“When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *science*.”

William Thomson, Lord Kelvin, 1824-1907

High Precision Measurements

- Precision
- Precision power converters
- Voltage transducers
- Current transducers
- Calibration infrastructure
- Integration

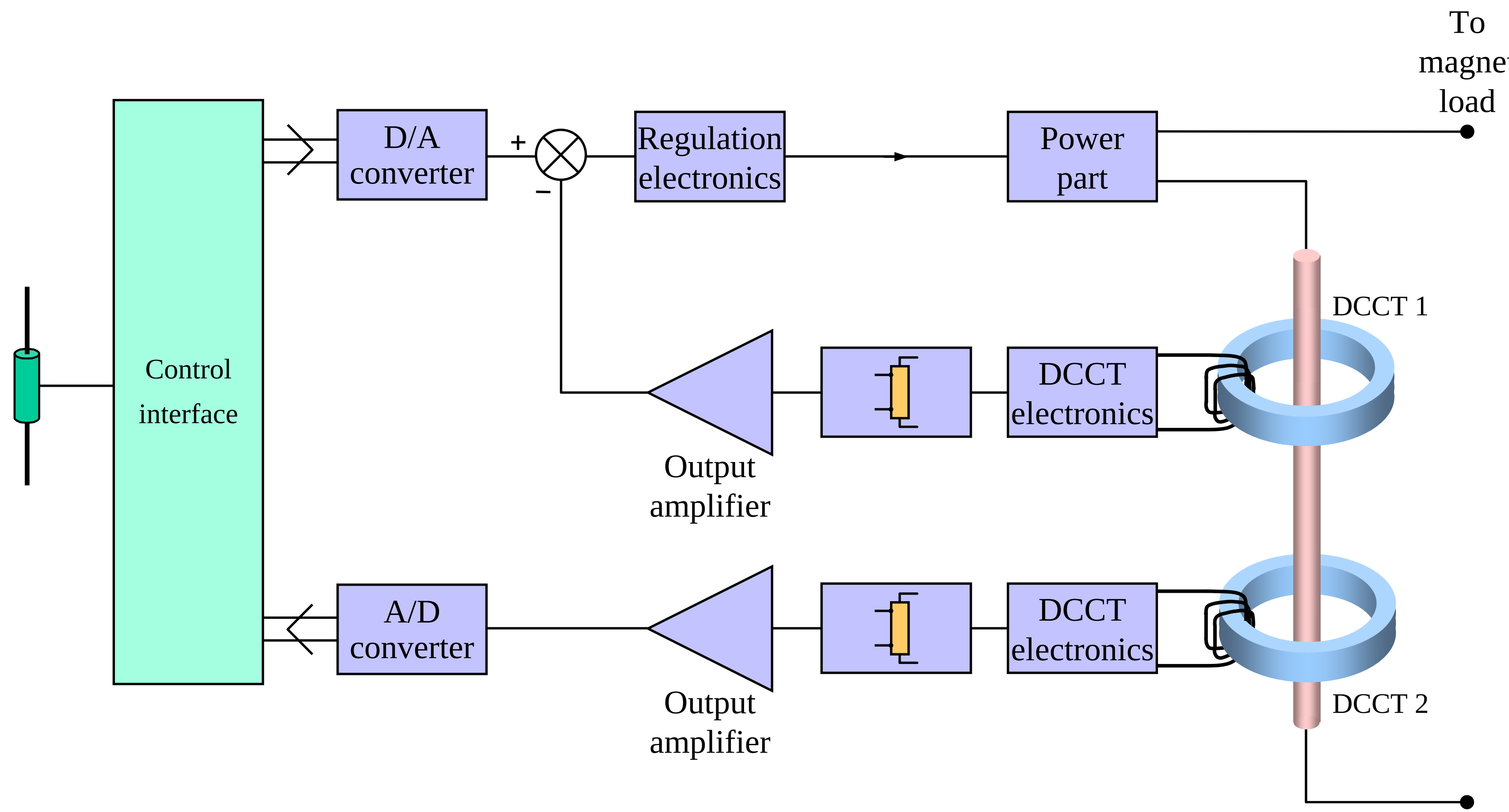
Precision

- Precision is a qualitative term
- Accuracy and Uncertainty are quantitative terms
- Device imperfections, measurement errors and measurement uncertainty
- ISO GUM defines terms and methods to express uncertainty in a standardised way

