Walther Meißner Institut

BAdW | BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Technische Universität München

Superconductivity and Low Temperature Physics I

Lecture Notes
Winter Semester 2022/2023

R. Gross

Superconductivity

General Remarks on the Courses to the Field
Superconductivity and Low Temperature Physics

1. **Superconductivity and Low Temperature Physics I + II**
   → Part I (WS 2022/2023): Foundations of Superconductivity — This lecture
   → Part II (SS 2023): Foundations of Low Temperature Physics and Techniques

2. **Applied Superconductivity I + II**
   Note!
   → WS 2022/23 and SS 2023, 2 hrs lecture + 2 hrs exercises
   → Josephson-Effect, Superconducting Electronics, Qubits, Quantum Circuits, Quantum Microwaves,….

3. **Seminars (WS 2022/2023, WMI seminar room)**
   → Advances in Solid State Physics (TUE 10:15-11:30)
   → Superconducting Quantum Circuits (TUE 14:30-16:00)
   Topics available

Further information: https://www.wmi.badw.de/teaching
→ announcement of lectures
→ downloads of lecture notes, exercise sheets, handouts…
→ seminar topics

Nobel Prizes in Physics related to LT Physics

year	name	discovery
1913	Heike Kamerlingh Onnes	"For his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"
1962	Lev Davidovich Landau	"for his pioneering theories for condensed matter, especially liquid helium"
1972	John Bardeen, Leon Neil Cooper and Robert Schrieffer	"for their jointly developed theory of superconductivity, usually called the BCS-theory"
1973	Brian David Josephson	"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effect"
1978	Pjotr Kapiza	"for his basic inventions and discoveries in the area of low-temperature physics"
1985	Klaus von Klitzing	"for the discovery of the quantized Hall effect"
1987	Johannes Georg Bednorz and Karl Alex Müller	"for their important break-through in the discovery of superconductivity in ceramic materials"
1996	David M. Lee, Douglas D. Osheroff und Robert C. Richardson	"for their discovery of superfluidity in helium-3"
1997	Steven Chu, Claude Cohen-Tannoudji and William D. Phillips	"for development of methods to cool and trap atoms with laser light" See Laser cooling.
1998	Robert B. Laughlin, Horst Ludwig Störmer and Daniel Chee Tsui	"for their discovery of a new form of quantum fluid with fractionally charged excitations". See Quantum Hall effect.
2001	Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman	"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"
2003	Alexei Abrikosov, Witali Ginsburg and Anthony James Leggett	"for pioneering contributions to the theory of superconductors and superfluids"
2016	David J. Thouless, F. Duncan M. Haldane, J. Michael Kosterlitz	”for theoretical discoveries of topological phase transitions and topological phases of matter”

Contents of Lecture

Superconductivity and Low Temperature Physics I

Introduction

1. Basic Properties of Superconductors
2. Phenomenological Models of Superconductivity:
   - London equations
   - macroscopic quantum model
   - Ginzburg-Landau theory
3. Thermodynamics
4. Microscopic (BCS) theory
5. Flux pinning and critical currents
6. High Temperature Superconductivity
7. Applications

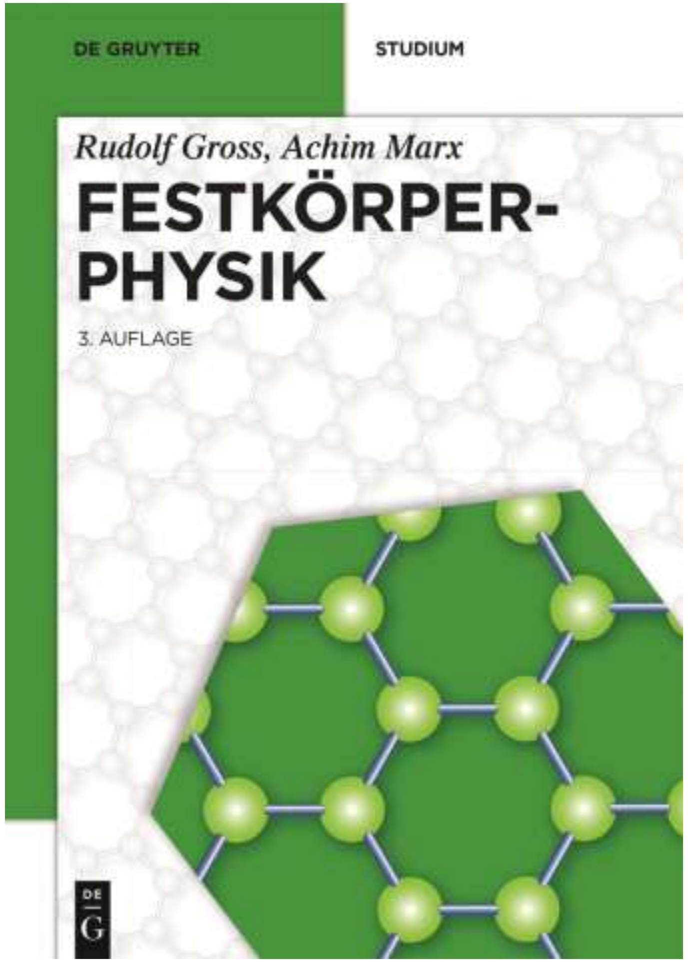
Superconductivity and Low Temperature Physics II

1. Bose-Einstein condensation
2. Superfluid Helium (^{4}He and ^{3}He)
3. Quantum Interference Effects in Mesoscopic Conductors
4. Low Temperature Techniques (generation and measurement of low temperatures)

Literature

- Werner Buckel, Reinhold Kleiner, *Supraleitung – Grundlagen und Anwendungen*, VCH-Verlag, Weinheim (2013).
- Fossheim, Sudbo, *Superconductivity*, Wiley (2005)
- M. Tinkham, *Introduction to Superconductivity*, McGraw-Hill, New York (1975).
- J.F. Annett, *Superconductivity, Superfluids and Condensates* (2004)
- V.V. Schmidt, *The Physics of Superconductors* (1997)
- J. R. Waldram, *Superconductivity of Metals and Cuprates* (1996)
- D.R. Tilley and J. Tilley, *Superfluidity and Superconductivity*
- P. Komarek, *Hochstromanwendungen der Supraleitung* (1995)
- T. P. Sheathen, *Introduction to High* T_c *Superconductivity* (1994)
- M. Acquarone, *High Temperature Superconductivity* (1996)
- WMI Lecture Notes https://www.wmi.badw.de/teaching/Lecturenotes

Literature



Rudolf Gross, Achim Marx

Title: Festkörperphysik, 3rd revised and extended edition
Publisher: Walter de Gruyter GmbH, Berlin/Boston
Published: January 2018
Language: German
ISBN 978-3-11-055822-7, ISBN 978-3-11-055918-7

13 **Supraleitung** 769

13.1 Geschichte und grundlegende Eigenschaften ... 772
13.1.1 Geschichte der Supraleitung ... 772
13.1.2 Supraleitende Materialien ... 780
13.1.3 Sprungtemperaturen ... 783
13.1.4 Grundlegende Eigenschaften ... 784

13.2 Thermodynamische Eigenschaften von Supraleitern ... 792
13.2.1 Typ-I Supraleiter im Magnetfeld ... 792
13.2.2 Typ-II Supraleiter im Magnetfeld ... 797

13.3 Phänomenologische Modelle ... 798
13.3.1 London-Gleichungen ... 798
13.3.2 Verallgemeinerte London Theorie – Supraleitung als makroskopisches Quantenphänomen ... 801
13.3.3 Die Ginzburg-Landau-Theorie ... 813

13.4 Typ-I und Typ-II Supraleiter ... 825
13.4.1 Mischzustand und kritische Felder ... 826
13.4.2 Supraleiter-Normalleiter Grenzflächenenergie ... 827
13.4.3 Vertiefungsthema: Zwischenzustand und Entmagnetisierungseffekte ... 829
13.4.4 Kritische Felder ... 830
13.4.5 Vertiefungsthema: Nukleation an Oberflächen ... 834
13.4.6 Vertiefungsthema: Shubnikov-Phase und Flussliniengitter ... 835
13.4.7 Vertiefungsthema: Flusslinien in Typ-II Supraleitern ... 838
13.4.8 Kritische Stromdichte ... 843

13.5 Mikroskopische Theorie ... 847
13.5.1 Attraktive Elektron-Elektron-Wechselwirkung und Cooper-Paare ... 849
13.5.2 Der BCS-Grundzustand ... 858
13.5.3 Energielücke und Anregungsspektrum ... 873
13.5.4 Quasiteilchentunneln ... 875
13.5.5 Thermodynamische Größen ... 879

13.6 Josephson-Effekt ... 883
13.6.1 Die Josephson-Gleichungen ... 883
13.6.2 Josephson-Kontakt mit Wechselspannung ... 888
13.6.3 Josephson-Kontakt im Magnetfeld ... 889
13.6.4 Supraleitende Quanteninterferometer ... 893

