

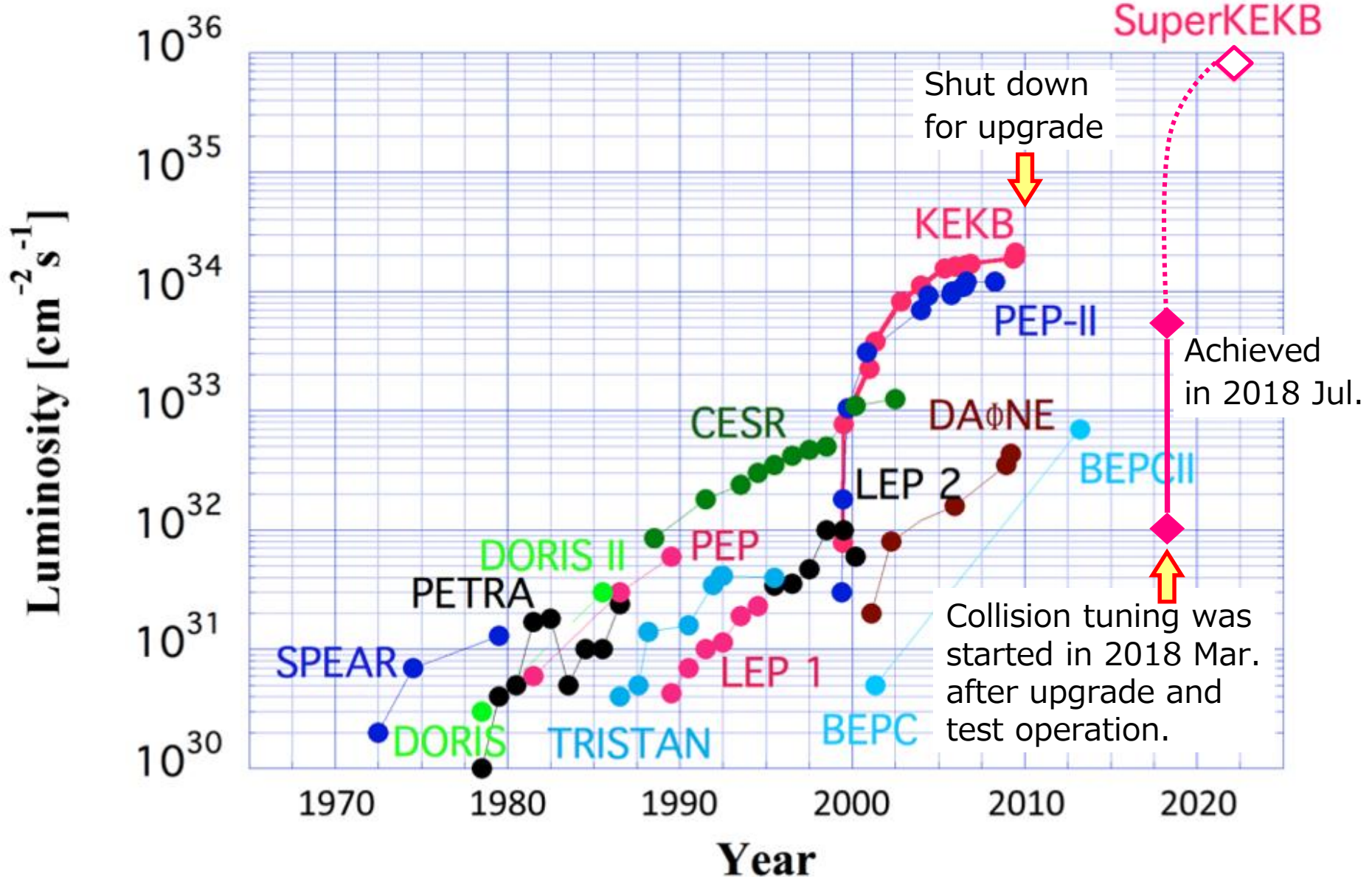
High-stability Power Supply System For SuperKEKB Final Focus Superconducting Magnets

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KEK

6th Power Converters for Particle Accelerators (POCPA)

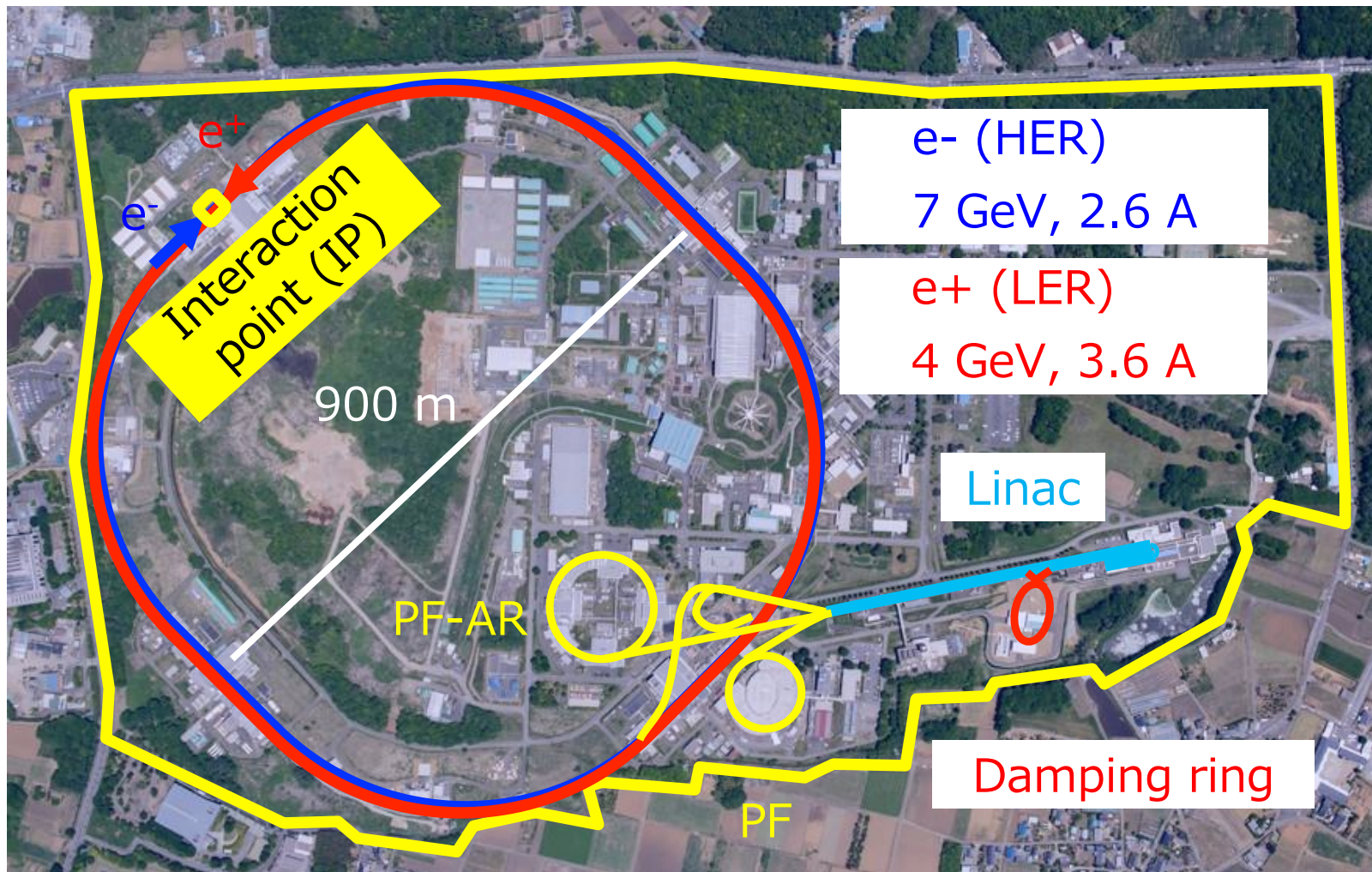
2019/Sep/26

History of peak luminosity (e⁺/e⁻ colliders)



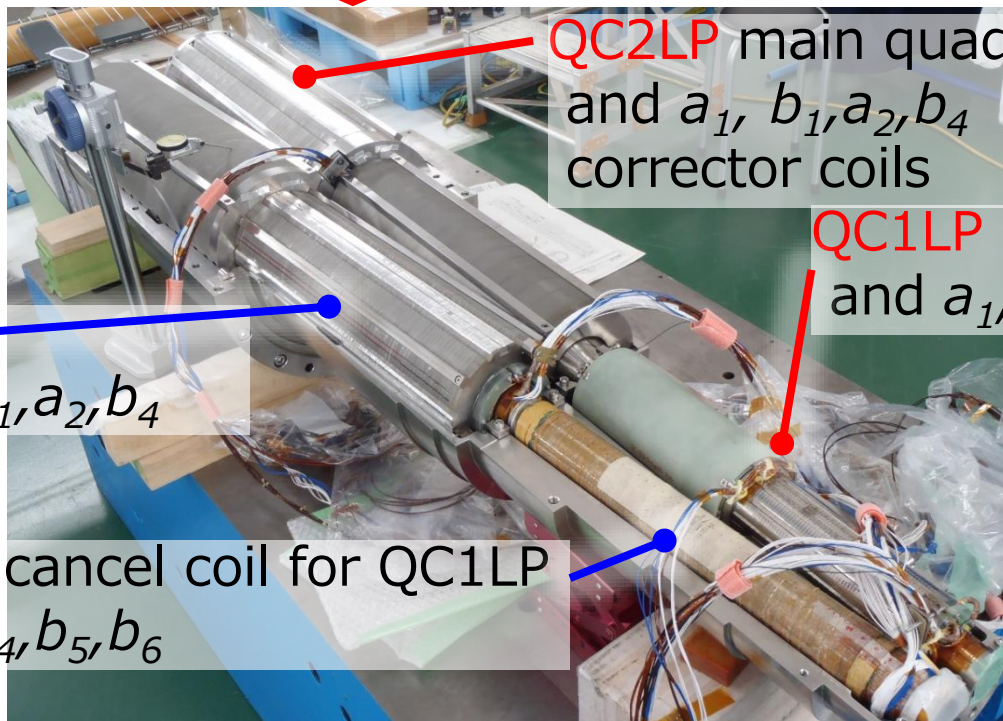
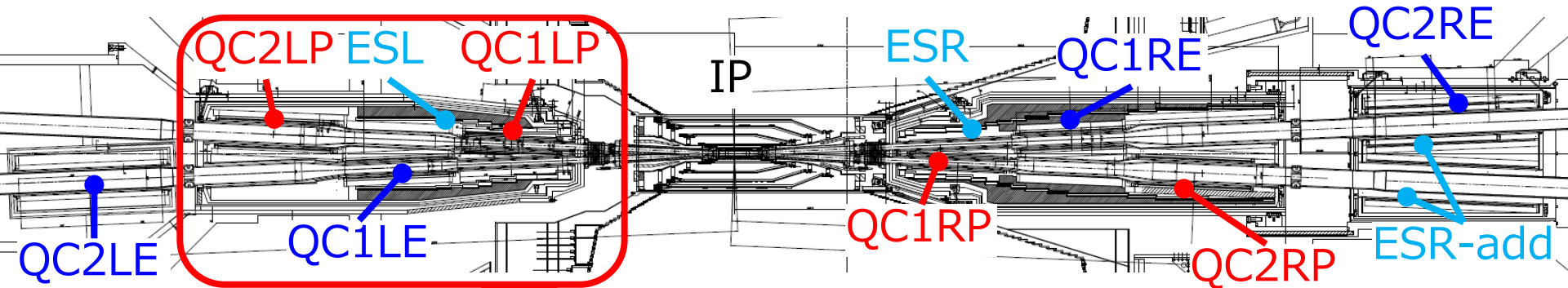
What is the SuperKEKB

- KEKB: The world's highest luminosity electron-positron collider.
- SuperKEKB: aiming 40 times higher luminosity.



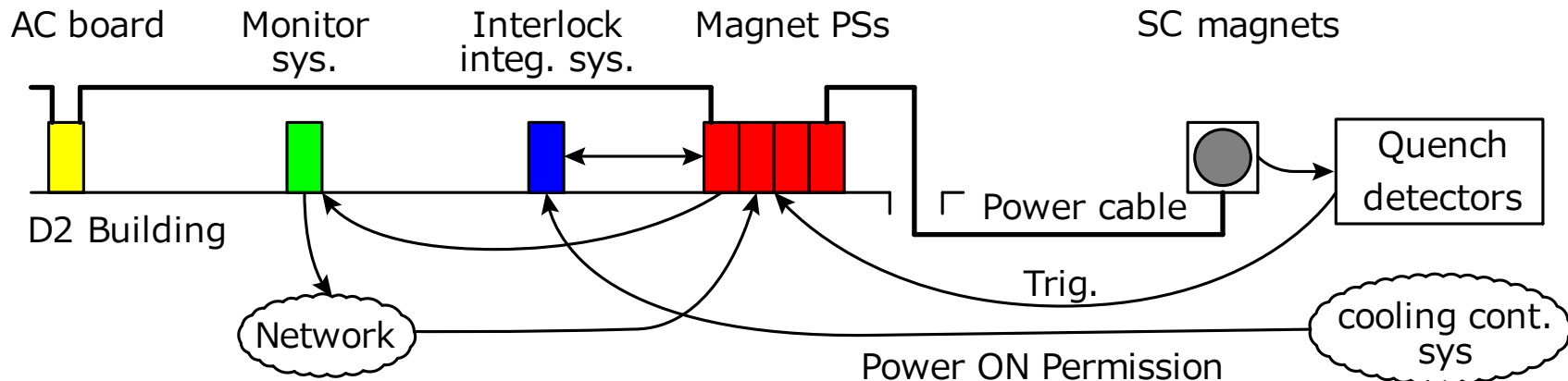
Final focus superconducting magnets around IP

Completely redesigned for SuperKEKB



Anti-solenoid coils (ESL, ESR, ESR-add) are also prepared against Belle II detector solenoid field.

System overview



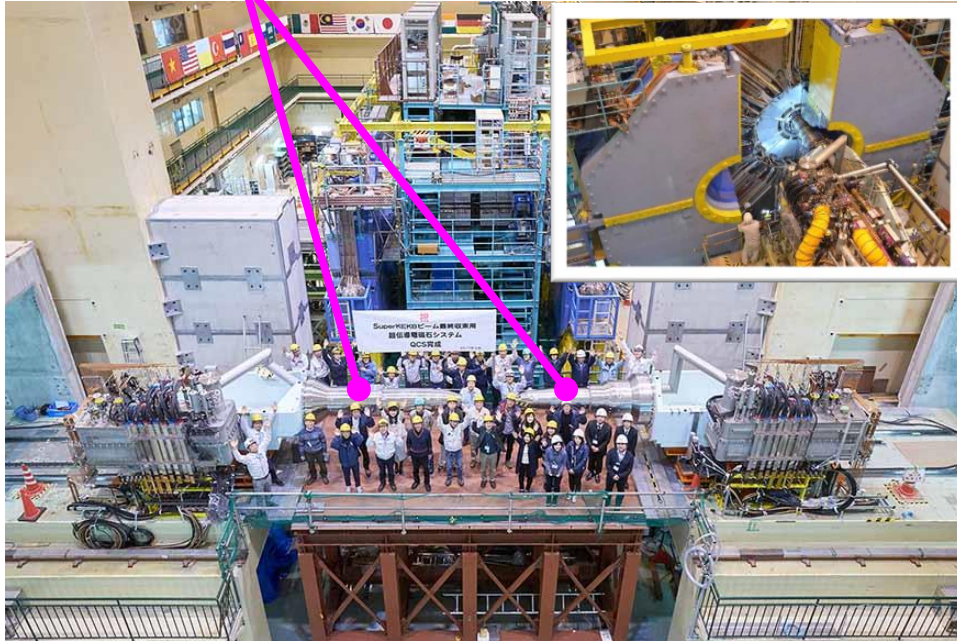
System consist of

- 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.**

Cabling works

SC magnets and Belle II at IP



Under the bridge, they were connected with power cables.

