Virginia Beach, VA
September 17-22, 2000

Bringing Power to the People

The Coming Age of Superconductivity

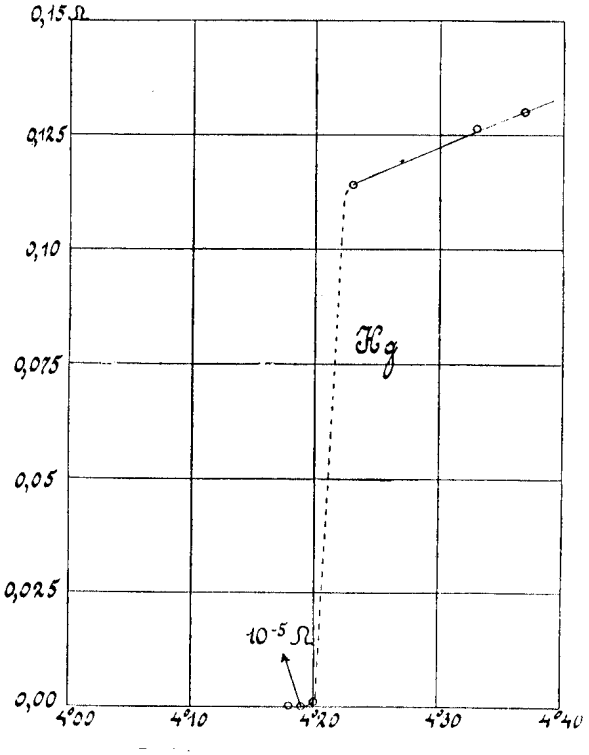
Paul M. Grant

Science Fellow

Electric Power Research Institute

Palo Alto, California USA

1911
A Big Surprise!

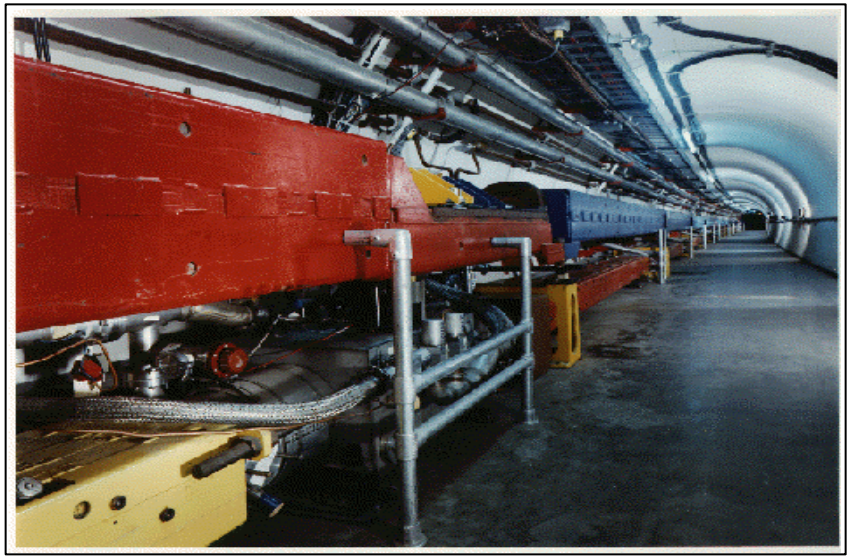


Thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*

H. Kamerlingh-Onnes (1911)

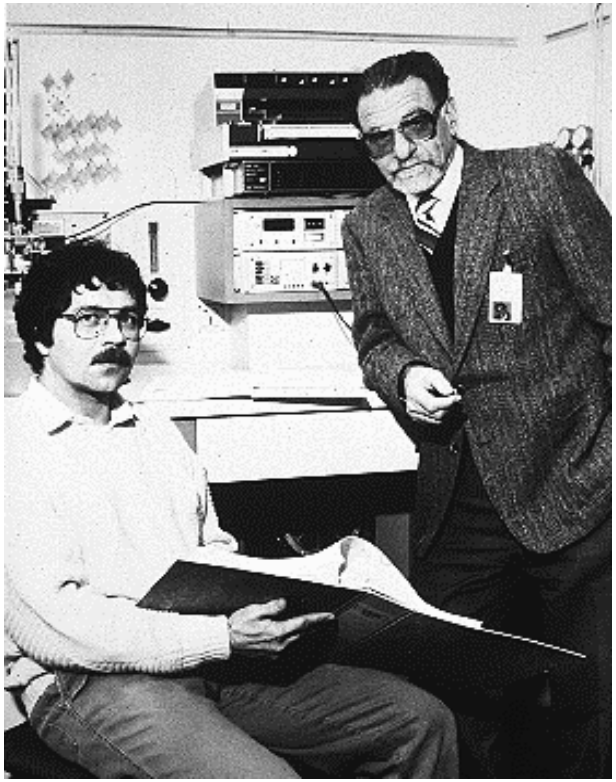
Superconductivity Today

Magnetic Resonance Imaging
Philips

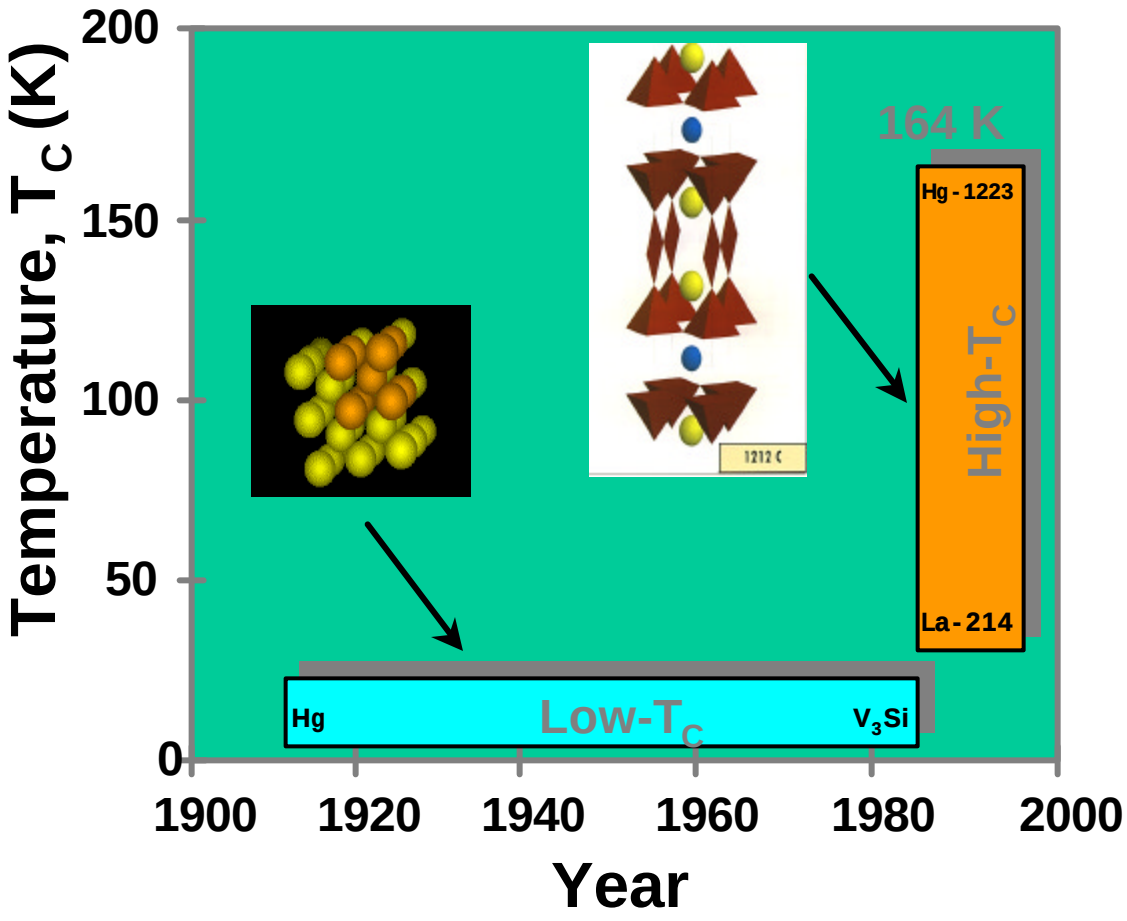


Tevatron
Fermi National Laboratory

Another Big Surprise!



Bednorz and Mueller
IBM Zuerich, 1986



1987
"The Prize!"

Associated Press

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

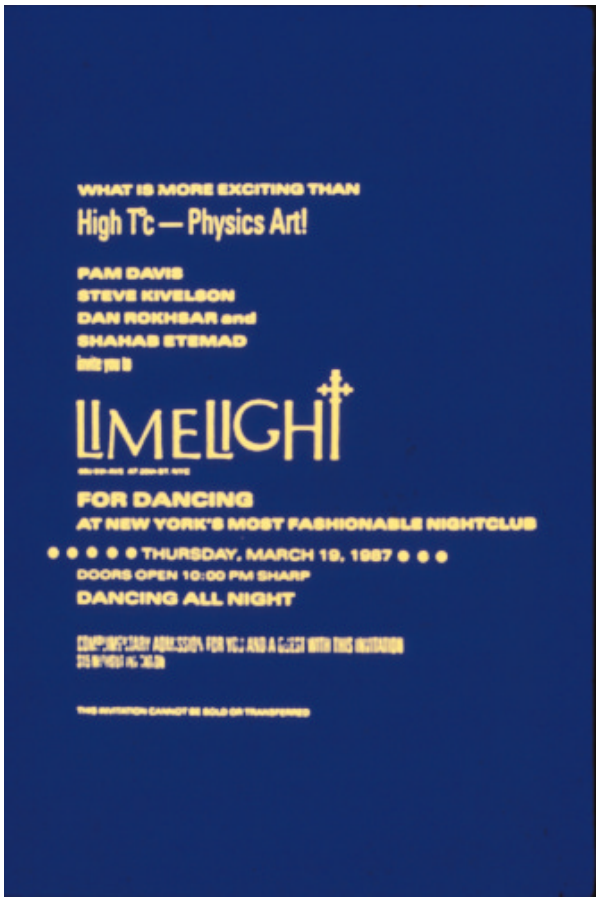
2 Get Nobel for Unlocking Superconductor Secret

Woodstock of Physics
NYC, 1987

Virginia Beach, VA

September 17-22, 2000

Physicists' Night Out!



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

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

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 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, 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.

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

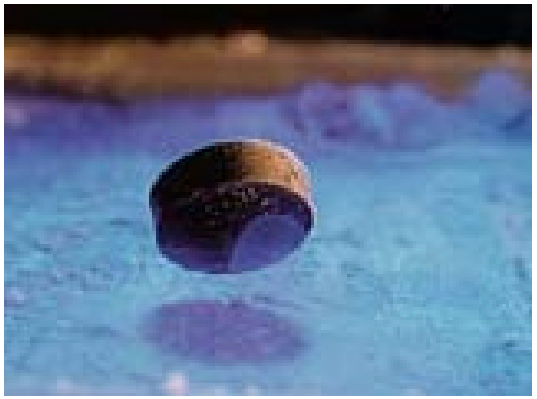
Opening act

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.

"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.

Fame



Pupils at Gilroy High School in California make their own high-temperature superconductor

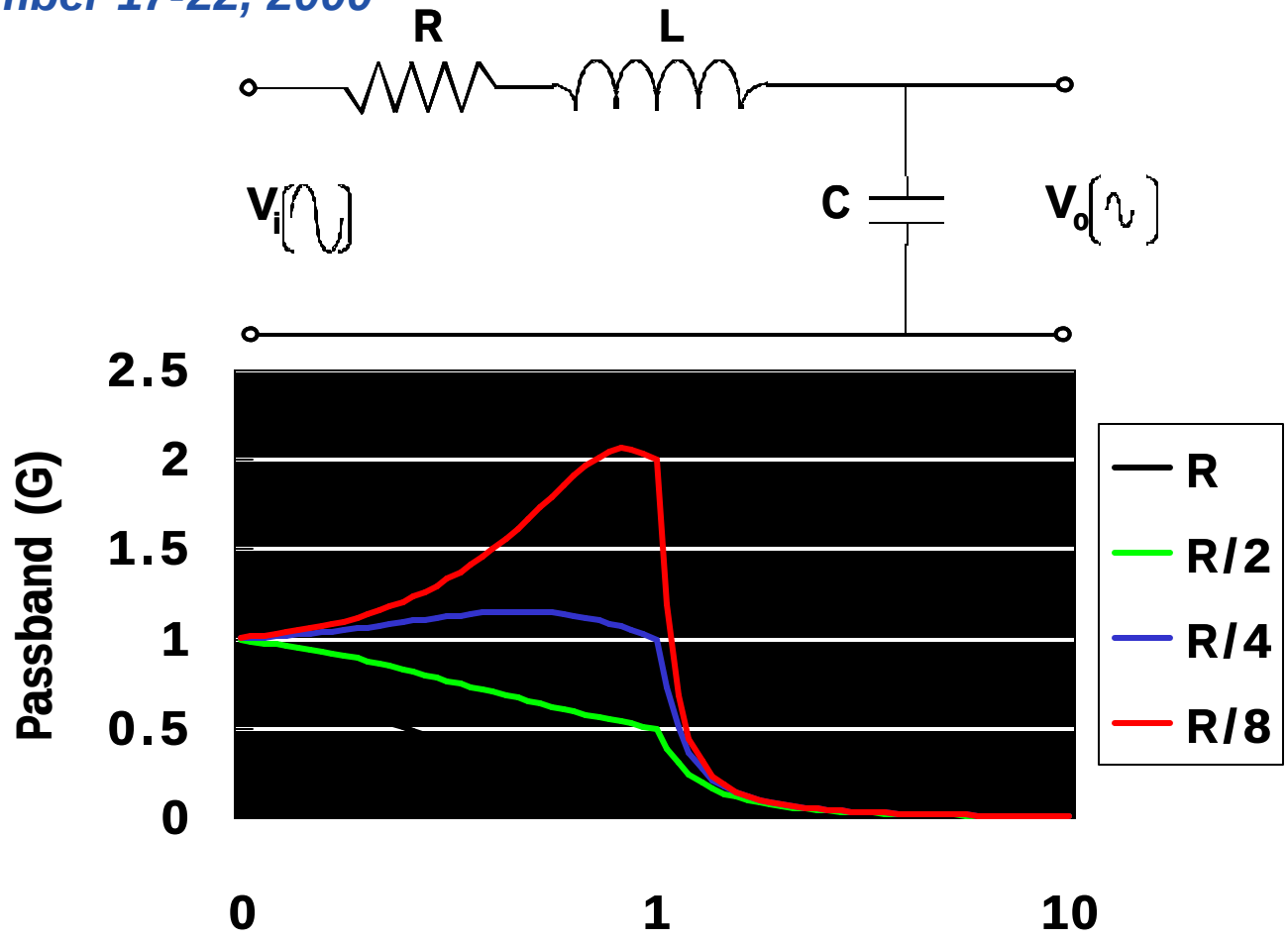
…but not fortune (yet!)

