



Superconductivity
Workshop
Charlotte, 24 May 1999

Insulated Conductors Committee

Superconductivity 101

A Primer for Engineers

Paul M. Grant

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EPRI

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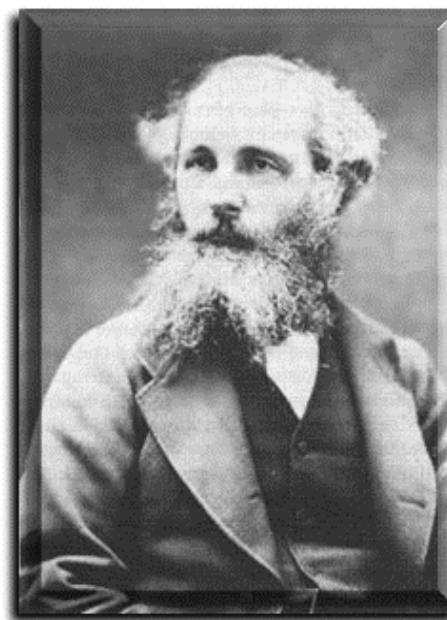
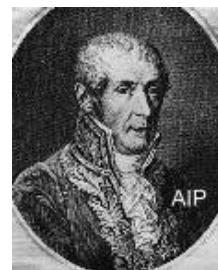
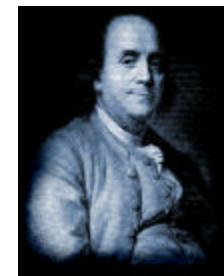
Superconductivity 101



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Fathers of Electricity



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Discoverers

Fathers of Electricity

Practitioners



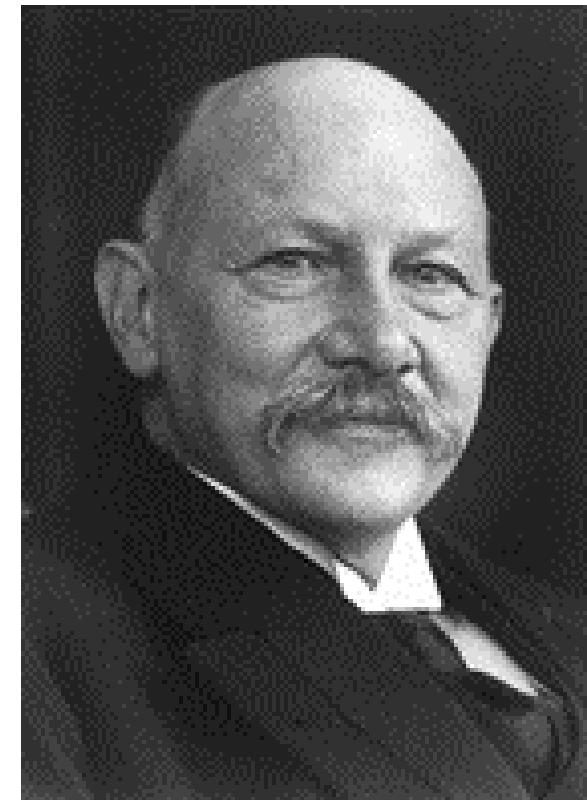
Fathers of Cryogenics



James Dewar

Dewar

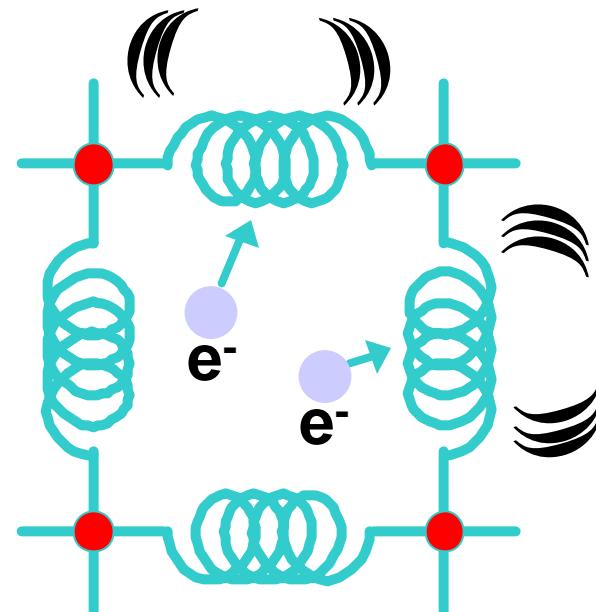
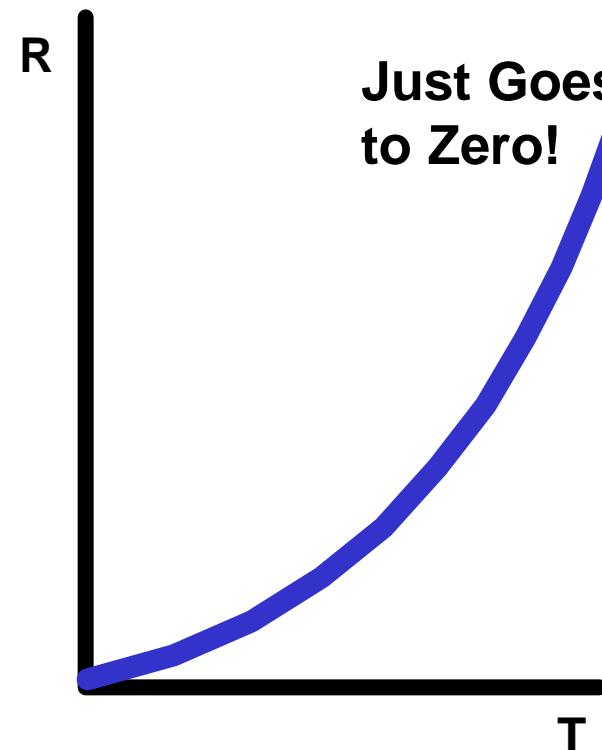
CH_4	112 K
O	90
N_2	77
Ne	27
H_2	20
He	4.2



Kammerlingh-Onnes

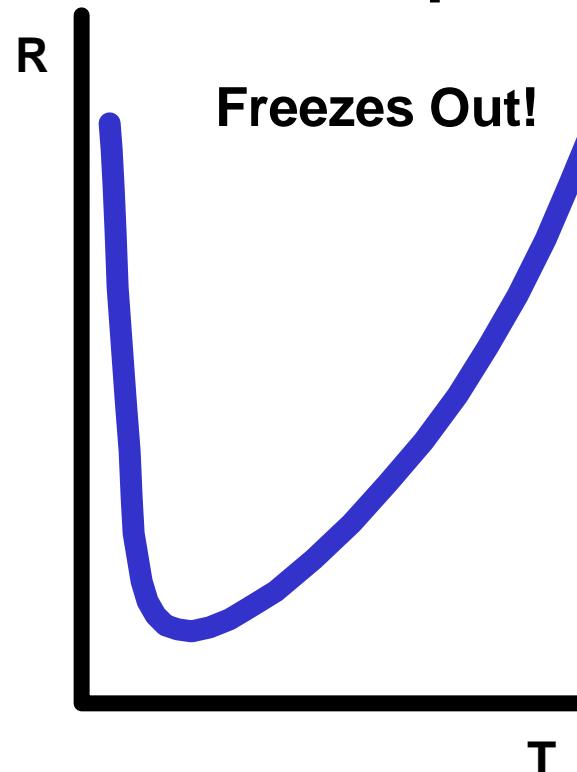
Models of Electrical Conductivity

The First Idea:



Models of Electrical Conductivity

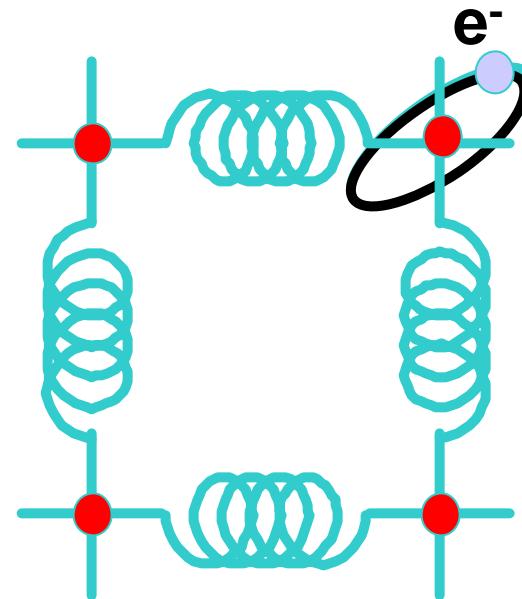
The Most Popular:



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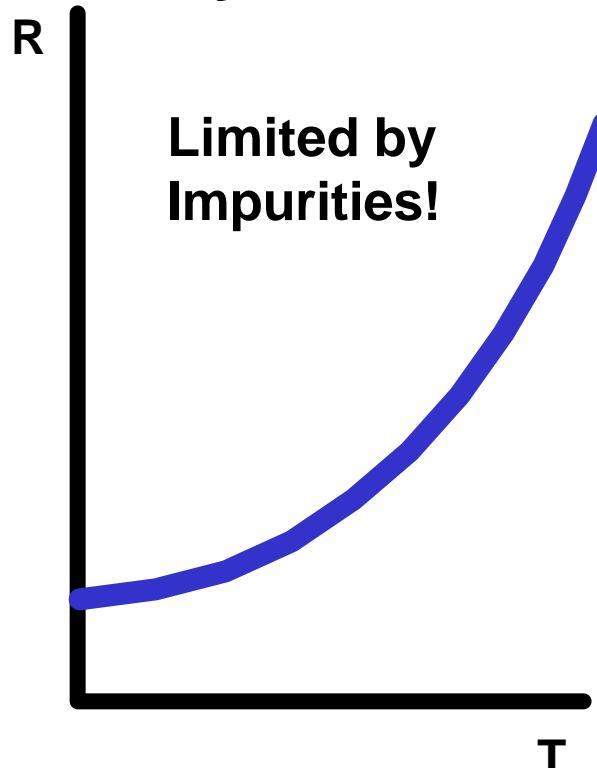
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Models of Electrical Conductivity

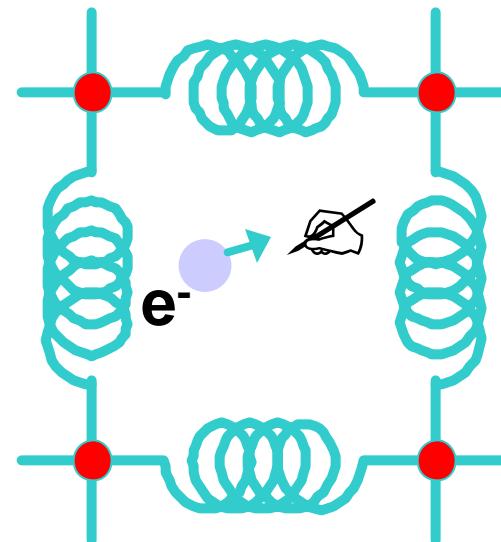
Reality:

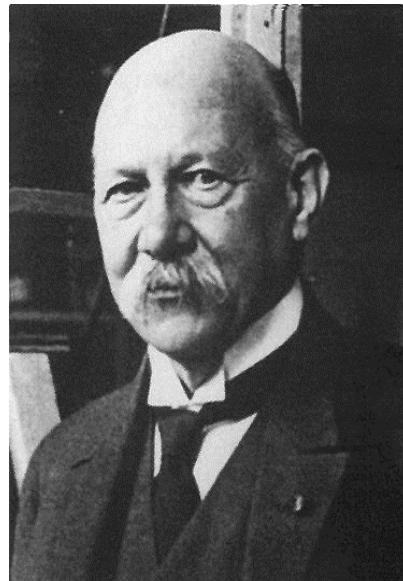
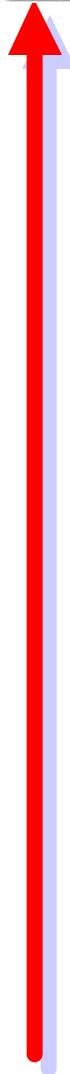


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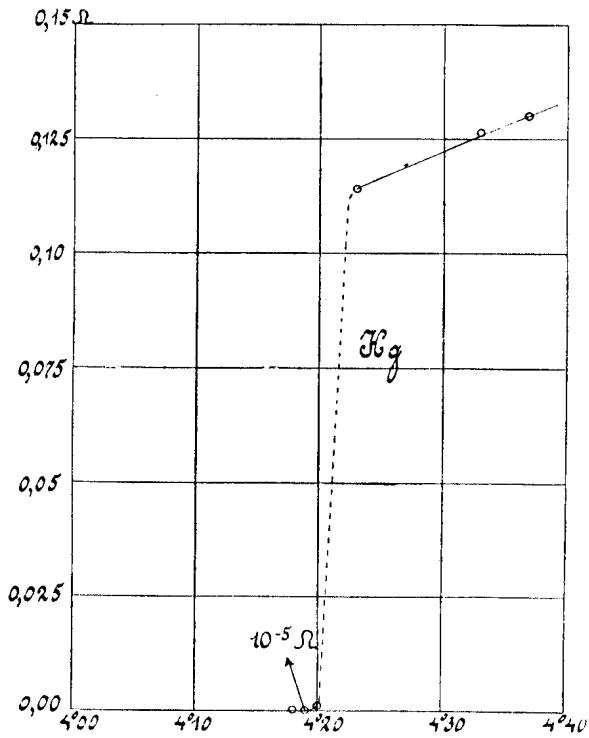




