Development of High-Precision Beam Position Monitor for the Korea-4GSR project

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4GSR Beam Diagnostics Group, PAL

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Introduction

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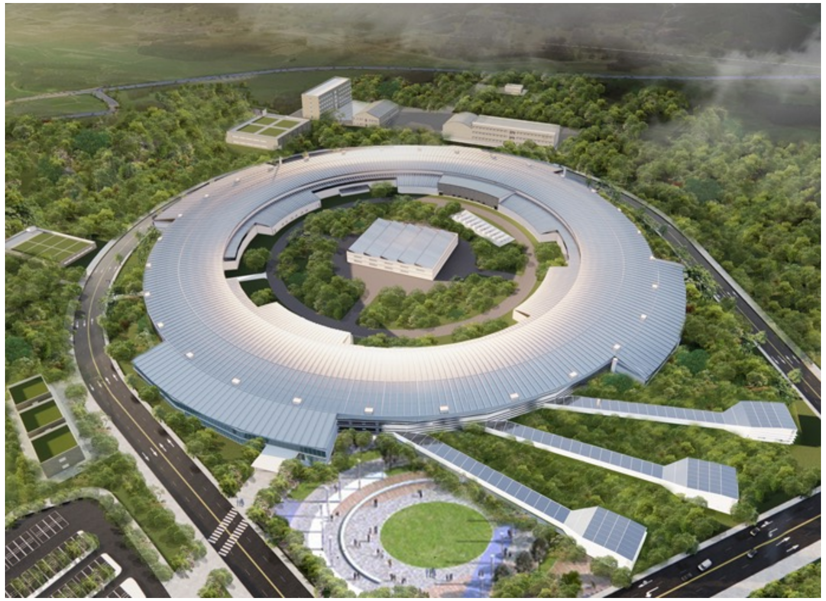
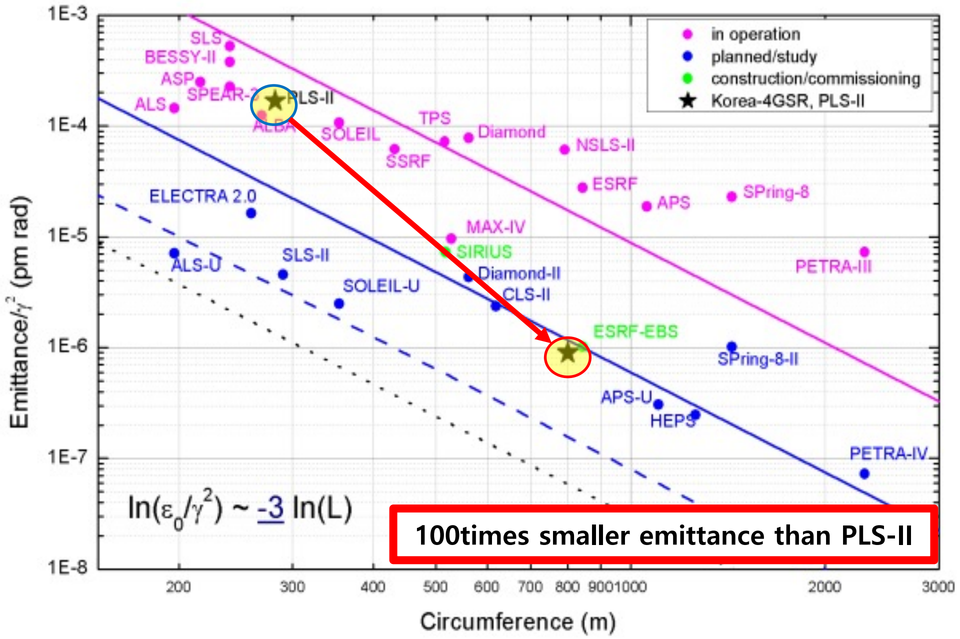
A requirement of new Beam position monitor system for Korea 4GSR





High brilliance ⇨ **Small beam size**

⇨ **Precise & stable orbit control with sub μm resolution**

For the fourth generation storage ring, it's more precise,
more accurate, and fast processing beam diagnostic devices are required.

Introduction

Purpose of Beam test at PLS-II Storage ring with 4GSR BPM pick-up

- **Validation of Prototype Performance**: Conducting beam tests in the PLS-II storage ring to evaluate the performance of the 4GSR BPM pick-up prototypes.
- **Beam Stability Analysis:** Ensuring that the BPM design minimizes longitudinal wake impedance to reduce heating an d beam instability. Direct comparison is challenging due to the different chamber sizes between PLS-II and 4GSR.
- **Real-world Comparison**: Comparing results from the PLS-II tests with expected outcomes for the 4GSR project to ass ess the prototype's effectiveness.
- **Custom BPM Test Installation**: Due to differences in the beam pipe's inner diameter between the PLS-II and 4GSR de signs, a new test BPM was created and installed to match the dummy chamber specifications in cell 7.
- **Resolution Measurement**: Testing aims to measure and optimize beam position resolution, aiding in finalizing the 4G SR BPM pick-up design before mass production.

