Introduction to Practical Exercises: Magnetic Measurements

Objectives, activities, and safety aspects

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CAS course on “Normal- and Superconducting Magnets”, 19.11–02.12.2023 St. Pölten, Austria

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HTL St. Pölten

Special thanks to Direktor Pfeffel and all technical staff who helped us set up the material.

Part I
Magnetic Measurement Exercises

Objectives and activities

Our goal

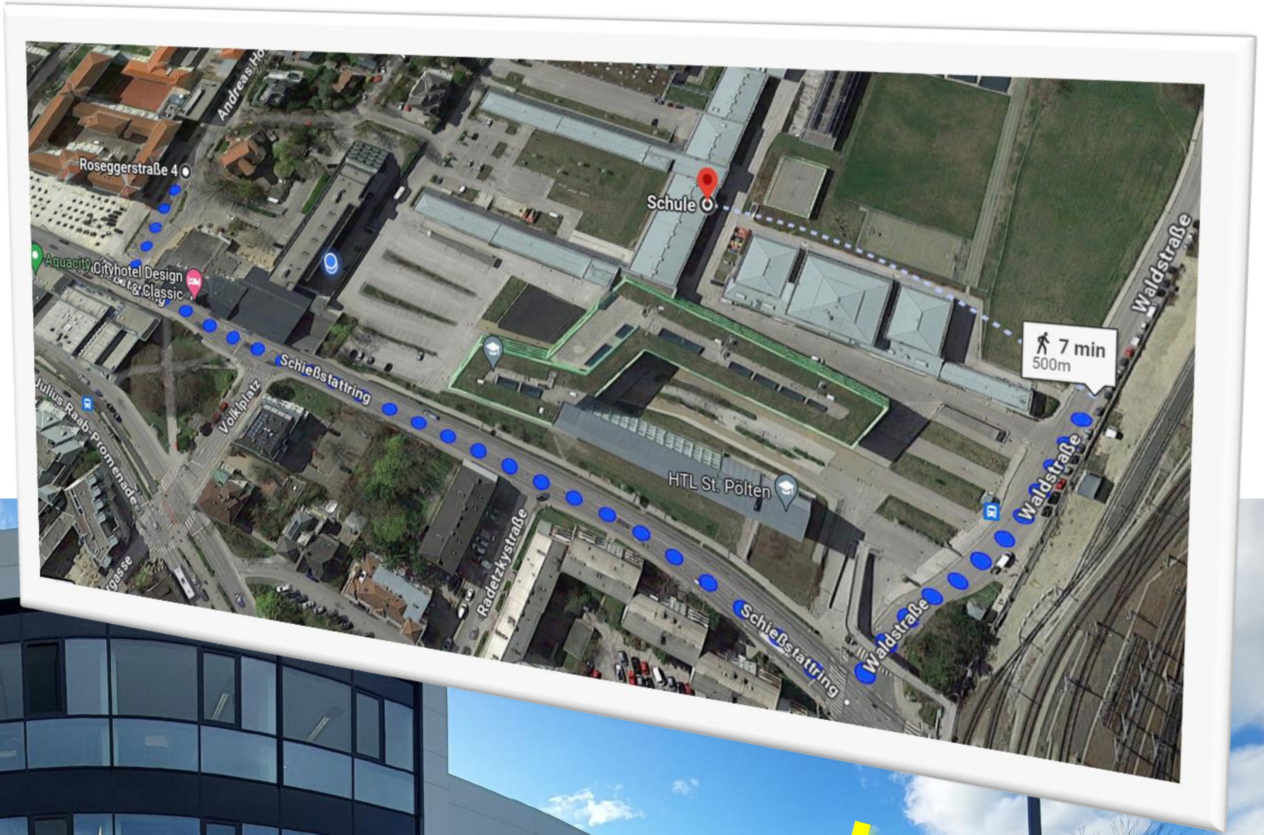
To give you all, as magnet designers, makers and users:

- A taste of hands-on experience with some of the most useful magnetic measurement techniques
- A feel for practical capabilities and limits of magnetic field instrumentation

Where ?

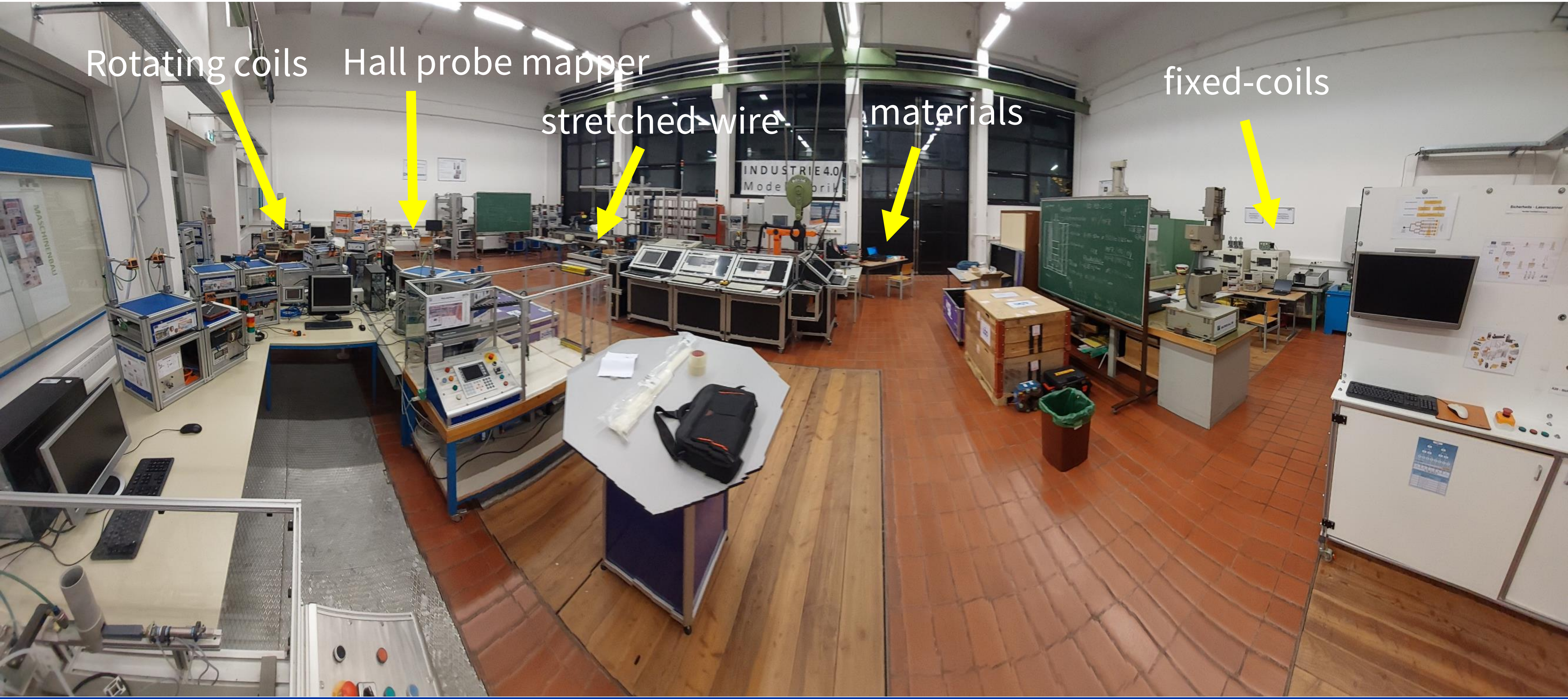
Facilities kindly made available by HTL St. Pölten, Elektrotechnik School

Courtesy Direktor M. Pfeffel



How to reach us

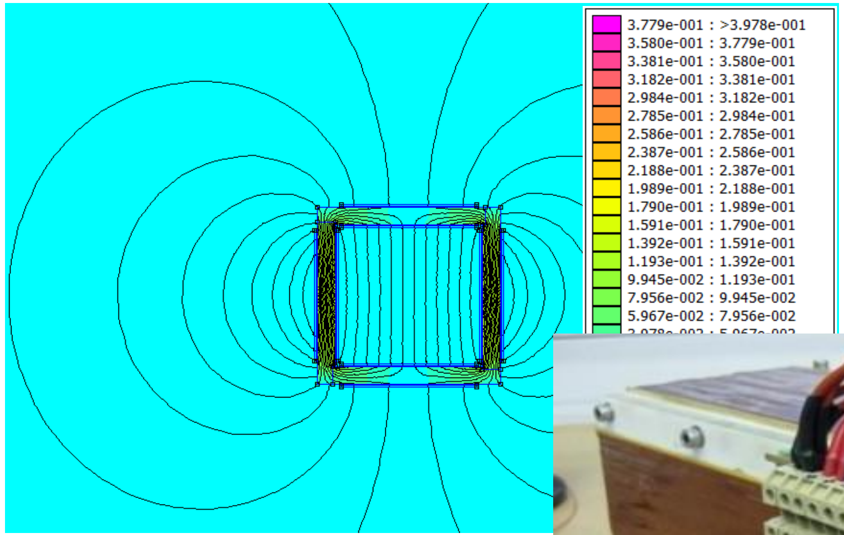
Room V039-1


Rotating coils
Hall probe mapper
stretched-wire
materials
fixed-coils
INDUSTRIE 4.0

