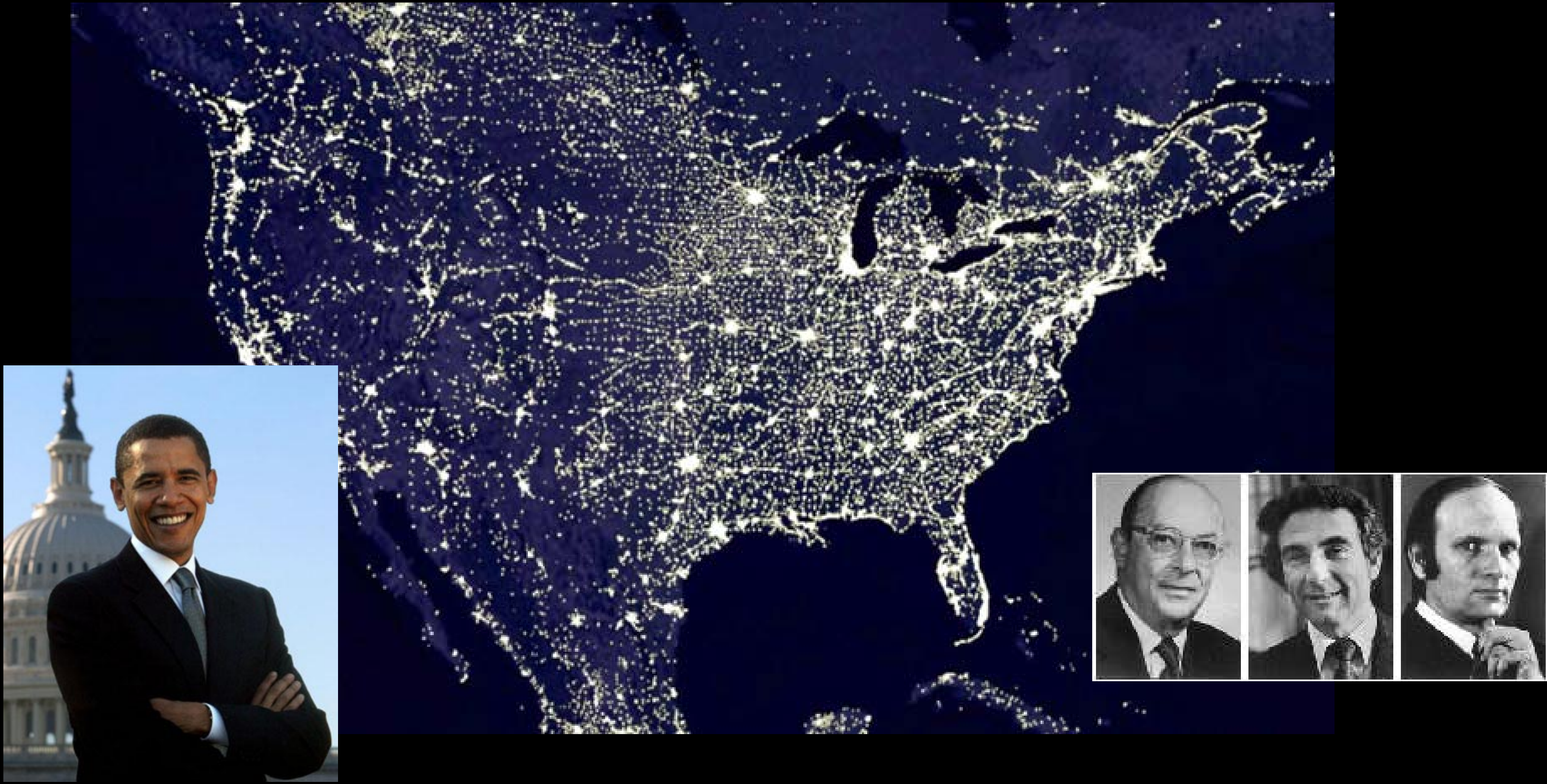
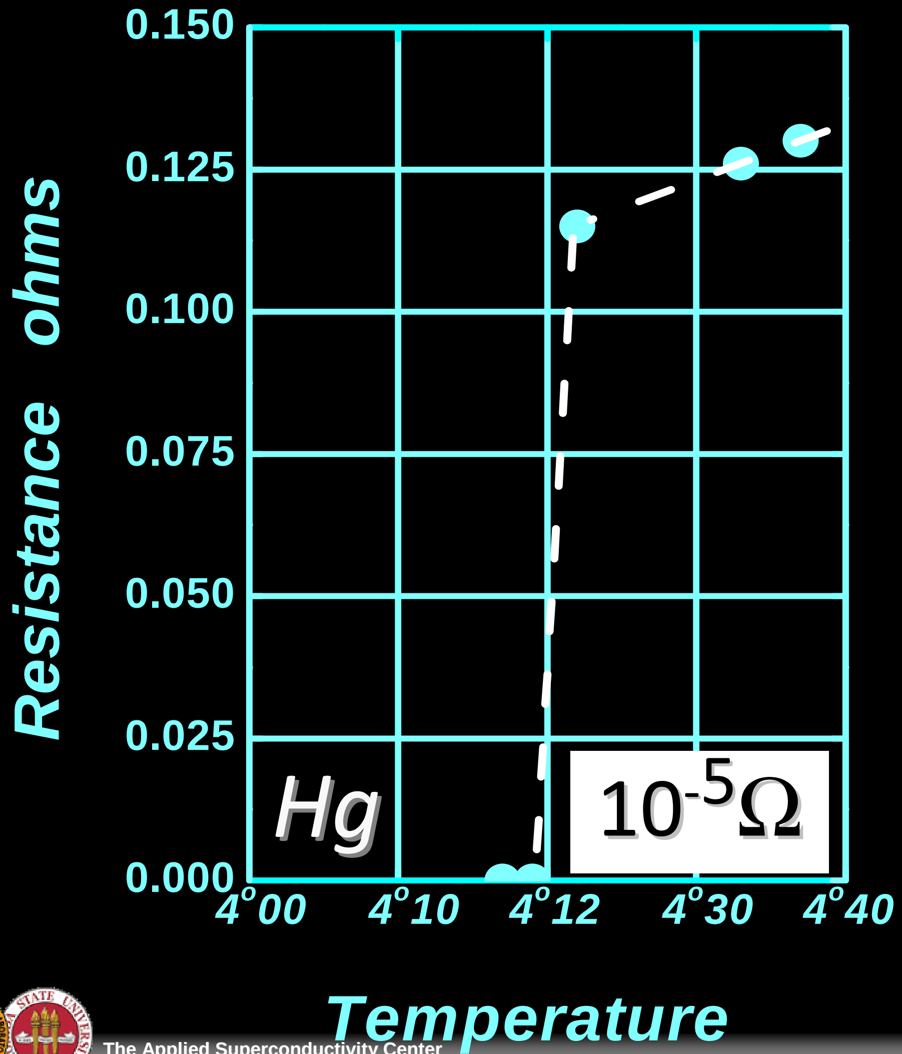
Superconductivity – from physics to power grid



The Discovery of Superconductivity

H. Kammerlingh Onnes, 1911, Lieden



Resistance goes to zero below a Critical Temperature, Tc

Important for the Power Grid …

What causes superconductivity?

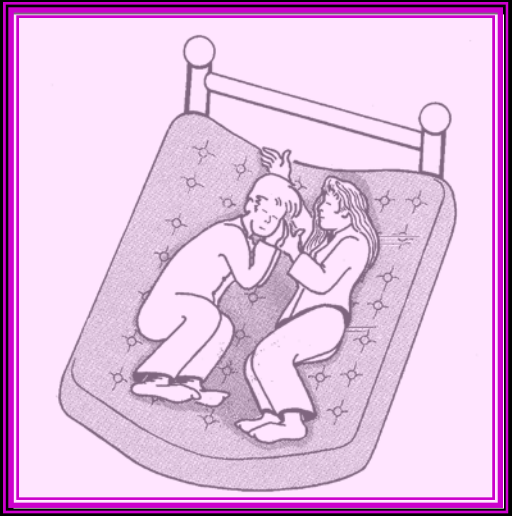
BCS Theory (Illinois, 1957)

Bardeen, **C**ooper and **S**chrieffer

- Electrons become coherent by pairing up into "**Cooper Pairs**"