Emerging Applications

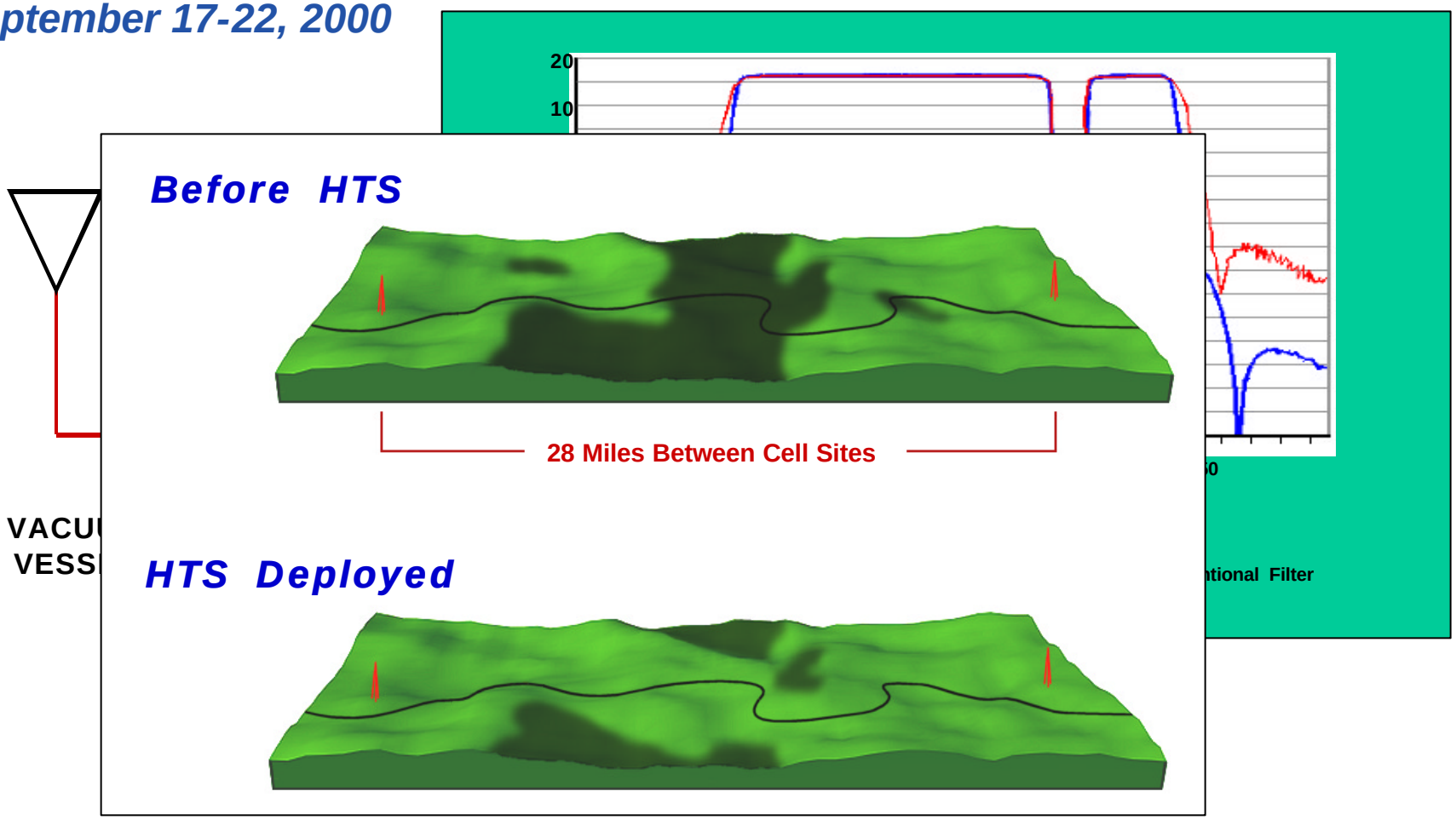
Small Scale (Electronic)

- Cellular Communications
- Medical Probes
- Digital Computers

rf-Filter

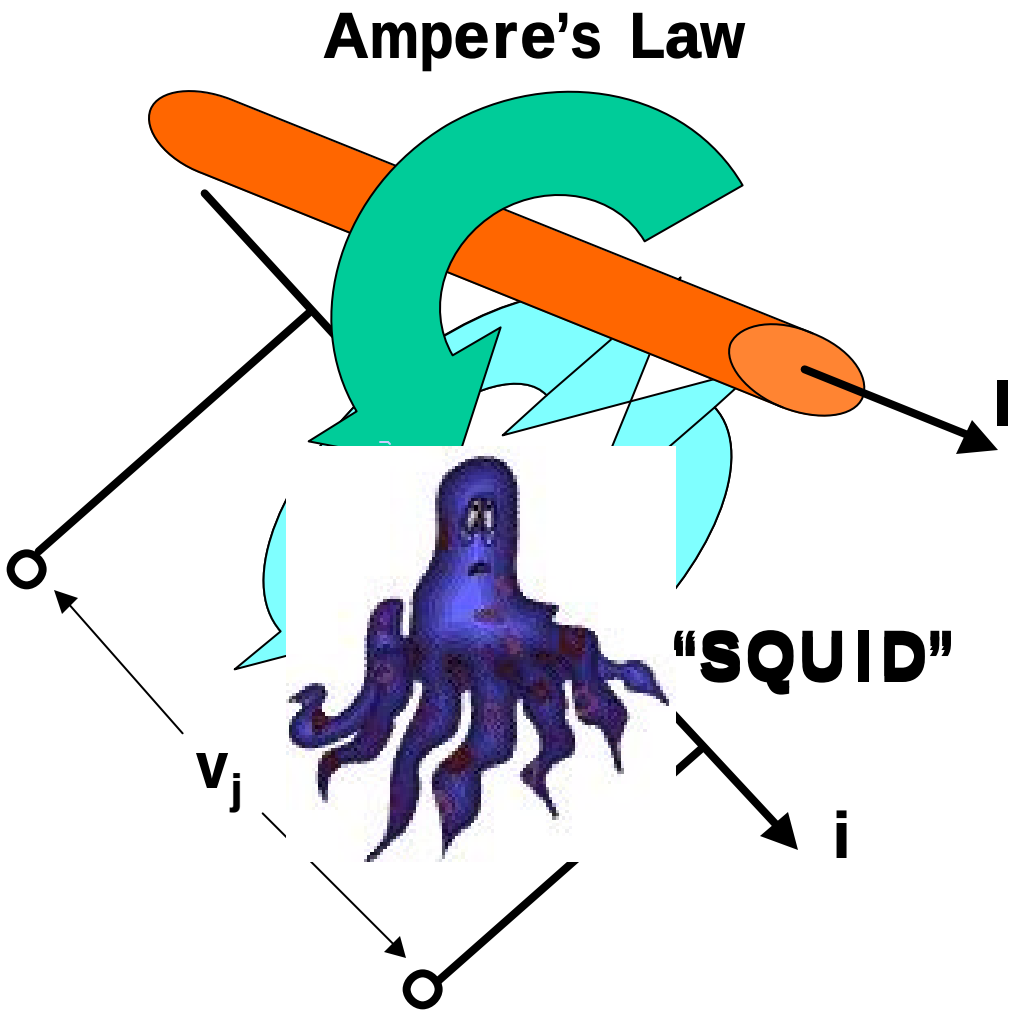

R
L
V_i
C
V_o
2.5
2
1.5
1
0.5
0
Passband (G)
0
1
10
Normalized Frequency
R
R/2
R/4
R/8