Test magnets

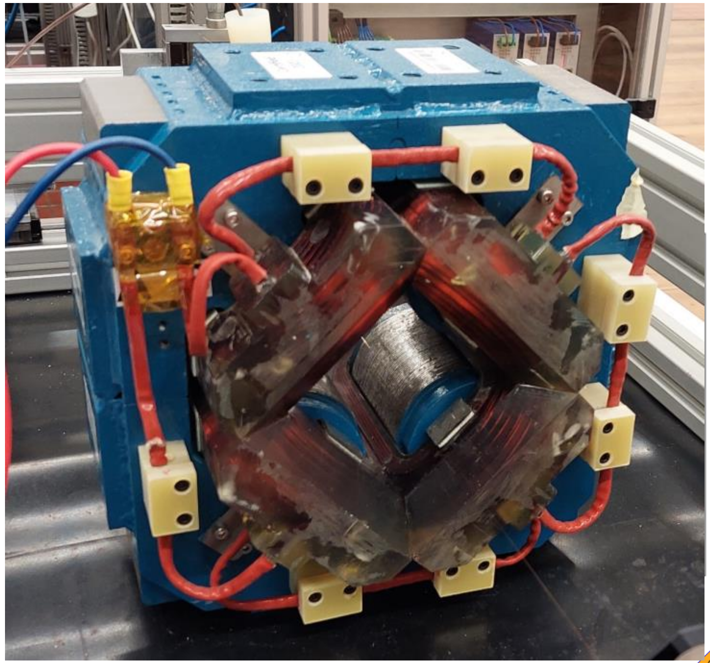
XY dipole corrector PXMCCATWAP

- 2D FEMM Model: 13.9 mT @ 12 A (Courtesy Antony Newborough, CERN)
- “Ugly quad” config possible



Quadrupole PXMCCATWAP

- 2D FEMM Model: 2.5 T/m @ 10 A (Courtesy Attilio Milanese, CERN)
- 3 nominally identical units installed



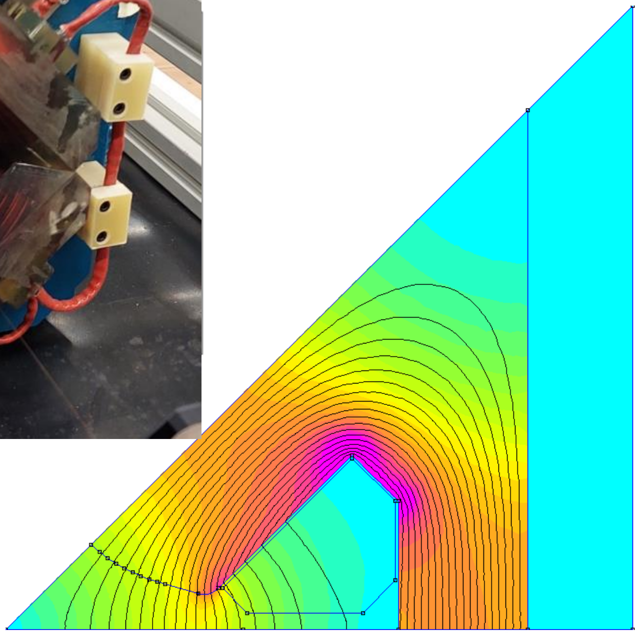
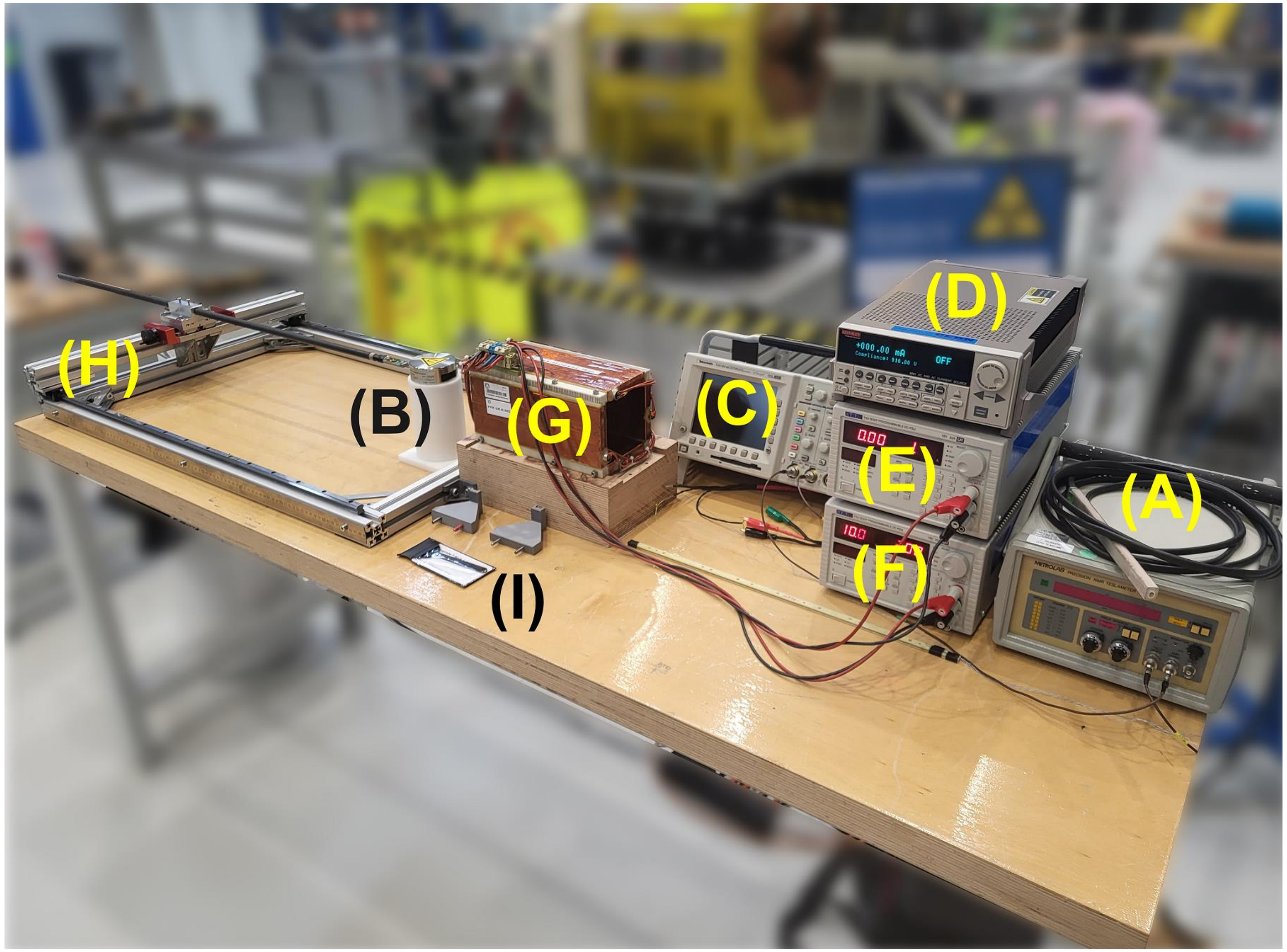
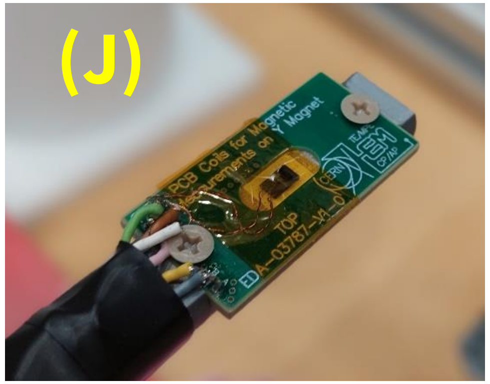


Table 1 –Hall Probes (Melvin Liebsch)





(A) NMR teslameter and probe (0.17 – 0.52 T)
(B) Calibration permanent magnet (0.290 T)
(C) Digital oscilloscope
(D) Keithley 6221 current source
(E) TSX unipolar power supply (for vertical field)
(F) TSX unipolar power supply (for horizontal field)
(G) Dipole corrector magnet (PXMCCATWAP)
(H) Mapper stage (50 x 700 mm stroke)
(I) Compass
(J) Uniaxial Hall sensor HE244 (0.2 V/T @ 2 mA)

Table 1 –Hall Probes

Goals

- Hall sensor calibration (sensitivity, zero field offset voltage)
- Polarity measurement
- Working principle of XY dipole correctors
- Determine the Sensor orientation with respect to the horizontal and vertical fields
- Mapping of XY dipole corrector (fringe field, ugly quad config)
- Basic usage and working principle of nuclear magnetic resonance (NMR) measurements

