



# Superconductivity

National Energy SuperGrid Workshop  
Crowne Plaza Cabana Palo Alto Hotel  
Palo Alto, California, November 6-8, 2002

Paul M. Grant

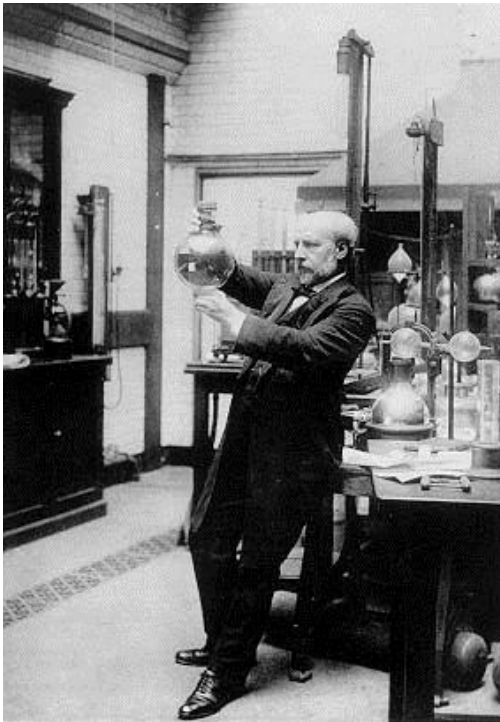
Science Fellow

SS&T

[pgrant@epri.com](mailto:pgrant@epri.com)

Electric Power Research Institute  
Palo Alto, California USA

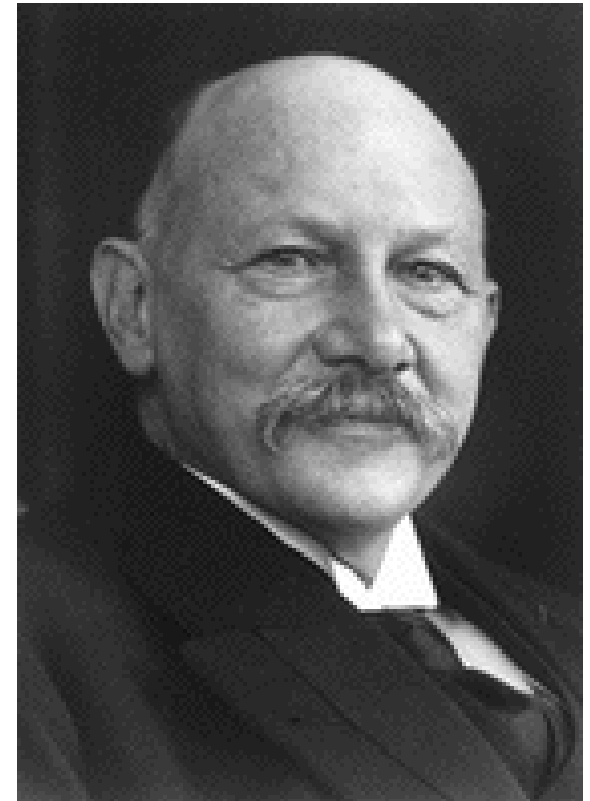
# Fathers of Cryogenics



*James Dewar*

**Dewar**

CH <sub>4</sub>	112 K
O	90
N <sub>2</sub>	77
Ne	27
H <sub>2</sub>	20
He	4.2



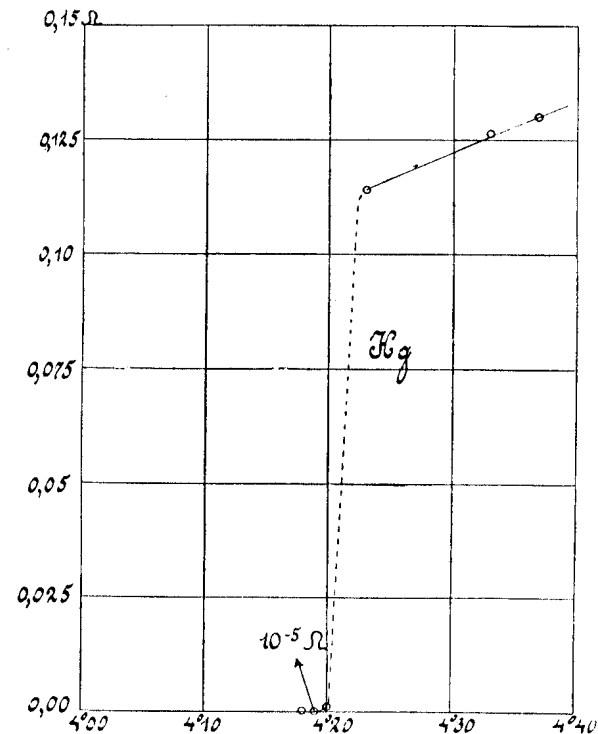
**Kammerlingh-Onnes**

# 1911: A Big Surprise!



Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

H. Kamerlingh-Onnes (1911)



# 1967: SC Cable Proposed!

538

PROCEEDINGS OF THE IEEE, VOL. 55, NO. 4, APRIL 1967

# Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOO

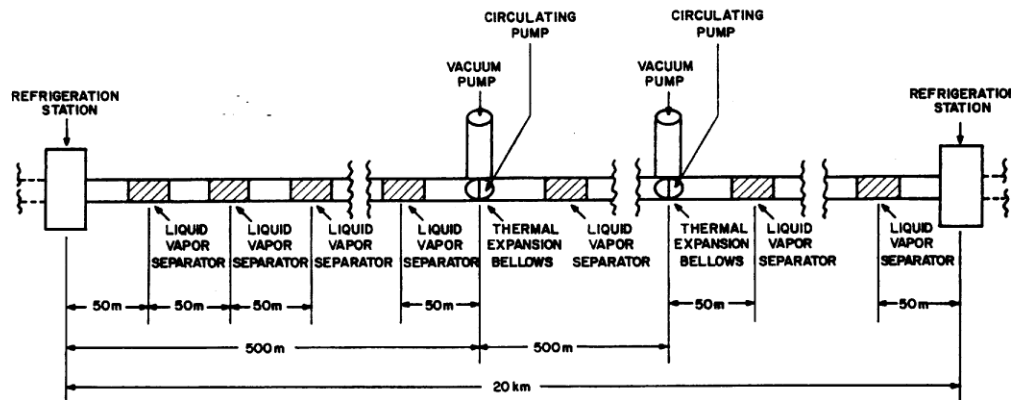


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

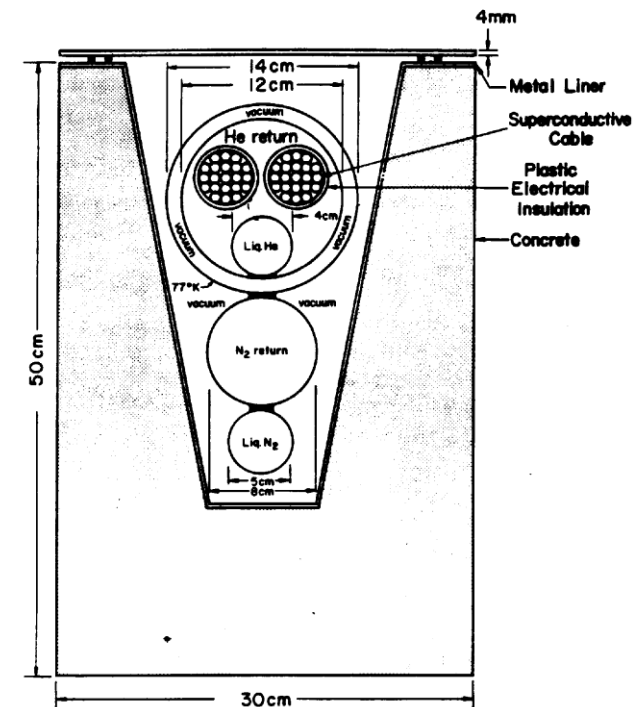


Fig. 1. Cross section of the 100-GW line.

