QCS power supply

Toshiyuki OKI
On behalf of the SuperKEKB magnet group

22nd KEKB Accelerator Review Committee

2018/MAR/15

Construction procedure and present status

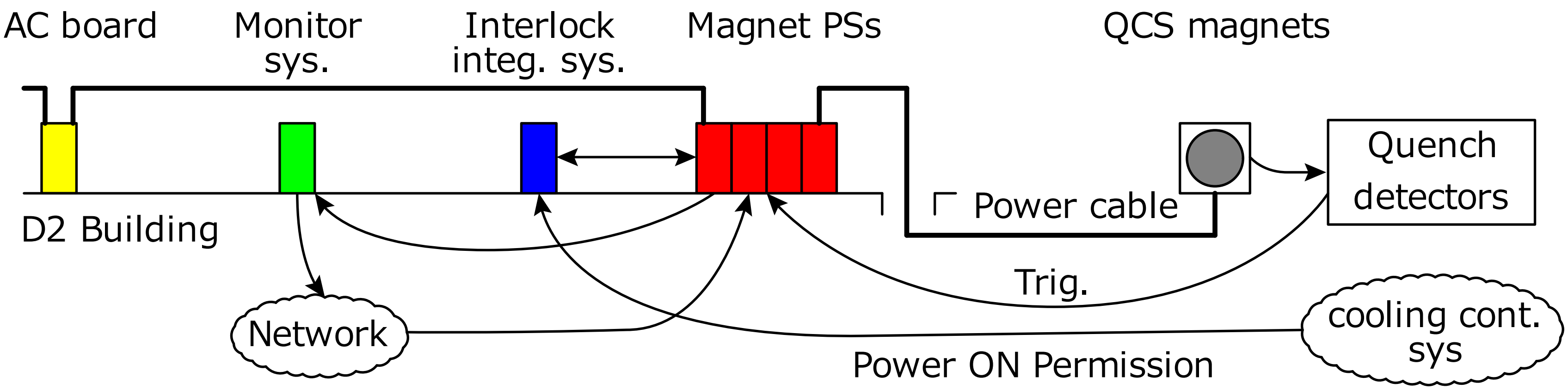
- ✓ System construction
- ✓ Full power test with actual load

Here we are ready to start Phase 2.

Today I show you:

- How the construction was carried out
- Preliminary performance test results
- Remaining issues

System overview



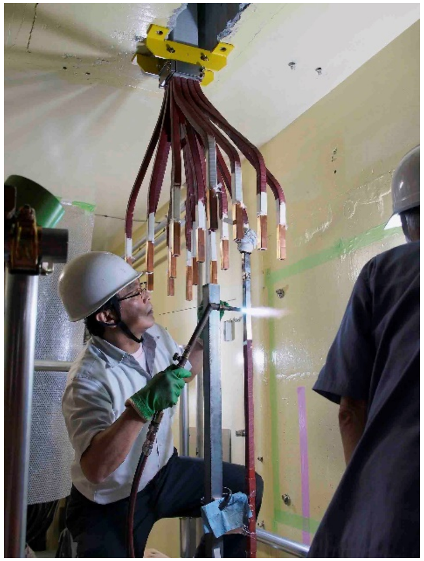
System consist of

- QCS 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.

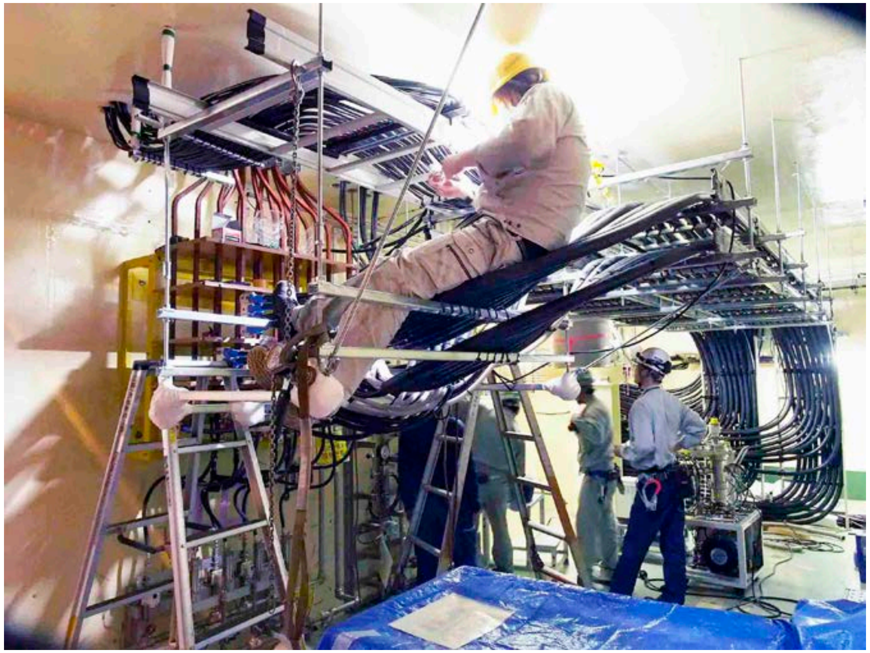
The system construction have been done as shown in following.

Cabling works

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



Under the bridge, they were connected with power cables.



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

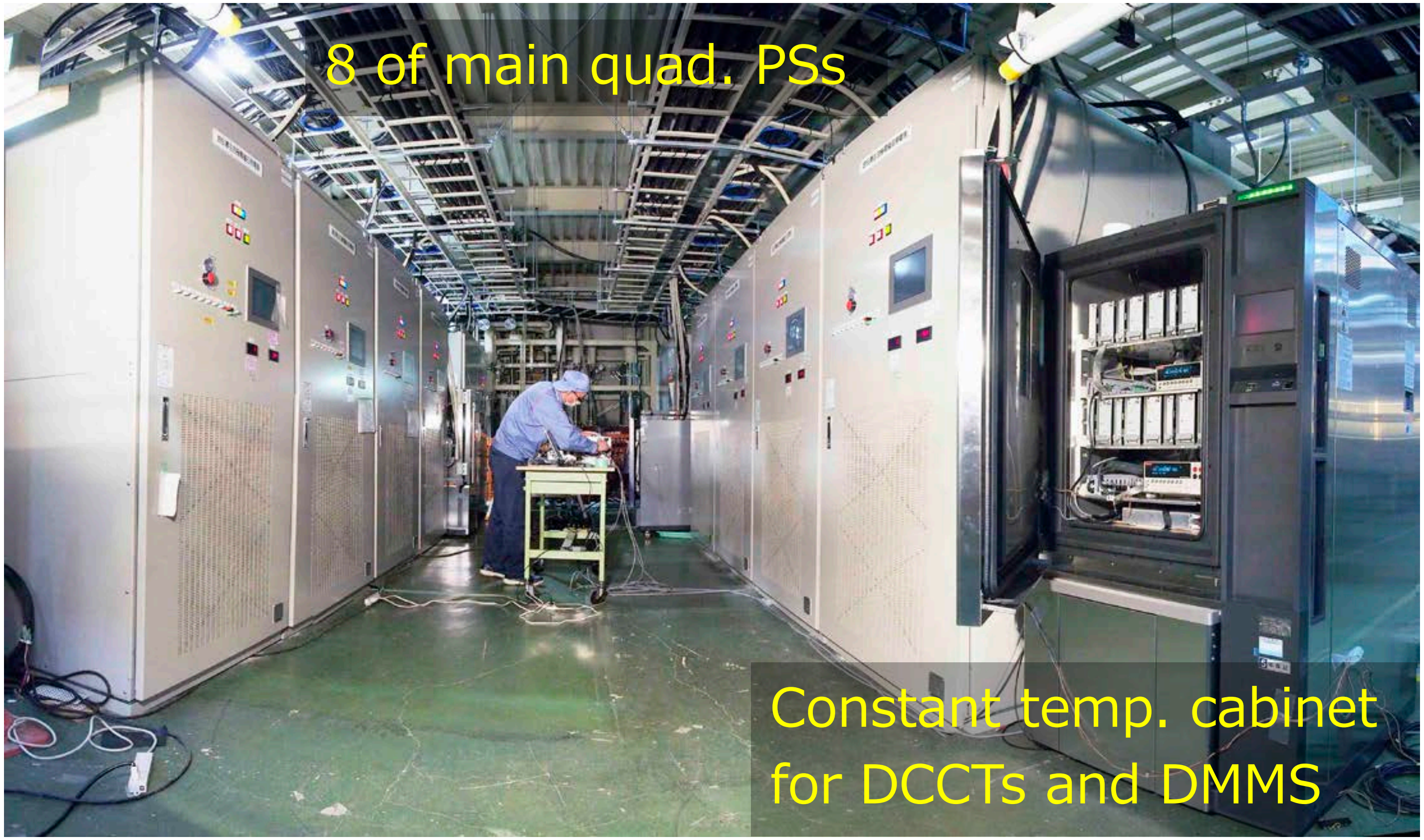
Yokogawa FA-M3 PLC

Keithley 2002 DMM

with 7001 switch sys.

Espec SU-642

Installation of power supplies



List of QCS 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)

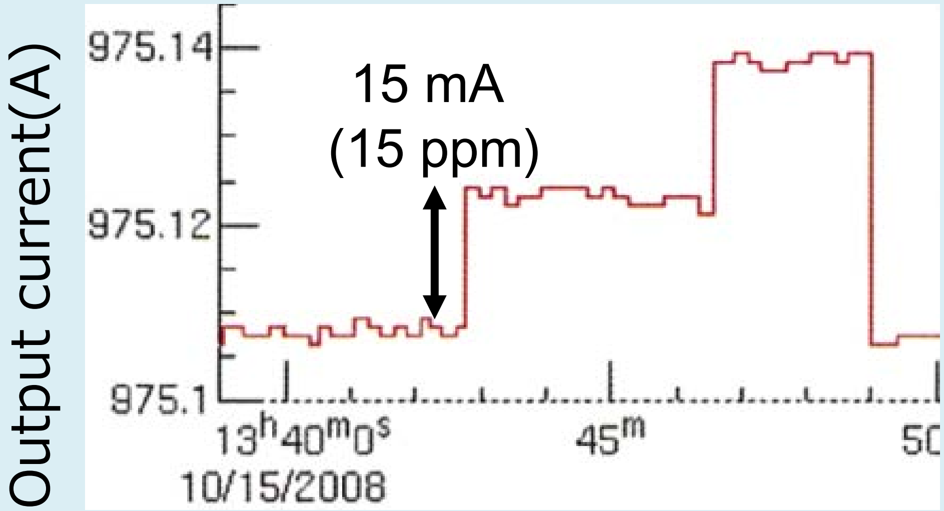
R&D items

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

R&D item 1: High current setting resolution

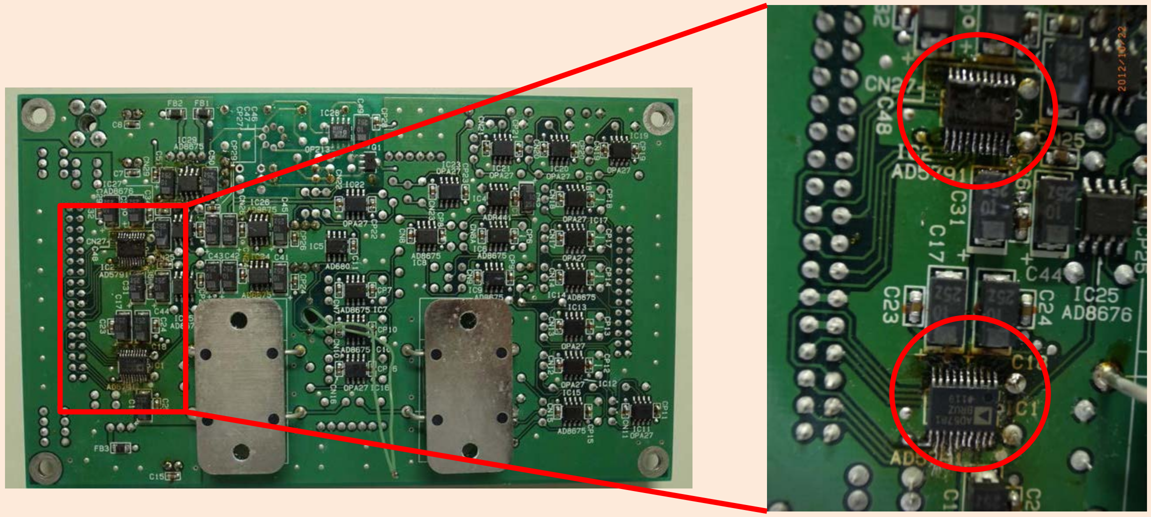
- Example of step response: 16-bit KEKB PS (1 kA, 700 V)

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.