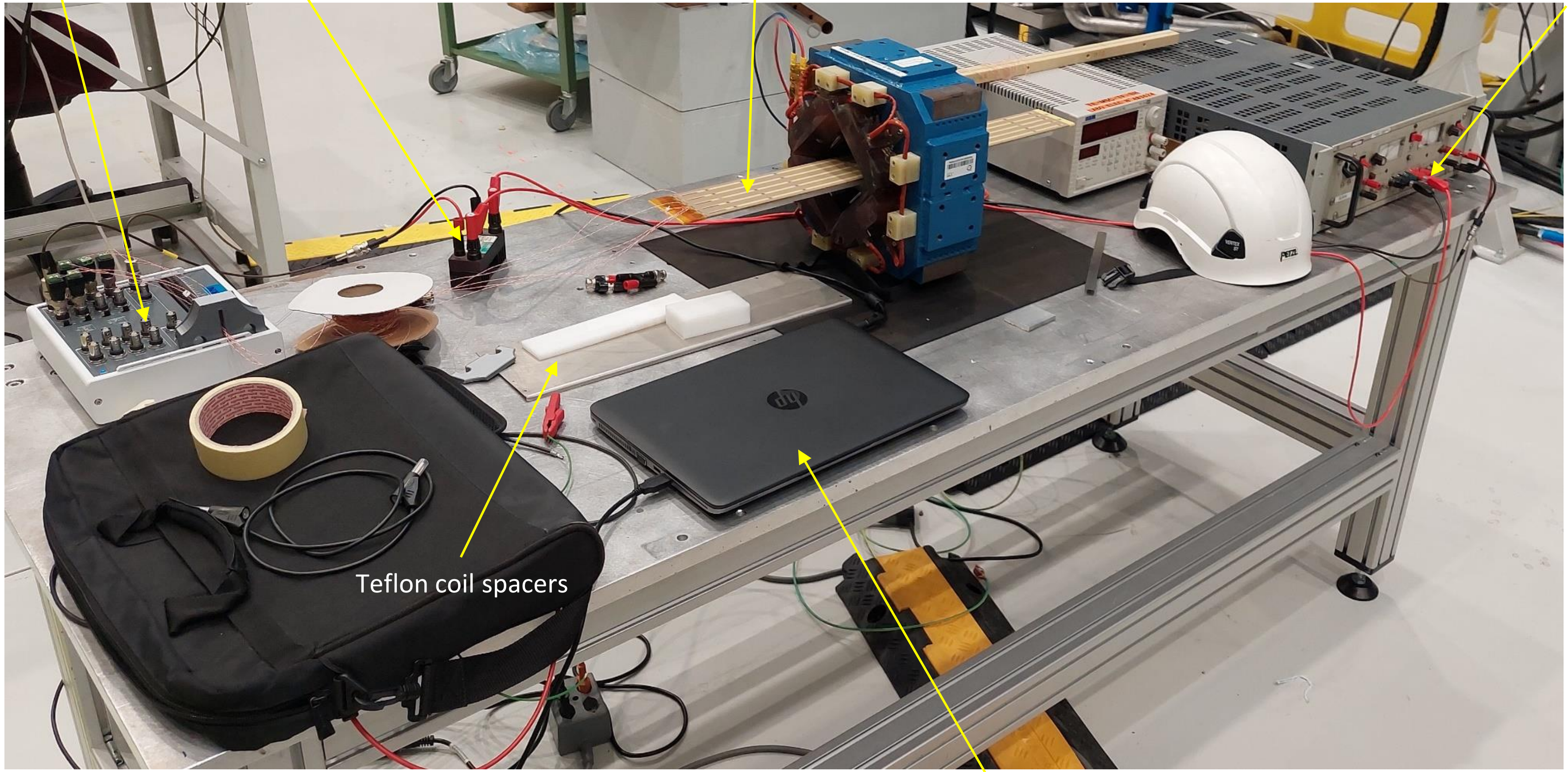
Table 2 – Fixed Induction Coils (Matthias Bonora)

High-precision 5 mΩ shunt for current measurement

NI 6366 USB DAQ, 8 ch., 16-bit 2 Ms/s

5× 16-turn, 24-layer, 2.3 m² XXX mm × XX mm PCB coil array

Kepco 6 A, 70 V voltage-controlled amplifier



Python scripts

Table 2 –Fixed Induction Coils

Goals

- Fixed PCB coil array integral measurement: gradient, centering, magnetic length, harmonics
- Dynamic effects: measurement of transfer function, AC eddy currents at different frequencies
- Degaussing, remanent field measurement
- Comparisons (to other instruments/teams)

Table 3 – Rotating Coil (Lucio Fiscarelli)

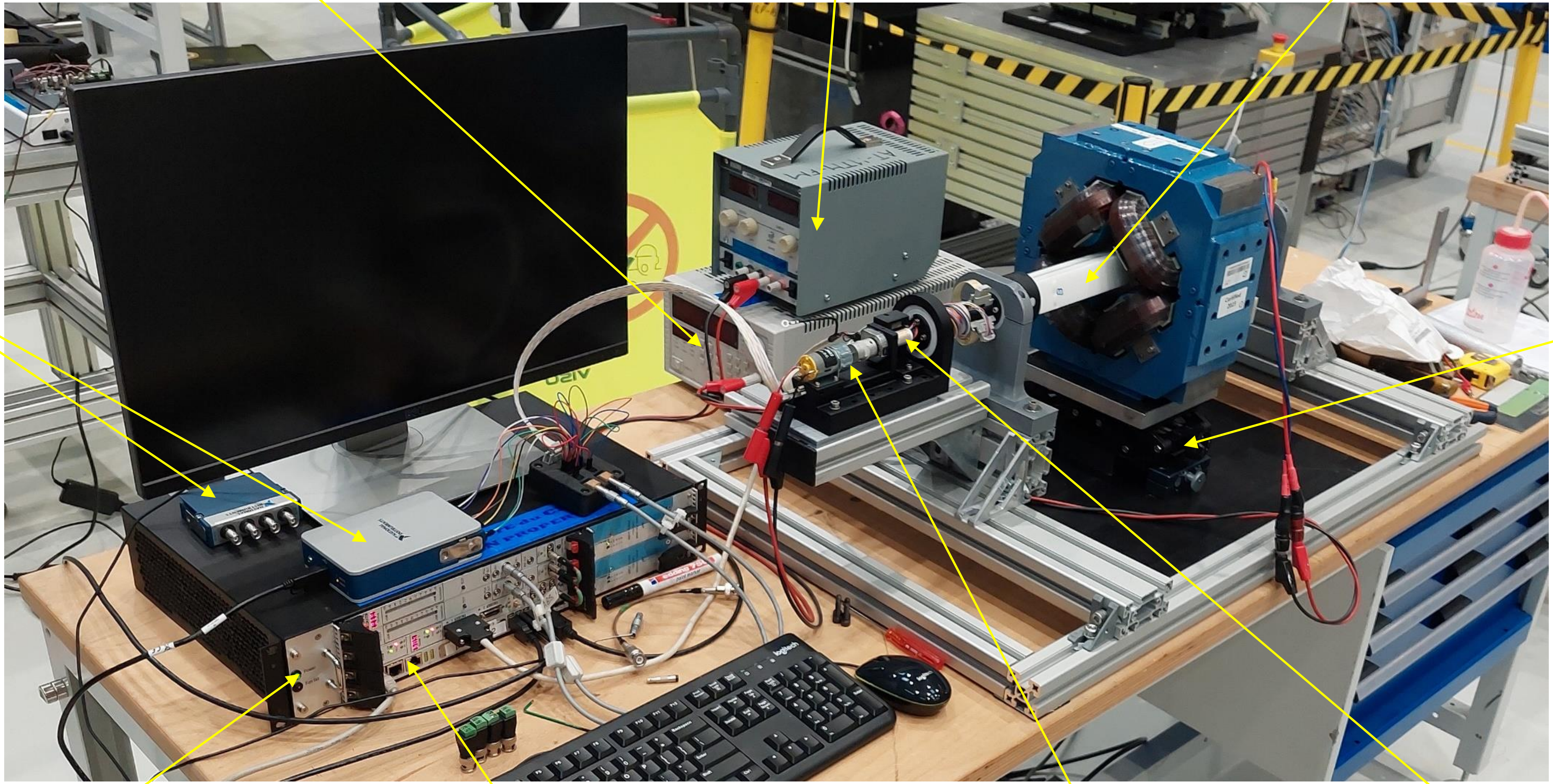
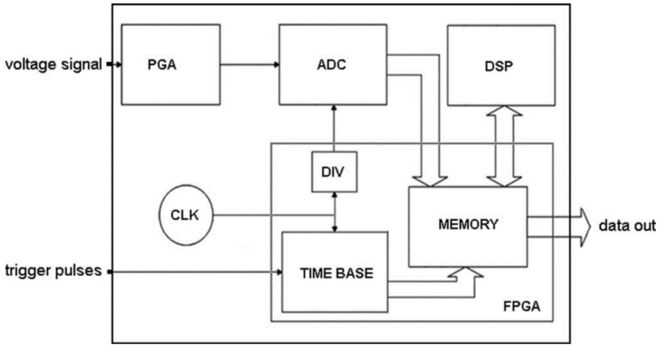


Table 3 – Rotating Coil

Fast Digital Integrator (FDI)

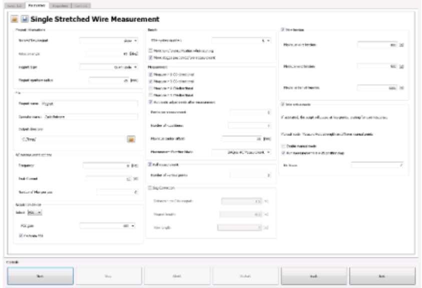
- 18-bit ADC at 500 kS/s
- Time base 50 ns
- Programmable gain from 0.1 to 100
- PXI bus interface

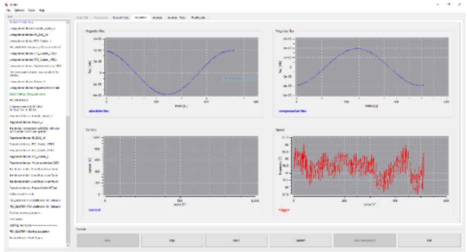


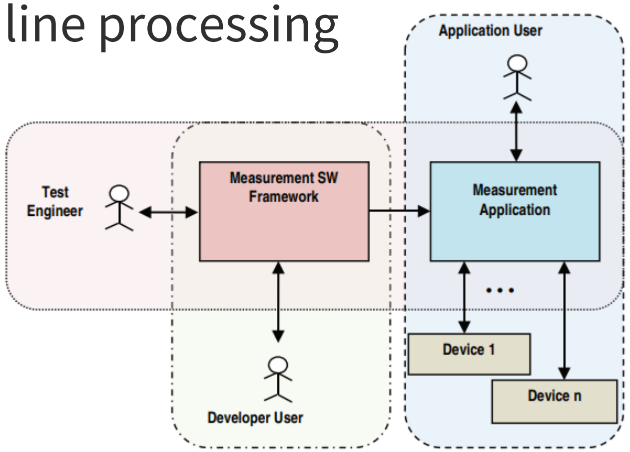
P. Arpaia, L. Bottura, L. Fiscarelli, L. Walckiers; Performance of a fast digital integrator in on-field magnetic measurements for particle accelerators. Rev. Sci. Instrum. 1 February 2012; 83 (2): 024702. https://doi.org/10.1063/1.3673000

