Superconductivity as a key technology from small electronics to large magnet applications

Academia – Industry matching event – Fostering collaborations in Superconductivity
May 27th- 28th 2013, Madrid, Spain

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Superconductivity as a key technology from small electronics to large magnet applications

Acknowledgement

All colleagues working in this field

All members of CIGRE WG D1.38

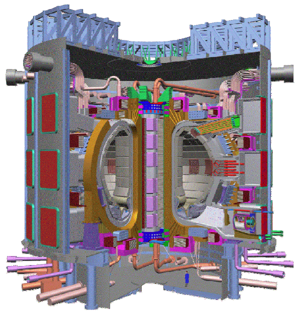
All members of IEA Implementing Agreement
for a Cooperative Programme for Assessing the
Impacts of High-Temperature
Superconductivity on the Electric Power Sector

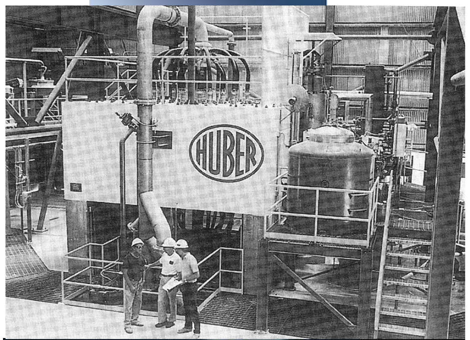
And all members of ITEP at KIT

Superconductivity as a key technology from small electronics to large magnet applications

← **Medicine**

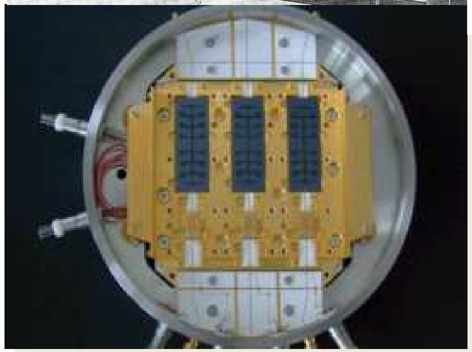
Science →





← **Energy**

Engineering →



← **Transport**

Electronics →

Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

Cyclotrons
MRI applications

← Medicine

Science →

Accelerator magnets
Particle detectors magn.
Supercond. cavities

Fusion
Wind generators

← Energy

Engineering →

← Transport

Electronics →

SQUIDS for biomedicine

Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

In red –topics covered by my presentation

Applications	Field	Applications
Cyclotrons **MRI applications**	← **Medicine**	
	Science →	**Accelerator magnets** **Particle detectors magn.** **Supercond. cavities** **High field magnets**
Fusion **Wind generators** **Power applications**	← **Energy**	
	Engineering →	**Magnetic separation** **Magnetic heating**
Levitation	← **Transport**	
	Electronics →	**SQUIDS for biomedicine** **Detectors**

Superconductivity as a key technology from small electronics to large magnet applications

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Cyclotrons
MRI applications

Fusion
Wind generators
Power applications

Levitation

State-of-the-Art
Highlights
Research Directions

Accelerator magnets
Particle detectors magn.
Supercond. cavities
High field magnets

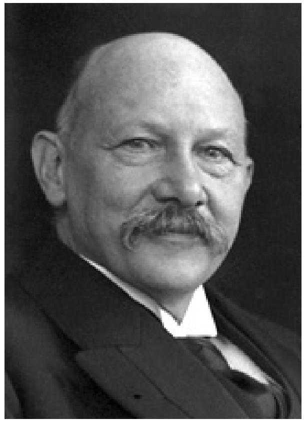
Magnetic separation
Magnetic heating

SQUIDS for biomedicine
Detectors

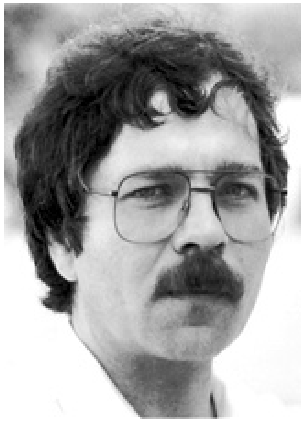
Motivation
What is the advantage of superconductivity?

Superconductivity offers

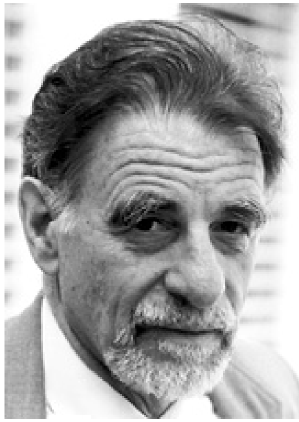
- Highest current densities, at zero DC resistance and at high magnetic fields
- peculiar magnetic behaviour with Meissner-Ochsenfeld effect and flux pinning
- Josephson effect



Heike Kamerlingh Onnes



J. Georg Bednorz



K. Alexander Müller

Walther Meissner

Robert Ochsenfeld

Brian D. Josephson

Motivation

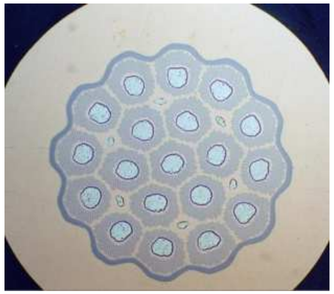
Technical Superconductors – Key towards Applications

Material	T_c [K]	B_{c2}[T]	Short name
NbTi	9.3	14.5	NbTi
Nb_3SN	18.3	27.9	Nb_3Sn
MgB_2	~ 39 K	17	MgB_2
$Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_y$ (y = 8 ÷ 10)	~ 110	> 100	Bi 2223 (1G)
$Bi_2Sr_2CaCu_2O_y$ (y = 8 ÷ 10)	~ 80	> 100	Bi 2212
$REBa_2Cu_3O7_{-x}$ (RE: Y, or other rare earth elements)	~ 90	> 100	Y 123 (2G)

NbTi

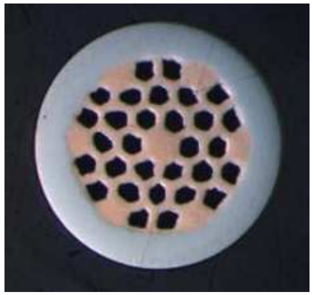
Picture: EAS

Nb_3Sn



Picture: EAS

MgB_2

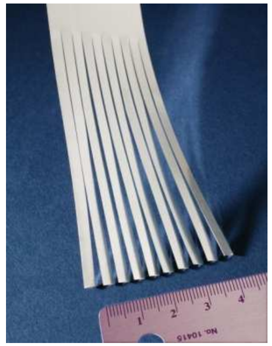


Picture: KIT

Bi 2223-1G

Picture: EHTS

ReBCO123-2G



Picture: AMSC

Superconductivity as a key technology from small electronics to large magnet applications

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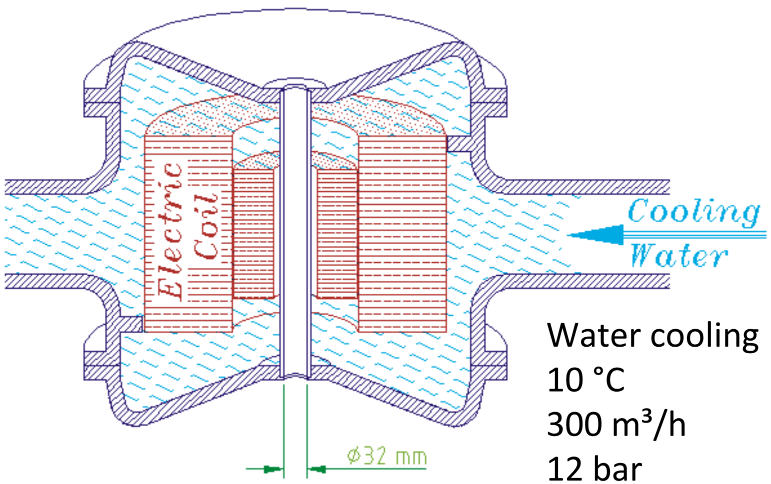
Fusion Wind generators Power applications	← Energy		Engineering →	Magnetic separation Magnetic heating
Levitation	← Transport		Electronics →	SQUIDS for biomedicine Detectors

Superconducting High Field Magnets
Energy Efficiency

20 T Bitter-Magnet

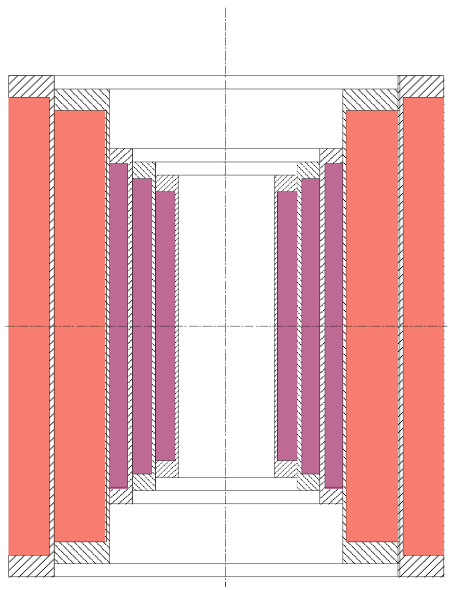


Water cooling
10 °C
300 m³/h
12 bar

Power Supply
6 MW (20 kA, 300 V)

20 T NTSL-Magnet (KIT)

B_0 = 20 T, ∅ = 185 mm



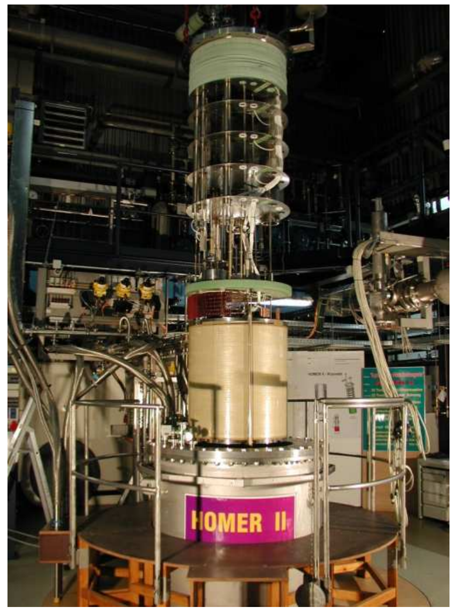


Figure: KIT

Cooling Power
< 15 kW

Superconductivity enables a considerable increase in energy efficiency.

Superconducting High Field Magnets
State-of-the-Art

Hybrid magnets
(LTS as background and resistive insert)

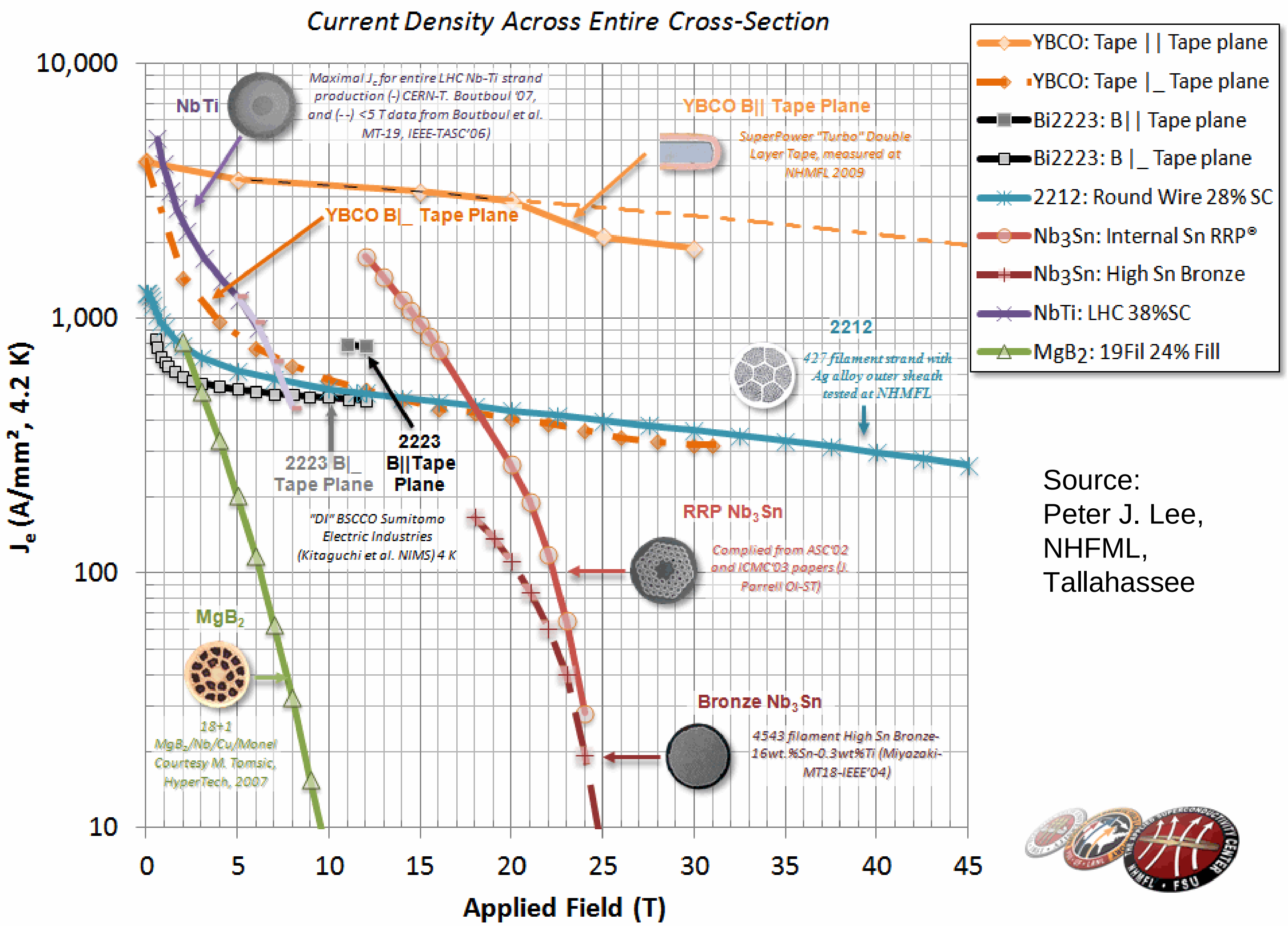
Location	Field (T)	Power (MW)	Bore (mm)
Tallahassee	45	30	32
Tsukuba	37	15	32
Sendai	31	7	32
Nijmegen	45	20	32
Grenoble	42	22.5	34
Hefei	40	20	32
Berlin	25	4	50

Source: Mark Bird, Progress in High Field Magnets, MT21, Hefei 2009

Under construction

1) Bruker Press Release: BEST Reports Improved In-Field Critical Current Performance of its Second Generation High-Temperature Superconductor YBCO Tapes, June 28, 2010

Superconducting High Field Magnets
Materials and their maximum Field applicability



Source:
Peter J. Lee,
NHFML,
Tallahassee

Superconducting High Field Magnets
State-of-the-Art of HTS Magnets

Year	HTS	$B_A+B_{HTS}=B_{tot}$ (T)	J_{ave} (A/mm^2)	Stress (MPa)*	Stress (MPa)**
2003	BSCCO	20+5=25	89	125	175
2008		20+2=22	92	69	109
2008		31+1=31	80	47	89
2007	YBCO	17+7.8=26.8	259	215	382
2008	YBCO	31+2.8=33.8	460	245	324
2009	YBCO	20+7.2=27.2	211	185	314
2009	YBCO	220+0.1=20.1	241	392	~ 611

* $J_{ave} \cdot B_A \cdot R_{max}$

** $J_E \cdot B_A \cdot R_{max}$

Source: Mark Bird, Progress in High Field Magnets, MT21, Hefei 2009

Picture: NHFML Tallahasseee

2.8 T in 31 T = 33.8 T SuperPower YBCO in NHMFL coil (OD=3,5 cm)

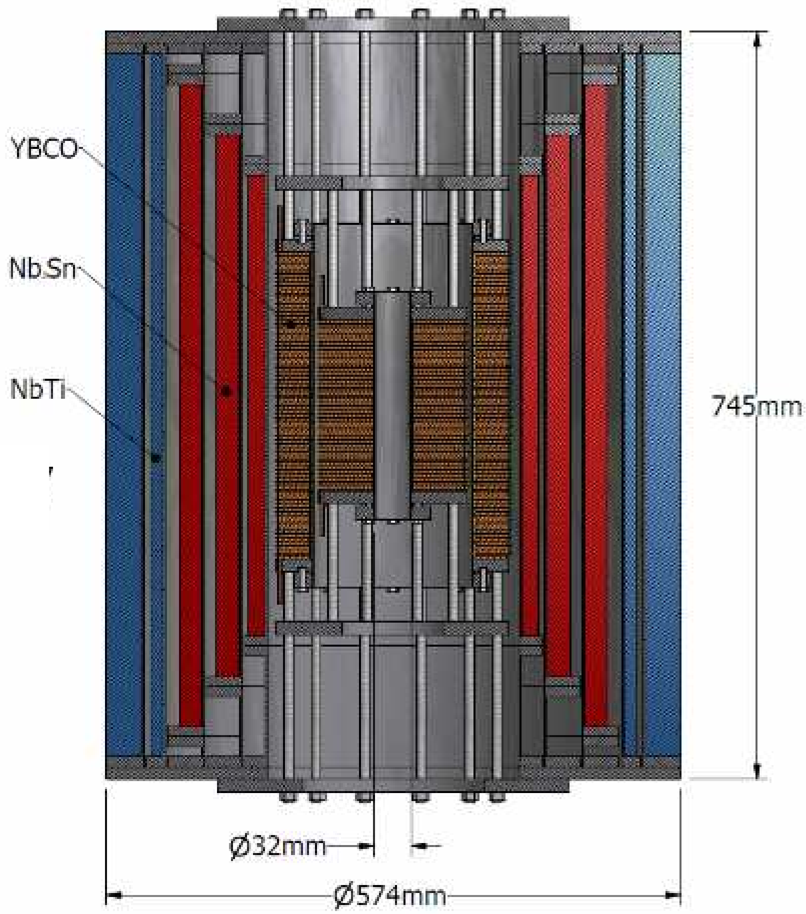
Many activities to develop HTS magnets and magnet inserts.