The underlying lattice acts as the "glue" for pairing electrons

*Strength of this glue is the **"Energy Gap"***

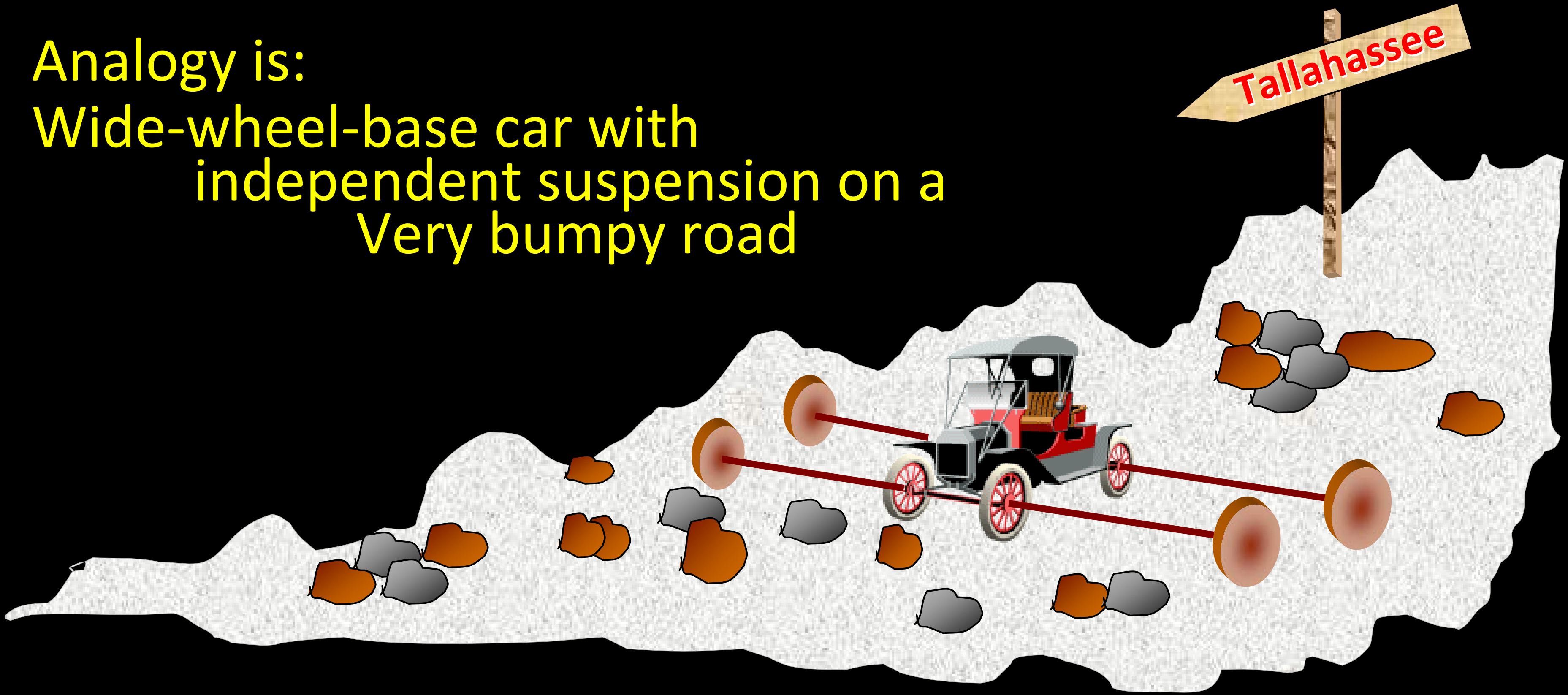


Soft Mattress Analogy

Cooper Pairs are Correlated Electrons: Transport electricity without Resistance

Analogy is:

Wide-wheel-base car with
independent suspension on a
Very bumpy road

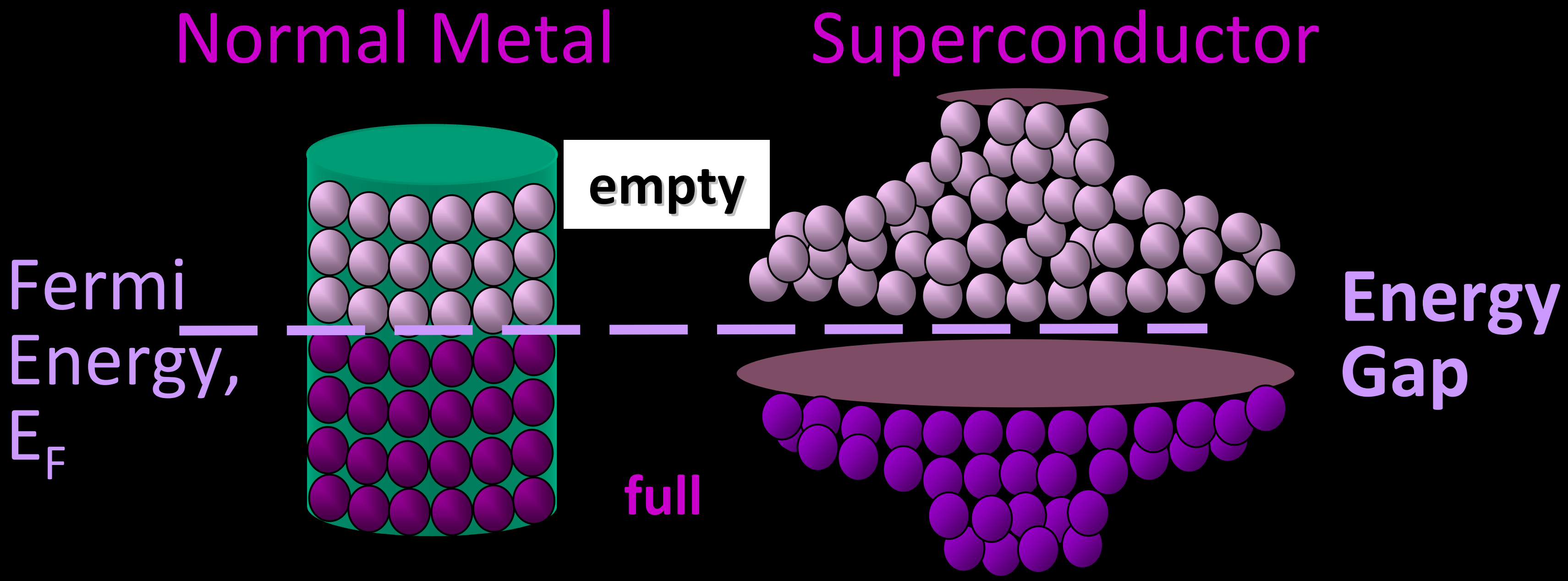


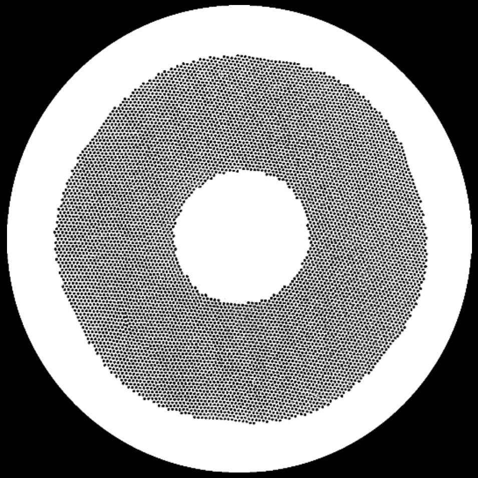
A single wheel will be scattered from the road.

Truck with “correlated wheels” travels smoothly

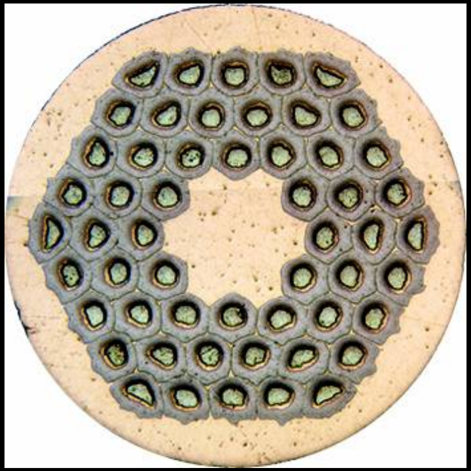
The energy gap:

Broken phase symmetry lowers electron energy

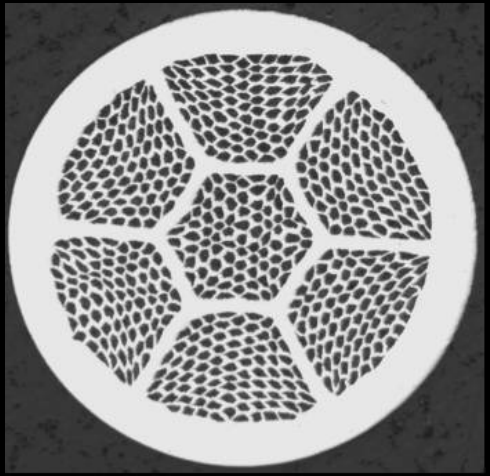




Nb47Ti filaments in Cu



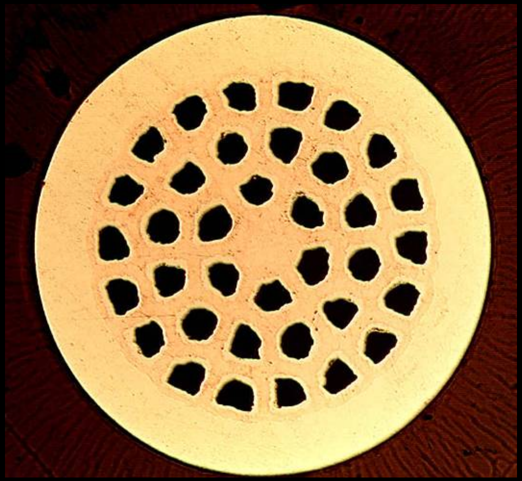
Nb_3Sn filaments in Cu



Bi-2212 in silver

Bi-2223 filaments in silver

The preferred conductor form is as many superconducting filaments embedded in ~1 mm diameter wire which has a good normal (i.e. not superconducting) conductor in parallel – silver must be used with the Bi cuprates because oxygen needs to pass through the matrix to get best properties in the Bi-HTS