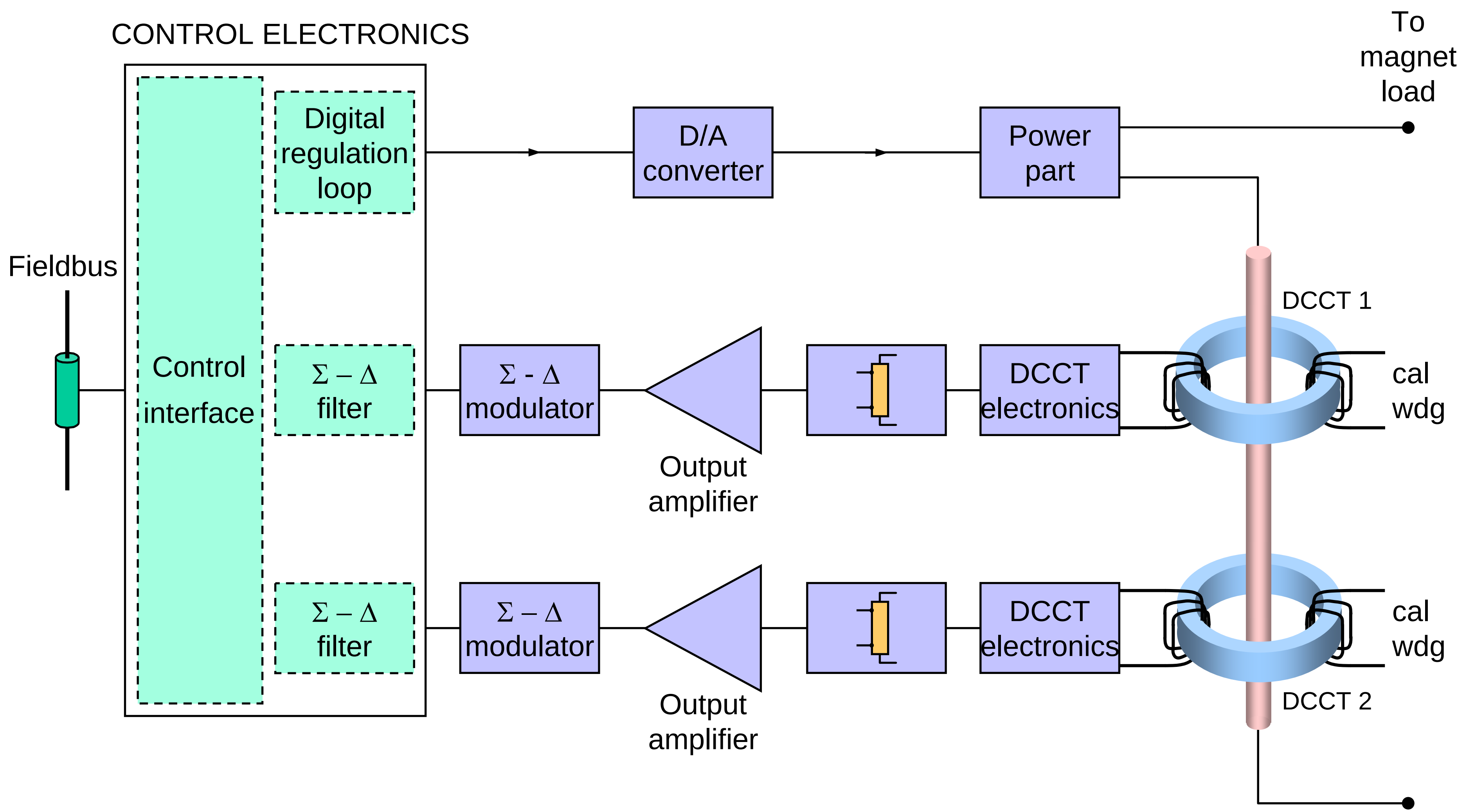
Precision Power Converters

- User specifications
  - Voltage output or current output ?
  - Pulsed or DC ?
  - Type of load
  - Performance
  - Reliability
  - etc
- System (=converter) design specifications
  - Configuration
  - Power topology
- Component specifications

Analogue converter control



LHC converter control



Accuracy budget

	Device spec		LHC machine impact		
	ppm of FS	ppm of value	Stability	Reproducibility	Accuracy
Device			1/2 hr	1-day	1 year
DCCT 120 A					
Zero uncertainty (hyst etc.)	20	0	0	0	20
Repeatability	3	0	0	3	3
Uncomp non-linearity	50	0	0	0	50
LF noise, 0.1-10 Hz	10	0	10	10	10
Stability 1/2 hr, 1-100 mHz	0	10	10	0	0
Gain drift 24 hr	0	10	0	10	0
Gain drift 1 year	0	100	0	0	100
Gain Temp Coeff	0	5	0	25	50
Offset drift 24 hr	10	0	0	10	0
Offset drift 1 year	40	0	0	0	40
Offset Temp Coeff	3	0	0	15	30
DCCT total			20	73	303
A/D converter, 16 bit succ. approx.					
Uncomp non-linearity	45	0	0	0	45
LF noise, 0.1-10 Hz	10	0	10	10	10
Stability 1/2 hr, 1-100 mHz	0	0.4	0.4	0	0
Gain drift 24 hr	0	0.5	0	0.5	0
Gain drift 1 year	0	100	0	0	100
Gain Temp Coeff	0	2	0	10	20
Offset drift 24 hr	0.2	0	0	0.2	0
Offset drift 1 year	50	0	0	0	50
Offset Temp Coeff	0.6	0	0	3	6
A/D total			10.4	23.7	231
Miscellaneous			5	10	100
Total			35.4	106.7	634
LHC committment			50	100	1000
Conditions					
Temp change (K)			0	5	10
No special temp ctrl					

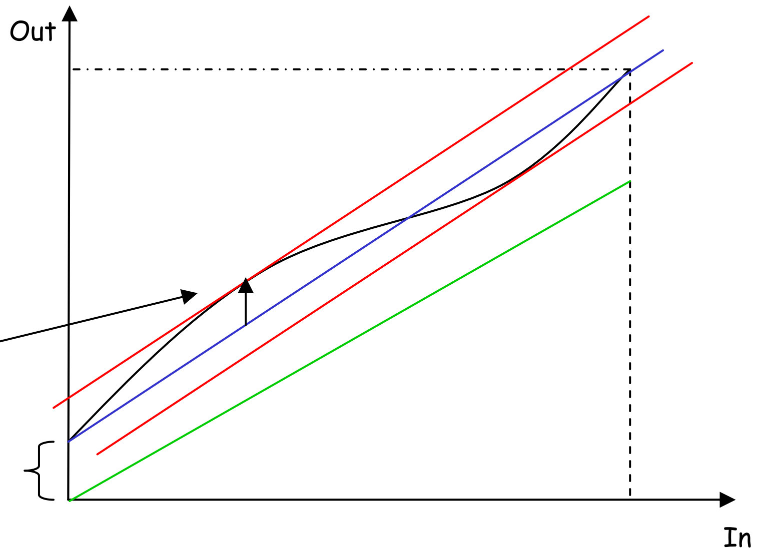
vs. actual performance …

	Device performance				LHC machine impact					
	ppm of FS		ppm of value		1/2 hr Stability		Reproducibility 1 day		Accuracy 1 year	
Device	Spec	Real	Spec	Real	Spec	Real	Spec	Real	Spec	Real
DCCT 120 A										
Zero uncertainty (hyst etc.)	50	3			0	0	0	0	50	3
Settling after change			0	30						
Repeatability	3	3			0	0	3	3	3	3
Uncomp non-linearity	50	50			0	0	0	0	50	50
LF noise, 0.1-10 Hz	0	3			0	3	0	3	0	3
Stability 1/2 hr, 1-100 mHz	10	15			10	15	10	15	10	15
Gain drift 24 hr			10	10	0	0	10	10	0	0
Gain drift 1 year			100	100	0	0	0	0	100	100
Gain Temp Coeff			5	10	0	0	25	50	50	100
Offset drift 24 hr	10	10			0	0	10	10	0	0
Offset drift 1 year	40	40			0	0	0	0	40	40
Offset Temp Coeff	3	2			0	0	15	10	30	20
DCCT total					10	18	73	101	333	334
A/D converter, 16 bit succ. approx.										
Uncomp non-linearity	60	240			0	0	0	0	60	240
LF noise, 0.1-10 Hz	60	60			60	60	60	60	60	60
Stability 1/2 hr, 1-100 mHz					0	0	0	0	0	0
Gain drift 24 hr			30	30	0	0	30	30	0	0
Gain drift 1 year			100	100	0	0	0	0	100	100
Gain Temp Coeff			3	3	0	0	15	15	30	30
Offset drift 24 hr	10	10			0	0	10	10	0	0
Offset drift 1 year	50	50			0	0	0	0	50	50
Offset Temp Coeff	0.6	1			0	0	3	5	6	10
A/D total					60	60	118	120	306	490
Miscellaneous					5	5	10	10	100	100
Total					75	83	201	231	739	924
LHC committment					50	50	100	100	1000	1000
Conditions										
Temp change (K)					0	0	5	5	10	10
No special temp ctrl										

Specifications 1

- Stability – Noise
  - Ground noise - Common mode rejection
  - Power supply noise - rejection
  - Interference, conducted or radiated (Charroy)
  - 50 Hz pickup
  - Modulation residues
  - Amplifier noise
  - Reference noise
  - Humidity influence – Leakage paths
  - Contact resistance and emf's
- Resolution

Specifications 2



- Accuracy
  - Offset
  - Gain
  - Linearity
- Temperature behaviour
  - Offset and gain change
  - Amplifiers
  - Resistors
  - Capacitors
  - Instability/Oscillations