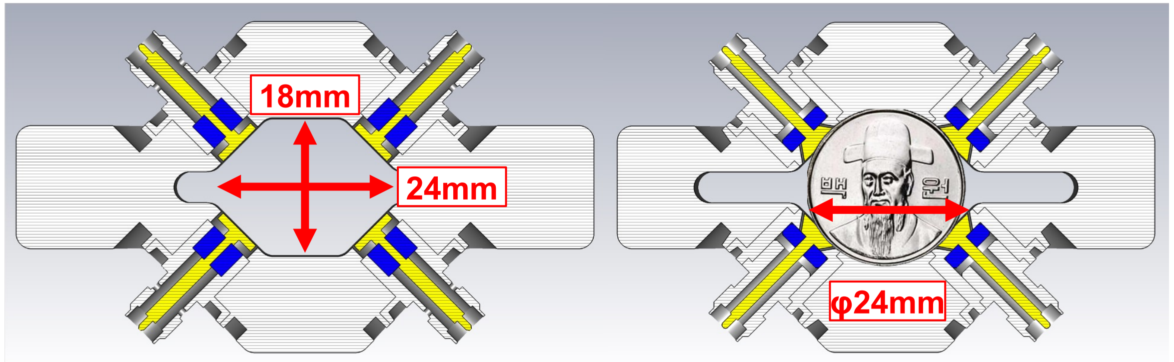
4GSR BPM development for Korea 4GSR

4GSR Button BPM development

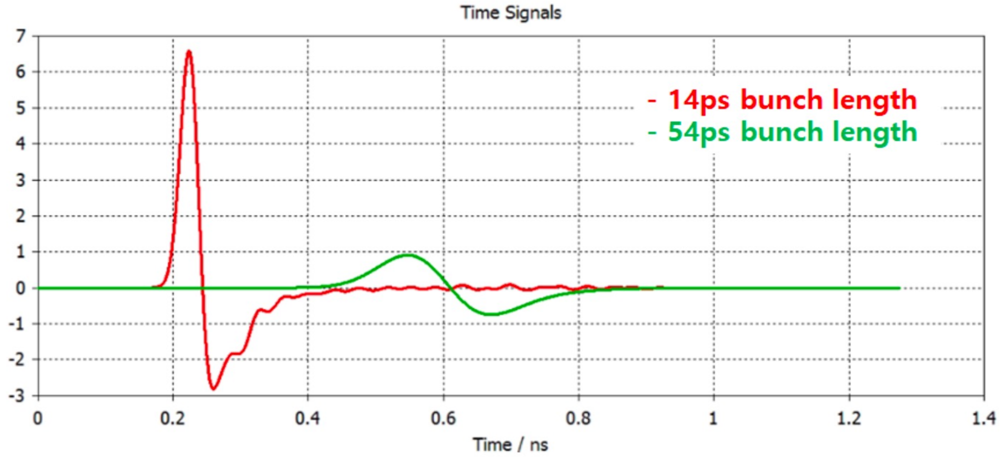
Development strategy of 4GSR Beam Position Monitor

Key Points of 4GSR BPM Pick-up Design:
1. Minimize longitudinal wakefields.
2. Address challenges with insulator materials (e.g., SiO2).
3. Suppress ringing signals within 2 ns for BbB feedback.
4. Ensure impedance matching for signal efficiency.
5. Avoid trapped modes in button gaps.
6. Enhance signal sensitivity for higher resolution.
7. Optimize signal strength based on bunch length.

Design Considerations:
- **Small Button Head**: Reduces wakefields but lowers signal strength.
- **Fixed Chamber Design**: Set by the vacuum group, limiting modifications.
- **Geometry**:
- **Storage Ring**: Octagonal shape.
- **Booster Ring**: Round shape.



SiO_2 Glass & Al2O3 Ceramic Feedthrough antenna BPM for 4GSR



Development of 4GSR BPM Pick-up

Fabrication of Button pick-up for 4GSR BPM

Two BPM pickup antennas have been developed for the 4GSR project:

1. **SiO_2 BPM**:
   - Uses a SiO_2 glass insulator (dielectric constant: 4).
   - Shifts longitudinal wake impedance to higher frequencies, reducing thermal loss and improving signal clarity.
   - Composed of molybdenum pins and housed in ASTM-F15 material.
2. **Al_2O_3 BPM**:
   - Features a cone-shaped design with an Al_2O_3 insulator (dielectric constant: 9.9).
   - Optimized to perform similarly to the SiO_2 BPM despite its higher dielectric constant.
   - Contains titanium pins and is enclosed in SUS316 stainless steel.

Optimization:

- Extensive 3D simulations were used to minimize ringing and enhance beam position resolution.

Proto-type Fabrication

TDR & Tolerance Measurement of 4GSR BPM Pick-up Antenna

TDR & Tolerance Measurement of 4GSR BPM Pick-up Antenna

• **Purpose**: TDR (Time Domain Reflectometry) is used to measure impedance and detect discontinuities in BPM structures, providing a method to calculate capacitance. Tolerance is most important points for mass production of Pick-up antenna. We measured all of proto-type pick-up tolerance and right table shows sampled results.

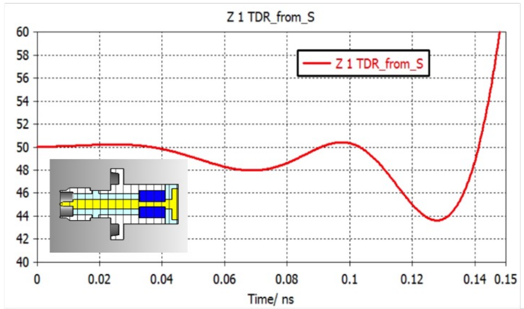
• **TDR measurement method**: A fast-rise time pulse is sent along the transmission line, and the reflections are analyzed. Capacitance C is calculated using the time delay between the transmitted and reflected signals, along with the characteristic impedance of the transmission line.

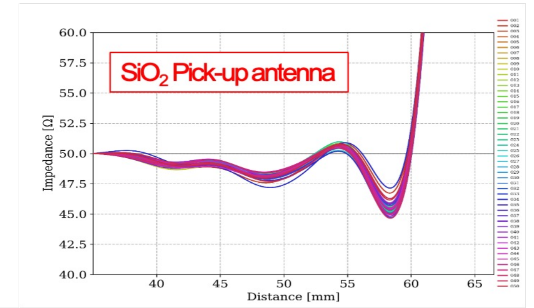
• **Measurement Results:**

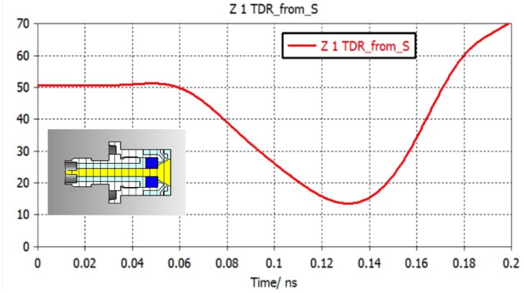
• **SiO2 BPM**: Expected capacitance ≈ 1.5 pF; good agreement between simulation and measurement, showing a small standard deviation.