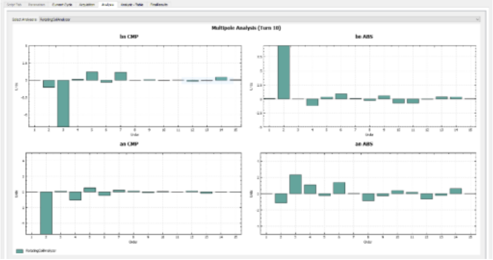
Flexible Framework for Magnetic Measurements (FFMM)

- Open software framework
- C++
- Based on free libraries (PoCo, Qt, …)
- Motion control, acquisition, and online processing









Pasquale Arpaia, Marco Buzio, Lucio Fiscarelli, Vitaliano Inglese; A software framework for developing measurement applications under variable requirements. Rev. Sci. Instrum. 1 November 2012; 83 (11): 115103. https://doi.org/10.1063/1.4764664

Table 3 – Rotating Coil

Goals

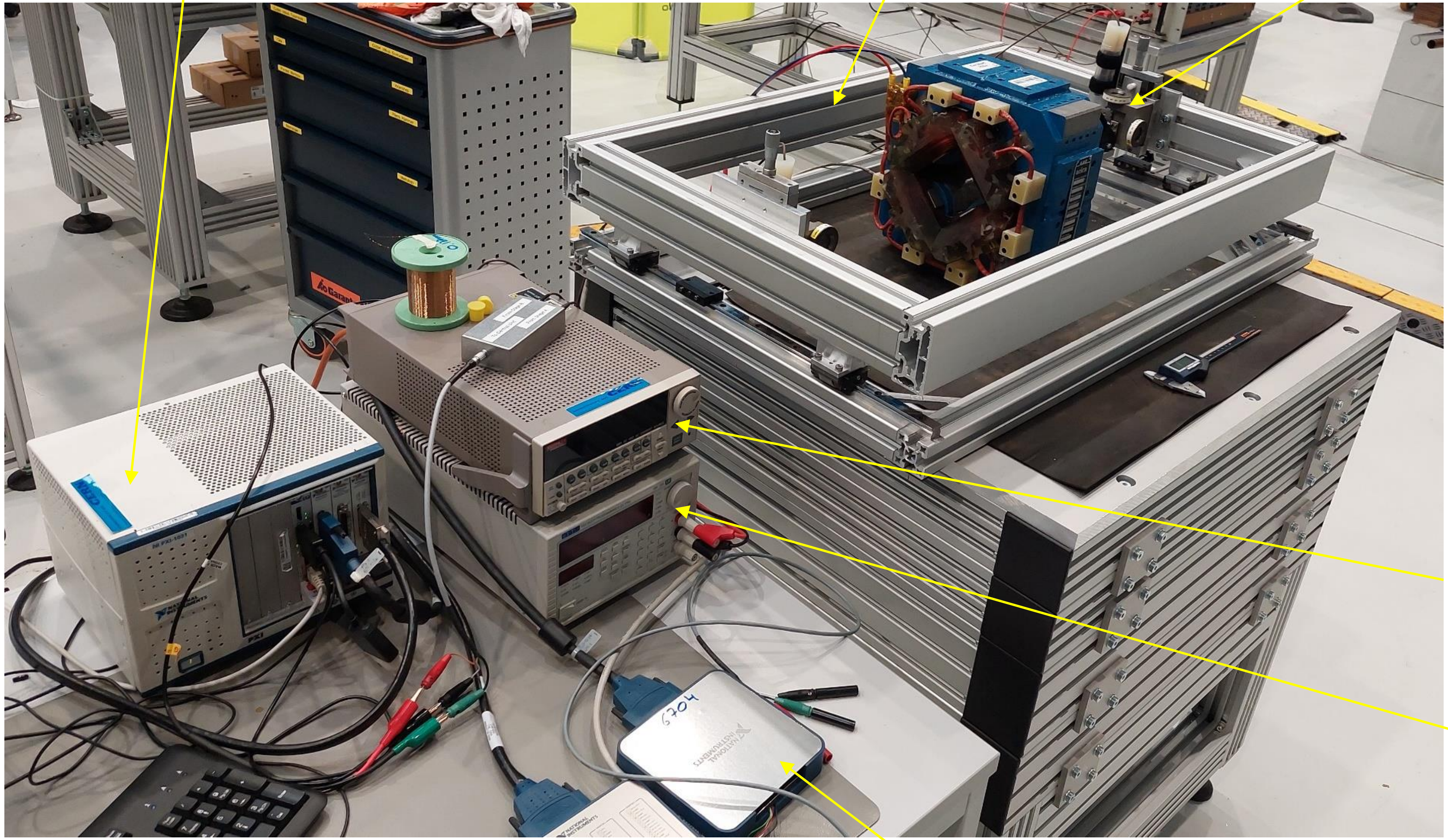
- Basics of a rotating-coil system (search coil, encoder, integrator)
- Calculation of coil sensitivity, post-processing of the acquired signals
- Standard measurement (gradient, centering, harmonics)
- Measurement at different currents (comparison with dynamic measurement)
- Harmonic feed-down (move coil transversally)
- Impact of rotation speed, effect of integration, effect of signal bucking
- Impact of magnetic perturbations (harmonics and symmetries)
- Comparisons (to other instruments/teams)

Table 4 – Stretched Wire (Carlo Petrone)

NI PXI express crate with analog control and acquisition modules
PXI-6123 8 ch. × 16-Bit @ 500 kS/s/ch.

Stretched wire support frame

micrometric XY wire end supports



manual wire translation tracked
by ….. (XXX µm precision)

Keythley 6221 AC current source for vibrating wire

TT TSX 1820P 18 V, 20 A programmable power supply

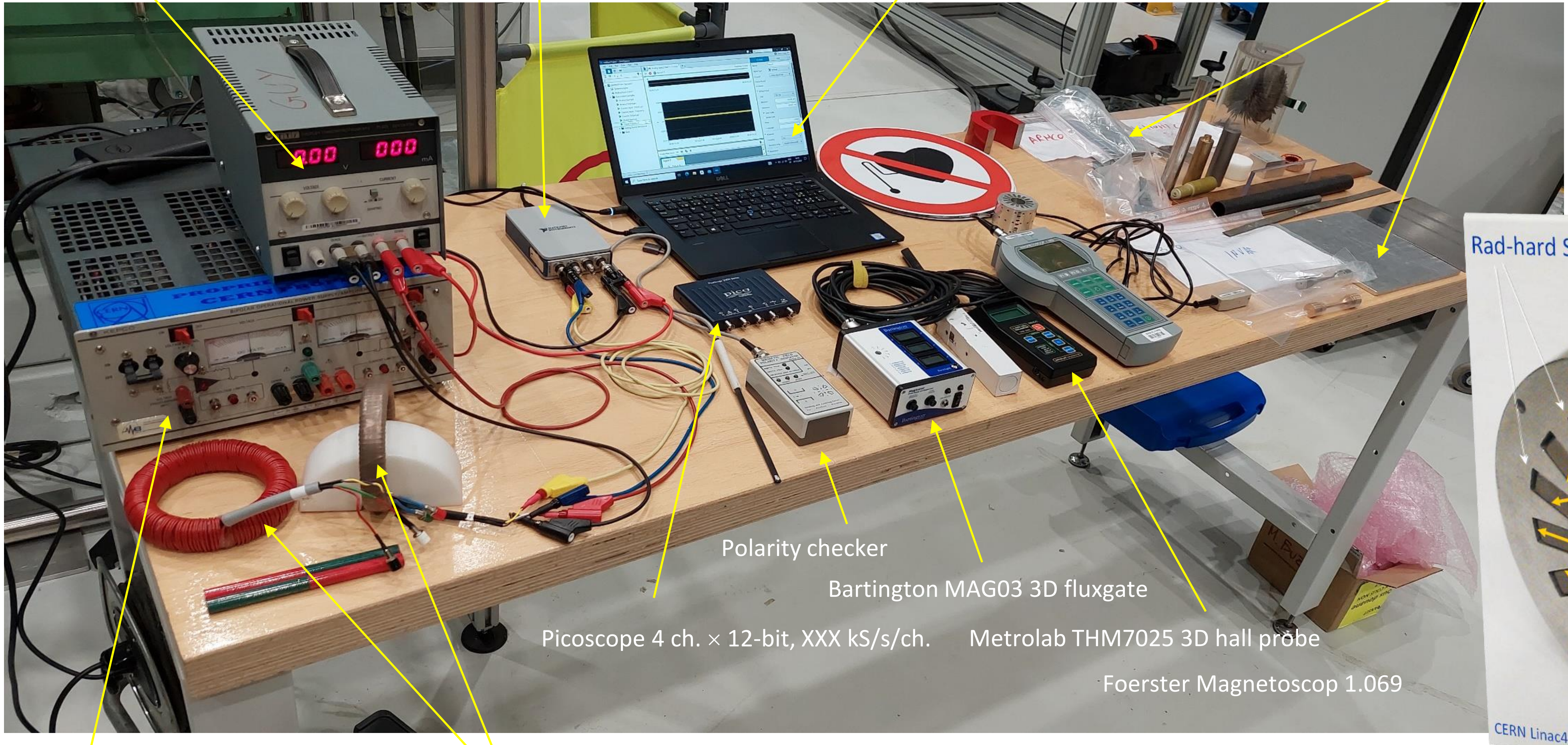
NI DAQ screw-terminal interfaces

Table 4 – Stretched Wire

Goals

- Working principle of the single stretched wire SSW measurement technique
- Integrator drift correction
- Determine the magnetic center and gradient using the SSW technique
- Working principle of the oscillating wire technique
- Validate the central position by the oscillating wire
- Comparisons (to other instruments/teams)

