Lecture #1

Introduction to Superconducting *Magnets*

—Prefaced with a Brief History of Magnet Technology—

Yukikazu Iwasa

Francis Bitter Magnet Laboratory
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139

CEA, Saclay

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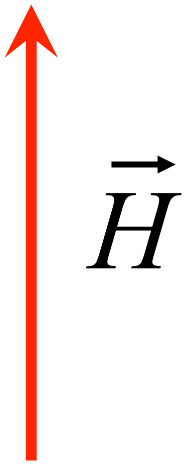
Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Outline

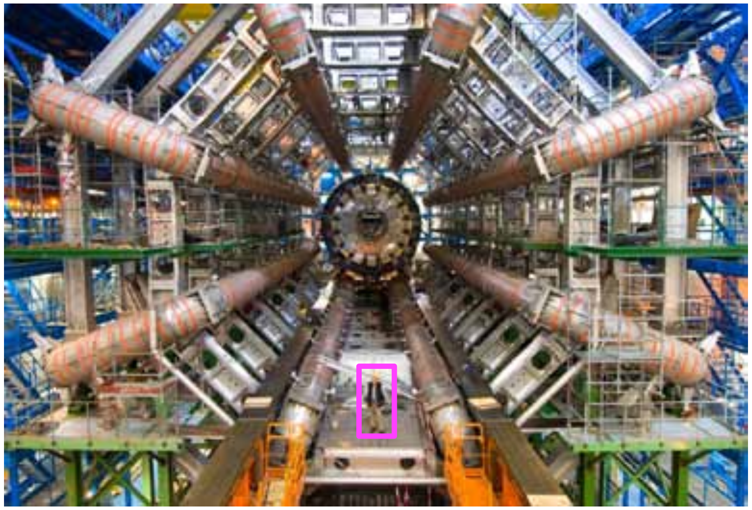
- A brief history of magnetism
- Two types of superconductor
- LTS vs. HTS
- Key magnet Issues vs. T_{op}
- Mechanical integrity
- Superconductivity enabling for electric power applications?
- Enabling superconducting magnets
- *Present* Magnet Technology: Selected Permanent Magnet Applications
- Selected Permanent Magnets in Modern Automobiles
- Future
- JR Central Maglev
- MRI world-wide distribution
- Four stages in a successful project

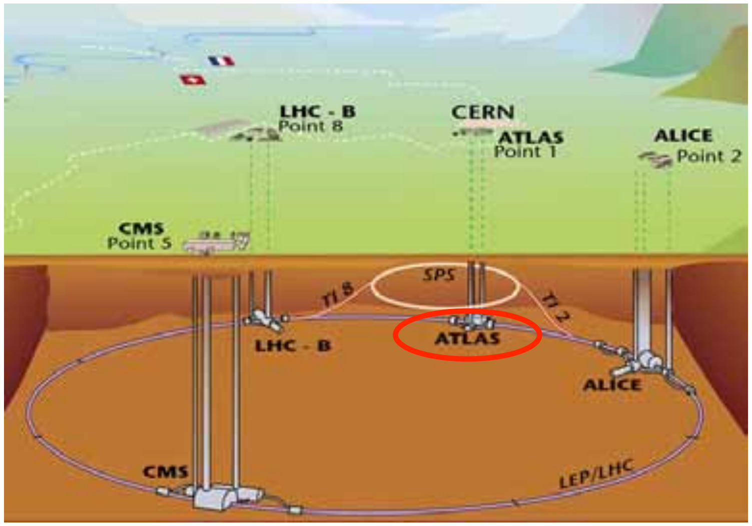
Magnetic Field – Two Distinct Views

Users’ (Physicists; Doctors)



Magnet Engineer's





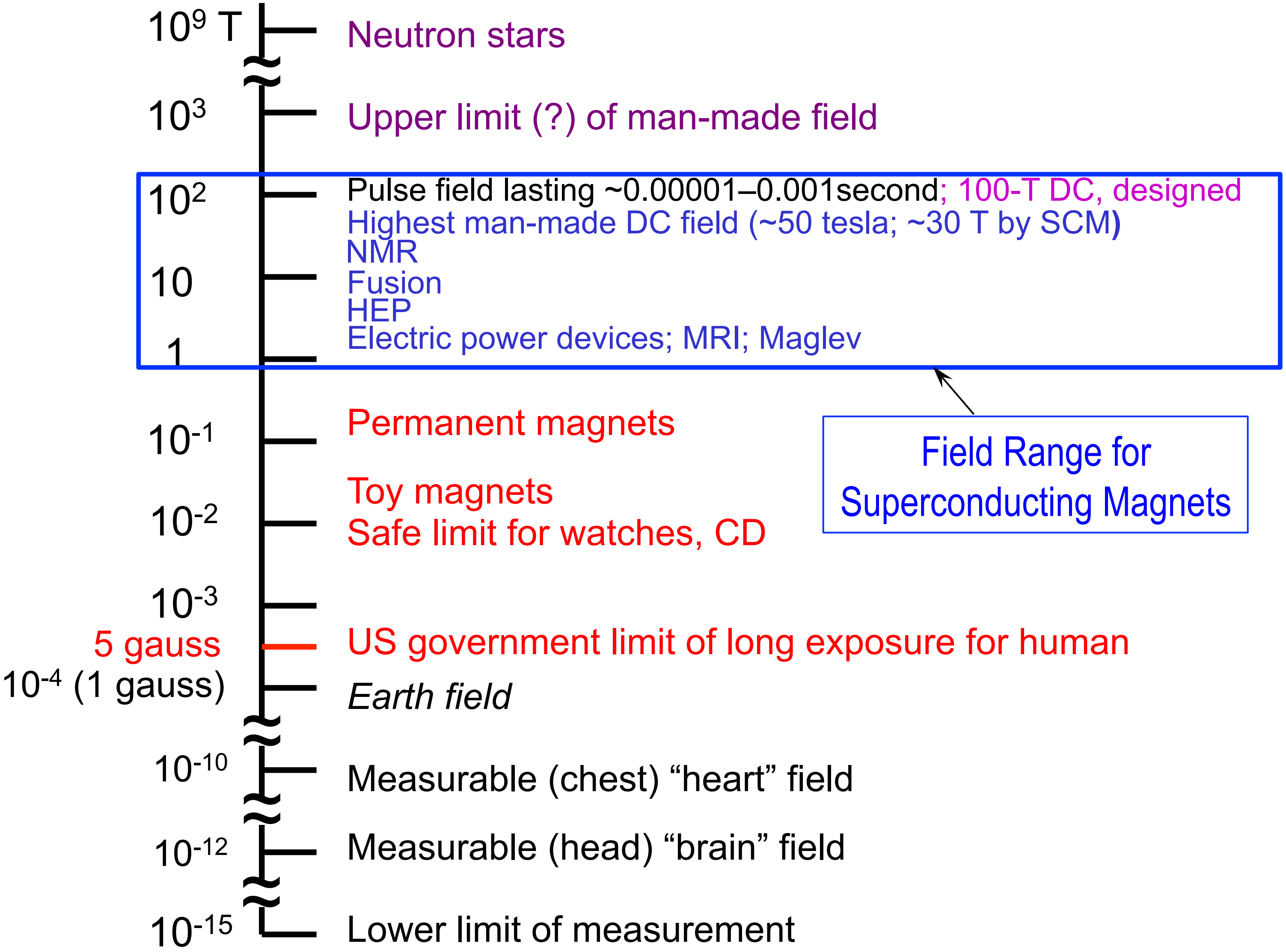
High Energy Physics

MRI Magnet

Adrian Thomas, Siemens

Gert Mulder,
Philips

Magnetic Field Spectrum



10^9 T	Neutron stars
10^3	Upper limit (?) of man-made field
10^2	Pulse field lasting ~0.00001–0.001second; 100-T DC, designed Highest man-made DC field (~50 tesla; ~30 T by SCM) NMR
10	Fusion HEP Electric power devices; MRI; Maglev
1	
10^{-1}	Permanent magnets
10^{-2}	Toy magnets Safe limit for watches, CD
10^{-3}	
5 gauss	US government limit of long exposure for human
10^{-4} (1 gauss)	*Earth field*
10^{-10}	Measurable (chest) “heart” field
10^{-12}	Measurable (head) “brain” field
10^{-15}	Lower limit of measurement

Field Range for Superconducting Magnets

A Brief History of Magnetism: Early Years

Lodestone: magnetized mineral (magnétite)---naturally occurring magnet

Electromagnet

Thales (~600 B.C.) Studied magnetism

Chinese fortune tellers (~200 B.C.)

Chinese sailors (850-1050) for navigation

Peregrinus (1269) Magnet: Poles; compass

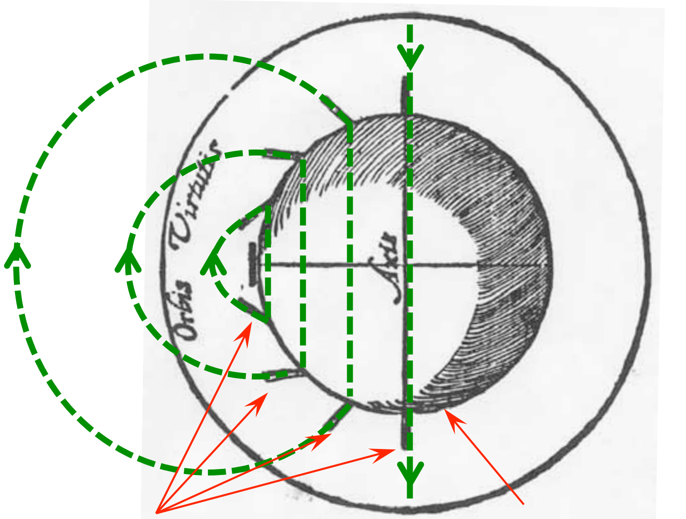
Gilbert (1600) Earth: Spherical magnet

Franklin (1752): Lightning = Electricity

Oersted(1819) $I \Rightarrow H$ field

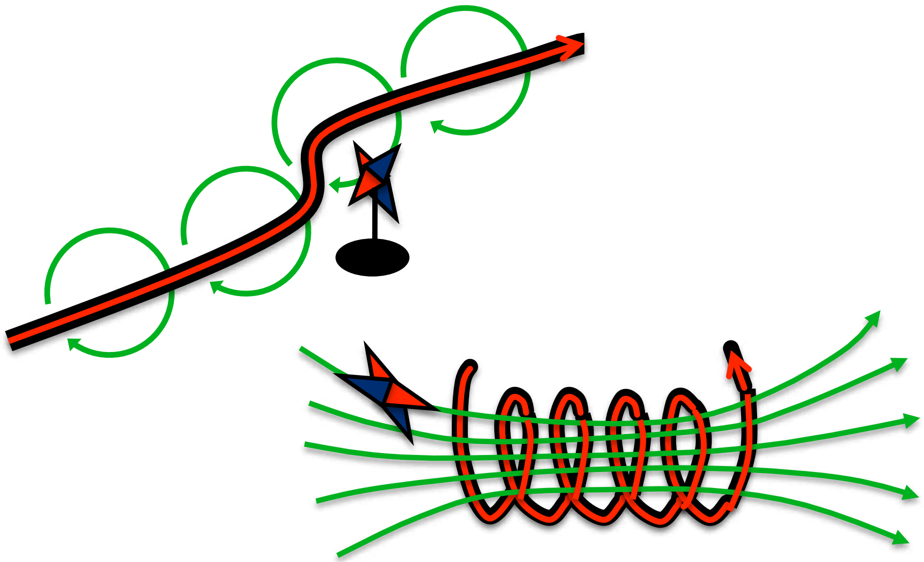
Iron objects becoming magnetized during thunderstorm

William Gilbert *De Magnette* (1600)



Lodestone needles

Lodestone sphere



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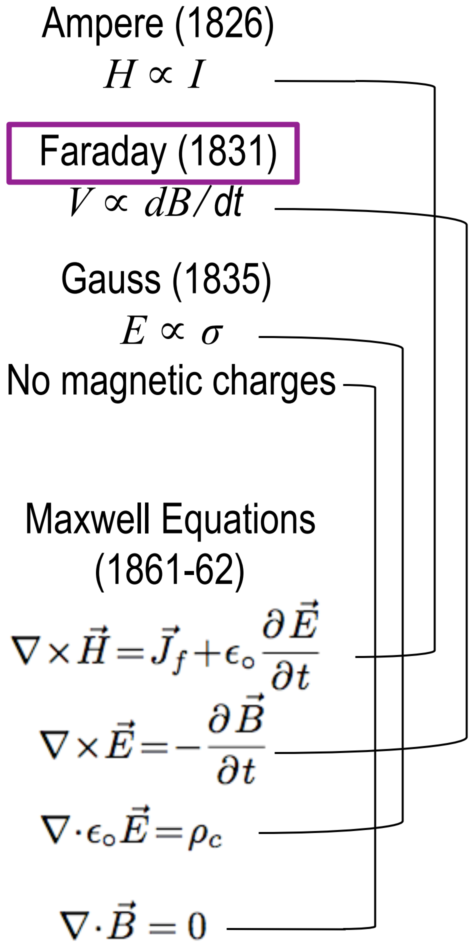
<iwasa@jokaku.mit.edu>

A Brief History of Magnetism: Michael Faraday



Ampere (1826)

$H \propto I$

Faraday (1831)

$V \propto dB/dt$

Gauss (1835)

$E \propto \sigma$

No magnetic charges

Maxwell Equations (1861-62)

$$\nabla \times \vec{H} = \vec{J}_f + \epsilon_o \frac{\partial \vec{E}}{\partial t}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \epsilon_o \vec{E} = \rho_c$$

$$\nabla \cdot \vec{B} = 0$$

1791-1867

Faraday lecturing on “Faraday disk” at Royal Institution (c. 1840)

Faraday’s Law of Induction Regarded as the *Greatest* Single Electrical Discovery in History

