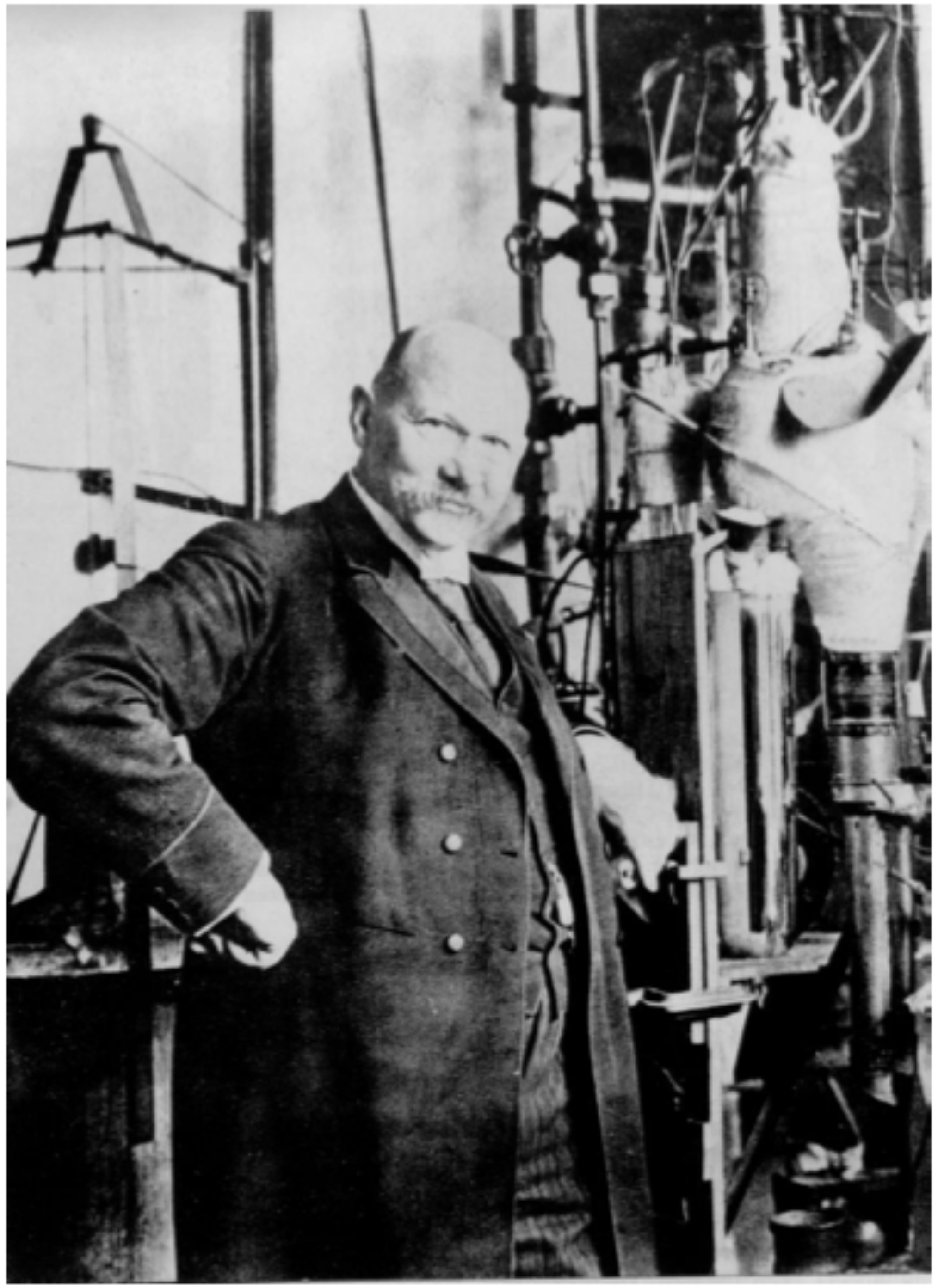
