

Magnet Power Supply System

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- Test results of the megawatt-class power supply
 - setting resolution
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- Power supplies for the superconducting Magnets

New Power supplies to be manufactured for SuperKEKB (1/)

Power	# of power supplies	Loads
< 70 kW	23*	Damping Ring (Q, B ...)
< 630 kW	2†	Damping Ring (Bends.)
< 30 kW	30‡	Damping Ring (Q, SX)
< 50 kW	91‡	Local Q
< 0.8 kW(± 10 A)	29†+~70‡	Steerings, Corrections, ...
0.35 kW (± 70 A)	4‡+36♦	QCS corrections

*:in FY2011; †: in FY2012; ‡: in FY2013; ♦: in FY2014 or later.

Target spec. (except for steerings)

Setting resolution	20-bit
Stability	< 20 ppm / day
Ripple	< 10 ppm

Comparable with the spec. for KEKB power supplies.

New Power supplies to be manufactured for SuperKEKB (2/

Power	# of power supplies	Loads
0.95 MW	2*	LER / HER Bends.
0.4~1 MW	8* / 1†	LER / HER Wiggs.
< 20 kW (< 2 kA)	5‡+7♦	QCS main, Solenoid

*:in FY2011; †: in FY2012; ‡: in FY2013; ♦: in FY2014 or later.

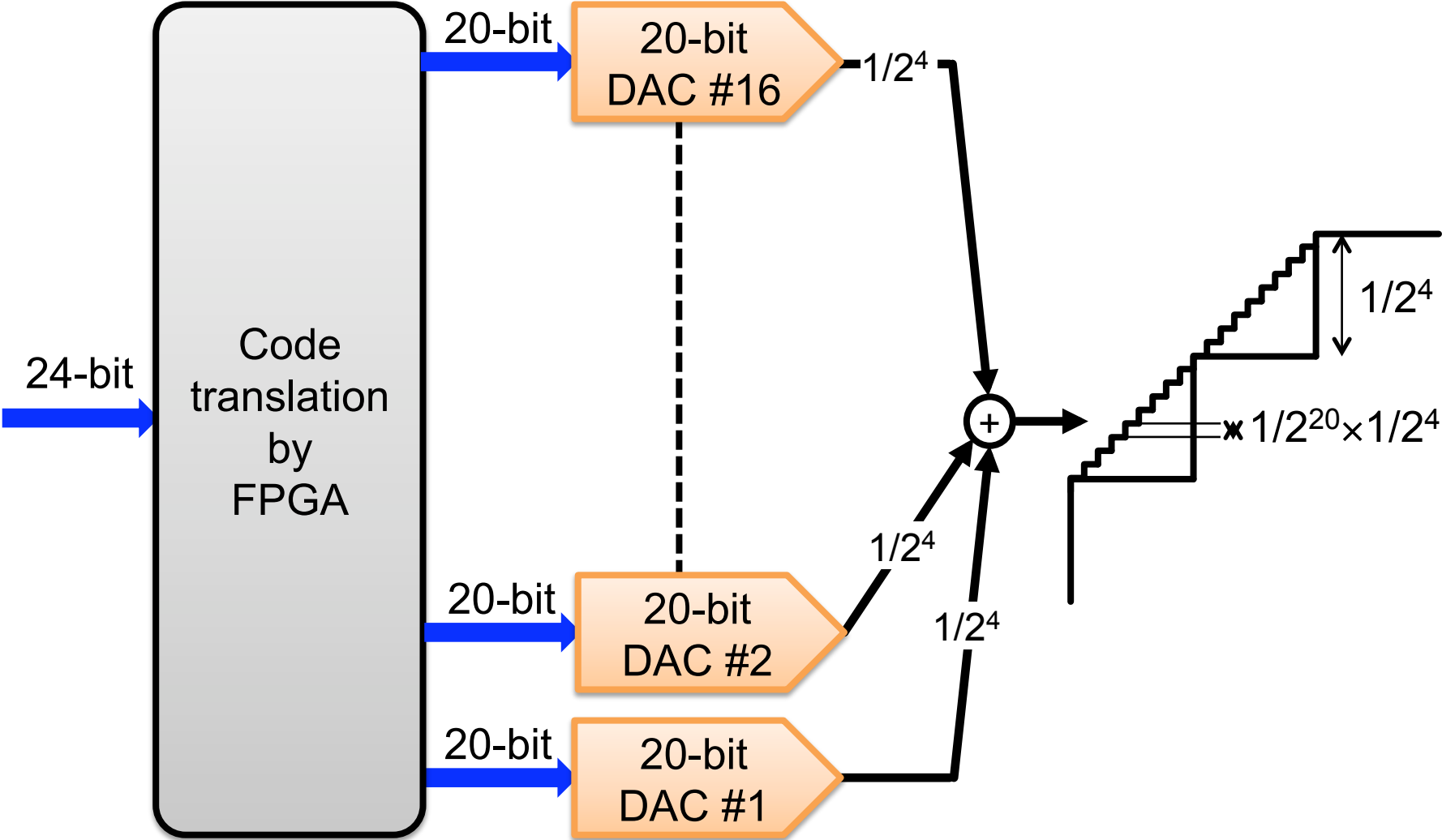
Higher performances are required.

Target spec.

