SHANGHAI JIAO TONG UNIVERSITY
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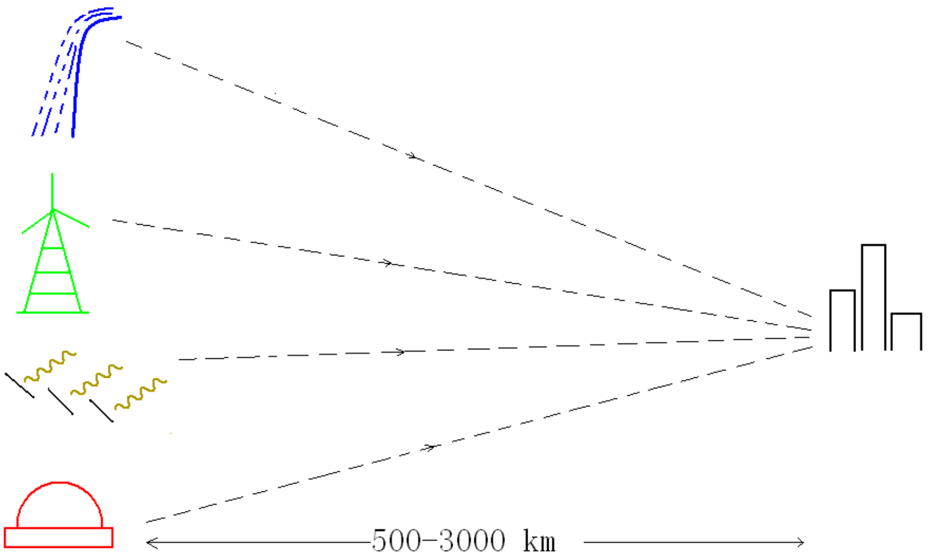
ELECTRICAL POWER GENERATION

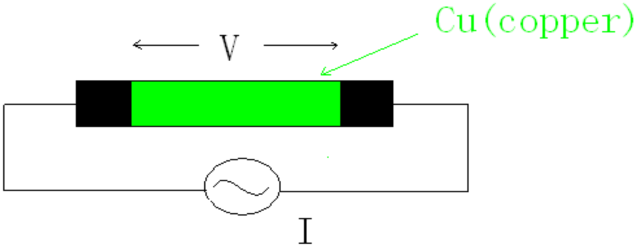
	US	China	World
Total annual electricity production (10^{12} kwh)	~4	~3	~19
Fraction dissipated in transmission	~8%	~7%	
Fraction from non-fossil sources	~30% (mostly nuclear)	~15% (mostly hydro)	~35%(+) (nuclear +hydro)



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

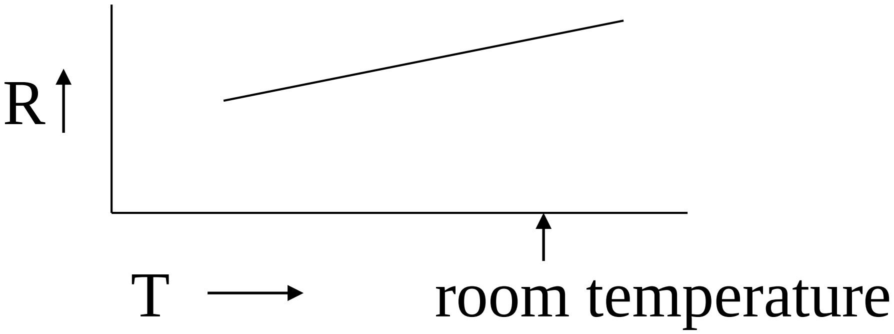
WHAT CONTROLS ELECTRICAL TRANSMISSION LOSSES?

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.