To reach the SC magnets, water cooled hollow conductors are installed through a concrete bridge.



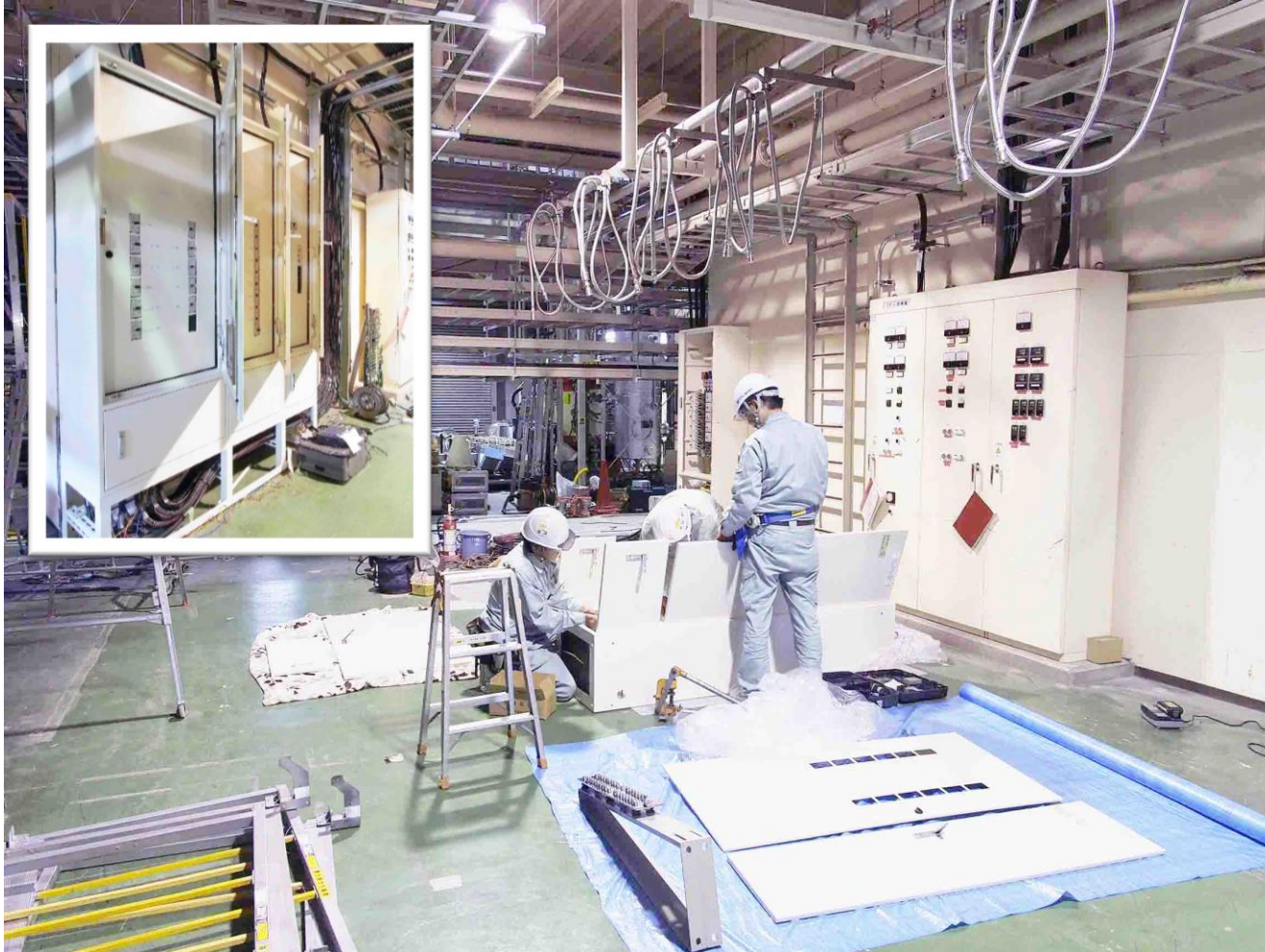
To much cabling works was carried out

The power cables come from IP to the D2 power supply building.



AC power distribution station

AC power is distributed by newly installed board, where some breakers or transformer in the primary line were also renewed.



Interlock integration/distribution system and current monitor system



Yokogawa FA-M3 PLC
Keithley 2002 DMM
with 7001 switch sys.
Espec SU-642

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)

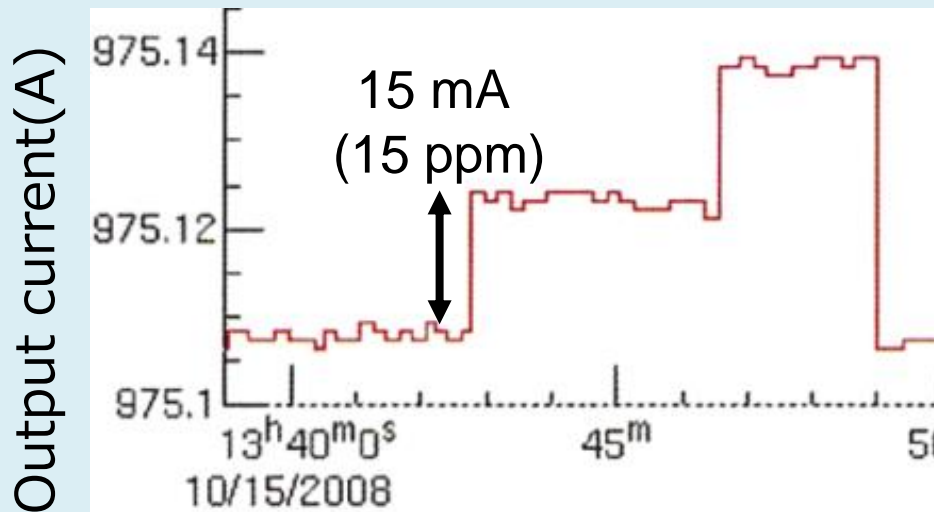
R&D items

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

R&D item 1: High current setting resolution

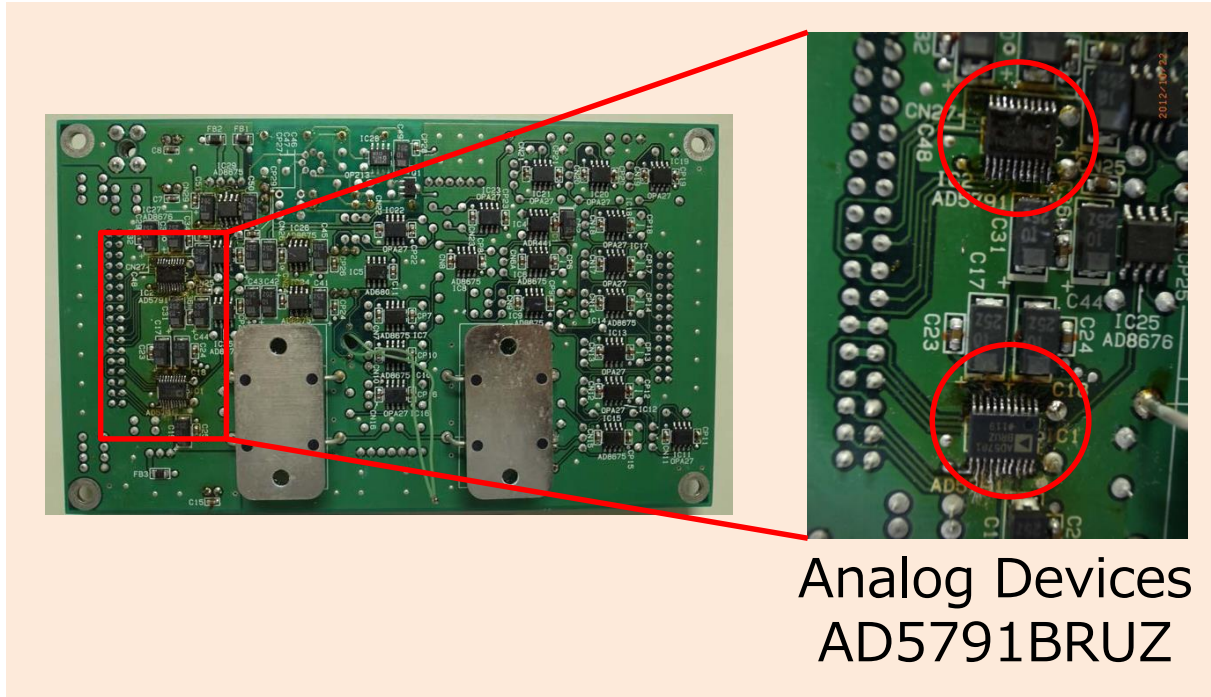
- Example of step response: 16-bit KEKB PS (1 kA, 700 V)

Current setting value is changed by 1 bit.

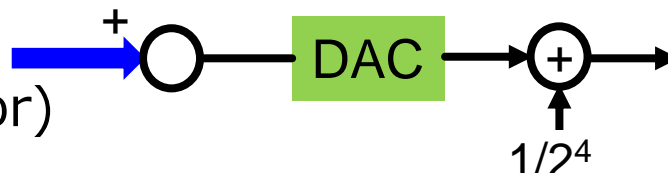


- Aiming 2 ppm stability, 0.1 ppm of setting resolution is required.
- 24-bit control board is developed using two 20-bit DACs. Analog Devices AD5791 is suitable due to its monotonicity spec.

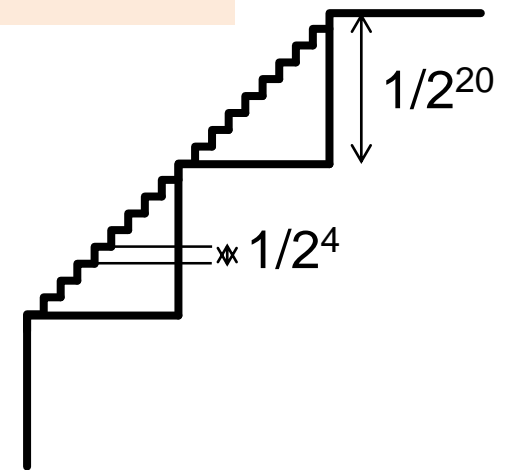
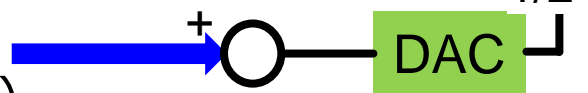
R&D item 1: Developed 24-bit board



Setting value
in 20-bits (major)

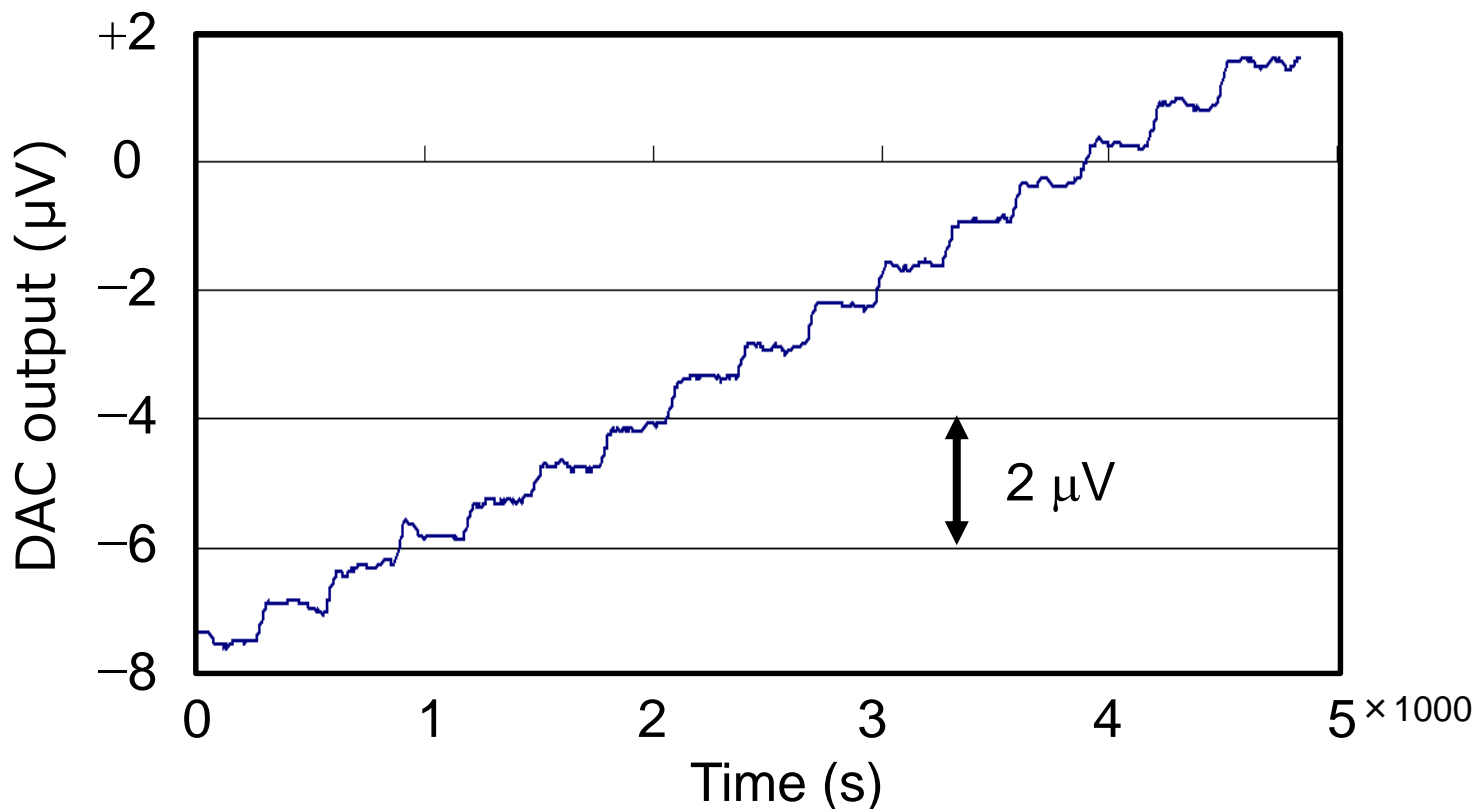


Setting value
in 4-bits (minor)



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

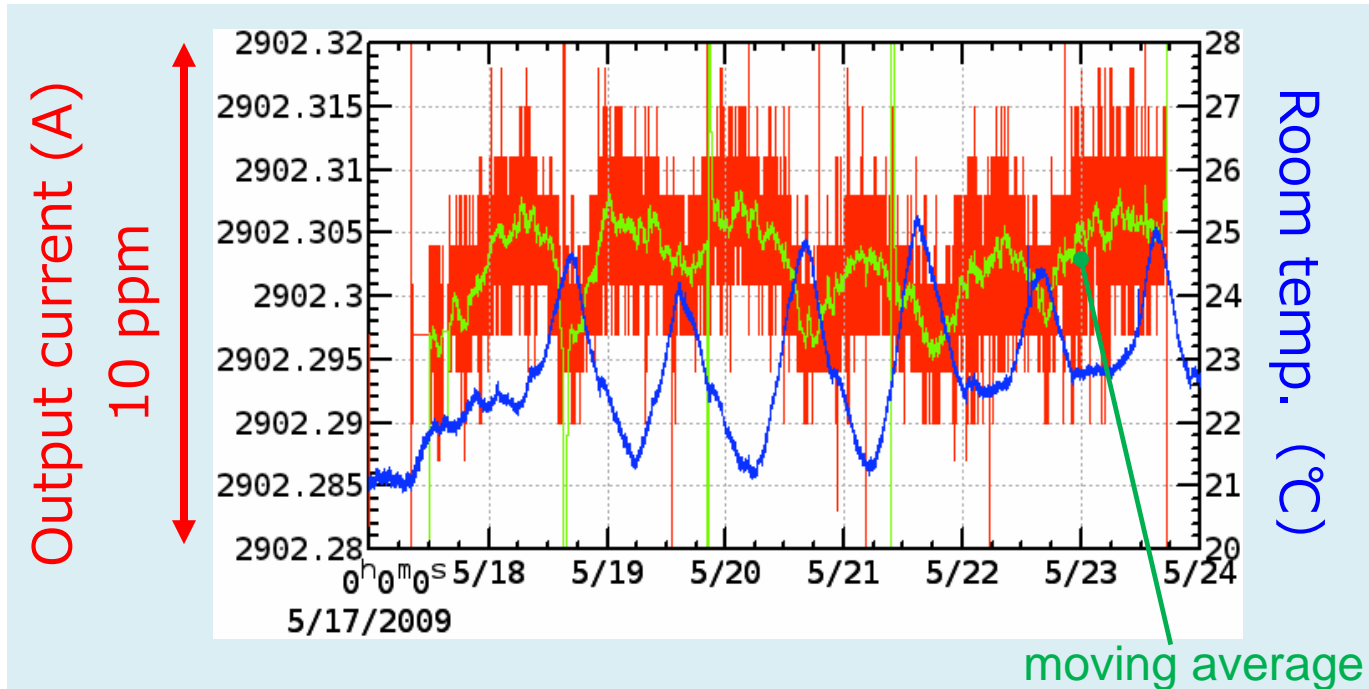
- Increasing DAC input digital value by 1 LSB, DAC output voltage is measured by Keithley 2002 DMM.



