High Temperature Superconductor Power Applications

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High Temperature Superconductor Power Applications

Motivation

Conventional Power System Equipment

- Cables, Rotating Machines, Transformers

New Power System Equipment

- Current Limiters, SMES

Summary

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Summary

Motivation and Benefits

Design Aspects

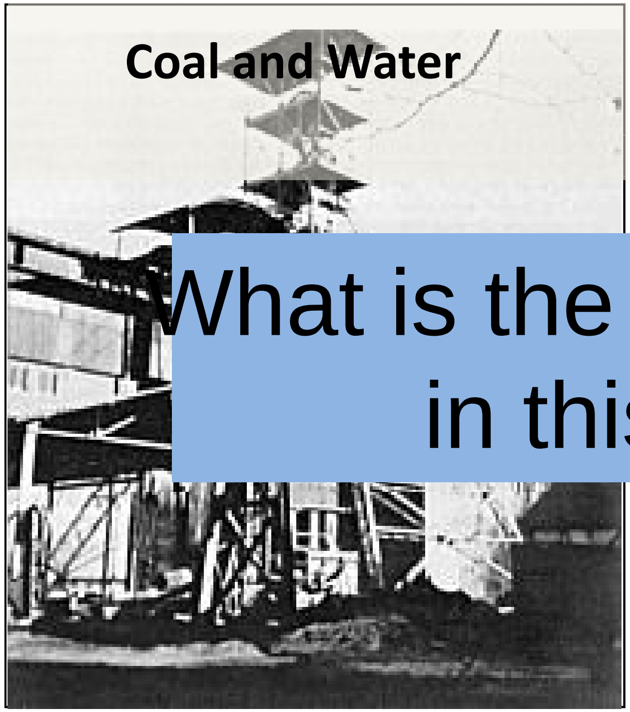
State-of-the-Art

Motivation

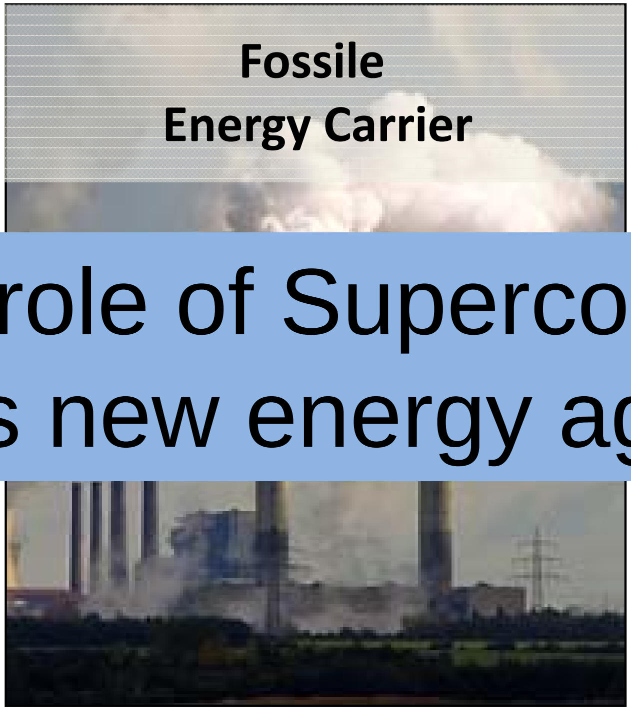
19. Century

20. Century

21. Century



Coal and Water



Fossile Energy Carrier

Sustainable Energy

What is the role of Superconductivity in this new energy age?

„Load and generation is locally coupled“

„Generation follows load“

„Load follows generation“ (Intelligent Systems)

The 21st century is a step into a new energy age

Motivation
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 %

Motivation

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 %

Motivation
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**

Superconductivity facilitates

- Superconducting fault current limiters
- Fault current limiting systems
- Superconducting magnetic energy storage