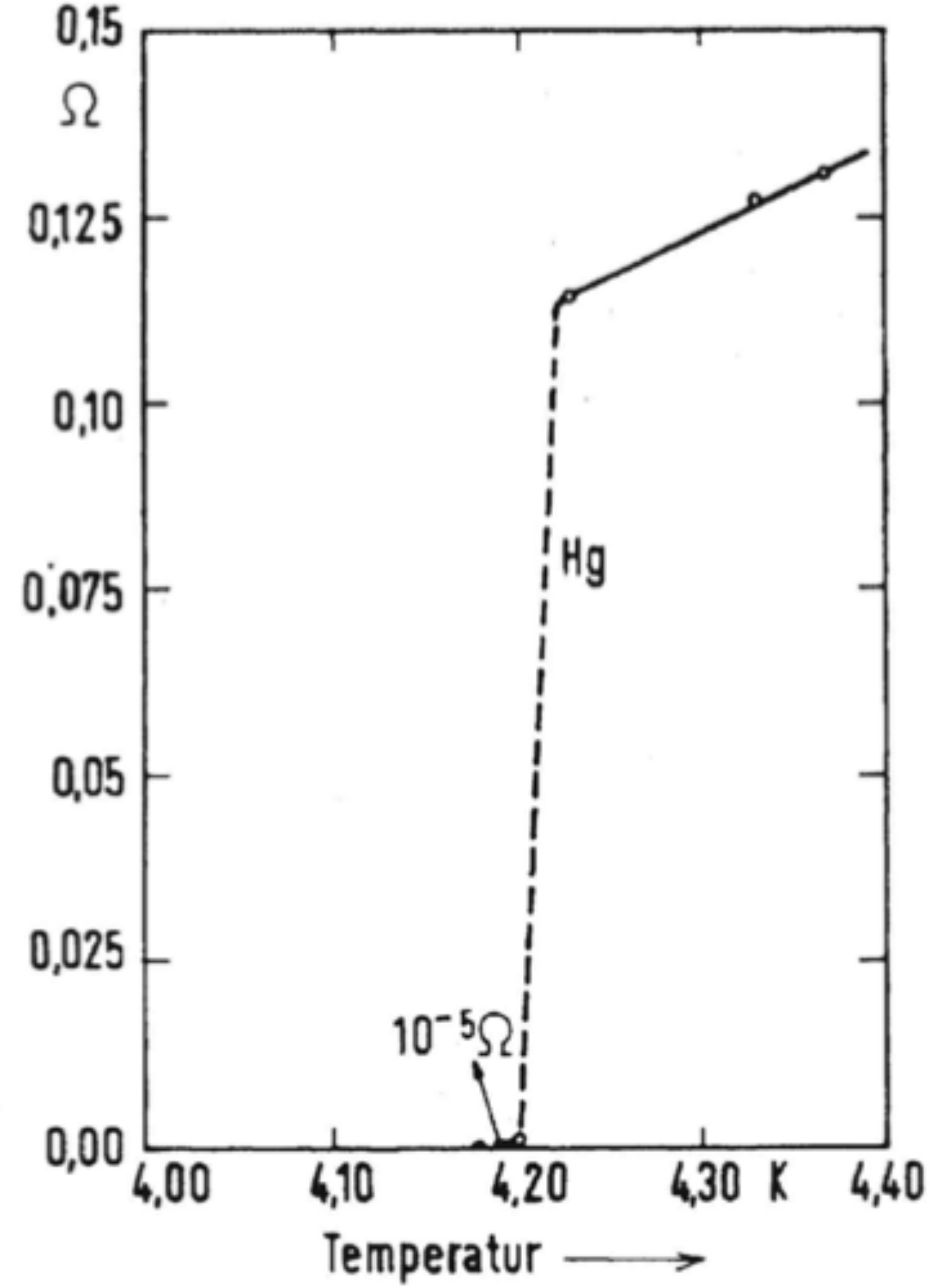
History of Superconductivity (SC)

