A Diamond Sensor for Position Resolving Measurements at the European XFEL

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European XFEL
X-ray Photon Diagnostics (XPD)

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EuXFEL XPD Diamond Team:
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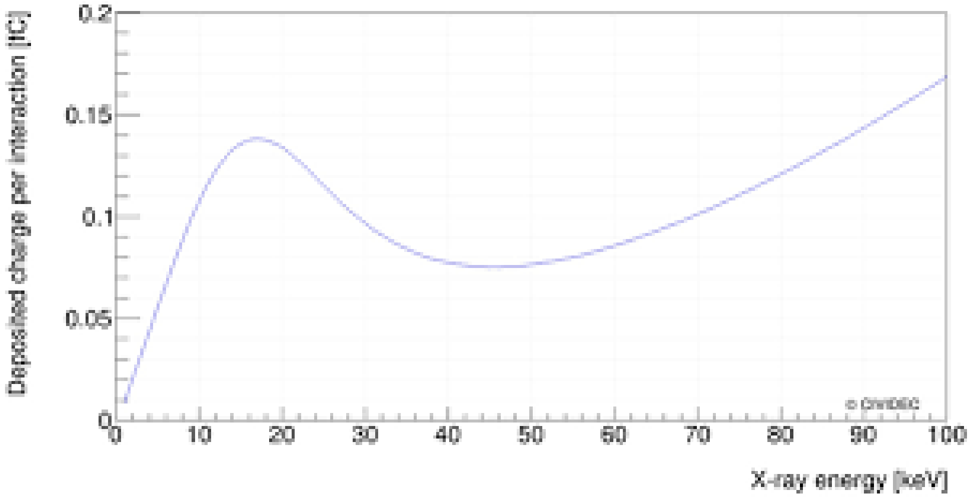
Diamond: Sensor Material

- **Superior Properties**[1]
  - Large band-gap (*5.48 eV*) → low intrinsic charge density → high T operation
  - High intrinsic resistivity (*>>10^{11} Ω/cm*) → low leakage current
  - High electron (*1900-4500 cm^2/Vs*) / hole mobilities (*1800-3500 cm^2/Vs*) → fast collection of charge carriers
  - Low dielectric constant (*5.72*) → low capacitance
  - High displacement energy (*43 eV*) → radiation-hardness
  - High dielectric strength (*10^7 V/cm*) → high field operation
  - High thermal conductivity (*2000 $Wm^{-1}K^{-1}$*) → quick heat dissipation
  - Low Z (tissue equivalent), low absorption
  - High sensitivity

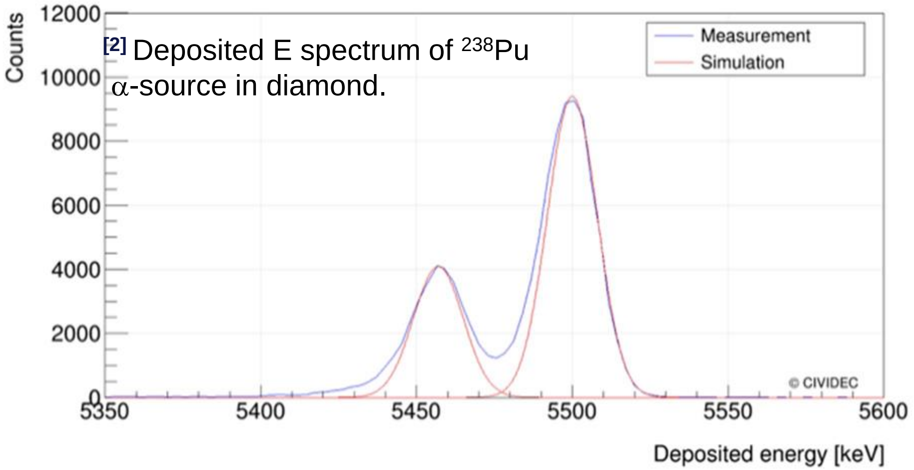
1. M. Pomorski, “Electronic Properties of Single Crystal CVD Diamond and its Suitability for Particle Detection in Hadron Physics Experiments”, PhD Thesis, Johann Wolfgang Goethe Universität, Frankfurt, Germany (2008).

Diamond: Particle Detection

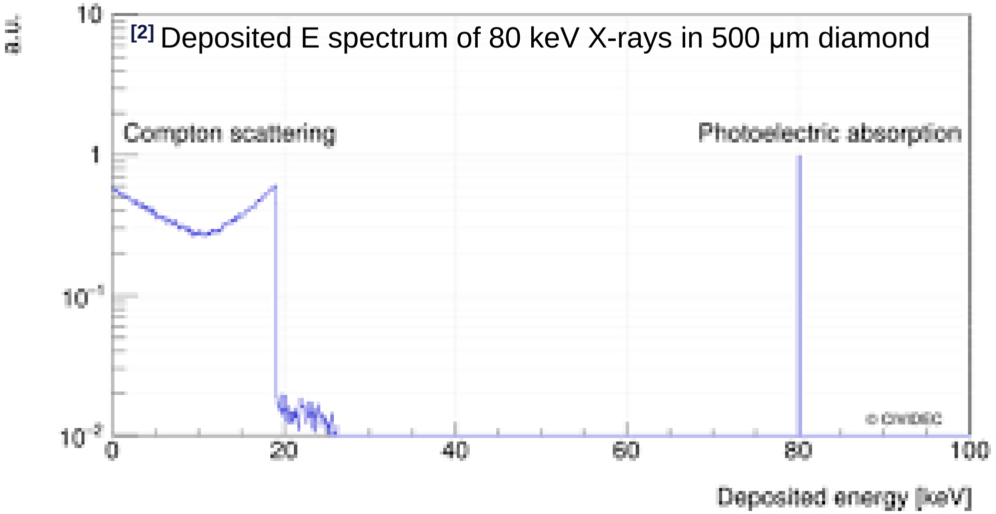
- **Charged Particles**
  - Alpha, beta, high energy ions
- **Neutral Particles**
  - Neutrons (E_n >5.8 MeV high cross section)
  - Photons (E_γ >5.5 eV)
  - Thermal neutrons



[2] Distribution of the deposited charge per interacting photon for X-rays in 500 µm diamond.



[2] Deposited E spectrum of ^{238}Pu α-source in diamond.



[2] Deposited E spectrum of 80 keV X-rays in 500 µm diamond

2. C. Weiss et al, “Particle Interactions with Diamond Detectors”, 8th Int. Beam Instrum. Conference IBIC2019, Malmö, Sweden (2019).

Diamond: Detector Development

Natural Diamond

1920's	Naturals demonstrate UV response.
1940's	Naturals used to detect ionising nuclear radiation
1950's	
1960's	
1962	Photoconductivity of naturals investigated
1970's	Advances made in forming electrical contacts to diamond
1980's	Commercial xray dosimeters for medical applications.

Polycrystalline CVD Diamond

early 1990's	Advances made in quality of polycrystalline CVD diamond Suggested use of pCVD in Super Conducting Super Collider. Commercial solar blind UV detector.
late 1990's	Beam position monitors for synchrotrons Charge Collection distance > 200 microns achieved suitable for high energy physics detector applications.

Single Crystal CVD Diamond

2000's	High purity single crystal CVD diamond with superior electronic characteristics.

Diamond Detector Applications

- Particle Physics: tracker, beam monitor
- Dosimetry: hadron radiotherapy, radiation exposure monitoring, calibration
- Nuclear applications: neutron spectrometry, reactors, homeland security, nuclear fusion experiments
- Synchrotrons: beam monitor
- UV detection: flame detectors, solar applications (ESA), photolithography, military application
- α/β: air flow, nuclear waste incineration, military
- FEL: beam diagnostics

Overview of Diamond Detectors

- Diamond detectors used as
  - HEP detectors (e.g. CERN, FermiLab)
  - Heavy Ion Detectors (e.g. GSI, Nordhia)
  - X-ray detectors at synchrotrons (e.g. DLS, ESRF)
  - Neutron detectors (e.g. CEA, Los Alamos, ITER)

At XPD we call it a diamond sensor to distinguish it from diamond particle detectors

- At FELs: huge pulse energy, short pulses
  - Current diamond detectors are too sensitive
  - High Z coating materials → radiation damage
  - Structured electrodes → distortion of coherent beam

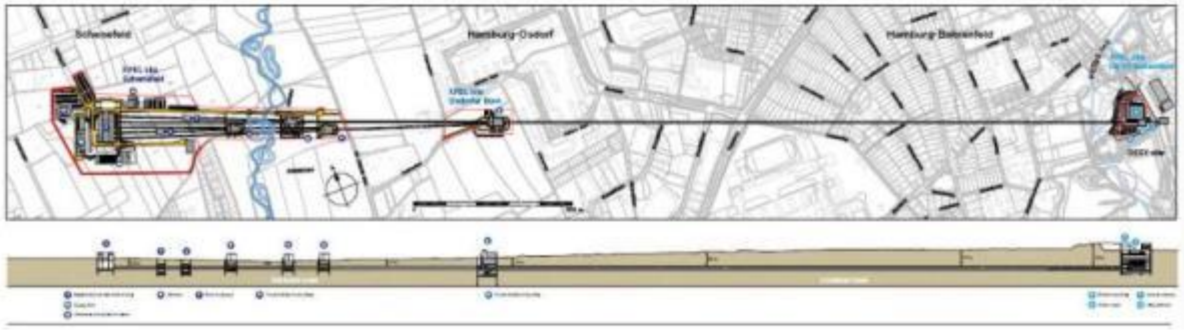
→ Diamond sensors must be adapted for FEL applications