Motivation
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

Motivation
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
- inflammable

Motivation
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

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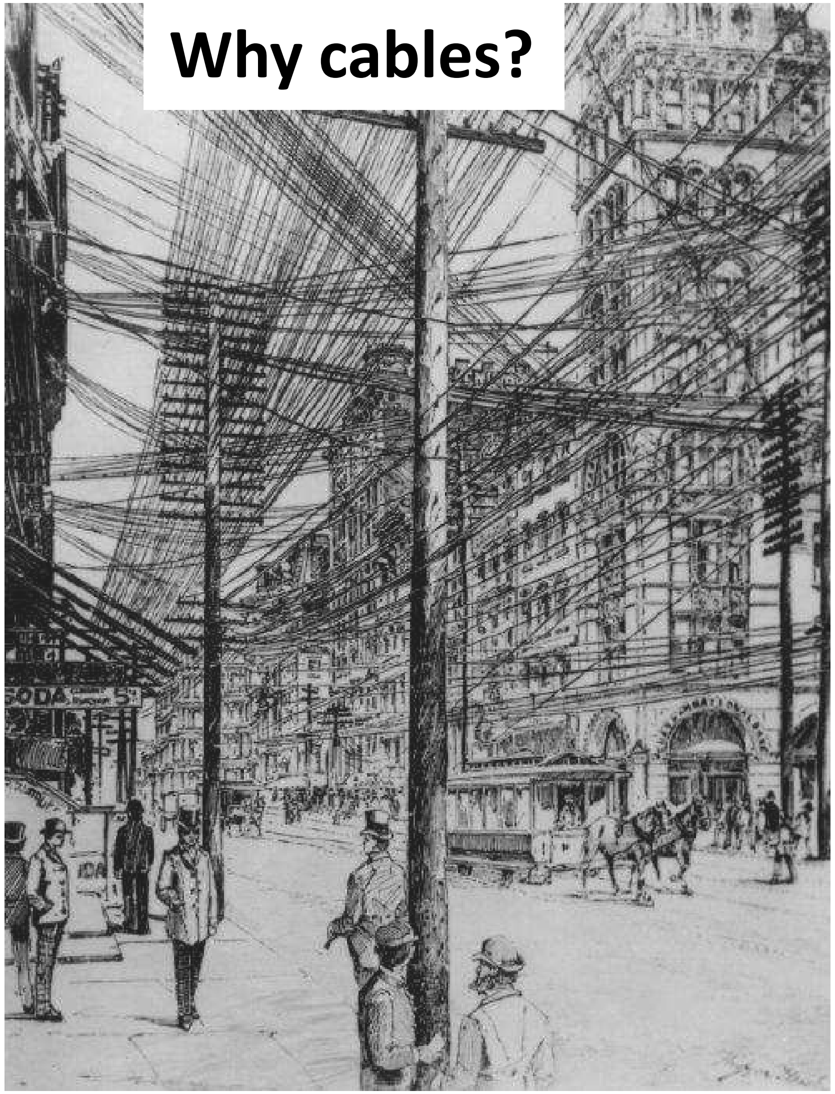
Summary

Superconducting Cables
Motivation and benefits

Why superconducting cables?

Why cables?

