CAN SUPERCONDUCTORS HELP WITH ENERGY AND ENVIRONMENTAL PROBLEMS?*

A. J. Leggett

Department of Physics,
University of Illinois at Urbana-Champaign

GYSS

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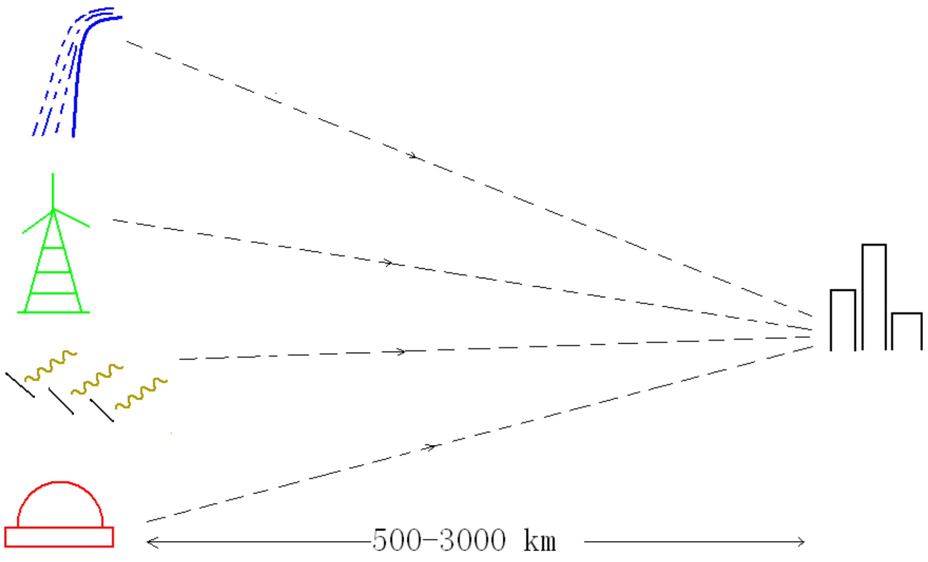
ELECTRICAL POWER GENERATION

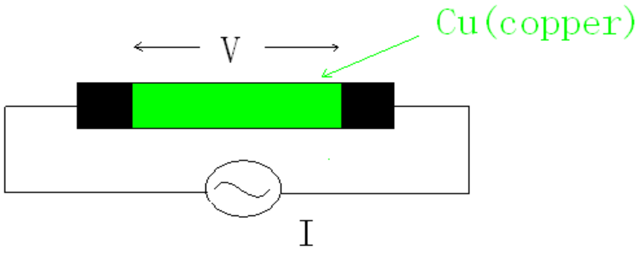
	US	China	World
Total annual electricity production (10^{12} kwh)	~4	~3	~19
Fraction dissipated in transmission	~8%	~7%	
Fraction from non-fossil sources	~30% (mostly nuclear)	~15% (mostly hydro)	~35%(+) (nuclear +hydro)



With increased use of non-fossil sources, fraction of generated energy dissipated in transmission is likely to increase substantially over next few decades, unless…

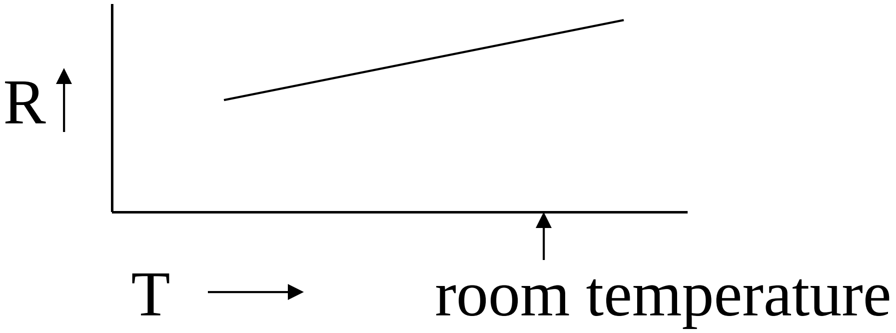
WHAT CONTROLS ELECTRICAL TRANSMISSION LOSSES?