Superconducting High Field Magnets
Examples of Further HTS Magnet Objectives

NHFML	32 T all superconducting solenoid
BNL	35 T hybrid solenoid (HTS and NbTi)
KIT	> 28 T HTS solenoid insert for NMR

Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Field uniformity	$5x10^{-4}$ 1cm DSV
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ

32 TESLA SUPERCONDUCTING MAGNET



Source: NHFML, Tallahassee, US

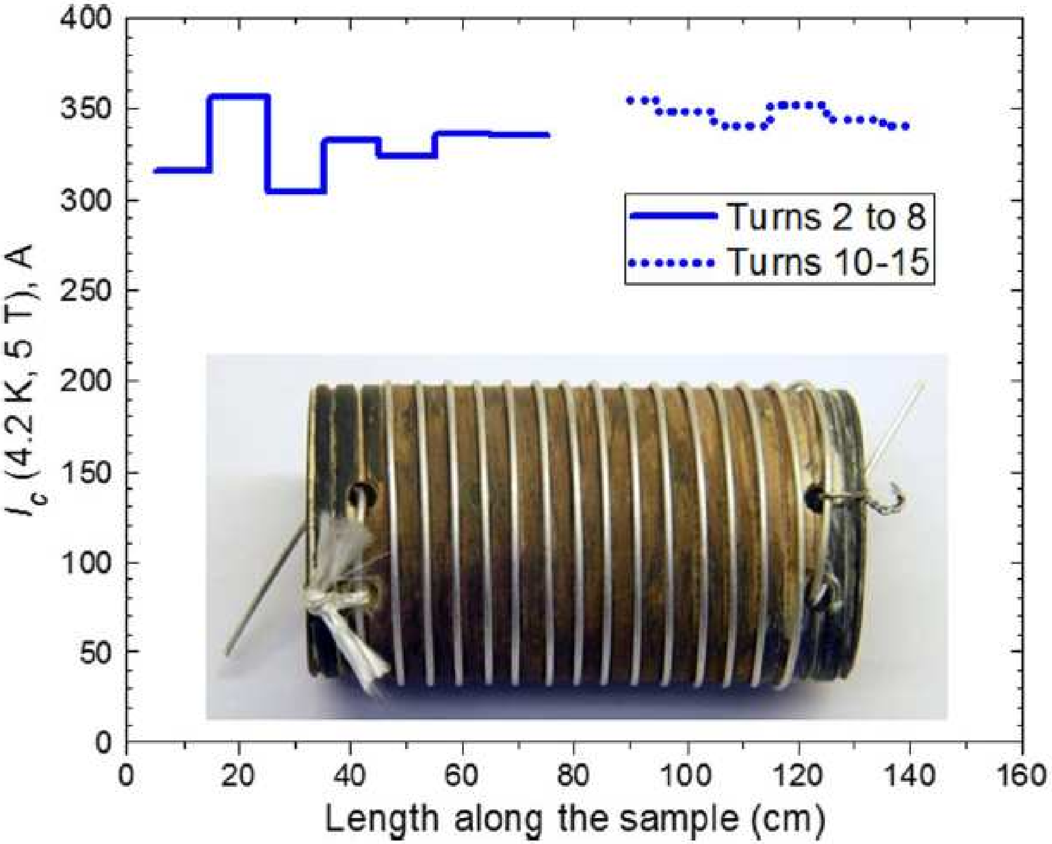
Superconducting High Field Magnets
Application of 2G HTS Tapes in first commercial R&D Magnets

Source: www.cryogenic.co.uk

Central field at 4.2 K	20 T
Central field at 2 K	22 T
Max. op. current	200 A
Inductance	100 H
0 to 18 T	20 min
18 T to B_{max}	17 min
Central field homogeneity	0.1 % in 10 mm
Clear central bore	30 mm
Overall diameter	350 mm
Overall height	650 mm

Source: www.cryogenic.co.uk

Superconducting High Field Magnets
Recent progress in Bi2112 by swaging



Jianyi Jiang, Hanping Miao, Yibing Huang, Seung Hong, Jeff A. Parrell, Christian Scheuerlein, Marco Di Michiel, Arup K. Ghosh, Ulf P. Trociewitz, Eric E. Hellstrom, and David C. Larbalestier
Reduction of Gas Bubbles and Improved Critical Current Density in Bi-2212 Round Wire by Swaging
IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013 6400206

Superconducting High Field Magnets
Research Direction

- Develop HTS inserts for high field magnets
    - Coil winding
    - Stability (electrical, mechanical)
    - Quench detection
    - Conductor concept
    - Homogeneity
    - Cryogenics
    - …
- Increase magnetic fields (far) beyond 20 T in fully superconducting magnets
- Improve material properties at high fields

HTS will increase the magnetic field of superconducting magnets or will enable more compact magnets.

Superconducting High Field Magnets
Economic Feasibility of High Temperature Superconductors?

	4.2 K, 6 T	**4.2 K, 10 T**
NbTi wire 0.85 mm diameter Cu/Sc 1.3/1 Filaments 54	2.5 $/kA m	20 $/kA m
YBCO tape 4 mm tape width	125 $/kA m ⊥ 33 $/kA m ‖	150 $/kA m ⊥ 35 $/kA m ‖

Todays cost assumptions:
NbTi 200 $/kg
YBCO 30 $/m

A replacement of LTS by HTS wire in permanent magnets seems technically feasible but will take place commercially only if HTS competes price performance ratio of LTS

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Levitation	← Transport	
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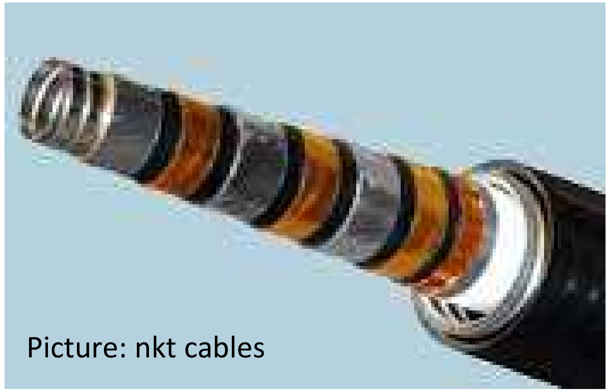
Superconducting AC Cables
Benefits of Superconducting Cables

- Higher power or lower voltage at same or smaller diameter
- Simplified network structures by reducing the number of voltage levels
- Reduce number of substations especially in urban areas
- Simplified right of way because of small cable diameter (3 in 1 design)
- Economic benefits in comparison to high voltage equipment
- No electromagnetic outer fields
- Simplified admission procedure of medium voltage cables in comparison to high voltage cables

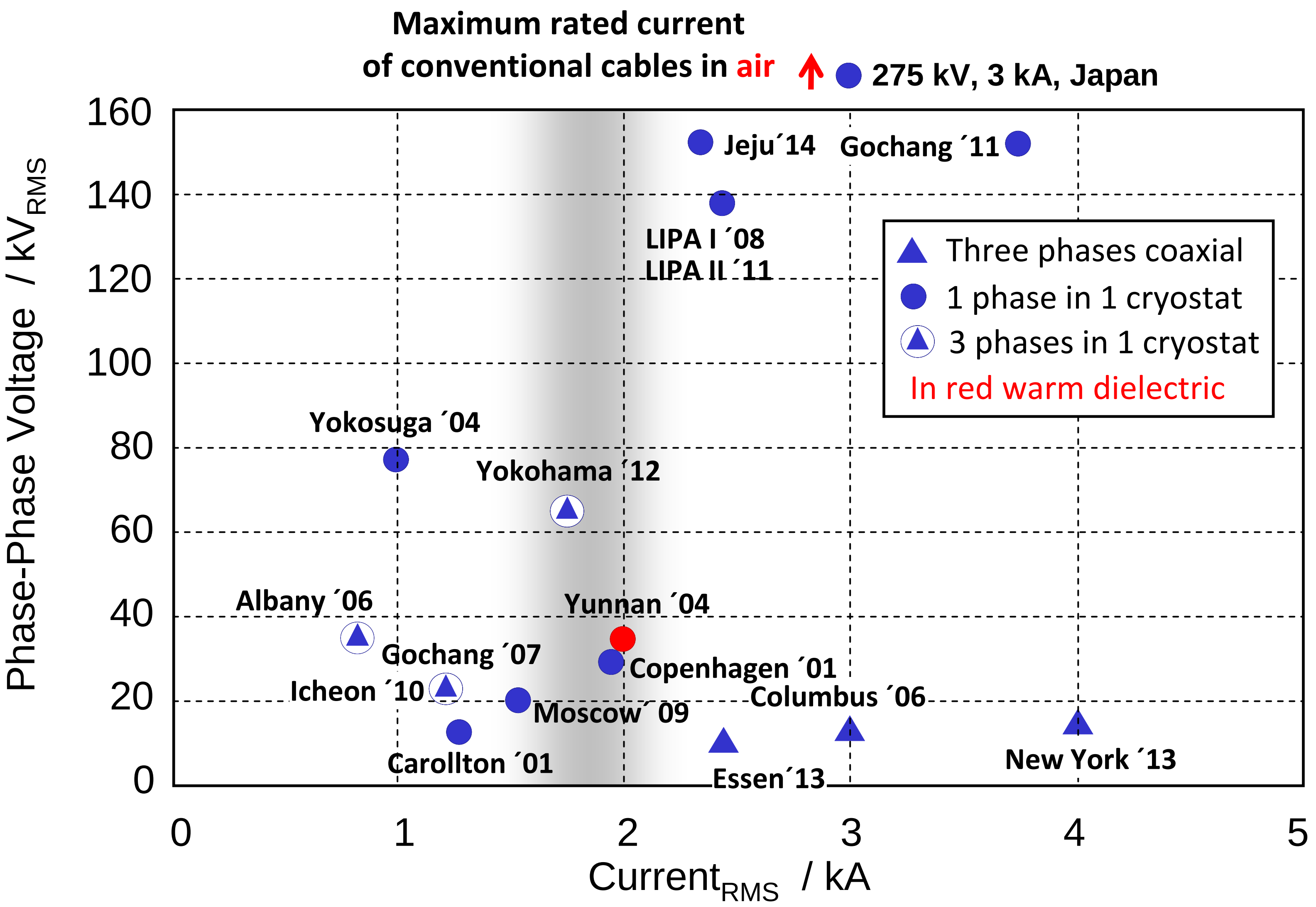


Picture: nkt cables

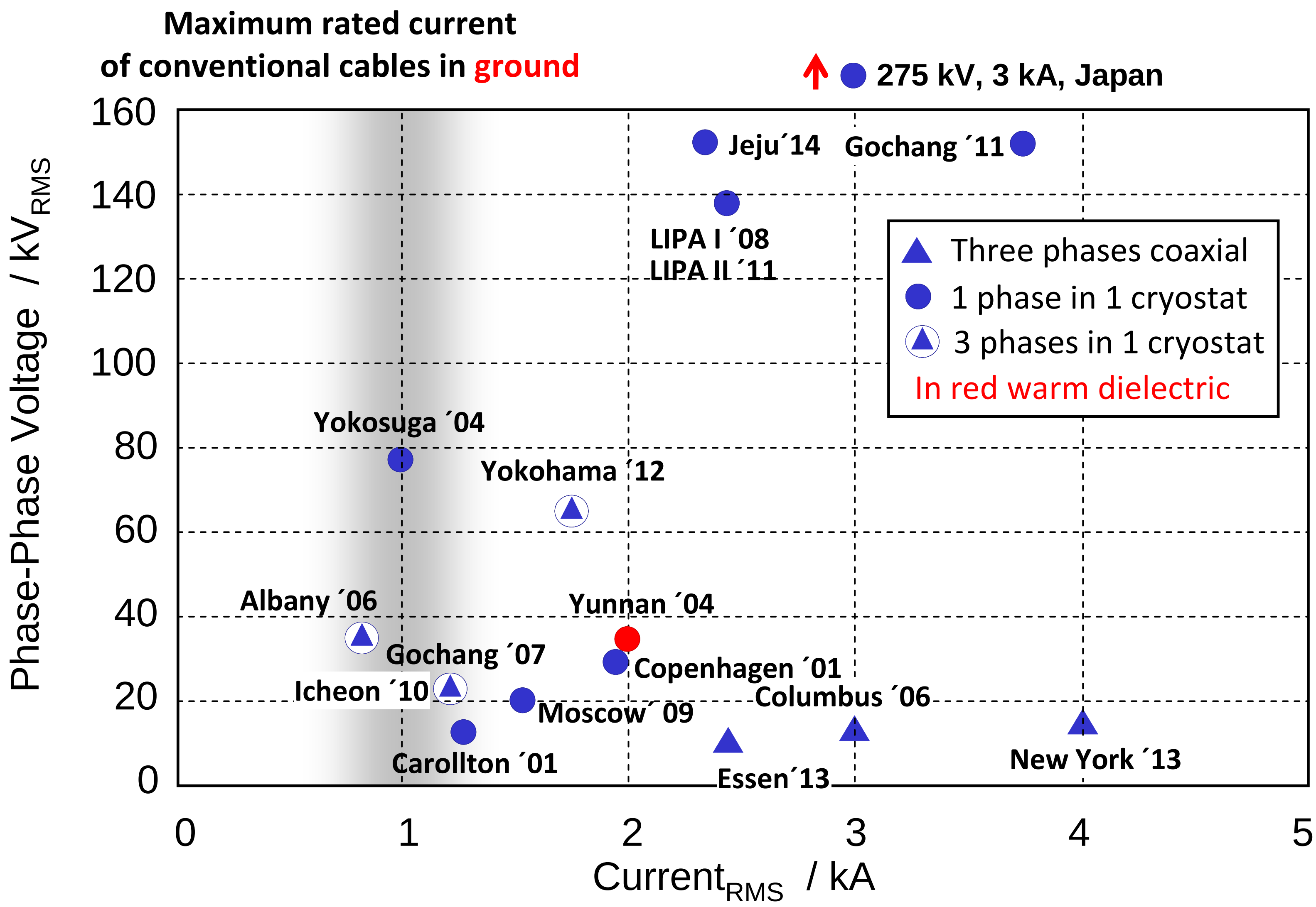
Superconducting AC Cables
State-of-the-Art of HTS AC Cables

Manufacturer	Place/Country/Year [1)]	Type	Data	HTS
Innopower	Yunnan, CN, 2004	WD	35 kV, 2 kA, 33 m, 3-ph.	Bi 2223
Sumitomo	Albany, US, 2006	CD	34.5 kV, 800 A, 350 m, 3-ph.	Bi 2223
Ultera	Columbus, US, 2006	CD	13.2 kV, 3 kA, 200 m, 3-ph.	Bi 2223
Sumitomo	Gochang, KR, 2006	CD	22.9 kV, 1.25 kA, 100 m, 3-ph.	Bi 2223
LS Cable	Gochang, KR, 2007	CD	22.9 kV, 1.26 kA, 100 m, 3-ph.	Bi 2223
Sumitomo	Albany, US, 2007	CD	34.5 kV, 800 A, 30 m, 3-ph.	YBCO
Nexans	Hannover, D, 2007	CD	138 kV, 1.8 kA, 30 m, 1-ph.	YBCO
Nexans	Long Island, US, 2008	CD	138 kV, 1.8 kA, 600 m, 3-ph.	Bi 2223
Nexans	Spain, 2008	CD	10 kV, 1 kA, 30 m, 1-ph	YBCO
Sumitomo	Chubu U., JP, 2010	CD	10 kV, 3 kA DC, 20 m, 200 m	Bi 2223
VNIIKP	Moscow, RU, 2010	CD	20 kV, 1.4 kA, 200 m	Bi 2223
Nexans	Long Island, US, 2011	CD	138 kV, 2.4 kA, 600 m, 1-ph.	YBCO
LS Cable	Gochang, KR, 2011	CD	154 kV, 1 GVA, 100 m, 3-ph.	YBCO
LS Cable	Seoul, KR, 2011	CD	22.9 kV, 50 MVA, 400 m, 3-ph.	YBCO
Sumitomo	TEPCO, JP, 2012	CD	66 kV, 5 kA, 15 m	
Furukawa	TEPCO, JP, 2012	CD	275 kV, 3 kA, 30 m	Bi 2223
Sumitomo	Yokohama, JP, 2012	CD	66 kV, 200 MVA, 240 m, 3-ph.	Bi 2223
Ultera	New York, US, 2015	CD	13.8 kV, 4 kA, 170 m, 3-ph.	YBCO
Nexans	Essen, Germany, 2013	CD	10 kV, 40 MVA, 1000 m, 3 ph.	Bi 2223
LS Cable	Jeju Island, Korea, 2014	CD	154 kV, 2.25 kA, 500 m, 3 ph.	YBCO

Superconducting AC Cables
State-of-the-Art of HTS AC Cable Field Tests



Superconducting AC Cables
State-of-the-Art of HTS AC Cable Field Tests



Superconducting AC Cables
State-of-the-Art

Columbus

Ultera
13.2 kV, 3 kA, 200 m
Triaxial™ Design
BSCCO 2223
Energized 2006
High reliability

Figure: Ultera

LIPA

Nexans
138 kV, 2.4 kA, 600 m
Single coaxial design
BSCCO 2223
Energized 2008

Figure: Nexans

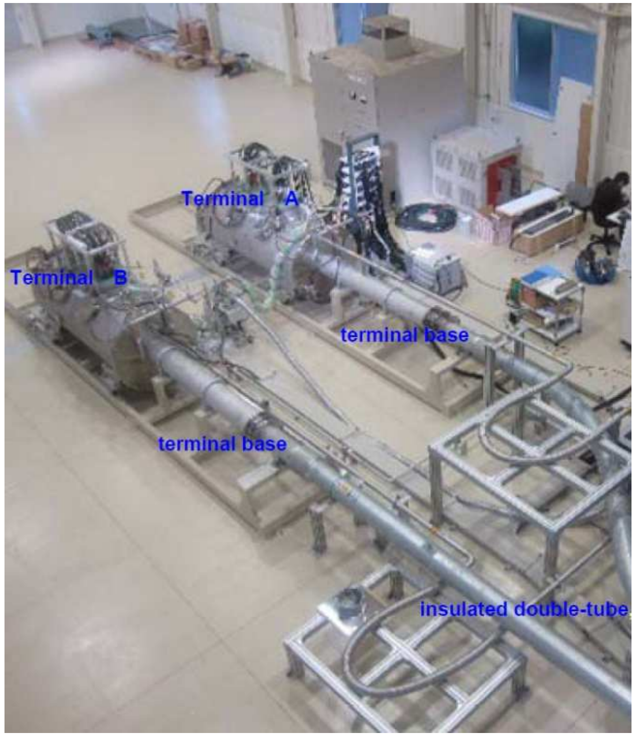
Gochang

Figure: LS Cable

LS Cable
22.9 kV, 50 MVA, 100 m
BSCCO 2223
Energized 2007
500 m field test with YBCO in 2011

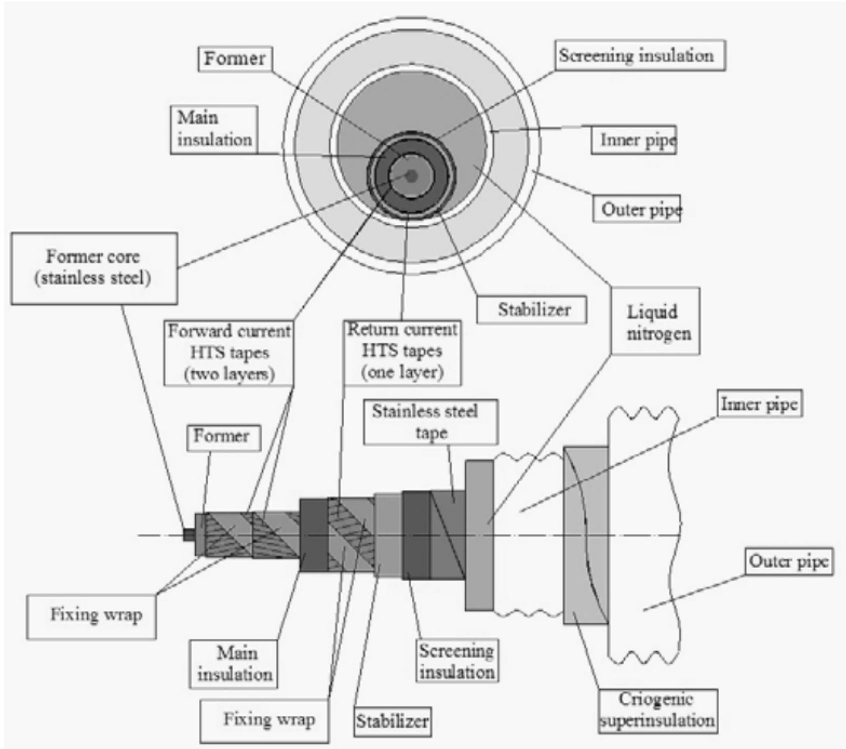
Superconducting DC Cables
State-of-the-Art

DC Cable in Japan



Chubu University
10 kV, 1.2 kA, 200 m
Energized 2010

DC Cable in Russia



V.E Sytnikov, et. al. "HTS DC cable line project: on-going activities in Russia", IEEE/CSC & ESAS European Superconductivity News Forum (ESNF) No. 23 January 2013

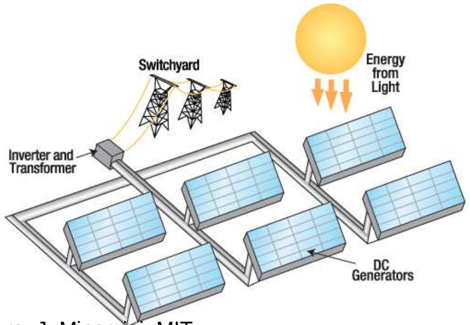
Customer: General Grid Company
20 kV, 2.5 kA, 2500 m
First full scale sample in 2013
Cable laying in 2015
Experimental operation in 2016

Superconducting DC Cables
Applications

Industry high current lines

Picture: Vision Electric

Connect renewables

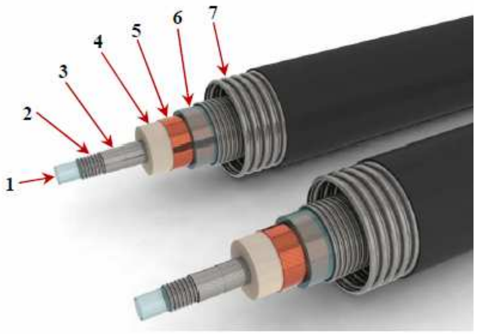


Picture: J. Minervini, MIT

Supply data centers

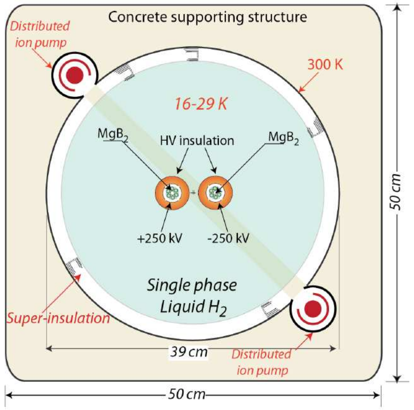
Picture: J. Minervini, MIT

Grounding of HVDC Lines



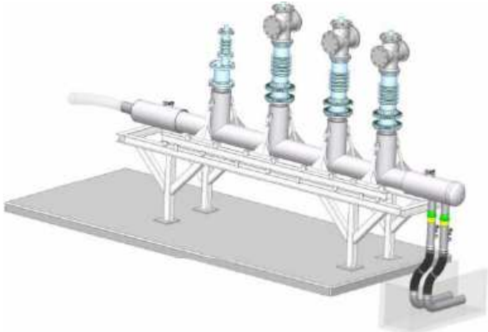
Picture: Nexans

Larger power, long distance transmission



Picture: C. Rubbia, IASS

Degaussing of ships



Picture: B. Fitzpatrick, HTS Peerreview2010

Superconducting Cables
Research Direction

- Lower cost and higher performance of HTS material
- Improved reliability and availability of the cooling system
- Improved thermal insulation at reduced cost
- Work on standards
    - CIGRE Technical brochure available in 2013
- Demonstrate reliability and availability in long-term field installations

Superconducting cables are very close to commercialization.

