

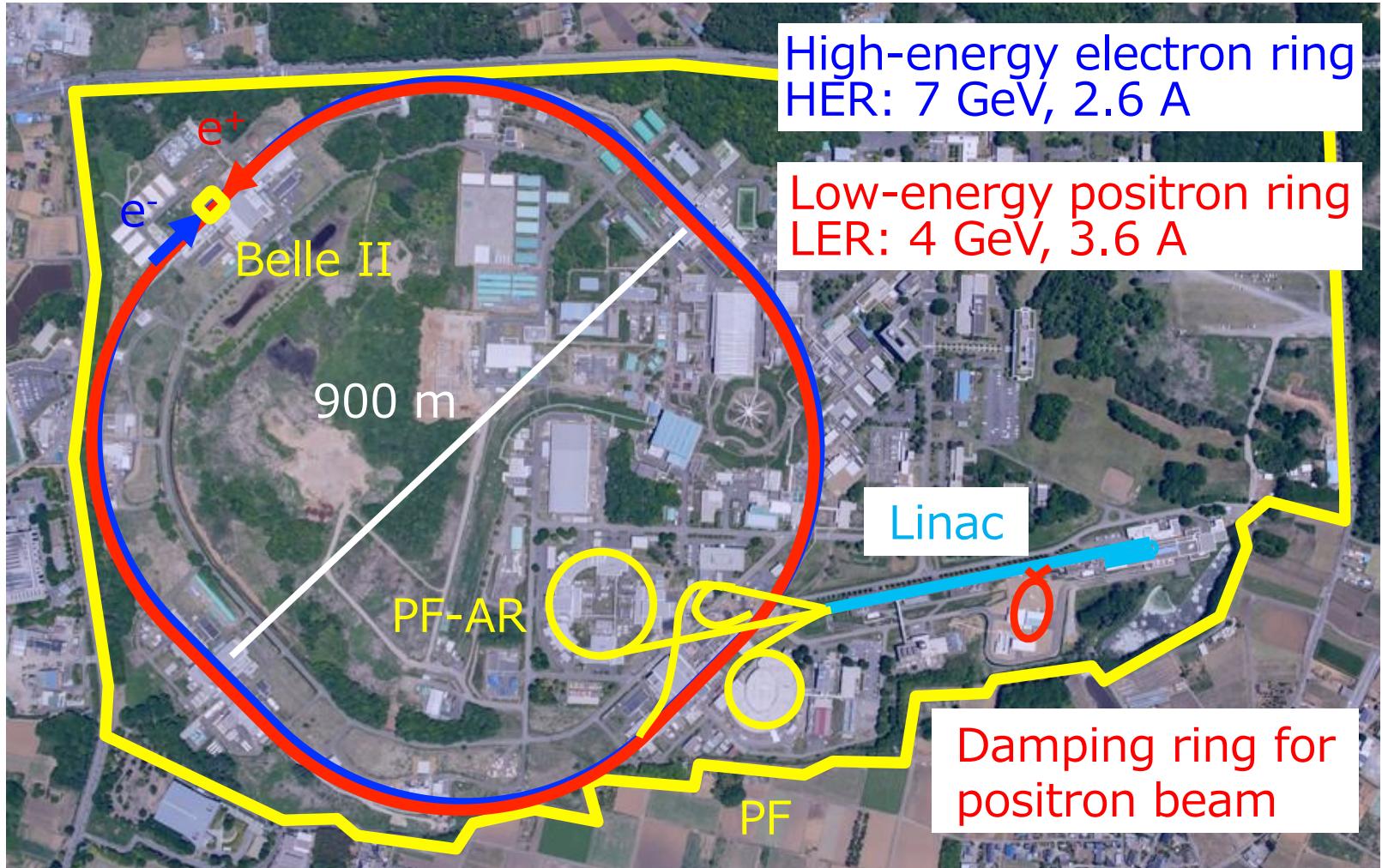
Phase 3 beam commissioning of SuperKEKB

OKI, Toshiyuki (KEK)
on behalf of the SuperKEKB commissioning group

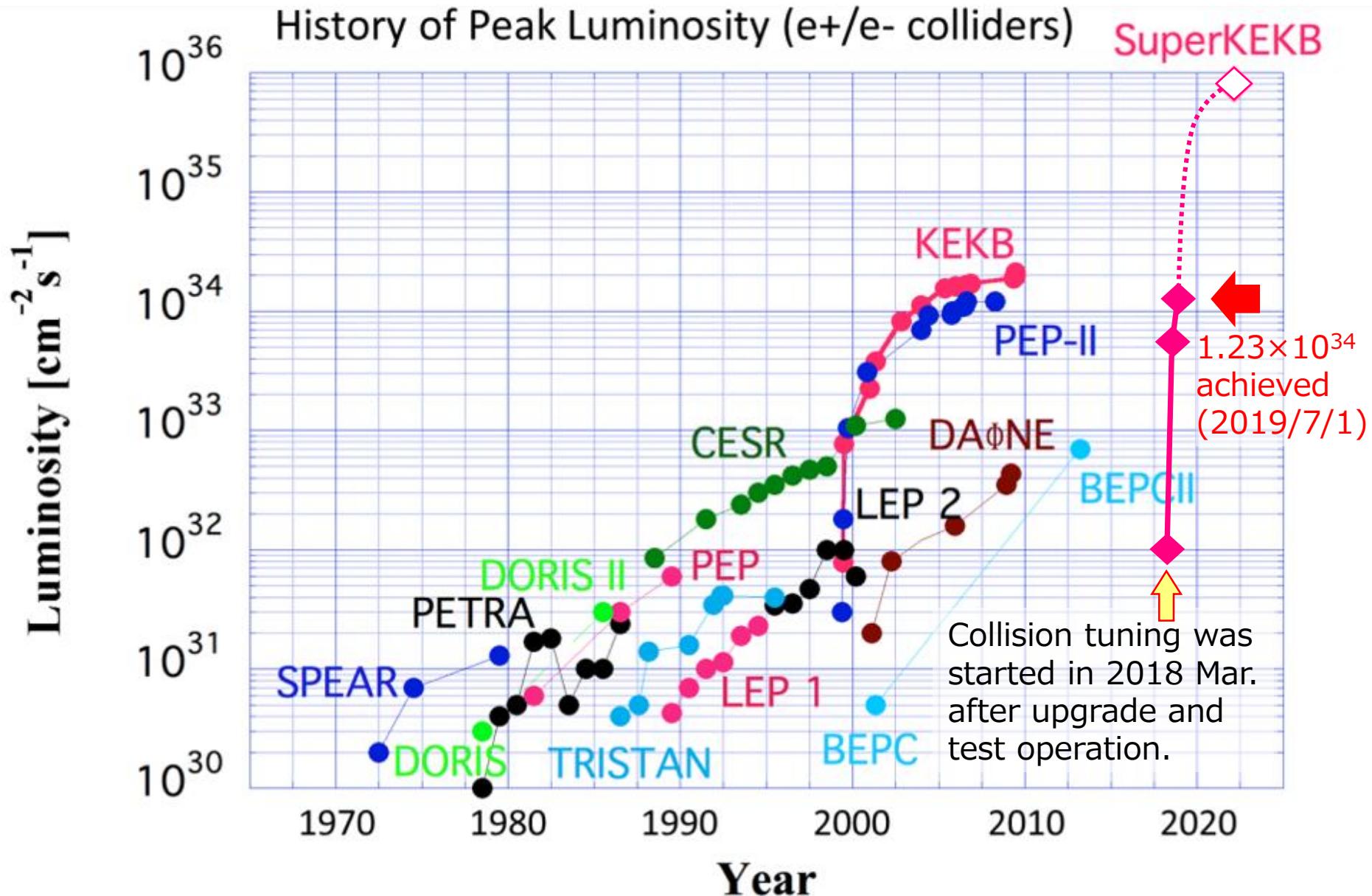
2019/JUL/13th
EPS-HEP2019

Top view of SuperKEKB collider

SuperKEKB: asymmetric-energy electron-positron collider
constructed by upgrading the KEKB B-factory



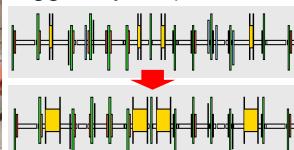
Aiming for 40 times higher luminosity than KEKB



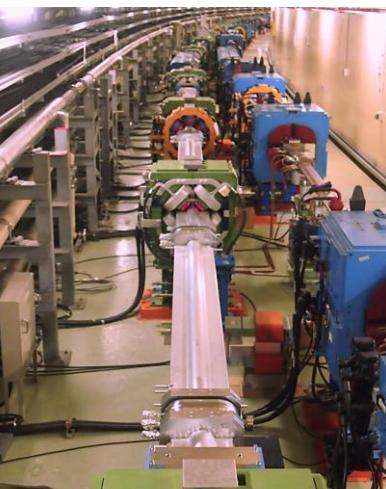
Upgrades to be 40 times higher luminosity



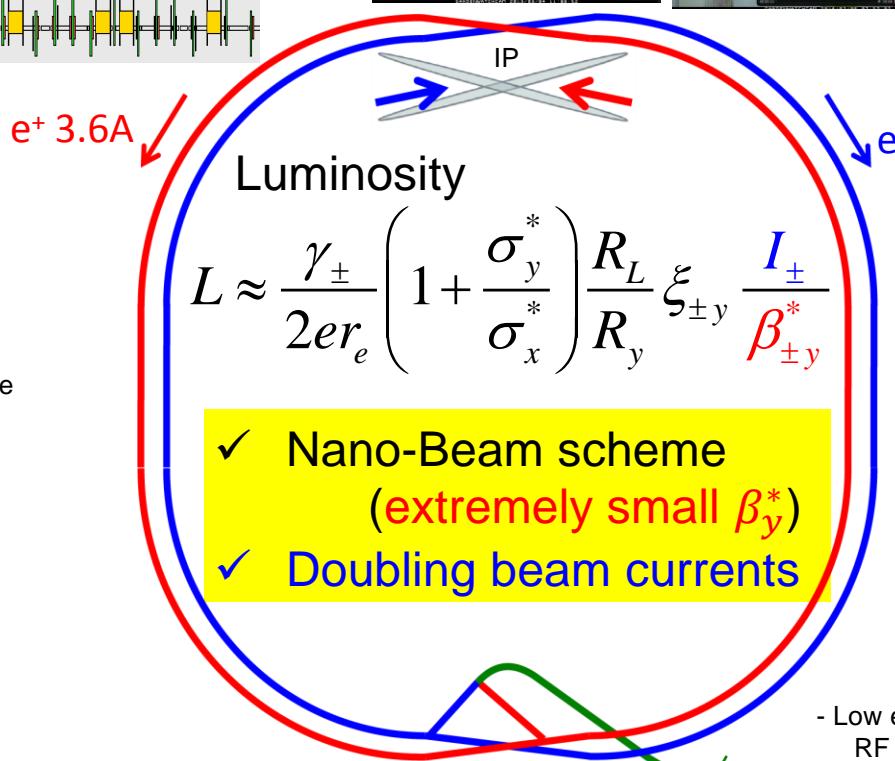
Redesign the lattice to squeeze emittance (replace short dipoles with longer ones, increase wiggler cycles)



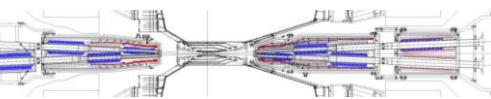
All of LER main bends (100, 4m) are installed instead of shorter one.



Replace beam pipes with TiN-coated beam pipes with antechambers



- Low emittance
RF electron gun
- Upgrade positron capture section
Injector Linac upgrade
New e+ Damping Ring



New final focus SC magnets at IP

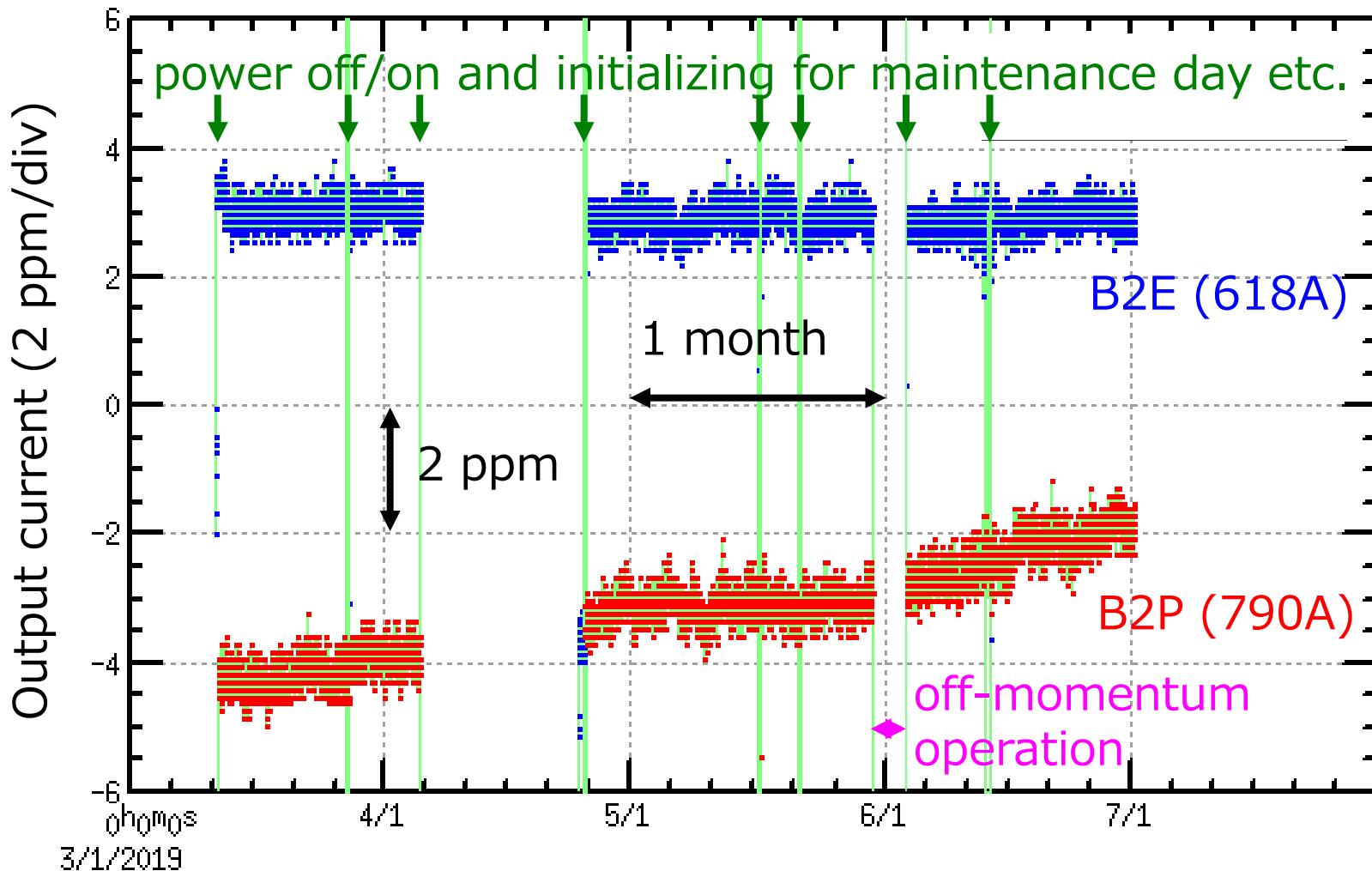


Upgrading (LER) and new (HER) wigglers



Reinforce RF systems for higher beam currents

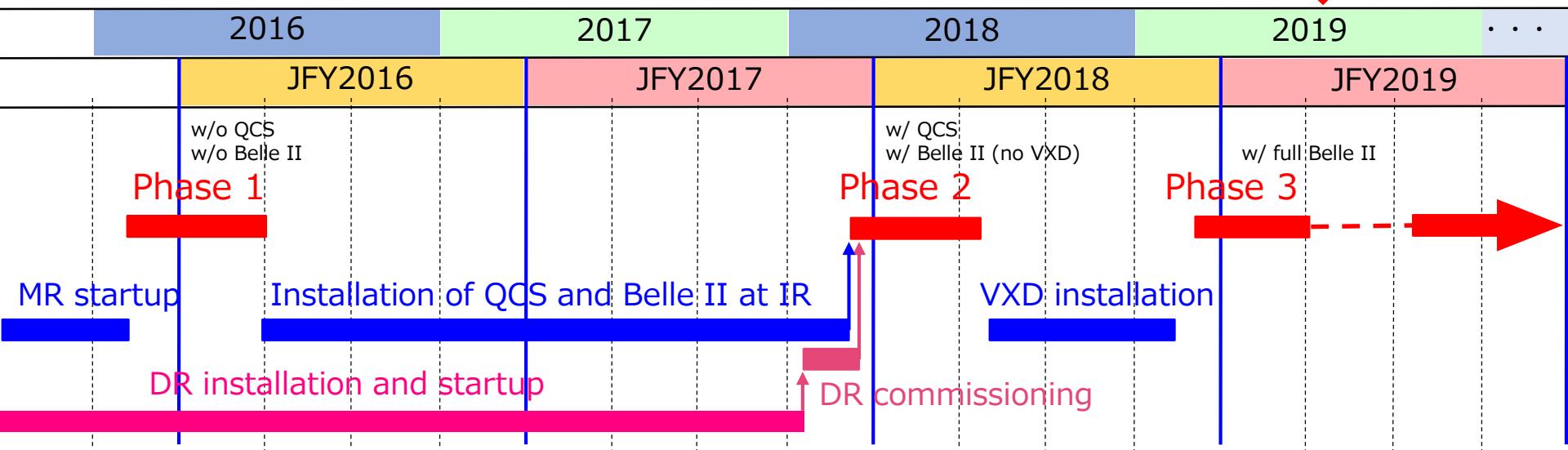
Stability of main bending magnet PSs (860A, 1.1kV)



- Newly developed 24-bit board and digital FB control are used.
- 2.0~4.0 ppm stability obtained over Phase 3 operation.
- Good repeatability after power off and initializing operation.