Table 5 – Magnetic materials (Marco Buzio)



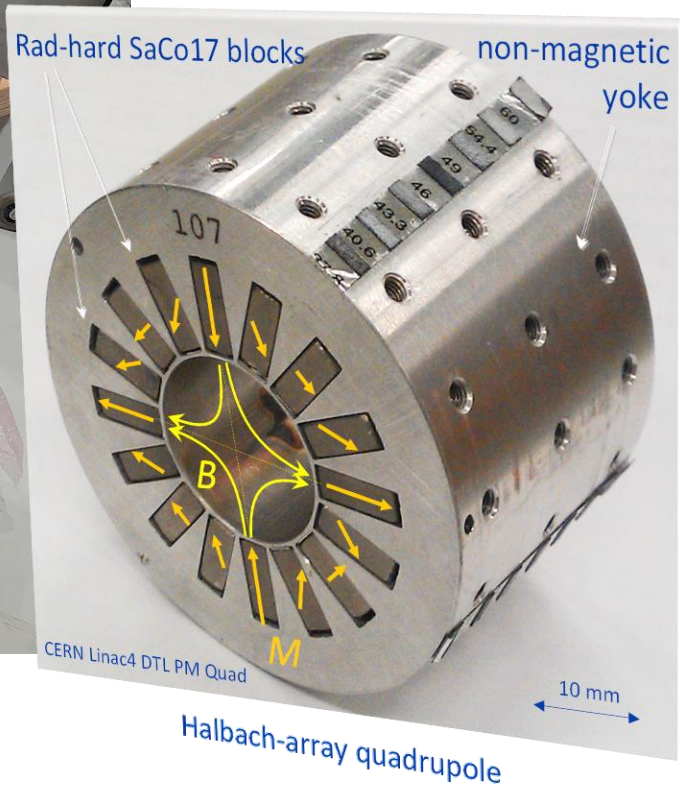


Table 5 – Magnetic materials

Goals

- Identify various kinds of magnetic and non-magnetic materials with the help of permanent magnets, Foerster permeameter
- Measure the impact of welds, cold work …
- Measure Permanent Magnet samples (Hall probe)
- Measure hysteresis loop of ring steel samples with fluxmetric method (magnetization curves, degaussing …)
- Measure effectiveness of magnetic shields with a Hall probe/Fluxgate

Part II
Safety aspects

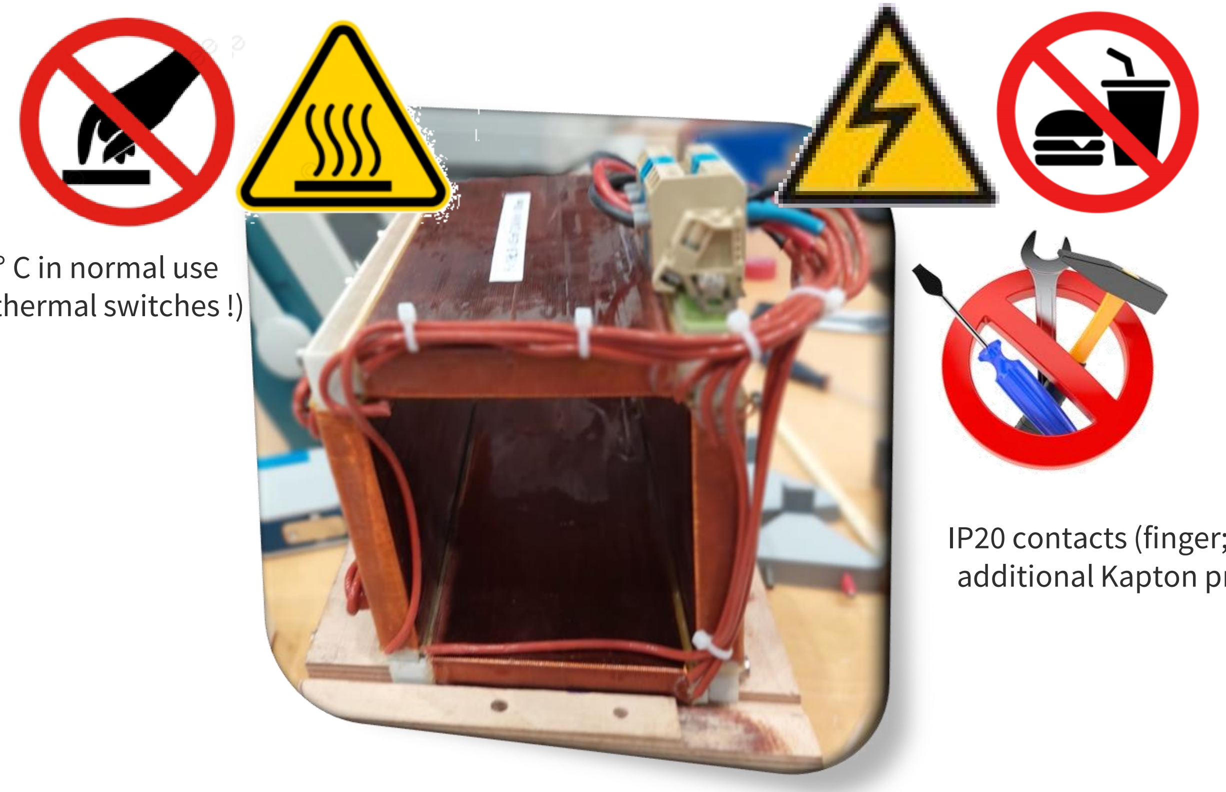
- Electrical hazards
- Magnetic hazard
- Mechanical hazards

Electrical hazards

Electrical hazards

- All equipment CE standard, grounded
- Max. ratings of power supplies: 76 V *or* 32 A *or* 432 W
- Operational levels: 50 V (ELV range) 10 A or 200 W

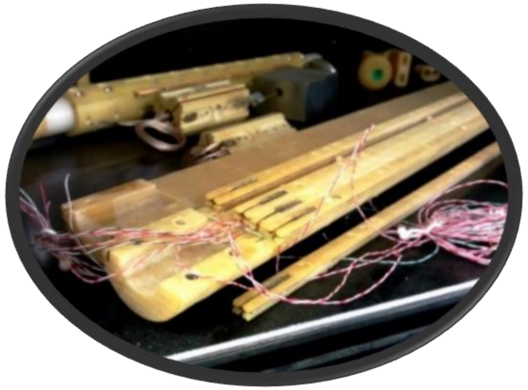
NO SPECIFIC RISK



T ≤ 40° C in normal use
(but no thermal switches !)

IP20 contacts (finger; no water)
additional Kapton protection.

Our own induction coils
are voltage generators (<10 V)
(transformer secondary)



Electrical hazard – circuit break examples

- In case of sudden lead disconnection energy stored in the inductor $E = \frac{1}{2} LI^2$ is released quickly
- Overvoltage → risk of electrical arc, irreversible insulation damage

LHC main NbTi quadrupole

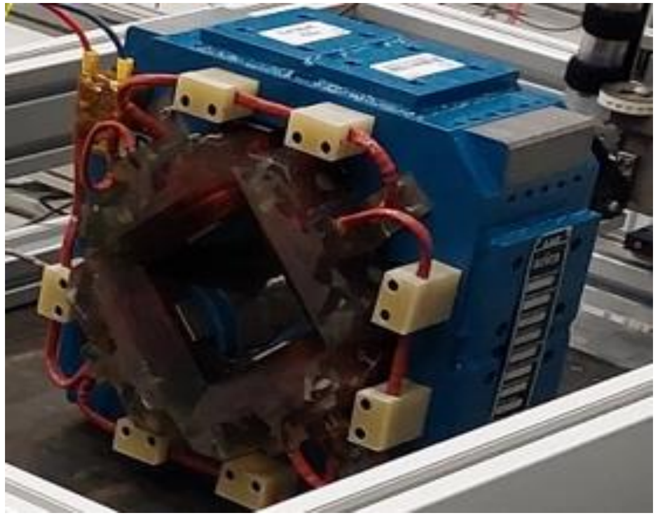
- *L*=11.2 mH
- Warm test *I*=2 A, *E*=0.02 J
- No damage !