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

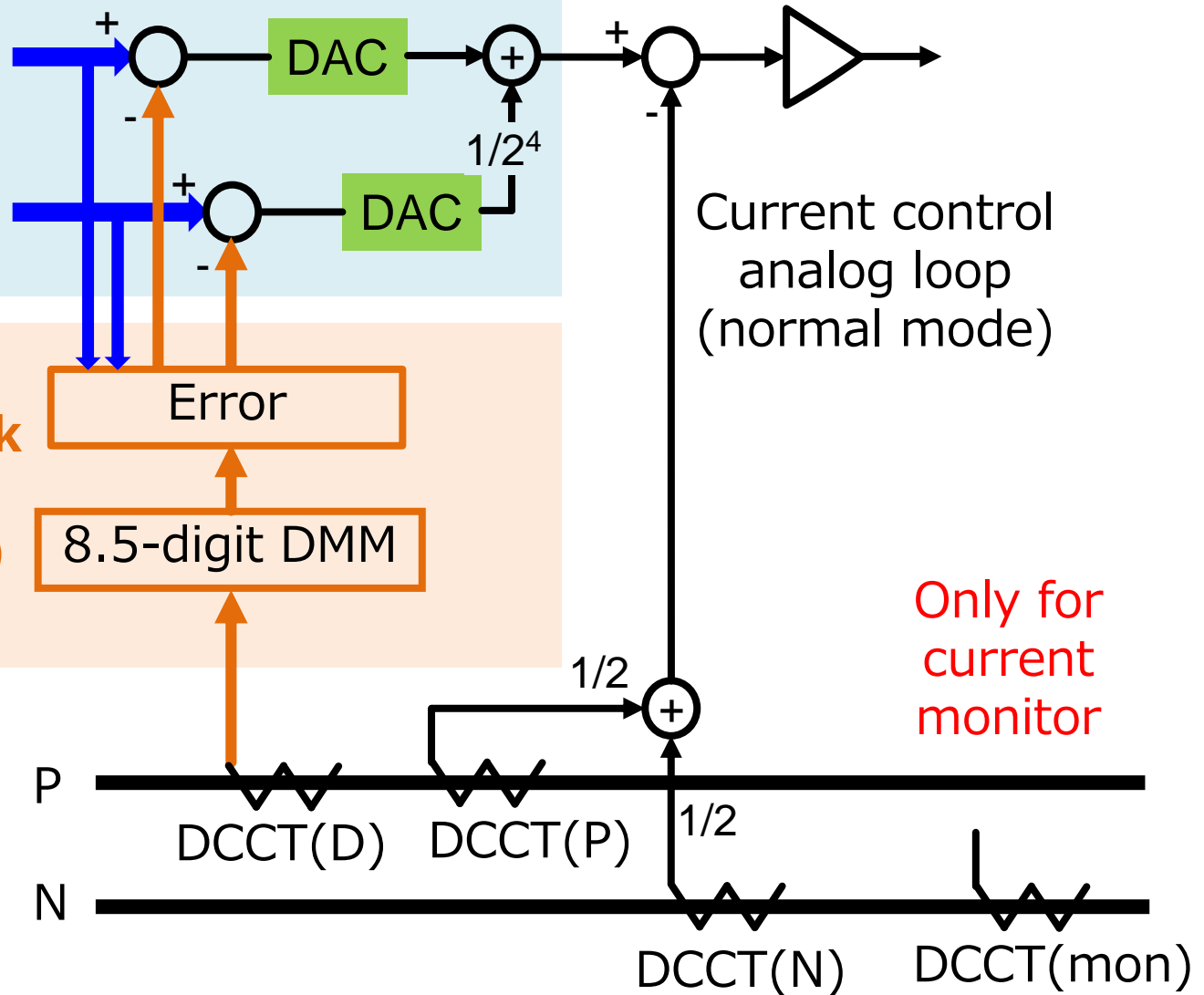
24-bit control board

Major setting value (20 bits)

Minor setting value (4 bits)

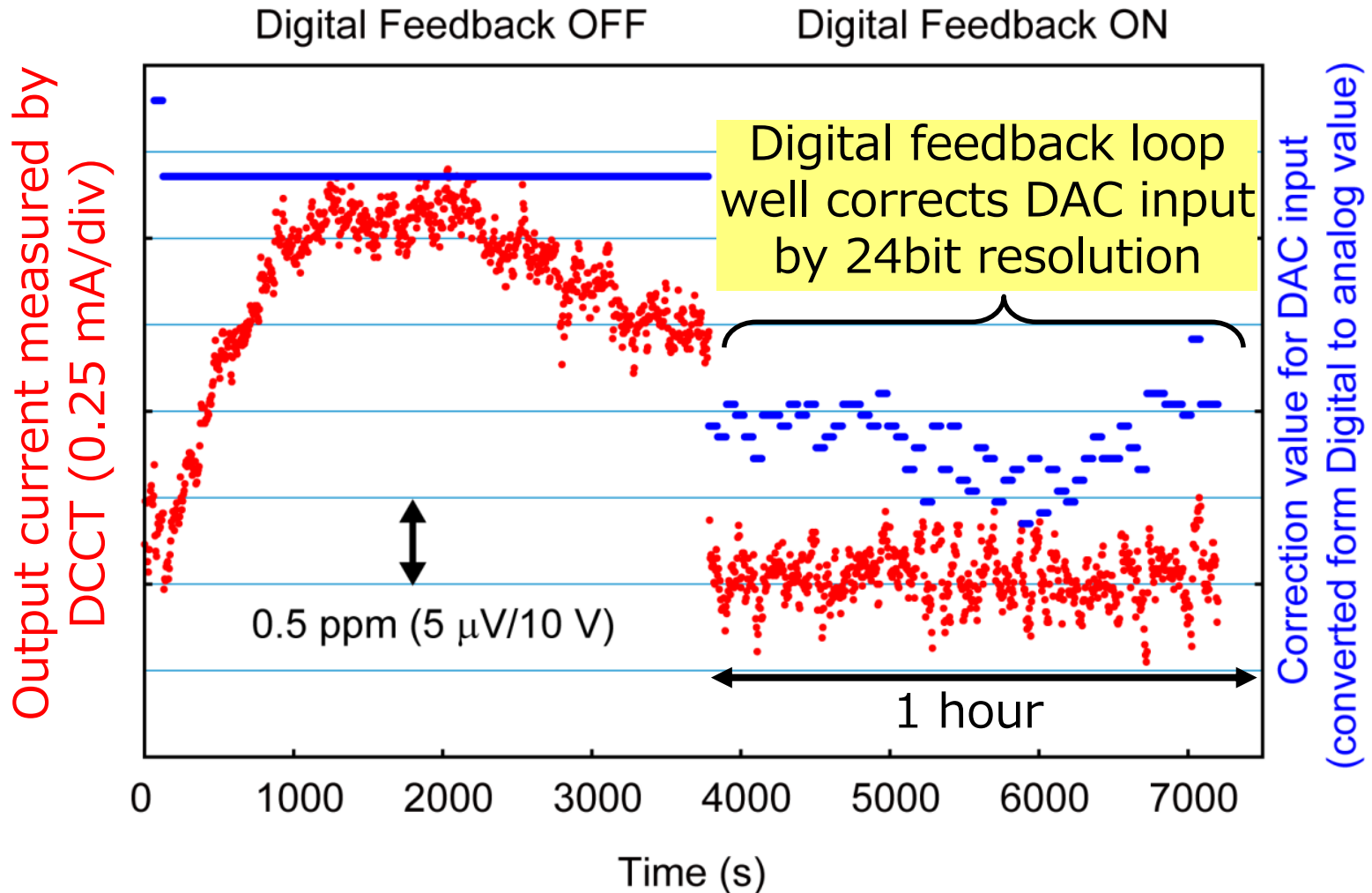
Digital feedback loop
(typ. 60 s rep.)

Output terminal



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 G Ω input impedance (DMM), 0.1 ppm = 10 μ V



+08.0101205 VDC
Range: 20 VDC

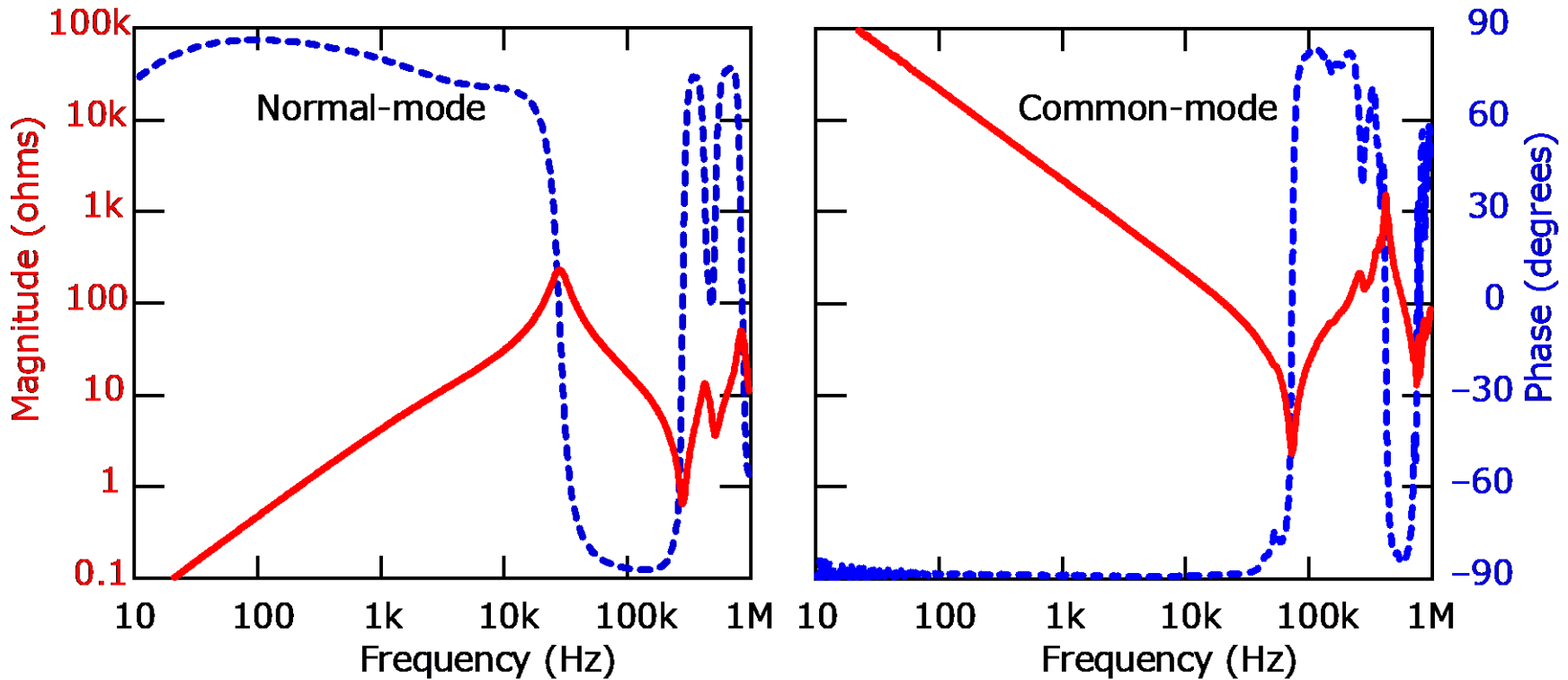
This digit



Ground
connection
should be
separated
each other.

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

- Example of the load impedance (QC1LP)

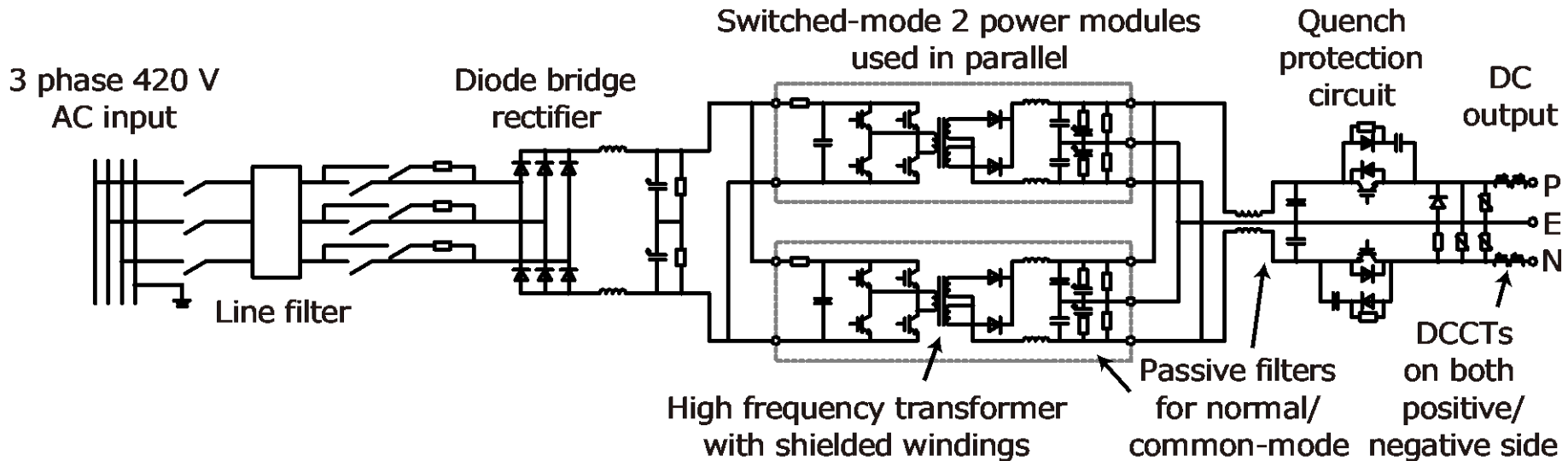


- Normal-mode impedance < several tens of Ω in the low freq. (<10 kHz) range: Possibility of large current ripple.
- Common-mode impedance < several tens of Ω in the high freq. (>10 kHz) range: Possibility of large switching noise.
- Symmetrical design of circuit is essential to reduce ripple and noise.

