TODAI Forum “Renewable Energy and Related Technologies”

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High-T_c Superconducting Technologies and Their Future Power Applications

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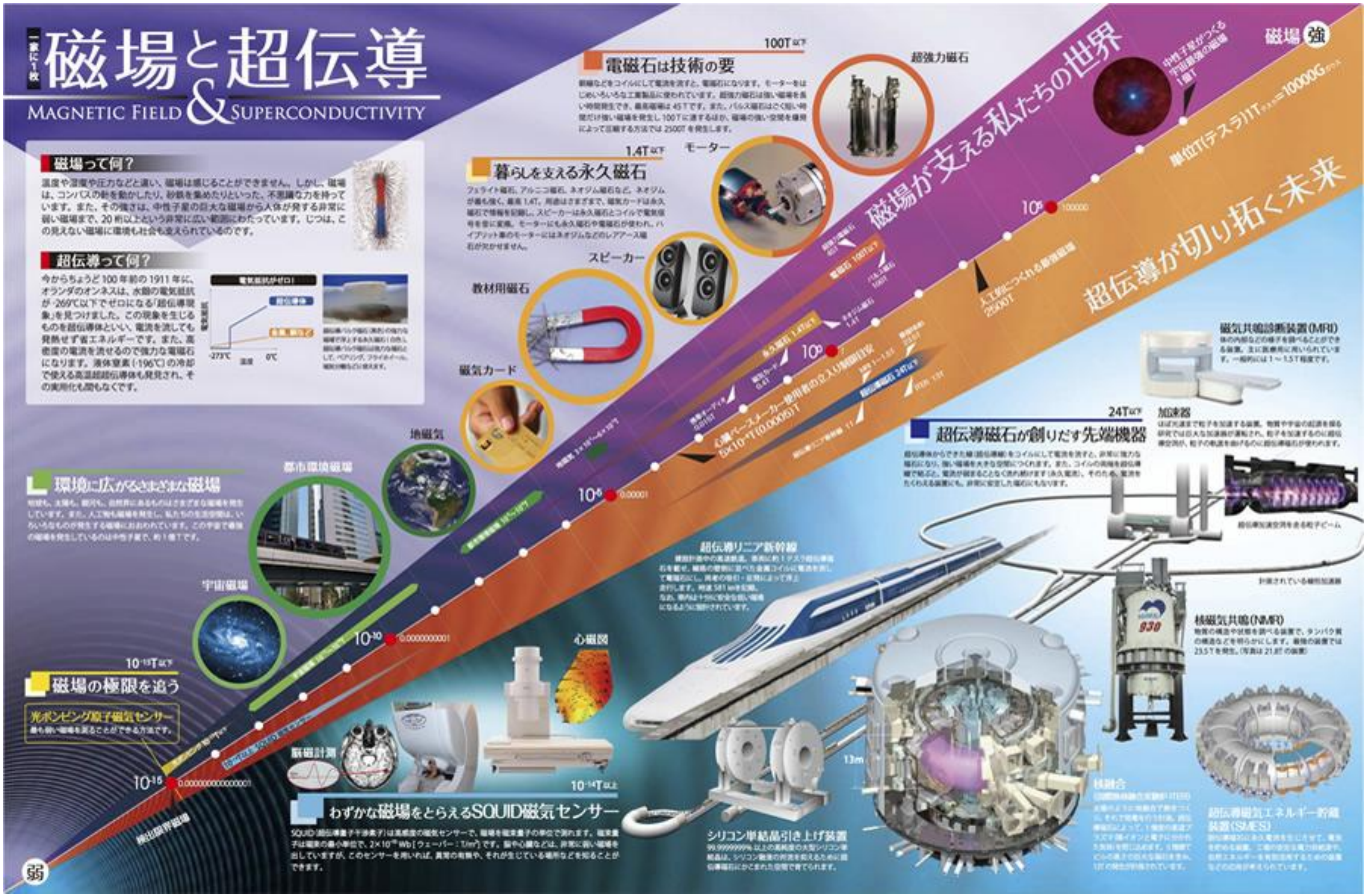
Poster for Science & Technology Week, 2011 (METI)



Outline

1. **Characteristics of Superconductivity**
2. **Specialty of Superconducting Technology**
3. **Current status high-T_c superconducting materials and their applications**
4. **Future problems of the earth and possible application of superconducting technologies**
5. **Summary**

1. Characteristics of Superconductivity

Attractive point of superconductivity

1911 Discovery of superconductivity
1913 Fabrication of superconducting lead coil

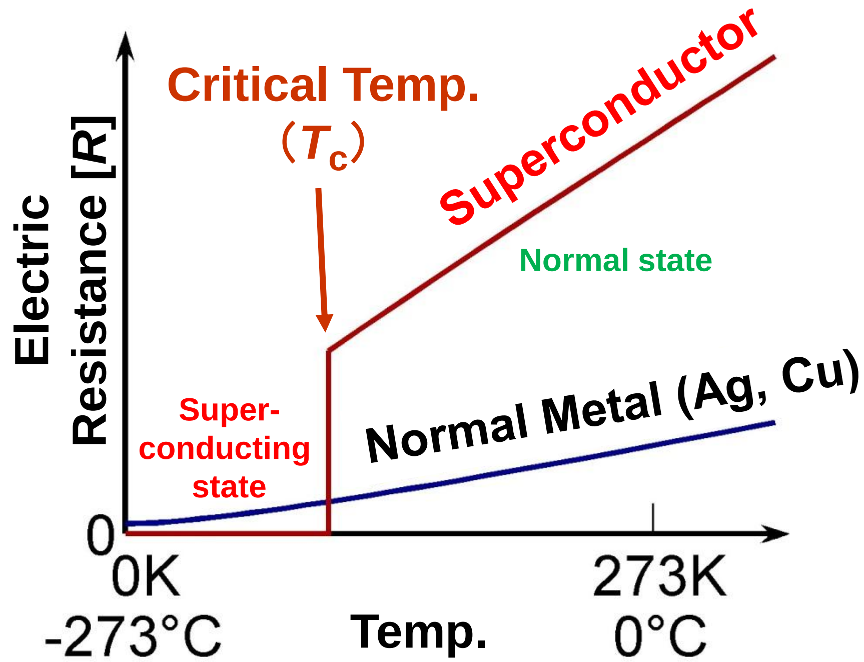
Why the superconductor is still expected as for future materials, whereas it has 100 years history for material developments?

Electric resistance *R* = 0

- **Superconducting materials have innate abilities for contributing environmental & energy problems and future society**
- **No competitive materials in principle**
- **Only one problem --- low temperature technology**

Effects of Zero Resistance [$R = 0$]

$R = 0$ for DC current



$i^2R = 0$

Low energy loss
＋High current density

Cables with low loss & large capacity

Superconducting magnet
- high field generation
- large field volume
- compact, lightweight

Compact magnets (MAGLEV)
Energy storage
High resolution NMR, MRI

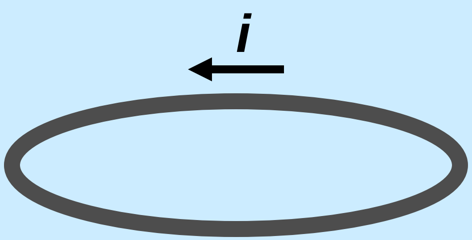
$R = 0$ for fine wires

Low loss integrated cuicuit

$L / R = \infty$

Persistent current circuit

Persistent current at closed superconducting circuit



Ring of superconductor

$$i\,(t) = i\,(0)\; e^{-(R/\,L)t}$$

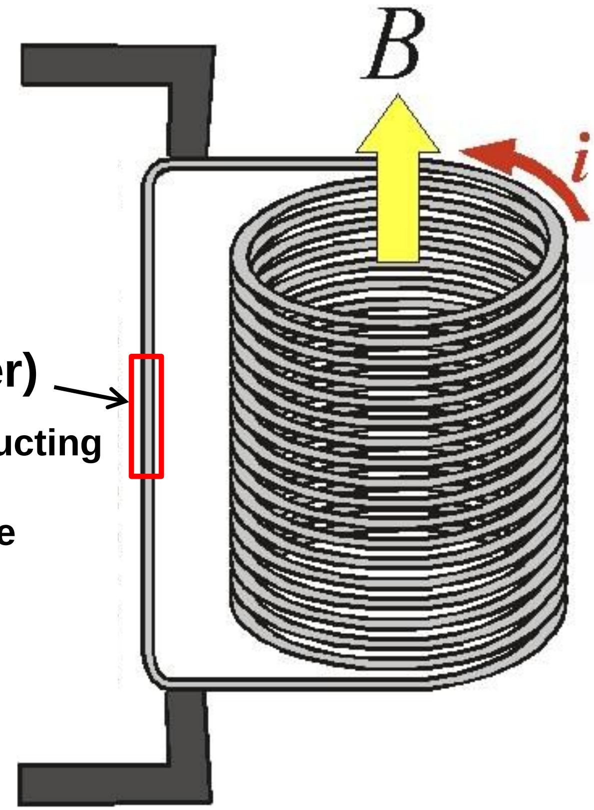
R: 0

L: self-inductance of the coil

Power current does not change perpetually, longer than the life of the earth.

Persistent current

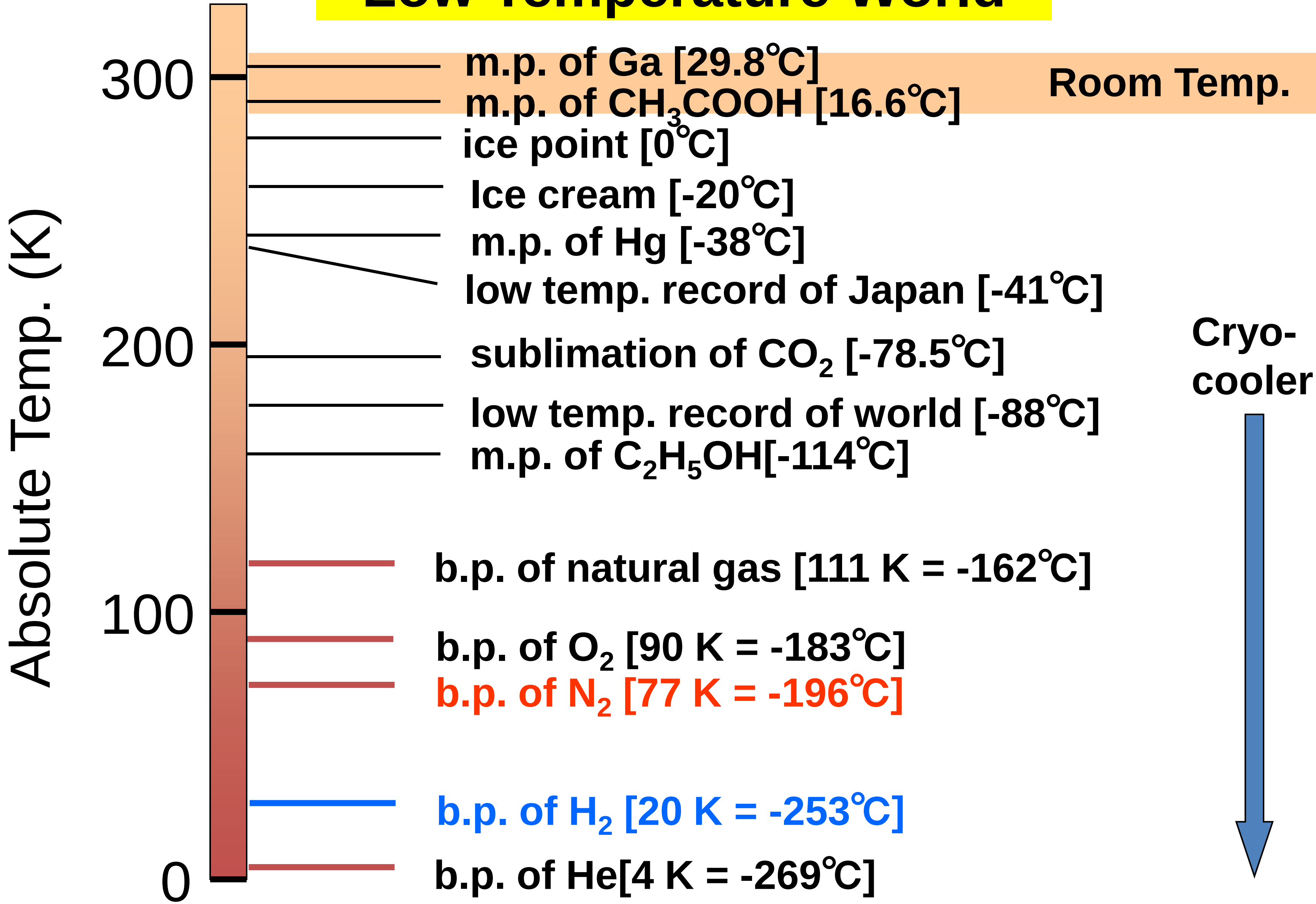
Persistent current circuit



Electric power is stored as magnetic energy.

Quite stable magnetic field

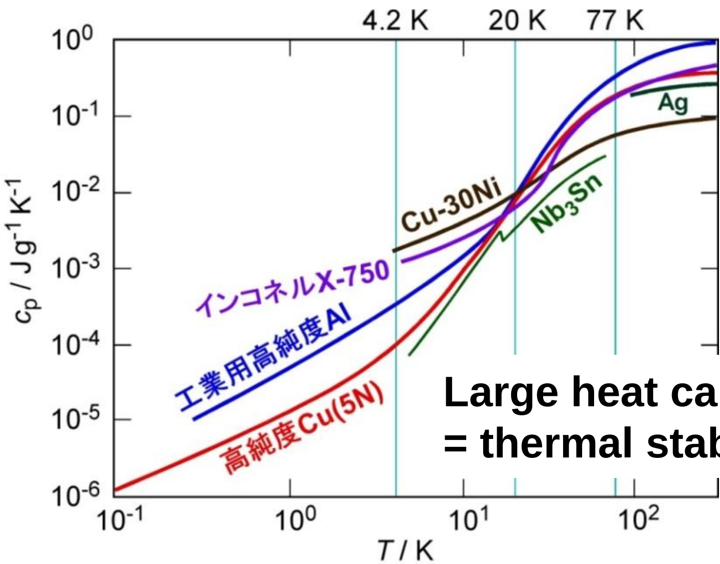
Low Temperature World



Liq. N_2： 66 K(low *p*)~77.3 K(1 bar)、liq. H_2： 14 K(low *p*)~20.3 K(1 bar)
Liq. He： 1.8 K(low *p*)~4.2 K(1 bar)

Advantages of Applications at High Temperature

heat capacity vs temp.

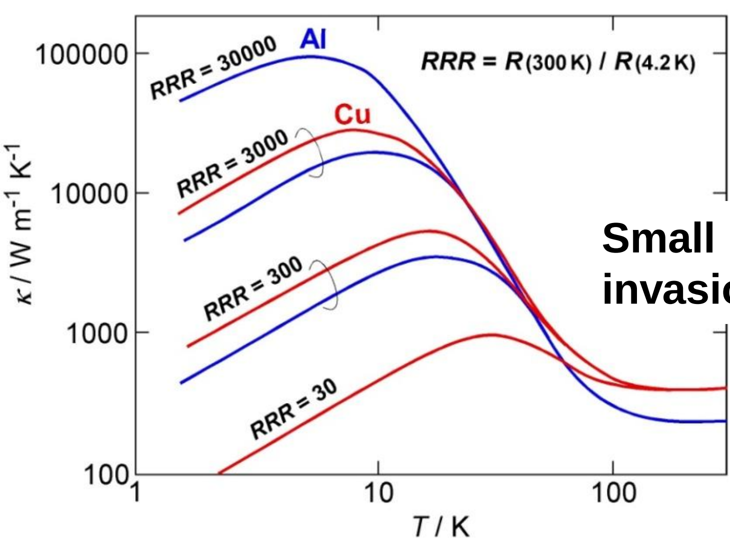


Large heat capacity = thermal stability

Properties of coolant (per ℓ, @b.p)

coolant	b.p (K)	density (g/ℓ)	latent heat (kJ/ℓ)
He	4.2	125	2.6
H_2	20.3	71	31.7
Ne	27.1	1204	105.0
N_2	77.4	804	160.1
CH_4	111.6	415	211.6

thermal conductivity vs temp.