Hearing a Pin Drop

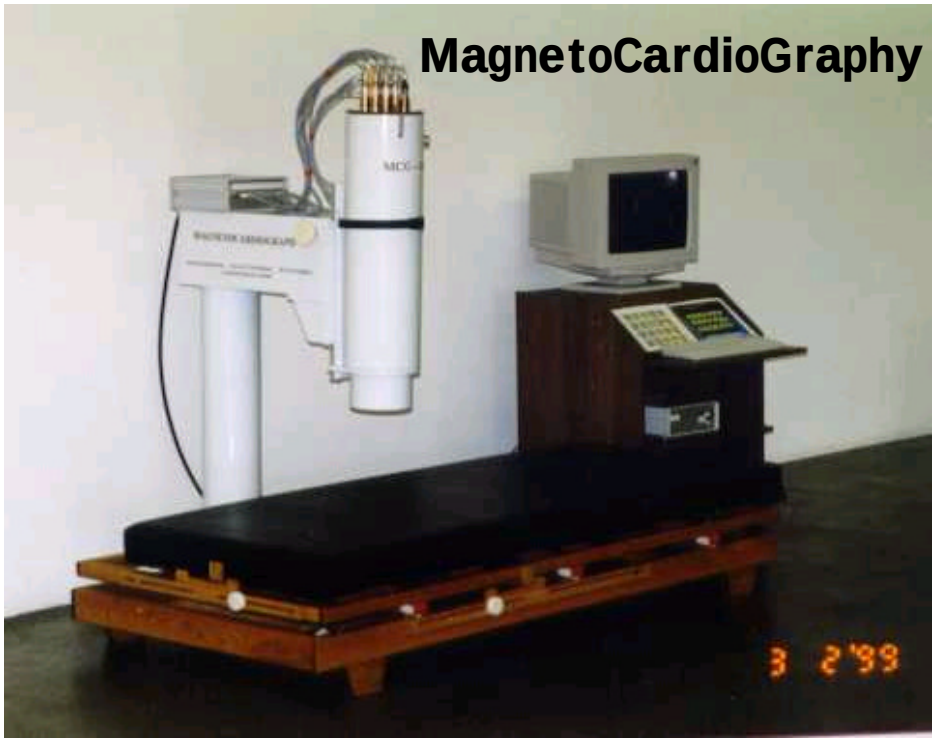


Increase Range/Coverage

Those Magnetic Moments

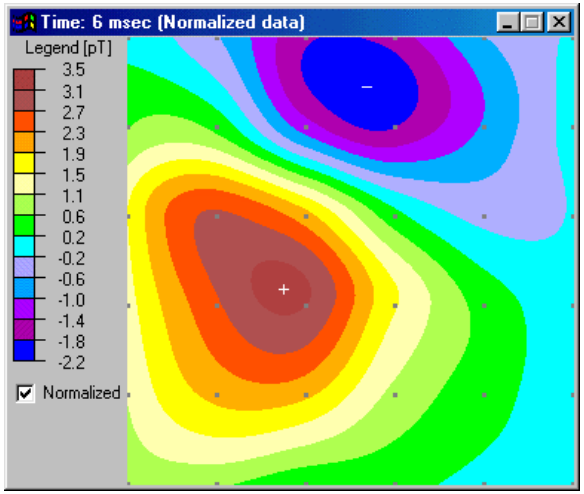


MagnetoTomaGraphy

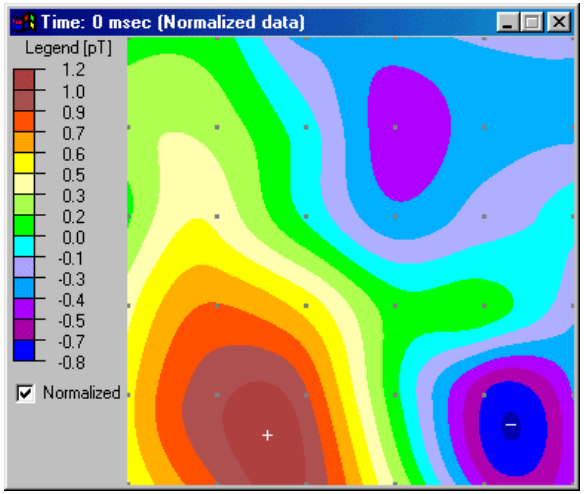


Cryogenic Electronic Systems

http://www.ces-squid-systems.com/



Healthy Heart

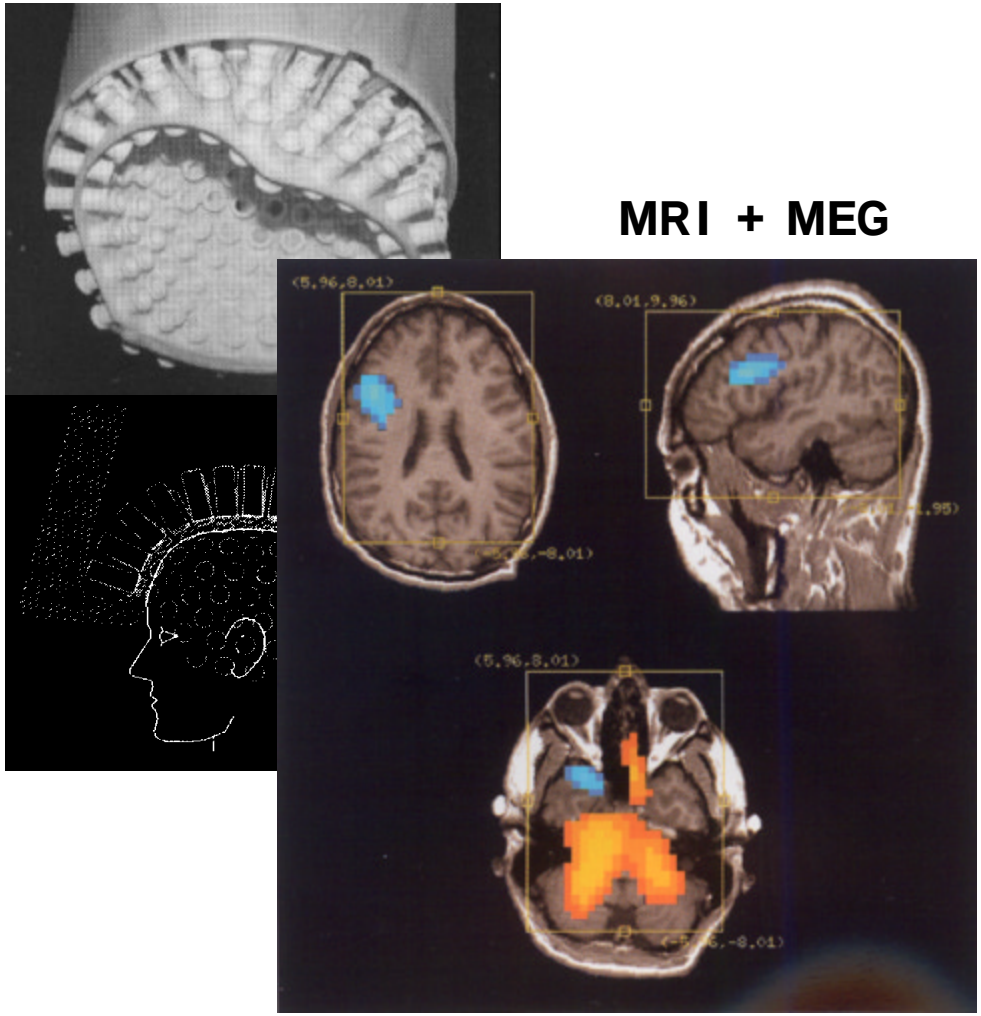


Ischemic Heart - Early Stages

MagnetoTomaGraphy

MagnetoEncephloGraphy

MRI + MEG

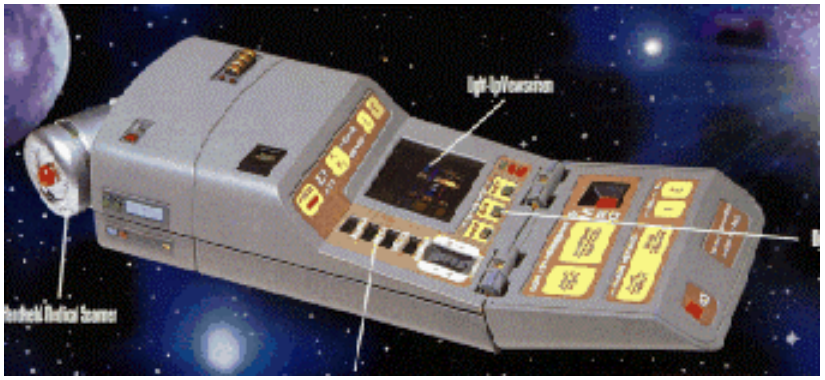


Speech Center Pathologies

Virginia Beach, VA
September 17-22, 2000

TRICORDER

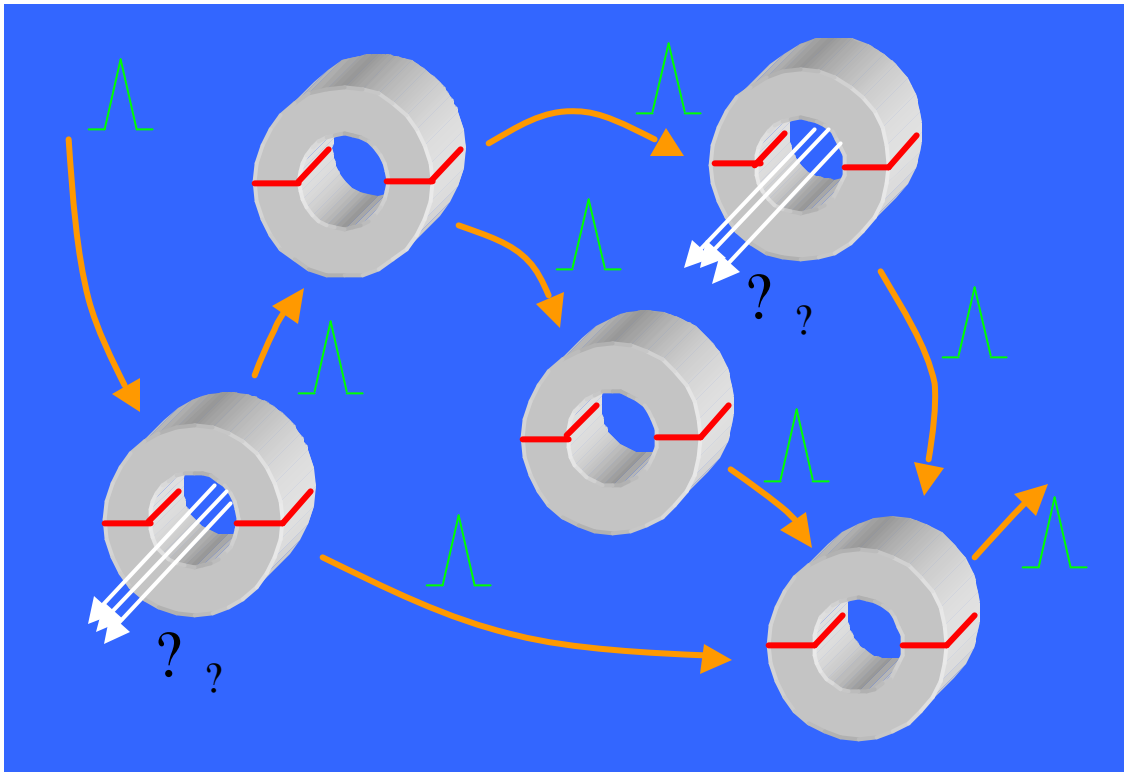
The Magnetodiagnostic Endgame



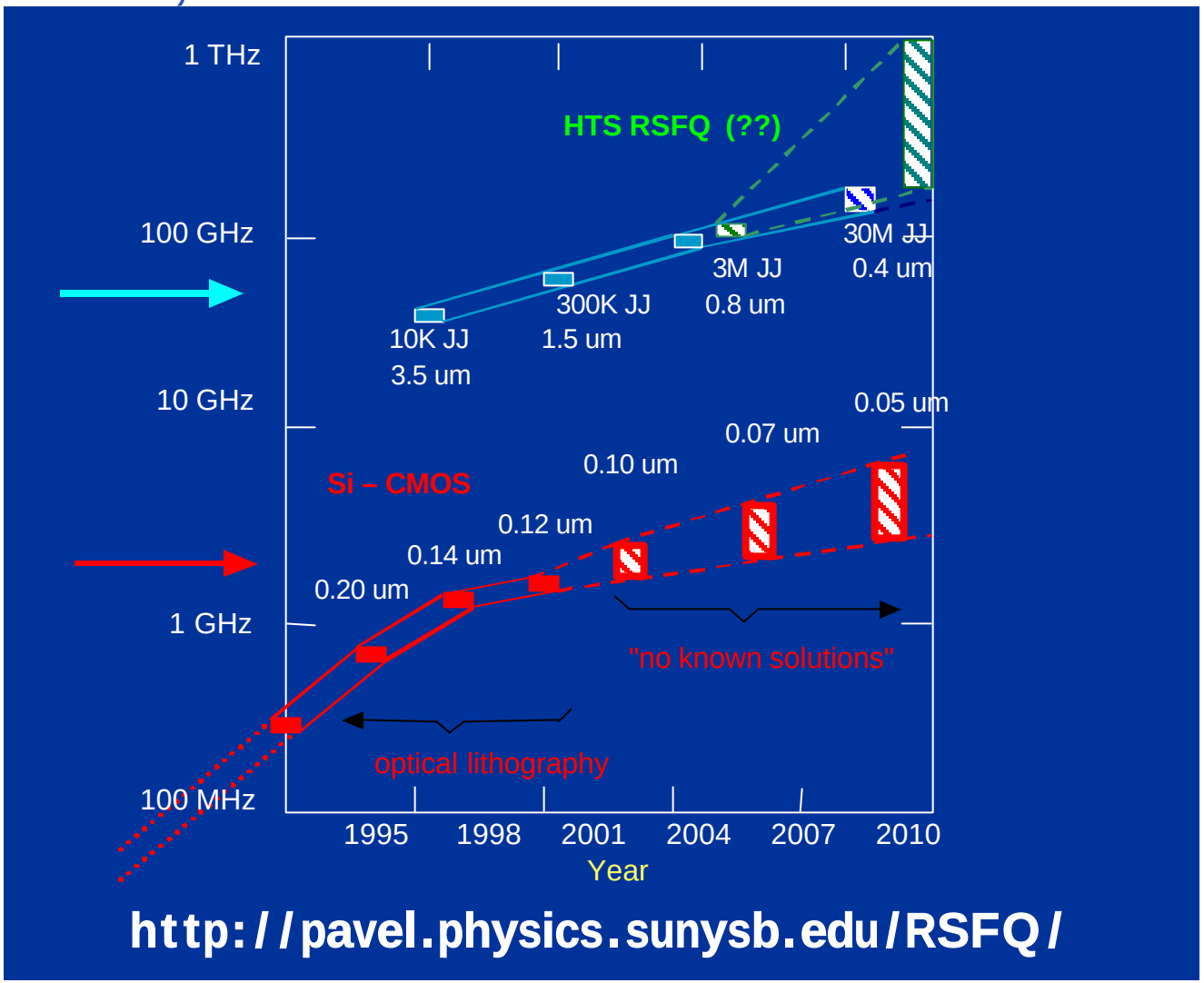
P. M. Grant

"1's" & "0's"

Rapid Single-Flux Quanta



"1's" & "0's" Petaflops



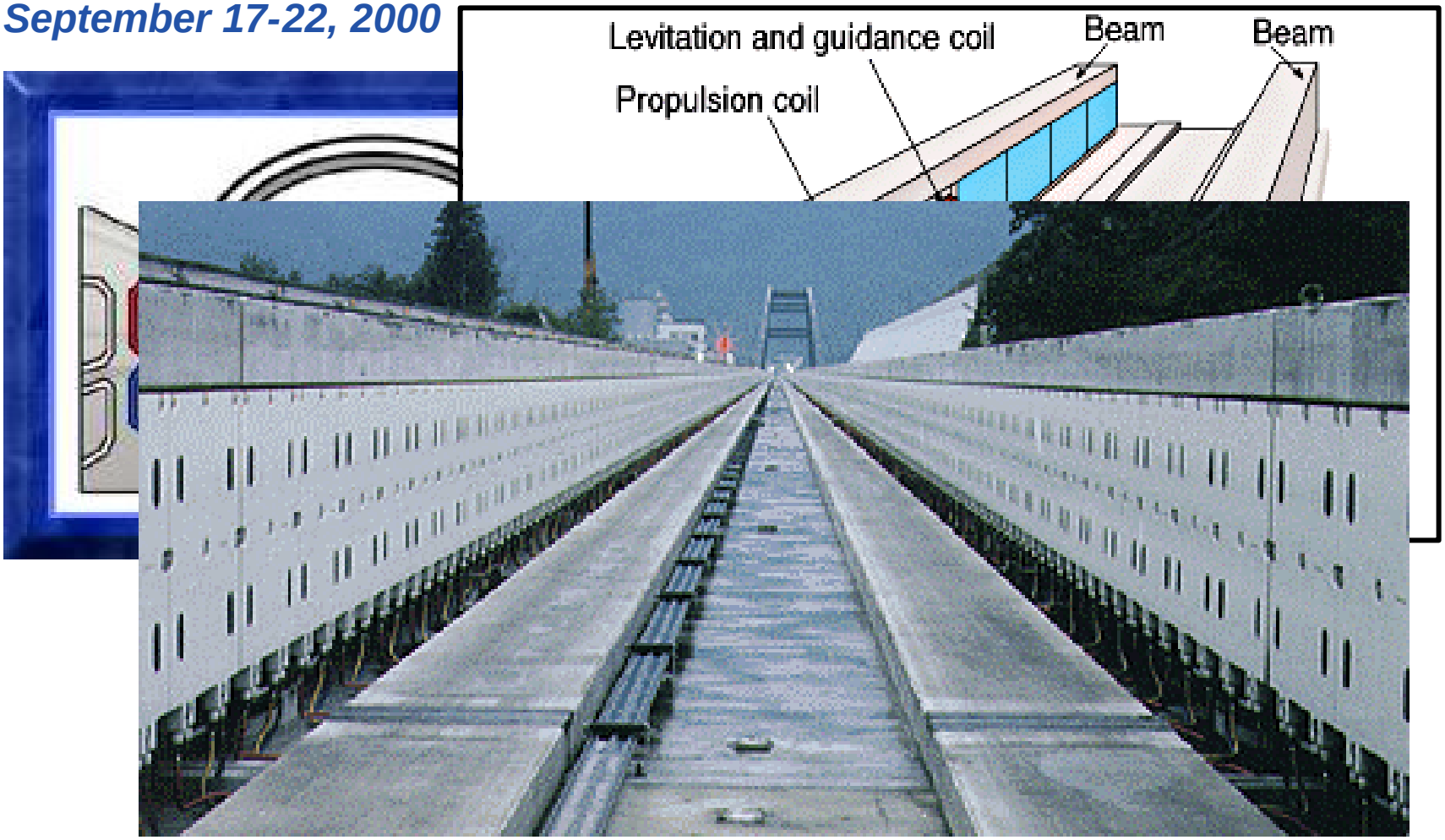
Emerging Applications

Large Scale (Power)

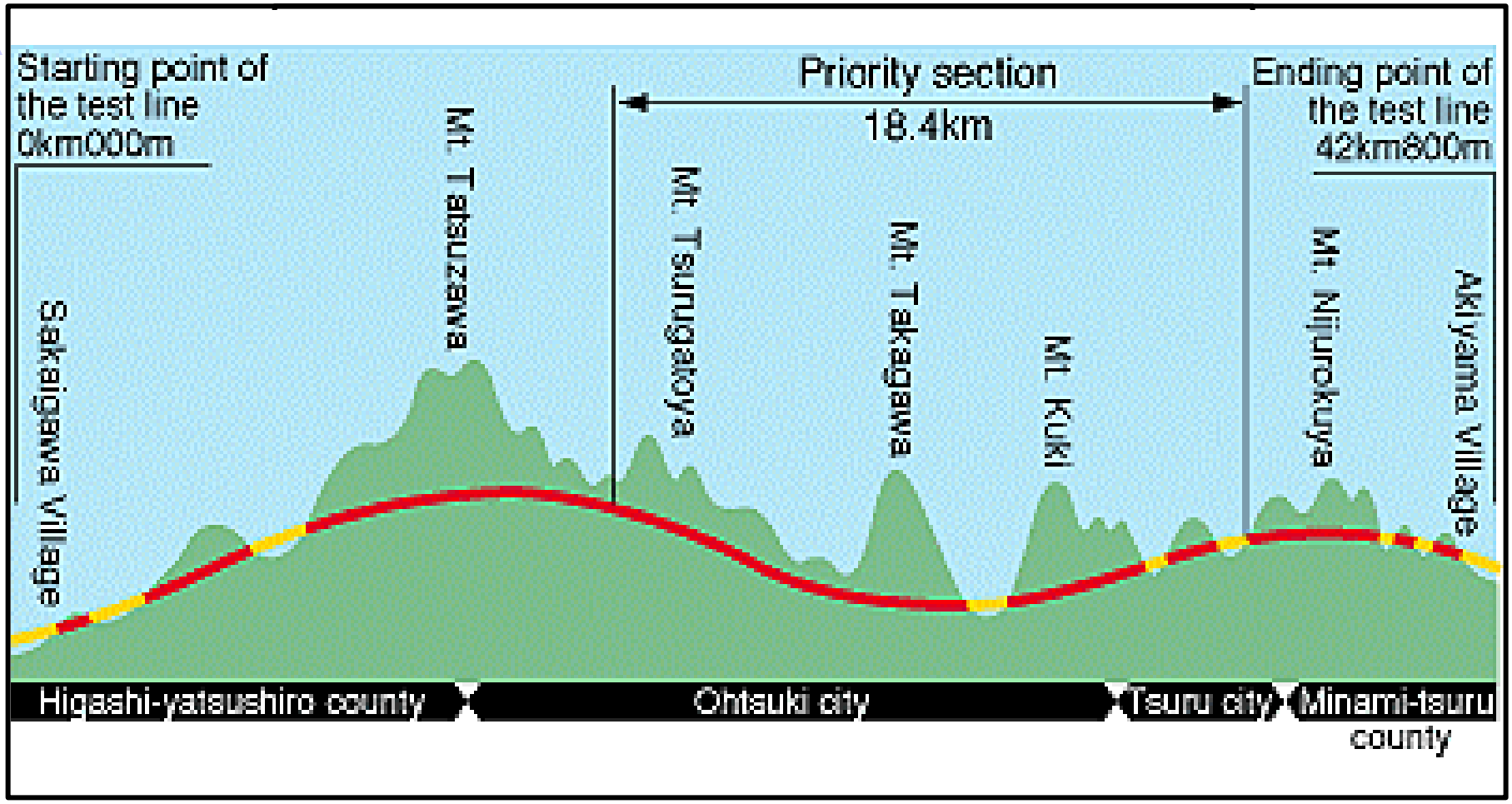
- Maglev Trains
- SMES
- HTS Wire
  - *Motors*
  - *Transformers*
  - *Cables*