For a given current, the loss is proportional to the resistance (R). The resistance is proportional to the distance over which power is transmitted, but for fixed distance depends on the material.



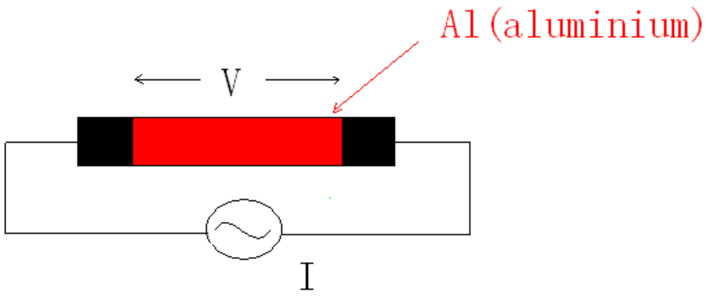
R=V/I

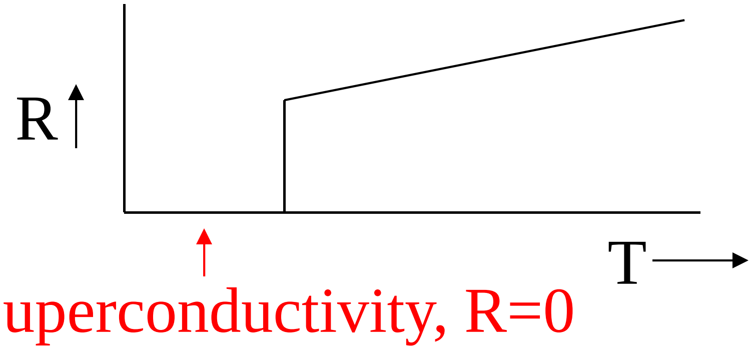
R depends on temperature (T):e.g., for Cu



So no great gain by cooling power lines.

But:





EXPERIMENTAL FACT:

For temperature below some “critical” temperature T_c (which depends on the material) and current below some “critical current density J_c (ditto), many materials including Al are superconductors, I.e., have zero (dc)[*] resistance. If we could use superconductors for long-distance power transmission, we would have

ZERO TRANSISSION LOSS!

Some other advantages of using superconductors for transmissional storage of electrical energy:

Automatic quenching of “runaway” current

High current density ⟹ smaller transmission lines (e.g. underground)

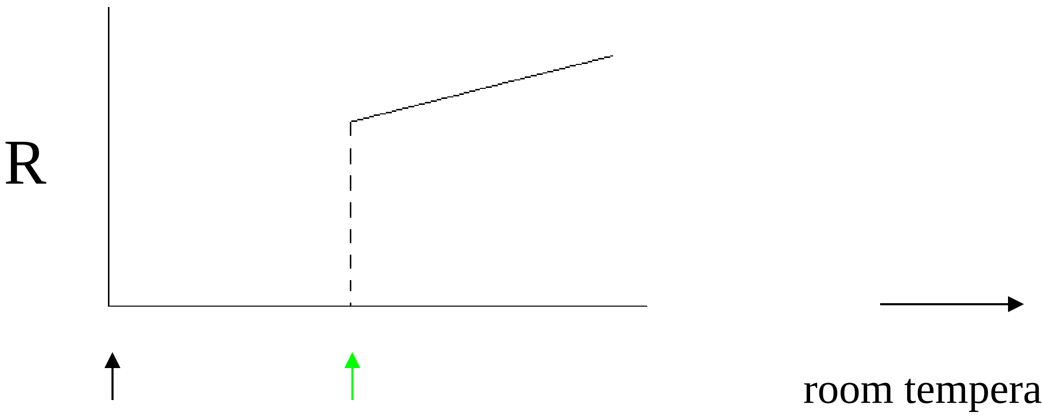
Lossless magnetic energy storage

……

ALAS, ONE SLIGHT PROBLEM:

