PLS-II 빔라인 성능 향상 방안

: Part1) 빔라인 증개설 현황

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PAL 포항가속기연구소

Outline

- ❖ 빔라인 증개설 현황 (Part1)
  - ❖ 신규 빔라인 증설: 2C 고에너지 엑스선 융합 분석 (HEXA) 빔라인
  - ❖ 빔라인 개선 및 전환: 4B 고속 분말회절 (HRPD-II) 빔라인

- ❖ 장치개발팀 개요 및 방사광 광학장치 개발 (Part2)
  - ❖ PLS-II 빔라인부 장치개발팀 개요
  - ❖ X-선 광학 연구실 (연구소 연구실)
  - ❖ 광학 RnD 빔라인 (11B SURF)

PLS-II 빔라인 증개설 계획

❖ 목적 및 필요성

- (증설) 차세대 에너지/친환경 소재 특화 연구를 위해 원자/분자/입자 수준에서 실시간/실제 시스템 기반 분석 요구
  : **실시간 XAS/XRD 분석과 고에너지 기반 고도화된 신규 융합 빔라인** 필요
- (개설) 운영기간 15년 이상 노후화된 휨자석 빔라인들의 성능개선으로 연구 트렌드에 맞추어 실험기법 개선 요구
  : **휨자석 빔라인에 대한 활용성 개선**과 **이용자 실험 요구 및 연구경쟁력 높은 실험 기법으로의 전환** 필요

❖ 빔라인 증개설 목표

- **BL2C 고에너지 X-선 융합분석 빔라인 증설** (4년, 총 70억)
  : 소재의 화학적/구조적 변화 추적, 실시간 구조 분석 및
  고에너지 활용 신규 융합분석기법 지원
- **BL4B 고속 분말회절 빔라인 전환** (4년, 총 30억)
  : 기존 X-선 미세회절 기법에서 신규 고속 & 고분해능
  분말회절 기법 전환하여 빔라인 효율성 향상
- 2027년 상반기 이용자 지원 시작

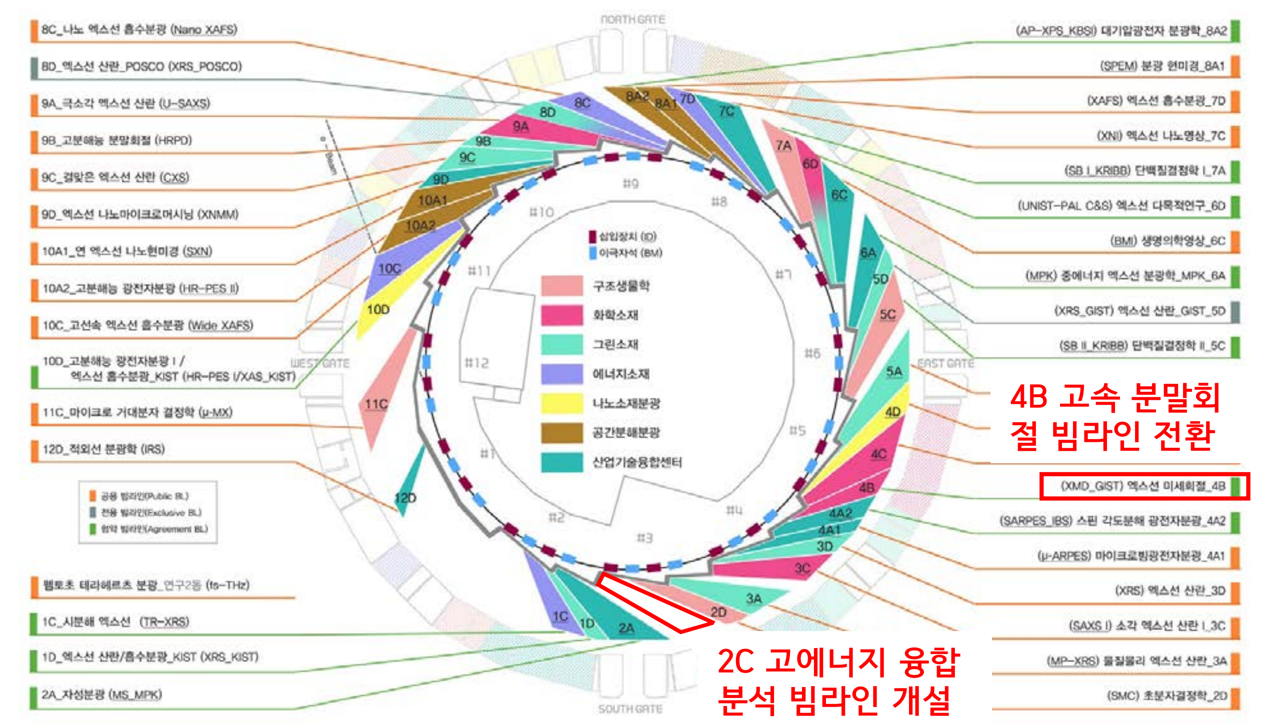


그림 1. PLS-II 증개설 빔라인 위치

BL2C 고에너지 엑스선 융합분석 빔라인 개요

❖ 구축 필요성

- **에너지/친환경 소재 연구 수요 증가에 대응**하기 위해 **융복합연구 수행 가능한 융합분석 다목적 빔라인** 구축 필요
- **30keV 이상 고에너지 X-선 활용** 가능한 PLS-II 빔라인 부재에 따른 신규 빔라인 필요
- 높은 이용자 빔타임 경쟁률 해소를 통한 **이용자 지원 환경 개선**

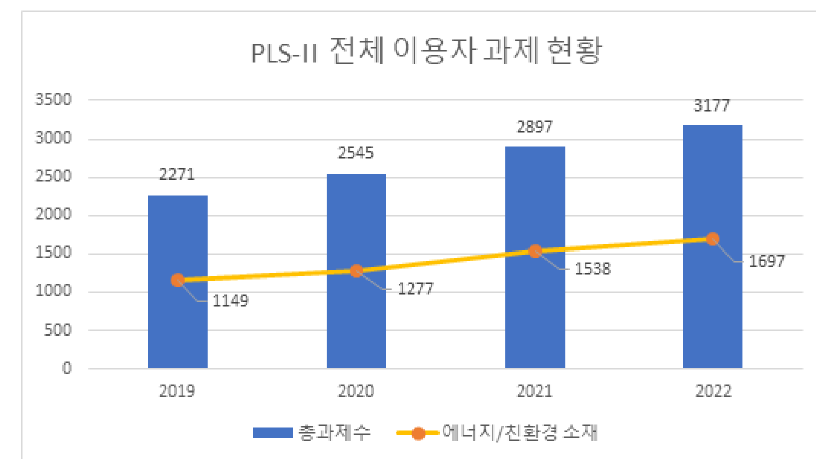


그림 2. PLS-II 이용자 과제 중 에너지/친환경 소재 연구 비율

❖ 주요 기법

- X-ray absorption spectroscopy (XAS)
- High energy X-ray diffraction (XRD)
- XAS/XRD multi-modal analysis
- Continuous energy scan with sub-minute time scale
- Extended X-ray absorption fine structure (EXAFS)
- X-ray fluorescence (XRF)
- Pair distribution function (PDF) analysis

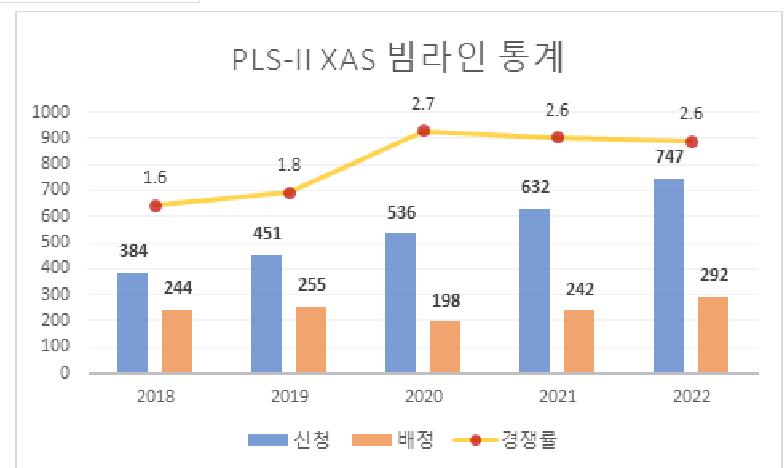


그림 3. PLS-II XAS 빔라인 신청 및 배정 과제 현황

❖ 해외 빔라인 현황

- 주요 방사광 가속기에서 **XAS/XRD 분석기법을 융합 활용 할 수 있는 빔라인을 운영 또는 건설 중**
- 고에너지 (30keV 이상) 빔라인의 경우 광원발생 장치로 undulator 또는 wiggler를 사용
- **다양한 검출기를 활용하여 여러 분석기법 지원**하고 있음

	대형가속기		중형가속기						
	ESRF (ID16B)	Spring-8 (BL36XU)	CLS (HXMA)	Balder (MAX IV)	QAS (NSLS-II)	BESSY II (BAMline)	Diamond (CoreXAS)	SLS Debye (건설중)	PLS-II HEXA (건설중)
에너지,링크기	6GeV, 844.4m	8.0GeV, 1436m	2.9GeV, 170.9m	3.0GeV, 528m	3.0GeV, 792m	1.7GeV, 240m	3.0Gev, 561.6m	2.4GeV, 288m	3.0GeV, 281m
광원	U	IU	Superconducting Wiggler	In-vacuum Wiggler	3-pole Wiggler	SCW-7T	BM	Superbend	Multipole Wiggler
가용 에너지	6 ~ 65 keV	4.5 ~ 35 keV	5 ~ 40 keV	4 ~ 40 keV	4.7 ~ 31 keV	4.5 ~ 60 keV	2 ~ 35 keV	4.5 ~ 60 keV	5 ~ 45 keV
광학장치	DWM, HFM, DCM Si(111/311), KB	Q-DCM Si(111), DCM Si (220), HFM, VFM	VCM, DCM Si(111/220) VFM, KB	VCM, DCM Si(111/311) VFM	VCM, DCM Si(111) Toroidal	DCM Si(111/311), DMM	VCM, DCM Si(111/311) DFM	HCM, HVM, Q-DCM, DCM	VCM, DCM Si(111/311), Toroidal, KB
빔 사이즈 (H x V)	1 x 1 ㎛^{2} 50 x 50 ㎚^{2}	100 x 100 ㎚^{2}	0.5 x 0.1 ㎜^{2} 4 x 2 ㎛^{2} (KB)	0.5 x 2 ㎜^{2} 50 x 50 ㎛^{2}	1.5 x 10 ㎜^{2} 0.5 x 0.5 ㎜^{2}	10 x 10 ㎜^{2} 1.5 x 1.5 ㎛^{2}	200 x 250 ㎛^{2}	-	< 500 ㎛^{2} < 10 ㎛^{2}
활용 기법	XAS, XRD, XRF, Tomography, X-ray Imaging	XAS, time-resolved XAS/XRD, XAS imaging, HAXPES	XAS, XRD ,high pressure XRD	XAS, XRD, XES, PDF, XRF	XAS, XRD, DRIFTS	XAS, XRF, Tomography, Radiography	XAS, XRD, XRF	XAS, XRD, SAXS, PDF	XAS, XRD XAS/XRD 융합분석, 고에너지 융합분석
검출기	3-element SDD, 7-element SDD, FReLoN 4M	25-element Ge detector, 4-element SDD, 2D pixel array detector	32-element Ge, 4 element Vortex, Rayonix SX165	Ionization chambers, 7-element SDD, PIPS, Eiger 1M	Ionization chambers, SDD, PIPS, PerkinElmer 1621	4-element SDD, pnCCD, sCMOS, Bruker X-Flash, e2V Si-Li	4-element SDD, MYTHEN	정보 없음	7-element SDD, EIGER2 CdTe 4M, Ionization chamber

* **광원** : **U** (undulator), **IU** (in-vacuum undulator), **SCW** (super conducting wiggler), **MPW** (multipole wiggler), **Superbend** (superbending magnet), **BM** (bending magnet)
* **광학장치** : **DWM**(double white beam mirror), **HFM** (horizontal focusing mirror), **VFM** (vertical focusing mirror), **VCM** (vertical collimating mirror), **DFM** (double focusing mirror), **TFM** (toroidal focusing mirror), **DMM** (double-multilayer-monochromator)

2C HEXA (High Energy X-ray combined Analysis) 빔라인

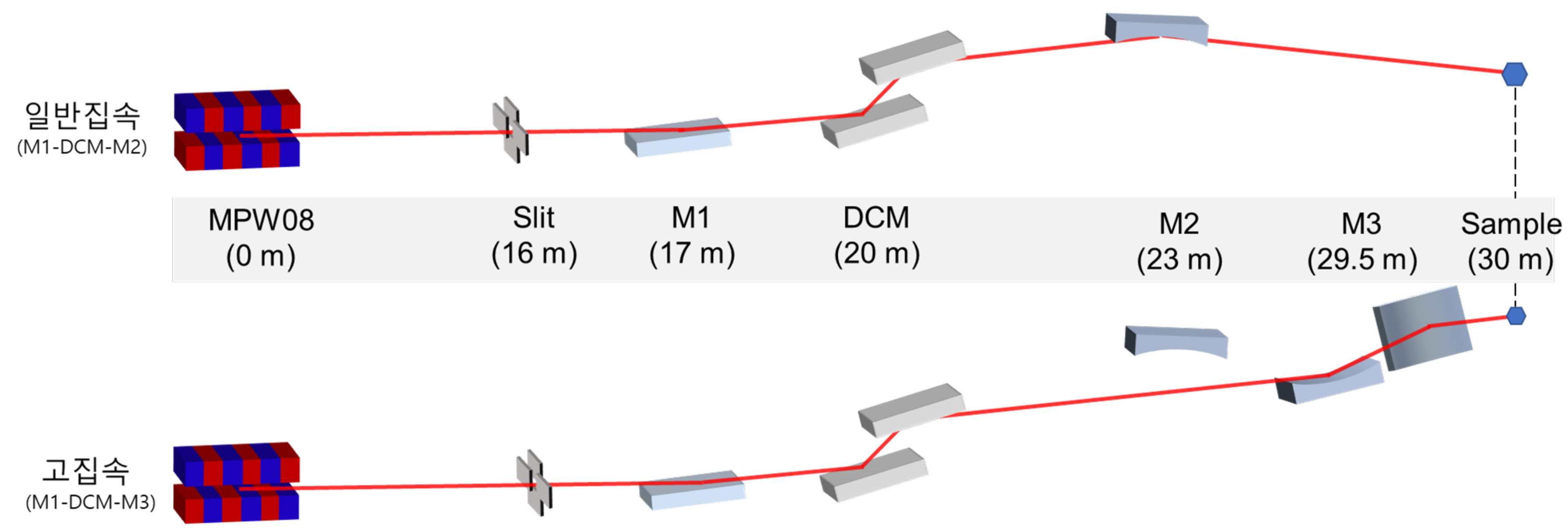


그림 4. 고에너지 X-선 융합분석 빔라인 주요 optics

Source	Multipole wiggler insertion device
Available energy range	5-45 keV (1.5 ~ 0.27Å)
Photon flux	> 10^{12} ph/s
Optics	Si(111)/Si(311) DCM for continuous energy scan (sub-minute time scale) Vertical collimating mirror (M1), Toroidal focusing mirror (M2), KB mirror (M3)
Energy resolution (ΔE/E)	10^{-4} (@ 5-25 keV) / 10^{-5} (@ 20-45 keV)
Beam size (@sample position)	Focused : 150 x 70 μm^2 / Microfocused : 8 x 2 μm^2
End station	Ionization chambers, multi-element SDDs, Large-area 2D X-ray detector

Science & Application

❖ Operando XAS/XRD multi-modal analysis

- Rechargeable batteries, (electro)catalysis, photovoltaic materials
- Quasi-simultaneous measurement of a single sample in the same environment

: Bulk structure analysis from XRD at fixed energy + Local structure analysis from XAS with continuous scan

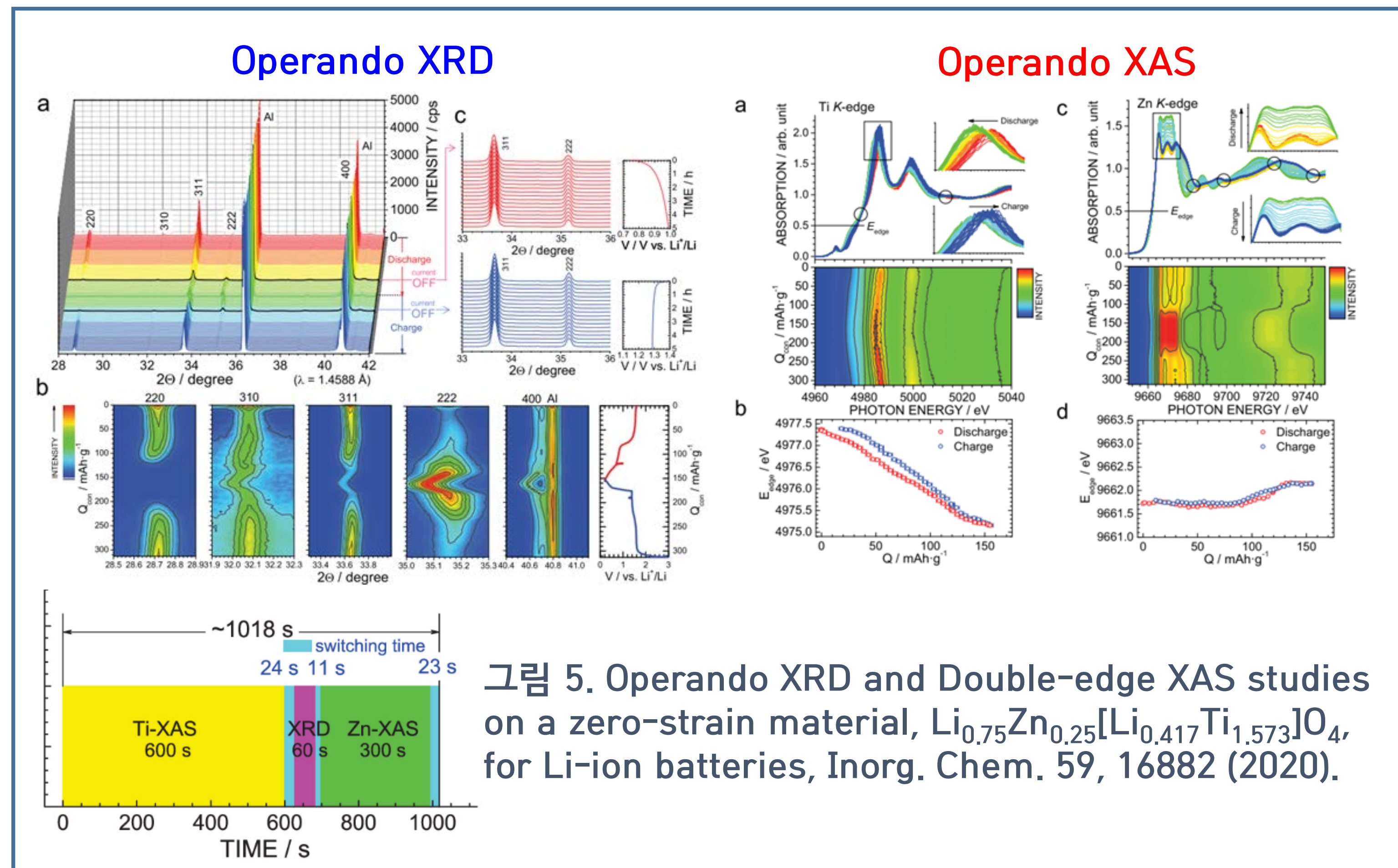


그림 5. Operando XRD and Double-edge XAS studies on a zero-strain material, $Li_{0.75}Zn_{0.25}[Li_{0.417}Ti_{1.573}]O_4$, for Li-ion batteries, Inorg. Chem. 59, 16882 (2020).

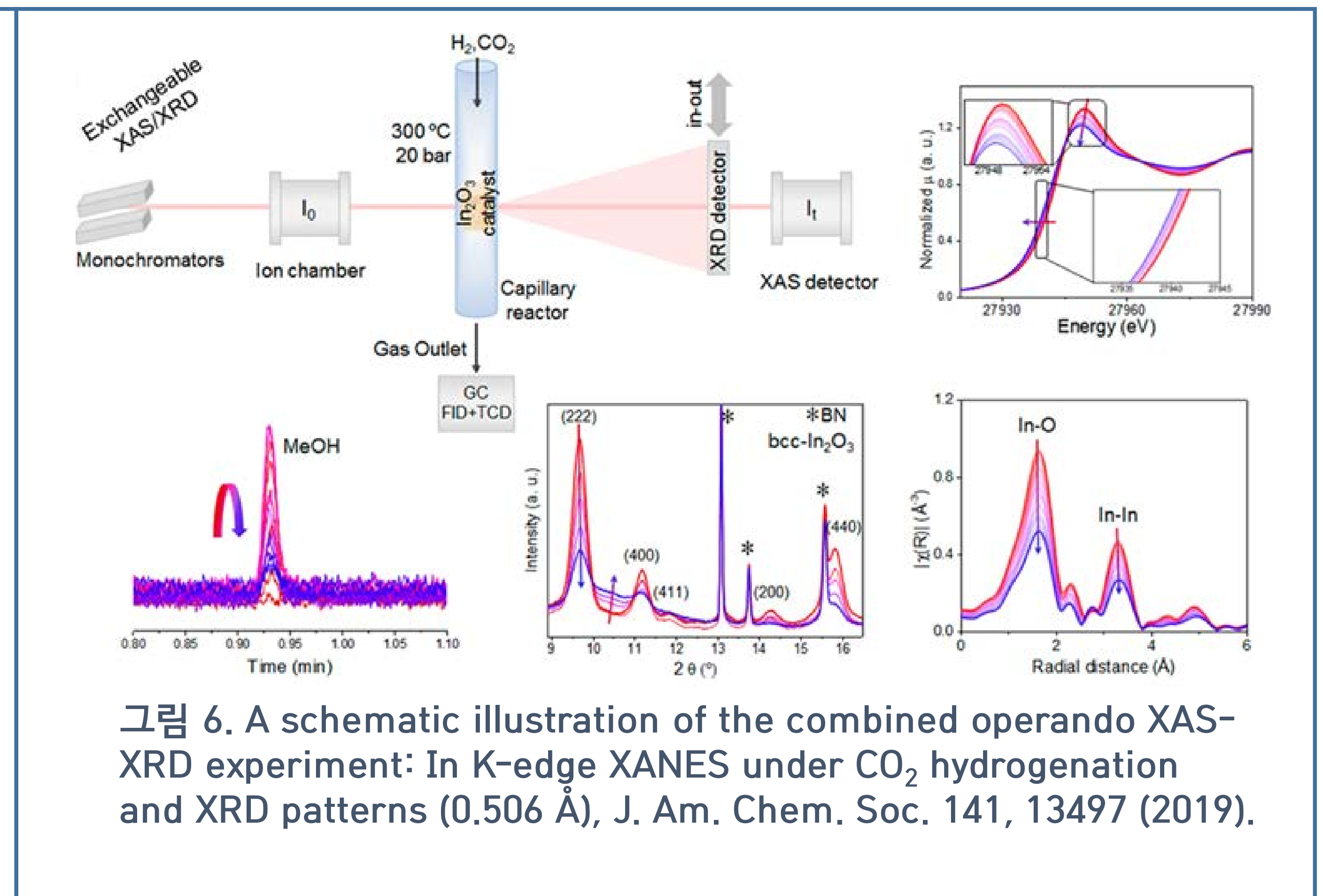


그림 6. A schematic illustration of the combined operando XAS-XRD experiment: In K-edge XANES under CO_2 hydrogenation and XRD patterns (0.506 Å), J. Am. Chem. Soc. 141, 13497 (2019).

