MR magnets
&
Superconducting magnets(QCS)

Shu Nakamura

on behalf of the SuperKEKB magnet Group and QCS group

Outline

- Group members
- Answer for the last recommendation
- Magnet
  - Rotating Sextupole magnet
  - Realignment of QKARP
  - Troubles
  - Survey and alignment
- QCS
  - Quench
- Summary

Members and Tasks

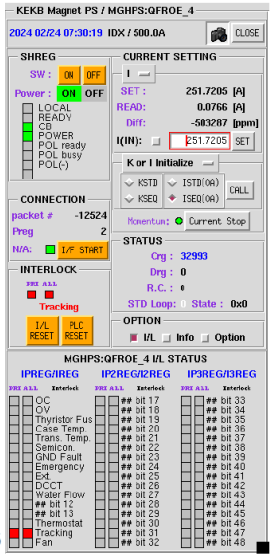
MR Magnet group	
Prof.	S. Nakamura (Leader) M. Masuzawa
Assist. Prof.	R. Ueki
Tech. Staff	T. Nagasaki M. Furusawa

QCS group	
Assoc. Prof.	T. Oki (Leader) Y. Arimoto
Assist. Prof.	X. Wang
Tech. Staff	K. Aoki
Senior Researcher	N. Ohuchi

Magnet design, fabrication, and field measurements.
Cryogenics for QCS.
Power supplies, installation, and maintenance.
Survey and alignment.

Unintended current reduction

The power supply(QFROE_4) sometimes unintentionally reduces the output current.
The only interlock the power supply displays is “Tracking”, but the output current is zero A.
A malfunction due to noise in the control circuit is suspected.
The control power supply was replaced, but the problem recurred.
Other measures are under consideration.



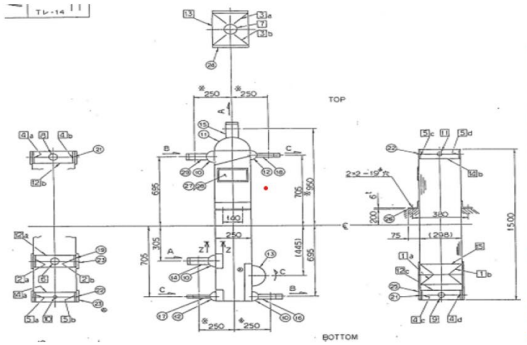
R18.1: Fix the power converter for QFROE_4.

⇒ Replace all control power supplies this winter.
As these delivery times take more than six months, we could not carry out the replacement last summer.

Reducing the use of LN_2: consideration of additional heat exchangers

- To reduce the LN_2 quantity consumed for the cryogenic system (**ECO-system**), we have started to discuss about the installation of the additional heat exchanger.
- The amount of the LN_2 quantity is 3500 L/day for the QCS-R and QCS-L helium cryogenic systems. The cost of the LN_2 per year is about 40 MJ¥ (267 kUS$).
- By the additional heat exchanger, the amount of the LN_2 consumption can be reduced to be smaller than the half.
- For the installation, the cost is estimated to be 17 MJ¥ × 2 units. The work period in the practical setting is about 2 months (and for construction of the heat exchanger, 9 months).
- There is no risk for the additional heat exchanger, and the exchanger enhance the stability of the helium refrigerator.

Reducing the use of LN_2: Thermal condition of QCS cryogenic system

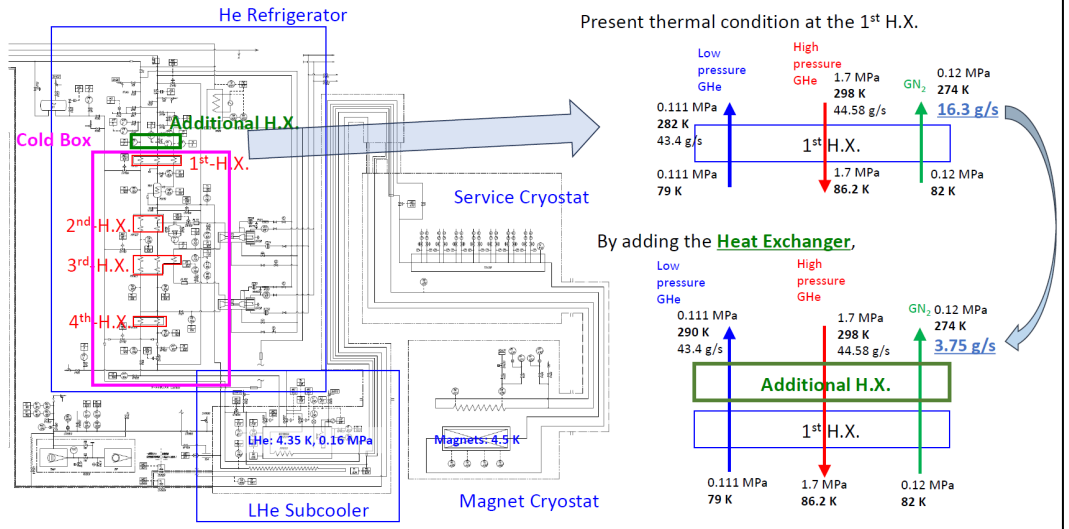


1st Heat Exchanger between high and low-pressure helium gases and nitrogen gas .
The additional heat exchanger is expected to be one third of the 1st H.X..

Location of the additional heat exchanger

QCS-R Helium refrigerator and sub-cooler

Reducing the use of LN_2: Thermal condition of QCS cryogenic system



R19.1: Add a heat exchanger to reduce liquid nitrogen consumption as proposed.

⇒ The 0th heat exchanger will be installed as soon as possible.

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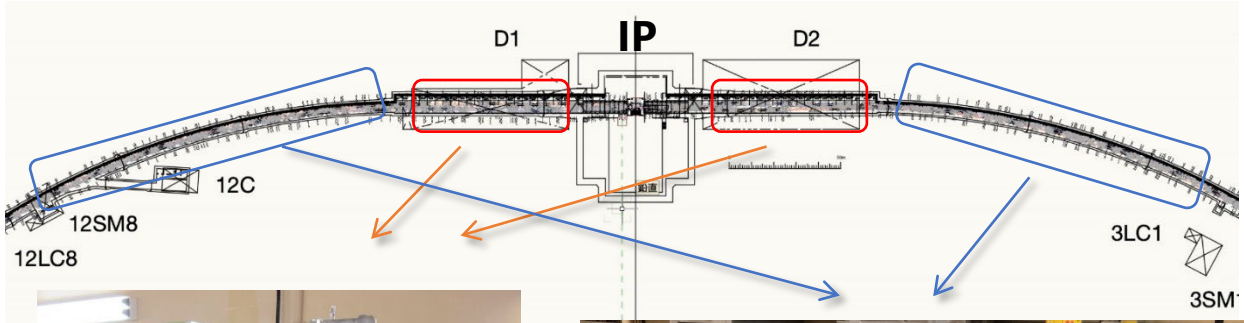
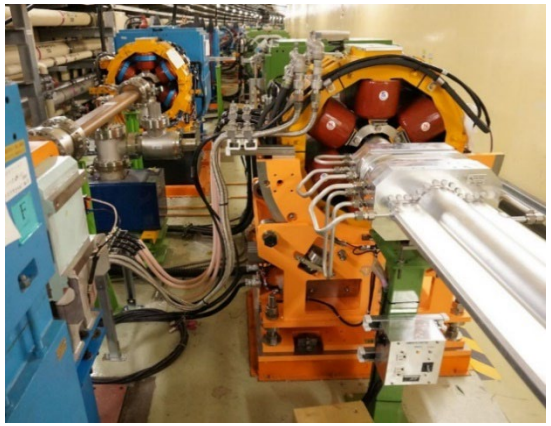
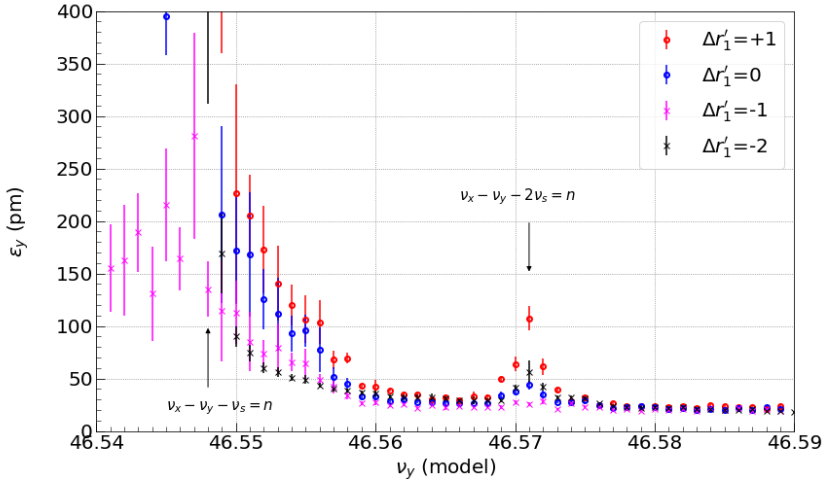
Sextupole Magnets on Tilting Tables





In LER, twenty-four skew sextupole magnets are installed on the tilting stage to tilt those magnets which generate sextupole and skew sextupole magnetic fields. A pulse motor which is fixed on the base frame, rotates the straight worm gear. The worm gear is engaged with the helical gear on the rotating frame, and then the sextupole magnet fixed on the rotating frame are tilted. The rotation center and the magnetic center are adjusted within 0.1 mm.

In December 2021, we performed systematic beam tests and confirmed that the emittance increase due to the primary and secondary synchro-beta coupling resonance can be controlled without disturbing the beam injection and optics.

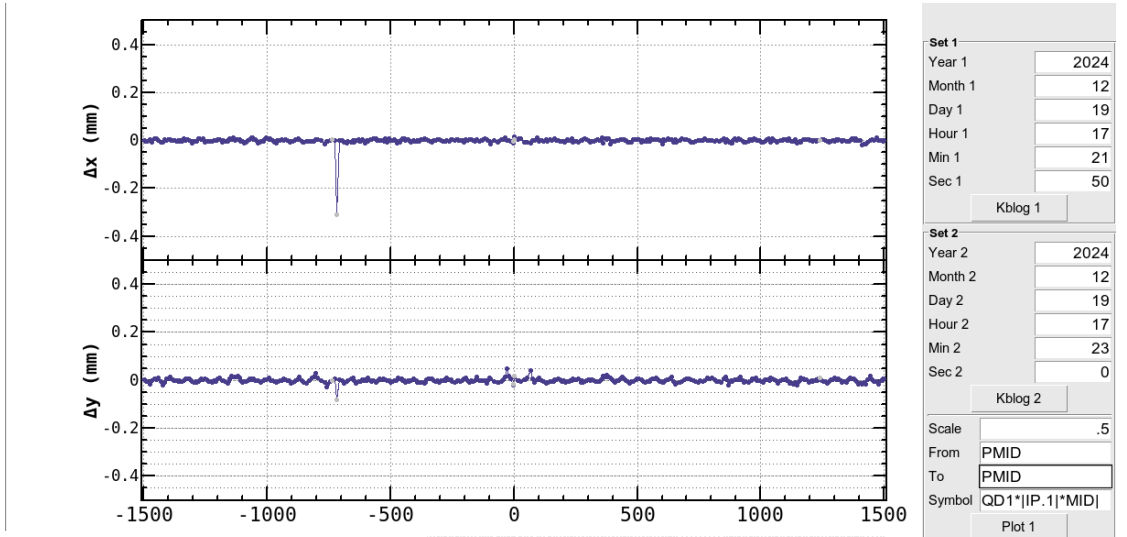


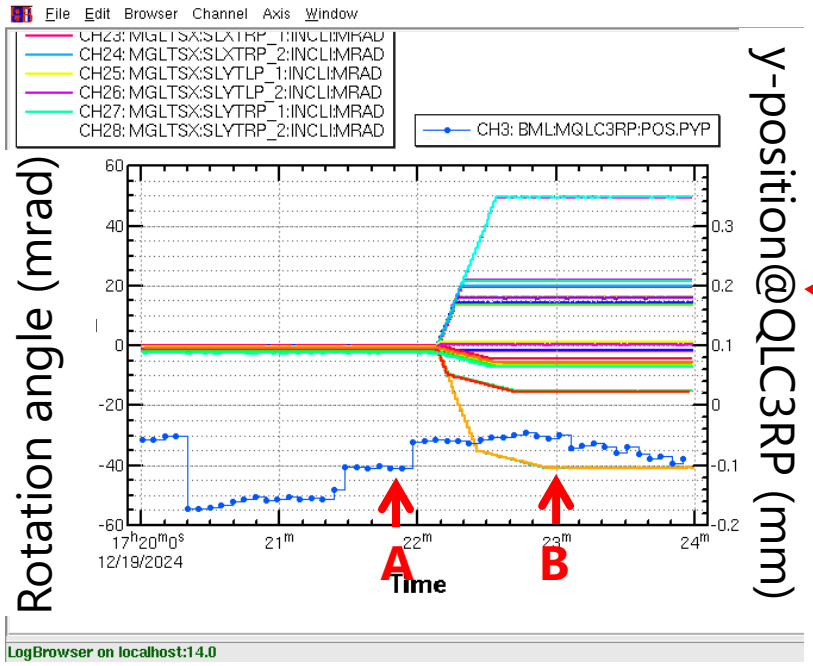
Sextupole Magnets on Tilting Tables

2024c, we performed a resonance correction study with a new sextupole set and a magnet rotation study on the beam.
(β_y^* = 1mm, LER current = 50mA)

