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Superconductivity & Power Cables

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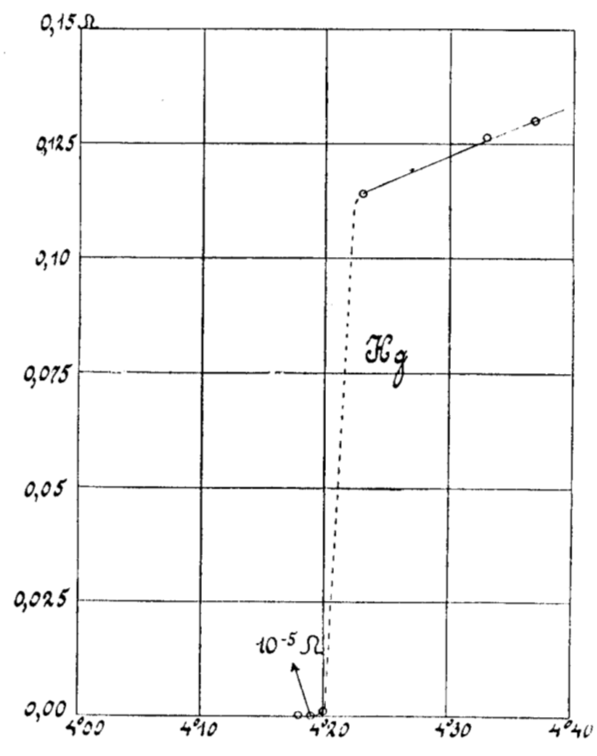
EPRI Workshop on SCDC Cables
12 - 14 October 2005, Palo Alto

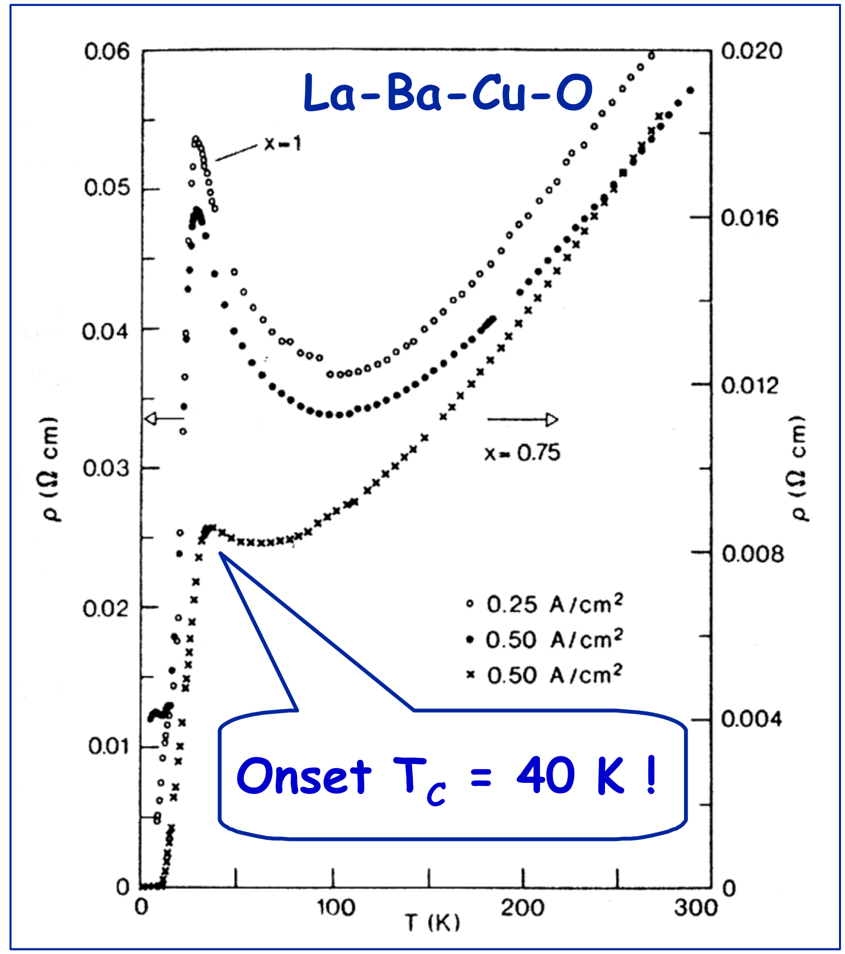
Outline

- Critical State Parameters (T_C, J_C, H^*, ω) relevant to power applications of superconductivity
- Properties of presently and soon to be available HTSC tapes and wires
- Brief overview of present HTSC cable projects
- Re-visit Garwin-Matisoo & LASL LTSC dc cable concepts
- Efficacy of cryo-resistive cables and HTSC wire costs (tomorrow)

The Discoveries

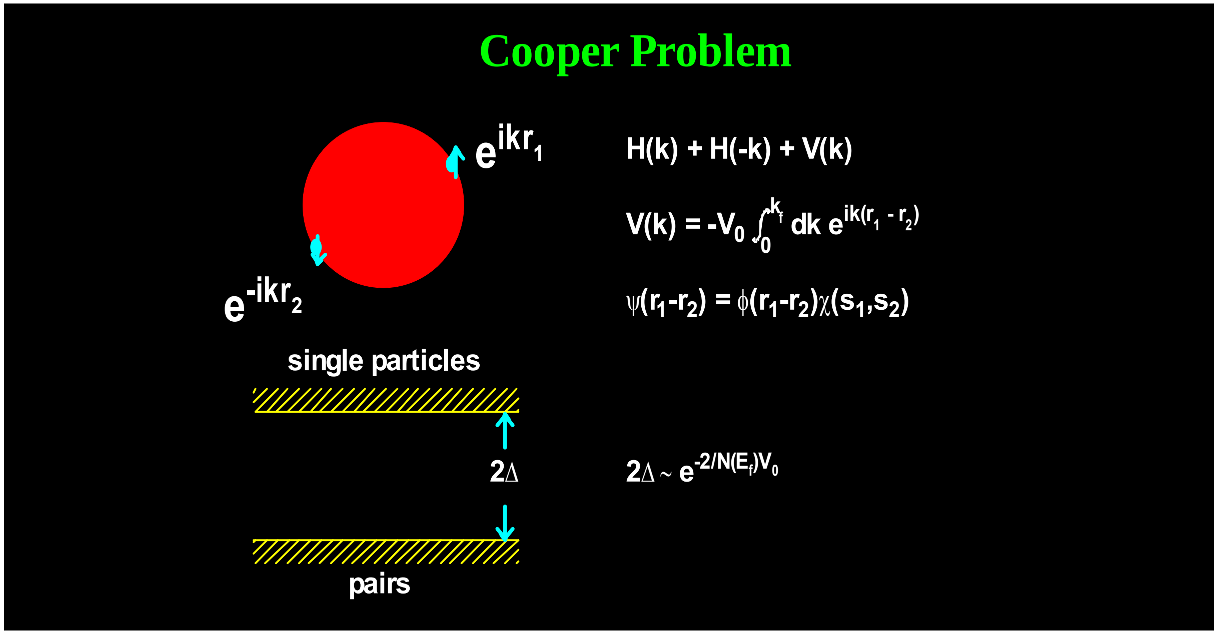


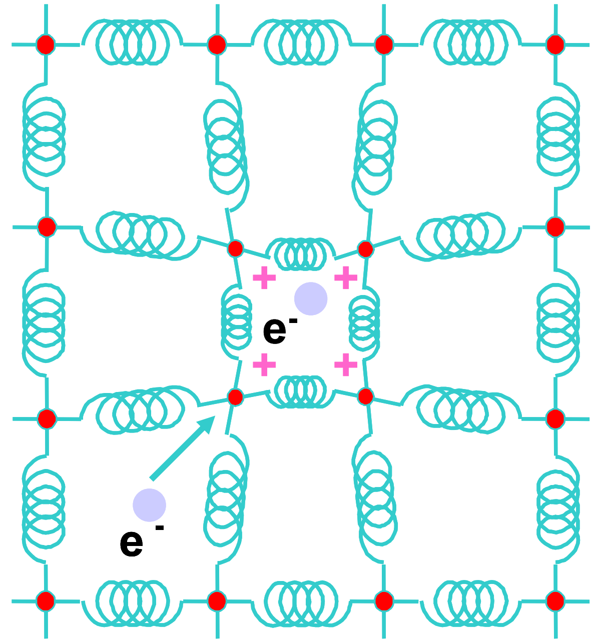
Leiden, 1911

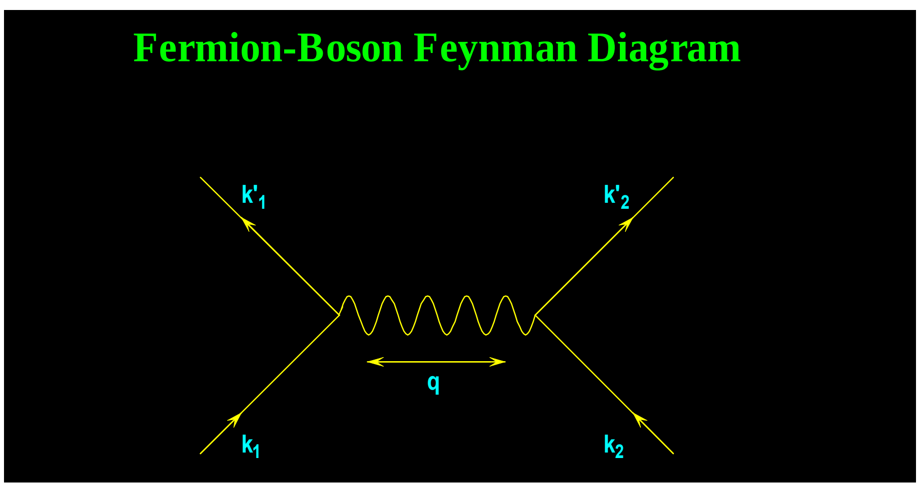


Zürich, 1986

Superconductivity 101







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

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

$$\lambda = 0.28,$$

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

GLAG

$$G[\phi] \approx \int d^3r[\frac{1}{2m^*}(-i\hbar\nabla + e^* A)\phi^*(i\hbar\nabla + e^* A)\phi + a\phi\phi^* + \tfrac{1}{2} b\phi\phi^*\phi\phi^*]$$