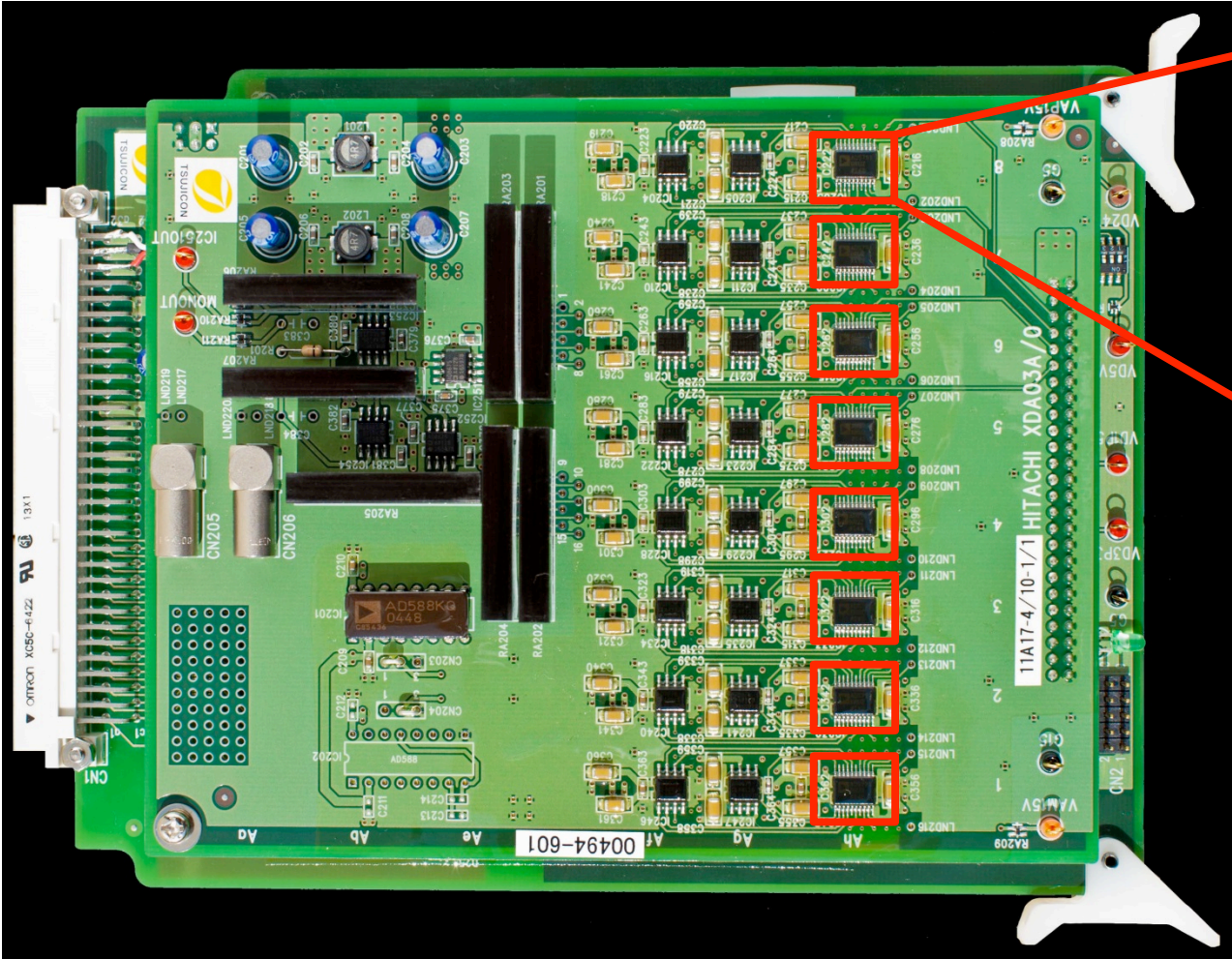
Setting resolution	24-bit
Stability	< 2 ppm / day
Ripple	< 1 ppm

24-bit current-setting resolution

New commercial use 20-bit DAC was released in 2010 by Analog Devices. Summing the output of sixteen ($= 2^4$) 20-bit DAC's.



