Superconductors: visualization and applications

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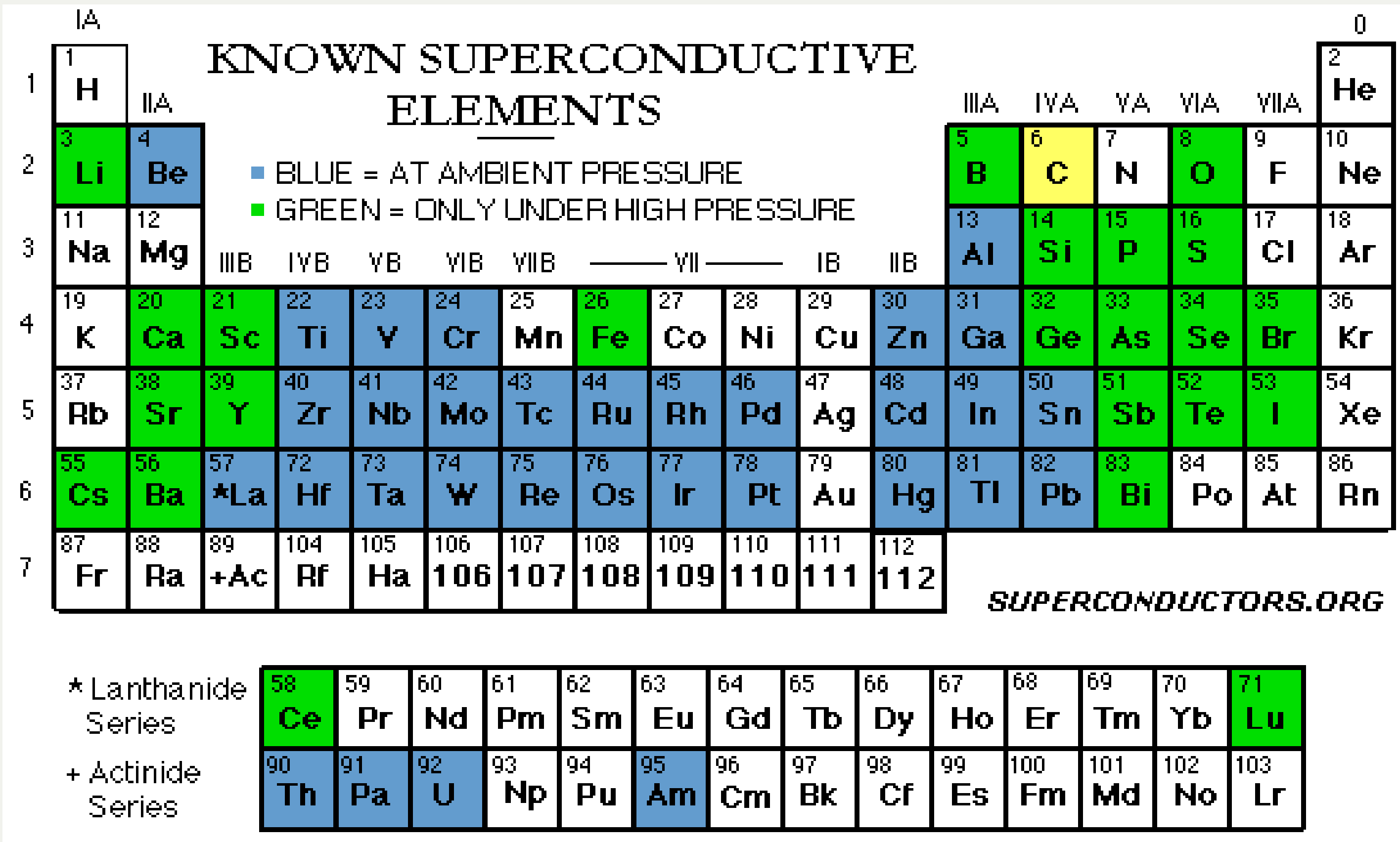
What is a Superconductor?

- A superconductor is a very pure metal, an alloy or a compound that allows electricity to be transmitted with minimal losses.
- A higher current flow may occur with lower energy losses than common conductors.
- Many elements can be coaxed into a superconductive state with the application of high pressure.

Superconductive elements



Type 1 Superconductors

- are very pure metals characterized as the “soft“ superconductors
- were discovered first and require the coldest temperatures to become superconductive
- they exhibit a very sharp transition to a superconducting state and
- "perfect" diamagnetism - the ability to repel a magnetic field completely
- have too low critical magnetic field Bc and are not attractive to industry
- have different crystal lattices – FCC, BCC, HEX, TET, ORC, RHL
- BCS theory explains the behaviour of these superconductors by means of Cooper pairs

Examples of type 1 superconductors

(Tc – critical temperature; Bc – critical magnetic field)

Material	*Tc [K]*	*Bc [T]*
Ti (metal)	0.40	0.0056
Zn	0.85	0.0054
Al	1.18	0.0105
In	3.41	0.0281
Sn	3.72	0.0281
Hg	4.15	0.0413
Pb	7.19	0.0803

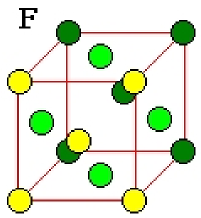
Examples of type 1 superconductors

(FCC – face centered cubic; BCC – base centered cubic)

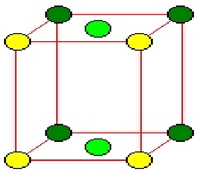
Material	*Tc [K]*	Crystal lattice
Lead (Pb)	7.196	FCC
Thorium (Th)	1.175	FCC
Aluminium (Al)	1.083	FCC
Iridium (Ir)	0.1325	FCC
Rhodium (Rh)	0.000325	FCC
Tantalum (Ta)	4.47	BCC
Molibdenum (Mo)	0.915	BCC
Tungsten (W)	0.0154	BCC

Superconductors of type 1 with different crystal lattice

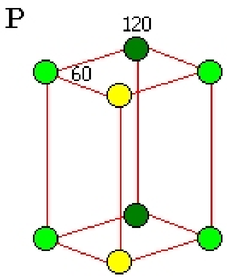
Pb – Tк =7.196 K
Bc = 0.08 T
Lattice FCC



Mo – Tк = 0.915 K
Lattice BCC



Zn – Tк = 0.85
Lattice HEX



Examples of type 1 superconductors

(HEX – hexagonal crystal lattice)

Material	*Tc [K]*	Crystal lattice
Lantanium (La)	4.88	HEX
Thallium (Ta)	2.38	HEX
Rhenium (Re)	1.697	HEX
Zinc (Zn)	0.85	HEX
Osmium (Os)	0.66	HEX
Zirconium (Zr)	0.61	HEX
Americium (Am)	0.60	HEX
Cadmium (Cd)	0.517	HEX
Ruthenium (Ru)	0.49	HEX
Titanium (Ti)	0.40	HEX
Hafnium (Hf)	0.128	HEX
Beryllium (Be)	0.023	HEX