R&D item 3: Symmetric circuit design



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



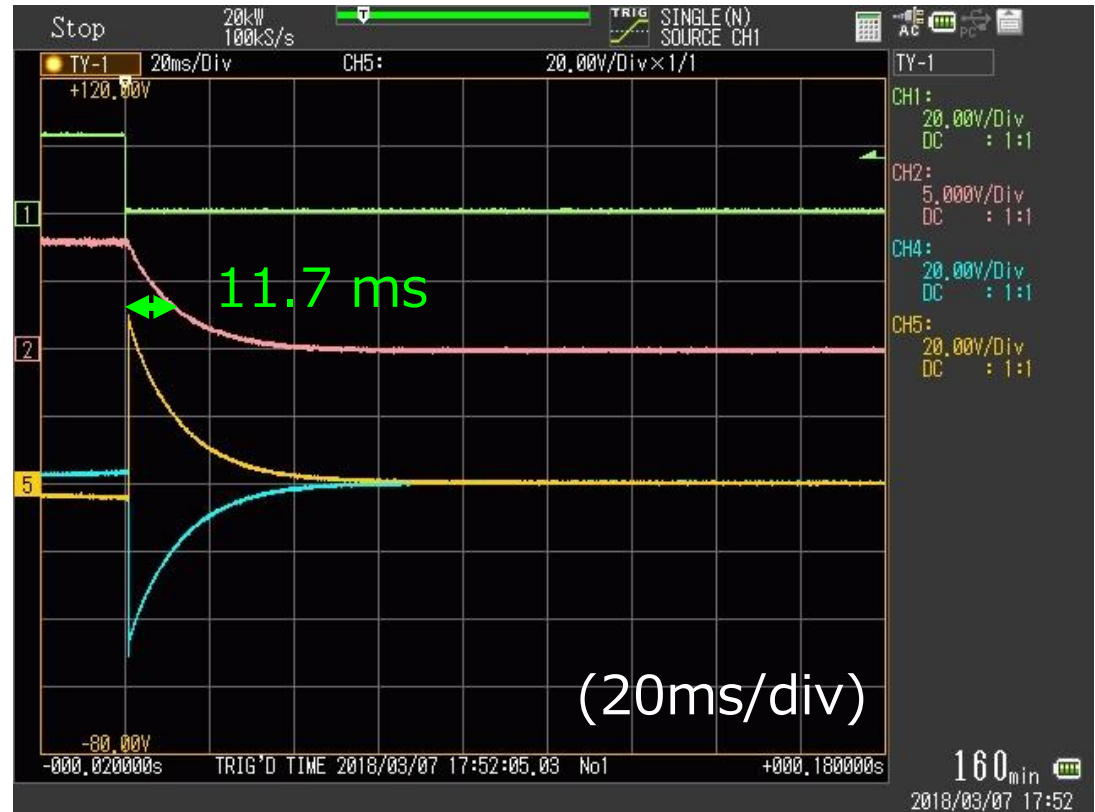
Full power test: quench protection trip test (QC1LP)

Trig. from Q.D.

Output current 1.6 kA ↑
(1kA/div)

Output voltage 100 V ↓
(20V/div)

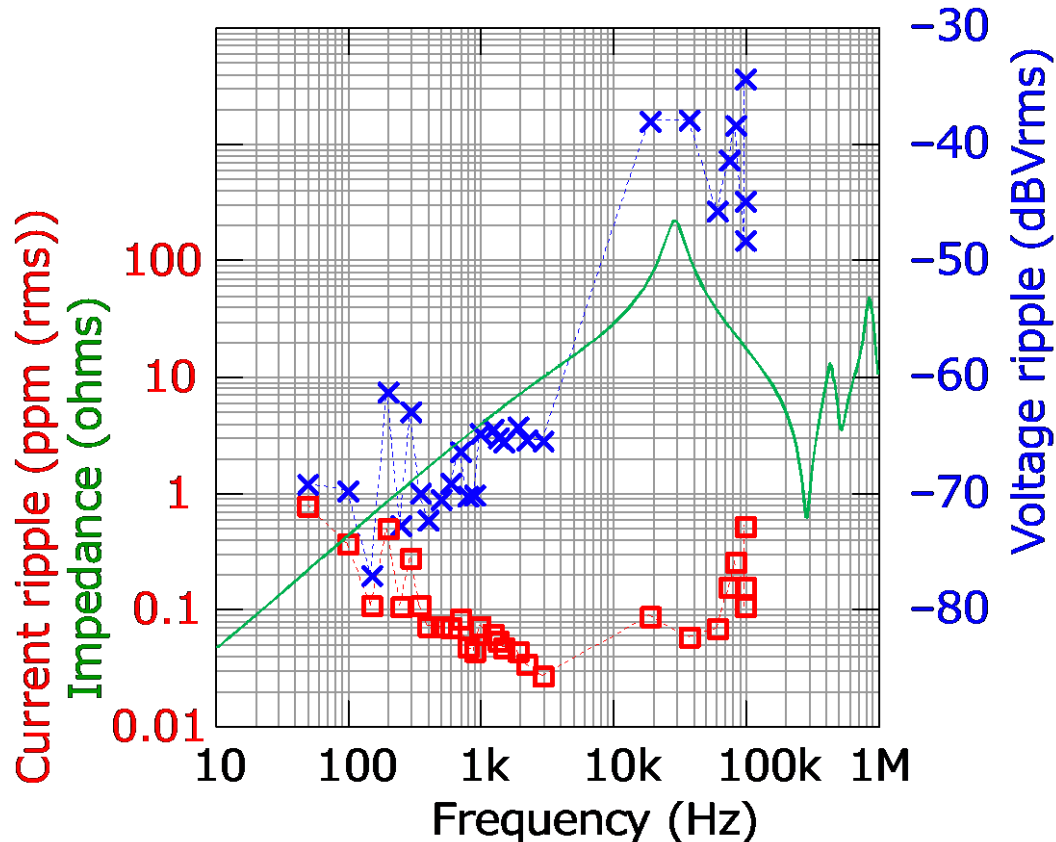
V_{PE}
 V_{NE}



- 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 $V_{PE} - V_{NE}$: $96 \text{ V} = 1.6 \text{ kA} \times 60 \text{ m}\Omega$

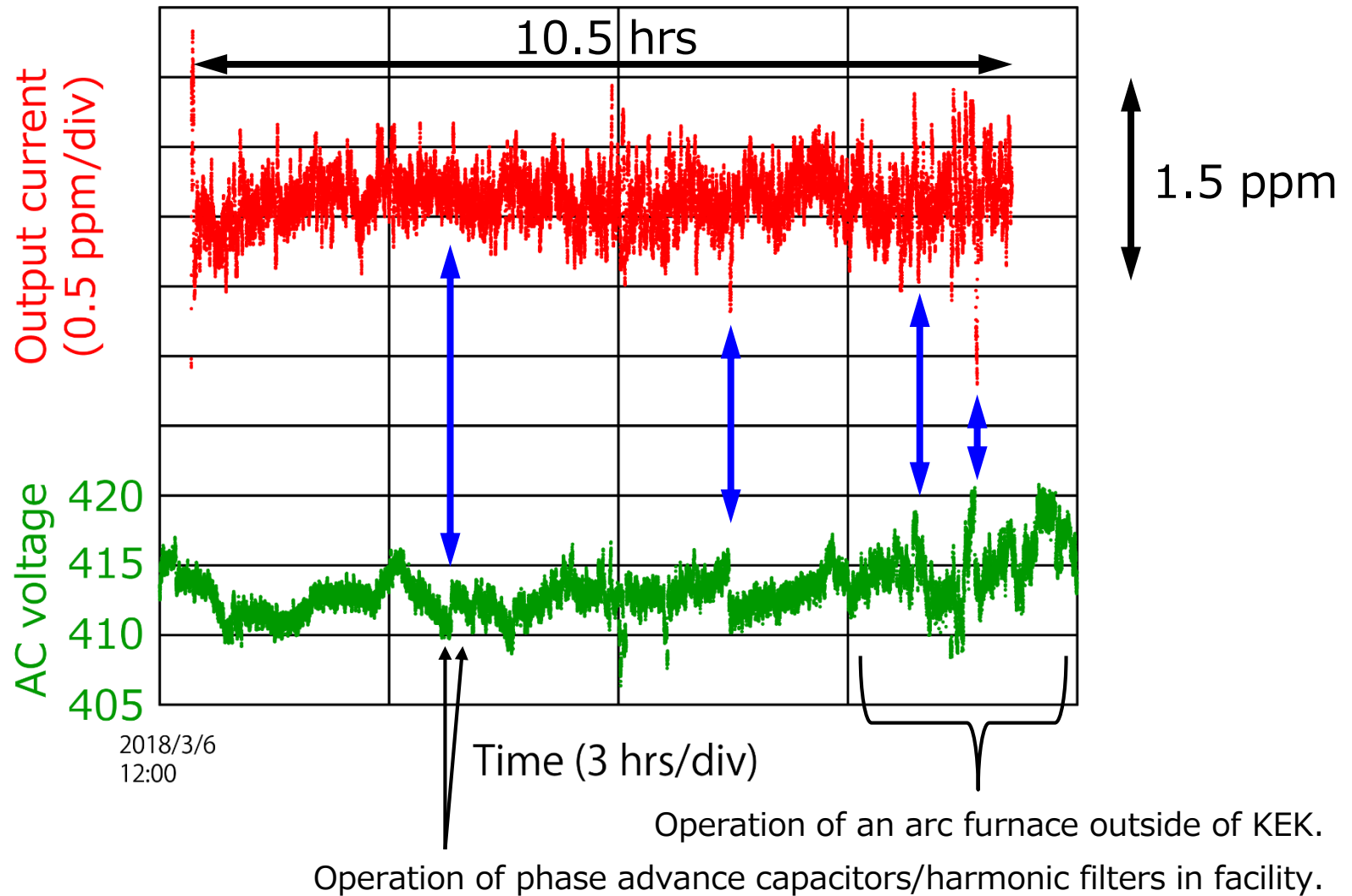
Performance test results 1: QC1LP current ripple

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



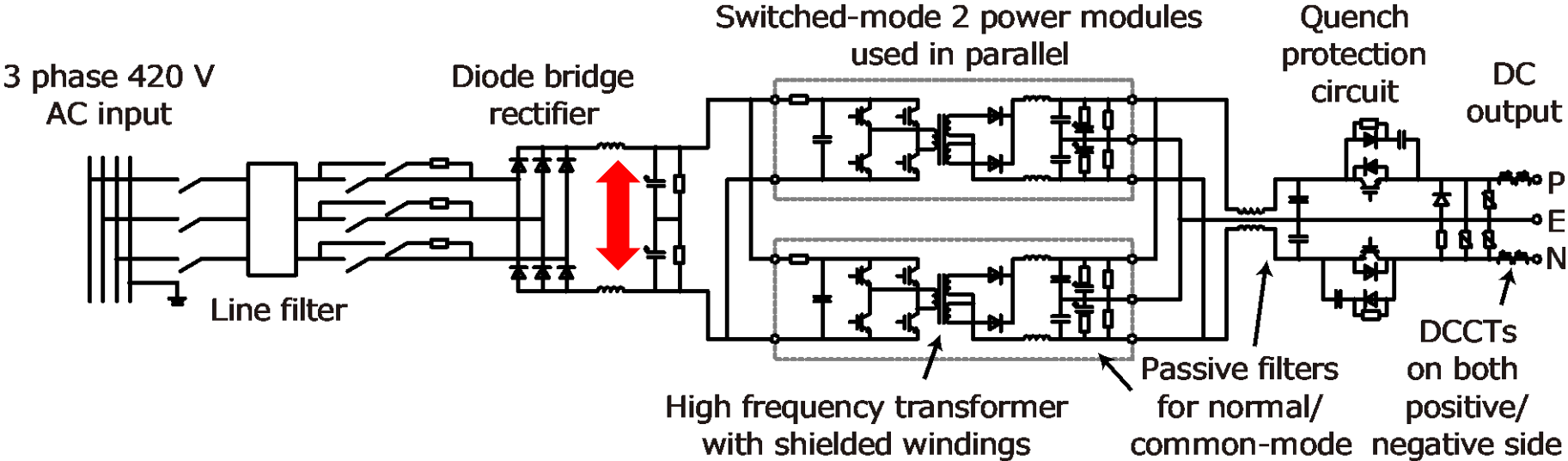
- Less than 1 ppm of normal-mode ripple and noise.
- Common-mode components are also measured: 0.5 ppm@57 kHz in the maximum.

Performance test results 2: QC2RE stability

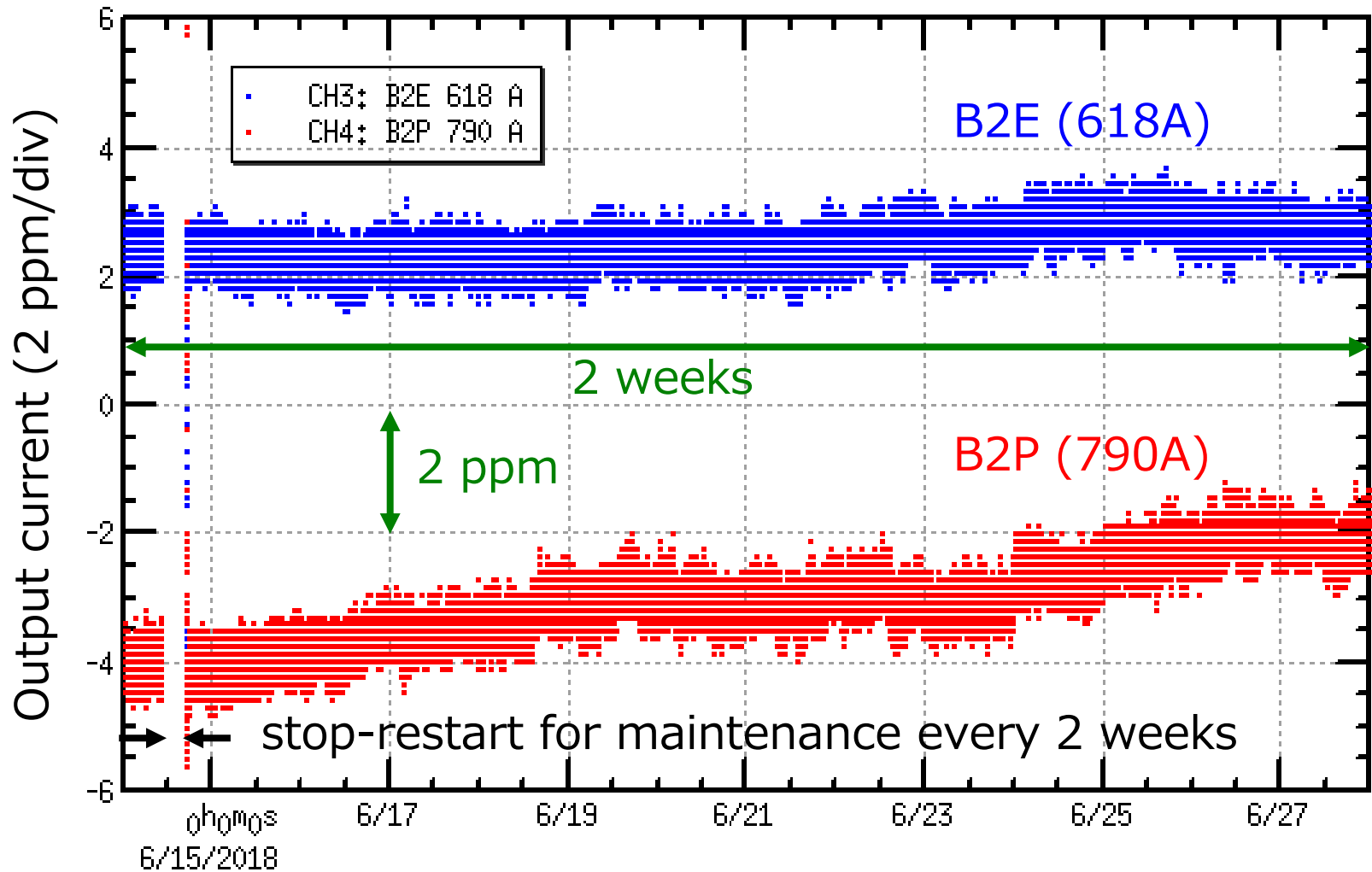


- ~1.5 ppm / 10.5 hrs of current stability is obtained.
- The rapid change in AC voltage leads to makes stability worse.