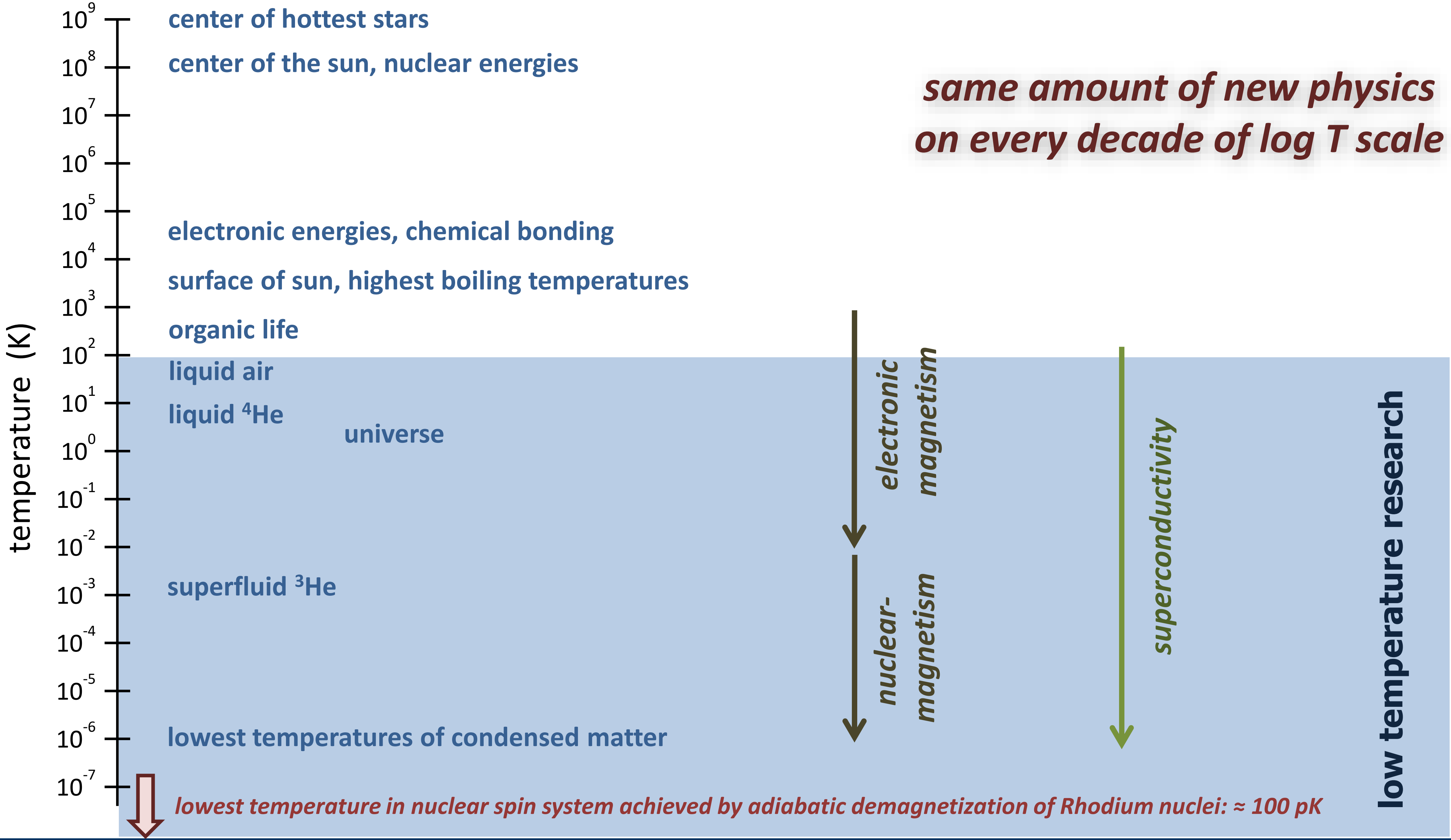
13.7 Kritische Ströme in Typ-II Supraleitern ... 895
13.7.1 Stromtransport im Mischzustand ... 896
13.7.2 Lorentz-Kraft ... 898
13.7.3 Reibungskraft ... 900
13.7.4 Haftkraft ... 901

13.8 Unkonventionelle Supraleitung ... 903
13.9 Kuprat-Supraleiter ... 905
13.9.1 Strukturelle Eigenschaften ... 906
13.9.2 Elektronische Eigenschaften ... 907
13.9.3 Supraleitende Eigenschaften ... 912

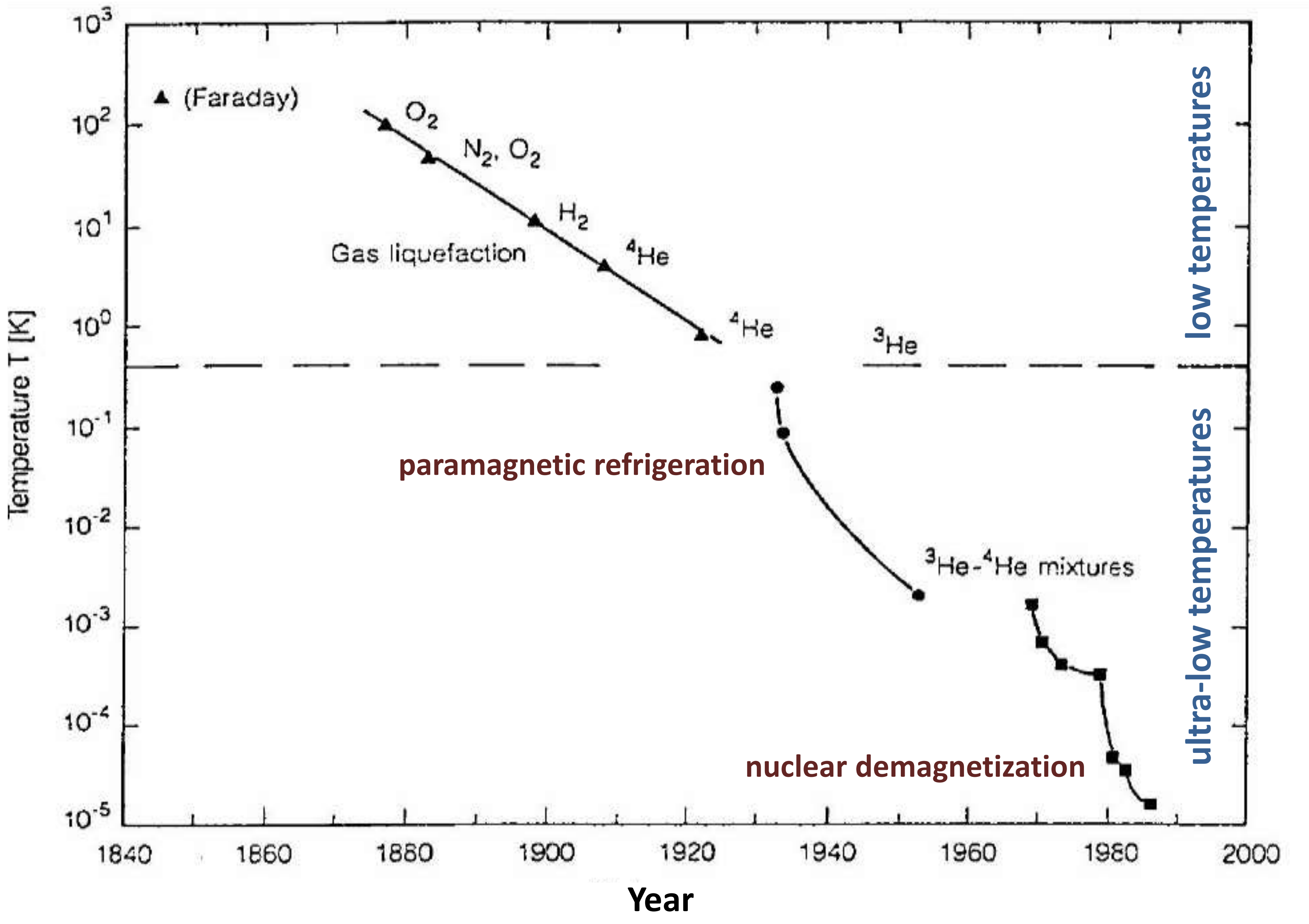
Literatur ... 921

Introduction

Temperature Scale



Generation of Low Temperatures



R. Gross and A. Marx , © Walther-Meißner-Institut (2004 - 2022)

Low Temperature Technology

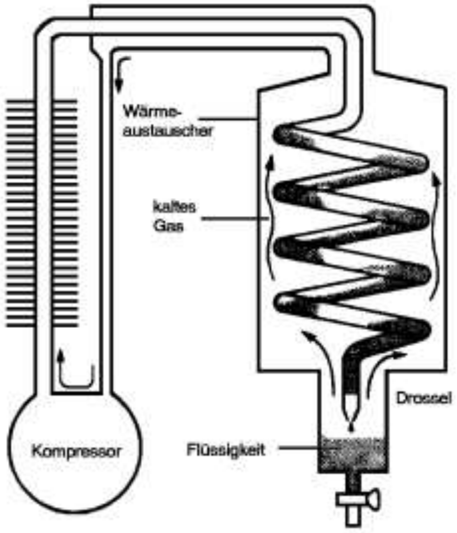
1868 offer of chair at the Polytechnische Schule München (now TUM)