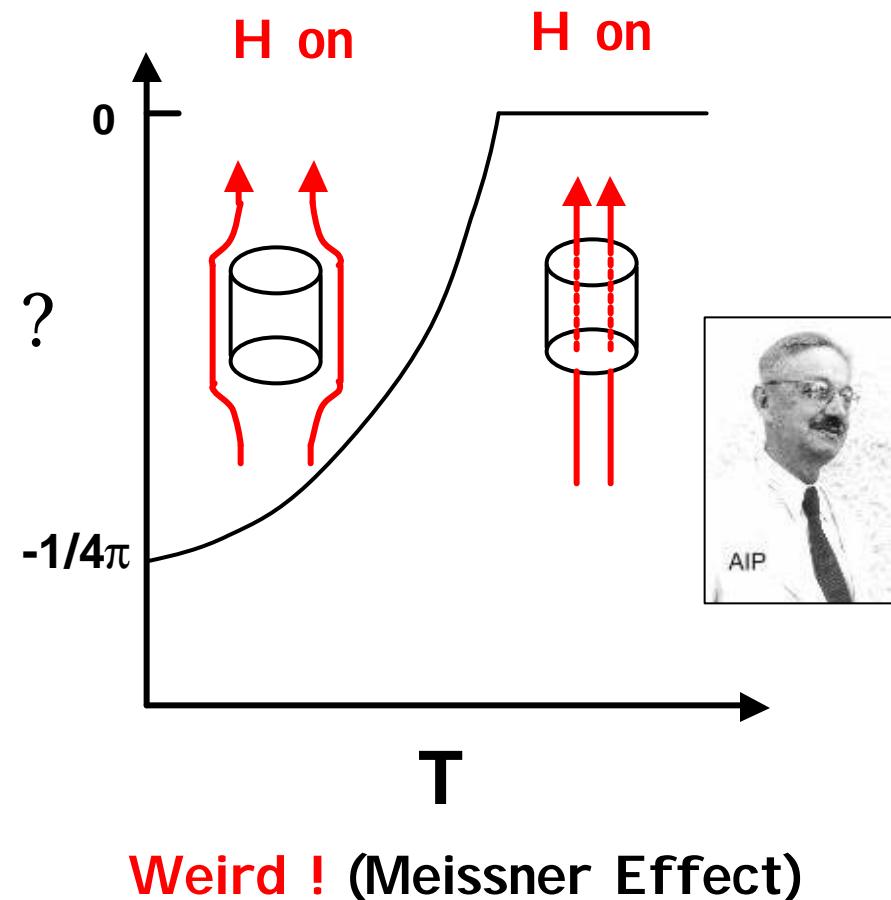
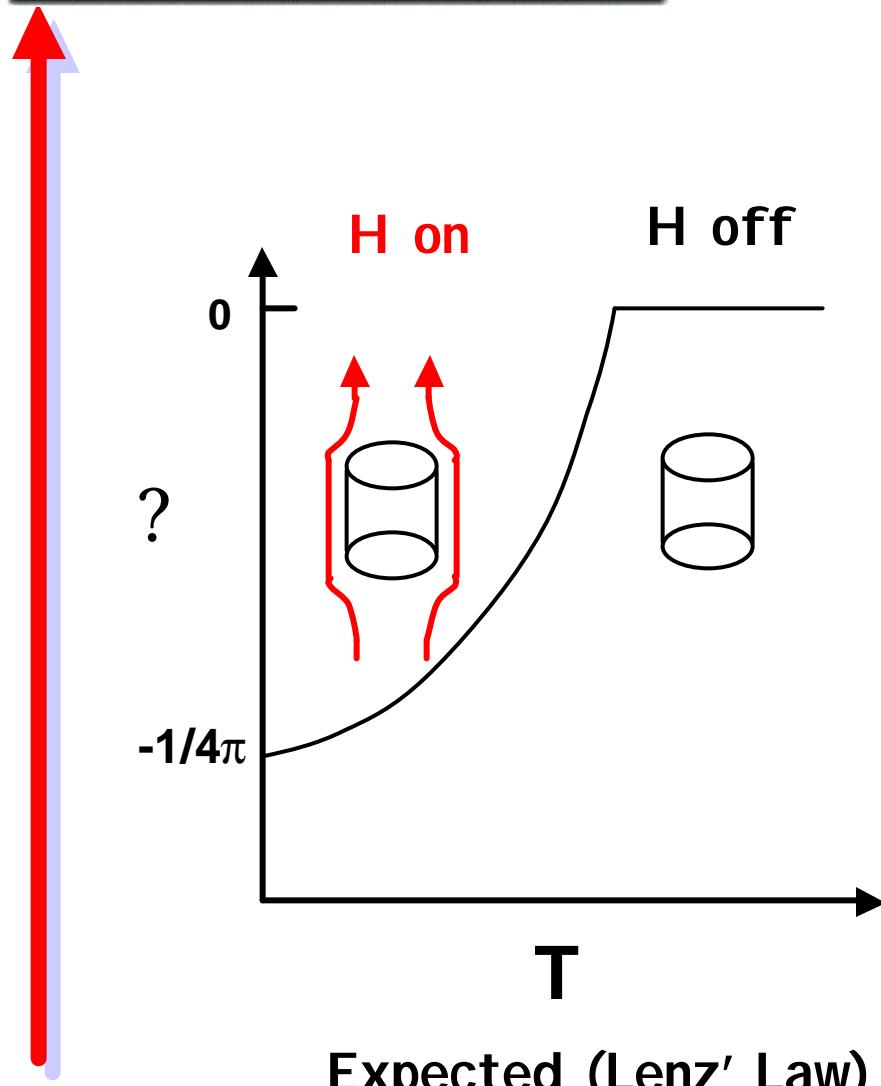
Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

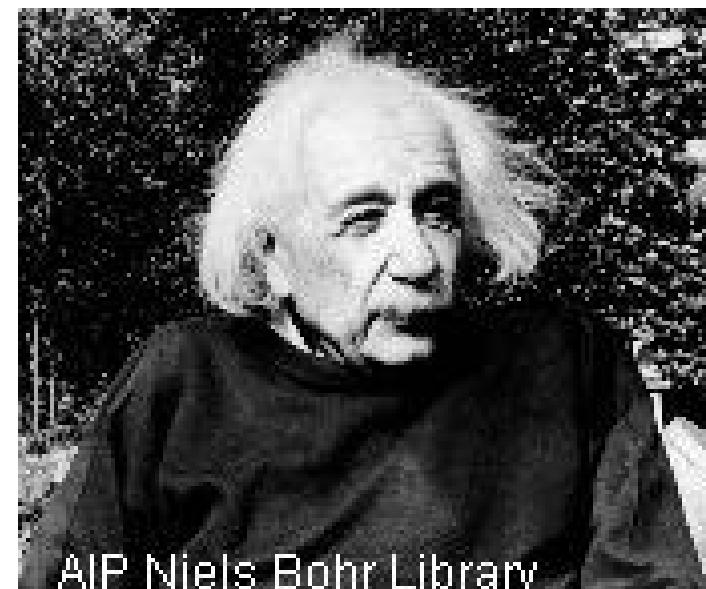
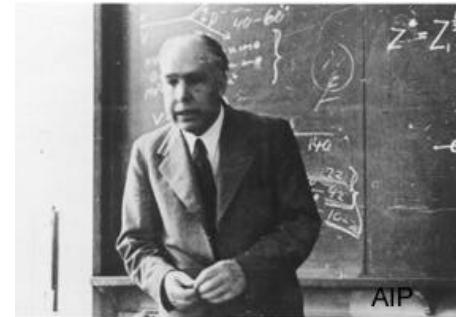
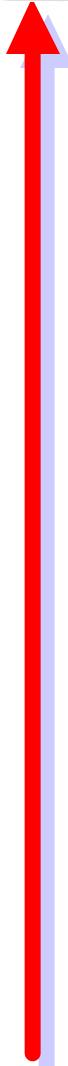
H. Kamerlingh-Onnes (1911)

1911 A Big Surprise!

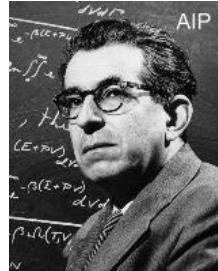
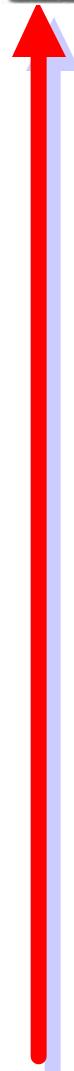


Magnetic Properties





They all tried...
and failed!



Fritz
London



Lev
Landau



Irwin
Froehlich

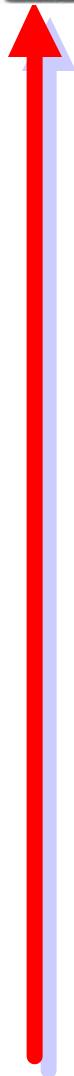
They came close...

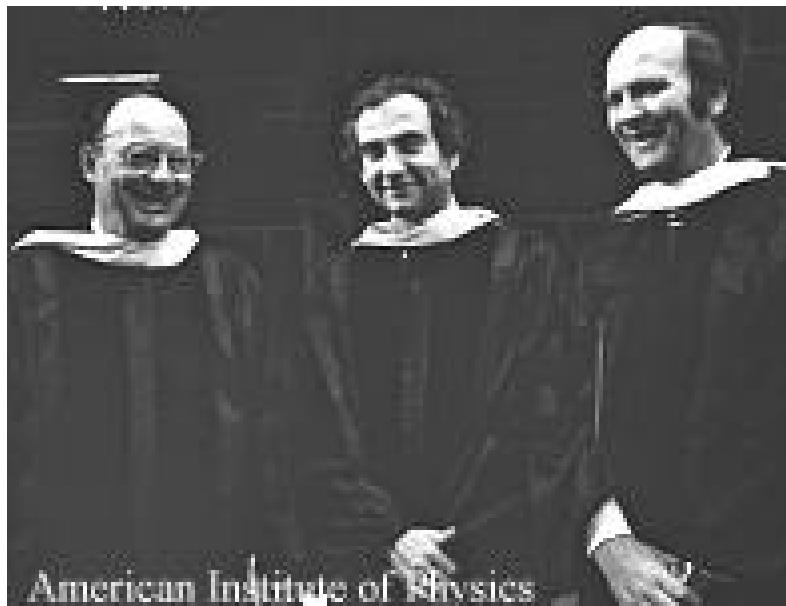
"The B-field does penetrate."

$$\mathbf{E} \sim \lambda^2 \frac{d\mathbf{J}}{dt}, \quad \mathbf{B} \sim \lambda^2 \nabla \times \mathbf{J}$$

"Since SC is a second-order phase transition, there must be an order parameter involved."

" T_c depends on the mass of the atoms (isotope effect), so the SC must be tied to lattice vibrations (phonons)."

 **B ----- C ----- S**



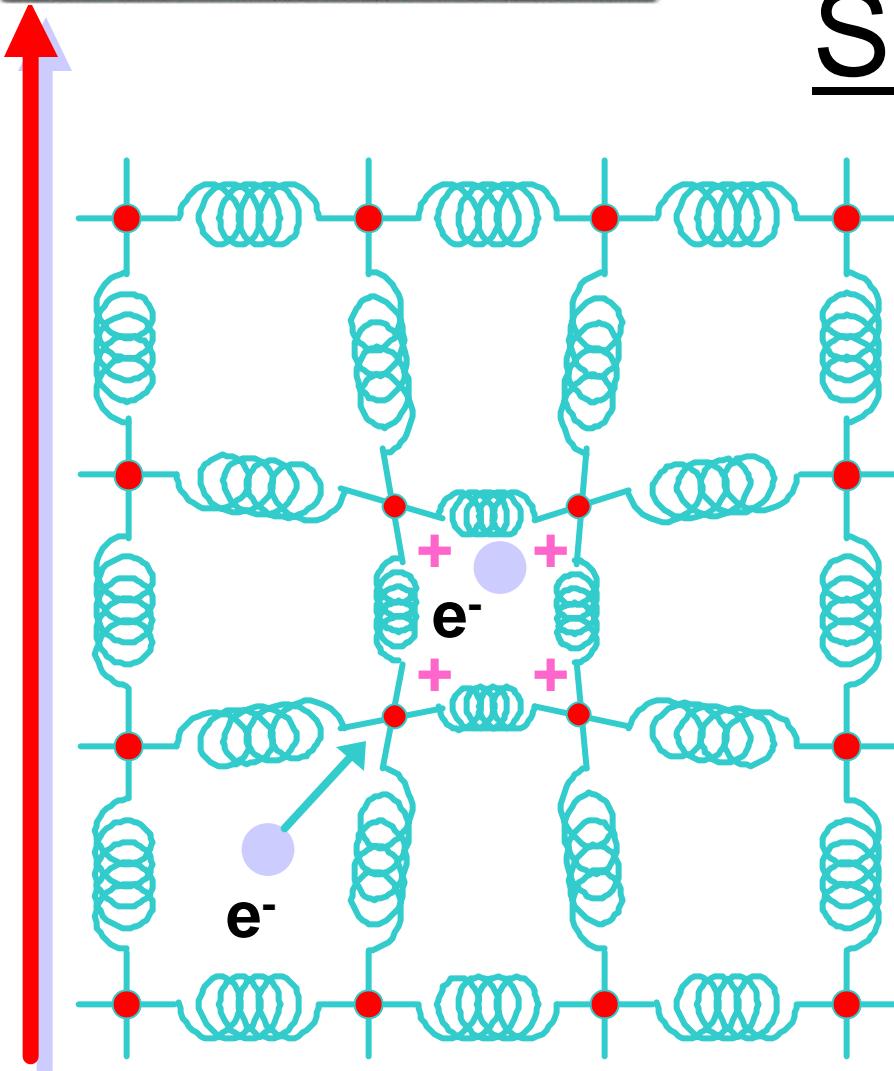
They Got It Right!