Examples of type 1 superconductors

(TET – tetragonal; ORC – orthorombic; RHL – rhombohedral crystal lattice)

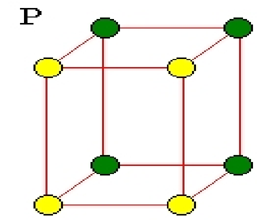
Material	*Tc [K]*	Crystal lattice
Tin (Sn)	3.72	TET
Indium (In)	3.41	TET
Protactinium (Pa)	1.40	TET
Gallium (Ga)	1.083	ORC
Uranium (U)	0.20	ORC
Mercury (Hg)	4.15	RHL

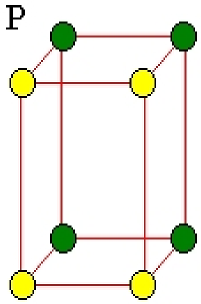
Superconductors of type 1 with different crystal lattice

Sn - Tк = 3.72 K

Bc = 0.0305 T

Lattice TET





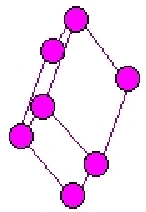
Ga - Tк = 1.083 K

Lattice ORC

Hg - Tк = 4.15 K

Bc = 0.0413

Lattice RHL



Type 2 Superconductors

- Elements (V, Tc, Nb), compounds or alloys, copper perovskites, rare ferromagnetic superconductors, superconducting pyrochlore crystals - known as the "hard"superconductors
- differ from Type 1 in that their transition from a normal to a superconducting state is gradual across a region of "mixed state" behaviour
- have two critical magnetic fields – Bc1 and Bc2. Below Bc1 the superconductor excludes all magnetic field lines. At field strengths between Bc1 and Bc2 the field begins to intrude into the material. When this occurs the material is said to be in the mixed state, with some of the material in the normal state and part still superconducting. At Bc2 the superconductor stops superconducting.
- with high critical temperature, critical current and critical magnetic field
- extremely attractive to industry
- crystal lattice – TET, ORTH
- the behaviour of these superconductors is not explain yet

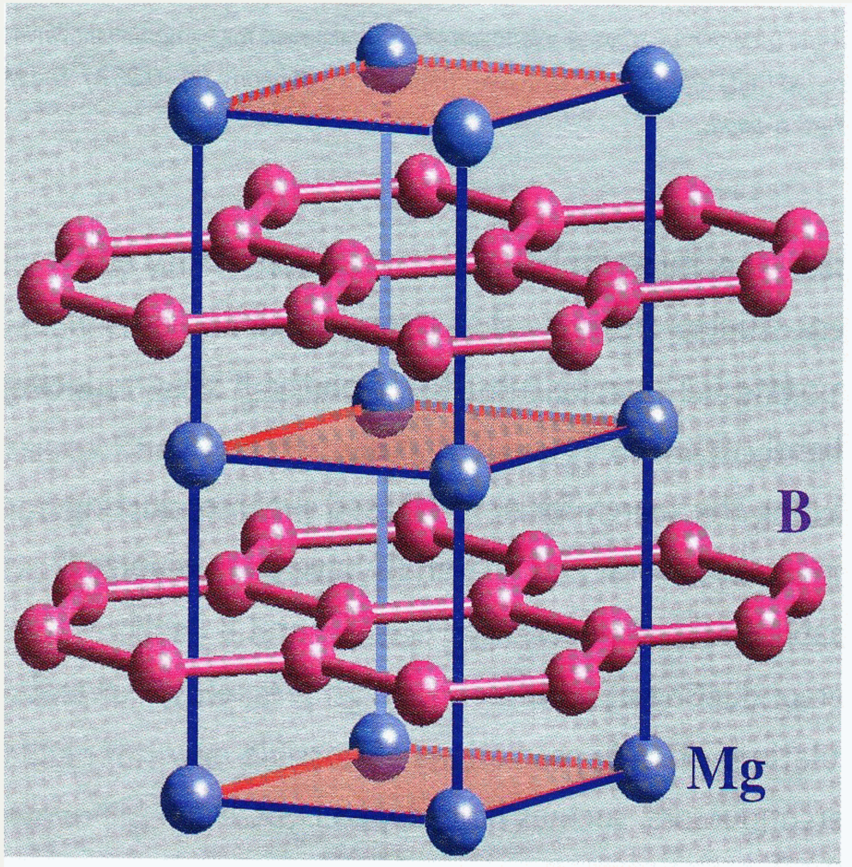
Examples of type 2 superconductors

(Tc – critical temperature; Bc – critical magnetic field)

Material	*Tc [K]*	*Bc [T]*
Nb (metal)	9.5	0.2
Nb – Ti (alloy)	9.8	10.5
NbN (metalloid)	16.8	15.3
Nb3Sn (intermetalic)	18.3	24.5
Nb3Al	18.7	31.0
Nb3Ge	23.2	35.0
MgB2 (compound)	39	15
YBa2Cu3-xOx	93	150
Bi2Sr2Cax-1CuxO2x+4	130	108

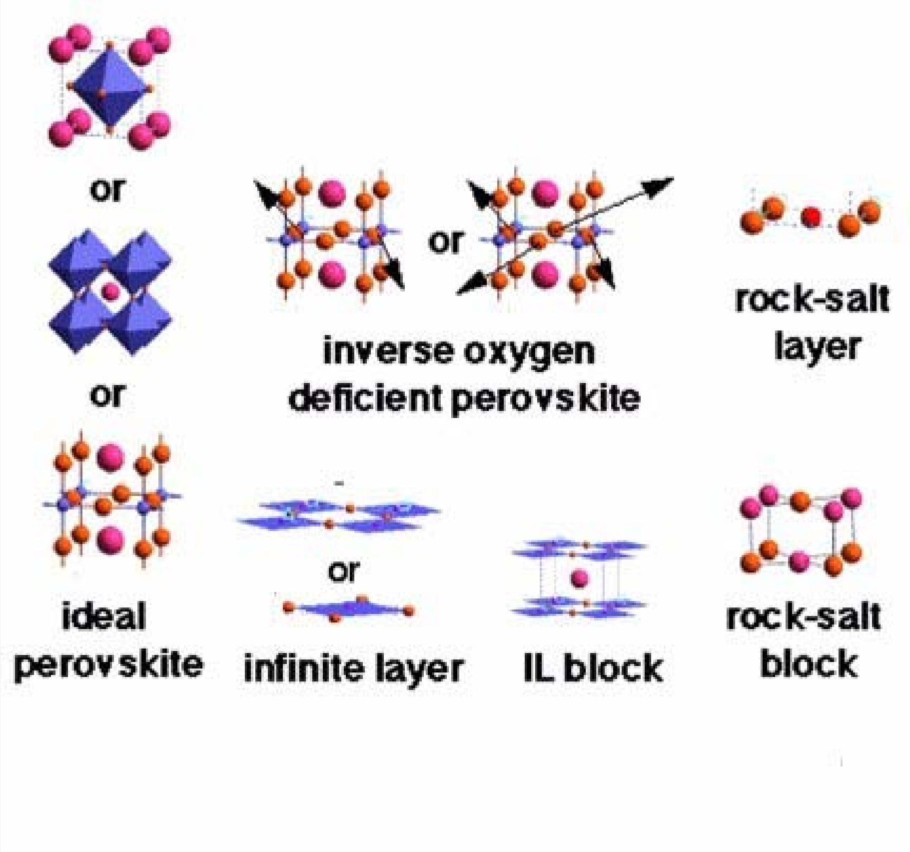
Superconductor MgB2

- MgB2 – Tk = 39 K
  HEX crystal lattice
- Discovered - 2001
  Akimitsu –Nagamatsu
- Upper critical field
  14 -39 T
- Lower critical field
  27 - 48 mT
- Low cost, light-weight and suitable for wires and thin films



Examples of type 2 superconductors

Building blocks used to construct the structures of cuprate superconductors.