IN MOST MATERIALS, T_c IS VERY LOW!

e.g.Al: superconductivity



Absolute zero

(0 K, -273.15 C)

T_c

(1.3K, -271.8 C)

room temperature

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[*] Ac resistance is nonzero but extremely small at low (~50 Hz) frequencies

OUR UNDERSTANDER OF (TRADITIONAL) SUPERCONDUCTIVITY

The occurrence of superconductivity in a material such as Al can be understood in terms of a theory due to Bardeen, Chooper, and Schrieffer (1957), ("BCS") roughly as follows:

According to the principles of quantum mechanics, "particles" can be classified into two types:

"fermions"-- very xenophobic

"bosons"– very gregarious

Under appropriate conditions, bosons display the phenomenon of "Bose Einstein condensation (BEC)": all must behave in exactly the same way. ("platoon of well-drilled soldiers")

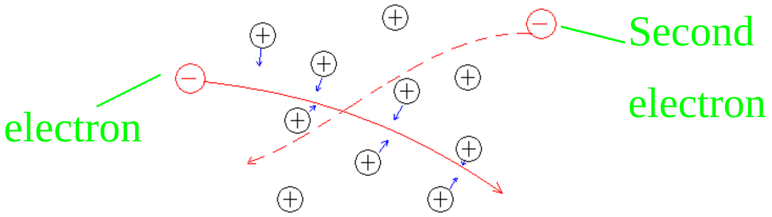
Electrons in materials are fermions, so cannot undergo BEC directly. However,

2 fermions = 1 boson

So, if electrons can form pairs ("di-electronic molecules") then the pairs can undergo BEC.

To form "molecules", electrons must experience an effective attraction. But Coulomb interaction is repulsive!

In BCS theory, this repulsion may be outweighed by effective attraction due to polarization of the ionic lattice:



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Molecule
of the
Year

en complete

the
Bose-Einstei
Condensate

Superconductivity was discovered in 1911, and for the next 75 years was found to occur only under ~25 K (-248 °C). To get to such low temperature one must to cool material with liquid helium. So while it's practical to use superconductors for e.g., geophysical magnetometry, application to large scale power transmission out of the question (not enough helium in the world!)

WHY IS T_c SO LOW?

BCS theory gives an explanation:

$T_c \sim T_D \times$ ⟵ Dimensionless factor
F ↑

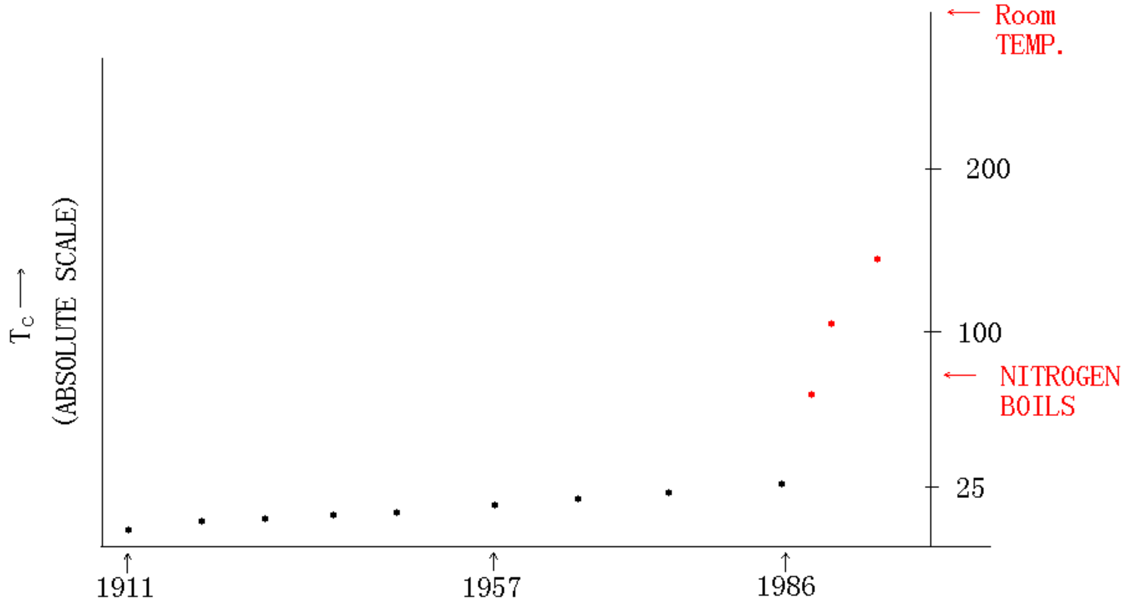
Characteristic ("Debye") temperature of ionic lattice, typically~room temperature.