$$-(i\partial\nabla - \mathcal{A})^2 f + f(1 - f^2) = 0$$

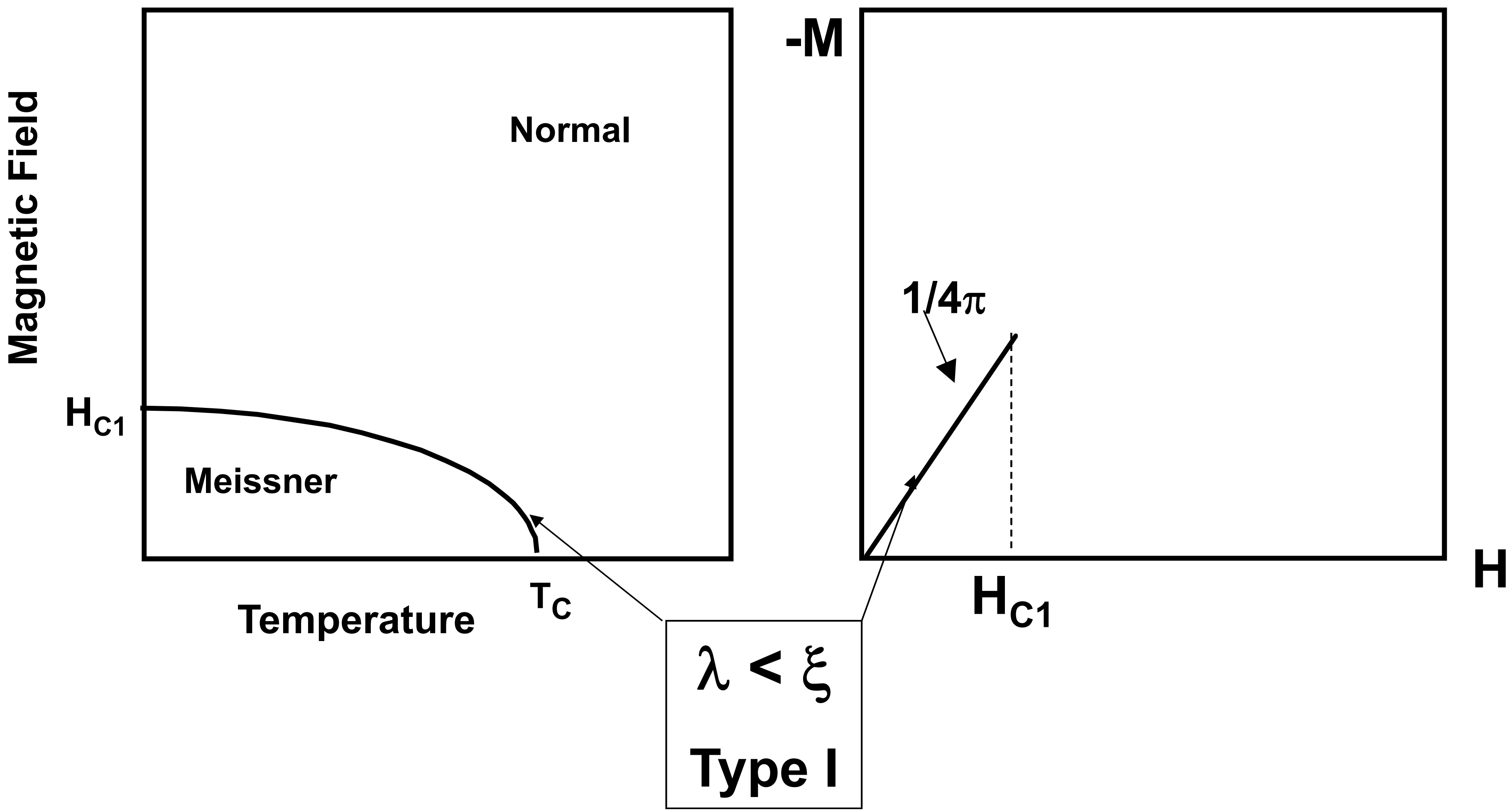
$$\kappa^2 \nabla \times (\nabla \times \mathcal{A}) + \tfrac{1}{2} i(f^* \nabla f - f \nabla f^*) + \mathcal{A} f^2 = 0$$