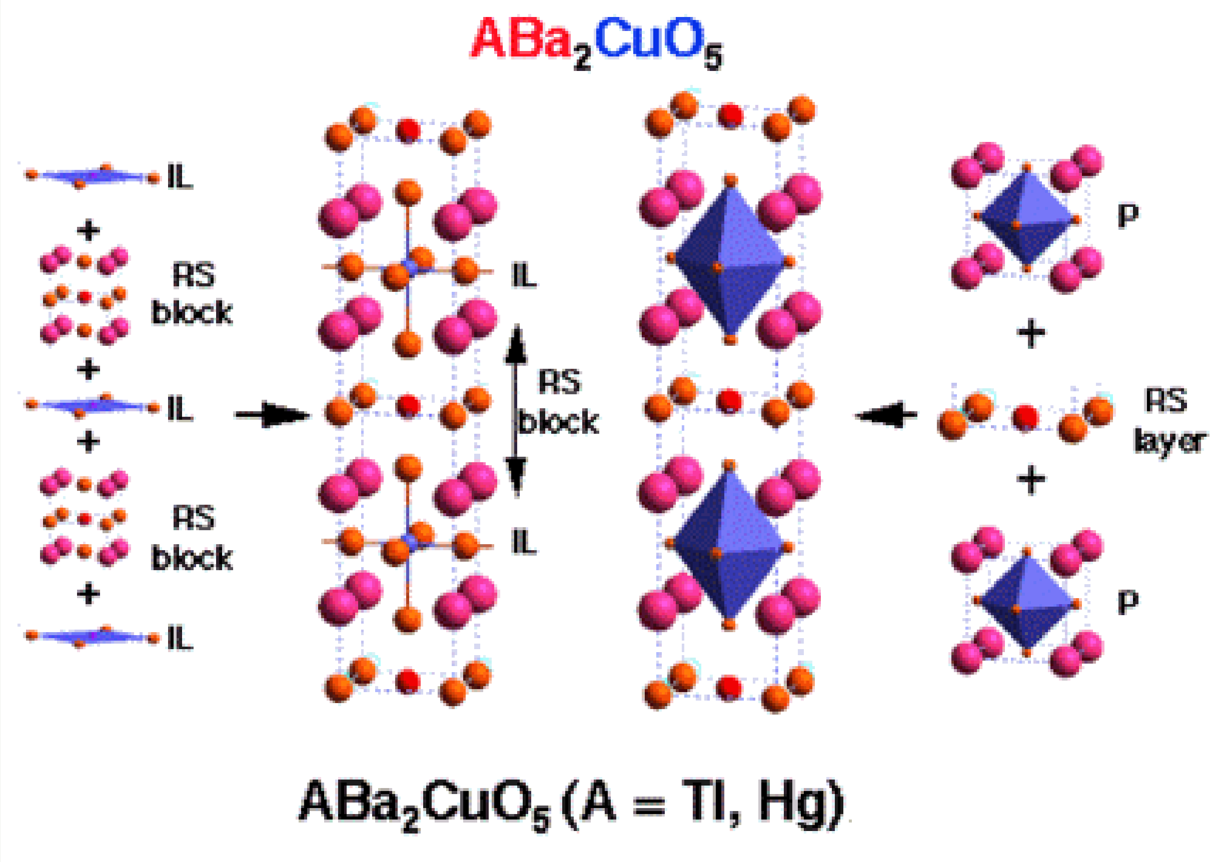
Examples of type 2 superconductors

(Tc – critical temperature; TET – tetragonal crystal lattice)

Material	*Tc [K]*	Crystal lattice
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$	138	TET
$HgBa_2Ca_2Cu_3O_8$	133 - 135	TET
$HgBa_2Ca_3Cu_4O_{10+}$	125 - 126	TET
$HgBa_2CuO_{4+}$	94 - 98	TET
$Tl_2Ba_2Ca_2Cu_3O_{10}$	127- 128	TET
$Tl_2Ba_2CaCu_2O_6$	138	TET
Tl_2Ba_2CuO	95	TET
$NdBa_2Cu_3O_7$	96	TET
$YBa_2Cu_3O_7$	92	TET

Examples of type 2 superconductors

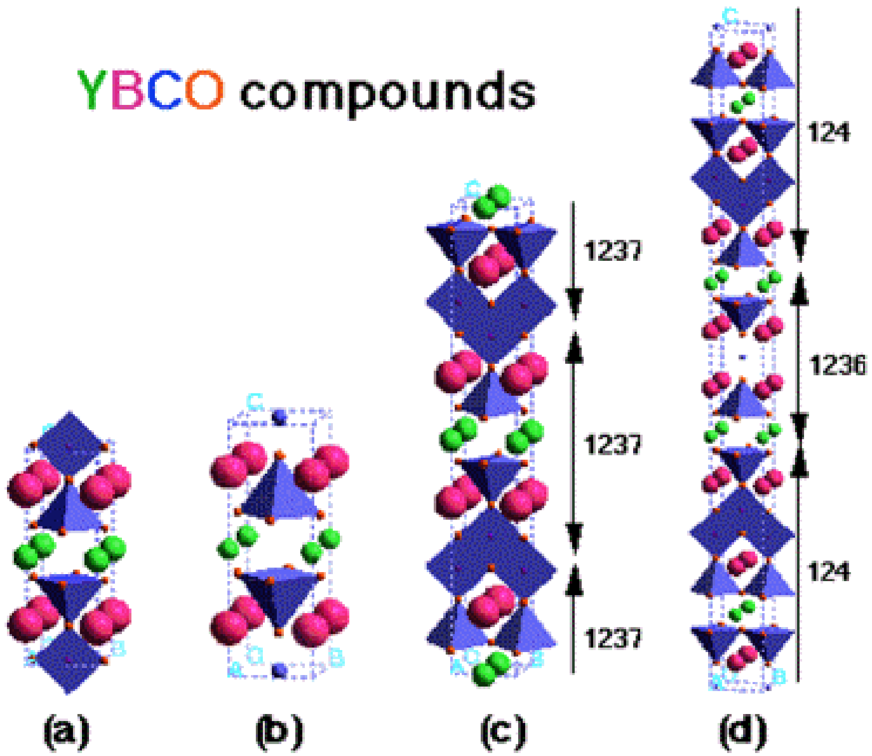
ABa_2CuO_5 compounds ($T_к$ ~ 100 K)