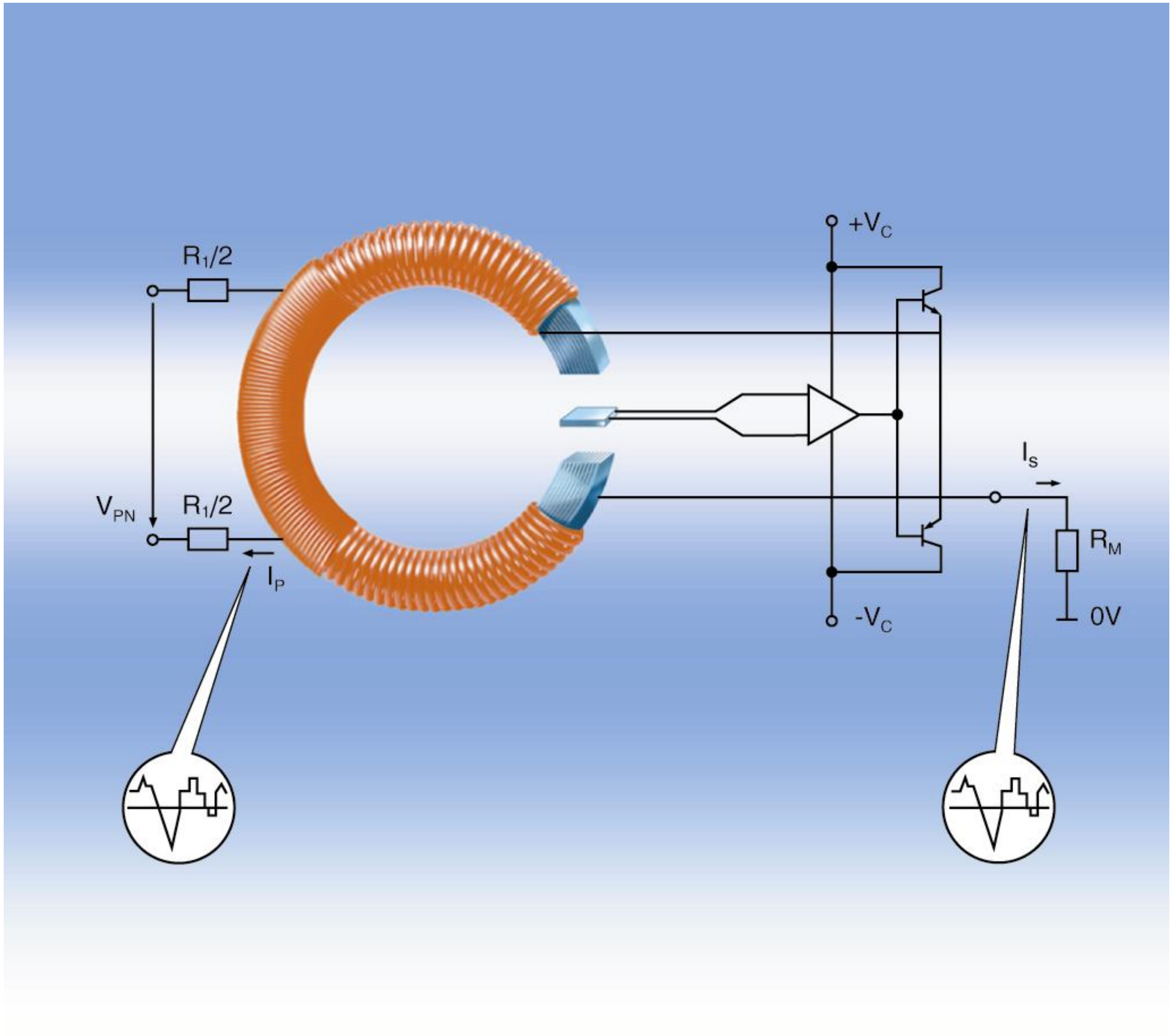
Specifications 3

- Settling behaviour
  - Bandwidth related
  - Thermally related
- Repeatability and reproducibility
- Long term drift
  - Material ageing or stress modification
  - Resistors, amplifiers
  - Humidity

Voltage transducers

- Problems you may face:
  - Isolation
  - High voltage
  - High frequency performance
- Solutions:
  - Isolation amplifiers
  - High voltage dividers
  - Precision resistors easily available
  - Compensation for stray capacitance
- Relatively easy to verify performance

LEM Voltage Transducer



Accuracy range:

0.2 – 1 %

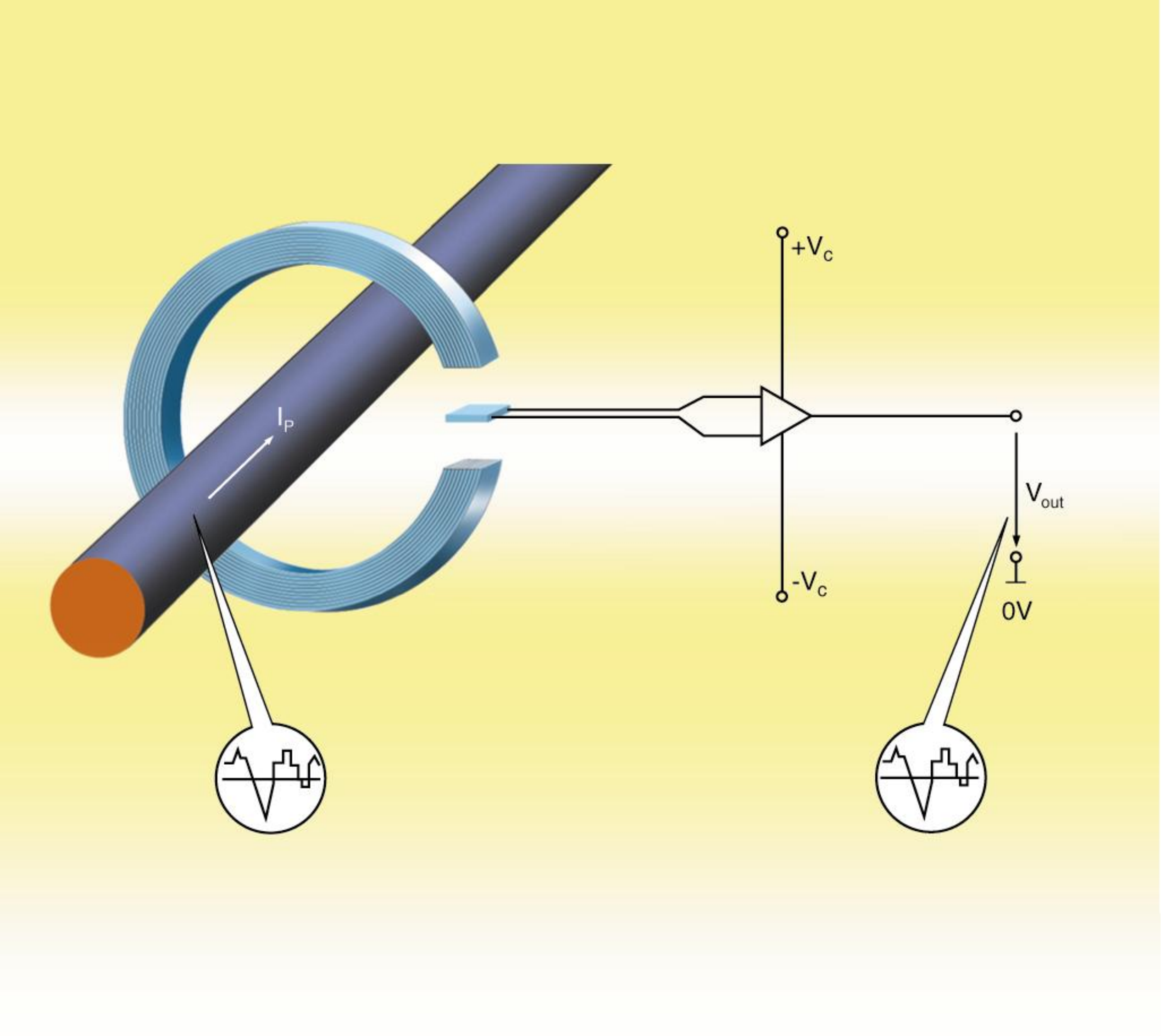
Current Transducers, Principles

- Current measuring resistors
  - Current range: 0 - 20 kA
  - Accuracy range: 10^{-2} - 10^{-6}
  - No isolation
  - DC up to MHz with low inductance design
- AC passive current transformers
  - Accuracy: 10^{-2} to 10^{-3} for 1-50 kA
  - Needs magnetising energy
  - Limited bandwidth, no DC
  - Good isolation, kV easy
- Optical fibres
  - Accuracy: 10^{-2} to 10^{-3}
  - Excellent isolation

Magnetic Flux Principle

- Measure field around conductor – Hall probe – open loop system
- Flux compensation around conductor, sense zero flux
  - Hall effect sensor
    - 10^{-3} accuracy
  - magnetic modulation
    - Second harmonic detector
    - Peak current sensing
    - Separate DC and AC loops
    - 10^{-6} accuracy achievable in current ratio
  - Burden resistor/output amplifier

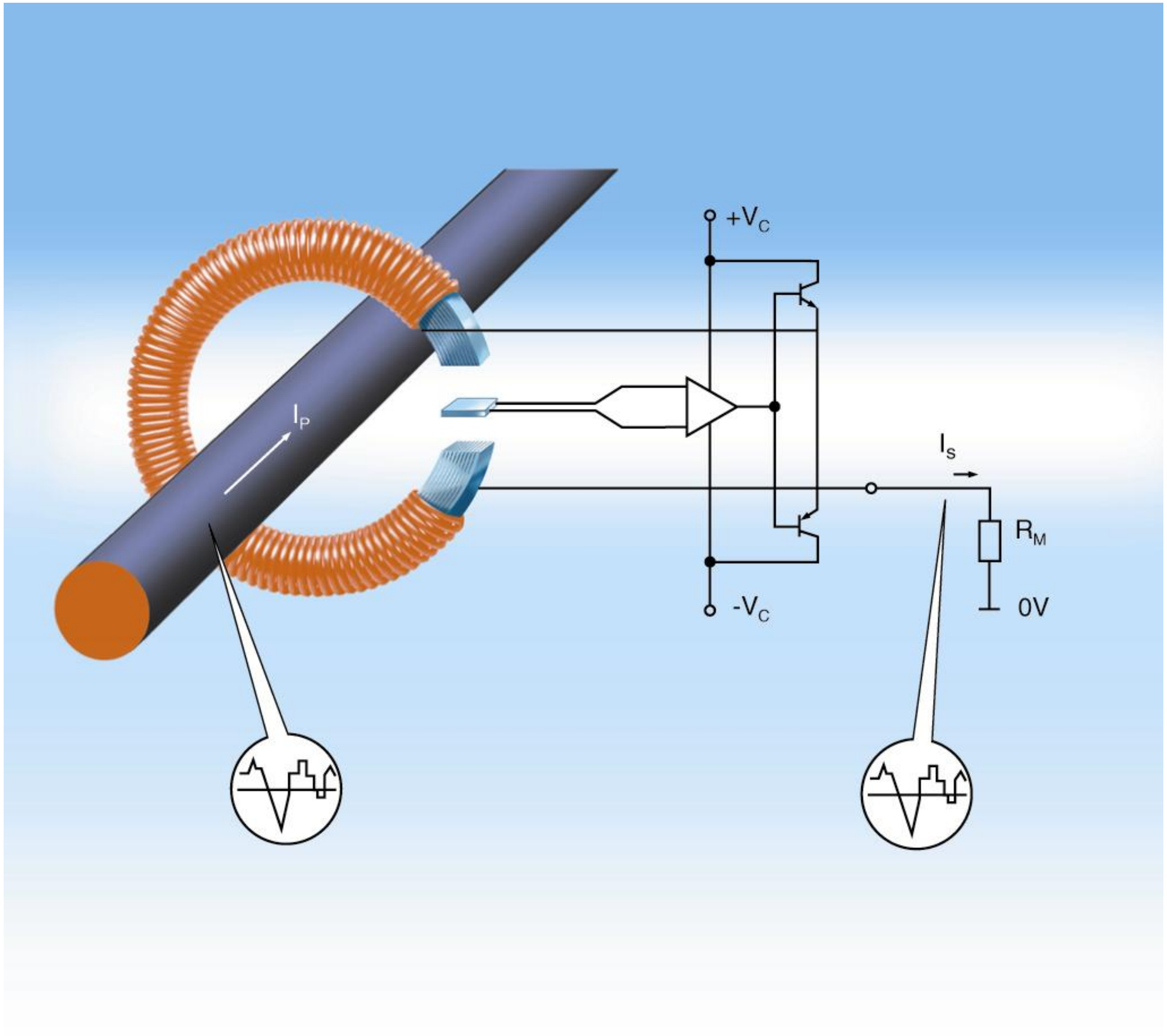
LEM Current Transducer 1



Accuracy range:

1 – 2 %

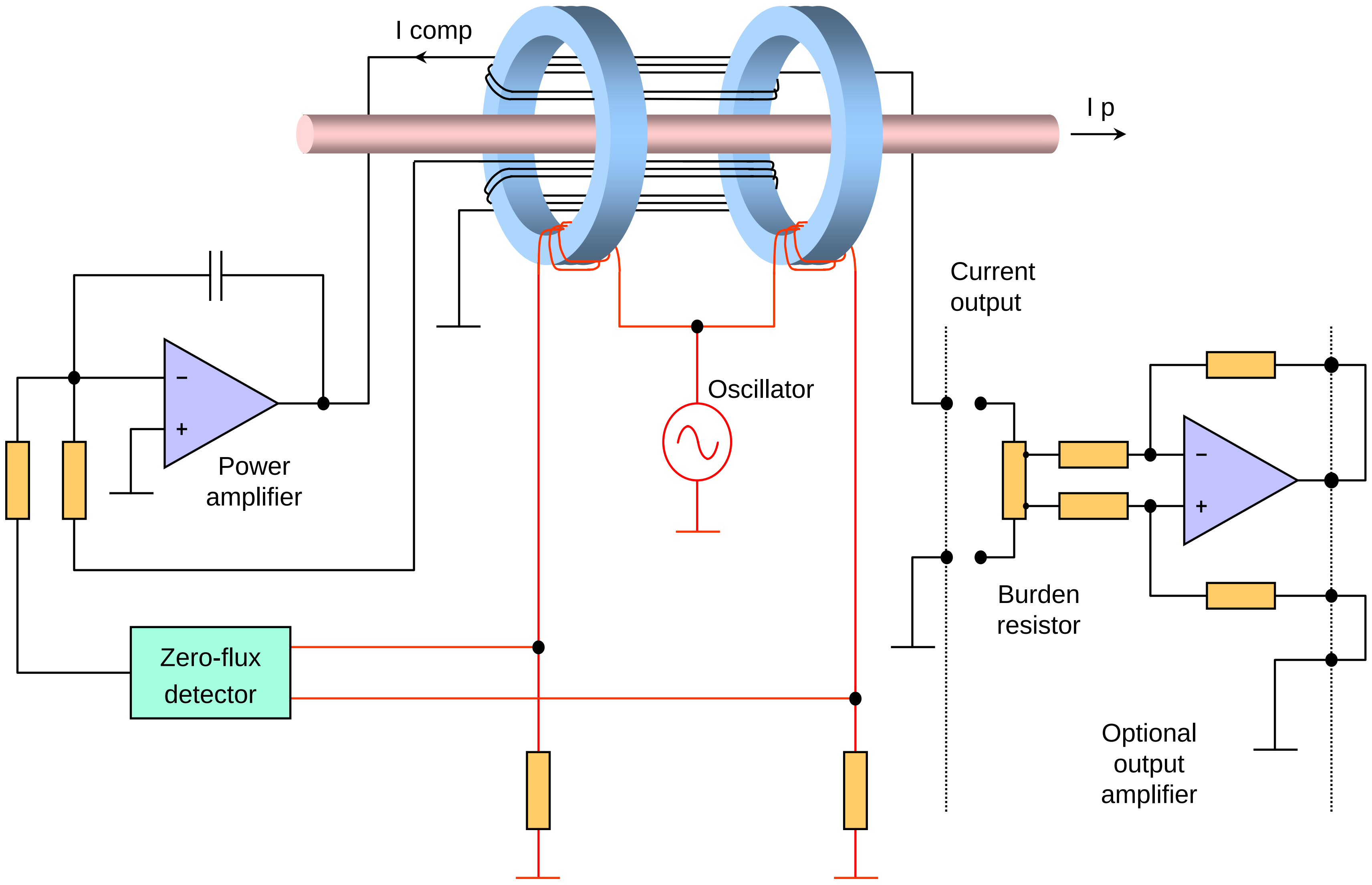
LEM Current Transducer 2



Accuracy range:
0.2 – 1 %

Linearity error:
< 0.1 %

DCCT Principle



DCCTs on the Market

Zero-flux transducer performance

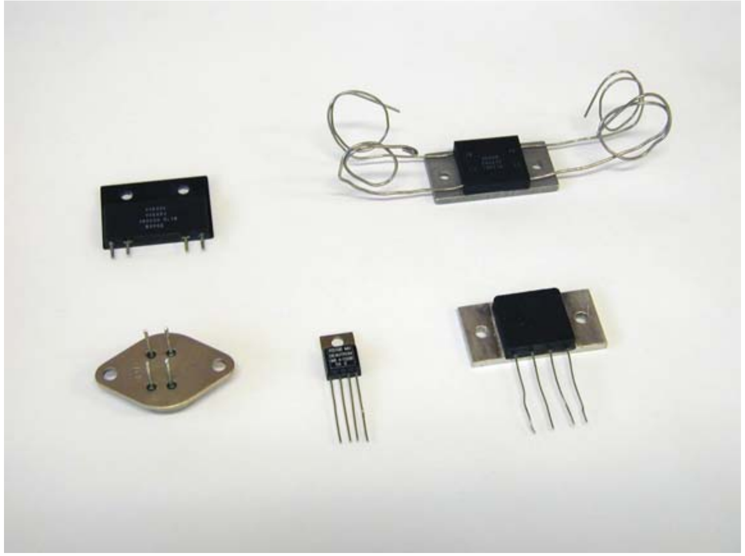
- Current ratio accuracy
  - 0.1 – 10 ppm
- Current/voltage conversion accuracy
  - 1 – 1000 ppm
- Accuracy vs. frequency
  - Loop gain important
  - Difficult to measure
- Noise and sources of noise
- Hysteresis

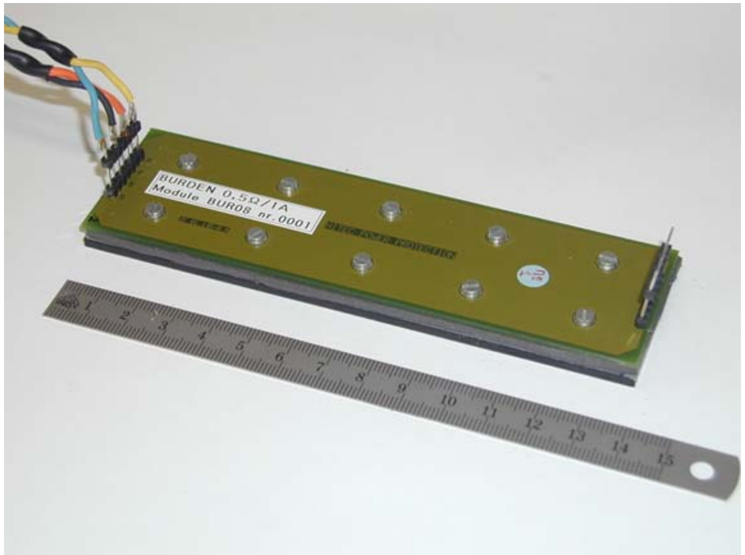
Current measuring resistors 1

- Resistance is defined as R=U/I
- It is a material property, not a constant
- It changes with temperature, humidity, pressure, mechanical stress
- Cu, Al, Ag, Au etc. ~ 4000 ppm/K
- Good materials are NiCr, Manganin, Zeranin, Evanohm – 1-100 ppm/K
- Packaging is crucial to performance

Current measuring resistors 2

- Four terminals are compulsory for low value resistors
- Cooling can be by air, oil, grease etc.