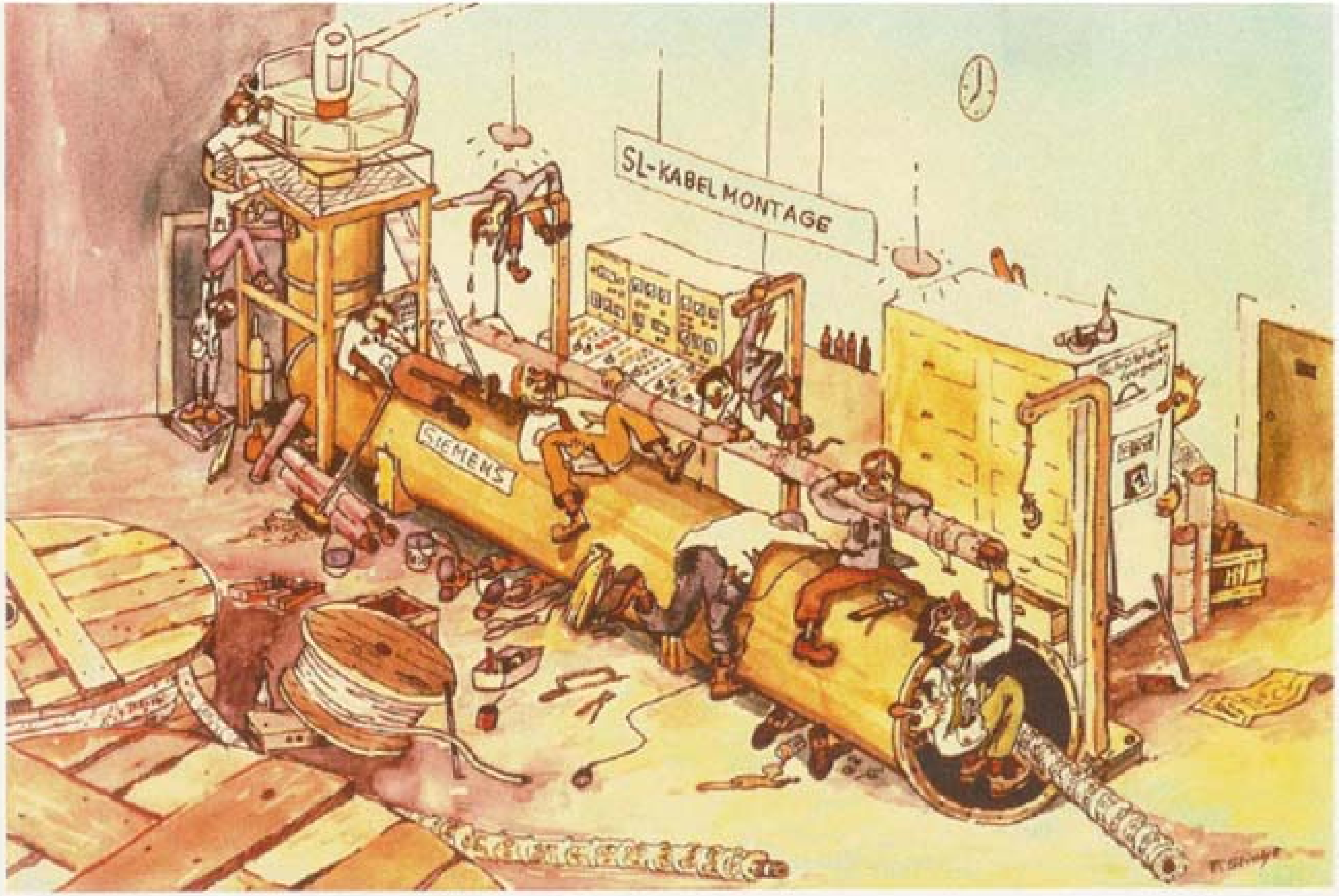


Manhattan „above ground“ at 1880

Manhattan „underground“ at 2003

SC cables enable
higher current at small diameter or
high capacity at lower voltage

Superconducting Cables
Why not LTS Cables in Power Systems?



Courtesy: Dr. Heinz-Werner Neumüller, former Siemens Corporate Technology

Superconducting AC Cables

Why no long distance transmission with AC Cables?

Long distance (> 100 km) transmission of high power (> 1 GW) ?