$$\phi = (|a|/b)^{1/2} f$$

$$A = (\Phi_0 / 2\pi\xi)\mathcal{A}$$

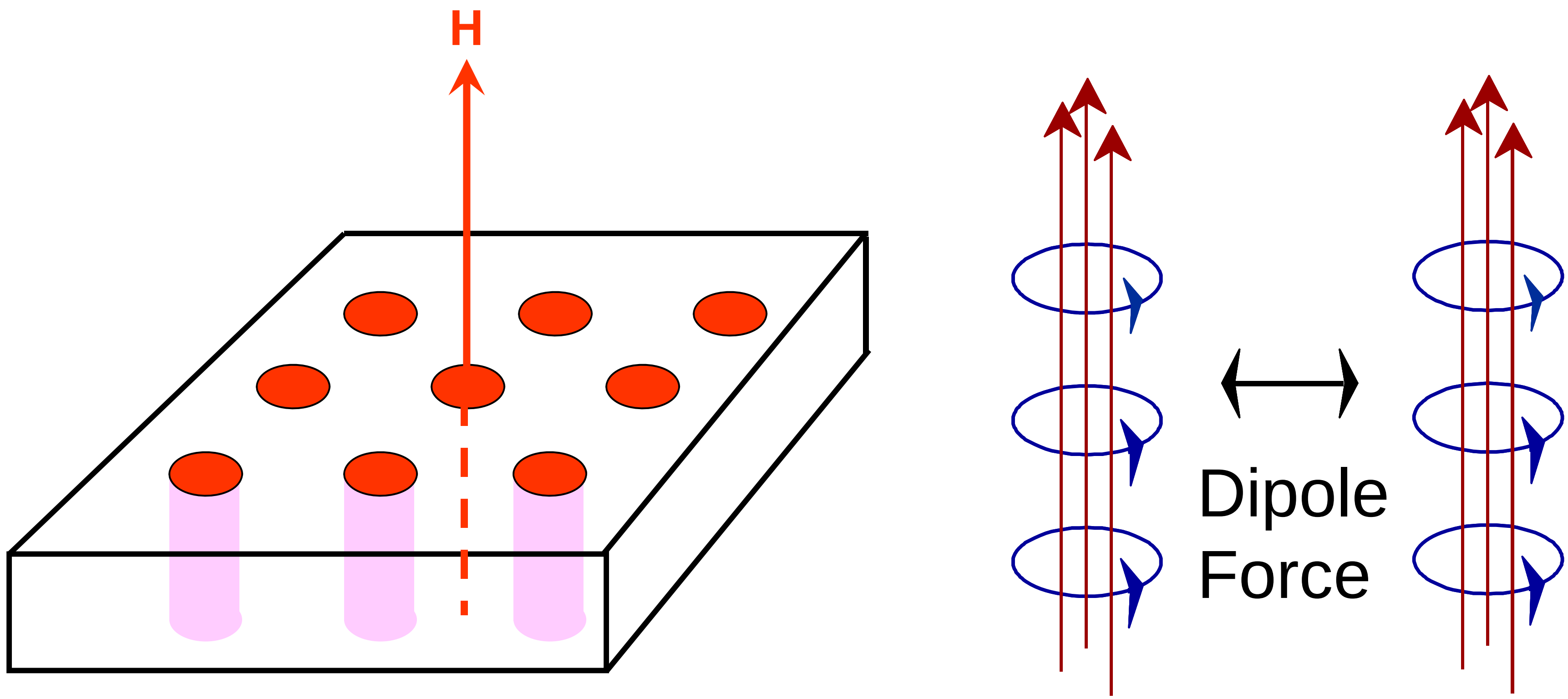
$$\kappa = \lambda_L / \xi$$

The Flavors of Superconductivity

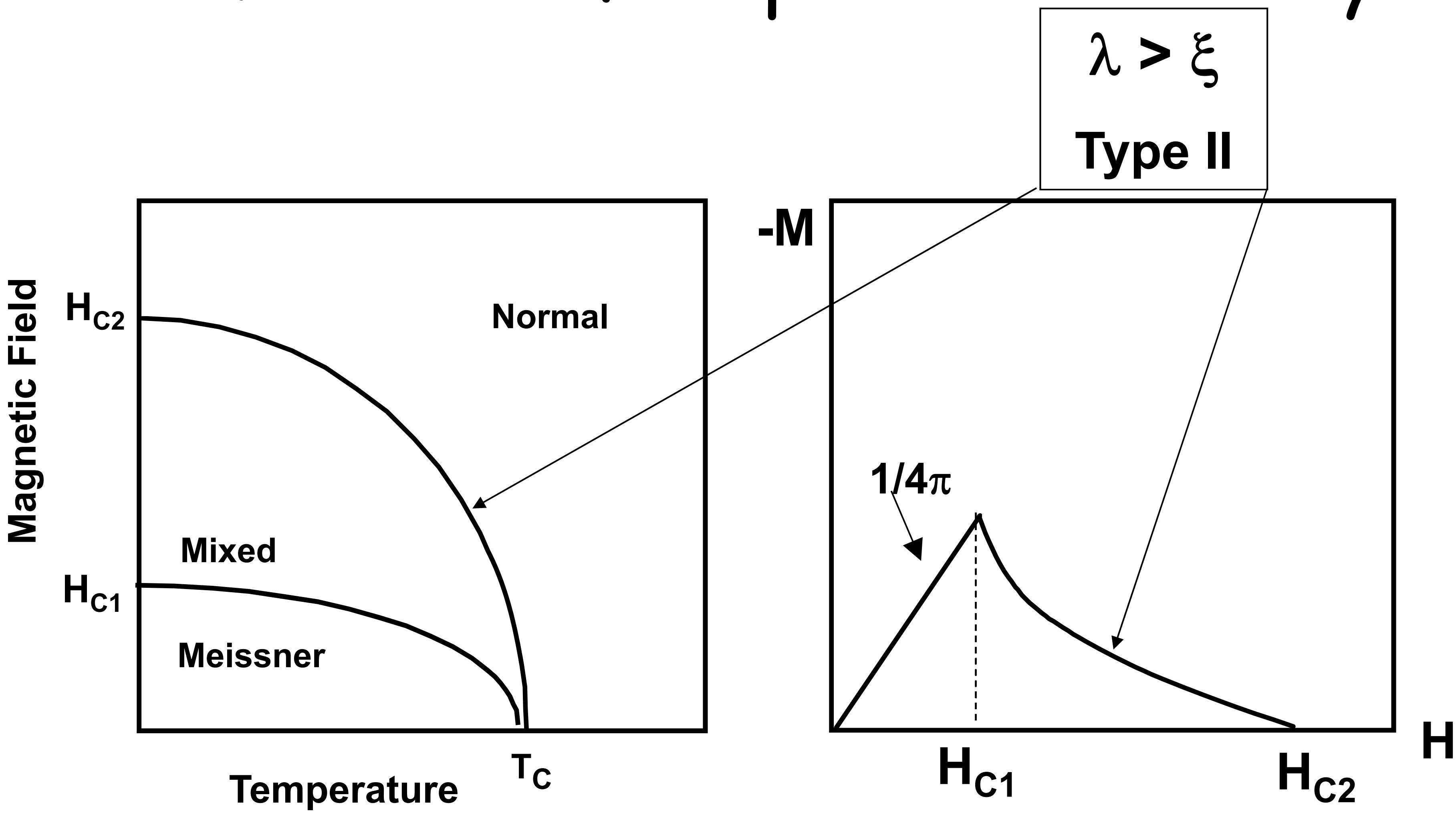


Abrikosov Vortex Lattice

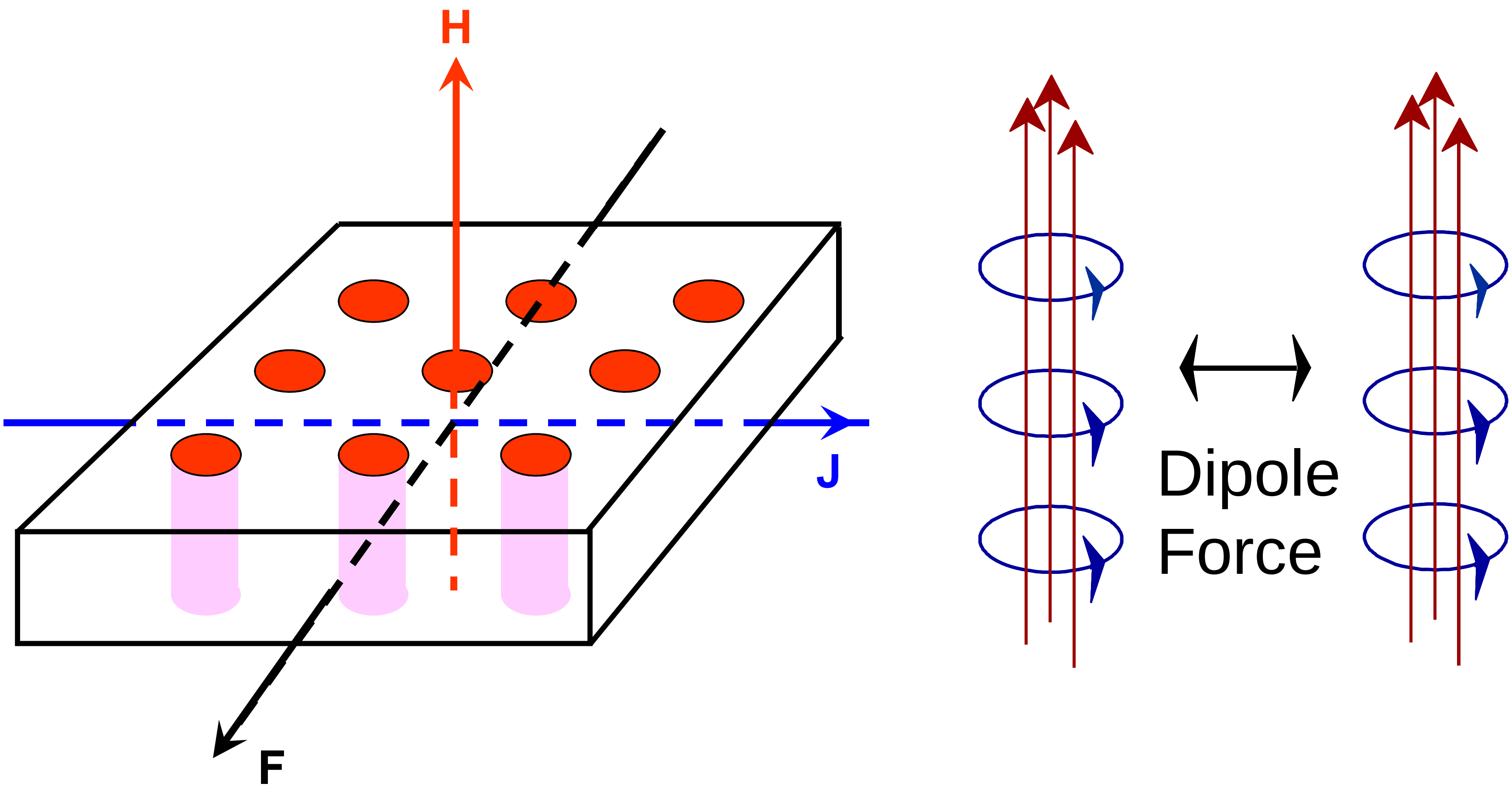
$$\lambda > \xi$$



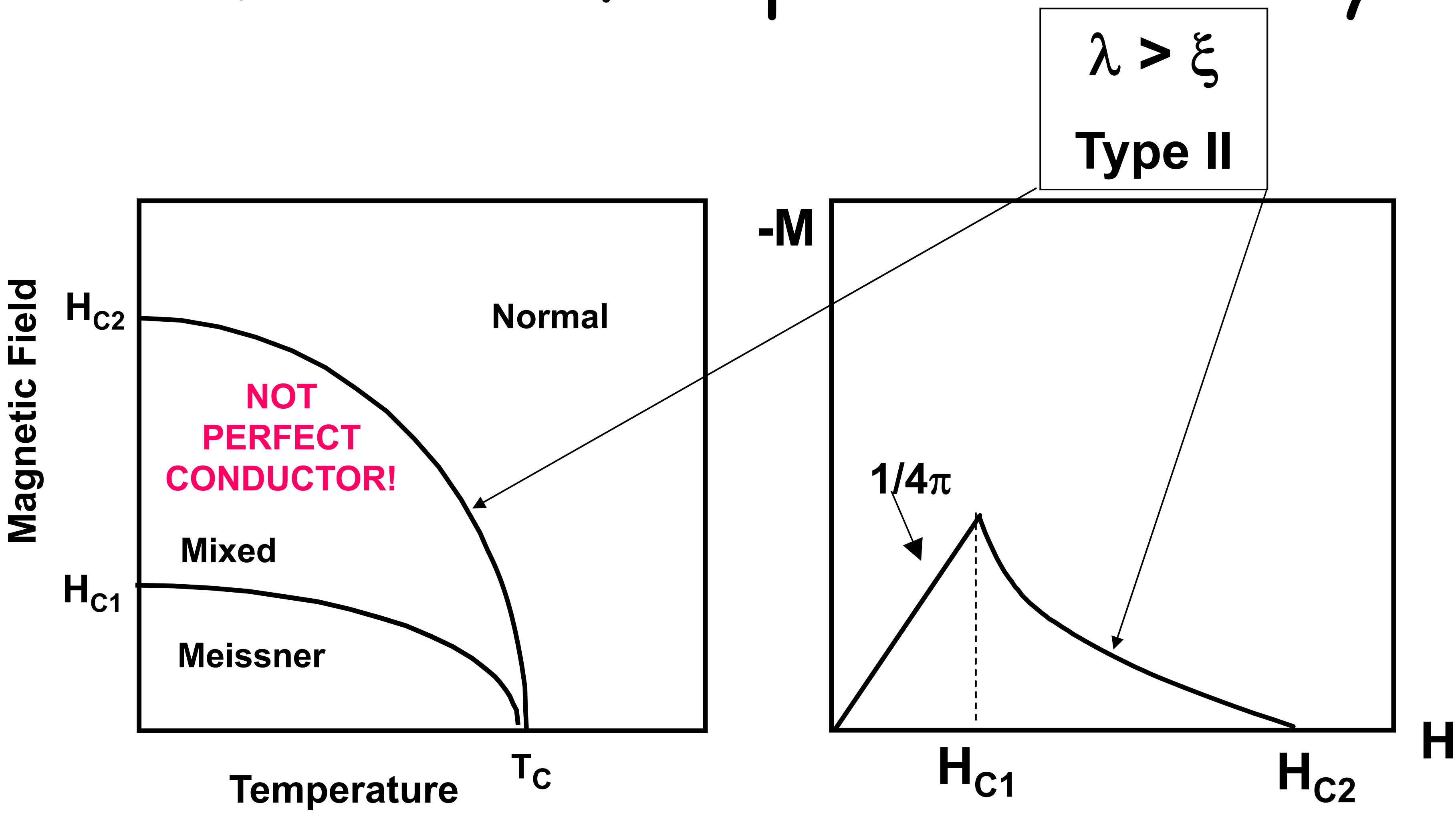