Small heat invasion

Efficiency of cooling

COP: coefficient of performance

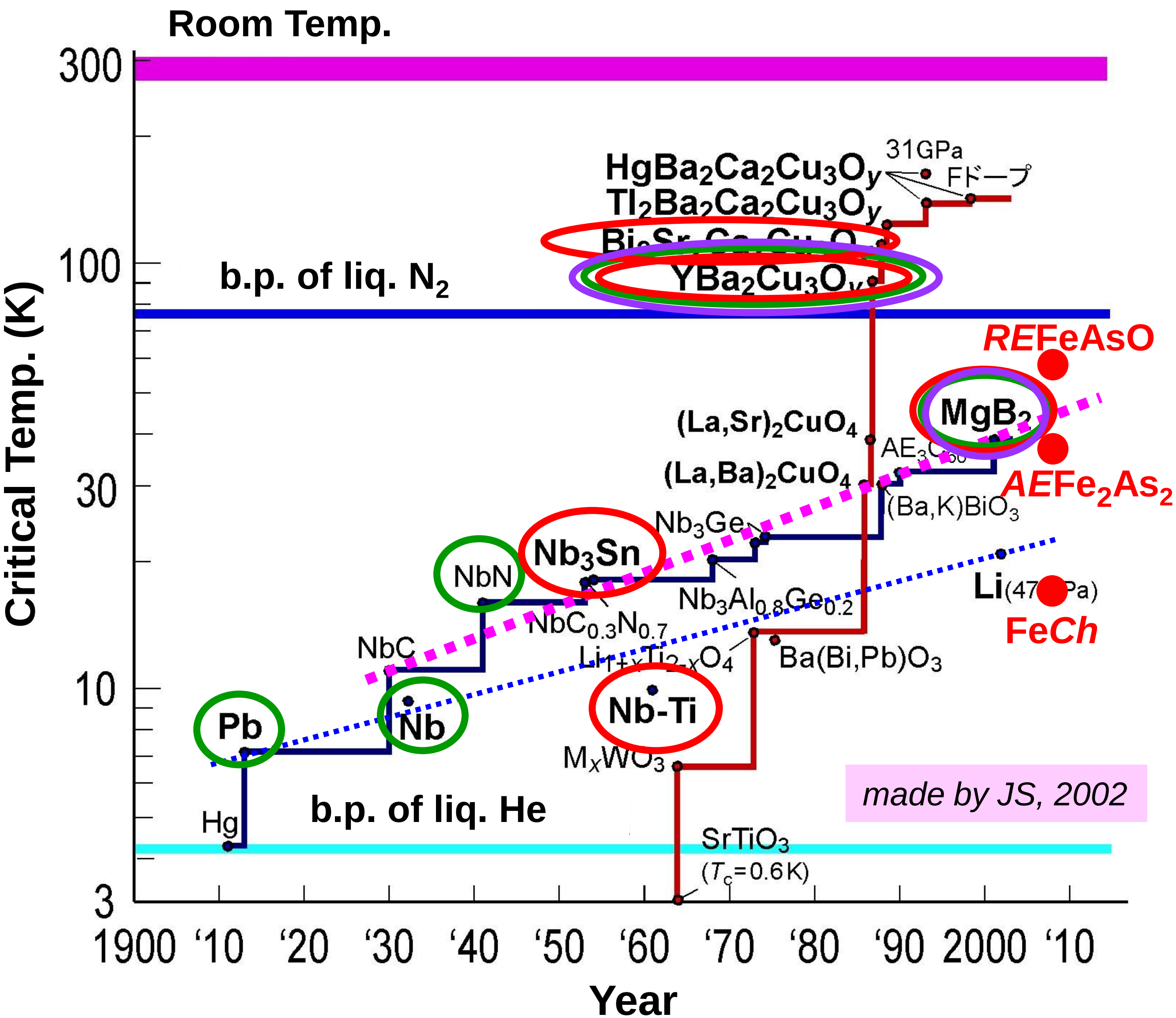
$$\mathrm{COP} = \frac{T_{(\mathrm{low}\ T)}}{T_{(\mathrm{high}\ T)} - T_{(\mathrm{low}\ T)}}$$

When $T_{(\mathrm{high}\ T)}$ = 300 K,

$T_{(\mathrm{low}\ T)}$ = 4.2 K : COP = 0.014

$T_{(\mathrm{low}\ T)}$ = 77 K : COP = 0.35

History of superconducting materials with changes of record-high T_c



Superconducting materials

- Tapes & Wires
- Electronic Devices
- Bulks

2. Specialty of Superconducting Technology

Superconducting Technology

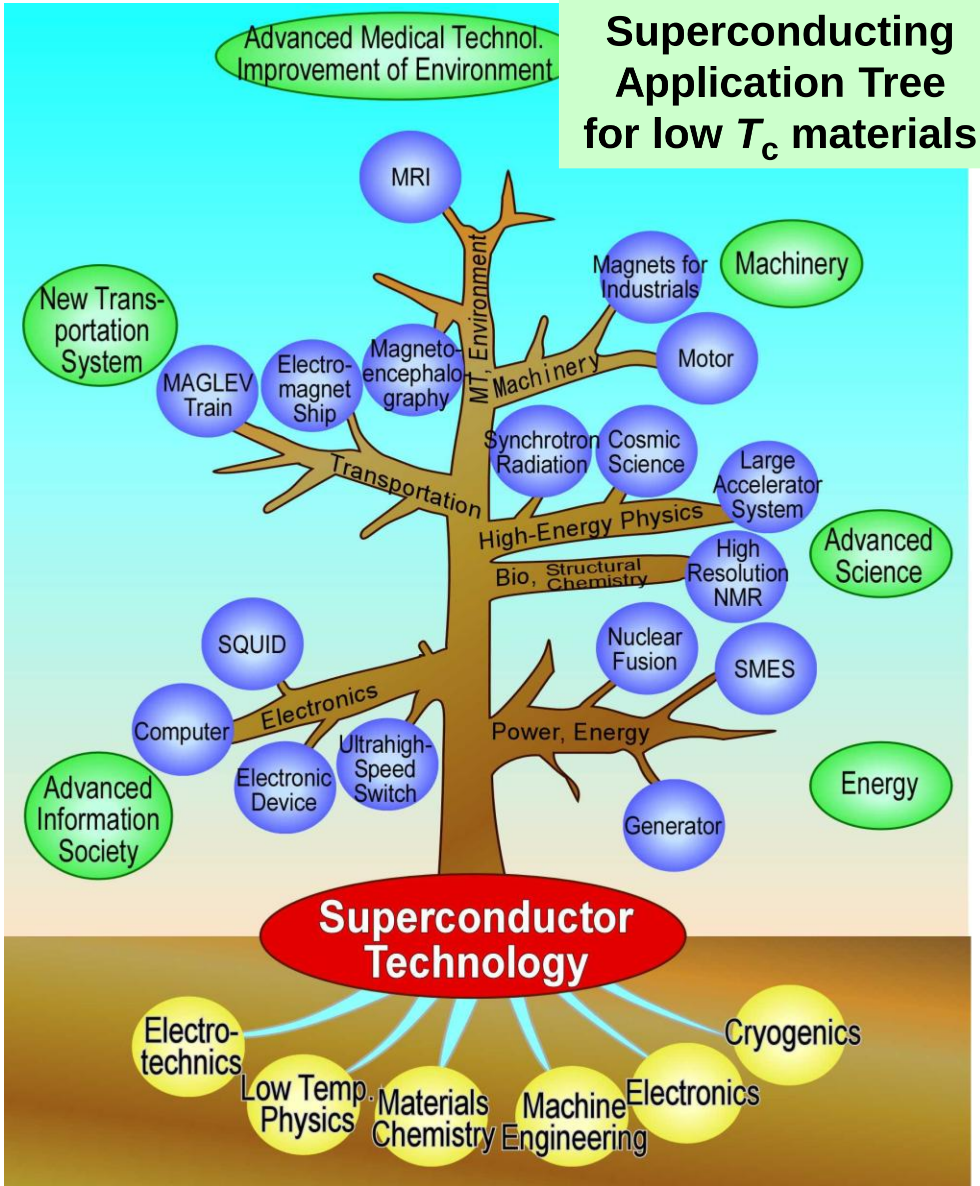
Characteristics & properties	Materials & apparatuses	Operation
derivation of high intrinsic performance of materials	high performance	under stable state
design, selection of materials, optimization of performance	synthesis techniques	cooling & operation technologies

Characteristics of superconducting technology (from researchers side)

- from synthesis at high temp. to evaluation of properties at low temp.
- cooperation and fusion of knowledge based on various academic fields

Superconducting materials are only the materials for users, who don't have any interests in compounds, construction of the materials and their microstructures.

Conventional low T_c superconducting materials and their applications



Superconducting Application Tree for low T_c materials

Applications opened by strong wishes

health, long life, new science

Even today, more than 90% of superconducting materials are of metallic superconductors

wires: Nb-Ti alloy (~98%: T_c~10 K)
Nb_3Sn (~1 %: T_c~18 K)

almost all wires for magnets

Electronic devices: Nb (T_c~9 K)

These must be cooled down to 4 K.
by liq. He or cryocooler.

Examples of application of metallic superconducting wires

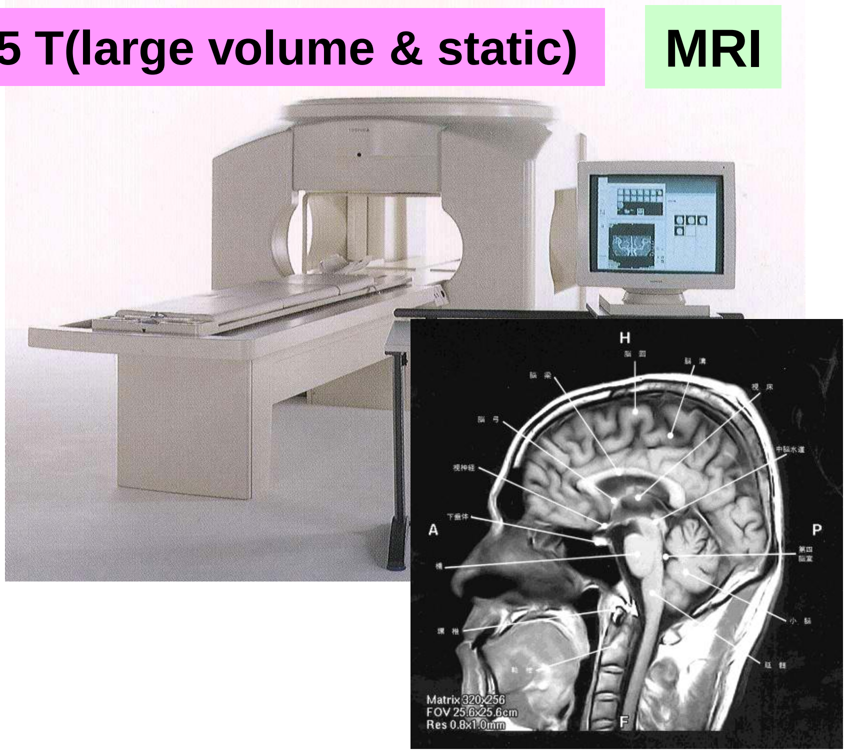
MAGLEV TRAIN

Chuo highway

5 T-class magnet

MRI

1.5 T(large volume & static)



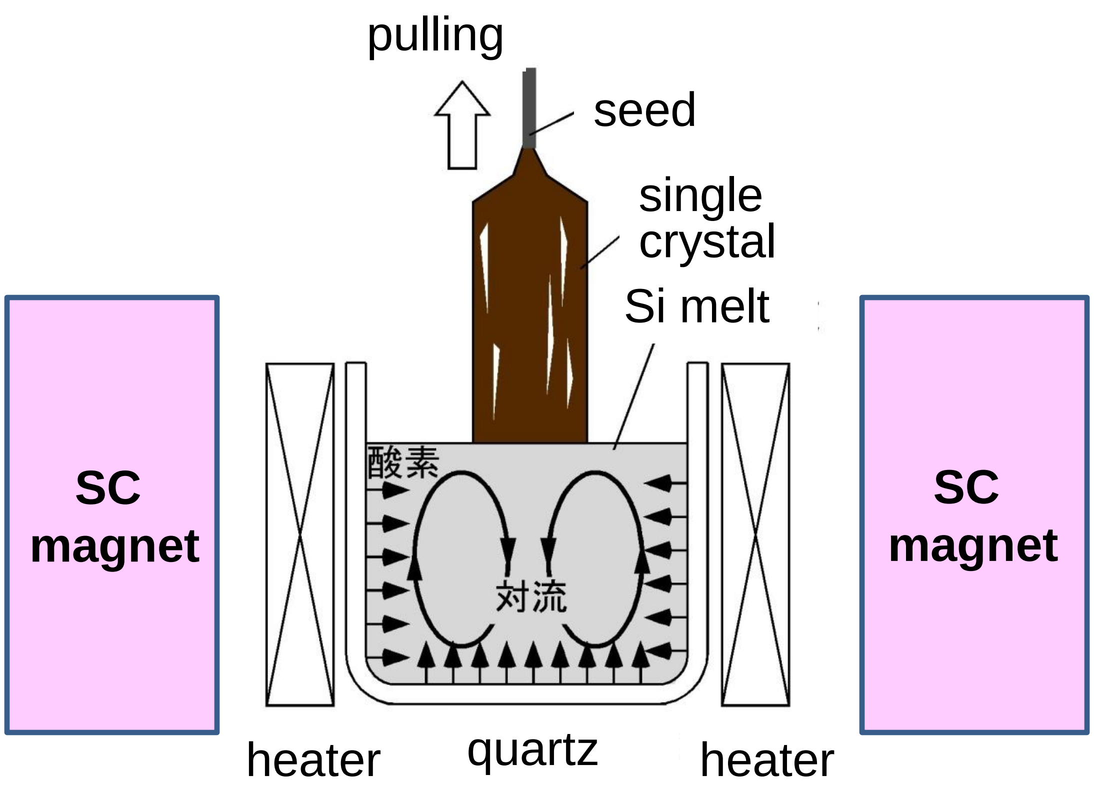
High Resolution NMR: 920 MHz

21.6 T (high & static)

Large Hadlon Collider

27 km in length

Superconducting magnet for single crystal growth of silicon



Crystal growth by Czochralski method
High purity > 9 N
large diameter, 12 inch

Large superconducting magnet mainly made by Nb-Ti

Bi(Pb)2223 magnet
(Toshiba, ShinEtsu, SEI)

Suppression of convection of silicon melt by magnetic field, ~0.4 T

Problem : contamination of oxygen from quartz crucible

Obstacles for low-T_c superconductors

Applications at low temperatures (~4 K)

cooled by liq. He or cryocoolers consuming large electric power

Problems of He --- expensive, sparse resource, small vaporization heat

Limitation of material design --- thermal stability is needed

Limitation of system design --- expensive and ingenious cooling system

⬇

- Isolated apparatus (not portable system)
- hardness in development of large scale and versatile systems

Superconducting Technology = special & expensive ⇒ limited users

⇒ Developed in fields with strong demands: medical, military, advanced science

Unsuitable for applications contributing to environmental and energy problems

Limitation due to upper critical field H_{c2}

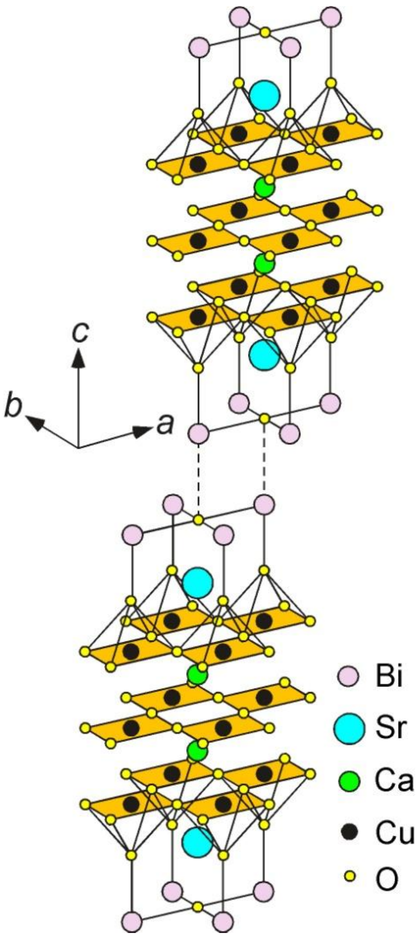
High field generation above 25 T is difficult.

--- not available for super high resolution NMR and actual fusion reactor

Crystal structures of representative high-T_c superconductors

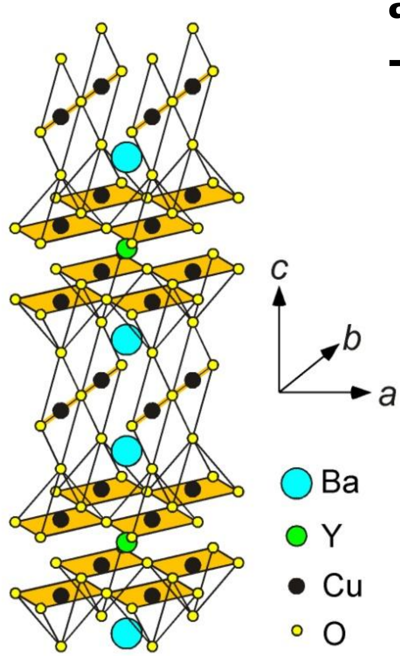
Layered crystal structure

Stacking of non-superconducting and superconducting layers -- anisotropic properties



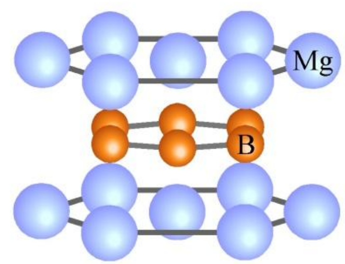
$Bi_2Sr_2Ca_2Cu_3O_y$

Bi-based superconductor

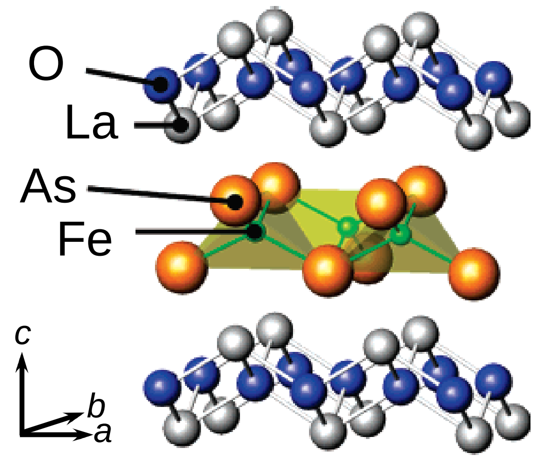


$YBa_2Cu_3O_y$

RE123 superconductor (RE: trivalent rare-earth)