Cost comparison of overhead transmission line with conventional cable

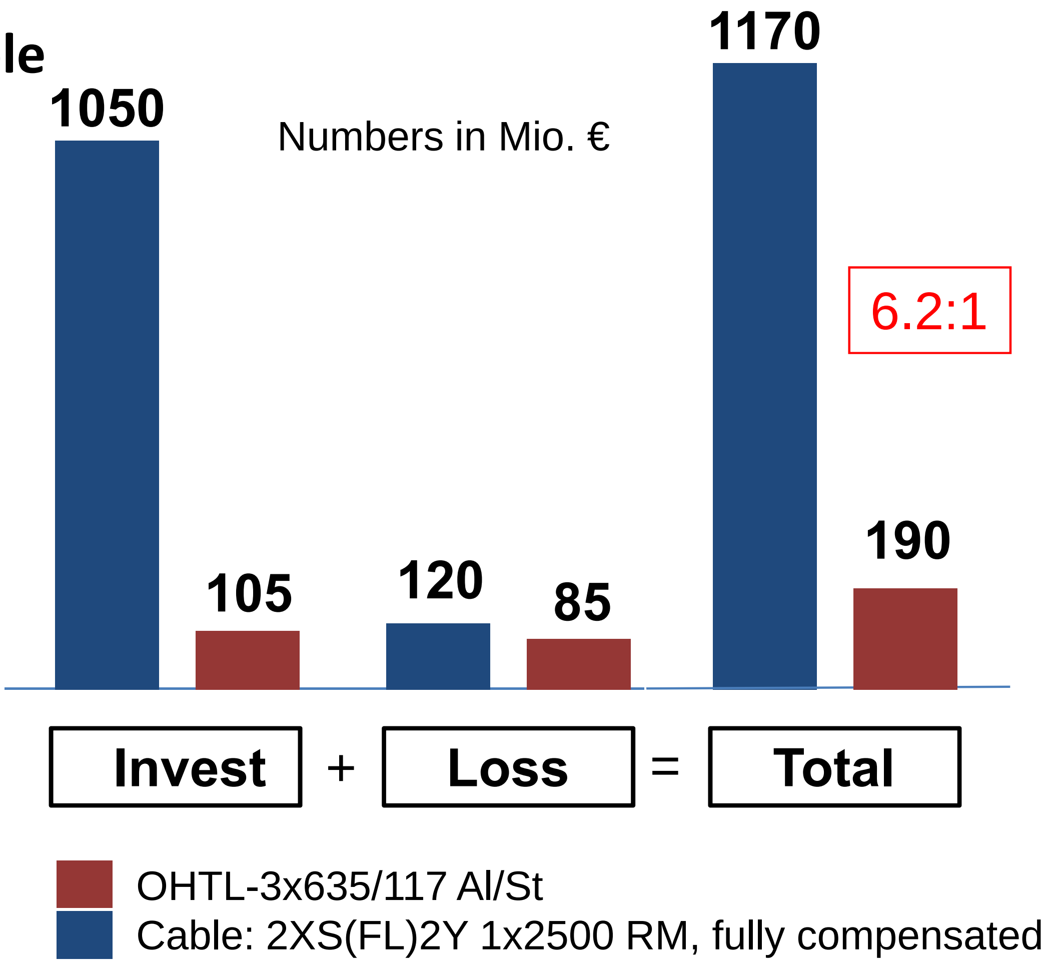
110 km distance

380 kV transmission voltage

2 Systems overhead transmission line

4 Systems 380 kV conventional cable

Conventional AC cables are not yet used for long distance high power transmission.
Why should we use HTS AC cables?