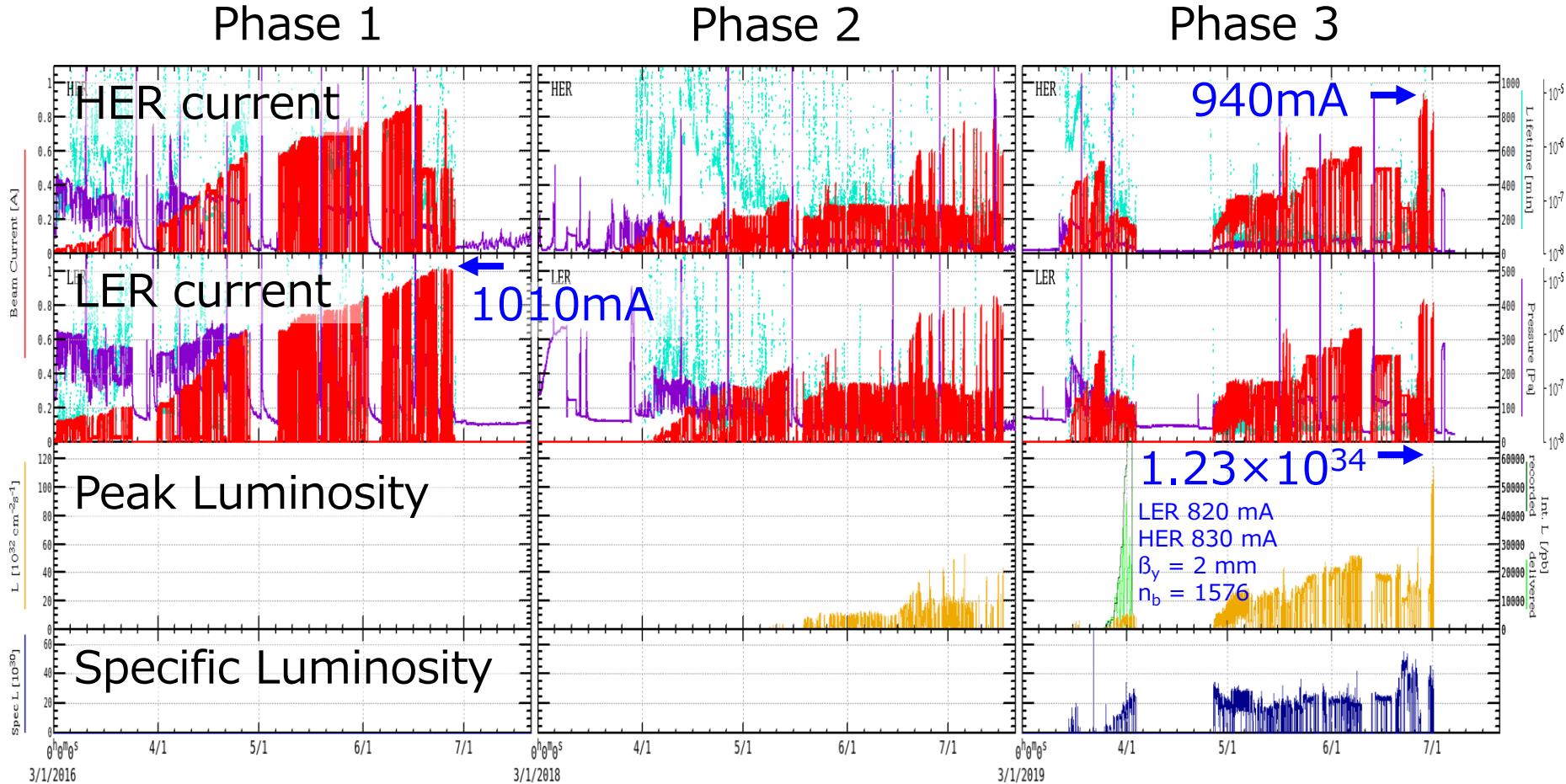
Commissioning in a phased manner

we are here
↓



- Phase 1 :
Basic machine test without collision/
Low emittance beam tuning/Vacuum scrubbing
- Phase 2 :
Squeezing beta at IP/"nano-beam" collision tuning/
Physics run w/o VXD starts under BG study
- Phase 3 :
Physics run starts with a fully equipped Belle II detector
Further collision tuning and collimator tuning/cont. inj.

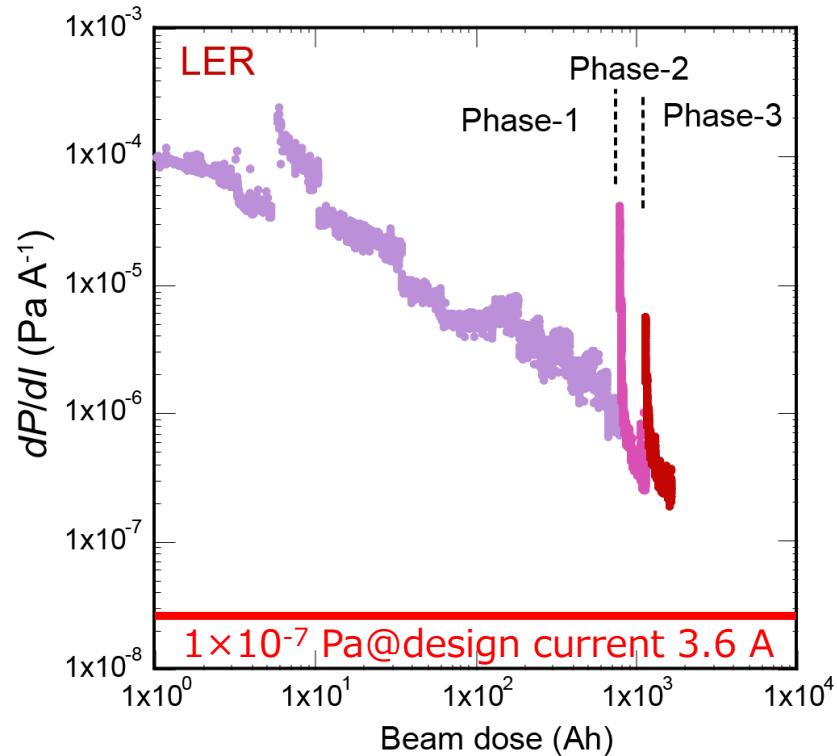
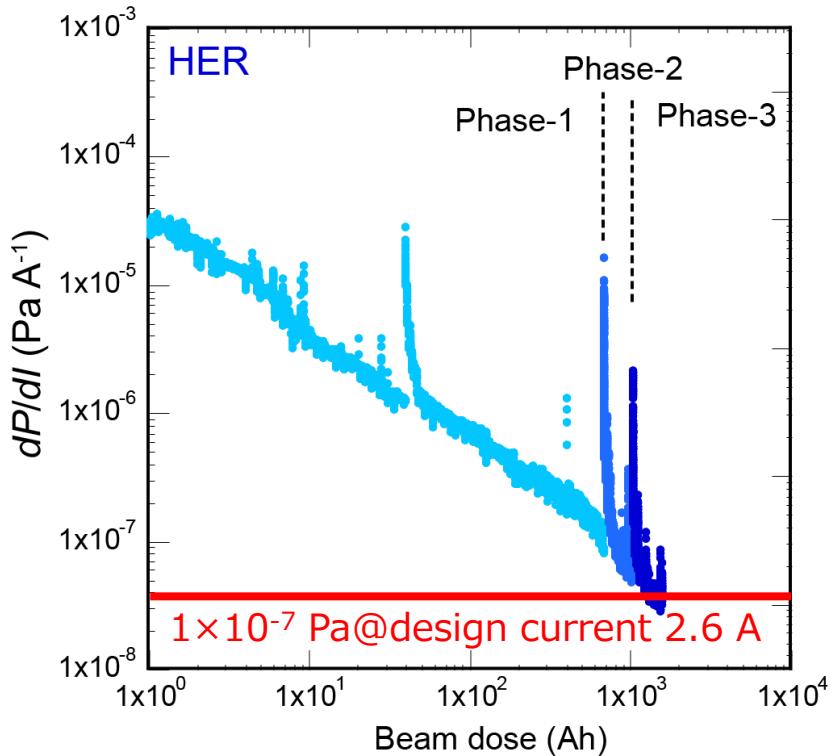
History of phase 1, 2, 3 beam commissioning



- No collision
Vacuum scrubbing
- Squeezing
- Collision tuning
- Physics run starts
- Physics run starts with full Belle II
- Further tuning and continuous injection

Status of ring vacuum pressures

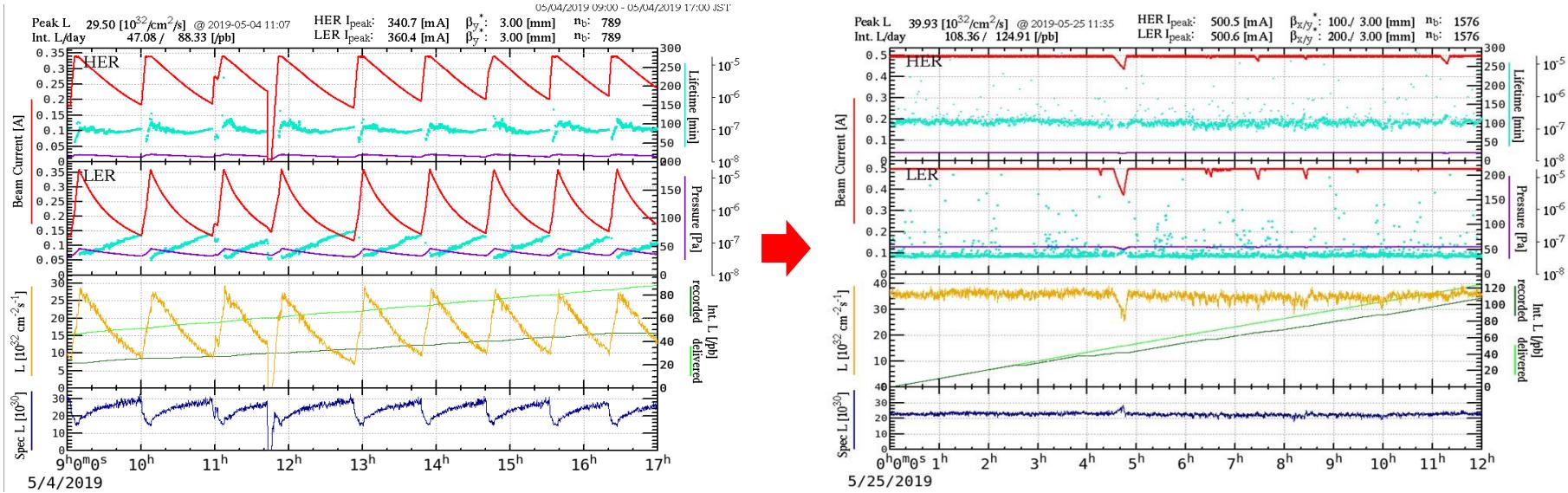
Average ring vacuum pressures normalized by a unit beam currents.



- Vacuum pressure should be kept lower than 1×10^{-7} Pa, in order to increase beam lifetime and decrease beam-gas detector background.
- HER vacuum pressure has reached the target value.
- Further scrubbing (5 kAh for 1/3 pressure) is necessary for LER, where newly installed beam pipes are used.

Continuous injection

In Phase 3, “continuous injection” starts, so that e- and e+ beams are continuously injected into HER and LER.



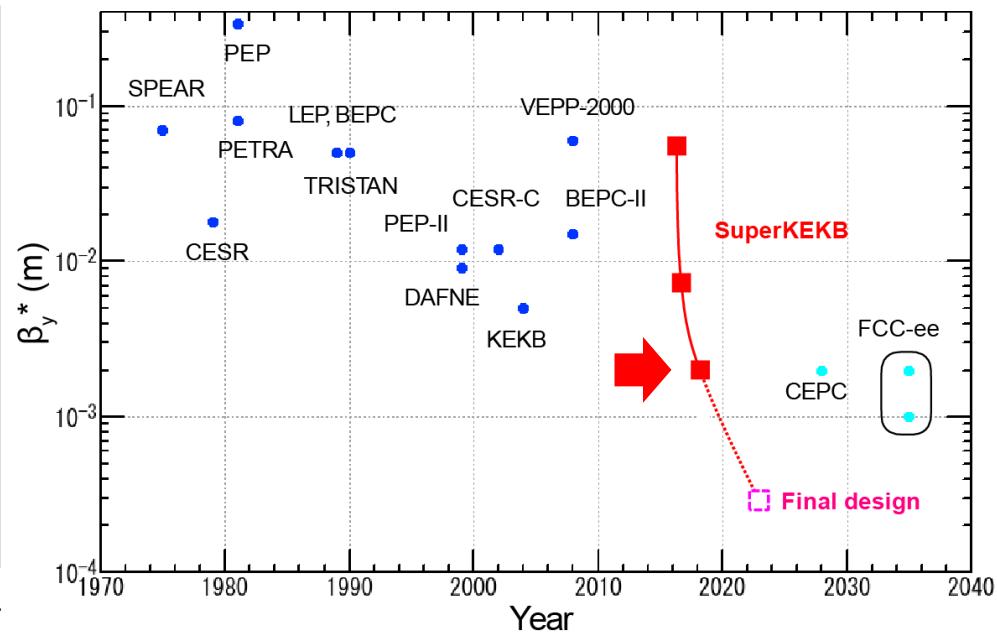
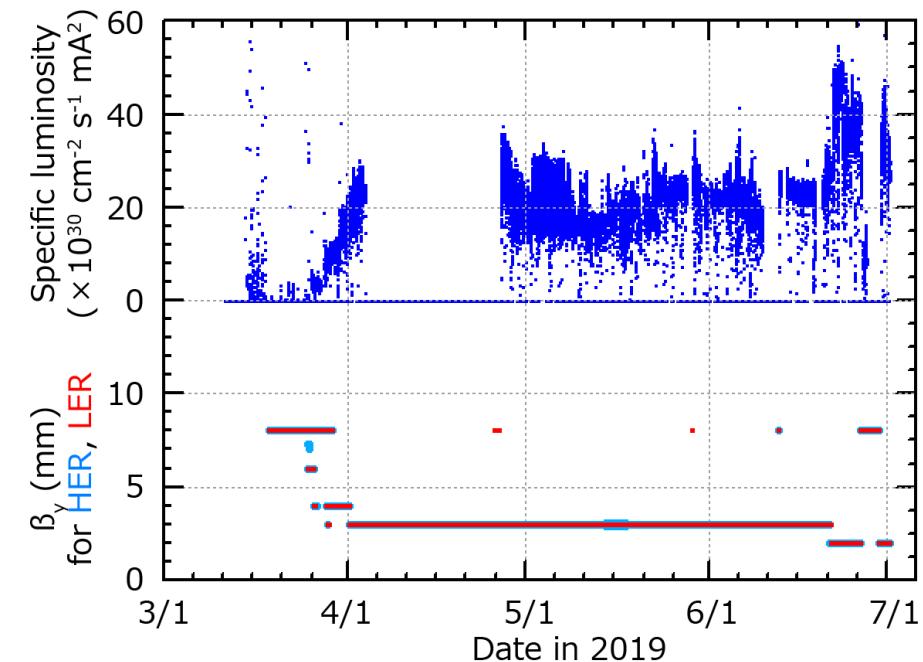
- It is realized after successful background reduction by elaborate tunings of injection parameters and collimators.
- Stored beam currents are kept constant, and **integrated luminosity is increased**.

Squeezing beta function

Luminosity is increased by smaller vertical beta function at IP.

$$L \approx \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{R_L}{R_y} \xi_{\pm y} \frac{I_{\pm}}{\beta_{\pm y}^*}$$

Beta function is squeezed gradually.

