Conductors and Superconductors

Resistance is useless!


No – nothing to do with clippies

Nor with world famous orchestras

Superconductors
A definition

A superconductor is a material which has no resistance to electricity. When passing current through a superconducting material there is no loss of electrical power

What is an electrical Conductor?

A material or an object that allows the passage of an electric current

Electrical conductors contain electric charges (usually electrons) that are relatively free to move through the material; a voltage applied across the conductor therefore creates the electric current.

A quick look at the Periodic Table

Metals; non-metals
and semiconductors

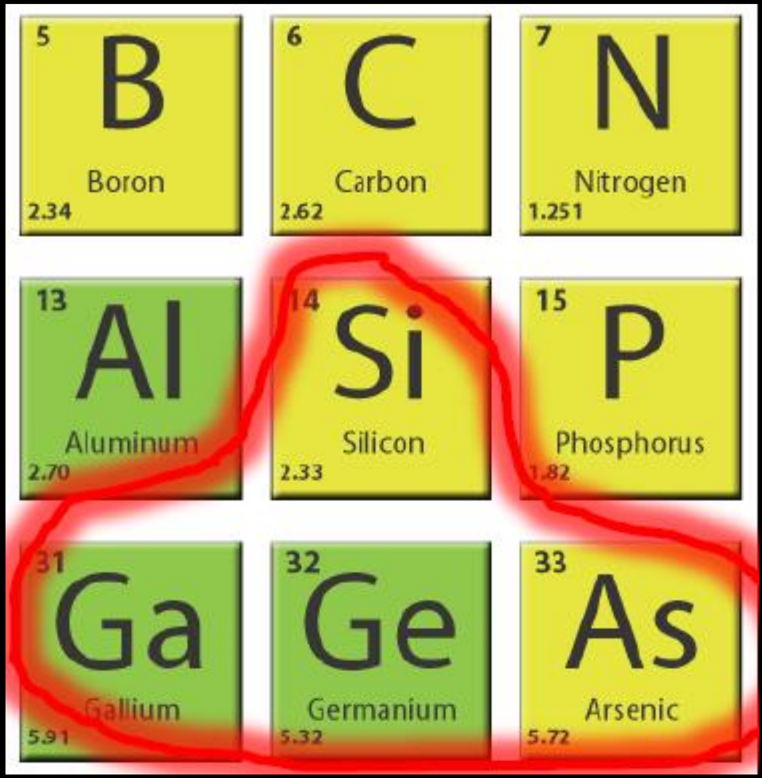
The Periodic Table of elements - I

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

The Periodic Table of elements - II

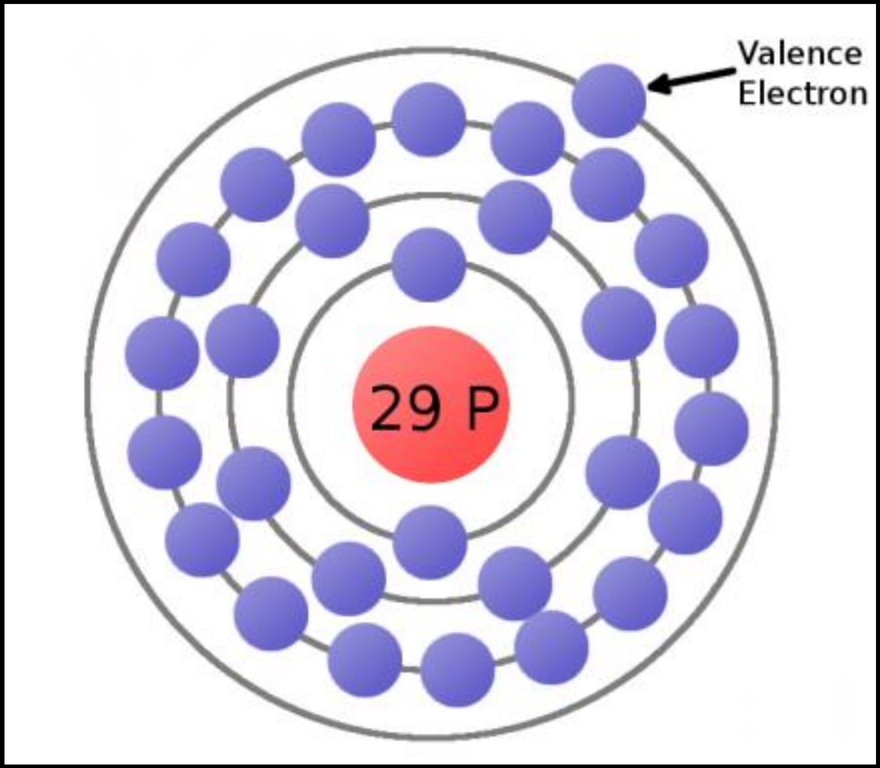
Semiconductors



Why do metals conduct?

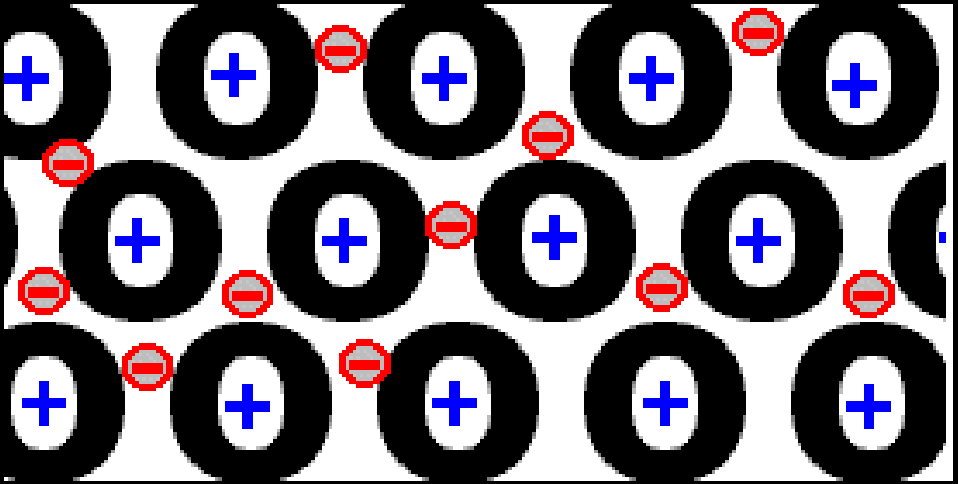
Metal atoms have outer electrons which are not tied to any one atom. These electrons can move freely within the structure of a metal when an electric current is applied. There are no such free electrons in covalent or ionic solids, so electrons can't flow through them - they are non-conductors

The Copper atom has 29 electrons

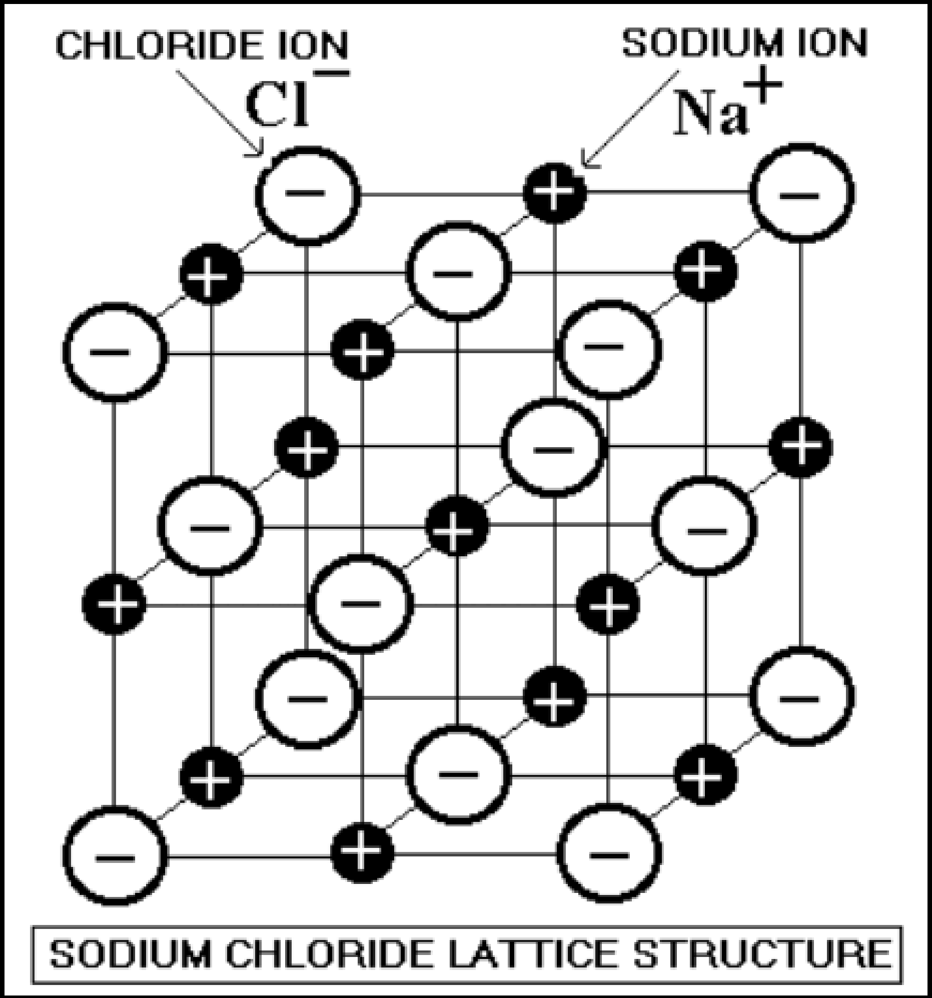


The outer shell has one loose electron

These outer "valence band" electrons are free to move through the copper crystal lattice



Example of a typical crystal lattice for a non conducting ionic crystal



Resistance is useless!

