Commissioning Status of EUV Accelerator

- EUV synchrotron and metrology facilities

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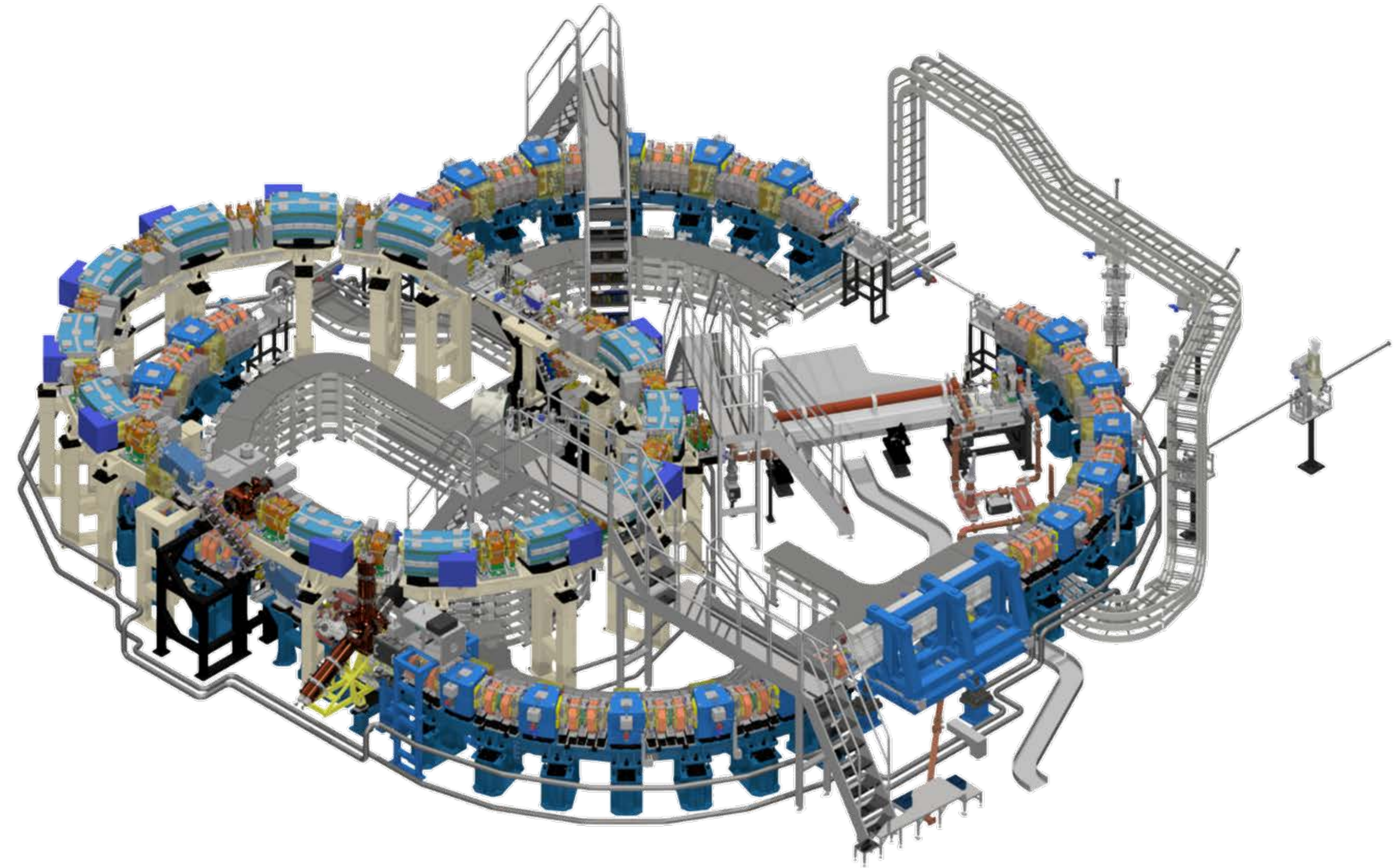
December 14, 2023

Project Overview

❖ **PAL-EUV is a new Low Energy Synchrotron Light Source, funded from Korean Government**

- **Provide a synchrotron radiation at EUV range**
- **Application mainly for semiconductor R&D**
- **Construction project from 2020.2 to 2023.4 (39 months)**



❖ **Table of contents**

- PAL-EUV synchrotron
- PAL-EUV synchrotron commissioning status
- EUV metrology and inspection applications

EUV Lithography

Photolithography is a critical technology in semiconductor scale down

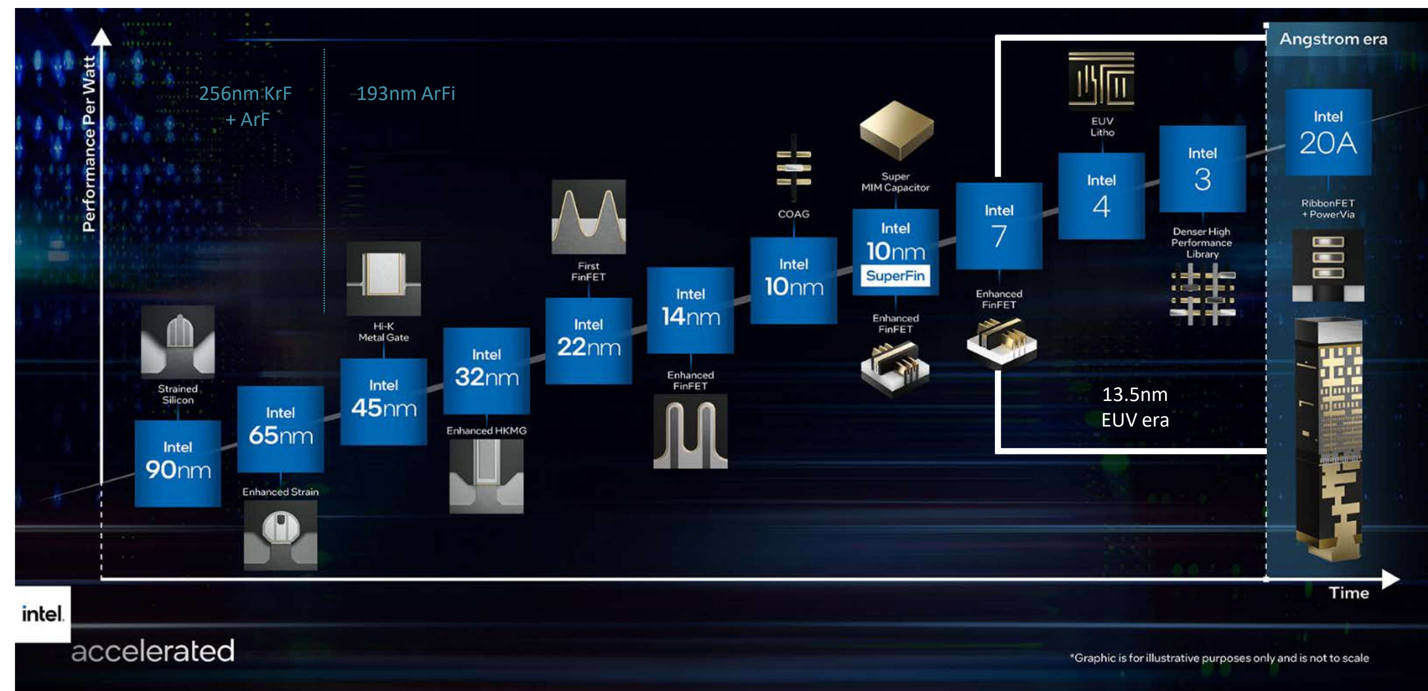
EUVL involves transferring designed circuit patterns from a mask onto a wafer, enabling the replication of IC device for semiconductor

Moore's Law (Why EUV Lithography)

Extreme Ultraviolet Lithography (EUV), utilizing a streamlined nanolithography process, enables precise implementation of nano-scale patterns

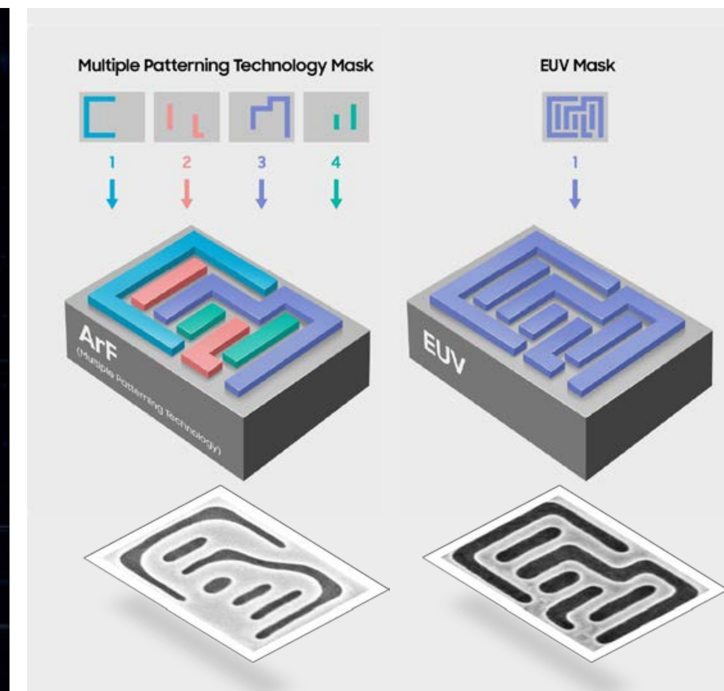
Operating at a 13.5nm wavelength with 92eV energy, EUV exhibits a unique property of universal absorption by all materials on Earth

With its wavelength being 14 times shorter than conventional Deep Ultraviolet (DUV) processes, EUV presents substantial advantages for device fabrication



Intel process technology roadmap

source: Intel



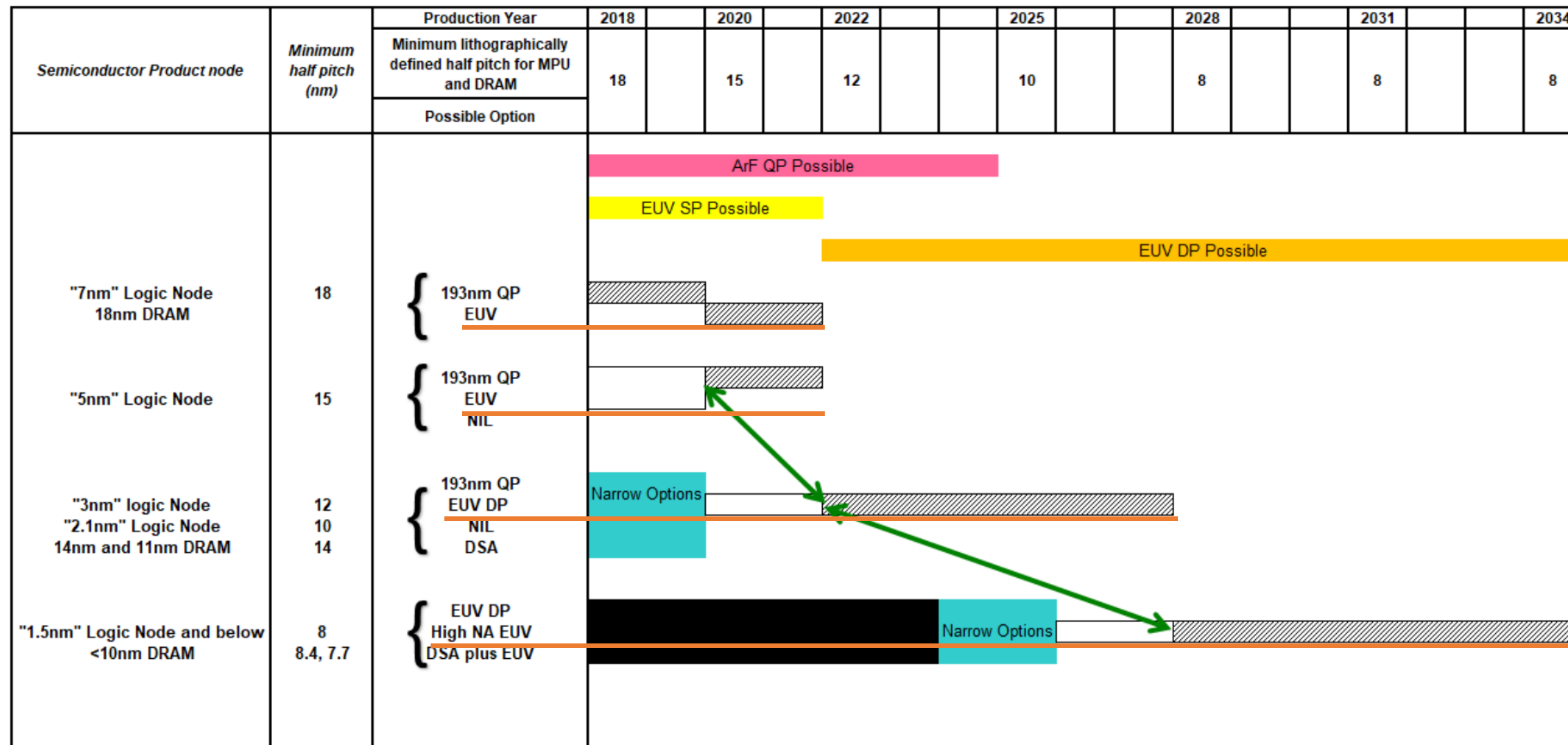
source: SAMSUNG

POHANG ACCELERATOR LABORATORY

EUV Lithography

EUV Lithography is the current and future solution for semiconductor patterning

PAL-EUV is dedicated infrastructure for the EUV materials and process research



INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS (2020 EDITION LITHOGRAPHY)