Source: B. Oswald, Freileitung/Erdkabel, 14.5.2009, Berlin

Superconducting Cables

1 phase in 1 cryostat – cold dielectric design

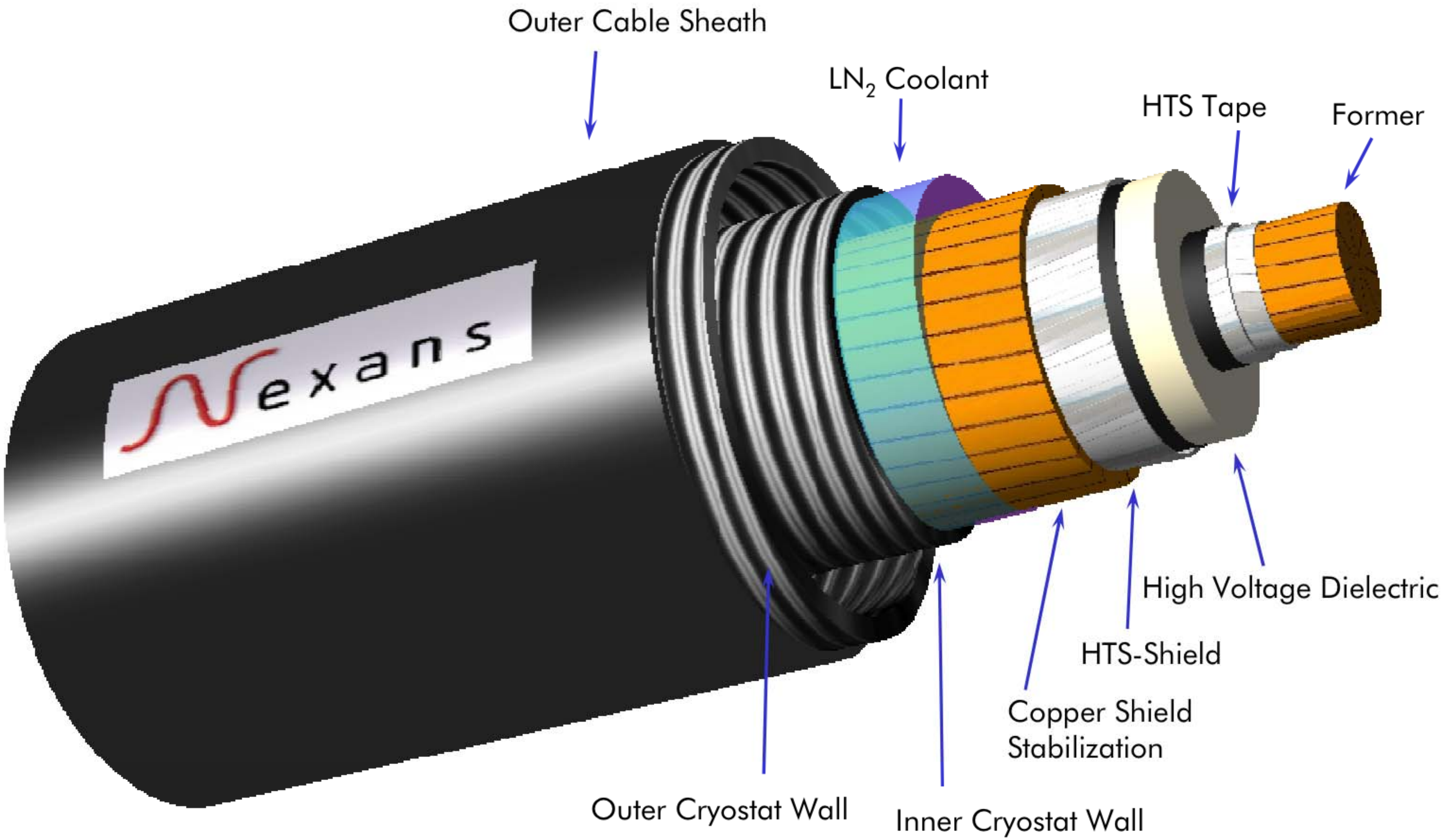
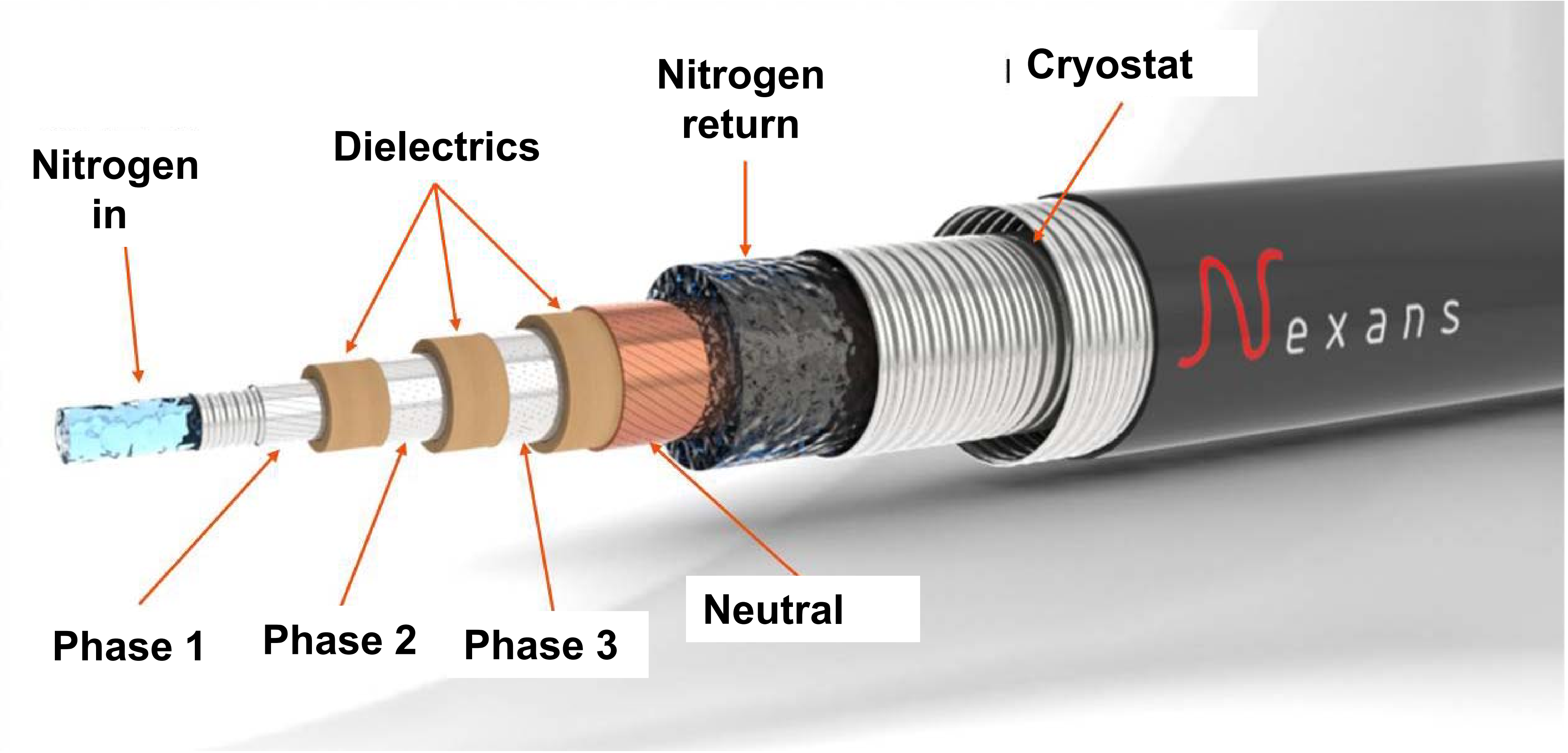