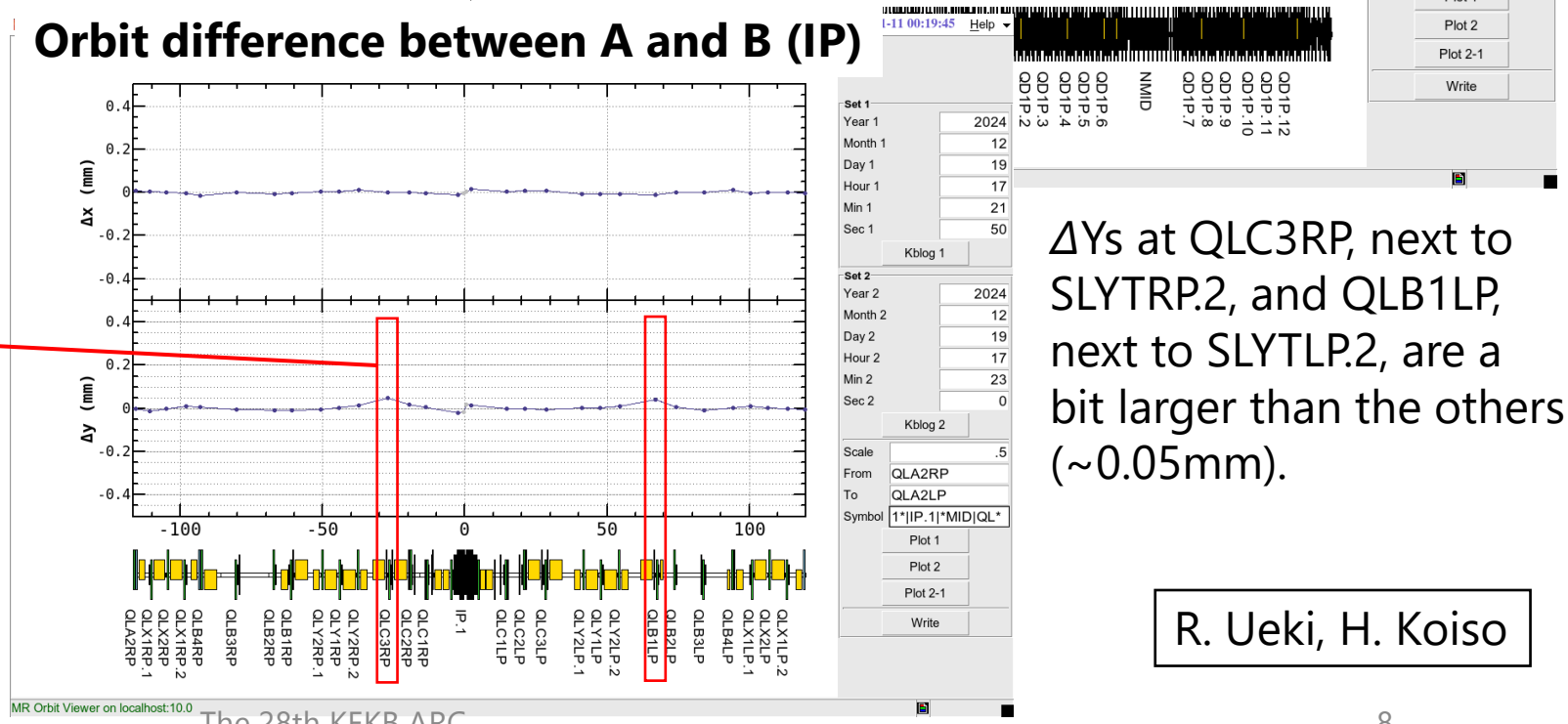
The trial of a magnet rotation on the beam succeeded.
- No beam abort
- Negligible orbit disturbance

Orbit difference between A and B (Whole ring)





Orbit difference between A and B (IP)



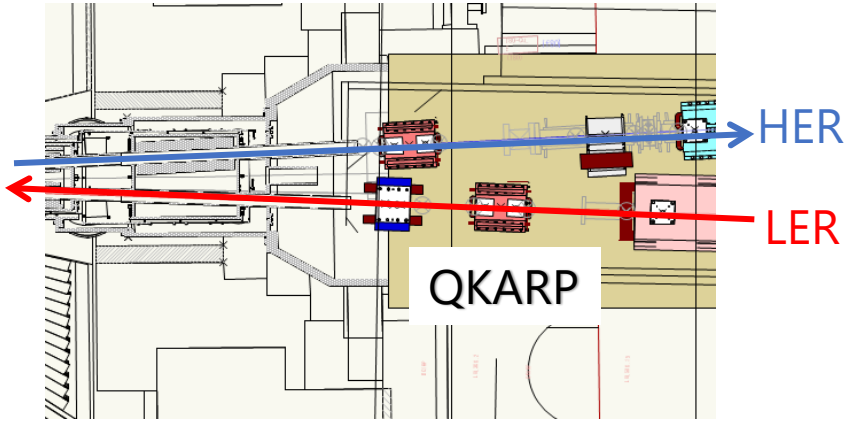
*Δ*Ys at QLC3RP, next to SLYTRP.2, and QLB1LP, next to SLYTLP.2, are a bit larger than the others (~0.05mm).

R. Ueki, H. Koiso

Realignment of QKARP

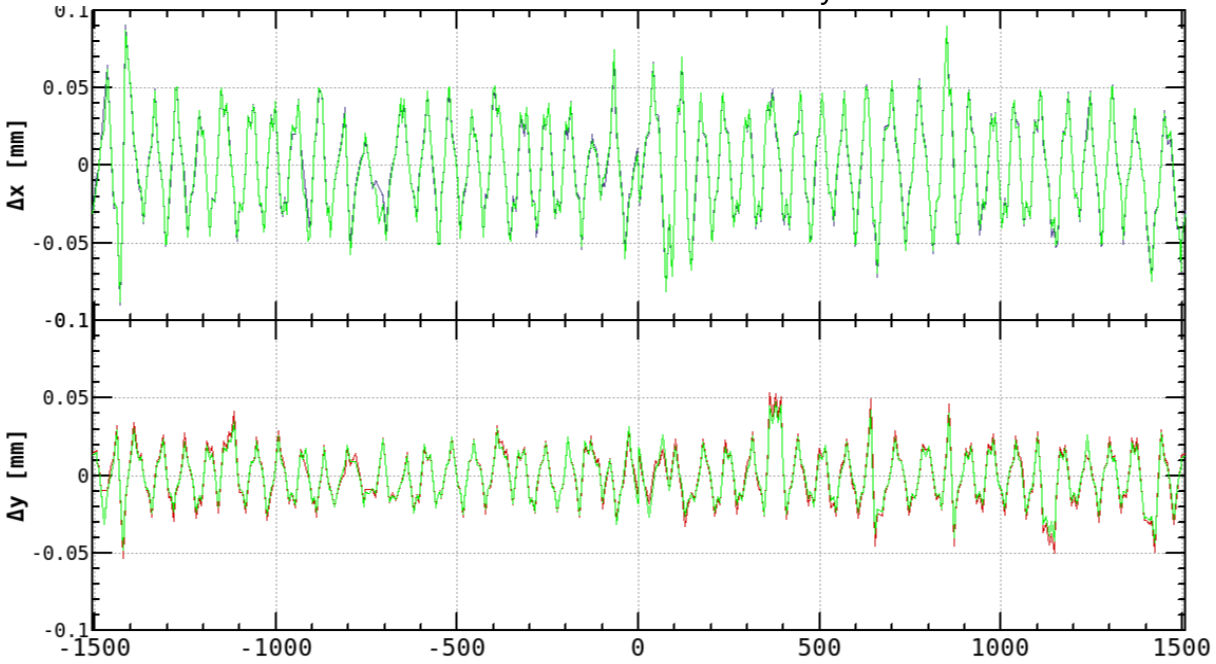
IP tilt knob is using QKARP.
When the knob changed dramatically, an orbit deformation appeared, and it made beam loss.

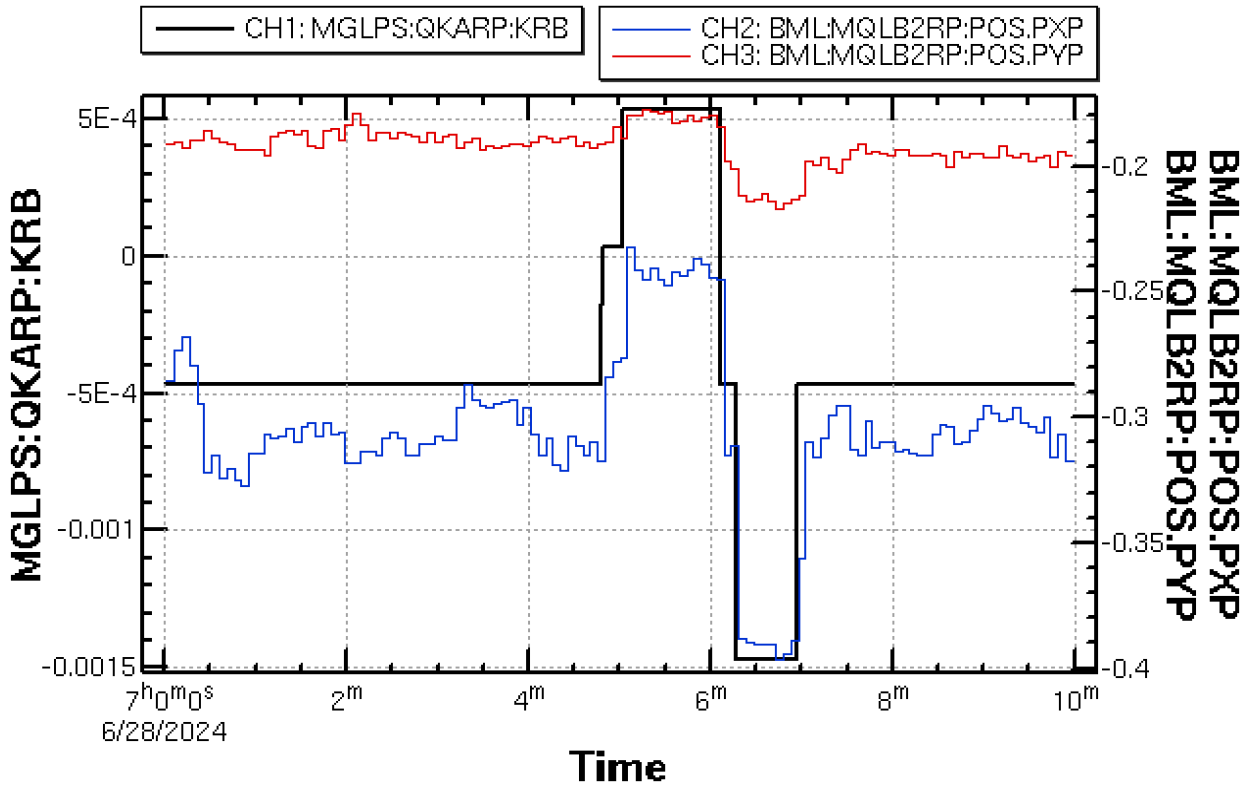
The optics group measured the kick angle corresponding to the orbit changes caused by the QKARP.
This k-value is equivalent to a vertical position sift of -1.9mm.



H. Sugimoto

2024b (2024/Jun/28) $(\beta_x^*, \beta_y^*) = (80, 0.9)$mm





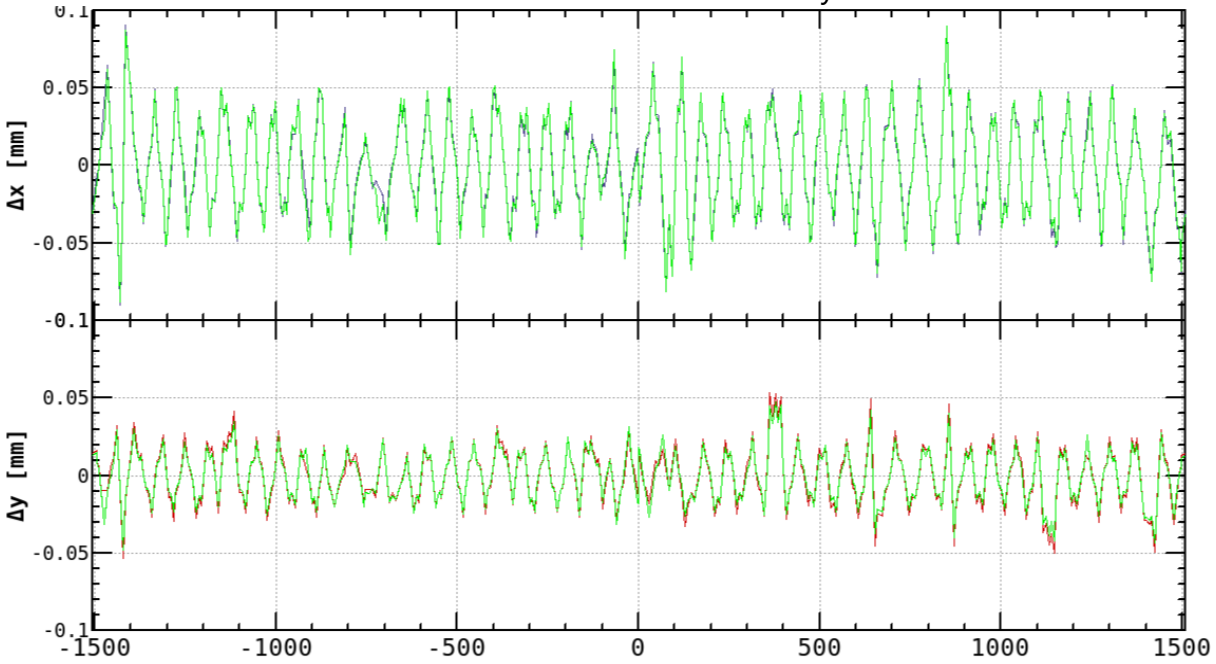
Realignment of QKARP

The orbit difference when the QKARP's K1 changes +1e-3 m^{-1}.

