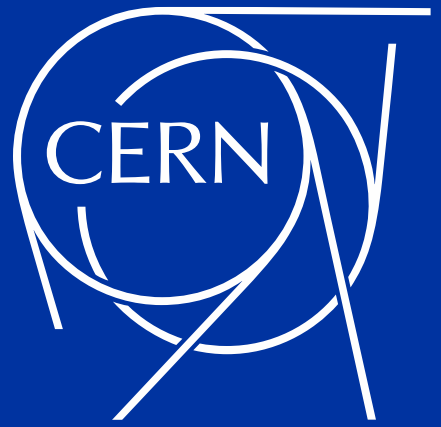


Engineering at CERN

The perspective of an Electronics Engineer on powering systems, measurement, precision, and more

International Teacher Weeks Programme 2026

Nikolai Beev, SY-EPC-HPM

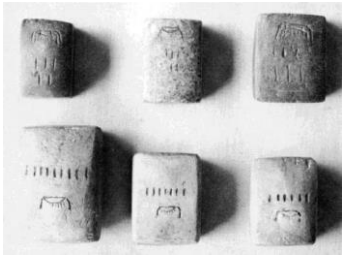
05/08/2026

Overview

- Metrology
  - Units and quantities – definitions and realization
  - Standards for electrical quantities
  - Electrical measurement devices – basic concepts and characteristics
- Electrical powering of normal-conducting and superconducting magnets for particle accelerators
  - Types of power converters
  - Precision requirements for LHC and HL-LHC
- High-precision measurement and control of high currents
- System-level challenges and solutions
- A bit on particle traps and antimatter

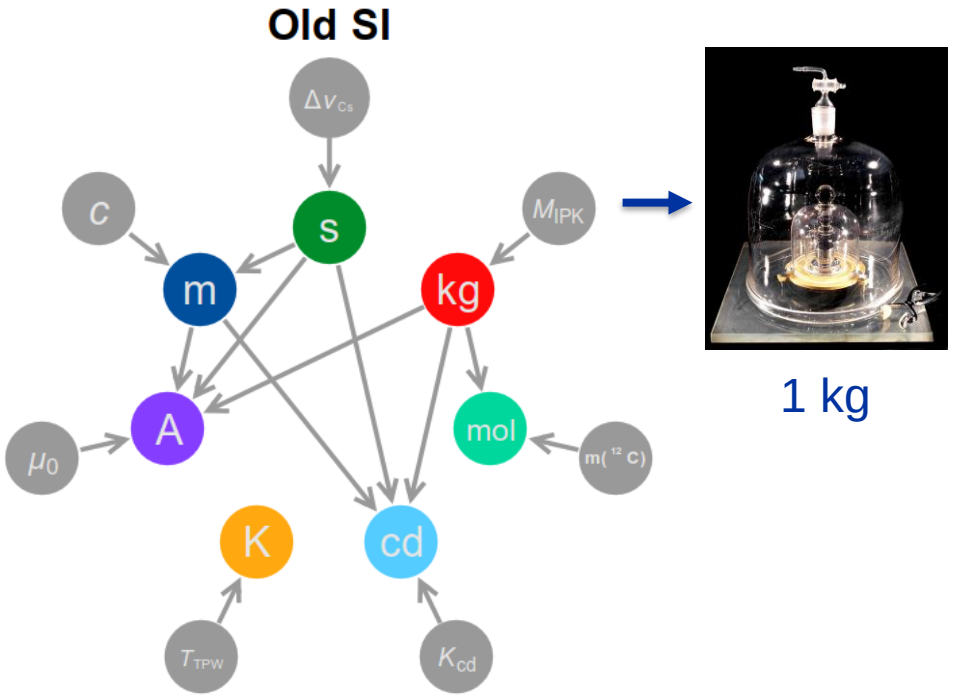
Metrology 101

- **Science of measurement (μέτρον + λόγος)**
  - Fundamental (scientific)
  - Applied (technical, industrial)
  - Legal
- **Early examples of weights and measures – 3000 years BC**



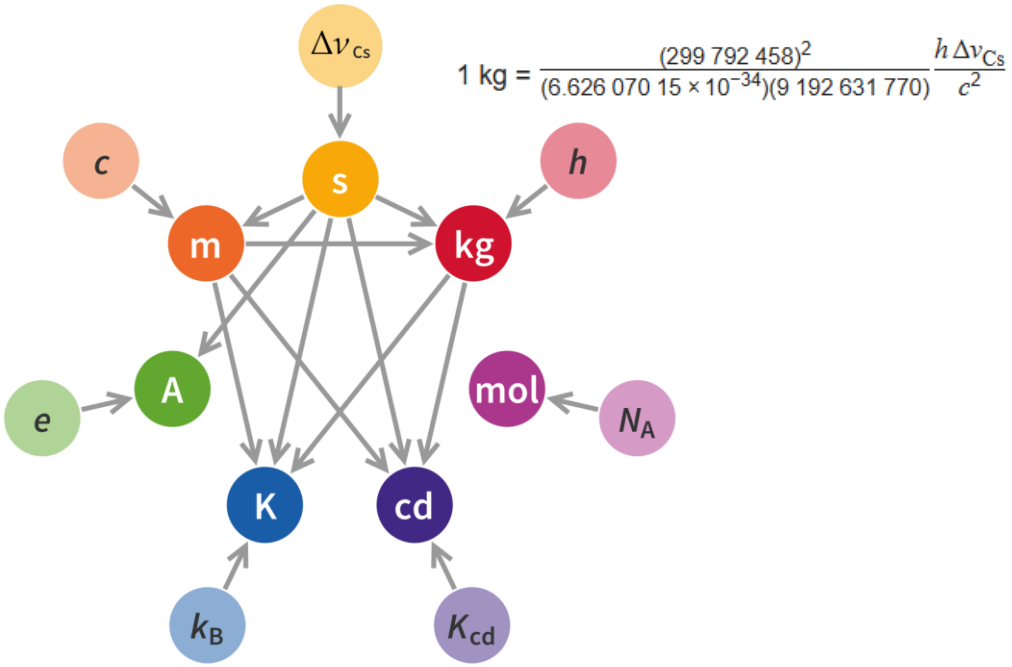
- **Modern history**
  - Metric system – France – 1795
  - Metre convention – 1875, signed by 17 countries in Paris
  - International System of Units SI – 1960
  - Redefinition of the SI base units – 2019

SI base units – 2019 redefinition



1 kg

New SI



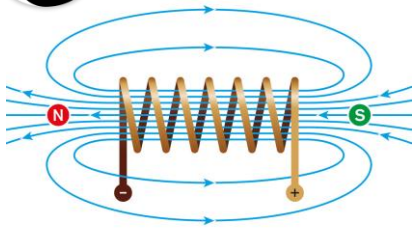
"The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one **metre** apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} **newtons** per **metre** of length."