Science & Application

❖ **High X-ray energy application (>30 keV)**

- High flux / High penetration / Low absorption
- XRD of real battery cells (pouch type, large volume, etc.)
- Samples in extreme environments (high temperature, high pressure, etc.)
- Total scattering (PDF analysis) of nano-crystals/amorphous materials

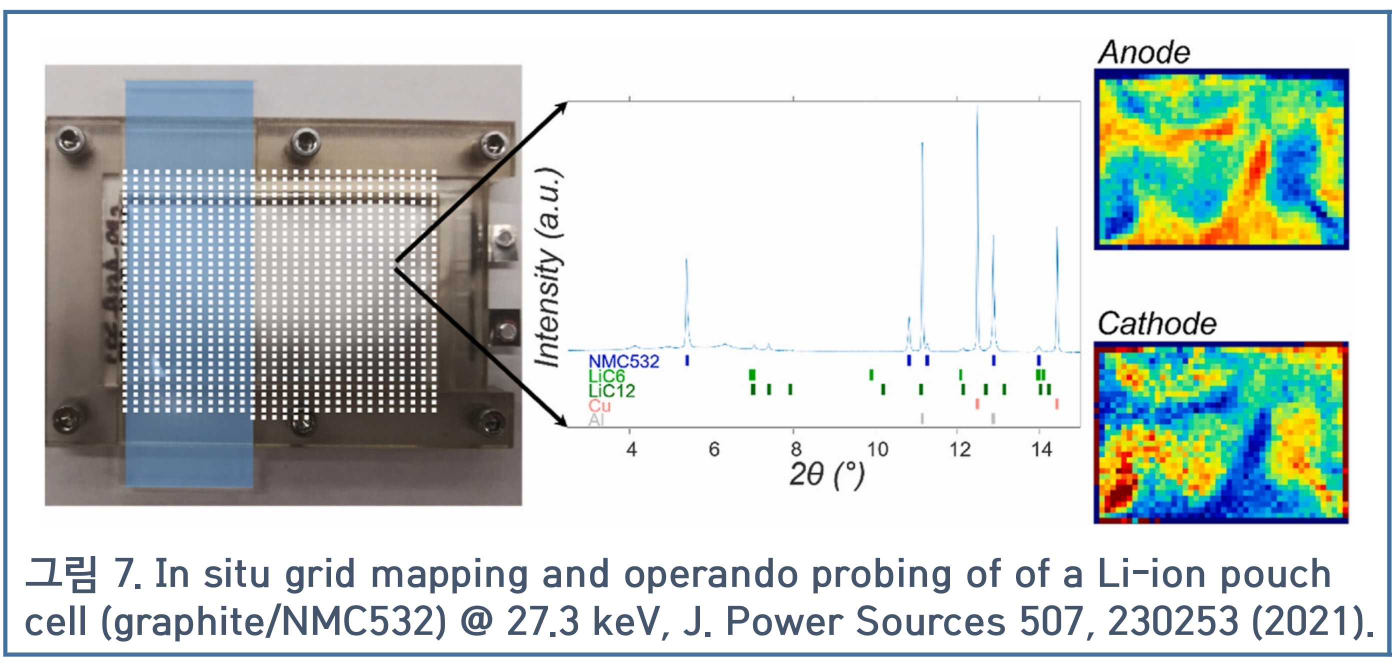


그림 7. In situ grid mapping and operando probing of of a Li-ion pouch cell (graphite/NMC532) @ 27.3 keV, J. Power Sources 507, 230253 (2021).

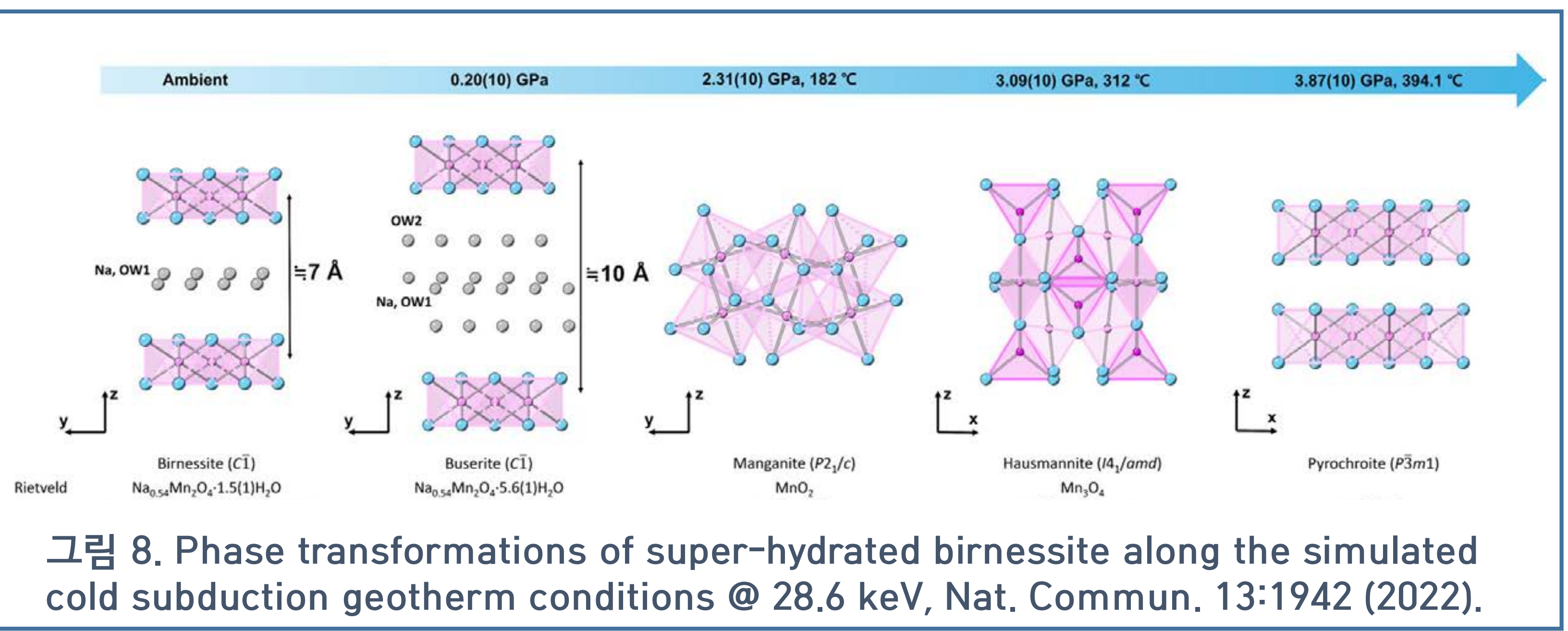
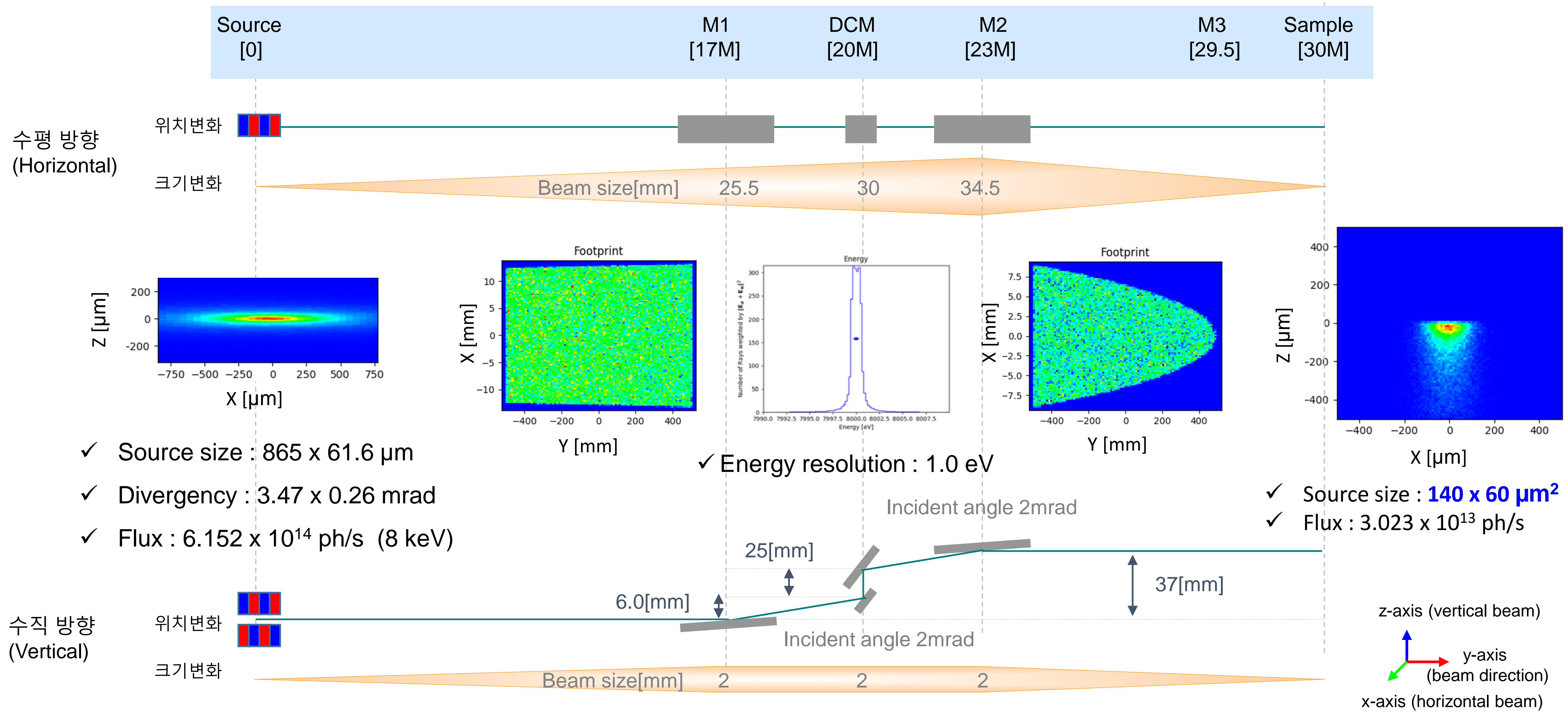
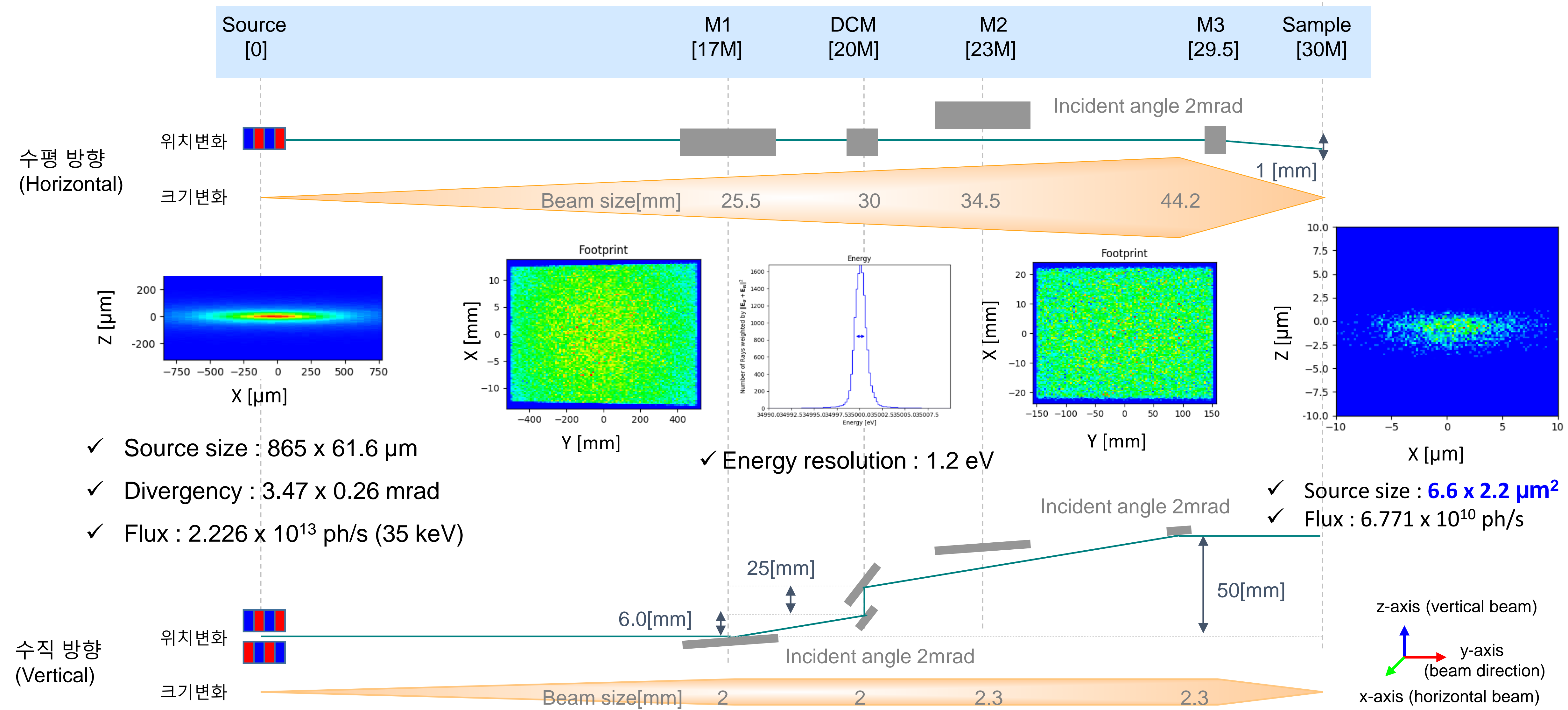


그림 8. Phase transformations of super-hydrated birnessite along the simulated cold subduction geotherm conditions @ 28.6 keV, Nat. Commun. 13:1942 (2022).

Beamline ray tracing (일반 집속 모드 @ 8keV)



Beamline ray tracing (고집속 모드 @ 35keV)



PAL 포항가속기연구소

2C HEXA 빔라인 건설 예상 일정

고에너지 X-선 융합분석 빔라인	2023 Q1–Q4 / 2024 Q1–Q4 / 2025 Q1–Q4 / 2026 Q1–Q4 / 2027 Q1–Q3
방사광 발생장치	설계, 발주 → 압고, 설치, 확인 → Front-end 최종 확인
빔라인 장치(Front-end)	설계 → 구매 발주, 조립, 설치 및 확인 →
거울 장치 (M1)	설계 및 발주 → 입고, 확인 → 설치 →
거울 장치 (M2)	설계 및 발주 → 입고, 확인 → 설치 →
거울 장치 (M3)	설계 → 구매 발주 및 설치 →
단색화 장치 (DCM)	설계 → 발주 → 입고, 확인 및 설치 → PTL 최종 확인 및 빔진단
빔라인 장치(PTL)	상세 설계 → 구매 발주, 조립, 설치 및 확인 →
실험 허치 & 인터락 시스템	상세 설계 → 구매 발주, 조립, 설치 및 확인` →
XAS, XRD 검출 시스템	상세 설계 → 구매 발주 및 설치 →
빔라인 제어/DAQ 시스템	설계 및 구매 → 제어 및 확인 →
방사선 인허가 작업	방사선 인허가 준비 및 승인 →
빔라인 commissioning	빔라인 시운전 → 빔라인 구축완료 및 ZEUS등록
구축 완료 및 ZEUS 등록	최종 확인 및 시운전 →
빔라인 운영 서비스	이용자 지원 시작 →

'23 Q3 NFEC 상시심의, CDR 완료 / Q4 TDR 진행 중

빔라인 개선 및 전환

❖ **노후 휨자석 빔라인 개선 및 분석기법 전환 제안 ('23년 사업계획서)**

- 완공 후 15년 이상 된 휨자석(BM) 빔라인 1기에 최신 실험기법 도입으로 산업적 활용도 및 연구경쟁력 제고
- 한정된 운영예산으로 삽입장치 위주 성능향상 진행, 투자 부족했던 **휨자석 빔라인의 전략적 개선 필요***
- 휨자석 빔라인 중 연구 트렌드 변화 및 실험 설비 노후화로 활용도가 약화된 X-선 미세회절 빔라인(BL4B)을 산학연의 연구 수요를 고려한 고속 분말회절 (HRPD-II) 빔라인으로 성능개선 추진

* 포항 3세대 방사광가속기 빔라인 효율화 검토 요청 ('19년, 56차 방사광가속기 운영위원회)

연도	예산 (백만원)	주요계획
1차년도 ('23)	169	▪ 빔라인 상세설계 ▪ 빔라인 1기에 대해 저장링으로부터 빔을 인출하는 Front-end 구간 개선
2차년도 ('24)	165	▪ 빔전송구간 (Photon-Transfer-Line, PTL) 개선
3차년도 ('25)	1,500	▪ 빔을 집속하는 거울장치와 단색화 빔을 만들어 내는 광학장치(분광기, 집속거울 등) 및 검출기 발주
4차년도 ('26)	1,166	▪ PTL을 거쳐 실험구간인 End-station에 인출된 빔을 각종 실험기법의 데이터 획득을 위한 시료조절장치, 검출기 설치 및 최적화 정렬과 시운전
계	**3,000**	

그림 9. 2023년 방사광가속기공동이용연구지원사업 예산요구서 중

고속 분말회절 (HRPD-II) 빔라인 개요

❖ 구축 필요성

- 고분해능 분말회절 (HRPD) 기법은 산학연의 다양한 이용자가 활용 중이며, 이용자 수요 가장 많은 기법 중 하나임
- PLS-II 빔라인 중 분말회절 전용 빔라인은 9B HRPD가 유일함
- 실시간 실험 기법 및 다양한 환경 실험 가능한 고속 분말회절 빔라인 (HRPD-II) 필요

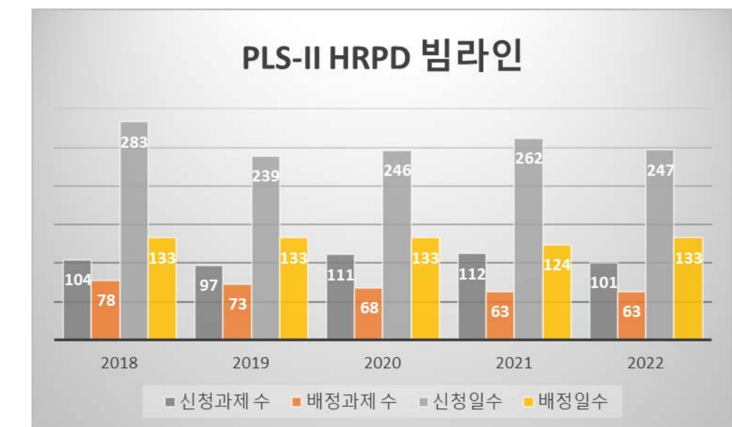


그림 10. PLS-II HRPD 빔라인 신청과제 및 배정과제 현황

HRPD Gen. I
Multi-detector system with analyzer crystals
: Extremely high angular resolution but slow

- Angular resolution < 0.015° (9B)
- Long measurement time
  ≈ 2h for Rietveld Refinement Analysis
- Bragg-Brentano geometry
- Large amount of samples required

HRPD Gen. II
1D Micro-strip detectors (MYTHEN)
: High angular resolution and fast

- Angular resolution ≈ 0.02~0.03°
- Fast data acquisition < 5 min.
  → High throughput by using robotic arms
- Transmission geometry
- Tiny samples (in a capillary tube) with high S/N ratio

그림 11. 분말회절 빔라인 비교

❖ 해외 PD 빔라인 현황

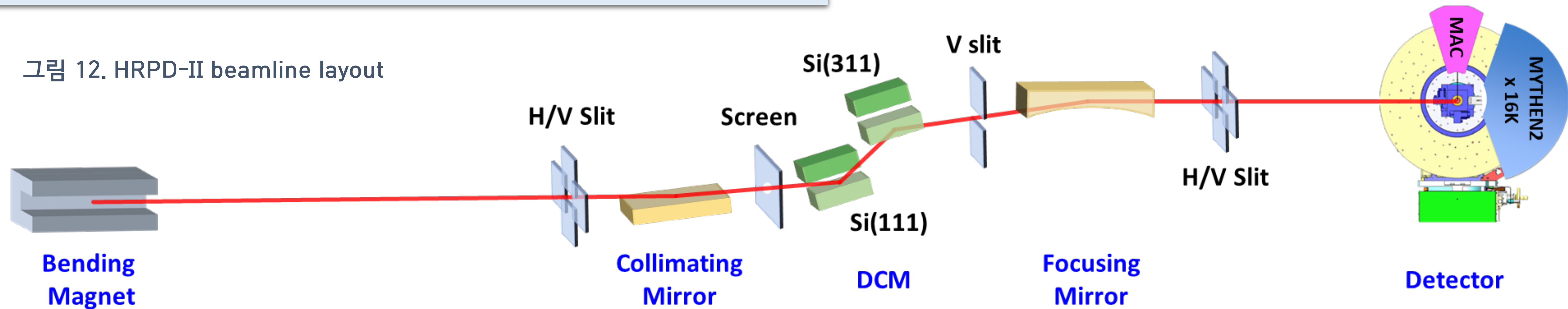
- 해외 PD 빔라인의 경우 12~16keV대를 주로 사용 중, 고에너지 가속기 빔라인에서 30keV 이상 사용
- 기존의 MAC (Multi-Analyzer Crystals, 현 9B 방식) 기반 extreme high resolution에서
  1D microstrip detector 기반의 acceptable high resolution & high-throughput PD 빔라인으로 전환 중

	ESRF (ID22)	Spring-8 (BL02B2)	APS (11BM)	SLS (MS-PD)	SOLEIL (CRISTAL)	ALBA (MSPD)	Elettra (MCX)	TPS (19A) (Taiwan)	LNLS (Brazil)
광원	U23	BM	BM	CPMU U14	U20	SCW30	BM	CU15	BM
광학장치 (Mirror, DCM)	Transfocator Si(111)	VCM, VFM Si(111)	VCM, VFM Si(111)	VCM, VFM Si(111)	VCM, VFM Si(111)	VC/FM, KB Si(111)	VCM, VFM Si(111)	HFM, PM DCM	VFM, Si(111) Si(111)/(311)
가용 에너지 (main E) [keV]	6-80 (15, 30)	12-37 (12, 25, 35)	15-35 (30)	5-38 (13)	5-30	8-50 (14)	6-21 → ?	10-40 (16)	6-14 (8, 12) → 5-30
빔 사이즈 mm(H) x mm(V)	1x1 1x0.1	3x0.7 0.1x0.1	1.5x0.5	0.13x0.04	0.45x0.03 1.5x1.2	0.015x0.015 5x(0.7-1.5)	5x1 0.3x0.3	0.5x0.5 0.025x0.025	2x0.7 → 1.7x1.1
검출기 (업그레이드)	9MAC Si(111), XRD 1611(flat panel detector)	IP detector, MYTHEN2 6K+6K	12MAC Si(111)	MAC, MYTHEN2 x 24K, Pilatus 6M	MAC, CCD, IP,MYTHEN2 x 9K	MAC, CCD MYTHEN2 x 8K	MAC, CCD MYTHEN2 x 29K	MAC, IP MYTHEN2 x 18K	MYTHENx24K (320μm thick) → MAC+ Pimega450D
각분해능 for LaB_6	0.003°@31keV for Si (MAC)	0.015° @25keV for Si (MYTHEN, 0.2mm cap.)	0.005°@30keV for SiO_2 (MAC)	0.016°@ 15.5keV for Si (MYTHEN, 0.3mm cap.)	0.004° @25keV (MAC) <0.02° (MYTHEN)	0.005°(MAC) 0.02°(MYTHEN)	0.016° @15keV (MAC)	0.007° (MAC) 0.015°(MYTHEN, 0.2mm cap.) 0.08-0.1° (IP)	0.008°@15keV (MAC) 0.07°(Pimega)
업그레이드	-	2017	-	2012, 2017	2019	2021	진행 중	2021	2023 (예정)

✓ 광원: U-Undulator, BM-Bending Magnet, W-Wiggler
✓ VCM: Vertical Collimating Mirror, VFM: Vertical Focusing Mirror
✓ DCM sagittally bent for horizontal focusing: APS, SLS, SOLEIL, Elettra, LNLS
✓ MAC: Multi Analyzer Crystals, IP: Image Plate, CCD: Charge-Coupled Device

4B 고속 분말회절 (HRPD-II) 빔라인

그림 12. HRPD-II beamline layout



Source	Bending magnet (PLS-II BL4B port)
Available energy range	8-30 keV (1.55-0.4Å)
Photon flux	~10^{10} (minimum)
Optics	Si(111)/Si(311) DCM, Vertical collimating mirror (M1), Toroidal focusing mirror (M2)
Energy resolution (ΔE/E)	2×10^{-4}
Beam size (@sample position)	100 ㎛ (H) x 100 ㎛ (V)
Angular resolution (LaB_6 @15keV)	<0.015˚ (Analyzer Crystal), <0.03˚ (MYTHEN-II)
End station	High resolution position sensitive detector, MYTHEN2 (2θ ~80˚, 16K modules) + Ge(111) MAC (Multi-Analyzer Crystals) with 3-circle (ω, 2x2θ) diffractometer

Science and Application

❖ **Crystal structure analysis from high resolution powder X-ray diffraction patterns**

- Structure determination of new powder samples
- Structure refinement of polycrystalline materials
- Quantitative phase analysis of multiphase materials
- Tracing phase transition process from crystalline lattice changes

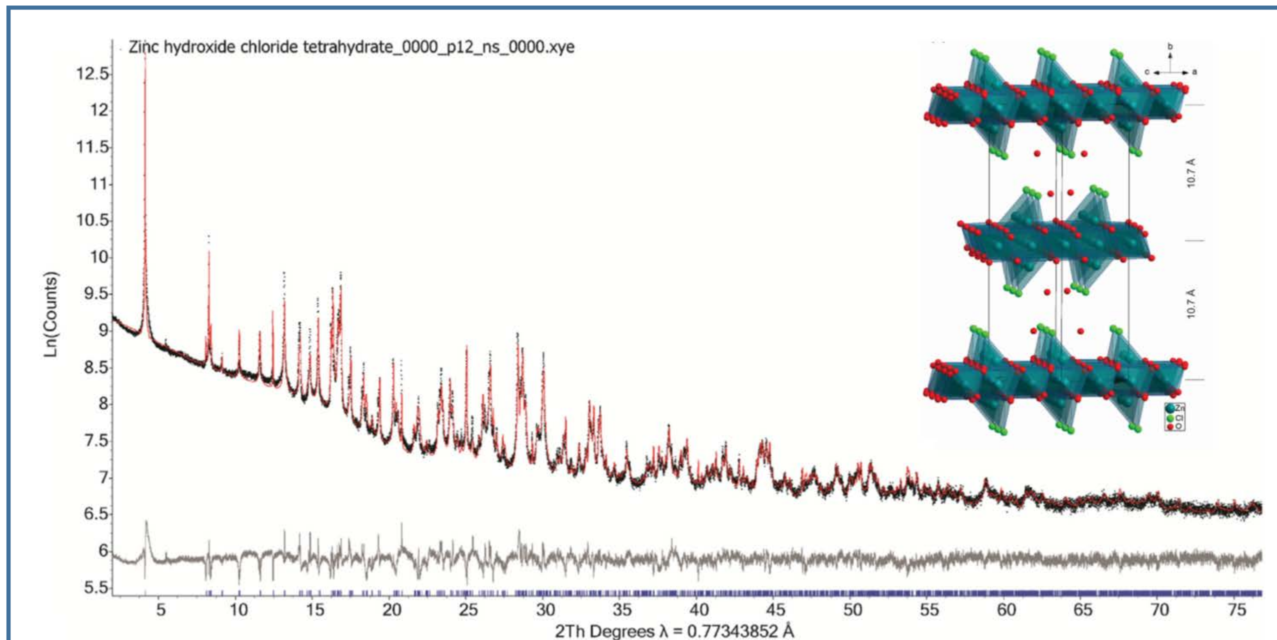


그림 13. Structure determination of Zn hydroxide chloride samples from SPXRD (0.3mm capillary@16keV, MYTHEN2), J. Solid State Chem. 290, 121483 (2020).