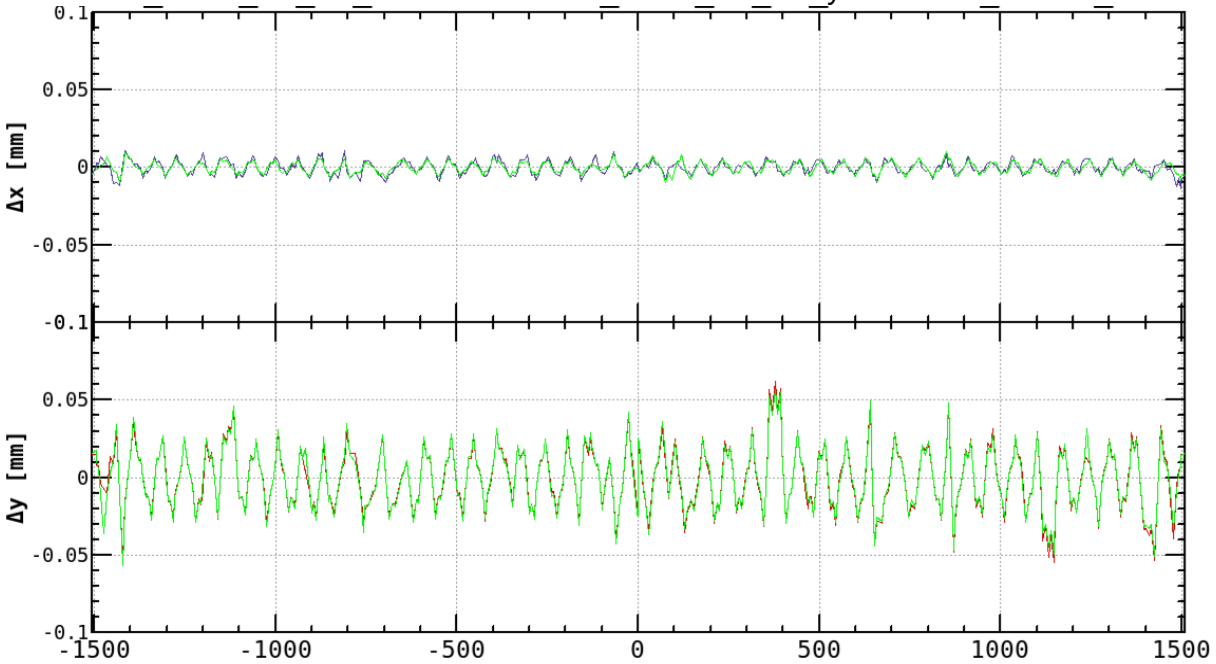
The horizontal orbit fluctuation in 2024c has been smaller than in 2024b.
This improvement results from moving QKARP vertically by -1.9mm during the summer shutdown.

H. Sugimoto

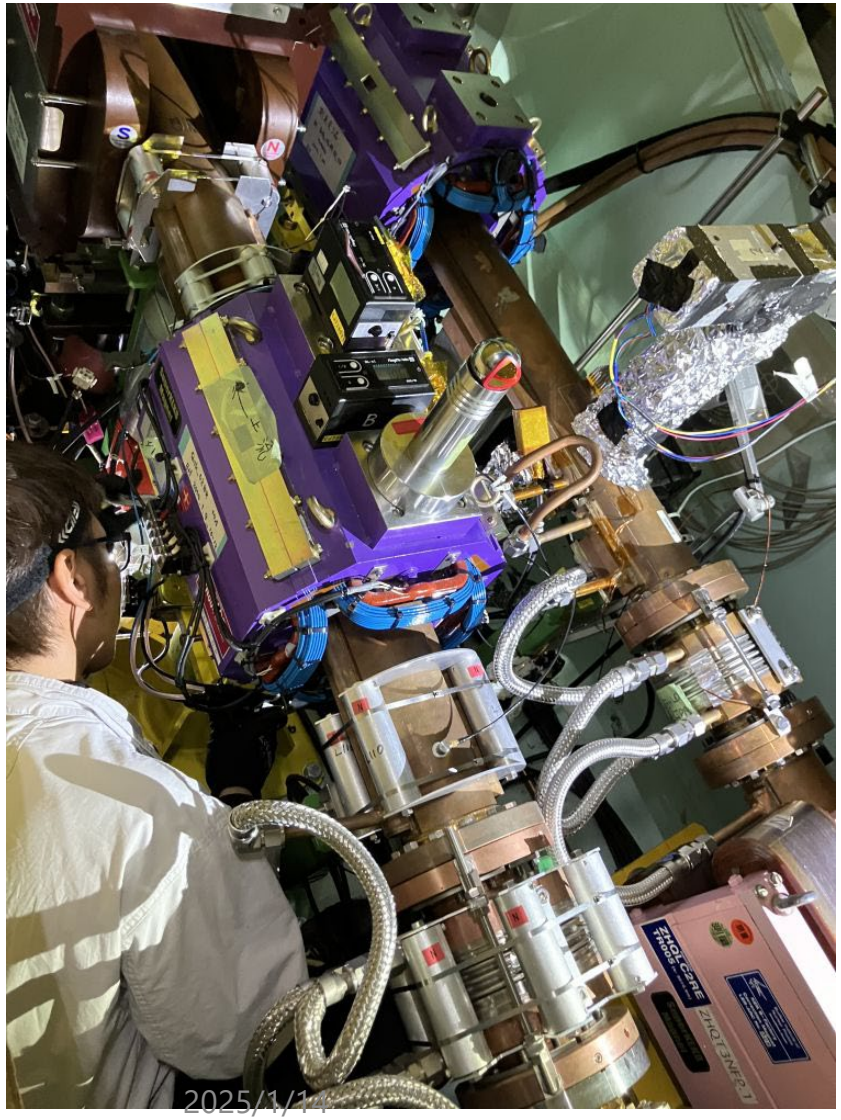
2024b (2024/Jun/28) (β_x^*, β_y^*) = (80, 0.9)mm

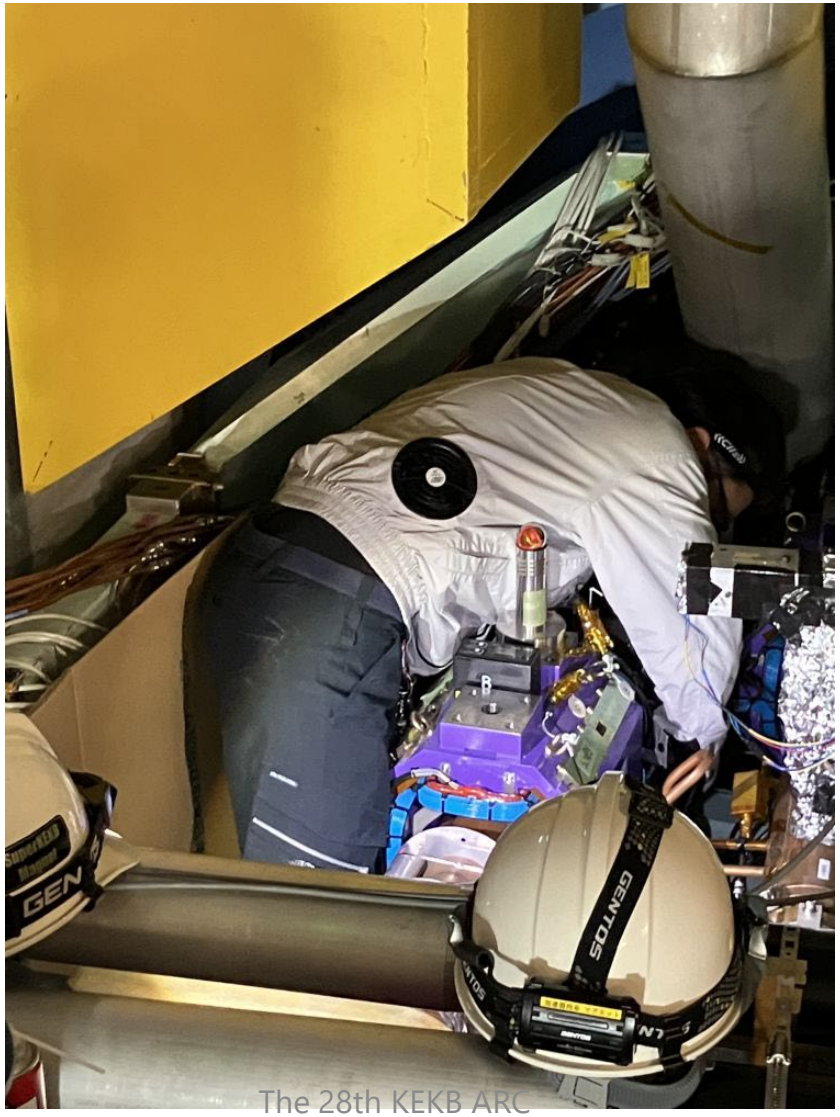


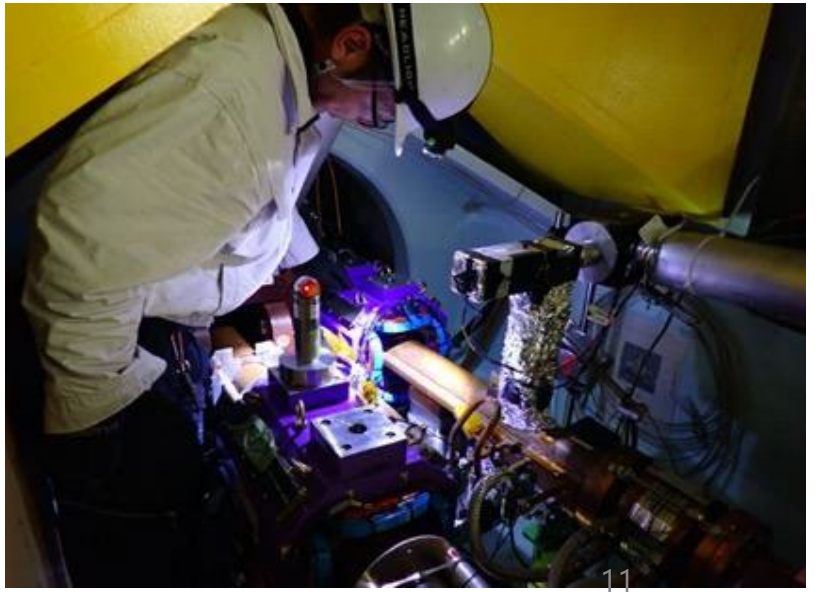
2024c (2024/Nov/9) (β_x^*, β_y^*) = (80, 1)mm



Realignment of QKARP





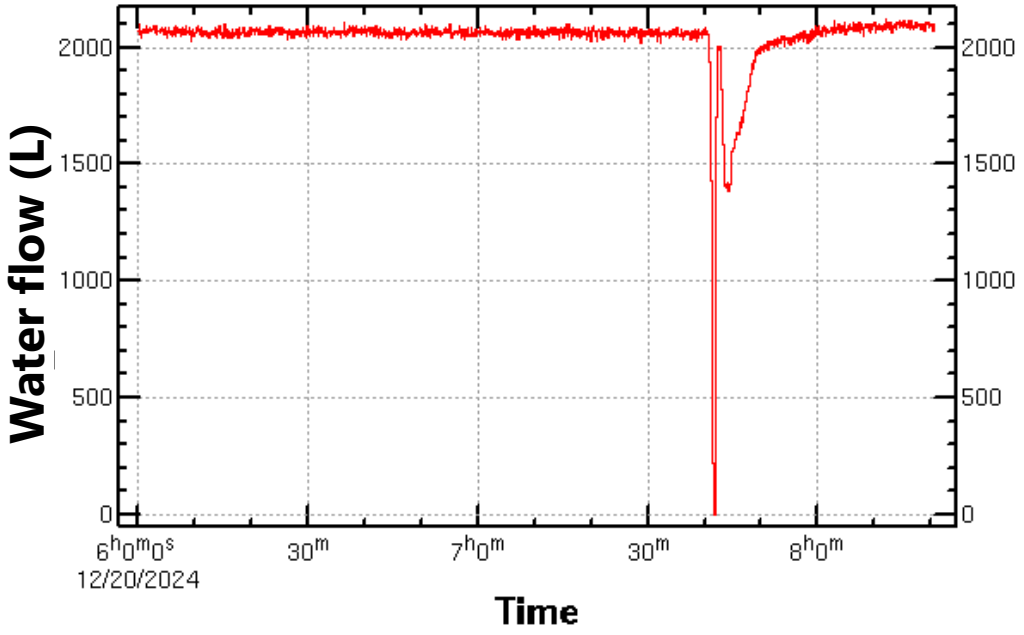


Beam abort due to magnet trouble

1750 water-cooled magnets are installed in SuperKEKB MR.
Pure cooling water is supplied to these magnets at the 8-location pump system.

A misoperation accidentally stopped one of the cooling water pumps on Dec. 20, 2024.
Then, some magnet power supplies were down, and the beam was aborted.

The last beam abort due to a magnet interlock occurred on Oct. 17, 2019.



Although this incident was unfortunate, regular maintenance ensures the system remains healthy.
Thanks to the maintenance, water purity is improving in one pump system.