MgB_2 filaments in Cu

Low Temperature Superconductors

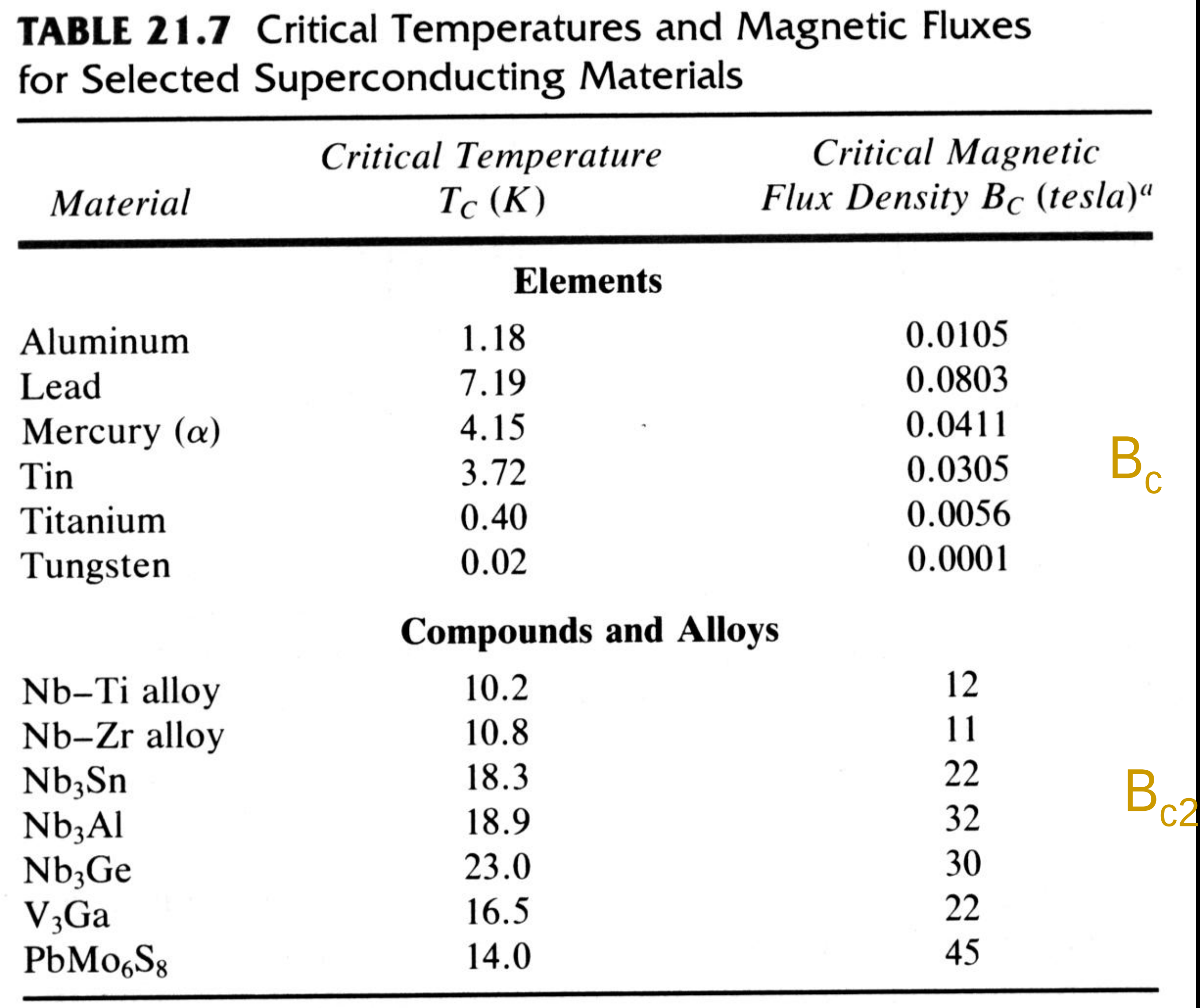


TABLE 21.7 Critical Temperatures and Magnetic Fluxes for Selected Superconducting Materials

Material	*Critical Temperature* T_C *(K)*	*Critical Magnetic Flux Density* B_C *(tesla)*[a]
	Elements	
Aluminum	1.18	0.0105
Lead	7.19	0.0803
Mercury (α)	4.15	0.0411
Tin	3.72	0.0305
Titanium	0.40	0.0056
Tungsten	0.02	0.0001
	Compounds and Alloys	
Nb–Ti alloy	10.2	12
Nb–Zr alloy	10.8	11
Nb_3Sn	18.3	22
Nb_3Al	18.9	32
Nb_3Ge	23.0	30
V_3Ga	16.5	22
$PbMo_6S_8$	14.0	45

Type I

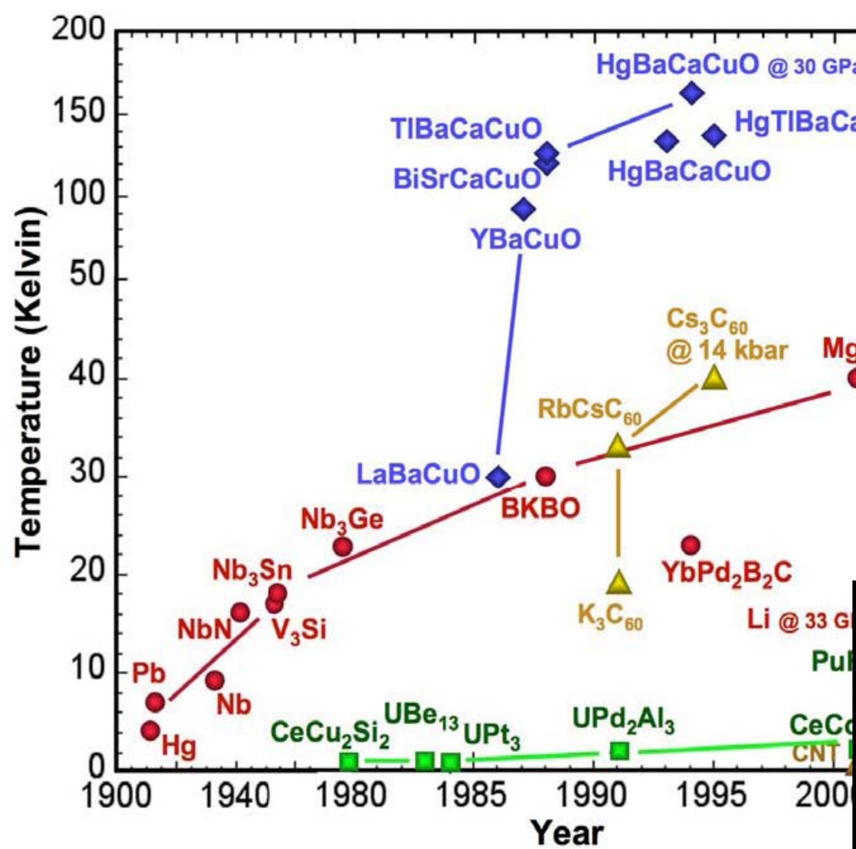
B_c

Type II

B_{c2}

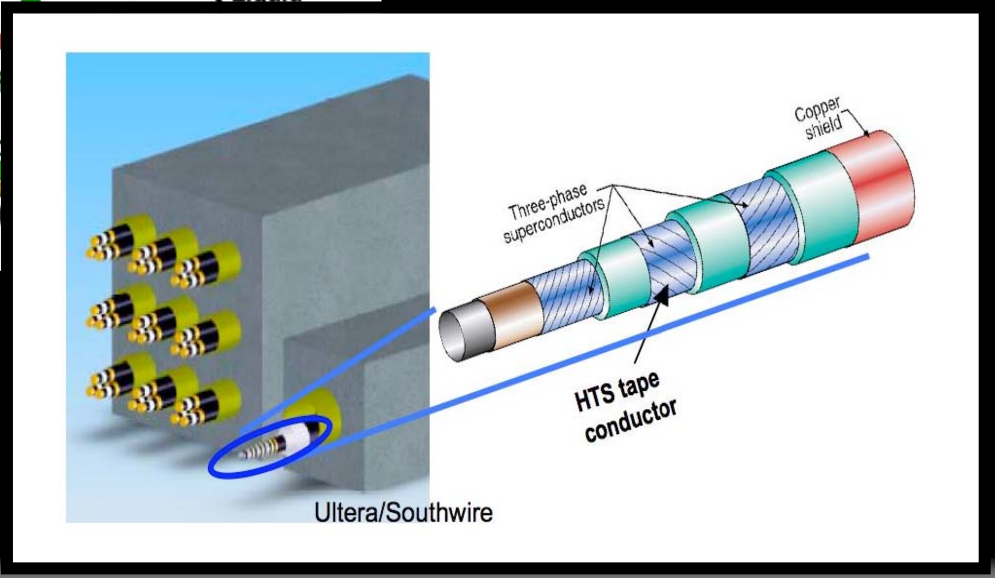
High-Temperature Superconductivity

Bednorz and Müller, 1986, Zürich



Today:

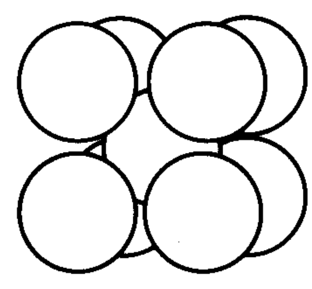
- Over 5,500 cell-phone towers contain high-temp SCs