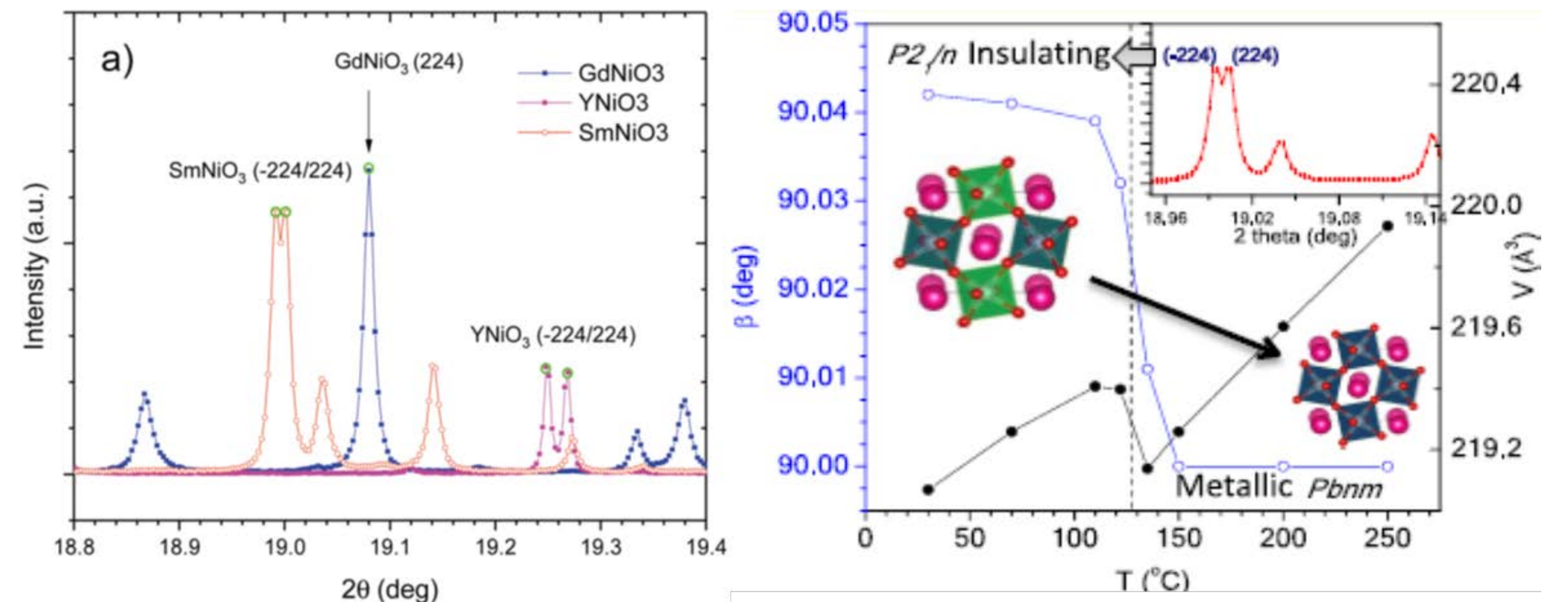


그림 14. Structure changes during metal-insulator transition of $RNiO_3$ perovskites from SPXRD (0.7mm capillary @28keV), Dalton Trans. 50, 7085 (2021). Inorg. Chem. 58, 11828 (2019).

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Science and Application

❖ In situ (Operando) experiments

- Understanding phase transformation mechanism during real-time/environmental experiments

  : temperature, gas adsorption/desorption, photo/electrochemical reaction

- Time-resolved synchrotron powder X-ray diffraction studies (sub-minute scale)

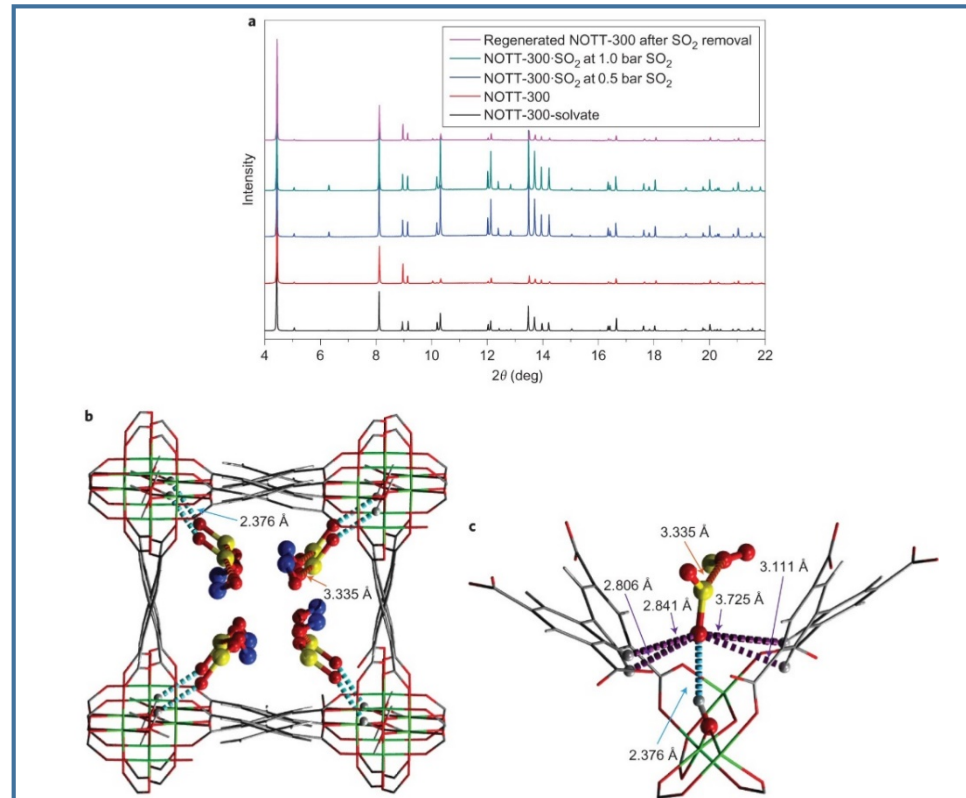

그림 15. SPXRD patterns and crystal structure of MOF samples depending on SO_2 adsorption, Nature Chem. 4, 887 (2012).

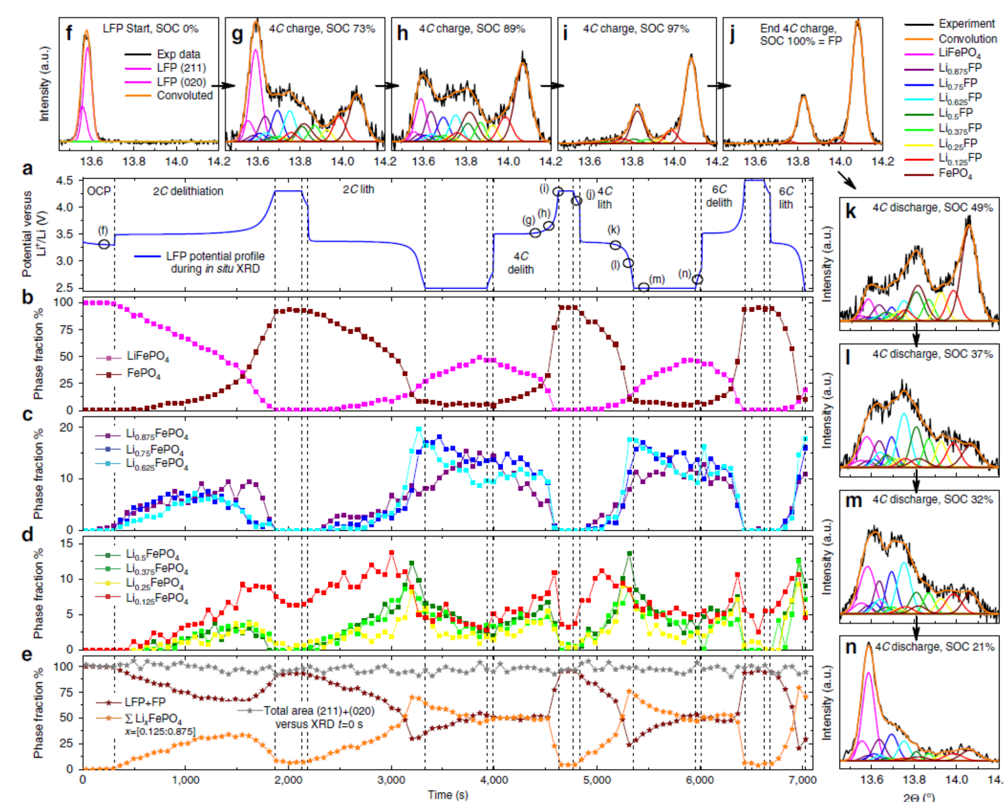

그림 16. Deconvolution of 9 intermediate-phases of $LiFePO_4$ during dis/charging at a rate of 4C, Nature Commun. 6:8169 (2015).

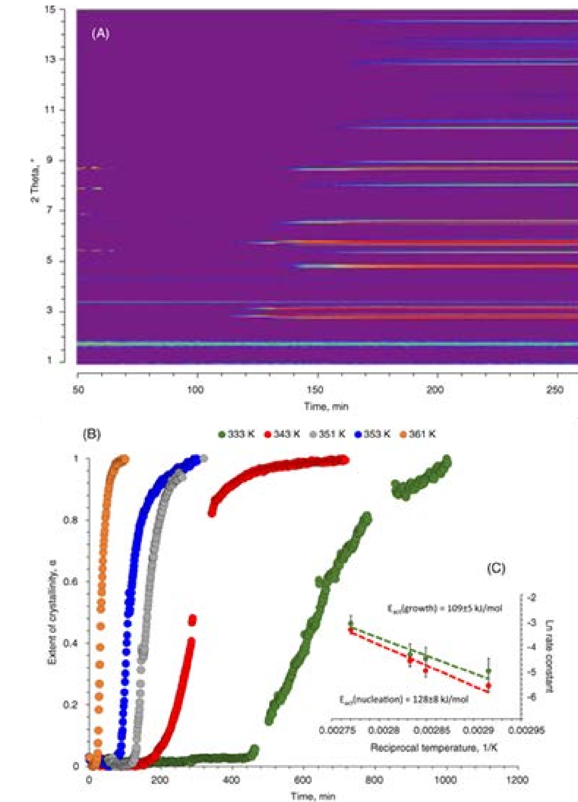

그림 17. Time-resolved SPXRD of MOFs (MIL-53) crystallization, Nature Commun. 13:3762 (2022).

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Science and Application

- ❖ Structure analysis of radiation-damaged/non-ambient sample
- ❖ A tiny amount of sample (mg scale) measurement
- ❖ Materials screening & designed based on high throughput SPXRD data
- ❖ SPXRD data for industrial mass production powders

그림 18. An example of powder samples in a capillary tube for transmission mode SPXRD

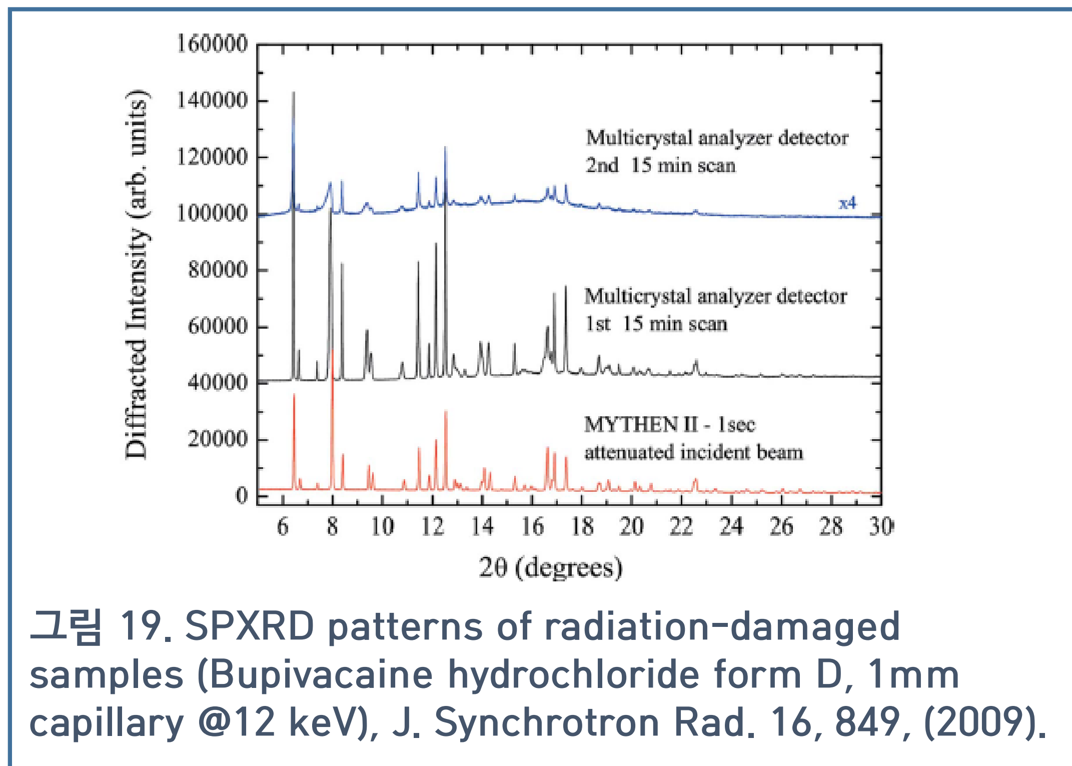

그림 19. SPXRD patterns of radiation-damaged samples (Bupivacaine hydrochloride form D, 1mm capillary @12 keV), J. Synchrotron Rad. 16, 849, (2009).

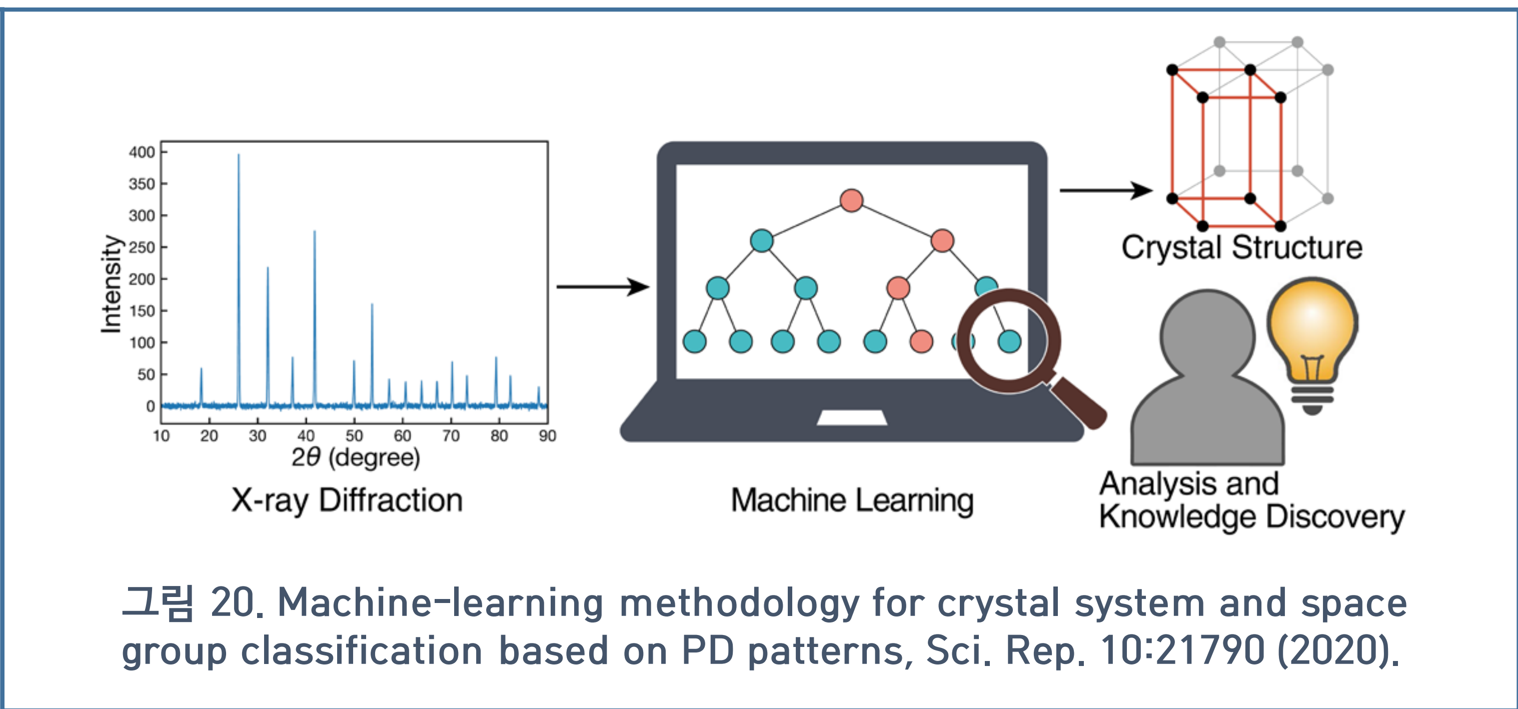

그림 20. Machine-learning methodology for crystal system and space group classification based on PD patterns, Sci. Rep. 10:21790 (2020).

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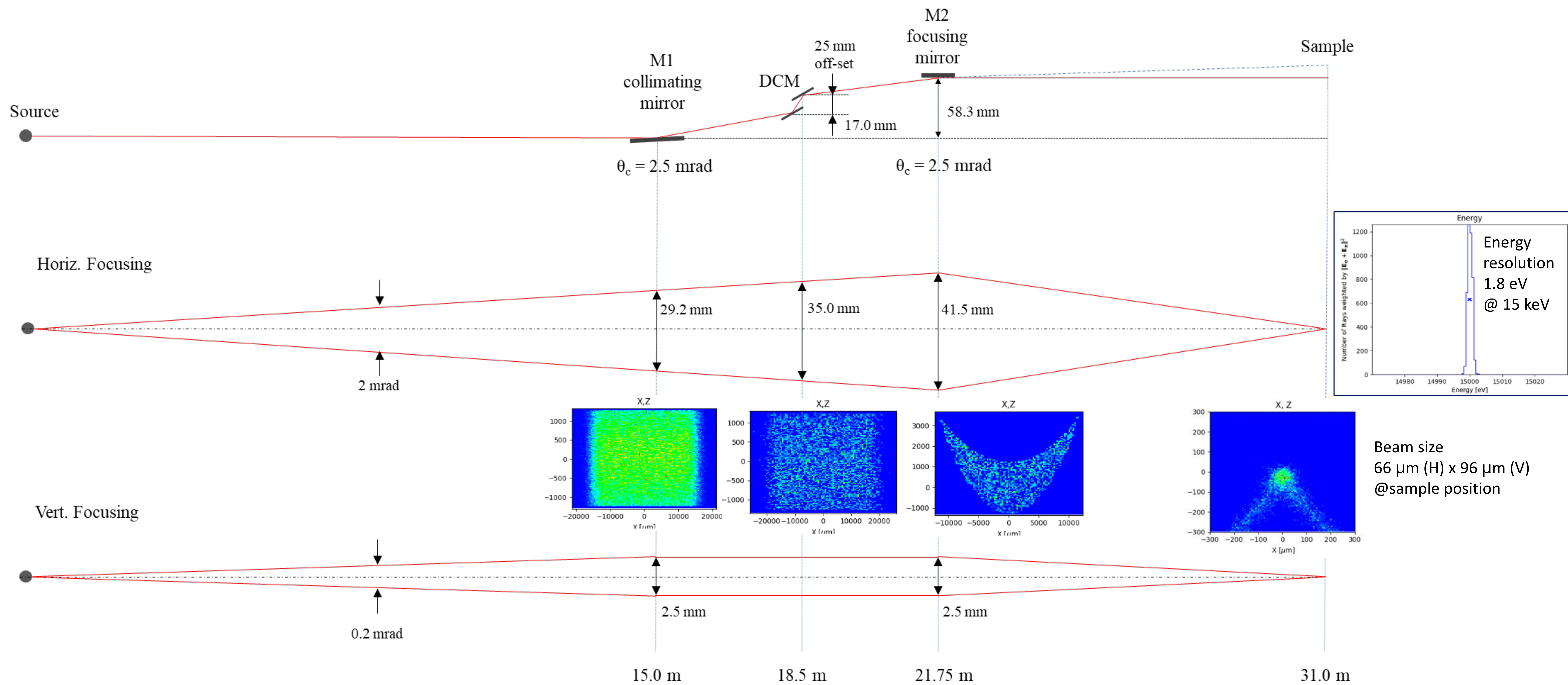
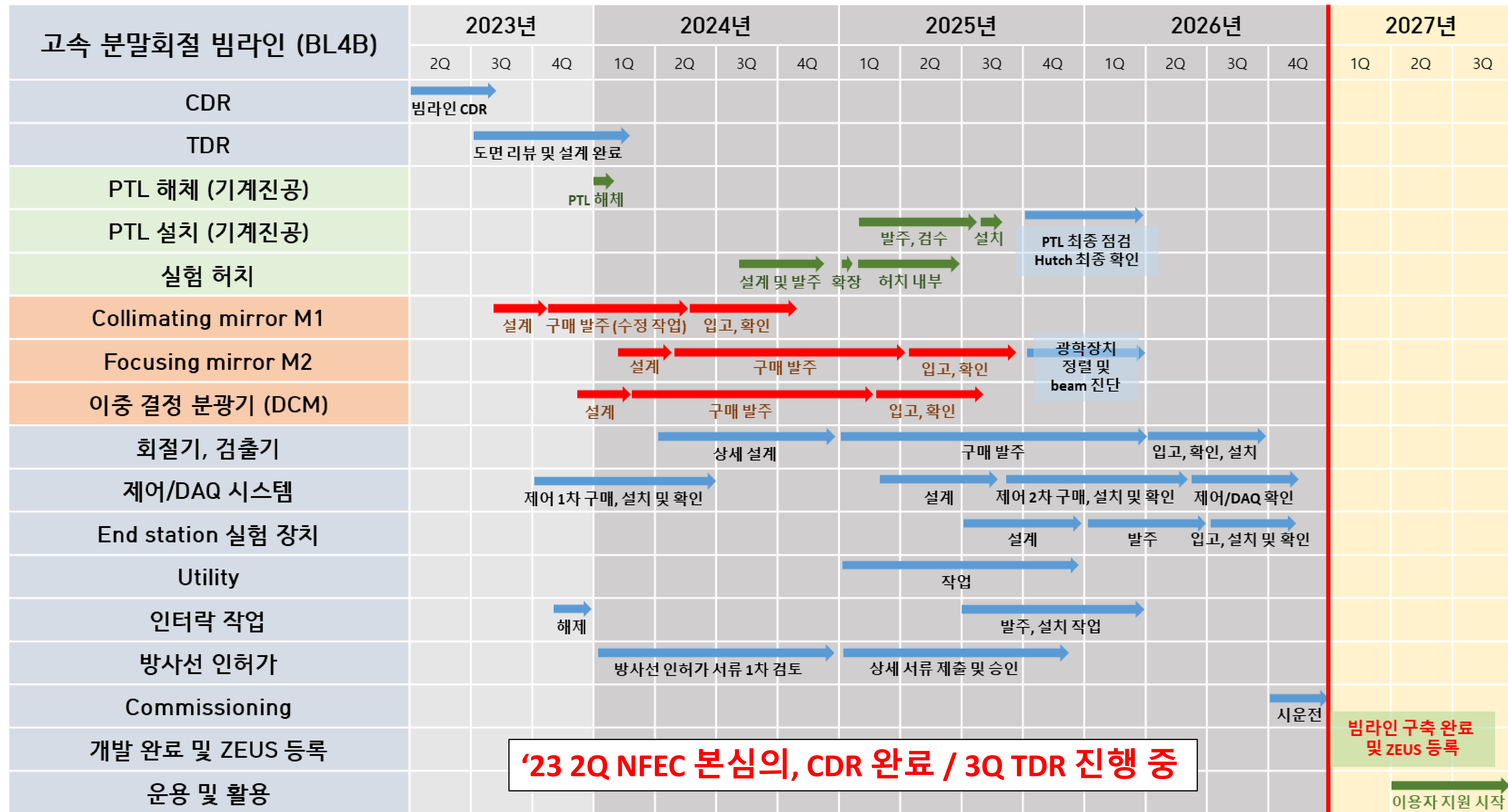
Beamline ray tracing (@ 15keV)