Diamond Sensors for X-ray Photon Diagnostics

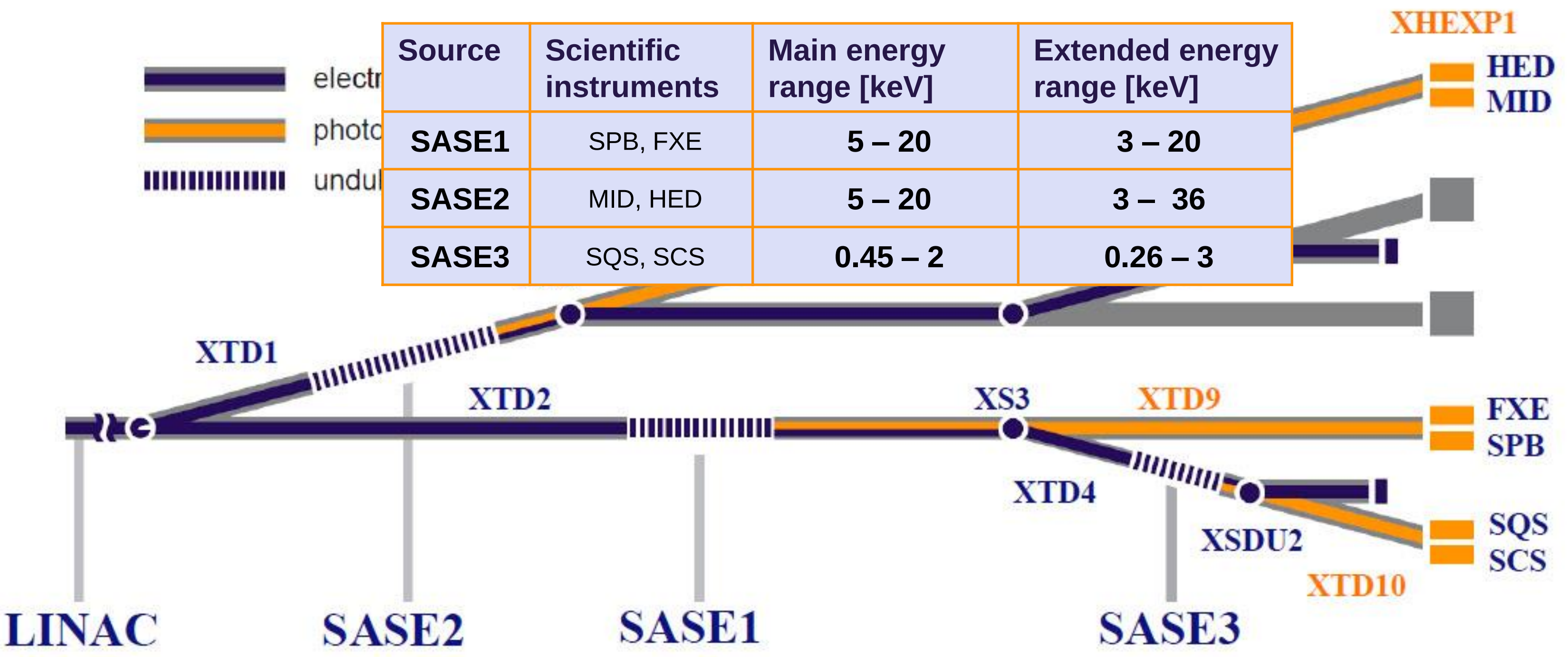
- Requirements for continuous measurements
  - Position: required beam stability ~10% of beam size
  - Intensity: accuracy and linearity required to be ≤ 1%
  - Timing: 10 Hz (train resolved) or MHZ rate (pulse resolved)

- The dedicated sensor should have
  - Minimal beam interference
  - Reliable functioning with almost no maintenance
  - Compatibility to beamline
  - Long lifetime under radiation load

XFEL.EU Facility Layout (photon part)

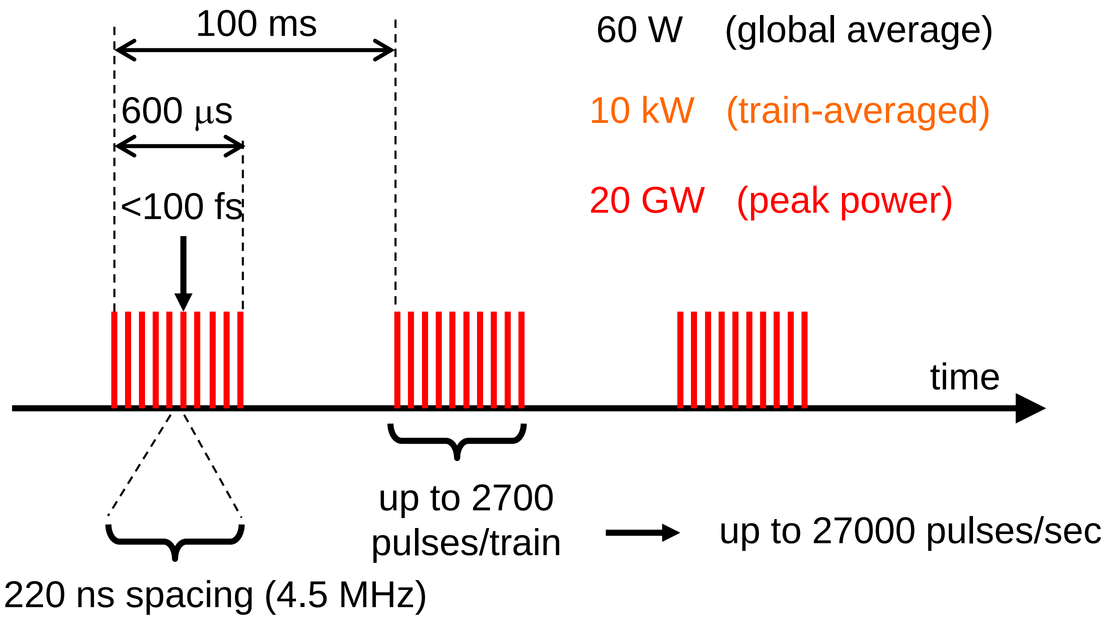


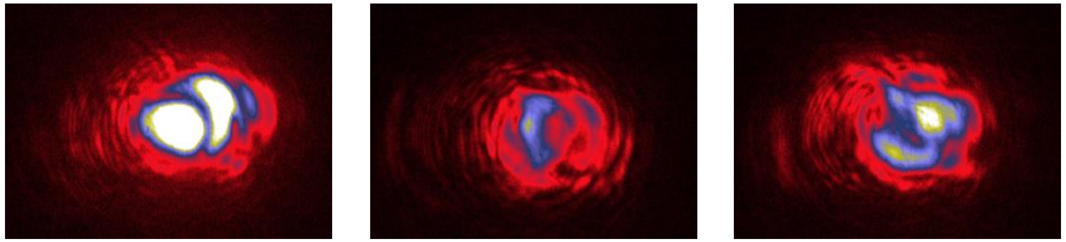
Source	Scientific instruments	Main energy range [keV]	Extended energy range [keV]
SASE1	SPB, FXE	**5 – 20**	**3 – 20**
SASE2	MID, HED	**5 – 20**	**3 – 36**
SASE3	SQS, SCS	**0.45 – 2**	**0.26 – 3**



FEL beam properties (SASE1 and SASE2 undulators)

- Transversal highly coherent beam
- Photon energy 5-20 keV
  in future up to 50 keV
- Pulse energy from a few µJ to ~ 4 mJ
  (~ 10^{12} photons per pulse)
- Pulse length ~ 50 fs
- Due to SASE process:
  shot to shot fluctuations





Example of three adjacent FEL pulses after monochromator –
each pulse can even have different LASER modes

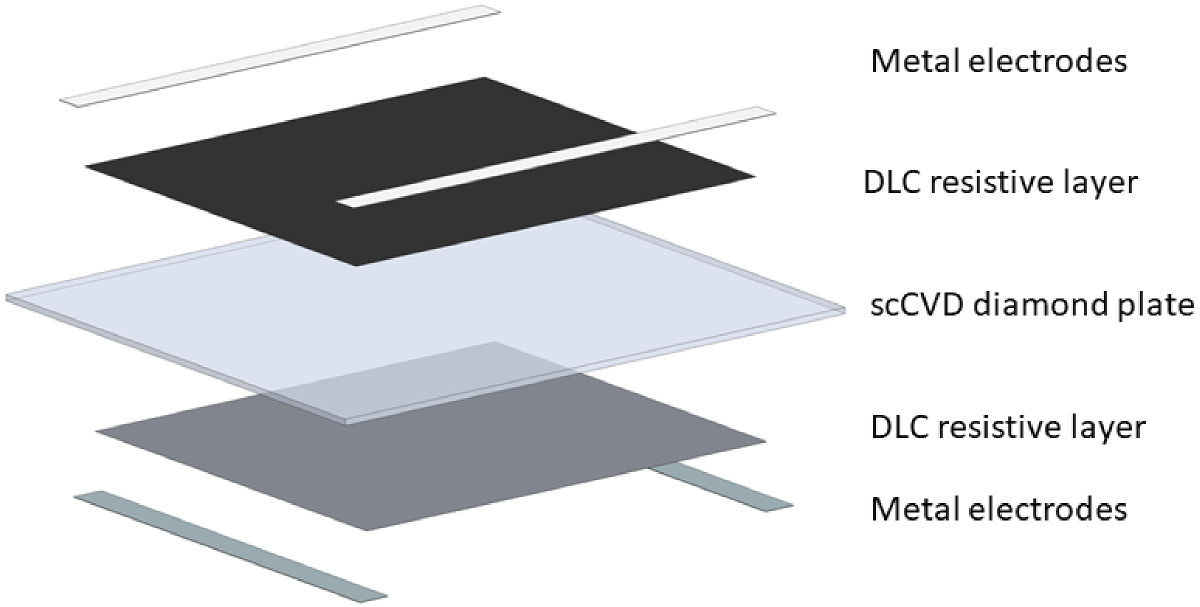
Diamond Sensor at XFEL.EU for pulse resolved position measurements