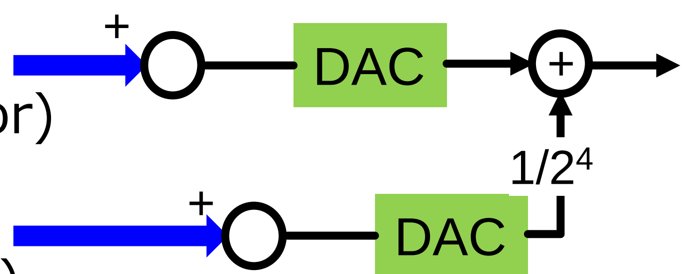
R&D item 1: Developed 24-bit board

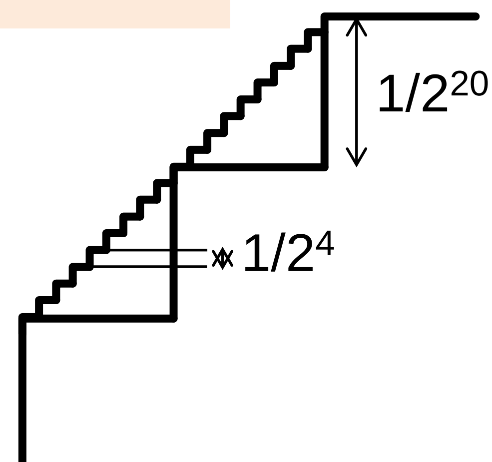


Analog Devices
AD5791BRUZ

Setting value
in 20-bits (major)

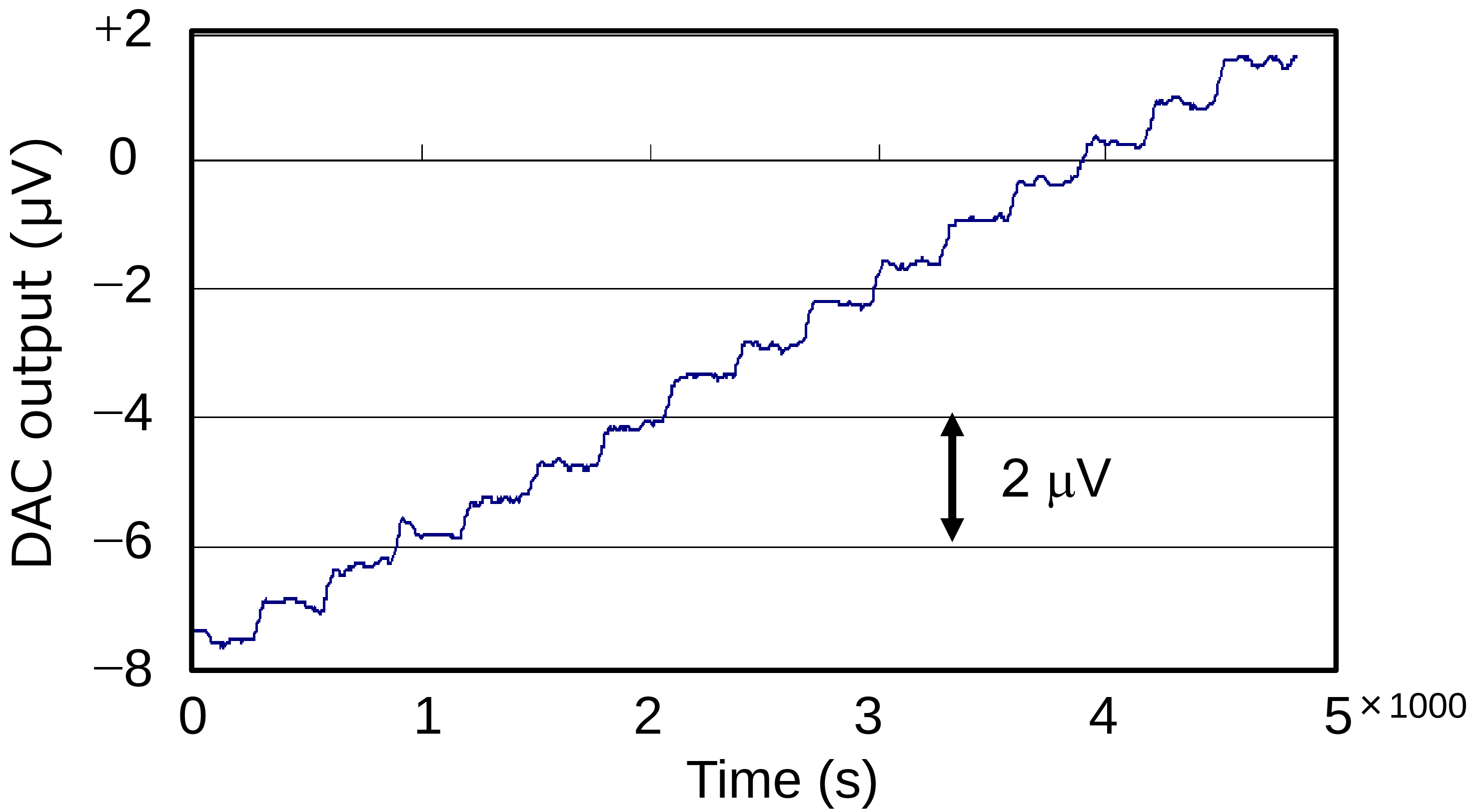
Setting value
in 4-bits (minor)





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.

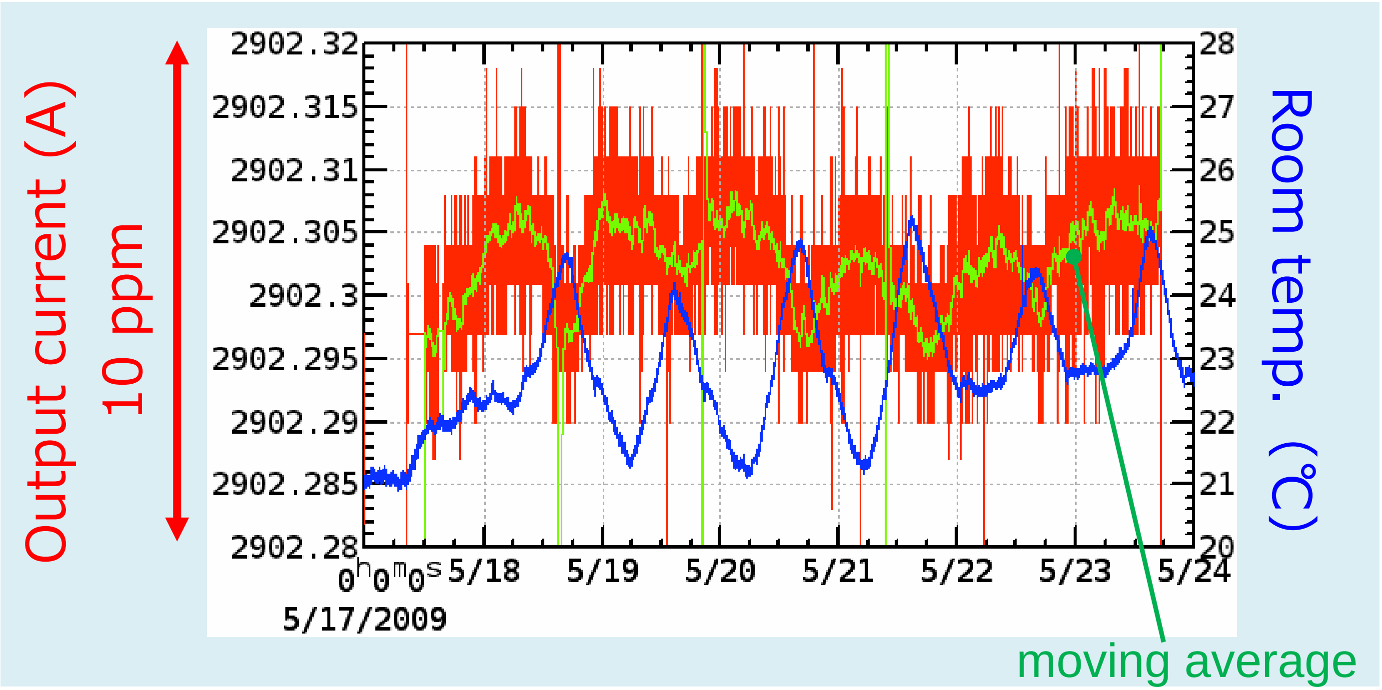


Monotonic 1 LSB response,

that is corresponds to 0.6 μV/10 V F.S, is obtained.

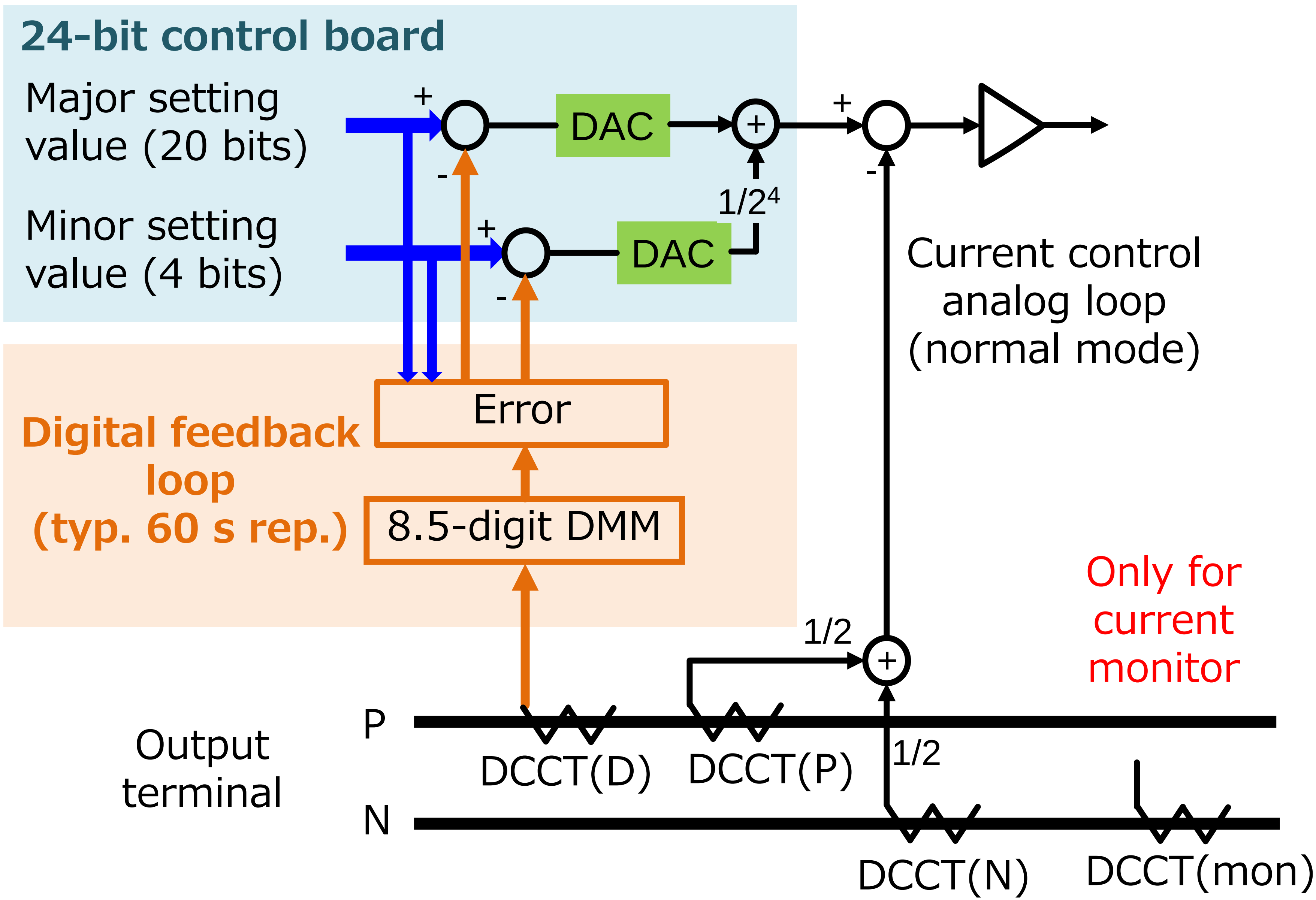
R&D item 2: High stability

- Example of stability: KEKB QCS PS (4 kA, 15 V)



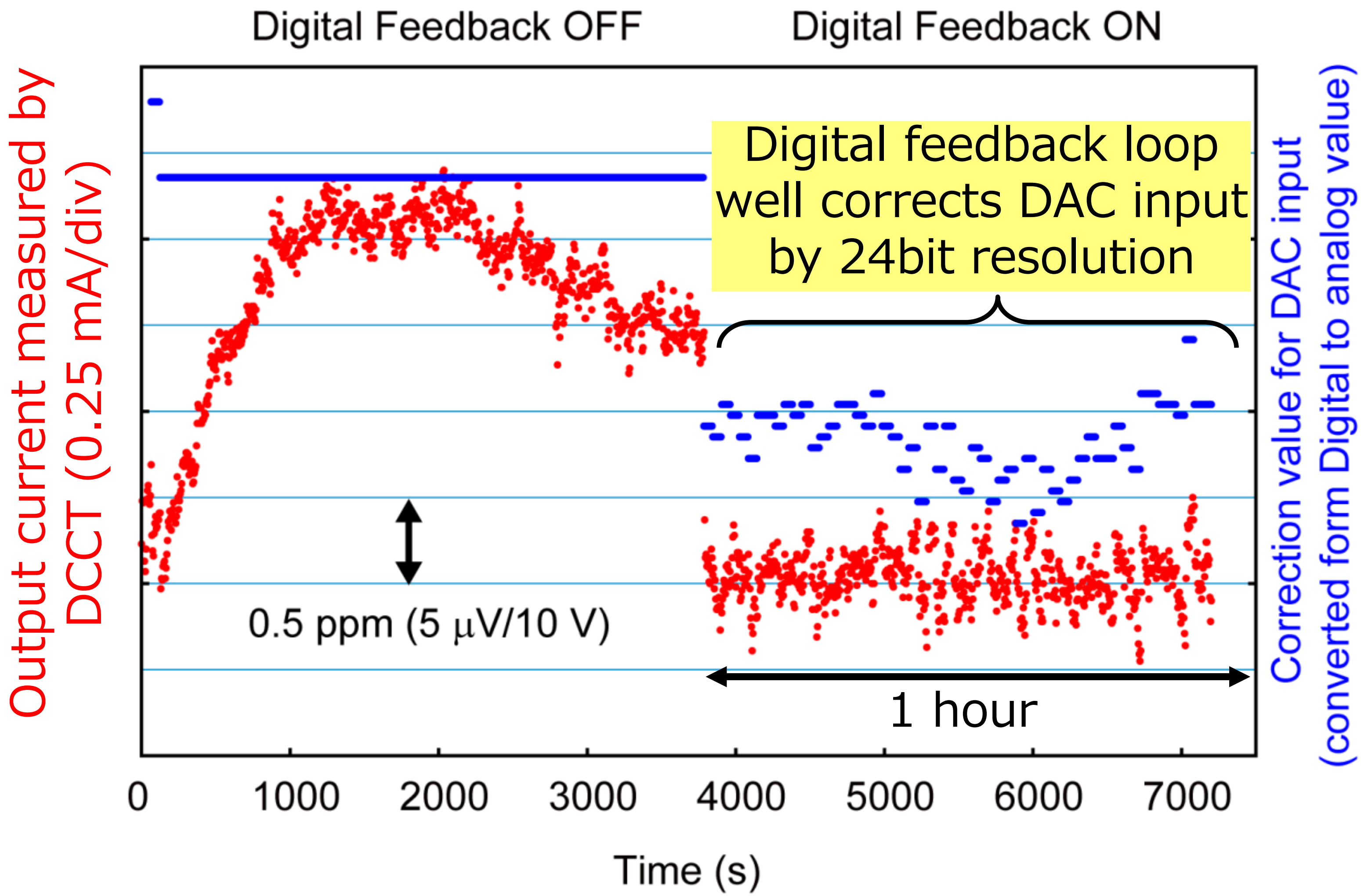
- Typ. stability is 10 ppm (peak to peak)/week.
- Resulting in 1 ppm/K of temp. coeff., although a temp. controlled box and low temp. coeff. parts were used.
- In order to suppress such a fluctuation in the output current, following digital feedback control is developed.