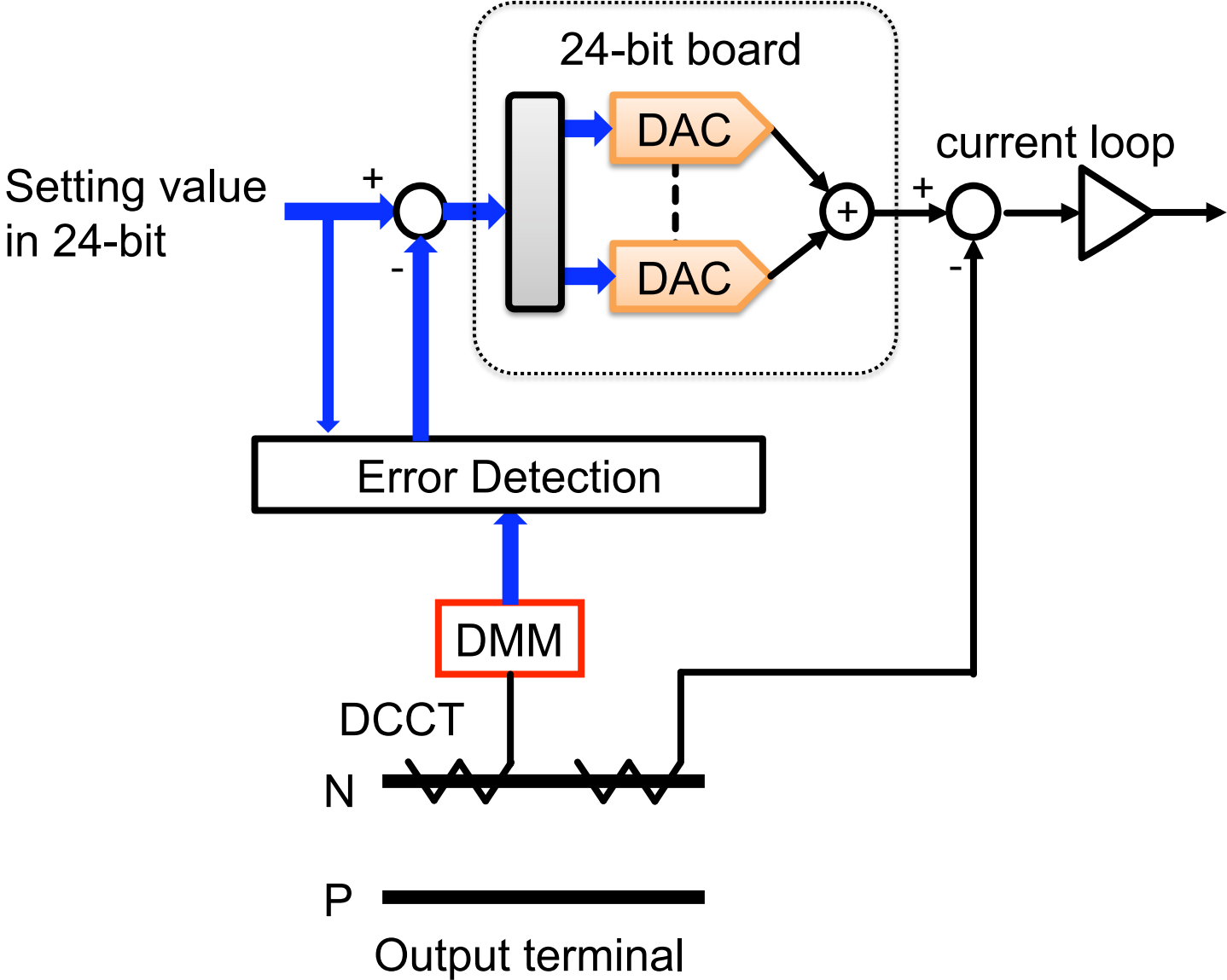
24-bit control board



Analog Devices
AD5791BRUZ

Eight DACs are placed each side of the board

Digital feed back control for high current stability



B2P Power supply (LER Bend) under testing at factory

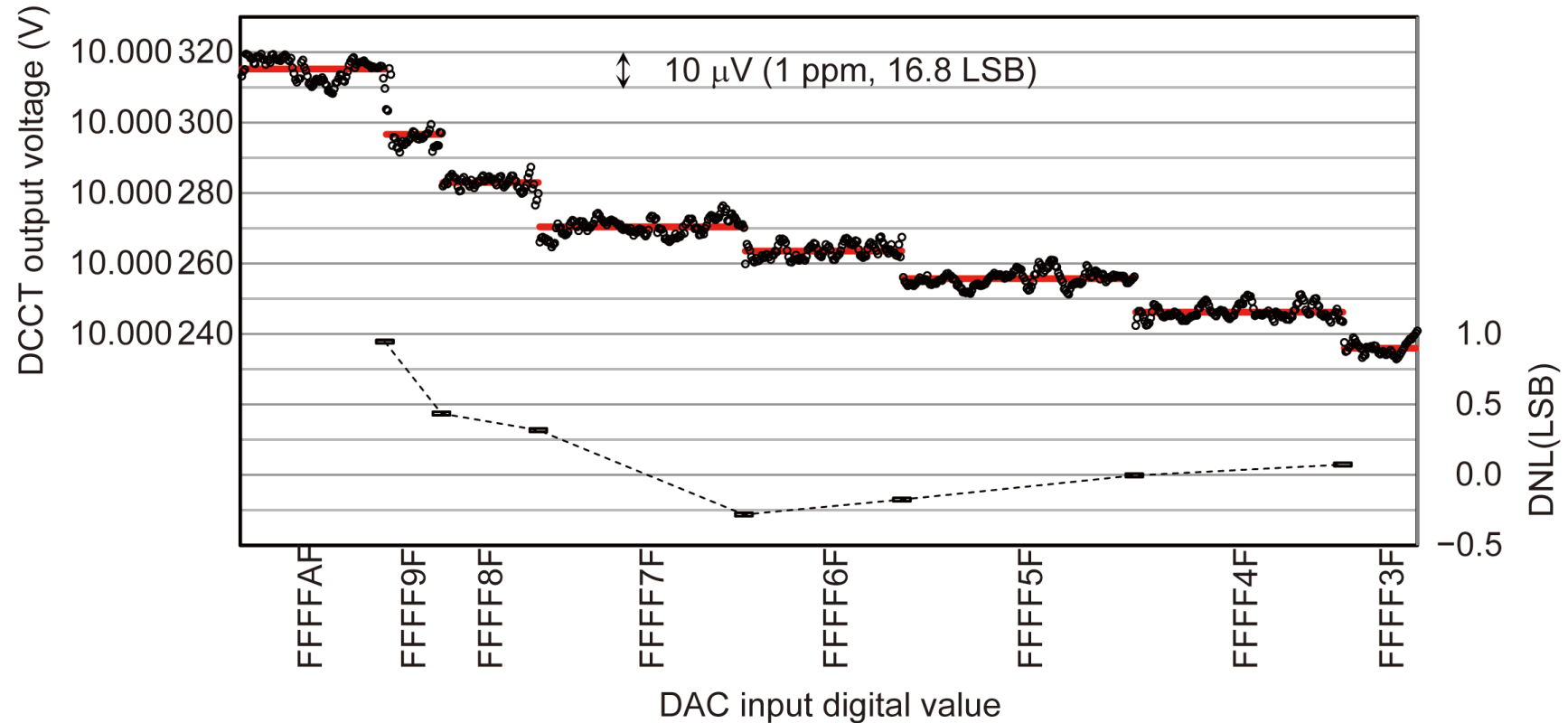


860 A, 1100 V (946 kW)

Test result: setting resolution (BWDNLP)

Power supply was operated in the rated current of 1400 A with a dummy load. Output current was measured by a DCCT and DMM(10 V range, 2 PLC, 10 moving Fit)