The Flavors of Superconductivity



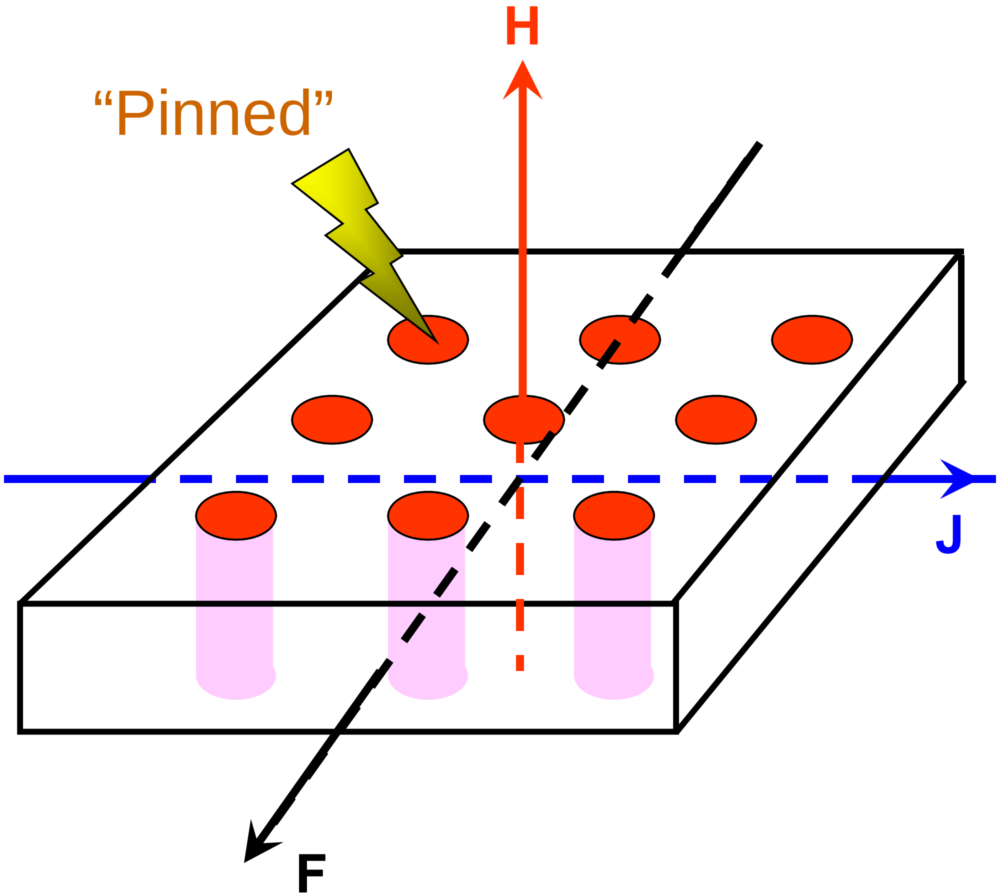
Abrikosov Vortex Lattice

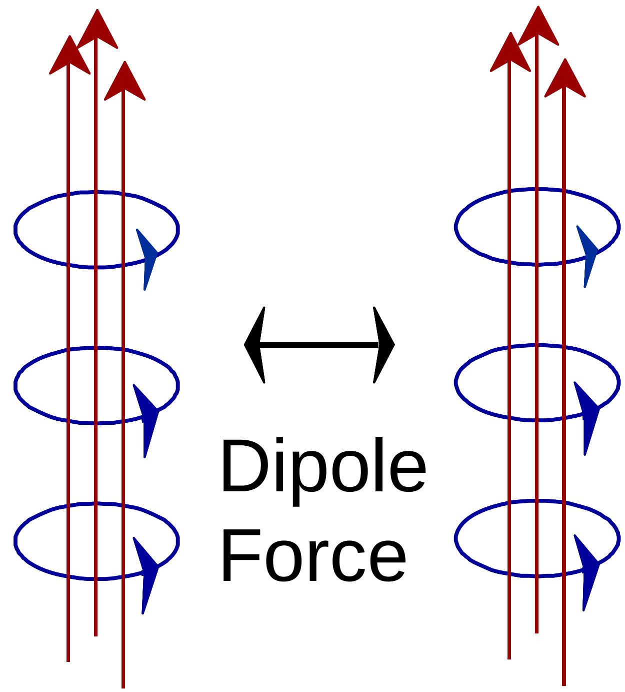


The Flavors of Superconductivity

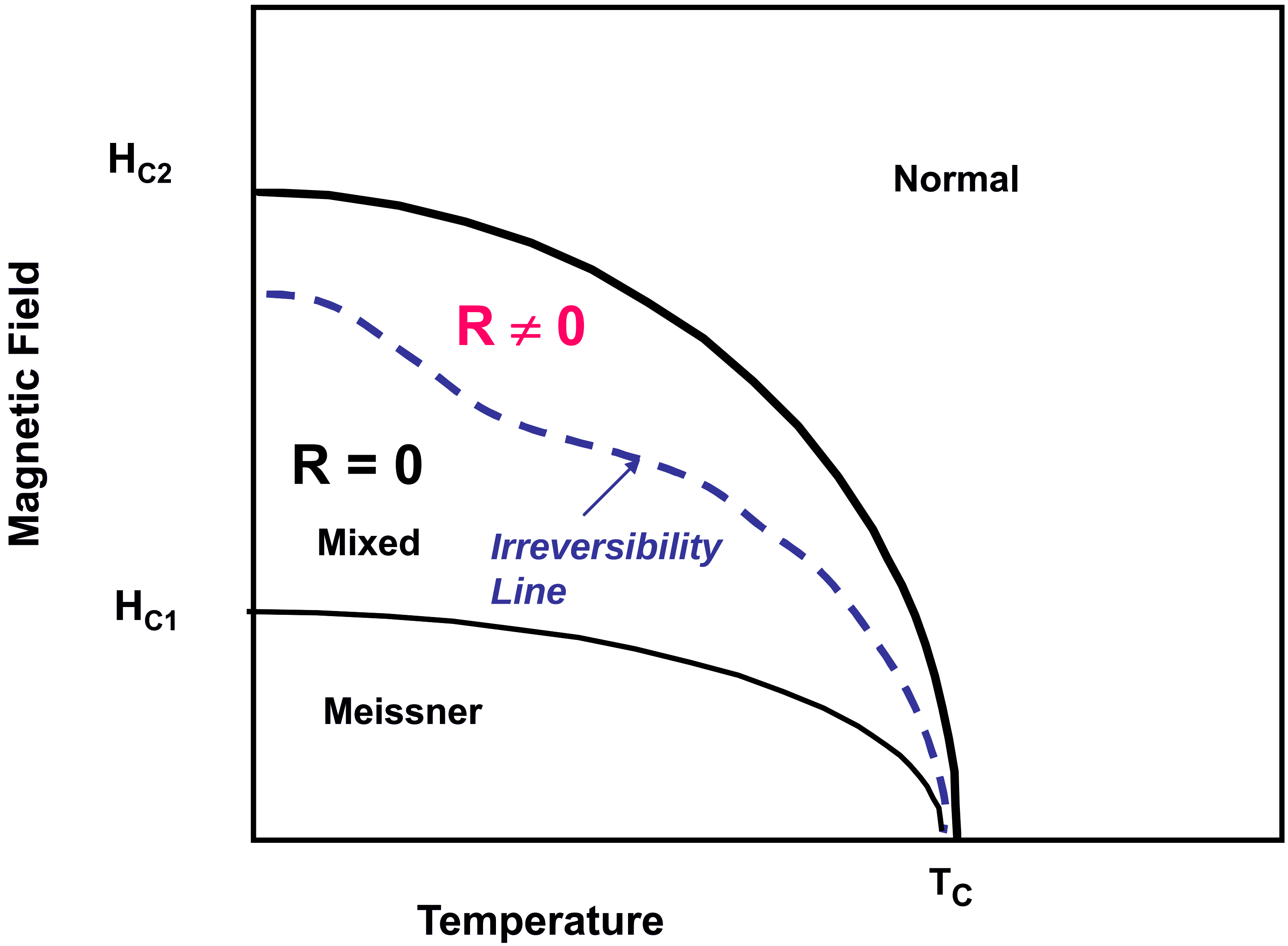


Abrikosov Vortex Lattice

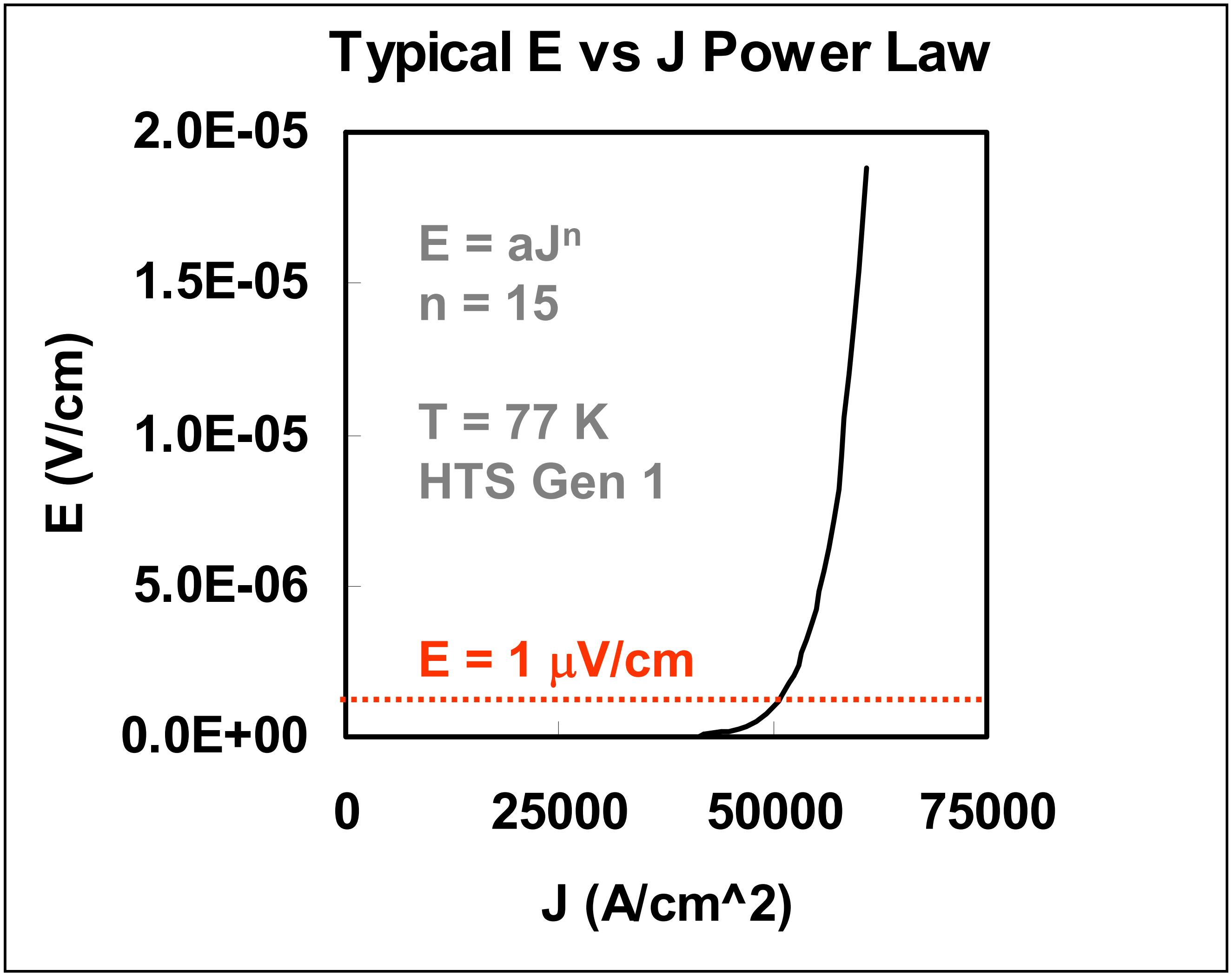




