Development Status of Beam Diagnostics for Korea-4GSR-BIG and PLS-II

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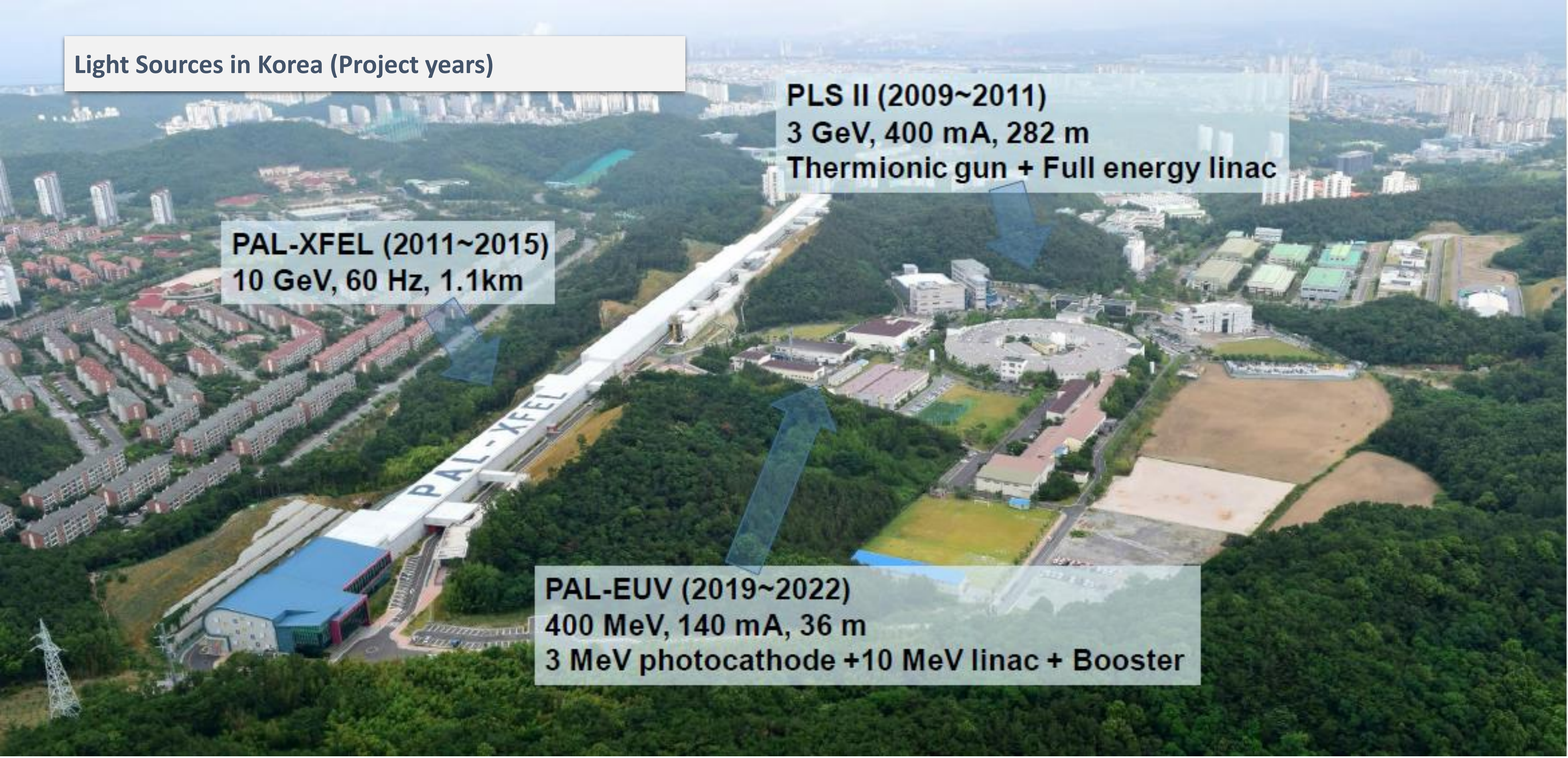
POHANG ACCELERATOR LABORATORY

Contents

- Brief Introduction to Korea-4GSR Project
    - Timelines, budget, governance & manpower
    - Representative beam parameters
    - Construction status

- Recent Development of Beam Diagnostics for Korea-4GSR and PLS-II
    - Overall beam diagnostics configuration
    - Online filling pattern & bunch length monitor
    - Beam loss monitor

Light Sources in Korea (Project years)



4GSR Outline

❖ **Multipurpose Synchrotron Radiation Construction Project**

- Period: 2021 July to 2027 June (6yrs)
- Budget: 1.0454 Trillion KRW (≈ USD 750M)
- Land: 540,000 ㎡ / Building: 69,400 ㎡
- Location: Ochang, Chungcheongbuk-do

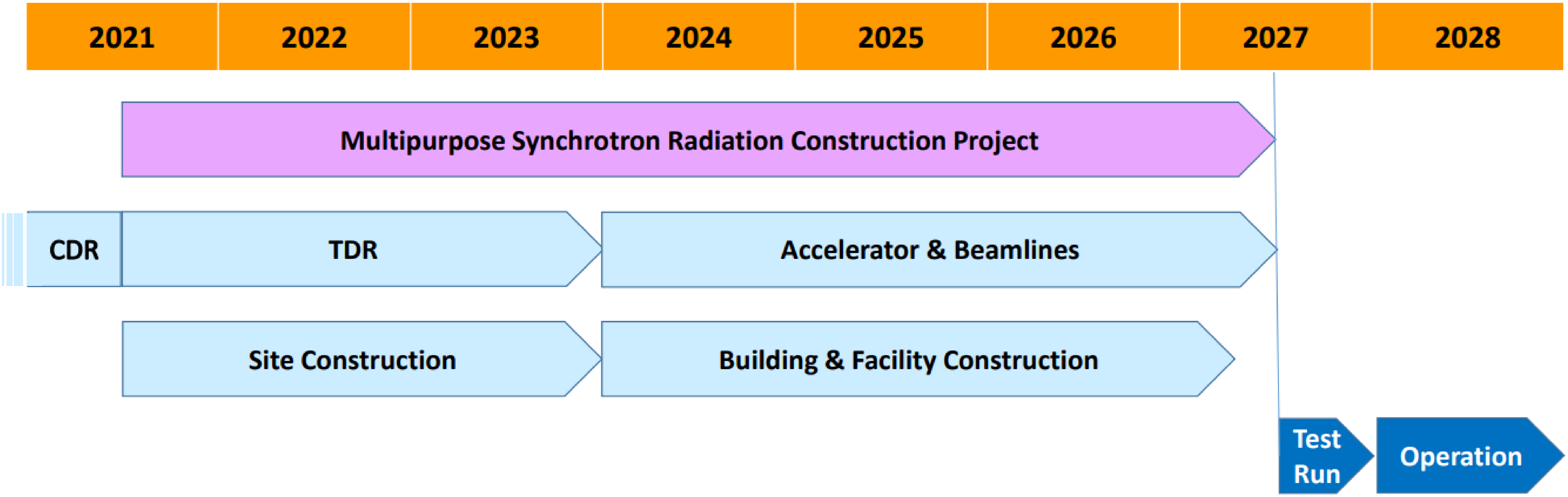
<4GSR Project Budget Plan> (Million USD)

Years	2021	2022	2023	2024	2025	2026	2027	Sum
Machine	8	44	77	172	180	97	28	606
Site	72	72	-	-	-	-	-	144
Sum	80	116	77	172	180	97	28	750

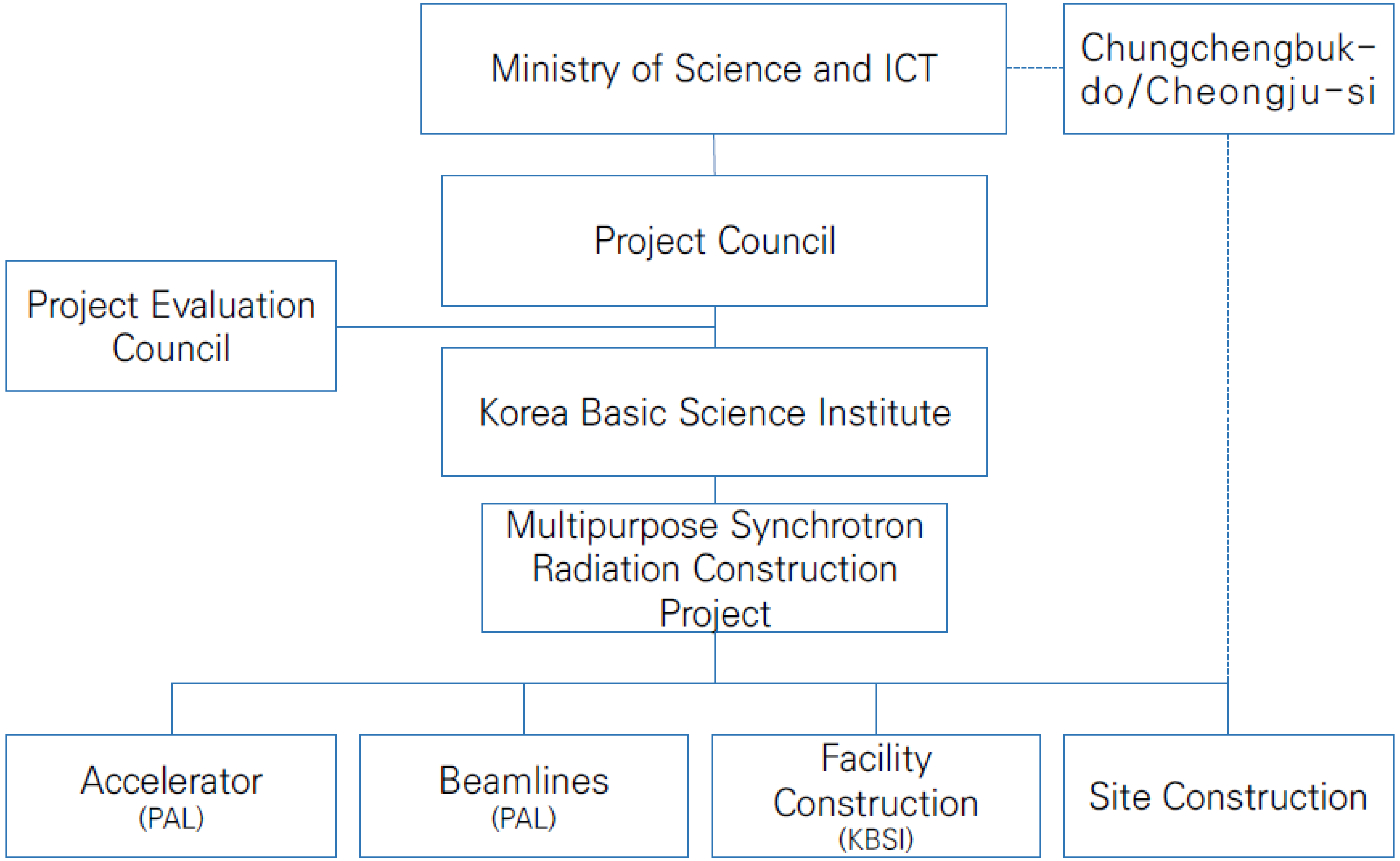
Specifications

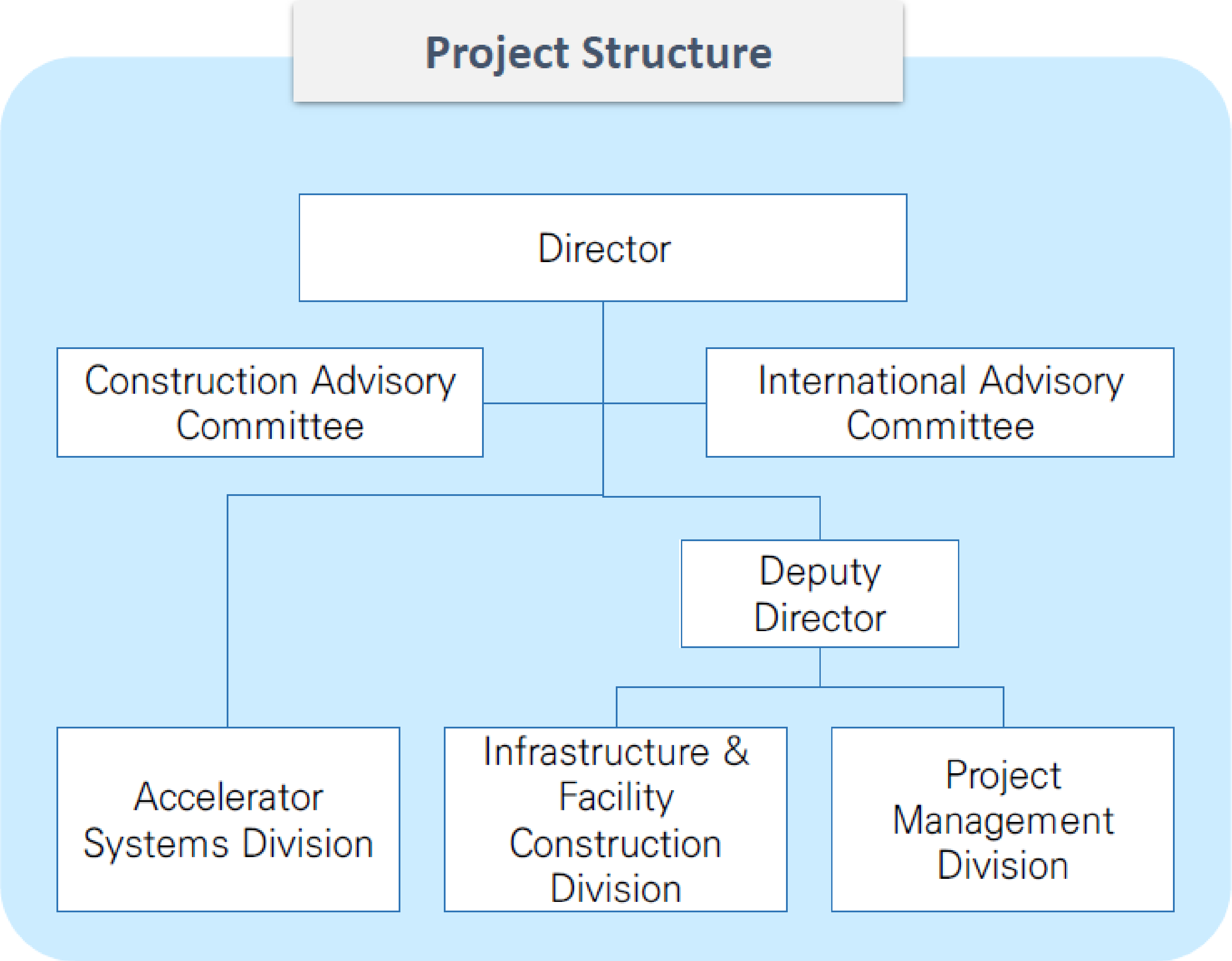
- Beam Energy: 4 GeV
- Beam Emittance: less than 100 pm·rad (CDR: 58 pm·rad)
- Circumference: 800m
- Beamlines : more than 40
- Accelerator: Gun, Injector LINAC, 4 GeV Booster
- Lattice: MBA-7 Bend Achromat