4B HRPD-II 빔라인 건설 예상 일정



PLS-II 빔라인 성능 향상 방안

: Part2) 장치개발팀 개요 및 광학장치개발

박병규 팀장 (PLS-II 빔라인부 장치개발팀)

2023.10.12(목)

장치개발팀의 현황 및 업무 요약

PLS-II 빔라인부 장치개발팀

- **기계/진공 부문** (현재 6명 – 2명 겸직)
- **광학장치 부문** (현재 3명 – 2명 겸직)
- **전기/전자-제어/DAQ 부문** (현재 5명 – 2명 겸직)

PLS-II 빔라인부 장치개발팀의 역할

- ❖ PLS-II 36기 빔라인 유지보수, 실험장치 유지보수 지원
- ❖ PLS-II 신규 빔라인 건설 및 장치 개발
- ❖ 전기, 공기압, LCW(냉각수), LN_2 등의 공급 체계 관리 및 공급
- ❖ 전자장비 및 제어장치 개발과 기술 지원
- ❖ 제어 및 DAQ 소프트웨어 제작과 기술 지원, 표준화 진행
- ❖ 공용 장비 운영 및 소모성 물품의 관리

2023년 이후 연구단내 주요 사업 및 이슈

- ❖ 빔라인 신규 건설: 2C X-선 융합분석 빔라인 (2023 - 2026)
- ❖ 빔라인 개설: 4B HRPD-II 빔라인 (2023 - 2026)
- ❖ 광학장치 개발/제작용 클린룸 확장: X-ray optics Lab. (2023)
- ❖ 광학장치 개발/평가용 빔라인 확보 및 구축 (2023 - 2025)
- ❖ 실험 장치 설계/개발 역량 강화를 위한 인력 확보
  - 2023년 1명 (+ 3명 예정) 채용. 2024년 3명 신규 채용 필요 (절대 인력 부족 및 연도별 은퇴 인력 지속적 발생)

X-선 광학 연구실 중장기 목표 (연구소 연구실)

*해외 가속기 연구소 현황

Facility	Beamline
APS/USA	**1-BM-B,C**
SLS/Swiss	X05DA
ESRF/France	BM05
Diamond/UK	B16
SPring-8/Japan	BL29XU
BESSY-II/Germany	Optics Beamline
SOLEIL/France	METROLOGIE

X-ray Optics Development

X-ray Optics Lab.

PLS-II 노후 광학계 개선을 통한 빔라인 성능 향상

신규 광학계 측정 평가를 통한 검증

X-선 거울 자체 개발을 통한 빔라인 적용 및 기술력 향상

Optics Test Beamline

기존 광학계 안정성 평가 및 성능 개선

빔 특성 평가 및 광학 장치 실증 평가

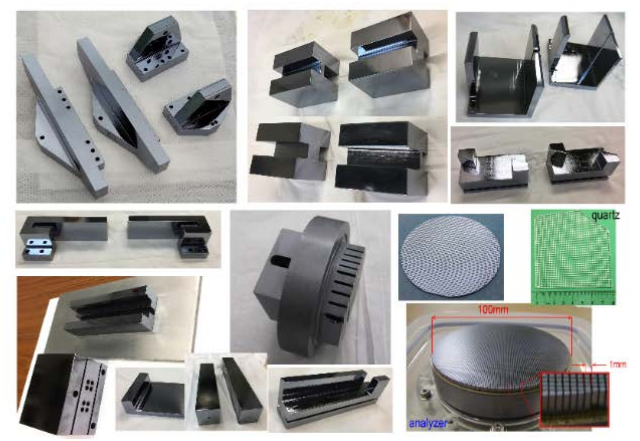
광학 장치 국산화 개발 및 기술력 향상

X-선 광학계 관련 핵심 기술 개발을 통한 X-선 광학 소자 국산화 및 빔라인 성능 향상에 기여

광학실 및 테스트 빔라인 보유 해외 가속기 연구소 현황

Name & Affiliation
Assoufid, Lahsen (XSD-OPT) Group Leader/Physicist
Conley, Raymond (XSD-OPT)
Huang, XianRong (XSD-OPT) Physicist
Kasman, Elina (XSD-OPT) Optics Fabrication Specialist
Macrander, Albert (XSD-OPT) Senior Physicist
Stone, Brandon (XSD-OPT) Senior Scientific Associate
Pennell, Christina (XSD-OPT) Administrative Assistant
Qian, Jun (XSD-OPT) Metrology specialist
Shi, Bing (XSD-OPT)
Shi, Xianbo (XSD-OPT)
Rebuffi, Luca (XSD-OPT)
Shvydko, Yury (XSD-OPT) Senior Physicist
Smither, Robert (XSD-OPT)
Wojcik, Michael (XSD-OPT) Physicist

Crystal Optics



Examples of crystal optics fabricated in OPT

Expertise includes:

1. Designing crystal optics with X-ray dynamical-theory calculations and modeling to achieve desired resolution, efficiency, acceptance, etc., In-house dynamical theory software HXRD is available upon request.
2. Fabricating and refurbishing ultrahigh-quality crystal optics (Si, Ge, quartz, sapphire, diamond), from precise orienting, cutting/dicing, grinding, etching, to strain-free polishing
3. X-ray characterization and testing of crystal optics using X-ray topography and double-crystal rocking curve imaging.

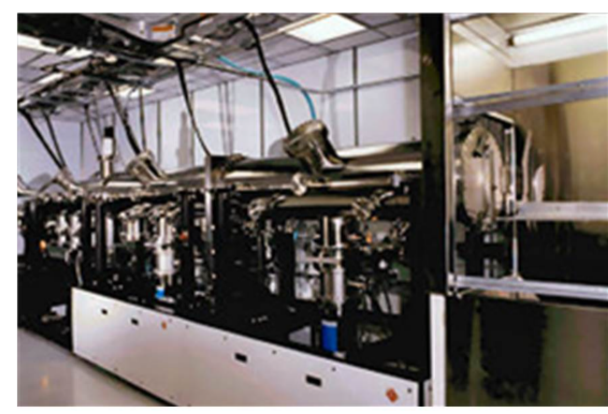
Work requests can be submitted by filling the Optics Group's work request from.

Mirrors and Multilayer Optics

Objective: Develop and fabricate single and multilayer thin film optics, as well as experimental samples, primarily for APS beamlines and users. Staff are available for consultation regarding thin-film deposition materials selection and general optical component design or simulation. The deposition laboratories include: 1) Class 10,000 clean room that houses a large DC sputtering system and a small deposition system; 2) Class 100, 000 clean room that house a rotary deposition system and a laboratory x-ray reflectometer for evaluation of single and multilayer thin film optics; and 3) Class 10,000 class cleanroom that is used for beamline optical system mounting and for the development of the future APS mirror/multilayer modular deposition system. These laboratories are conveniently located near 1-BM Optics and Detector Testing beamline, in the APS experiment hall floor.

Work requests can be submitted by filling the Optics Group's work request from.

(1.5 m) Sputter Deposition System



Our 1.5m deposition system accepts maximum substrate dimensions of 150 cm long, 20 cm wide, and 14 cm thick. Four sources combined with a broad-beam ion mill provide for a wide variety of mirror and sample coatings.

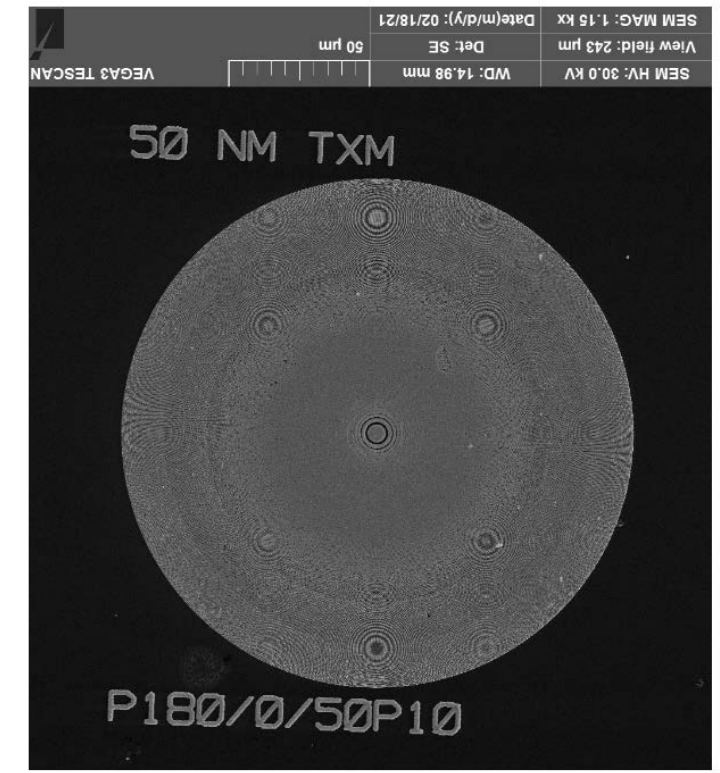


Figure 1: SEM image of a 50 nm zone plate, 180 μm diameter, and 1000 nm thick Au.

광학실 및 테스트 빔라인 보유 해외 가속기 연구소 현황

Optical Metrology

The Metrology Laboratory role is to

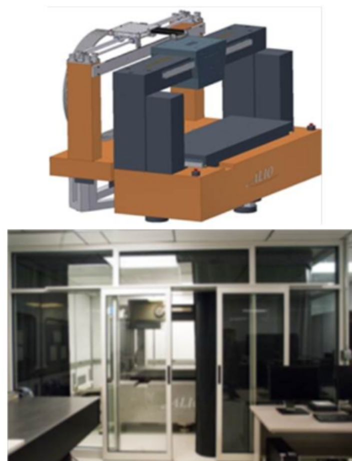
- Evaluate optical quality of x-ray mirrors and substrates for APS beamlines and users, in order to ensure compliance with the user's specifications in terms of figure error and finish.
- Characterize x-ray mirror-bender assemblies and specialized optics.
- Support in-house optics development by providing accurate metrology data
- Carry out joint R&D programs to develop new metrology measurement techniques and instrumentation.

The metrology lab houses an array of non-contact profilers customized to evaluate optics and cover the wide range of surface spatial frequencies that are relevant to x-ray optics. These include a slope measuring system (i.e.; a long trace profiler), a laser figure interferometer; a microscope interferometer for surface roughness measurements with microstitching capability.

These instruments are housed in a class 10,000 cleanroom located on the APS experiment hall floor, near sector 1.

Work requests can be submitted by filling the Optics Group's work request form

Slope Measuring System (Long Trace Profiler - LTP)



X-ray Beam Wavefront Sensors, Characterization and Diagnostic

The optics group develops advanced wavefront sensing and coherence measurement techniques to support APS optics development and beamline characterization and diagnostic. Examples of applications include

- At-wavelength metrology of X-ray optics (lenses, mirrors, crystals, and windows)
- Beamline wavefront sensing and coherence measurements
- Real-time beamline diagnostic (wavefront monitor for optics alignment, aberration, and vibration correction) Content not in container, usually a preliminary description.

Advanced techniques on wavefront and coherence measurements

The optics group is exploring various coherence characterization and wavefront sensing techniques based on grating interferometry and speckle tracking. A state-of-the-art wavefront-sensing technique based on coded-mask technology and deep learning was recently developed [Z. Qiao, X. Shi, M. J. Wojcik, L. Rebuffi, and L. Assoufid, Appl. Phys. Lett. **119**, 011105 (2021), DOI: 10.1063/5.0053553]. This fast, high-resolution method is critical for real-time wavefront characterization and monitoring.

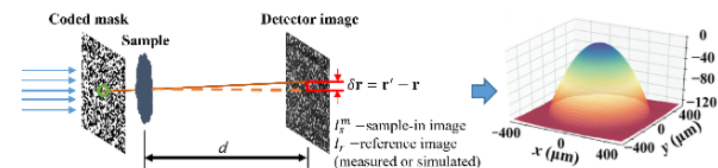


Figure 1: (Left) Schematic of the coded-mask-based X-ray wavefront sensing technique and (right) reconstructed phase of a Be refractive lens.

1-BM Optics and Detectors Testing Beamline

The optics and detector testing capabilities support the missions of the Optics (OPT) and Detectors (DET) groups to develop new technologies as well as to characterize or calibrate optics and detectors produced at other labs and by industry. The beamline primarily serves the testing needs of the OPT and DET groups, but it also has a General User program. Frequent access to a repeatable testing setup is difficult to accommodate at other beamlines set up to serve specific user communities. The flexibility to accommodate different set-ups at 1-BM addresses this need. The beamline provides a wide horizontal beam for monochromatic and white-beam topography of samples up to 100 mm in width. A novel white-beam shutter with millisecond-response allows controlled exposures (as short as 50 msec) for topography. Various conditioning crystals have been fabricated to condition the beam after the monochromator, and sample crystals can then be studied in an overall (+ - - +) x-ray optical configuration. With this crystal configuration rocking curve topography of samples can be done with an optimized narrow angular resolution function. Other optics testing tools and capabilities include 1) a moveable platform for Talbot diffraction grating-based interferometry and speckle tracking for optics wavefront characterization, and 2) a moveable microscope setup for testing zone plates and multilayer Laue lens optics at low and moderate resolution.

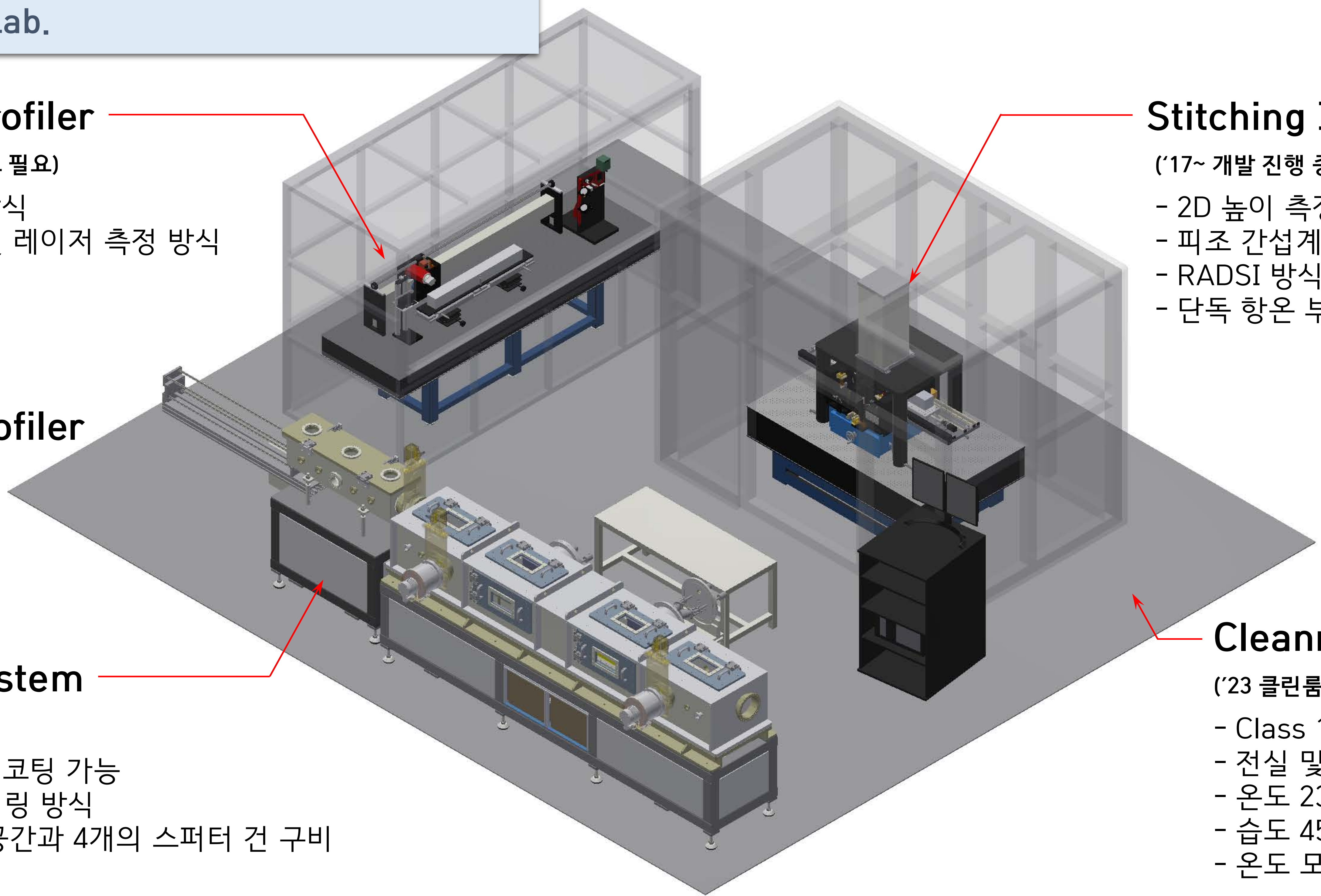
Current optics Testing Capabilities include

- Monochromatic topography
- White beam topography
- Talbot grating interferometry
- K-B mirrors testing
- Zone plate and multilayer layer Laue (MLL) testing.

Experiment proposal requests can be submitted using the APS Users proposal portal

More Information on 1-BM Optics and Detectors Testing Beamline

X-ray Optics Lab.



Long Trace Profiler

(~'00, 노후화, 업그레이드 필요)

- 1D 기울기 측정 방식
- 오토콜리메이터 및 레이저 측정 방식
- 단독 항온 부스

3D Optical Profiler

('17 구매품)

- 표면 조도 측정

Deposition System

('19~ 개발 진행 중)

- 단층 및 다층 박막 코팅 가능
- 마그네트론 스퍼터링 방식
- 2 개의 프로세스 공간과 4개의 스퍼터 건 구비

Stitching Interferometer

('17~ 개발 진행 중)

- 2D 높이 측정 방식
- 피조 간섭계 타입
- RADSI 방식의 스티칭
- 단독 항온 부스

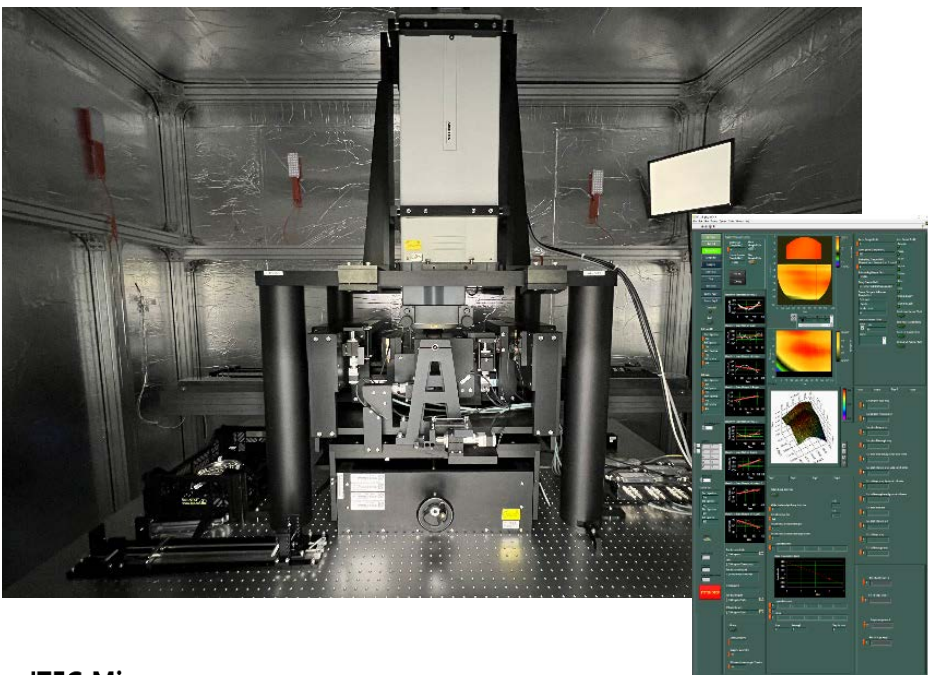
Cleanroom

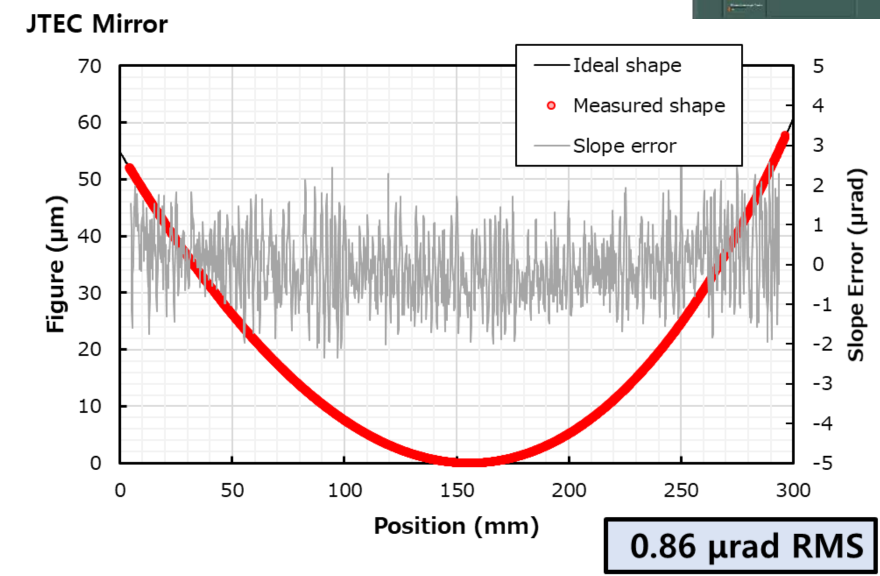
('23 클린룸 확장 진행 중)

