Zukünftige Entwicklungen der HTS Anwendungen in der Energietechnik

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Institut für Technische Physik

Workshop Neueste Entwicklungen auf dem Gebiet der LT/HT – Supraleiter
Hanau 10.3.2016

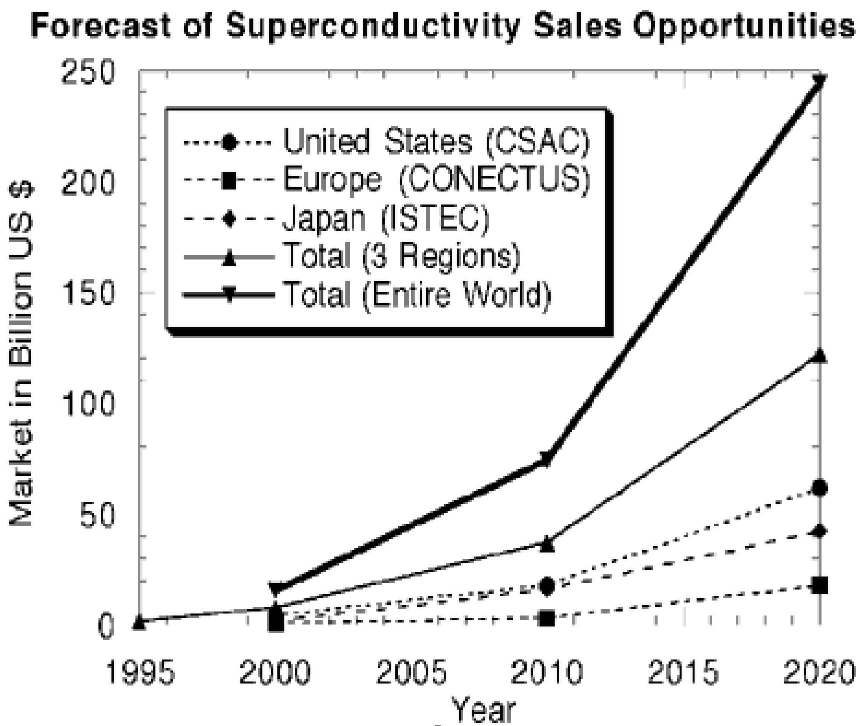
KIT-ZENTRUM ENERGIE

Future Development of …

„A telephone has too many severe deficits for a communication method. This device has no use for us“
Manager Western Union, 1876

„There is no reason why anyone would like to have a computer at home“
Ken Olson, President, CEO and founder of Digital Equipment Corp., 1977

Future Development of …



Source: ISIS 1996

Future Development of HTS Power Applications

Table of Content

- Motivation for new energy technology
- Power cables
- Rotating machines
- Transformers
- Fault Current Limiters
- SMES
- Summary

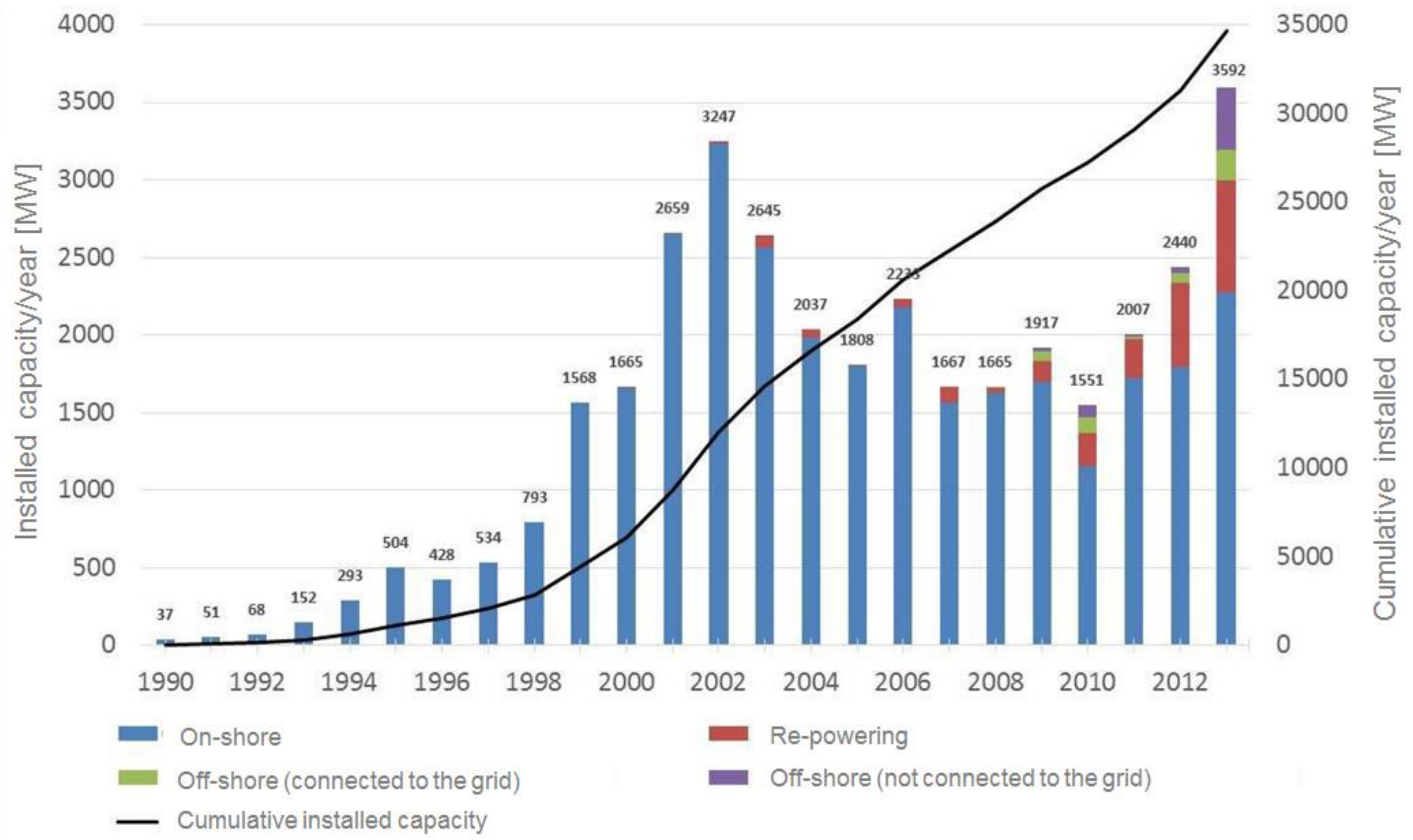
(Power cables, Rotating machines, Transformers, Fault Current Limiters, SMES:)