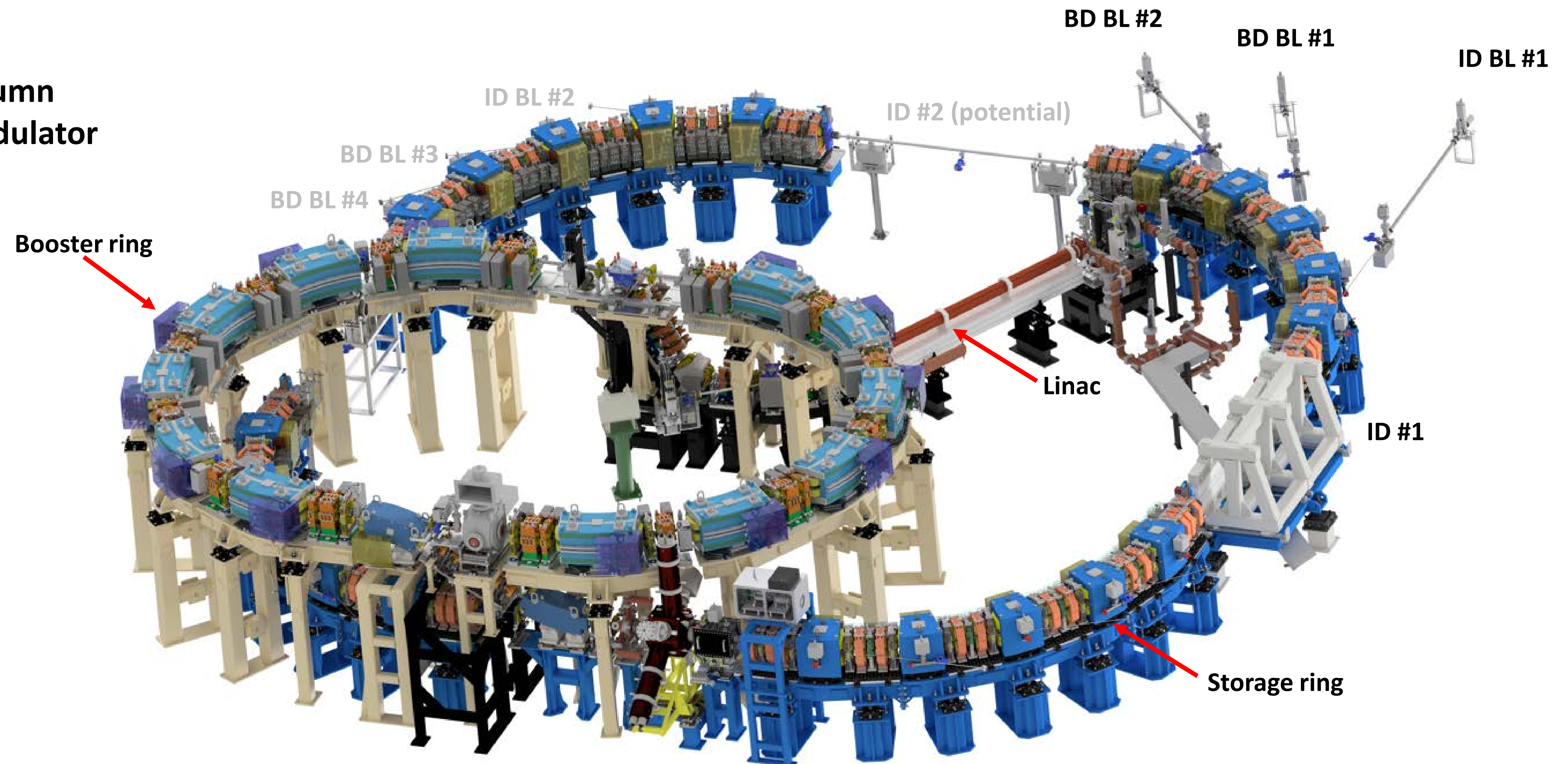
PAL aerial view

PAL-EUV Accelerator

Injector Linac (to 20 MeV)
- Photocathode gun + 3 m accelerator column
- 10 MW S-band klystron + solid state modulator

Booster Ring (from 20 to 400 MeV)
- 2 straights for injection/extraction
- 500 MHz PLS cavity (reuse)

Storage Ring (400 MeV)
- 4 straights for injection and three IDs
- 500 MHz RI cavity
- 1500 MHz harmonic cavity



Injector Linac

❖ **20 MeV Linac of the simplified PAL-XFEL injector design**

- Beam energy : 20 MeV

- Bunch charge : 10 ~ 100 pC

- Transverse normalized emittance : 0.5 mm mrad

- 0.5 Hz repetition rate (120 Hz design at PAL-XFEL)

❖ **Components**

- **Photocathode Laser**

  (frequency: 2856 MHz, 1.46 cell standing-wave)

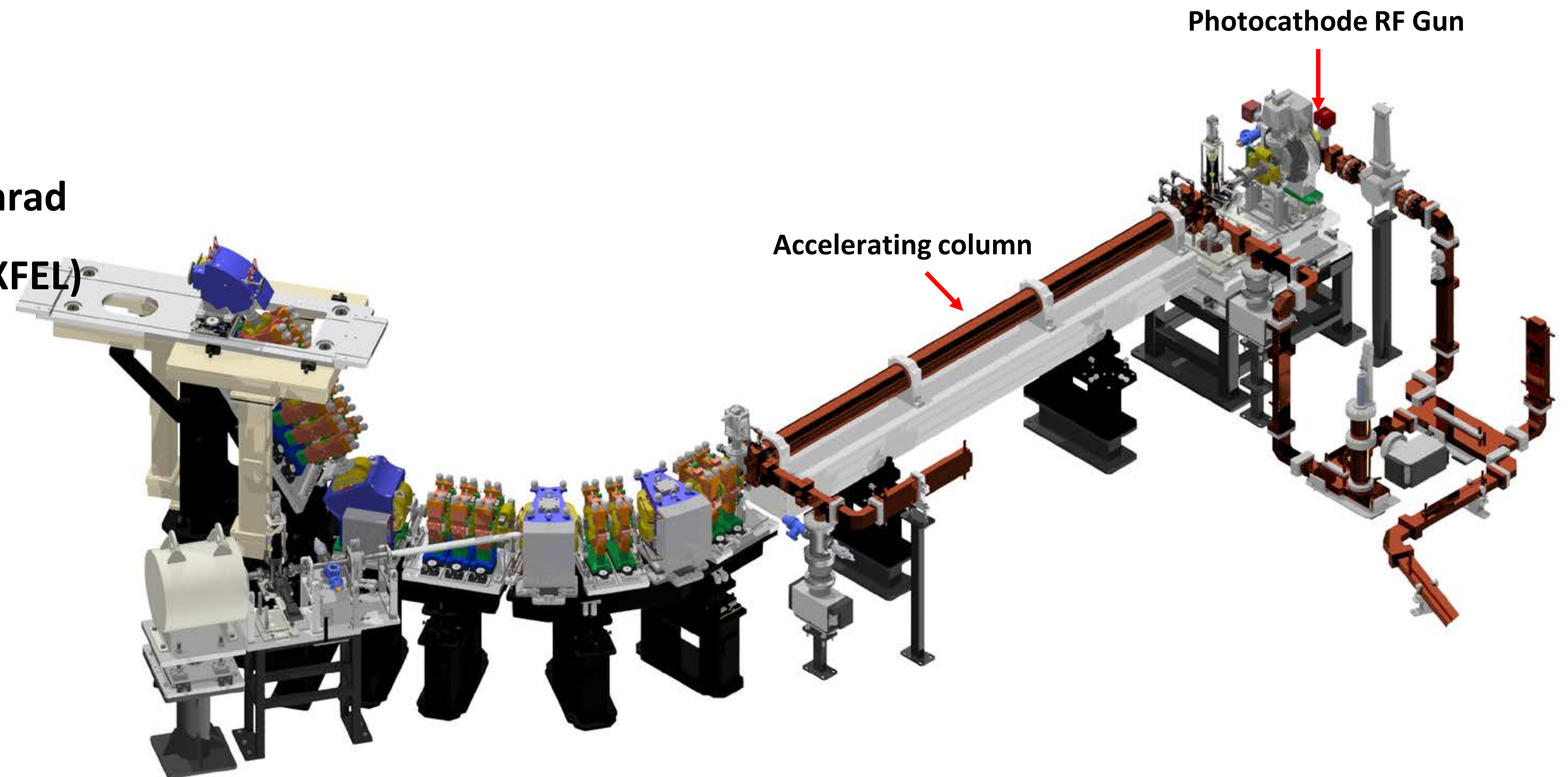
- **Photocathode Laser**

  (Industry type amplifier system, 150 μJ at 257 nm,

  5 ps FWHM pulse length)

- **Accelerating column**

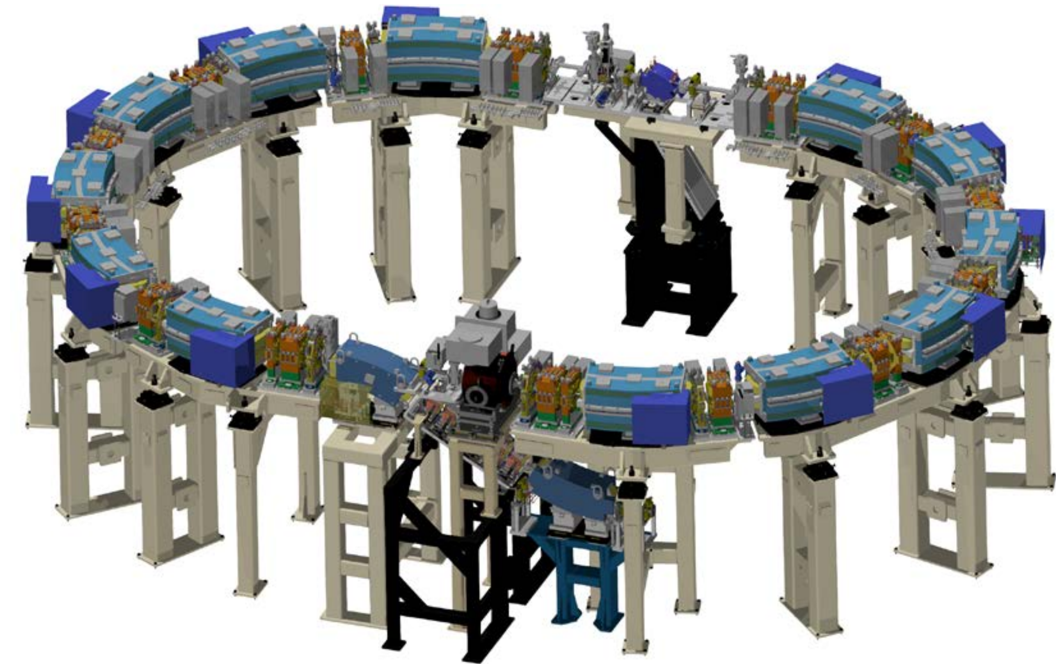
  (frequency: 2856 MHz, 3 m constant-gradient traveling wave)