There has to be a regime where the lattice vibrations act to bind electrons together rather than scatter them with loss as given by Ohm's Law.

Bardeen: "It's a macroscopic quantum state"

Cooper: "It's got twice the charge you'd expect"

Schrieffer: " Ψ 's a statistical wavefunction"



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Superconductivity 101

Physics of Superconductivity

Electrons Pair Off!

BCS Equation

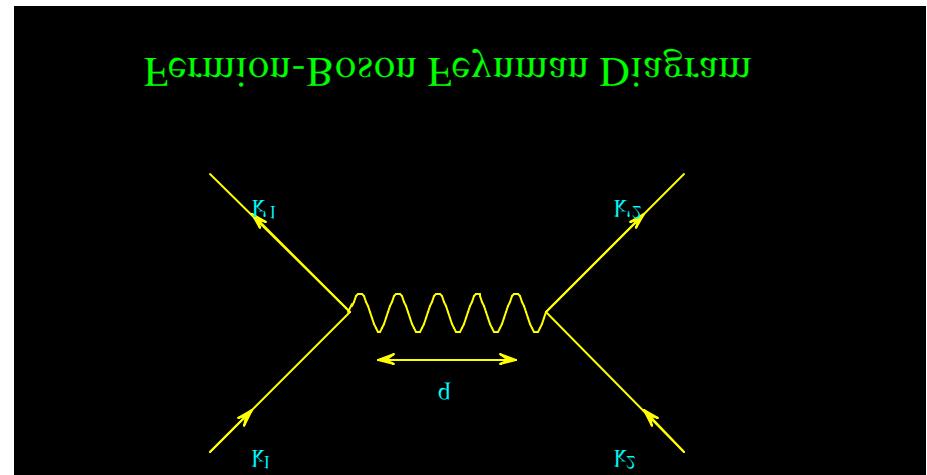
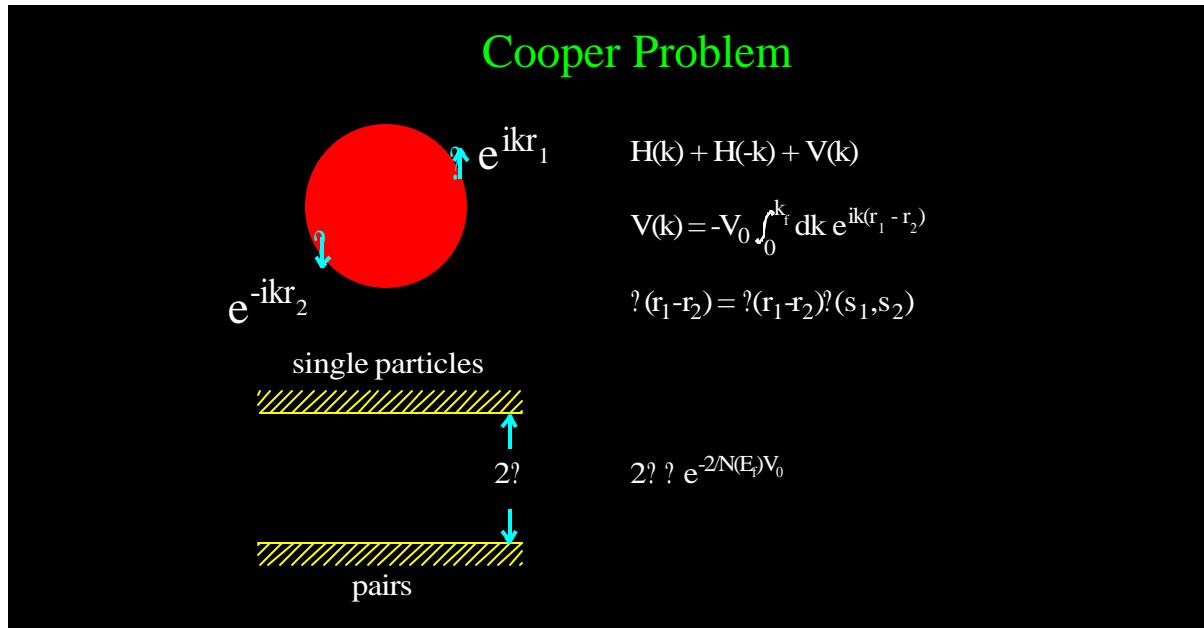
$$T_C \approx 1.14 \cdot \frac{1}{\Delta} \exp\left(\frac{1}{\Delta}\right)$$

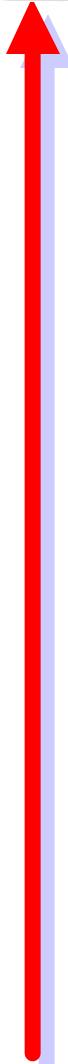
$$\Delta \approx 275 \text{ K},$$

$$\frac{1}{\Delta} \approx 0.28,$$

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

“Cooper’s Problem”



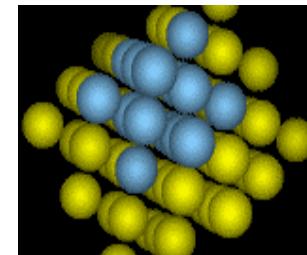
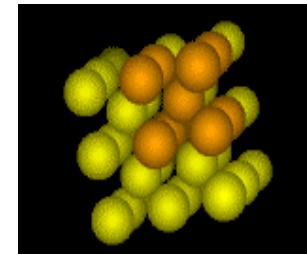
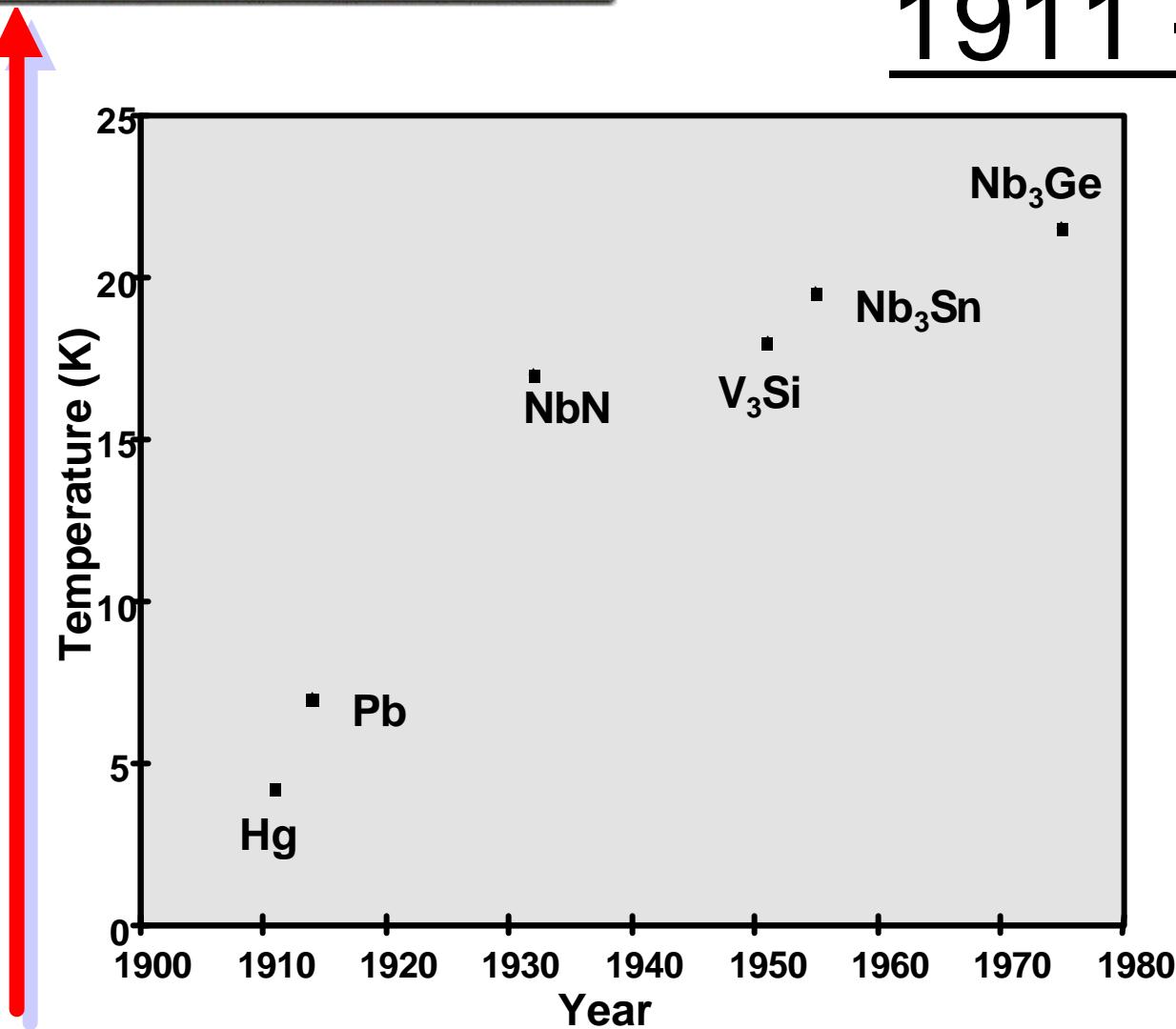


Important Numbers in Superconductivity

Transition Temperature, T_c	Way below 300 K
Critical Current Density, J_c	$10^{-2} - 10^6 \text{ A/cm}^2$
Critical Magnetic Field, H_c	$10^{-4} - 10 \text{ T}$
London Penetration Depth, λ	$10 - >1000 \text{ \AA}$
Pippard Coherence Length, ?	$10 - >1000 \text{ \AA}$
G-L Parameter, $\kappa = \lambda / ?$	0.01 - 100

NB! All these numbers depend on each other. E.g., $H_c \sim \lambda$?

T_c vs. Year: 1911 - 1980



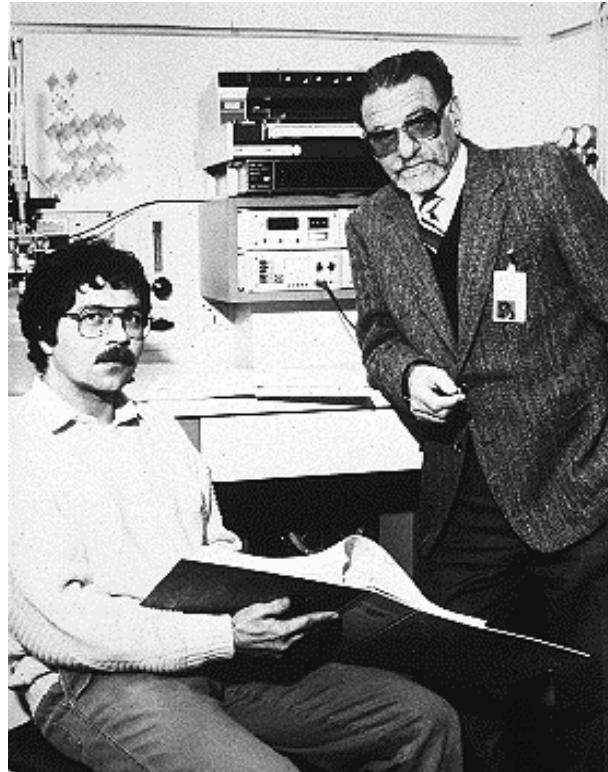
Cubic Metals

MRI & “Big Physics”



Magnetic Resonance Imaging
Philips

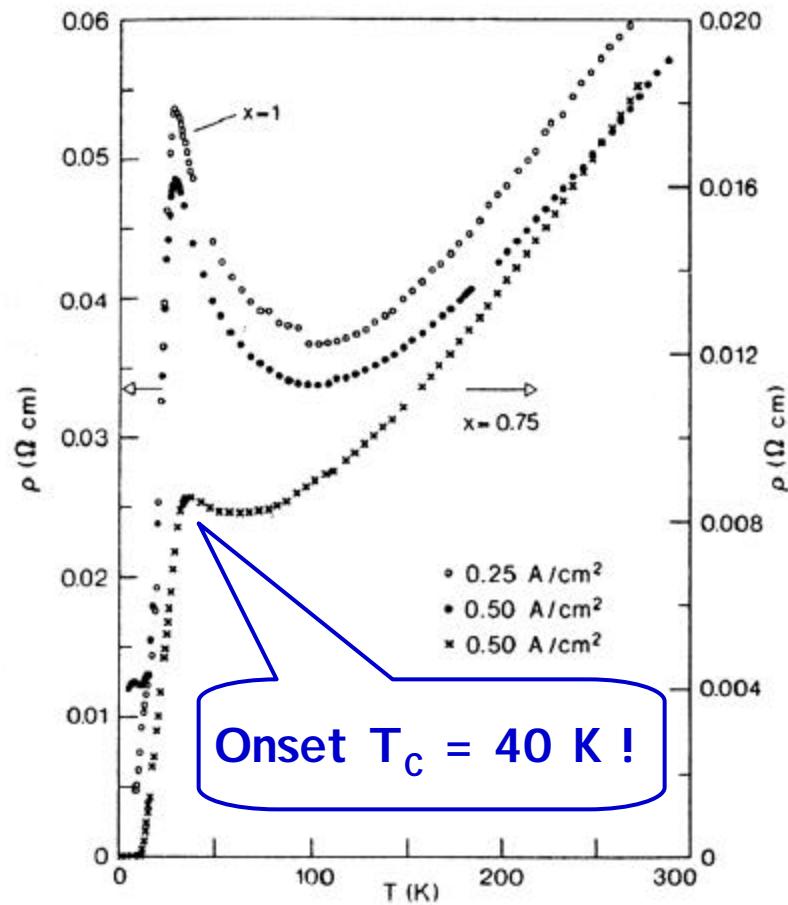
Tevatron
Fermi National Laboratory

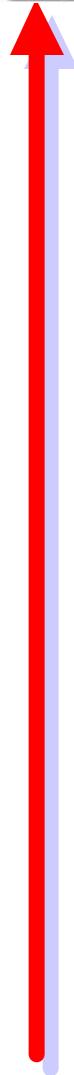


Bednorz and Mueller
IBM Zuerich, 1986

1986

Another Big Surprise!