Strainer just before a pump

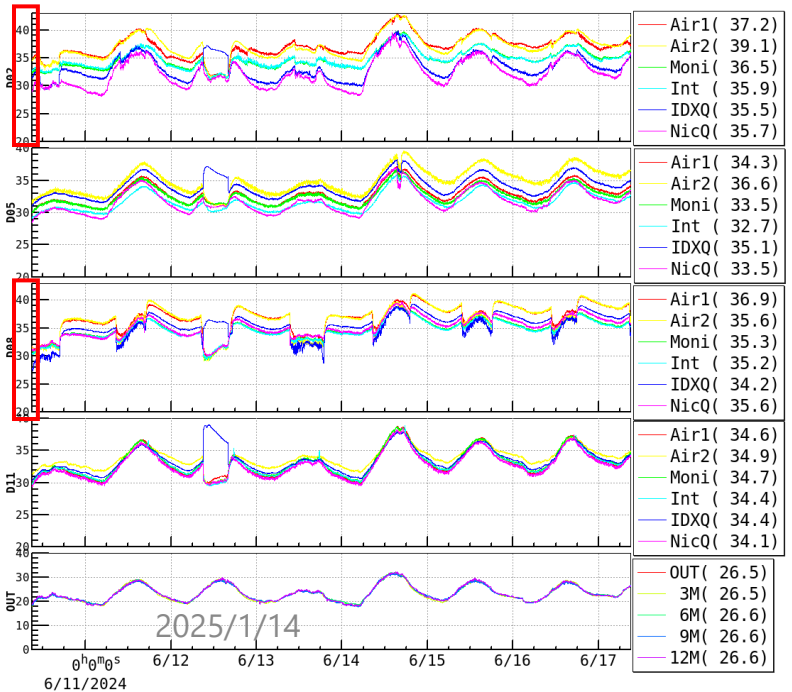
Beam abort due to power supply trouble

Power supply down due to high room temperature

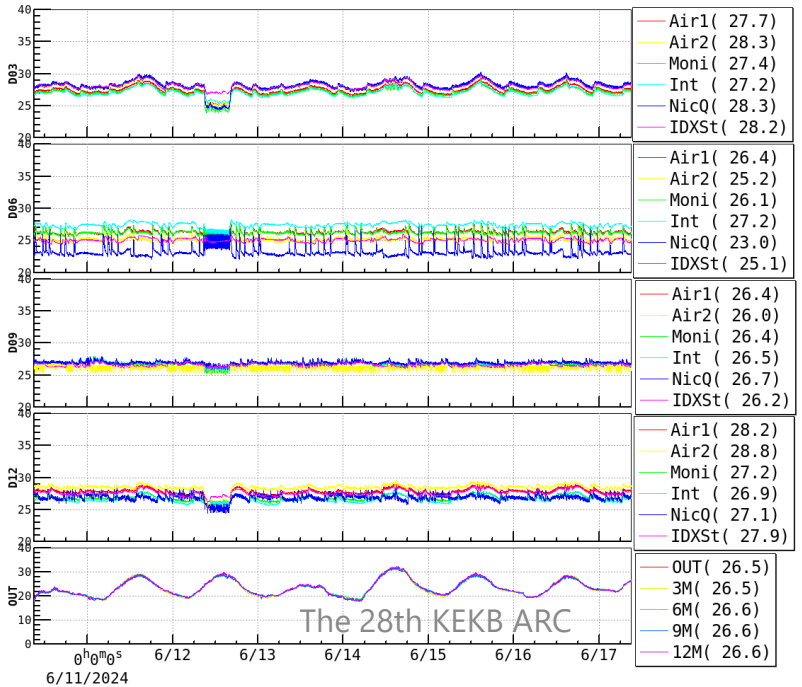
About 2800 power supplies are used for MR magnets.
The power supplies are installed in the 8 buildings, 4 large and 4 small buildings.

BLC2LP was sometimes stopped by the interlock signal from the switching device due to high temperature since Mar. 2024.
Then, we supplied cooled air to BLC2LP, but the accidental stop occurred again in June 2024.
The room temperature was over 40 ℃ at that time.

Room temp.
in the large buildings without air conditioners .



Room temp.
in the small buildings with air conditioners .



BLC2LP

Beam abort due to power supply trouble

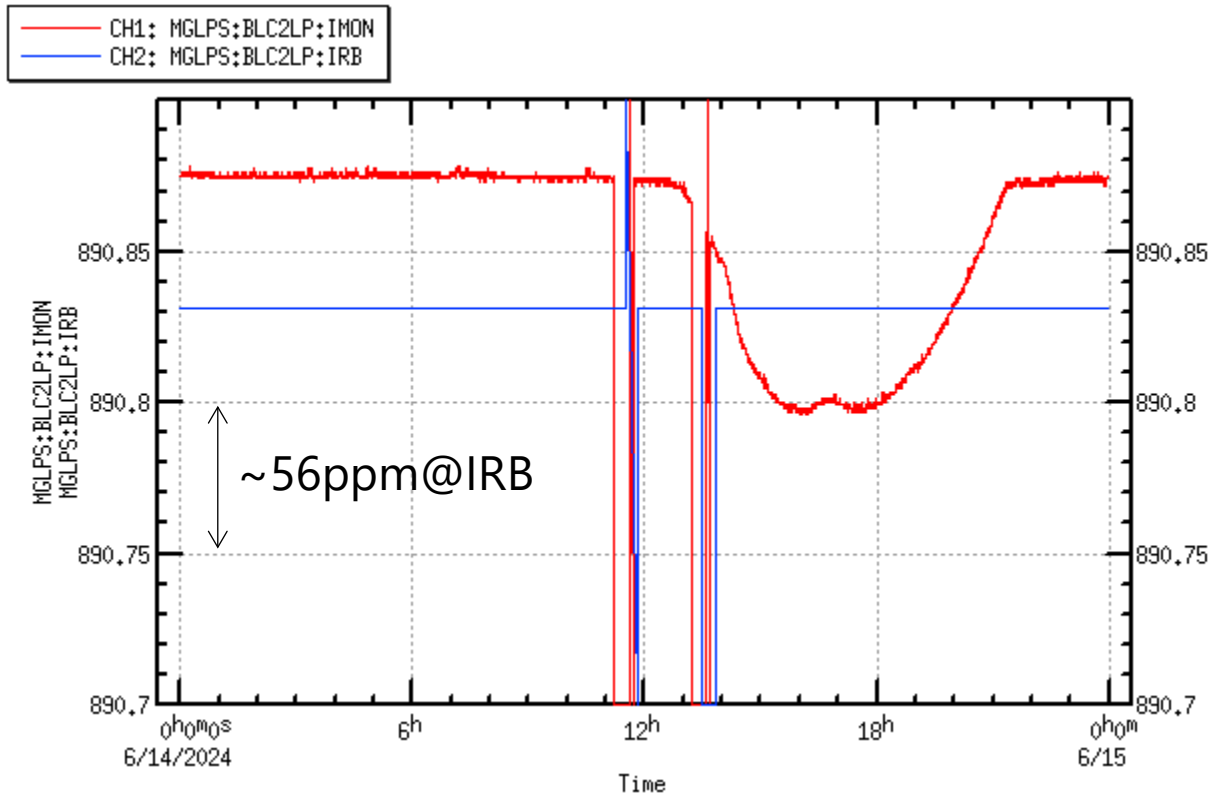
Power supply down due to high room temperature

June 14

2024-06-14 15:31:49.003	MG (LER)	MINOR	Magnet PS QLC3LP NA or IL
2024-06-14 15:13:15.186	MG (LER)	MINOR	Magnet PS BWSOP_26 NA or IL
2024-06-14 15:11:30.244	MG (HER)	MINOR	Magnet PS QLA4LE NA or IL
2024-06-14 14:58:20.222	MG (HER)	MINOR	Magnet PS QLA6LE NA or IL
2024-06-14 13:28:42.835	MG (LER)	OK	
2024-06-14 13:12:00.861	MG (LER)	MAJOR	Magnet PS BLC2LP NA or IL
2024-06-14 11:28:57.435	MG (LER)	OK	
2024-06-14 11:12:49.912	MG (LER)	MAJOR	Magnet PS BLC2LP NA or IL

Power supply doesn't go down, but the thermostat in the power supply is out of range.

Power supply(BLC2LP) go down.



BLC2LP@D2
Rated current : 1100A
This PS stopped twice in a short time due to an interlock caused by the switching device error.
The output current drifted.

The thermostat in the power supply does not seem to stabilize the temperature.

Beam abort due to power supply trouble

Power supply down due to high room temperature

June 14

2024-06-14 15:31:49.003	MINOR	Magnet PS QLC3LP NA or IL
2024-06-14 15:13:15.186	MINOR	Magnet PS BWSOP_26 NA or IL
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2024-06-14 13:28:42.835	OK	
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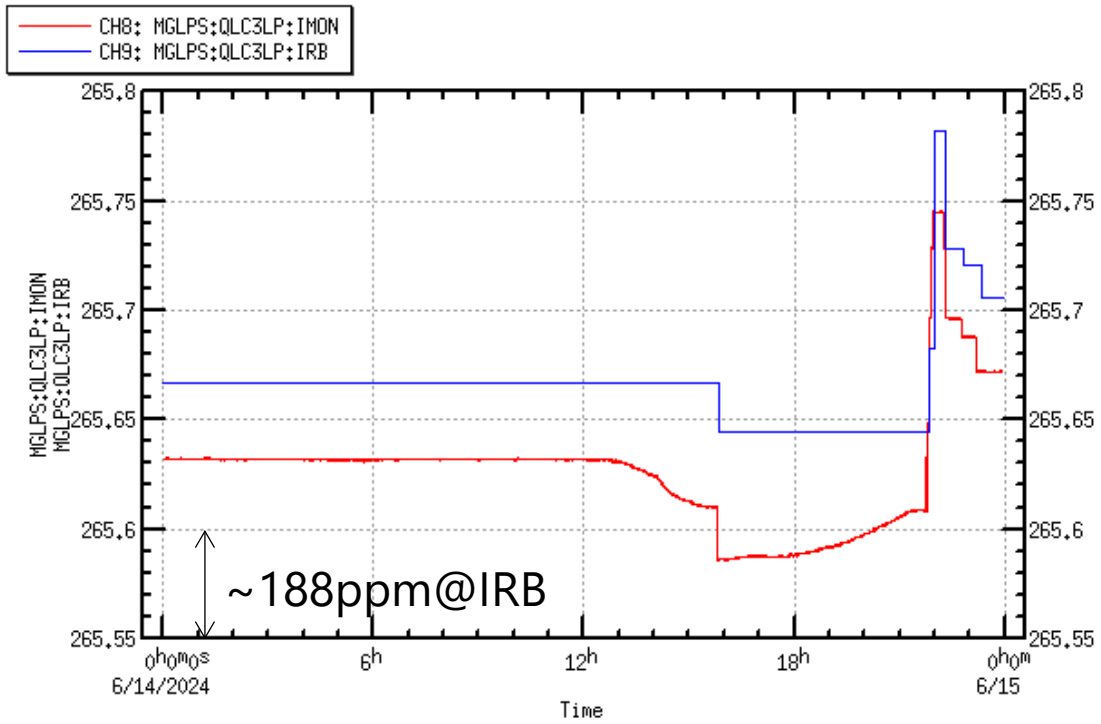
Power supply doesn't go down, but the thermostat in the power supply is out of range.

Power supply(BLC2LP) go down.

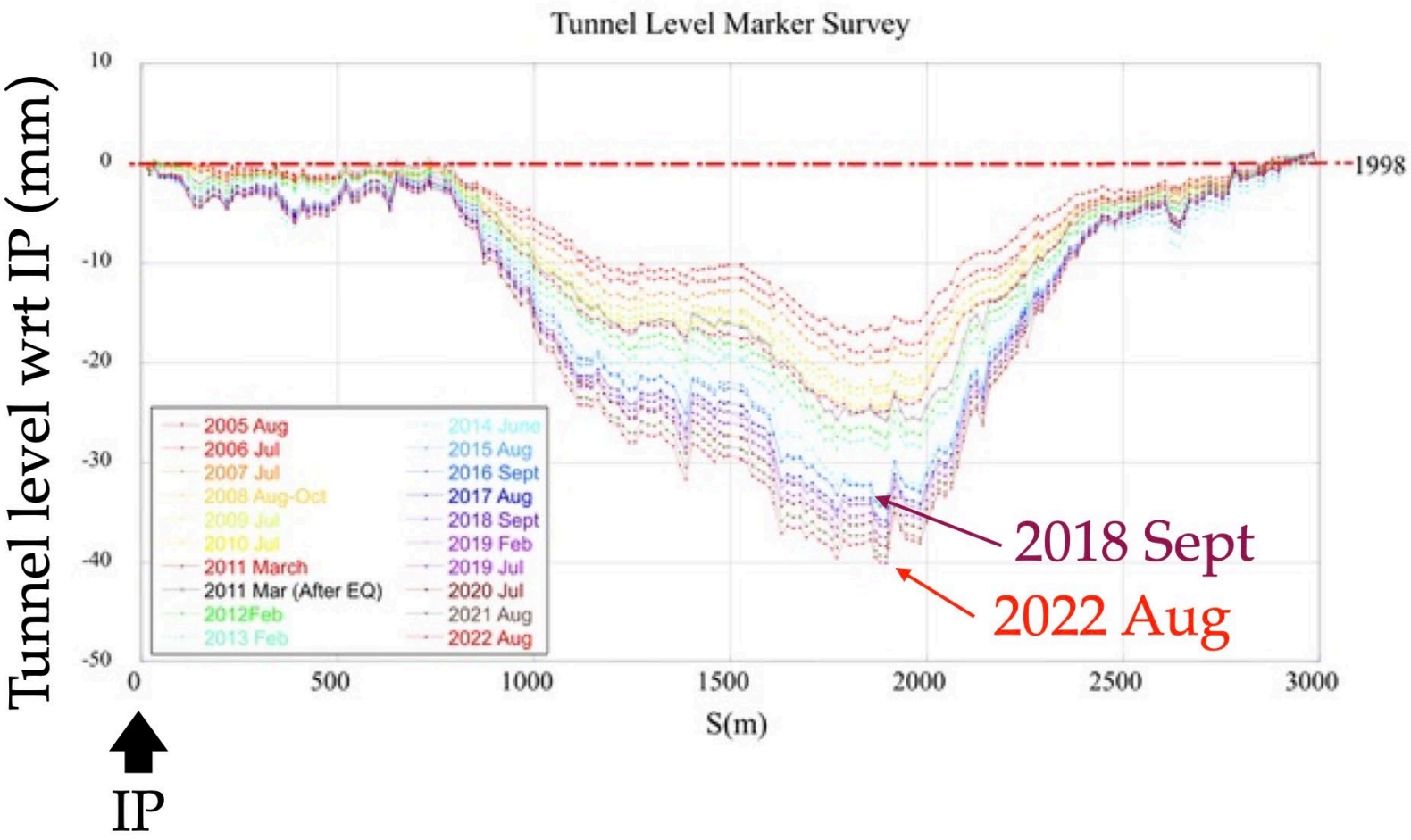


QLC3LP@D2
Rated current : 500A
The PS did not stop, but the output current drifted regardless of the command value.

