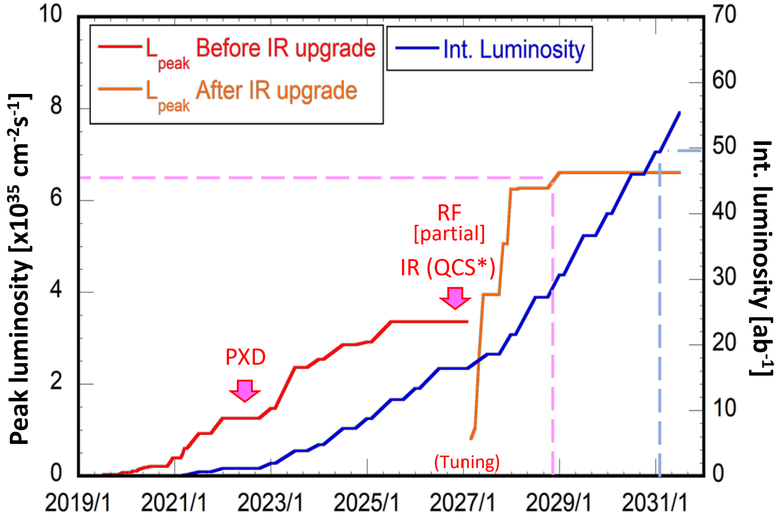
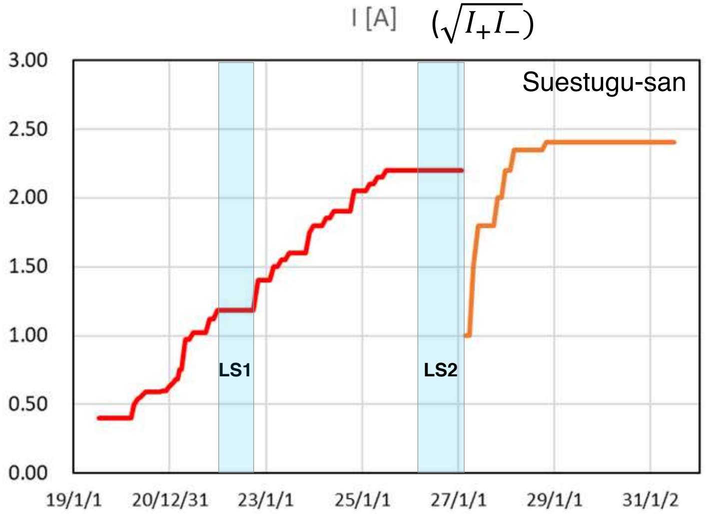
# Central Drift Chamber

- The CDC in Belle was operating very successfully at KEKB
- The Belle II CDC is an adiabatic evolution of this successful design
- However, the background situation at SuperKEKB is significantly more challenging than anticipated at the design stage
- As its name says, the CDC is **central** to the Belle II physics program
  - tracking, triggering, PID
- Questions
  - How compatible are the presently considered running/upgrade scenarios with the projected development of CDC performance?
  - What options do we have to mitigate possible serious performance degradation
    - between LS1 and LS2 ?
    - in LS2 (whenever it will happen) ?



# Concerns

- Uncertainties are still significant, but there are justified concerns related to
  - use of He/$C_2H_6$ gas mixture in high background environment: ageing
    - integrated charge per wire length will substantially exceed the Belle level
    - temporary and local appearance of Malter effect seen very early on (this triggered the formation of the CDC task force in 2018)
      - L54 kept off/standby until 2020c; since Dec 2020 it was turned on again and operating stably since then √
    - vulnerability against increasing injection background
  - hit rate limitations
    - space charge effects (→ efficiency, dE/dx resolution)
    - occupancy for tracking
      - even amplified by cross talk
  - radiation hardness of frontend electronics
- Safety factors at design parameters of SuperKEKB are marginal

Addressed by existing EoI



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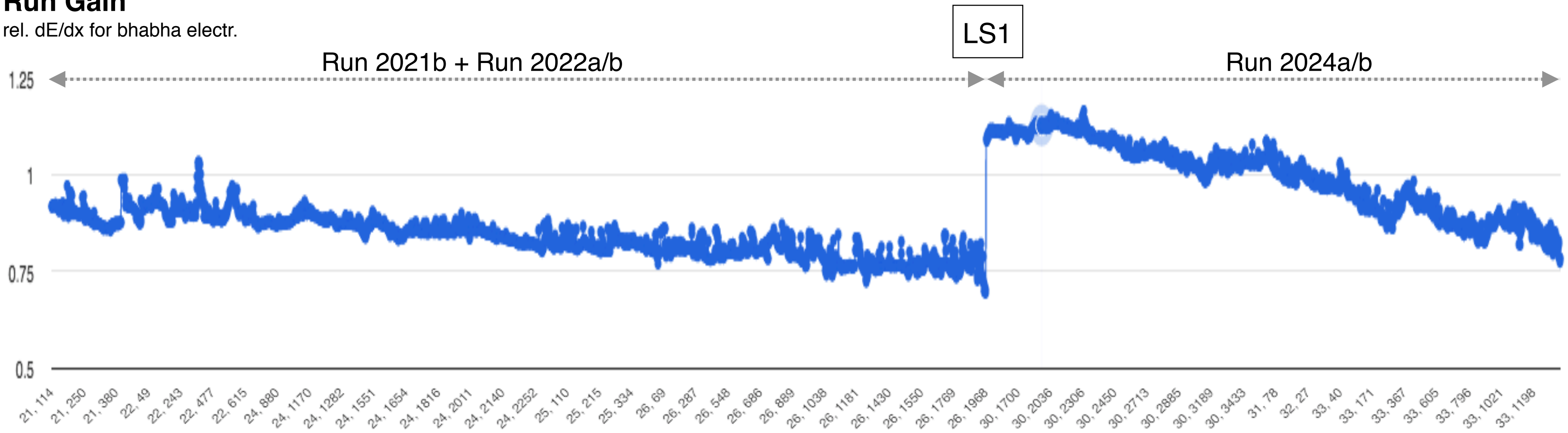
# Run Gain Variations before and after LS1

**Run Gain**

rel. dE/dx for bhabha electr.



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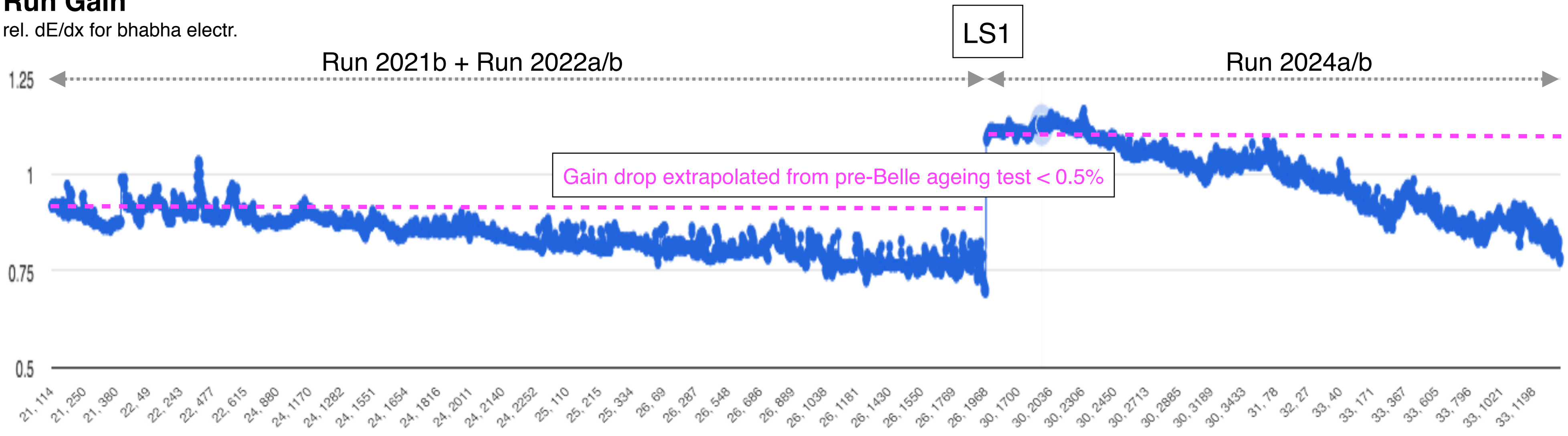
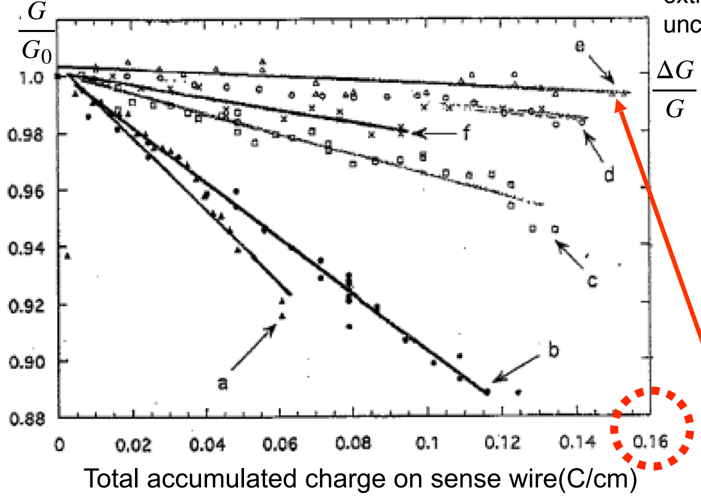



- Observed gain variation, mainly due to inadvertent changes in gas conditions and increasing beam background, completely masks expected gain loss extrapolated from pre-Belle ageing study
  - pre-LS1: too high (~10x) $H_2O$ level (unreliable $H_2O$ & $O_2$ monitors)
  - post-LS1: $H_2$ fraction reaching ~7%

### Pre-Belle ageing study

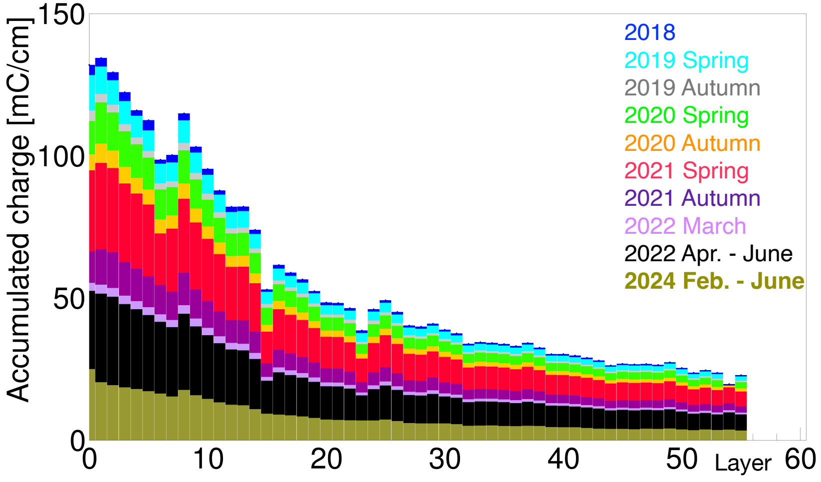



sizeable extrapolation uncertainty

$$\frac{\Delta G}{G} \sim \frac{6\,\%}{\mathrm{C/cm}}$$

a: '93 Plastic tube
b: '93 Plastic tube + O2 filter
c: '94 Plastic tube
d: '94 SUS tube
e: '94 SUS tube + $O_2$ filter
f: '94 Plastic tube

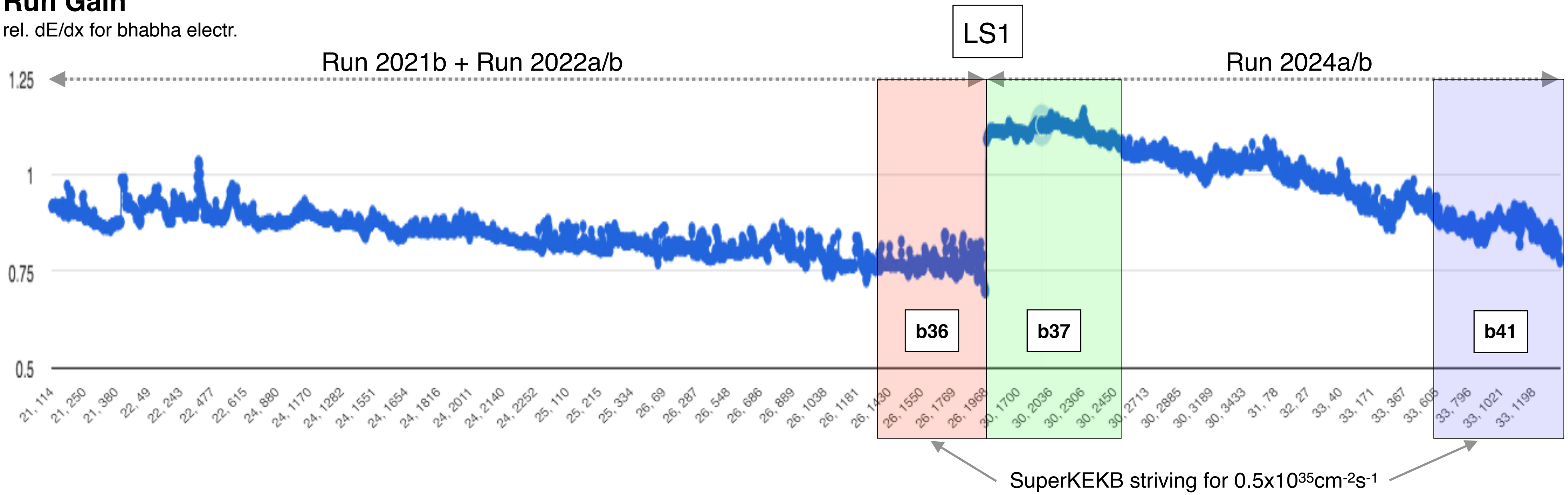
### Belle II 2018-2024



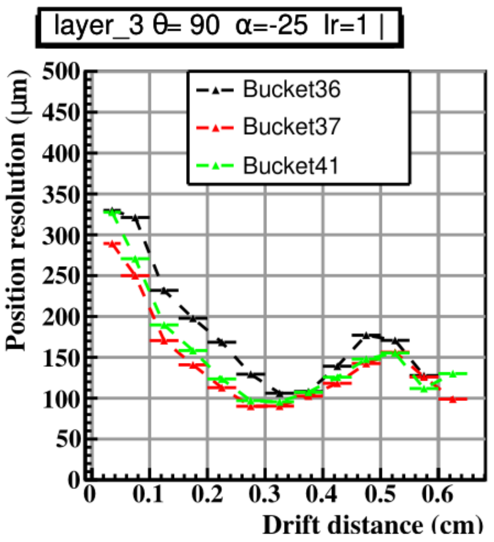
# Run Gain Variations before and after LS1