Project Timeline



Project Governance



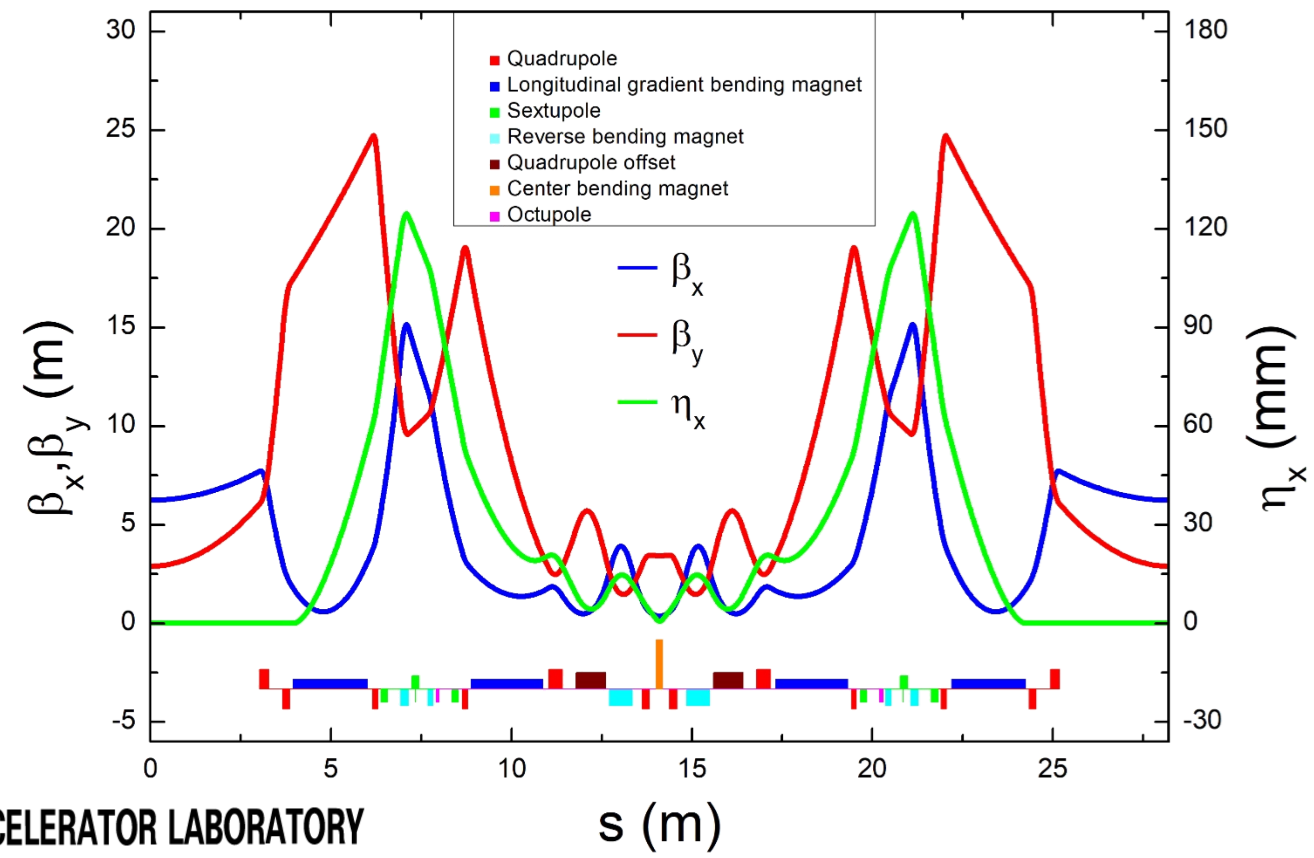


Manpower

		2022	2023	2024	2025	2026	2027
Director		1	1	1	1	1	1
KBSI	Vice Director	1	1	1	1	1	1
	Accelerator System	4	6	11	14	26	37
	Infrastructure & Facility	9	15	15	15	15	15
	Project Management	10	18	19	19	19	19
		24	40	46	49	61	72
PAL	Accelerator	85	92	105	109	117	117
	Beamlines	67	72	79	85	87	87
	Project Management	23	25	26	26	25	23
		175	189	210	220	229	227
Total		200	230	257	270	291	300

Lattice Design

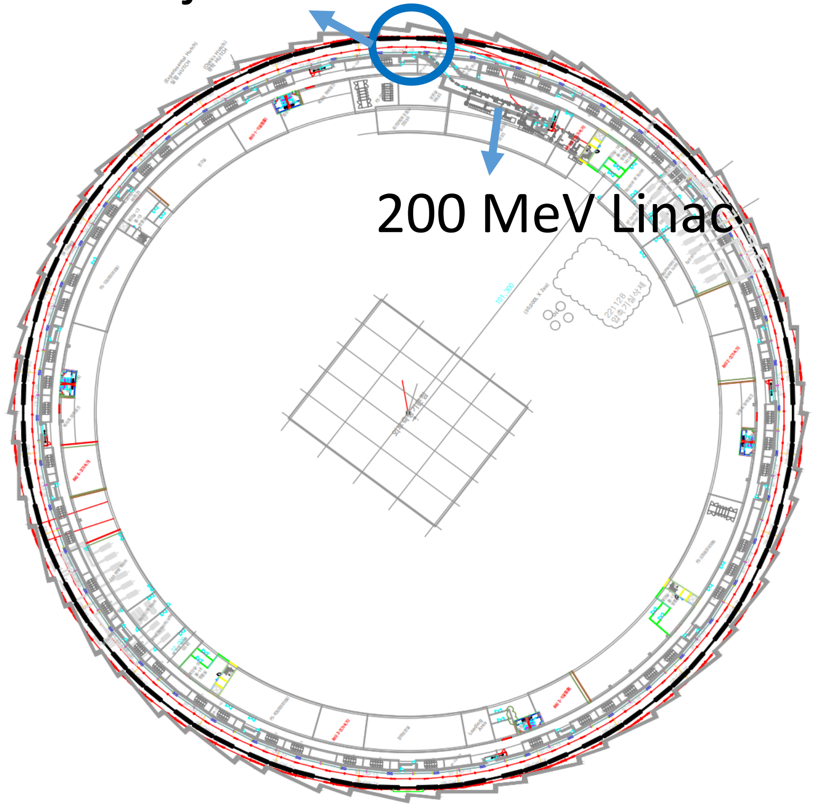
- **The storage ring is a 800 m – 4 GeV – 28-cell ring with natural emittance of 62 pm**
- **The unit cell is a H7BA with 2-T center bend**
- **It exploits longitudinal gradient bends (LGBMs) and reverse bends (RBs) to suppress emittance**

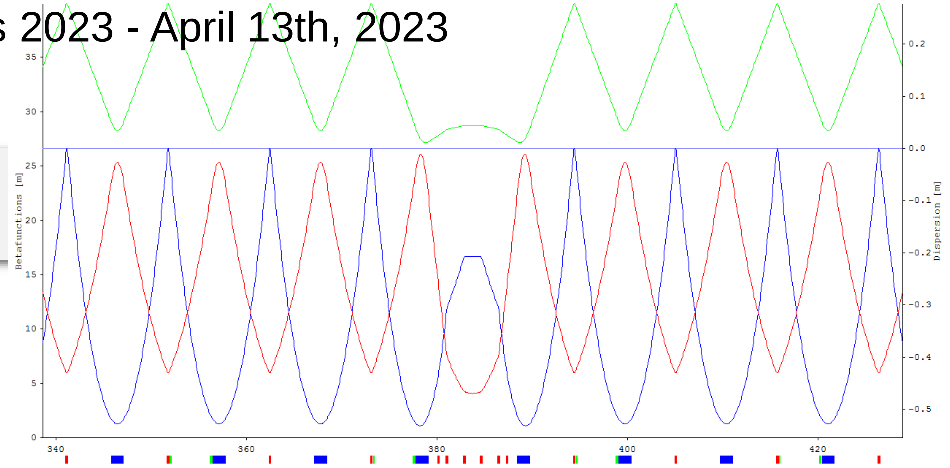


Parameters	Value
Energy (GeV)	**4**
Circumference (m)	**799.297**
Emittance (pm)	**62**
Tunes (H,V)	**68.10, 23.18**
Natural chromaticity (H,V)	**-110, -84.7**
Chromaticity (corrected) (H,V)	**4.5 , 3.5**
Hor. Damping partition	**1.84**
Momentum compaction	$\mathbf{0.78 \times 10^{-4}}$
Energy spread (σ_δ)	$\mathbf{1.26 \times 10^{-3}}$
Energy loss per turn (MeV)	**1.098**
Beam current (mA)	**400**
Bunch length (σ_z) (mm)	**4.06 / 16.23**
# of Beamline	**24 (ID)** **28 (2 T Bend)**

Injection system

- **Photo-cathod Gun & 200 MeV Linac**
- **Booster Ring : 2 Hz, 773 m, FODO**
- **Injection & Extraction**

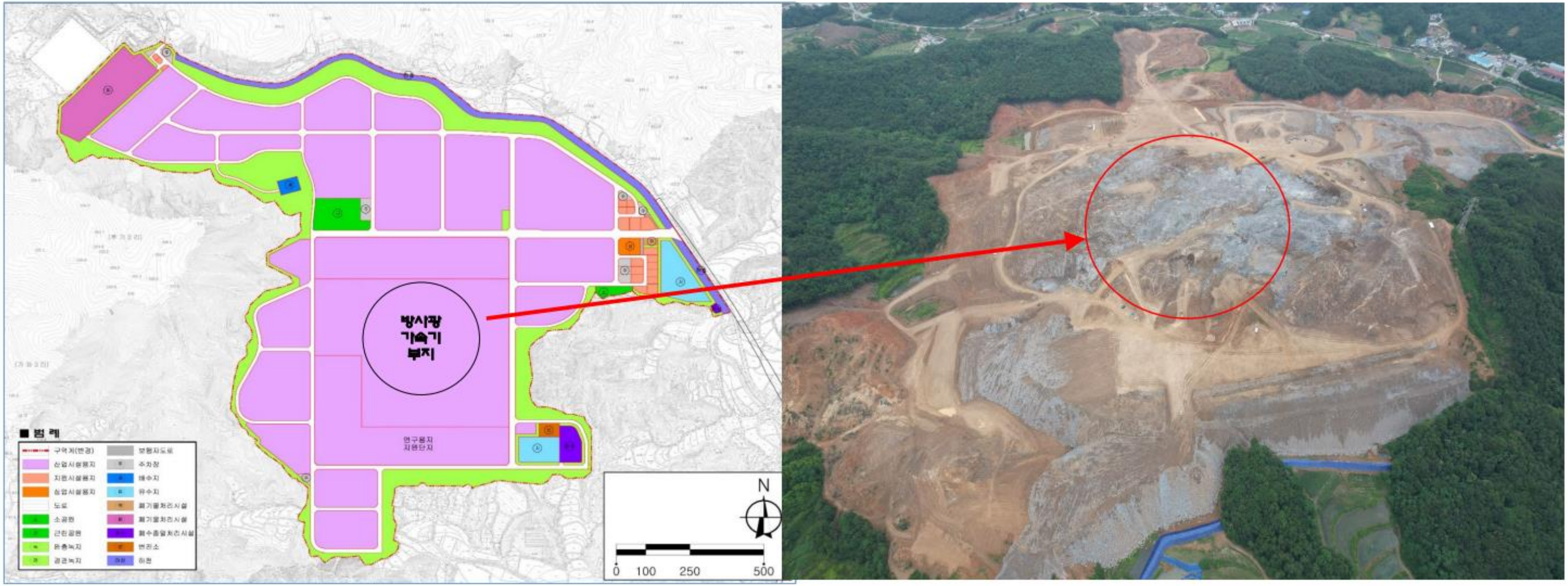




773 m Booster		Value	Unit
Design Parameters	Length	772.893	m
	Electron Energy	0.2 - 4	GeV
	Natural Emittance at 4 GeV	7717	pm rad
	Natural Emittance at 200 MeV	19	pm rad
	Momentum compaction	0.000925	
Tune and Chromaticity	Horizontal Tune	19.195	-
	Vertical Tune	14.19	-
	Natural Horizontal Chromaticity	-27.7	-
	Natural Vertical Chromaticity	-19.3	-
	Horizontal Chromaticity	3	(target)
	Vertical Chromaticity	3	(target)

Radiation related quantities at 4 GeV	Energy Loss per Turn	1671.3	keV
	Energy Spread	0.107	%
	Horizontal Damping Time	8.4	ms
	Vertical Damping Time	12.3	ms
	Longitudinal Damping Time	8.1	ms
	Synchrotron Frequency	4217	Hz
	Synchrotron Tune	0.01087	
	Bunch Length	11.17	mm
Radiation related quantities at 200 MeV	Energy Loss per Turn	0	keV
	Energy Spread	0.005	%
	Horizontal Damping Time	67044	ms
	Vertical Damping Time	98724	ms
	Longitudinal Damping Time	64632	ms
	Synchrotron Frequency	20682	Hz
	Synchrotron Tune	0.053	
	Bunch Length	0.11	mm

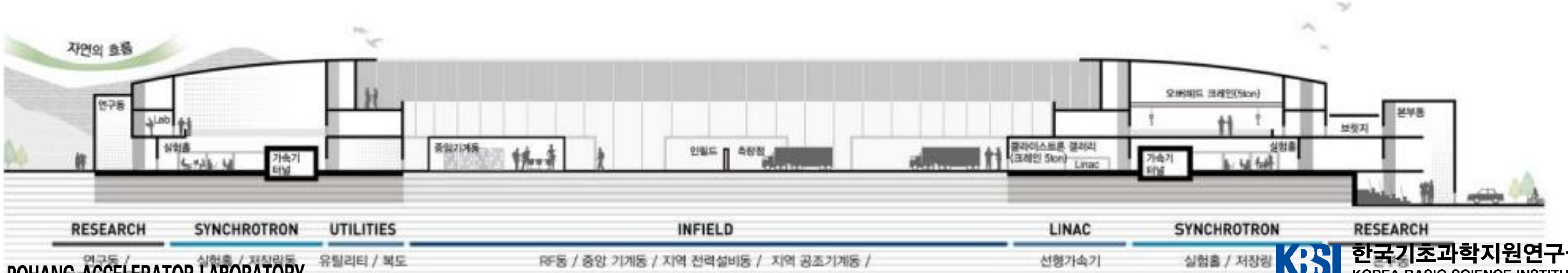
Construction Site



4GSR Design – Building Design Company (Haenglim*)

* Designed PAL-XFEL


유틸리티
유틸리티
가속기제어실
가속기제어실
가속기시설 통합관제
모니터링
Mass con'c
BED ROCK
전력설비동/유틸리티
연구목적에 따라 4개
영역으로 조닝별 전력설비
복도(MPS)
터널내부 전력인입을
위한 MPS 배치
저장링 터널
방사선 차폐를 위한
고밀도 콘크리트 설계
실험실 HUTCH
연구목적에 따른 제어,
실험,광학 HUTCH
실험홀
가속기 터널,실험홀,연구실 기초를
분리하여 진동 전달 차단
복도
지게차 및 사람의
통행을 위한 통로


자연의 흐름
연구동
Lab
실험홀
가속기
터널
중앙기계동
인필드
측정점
클라이스트론 갤러리
(크레인 5ton)
Linac
오버헤드 크레인(5ton)
가속기
터널
실험홀
브릿지
본부동
RESEARCH
SYNCHROTRON
UTILITIES
INFIELD
LINAC
SYNCHROTRON
RESEARCH
유틸리티 / 복도
RF동 / 중앙 기계동 / 지역 전력설비동 / 지역 공조기계동 /
선형가속기
실험홀 / 저장링

The Project Introduction Summary

❖ **Multipurpose Synchrotron Radiation Project**

- The project aims to build 4 GeV storage ring with an emittance less than 100 pm
- Its circumference will be 800m
- It can host more than 40 beamlines. Initially, 10 beamlines will be ready.

❖ **2 Institutions working together**

- KBSI: Leading institution in charge of Building and Facility
- PAL: Partner institution in charge of Accelerator and Beamlines

❖ **Construction will be completed by 2027**

- Building design began in September, 2022 and will be completed by 2023
- TDR will be finished by 2023
- Construction will be started in spring, 2024

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Configuration of Beam Diagnostic Device for the Korea-4GSR Project

CODE	Type	Measurement	Number of Devices				
			LINAC	LTB	BS	BTS	MR
1	Beam Position Monitor (BTN/STRL)	Position	8	5	**77**	6	**292**
2	Beam Profile Monitor (YAG/OTR)	2D Profile, Emittance, Energy	7	6	1	7	1
3	Soft-X-ray Diagnostic Beamline	SR Beam Size, Emittance					1
4	Visible Light Diagnostic Beamline	SR Beam Size, Emit., Bunch			1		2
6	AC Current Transformer (ICT/FCT)	Beam Current	3	1	1	1	1
7	DC Current Transformer (CWCT)	Beam Current			1		2
8	Bunch Filling Pattern Monitor	Filling Pattern Monitor					1
9	Streak Camera	Bunch Profile, Pattern					1
10	Photon Beam Position Monitor	Photon Beam Position					30
11	Beam Loss Monitor(FAST-PMT)	Beam Loss (sensitive, BbB)			5		30
12	Beam Loss Monitor(SLOW-Scintillating Fiber)	Beam loss (position)	1	1	4	1	8
13	Energy Monitor	Beam Energy (spin)			1		1
14	Tune Monitor	Tune			1		1
15	TFS/LFS	Feedback					2
16	Vibration Monitors	Mechanical Vibration					56
17	Calibration & Meas. Tools	Cal. Stage, Elec. Dev. Tool					1
Total Number of Instruments per Section			**19**	**13**	**92**	**15**	**430**

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Task Priority & Development Status

1. RF pick-up : Background study > simulation > **prototyping** > test > design upgrade > mass production > inspection > assembly > installation
2. Beam Loss Monitor (SLOW) > prototyping > **beam test at PLS-II** > upgrade > mass production
3. BPM Electronics : study > **prototyping** > debugging > mass production
   (BBB-TFS/LFS, Bunch resolved energy measurement in injector LINAC)
4. ~~Strip-line BPM > allocation/drawing > **simulation design** > fabrication > installation~~
5. BPRM-CT-SLIT > **design study** > fabrication (YAG/GaGG/OTR-SLIT All In One Chamber, Inj-Scr-Mon)
6. Tune Monitor :
   Analog Method (Spectrum Viewer & FM source + Tune Kicker (TFS hybrid)) : Kicker : **design** > manufacturing
   Digital Method (with TFS) : **design study** > prototyping > manufacturing
7. TFS/LFS : build in 2nd phase
   Tr. kicker, Ln. damped cavity : **design study** > prototyping > manufacturing
8. Streak Camera : **ready for purchasing** > purchasing (y2025)
9. Filling pattern monitor : prototyping > **beam test at PLS-II**
10. CT (DCCT/FCT/ICT) : **specification study** > wake-field-shield manufacturing > test
13. ~~High Precision Energy Monitor : study > **machine study** > algorithm implementation to Digital Tune Monitor system~~
14. Diagnostic Beamlines & Hutches : **design study**