Survey and alignment

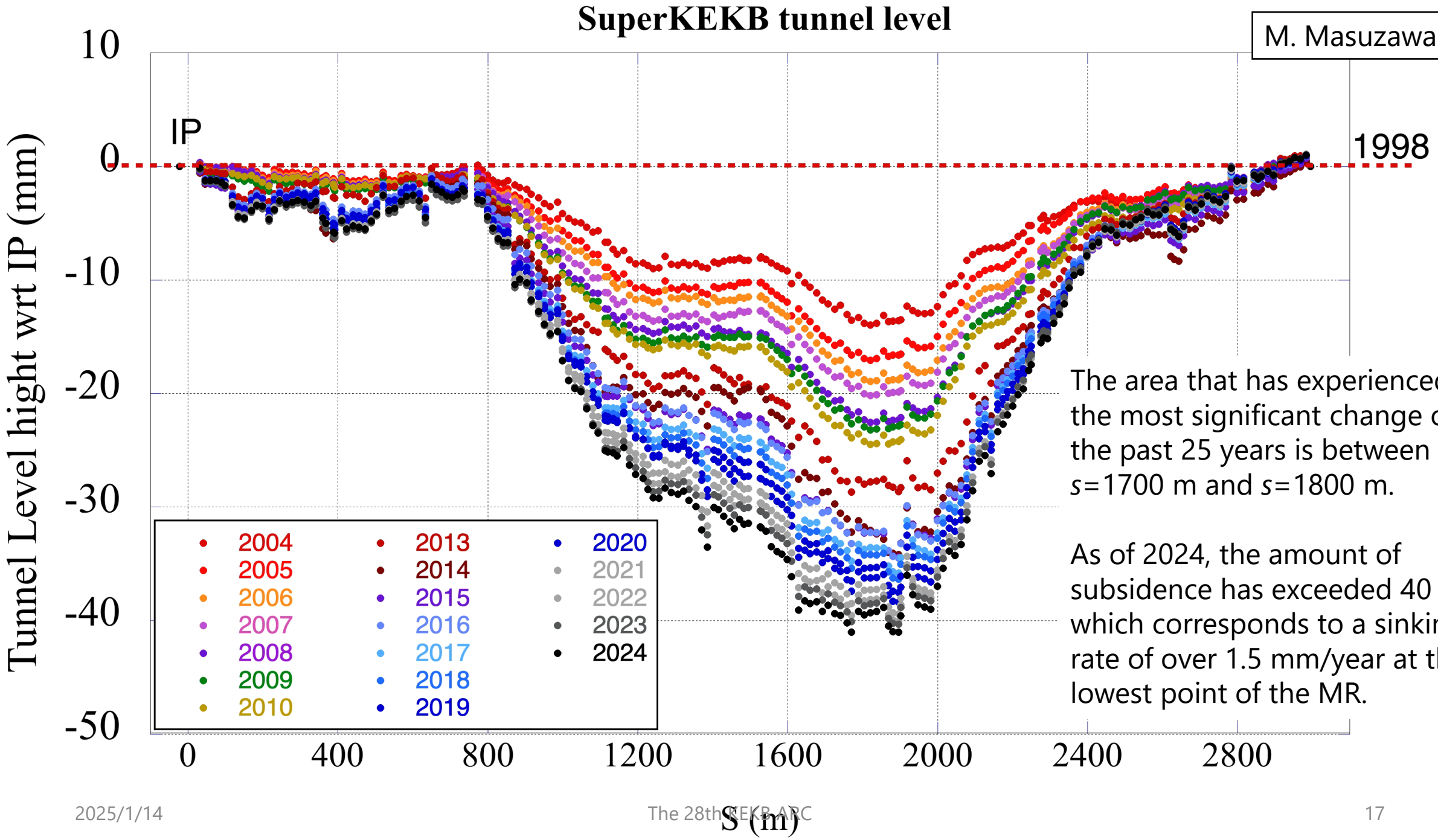
"MR magnets and QCS" Y. Arimoto
The 26th KEKB Accelerator Review Committee (2022/12/13)

Tunnel level variation every year wrt IP



- The tunnel level goes down about 5 mm from 2018 to 2022.

M. Masuzawa



The area that has experienced the most significant change over the past 25 years is between s=1700 m and s=1800 m.

As of 2024, the amount of subsidence has exceeded 40 mm, which corresponds to a sinking rate of over 1.5 mm/year at the lowest point of the MR.

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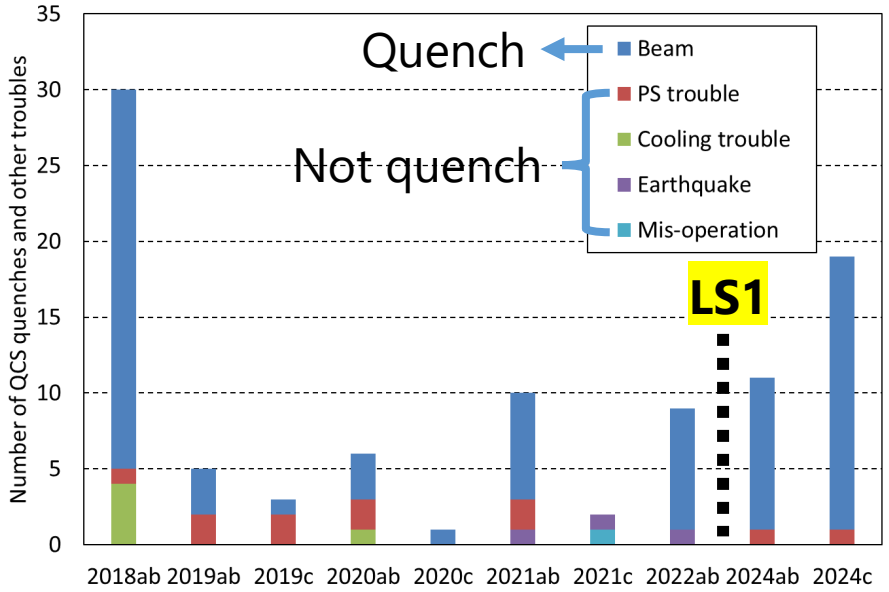
2024c QCS quenches

X. Wang

Number of QCS quenches and other troubles

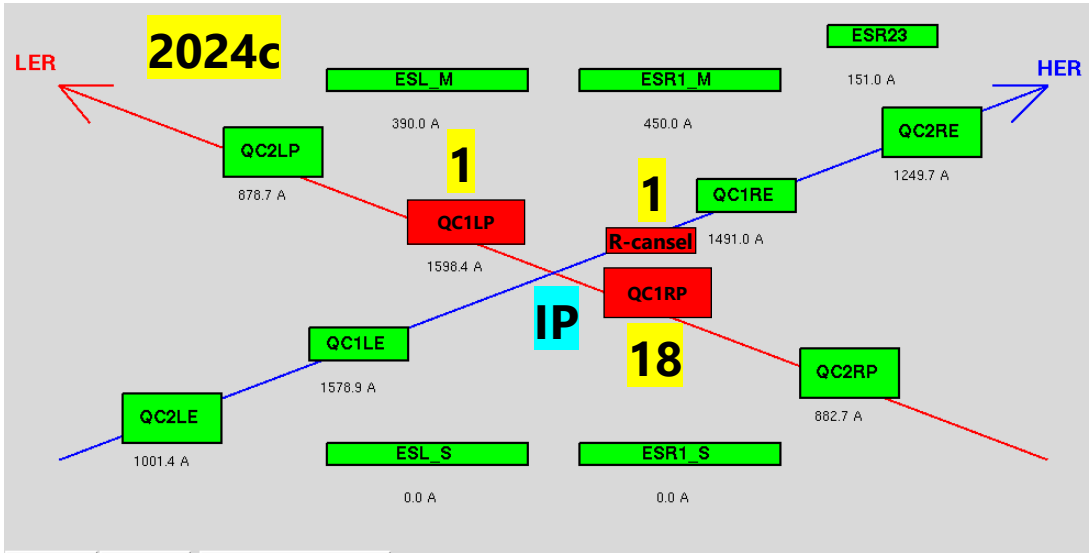


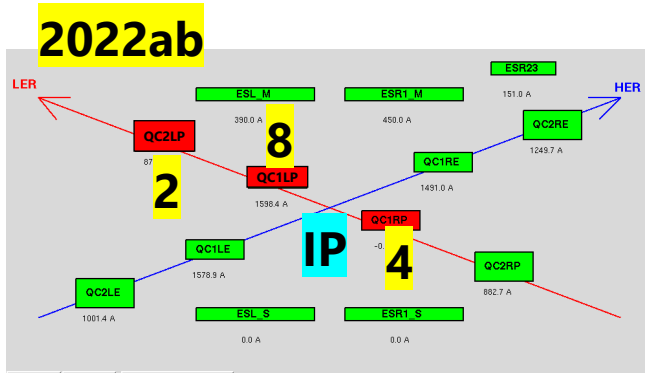
2024c
18 quenches
1 P.S. trouble

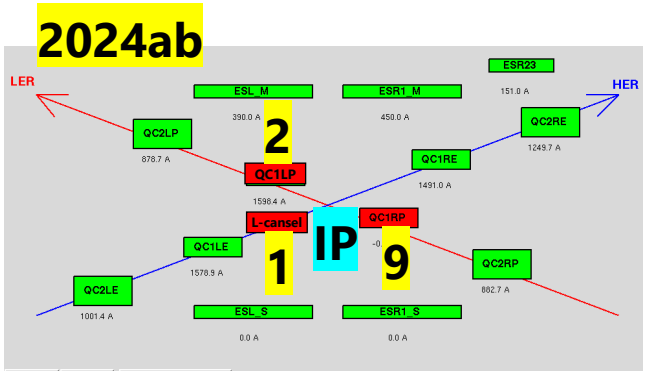
	Quench / Operating period
2022ab	8 / 5 month(Feb.-Jun.)
2024ab	10 / 5 month(Feb.-Jun.)
2024c	18 / 2.5 month(Oct.-Dec.)

Frequency of QCS quenches in 2024c was 3.6 times higher than that in 2024ab.

Location of quenched magnets





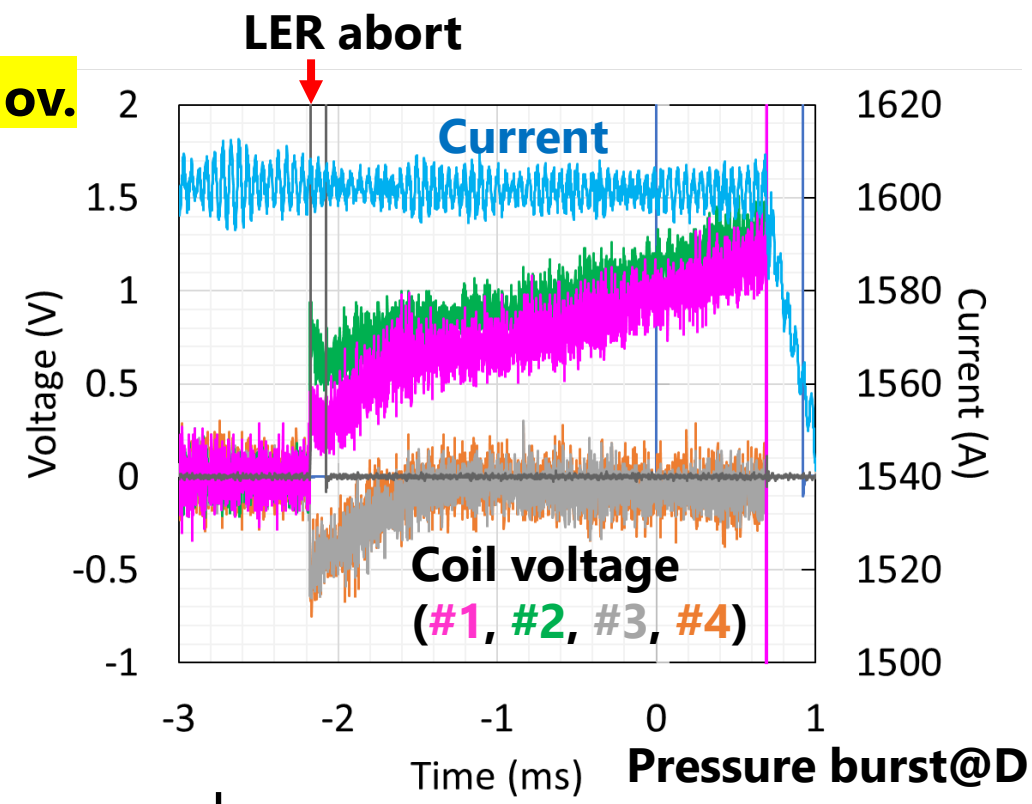


Before LS1, most quenches were observed on QC1LP.
After LS1, most quenches were observed on QC1RP.

QC1RP quenches on 2 Nov. and 17 Dec.