. NESGW Talk (Palo Alto, 6 Nov 02) .5

100 GW dc, 1000 km !



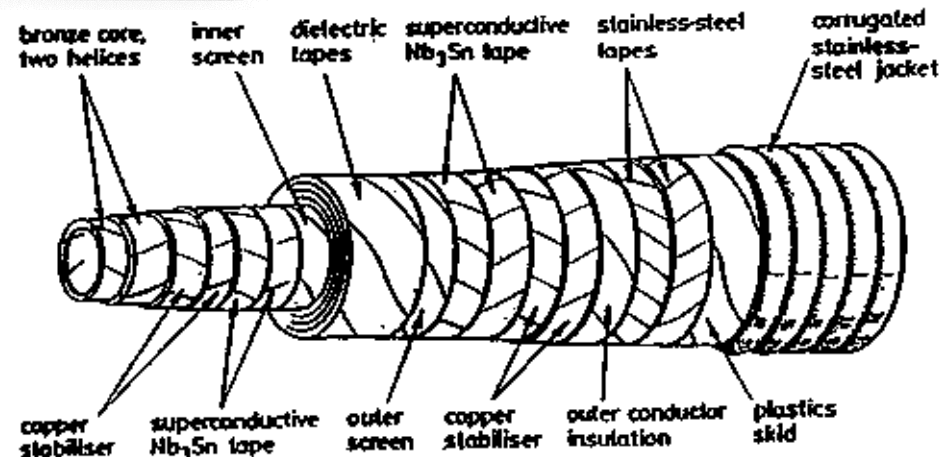
# Brookhaven LTS ac Cable 1975-86



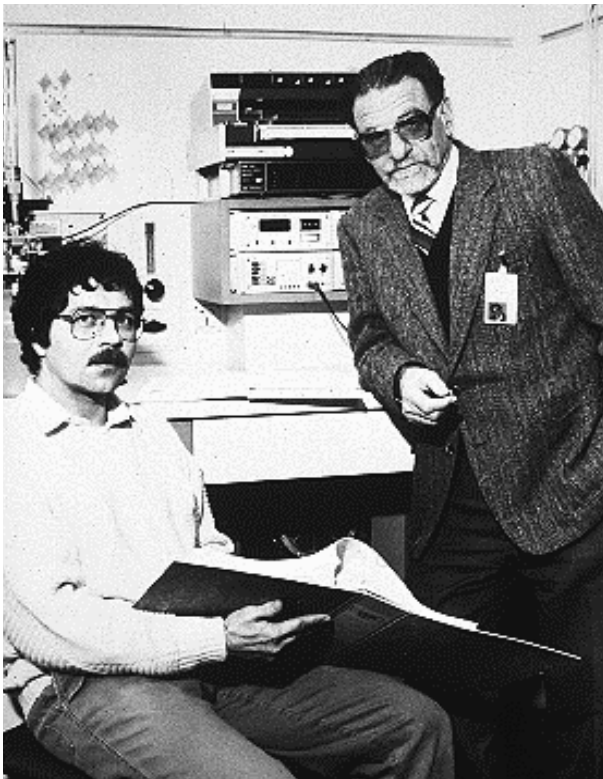
- Technical Success
- Economics Unclear

135 kV, 1000 MVA, 3 $\phi$ , 115 m

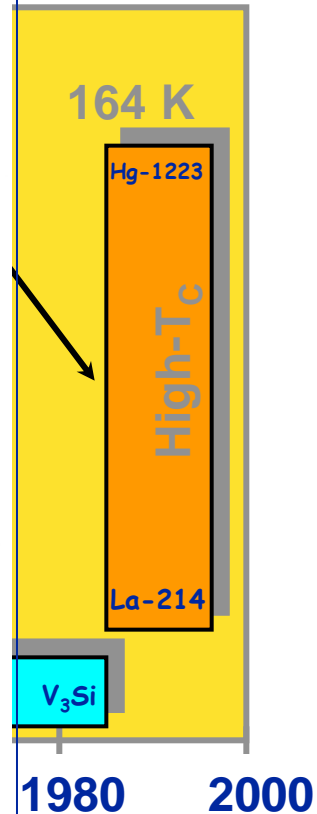
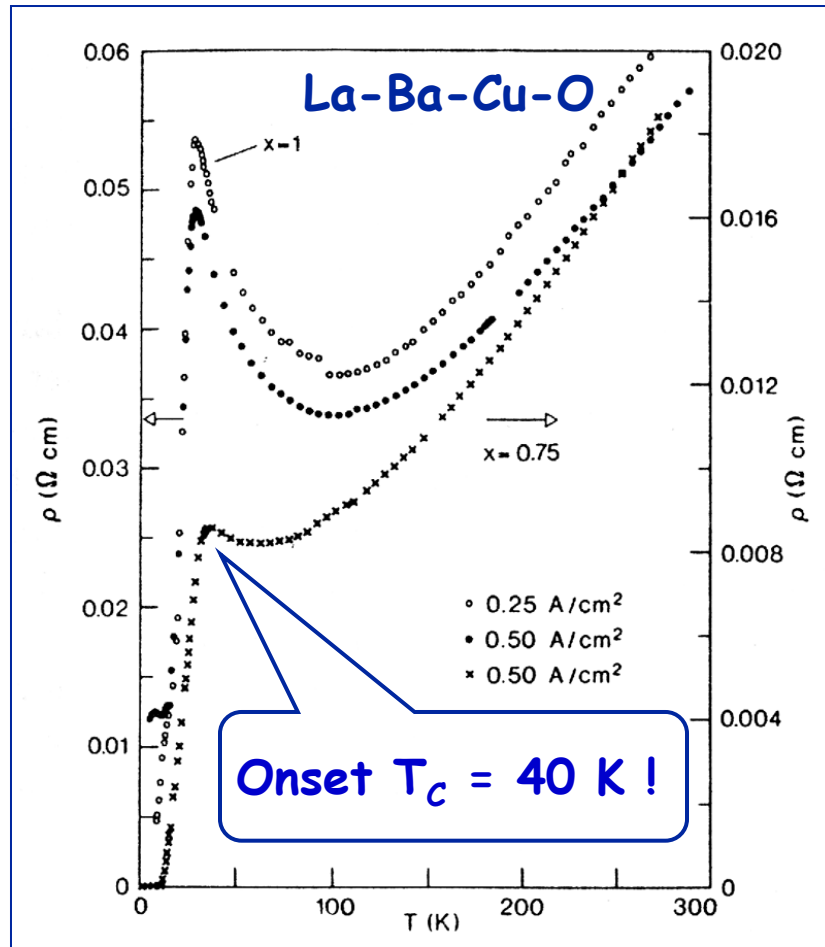
Nb<sub>3</sub>Sn, 7-9 K



# 1986: Another Big Surprise!



Bednorz and Mueller  
IBM Zuerich, 1986



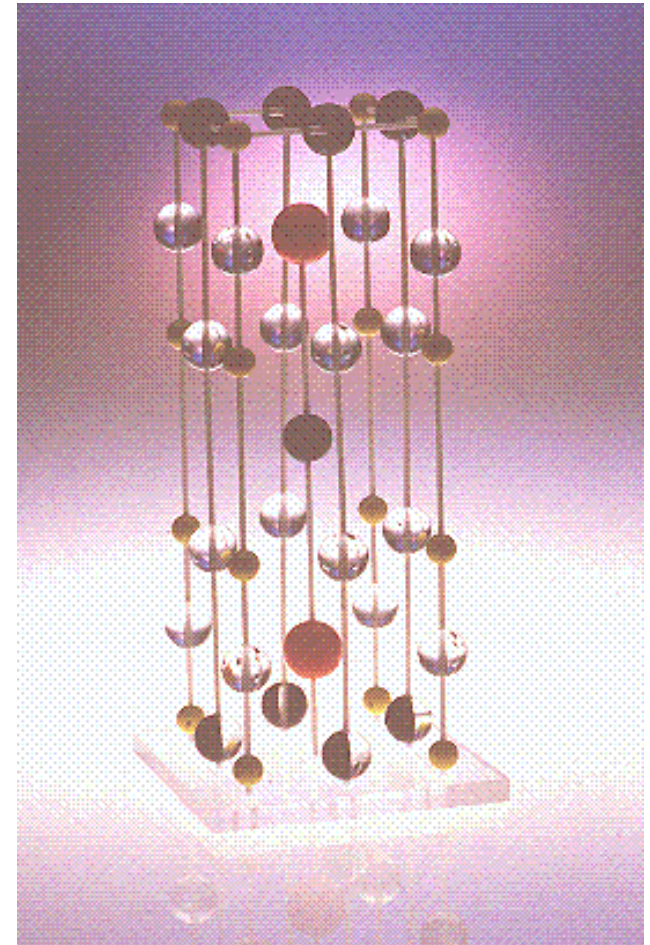
# 1987: "The Prize!"



J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

*2 Get Nobel for Unlocking Superconductor Secret*

# March 3, 1987: "123" Structure IBM Almaden Research Center



# Woodstock of Physics NYC, 1987

## Physicists' Night Out!

WHAT IS MORE EXCITING THAN  
**High T<sub>c</sub> — Physics Art!**

PAM DAVIS  
STEVE KIVELSON  
DAN ROKHSAR and  
SHAHAN ETEMAD  
Introduce

**LMELIGH**

1000-1000 47 200-01 5000

**FOR DANCING**  
**AT NEW YORK'S MOST FASHIONABLE NIGHTCLUB**

• • • • • THURSDAY, MARCH 19, 1987 • • • • •

DOORS OPEN 10:00 PM SHARP  
**DANCING ALL NIGHT**

COMPANIMENT AVAILABLE FOR YOU AND A GUEST WITH THIS INVITATION  
\$20.00 PER PERSON

THIS INVITATION CANNOT BE SOLD OR TRANSFERRED

. NESGW Talk (Palo Alto, 6 Nov 02) .10

## commentary

### Woodstock of physics revisited

Ten years have passed since the now famous American Physical Society meeting that heard the first breathless accounts of high-temperature superconductivity. Now, in calmer times, practical applications are emerging.

#### Paul M. Grant

Snap quiz: who can tell me the winner of the 1987 Super Bowl? Not most physicists, I suspect, for whom it was certainly eclipsed by two events of far greater consequence that shared the early months of that year. One, the discovery of Supernova 1987A, perhaps portended the other: the announcement of superconductivity above liquid-nitrogen temperature on planet Earth—a dream fulfilled for many condensed-matter physicists like myself, whose careers had orbited around this elusive star.

The successful sighting fell to W. K. Wu and C. W. (Paul) Chu and their teams of students and postdocs at the Universities of Alabama and Houston, following only five months after the publication in autumn 1986 by Georg Bednorz and Alex Müller at IBM Zürich of their discovery of superconductivity in a previously unexplored class of compounds, the layered copper-oxide perovskites.

The 'inside' story of the hectic interval between the first week in January 1987—when an announcement of the confirmation of Bednorz and Müller's discovery first brought 'high-temperature superconductivity' to wide public attention—and the week of the American Physical Society's March meeting, remains to be told. Suffice it to say that this period, and the last three months of 1986, were replete with incredulity, credulity, excitement, secrecy and a sense of immediacy in competition with one's peers, all of which resulted in, frankly, a substantial amount of intrigue and suspicion. All who participated surely came to understand, if they had not done so before, that physics is not only a science but, perhaps more significantly, an



Rising stars: Müller and Chu with Shoji Tanaka (right), whose Tokyo laboratory provided one of the first confirmations of Bednorz and Müller's discovery.

intensely human pursuit—something they do not teach you in graduate school.

The programme of the March meeting, held each year in a different US city, is 'cast in concrete' early the preceding December; thereafter, an absolute policy of no alterations prevails. By the deadline of 5 December 1986, for the 1987 meeting at the Hilton hotel in New York City, only one abstract had been accepted on the new materials: 'Specific heat of Ba-La-Cu-O superconductors' by Rick Greene and his collaborators at IBM Yorktown. But the explosion of results that appeared in the new year prompted the meeting's organizers to take an unprecedented step. Brian Maple of the University of Cal-

ifornia, San Diego, was asked to put together a special post-deadline evening session devoted entirely to the discovery.

All those wishing to report results would be granted five minutes each, in order of the arrival of their request to take part—and did the requests rain in, reaching a downpour in the two weeks before the meeting, as confirmations of the Wu-Chu measurements were made. All in all, 51 presentations were to be given throughout the evening and early morning of Wednesday and Thursday, 18 and 19 March. That memorable and riotous session was to become our 'Woodstock of physics', so named in honour of the village only 50 miles north where, in an obscure farmer's muddy field in 1969, the rock concert occurred that defined a generation of youth the world over.

#### Opening act

A few personal observations and anecdotes may help to convey the colour of that week in midtown Manhattan. Excitement was running high even before Wednesday night. On Monday, the opening day, the press were already beginning to catch some of us to be interviewed. That noon my colleague Ed Engler and I went to lunch at a nearby Brew 'n' Burger and found Alex Müller sitting by himself in a corner booth, attempting to escape the turmoil at the Hilton. At the time he was not yet widely recognizable to those attending the meeting or to the press—a situation that would soon change.



