Beam Current-Temperature Dependence and Specific Luminosity Correlation with Machine Environments at SuperKEKB

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Outline

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- Beam Current and Temperature Study during April 2026
- Correlation of Specific Luminosity with 43 PVs during April 2026
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Introduction

Motivation

Increasing beam current is important for improving luminosity, but it can also affect the beam pipe thermal environment.

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Understanding the dependence of beam pipe temperature on beam current helps characterize the thermal response under different machine conditions.

↓

Specific luminosity can exhibit variations even under relatively stable beam current conditions.
Increasing beam current is important for improving luminosity, but it can also affect the beam pipe thermal environment.

↓

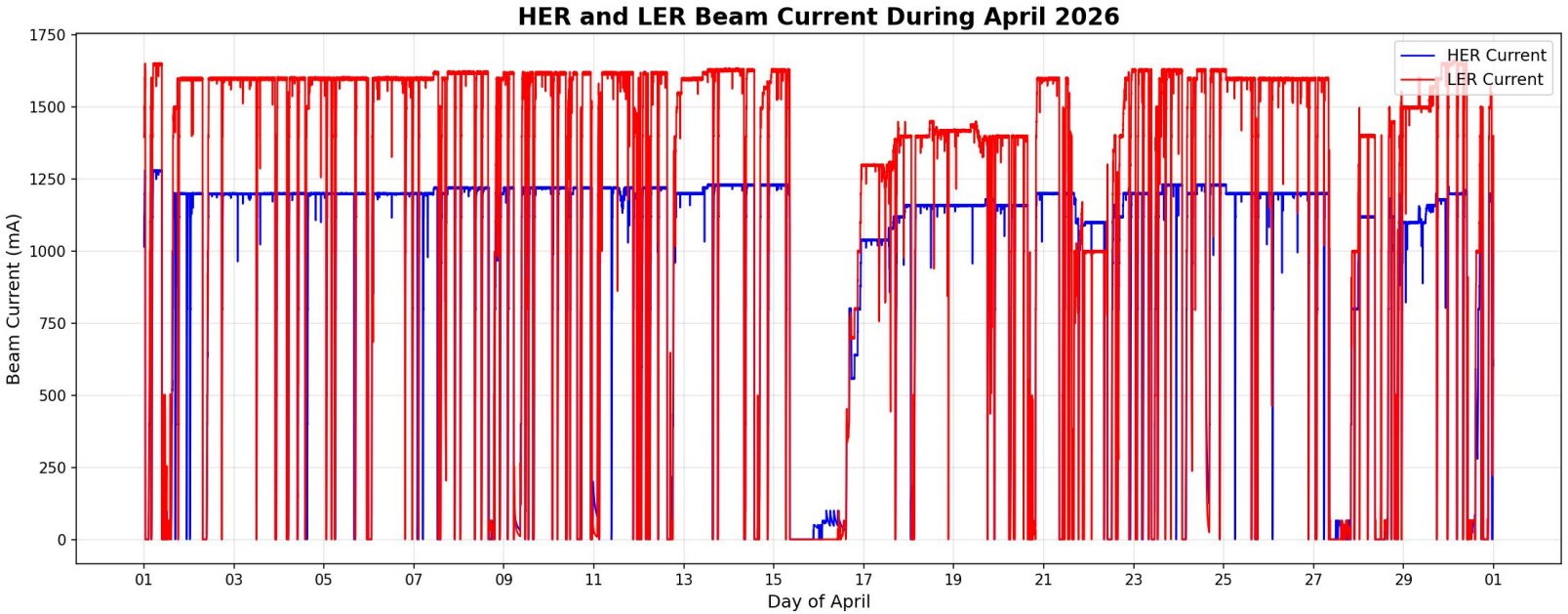
Understanding the relationship between machine conditions, environmental response, and specific luminosity may help identify parameters relevant to SuperKEKB performance.

Objectives

1. Characterize the beam current and temperature dependence during April 2026.
2. Identify machine/environmental PVs associated with specific luminosity using multiple correlation methods.
3. Investigate machine parameters associated with specific luminosity change in selected time periods.

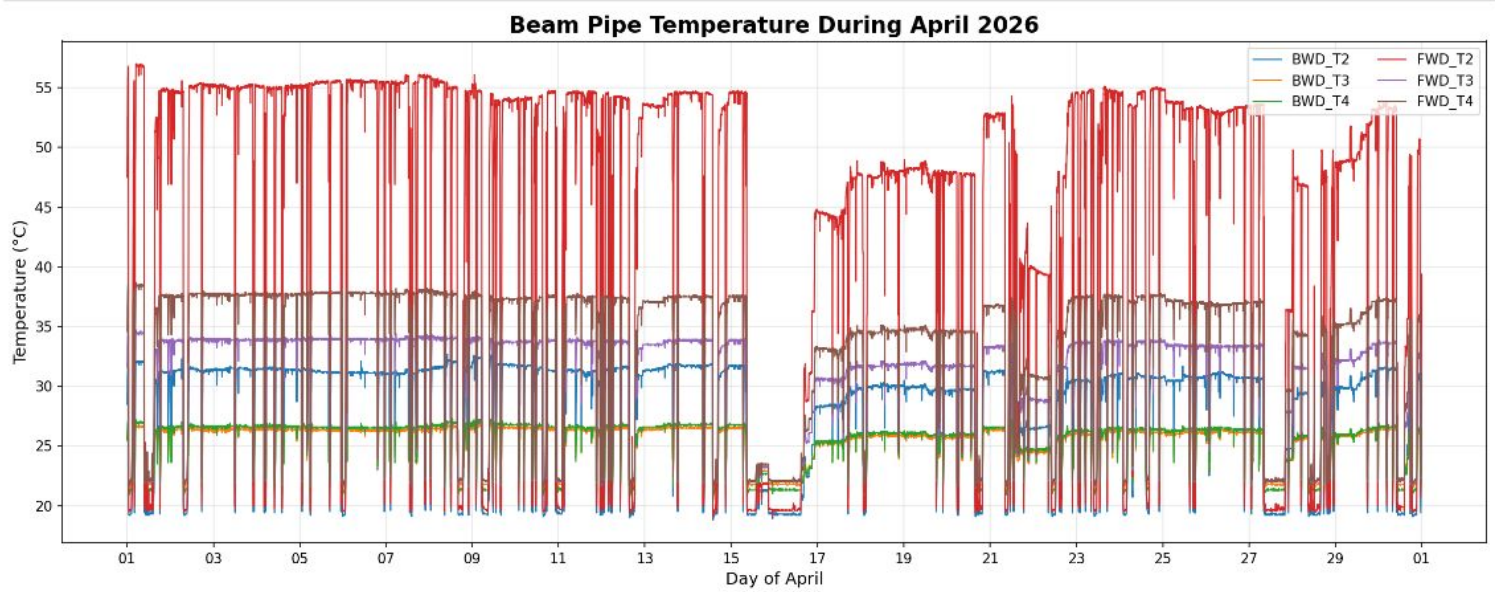
Beam Current and Temperature Study during April 2026

Beam Current vs Time Plot

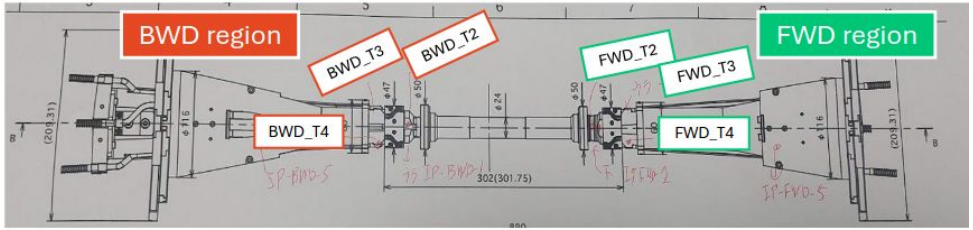


The ratio of HER and LER current generally constant (**4:5**).
Many current drops correspond to beam aborts.

Beam Pipe Temperature vs Time Plot

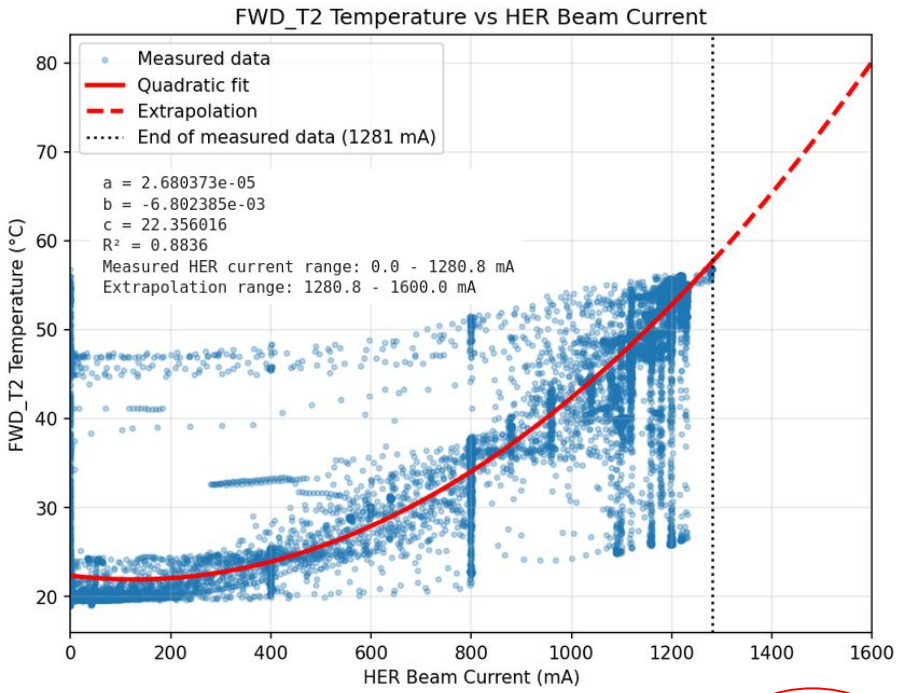


FWD temperatures are consistently **higher** than the **BWD temperatures**.