George Simon Ohm

Born 1787 in Erlangen, Bavaria

- Ohm discovered that current flow in a wire is proportional to cross sectional area and inversely proportional to length
- Published his law in 1827.
- Ideas dismissed by colleagues
- Resigned from teaching and lived in shame and poverty
- Efforts recognised in 1849
- Became professor in Munich

Ohm's Law

Ω

$V = I * R$

Or….

Ohm's Law

$$\Omega$$

Voltage=Current * Resistance

Ohm defined the fundamental relationship between resistance; current and voltage

The symbol for resistance is the Greek letter Omega Ω

Resistance is measured in OHMS

Why cables get hot and why we use high voltage for transmission lines

Power is measured in WATTS

Watts = Current * Voltage or $W = I*V$

Substituting for voltage in Ohm's law
We get $W = I^2R$. This the so-called Joule heating effect of an electrical current

Why cables get hot and why we use high voltage for transmission lines

So for every reduction in cable DIAMETER by 50%, the resistance increases fourfold and for a given fixed current the power loss increases by four times!

Why cables get hot and why we use high voltage for transmission lines

But we need to move a lot of power around the country so we do so at very high voltage to minimise losses. Each doubling of voltage halves the current and reduces the Joule heating by a factor of four

A very hot "cable"

132 kV power distribution

3 phase distribution, so three cables per side of the pylon

275 kV power distribution

Double wire "bundles" to reduce corona losses

400 kV power distribution

Four wire "bundles" spaced to reduce corona losses

400 kV line re-cabling - I

You need a good head for heights. Also you need to make sure that the electricity is disconnected…

400 kV line re-cabling - II

New cables being winched into position

Corona ring

400 kV line re-cabling - III

Note the massive size of the suspensory insulators

Electrical resistance increases with temperature

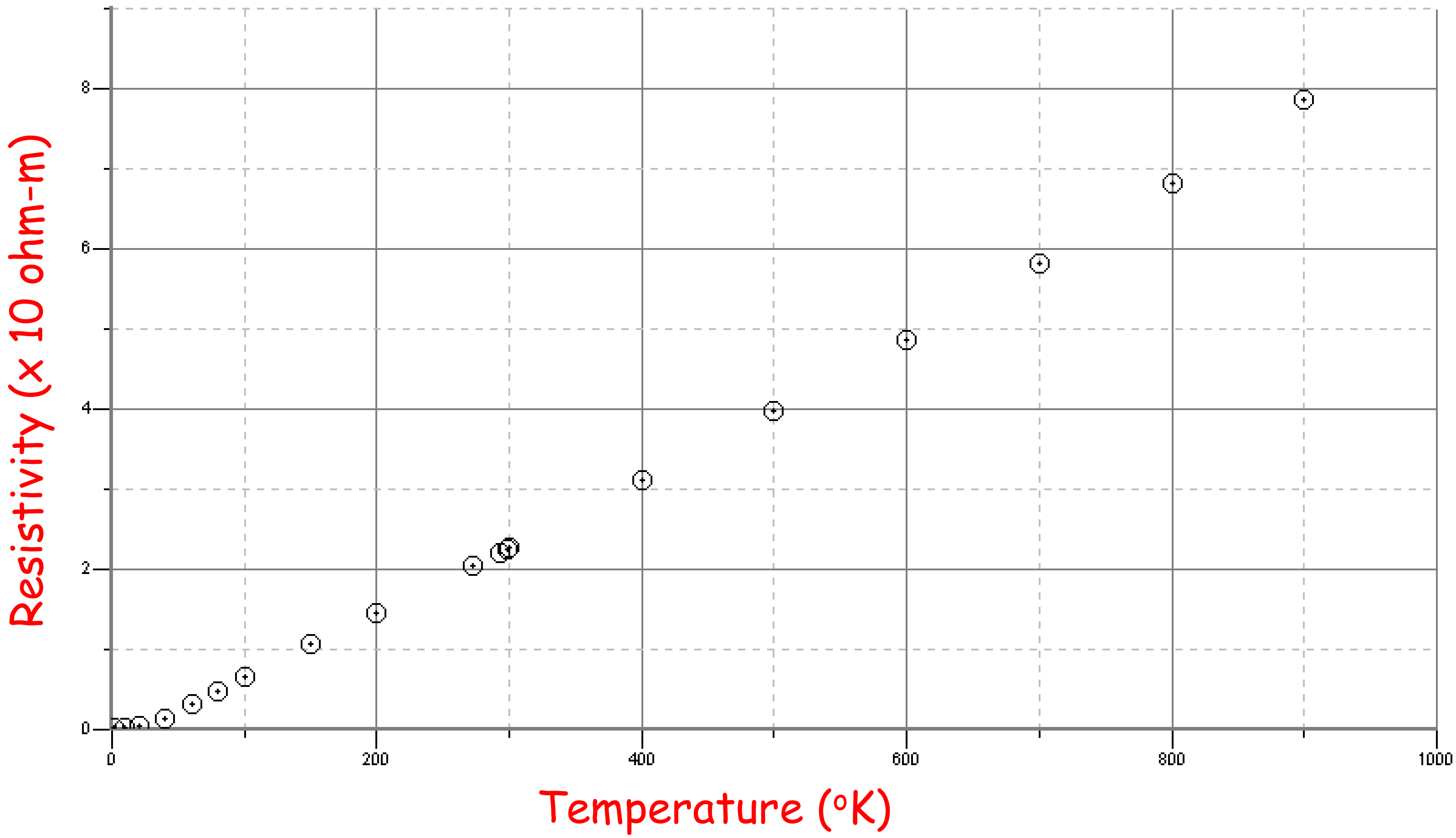
$R=R_0\{1 + \alpha(T-T_0)\}$ Where α is the temperature coefficient

Temperature coefficients of resistivity of some metals ($10^{-3}/^{o}C$)

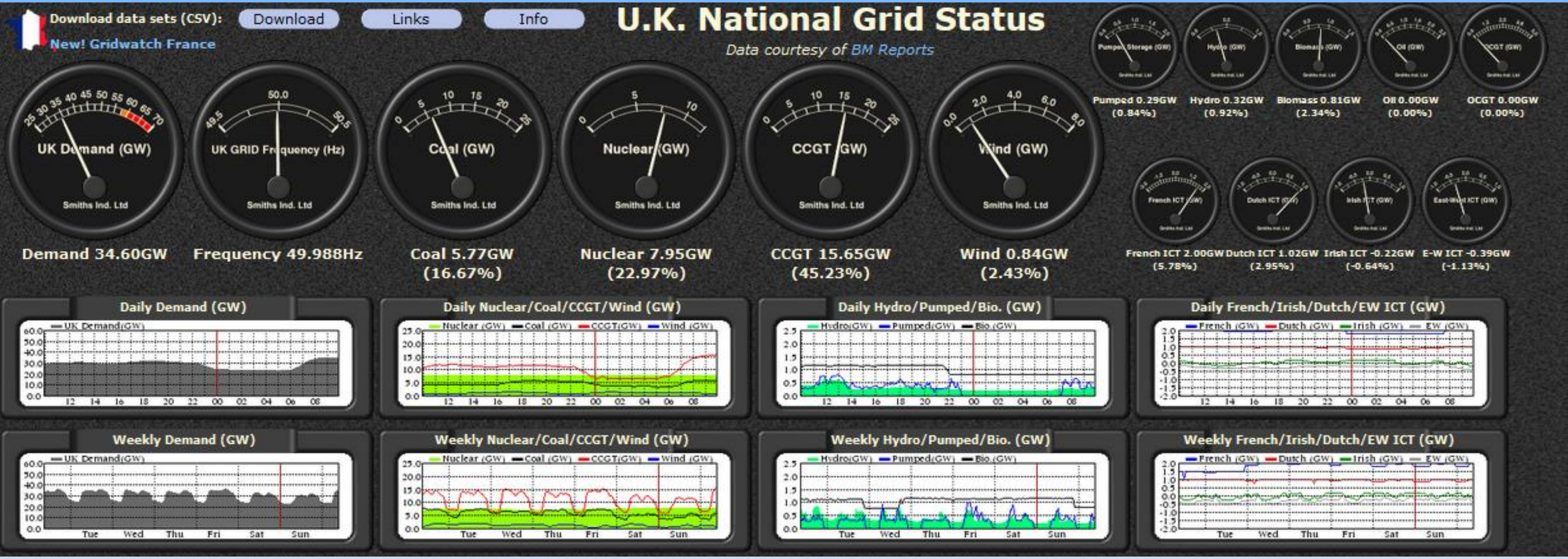
Silver	3.0
Copper	3.9
Iron	5.0
Aluminium	3.9