Feedback control of the DC voltage for chopper

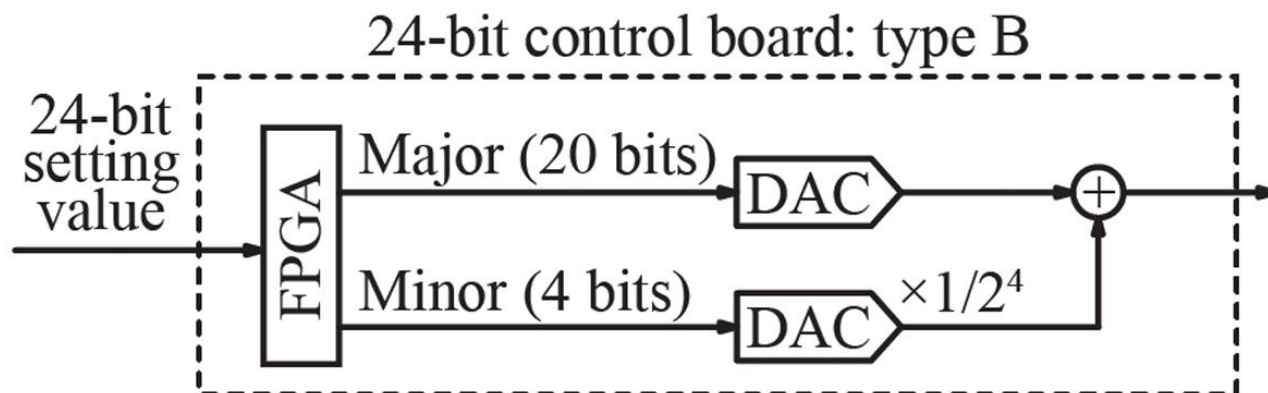
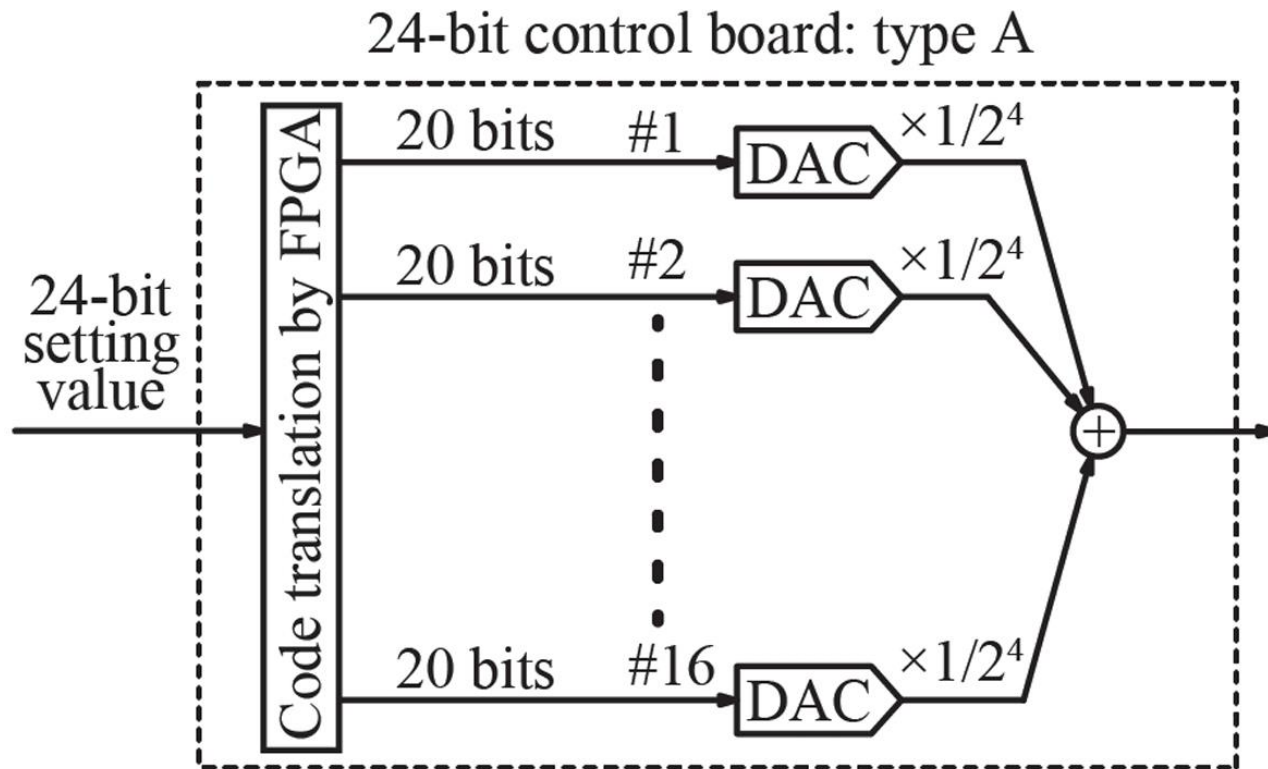


Stability of main bending magnet PSs (860A, 1.1kV)



- 24-bit board and digital FB control are employed similar to SC PS.
- 2.0~3.5 ppm/2weeks stability. **No spike due to switch mode rectifier.**
- Good repeatability after 8 hrs. of power off. and initializing operation.

Another type of 24-bit board assuring monotonicity



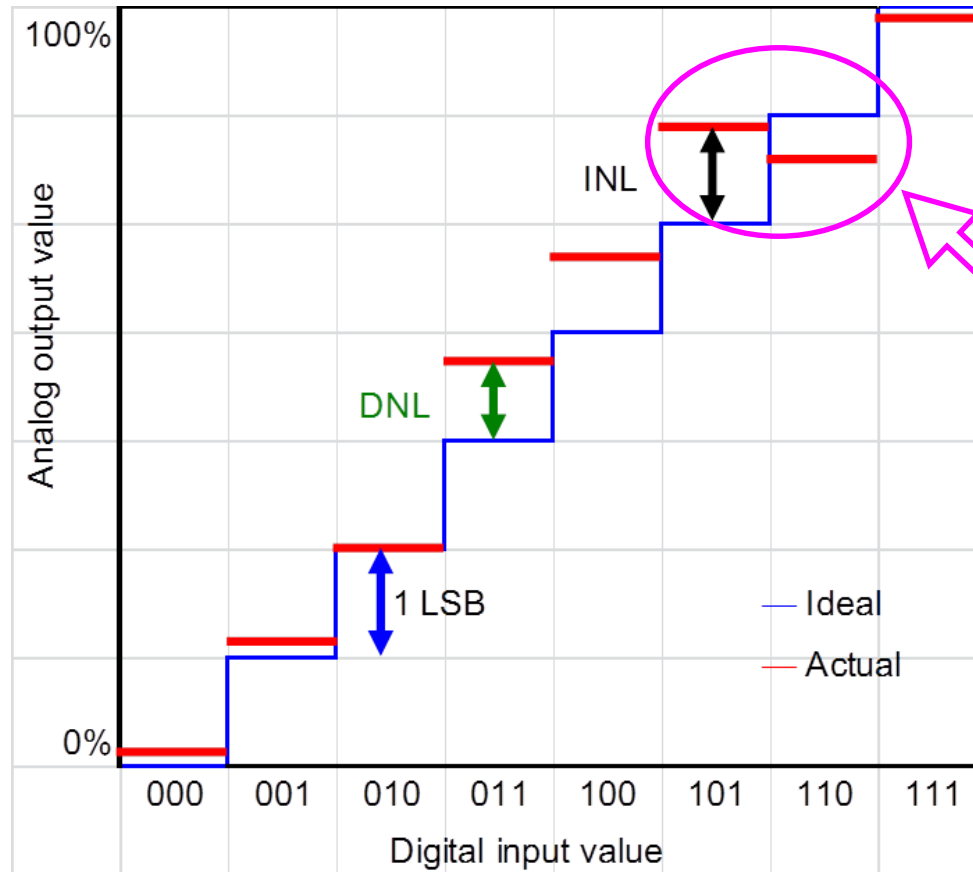
Summary

- SuperKEKB is an electron-positron collider that aims 40 times higher peak luminosity than one of the past KEKB.
- Final focus superconducting magnets are key devices to achieve such a high luminosity, and a high stability and a low ripple specifications for its output current are required.
- The developed power supply employed a 24-bits control board, a digital feedback control scheme, and a symmetric circuit design.
- In the test results, 1.5 ppm / 10.5 hrs of current stability and less than 1 ppm ripple are obtained.
- These power supplies were applied to the SuperKEKB collision operation and worked well. Further improvement is necessary to reduce spikes due to a rapid change in AC voltage.

Back-up slide

Non linearity and monotonicity

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



Lose monotonicity

AD7846K (16-bit): DNL ± 0.5 LSB max

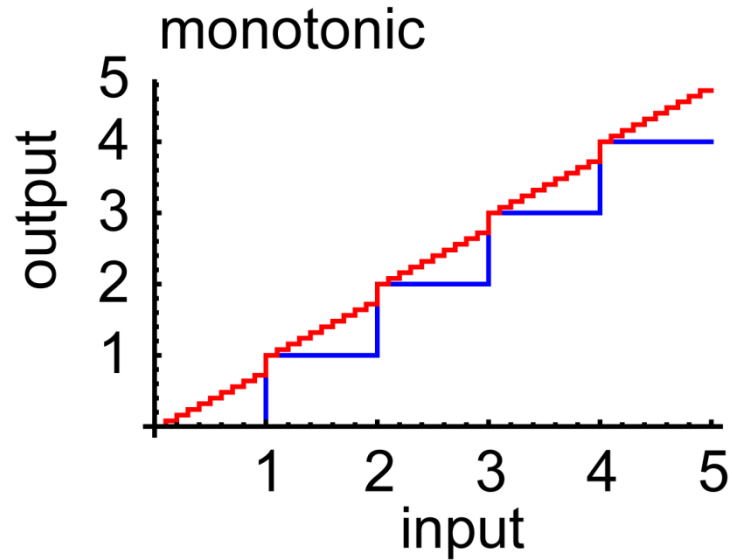
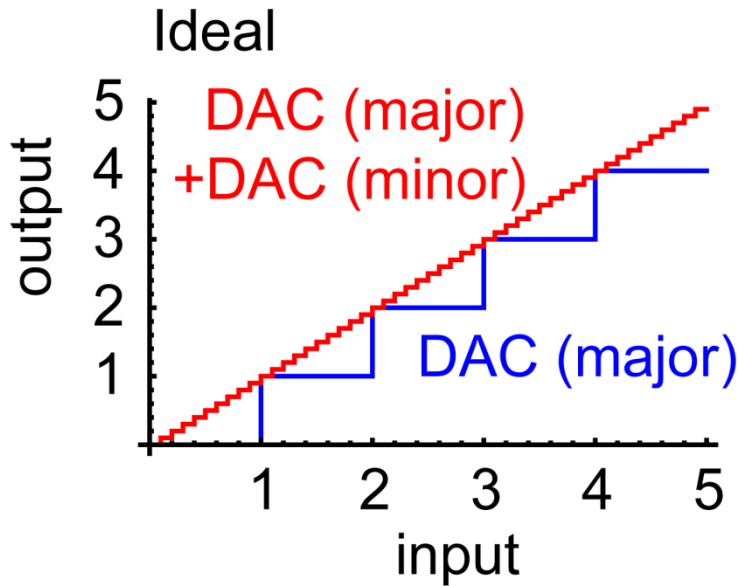
INL ± 2 LSB

AD5791B (20-bit): DNL ± 0.75 LSB typ. (test result: $< \pm 0.1$ LSB)

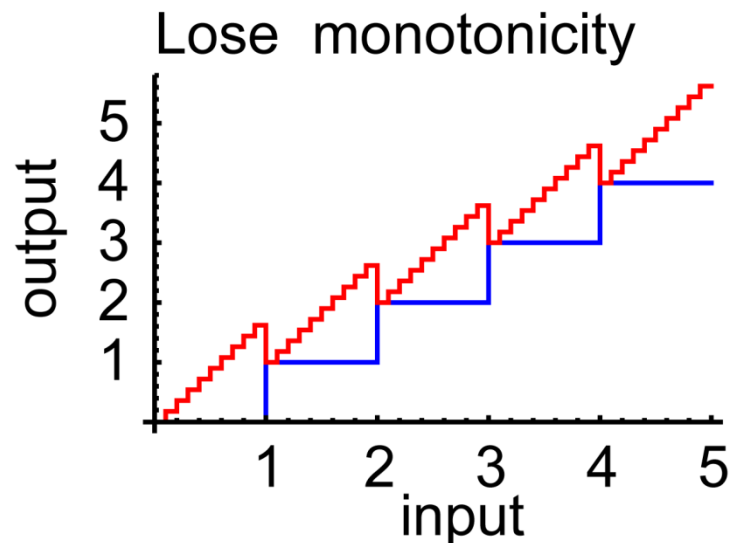
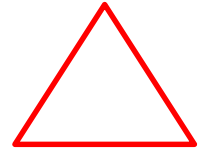
INL ± 0.5 LSB typ. (test result: $-0.2 \sim +0.6$ LSB)

Why sixteen DAC's 24-bit system?

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



Not so bad



Bad

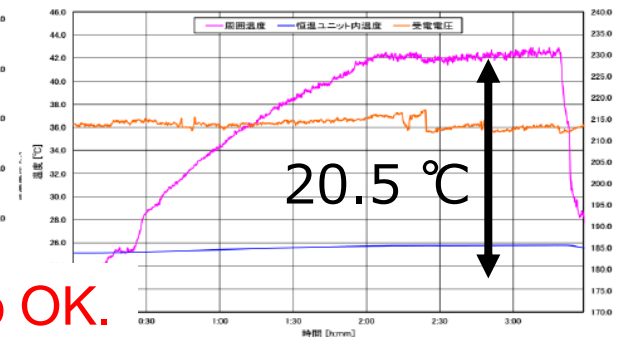
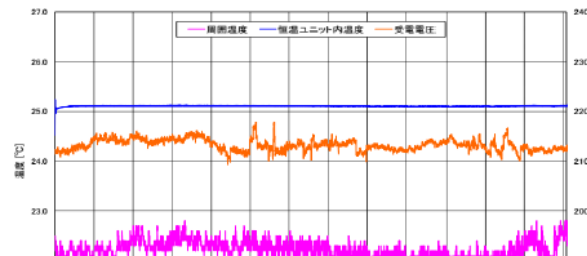
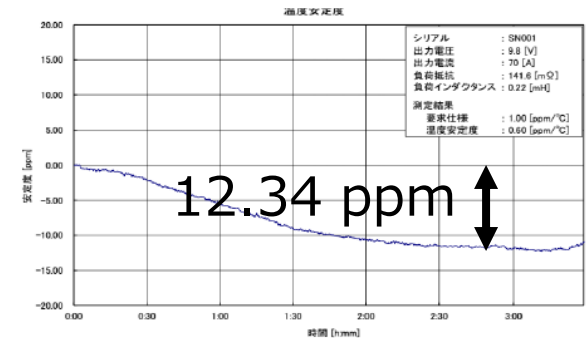
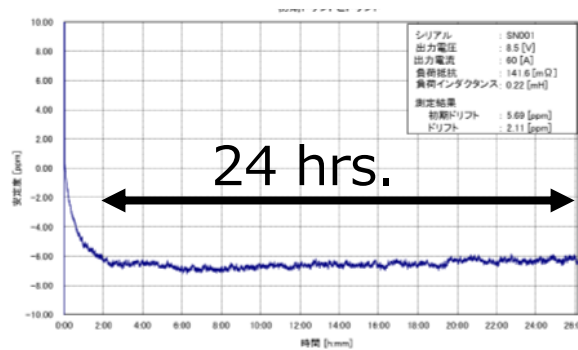


SC corrector power supply

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/°C

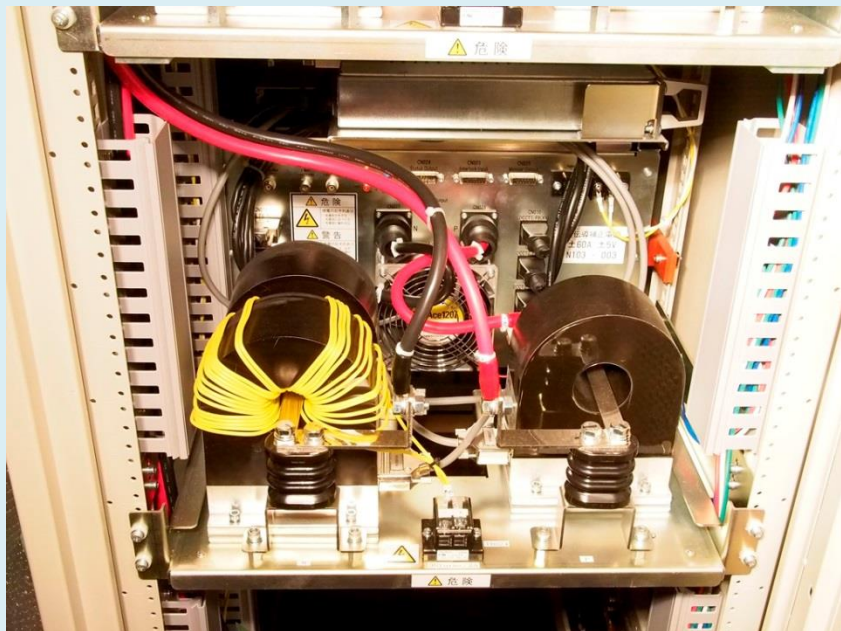


Ripple, noise, quench protection test and so on: also OK.