1908	Liquid He (H.K. Onnes, Leiden)	
1911	Observation of Superconductivity (H. K. Onnes, Leiden) $\rho = 0$	Nobel prize 1913
1933	Meissner-Ochsenfeld effect $B = 0$	
1935	London Theory (phenomenological) – linear electrodynamics of SC	
1950	Ginzburg-Landau theory (phenomenological) – from the theory of phase transitions, order-parameter (V. Ginzburg)	Nobel prize 2003
1953	Type-II superconductor, vortices (A. Abrikosov)	Nobel prize 2003
1957	microscopic BCS theory (Bardeen, Cooper, Schrieffer)	Nobel prize 1972
1957	exp. determination of the energy gap from IR-absorption (Glover, Tinkham)	
1960/61	exp. determination of the energy gap from tunneling experiment (I. Giaever)	Nobel prize 1973
1960	Flux quantization (Doll, Näbauer; Deaver, Fairbank)	
1962	Josephson effect – theory (B.D. Josephson)	Nobel prize 1973
1963	exp. discovery of dc Josephson effect (Anderson, Rowell)	
up to 1986	highest T_c=23K in Nb_3Ge Main development direction — applications: Energy transfer, SC electronics	
1986	Discovery of high-T_c superconductor (HTS) LaBaCuO (J.G. Bednorz, K.A. Müller) Record $T_c = 133\,K$ in $HgBa_2Ca_2Cu_3O_8$	Nobel prize 1987
2004	Superconductivity is large and modern research field	

Superconductivity was discovered by Kamerlingh-Onnes in 1911 in mercury (Hg), having $T_c \approx 4$ K

".. Mercury has passed into a new state, which on account of its extraordinary electrical properties may be called the superconductive state"





Dependence of the resistance on temperature

	T_c [K]	Discovery
Hg	4.15	1911
Pb	7.20	
Nb	9.20	
Nb_3Sn	18.3	1952
Nb_3Ge	23	1972
MgB_2	40	2001

Table 1.1: "LTS" (low-T_c superconductors), "conventional superconductors"

Can be amorphous or polycrystalline.