Superconducting Rotating Machines

Benefits

Smaller volume and weight

- Half the weight and volume
- Two times higher power density

Less resources

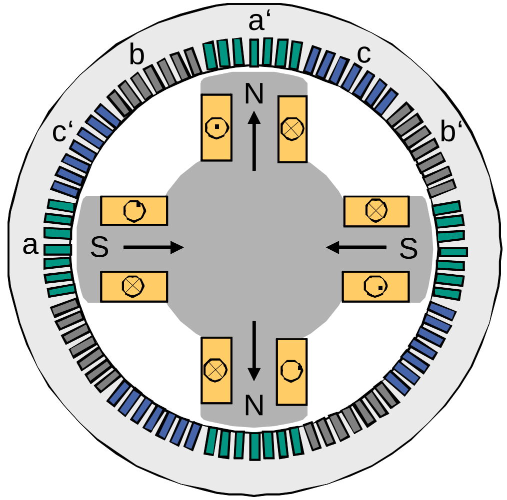
- Higher efficiency
- Less material

Improved operation parameters

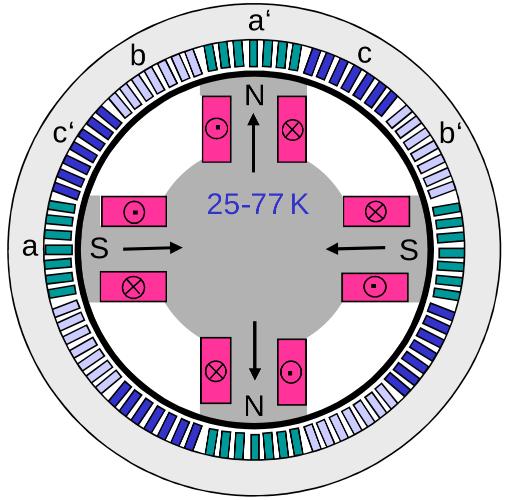
- Lower voltage drop (x_d~ 0.2-0.3 p.u.)
- Higher stability
- Higher torque and dynamics
- Higher ratio of breakdown torque to nominal torque
- More reactive power

Enables new drive and generator systems

Conventional synchronous machine

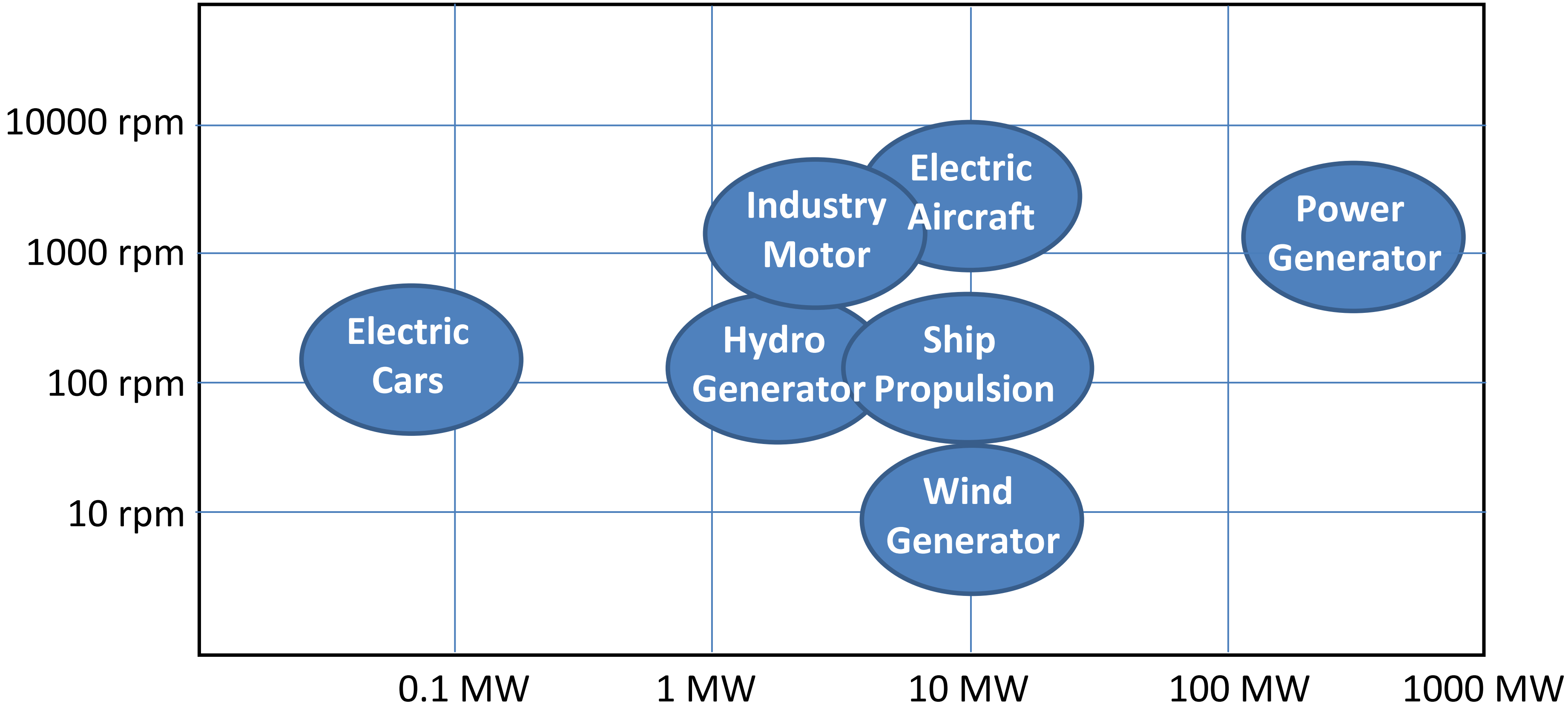


Superconducting synchronous machine



$B = 2$ T
$A_1 = 2$ p.u.
$P = 4$ p.u.
<u>Losses</u>
$P_{Cu,stat} = 2$ p.u.
$P_{Cu,rot} = 0$ p.u. $+ P_{Cool}$
$P_{Fe} = 0.6$ p.u.

Superconducting Rotating Machines
For which Application?



There are many potential applications for HTS rotating machines that differ very much in rating, torque and speed.

Superconducting Rotating Machines
State-of-the-Art of large scale Motors and Generators

Manufacturer / Country	Machine	Timeline
AMSC (US)	5 MW demo-motor	2004
	8 MVA, 12 MVA synchronous condenser	2005/2006 (**Field test**)
	40 MVA generator design study	2006
	36 MW ship propulsion motor 8 MW wind generator design study	2008 2010
GE (US)	100 MVA utility generator	2006 (discontinued)
	5 MVA homopolar induction motor	2008
LEI (US)	5 MVA high speed generator	2006
Reliance Electric (US)	10.5 MVA generator design study	2008
Kawasaki (JP)	1 MW ship propulsion	200?
IHI Marine, SEI (JP)	365 kW ship propulsion motor	2007
	2.5MW ship propulsion motor	2010
Doosan, KERI (Korea)	1 MVA demo-generator	2007
	5 MW motor ship propulsion	2011
Siemens (Germany)	4 MVA industrial generator	2008 (**Field test**)
	4 MW ship propulsion motor	2010
Converteam (UK)	1.25 MVA hydro-generator	2010
	500 kW demo-generator	2008
	8 MW wind generator design study	2010
Tecnalia /Acciona (Spain)	500 kW wind generator demonstrator	2016

Superconducting Rotating Machines
State-of-the-Art

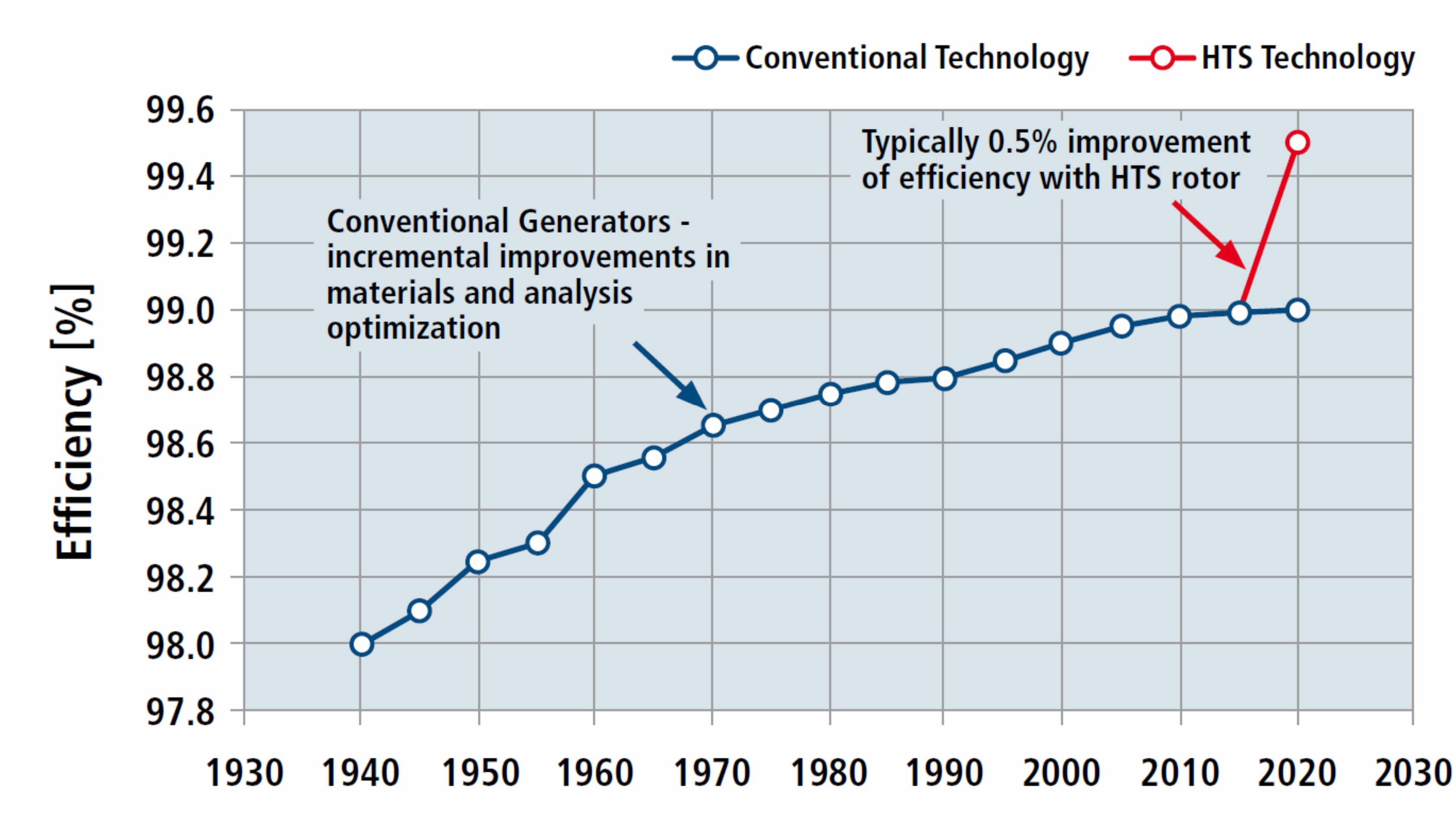
Ship Propulsion	EU „Hydrogenie“ Hydrogenerator	Ship Propulsion
		
AMSC 36.5 MVA, 6 kV 120 rpm 8 poles, 75 tons Efficiency > 97 % Dimensions: 3,4 m x 4,6 m x 4,1 m	GE/(Converteam) 1.790 MW, 5.25 kV 214 rpm, 77.3 kNm 28 poles, 32.7 tons 4.7 m x 5.2 m x 3.5 m Test in 2012	Siemens 4 MW, 3.1 kV 120 rpm, 320 kNm 37 tons 50 km HTS Test in 2010

Picture from:
Nature Physics 2, 794 - 796 (2006)
doi:10.1038/nphys472
Wired for the future
John Clarke & David C. Larbalestier

Image Courtesy of Converteam

Image Courtesy of Siemens

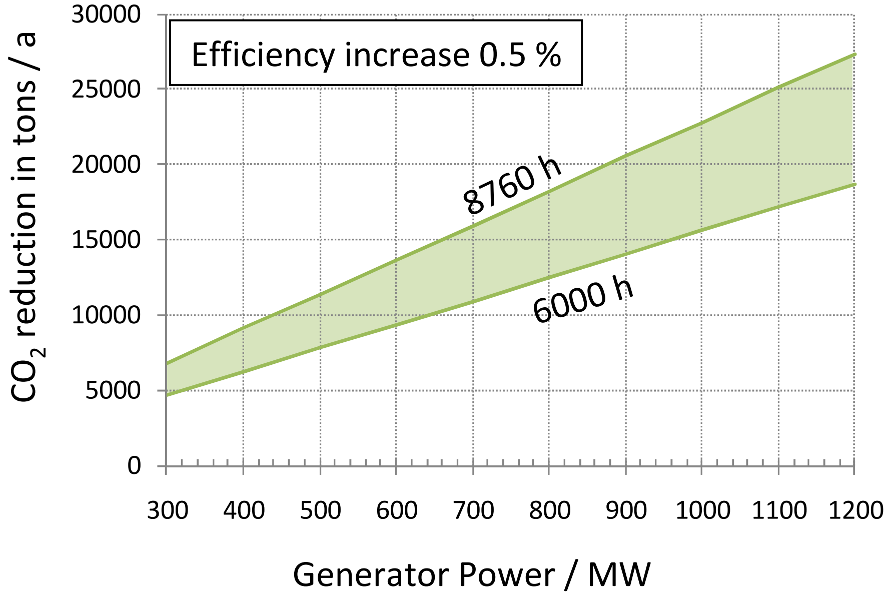
Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators



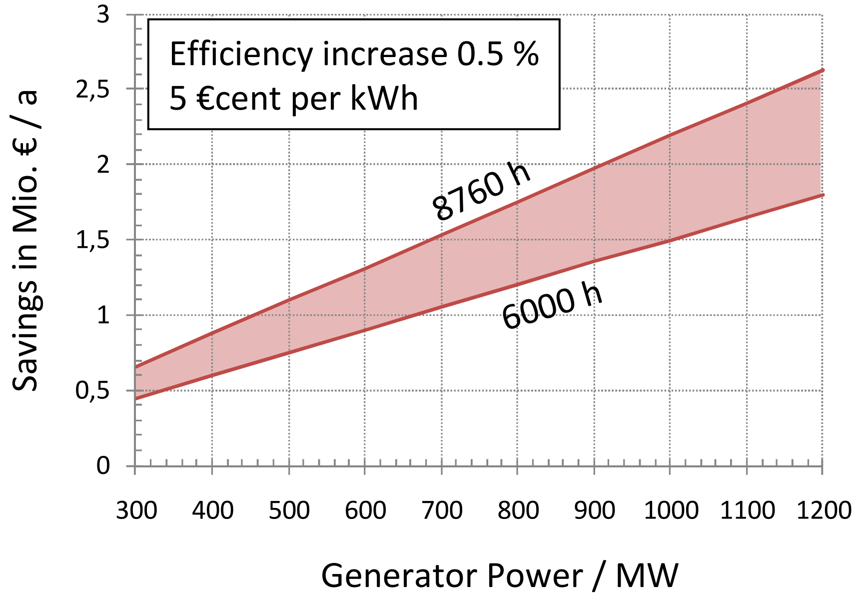
Source: High-Temperature Superconductivity for Power Engineering, Materials and Applications, Accompanying Book to the Conference ZIEHL II, Future and Innovation of Power Engineering with High-Temperature-Superconductors, 16-17 March 2010, Bonn, Germany

Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators

CO_2 reduction per generator
in tons / a 1)



Savings per generator
in Mio. € / a



With an increase in efficiency of 0.5 % a considerable cost saving can be expected.

1) 1 kWh=520 g CO_2 (actual German Energy Mix)

Superconducting Rotating Machines
HTS High Torque Machines for Industry Applications

Data

- Power 156 kW
- Speed 57 rpm
- Torque 26000 Nm
- Efficiency 99.6 %
- Dynamic > 10000 rpm/s
- YBCO length 4 km, 4mm width
- Superconducting stator
- Permanent magnets in rotor

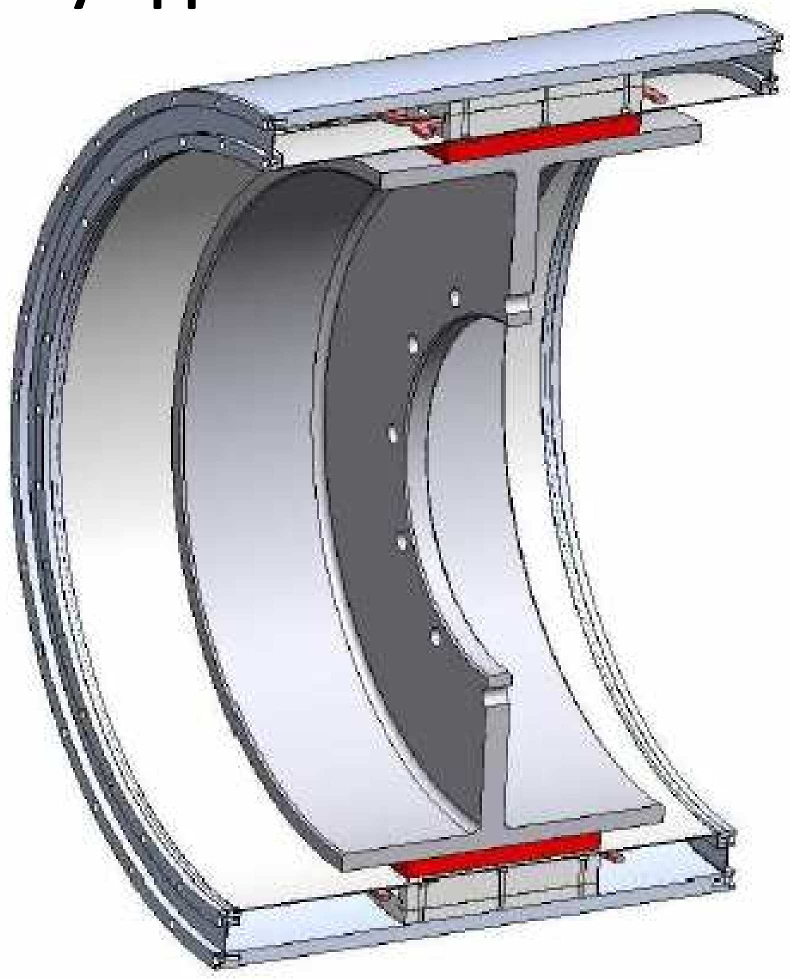


Figure: Oswald Company, Miltenberg, Germany

High dynamics and force density with HTS machines

Superconducting Rotating Machines
Research Directions

- Higher performance at lower cost
- Reliable and robust winding concepts
- Efficient and adaptable cooling
- Long-term demonstration in real application (no longer in test labs)
- Many applications
    - Ship propulsion
    - Wind generators
    - Power generators
    - High Torque machines
    - ….