MgB_2

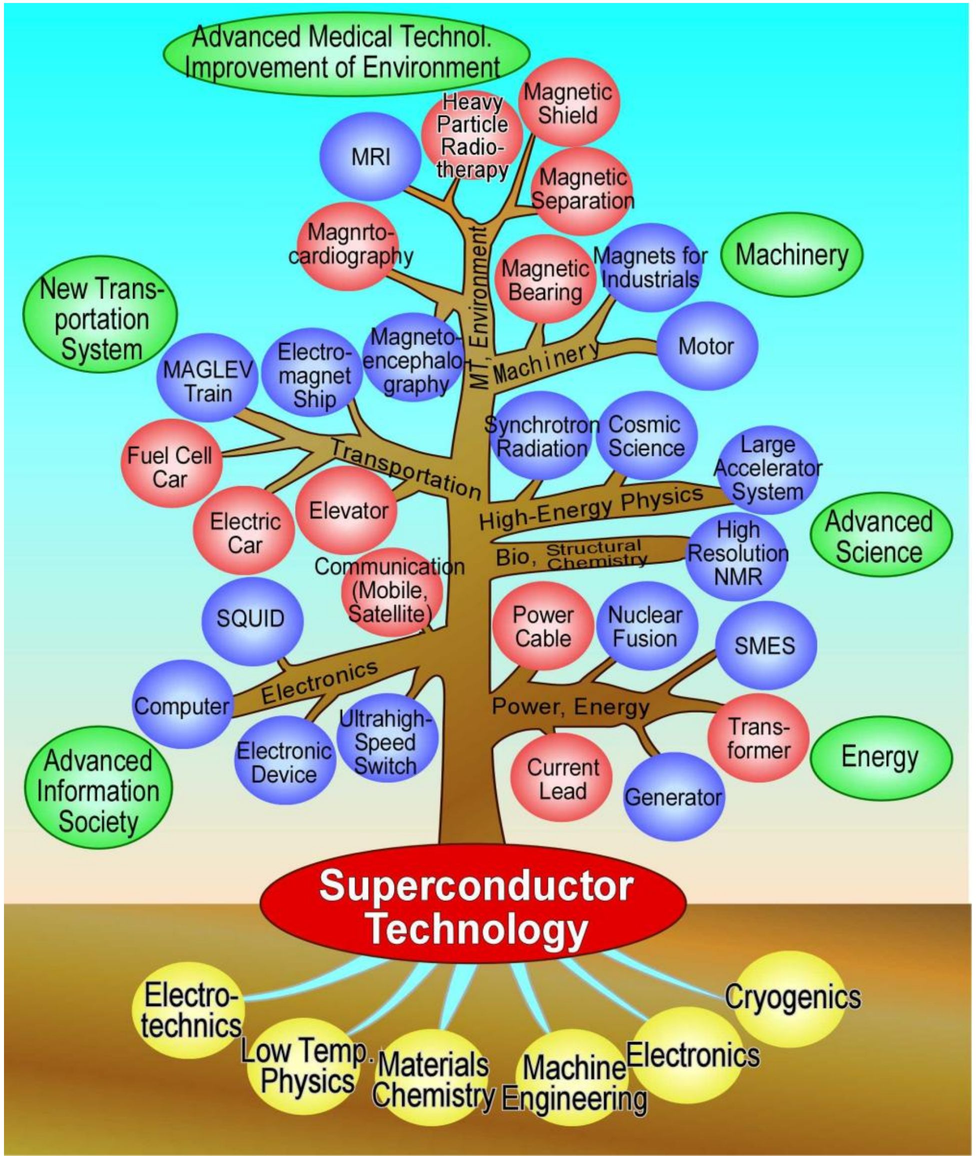


LaFeAsO

Iron-based superconductor

Superconducting Applications in Future

Easy cooling system without using liq. He



Popularization of superconducting systems

Enlargement of application fields

(high temp., high field, long length, portable, etc.)

+

Increase of social requirement

(environmental & energy problems advanced medical care & science)

3. Current status high-T_c superconducting materials and their applications

High-T_c superconducting tapes & wires for future applications

Bi-based cuprate (Bi(Pb)2223 : T_c ~112 K) [1st generation : 1990~]

Ag-sheathed tape fabricated by cold rolling and sintering

Production scale: 1000 km a year [mainly by Sumitomo Electric]

J_c (77 K) ~6 x 10^4 A/cm^2, J_e (77 K) ~ 2 x 10^4 A/cm^2

RE123 (T_c ~ 92 K) [2nd generation : 1991~]

Thin Coated Conductor

Production scale : ~700 km a year [SuperPower, AMSC, Fujikura]

J_c (77 K) ~ 2 x 10^6 A/cm^2, J_e (77 K) ~ 2 x 10^4 A/cm^2

high J_c in magnetic field (20~65 K)

MgB_2 (T_c < 39 K) [New metallic superconductor : 2003~]

Metal sheath wires & tapes [Columbus, HyperTech]

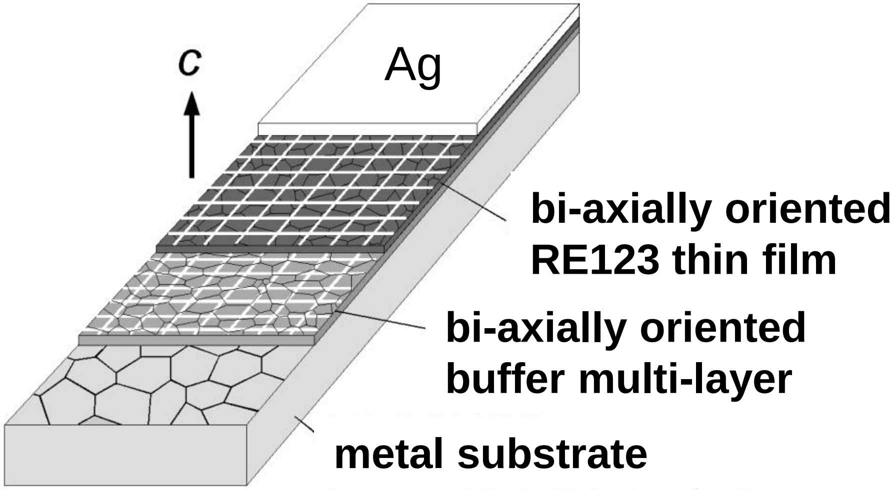
J_c (20 K) > 1 x 10^5 A/cm^2, J_e (20 K) > 2 x 10^4 A/cm^2

persistent current circuit can be made.

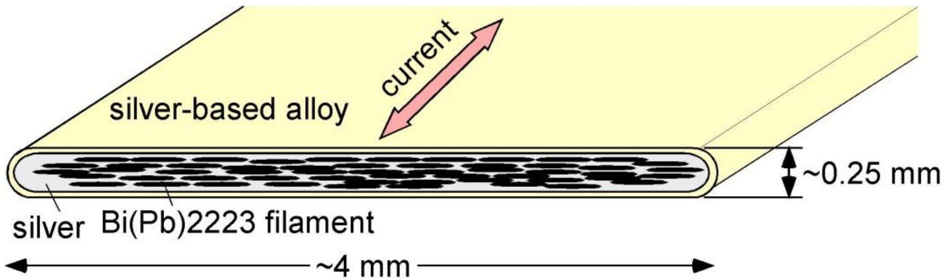
Structure of RE123 and Bi(Pb)2223 tapes

Improvement of properties
= enlargement of application fields and decreasing cost

RE123 tape (Coated Conductor)



Bi(Pb)2223 tape (Ag-sheathed)



J_c ~ 2 x 10^6 A /cm^2 at 77 K

Thin and mono superconducting layer

Ratio of RE123 layer : 1~3%

J_c ~ 6 x 10^4 A /cm^2 at 77 K

Multi-filament (55~121 filaments)

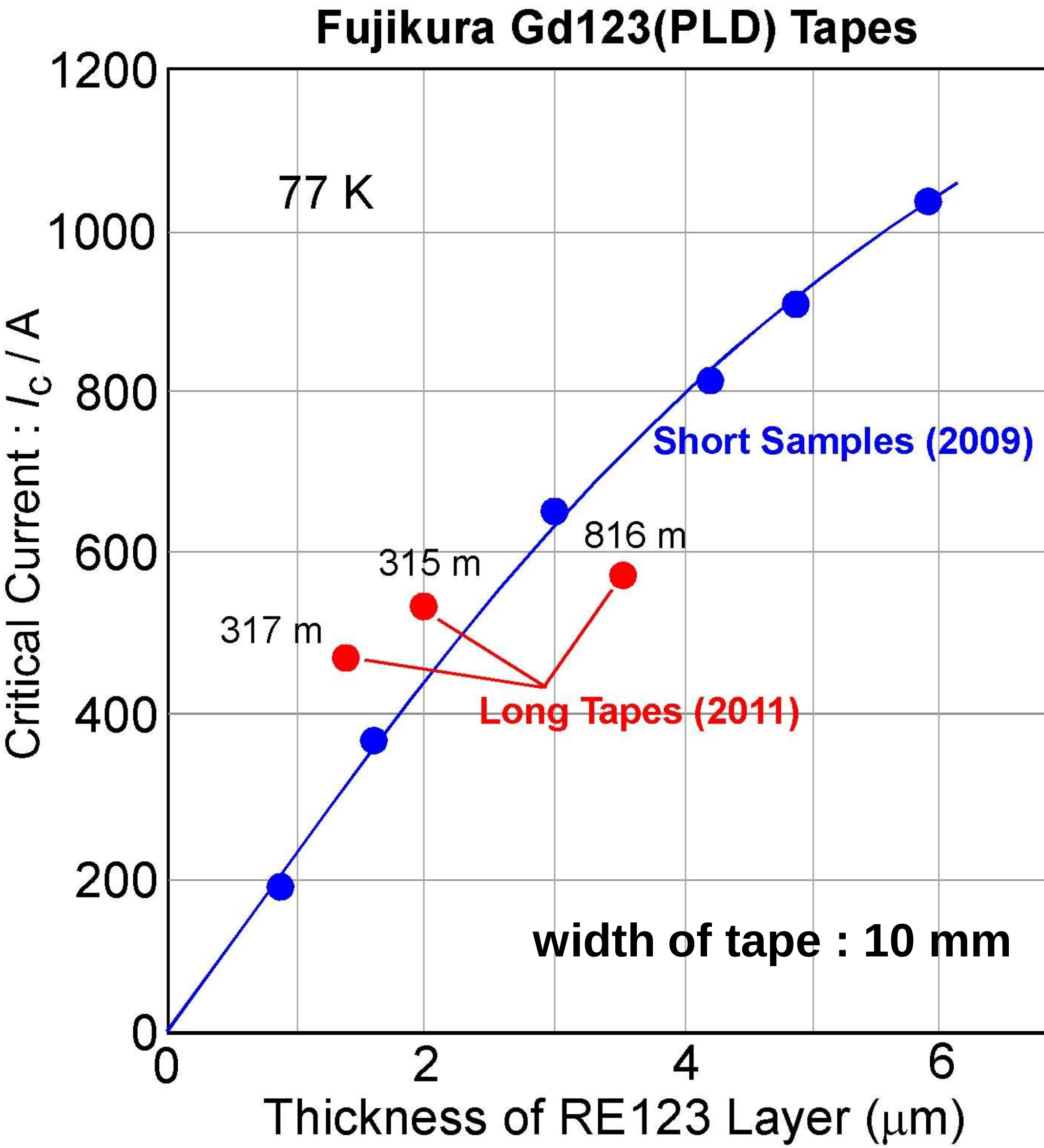
Ratio of Bi(Pb)2223 filament: ~40%

Strategy for improving properties

Increase of RE123 layer thickness without decreasing J_c

Enhancement of J_c in Bi(Pb)2223 filaments

Increase in critical current of RE123 conductor by increasing thickness of RE123 layer



Records of RE123 tapes

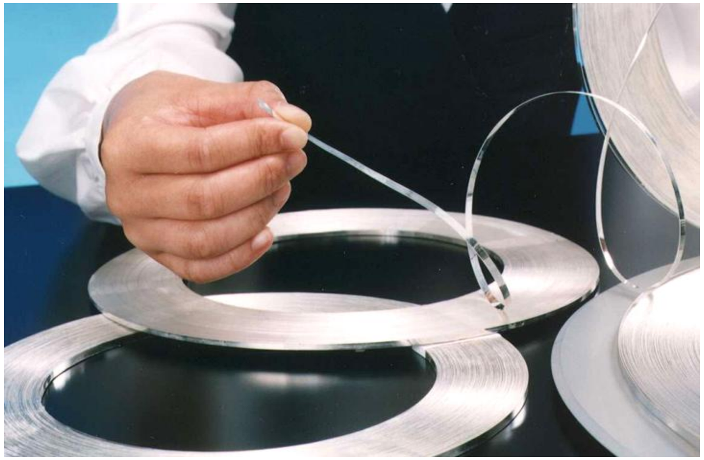
critical current : 1040 A (77 K) [Fujikura]

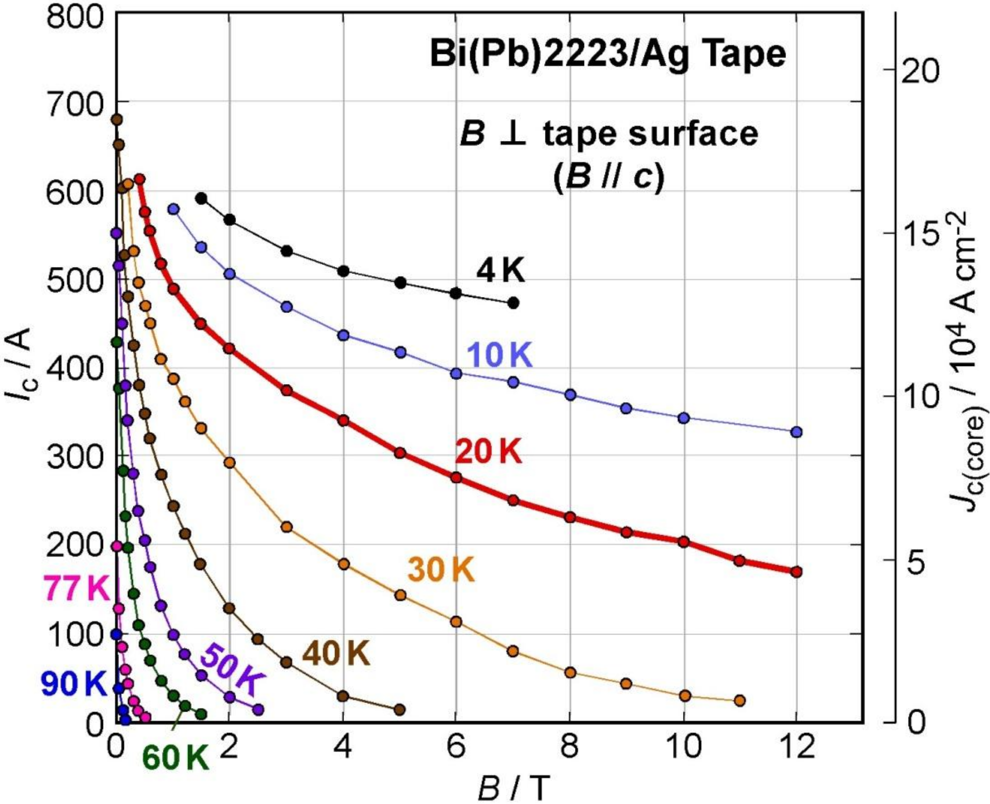
length : 1300 m [SuperPower]

length x critical current : 816 m x 572 A [Fujikura]

DI-BSCCO® Tape [Bi(Pb)2223]

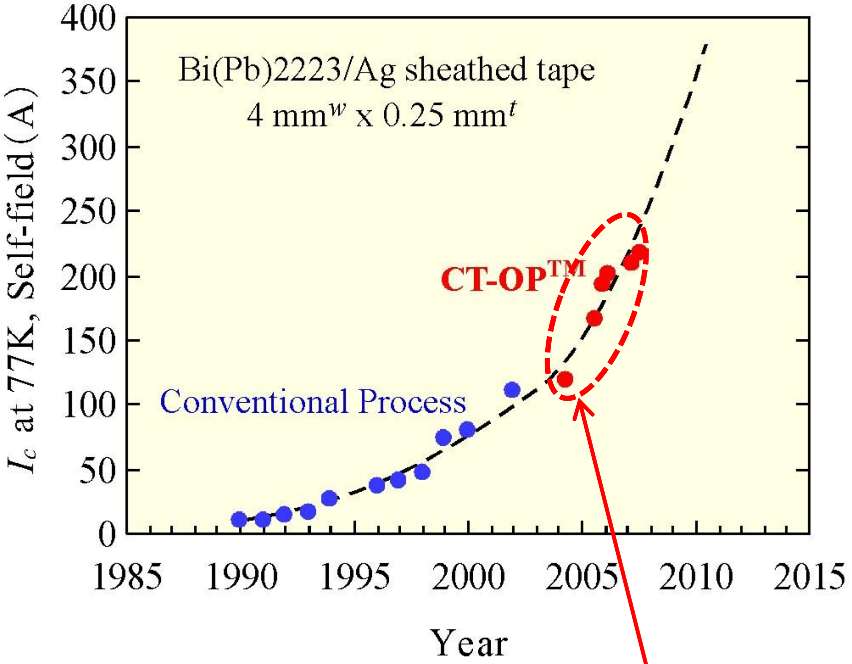
Improvement of characteristics of Bi2223 filaments by adopting CT-OP method (ConTrolled Over Pressure)



