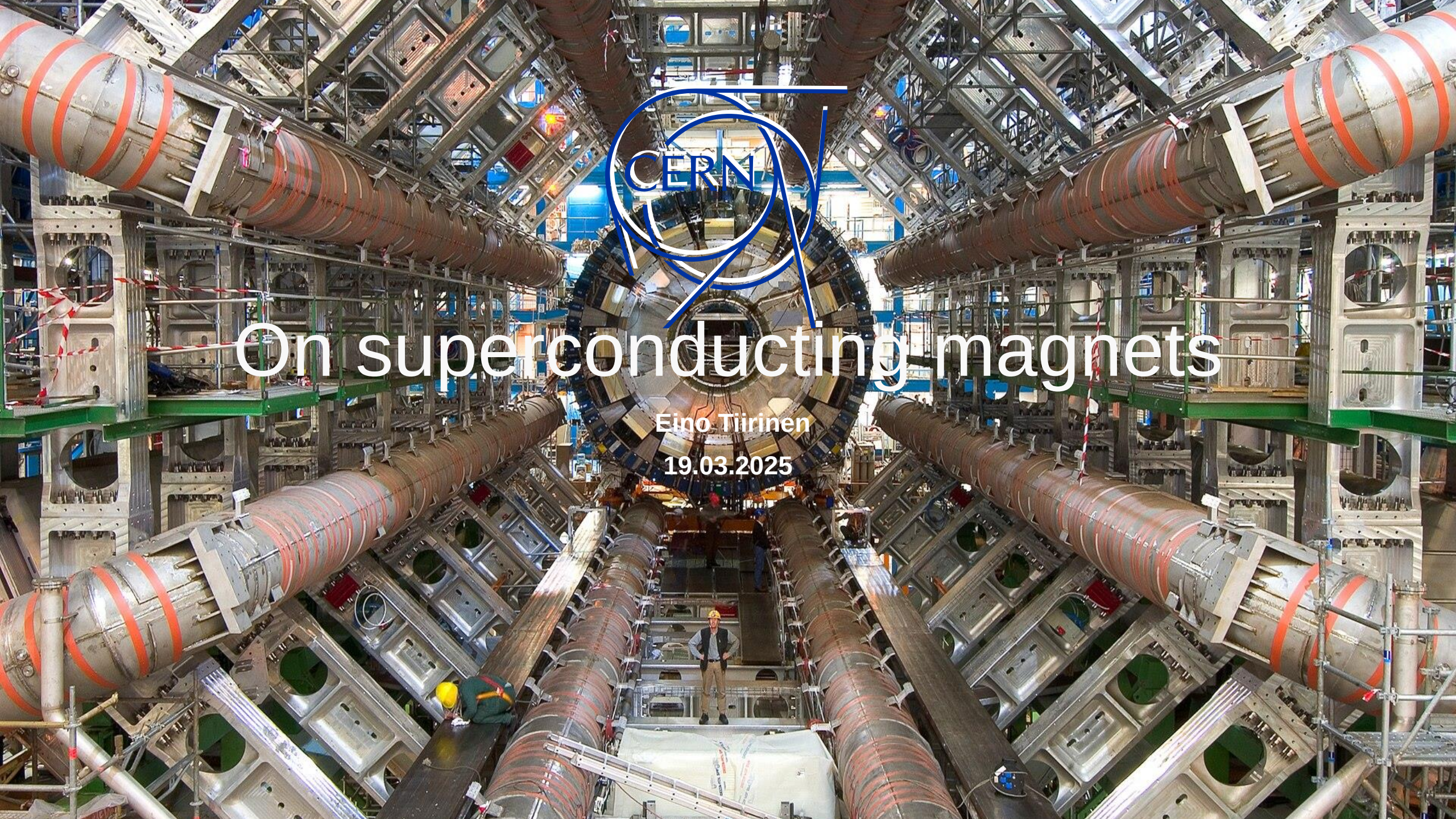


On superconducting magnets

Eino Tiirinen

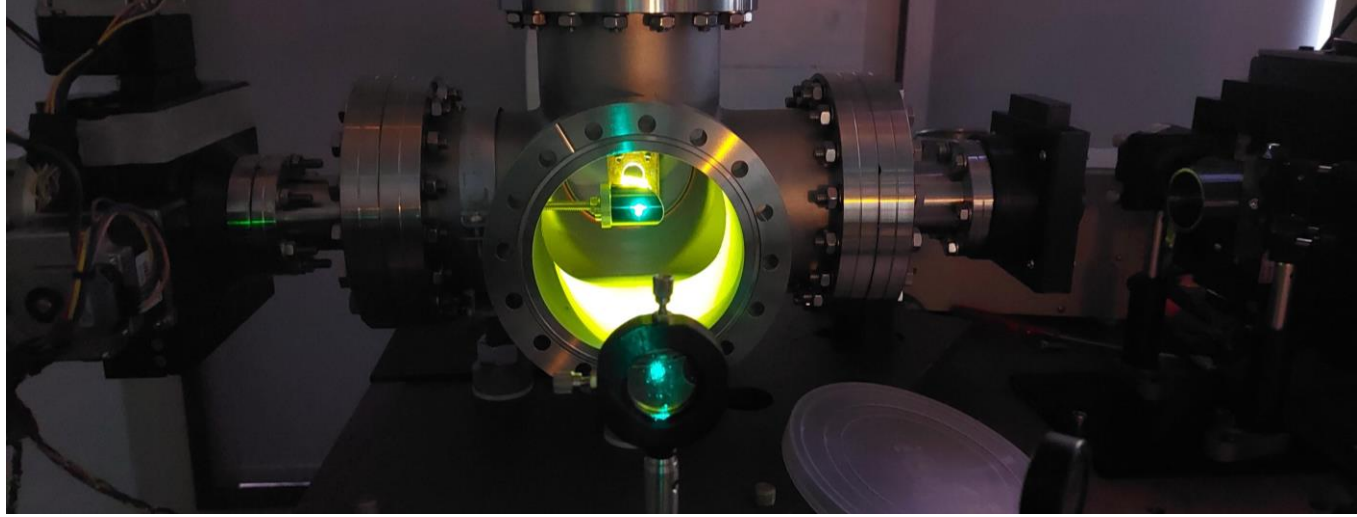
19.03.2025

Outline

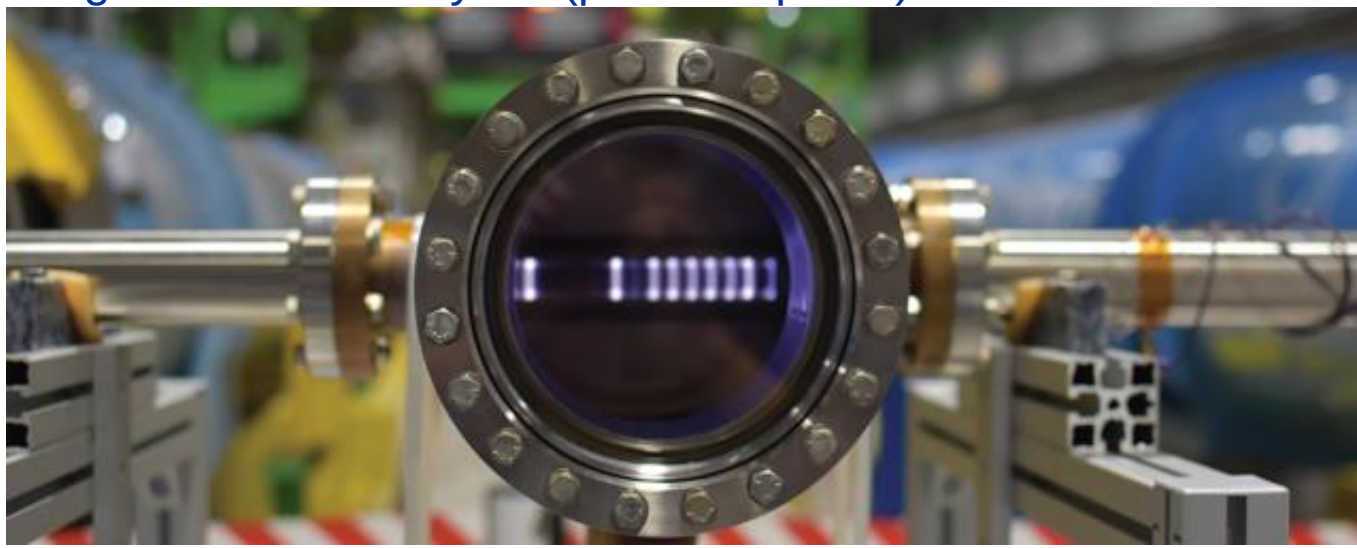
- Introduction
- Principles of superconductivity
- Timeline of historic events in superconductivity
- Superconducting materials
- Superconducting magnets
- The Split Coil Solenoid demonstrator
- Recent developments in the superconducting magnets field
- Other applications

Academic background

- **Experimental physicist**
- **BSc University of Tartu – Material science 2022**
  - Laboratory of Ionic Crystals (Marco Kirm), supervisors Vitali Nagirnõi, Ivo Romet
  - *Recent advances in time-resolved luminescence spectroscopy at MAX IV and PETRA III storage rings*
- **CERN Technical studentship 2022-2023**
  - Vacuum group, surface physics
  - *Estimation of the thermal radiation induced desorption yield for hydrogen and helium at liquid helium temperatures, Journal of Vacuum*
- **Currently : MSc Physics UT (in progress)**
- *"Design and commissioning of a superconducting demonstrator magnet with Rapid quench transformation, a novel quench detection and protection concept."*



Justifying an optical system by maximising luminesence signal from YAG-crystal (personal photo)