R&D item 2: Digital feedback control



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

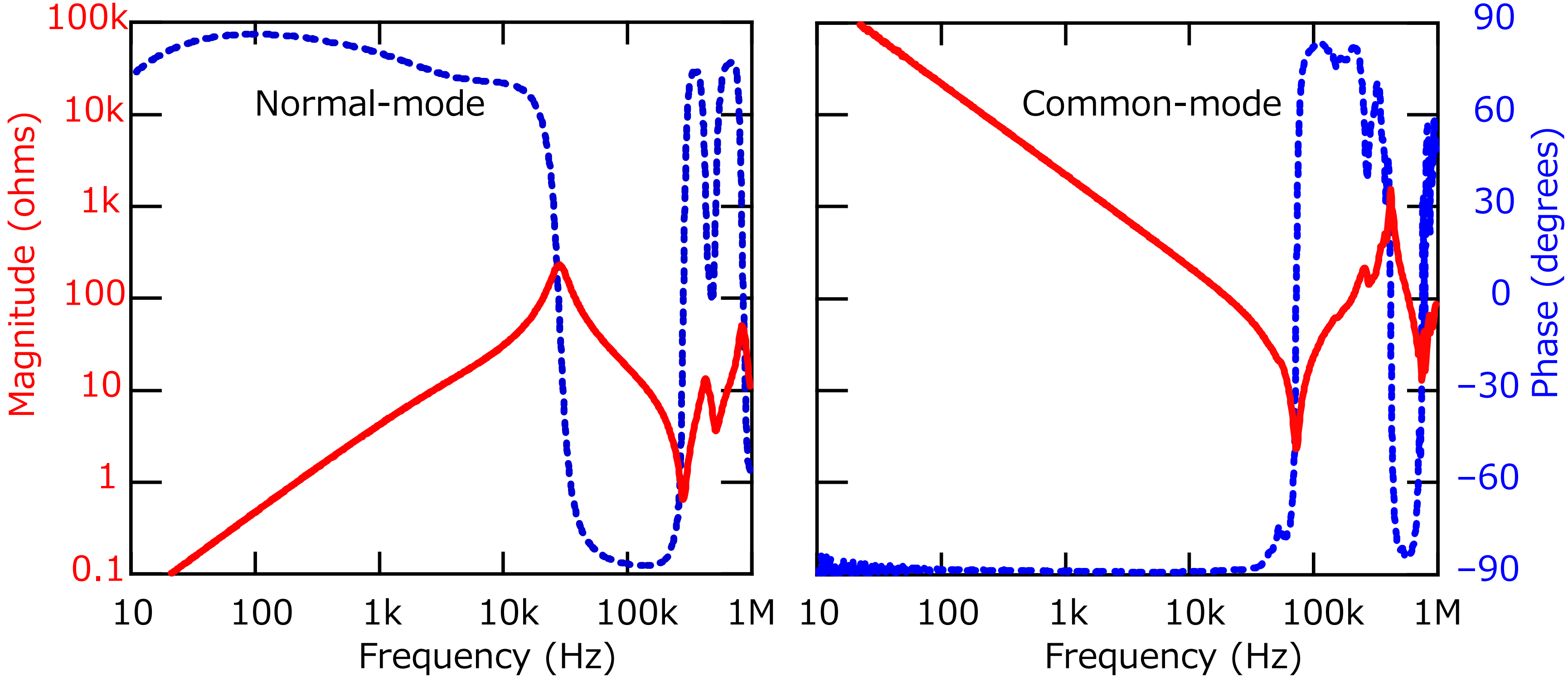
- Performed by using a medium-class power supply (15 V, 500 A).



1 ppm / h stability with low σ = 0.16 ppm

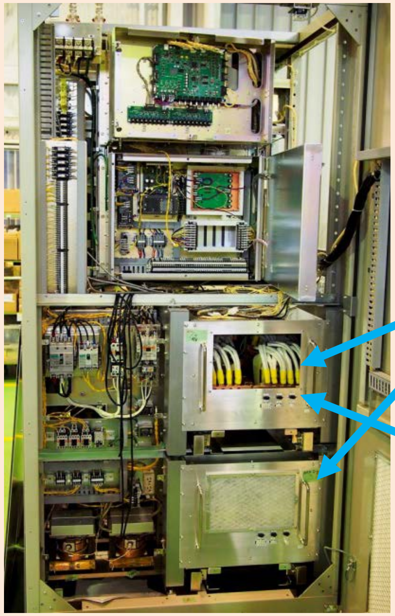
R&D item 3: Low ripple for low impedance load

- Example of the load impedance (QC1LP)

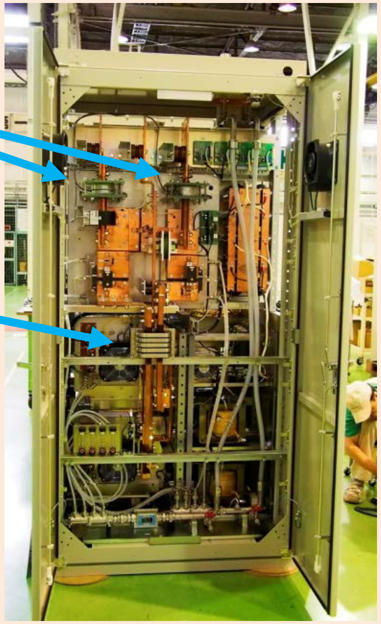


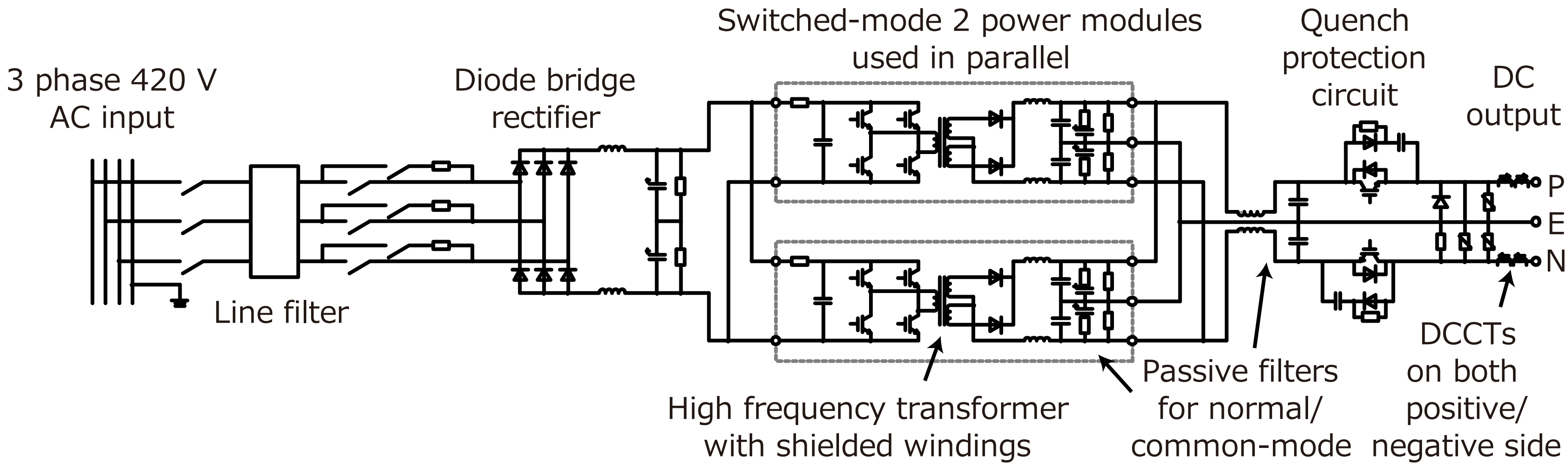
- Normal-mode impedance < several tens of Ω in the low freq. (<10 kHz) range: Possibility of large current ripple.
- Common-mode impedance < several tens of Ω in the high freq. (>10 kHz) range: Possibility of large switching noise.
- Symmetrical design of circuit is essential to reduce ripple and noise.

R&D item 3: Symmetric circuit design



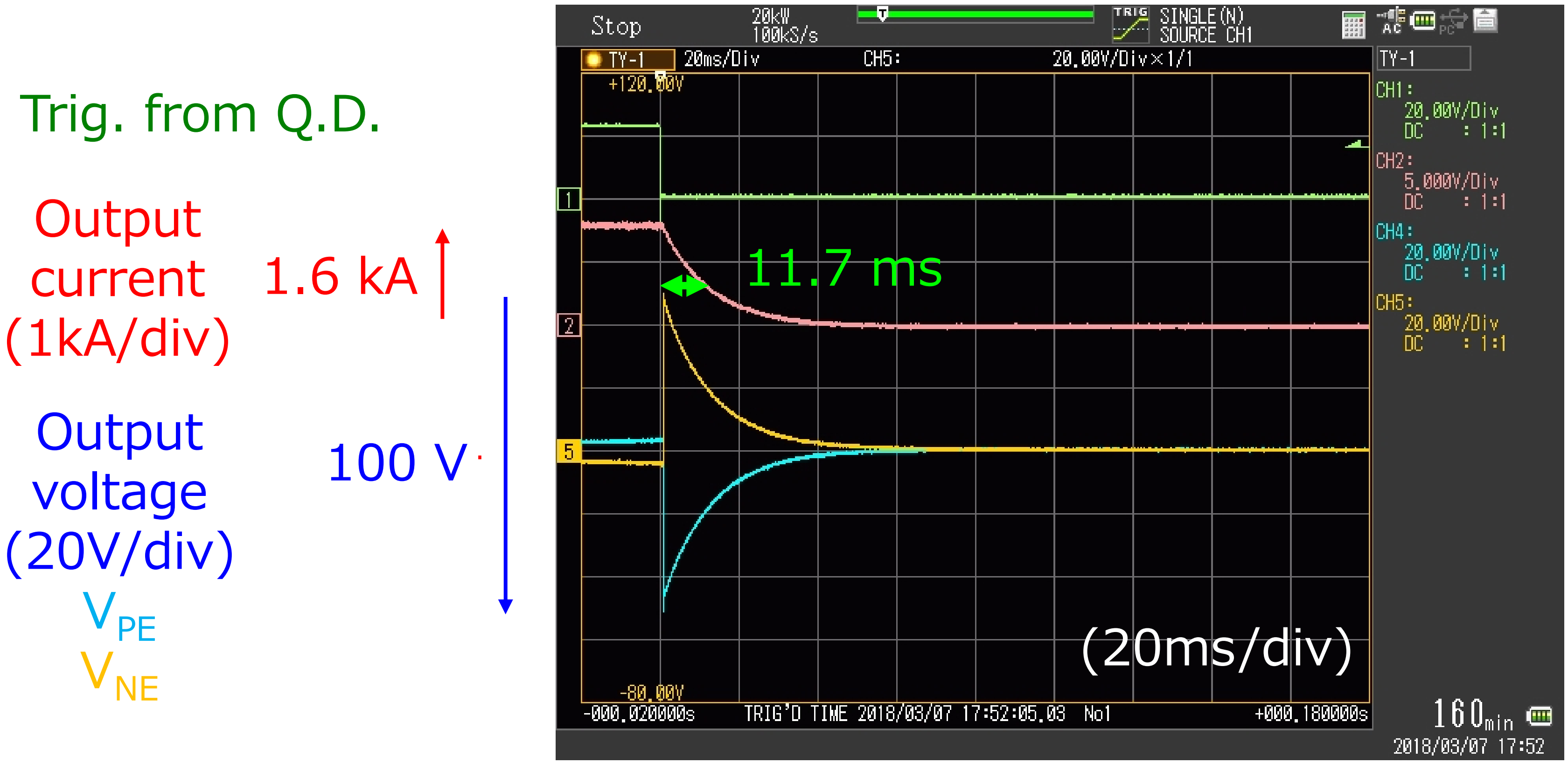
- ✓ DCCTs on both output terminals.
- ✓ Symmetric circuit structure with respect to ground.
- ✓ Shielded high-frequency transformer





Full power test with actual load

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



- Good agreement with estimations

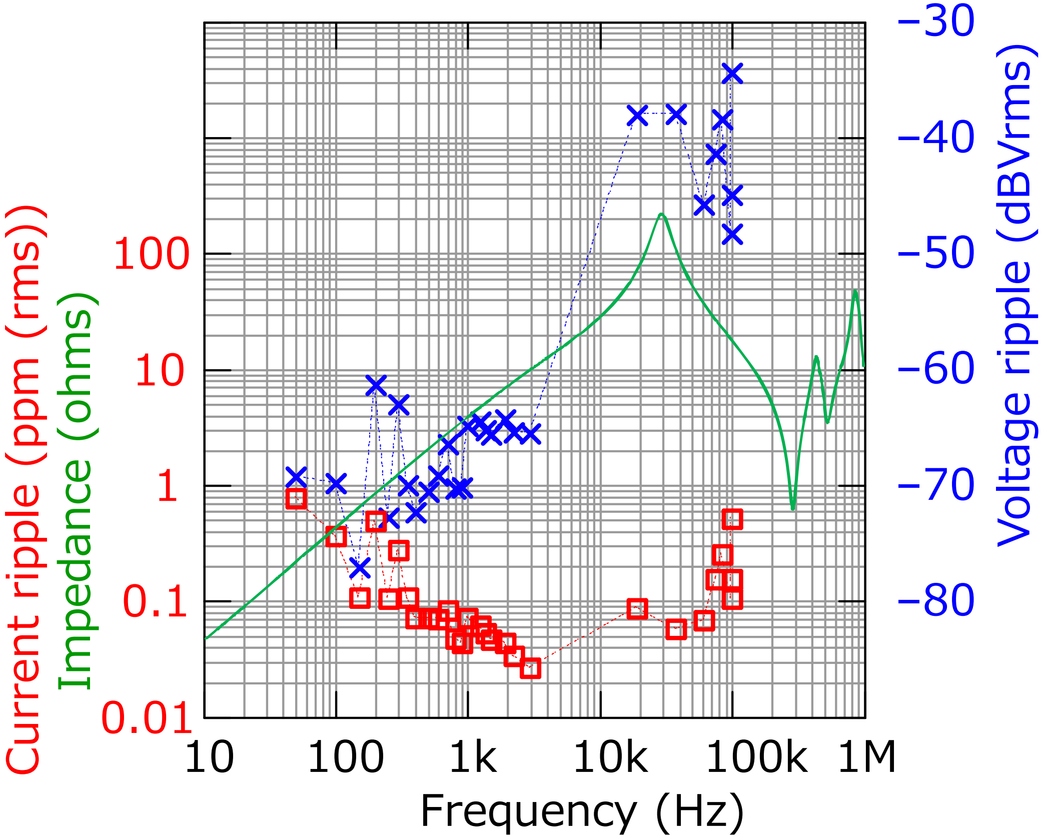
  Decay time constant : 14.2 ms=0.9 mH / (3.5 mΩ + 60 mΩ)