MagLev

Yamanashi Test Line

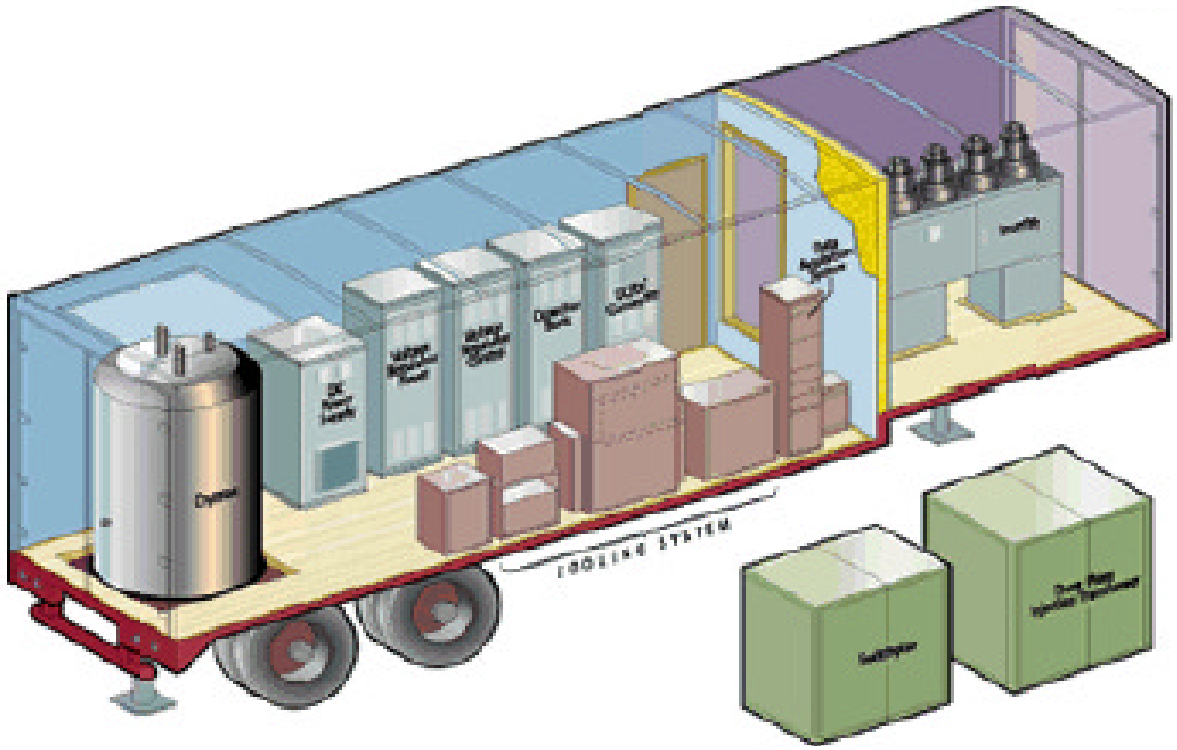


MagLev
Yamanashi Test Line



SMES

Superconducting Magnetic Energy Storate



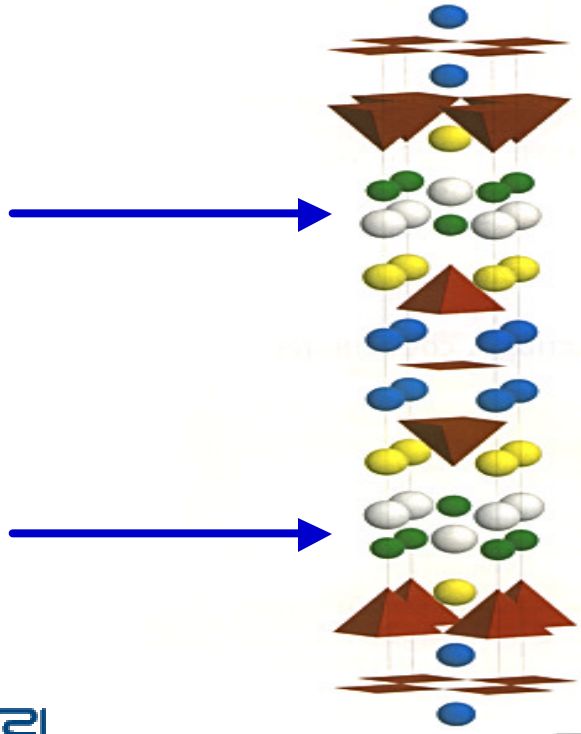
From Supply

HTS Tape

Gen I: It's Here!

"The Miracle of 1989"

Bi-2223



Pb-stabilized

$Bi_2Sr_2Ca_2Cu_3O_x$

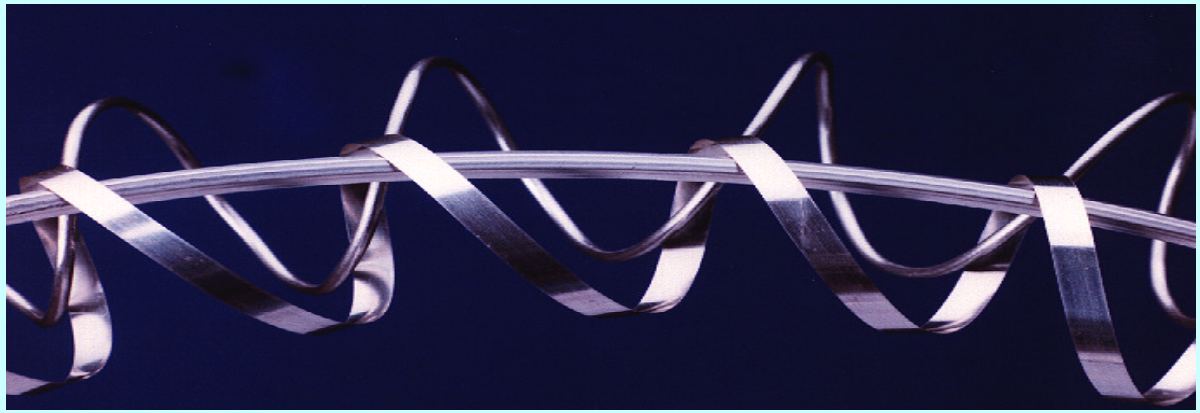
T_C = 110 K

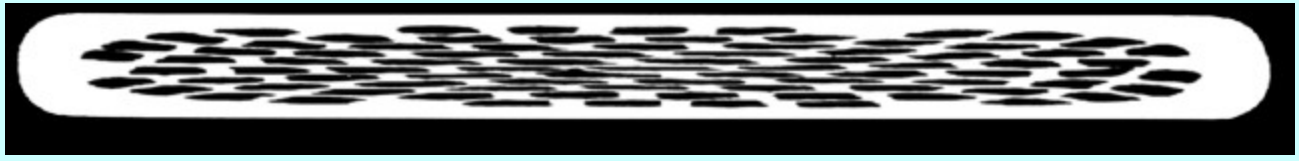
$J_C > 10^5$ A/cm^2

HTS Tape

Gen I: It's Here!

"The Miracle of 1989"

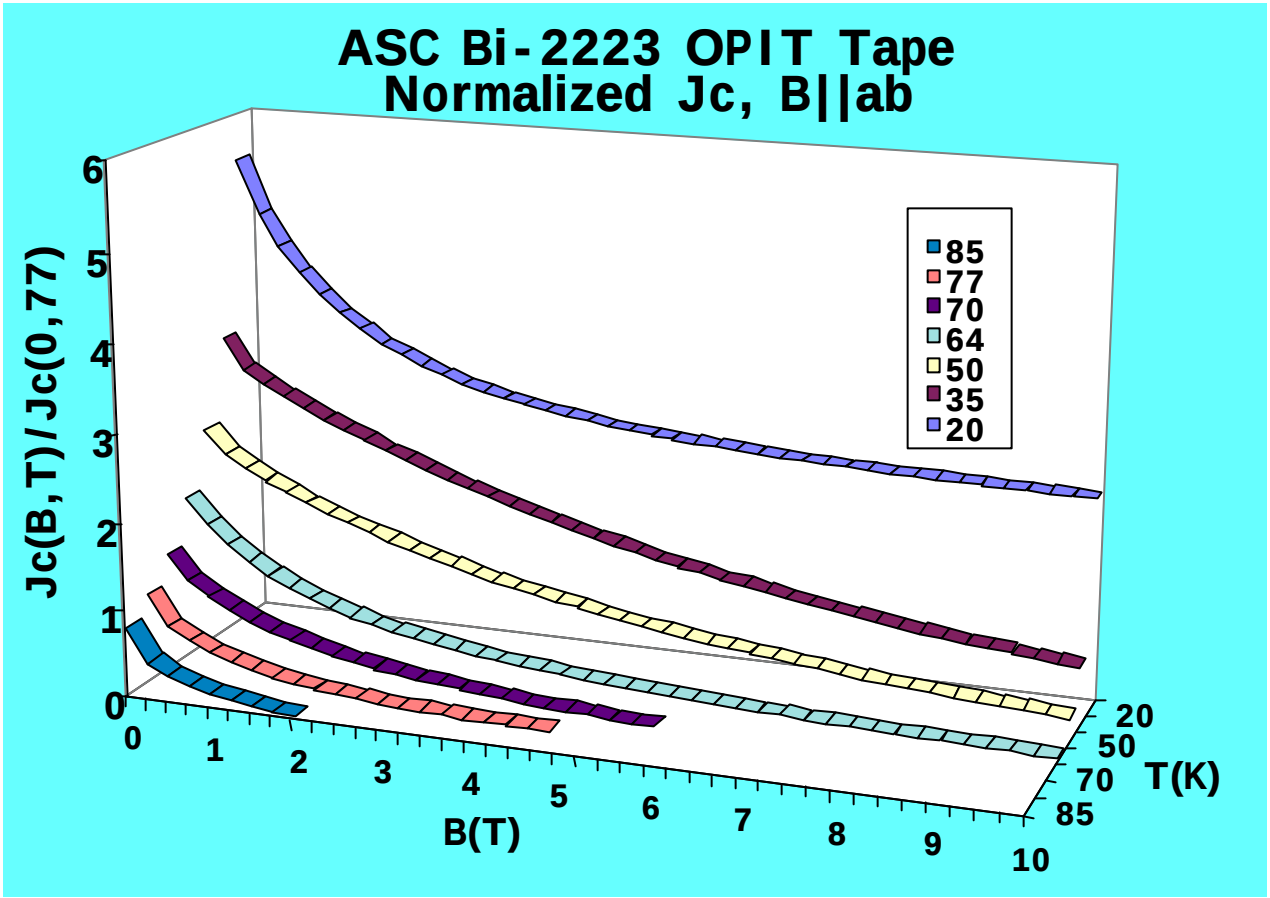




HTS Tape

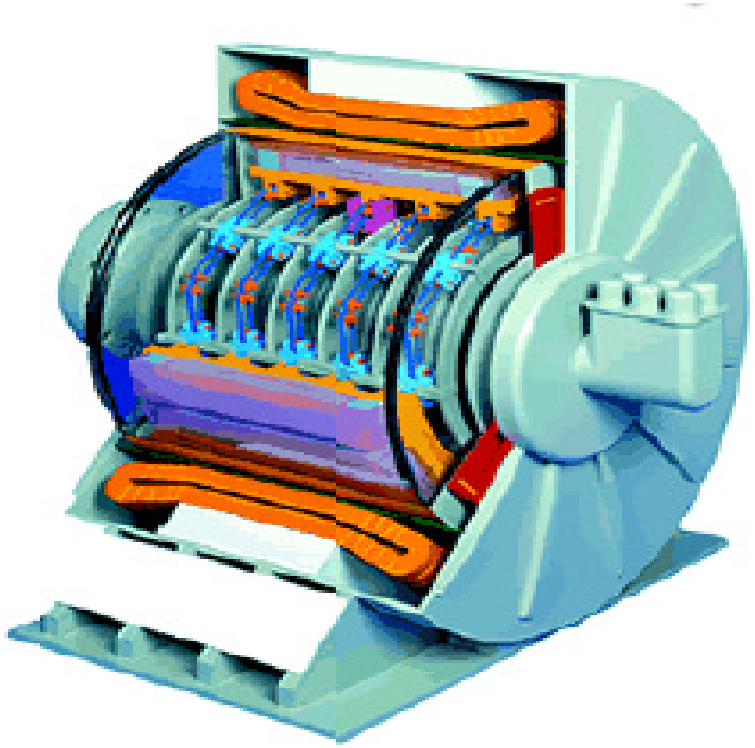
Gen I: It's Here!