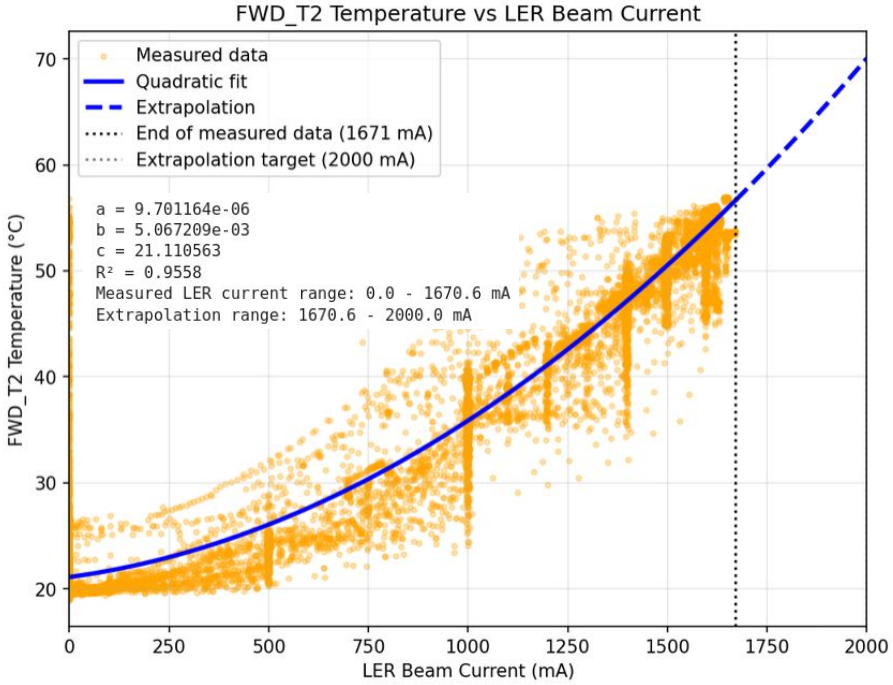


Quadratic Fitting Results $T = aI^2 + bI + c$

The fitting result for FWD_T2 (the highest temperature sensor):



Projected FWD_T2 temperature at HER = 1600 mA: 80.09 °C



Projected FWD_T2 temperature at LER = 2000 mA: 70.05 °C

Quadratic Fitting Results $T = aI^2 + bI + c$

Overall fitting results for all sensors:

	Temperature	Beam	a (I^2)	b (I)	c	R^2
0	BWD_T2	HER	9.282e-06	-2.194e-03	20.168	0.9210
1	BWD_T2	LER	2.909e-06	2.393e-03	19.935	0.9306
2	BWD_T3	HER	3.695e-06	-1.019e-03	22.120	0.9159
3	BWD_T3	LER	1.155e-06	8.417e-04	22.032	0.9205
4	BWD_T4	HER	4.201e-06	-1.072e-03	21.703	0.9287
5	BWD_T4	LER	1.233e-06	1.118e-03	21.634	0.9105
6	FWD_T2	HER	2.680e-05	-6.802e-03	22.356	0.8836
7	FWD_T2	LER	9.701e-06	5.067e-03	21.111	0.9558
8	FWD_T3	HER	8.718e-06	-1.899e-03	22.970	0.8852
9	FWD_T3	LER	3.037e-06	2.071e-03	22.561	0.9517
10	FWD_T4	HER	1.166e-05	-2.797e-03	23.308	0.8783
11	FWD_T4	LER	4.230e-06	2.340e-03	22.732	0.9560

It would be interesting to see which one contributes more: aI^2 or bI??

For comparison: I_HER = 1200 mA & I_LER = 1500 mA

Count the contribution of aI^2 and bI for each sensor and beam current.

Quadratic Fitting Results

	Temperature	Beam	I (mA)	aI² (°C)	bI (°C)
0	BWD_T2	HER	1200	13.37	-2.63
1	BWD_T2	LER	1500	6.55	3.59
2	BWD_T3	HER	1200	5.32	-1.22
3	BWD_T3	LER	1500	2.60	1.26
4	BWD_T4	HER	1200	6.05	-1.29
5	BWD_T4	LER	1500	2.77	1.68
6	FWD_T2	HER	1200	38.60	-8.16
7	FWD_T2	LER	1500	21.83	7.60
8	FWD_T3	HER	1200	12.55	-2.28
9	FWD_T3	LER	1500	6.83	3.11
10	FWD_T4	HER	1200	16.78	-3.36
11	FWD_T4	LER	1500	9.52	3.51
12	FWD_T2	HER	1200	38.60	-8.16
13	FWD_T2	HER	1200	38.60	-8.16
14	FWD_T2	LER	1500	21.83	7.60

$$T = aI^2 + bI + c$$

$aI^2 > bI$

The **quadratic term contributes more strongly** to the temperature.

Possible caused:

- If $\Delta T \propto I$, it could be caused by
  - Synchrotron radiation heating
- If $\Delta T \propto I\text{^}2$, it could be caused by
  - Resistive-wall heating
  - RF heating due to HOM or wake-field
  - Beam loss

That means **these fenomena** possibly **has a greater impact on the heating**.

Combined HER/LER Quadratic Fitting

$$T = aI_{HER}^2 + bI_{HER} + cI_{LER}^2 + dI_{LER} + e$$

Beam pipe temperature is affected by both HER and LER beam currents.

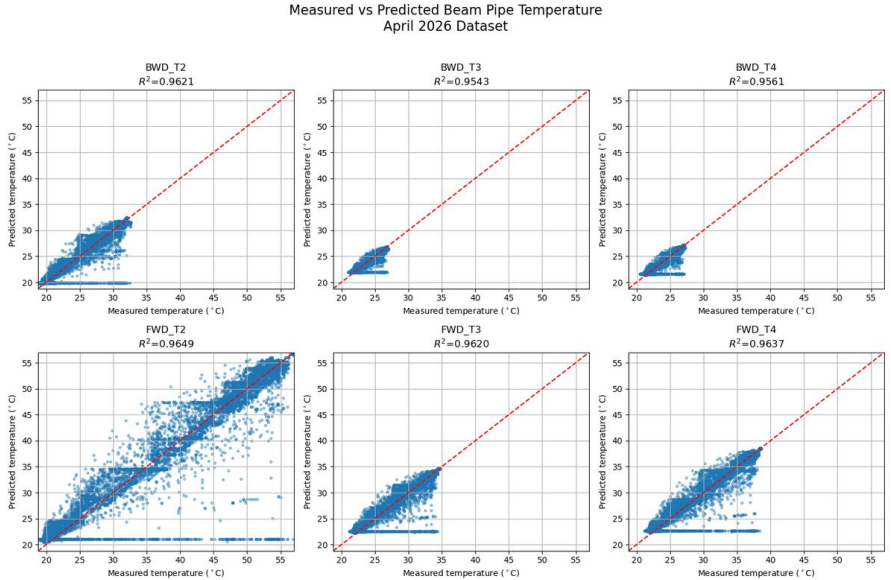
A combined fit is therefore used to model their joint effects within a single temperature model.

The Fitting results for April 2026:**

Start Time : 2026-04-01 00:00:00
End Time : 2026-04-30 23:57:00
Number of Points : 43186

	Temperature	a (HER²)	b (HER)	c (LER²)	d(LER)	e (Intercept)	R²
0	BWD_T2	0.000005	-0.001550	1.860000e-06	0.000887	19.840	0.9621
1	BWD_T3	0.000002	-0.000783	6.900000e-07	0.000332	21.998	0.9543
2	BWD_T4	0.000003	-0.000851	6.700000e-07	0.000329	21.584	0.9561
3	FWD_T2	0.000009	-0.004368	7.510000e-06	0.003773	21.014	0.9649
4	FWD_T3	0.000003	-0.001620	2.240000e-06	0.001639	22.528	0.9620
5	FWD_T4	0.000004	-0.001970	3.280000e-06	0.001925	22.699	0.9637

***However, because the HER/LER current ratio remains nearly constant, the fit result might have some ambiguity.*



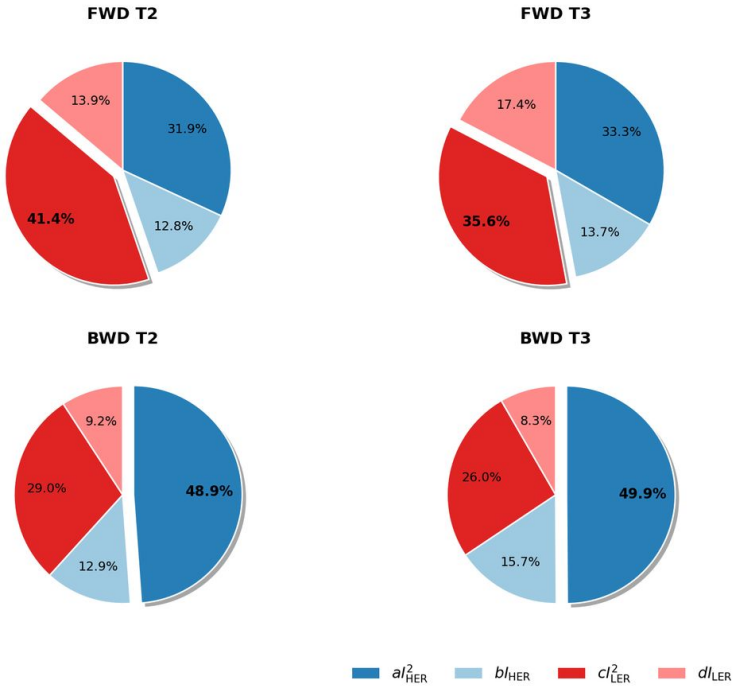
Combined HER/LER Quadratic Fitting

$$T = aI_{HER}^2 + bI_{HER} + cI_{LER}^2 + dI_{LER} + e$$

Relative contribution of HER and LER current terms:**

**Evaluated at I_HER = 1200 mA and I_LER = 1500 mA.*

```
============================================================
FWD_T2 EXTRAPOLATION — COMBINED HER/LER FIT
============================================================
HER Current : 1600 mA
LER Current : 2000 mA
Predicted FWD_T2 Temperature : 74.73 °C (dangerous?)
============================================================
```



FWD → The **quadratic term** of **LER current** is dominant.

BWD → The **quadratic term** of **HER current** is dominant.

***As it mentioned in the previous slide, the fitting coefficients might be biased.*

Combined HER/LER Quadratic Fitting

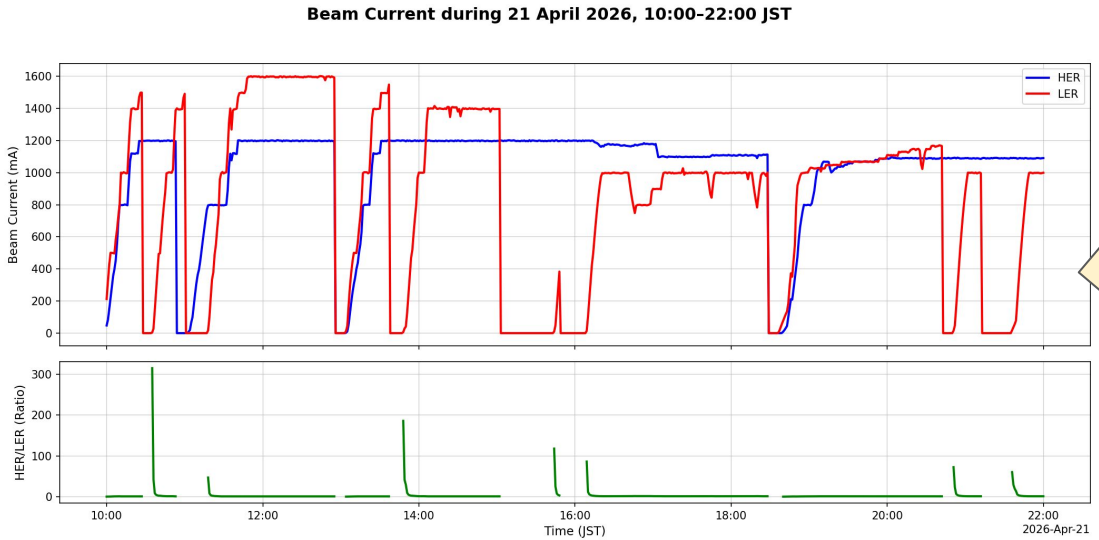
$$T = aI_{HER}^2 + bI_{HER} + cI_{LER}^2 + dI_{LER} + e$$

Since the ratio between HER and LER current ≈ 0.8 most of the time during April 2026.