SPS main dipole

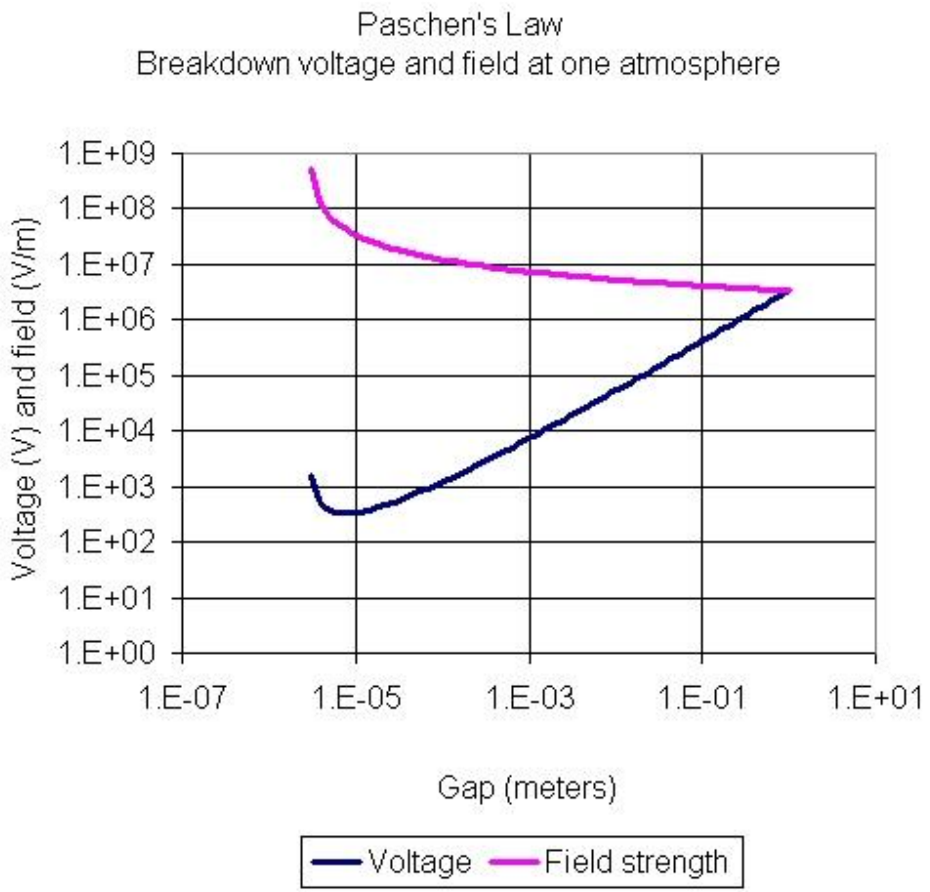
- L=7.9 mH, I=6 kA, E=140 kJ
- Accident occurred during nominal ramp

Electrical hazard – CAS exercises

L=4 mH, *I*=10 A, *E*=0.2 J



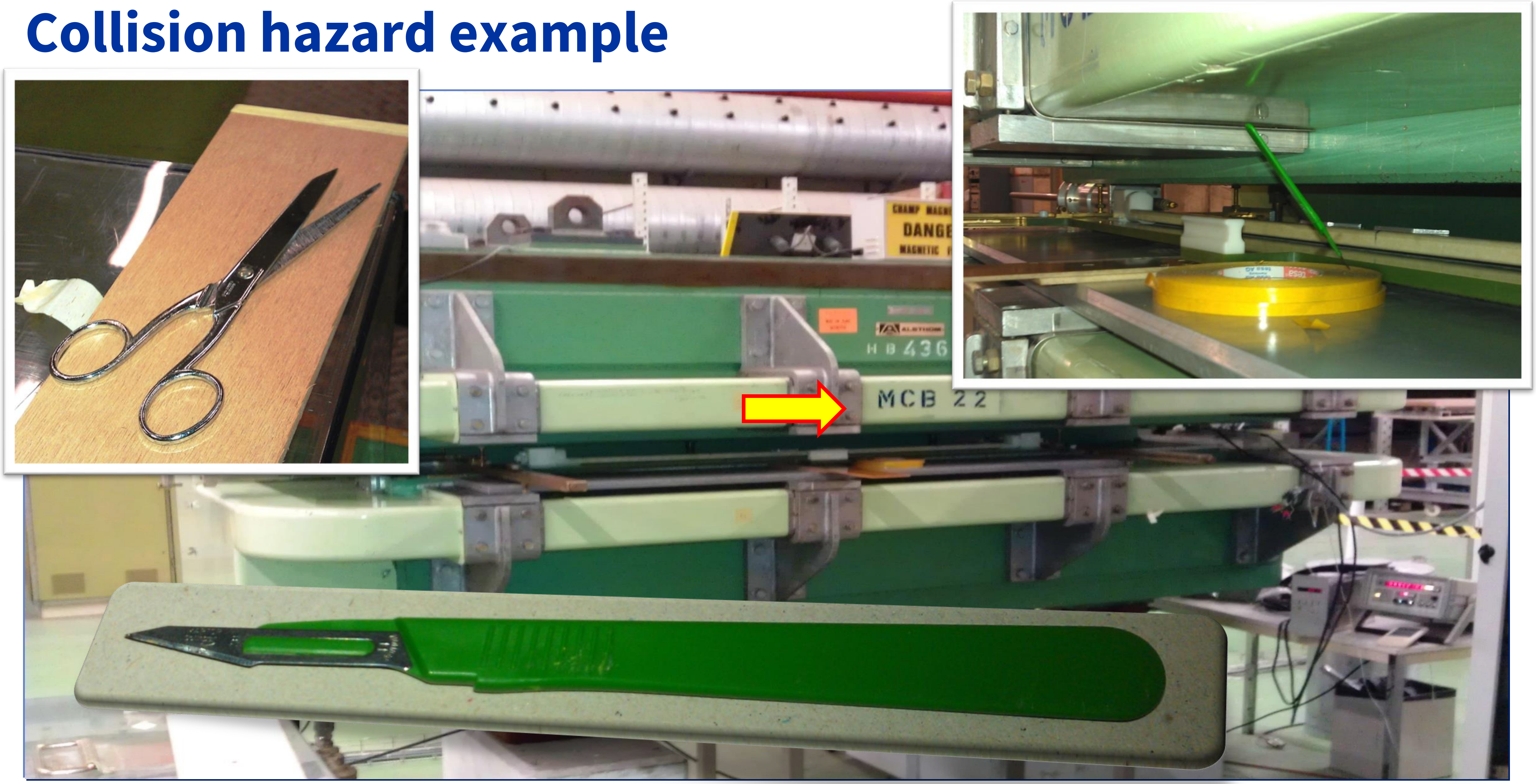
L=32 mH, *I*=10 A, *E*=1.6 J



Overvoltage difficult to predict
general safe distance in air @ 1 bar = 0.5 m

Magnetic field hazards

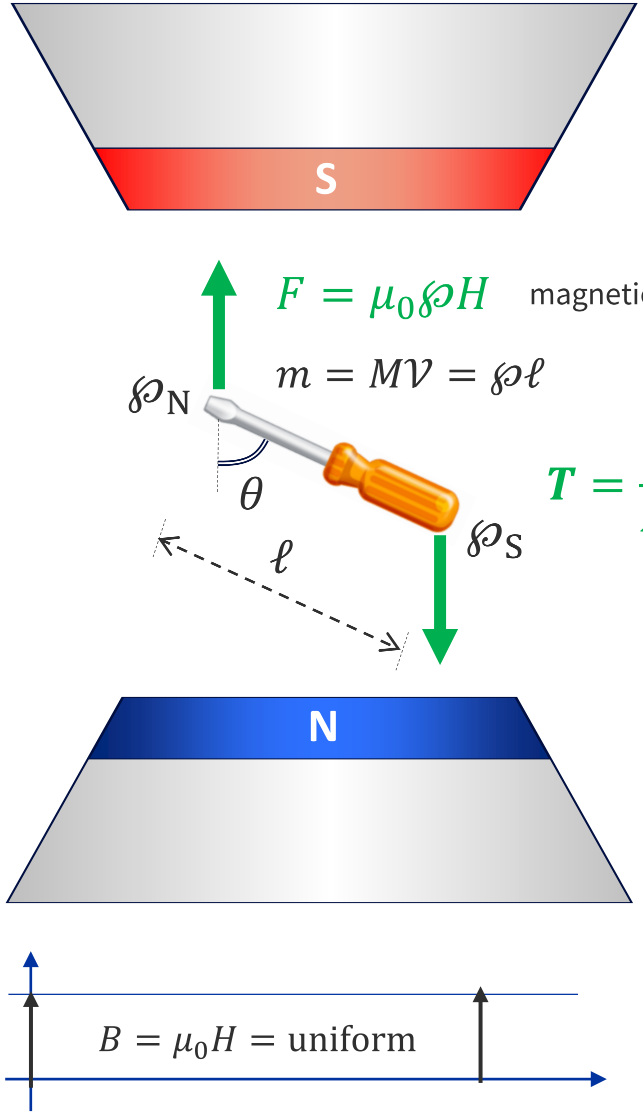
Collision hazard example



Magnetic forces on ferromagnetic objects

elongated object $N \approx 0$, $\mu_r \to \infty$ magnetized along easy axis

$$M = \frac{\mu_r - 1}{1 + N(\mu_r - 1)} H_{\parallel} \approx \frac{1}{N} H \cos\theta$$