- **Goal [1,2]:**
  - Position and intensity measurement at 4.5 MHz for hard X-rays
    - ► Position: required beam stability ~10% of beam size (~ 0.1 – 1 mm)
    - ► Pulse energy: accuracy and linearity required to be ≤ 1%, from 100 µJ to 2 mJ
    - ► Timing: MHZ rate (pulse resolved) and train averaged (10 Hz)
    - ► Photon energy: from below 10 keV up to > 50 keV
  - Non-invasive, avoiding of wavefront distortion

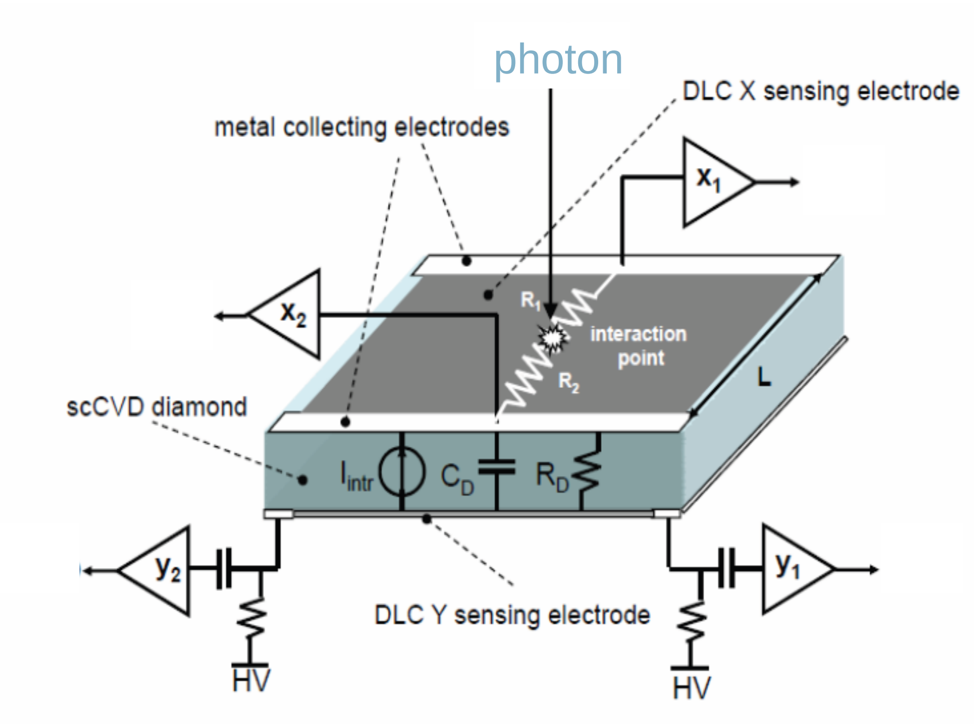
3. W. Freund, "First Tests of a Diamond Detector at European XFEL", Adamas Workshop, GSI, Germany (2019).
4. T. Roth, W. Freund, U. Boesenberg, G. Carini, S. Song, G. Lefeuvre, A. Goikhman, M. Fischer, M. Schreck, J. Grünert & A. Madsen, A. "Pulse-resolved intensity measurements at a hard X-ray FEL using semi-transparent diamond detectors", J. Synchrotron Rad. 25, 177-188 (2018).

Diamond Position Sensitive Sensor

- ***Diamond Slab***
  - Electronic grade scCVD diamond
- ***Resistive Layer (e.g. DLC)***
  - Only non-structured carbon in beam
- ***Metal Collecting Electrodes***
  - Sputter coated Al



Diamond Position Sensitive Sensor



- Working principle: solid state ion chamber

- ***Duo-lateral PSD***

Position coordinates from signal division

$$X = \frac{A(x_1) - A(x_2)}{A(x_1) + A(x_2)} \cdot \frac{L}{2}$$

$$Y = \frac{A(y_1) - A(y_2)}{A(y_1) + A(y_2)} \cdot \frac{L}{2}$$

$$\sigma_{pos} \sim {}^{L \cdot \sigma_{ele}}/_{IO}$$

$$IO = A(x_1) + A(x_2)$$

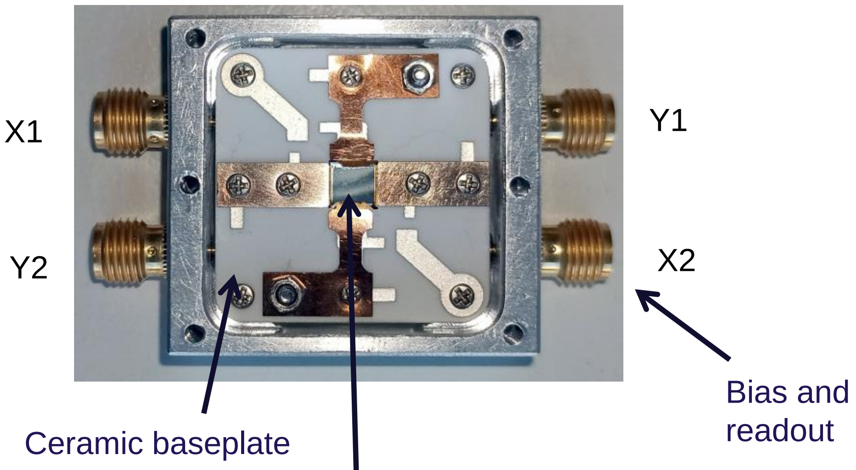
and/or $IO = A(y_1) + A(y_2)$

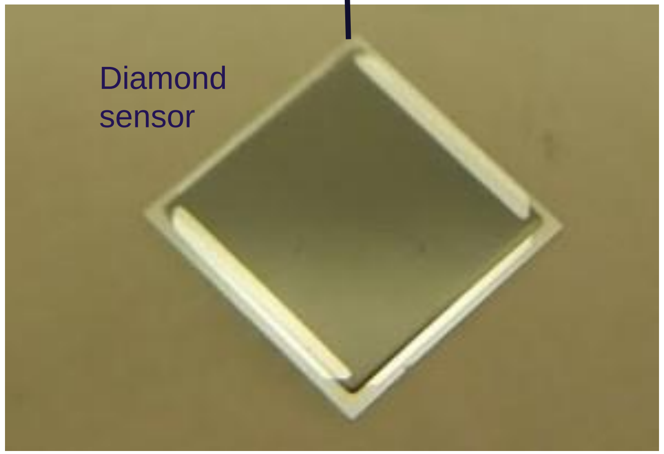
5. M.Pomorski et al., Phys. Status Solidi A **206**, No. 9, 2109–2114 (2009) / **DOI** 10.1002/pssa.200982229

The First Diamond Sensor Assembly

- 4x4 mm², 40 µm thick single crystal CVD, electronic grade
- DLC layer: surface resistance of 350 Ω and 750 Ω (processed by M. Pomorski, CEA)
- Aluminum contacts at the edges

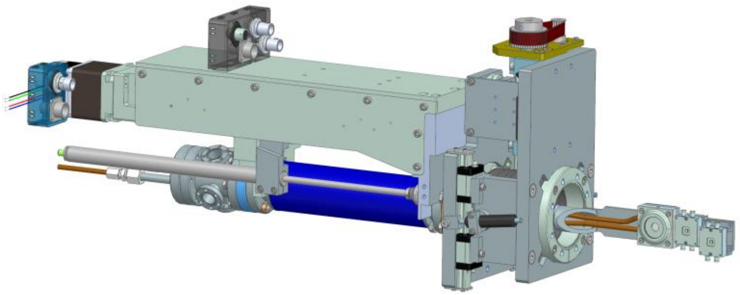
- Why duo-lateral and not e.g. four-quadrant ?
  - SASE-FEL jitters in energy, position, shape:
    non-gaussian beam with big deviation from the center
    → no reliable measurement (4-quadrant)
  - FEL is highly coherent:
    non-homogenous contacts introduce wavefront distortion

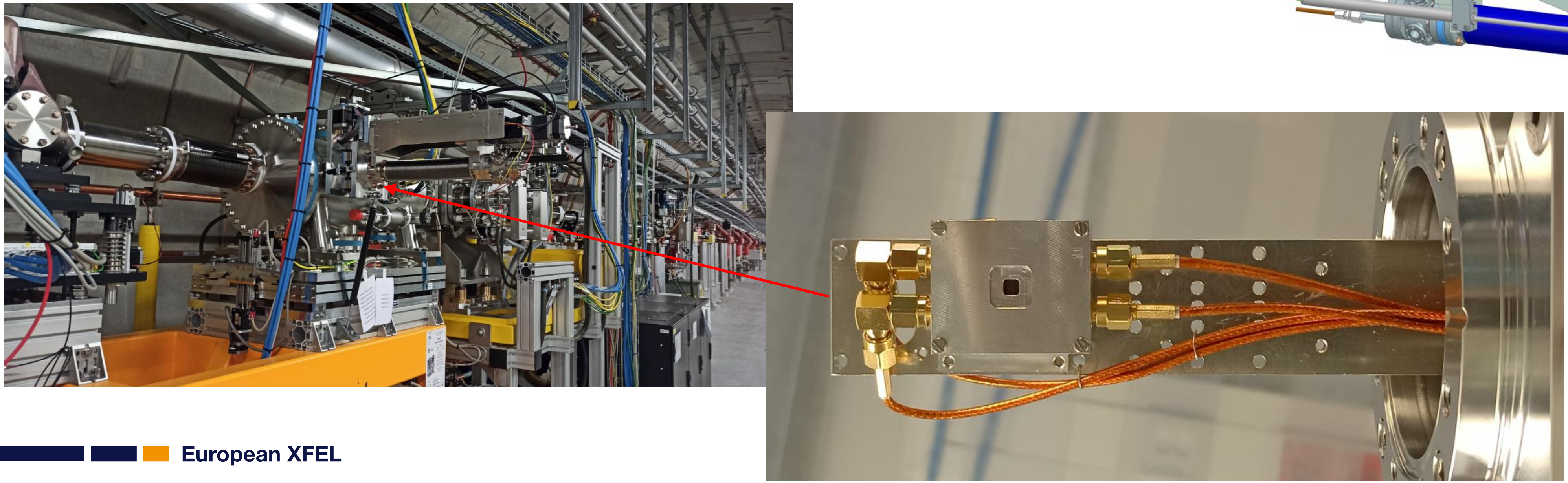




Diamond Sensor in SASE2 Undulator Tunnel XTD1

- Duolateral detector installed in 2022 after e-beam separation, close to SASE2 undulator (~200 m)
  - First functional test in July 2022, three further tests up to now
- Upstream beam optics: only slits, filters, optional mono (no additional source of jitter)