The previous fit result has ambiguity.

We choose smaller time series where the ratio between HER and LER is not constant.

This will tell us the fitting coefficients (a, b, c, d, e) better.



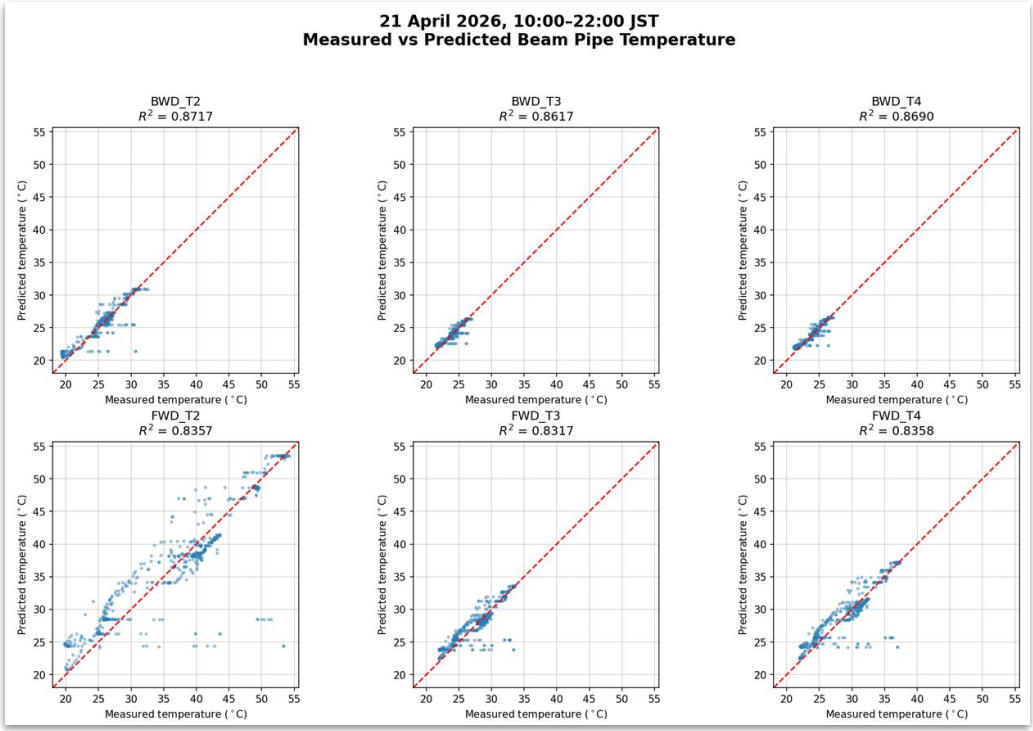
Therefore the April 21, 10:00-22:00 JST might be a good candidate for the next fitting.

Combined HER/LER Quadratic Fitting

$$T = aI_{HER}^2 + bI_{HER} + cI_{LER}^2 + dI_{LER} + e$$

The Fitting results for April 21, 10:00-22:00 JST:

	Temperature	a(HER²)	b(HER)	c(LER²)	d(LER)	e(Intercept)	R²
0	BWD_T2	0.000007	-0.005335	2.570000e-06	-0.000706	21.365	0.8717
1	BWD_T3	0.000003	-0.002557	1.030000e-06	-0.000288	22.549	0.8617
2	BWD_T4	0.000004	-0.002985	9.500000e-07	-0.000231	22.248	0.8690
3	FWD_T2	0.000015	-0.015078	6.250000e-06	0.005676	24.362	0.8357
4	FWD_T3	0.000006	-0.005766	2.200000e-06	0.001643	23.791	0.8317
5	FWD_T4	0.000007	-0.007079	2.980000e-06	0.002430	24.193	0.8358



Combined HER/LER Quadratic Fitting

$$T = aI_{HER}^2 + bI_{HER} + cI_{LER}^2 + dI_{LER} + e$$

Fitting results for April 21, 10:00-22:00 JST:

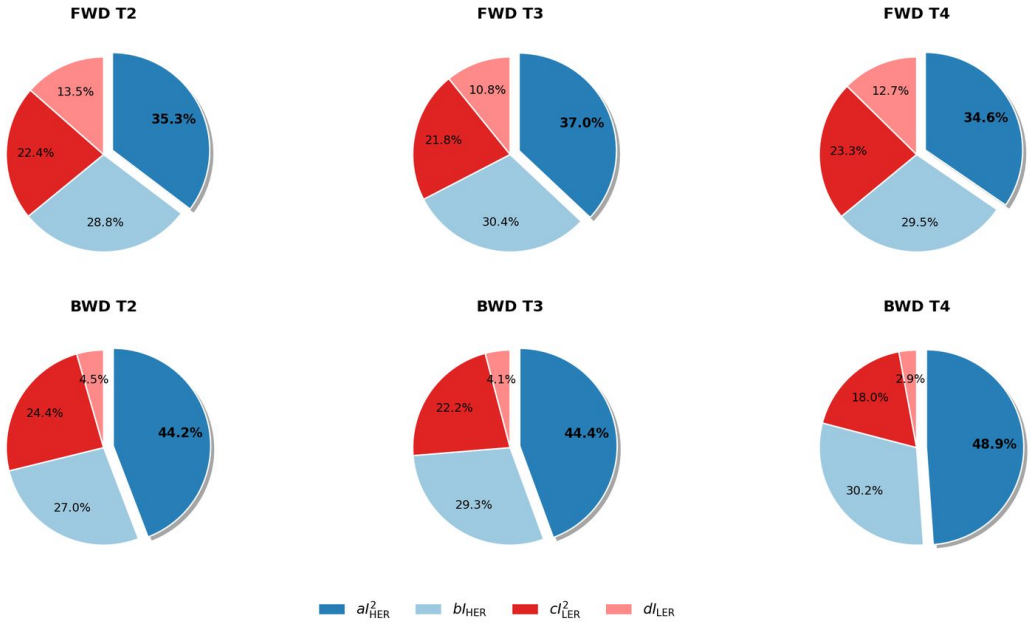
	Temperature	a(HER²)	b(HER)	c(LER²)	d(LER)	e(Intercept)	R²
0	BWD_T2	0.000007	-0.005335	2.570000e-06	-0.000706	21.365	0.8717
1	BWD_T3	0.000003	-0.002557	1.030000e-06	-0.000288	22.549	0.8617
2	BWD_T4	0.000004	-0.002985	9.500000e-07	-0.000231	22.248	0.8690
3	FWD_T2	0.000015	-0.015078	6.250000e-06	0.005676	24.362	0.8357
4	FWD_T3	0.000006	-0.005766	2.200000e-06	0.001643	23.791	0.8317
5	FWD_T4	0.000007	-0.007079	2.980000e-06	0.002430	24.193	0.8358

The **quadratic term** of **HER current** is dominant **for all sensors.**

Compared with **the full April fit, the selected period fit** shows a **larger HER contribution**, especially for the **FWD sensors**.

Relative contribution of HER and LER current terms:

**Evaluated at I_HER = 1200 mA and I_LER = 1500 mA.*



Correlation of Specific Luminosity with 43 PVs during April 2026

43 Selected PVs + Anchor PV

Since downloading and analyzing all ~140k PVs takes very long time, we first try smaller samples, picking up the following PVs.

Beam Current**:

- BMHDCCT:CURRENT
- BMLDCCT:CURRENT

QC1 BPM Position**:

- BMH:MQC1LE:POS.PXP
- BMH:MQC1LE:POS.PYP
- BMH:MQC1RE:POS.PXP
- BMH:MQC1RE:POS.PYP
- BML:MQC1RP:POS.PXP
- BML:MQC1RP:POS.PYP
- BML:MQC1LP:POS.PXP
- BML:MQC1LP:POS.PYP

XRM Beam Size**:

- BMHXRM:BEAM:SIGMAX
- BMHXRM:BEAM:SIGMAY
- BMLXRM:BEAM:SIGMAX
- BMLXRM:BEAM:SIGMAY

Paraffin BWD T1-T10:

- B2_IR:paraffin:BP_BWD:T1
- B2_IR:paraffin:BP_BWD:T2
- B2_IR:paraffin:BP_BWD:T3
- B2_IR:paraffin:BP_BWD:T4
- B2_IR:paraffin:BP_BWD:T5
- B2_IR:paraffin:BP_BWD:T6
- B2_IR:paraffin:BP_BWD:T7
- B2_IR:paraffin:BP_BWD:T8
- B2_IR:paraffin:BP_BWD:T9
- B2_IR:paraffin:BP_BWD:T10

Paraffin FWD T2-T10:

- B2_IR:paraffin:BP_FWD:T2
- B2_IR:paraffin:BP_FWD:T3
- B2_IR:paraffin:BP_FWD:T4
- B2_IR:paraffin:BP_FWD:T5
- B2_IR:paraffin:BP_FWD:T6
- B2_IR:paraffin:BP_FWD:T7
- B2_IR:paraffin:BP_FWD:T8
- B2_IR:paraffin:BP_FWD:T9
- B2_IR:paraffin:BP_FWD:T10

Room Temperature T1-T8:
**Room temperature of where the feedback module is installed.*

- FB_RM:T01
- FB_RM:T02
- FB_RM:T03
- FB_RM:T04
- FB_RM:T05
- FB_RM:T06
- FB_RM:T07
- FB_RM:T08

Luminosity:

- B2_nsm:get:ECL_LUM_MON:lum_acc_20

Number of Bunches:

- CGHINJ:BKSEL:NOB_SET

Specific Luminosity (Anchor PV):

- **CG_OPR:SpecificLuminosity**

**note:
H = HER (-) PXP = Horizontal Beam Position SIGMAX = Horizontal Beam Size
L = LER (+) PYP = Vertical Beam Position SIGMAY = Vertical Beam Size

Introducing Correlation Methods

The `pvana-corr` tool in the **PV Analysis framework** currently provides four correlation methods:

- Pearson Correlation (pearson)
- Kolmogorov Smirnov Correlation (ksc_raw)
- Mutual Information (mi)
- Distance Correlation (dcor)

All four methods are compared because each one measures relationships from a different perspective.