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

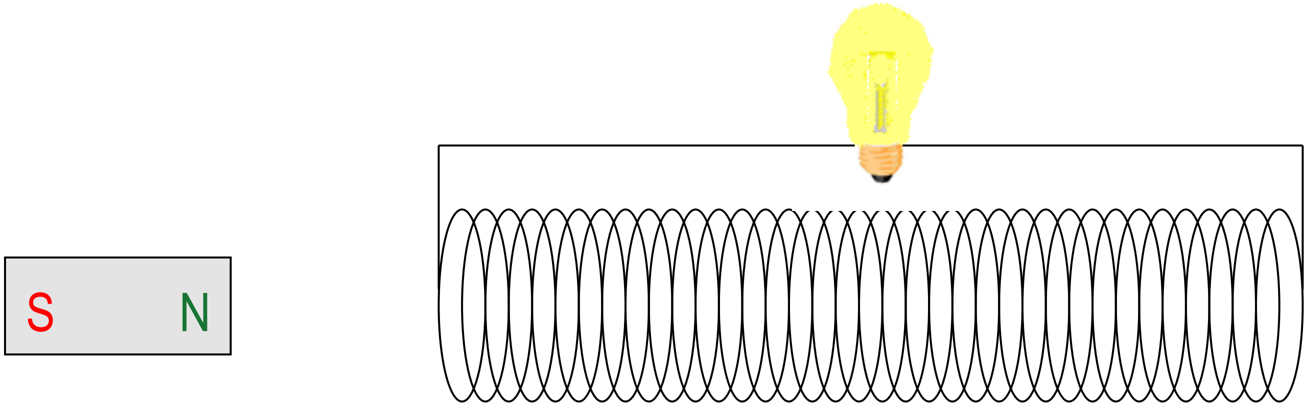
A Brief History of Magnetism: Faraday's Law

$$\oint_C \vec{E}\cdot d\vec{s} = -\frac{d}{dt}\int_S \vec{B}\cdot d\vec{A}$$

Terminal *Voltage* = *Time-Varying Magnetic Induction* within the loop
This time variation may be achieved by mechanical motion

The first experimental proof, by Michael Faraday, connecting two sources of power: electric & mechanical ⇒ generator/motor

"Why sir, there is a very good chance that you will soon be able to tax it"



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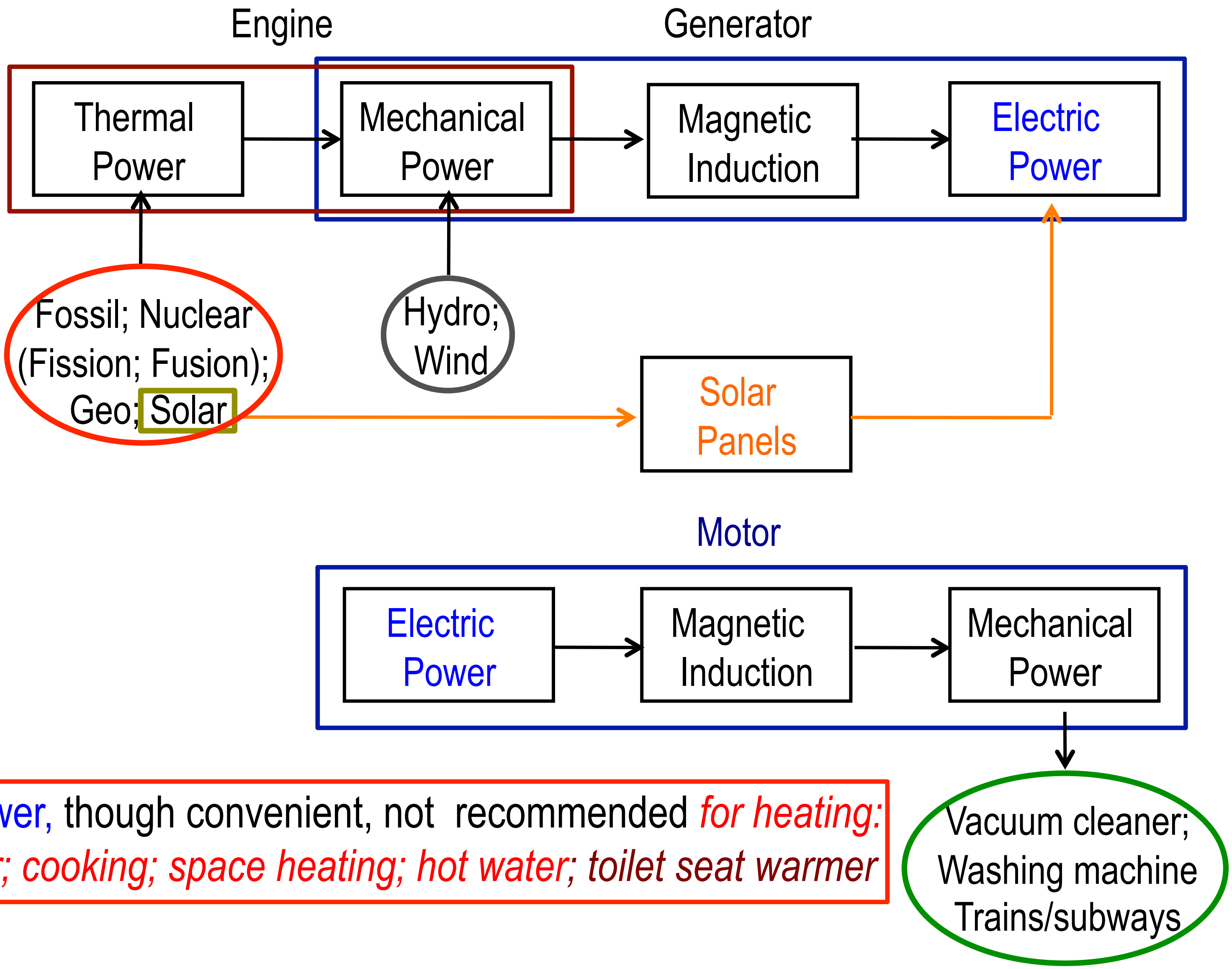
A Brief History of Magnetism: *Magnetic Induction*



Engine

Generator

Thermal Power

Mechanical Power

Magnetic Induction

Electric Power

Fossil; Nuclear (Fission; Fusion); Geo; Solar

Hydro; Wind

Solar Panels

Motor

Electric Power

Magnetic Induction

Mechanical Power

Vacuum cleaner; Washing machine Trains/subways

Electric power, though convenient, not recommended *for heating:*
Cloth dryer; cooking; space heating; hot water; toilet seat warmer

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

A Brief History of Magnetism: *Cryogenics*

LO_2 & LN_2
(1877)

Dewar
(1898)
LH_2 (20 K)

Kamerlingh
Onnes
(1908)
LHe (4.2 K)

聽而易忘,
見而易記,
做而易懂
孔子
(550 BC-479 BC)

I hear, I forget,
I see, I remember,
I do, I understand
Confucius


1853-1926


Door meten tot weten

Through measurement to knowledge

A Brief History of Magnetism: *Electromagnet & Permanent Magnet*

Jamin*
(1873)
1^{st} Permanent magnet (PM) (Steel-based)

* Jules C Jamin
(1818-1886)

Most electromagnets relied on iron to enhance field strengths

P Curie
(1895)
T_{curie}

$\overset{T_{curie}}{\longrightarrow} T$
Ferro | Para

Kamerlingh Onnes
(1911)
Superconductivity

$\downarrow$

1^{st} superconducting electromagnet *failed* (1916)

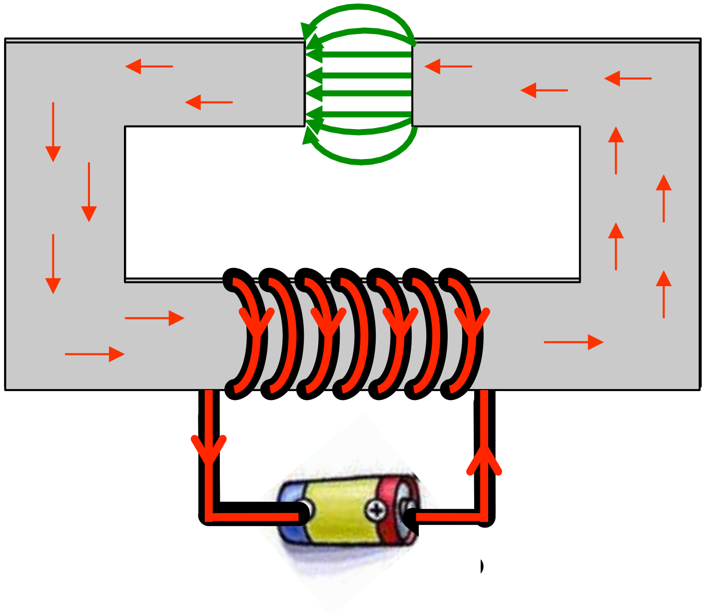
Honda/
Takei
(1917)
Co-added W-iron PM

Debye/
Giauque
(1926)
$\left.\frac{\partial T}{\partial H}\right|_S$
$T \rightarrow 0$

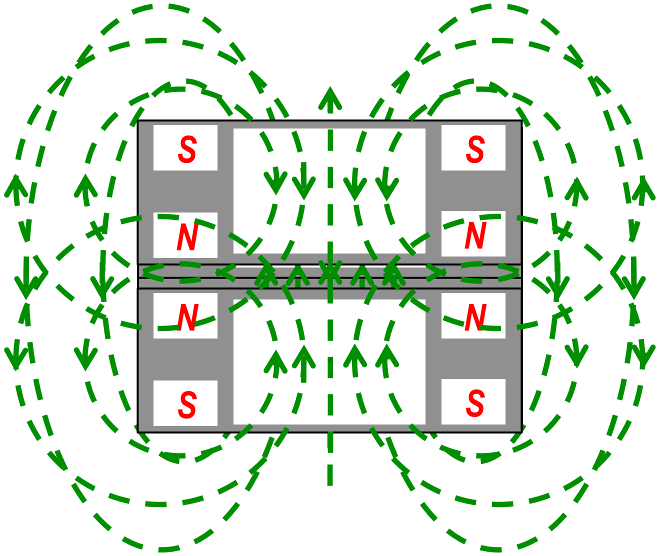
Néel
(~1930)
T_N

$\overset{T_N}{\longrightarrow} T$
Antiferro | Para

Mishima
(1932)
AlNiCo



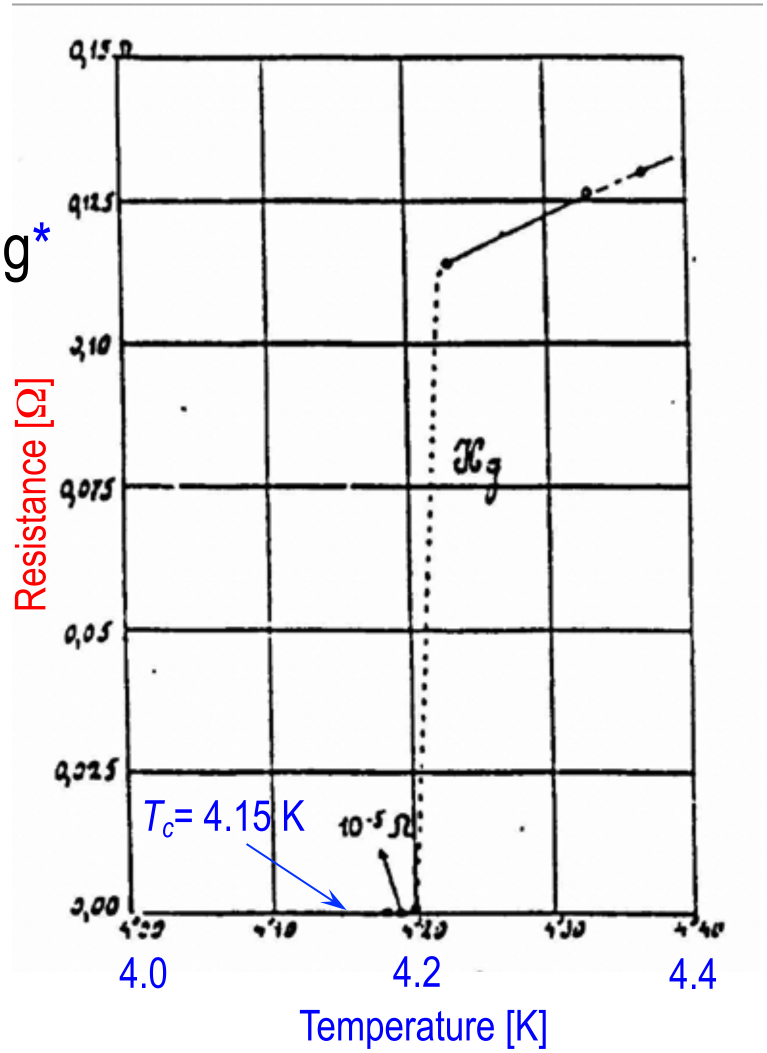
Like Poles Repel, Unlike Poles Attract



Heike Kamerlingh Onnes (1853-1926)

- 1908: First to liquefy helium
- 1911: First to discover superconductivity in Hg*
  (T_c= 4.15 K)
- Existence of J_c with Hg
- 1913: First SC (Pb) magnet failed
  Nobel Prize in Physics
- 1914: Existence of H_c with Pb* & Sn*

* Low-temperature superconductor (LTS)



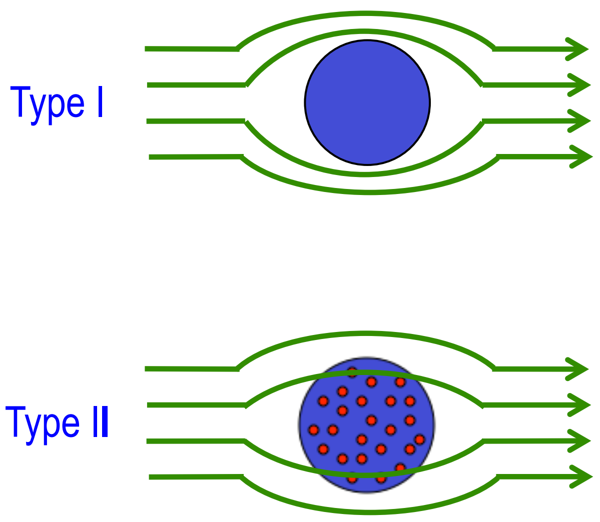
A Brief History of Magnetism: Superconductivity *after* Kamerlingh Onnes