- Class 1000
- 전실 및 에어샤워 구비
- 온도 23 ± 0.5℃
- 습도 45 ± 5%
- 온도 모니터링 시스템

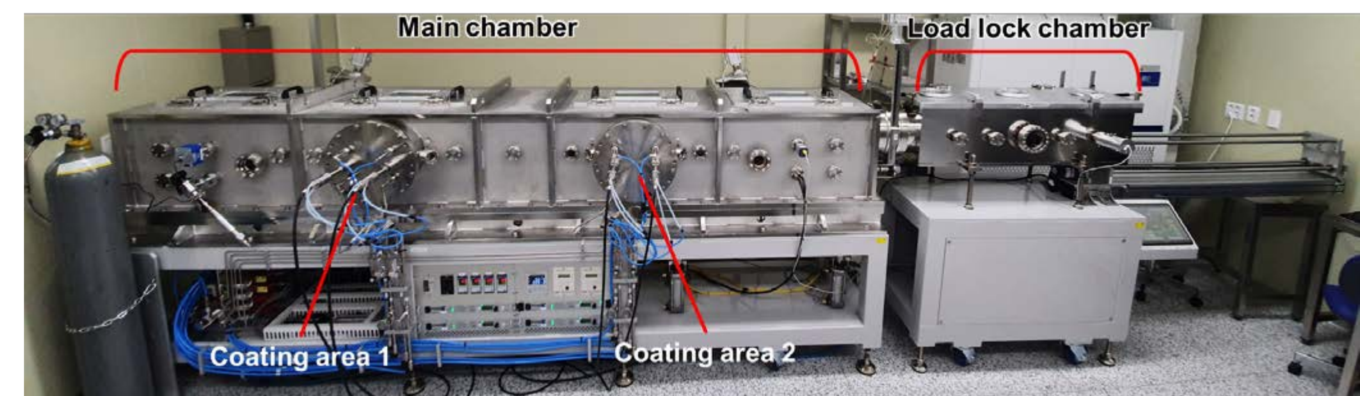
X-ray Optics Lab. (핵심 기술 개발)

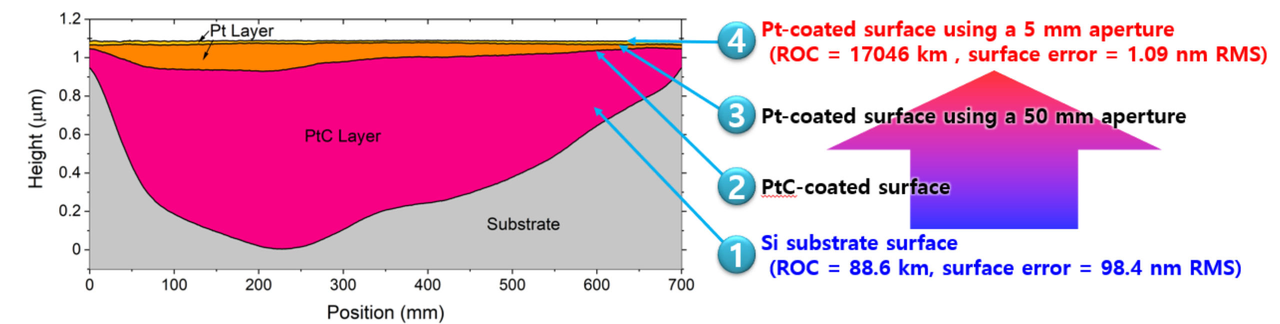
측정 장치 개발



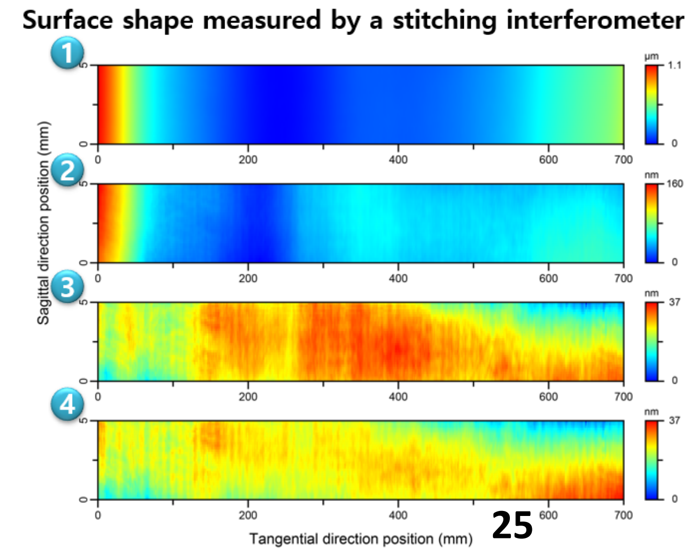


코팅 장치 개발

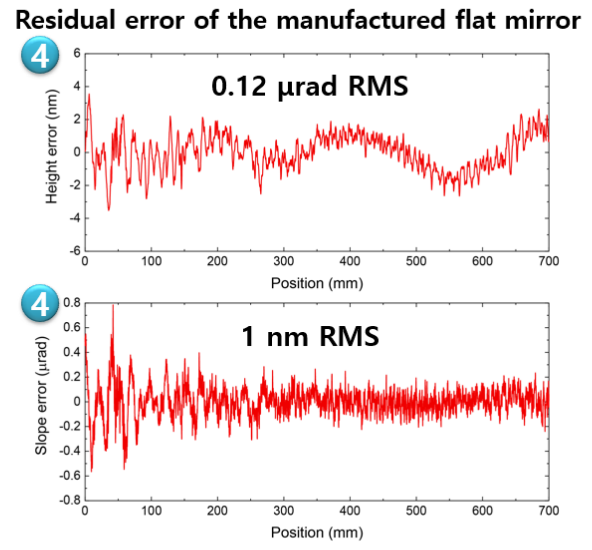




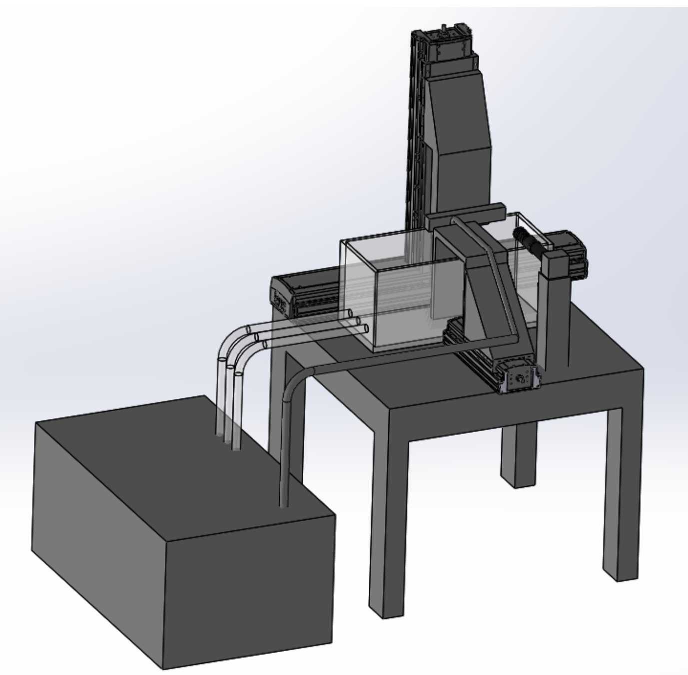
Surface shape measured by a stitching interferometer

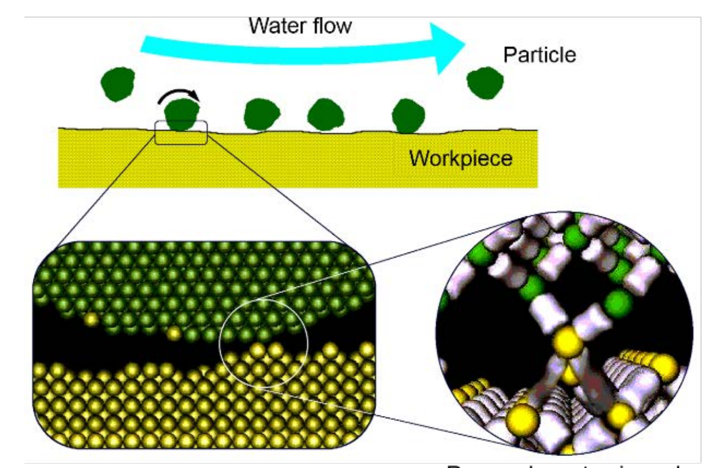


Residual error of the manufactured flat mirror



가공 장치 개발 (계획)





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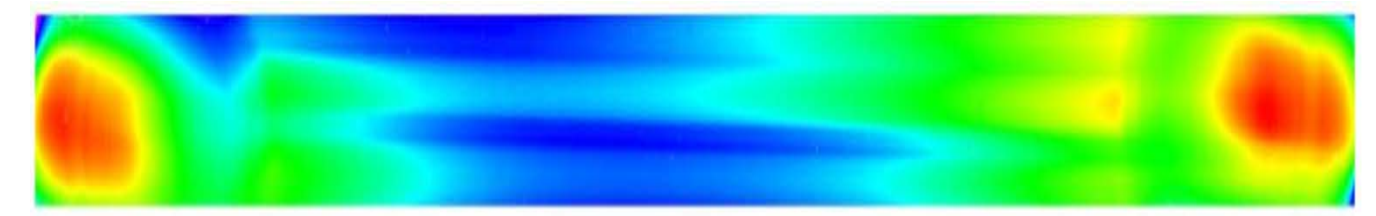
측정 장치 개발

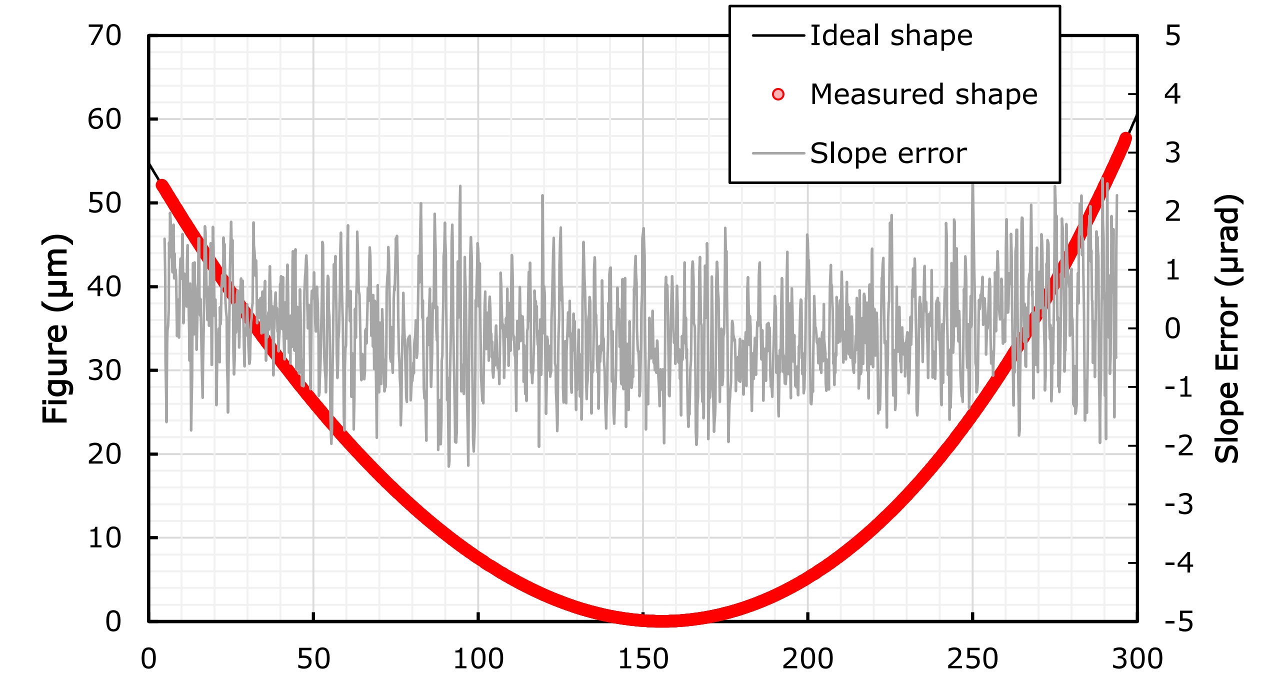
- Sample mirror size
  : (max) X 100 mm, Y 100 mm, Z 1000 mm
- Fizeau interferometer type stitching interferometer

Measured by PAL 600 mm x 50 mm

Measured by KBSI

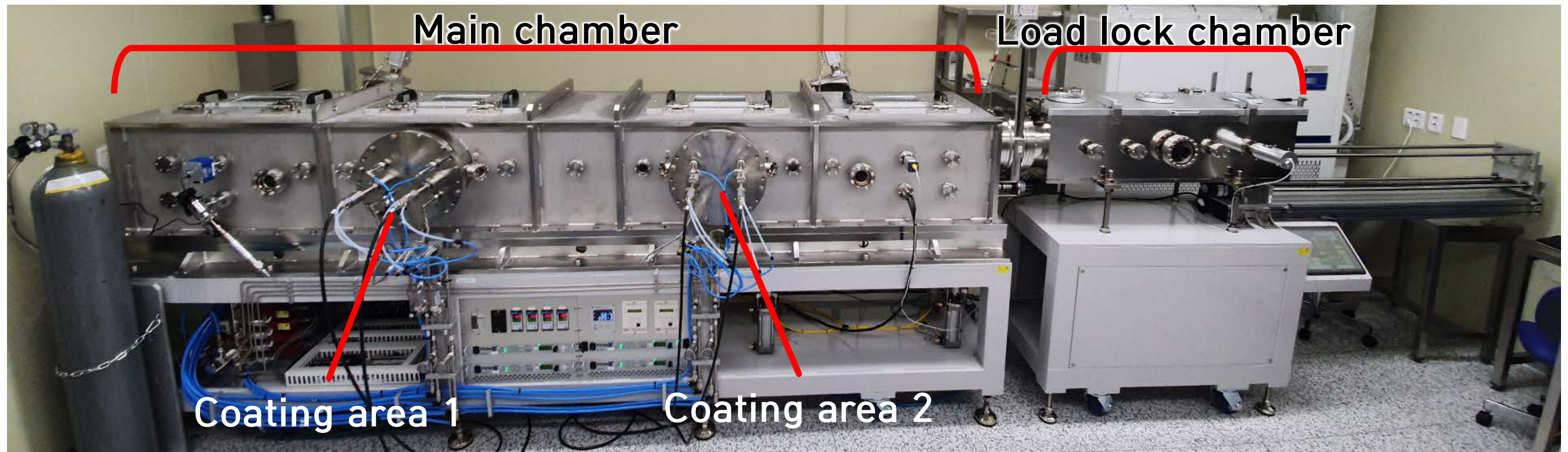


Made by JTEC

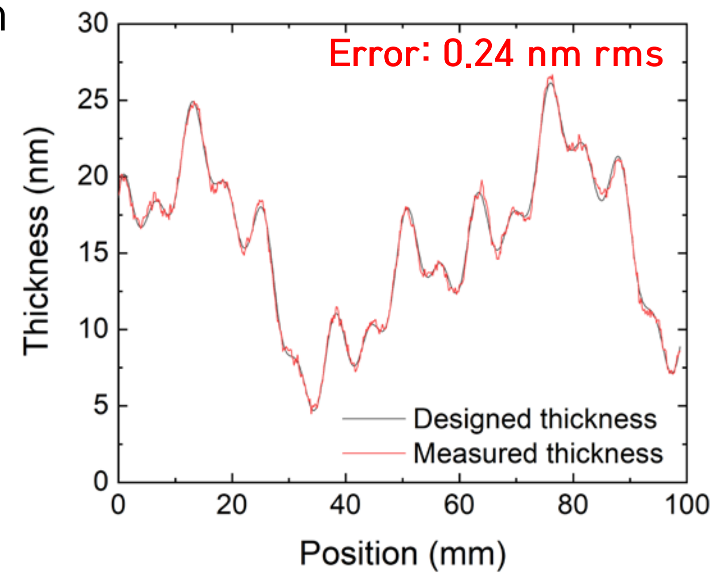


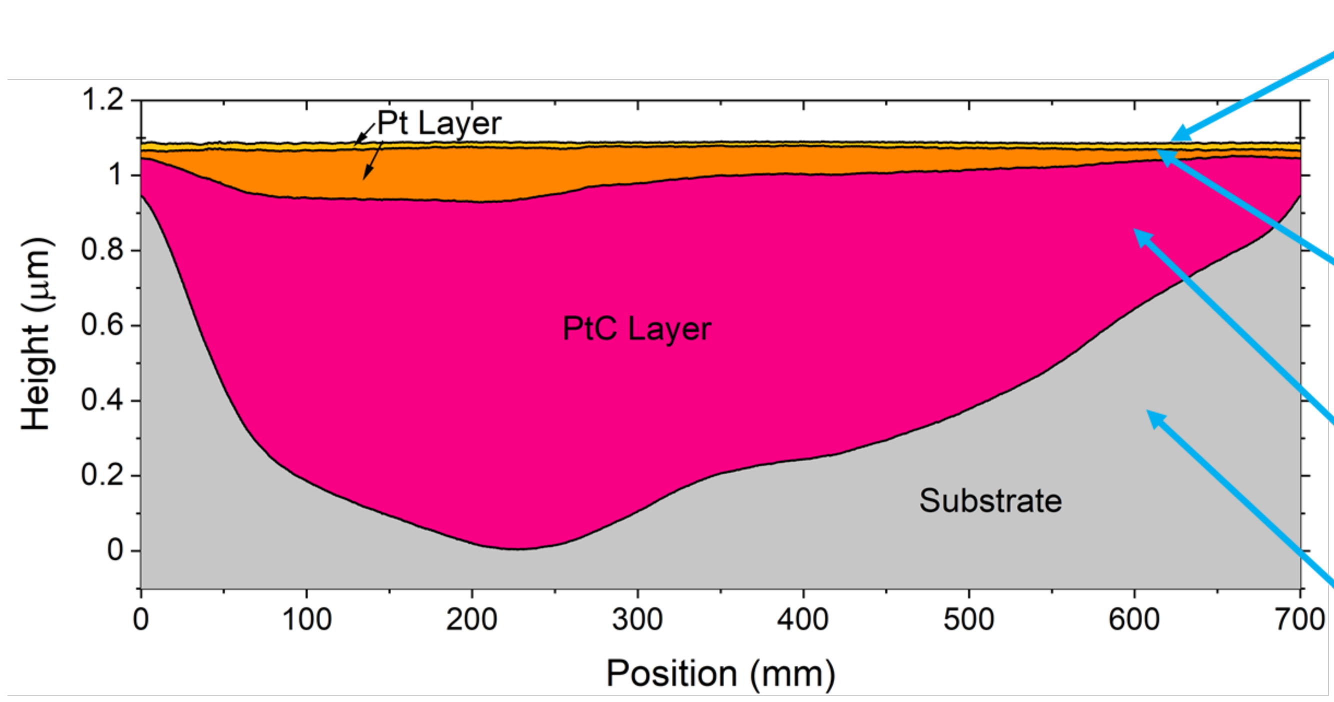
0.86 μrad RMS

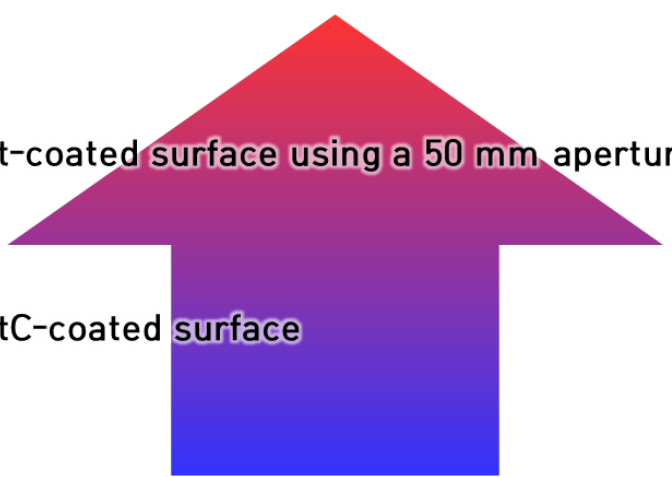
코팅 장치 개발

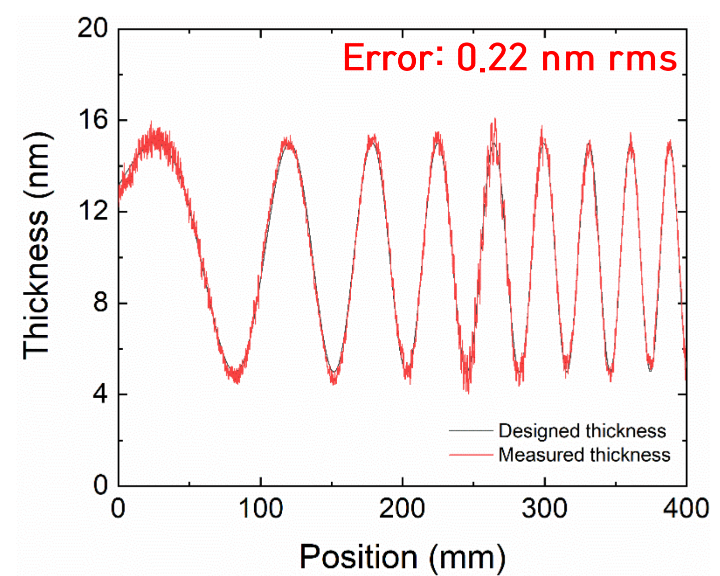


- Sample mirror size
  : (max) 100 mm, 100 mm, 1000 mm
- Single layer / multilayer coating
- Differential deposition
- Co-deposition









코팅 장치 개발

Surface shape measured by a stitching interferometer

1 (μm, 0 – 1.1)

2 (nm, 0 – 160)

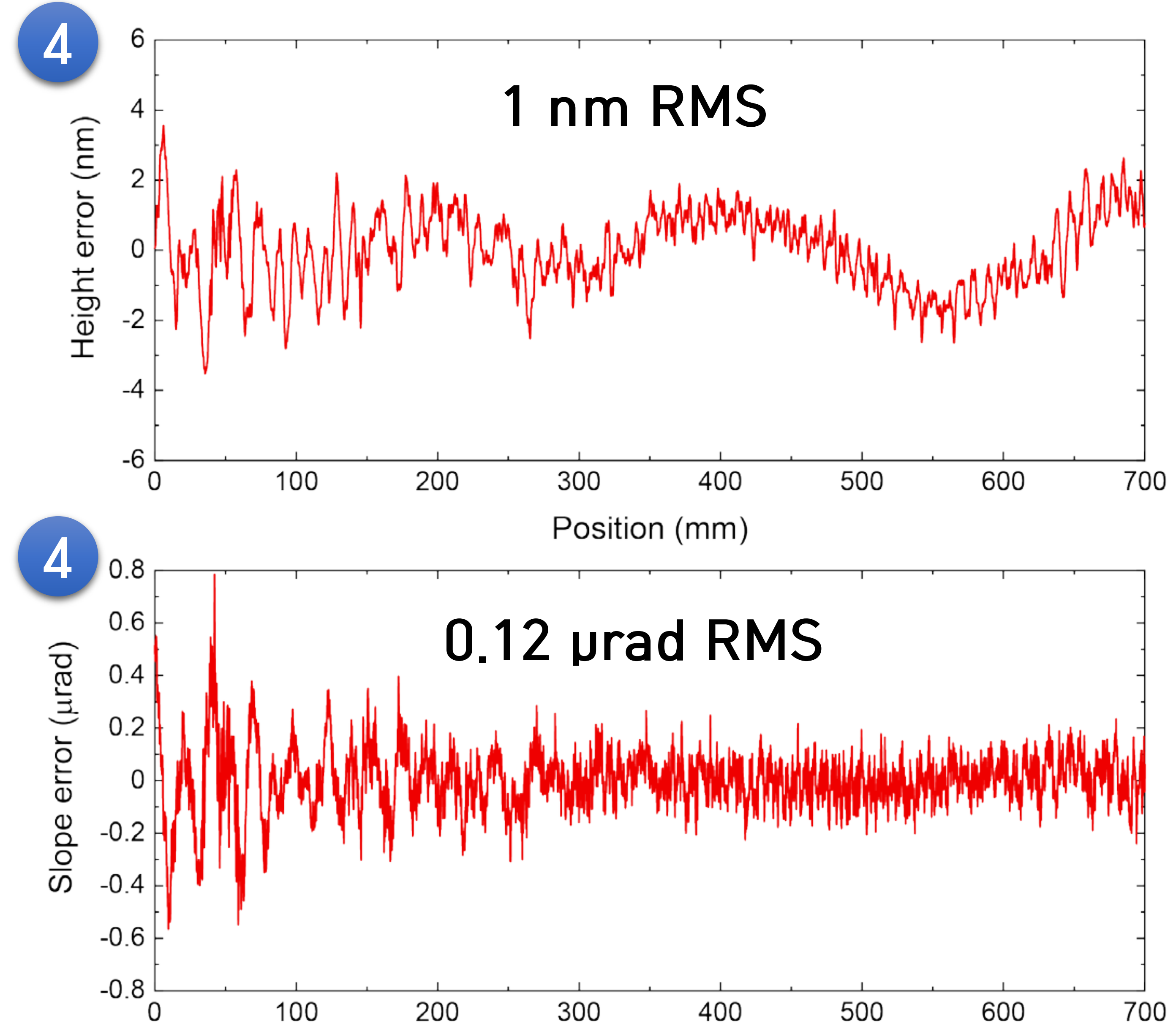
3 (nm, 0 – 37)