1987
"The Prize!"



Associated Press

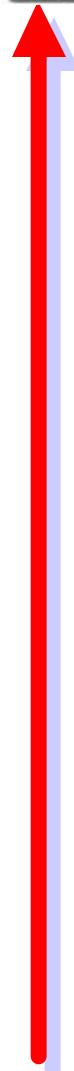
J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret



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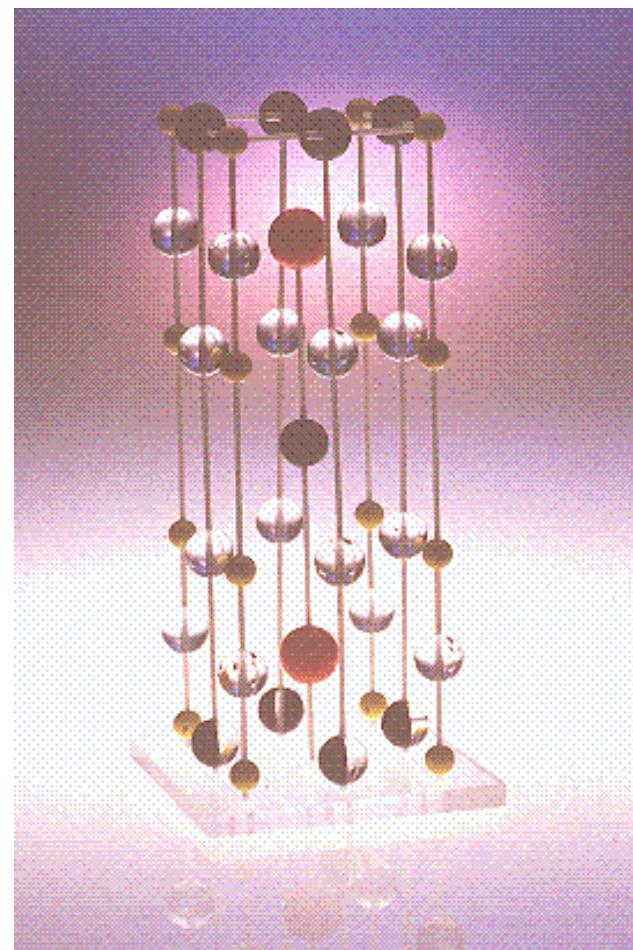


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Superconductivi

March 3, 1987
“123” Discovered

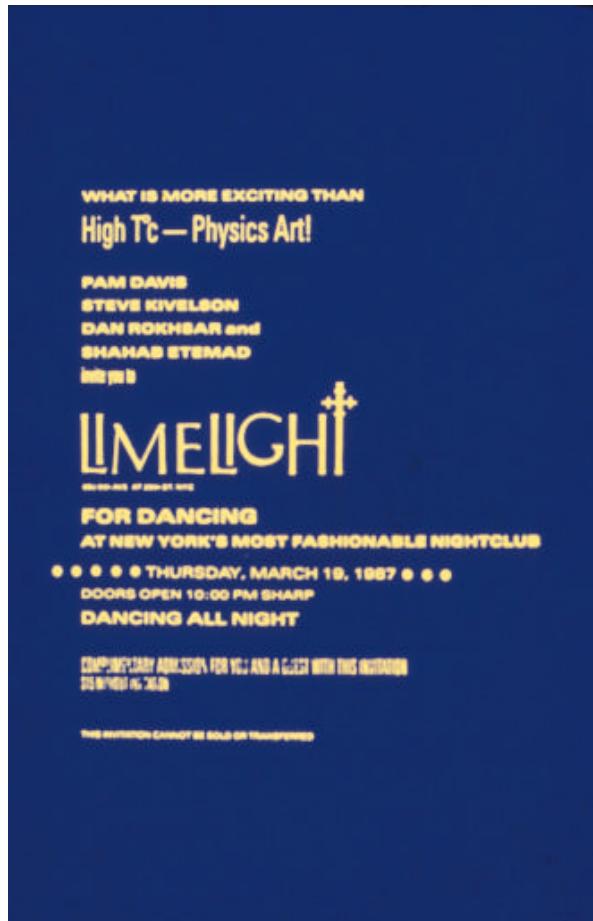




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Physicists' Night Out!



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Superconductivity 101

Woodstock of Physics NYC, 1987

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 paled 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 Müller¹ 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 material: '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 California, San Diego, was asked to put together a special post-deadline evening session devoted entirely to the discovery.

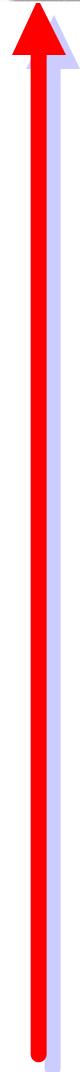
All those wishing to report results would be granted five minutes each, in order of the arrival of their request to take part — and did the requests rain in, raining a downpour in the two weeks before the meeting, as confirmations of the Wu-Chu measurements were made. All in all, 51 presentations were 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 tumult 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.



NATURE/VOL 313/19 MARCH 1991

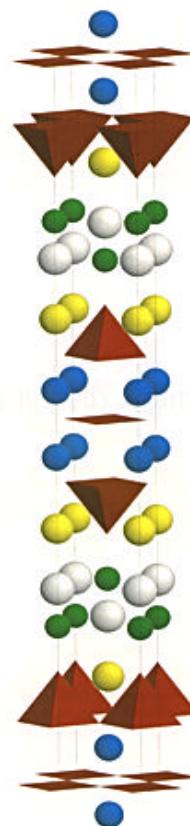


HTS Layered Perovskites

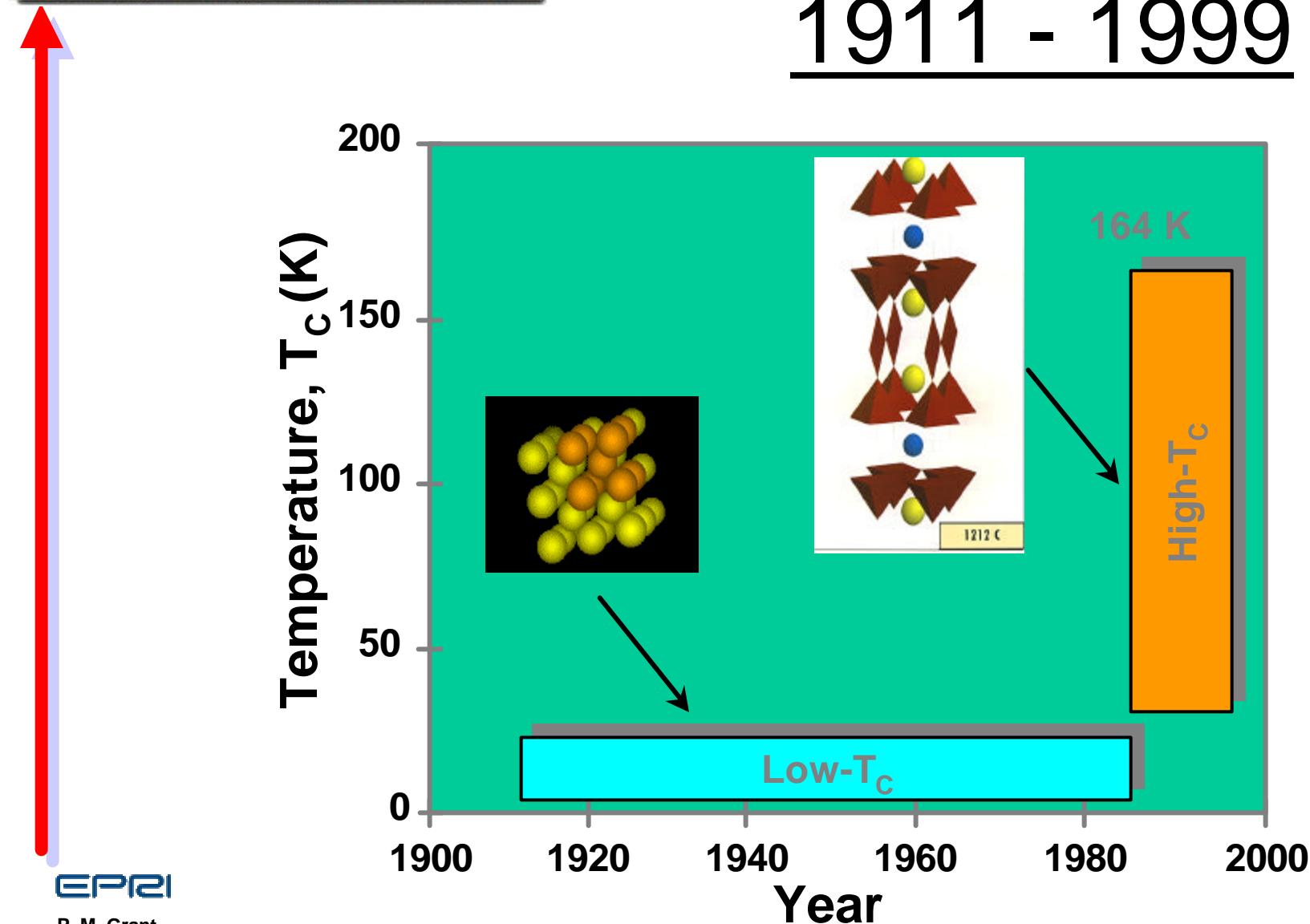
Y-123



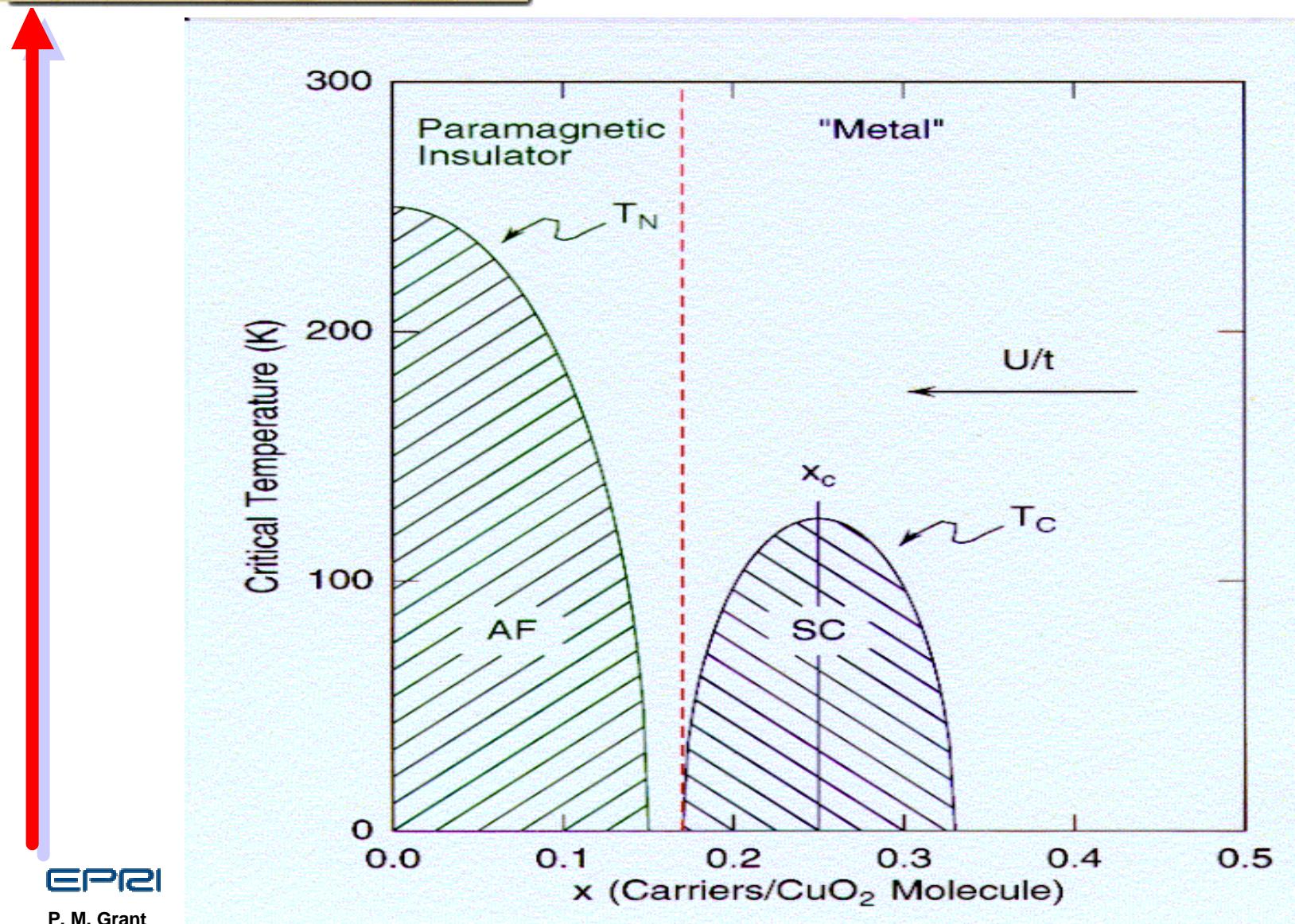
Bi-2223



T_c vs. Year: 1911 - 1999



HTSC Phase Diagram





Phil Anderson

HTS Theories

"It can't be just an accident that high temperature superconductivity occurs in a host material whose insulating state is an antiferromagnet, and, which when doped with holes to a level where magnetic behavior disappears, we get superconductivity."