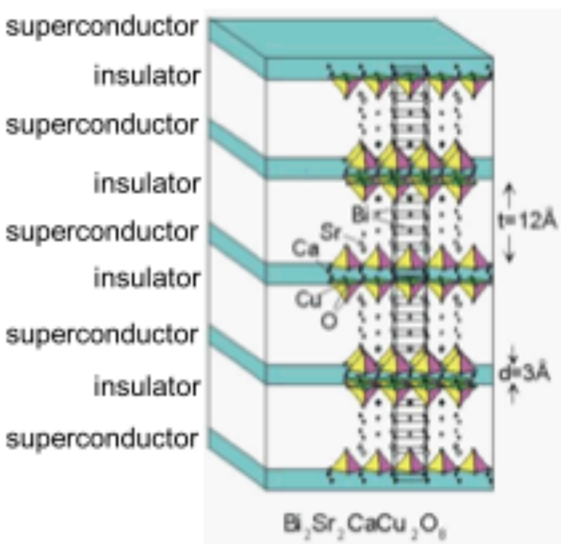
1.2.2 Doped copper oxides

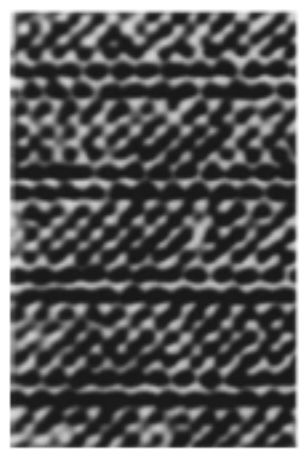
	T_c [K]	Discovery
$La_{2-x}Sr_xCuO_{4-y}$	30	1987
$YBa_2Cu_3O_7$	90	1988
$Bi_2Sr_2CaCu_2O_8$	90	1988
$Tl_2Ba_2CaCu_2O_8$	90	1988
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	1988
$HgBa_2CaCu_3O_8$	*135	1993

* at $p = 1$ bar, under pressure up to 160 K

Table 1.2: high-T_c superconductors (HTS), more correct: cuprate superconductors

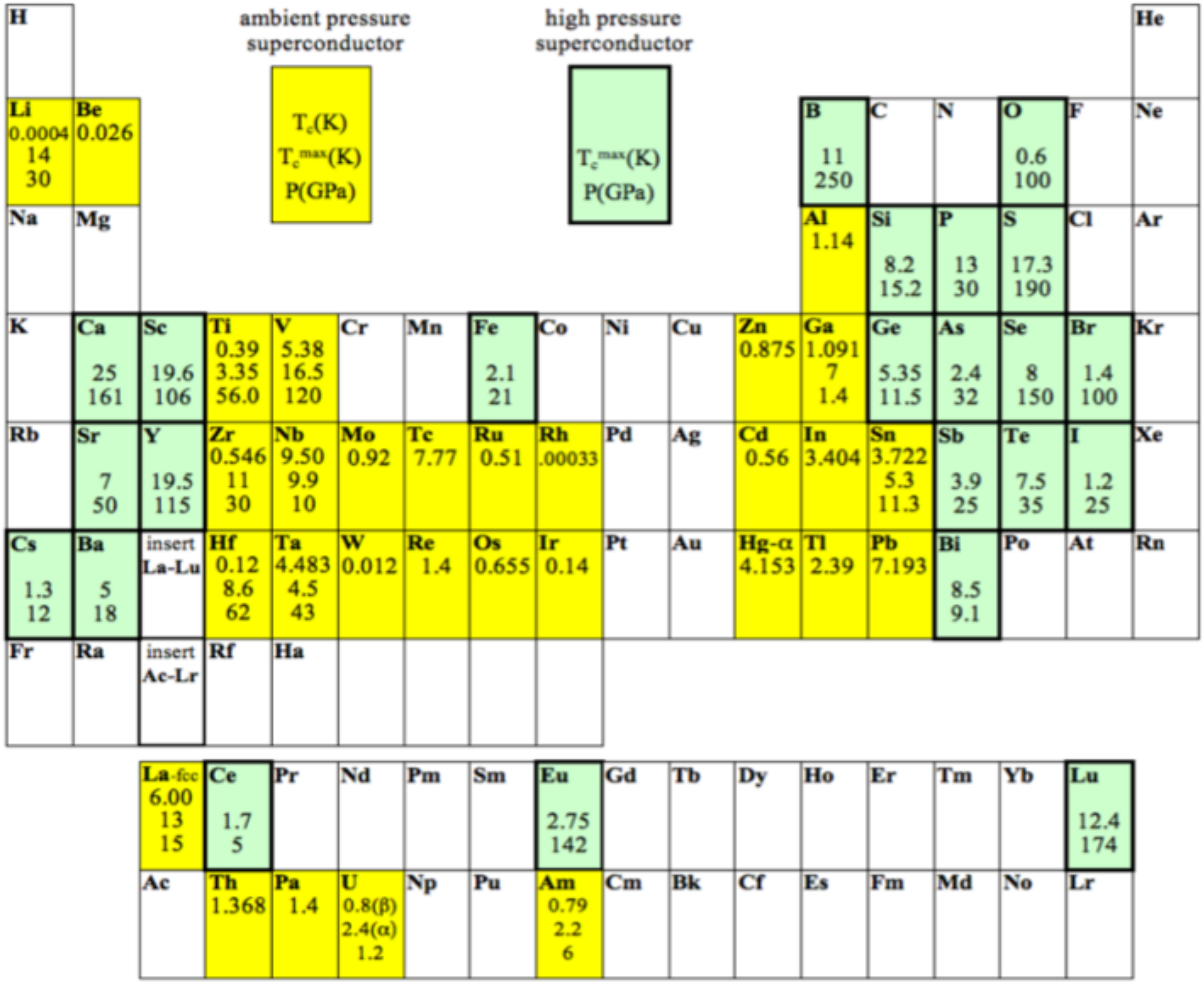
For HTS the crystal structure and defects are very important.





