips touching the **FWHM of the photon beam**. This leaves the central region untouched for the **user beam**, making it **minimally invasive**.



Parameters for optimisation:
- Blade extension angle (β)
- X & Y separation
- Aperture diameter (A)



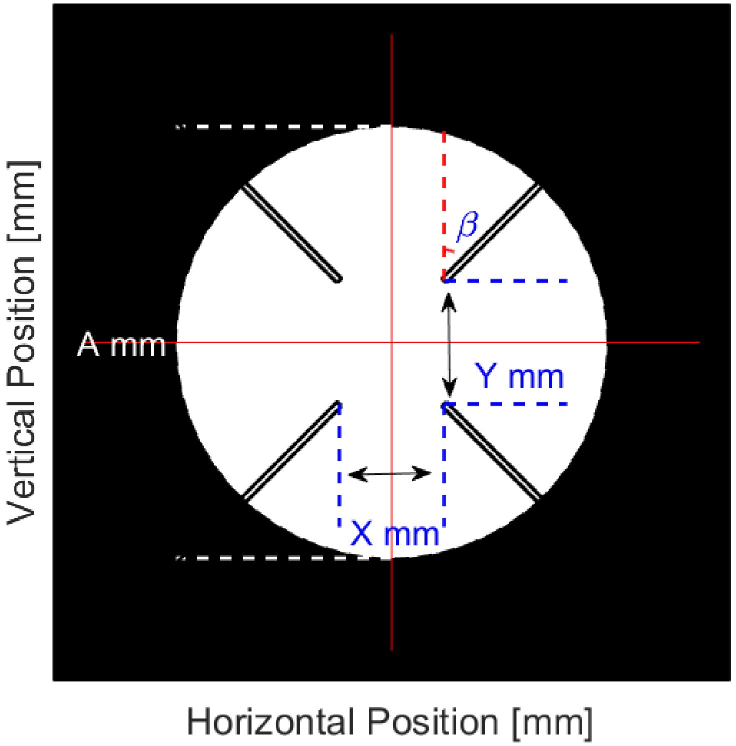
- X-ray beam simulated using SRW[1] to give transverse power density distribution.

[1] O.Chubar and P. Elleaume , "Synchrotron Radiation Workshop (SRW)". Computer software. 2013 https://www.osti.gov//servlets/purl/1231615

XBPM Design Principles: The caveats

- The optimal blade location is not always the theoretical 'ideal' based on FWHM[1]. Multiple factors in compromise of optimisation and safety:

    1. **Power incident on the blades below the damage threshold**
    2. **Shadowing effects between XBPM-01 & XBPM-02**
    3. **Sensitivity to beam movements**