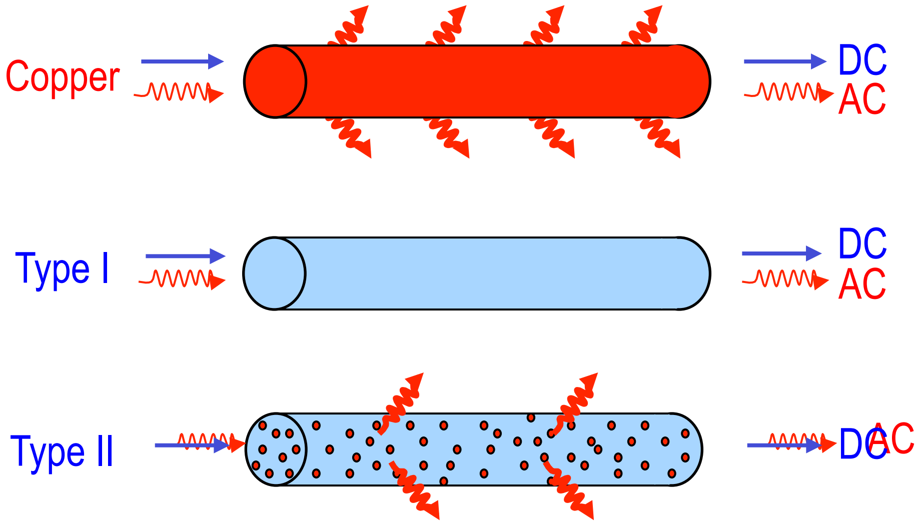
Meissner/
Ochsenfeld
(1934)
"Meissner Effect"

Perfect diamagnetism of
Type I superconductor

GLAG theory
Ginzburg/Landau/
Abrikosov/Gorkov
(1950)
Magnetic behavior of
Type II superconductors

BCS theory
Bardeen/Cooper/Schrieffer
(1957)
Microscopic theory of
superconductivity





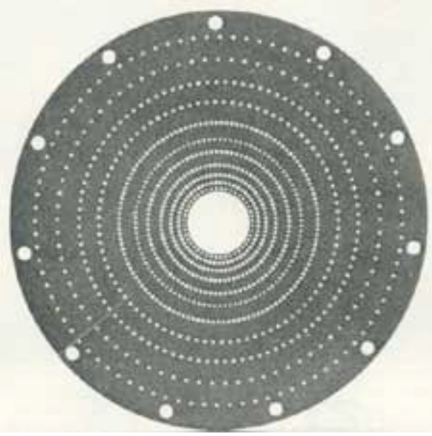
A Brief History of Magnetism: High-Field *Ironless* Electromagnets

Bitter
(1930s)

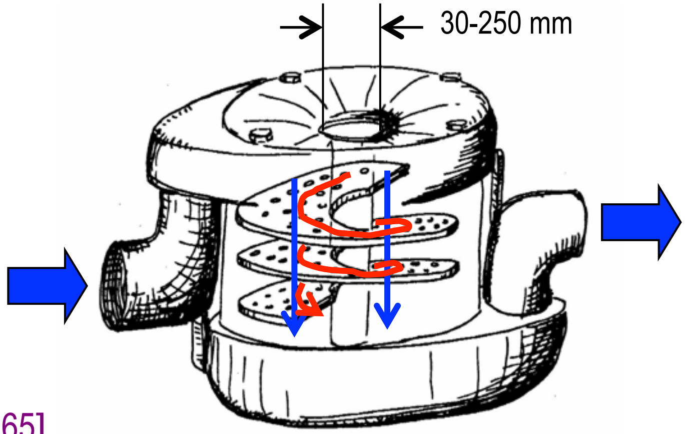
1st high-field (>10 T) *ironless* electromagnets: $H \propto I$


1902-1967

Francis Bitter at Boston Edison substation testing his magnet (c. 1935)



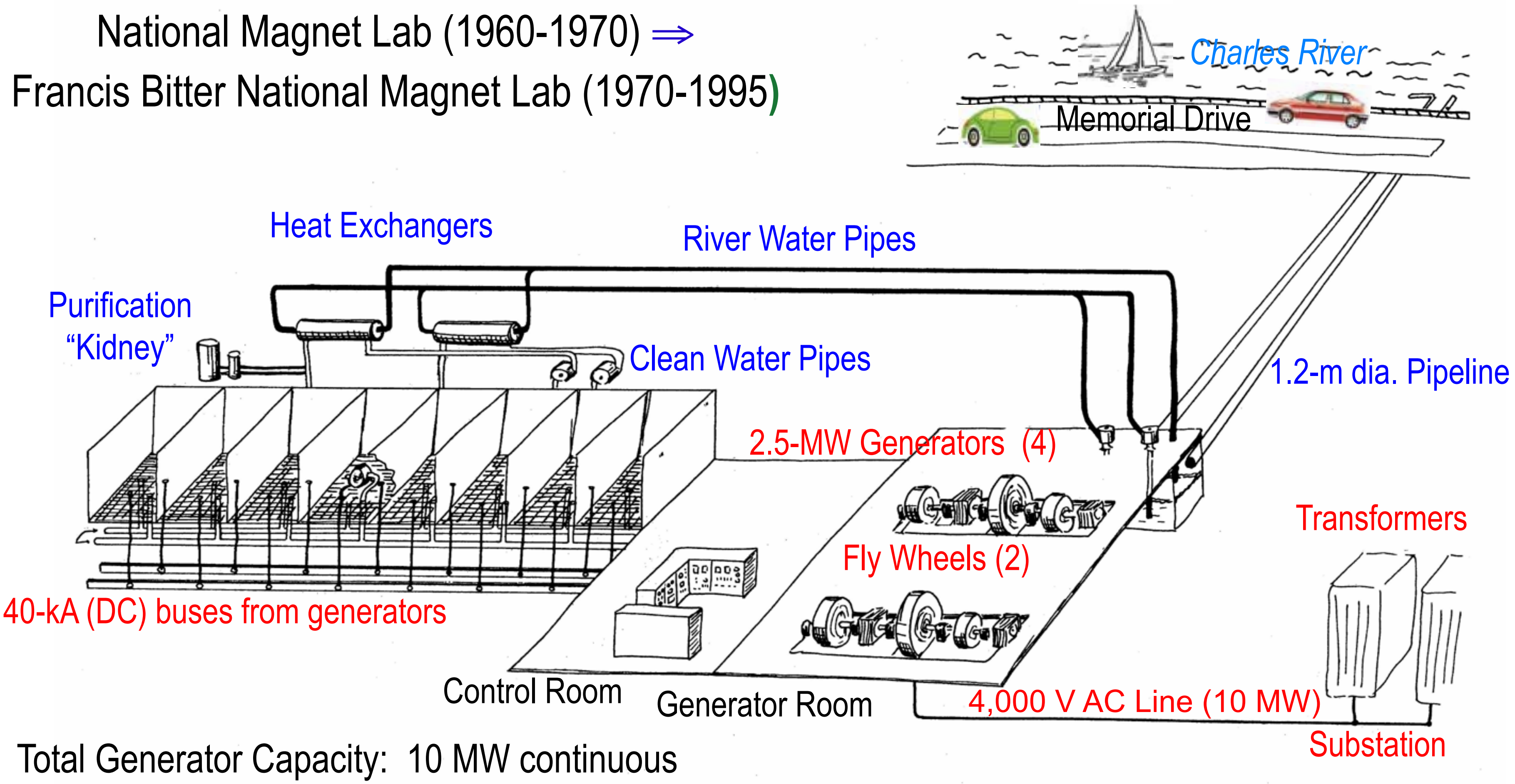
“Bitter” plate silhouette



[B/W drawing by Henry Kolm (NML, 1965)]

A Brief History of Magnetism: *1st National Magnet Lab at MIT*

National Magnet Lab (1960-1970) ⇒
Francis Bitter National Magnet Lab (1970-1995)

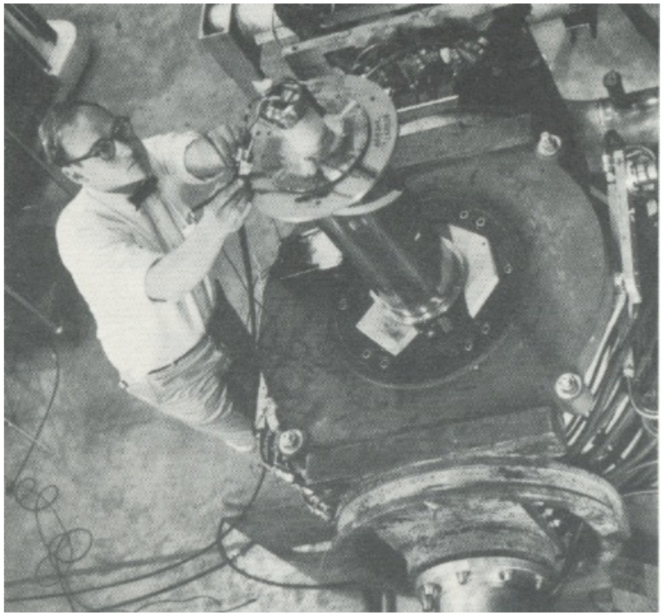


Total Generator Capacity: 10 MW continuous
12 MW, 15 min.
32 MW, 3 s (fly wheels)

[Based on Henry Kolm (NML, 1965]

A Brief History of Magnetism: MIT National Magnet Lab

Montgomery
1st 25-T “Bitter” magnet at NML (1965)



Bruce Montgomery running his experiment with a 25-T “Bitter” magnet (1966)

Dr. Kyoji Tachikawa measuring his V_3Ga samples (1967)

A young engineer with the technician Charlie Park (1930-1996) assisting Dr. Tachikawa’s experiment (1967, by K. Tachikawa)

A Brief History of Magnetism: Cryogenics & Early Superconducting Magnets

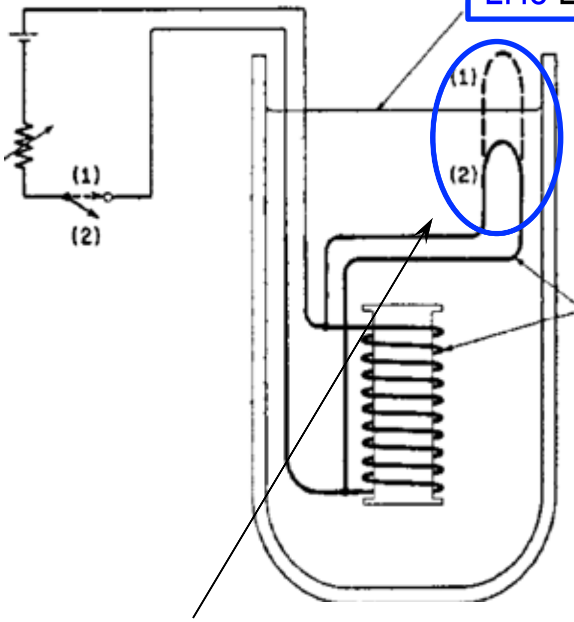
Collins (1946) 1st large-scale He liquefier

Yntema (1955)

1st 0.71-T Superconducting (Nb) magnet (I_{op}= 1.8 A) at 4.2 K (LHe)

Autler (1960) 1st *persistent-mode* 0.43-T superconducting magnet

Prof. Sam Collins with his favorite toy (c. 1963)



LHe Level

Nb wire
ϕ0.127 mm

A clever Persistent-Current-Switch:
Up *resistive*; down *superconducting*

from Stan Autler (MIT Lincoln Lab),
Rev. Sci. Instr 31, 369 (1960)

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

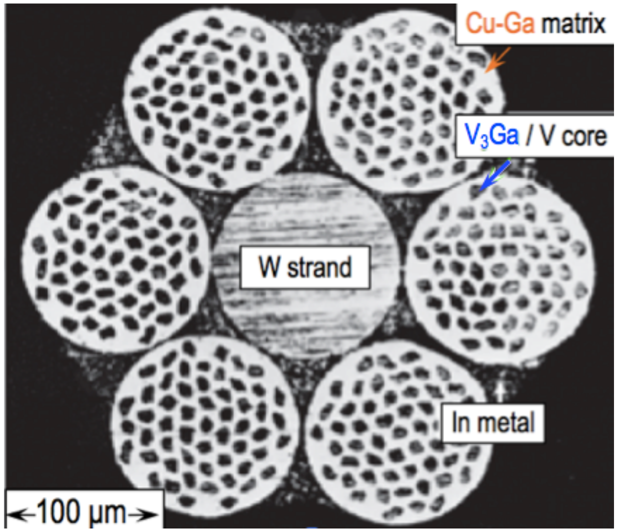
A Brief History of Magnetism: Low-Temperature Superconductors (LTS)

Wong (1964) SUPERCON 1st Commercial Superconductor Manufacturer

Tachikawa (1964) "Bronze" process V_3Ga & Nb_3Sn

Multifilamentary LTS (late 1960s)

Dr. James Wong of Supercon inspecting 1st commercially available (from Supercon) multifilamentary NbTi wire (1970)



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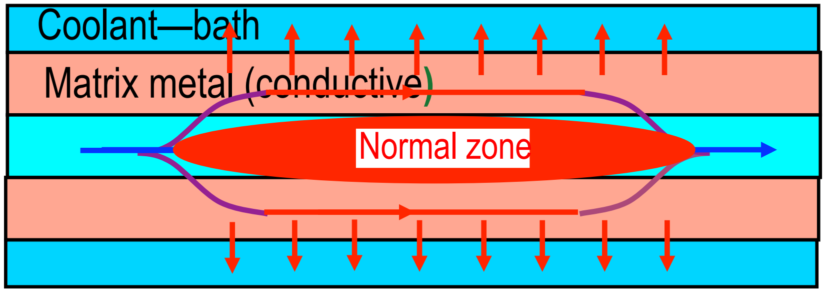
<iwasa@jokaku.mit.edu>

A Brief History of Magnetism: Stability of Superconductivity

Stekly Cryostability
(1964)

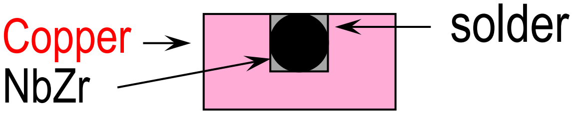
Adiabatic stability
(formulated in the 1970s & 1980s)

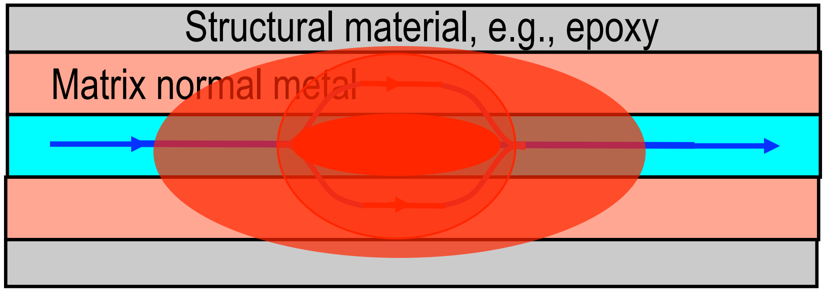


- Disturbance can be “large”
- Stability established by making:

Joule heating = cooling

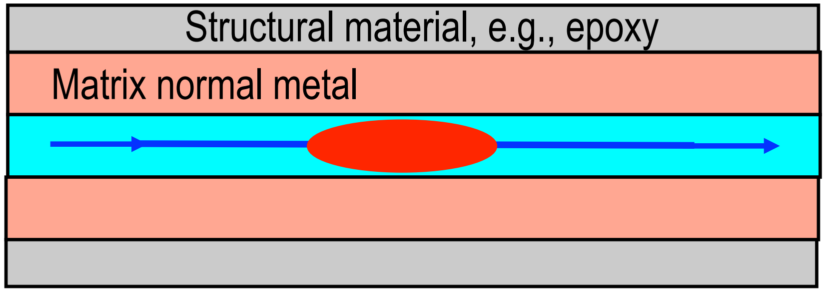
1st NbZr/Cu “composite” by Stekly





- Disturbance energy > Energy margin

⇒ Quench



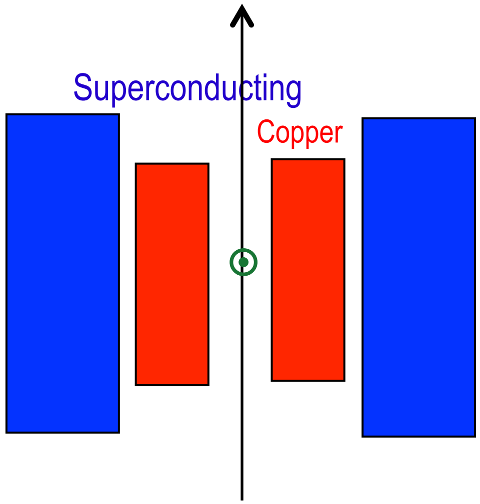
- Disturbance energy < Energy margin

⇒ Recovery

A Brief History of Magnetism: New Magnet Applications

Hybrid magnet
Montgomery/Wood
(1968)

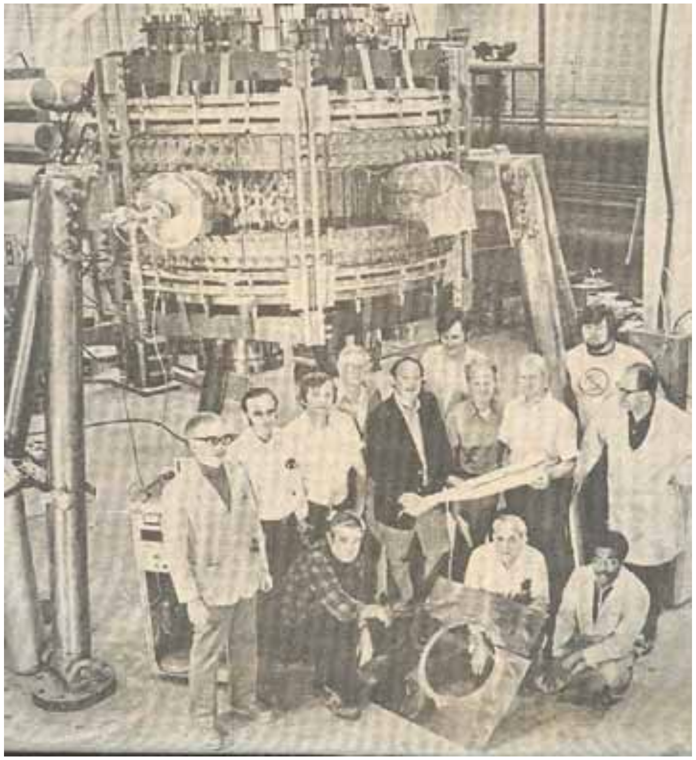
Copper + Superconducting



High-field magnet labs with
hybrid magnets to follow:
Nijmegen
Tohoku U
Grenoble
NRIM (NIMS)
NHMFL

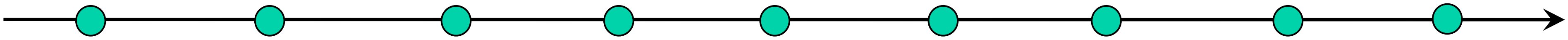
Mat Leupold and 鈴木英元 (昭和電線)
celebrating after successful run of
35-T Hybrid III (FBNML, 1991)

High-field (10 T) tokomak,
ALCATOR (ALto CAmpus TORus)
(1969)



Montgomery, engineers, and technicians
FBNML (1978)

A Brief History of Magnetism: LTS for Conventional Technologies



Silicon Processing Utech/ Flemings (1966)

HEP Dipole & quadrupole Sampson (1968)

"Magnetic Filteration" (Magnetic separation) Kolm/ Montgomery (1969)

HEP Bubble chamber Purcell (1969)

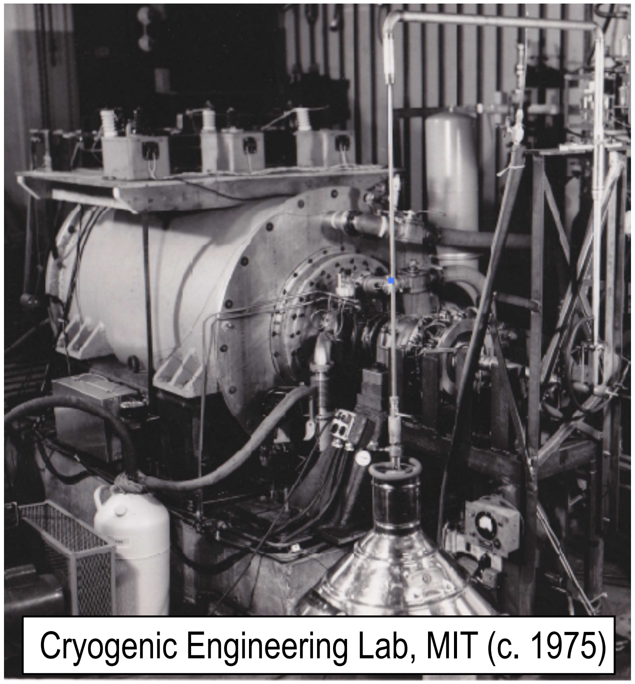
Rotating machines Smith/Kirtley (1970)

MAGLEV Powell/ Danby (1971)

SMES Boom (1972) Rogers (1979) Shintomi (1983)

Motor Levedahl (1972) Naval ship Propulsion Superczynski (1977)

Transmission Forsyth (1975)



Cryogenic Engineering Lab, MIT (c. 1975)

Prof. Joseph Smith explaining the 3-MVA generator to Japanese visitors (c. 1973)

ML500 517 km/h (1979)

Japan National Railways
Railway Technical Research Institute

A Brief History of Magnetism: LTS for Conventional Technologies

0.5-T MRI
Oxford
Instruments
(1980)

HEP
Detector
magnet
Desportes
(1980)

Transformer
Riemersma
(1981)

500-MHz
NMR
Williams
(1981)

FCL
Rogers
(1983)

HEP
Tevatron
(1983)

Tokamak
ITER
began
(1989)

Tokamak
Tore Supra
(1996)
Triam
(1997)

Stellarator
LHD
(1999)

45-T
Hybrid
magnet
NHMFL
(1999)

900-MHz
NMR
NHMFL
(2000)

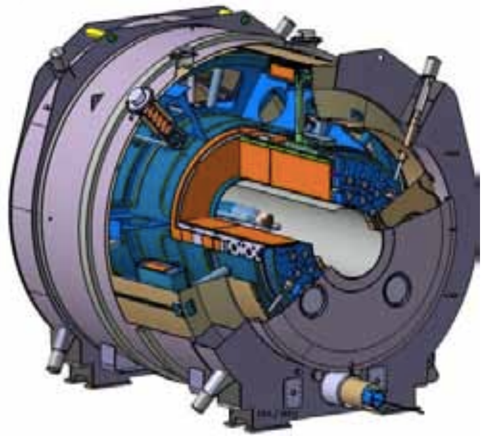
930-MHz
NMR
NRIM
(2002)

1000-MHz
NMR
Bruker
(2009)

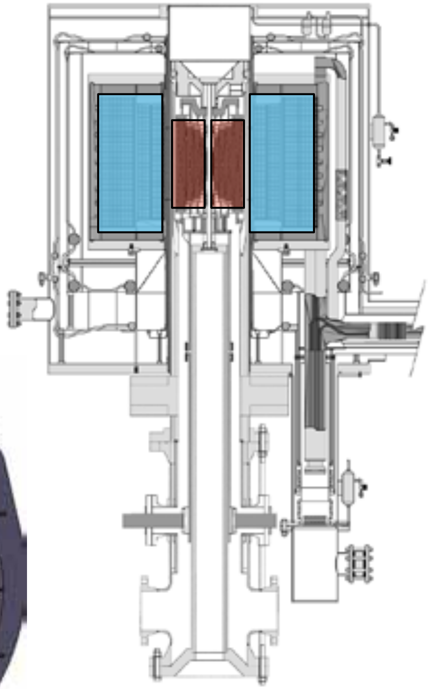
LHC
HEP
CERN
(2013)

Iseult
500-MHz
MRI
CEA
(2017)

LHC (CERN)



Iseult (CEA)



45-T (11 T/34 T)
32-mm RT bore
hybrid magnet
(NHMFL)

A Brief History of Magnetism: High-Temperature Superconductors (HTS)

Bednorz/Müller
(1986)
HTS
LaBaCuO
T_c=35 K

Chu/Wu
(1987)
YBCO
(93 K)

Yurek &
3 others
AMSC
(1987)
1st HTS
manufacturer

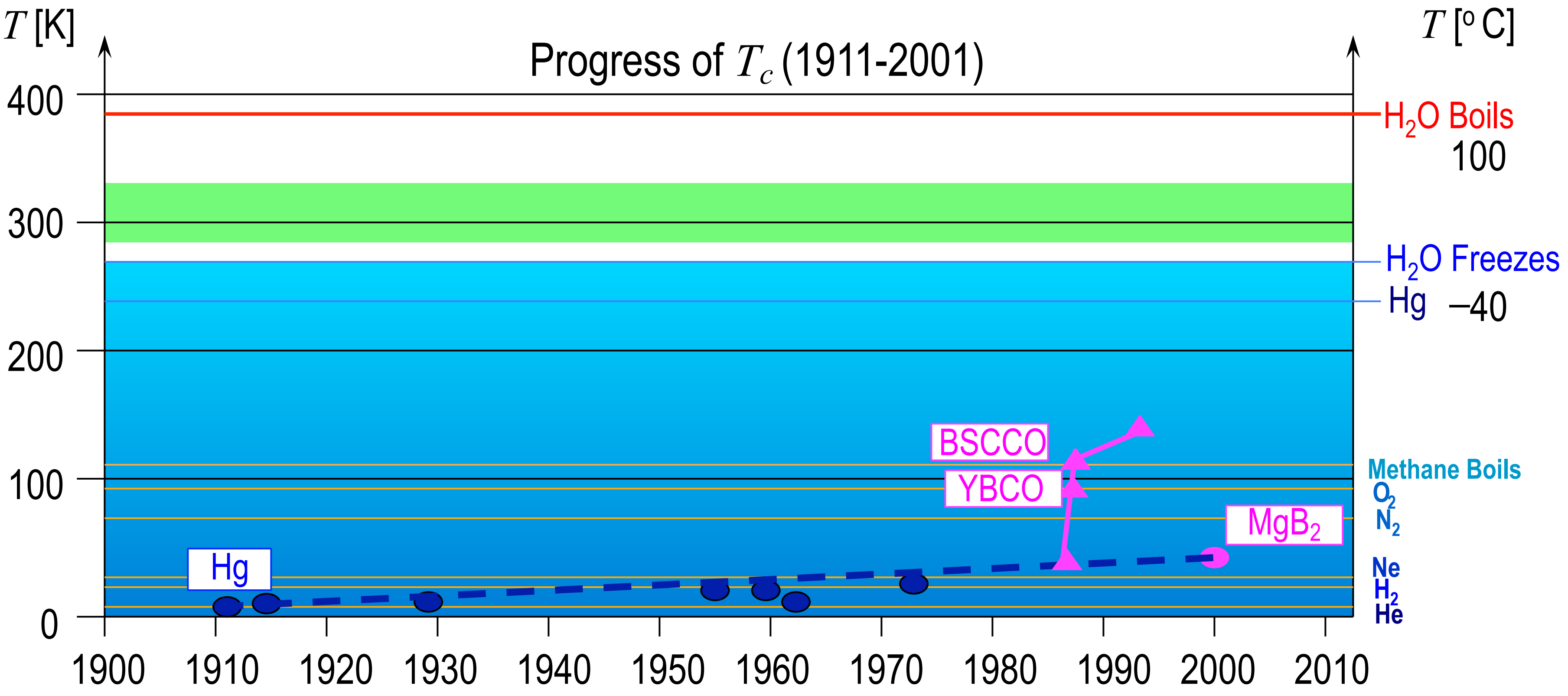
ISTEC
(1988)