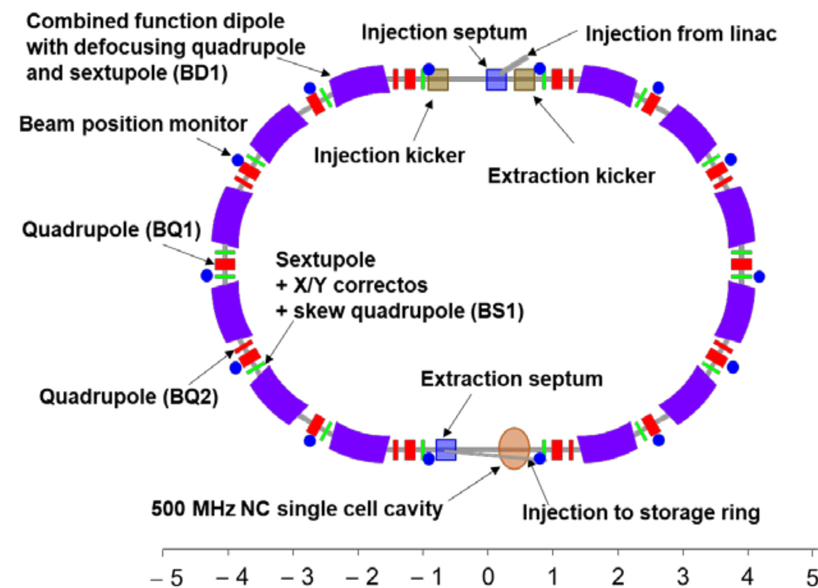


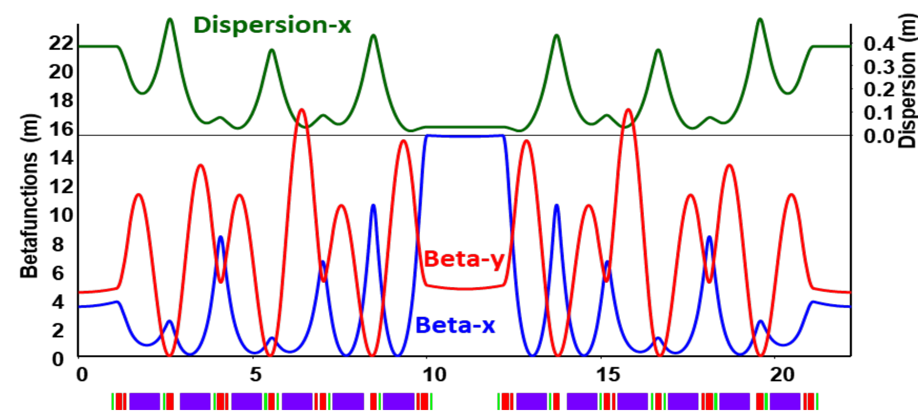
Booster Ring

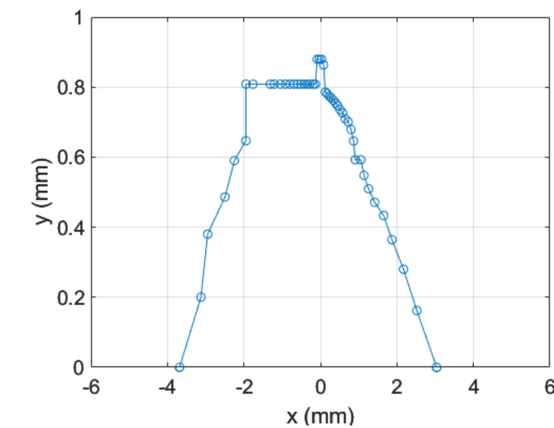
❖ **Specifications**

- **Beam energy : 400 MeV (20~400 MeV E ramping)**
- **Circumference : 22.2 m (500 MHz, 37 harmonic)**
- **Emittance : 4.2 nm Horizontal emittance**
- **Repetition rate : 0.5 Hz**









Booster ring dynamic aperture
Calculation (2023.10)

Booster Ring

❖ Specifications

- Beam energy : 400 MeV (20~400 MeV E ramping)
- Circumference : 22.2 m (500 MHz, 37 harmonic)
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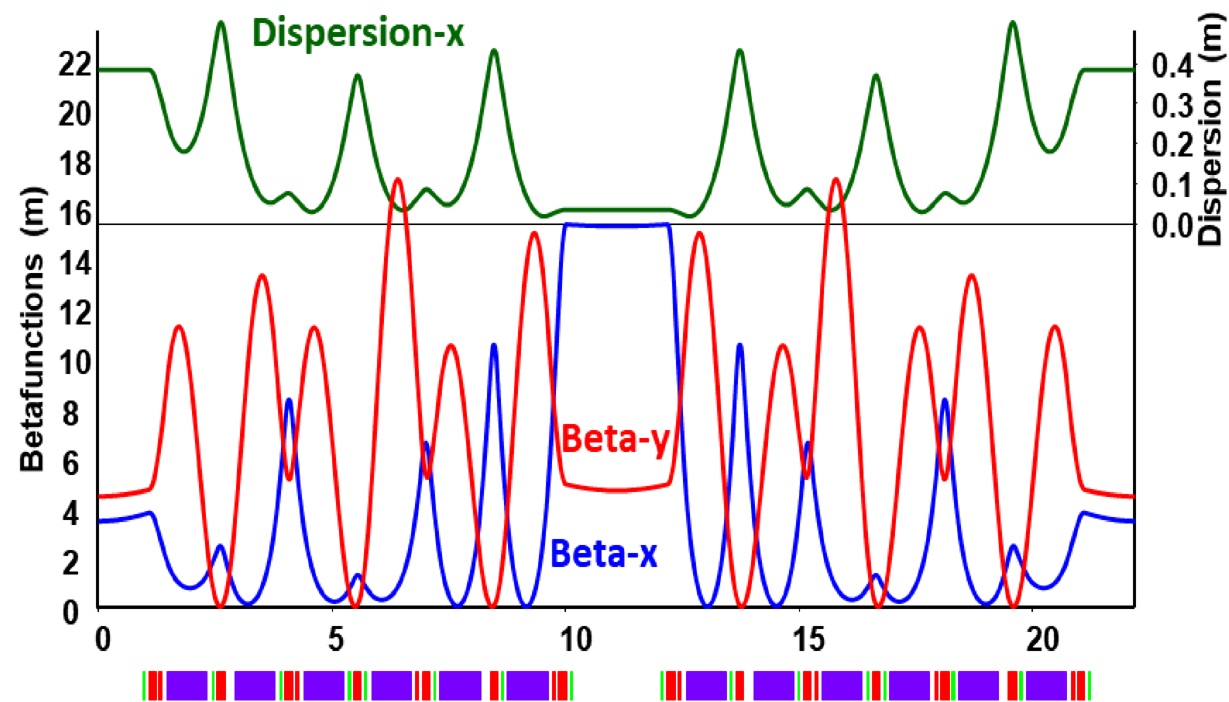
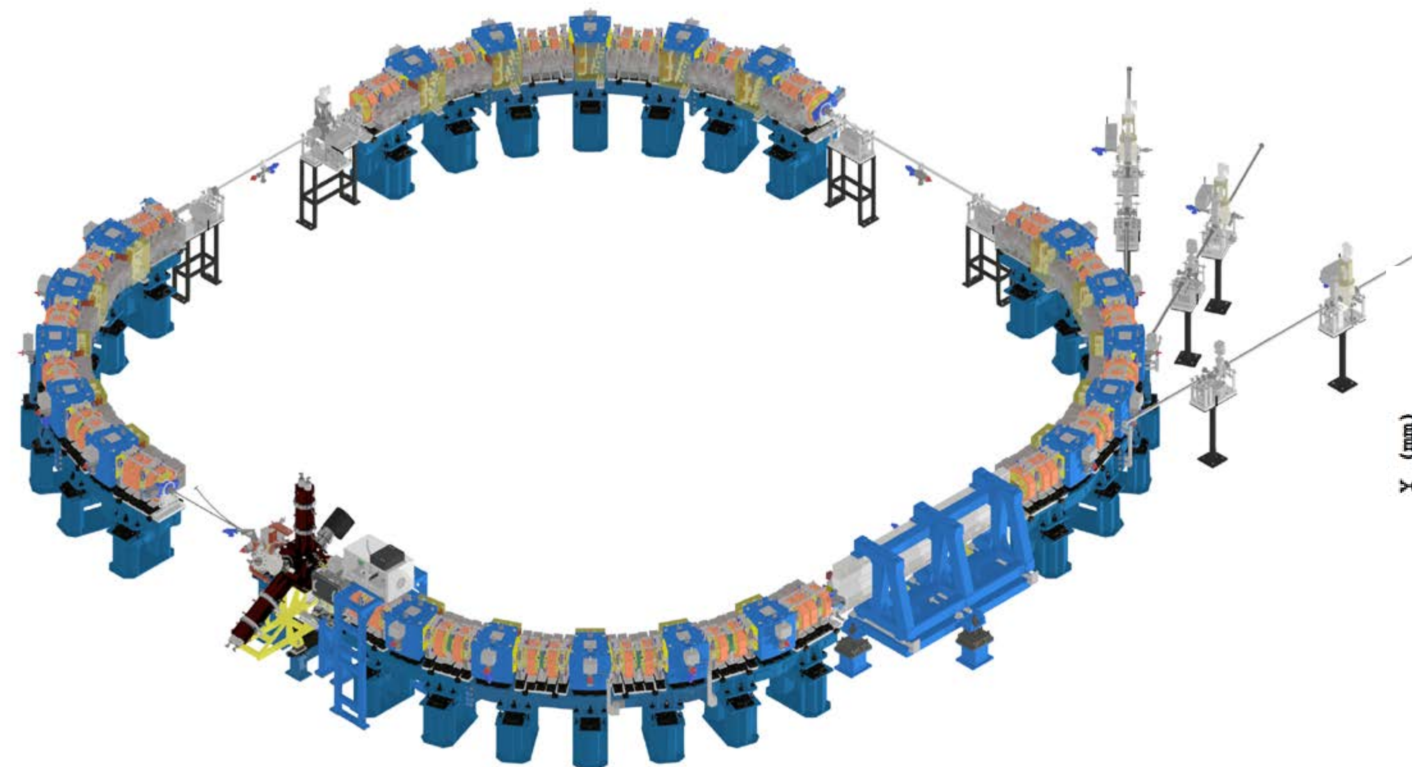
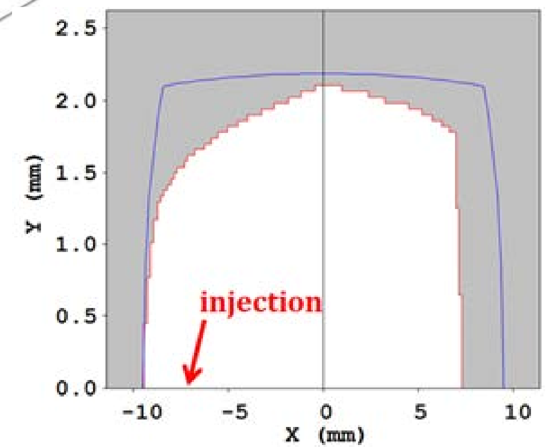


Parameters	Value at 400 MeV
Circumference [m]	22.2
Harmonic number	37
Emittance X [nm]	5.85
Tune X	4.431
Tune Y	3.321
Chromaticity X, natural	-11.49
Chromaticity Y, natural	-18.55
Chromaticity X	0.94
Chromaticity Y	0.99
Alpha	0.0326
dE/turn [keV]	1.4
Energy spread (E-4)	4.1
Damping time X (rms)	20.0
Damping time Y (rms)	42.5
Damping time S (rms)	48.7

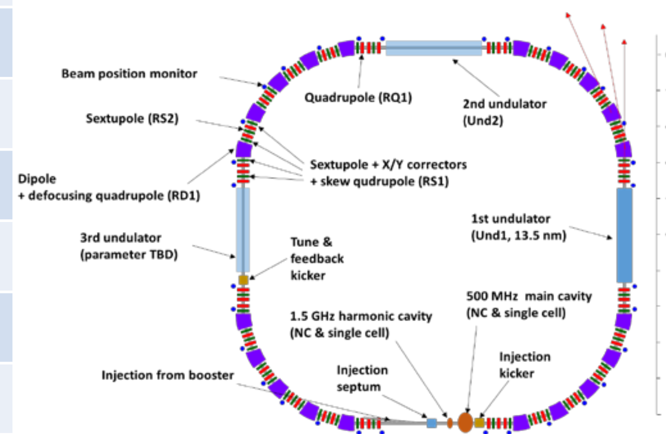
Storage Ring Design Parameters

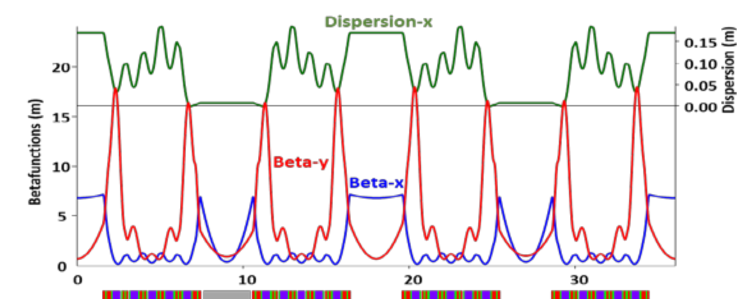
Parameters	Values at 400 MeV
Circumference	36 m
Harmonic number	60
Beam current	140 mA
Emittance_X (nm)	1.16
Tune_X	7.153
Tune_Y	3.044
Chromaticity X, natural	-10.66
Chromaticity Y, natural	-16.71
Chromaticity X, corrected	1.0
Chromaticity Y, corrected	1.0
Alpha	0.0104
dE/turn (keV)	1.7
Energy spread (E-4)	3.82
Damping time X (ms)	30.7
Damping time Y (ms)	56.7
Damping time S (ms)	49.0

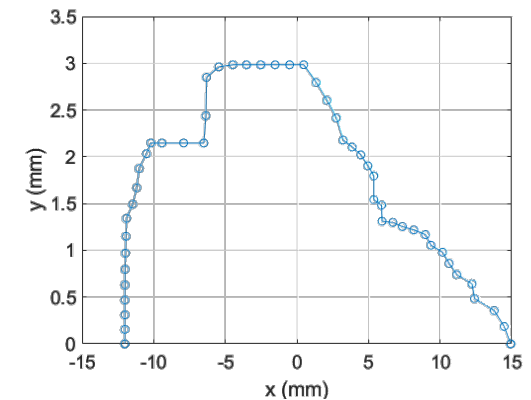




Storage ring dynamic aperture (2020)