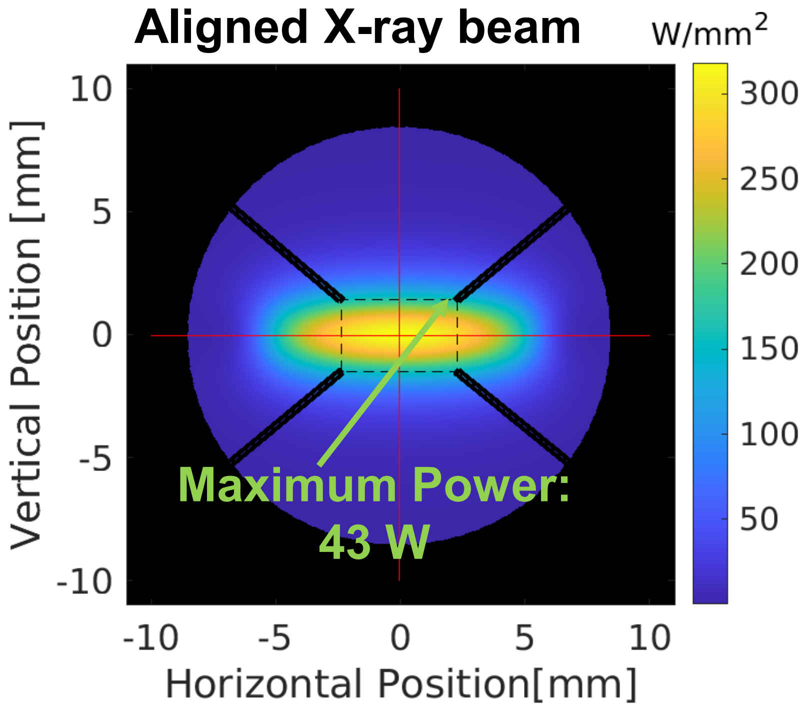


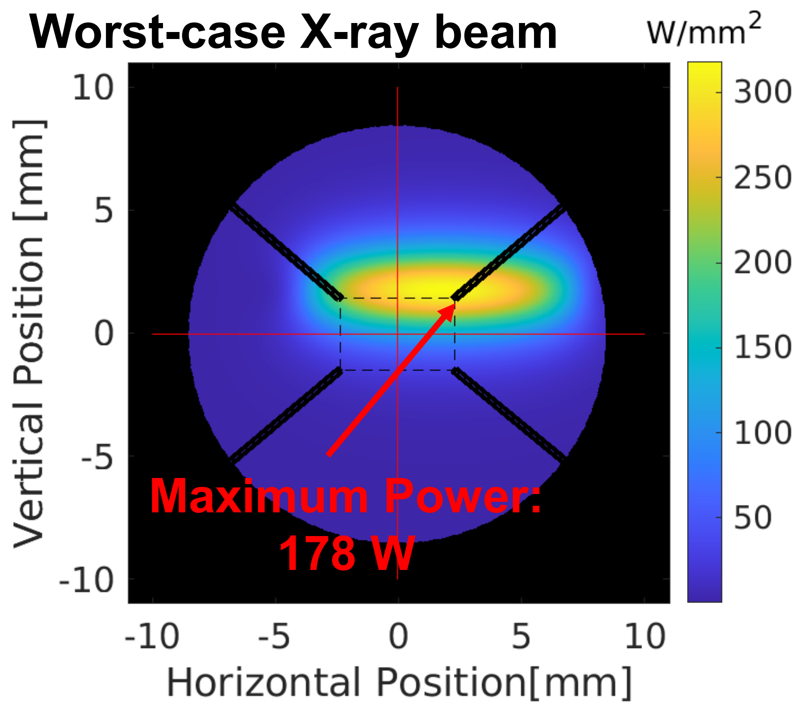
Parameters for optimisation:
- Blade extension angle (β)
- X & Y separation
- Aperture diameter (A)

[1] P Ilinski 2013 J. Phys.: Conf. Ser. 425 042006

1:Power on Blades

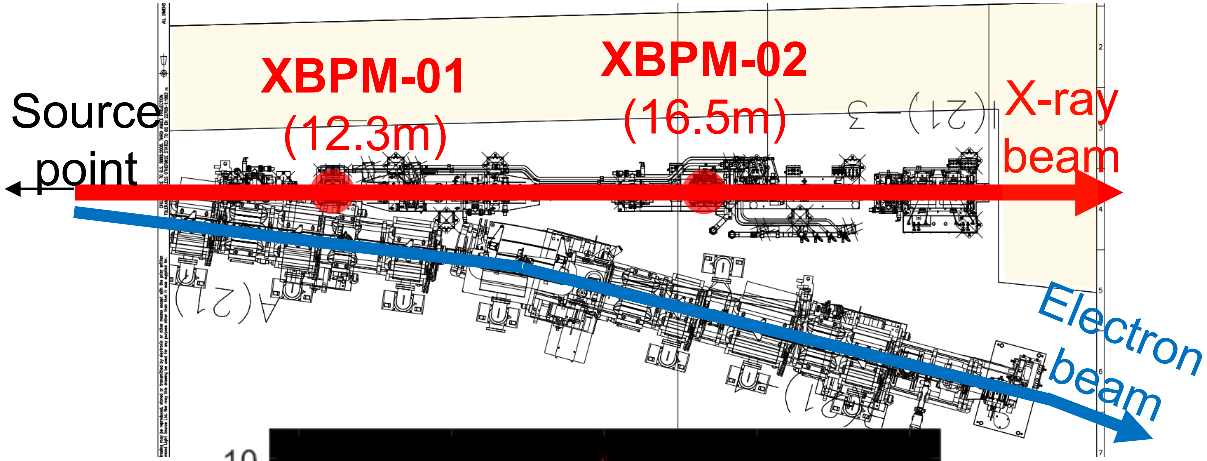
- Simulations **assume perfect beam** alignment; potential **offsets of the electron beam** could **increase power** on one blade. (Max. allowed 50W)
- **Machine protection limit** of the electron beam offset at the EBPMs (**±0.25 mm**) was simulated.
- If **power is too high**, simulated **blades are retracted** until a safe location is found for design.