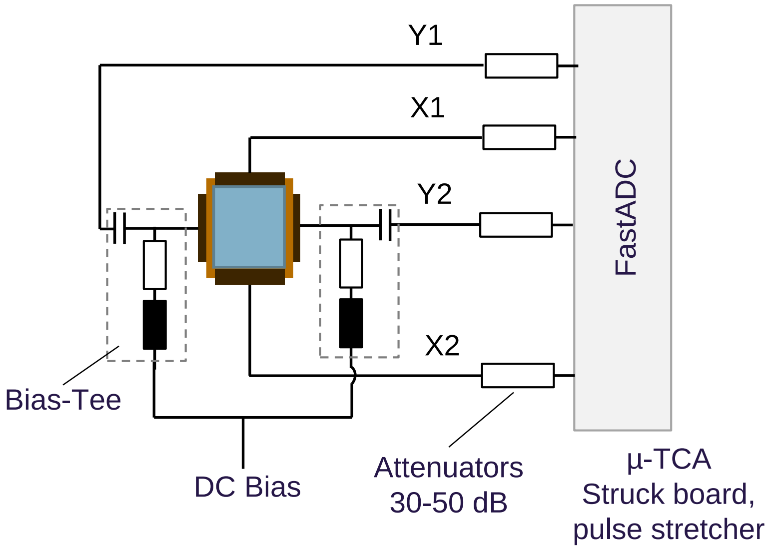




Measurement setup

- µ-TCA crate with FastADC
  - Struck ADC board, 108 M samples/s
  - Pulse stretchers on RTM board

- Large signal from FEL pulses
  - 30 dB attenuators, no amplifiers
  - test in January: 50 dB attenuation



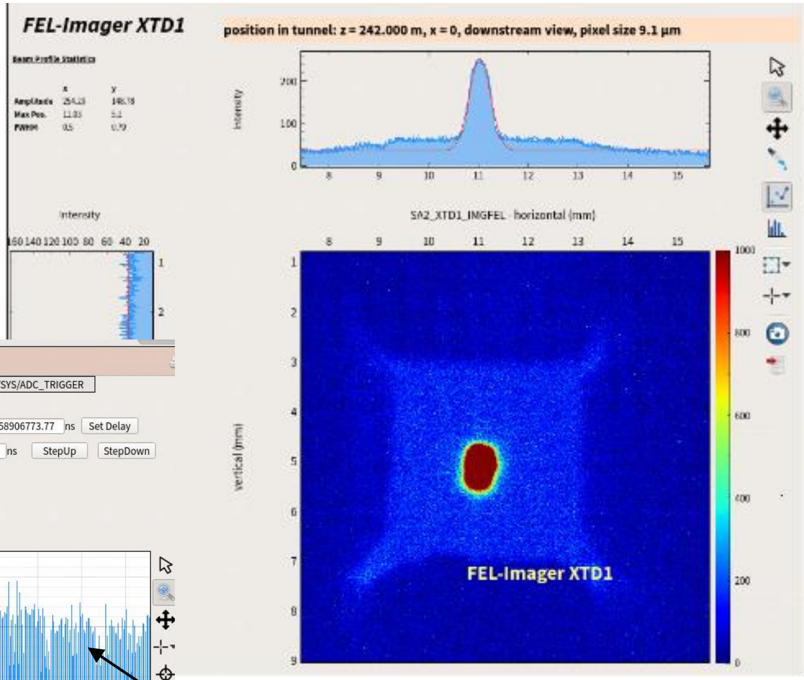
Diamond Detector at the SASE2 FEL beamline

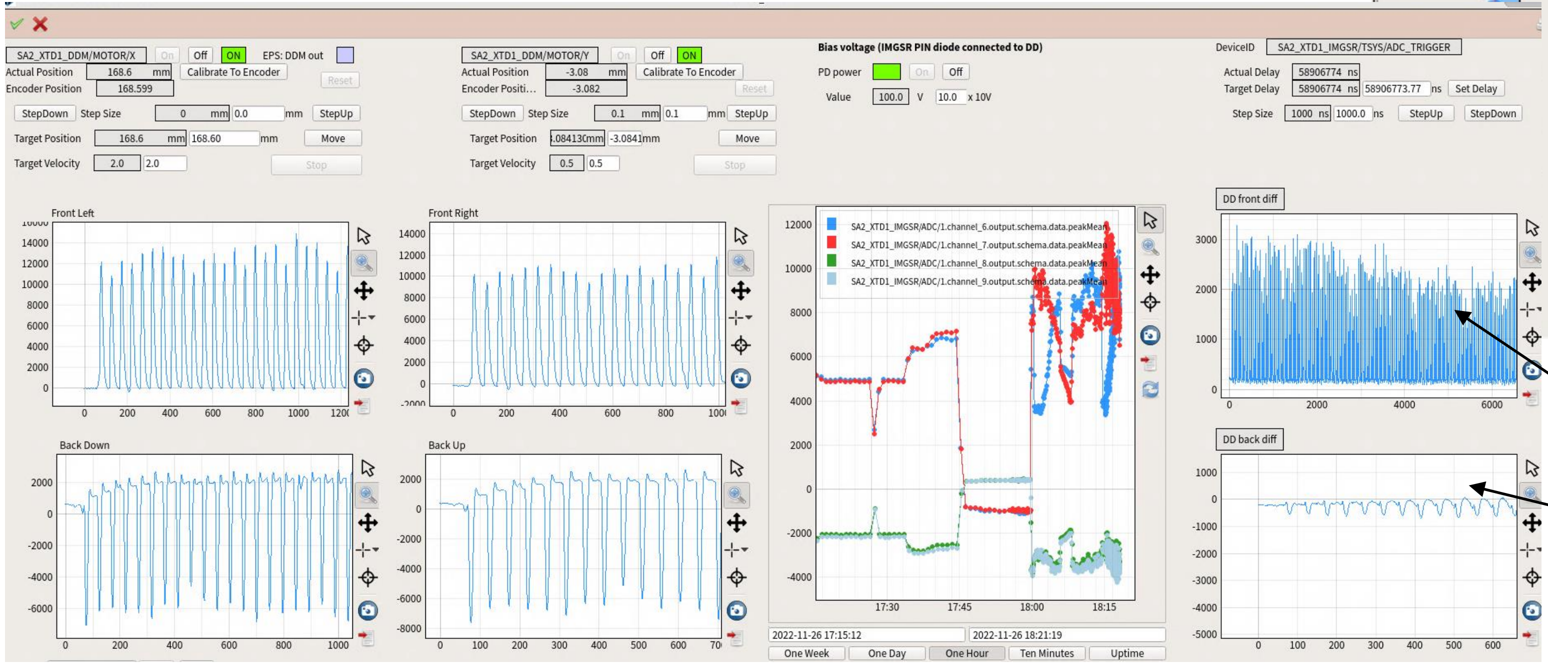
The measurements were performed mainly under these conditions:

Date	Beam Energy	Pulse Energy	No of Bunches
24.11.2022	**20 keV**	**190 μJ**	**2**
26.11.2022	**27 and 30 keV**	**34-45 μJ**	**1-150**
27.11.2022	**9 keV**	**12-45 μJ**	**1-30**
21.01.2023	**7 keV**	**~ 100 μJ**	**1-20**
13.04.2023	**11 and 14.4 keV**	**~ 130 μJ**	**1-150**

Summary of Measurements

- Train with up to 150 bunches at 2.2 MHz
- Raw signal from FastADC with pulse stretcher
- Positive signal: front electrodes
- Negative signal: rear electrodes (bias applied)