TEM, Jülich, ISI

30 elements superconduct at ambient pressure, 23 more superconduct at high pressure.



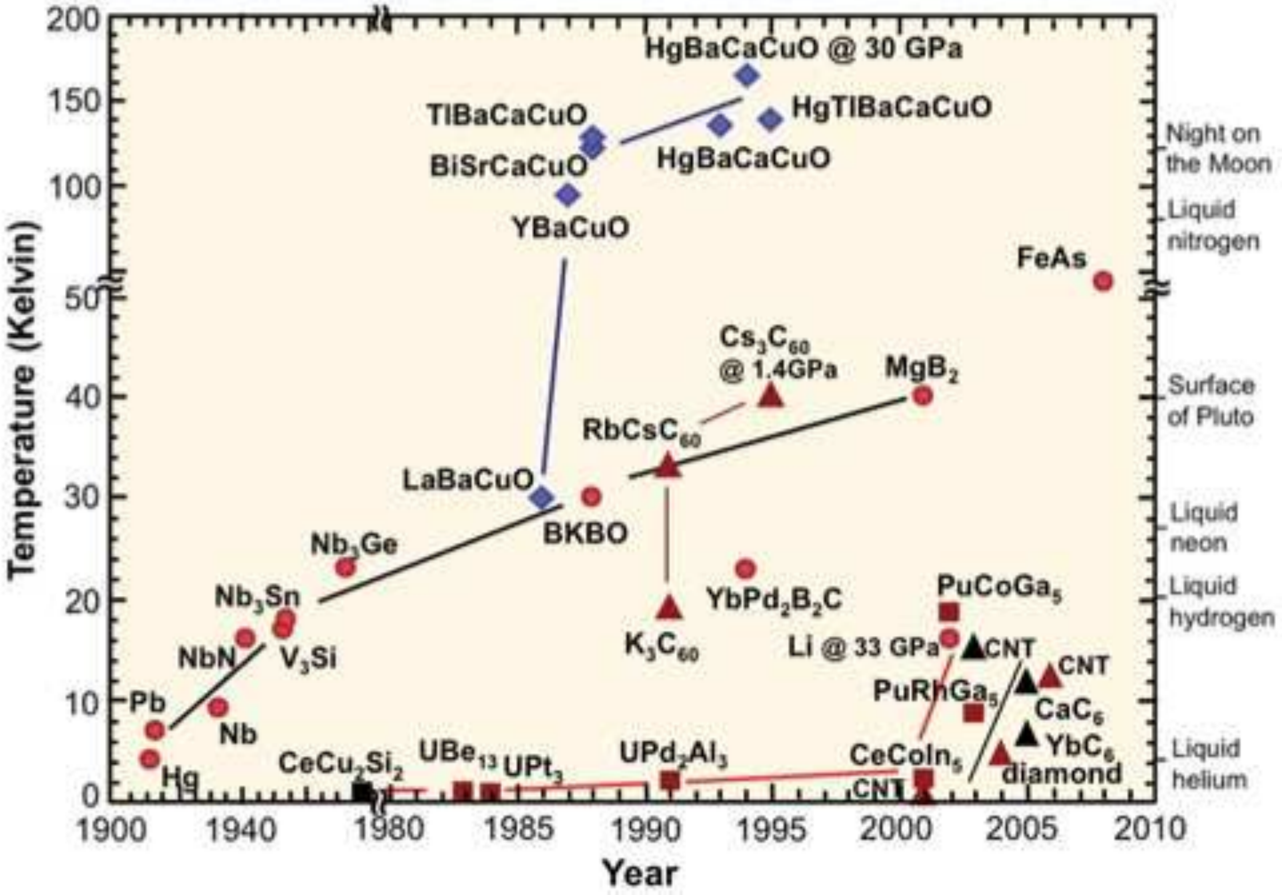
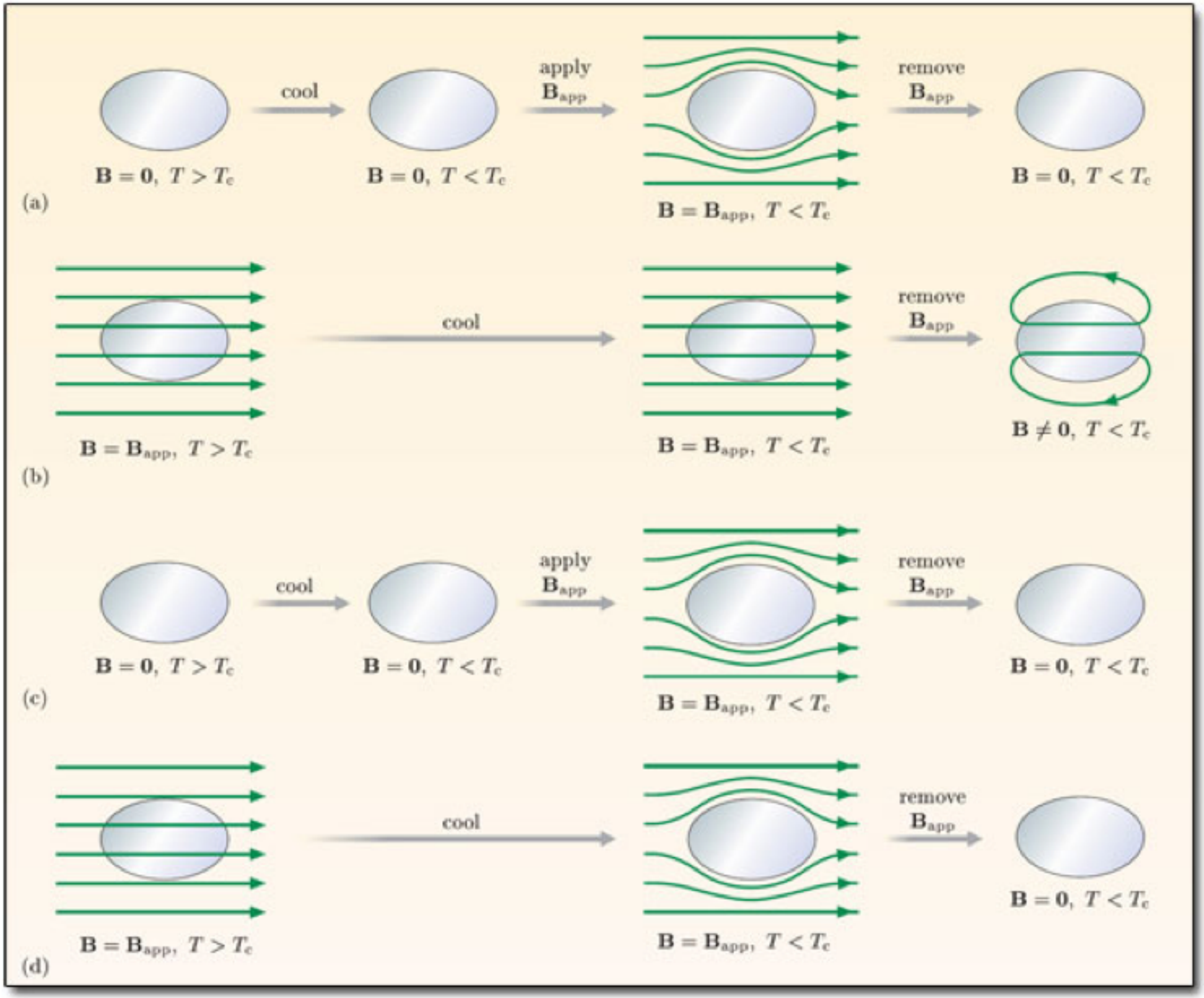