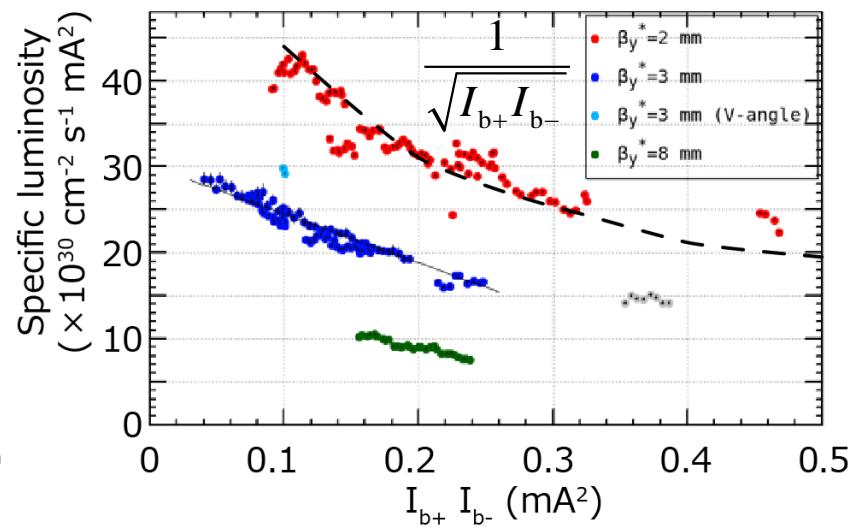
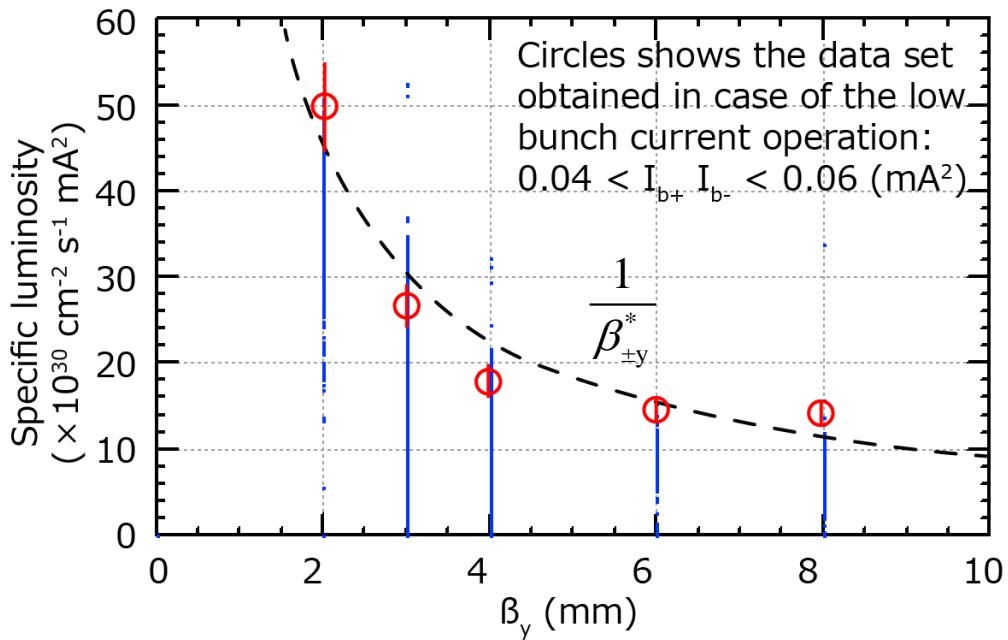


Smallest $\beta_y^* = 2$ mm is achieved up to now.
(final design = 0.3 mm)

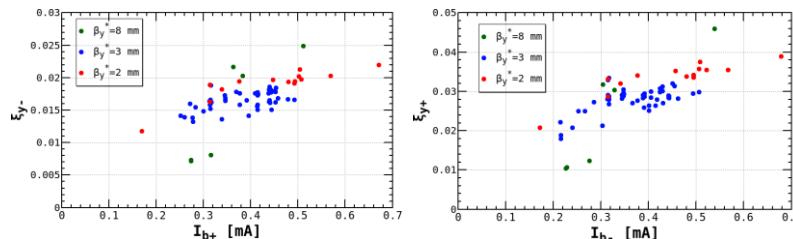
Specific luminosity

Spec. luminosity: normalized by bunch current product \times # of bunch.

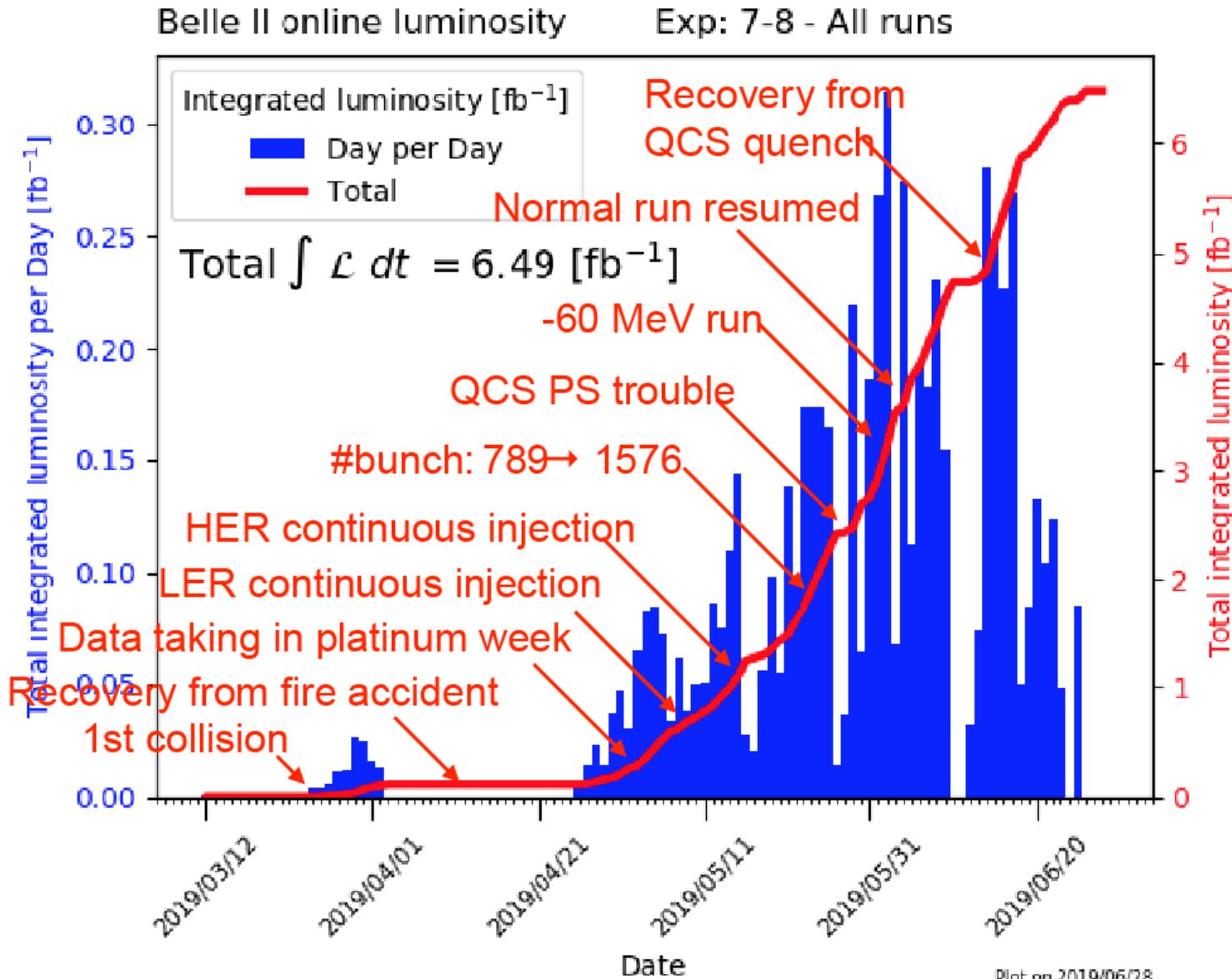
$$L_{\text{sp}} = \frac{L}{I_{b+} I_{b-} n_b} \propto \frac{\xi_{\pm y}}{\beta_{\pm y}^* \sqrt{I_{b+} I_{b-}}}, \quad \text{where } I_{b\pm} = I_{\pm} / n_b$$



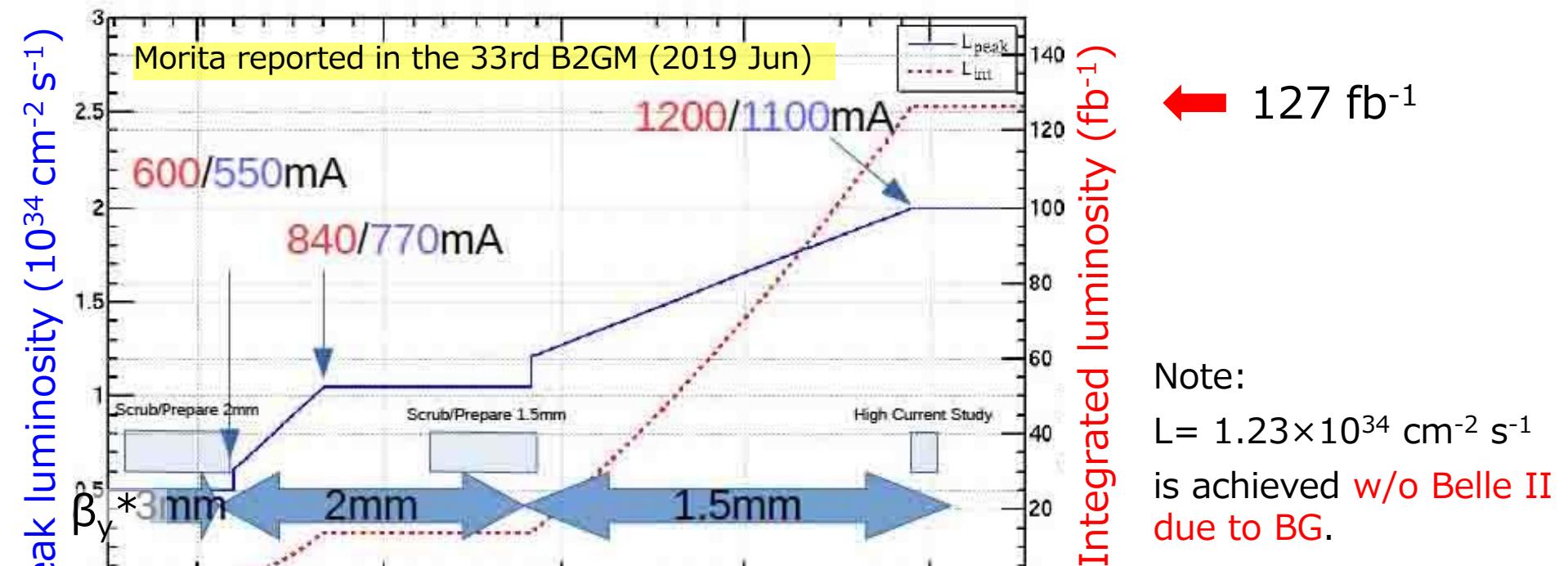
L_{sp} is increased by squeezing β_y^* .
 $(\xi_{\pm y} \text{ can be kept while squeezing})$



Status of physics run on phase 3 commissioning



Luminosity projection (2019 Oct. – 2020 Jun.)



Note:
 $L = 1.23 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
is achieved w/o Belle II
due to BG.

Assumptions

- No machine study time for future beam development
- Detector background independent of β_y^*
- $\times 2$ improvement of CDC current limit
- No current limit for protecting detector

Summary

- SuperKEKB is an electron-positron collider that aims for a 40 times higher peak luminosity than that of KEKB.
- Indeed, many of accelerator components have been upgraded.
- Newly developed 24-bit control board and digital feedback control scheme are used for main bending magnet power supplies, so that 2.0~4.0 ppm stability was obtained over Phase 3 operation.
- Full scale physics run has started.
- The “nano beam scheme” collision was demonstrated down to $\beta_y^* = 2 \text{ mm}$.
- Continuous injection for both rings is used in regular operation.
- Peak luminosity of $1.23 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ was recorded at $\beta_y^* = 2 \text{ mm}$, LER 820 mA, HER 830 mA, 1576 bunches.
- Although there are several issues for challenging higher luminosity, we will keep trying to solve them.

Key issues for higher luminosity (1/2)

- Stored beam current

No issues at present. Current will be increased, watching for overheating of vacuum components. Several RF klystrons for high-power RF system will be add in future for the design beam current.

- Tuning

Injection-, optics-, tune-, collision- (offset, angle, waist, phase, ···), collimators-, such a further beam tuning is necessary. V-angle tuning improves a Lsp. Beam-beam parameter is still half of its design. Beam blowup is observed in LER, which is not yet understand.

- Quench on the final focus superconducting magnet

Collimator tuning reduces the number of quench occurrences at present. For more squeezing of beam, additional collimators may be required. Additional fast beam abort signal may be helpful for a quench protection.

Key issues for higher luminosity (2/2)

- LER beam transport lines

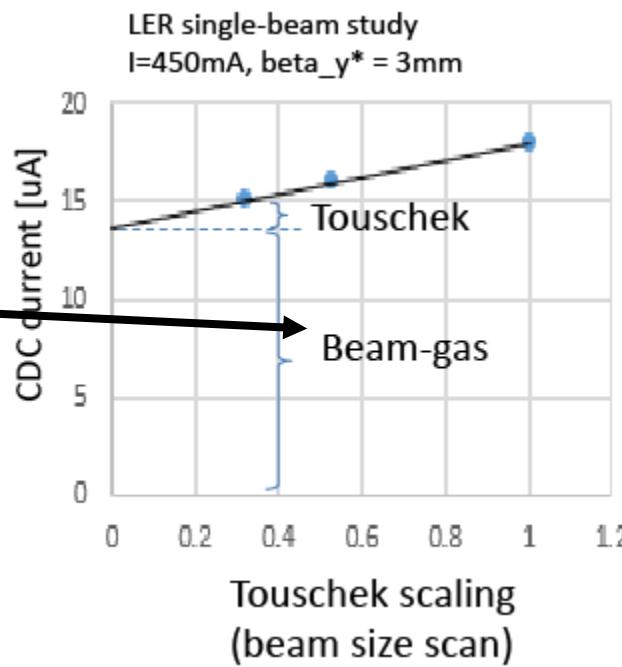
Injection beam emittance is a little bit larger than expected. Extracted beam emittance from a dumping ring is small enough, so that BT will be check the reason.

- Background

Further scrubbing (5 kAh for 1/3 pressure) is necessary for LER.

Dominant source is LER beam gas BG.

Touschek BG is small enough, due to newly installed horizontal collimators.

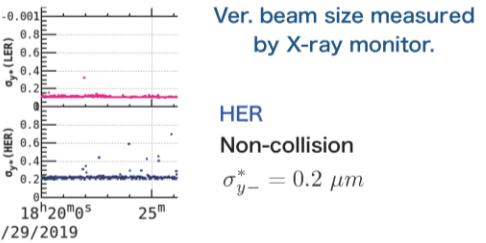
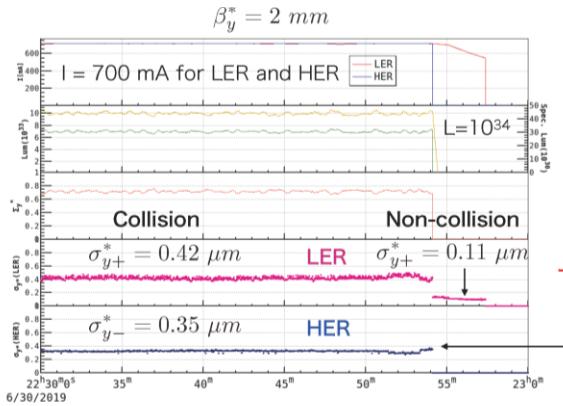


- Beam-dust events (called UFO's at LHC) ?

Pressure bursts are observed occasionally.

Preliminary test result presented by Nakayama in the 23rd KEKB Accelerator Review Committee

Beam-beam blowup



The blow-up in the LER is significantly larger than the HER.

The HER vertical beam size is adjusted by using HER emittance control knob (ver. dispersion) in order to equalize the beam size as much as possible.



We used one-cycle injection (Kaji-san);
the injection is one time for each bucket.

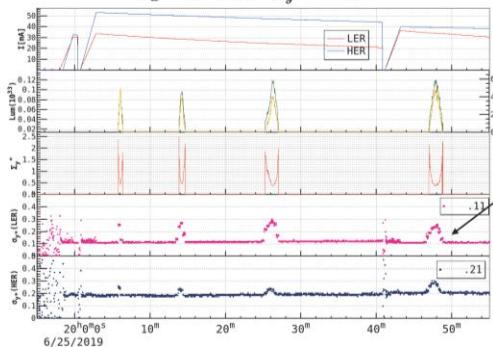
In case of 789 bunches, it takes about 2 min for 6.25 Hz rep. to fill all buckets.

The bunch current is adjusted by linac beam with RF-gun and FC STB to make a small bunch current.

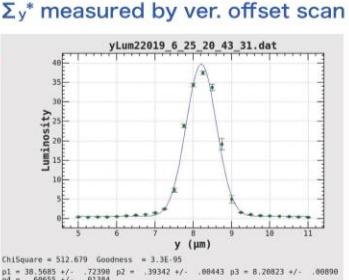
Beam profile is measured by LumiBelle2 (fast luminosity monitor) with ver. bump height or RF room phase scan.

The bunch current is less than 0.04 mA/bunch

$$\beta_x^* = 80 \text{ mm } \beta_y^* = 2 \text{ mm}$$



Beam-Beam blow-up was observed even though 0.04 mA/bunch.



Σy^* (BB scan)	Σy^* (Lum)	Σy^* (XRM)	σ_{y+}^* (XRM)	σ_{y-}^* (XRM)
0.393 μm	0.38 μm	0.378 μm	0.234 μm	0.297 μm

consistent with each other

Beam blowup is observed in LER, but it is not yet clear why it happens.

