The SuperCable:
Dual Delivery of Chemical and Electric Power

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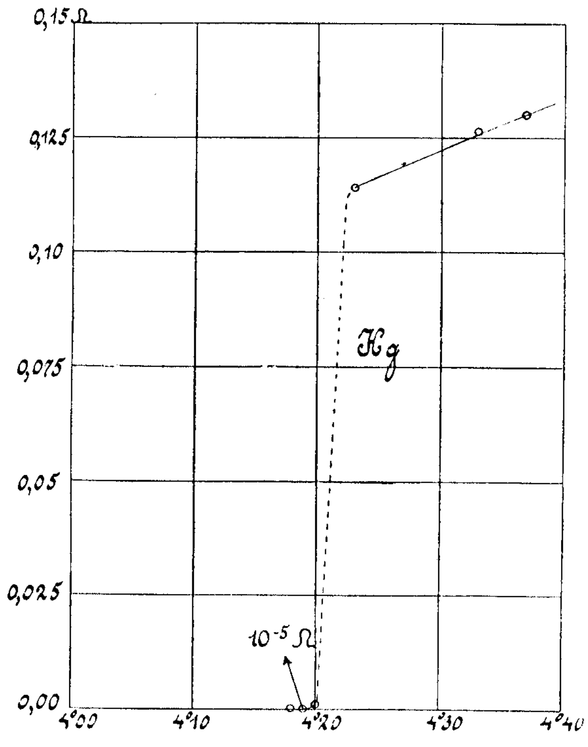
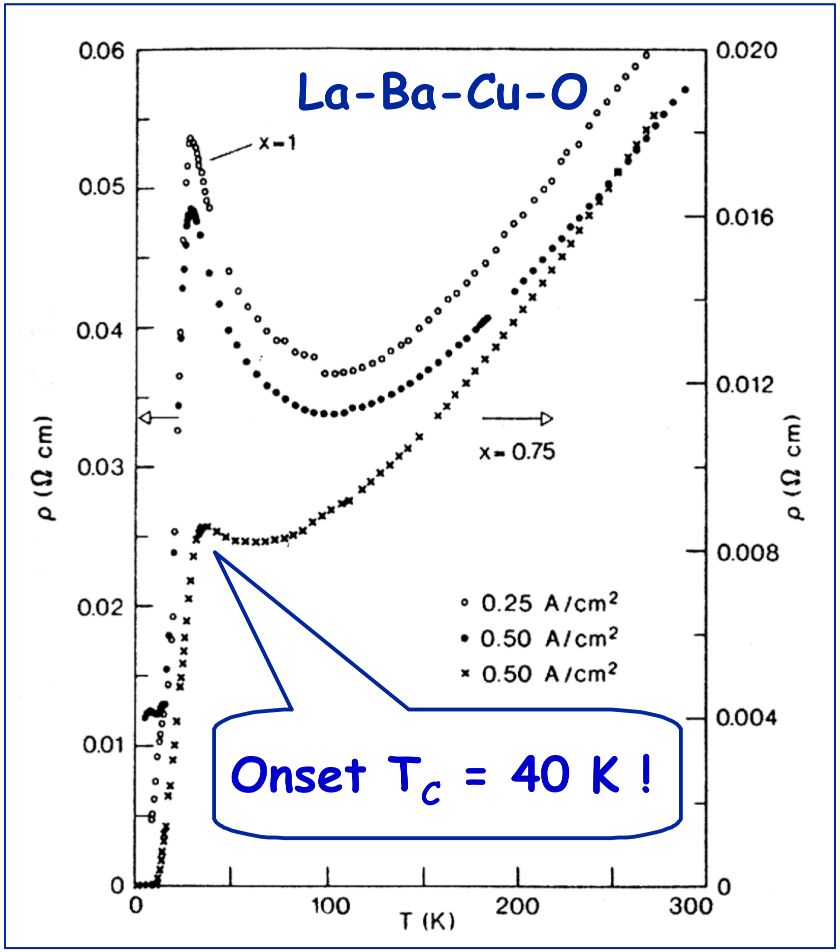
2004 SuperGrid 2
25 - 27 October 2004, Urbana, Il

Technical Plenary Session – Levis Faculty Center -- UIUC
Monday, 25 October 2004, 9:30 AM

The Discoveries



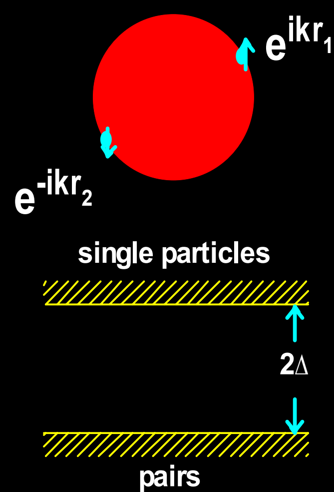
Leiden, 1914



Zürich, 1986

Superconductivity 101

Cooper Problem

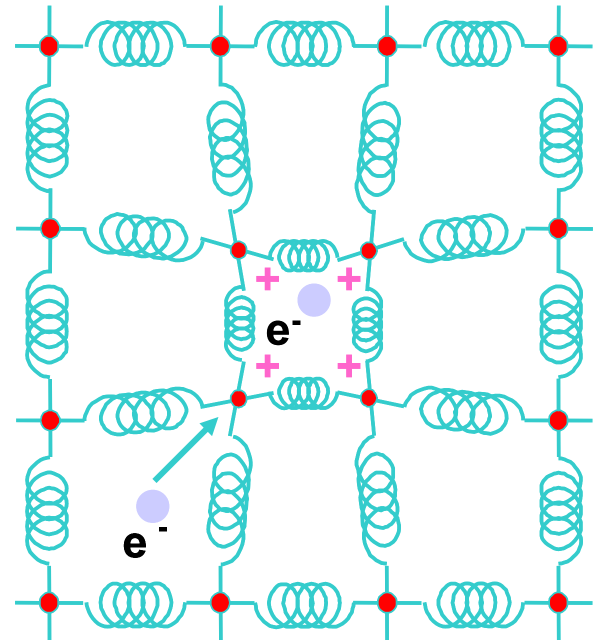


$H(k) + H(-k) + V(k)$

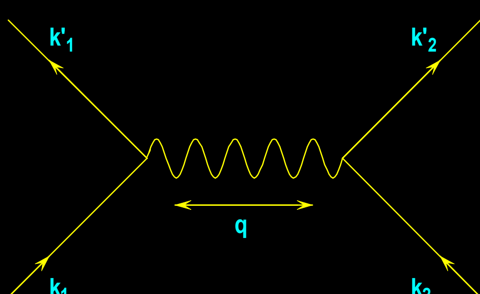
$V(k) = -V_0 \int_0^{k_f} dk\, e^{ik(r_1 - r_2)}$

$\psi(r_1 - r_2) = \phi(r_1 - r_2)\chi(s_1, s_2)$

$2\Delta \sim e^{-2/N(E_f)V_0}$



Fermion-Boson Feynman Diagram



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

$\theta_D = 275$ K ,

$\lambda = 0.28$,

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

GLAG

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

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

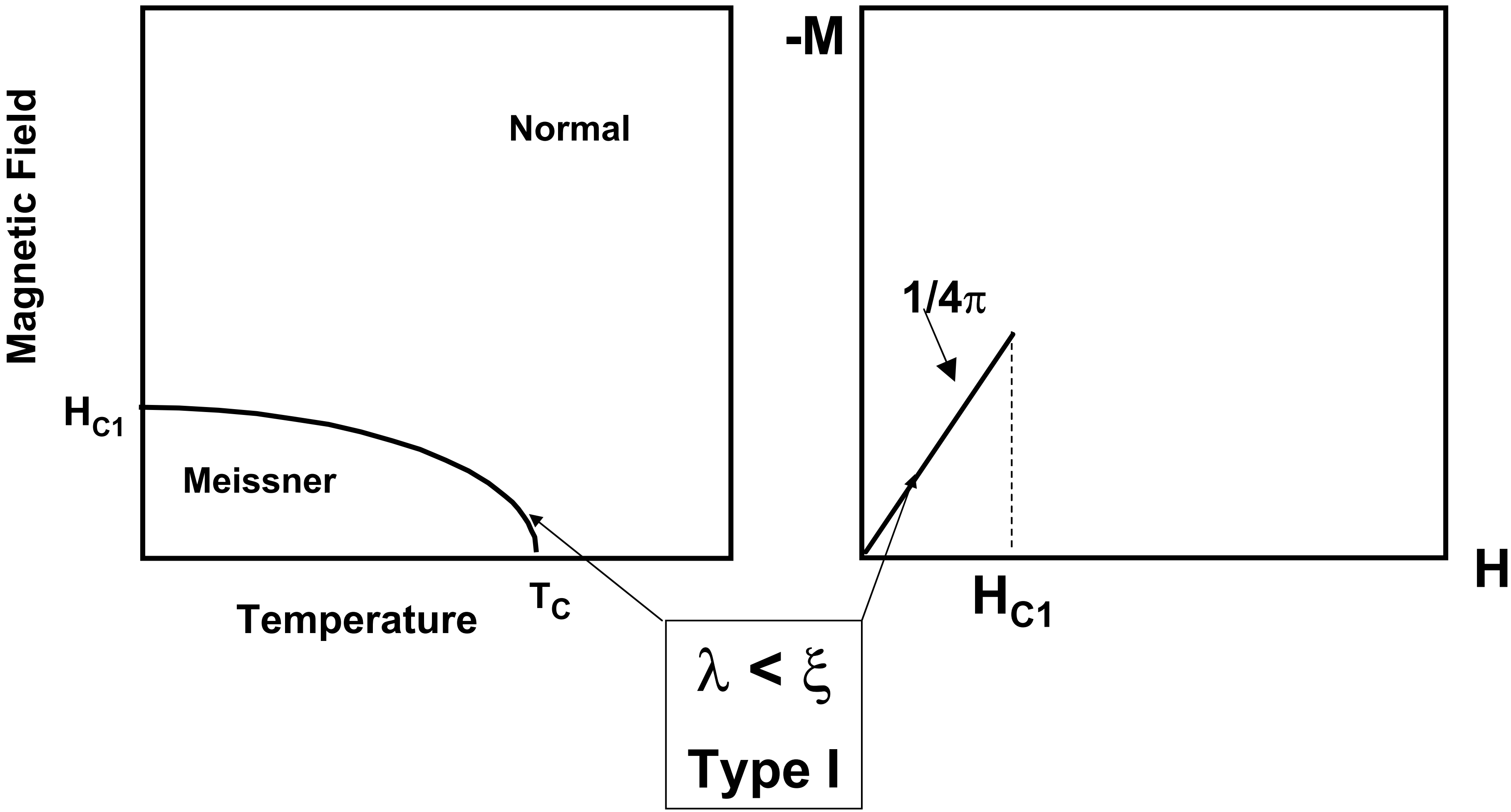
$$\kappa^2\nabla\times(\nabla\times\mathcal{A}) + \tfrac{1}{2}i(f^*\nabla f - f\nabla f^*) + \mathcal{A}f^2 = 0$$