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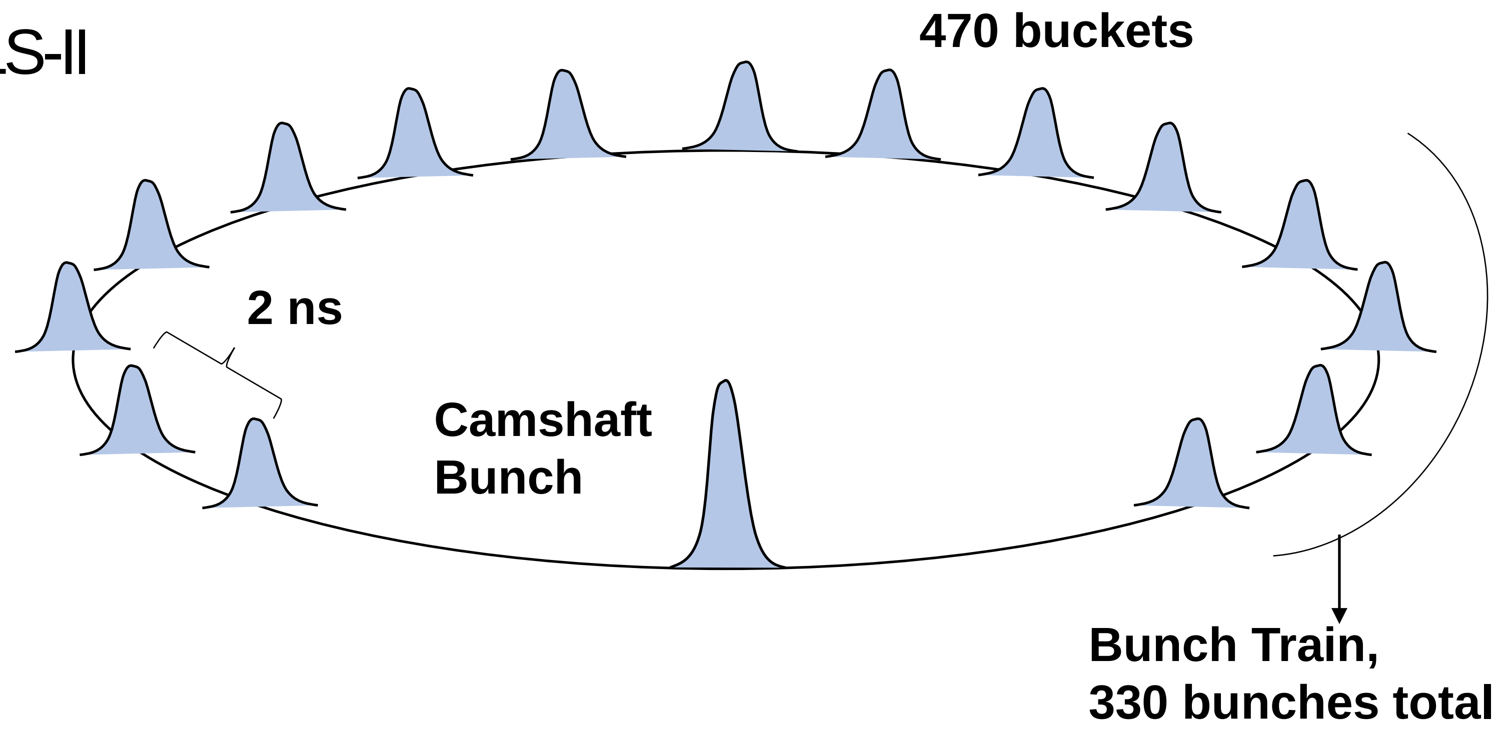
Bunch by Bunch Fill Pattern & Bunch Length Monitor

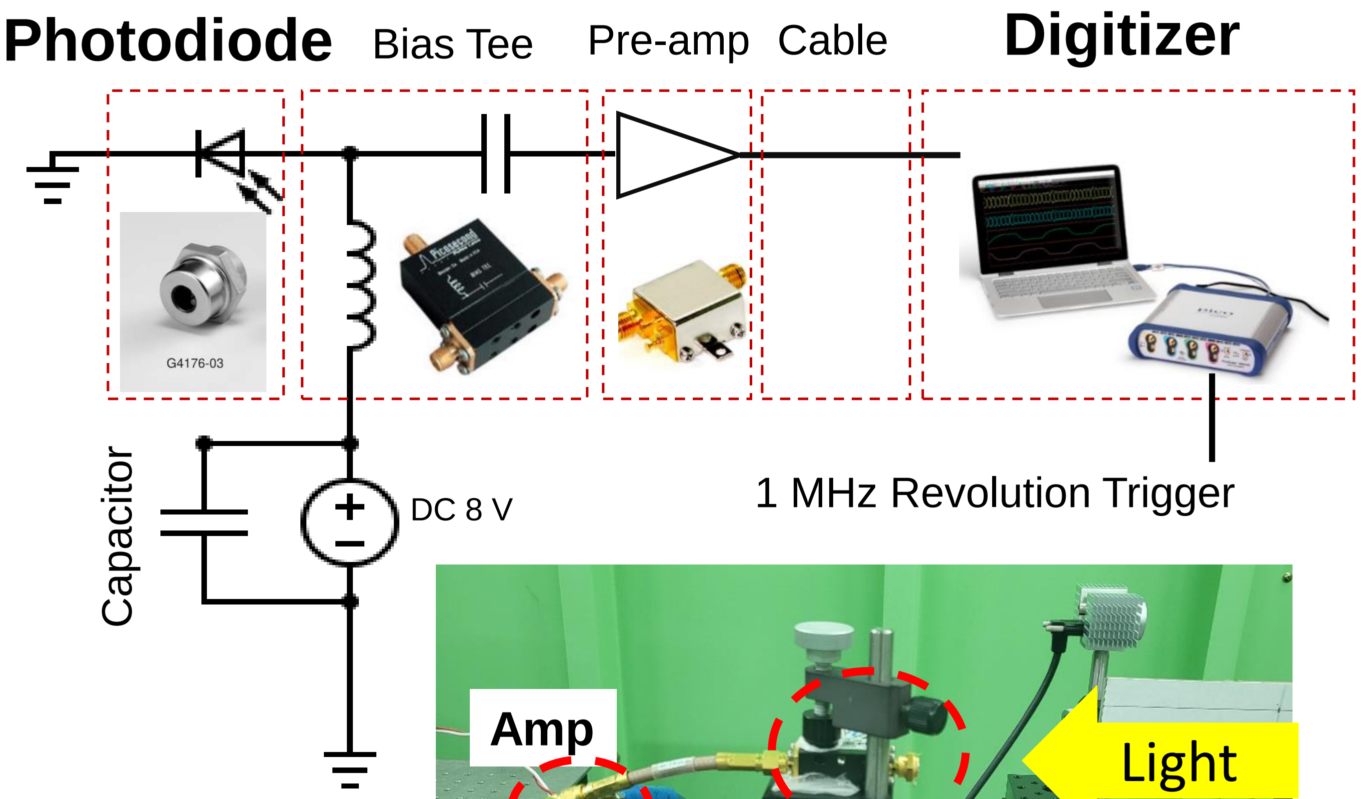
Measurement of Longitudinal Beam Properties

- Hybrid filling patterning for a time resolved experiment in PLS-II
  - 330 bunches + gap + **single bunch** + gap
- Longitudinal beam instabilities in Korea-4GSR
  - Ln. wake impedance mainly induced by NC cavities
- Measurement method candidates
  - Streak Camera
    - Less than 1 ps temporal resolution
    - Difficult to measure in an online and a continuous way
  - BPM sum value or FCT
    - An on-line & TbT measurement
    - Filling pattern monitoring only
  - **Photodiode**
    - The temporal resolution of 1.2 ~ 3 ps
    - Online BbB bunch length, phase, & filling pattern measurement at the same time (AS people had already shown online filling pattern meas. using PD)

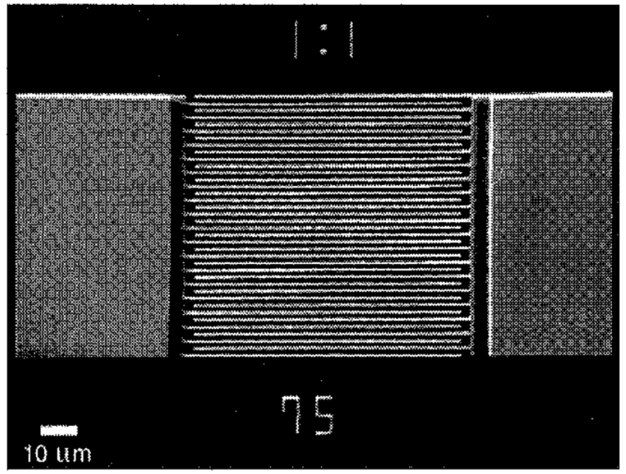


PLS-II Parameter	Value	Unit
Beam Energy	3	GeV
Beam Current	400	mA
Circumference	281.82	m
RF Frequency	499.97	MHz
RMS Bunch Length	6.4	mm

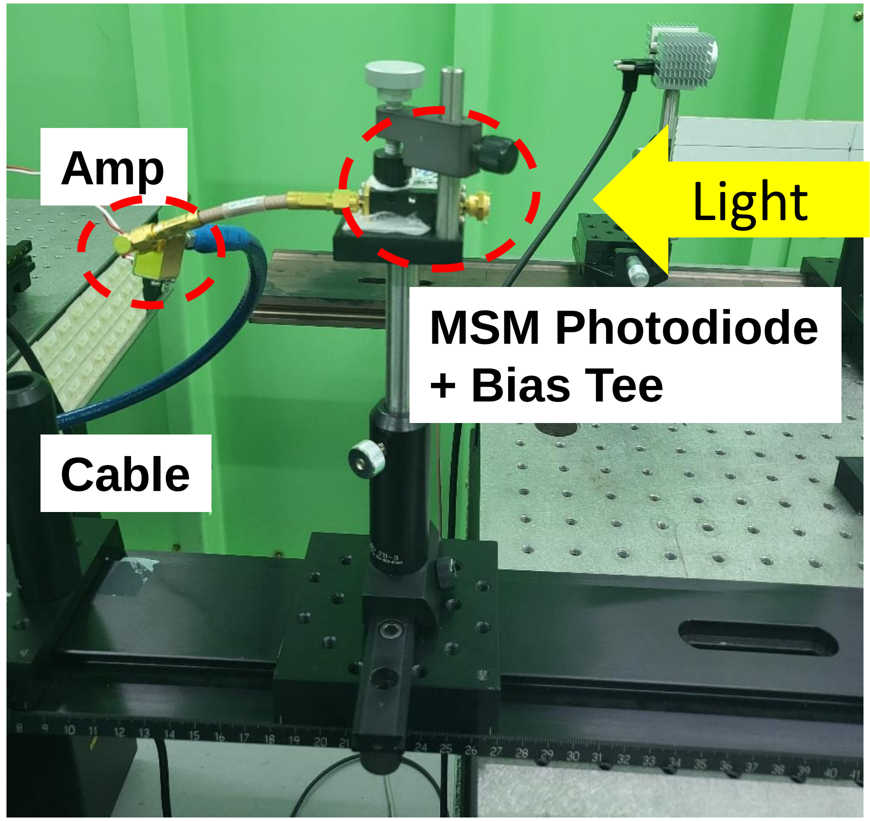
Experimental Setup



Component	Input BW
Photodiode	**10 GHz**
Bias Tee	26 GHz
Amplifier	14 GHz
Cable	26.5 GHz
Digitizer	**16 GHz**



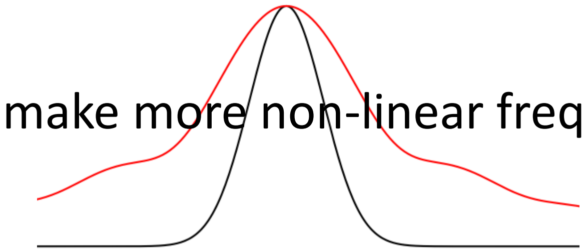
P. R. Berger, 1996



Schottky diode's potential barrier MSM → Rise time ~ 35 ps @ 7 V bias (G4176-03 Hamamatsu)

The diode's Point Spread Function is still much larger than the real bunch length.

And other RF components make more non-linear frequency response



→ Signal processing method is mandatory for precise reconstruction.

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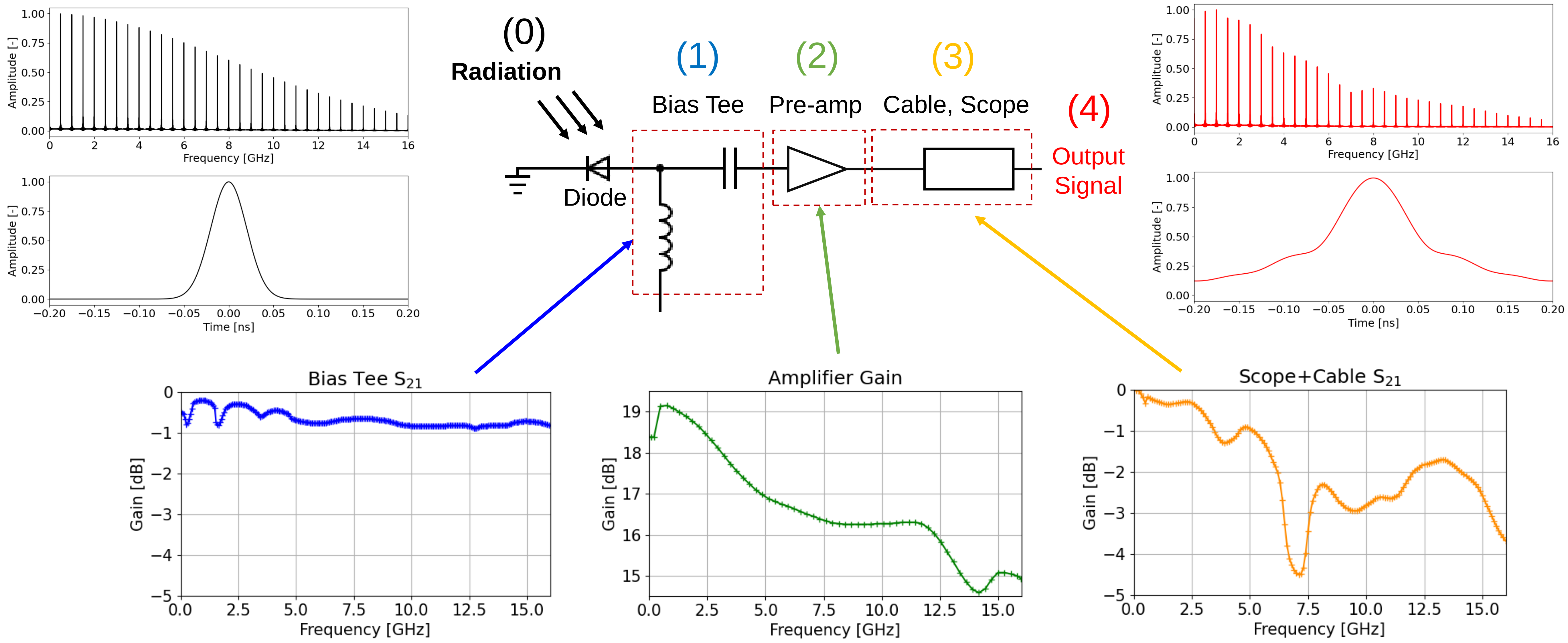
Frequency Response for Each Device



→ The measured signal is distorted strongly by the frequency response of analog components.