4 (nm, 0 – 37)

Sagittal direction position (mm)

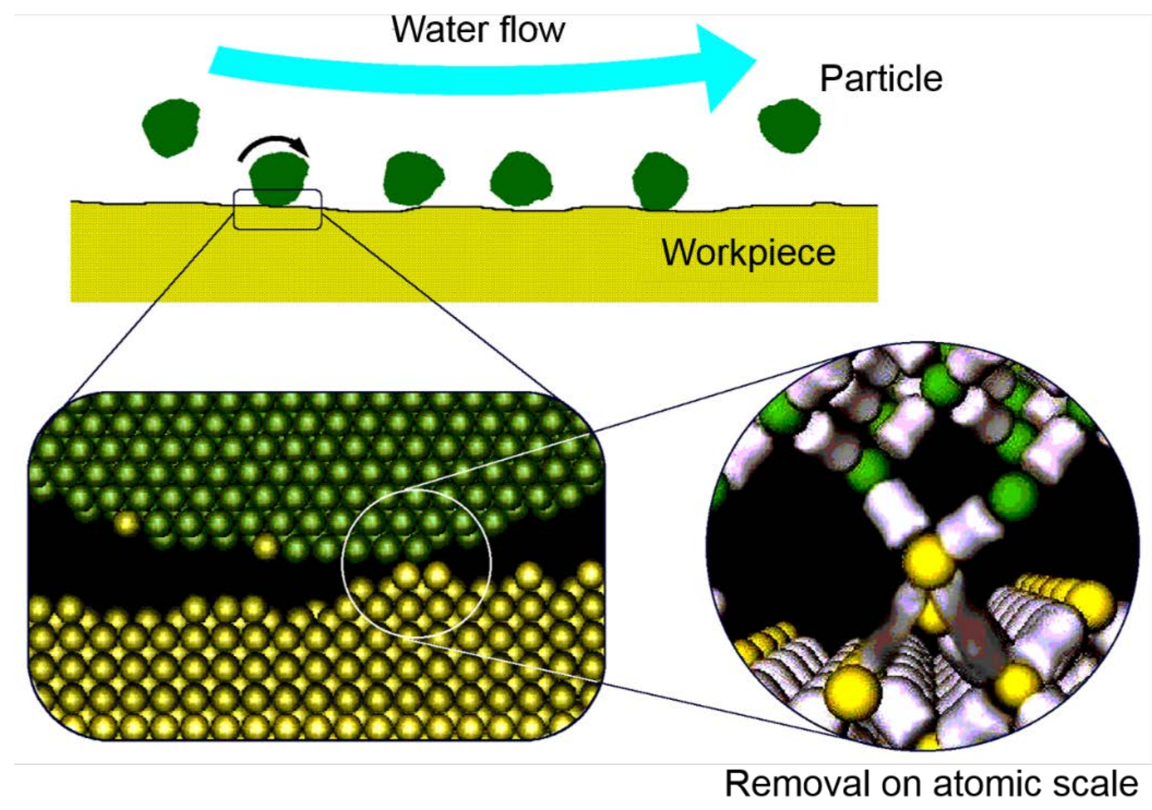
Tangential direction position (mm)

Residual error of the manufactured flat mirror



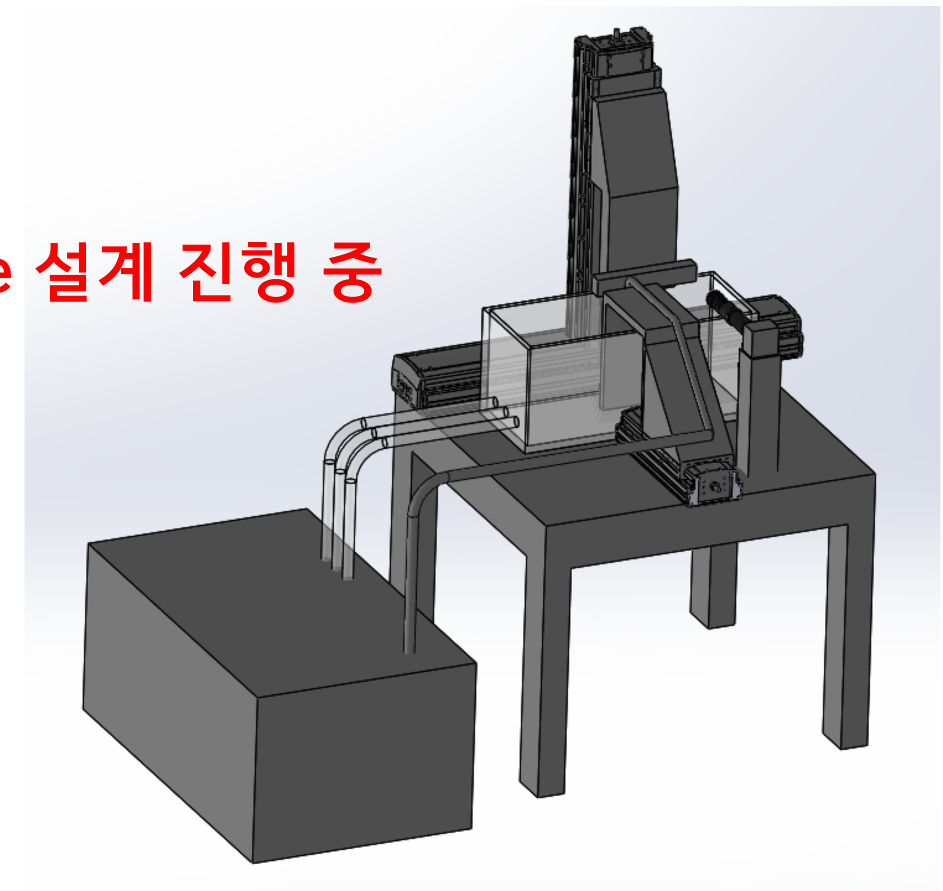
가공 장치 개발 (계획)

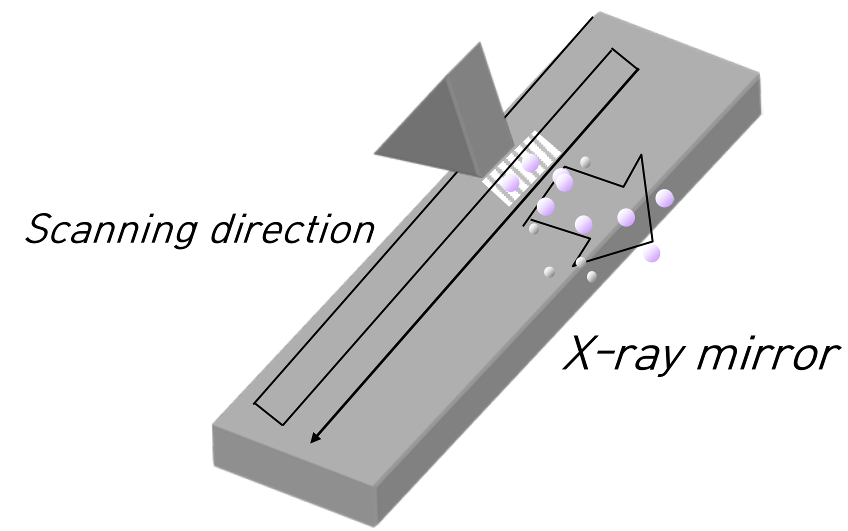
Elastic Emission Machining (EEM)

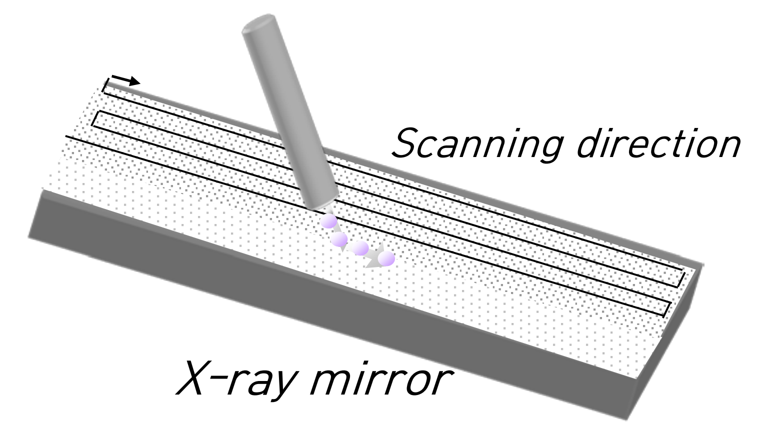


Topmost atoms on the workpiece will pr eferentially adhere to and move onto the surface of the powder particle.

Proto-type 설계 진행 중





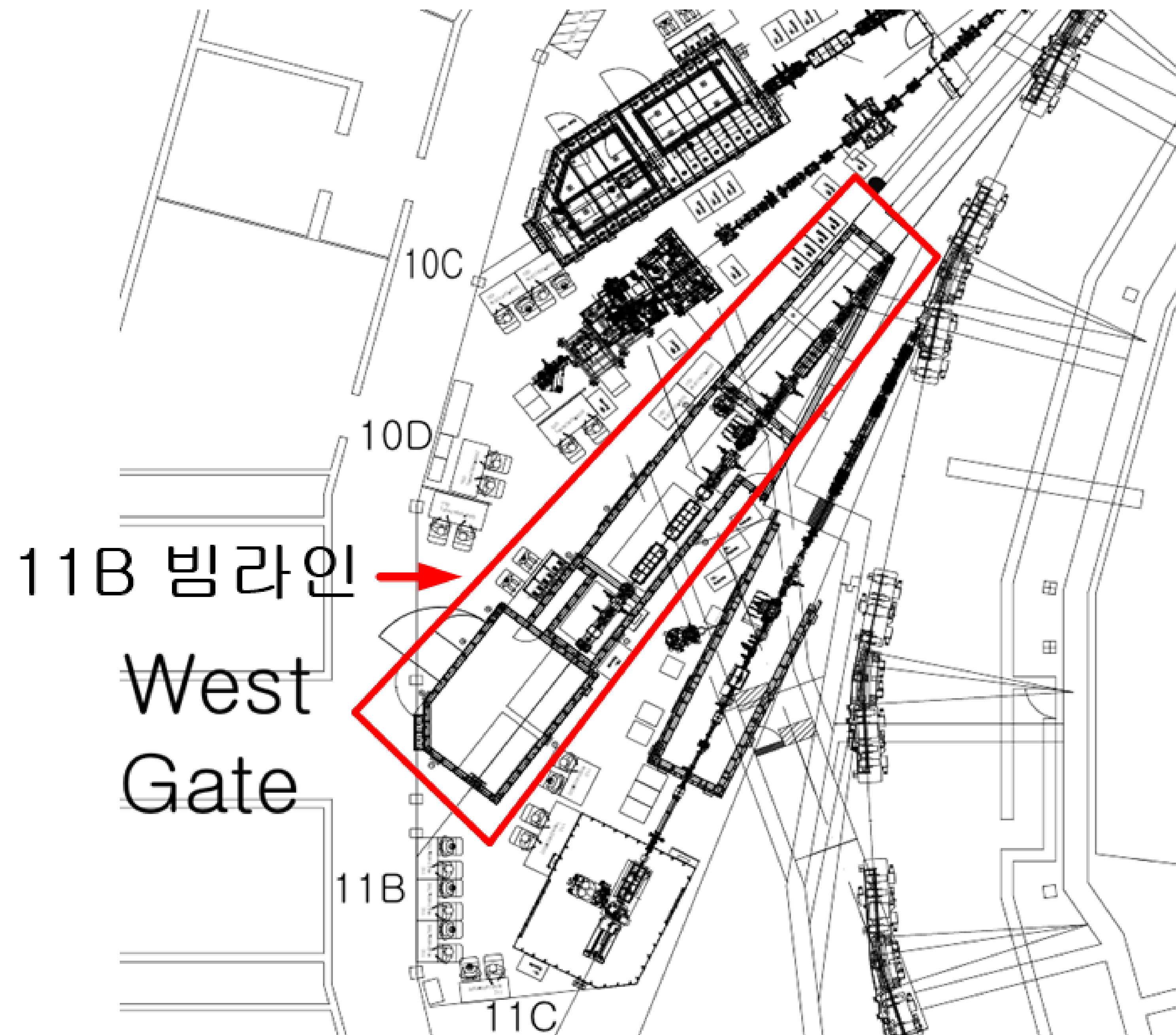


Optics Test Beamline

❖ 11B SURF

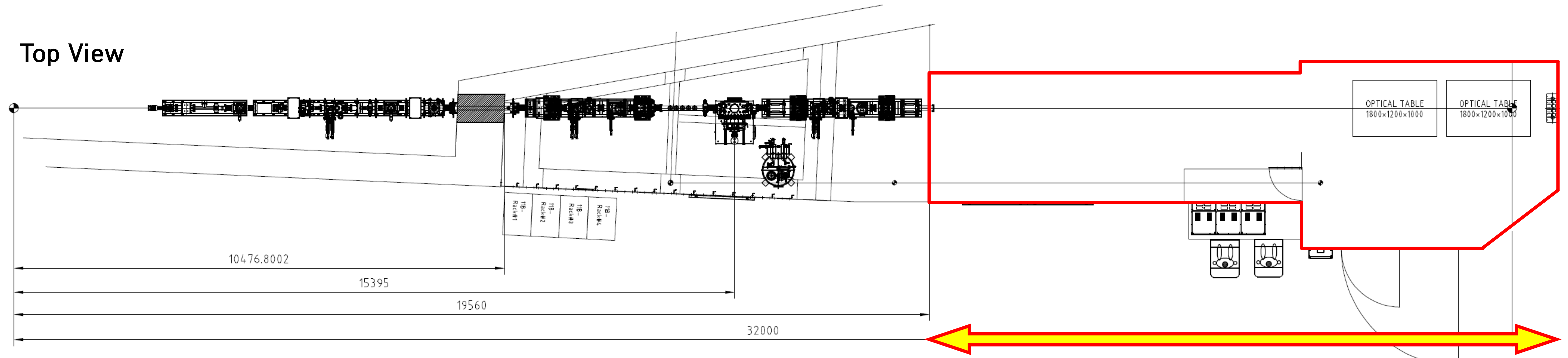
(Synchrotron Utilized Optics RnD Facility)

- Beam port: 11B
- Ring energy: 3 GeV
- Ring current: 400 mA
- Bend angle: 0.2618 rad
- Bending radius: 6.875 m
- Central field: 1.4557 T
- Gap at the center: 34 mm
- Size of beam fan: 14H x 0.17V mrad

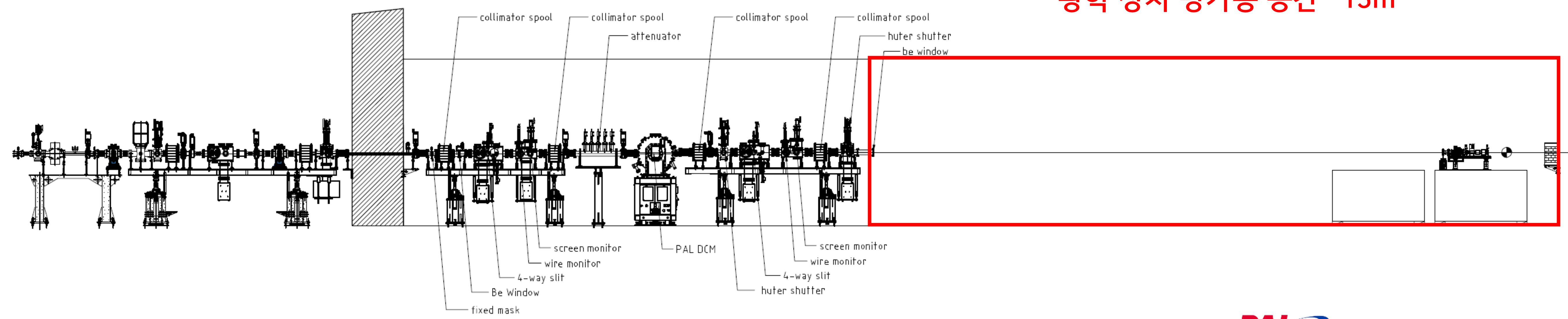


Optics Test Beamline

Top View



Side View



PAL 포항가속기연구소

Optics Test Beamline

❖ 빔라인 사양

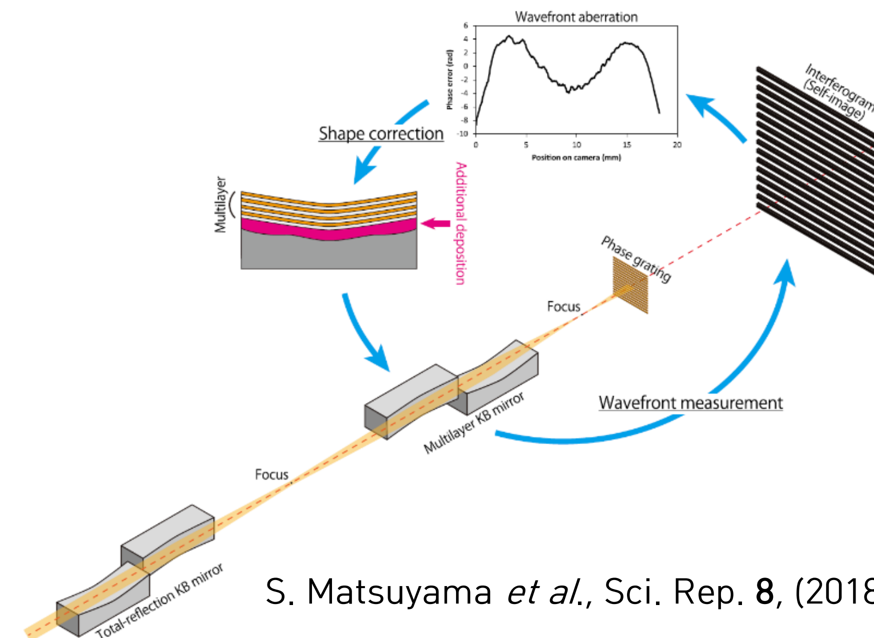
- Light source: Bending magnet
- Photon energy: 5 ~ 50 keV
- Energy resolution: $\triangle E/E \sim 1 \times 10^{-4}$
- Flux: > 1×10^{12} photon/sec
- Main devices
  : optics (mirror, monochromator)
  beam diagnostic device
  focusing optics
  exp. system

❖ 빔라인을 통한 연구분야

- X-선 광학 소자 및 광학 장치의 성능 검증 및 캘리브레이션
- 광학실과의 협력을 통한 on- & off-line 측정 평가
- 산업체의 방사광가속기 관련 장치 개발 지원을 통해 국가 핵심 기술 장치 개발 국산화에 기여

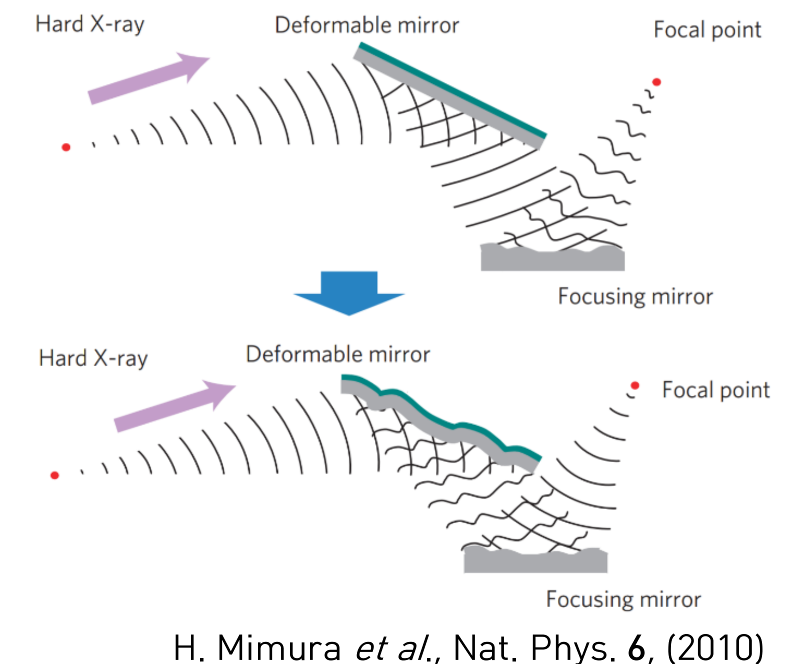
❖ 다양한 실험기법 적용 및 신규 개발

Talbot-grating interferometry



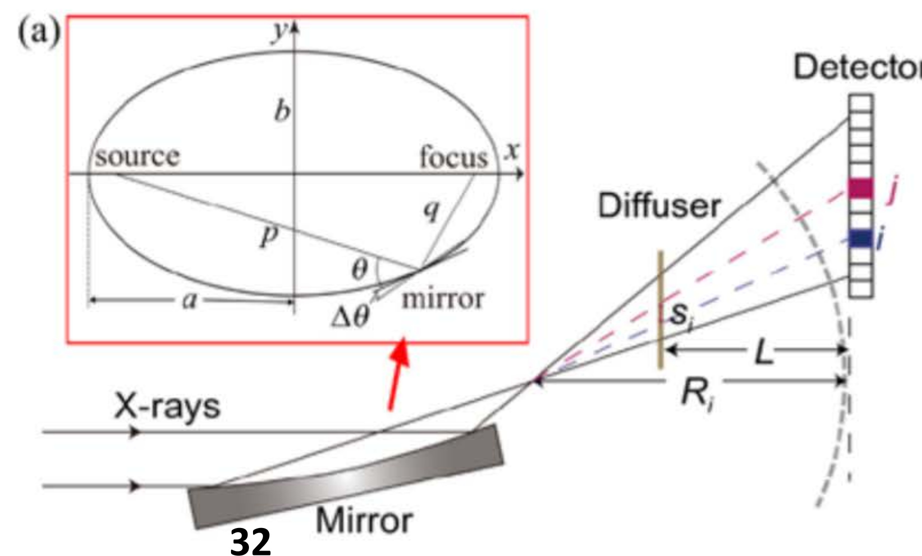
S. Matsuyama *et al.*, Sci. Rep. **8**, (2018)

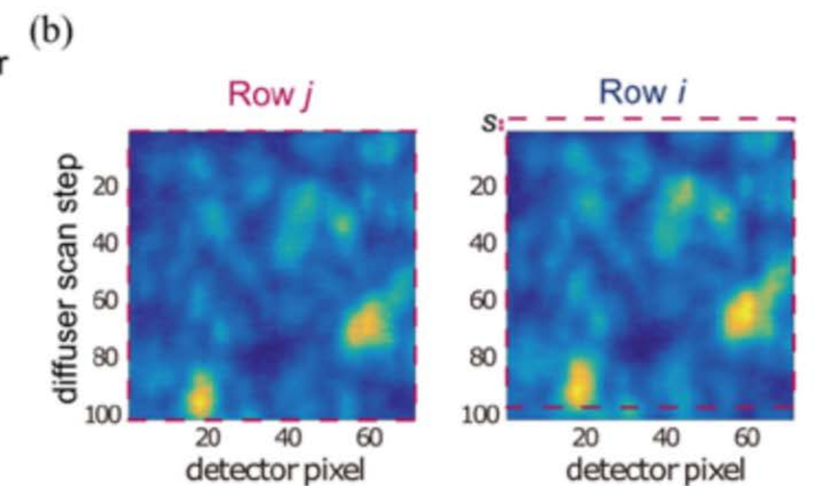
X-ray focusing optics test



H. Mimura *et al.*, Nat. Phys. **6**, (2010)

Speckle-based metrology





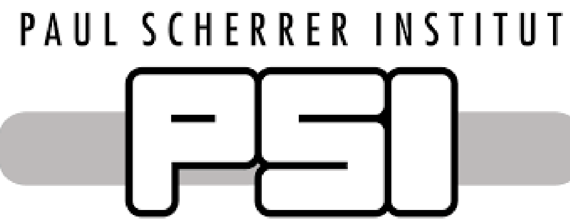
T. Zhou *et al.*, Opt. Express **26**, (2018)

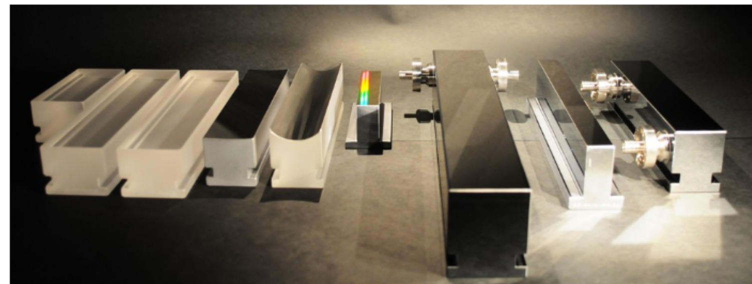
X-선 광학 장치 개발 및 평가 계획

	2024	2025	2026	2027	2028
X-ray Mirror 개발	PLS-II 노후 Mirror 개선 (2024–2025)		PLS-II Upgrade 빔라인 Mirror 개발 (2026–2028)		
	4GSR Mirror 개발 (2024 하반기–2026)				
			XFEL Mirror 개발 (2026–2028)		
광학장치 개발 및 평가	Mirror 및 광학장치 평가 빔라인 구축 (2024–2025 전반기)	빔 특성 평가 기법 모색 (2025 하반기–2026)		빔 특성 및 광학계 특성 평가 (2027–2028)	
	PLS-II 광학장치 성능 개선 및 평가 (2024 하반기–2028)				
		4GSR 국산화 광학장치 평가 (2025–2027)			
필요 인력 : 총 4인 필요	박사후연구원 +1 기술원 +1	선임연구원 +1	박사후연구원 +1		
필요 예산 : 총 26억 필요	11B 장치 구축 LTP 업그레이드 거울 가공 장치 : 총 6억 소요	백색광 간섭계 스티칭 시스템 벤치 / 세정 시스템 거울 기판 : 총 8억 소요	거울 가공 장치 거울 기판 11B 신규 장치 구축 : 총 6억 소요	AFM 장비 거울 기판 : 총 4억 소요	

참고 자료

광학실 및 테스트 빔라인 보유 해외 가속기 연구소 현황





OPTICS - X05DA and Metrology Laboratory

Beamline X05DA

The mission of the **Optics Test Beamline** at the bending magnet X05DA is optics and instrumentation related R & D, in-house research and training. The main performance parameters of the Si(111) cannel-cut monochromator with toroidal focusing mirror are summarized in the following table.