Current Situation:

- The pair coupling is believed to be magnetically mediated.
- The normal conducting state is believed not to be a Landau liquid.
- The superconducting state is domain-like, occurring as electronic "stripes."

However, there is yet no generally accepted model today!

Boson Flavors



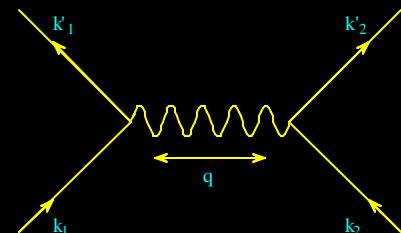
Hubbard Hamiltonian

$$H = \sum_i [t(c_i c_{i+1}^* + h.c.) + U n_i^\uparrow n_i^\downarrow]$$

t = Hopping Integral

U = Coulomb Repulsion

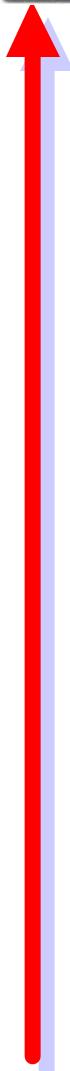
Fermion-Boson Feynman Diagram





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Ultimate Boson

Put-ons!

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Superconductivity 101

GLAG

$$\begin{aligned}
 G[?] &= ?d^3r \left[\frac{1}{2m^*} (?i\Box? - e^* A) ? * (i\Box? - e^* A) ? ? a ?? * ? \frac{1}{2} b ?? * ?? * \right] \\
 &\quad ? (i ?? - A)^2 f ? f(1 ? f^2) ? 0 \\
 &\quad ?^2 ? ? (? - A) ? \frac{1}{2} i(f^* f - f^* f) ? Af^2 ? 0
 \end{aligned}$$



Lev Gor'kov

$$? ? (|a|/b)^{1/2} f$$

$$A ? (?_0 / 2 ??) A$$

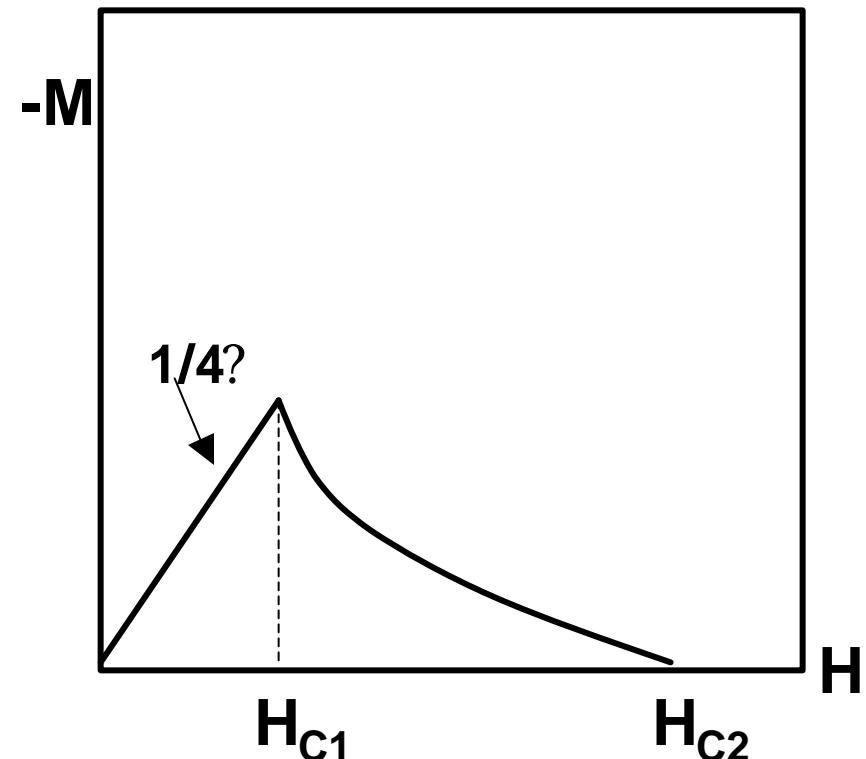
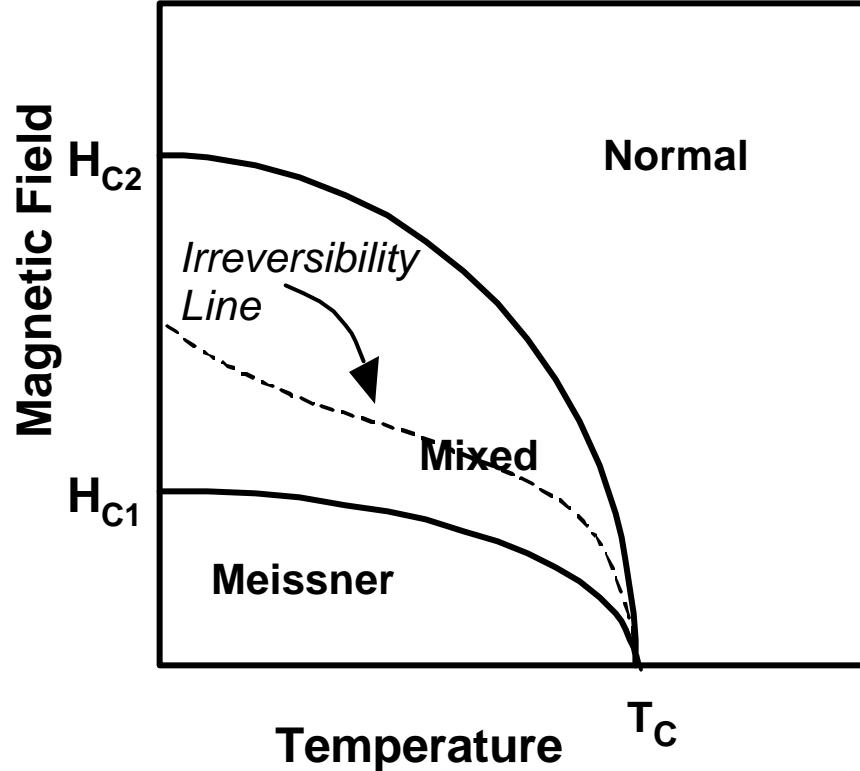
$$? ? ?_L / ?$$

$$? ? 1/\sqrt{2} \quad \text{I}$$

$$? ? 1/\sqrt{2} \quad \text{II}$$

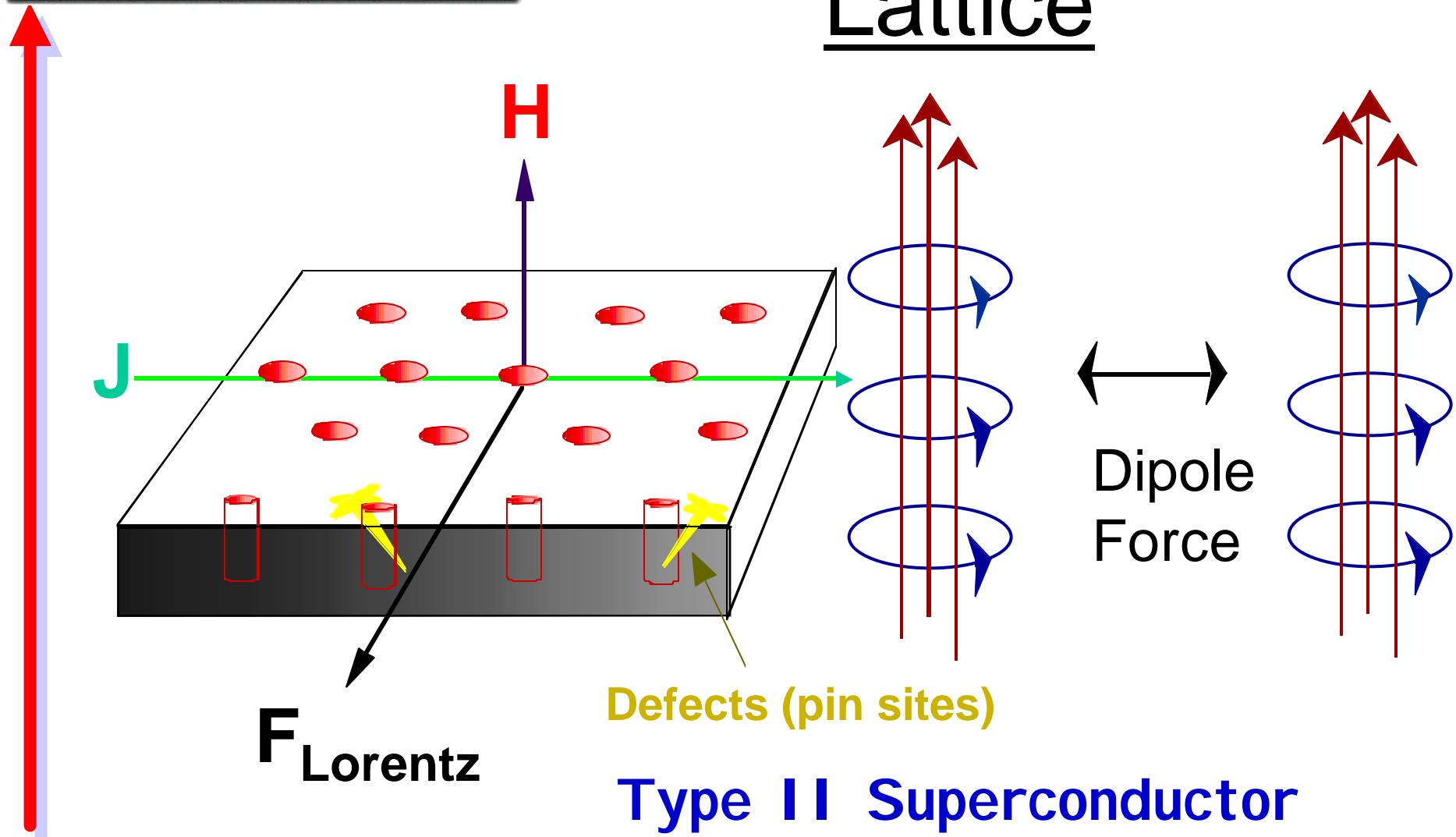
Type II

Superconductivity



Abrikosov Vortex

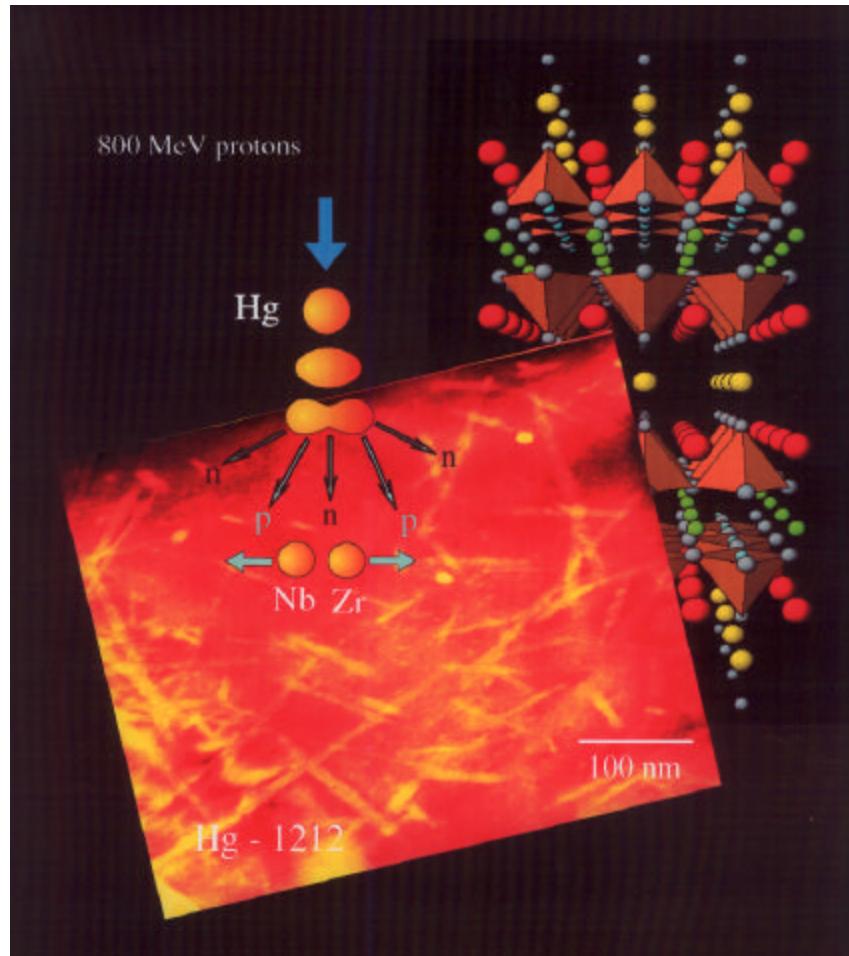
Lattice



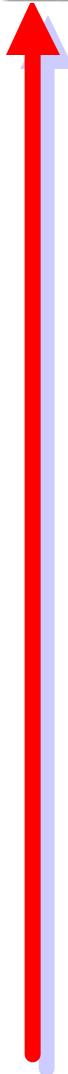
Type II Superconductor
in the Mixed State