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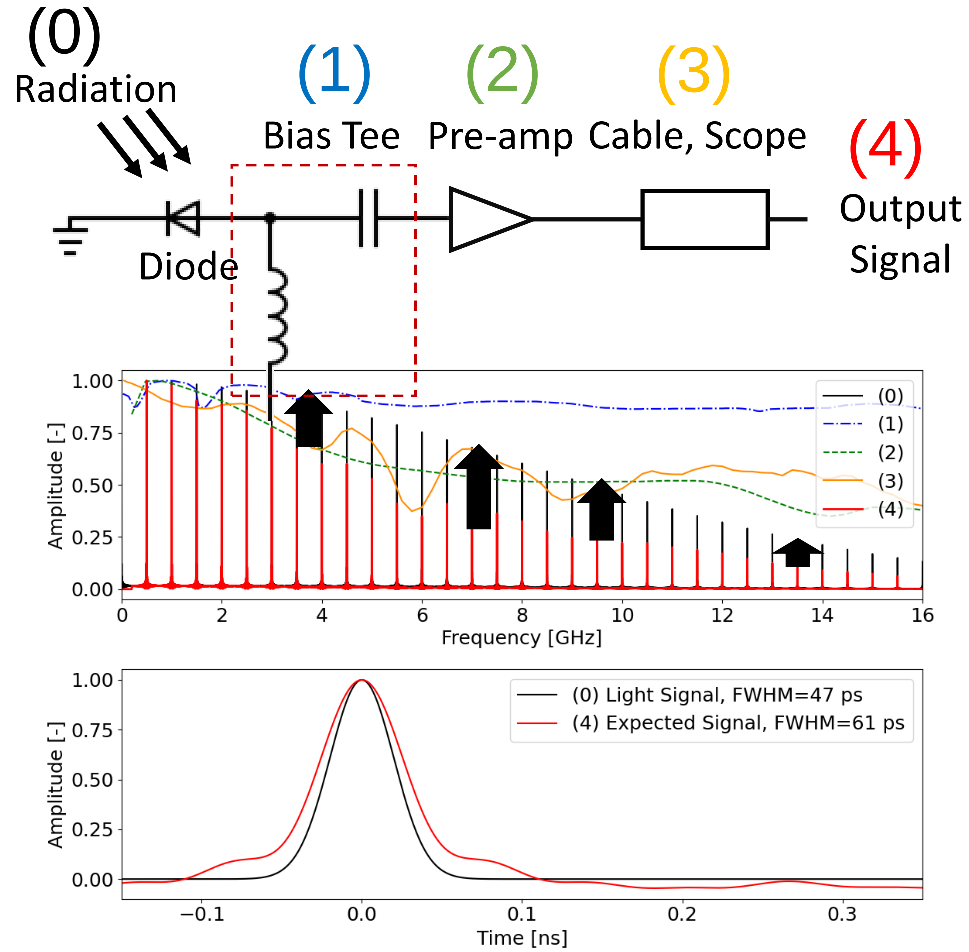
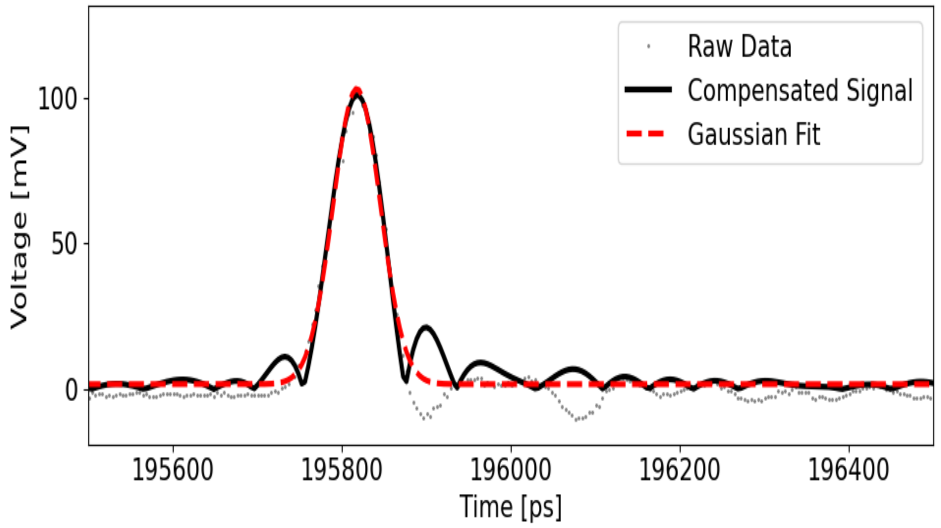
Frequency Response Compensation vs Gaussian Deconvolution

	Frequency Response Compensation (A)	Gaussian Deconvolution (B)
Pros	• Still fast & accurate	• Very fast
Cons	• Frequency response can be changed according to circumstance. (ex. Temp, Connection …)	• Inaccurate (Contains error due to Gaussian assumption)



[Procedure for A]
Compensation (FFT→IFFT)
→ Gaussian fit → done



[Procedure for B]
Gaussian fit → $\sigma_y^2 = \sigma_x^2 + \sigma_h^2$ → done

$$y(t) = x(t) * h(t) = \int x(\tau)h(t-\tau)d\tau$$

System response function
: $h_{sys} = h_{PD} * h_{bias\ T} * h_{amp} * \cdots$

$$\sigma_y^2 = \sigma_x^2 + \sigma_h^2$$

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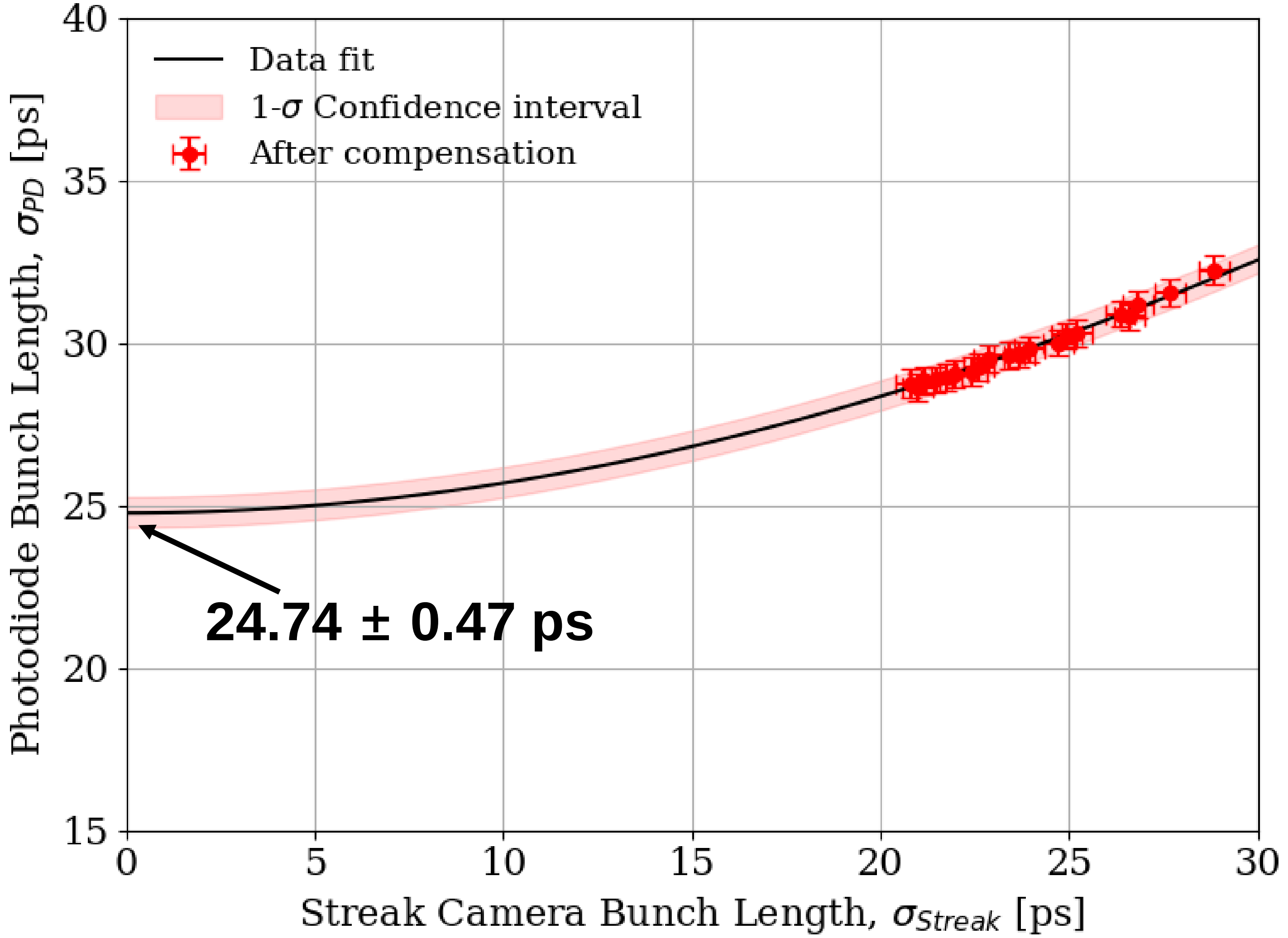
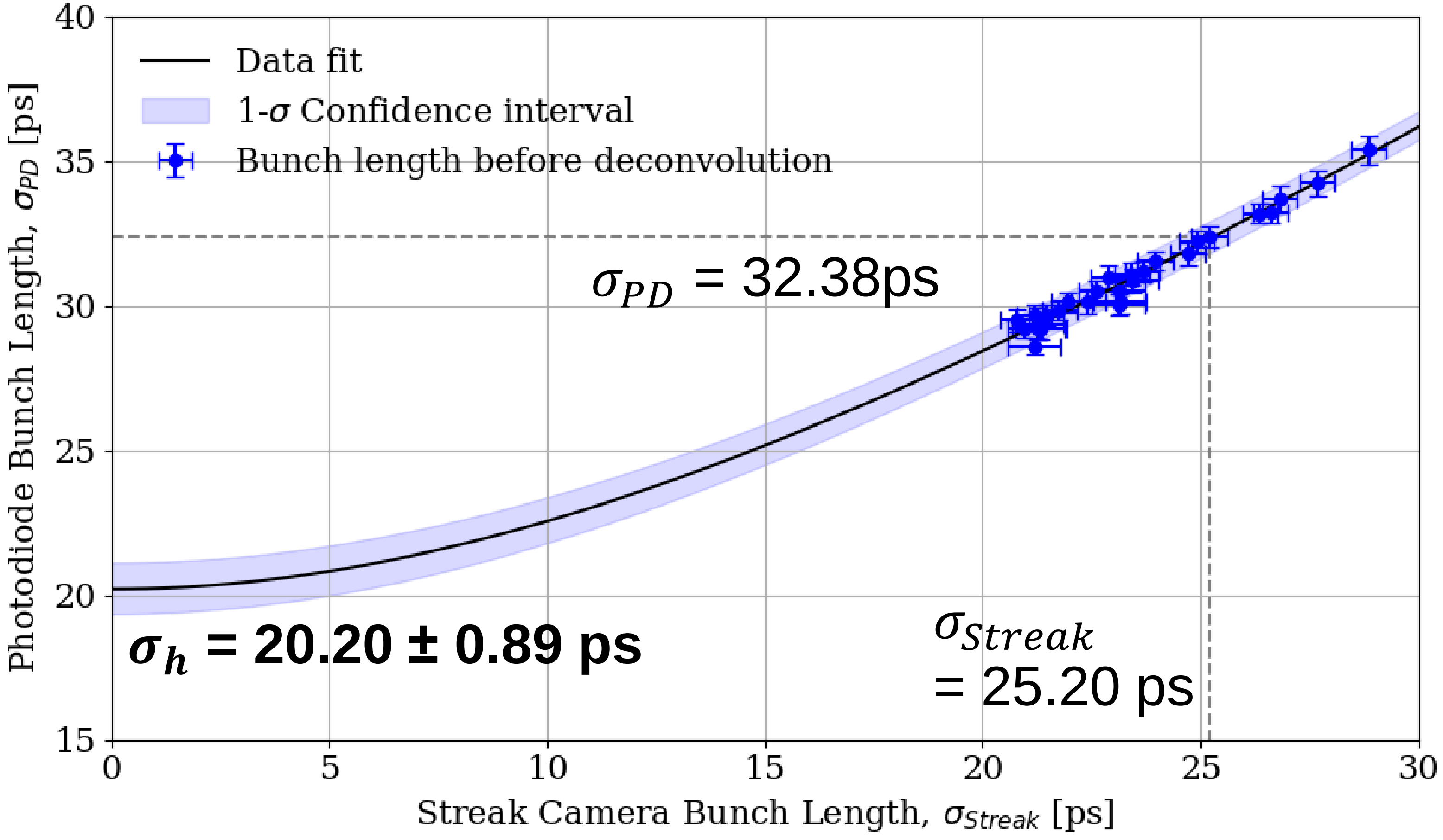
Frequency Response Compensation vs Gaussian Deconvolution





$$\sigma_{PD} = \sqrt{\sigma_{PD}^2 - \sigma_h^2} = \sqrt{(32.38\,ps)^2 - (20.20\,ps)^2}$$

$$= 25.31\,ps$$ *(Ln. beam size)*

$$\sigma_{Streak} = 25.20\,ps$$

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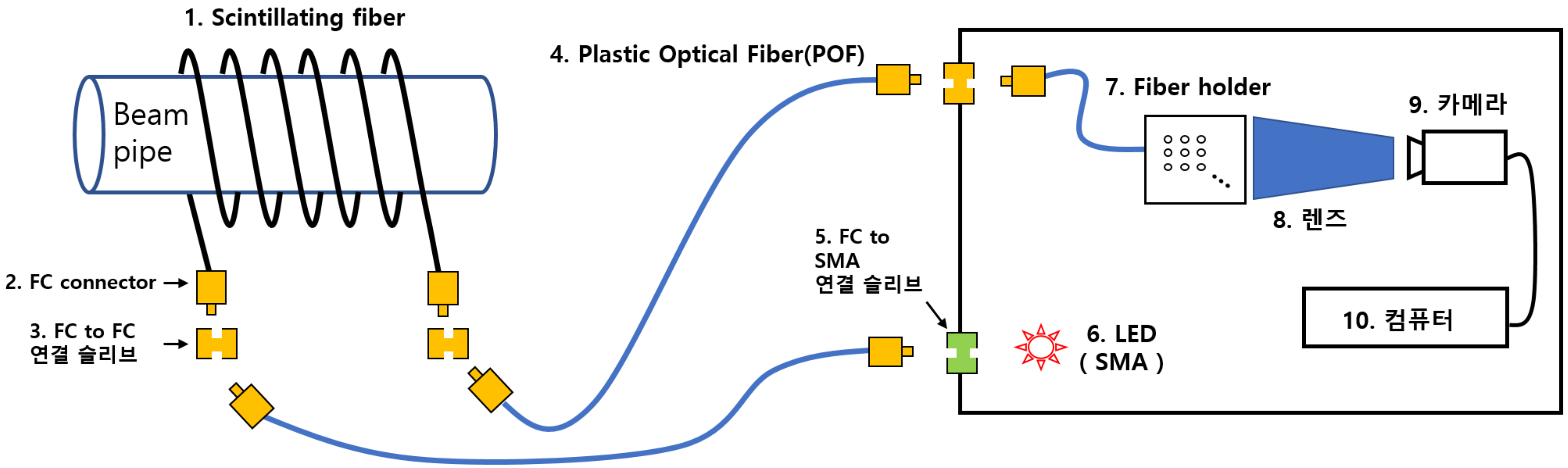
Cheap & Easy-to-Make Beam Loss Monitor Development

Cheap & Easy-to-Make Beam Loss Monitor Development

- 100 Sample/sec/ch x 32ch of BLM was developed by using scintillation fibers and CMOS camera
- Possible to detect beam loss location with a millisecond-level temporal resolution
- The main idea originated from PSI; IBIC2021, C. Ozkan Loch et al., "CMOS BASED BEAM LOSS MONITOR AT THE SLS"



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Detector Hardware

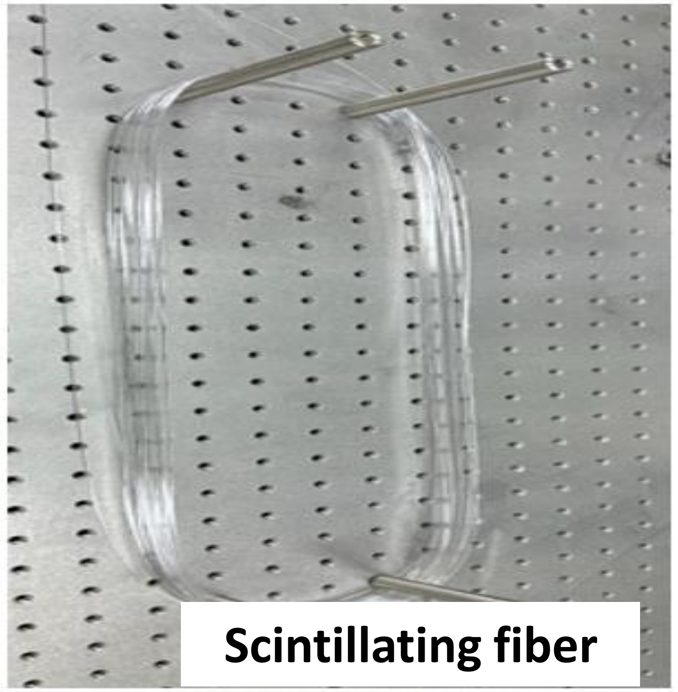
- **Fibers**

1. Scintillating fiber

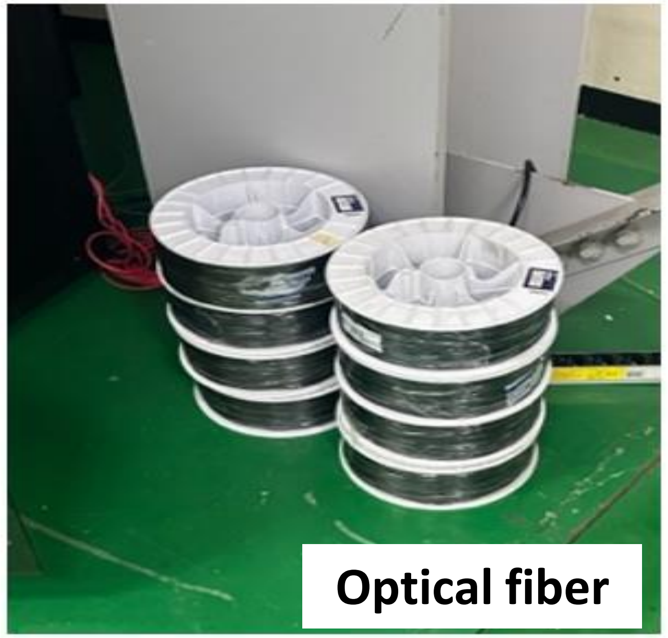
	Kurary (SCSF-78)	Saint-gobain (BCF-12)
Diameter [mm]	1	1
Min. Bending Dia. [mm]	~ 80	~ 100
Emission peak [nm]	**450**	**435**
Decay time [ns]	2.8	3.2
# of Photons per MeV*	High	~ 8000

* Only saint-gobain quotes the light yield.
** As both companies only offer raw fiber, the use of a fiber installation box is necessary.