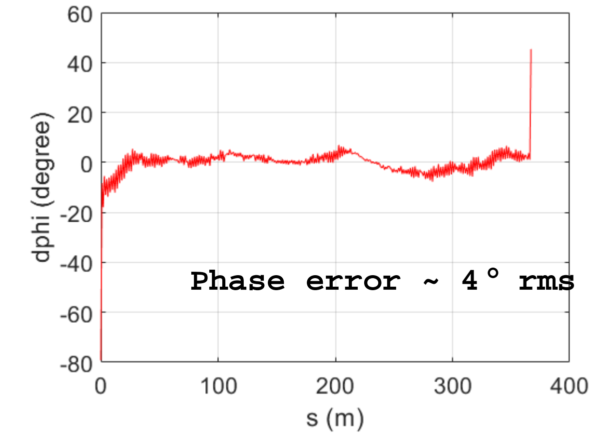


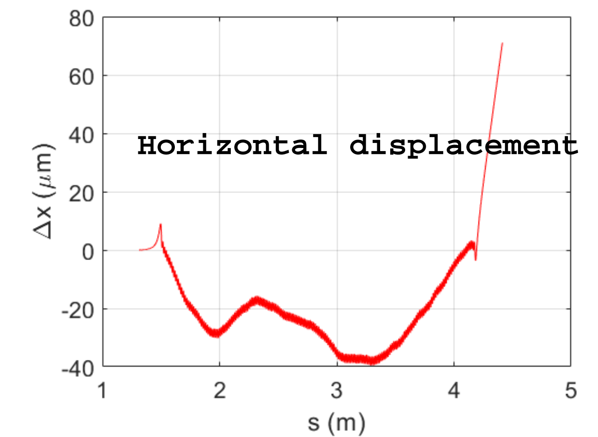


Storage ring dynamic aperture (2023.11)

Undulator

Hybrid, out-vacuum undulator
Period length : 14.6 mm
Total magnetic length : 2.7 m, 183(+2) periods
Field center height : 1.2 m
Magnetic gap : 8.8 mm
K-value : 0.502
Peak field : 0.368 T
Phase error < 10 °
(only fundamental wavelength used)
Magnetic material : NdFeB 47HN
Pole material : Vanadium Permendur



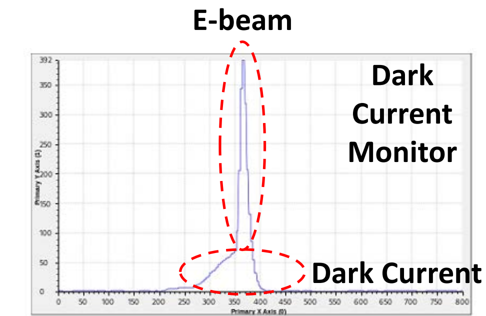


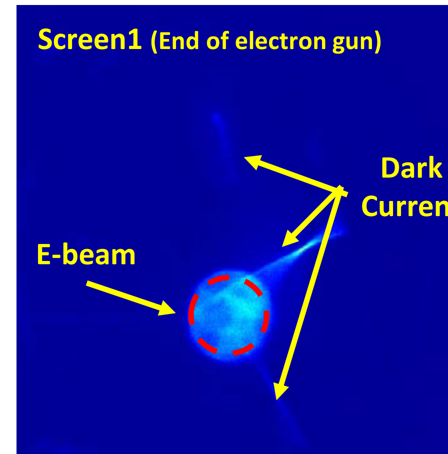
PAL-EUV Accelerator Installation (2022.5 - 11)

E-beam Generation / Transport

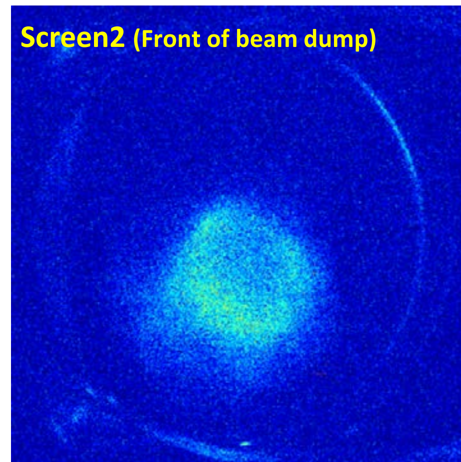
❖ **2023. February**

- Repetition rate: 0.5 Hz
- Charge: Max 100 pC
- Energy: 3 MeV @ end of E-gun
  20 MeV @ end of Linac





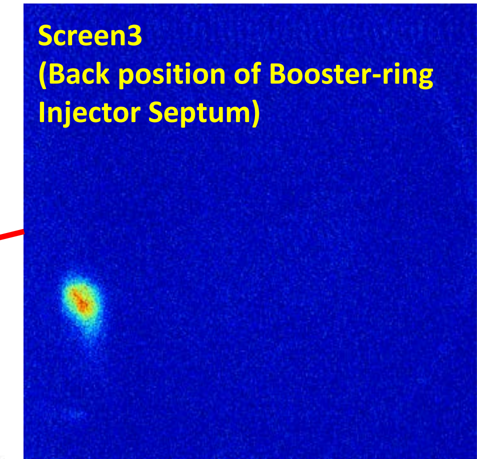
e-beam



Booster-ring Injection / DC Operation

❖ **2023. February ~ March**

- Repetition rate: 0.5 Hz
- Energy: 20 MeV



Booster-ring Injection kicker

Booster-ring Injection Septum

BPM BC1-5

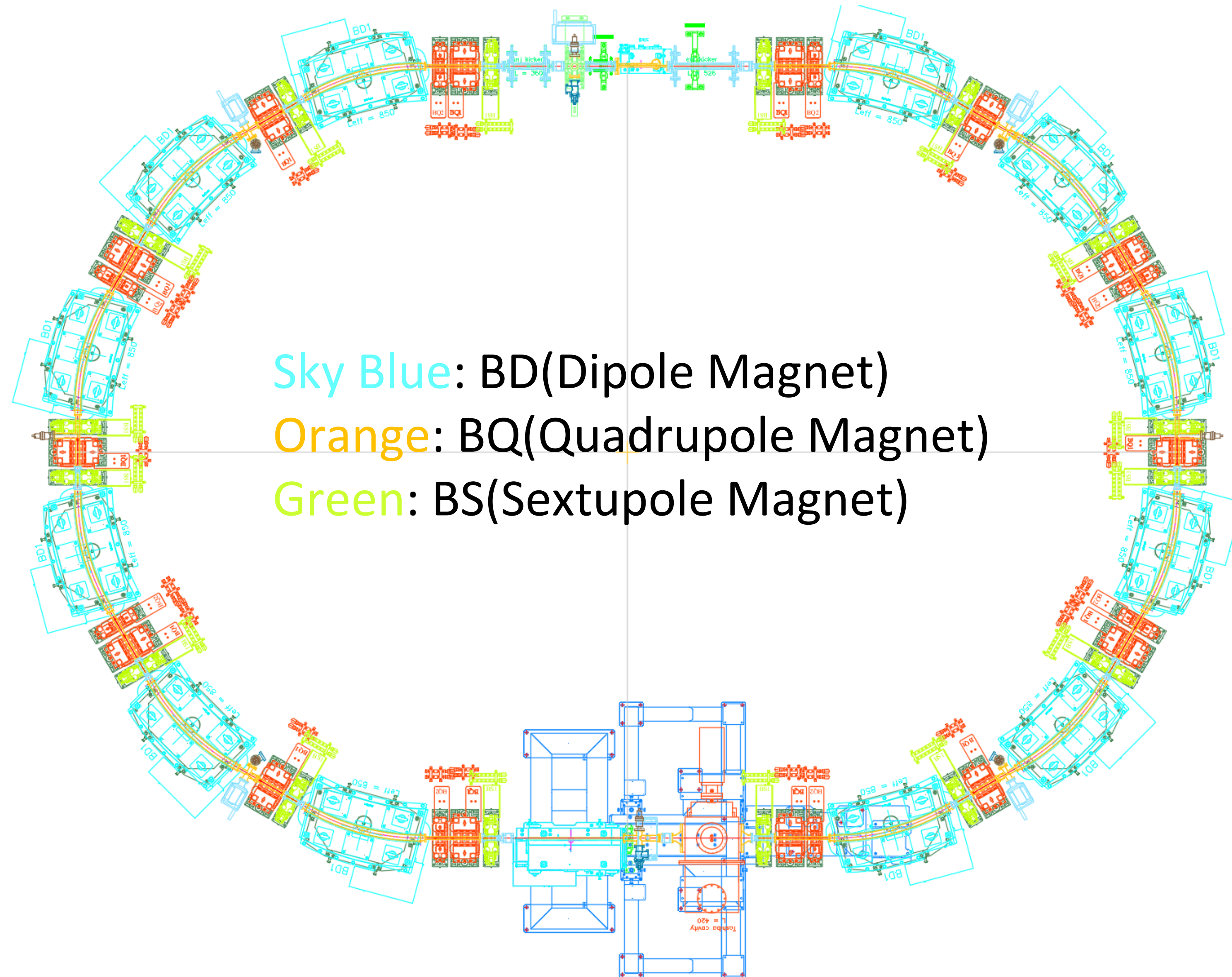
e-beam

BPM BC1-5 Oscilloscope signal

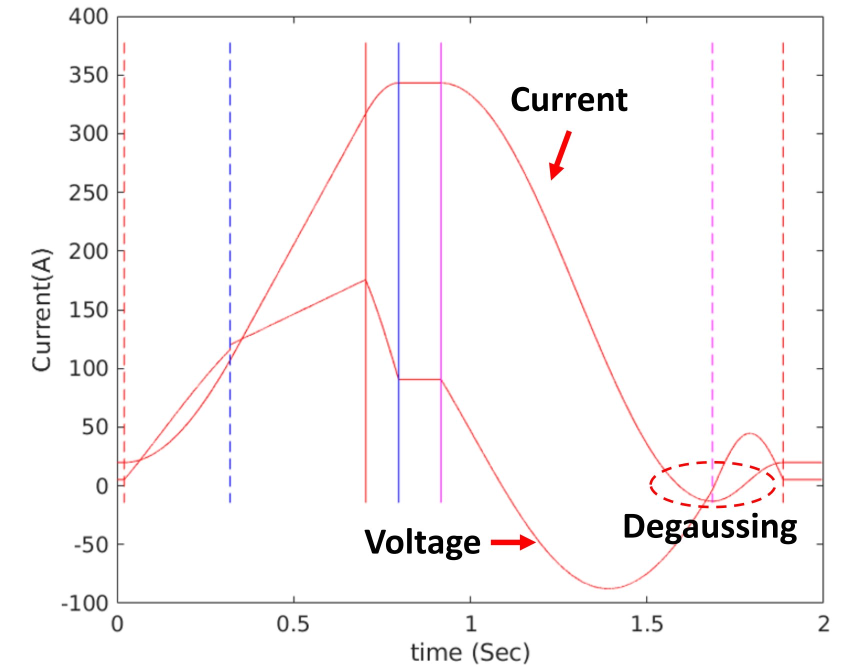
Booster Ring 1st Ramping (Energy)

❖ **2023. April ~ July**

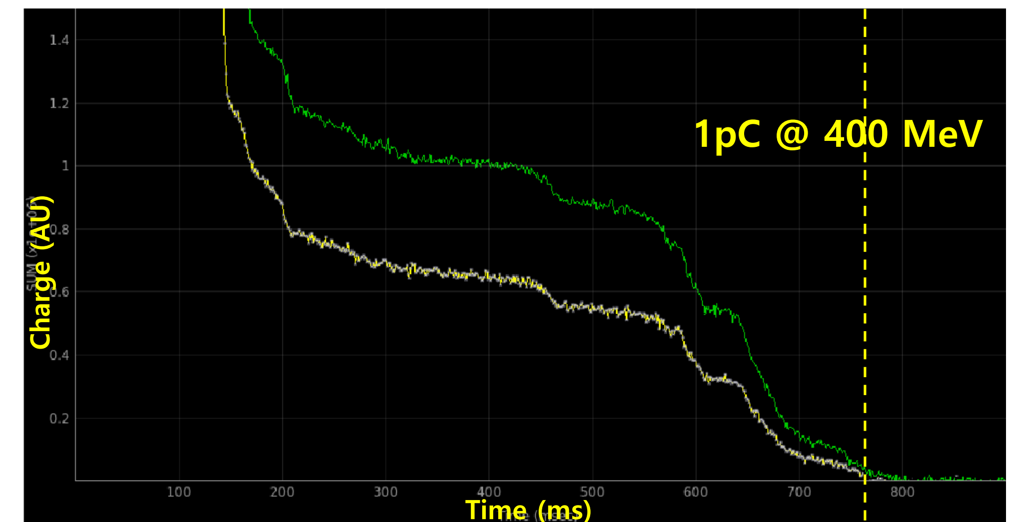
- BD(1SET), BQ(11SET), BS(8SET) Ramping
- Energy(Charge): 20 MeV(100 pC) → 400 MeV(1pC)



BD Ramping Waveform (cos-like)