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

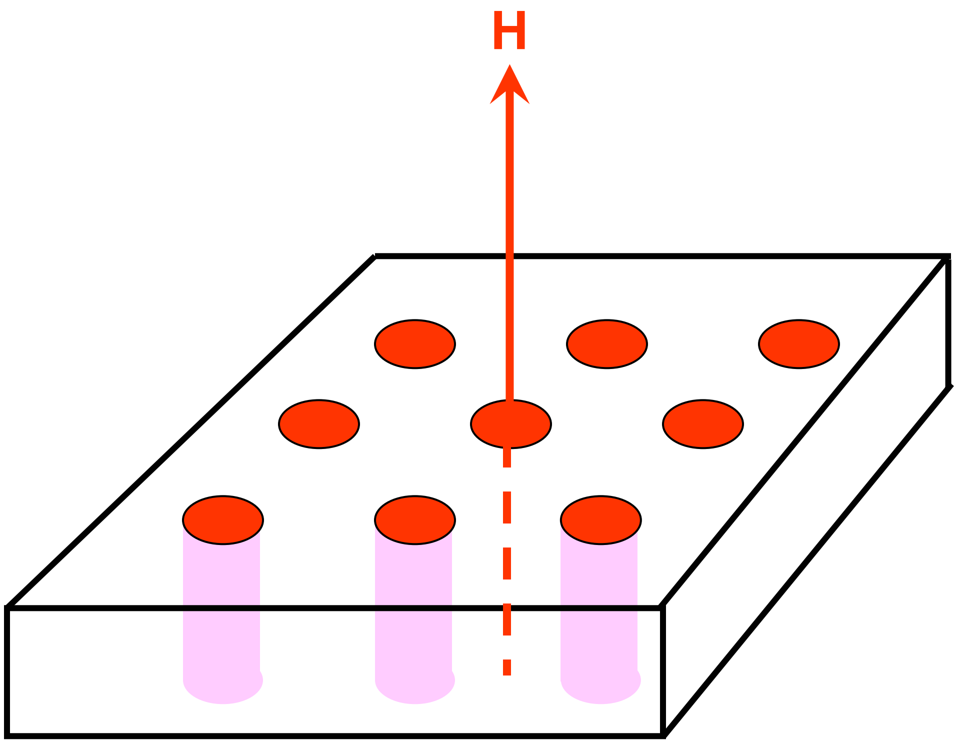
$$A = (\Phi_0 / 2\pi\xi)\mathcal{A}$$

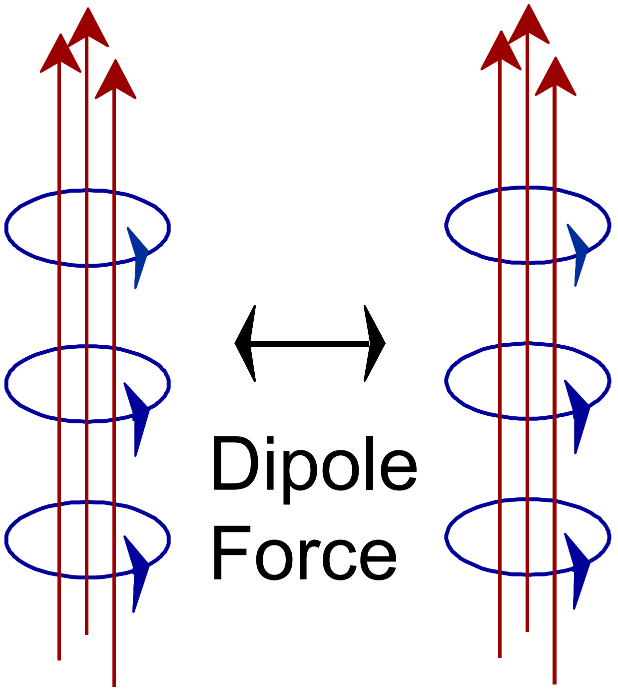
$$\kappa = \lambda_L / \xi$$

The Flavors of Superconductivity

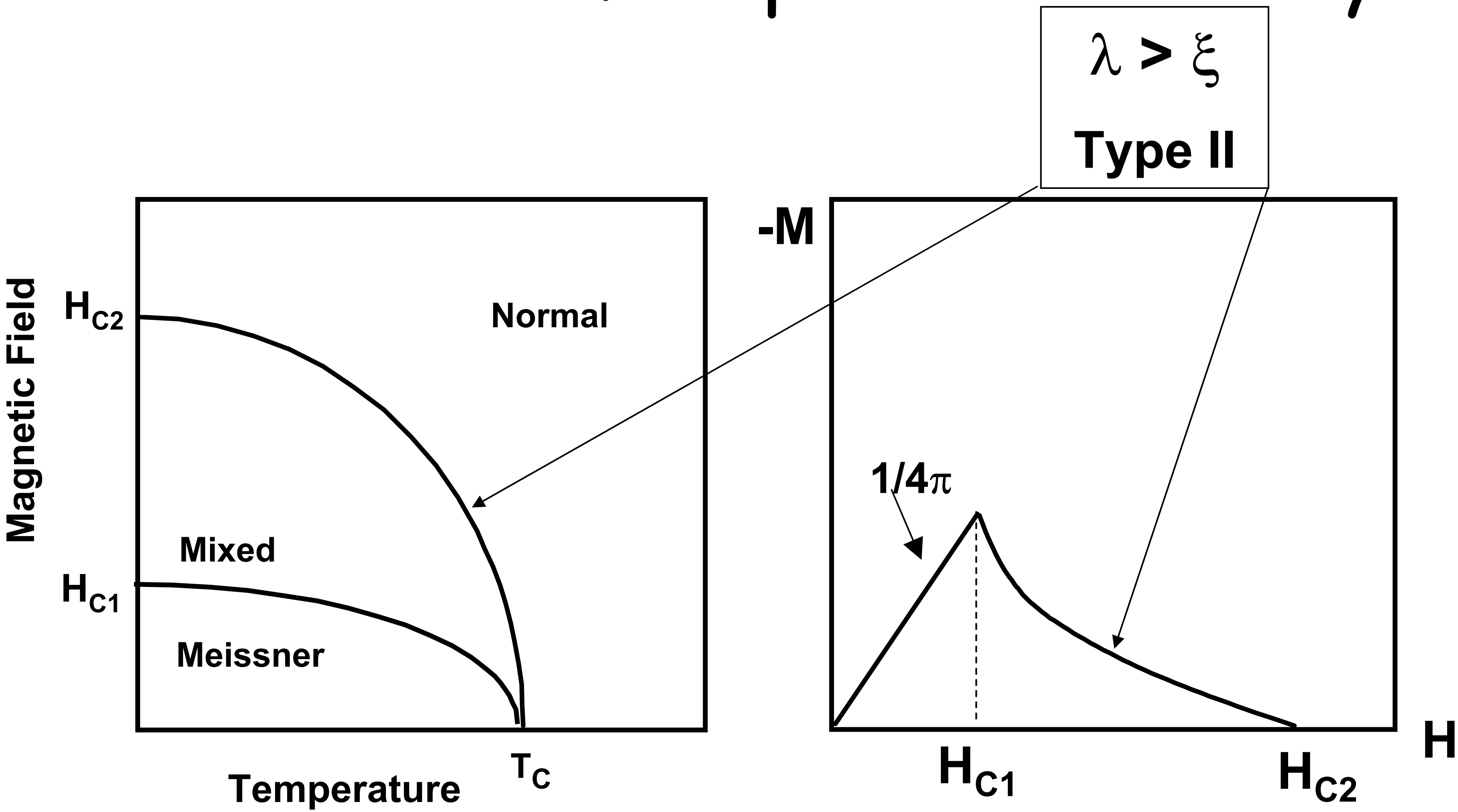