In BCS theory, there are strong arguments that the factor F can never exceed ~0.1

⟹ T_c always $\lesssim$ 30 K (-243°C)

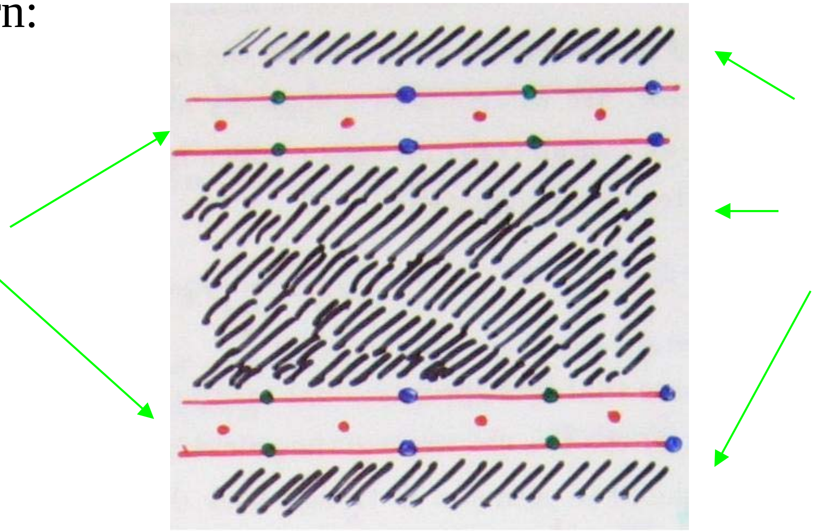
…….

AND YET…



THE HIGH-TEMPERATURE (CUPRATE) SUPERCONDUCTORS

Generic Pattern:



CuO_2

Coper oxide)

planes

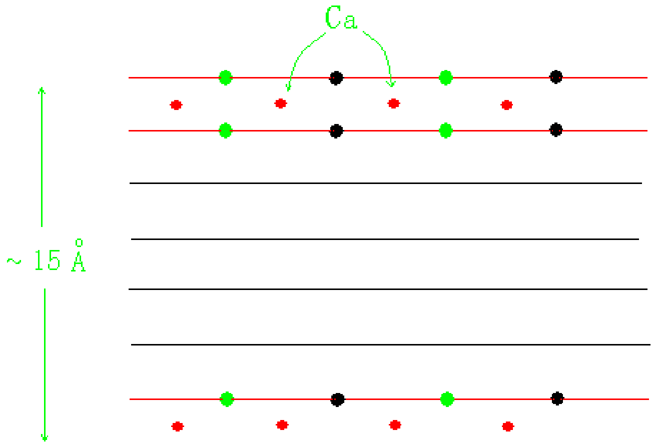
“charge reservoir” layers

example:

BSCCO-2212

($Bi_2Sr_2CaCu_2O_8$)

(T_c=95K)



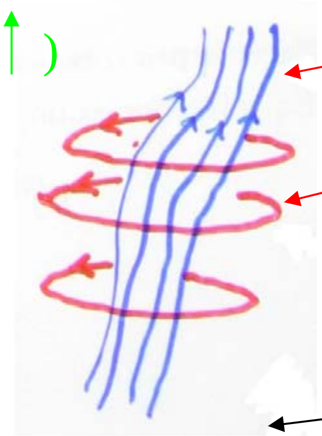
CuO_2
CuO_2
SrO
BiO
BiO
SrO
CuO_2
CuO_2

Critical current is very high along CuO_2 planes (→),

much smaller perpendicular to planes (↑)

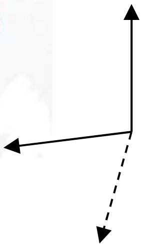
In practice, critical current usually determined by motion of vortices, which always occur in a large magnetic field: vortex moves perpendicular to field and to current, and thereby produces voltage

⟹ nonzero resistance.



Magnetic field

Circulating current



field

current

Motion of vertex

APPLICATION OF HIGH-TEMPERATURE SUPERCONDUCTIVITY TO GRID:

2 MAJOR AVENUES OF RESEARCH

1.Using existing (cuprate) high-temperature superconductors

(BSCCO, YBCO($YBa_2Cu_3O_{6+x}$),…)

Already practical for special purposes (e.g. transformers, current fault limiters, offshore wind power…). Also, pilot cables (up to ~1 km) already in operation.

But, for large-scale power transmission, need (inter alia)

- large reduction in manufacturing cost

(currently >> Cu)

- reduction in cost of refrigeration (50-77K)

- most importantly: increase in $J_c(H,T)$

critical current

magnetic field

temperature

Since the factor limiting electrical current is motion of vortices, most promising route to higher J_c is to final better ways to pin vortices.

(ex.:irradiate with fast ions so as to produce “columnar ” defects)

What microscopic conditions are best for pinning of vortices? A major challenge to current microscopic theory of superconductivity in cuprates!

2nd major avenue of research:

2. By understanding superconductivity in cupraters, or otherwise, find better high-temperature superconductors (ideally: T_c>room temperature, “large” $J_c(H,T)$).

Problem: we don’t understand superconductivity in the cuprates! (in particular, why T_c is so high).

Recall: to form “di-electronic molecules” appear to need effective attractive between electrons. In BCS theory this can be provided by polarization of ionic lattice. (but then predicts $T_c \lesssim$ 30K).

Anyway, much evidence that in cuprates effect of ionic lattice is at best secondary.

So, much get superconductivity out of Coulomb repulsion between electrons!

This is a MAJOR challenge for theoretical condensed matter physics (~10^4 papers since 1986)

If we can solve it, then we may know where to look for room temperature superconductivity in the “haystack” of possible compounds. (no. of possible 5-element compounds ~10^{10} $\Rightarrow$ 10^6 person-years of research!)

My guess: look for

Strongest possible repulsion

Strongly layered (2D) structure

weak inter-layer tunneling contact

anomalous optical properties (“MIR peak”)

SUMMARY

1. In principle, superconductors could greatly improve the electrical grid, saving a large fraction of the energy currently dissipated in transmission.
2. However, the "classic" (pre-1986) superconductors have much too low values of T_c and J_c to be practical.
3. The high-temperature (cuprate) superconductors are much more promising, but still need improvement, in particular to increase J_c.
4. There seems no reason in principle why we should not get (robust) superconductivity at room temperature.
5. However, to know where to look for it we urgently need to understand superconductivity in the cuprates. Most fundamental theoretical question ⟹ most practical application!

WILL WE HAVE ROOM-TEMPERATURE SUPERCONDUCTIVITY BY 2050? MY BET: YES!