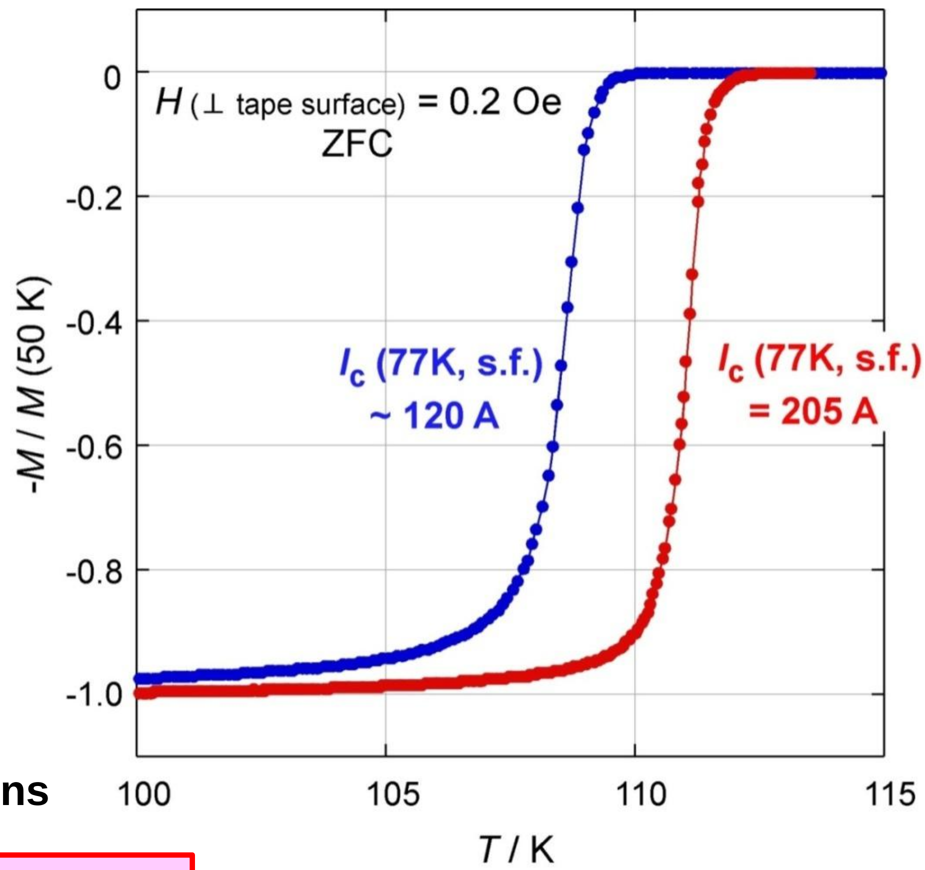


I_c (77 K, s.f.) : ~ 200 A (4 mm^w x 0.25 mm^t)
length : ~ 2 km (each tape)
total length per one batch: > 50 km

Improvement of critical current properties of Bi2223 tapes by an increase in T_c



Homogeneous properties over long tapes enabled optimization of synthesis conditions



records of Bi(Pb)2223 tapes

critical current： 250 A (77 K) [SEI]

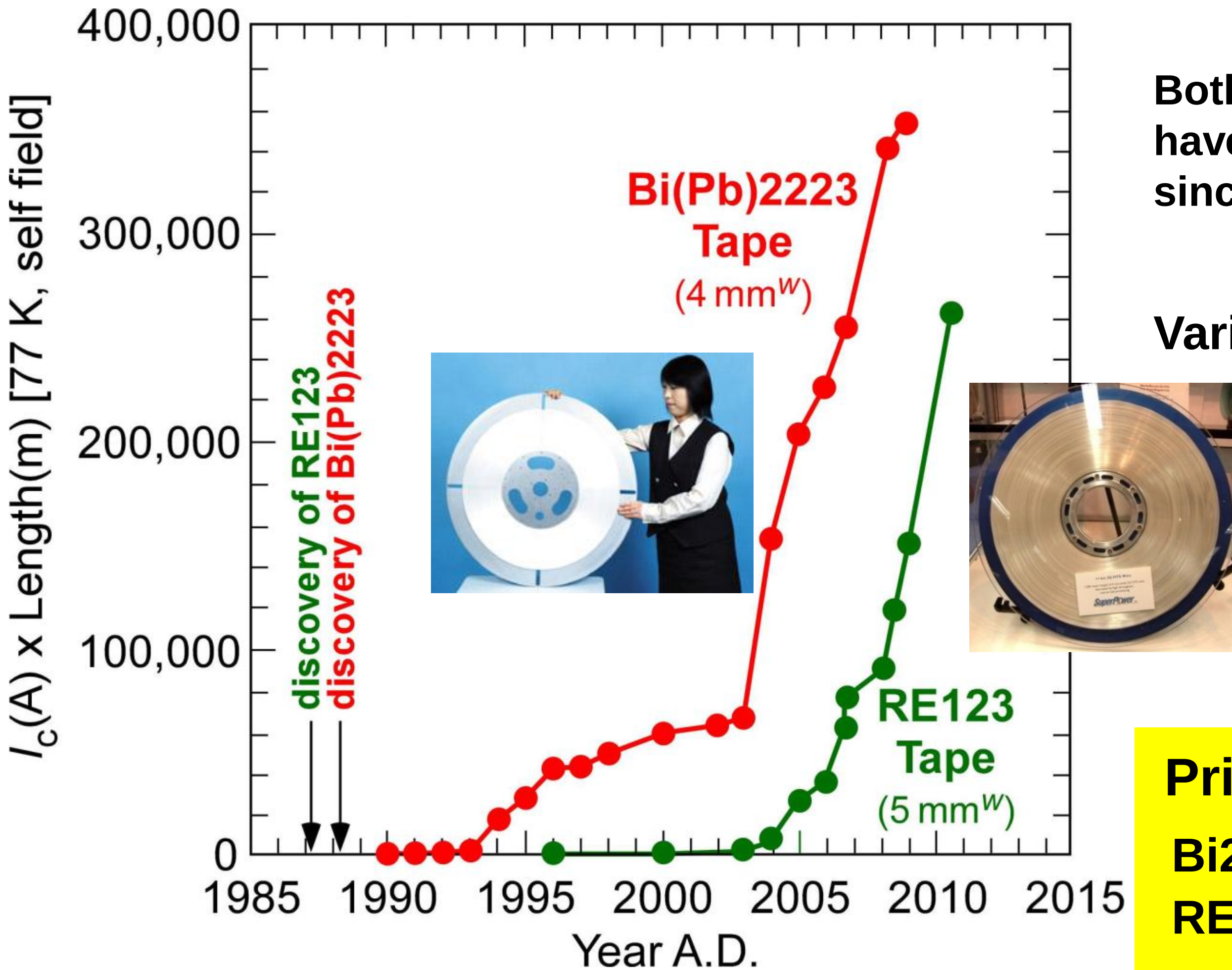
length： 3000 m [EST]

length x critical current： 2084 m x 176 A [SEI]

Only 2.5 K increase of T_cの largely enhanced I_c (SEI - U. Tokyo)

Superconducting materials = Growing materials

History of I_c x L values of high-T_c superconducting tapes



Both properties and productivity have been dramatically improved since 2004.

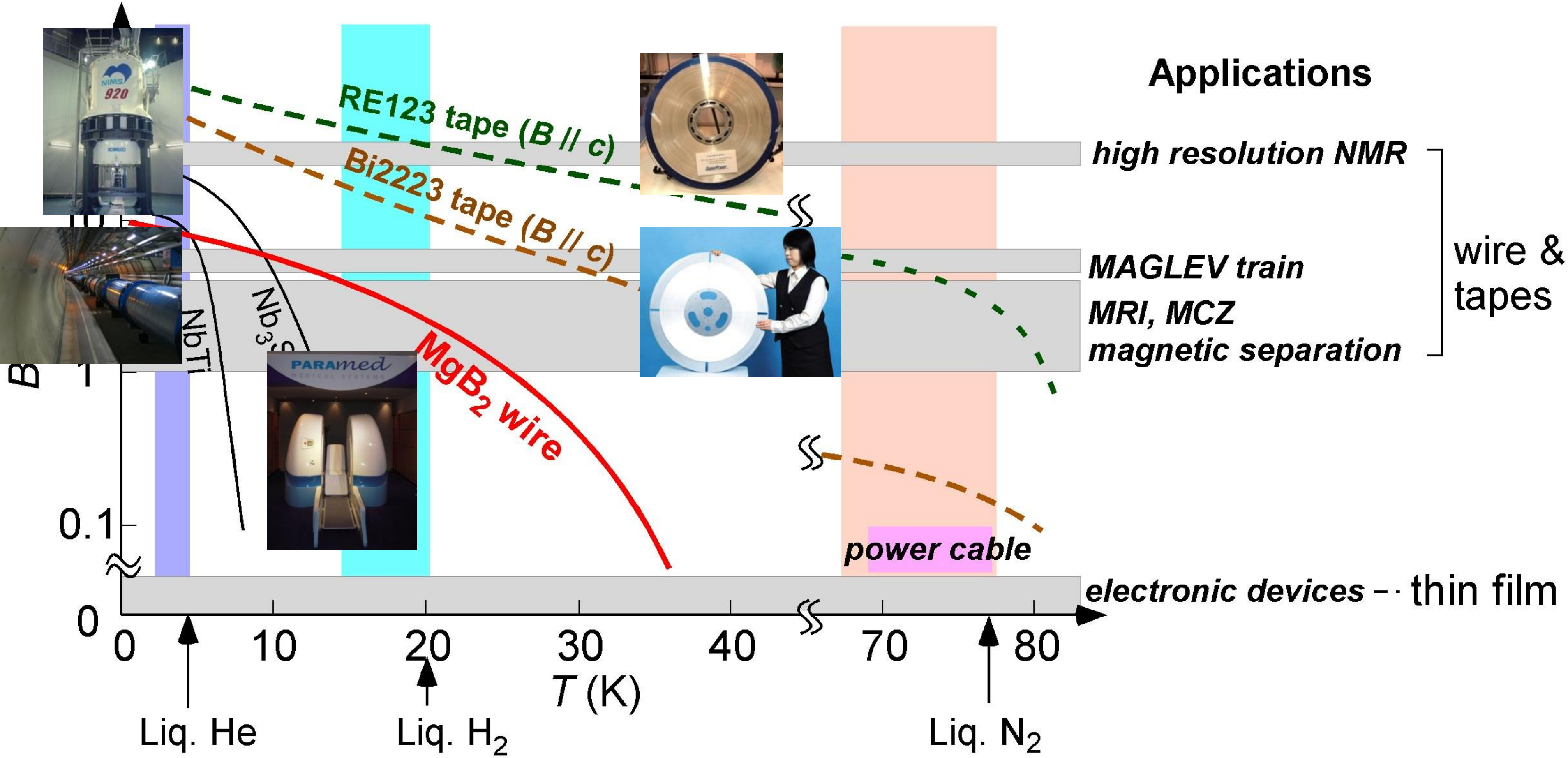
Various practical applications

Price of conductors (2012)

Bi2223	**¥10~15 / Am**
RE123	**< ¥50 / Am**
copper	**¥~5 / Am**

Applicable conditions of superconducting materials

J_E > 100 A/mm^2 for long length conductors



Required J_e depends on applications.

eg. MAGLEV train

by Central Japan Railway

Superconducting magnet using Nb-Ti

$J_e > 4 \times 10^4$ **A/cm^2 (5 T)**

+ persistent current circuit

to obtain large force for levitation and running

eg.: transmission cable

by Sumitomo Electric Industries

Bi2223 high-T_c cable

$J_e \sim 1 \times 10^4$ **A/cm^2**

(cooled by liq. N_2)

+ low AC loss [in case AC cable]

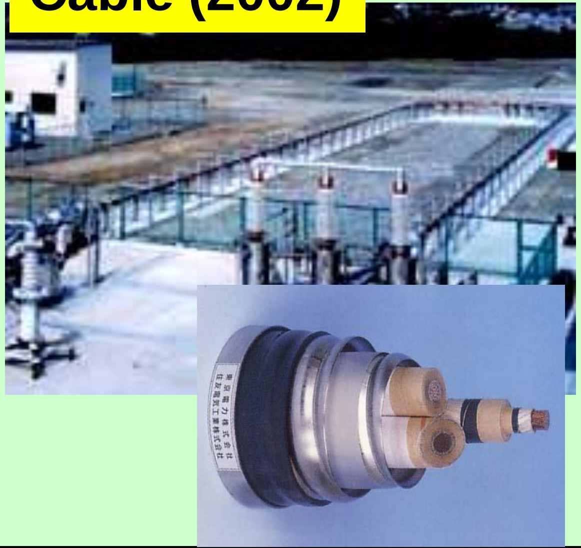
Examples of practical application of Bi(Pb)2223 tapes

Bi(Pb)2223 tape

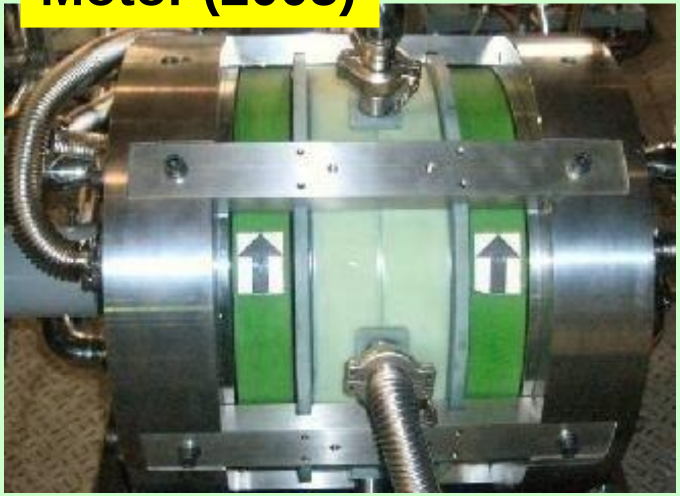
1000 km/year (2005)

Magnet for MAGLEV (2005)

Cable (2002)



Motor (2005)



Transformer (under development)

Cooled by liq. N_2

Motivation of development of superconducting cables

very low power loss = saving energy

Electric power loss of grids of Japan
--- ~5% of total = ~5 GW (Joule heat) in Japan.
(More than 20 times in the world)

Superconducting cable can contribute to long distance and/or large capacity grid.

power transmission with high current density = saving space

Increase in electricity usage at highly dense metropolitan area will need superconducting grids.

Tokyo area and other many 10M-class metropolitans in the world

New motivation --- coordination with renewable energy

Other advantages --- noncombustibile, electromagnetic wave free

AC cable and DC cable

AC cable

- Most of grids are AC
- Superconducting cable can increase capacity by replacement .

  AC loss of superconducting cables must be suppressed, because it increase power consumption of the cooling system.

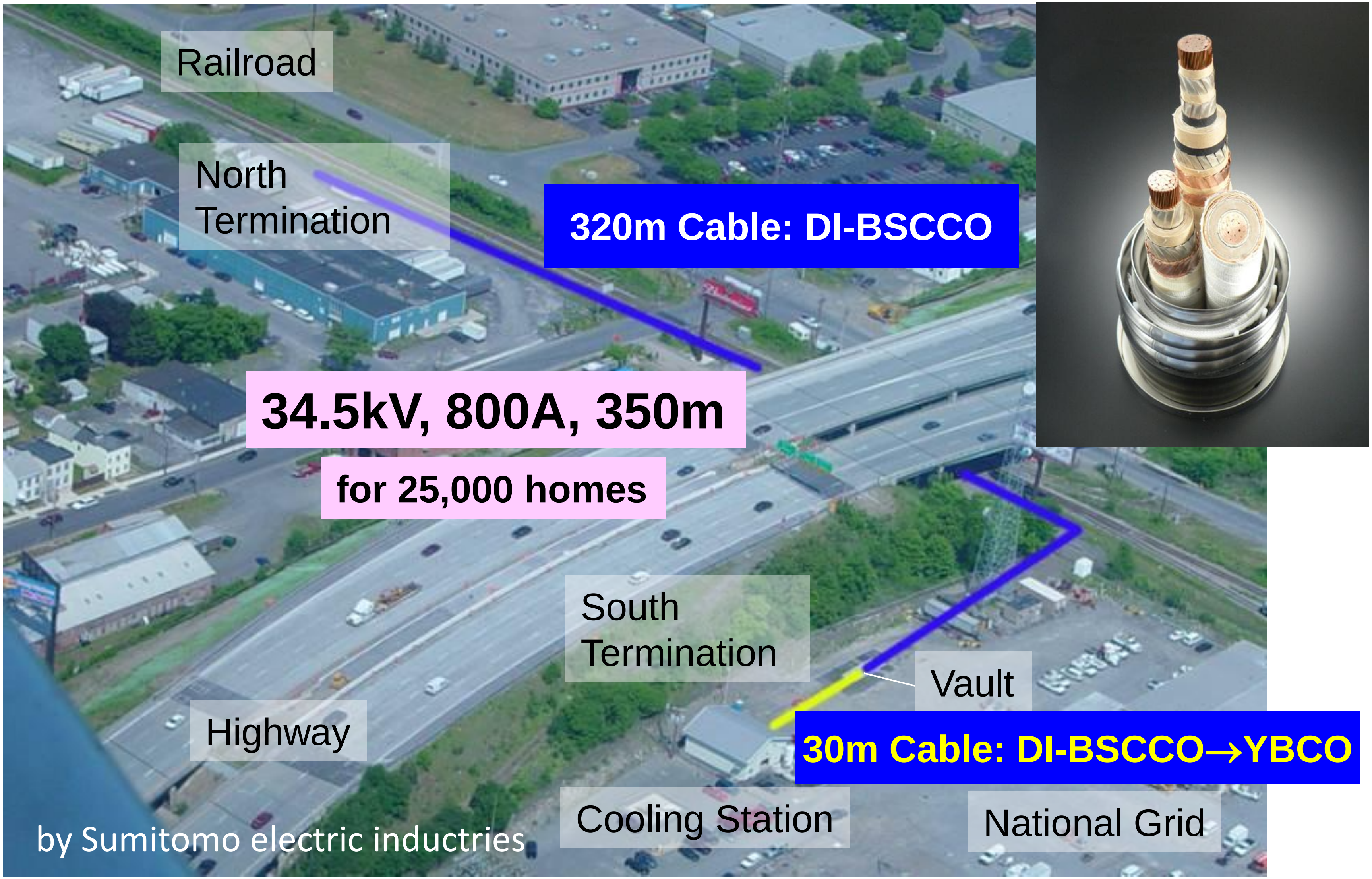
DC cable

- In Japan, connections between 50 and 60 Hz area or undersea cables, Hokkaido-Aomori and Wakayama-Tokushima
- Feeder of railway --- DC electrified section = 11800 km(2007.3)
- In EU, long high voltage DC cables in operation
- Superconducting cable can increase capacity by replacement .