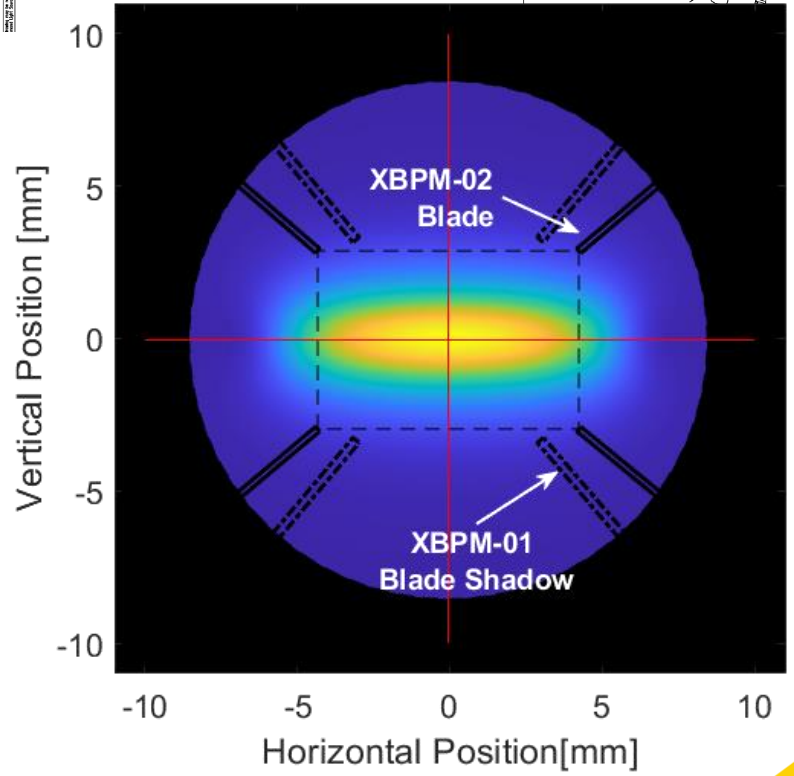




2:Shadowing

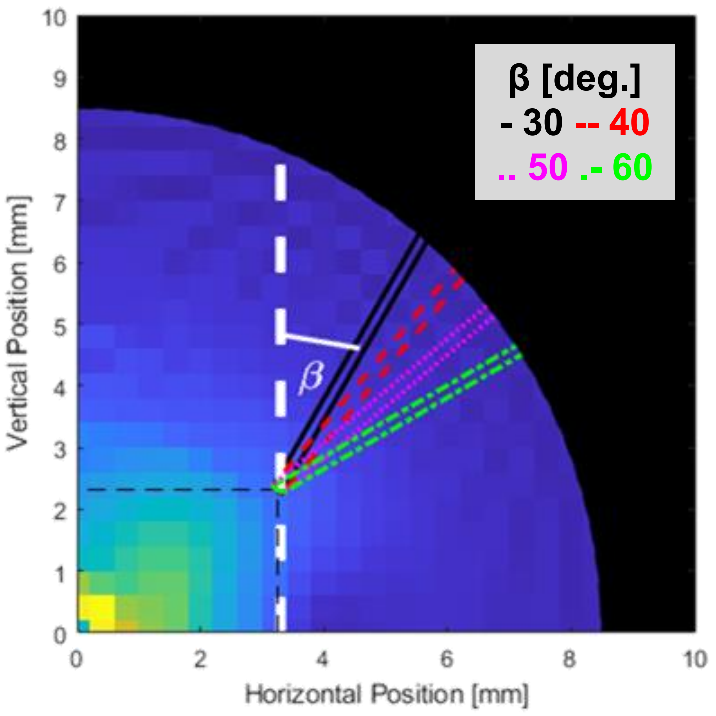
- **XBPM-01 blades can potentially block the X-ray beam**, shadowing XBPM-02 blades behind them.
- Shadowing **reduces the sensitivity of XBPM-02**, due to fewer incident photons.
- A shadowing analysis ensures **minimum separation between blades > 0.8 mm.**