  magnet cable + protection R

  Induced voltage V_{PE}-V_{NE} : 96 V=1.6 kA×60 mΩ

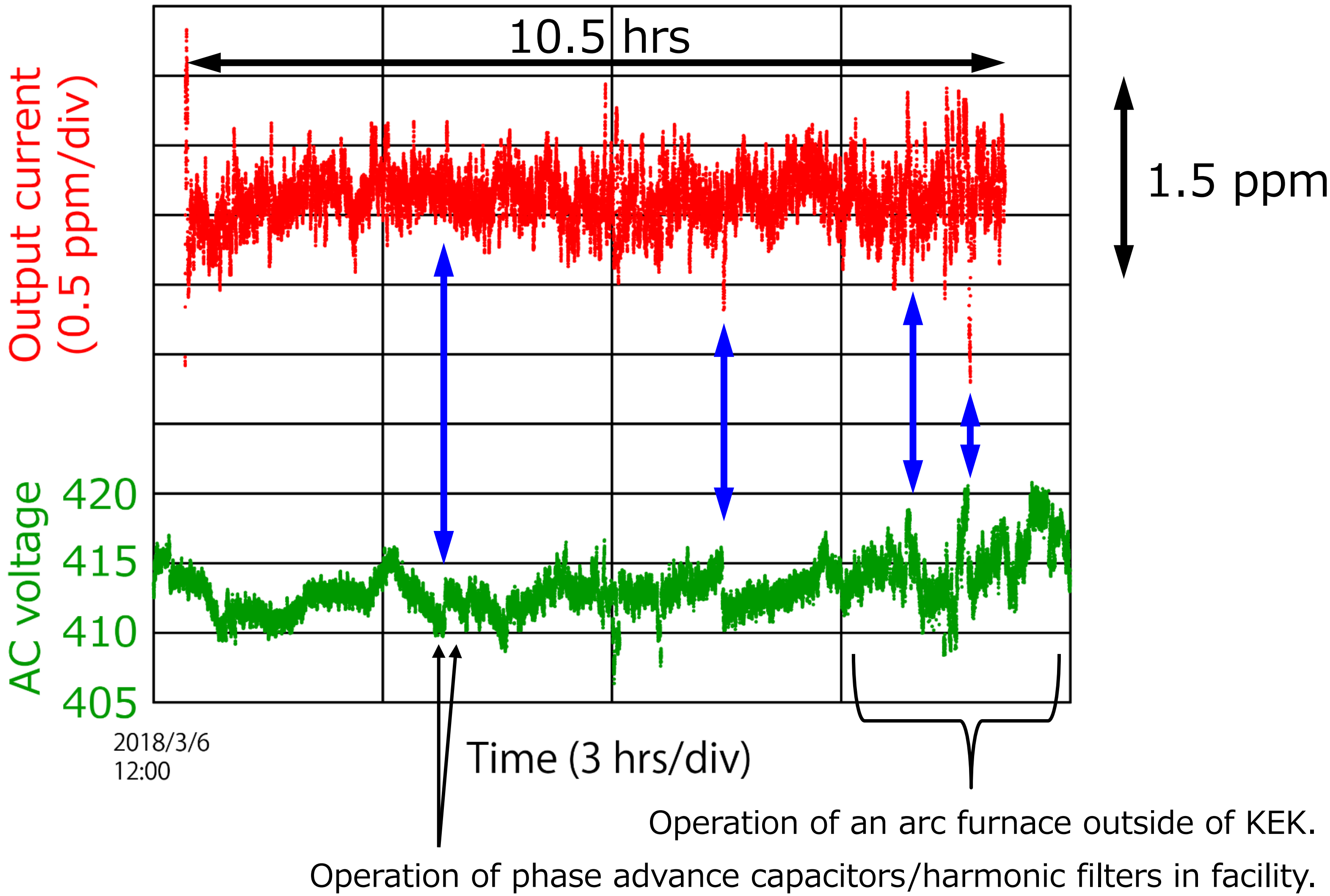
Performance test results 1: QC1LP current ripple

- 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



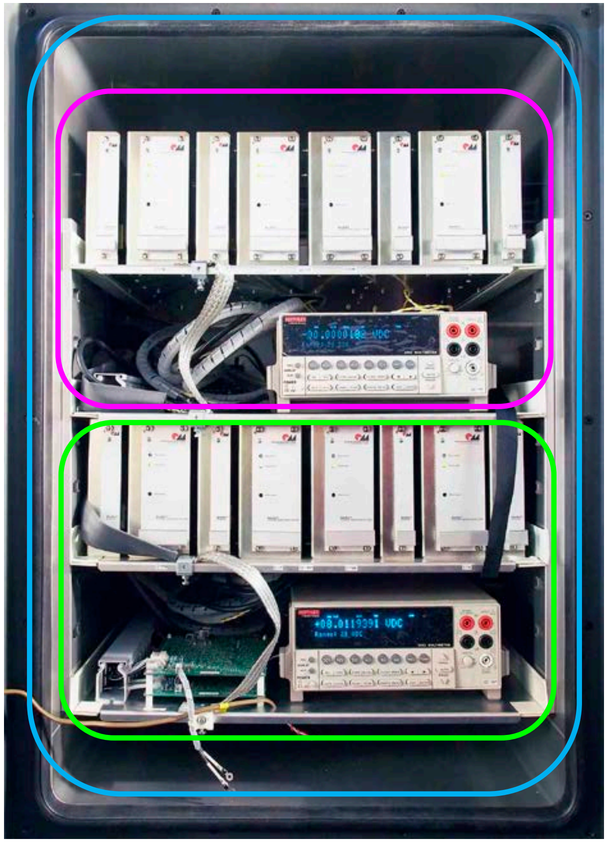
- ~1.5 ppm / 10.5 hrs of current stability is obtained.
- The rapid change in AC voltage leads to makes stability worse.

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

This digit

2 set of DCCTs and DMM inside a constant temp. cabinet



Ground connection should be separated each other.

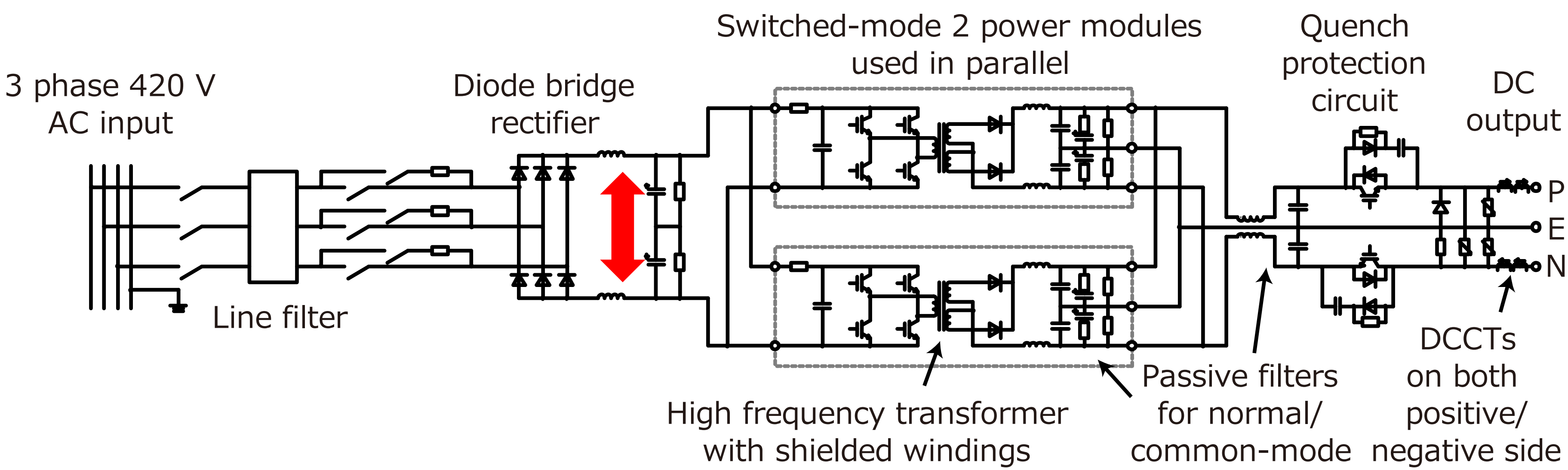
Summary and remaining issues

- ✓ System construction and full power test have been finished, so that we are ready to start Phase 2.
- ✓ Note for main quad. power supply, following is obtained:

  1.5 ppm of ultra-high stability and 1 ppm of low ripple

- ✓ Correction coils and anti-solenoid PSs are also works well.
- Improvement of the current monitoring system is also considered. The current signals are coupled each other due to unintentional coupling of the ground wires. These isolation is necessary.
- To reduce the influence of rapid change in AC voltage to the current stability of main quad. PSs, we will try to consider···
  - Further optimization of the feedback parameters,
  - Installation an AC reactor into the primary line,
  - To discuss with facility person for optimization of the operation of phase advance capacitor and harmonic filter in facility,
  - Suppression of the change in the DC voltage for chopper.

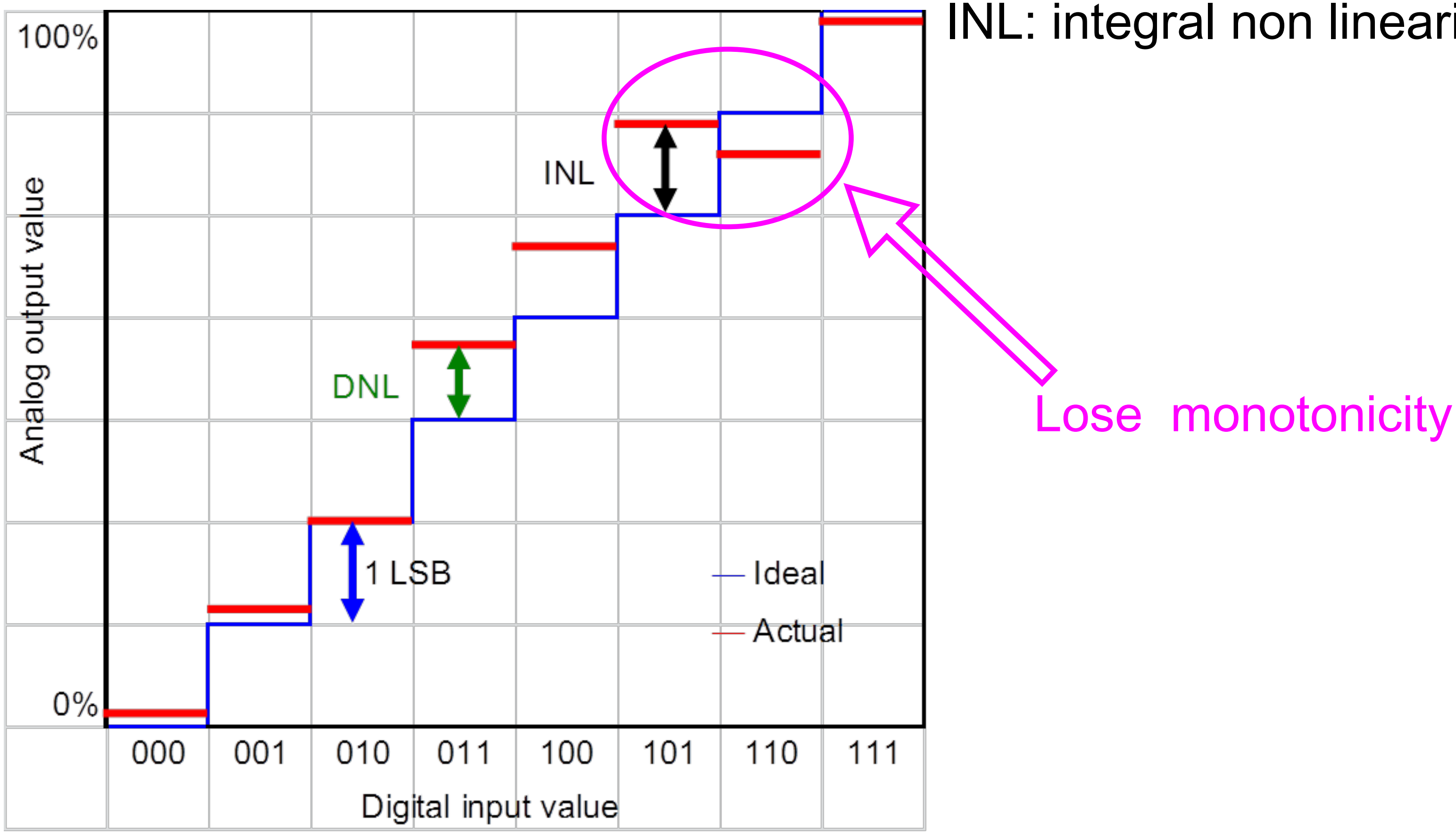
Feedback control of the DC voltage for chopper



Back-up slide

Non linearity and monotonicity

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

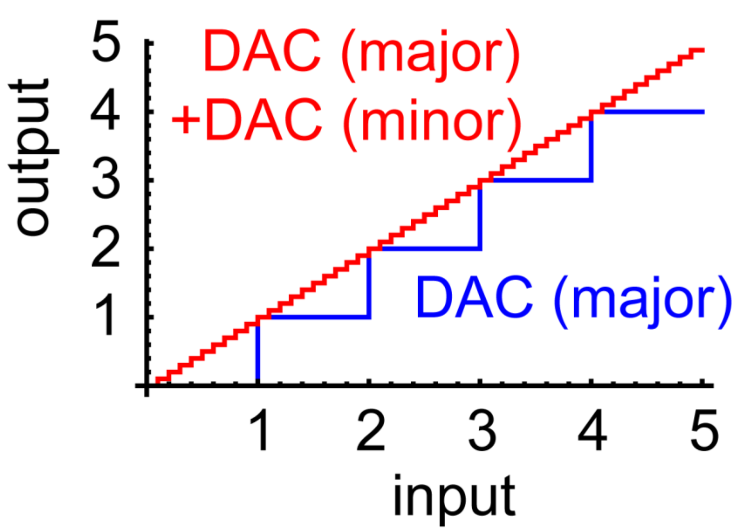


AD7846K (16-bit): DNL ±0.5 LSB max
INL ±2 LSB
AD5791B (20-bit): DNL ±0.75 LSB typ. (test result: <±0.1 LSB)
INL ±0.5 LSB typ. (test result: -0.2 ~ +0.6 LSB)

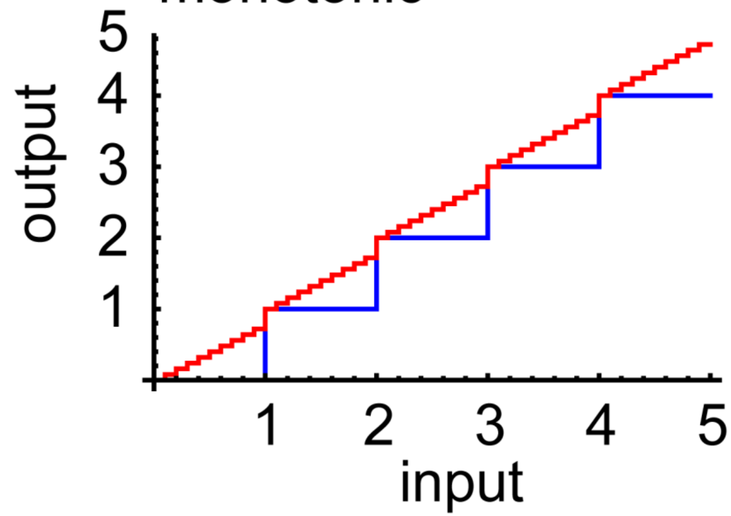
Why sixteen DAC's 24-bit system?