Benefits

State-of-the-art

Future R&D directions

The Energy Future
More Renewable Energy
Development of wind energy in Germany

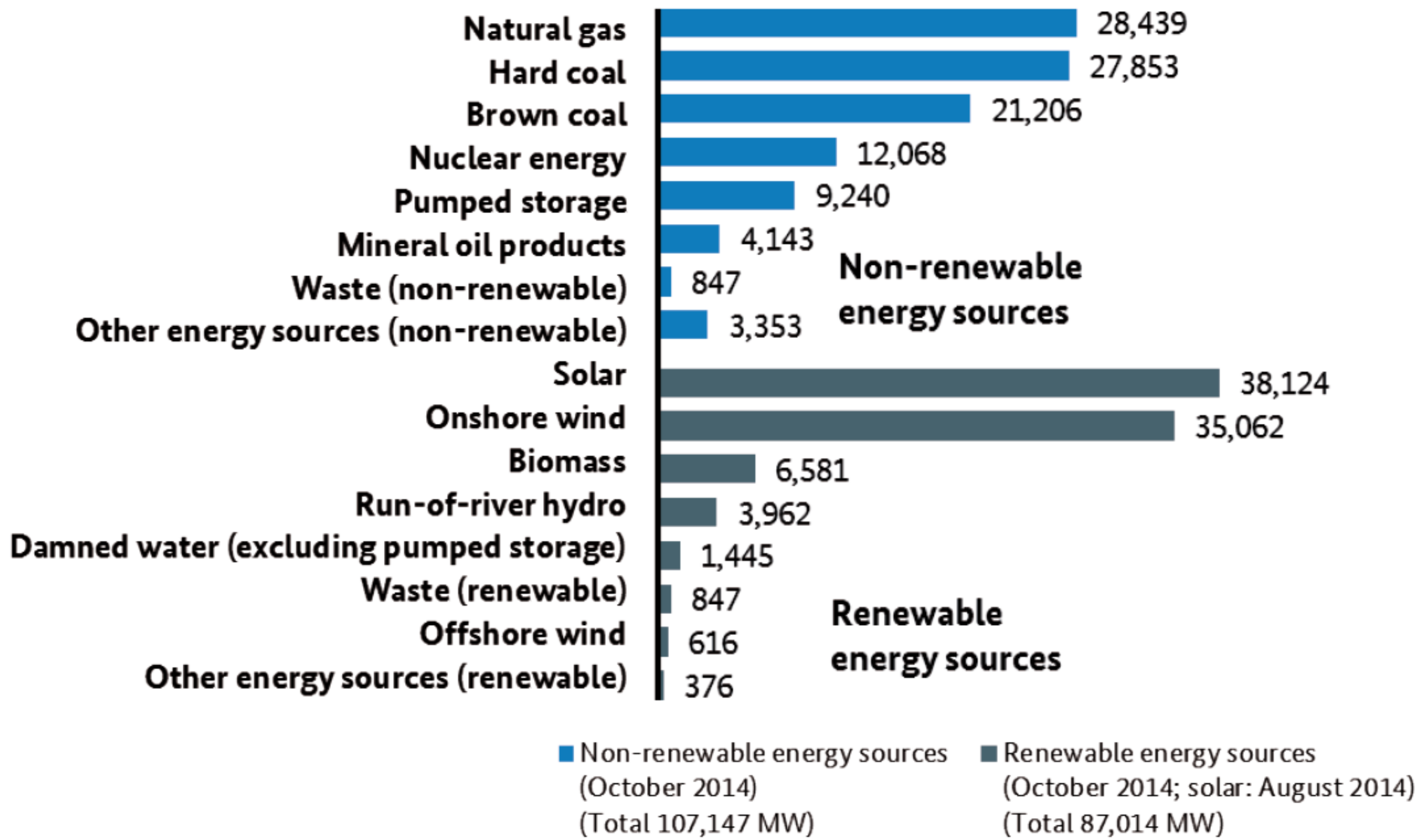


Source: DEWI Statistics 2013

The Energy Future

More Renewable Energy

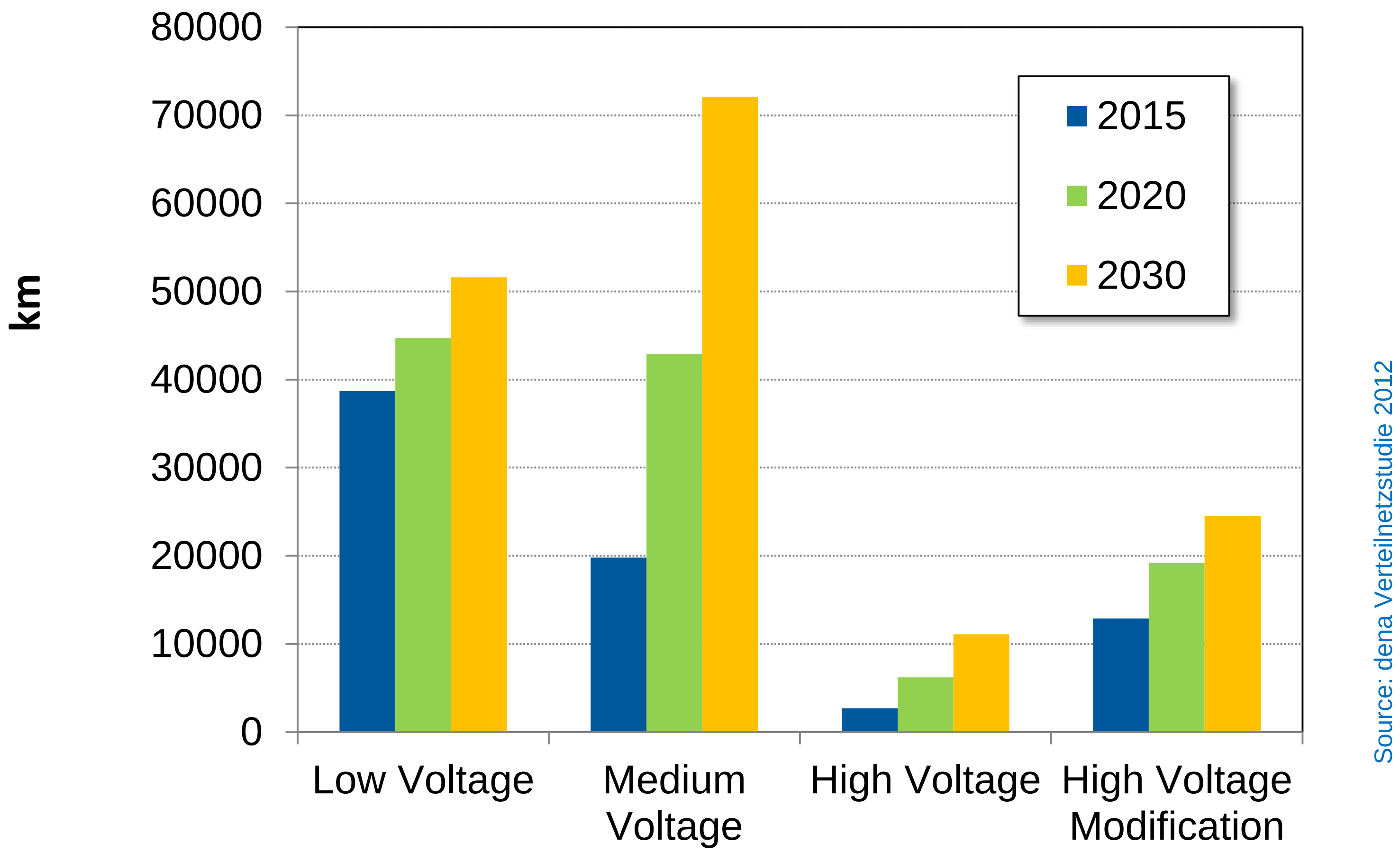
Installed electric generation capacity in Germany 2014 (MW)



Quelle: Daten aus Monitoringbericht Bundesnetzagentur 2013

The Energy Future

Need for Network Extension



The Energy Future
More Electricity Exchange

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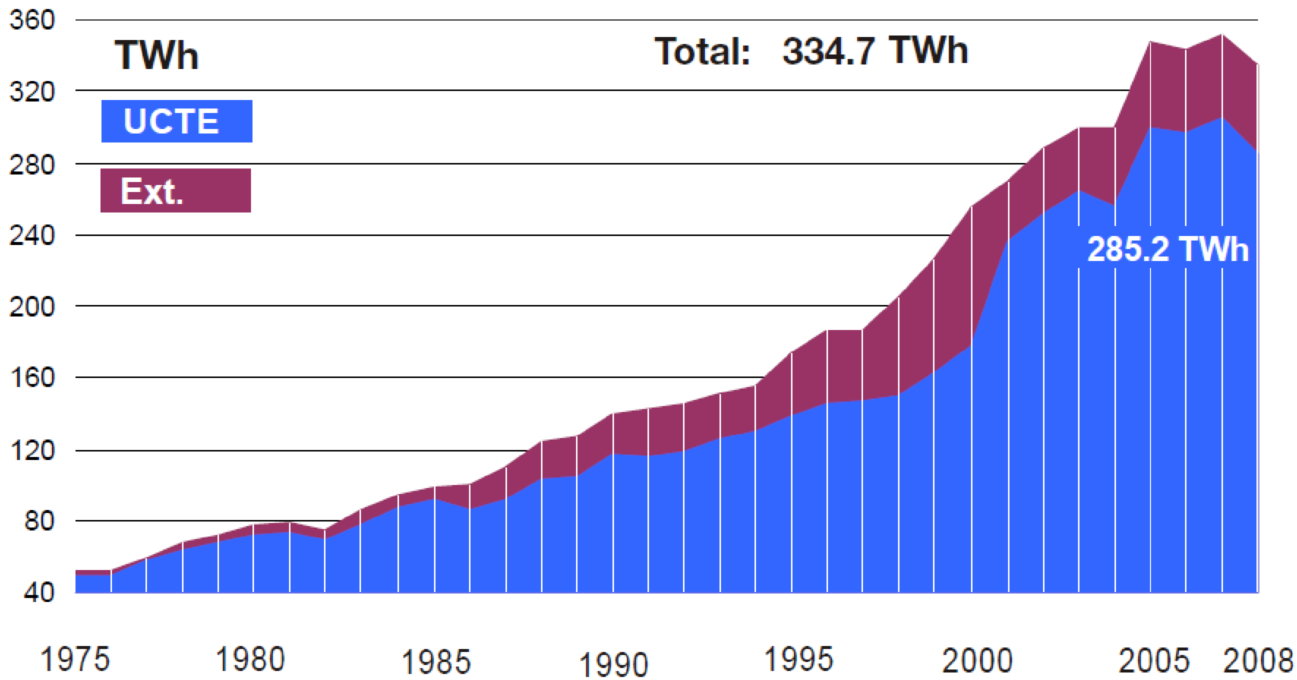
Sum of electricity exchanges of the UCTE in TWh
Source: UCTE database as of 02 April 2009



From year 2001 sum of exchanges UCTE include CZ, HU, PL, SK
From year 2003 sum of exchanges UCTE include RO and BG
From June 2007 sum of exchanges UCTE include DK_W
Ext. = exchanges with third countries

The Role of Superconductivity for Power Applications

Superconductivity

- Highest current densities

  at zero DC resistance and at high magnetic fields

Impact on Power Applications

- **Improved energy efficiency** →

Application examples	Loss reduction
Generators (some MVA) Generators (> 100 MVA)	30-40 % 40-50 %
Transformers stationary Transformers mobile	~ 50 % 80-90 %
Magnetic heating	~ 50 %
Magnetic separation	> 80 %
HTS currents leads	70-80 %
HTS high field magnets	> 90 %

The Role of Superconductivity for Power Applications

Superconductivity

- Highest current densities
  at zero DC resistance and at high magnetic fields

Impact on Power Applications

- Improved energy efficiency
- **Higher power density** →

Volume and weight reduction	
Generators	30-50 %
Transformers	30-50 %
Cables	> 50 %

The Role of Superconductivity for Power Applications

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Superconductivity

- Highest current densities

  at zero DC resistance and at high magnetic fields

Impact on Power Applications

- Improved energy efficiency
- Higher power density
- **New technology** →

Superconductivity facilitates

- Superconducting fault current limiters
- Fault current limiting systems
- Superconducting magnetic energy storage
- High field magnets

The Role of Superconductivity for Power Applications

Superconductivity

- Highest current densities
  at zero DC resistance and at high magnetic fields

Impact on Power Applications

- Improved energy efficiency
- Higher power density
- New technology
- **Higher power quality** →

Higher power quality

- Low impedance of superconducting power equipment
- High short-circuit capacity of grids with fault current limiters
- Fast compensation of disturbances with superconducting magnetic energy storage

The Role of Superconductivity for Power Applications

Superconductivity

- Highest current densities

  at zero DC resistance and at high magnetic fields

Impact on Power Applications

- Improved energy efficiency
- Higher power density
- New technology
- Higher power quality
- **Environment-friendly** →

Liquid Nitrogen

- is used as cooling liquid and electrical insulation
- easily available
- non-flammable

Future Development of HTS Power Applications

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Benefits of Superconducting AC Cables

User

- Higher transmission capacity at lower voltage
  - Avoid high voltage equipment in urban areas
- Higher transmission capacity at lower diameter
  - Flexible laying, less underground work
- Three phases in one cable up to high capacities
  - Less right of way, fast cable laying, less underground work