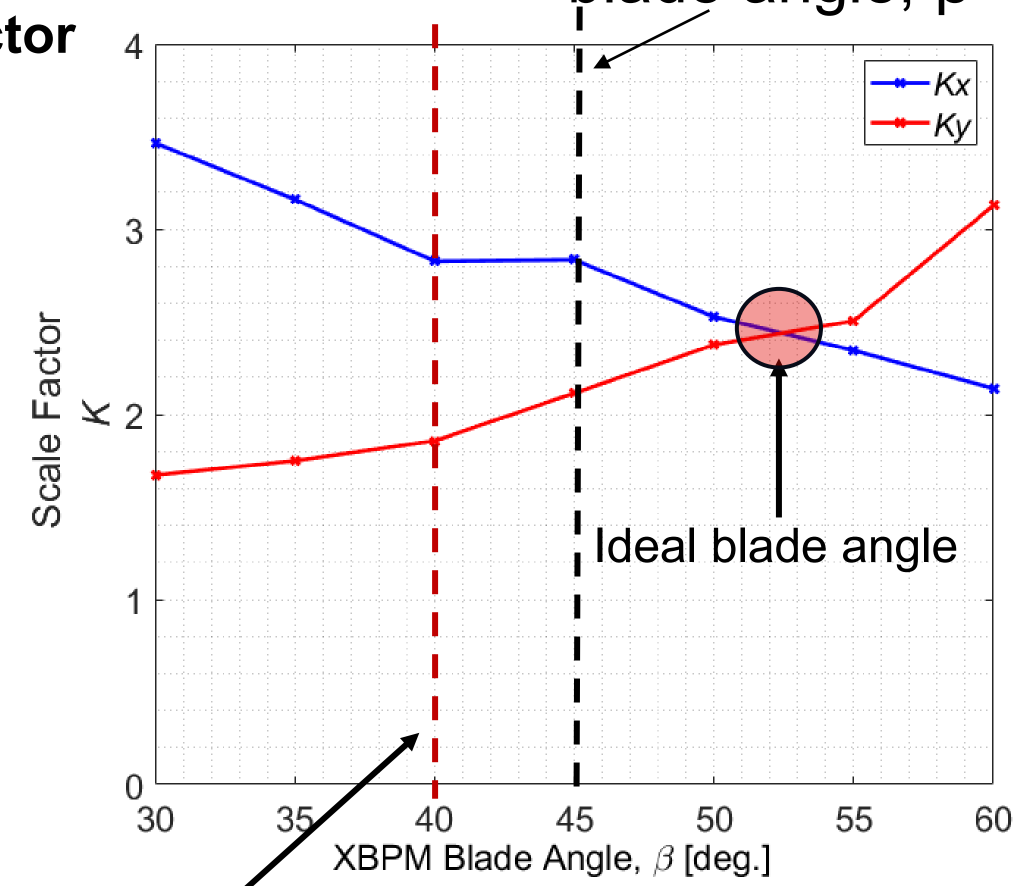


3:Sensitivity

- Changes to **blade position** and **blade angle** used in simulations significantly **affect the calculated scale factor** of the device.
- **Equal sensitivity in both axes is optimal.**