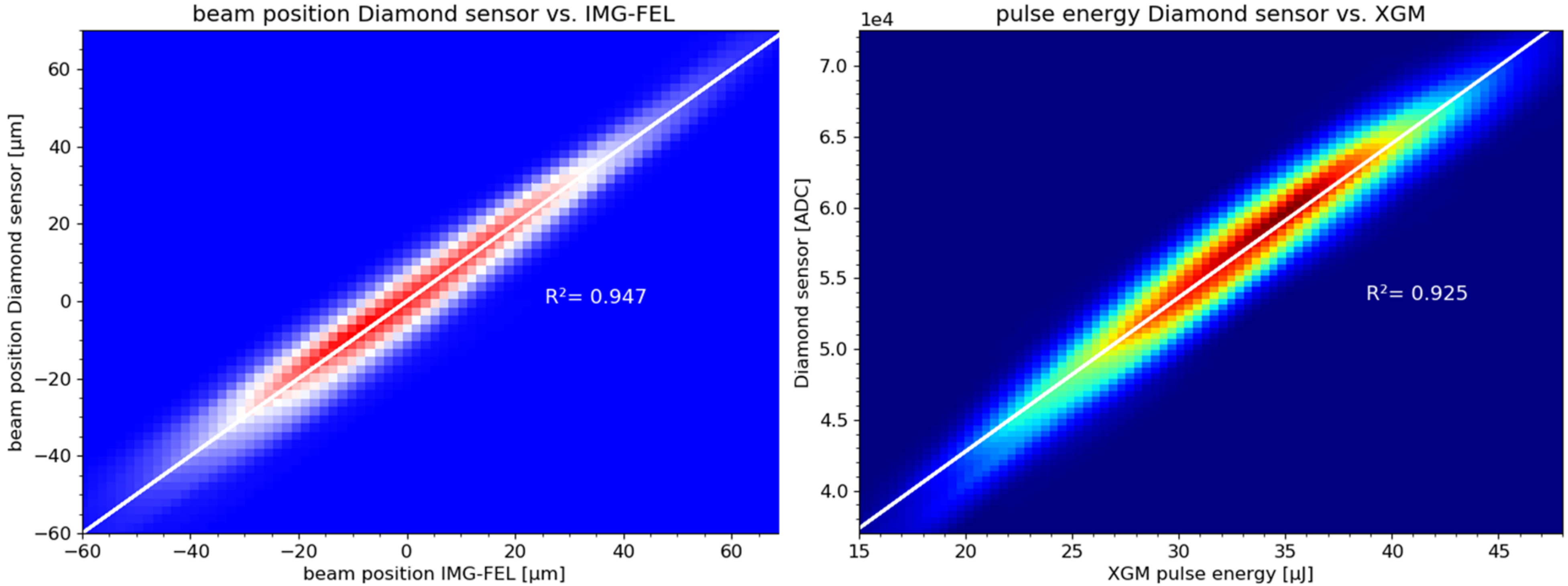




- Virtual FPGA channels
  - Difference of front signals
  - Difference of rear signals (centred)

Diamond vs FEL Imager and XGM

- November measurements (27 keV, 34 uJ) / correlation plots
  - FEL-imager position: 2 bunches per train
  - XGM-pulse energy

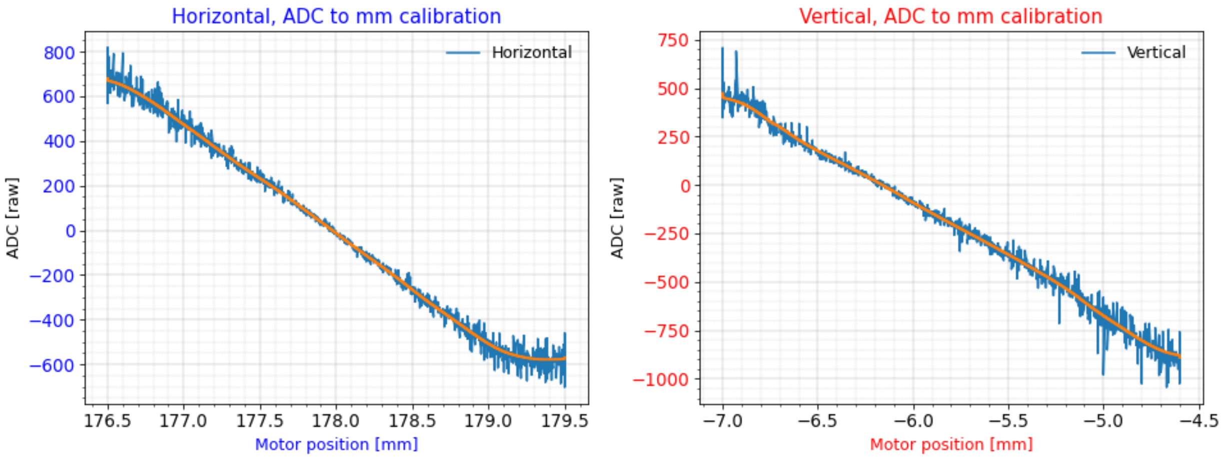


Run 054

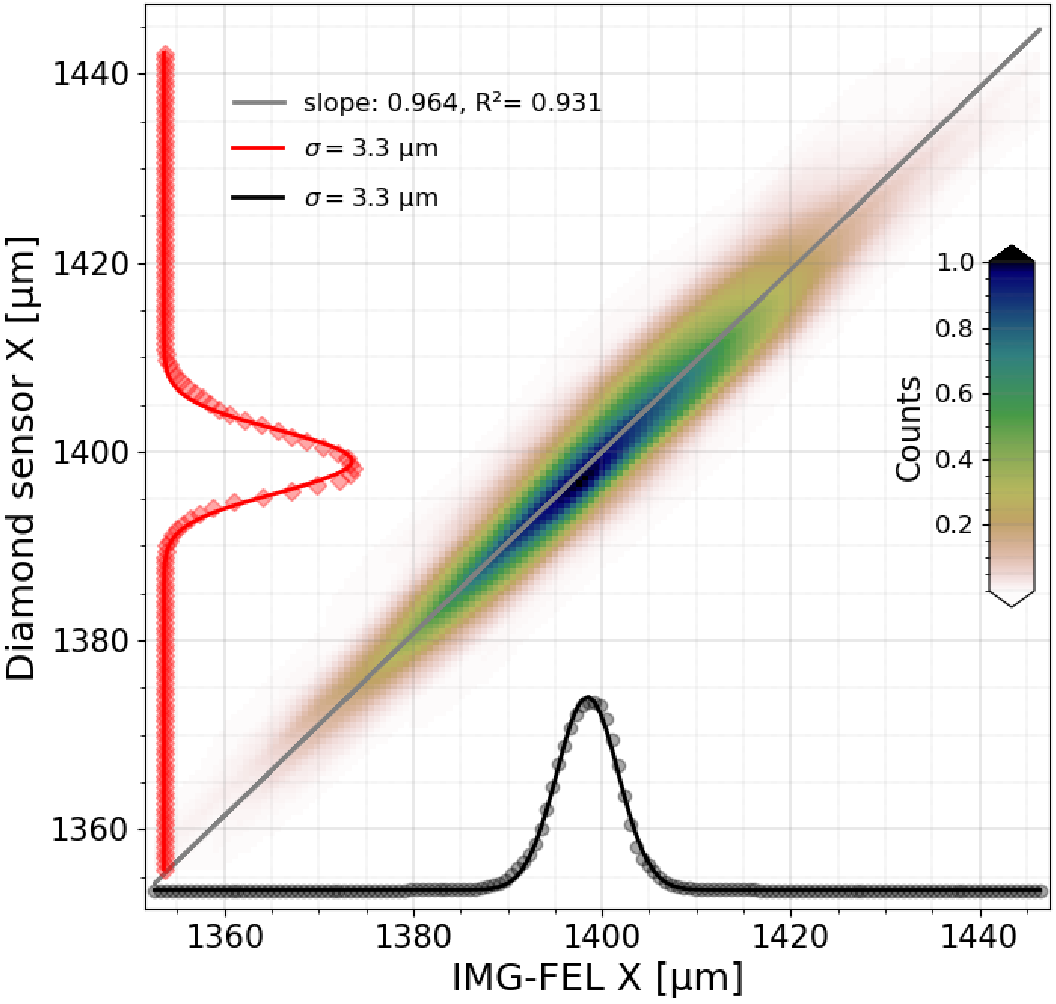
6. W. Freund, T. Çonka Yıldız, J. Liu and J. Grünert, European XFEL & DESY Photon Science Users' Meeting, 23-27.01.2023, Hamburg, Germany

Comparison: beam position from FEL imager and Diamond sensor

- Tests in April
- Beam: 11 keV / ~ 120 µJ
- 30 bunches at 2.2 MHz



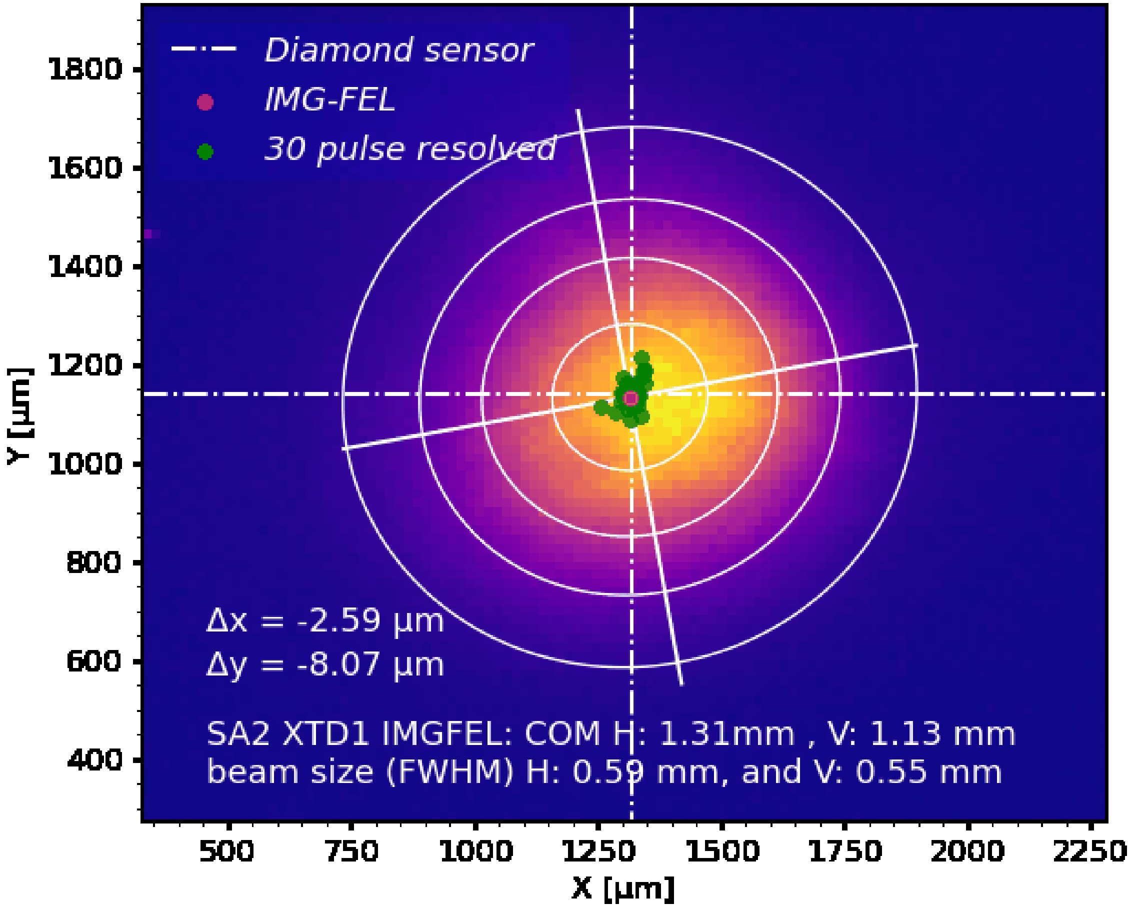
Sensor calibration with manipulator motor motion