Examples of type 2 superconductors

YBCO compounds

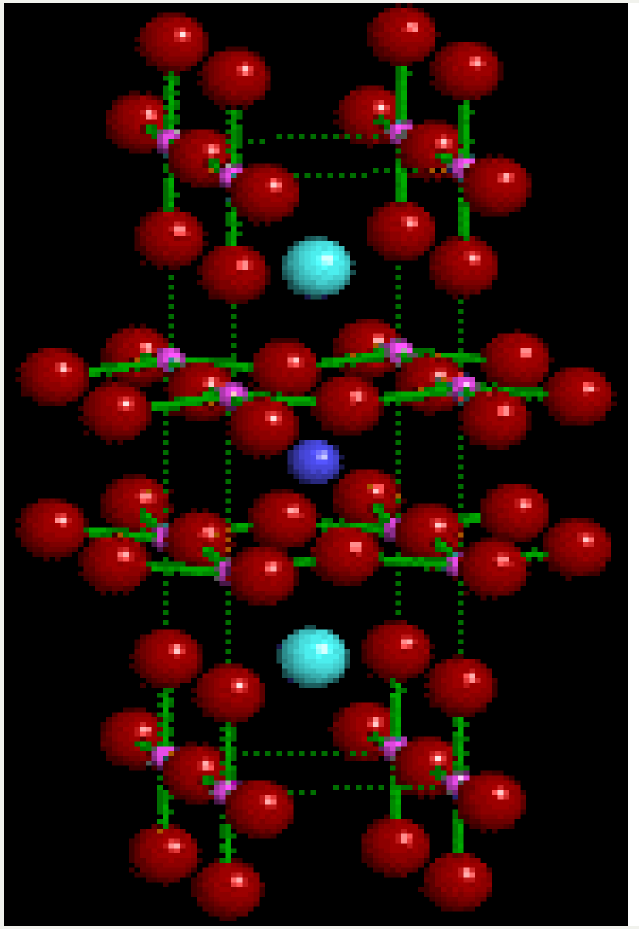
(Tк ~ 90 K)



(a) $YBa_2Cu_3O_7$, (b) $YBa_2Cu_3O_6$, (c) $YBa_2Cu_4O_8$
(d)$Y_2Ba_4Cu_7O_{15}$.

Examples of type 2 superconductors

$YBa_2Cu_3O_7$



Examples of type 2 superconductors

(Tc – critical temperature; ORTH - orthohedral crystal lattice)

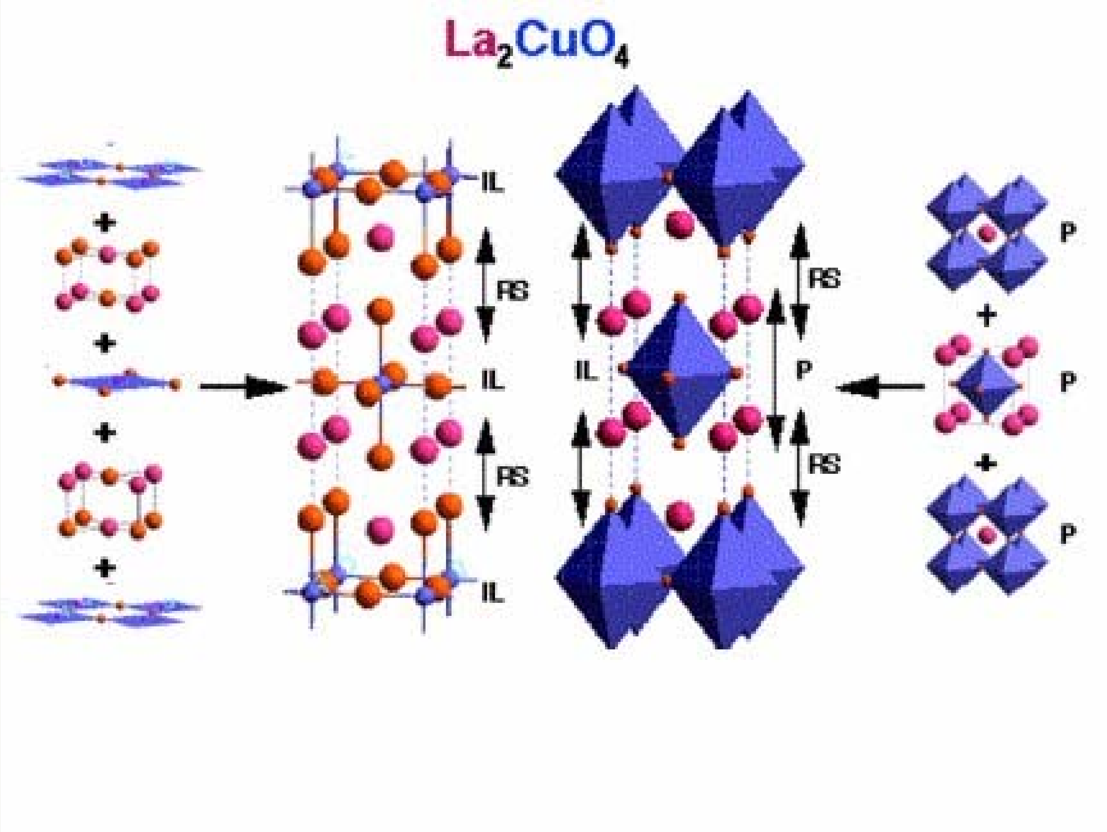
Material	*Tc [K]*	Crystal lattice
SnInBa4Tm3Cu5Ox	133	ORTH
SnInBa4Tm4Cu6Ox	88	ORTH
Sn4Ba4Y3Cu7Ox	80	ORTH
Bi2Sr2Ca2Cu3O10	130	ORTH
Bi2Sr2CaCu2O8	91 - 92	ORTH
Pb3Sr4Ca2Cu5O15	100 - 104	ORTH
AuBa2Ca3Cu4O13	99	ORTH
AuBa2Ca2Cu3O9	30	ORTH

Examples of type 2 superconductors

Material	*Tc [K]*	Type
La2Ba2CaCu5O9+	79	Copper perovskite
La2CaCu2O6+	45	Copper perovskite
SrNdCuO	40	Copper perovskite
MgB2	39	Binary alloy
Nb3Ge	23.2	Binary alloy
Nb	9.25	Elemental type
V	5.40	Elemental type
RuSr2(Cd,Eu,Sm)Cu2O8	58	Rare ferromagnetic
KOs2O6	9.6	Pyrochlore crystal

Examples of type 2 superconductors

Structure of La2CuO4



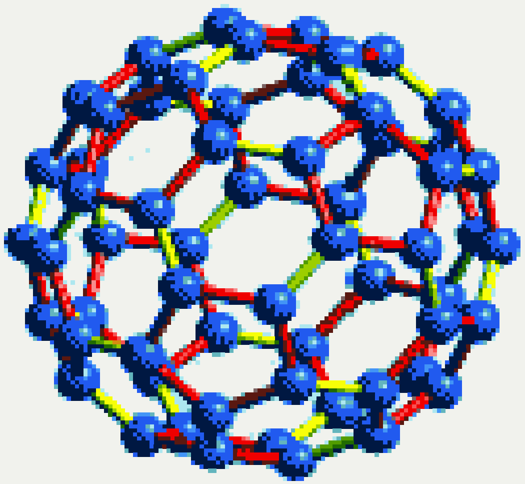
Atypical superconductors

- Fullerenes
- Organic superconductors
- Borocarbides
- Heavy Fermions
- Ruthenates
- Tungsten-bronze systems
- Fluoroargentates

Examples of Atypical Superconductors

Fullerenes

The fullerene – also called a buckminsterfullerene or "buckyball" exists on a molecular level when 60 carbon atoms join in a closed sphere.