"The Miracle of 1989"



Motors

NAVY HTS
SUPERDRIVE



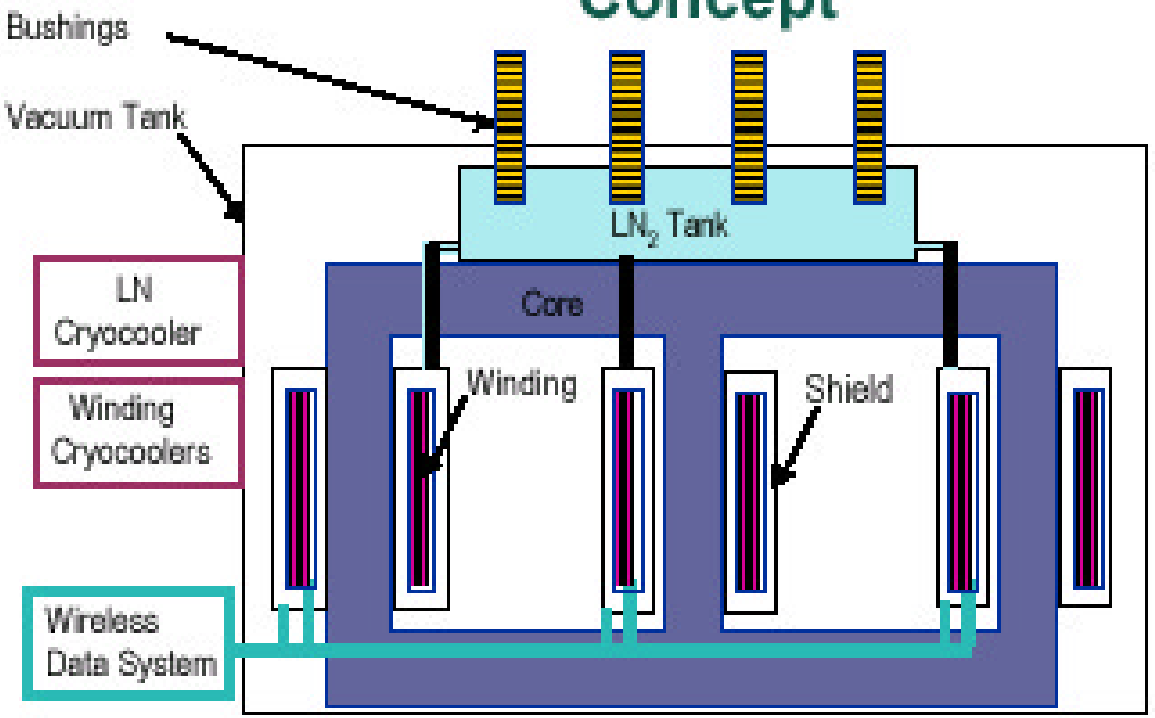
- **25,000 hp**
- **Small, Light (1/5 Conventional)**
- **High Power Density**
- **Quiet**
- **Robust**

http://www.amsuper.com/navy.htm

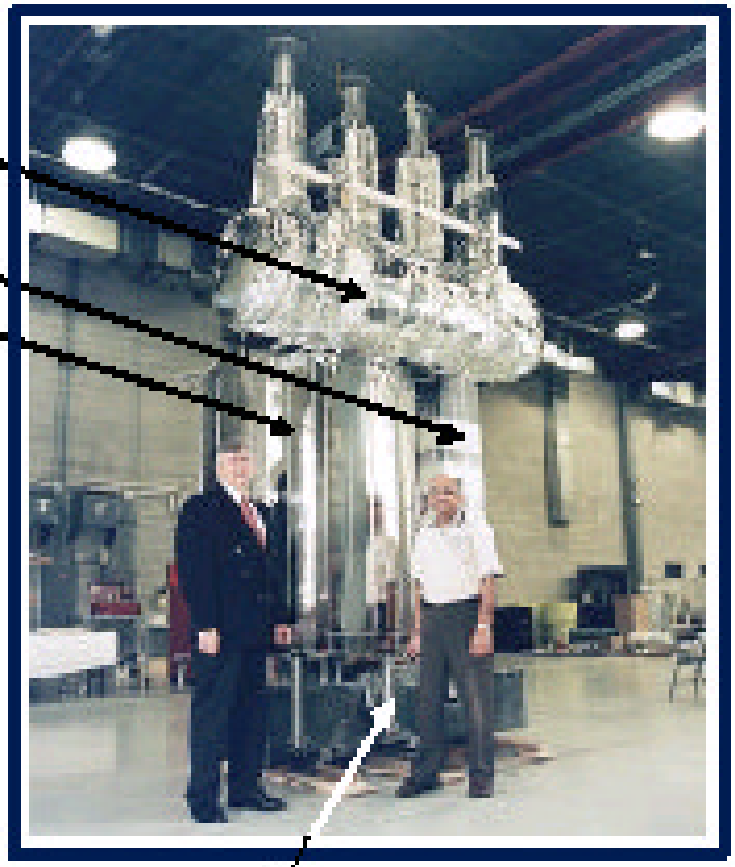
Transformers

Waukesha, IGC, ORNL, DOE

5/10-MVA and 30/60-MVA HTS Transformer Concept



Transformers

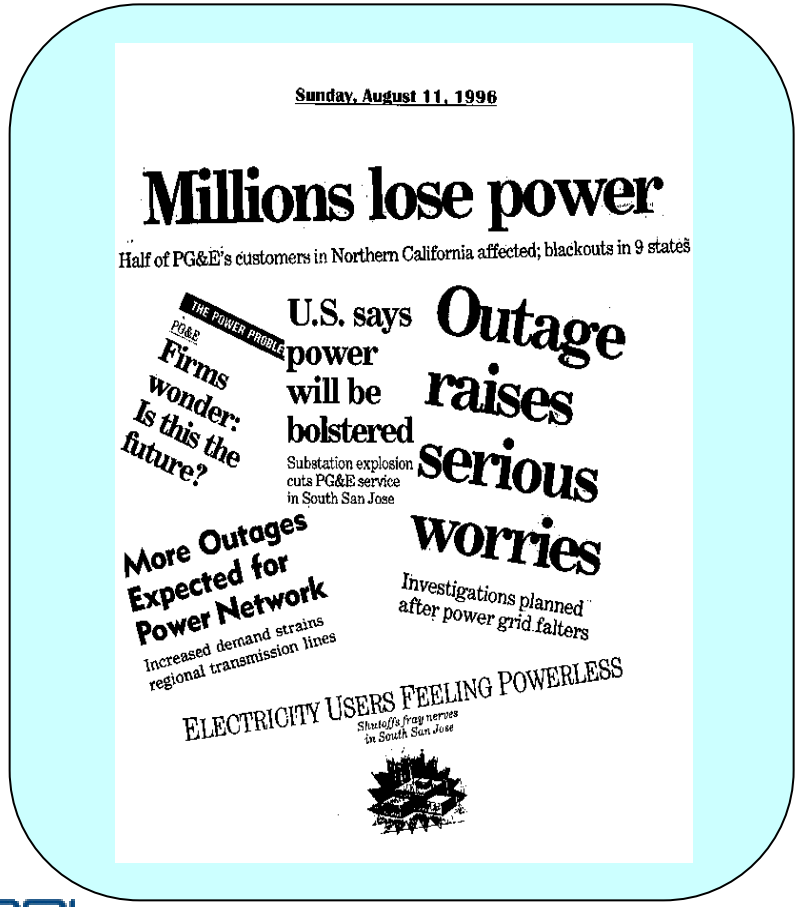


- **24.9 kV/4.2 kV**
- **67 A/694 A**
- **3?, ?/Y**
- **Fault tolerant**
- **Efficient**
- **Smaller Footprint**
- **Oil-free**

http://www.ornl.gov/HTSC/htsc.html

Electricity: A Life Necessity

California, Summer 1996



Sunday, August 11, 1996

Millions lose power

Half of PG&E's customers in Northern California affected; blackouts in 9 states

THE POWER PROBLE

PG&E Firms wonder: Is this the future?

U.S. says power will be bolstered

Substation explosion cuts PG&E service in South San Jose

Outage raises serious worries

Investigations planned after power grid falters

More Outages Expected for Power Network

Increased demand strains regional transmission lines

ELECTRICITY USERS FEELING POWERLESS

Shutoffs fray nerves in South San Jose

Quebec, Winter 1997

It's Crowded Down There

Power Outrage

"We are sick and tired of them, and they had better change!"

Chicago Mayor Richard Daley on the August 1999 Blackout

1967 SC Cable !

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

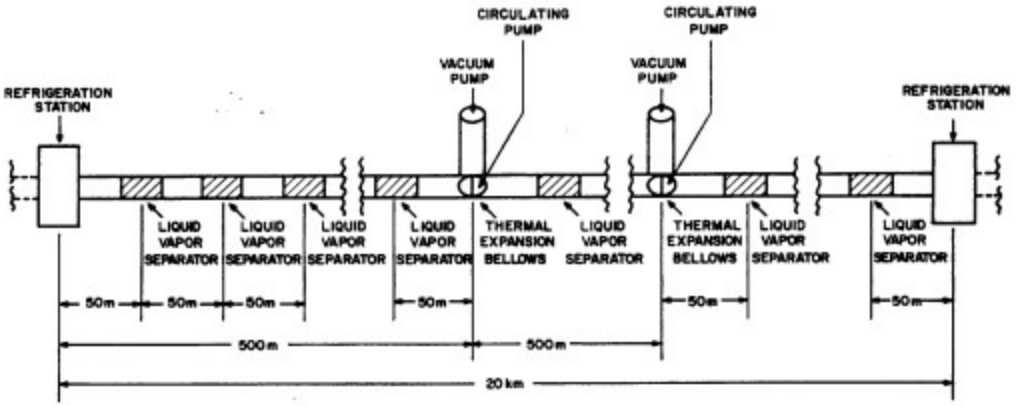


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

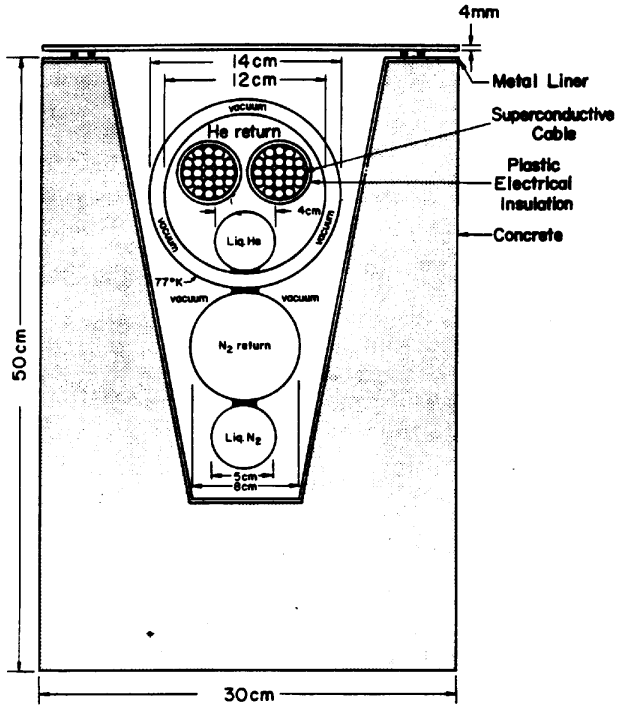
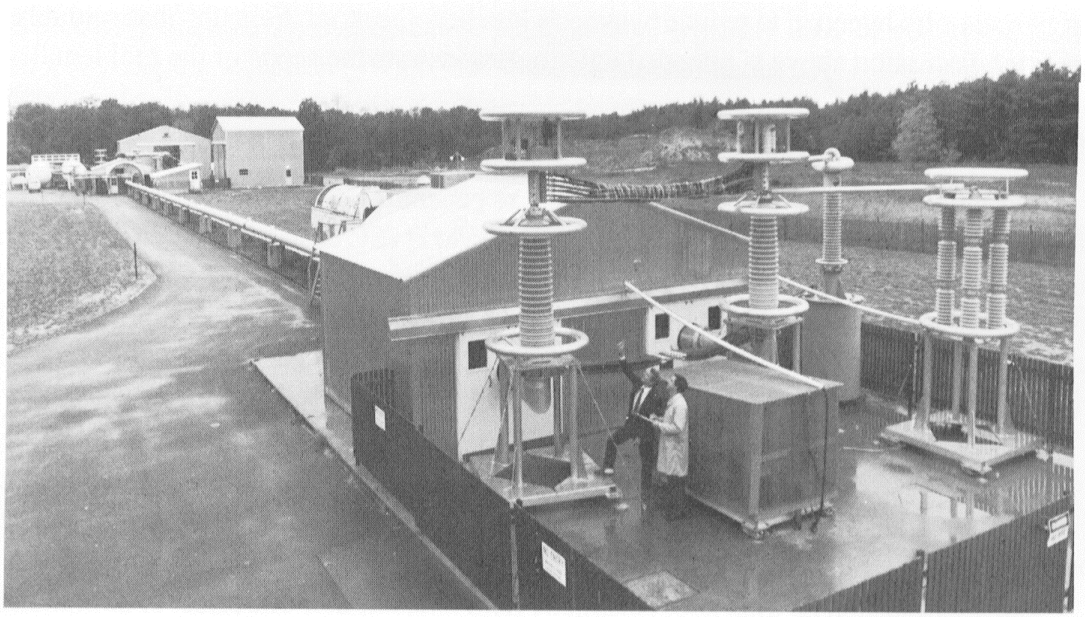


Fig. 1. Cross section of the 100-GW line.

100 GW dc, 1000 km

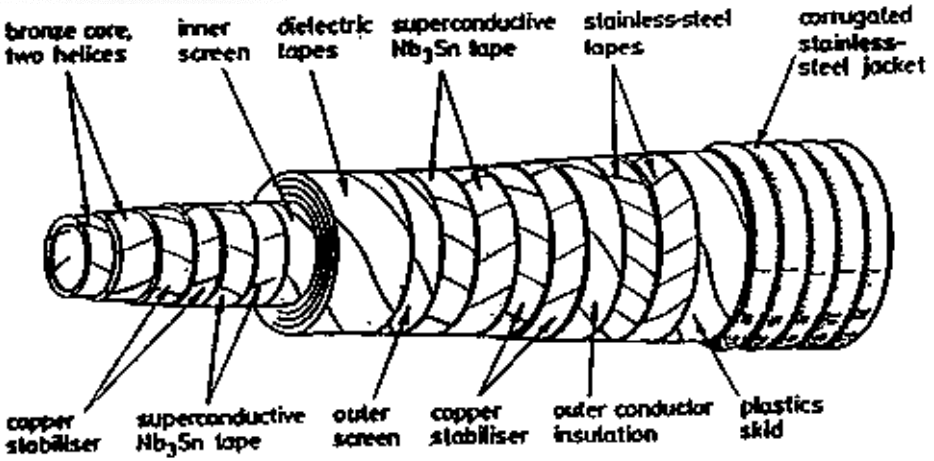
Brookhaven LTS ac Cable 1975-86



- **Technical Success**
- **Poor Economics**

135 kV, 1000 MVA, 3?????? m

Nb_3Sn, 7-9 K



HTS Cables: They're Here!