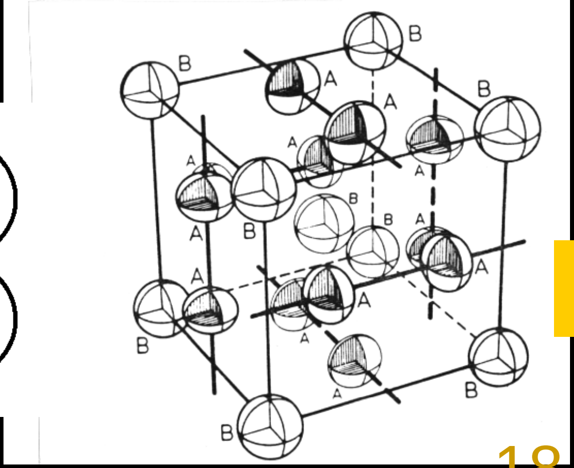
Ultera/Southwire

Higher Tc – greater complexity

Nb-Ti

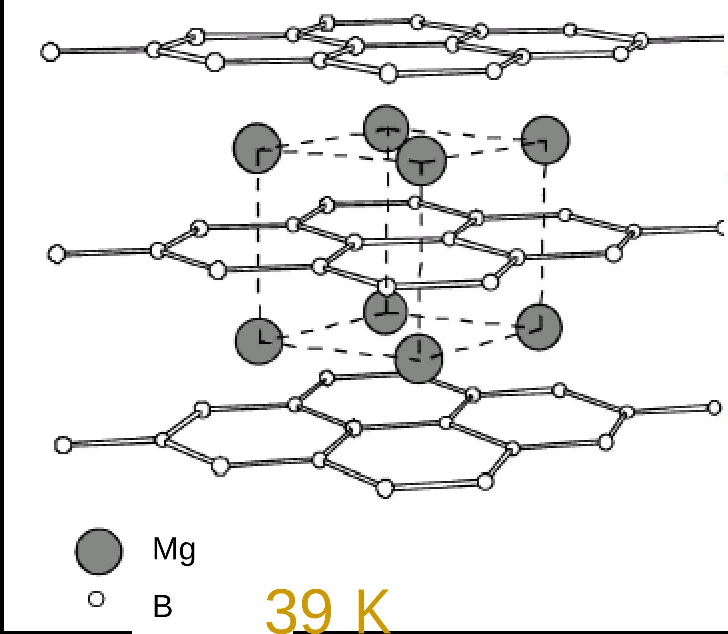


9 K



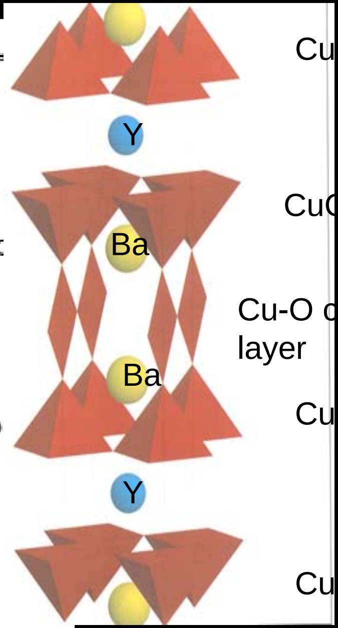
Nb_3Sn

18-23 K



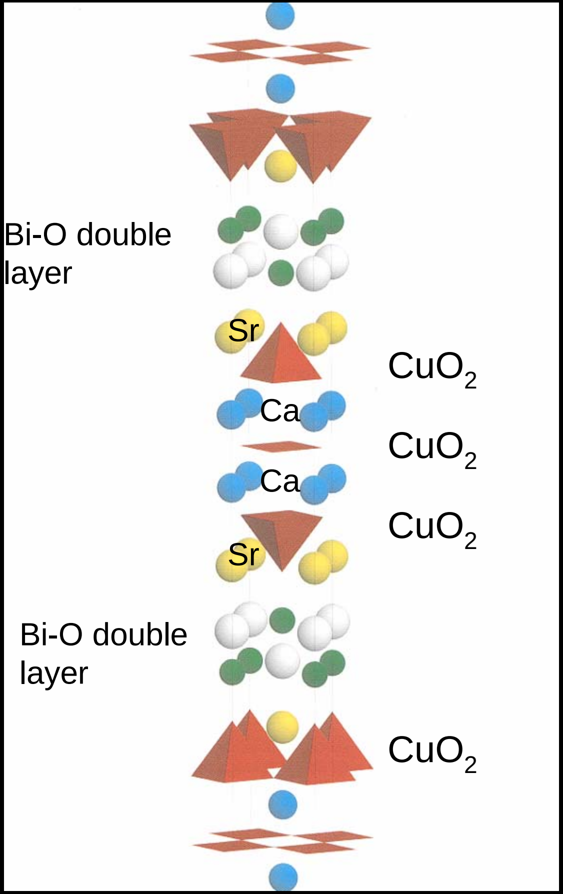
39 K

MgB_2



92-95 K

YBCO

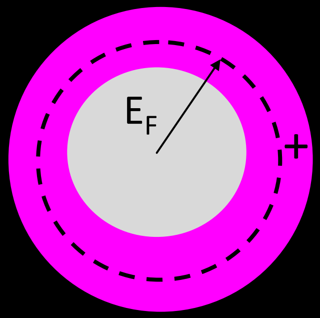


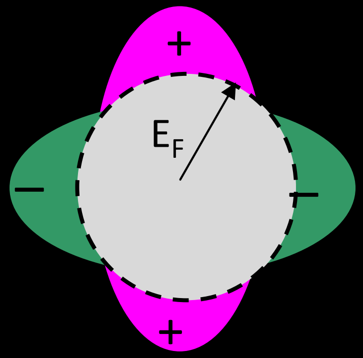
110 K

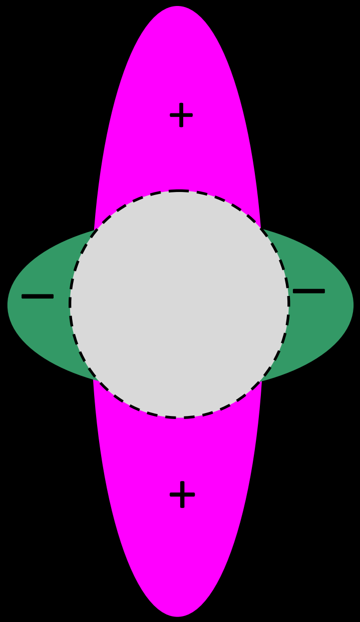
Bi-2223

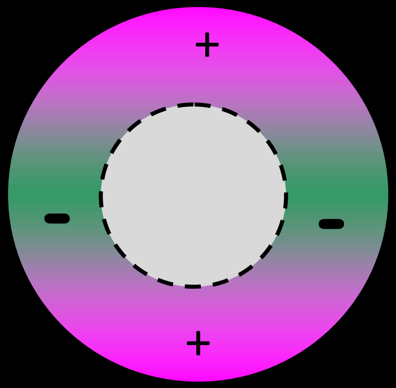
Energy Gap of a Superconductor:

Conventional, unconventional and mixed states:



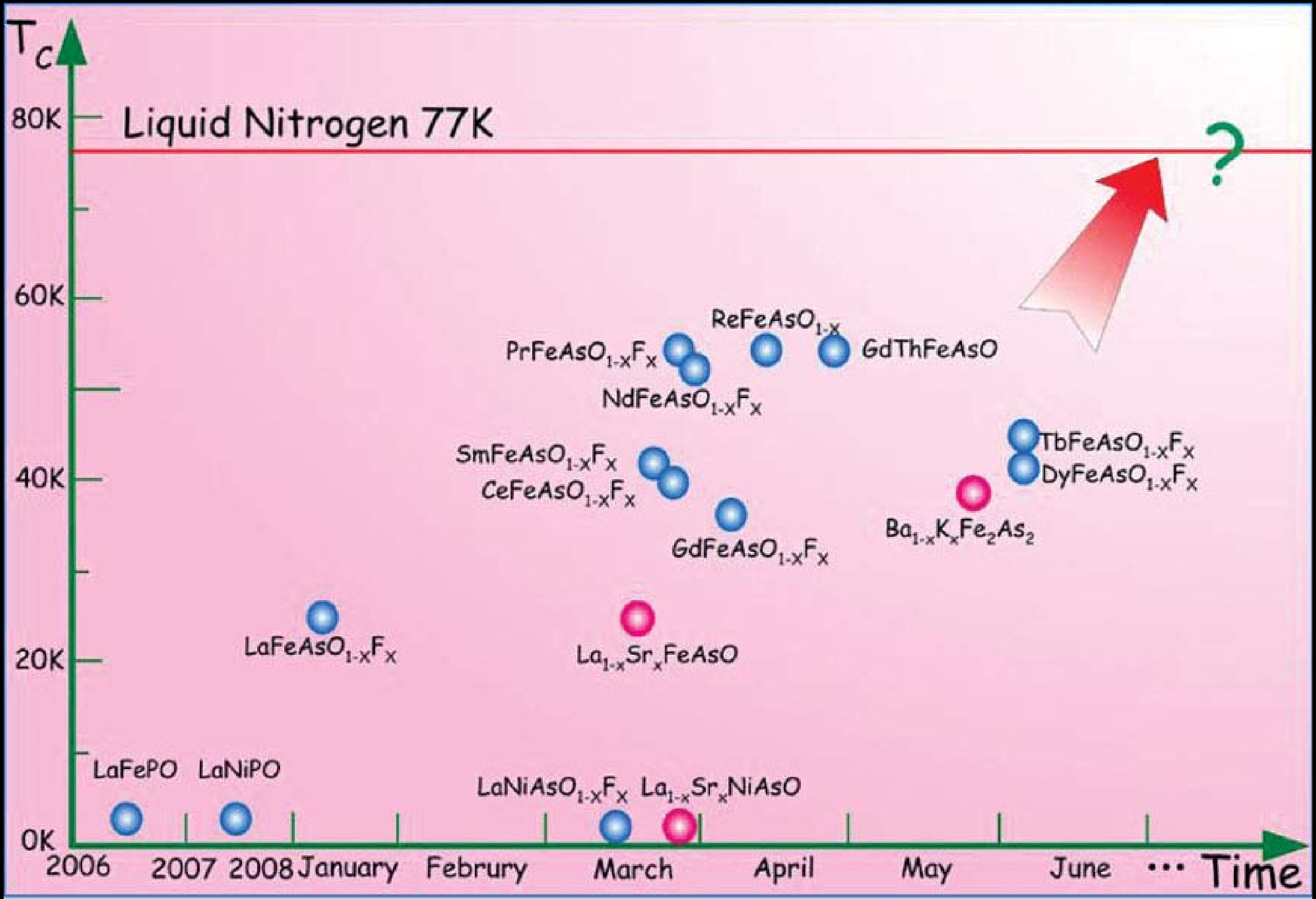






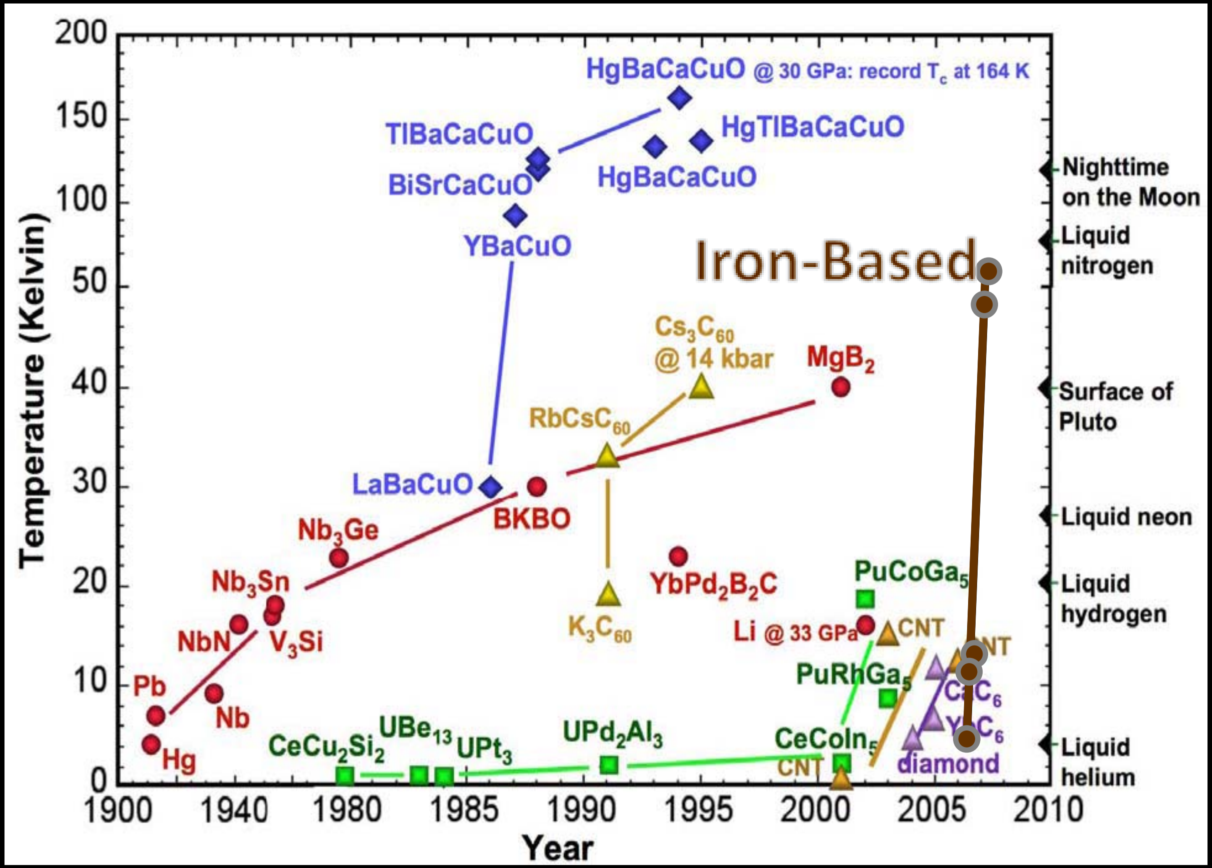
2008 - New Iron Age!

Iron-based HTS !!!



Today's "Tc vs. Time" with NEW HTS

The First HTS are NOT UNIQUE!!!



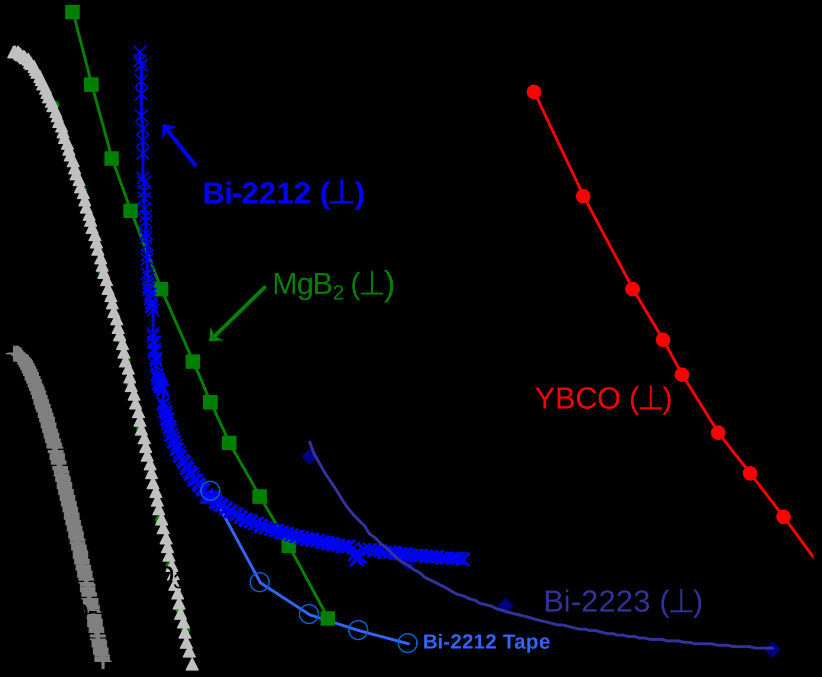
A SECOND class of HTS found, so there MUST be a THIRD!

Needed for understanding HTS etc.,…

and

the Power Grid

Applications



The NHMFL 900-MHz
Ultra-Wide Bore (2004)

We can make fields up to ~2/3 of the transition line

State of the art Nb_3Sn 900 MHz NMR magnet, operating in persistent mode at 21T, 950 MHz

Superconductivity at 500 km/hr

Japanese railways MagLev train

First LTS, now HTS – wire-wound magnets, not bulk lumps!

- Yamanashi Test Site, Japan
- 33 km long, >500 Km/hr
- Segment of Tokyo-Osaka new line

MRI Magnets

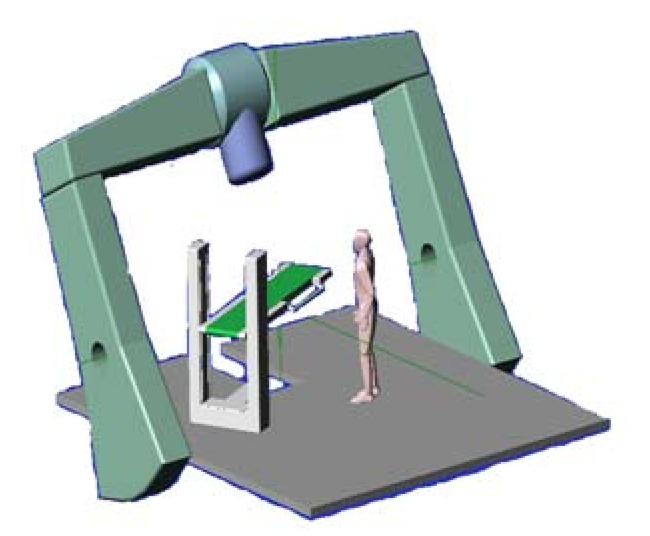
Closed (1-3 Tesla) and open (0.3T) MRI magnets both use Nb-Ti with a transition temperature (Tc) of only 9K, ~-450F.

Cooled only by liquid helium until late 2006 - new MgB_2 MRI machine can now operate without liquid on a refigerator

Nb_3Sn could make Proton Therapy cancer treatment affordable

Problem:

- One room plus equipment: >$50 million
- Four rooms plus equipment: >$100 million
- Big problem to manage project,



Solution: High-field weak focusing cyclotron

- Superconducting magnets reduce size of accelerator
- Allows retrofit into existing space
- Cost – less than $15M

Controlled Thermonuclear Fusion requires intense fields to “bottle” the plasma

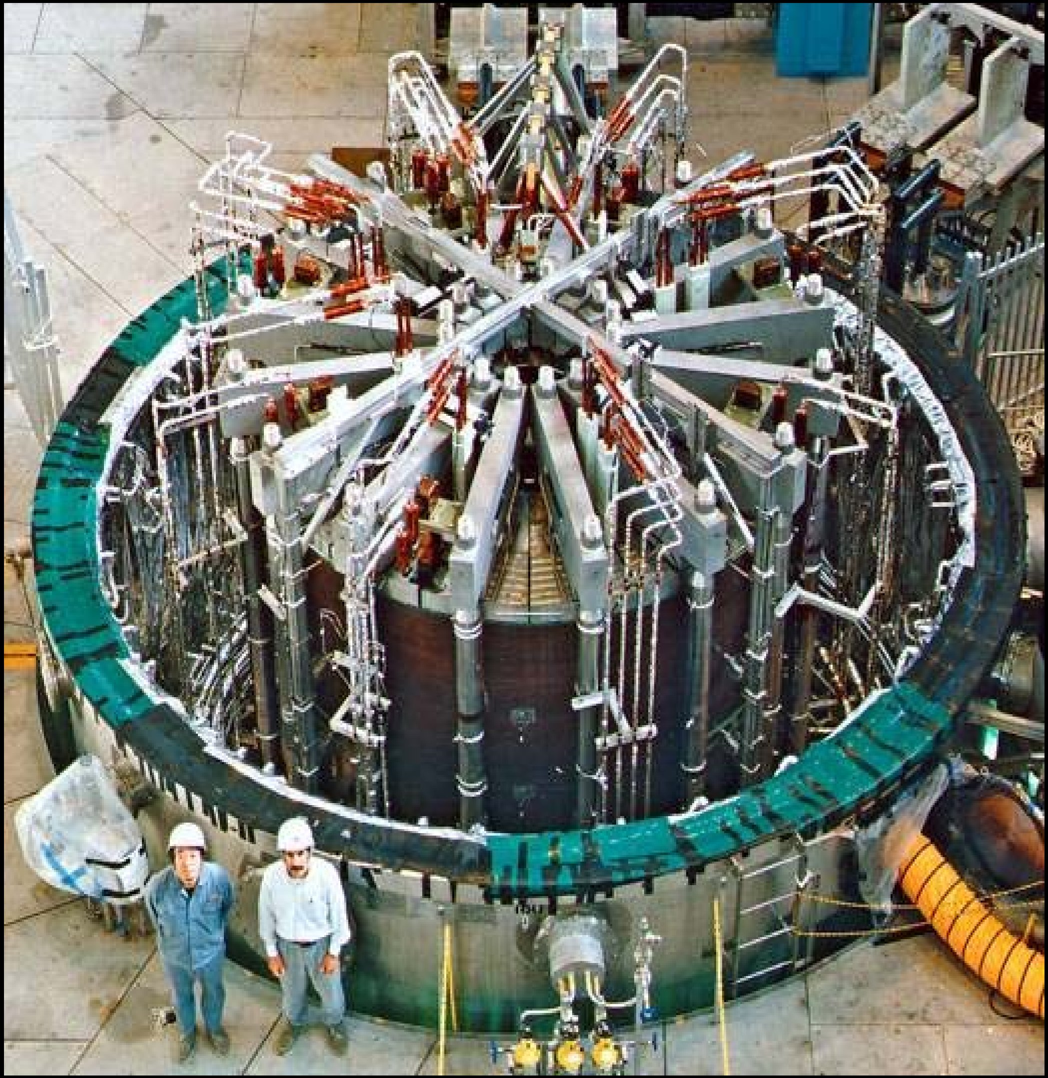
The world's most powerful pulsed superconducting magnet: ITER CS Model Coil.