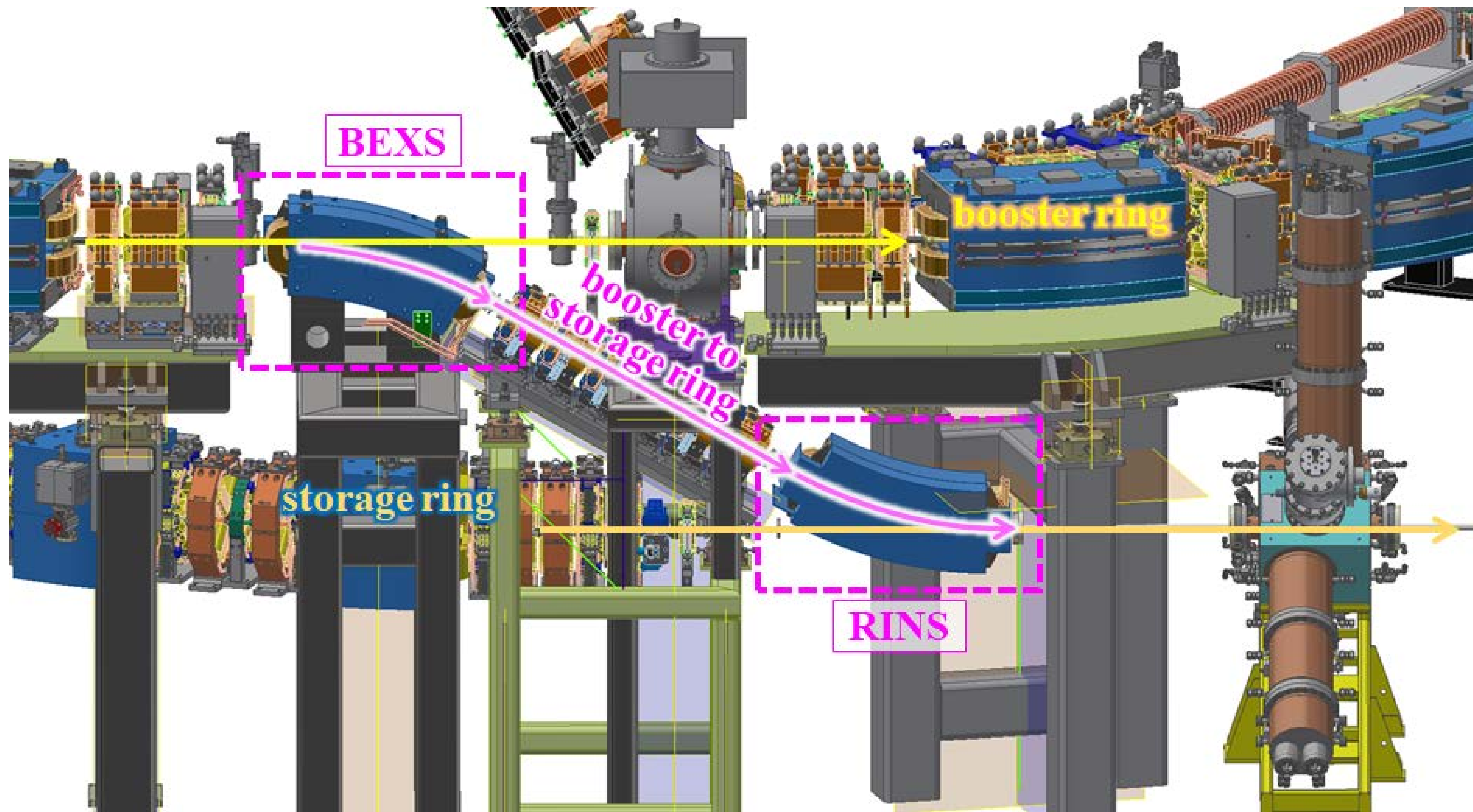
BPM BC1-5 BPM Electronics (Libera Spark-EL) sum signal



Booster-ring Extraction Practice

❖ **2023. August ~**

- DC and Ramping Operation after BEXS & RINS power ON



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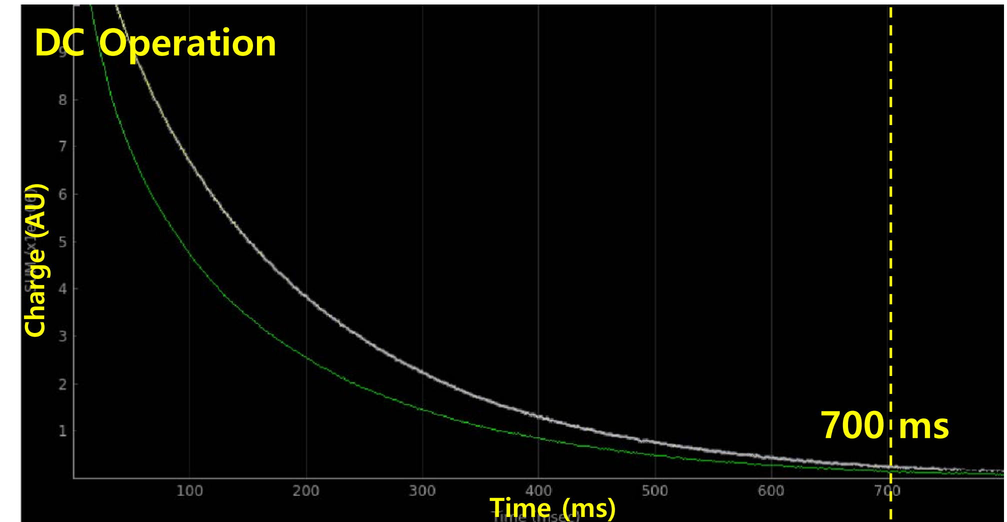
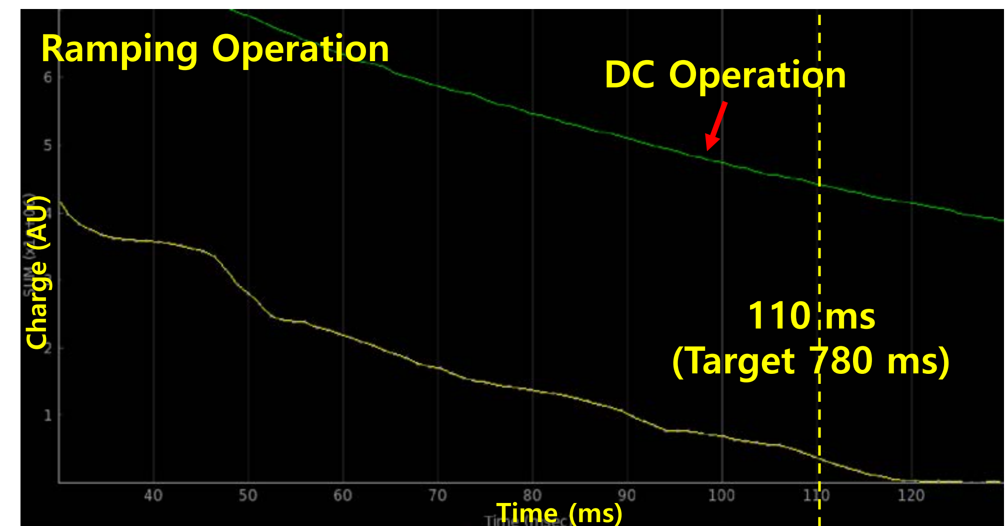


BPM BC1-5 BPM Electronics (Libera Spark-EL) sum signal



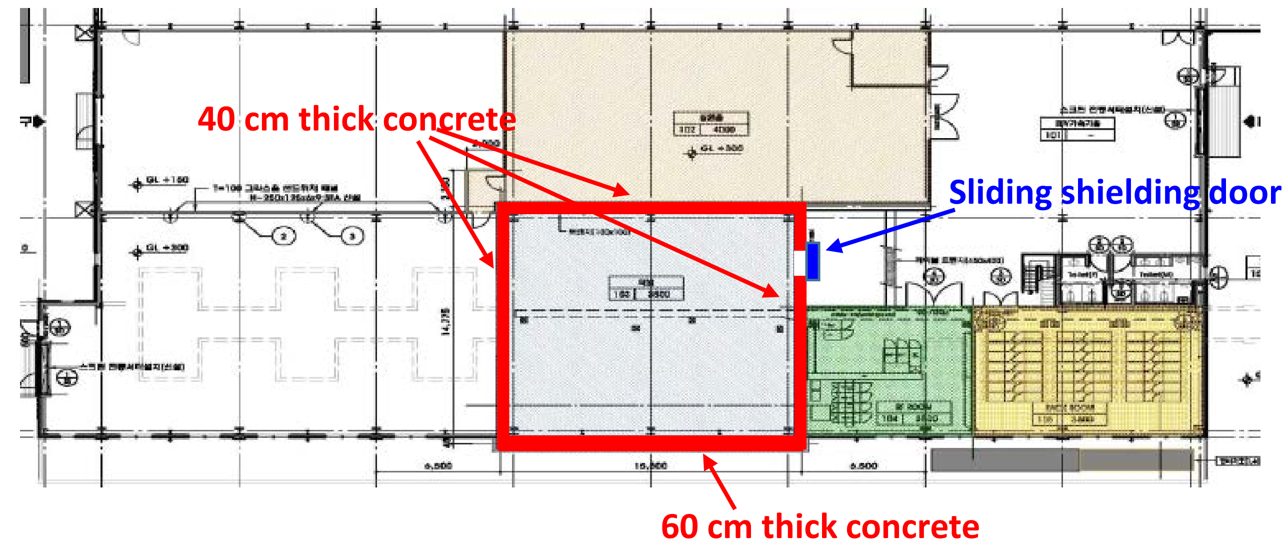
*BEXS: Booster-ring Extraction Septum
RINS: Storage-ring Injection Septum

Radiation Safety

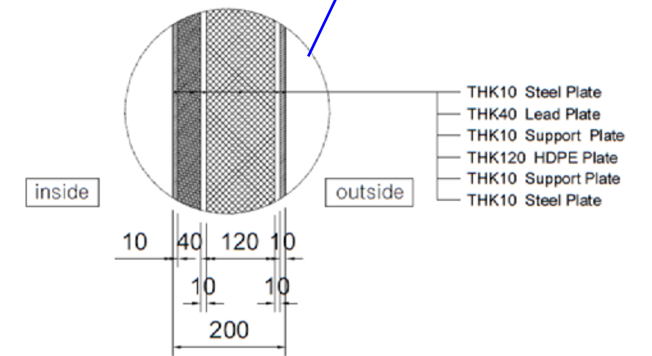
Beam loss scenario, dose estimation, 'personal safety & interlock system' introduced in IAC 2021

Tunnel enclosed with concrete wall

Tunnel ceiling covered with 40 cm concrete blocks



Sliding shielding door



Radiation monitor system and personal safety system installed

Commissioning schedule

		2023												2024											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Original Plan	Machine Commissioning																								
	User operation																								
Modified plan	Machine Commissioning																								
	User operation																								
	goal	**commissioning (including demo-experiment) and machine study**																				User operation			

Modified PAL-EUV commissioning plan

23.2 : EUV machine commissioning start
23. 11 : Booster Ring electron beam extraction, storage ring electron beam injection
24. 1 : Electron beam store at Storage Ring
24. 2 : EUV generation
24. 3-4 : Beam current increase
24. 5-6 : Maintenance
24. 7~8 : In-house experiment
24. 9~ : User operation

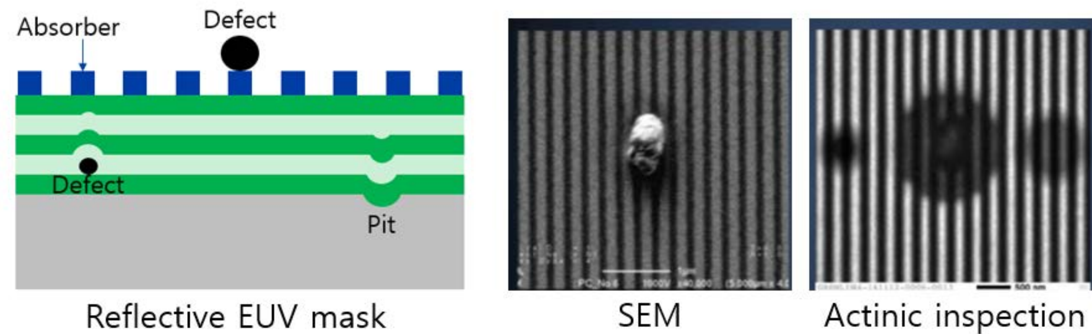
*** Remark**

- Sharing know-how by participating in the commissioning process with 4GSR research team

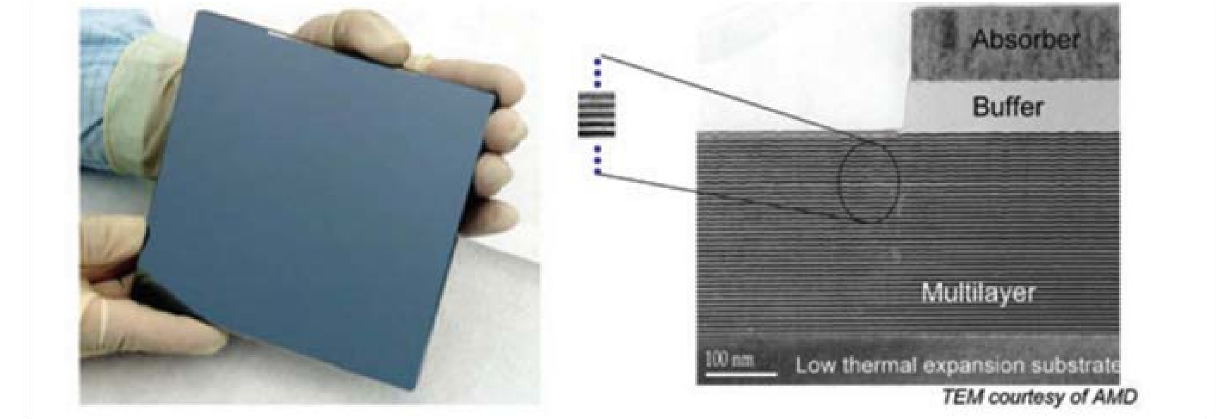
Beamlines : Mainly EUV Actinic Research

Actinic Research

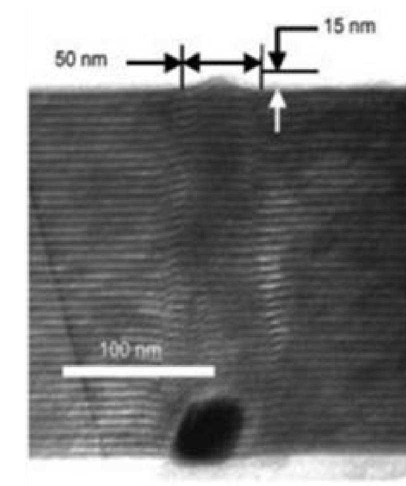
- EUV actinic mask imaging and inspection (current project)
- EUV resist patterning (plan)
- EUV actinic pellicle metrology (plan)
- EUV process optimization research (plan)