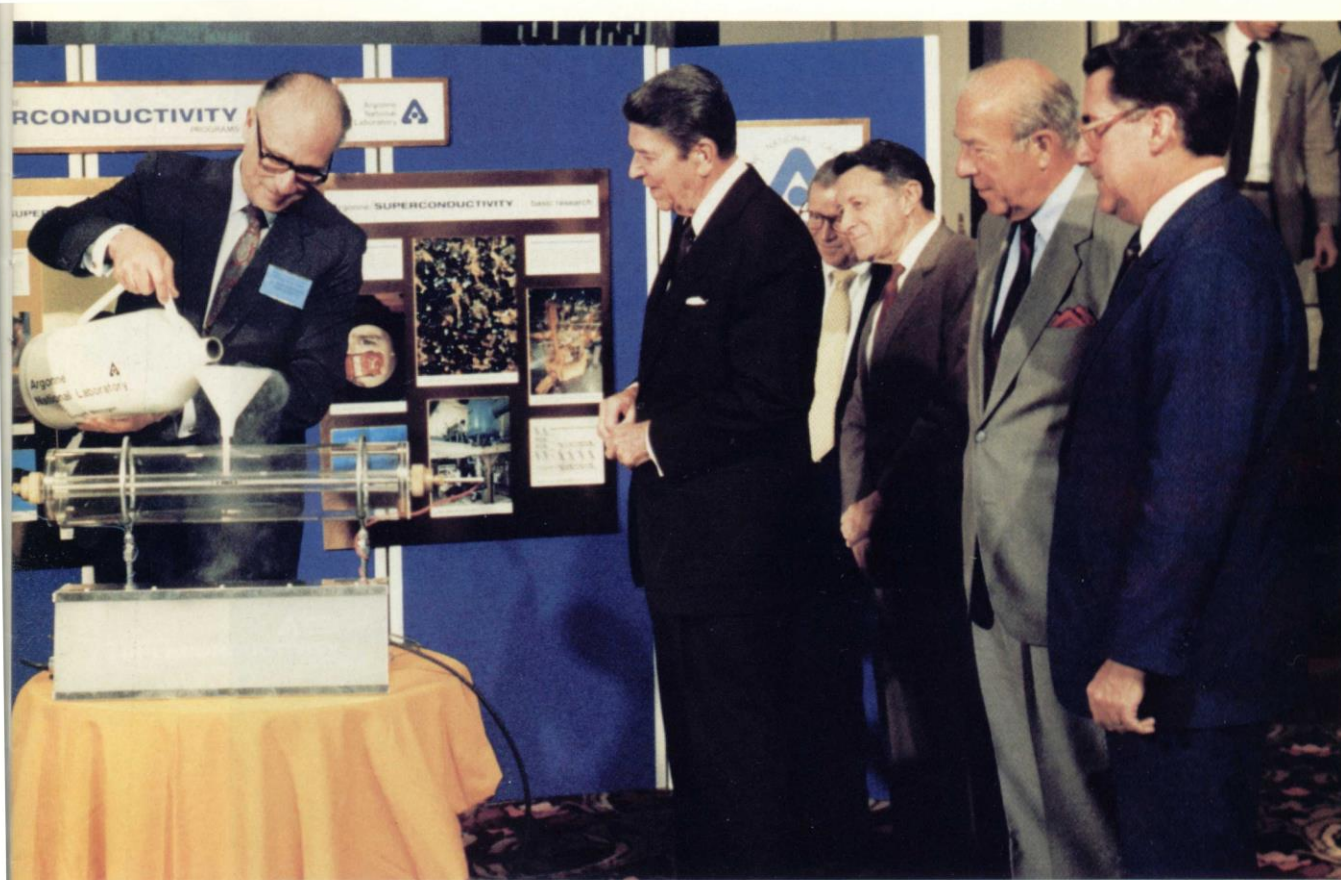
Fever pitch: the room filled with overflowing with physicists eager for news of superconductivity.

NATURE | VOL 386 | 13 MARCH 1997

115

EPRI

# "The Great Communicator"



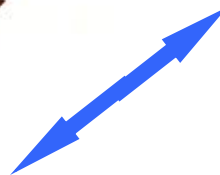
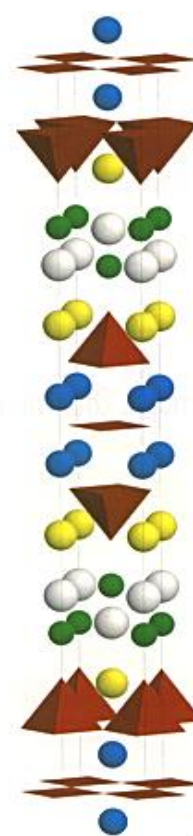
*Alan Schriesheim, Director of Argonne National Laboratory, demonstrates superconductivity to the President, Chief of Staff Howard Baker, Secretary of Defense Caspar Weinberger, Secretary of State George Shultz and Secretary Herrington.*

# HTS Layered Perovskites

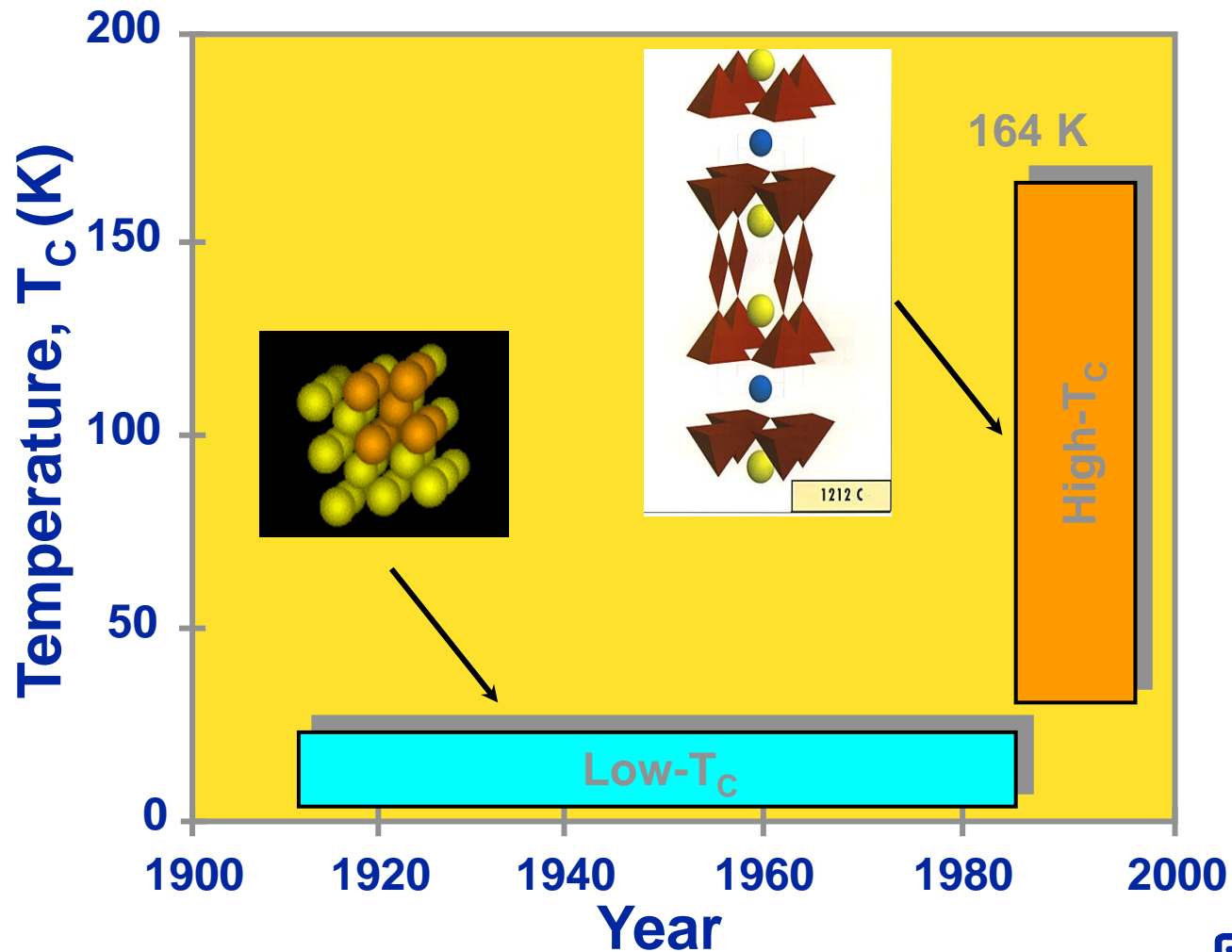
Y-123



Bi-2223



# $T_c$ vs. Year: 1911 - 1999



# Nature, 1 March 2001

*How was it ever missed!*

## Superconductivity at 39 K in magnesium diboride

Jun Nagamatsu\*, Norimasa Nakagawa\*, Takahiro Muranaka\*,  
Yuji Zenitani\* & Jun Akimitsu\*†

\* Department of Physics, Aoyama-Gakuin University, Chitosedai, Setagaya-ku,  
Tokyo 157-8572, Japan

† CREST, Japan Science and Technology Corporation, Kawaguchi, Saitama 332-  
0012, Japan