Environment

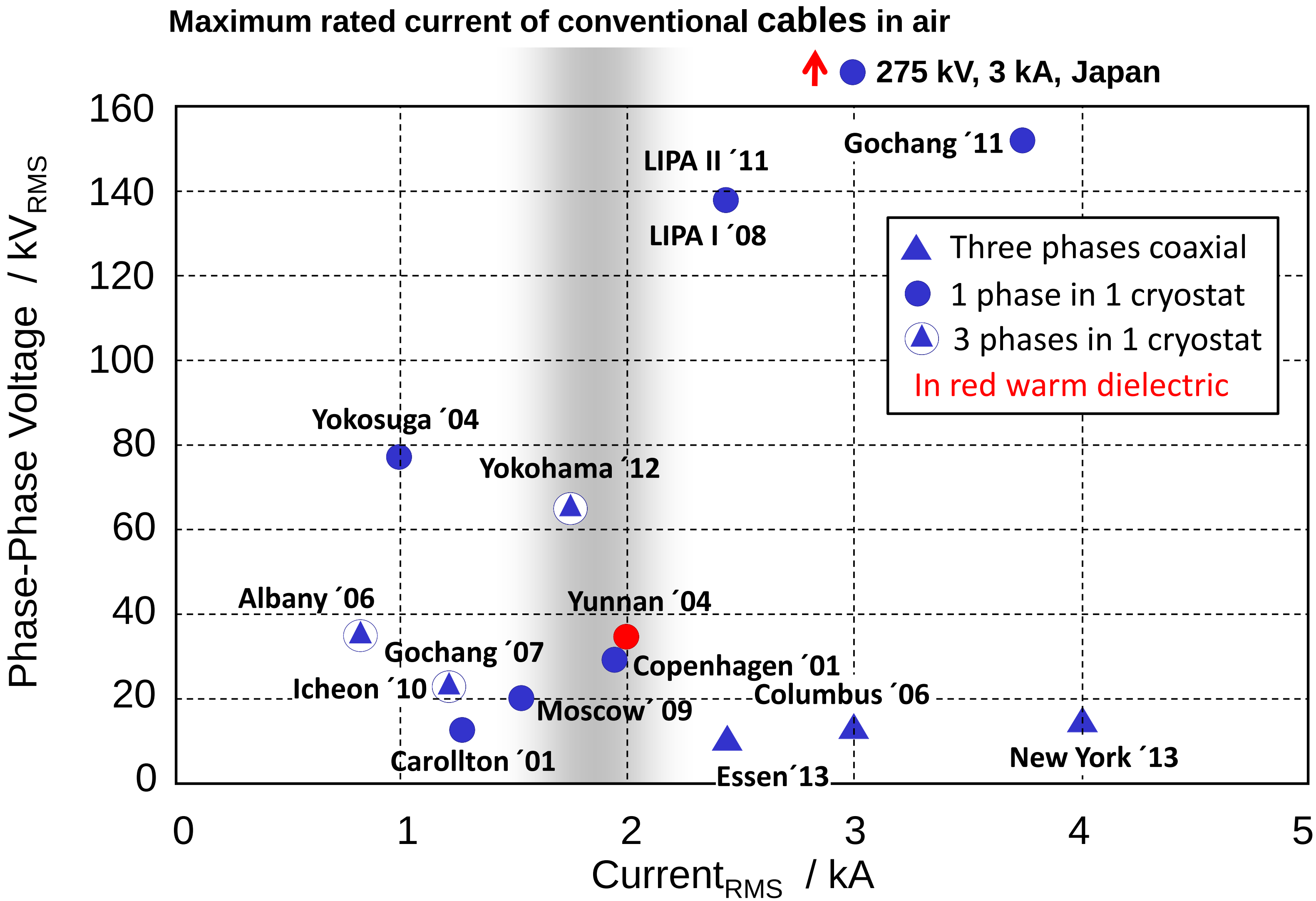
- Electromagnetic compatible
- Potential of lower losses
- No ground heating

Operation

- Low impedance
- Operation at natural load

Enables unique cable systems and new power system structures

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



Superconducting AC Cables
State-of-the-Art

Columbus

Figure: Ultera

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

LIPA

Figure: Nexans

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

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 AC Cables
State-of-the-Art

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Partner: RWE, Nexans, KIT

Objective: Development and field test of a 1km, 40 MVA, 10 kV superconducting cable in combination with a superconducting fault current limiter

Start: September 2011

Comissioning: April 2014

AMPACITY
Smart grids for the city

VORWEG GEHEN

Nexans

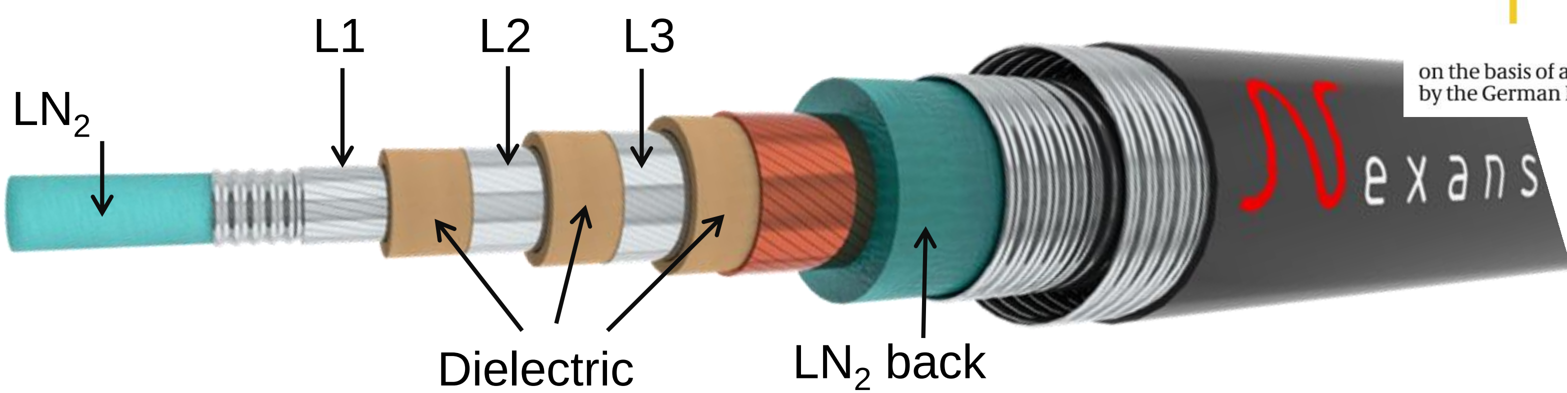
Karlsruhe Institute of Technology

PtJ Projektträger Jülich
Forschungszentrum Jülich

Supported by:

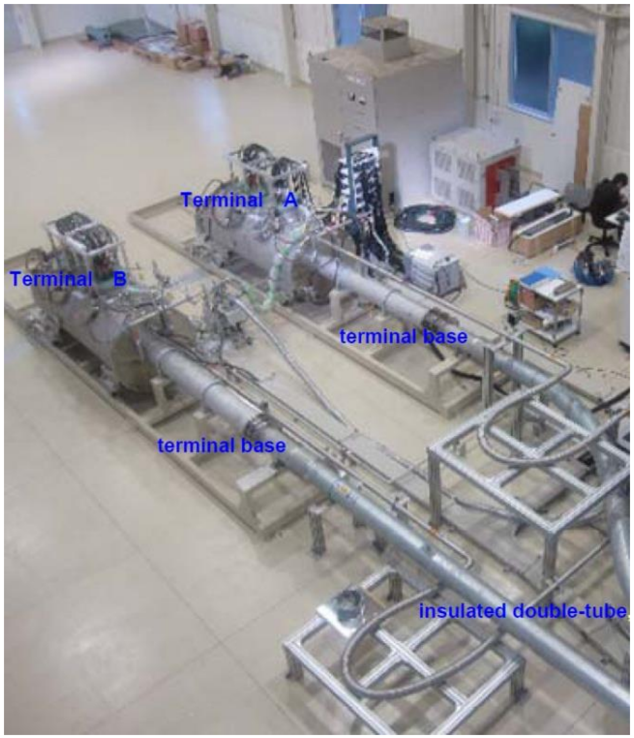
Federal Ministry
of Economics
and Technology

on the basis of a decision
by the German Bundestag



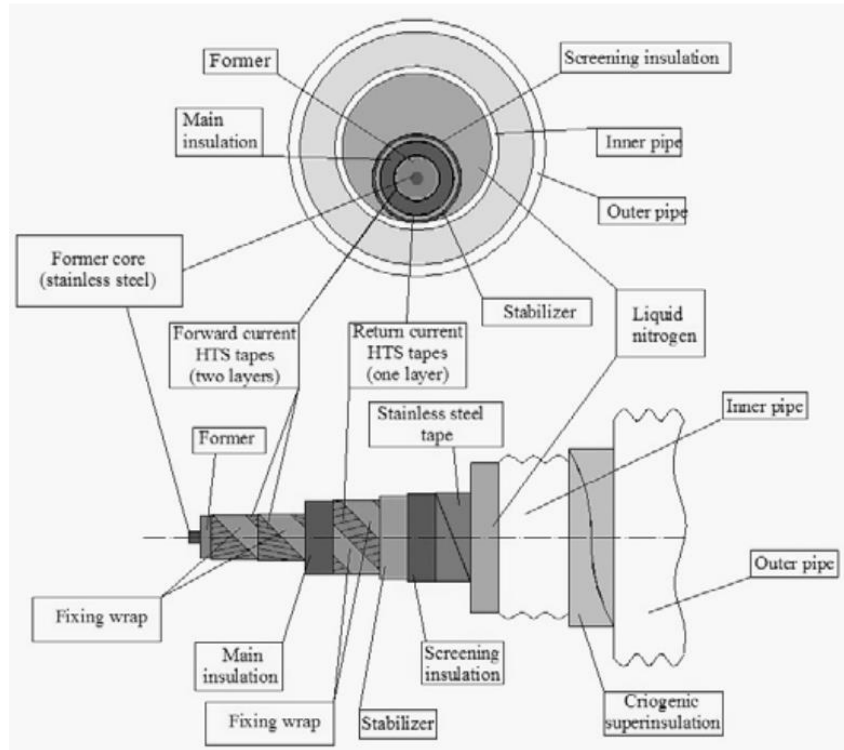
Superconducting DC Cables
State-of-the-Art