Courtesy: Center for X-ray optics, Lawrence Berkely National Laboratory



Detailed TEM cross section showing the repetitive +40 pairs of Mo/Si thin layers with buffer and absorber top films. (Photos courtesy of AMD)



TEM cross section of a multilayer defect grown over an intentionally deposited 60-nm diameter gold particle. (Photo courtesy of Lawrence Livermore National Laboratory)

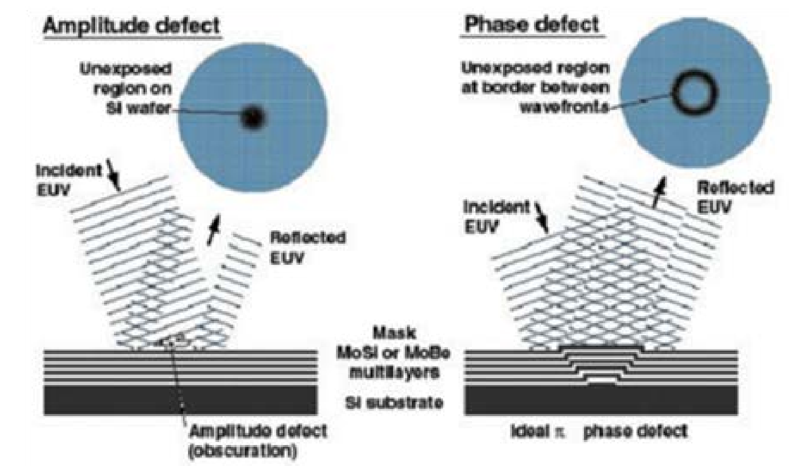
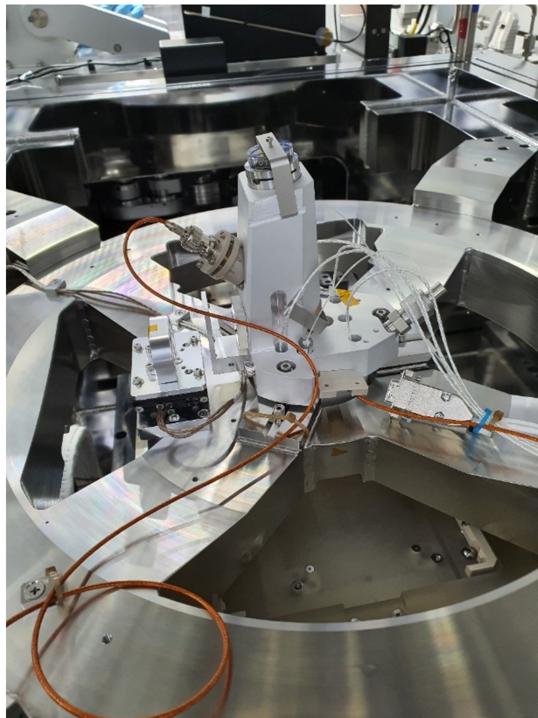


Figure courtesy of Lawrence Livermore National Laboratory

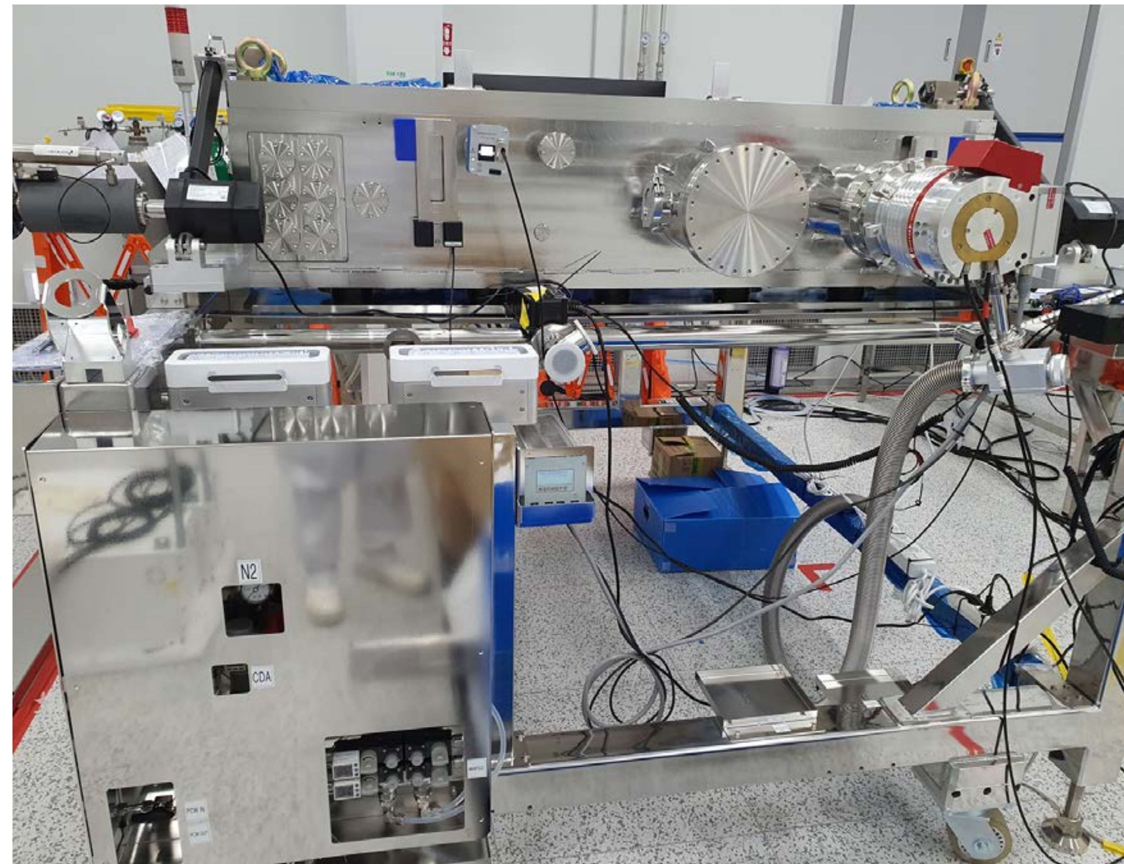
Courtesy: Vivek Bakshi et al., International SEMATECH, Austin, TX, USA
(Extreme Ultraviolet Lithography: status and challenges ahead)

Mask Inspection System

Mask inspection module



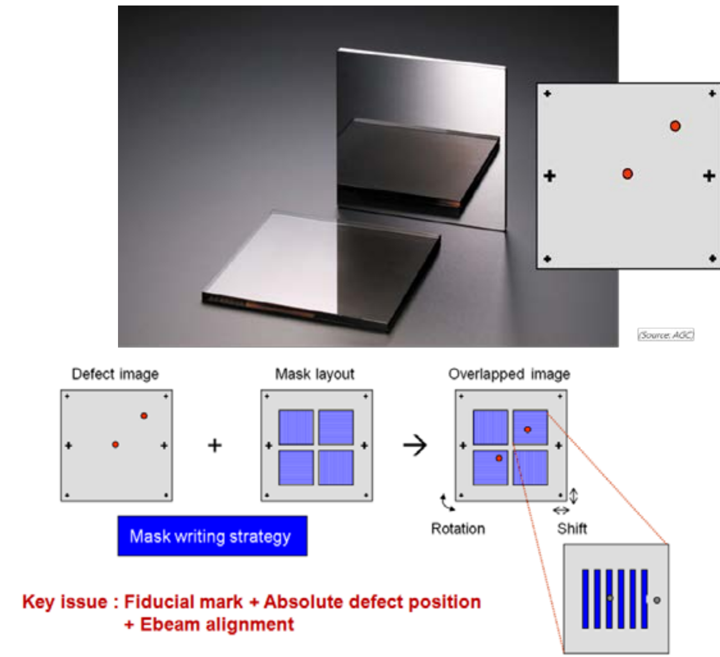
EUV beam condensing system



Nano positioning system

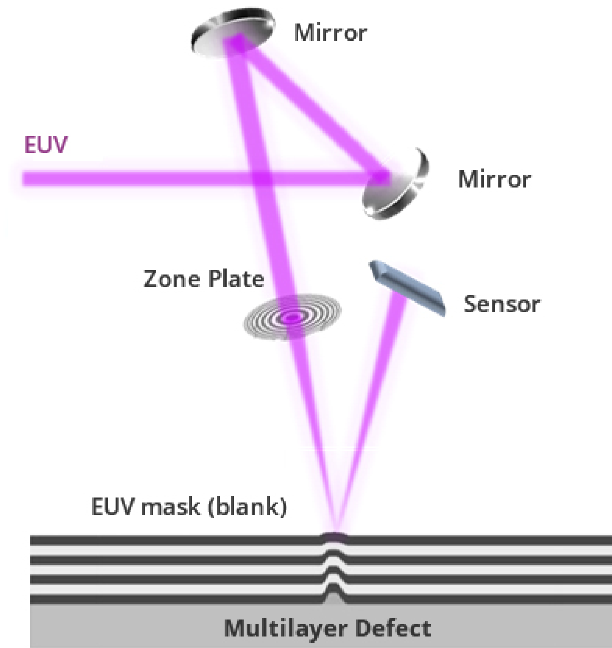
Beamlines : EUV Actinic Research

Mask metrology

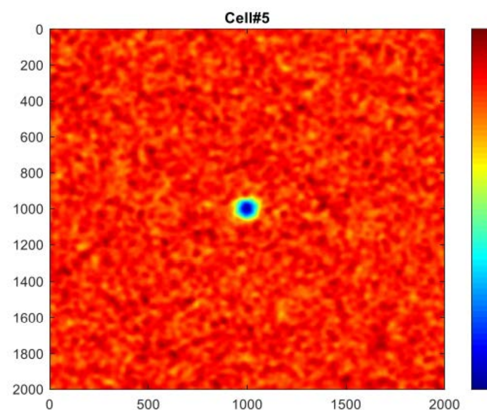


출처: Proc. of SPIE Vol. 7969 796902-9

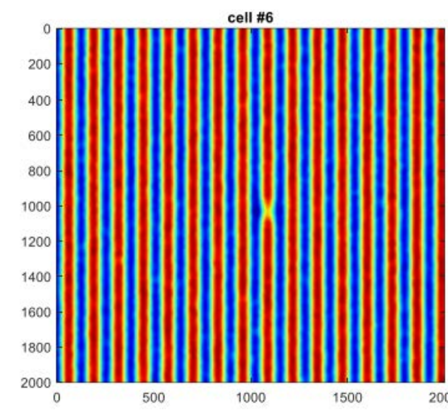
PAL-EUV actinic mask pattern inspection system