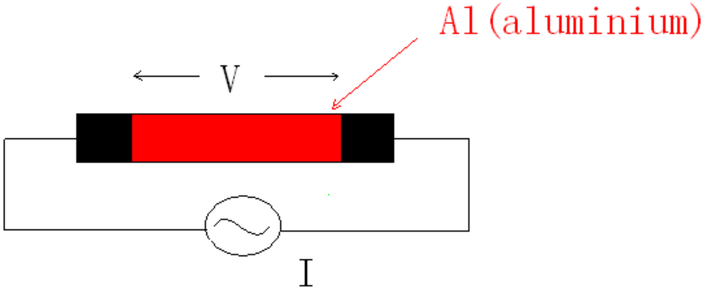
R=V/I

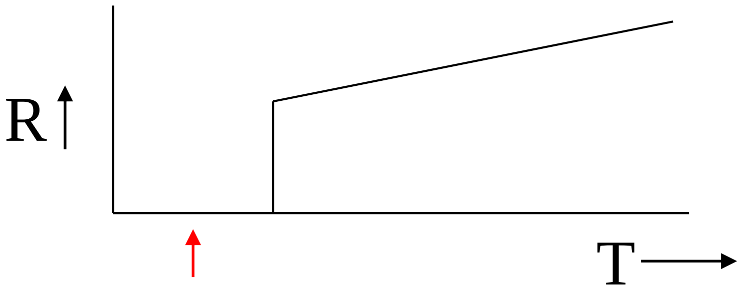
R depends on temperature (T):e.g., for Cu



So no great gain by cooling power lines.

But:





Superconductivity, R=0

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)

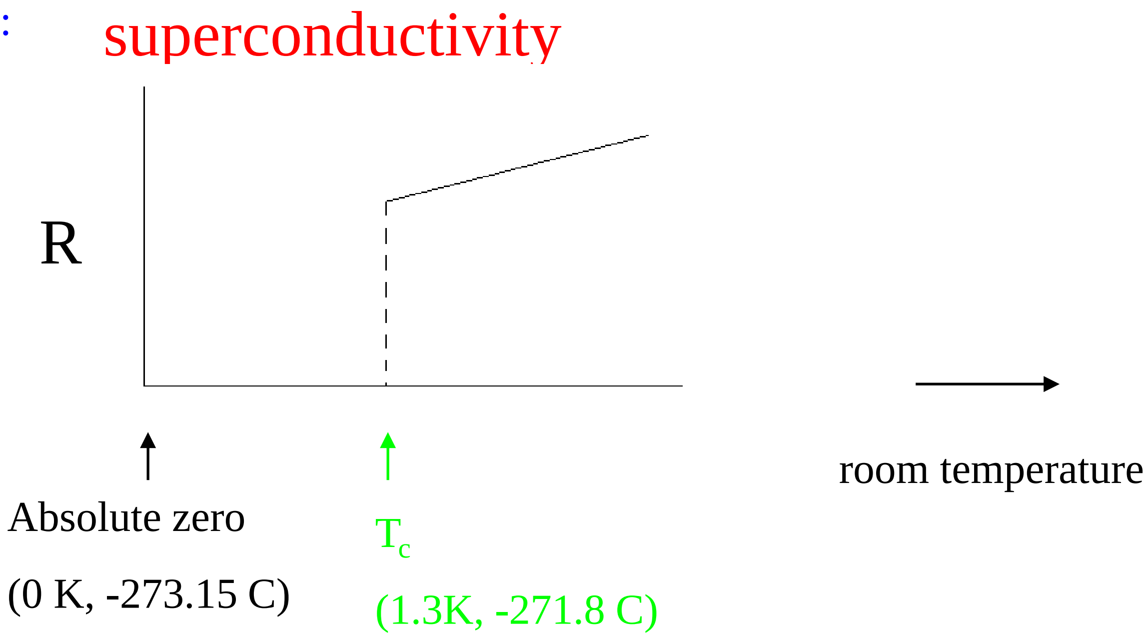
Lossless magnetic energy storage

……

ALAS, ONE SLIGHT PROBLEM:

IN MOST MATERIALS, T_c IS VERY LOW!

e.g.Al:



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

Superconductivity was discovered in 1911, and for the next 75 years was found to occur only under ~25 K (-248 ^{o}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:

$T_c \sim T_D \times F$ ← Dimensionless factor

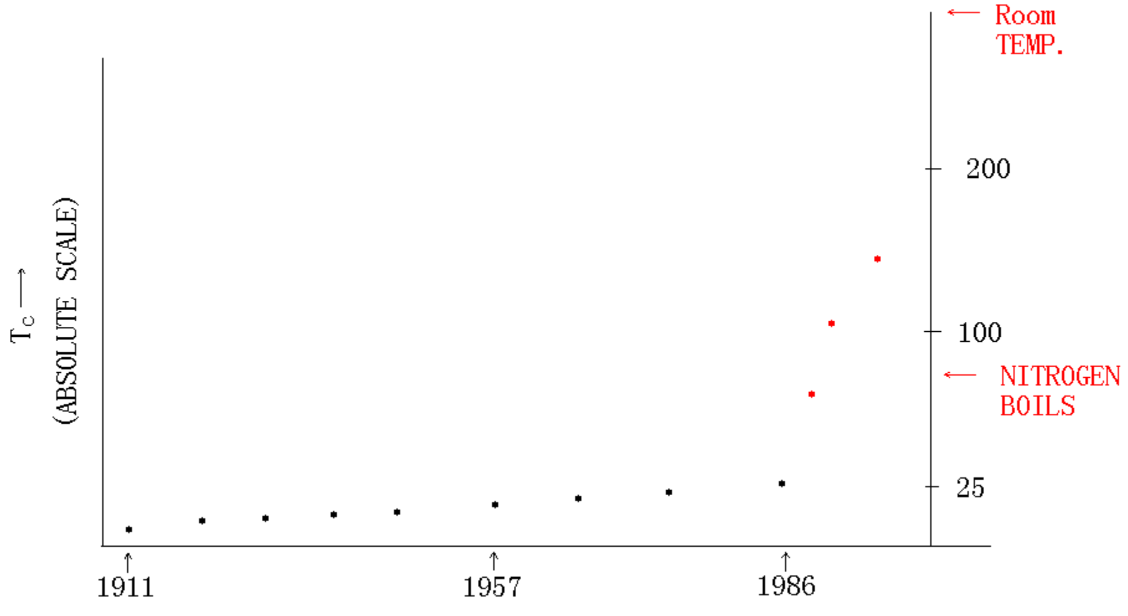
Characteristic ("Debye") temperature of ionic lattice, typically~room temperature.

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

$\Rightarrow$ T_c always $\lesssim$ 30 K (-243^{o}C)

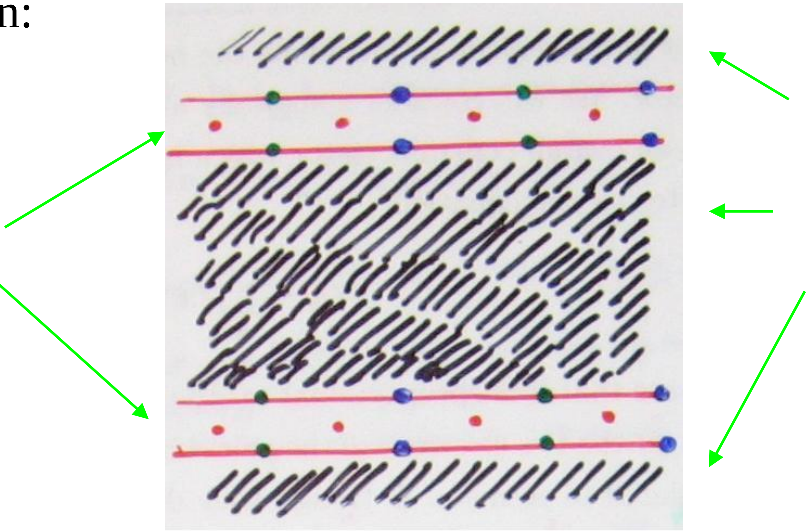
…….