$Na_2Rb_{0.5}Cs_{0.5}C_{60}$ – T_c = 8 K

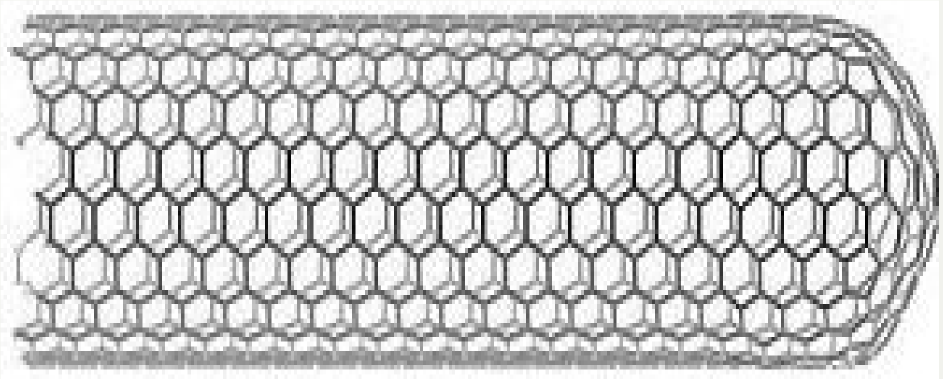
Cs_3C_{60} – T_c = 40 K

K_3C_{60} – T_c = 18 K

C-60 doped with the interhalogen compound ICl – T_c = 60-70 K

Examples of Atypical Superconductors

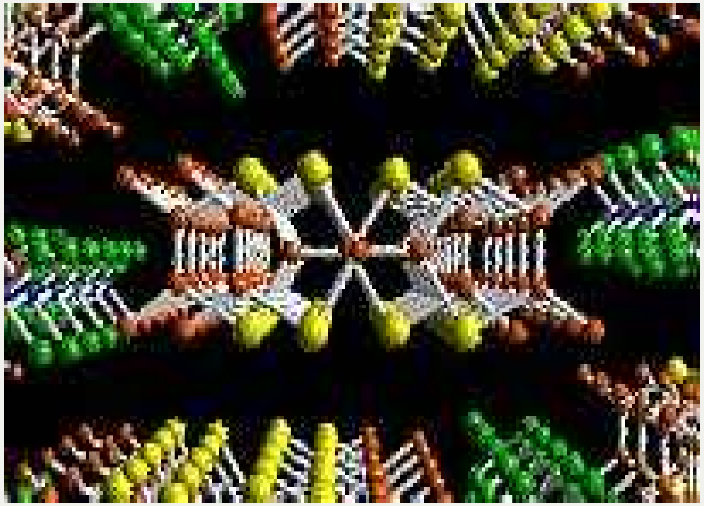
Superconductor that conducts in single-walled carbon nanotubes at 15 K. This was discovered by Chinese researchers in 2001.



Examples of Atypical Superconductors

Organic superconductors

Organic superconductors are composed of an electron donor (the planar organic molecule) and an electron acceptor (a non-organic anion).

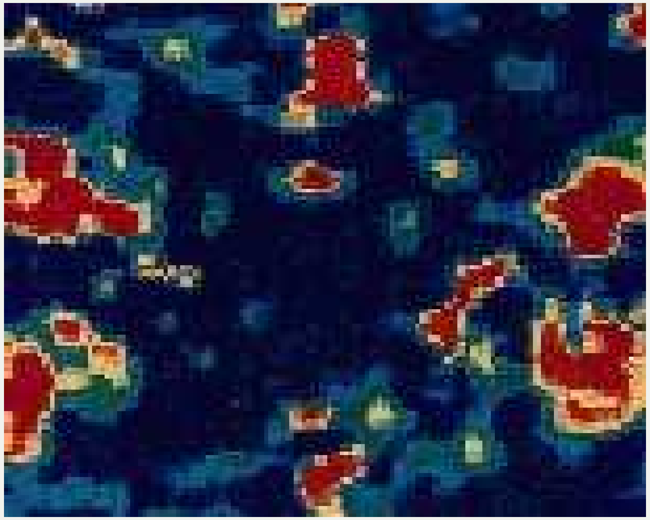


- $(TMTSF)_2PF_6$ (in figure)
- $(BETS)_2GaCl_4$
- $(TMTSF)_2ClO_4$

Examples of Atypical Superconductors

Heavy fermions compounds

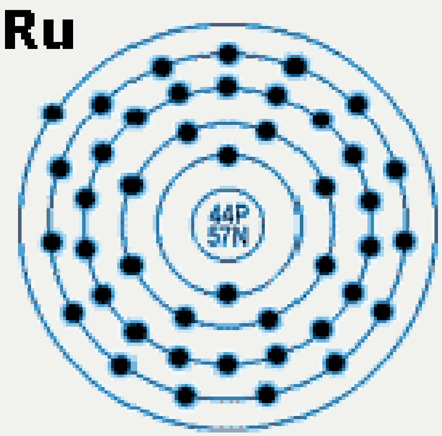
- CeCoIn5 – Tc = 2.3 K
- UPd2Al3 – Tc = 2 K
- Pd2SnYb – Tc = 1.79 K
- URu2Si2 – Tc = 1.2 K
- UNi2Al3 – Tc = 1 K
- Al3Yb – Tc = 0.94 K
- UBe13 – Tc = 0.87 K
- CePt3Si – Tc = 0.75 K
- UPt3 – Tc = 0.48 K (in figure)



Examples of Atypical Superconductors

Ruthenates

- Sr_2RuO_4 – Tc = 1.5 K
- SrRuO – Tc = 1.5 K
- $SrYRuO_6$ – Tc = 1.5 K
- $RuSr_2(Gd,Eu,Sm)Cu_2O_8$ – Tc = 58 K



Tungsten-bronze system

- $Na_{0.05}WO_3$ – Tc = 91 K

Fluoroargentates

- Be-Ag-F Tc = 64 K

Applications of Superconductors - 1

- **Superconducting magnets**
- **Superconducting cables -** First HTS cable installation in a utility network is scheduled for the year 2000.
  - The first HTS coaxial HTS cable demonstration is scheduled for that same year.
  - The first commercial sales of HTS cable wires are expected shortly after 2001
- **Superconducting wires**