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

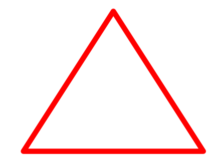
Ideal



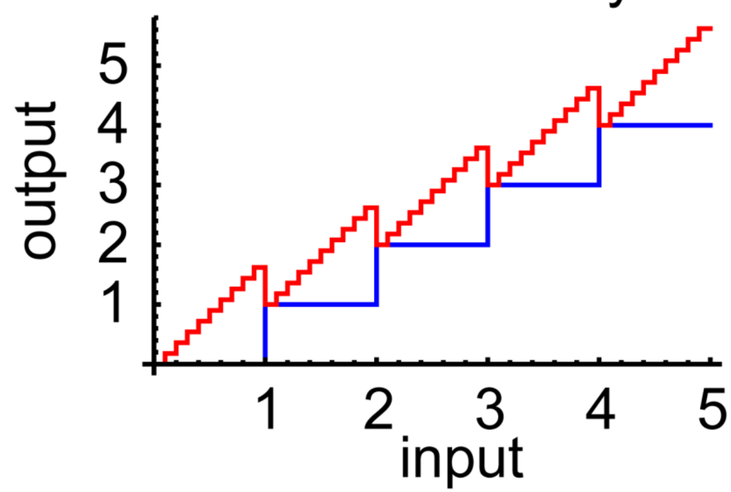
monotonic



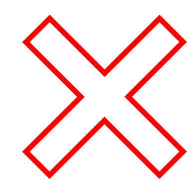
Not so bad



Lose monotonicity



Bad

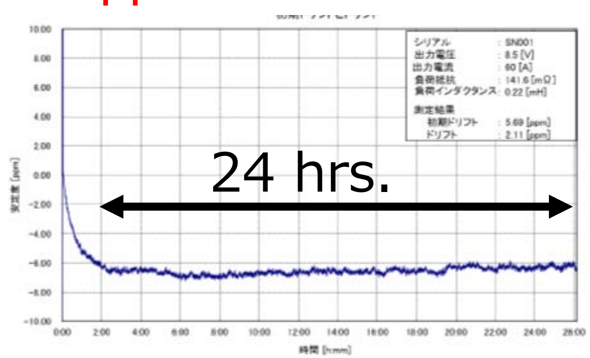


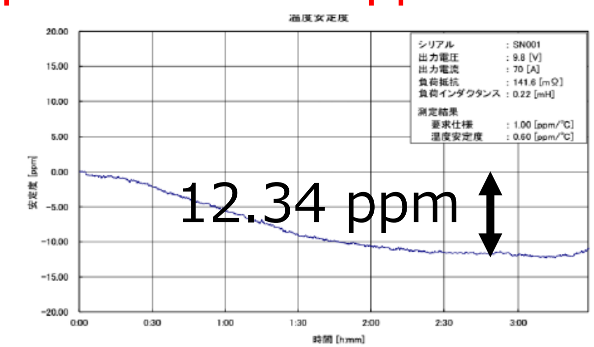
QCS corrector power supply

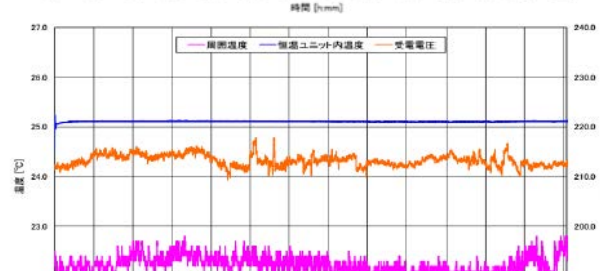
45 of QCS corrector power supplies was fabricated.

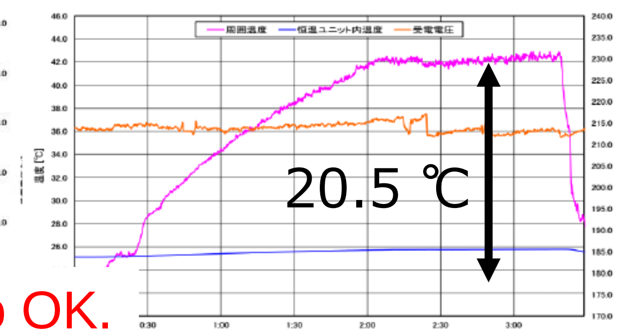
Rated output	DC ± 70 A, 10 V
Current setting resolution	< 1 ppm
Current stability	< 5 ppm/8 hrs.
Current ripple (< 10kHz)	< 5 ppm (rms)
Current noise (> 10kHz)	< 5 ppm (0-peak)

Test results: Stability 2.1 ppm/24 hrs. with temp. coeff. of 0.6 ppm/℃







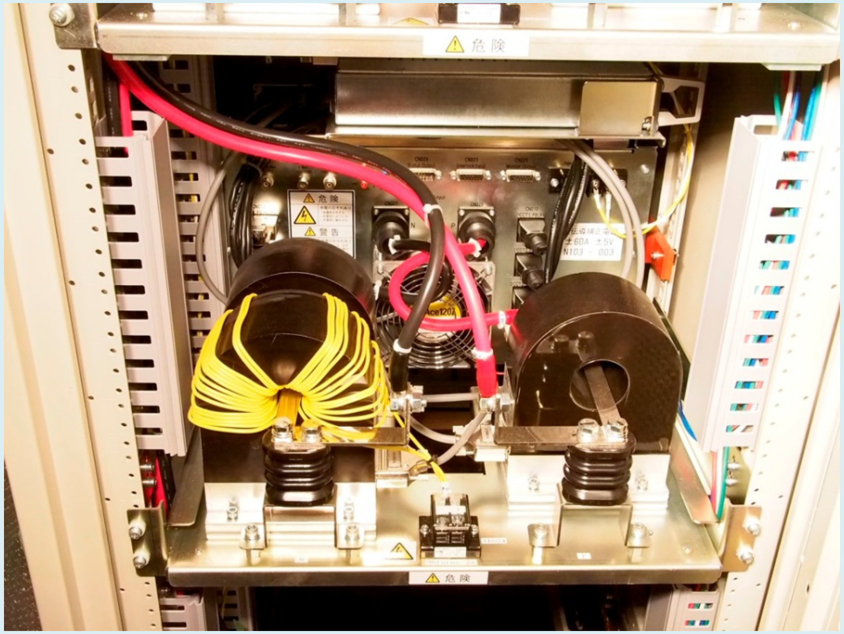


Ripple, noise, quench protection test and so on: also OK.

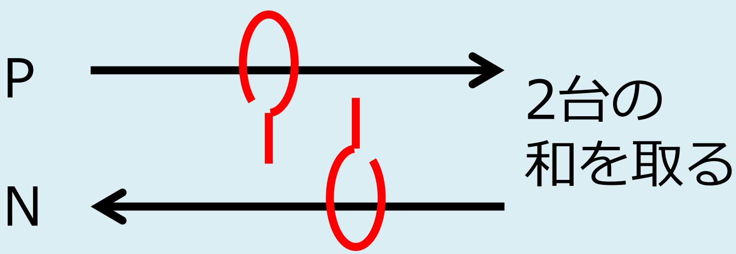
超伝導補正電磁石電源でのDCCTのコストダウン

仕様：60 A- 5 V
5 ppm/8時間

改造前

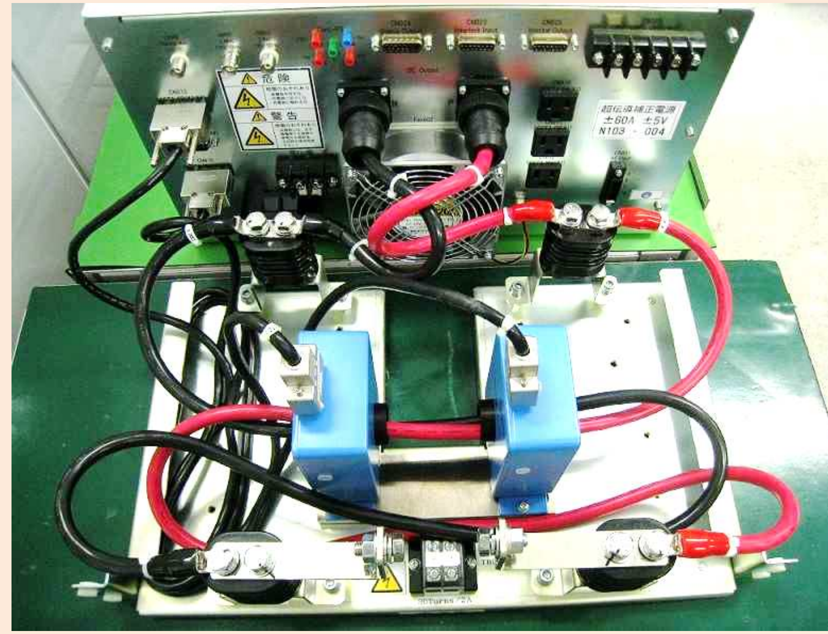


・TOPACC （88万円/台）
・計3台（制御×2、モニタ× 1）

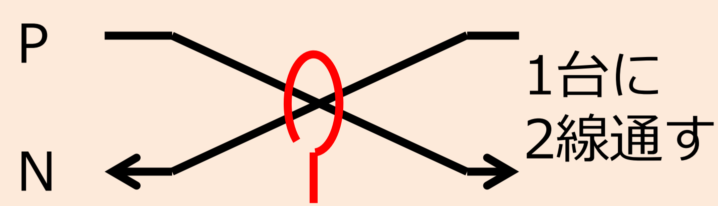


・電源45台分：11,880万円

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）

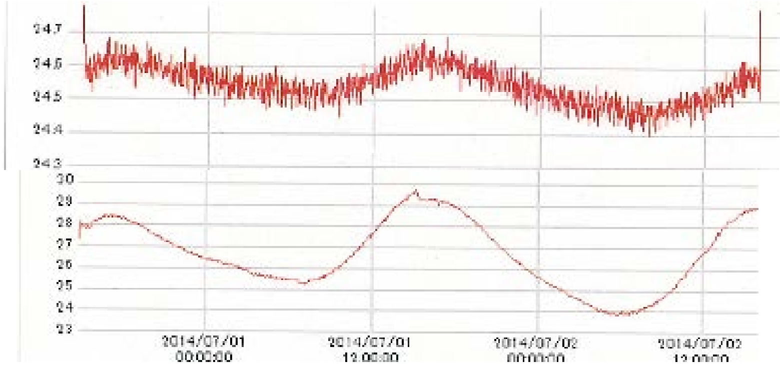
- 0.125 ppm/K (AD5791 DAC with Buffer amps.)
- 0.5 ppm/K (TOPACC optionalの場合：標準は1.5 ppm/K)
- 0.3 ppm/K (Keithley 2002)

恒温槽（espec LU-123）の温度変化（2日間実測）

・周囲温度変化　5.5 ℃に対して、
　恒温槽内温度変化　0.2 ℃

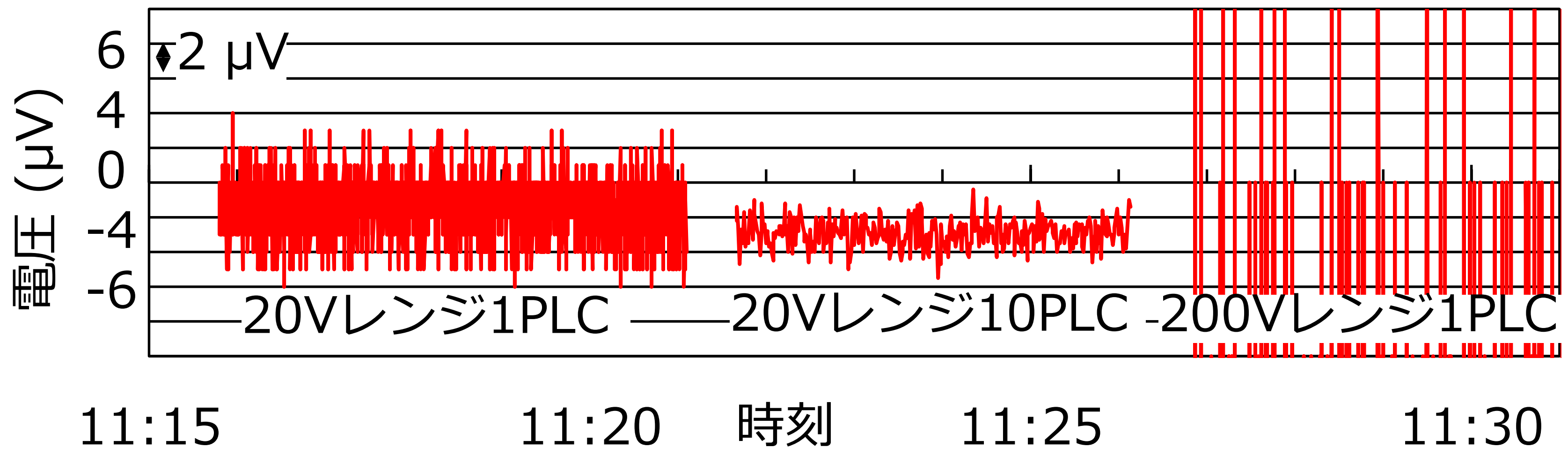
デジタル帰還制御の温度係数の見積

・(0.5+0.3)×0.2=0.16 ppm程度
・(1.5+0.3)×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	σ×2√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