Current measuring resistors 3

- The output voltage is a trade-off between noise/thermal emf's and power dissipation
- Temperature coefficient measured at low power
- Power coefficient measured at one temperature
- Hysteresis

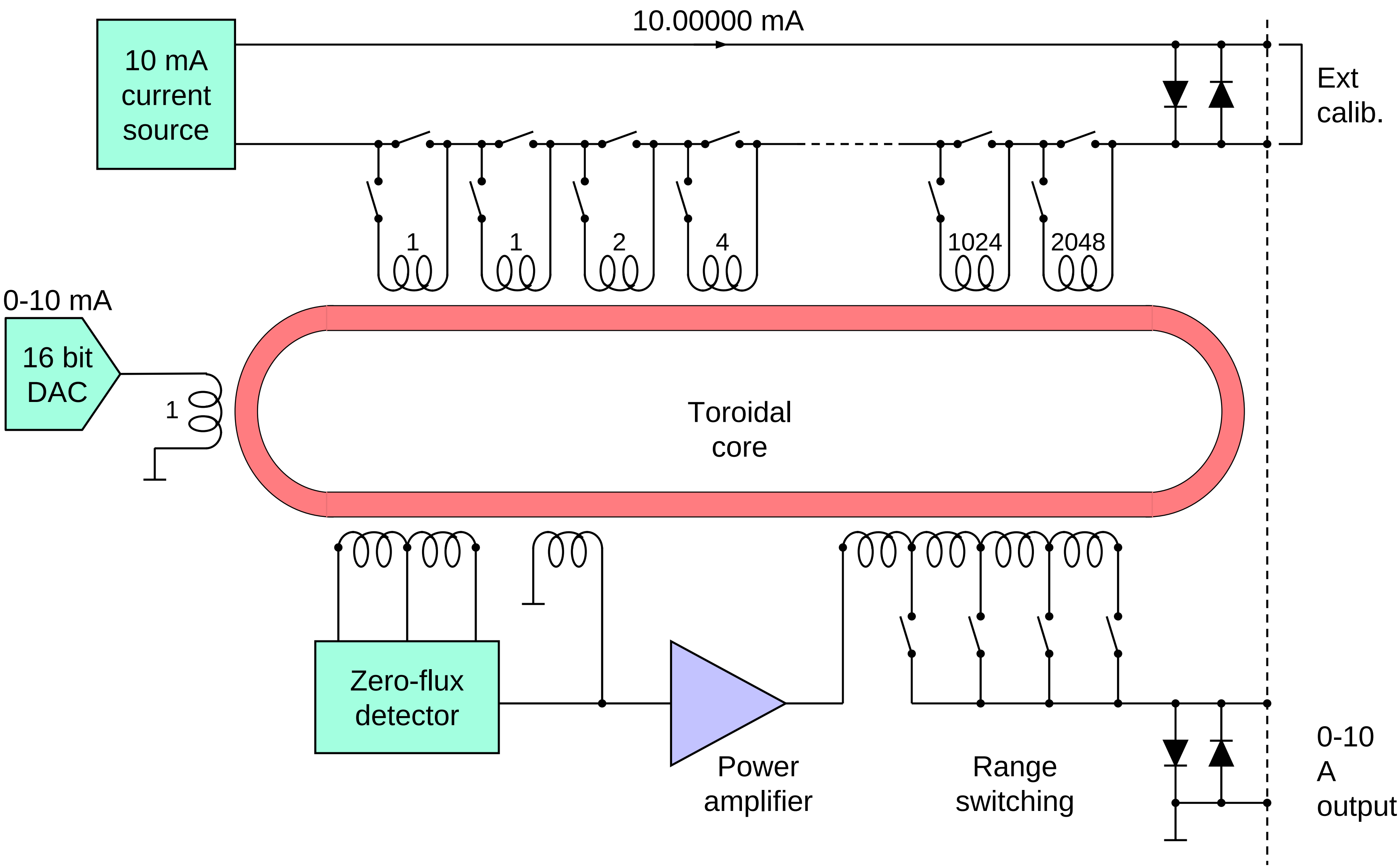
Calibration infrastructure 1
Standards

- Standards
  - Voltage, 10 V zener based
  - Resistance, 1 Ω - 10 kΩ
  - Current, 10 mA
  - Accuracy 10^{-6}
- Reference DCCTs

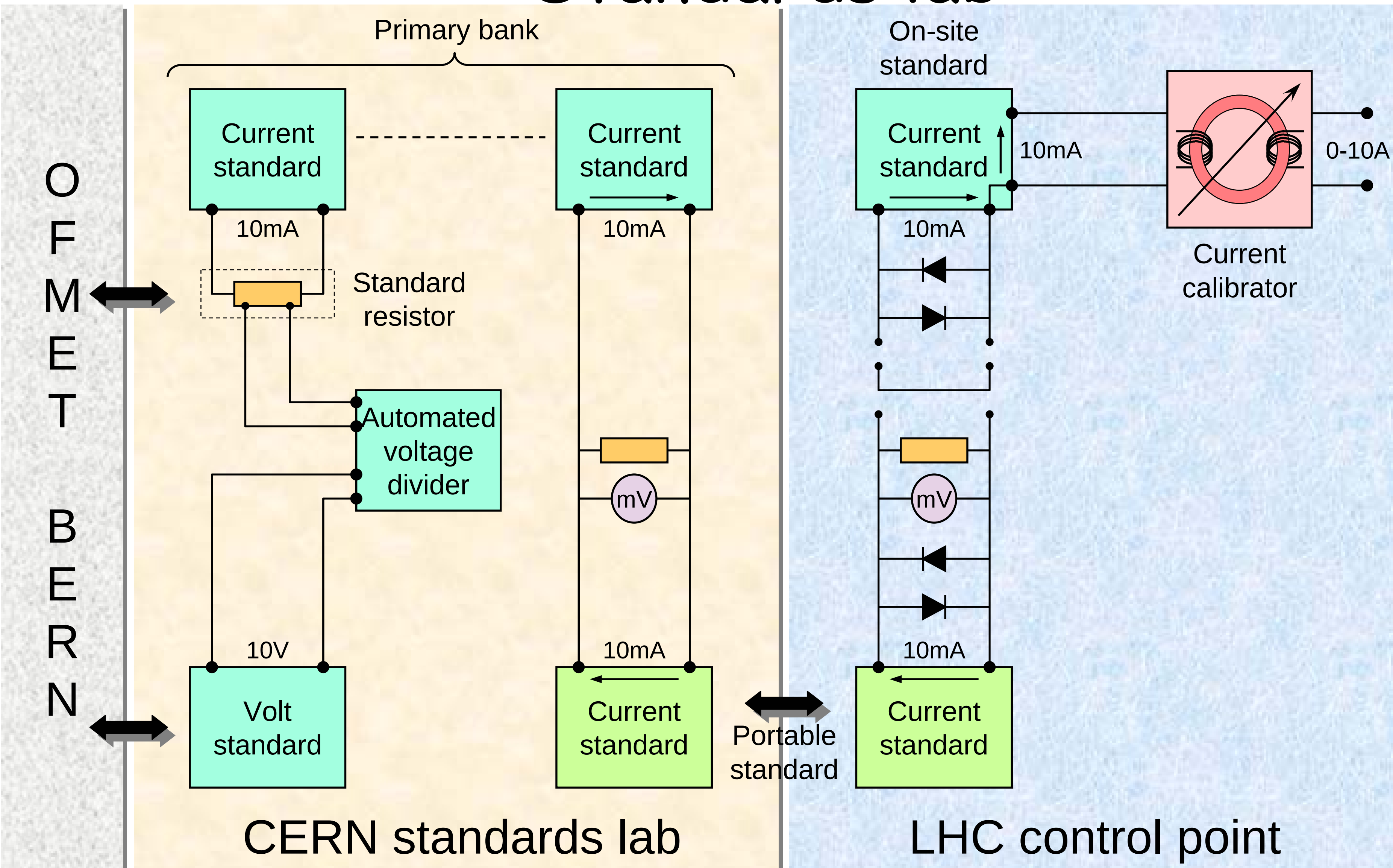
Calibration infrastructure 2

- Current calibrator
  - Principle: inverted DCCT, multiplies current up to max 10 A
  - Calibrates DCCTs with special winding
  - Calibrates burden/output amp directly
  - Fully computer controlled
- DCCT testbeds
  - Calibrates DCCTs by providing the full primary current with a known value