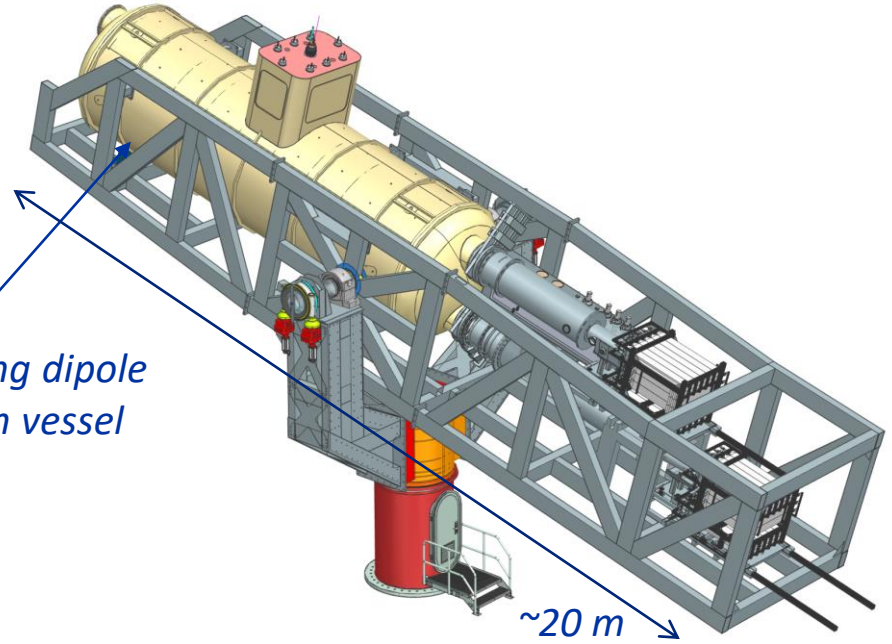


Ar-plasma glow during carbon-coating deposition with magnetron sputtering, Photo: Giovanni Marinaro,CERN

EP Research & Development group

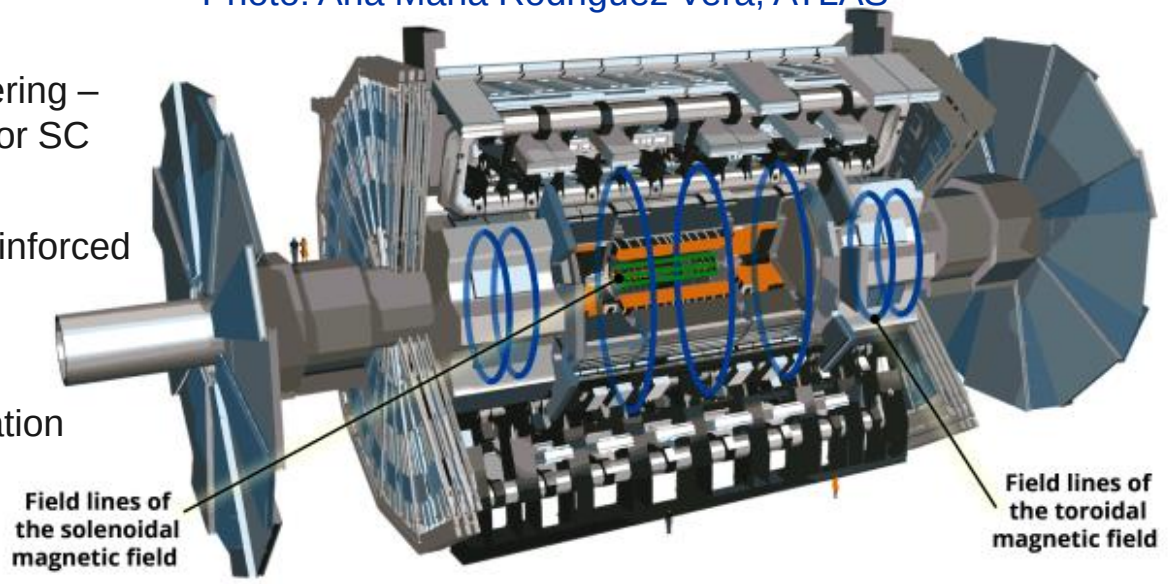
- **Programme:**
  - European Committee for Future Accelerators 2021 roadmap
  - Key detector technologies that will be needed for the next generation of experiments
  - Work Package 8: Focus on technologies for superconducting detector magnets
- **Fields:**
  - Advanced magnet powering – current leads, busbars for SC magnets
  - Aluminium-Stabilized reinforced superconductors
  - Demonstrator magnets
  - Control and instrumentation

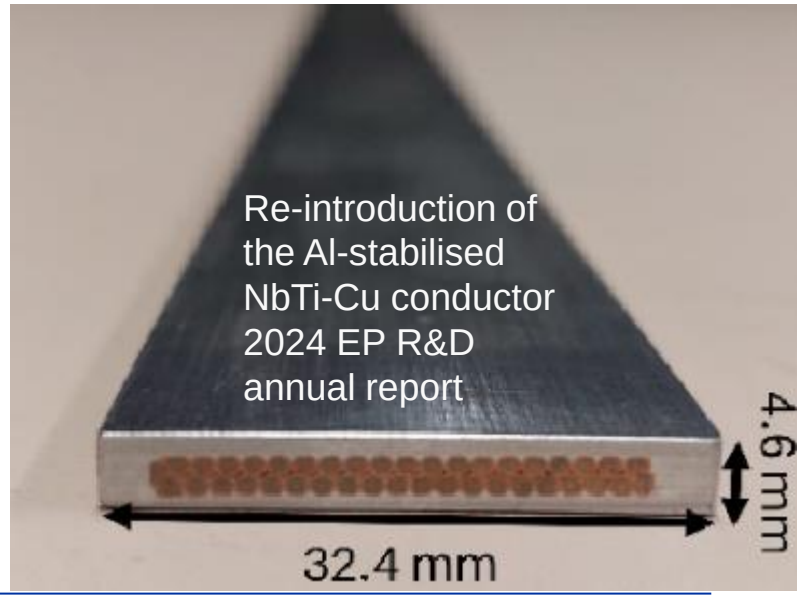
Figures. M.Mentink et al. BabyIAXO Axion Helioscope Superconducting Dipole