Comparison: beam position from FEL imager and Diamond sensor

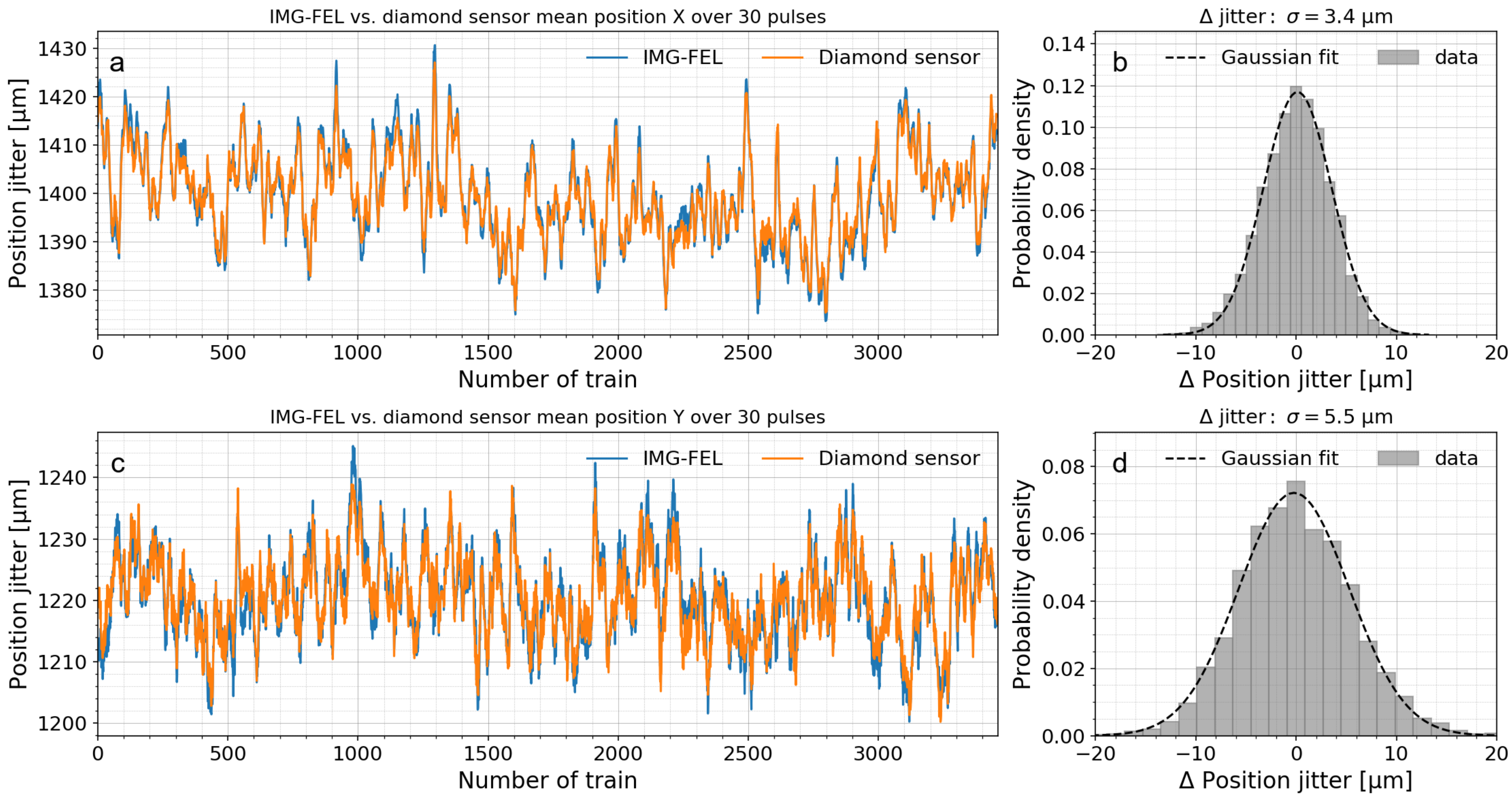
- Tests in April
- Beam: 11 keV / ~ 120 µJ
- 30 bunches at 2.2 MHz

Video of 100 trains:
Red dot: fitted COM position from IMG-FEL
Green dots: single shot beam position from diamond sensor
Ellipse: fitted beam size (2d gaussian fit with angle)
Dashed cross: diamond sensor mean over train



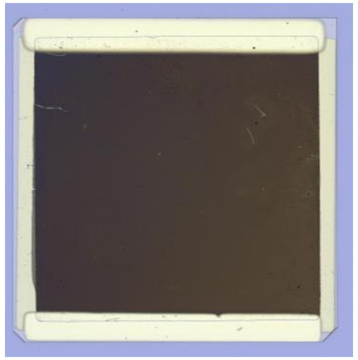
7. T. Çonka Yıldız, W. Freund, J. Liu, M.Pomorski and J. Grünert, *Pulse-resolved beam position measurements of high energy X-ray pulses at MHz rate with a diamond sensor*, Optica **10**, Issue 8, 963-964 (2023) / **DOI** 10.1364/OPTICA.495437

Position measurement uncertainty

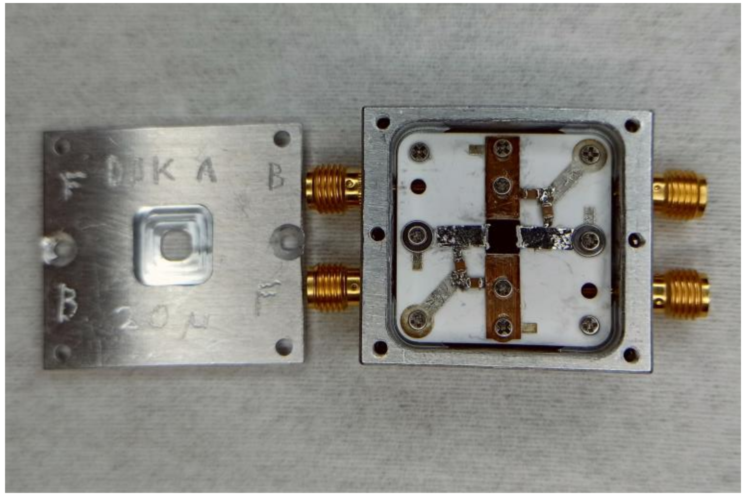


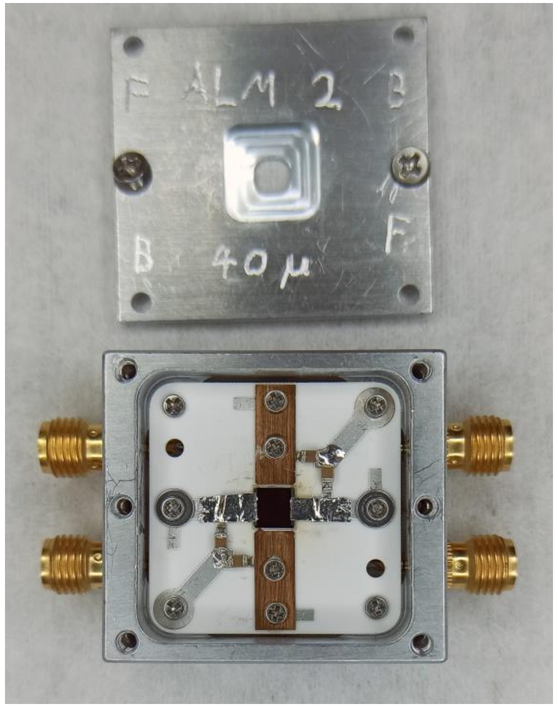
New Sensors

EuXFEL XPD: W. Freund, T. Çonka Yıldız and J. Grünert
Uni Augsburg: M. Schreck
GSI: M. Kiš and M. Träger



- New sensors produced
  - 20 and 40 µm thick sensors
  - Ion-implanted electrodes with lower resistance, processed by Uni Augsburg
  - Electrodes produced at GSI via metallization by sputter deposition
  - New low resistance sensors tested first at our laser lab and then at SASE1 / FXE (June 23) and at SASE2 / MID (August 23)