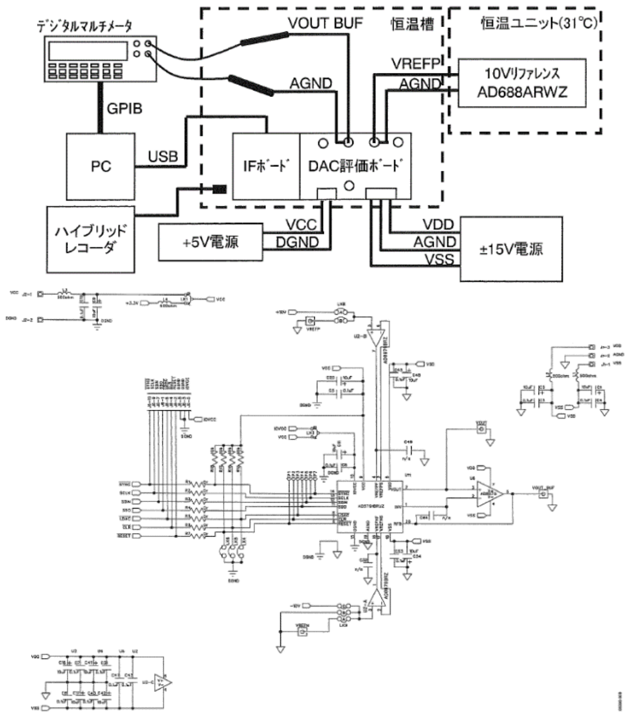
10 Vの0.1 ppm = 1 μV

仕様とよく合っている。

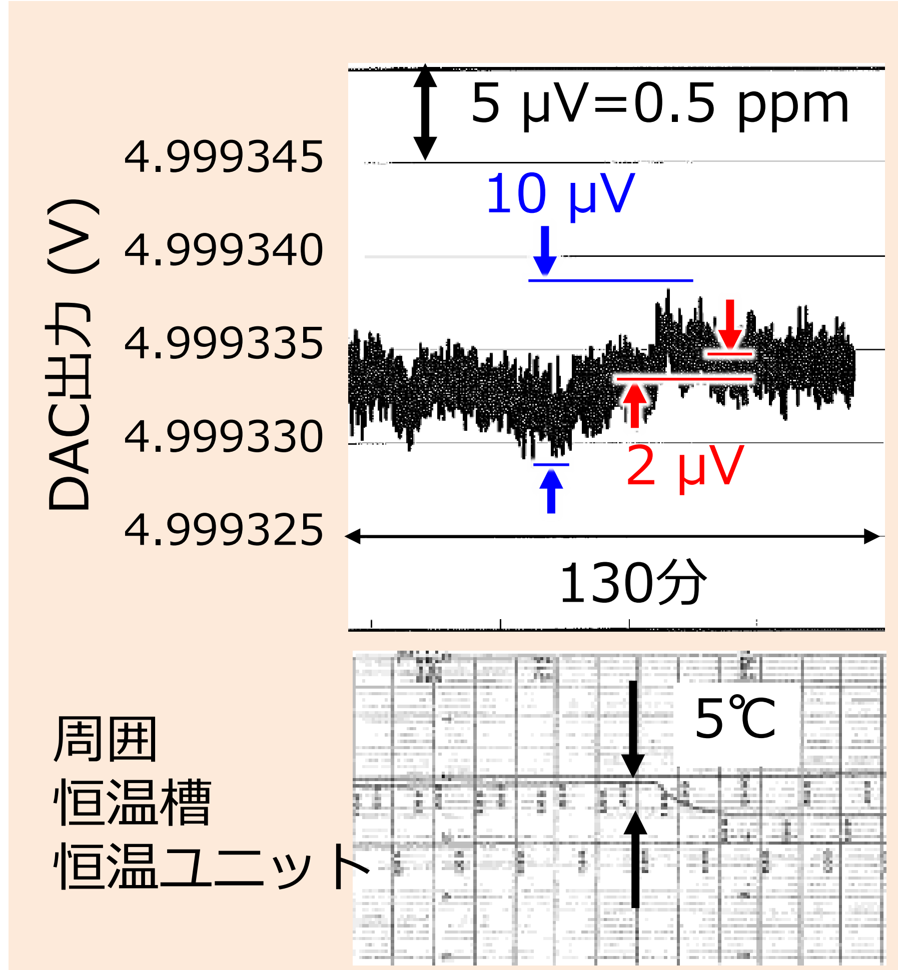
20 Vレンジ、10 PLCなら、0.1 ppm以下の制御に使える

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 μV/℃
AD8676		0.6 μV/℃
AD8675		0.6 μV/℃
1.25 μV/℃	→	0.125 ppm/℃



温度係数：0.04 ppm/℃

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)

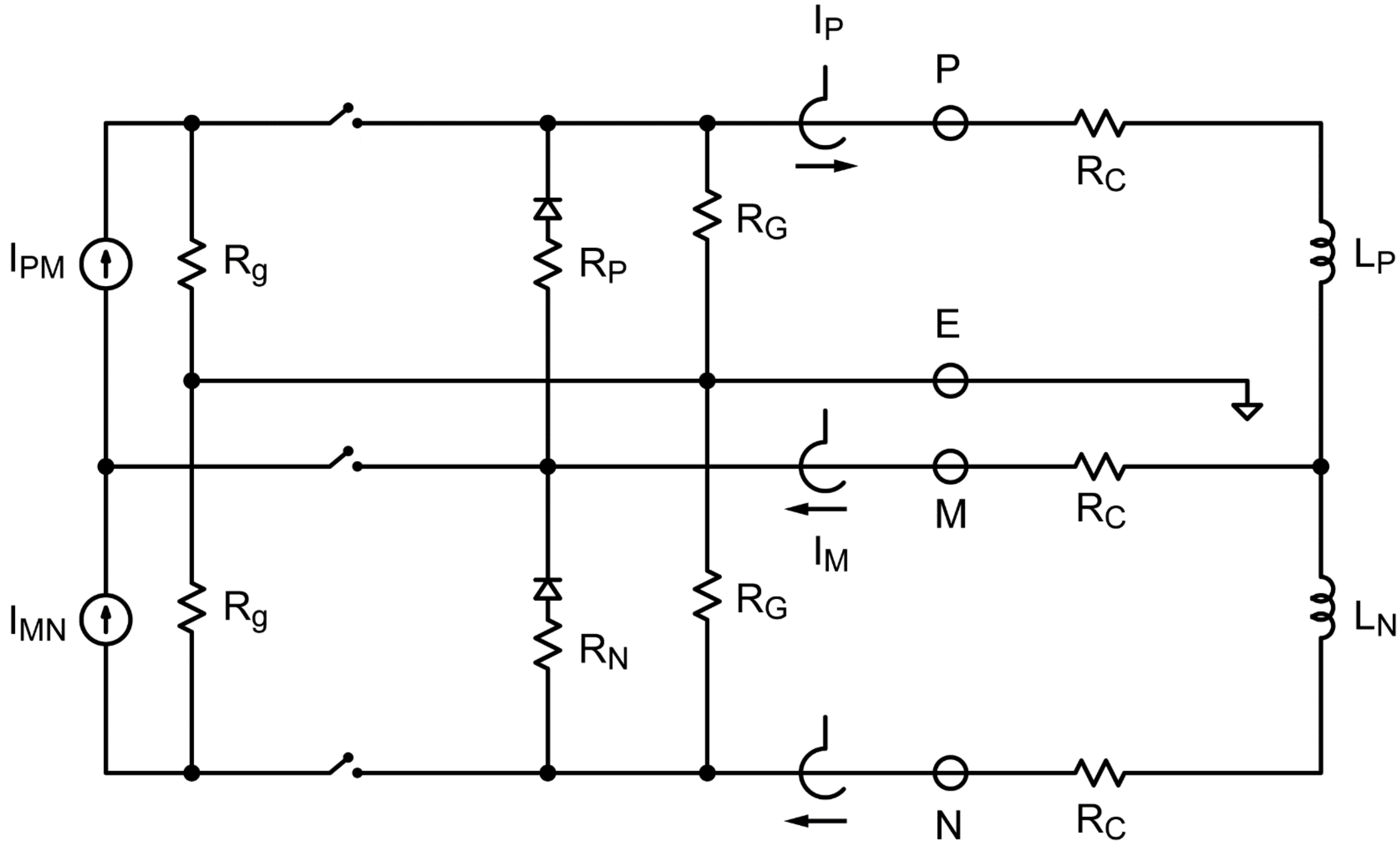
・温度係数：0.5 ppm/K (TOPACC optionalの場合：標準は1.5 ppm/K)

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

ELS/ESR1電源の電流制御：中間タップのある三端子出力系



I_{PM}, I_{MN}：P, N側主電源出力電流

R_g：遮断時に解放される主電源出力端電位を
　　接地に対して対称に定める接地抵抗

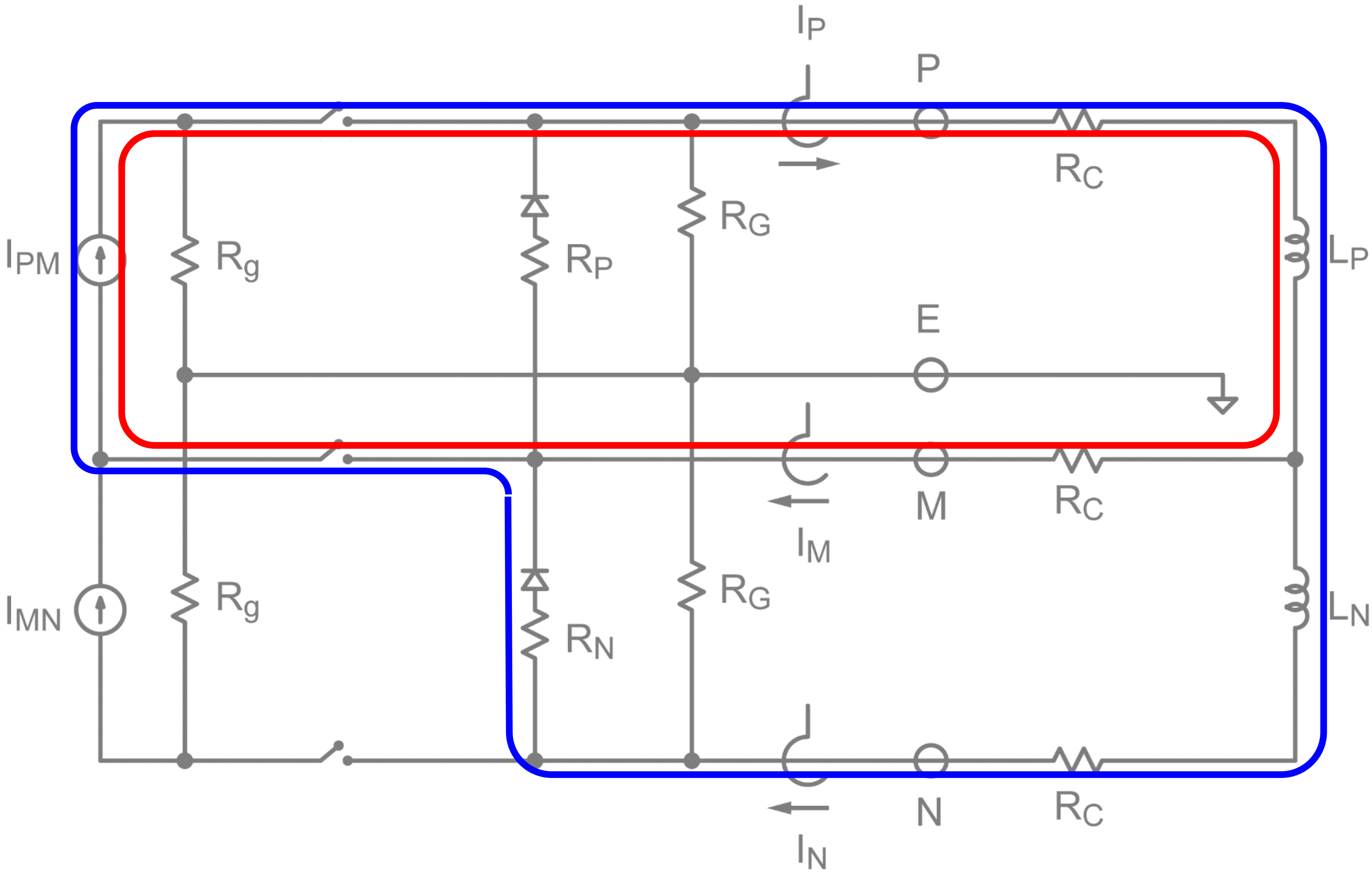
R_P, R_N ：P, N側保護抵抗　($L_P/R_P = L_N/R_N$)