2. Optical fiber
   - 1 mmD optical fiber was used
   - black-jacketed optical fiber for blocking external light
     - → only one company's product is available (TORAY)



Scintillating fiber



Optical fiber

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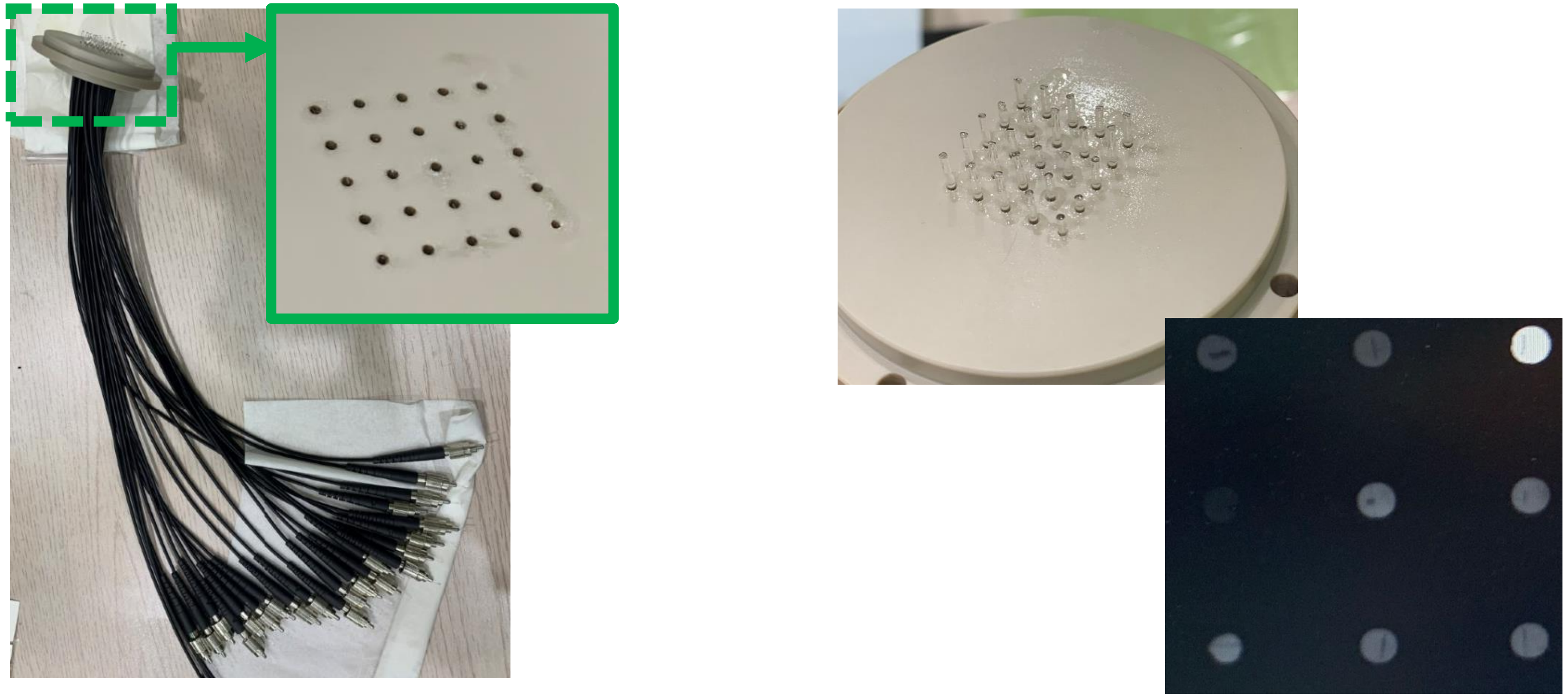
Monitoring Screen



Fiber holder (left) and polished cross-section of array-side (right)

- **Fiber holder**
  - 5 x 5 array for multi-channel analysis
  - FC connector part is polished using dedicated polishing tools
  - Some damage on fiber of 5 x 5 array component due to a careless polishing by hand

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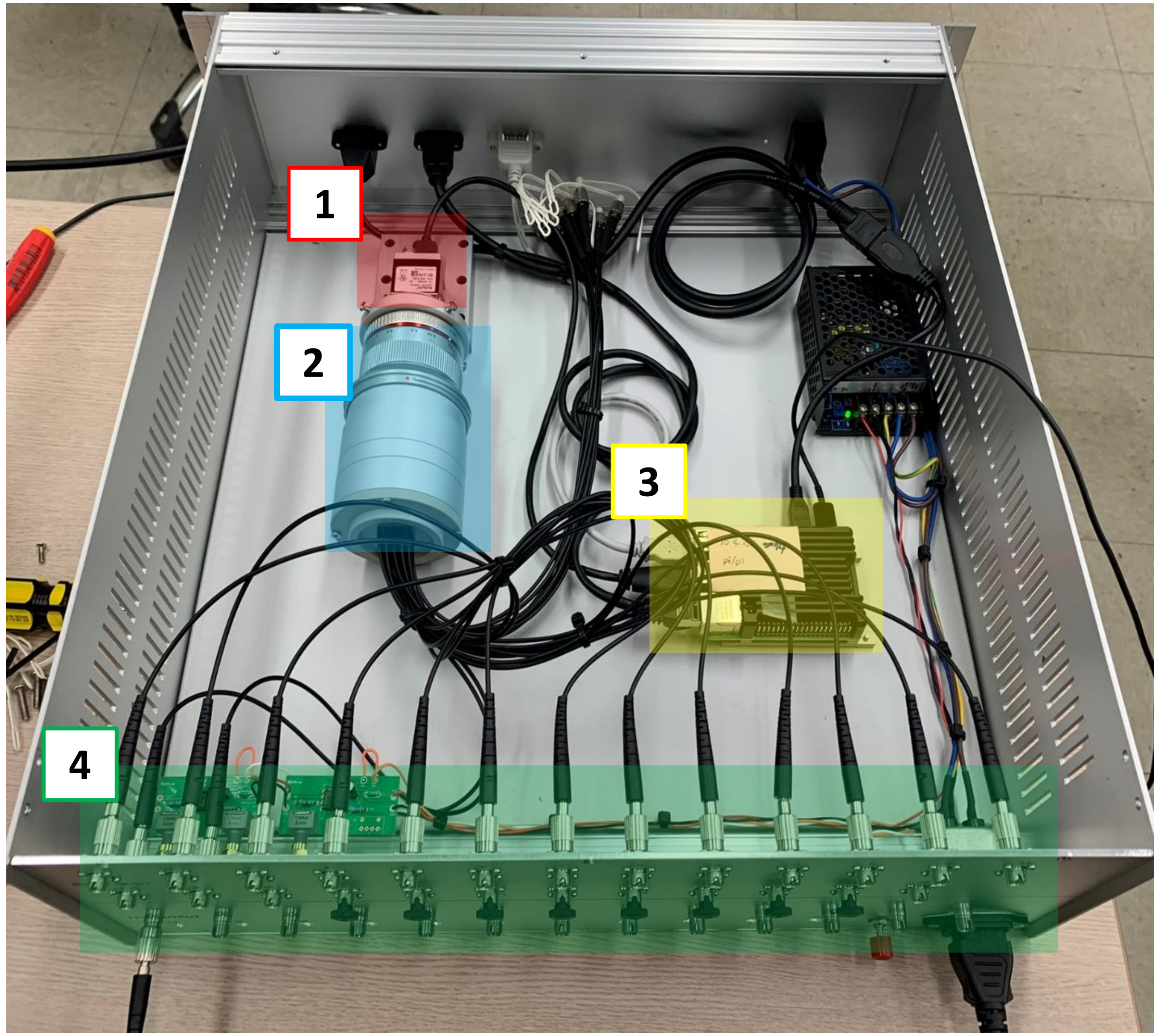
Combination of Read-out & Processing Modules



1. Camera
2. Fiber holder + lens
3. Raspberry Pi 4
4. Fiber/LED Connectors

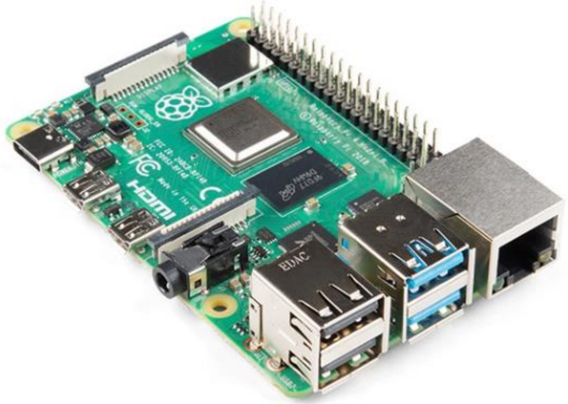
Reference paper : Ozkan Loch, C., Ischebeck, R., & Stampfli, A. (2021). CMOS Based Beam Loss Monitor at the SLS. Proceedings of the 10th International Beam Instrumentation Conference, IBIC2021, Rep. of Korea. https://doi.org/10.18429/JACOW-IBIC2021-TUOB02

Electronics & Control Platforms

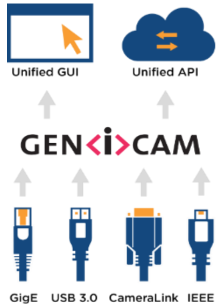
- Camera

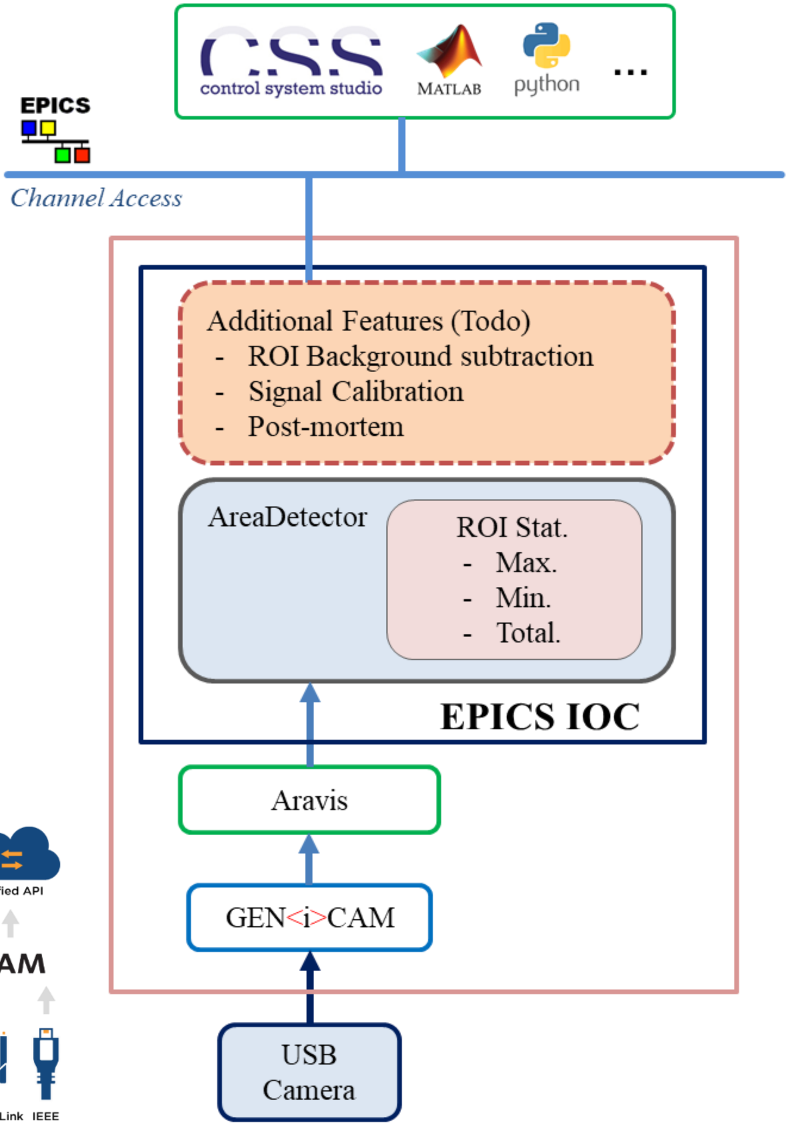
Model	Basler acA720-520um
Interface	**USB 3.0**
Sensor	IMX287 CMOS (1/2.9")
Sensor Resolution	720 px x 540 px
Max. **Frame Rate***	**525 fps**
Pixel Bit Depth*	8/12 bits
QE	**~ 60 % at ~ 450 nm**