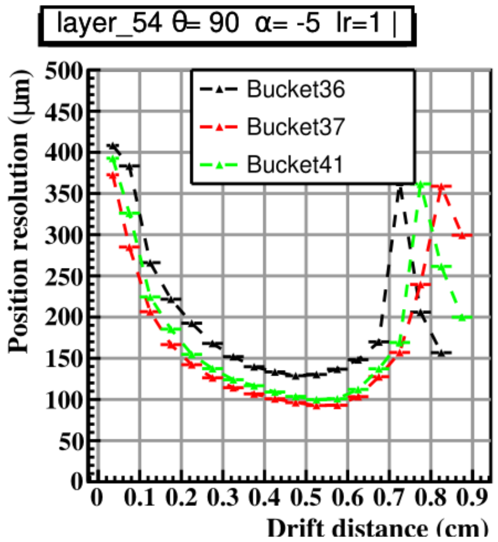
**Run Gain**

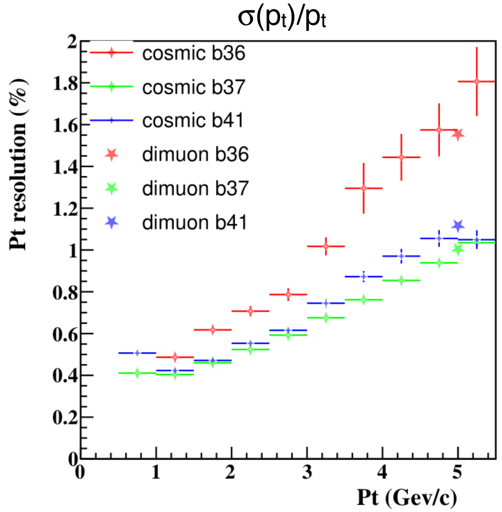
rel. dE/dx for bhabha electr.

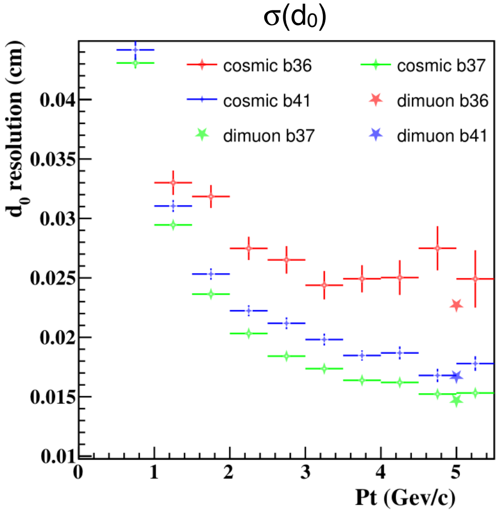


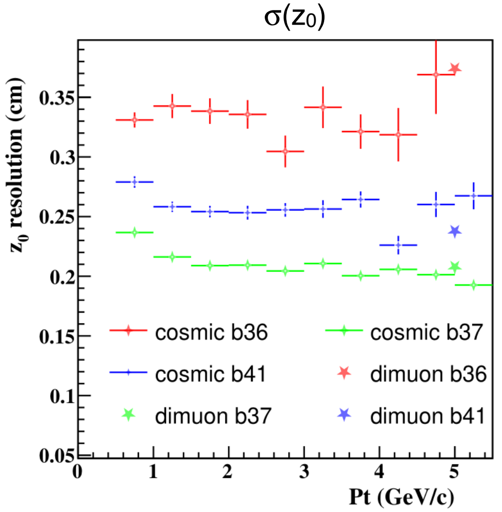

- Observed gain variation, mainly due to inadvertent changes in gas conditions and increasing beam background, completely masks expected gain loss extrapolated from pre-Belle ageing study
  - pre-LS1: too high (~10x) $H_2O$ level (unreliable $H_2O$ & $O_2$ monitors)
  - post-LS1: $H_2$ fraction reaching ~7%
- Gain loss at end of Run 2022b resulted in significant performance degradation of CDC-only tracking
  - number of CDC hits on tracks → reduced hit- and trigger-efficiency
  - hit position and track parameter resolution $\sigma(p_t)$, $\sigma(d_0)$, $\sigma(z_0)$
- Impact of gain drop during 2024a/b also visible, but much smaller
  - modified $O_2$/$H_2O$ removal systems expected to restore b37 conditions



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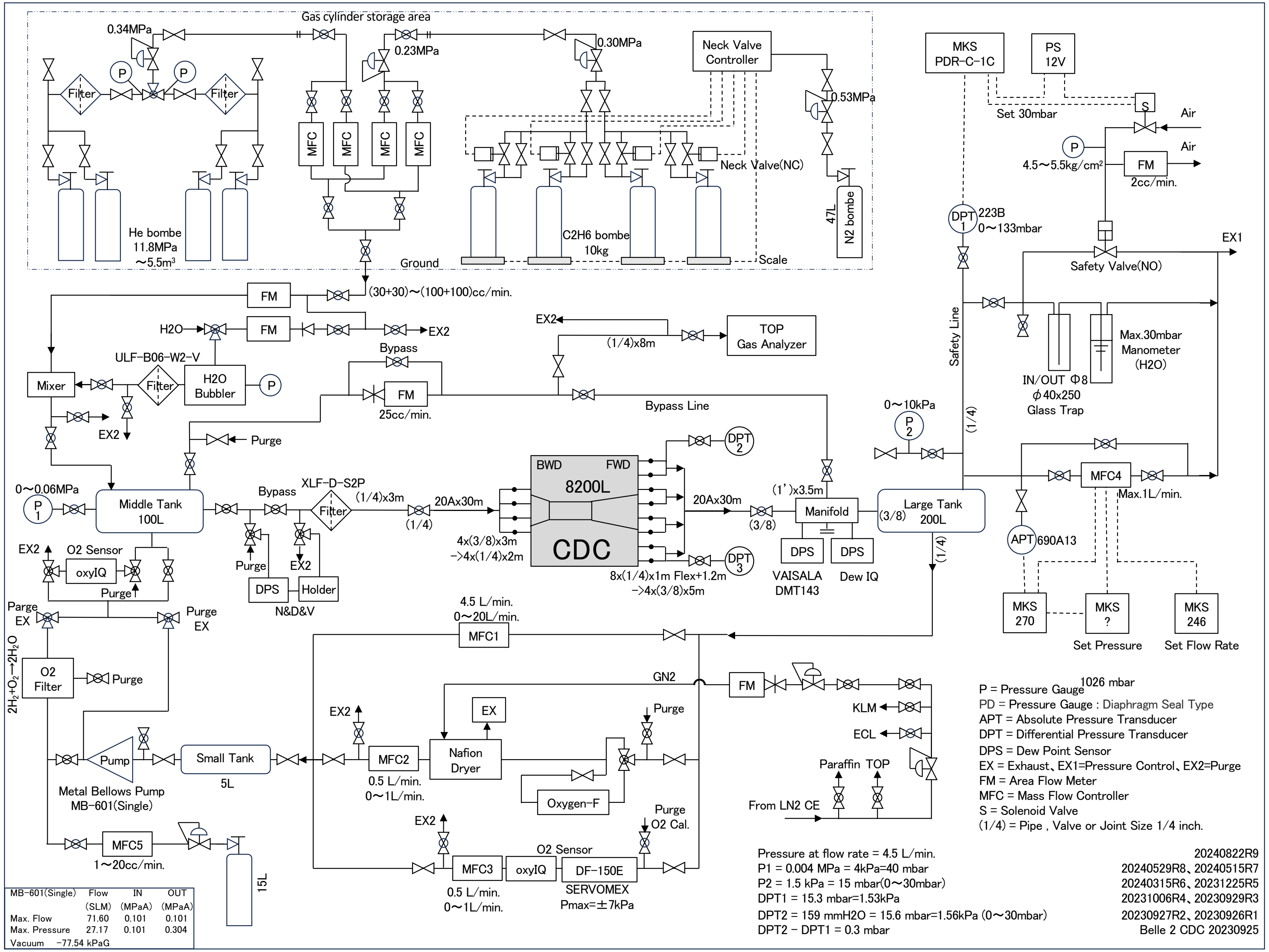
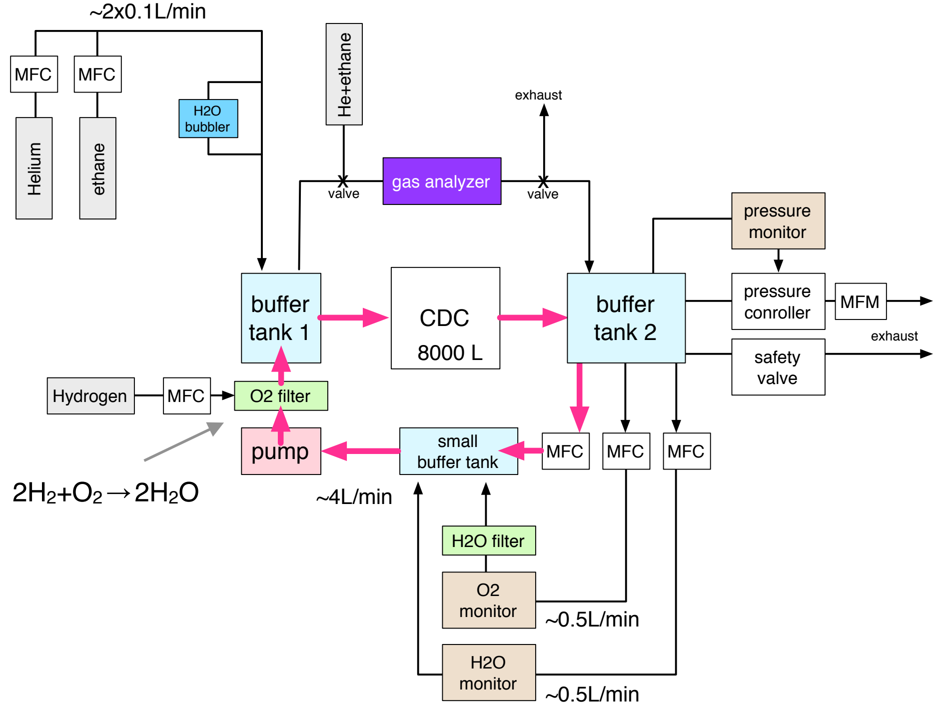
# CDC Gas System

## Current layout (including many LS1 improvements)




## Simplified and somewhat outdated principle



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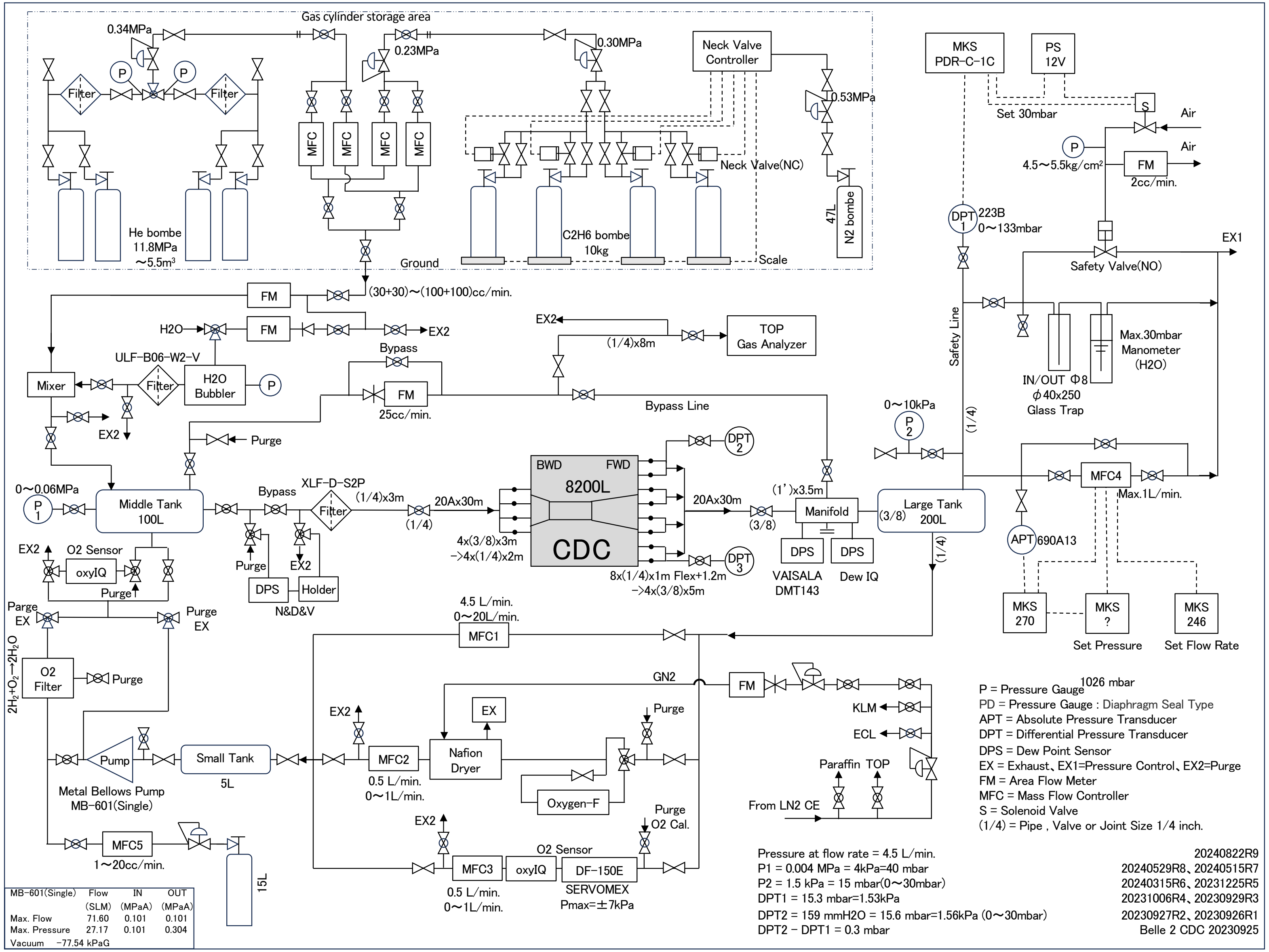