The current calibrator principle



The transfer scheme from the Standards lab



The Current Calibrator

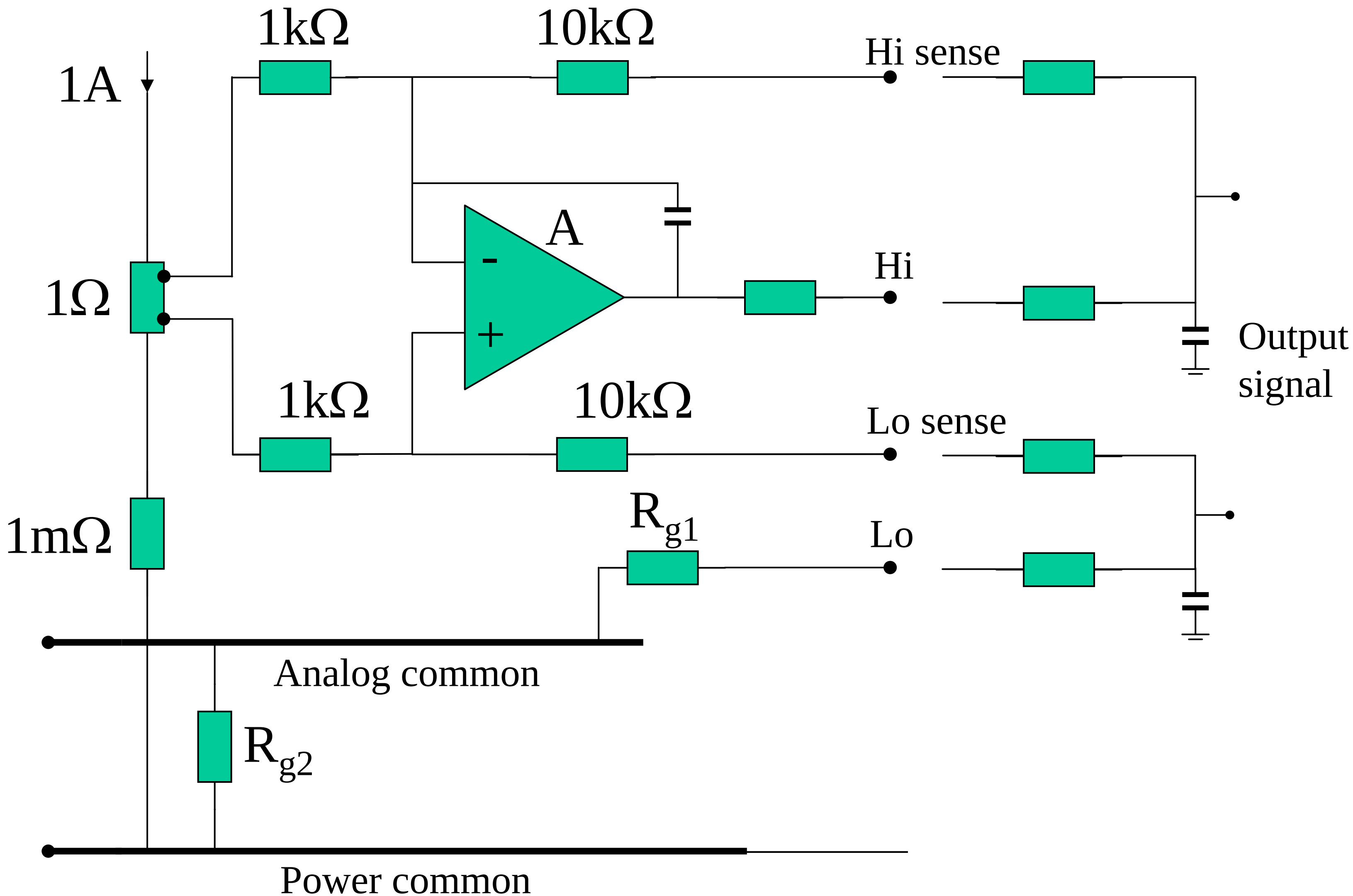
DCCT testbeds

6 kA

20 kA

Integration and other problems

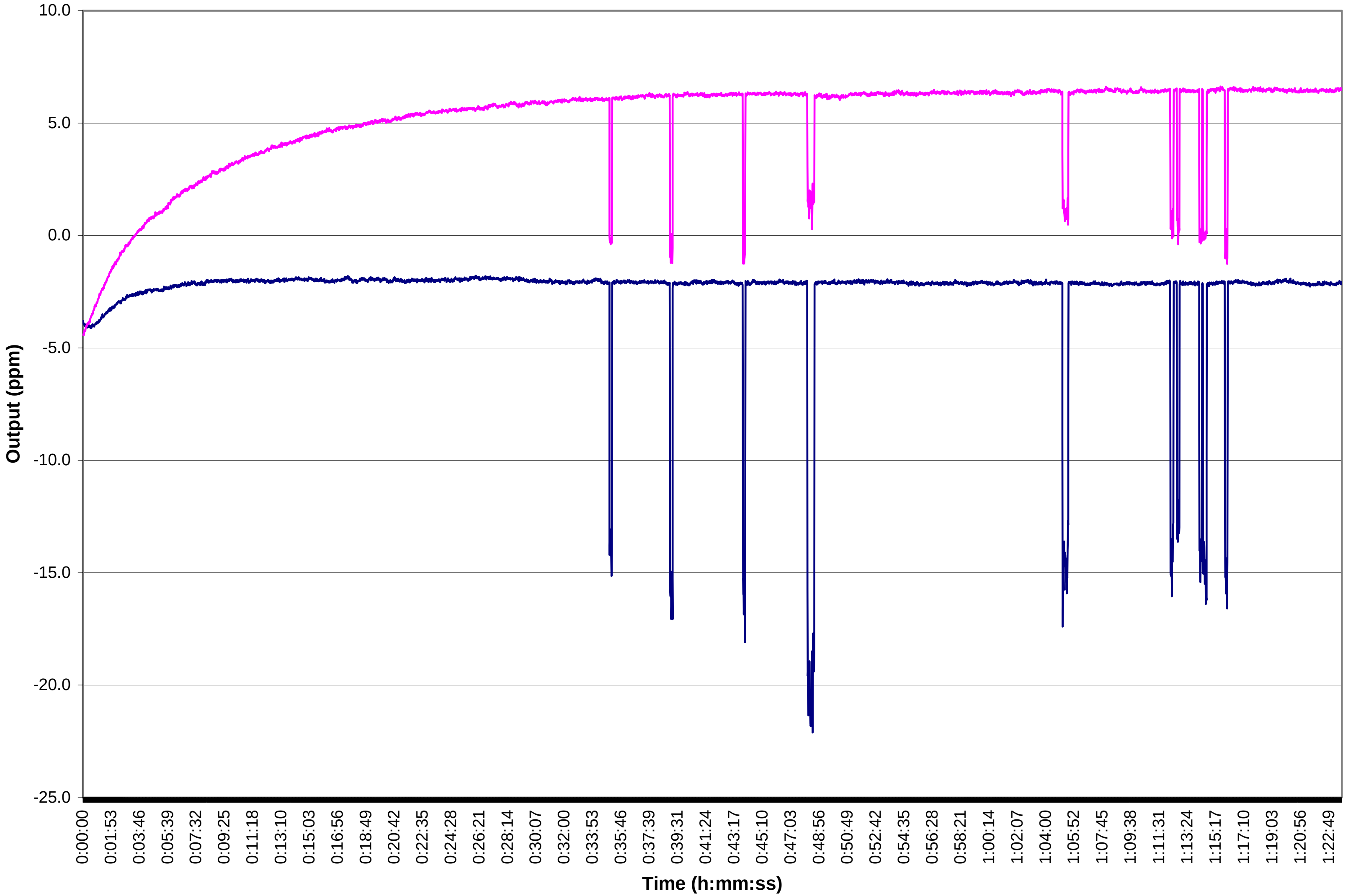
- Grounding – Distance DCCT to electronics
- Common mode voltages
- Power supply noise – rejection
- “Negligible” resistance
- 4 wire configuration - not always a solution
- Avoid resistive loading – use buffer amps
- Insufficient amplifier gain
- Instrumentation amplifiers
- Amplifier stability
  - Decoupling
  - Power amplifiers
  - Cascade amplifiers
- Load problem – dR/dt => dI/dt @ V= const
- External field sensitivity