Maeda
(1988)
BSCCO

Sumitomo
Electric
(1988)
Bi2223

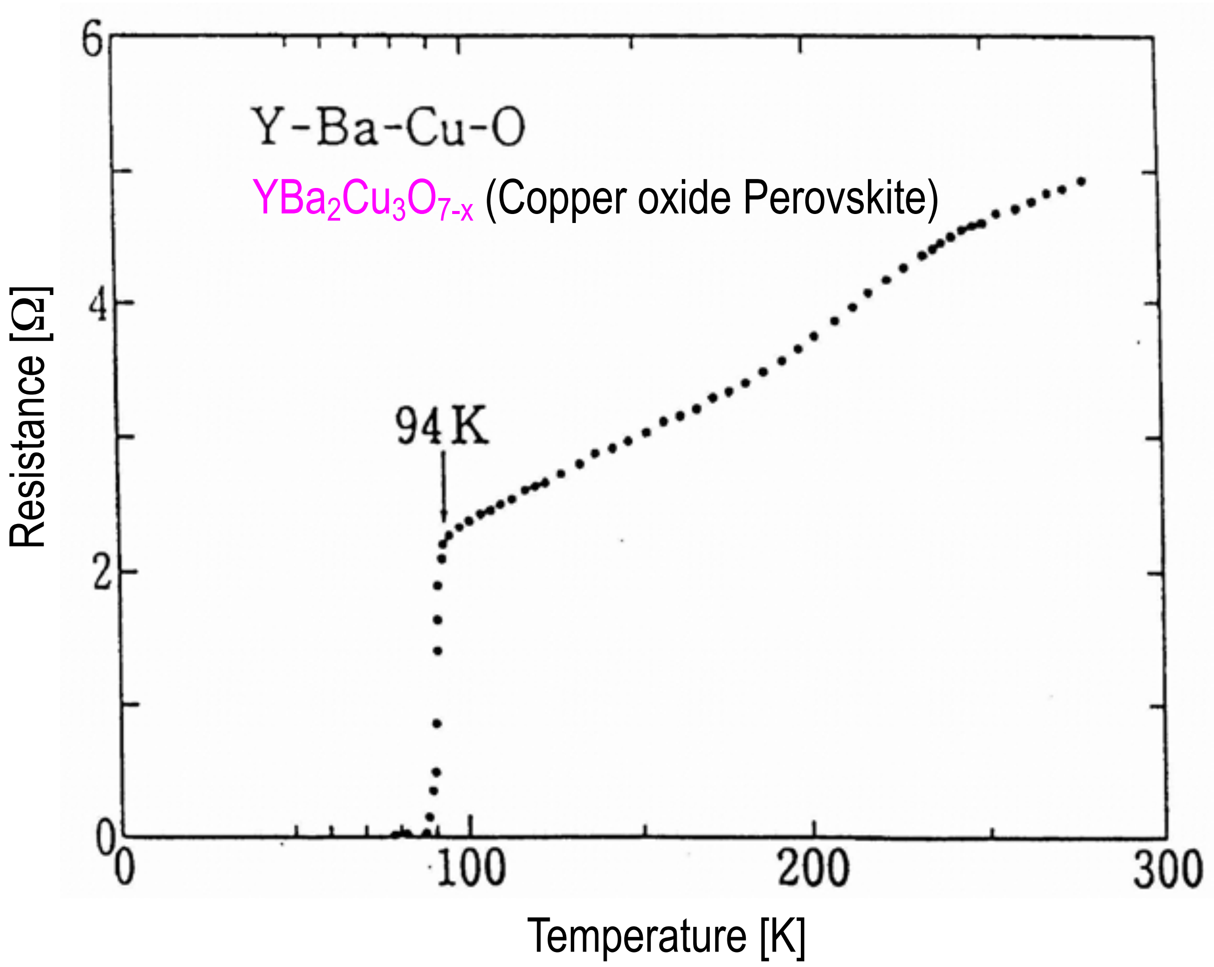
Fujikura
(1988)
Coated YBCO

Akimitsu
(2001)
MgB_2



Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

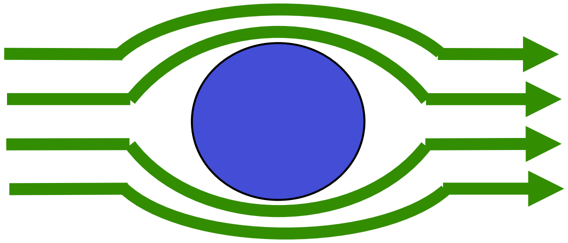
High-Temperature Superconductor (HTS)



Two Types of Superconductors

Type I

- Zero electrical resistance, $R = 0$, under DC or AC conditions; *no Ohmic loss*
- Exhibits the Meissner effect $H = 0$; magnetic flux is excluded



Material	T_c [K]	$\mu_o H$ [gauss*]
Zn	0.9	53
Al	1.2	99
In	3.4	276
Sn	3.7	306
Hg	4.15	413
Ta	4.5	830
Pb	7.2	803

* 1 gauss = 0.0001 tesla
Earth magnetic field: ~0.7 gauss

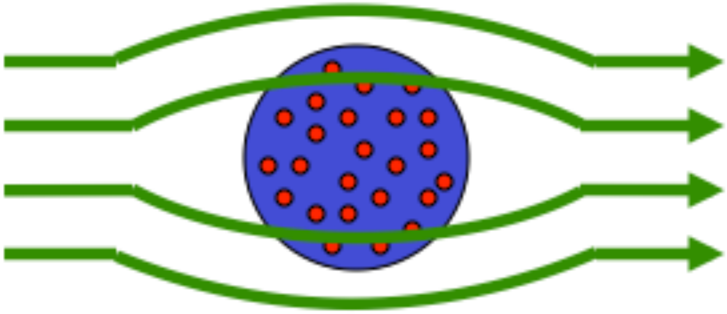
Critical fields too small to be useful for practical magnets

The reason the first superconducting magnet (Pb) by Kamerlingh Onnes in 1913 failed

Two Types of Superconductors

Type II

- Exhibits the "mixed" magnetic state
  - Normal "islands" ("vortex") in a superconducting sea



  - Permits partial penetration of magnetic flux
- Suitable for *practical (and high-field)* magnets
- *Slightly resistive* under AC conditions

Material	T_c [K]	$\mu_o H$ [tesla]
Nb (metal)	9.1	0.2
NbTi (alloy)	9.8	10.5 (4.2 K)
NbN (metalloid)	16.8	15.3 (4.2 K)
Nb_3Sn (compound)	18.2	24.5 (4.2 K)
Nb_3Al	18.7	31.0 (4.2 K)
Nb_3Ge	23.2	35.0 (4.2 K)
MgB_2 (compound)	39	>15
YBaCuO (oxide)	93	150
BiSrCaCuO		
$Bi_2Sr_2Ca_1Cu_2O_8$ (Bi2212)	85	~120
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223)	110	~110
HgBaCaCuO	>130	"high"

1 tesla (T) = 10,000 gauss

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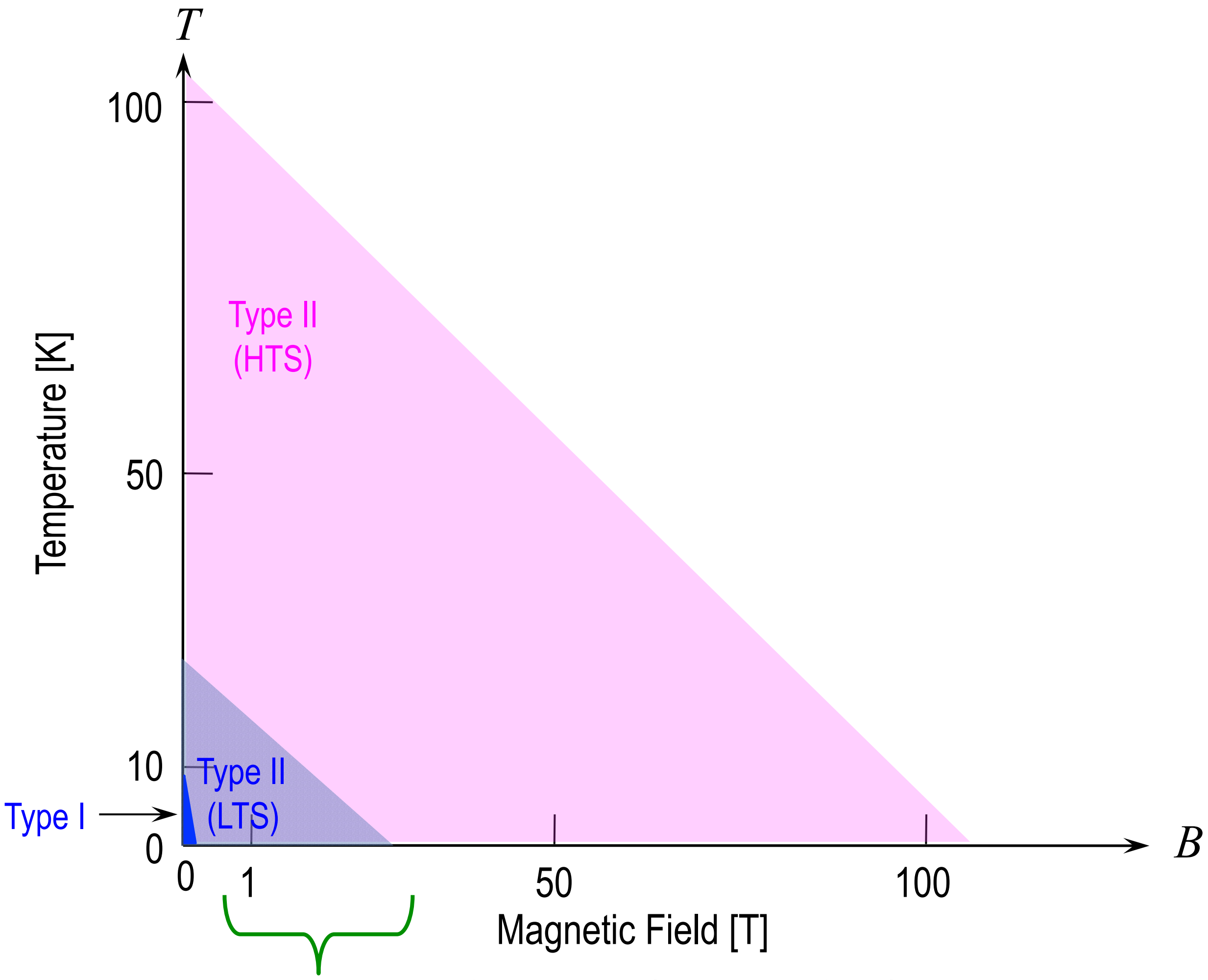
<iwasa@jokaku.mit.edu>

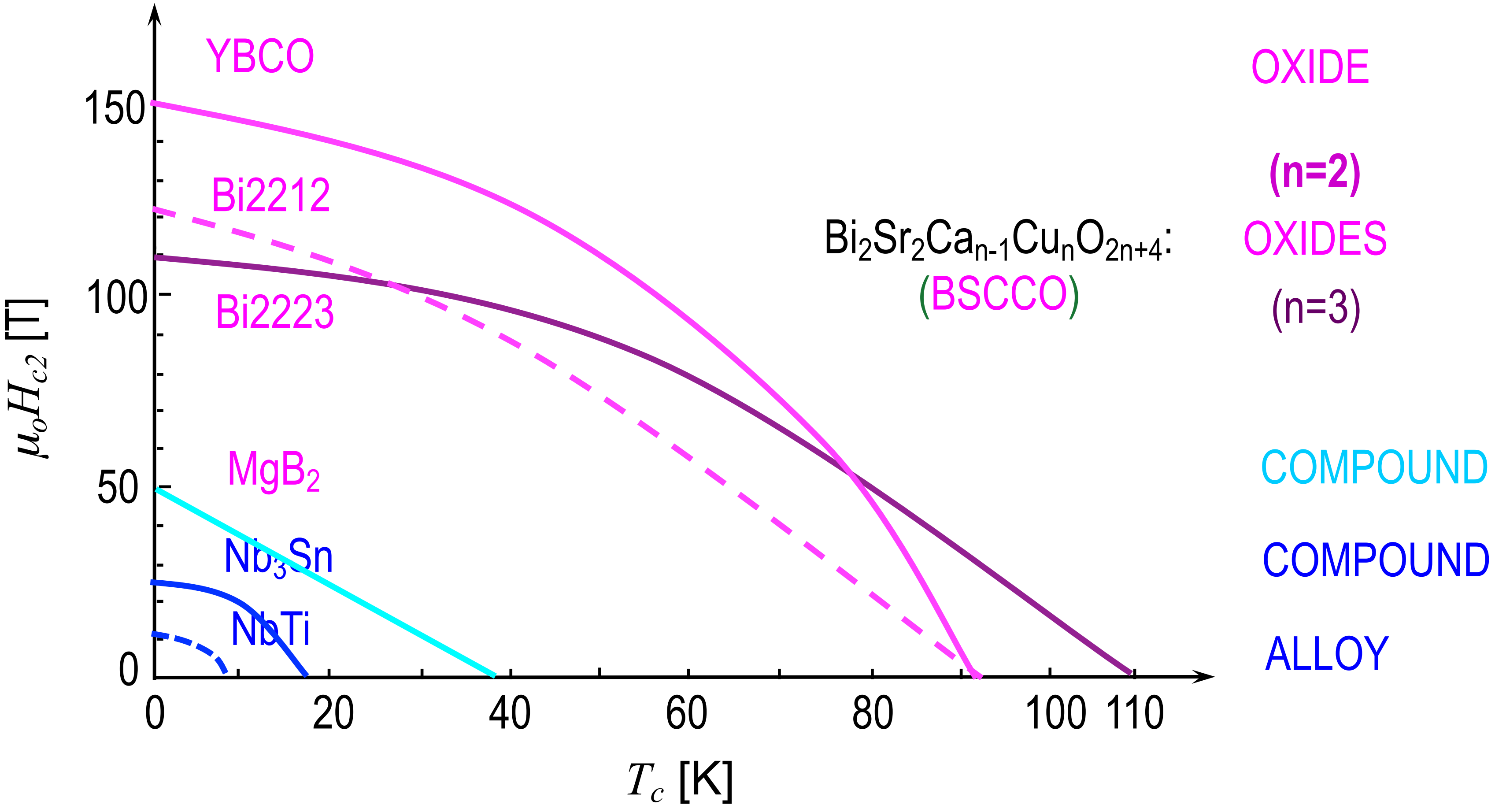
Ballpark Field & Temperature Ranges of Types I and II Superconductors



Field range of *practical (and high-field)* magnets

LTS & *HTS*

$\mu_o H_{c2}$ *vs.* T_c *Plots for LTS & HTS*



"Magnet-Grade" Superconductors

Magnet-grade superconductors meet rigorous magnet specifications as well as readily available commercially