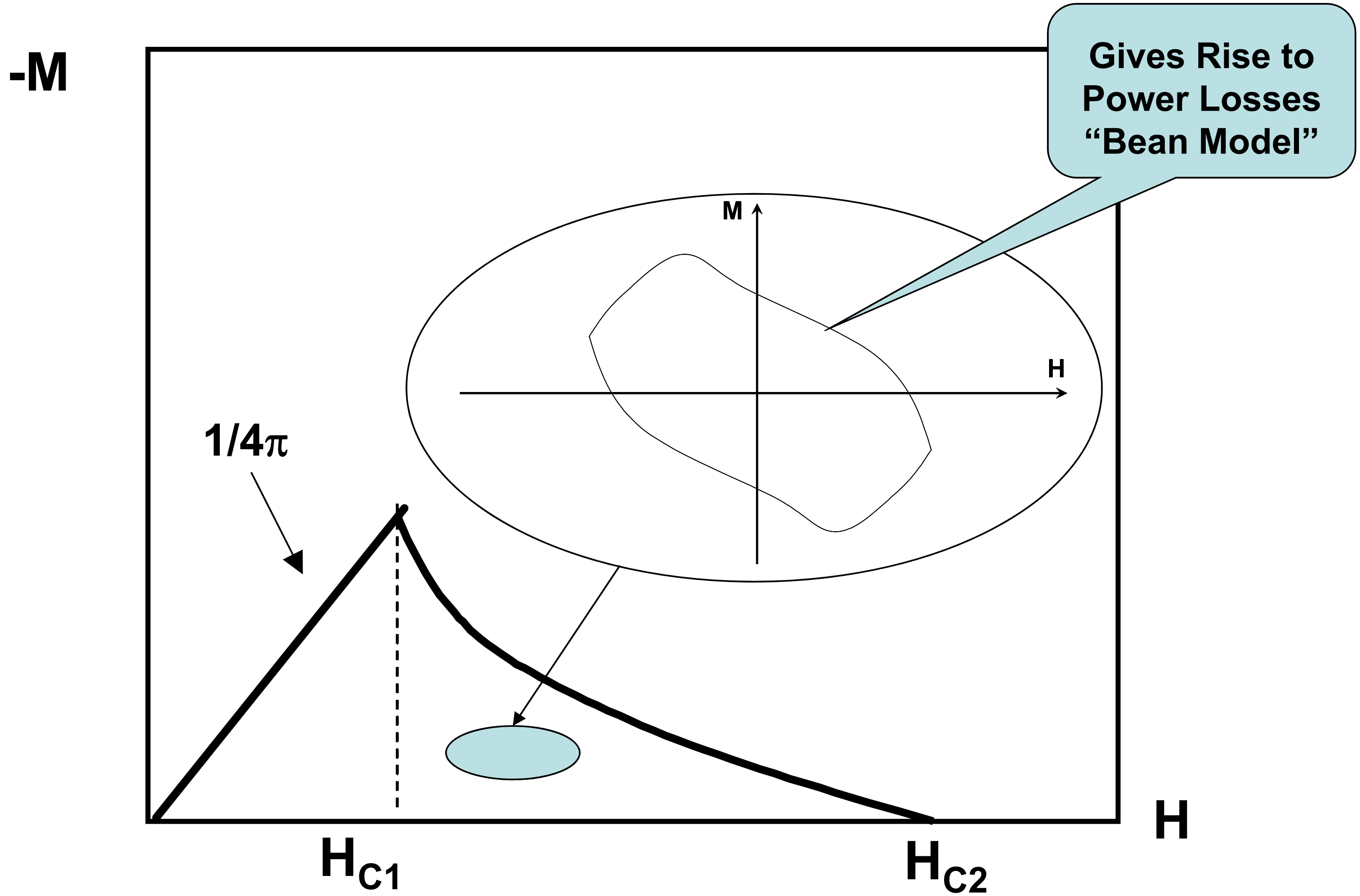
The Flavors of Superconductivity



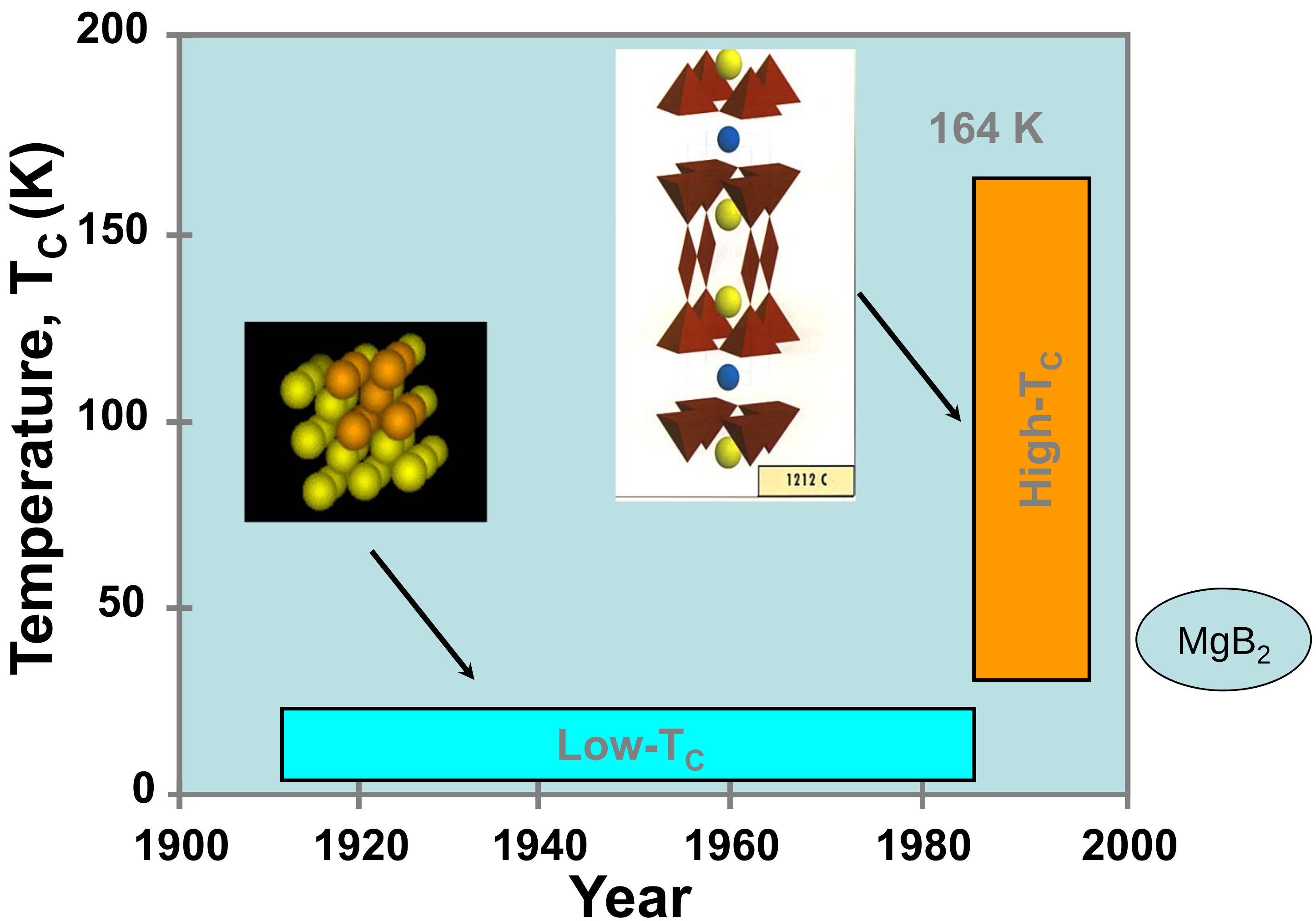
No More Ohm's Law



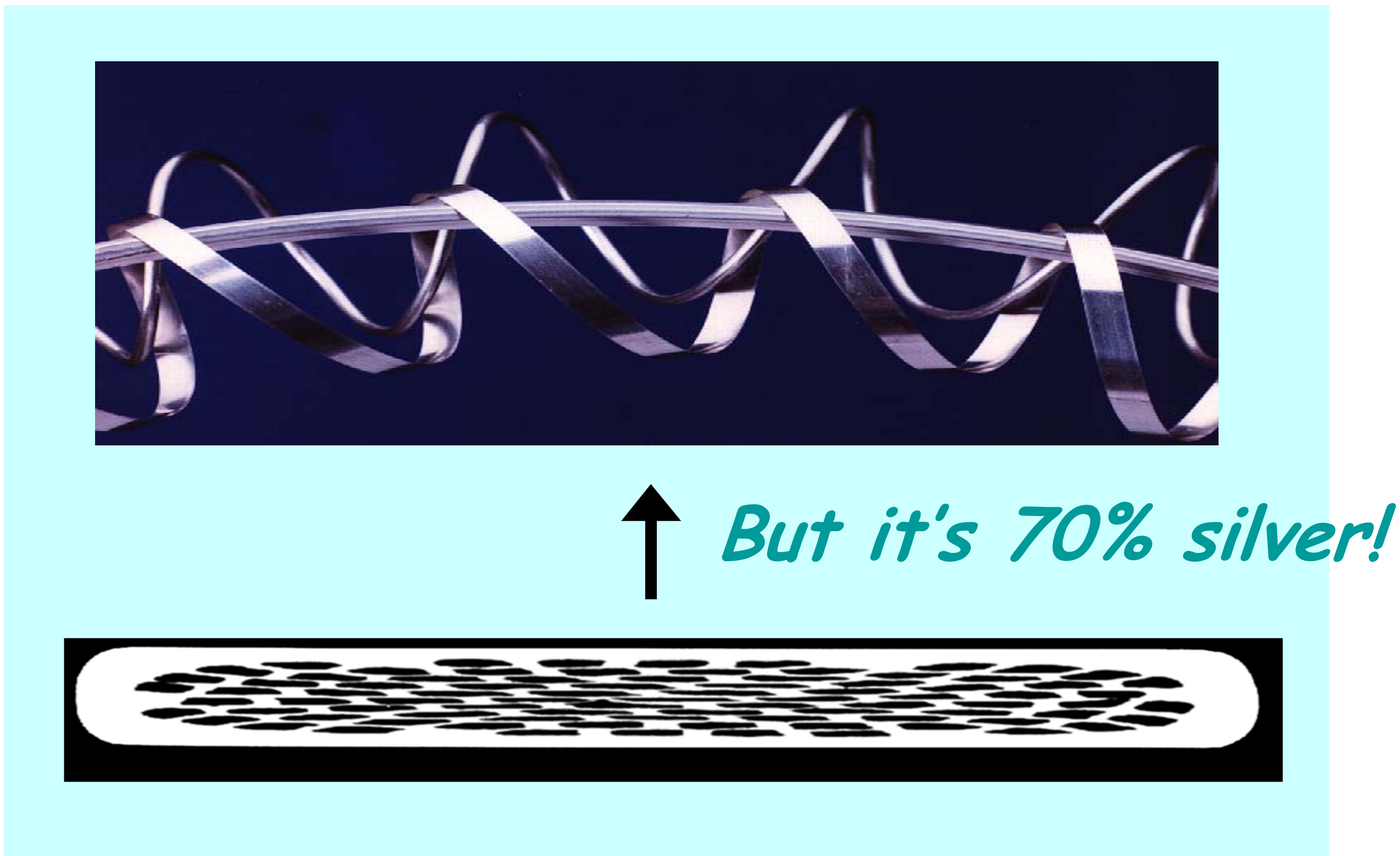
ac Hysteresis



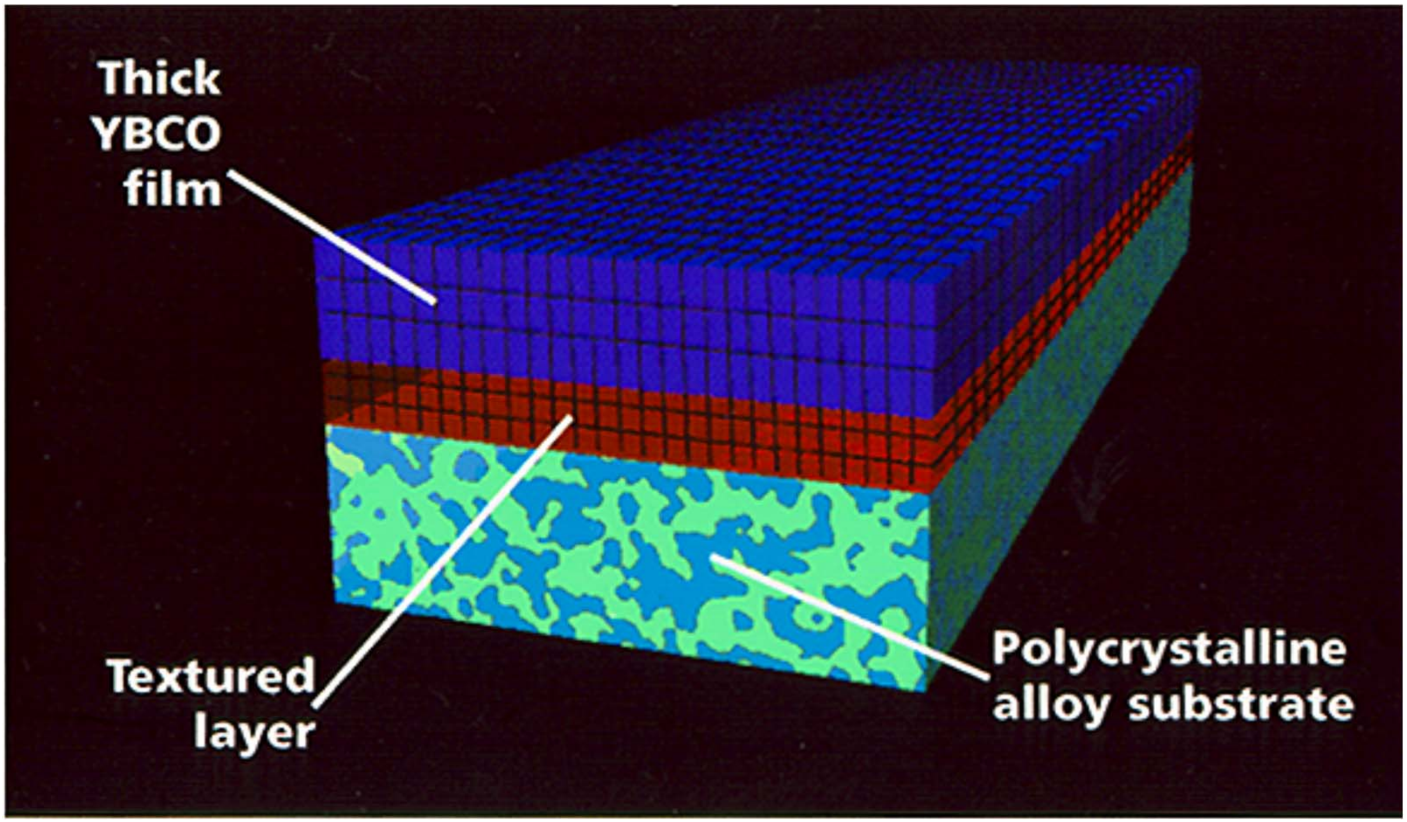
T_C vs Year: 1991 - 2001



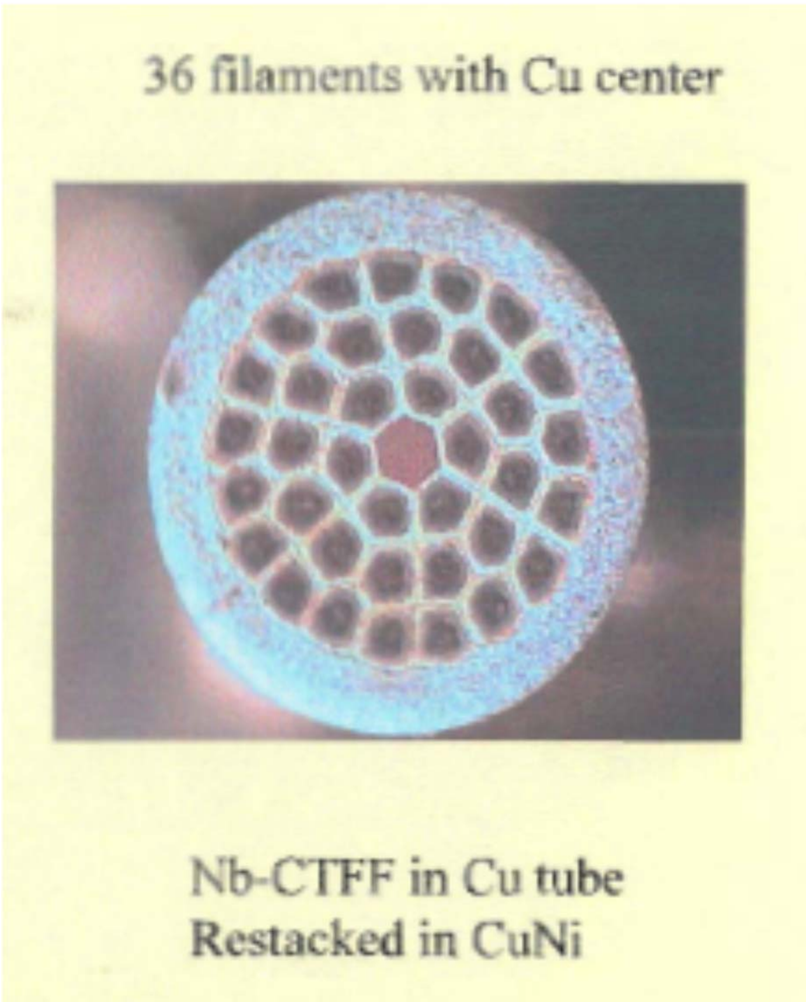
HTSC Wire Can Be Made!