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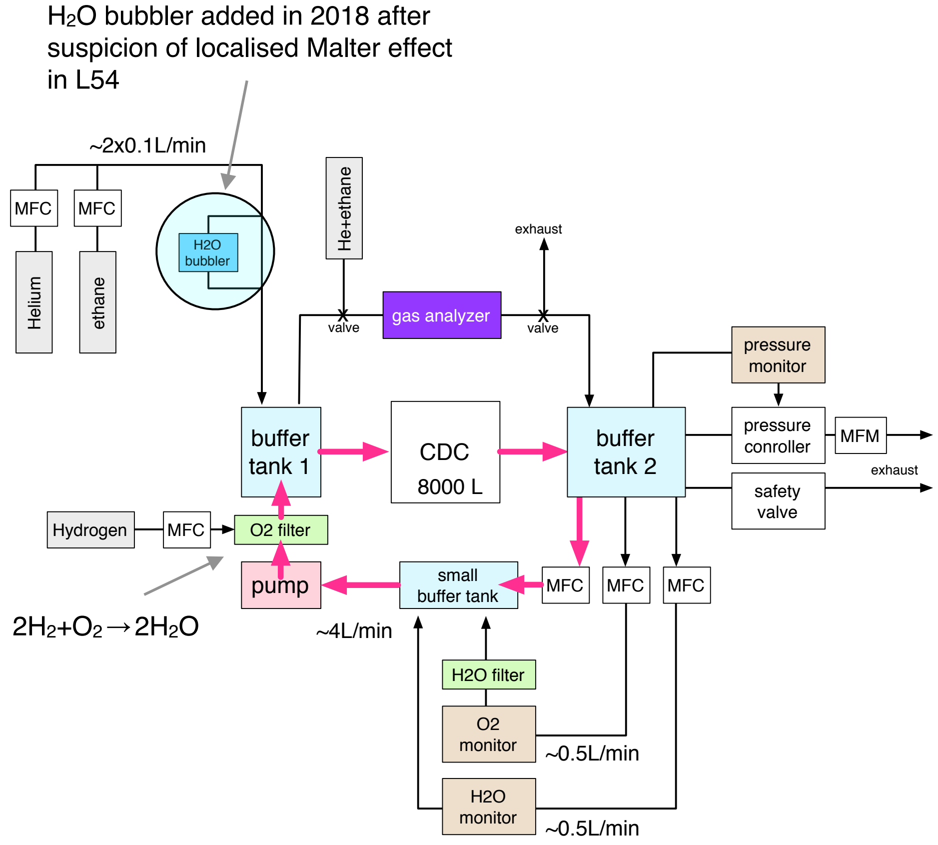
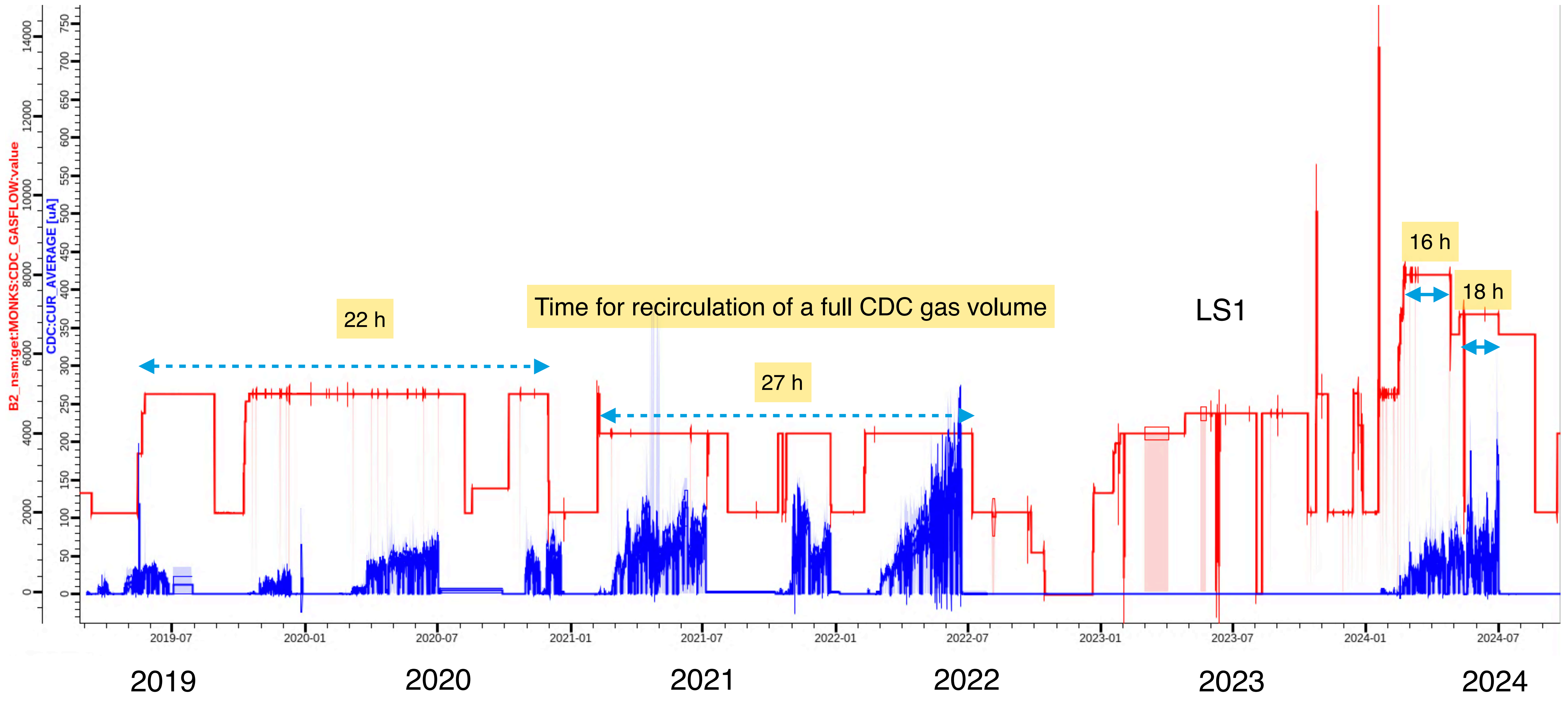
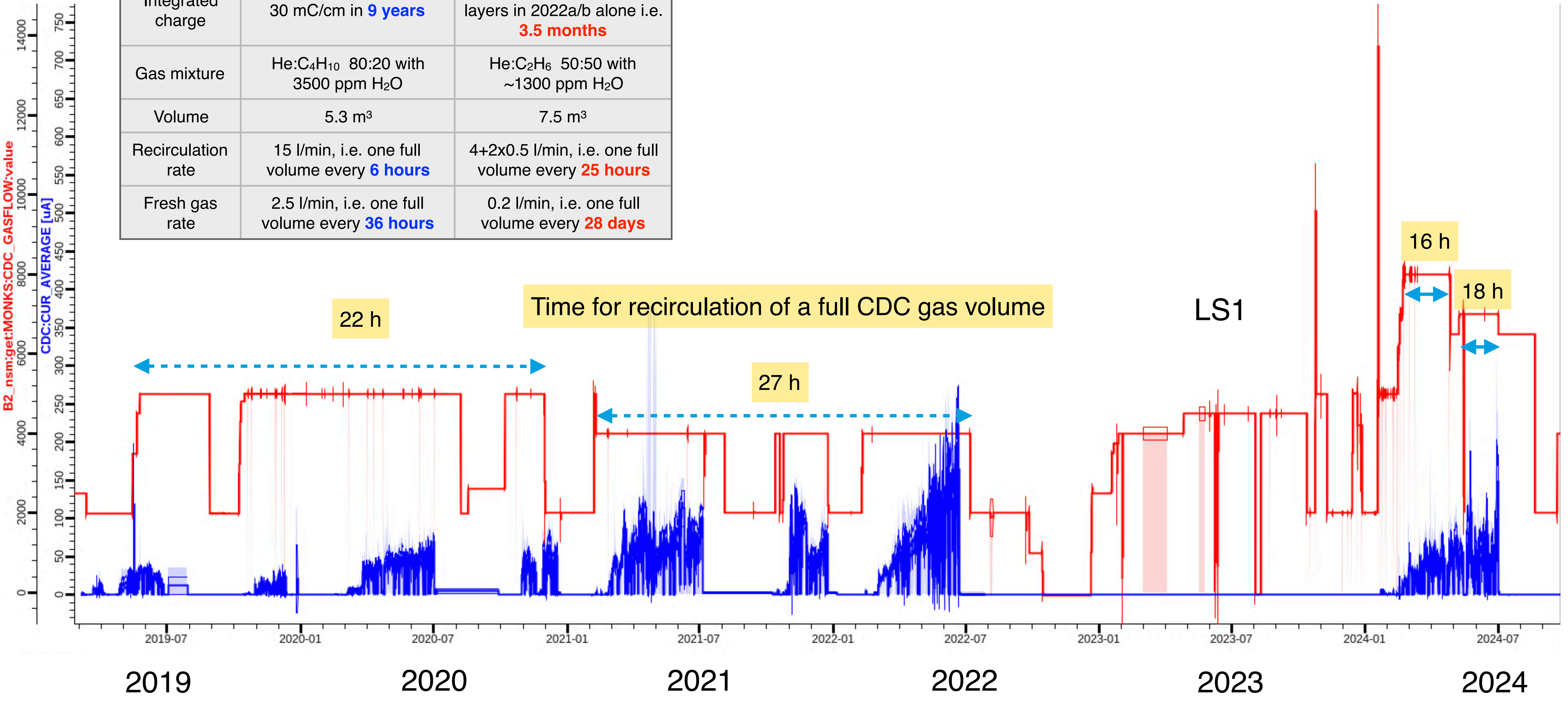


# Gas Recirculation Rate

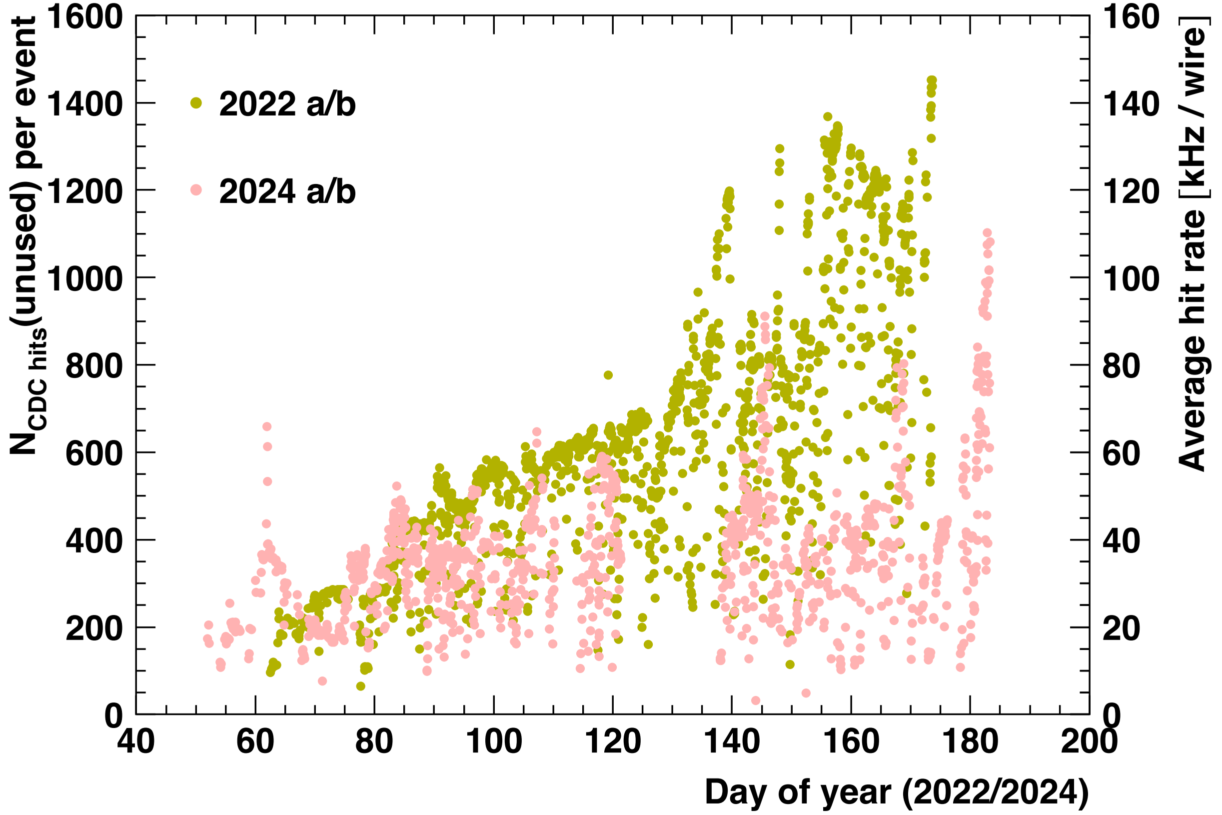


# Gas Recirculation Rate

| | BaBar DCH | Belle II CDC |
|---|---|---|
| Integrated charge | 30 mC/cm in **9 years** | 30 mC/cm for innermost layers in 2022a/b alone i.e. **3.5 months** |
| Gas mixture | He:$C_4H_{10}$ 80:20 with 3500 ppm $H_2O$ | He:$C_2H_6$ 50:50 with ~1300 ppm $H_2O$ |
| Volume | 5.3 $m^3$ | 7.5 $m^3$ |
| Recirculation rate | 15 l/min, i.e. one full volume every **6 hours** | 4+2x0.5 l/min, i.e. one full volume every **25 hours** |
| Fresh gas rate | 2.5 l/min, i.e. one full volume every **36 hours** | 0.2 l/min, i.e. one full volume every **28 days** |