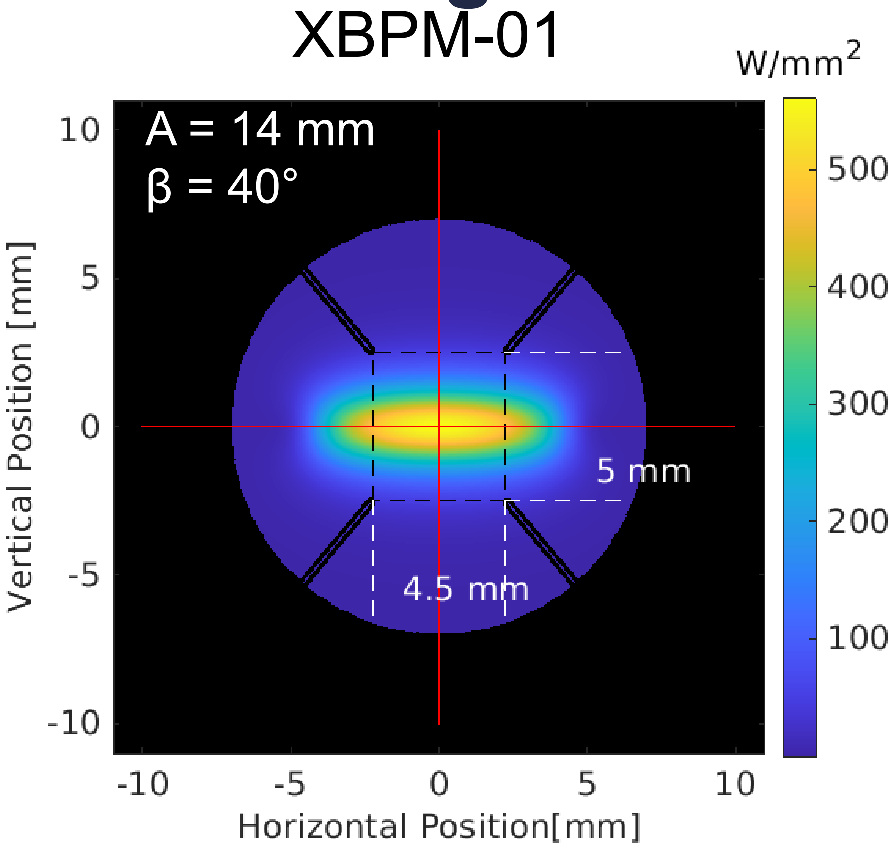


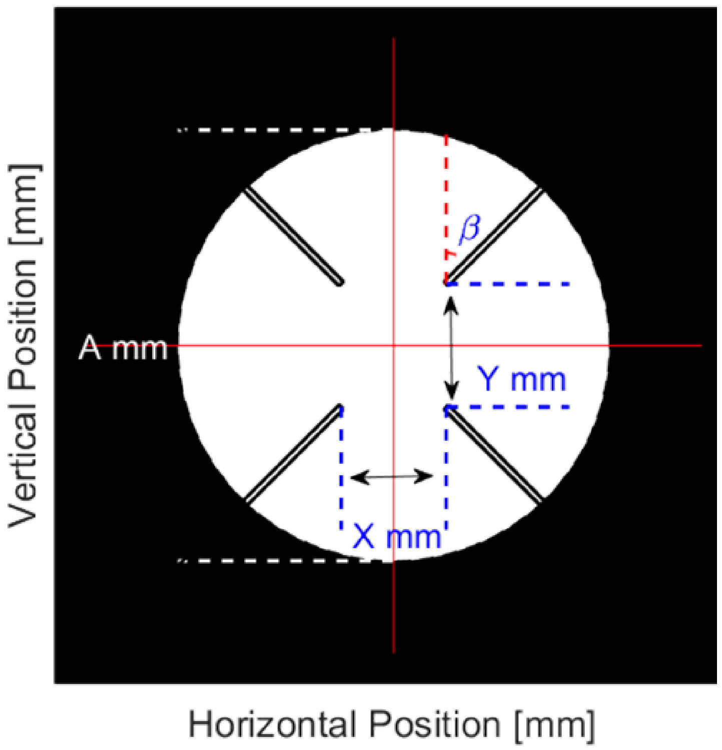
Current XBPM-01 blade angle, β

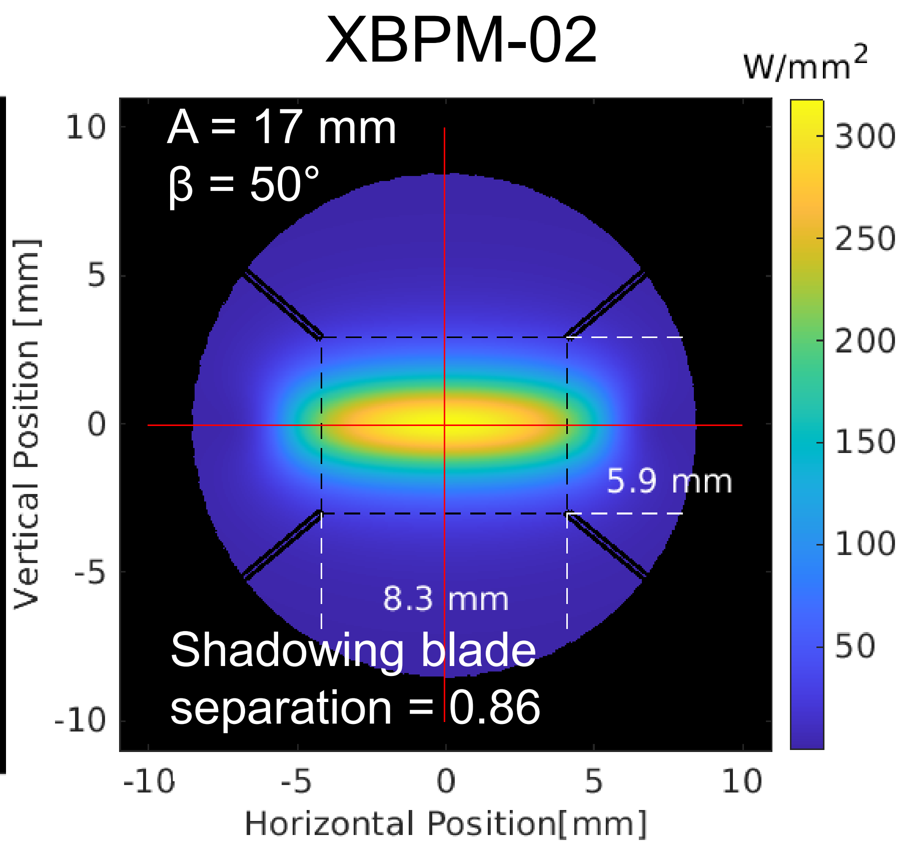


Compromised blade angle to keep **consistent** across XBPM blade holders

Final Design







Final design parameters sent to FMB for the manufacturing **having optimised for:**

1. **Power incident on the blades below damage threshold**