Figure 1.1: Timeline of superconductors and their transition temperatures (from Wikipedia).



cool
apply
$\mathbf{B}_{app}$
remove
$\mathbf{B}_{app}$
$\mathbf{B} = \mathbf{0},\ T > T_c$
$\mathbf{B} = \mathbf{0},\ T < T_c$
$\mathbf{B} = \mathbf{B}_{app},\ T < T_c$
$\mathbf{B} = \mathbf{0},\ T < T_c$
(a)
cool
remove
$\mathbf{B}_{app}$
$\mathbf{B} = \mathbf{B}_{app},\ T > T_c$
$\mathbf{B} = \mathbf{B}_{app},\ T < T_c$
$\mathbf{B} \neq \mathbf{0},\ T < T_c$
(b)
cool
apply
$\mathbf{B}_{app}$
remove
$\mathbf{B}_{app}$
$\mathbf{B} = \mathbf{0},\ T > T_c$
$\mathbf{B} = \mathbf{0},\ T < T_c$
$\mathbf{B} = \mathbf{B}_{app},\ T < T_c$
$\mathbf{B} = \mathbf{0},\ T < T_c$
(c)
cool
remove
$\mathbf{B}_{app}$
$\mathbf{B} = \mathbf{B}_{app},\ T > T_c$
$\mathbf{B} = \mathbf{B}_{app},\ T < T_c$
$\mathbf{B} = \mathbf{0},\ T < T_c$
(d)