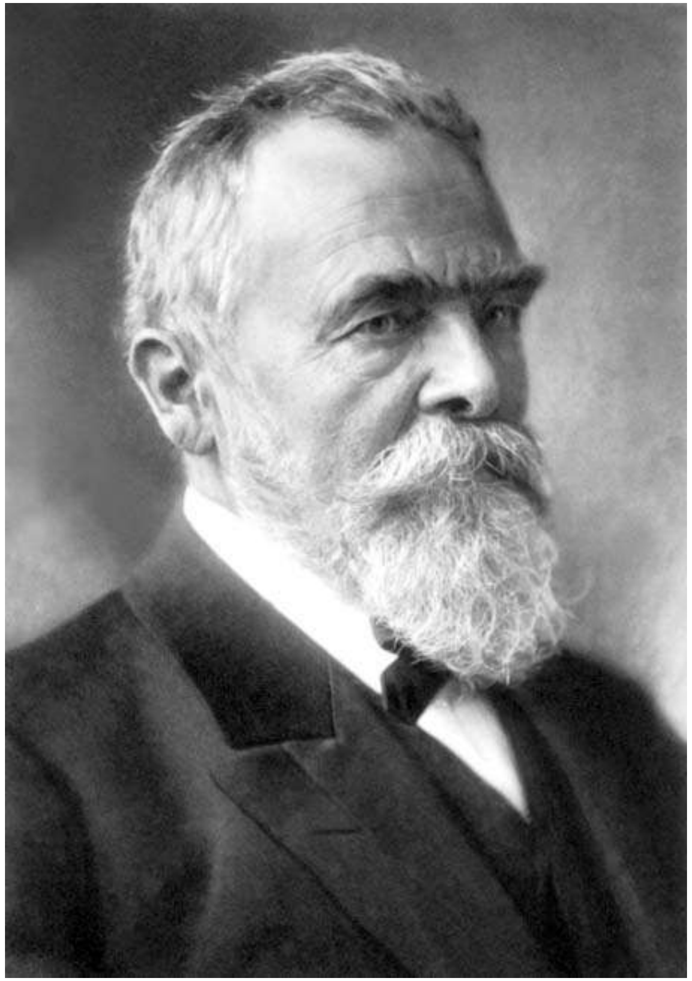
1873 development of cooling machine allowing the temperature stabilization in beer brewing

21.06.1879 foundation of „***Gesellschaft für Linde's Eismaschinen AG***" together with two beer brewers and three other co-founders

1892 - 1910 re-establishment of professorship

12.05.1903 patent application: „***Lindesches Gegenstrom-verfahren***" liquefaction of oxygen (-182°C = 90 K)





Carl Paul Gottfried von Linde

* 11. Juni 1842 in Berndorf, Oberfranken

† 16. November 1934 in Munich

Low Temperature Technology

1930 Linde AG uses the first cooling turbines for the generation of low temperatures

turbines have higher efficiency and therefore are used today in all larger liquefaction machines

e.g. He liquefier at the Walther-Meißner-Institut

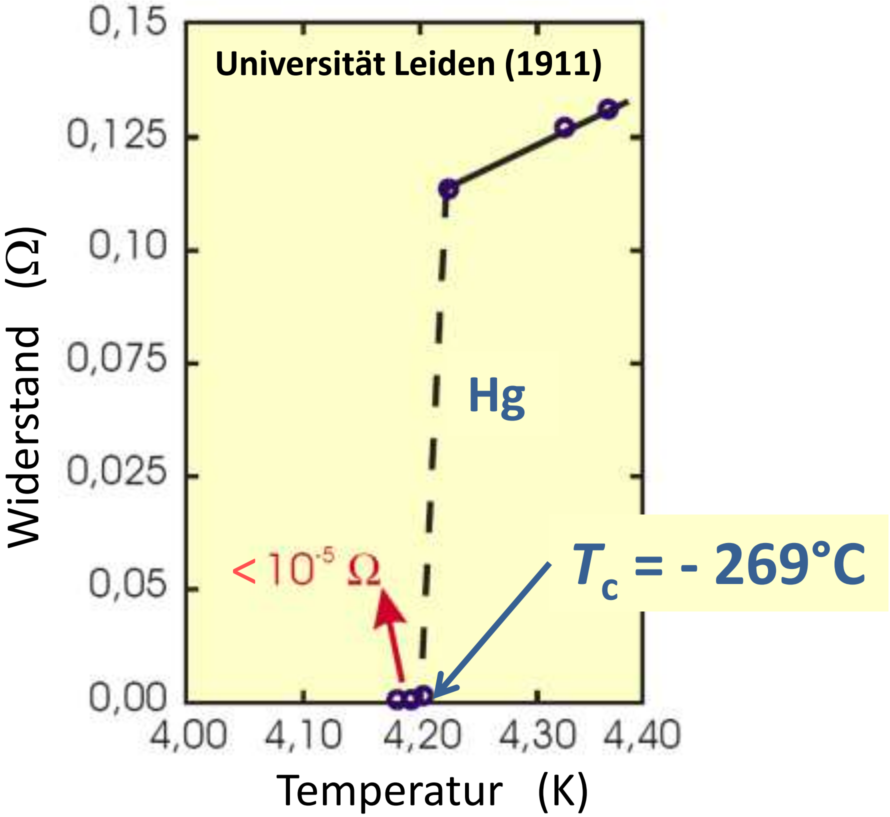
1947 first commercial He liquefier (design by engineer Collins, therefore denoted as „Collins“ machine)

Arthur D. Little Inc. (today CTI)

1966 ***Hall*** et al. and ***Neganov*** et al. develop ^{3}He/^{4}He dilution refrigerators, generation of temperatures down to 2 mK

Discovery of Superconductivity (1911)

Heike Kammerlingh Onnes (1853-1926)



H. K. Onnes, Comm. Leiden 120b (1911)

- **Helium liquefaction: 1908**
- **discovery of superconductivity: 1911**

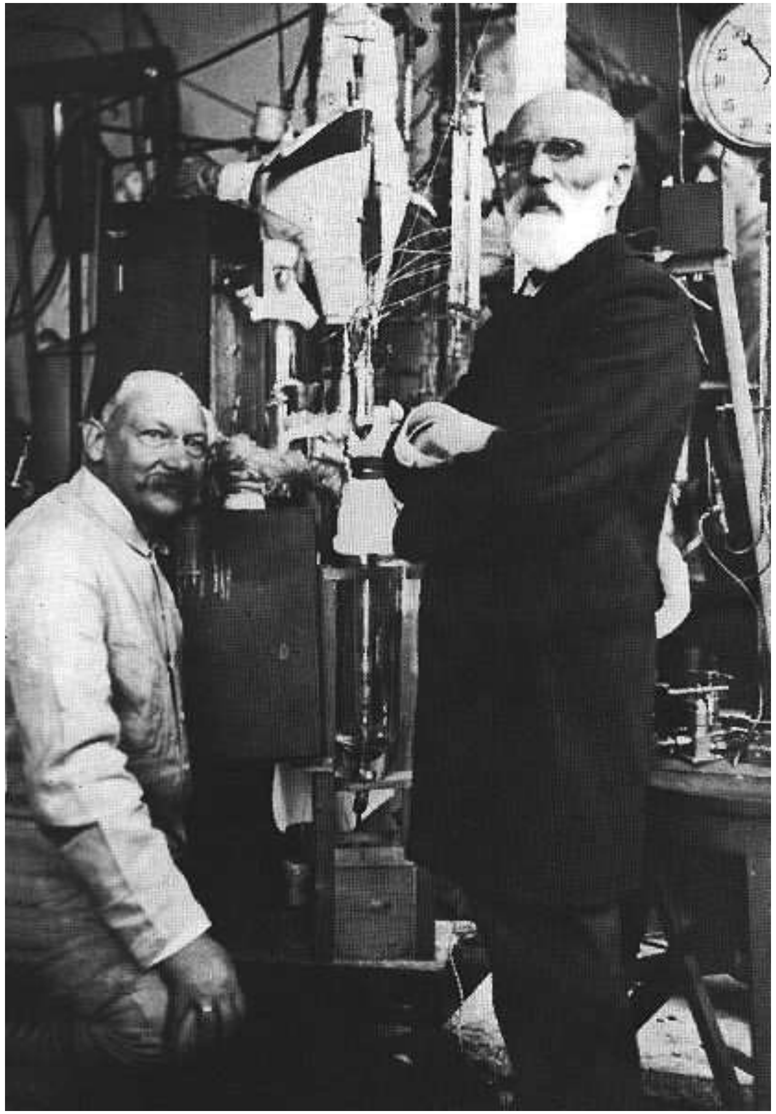
Nobel Price in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia to the production of liquid helium"