So for a 100 °C rise in temperature an aluminium conductor will increase in resistance by 1.39 times and the Joule heating effect (or power losses) will increase by the same amount

Resistivity of Gold

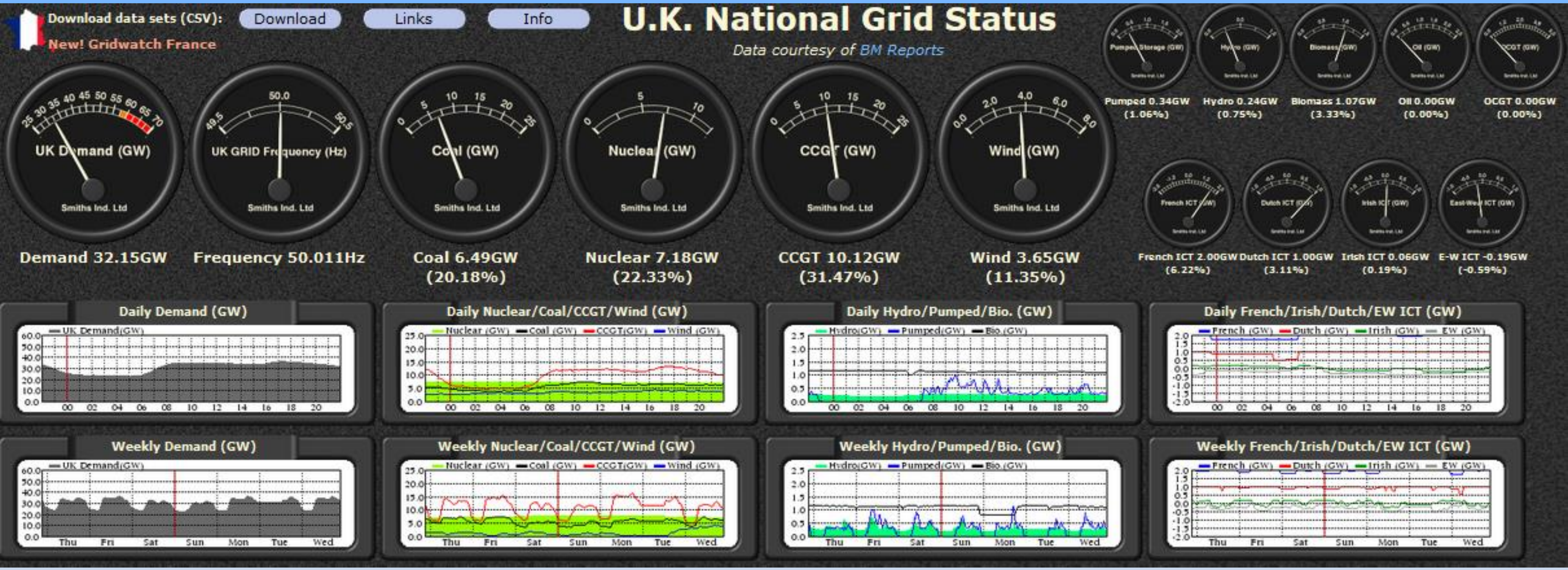


How much power do we need? What sources does it come from?



Supply and demand overview 10:00 15th June

How much power do we need? What sources does it come from?



Supply and demand overview 22:00 17th June

A closer look at the details

Monday 15th June 2015 10:00 am

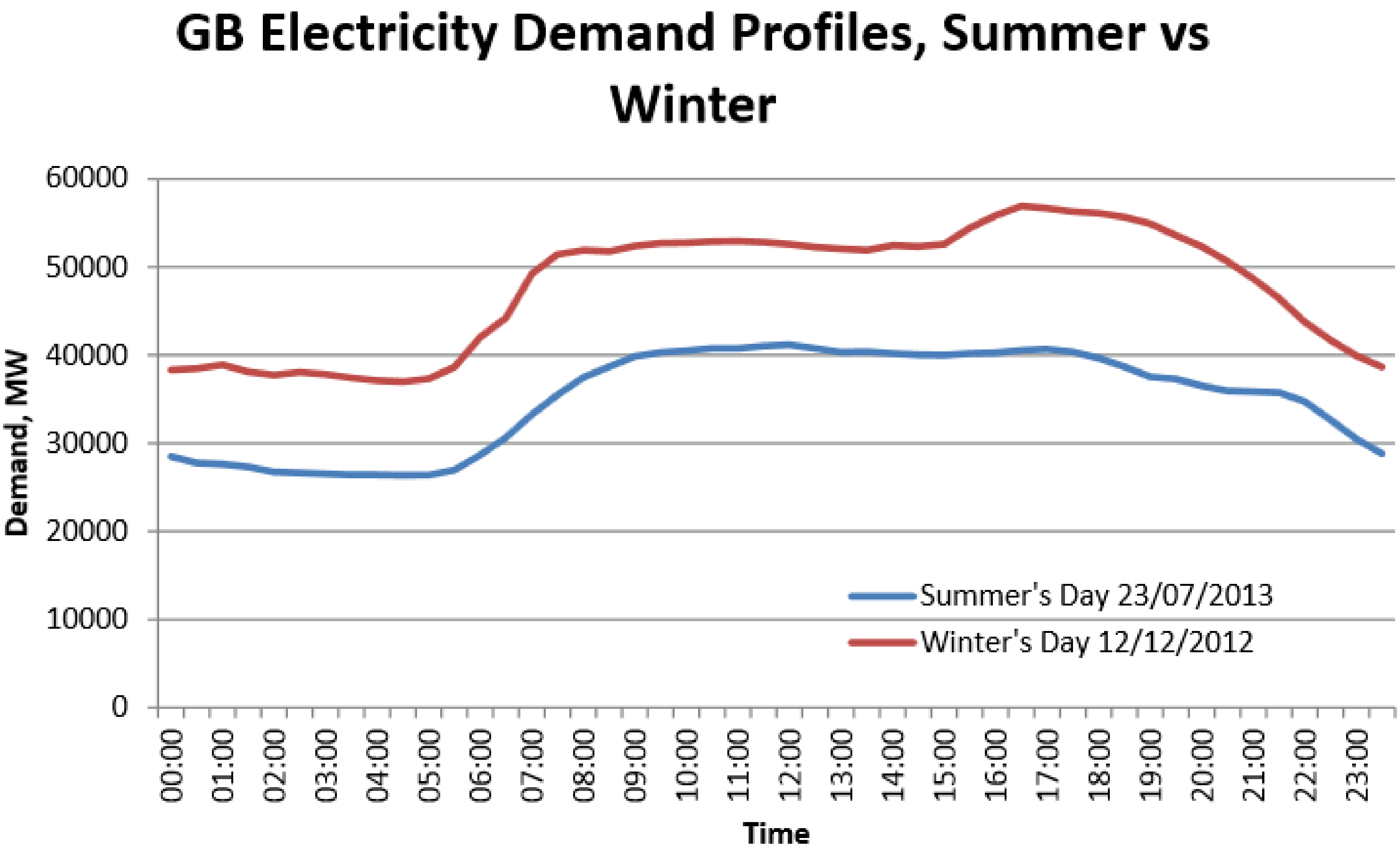
Demand	34.50 Gigawatts
Coal	16.67% Base load
Nuclear	22.97% Base load
Combined cycle gas turbine	45.23% Instant ON-OFF
Wind	2.38% (can go as high as 12%)
Pumped storage	0.84%
Hydroelectric	0.93%
Biomass	2.35%
French connector	5.80% (nuclear)
Dutch connector	2.90% (wind?)