BabyIAXO experiment, to be hosted at DESY

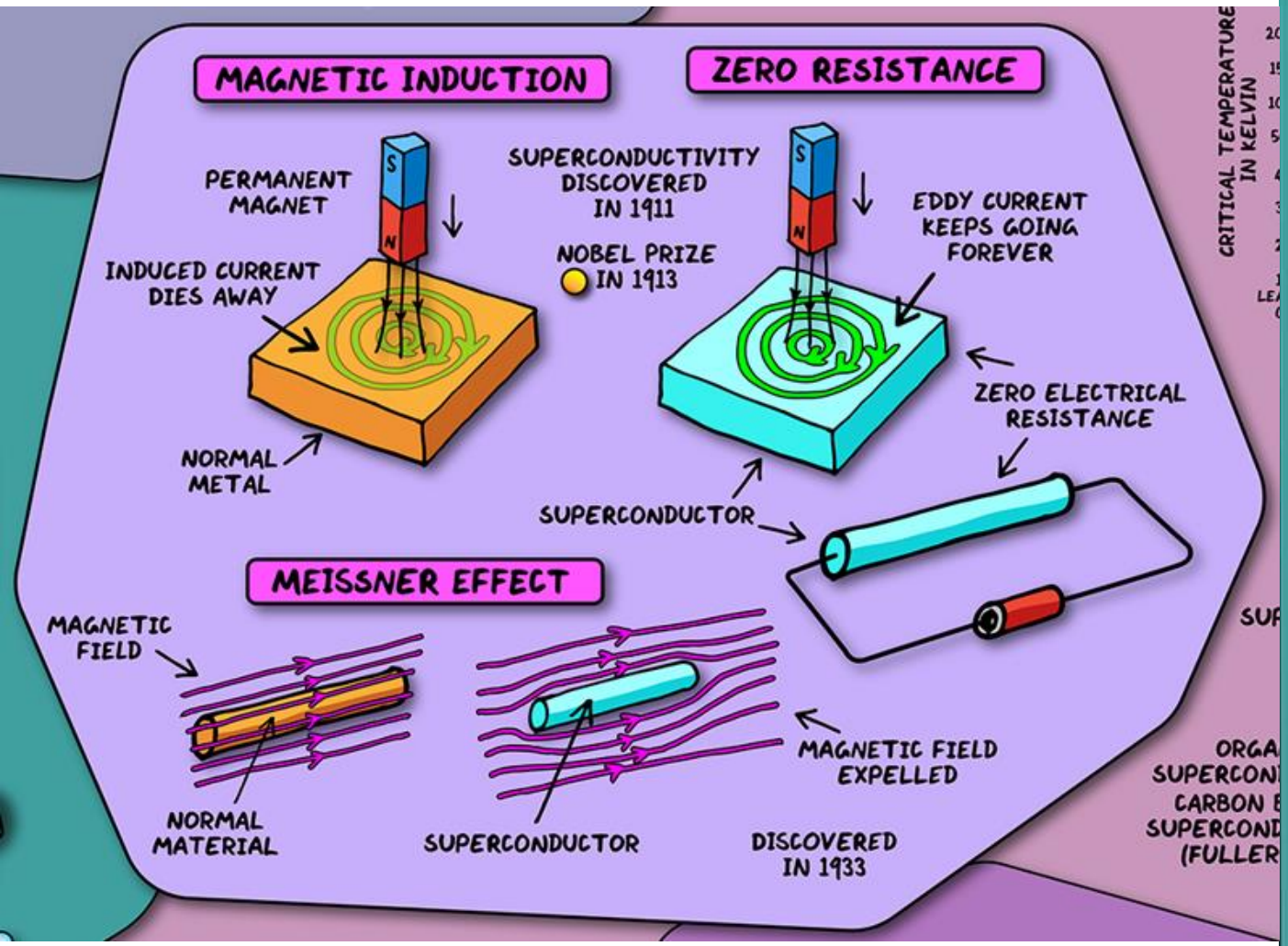
Photo: Ana Maria Rodriguez Vera, ATLAS

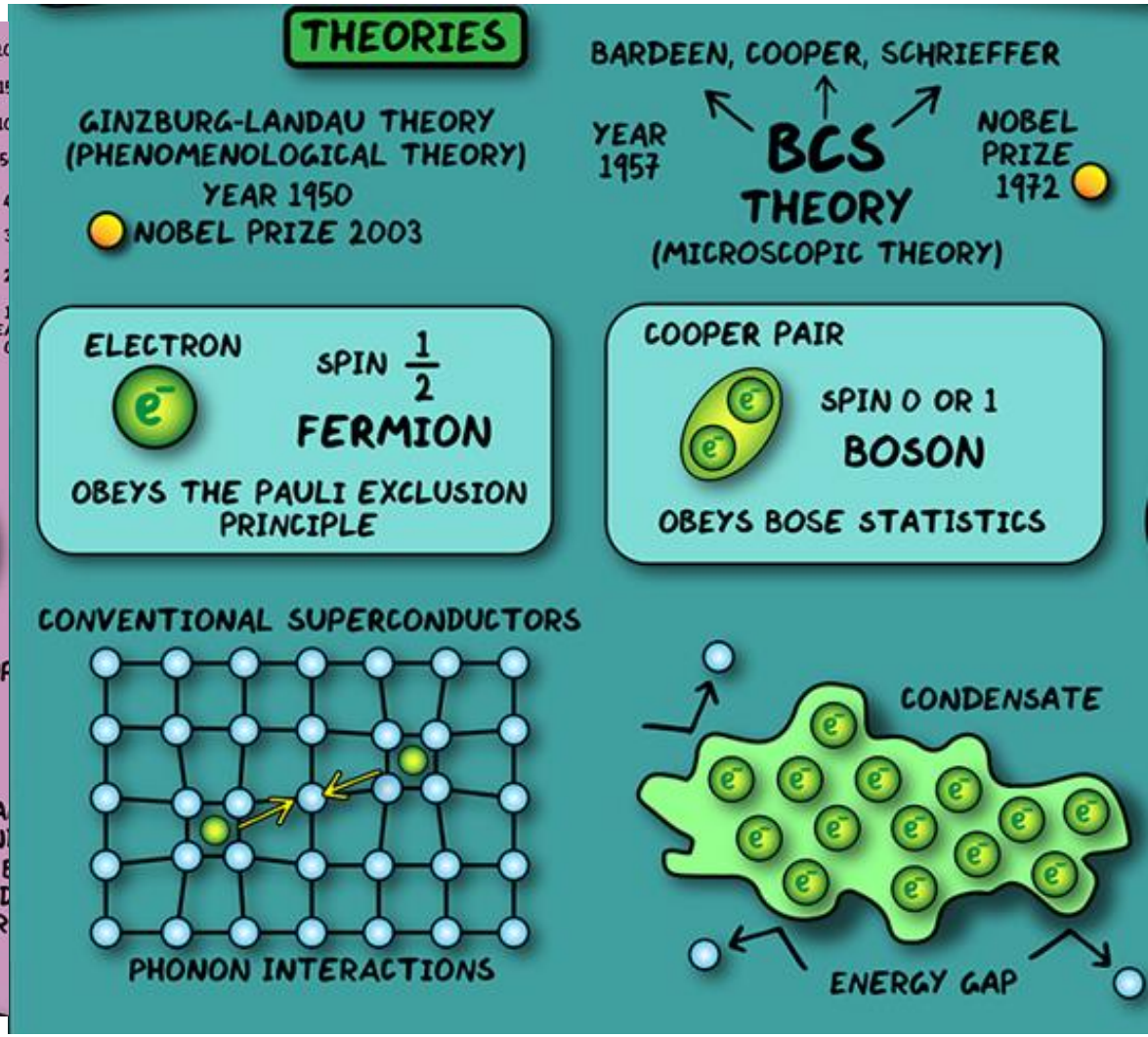




Principles of superconductivity

Dominik Walliman, **Domain of Science**

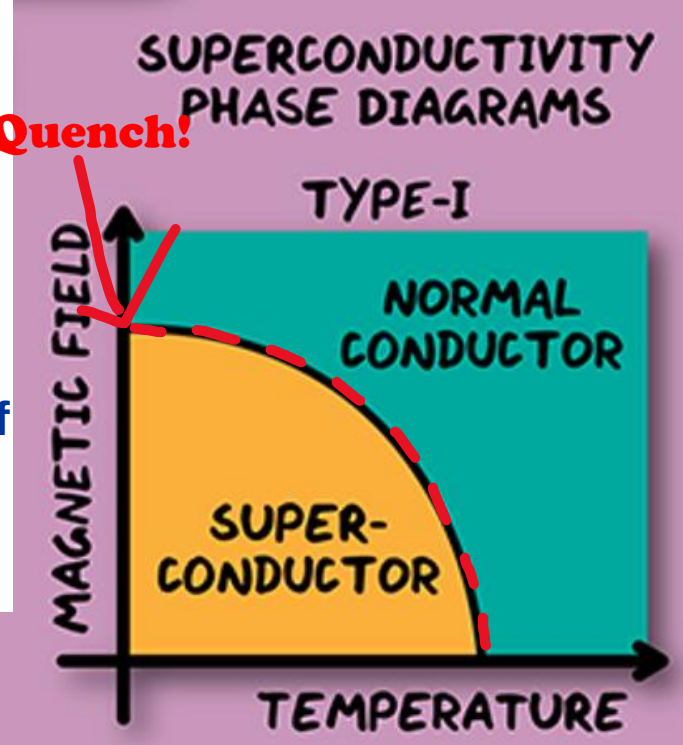


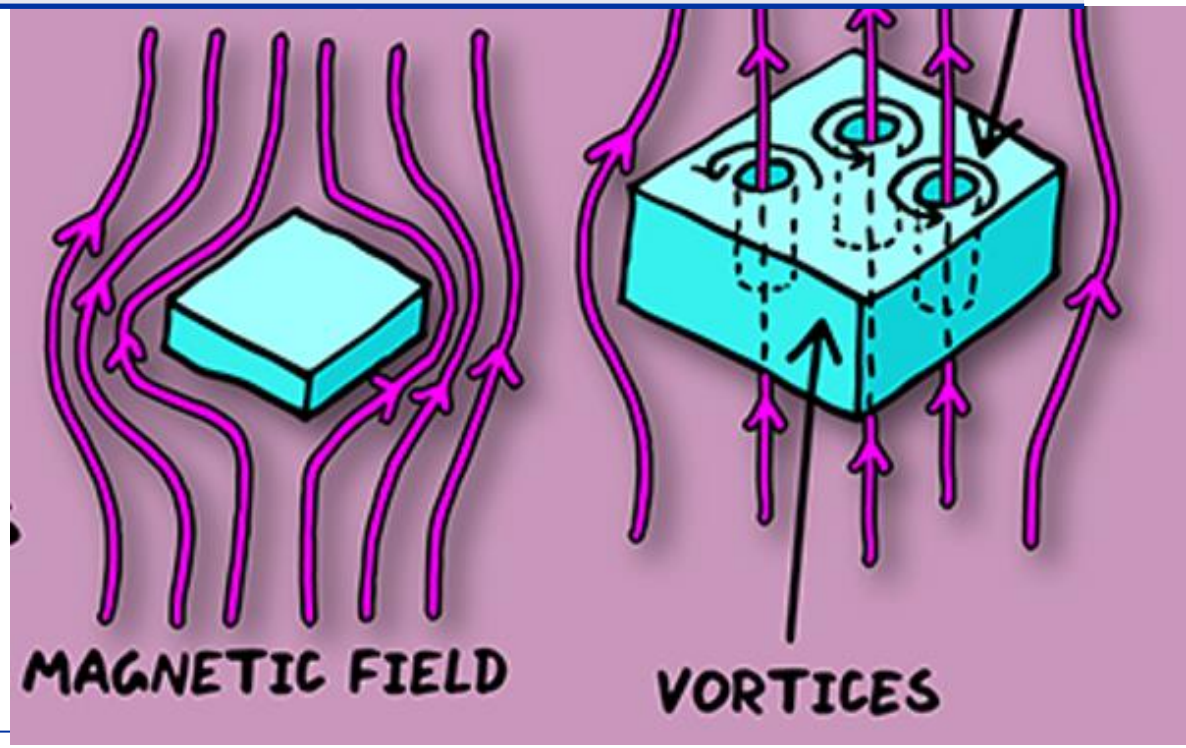


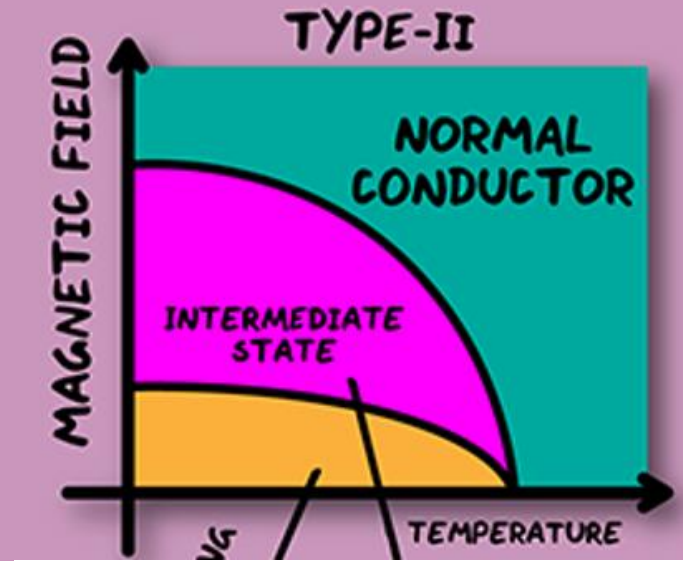
On the matter of superconductors

Conductor	Tc(B=0) [K]	Bc(T=0) [T]
NbTi	9.5	14.4
Nb_3Sn	18.3	28-30
Bi_2-Sr_2-Ca_n-Cu_n-O_{2n+4+X} **2212**	95	>100
$BSCCO$ **2223**	110	>100
$YBa_2Cu_3O_{7-x}$	93	>100

Dominik Walliman, **Domain of Science**







- Most practical superconductors are Type II
  - High J_c
  - Higer B_c for size
  - Higher T_c

  Type I
  - Pure metals – more expensive
  - Mech properties?