2. **Shadowing effects between XBPM-01 & XBPM-02**
3. **Sensitivity to beam movements**

Optimising for beam sensitivity: APPLE insertion devices

- **A**dvanced **P**lanar **P**olarised **L**ight **E**mitting undulators.

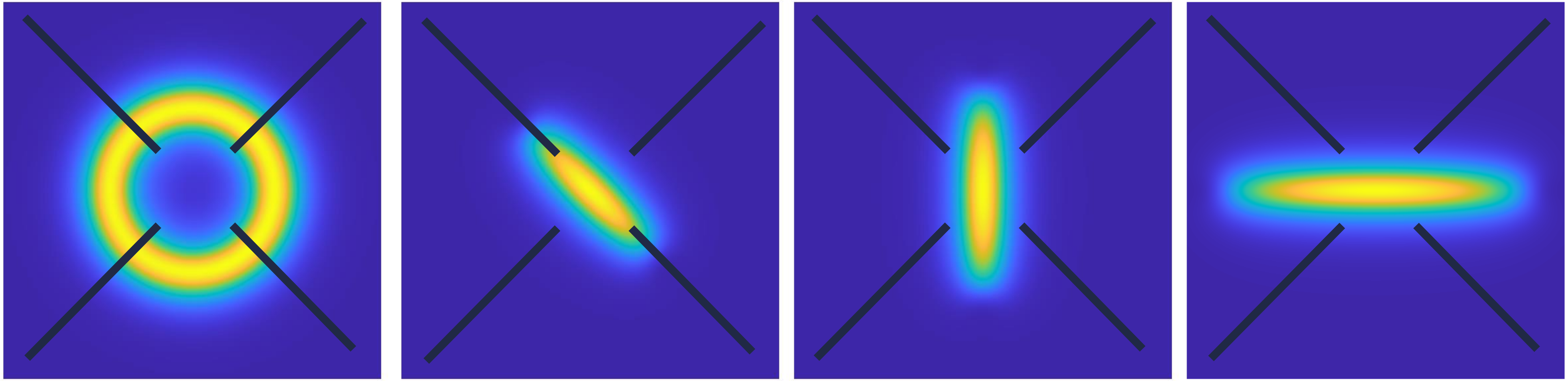
- Insertion devices **which allow for different polarization** states including circular polarization to limit on axis power at low energy.