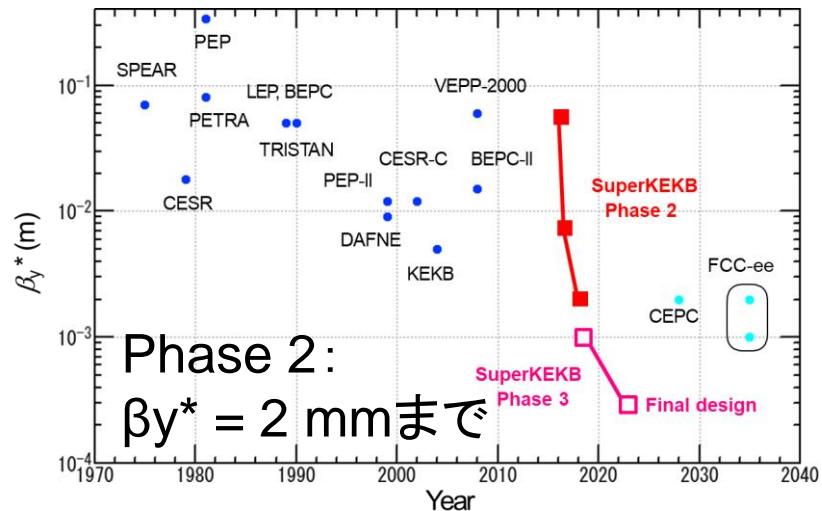
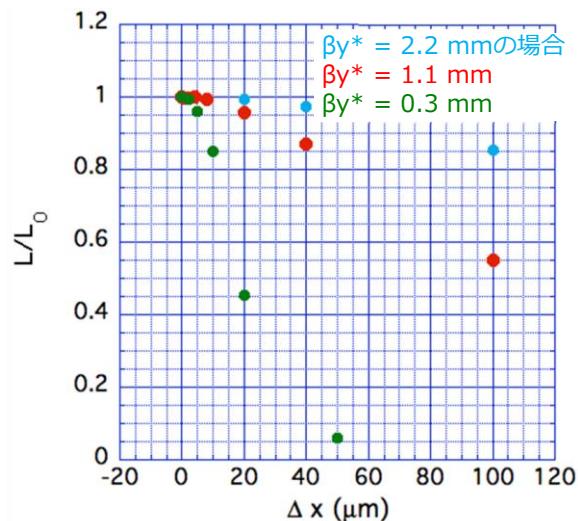
Back-up slide

SuperKEKBでのビーム衝突： KEKBと比べて20倍細いビーム

- ・ナノサイズビームを如何に衝突、維持するか：最も重要な課題の一つ

LERの比較	SuperKEKB	KEKB
β_x^* / β_y^*	32 mm / 0.27 mm	1200 mm / 5.9 mm
σ_x^* / σ_y^*	10 μm / 48 nm	147 μm / 940 nm

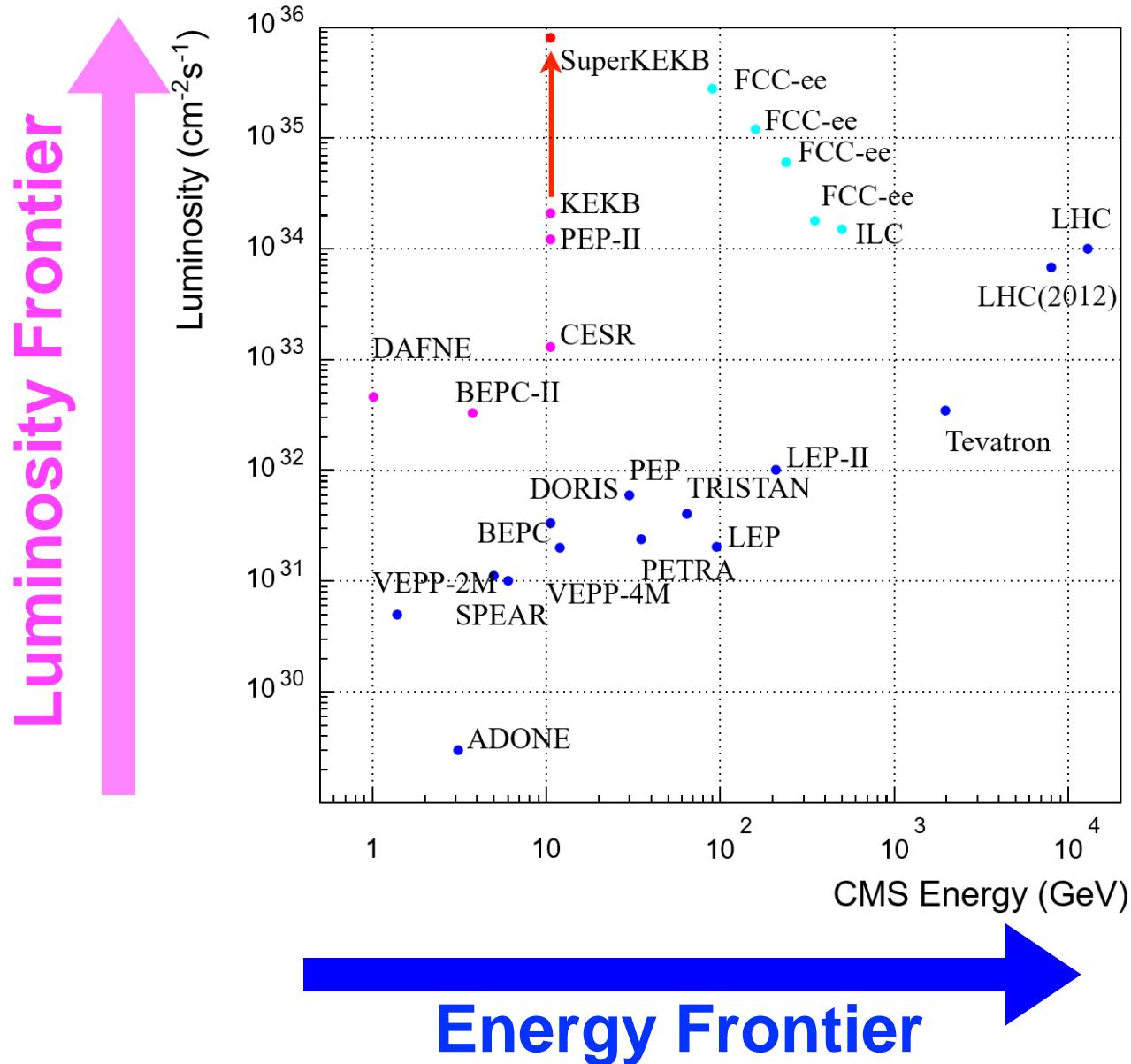
- ・水平方向に衝突ビームがずれた時のルミノシティの減少率（大見氏計算）



β_y^* を絞るほど、水平方向にずれた時のルミノシティ減少が厳しい

水平方向衝突軌道保持フィードバックシステムとして、PEP-IIで実績のあるデザリングシステムをSuperKEKBで初めて導入した。

ルミノシティ／エネルギー フロンティア



ルミノシティとは

単位時間あたりに生成される物理事象数

ルミノシティ

=

- ・出会いの頻度、輝度
- ・加速器の性能で決まる

反応断面積

×

- ・自然法則で決まる
- ・ドウシヨウモナイ

例： $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ の場合

反応断面積 10^{-33} cm^2

ルミノシティ $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

B・反B中間子が毎秒10ペア生成される

物理事象数を増やすにはルミノシティを上げるしかない。

ビーム・バンチの粒子数

$$L = \frac{N_+ N_- f}{4\pi \sigma_x^* \sigma_y^*} R_L$$

バンチ同士の衝突頻度

衝突点での水平・垂直ビームサイズ

幾何学的に決まる減衰率

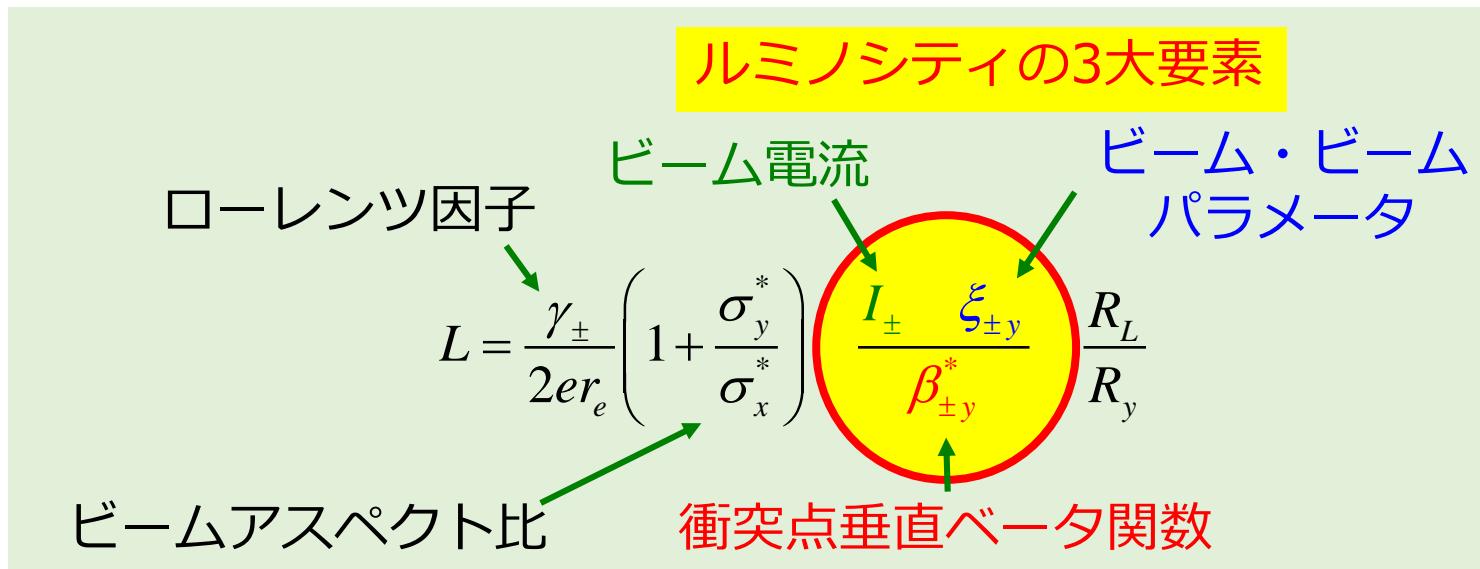
ルミノシティの式変形：ビーム・ビームパラメータ ξ の導入

- ・バンチ内粒子数を増やせば、ルミノシティは幾らでも上がるか？
- ・衝突ビームサイズを小さくすれば、…？
→否：衝突する互いのビームが及ぼしあう力でビームサイズ増大
- ・衝突の強さを表す無次元量：ビーム・ビームパラメータ ξ

$$\xi_{\pm y} = \frac{r_e}{2\pi\gamma_{\pm}} \frac{N_{\mp} \beta_y^*}{\sigma_y^* (\sigma_x^* + \sigma_y^*)} R_y$$

←いろいろ制限があって
あまり大きくできない

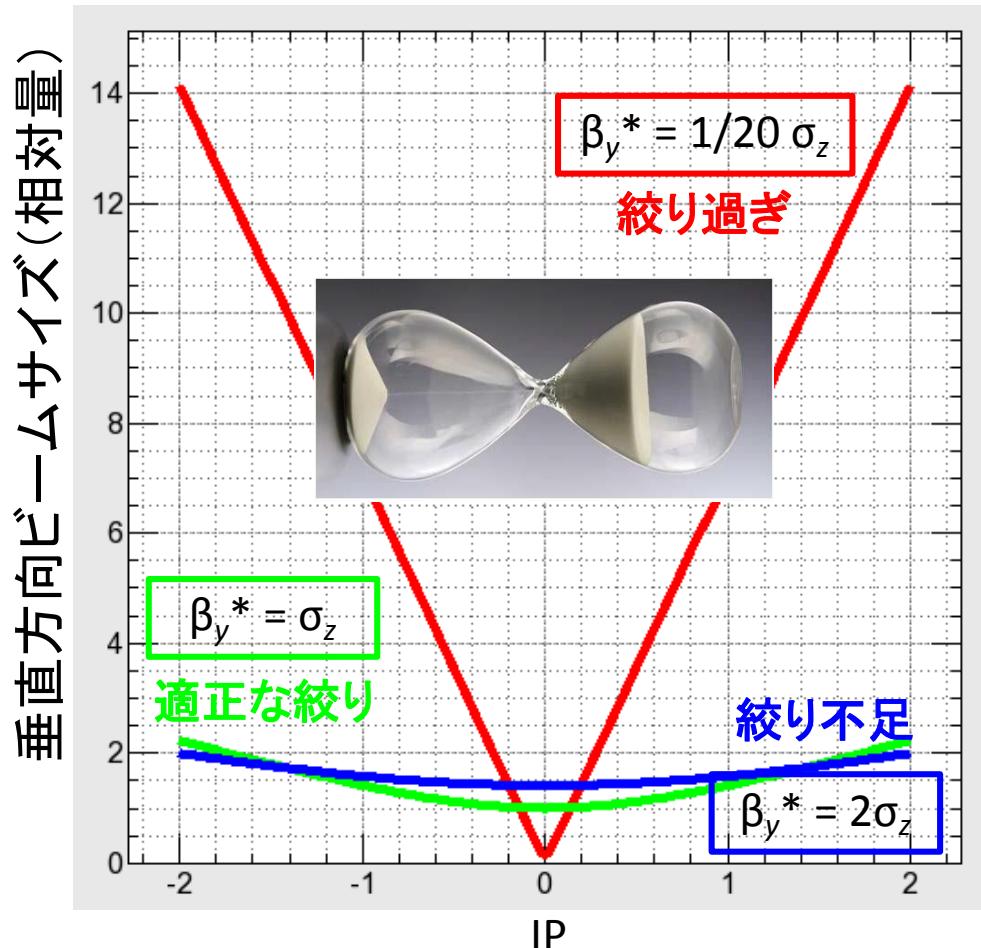
を導入してルミノシティを表現すると…



SuperKEKB: ベータを1/20絞り、ビーム電流を2倍に！

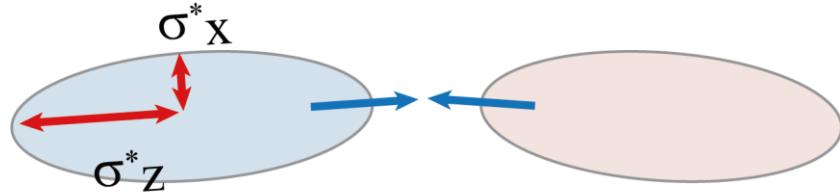
ベータを絞る制限：砂時計効果

- ・ルミノシティを上げるためにベータを絞りたい。どこまで絞れるか?
→絞りすぎると、衝突点(IP)の前後で砂時計の様にビームが太る。
→せいぜい、ビーム同士が重なる長さ程度しか絞れない。

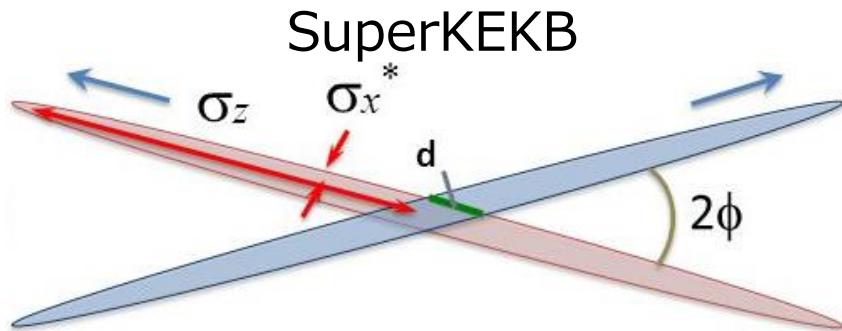


水平方向のビーム幅を絞る + 水平方向に大交差角を付ける
→ 砂時計効果を緩和できる (ナノビーム・スキーム)

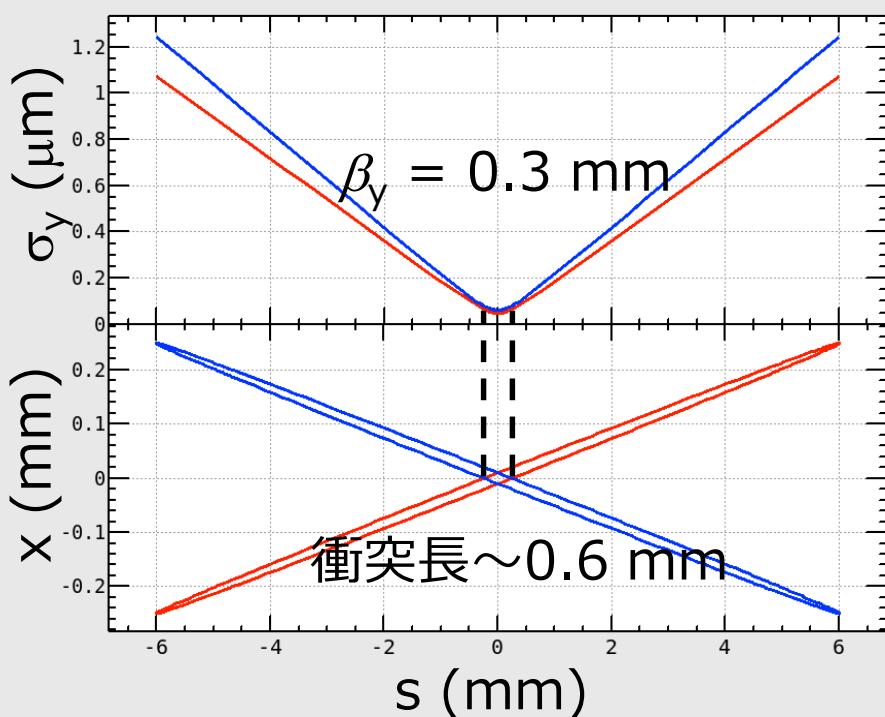
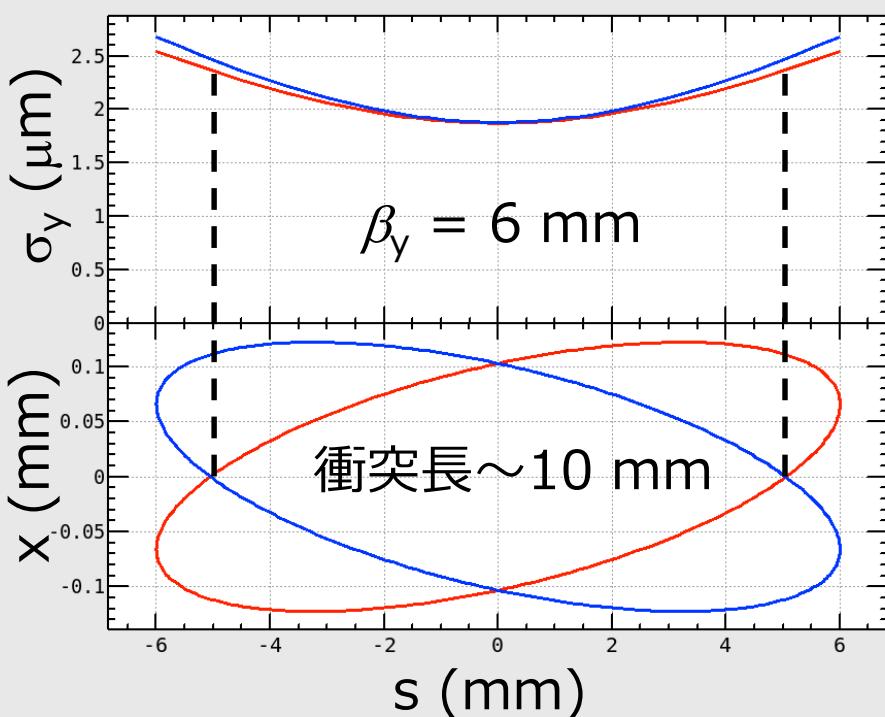
KEKB