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

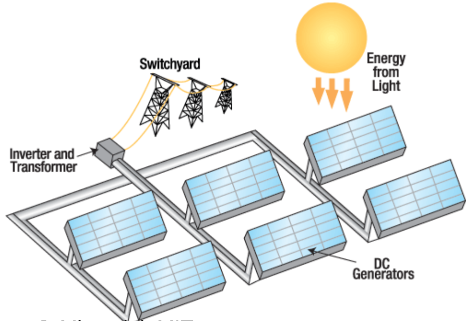
Superconducting DC Cables

Applications

Industry high current lines

Picture: Vision Electric

Connect renewables

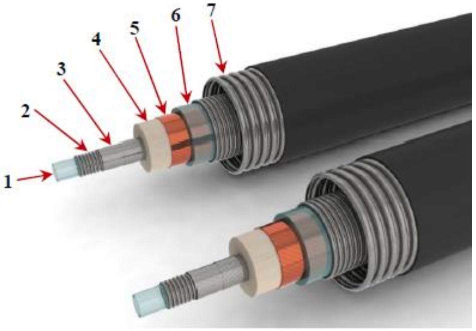


Picture: J. Minervini, MIT

Supply data centers

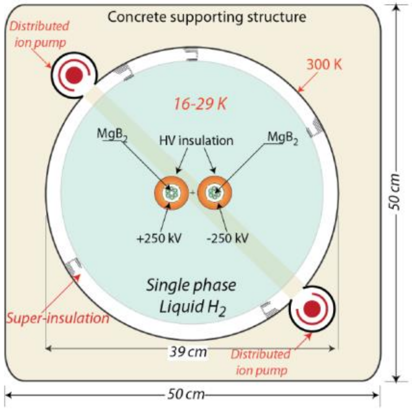
Picture: J. Minervini, MIT

Grounding of HVDC Lines



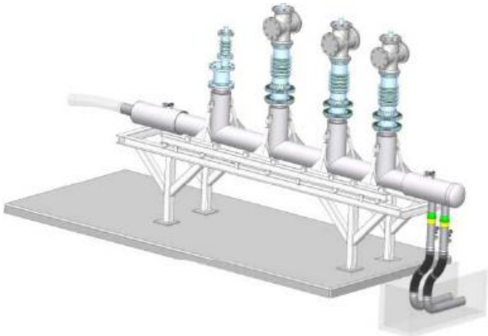
Picture: Nexans

Larger power, long distance transmission



Picture: C. Rubbia, IASS

Degaussing of ships



Picture: B. Fitzpatrick, HTS Peerreview2010

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Research Direction

- Lower cost and higher performance of HTS material
- Improved thermal insulation at reduced cost
- Work on standards (e.g. How to perform a routine or factory test of HTS cables?)
- Demonstrate reliability and availability in long-term field installations

- Confirmed superconducting cable installations in Chigaco, Seoul and at Tennet.

Superconducting cables are very close to commercialization.

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Future R&D directions

Benefits of Superconducting Rotating Machines

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Smaller Volume and Weight

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

Less Ressources

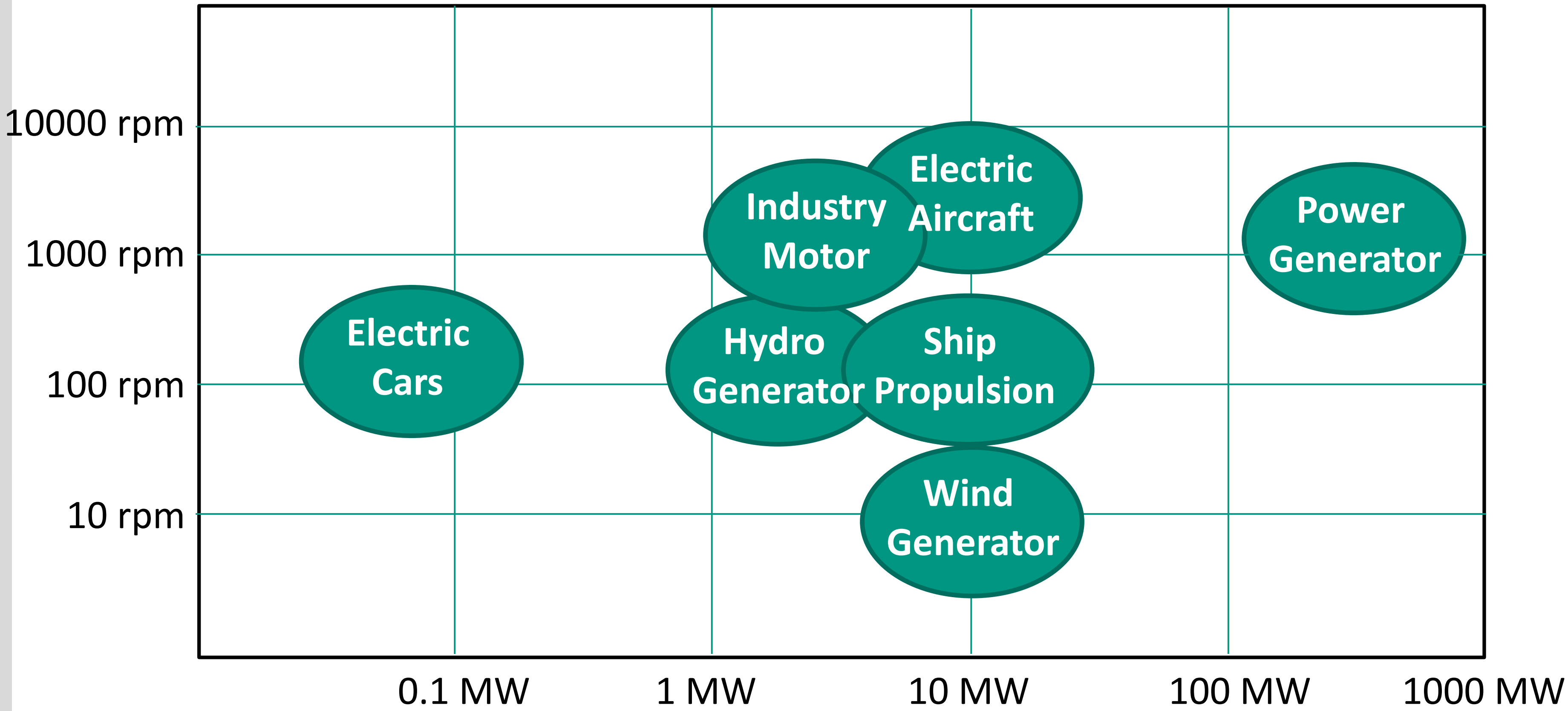
- Higher efficiency
- Less material

Improved Operation Parameters (e.g. synchronous generator)

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

Enables new drive and generator systems

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)	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

Superconducting Rotating Machines
State-of-the-Art

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

EU „Hydrogenie“
Hydrogenerator


Image Courtesy of Converteam

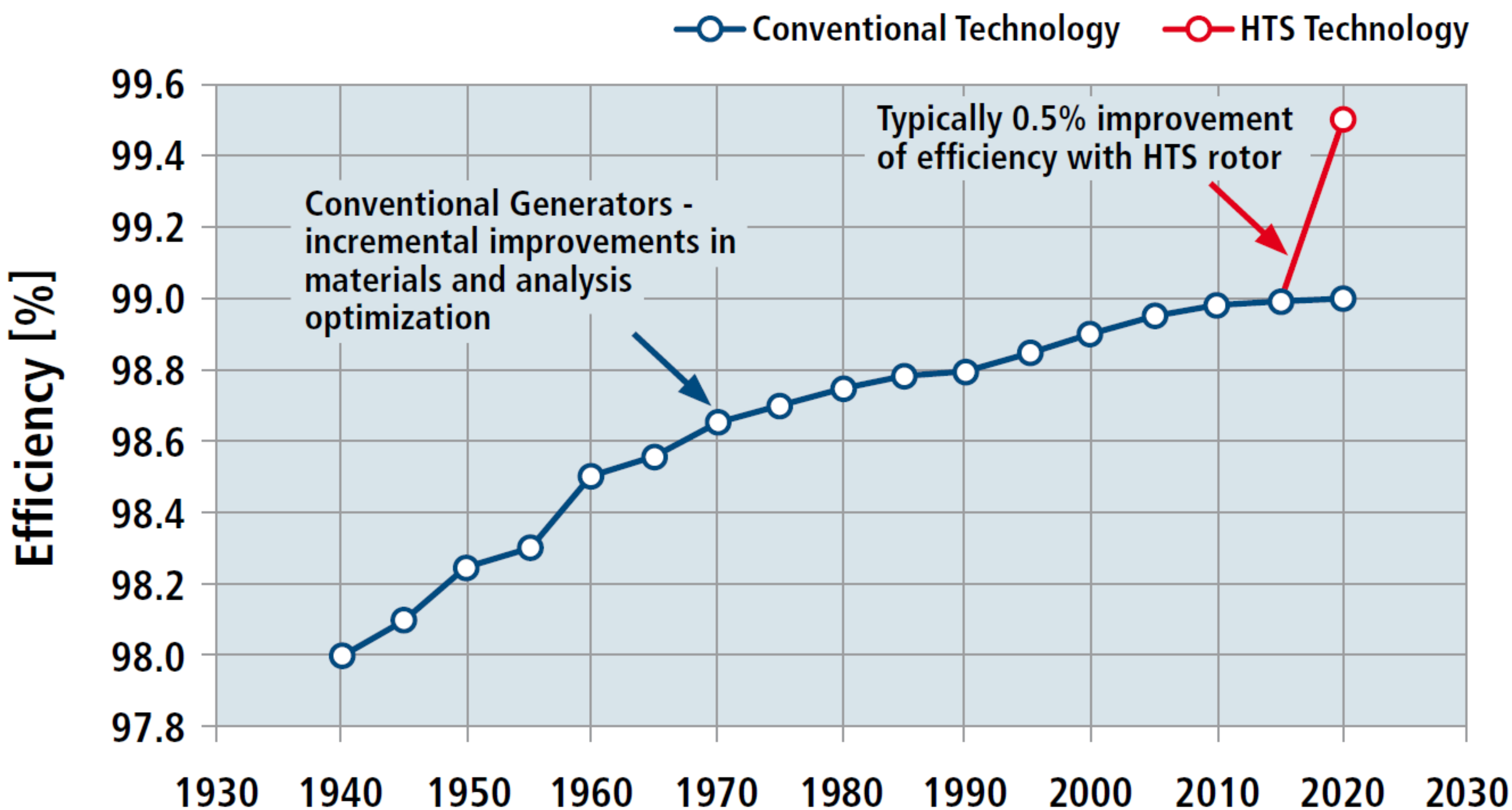
GE/(Converteam)
1.790 MW, 5.25 kV
214 rpm, 77.3 kNm
28 poles, 32.7 tons
4.7 m x 5.2 m x 3.5 m
Test in 2012