A closer look at the details

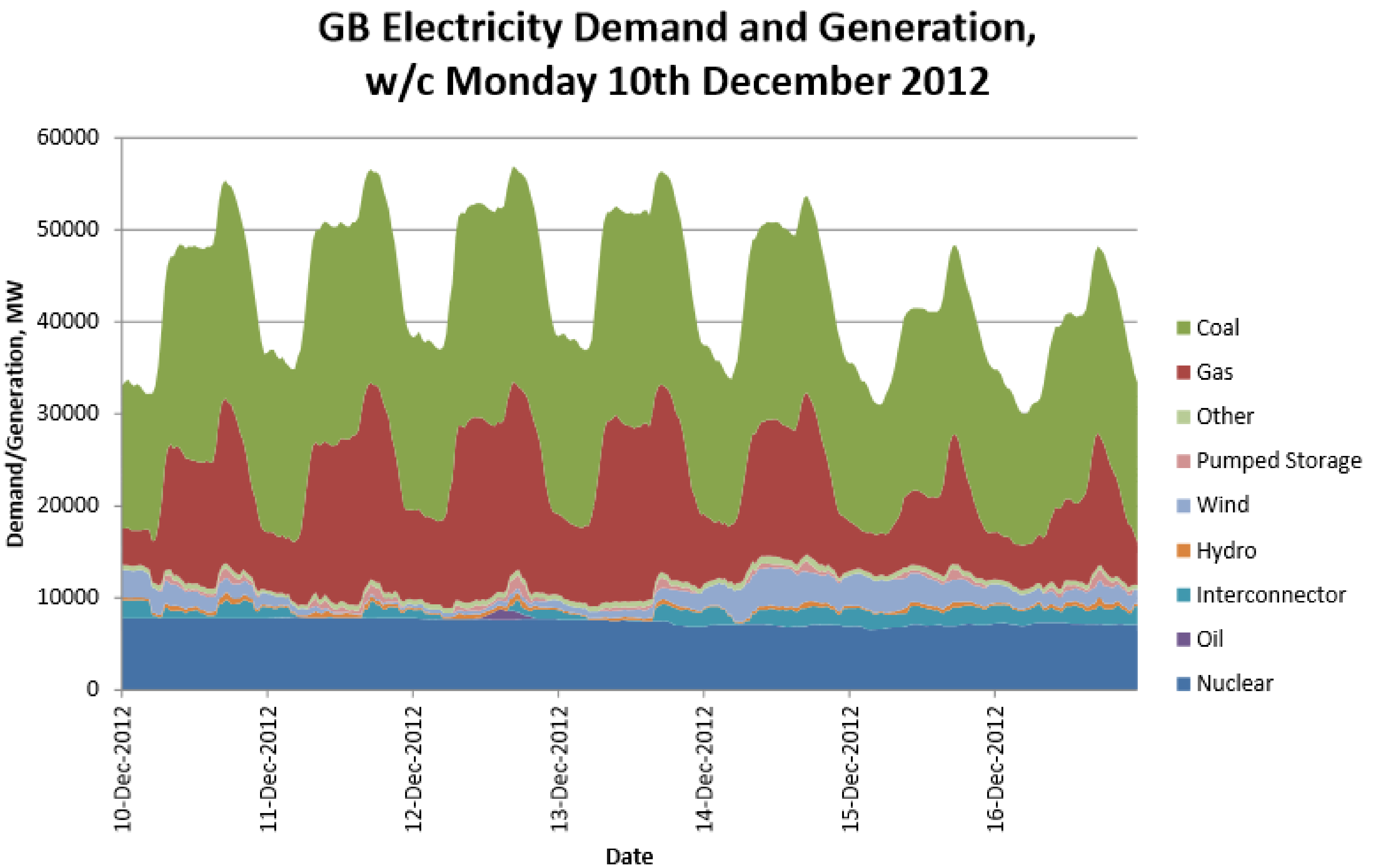
Monday 15th June 2015 10:00 am

Demand	32.15 Gigawatts
Coal	20.18% Base load
Nuclear	22.33% Base load
Combined cycle gas turbine	31.47% Instant ON-OFF
Wind	11.35% (can go as high as 12%)
Pumped storage	1.06%
Hydroelectric	0.75%
Biomass	3.33%
French connector	6.22% (nuclear)
Dutch connector	3.11% (wind?)

Daily and seasonal variation



A difficult winter week



I^2R Power losses in the UK National Grid

Joule heating in network of 400kV; 275kV and 132kV cables: 858 MW

Fixed losses: 266 MW (consists of corona and iron losses; can be 100 MW higher in adverse weather)

Substation transformer heating losses: 142 MW

Generator transformer heating losses: 157 MW

Total losses: 1,423 MW (2.29% of peak demand)

I^2R Power losses beyond the EHV network

Although overall losses in the national grid are low, there are significant further losses in onward electricity distribution to the consumer, causing a total distribution loss of about 7.7%. However losses differ significantly for customers connected at different voltages;