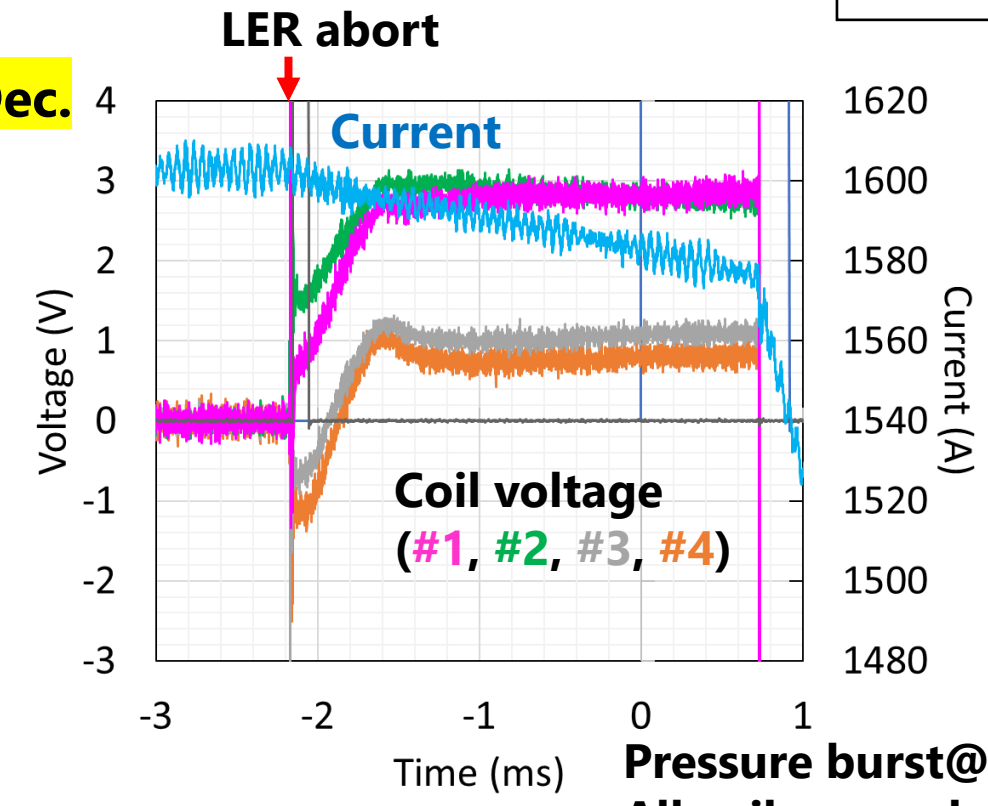
X. Wang

2 Nov.

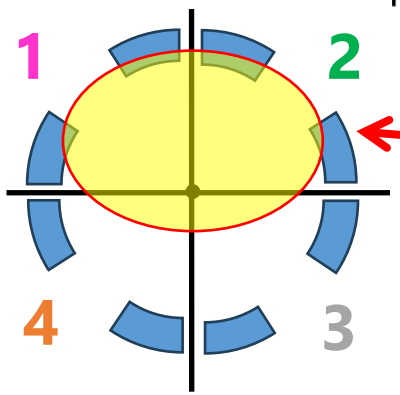


Pressure burst@D10
Coils #1 and #2 quenched

17 Dec.



Pressure burst@D04
All coils quenched



MR outside

Magnet cross-section from LER upstream

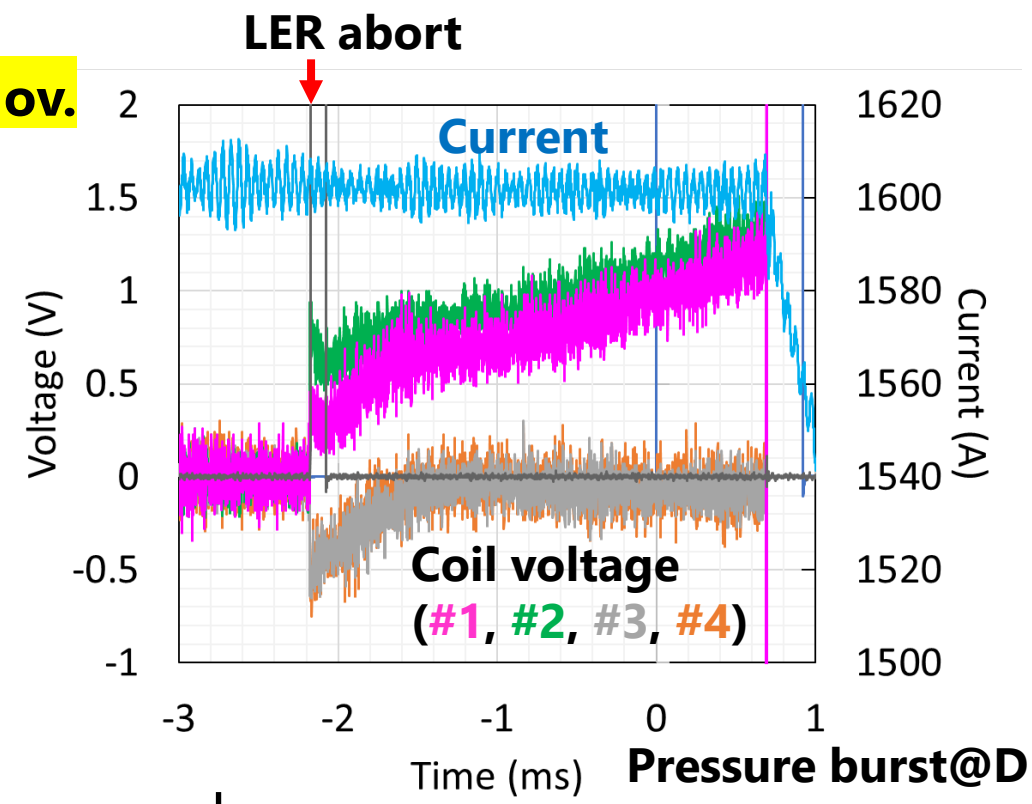
From the quench voltages, it is estimated that the beam loss to the QC1RP coil mainly occurred at the top half of the magnet.

When the pressure burst occurs at D4, closer to the IR, all coils of QC1RP quenched in most events.

QC1RP quenches on 2 Nov. and 17 Dec.

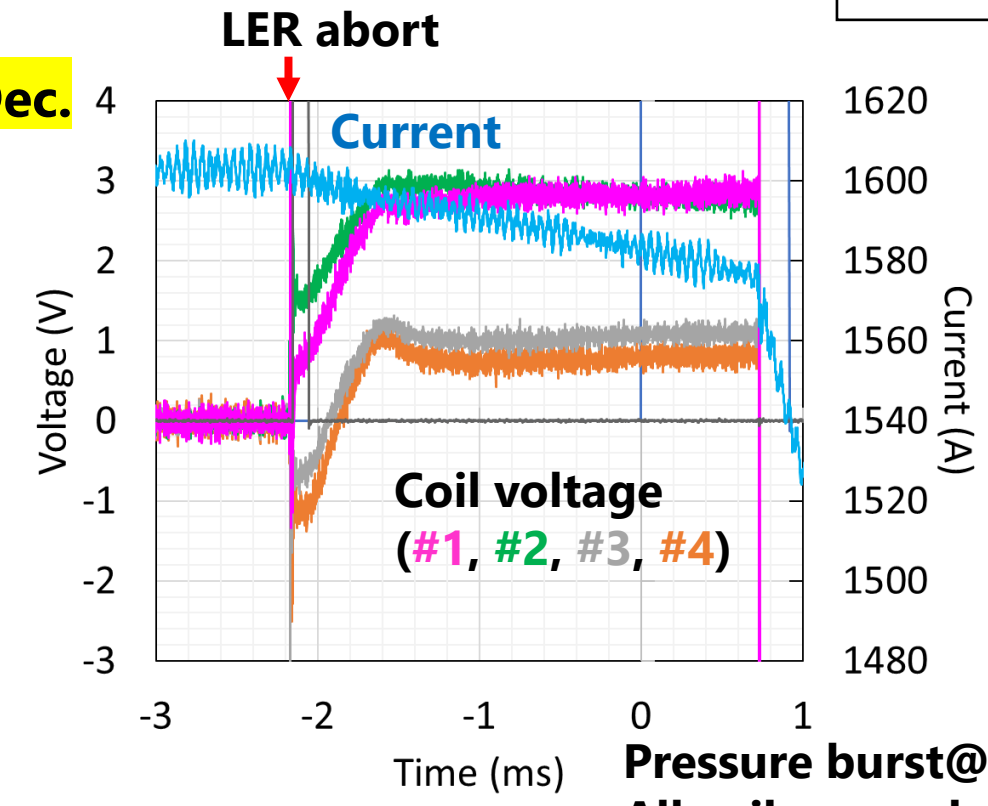
X. Wang

2 Nov.

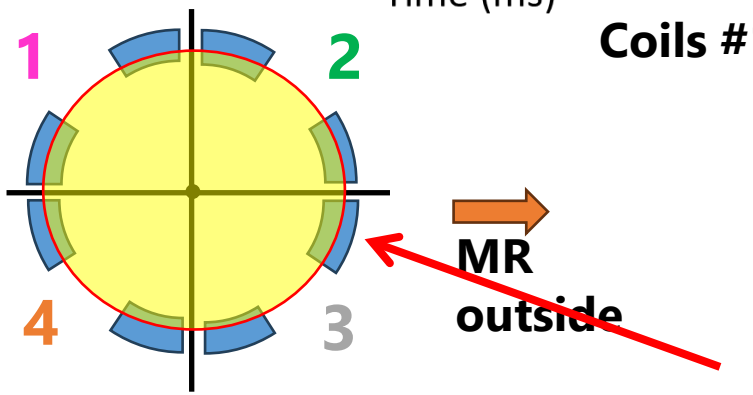


Pressure burst@D10
Coils #1 and #2 quenched

17 Dec.



Pressure burst@D04
All coils quenched



Magnet cross-section from LER upstream

From the quench voltages, it is estimated that the beam loss to the QC1RP coil mainly occurred at the top half of the magnet.

When the pressure burst occurs at D4, closer to the IR, all coils of QC1RP quenched in most events.

2024c QC1RP quench list

Most of the quenches were due to SBL events.
Two quenches were due to kicker malfunctions.

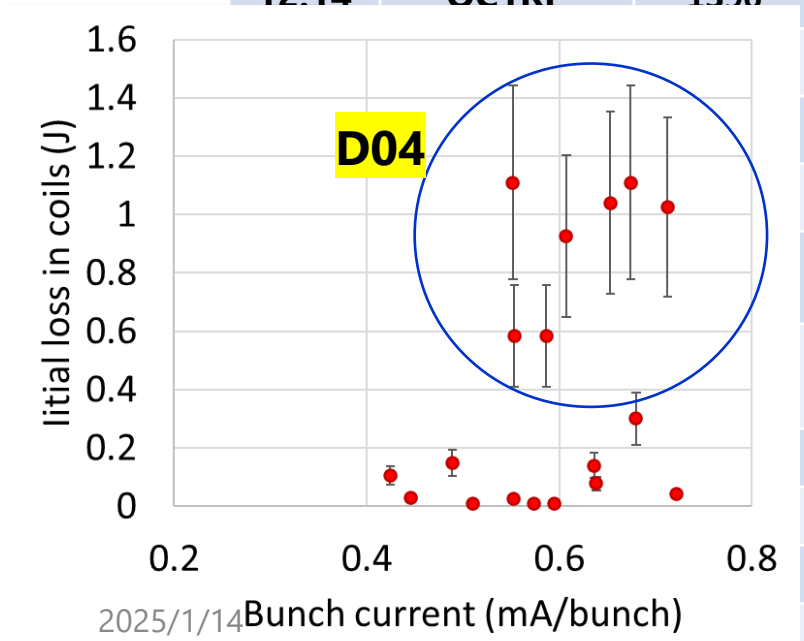
X. Wang

Date	Quench magnets	LER beam (mA)	Bunch I (mA/bunch)	Initial loss/region in coil (mJ)/(%)	BCM loss	Pressure burst	Remarks
10.28	QC1RP	1197	0.51	8 / 0.4%	11%	D10	SBL
11.2	QC1RP, b1	1147	0.49	150 / 8%	6.7%	D10	SBL
11.3	QC1RP	1046	0.45	30 / 1.5%	6.6%	D10	SBL
11.5	QC1RP	996	0.42	105 / 5%	8.8%	D10	SBL
11.10	QC1RP	1296	0.55	25 / 1%	12.3%		Kicker failure
11.11	QC1RP, b1	1595	0.68	300 / 16%	50.6%	D10	SBL
12.9	QC1RP	1498	0.64	75 / 4%	10.4%	D04	SBL
12.11	QC1RP, b1, a2	1376	0.59	580 / 31%	25.3%	D04	SBL
12.14	QC1RP	1396	0.60	8 / 0.4%	34.3%	D05, D11	SBL
12.15	QC1RP, b1, a2	1298	0.55	580 / 31%	15.9%	D04, D02	SBL
12.17	QC1RP, b1, a2	1295	0.55	1100 / 59%	35.8%	D04	SBL
12.19	QC1RP, b1, a2	1582	0.67	1100 / 59%	6.9%	D04	SBL
12.21	QC1RP	1347	0.57	8 / 0.3%	12.5%	D06	Kicker failure
12.21	QC1RP, b1, a2	1425	0.61	930 / 49%	-	D04	SBL
12.23	QC1RP	1495	0.64	140 / 8%	-	D06, D04	SBL
12.24	QC1RP, b1, a2	1534	0.65	1040 / 55%	21.9%	D04	SBL
12.25	QC1RP	1695	0.72	43 / 2%	27%	D10	SBL
12.26	QC1RP, b1, a2	1674	0.71	1030 / 54%	12.6%	D04, D08	SBL

Comparison with bunch current

When the pressure burst occurred at D4, the initial loss and quench region in the coil were larger than that of other quenches in most events.

Date	Quench magnets	LER beam (mA)	Bunch I (mA/bunch)	Initial loss/region in coil (mJ)/(%)	BCM loss	Pressure burst	Remarks
10.28	QC1RP	1197	0.51	8 / 0.4%	11%	D10	SBL
11.2	QC1RP, b1	1147	0.49	150 / 8%	6.7%	D10	SBL
11.3	QC1RP	1046	0.45	30 / 1.5%	6.6%	D10	SBL
11.5	QC1RP	996	0.42	105 / 5%	8.8%	D10	SBL
11.10	QC1RP	1296	0.55	25 / 1%	12.3%		Kicker failure
11.11	QC1RP, b1	1595	0.68	300 / 16%	50.6%	D10	SBL
12.9	QC1RP	1498	0.64	75 / 4%	10.4%	D04	SBL
12.11	QC1RP, b1, a2	1376	0.59	580 / 31%	25.3%	D04	SBL
12.14	QC1RP	1396	0.60	8 / 0.4%	34.3%	D05, D11	SBL
			0.55	580 / 31%	15.9%	D04, D02	SBL
			0.55	1100 / 59%	35.8%	D04	SBL
			0.67	1100 / 59%	6.9%	D04	SBL
			0.57	8 / 0.3%	12.5%	D06	Kicker failure
			0.61	930 / 49%	-	D04	SBL
			0.64	140 / 8%	-	D06, D04	SBL
			0.65	1040 / 55%	21.9%	D04	SBL
			0.72	43 / 2%	27%	D10	SBL
			0.71	1030 / 54%	12.6%	D04, D08	SBL



X. Wang

Summary

- Rotating sextupole magnets are well aligned to the beam orbit, and they can be tilted in an on-beam situation.
- QKARP was moved to adjust the magnetic center to the beam orbit. Then, the orbit fluctuation was reduced.
- Beam abort due to magnet trouble happened for the first time in a while.
- The magnet power supplies were troubled due to high room temperature, which often happened during spring operations. It may become hard to run in early summer.
- As of 2024, the amount of tunnel subsidence has exceeded 40 mm. The impact of this level of subsidence on the performance of SuperKEKB, particularly regarding the deterioration of vertical emittance, remains within acceptable limits.
- Many quenches have occurred in 2024c. The leading cause is SBL.