- Currently, there are 5 magnet-grade superconductors

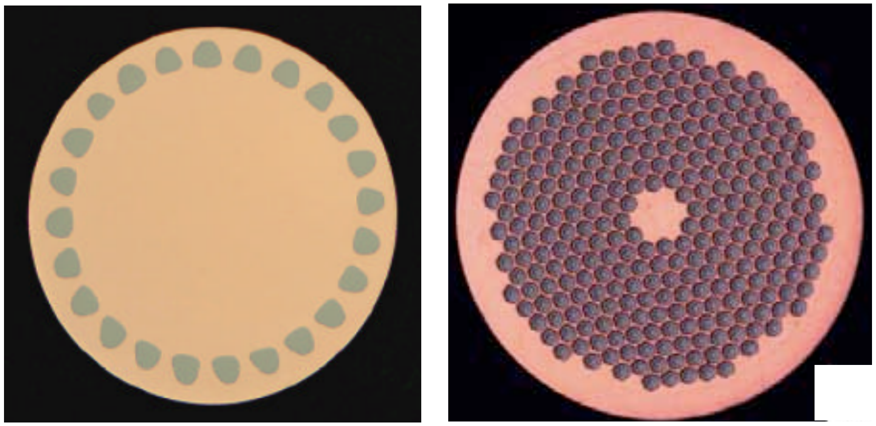
Material	Discovered	T_c [K] / B_{c2} [T]	Cost [$/kA m]	Remarks
NbTi	1961	10 / 14	0.5—1.5	< 12 T; easiest to use
Nb_3Sn	1954	18 / 26	5—10	> 12 T; wind-and-react
YBCO	1987	93 / 150	300—500	Only in tape [a]; [b]
Bi2223	1988	105 / 120	200—300	Only in tape [a]; [b]
MgB_2	2001	39 / 20	5—100	may compete with NbTi; [b]

[a] Generally for >25 T magnets

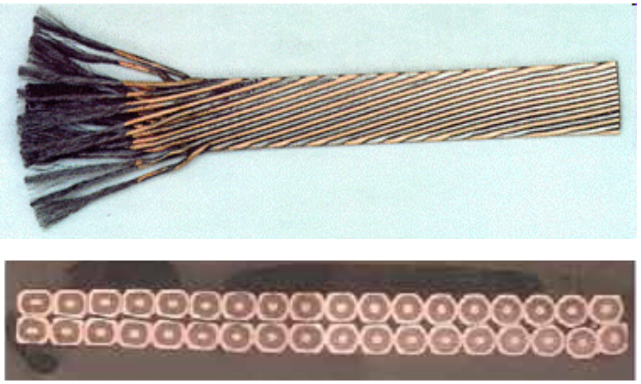
[b] Easier than LTS for cryocooled (i.e., LHe free) magnets; also $\geq$ 10-K operation possible

LTS (NbTi; Nb3Sn)

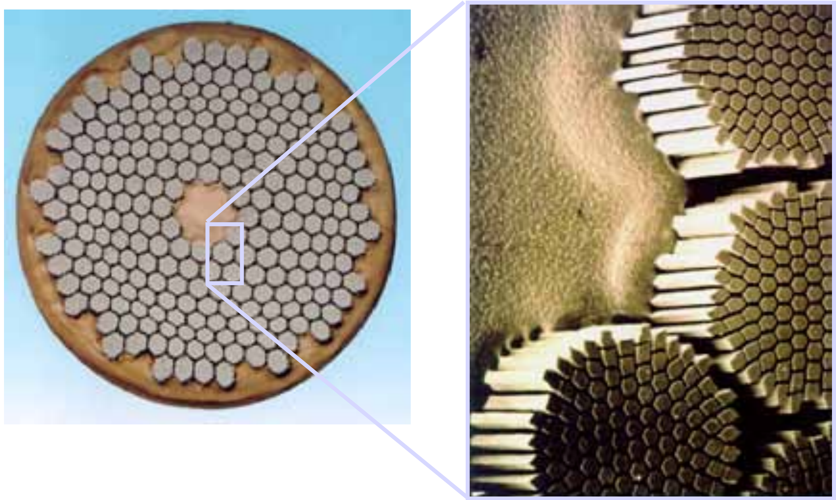
Wires ($\phi \sim$1-mm; Filament: ~10-50 µm)



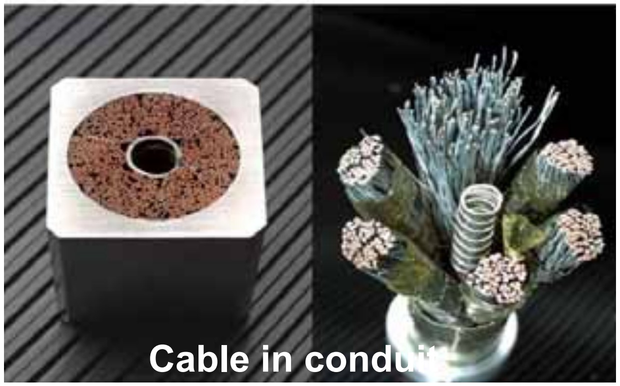
Cables (Width: 1-5 cm)



Restacked wires



ITER Nb3Sn Conductor: ~5 cm

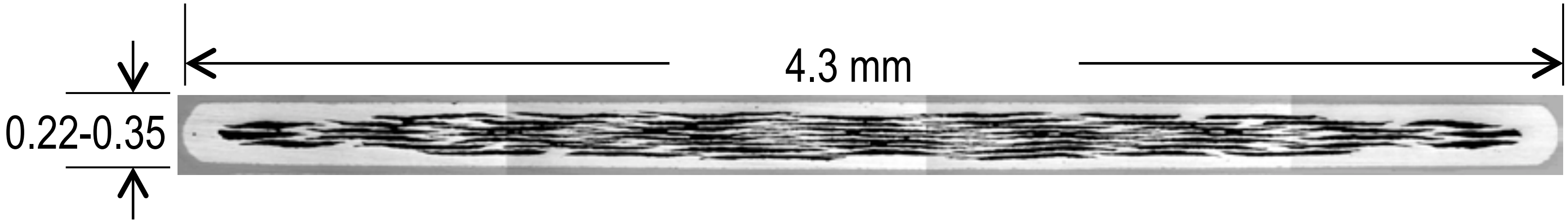


Bi2223

- Available only in *tape*

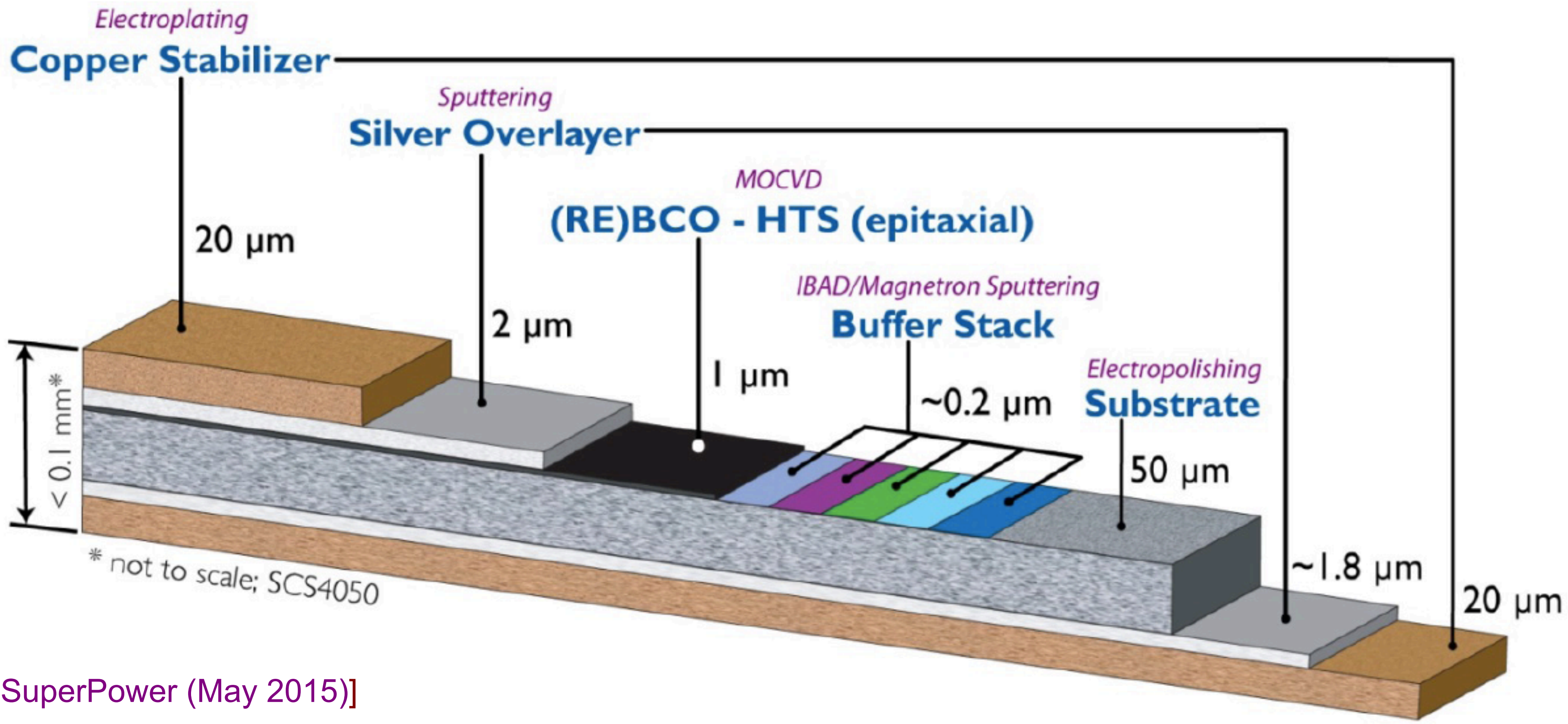
- Difficult to reduce AC losses — *suitable for DC coils*

An Example of Sumitomo Electric Bi2223



RE(Rare Earth)BCO

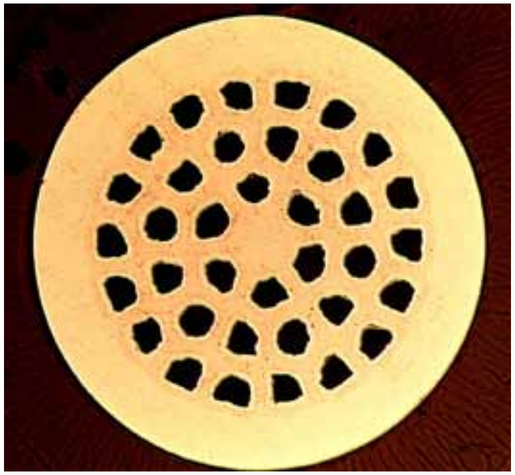
- Available only as *TAPE* — *same negative point as* Bi2223
- Even AFTER MORE THAN *20* years, *still the longest available < 500 m*



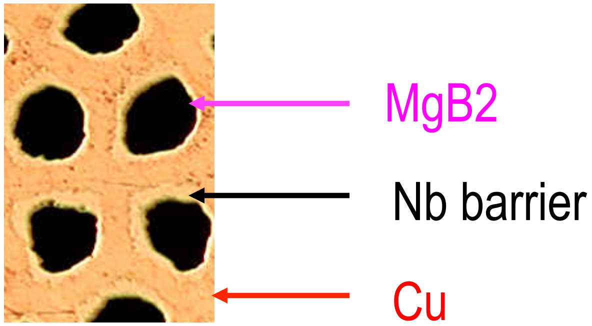
[SuperPower (May 2015)]

MgB2

- Available as WIRE
- Considered by many, still unproven, to be *price-competitive* against NbTi
- J_c (>10 K) still much less than that of NbTi (@4.2 K)
- More brittle than NbTi

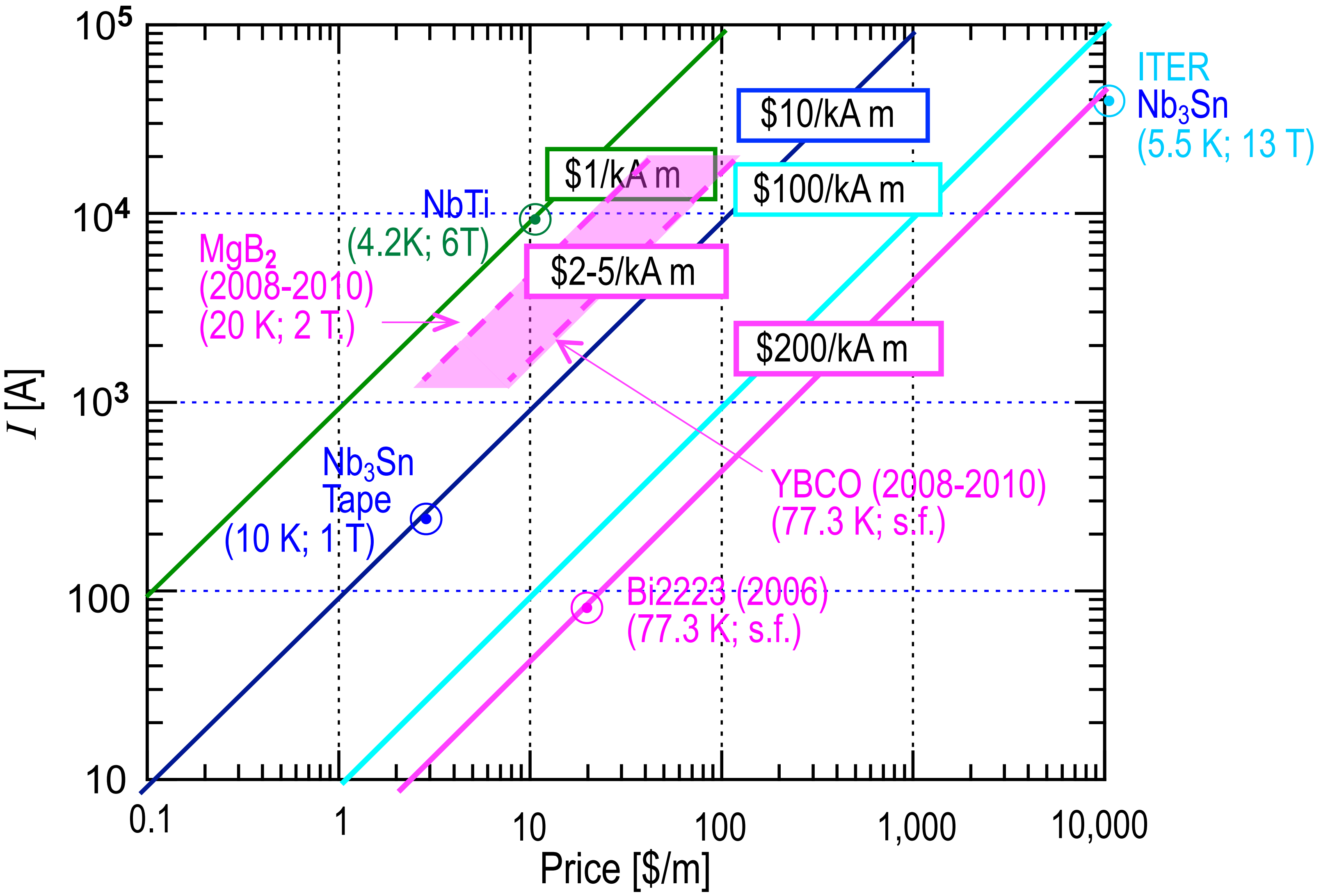


0.87 mmϕ 36-filament wire



[Mike Tomsic (Hyper Tech)]