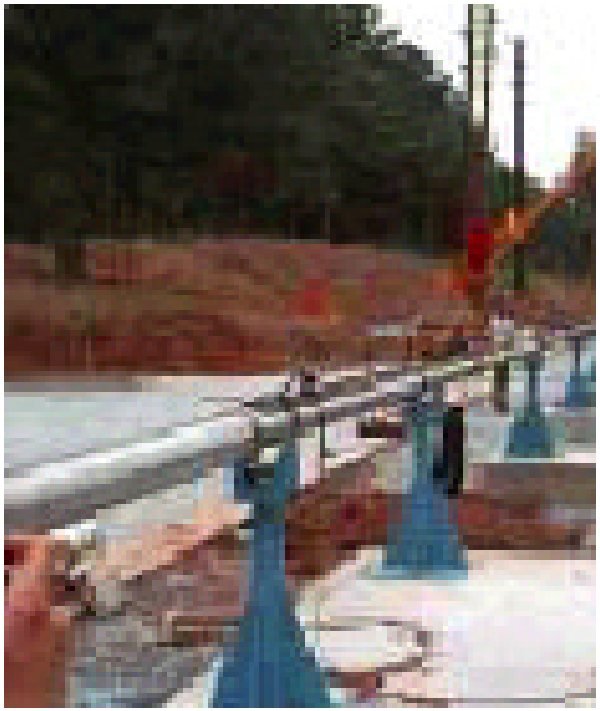
12,400 Volts

1,250 Amps

3 Phase

Southwire Cable Plant
Carrolton, Ga.

...and Running!



18 Feb 2000
>2500 hours!

Georgia Governor and Energy Secretary

DTE HTS Cable

ENERGY SECRETARY RICHARDSON OPENS GATEWAY TO ELECTRICITY SUPERHIGHWAY

- Detroit Edison to begin use in 2001. $5.5 M project in innerurban substation
- Pirelli, ASC, Lotepro, EPRI, DOE
- "...help U.S. build ... its competitive position in world market for HTS applications." *DOE Sec. Richardson*
- "...revitalize older urban area in non-intrusive, environmentally friendly way." *R. J. Buckler, DTE CEO*

NY Times, 11/3/98

Power Line Makes Use Of a Miracle Of Physics

By MALCOLM W. BROWNE

After 87 years of alternating exuberance and disappointment, and a decade after a famous conclave of physicists at which the key to success seemed to be within reach, the world's first superconducting power line is about to become a reality.

A superconducting line is one that will conduct huge electrical currents with far less resistance than that of a line made of metal wire, and that therefore conserves energy.

The first large-capacity superconducting line, to begin operation by mid-2000 in Detroit, will be only 400 feet long. But it will use only 250 pounds of a new kind of superconducting wire to carry as much current as the 18,000 pounds of copper wire the line will replace.

Experts say the line will demonstrate the practicability of large-scale superconducting power transmission and will be the first of many such lines. In announcing a contract providing for Federal support for the project, Energy Secretary Bill Richardson predicted two weeks ago that power lines like this one, exploiting the special properties of "high-temperature superconductors," could eventually save the nation $6 billion a year. Another benefit is that the electricity industry could sharply reduce the pollution created by generating plants.

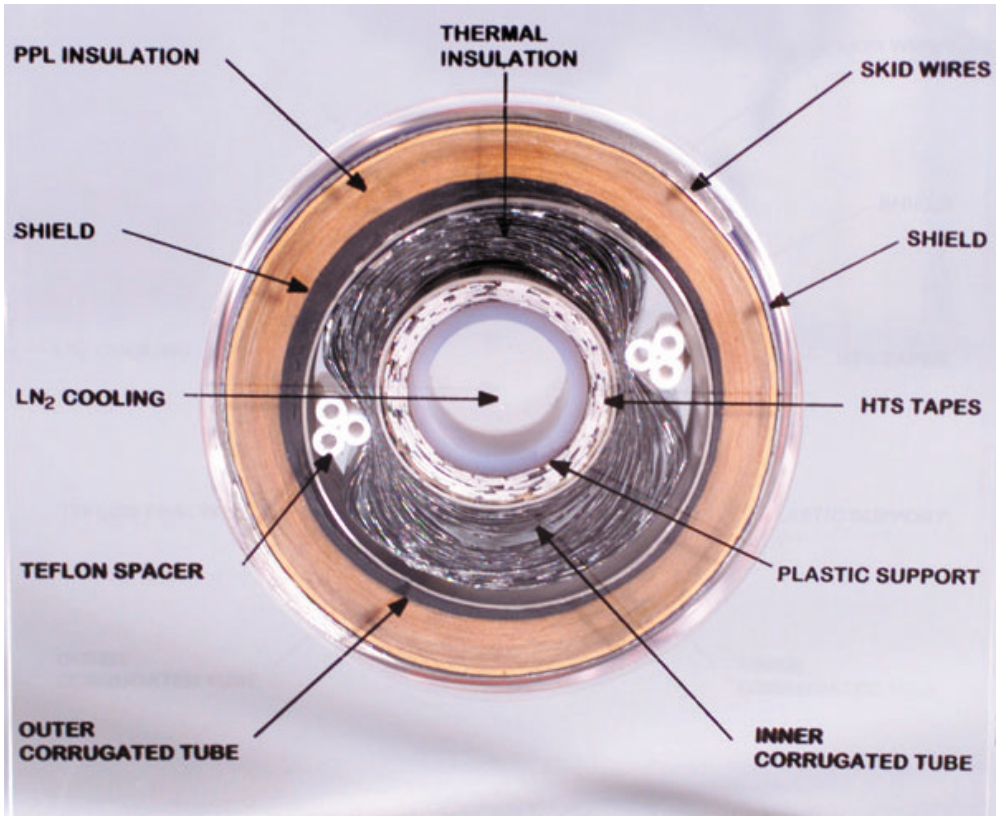
Lengths of the same superconducting cable up to 50 yards long have already been successfully tested, said Dr. Paul M. Grant, an expert in superconductivity at the Electric Power Research Institute in Palo Alto, Calif.

DTE Project

- Cable Specs
  - 130 m, 24 kV, 3 ?, 3000 A_{rms}, LN_2
  - Substation Location, 4” Dia. Surface Ducts
- Advantage to Utility
  - 1:1 Overhead to Underground
  - Elimination of 120 kV Subtransmission System Due to Lower I^2R and CV^2 Losses
  - Utilize Existing 4” Conduit Infrastructure

Then and "Soon"