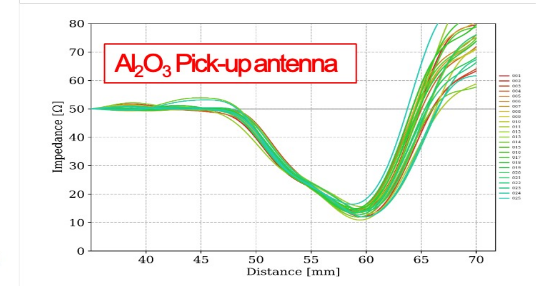
• **Al2O3 BPM**: Expected capacitance ≈ 4 pF; meets specifications but shows wider standard deviation due to manufacturing challenges.

• **Challenges**: While precision machining of the Al2O3 BPM pick-up can be improved with additional production cost, maintaining concentricity after brazing has proven challenging, even in cases like SOLEIL. Additionally, due to the structural limitations of having high capacitance, the SiO2 pick-up design demonstrates superior signal sensitivity compared to the Al2O3 design.









Antenna Number	Pin Antenna Diameter				Flange Outer Diameter				Flange Welding ripple Diameter			
	Measurements			Average	Measurements			Average	Measurements			Average
3	6	6	6	6.00	7.67	7.67	7.67	7.67	13.67	13.67	13.66	13.67
14	6.01	6	6.01	6.01	7.68	7.68	7.69	7.68	13.67	13.69	13.68	13.68
28	5.99	6.01	6.01	6.00	7.67	7.67	7.67	7.67	13.68	13.67	13.68	13.68
39	6	6.01	6	6.00	7.68	7.67	7.68	7.68	13.67	13.68	13.68	13.68
41	6	6	6.01	6.00	7.68	7.66	7.67	7.67	13.68	13.69	13.67	13.68
Average (mm)				6.00				7.67				13.68
STD (mm)		SiO2		0.002				0.01				0.005
STD (%)				0.04				0.07				0.04

Antenna Number	Pin Antenna Diameter				Flange Outer Diameter				Flange Welding ripple Diameter			
	Measurements			Average	Measurements			Average	Measurements			Average
2	5.96	5.96	5.96	5.96	10.3	10.29	10.3	10.30	13.69	13.7	13.69	13.69
7	5.99	5.99	5.99	5.99	10.31	10.3	10.31	10.31	13.74	13.73	13.74	13.74
13	5.96	5.97	5.96	5.96	10.33	10.33	10.32	10.33	13.68	13.75	13.73	13.72
19	6	5.98	5.98	5.99	10.28	10.3	10.27	10.28	13.66	13.68	13.7	13.68
23	5.95	5.95	5.96	5.95	10.29	10.28	10.27	10.28	13.69	13.69	13.69	13.69
Average (mm)				5.97				10.30				13.70
STD (mm)		Al2O3		0.01				0.02				0.02
STD (%)				0.25				0.16				0.15

Beam test results at PLS-II Storage ring

Beam Tests of 4GSR BPM Prototypes in PLS-II Storage Ring

Preparation for Beam Tests

• **Objective**: Conduct beam tests using prototype antennas in PLS-II to evaluate performance.

• **Constraint**: Reducing the inner diameter to 4GSR design size could increase impedance and cause beam instability.

• **Solution**: Manufacture and install a new test BPM matching the dummy chamber specifications in cell 7.

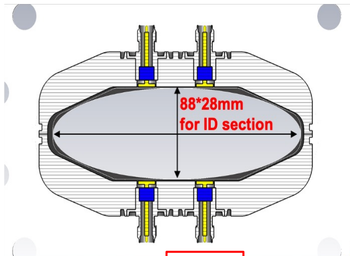
• **Simulation & Results**:

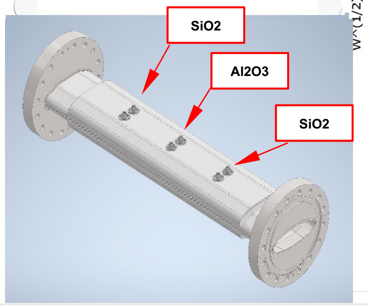
• CST simulations show the SiO_2 antenna provides ~50% stronger output signals compared to Al_2O_3.

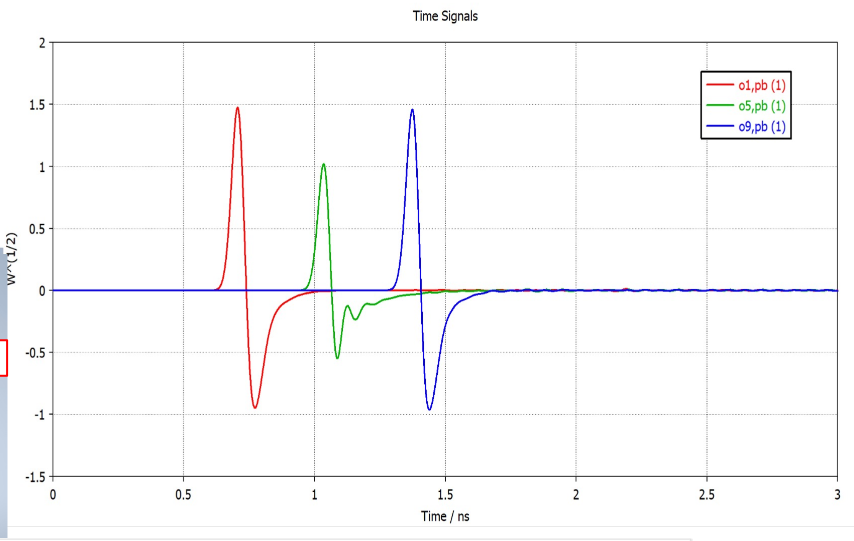
• 12 BPM pick-ups installed in sets of three (SiO_2, Al_2O_3, SiO_2), spaced 10 cm apart.