Abrikosov Vortex Lattice





The Flavors of Superconductivity



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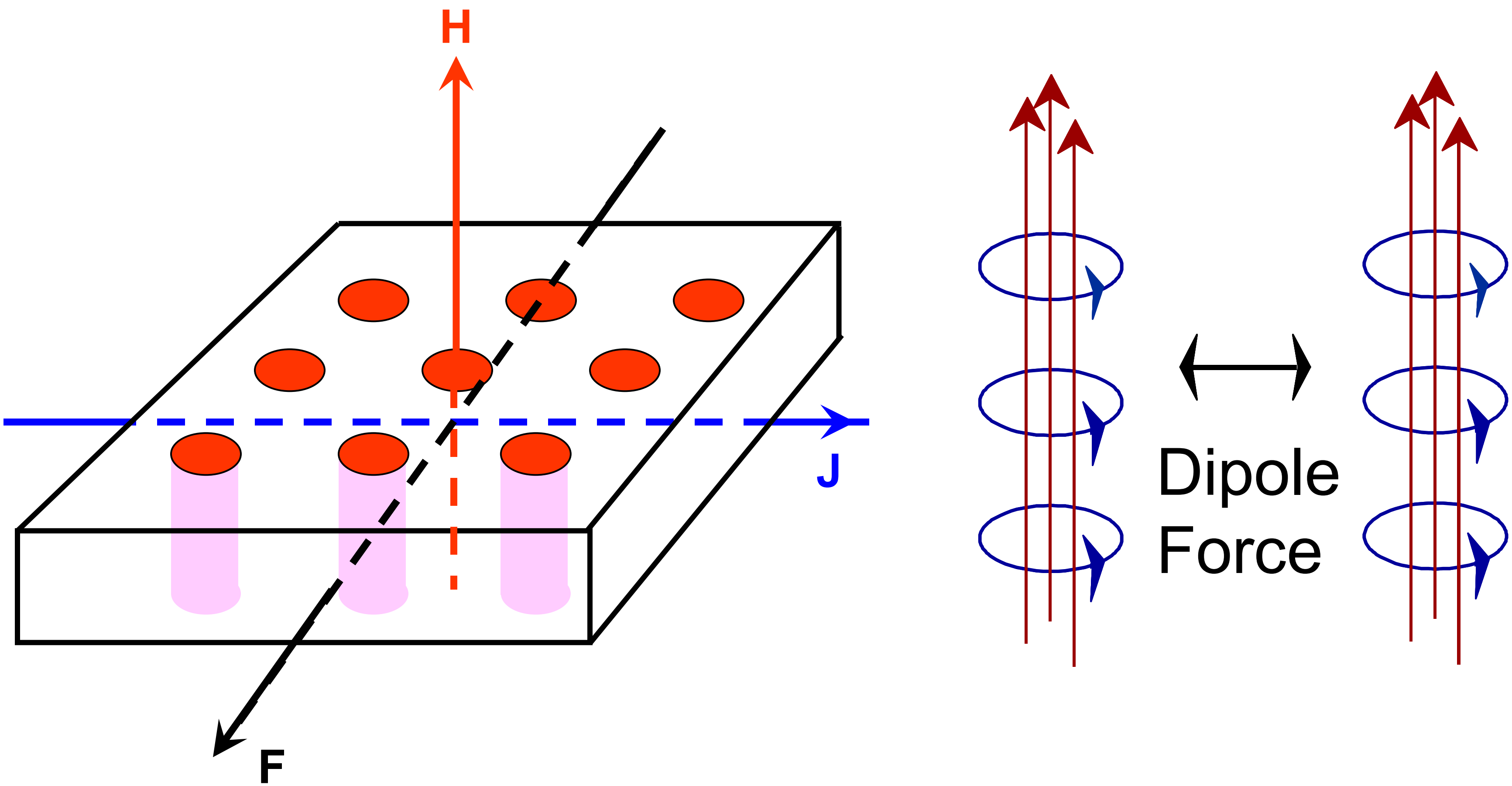
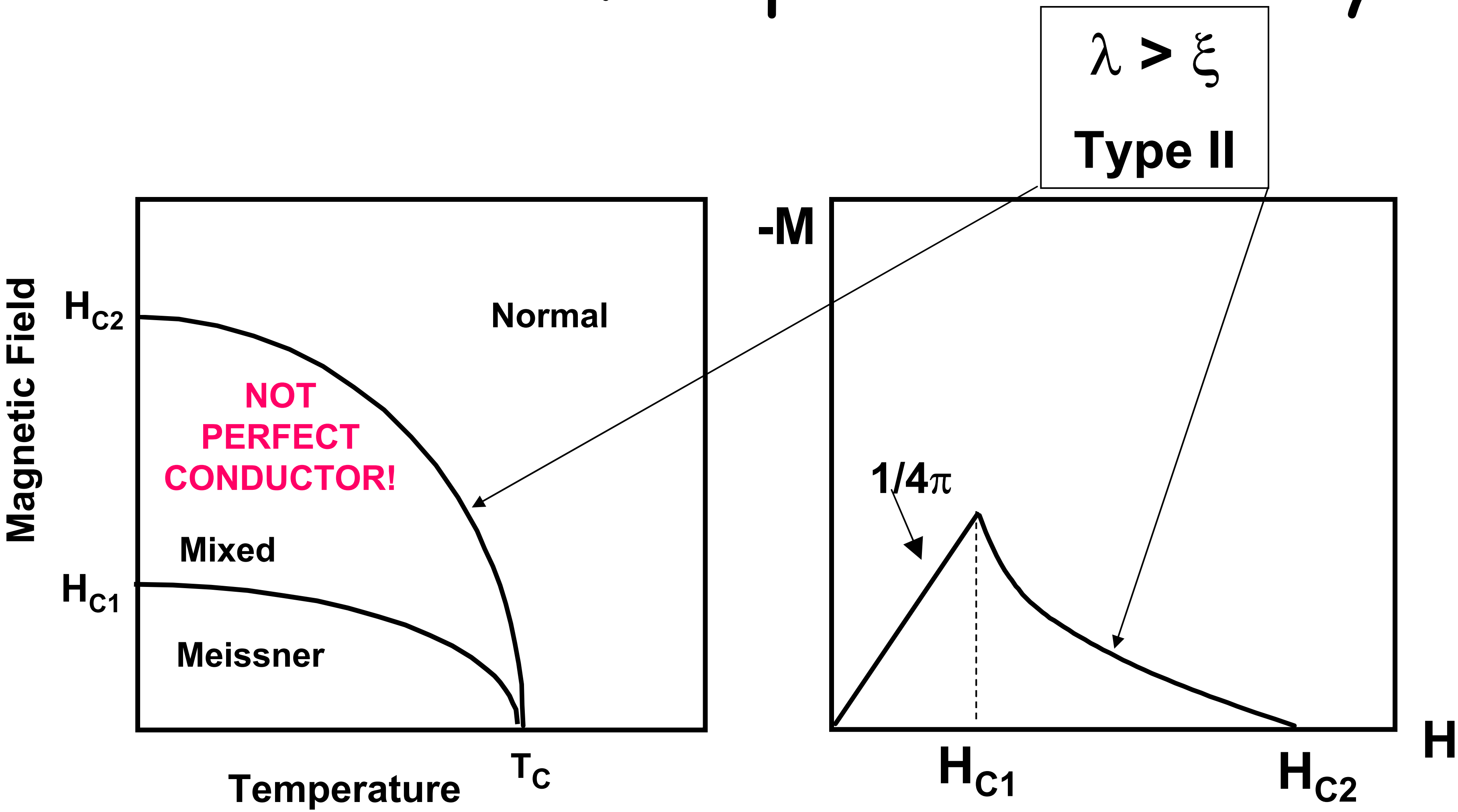
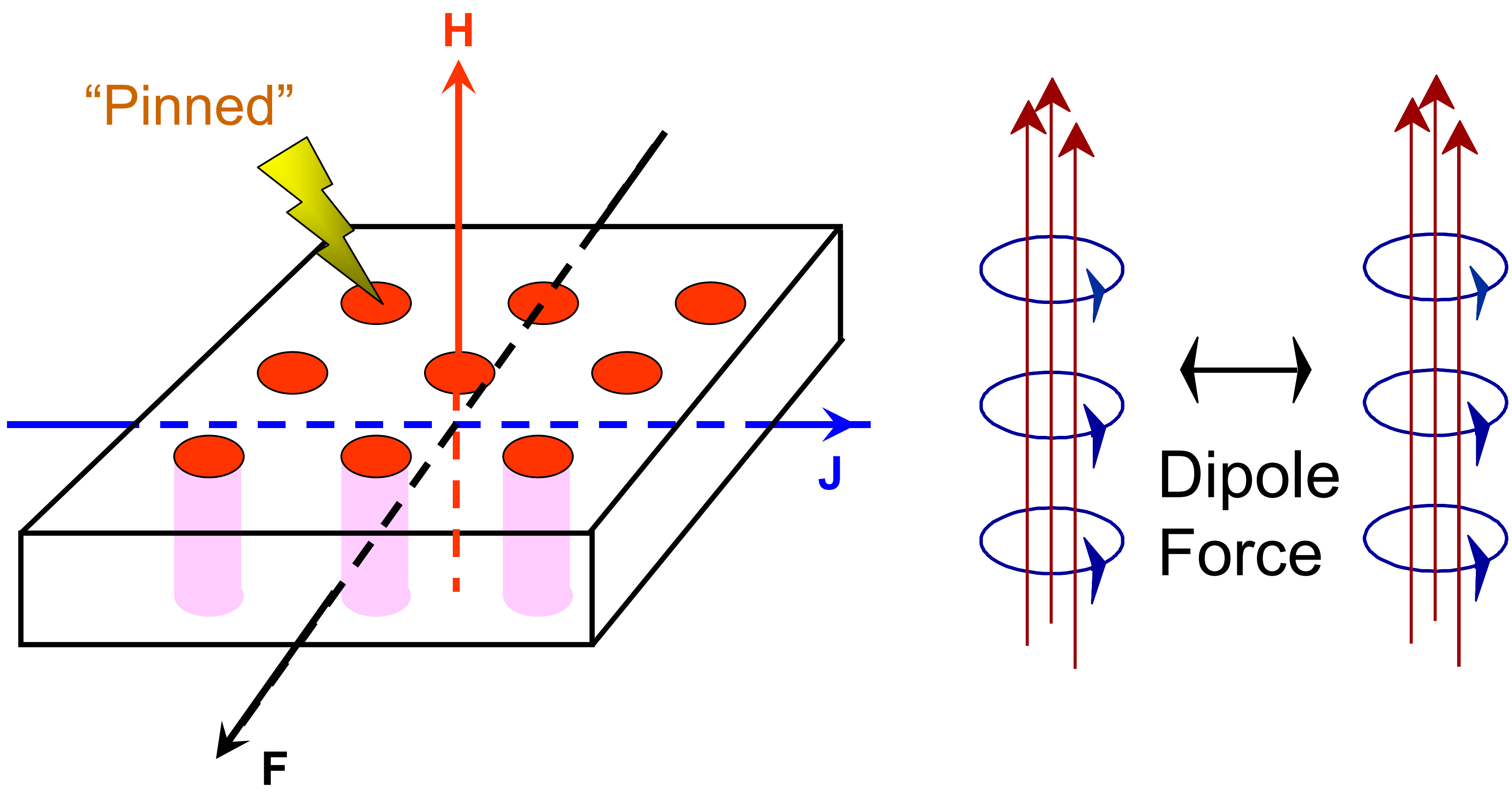