Ship Propulsion

Image Courtesy of Siemens

Siemens
4 MW, 3.1 kV
120 rpm, 320 kNm
37 tons
50 km HTS
Test in 2010

Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators

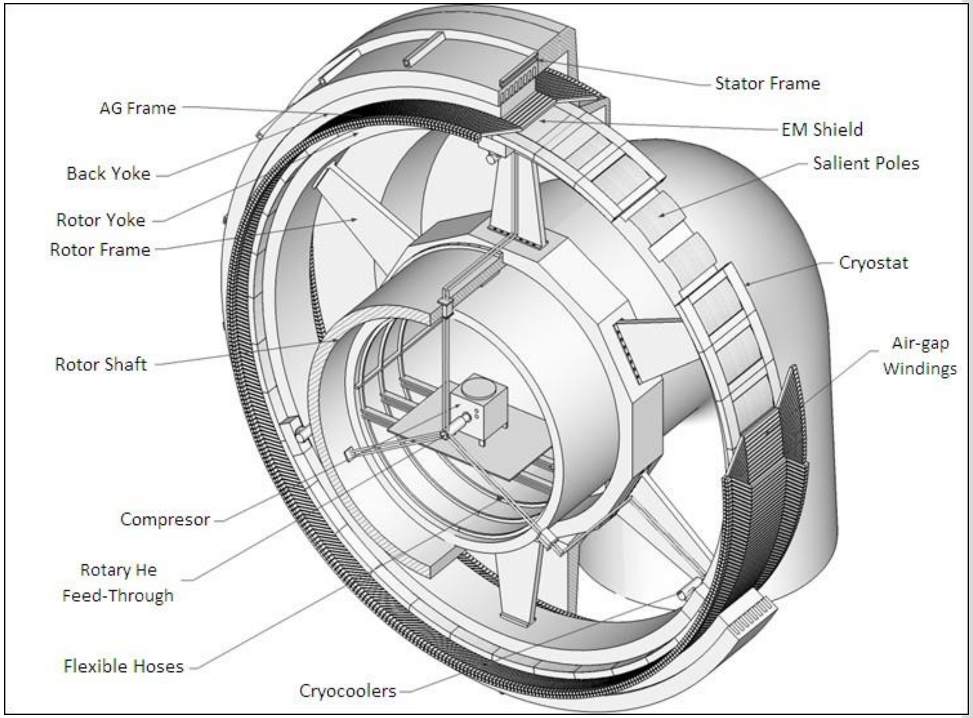


Source: High-Temperature Superconductivity for Power Engineering, Materials and Applications, Accompanying Book to the Conference ZIEHL II, Future and Innovation of Power Engineering with High-Temperature-Superconductors, 16-17 March 2010, Bonn, Germany

Superconducting Rotating Machines
HTS Wind Generators

Suprapower Projekt (www.suprapower.fp7-eu)

- 10 MW; 8.1 rpm and 11.8 MN·m
- MgB_2 SC field coils, 126 A per turn
- Air-gap armature winding
- 60 warm iron poles
- 11.9 m air-gap diameter
- 0.52 m stack length
- Overall weight including structural mass ~ 200 t
- Drive train cost < 280 k€/MW
- Efficiency at full load over 95%
- Yearly maintenance interval



SC wind generator according to TECNALIA's concept (US2012306212A1)

Superconducting Rotating Machines

R&D 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

Future Development of HTS Power Applications

KIT Karlsruher Institut für Technologie

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Benefits

State-of-the-art

Future R&D directions

Benefits of Superconducting Transformers

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Manufacturing and transport

- Compact and lightweight (~50 % Reduction)

Environment and Marketing

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

Operation

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

Enables a new class of transformers

Superconducting Transformers
State-of-the-Art

Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA, 18,42 kV/420V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric	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	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	Fuji Electric	Railway	4 MVA, 25 kV/1.2 kV	1	2004	Bi 2223
Japan	Kuyshu Uni.	Demonstrator	2 MVA, 66 kV/6.9 kV	1	2004	Bi 2223
China	IEE CAS	Demonstrator	630 kVA, 10.5 kV/400 V	3	2005	Bi 2223
Japan	U Nagoya	Demonstrator	2 MVA, 22 kV/6,6 kV	1	2009	P-Bi 2223/S-YBCO
Japan	Kyushu Uni	Demonstrator	400 kVA, 6.9 kV/2.3 kV	1	2010	YBCO
Germany	KIT	Demonstrator	60 kVA, 1 kV/600 V	1	2010	P-Cu/S-YBCO
USA	Waukesha	Prototype	28 MVA, 69 kV	3	Not completed	YBCO
Australia	Callaghan Innovation	Demonstrator	1 MVA, 11 kV/415 V	3 Dy	2013	YBCO
China	IEE CAS	Demonstrator	1.25 MVA, 10.5 kV/400 V	3 Yyn0	2014	Bi 2223
Germany	KIT/ABB	Demonstrator	577 kVA, 20 kV/1 kV	1	2015	P-Cu/S-YBCO

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

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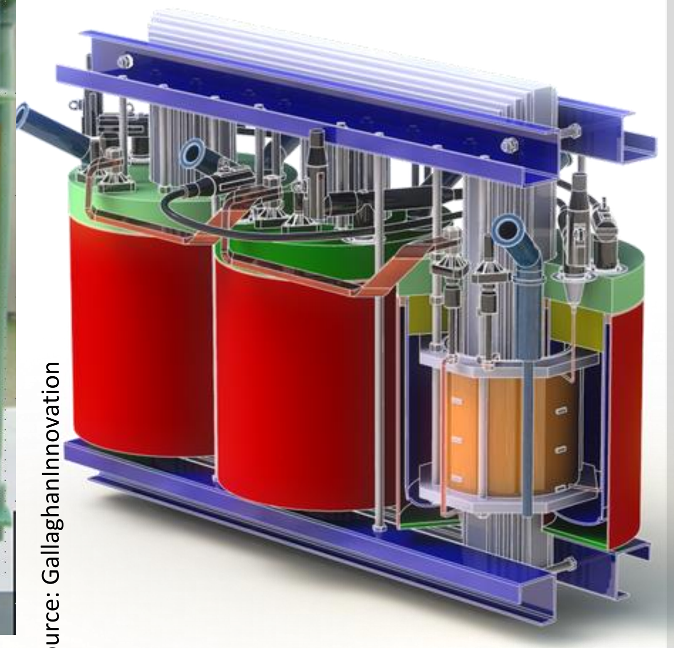
Karlsruhe Institute of Technology	Nagoya University	Gallaghan Innovation


Copyright: KIT


Courtesy: N. Hayakawa


Source: GallaghanInnovation

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60 kVA Demonstrator
1kV/0.6 kV
Primary copper
Secondary YBCO tapes
Successful test in 2010
Recovery under nominal load