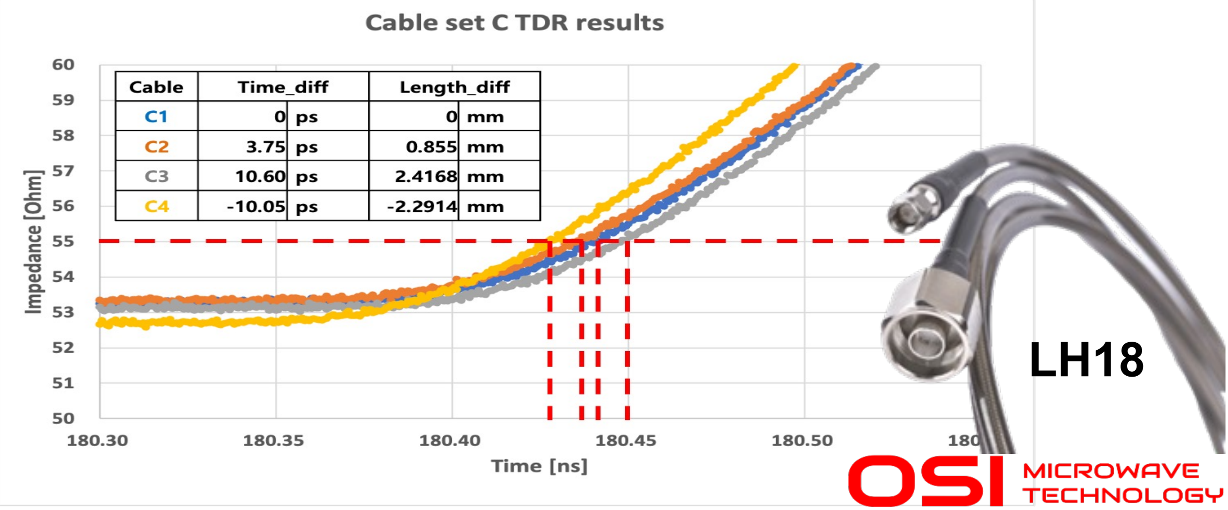
• **Analysis Requirement**: Compare key parameters of PLS-II and 4GSR storage rings to align expectations and test results.

• **Trial of New Cables for 4GSR BPM**: New cables were tested and installed with phase matching optimized to within 20 ps to reduce beam position measurement errors. The flexible cables allowed for seamless installation from BPM to electronics, facilitating beam tests.





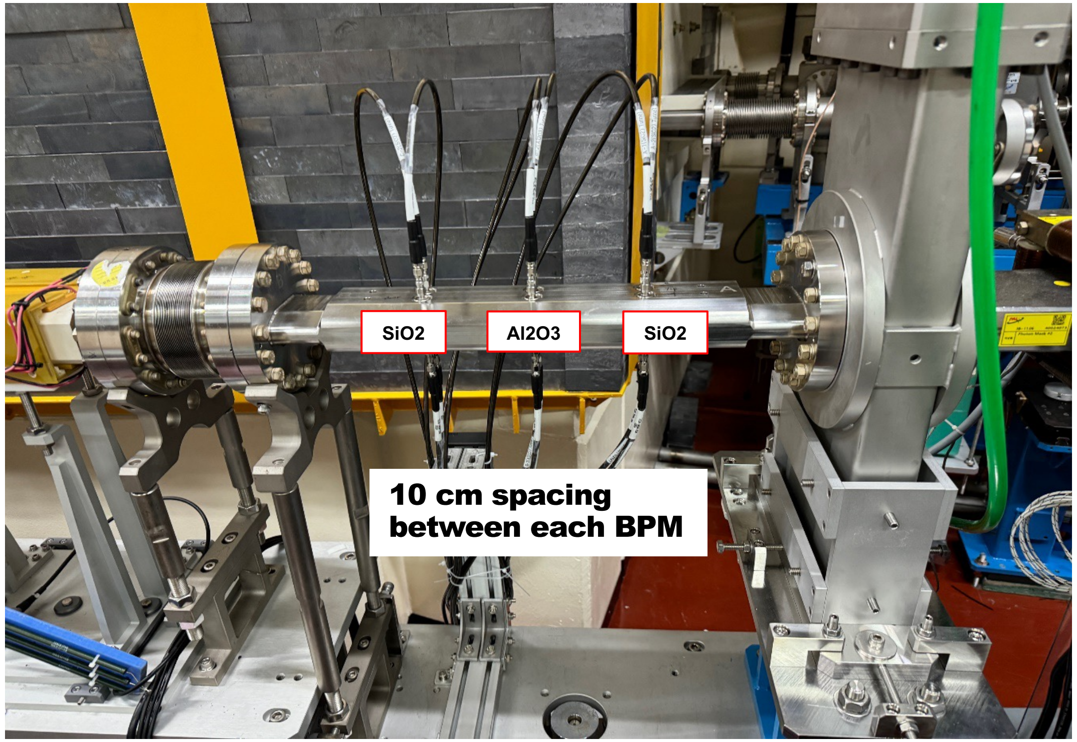




Cable	Time_diff		Length_diff	
C1	0	ps	0	mm
C2	3.75	ps	0.855	mm
C3	10.60	ps	2.4168	mm
C4	-10.05	ps	-2.2914	mm