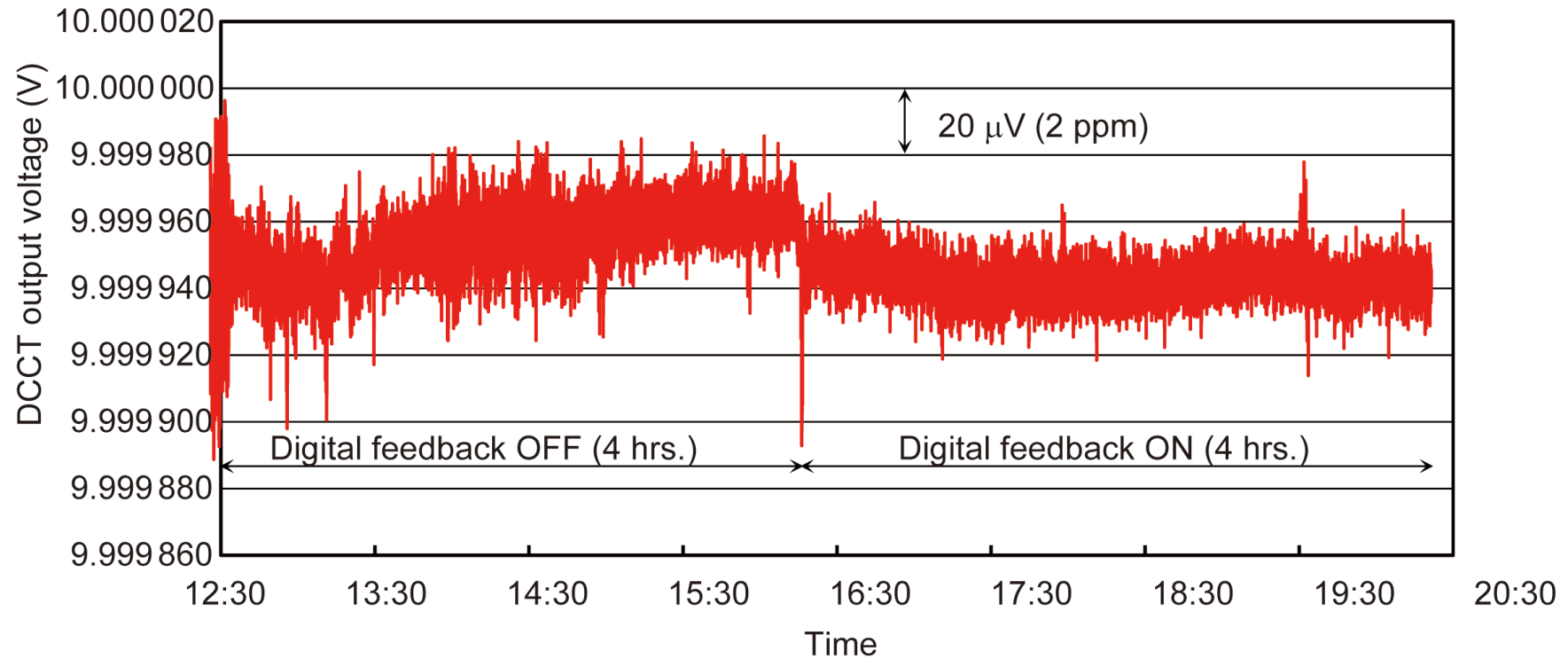
Decreasing DAC input digital value by 16 least significant bit (LSB).



Monotonic response was obtained for 16 LSB step.
Higher resolution can be expected.

Test result: current stability (B2P)

Power supply was operated in the rated current of 860 A with a dummy load. Output current was measured by a DCCT and DMM(10 V range, 2 PLC, 10 moving Fit)

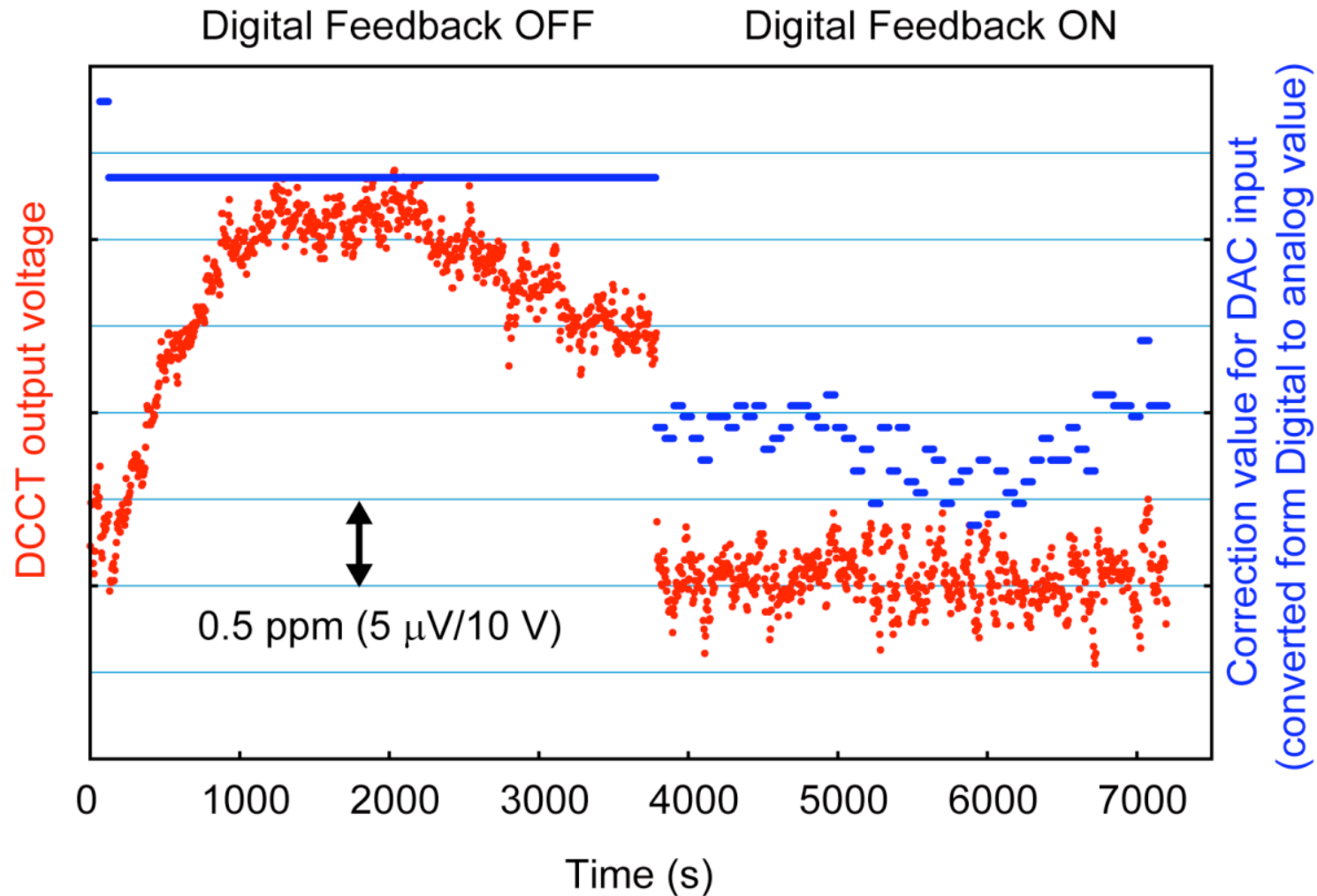


High current stability was achieved:
1.2 ppm/4 hrs. as a mean value with low σ (0.67 ppm)

Test result: current stability (7.5 kW medium-class PS)

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

measured by DMM (20 V range, 50 PLC, 10 moving Fit)



More higher stability: 1 ppm (peak to peak)/hr. with low σ (0.16 ppm)

Power supplies for the superconducting Magnets

- to be fabricated in FY2013 for the left-side of I. P.

