“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
LHC converter control
## Accuracy budget

<table>
<thead>
<tr>
<th>Device</th>
<th>Device spec</th>
<th>LHC machine impact</th>
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<tr>
<td></td>
<td>ppm of FS</td>
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<td>Stability 1/2 hr, 1-100 mHz</td>
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<tr>
<td>Gain drift 24 hr</td>
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<tr>
<td>Gain drift 1 year</td>
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<td>Offset Temp Coeff</td>
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<tr>
<td>DCCT total</td>
<td>20</td>
<td>73</td>
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</table>

| 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 commitment | 50 | 100 | 1000 |

### Conditions
- Temp change (K) | 0 | 5 | 10
- No special temp ctrl
### Device performance vs. actual performance...

<table>
<thead>
<tr>
<th>Device Spec</th>
<th>Real</th>
<th>DCCT 120 A</th>
<th>Zero uncertainty (hyst etc.)</th>
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<td>10</td>
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<td>15</td>
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<td>Gain drift 1 year</td>
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<td>100</td>
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<td>Offset drift 24 hr</td>
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<td>DCCT total</td>
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<td>50</td>
<td>100</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

**A/D converter, 16 bit succ. approx.**

| Uncomp non-linearity | 60 | 240 | 0 | 0 | 0 | 0 | 60 | 240 | 0 | 0 | 60 |
| LF noise, 0.1-10 Hz | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 0 | 0 | 60 |
| Stability 1/2 hr, 1-100 mHz | 30 | 30 | 0 | 0 | 30 | 30 | 0 | 0 | 50 | 50 | 100 |
| Gain drift 24 hr | 100 | 100 | 0 | 0 | 0 | 0 | 100 | 100 | 0 | 0 | 100 |
| Gain Temp Coeff | 3 | 3 | 0 | 0 | 15 | 15 | 30 | 30 | 0 | 0 | 50 |
| Offset drift 24 hr | 10 | 10 | 0 | 0 | 10 | 10 | 0 | 0 | 50 | 50 | 100 |
| Offset drift 1 year | 50 | 50 | 0 | 0 | 0 | 0 | 50 | 50 | 0 | 0 | 50 |
| Offset Temp Coeff | 0.6 | 1 | 0 | 0 | 3 | 5 | 6 | 10 | 0 | 0 | 50 |
| A/D total | 60 | 60 | 118 | 120 | 306 | 490 | 50 | 50 | 100 | 100 | 1000 |
| Miscellaneous | 5 | 5 | 10 | 10 | 100 | 100 | 50 | 50 | 100 | 100 | 1000 |
| **Total** | | | 75 | 83 | 201 | 231 | 739 | 924 | 50 | 50 | 100 |
| **LHC commitment** | | | 50 | 50 | 100 | 100 | 1000 | 1000 | 100 | 100 | 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

- Zero-flux detector
- Power amplifier
- Oscillator
- Current output
- Burden resistor
- Optional output amplifier
- I_{comp}
- I_p
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

- Resistance is defined as $R = \frac{U}{I}$
- It is a material property, not a constant
- It changes with temperature, humidity, pressure, mechanical stress
- Cu, Al, Ag, Au etc. $\sim 4000$ 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 \( \Omega \) - 10 k\( \Omega \)
  - 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

- 10 mA current source
- 0-10 mA current source
- 16 bit DAC
- Toroidal core
- Zero-flux detector
- Power amplifier
- Range switching
- Ext calib.
The transfer scheme from the Standards lab

Current standard 10mA

Volt standard 10V

Standard resistor

Automated voltage divider

Primary bank

Current standard 10mA

Portable standard

CERN standards lab

LHC control point

On-site standard

Current standard 10mA

Current calibrator

0-10A

10mA

mV

CAS2004 High Precision Measurements - Gunnar Fernqvist/CERN
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 – $dR/dt \Rightarrow dI/dt @ V= \text{const}$
- External field sensitivity
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
References

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• Bendat, Piersol, Random data analysis and measurement procedures, 3rd ed. 2000
• Ramirez, The FFT-fundamentals and concepts, 1985
• Moore, Miljanic, The current comparator, 1988
Future challenges

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