- 8 APPLE Insertion Devices to be installed in Diamond-II:
  - 7 × APPLE-II
  - 1 × APPLE-Knot

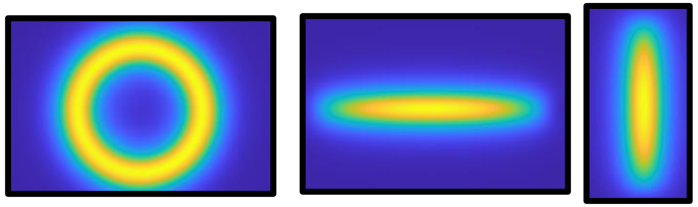
Optimising for Beam Sensitivity: Polarisation

- Different polarisations mean **significant differences in the profiles observed.**
- **High fields lead to significant power loads** on the XBPMs.
- Blade positions optimised for sensitivity **for a given polarisation.**
- Designed such that in all other polarisations**, power limits on blades won't be exceeded**

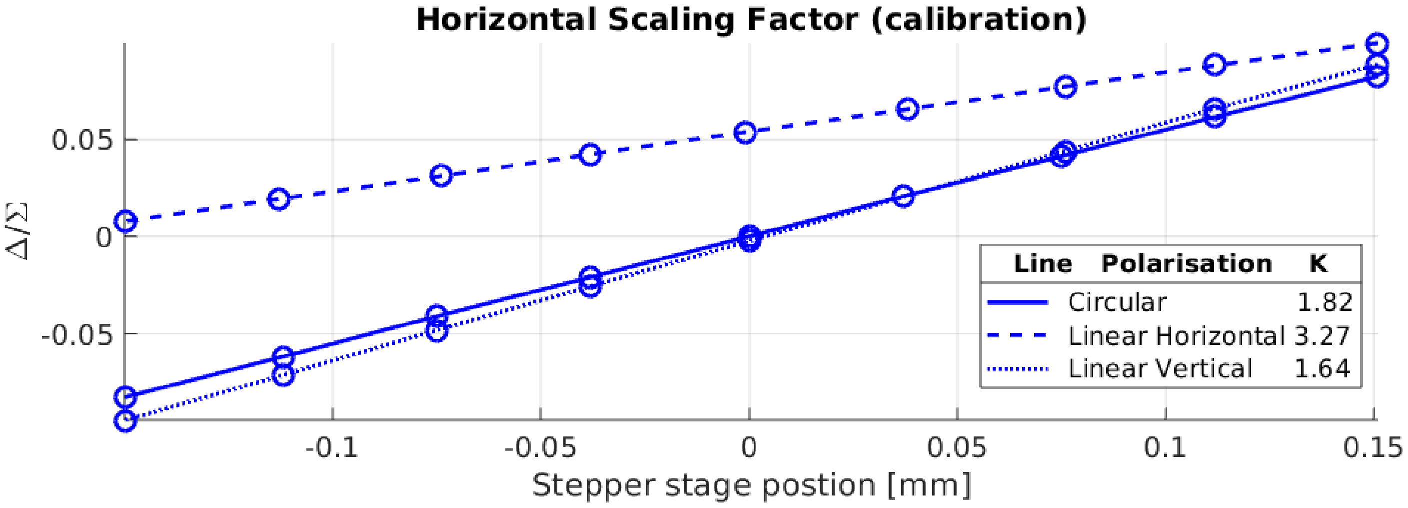
Circular **Inclined** **Vertical** **Horizontal**