Beam Tests of 4GSR BPM Prototypes in PLS-II Storage Ring

Installation of test BPM at PLS-II

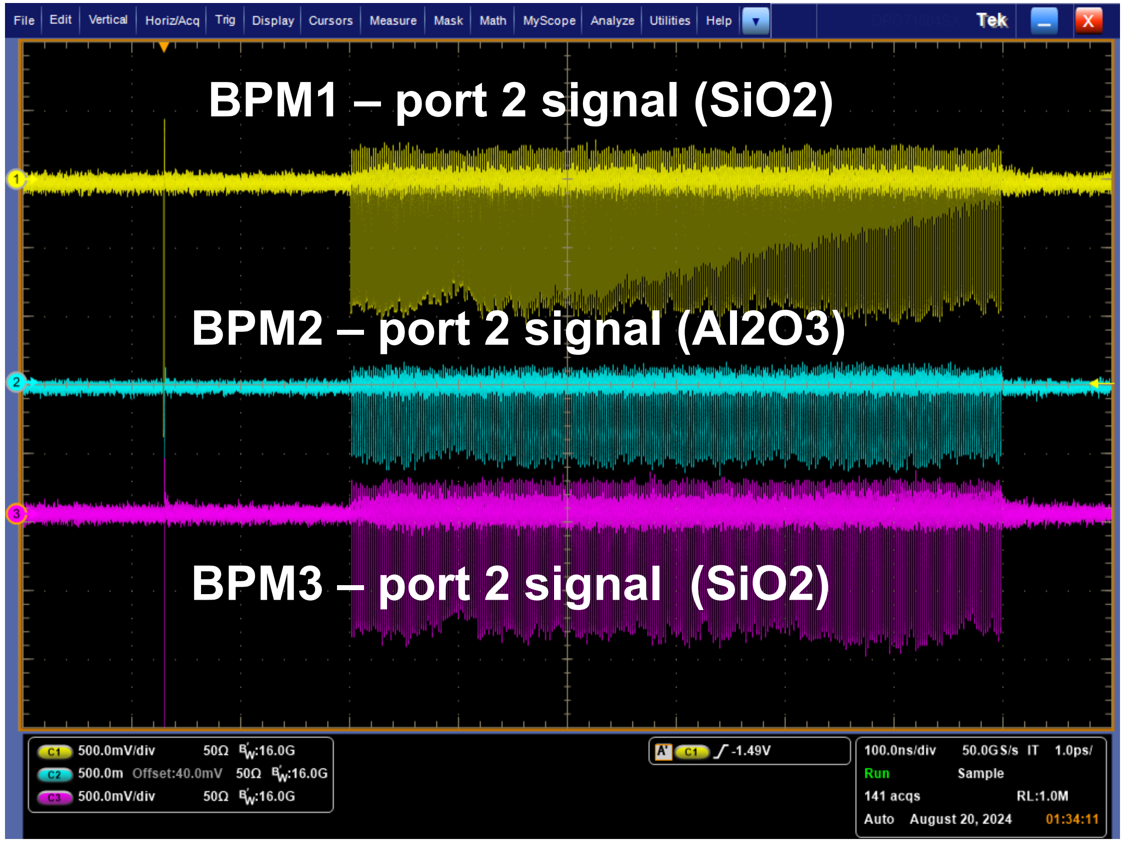


Inside Tunnel at #7 Cell Straight section

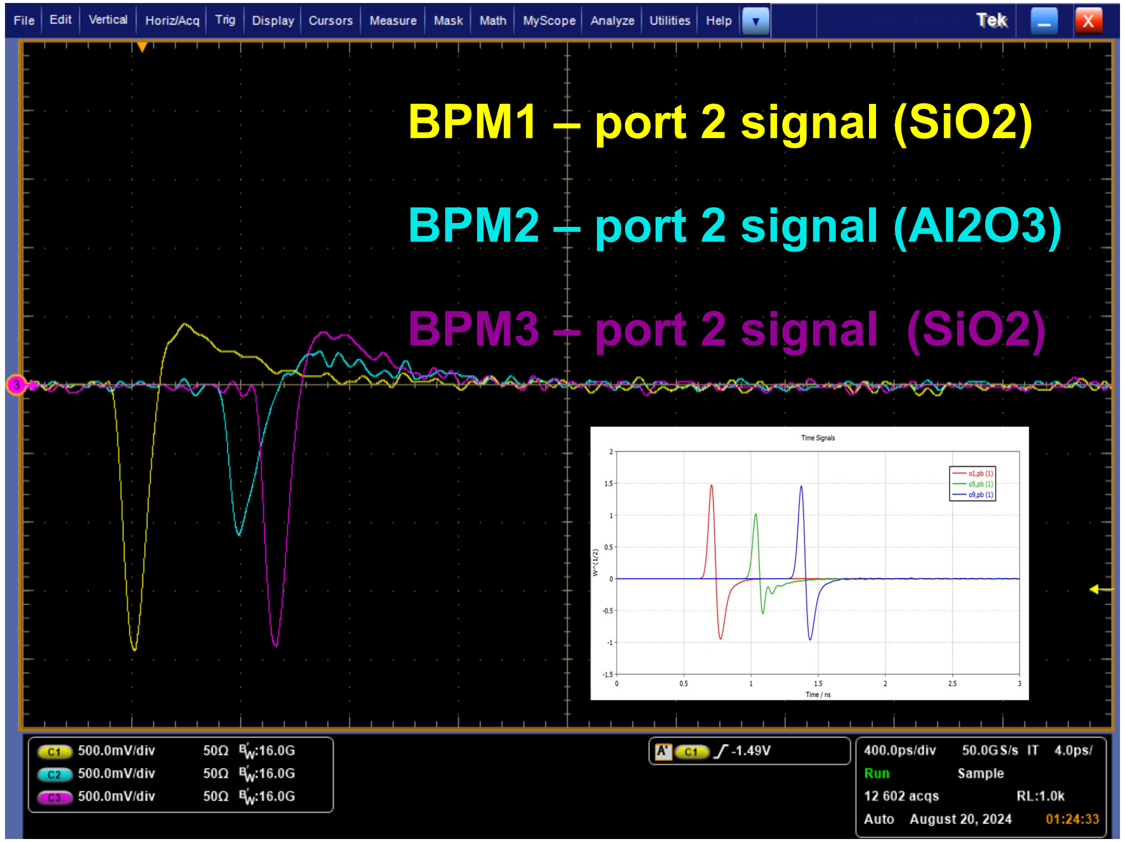
Control shed at #7 Cell

Beam Tests results of 4GSR BPM Prototypes in PLS-II Storage Ring

Signal waveform of test BPMs at PLS-II

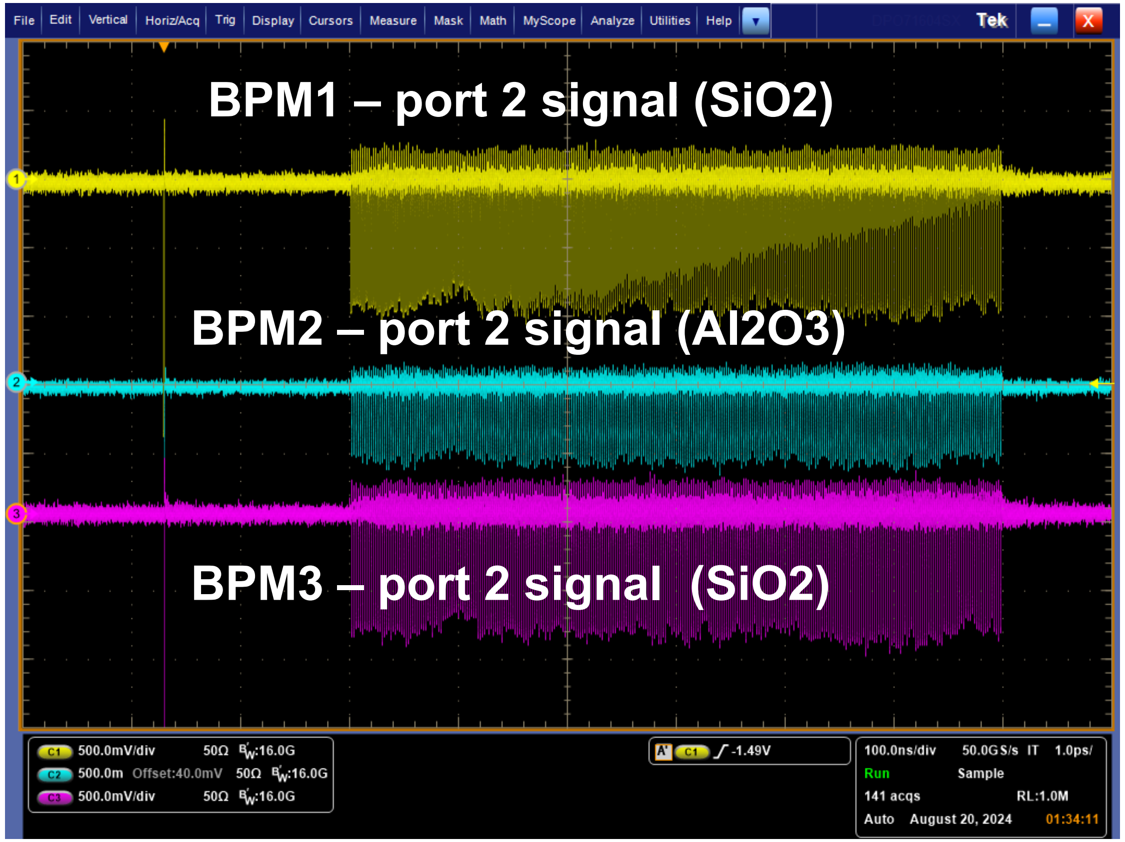


Camshaft signal figure

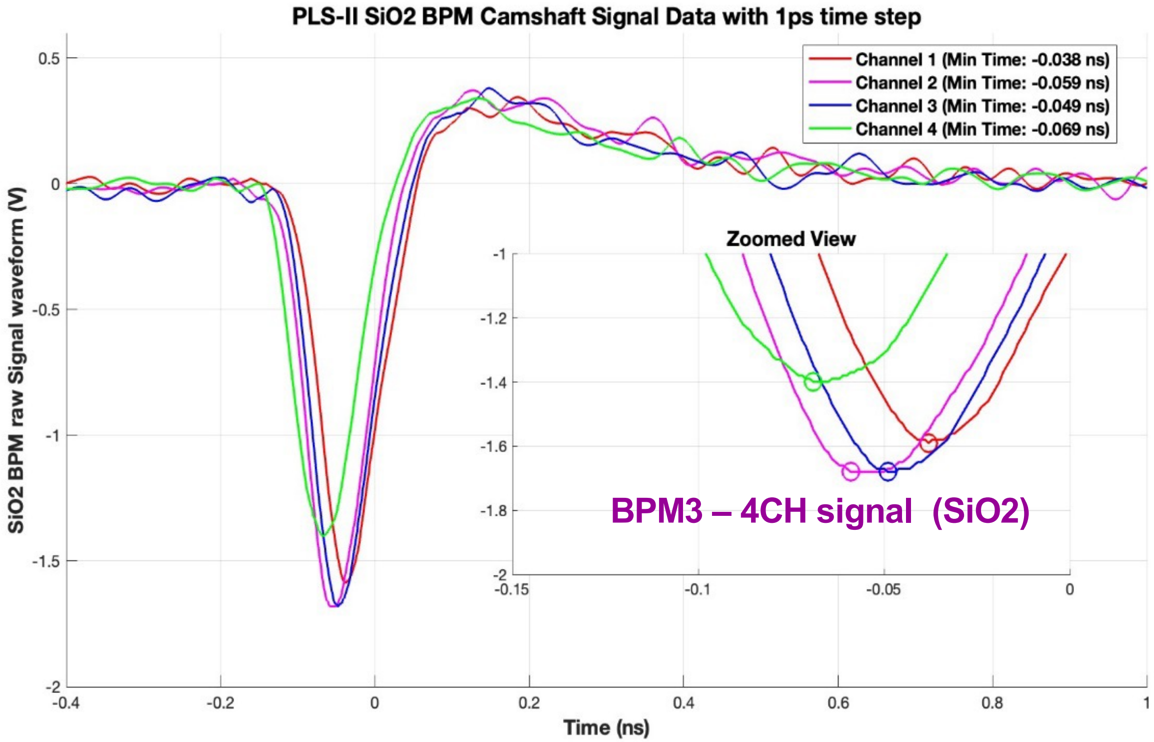


Beam Tests results of 4GSR BPM Prototypes in PLS-II Storage Ring

Signal waveform of test BPMs at PLS-II