Hg-1212:

Fission-Induced Defects



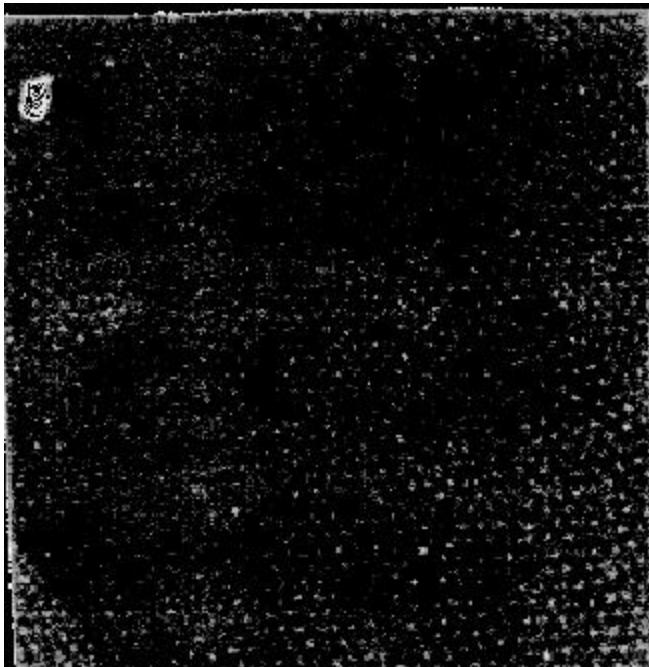
- L. Krusin-Elbaum, et al., Nature
- World record H_{irr} at 77 K in Hg-1212
- Hg-1212 Prototype Tapes made at TCSUH
- Potential for high-field magnet inserts



Extrinsic Pinning

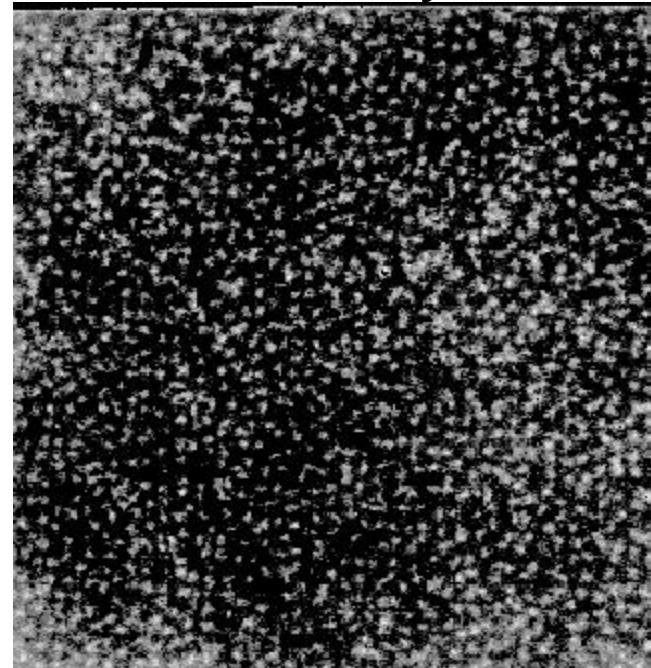
DECORATED VORTEX ARRAYS

clean



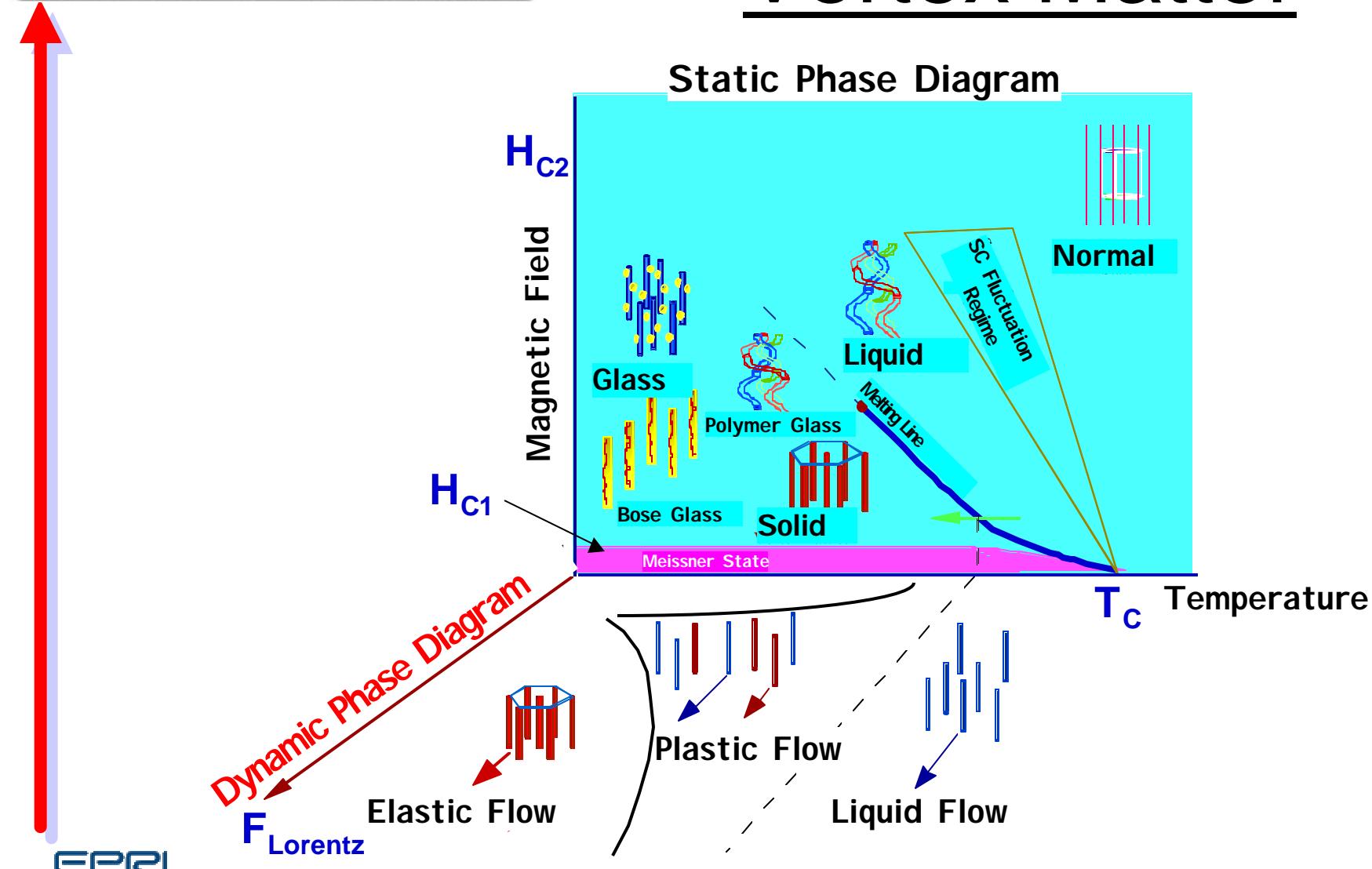
10⁻⁶m

with random heavy ion tracks

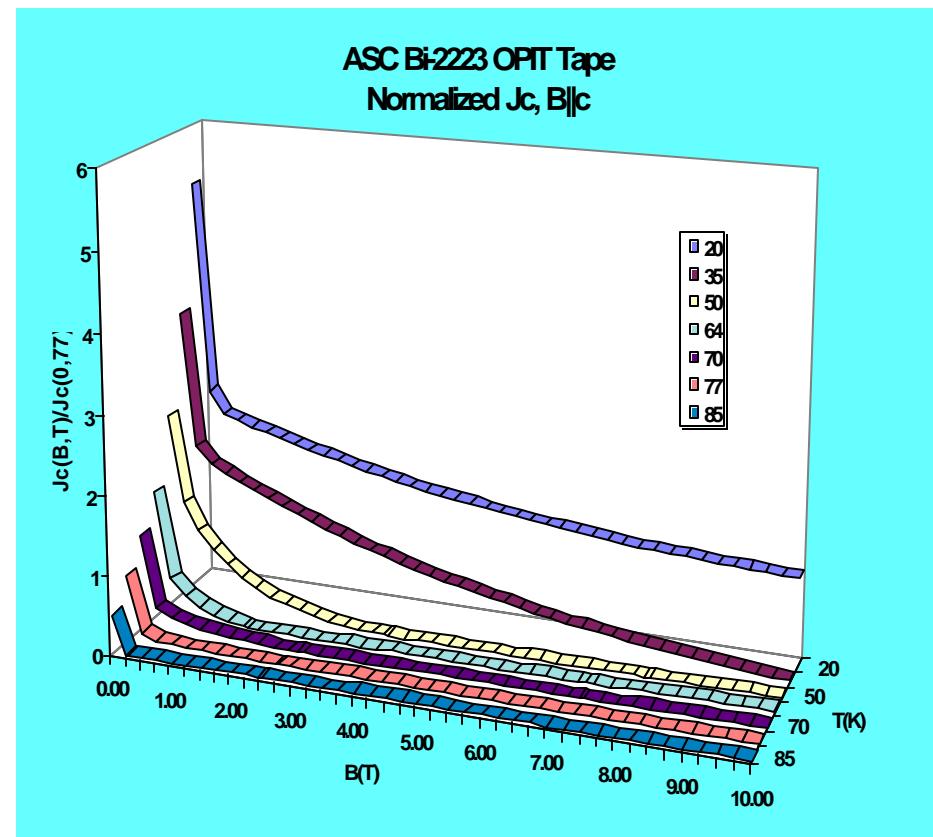
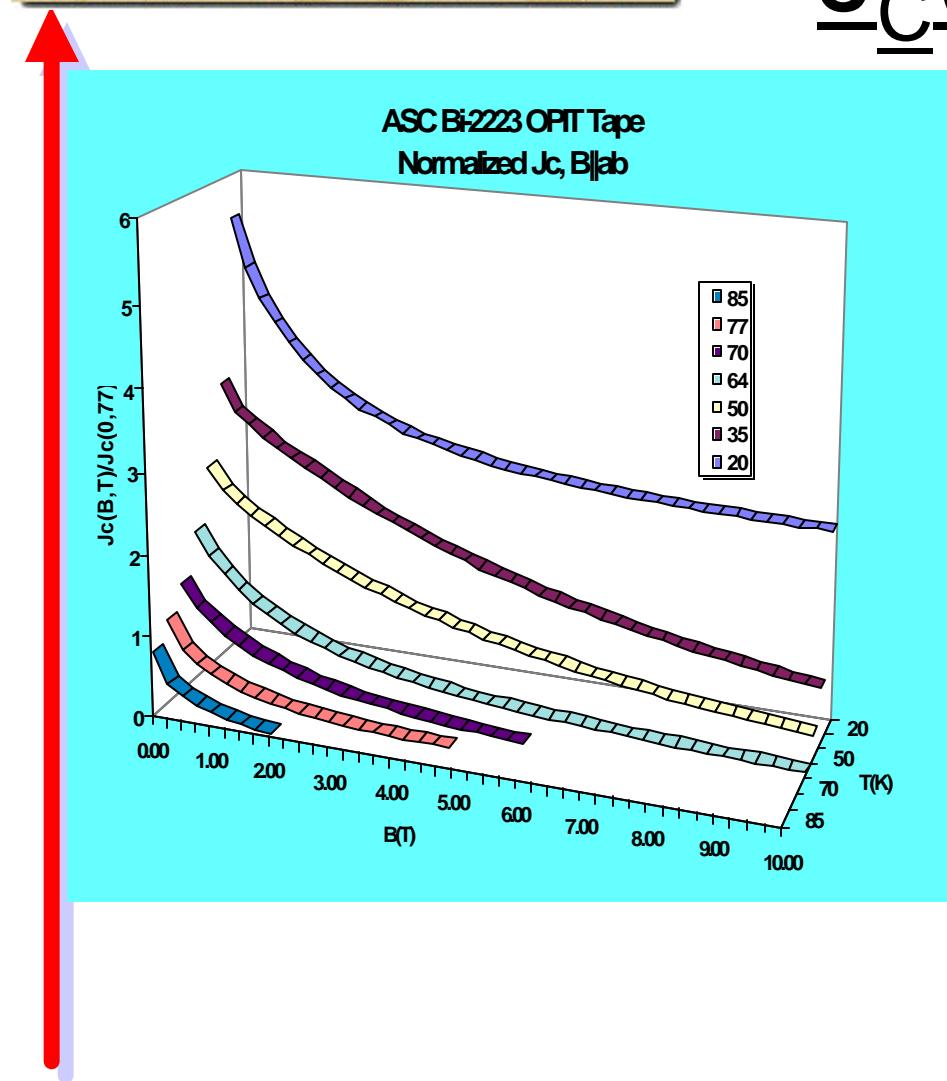