It can be expected, that within the next decade
first commercial applications will be in the market. [1)]

1) „Status of Development and Field Test Experience with High-Temperature Superconducting Power Equipment, Working Group D1.15, June 2010

Superconducting Transformer
Benefit of Superconducting Transformers

Manufacturing and transport

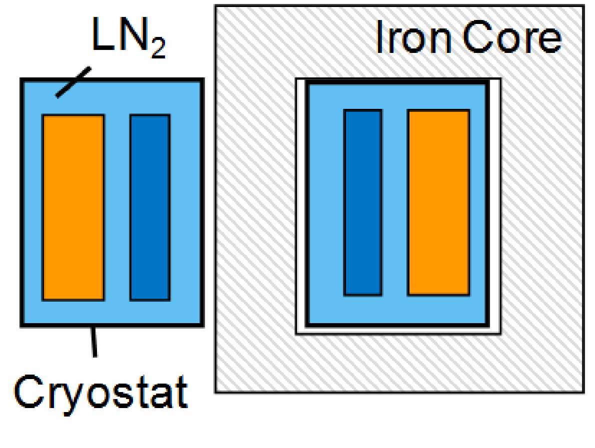
- Compact and lightweight (~50 % Reduction)

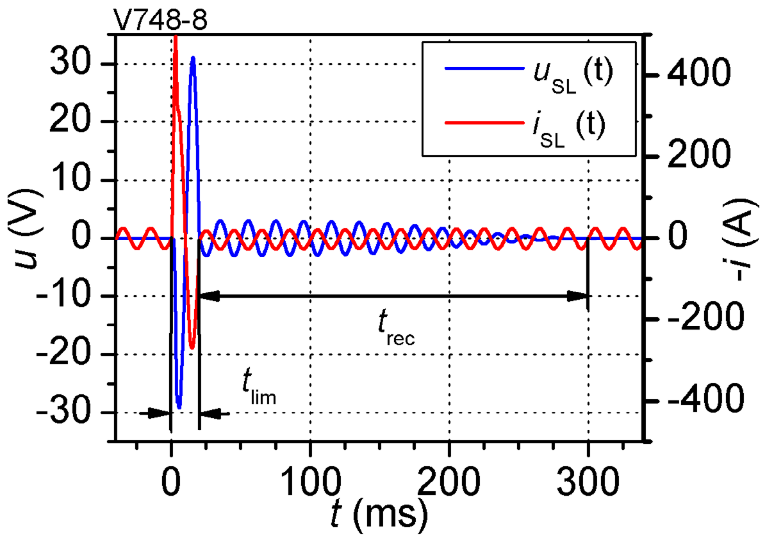
Environment and Marketing

- Energy savings (~50 % Reduction)
- Ressource savings
- Inflammable (no oil)

Operation

- Low short-circuit impedance
    - Higher stability
    - Less voltage drops
    - Less reactive power
- Active current limitation
    - Protection of devices
    - Reduction of investment





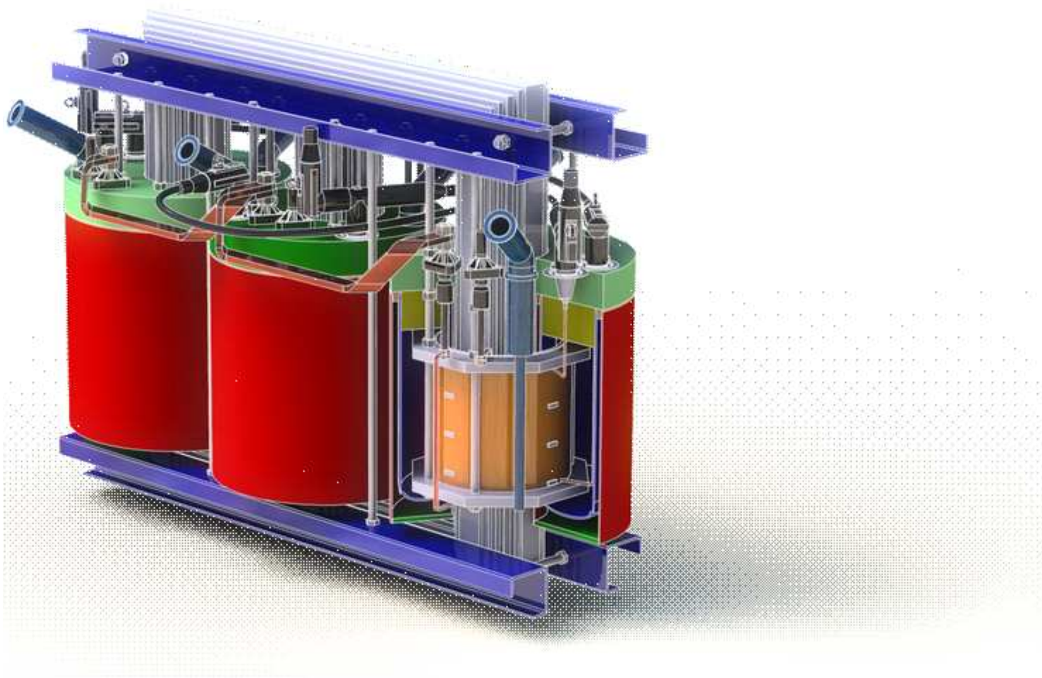
Superconducting Transformers
State-of-the-Art

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA/18,42 kV/420 V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric Kyushu Uni	Demonstrator	500 kVA/6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA/5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA/13,8 kV/6,9 kV	1		Bi 2223
USA	Waukesha	Demonstrator	5 MVA/24,9 kV/4,2 kV	3 Dy		Bi 2223
Japan	Fuji Electric U Kyushu	Demonstrator	1 MVA/22 kV/6,9 kV	1	< 2001	Bi 2223
Germany	Siemens	Railway	1 MVA/25 kV/1,4 kV	1	2001	Bi 2223
EU	CNRS	Demonstrator	41 kVA/2050 V/410 V	1	2003	P-YBCO S- Bi 2223
Korea	U Seoul	Demonstrator	1 MVA/22,9 kV/6,6 kV	1	2004	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA/22 kV/6,6 kV	1	2009	P-Bi 2223 S-YBCO
Germany	KIT	Demonstrator	1 MVA, 20 kV	1	2015	P-Cu/S-YBCO
USA	Waukesha	Prototype	28 MVA/69 kV	3	2013	YBCO
Japan	Kyushu	Demonstrator	2 MVA	1	2011	YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA	3	2013	YBCO

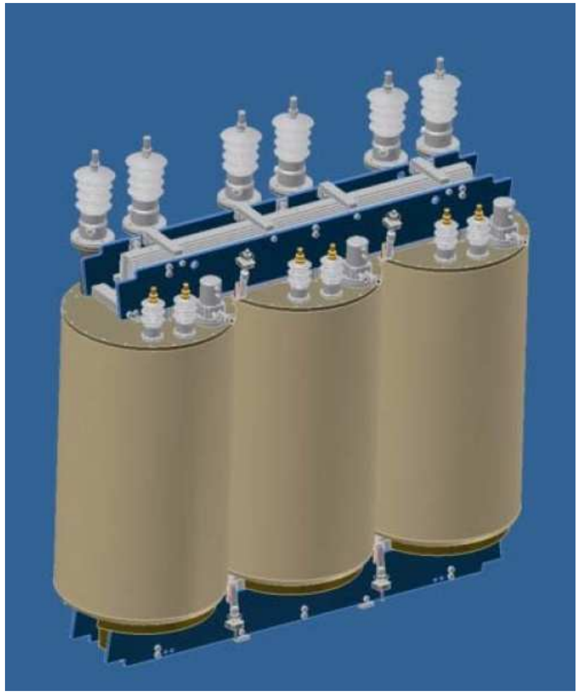
Active current limitation

Superconducting Transformers
State-of-the-Art of Current Limiting Transformers

versity | Waukesha/SuperPower



Source: Waukesha

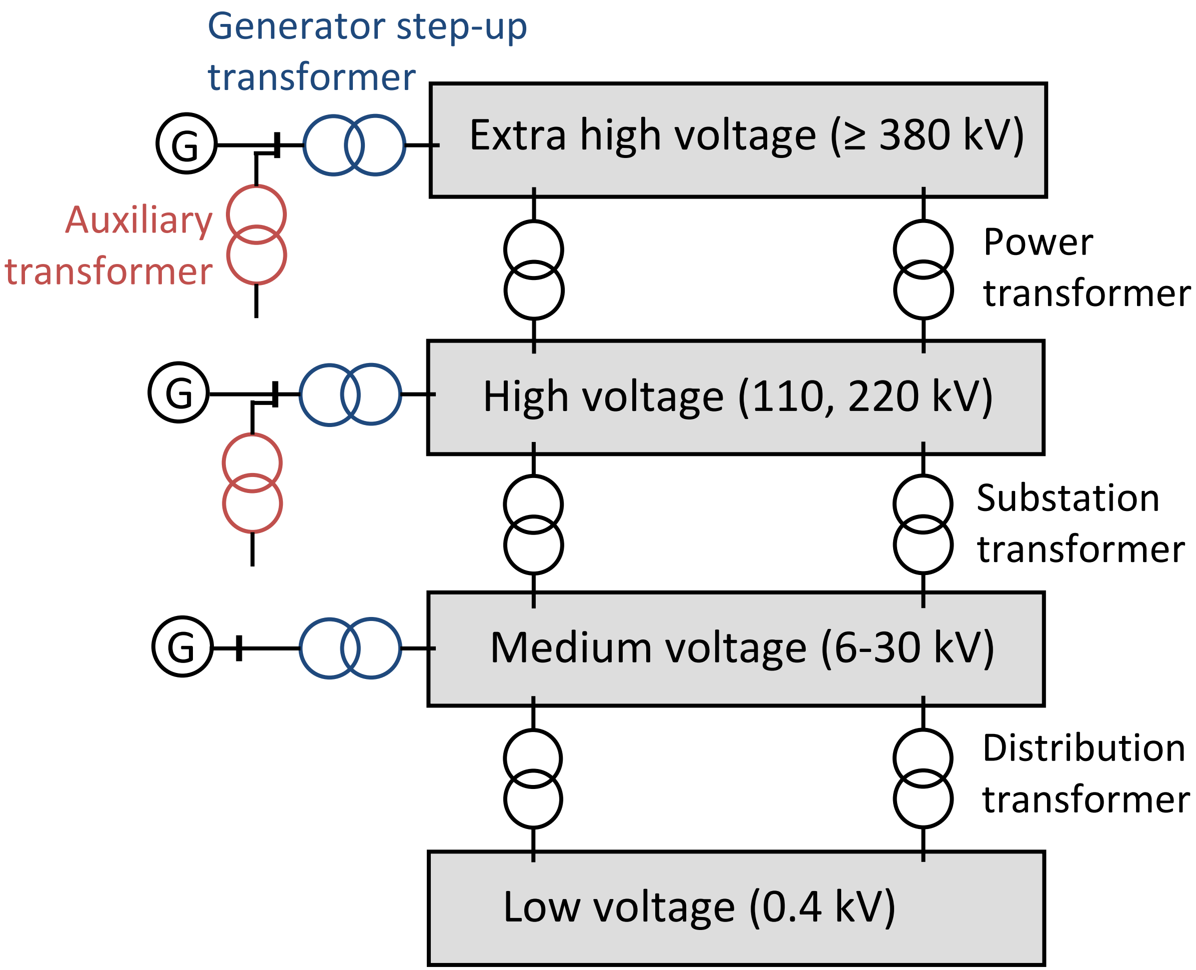


1 MVA Demonstrator
11 kV/415 V
Primary YBCO
Secondary YBCO Roebel cond.
Test in 2013

2 MVA Demonstrator
22kV/6.6 kV
Primary Bi 2223 tapes
Secondary YBCO tapes
Successful test in 2009

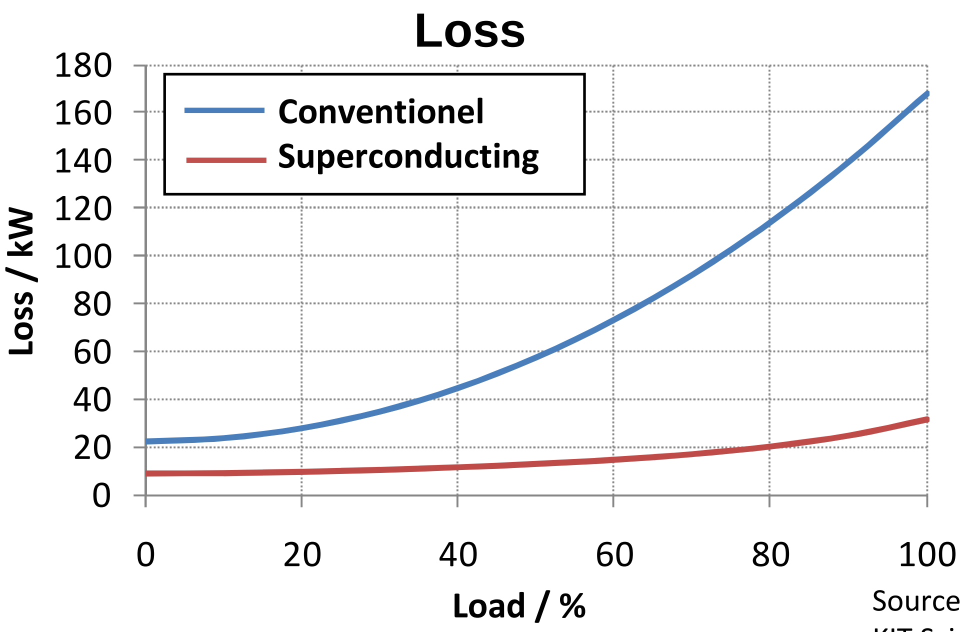
28 MVA Prototype
69 kV
Primary and secondary with
YBCO tapes
Test planned in 2013

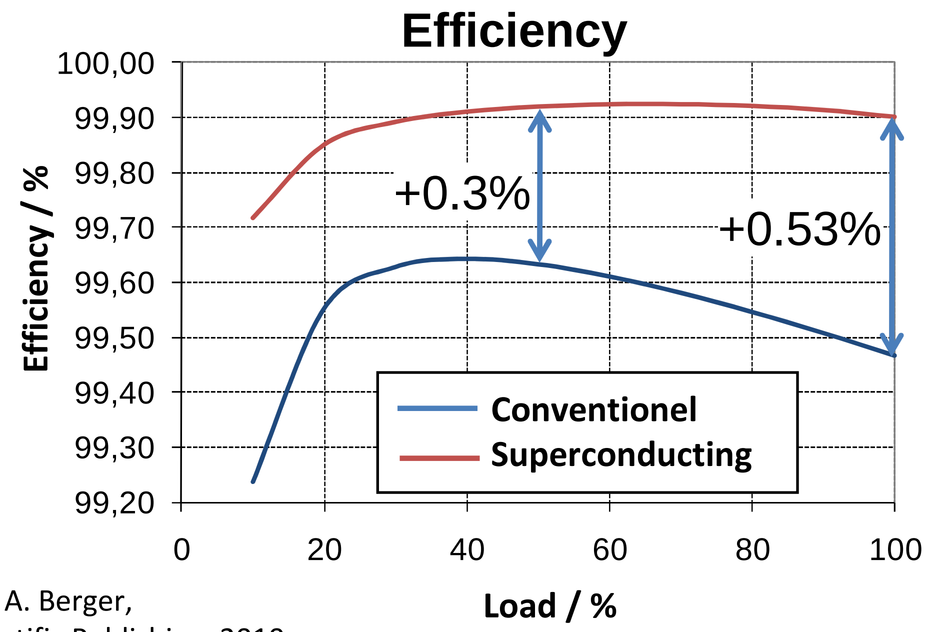
Superconducting Transformers
Applications



In general electricity passes 4-5 transformers from generation to load !

Superconducting Transformers
Energy Efficiency (Example 31,5 MVA Transformer)





Source: A. Berger,
KIT Scientific Publishing, 2010

Power Transformers in Europe

Type	Number	Capacity GVA
380 kV/220kV	689	311,8
220 kV/< 220 kV	2612	336,6
380 kV/< 220 kV	791	215,6

From entsoe, Statistical Yearbook 2008

- In 2007 the world electricity generation was 19,771 TWh[1)].
- The total power loss in Europe is appr. 6.5 %.
- Appr. 40 % of the loss is caused in transformers.

1) IEA key world energy statistics 2009

Superconducting Transformers

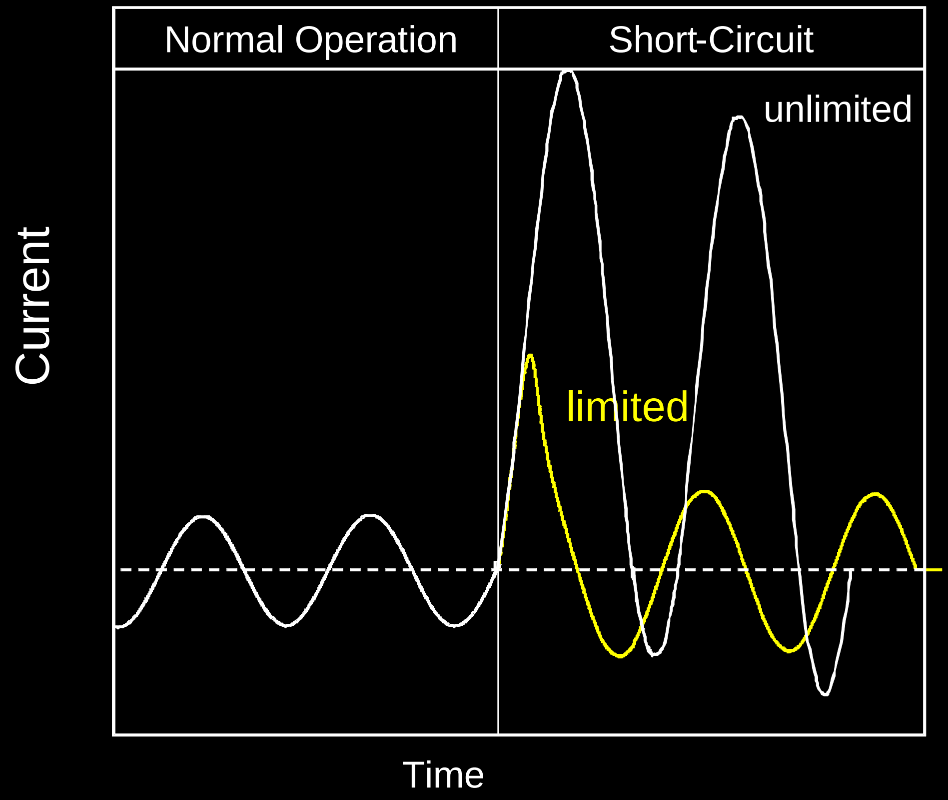
Research Directions

- Develop first large scale demonstrators and prototypes
- Develop wire concepts with reduced AC loss, stability and increased field performance
- Include current limitation (to compensate higher investment cost)
- Develop reliable cryogenic high voltage insulation concepts

Superconducting transformers need further demonstrator and prototype development.