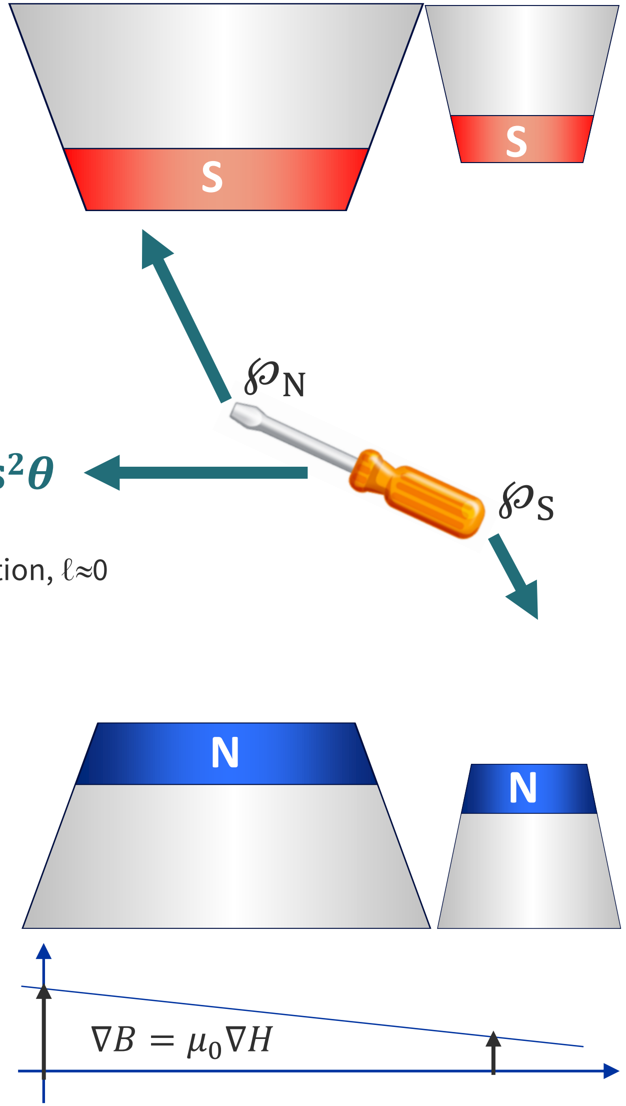
$$F = \mu_0 \wp H$$ magnetic pole formulation, $\ell \to \infty$

$$m = M\mathcal{V} = \wp\ell$$

$$T = \frac{1}{N}\frac{B^2\mathcal{V}}{\mu_0}\cos\theta\sin\theta$$

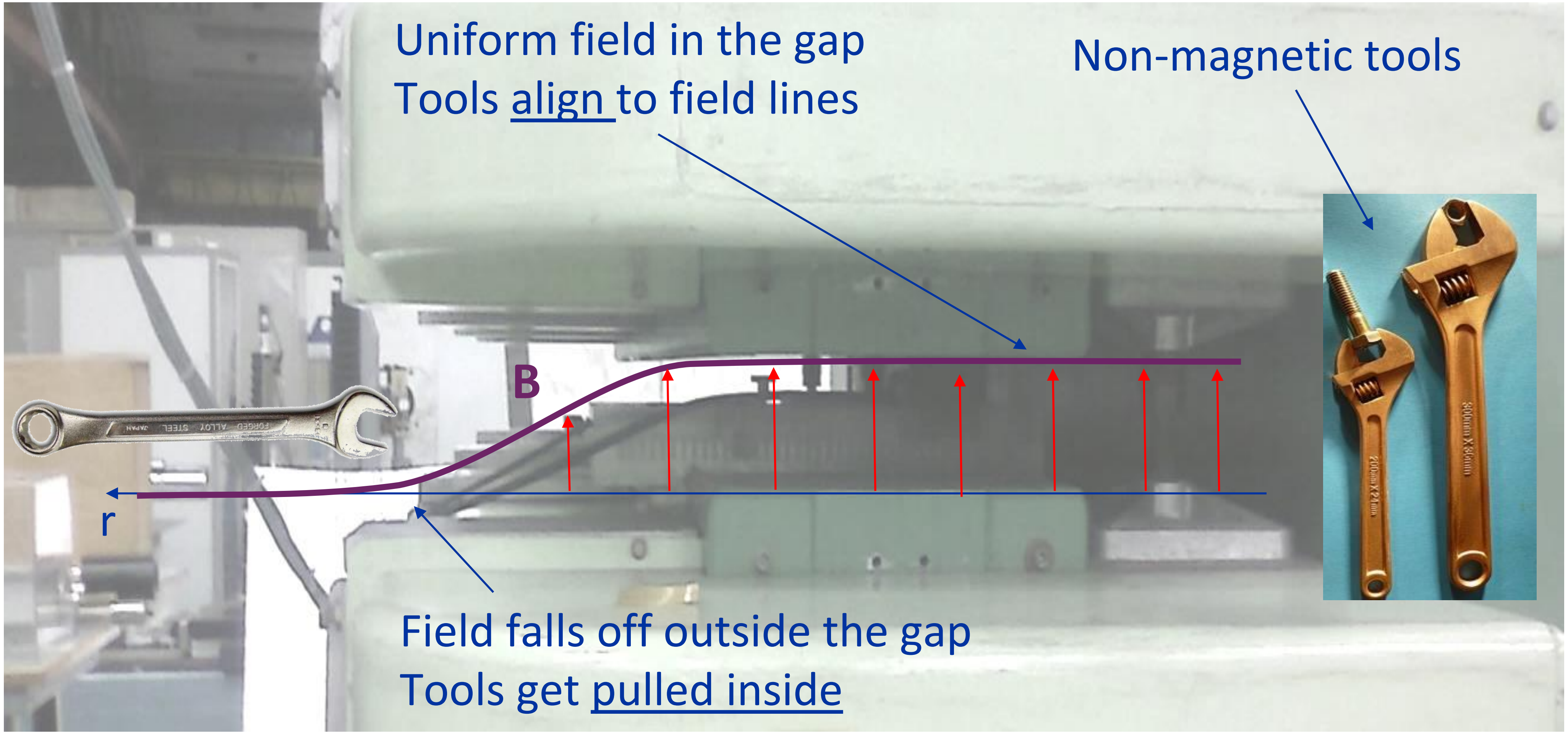
$$F = m\nabla B = \frac{1}{N}\frac{B\nabla B\mathcal{V}}{\mu_0}\cos^2\theta$$

Elementary dipole moment approximation, $\ell \approx 0$



ferromagnetic bodies align to the field,
are attracted towards stronger field

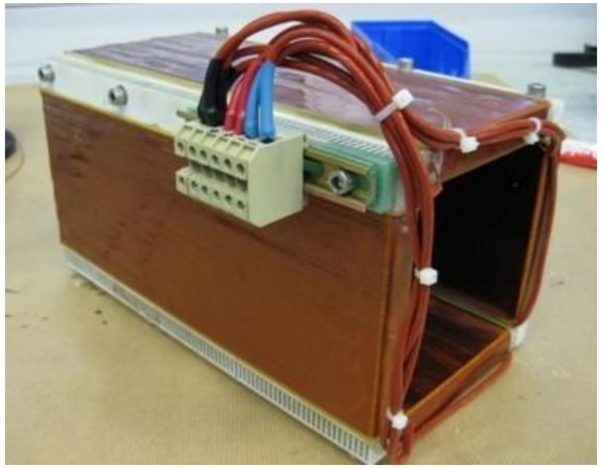
Ferromagnetic objects and large magnets

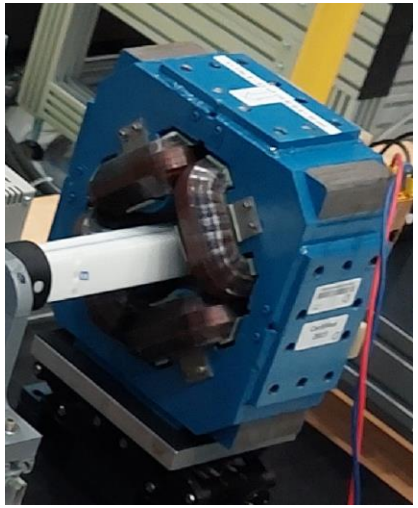


Recommended safety limit for standard tools:

Action level **B ≥ 3 mT** if generated by a source ≥ **100 mT** *(Directive 2013/35/EU)*

Magnetic field sources – CAS exercises


B≤10 mT @ 10 A


B≤73 mT

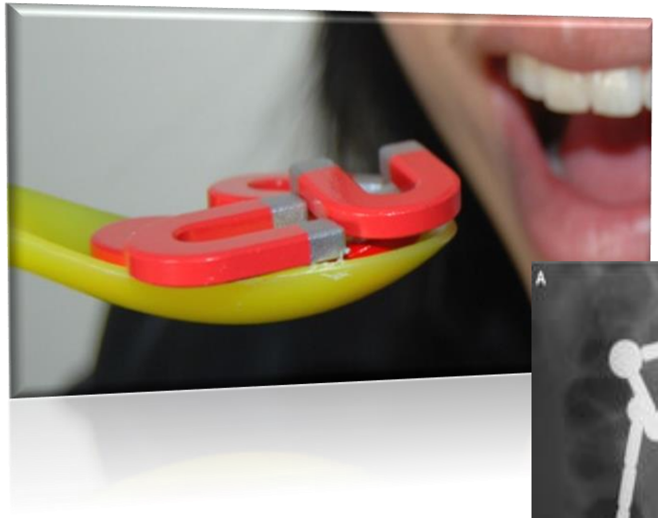
B = 290 mT

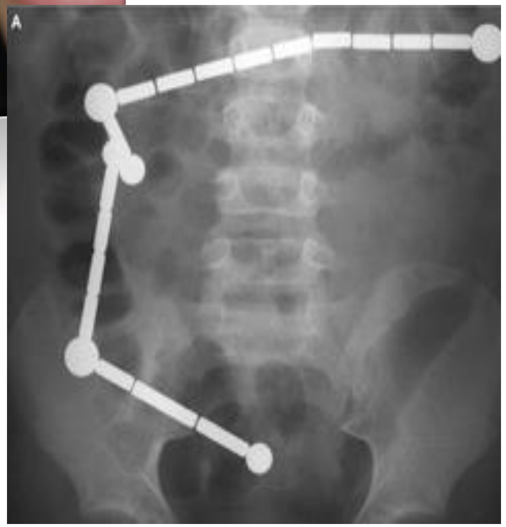

B = 400 mT

- Electromagnets not a relevant projectile effect risk
- Permanent magnets: 3 mT threshold exceeded closer < 50 mm.
  Gap is very small, *however* please do not approach with ferromagnetic objects