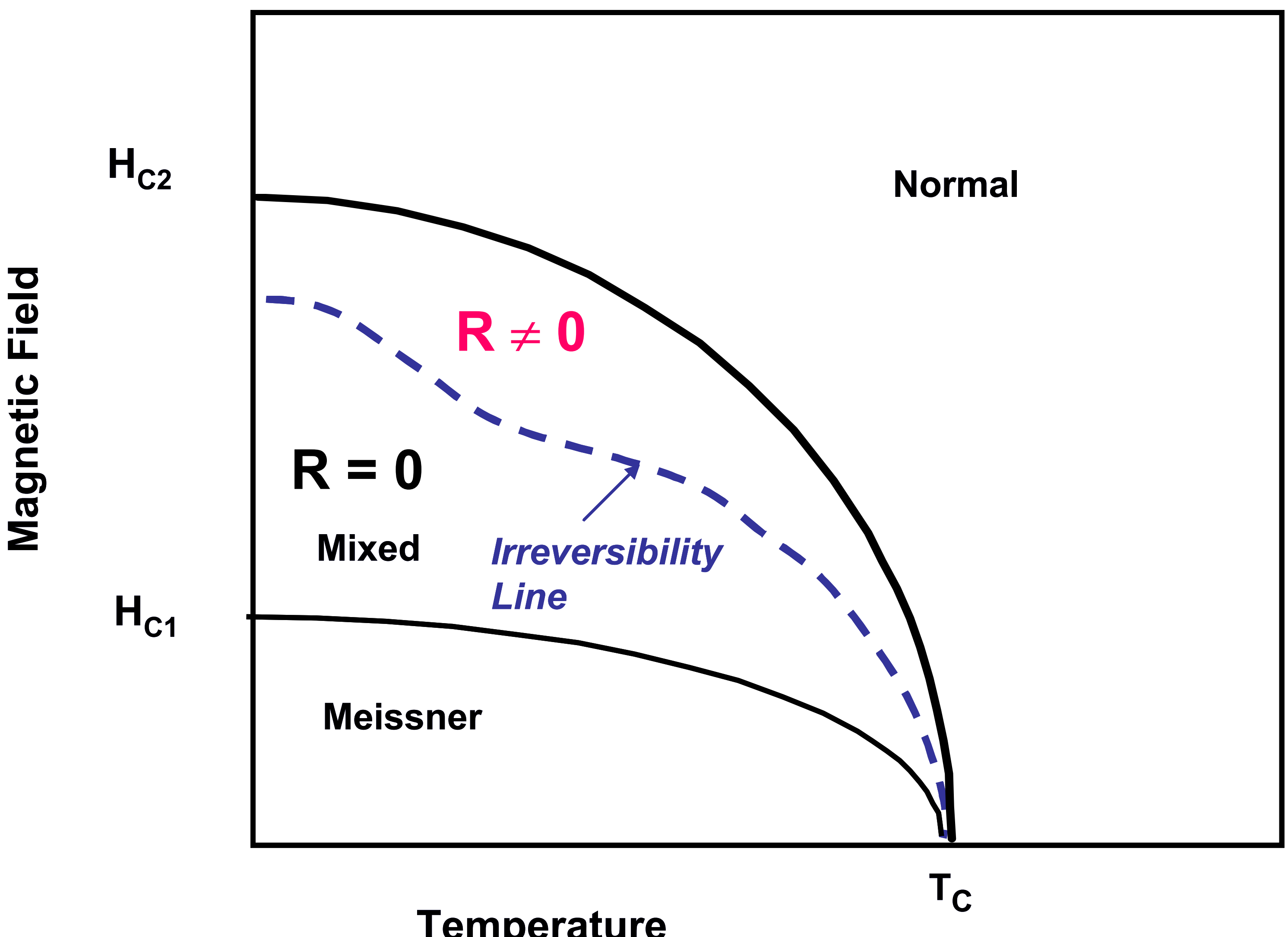
The Flavors of Superconductivity



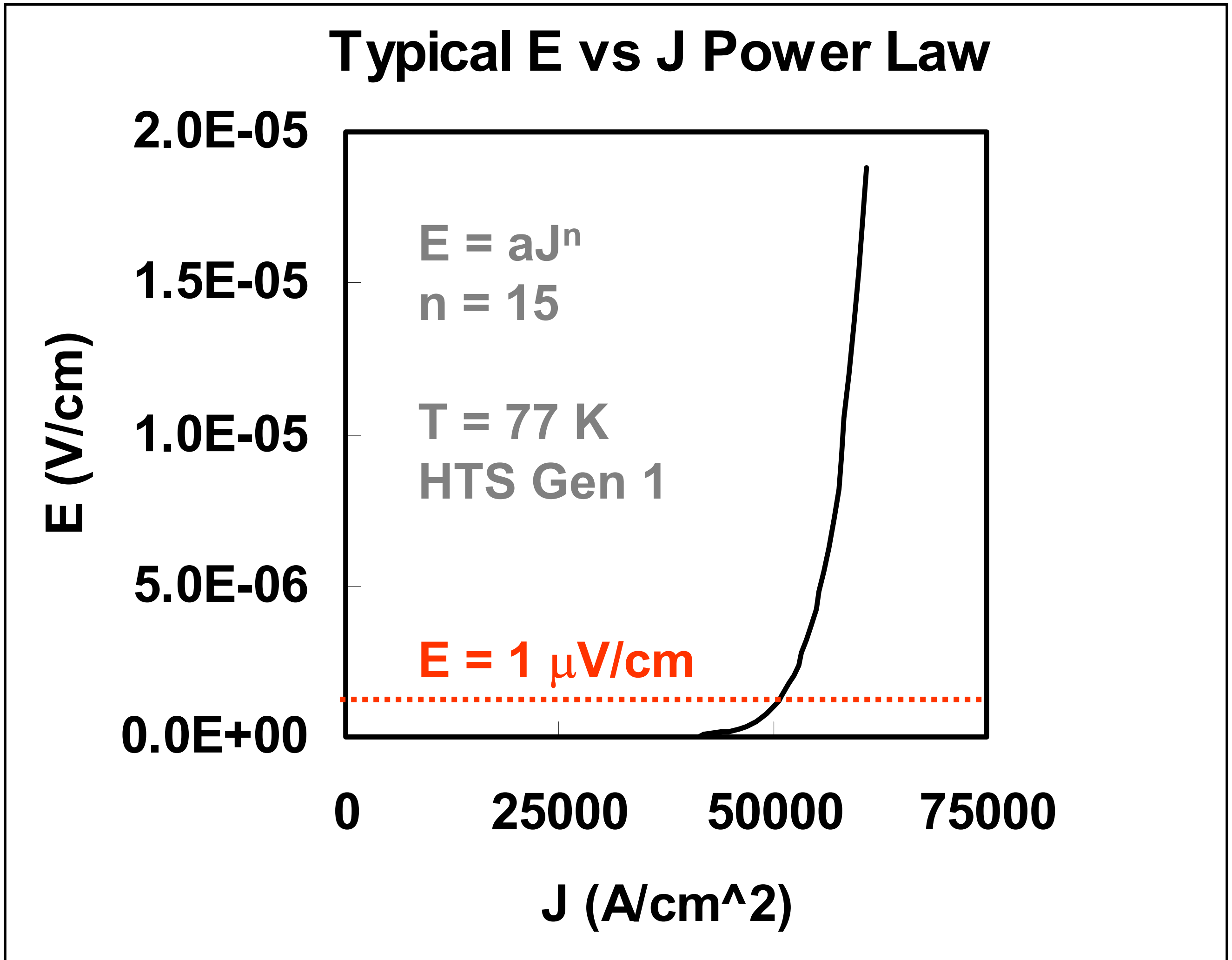
Abrikosov Vortex Lattice



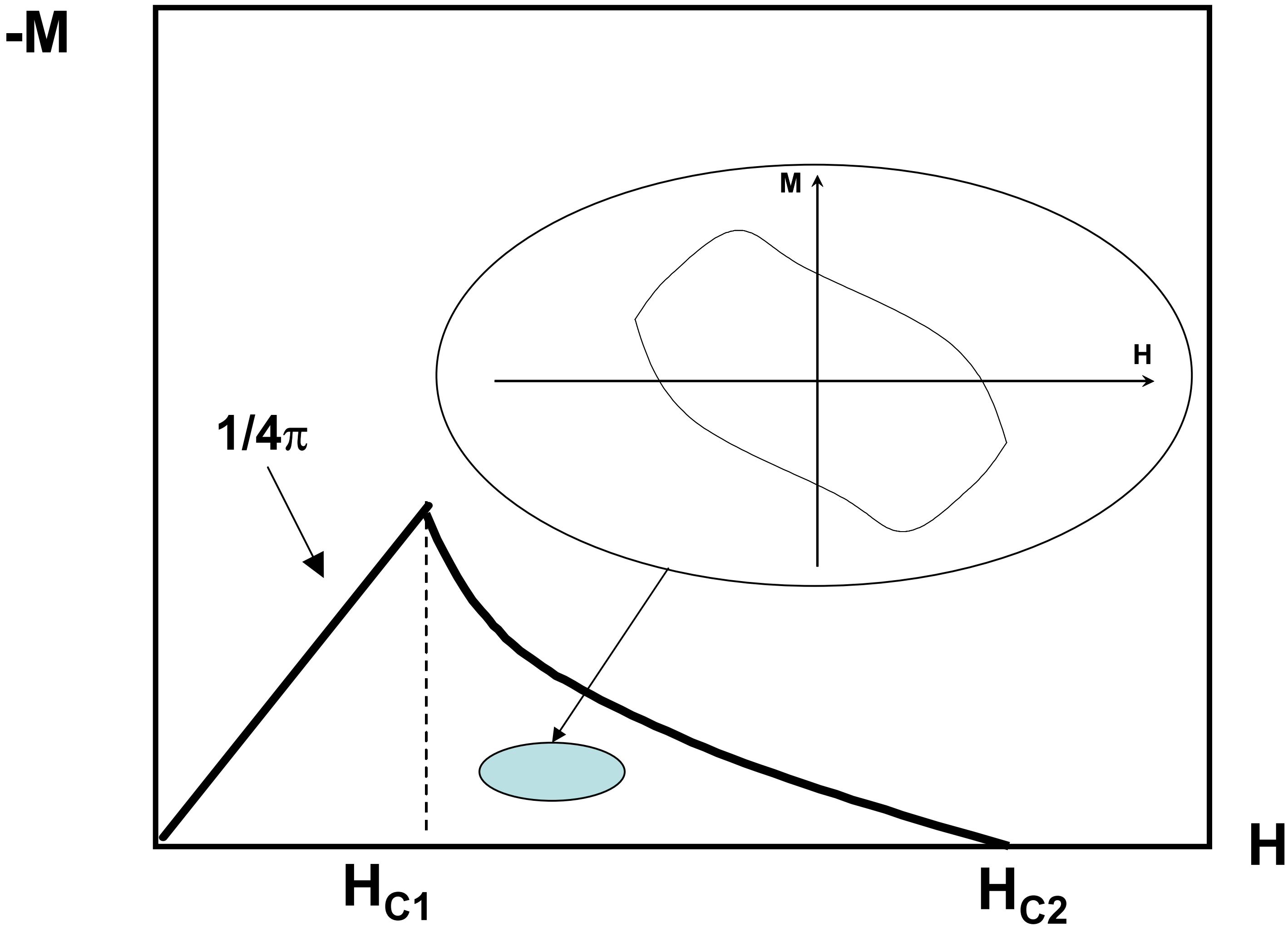
The Flavors of Superconductivity



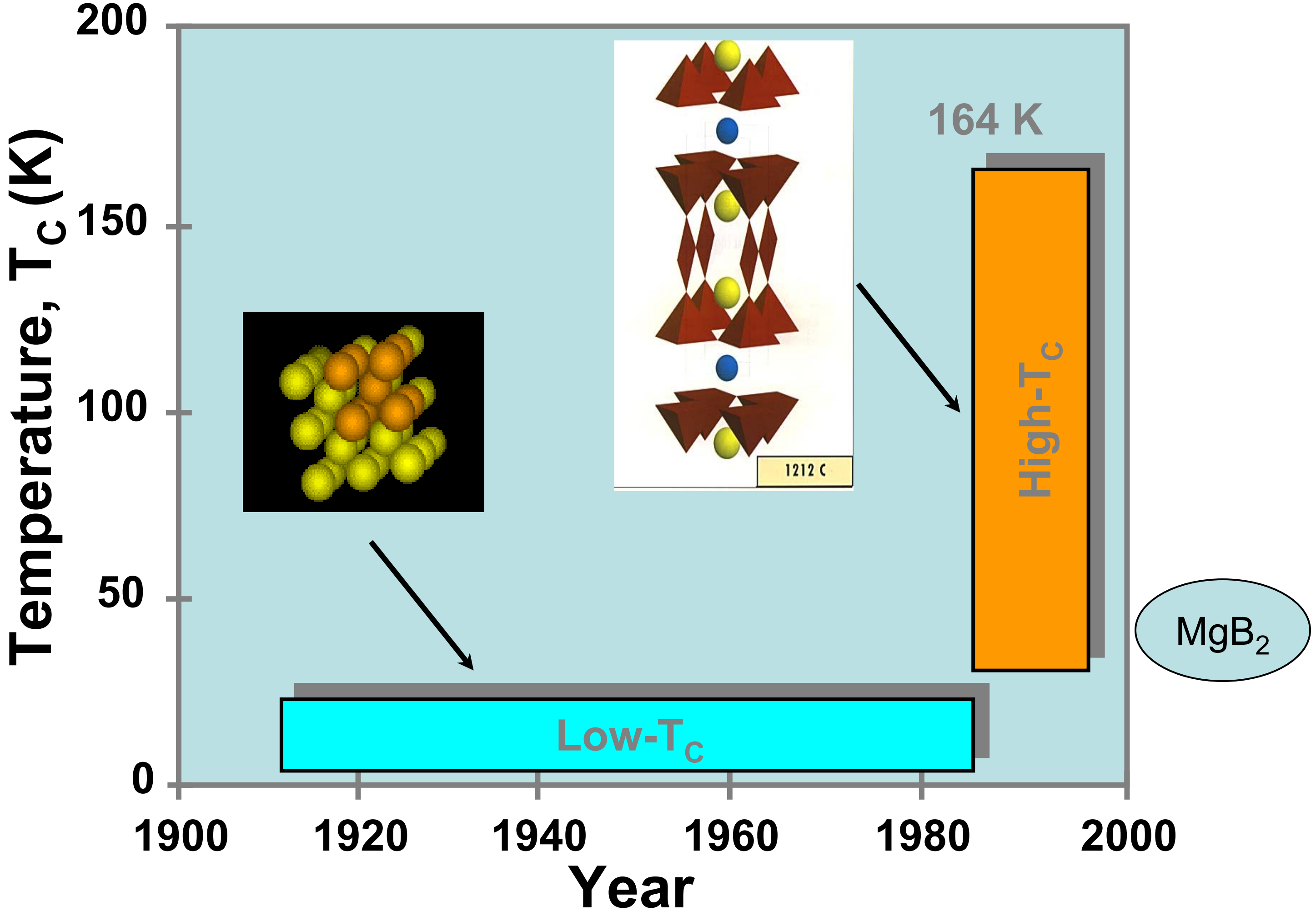
No More Ohm's Law



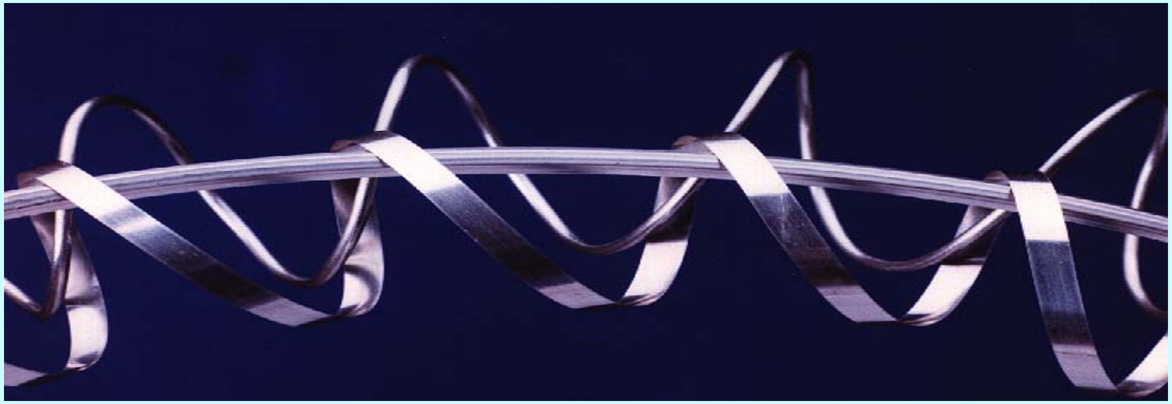
ac Hysteresis



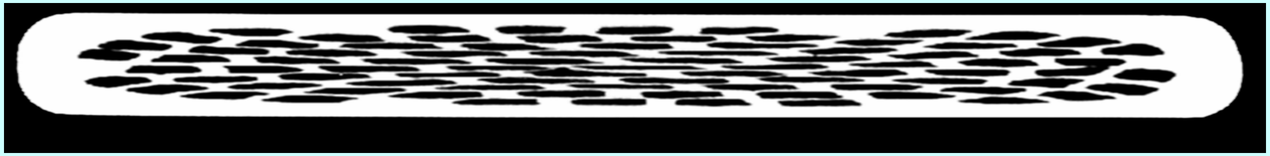
T_C vs Year: 1991 - 2001



HTSC Wire Can Be Made!