Method	What does it measure?	How is the score interpreted?
pearson	Measures how **closely two signals follow a straight line trend**. In `pvana-corr` the signals are first aligned to a common 1 second time grid.	−1 to +1. The sign shows the direction
ksc_raw	Measures correlation while keeping the original measurement times. **Measurements that are closer together in time receive more weight.**	−1 to +1. The sign shows the direction
mi	Measures how **much information two signals share**. It can identify relationships that are not well represented by a straight line.	A higher value means stronger dependence; no direction
dcor	Measures the **overall dependence between two signals** using distances between data points. It can detect both linear and nonlinear relationships.	0 to 1. A higher value means stronger dependence; no direction

Correlation Results

Pearson:

Linear trend

Ranking	PV Name	Raw Samples (n)	corr	|corr|
1	BML:MQC1RP:POS.PXP	529,654	-0.039824	0.039824
2	BMHDCCT:CURRENT	2,590,425	-0.030228	0.030228
3	BMLDCCT:CURRENT	2,590,412	-0.029729	0.029729
4	BML:MQC1LP:POS.PXP	529,654	-0.028593	0.028593
5	B2_IR:paraffin:BP_BWD:T1	208,083	-0.028288	0.028288
6	B2_IR:paraffin:BP_BWD:T2	208,369	-0.028099	0.028099
7	B2_IR:paraffin:BP_FWD:T2	236,838	-0.027662	0.027662
8	B2_IR:paraffin:BP_BWD:T6	171,355	-0.027640	0.027640
9	B2_IR:paraffin:BP_FWD:T4	212,500	-0.027146	0.027146
10	B2_nsm:get:ECL_LUM_MON:lum_acc_20	2,097,546	-0.027058	0.027058

The highest-ranked PVs include:

- **beam position** near the interaction point (MQC1R/L position monitors)
- **beam current** (HER and LER DCCT)
- **paraffin temperature** sensors.

These PVs are likely associated with the beam conditions around the interaction region.

However, it is important to note that **the Pearson coefficients are relatively small** ($|r| < 0.04$), indicating that **none of these variables has a strong linear correlation with Specific Luminosity.**

Correlation Results

KSC Raw:

Time weighted correlation

Ranking	PV Name	Raw Samples (n)	corr	|corr|
1	B2_IR:paraffin:BP_BWD:T10	163,439	0.116210	0.116210
2	BMH:MQC1LE:POS.PYP	529,654	0.066236	0.066236
3	BML:MQC1RP:POS.PYP	529,419	0.061595	0.061595
4	BML:MQC1RP:POS.PXP	529,654	-0.031170	0.031170
5	BMH:MQC1LE:POS.PXP	529,446	0.030309	0.030309
6	BML:MQC1LP:POS.PXP	529,654	0.026293	0.026293
7	B2_IR:paraffin:BP_BWD:T1	208,083	-0.020896	0.020896
8	B2_IR:paraffin:BP_FWD:T2	236,838	-0.020336	0.020336
9	BMHXRM:BEAM:SIGMAX	1,260,849	0.018859	0.018859
10	B2_IR:paraffin:BP_FWD:T4	212,500	-0.018784	0.018784

The highest-ranked PVs include:

- **paraffin temperature** sensor (BWD T10)
- **QC1 beam position** monitors (MQC1LE and MQC1RP)
- **Beam Size**

Unlike Pearson, KSC places **more QC1 BPM signals** near the top.

This suggests that **timestamp handling** influences which PVs receive the highest ranks.

Correlation Results

MI:

Shared information

Ranking	PV Name	Raw Samples (n)	corr	|corr|
1	B2_nsm:get:ECL_LUM_MON:lum_acc_20	2,097,546	1.743760	1.743760
2	CGHINJ:BKSEL:NOB_SET	3	1.721301	1.721301
3	BMLDCCT:CURRENT	2,590,412	1.299211	1.299211
4	BMHDCCT:CURRENT	2,590,425	1.243701	1.243701
5	B2_IR:paraffin:BP_FWD:T2	236,838	1.127172	1.127172
6	B2_IR:paraffin:BP_FWD:T4	212,500	1.068661	1.068661
7	B2_IR:paraffin:BP_BWD:T2	208,369	1.038699	1.038699
8	B2_IR:paraffin:BP_FWD:T3	215,801	0.985654	0.985654
9	B2_IR:paraffin:BP_BWD:T6	171,355	0.967682	0.967682
10	BMHXRM:BEAM:SIGMAX	1,260,849	0.908225	0.908225

The highest-ranked PVs include:

- **ECL luminosity monitor**
- **number of bunches** (*only 3 raw samples*)
- **beam current** (HER and LER DCCT)
- **paraffin temperature** sensor (FWD T2)

MI highlights the luminosity monitor and beam current, showing shared information that **may not be purely linear**.

The number of bunches result is **not reliable** because it contains only three raw samples.

Correlation Results

dCor:

Overall dependence

Ranking	PV Name	Raw Samples (n)	corr	|corr|
1	CGHINJ:BKSEL:NOB_SET	3	0.577263	0.577263
2	B2_IR:paraffin:BP_BWD:T7	183,034	0.164399	0.164399
3	B2_IR:paraffin:BP_FWD:T7	217,716	0.154900	0.154900
4	B2_IR:paraffin:BP_FWD:T5	228,092	0.146148	0.146148
5	B2_IR:paraffin:BP_BWD:T6	171,355	0.142545	0.142545
6	B2_IR:paraffin:BP_BWD:T5	166,850	0.142067	0.142067
7	B2_IR:paraffin:BP_FWD:T6	268,436	0.139100	0.139100
8	BMHDCCT:CURRENT	2,590,425	0.137974	0.137974
9	BMLDCCT:CURRENT	2,590,412	0.137865	0.137865
10	B2_IR:paraffin:BP_BWD:T3	195,178	0.135852	0.135852

The highest-ranked PVs include:

- **number of bunches** (only 3 raw samples)
- **paraffin temperature** sensors (BWD and FWD)
- **beam current** (HER and LER DCCT; ranks 8 and 9)

dCor can detect both **linear and non-linear dependence**. The high ranks of several paraffin temperature sensors suggest that their relationship with Specific Luminosity **may not follow a simple straight line trend**.

The number of bunches result is **unreliable** because it is based on only three raw samples.

Correlation Results

Overall Ranking:

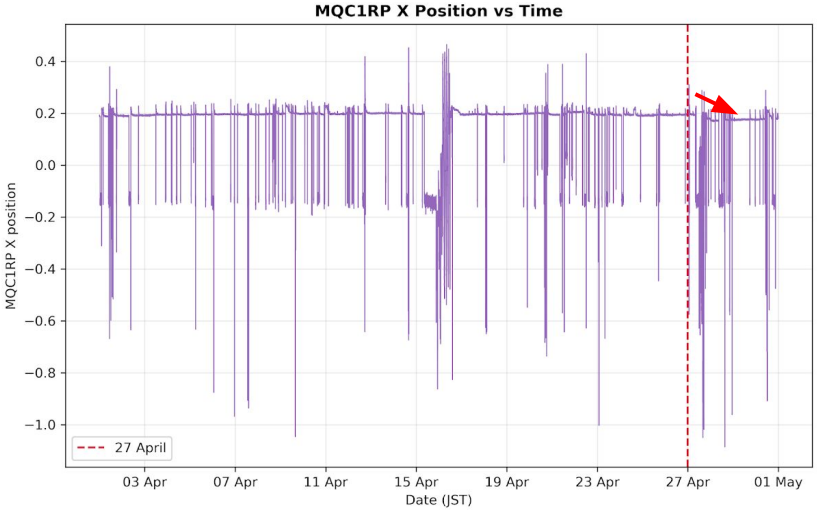
Overall Rank	PV	Pearson	dCor	MI	KSC	Pearson_Rank	dCor_Rank	MI_Rank	KSC_Rank	Average Rank
1	BMLDCCT:CURRENT	0.029729	0.137865	1.299211	0.013238	3.000000	9.000000	3.000000	16.000000	7.75
2	BMHDCCT:CURRENT	0.030228	0.137974	1.243701	0.011744	2.000000	8.000000	4.000000	19.000000	8.25
3	B2_IR:paraffin:BP_BWD:T2	0.028099	0.131491	1.038699	0.016355	6.000000	12.000000	7.000000	12.000000	9.25
4	B2_IR:paraffin:BP_FWD:T4	0.027146	0.113580	1.068661	0.018784	9.000000	18.000000	6.000000	10.000000	10.75
5	B2_IR:paraffin:BP_BWD:T1	0.028288	0.109719	0.904689	0.020896	5.000000	21.000000	11.000000	7.000000	11.00
6	B2_IR:paraffin:BP_BWD:T6	0.027640	0.142545	0.967682	0.010078	8.000000	5.000000	9.000000	24.000000	11.50
7	B2_IR:paraffin:BP_BWD:T5	0.026064	0.1					15.000000	11.000000	11.50
8	BML:MQC1RP:POS.PXP	0.039824						22.000000	4.000000	11.75
9	B2_IR:paraffin:BP_FWD:T3	0.027052	0.1					8.000000	13.000000	12.00
10	CGHINJ:BKSEL:NOB_SET	0.008511	0.577263	1.721301	—	33.000000	1.000000	2.000000	—	12.00

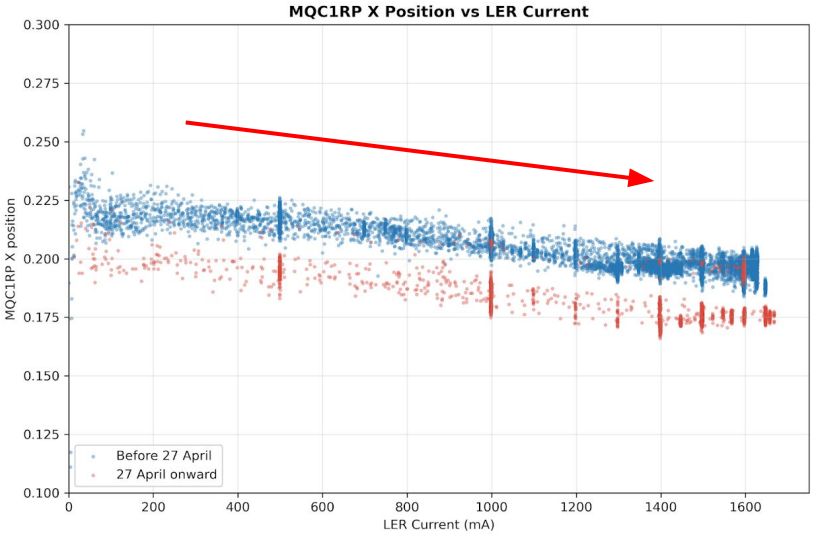
The presence of Beam Position PV was **less expected**. Therefore, we need to investigate more using 2-D plot.

Overall, the ranking seems reasonable.