at high voltage the total losses are about 2.6%

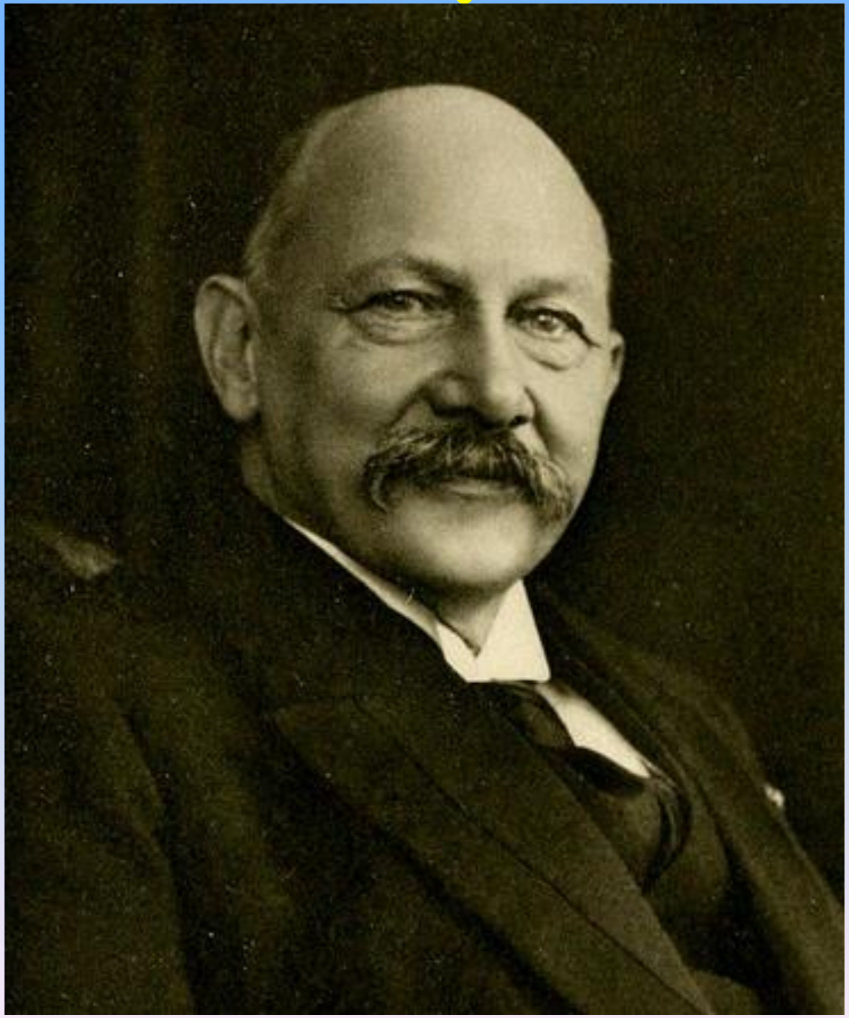
at medium voltage 6.4%

and at low voltage 12.2%

So 10% of our electricity is lost between the generator and the end user

Now back to Superconductors

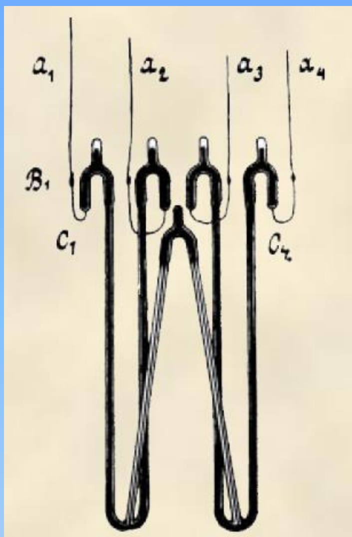
The discoverer of superconductivity



Kamerlingh Onnes
21 September 1853 – 21 February 1926
Nobel laureate 1913

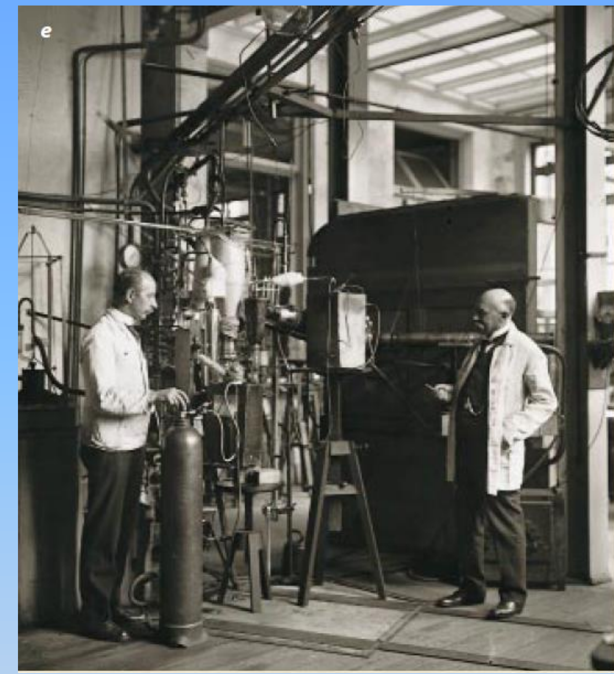
In 1911 Onnes reported that mercury displayed zero resistance when cooled to 4.19 degrees

Superconductivity- discovery I



1895 William Ramsay in England discovered helium on the earth
1908 H. Kamerlingh Onnes liquefied helium (boiling point 4.22 K)

Resistivity at low temperatures
Pure mercury (could be repeatedly distilled producing very pure samples).



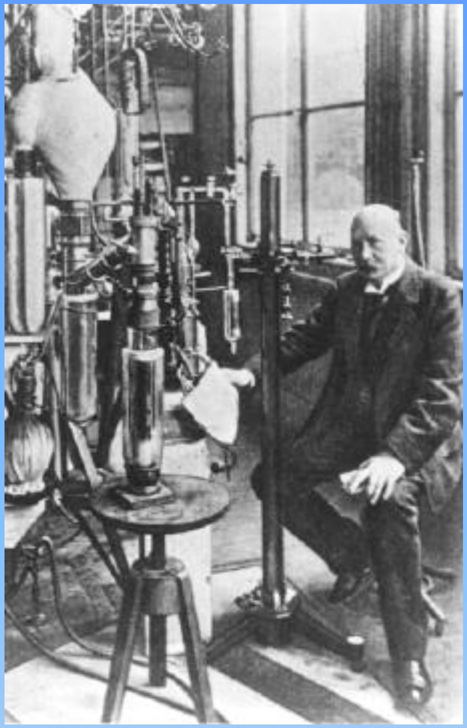
Repeated resistivity measurements indicated zero resistance at the liquid-helium temperatures. It **was assumed that there was a short circuit!**

But during one repetitive experimental run, a young technician fall asleep. The helium pressure (kept below atmospheric) slowly rose and, therefore, the boiling temperature rose. As it passed above 4.2 K, suddenly resistance re-appeared.

Hg T_C=4.2K

From: Rudolf de Bruyn Ouboter, "*Heike Kamerlingh Onnes's Discovery of Superconductivity*", Scientific American March 1997

Superconductivity- discovery II

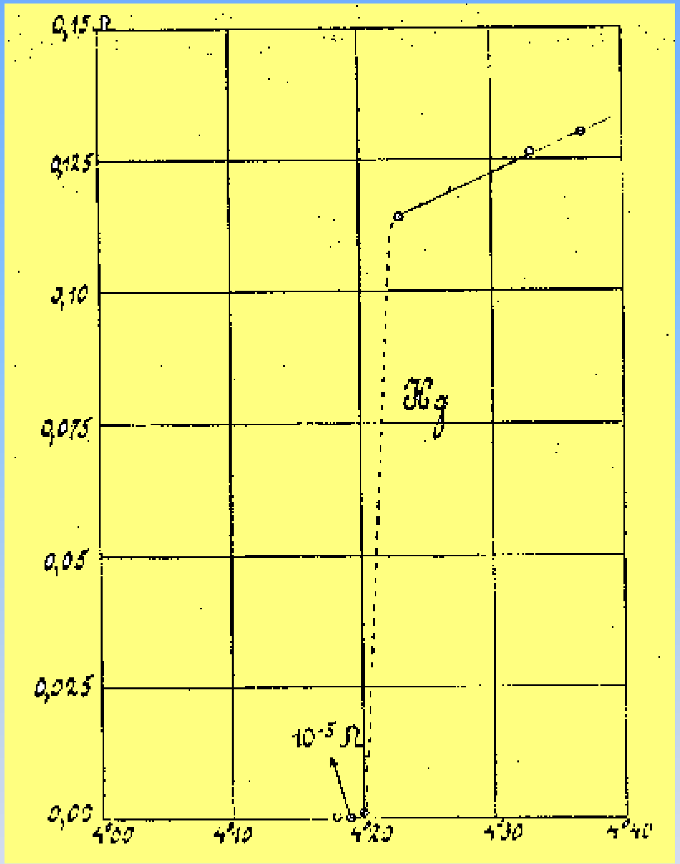


Liquid Helium (4K) (1908). ***Boiling point*** 4.22K.

Superconductivity in Hg T_C=4.2K (1911)

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

H. Kamerlingh Onnes 1913 (Nobel prize 1913)



Resistivity R=0 below T_C; ($R<10^{-23}$ Ω·cm, 10^{18} times smaller than for Cu)

Further discoveries to 1993

1911-1986: "Low temperature superconductors" Highest T_C=23K for Nb_3Ge

1986 (January): High Temperature Superconductivity $(LaBa)_2 CuO_4$ T_C=35K

K.A. Müller und G. Bednorz (IBM Rüschlikon) (Nobel prize 1987)

1987 (January): $YBa_2Cu_3O_{7-x}$ T_C=93K

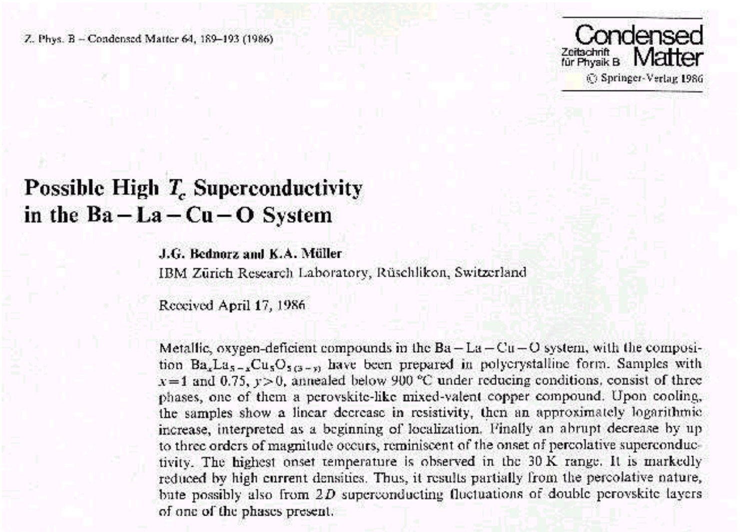
1987 (December): Bi-Sr-Ca-Cu-O T_C=110K,

1988 (January): Tl-Ba-Ca-Cu-O T_C=125K

1993: Hg-Ba-Ca-Cu-O T_C=133K

(A. Schilling, H. Ott, ETH Zürich)

Muller and Bednorz IBM 1986



Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Condensed Matter
Zeitschrift für Physik B
© Springer-Verlag 1986