衝突長 ~ バンチ長



衝突長 ≠ バンチ長



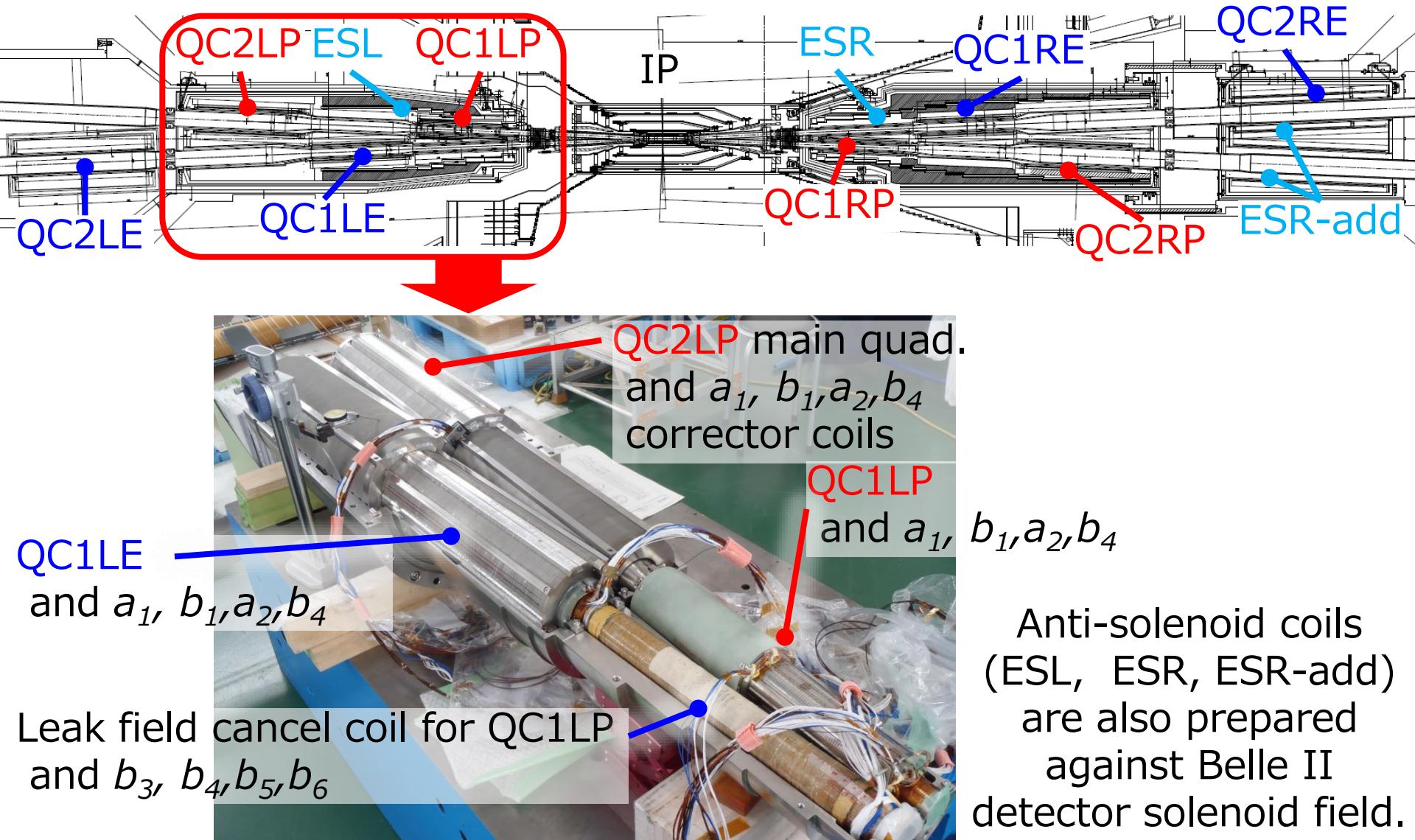
SuperKEKB加速器の設計パラメーター

パラメータ	KEKB		SuperKEKB		単位	
	LER(e^+)	HER(e^-)	LER	HER		
ビームエネルギー	E_b	3.5	8	4	7	GeV
半交差角	Φ	11		41.5		mrad
水平エミッタنس	ε_x	18	24	3.2	4.6	nm
エミッタنس比($\varepsilon_y/\varepsilon_x$)	κ	0.88	0.66	0.27	0.25	%
衝突点での β 関数	β_x/β_y	1200/5.9		32/0.27	25/0.30	mm
ビーム電流	I_b	1.64	1.19	3.6	2.6	A
ビーム・ビーム パラメーター	ξ_y	0.129	0.090	0.088	0.081	
ルミノシティ	L	2.1×10^{34}		8×10^{35}		$\text{cm}^{-2}\text{s}^{-1}$

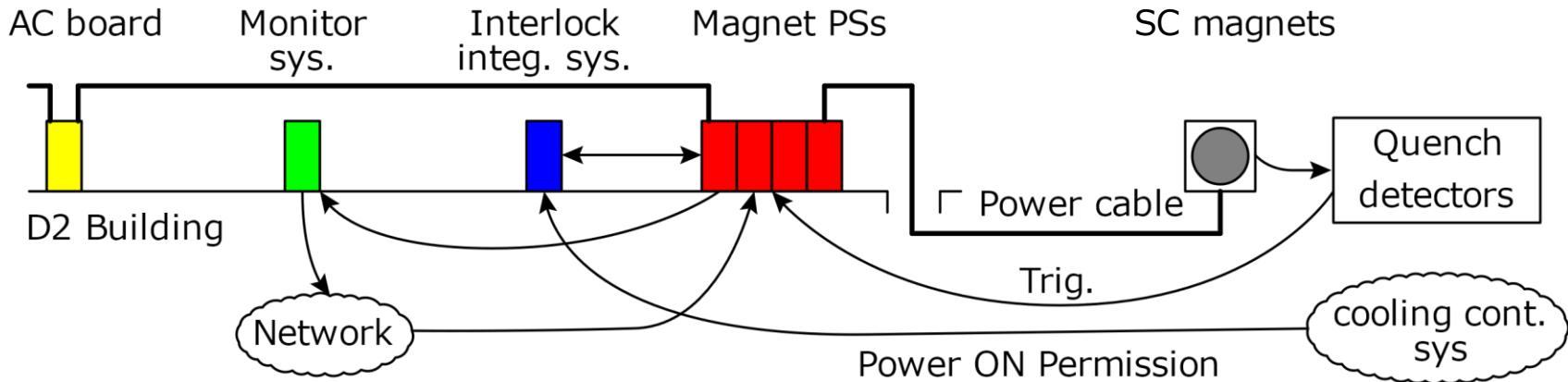
- ・交差角を大きく、水平ベータ関数を小さくして砂時計効果を緩和
- ・垂直 β 関数を1/20に絞って、ビーム電流を2倍
- ・まずはKEKBのデザイン値 10^{34} を、→40倍のルミノシティを目指す！

Final focus superconducting magnets around IP

Completely redesigned for SuperKEKB



System overview



System consist of

- SC magnets, quench detection and cooling control system,
- Magnet power supplies,
- AC power distribution board,
- Interlock integration and distribution system,
- Current monitor system and
- Remote control system.

The system is integrated with other systems.

Installed power supplies



List of SC magnet power supplies

Rated output	# of PSs	Load
2 kA, 15 V	8	Main quad.
± 70 A, ± 10 V	43 (+2 spare)	correction coil
410 A, 15+15 V	1	ESL
455 A, 15+30 V	1	ESR1
155 A, 15 V	1	ESR23

Special power supplies for ...

- Main quadrupole magnet:
2 ppm ultra high stability and 1 ppm low ripple.
- Correction coils:
5 ppm high stability with low cost.
- Anti-solenoid:
ESL and ESR1 has a middle tap. Current for each two sections divided by the tap should be controlled independently.

Development of main quad. power supply

Aiming spec.

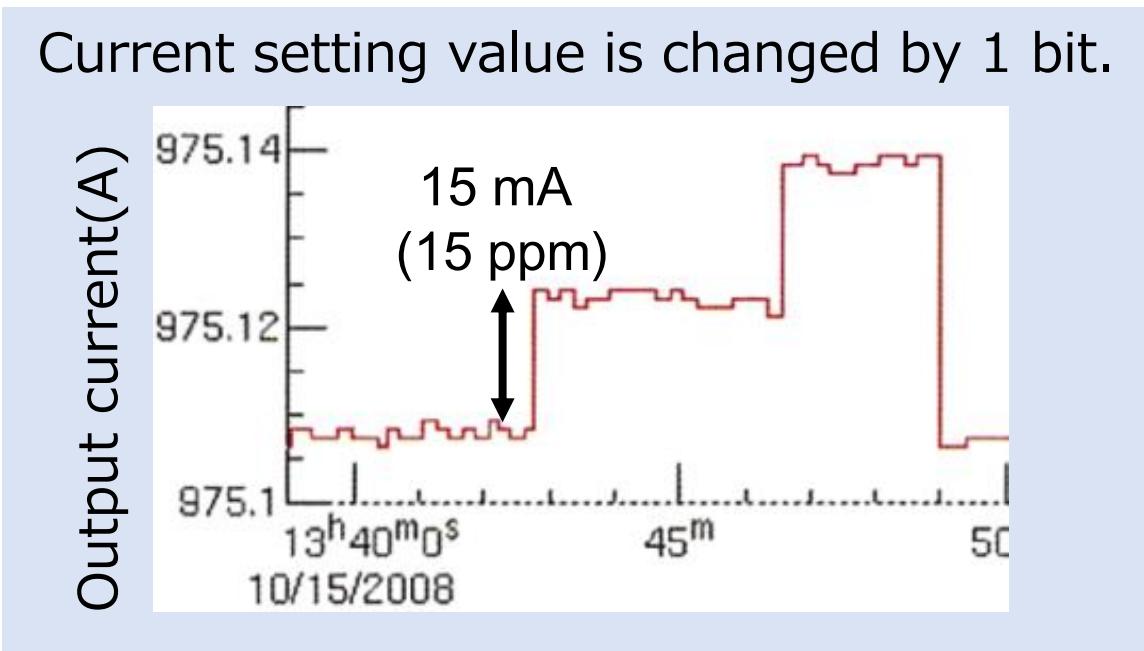
Rated output	DC 2 kA, 15 V
Current setting resolution	< 0.1 ppm
Current stability	< 2 ppm/8 hrs.
Current ripple (< 10kHz)	< 1 ppm (rms)
Current noise (> 10kHz)	< 1 ppm (0-peak)

R&D items

-
1. High current setting resolution
 2. High stability
 3. low ripple
-

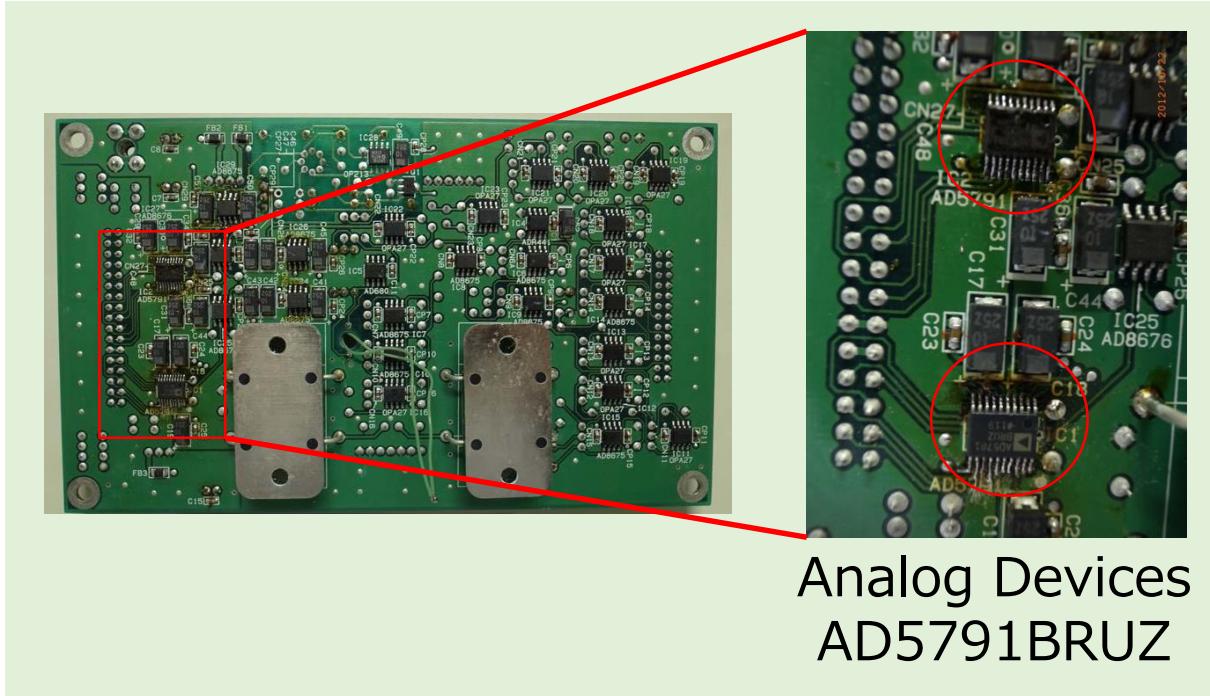
R&D item 1: High current setting resolution

- Example of step response: 16-bit KEKB PS (1 kA, 700 V)



- Aiming 2 ppm stability, 0.1 ppm of setting resolution is required.
- 24-bit control board is developed using two 20-bit DACs. Analog Devices AD5791 is suitable due to its monotonicity spec.

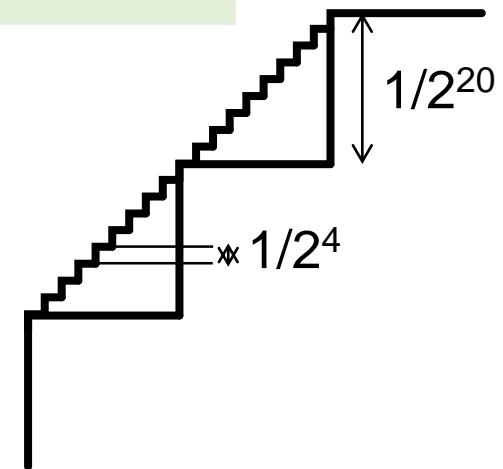
R&D item 1: Developed 24-bit board



Setting value
in 20-bits (major)

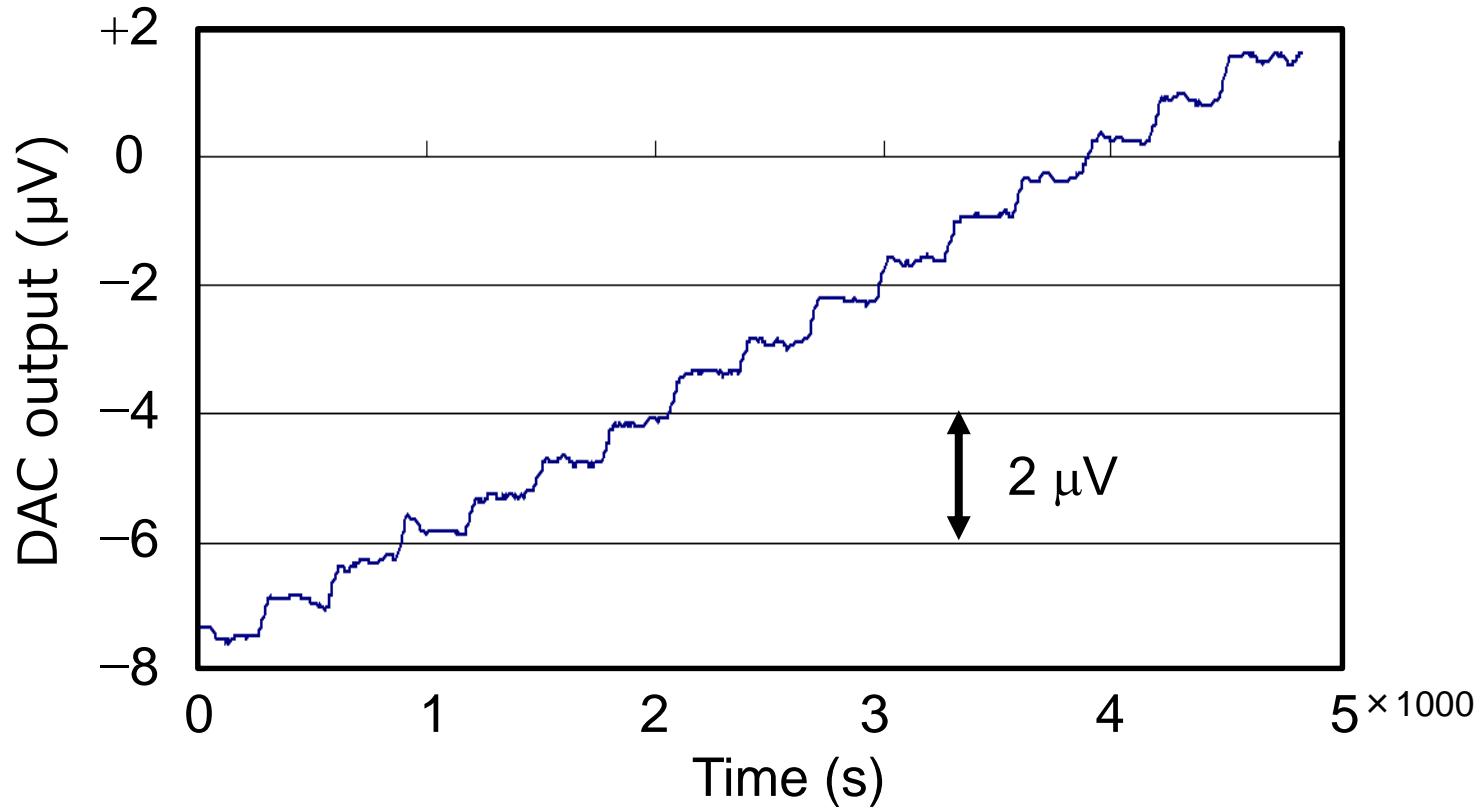


Setting value
in 4-bits (minor)