1000 A_{rms}

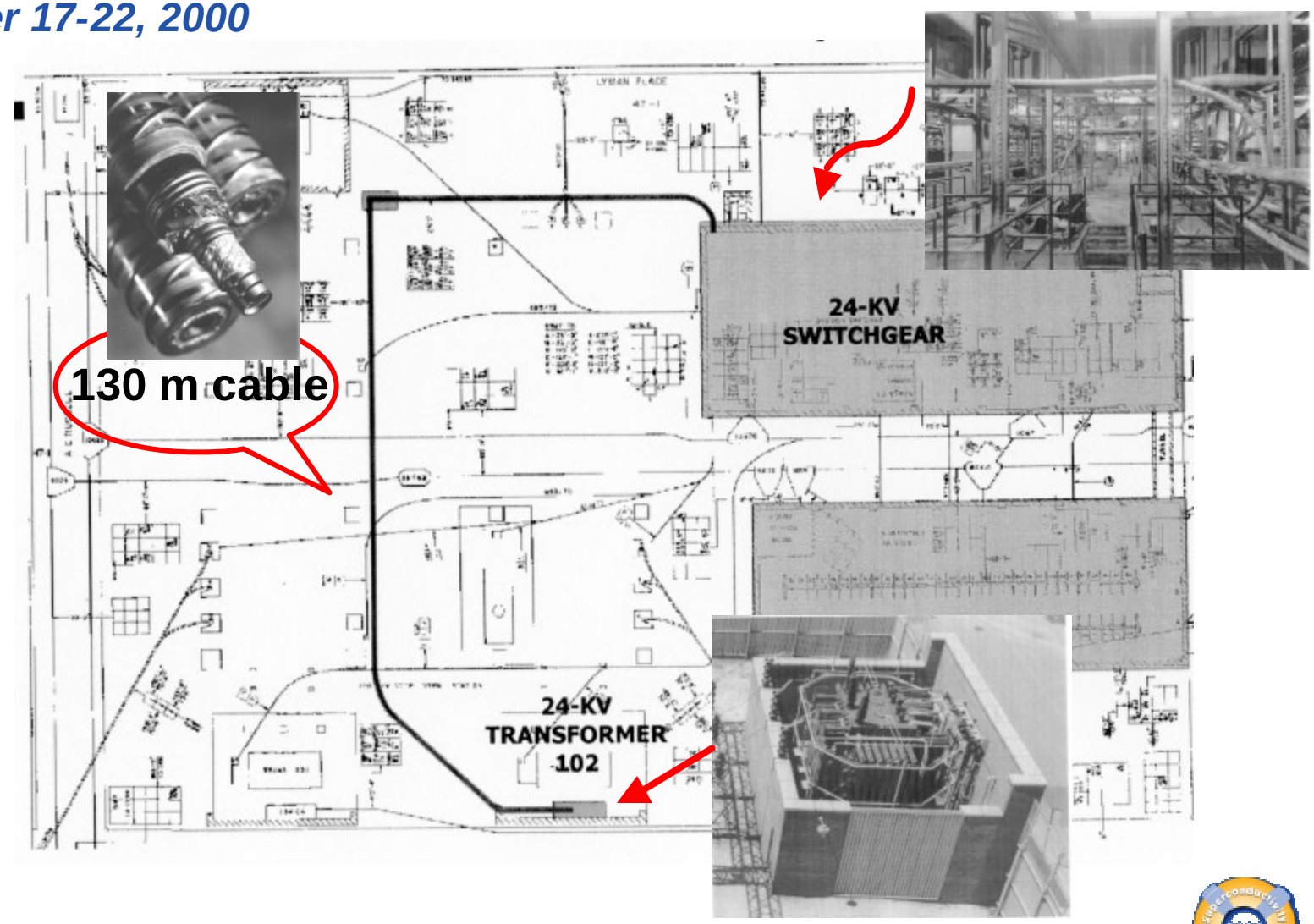


3000 A_{rms}

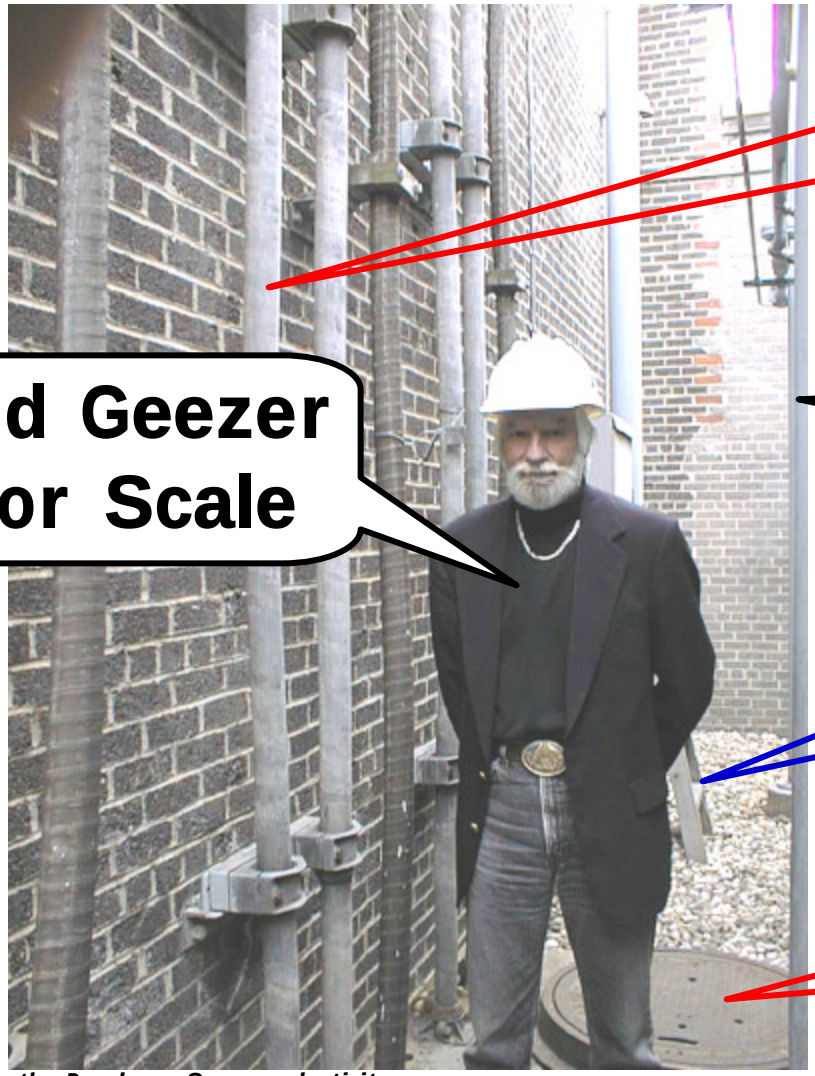
Frisbie Substation

Frisbee Substation

Frisbie Layout



Transformer & Cryostation Site



Incoming Lines

Back Side of Transformer 101

Old Geezer for Scale

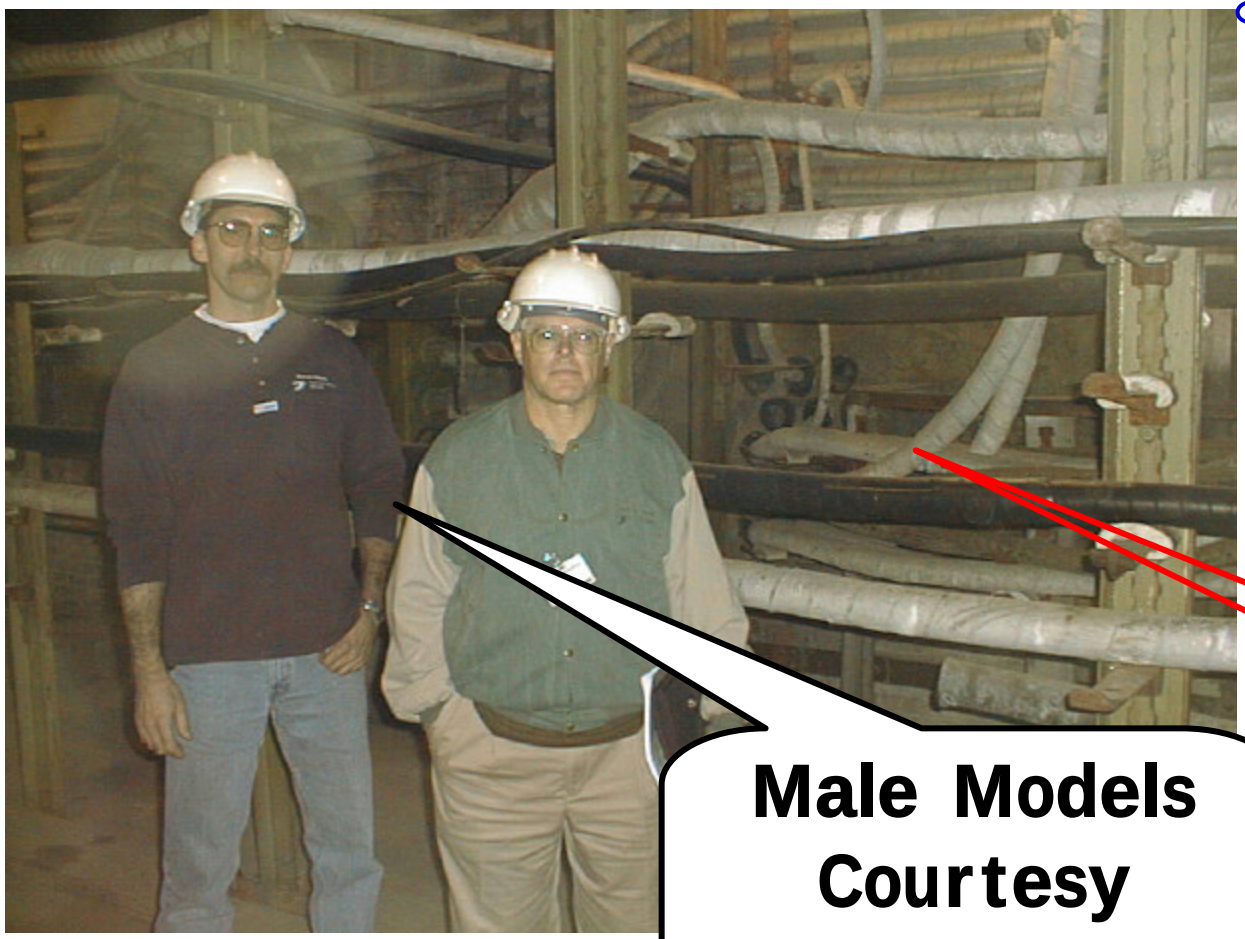
Cryostation (near ladder)

Manhole "13446"

"Manhole 13465"

Location of Future Joint

Distribution Bldg Basement



Terminations Two Floors Up

Male Models Courtesy Detroit Edison

Incoming Lines from Substation Yard

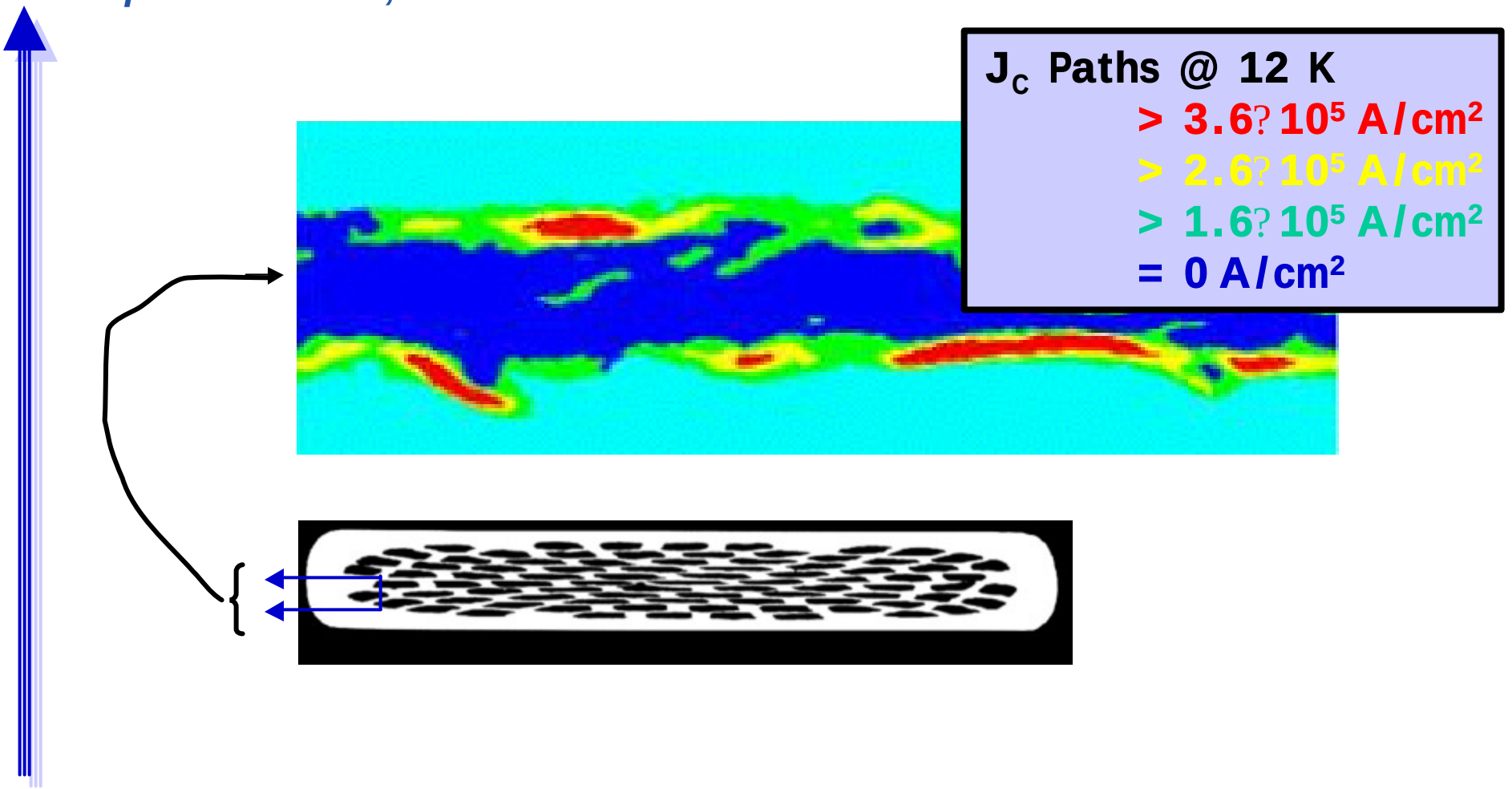
7 Sept 2000
Livorno-Ferraris

Clever Placement of Personnel to hide Pirelli proprietary technology

7 Sept 2000
Livorno-Ferraris

No hablo italiano

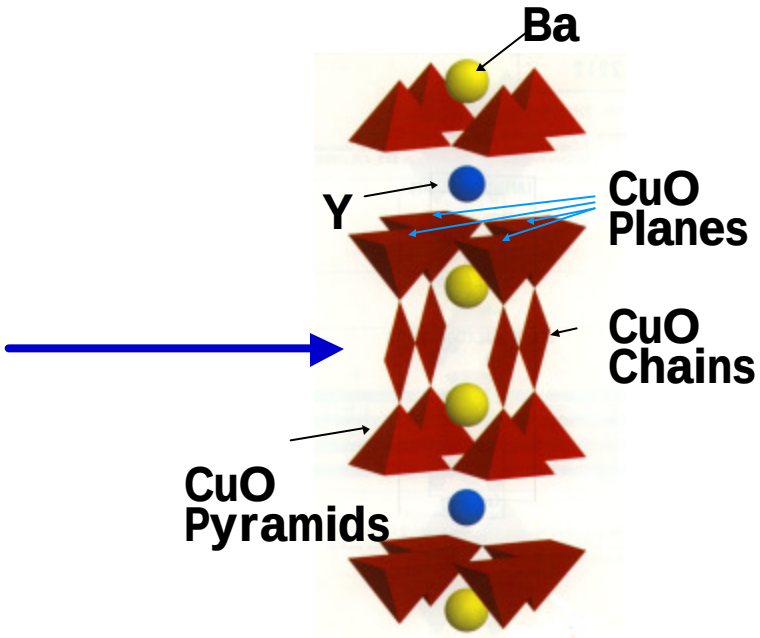
But…Gen I has Problems…
Silver is one…



HTS Tape

Gen II: It's Coming!

"1-2-3 is Better"