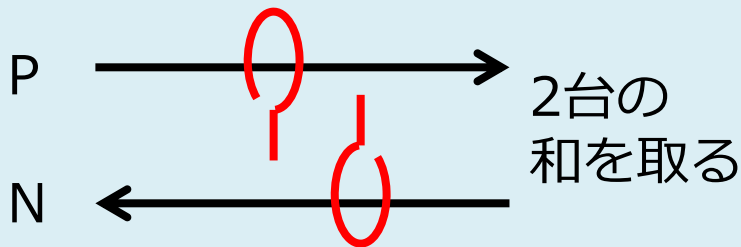
超伝導補正電磁石電源でのDCCTのコストダウン

仕様：60 A- 5 V
5 ppm/8時間

改造前

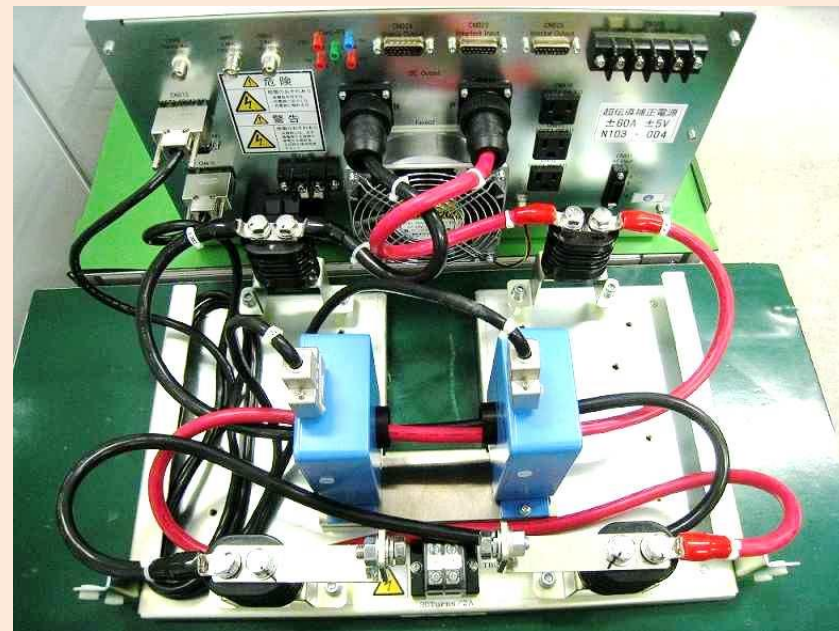


- TOPACC (88万円/台)
- 計3台 (制御×2、モニタ×1)

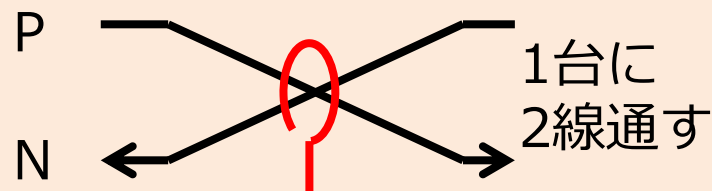


- 電源45台分：11,880万円

改造後



- MACC Plus (11万円/台)
- 計2台 (制御×1、モニタ×1)



- 電源45台分：990万円

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)

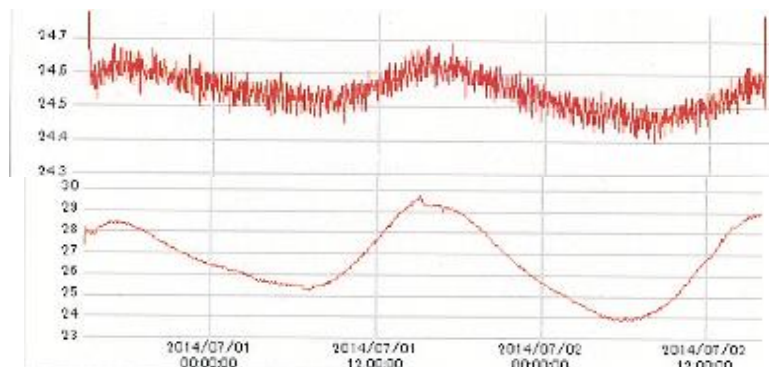
恒温槽（espec LU-123）の温度変化（2日間実測）

- ・ 周囲温度変化 5.5 °C に対して、
恒温槽内温度変化 0.2 °C



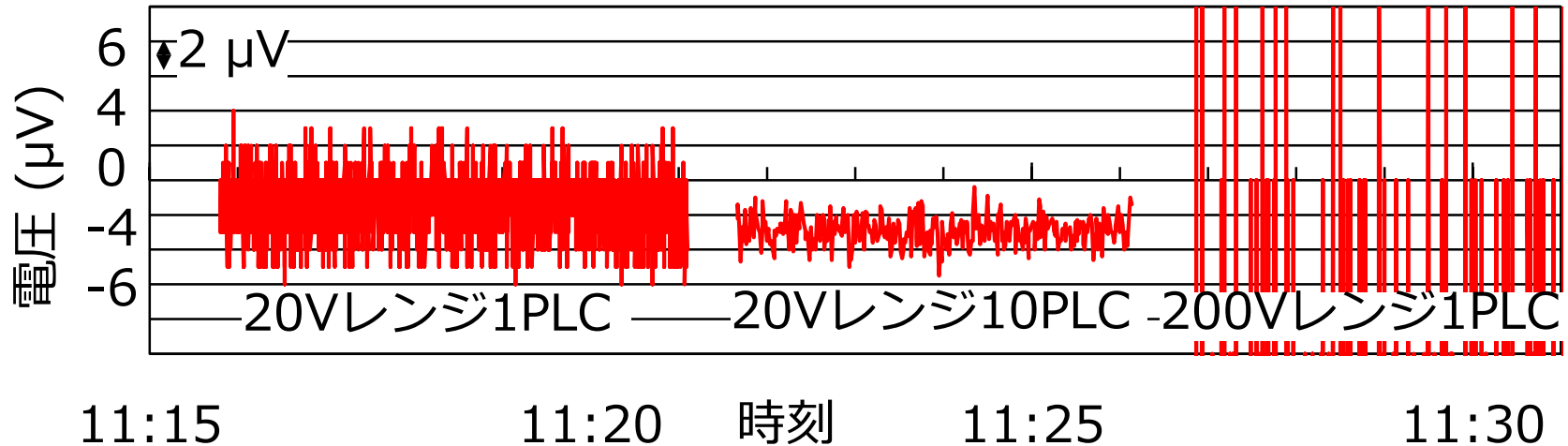
デジタル帰還制御の温度係数の見積

- ・ $(0.5+0.3) \times 0.2 = 0.16$ ppm程度
- ・ $(1.5+0.3) \times 0.2 = 0.36$ 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

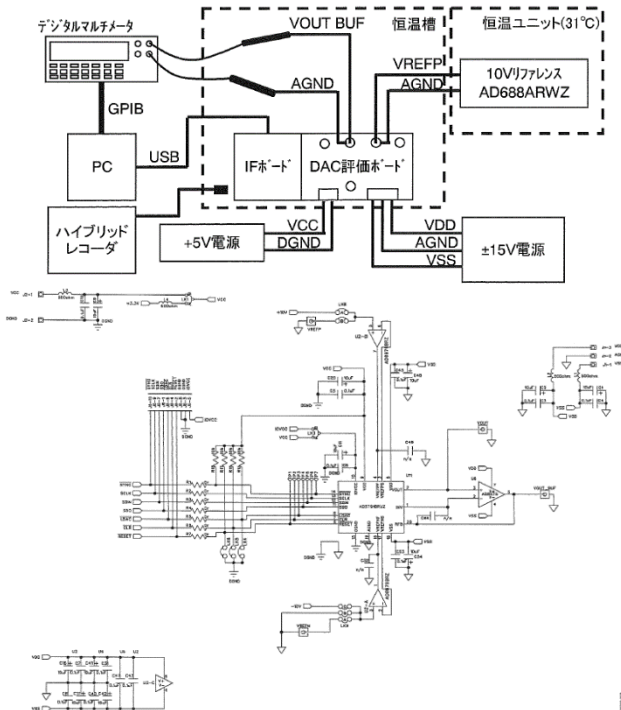
仕様とよく合っている。

20 Vレンジ、10 PLCなら、0.1 ppm以下の制御に使える

10 Vの0.1 ppm = 1 μV

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)

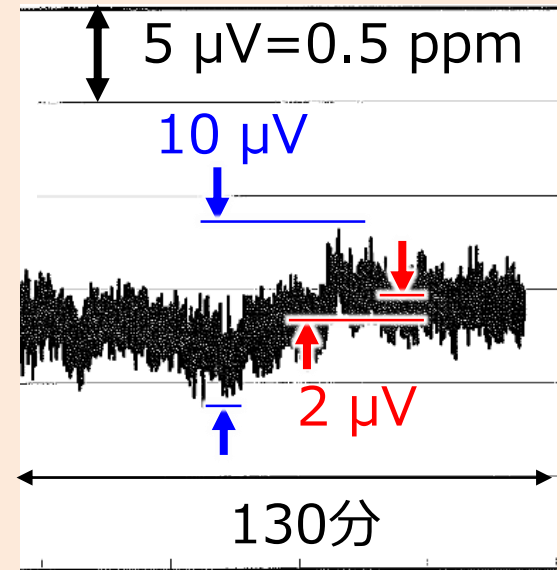


AD5791	0.05 $\mu\text{V}/^\circ\text{C}$
AD8676	0.6 $\mu\text{V}/^\circ\text{C}$
AD8675	0.6 $\mu\text{V}/^\circ\text{C}$

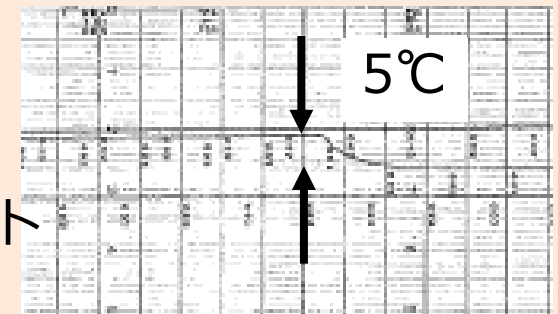
1.25 $\mu\text{V}/^\circ\text{C}$ → 0.125 ppm/ $^\circ\text{C}$

DAC出力 (V)

4.999345
4.999340
4.999335
4.999330
4.999325



周囲
恒温槽
恒温ユニット



温度係数 : 0.04 ppm/ $^\circ\text{C}$

ゆらぎ幅 : 1 ppm/2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）

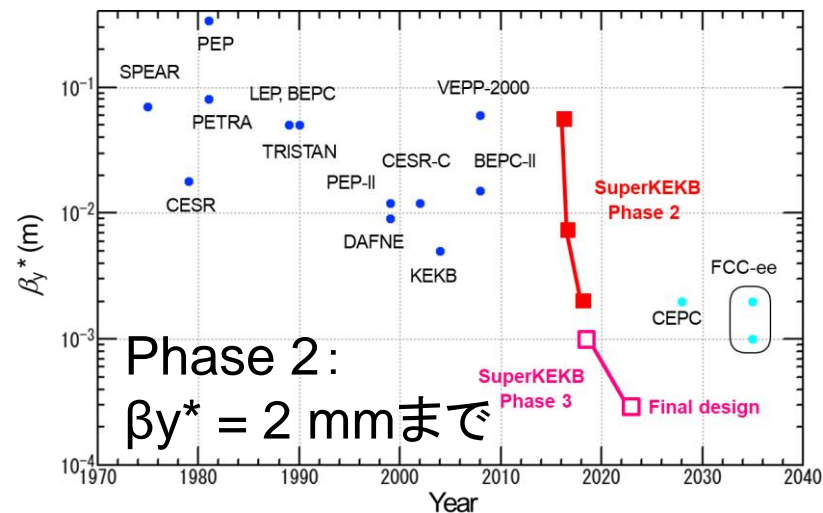
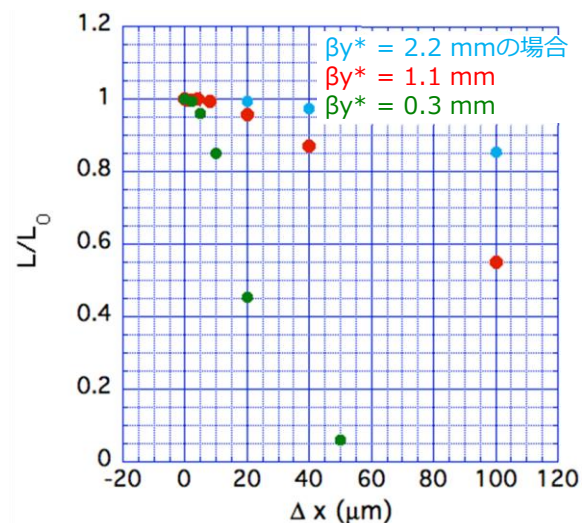
- ・ノイズ幅：0.06 ppm (rms)
- ・温度係数：0.3 ppm/K