"The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the **elementary charge** *e* to be 1.602 176 634 x 10^{-19} when expressed in the unit C, which is equal to A s, where the **second** is defined in terms of Δv_{Cs}."

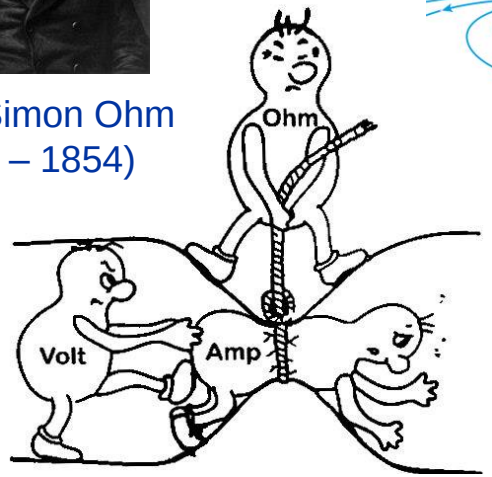
Electromagnetic units and quantities

Georg Simon Ohm
(1789 – 1854)

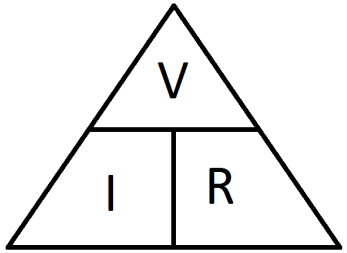
Electro-



magnetism



Alessandro Volta
(1745 – 1827)



I = V/R

V = IR

R = V/I

Ohm's law

André-Marie Ampère
(1775 – 1836)

Unit of	Name	Symbol	Definition through SI base units
Power	**watt**	**W**	J/s = kg.m^2/s^3
Electric charge	**coulomb**	**C**	A·s
Electric potential	**volt**	**V**	J/C = kg m^2/A s^3
Electrical resistance	**ohm**	**Ω**	V/A = kg·m^2/s^3·A^2
Electrical conductance	**siemens**	**S**	Ω $^{-1}$ = kg^{-1} m^{-2} s^3 A^2
Electrical capacitance	**farad**	**F**	A^2·s^4/kg·m^2
Magnetic flux	**weber**	**Wb**	kg m^2/s^2 A
Magnetic flux density	**tesla**	**T**	Wb/m^2 = kg/s^2 A
Electrical inductance	**henry**	**H**	kg m^2/s^2 A^2
	…		

James Clerk Maxwell
(1831 – 1879)

$$\nabla . E = \frac{\rho}{\epsilon_0} \quad (1) \quad \text{Gauss' law}$$

$$\nabla . B = 0 \quad (2) \quad \text{Magnetic monopoles}$$

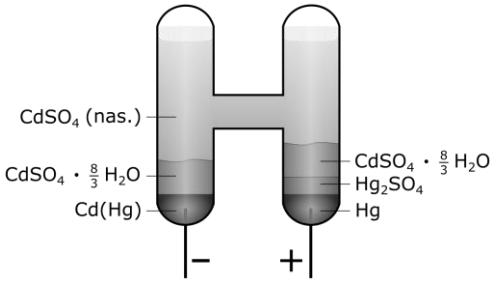
$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (3) \quad \text{Faraday's law}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad (4) \quad \text{Ampere-Maxwell law}$$

The Maxwell equations

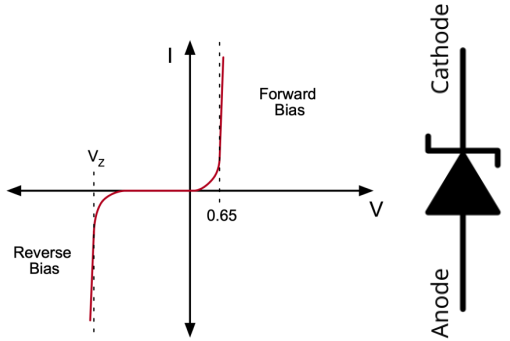
Standards for electrical quantities

V

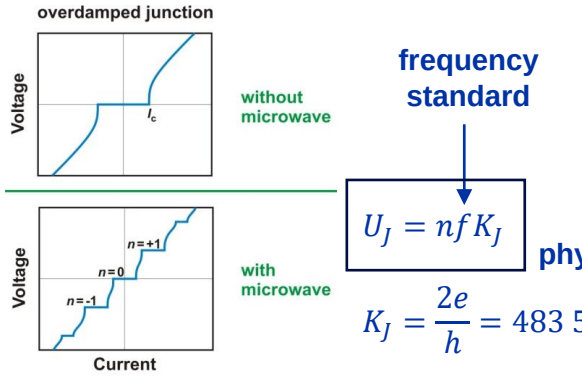


U = 1.018638 V

Weston cell (1893)

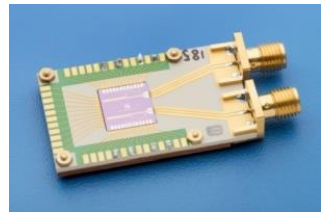


Zener diode (~1950)



frequency standard

$$U_J = nfK_J$$

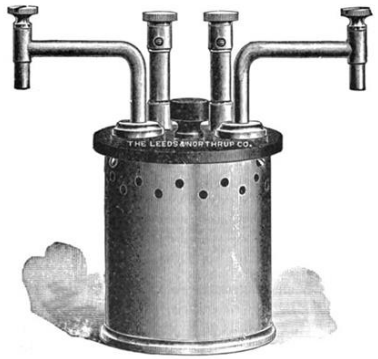


physical law

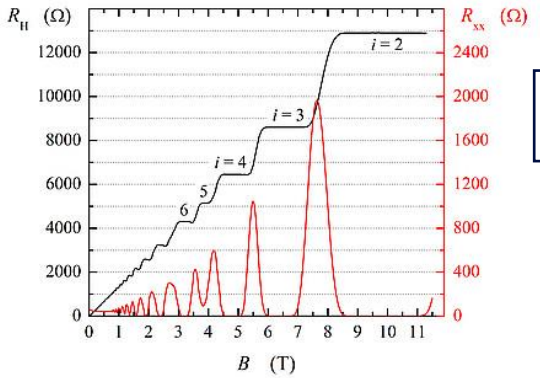
$$K_J = \frac{2e}{h} = 483\,597.848\,4\ldots\ 10^9\ Hz\,V^{-1}$$