Timeline of superconductivity

1908 – Heike Kammerligh Onnes liquifies helium in Leiden, NL

1913 – Superconductivity (Type 1) is observed in Hg by Onnes - Nobel prize in Physics in 1913

1928-1930 – Three new superconductors discovered Ta (Tc= 4.4K), Th (Tc=1.4 K), Nb (Tc = 9.2 K) at PTR Berlin

1933 – Meissner-Ochsenfeld effect discovered -> Type II superconductivity Lev Shubnikov

1935 – London equations, supplement to Maxwell equations, theory of Type II superconductors

1950 – Ginsburg-Landau modify London equations – Nobel prize in 2003

1954 – Construction of first superconducting magnet G.Yntema University of Illinois, USA

1957 – BCS theory for microscopic explanation of Low Temperature Superconductivity – 1972 Nobel prize

1960 – Josephson effect, Nobel prize in 1973

1986 – Müller, Bednorz discover High Temperature superconductivity at 35 K in Ba-La-copper oxide, Nobel prize 1987

1987 – new HTS „YBCO“ material at Tc= 92 K is found (Liquid Nitrogen T=77 K)

1987 – P.W Anderson theory of HTS

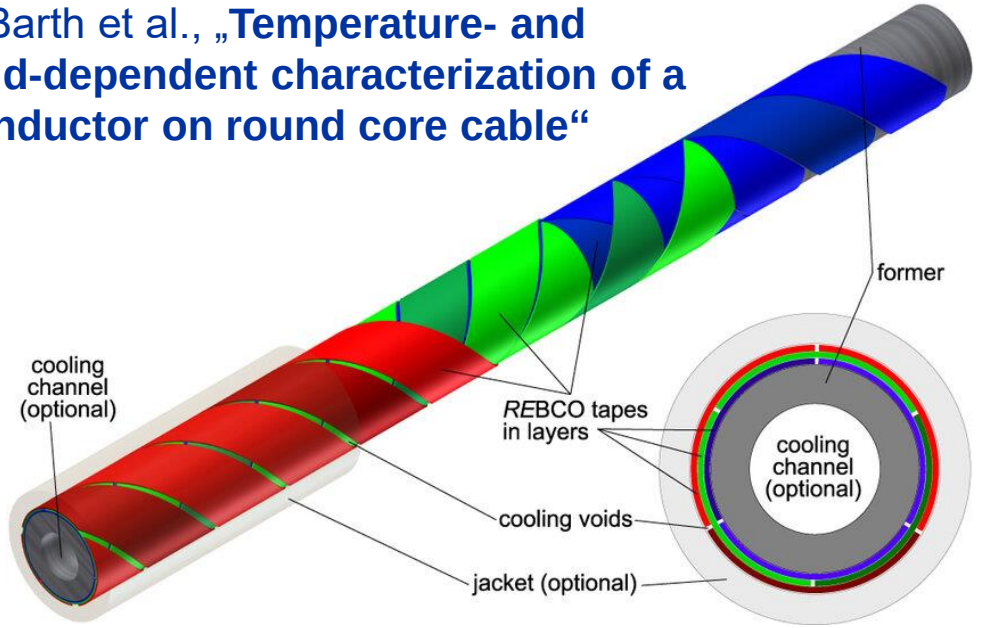
?

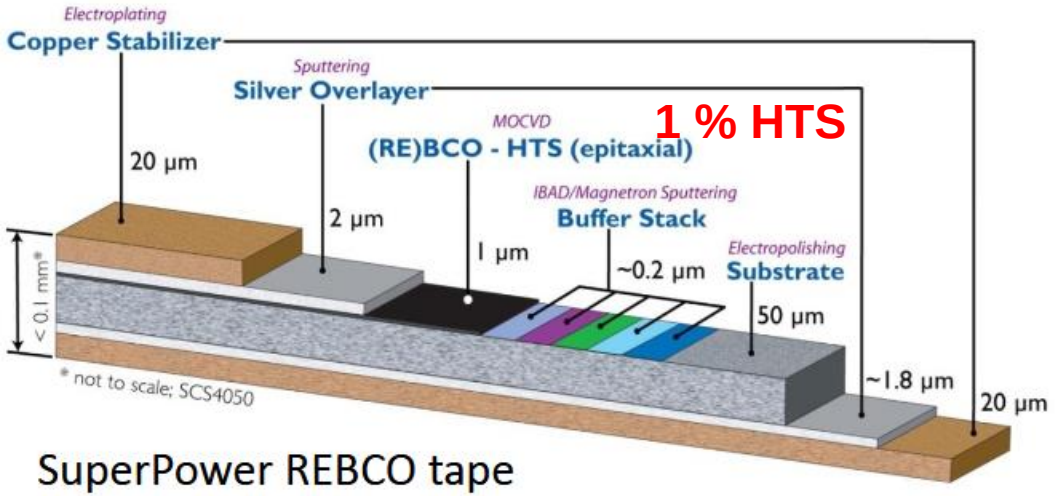
Why not HTS?

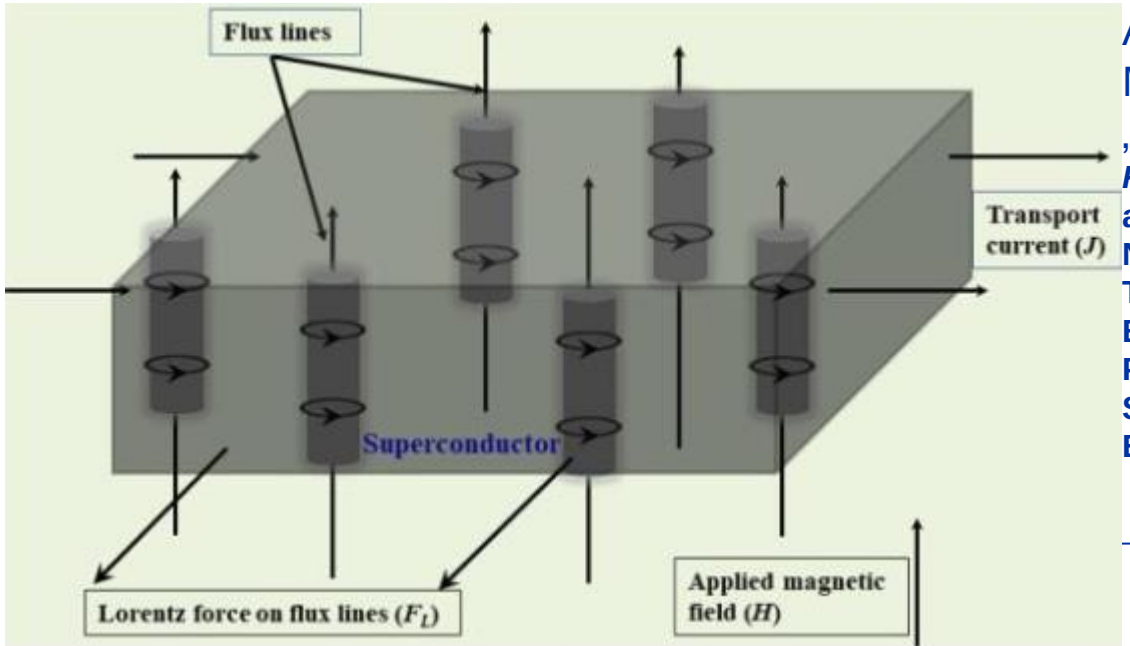
- **Thermomechanical concerns –**
  - Brittleness
- **Wire vs manufactured conductor**
  - Large bending radius
- **Wire 1D, tape 2D, cable 3D**
- **HTS Delamination, strain limit 0.4%**
- **Flux pinning → current redistribution**
- **Poor heat conductivity → slow quench propagation**

- J. Fleiter **„Rutherford cables for HL-LHC magnets, CERN“**

C.Barth et al., **„Temperature- and field-dependent characterization of a conductor on round core cable“**







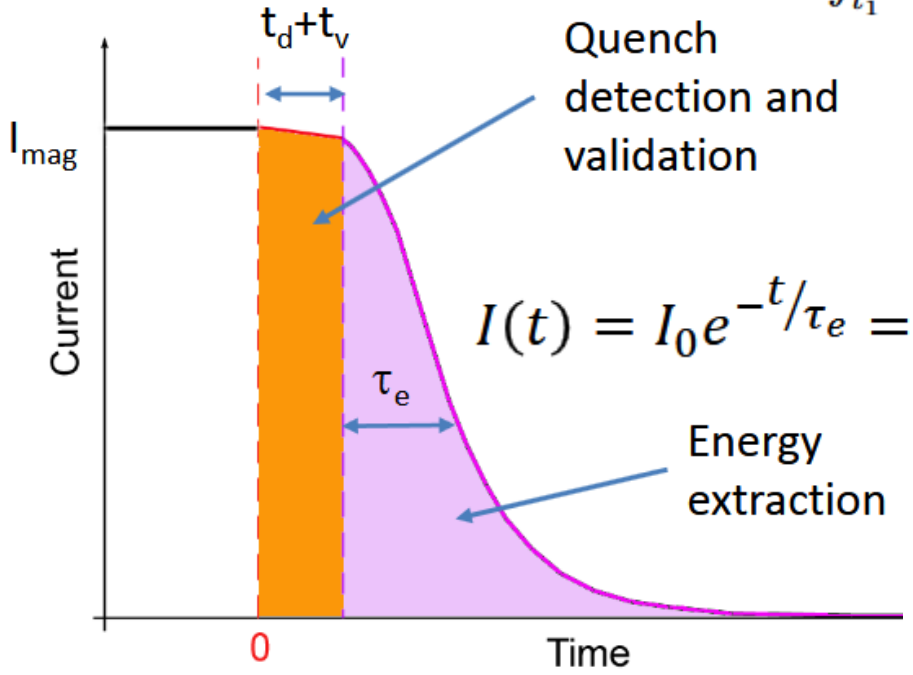
A. K. Jha, K. Matsumoto **„Superconductive *RE*BCO Thin Films and Their Nanocomposites: The Role of Rare-Earth Oxides in Promoting Sustainable Energy“**

Ensuring magnet longevity

- No current sharing in LTS
- In HTS current sharing over whole temperature range
- Adiabatic hotspot and quench load

M. Marchevsky, „Quench detection and protection for HTS accelerator magnets“

$$\int_{t_1}^{t_2} J^2(t)dt = \int_{4.2}^{T_{max}} \frac{\gamma C_p(T)}{\rho(T)} dT$$