150 tons

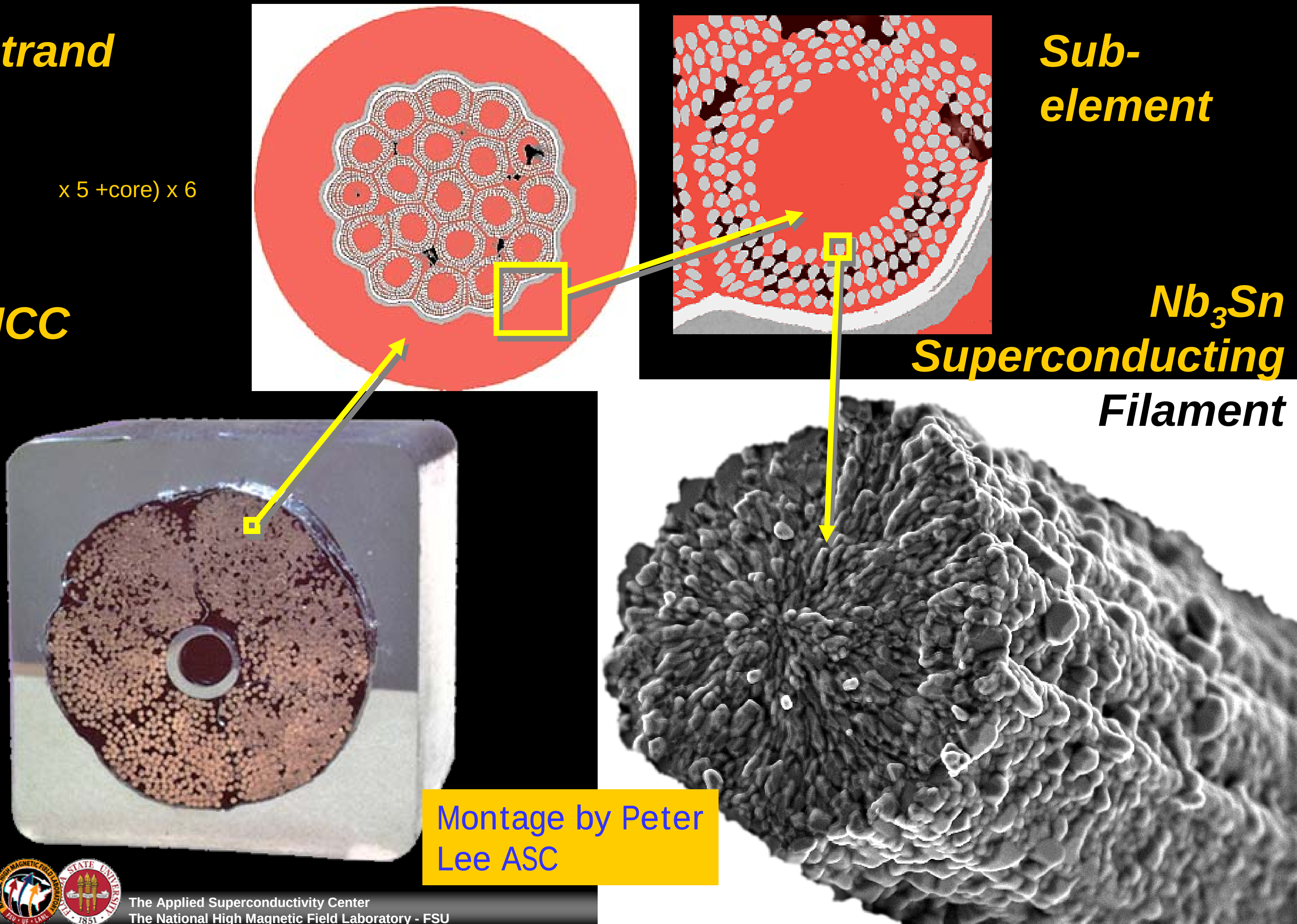
13 T
(approximately 260 thousand times more powerful than the earth's magnetic field).

The magnet consists of two modules, the inner module fabricated in the US and the outer fabricated in Japan. The two coils were combined at the Naka Fusion Research Establishment test facility of the Japan Atomic Energy Research Institute, JAERI.

Photo courtesy of and copyright retained by JAERI.



The Cable-in-Conduit, 60kA conductor



Strand

x 5 +core) x 6

CICC

Sub-element

Nb$_3$Sn Superconducting Filament

Montage by Peter Lee ASC

International Thermonuclear Experimental Reactor (ITER)

BBC NEWS

News Front Page

RELA

ON EDITOR

"F Ear Jero

"Not d irrespon outcome for humani that it was essentially in

In a fusion reac nuclei - the hyd fused together to

To use controlled fu source, it is necessa exceeding 100 million

NEWSFOCUS

With its big political hurdle behind it, the make-or-break project must run a gantlet of technical challenges to see whether fusion can fulfill its promise of almost limitless energy

ITER's $12 Billion Gamble

ABINGDON, U.K., AND GARCHING, GERMANY— Several times a year, hunters gather in the forests around Saint Paul lez Durance in southern France to shoot wild boar. Over the coming decade, however, a portion of their hunting ground will be cleared, and the town's cafés will gradually fill up with newcomers from San Diego and Seoul, Moscow and Munich, Naka and New Delhi. Rising out of that forest clearing will be a 20,000-tonne experiment that just might point a way out of the world's looming energy crisis.

In November, politicians representing more than half the world's population will sign an agreement that fires the starting pistol for the International Thermonuclear Experimental Reactor (ITER). Although first mooted in 1985, ITER has so far existed only on paper. The governments of China, the European Union (E.U.), India, Japan, South Korea, Russia, and the United States are now ready to hand over a $6 billion check for ITER's construction, followed by a similarly sized one for 20 years' operation. Then it is up to an international team of scientists and engineers to show that the thing will work.

If it does, the rewards could be huge. With the global population due to climb from 6.5 billion to 8.1 billion by 2030 and the economies of China, India, and others hungry for power, many new generating plants will have to be built. The choices are stark: Burn more coal, with the inevitable impact on climate; build new nuclear fission plants and deal with the radioactive waste and risk of terrorism; or try alternative sources such as solar power, although this option remains expensive and lacks efficiency.

But there is an outside bet: fusion. If it can be built, a fusion power station would emit no greenhouse gases and produce little radioactive waste, it cannot explode in a runaway reaction, and its fuel is found in seawater in virtually limitless quantities. Such a plant, unlike alternative sources, would produce the steady, reliable baseload power that cities need. And the economics are astounding: A 1-gigawatt coal-fired plant burns about 10,000 tonne of coal per day, whereas a 1-gigawatt fusion plant would need roughly 1 kilogram of deuterium-tritium fuel.

We're not even close yet, however. Indeed, skeptics joke that "Fusion is the power of the future and always will be." The sun is a gigantic fusion reactor, but recreating the conditions here on Earth in which atomic nuclei collide with such force that they fuse together has proved fiendishly difficult. A few dozen examples of the currently favored reactor design—a doughnut-shaped vessel known as a tokamak—have been built since the 1950s, but only a handful have managed to get fusion in their plasma. In 1997, the Joint European Torus (JET) in Abingdon, U.K., the biggest existing tokamak, managed to produce 16 megawatts, but that was only 65% of the power used to keep the reaction running.

By studying those earlier reactors, plasma physicists have derived scaling laws that predict that a bigger tokamak (ITER is twice the size of JET in linear dimensions) would overcome many of the problems. But ITER is not a prototype power plant; it is an experiment designed to finally decide whether taming the sun's energy to generate electricity is even viable. ITER aims to produce 500 megawatts of power, 10 times the amount needed to keep it running. But a moneymaking energy utility would need several times that amount, and it would have to keep on doing it steadily for years without a break.

ITER needs to show such performance is at least possible. But it faces many challenges: Scientists and engineers need to find a lining for its inner walls that can withstand the intense heat; they must tame the plasma instabilities that plague existing reactors; and they must find a way to run the reactor in a steady state rather than the short pulses of existing reactors. ITER must do all of this and, for the first time, maintain the plasma temperature with heat from the fusion reaction itself rather than an external source.