Josephson effect (1962)
Nobel prize - 1973

Ω



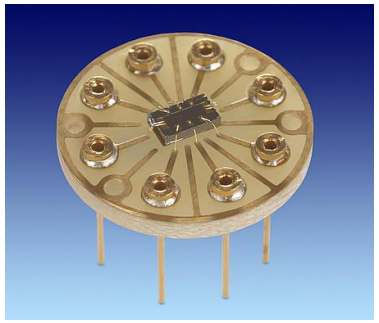
Standard resistors



$$R_H = \frac{h}{e^2 n}$$

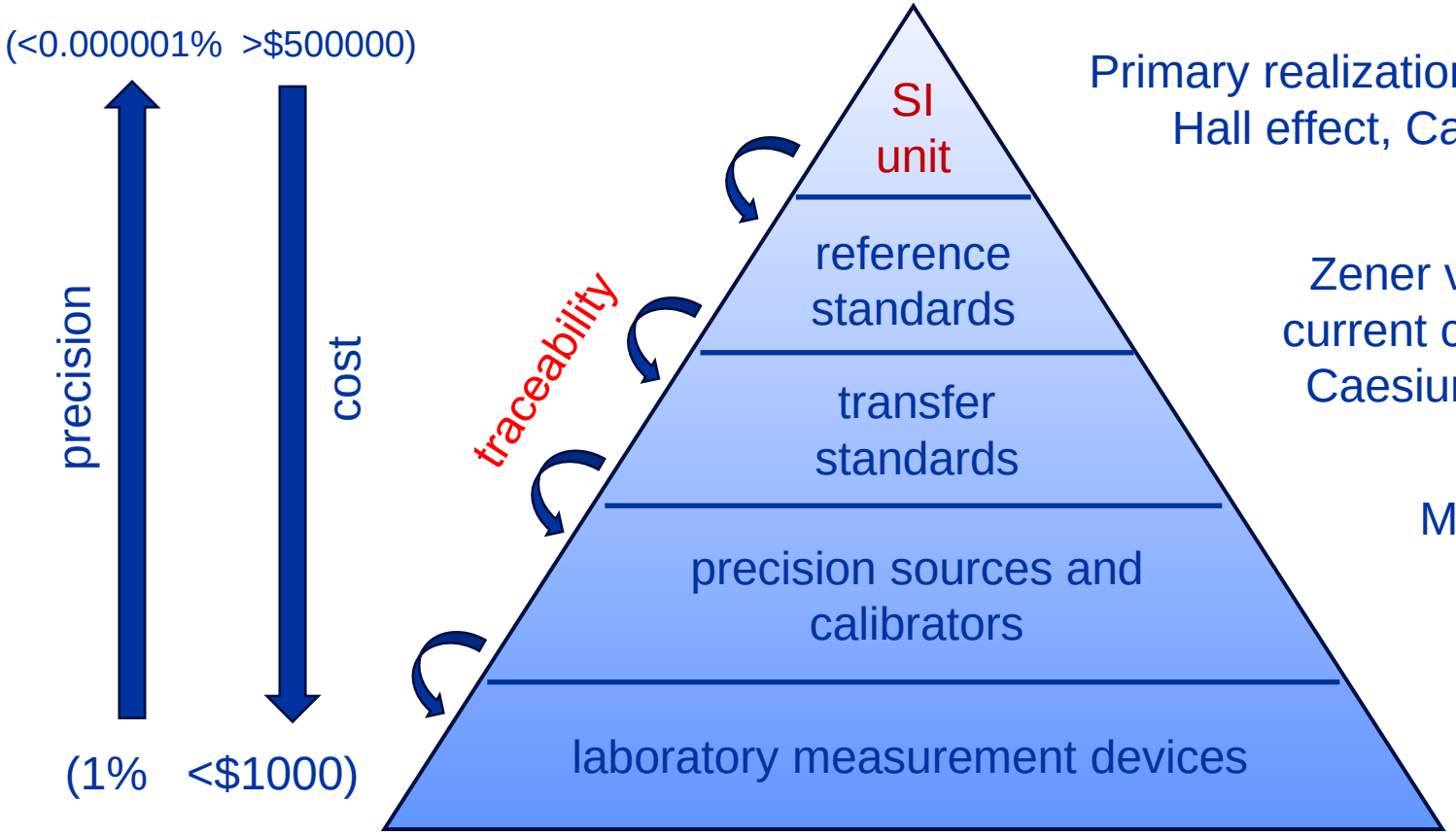
physical law

$$R_K = \frac{h}{e^2} = 25812.80745\ \Omega$$



Quantum Hall Effect – Klaus von Klitzing (1980)
Nobel prize - 1985

The metrological pyramid



Primary realization: Josephson voltage standards, Quantum Hall effect, Caesium fountain clocks, Kibble balance

Zener voltage standards, standard resistors, current comparators, AC/DC transfer standard, Caesium and Rubidium frequency standards

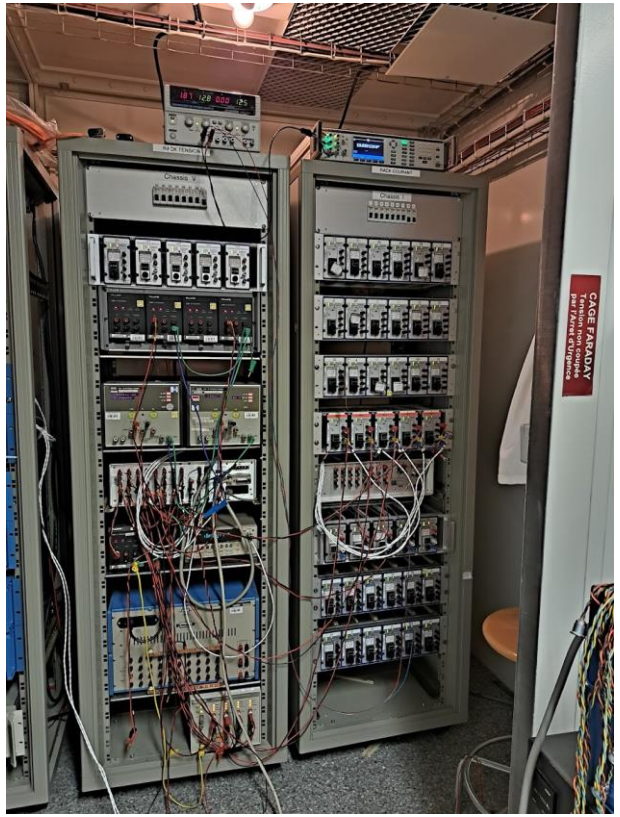
Multi-function calibrators, automated test equipment, waveform generators

Portable measurement instruments, power supplies, signal sources

Electronic measurement devices

- Conversion of quantities
- Built-in references (U, R)
- Sensitivity / resolution
- Ranges, dynamic range
- Measurement time
- Precision / accuracy
- Linearity
- Calibration
- Cost, use, support