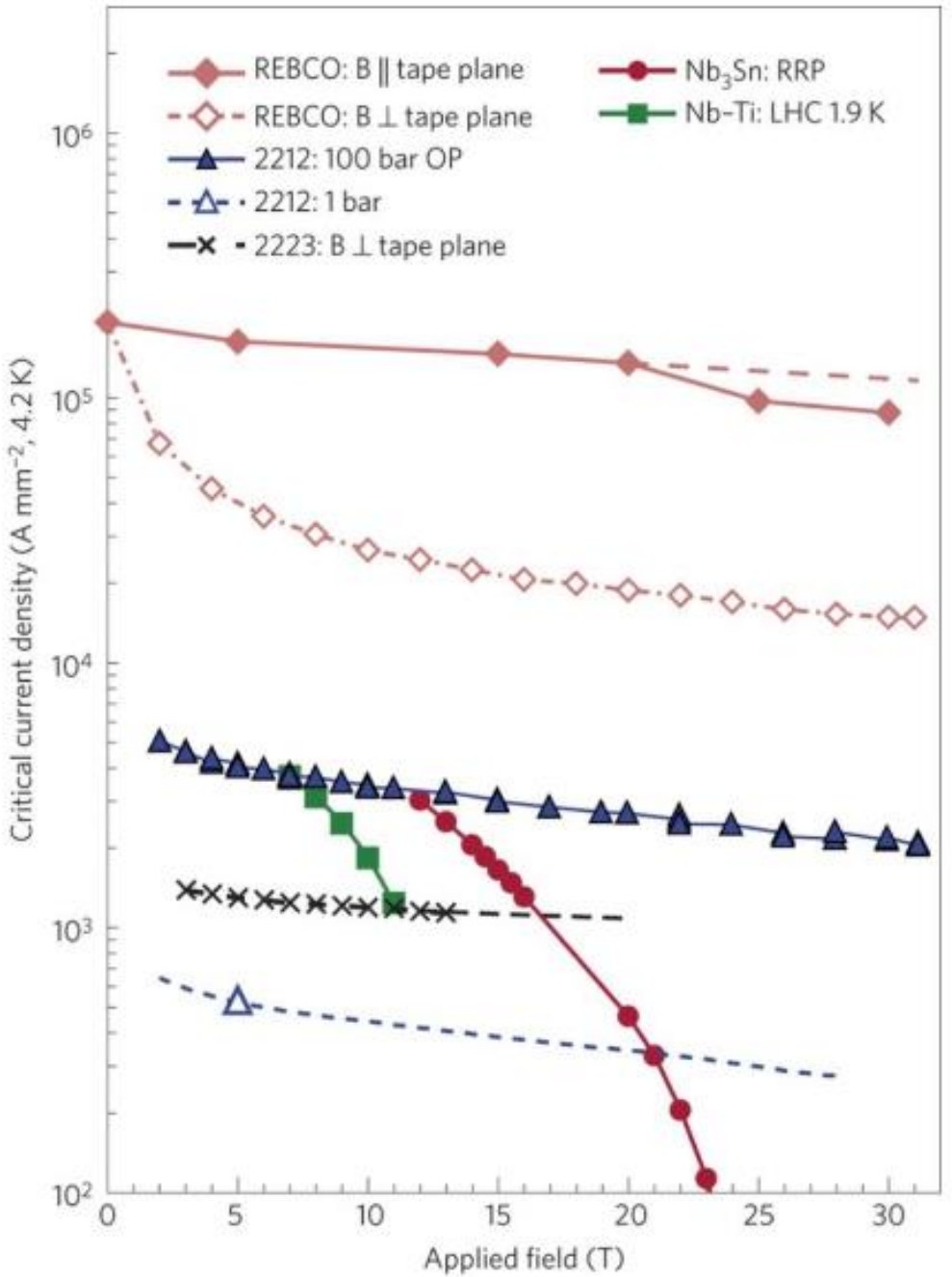


T_{max}=100 K

$$I(t) = I_0 e^{-t/\tau_e} = I_0\, e^{\frac{-t(R_{mag}(t)+R_{dump}}{L}}$$

$\tau_e \approx 1\ s$ for ATLAS Barrel Toroid magnet at 24 kA

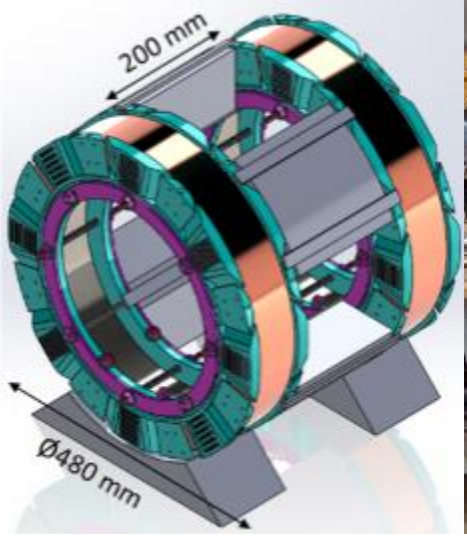
For quench protection $t_d + t_V \approx 100$ ms

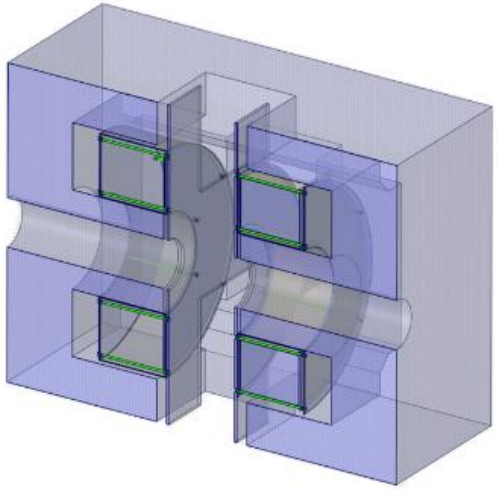


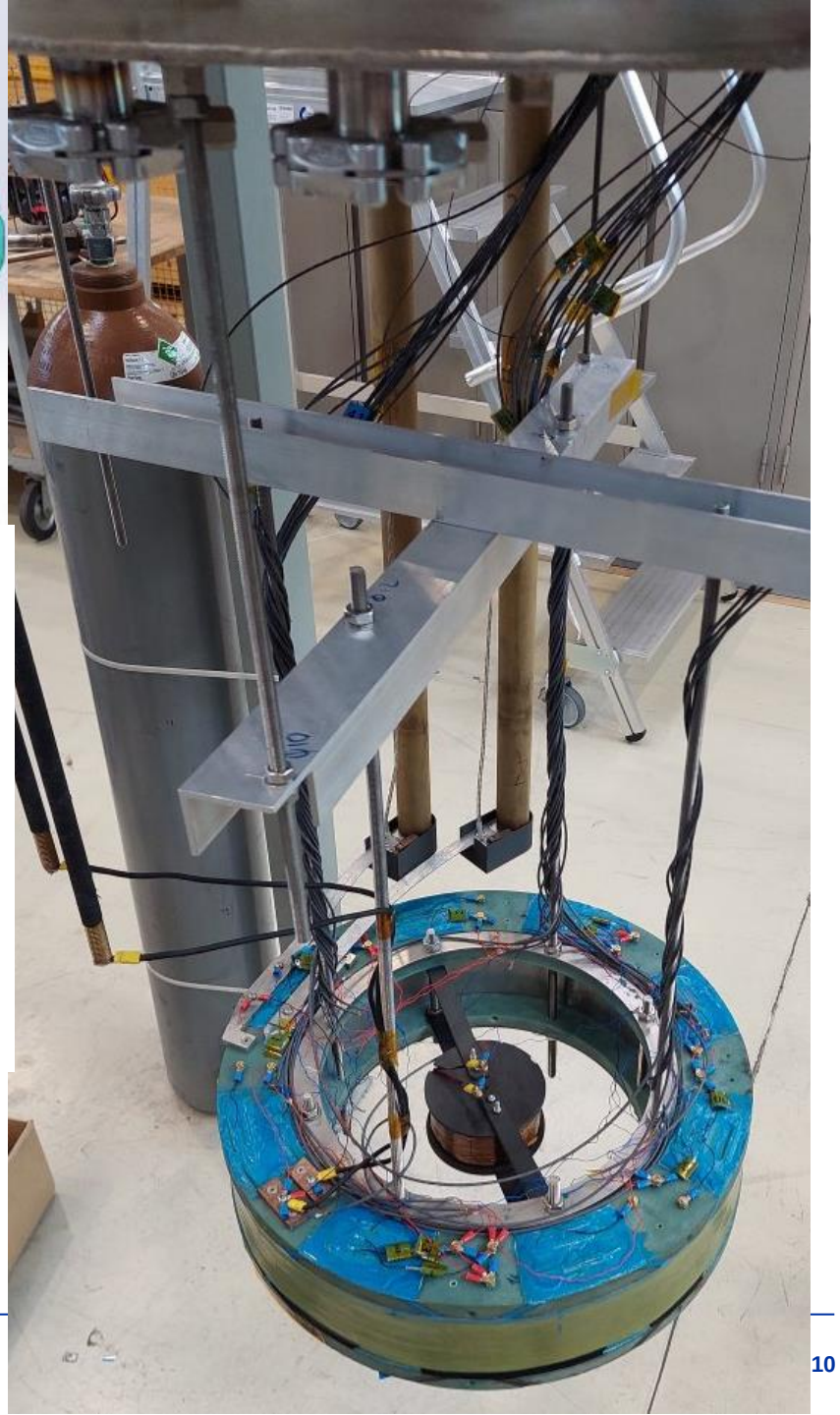
D. C. Larbalestier et al., “Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T”

The Split Coil Solenoid Demonstrator

- A versatile configuration -> axial or transverse
- Co-wound from NbTi and Cu
- **Motivation**
  - To demonstrate novel quench protection and detection principle – Rapid Quench Transformation
  - To keep expertise of magnet manufacturing EP R&D group