  Connection of PV plants and very long distance cables are also considered.

First demonstration at actual power system

Albany Cable Site (Aug. 2006-), NY, USA



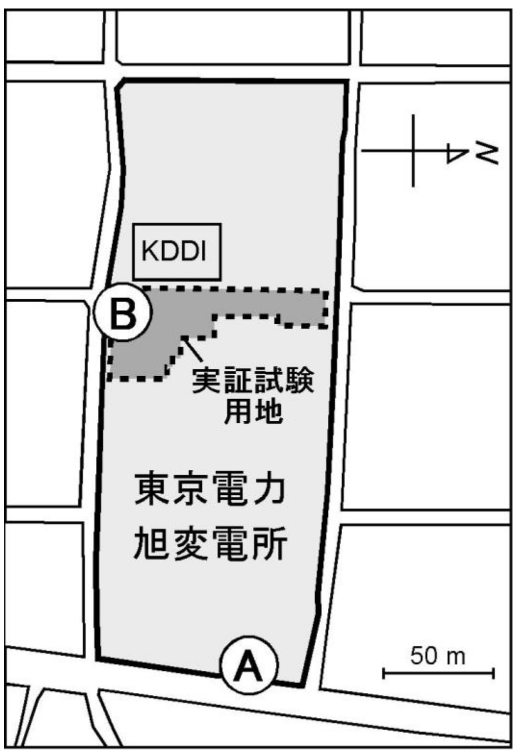
A 350 m cable needs long tapes with100 km in length in total.

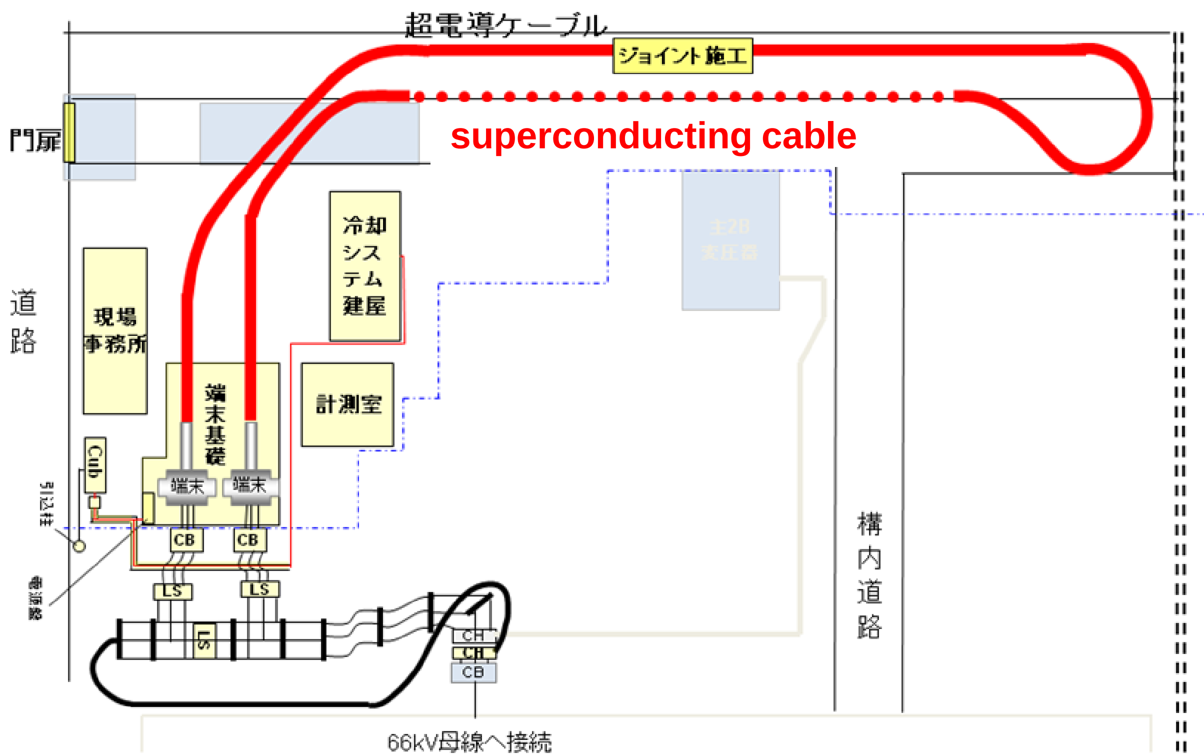
NEDO "Project on High-T_c Superconducting Cable" (2007-2014)

First program on installing superconducting cables in the practical power system (66 kV - 3 kA : to ~50,000 homes)

TEPCO－SEI－Mayekawa

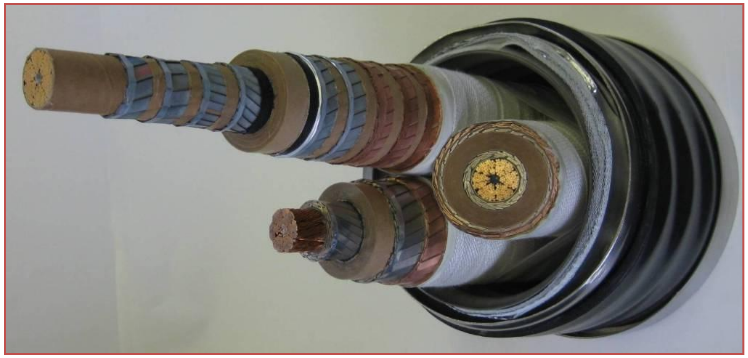
A new 230 m superconducting cable is installed in Asahi substation in Yokohama city to probe reliability of the total system (construction, operation and maintenance).





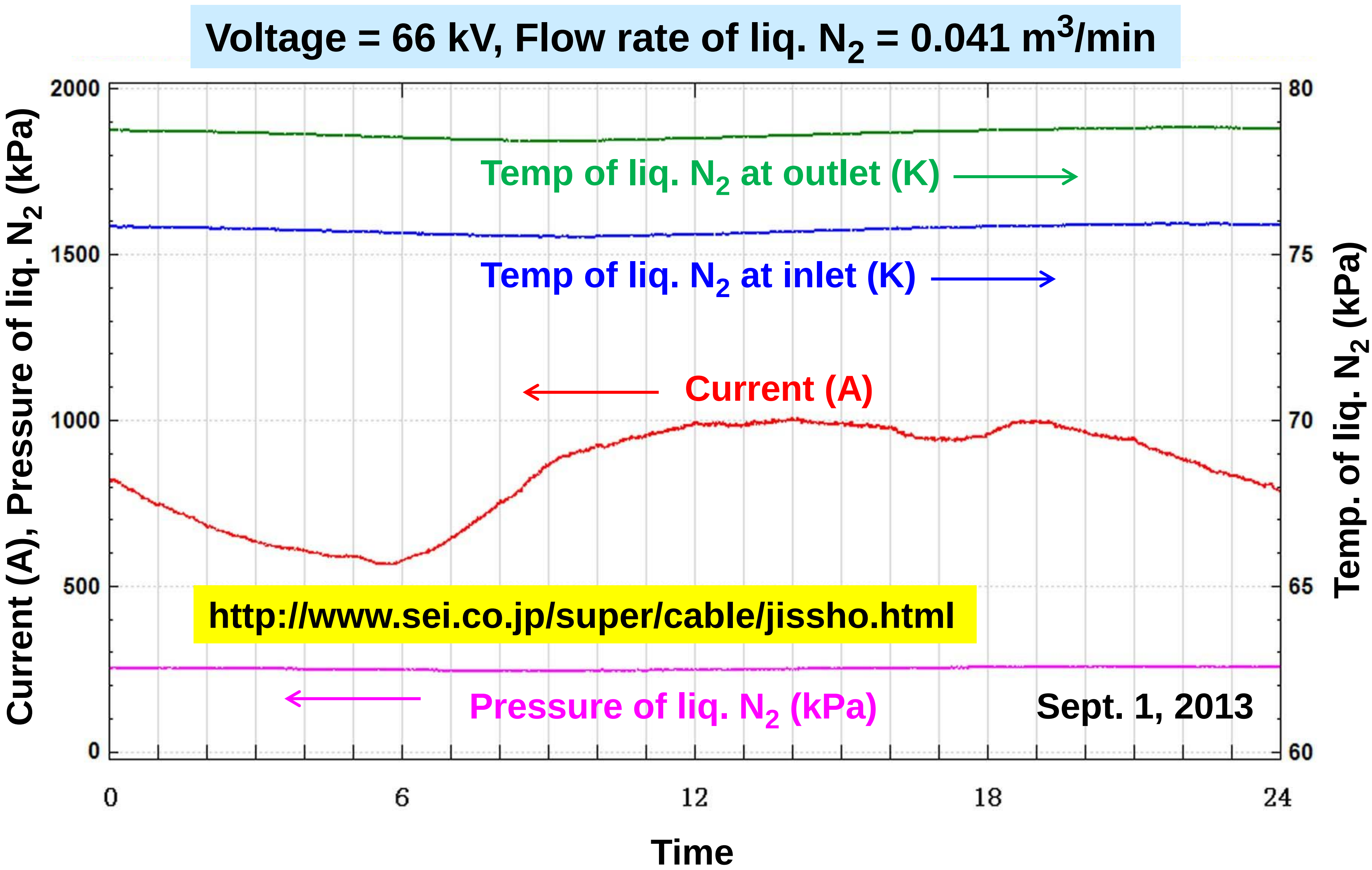
Map of Test Field (by TEPCO)

Superconducting Cable Connected to Grid
Since Oct. 29, 2012



Photos by Sumitomo Electric Industries

Operating Situation of Superconducting Cable



Superconducting cable projects in the World

Country/Area	Project	AC/DC	*V* / kV	*I* / kA	Length/m	Place	HTSC	Status
Japan	TEPCO-SEI	AC	66	1	100	CRIEPI	Bi	trial termination (2002)
	CEPCO-Furukawa	AC (1p)	77	1	500	CRIEPI	BI	trial termination (2005)
	Chubu Univ.	DC	20	2	200	Chubu Univ.	Bi	in operation
	Y-system power device	AC	66	5	15	Kumatori test station	Y	trial termination (2013)
		AC	275	3	30	Shenyang Furukawa	Y	trial termination (2012)
	Demonstration PJ	AC	66	3	250	TEPCO substation	Bi	in operation (2012/10～)
	Demonstration of DC cable	DC	each ～50 MVA		500, 2000	Ishikari, Hokkaido	Bi	starting in 2014
USA	Albany	AC	34.5	0.8	350	grid (distribution line)	Bi/Y	trial termination (2008)
	OHIO	AC	13.2	3	200	grid (substation)	Bi	trial termination (2012)
	LIPA	AC	138	2.4	600	grid (cable)	Bi/Y	in operation
	Hydra	AC	13.8	4	200	grid (cable)	Y	starting in 2014
Mexico	CASAT	AC	13.8	1.75	17	water power plant	Bi	scheduled
Europe	Denmark	AC	30	0.2	30	grid (substation)	Bi	trial termination
	VNIIKP(Rus)	AC	20	1.4	200	factory	Bi	connecting to grid
	St.Petersburg (Rus)	DC	20	2.5	2,500	grid (system connection)	Bi	connecting to grid in 2015
	Essen (Germany)	AC	10	2.3	1,000	grid (cable)	Bi	starting in 2013
China	Yunnan	AC	35	2	33.5	grid (substation)	Bi	trial termination
	Lanzhou	AC	10.5	1.5	75	factory	Bi	in operation
	Electric Works	DC	1.5	10	380	Al smelting plant	Bi	Installed, waiting for cooling
Korea	KEPCO	AC	22.9	1.25	100	test station	Bi	in testing
	DAPAS(1)	AC	22.9	1.25	100	test station	Bi	trial termination
	DAPAS(2)	AC	154	3.75	30, 100	test station	Y	trial termination
	GENI	AC	22.9	1.25	500	grid (Icheon substation)	Y	trial termination (2013)
	JEJU	DC	80	3.12	500	grid (GuemAk C/S)	Y	connecting to grid in 2014
	JEJU	AC	154	1.87	1,000	grid (GuemAk C/S)	Y	connecting to grid in 2015

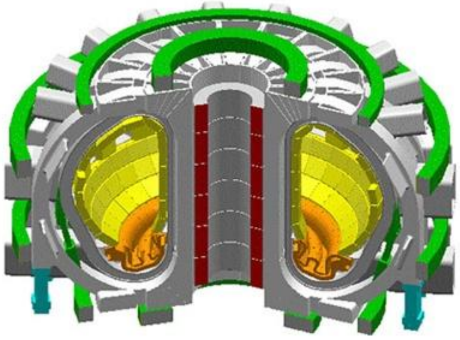
Current status and future of superconducting magnet

HR-NMR → Ultra HR-NMR 1.3 GHz or more

Static field above 30 T

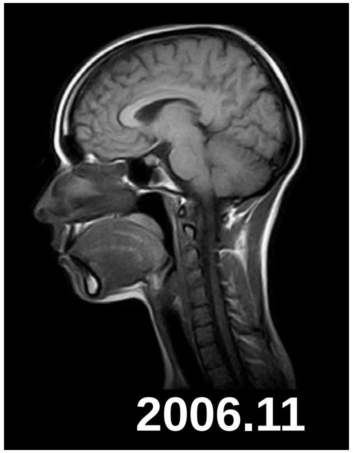
ITER(fusion reactor)

Huge magnet > 13 T



will be finished in 2016

MRI for medical use: Nb-Ti → MgB_2 [operating @ ~20 K]



SUPER CAR (Electric Vehicle with Superconducting Motor)

Motor : Bi(Pb)2223

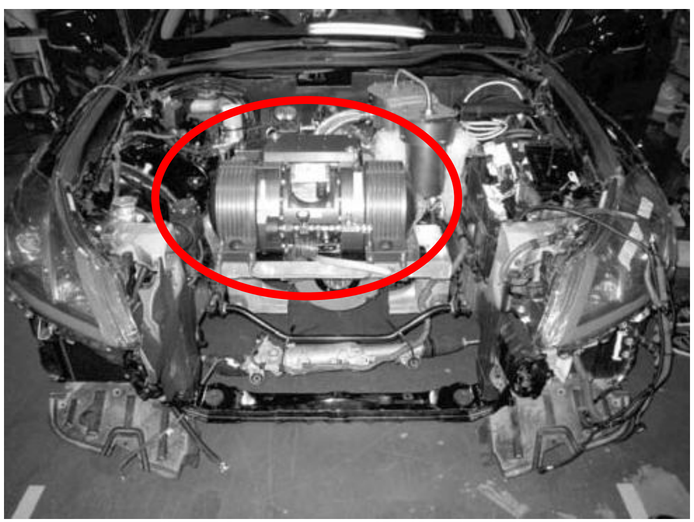
Cooling : Liq. N_2

closed system with cryocooler

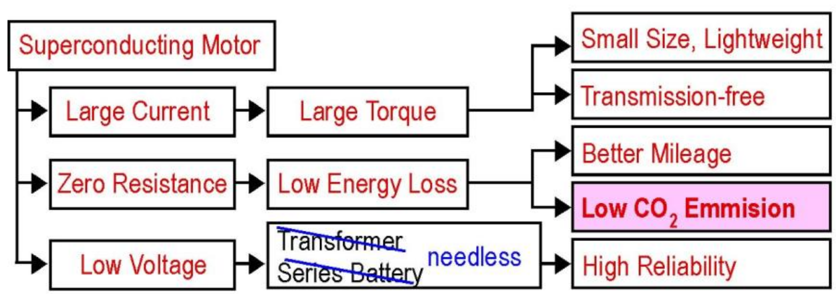
Max. Torque:136 Nm (1540 rpm)

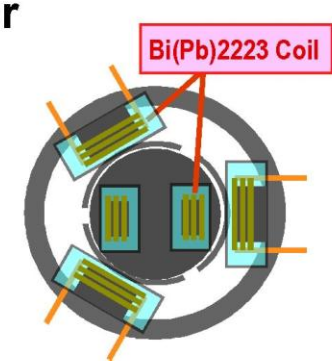
Max. Power: 30 kW (2200 rpm)