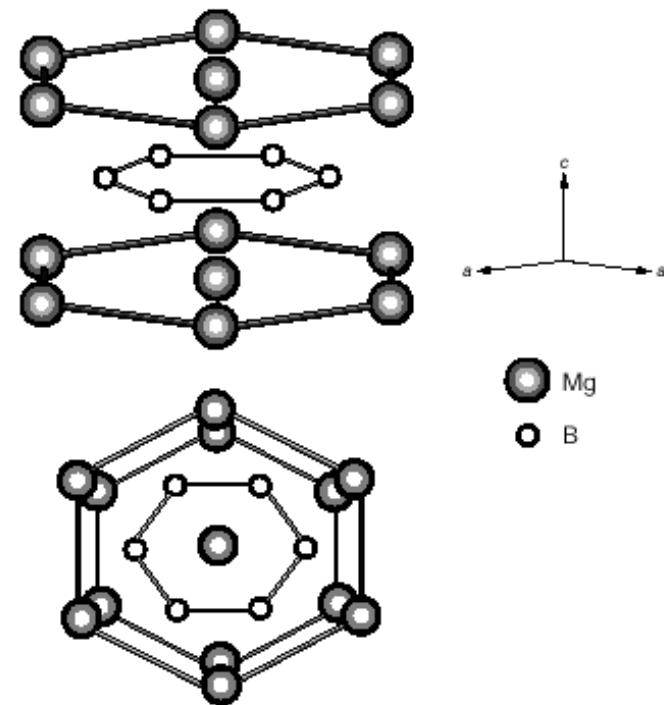
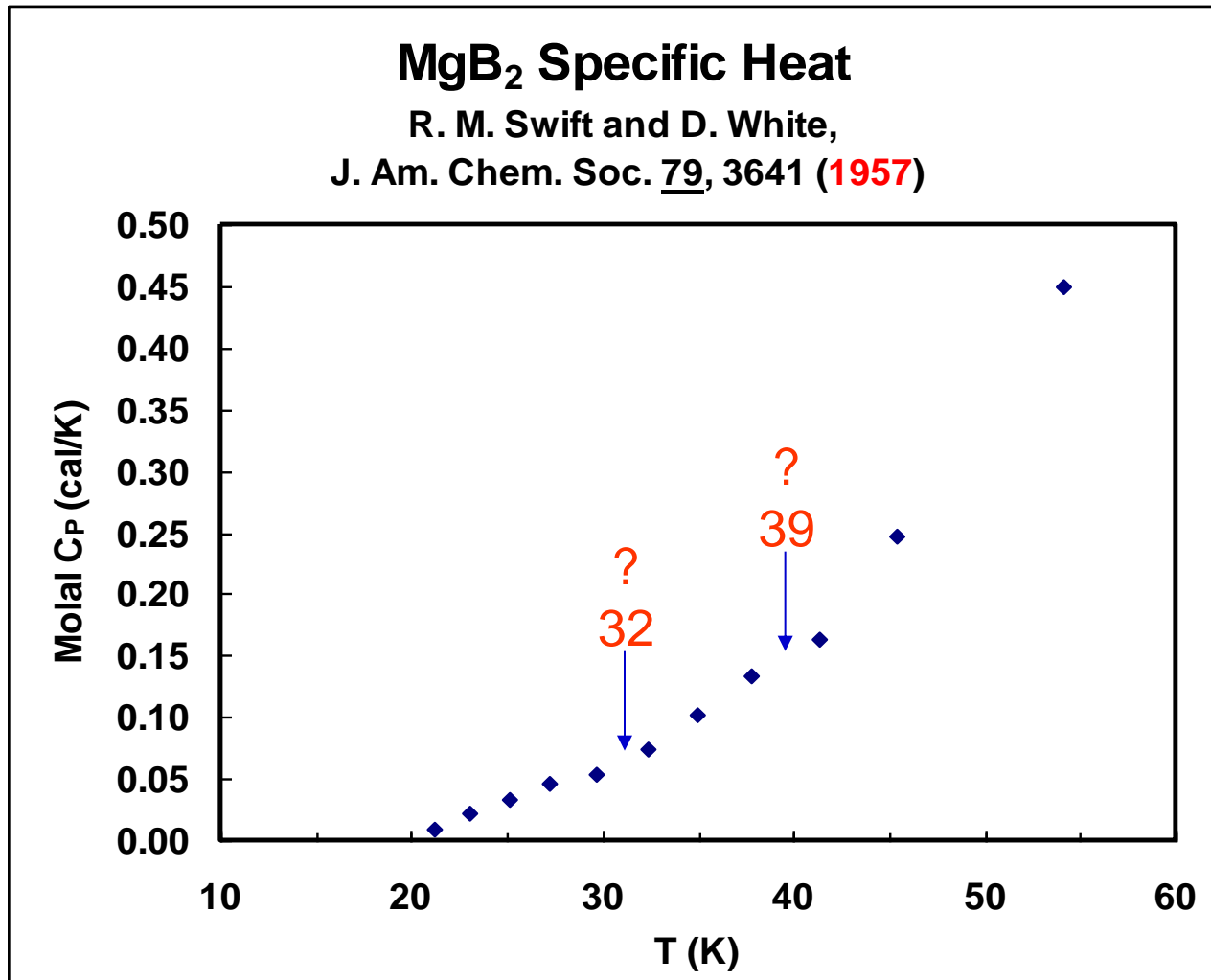
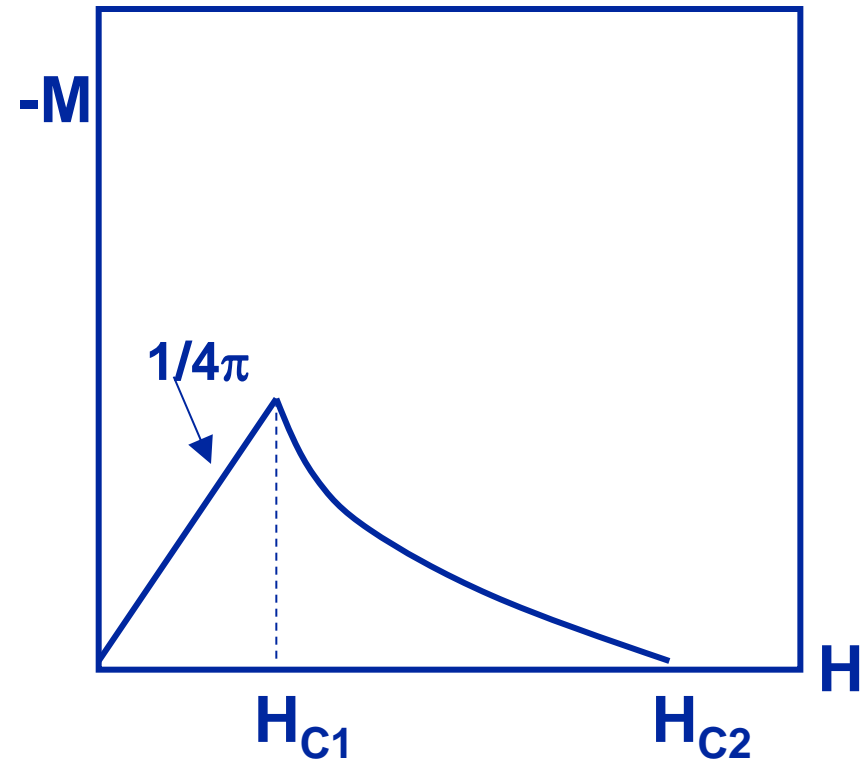
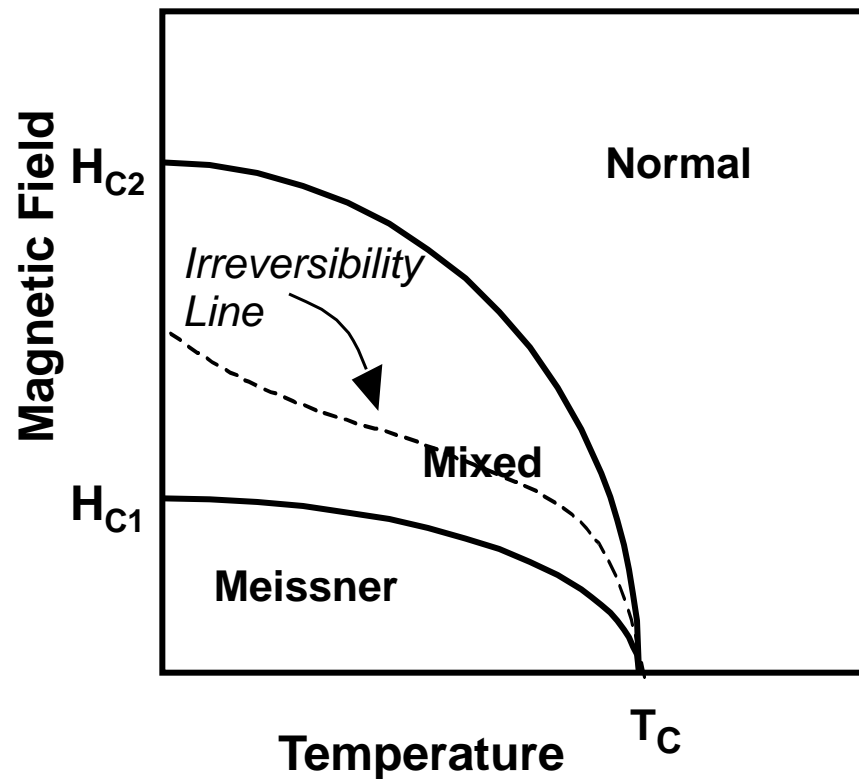


Figure 2 Crystal structure of MgB<sub>2</sub>.

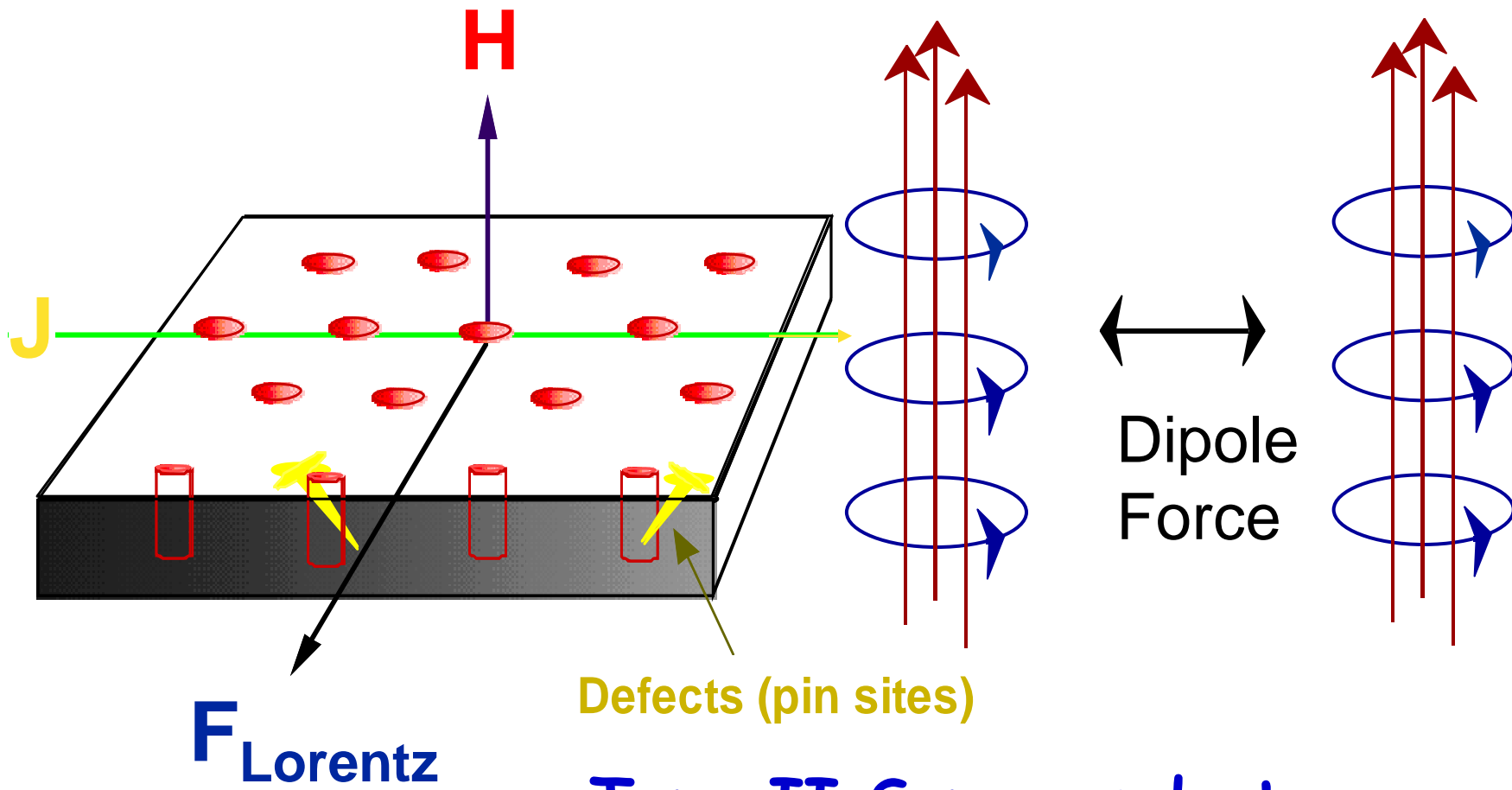
# Maybe It Wasn't!