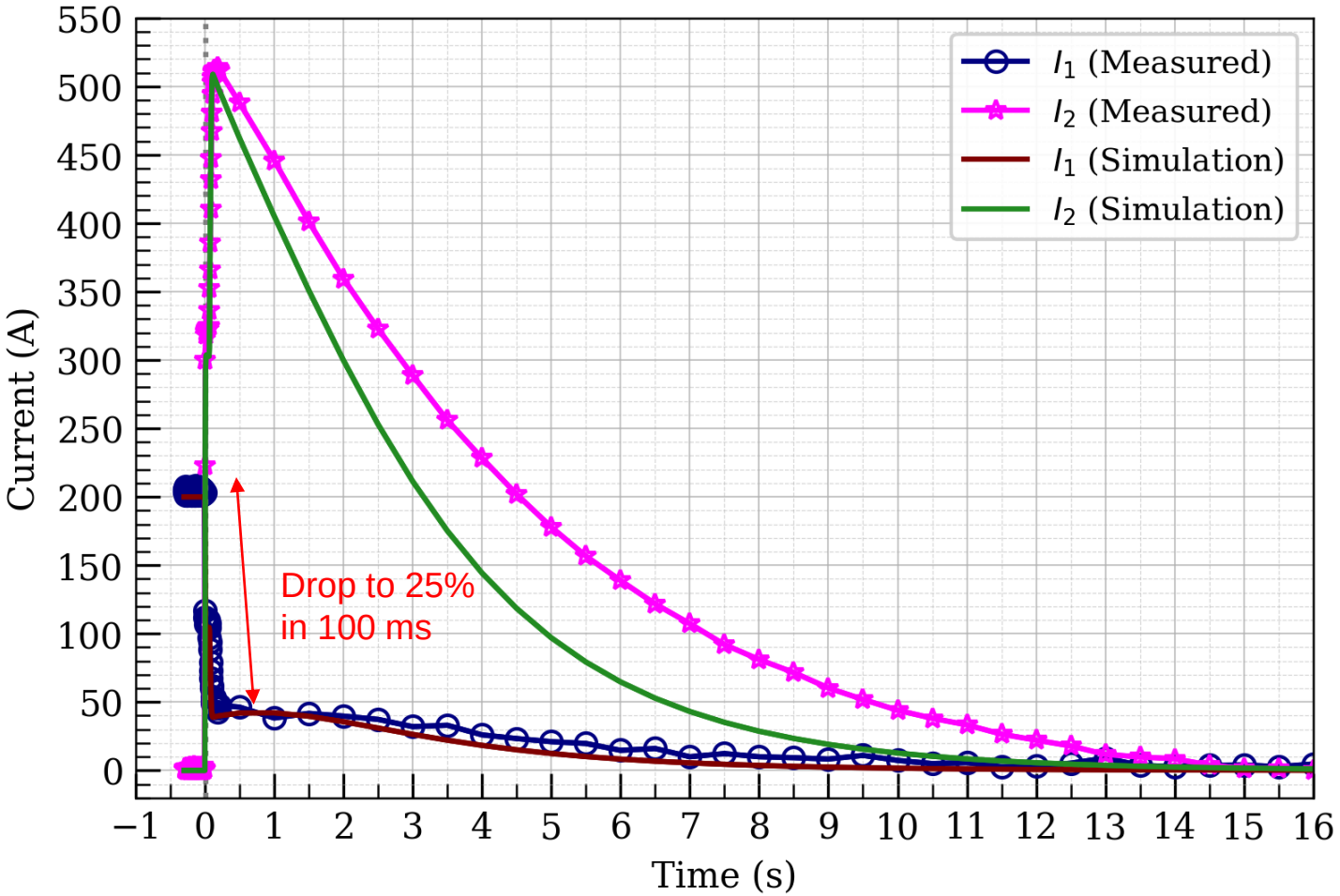


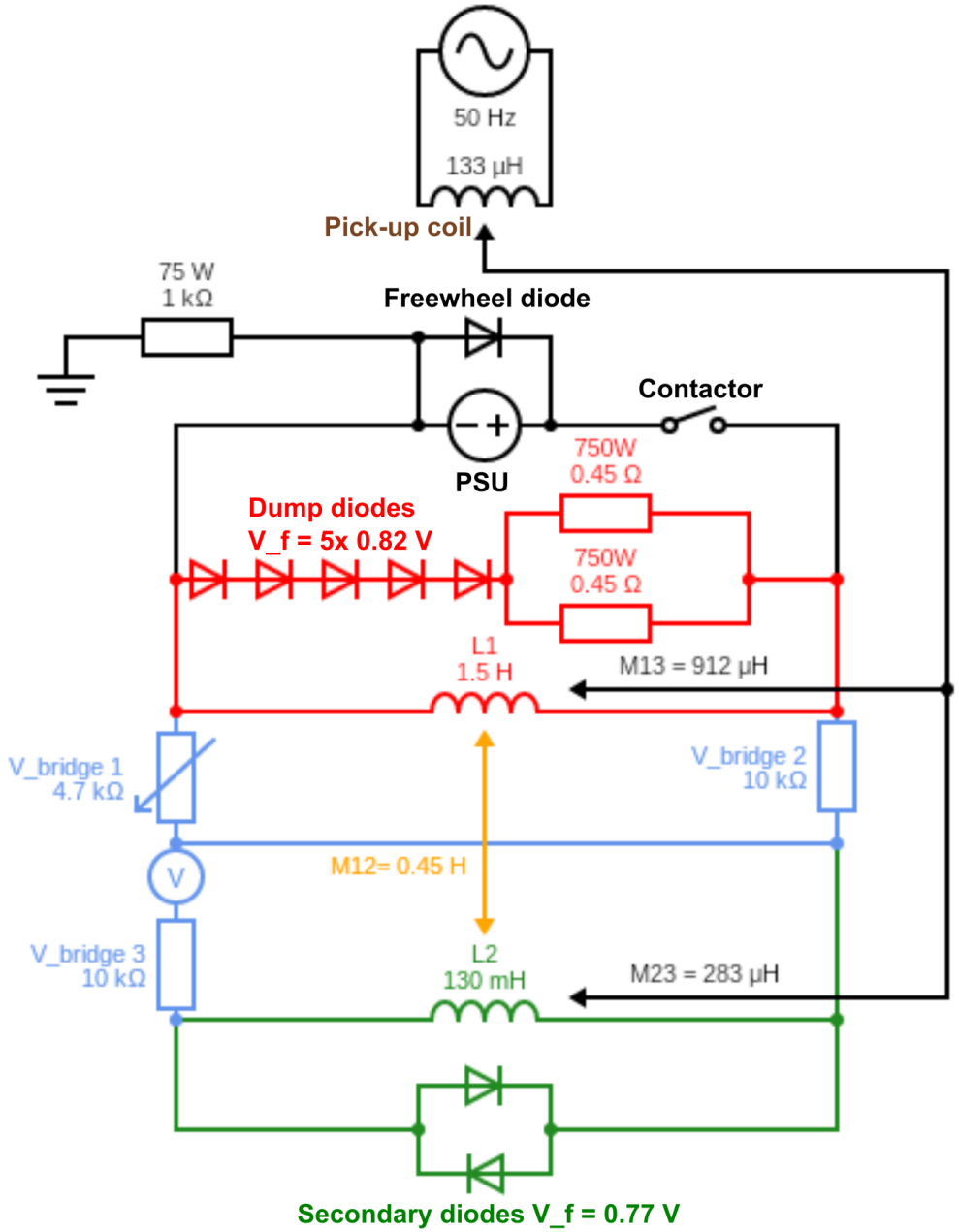




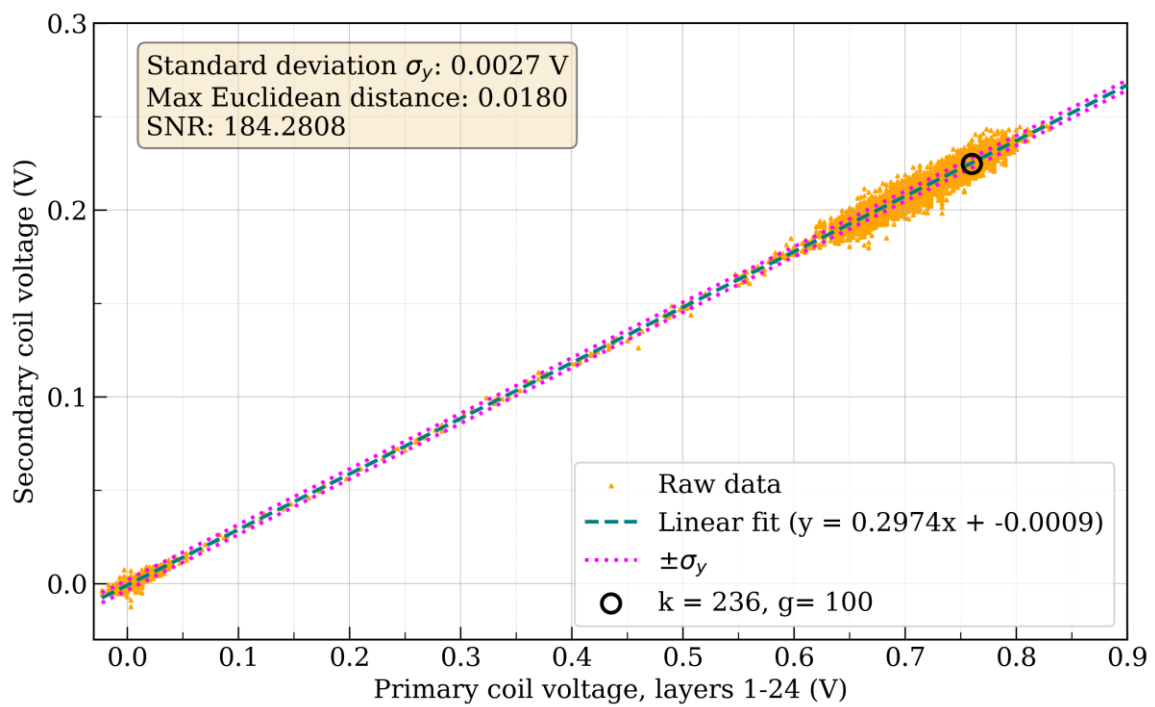
Technical parameters	
$B_{nominal}$	1 T
NbTi coil Inductivity	1.51 (H)
Cu coil Inductivity	0.13 H
$I_{nominal}$	200 A
Stored magnetic energy	30 kJ
$T_{operation}$	4.2 K
Center bore	400 mm