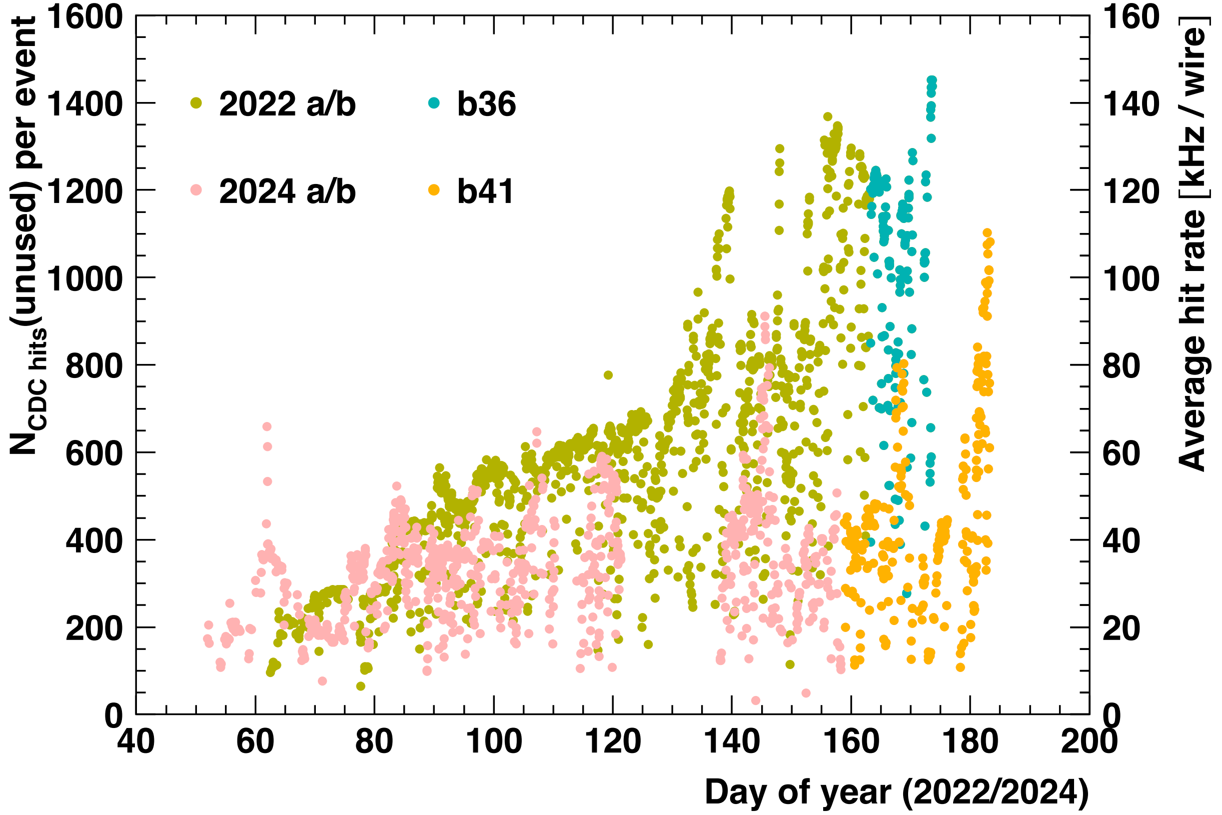


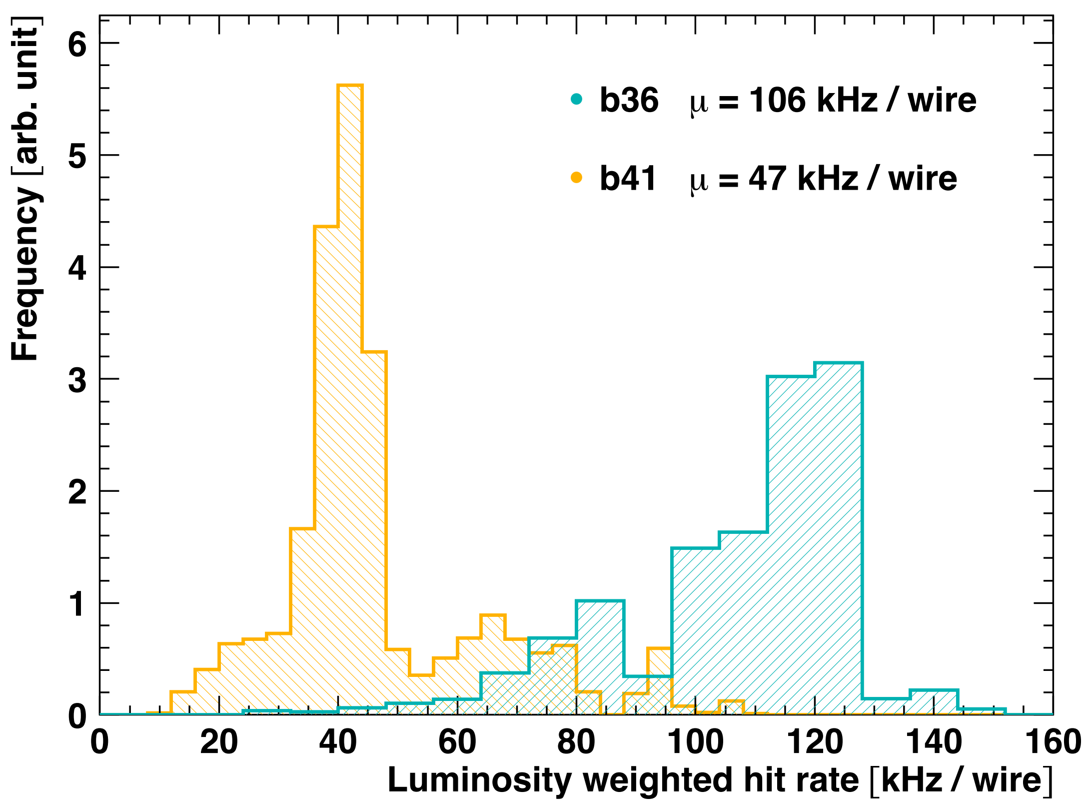
# Evolution of Beam-related CDC Background in 2022/2024




- Use number of CDC hits that are not associated with tracks as an indicator of CDC background
- Varies greatly with machine and beam conditions

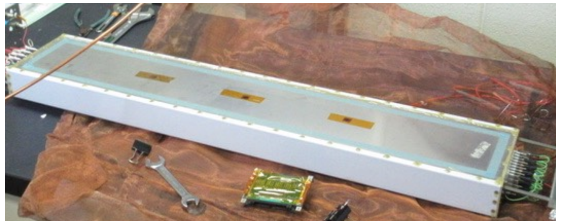
# Evolution of Beam-related CDC Background in 2022/2024

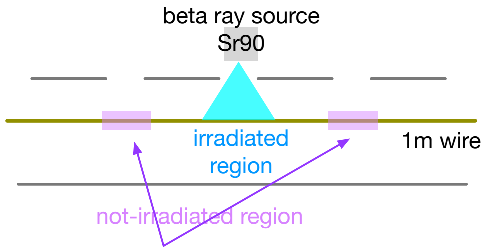


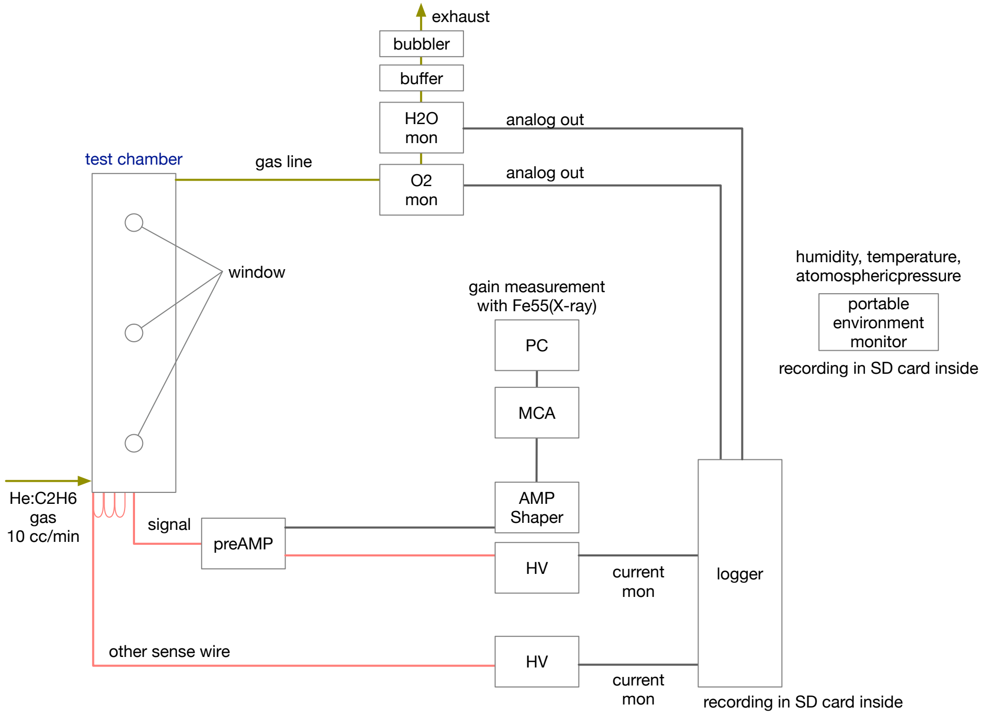




- Use number of CDC hits that are not associated with tracks as an indicator of CDC background
- Varies greatly with machine and beam conditions
  - difference of more than a factor of two between b36 (2022b, damaged collimators) and b41 (2024b)
- Hit rates already reach >100 kHz/wire when trying to approach L = 0.5x10$^{35}$ cm$^{-2}$s$^{-1}$