Nagoya University

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

Gallaghan Innovation

1 MVA Demonstrator
11 kV
Primary and secundary with YBCO tapes
Tests in 2013

Superconducting Transformers
1 MVA Demonstrator at KIT

Primary winding: Copper

20kV / 28,87A

Secondary winding: YBCO tapes

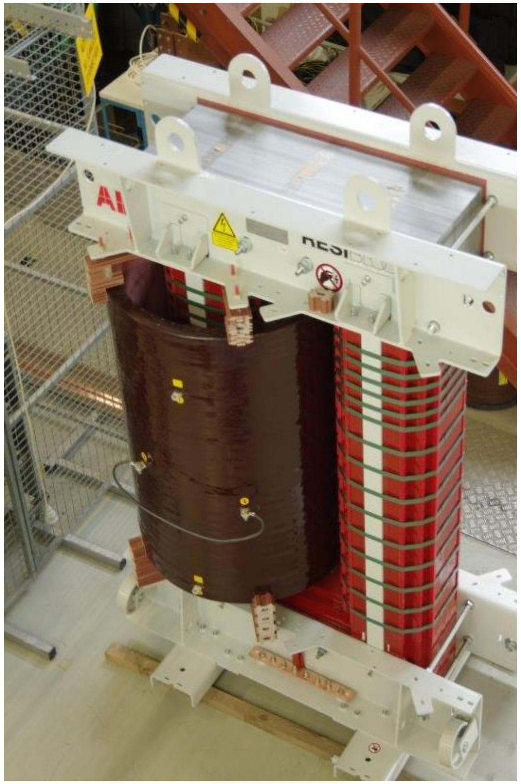
1kV / 577,35A

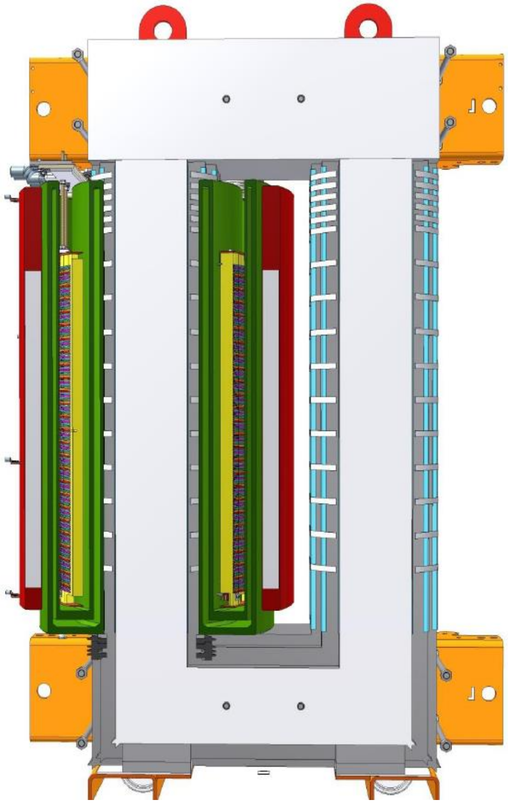
Short-circuit voltage u_k < 3%

Warm iron core

B_{max} in core = 1,5T

LN_2 at 77 K





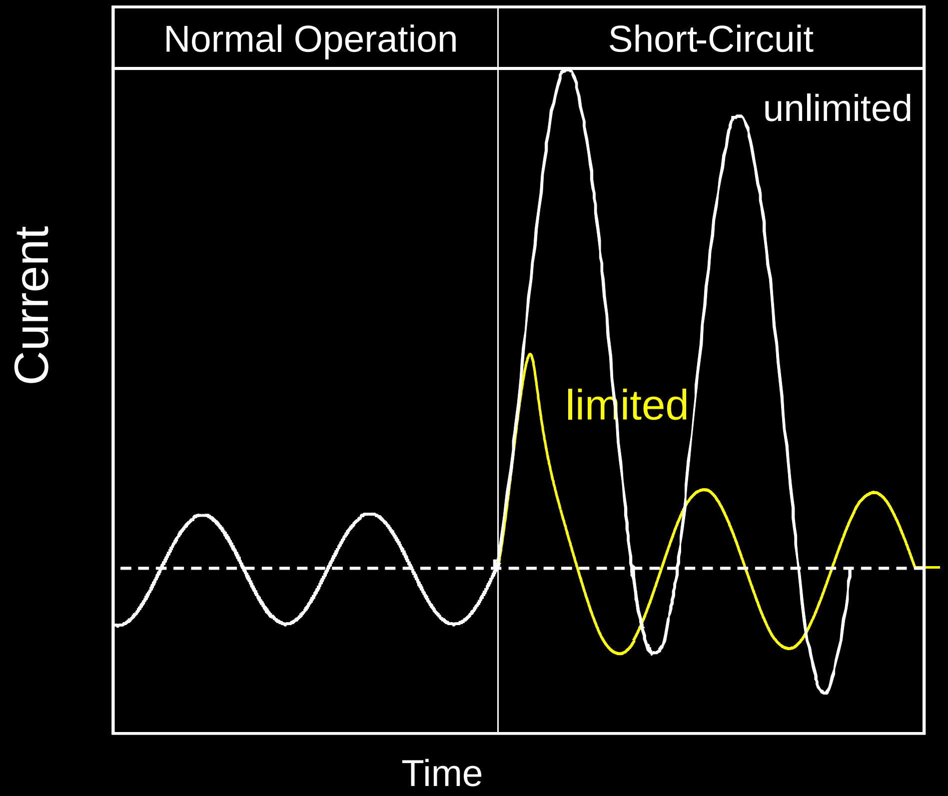
Status 2016 – Pretests finished, Final tests start in the next weeks

Superconducting Transformers

Research Directions

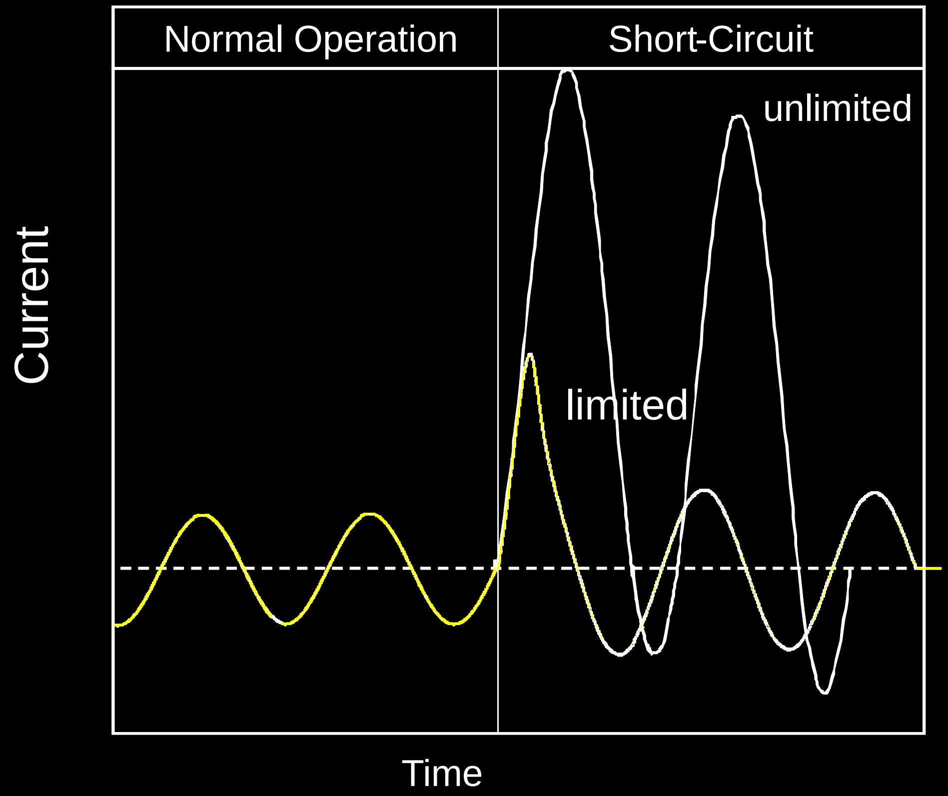
- Develop first large scale demonstrators and prototypes
- Develop wire concepts with reduced AC loss, stability and increased field performance
- Include current limitation (to compensate higher investment cost)
- Develop reliable cryogenic high voltage insulation concepts

Superconducting transformers need further demonstrator and prototype development.



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



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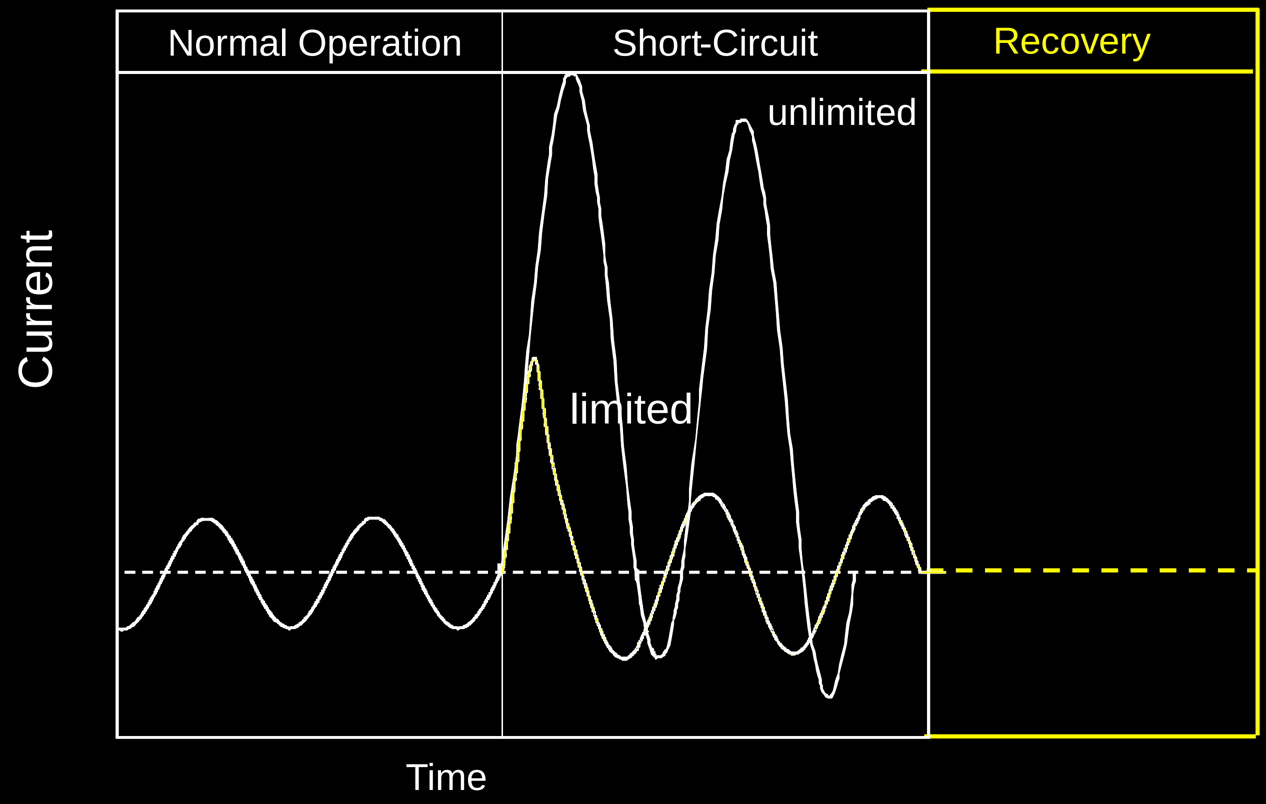

Ideal Fault Current Limiter

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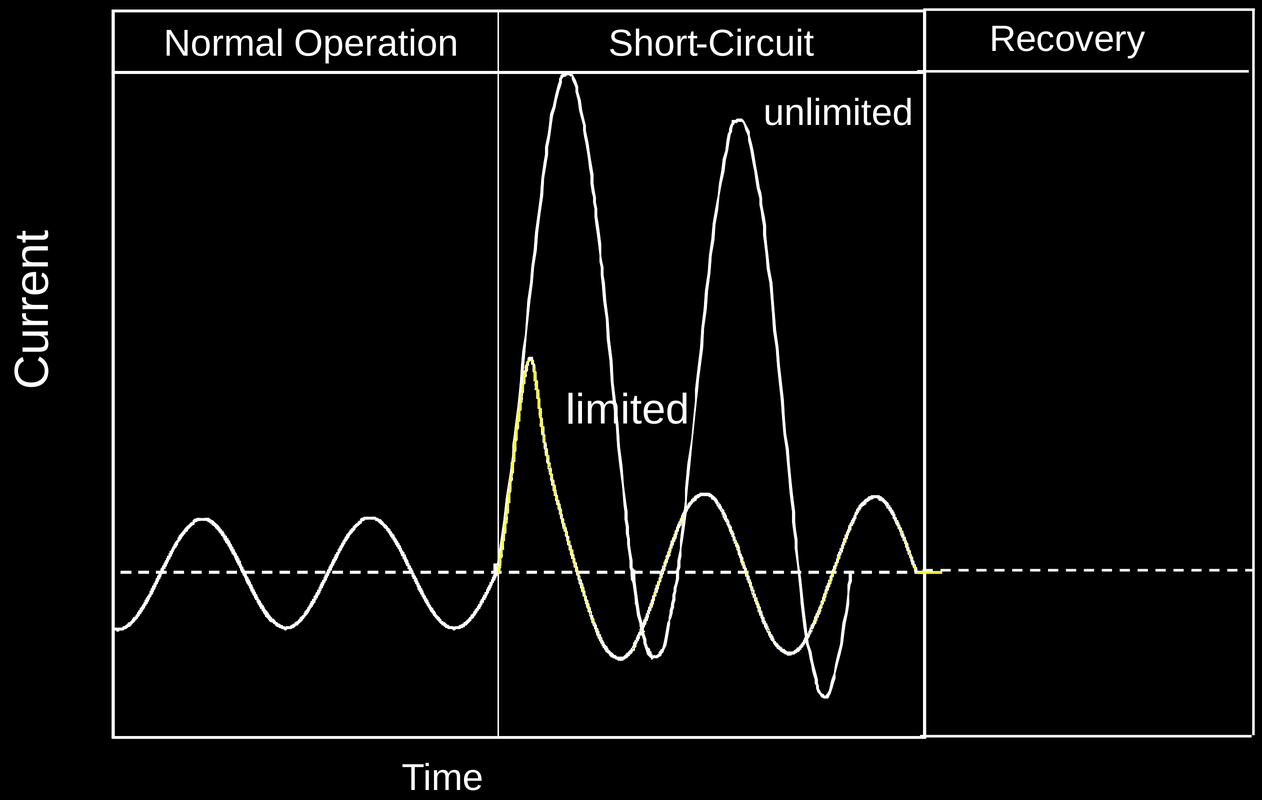