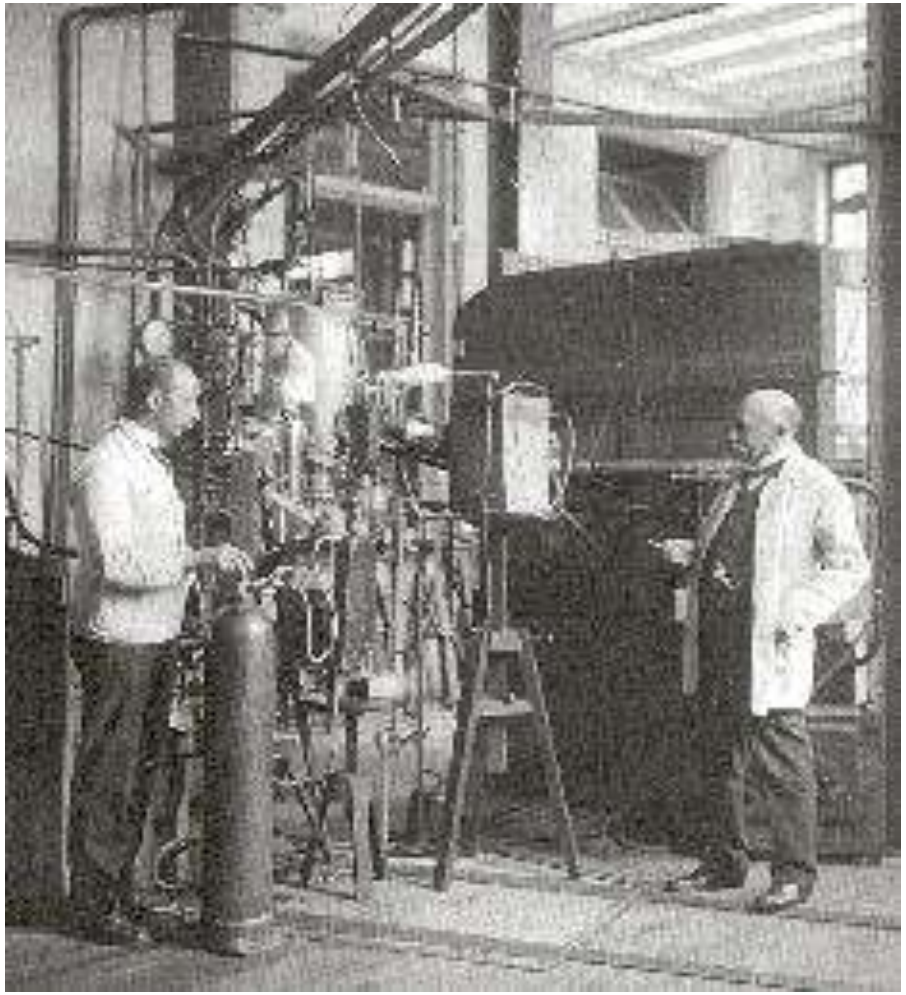
choice of name:

infinite electrical conductivity **→** **superconductivity**

Discovery of Superconductivity (1911)



Kammerlingh Onnes and van der Waals



Kammerlingh Onnes and Techniker Flim

Discovery of the Meißner-Ochsenfeld Effect (1933)

Robert Ochsenfeld
(1901 – 1993)

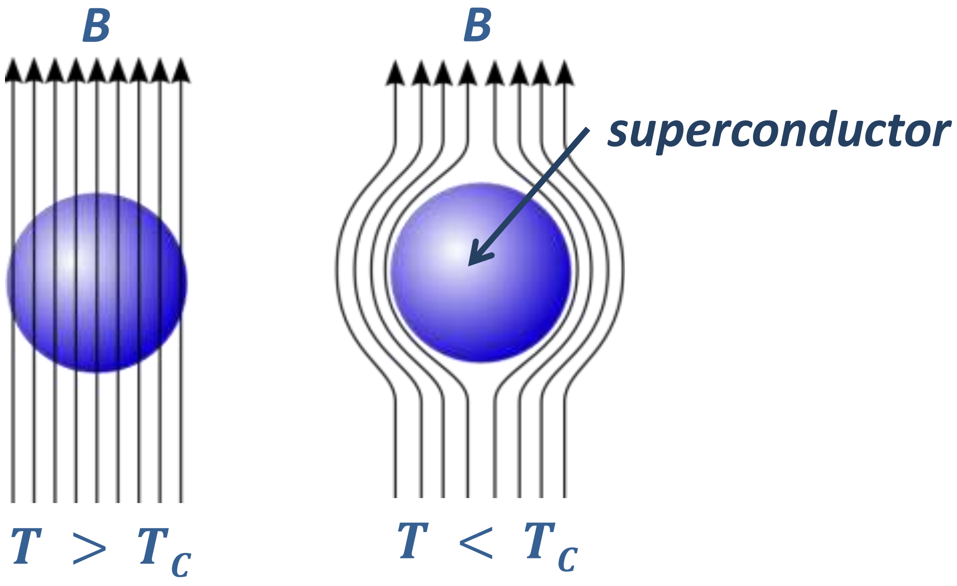
perfect diamagnetism

Walther Meißner
(1882 – 1974)

W. Meißner, R. Ochsenfeld,
Ein neuer Effekt bei Eintritt der Supraleitfähigkeit,
Naturwissenschaften 21, 787 (1933).

Discovery of the Meißner-Ochsenfeld Effect (1933)

Walther Meißner (1882 – 1974)



superconductors perfectly expel magnetic field

$$B_{\text{in}} = (1+\chi)\ B_{\text{ex}} = 0$$

(χ = magnetic susceptibility

➡ **ideal diamagnetism, $\chi = -1$**

choice of name for perfect diamagnetism:

Meißner-Ochsenfeld Effect

Walther Meißner (1882 – 1974)

1913 – 1934 building and heading of low temperature laboratory at the Physikalisch-Technischen-Reichsanstalt, liquefaction of H_2 (20K)

7.3.1925 first liquefaction of He in Germany (4.2 K, 200 ml), 3rd system world-wide besides Leiden and Toronto

1933 discovery of perfect diamagnetism of superconductors together with Ochsenfeld
➔ ***Meißner-Ochsenfeld Effect***

1934 offer of chair at the Technische Hochschule München (now TUM)

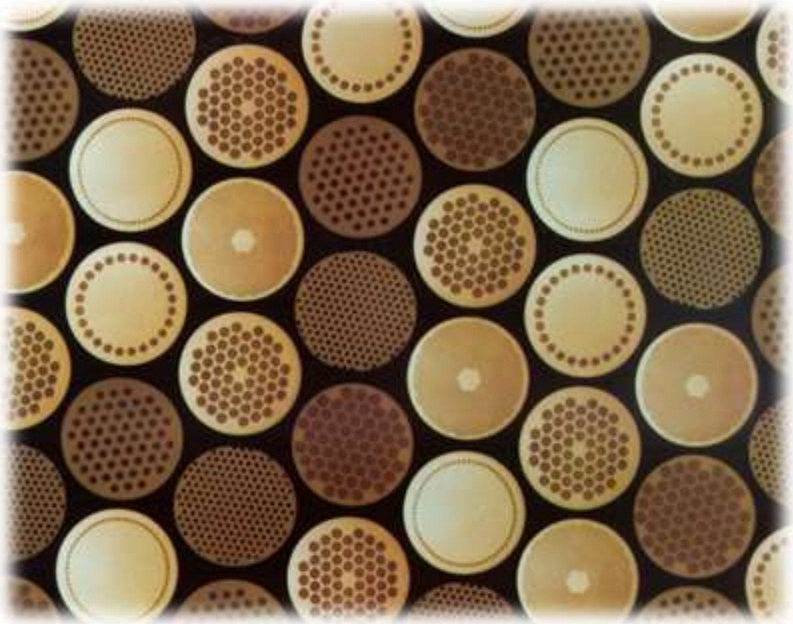
1946 – 1950 president of the Bayerischen Akademie der Wissenschaften

1946 foundation of the commission for Low Temperature Research
→ ***Walther-Meißner-Institut***

Walther Meißner
* 16. Dezember 1882 in Berlin
† 15. November 1974 in Munich

Applications
Of
Superconductivity

Superconducting Wires, Tapes, and Cables



Superconducting Wires:
NbTi, Nb_3Sn in Cu-matrix

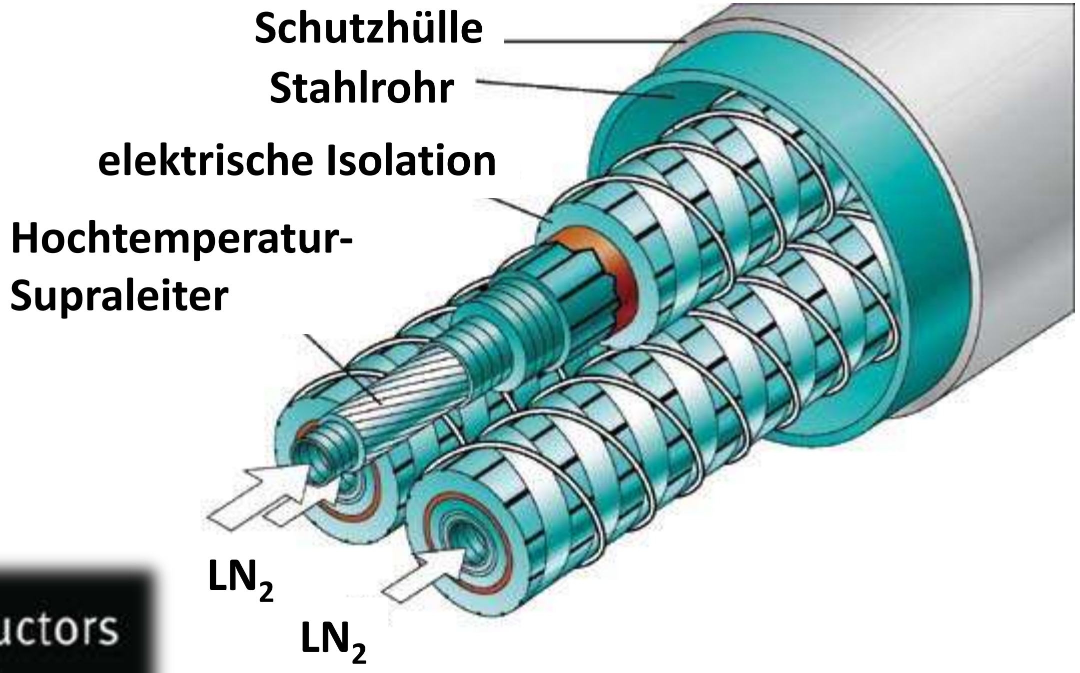
HTS tapes

Superconducting Wires

Bruker EST

Von Hand werden bei Bruker EST in Hanau Stangen aus NbTi und Kupferrohre gebündelt. Daraus entstehen dünne supraleitende Drähte, die zahlreiche NbTi-Filamente in einer Kupfermatrix enthalten (links).