- Processor
  - Raspberry Pi 4



- Control
  - EPICS + Area Detector Module

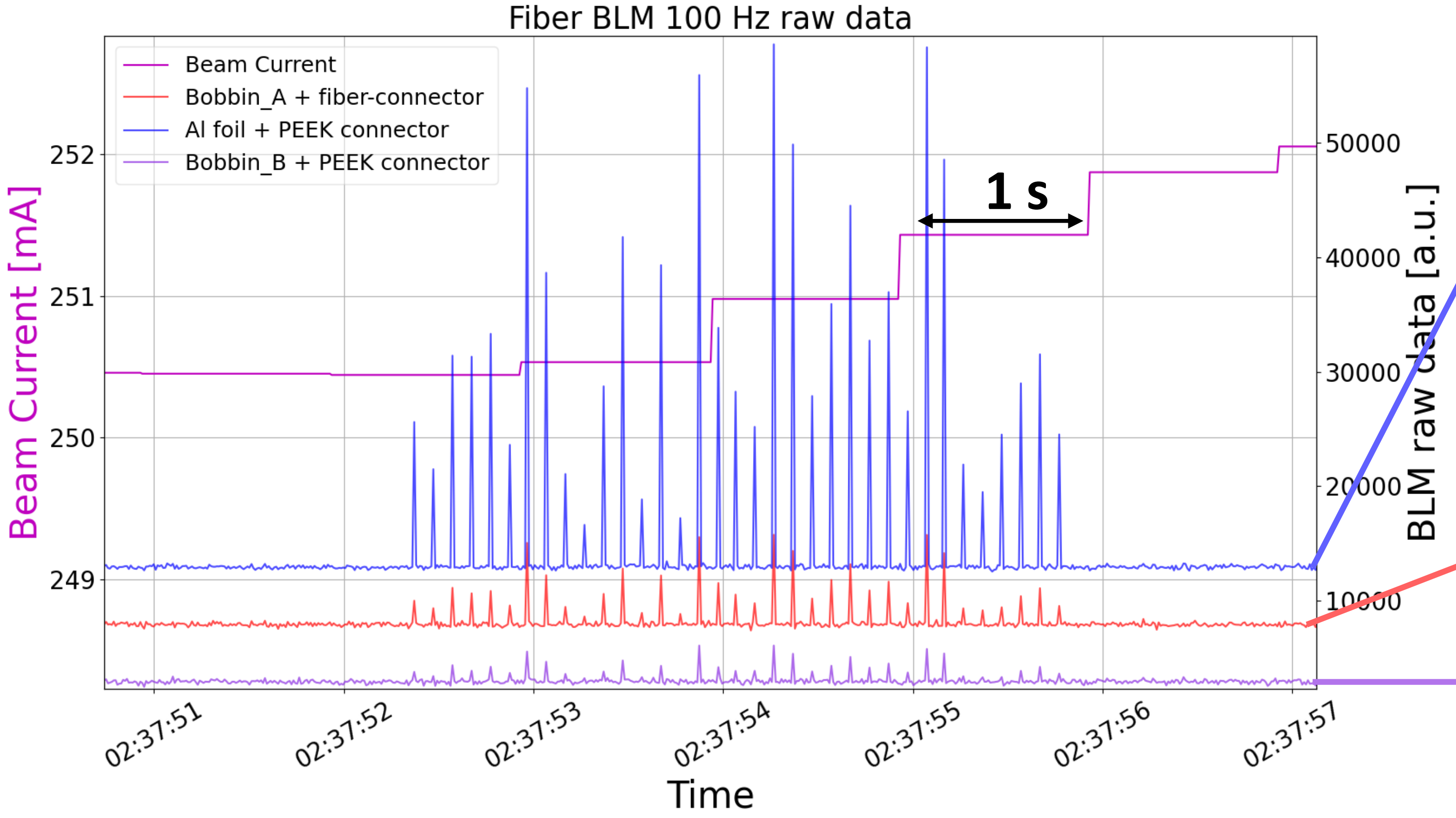


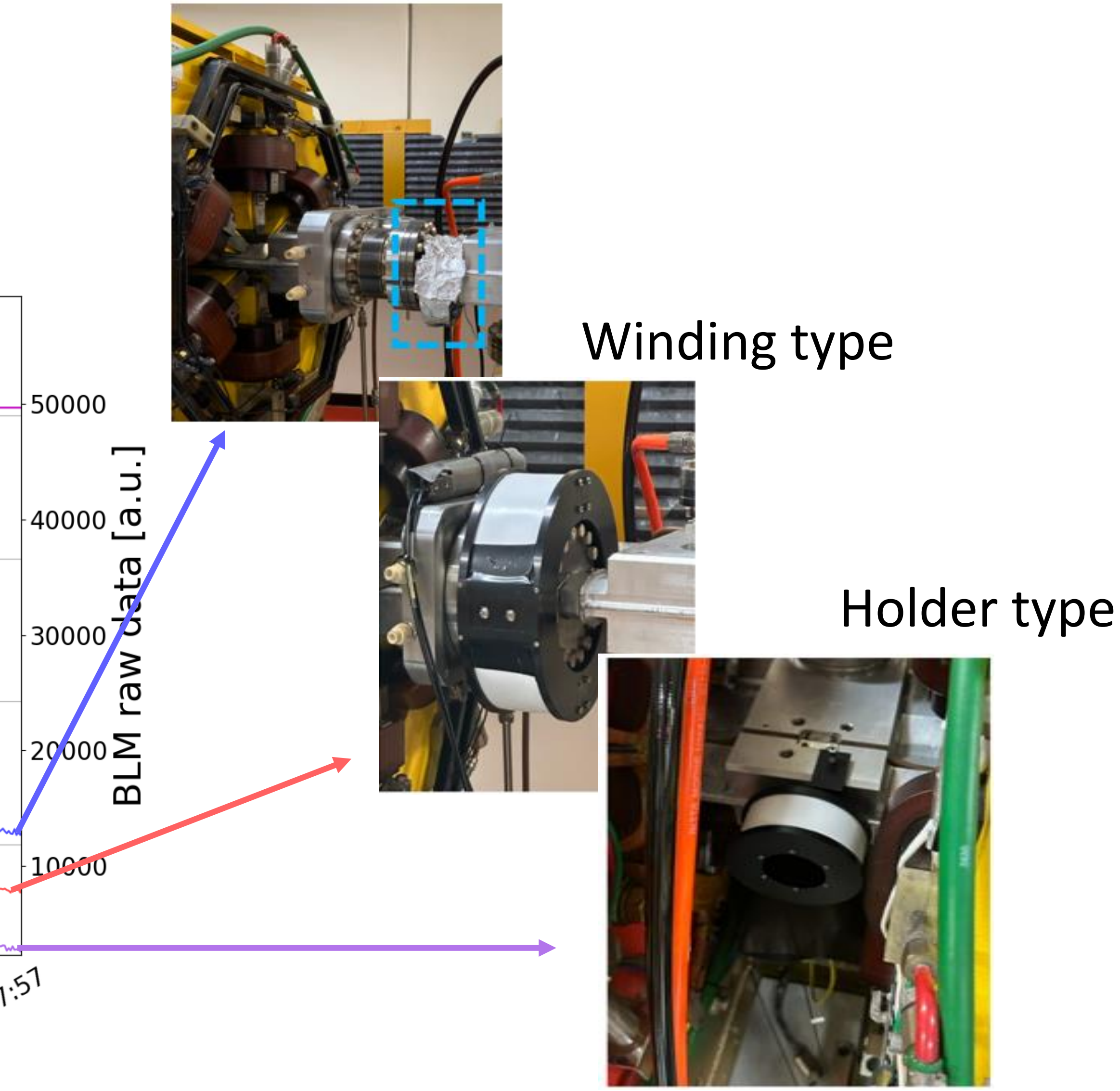


DAQ layout

Test results

- Beam loss was well measured every 10 min. when the top-up injection
- We will install this BLM to overall our accelerator facility soon
  - Three read-out modules and about 100 detectors



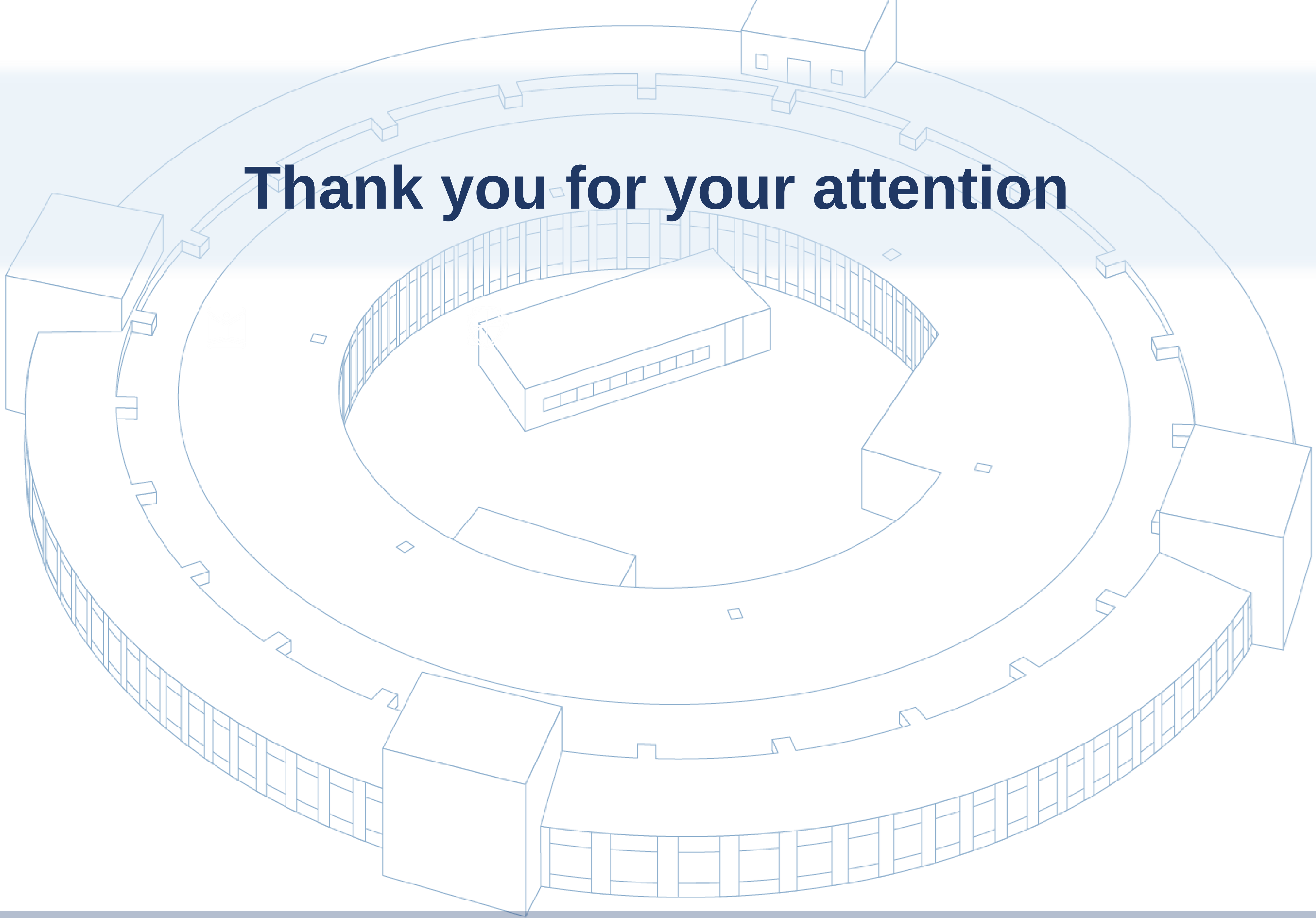


Beam loss signal when an electron beam is injected

Summary

- Since late 2021, Korea-4GSR Project (diffraction limited storage ring construction project) has been conducted by two institutions with 750M USD
  - KBSI (Korea Basic Science Institute) for facility construction
  - PAL for the accelerator and beamline construction
  - The energy of 4 GeV, circumference of 800 m, and natural emittance of 61 pm
- Two types of beam diagnostic devices were recently developed and tested
  - We have experimentally demonstrated an online bunch-by-bunch diagnostics that enables **filling pattern** (~ 3 μA resolution) and **bunch length** (~ 1 ps resolution) monitoring with visible light at the PLS-II storage ring
  - A cheap and easy-to-make beam loss monitor (100 sample/sec/ch x 32 ch) was quickly developed, installed, and worked well.

Thank you for your attention



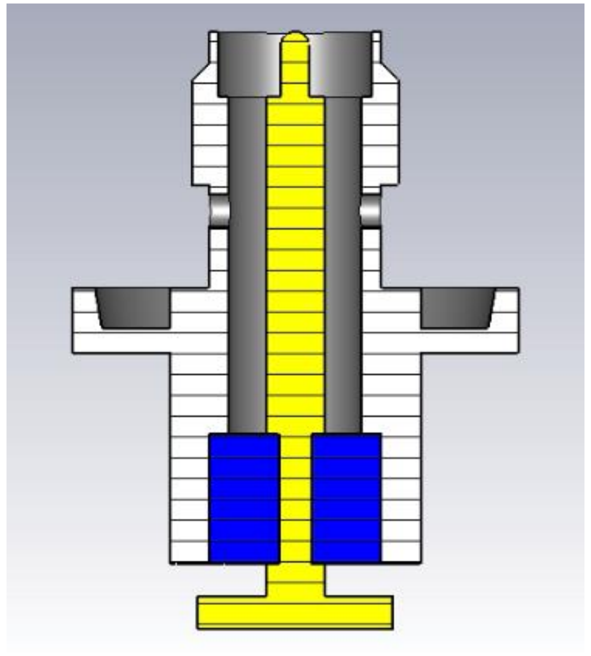
Backup slides

Beam Position Monitoring

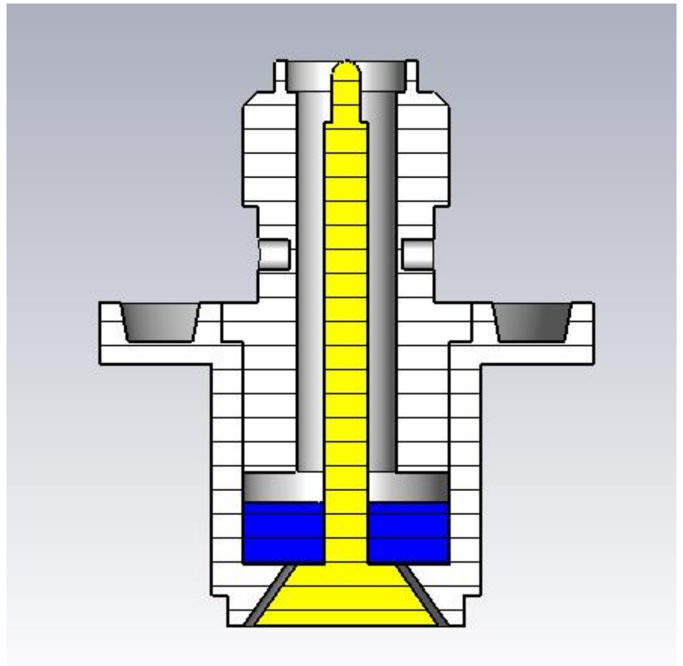
- Two types were designed & Ready for prototyping
  - A : Borosilicate Glass, B : Alumina Ceramic
- Max. temperature rising and trap modes were evaluated and optimized by 3D FEM simulations.

Power dissipation Per button	Type A (PETRA IV & VESSY)	Type B (SIRIUS & SOLEIL-II)
54ps	< 0.1 W	< 0.1 W

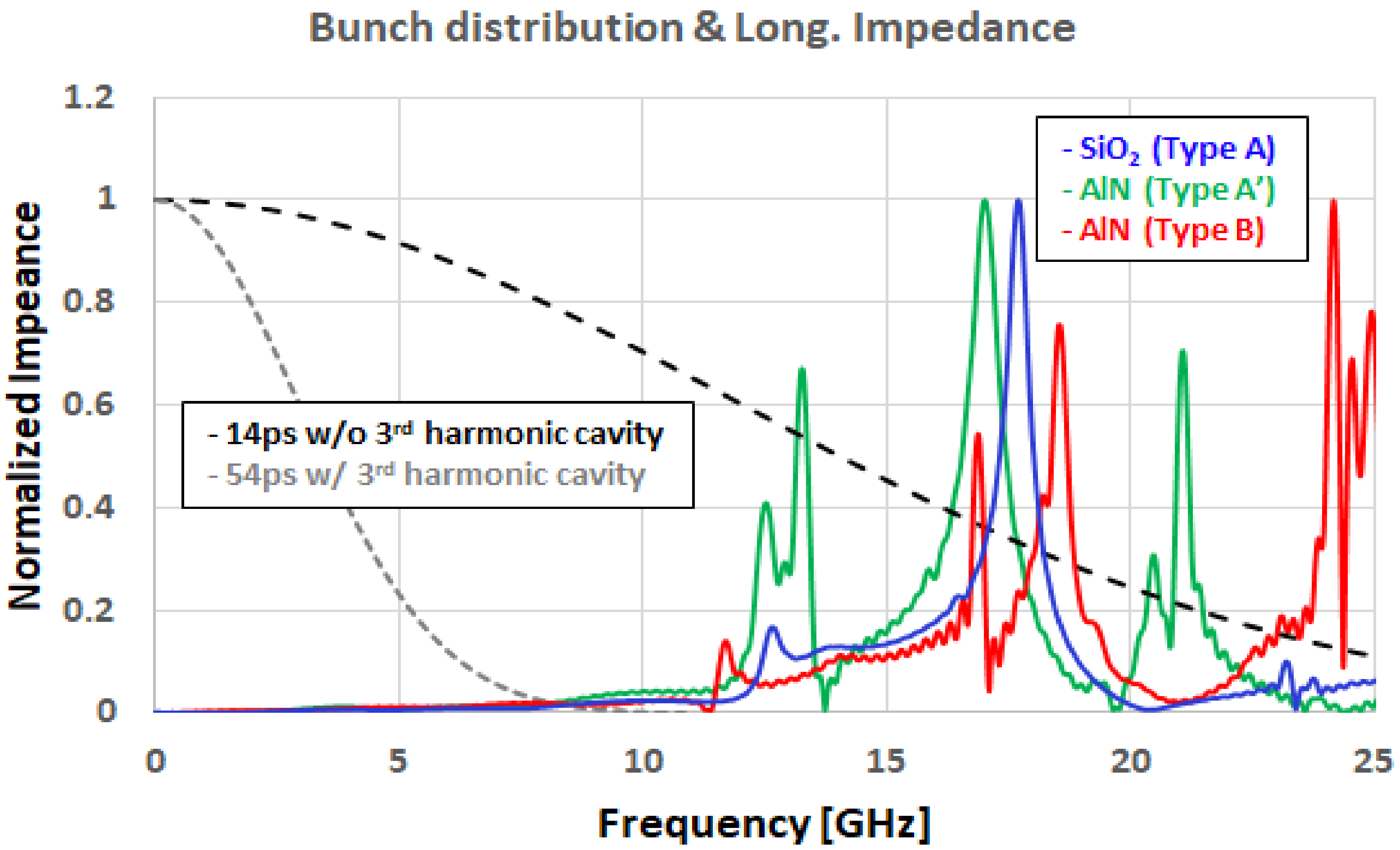
Special Case (w/o harmonic cavity) : Type A 1.5 Watt, Type B 0.5 Watt



Type-A
(Borosilicate Glass: e=4)



Type-B
(Alumina Ceramic: e=9.9)