(1) 4 power supplies for 4 quadrupole magnets each

2000 A, 8 V (QC1LE)

1250 A, 5 V (QC2LE)

1800 A, 8 V (QC1LP)

1000 A, 5 V (QC2LP)

(2) 1 power supply for a solenoid

400 A, 15 V (ESL)

Resolution	24-bit
Stability	< 2 ppm / 8 hrs.
Ripple	< 1 ppm

(3) 4 or more bipolar power supplies for correction coils

± 70 A, ± 5 V

Resolution	20-bit
Stability	< 20 ppm / 8 hrs.
Ripple	< 5 ppm

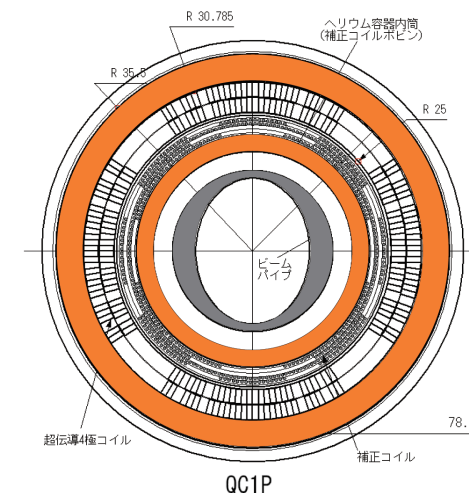
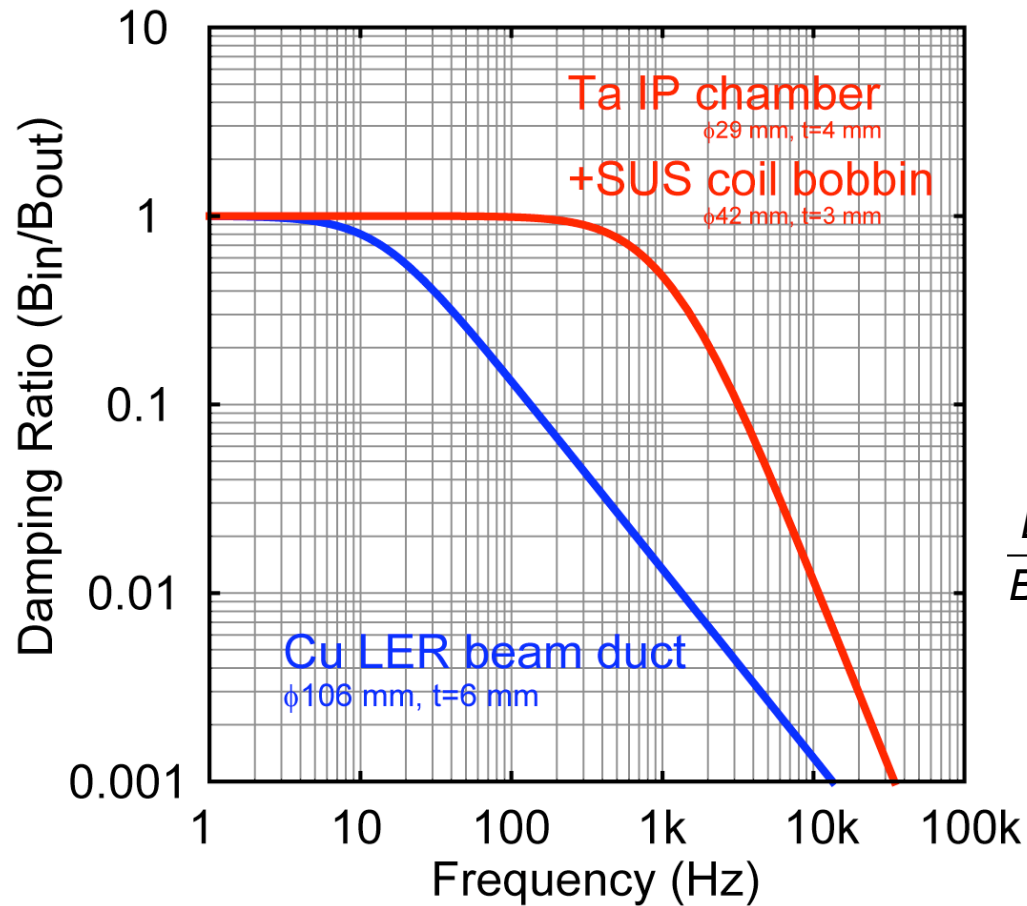
Detailed parameters for the power supplies of (1) and (2)

	Quadrupoles				Solenoid
	QC1LE	QC2LE	QC1LP	QC2LP	ESL
Operating current (A)	1577	977	1625	877	348
Stored energy (kJ)	4.38	10.38	1.43	3.66	171
Inductance (mH)	2.19	13.28	0.88	7.32	2138
Resistance of cable (mΩ)	1	2	1	2	5
Withstanding voltage (V)	200	200	200	200	400
Rated output current (A)	2000	1250	1800	1000	400
Rated output voltage (V)	8	5	8	5	12
Protection Resistor (Ω)	0.10	0.16	0.11	0.20	1.0
Allowed time delay for protection circuit (ms)	< 20	< 20	< 20	< 20	< 100

Low inductance may lead to ripples/noises.