Superconducting HTS cables



Fabrication of superconducting tapes

SuperLink

World's longest superconductor cable "SuperLink

Start clear for Munich's super superconductor

Source: Energy & Management Powernews, October 26, 2020

The German Federal Ministry of Economics (BMWi) has given its OK for the realization of the world's longest superconductor cable in Munich, the "SuperLink".

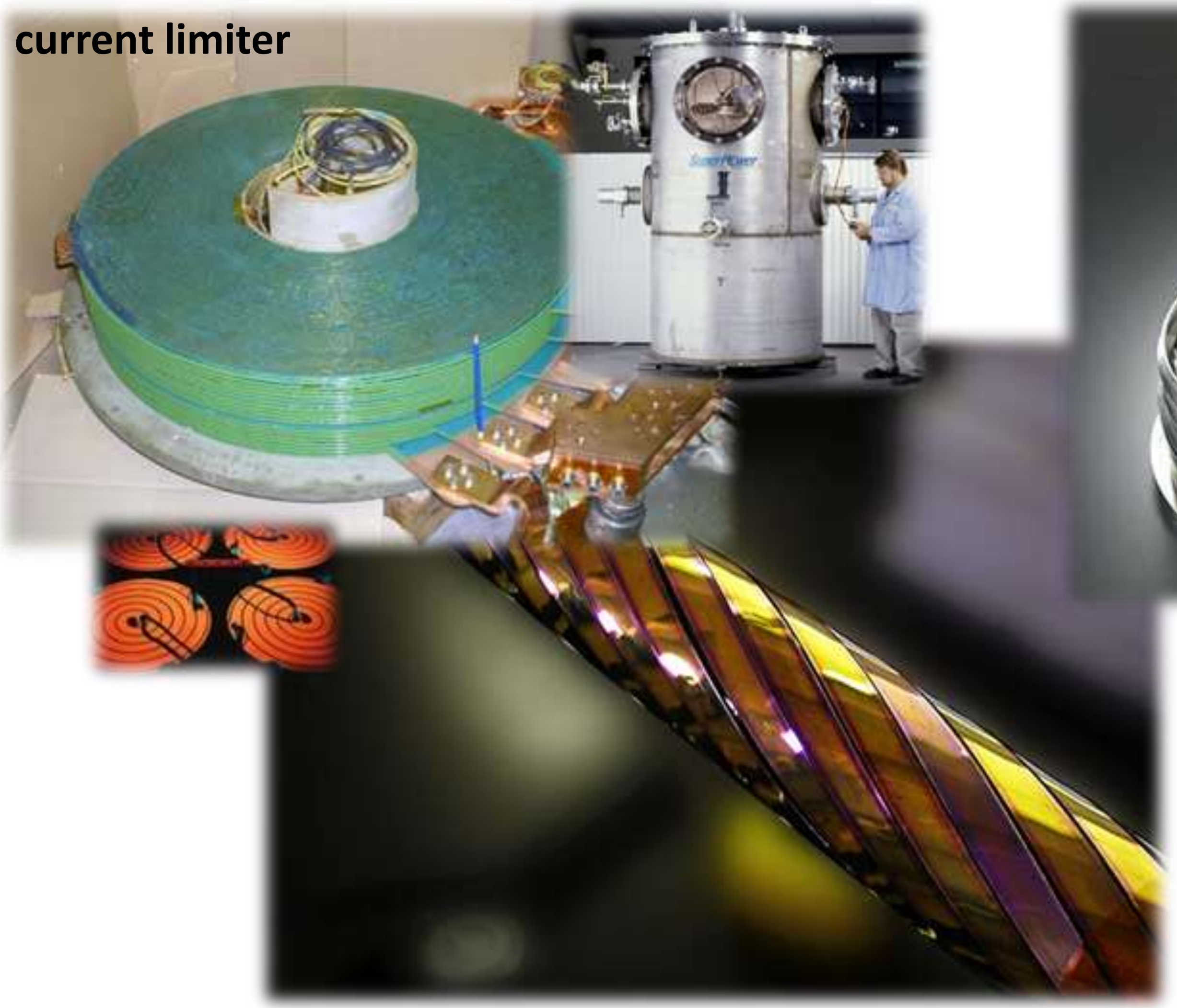
The network subsidiary of Stadtwerke München SWM Infrastruktur (SWMI) wants to realize the world's longest superconductor cable in Munich with a length of twelve kilometers. For the design, development and testing of the necessary components, SWMI and five partners have applied to the BMWi for a funding project, which has now been approved.

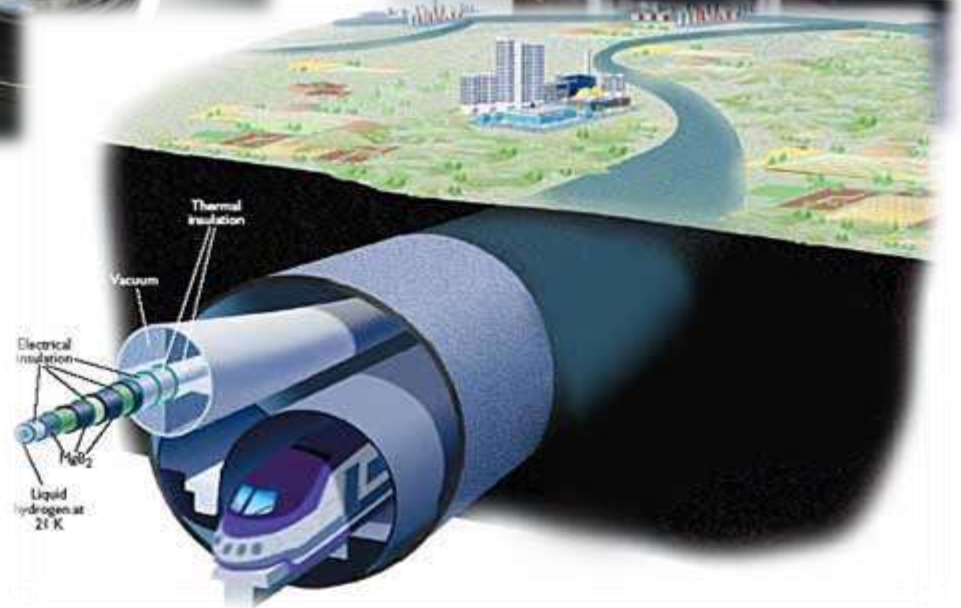
Within two years, SWMI, the industrial gases group Linde, the superconductor manufacturer Theva, the cable manufacturer NKT, the South Westphalia University of Applied Sciences and the Karlsruhe Institute of Technology want to develop all the components for Superlink and test them in the Menzing substation in SWMI's network for six months under real operating conditions.

On successful completion of the development project, the twelve-kilometer high-voltage line between the main Menzing substation and the South Energy Site in Sendling will be built as a "high-temperature superconductor" (HTS). The special feature of this technology is the extreme compactness of the line compared with conventional underground cables and overhead lines. As a result, civil engineering costs and the associated disruption to the surrounding environment can be significantly reduced. Superconductors are capable of carrying electric current with virtually no resistance. However, they require very low temperatures to function. The planned Munich Superlink will use a ceramic high-temperature superconductor (HTS) cooled to temperatures around minus 200 degrees using liquid nitrogen. The line is to operate at a voltage of 110 kV.