Specialized electrical metrology infrastructure



Reference and transfer standards for voltage and current

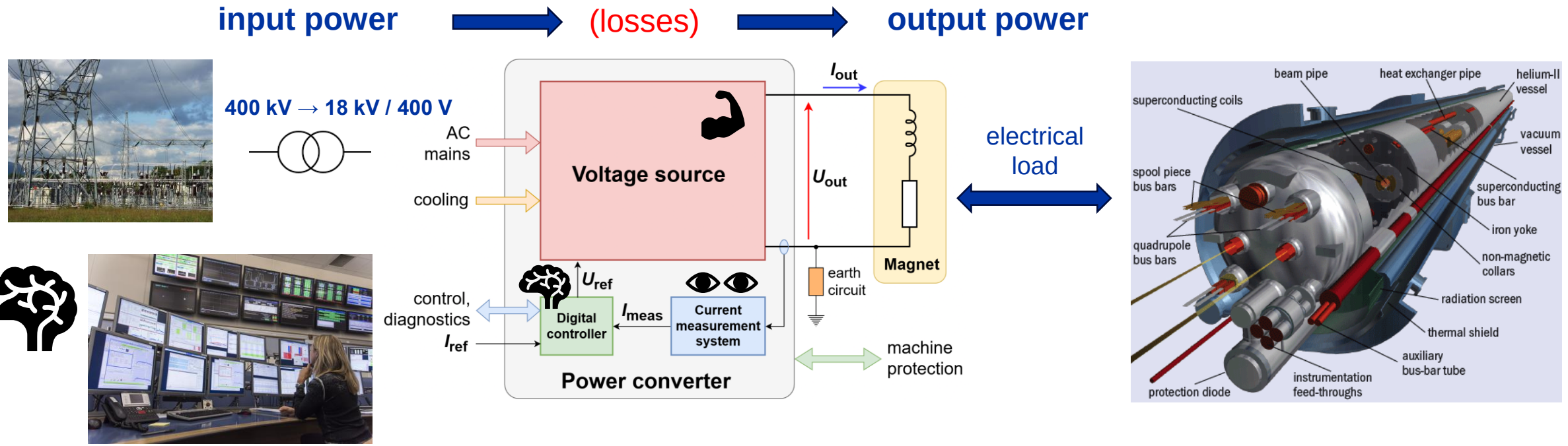
Reference current source for high-precision testing of direct-current current transformers (DCCTs)

Mobile current calibrator in the LHC tunnel

Testbed for DCCT testing with primary current up to 20000 A

Electrical powering of magnets

- Electromagnets are powered with **current**
- The power section of a converter is a **voltage source**
- Principle: precision measurement of the output current, closed negative feedback loop
- The precision of the output current depends **directly** on the measurement



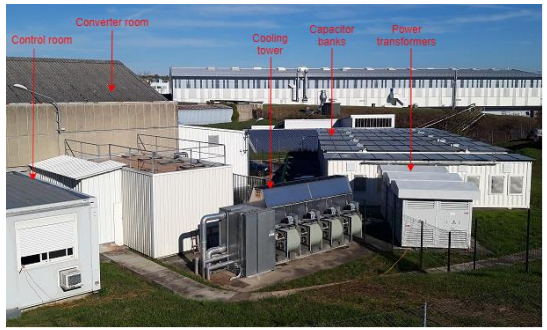
Power converters for accelerator magnets

Warm (normal-conducting) magnets in fast-cycled machines

high voltage + high current

Example: PS (1959, circumference 628 m)

Chain of 101 magnets with combined function
L = 0.9 H
R = 0.35 Ω
Machine cycle: 1.2 s



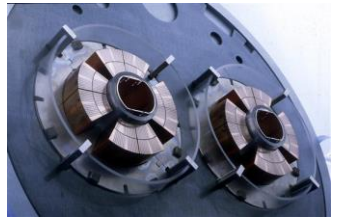
POPS Power Converter
6000 A, 10000 V
→ **60 MW** (peak)
4 MW (average)
→short-term energy storage in capacitor banks

Superconducting magnets in slow-cycled machines

low voltage + high current

Example: Main quadrupoles in LHC

Chain of 24 double-aperture magnets per sector
L = 0.26 H
R ≈ 0.001 Ω
Nominal current 11850 A
Rise time ≈ 30 min