↑ ***But it's 70% silver!***



Finished Cable

Reading Assignment

1. **Garwin and Matisoo, 1967 (100 GW on Nb_3Sn)**
2. **Bartlit, Edeskuty and Hammel, 1972 (LH_2, LNG and 1 GW on LTSC)**
3. **Haney and Hammond, 1977 (Slush LH_2 and Nb_3Ge)**
4. **Schoenung, Hassenzahl and Grant, 1997 (5 GW on HTSC, 1000 km)**
5. **Grant, 2002 (SuperCity, Nukes+LH_2+HTSC)**
6. **Proceedings, SuperGrid Workshop, 2002**

These articles, and much more, can be found at www.w2agz.com, sub-pages SuperGrid/Bibliography

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

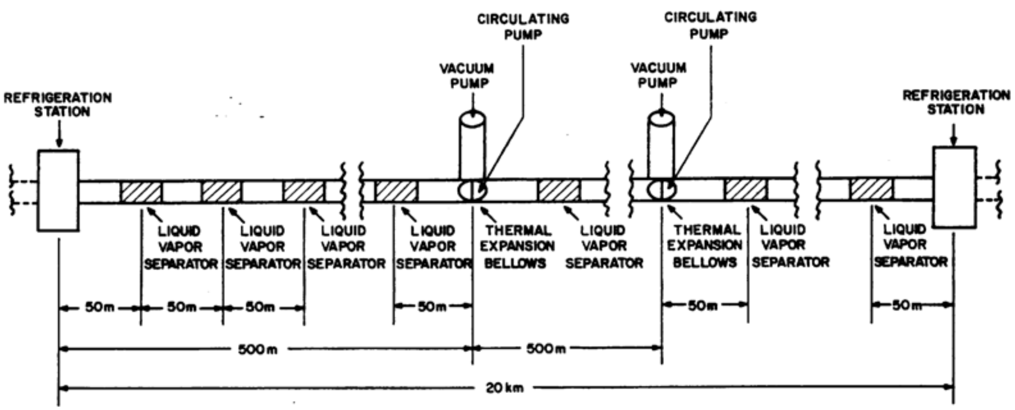


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

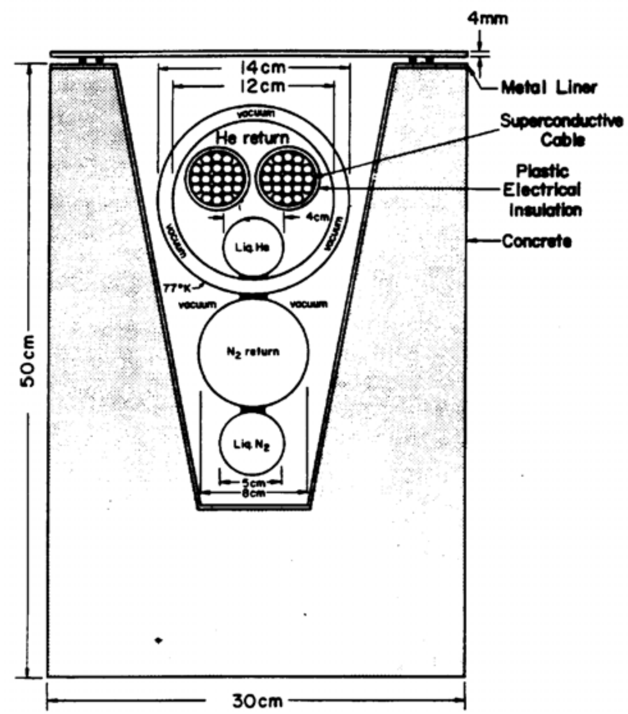
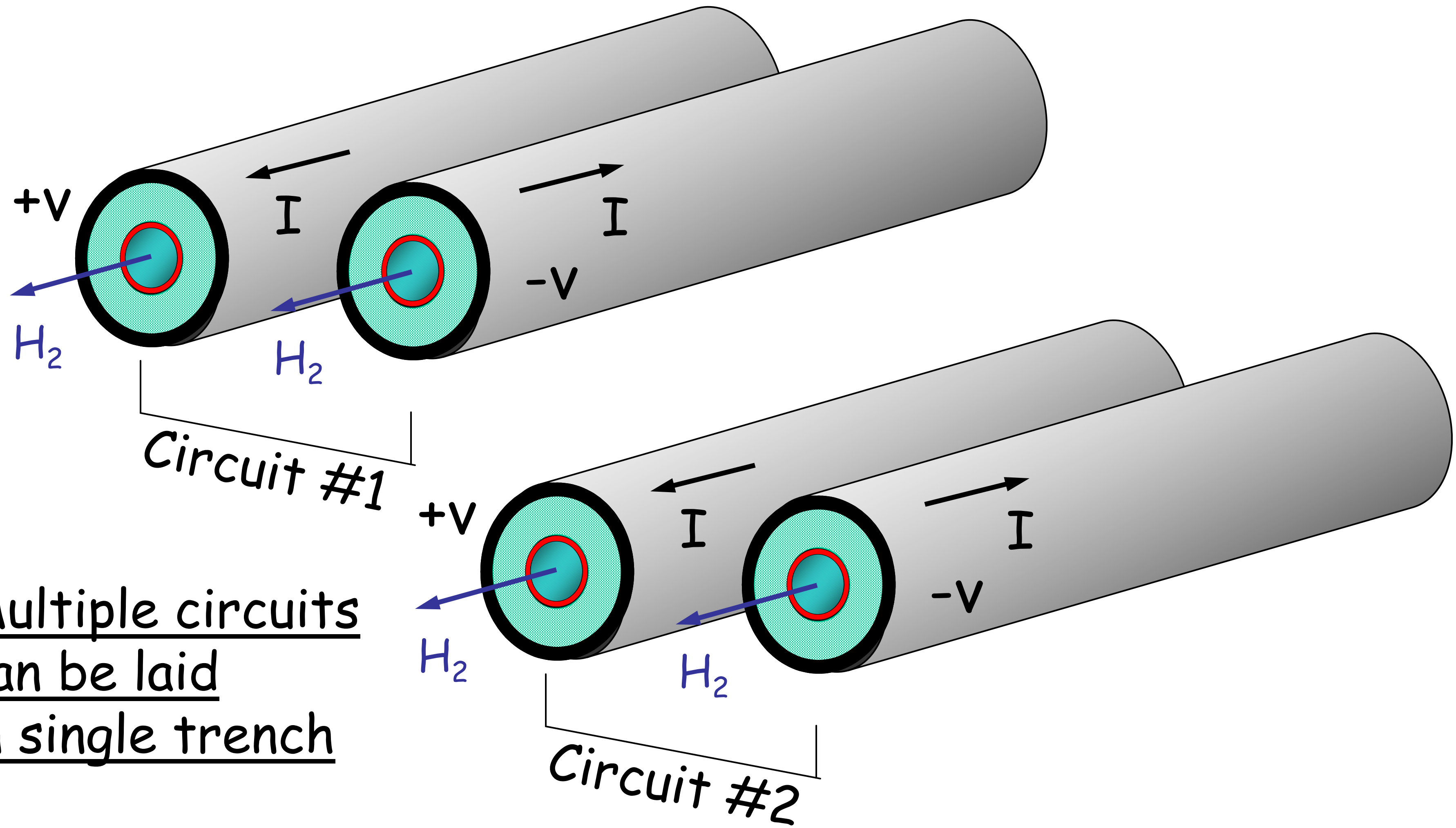


Fig. 1. Cross section of the 100-GW line.

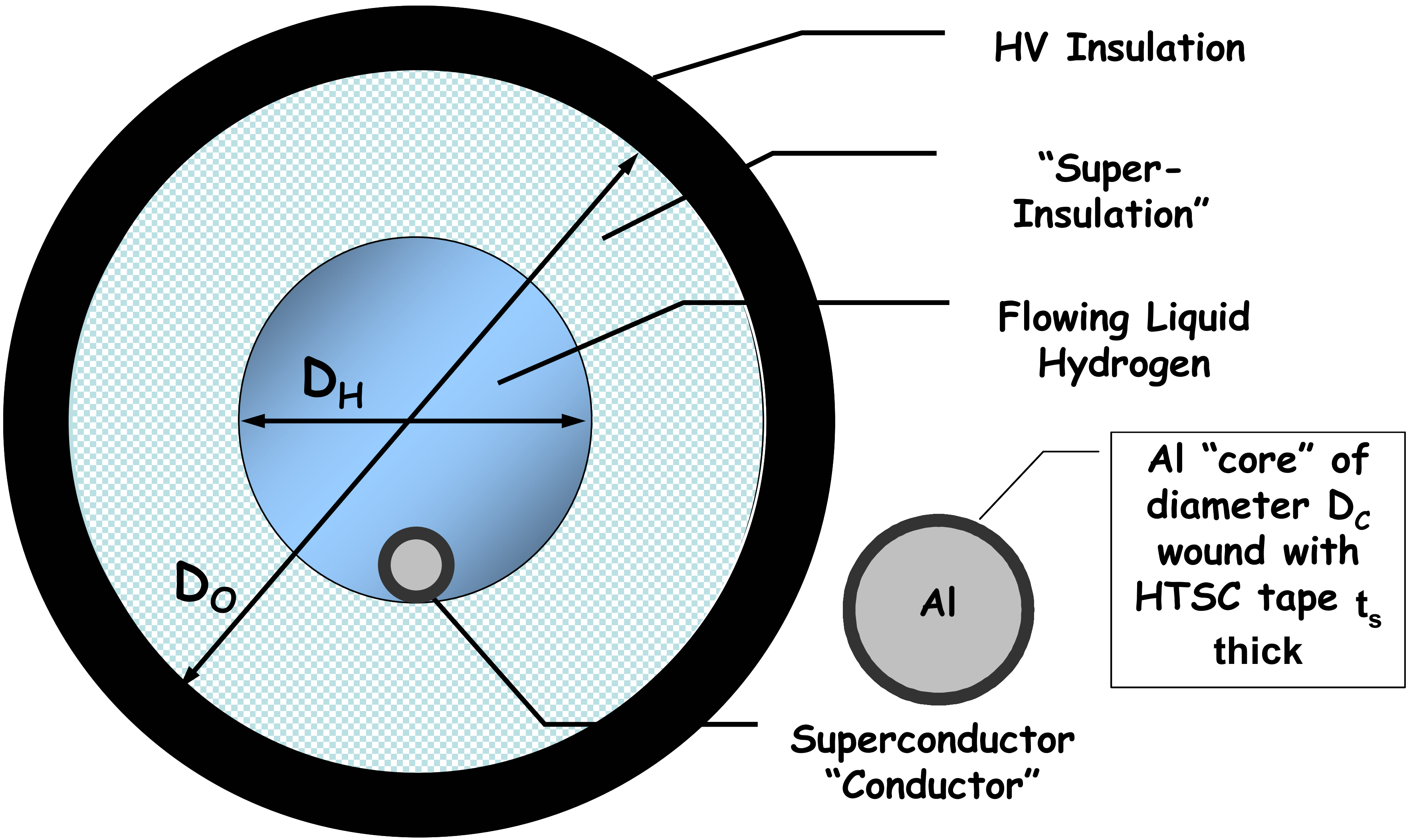
100 GW dc, 1000 km !