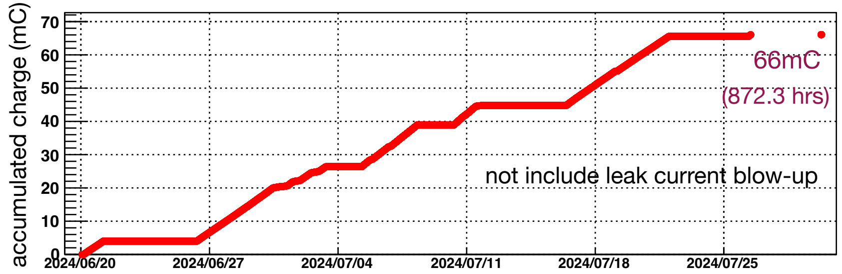
# Ongoing Ageing Test

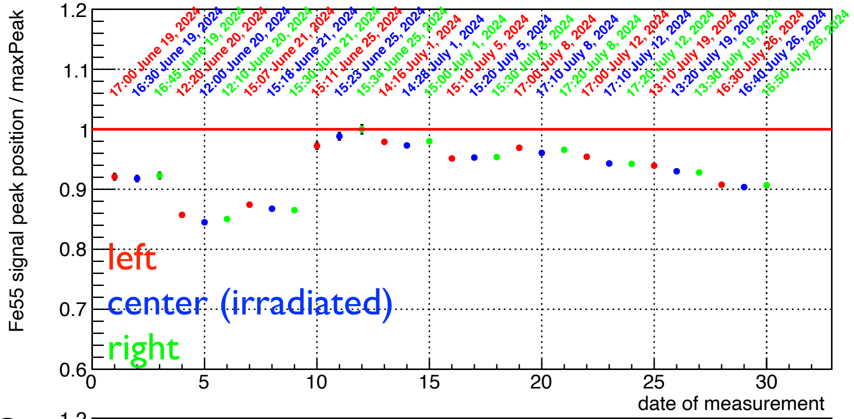


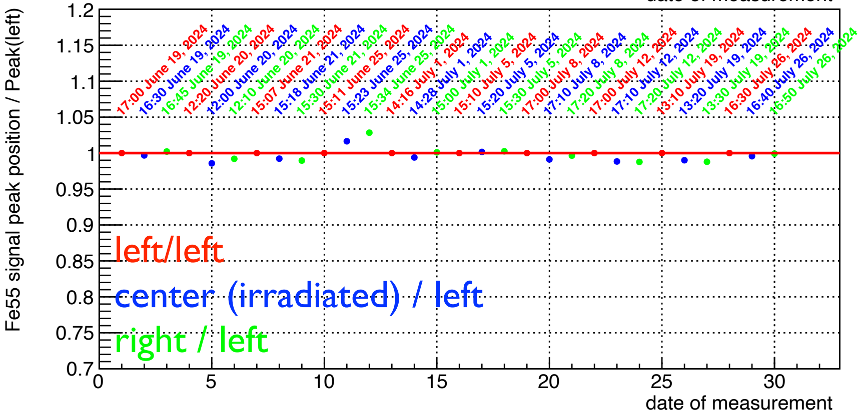



## Initial results

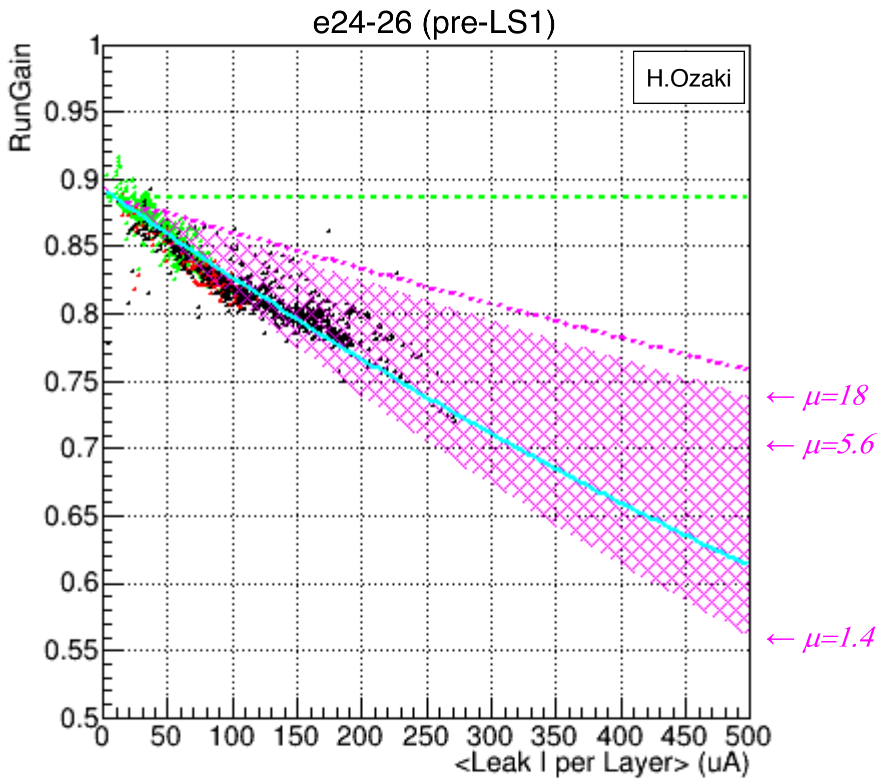


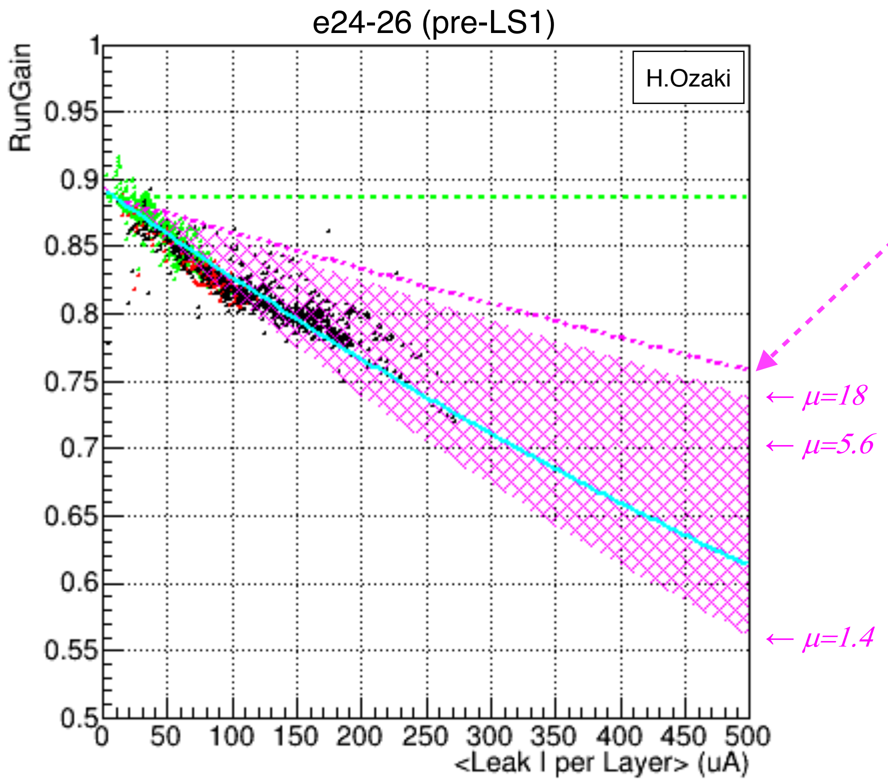

- Goal: reproduce pre-Belle result
- So far, no evidence of ageing at 66 mC/cm accumulated charge
- If unacceptable ageing rate is observed, repeat test with a hydrocarbon-free gas mixture
- Caveats
  - difficult to achieve multi-C/cm regime with this set-up
  - gas volume exchange rate similar to CDC, but
    - no recirculation (injection of fresh He/$C_2H_6$)
    - very low ratio of irradiated volume to test chamber volume compared to CDC

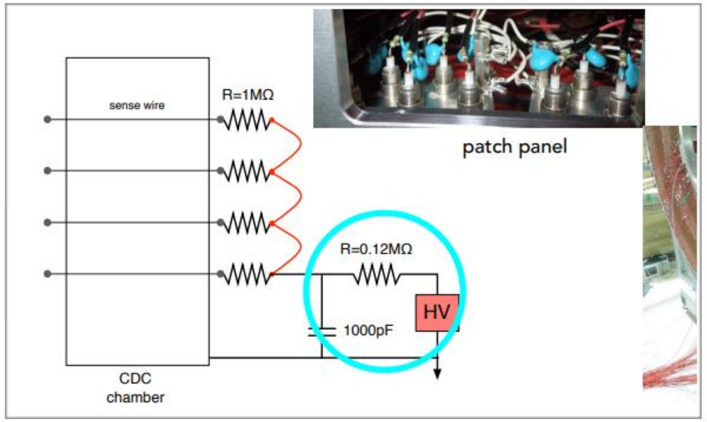
# Background Dependence of Run Gain




- Pre-LS1 run gain found to be significantly dependent on chamber current

# Background Dependence of Run Gain




(1) Estimated gain reduction due to voltage drop across resistor in HV distribution

(2) H.Ozaki: „I calculated the voltage drop [due to space charge] by solving the Poisson eq. for a geometry similar to Belle2 CDC (multi-square cells w/o staggering), instead of using a simple formula derived for a cylindrical tube in 1969.“

- Pre-LS1 run gain found to be significantly dependent on chamber current
- Ozaki-san (KEK) tried to model this dependence, taking into account
  (1) gain reduction due to **voltage drop** across resistor in HV distribution
    - significant improvement expected from resistor replacement in LS1
  (2) **space charge** as a function of ion mobility $\mu$
    - (1)+(2) can reasonably reproduce pre-LS1 gain drop assuming $\mu$ = 1.4 ~ 6 $cm^2/V/s$
    - some tension with estimated value of $\mu$ = 10 ~ 20 $cm^{-2}/V/s$ in $He/C_2H_6$ estimated by Rob Veenhof (CERN)



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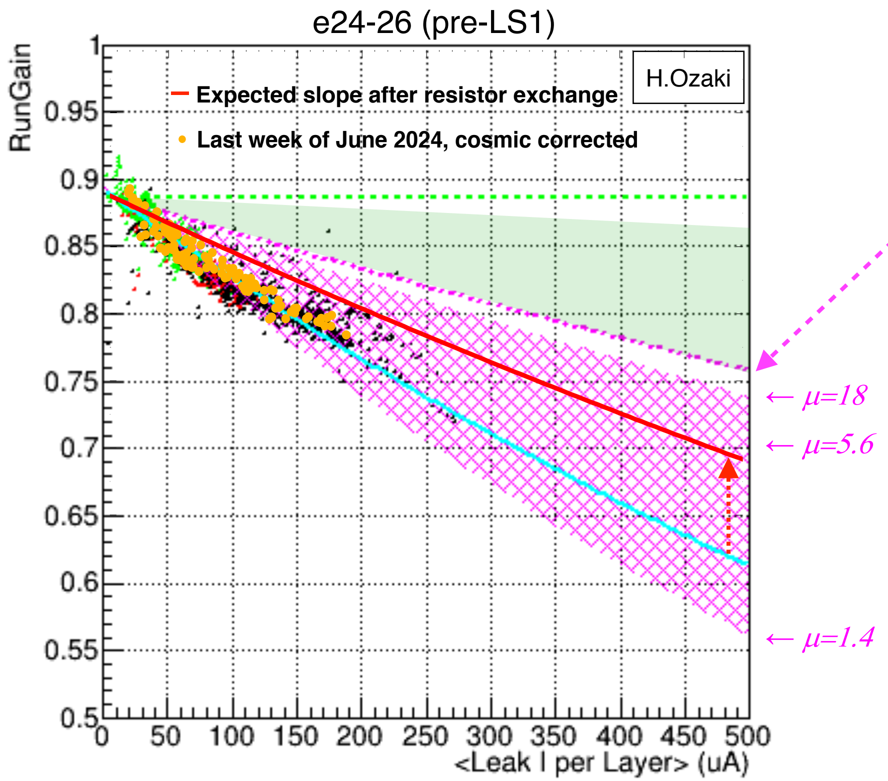
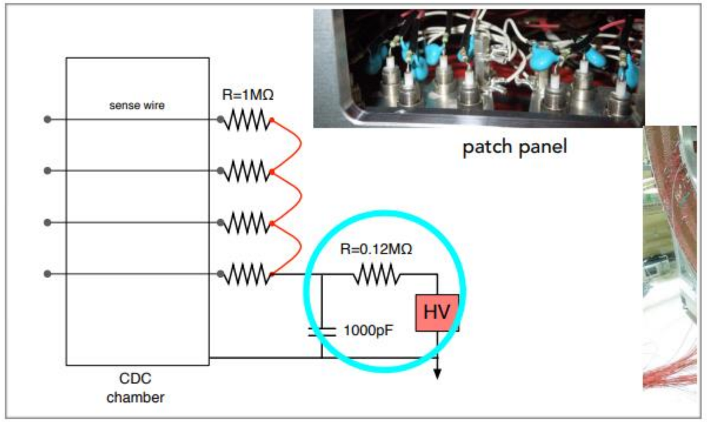
# Background Dependence of Run Gain




Expected slope change due to resistor replacement

(1) Estimated gain reduction due to voltage drop across resistor in HV distribution

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    - some tension with estimated value of μ = 10 ~ 20 $cm^{-2}/V/s$ in $He/C_2H_6$ estimated by Rob Veenhof (CERN)
- Contrary to expectation, no significant change in slope seen after LS1
  - i.e. no visible effect of resistor exchange
    ⇒ so far have only partial understanding of the gain drop



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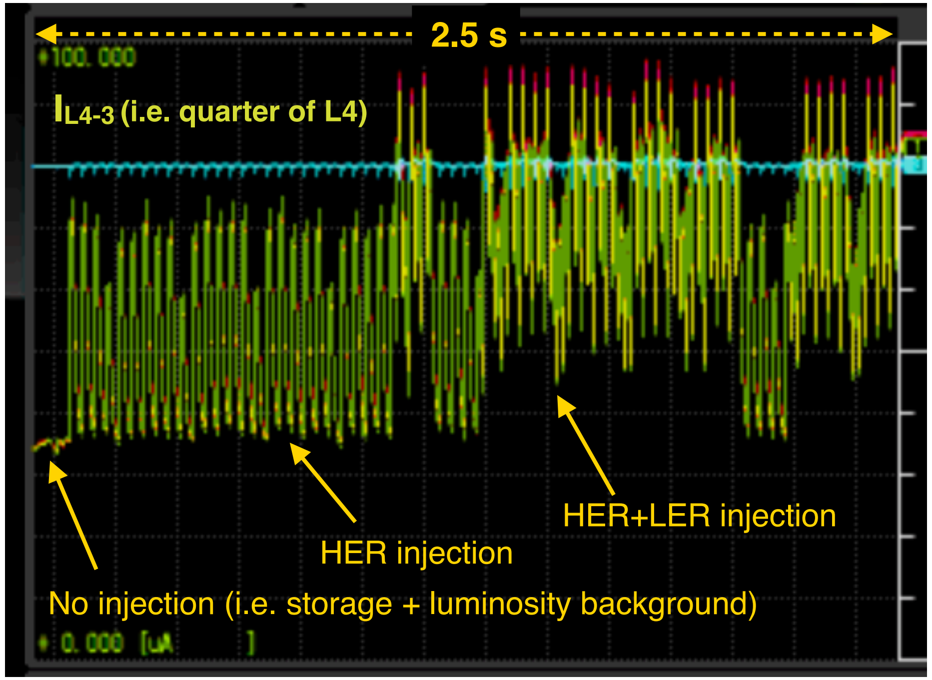
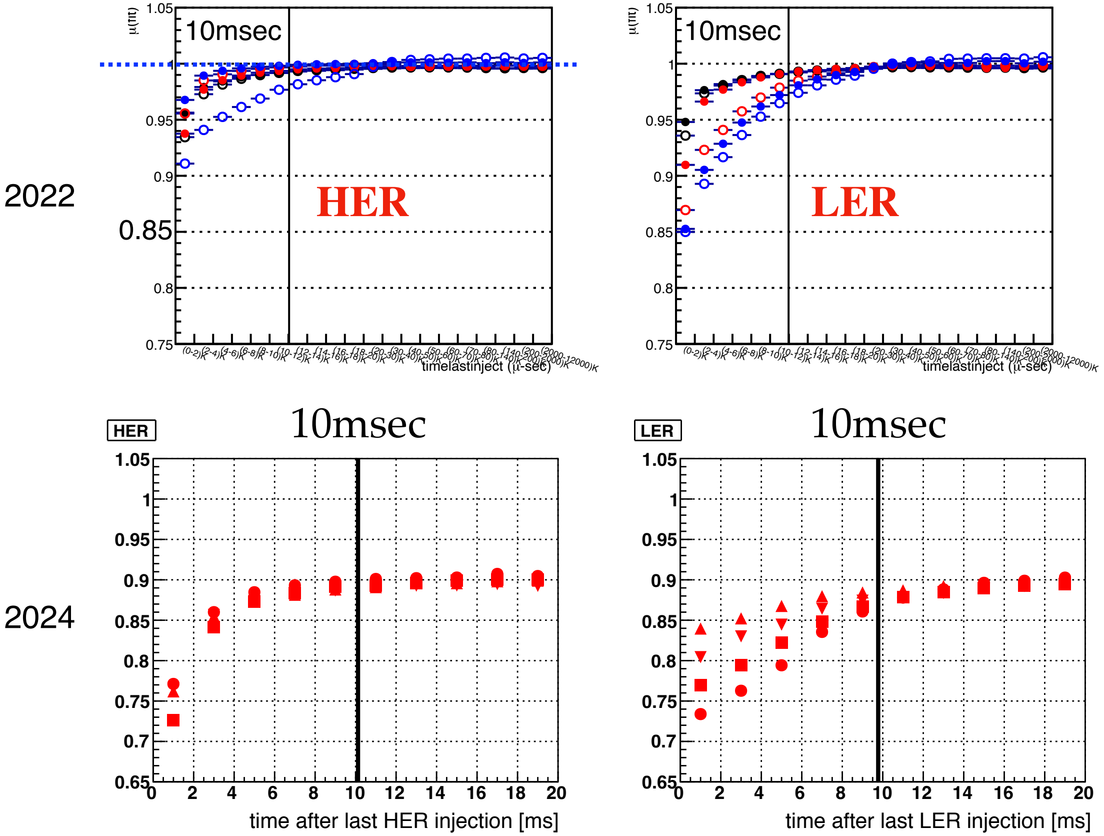
# Zoom in: Short-term Effect of Injection on CDC Gain