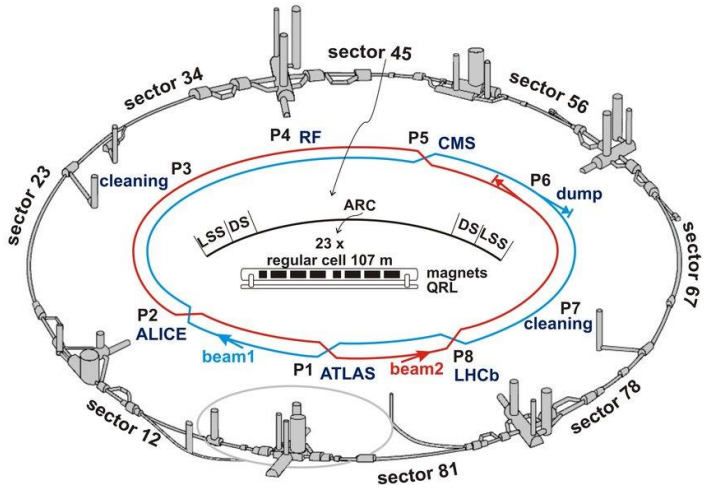


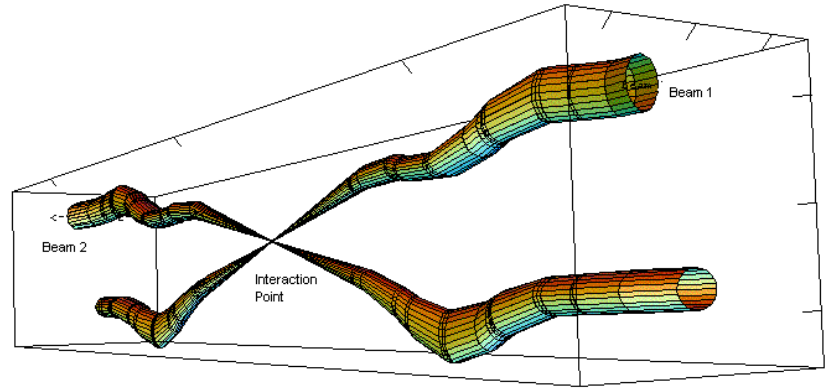
RPHE Converter

13000 A, 18 V
265 kW (peak)
losses ≈ 30 kW

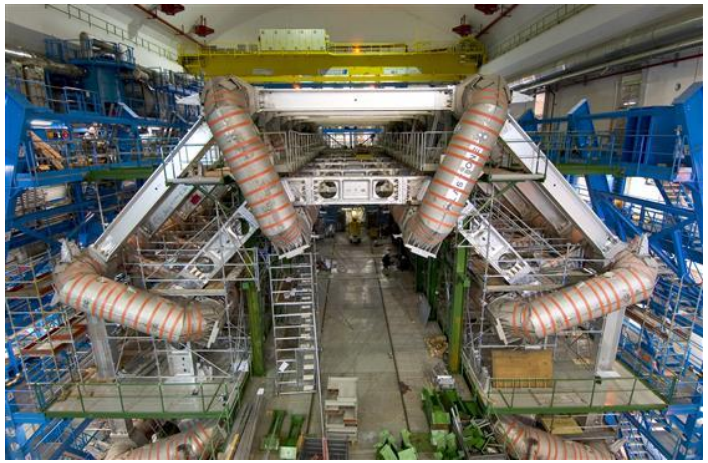
Powering of LHC magnets

- **Approximately 9300 magnets –** dipoles (1232), quadrupoles (858), correctors (>6000) ...
- **Mostly superconducting –** only about 100 normal-conducting
- **Range of currents –** from **60 A** (correctors) to **31000 A** (ALICE solenoid)
- **The main dipoles and quadrupoles (QF/QD) are separated into 8 sectors** → 24 chains with high-precision powering and maximum current of 13000 A
- **Inner Triplets –** focusing of the beams at the interaction points – system of 4 quadrupole magnets and 3 power converters, in total 8 systems
- **Special magnets for the experiments –** solenoids, toroids, dipoles…





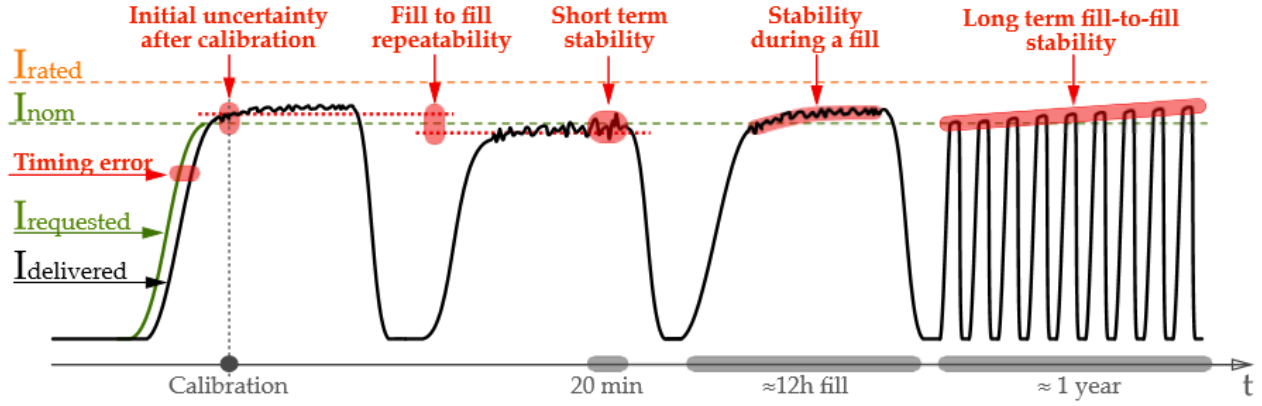
Relative beam sizes around IP1 (Atlas) in collision



Precision powering requirements for LHC

- **Stable powering → stable magnetic field**
  → <u>fine control of beam parameters</u>
- **The highest requirements are for these systems:**
  - Main dipoles – matching of the 8 sectors
  - Main quadrupoles – matching of the 8 sectors + stability of Q_X and Q_Y (betatron tune)
  - Inner triplets: stability of the interaction point and control of the number of events

- **Differentiated requirements for the magnet current:**
  - Noise (0.1 – 500 Hz)
  - Short-term stability
  - Fill stability
  - Repeatability
  - Long-term stability (over 1 year)
  - Temperature dependence



Precision requirements for HL-LHC

	PC REQUIREMENTS SUMMARY - ACCURACY CLASSES				
	0	1	2	3	4
Resolution [ppm]	0.5	0.5	1.0	1.0	1.0
Initial uncertainty after cal [2xrms ppm] normal	2.0	2.0	3.0	7.0	10.0
Linearity [ppm] [max abs ppm] uniform	2.0	2.0	5.0	8.0	9.0
Stability during a fill (12h) [max abs ppm] uniform	0.7	1.9	5.0	8.0	9.5
Short term stability (20min) [2xrms ppm] normal	0.2	0.4	1.2	2.0	5.0
Noise (<500Hz) [2xrms ppm] normal	3.0	5.0	7.0	15.0	19.0
Fill to fill repeatability [2xrms ppm] normal	0.4	0.8	2.6	4.0	5.0
Long term fill to fill stability [max abs ppm] uniform	8.0	8.0	19.0	40.0	45.0
Temperature coefficient [max abs ppm/C] uniform	1.0	1.2	2.5	5.5	6.5
12h Delta T for HL-LHC [max C] constant	0.5	1.0	5.0	5.0	5.0
1 y Delta T for HL-LHC [max C] constant	0.5	1.0	5.0	5.0	5.0

New accuracy class for HL-LHC
14000 A and 18000 A power converters

- Numerical values in **ppm** (part per million) = 10^{-6}
- **1 ppm** = 1% of 1% of 1% = 1 ‰ of ‰ = 0.0001 %
- **1 ppm** of 18000 A = 0.018 A (18 mA); 1 ppm of 10 V = 10 µV
- **1 ppm** of 100 km = 10 cm
- The requirements are defined for the output current, but in practice they refer to the capabilities of the measurement system

Direct-Current Current Transformers (DCCTs)

- **Principle:** magnetic modulator + detection of zero magnetic flux + compensation current + current transformer
- Conversion of high current (10 A – 30 kA) into secondary low current (0.1 A – 10 A) using exact ratio of turns
- The secondary current is converted to voltage across a highly precise resistor (Ohm's law!)
- Collaboration of CERN with industrial partners

Example:

LHC, Accuracy Class 1 DCCT

Primary current: 13000 A

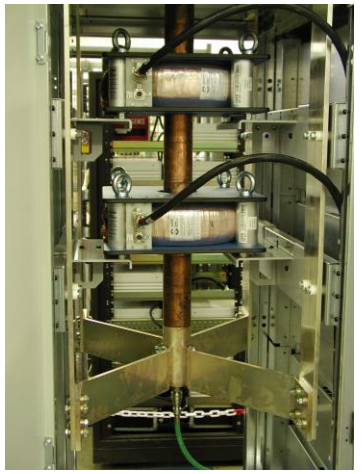
Turns ratio: 1:2600

Secondary current: 5 A

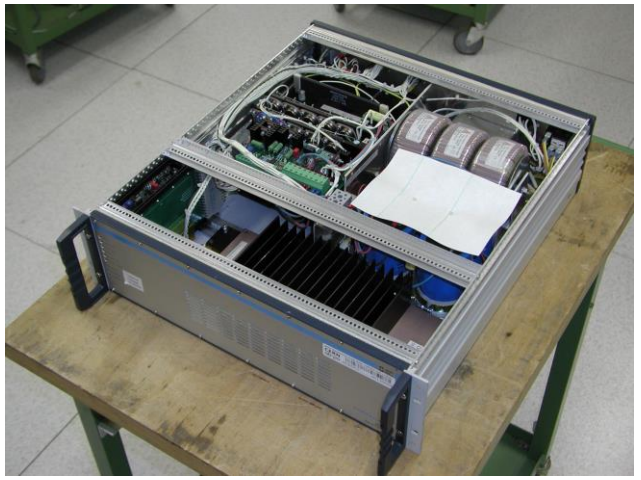
Burden resistor: 0.2 Ω

Calibration winding: 1:2600 (5 A)

Measurement stability: <1.5 ppm (12 hours)



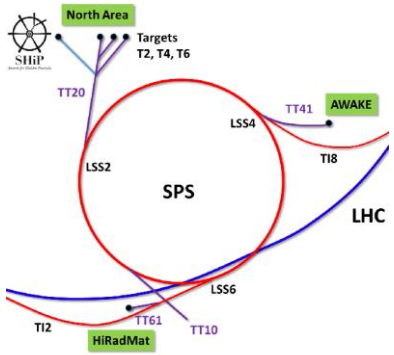
magnetic head



electronics chassis

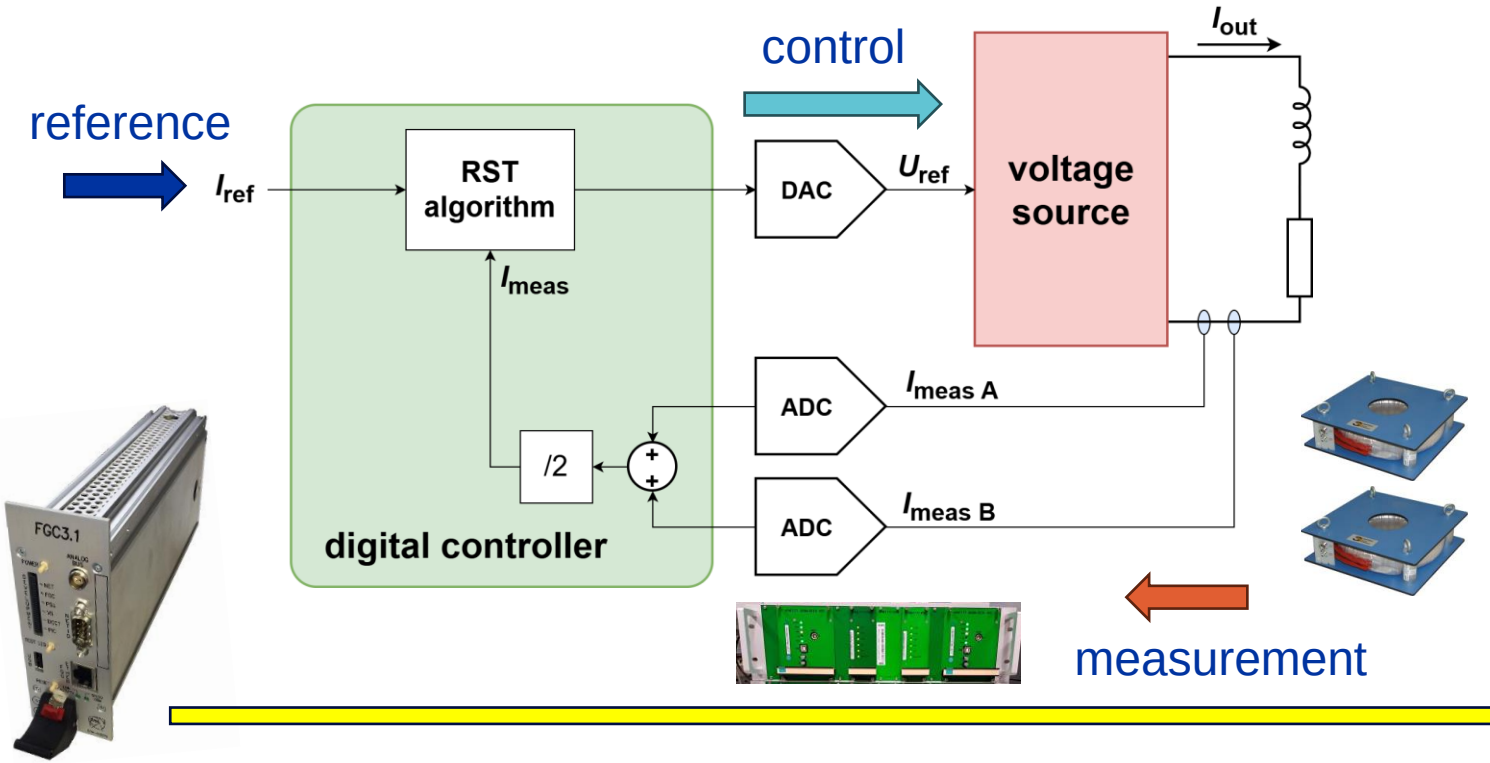
High-precision digitizers developed at CERN