Max. Speed: > 80 km / h



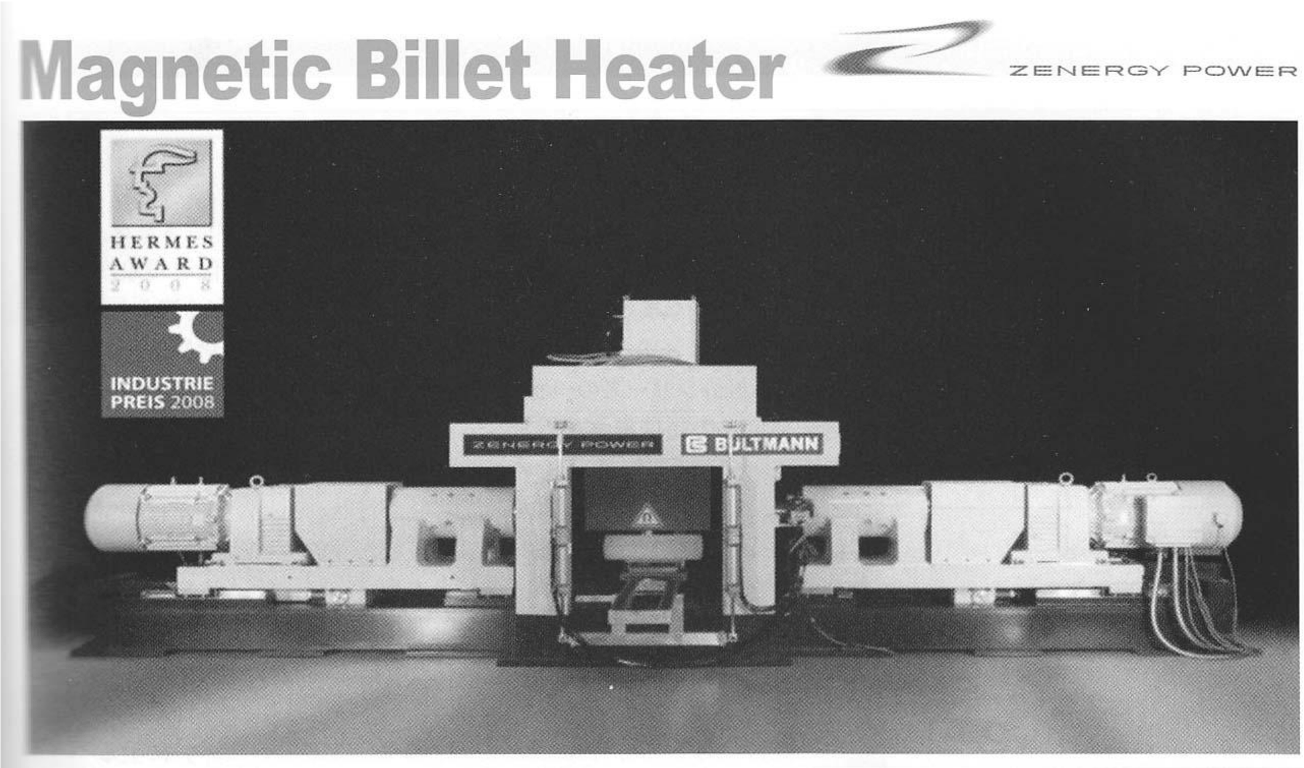
Merits of Superconducting Mortor





More Suitable for Large Vehicles, Buses & Large Trucks

New example of industrial application：Magnetic induction heater for billets



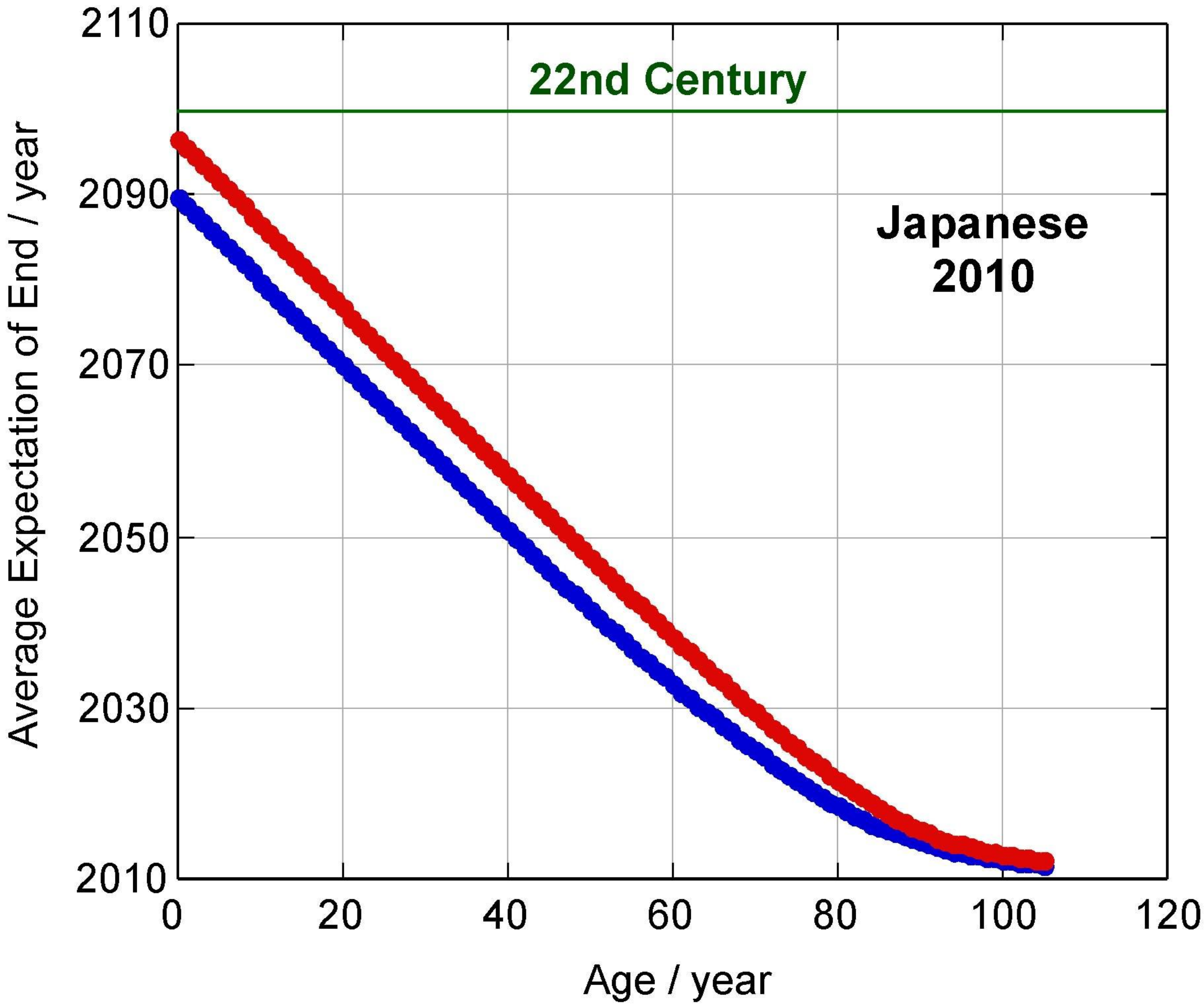
Induction heating of metal billet in Bi2223 coils → extrusion molding

Compared with conventional inductive heating,
50% power saving, 30% increase in productivity, homogeneous temp.

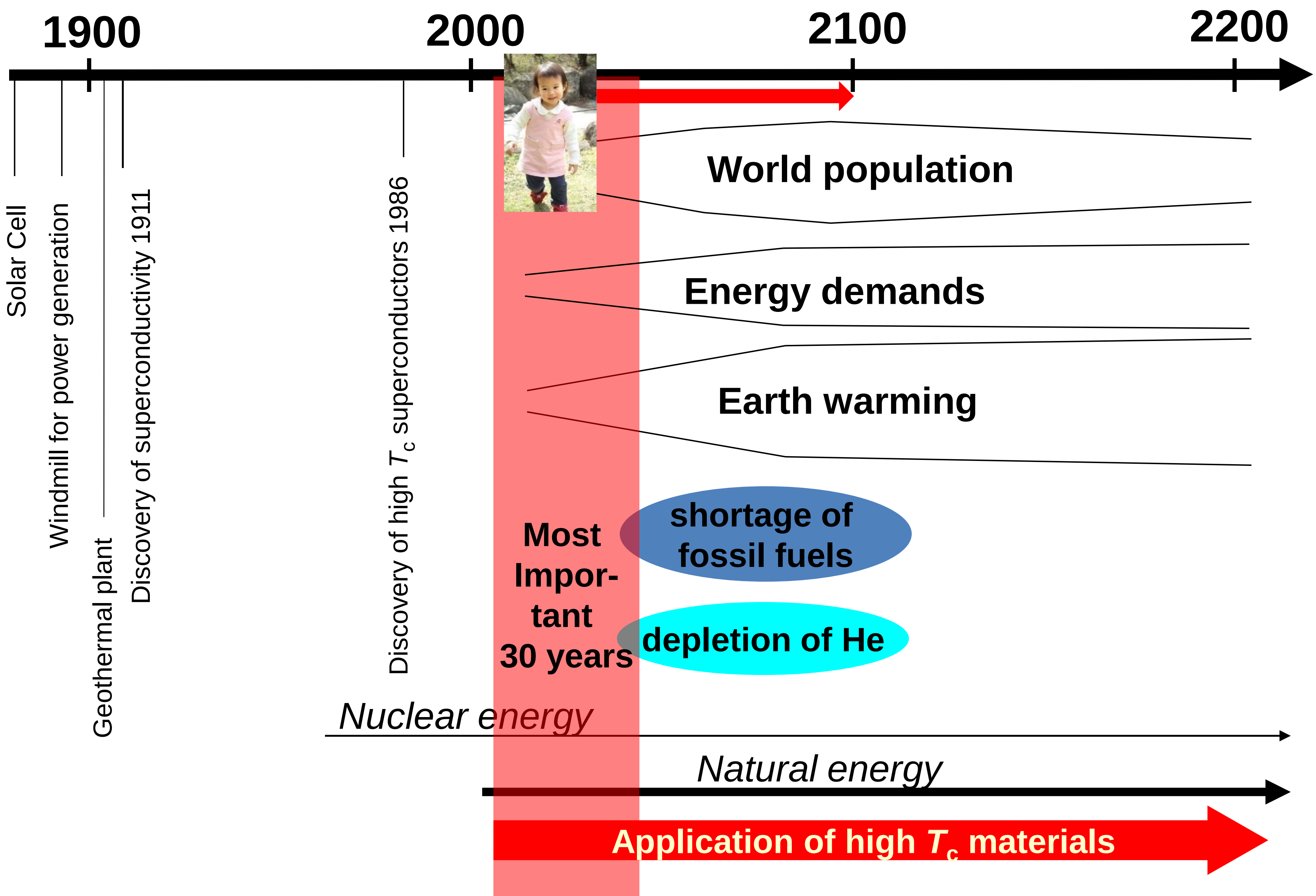
New industrial application of superconducting system will continuously increase.

4. Future problems of the earth and possible application of superconducting technologies

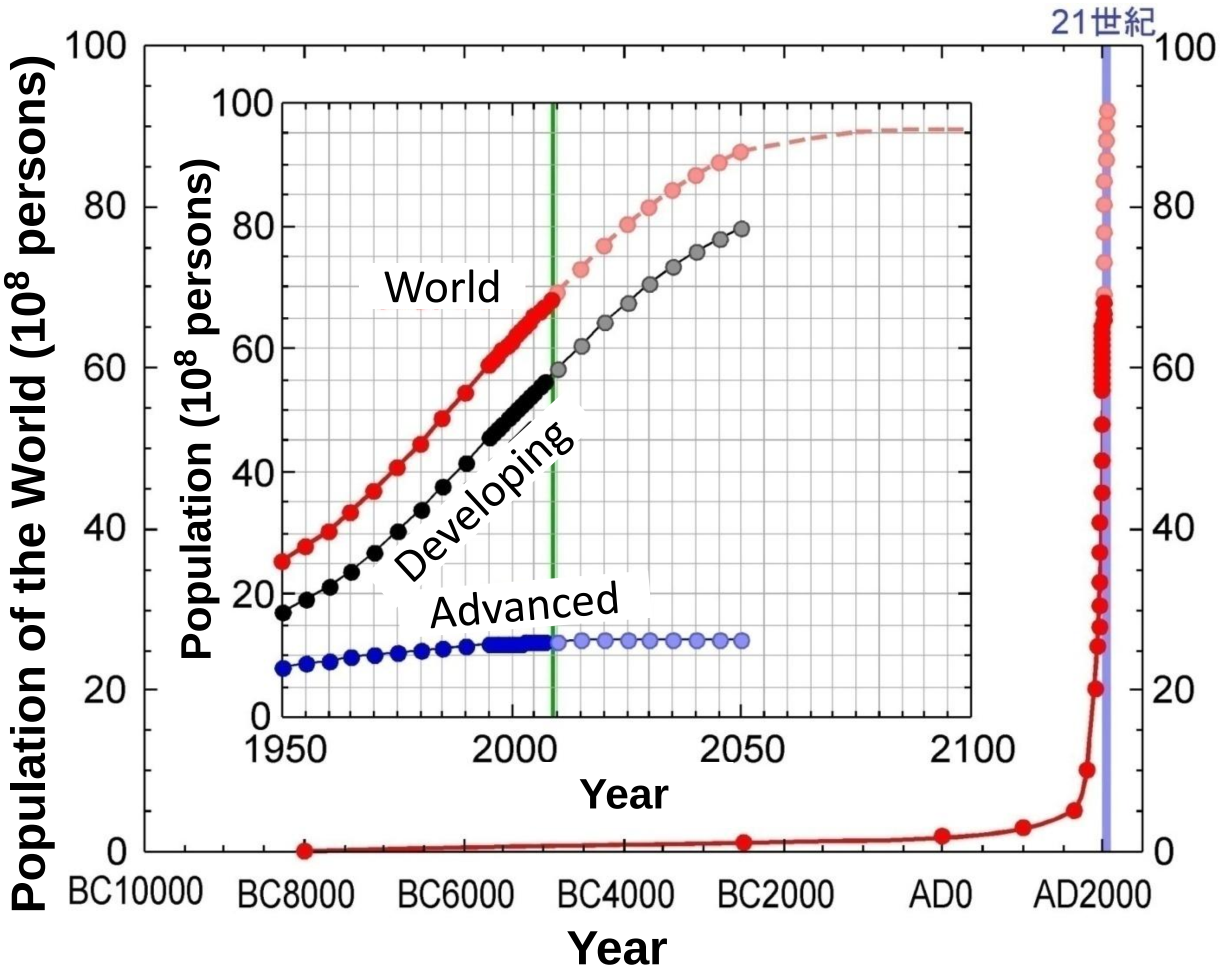
Life expectancy of us and our children



Future problems of the earth



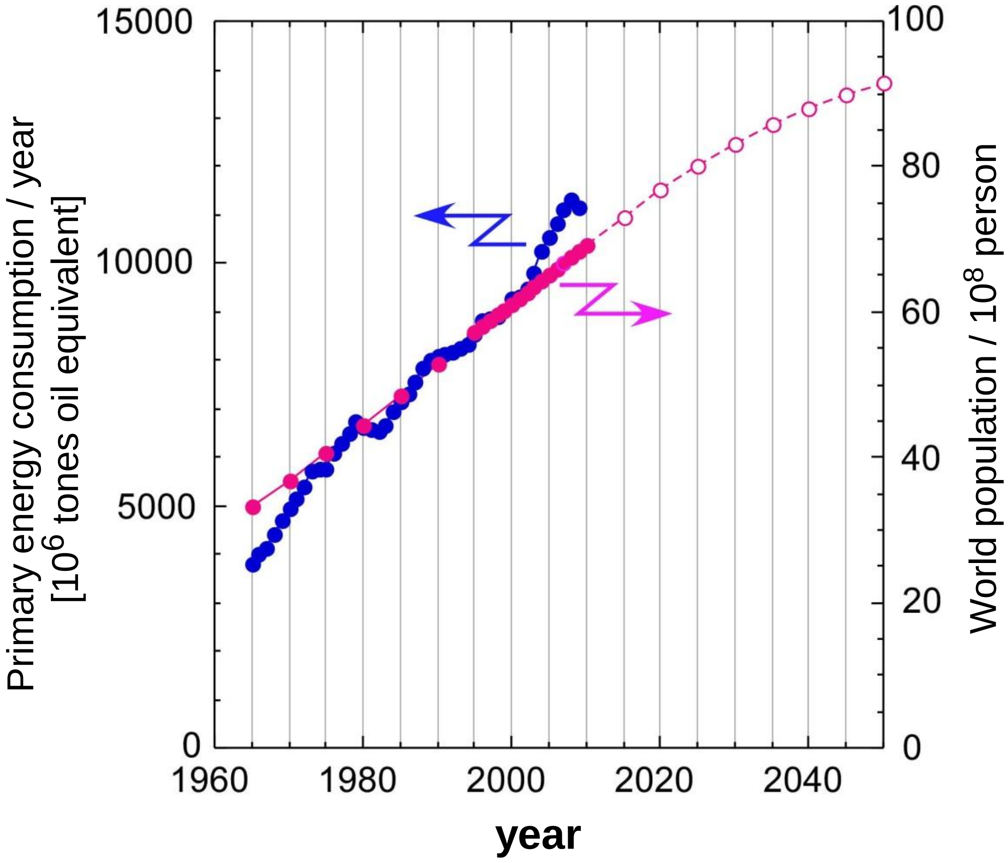
Increase in world population = Increase in energy users

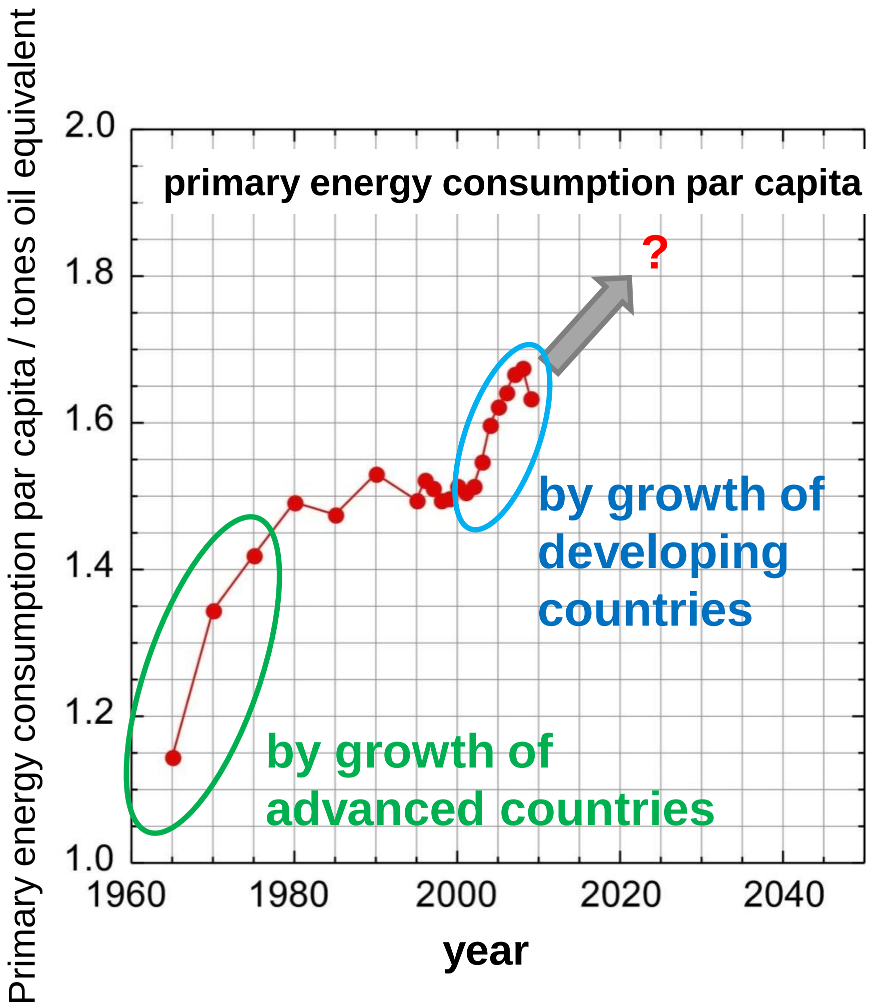


Population of advanced countries had increased for 150 years after the industrial revolution. ⇒ constant (now) ⇒ slight decrease (in future)

Increases in population of developing countries will continue until the late 21st century.