Applications of Superconductors - 2

- **Scanning SQUID microscope**
- **Devices that use the absence of resistance of superconductors**
  - High current superconducting wires.
  - Radio Frequency filters in cell phone receivers
- **Superconducting quantum devices**
  - To define the Volt
  - "Quantum Metrology"
  - As magnetic field detectors

Applications of Superconductors - 3

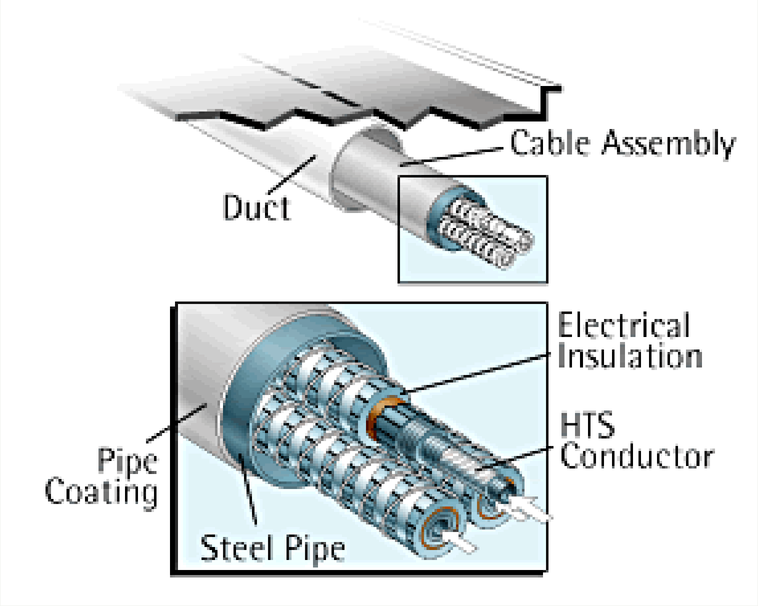
Magnetic levitation trains (MagLev) in Japan

Repulsive force from the induced current on a conducting guideway levitates the train.

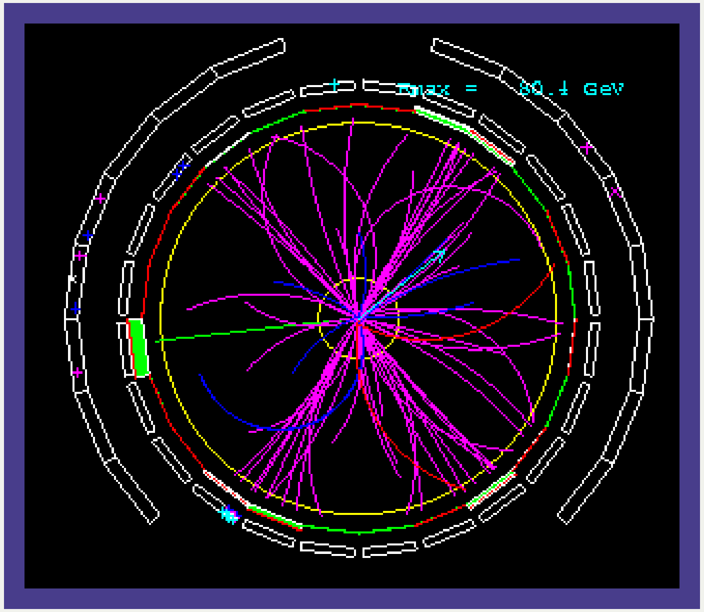
Applications of Superconductors - 4

High Currents in Tight Places

Transmission Line

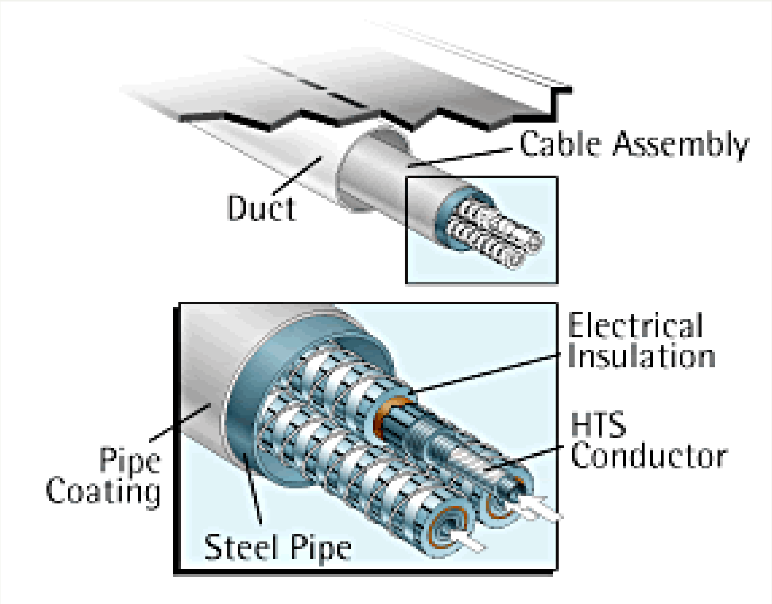


Superconducting magnet



Applications of Superconductors - 5

Power Transmission



- First HTS cable installation in a utility network is scheduled for the year 2000.
- The first HTS coaxial HTS cable demonstration is scheduled for that same year.
- The first commercial sales of HTS cable wires are expected shortly after 2001.
- The warm dielectric cable configuration features a conductor made from HTS wires wound around a flexible hollow core. Liquid nitrogen flows through the core, cooling the HTS wire to the zero resistance state. The conductor is surrounded by conventional dielectric insulation. The efficiency of this design reduces losses.

Applications of Superconductors - 6

Superconducting magnet being built at University of Illinois

String of SC Magnets - 7

Relativistic Heavy Ion Collider RHIC), ~ 4 miles of SC magnets.
Brookhaven National Laboratory