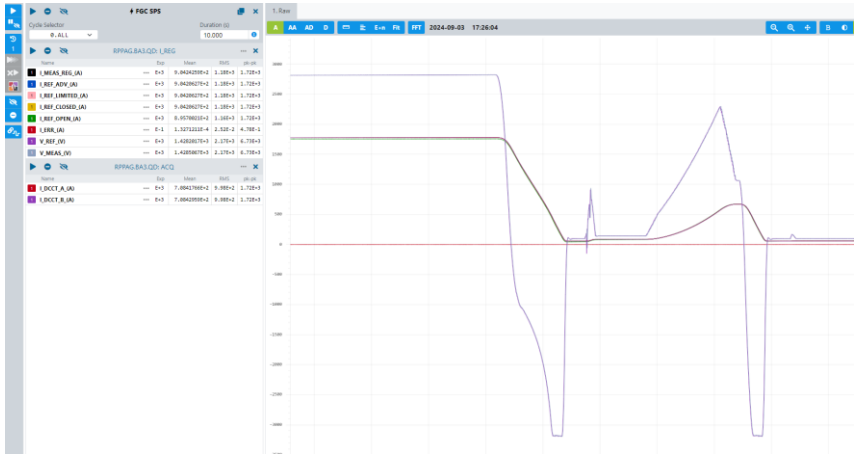
- Only a few high-end digital voltmeters would meet the requirements for voltage measurement
- The first high-precision digitizers were developed specially for LHC in the early 2000s. There are still about 60 of them operating
- New, stricter requirements for HL-LHC → development of new digitizers with **higher metrological performance**
  - ➢ Approximately 100 units will be installed in HL-LHC before 2030
  - ➢ 20 units are already installed in the IT String test facility (SM18)
  - ➢ 6 units have been in operation for the SPS mains (dipoles, quadrupoles) since the beginning of 2024
  - ➢ Characterization with Josephson voltage standards at PTB-Braunschweig (2022, 2025)



Digital control

- All control loops for magnet current at CERN are realized digitally
- All control loop and calibration parameters are stored in a database
- The hardware is interchangeable
- Measurement signals are accessible in real time

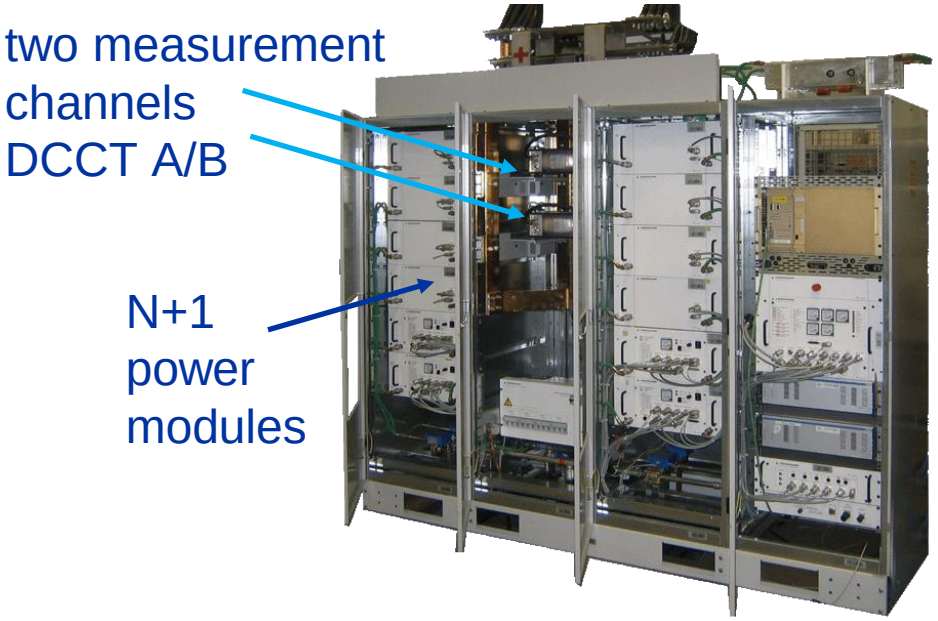




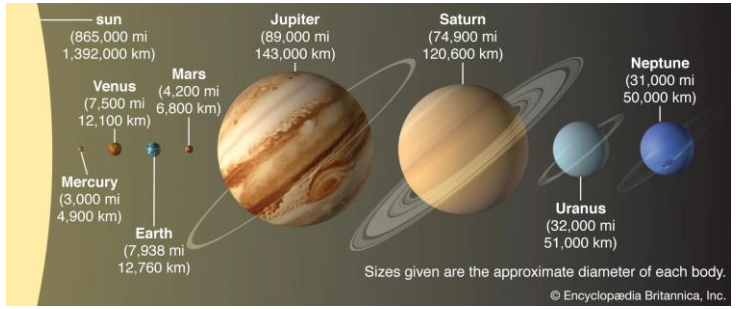
analysis, diagnostics

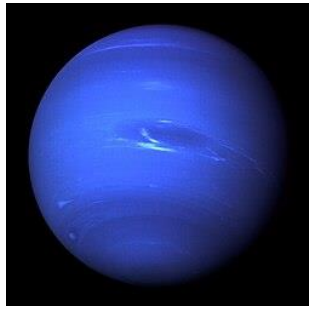
System-level challenges and solutions

- **Reliability**
  - Large number of systems (>5000 in the entire complex)
  - Normal operation: 24/7, 20-30 years
  - High-reliability protection chains and interlocks
  - Electromagnetic compatibility (emissions, susceptibility)
- **Field support**
  - Modular systems – redundancy of power modules
  - Measurement systems – redundancy, UPS powering, hot spares
  - Real-time and post-mortem diagnostics
  - Preventive and corrective maintenance
- **Operation in ionizing radiation environment**
  - Dependence on the physical location
  - Radiation-tolerant electronic components – single-event errors (SEE) or total ionizing radiation dose (TID)
  - Special infrastructure at CERN for accelerated testing for radiation tolerance



Antimatter also matters

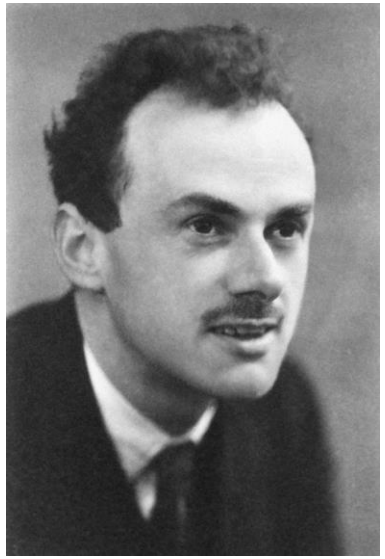




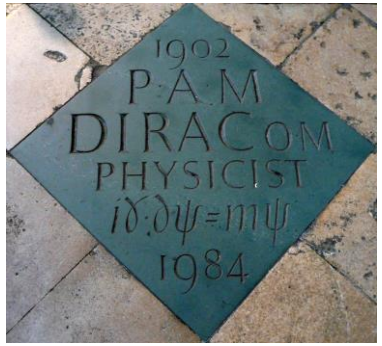
Ψ

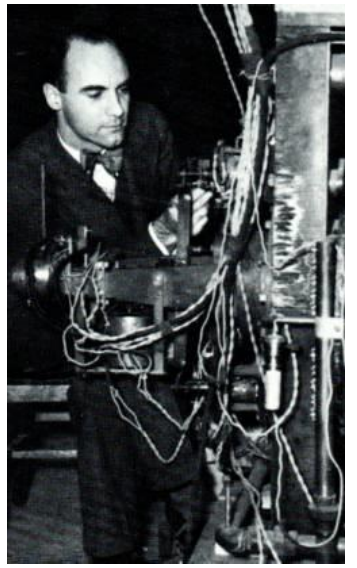
Urbain Le Verrier
(1811 – 1877)