Figure: R. Soika, “Superconducting Power Cables” ESAS Summer School on Materials and Applications on Superconductivity, Karlsruhe 2010

Superconducting Cables
3 phases in 1 cryostat – cold dielectric design

Figure: LS Cable

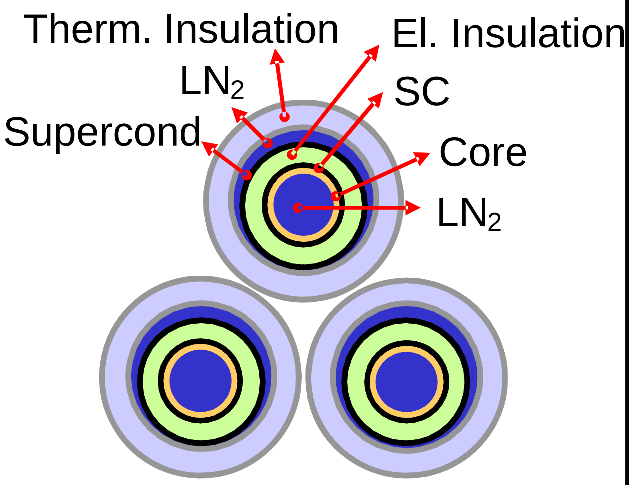
Superconducting Cables
3 concentric phases in one cryostat – cold dielectric design



Superconducting Cables

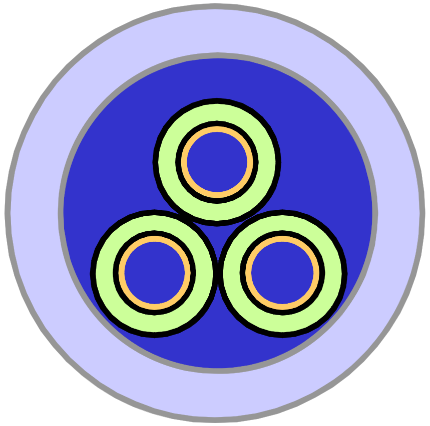
Cable Types

1 phase in 1 cryostat



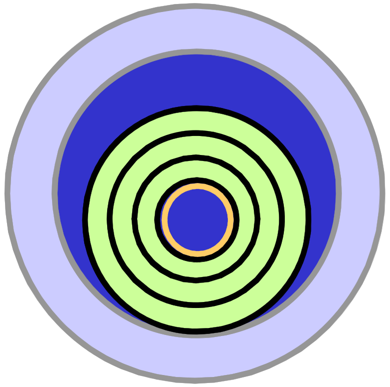
- No strayfield
- Longest lengths
- Highest voltages