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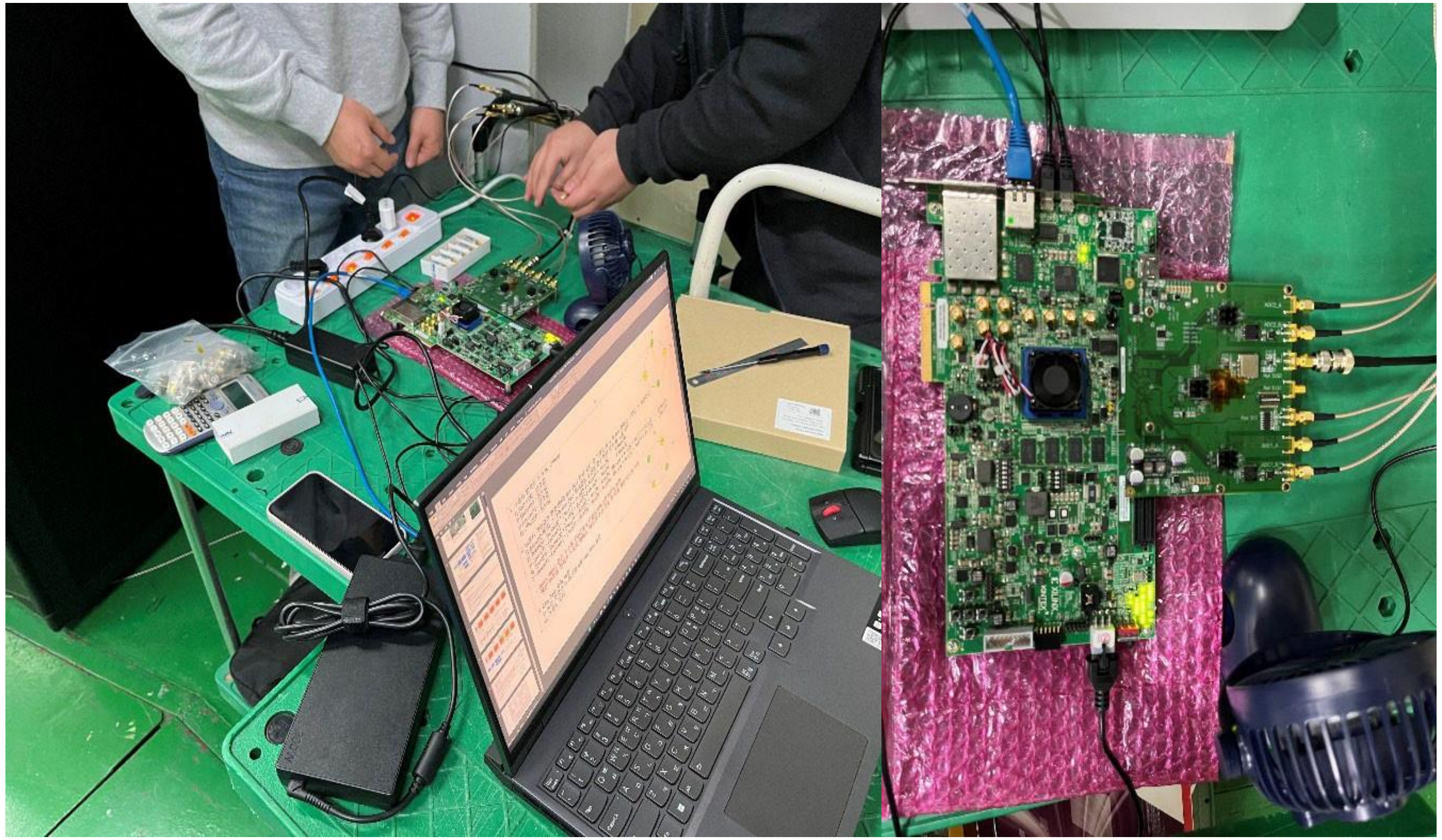
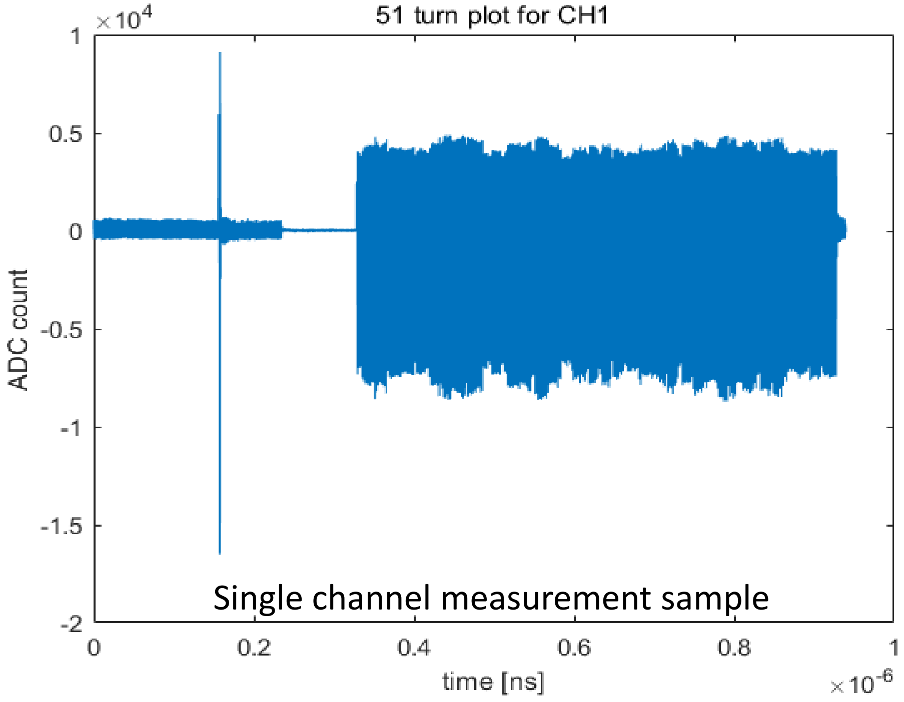
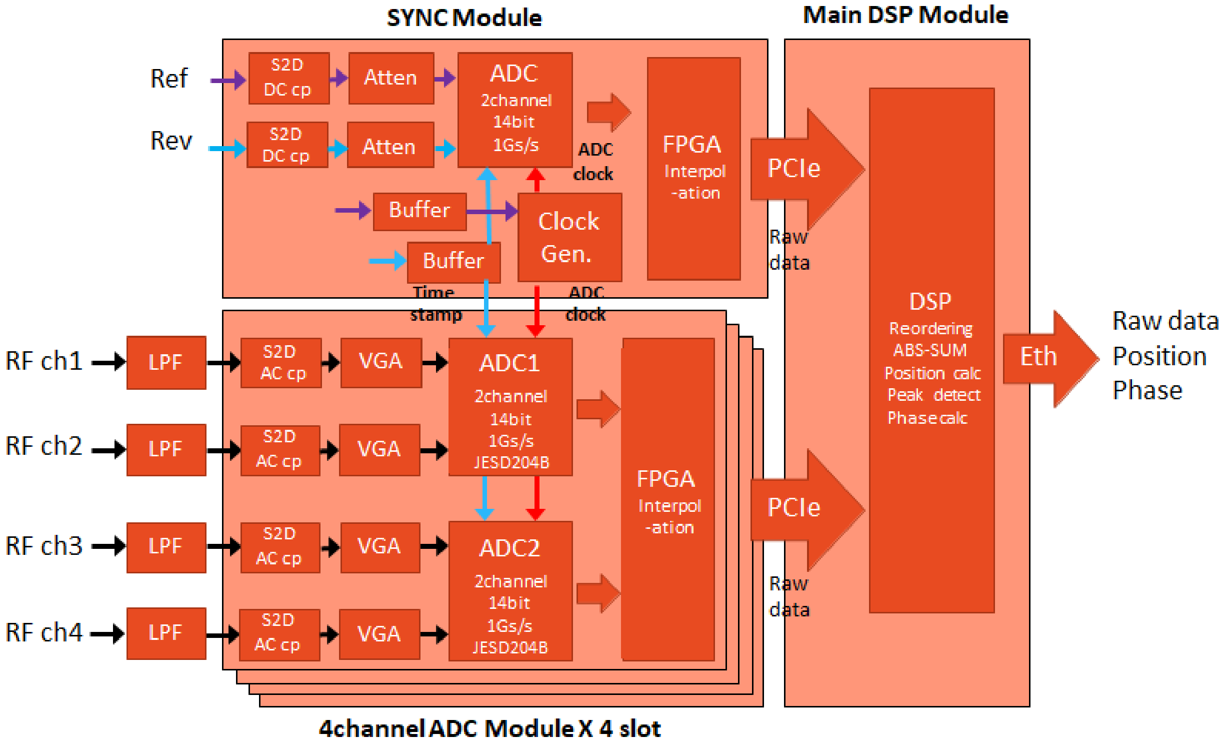
BPM Electronics Development

- 1 GS/s, 14-bit ADC, Time domain BPM electronics development is on-going
  - Simple read-out module >> BbB analyzing module >> TFS/LFS module





Single channel measurement sample



Schematic Diagram of Functionality

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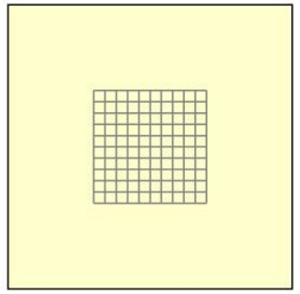
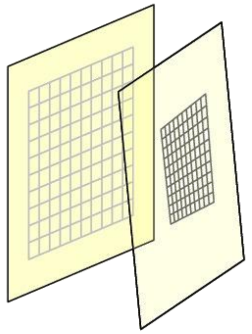
BPRM

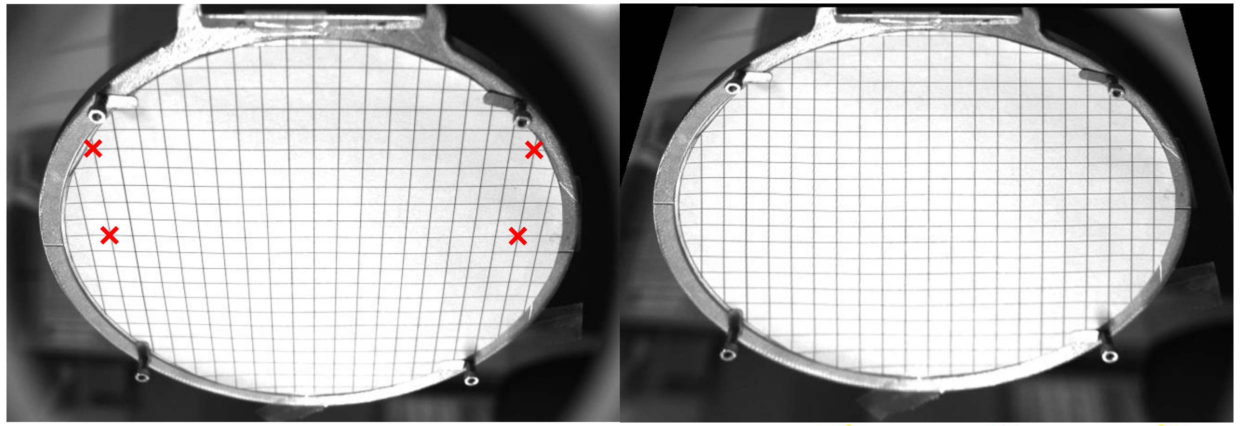
- The same technology used in PLS-II will be adopted
  - Position calibration method with +-50 um resolution
  - Image processing code & control service code
- New technique will be developed
  - OTR : silver coated wafer
  - Vacuum chamber : multi-purpose identical chamber
- Locations
  - Many units will be installed in LINAC, LTB, BTS for beam matching
  - One or two units will be installed BR, SR for first-turn measurement

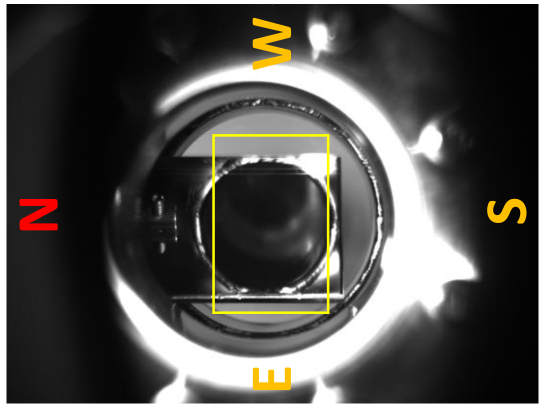


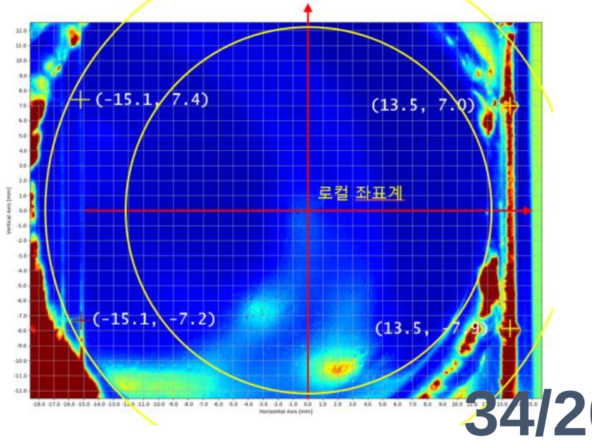


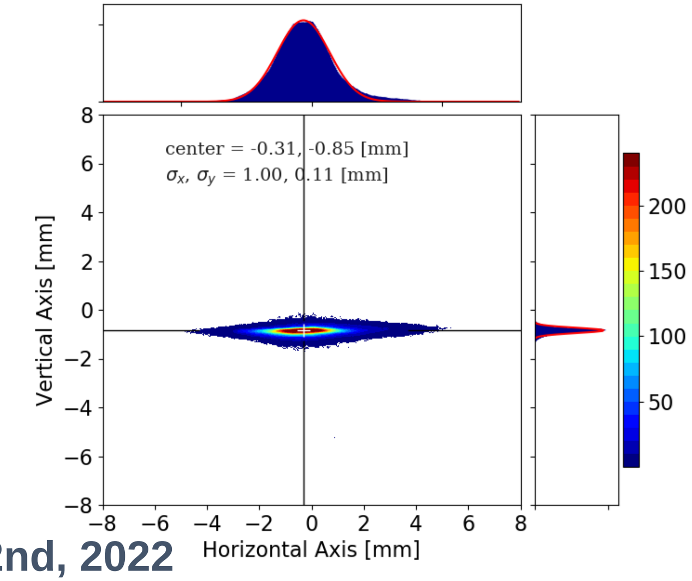
$$w_0 \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & j \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

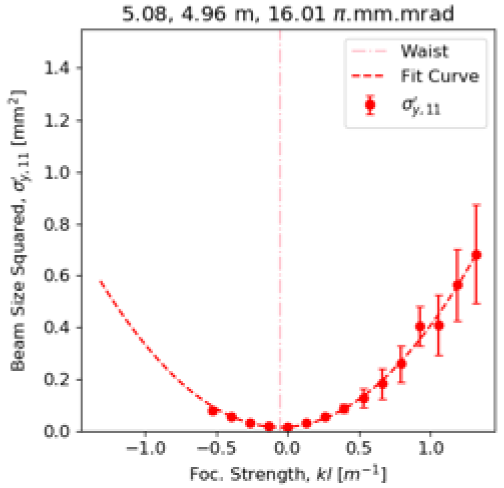
$$(x, y) \mapsto (u, v) = \left(\frac{ax + by + c}{gx + hy + j}, \frac{dx + ey + f}{gx + hy + j} \right).$$











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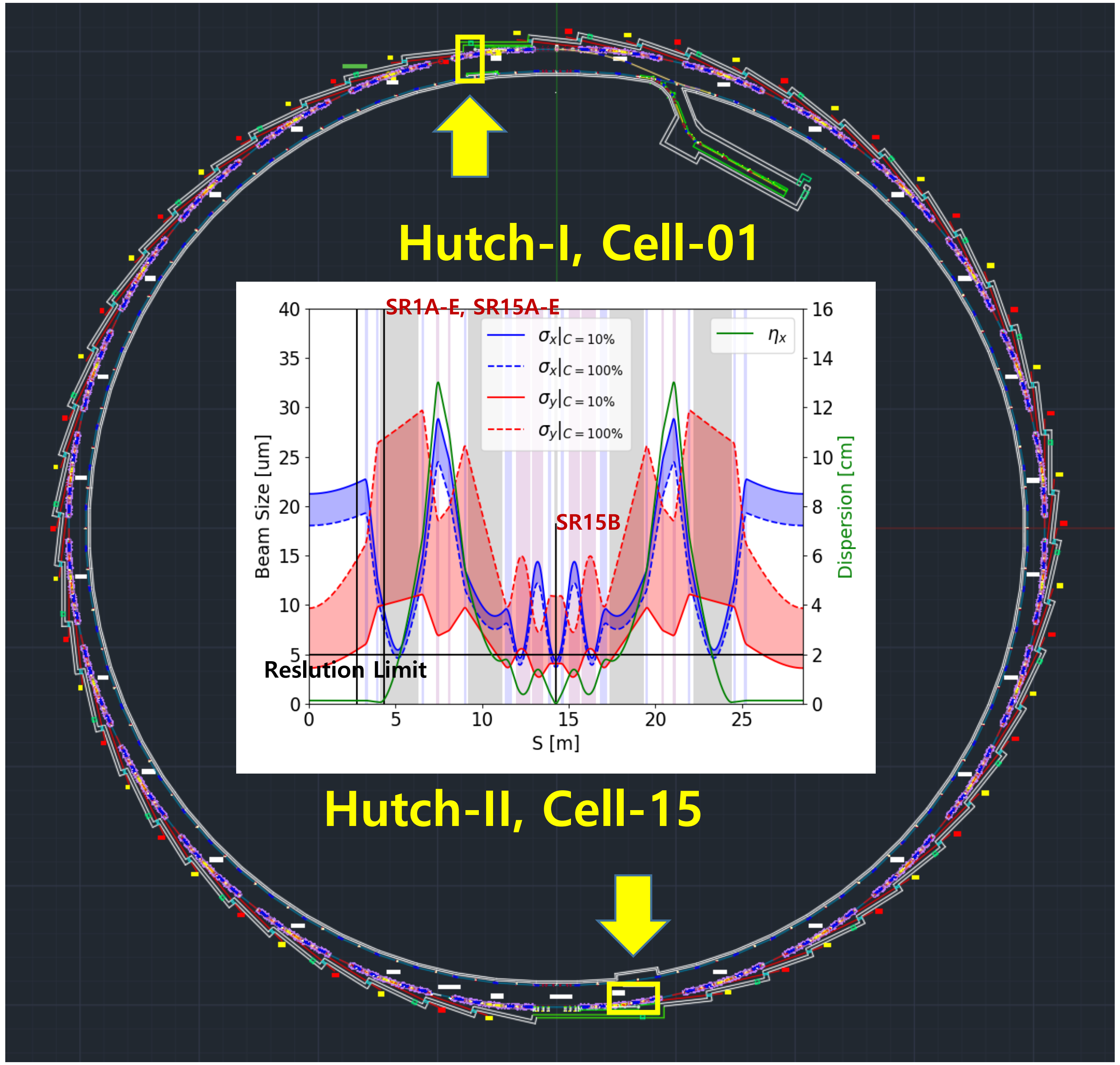
Diagnostic Beamlines (Beam Size, Emittance, Bunch Length, Fill-pattern)