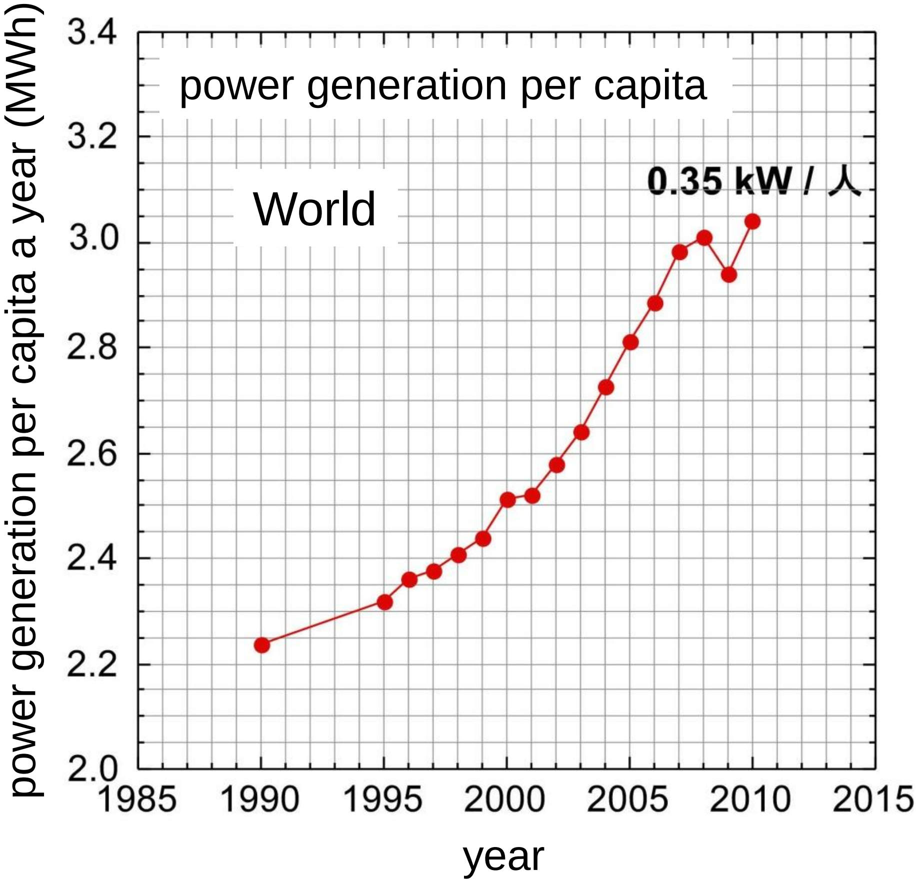
Continuous increase in primary energy consumption



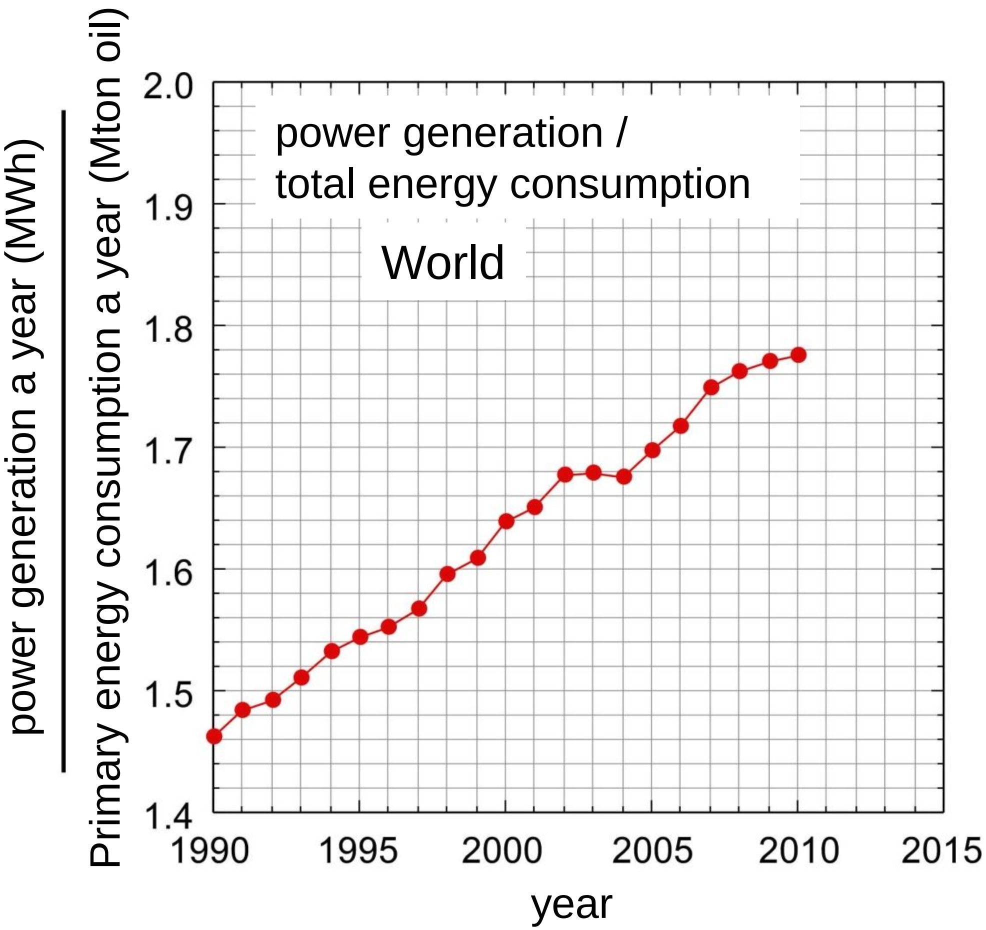


Statistical Review of World Energy 2010(BP)

Increase in the rate of utilization of electric power



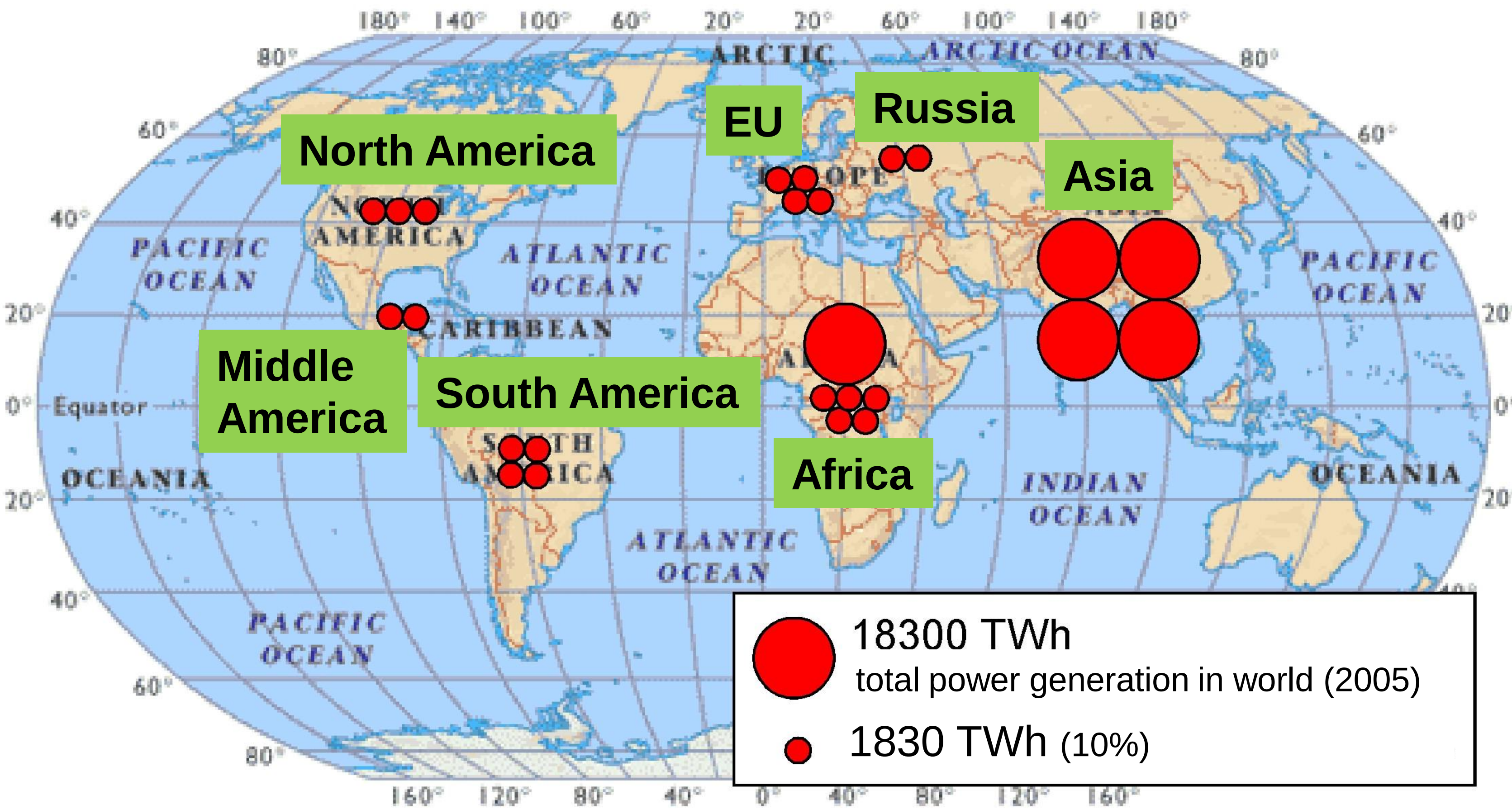
Power consumption per capita is increasing year by year.



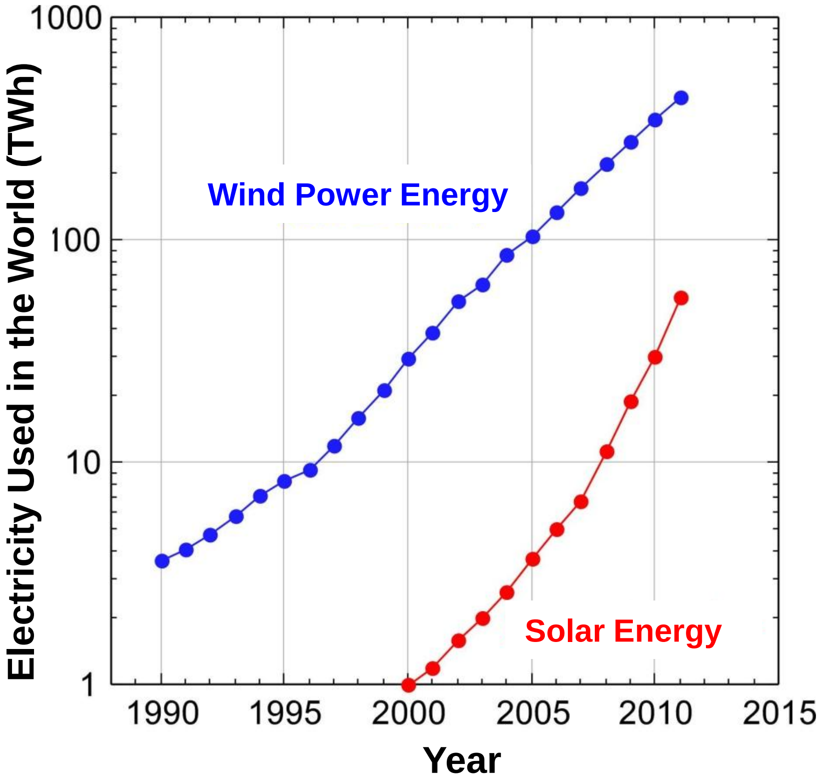
Rate of utilization of electric power in the energy consumption is increasing.

Electricity Demands of World in Far Future

Assuming all countries become advanced ones at 2050～2100, 6 times larger electricity than today will be needed.



Combinations of Renewable Energy Power Plants and Superconducting Devices

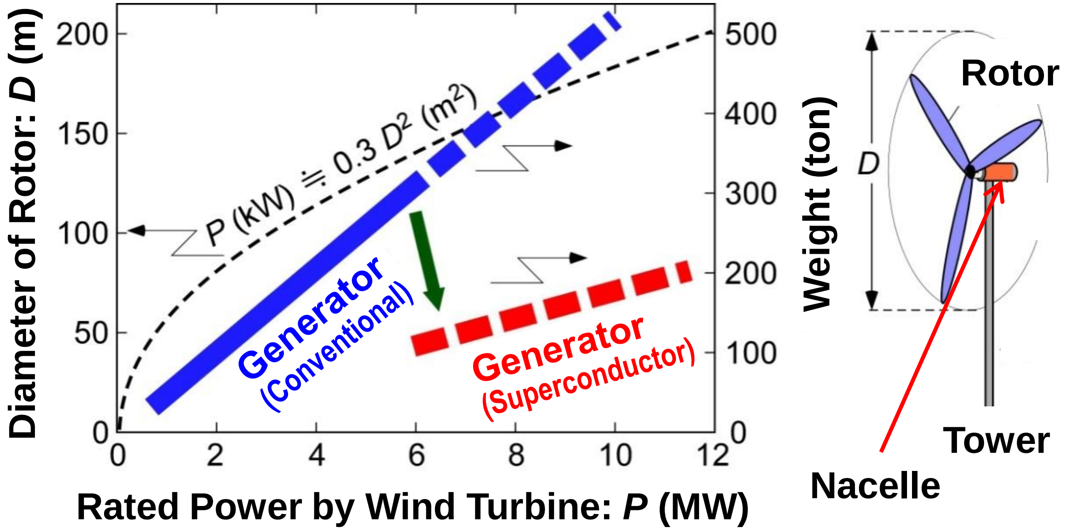


PV power generation --- DC, low voltage

GW-class power plant
⇒ large DC current ⇒ Grids to Cities

Using superconducting transmission cable is the best way to carry current.

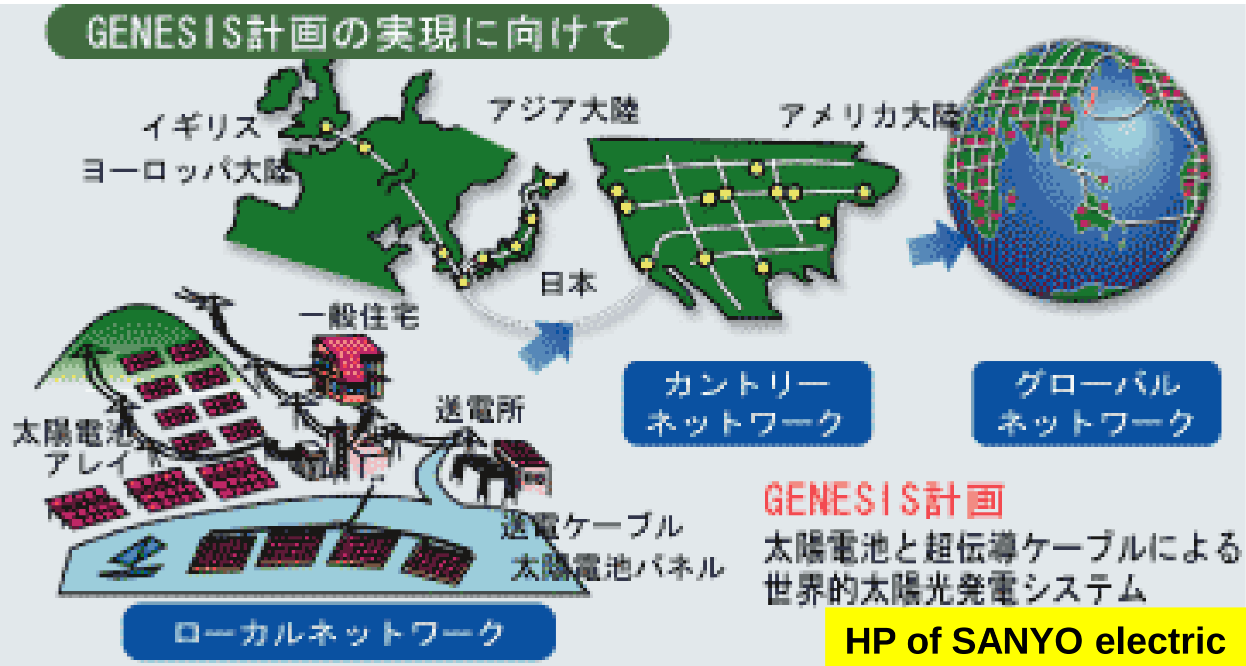
Large wing turbine generator (> 7MW)
⇒ Very heavy to put at the top of tower



Renewable Energy and Superconducting Grids

DC superconducting grid --- long distance, large capacity with high energy density

Superconducting cables will not be expensive in future.