Ideal Fault Current Limiter **SCFCL**

- 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

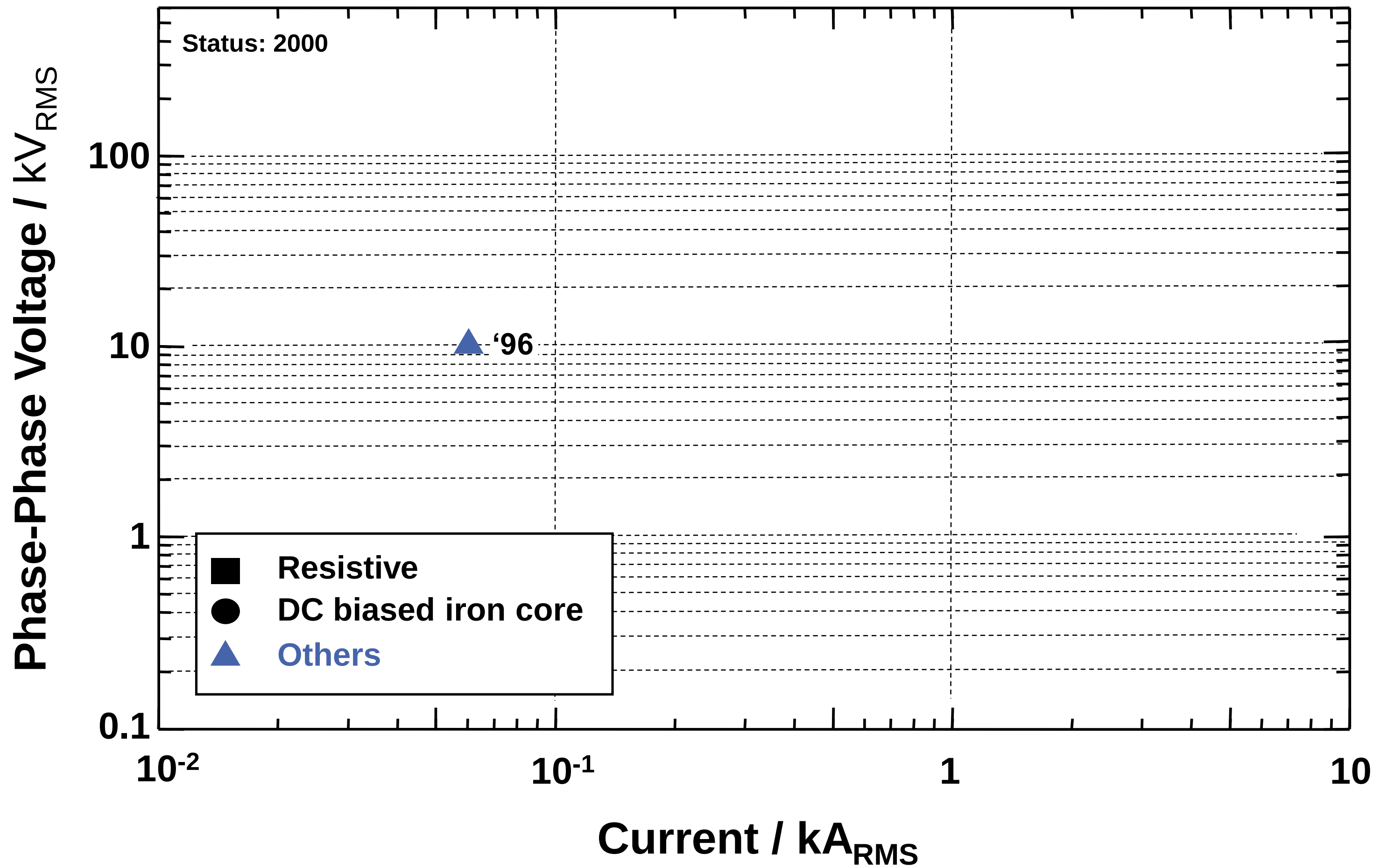
Increase availibity and reliability

- e.g. by coupling power systems

Reduce losses and CO_2 emissions

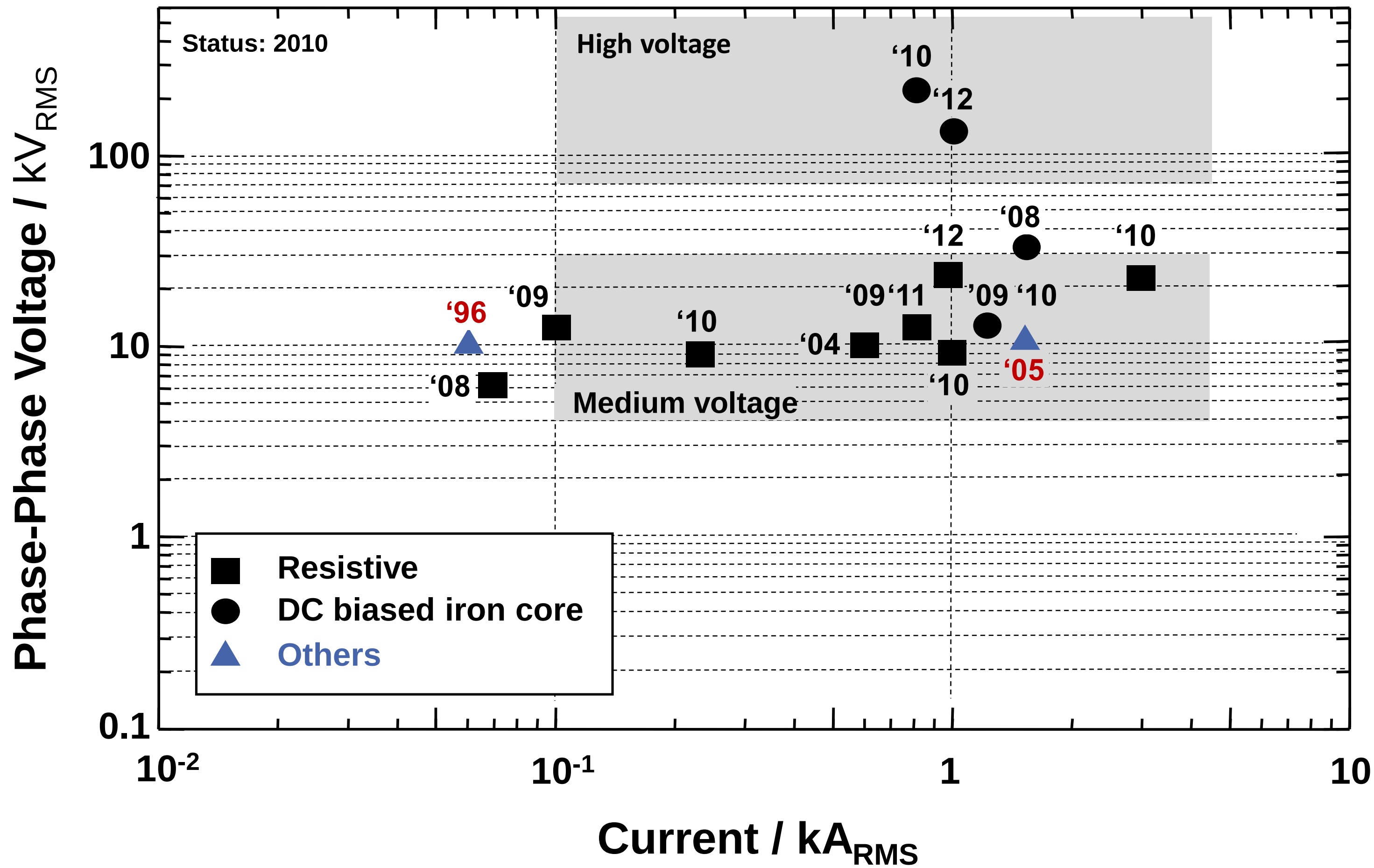
- e.g. equal load distribution with parallel transformers

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
Major projects on resistive type SFCL