10⁻⁶m

Vortex Matter

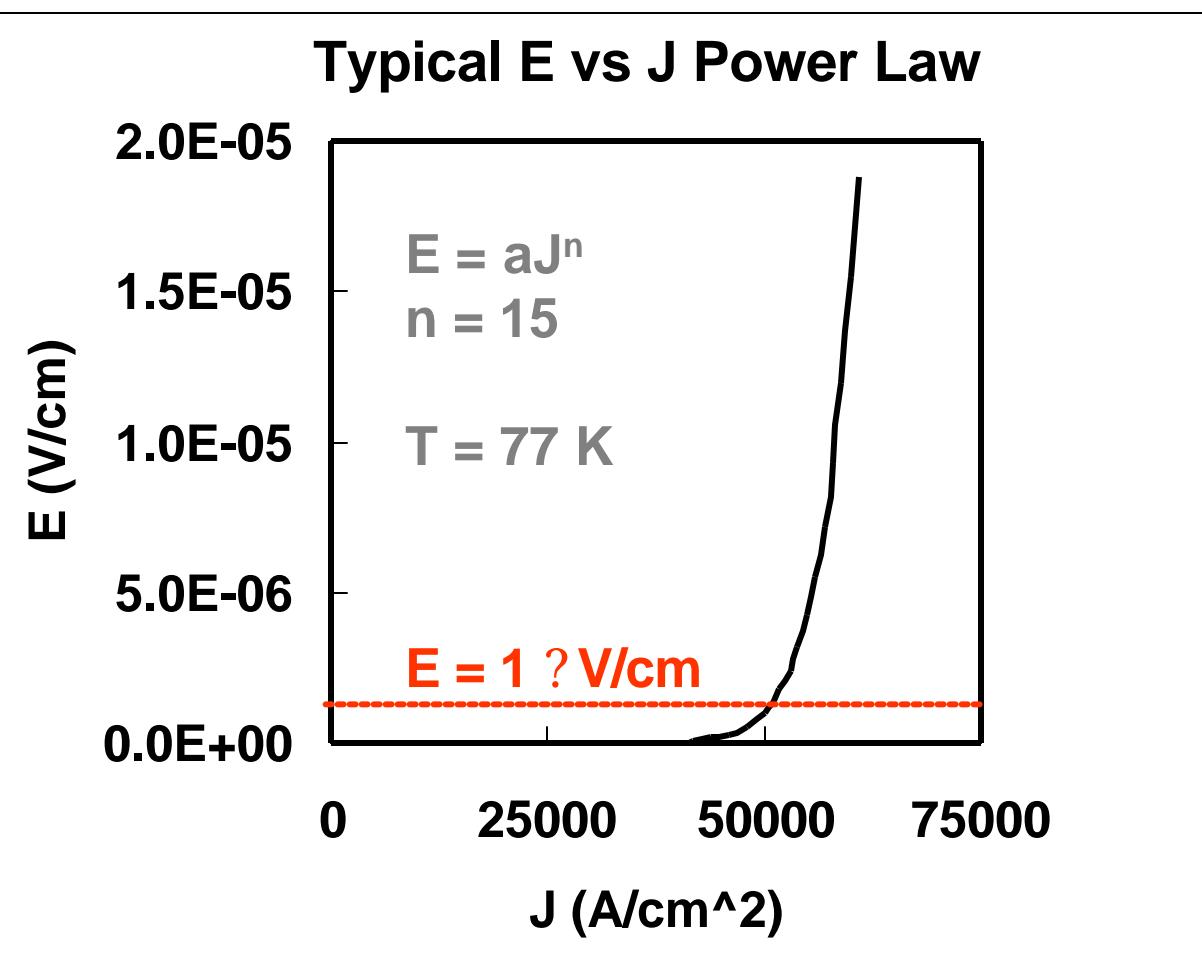


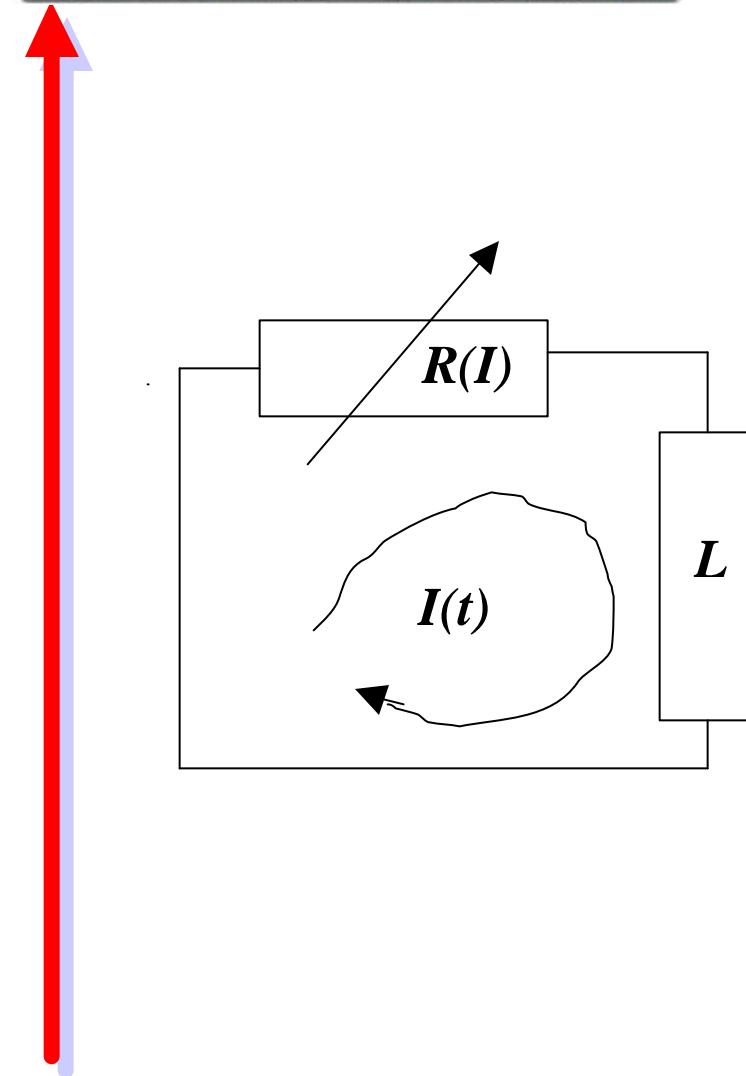
$J_C(B, T)$ for BSCCO



BSCCO OPIT/Ag

E-J Characteristic





Solenoid

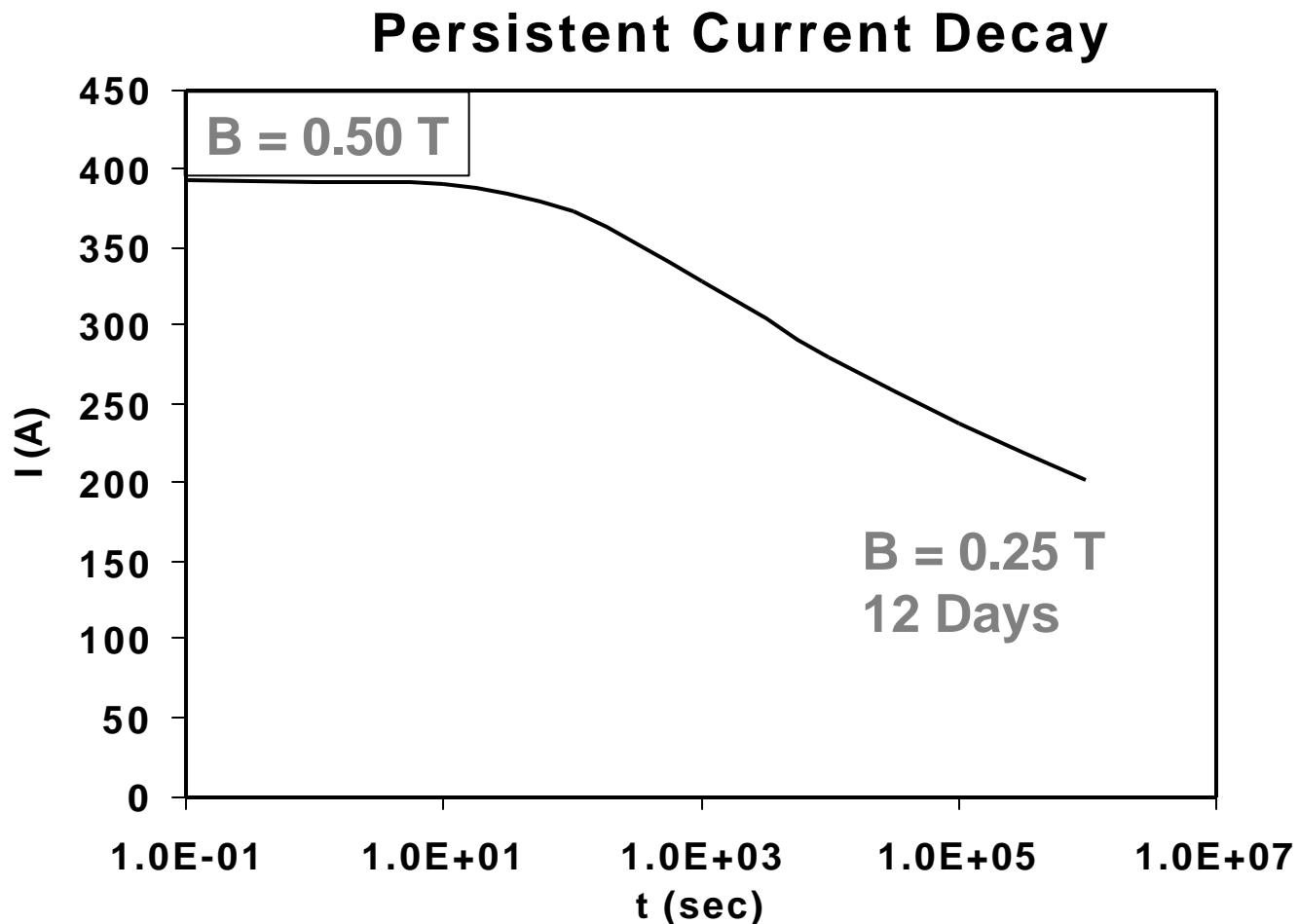
Loop Current: $t > t_0$

$$bI^n \stackrel{?}{=} L \frac{dI}{dt} \stackrel{?}{=} 0$$

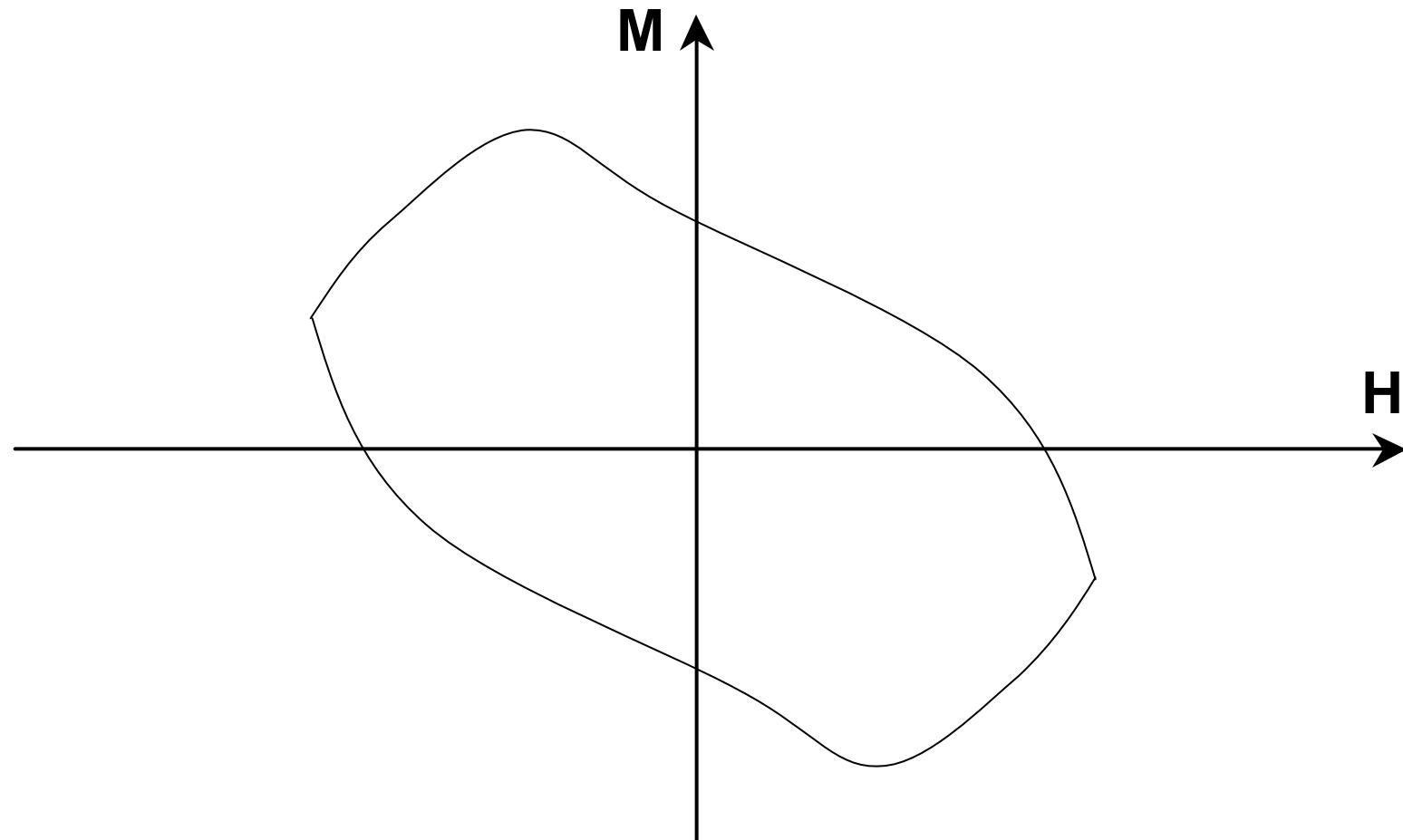
$$I(t) \stackrel{?}{=} \frac{?b(n \stackrel{?}{=} 1)}{L}(t \stackrel{?}{=} t_0) \stackrel{?}{=} I_0^{1 \stackrel{?}{=} n} \stackrel{?}{=}$$

"Persistent"

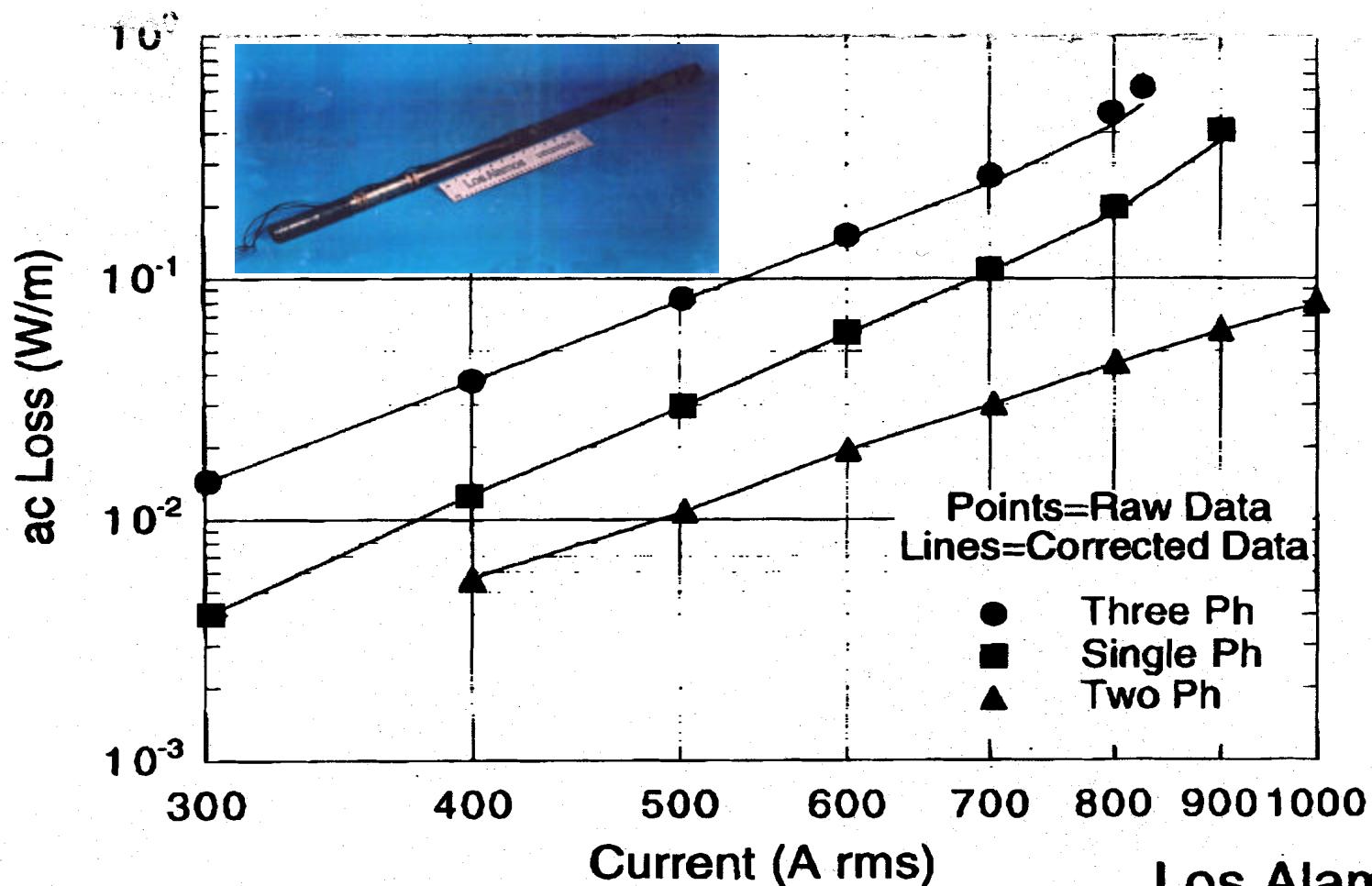
Current Decay



Type II Hysteresis



Hysteretic ac Loss





Superconductivity Workshop

Charlotte, 24 May 1999

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PHYSICS TODAY
MAY 1998

THE FIRST FIFTY YEARS

A red arrow points upwards from the bottom left towards the IEEE logo.

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Superconductivity 101

The Future 2028

PHYSICS TOMORROW: ESSAY CONTEST WINNER



RESEARCHERS FIND EXTRAORDINARILY HIGH TEMPERATURE SUPERCONDUCTIVITY IN BIO-INSPIRED NANOPOLYMER

Paul M. Grant
May 2028

Paul Grant is in the business of tomorrow's physics at the Electric Power Research Institute in Palo Alto, California. As a principal research engineer at EPRI, he recommends and assesses health impact and anticipated developments in frontier science and technology, looking for their potential impact on the global energy enterprise.

Prior to joining EPRI in 1993, he spent 28 years at IBM's Almaden Research Center, where he investigated the fundamental properties of exotic superconductors, conductors and magnetic materials. He says he wrote this essay out of frustration and revenge for the years he spent passing high T_c in organic metals when he should have started out with copper oxide perovskites.

He received his PhD in applied physics from Harvard University in 1965. Frequently sought out by the media for commentary on developments in superconductivity, he has been quoted in leading US and international newspapers and widely circulated weekly periodicals, and has appeared on several television specials on superconductivity.

Forty-two years ago, Johannes Georg Bednorz and Kari Alex Müller shocked the world with their unexpected discovery of superconductivity in layered copper oxide perovskites at temperatures substantially higher than previously thought possible. The history of this breakthrough is well known, and a large number of milestones have been passed over the succeeding years, culminating in 2002 with $As_{2223}-8$, a triple-layer CuO complex with an ambient-pressure transition temperature of 175 K, synthesized by Paul Chu and co-workers at IBM. Such materials have found a number of commercializations and electric power applications, especially in distribution cables, transformers and passive RF filters, but remain limited by the need for cryogenic packaging.