Beam currents, paraffin temperatures, and the number of bunches appear among the highest ranked variables, although **their relationships with specific luminosity may not necessarily be direct.**

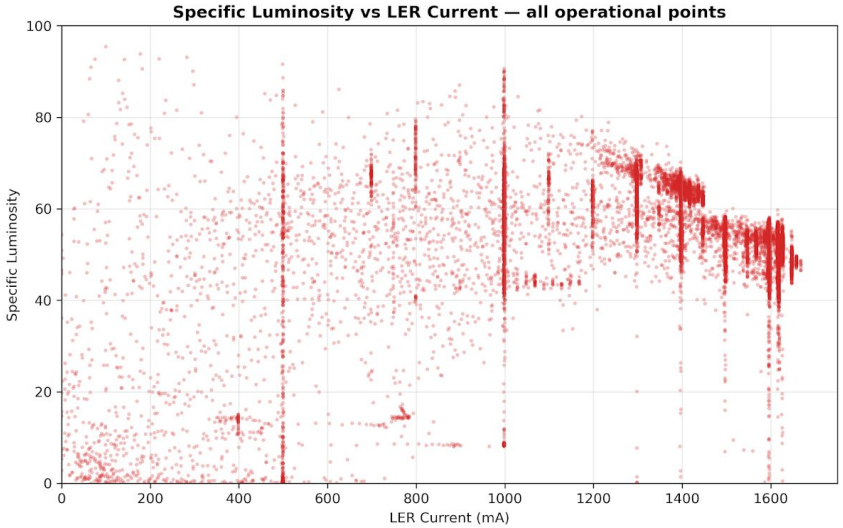
QC1RP BPM Visual Investigation

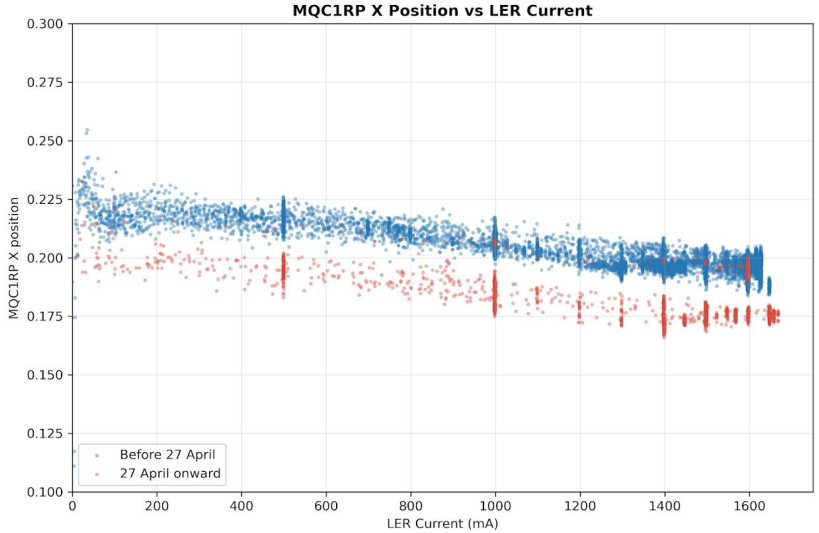




From 27 April onward, the beam position shifts to a lower band.
Both bands in the right graph show a similar negative trend with increasing LER current, suggesting a position offset under a different operating condition.

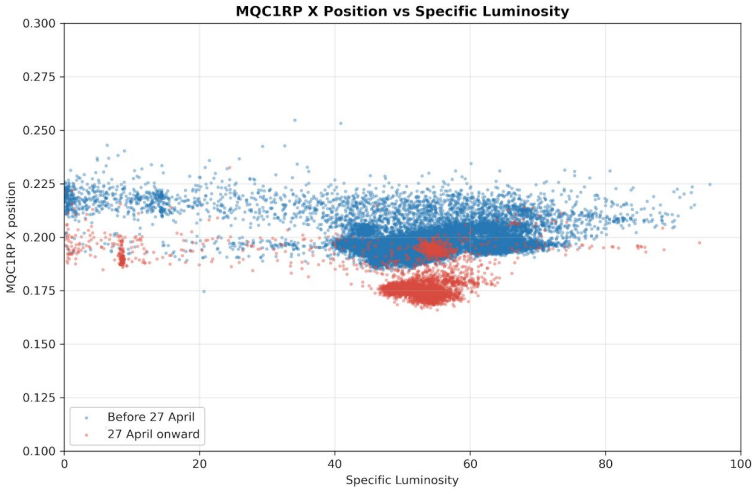
QC1RP BPM Visual Investigation

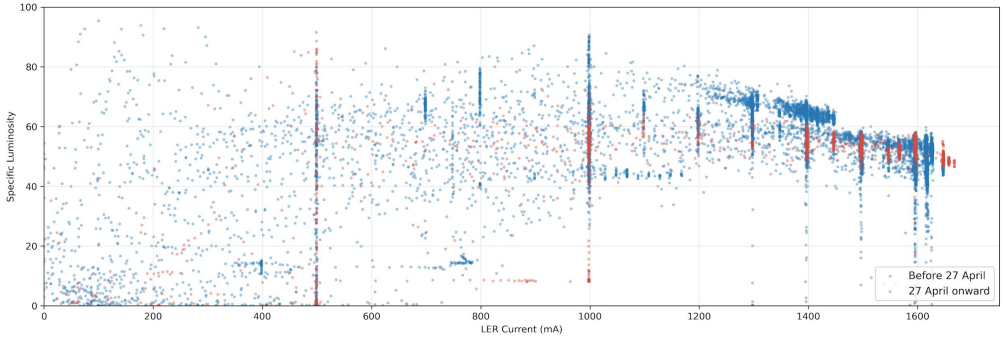




A negative slope island is observed in the Lsp LER current plot at approximately 1200–1600 mA. The BeamPos-LER current plot shows two approximately parallel bands across a broader current range. The lower band mainly consists of data from 27 April onward, suggesting a change in operating conditions.

QC1RP BPM Visual Investigation

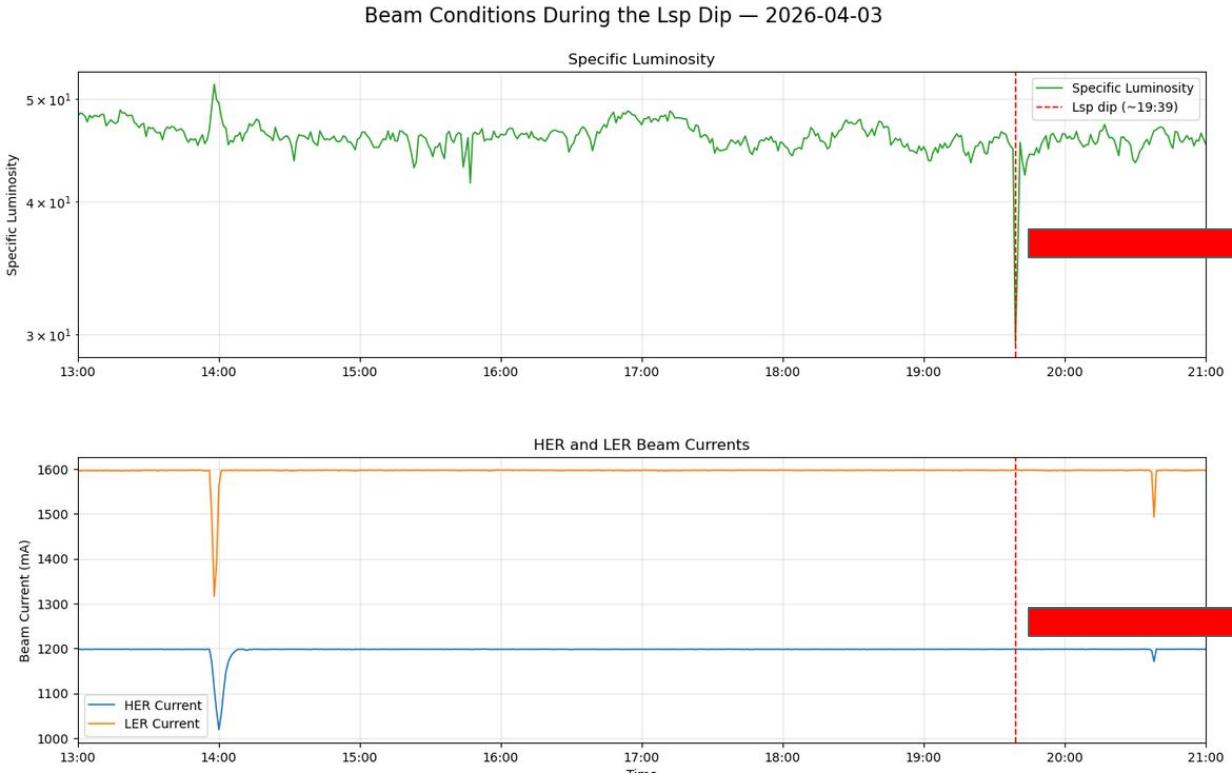




The BeamPos Lsp plot contains two bands and a lower island.
The lower island is dominated by data from 27 April onward, suggesting that the structure reflects different operating conditions.

Correlation of Specific Luminosity with All ~140k PVs during Selected Time Range

Selected Time Range: April 3, 2026, 13:00–21:00



A dip in specific luminosity occurs at approximately 19:39 JST.

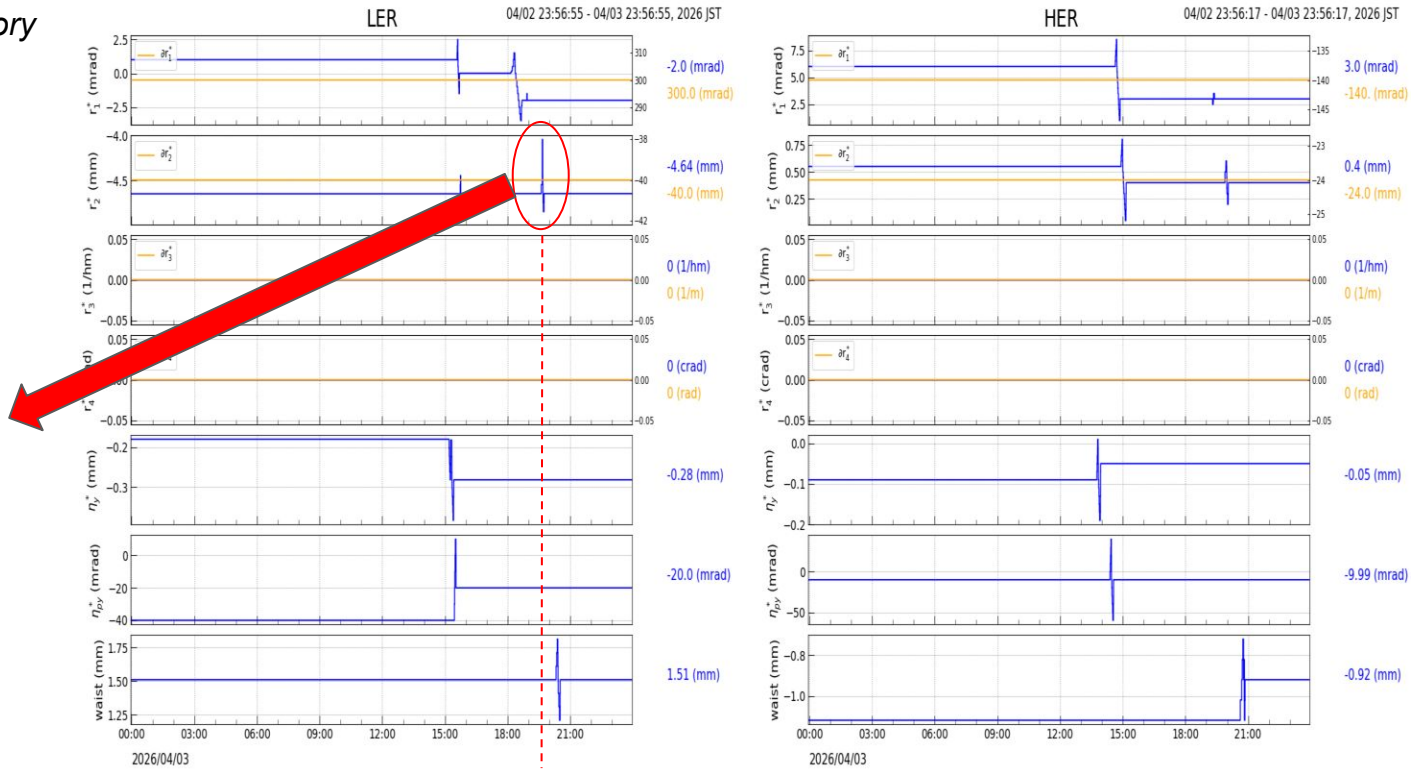
Both HER and LER beam currents remain stable during the dip.