AND YET…



THE HIGH-TEMPERATURE (CUPRATE) SUPERCONDUCTORS

Generic Pattern:



CuO_2

Coper oxide)

planes

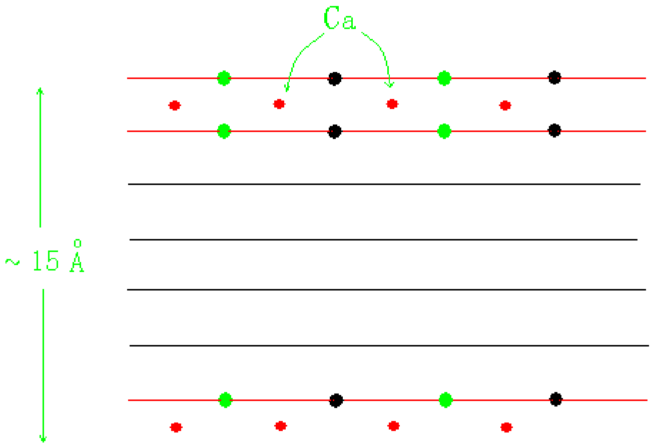
“charge reservoir” layers

example:

BSCCO-2212

$(Bi_2Sr_2CaCu_2O_8)$

$(T_c=95K)$



CuO_2

CuO_2

SrO

BiO

BiO

SrO

CuO_2

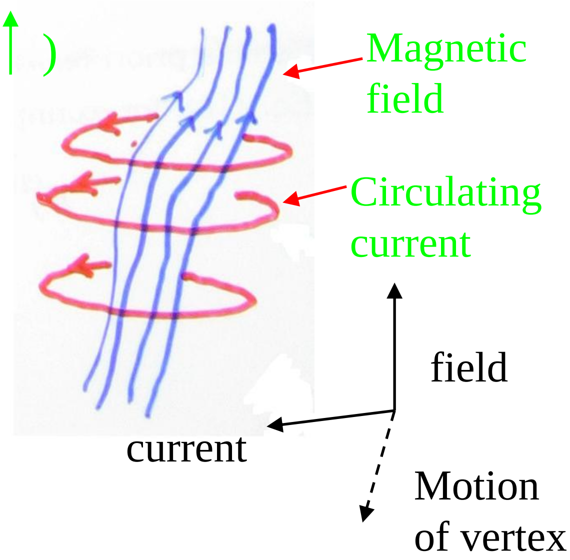
CuO_2

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.



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 $J_c(H,T)$

temperature

critical current

magnetic field

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!

2^{nd} 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} $\Longrightarrow$ 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”)

Other (actual and potential) applications:

Superconducting levitation:

(Condensation energy of YBCO at $T = 0 \sim 0.5\ \mathrm{MJ/m^3}$: energy neccessary to levitate Tosanoumi $\sim 15\ \mathrm{J}$. ← sumo wrestler

main problem: "mobile" supply of liquid N2!

again, room-temperature superconductivity would solve problem....

Magnetometry:

Recall that for dc SQUID

$$I = I_{c0}|\cos\pi\Phi/\Phi_0|$$

⇒ very accurate measurement of Φ, hence of B.

applications: magnetoencephalography, geographical prospecting...

Quantum computing:

needs set of two-state systems ("qubits") such that one can prepare and manipulate quantum superpositions of form

$$\Psi = a|\uparrow\rangle + b|\downarrow\rangle$$

while minimizing effects of decoherence. Prima facie optimal candidates:

microscopic systems well shielded from environment (nuclear spins, trapped single ions...) But...