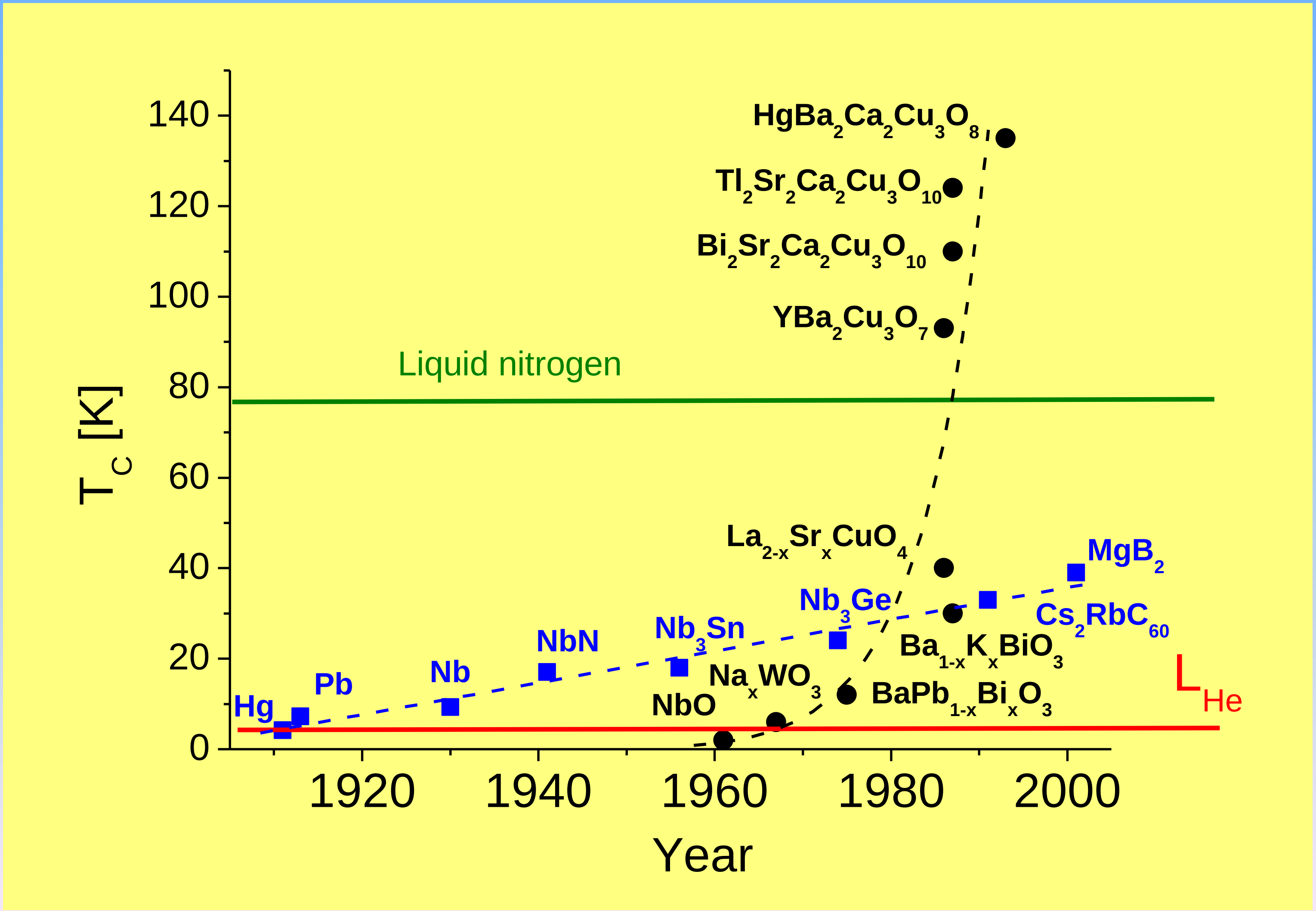
Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

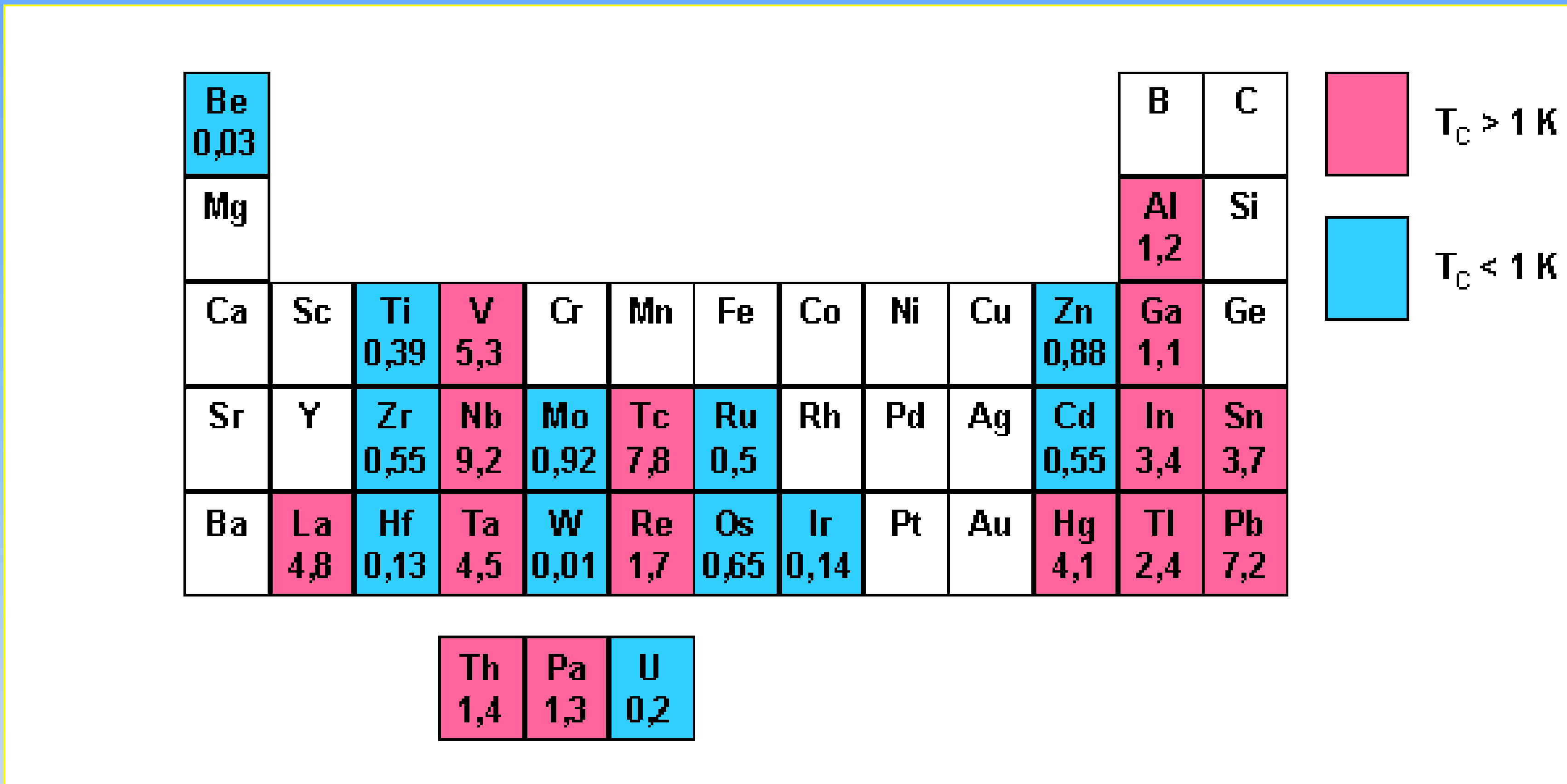
Received April 17, 1986

Metallic, oxygen-deficient compounds in the Ba – La – Cu – O system, with the composition $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ have been prepared in polycrystalline form. Samples with $x=1$ and 0.75, $y>0$, annealed below 900 °C under reducing conditions, consist of three phases, one of them a perovskite-like mixed-valent copper compound. Upon cooling, the samples show a linear decrease in resistivity, then an approximately logarithmic increase, interpreted as a beginning of localization. Finally an abrupt decrease by up to three orders of magnitude occurs, reminiscent of the onset of percolative superconductivity. The highest onset temperature is observed in the 30 K range. It is markedly reduced by high current densities. Thus, it results partially from the percolative nature, bute possibly also from 2D superconducting fluctuations of double perovskite layers of one of the phases present.