HP of SANYO electric

GENESIS project (1989)

by Y. Kuwano at SANYO electric.

worldwide PV plants
＋DC superconducting grid

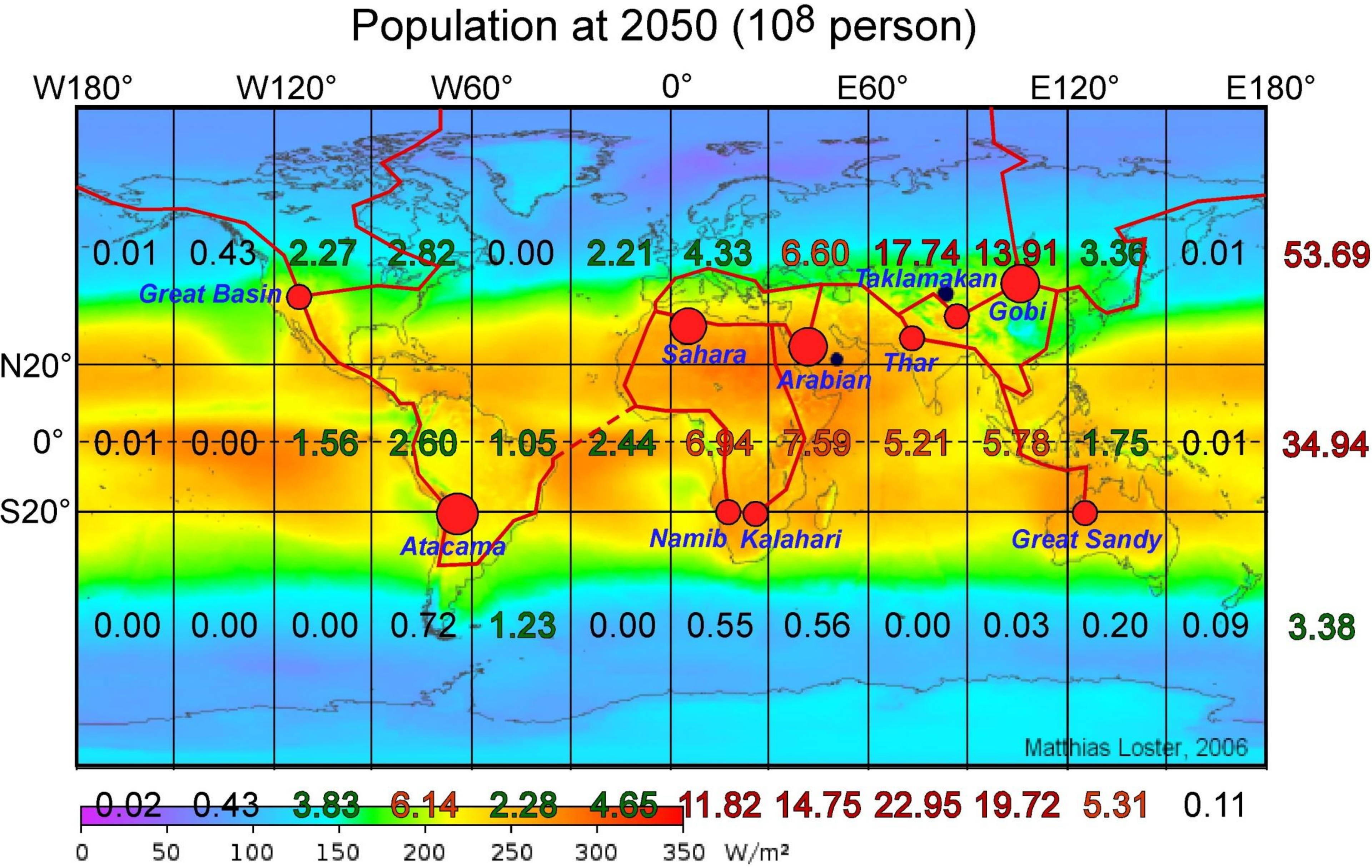
Wind electricity can be connected.

Global **E**nergy **N**etwork **E**quipped with **S**olar cells and **I**nternational **S**uperconductor grids

Merit of worldwide grid ---
equalization of electrical needs by day-and-night and seasons

Clean power supply for developing countries
New construction of power system may be easier for countries with infant infrastructure.

Minimum Superconducting Grid Covering World



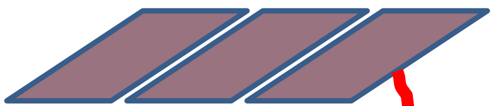
TAO (University of Tokyo Atacama Observatory) Project

Conducted by Professor Y. Yoshii, University of Tokyo

Infrared Telescope at 5640 m
[Now] 1 m diameter small telescope
⇒ [Near Future] Large telescope with 6.5 mϕ needs large electricity

TAO Project ＋ 1st Step of GENESIS Project
＝ Solar TAO Project

Photovoltaic Cells (~20 MW)



DC Superconducting Cable
(~ 1 km)

Battery

~50 km

San Pedro de Atacama, Chile

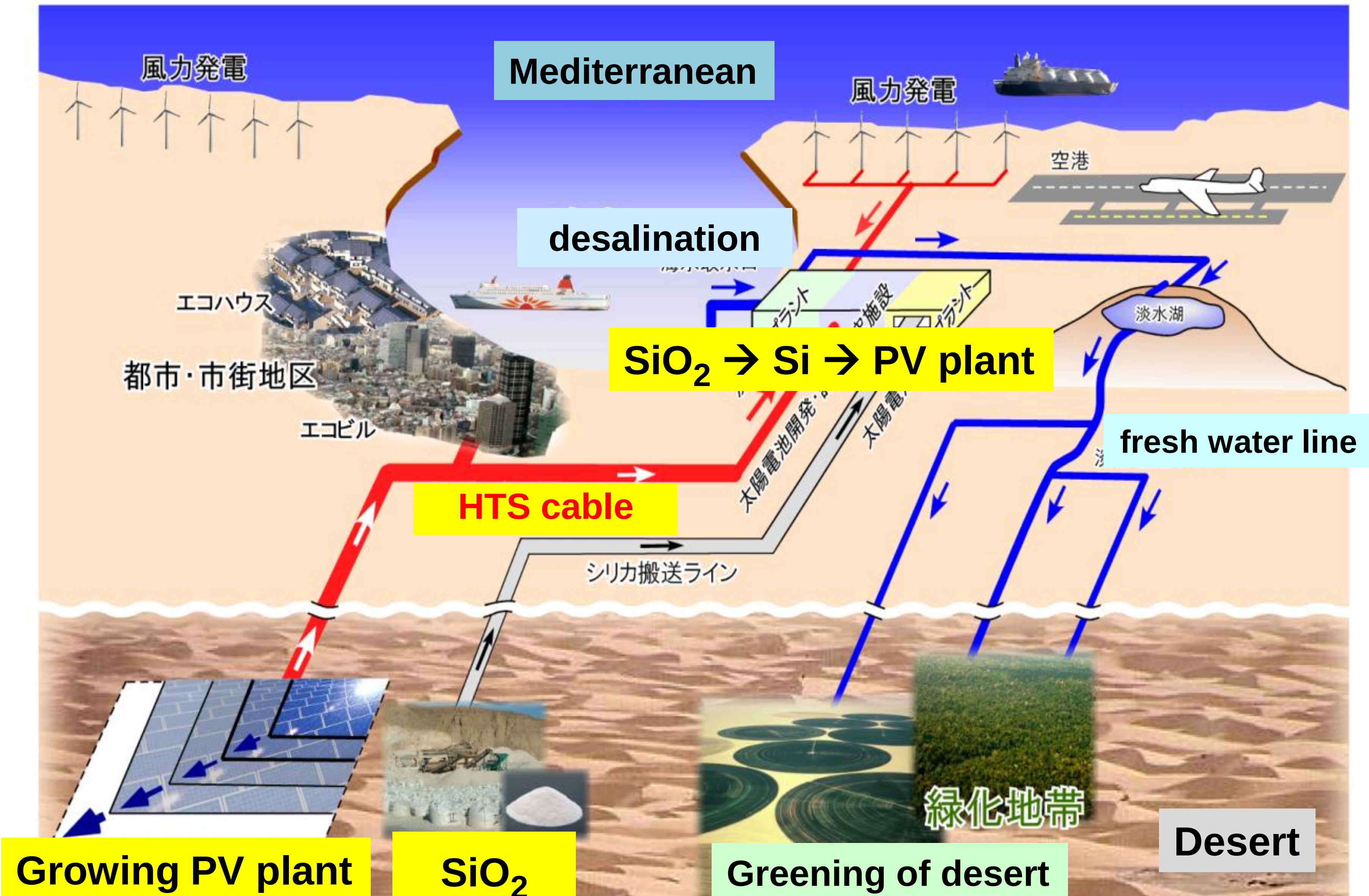
Merits of PV power generation in Atacama

clear sky + weak wind (no sandblasting)
--- predictable power generation
with high efficiency

Sahara Solar Breeder Project (@Algeria)

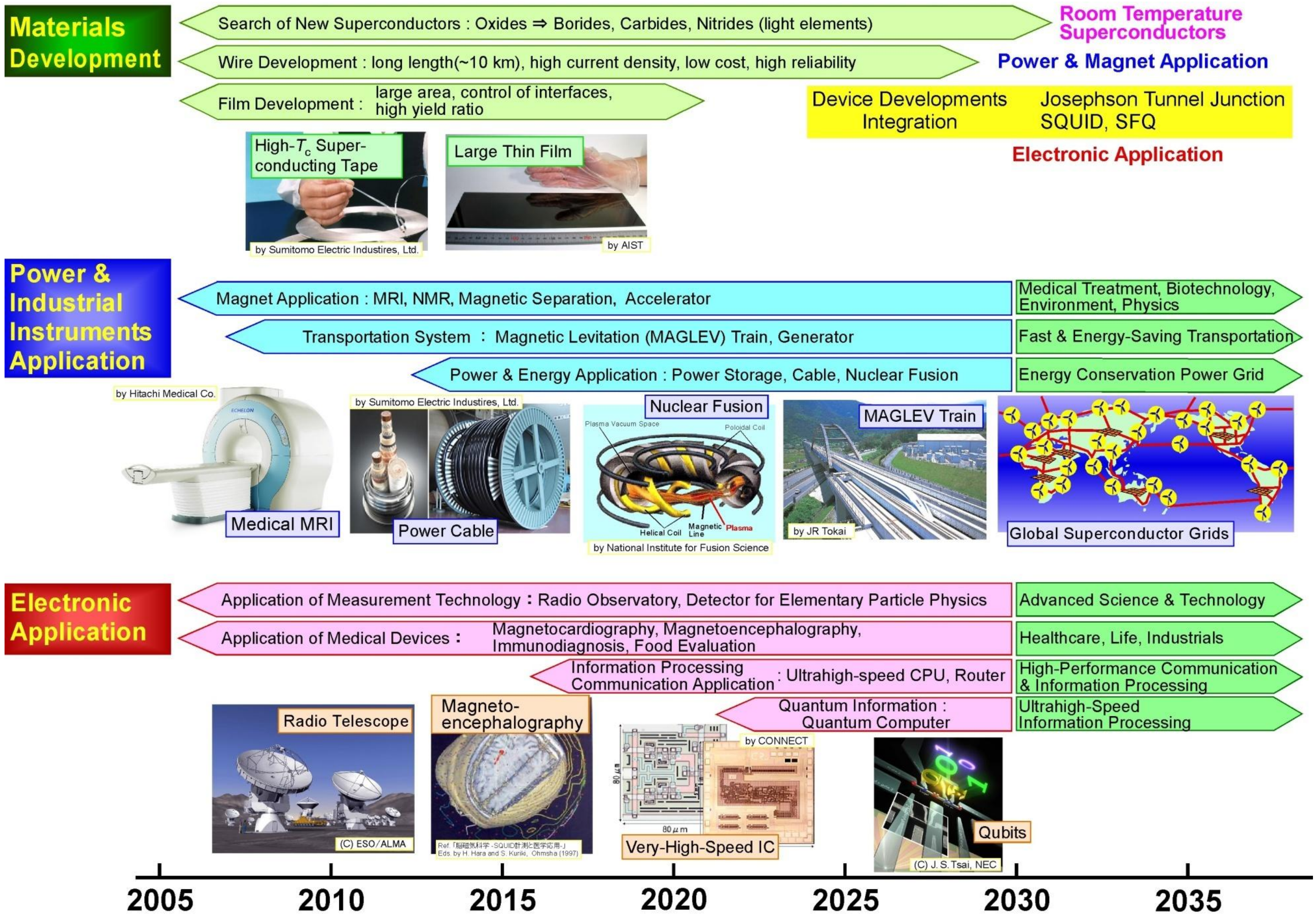
Proposed and promoted by Prof. Koinuma *et al*.

PV plant power → desert dust (SiO_2) → Si → growing PV plant



Academic Roadmap of Superconducting Technologies

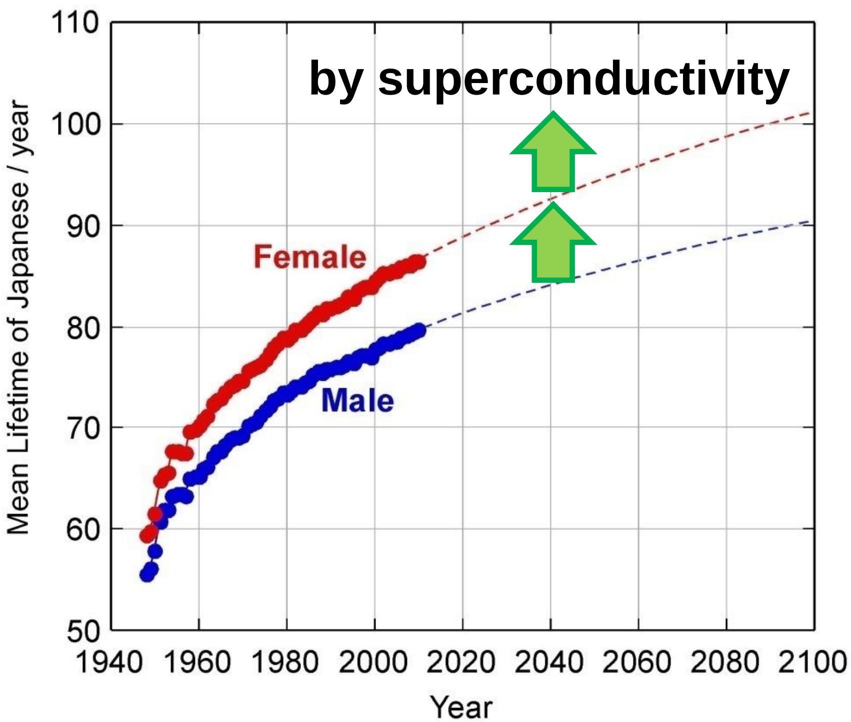
(by JSAP, 2010)



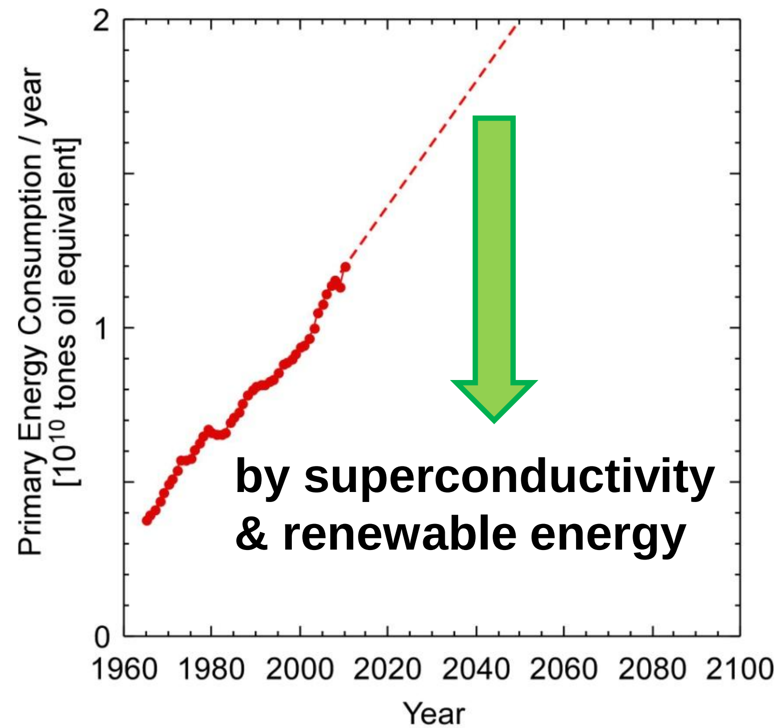
5. Summary

R&D side should increase

“attractive points of superconducting materials and systems”
by showing excellent effects through extensive applications.



Data by Ministry of Health, Labour and Welfare



Statistical Review of World Energy 2011 [BP]

Politics and management side should consider

“investment for new infrastructure including superconducting technology”
= “investment for far future under responsibility of future world”.


Gracias !