ABMI blank defect



APMI pattern defect

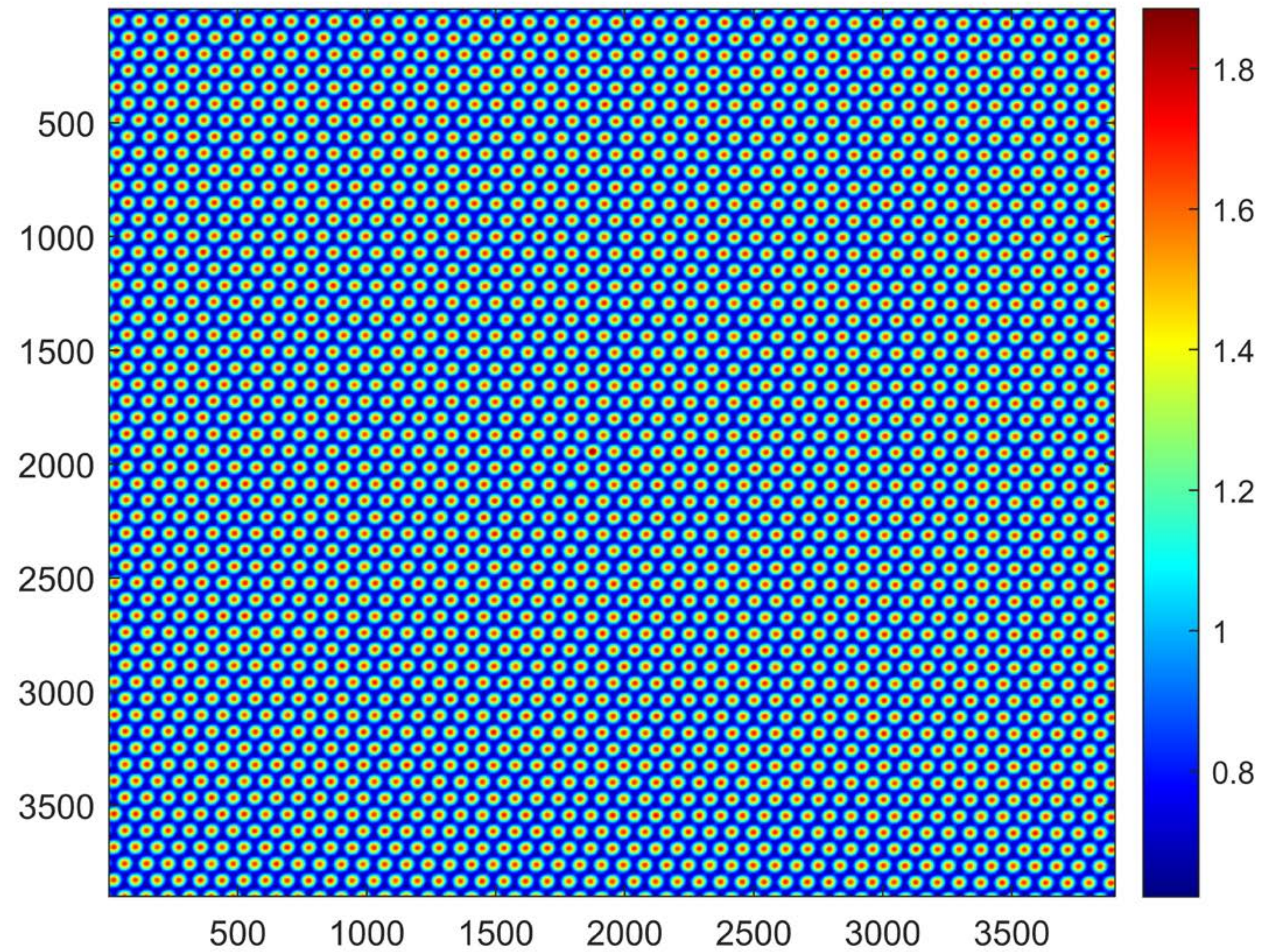


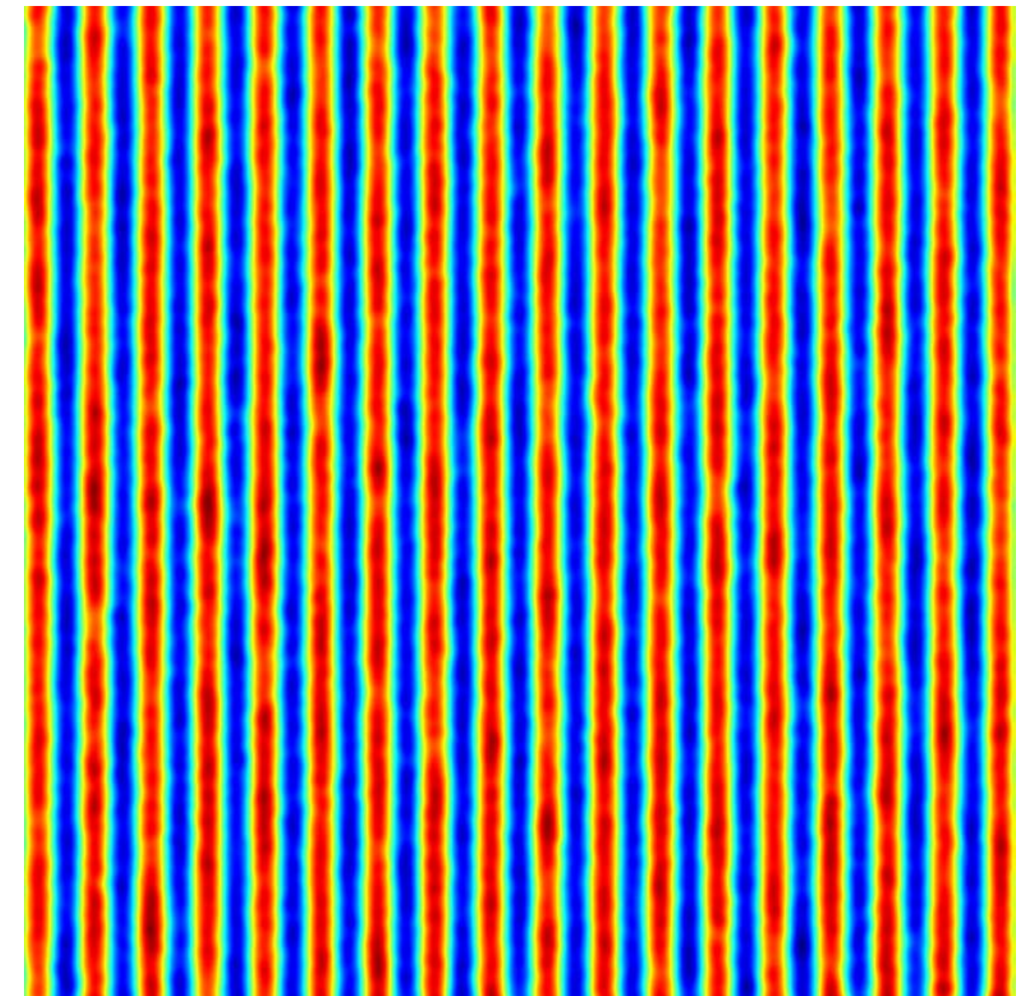
APMI pattern measurement

CD	ISO Vertical	V-L/S	ISO Horizontal	H-L/S
60 nm				
70 nm				
80 nm				
90 nm				
100nm				

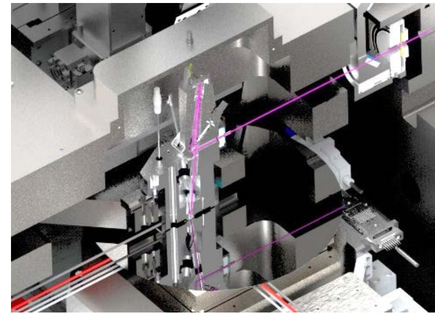
Beamlines : EUV Actinic mask review

Scanning reflective Imaging research 16nm HP

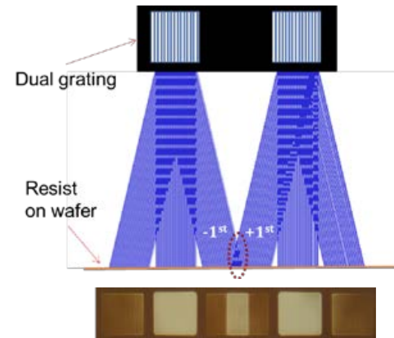




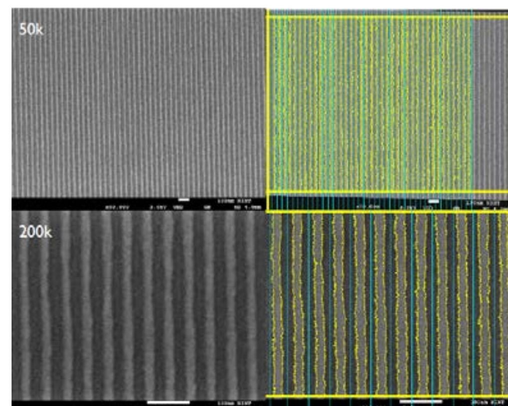
Scientific case study : EUV patterning



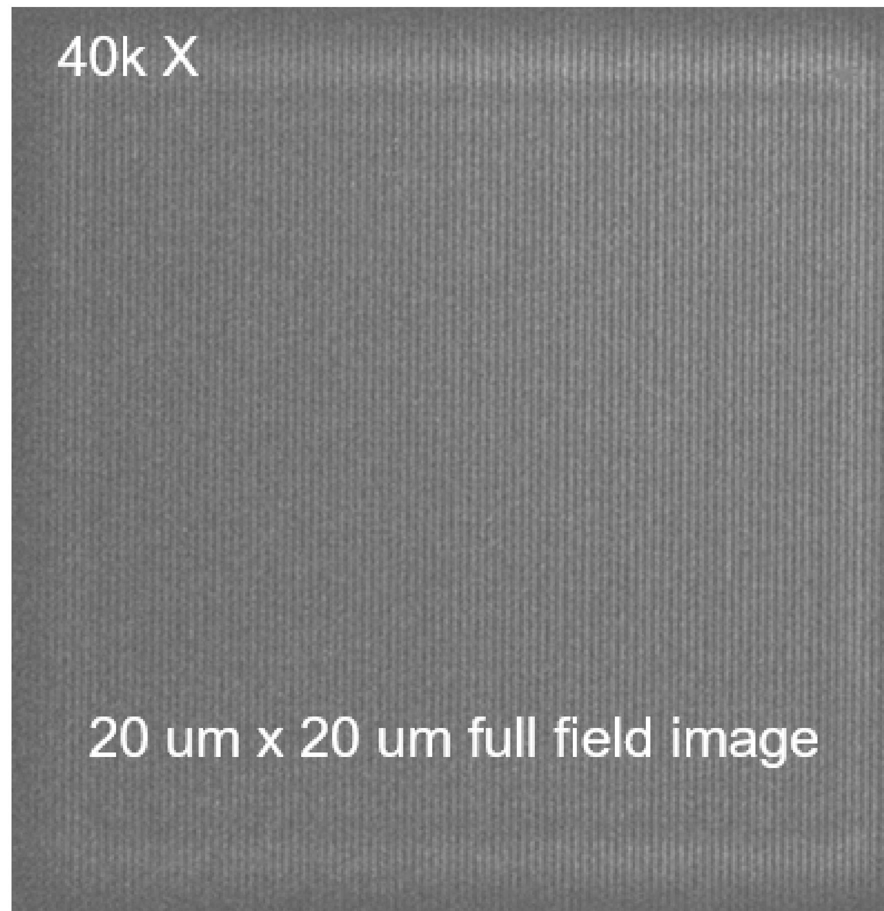
EUV interference lithography

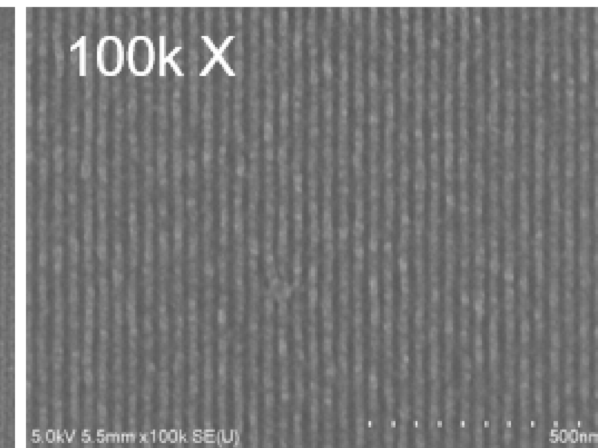


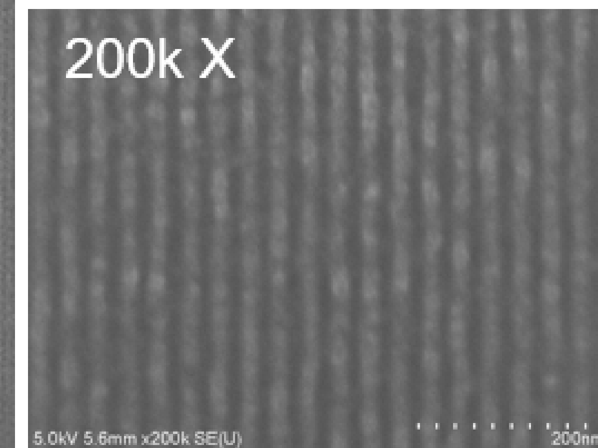
patterning



Metro LER

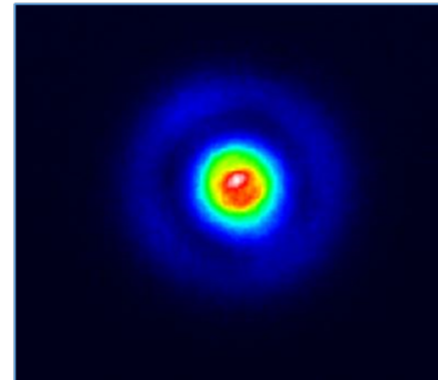


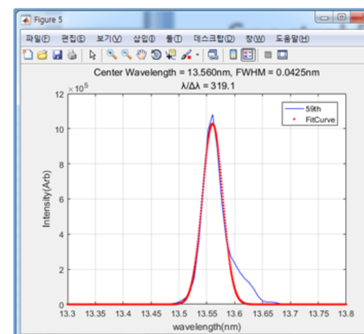


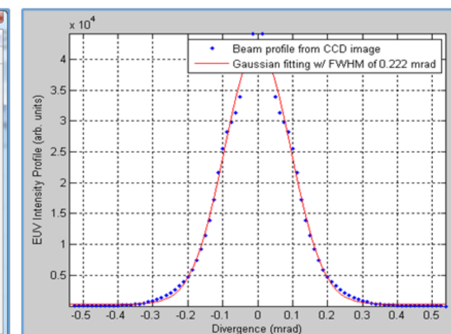


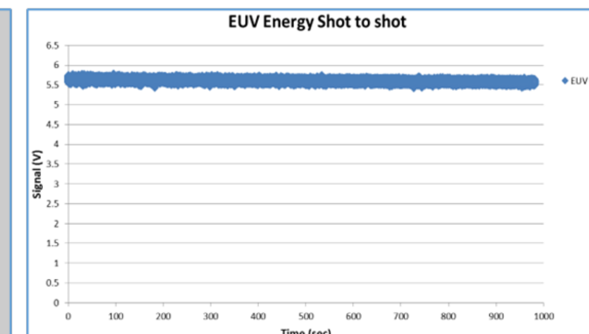
Beamlines : High-Harmonic EUV source

Description	Specification	Acceptance Test Method
1. EUV power	〉80 nW @ Full size (〉40 nW @ 0.3 mrad)	X-ray Photodiode measurements
2. EUV divergence	〈0.3mrad @ FWHM	X-ray CCD measurements
3. EUV long-term pointing Error	〈50urad @ rms	X-ray CCD measurements
4. EUV Long-term Power Drop-rate	〈 10% @ 48hr	X-ray CCD Or X-ray Photodiode measurements
5. EUV shot to shot pointing Error	〈5urad @ rms	Fast X-ray CCD measurements
6. EUV Shot to shot Energy Error	〈 1% @ rms	X-ray Photodiode measurements
7. IR focus shot-to-shot position Error	〈 1.5 um @ rms	IR Imaging Microscope
8. EUV Wave-front Error & Stability	λEUV/30 @ FWHM	EUV Wavefront Sensor
9. Spectral Bandwidth & CW Stability	λ/Δλ 〉280	X-ray Spectrometer