Superconductivity now found at liquid nitrogen temperatures by 1986



T_c for superconducting elements



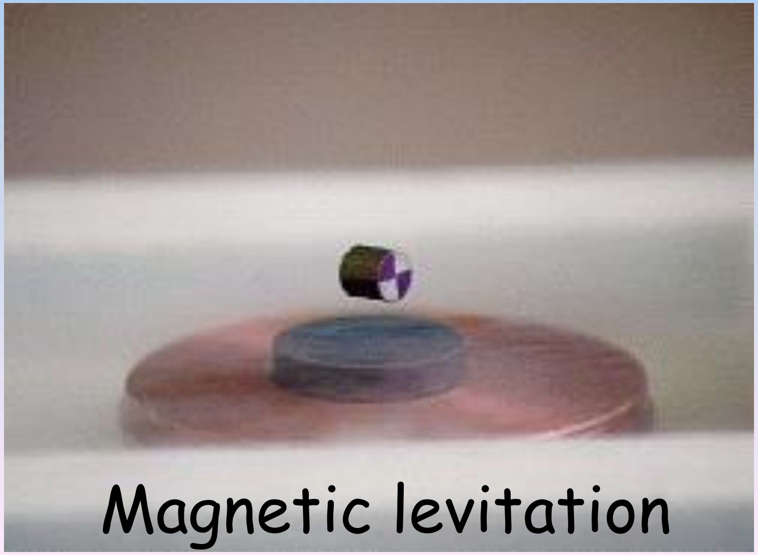
No ferromagnetic elements are superconducting
The best conductors (Ag, Cu, Au) are *not* superconducting
Nb has the highest T_c = 9.2K from all the elements

Meissner-Ochsenfeld-effect

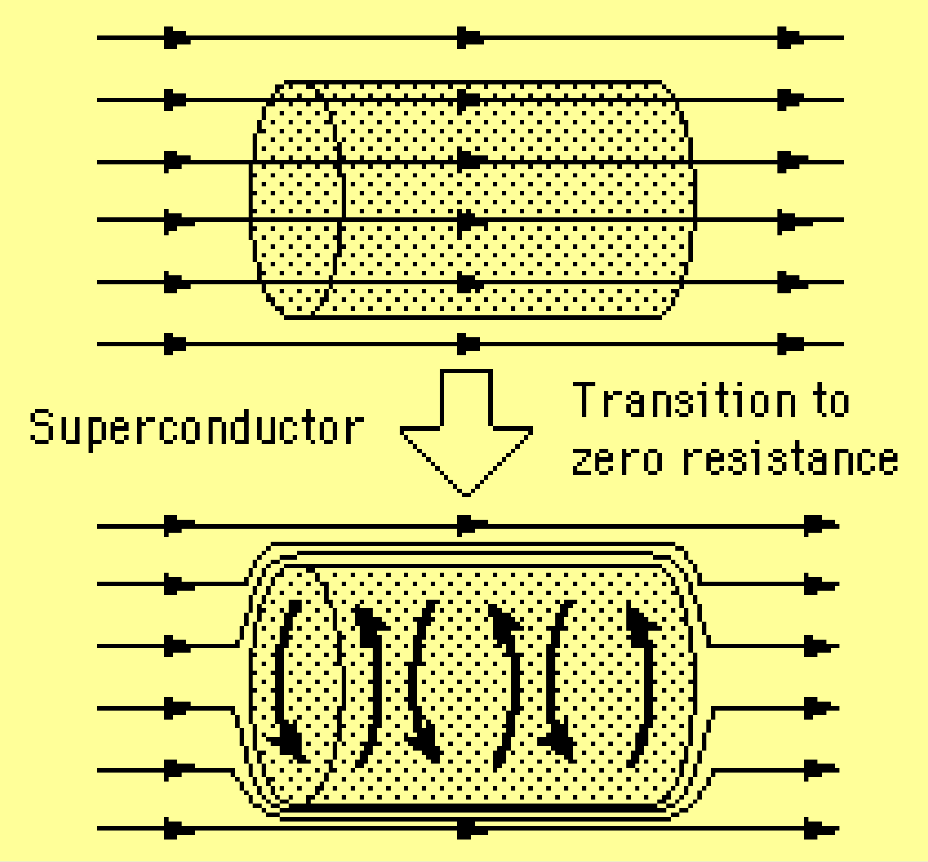
A superconductor is a perfect diamagnet. Superconducting material expels magnetic flux from the interior.

W. Meissner, R. Ochsenfeld (1933)

On the surface of a superconductor ($T<T_C$) superconducting current will be induced. This creates a magnetic field compensating the outside one.



Magnetic levitation



Screening (shielding) currents

No physics today !

It all gets very complicated and a fair number of Nobel prizes have been won in the area of superconductor research.

In 1957 Bardeen, Cooper and Schrieffer developed the BCS theory of superconducting and were awarded a Nobel prize

Since that time there have been many developments (and Nobel prizes) with the current record standing at 138^{o}K.

Practical applications - I

Superconducting magnets and RF cavities

First used in a superconducting accelerator at Fermilab

Practical applications - II

The MRI scanner

Used in MRI scanners, where a very high field strength is required. MRI scanners need extremely powerful magnets and these use superconducting materials

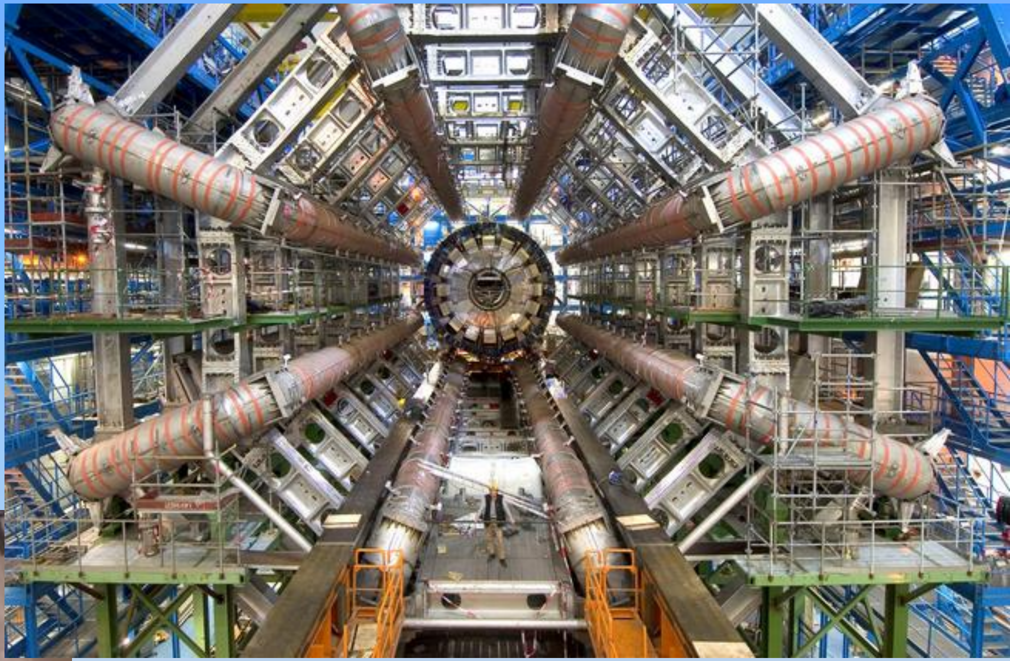
Practical applications - III

Superconducting magnets – even more

The world's biggest, most complex (and most expensive) installation is located at CERN and used on the Large Hadron Collider

Dipole magnets, one of the most complex parts of the LHC, are used to bend the paths of the particles.
There are 1,232 main dipoles, each 15 metres long and weighing in at 35 tonnes.
If normal magnets were used in the 27 km-long LHC instead of superconducting magnets, the accelerator would have to be 120 kilometres long to reach the same energy.
Powerful magnetic fields generated by the dipole magnets allow the beam to handle tighter turns.