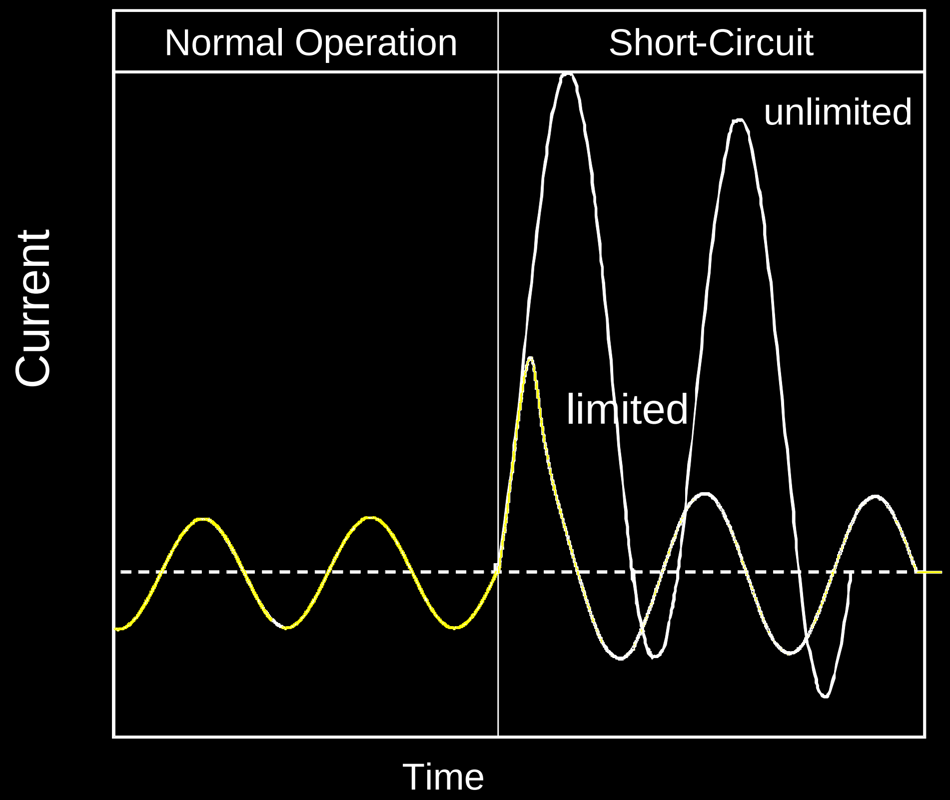
Superconducting Fault Current Limiters

[redacted]



Ideal Fault Current Limiter

- **Fast short-circuit limitation**
- No or small impedance at normal operation
- Fast and automatic recovery
- Fail safe
- Applicable at high voltages
- Cost effective



Ideal Fault Current Limiter

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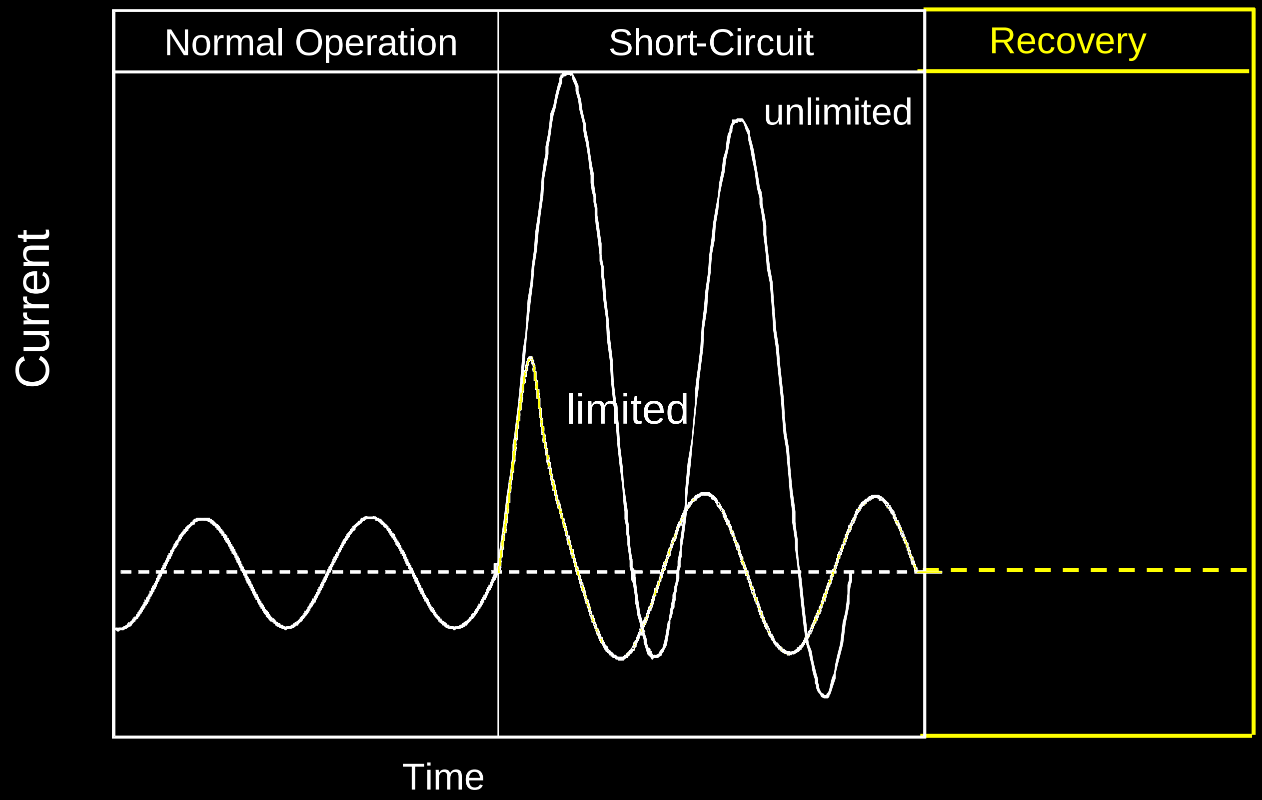
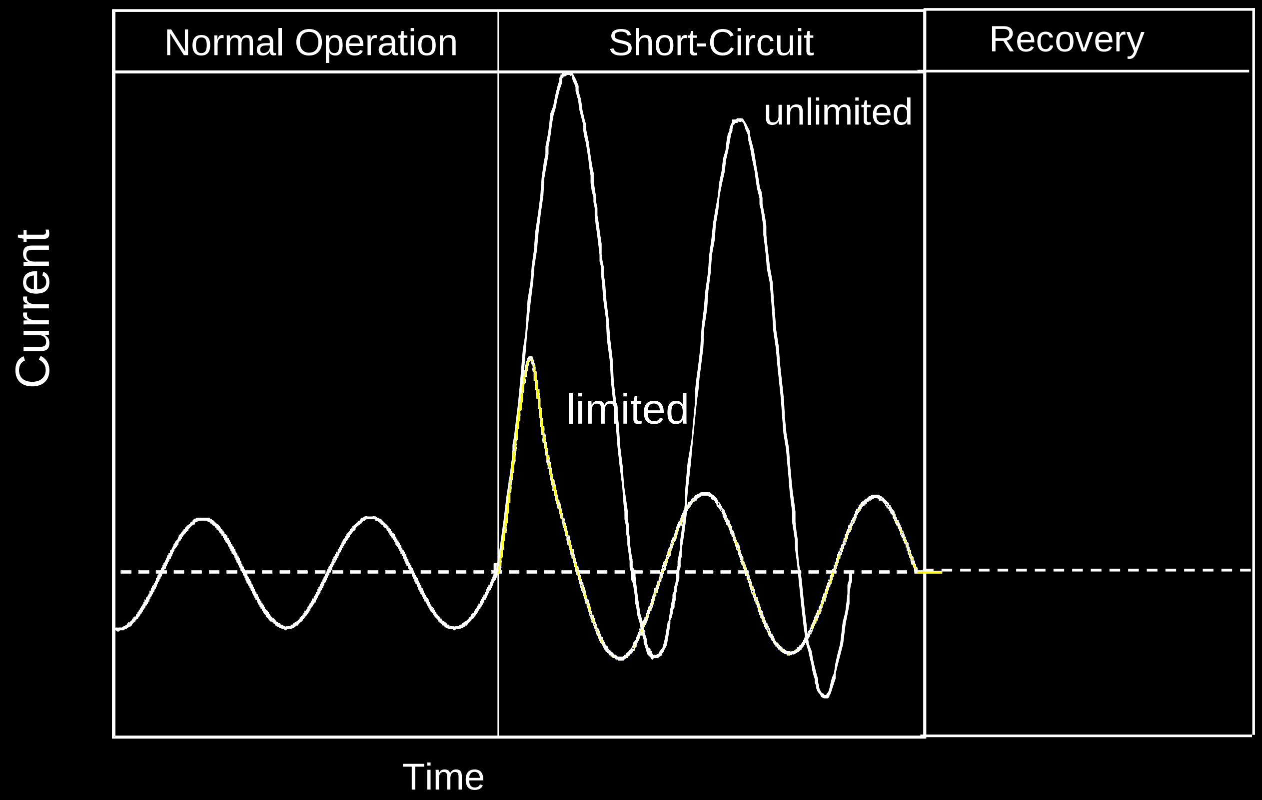


Ideal Fault Current Limiter

- Fast short-circuit limitation
- No or small impedance at normal operation
- **Fast and automatic recovery**
- Fail safe
- Applicable at high voltages
- Cost effective



Ideal Fault Current Limiter **SCFCL**

- Fast short-circuit limitation ✓
- No or small impedance at normal operation ✓
- Fast and automatic recovery ✓
- Fail safe ✓
- Applicable at high voltages ✓
- Cost effective ✓

Superconducting Fault Current Limiters
Economic Benefits

Delay improvement of components and upgrade power systems

e.g. connect new generation and do not increase short-circuit currents

e.g. couple busbars to increase renewable generation and keep voltage bandwiths

Lower dimensioning of components, substations and power systems

e.g. FCL in power system auxiliary

Avoid purchase of power system equipment

e.g. avoid redundant feeders by coupling power systems

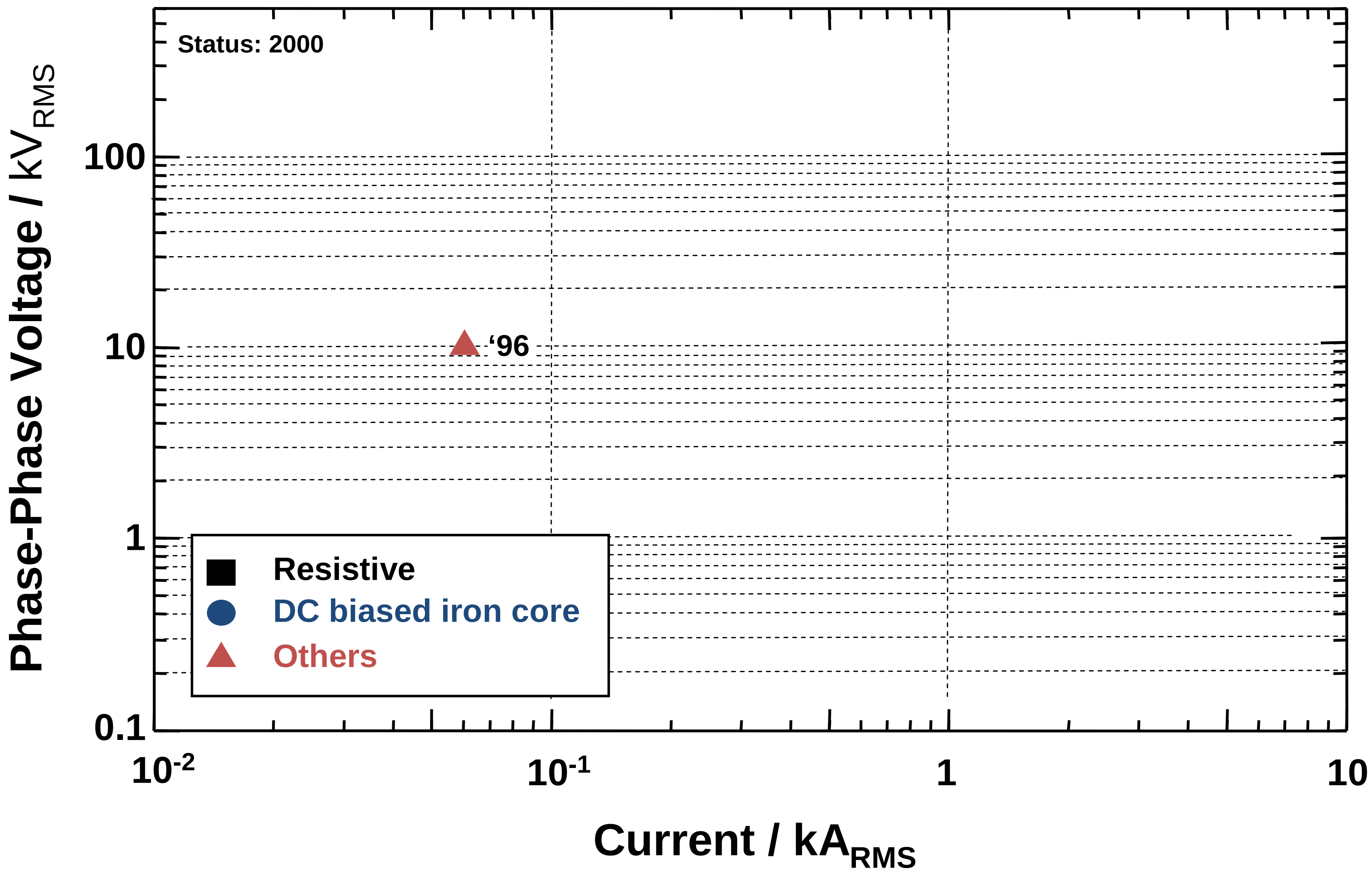
Increase availibity and reliability

e.g. by coupling power systems

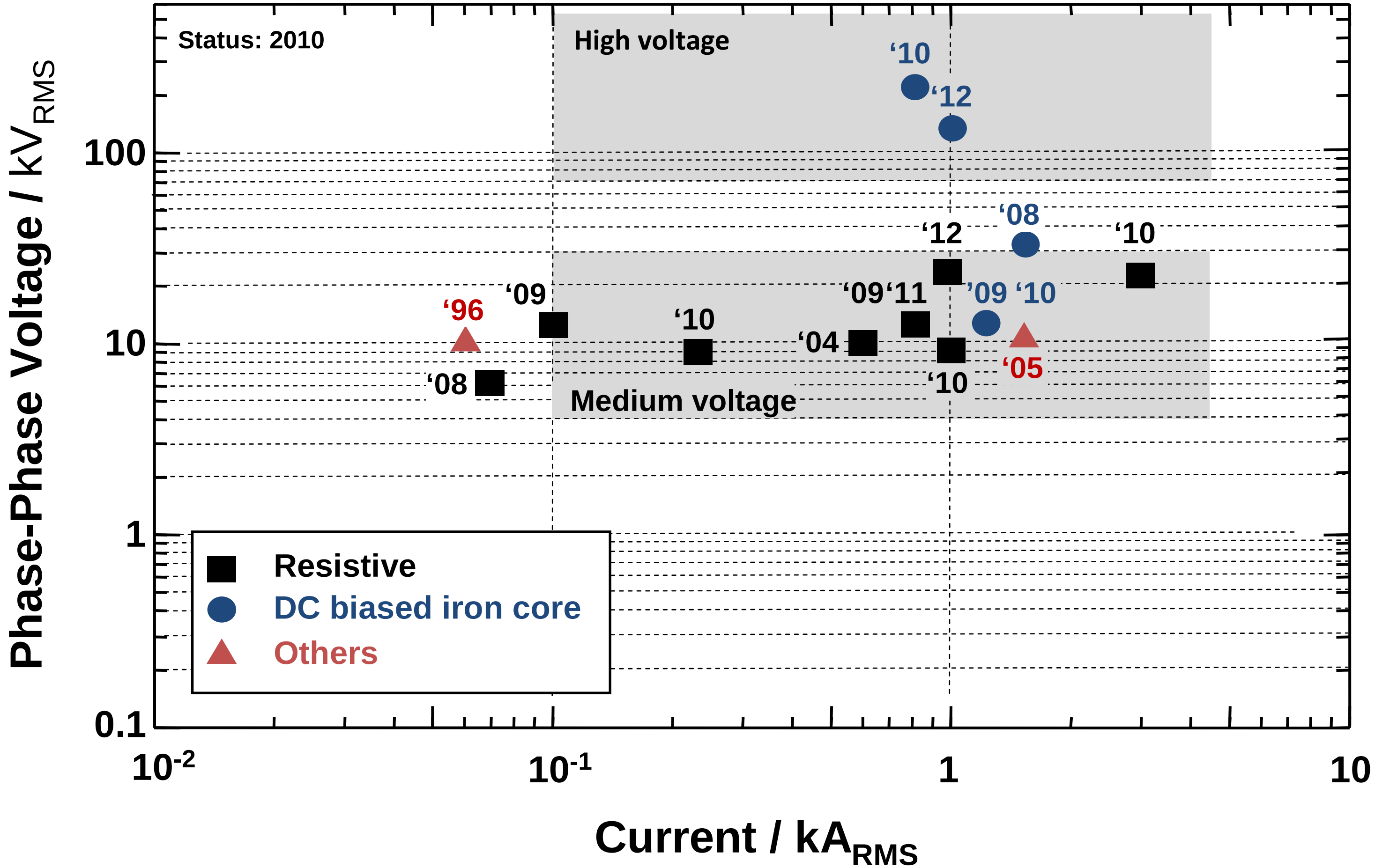
Reduce losses and CO_2 emissions

e.g. equal load distribution with parallel transformers

Superconducting Fault Current Limiters
Successful SCFCL **Field Tests** until 2000



Superconducting Fault Current Limiters
Successful and planned SCFCL Field Tests - Status by 2010



A considerable number of SCFCLs field tests have been performed within the last years.

Superconducting Fault Current Limiters
State-of-the-Art

Nexans SuperConductors

Courtesy: Nexans SuperConductors

Resistive Type
12 kV, 800 A, 120 ms
YBCO material
Power system auxiliary
Energized 2011

Innopower

DC Biased Iron Core Type
220 kV, 800 A
Bi 2223 tapes
Substation
Energized 2012

KEPRI

Hybrid type
22.9 kV, 3 kA
YBCO tapes
Substation
Energized 2011

Superconducting Fault Current Limiters
Application Examples

Commercial Projects

Bi 2212 bulk

12 kV, 100 A
Bi 2212 bulk

12 kV, 800 A
Bi 2212 bulk

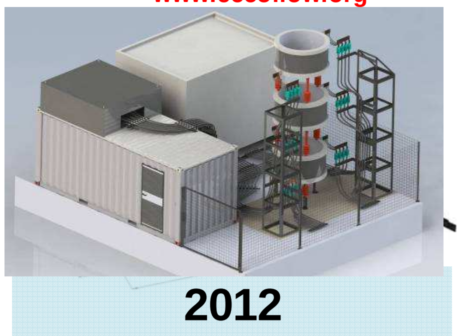
12 kV, 400 A
Bi 2212 bulk

YBCO tapes

10 kV, 600 A
YBCO tapes

20 kV, 1 kA
YBCO tapes

www.eccoflow.org



10 kV, 2.3 kA
YBCO tapes

Superconducting Fault Current Limiters

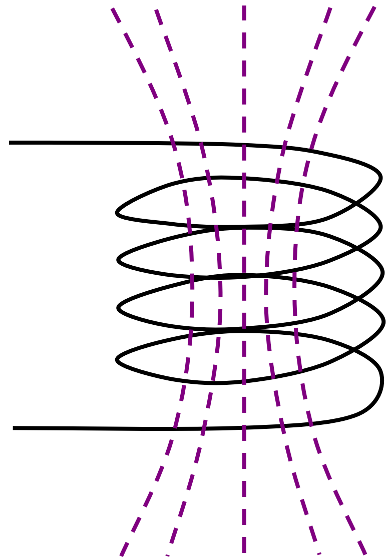
Research Directions

- Develop compact and inexpensive medium voltage SCFCLs
- Develop high voltage SCFCL demonstrators and prototypes
- Demonstrate and improve reliability with long term tests
- Develop tests standards
    - IEEE test guide for FCLs available soon
- Show value proposition and „educate costumer“

SCFCLs are very close to commercialisation.