Current-Carrying Capacity vs. Price/Length Plots



Remarkably, HTS prices in 2016 *not much different* from these ~2006 prices

Positive Aspects of Superconductivity

$R = 0$ under *DC* conditions: $I^2R = 0$

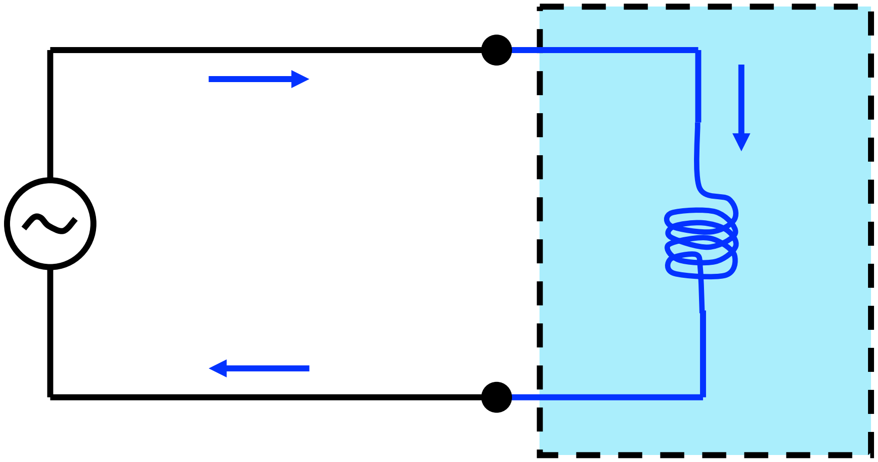
- Can generate a large magnetic field over a large volume
- Can generate a "*persistent*" magnetic field:

$$\frac{dH}{dt} = 0$$

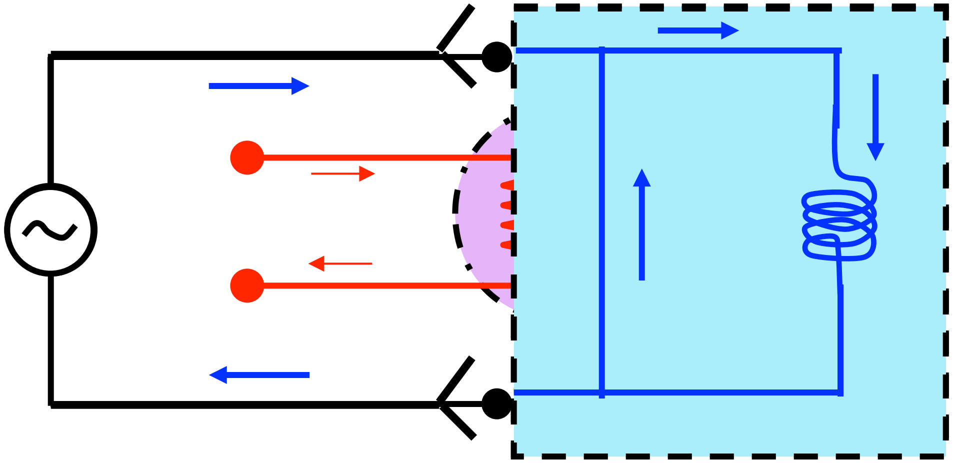
Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Two Modes of Operation

Driven System ($I^2R = 0$)



Persistent-Mode System ($dB/dt = 0$)



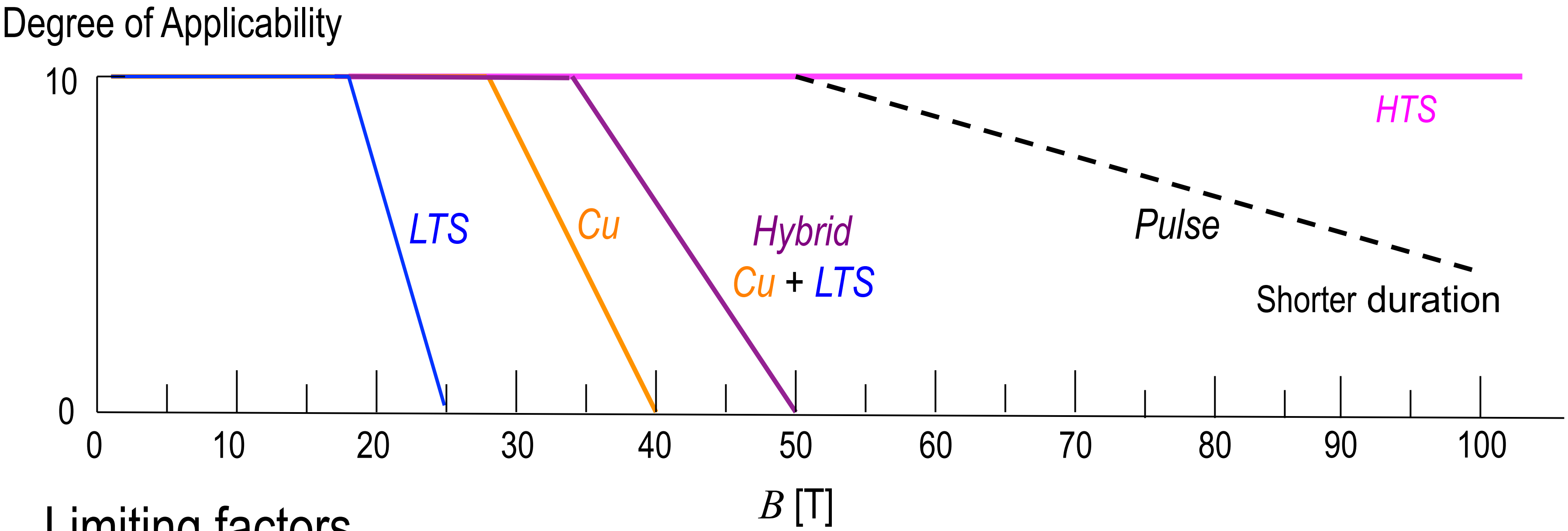
Standard
operation
mode for MRI
magnets

Magnet Types, Maximum Fields, Applications

Type	B_{max} [T]	i.d. [mm]	Applications (partial list)
Solenoid	45	~50	Hybrid magnet (NHMFL)
	30.5	~50	1.3 GHz LTS/HTS NMR (2020)
	23.5	~50	1 GHz LTS NMR (2009)
	3-12	50-300	Research
	1-17.5	~1000	MRI (1-3 T: clinical) >3 T (research)
	1.5	~2000	Magnetic separation
Dipole	3-15	50-80	High Energy Physics; 8.3 T (LHC)
Quadrupole	<10 (max)	50-80	High Energy Physics
Racetrack	<6	<2000	Electric power devices
Toroid	3-16	<10000	Fusion; 13 T (ITER)
(solenoidal)	5-10	<5000	SMES

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

High-Field Magnets



Limiting factors

LTS: $J_c(B)$

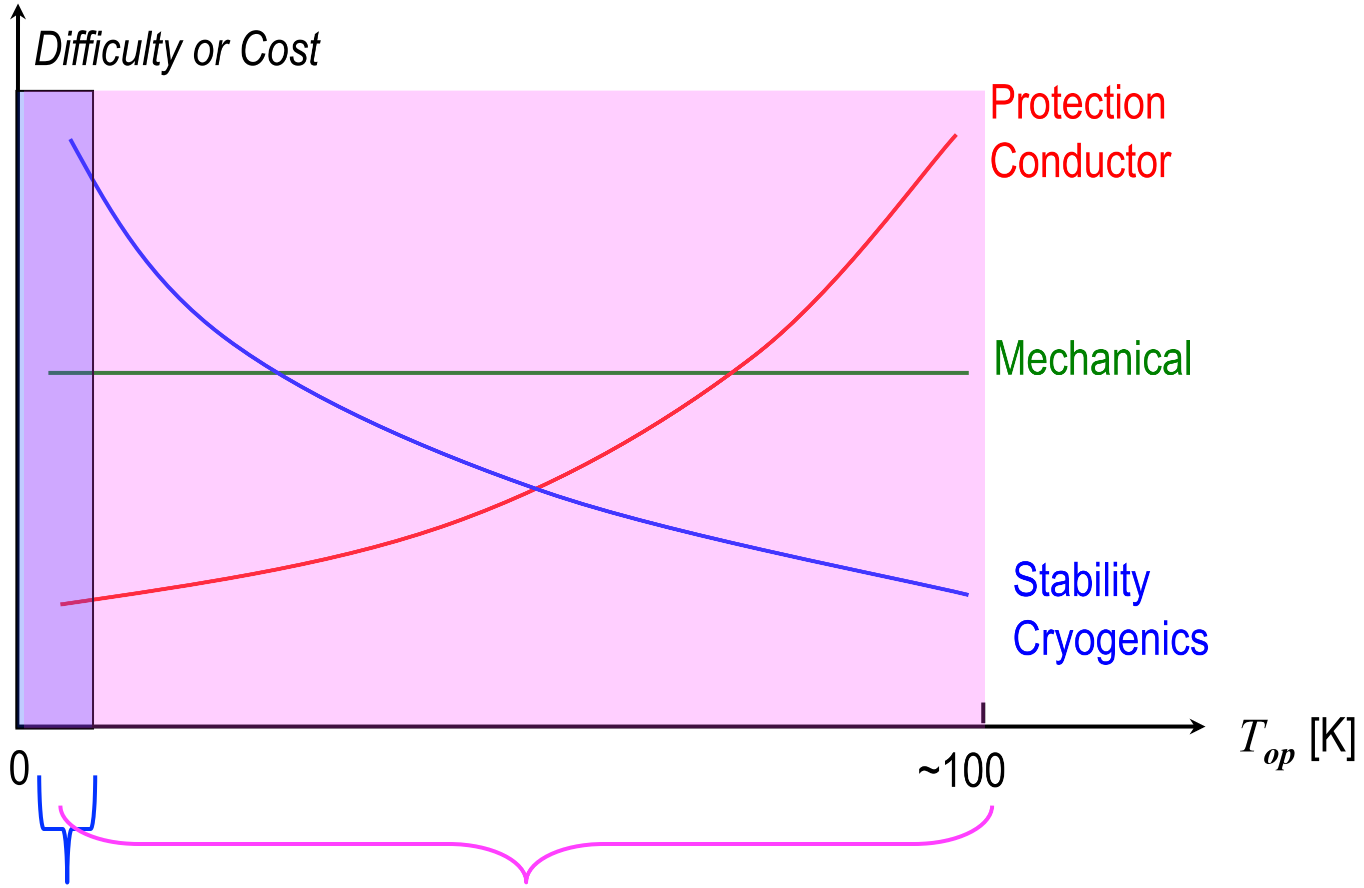
Cu: Material strength of copper and copper alloys; Power

Hybrid: Combination of Cu & LTS

Pulse: Material strength of high-strength steel alloys; Power

HTS: $J_c(B)$; material strength of reinforcement steel alloys

Key Magnet Issues vs. T_{op}

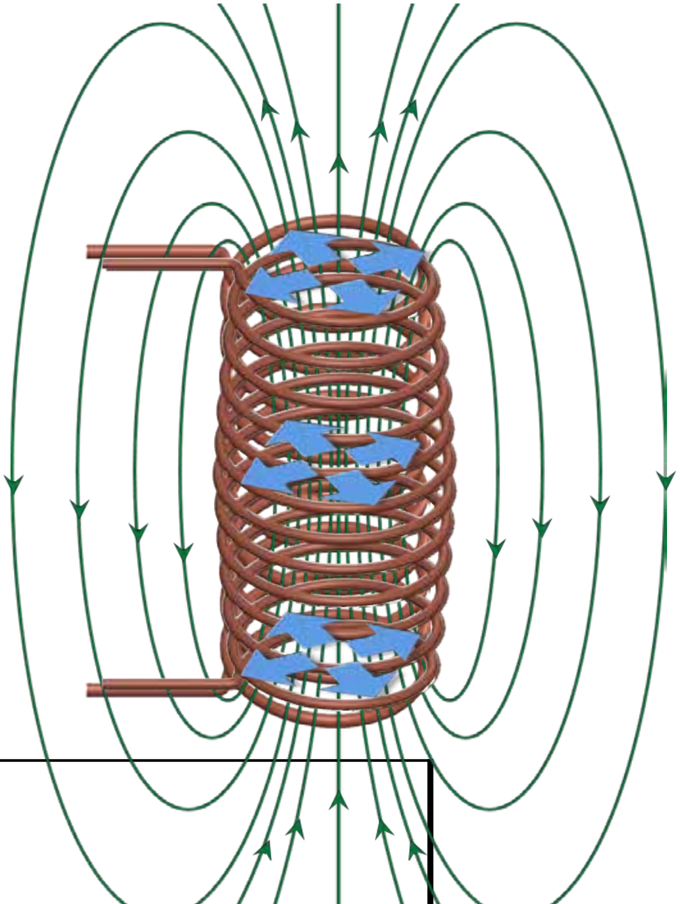


Range of Operation
for LTS Magnets

Range of Operation
for HTS Magnets

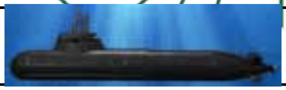
Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Mechanical Integrity



Magnetic pressure, $B^2/2\mu_\text{o}$

High-field magnet in a class by itself

Undersea Depth [m]	P_m [atm]	B [T]	f [GHz]	*Remarks*
300	30	2.7	0.12	Maximum for submarines 
11,000	1,100	16.5	0.7	Deepest sea bottom: *Challenger Deep* 
22,100	2,210	23.5	1.0	High-strength stainless steel yields at 14,000 atm
400,000	40,000	100	4.26	

Will Superconductivity Succeed in Many Areas?

Enabling vs. Replacing

Technology	*Performance*	*Competitor*	*Criterion*
Enabling	Yes	No	Performance
Replacing	No	Yes	Cost

- Even for enabling applications, *cost still very important*, for commercial products & even for funding agencies

Is Superconductivity Enabling?