R_G：遮断時にP, N端子電位を接地に対して対称に定める接地抵抗

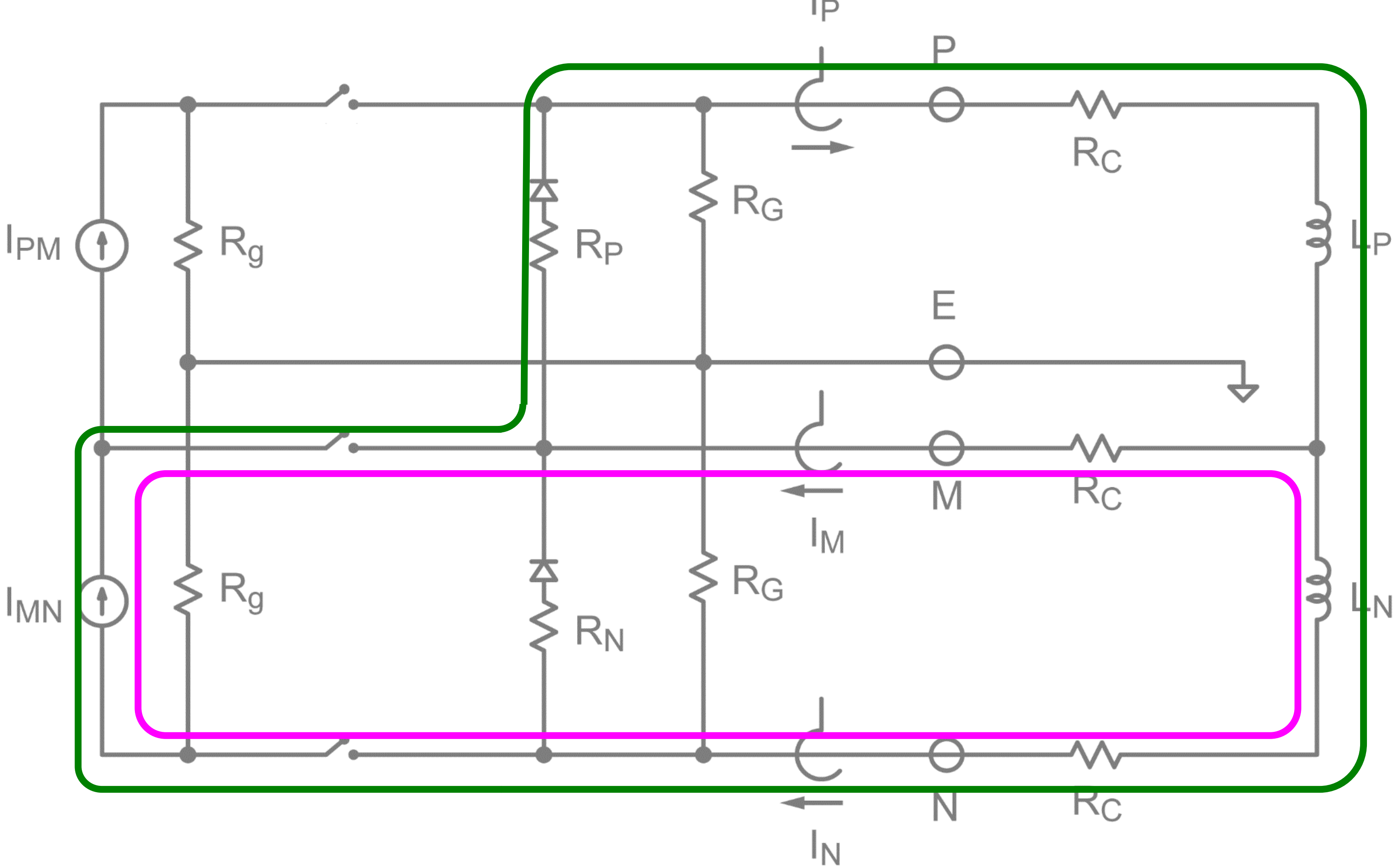
I_P, I_M, I_N：電流モニターによる計測値

P, E, M, N:電源出力部の端子

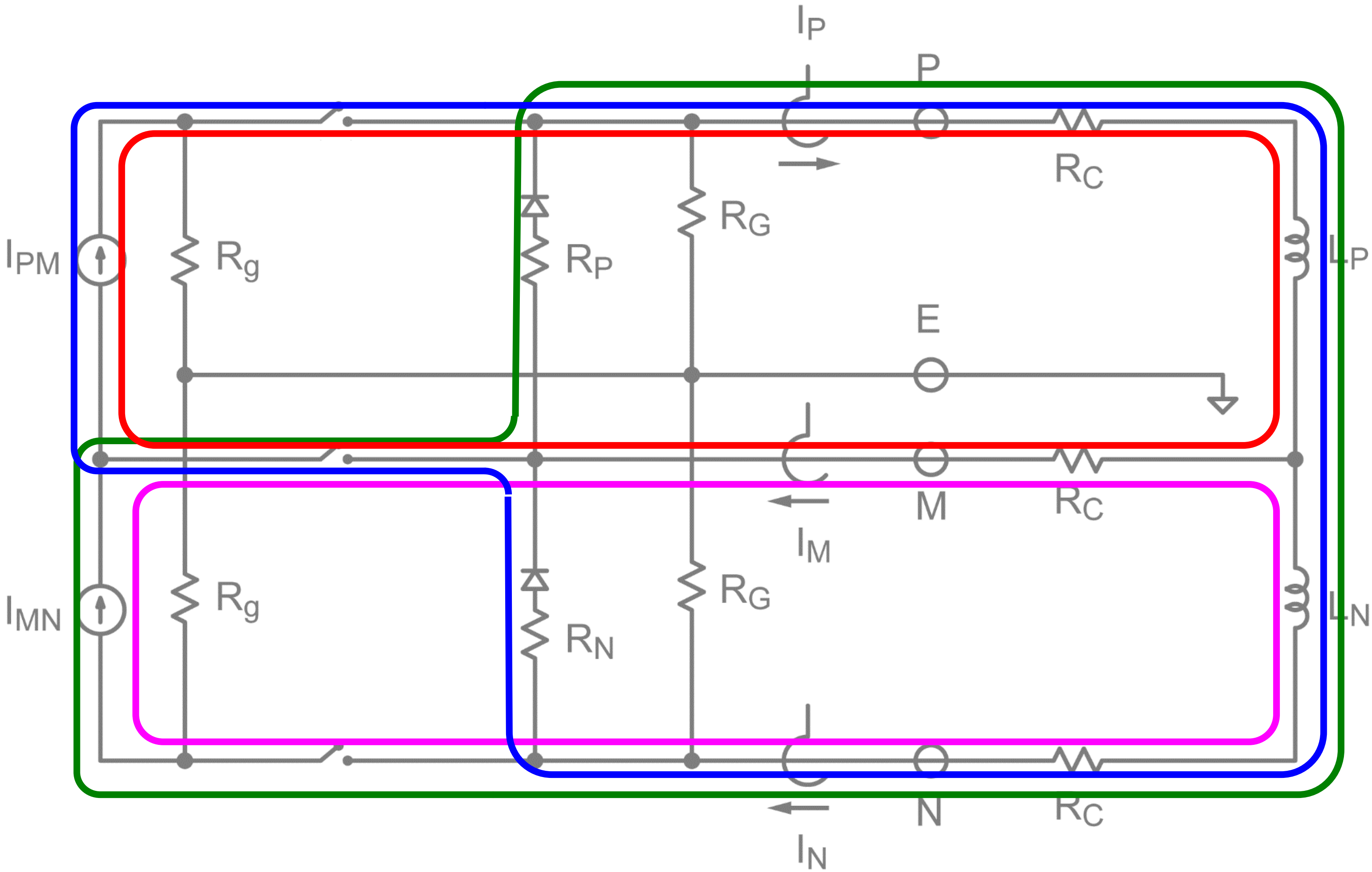
R_C：ケーブル抵抗



・I_{PM}の流れる経路：
ダイオードがあるので赤ループの他に青ループにも流れる。
ケーブル抵抗R_C×2が最大22mΩに対して、保護抵抗は120～810mΩなので、
無視できない大きさの電流が青ループに流れる。

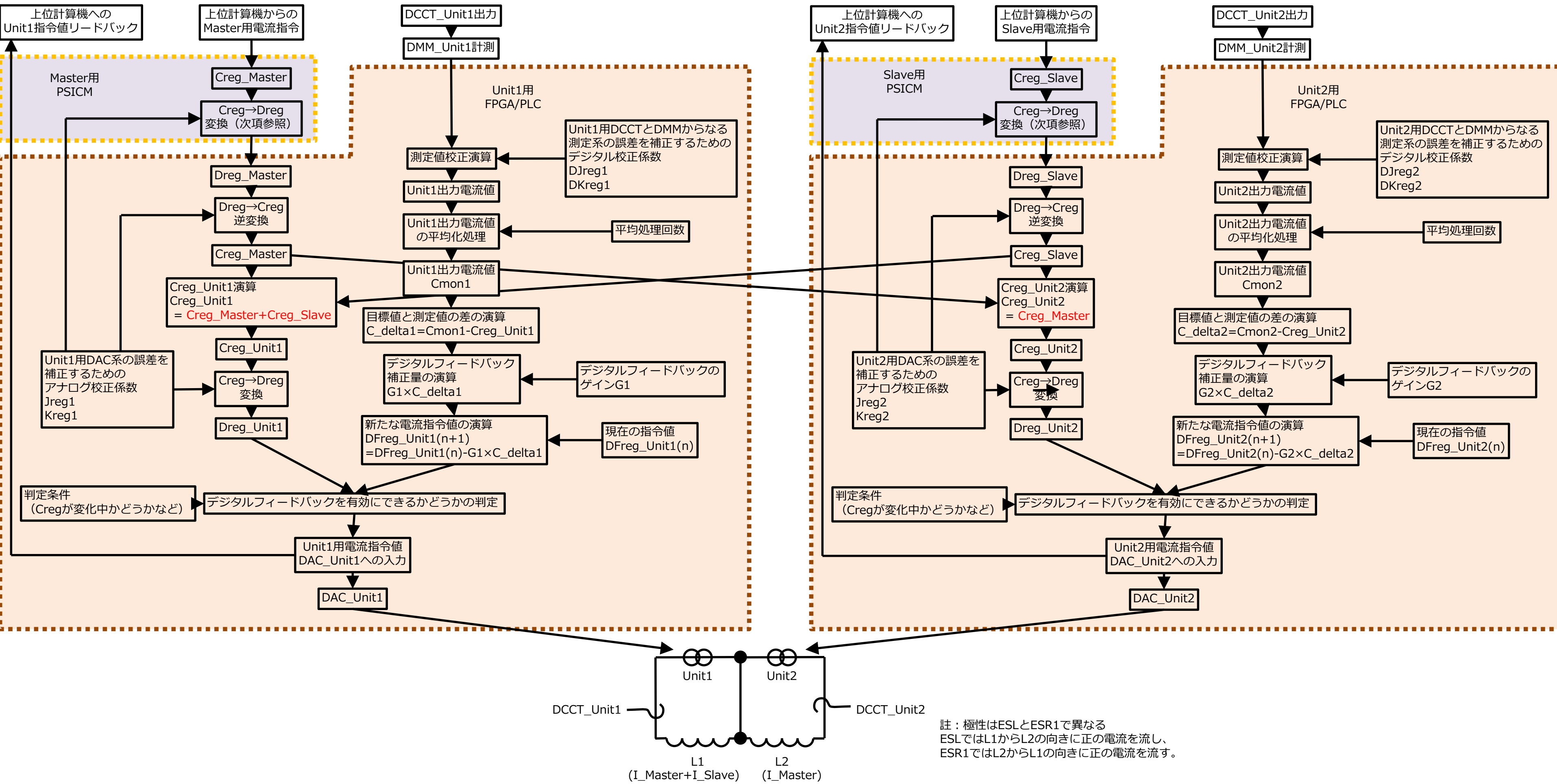


・I_{MN}の流れる経路：同じく。



- I_{PM}とI_{MN}の流れる経路を重ね合わせると…
- L_Pを流れる電流はI_P、L_Nを流れる電流はI_N
- I_{PM}の一部（青）はI_Nを流れ、I_{MN}の一部（緑）はI_Pを流れ、結合している。
- I_P、I_Nの計測値を連立させ、結合を分離し、I_{PM}とI_{MN}を独立に制御する。

ESL/ESR1電源の電流指令

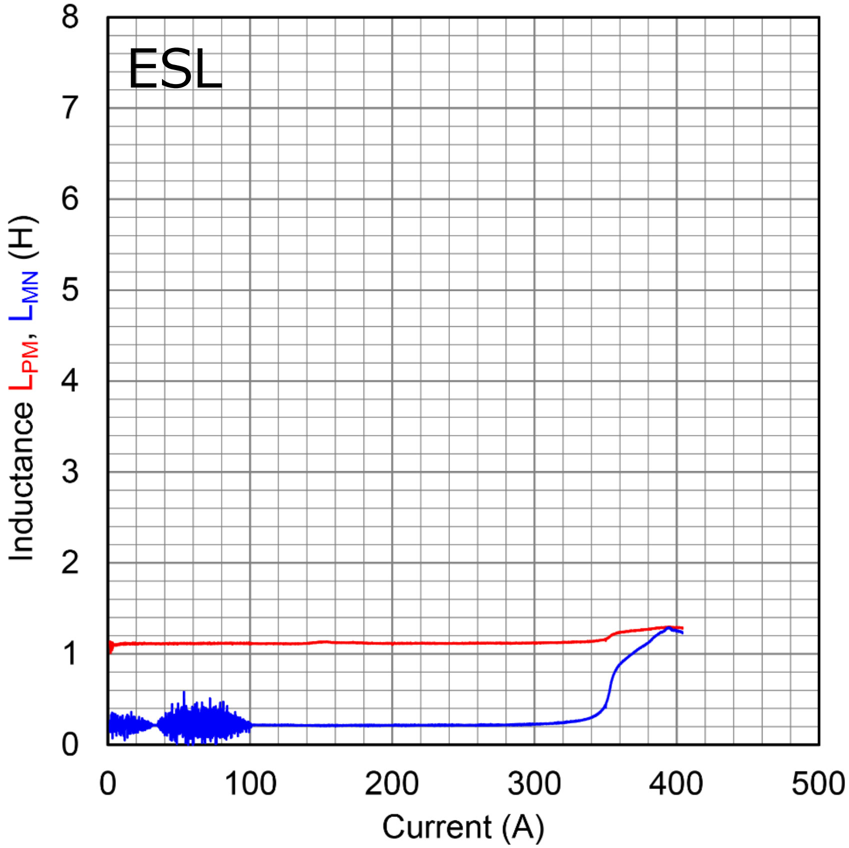


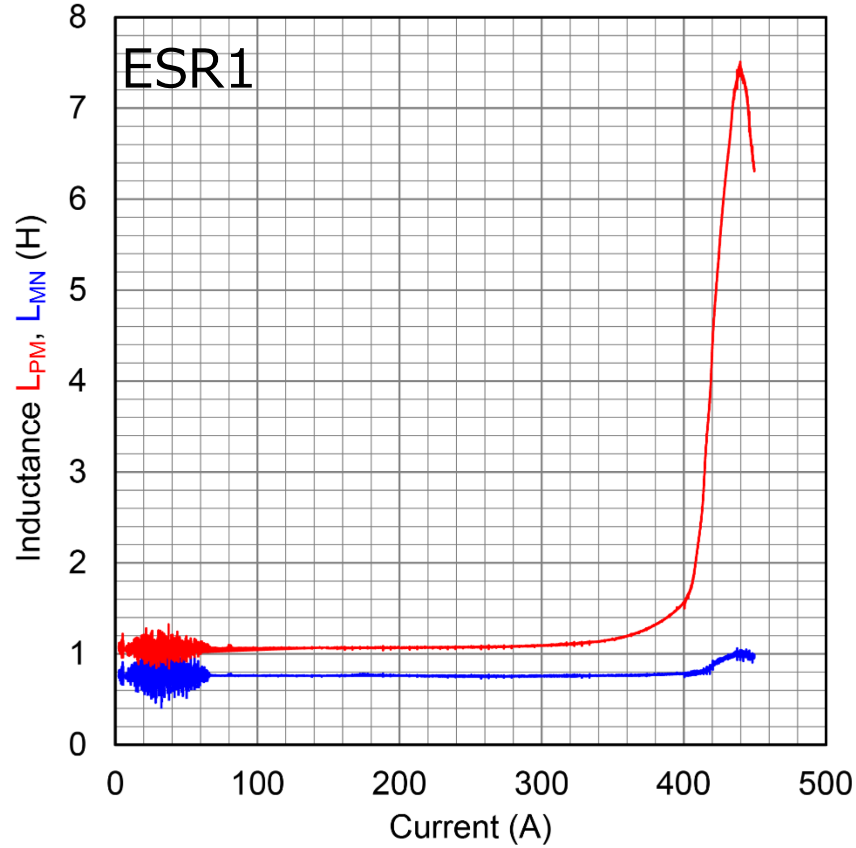
註：極性はESLとESR1で異なる
ESLではL1からL2の向きに正の電流を流し、
ESR1ではL2からL1の向きに正の電流を流す。