Coated HTSC Conductors
Generation II Wire



MgB_2 Wire



- "Discovered" in 2001
- One month later we have several meters of wire
- Today kilometer lengths are available for sale

Finished Cable

Puji Substation, Kunming, China

HTSC Cable Projects Worldwide – Past , Present and Future

Two IBM Physicists (1967)

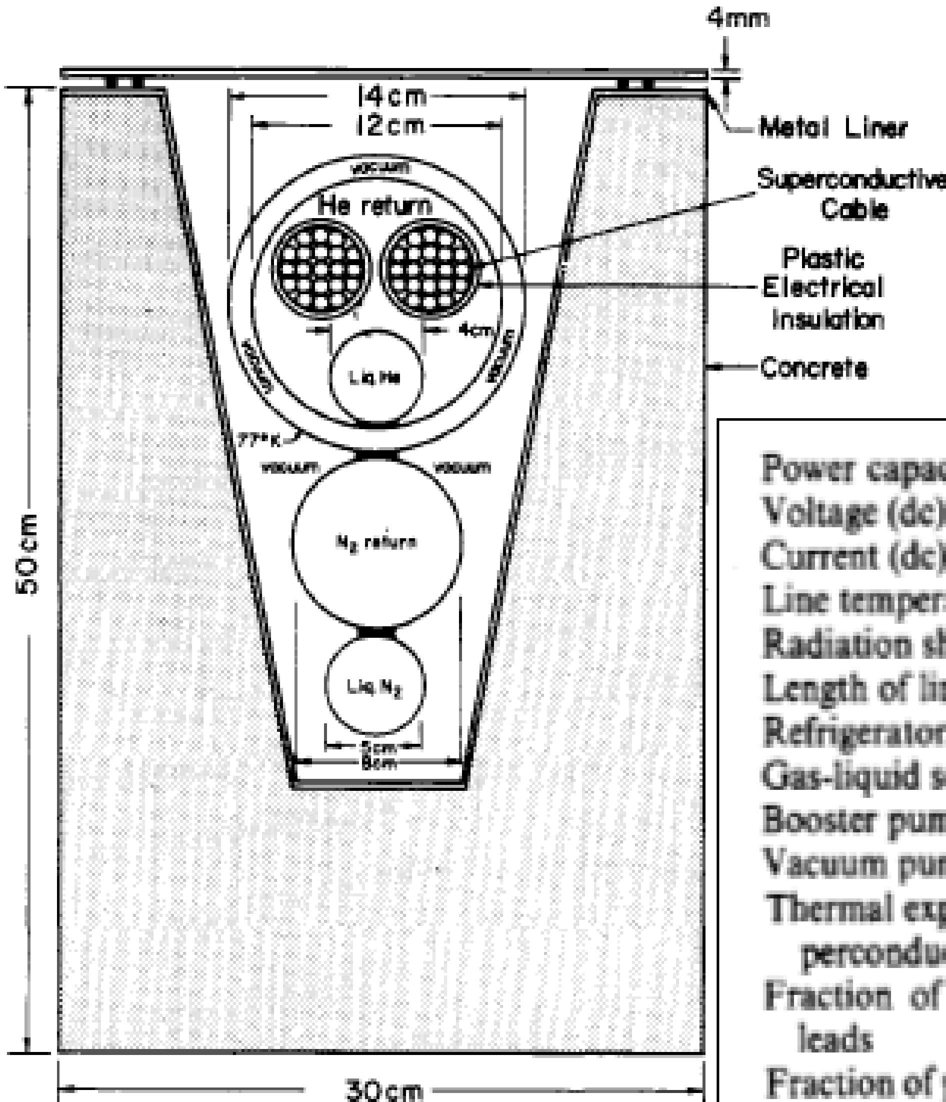
Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOO

- Nb_3Sn (T_C = 18 K) @ 4.2 K
- 100 GW (+/- 100 kV, 500 kA)
- 1000 km
- Cost: $800 M ($8/kW) (1967)

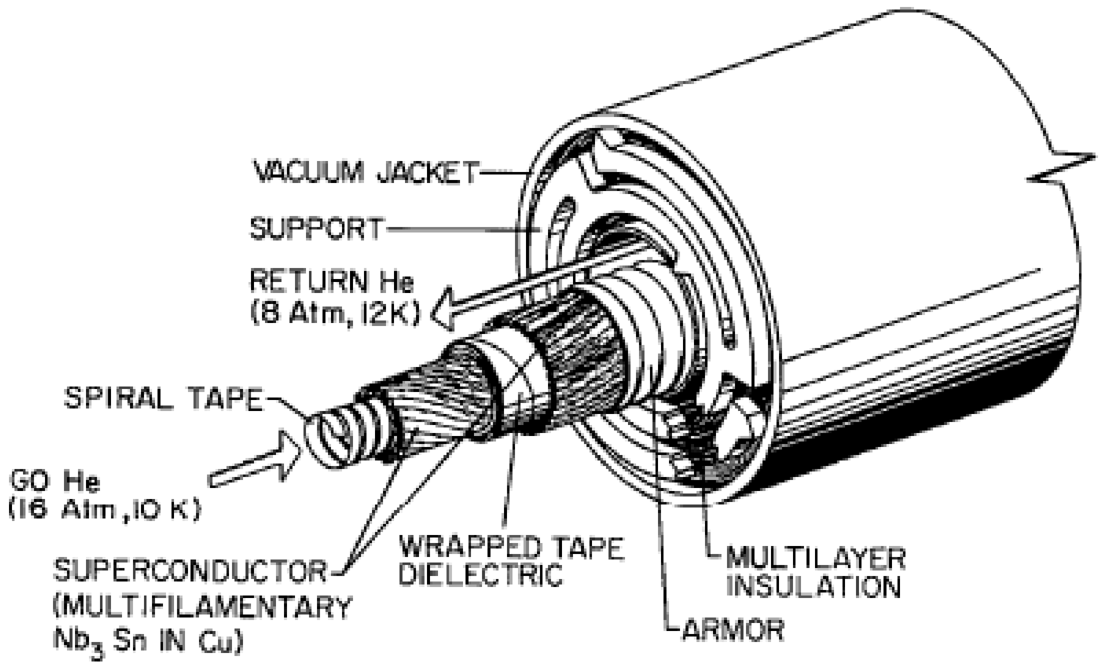
$4.7 B Today!

G-M Specs



Power capacity	100 GW (10^{11} W)
Voltage (dc)	200 kV (2×10^5 V)
Current (dc)	0.5×10^6 A
Line temperature	4.2°K (liquid helium)
Radiation shield	77°K (liquid nitrogen)
Length of line	1000 km
Refrigerator spacing	20 km
Gas-liquid separator spacing	50 m
Booster pump spacing	500 m
Vacuum pump spacing	500 m
Thermal expansion bellows 1.5 m long (superconductors wound helically) spacing	500 m
Fraction of power dissipated in line and leads	$<10^{-7}$
Fraction of power used for refrigeration	$<10^{-3}$

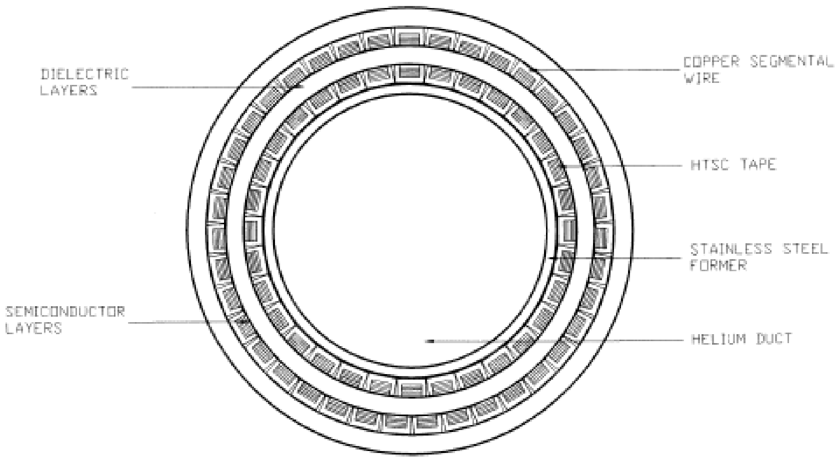
LASL SPTL (1972-79)



Specifications

- 5 GW
  (+/- 50 kV, 50 kA)
- PECO Study
  (100 km, 10 GW)

BICC HTSC dc Cable (1995)



Design Target

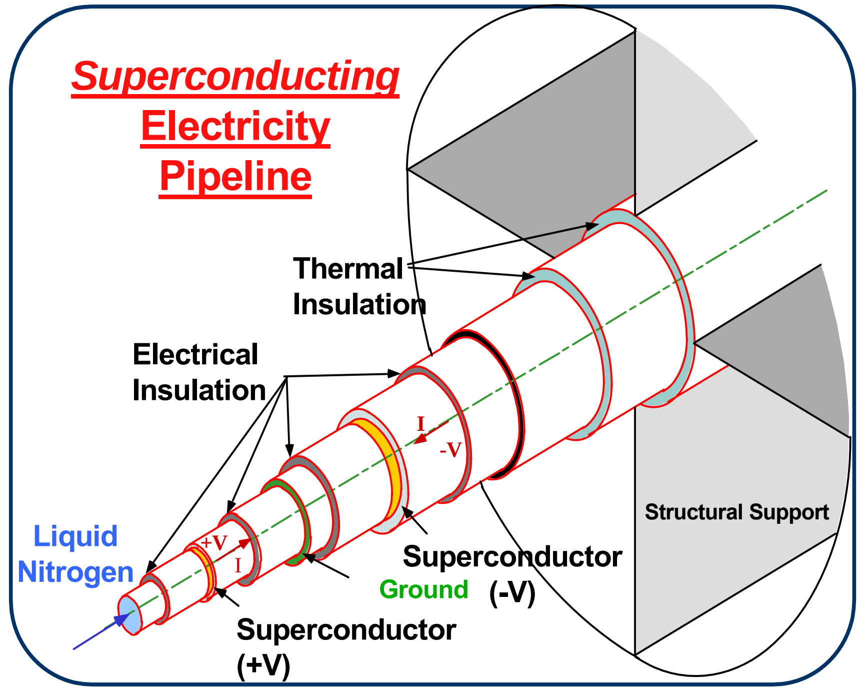
- 400 MW, 100 km
- Flowing He, 0.2 kg/s, 2 MPa, 15 – 65 K
- Cooling Losses: 150 kW