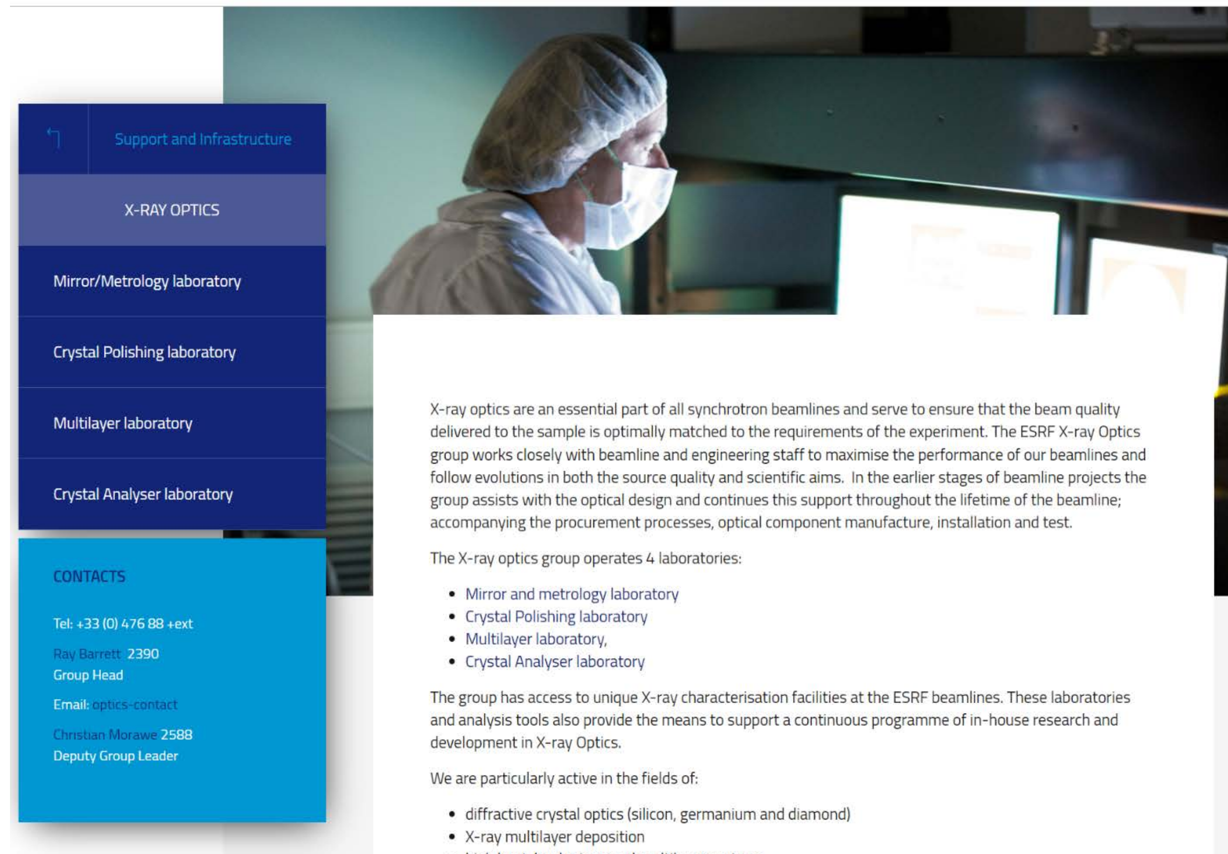
Energy range	5.5 - 22.5 keV
Flux at 10 keV	›1 x 10^{11} photons /sec /400 mA
Energy resolution	0.03%
Focused spot size	140 µm x 70 µm (h x v)

More information about the beamline in: U. Flechsig et al., **"The Optics Beamline at the Swiss Light Source"**, Nuclear Instruments and Methods A, **609** (2009), pp. 281-285, doi: **10.1016/j.nima.2009.07.092**.

Metrology Laboratory

The mission of the **Metrology Laboratory** in the class 10000 cleanroom WSLA/022 is quality measurement of X-ray optics. There are three main instruments: the Long Trace Profiler (LTP) for 1d figure measurements, the Zygo Verifire ATZ interferometer for 2d figure measurements and the Zygo NewView 5010 for roughness measurements.

X-RAY OPTICS



X-ray optics are an essential part of all synchrotron beamlines and serve to ensure that the beam quality delivered to the sample is optimally matched to the requirements of the experiment. The ESRF X-ray Optics group works closely with beamline and engineering staff to maximise the performance of our beamlines and follow evolutions in both the source quality and scientific aims. In the earlier stages of beamline projects the group assists with the optical design and continues this support throughout the lifetime of the beamline; accompanying the procurement processes, optical component manufacture, installation and test.

The X-ray optics group operates 4 laboratories:

- Mirror and metrology laboratory
- Crystal Polishing laboratory
- Multilayer laboratory,
- Crystal Analyser laboratory

The group has access to unique X-ray characterisation facilities at the ESRF beamlines. These laboratories and analysis tools also provide the means to support a continuous programme of in-house research and development in X-ray Optics.

We are particularly active in the fields of:

- diffractive crystal optics (silicon, germanium and diamond)
- X-ray multilayer deposition
- high heat-load mirror and multilayer systems

Science | Optics and Metrology

Optics and Metrology | Staff | Publications | B16

The successful exploitation of the intense, brilliant and coherent light from Diamond is strongly dependent on the quality and performance of beamline optics. The Optics and Metrology group provide expert support to Diamond beamlines in the design, procurement, acceptance testing and optimisation of all beamline optics.

To extend Diamond's capability and achieve world leading performance, the group is also actively involved in research and development in the field of X-ray optics and specialised optical systems. B16, Diamond's Test beamline, is also part of the Optics and Metrology group.

The main activities of the group are:

- Optics design and simulation of beamlines
- Specification and procurement of beamline optics
- Optical Metrology of x-ray optics
- B16 Test beamline
- At-wavelength (i.e. using x-rays) metrology of x-ray optics
- Precision metrology: high precision motion and vibration testing of beamline components
- Support beamline scientists in commissioning and optimisation of beamline optics (bimorph mirrors, bendable mirrors, monochromators, CRLs ...)
- Development of micro- / nano- focusing optics (refractive, reflective)
- Polarisation characterisation of soft x-ray beamlines
- Development of wavefront propagation codes for partially-coherent synchrotron radiation
- Research and development in x-ray optics

Instruments

B16 Test Beamline

This is a flexible and versatile beamline for testing new developments in optics and detector technology and for trialling new experimental techniques. The beamline provides both white and monochromatic X-rays in several operational modes.

More information

Energy: 4 - 45 keV

Imaging | X-ray Diffraction | Microscopy | Topography | XRR: X-ray Reflectivity

포항가속기연구소 국내자문위원회

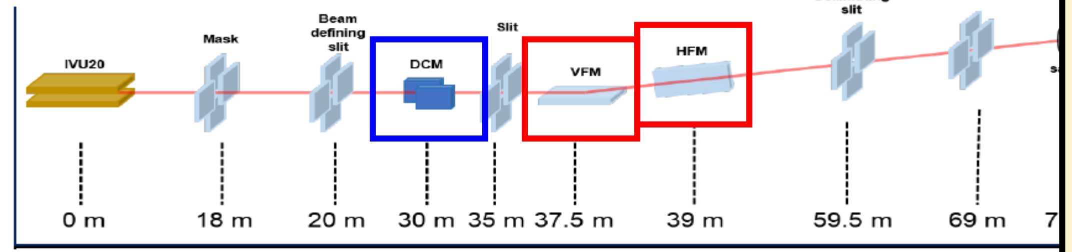
Beamlines of 4GSR

Diffractive Optics
DCM (PGM) : 11
Zone plate : 1

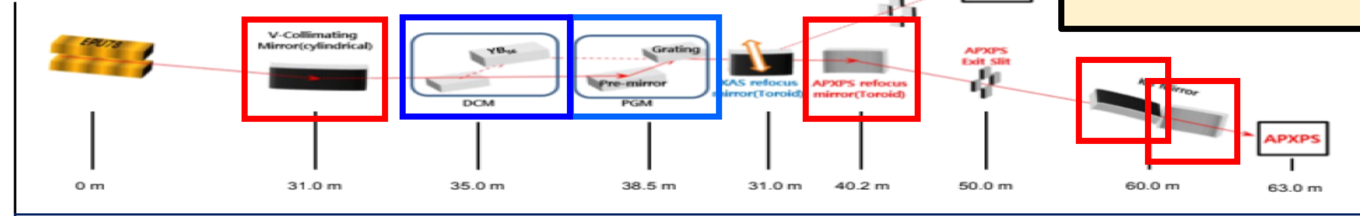
Refractive Optics
CRL : 1

Reflective Optics
Mirror : 31

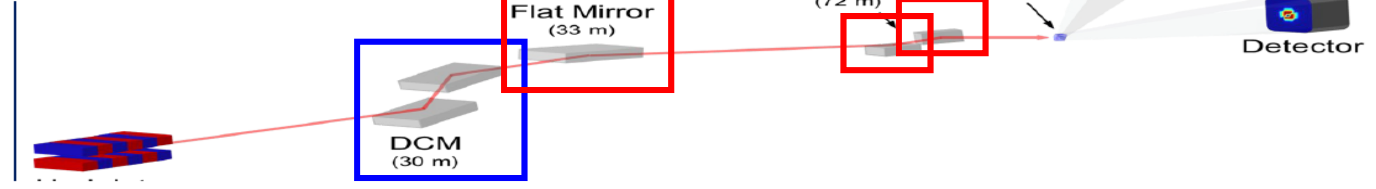
BioPhama-BioSAXS



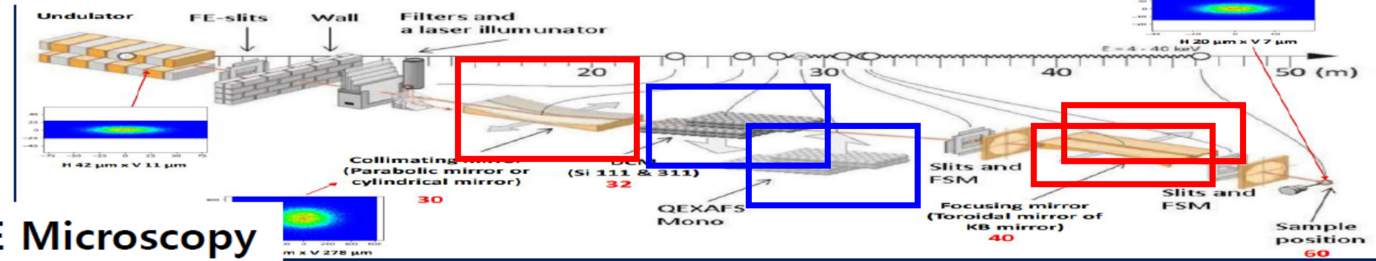
Soft X-ray NanoProbe



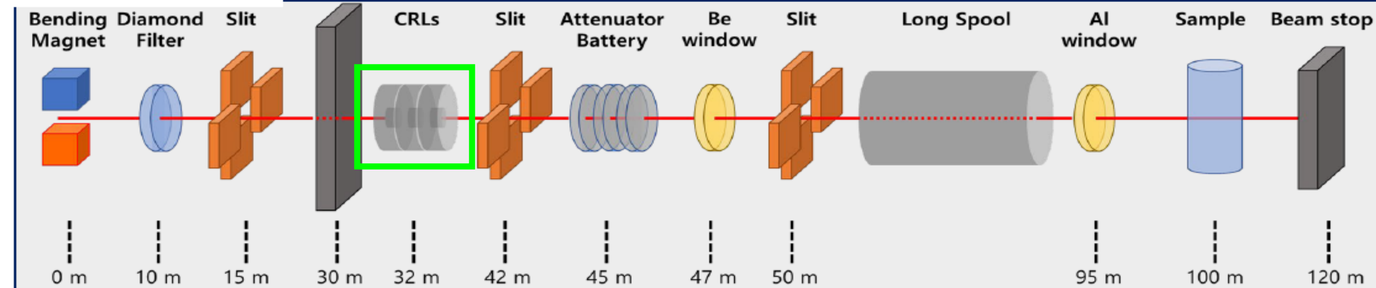
CoXRD(CDI)



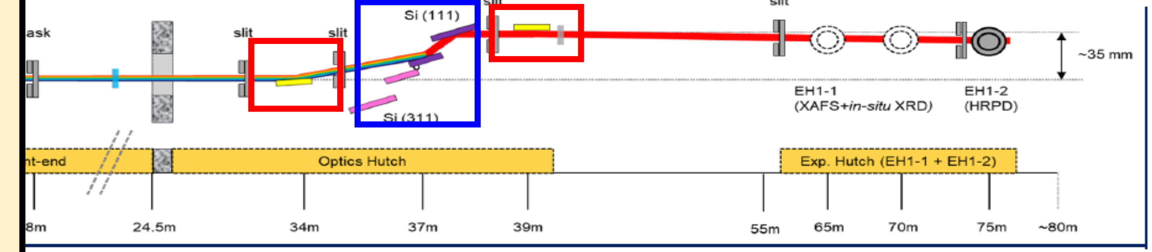
RealTimeXAFS



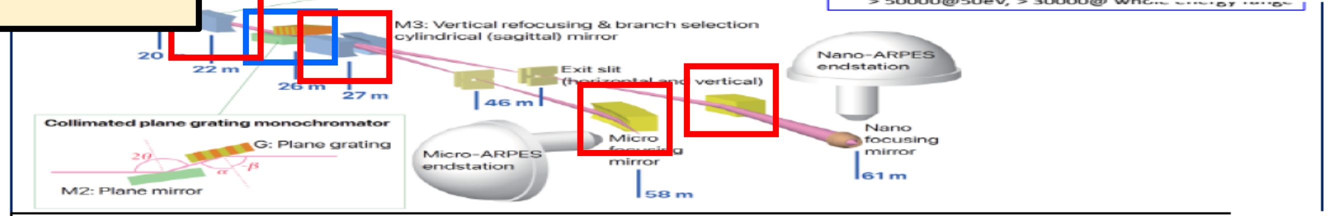
HE Microscopy



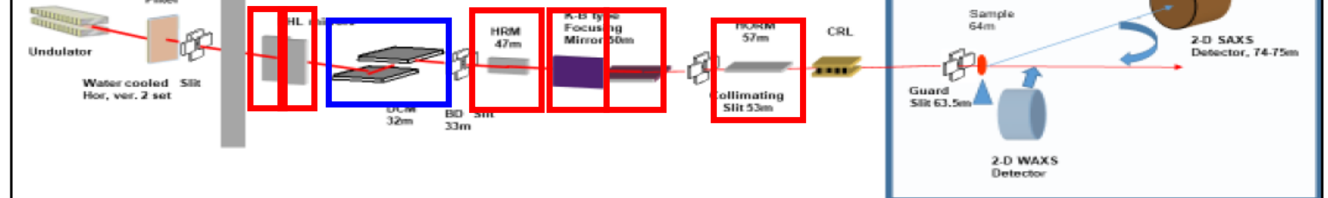
Mat. Structure Anal.