# Type II Superconductivity



# Abrikosov Vortex Lattice



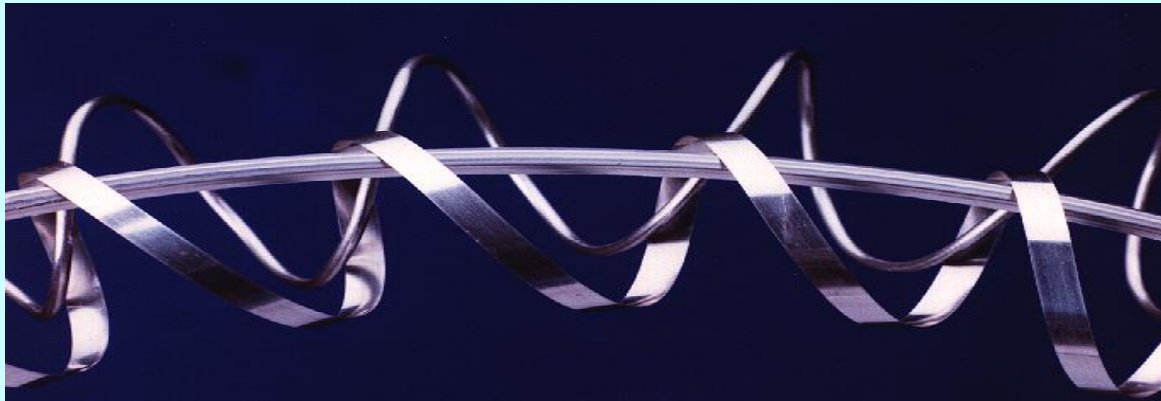
Defects (pin sites)

Type II Superconductor  
in the Mixed State

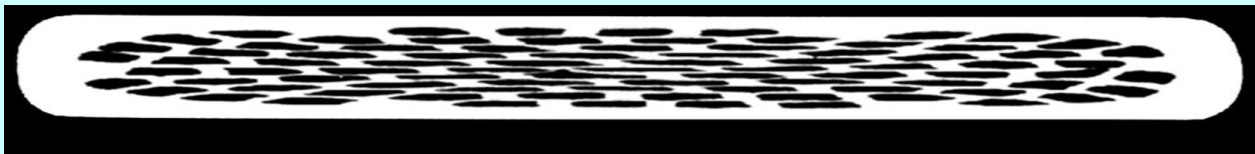
EPRI

# HTSC Wire Can Be Made!

*“The Miracle of 1989”*

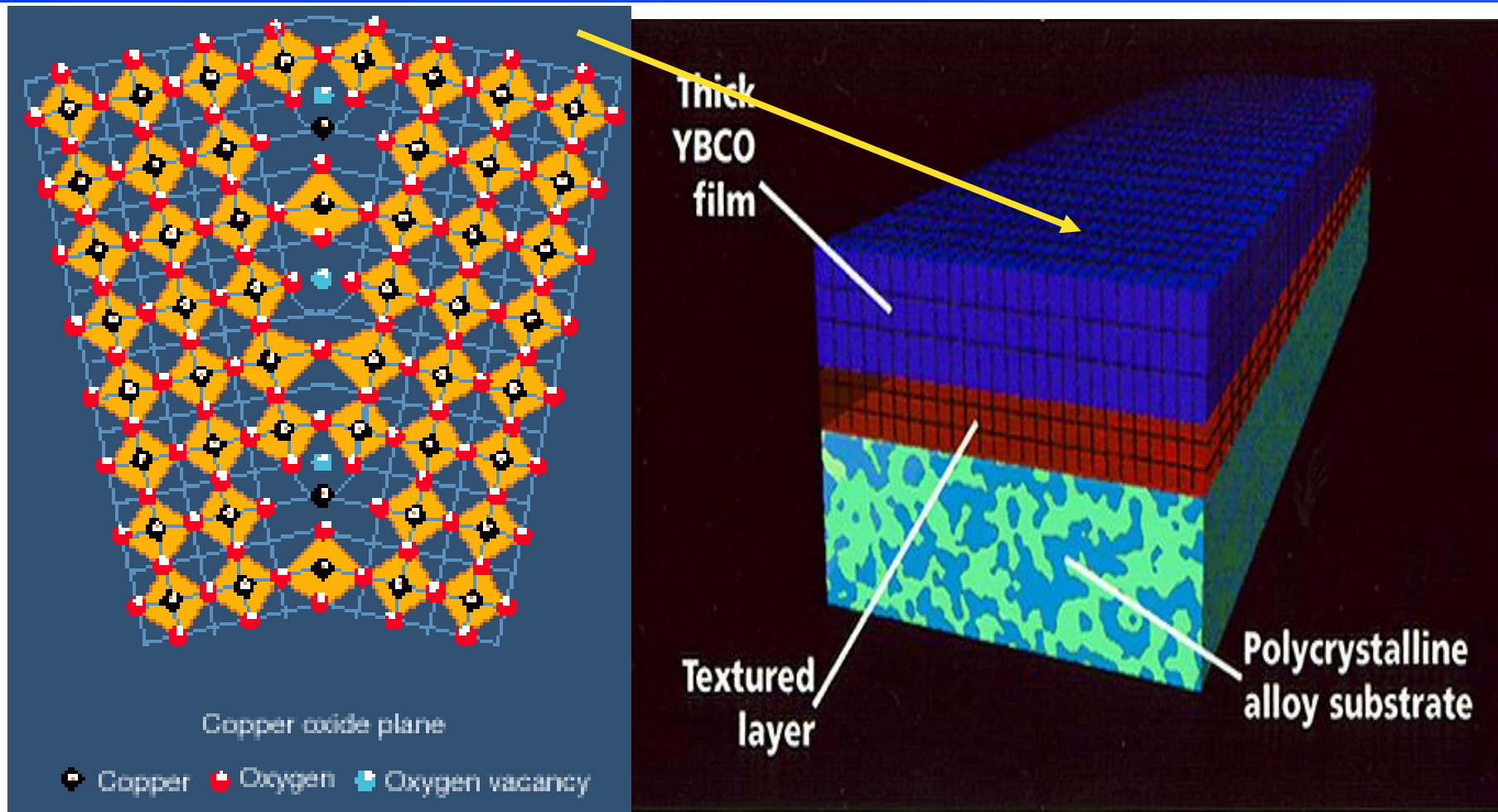


*But it's 70% silver!*

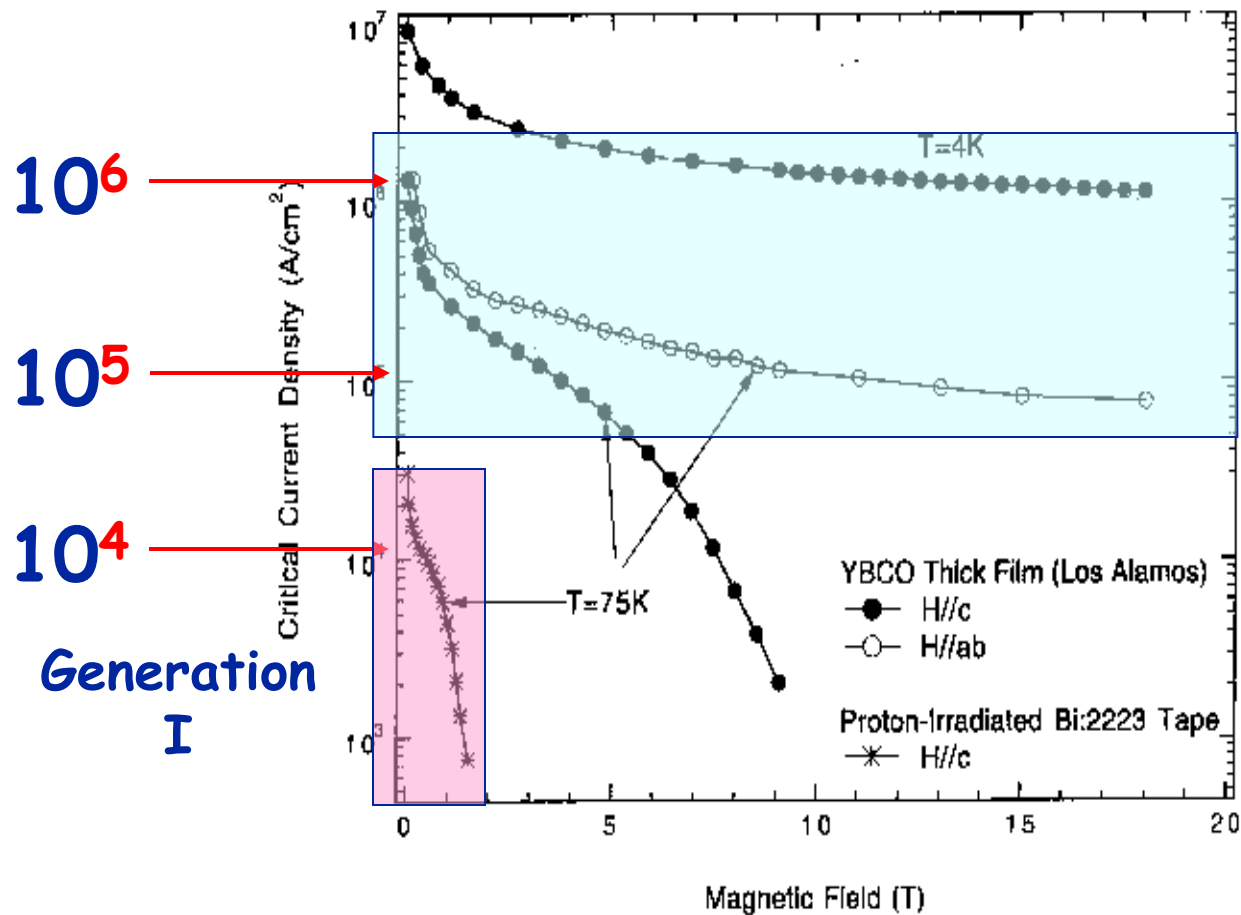


# Coated Conductors

## *Generation II Wire*



# LANL's Finest



Generation  
II

Generation  
I

# Nature, 31 May 2001

Superconductivity

## Rehearsals for prime time

Paul Grant

Superconductivity seems to have been forever waiting in the wings. Although superconducting power cables are about to go live, will the newest material, magnesium diboride, become the class act of the future?

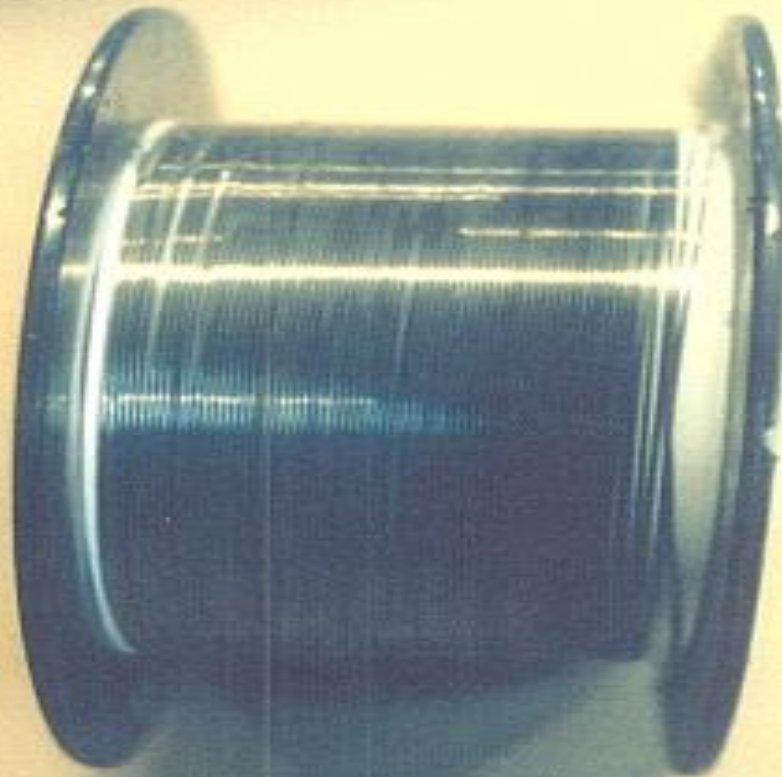
## High critical currents in iron-clad superconducting $\text{MgB}_2$ wires