Worst conditions reached at the end of 2022b

$I_{HER}$ = 1035 mA, Q = 1.7 nC, rep rate = 25 Hz
$I_{LER}$ = 1293 mA, Q = 2.0 nC, rep rate = 21 Hz
$n_{bunch}$ = 2346, 2-bunch injection for both beams




dE/dx vs time after last injection




- Level of injection background varies greatly with time and injection parameters, e.g.
  - bunch charge; 1- or 2-bunch injection; repetition rate (so far limited to 25 Hz per beam); injection duty cycle
- Generally very similar time dependence before and after LS1
  - typically takes 10-20 ms to return to base level
- However, due to the reduced beam lifetime caused by the Touschek effect, to achieve the target beam currents, the bunch charge must be increased, the 2-bunch injection mode must be used consistently, and a high injection duty cycle is required
- Note: Doubling repetition rate to 2x50 Hz being considered for LS2
  - $\Rightarrow \overline{\Delta t_{inj}}$ = 10 ms, i.e. will never operate in stable regime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# LS2 Machine Upgrade Plans under Consideration

## Requested upgrade during LS2

| Gain | Item | Start timing and duration | Cost | Overview | Priority | Comments |
|---|---|---|---|---|---|---|
| Increase beam current | **Linac current reinforcement** | Under estimation | ~6B JPY | Doubling the injection current e.g. by increasing the repetition rate for both electron and positron beams. | ★★★ | 2x25 Hz → 2x50 Hz |
| Increase beam current | **High power RF reinforcement** | Start: 2029 or later<br>Duration: half of year or more | ~2B JPY | Increase max. HER current to over 2.0A by adding additional RF stations, reinforcing the SCC cooling system, and installing more HOM dampers. | ★★★ | |
| Stabilize operation | **Linac LLRF timing system upgrade** | Under estimation | ~2B JPY | Improve the stability of the beam injection by updating the LLRF control system | ★★★ | |
| Stabilize operation | **Mechanical isolation of BPM and Q magnet in Tsukuba straight line** | In LS2<br>Duration: about 1 year | O(0.1B) JPY | Mechanically isolate the BPM and the quadrupole magent near the sextupole magnet in order to eliminate optical disturbances caused by thermal deformation of the beam pipe due to synchrotron radiation | ★★★ | |
| Stabilize operation | **Mechanical isolation of BPM and Q magnet in arc sections** | Can be done step-by-step in normal shutdowns.<br>Duration: multiple years | ~1B JPY | Mechanically isolate the BPM and the quadrupole magent near the sextupole magnet in order to eliminate optical disturbances caused by thermal deformation of the beam pipe due to synchrotron radiation | ★★ | Effectiveness is currently under review. Initially, we would like to proceed with modifications only in the Tsukuba straight section to check the effects |
| Stabilize operation | **Improve air conditioning in power supply building** | Under estimation | ~1B JPY | Due to the excessively high room temperature in the power supply building, the output of the magnet power supply becomes unstable (especially in June) | ★★ | We should first consider the idea of continuous operation through the New Year period (no winter shutdown) to eliminate the need for operations during warmer seasons. |
| Stabilize operation | **Fast MR BPM readout electronics** | Under estimation | ~1.6B JPY | Renew the BPM readout circuits for measures against aging and faster beam tuning | ★ | |

## Other possible ideas under investigation

| Gain | Item | Start time and duration | Cost | Overview | Comments |
|---|---|---|---|---|---|
| Increase beam current | **Upgrade LINAC RF gun** | Under estimation | Under estimation | Upgrade RF gun for lower emittance in electron beam | Backup plan in case the performance of the current electron gun does not improve. |
| Increase beam current | **HER straight BT line** | Under estimation | Under estimation | Gain and necesity are to be investigated | Need arrangement with PF and PF-AR |
| Increase specific luminosity | **Optimization of beam crossing angle with crab cavity** | Under estimation | Under estimation | Effectively reduce the beam crossing angle with crab cavity. Effectiveness and feasibility are to be investigated. | |

# Background Extrapolation before and after LS2

| Setup | Before LS2 | Target | Design |
|---|---|---|---|
| $\beta^*_y$(LER/HER) [mm] | 0.6/0.6 | 0.27/0.3 | 0.27/0.3 |
| $\beta^*_x$(LER/HER) [mm] | 60/60 | 32/25 | 32/25 |
| $\mathcal{L}$ [$\times 10^{35}$ cm$^{-2}$s$^{-1}$] | 2.8 | 6.0 | 8.0 |
| $I$(LER/HER) [A] | 2.52/1.82 | 2.80/2.00 | 3.6/2.6 |
| $\bar{P}_{\mathrm{eff.}}$(LER/HER) [nPa] | 48/17 | 52/18 | 133/133 |
| $n_b$ [bunches] | 1576 | 1761 | 2500 |
| $\varepsilon_x$(LER/HER) [nm] | 4.6/4.5 | 3.2/4.6 | 3.2/4.6 |
| $\varepsilon_y/\varepsilon_x$(LER/HER) [%] | 1/1 | 0.27/0.28 | 0.27/0.28 |
| $\sigma_z$(LER/HER) [mm] | 8.27/7.60 | 8.25/7.58 | 6.0/6.0 |
| $CW$ | ON | OFF | OFF |

- In recent years we have achieved reasonable agreement between measured and simulated beam-induced backgrounds (excl. injection…)
- Allows reasonably good prediction of background levels up to LS2
- However, no optics yet available for post-LS2 machine setup
- Different scaling factors of scenarios account for associated uncertainties

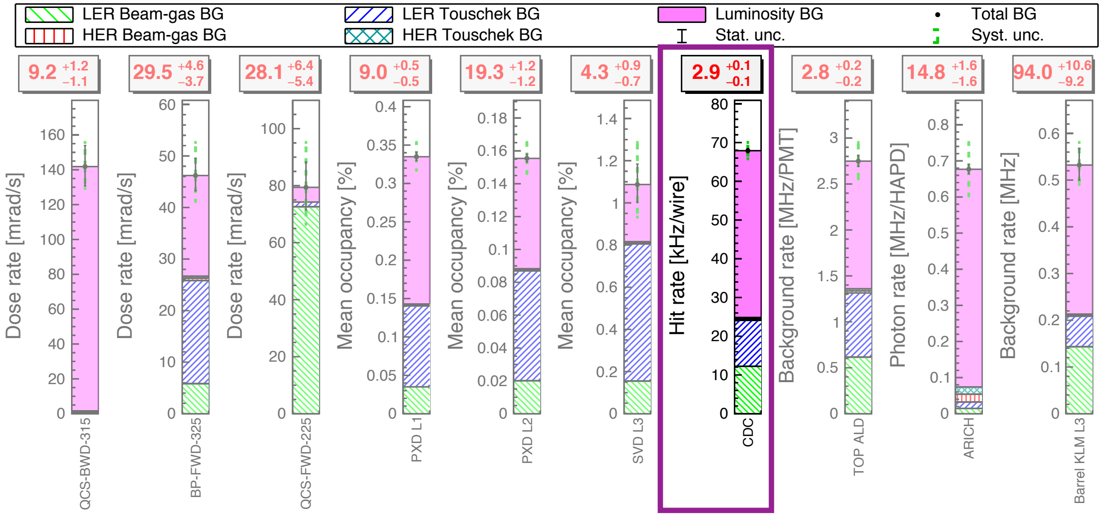



Figure 3.4: Estimated Belle II background composition for predicted beam parameters Before LS2. Each column is a stacked histogram of BG rates from dedicated MC samples scaled with average Data/MC ratios listed in Table 3.3. The red numbers in rectangles are detector safety factors, showing that Belle II should be able to operate safely until a luminosity of $2.8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ with some important caveats, discussed in the text.

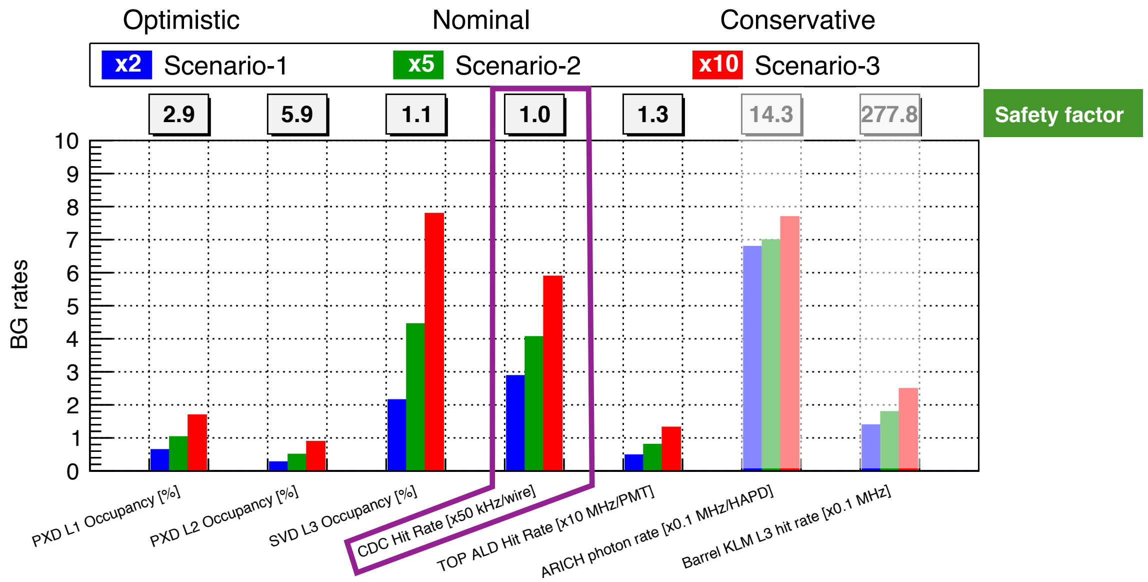
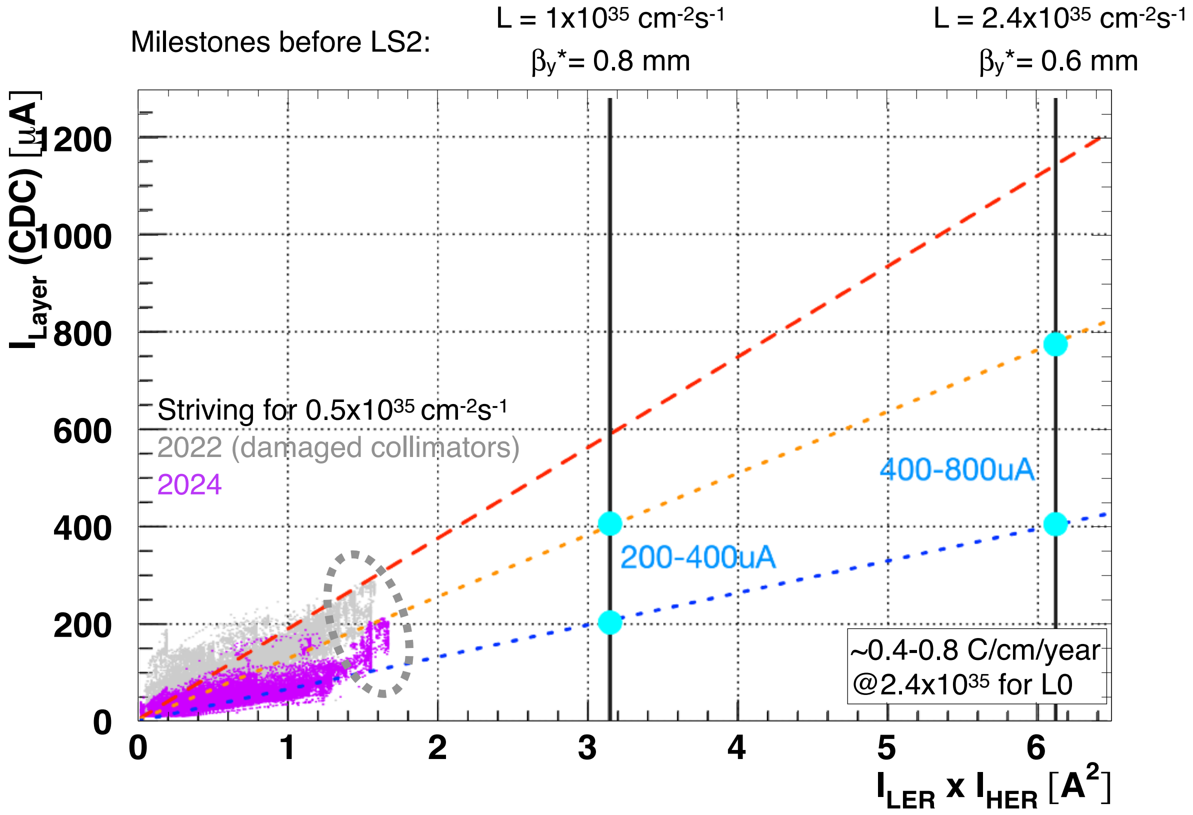