Prototype Specs

- 400 MW
  - +/- 20 kV, 10 kA
- Length: 1.4 m
- Diameter: 4 cm
- He (4.2 – 40 K)

e-Pipe

CYPRUS
Nicosia
Mediterranean Sea
LEBANON
Beirut
Damascus
SYRIA
Latakia
Hims
Golan Heights*
Haifa
ISRAEL
Jerusalem
Gaza Strip
Amman
West Bank*
JORDAN
Al Aqabah
Alexandria
Cairo
EGYPT
Luxor
Aswān
Tropic of Cancer
Administrative Boundary
Gulf of Suez
Gulf of Aqaba
Tabūk
Ha'il
Medina
Yanbu al Bahr
Hala'ib
SAUDI
ARABIA
Riyadh
Hafar al Batin
Dhahran
Manama
QATAR
Persian Gulf
KUWAIT
Kuwait
Bandar-e Būshehr
IRAQ
Baghdad
Al Hillah
Al Kut
An Nasiriyah
Al Basrah
Mosul
Karkūk
Tigris
Euphrates
Bākhtarān
Arak
Dezful
Ahvāz
Ābādān
Tehrān
Qom

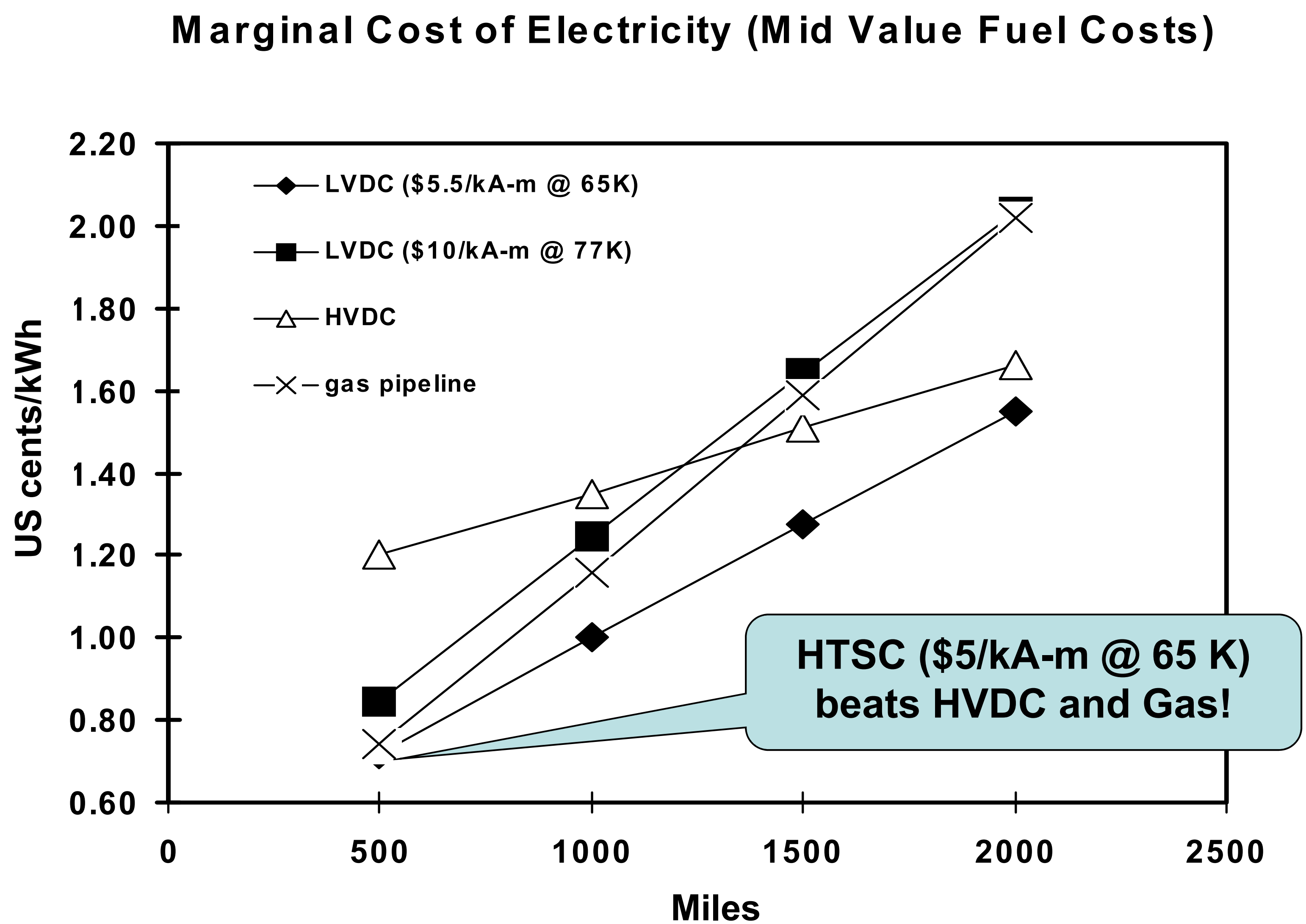


Superconducting
Electricity
Pipeline
Thermal
Insulation
Electrical
Insulation
Liquid
Nitrogen
+V
I
-V
Superconductor
(+V)
Ground
Superconductor
(-V)
Structural Support

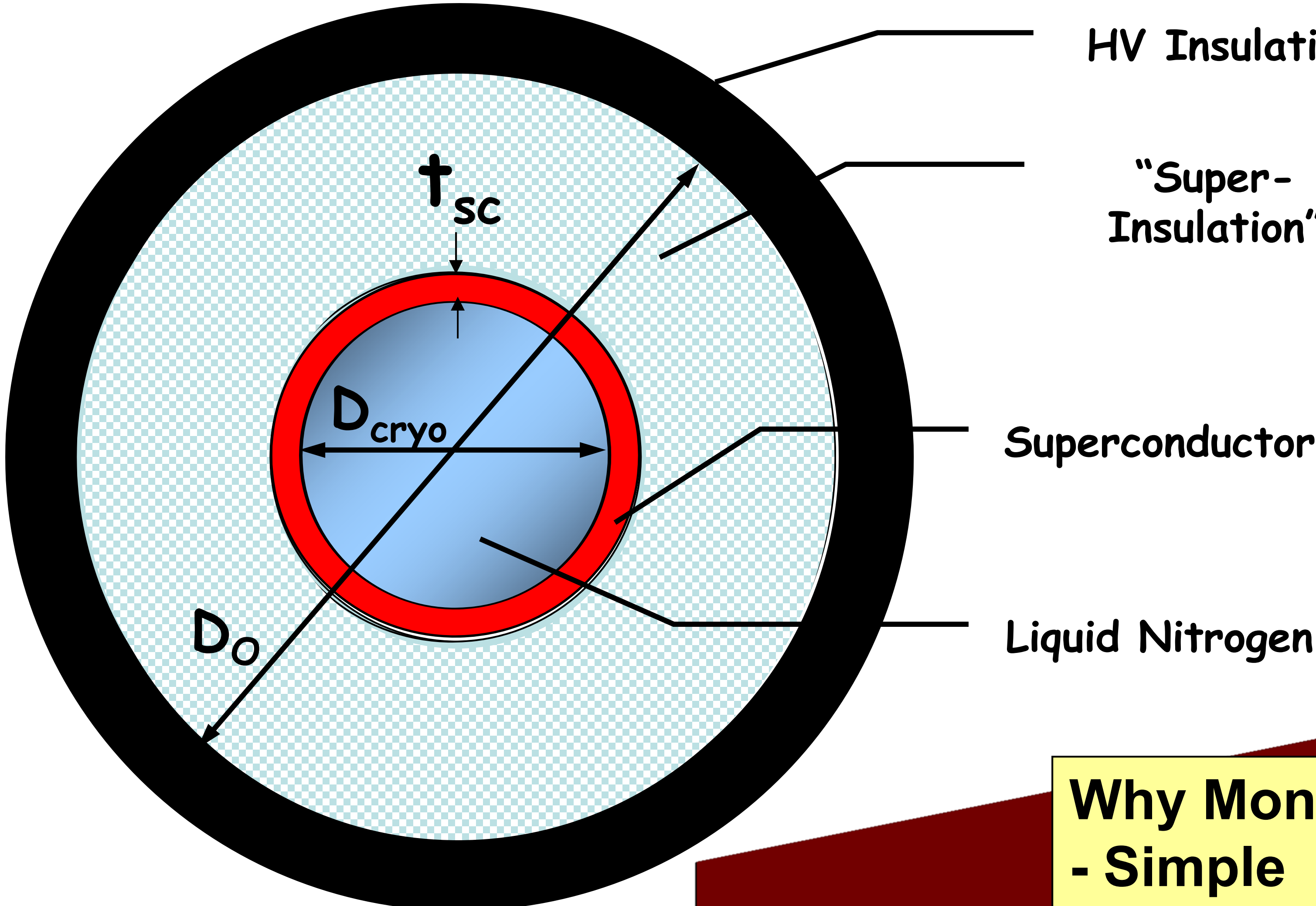
e-Pipe Specs (EPRI, 1997)

Capacity	5 GW (+/- 50 kV,50 kA)
Length	1610 km
Temperature Specs: - 1 K/10 km @ 65 K - 1 W/m heat input	- 21.6 kliters LN_2/hr - 100 kW coolers - 120 gal/min
Vacuum: - 10^{-5} – 10^{-4} torr	- 10 stations - 10 km spaced - 200 kW each

e-Pipe/Gas/HVDC Cost Comparison

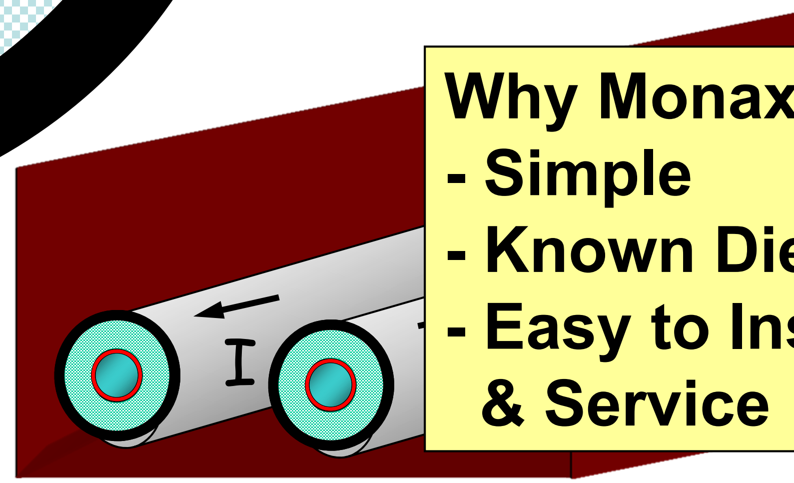


HTSC dc Cable



Garwin – Matisoo

Revisited !