"Hydricity" SuperCables



<u>Multiple circuits</u>
<u>can be laid</u>
<u>in single trench</u>

SuperCable



HV Insulation
"Super-
Insulation"
Flowing Liquid
Hydrogen
D_H
D_O
Al
Al "core" of
diameter D_C
wound with
HTSC tape t_s
thick
Superconductor
"Conductor"

Power Flows

Electricity

$P_{SC} = 2|V|IA_{SC}$, where

P_{SC} = Electric power flow
V = Voltage to neutral (ground)
I = Supercurrent
A_{SC} = Cross-sectional area of superconducting annulus

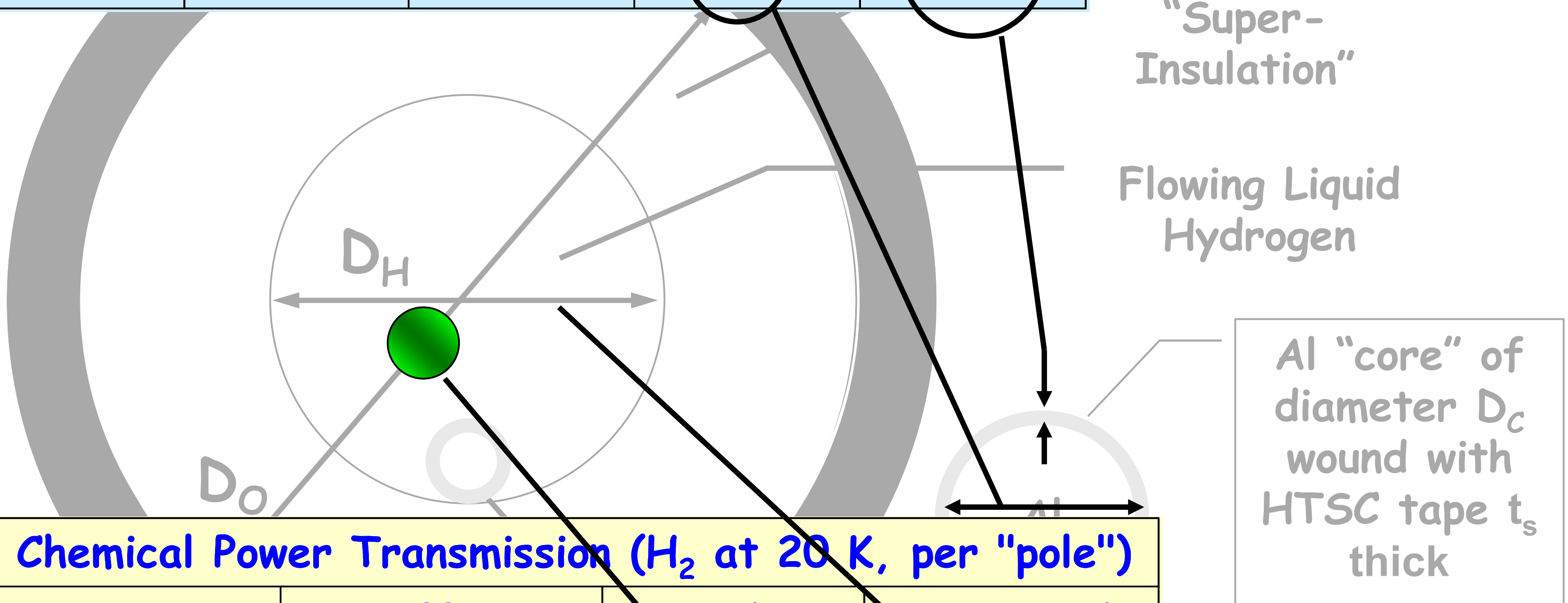
Hydrogen

$P_{H2} = 2(Q\rho vA)_{H2}$, where

P_{H2} = Chemical power flow
Q = Gibbs H_2 oxidation energy (2.46 eV per mol H_2)
ρ = H_2 Density
v = H_2 Flow Rate
A = Cross-sectional area of H_2 cryotube

Power Flows: 5 GW_e/10 GW_{th}

Electrical Power Transmission (+/- 25 kV)				
Power (MW_e)	Current (A)	HTS J_C (A/cm^2)	D_C (cm)	t_S (cm)
5,000	100,000	25,000	3.0	0.38



Chemical Power Transmission (H_2 at 20 K, per "pole")			
Power (MW_{th})	D_H-effective (cm)	H_2 Flow (m/s)	D_H-actual (cm)
5,000	40	4.76	45.3

Radiation Losses

$W_R = 0.5\varepsilon\sigma\,(T^4_{amb} - T^4_{SC})$, where

W_R = Power radiated in as watts/unit area
$\sigma = 5.67\times10^{-12}\ W/cm^2K^4$
T_{amb} = 300 K
T_{SC} = 20 K
ε = 0.05 per inner and outer tube surface
D_H = 45.3 cm

W_R = 16.3 W/m

Superinsulation: $W_R^f = W_R/(n-1)$, where

n = number of layers = 10

Net Heat In-Leak Due to Radiation = 1.8 W/m

Fluid Friction Losses

$p_{loss} = \lambda\ (l / d_h)\ (\rho\ v^2 / 2)$

where

p_{loss} = pressure loss (Pa, N/m^2)

λ = friction coefficient

l = length of duct or pipe (m)

d_h = hydraulic diameter (m)

$$W_{loss} = M\ P_{loss} / \rho,$$

Where M **= mass flow per unit length**
P_{loss} **= pressure loss per unit length**
ρ **= fluid density**

$$1 / \lambda^{1/2} = -2{,}0 \log_{10} [\ (2{,}51 / (Re\ \lambda^{1/2})) + (\varepsilon / d_h) / 3{,}72\ ]$$

Fluid	Re	ε(mm)	D_H (cm)	v (m/s)	ΔP (atm/10 km)	Power Loss (W/m)
H (20K)	2.08×10^6	0.015	45.3	4.76	2.0	3.2

Heat Removal

$dT/dx = W_T/(\rho v C_P A)_{H2}$, where

dT/dx = Temp rise along cable, K/m
W_T = Thermal in-leak per unit Length
ρ = H_2 Density
v = H_2 Flow Rate
C_P = H_2 Heat Capacity
A = Cross-sectional area of H_2 cryotube

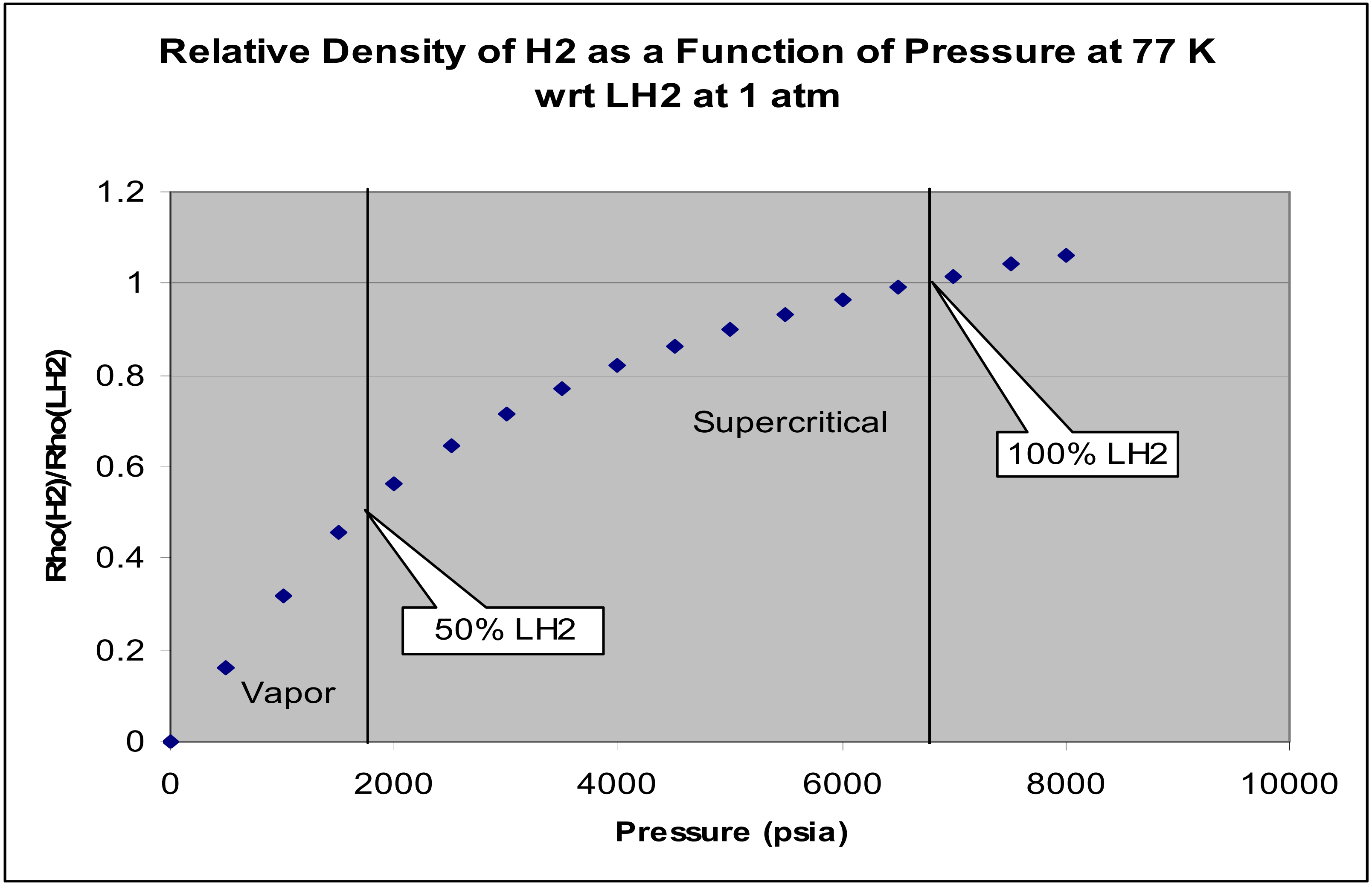
SuperCable Losses (W/M)					K/10km
Radiative	**Friction**	**ac Losses**	**Conductive**	**Total**	**dT/dx**
1.8	**3.2**	**1**	**1**	**7**	**10^{-2}**

SuperCable H_2 Storage

Some Storage Factoids	**Power (GW)**	**Storage (hrs)**	**Energy (GWh)**
TVA Raccoon Mountain	1.6	20	32
Alabama CAES	1	20	20
Scaled ETM SMES	1	8	8