Camshaft signal figure for BPM3 with SiO2

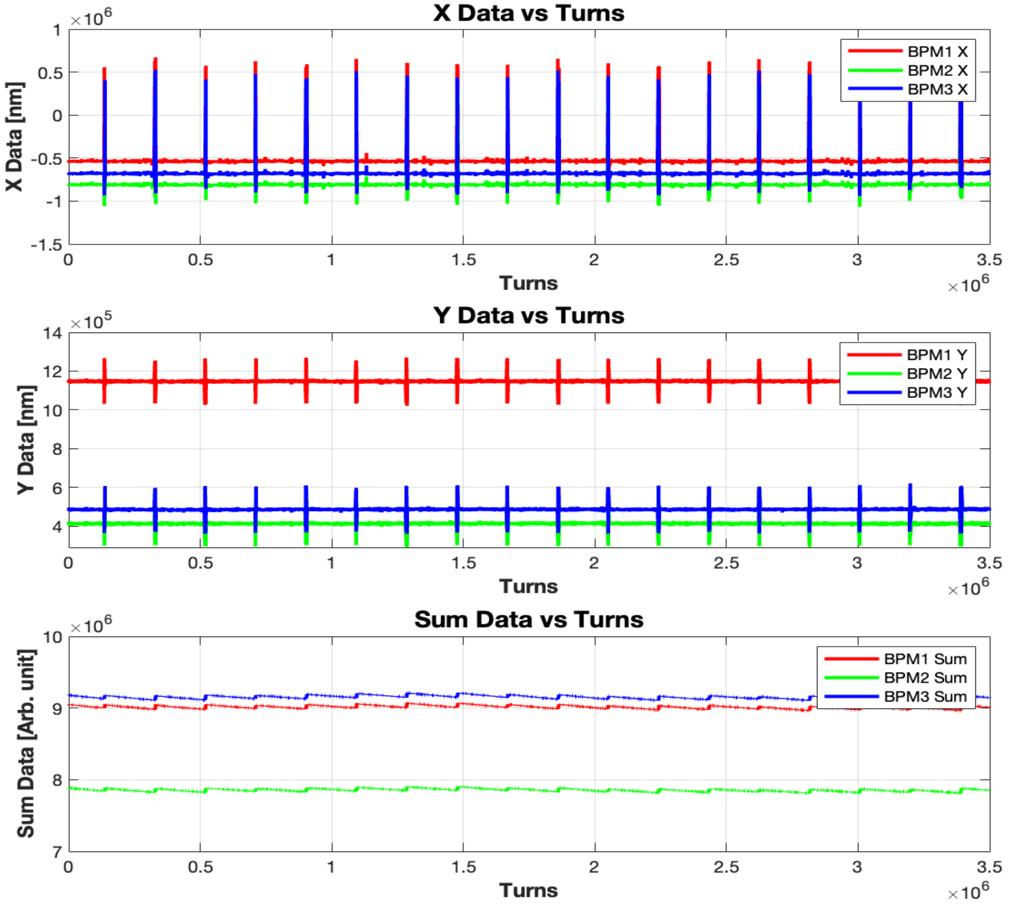


- ✓ New cable was able to manage approximately **under 2.5mm tolerance** of length delay matched under **30,000mm long** cable assembly in an array of **4 sets**

Beam Position Resolution Measurements

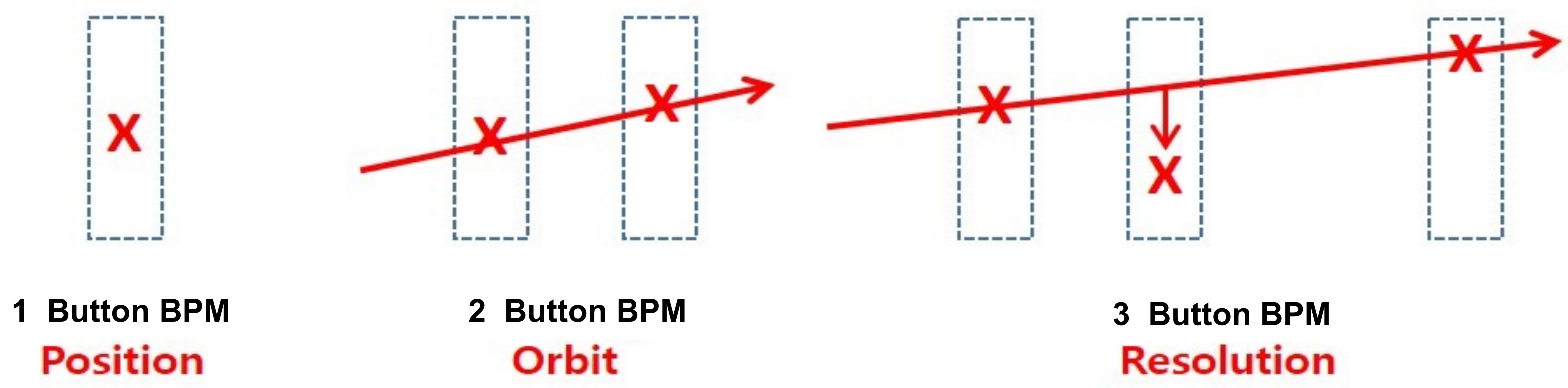
Turn by Turn(TbT) BPM Data Acquisition during 3.5 million turns

- **System & Synchronization**:
- Beam position resolution measured using the Libera Brilliance+ system.
- Libera Brilliance+ synchronized with the master oscillator and trigger signal fro m the 7th cell of the PLS-II storage ring.
- Three BPMs confirmed synchronized via BPM electronics.
- **Data Collection**:
- 1000 TbT data points collected and repeated 3500 times, resulting in 3.5 million data turns.
- Captured stabilized beam orbit and beam position oscillations during top-up inj ection in both X and Y directions.
- **Analysis & Results**:
- Standard deviation of beam trajectory in X and Y directions calculated for stabili ty assessment.
- Beam positions included offsets due to installation in the dummy chamber and challenges in performing Beam-Based Alignment (BBA).