Damping ratio of alternating magnetic field

Eddy current damps the magnetic field inside of beam pipe.



$$\frac{B_{in}}{B_{out}} = \frac{1}{\sqrt{1 + \left(\mu_0 \pi \frac{bt}{\rho} f \right)^2}}$$

b : outer diameter
 t : thickness
 ρ : conductivity

Beam pipe at IP is made of lower conductivity material, so that the damping effect cannot be expected: low ripple PS is essential. An additional reactance will be required as a component of passive filter. Active filter or improved minor feedback loop may also be required.

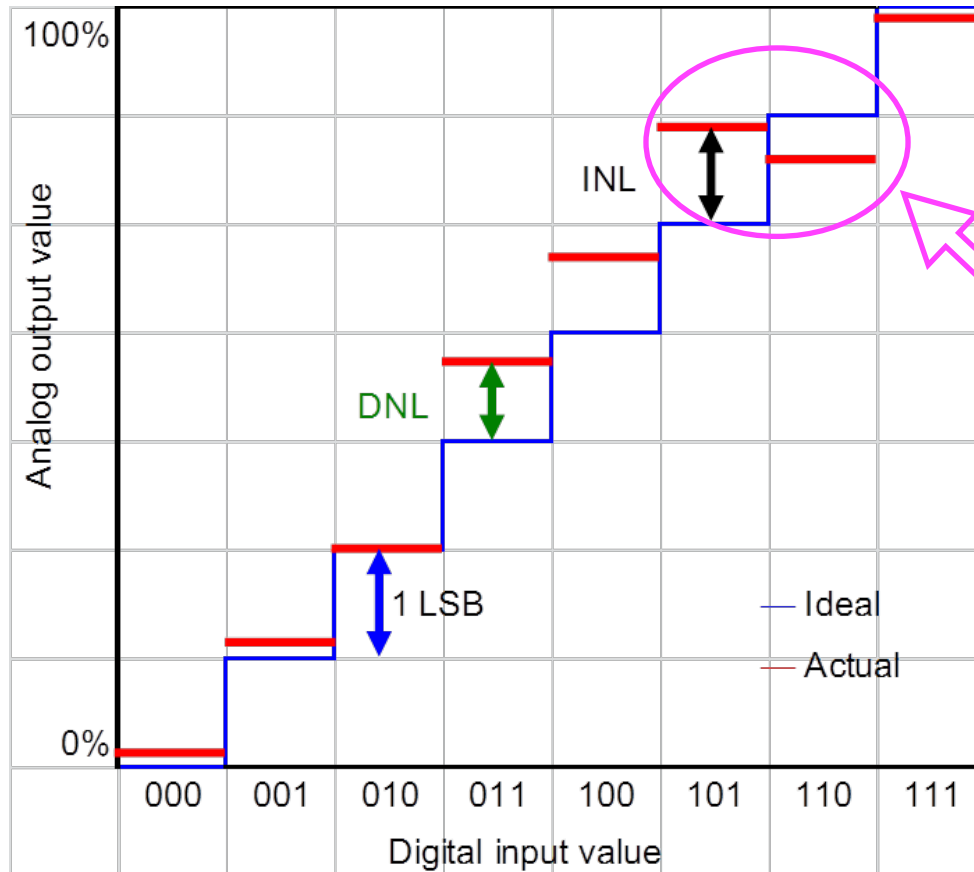
Summary

- Small/medium/Large-class power supplies have been manufactured.
- For the high-spec. power supplies, 24-bit setting resolution and digital feedback system have been developed and applied. The test results are satisfactory.
- The most challenging task will be required for QCS power supplies: the ripple/noise will be a key issue.
- Overhaul has been in progress for reused power supplies.

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

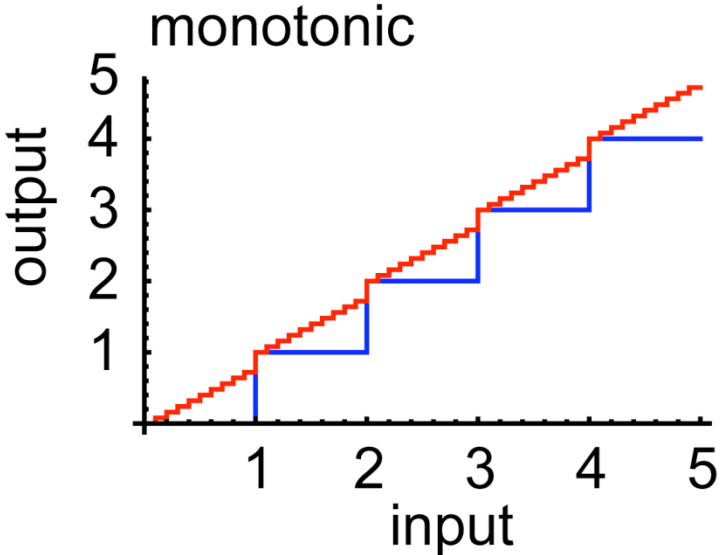
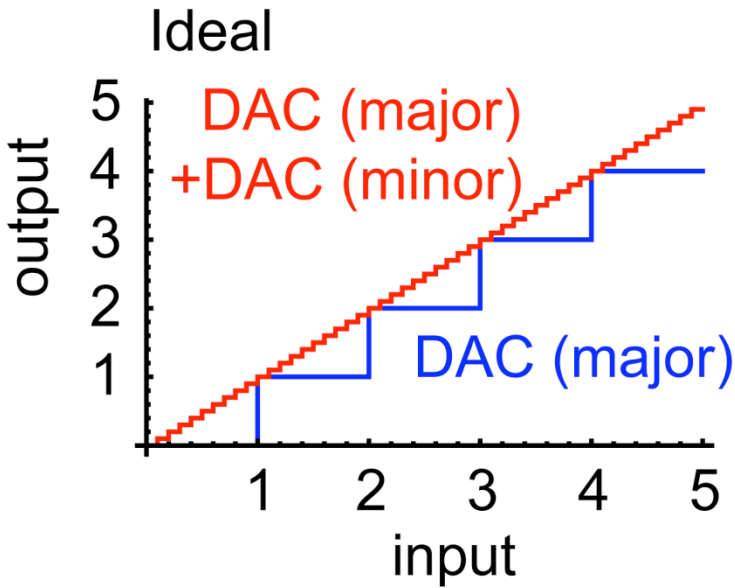
INL ± 2 LSB