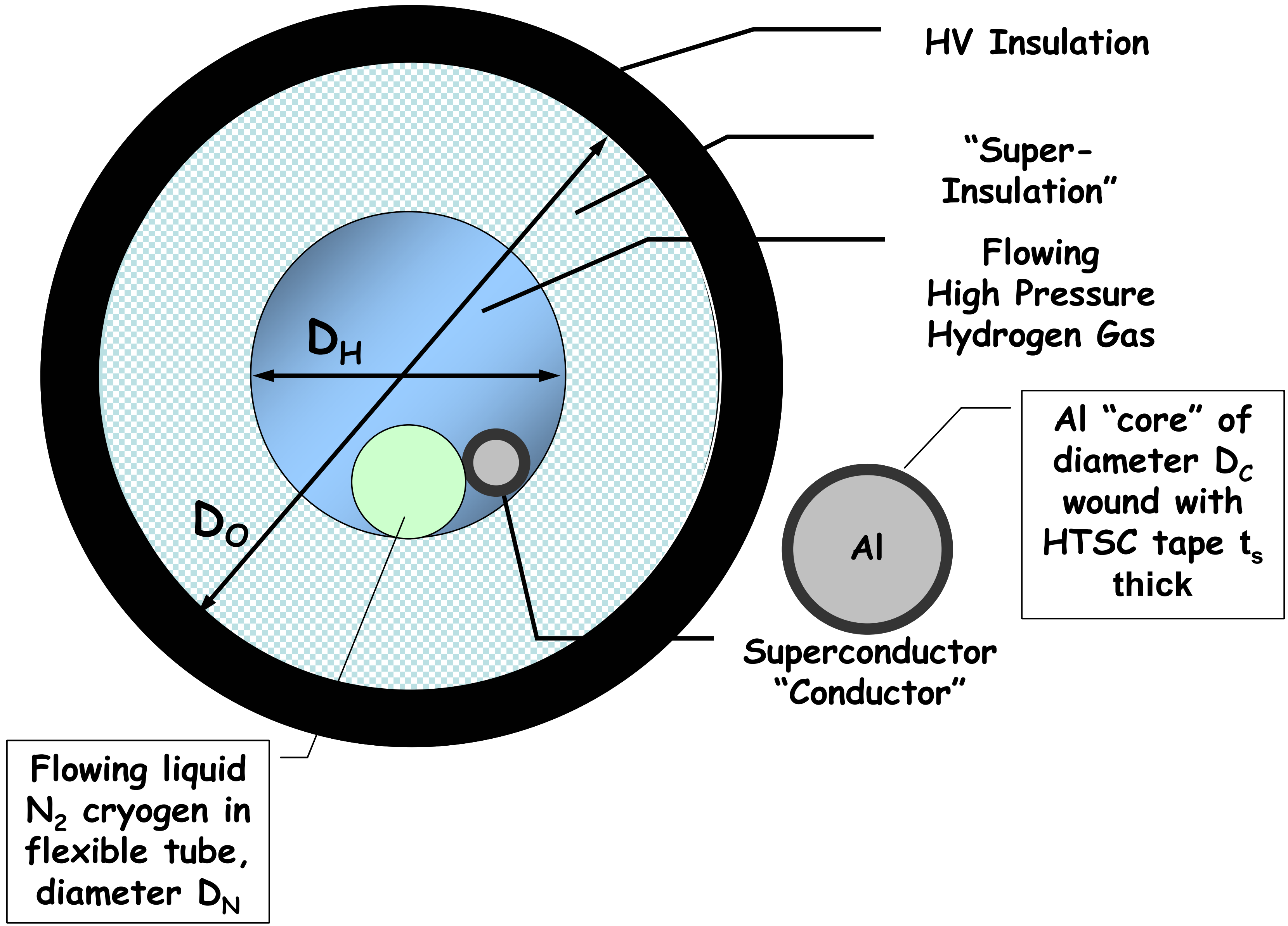
One Raccoon Mountain = 13,800 cubic meters of LH2

LH_2 in 45 cm diameter, 12 mile bipolar SuperCable
= Raccoon Mountain



H_2 Gas at 77 K and 1850 psia has 50% of the energy content of liquid H_2 and 100% at 6800 psia

“Hybrid” SuperCable



Electrical Issues

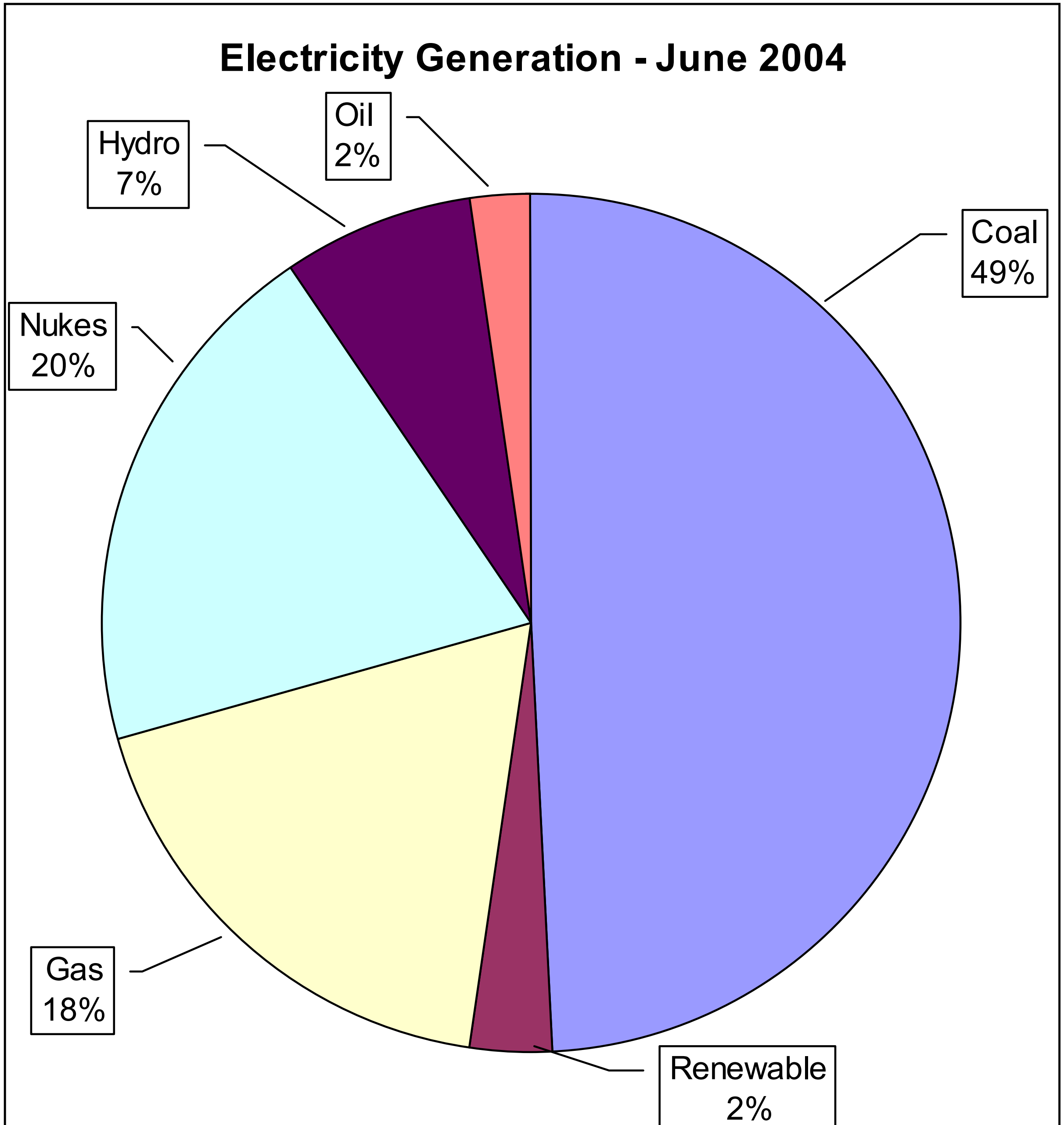
- Voltage – current tradeoffs
  - "Cold" vs "Warm" Dielectric
- AC interface (phases)
  - Generate dc? Multipole, low rpm units (aka hydro)
- Ripple suppression
  - Filters
- Cryogenics
  - Pulse Tubes
  - "Cryobreaks"
- Mag Field Forces
- Splices (R = 0?)
- Charge/Discharge cycles (Faults!)
- Power Electronics
  - GTOs vs IGBTs
  - 12" wafer platforms
  - Cryo-Bipolars

Construction Issues

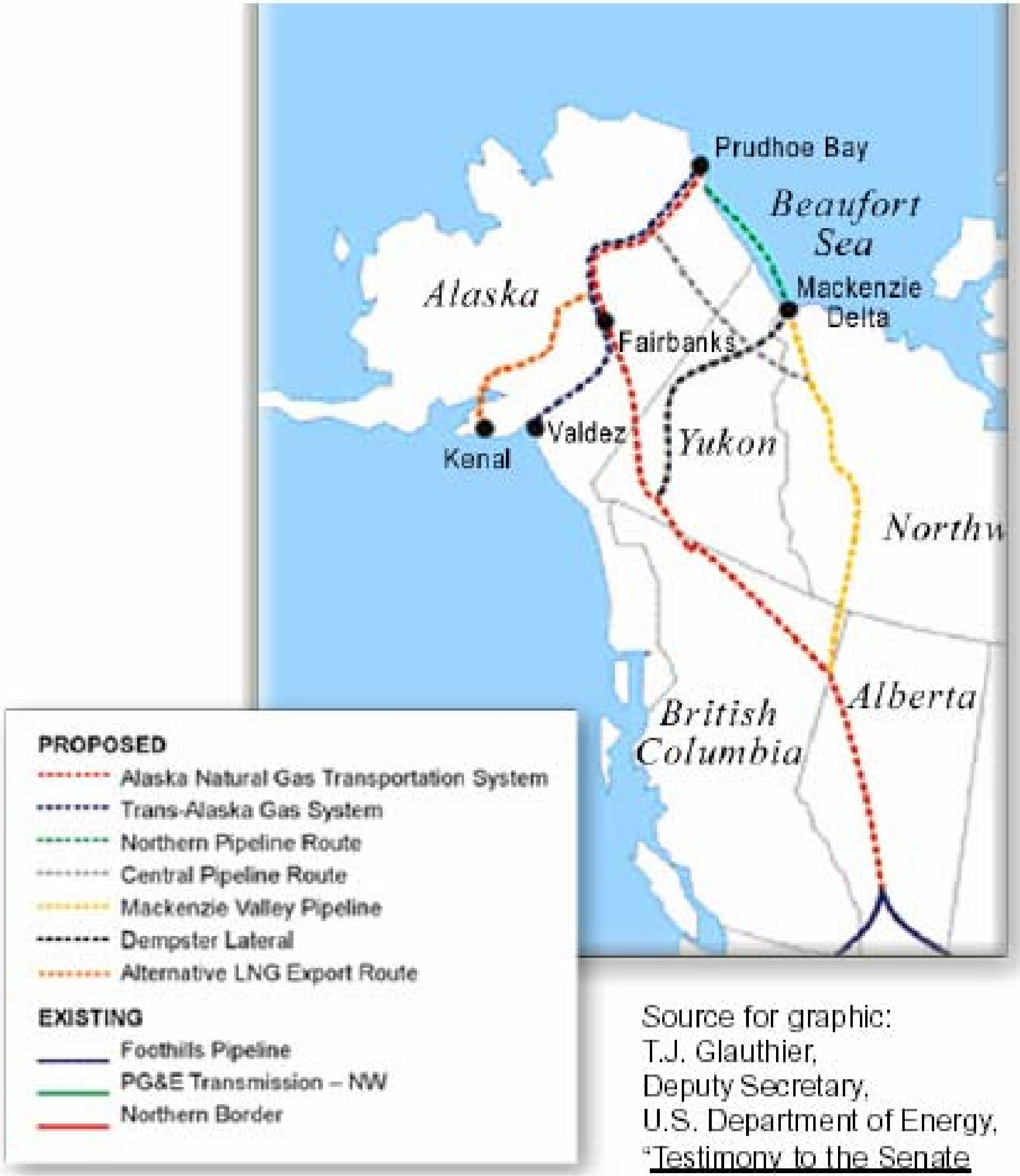
- Pipe Lengths & Diameters (Transportation)
- Coax vs RTD
- Rigid vs Flexible?
- On-Site Manufacturing
  - Conductor winding (3-4 pipe lengths)
  - Vacuum: permanently sealed or actively pumped?
- Joints
  - Superconducting
  - Welds
  - Thermal Expansion (bellows)