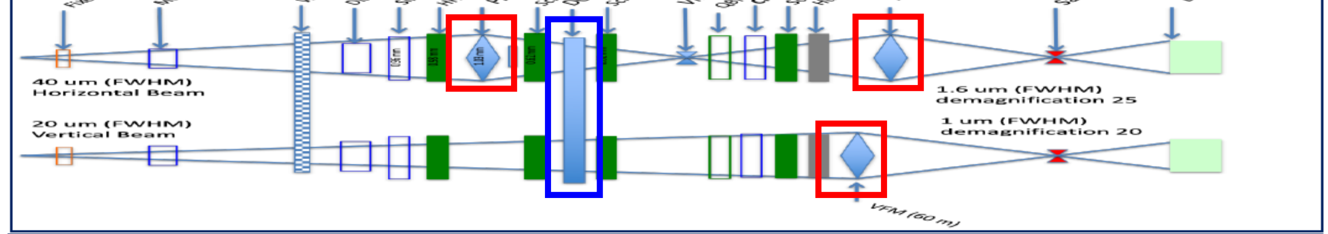
NanoARPES



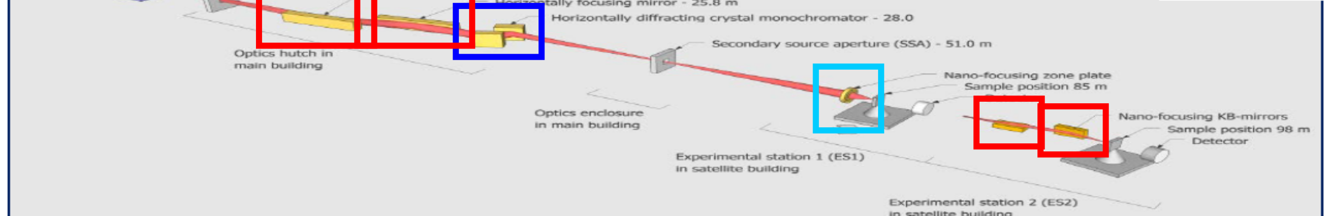
CoSAXS



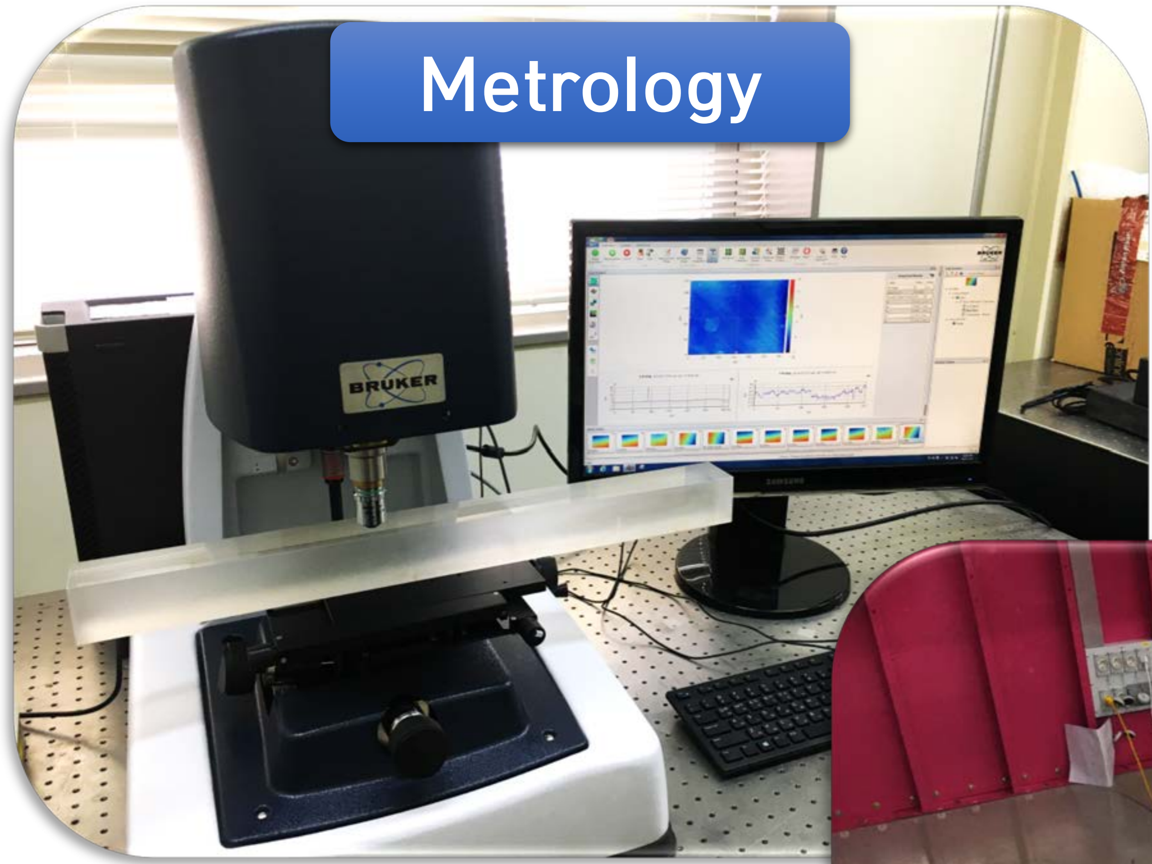
NanoMX

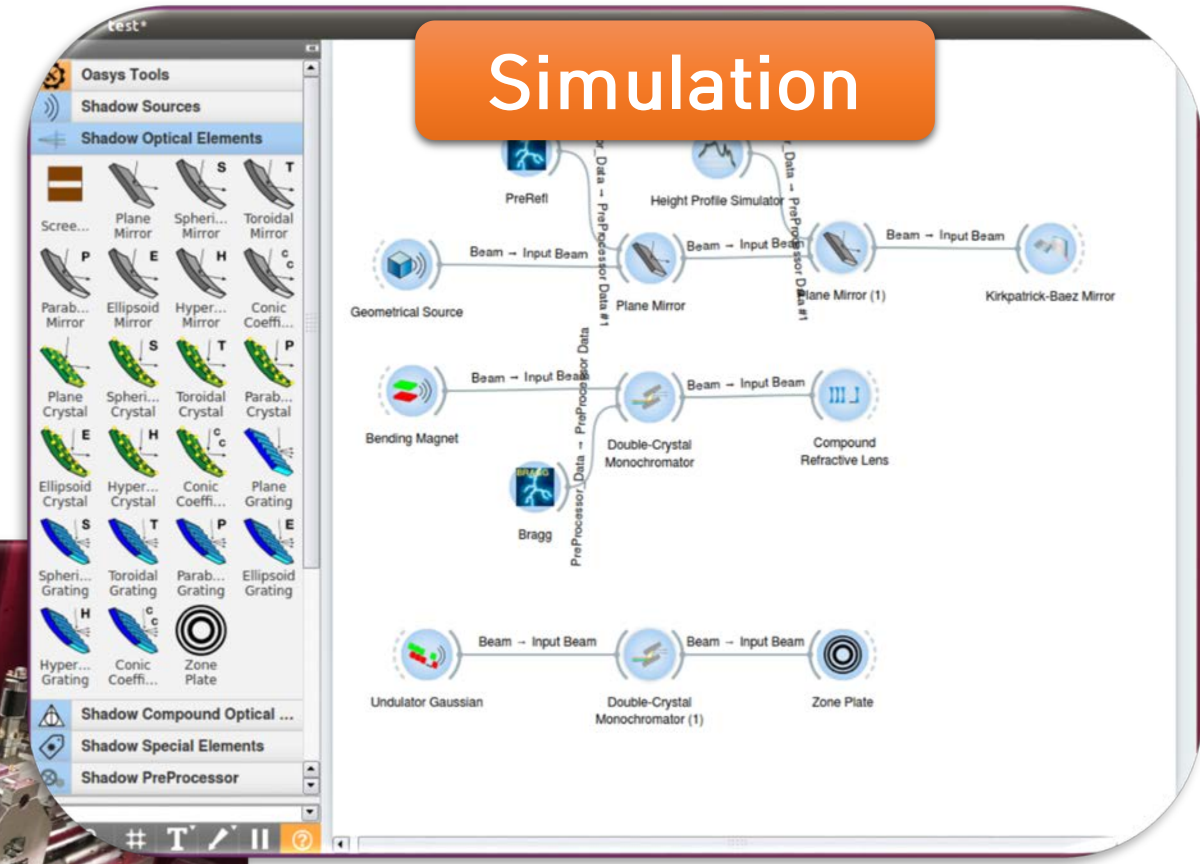


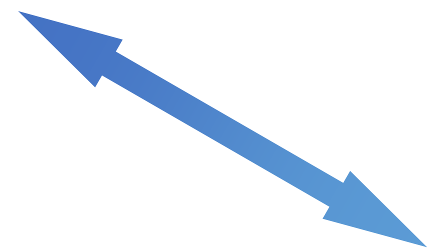
NanoProbe

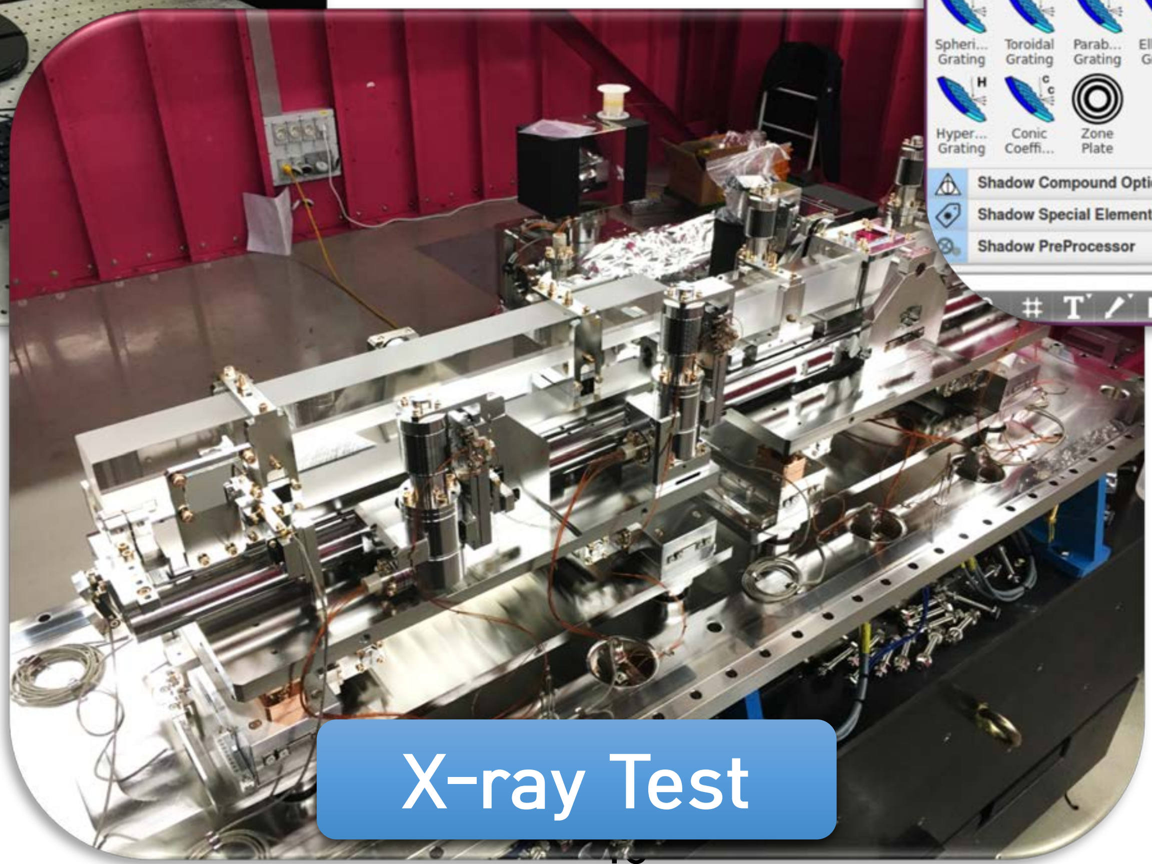


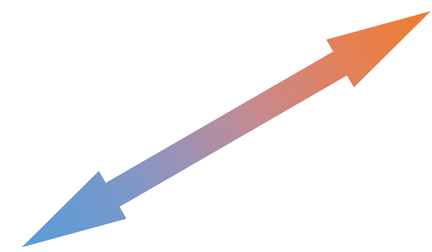
X-ray Optics Lab for Beamline Support



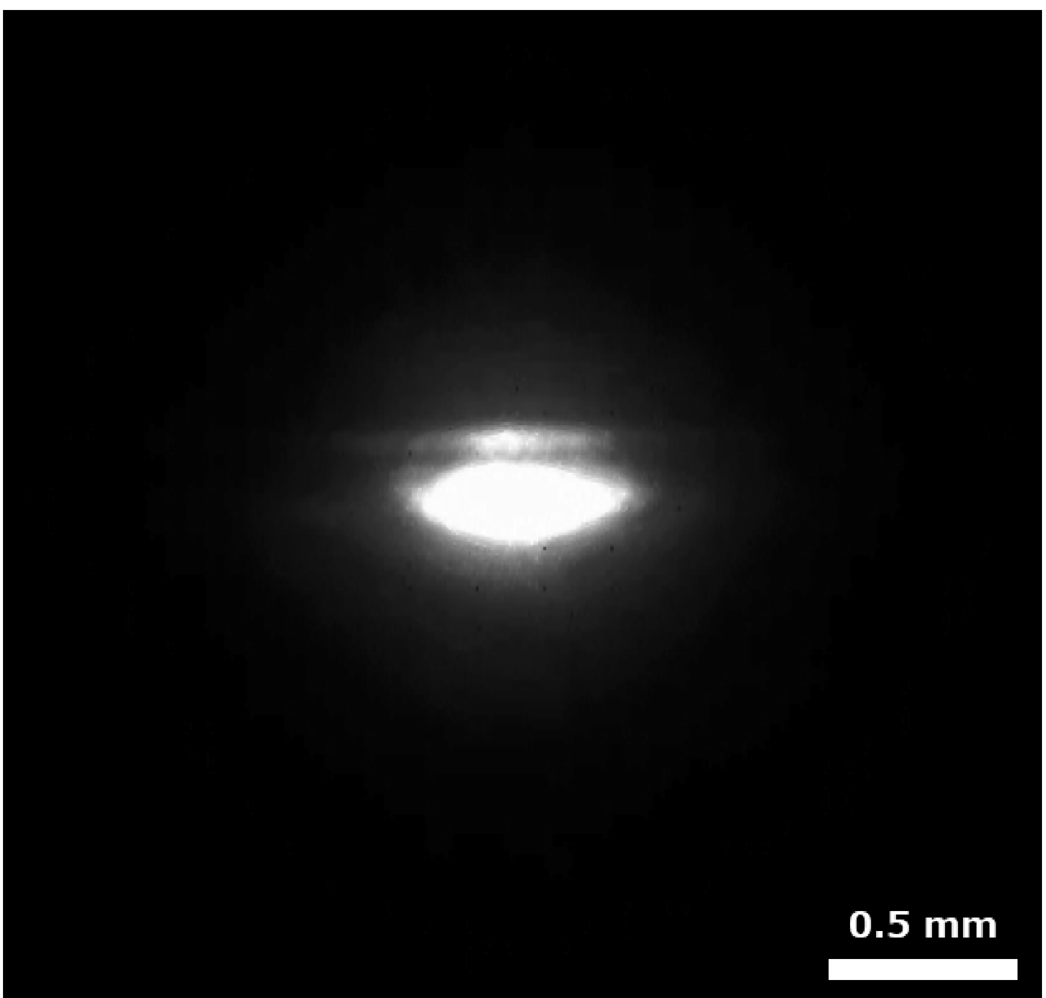






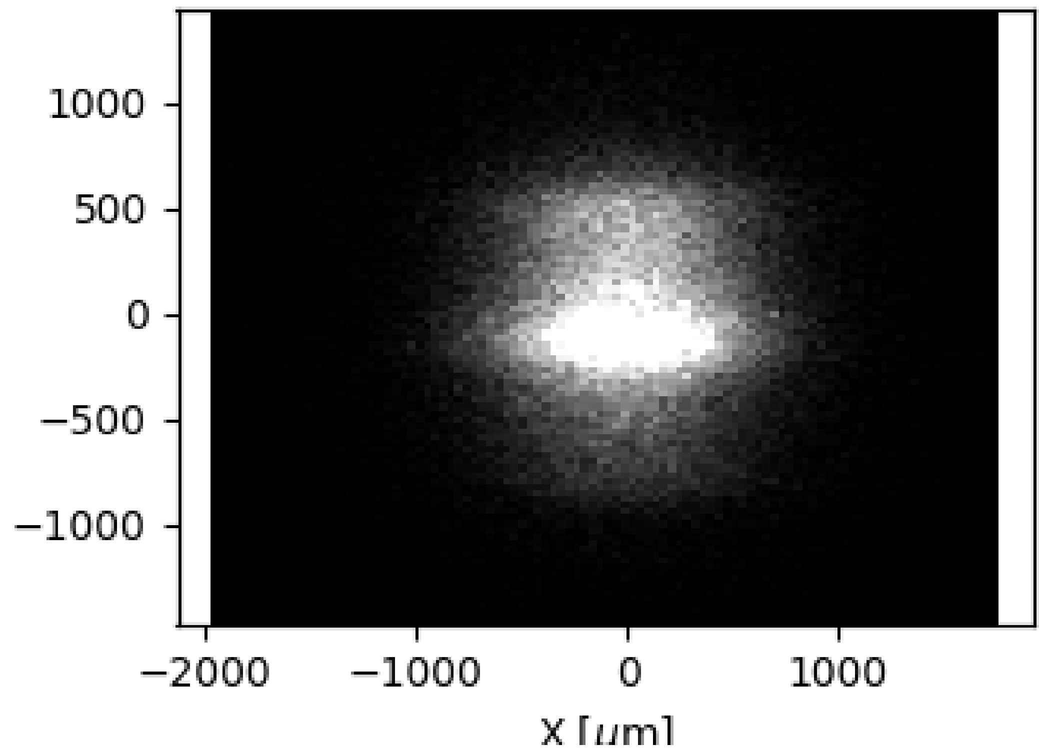


Wavefront Improvement of PAL-XFEL

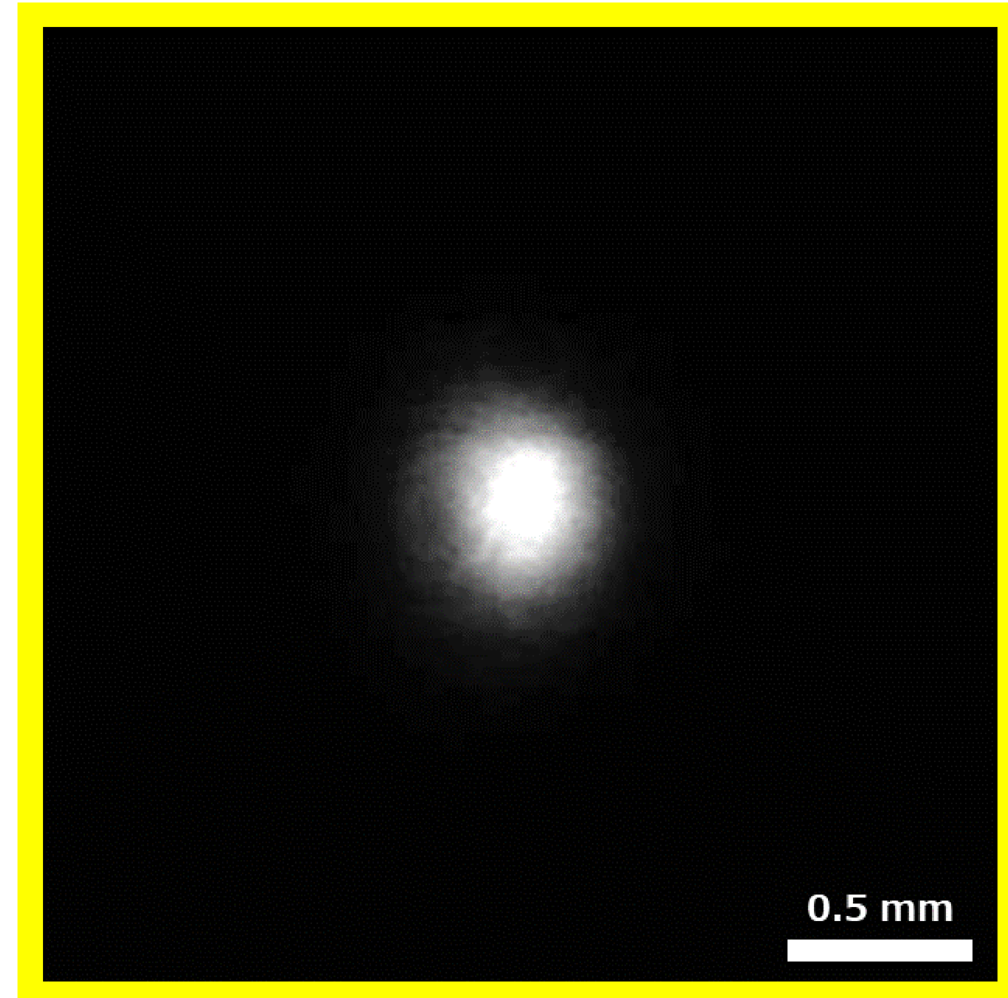


Date: 2017.04.24
Photon energy: 9.9 keV
Position: EH2 Girder3
Distance: ~60 m (from M1)

[Simulated data]



Source size: ~50 μm
Divergence: ~5 μrad
Shape error: sinusoidal type
Wavelength: 150 mm
Amplitude: 4 nm



Date: 2022.04.08
Photon energy: 9.0 keV
Position: EH2 Girder3
Distance: ~60 m (from M1)

Types of X-ray Mirrors - Shape

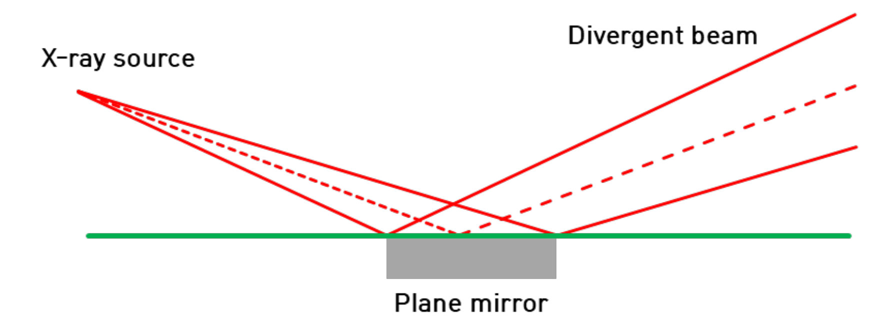
0D	**Plane Mirror** (Flat mirror)				
1D	**Cylindrical Mirror** (Cylinder)		**Parabolic Mirror** (Parabola)	**Hyperbolic Mirror** (Hyperbola)	**Elliptical Mirror** (Ellipse)
2D	**Spherical Mirror** (Sphere)	**Toroidal Mirror** (Toroid)	**Paraboloidal Mirror** (Paraboloid)	**Hyperboloidal Mirror** (Hyperboloid)	**Ellipsoidal Mirror (Spheroidal)** (Ellipsoid)

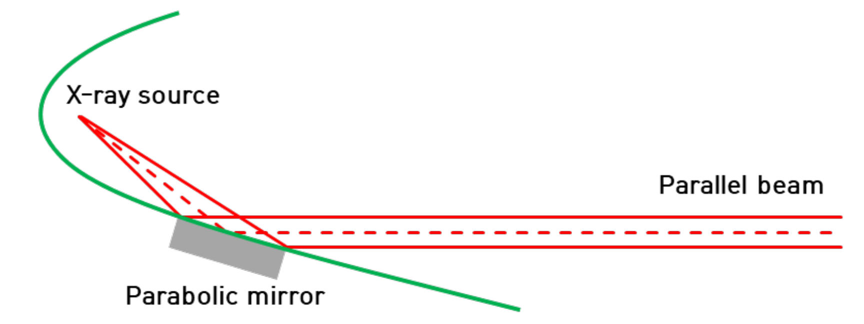
1D (tangential cylinder)

0D

1D (sagittal cylinder)

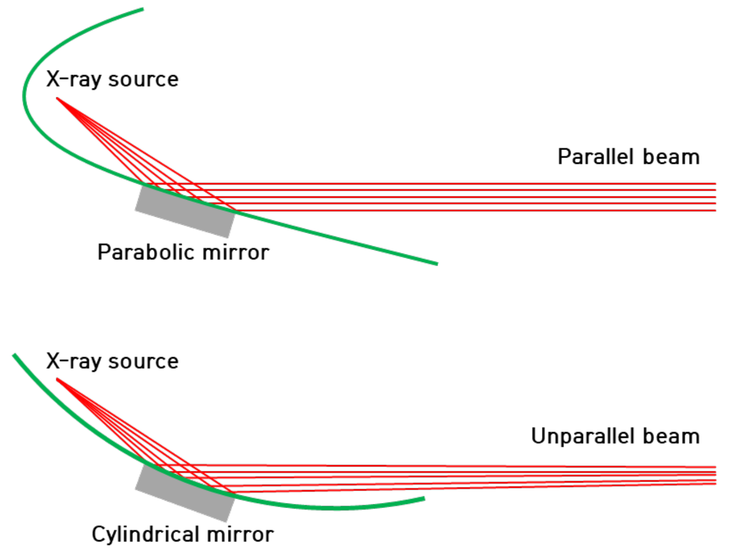
2D



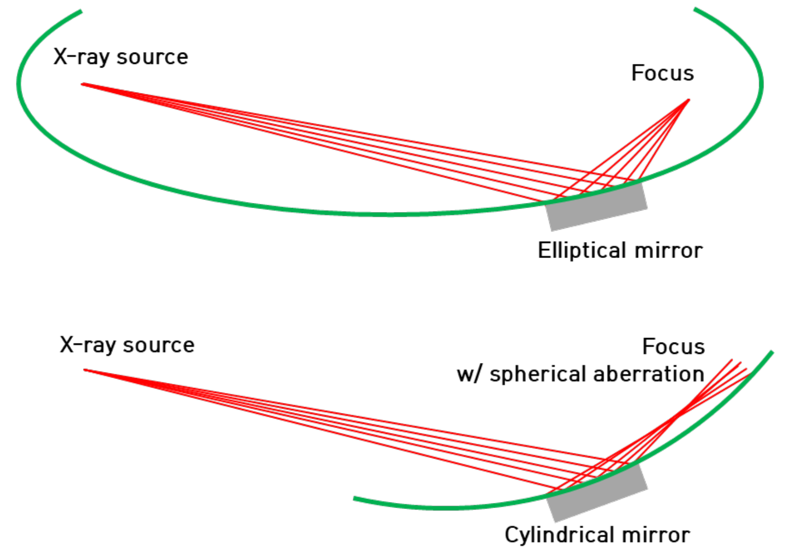


Types of X-ray Mirrors - Purpose

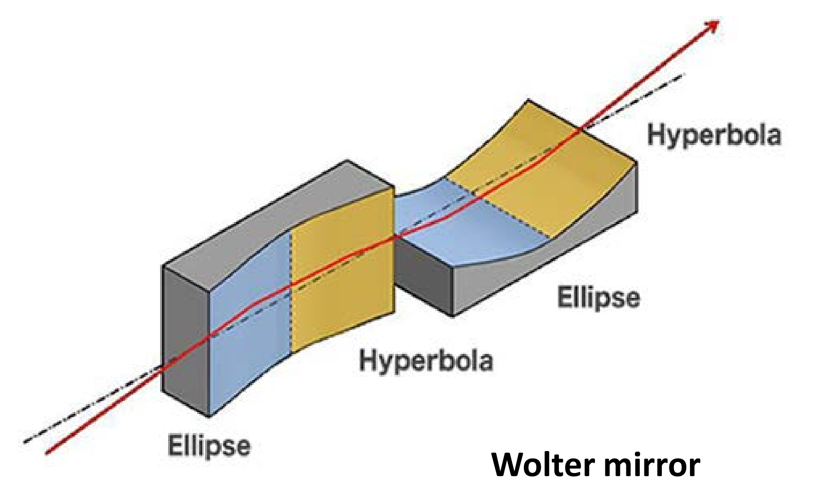
Collimating mirror



Focusing mirror **(Demagnification optics)**

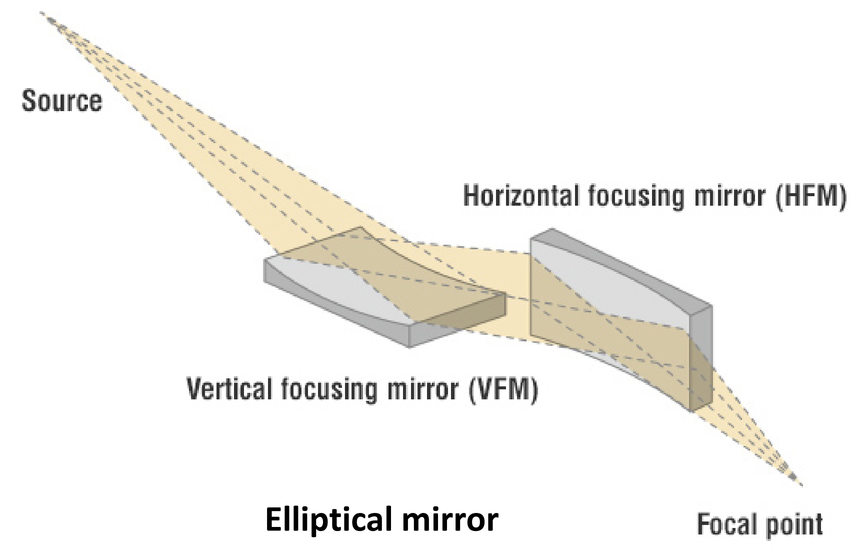


Imaging mirror **(Magnification optics)**



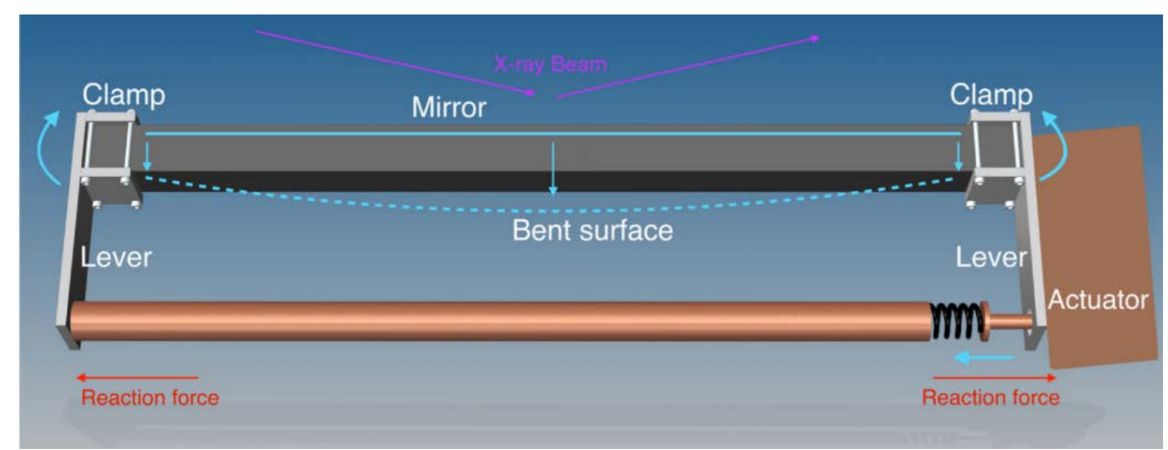
Wolter mirror

- KB mirror (KB geometry)



Elliptical mirror

- Bendable mirror (bending mirror)



- Deformable mirror (bimorph mirror)