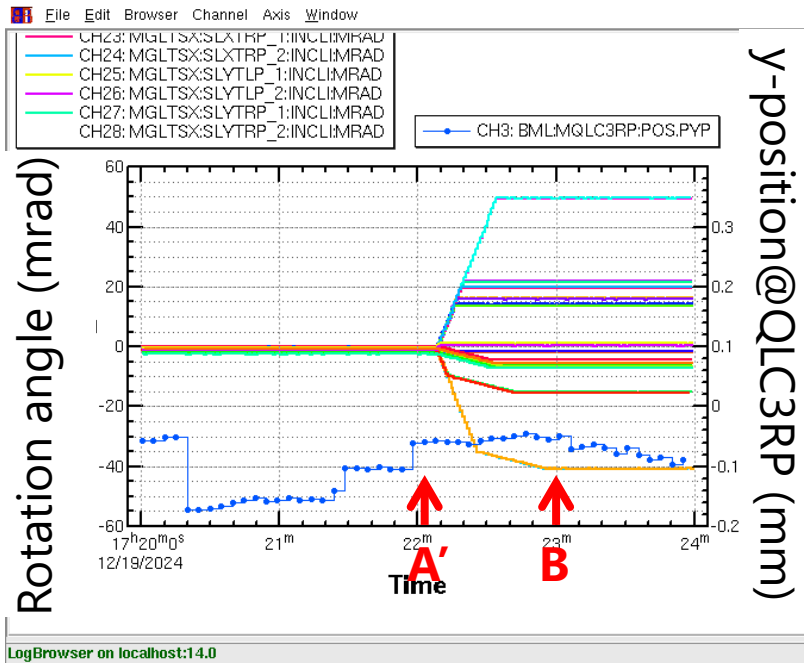
Appendix

Sextupole Magnets on Tilting Tables

2024c, we performed a resonance correction study with a new sextupole set and a magnet rotation study on the beam.
(β_y^* = 1mm, LER current = 50mA)

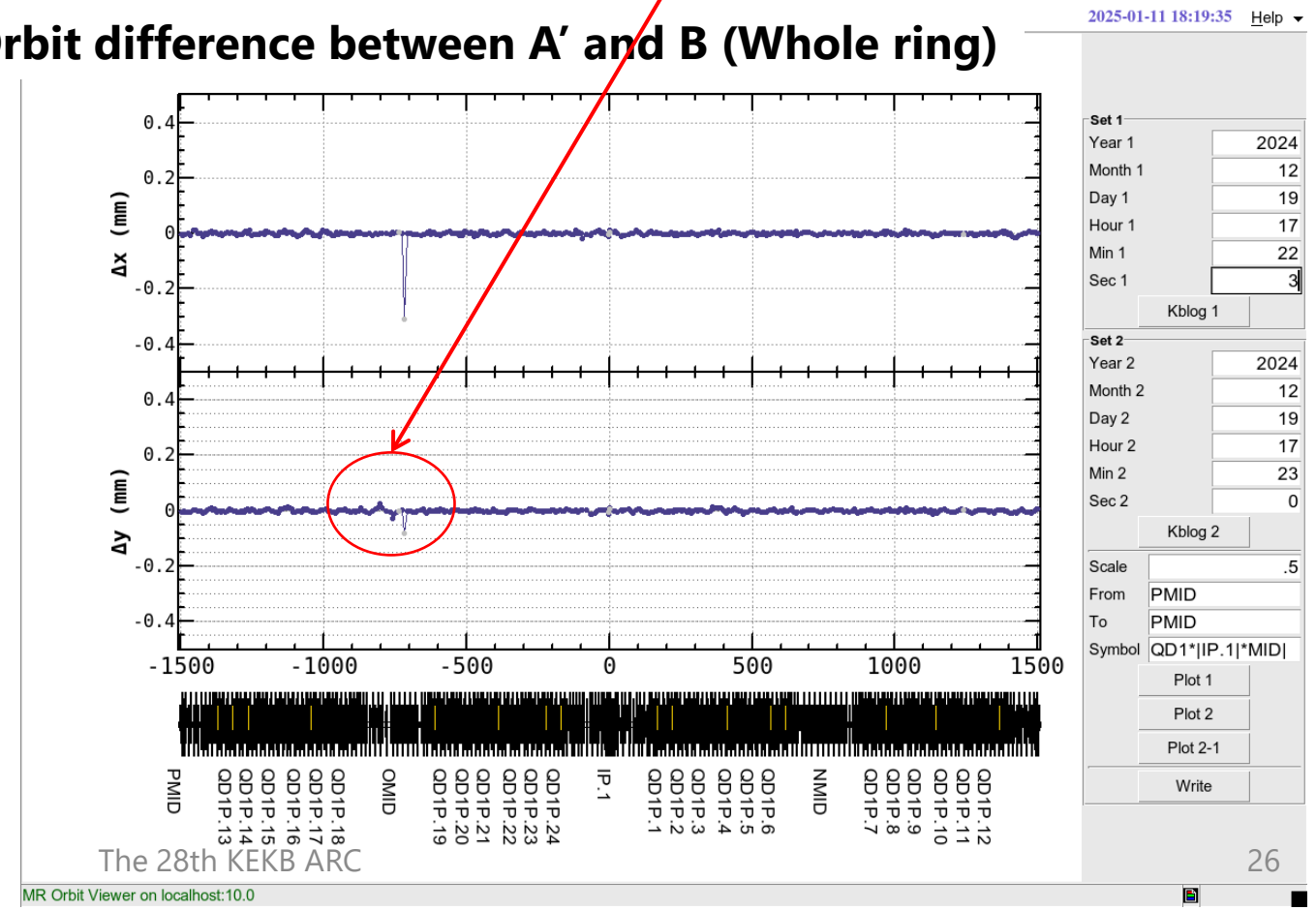
The trial of a magnet rotation on the beam succeeded.

- No beam abort
- Negligible orbit disturbance



ΔY around SNAP.1 and SNAP.2 is a bit larger than the others.

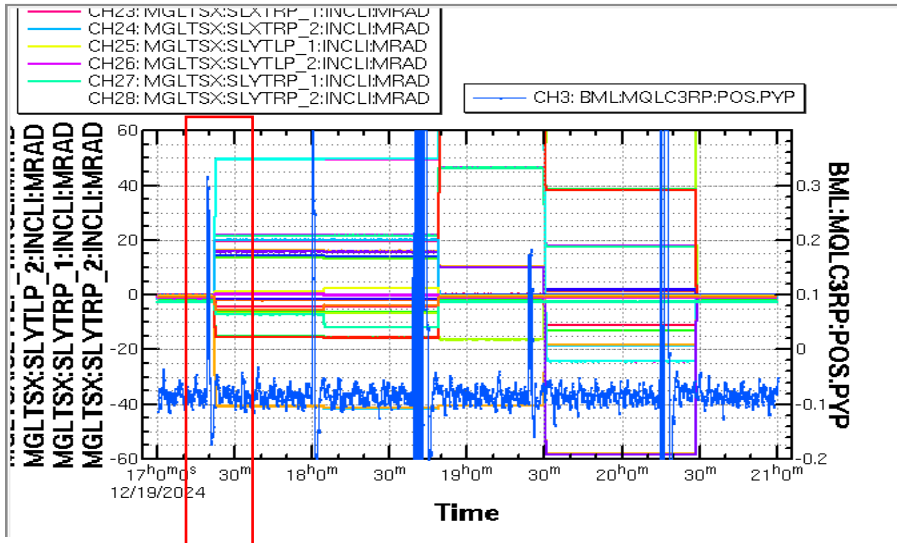
Orbit difference between A' and B (Whole ring)

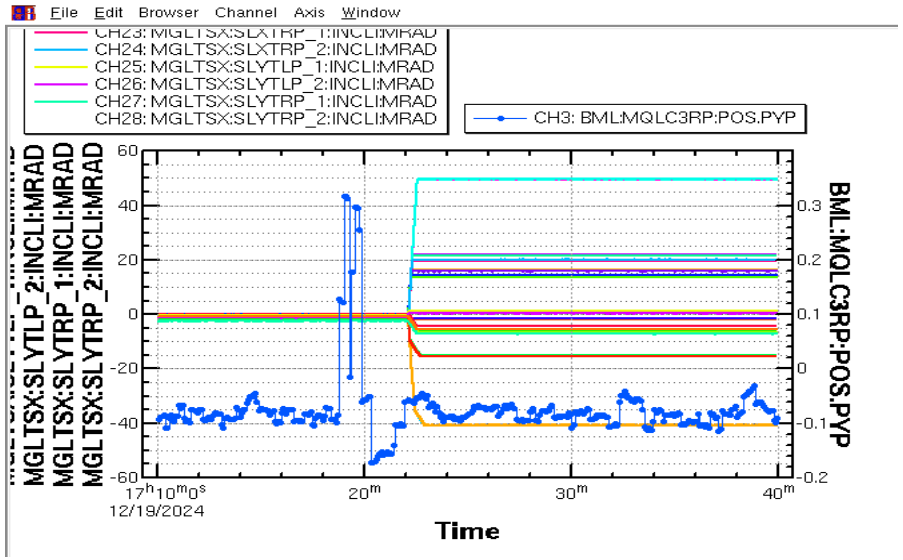


Sextupole Magnets on Tilting Tables

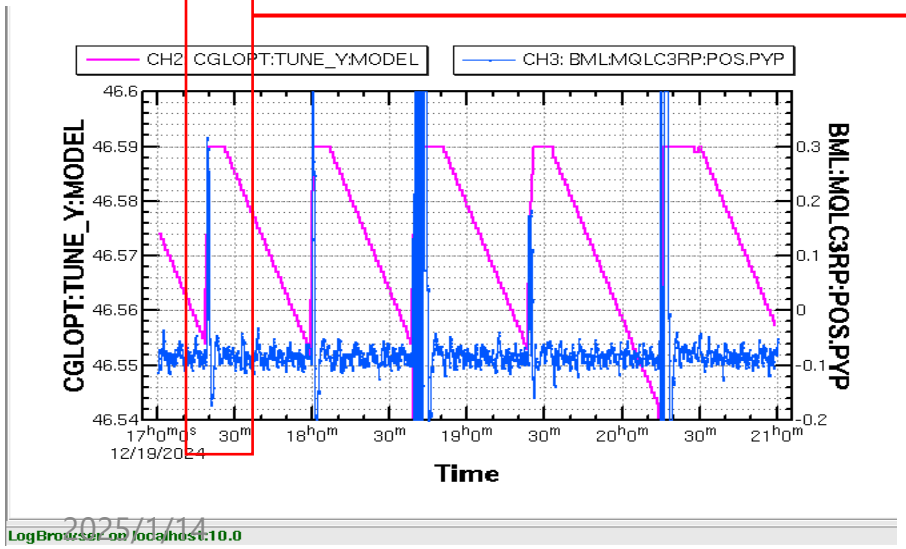
dY@MQLC3RP moves significantly when the V tune is changed dramatically.
The orbite fluctuation is slight when the rotation angle changes.