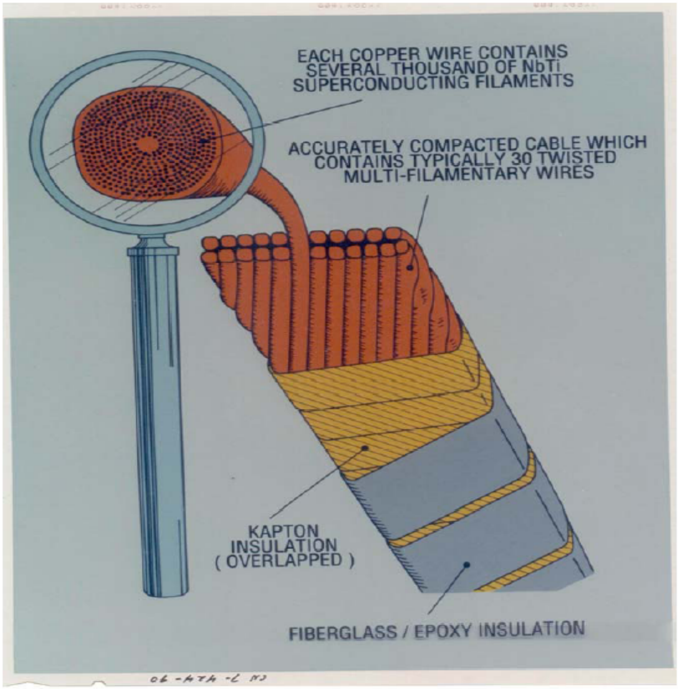
Applications of Superconductors - 8

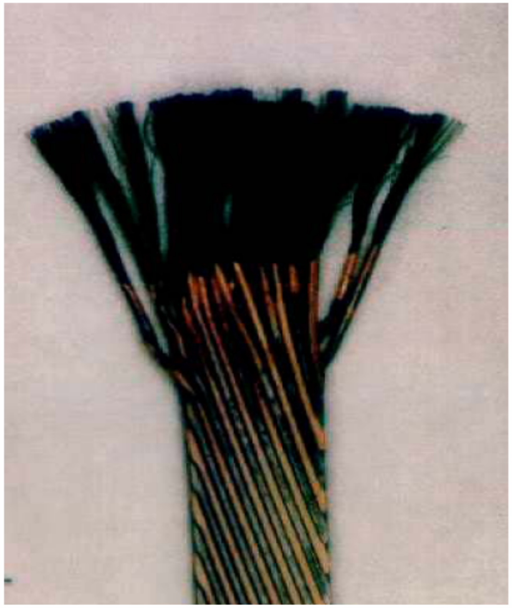
HTS power cables can carry two to ten times more power in equally or smaller sized cables

Applications of Superconductors - 9

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

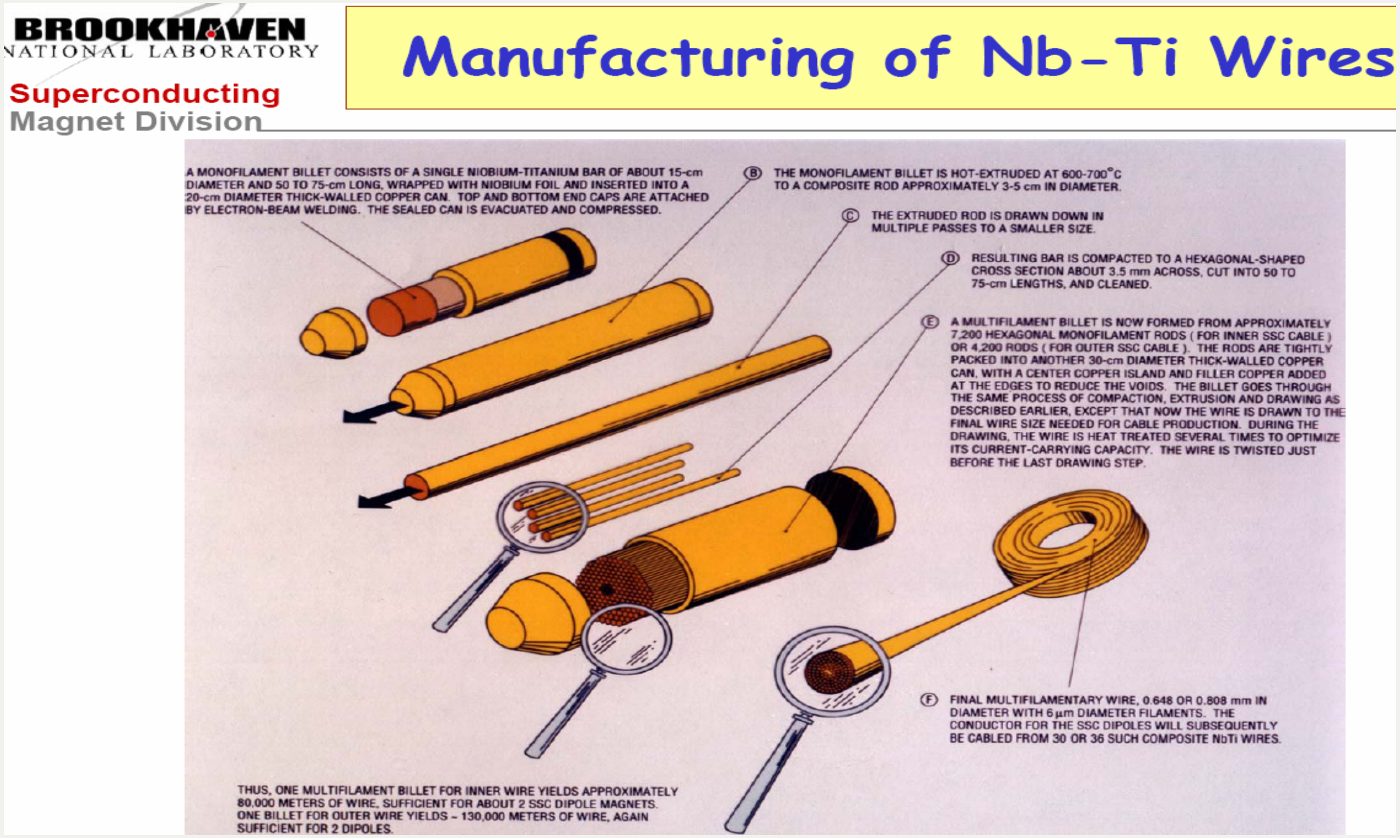
A Typical Superconducting Cable





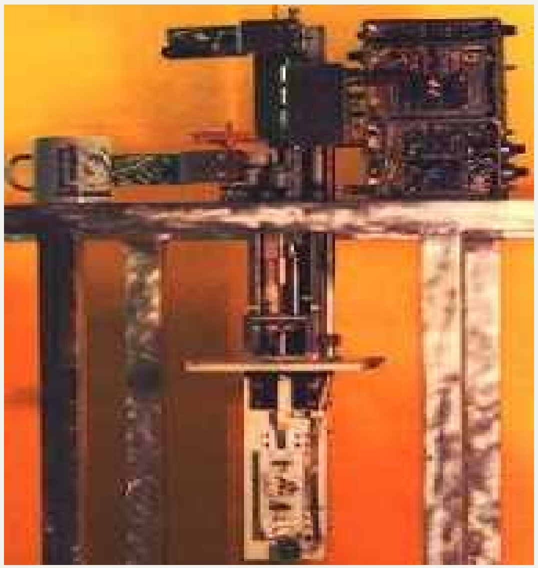
Filaments in an actual cable
(Filament size in SSC/RHIC magnets: 6 micron)