Applications of superconductivity

- ***power applications*** ***(transport and storage of energy***





Fault Current Limiters

Fault Current Limiter in the power station Boxberg of Vattenfall

Nexans Superconductors GmbH

(Source: Physik Journal 6, 2011)

Generators

Zenergy Power GmbH

(Source: Physik Journal 6, 2011)

superconducting rotor to be used in hydroelectric power station

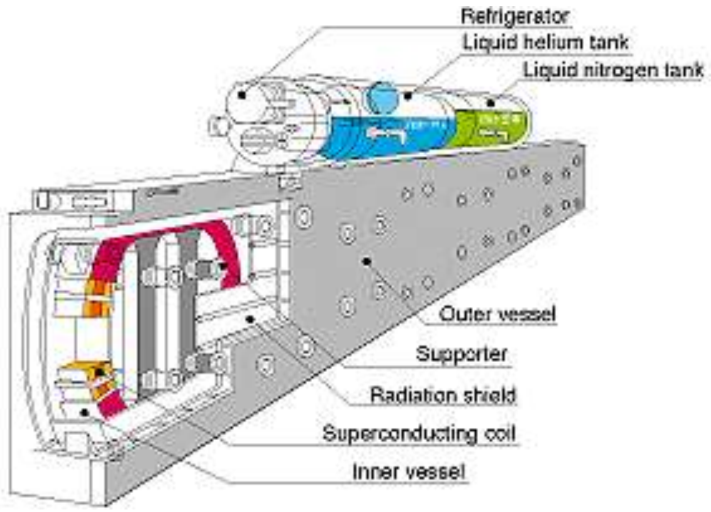
Superconducting Magnets

(Source: Physik Journal 6, 2011)

Applications of superconductivity

- *transportation systems and traffic*

Jap. Yamanashi MAGLEV-System

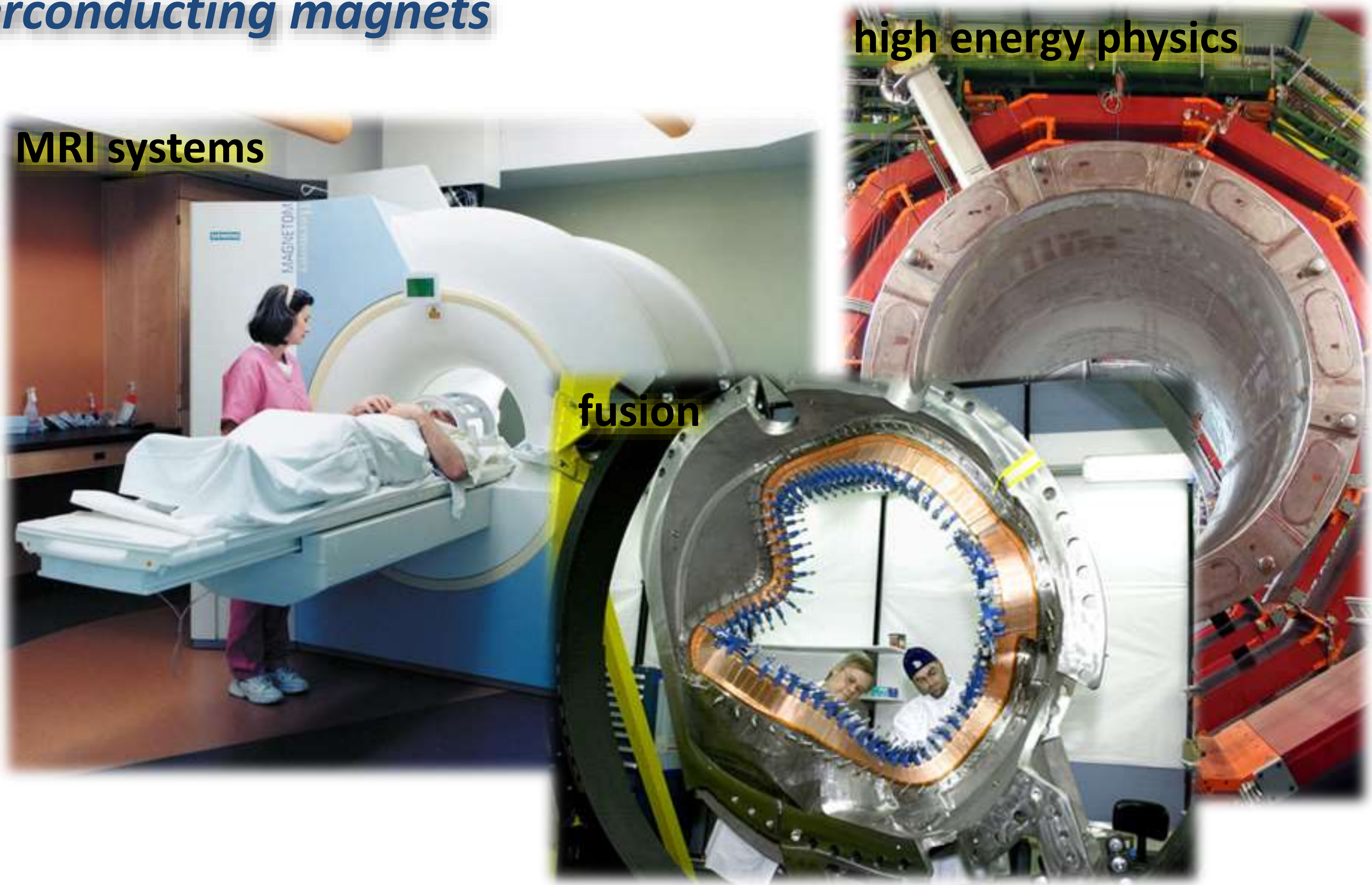


maximum velocity:
581 km/h (02. 12. 2003)

(42.8 km long test track between Sakaigawa and Akiyama, Japan)