Inside the Large Hadron Collider



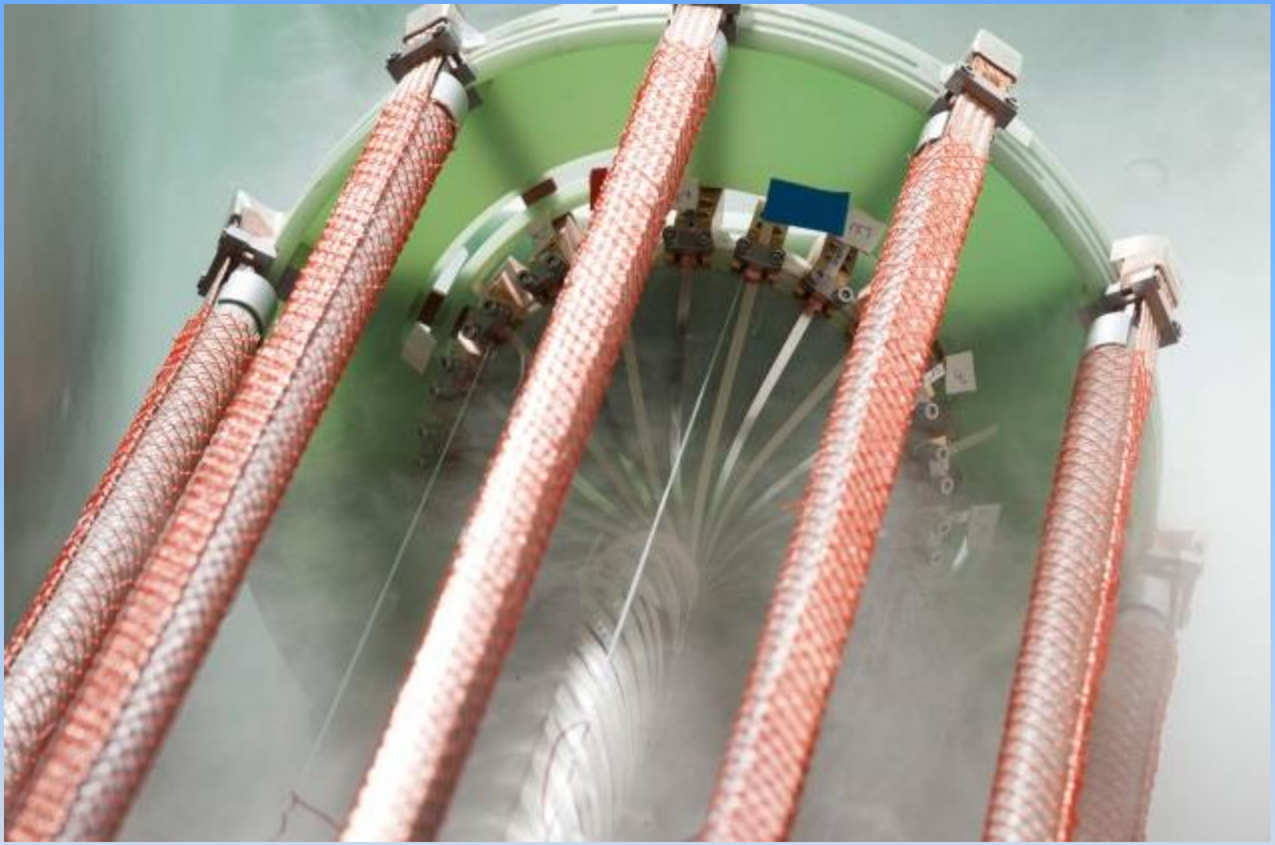
Practical applications - IV

But if superconducting materials can be engineered into cables it is possible to think of many applications in power distribution.

Remember !

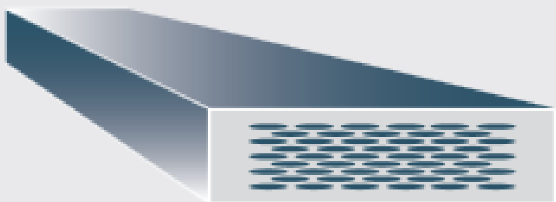
Resistance is useless!

Superconducting power cables



First generation power cable

BiSrCaCuO material “powder in tube” technology

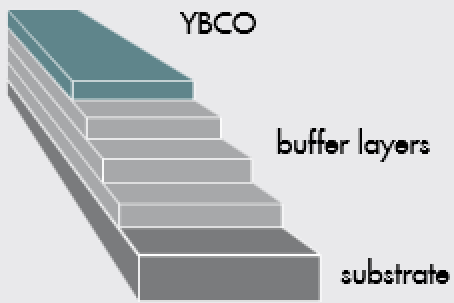


BSCCO: $Bi_2Sr_2Ca_2Cu_3O_{10}$
(Bi-2223)

- multifilamentary structure in silver matrix
- available in km length
- conductor current densities of 100 A/mm² and above commonly available at 77 K

Next generation power cable

YBa2Cu3O7 "coated conductors" technology

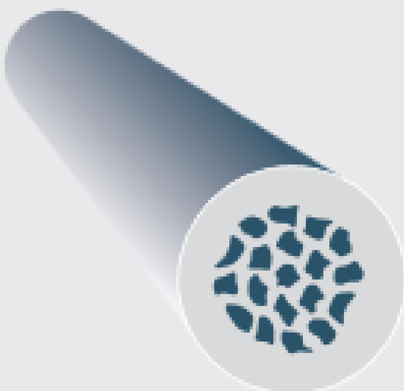


YBCO: $YBa_2Cu_3O_7$ (Y-123)

- coated conductor with multilayer structure
- current densities approaching 100 A/mm² at 77 K in tape lengths of hundreds of meters
- current densities and available tape length rapidly improving
- inherently better price/performance ratio than BSCCO
- number of buffer layers and materials depend on manu-facturer

Latest generation power cable

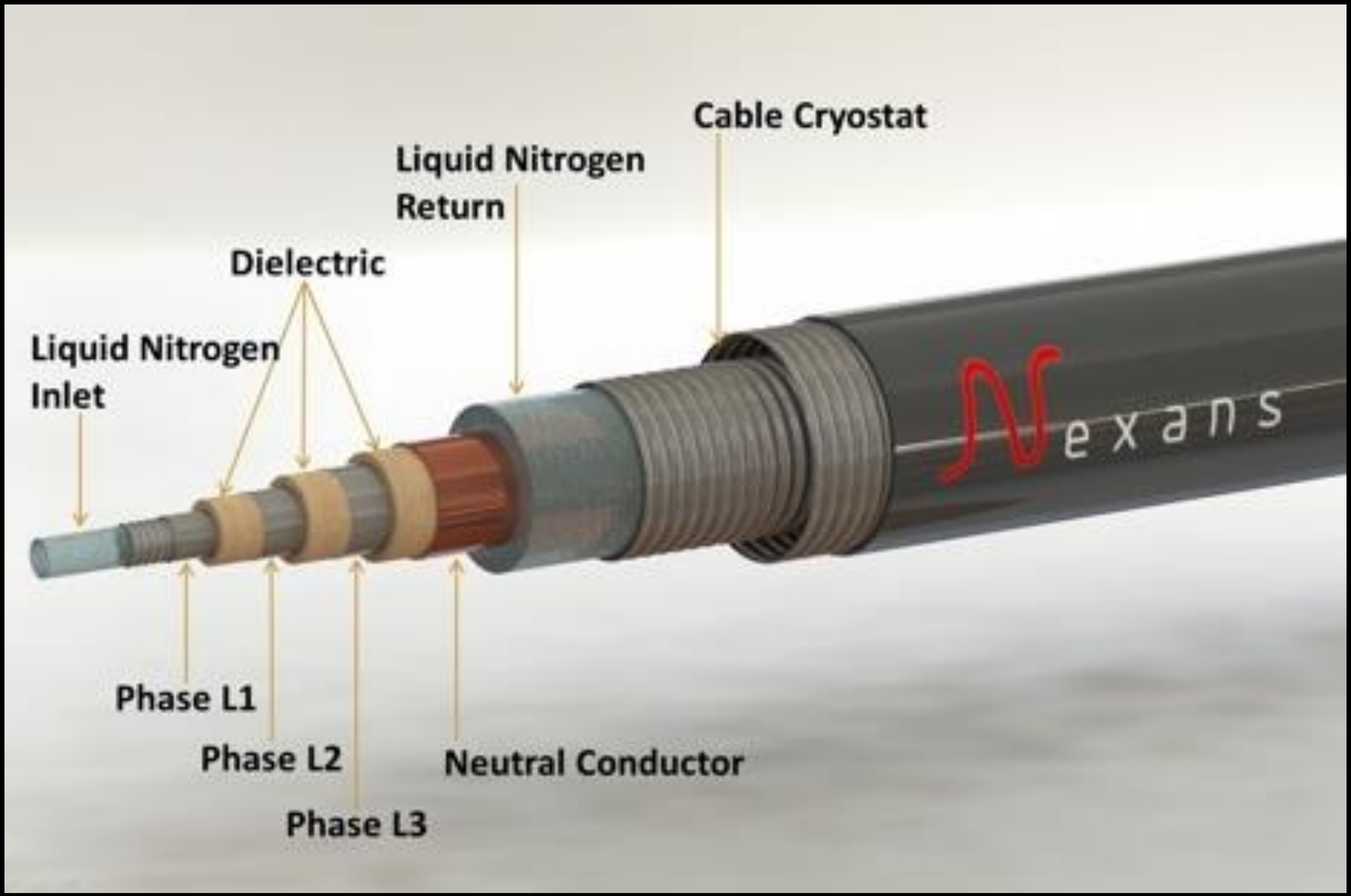
“multi-filament structure” technology MgB_2



MgB_2

- multifilamentary structure in matrix
- available in km length
- current densities of 1000 A/mm^2 available at 20K

A practical 3-phase cable



Terminating the cryogenics