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

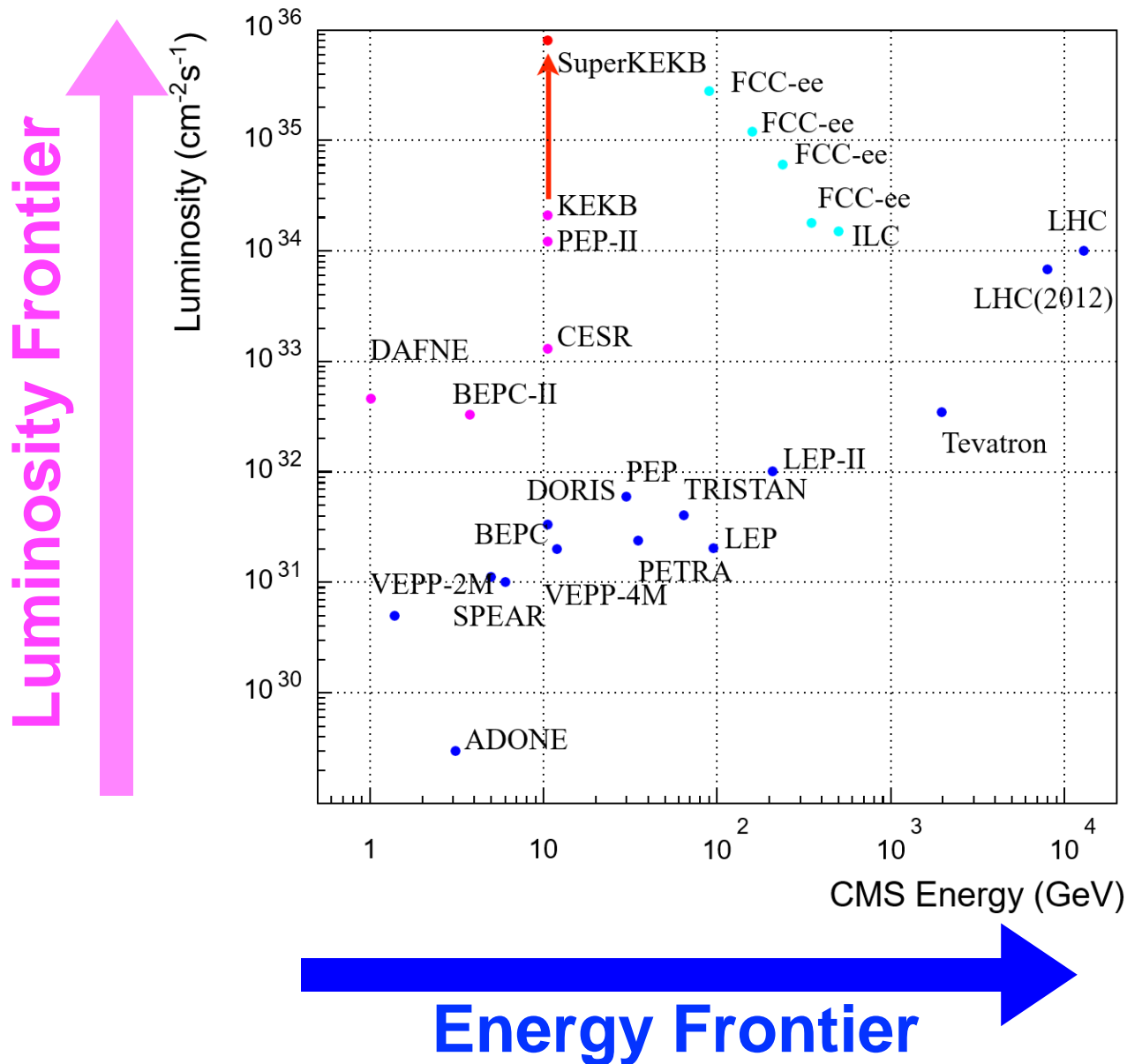
- ・ 水平方向に衝突ビームがずれた時のルミノシティの減少率（大見氏計算）



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

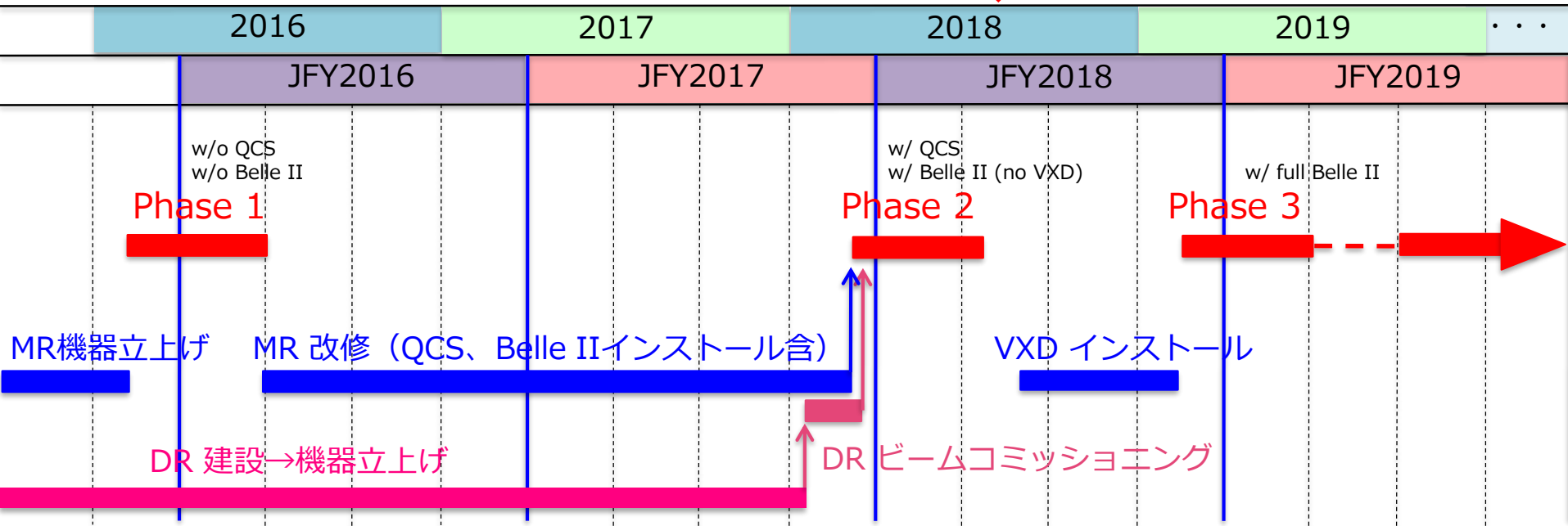
水平方向衝突軌道保持フィードバックシステムとして、PEP-IIで実績のあるデザリングシステムをSuperKEKBで初めて導入し

ルミノシティ／エネルギーフロンティア



現在どのような段階にあるのか

いまここ



- 2010/6にKEKBの運転を停止して5年にわたる大改修を進めてきた。
- Phase 1：衝突させない周回運転でビーム調整。ビームダクト真空焼き。
- Phase 2：衝突運転を始める。ベータを絞り、各種衝突調整を実施。
→「ナノビーム方式」を実証できた。BelleのBGレベルも確認。
- Phase 3：VXDを入れた完全な状態のBelle IIで物理ランを予定。
目標のピーク・ルミノシティ $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ を目指す。

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

バンチ同士の衝突頻度

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

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

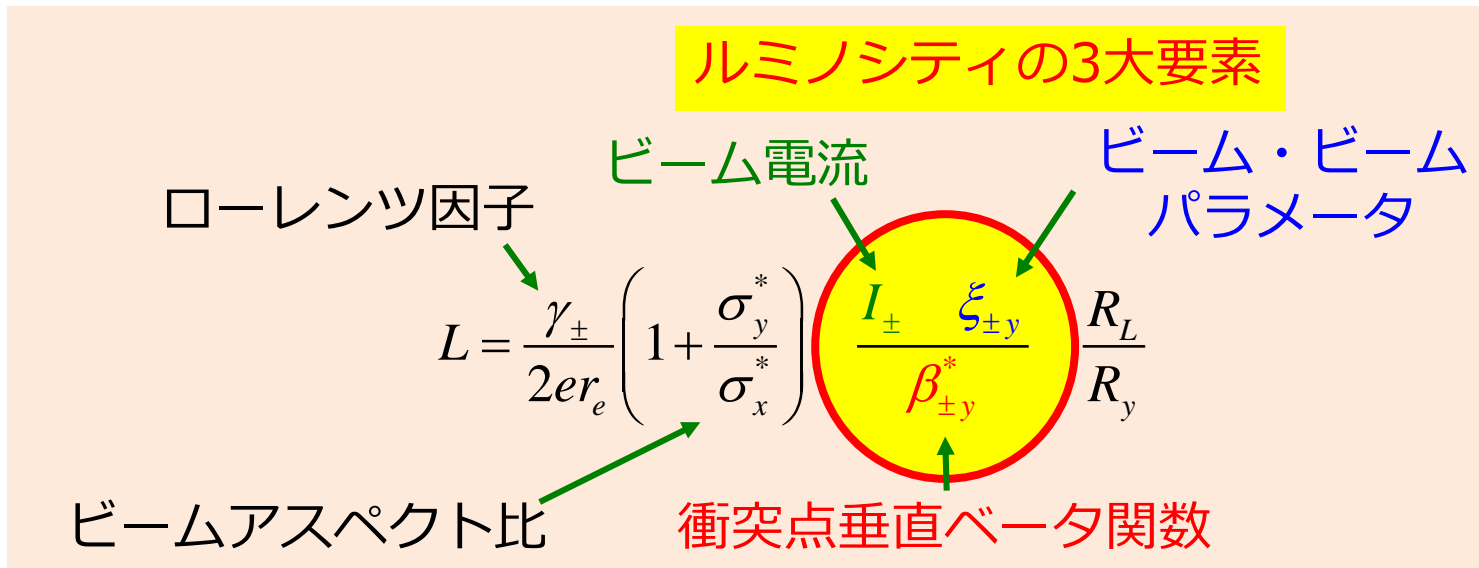
ルミノシティの式変形：ビーム・ビームパラメータ ξ の導入

- ・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

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

←いろいろな制限があって
あまり大きくできない

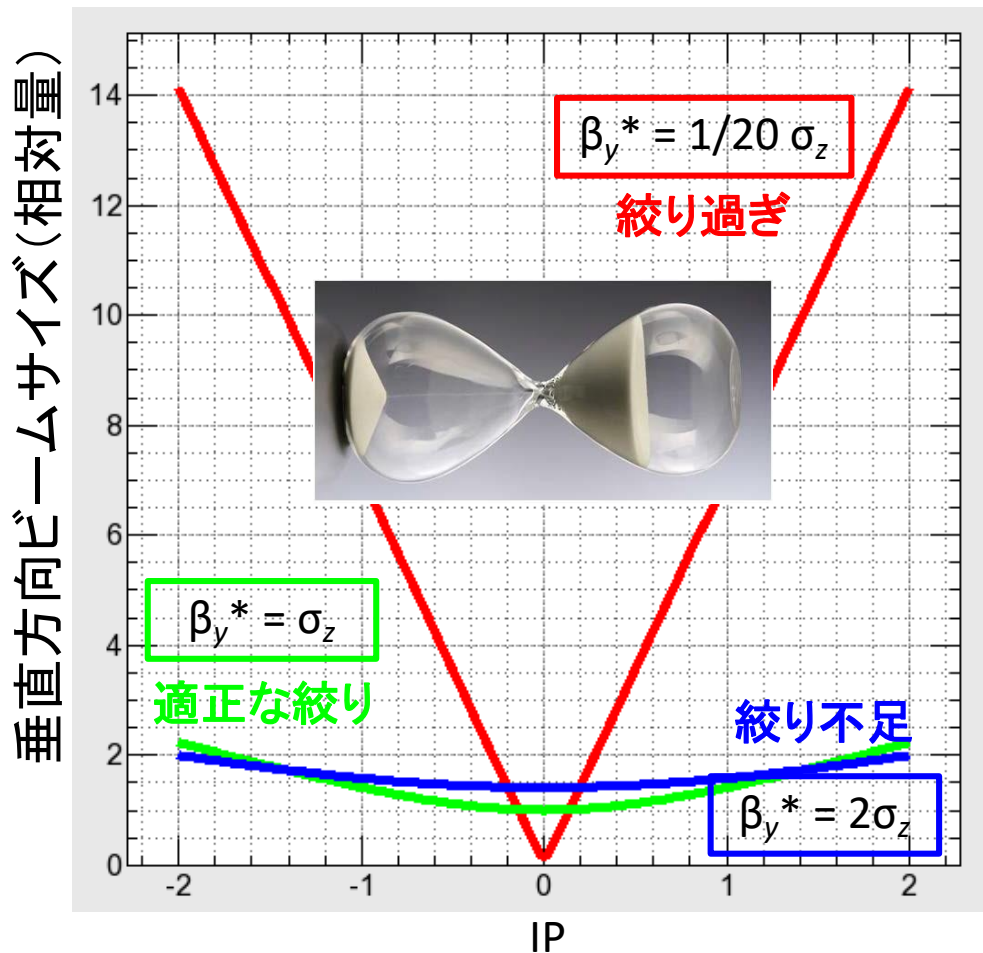
を導入してルミノシティを表現すると…



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。

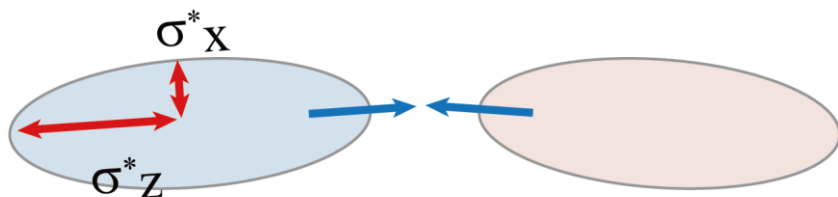


どうすれば絞れるか

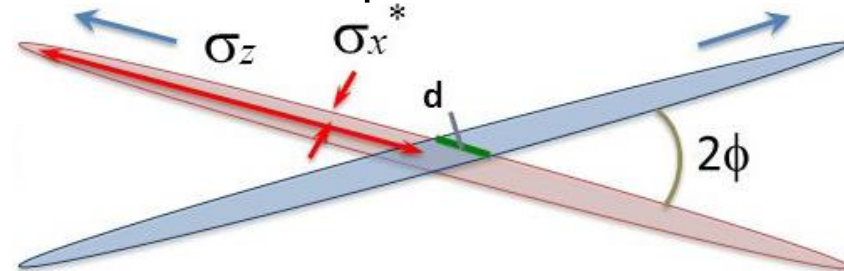
水平方向のビーム幅を絞る + 水平方向に大交差角を付ける →砂時計効果を緩和できる (ナノビーム・スキーム)