Applications of superconductivity

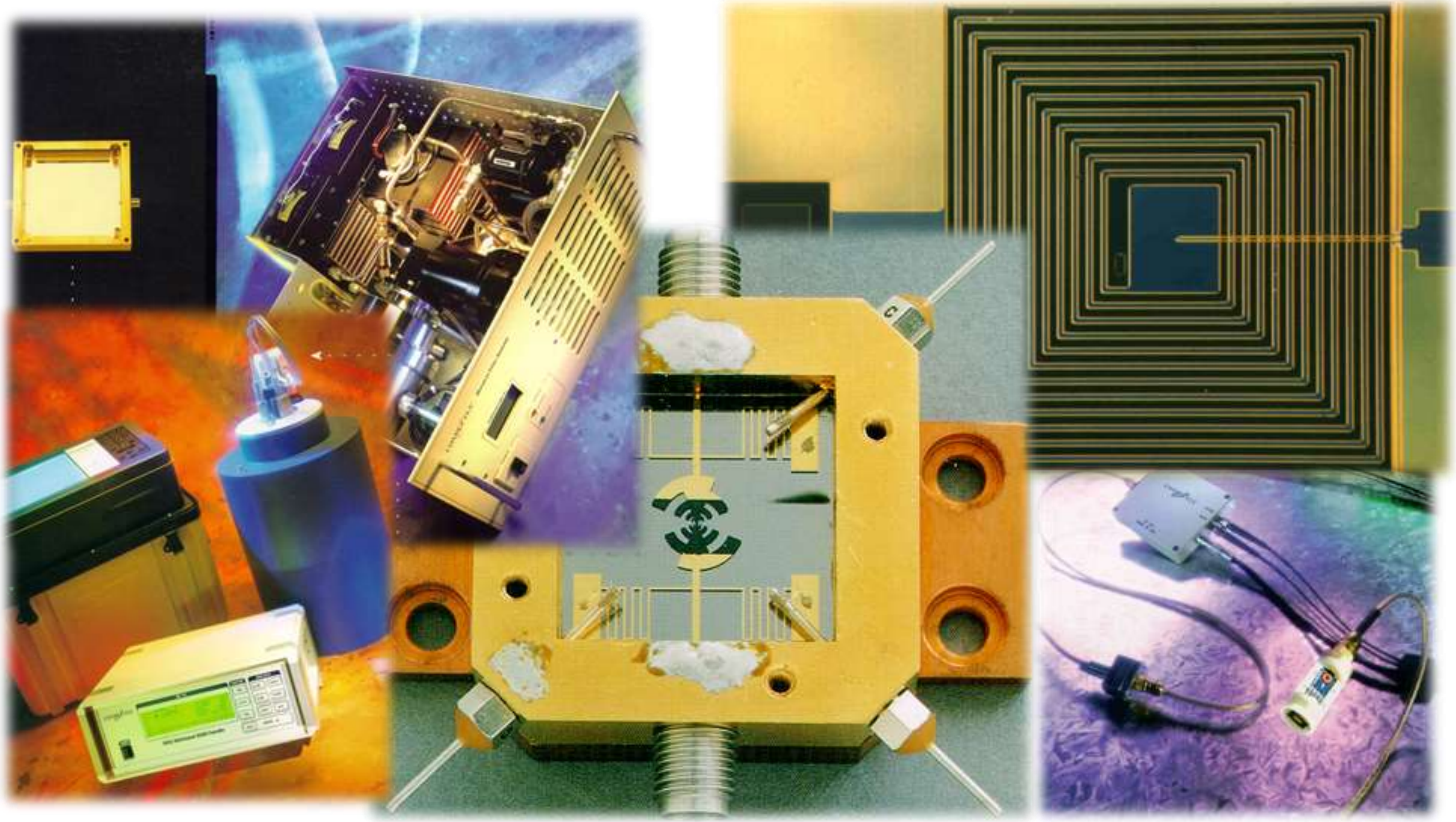
- *superconducting magnets*



MRI Systems

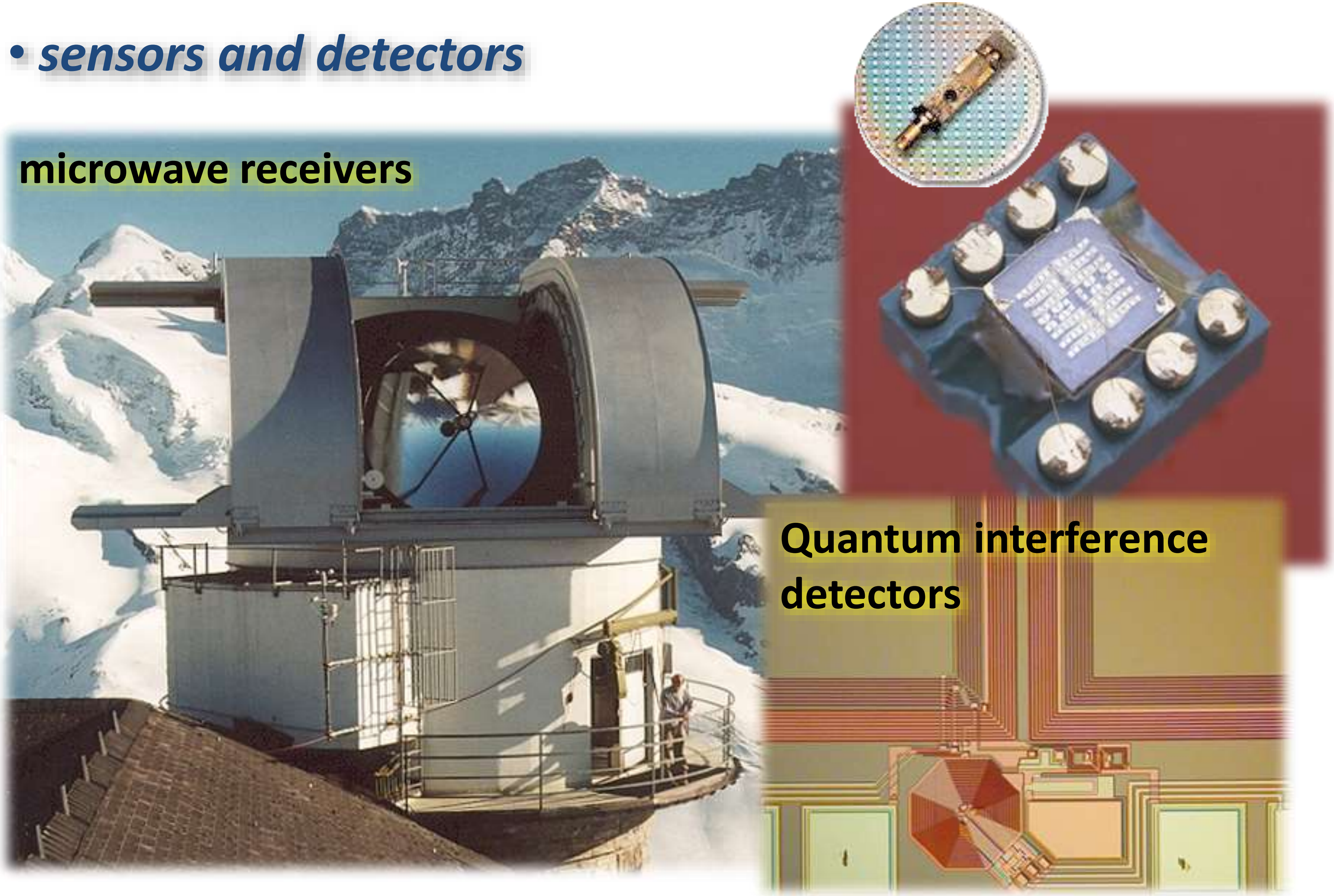
Applications of superconductivity

- ***information and communication systems***



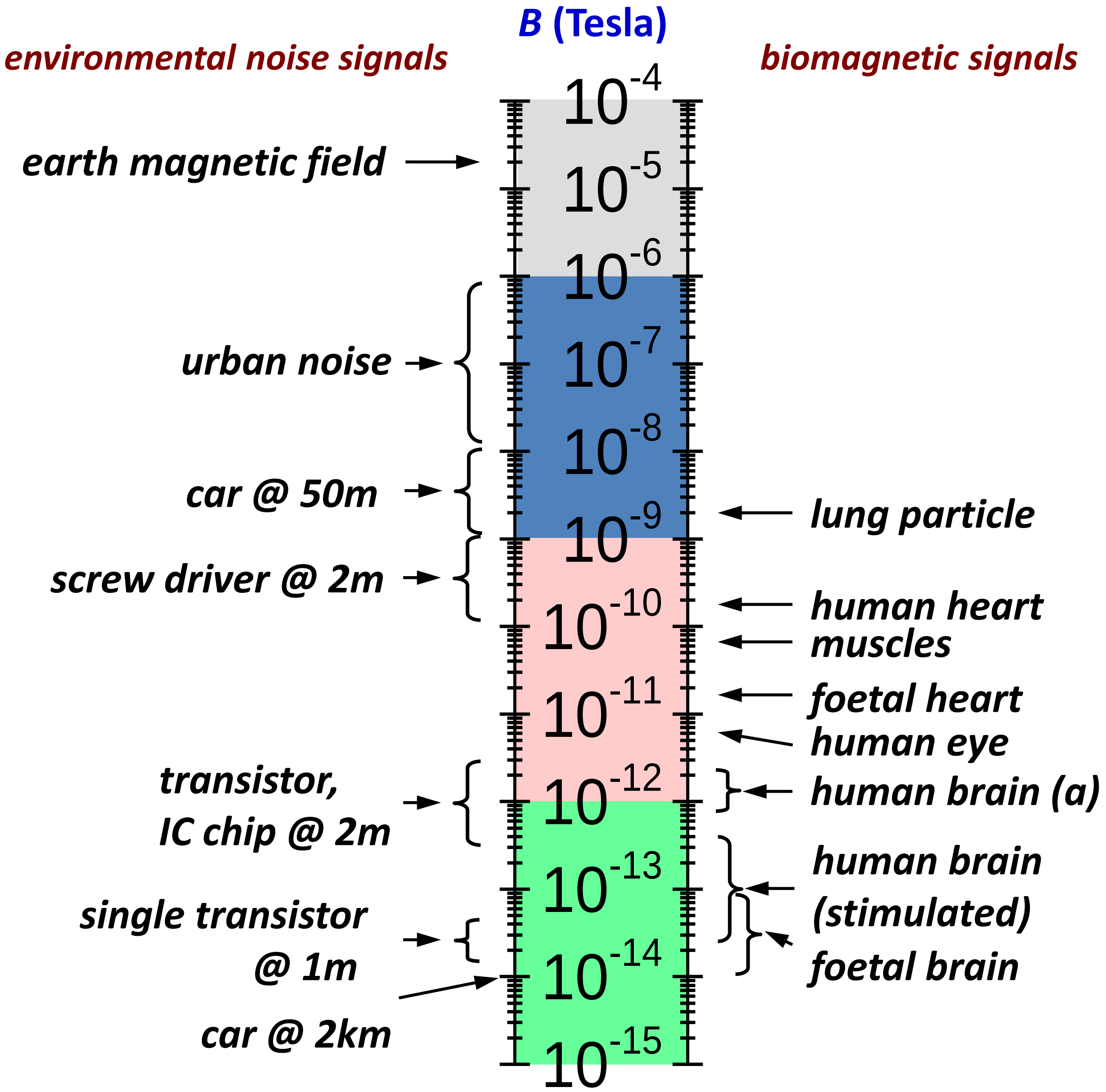
Applications of superconductivity

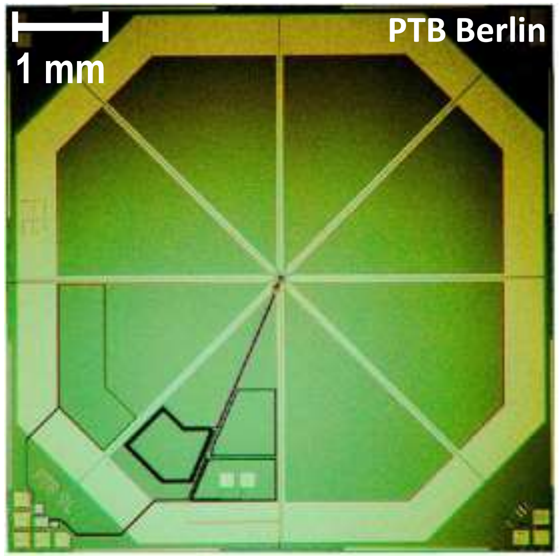
- *sensors and detectors*



Radio Astronomy

Biomagnetism



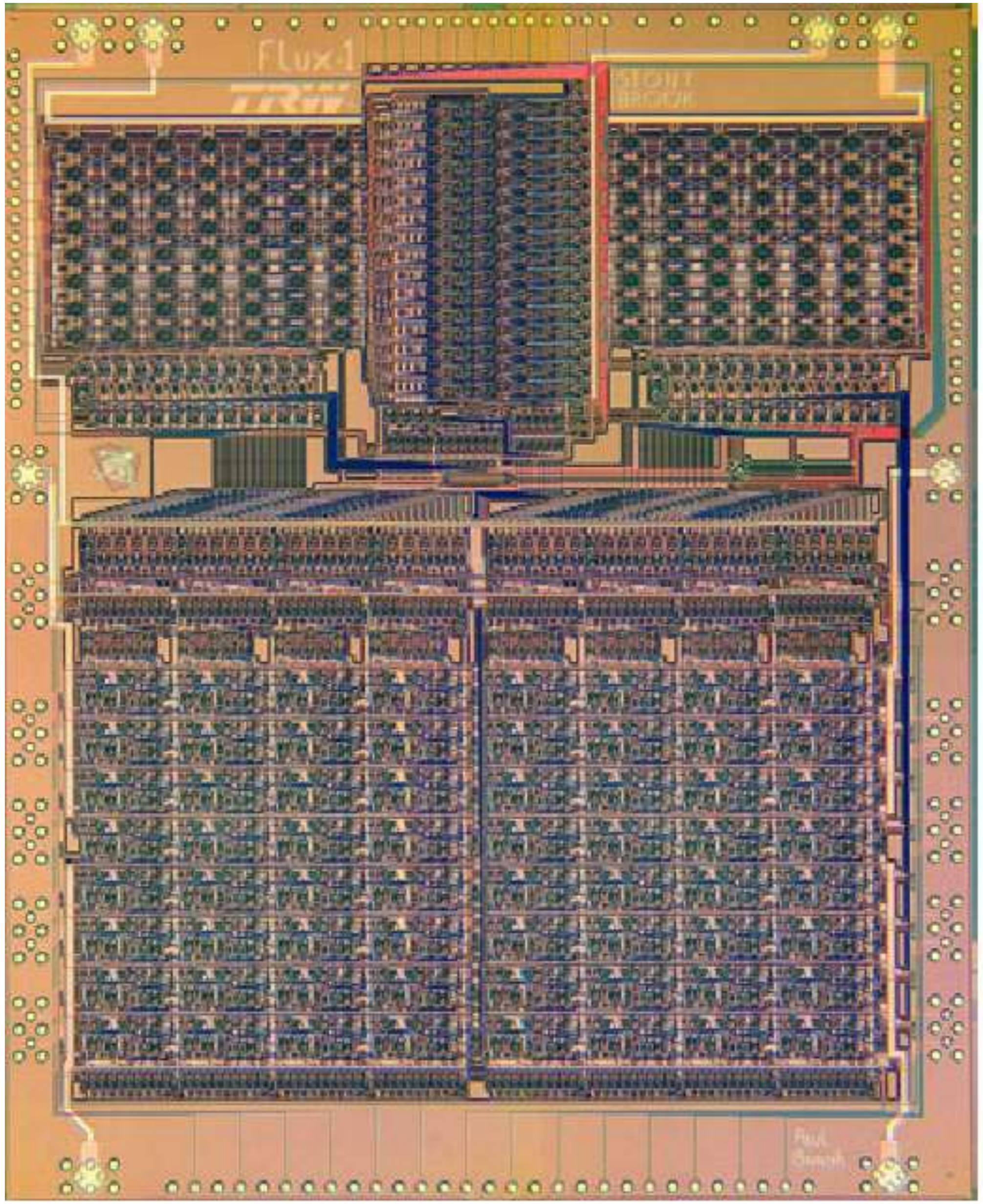


Superconducting Quantum Interference Detector (SQUID)

sensitivity:
a few fT/√Hz

Biomagnetism

Josephson Computer



FLUX-1

- the first RSFQ MPU
- 8 bit ALU array
- 16 word instruction memory
- 70,000 JJs
- 14 mW
- 20-22 GHz @ *F* = 2.0 um

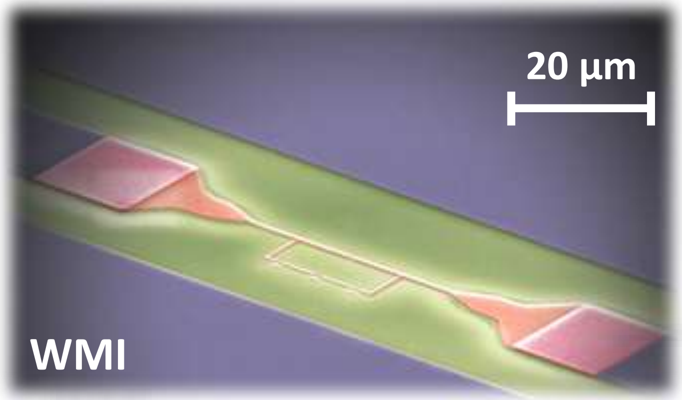
  (⇒ 120-140 GHz @ 0.3 um)
- TRW's 4-metal process