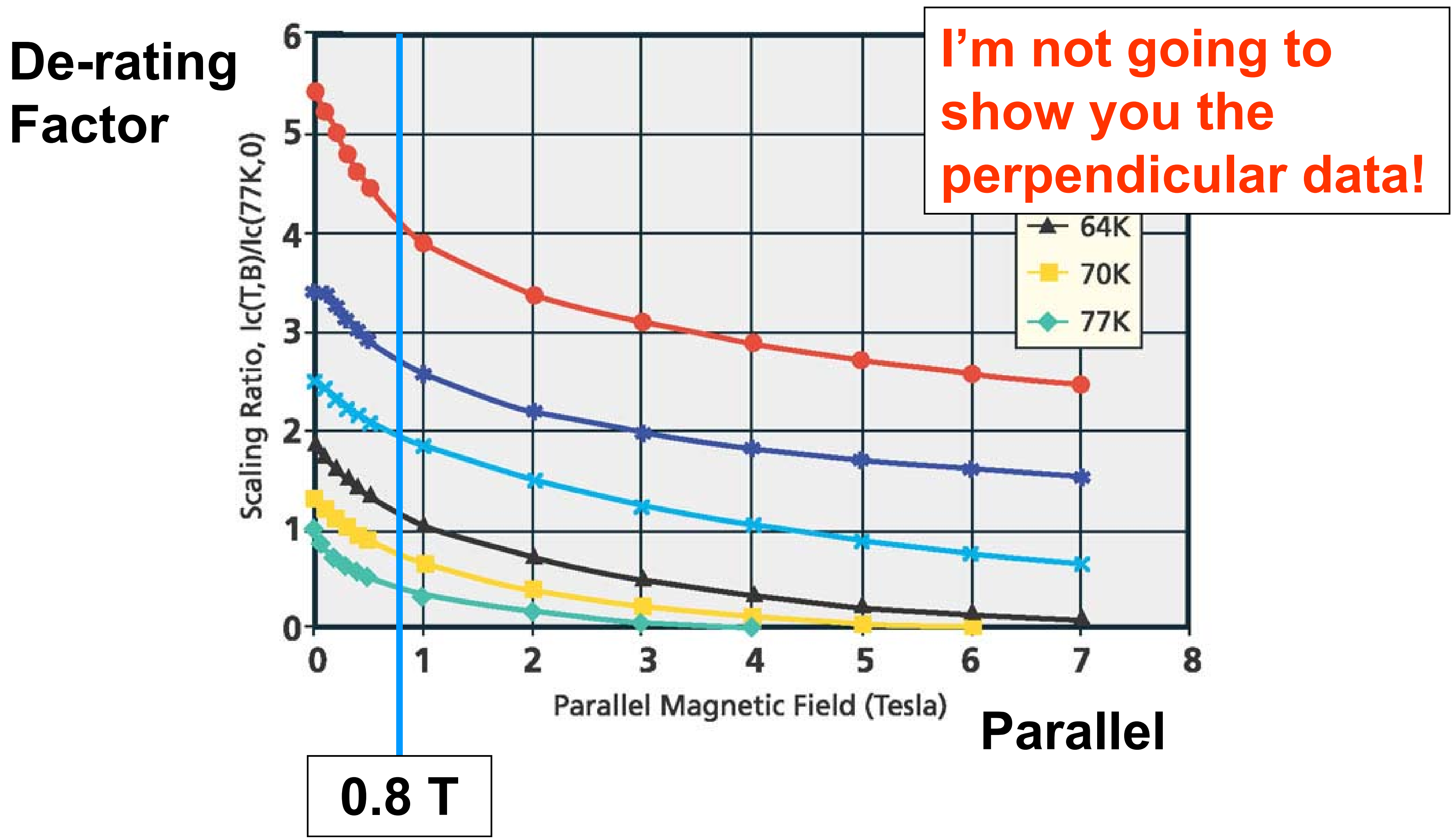


Why Monaxial?
- **Simple**
- **Known Dielectric**
- **Easy to Install & Service**

SCDC Cable Parameters

- Power = 5 GW
- Voltage = 25 +/- kV
- Current = 100 kA
- Jc = 25000 A/cm^2
- Dcryo = 5 cm
- A* = 3.629 cm^2
- t(sc) = 0.243 cm
- R* = 1.075 cm
- B = 0.8 T

AMSC Tape Jc(T, B)



High Amplitude Transient Current Losses (ac & energize)

"Bean Model"

$$H = 4 \times 10^{-9} I_0^2 F \quad \text{W/cm}$$

Io (A)	F (Hz)	H (W/m)
100,000	60	2.4×10^5
100,000	1/hour	0.3
100,000	1/day	0.01

Possibly could reverse line in one hour!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10}(\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

Load Fluctuation Losses over a 1 hour period

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	4×10^{-7}
10	10000	500	4×10^{-4}
20	20000	1000	3×10^{-3}
30	30000	1500	1×10^{-2}

OK, as long as changes occur slowly!

Small Amplitude Losses (Load Fluctuations)

$$H = \frac{4 \times 10^{-10} (\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

…and sometimes even when they're fast!

Consider 1 MW worth of customers coming in and out every millisecond, (*e.g., 10,000 teenagers simultaneously switching 100 W light bulbs on and off*) resulting in ΔI = 20 A, but a heat load of only 10 μW/m

Small Amplitude Losses (Ripple)

$$H = \frac{4 \times 10^{-10}(\Delta I)^3 F}{J_c R^2} \quad \text{W/cm}$$

3-Phase Converter: F = 360 Hz

Δ (%)	ΔI (A)	ΔP (MW)	H (W/m)
1	1000	50	0.50
2	2000	100	3.99
3	3000	150	13.46
4	4000	200	31.91
5	5000	250	62.32

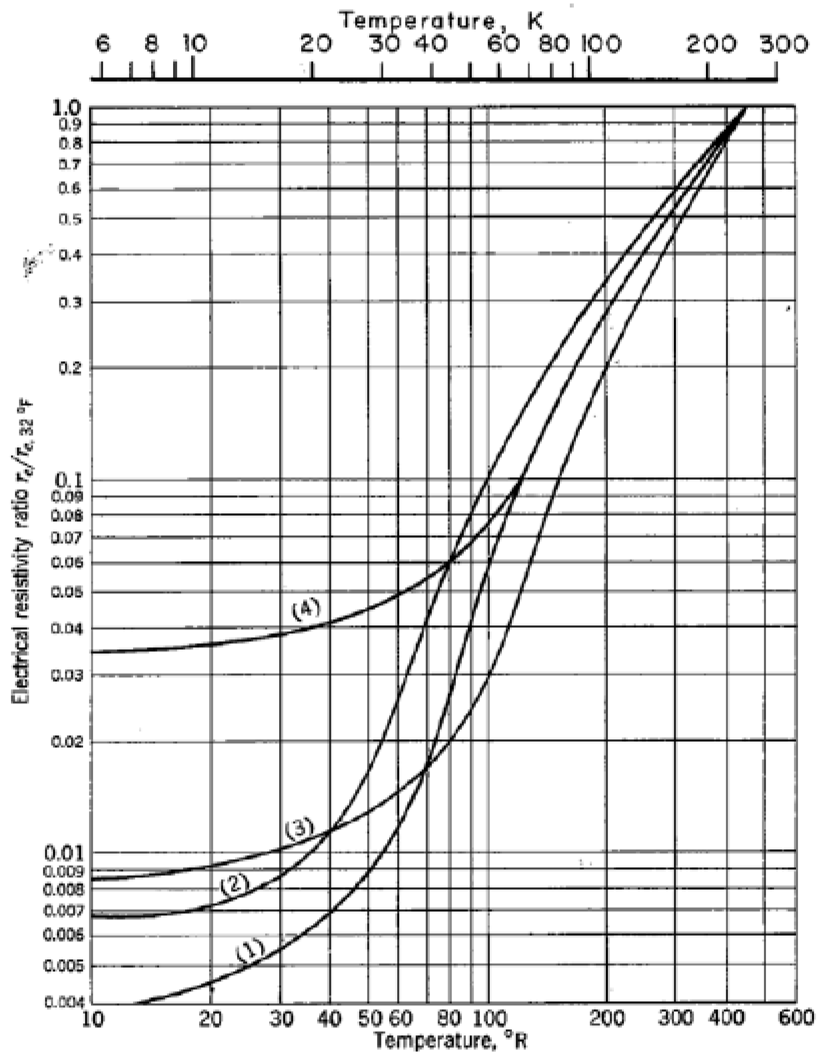
HTSC Wire C/P

- 2010 AMSC "Long Length" Quote:
  - 50 – 75 \$/kA×m (77 K, 0.1 T, 1 μV/cm)
  - Gen 1 or 2 ?   Doesn't matter !

- MgB_2 2006 "12 km" Projection:
  - 1.50 \$/kA×m (20 K, 0.2 T, 1 μV/cm)

Temperature Dependence of the Resistivity of Metals

Electrical Resistivity Ratio for Several Materials at Low Temperatures: (1) Copper; (2) Silver; (3) Iron; (4) Aluminum (Stewart and Johnson 1961).



"J_C's" of Common Metals (77 K)

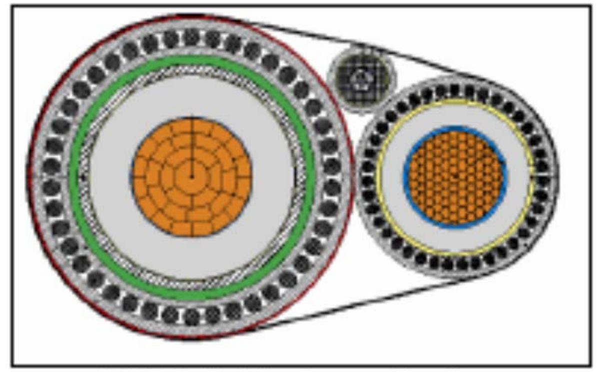
TABLE I

COST/PERFORMANCE FOR COMMON WIRE METALS AT 15 MW/CC DISSIPATION[a]

Metal	ρ Ωcm	D g/cm^3	Price ¢/g	J_E^V A/cm^2	J_E^W A/cm^2	C/P $/kA× m
Cu	2.5×10^{-7}	8.92	0.20	4.00	245	7.21
Al	2.4×10^{-7}	2.70	0.15	4.17	250	1.66
Ag	2.9×10^{-7}	10.5	15.3	3.45	227	705

[a]Power dissipation defined as equivalent to an HTSC wire transporting 15,000 A/cm^2 sustaining a voltage drop of 1μV/cm, or 15 mW/cm^3. J_E^V is the volume equivalent current density with respect to the HTSC wire, and J_E^W the power dissipation equivalent.

NEPTUNE
Regional Transmission System™



HVDC Cable Cross-Section

<u>Pirelli (GS)</u>
<u>Energy Cables</u>

$190 M

<u>Sayerville, NJ → Levittown LI, NY</u>

- **600 MW (+/- 250 kV, 1200 A)**
- **65 miles (105 km)**
- **$400 M**
- **2007**

<u>Financials</u>

40 yrs @ 4%:	$ 20M
LOM:	1 M
NOI (100%):	5 M

T 77 K	C/P $/kA×m	Cost ($M)
Cu	7	1.8
HTSC	100	25.1

EMPIRE CONNECTION

HTSC Cost = $87 M

Specifications

2-1000 MW HVDC Bipolar Circuits

- Circuit 1: 130 miles, Greene County → Bronx County
- Circuit 2: 140 miles, Albany County → New York County
- Each Circuit: +/- 500 kV, 1000 A Bipolar (2 cables ea.)

Financials

$750 M ($400 M "VC", $350 M "Futures")

- Loan Payment (4%, 40 yrs, 750 M$) = 35 M$/yr
- Labor, Overhead, Maintenance = 5 M$/yr
- Tariff = 0.5 ¢/kWh
- Profit (NOI) @ 50% Capacity = 4 M$/yr
- Profit (NOI) @ Full Capacity = 48 M$/yr

Why didn't it go forward?

See Muller articles on www.w2agz.com/scdc.htm

Bakun HEP

Table 18. Bakun Submarine Cable Project

Items		Contents
Customer		Bakun Hydro Electric Co.
Hydraulic Power		2,520MW （6,785GWh／Year)
Transmission Cable	OHL	B·H P P～TG. DATU 660km 2 Bipole（4 Cables)
	Submarne cable	TG. DATU～TG. SEDILI 670km 4～6 Cables ±500kV 1×2,100mm^2 1,420A（710MW）／Cable； Loss：4.5% Total Transmission Power：2.13GW
Construction Period		7 years
Predicted Construction Cost		5 B$

T 77 K	C/P $/kA×m	Cost ($M)
Cu	7	4.7
HTSC	100	67