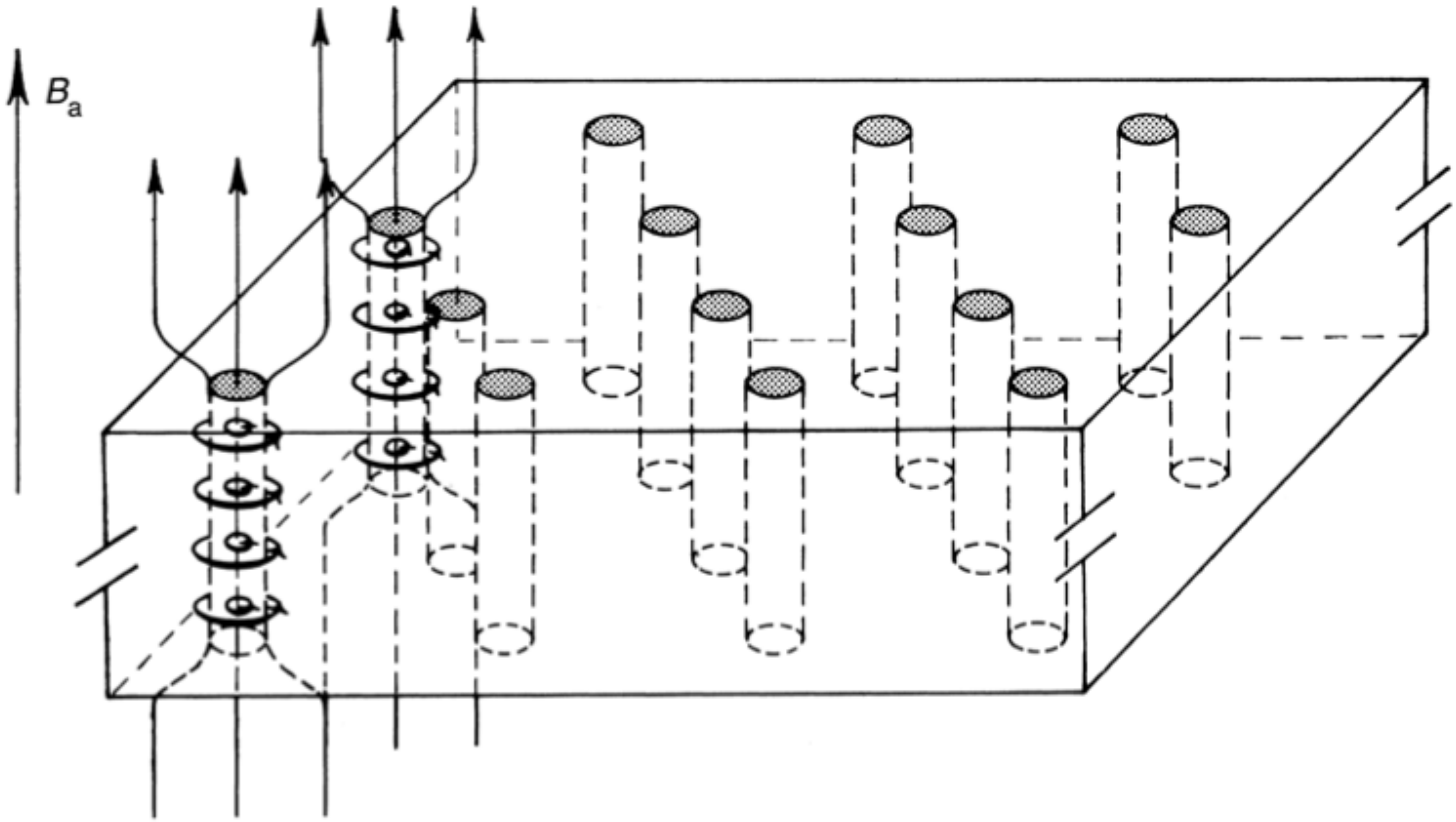


Fig. 1.8 Schematic diagram of the Shubnikov phase. The magnetic field and the supercurrents are shown only for two flux lines.

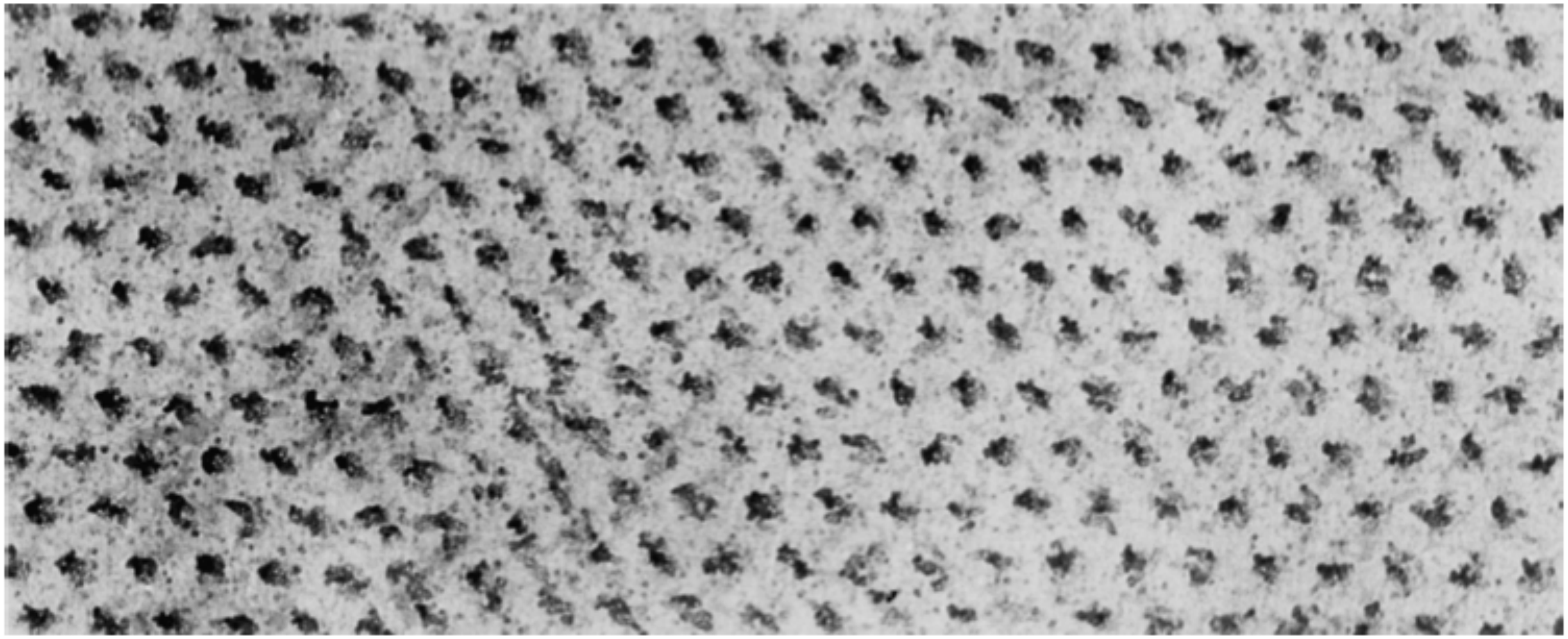


Fig. 1.9 Image of the vortex lattice obtained with an electron microscope following the decoration with iron colloid. Frozen-in flux after the magnetic field has been reduced to zero. Material: Pb + 6.3 at.% In; temperature: 1.2 K; sample shape: cylinder, 60 mm long, 4 mm diameter; magnetic field $\mathbf{B}_a$ parallel to the axis. Magnification: 8300×. (Reproduced by courtesy of Dr. Essmann).