This suggests that another machine parameter may be associated with the sudden decrease in specific luminosity.

Selected Time Range: April 3, 2026, 13:00–21:00

The SuperKEKB IP knob history shows that...

The LER IPr2 knob was adjusted around the time of the dip.



We therefore examine the correlations between all PVs and specific luminosity within this selected time window. If ‘CGLOPT:IPr2’ ranks highly, it would indicate that the framework can recover this known operational change.

Correlation Result for April 3, 2026, 13:00–21:00

Overall Ranking	PV name	Pearson_rank	KSC_rank	MI_rank	dCor_rank	Average Rank
1	CG_OPT:CAP:SIGMAY	1	11	1	2	3.75
2	CGHCOL:BEAMBEAM:Y	3	58	3	9	18.25
3	CGLCOL:BEAMBEAM:Y					
4	B2_nsm:get:ECL_LUM_MON:lum_acc_20					
5	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20					
6	BTeBPM:MONTEKCBT2:WAVE2[0]					
7	CGLOPT:IPr2	60				
8	MGLPS:QC1RP:DMM2:STMR_CNT	287	549	139	126	275.25
9	MGLPS:QC1LP:DMM2:STMR_CNT	289	558	129	127	275.75
10	CO_KIKAI:AAH013	853	278	214	281	406.50
11	CG_OPT:CAP:SIGMAY:MEAS	6	180	1745	66	499.25
12	BMLXRM:BEAM:SIGMAY_FAST					
13	TM_LXRM:BEAM:SIGMAY_FAST	12	306	1662	99	519.75
14	RFHNC:D04H:DFBCNT:IQ3_A_CALC	337	381	479	1110	576.75
15	RFHNC:D04H:DFBCNT:IQ3_A_SET					
16	RFHNC:D04H:DFBCNT:IQ3_PHS					
17	RFHNC:D04H:WGPHC:ROT_360					
18	RFHNC:D04H:DFBCNT:IQ3_B_CALC	384	386	471	1106	586.75
19	RFHNC:D04H:DFBCNT:IQ3_B_SET	384	386	471	1106	586.75
20	RFHNC:D04H:DFBCNT:IQ3_C_SET	384	384	474	1108	587.50

Derived from measured luminosity; correlation is expected.

Beam transport PV; likely unrelated to luminosity.

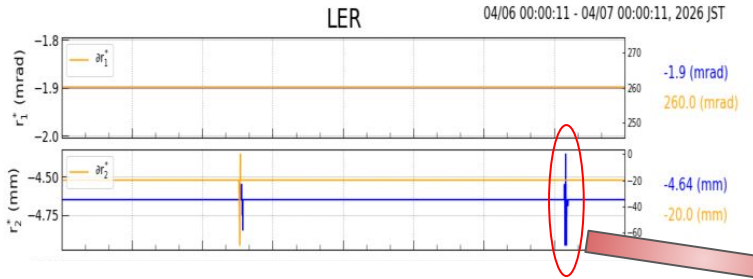
IP knob was scanned during this time range.

Beam size PVs are expected to relate to luminosity.

Magnet in LER and RF in HER PVs relevance to luminosity requires expert input.

Framework Validation: Identifying the LER IPr2 Knob

Overall Ranking	PV name	Pearson_rank	KSC_rank	MI_rank	dCor_rank	Average Rank
1	CG_OPT:CAP:SIGMAY	1	11	1	2	3.75
2	C[illegible]AMBEAM:Y	3	58	3	9	18.25
3	[illegible]:BEAMBEAM:Y	2	61	2	15	20.00
4	B2_nsm[illegible]N:lum_acc_20	4	130	5	22	40.25
5	B2_nsm:get:EC[illegible]ON:lu[illegible]rrected_20	5	131	4	23	40.75
6	BTeBPM:MONTEKCBT2:WAVE2[0]	302	103	10	33	112.00
7	CGLOPT:IPr2	60	343	197	395	248.75
8	MGLPS:QC1RP:DMM2:STMR_CNT	287	549	139	126	275.25
9	MGLPS:QC1LP:DMM2:STMR_CNT	289	558	129	127	275.75
10	CO_KIKAI:AAH013	853	278	214	281	406.50
				745	66	499.25
				657	98	517.75
				662	99	519.75



After excluding ranks 1–5, which are derived from measured luminosity, and rank 6, which is likely unrelated, CGLOPT:IPr2 becomes the highest ranked PV*.

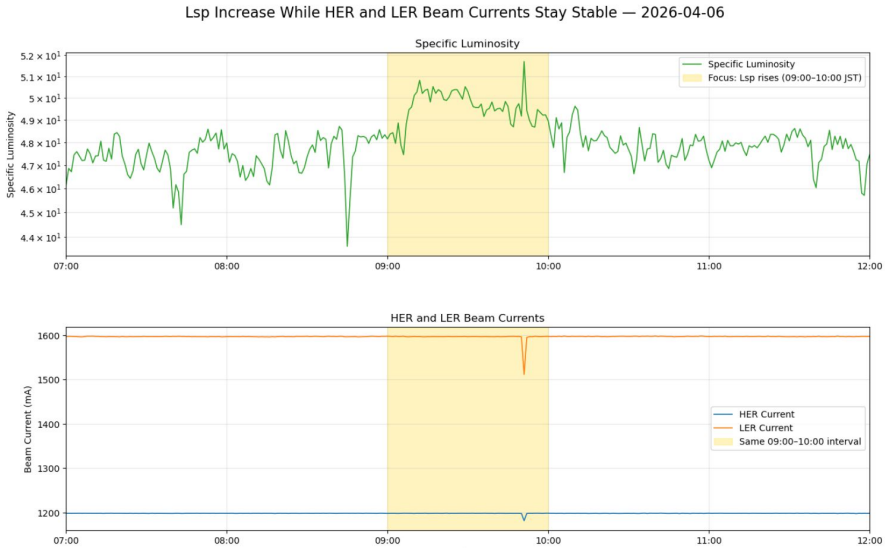
**Note that it was obtained after averaging the ranking score over four different correlation methods (single method cannot predict CGLOPT:IPr2 as the highest rank).*

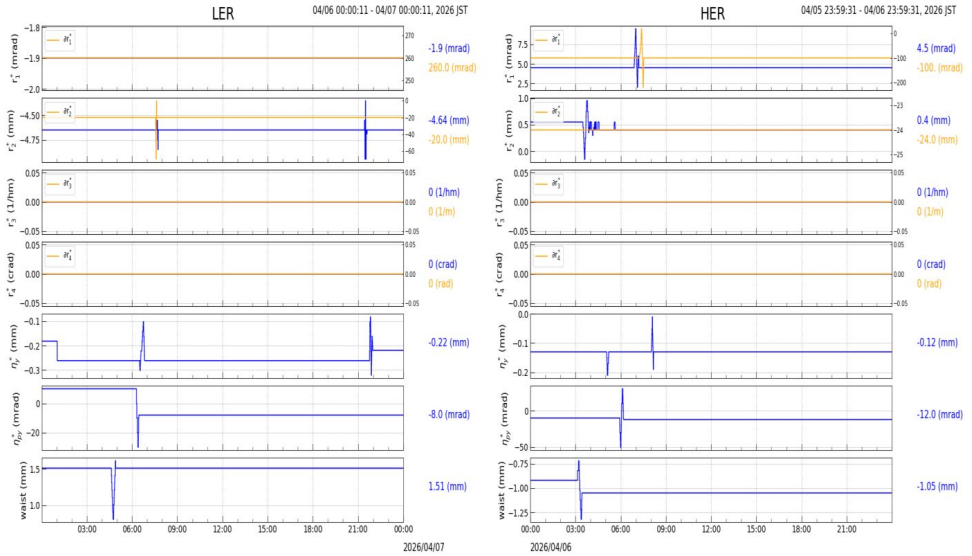
The LER IPr2 knob was adjusted around the time of the luminosity dip.

This shows that **our framework can recover a relevant operational change from approximately 140,000 PVs**.

Selected Time Range: April 6, 2026, 07:00–12:00 JST

Specific luminosity increases around 09:00–10:00 JST while both beam currents remain stable.





No IP knob tuning coincides with this increase.

We therefore investigate which other PVs are associated with this change in specific luminosity.

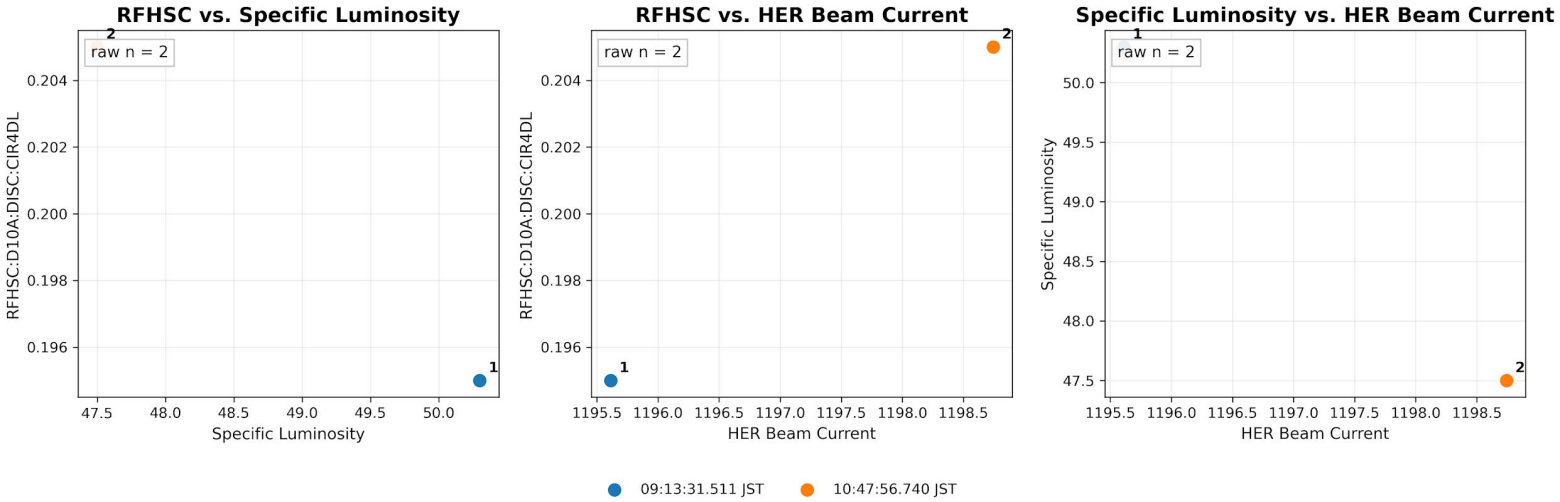
Correlation Result for April 6, 07:00-12:00