R&D item 1: Test result of 24-bit board

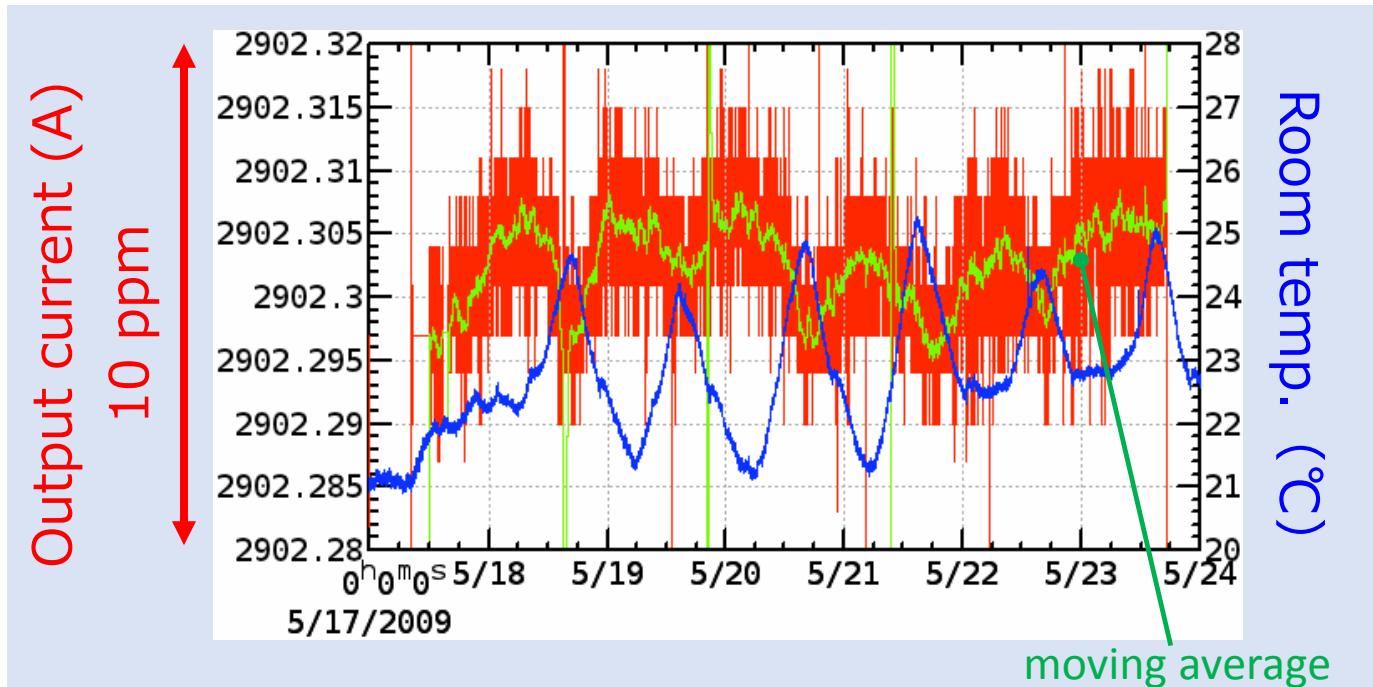
- Increasing DAC input digital value by 1 LSB, DAC output voltage is measured by Keithley 2002 DMM.



Monotonic 1 LSB response,
that is corresponds to $0.6 \mu\text{V}/10 \text{ V F.S.}$, is obtained.

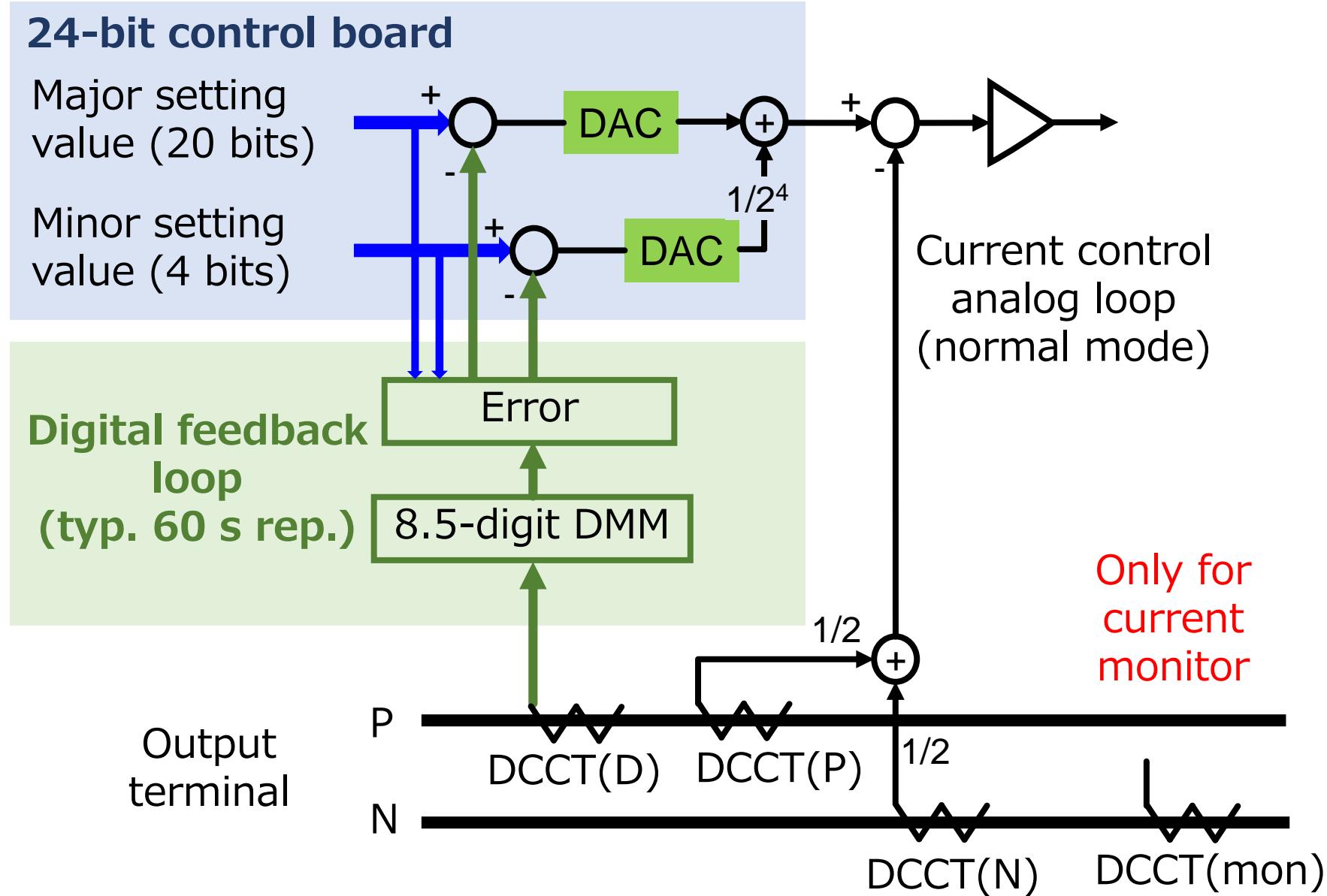
R&D item 2: High stability

- Example of stability: KEKB SC Main Q. PS (4 kA, 15 V)



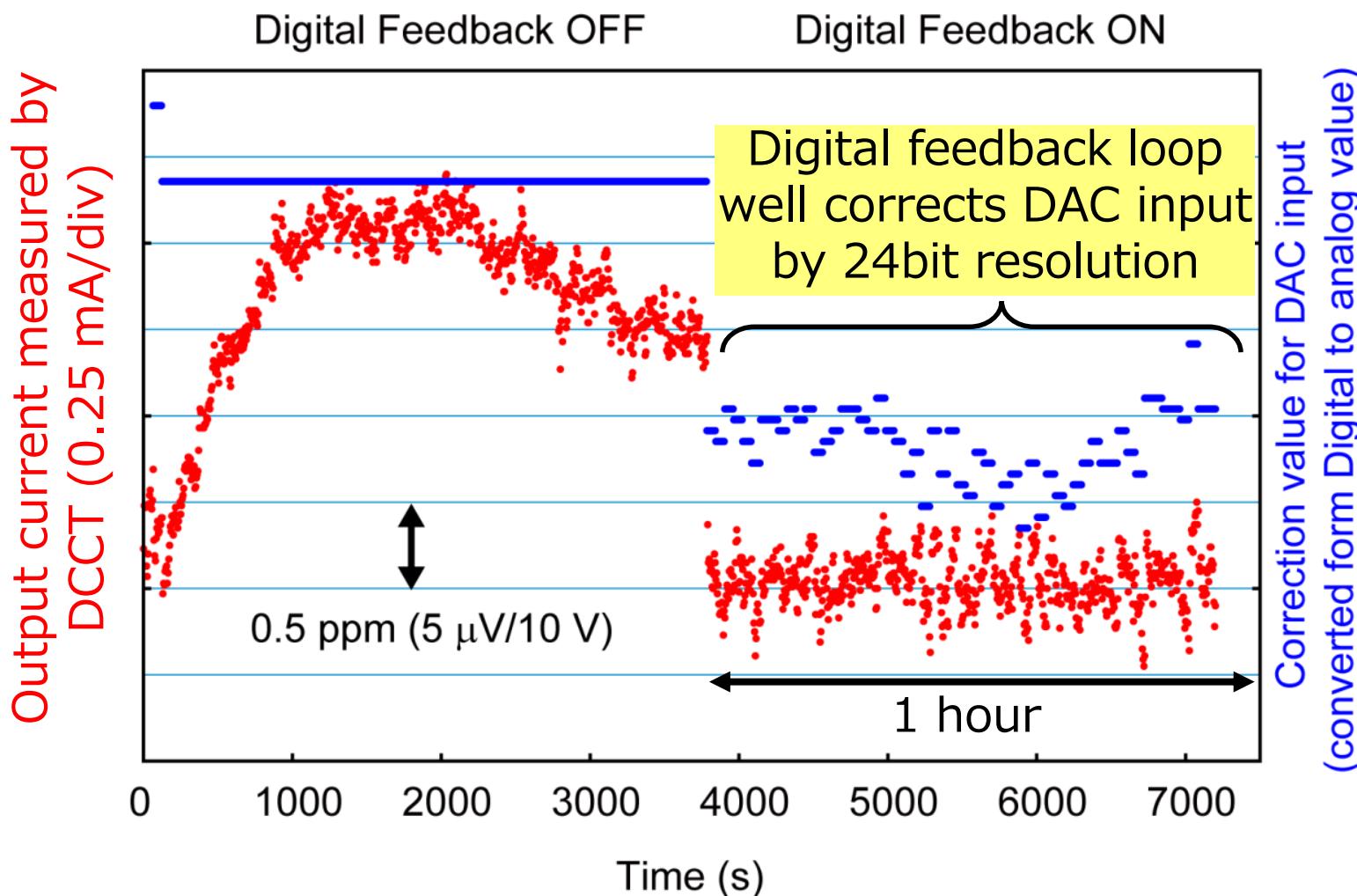
- Typ. stability is 10 ppm (peak to peak)/week.
- Resulting in 1 ppm/K of temp. coeff., although a temp. controlled box and low temp. coeff. parts were used.
- In order to suppress such a fluctuation in the output current, following digital feedback control is developed.

R&D item 2: Digital feedback control



R&D item 2: Test result of the digital feedback loop

- Performed by using a medium-class power supply (15 V, 500 A).



1 ppm / h stability with low $\sigma = 0.16$ ppm

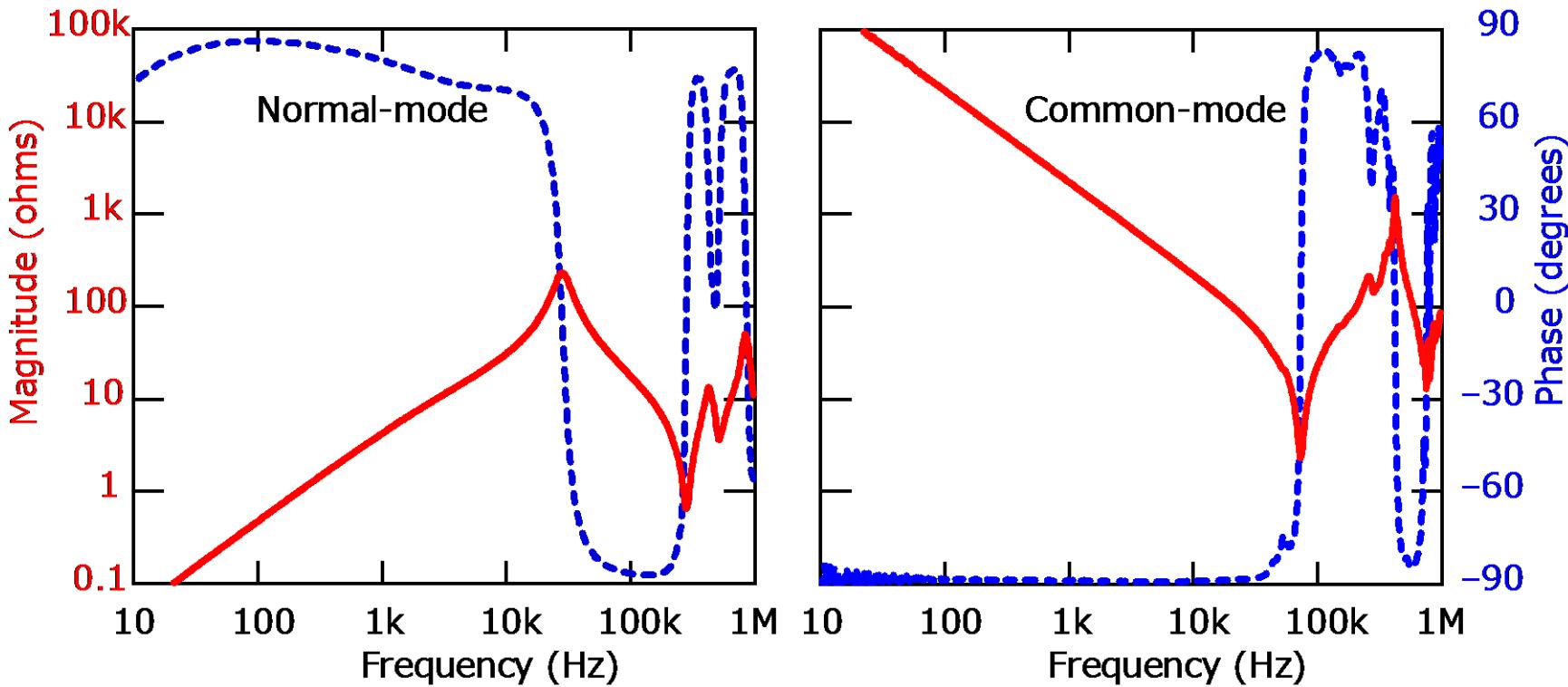
For high precision current measurement

- Low temp. coefficients equipment.
0.3 ppm/K (Keithley 2002), 1.5 ppm/K (TOPACC DCCT)
- Suitable grounding is a key point:
100 GΩ input impedance (DMM), 0.1 ppm = 10 μV



R&D item 3: Low ripple for low impedance load

- Example of the load impedance (QC1LP)

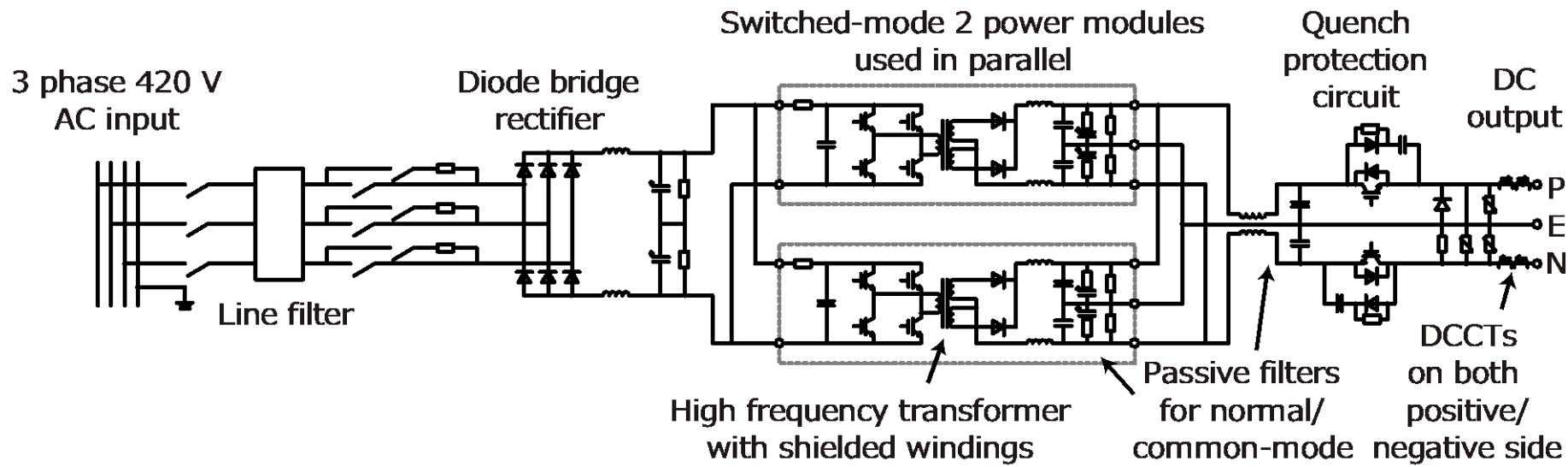


- Normal-mode impedance < several tens of Ω in the low freq. (<10 kHz) range: Possibility of large current ripple.
- Common-mode impedance < several tens of Ω in the high freq. (>10 kHz) range: Possibility of large switching noise.
- Symmetrical design of circuit is essential to reduce ripple and noise.