Johann Gottfried Galle
(1812 – 1910)

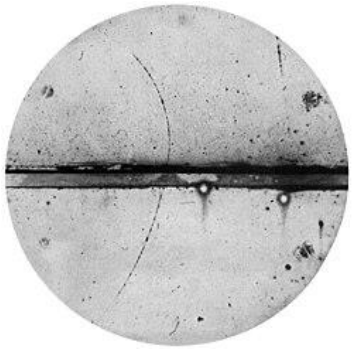


Paul Dirac
(1902 – 1984)

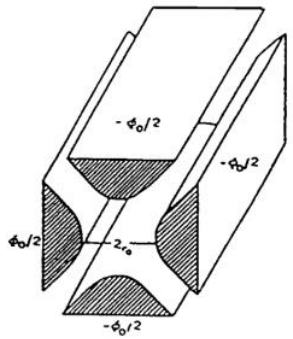


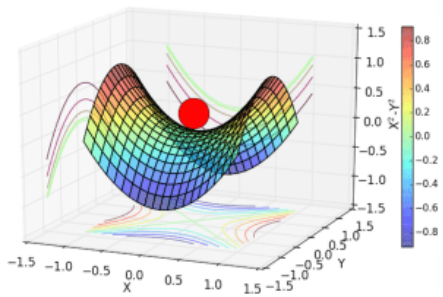


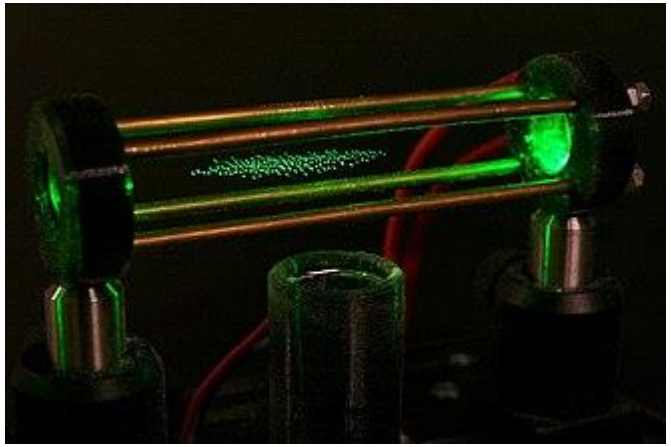
Carl David Anderson
(1905 – 1991)



Particle traps

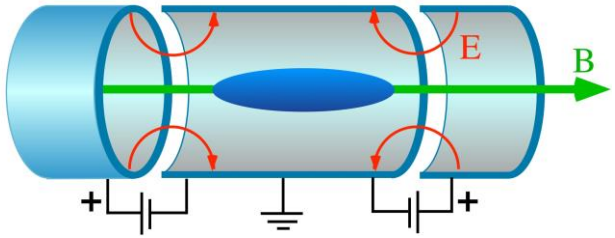


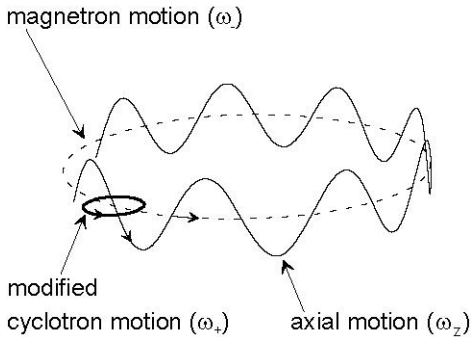




Paul trap

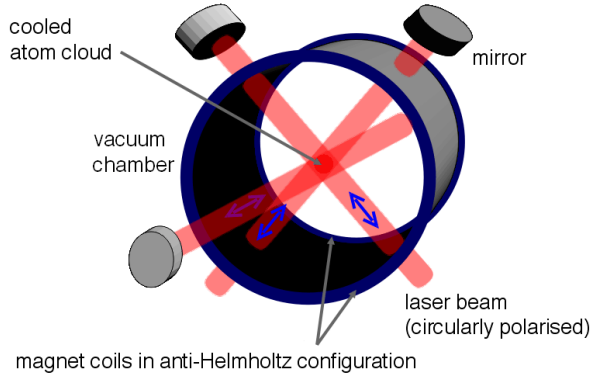
DC and RF electric fields



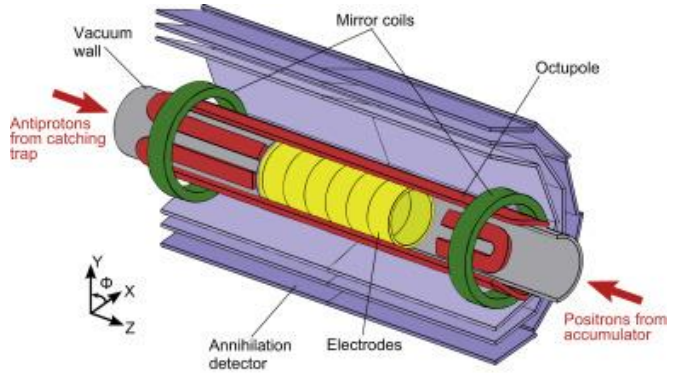


Penning trap

DC electric and magnetic fields

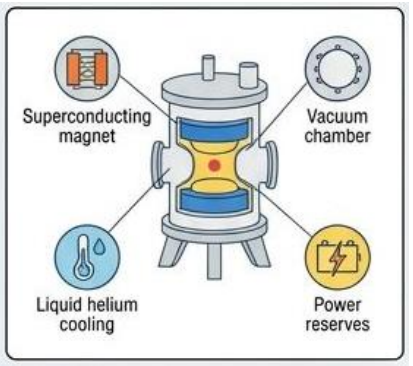


Magneto-optical trap



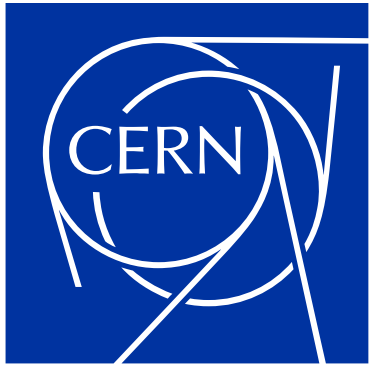
Magnetic trap

Transport of trapped antiparticles



- BASE experiment at AD
- 92 antiprotons
- Portable cryogenic Penning trap (only 1000 kg)
- So far only a short ride (CERN campus only)

Thank you!



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