Overall Ranking	PV name	Pearson_corr	KSC_corr	MI_corr	dCor_corr	Pearson_rank	KSC_rank	MI_rank	dCor_rank	Average Rank
1	CG_OPT:CAP:SIGMAY	-0.998918	-0.996504	9.193966	0.999786	1	1	1	1	1.00
2	CGLCOL:BEAMBEAM:Y	0.993433	0.993585	3.048808	0.995711	2	2	2	2	2.00
3	CGHCOL:BEAMBEAM:Y	0.979299	0.983260	2.705150	0.989192	3	6	3	3	3.75
4	B2_nsm:get:ECL_LUM_MON:lum_acc_20	0.962[illegible]								
5	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	0.962[illegible]								
6	B2_nsm:get:ECL_LUM_MON:lum_acc_in_phys_runs_20	0.583114	0.711245	1.997877	0.966837	68	130	9	11	54.50
7	B2_nsm:get:ECL_LUM_MON:lum_det_20	0.546625	0.702233	1.583962	0.940415	99	134	37	18	72.00
8	B2_nsm:get:ECL_LUM_MON:lum_det_corrected_20	0.550304	0.696450	1.584683	0.938906	97	141	36	19	73.25
9	RFHSC:D10A:DISC:CIR4DL	-0.484125	-0.990500	1.339583	0.845952	241	3	152	36	108.00
10	RFHSC:D10A:CRYOTEMP1	0.686023	0.983173	1.179194	0.778409	15	7	382	70	118.50
11	RFLNC:D08E:VALC:REF:UD	-0.456137	0.932971	1.371736	0.804020	344	25	120	61	137.50
12	CO_KIKAI:AAH009	-0.677594	-0.784720	1.159395	0.764185	21	75	423	87	151.50
13	RFLKLY:D05E:OUT2:TEMP	-0.47804[illegible]								[illegible]50
14	RFLNC:D05C:INTLCNT:DCCT	[illegible]								[illegible]75
15	RFLNC:D05A:INTLCNT:DCCT	-0.406818								[illegible].00
16	VALIP:D07_4U_L03_A02C1:CUR	-0.410279	-0.744127	2.026660	0.898021	568	102	6	28	176.00
17	RFLNC:D05E:DFBCNT:DCCT	-0.409800	-0.755869	1.701738	0.813139	575	94	26	54	187.25
18	RFLNC:D05B:INTLCNT:DCCT	-0.409056	-0.745689	1.730575	0.823999	581	101	24	44	187.50
19	BMLPS:BW3NRP_7_B:CURR:READ	-0.404691	-0.656589	1.886636	0.938900	620	164	14	20	204.50
20	RFLNC:D05D:INTLCNT:DCCT	-0.405840	-0.728073	1.592469	0.805956	613	114	35	58	205.00

Derived from measured luminosity; correlation is expected.

RF PV and other PV relevance to luminosity requires expert input.

The Fisrt Rank of RF PV Investigation



Raw evidence: 09:13 JST -> 0.195 | 10:47 JST -> 0.205

Only two RFHSC updates are available within the five hour window. Therefore, **the apparent high correlation is not statistically reliable and cannot establish a meaningful association with specific luminosity.**

Sparse Sampling Explains the High PV Rankings

Rank	PV name	n_raw
9	RFHSC:D10A:DISC:CIR4DL	2
10	RFHSC:D10A:CRYOTEMP1	2
11	RFLNC:D08E:VALC:REF:UD	2
12	CO_KIKAI:AAH009	5
13	RFLKLY:D05E:OUT2:TEMP	2
14–22	Various RF/beam related PVs	4–12
23	**CO_KIKAI:PPF2001**	**2,896**

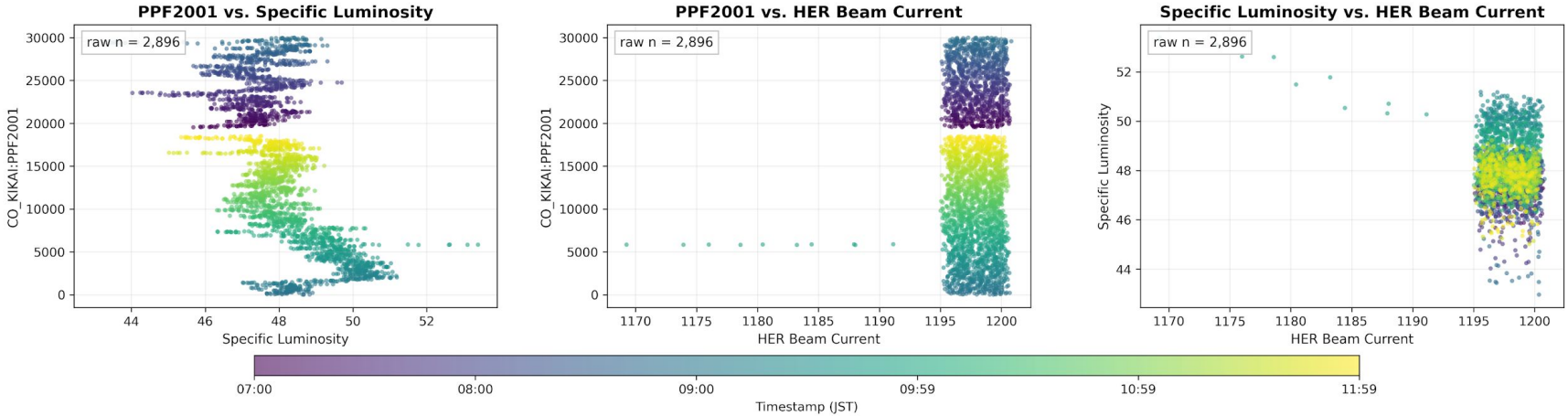
Ranks 9–22 contain only 2–12 raw samples.

Their high rankings are therefore not statistically reliable.

For future analyses, a minimum number of data points should be required before calculating the rankings.

Next: repeat the three plot investigation for CO_KIKAI:PPF2001 (it has the most sufficient data).

Rank 23 KIKAI PV Investigation



Raw evidence: n = 2,896 across 07:00–12:00 JST (no forward-fill).

PPF2001 decreases in time ordered bands while Lsp generally increases; HER current stays within a narrow range.

This structured association is suitable for expert follow up, but it does not demonstrate causation.

**The April 6 analysis did not identify a conclusive non trivial PV within the available time. Further investigation of the other highly ranked PVs is therefore left for future work.*

Summary & Next Steps

Summary

- Beam pipe temperatures increase nonlinearly with beam current, and the FWD sensors are generally hotter than the BWD sensors.
- The full April HER/LER fit result is ambiguous because the two currents have an almost constant ratio. A shorter period with a changing current ratio indicates a larger HER contribution, especially for the FWD sensors.
- Across four correlation methods, beam current, paraffin temperature, and QC1 beam position PVs consistently ranked among the 43 PVs most strongly associated with specific luminosity during April 2026. However, these rankings indicate association, not causation.
- For the April 3 luminosity dip, the all PV analysis recovered the known LER IPr2 knob adjustment from about 140,000 PVs. The April 6 candidates still require further validation.

Next Steps

- Repeat the HER/LER temperature fit using more periods with different current ratios to test whether the fitted contributions are stable.
- Investigate the top ranked QC1 BPM, beam size, and paraffin temperature PVs using time series and 2D plots under normal operating conditions.
- Apply minimum sample and data quality checks before ranking PVs, so very sparse signals are not overinterpreted.
- Validate the all PV analysis on additional luminosity dips and compare the results with operation logs and expert knowledge. For April 6, check the RFHSC candidate over a wider time range.

Acknowledgements

I would like to express my deepest gratitude to:

- **Associate Professor Hiroyuki Nakayama**, my supervisor, for his patient guidance, continuous support, and invaluable advice throughout this project. I am truly grateful for everything he taught me and for the time he dedicated to discussions and guiding my work.
- **The members of the Belle II Group**, for warmly welcoming me and giving me the opportunity to experience their research environment.
- **KEK and SOKENDAI**, for organizing KEK-SSP and providing the generous financial support and valuable research opportunity that made this experience possible. I am sincerely thankful for the opportunity to learn, conduct research, and experience life at KEK.

Appendix

Correlation Result for April 3, 2026, 13:00–21:00

Pearson:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	13295	-0.977116	0.977116
2	CGLCOL:BEAMBEAM:Y	17257	0.921548	0.921548
3	CGHCOL:BEAMBEAM:Y	17243	0.918728	0.918728
4	B2_nsm:get:ECL_LUM_MON:lum_acc_20	27991	0.789256	0.789256
5	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	27993	0.789252	0.789252
6	CG_OPT:CAP:SIGMAY:MEAS	21282	-0.691997	0.691997
7	B2_OPT:LER:emity_XRM	14376	-0.679688	0.679688
8	CGLOPT:EMIT_Y	14471	-0.678987	0.678987
9	BMLXRM:BEAM:EMITTY	14376	-0.678709	0.678709
10	B2_nsm:get:MONZDLMINT:ZDLM_INTVAL:value	11485	0.637022	0.637022
11	BMLXRM:BEAM:SIGMAY_FAST	28128	-0.594249	0.594249
12	TM_LXRM:BEAM:SIGMAY_FAST	28127	-0.594133	0.594133
13	CGLOPT:IP:SIGMAY	14471	-0.590134	0.590134
14	BMLXRM:BEAM:SIGMAY	14376	-0.589634	0.589634
15	BMLXRM:BEAM:SIGMAYatIP	14376	-0.589630	0.589630
16	B2_BGNET:LUMINOSITY_CDC_CUR_AVERAGE	28666	0.568831	0.568831
17	B2_BGNET:LUMINOSITY_SVD_FW_180	28699	0.568696	0.568696
18	B2_BGNET:LUMINOSITY_BP_BW_215	28699	0.568696	0.568696
19	B2_BGNET:LUMINOSITY_SVD_FW_240	28699	0.568696	0.568696
20	B2_BGNET:LUMINOSITY_SVD_FW_60	28699	0.568696	0.568696

KSC:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	RFHSC:D11C:DISC:KLYOUTREF	2	0.995219	0.995219
2	RFHSC:D11A:PZO:DETUNE	2	-0.994843	0.994843
3	RFHSC:D11A:DET:KLYIN	2	-0.991871	0.991871
4	RFHSC:D11D:DISC:KLYOUTREF	2	0.984345	0.984345
5	RFHSC:D10C:DET:AFTCOMBINER	2	-0.983453	0.983453
6	RFHSC:D11A:KAGC:REF	2	-0.982966	0.982966
7	RFHSC:D11A:KAGC:FBIN	2	0.981689	0.981689
8	VAHFBMM:QD3E17:H:ALM	2	0.975039	0.975039
8	VAHFBMM:QD3E33:H:ALM	2	0.975039	0.975039
8	VAHFBMM:QD3E37:H:ALM	2	0.975039	0.975039
11	CG_OPT:CAP:SIGMAY	13295	-0.973781	0.973781
12	VAHFBMM:QD3E1:H:ALM	2	-0.973482	0.973482
12	VAHFBMM:QD3E24:H:ALM	2	-0.973482	0.973482
12	VAHFBMM:QD3E8:H:ALM	2	-0.973482	0.973482
15	RFHNC:D04A:KAGC:FBIN	2	0.970081	0.970081
16	RFLKLY:D05E:VKREF	2	0.967728	0.967728
16	RFLKLY:D05EF:VKREF	2	0.967728	0.967728
16	RFLKLY:D05F:VKREF	2	0.967728	0.967728
19	RFHSC:D11C:DET:AFTCOMBINER	2	-0.966071	0.966071
20	RFHNC:D04E:KAGC:REF	2	-0.965134	0.965134