3 phases in 1 cryostat



- No strayfield
- compact design
- Low and medium high voltages

3 concentric phases in 1 cryostat



- No strayfield
- compact design
- Low amount of SC
- only for medium vpltage

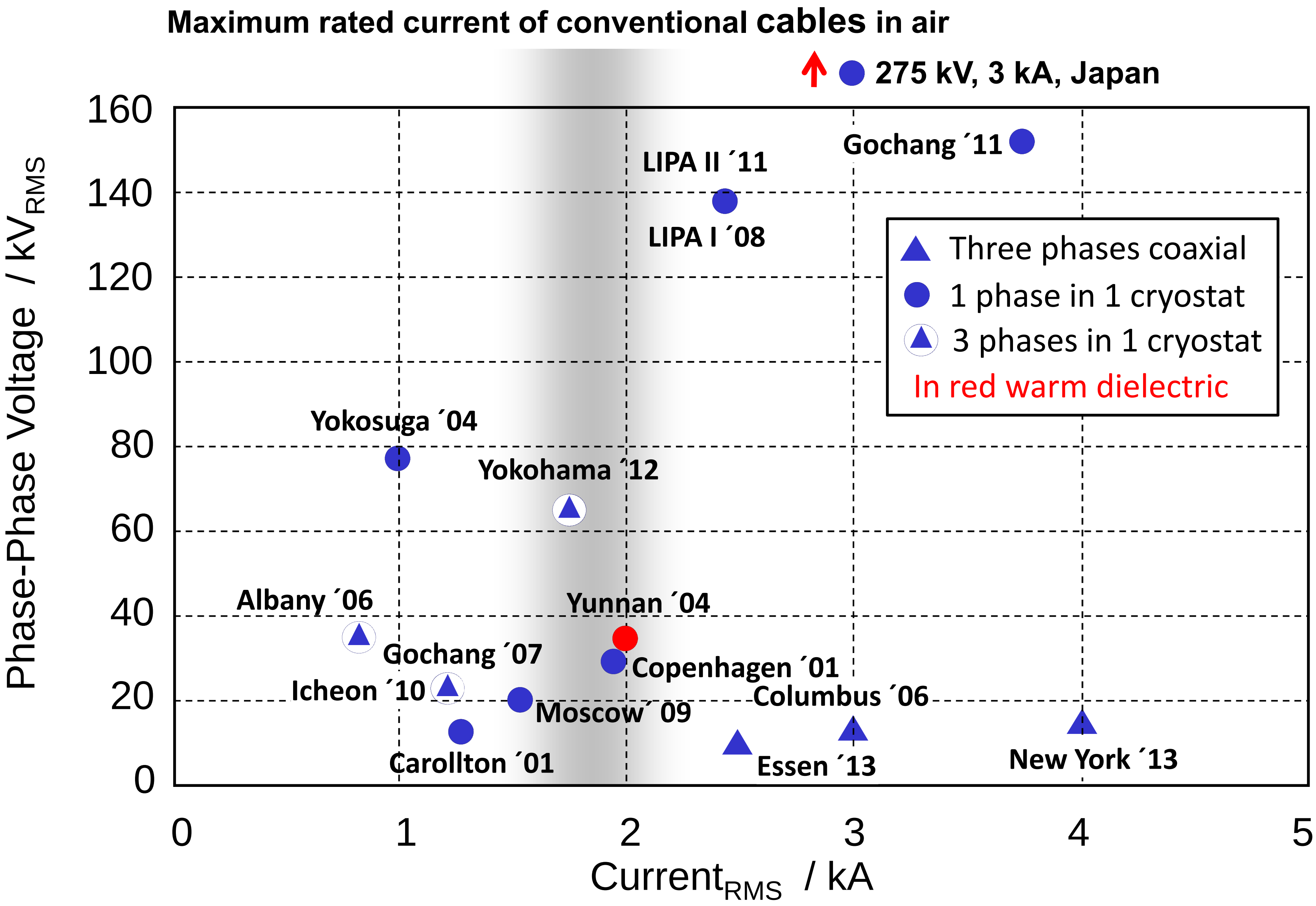
Superconducting AC Cables

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	Triax	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
Ultera	New York, US, 2013	Triax	13.8 kV, 4 kA, 240 m, 3-ph.	YBCO
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, 500 m, 3-ph.	YBCO
Sumitomo	Yokohama, JP, 2012	CD	66 kV, 200 MVA, 200 m, 3-ph.	Bi 2223
Sumitomo	TEPCO, JP	CD	66 kV, 5 kA	to be defined
Furukawa	TEPCO, JP	CD	275 kV, 3 kA	Bi 2223
Sumitomo	Chubu U., JP, 2010	CD	10 kV, 3 kA DC, 20 m, 200 m	Bi 2223
VNIIKP	Moscow, RU, 2010	CD	20 kV, 200 m	Bi 2223
Nexans	Essen, D, 2013	CD	10 kV, 2.4 kA, 1000 m, 3 ph.	Bi 2223