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

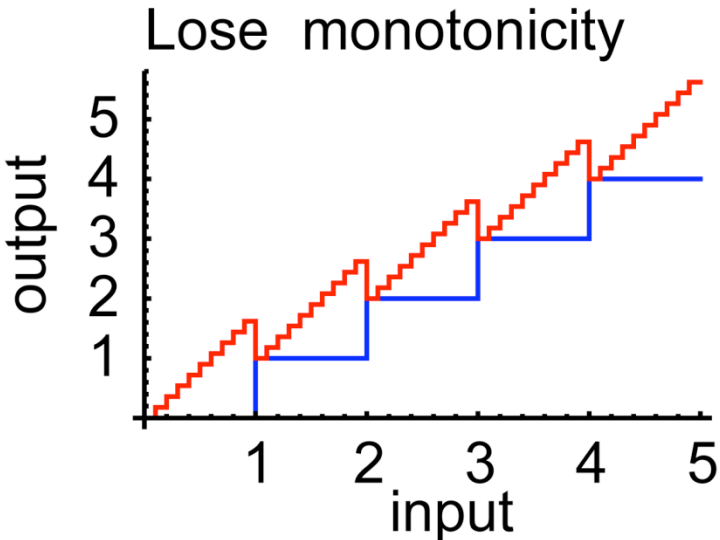
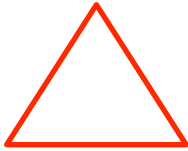
INL ± 0.5 LSB typ. (test result: $-0.2 \sim +0.6$ LSB)

Why sixteen DAC's 24-bit system?