1kΩ
10kΩ
Hi sense
1A
A
Hi
1Ω
Output
signal
1kΩ
10kΩ
Lo sense
R_{g1}
1mΩ
Lo
Analog common
R_{g2}
Power common

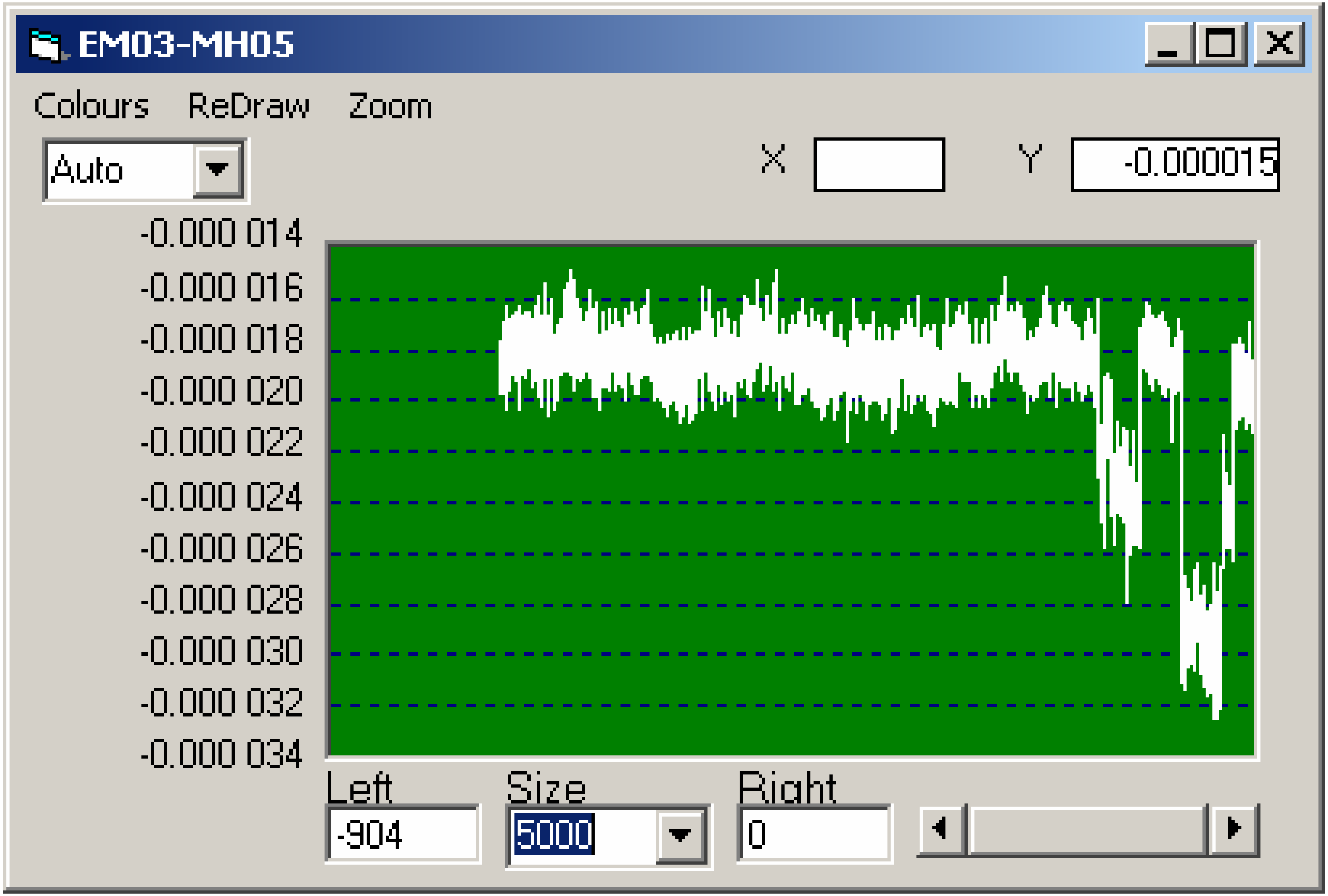
EMC problems in high precision

- Symptoms
  - Non-linearity
  - Unusual and unstable offset
- Tests
  - Use oscilloscope frequently – your best friend
  - RF exposure
  - Burst generator
  - Diagnose coupling mechanism
- Remedies
  - Grounding and Shielding
  - Filters
  - Consultants

Offset drift after power-up



Stability test of a DCCT



Conclusions

- Discourage exaggerated accuracy requests – direct and hidden costs
- Build conservative, with good margins
- Watch out for specmanship and quality control in industrial products
- Test in the lab, not in the machine
- Switch mode converters increase EMC problems at least an order of magnitude
- Presumption is the mother of all screw-ups

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- Appelo et al., The zero flux DC current transformer – A high-precision bipolar wide-band measuring device, IEEE Trans. Nucl. Sci., Vol NS-24, No 3, June 1977

Future challenges

- Create a better burden resistor
- Create a better current-to-voltage converter
- Create a truly digital DCCT