S. Jin, H. Mavoori, C. Bower & R. B. van Dover

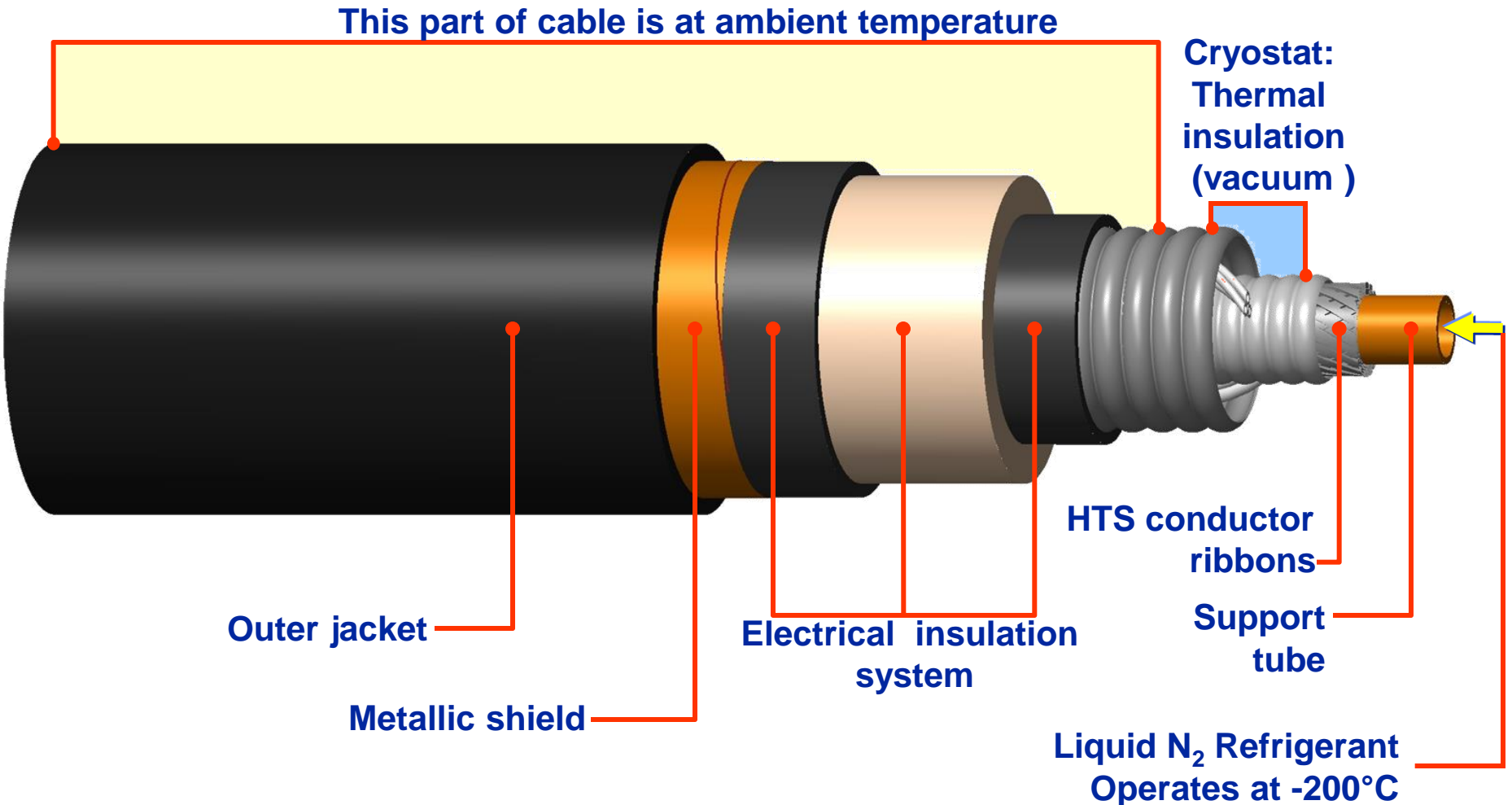
*Agere Systems/Lucent Technologies, Murray Hill, New Jersey 07974, USA*

# Cheap $\text{MgB}_2$ Wire Here Now!

60 meters of  $\text{MgB}_2$  Wire



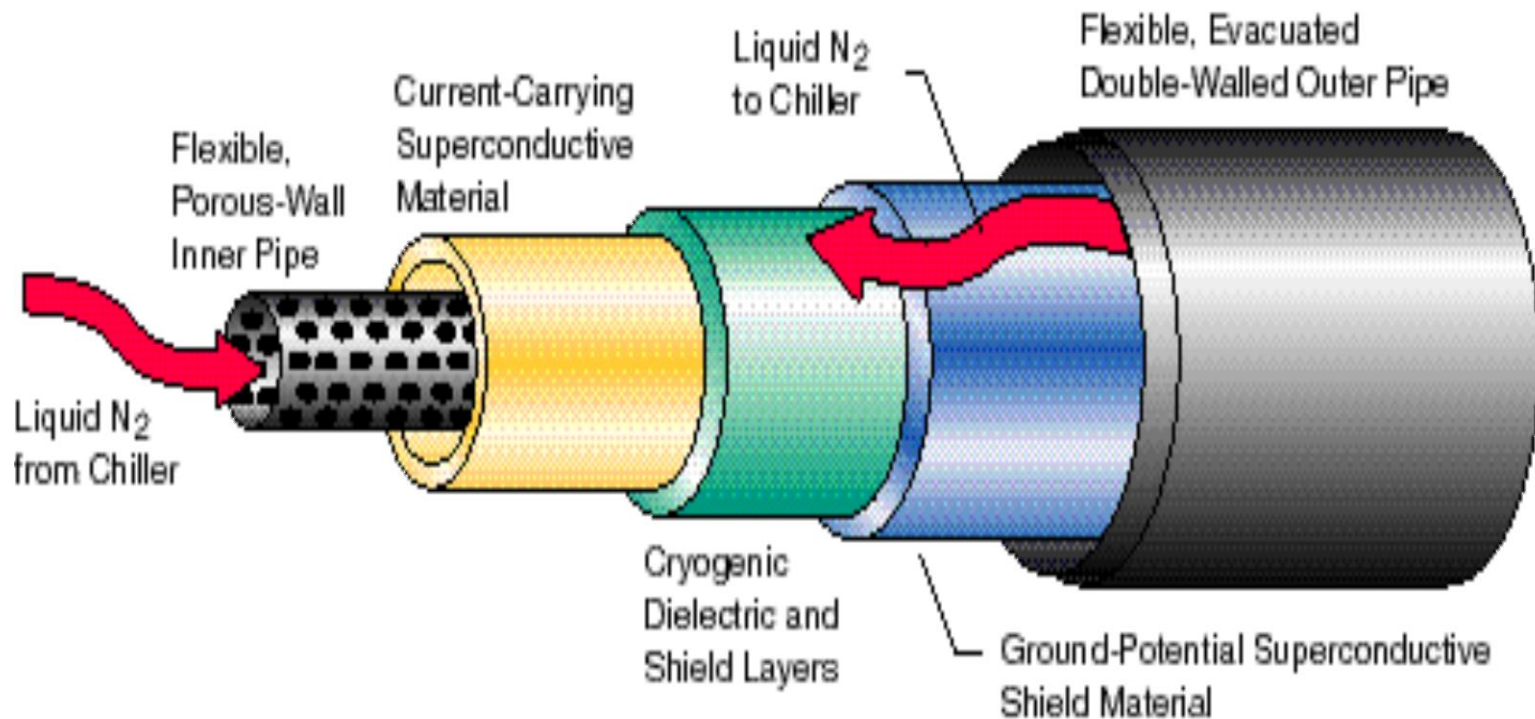
# WTD Cable Breakaway



# Finished Cable



# Cold Dielectric Cable



# HTS Cables: They're Here!



**12,400 Volts**

**1,250 Amps**

**3 Phase**

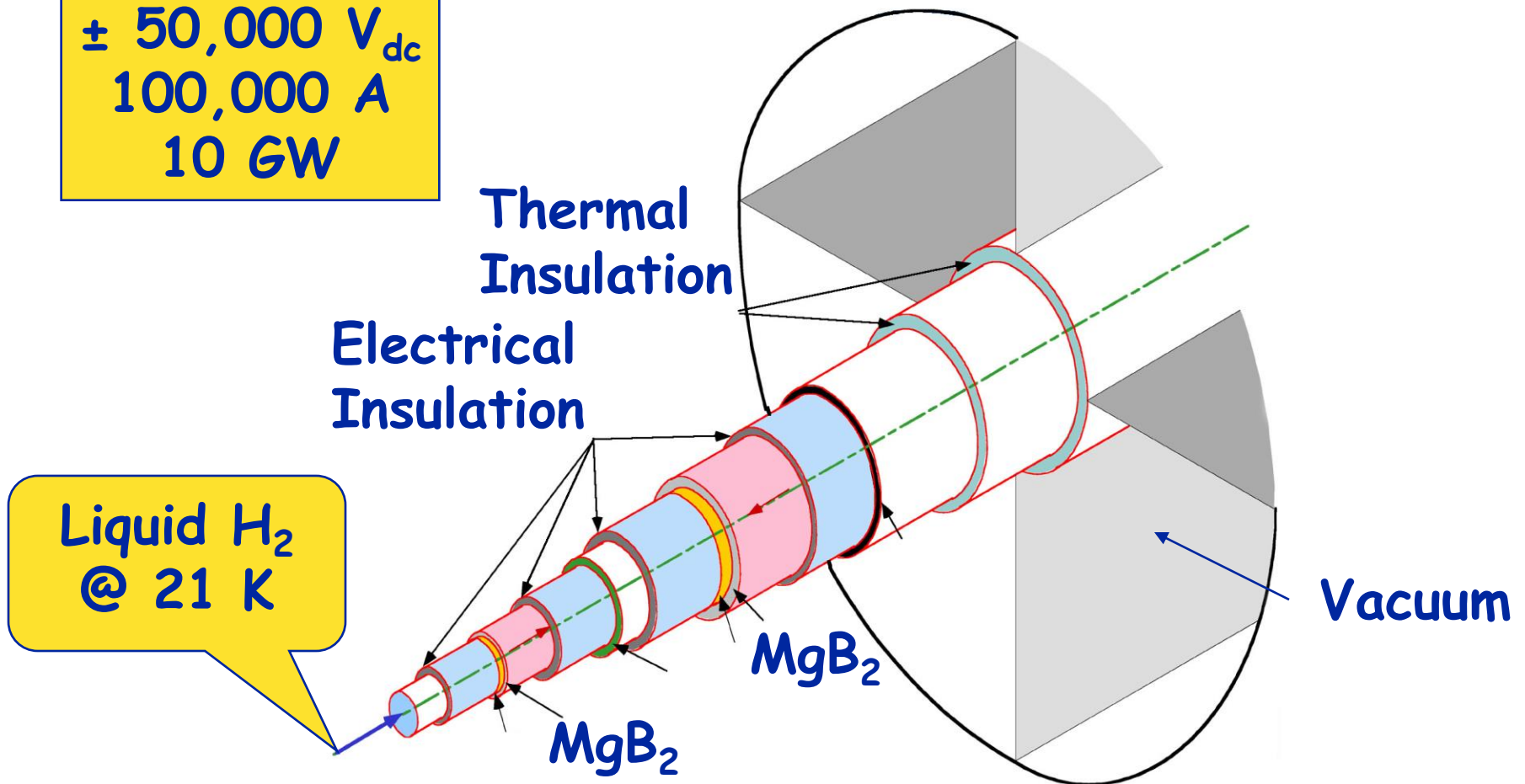
**Southwire  
Cable Plant  
Carrollton, Ga.**

# HTSC Cable Projects Worldwide

	1998	1999	2000	2005
<b>Pirelli</b>				
DOE	50m/115kV/2kA "EPRI"		130m/24kV/2.5kA 3ph "Frisbie"	900m/66kV/0.7kA 3ph "LIPA"
EdF			50m/225kV/2.6kA/3ph	
<b>Southwire</b>		30m/12.5kV/2.6kA/3ph		300m/15kV/3ph "AEP"
<b>IGC</b>			400m/35kV/3ph "Albany"	
<b>NKT</b>		30m/60kV/3kA/3ph "COP"		
<b>SEI/TEPCO</b>		30m/66kV/1kA "proto"	100m/66kV/1kA/3ph	Japanese National Program?