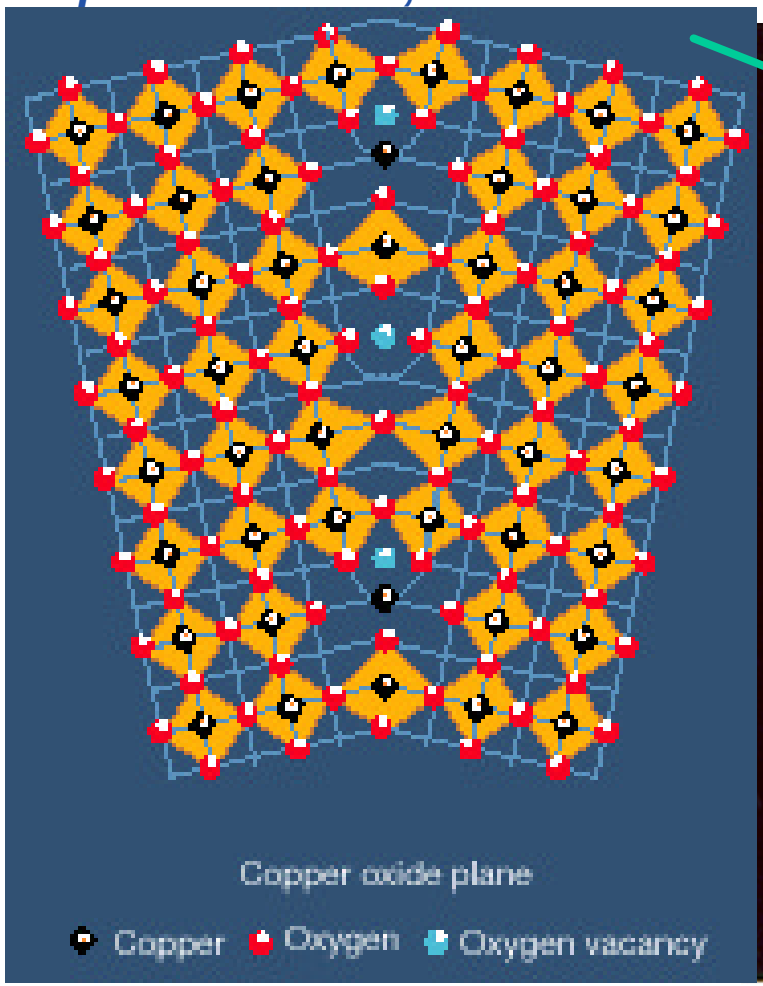
$YBa_2Cu_3O_{7-y}$

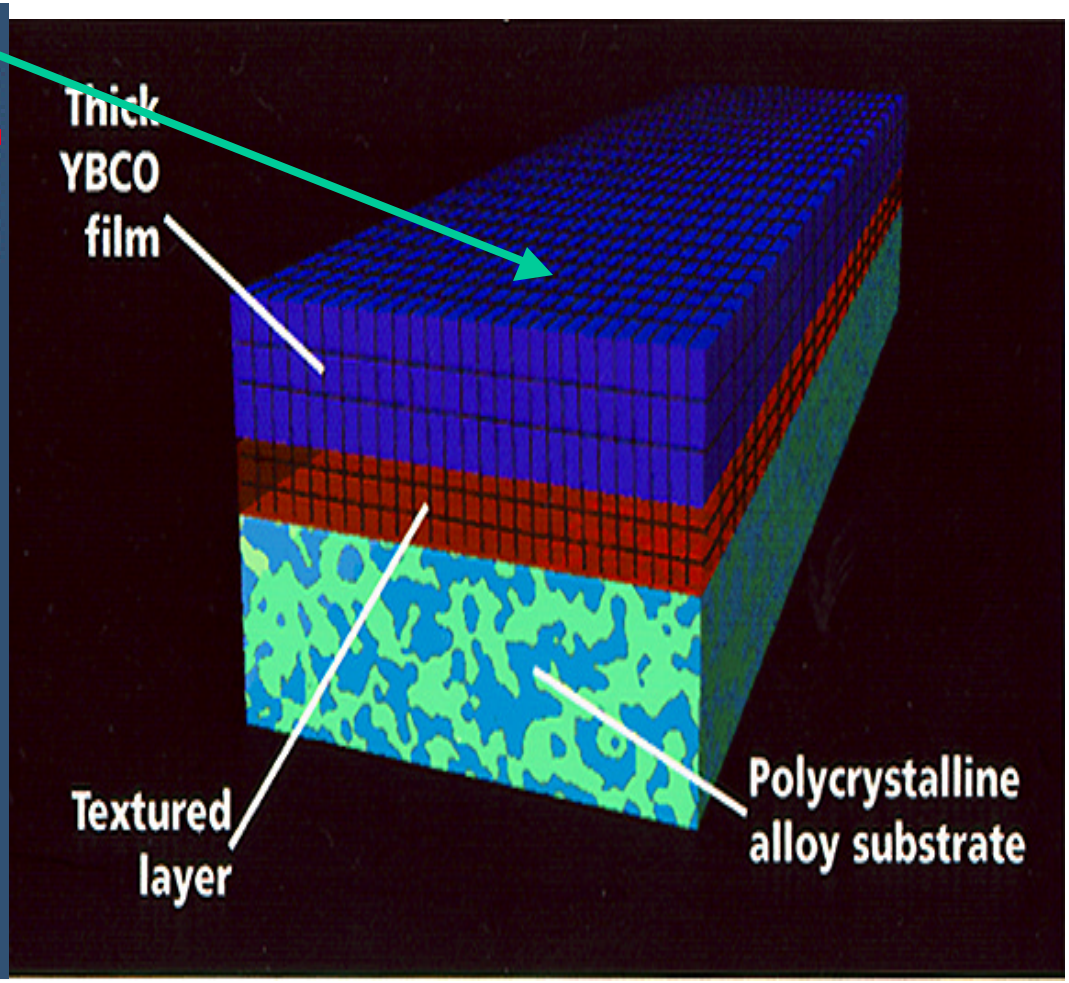
$T_C = 93\ K$

$J_C > 10^6\ A/cm^2$

$J_C > 10^5\ A/cm^2\ (1\ T)$

Coated Conductors
Generation II Wire





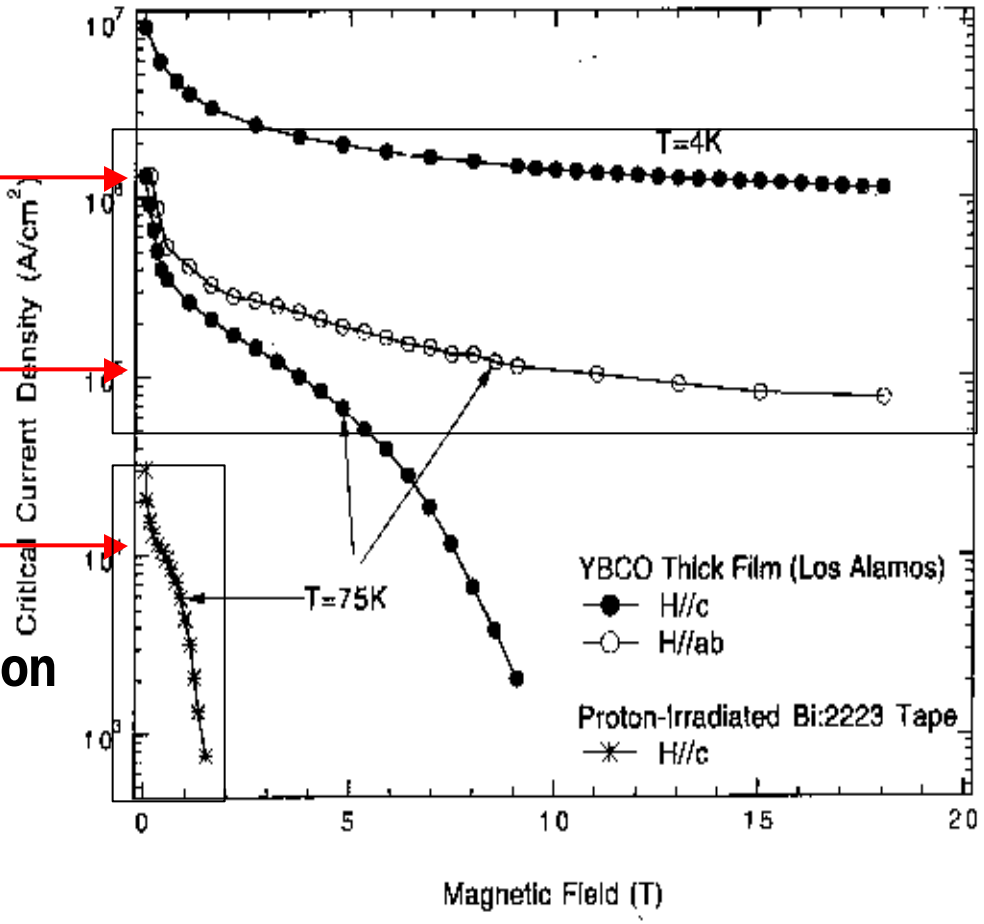
LANL's Finest

10^6

10^5

10^4

Generation I



Generation II

It's 2015

- **A World at Peace**

- Global Climate at Risk

- Continuing Industrialization Reaches All Corners of the Planet

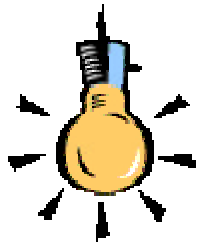
The Nuclear/Hydrogen Economy at last!

Laguna Genome

- State of Sonora, Mexico
- 2000 km² of Semi-Arid Arroyos Bordering El Golfo de Cortez
- "Greensite" Location of a New Biotech Industry/Residential Community of 50,000

Our Mission: To design and install the societally optimal energy and communication delivery system for Laguna Genome

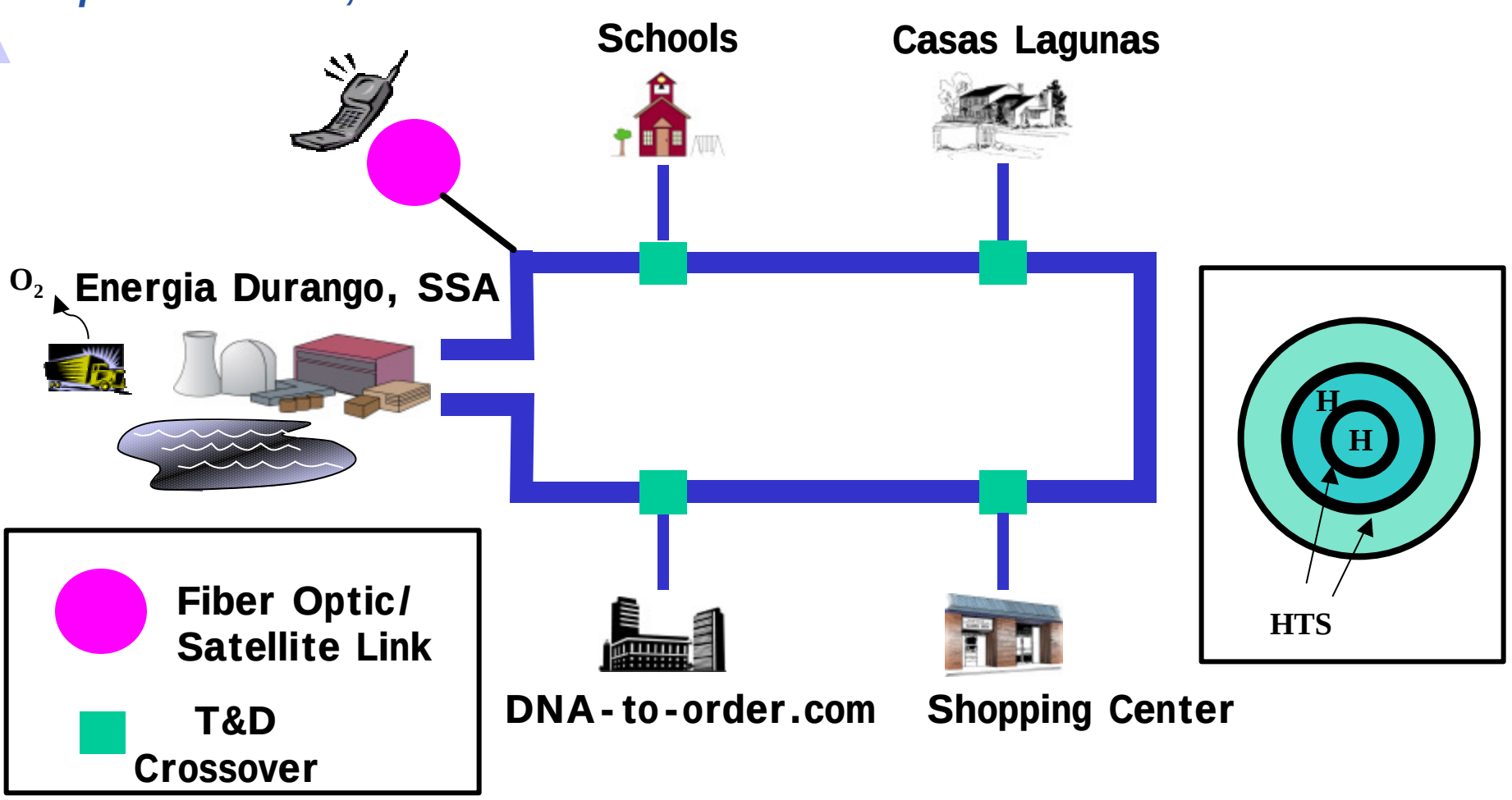
Solution



CyroEnCom

A foundation for energy and information delivery based on a spread of cryogenic technologies

Master Plan


Schools
Casas Lagunas
O_2
Energia Durango, SSA
H
H
HTS
Fiber Optic/
Satellite Link
T&D
Crossover
DNA-to-order.com
Shopping Center

Distribution

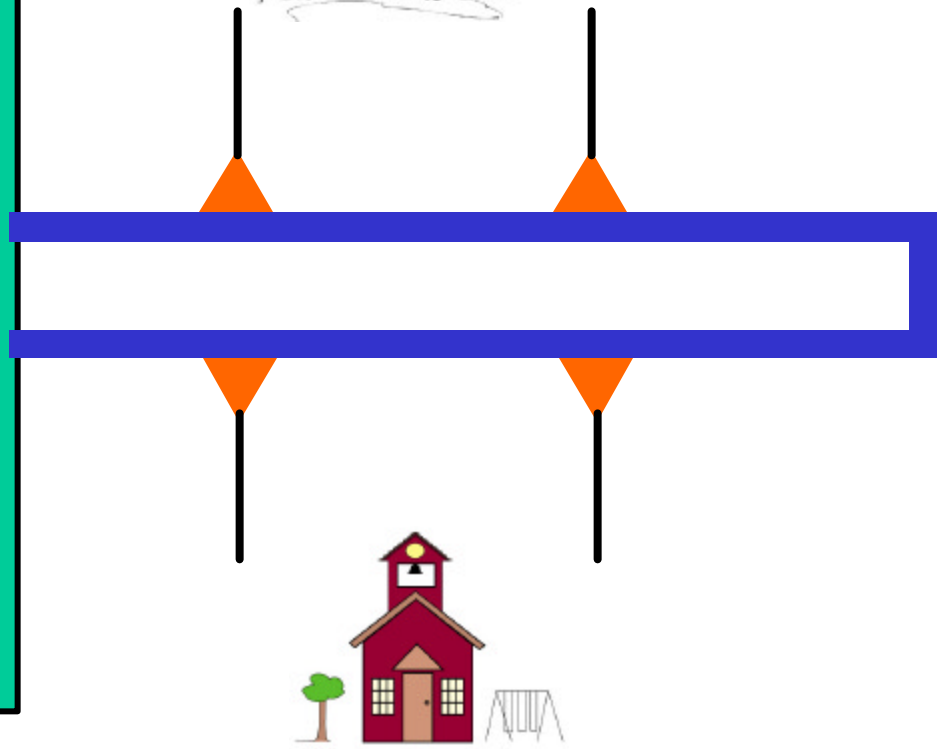
10 MW Community Substation

dc XFMR

H_2 Fuel Cell

PLC Com Injector

H_2 Storage



End Use

Streetside Service

---

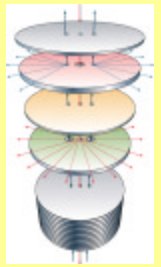
100 A @ +/- 25 Vdc

H_2 @ 200 K, 100 psi

PLC @ 5 MHz

H_2 Heat Exchanger for AC

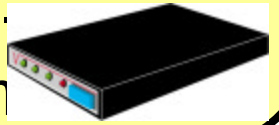
H_2 for Heat/Hot H_2O



Household Fuel Cell

Inv/Conv for Electricity

DSL Digital Modem



ASC 2000

Virginia Beach, VA

September 17-22, 2000

Gilroy High, Ca. May 28, 1987

76 New Scientist 30 July 1987

Do-it-yourself superconductors

It is extremely easy to make high-temperature superconductors. Schools in the United States and Britain have already produced their own samples. Here is the recipe

Paul Grant

ANY moderately equipped secondary school should be able to make and test high-temperature superconductors at very reasonable cost. This is already beginning to happen in the United States. On 29 May, nine high-school students and their chemistry teacher at Gilroy High School in California became the first group of pupils to make samples of the perovskite material and to demonstrate its superconducting properties by magnetic levitation. In Britain, pupils at Helsby High School in Cheshire have also made the new material (*New Scientist*, 9 July, p 14).

Gilroy is a small Californian agricultural community of population 23 000, about 130 kilometres south of San Francisco. The town, noted locally for its excellent garlic, was founded in the early 19th century by John Cameron Gilroy, a former sailor in the Royal Navy who, according to local legend, was either put to shore in nearby Monterey because of scurvy or jumped ship after hitting an officer.

The students and teacher at Gilroy High obtained the

After the "Woodstock of physics" meeting last March in New York City, when several thousand scientists stayed up for an all-night session on these new materials, I was asked to brief a team of visiting British journalists on our activity in high-temperature superconductivity, and also to lecture on the same topic to the administrative staff at our laboratory. For these assignments, I wanted to put together a simple yet dramatic demonstration of superconductivity-more than

"Shake 'n' bake" recipe for 1-2-3 ($YBa_2Cu_3O_{7-x}$)

Mix 1·13 grams yttrium oxide, 3·95 grams barium carbonate, 2·39 grams copper oxide
Compact
Grind in mortar and pestle
Bake in air at 950°C (1650 °F)
Regrind in mortar and pestle
Press into pellets
Bake pellets in flowing oxygen at 950 °C (1650 °F)
Allow to cool very slowly

Recipe by Heidi Grant

Left: Heidi Grant demonstrates superconductivity at the US National Science Foundation

"US high school chemistry class verifies discovery of High - T_c"

New Scientist, July 1987

Pupils at Gilroy High School in California make their own high-temperature superconductor

"Cooper Pairs"

The Future

2028

Is "Room Temperature" Superconductivity Possible? Why Not?

"Advances in superconductivity begin with the empirical search for new materials."
Bednorz and Mueller, Z. Phys., Sept., 1986

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 the lead technical forecaster at EPRI, he reconnoiters and assesses both current 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 science of exotic superconductors, conductors and magnetic materials. He says he wrote this essay out of frustration and revenge for the years he spent pursuing 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

Forty-two years ago, Johannes Georg Bednorz and Karl Alex Müller startled 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 related compounds were found over the succeeding years, culminating in 2002 with Au-2223—a triple-layer CuO complex with an ambient-pressure transition temperature of 175 K, synthesized by Paul Chu and his collaborators in Houston. Such materials have found a number of communications and electric power applications, especially in distribution cables, transformers and passive RF filters, but remain limited by the need for cryogenic packaging.

Now that limitation might be the stuff of history. At last month's general meeting of the North American Physical Society (NAPS), held in Cuernavaca with VR-holo simul-sessions in Waterloo, Newark, Wichita and Vic-

of Stanford University envisioned the possibility of very high temperature superconductivity in specially designed 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 could apply to any fermion pairing sustained by a general boson 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 William McMillan and Gerasim Eliashberg suggested that superconductivity mediated by lattice vibrations would not be possible above 30–40 K. To paraphrase Berndt Mathias, "You can't make a crystal structure that would be stable under such strong interactions."

Little's concept involved replacing the phonons—characterized by the Debye temperature—with excitons.

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

"…you get what you need!"

pgrant@epri.com