R&D item 3: Symmetric circuit design

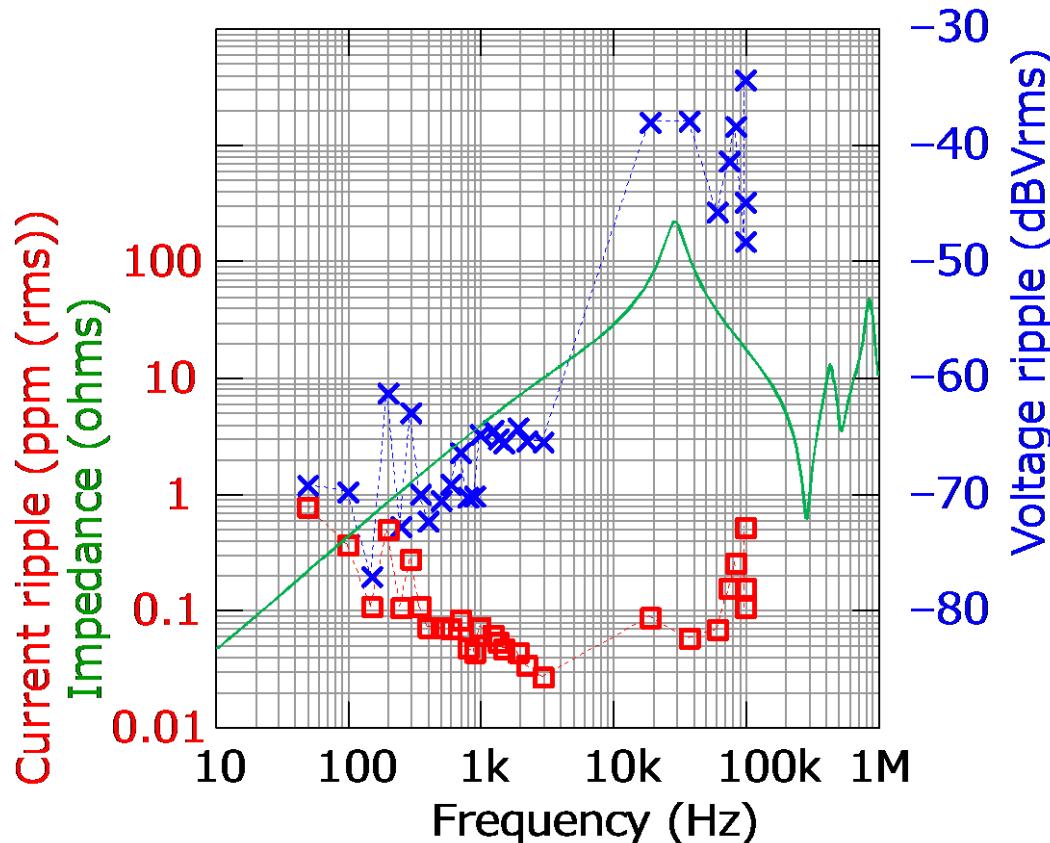


- ✓ DCCTs on both output terminals.
- ✓ Symmetric circuit structure with respect to ground.
- ✓ Shielded high-frequency transformer



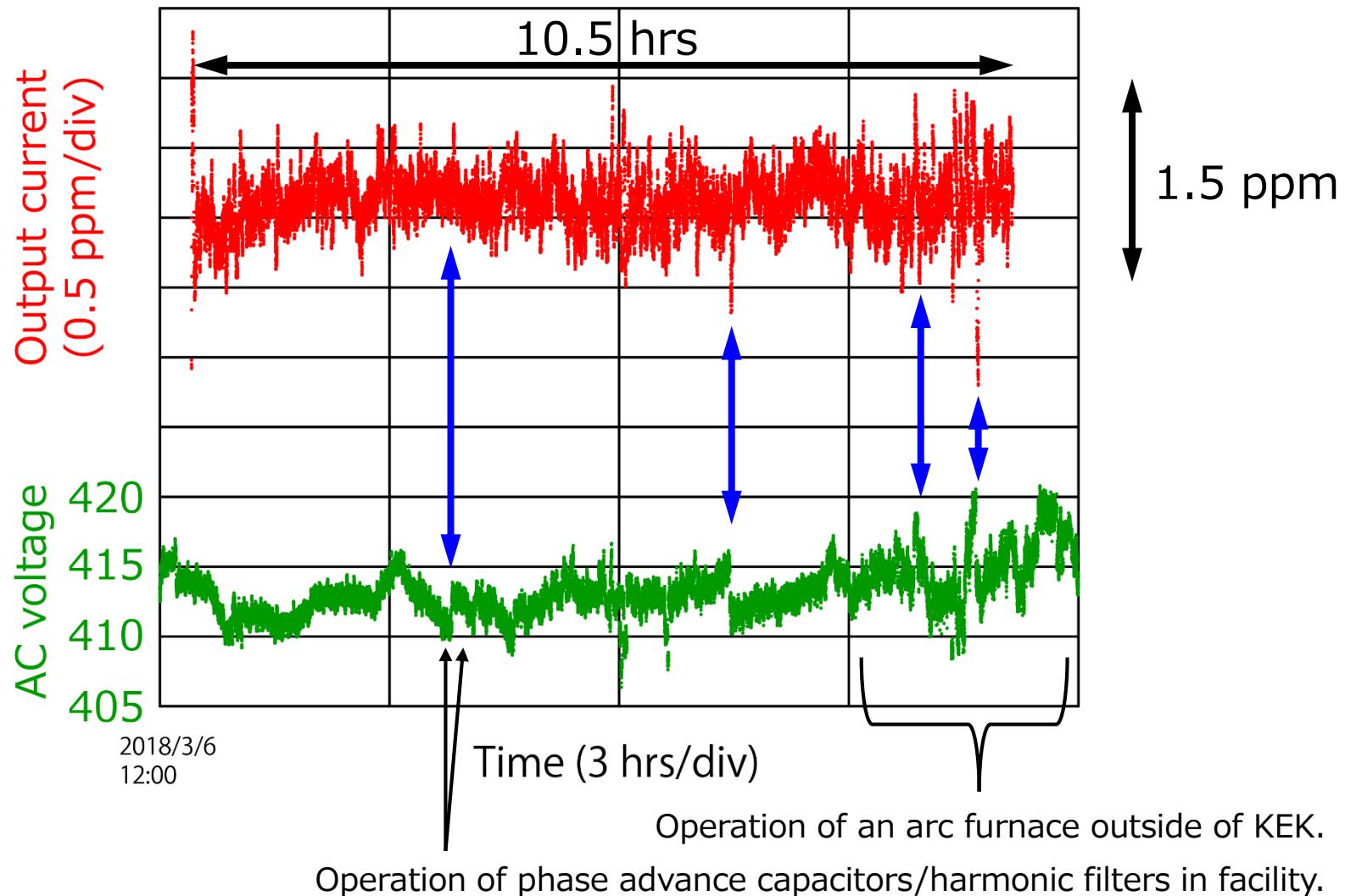
Performance test results 1: QC1LP current ripple

- Dividing the measured voltage ripple by the magnitude of the load impedance, the current ripple is obtained.



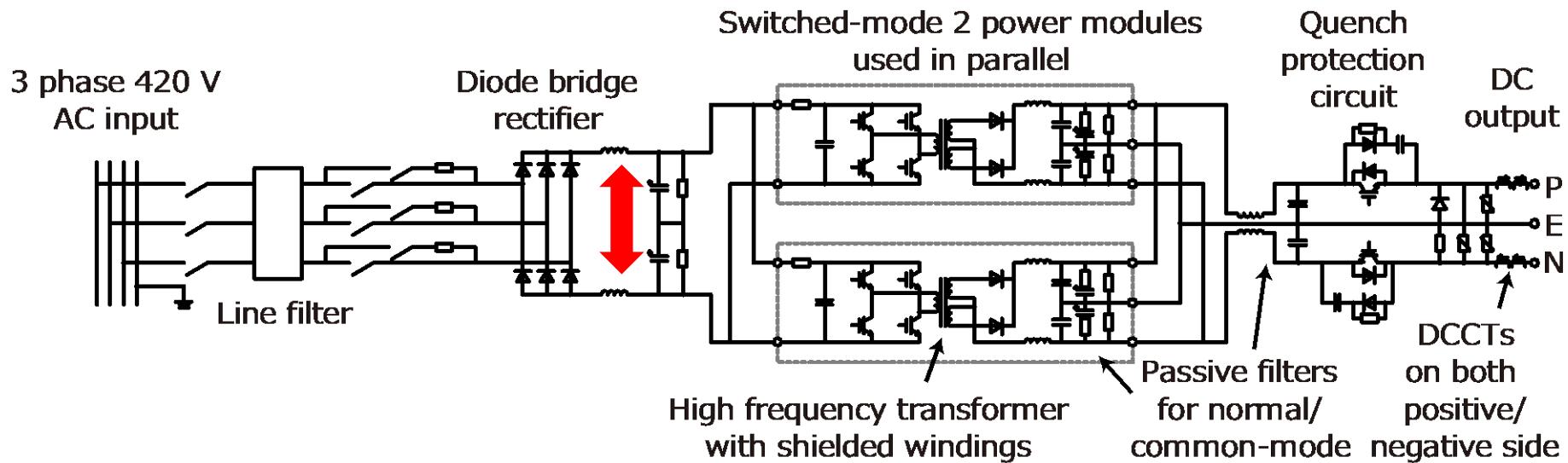
- Less than 1 ppm of normal-mode ripple and noise.
- Common-mode components are also measured: 0.5 ppm@57 kHz in the maximum.

Performance test results 2: QC2RE stability



- $\sim 1.5 \text{ ppm} / 10.5 \text{ hrs}$ of current stability is obtained.
- The rapid change in AC voltage leads to makes stability worse.

Feedback control of the DC voltage for chopper



Full power test with actual load

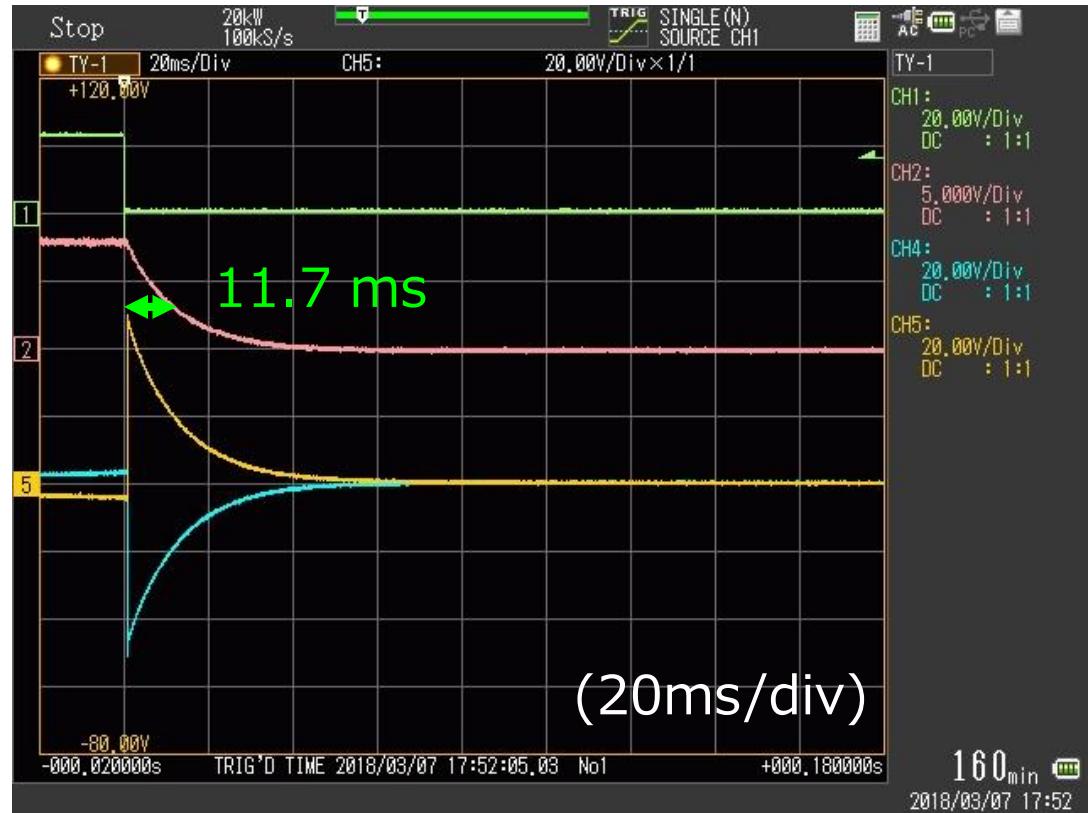
- Interlock test: ex. quench protection trip test result (QC1LP)

Trig. from Q.D.

Output current 1.6 kA ↑
(1kA/div)

Output voltage 100 V ↓
(20V/div)

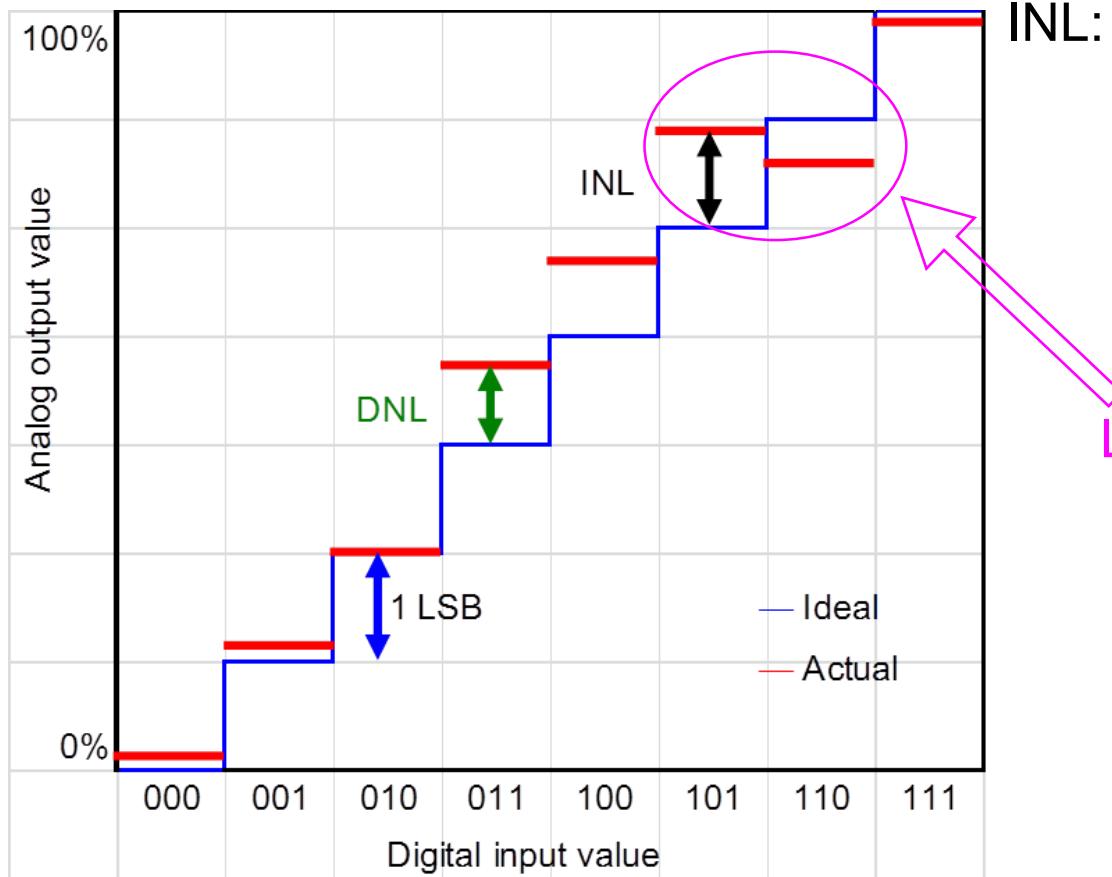
V_{PE}
 V_{NE}



- Good agreement with estimations
Decay time constant : $14.2 \text{ ms} = 0.9 \text{ mH} / (3.5 \text{ m}\Omega + 60 \text{ m}\Omega)$
magnet cable + protection R
Induced voltage $V_{PE}-V_{NE}$: $96 \text{ V} = 1.6 \text{ kA} \times 60 \text{ m}\Omega$

Non linearity and monotonicity

LSB: least significant bit
DNL: differential non linearity
INL: integral non linearity