# "The Energy Pipeline"

$\pm 50,000 \text{ V}_{\text{dc}}$   
100,000 A  
10 GW



# Energy Intensity Factoids

## Grant Household Power Requirements

<u>Watts</u>	Avg	Peak
Elect	2000	4000
Therm	4000	8000

*Does not include  
3 automobiles!*

## Peak Power for 250,000 GHE's

Electrical: 1000 MW

Thermal: 2000 MW

# Hydrogen Factoids

- 0.025 \$/kWh Electricity → 0.22 \$/kWh Hydrogen
- Hydrogen flowing @ 1 m/s → 0.6 MW/cm<sup>2</sup>
- Delivering 2000 MW Hydrogen → 67 cm dia pipe  
Electricity via superconductivity is essentially free!
- To power all cars in the US with hydrogen would require expropriating all present electric power generated in the US
- German studies show water emissions from powering all cars with hydrogen could cause changes in microclimate.

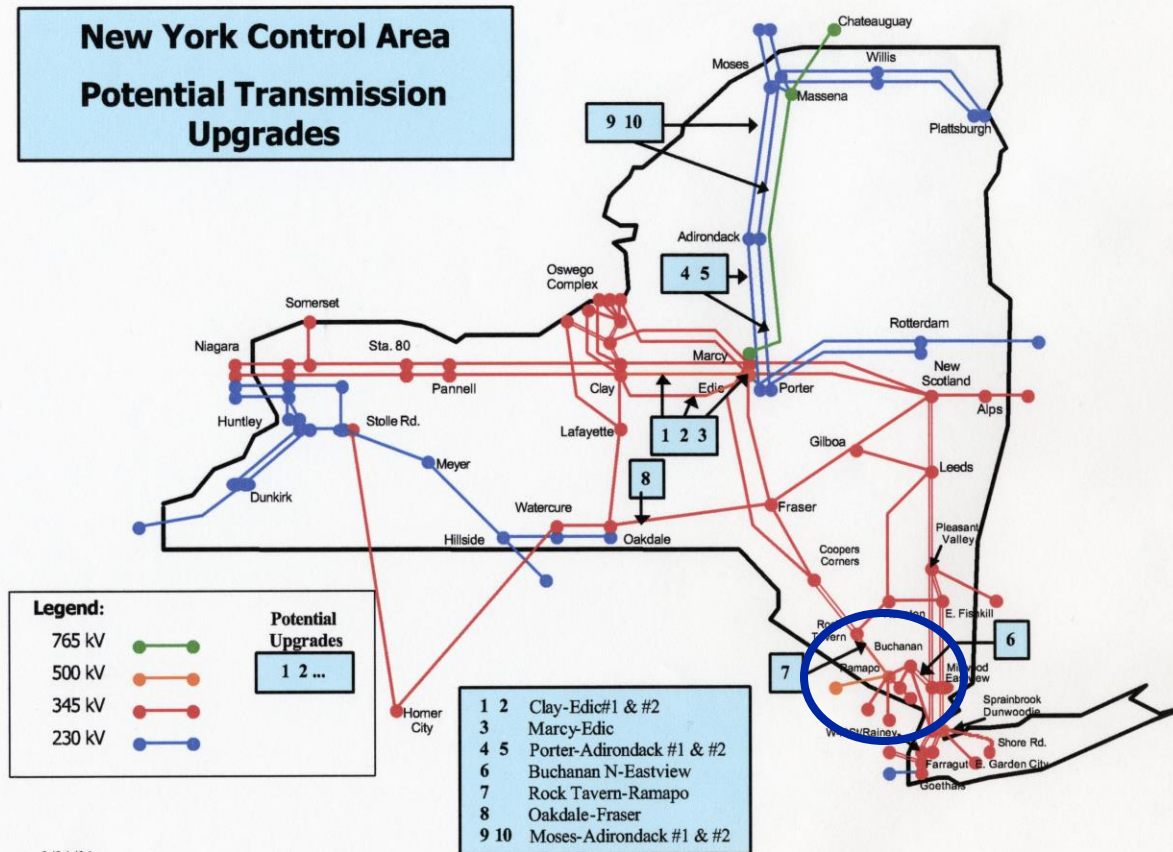
# Small Scale Demonstration



Nexans LH<sub>2</sub>  
Transfer Line



# Regional System Interconnections



3/21/01

2

# Issues (Superconductivity)

- Wire Cost & Performance
  - Gen I (BSCCO/Ag) 50 \$/kA×m
  - Gen II (Y123 CC) 10
  - $MgB_2$  2
  - NBTi 0.90
- Length
  - Gen I (BSCCO/Ag) > 1000 m
  - Gen II (Y123 CC) 10
  - $MgB_2$  > 100
  - NBTi > 1000
- Joints & Splices
  - HTSC TBD

# Issues (Cryogenic & Vacuum)

- Cryoplants: Cost & Performance
  - *Liquid or Gas?*
  - $ECE = 0.20 T_{cold} / (T_{sink} - T_{cold})$
  - *Cryo-unit Cost ~ \$5/W Rating*
- Vacuum
  - *Continuously pumped, periodic or sealed?*
  - *Distance between ports*
  - *Gettering materials*

# Issues (Cable Design/Power Control)

- Cable
  - *Parallel vs. Coaxial*
  - *Flexible vs. Rigid*
- Power
  - *Balance between Voltage & Current*
  - *dc vs. ac*
  - *ac Losses (ripple factor)*

Where there is no vision,  
the people perish...

*Proverbs 29:18*

# "You can't always get what you want..."



“...you get what you need!”

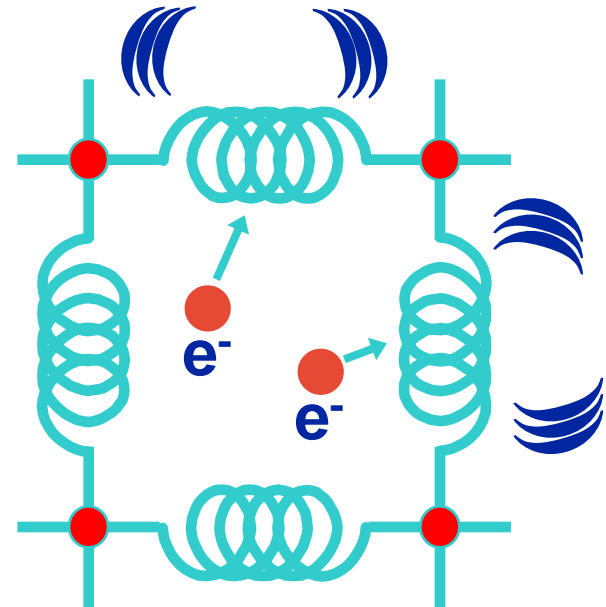
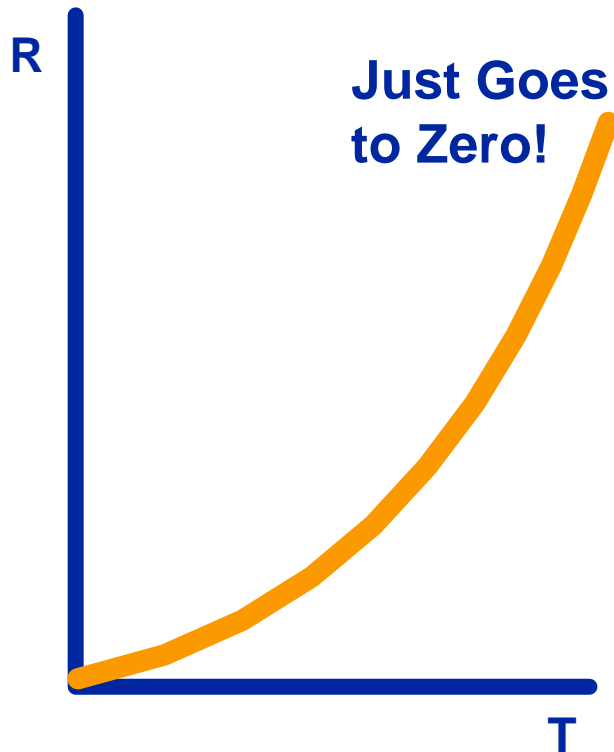


# Prologue: The Two Energy Lemmas

- I. Any discussion of the application of energy technology must involve, from the very start, an explicit social and political scenario
- II. The unique aspect of energy as a life-sustaining necessity separates it from the jurisdiction of many of the usual “laws” of economics

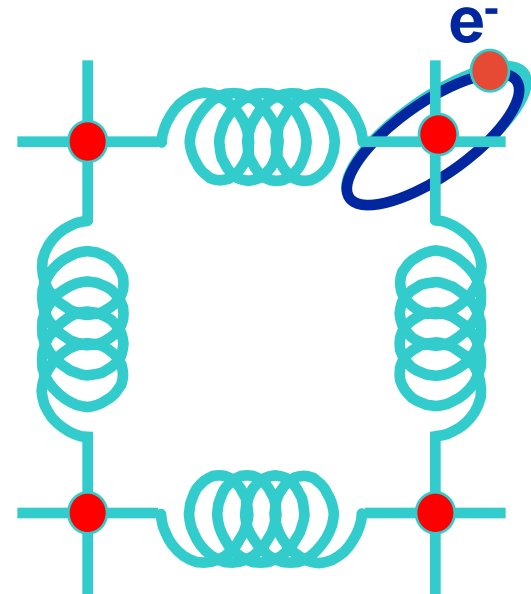
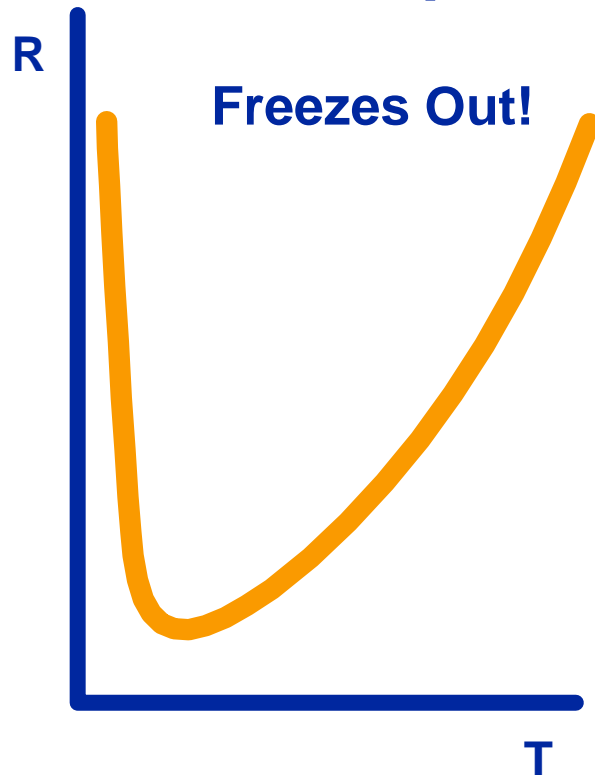
# Models of Electrical Conductivity