Now, however, the time might be the stuff of history. At last week's general meeting of the North American Physical Society (NAPS), held in Coeur d'Alene, Idaho, small-molecule

and polymer superconductors

and Gerardo Eshelby announced the

discovery of superconductivity at

greater than 600 K in a laboratory-

created, rationally designed polymeric structure, polymer

skirt to DNA. It is widely believed

that the discovery could profoundly

affect the future course of global en-

ergy development.

Organic roots

In the 1960s, physicist William Little

of Stanford University envisioned the possibility of using high temperature superconductivity in specifically de-

signed organic chain systems.¹ At

that time, the prevailing Bardeen-Cooper-Schrieffer (BCS) theory successfully explained all known superconductivity as being mediated by electron-phonon coupling. Little observed that BCS theory applied to any system of pairing sustained by a general house field, including, for example, one derived from excitons or magnons. In the weak-coupling limit, the BCS transition temperature, T_c , is typically about 10 K. Even the strong-coupling variant of BCS developed by Werner Kettner, Miller and Gerardo Eshelby suggested that superconductivity mediated by lattice vibrations would not be possible above 35–40 K. To paraphrase Bernd Matthias, "You can't make a crystal structure that would be stable under such extreme temperatures."

Little's concept involved replacing the phonons—characterized by the Debye temperature—with excitons, whose much higher characteristic energies are on the order of 2 eV, or 23 000 K. If excitons were to become the electrons' pairing "glue," superconducting with T_c as high as 600 K might be possible even under relatively weak coupling conditions. Little even proposed a possible realization of the idea: a structure composed of a conjugated polymer chain (polyene) dressed with highly polarizable molecules (aromatic) as end groups. In this case, the conjugated chain would be a normal metal with a single mobile electron per C-H molecular unit; electrons on separate

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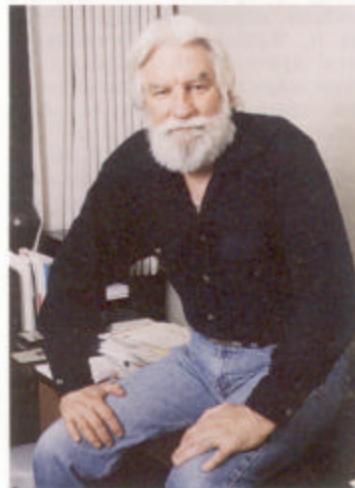


Superconductivity
Workshop
Charlotte, 24 May 1999

Insulated Conductors Committee

The Future

PHYSICS TOMORROW: ESSAY CONTEST WINNER



RESEARCHERS FIND
EXTRAORDINARILY HIGH
TEMPERATURE
SUPERCONDUCTIVITY IN
BIO-INSPIRED NANOPOLYMER

Paul M. Grant

May 2028

700 K !

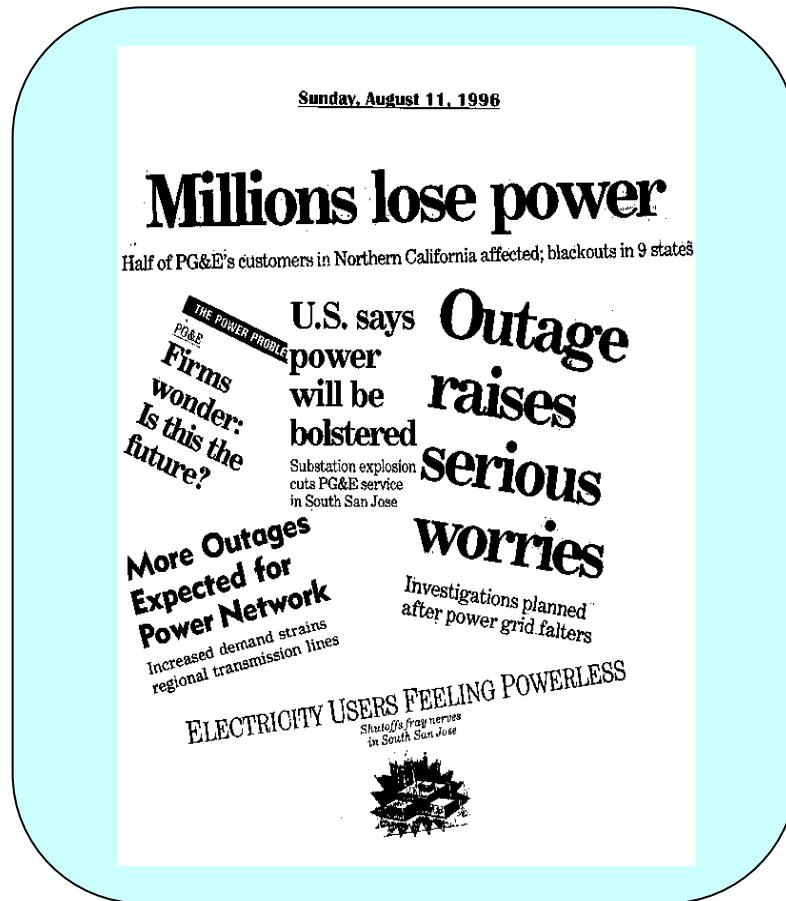
May, 2028

EPRI

P. M. Grant

Superconductivity 101

California, Summer 1996



Electricity: A Life Necessity



Quebec, Winter 1998



Superconductivity
Workshop
Charlotte, 24 May 1999

Insulated Conductors Committee



“You can’t always get
what you want...”



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P. M. Grant

Superconductivity 101

“...you get what you
need!”