Correlation Result for April 3, 2026, 13:00–21:00

MI:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	13295	8.820971	8.820971
2	CGLCOL:BEAMBEAM:Y	17257	3.219760	3.219760
3	CGHCOL:BEAMBEAM:Y	17243	2.705465	2.705465
4	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	27993	2.442966	2.442966
5	B2_nsm:get:ECL_LUM_MON:lum_acc_20	27991	2.442948	2.442948
6	B2_nsm:get:ECL_LUM_MON:lum_acc_in_phys_runs_20	27175	2.406103	2.406103
7	RFHSC:D11A:KAGC:FBIN	2	2.145497	2.145497
8	RFHSC:D11A:KAGC:REF	2	2.106614	2.106614
9	RFHSC:D11D:DISC:KLYOUTREF	2	2.095253	2.095253
10	BTeBPM:MONTEKCBT2:WAVE2[0]	2708	2.053266	2.053266
11	RFHSC:D11A:DET:KLYIN	2	1.998410	1.998410
12	RFHNC:D04A:KAGC:FBIN	2	1.847487	1.847487
13	CODBG:LER_DUMP	2	1.831317	1.831317
13	COLBG:SOFT:BS_DUMP_CALC	2	1.831317	1.831317
13	COLBG:SOFT:DUMP_CALC	2	1.831317	1.831317
16	CGLINJ:BEAM:REPETITION:REQ	2	1.824592	1.824592
17	CGLOPR:KEKB_INJECTION	2	1.821513	1.821513
18	RFHSC:D10C:DET:AFTCOMBINER	2	1.776706	1.776706
19	LIiEV:BEAM_REP:READ:KBP	2	1.758176	1.758176
19	LIiEV:SEPTUM_REP:READ:KBP	2	1.758176	1.758176

dCor:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CGLOPT:IP:BETA_X	201	1.184213	1.184213
2	CG_OPT:CAP:SIGMAY	13295	0.999182	0.999182
3	LIiEV:BEAM_REP:READ:KBP	2	0.969881	0.969881
3	LIiEV:SEPTUM_REP:READ:KBP	2	0.969881	0.969881
5	RFHSC:D11A:KAGC:FBIN	2	0.968716	0.968716
6	CGLINJ:BEAM:REPETITION:REQ	2	0.968661	0.968661
7	RFHSC:D11A:KAGC:REF	2	0.961572	0.961572
8	RFHSC:D11D:DISC:KLYOUTREF	2	0.961354	0.961354
9	CGHCOL:BEAMBEAM:Y	17243	0.960034	0.960034
10	CGLOPR:KEKB_INJECTION	2	0.955930	0.955930
11	CODBG:LER_DUMP	2	0.955930	0.955930
11	COLBG:SOFT:BS_DUMP_CALC	2	0.955930	0.955930
11	COLBG:SOFT:DUMP_CALC	2	0.955930	0.955930
14	RFHSC:D11A:DET:KLYIN	2	0.955697	0.955697
15	CGLCOL:BEAMBEAM:Y	17257	0.951647	0.951647
16	RFHNC:D04A:KAGC:FBIN	2	0.945555	0.945555
17	RFHNC:D04E:PIRANI1	2	0.944448	0.944448
18	RFHSC:D10C:DET:BEFCOMBINER	2	0.937232	0.937232
19	RFHSC:D10C:DET:AFTCOMBINER	2	0.931750	0.931750
20	RFHNC:D04A:DISC:MTDLOUT	2	0.928009	0.928009

Correlation Result for April 6, 2026, 07:00–12:00

Pearson:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	19790	-0.998918	0.998918
2	CGLCOL:BEAMBEAM:Y	19788	0.993433	0.993433
3	CGHCOL:BEAMBEAM:Y	19796	0.979299	0.979299
4	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	17505	0.962751	0.962751
5	B2_nsm:get:ECL_LUM_MON:lum_acc_20	17504	0.962750	0.962750
6	BM_BLM:D01:ADC:MEAN[27]	18000	0.840669	0.840669
7	BM_BLM:D01:ADC:MINI[27]	18000	0.823646	0.823646
8	BM_BLM:D01:ADC:MEAN[52]	18000	0.784825	0.784825
9	RFHSC:D11A:CRYOTEMP4	2	0.731426	0.731426
10	B2_nsm:get:ECL_LUM_MON:lum_max_det_day	6	-0.725129	0.725129
11	B2_nsm:get:ECL_LUM_MON:lum_max_det_corrected_day	6	-0.725129	0.725129
12	BM_BLM:D01:ADC:MINI[52]	18000	0.696287	0.696287
13	FB_RM:T05	9000	0.689386	0.689386
14	RF_REF:VODLCNT5:VODL:PULSE_COUNT	15	-0.688801	0.688801
15	RFHSC:D10A:CRYOTEMP1	2	0.686023	0.686023
16	MGHPS:ZVQD3E_23:REQVAL	180	-0.685955	0.685955
17	MGHPS:ZVQD3E_23:KDIR	180	-0.685949	0.685949
18	IGPF:HERDV:SRAM:PEAK2	19799	-0.684295	0.684295
19	FB_RM:T04	9000	0.679697	0.679697
20	CO_KIKAI:ANK519	225	-0.678844	0.678844

KSC:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	19790	-0.996504	0.996504
2	CGLCOL:BEAMBEAM:Y	19788	0.993585	0.993585
3	RFHSC:D10A:DISC:CIR4DL	2	-0.990500	0.990500
4	RFLNC:D07D:DFB:GAIN	2	0.989953	0.989953
5	CO_KIKAI:APF2072	2	0.985543	0.985543
6	CGHCOL:BEAMBEAM:Y	19796	0.983260	0.983260
7	RFHSC:D10A:CRYOTEMP1	2	0.983173	0.983173
8	RFHNC:D04A:2ATNC:OFST	2	0.982183	0.982183
9	FBL:BCM:I2SUM	19798	-0.973335	0.973335
10	B2_nsm:get:ECL_LUM_MON:lum_acc_20	17504	0.972238	0.972238
11	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	17505	0.972238	0.972238
12	CO_KIKAI:AAH018	2	0.968349	0.968349
13	MGHPS:ZVQT3NFE_2:REQVAL	42	0.963535	0.963535
14	MGHPS:ZVQT3NFE_2:KDIR	42	0.963388	0.963388
15	RFLNC:D07B:PIRANI2	2	-0.941405	0.941405
16	RFHSC:D11B:PZO:DETUNE	2	-0.937512	0.937512
17	RFLNC:D05F:WGPHC:ROT_360	2	-0.937223	0.937223
18	RFLNC:D05F:DFBCNT:IQ3_C_CALC	2	0.936964	0.936964
18	RFLNC:D05F:DFBCNT:IQ3_C_SET	2	0.936964	0.936964
20	RFLNC:D05F:DFBCNT:IQ3_A_CALC	2	0.936961	0.936961

Correlation Result for April 6, 2026, 07:00–12:00

MI:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	19790	9.193966	9.193966
2	CGLCOL:BEAMBEAM:Y	19788	3.048808	3.048808
3	CGHCOL:BEAMBEAM:Y	19796	2.705150	2.705150
4	RFLNC:D07D:PIRANI1	2	2.106092	2.106092
5	RFHNC:D04G:TNRCNT:DCCT	2	2.055172	2.055172
6	VALIP:D07_4U_L03_A02C1:CUR	12	2.026660	2.026660
7	B2_nsm:get:ECL_LUM_MON:lum_acc_20	17504	2.003592	2.003592
8	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	17505	2.003510	2.003510
9	B2_nsm:get:ECL_LUM_MON:lum_acc_in_phys_runs_20	17473	1.997877	1.997877
10	RFLNC:D05C:INTLCNT:DCCT	10	1.956366	1.956366
11	VAHIP:D07_4U_H14_A04C4:CUR	2	1.940344	1.940344
12	RFLNC:D08E:DET:AFTCOMBINER	2	1.930505	1.930505
13	RFLNC:D07B:PIRANI1	2	1.898789	1.898789
14	BMLPS:BW3NRP_7_B:CURR:READ	4	1.886636	1.886636
15	VAHIP:D05_4U_H09_A03C1:CUR	2	1.860096	1.860096
16	CGHOPT:IPeyd	13	1.826169	1.826169
17	RFLNC:D05A:DFBCNT:ACTROT_DCCT_MA	20	1.823841	1.823841
18	RFLNC:D05A:DFBCNT:ACTROT_DCCT	20	1.823796	1.823796
19	RFLNC:D07E:PIRANI1	2	1.815260	1.815260
20	RFLNC:D07A:CCG:AUX4	4	1.803067	1.803067

dCor:

Ranking	PV name	Raw samples (n)	corr	|corr|
1	CG_OPT:CAP:SIGMAY	19790	0.999786	0.999786
2	CGLCOL:BEAMBEAM:Y	19788	0.995711	0.995711
3	CGHCOL:BEAMBEAM:Y	19796	0.989192	0.989192
4	B2_nsm:get:ECL_LUM_MON:lum_acc_20	17504	0.979567	0.979567
5	B2_nsm:get:ECL_LUM_MON:lum_acc_corrected_20	17505	0.979564	0.979564
6	RFHNC:D04F:DFBCNT:DCCT	2	0.976489	0.976489
7	RFLNC:D07A:DET:CAV2IN	2	0.976098	0.976098
8	RFLNC:D08C:PIRANI1	2	0.973206	0.973206
9	RFLNC:D07E:KAGC:REF	2	0.970486	0.970486
10	VAHDIS:D12C:MEM_USED	2	0.966844	0.966844
11	B2_nsm:get:ECL_LUM_MON:lum_acc_in_phys_runs_20	17473	0.966837	0.966837
12	RFLNC:D07E:PIRANI1	2	0.956094	0.956094
13	RFHNC:D04G:INTLCNT:DCCT	2	0.955346	0.955346
14	RFLNC:D08E:DET:AFTCOMBINER	2	0.953546	0.953546
15	RFLNC:D07E:DET:AFTCOMBINER	2	0.952316	0.952316
16	RFLNC:D07D:PIRANI1	2	0.942885	0.942885
17	RFHNC:D04H:DFBCNT:DCCT	2	0.942600	0.942600
18	B2_nsm:get:ECL_LUM_MON:lum_det_20	17448	0.940415	0.940415
19	B2_nsm:get:ECL_LUM_MON:lum_det_corrected_20	17455	0.938906	0.938906
20	BMLPS:BW3NRP_7_B:CURR:READ	4	0.938900	0.938900

Thank You