Figure 3.5: Estimated beam background rates in Belle II for After LS2 operation at luminosity of $6.0\times10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The numbers in rectangles are detector safety factors for Scenario-2.

https://doi.org/10.1016/j.nima.2023.168550

# Future Operating Conditions very difficult to predict



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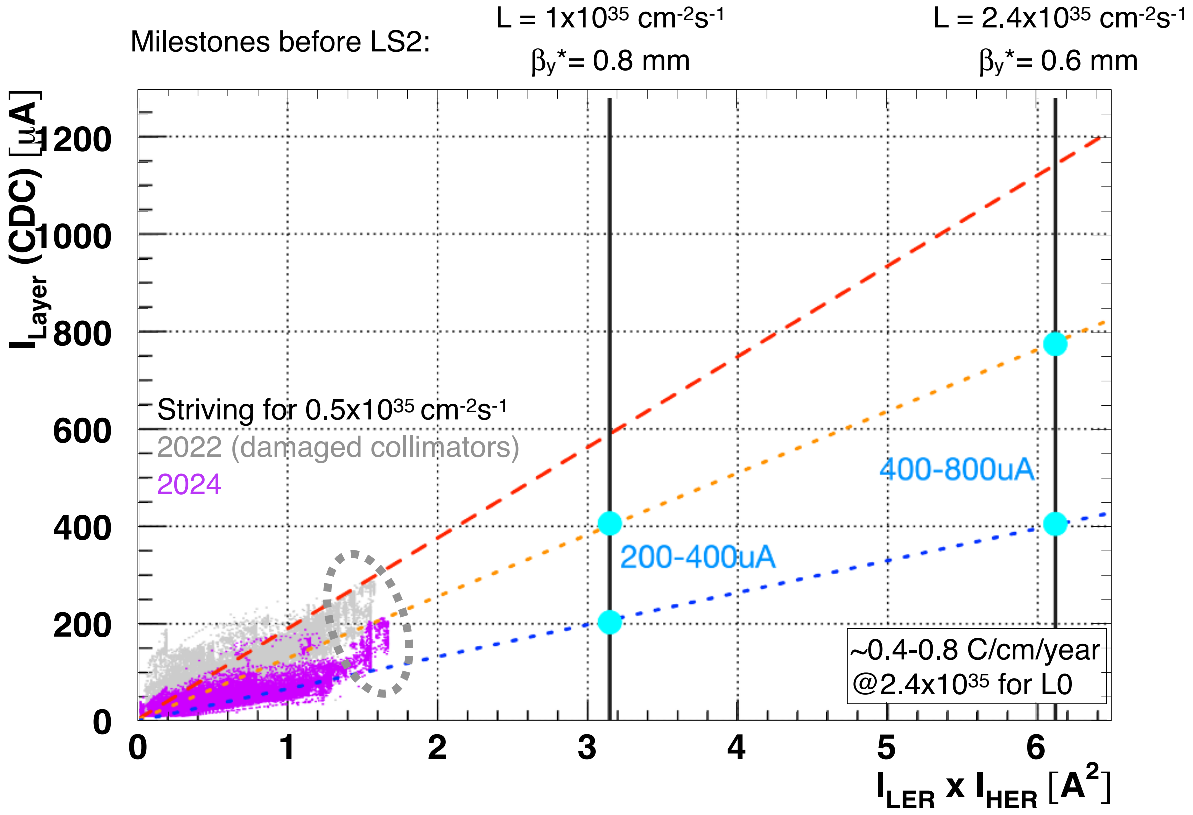
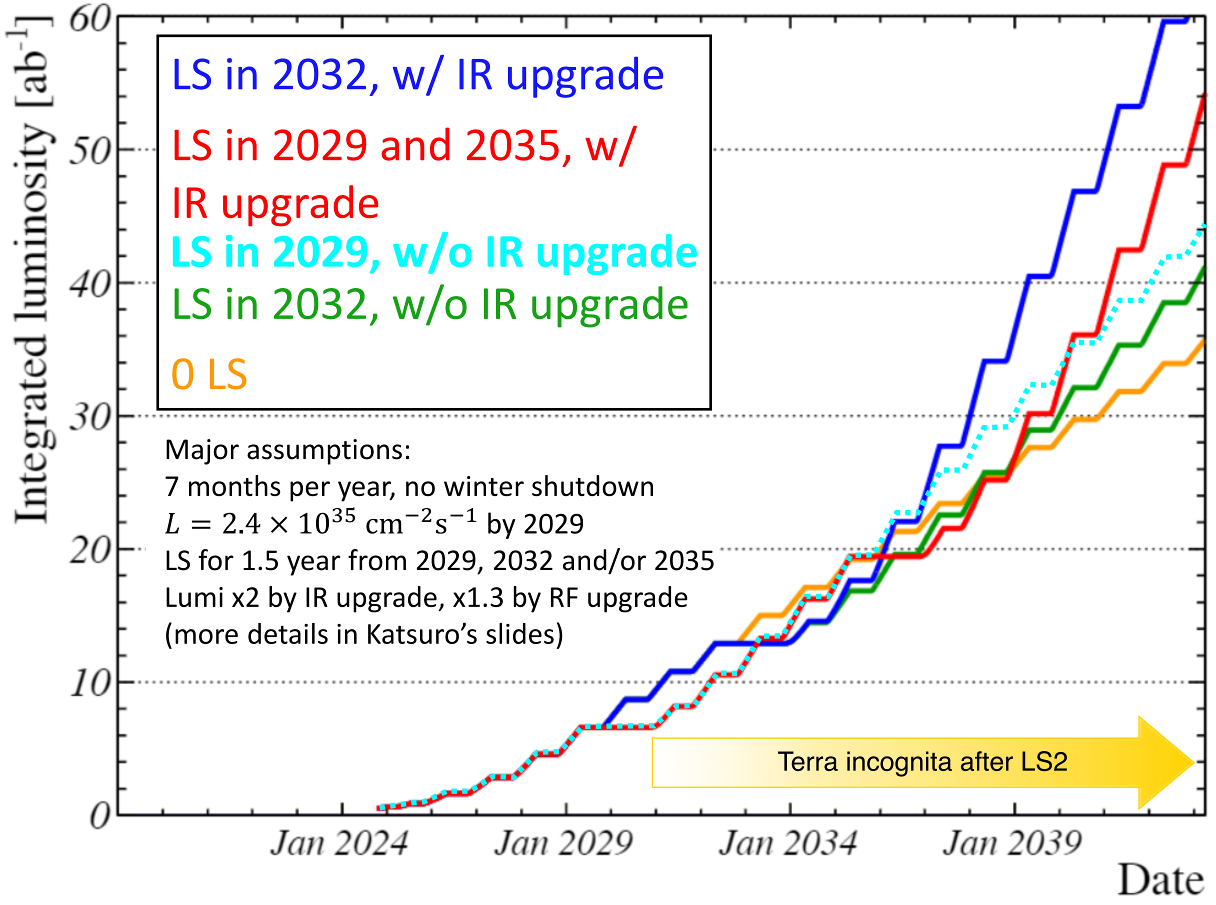



Shutdown scenarios M.Tobiyama (SuperKEKB)



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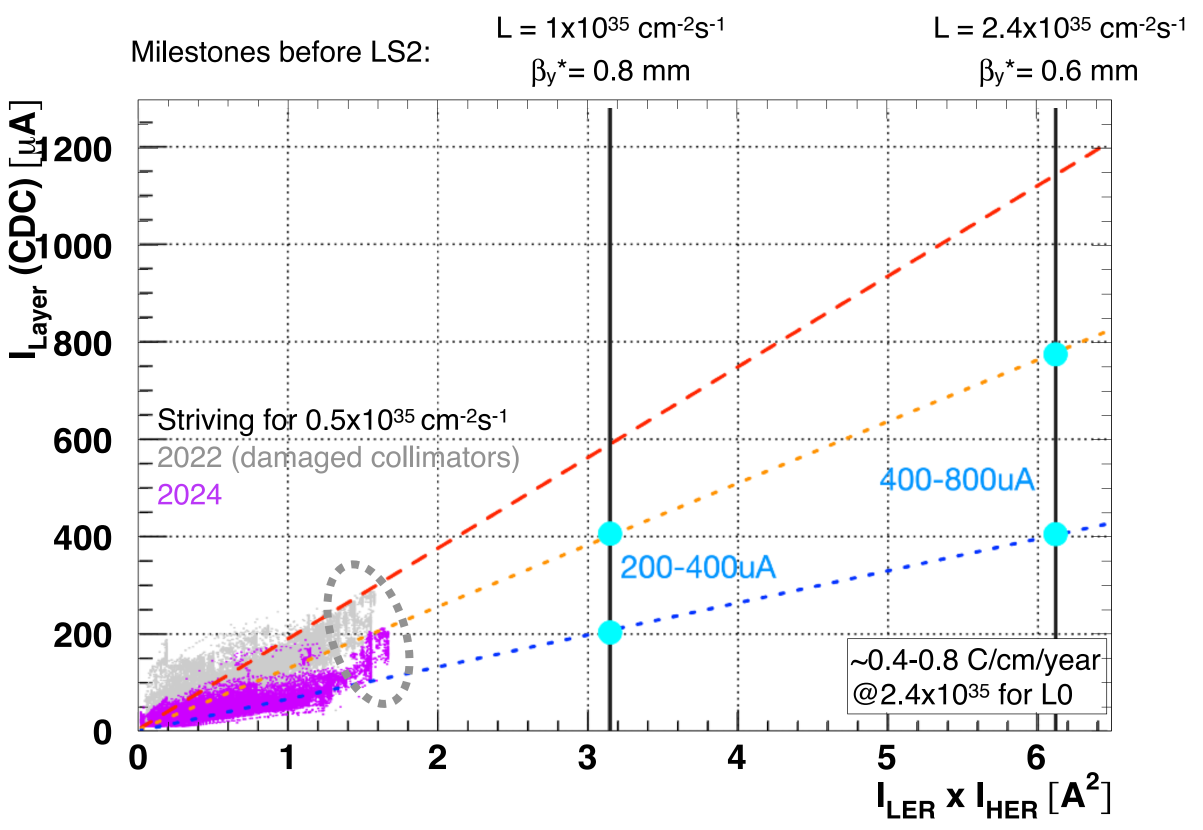
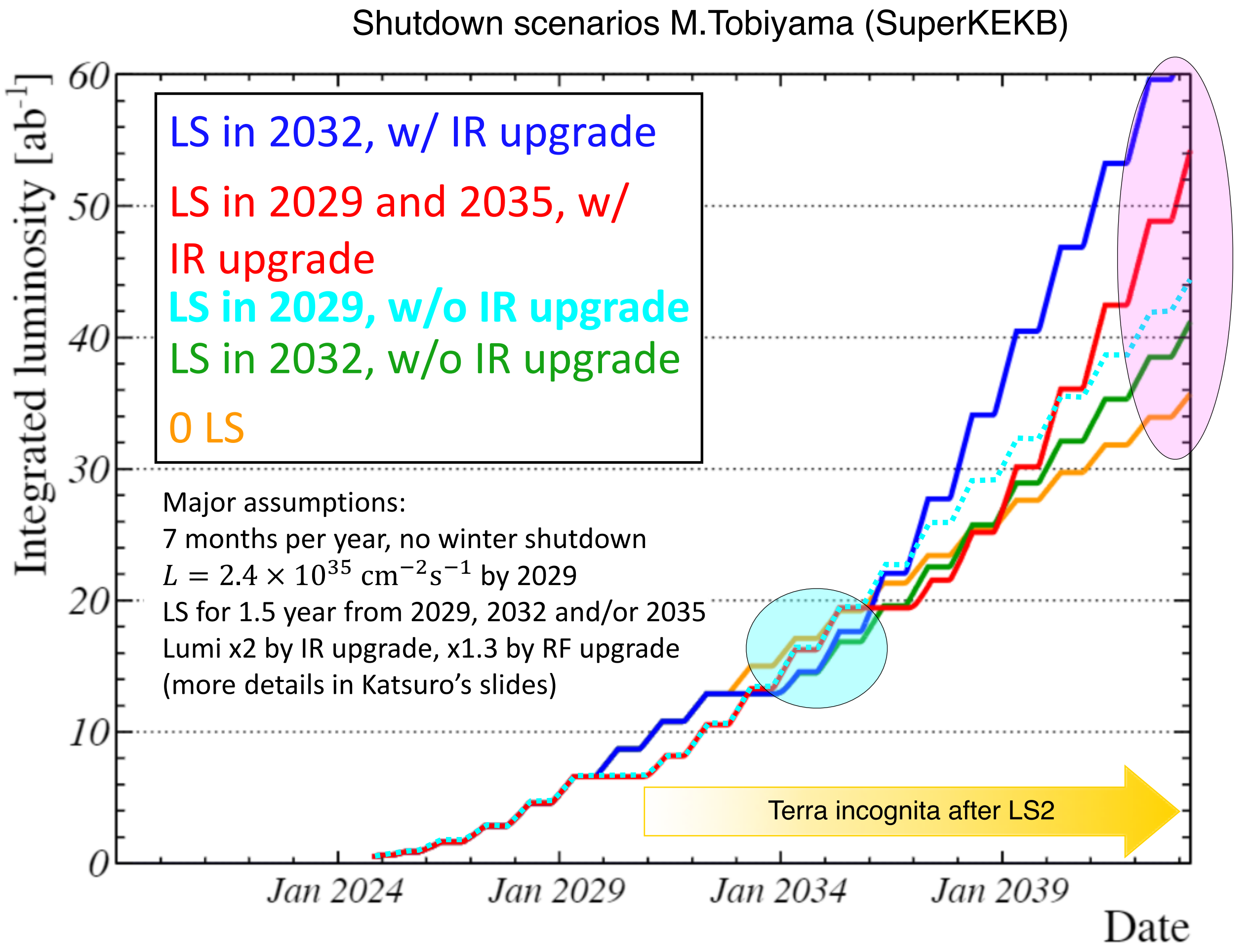