Jumpstarting the SuperGrid

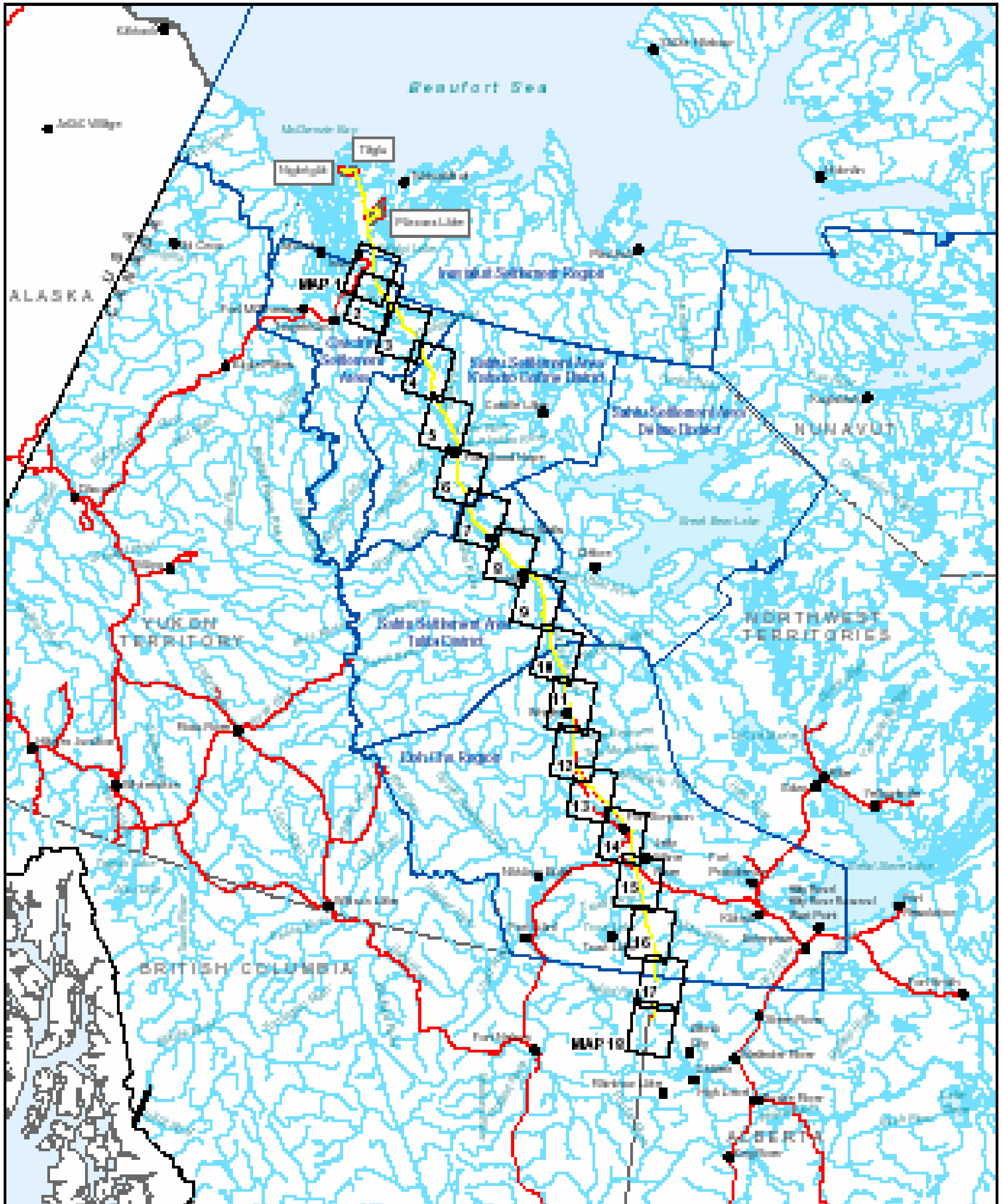
- Do it with SuperCables
- Focus on the next two decades
- Get started with superconducting dc cable interties & back-to-backs using existing ROWs
- As "hydrogen economy" expands, parallel/replace existing gas transmission lines with SuperCables
- Start digging


Electricity Generation - June 2004
Oil
2%
Hydro
7%
Coal
49%
Nukes
20%
Gas
18%
Renewable
2%

Al-Can Gas Pipeline Proposals



Source for graphic:
T.J. Glauthier,
Deputy Secretary,
U.S. Department of Energy,
"Testimony to the Senate Committee on Energy and Natural Resources"
(September 14, 2000).

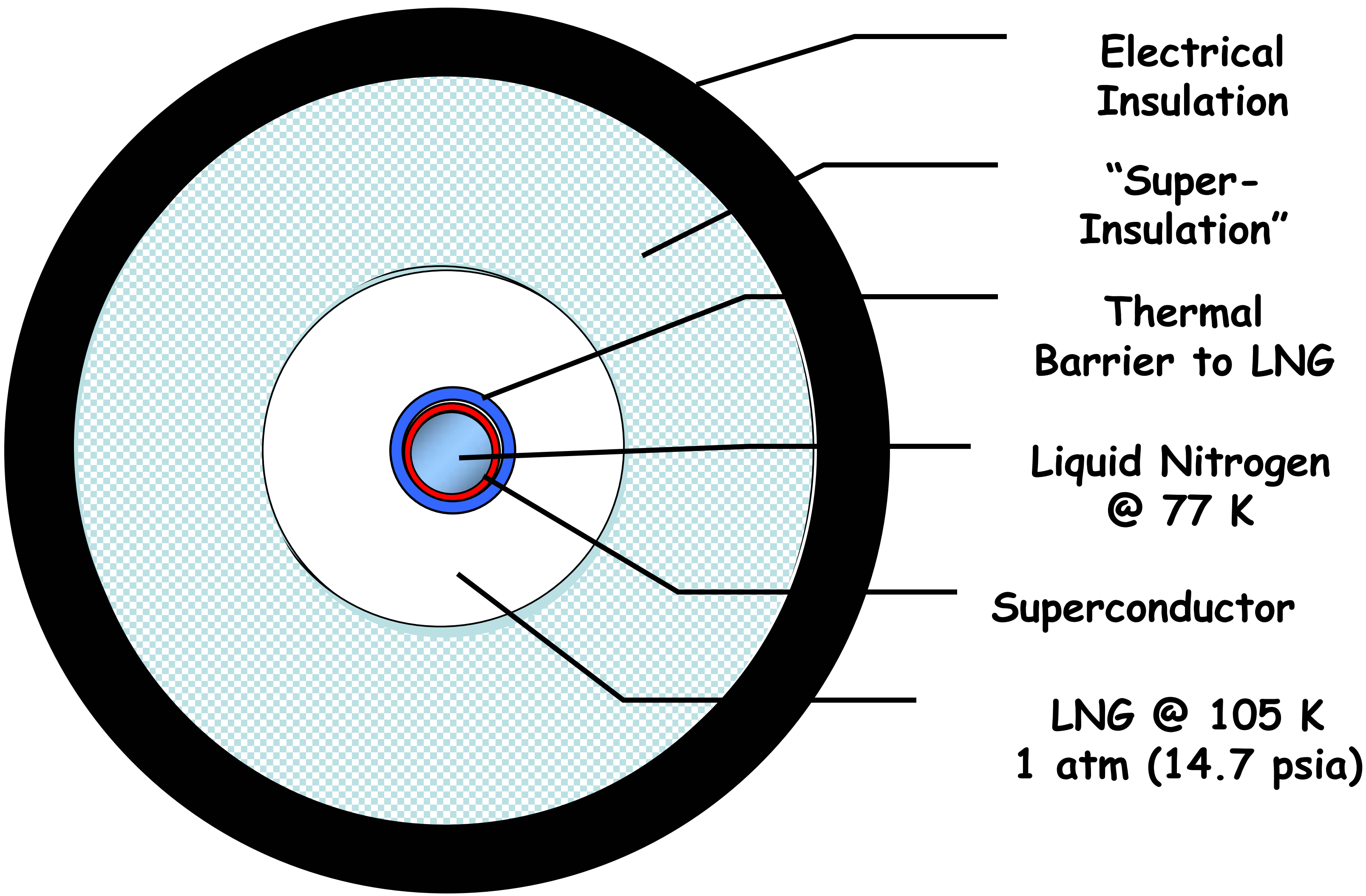


Mackenzie Valley Pipeline

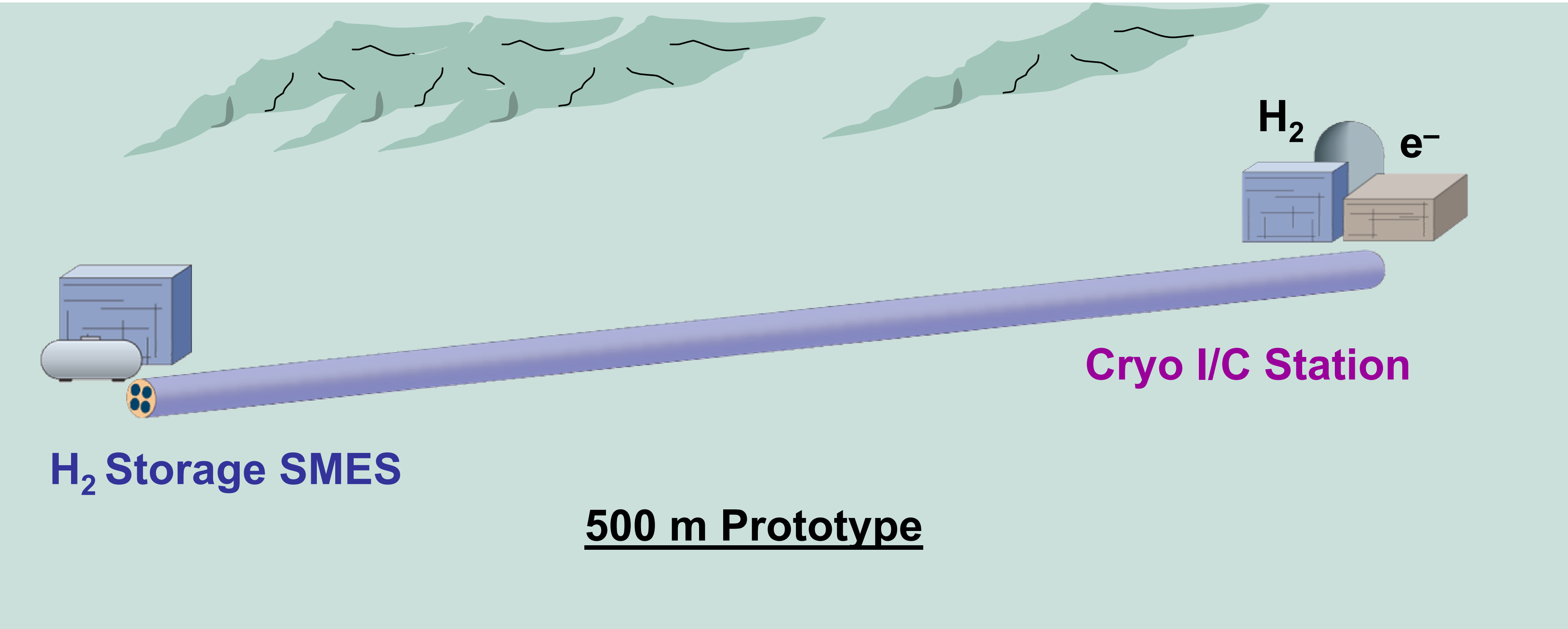
1300 km

18 GW-thermal

LNG SuperCable



SuperCable Prototype Project



"Appropriate National Laboratory"
2005-09

Regional System Interconnections