Permanent magnets hazards

- Assorted NdFeB magnets will be handed out to test magnetic materials, up to 0.4 T on-contact
- Keep away from credit cards, mechanical watches, mobile phones … and especially each other !
- Store in the boxes supplied when not in use





Description

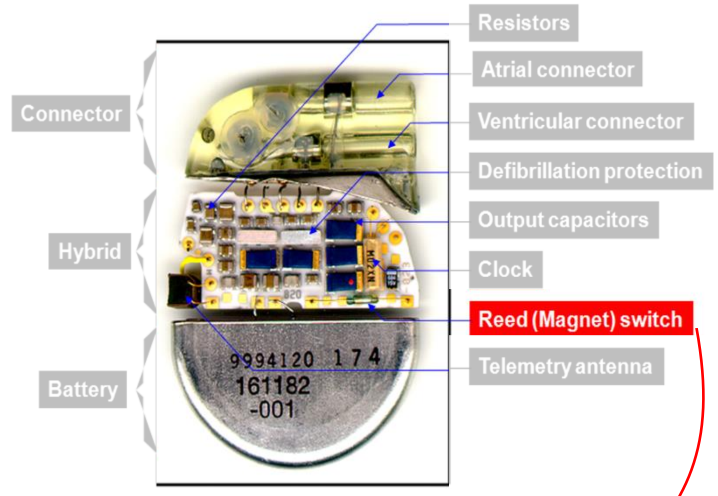
We call this magnet with reverence **THE DEATH MAGNET**.
We have no idea what you could reasonably do with this magnet

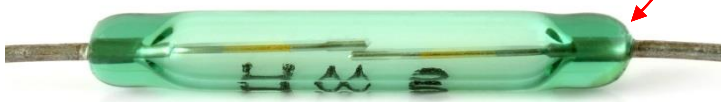
Item number	**Q-51-51-25-N**			**Price and rebate**
Strength	approx. 100 kg		1 pc.	68,09 EUR ea.
Displacement force	approx. 20 kg	from	3 pcs.	61,69 EUR ea.
Unit of Sale	1 piece	from	10 pcs.	55,98 EUR ea.
		from	20 pcs.	53,20 EUR ea.

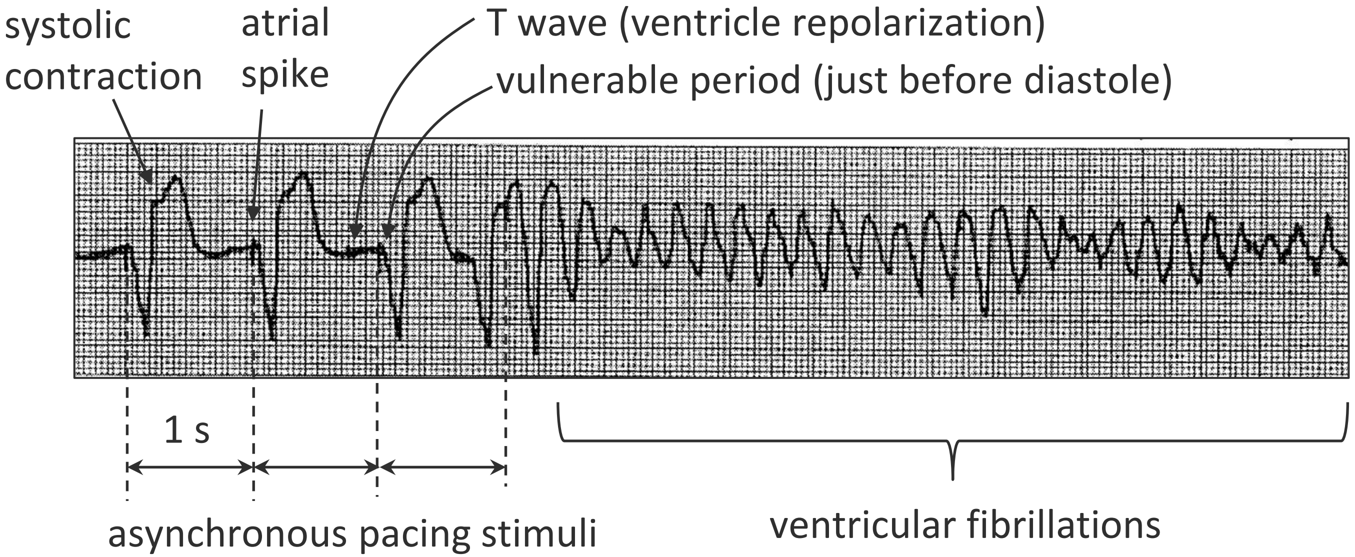
CERN staff only

Pacemakers

- Most cardiovascular implants switch into programming/diagnostic mode by applying an external field 1~10 mT:
  - ICV (Implantable Cardioverters/Defibrillators) → deactivate
  - PM (Pacemakers) → asynchronous (fixed) pacing mode
- Recent devices with Hall/GMR sensors can be locked out → "**MRI-conditional**", safe up to **3 T**
- But most PM have still *reed switches* with thresholds ≥ 0.7 mT
- ~**16 fatalities** (all MRI-related) reported before 2001

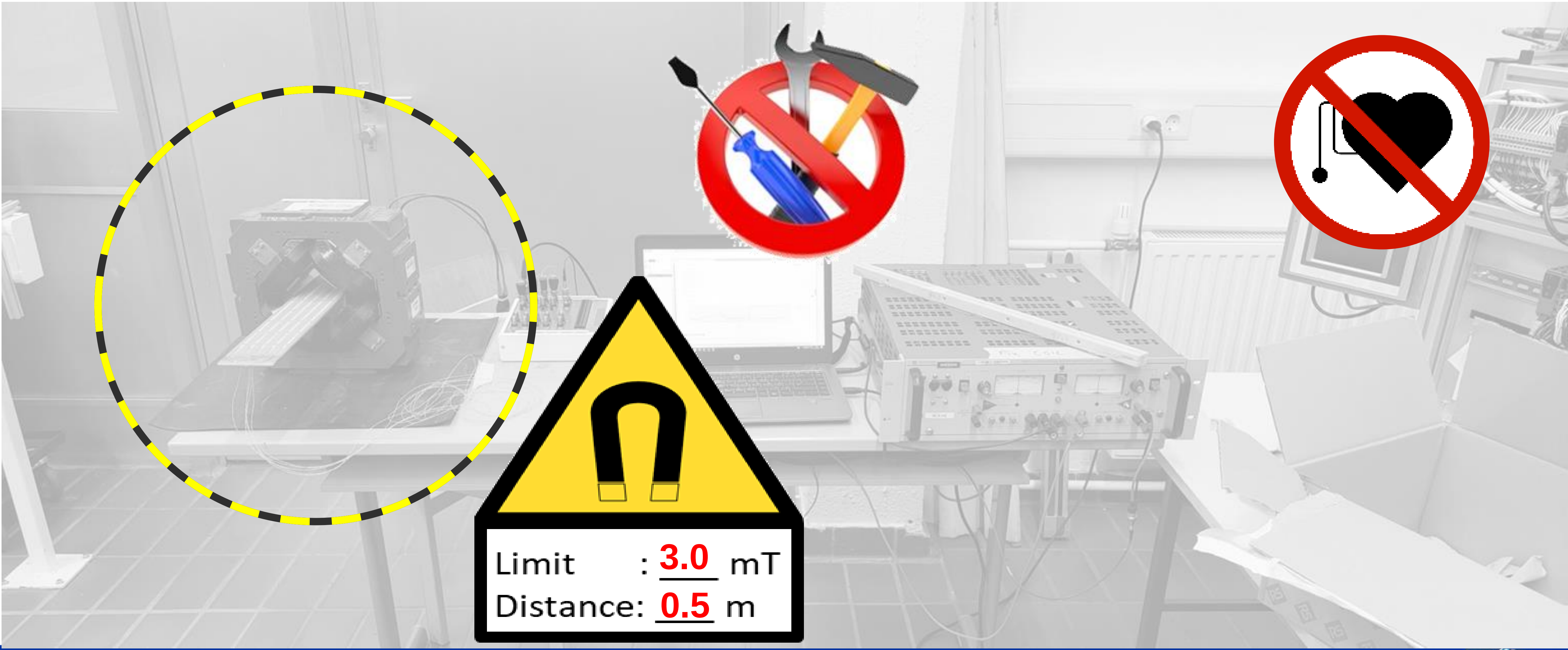






exposure to B > 0.5 mT is absolutely forbidden

Magnetic field hazard – legal obligations



Mechanical hazards

Mechanical hazards

Some exercises feature motorized moving parts.
Please do not touch them !

Floor is relatively uncluttered, still ….
~ 190 000 tripping work accidents/year in EU

Summary - safety rules

- Please let instructors make/unmake connections
- Bearers of **pacemakers, defibrillators, or any other kind of active implant** are **forbidden** to enter the exercise area
- Respect the min. distance of 0.5 m between any magnet and ferromagnetic objects
- Keep the permanent magnets you'll be given 0.5 m away from any other magnet, ferromagnetic object, and potentially sensitive personal items (telephone, watches, credit cards …)
- Watch your feet !

… and then have safe fun while training with magnets !