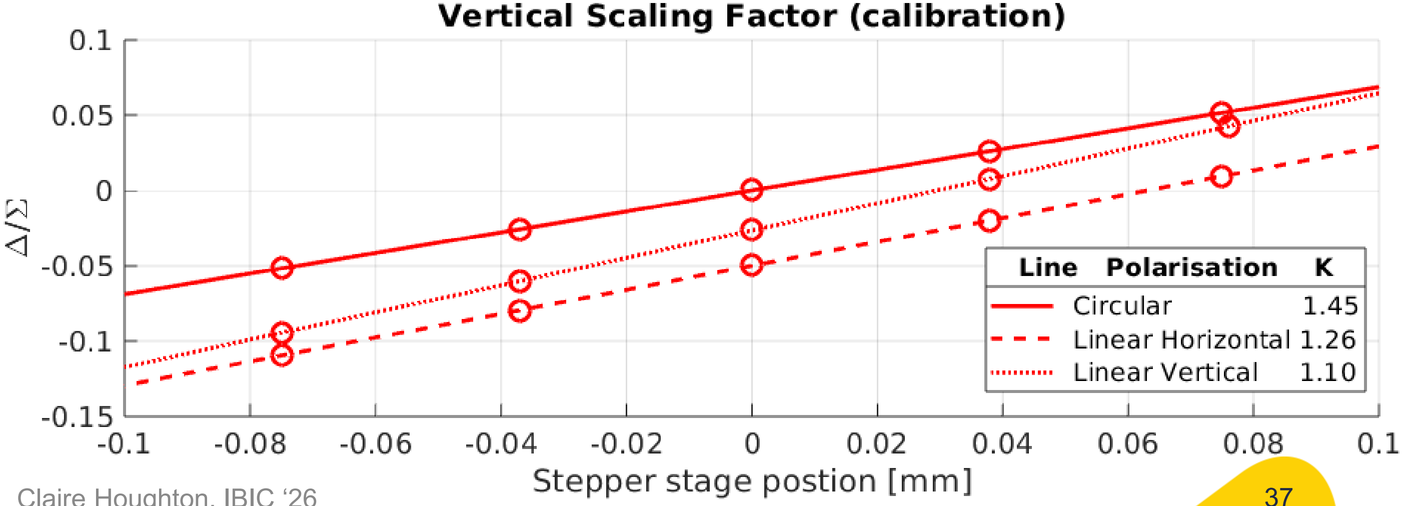


Sensitivity with Changing Polarisation



- Measured sensitivity of the I10 polarising undulator in Diamond.
- **Profile change** impacts measured beam position and **scaling factor**.
- **Reduced accuracy** is expected when operating at **certain polarisations**





Conclusion

- The upgrade of Front-End XBPMs in preparation for Diamond-II has started.
- We have **upgraded the hardware of ≈ 65% of existing XBPMs** ready for Diamond-II.
- Bespoke designs for **unique source** point requirements, i.e. **dual source** points, **bending magnet**, and **wiggler** source points.
- **→ XBPMs bespoke for each beamline**
- Acquisition hardware has been tested with the beam and currently meets the noise measurement requirements.
- Future proposals to include XBPMs in the Fast Orbit Feedback system.

Images showing the installation of I07 XBPM-02 (Oct.2024)

References

Used in this talk

- Diamond-II TDR: https://www.diamond.ac.uk/Diamond-II.html
- *P Ilinski 2013 J. Phys.: Conf. Ser. 425 042006*
- *O.Chubar and P. Elleaume , "Synchrotron Radiation Workshop (SRW)". Computer software. 2013 https://www.osti.gov//servlets/purl/1231615*
- *FMB Feinwerk- und Messtechnik GmbH. FMB Berlin – experts in vacuum and beamline technology. https://www.fmb-berlin.de/index.php/en/, 2026.*
- *ENZ Ingenieurbüro für Umweltelektronik & Automatisierung. LoCuM-4 Low Current Monitor:User Manual, 2011. Revision 1.7.*

For more information

- *Lorraine Bobb and Claire Houghton. Diagnostics in light sources I: Front-end X-ray beam position monitors. Proc. of. CAS BI 2025, 2026.*
- *P. Forck, P. Kowina, and D. Liakin. Beam position monitors. CAS 2008 - CERN AcceleratorSchool: Beam Diagnostics, Proceedings, pages 187–228, 2009*
- *Chris Bloomer and Guenther Rehm. Real-time calculation of scale factors of x-ray beam positionmonitors during user operation. In Proceedings of IBIC 2012, 2012.*

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