Superconducting Magnetic Energy Storage
Benefits

$$I = I_0 \, e^{-\frac{t}{\tau}} \qquad \tau = \frac{L}{R}$$



- Short reaction time (ms)
- Fast charge and discharge
- 0-100 % charging possible
- Independent supply of active and reactive power
- High efficiency
- No degradation
- Environmentally friendly

Stored Energy	$Q = \frac{1}{2} L I^2$
Power	$P = U_L \, I$
Energy Density	$\frac{Q_{max}}{V} = \frac{B^2}{2 \mu_0}$

Superconducting Magnetic Energy Storage
State-of-the-Art

Lead Institution	Country	Year	Data	Super-conductor	Application
KIT	D	1997	320 kVA, 203 kJ	NbTi	Flicker compensation
AMSC	USA		2 MW, 2,6 MJ	NbTi	Grid stability
KIT	D	2004	25 MW, 237 kJ	NbTi	Power modulator
Chubu	J	2004	5 MVA, 5 MJ	NbTi	Voltage stability
Chubu	J	2004	1 MVA, 1 MJ	Bi 2212	Voltage stability
KERI	Korea	2005	750 kVA, 3 MJ	NbTi	Power quality
Ansaldo	I	2005	1 MVA, 1 MJ	NbTi	Voltage stability
Chubu	J	2007	10 MVA, 19 MJ	NbTi	Load compensation
CAS	China	2007	0,5 MVA, 1 MJ	Bi 2223	-
KERI	Korea	2007	600 kJ	Bi 2223	Power-, Voltage quality
CNRS	F	2008	800 kJ	Bi 2212	Military application
KERI	Korea	2011	2.5 MJ	YBCO	Power quality
BNL	USA	2013	3 MJ	YBCO	Grid storage

Superconducting Magnetic Energy Storage
State-of-the-Art of HTS SMES Development

Chubu, Japan
Bridging voltage dips

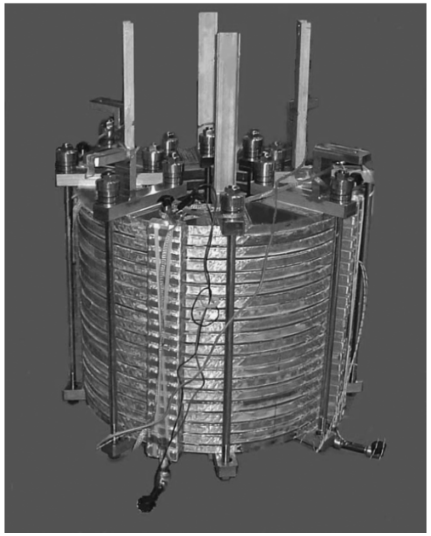


Figure: Chubu Electric

1 MJ , 1 MW
Bi 2212 tape
500 A,
5 K conduction cooled
Voltage: 2.5 kV

KERI, Korea
Power quality

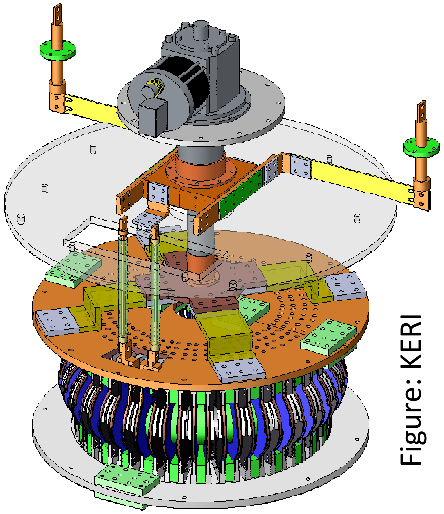


Figure: KERI

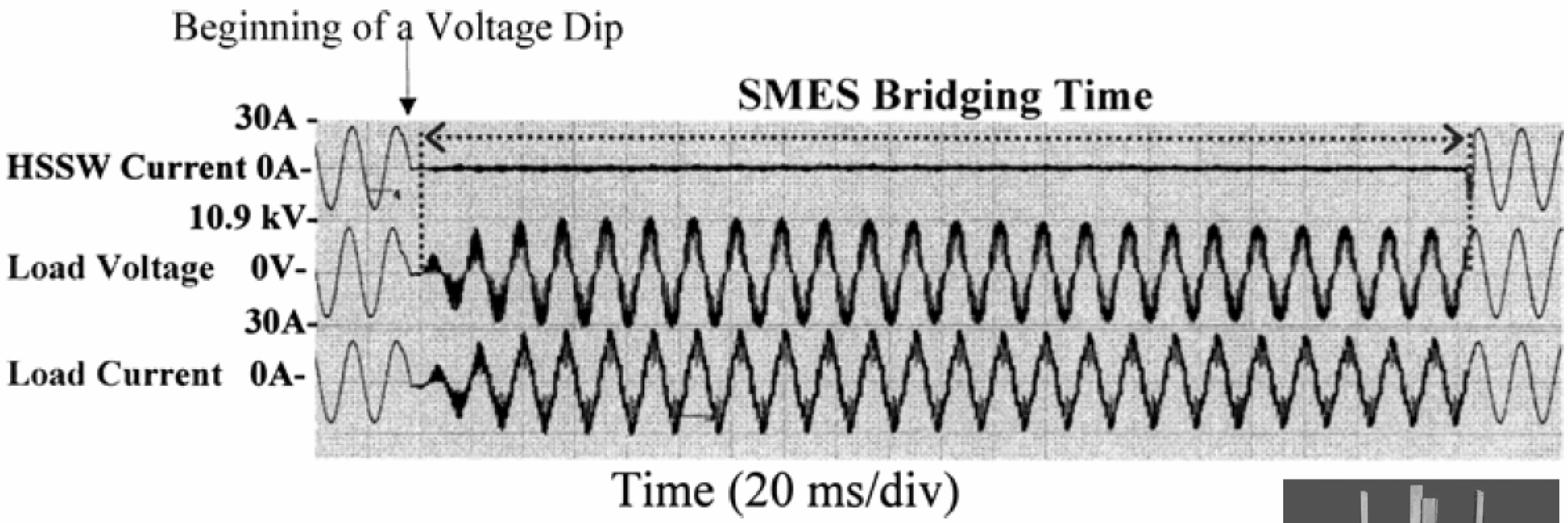
2.5 MJ
YBCO tape, 22 km
550 A
20 K conduction cooled
B_{maxII} 6.24 T
Test in 2011

CNRS, France
Military application

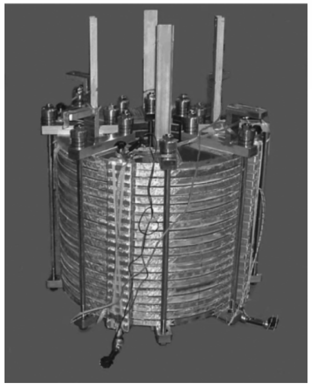
Figure: CNRS

814 kJ
Bi 2212 tape
315 A
20 K conduction cooled
Diameter : 300/814 mm
Height: 222 mm

Superconducting Magnetic Energy Storage
Test Experience of HTS SMES for bridging instantanous voltage dips



Source: IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005 1931
Development of MVA Class HTS SMES System for Bridging Instantaneous Voltage Dips
Koji Shikimachi, Hiromi Moriguchi, Naoki Hirano, Shigeo Nagaya, Toshinobu Ito, Junji Inagaki, Satoshi Hanai, Masahiko Takahashi, and Tsutomu Kurusu



SMES have demonstrated their technical feasibility many times.

Superconducting Magnetic Energy Storage

Research Direction

- Higher field performance at lower cost
- Reduction of AC loss
- Multistrand wires and tapes
- Develop modular SMES systems and hybrid SMES systems

SMES needs significant cost reduction.

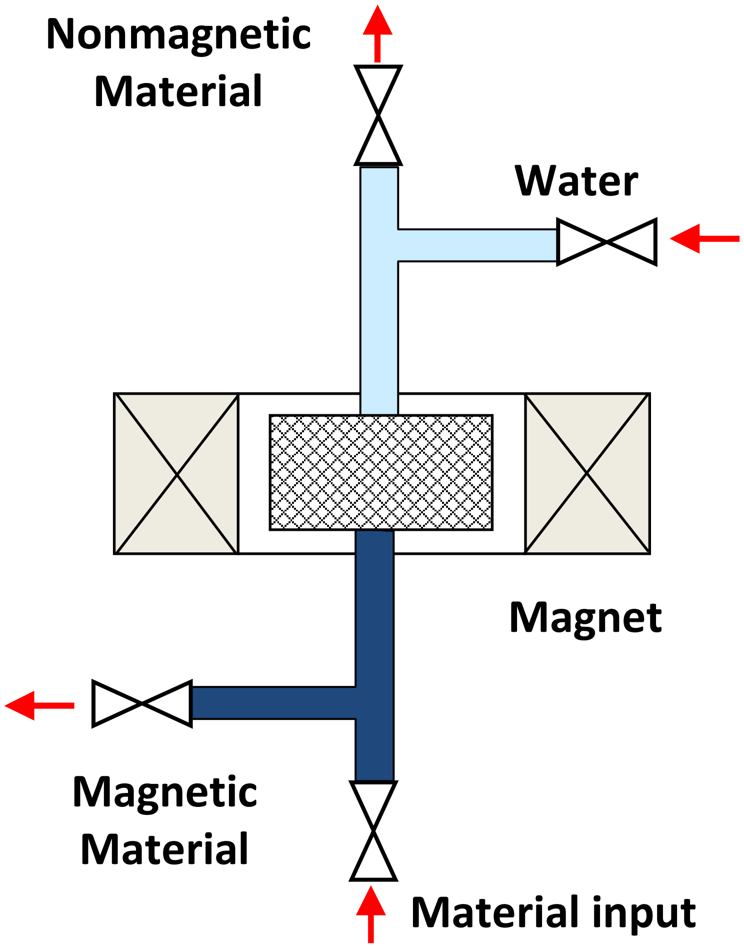
Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

In red – topics covered by my presentation

Applications	Field	Applications
Cyclotrons MRI applications	← Medicine Science →	Accelerator magnets Particle detectors magn. Supercond. cavities High field magnets
Fusion Wind generators Power applications	← Energy Engineering →	Magnetic separation Magnetic heating
Levitation	← Transport Electronics →	SQUIDS for biomedicine Detectors

Magnetic Separation
High Gradients



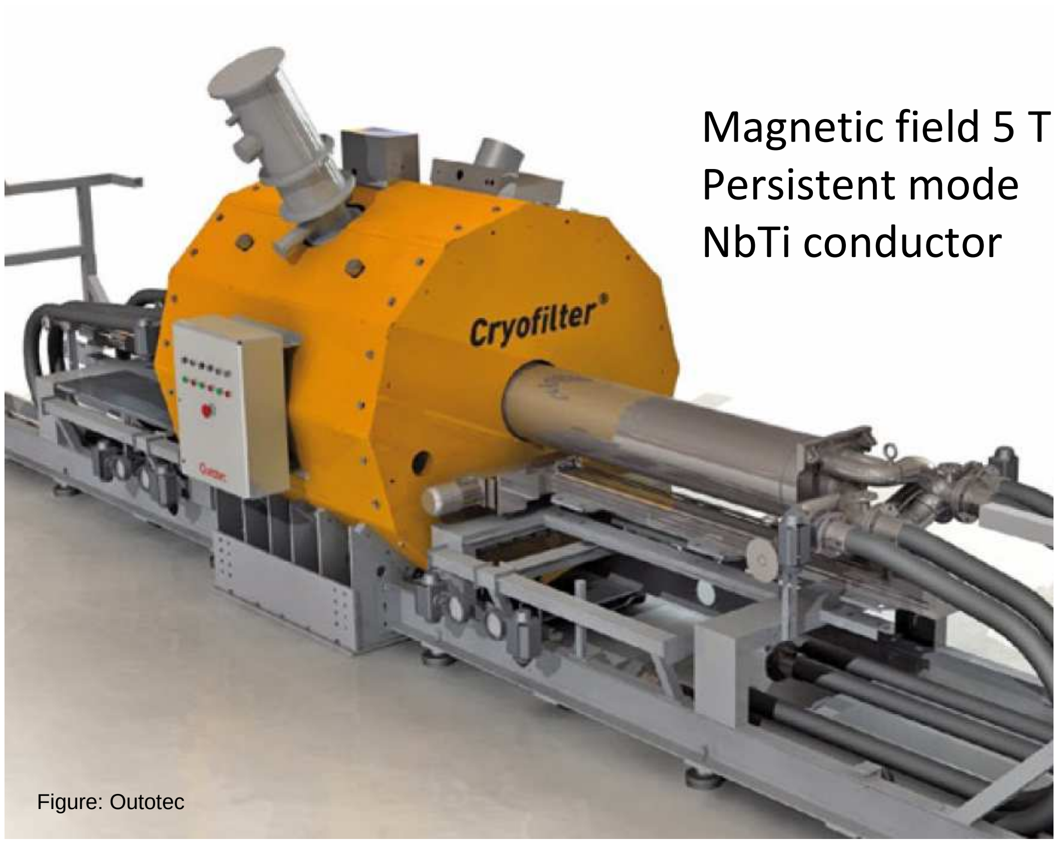


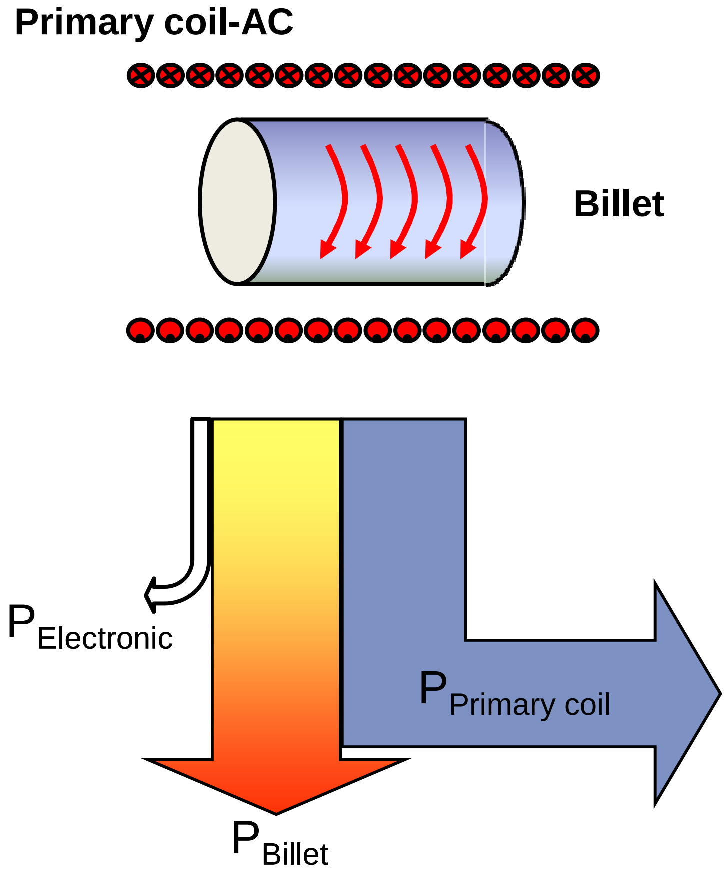
Figure: Outotec

Magnetic field 5 T
Persistent mode
NbTi conductor

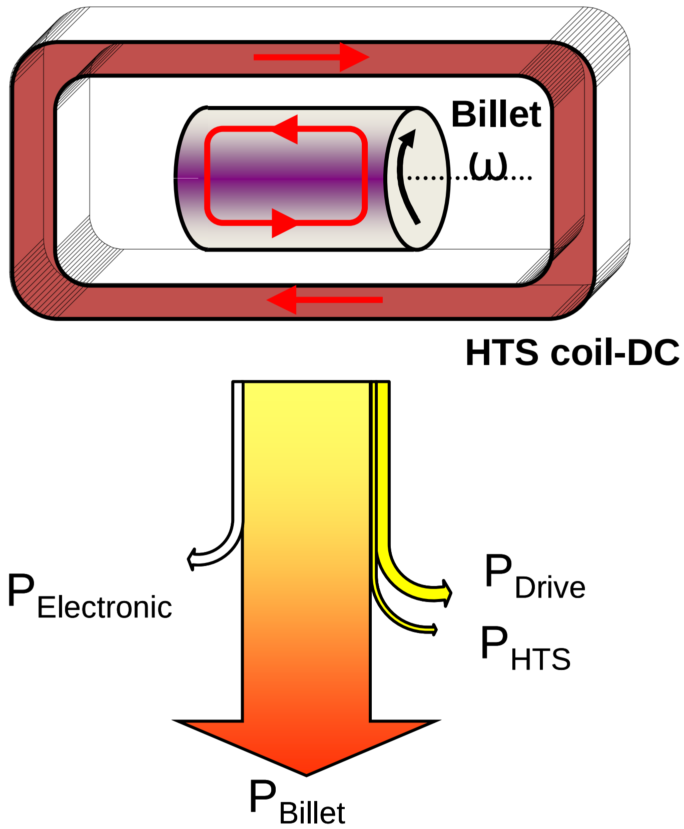
Industry solutions are offered for magnetic separation with LTS

Magnetic Heating
Motivation

Conventional Heating



HTS Magnetic Heating



Technology patented EP1582091, US7339145 (Sinvent AS, Norway)

Magnetic Heating
Benefits

Higher Efficiency

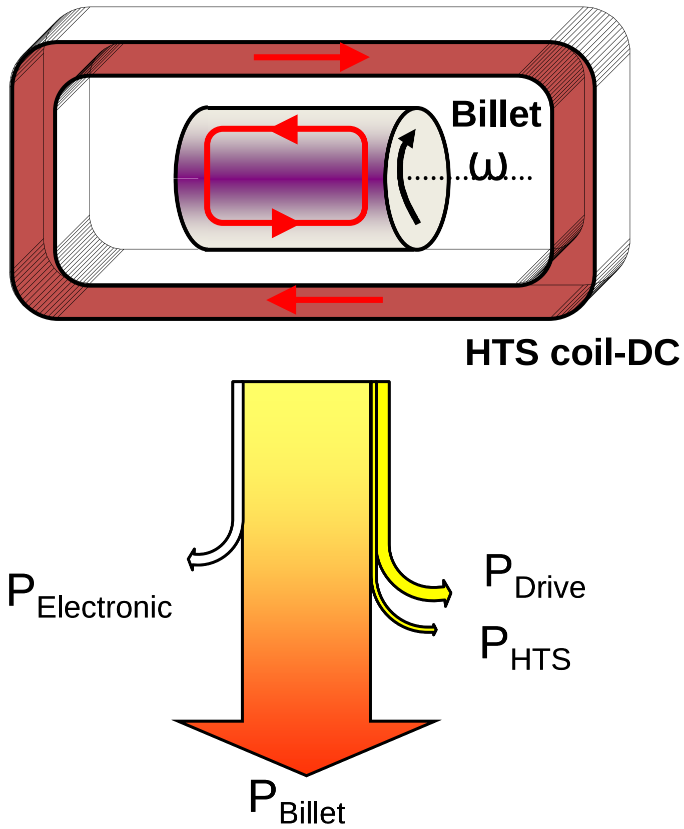
Faster Heating

Homogenous Heating

e.g. heating of 1 ton Aluminium with 0.5 MW heating power to 520°C:

• conventionel	280 kWh
• HTS magnetic heating	160 kWh

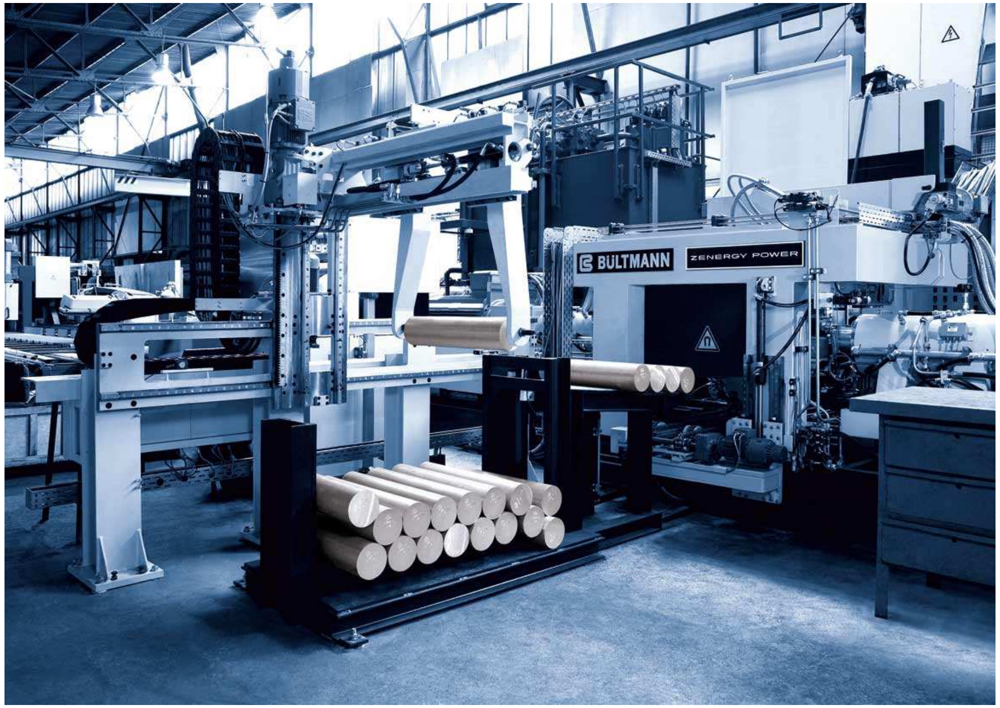
HTS Magnetic Heating



Technology patented EP1582091, US7339145 (Sinvent AS, Norway)

Magnetic Heating
State-of-the-Art

Date	Customer	Metal /Size	Country
Sept 2007	WeserAlu	Al 6”	Germany
Mar 2008	Wieland	Cu 16”	Germany
Jul 2009	Sapa	Al 16”	Italy
Oct 2009	N.N.	Cu 8”	Germany
Jan 2010	WeserAlu	Al 9”	Germany



Courtesy: Zenergy Power

Magnetic heating has been started to enter the market **but ….**

Lessons learned?

Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

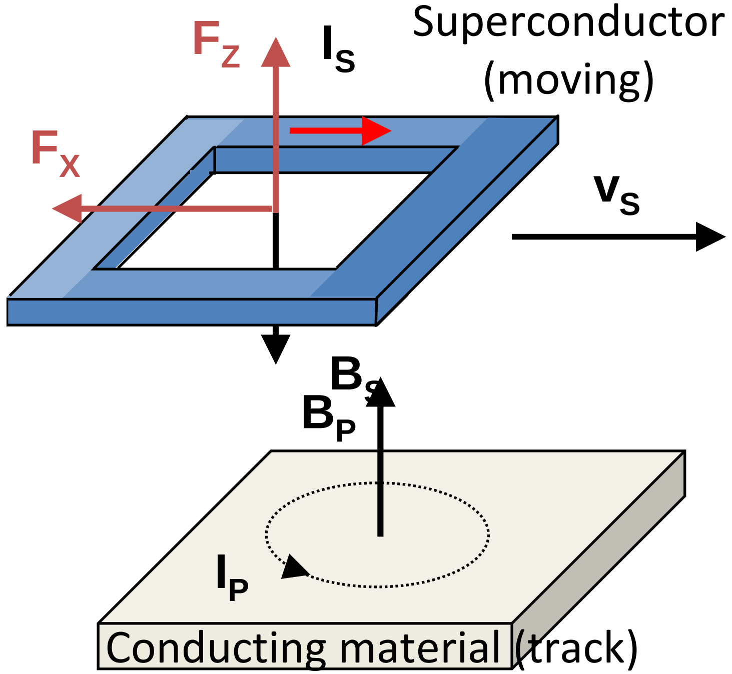
In red – topics covered by my presentation

Cyclotrons MRI applications	← Medicine	
	Science →	Accelerator magnets Particle detectors magn. Supercond. cavities High field magnets
Fusion Wind generators Power applications	← Energy	
	Engineering →	Magnetic separation Magnetic heating
Levitation	← Transport	
	Electronics →	SQUIDS for biomedicine Detectors

Transportation

Principles

Electrodynamic levitation

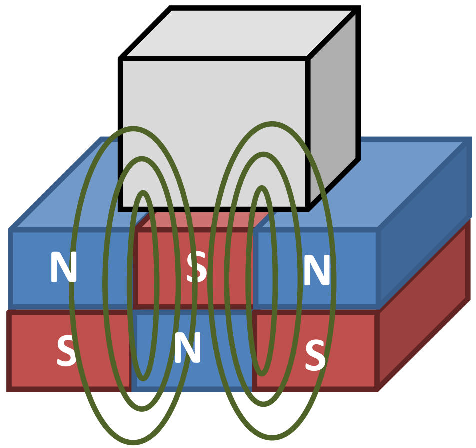


Major benefits

- Very high speeds
- self guiding at high speed

Superconducting levitation

Superconductor (moving)



Permanent magnets (track)

Major benefits

- Stable
- passive
- speed independant

Transportation
Electrodynamic Levitation

MLX01

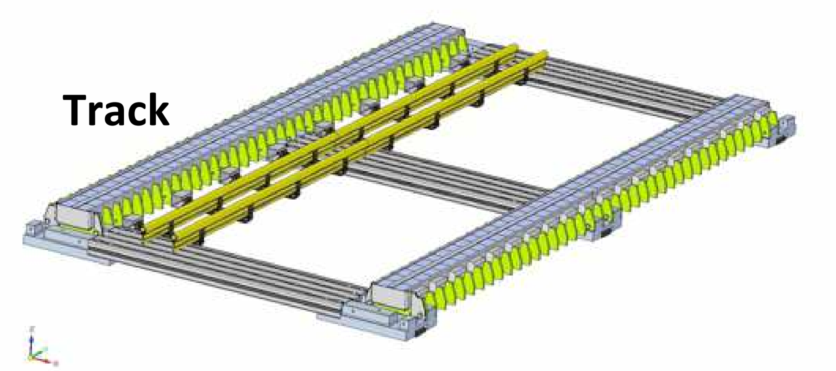
Superconducting magnet and a liquid helium tank on top of it

1977	7 km test line in Miyazaki Prefecture
1996	42.8 km test line in Yamanashi
Nov. 1997	first time speed with more than 500 km per hour
Dec. 2nd 2003	581 km/h – world speed record for all trains
May 18th 2011	Consent on Tokyo – Osaka line (505 km/h)

Extensive test experience with Yamanashi test line.

Transportation
Superconducting Levitation

Courtesy: evico



Vehicle

Length	2500 mm
Width	1200 mm
Rated load	600 kg
Superconductor	YBCO at 77 K
Max. acceleration	1 m/s²
Speed	20 km/h

Track

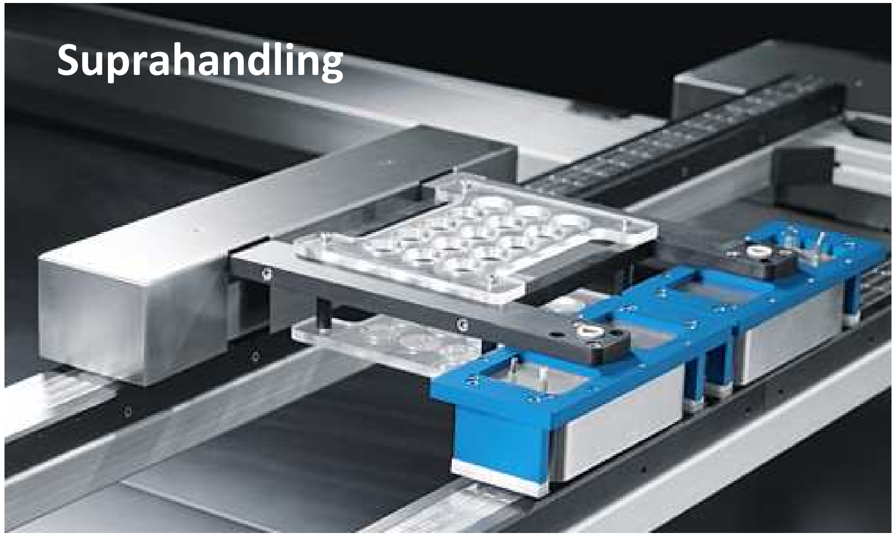
Track width	1000 mm
Length	80 m
Curve Radius	6.5 m
Field in air gap	0.6 T
Air gap	10 mm

80 m test line in operation at IFW in Dresden since 2011

Transportation
Superconducting Levitation

Picture: FESTO

Picture: FESTO

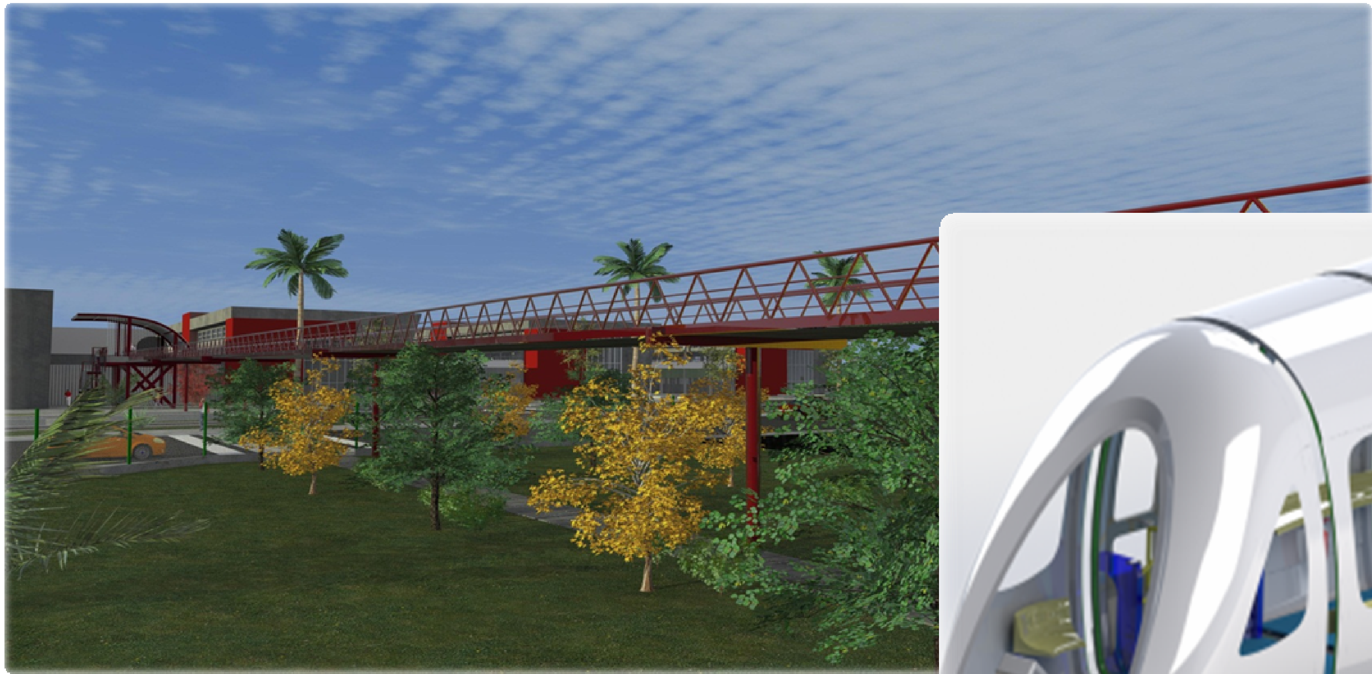


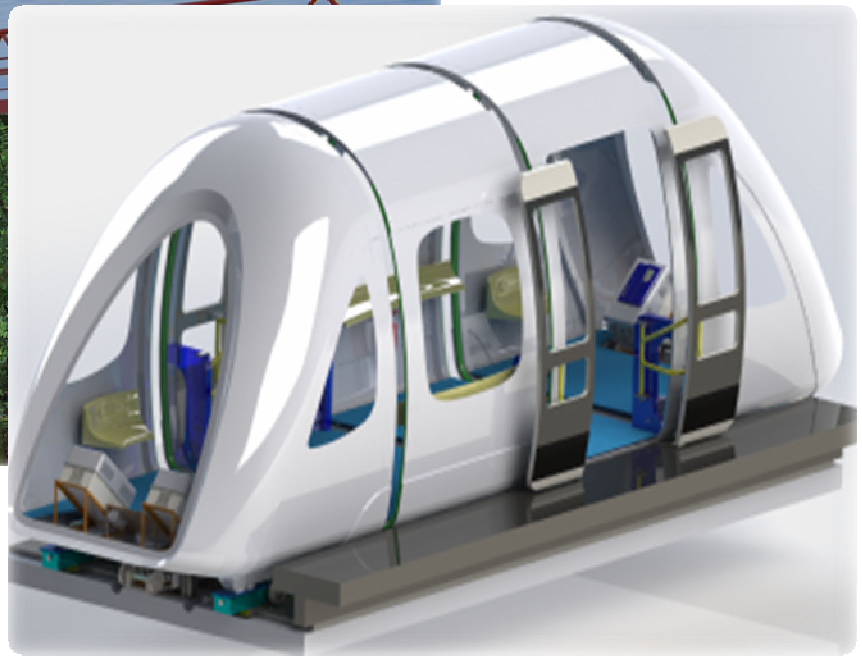
Track width: 600 mm
Air gap: 10 –15 mm
Max. acceleration: 2.4 m/s²
Max. speed: 8.6 km/h
Max. payload: One person, up to 120 kg
Magnets: 320 NdFeB magnets

Dimensions: 2,000 × 2,000 × 1,000 mm
Max. acceleration: 0.70 m/s²
Max. payload: 120 kg (X plane), 60 kg (Y plane)
X-axis: 2 large magnetic rails, 1,800 mm apart
Max. travel: 1,300 mm, Air gap: 10–15 mm
Y-axis: 2 small magnetic rails, 350 mm apart
Max. travel: 1,100 mm, Air gap: 5 –10 mm

First products demonstrated at Hannover Fair in 2013

Transportation
Superconducting Levitation





Source: Prof. Rubens Andrade
Laboratory for Applied Superconductivity – LASUP
Department of Electric Engineering
Federal University of Rio de Janeiro – COPPE – UFRJ

A MagLev vehicle track is being built with 200 m and it will connect 2 buildings at Federal University of Rio de Janeiro

Transportation
Superconducting Levitation

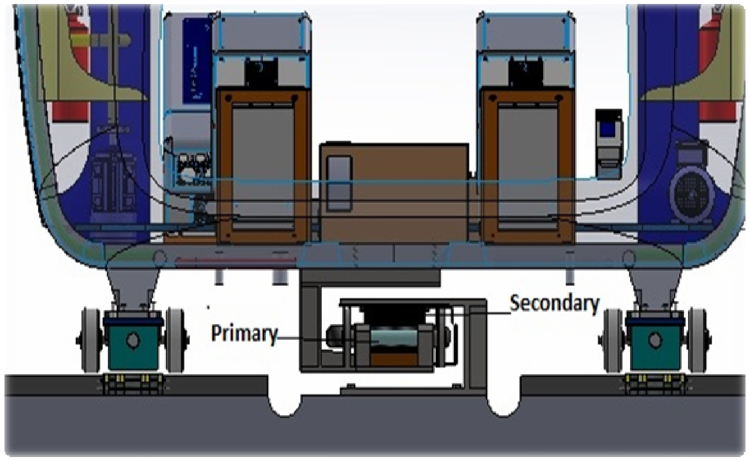
Test module constructed

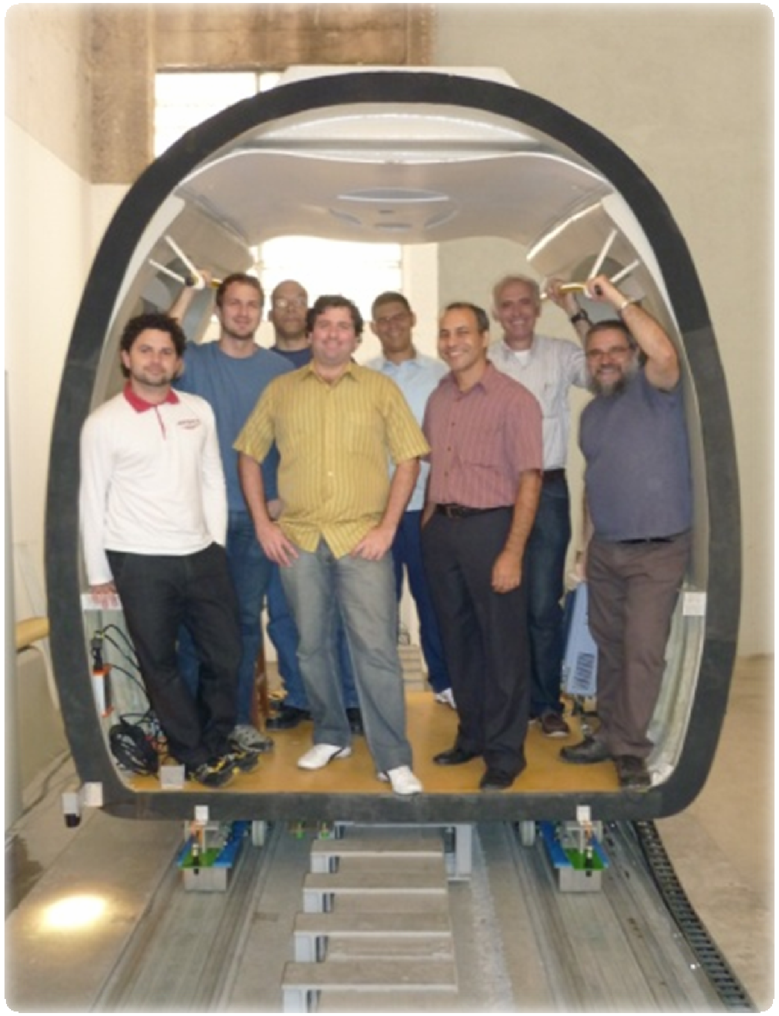
Module weights 750 kg

Supports 800 kg load

Linear induction motor

12 m Permanent Magnet Guideway





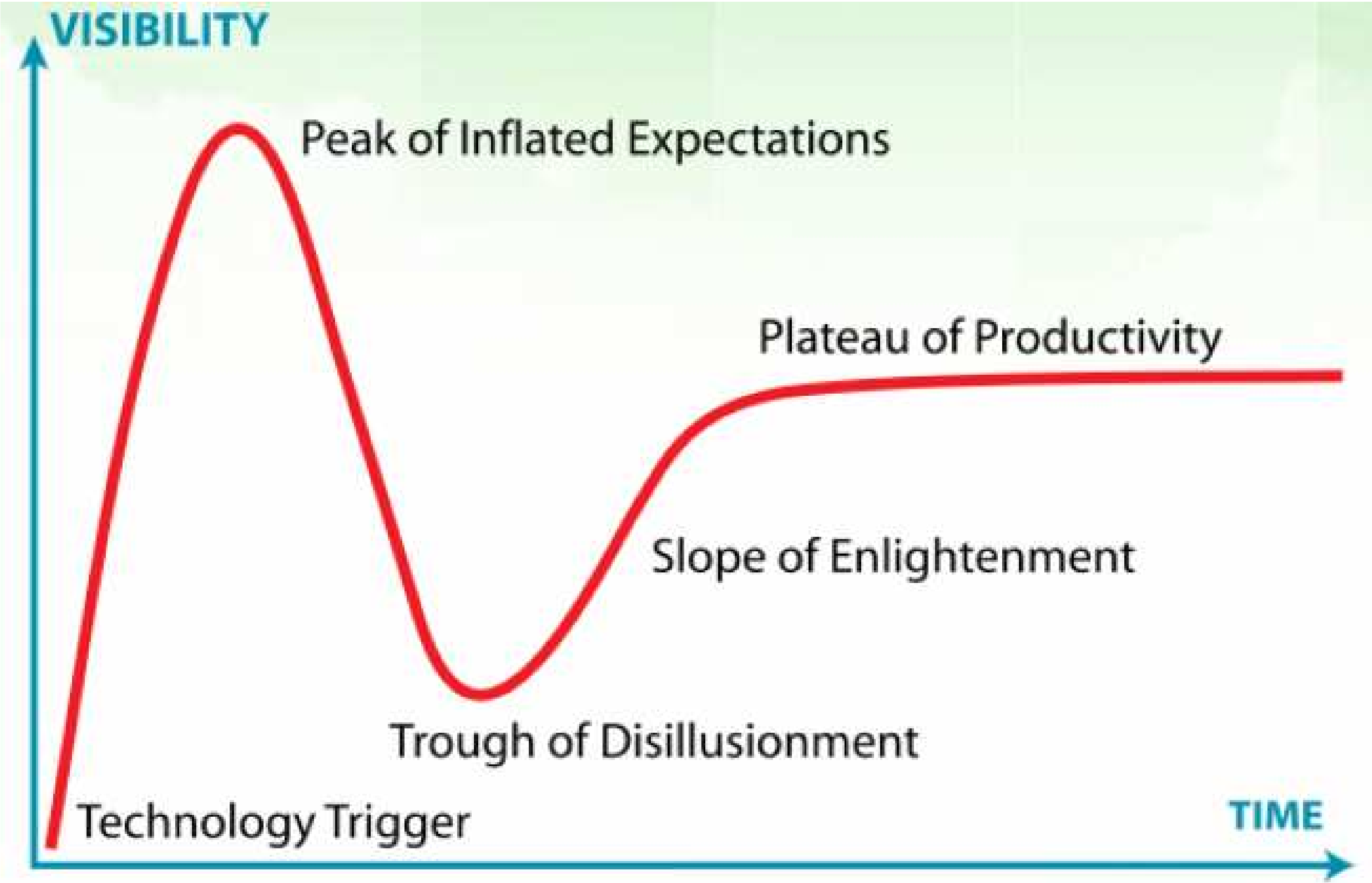
Source: Prof. Rubens Andrade
Laboratory for Applied Superconductivity – LASUP
Department of Electric Engineering
Federal University of Rio de Janeiro – COPPE – UFRJ