K. K. Likharev, SUNY Stony Brook

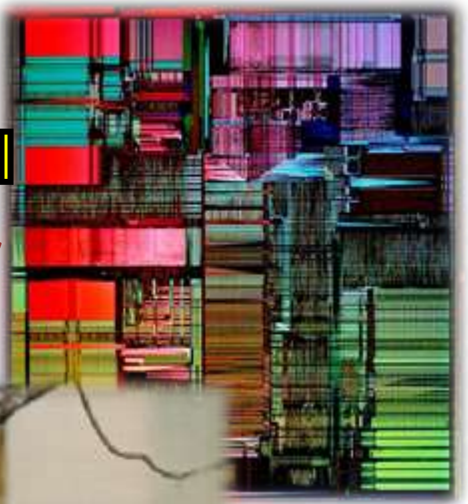
From mechanical to quantum mechanical IP

Enigma (1940)

superconducting Qubit



Intel dual-core 45 nm (2007)



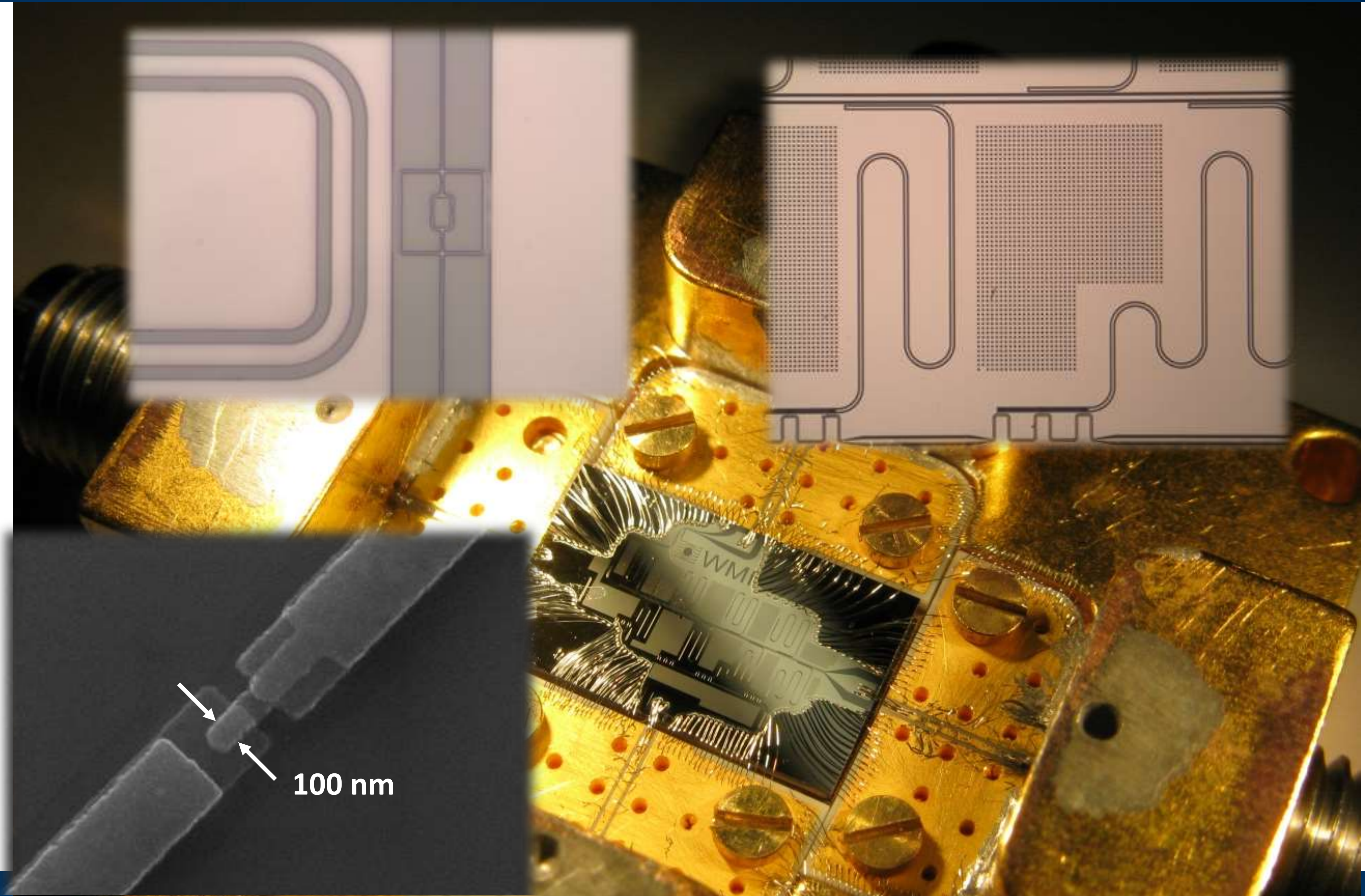
physics

technology

vacuum tubes
ENIAC (1946)

first transistor (1947)
Bardeen, Brattain, & Shockley

Superconducting Quantum Circuits



Quantum Information Processing

Collaborative Research Center 631 (2003-2015)
Solid-State Quantum Information Processing
spokesperson: R. Gross

Cluster of Excellence
Nanosystems Initiative Munich (2006-2019)
coordinator of RA on Quantum Nanophysics: R. Gross

Cluster of Excellence
Munich Center for Quantum Science & Technology (since 2019)
spokerspersons: I. Bloch, I. Cirac, R. Gross

Munich Quantum Valley (since 2021)