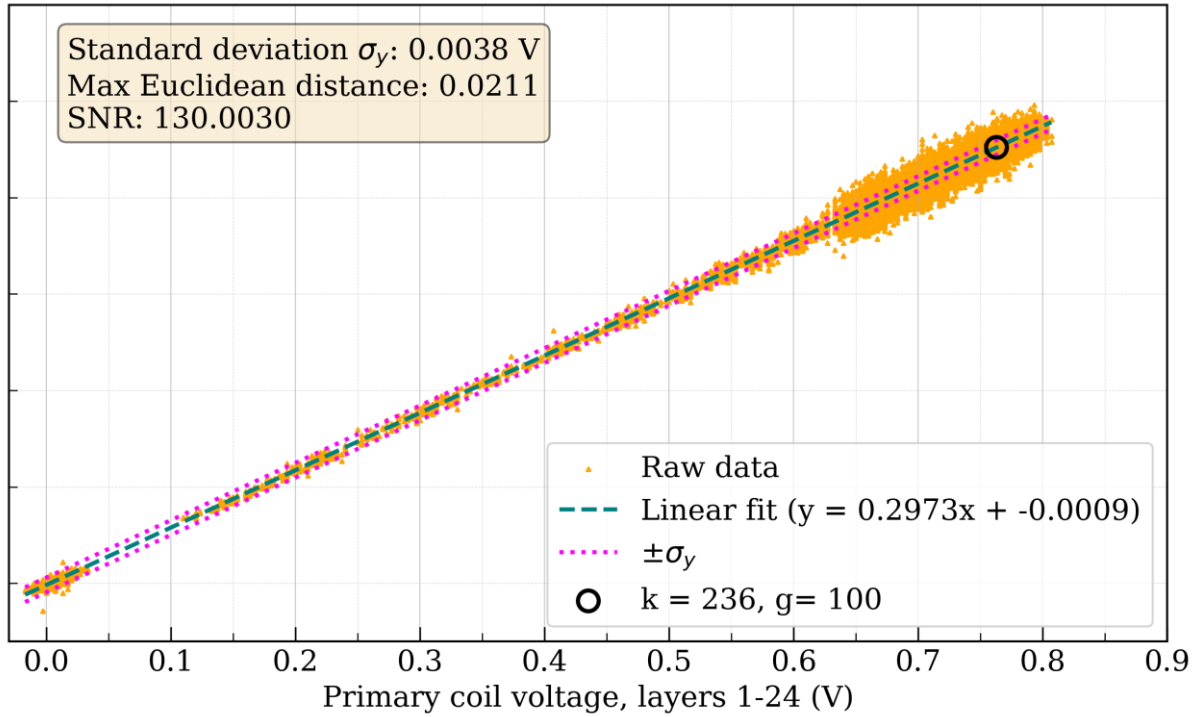
Discharge measurements

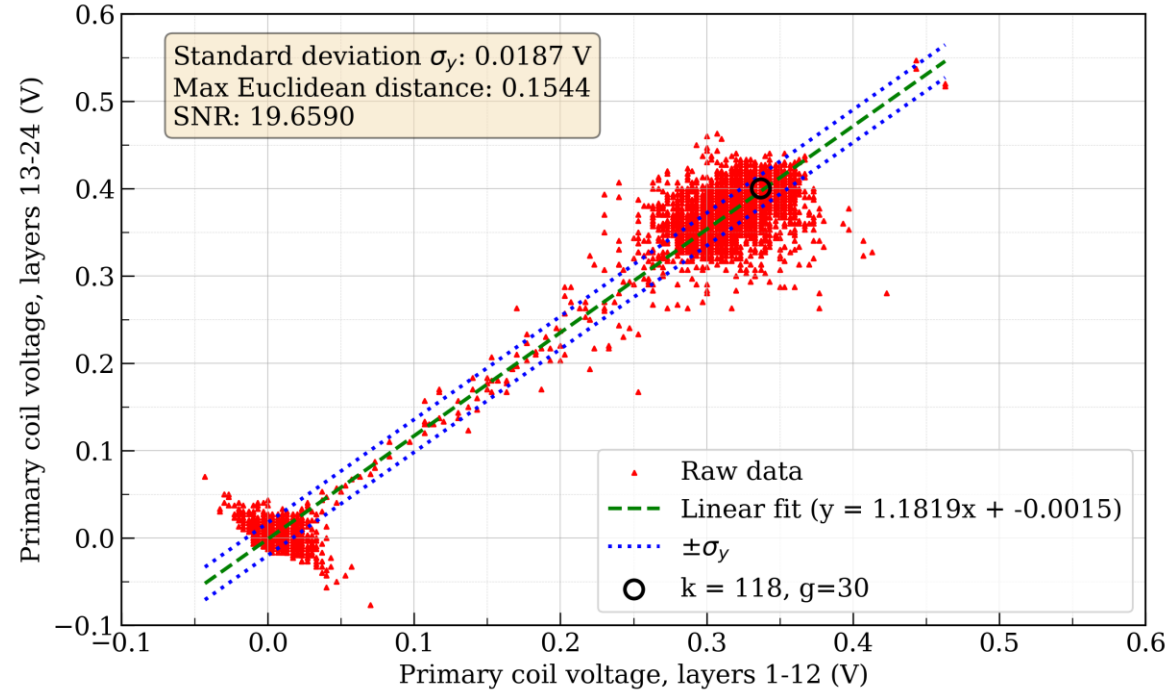


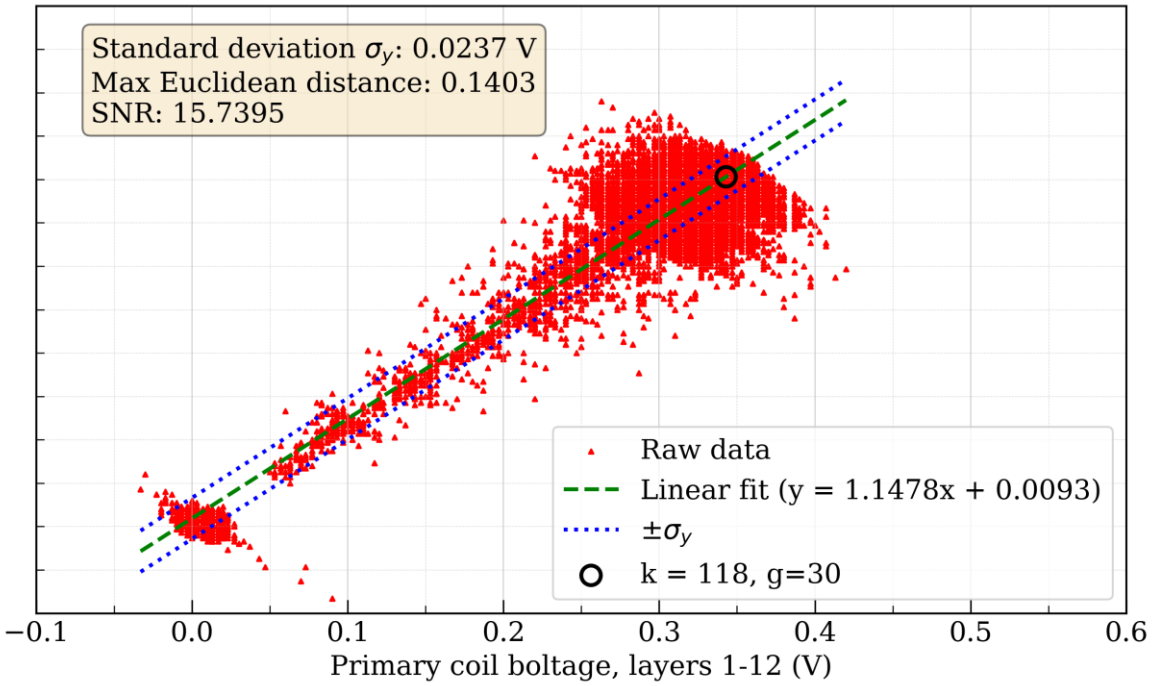


- Measured vs Finite-Element simulation of coil disharge over time
- T = 0 represents a magnet quench
- Secondary coil extracts most of the stored energy


Standard deviation σ_y: 0.0027 V
Max Euclidean distance: 0.0180
SNR: 184.2808
Raw data
Linear fit (y = 0.2974x + -0.0009)
$\pm\sigma_y$
k = 236, g= 100
Secondary coil voltage (V)
Primary coil voltage, layers 1-24 (V)


Standard deviation σ_y: 0.0038 V
Max Euclidean distance: 0.0211
SNR: 130.0030
Raw data
Linear fit (y = 0.2973x + -0.0009)
$\pm\sigma_y$
k = 236, g= 100
Primary coil voltage, layers 1-24 (V)


Standard deviation σ_y: 0.0187 V
Max Euclidean distance: 0.1544
SNR: 19.6590
Raw data
Linear fit (y = 1.1819x + -0.0015)
$\pm\sigma_y$
k = 118, g=30
Primary coil voltage, layers 13-24 (V)
Primary coil voltage, layers 1-12 (V)


Standard deviation σ_y: 0.0237 V
Max Euclidean distance: 0.1403
SNR: 15.7395
Raw data
Linear fit (y = 1.1478x + 0.0093)
$\pm\sigma_y$
k = 118, g=30
Primary coil boltage, layers 1-12 (V)

Context

Future Physics Experiments anticipated :

- **Colliders:**

  Alice3 (CERN), FCC-ee -hh –he (CERN), CLIC(CERN), Muon Collider (CERN), ILC (IDR,SLAC), CEPC (IHEP), Panda (GSI/Fair), EIC(BNL, J-Lab).

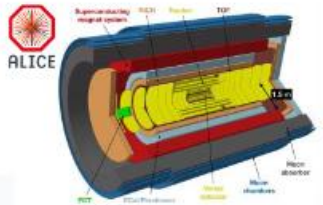
- **Non-Colliders:**

  Babylaxo (Desy), SHiP (CERN), Muon Beam Experiments (Comet-KEK, Mu2e-Fermilab), MadMax (Desy), AMS100 (RWTHAAchen)

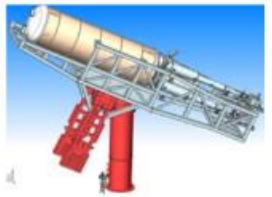
More than 15 projects with SC magnets

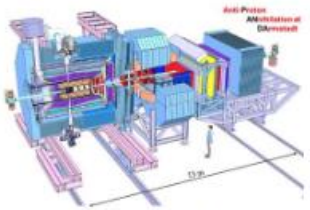
either:
- Under construction,
- Design phase,
- Conceptual phase.

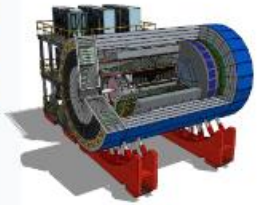
Mainly Alu-stabilized superconductors.