Status

Large Scale Energy Applications

	Technology Demonstration	Prototypes in field operation	First commercial products	Full market entry
LTS Fusion magnets		13		
HTS Fusion magnets	13			
AC Cable		13		
DC Cable		13		
Power generator	13			
Ship propulsion	13			
Hydro generator	13			
Wind generator	13			
Transformer	13			
MV FCL			13	
HV FCL		13		
HTS SMES		13		
LTS SMES	13			
Magnetic separation				13
Magnetic levitation		13		

Status
Large Scale Energy Applications



Superconductivity as a key technology from small electronics to large magnet applications

In blue – topics covered in this event

In red – topics covered by my presentation

Cyclotrons MRI applications	← Medicine Science →	Accelerator magnets Particle detectors magn. Supercond. cavities High field magnets
Fusion Wind generators Power applications	← Energy Engineering →	Magnetic separation Magnetic heating
Levitation	← Transport Electronics →	SQUIDS for biomedicine Detectors

Electronic Applications
Overview

Quantum Metrology

- Josephson Voltage Standard

SQUID

- Medicine (MKG, MEG, Pharmacy)
- Geophysical Exploration
- Non-Destructive Testing

Radiation Detectors

- Radio Astronomy
- Medicine, Spectroscropy
- Security

Digital Electronics

- ADC, DAC

Microwave Filters and Resonators

Quantum Computing

Electronic Applications
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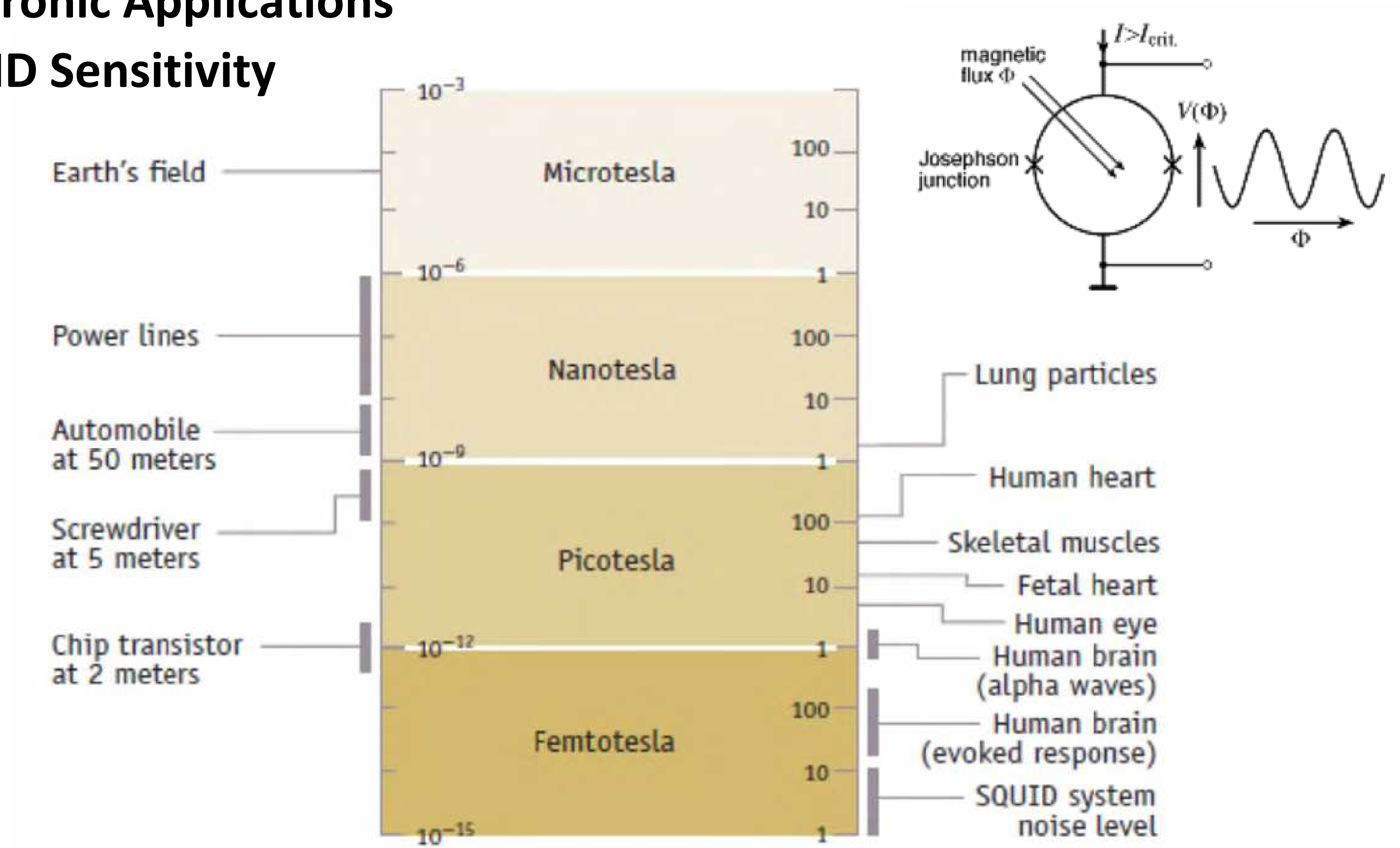
Electronic Applications
SQUID Sensitivity



Source: Brian Fishbine, SQUID Magnetometry, Los Alamos National Laboratory, 2003

SQUIDS achieve highest magnetic field sensitivity.
Applications are in medicine, non destructive testing and geophysics

Electronic Applications
SQUID Magnetometer for Geophysics

Functions

Sensitive receiver for transient electromagnetic measurement	Record the complete gradient tensor of the earth magnetic field.	Geomagnetic detection system for near-surface anomalies

Pictures: Supracon GmbH, Jena, Germany

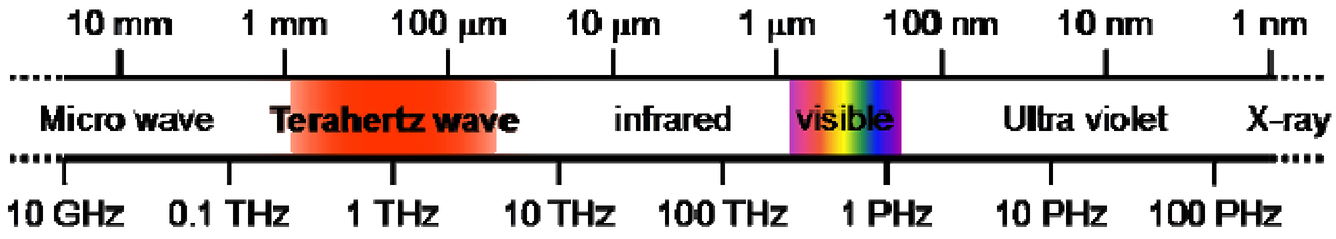
Purpose

Exploration of minerals	Localises and quantisises magnetic objects under ground or under water	Three-dimensional geomagnetic mapping of the ground

SQUIDS are commercial products for geophysics in a growing niche market.

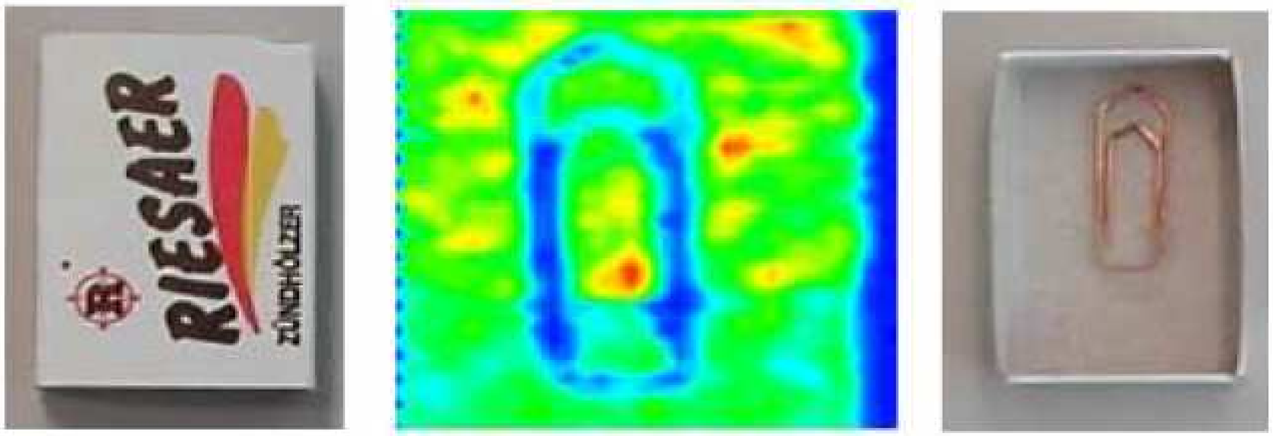
Electronic Applications

Terahertz Detectors - Security



Various Applications

- Medical Care (Tumor diagnostics)
- Security (detection of hidden weapons, explosives, drugs, etc.)
- Radio-Astronomy
- Remote Sensing and Exploration



Pictures: M. Siegel, KIT

Electronic Applications
Radiation Detectors – Radio Astronomy

Atacama Large Millimeter/submillimeter Array (ALMA)

http://www.almaobservatory.org/en

80-900 GHz
10 channel SIS receivers per antenna
1500 SIS mixers

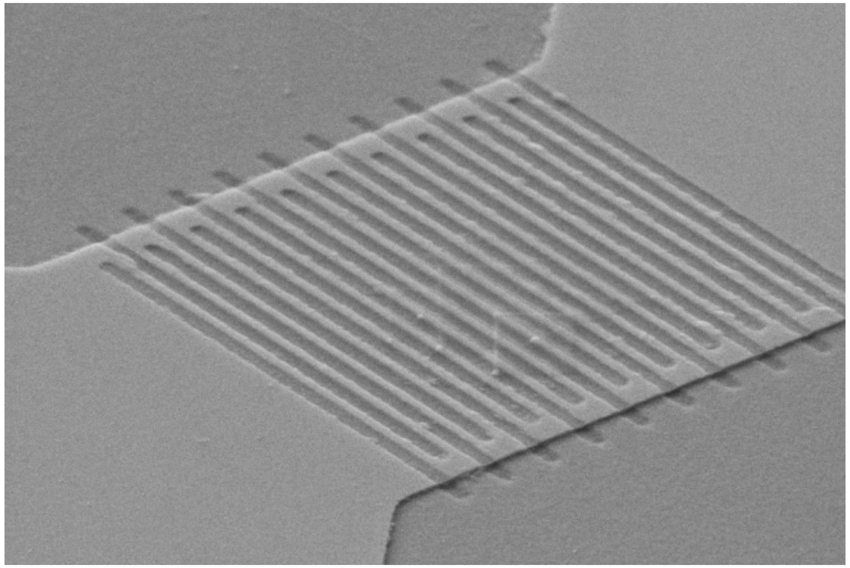
Front end receiver

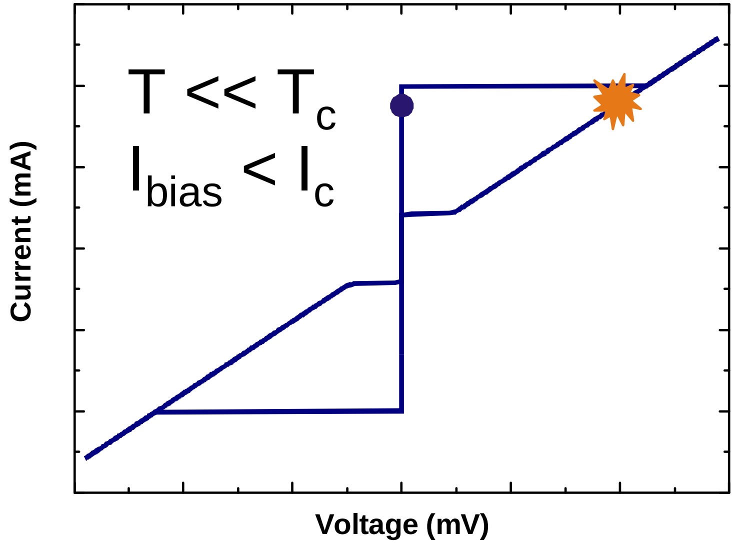
http://www.almaobservatory.org/en

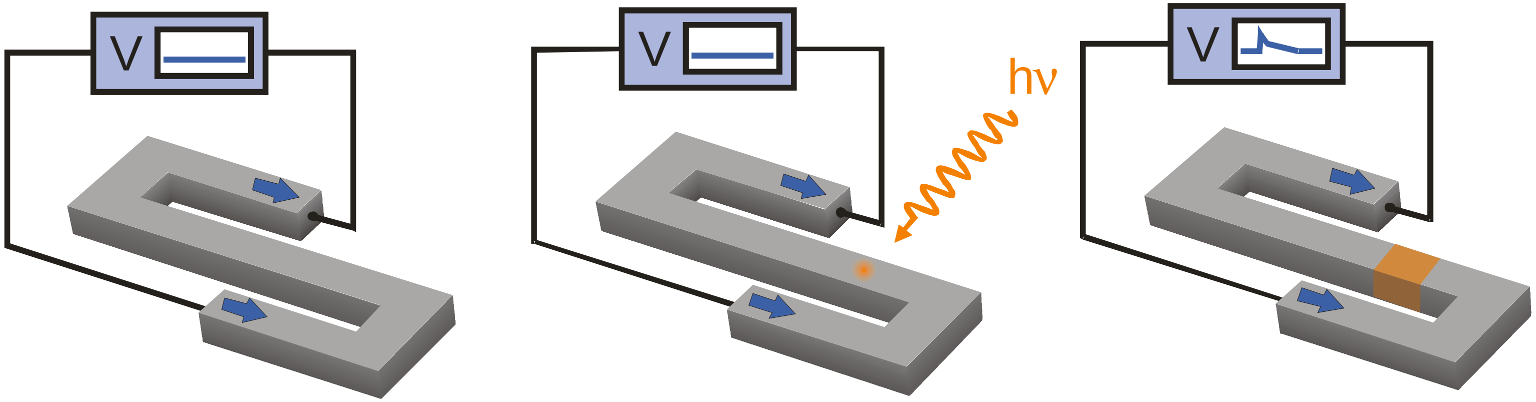
Terahertz detectors have reached maturity in a niche market. All radiotelescopes with more than 100 GHz use superconducting Terahertz detectors.

Electronic Applications

Single Photon Detectors - Principle







Single-photon sensitivity from visible to infrared spectrum, e.g. ultrafast spectoscropy

Superconductivity as a key technology from small electronics to large magnet applications

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MRI applications

← **Medicine**

Science →

Accelerator magnets
Particle detectors magn.
Supercond. cavities
High field magnets

Fusion
Wind generators
Power applications

← **Energy**

Engineering →

Magnetic separation
Magnetic heating

Levitation

← **Transport**

Electronics →

SQUIDS for biomedicine
Detectors

Outlook
Which Material for Large Scale Applications?

Magnet Applications	Technology Status	Present Favourite	Future Options
MRI Magnets	Commercial up to 3 T	NbTi	MgB_2, REBCO
NMR Magnets	Commercial up to 1000 MHz	NbTi, Nb_3Sn	REBCO
Accelerator magnets	In operation up to 9 T	NbTi	Nb_3Sn, REBCO, BSCCO
Fusion magnets	Demonstrator	NbTi, Nb_3Sn	REBCO
R&D and industry magnets	Commercial up to nearly 20 T	NbTi, Nb_3Sn	MgB_2, REBCO, BSCCO
Power System Applications			
Cables	Close to commercialisation	BSCCO, REBCO	MgB_2
Rotating machines	Demonstrators	BSCCO	REBCO, MgB_2
Transformers	Demonstrators	REBCO	-
Fault current limiters	Close to commercialisation	REBCO, BSCCO	-
SMES	Prototypes	NbTi	MgB_2, REBCO
Other Applications			
Current leads	Commercial up to a few kA	BSCCO	REBCO
Electrodynamic levitation	Demonstrator	NbTi	BSCCO, REBCO
Superconducting levitation	Demonstrator	REBCO	-

Outlook

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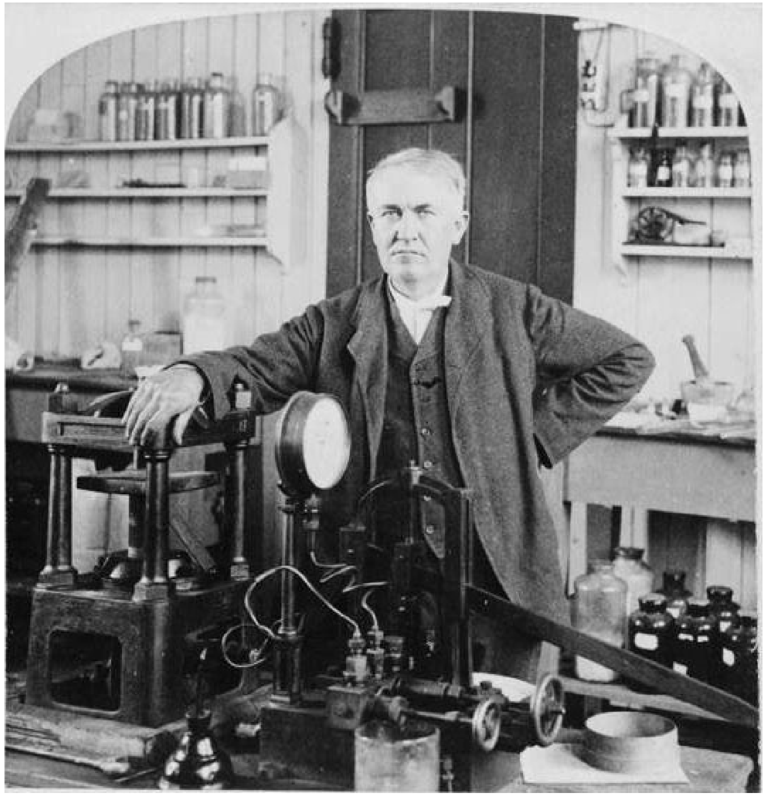
Thank you very much for your attention !

Outlook
What does Superconductivity needs in the Future?

I never did anything by accident, nor did any of my inventions come by accident, they came by **work**.
Thomas Alva Edison

Anything that won‘t sell I don‘t want to invent. Its **sale** is proof of utility and utility is success.
Thomas Alva Edison

Hard work + Sales = Success



Thomas A. Edison in his laboratory in New Jersey, 1901
Credit: Underwood & Underwood, publishers. "The most famous inventor of the age--Thos. A. Edison in his laboratory, East Orange, N.J., U.S.A." 1901. Prints and Photographs Division, Library of Congress.

Thank you very much for your attention !