Application	*In General*	*Yes, but only*
MRI (medicine)	Yes	> 0.5 T
HEP	Yes	> ~1 TeV
NMR/MRI (research)	Yes	> 2 T / > 3 T
High-B DC Magnet	Yes	> 2 T

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Superconductivity Enabling to Electric Power Applications?

Technology	*In General*	*Yes, but only*
Fusion	No	> 2050 (long research period)
SMES *	No	"Large" W h
Cable *	No	"Large" VA and "long" distance
Transformer *	No	"Compact"
FCL *	No	"Compact"
Motor/Generator *	No	"Compact"
Wind power *	No	"Compact"

* Cryogenics, now possible to be nearly as invisible as kitchen refrigerator, still, keeping T_{op} within a narrow range, can be a killer

Will wrist watches be as ubiquitous as they're now, if their T_{op} must be kept in the range 10—15° C?

Enabling Superconducting Magnets: MRI and NMR (≤500-MHz) & Research (>500-MHz NMR; >20-T Solenoids; HEP; Fusion)

Successful Marketplace Magnets

- Diagnostic MRI (hospitals)
- ≤500-MHz NMR magnets (Pharma labs: drug discovery/development)

Research Magnets

- >500-MHz NMR
- >20-T solenoids
- HEP
- Fusion

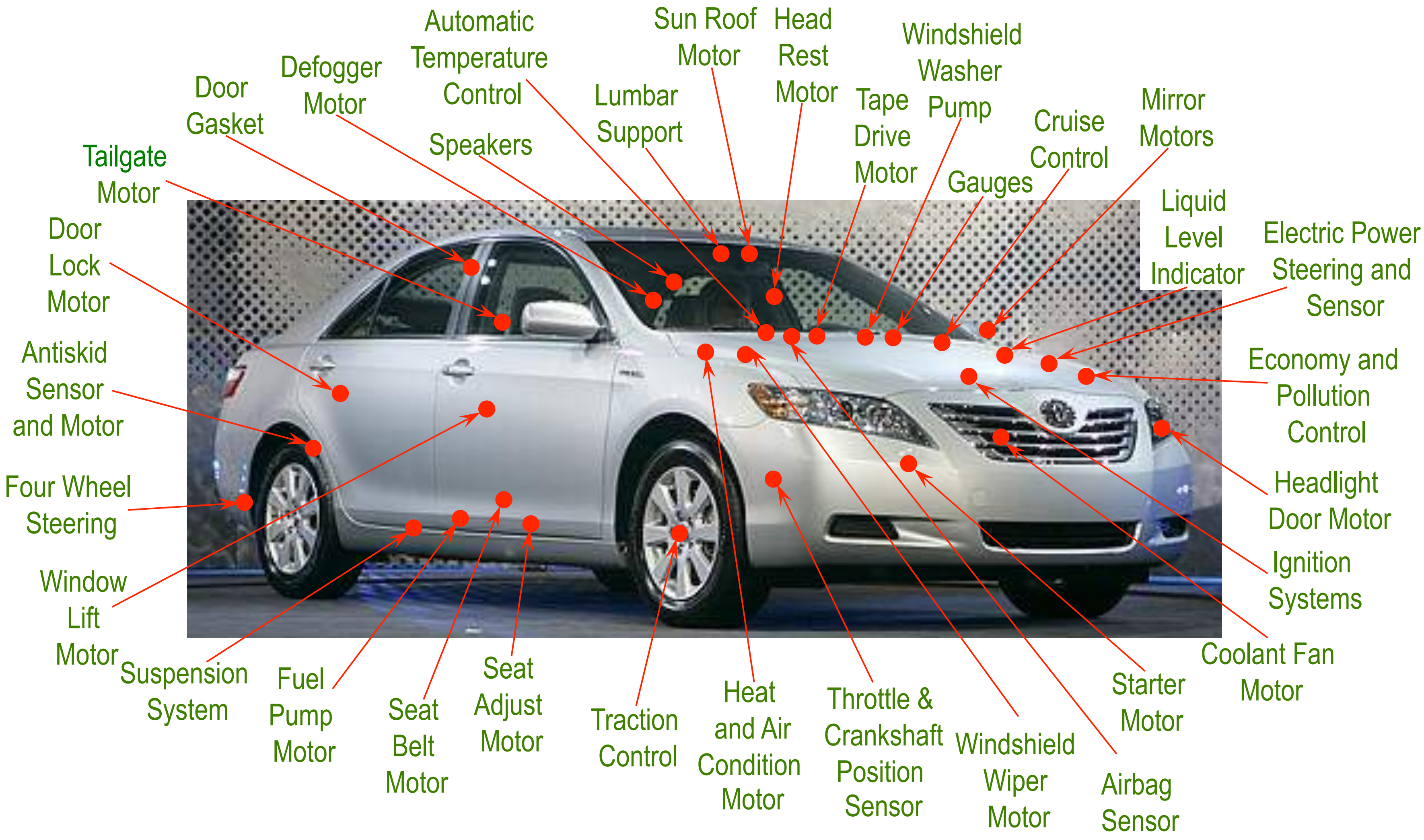
Present Magnet Technology: Selected Permanent Magnet Applications

- AC levitation melting (container-less melting of highly reactive metals in which AC fields provide both heating and levitation)
- Ballasts for normal fluorescent tube lights
- Eddy-current crack detectors
- Hotel keys
- Industrial ultrasonic cleaners
- Laboratory measuring instruments
- Magnetic microphones
- Metal detectors
- Industrial ultrasonic cleaners
- Racetrack starting gates
- Roadway car sensors that operate traffic lights
- Speakers
- Vending machine magnets that identify coins by induced eddy currents
- Video cameras

From James D. Livingston, *Driving Force: The Natural Magic of Magnets* (1996)

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Selected Permanent Magnets in Modern Automobiles



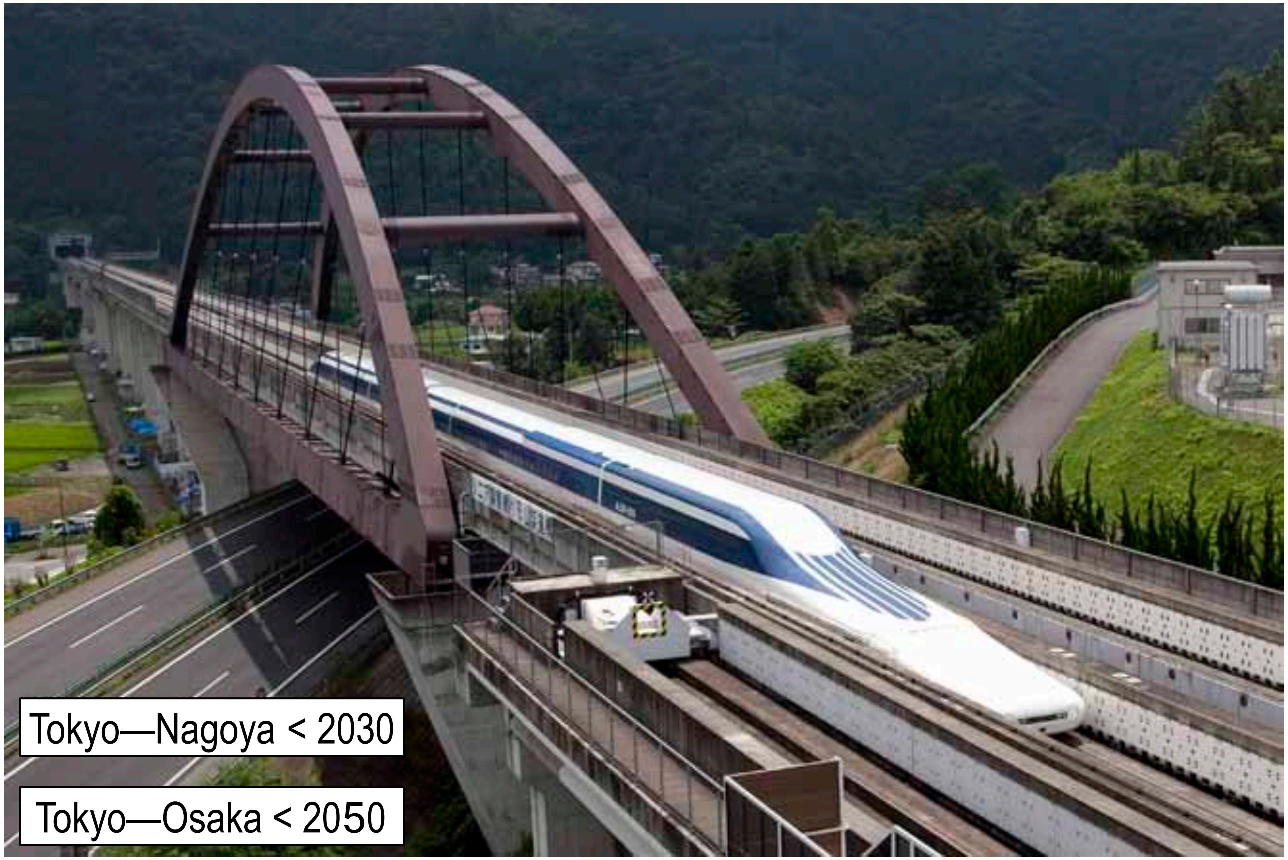
From James D. Livingston, *Driving Force: The Natural Magic of Magnets* (1996)

Future

Major Applications	Superconducting Magnet Technology
Outer space exploration	Sensors; possibly propulsion sources
Subatomic physics	Beyond LHC and beyond, beyond LHC
Ocean	Sensors; possible propulsion sources
Transportation	JR Central Maglev; more Maglev
Energy	Fusion: DEMO, NEXT; Solar; Wind; Hydro
Brain	NMR; MRI; something entirely new

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

JR Central Maglev



Tokyo—Nagoya < 2030

Tokyo—Osaka < 2050

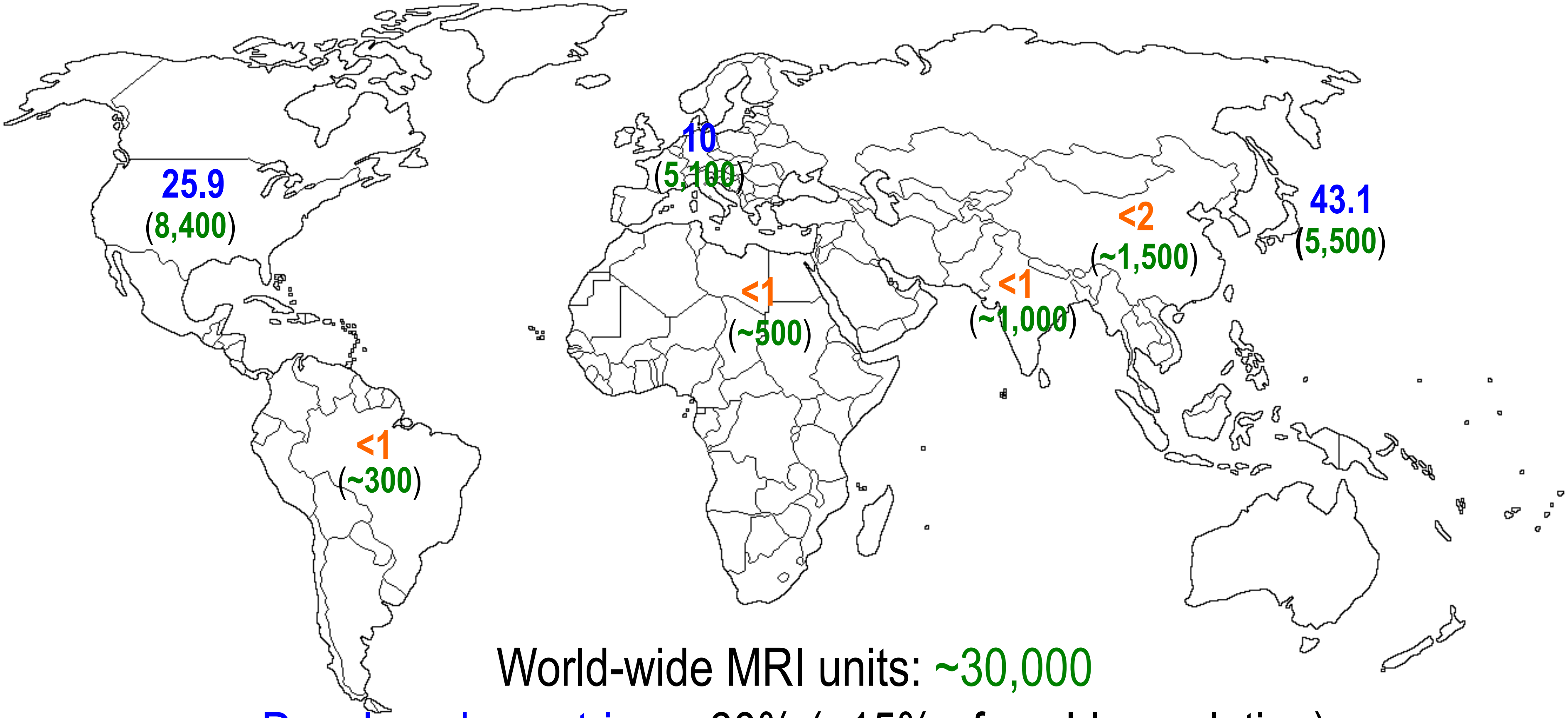
- Demonstrates superconducting maglev as a viable people mover
- Brings superconductivity much closer to the general public
  —up to this point only MRI has done this, but in a more limited way

Eikyu Kusano (JR Central)

MRI World-Wide Distribution

*MRI units per million population**

(Total Units)



World-wide MRI units: ~30,000

Developed countries: ~60% (~15% of world population)

Huge Market Potentials especially for LHe-free MRI magnets

* Based in Jiayin Ling data (2014)

Y Iwasa (MIT)
<iwasa@jokaku.mit.edu>

Four Stages in a Successful Project

1. A "brilliant idea" ⇒ a new project born
   - Unbounded enthusiasm; everyone wants to join in
   - Money pouring in; everything looks and smells *rosy*
2. Unexpected problems crop up
   - Usual schedule delays & obligatory cost overruns
   - Doubt sets in ⇒ *Are we sure we want to go on?*
3. Search for the guilty ⇒ Punishment of the *innocent*
4. Finally, success!
   - Awards and honors to the *non-participant*

Regardless, ALWAYS do your best, consistent with good citizenship

Merci beaucoup