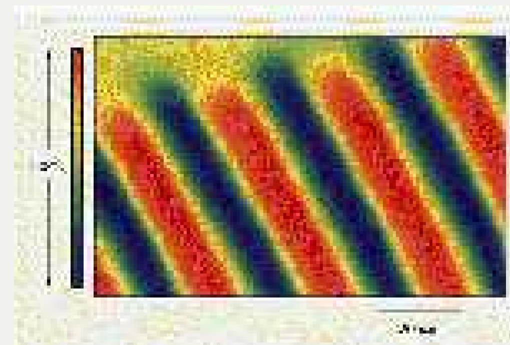
Applications of Superconductors- 10



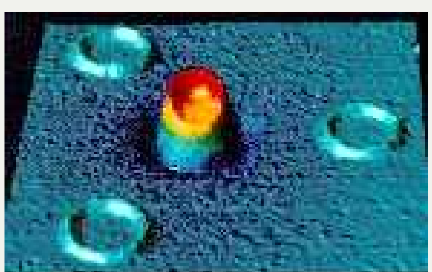
Applications of Superconductors - 11

Scanning SQUID microscope





A floppy disk as seen by a scanning SQUID microscope



Yttrium barium copper oxide

Other possible applications - 1

- Superconductor transformer
- Superconductor transistor
- Filters in Cell Phone Towers – Superconducting Filter
- SQUIDs (Superconducting Quantum Interference Devices): The most sensitive detectors of magnetic fields
- Superconductors are used in cell phone receivers, magnets, and now in transmission cables.

Other possible applications - 2

- The quantum properties of superconductors are used to define a voltage standard, measure small magnetic fields, and in Quantum Metrology.

- Currently the Large Hadron Collider (LHC) is one of the most powerful colliders in the world. It consists of a 27 km tunnel and employs large superconducting magnets. The collider uses over 5,000 superconducting magnets. The magnets in the LHC must be capible of producing fields of 8 Tesla, 100 000 times the strength of the Earths magnetic field! The LHC is capible of accelerating large ions, such as lead, to energies in excess of 1250 TeV.

Superconductors in Medicine - 1

1. Magnetic rezonance tomography

2. Biomagnetic measurements

- SQUID magnetometer
- Magnetoencephalanography (MEG systems)
- Magnetocardiography (MCG device)
- Magnetoneurography
- Gastroenterology
- Magnetopneumography
- Liver iron suspectometry

Superconductors in Medicine - 2

Nuclear Magnetic Resonance Imaging

Superconducting magnets are used to generate stable (both in space and time) magnetic field

MRI device

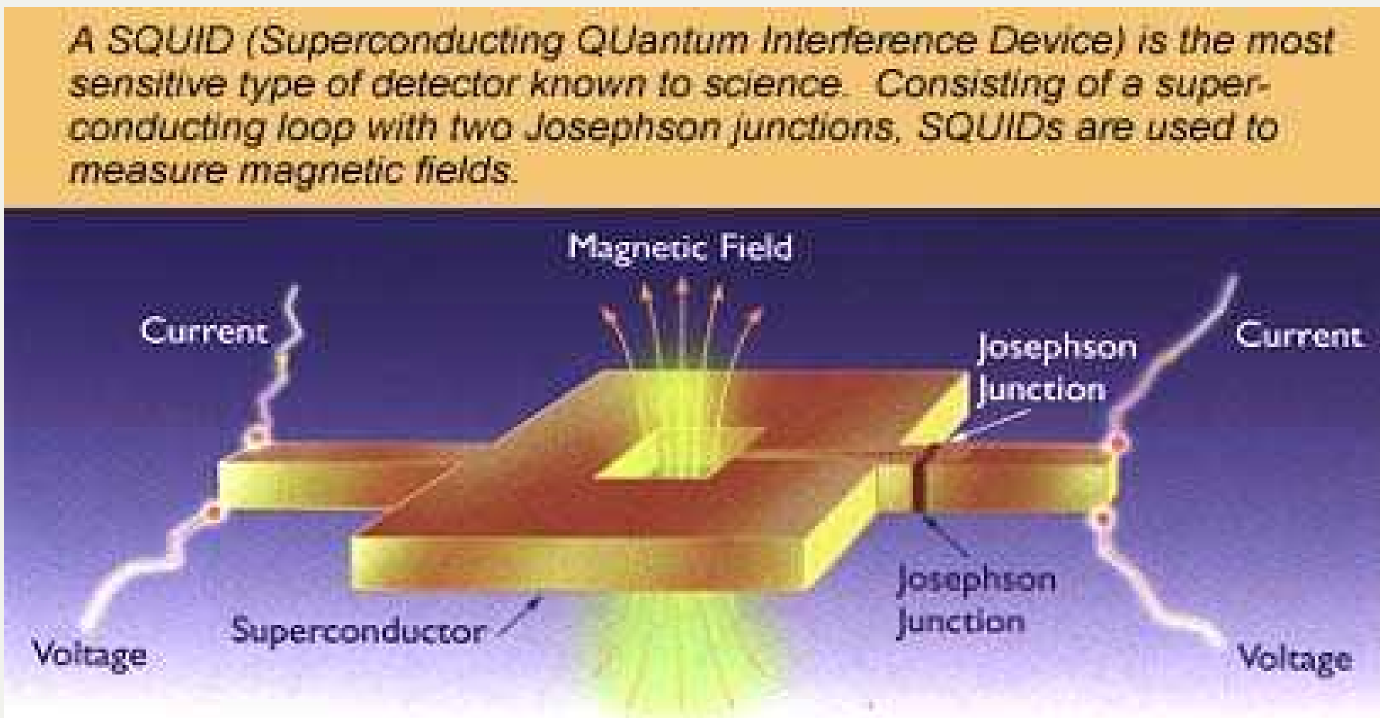
Superconductors in Medicine - 3

- *MRI scan of a human skull*

- MRI of lower human spine (image used with permission

Superconductors in Medicine - 4

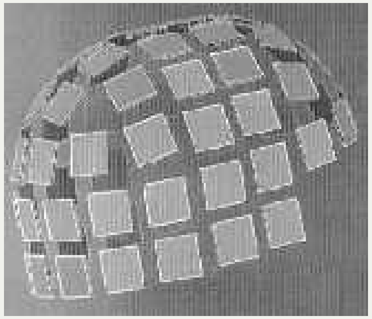
Superconducting Quantum Interference Device (SQUID)

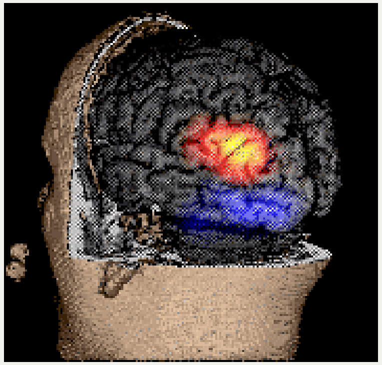


Superconductors in Medicine - 5

MEG systems

MEG systems consist of an array of low temperature SQUID sensors (37 to 255) in a dewar that surrounds the whole head





Superconductors in Medicine - 6

The medical MRI unit to the right projects a 0.1 Tesla homogeneous field 20cm above the top plate of the cryostat.

Conclusions

- Superconductivity is one of the most important phenomenon that must be studied from students of engineering specialities.
- The path from research experiments to commercial applications was made.
- It is difficult to predict the future applications but undoubtedly they will be extraordinary.