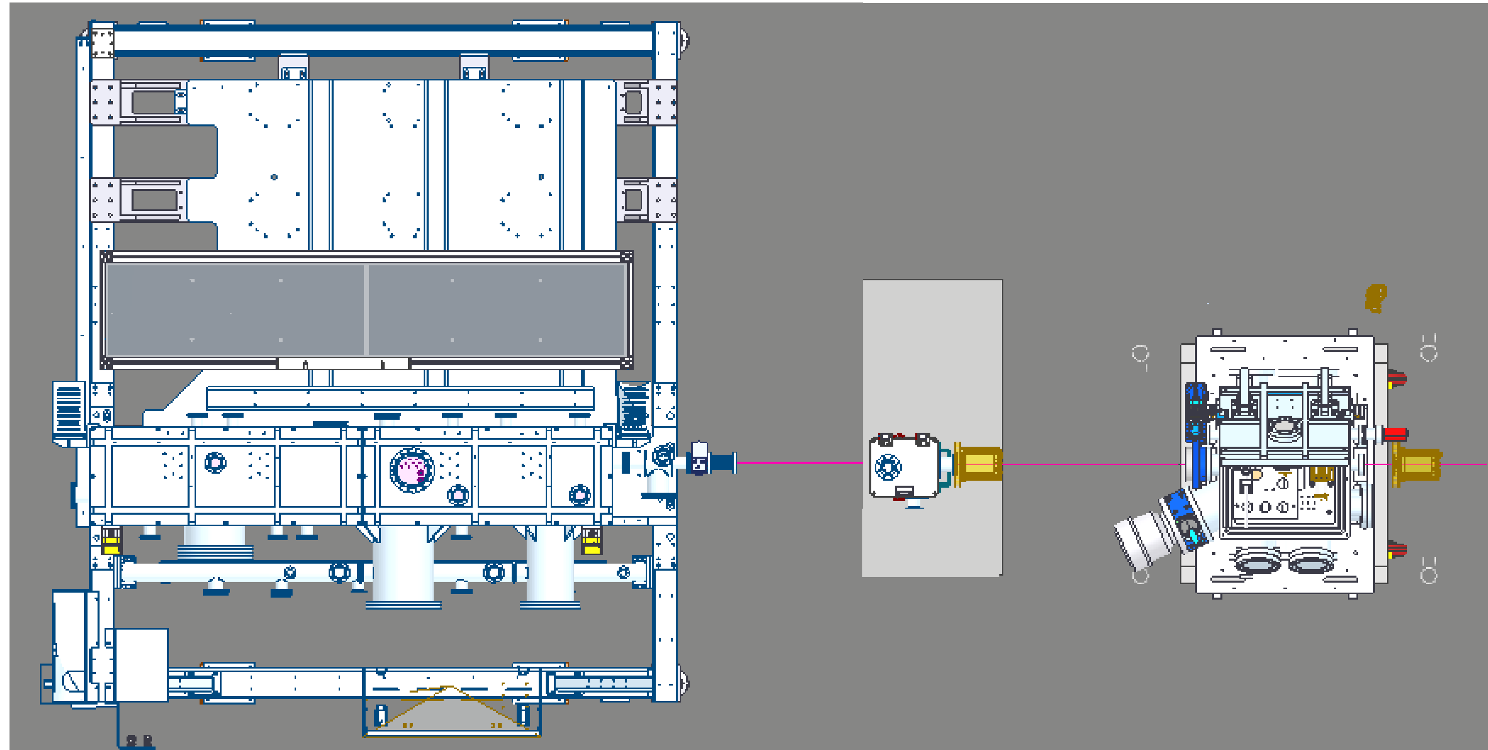


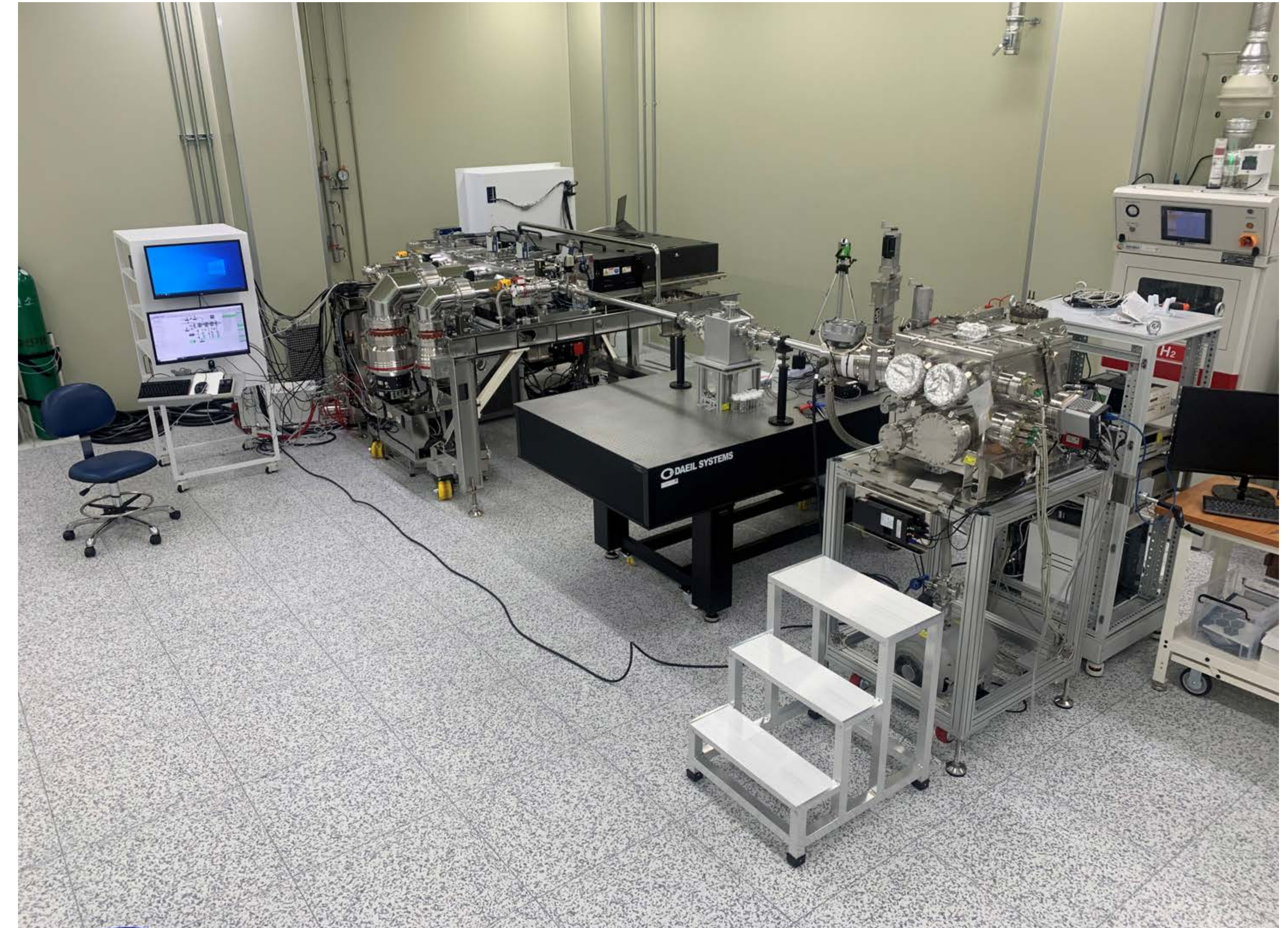


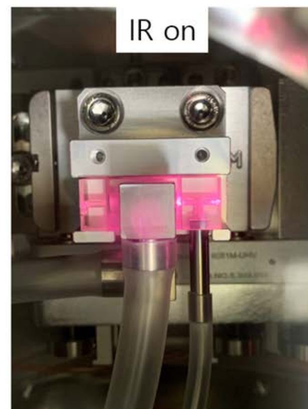


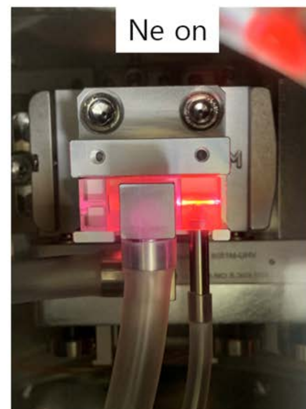


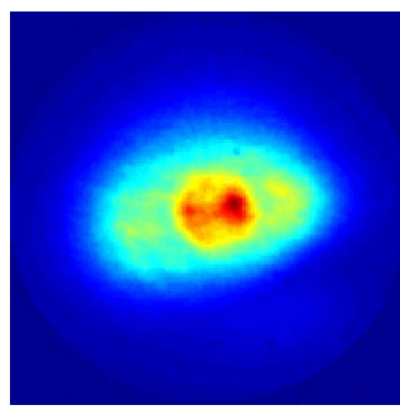
Beamlines : High-Harmonic EUV source





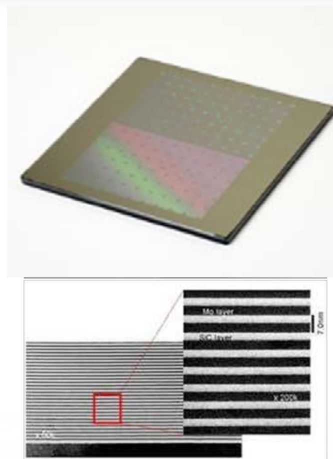


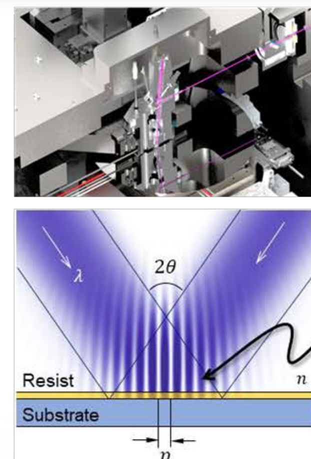


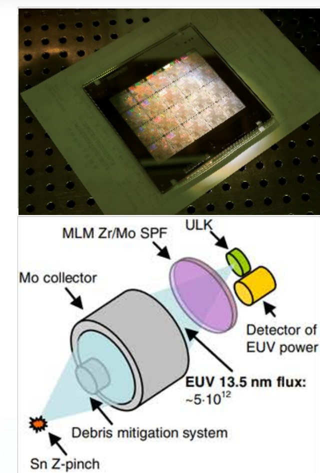


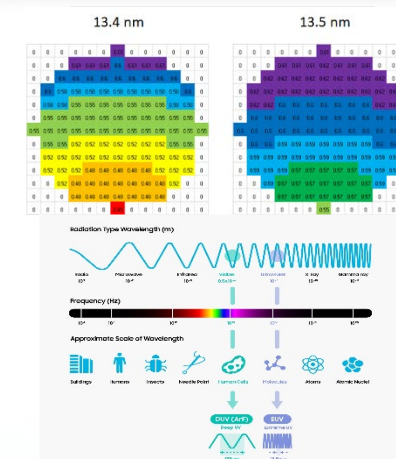
PAL-EUV metrology and inspection infrastructure

OoB study | Patterning | Material | Optic









EUV Infrastructure in the semiconductor ECO system

Summary and Future Plans

Best efforts have been paid to finish the project in time and on budget.

For the construction in a short period with a small team, technical challenges have been minimized from design stage.

Beam commissioning has started from February 2023.

Beam commissioning will continue until August 2024.

Beamline research has started with stand-alone high-harmonic generation EUV source.

EUV beam service for friendly users will start in late 2024.

Thanks to:

All staffs of Pohang Accelerator Laboratory