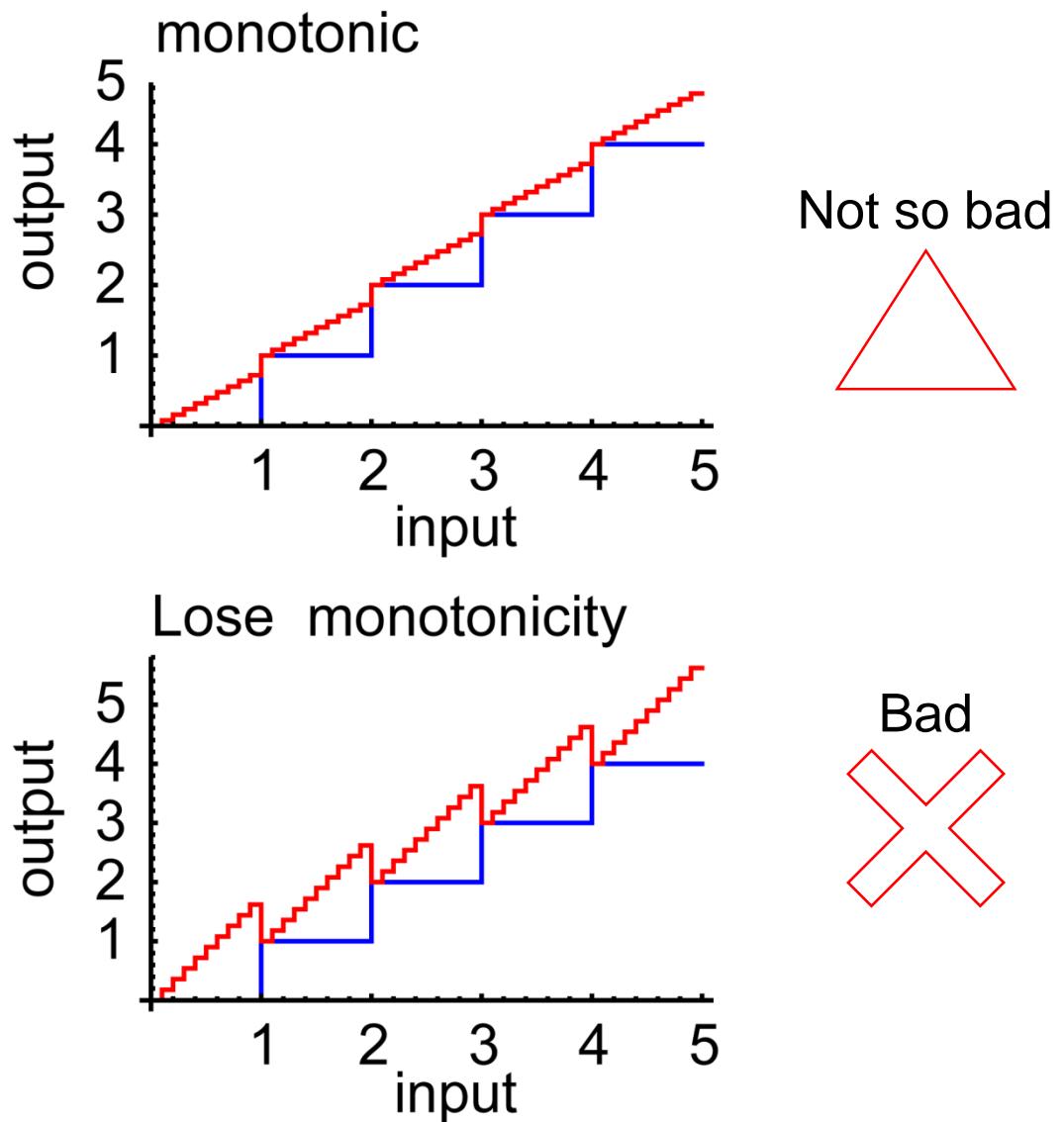
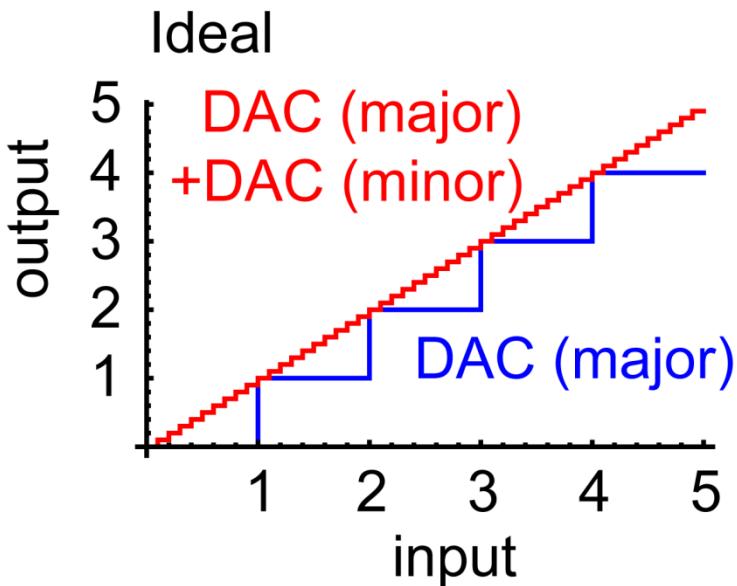


AD7846K (16-bit): DNL ± 0.5 LSB max
INL ± 2 LSB

AD5791B (20-bit): DNL ± 0.75 LSB typ. (test result: $<\pm 0.1$ LSB)
INL ± 0.5 LSB typ. (test result: $-0.2 \sim +0.6$ LSB)

Why sixteen DAC's 24-bit system?

Care must be taken to the monotonicity of two DAC's 24-bit system

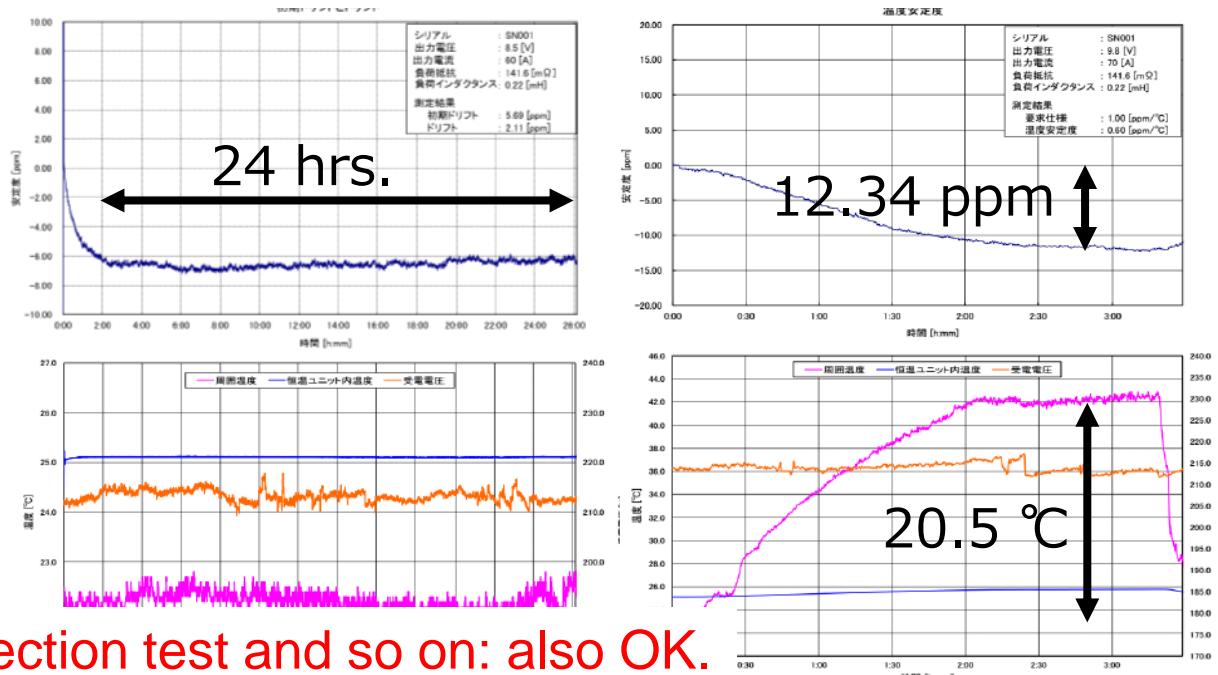


SC corrector power supply

45 of SC corrector power supplies was fabricated.

Rated output	DC \pm 70 A, 10 V
Current setting resolution	< 1 ppm
Current stability	< 5 ppm/8 hrs.
Current ripple (< 10kHz)	< 5 ppm (rms)
Current noise (> 10kHz)	< 5 ppm (0-peak)

Test results: Stability 2.1 ppm/24 hrs. with temp. coeff. of 0.6 ppm/ $^{\circ}$ C



Ripple, noise, quench protection test and so on: also OK.

主要構成要素の温度係数と恒温槽温度変化

主要構成要素の温度係数（仕様値）

- 0.125 ppm/K (AD5791 DAC with Buffer amps.)
- 0.5 ppm/K (TOPACC optionalの場合：標準は1.5 ppm/K)
- 0.3 ppm/K (Keithley 2002)

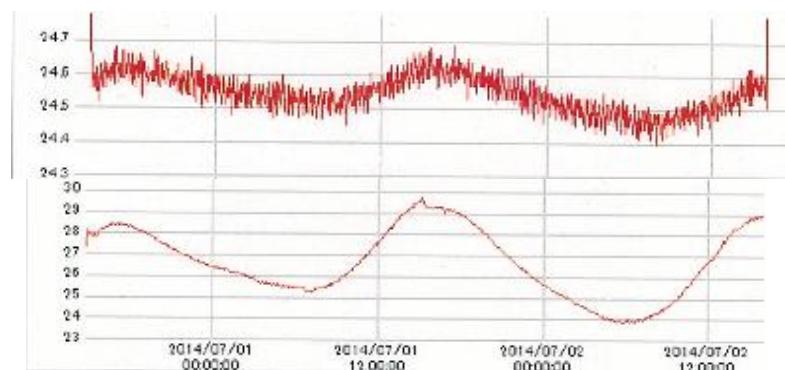
恒温槽 (espec LU-123) の温度変化（2日間実測）

- ・周囲温度変化 5.5 °Cに対して、
恒温槽内温度変化 0.2 °C



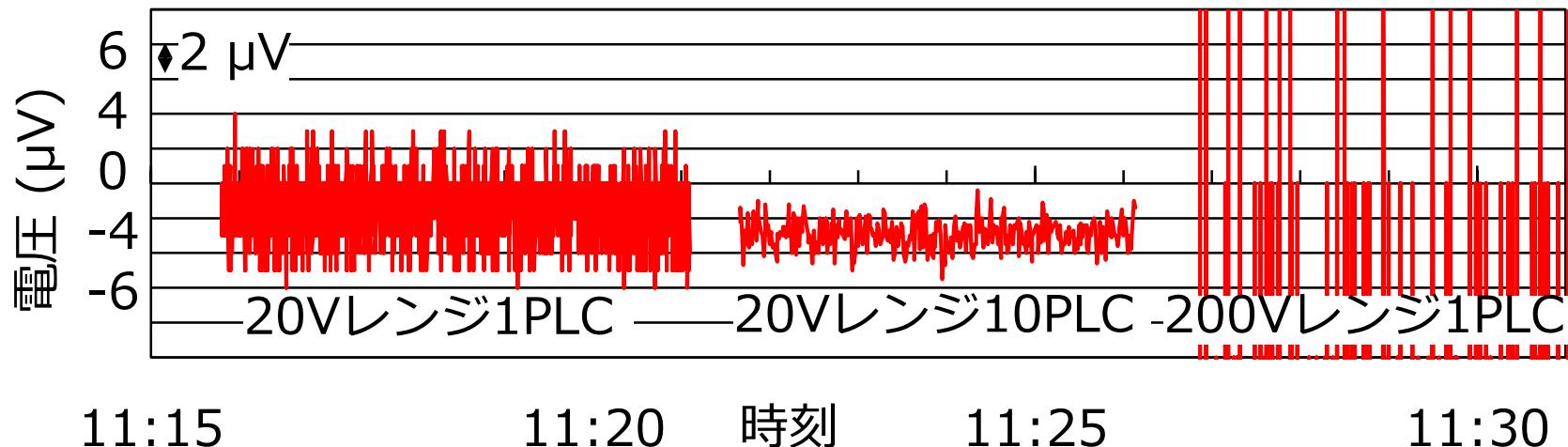
デジタルレギュレーションの温度係数の見積

- ・ $(0.5+0.3)\times0.2=0.16$ ppm程度
- ・ $(1.5+0.3)\times0.2=0.36$ ppm程度



DMM (keithley2002) のノイズ幅 (測定値)

- ・入力を短絡し、設定を変えて調べた。(ゼロ調整は未実施)



- ・まとめ

設定		測定結果(μV)		仕様
レンジ	PLC	標準偏差	$\sigma \times 2\sqrt{2}$	(μVrms)
20	10	0.8	2.3	0.6
20	1	1.7	4.7	1.6
200	10	17	47	20
200	1	37	105	50

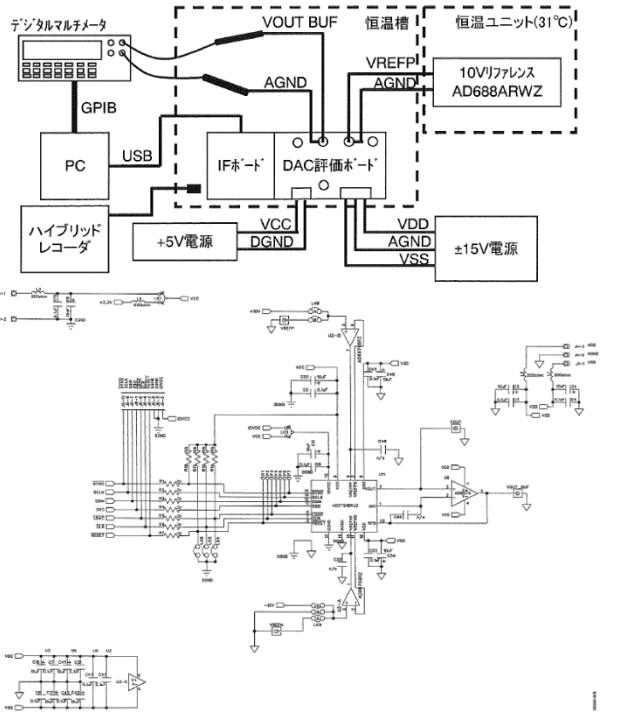
仕様とよく合っている。

$$10 \text{ V} \times 0.1 \text{ ppm} = 1 \mu\text{V}$$

20Vレンジ、10PLCなら、0.1 ppm以下の制御に使える

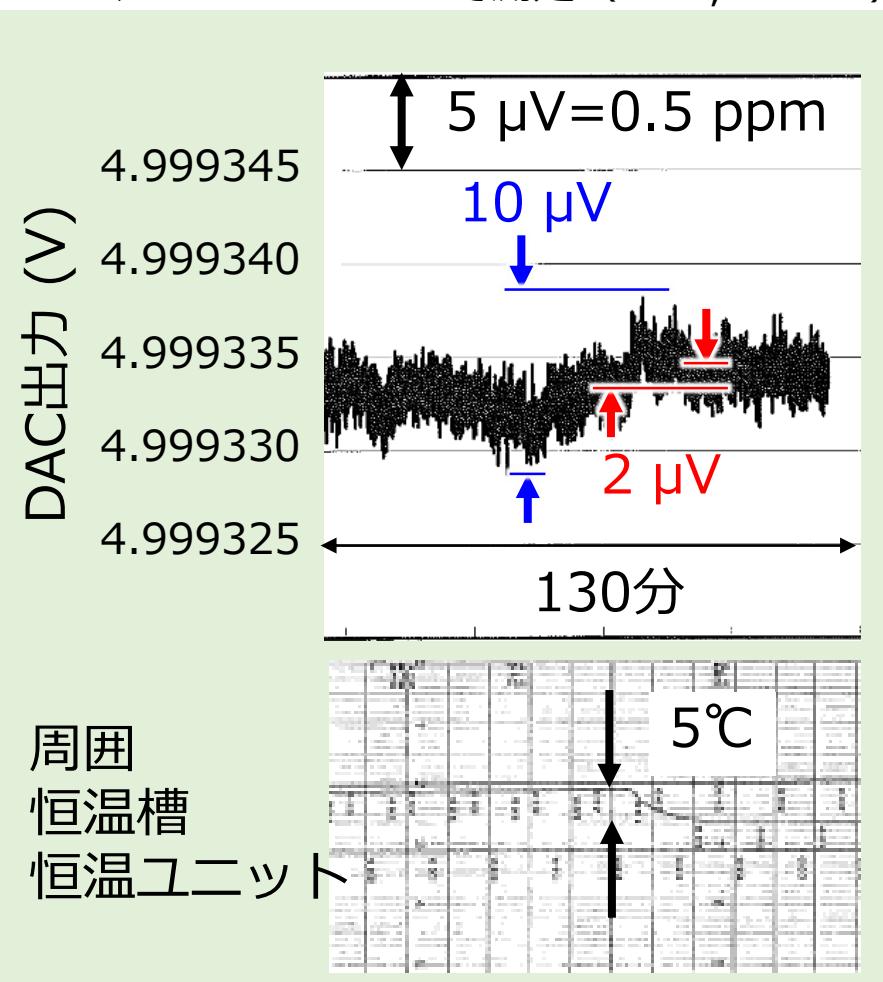
DAC出力の温度係数、変動幅の測定

- DAC AD5791 + バッファアンプ AD8675, 8676 : DMMで測定 (20 V, 10PLC)



AD5791	$0.05 \mu\text{V}/^\circ\text{C}$
AD8676	$0.6 \mu\text{V}/^\circ\text{C}$
AD8675	$0.6 \mu\text{V}/^\circ\text{C}$

$$1.25 \mu\text{V}/^\circ\text{C} \rightarrow 0.125 \text{ ppm}/^\circ\text{C}$$



温度係数 : $0.04 \text{ ppm}/^\circ\text{C}$
ゆらぎ幅 : $1 \text{ ppm}/2\text{時間}$

DCCT・DMMの測定誤差、温度係数（仕様値）

DCCT: Hitec社 TOPACC (10 Vフルスケール、帯域 : 500 kHz)

- ・リップル : 0.3 ppm (<100 Hz), 1.5 ppm (<10 kHz)
- ・温度係数 : 0.5 ppm/K (TOPACC optionalの場合 : 標準は1.5 ppm/K)

DMM: Keithley 2002 (10 Vに対する値。条件 : 20V レンジ、 10 PLC)

- ・ノイズ幅 : 0.06 ppm (rms)
- ・温度係数 : 0.3 ppm/K