ESL電源の目標仕様

定格出力	DC 410 A–30 V
ケーブル抵抗	R_c = 6.5 mΩ
負荷インダクタンス	L_P = 0.98-1.11 H L_N =0.42-1.40 H
保護抵抗	R_P = 0.81 Ω R_N = 0.12 Ω
電流設定分解能	< 1 ppm
電流安定度	5 ppm / 8 h
温度係数	0.25 ppm/degree
電流リップル	< 5 ppm
掃引速度	< 4 A/s

ESL/ESR1のインダクタンス

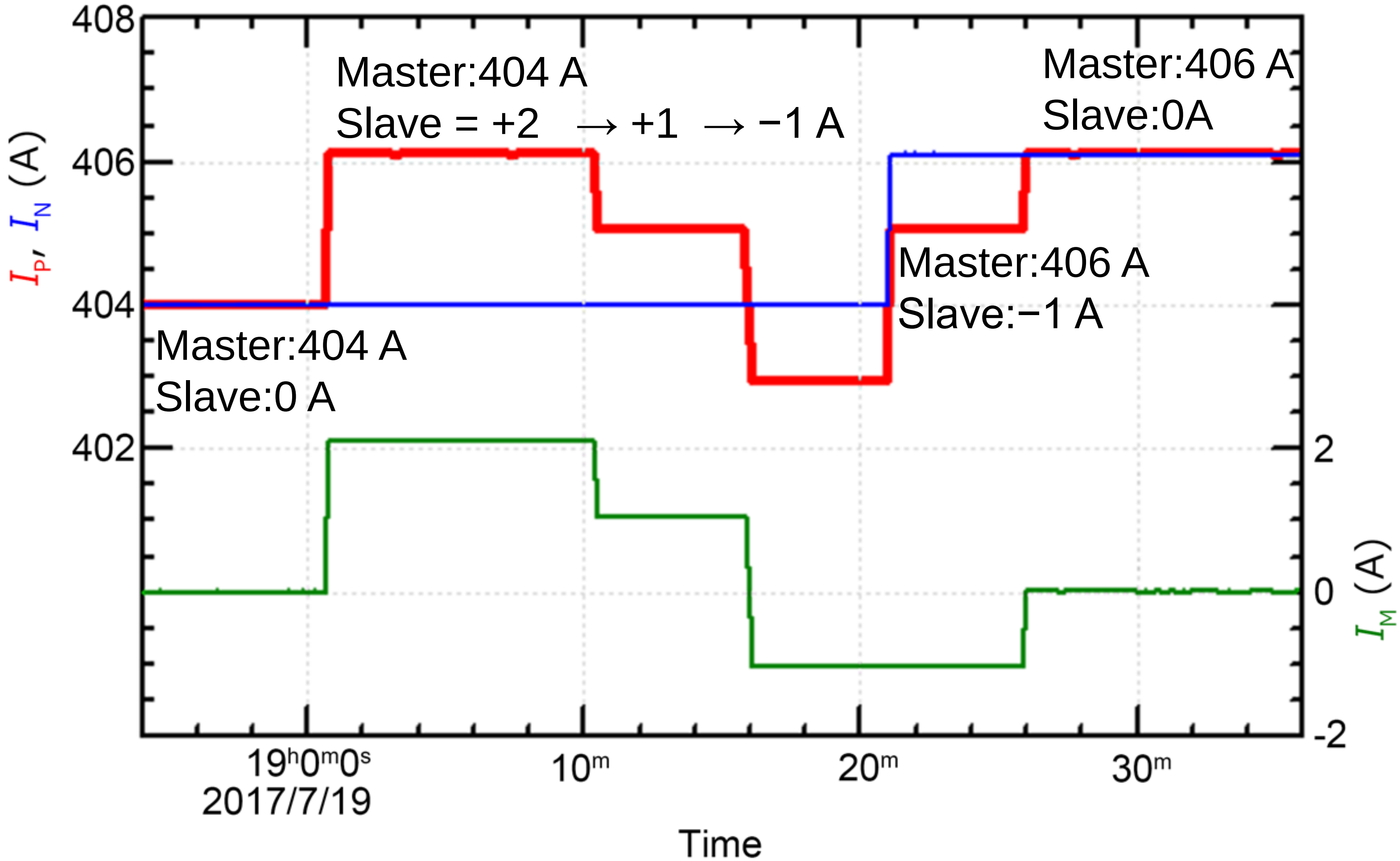




- Belleソレノイドを通電した状態。
- 電流掃引中の出力電圧を測定し、L=(V-IR)/(dI/dt)で得たもの。
- 運転電流値に応じて負荷のインダクタンスが変化する系。
  320A以上でBelle磁場と打消し合い、鉄心のあるコイルで飽和が緩和。

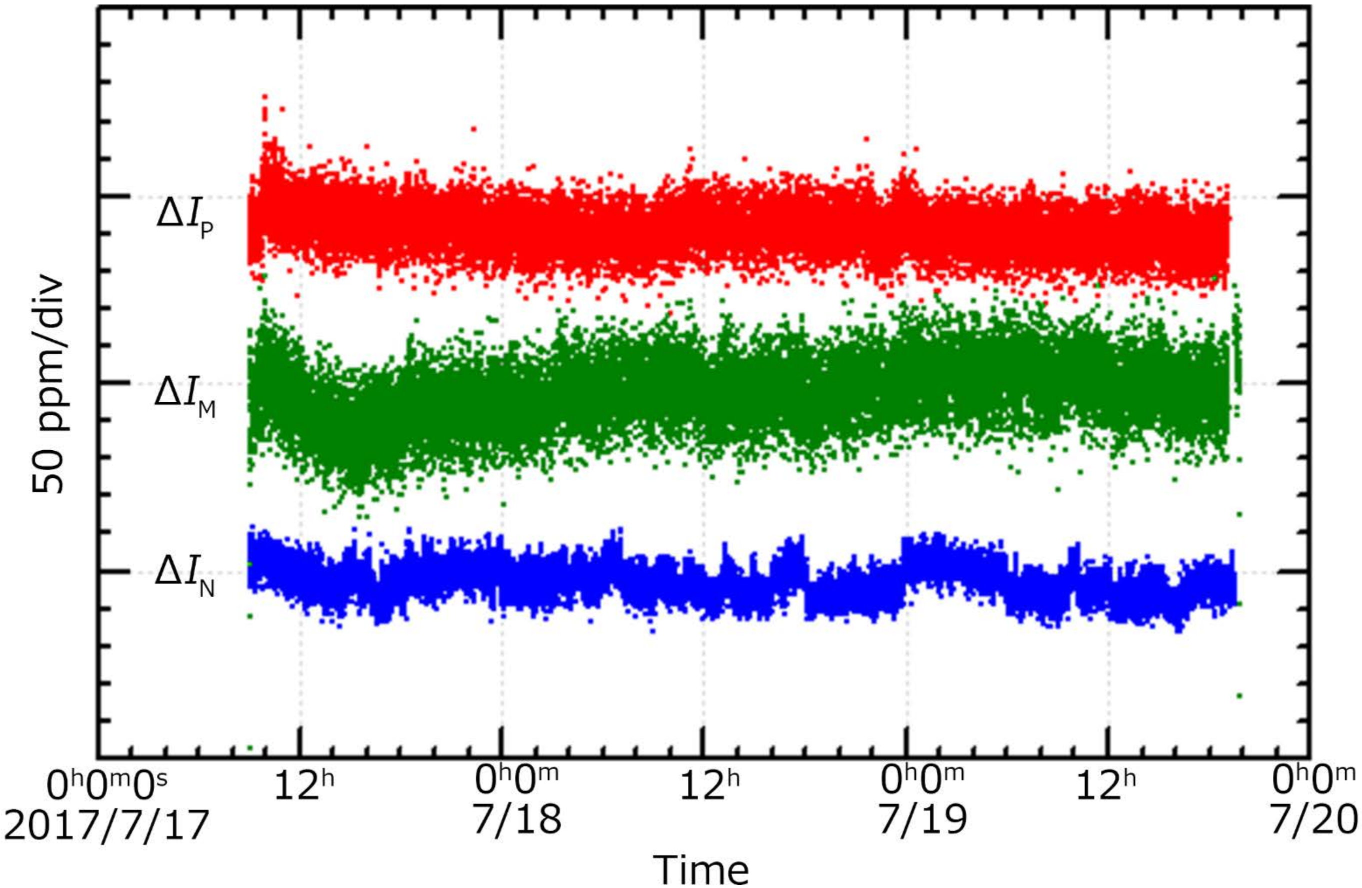
ESL電源の実負荷試験結果1:電流制御試験

- 電流指令値を変えて、P, N, M系統にある電流モニタ値をプロットした。
- I_PはI_Master+ I_Slaveに、I_NはI_Masterに、I_MはI_Slaveに対応。



指令通り応答している。

ESL電源の実負荷試験結果2：電流安定度



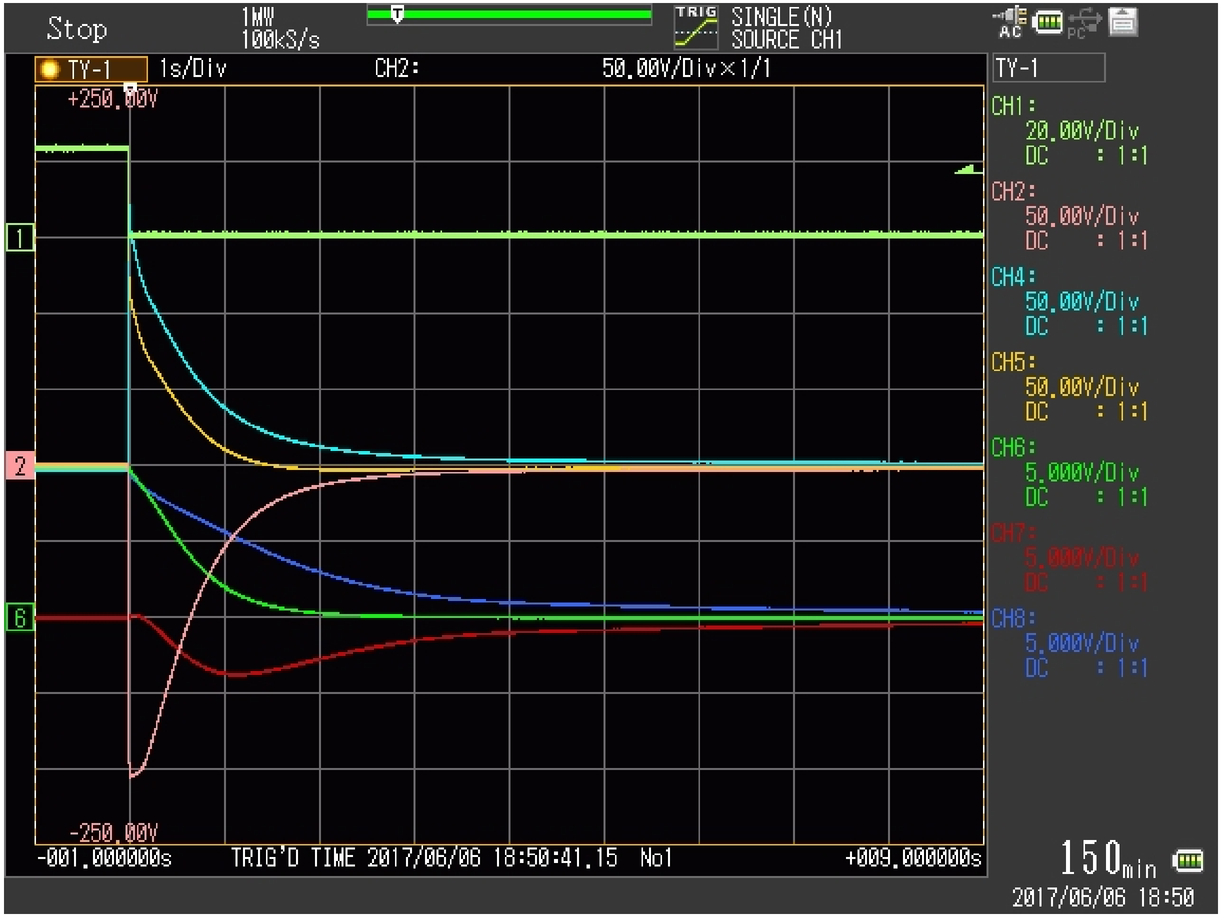
・I_Master = 404 A、I_Slave = 0 A、デジタルフィードバック無効での安定度。
・若干のドリフトがみられるものの、アナログ制御の温度依存性が小さいせいか、
　中央値として10 ppm/60時間程度の変動で済んでいる。
・計測系の外乱を抑えるための対策を秋に行う。

ESL電源の実負荷試験結果3：クエンチ保護試験

クエンチ検出器
トリガー

出力電圧
(50V/div)
PE, ME, NE

出力電流
(205A/div)
IP, IM, IN



・遮断直後に発生するPN間電圧、V_{PE} (-205 V) と V_{NE} (166 V) との差は371 Vで、
404 A × (0.81Ω [R_P]+0.12Ω [R_N]) = 375 Vで見積もった値と一致。

・励磁電流の減衰時定数は、I_PとI_Nの減衰時定数に差ができI_Mに差分の電流が流れている。
P側が見積の3倍速い。（時定数見積：P側1.1H/0.81Ω=1.35s, N側0.2H/0.12Ω=1.67s）
←コイルの超電導状態が崩れ、P側とN側に不平衡に常電導状態が生じているため。