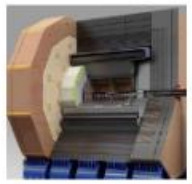


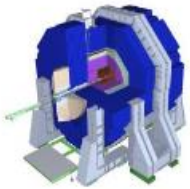
Alice-3


BabyIAXO

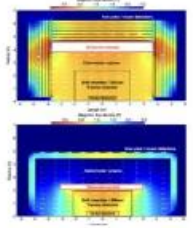

PANDA

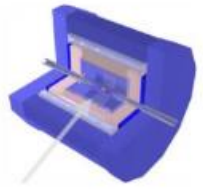

EIC

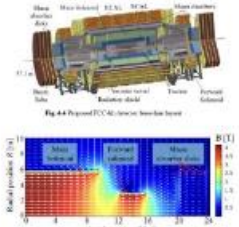

ILC-ILD

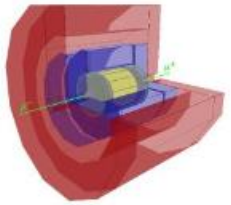

ILC-SiD

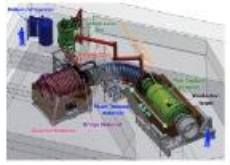

CLICdp


FCC-ee

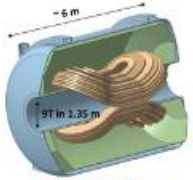

CPEC


FCC-hh

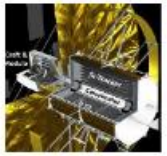

iMuC


Comet


Mu2e

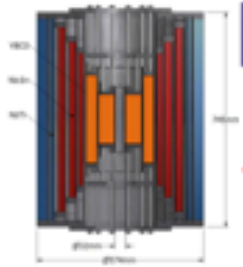


MadMax


AMS100

High-field magnets

Field-temperature phase diagram of technical superconductors



NATIONAL MAGLAB
User Magnet
32 T @ 4.2 K
REBCO/Nb_3Sn/Nb-Ti

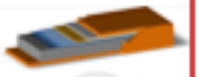
BRUKER
1.2 GHz NMR
28.2 T @ 2.2 K
REBCO/Nb_3Sn/Nb-Ti

C. Senatore „ Progress in REBCO Conductor Technologies for Ultra-High Field Applications“

NATIONAL MAGLAB
Little Big Coil
45.5 T @ 4.2 K
REBCO/Resistive

Commonwealth Fusion Systems
Toroidal Field Model Coil
20 T @ 20 K
REBCO

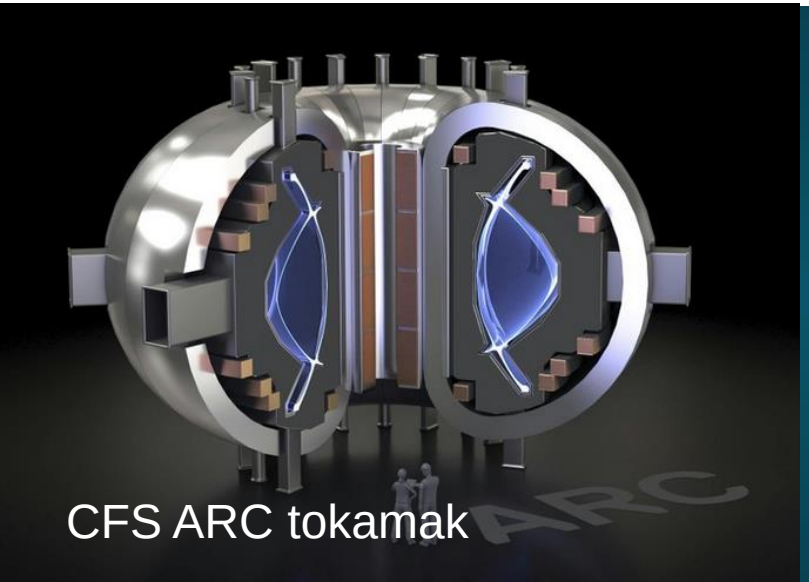
HTS: REBCO
BSCCO



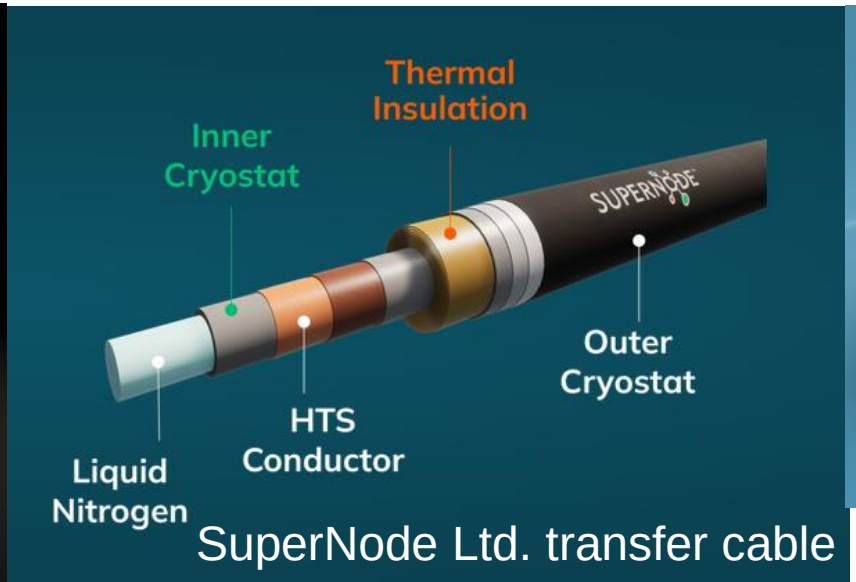
Magnetic field
50+ T
20 T
5 T
1 T
4.2 K
20 K
50 K
77 K
Temperature
High Temperature Superconductors
Low Temperature Superconductors

Other applications

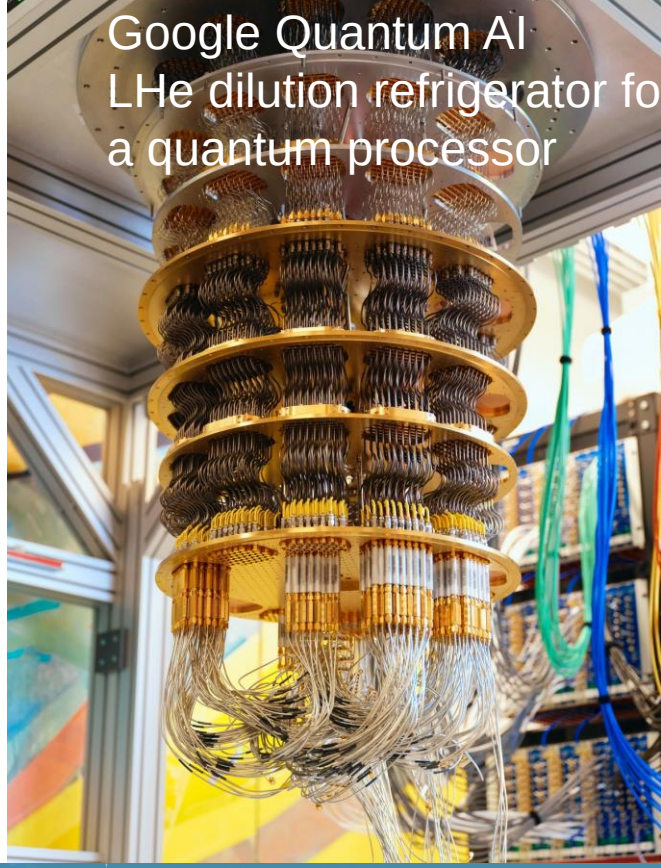
- Fusion
- Superconducting power transmission – SuperNode, English Channel
- Quantum computers – IQM, IBM, Google, Dwave
- SQUIDs – very sensitive magnetometers
  - MRI sensing elements
  - For gravitational wave research
  - Axion Dark Matter Experiment
- High-field MRI magnets – CEA Paris-Saclay 11.7 T for studies of the human brain
- NIMMs – a proposed synchrotron facility for Hadron Therapy

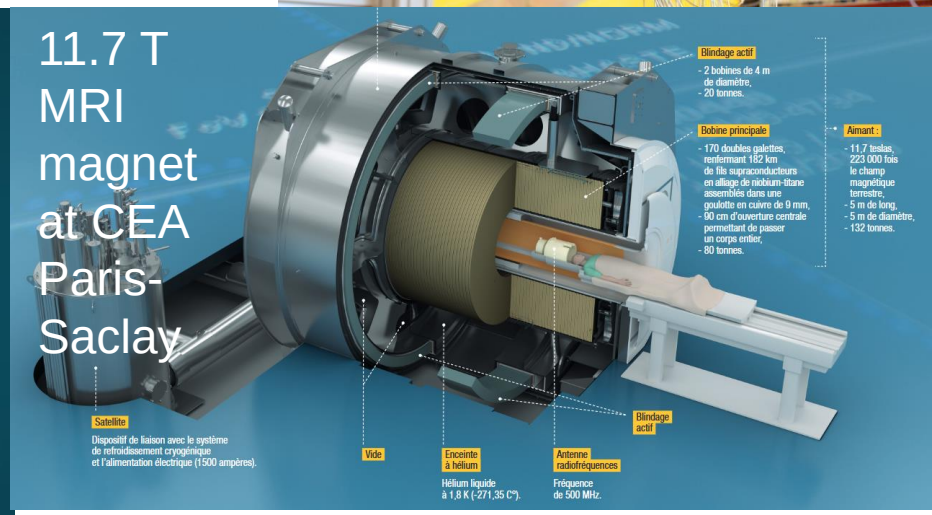


CFS ARC tokamak



SuperNode Ltd. transfer cable


Google Quantum AI
LHe dilution refrigerator fo
a quantum processor



11.7 T MRI magnet at CEA Paris-Saclay

References

- EP R&D 2024 annual report, CERN
- Dominik Walliman, Domain of Science Youtube channel 2021, „Map of superconductivity“
- Engineering Superconductivity," ed. Peter J. Lee, Wiley-Interscience, New York, 200
- Superconductivity Revised Edition V L Ginzburg / E A Andryushin
- Phys.org „How electrons split: New evidence of exotic behaviors“
- J. Fleiter Rutherford cables for HL-LHC magnets, CERN
- C.Barth et al., „Temperature- and field-dependent characterization of a conductor on round core cable“
- SuperPower brochure, Rebco SC4050
- A. K. Jha, K. Matsumoto „Superconductive *RE*BCO Thin Films and Their Nanocomposites: The Role of Rare-Earth Oxides in Promoting Sustainable Energy“
- M. Marchevsky, „Quench detection and protection for HTS accelerator magnets“
- D. C. Larbalestier et al., “Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T”
- B. Maddock and G. James, “Protection and stabilisation
- of large superconducting coils,”
- M.Mentink et al „BabylAXO Axion Helioscope Superconducting Dipole“
- M.Mentink &B.Cure EP R&D Day - WP8 Detector Magnets
- C. Senatore „ Progress in REBCO Conductor Technologies for Ultra-High Field Applications“
- SQUID, Wikipedia
- https://supernode.energy/technology/
- https://cfs.energy/
- https://quantumai.google/quantumcomputer
- https://www.cea.fr/presse/Pages/actualites-communiques/sante-sciences-du-vivant/voyage-aimant-IRM-projet-iseult.aspx

Questions?