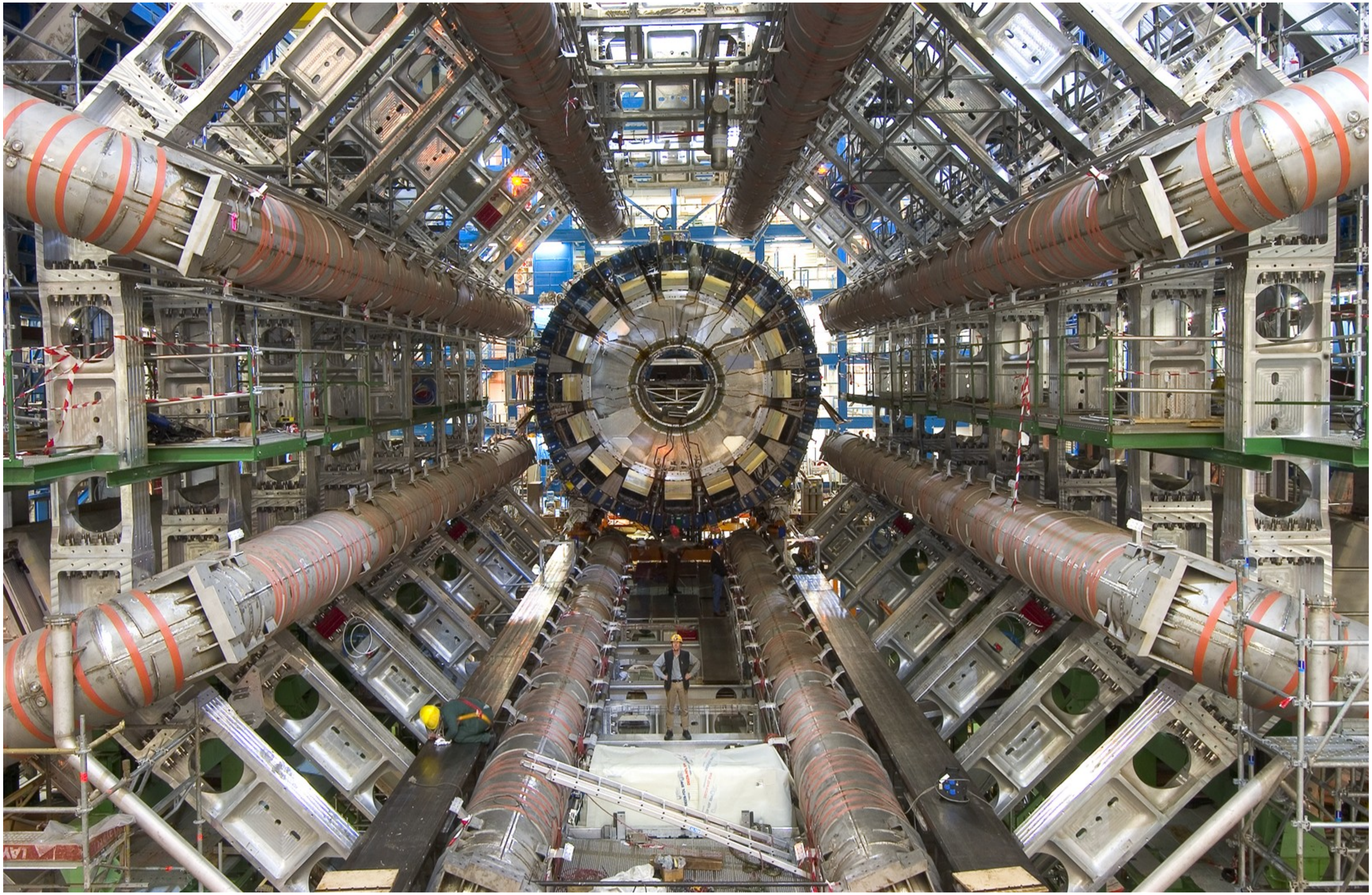


TABLE II SUPERCONDUCTING MATERIALS PROPERTIES IMPORTANT FOR COMMERCIALIZATION

T_c, H_c (margin, factor ~2)
J_c (better, J_e, the engineering current density, including insulation, stabilizer, etc.) (margin, factor ~2)
Insulation (what is the maximum voltage at quench, fault, resonance?)
ac loss
Ease of manufacturing; yield
Stability/stabilizers (different for HTS vs LTS); protection against quench
Cost (NbTi ~ $1/kA-m)
Asperities, sharp edges
Wire camber/straightness
Mechanical handling/strength (cycling, bending, tensioning)
Ability to join (superconducting for persistent applications; otherwise, upper limit of resistance)
Long-term life
Quality (uniformity; standard deviations)
Availability in needed forms (e.g.: length; multifilaments: transposed, twisted; cross-section)
Compatibility with the other materials/processes of the system
EHS (salvage)