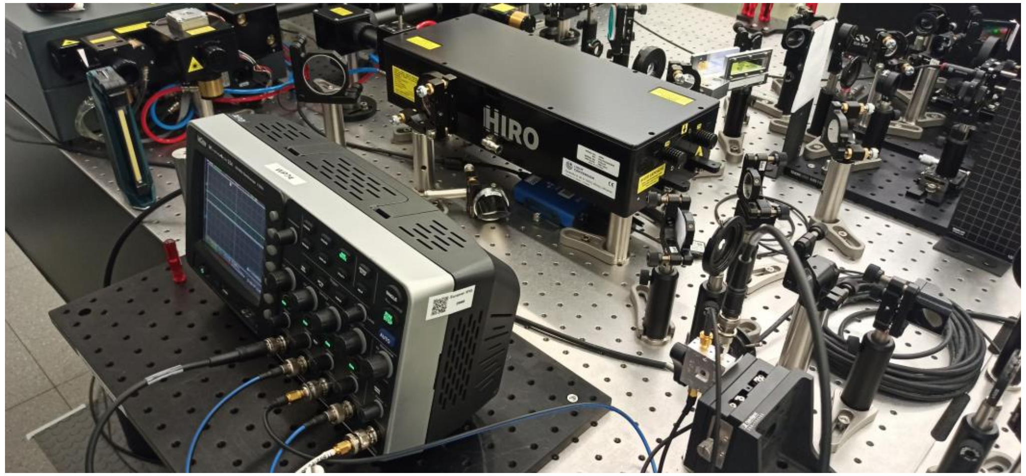


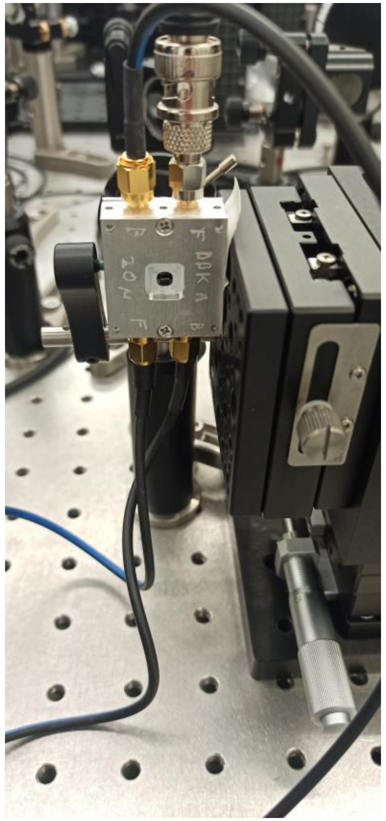


XPD Diamond Sensor tests at XPD Laser Lab

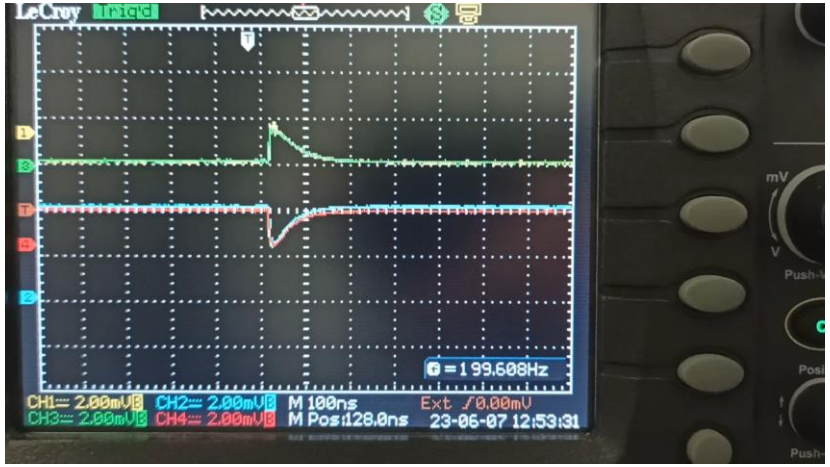
EuXFEL XPD: W. Freund, T. Çonka Yıldız, J. Liu and J. Grünert

- Two new diamond sensors, first tests to check the functionality





Diamond sensor test at the laser lab

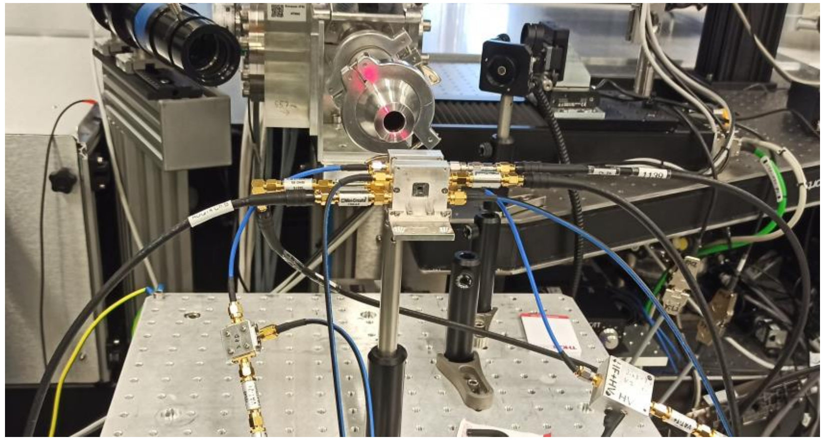


Signals from the diamond detector measured by an oscilloscope

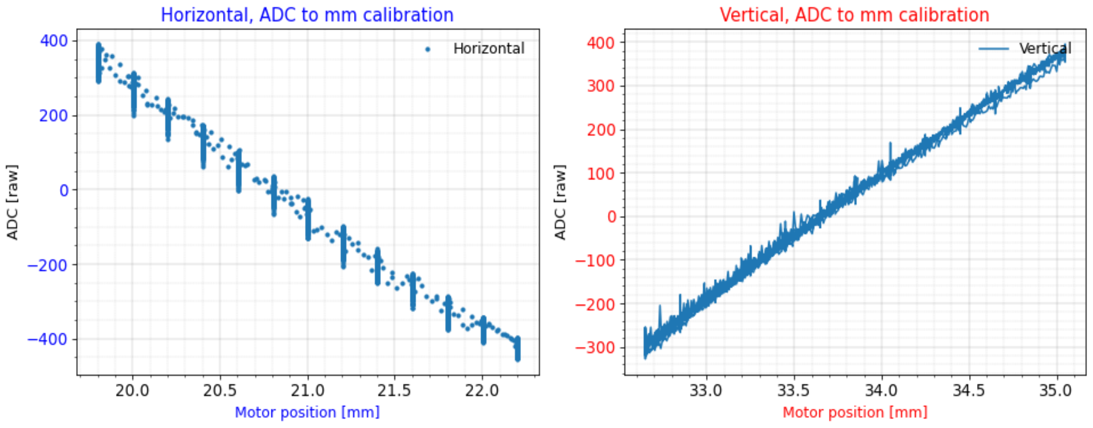
XPD Diamond Sensor tests at FXE, beamtime on 18. June

EuXFEL XPD: W. Freund, T. Çonka Yıldız, J. Liu and J. Grünert
EuXFEL FXE: D. Khakhulin, H. Yousef and C. Milne

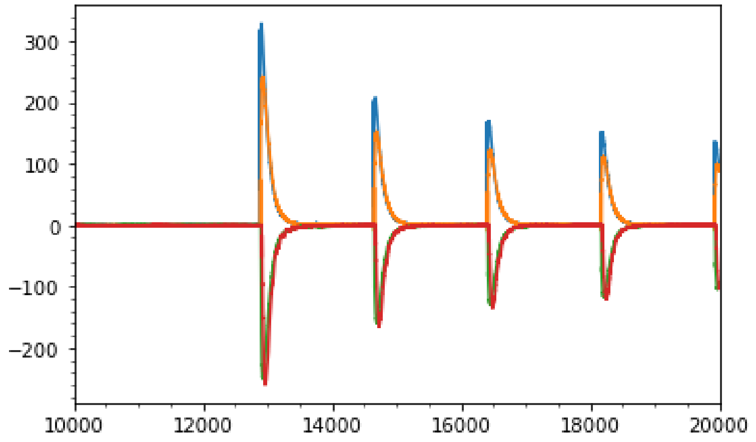
- Two new diamond sensors, test at FXE
  - Calibration scans with imagers (position) and XGM (intensity)
  - I0 monitor, Intensity Position Monitor (IPM) and Beam Imaging Unit (BIU3) to be correlated
  - Beam: 20 and 15 keV, 1-100 pulses per train
  - Beam size at detector ~ 0.5 mm
  - Bunch charge ~ 30 μJ



Diamond sensor assembly at FXE Hutch



Diamond detector position vs motor position



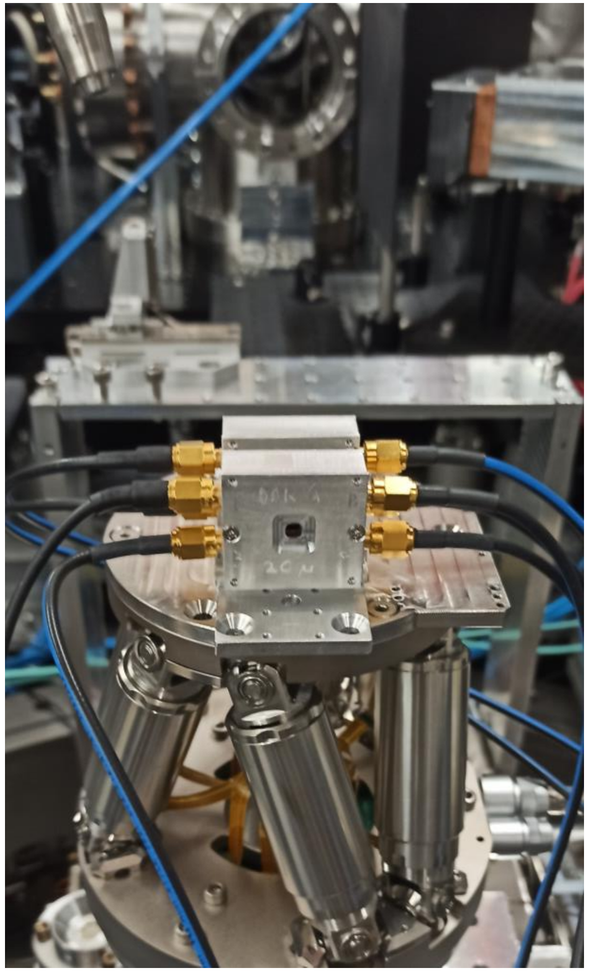
Signals from the diamond detector (DDK, run#93). All channels with baseline correction