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



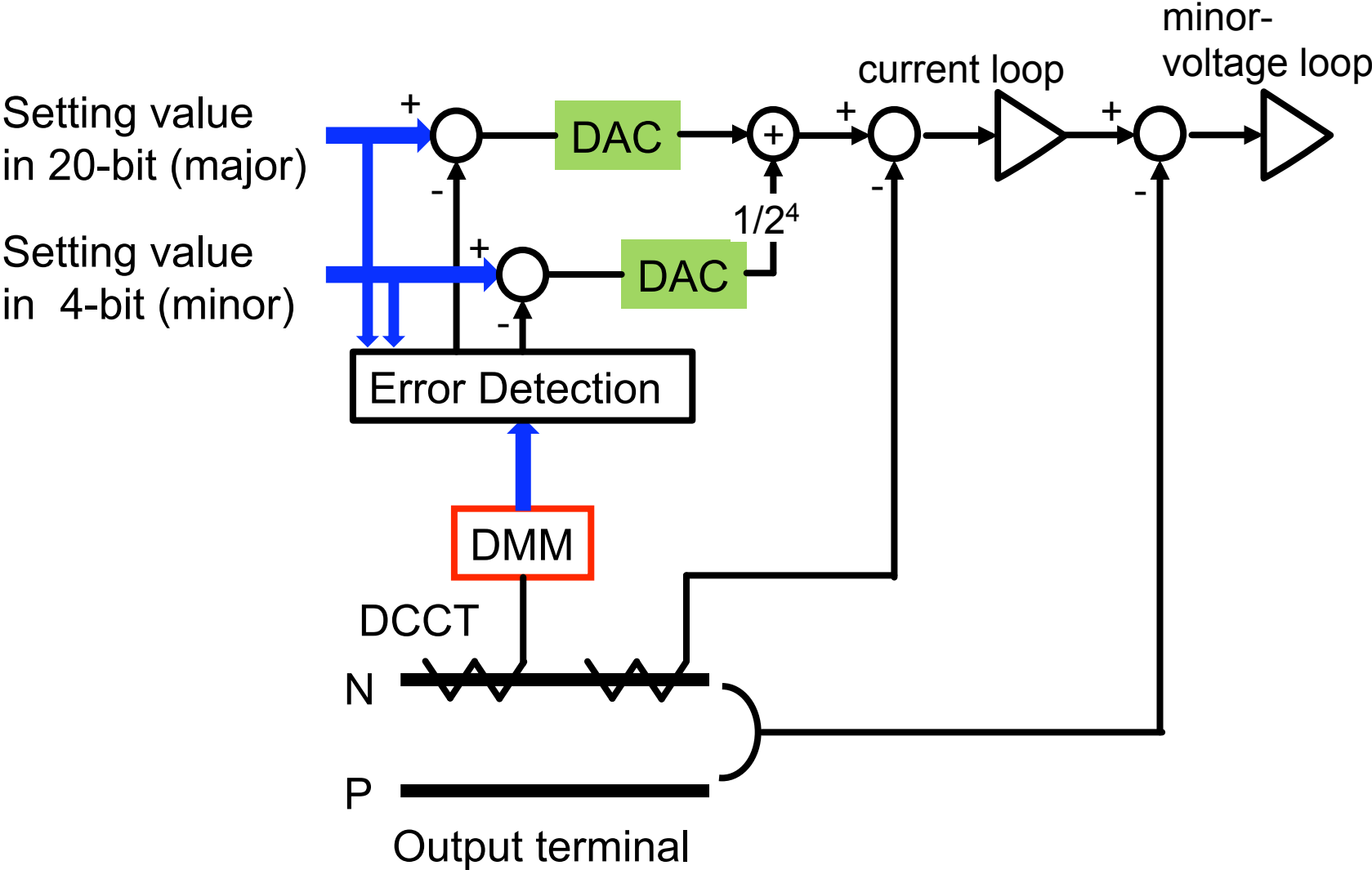
Not so bad



Bad



Digital feed back control for high current stability



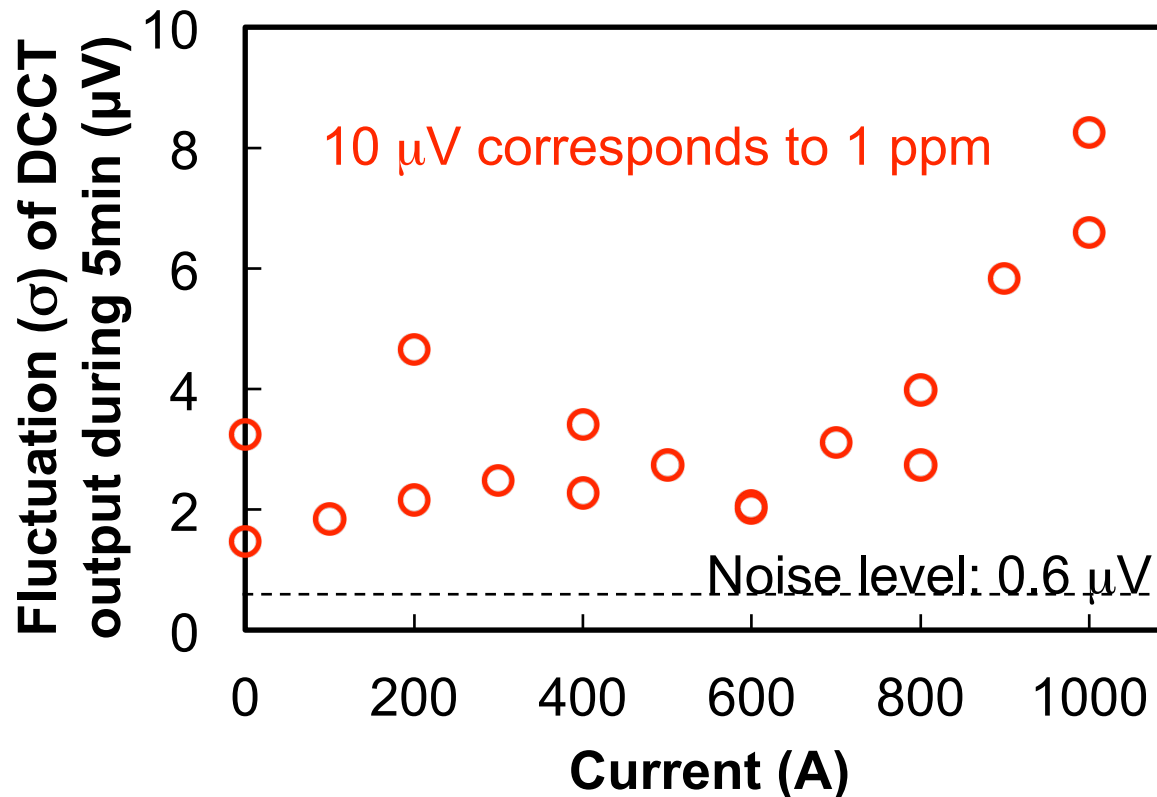
How much jitter on the measured current

For precious control, lower jitter is necessary on the current monitoring.
Current is measured by a DCCT and a DMM.

Power supply: Transistor-dropper type (1000 A-30 V).

DCCT: 1000 A / 10 V output

DMM: KEITHLEY 2002 (10 PLC, 20 V range)



Detailed parameters for the power supplies of (1) and (2)

Load parameters	Quadrupoles				Solenoid
	QC1LE	QC2LE	QC1LP	QC2LP	ESL
Operating current (A)	1577	977	1625	877	348
Stored energy (kJ)	4.38	10.38	1.43	3.66	171
Inductance (mH)	2.19	13.28	0.88	7.32	2138
Resistance of cable (mΩ)	1	2	1	2	5
Withstanding voltage (V)	200	200	200	200	400
Power supplies and quench protection circuits (resistor and SCR switch or circuit breaker)					
Rated output current (A)	2000	1250	1800	1000	400
Rated output voltage (V)	8	5	8	5	12
Protection Resistor (Ω)	0.10	0.16	0.11	0.20	1.0
Allowed time delay for protection circuit (ms)	< 20	< 20	< 20	< 20	< 100

Remote control operation, which provides by an ARCNET interface, is required.

Specifications in the current of the power supplies of (1) and (2)

	QC1LE, QC2LE, QC1LP, QC2LP	ESL
Short term stability	< 2 ppm/8 hrs	
Long term stability	< 10 ppm/month	
Ripple (< 10 kHz)	< 1 ppm (rms, total harmonic distortion)	
Noise (> 10 kHz)	< 10 ppm (zero-peak) (goal)	
Setting resolution	24 bit	
Ramp rate	10 A/s	4 A/s

Detailed parameters for the power supplies of (3)

Load parameters	Correction coils
Operating current (A)	-70 ~ +70
Stored energy (J)	0.54 ~ 21
Inductance of magnets L (mH)	0.22 ~ 8.7
Resistance of cable (mΩ)	25
Withstanding voltage (V)	200
Power supply and quench protection circuit (Diode)	
Rated output current (A)	± 70
Rated output voltage (V)	± 5
Current decay time with any time delay (ms)	< 100

Remote control operation, which provides by an ARCNET interface, is required.

Specifications in the current of the power supplies of (3)

Short term stability	< 20 ppm/8 hrs
Long term stability	< 100 ppm/month
Ripple (< 10 kHz)	< 5 ppm (rms, total harmonic distortion)
Noise (> 10 kHz)	< 50 ppm (zero-peak) (goal)
Setting resolution	20 bit
Ramp rate	10 A/s

Existing KEKB Power supplies

We have ~ 2300 power supplies:

Class	# of power supplies	Typical load
Small-class (< 10 A, 0.5 kW)	1885 To be reused after appropriate maintenance and overhaul : in progress.	Steering magnet etc
Medium-class (< 500 A, 100 kW)	368	Local Quads
Large-class (< 500 A, 500 kW)	14 To be reused. Current setting resolution will be improved by 20-bit DAC.	Quad families
Megawatt-class (< 1250 A, 1 MW)	6 Rubbished and replaced by newly developed PSs; in progress.	Beam-Current Monitors

Typical spec.

Stability	< 20 ppm / day
Ripple	< 10 ppm
Setting resolution	$< \pm 50$ ppm (16-bit DAC)