Lead Company	Year/Country [1)]	Data [2)]	Phase	Superconductor
ACCEL/NexansSC	D / ´04	12 kV, 600 A	3-ph.✓	Bi 2212 bulk
CESI RICERCA	Italy / ´05	3.2 kV, 220 A	3-ph.	Bi 2223 tape
Siemens / AMSC	D / USA / ´07	7.5 kV, 300 A	1-ph.	YBCO tape
LSIS	Korea /'07	24 kV, 630A	3-ph.	YBCO tape
Hyundai / AMSC	Korea / ´07	13.2 kV, 630 A	1-ph.	YBCO tape
KEPRI	Korea / ´07	22.9 kV, 630 A	3-ph.	Bi 2212 bulk
Toshiba	J / 2008	6.6 kV, 72 A	3-ph.✓	YBCO tape
Nexans SC	D / 2009	12 kV, 100 A	3-ph.✓	Bi 2212 bulk
Nexans SC	D / 2009	12 kV, 800 A	3-ph.✓	Bi 2212 bulk
RSE	I / 2011	9 kV, 250 A	3-ph.✓	Bi 2223 tape
RSE	I / 2012	9 kV, 1 kA	3-ph.✓	YBCO tape
KEPRI	Korea / 2011	22.9 kV, 3 kA	3-ph.✓	YBCO tape
Nexans SC	D / 2011	12 kV, 800 A	3-ph.✓	YBCO tape
AMSC / Siemens	USA / D / 2012	115 kV, 1.2 kA	3-ph.✓	YBCO tape
Rolls Royce	UK / -	11.5 kV, 400 A	3-ph.	MgB_2 wire
Nexans SC	D/2013	10 kV, 2.4 kA	3-ph. ✓	YBCO tape
Nexans SC	EU 2013	24 kV, 1 kA	3-ph. ✓	YBCO tape
Applied Materiaks	US /2013	15 kV / 1kA	3-ph. ✓	YBCO tape
Nexans SC	UK/2015	12 kV/1.6 kA	3-ph. ✓	YBCO tape
Applied Materials	US / 2016	115 kV	3-ph. ✓	YBCO tape

Plus more Projects in Russia, China, India

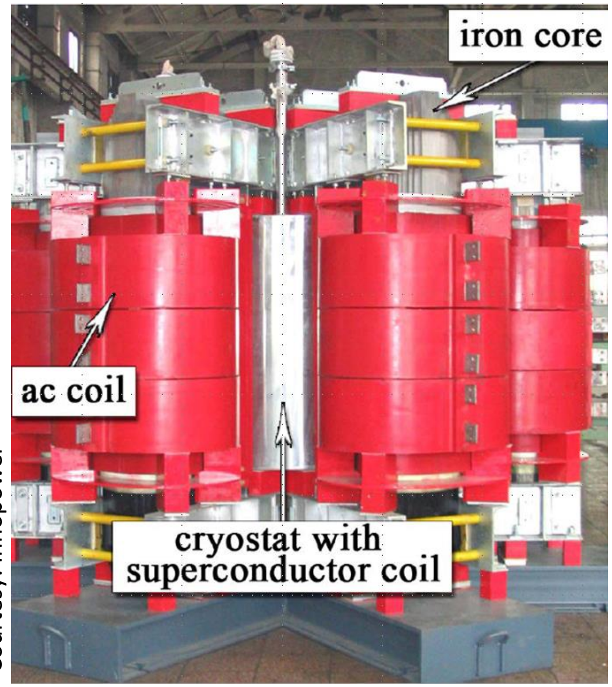
Superconducting Fault Current Limiters
State-of-the-Art

Nexans SuperConductors

Courtesy: Nexans SuperConductors

Resistive Type
12 kV, 800 A, 120 ms
Bi 2212 bulk material
Power system auxiliary
Energized 2009
First commercial system

Innopower



Courtesy: Innopower

DC Biased Iron Core Type
35 kV, 90 MVA
Bi 2223 tapes
Substation
Energized 2008

Zenergy Power

Courtesy: Zenergy Power

DC Biased Iron Core Type
15 kV, 1.2 kA, 60 cycles
Bi 2223 tapes
Substation Feeder
Energized March 9, 2009

Superconducting Fault Current Limiters
Application Example

12 kV, 1600 A resistive fault current limiter installed at Western Power Distribution, Chester Street, Birmingham, since end 2015

Picture: Courtesy Nexans

Superconducting Fault Current Limiters
Application Example

Resistive FCL installed since July 2013 for Silicon Valley Power, CA, USA

Normal operation
- Voltage 15 kV
- Current 1000 A

Current limitation at fault
- 23 kA auf 11.5 kA (50%)
- oder 5 kA to 3.5 kA (30%)

Recovery Under Load (RUL)
- 1 bis 3,5 s depends on short-ciruit current

Bild: Applied Materials

Superconducting Fault Current Limiters
Research Directions

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

Some manufacturers offer commercial applications.

Future Development of HTS Power Applications

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Table of Content

Superconducting Magnetic Energy Storage (SMES) Principle

Characteristic Data

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

SMES
Benefits

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Operation

- Short reaction time in ms
- Fast charge and discharge
- Full discharge possible
- Independant supply of active and reactive power
- High power density per volume and weight
- No degradation

Environment

- High efficiency > 95%
- Eco friendly

Attractive features

SMES
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

SMES
State-of-the-Art

Chubu, Japan
Bridging voltage dips

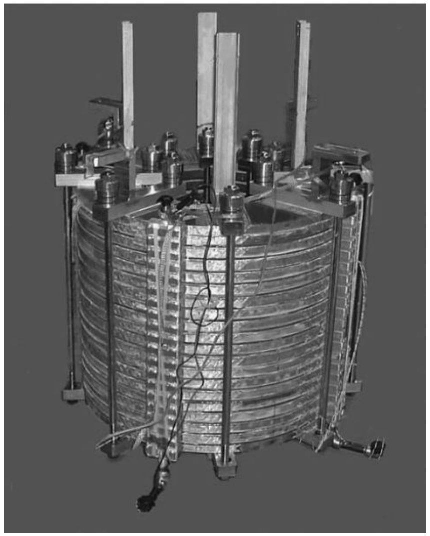

Figure: Chubu Electric

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

KERI, Korea
Power quality

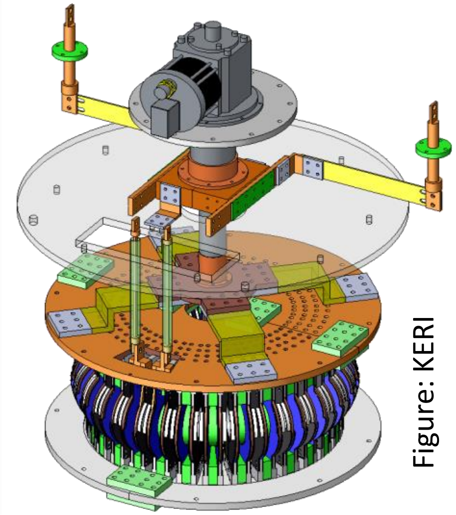

Figure: KERI

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

SMES
Future R&D

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

Future Development of HTS Power Applications

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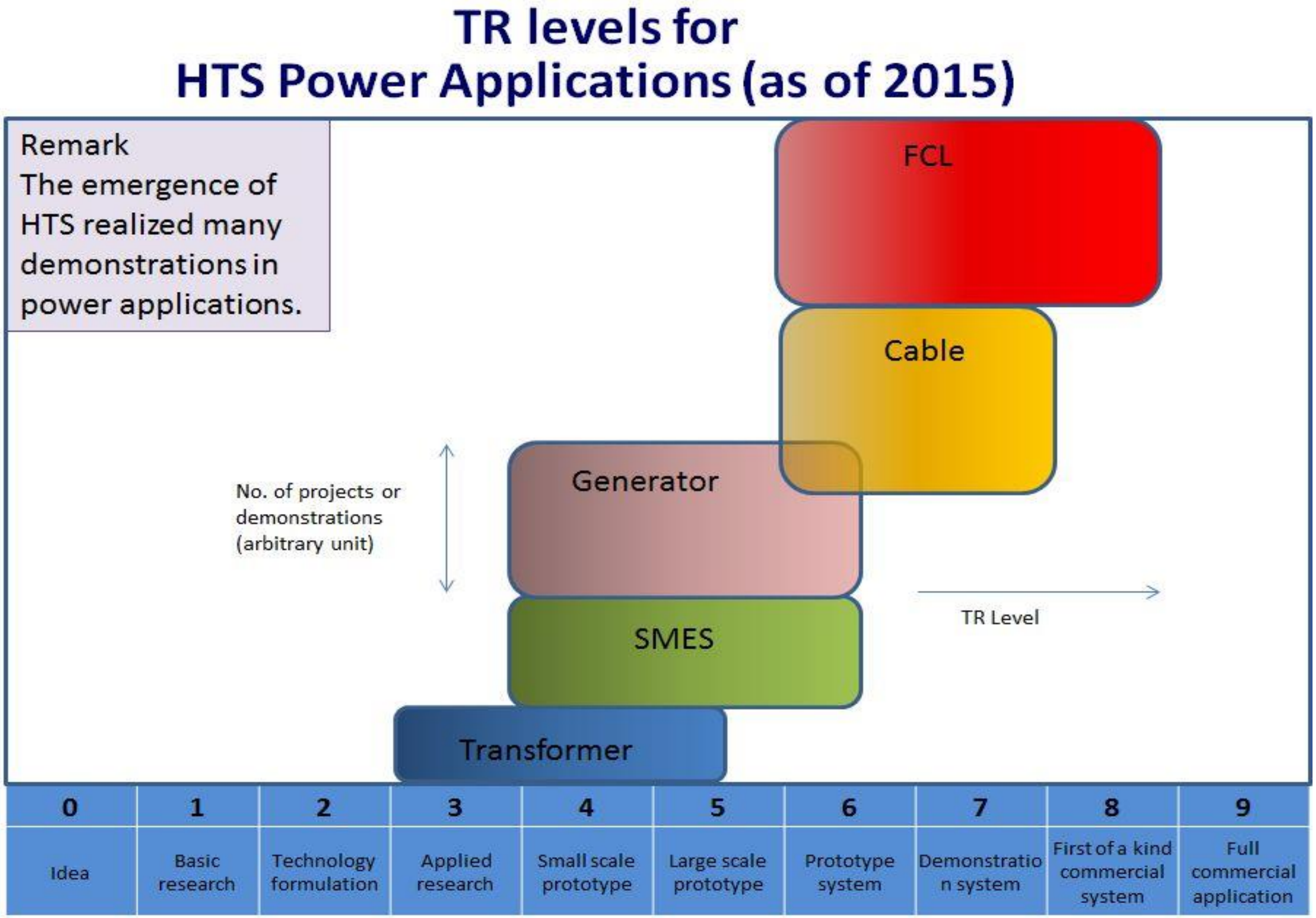
Table of Content

} Benefits

State-of-the-art

Future R&D directions

Technology Readiness of HTS Power Applications



Source: IEA High Temperature Superconductivity: A Roadmap for the Electric Power Sector 2015-2030