- **Beamlines and hutches**
  - Located on the rooftop of the tunnel
  - The number of mirrors will be minimized to reduce wavefront error → for accurate beam size & emittance measurement
  - Use of visible light for easy build and maintenance
- **Light sources**
  - [**SR1A-E, SR15A-E, BR1**] Beam size, emittance, mechanical vibration by using a visible light Interferometer
    - **SR1A-E, SR15A-E :** Bending magnet (LGB, 0.7 T) : almost dispersion free, right after the long straight section
    - **BR1 :** Bending magnet (booster synchrotron)
  - [**SR15B, BR1**] Online bunch length & fill-pattern, longitudinal beam instability by using a fast photo-diode
    - Beam instability by using Streak Camera
    - **SR15B :** Center-bend (main synchrotron)
    - **BR1:** Bending magnet (booster synchrotron), if needed

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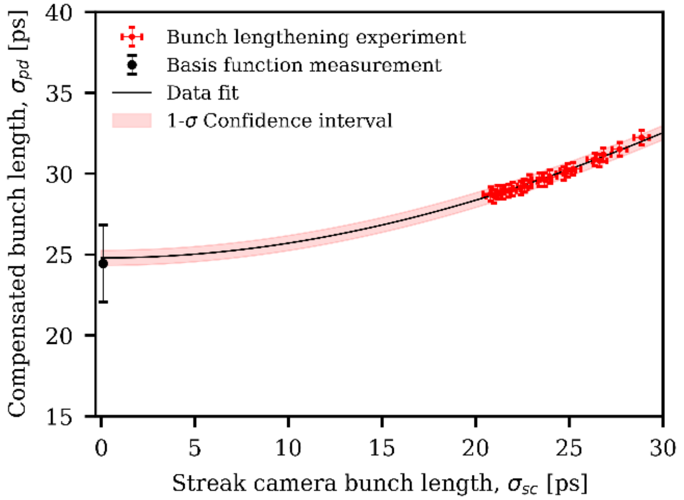
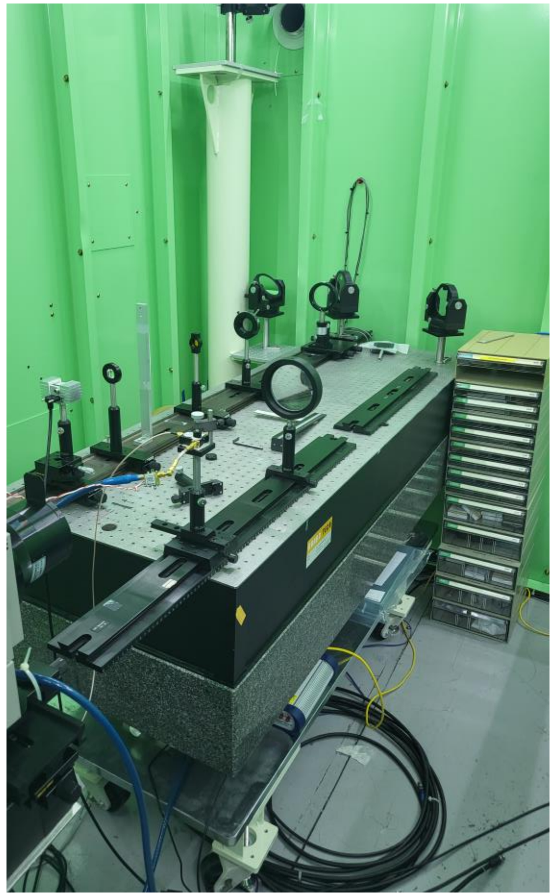
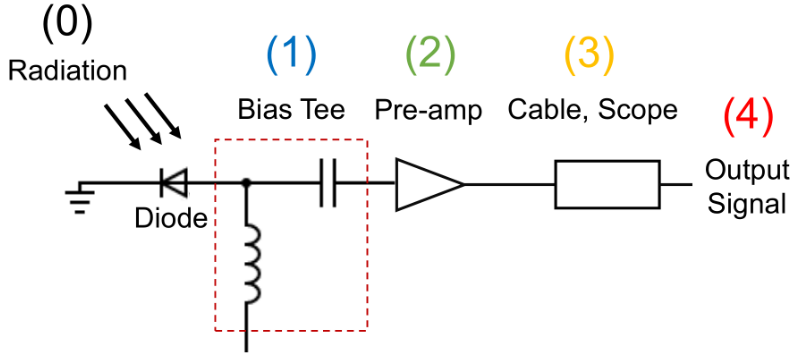
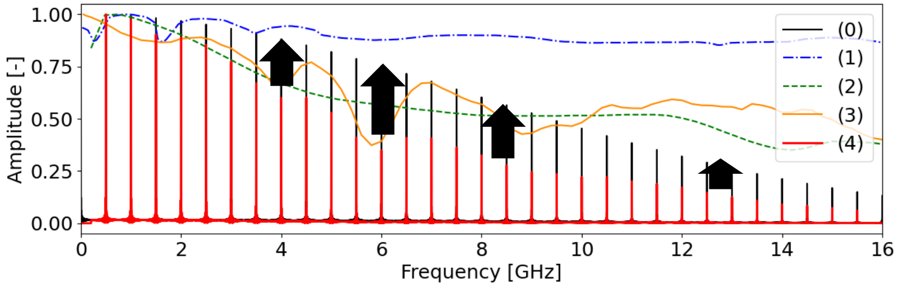
Online BbB Bunch Length Monitor

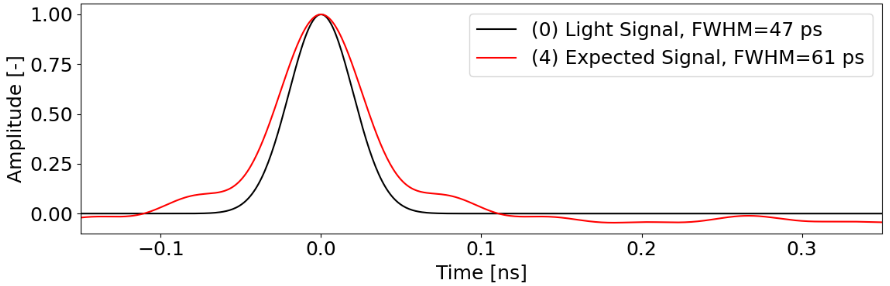
- Prototype finished. Currently operated in PLS-II. First upgrade is planned in 2023, for fast processing
  This will be used for Korea-4GSR
- Online monitoring of Bunch length (BbB), Longitudinal instability (in phase) & Filling pattern

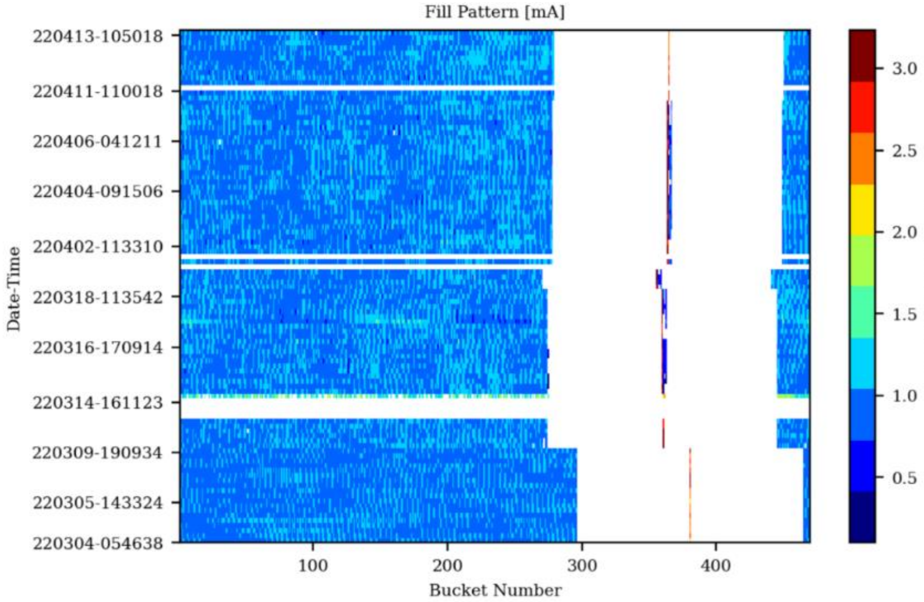


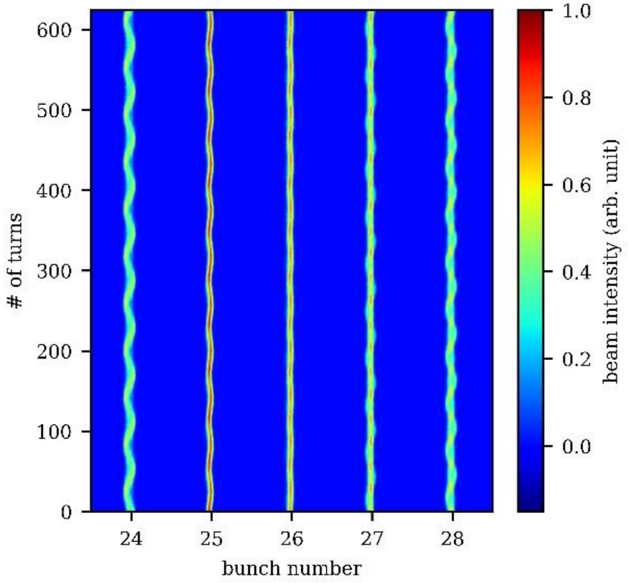






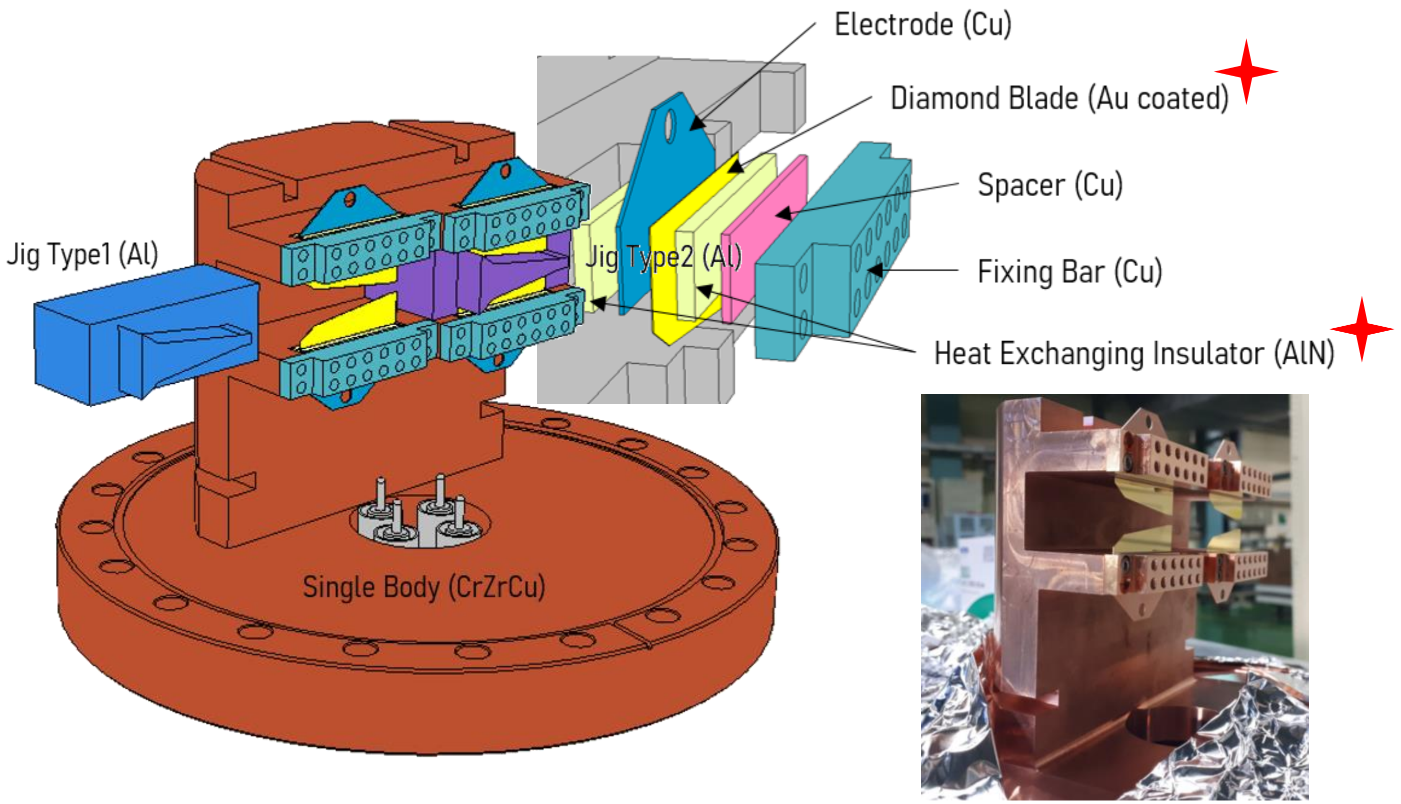




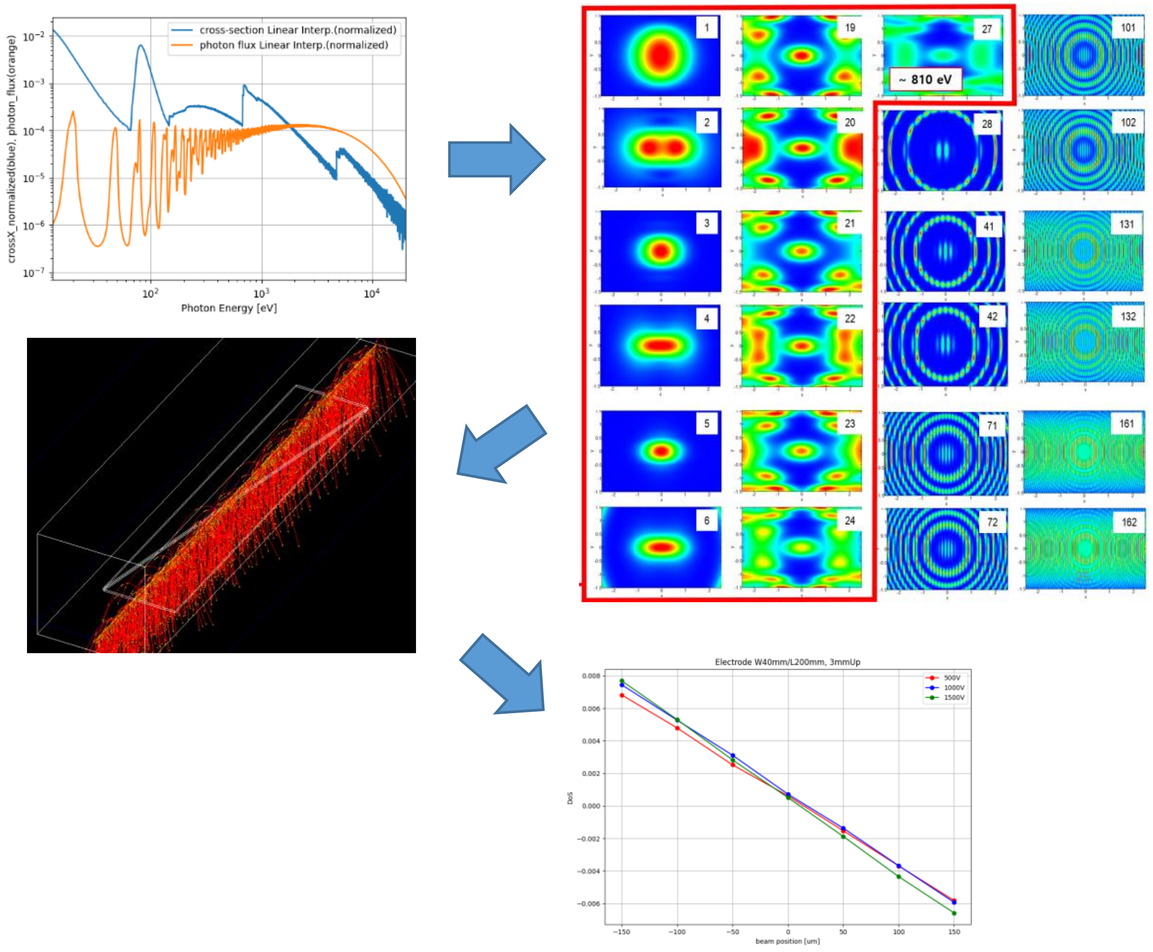


Photon Beam Position Monitor

- Diamond Blades (Hard X-ray)
  - Development completed (Installed in PLS-II, since 2020)
  - Available to scan full range photon beam (low heat depo.)
  - R/O module : Libera-photon current integrator
  - Impossible to remove a contamination photon generated by up/down-stream bending magnet, that is moving by SOFB



- Gas chamber (Soft X-ray)
  - In progress, build-up simulation process, and design optimization
  - Almost no contamination effect
  - Both center of charge and profile can be measured



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