Beam Position Resolution Measurements

Position residual calculation by using three 4GSR button BPMs with SVD method



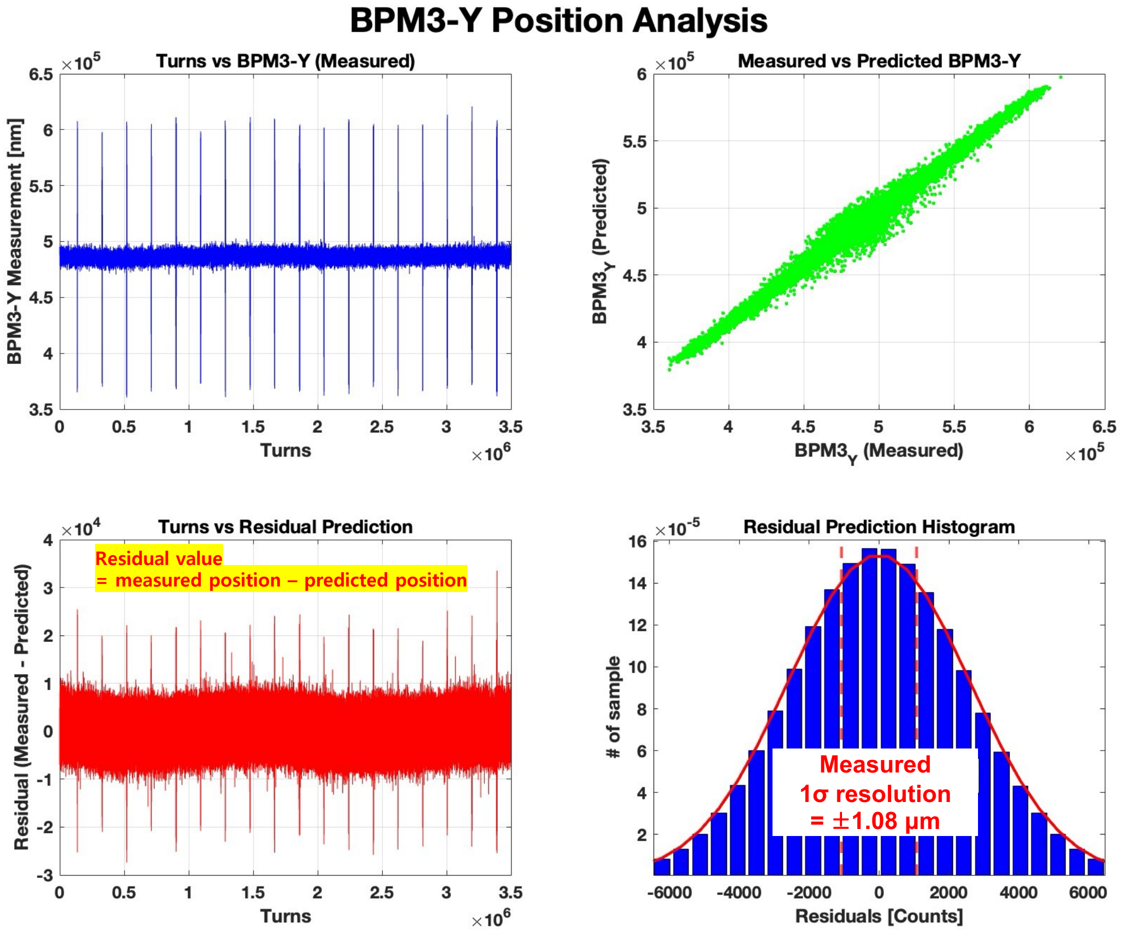
Predicted position(ADC counts) for BPM1-Y was calculated as follow equation,

- **Predicted position of BPM1-Y = a1*BPM2-Y+ a2*BPM3-Y+a3*BPM1-X+ a4*BPM2-X+ a5*BPM3-X +a6*BPM1-Sum+ a7*BPM2-Sum+a8*BPM3-Sum+ a9**
- **Residual of BPM1-Y = Measured BPM1-Y – Predicted BPM1-Y**
- **The beam position resolution proportional to 1/(beam charge).**

$$\text{Norm. Resolution} = \text{Geometrical factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured beam charge}}{\text{Nominal beam charge}}$$

Beam Position Resolution of BPM1-Y

SiO2 BPM1-Y with 3.5M turns TbT data with 300mA Top-up operation of PLS-II



TbT resol.	BPM-A	BPM-B	BPM-C
X-port (300mA/ 400mA exp.)	1.52 um / 1.14 um	2.70 um / 2.03 um	1.50 um / 1.13 um
Y-port (300mA/ 400mA exp.)	1.30 um / 0.975 um	2.16 um / 1.62 um	1.08 um / 0.81 um

$$\text{Norm. Resolution} = \text{Geo. factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured charge}}{\text{Nominal charge}}$$

$$= 1.08\ \mu m \times 300mA/400mA = 0.81\ \mu m\ @\ 400mA\ exp.$$

Summary

Project Overview:

- The Korean 4GSR project in Ochang is under construction with a target completion by 2027.

Prototype Development:

- A prototype pick-up antenna for 4GSR BPM was developed.
- TDR measurements and beam position resolution tests conducted at the PLS-II storage ring using a specially designed test BPM chamber.

Beam Test Results:

- Beam position resolution measured using turn-by-turn (TbT) data, achieving resolutions between 1 to 2.7 micrometers.

Next Steps:

- Finalize the pick-up antenna design based on test results.
- Plan mass production to align with the project completion target of 2027.

Thank you !