"There's no doubt that it's an experiment. But it's absolutely necessary. We have to build something like ITER," says Lorne Horton of the Max Planck Institute for Plasma Physics (IPP) in Garching, Germany. Researchers are reasonably confident that ITER can achieve the basic goals laid out in the project's plans, but there is less certainty about what comes after that. "I'm pretty confident ITER will work as advertised, but you can't be 100% sure," says Christopher

CREDIT: ITER

238 13 OCTOBER 2006 VOL 314 SCIENCE www.sciencemag.org

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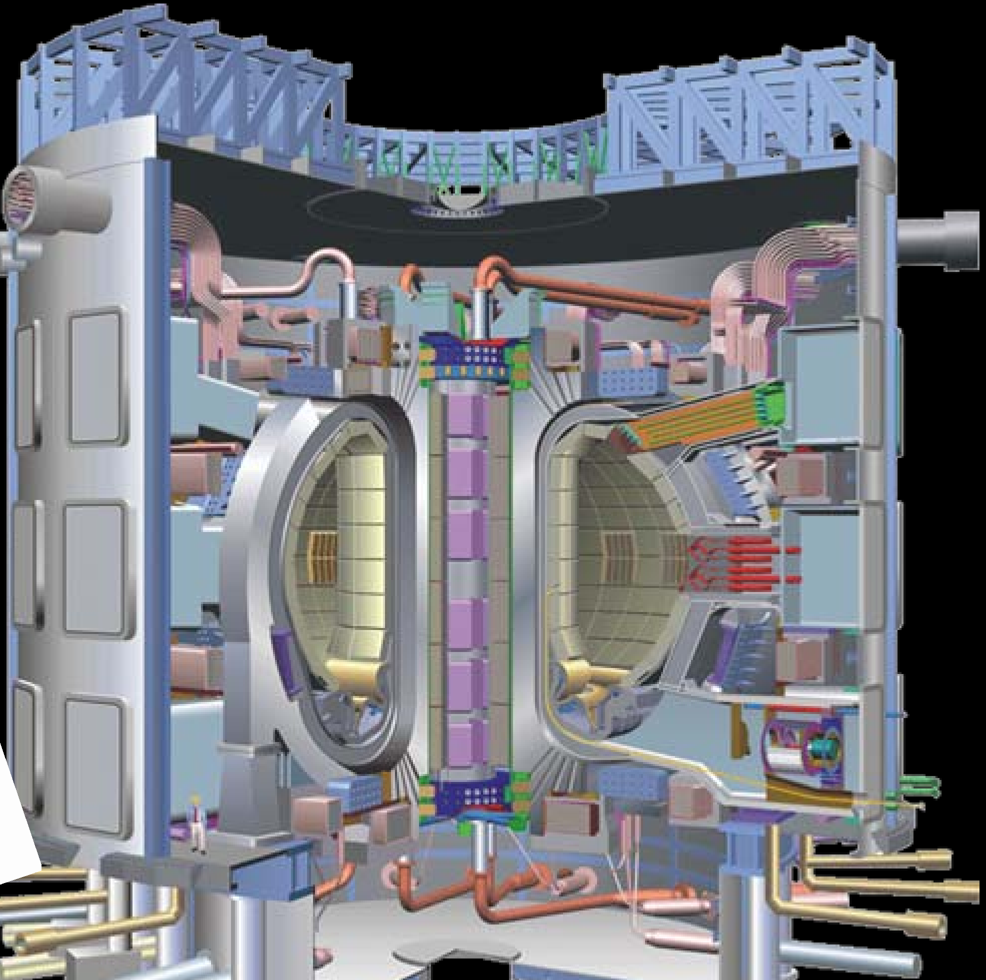


Construction starts 2007 – net power reactor

Largest US Accelerator: Fermilab – 1987 till now

Superconducting Tevatron energy-saver accelerator rings west of Chicago (Batavia, IL)

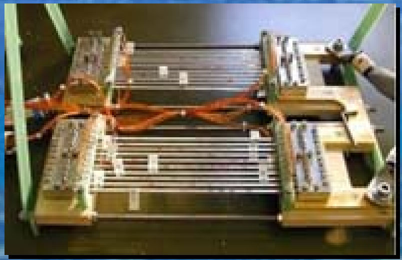
Nb-Ti at 4.5 T, 4.2 K

Large Hadron Collider-CERN

Mont Blanc

1500 tonnes of SC cables

3286 HTS Leads



1232 SC Dipoles

Lake Geneva

Switzerland

Large Hadron Collider

15000 MJ of magnetic energy

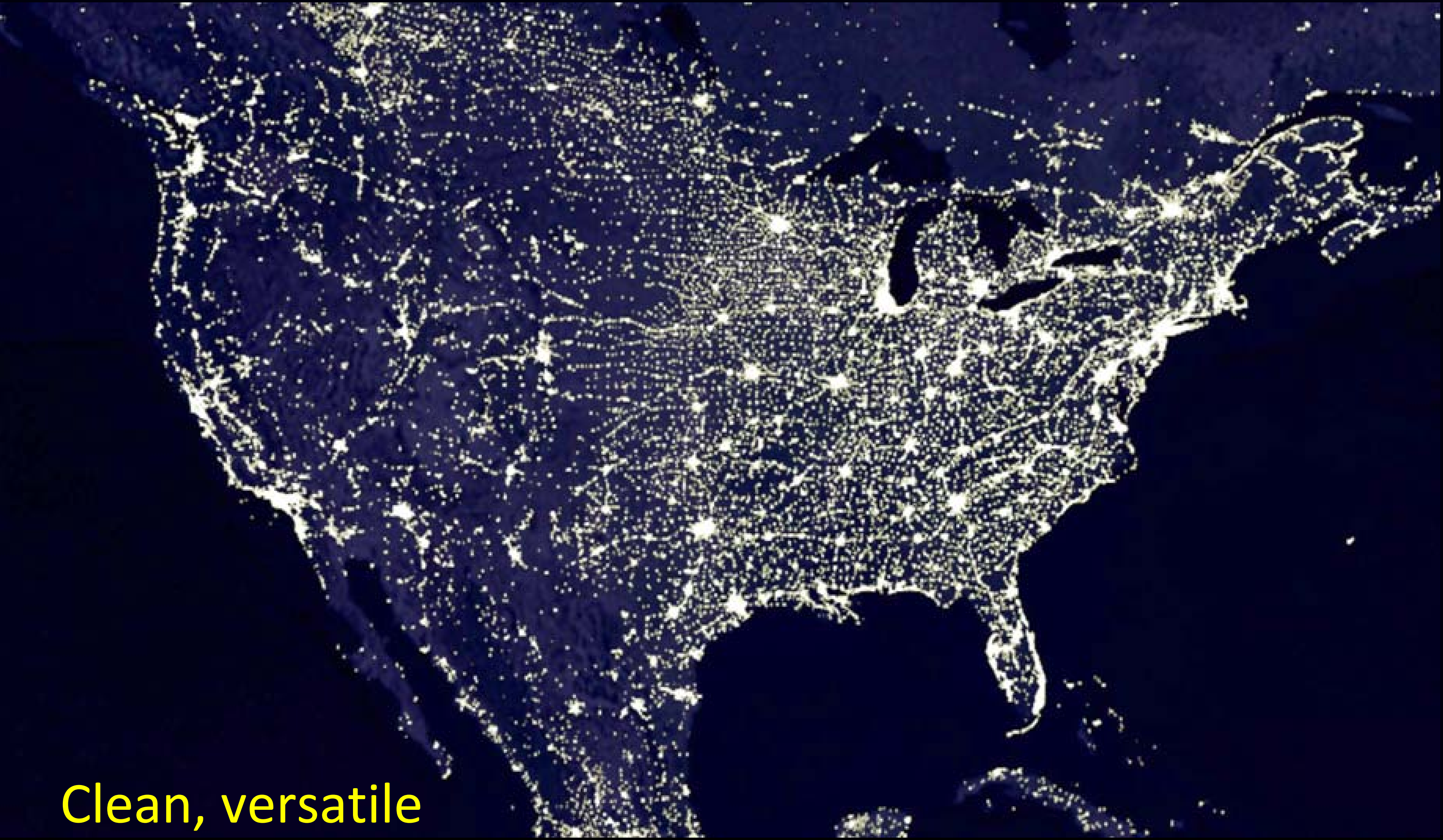
27 km Tunnel

France

Large HTS Motor

37MW HTS (Bi-2223) superconducting rotor for Navy ship – ready for test 2007

The Power Grid:
Triumph of 20th Century Engineering



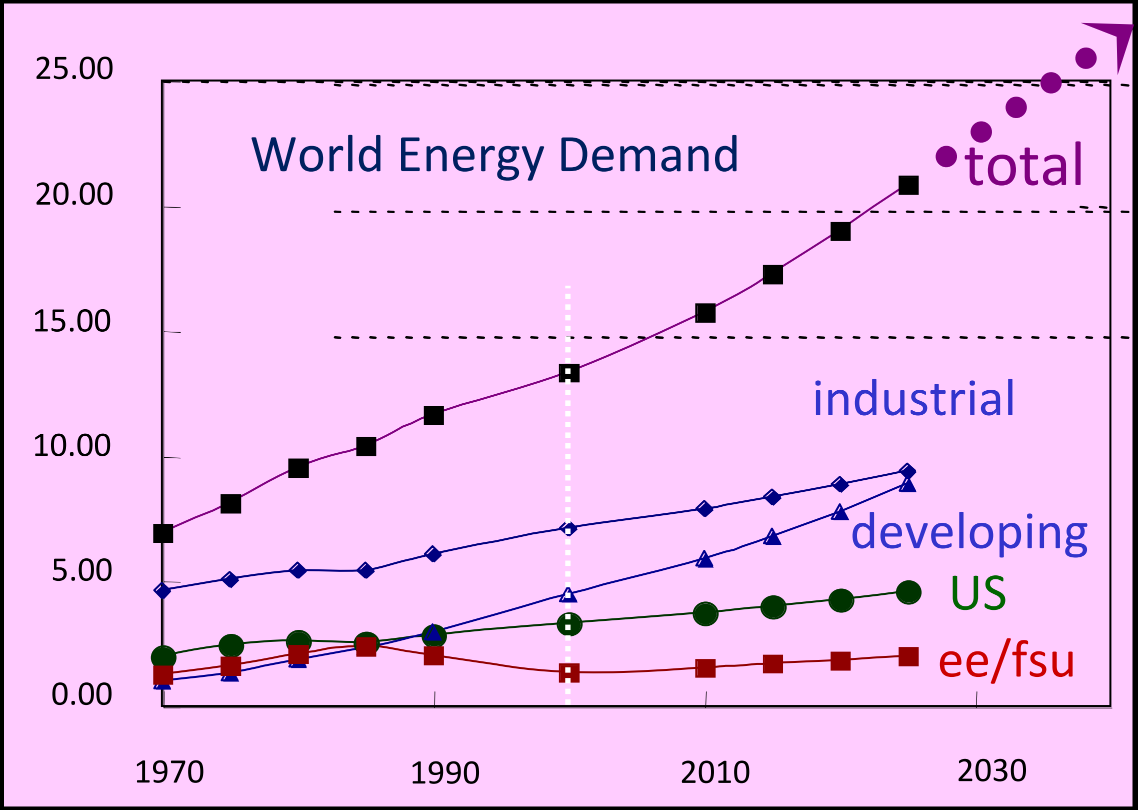
Clean, versatile

power everywhere … at the flick of a switch !