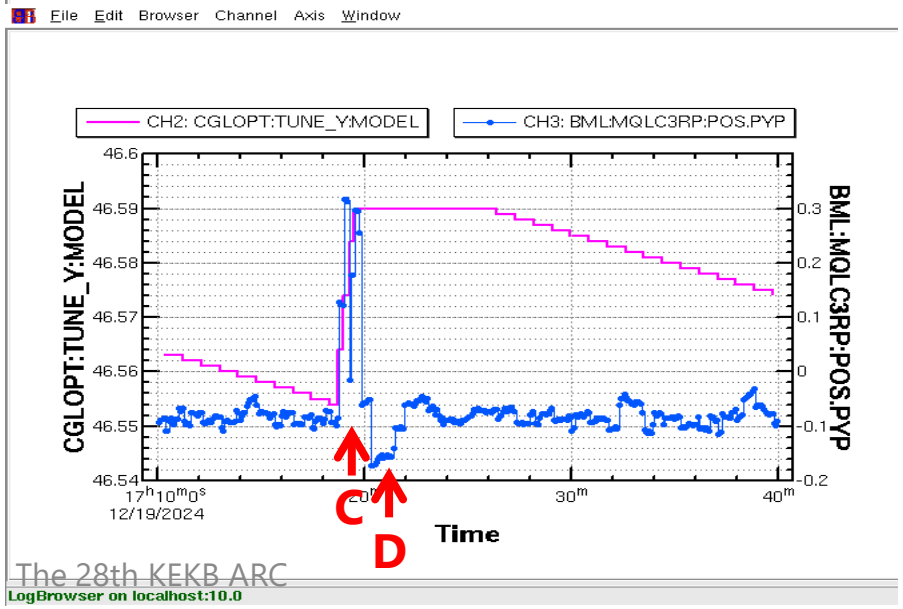
Rotation angle vs Beam y-position@QLC3RP





Vertical tune vs Beam y-position@QLC3RP

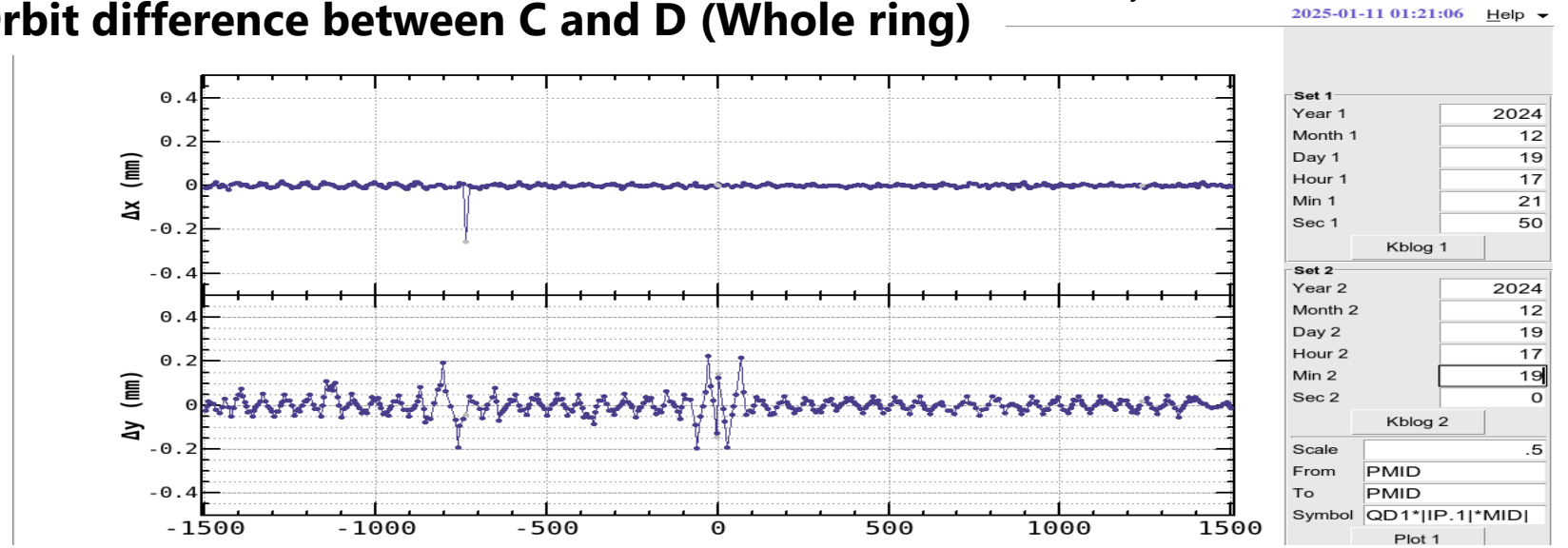


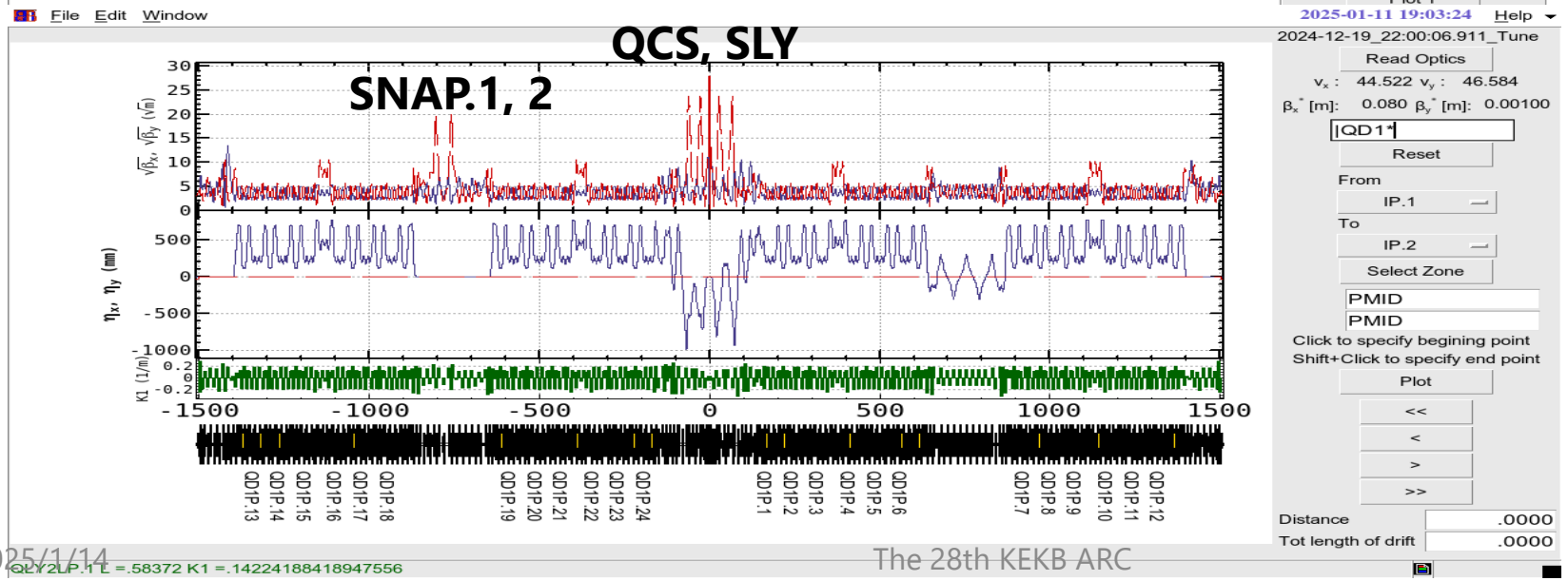


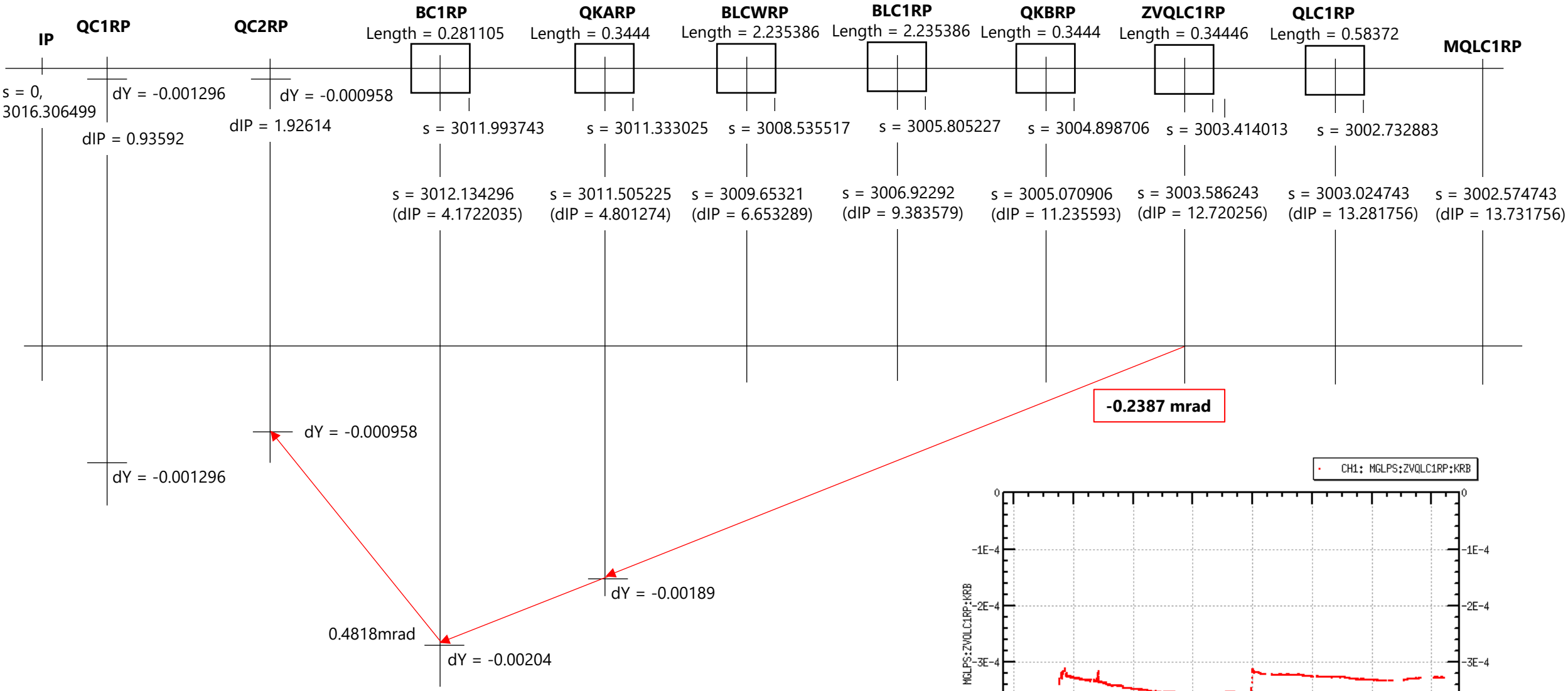
Sextupole Magnets on Tilting Tables

Where β_y is large, the vertical orbit fluctuation is significant.

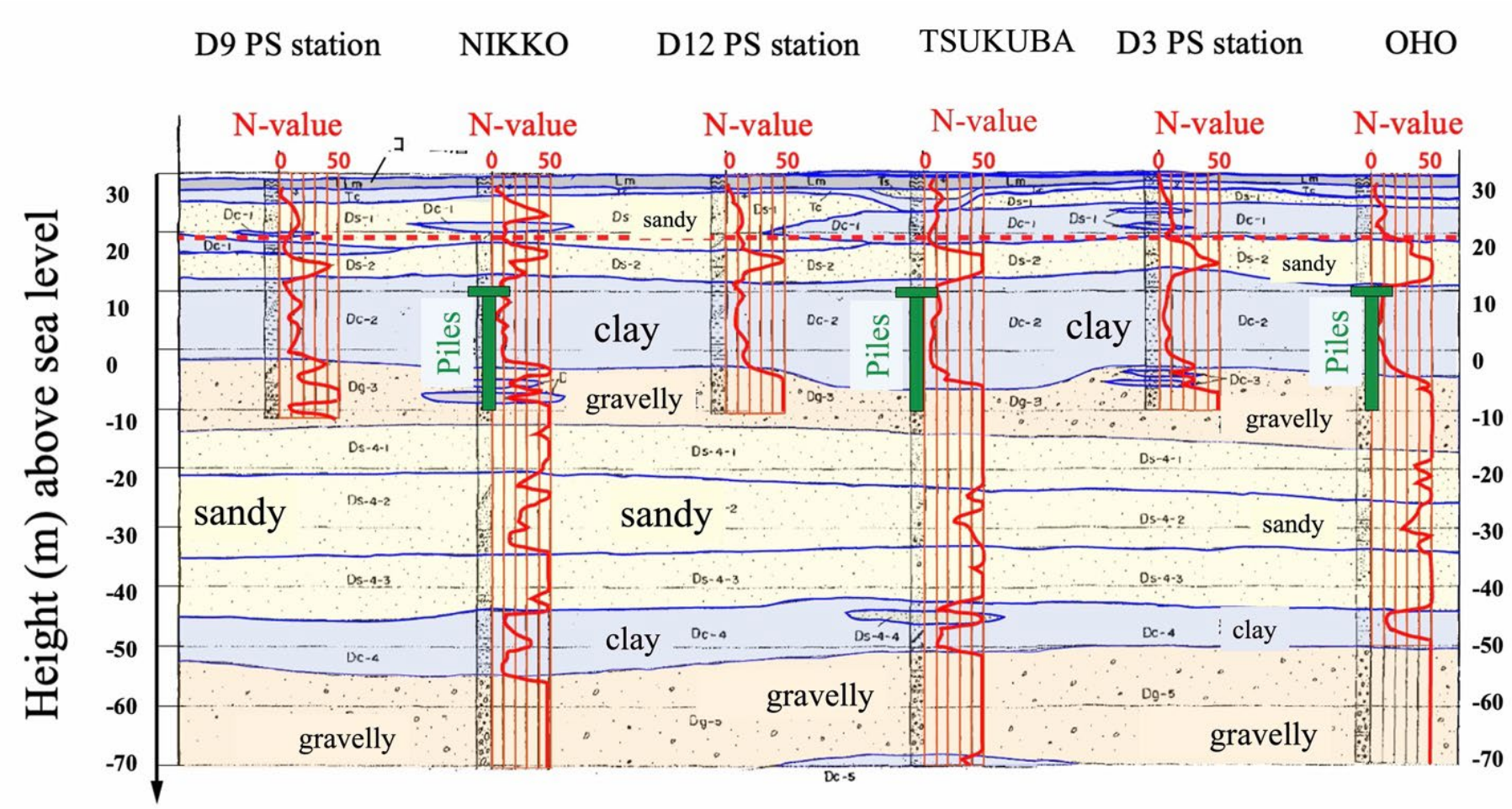
Orbit difference between C and D (Whole ring)







We know that the vertical position of the beam is at -1.89mm at QKARP.
The tilt angle from the nearest V-Steer(ZVQLC1RP) to QKARP is about -0.24mrad.
(In fact, the kick angle of ZVQLC1RP is about -0.3mrad.)
If it goes straight to BC1RP, the vertical position at BC1RP will be about -2mm.
To kick the beam up from BC1RP to QC2RP, a kick angle of about 0.7mrad is required.
This situation explains why the kick angle of BC1RP is positive and is close to the limit of 1mrad.



- The subsidence around the IP and the straight sections on either side of the IP is less pronounced than in the other arc sections of the MR. This reduced subsidence is attributed to the experimental halls being built on pile foundations, which have proven effective.
- At this stage, the impact of this level of subsidence on the performance of SuperKEKB, particularly regarding the deterioration of vertical emittance, remains within acceptable limits [5].
- However, some countermeasures may be necessary in the future to achieve the designed emittance of SuperKEKB. No trend indicating a halt in tunnel subsidence has yet been observed.

Quench voltage waveform of QC1RP