XPD Diamond Sensor tests at MID, beamtime on 12. August

EuXFEL XPD: W. Freund, T. Çonka Yıldız, J. Liu, R. Gautam and J. Grünert
EuXFEL MID: U. Boesenberg, A. Rodriguez-Fernandez, R. Shayduk, A. Zozulya, J. Hallmann, J. Wonhyuk and A. Madsen
EuXFEL XRO: Silja Schmidtchen and M. Vannoni

- Two new diamond sensors, test at MID
  - Calibration scans with imagers (position) and XGM (intensity)
  - Beam: 12 keV, 1-100 pulses per train
  - Intra-train pointing instability study
  - DESY (MDI) e-BPM electronics test

- Mirror vibration test with XRO
  - Horizontal excitation at 1 Hz of mirror M1 with piezo actuator
  - Position measurement with diamond sensor (MHz) and imager (10 Hz)

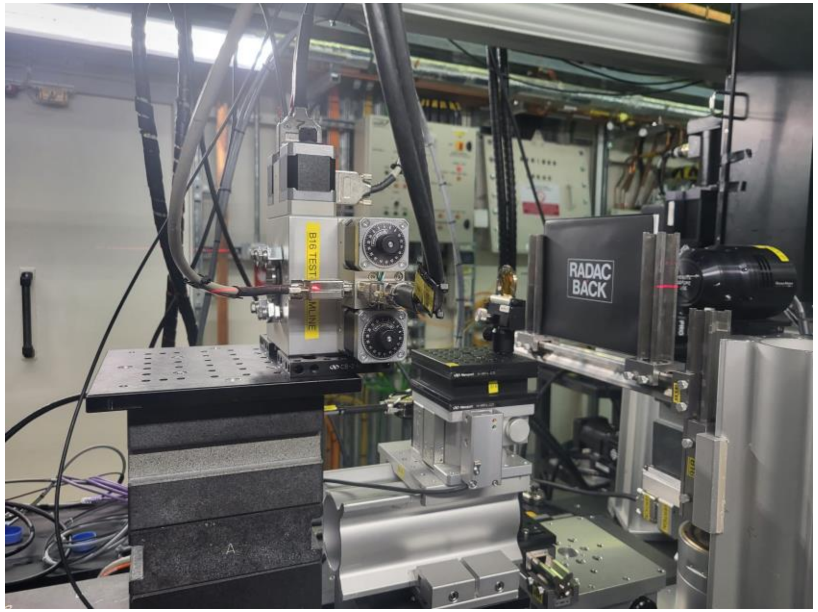


Diamond sensor assembly at MID Hutch

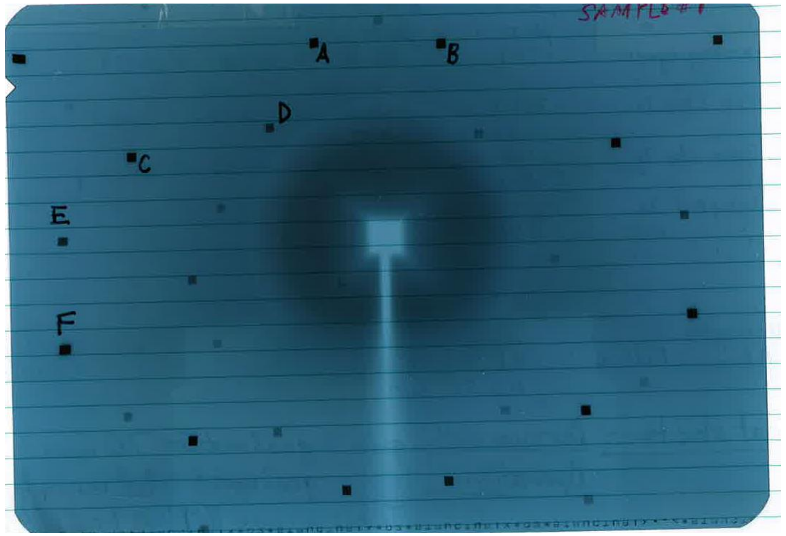
X-ray Topography Measurements at DLS

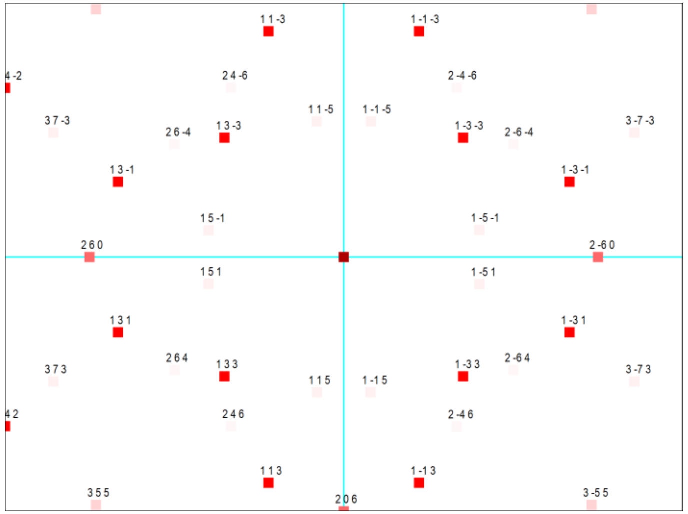
EuXFEL XPD: W. Freund, T. Çonka Yıldız and J. Grünert
DLS: J. Sutter, V. Dhamgaye, O. Fox, A. Malandain and K. Sawhney

- X-ray Topography measurements with two samples from Appsilon:
  - 9x9x0.1 mm^3
  - 6x6x0.05 mm^3
  - For comparison some samples from E6 (XRO)
  - All with an orientation (100)



XRT Setup at DLS B16



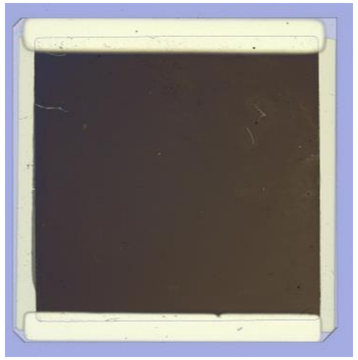


Laue Spots of (100) diamond measurement and LauPt simulation

Signals from the diamond detector (DDK, run#93). All channels with baseline correction

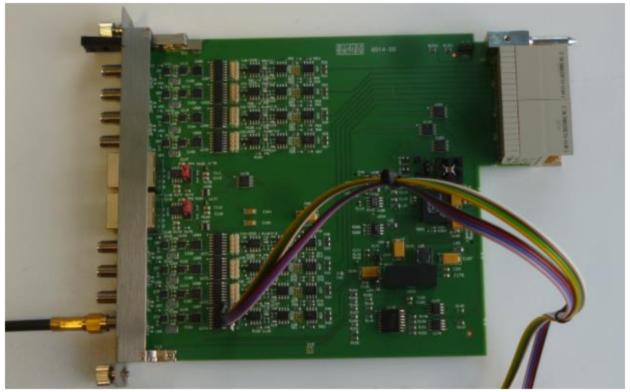
Further developments

- More sensors in production
  - 30 and 50 µm thick sensors (10 µm free-standing slab got broken during processing)
  - < 10 µm with frame, plasma etched (from CEA)



- New RTM board for FastADC and front end, prototype in production
  - Remote controllable attenuators (0-50 dB) and bias voltage (250 V)
  - Gaussian pulse shaper

- Control software (with data department support)
  - Online monitor, auto-calibration, correlation with other devices



Conclusions and outlook

- First high-speed position measurements performed at an FEL at MHz rate

- Current detector: too sensitive at high pulse energy or lower photon energy due to space charge effects
  - Diamond sensors are good at low pulse energy/standard photon energies (9-12 keV)
  - Saturation effects at higher pulse energy
  - Less sensitive at higher photon energy (> 15 keV) for full beam

- Need faster and less sensitive sensors
  - Lower surface resistance of electrodes (might compromise position accuracy)
  - Thinner detectors ~ 10 µm

- High-speed feedback systems → improvement of beam stability (accelerator/optics)

- Diamond sensors for very hard X-ray FEL (30 – 80 keV) where gas based devices become insensitive

Acknowledgments

- European XFEL for financing the R&D project for the development of diamond sensors
- MID team for former and current diamond detector tests and collaborations
- FXE team for beamtime enabling the tests of new detectors
- XRO for existing and future collaborations
- EEE for the modifications of the K-mono electronics
- Petr Smirnov for the RTM board development
- DESY MDI and accelerator team at BKR
- University of Augsburg: Matthias Schreck and Wolfgang Brückner
- GSI Darmstadt: Michael Träger and Mladen Kiš
- CEA: Michal Pomorski
- DLS Optics and Metrology Group for Topography Measurements

Universität Augsburg University

GSI Helmholtzzentrum für Schwerionenforschung GmbH

Thank you for your attention