The Energy Challenge

For production, delivery and use

- 2050 demand will Double
- 2100 demand will Triple



http://www.eia.doe.gov/oiaf/ieo/index.html

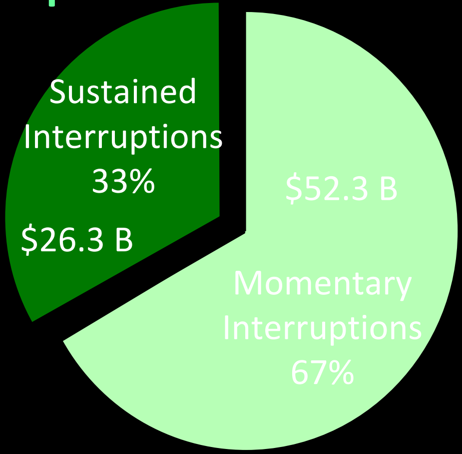
The 21st Century: New Challenges

Reliability

power quality

Power loss/customer

US	214 min/yr
France	53
Japan	6

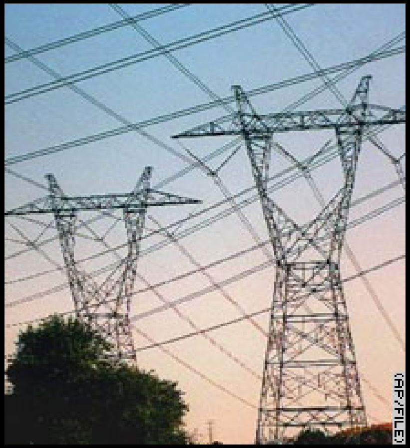


$79 B

economic loss (US)

efficiency

lost energy



In US

- 62% energy lost in production/delivery
- 8-10% lost in grid

- 2006: 40 GW lost
- 2030: 60 GW lost

First Working Prototype, DoE

Bixby substation, AEP, Columbus OH

13.8 kV, 2400 A 200 m cable system by Ultera (Southwire/nktcables)

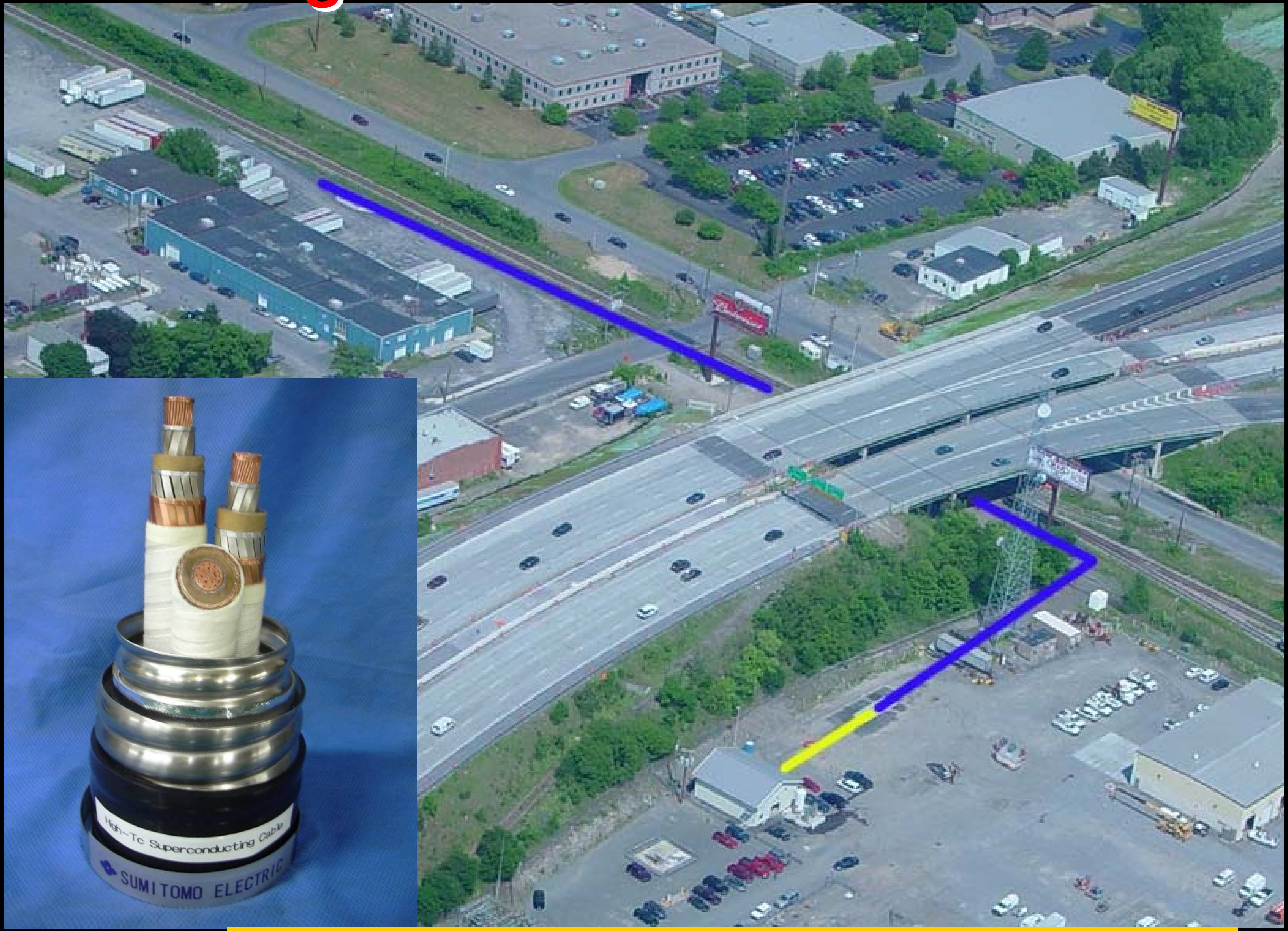
In-grid operation since July 2006

Dense urban areas (NYC here)

SC cables carry 5-times the current of copper of same diameter.

Flexible high-temperature superconducting wire can now be made in large reel-to-reel systems.

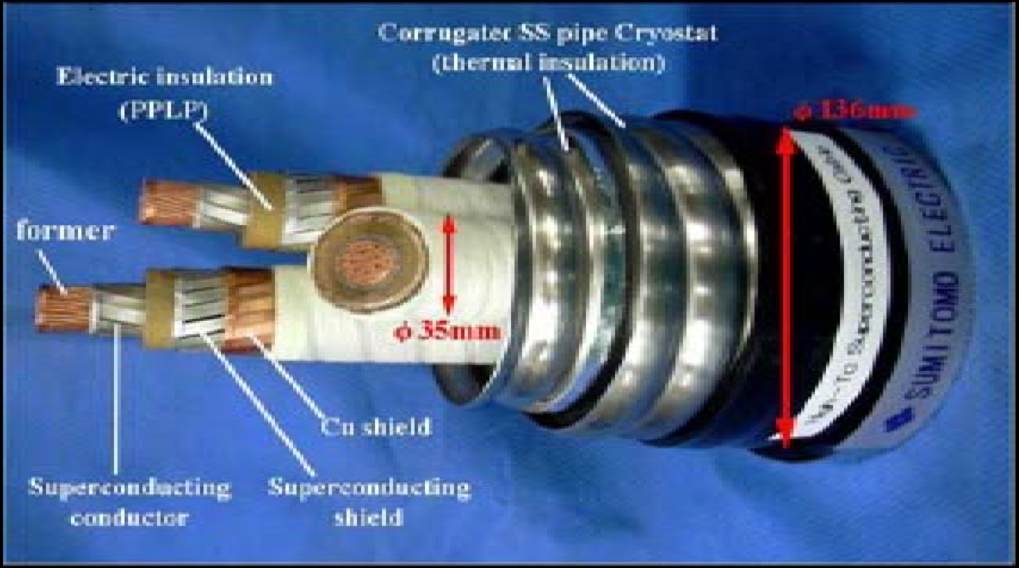
Large HTS Power cable



Bi-2223 cable -Albany New York – commissioned fall 2006

Second Generation (2G) HTS Cables

(as used in Albany and Columbus)



- Silver based (too expensive)
- Complicated multilayer technology (more expensive)
- Only 2% of cable is superconducting
  (no power density advantage)
- HTS materials are very anisotropic and brittle (low reliability)
- Still need lots of cooling (only a little expense and challenge)

History - Policy notes

- **1987** (HTS just discovered): A president promises significant research funding increases.

- **2006**: Another president promises to double funding.

- **2009**: New president!