## The First Idea:



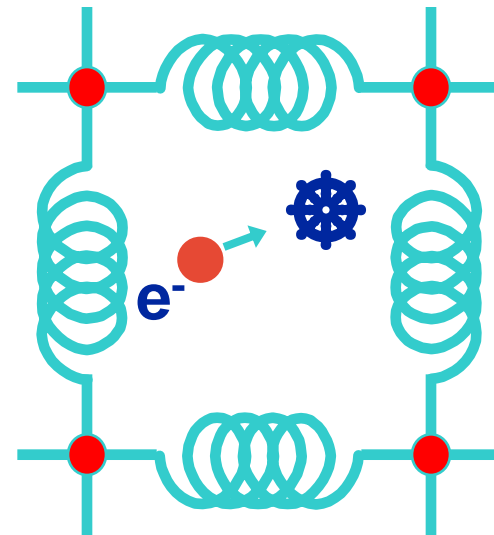
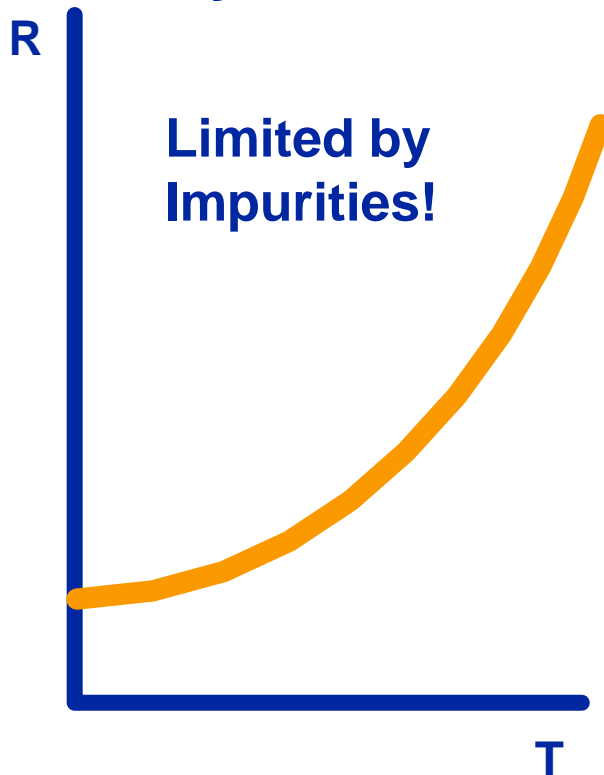
# Models of Electrical Conductivity

The Most Popular:

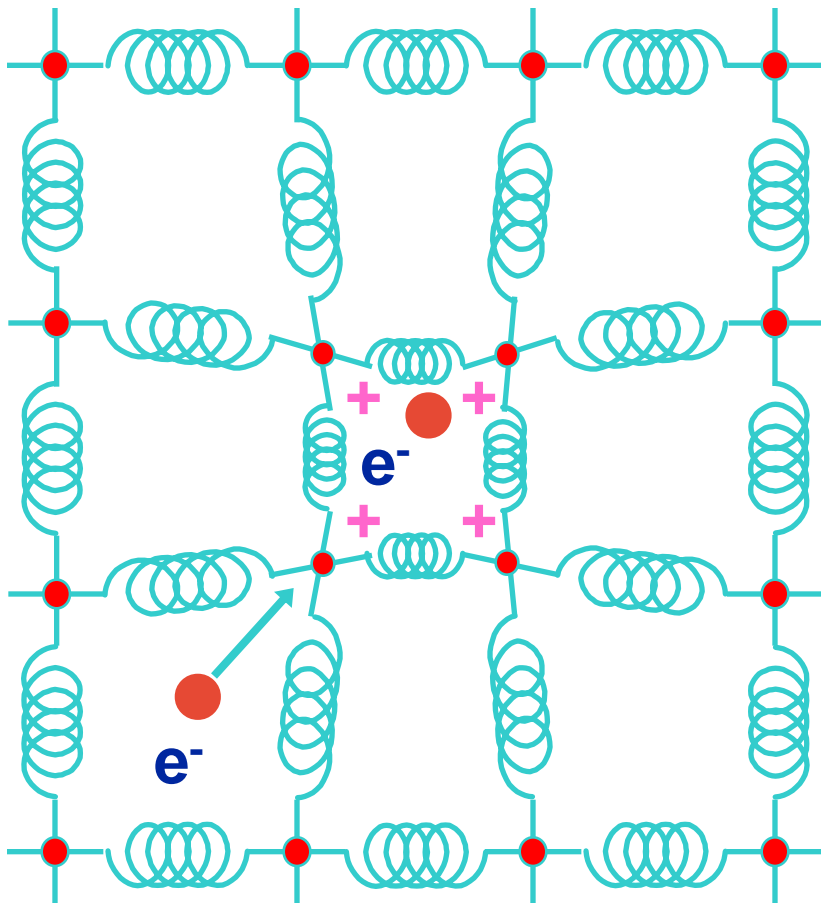


# Models of Electrical Conductivity

**Reality:**



# Physics of Superconductivity



**Electrons Pair Off!**

BCS Equation

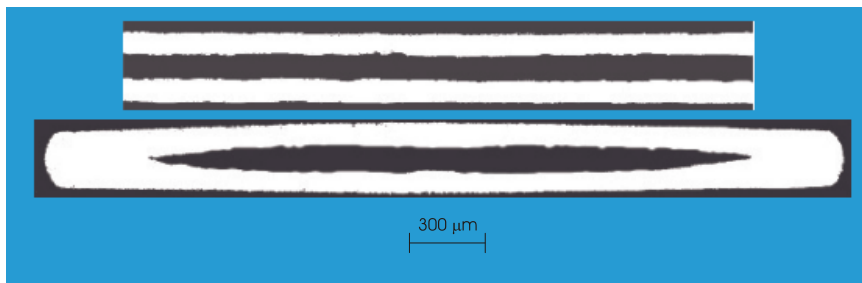
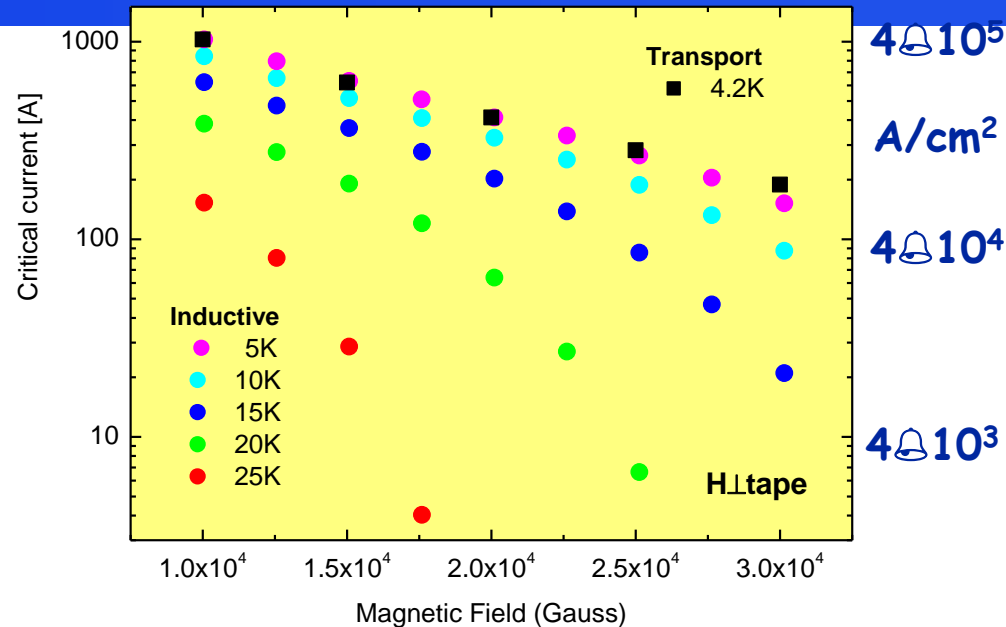
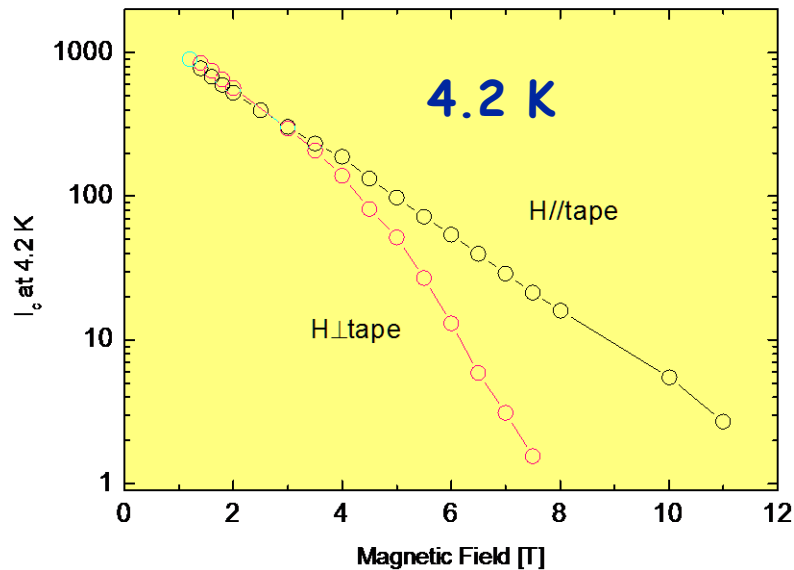
$$T_C = 1.14 \theta_D \exp(-1/\lambda)$$

$$\theta_D = 275 \text{ K},$$

$$\lambda = 0.28,$$

$$\therefore T_C = \underline{9.5 \text{ K}} \text{ (Niobium)}$$

# INFM-Genova Ni-Sheathed $\text{MgB}_2$ Tape



## Ex-Situ Sintered

Tape dimensions: 3.5 mm x 0.35 mm

Filling factor 20%  $A_{sc} = 2.5 \times 10^{-3} \text{ cm}^2$

Treated at 900°C for 2 hours in Ar

INFM-Genova, G. Grasso, A. Malagoli, V. Braccini, S. Roncallo, and A.S. Siri, Italy