- Uncertainties in the projections are very large for both the SuperKEKB upgrade path and the CDC performance response
- With improved control of CDC operating conditions in the future (e.g. gas conditions), the expected performance degradation up to LS2 may perhaps remain acceptable if pre-Belle ageing results are confirmed
- However, unless machine conditions magically improve dramatically after LS2, the deterioration in CDC performance seems likely to become unacceptably large in a period when the bulk of the Belle II data is expected to be collected

~ $\mathcal{O}$(3.5 – 7) C/cm ⇒ ΔG/G = $\mathcal{O}$(20 – 40)%

~ $\mathcal{O}$(7.5 – 15) C/cm ⇒ ΔG/G = $\mathcal{O}$(45 – 90)%

… assuming 6% per C/cm (pre-Belle study)

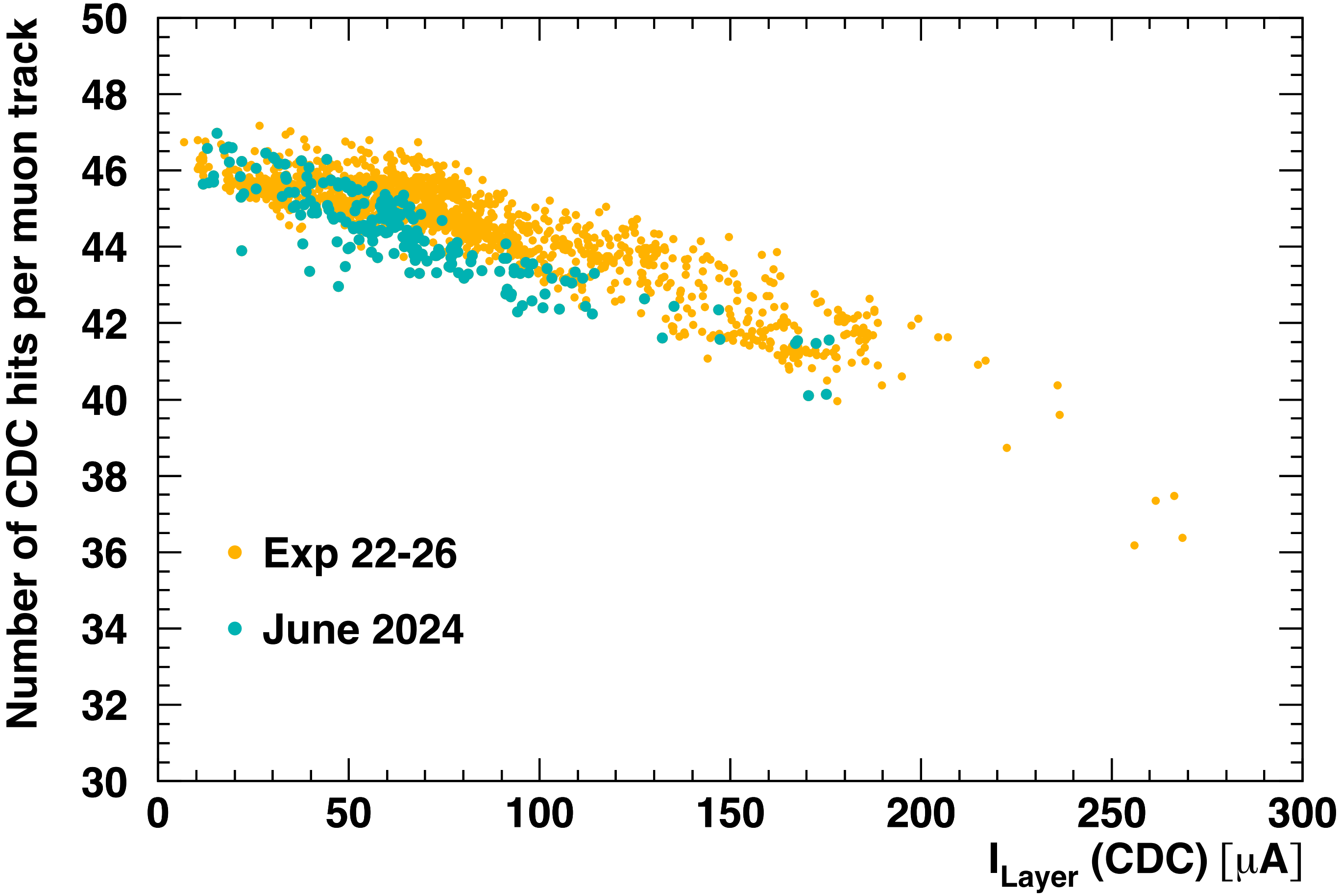
# Summary

- We should be prepared that tracking, PID and triggering might soon be compromised by background related performance degradation in the CDC

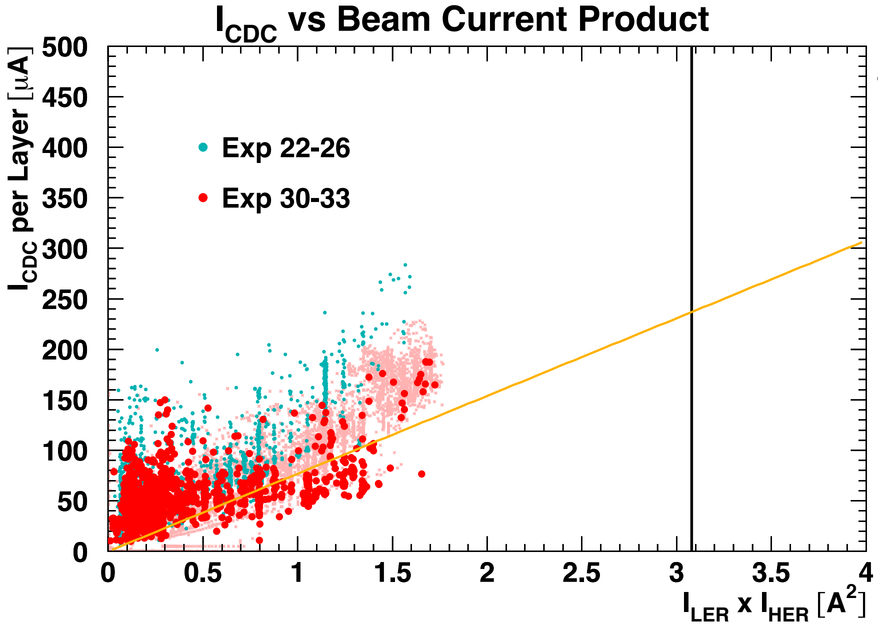
- Have to develop mitigation strategies now, because changes will require studies and a lot of preparation time

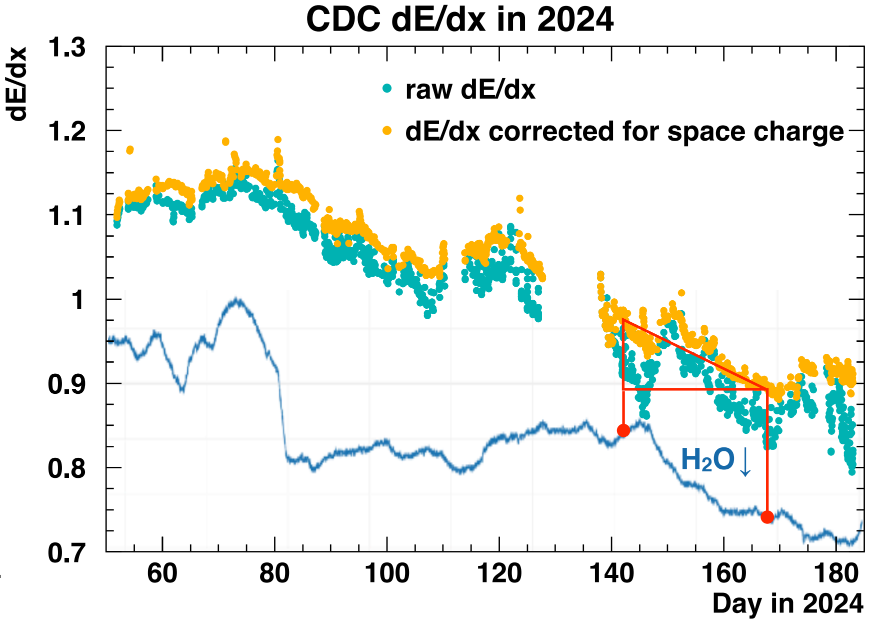
- Given the potential impact on the Belle II physics program the person power available for this highly important work should be increased

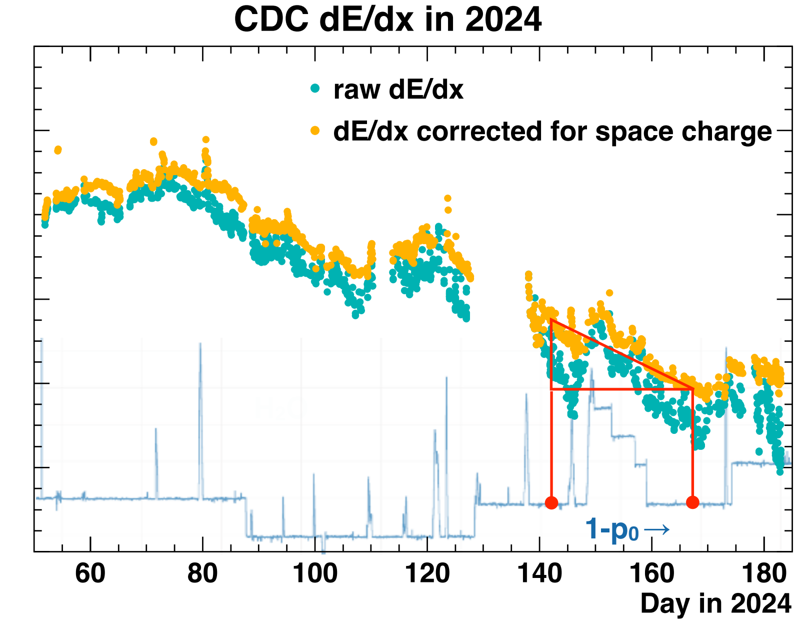
# Number of CDC Hits per Muon Track

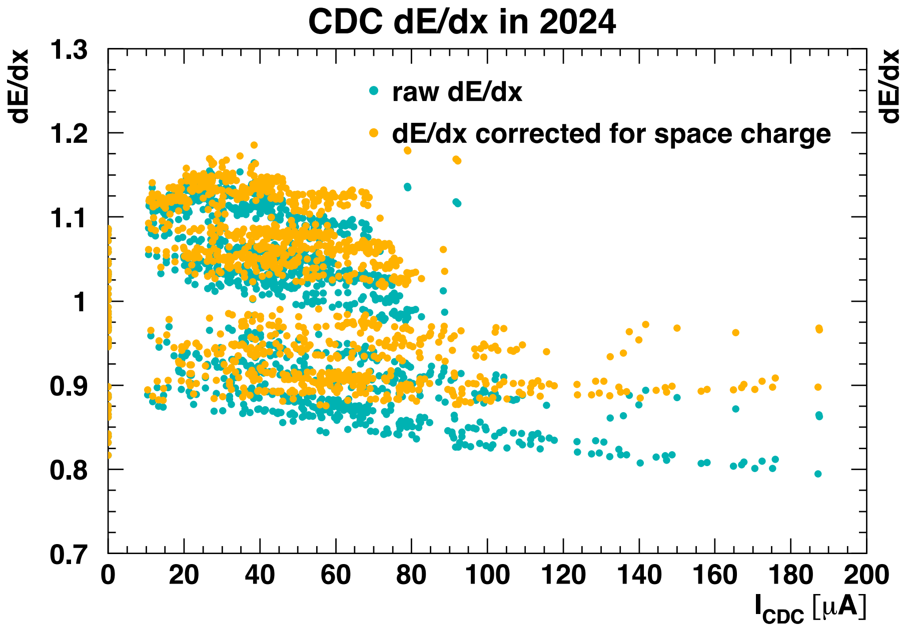


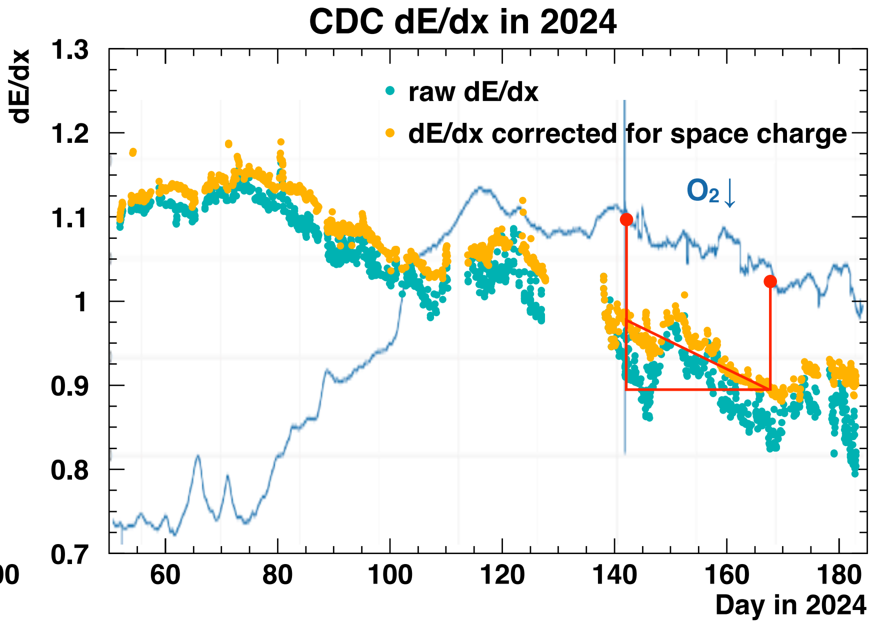
# CDC Operation in 2024




- Injection background in CDC generally lower than in Run1
  - however, towards end of 2024b approach 200μA again
- Variations in $I_{CDC}$, $p_0$, $H_2O$- and $O_2$-level affect run-averaged dE/dx values
  - but observed trends can't explain $\mathcal{O}$(8%) drop from mid-May to mid-June
- Possible causes
  - misleading gas sensor readings (again?)
  - overlooking other relevant parameters
  - ??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