KEKB

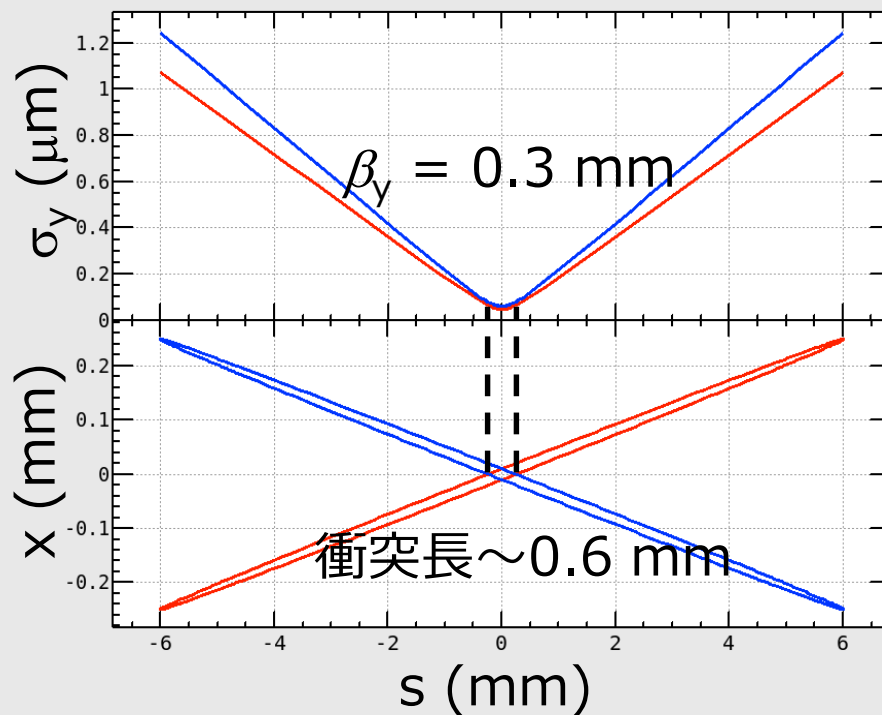
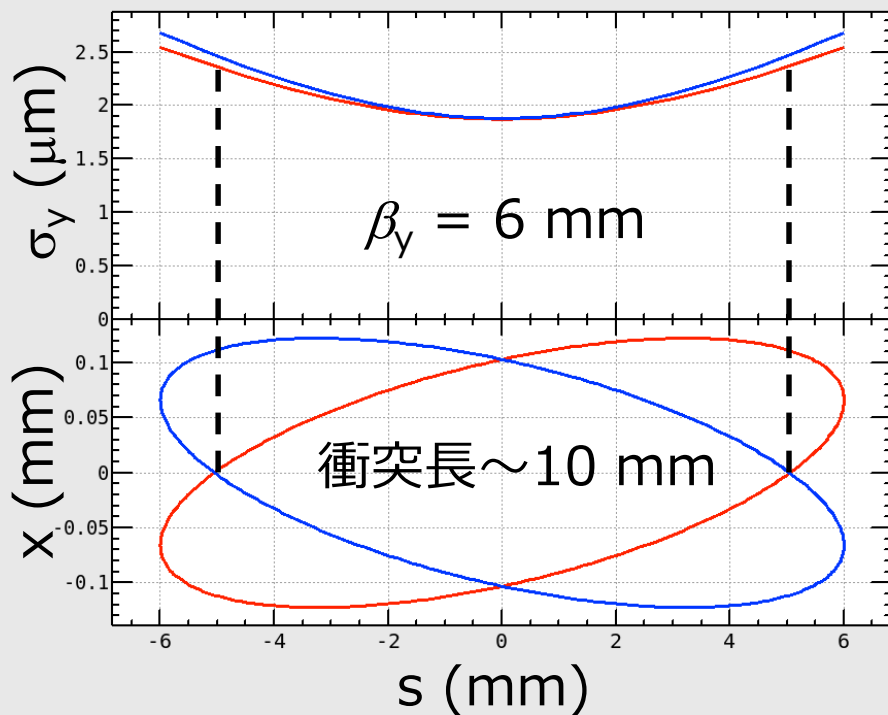
SuperKEKB



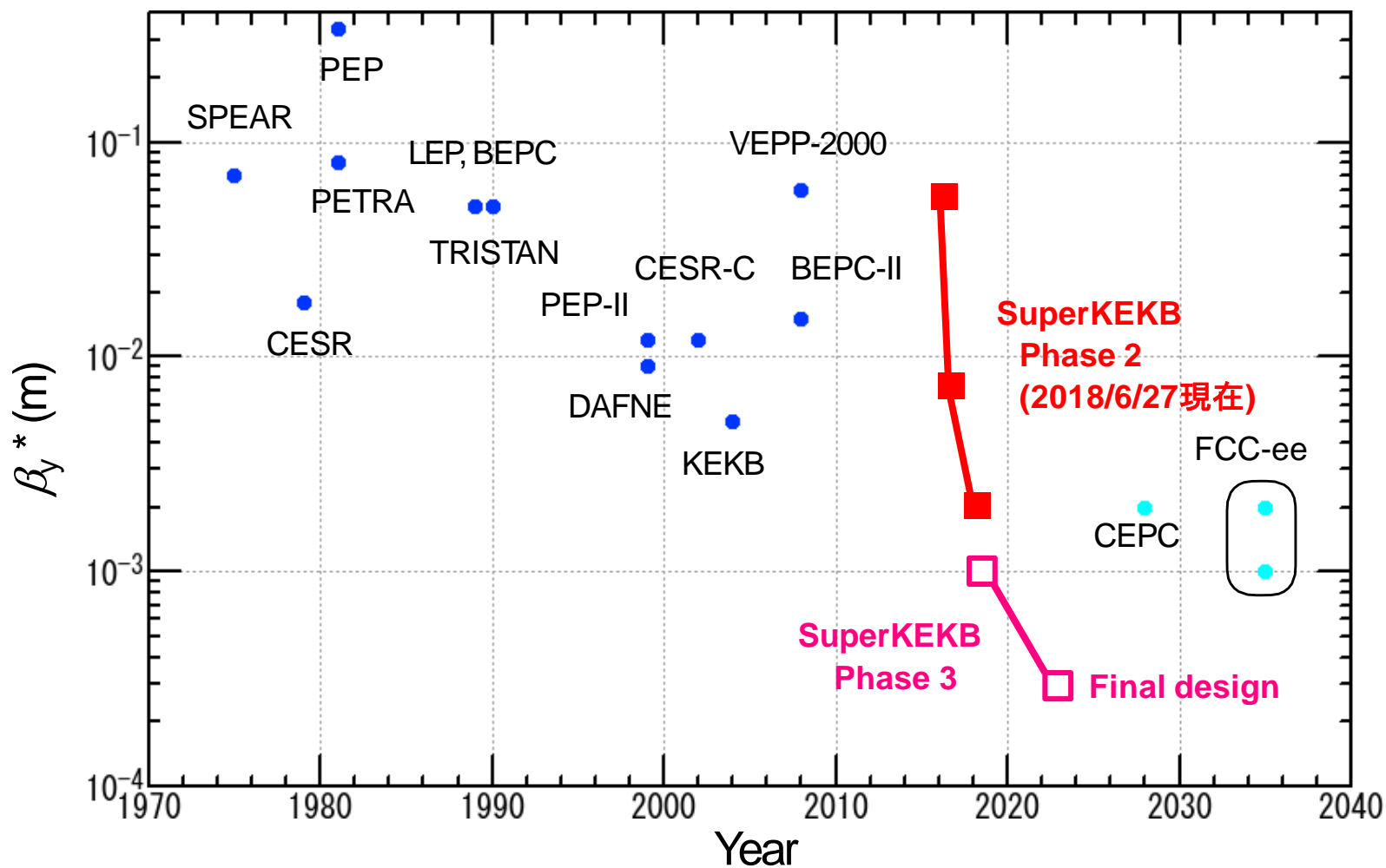
衝突長 ~ バンチ長



衝突長 ≠ バンチ長



世界最小 β_y^* への挑戦



2018/6/27現在、 $\beta_y^* = 2$ mmを達成

SuperKEKB加速器の設計パラメーター

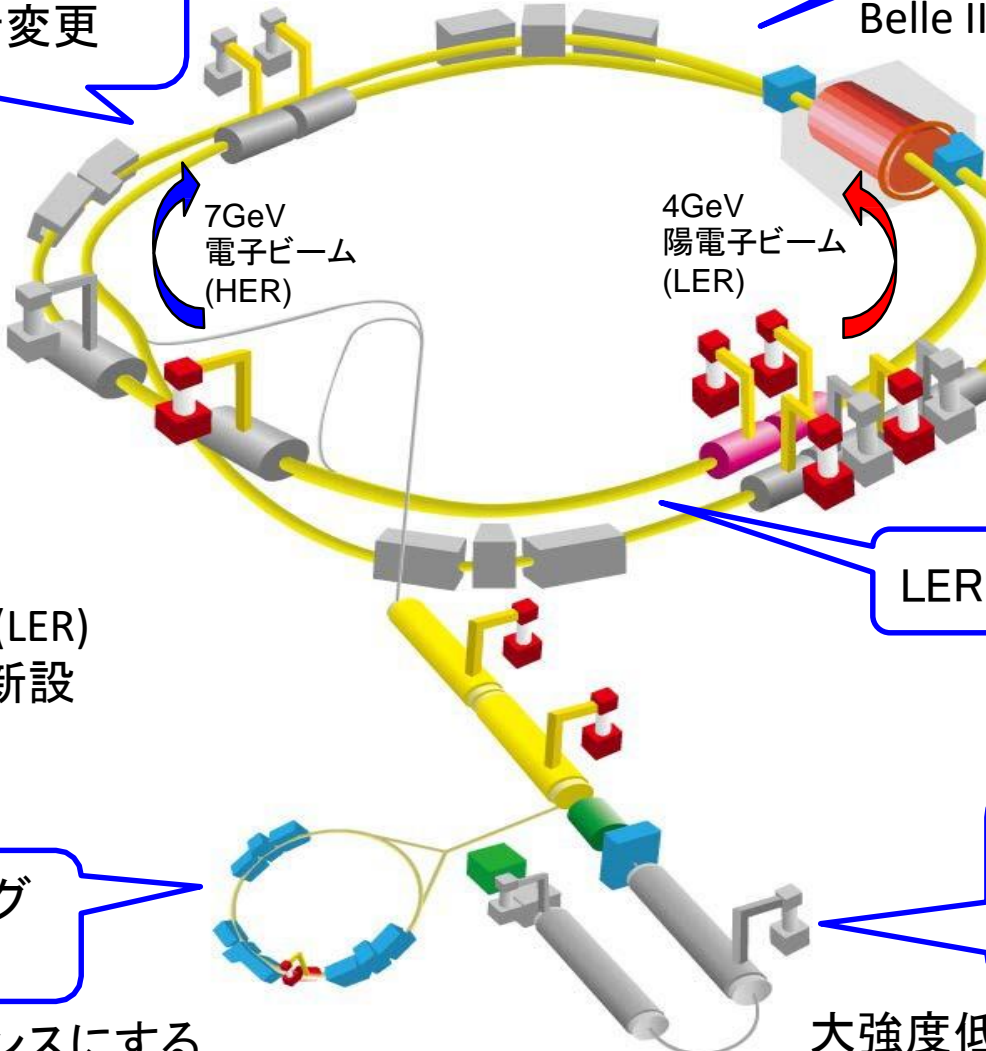
パラメータ		KEKB		SuperKEKB		単位
		LER(e ⁺)	HER(e ⁻)	LER	HER	
ビームエネルギー	E _b	3.5	8	4	7	GeV
半交差角	φ	11		41.5		mrad
水平エミッタンス	ε _x	18	24	3.2	4.6	nm
エミッタンス比(ε _y /ε _x)	κ	0.88	0.66	0.27	0.25	%
衝突点でのβ関数	β _x / β _y	1200/5.9		32/0.27	25/0.30	mm
ビーム電流	I _b	1.64	1.19	3.6	2.6	A
ビーム・ビーム パラメーター	ξ _y	0.129	0.090	0.088	0.081	
ルミノシティ	L	2.1 x 10 ³⁴		8 x 10 ³⁵		cm ⁻² 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10³⁴を、→40倍のルミノシティを目指す！

KEKB加速器からSuperKEKB加速器への大改修 — 低エミッタンス・ナノビーム化 —

大交差角配置

低エミッタンス実現のため
ビーム光学設計変更



最終収束系超電導
電磁石システム(QCS)
局所色収差補正部
等を全面的に改造

LER電子雲除去永久磁石

電子雲によるビーム
サイズ増大を防ぐ

入射器の改造

- 新型電子銃
- 陽電子源の改造

大強度低エミッタンスビーム生成

陽電子ダンピング
リング新設

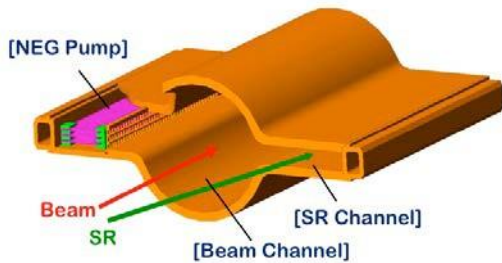
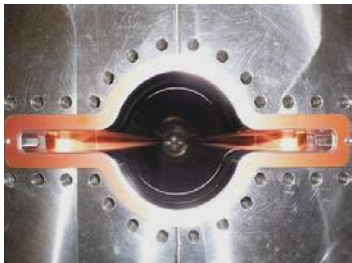
陽電子を低エミッタンスにする

- 偏向電磁石更新(LER)
- ウィグラー改造・新設

KEKB加速器からSuperKEKB加速器への大改修 — ビーム増強 —

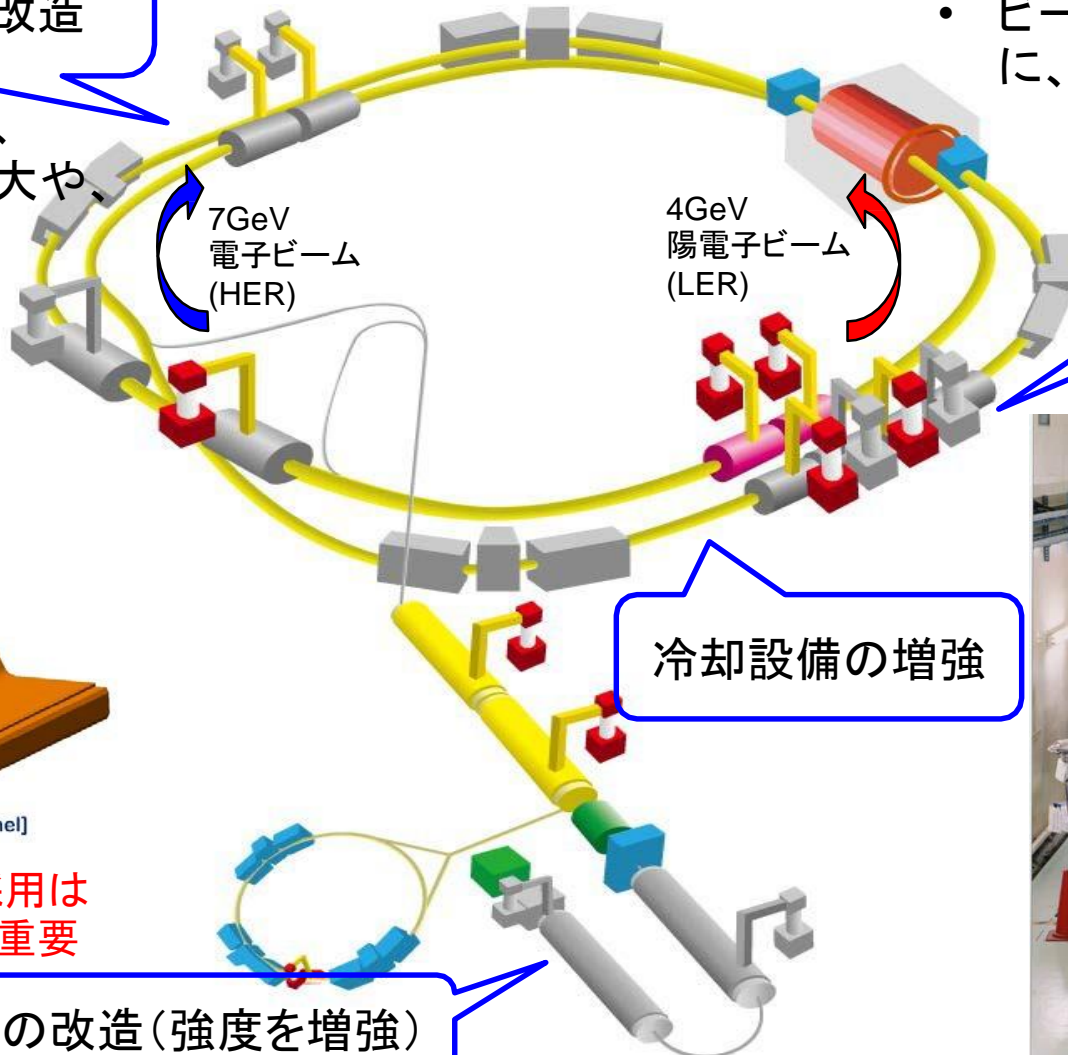
ビームパイプの交換等、
真空システムの改造

- 電子雲を抑制し、
ビームサイズ増大や、
不安定性を防ぐ
- 発熱対策



アンテナチャンバーの採用は
電流増強のためにも重要

入射器の改造(強度を増強)



- ビームに大電力を供給
- ビーム不安定を起こさず
に、安定に加速させる

高周波システム
の改造と増強

冷却設備の増強