Superconducting AC Cables

State-of-the-Art of HTS AC Cable Tests



Superconducting AC Cables
State-of-the-Art

Columbus

Ultera
13.2 kV, 3 kA, 200 m
Triaxial^{TM} 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 AC Cables
40 MVA, 10 kV, 1 km

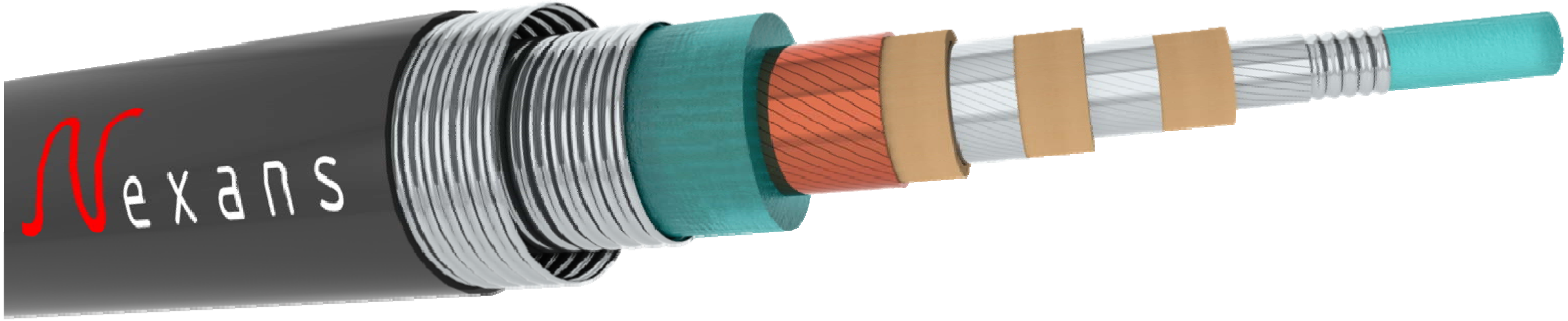
- Project partners: RWE, Nexans, KIT
- 10 kV, 2.3 kA (40 MVA), 1000 m
- HTS cable with HTS FCL
- Project started in September 2011
- Prototype test successfully finished
- Commissioning by end of 2013

AMPACITY
Smart grids for the city

VORWEG GEHEN

Nexans KIT

Supported by:
Federal Ministry of Economics and Technology
on the basis of a decision by the German Bundestag



Worlds first HTS system installation in a city center connecting two substations

Superconducting DC Cables

Where are the Applications for HTS DC Cables?

Industry high current lines

Figure: Vision electric

Integrate Renewables

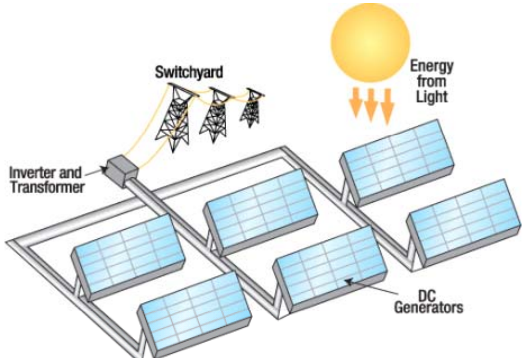


Figure: J. Minervini, MIT

Connection of Datacenter

Figure: J. Minervini, MIT

Partly grounding of HVDC lines

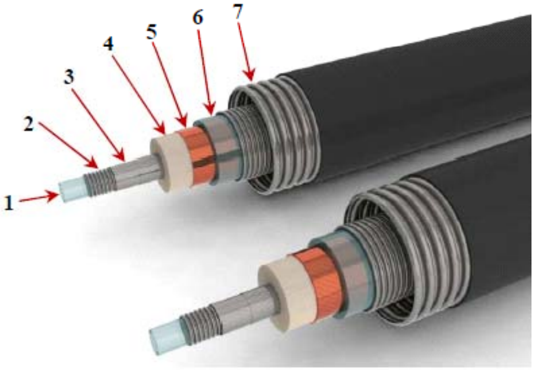


Figure: Nexans

GW long distance transmission

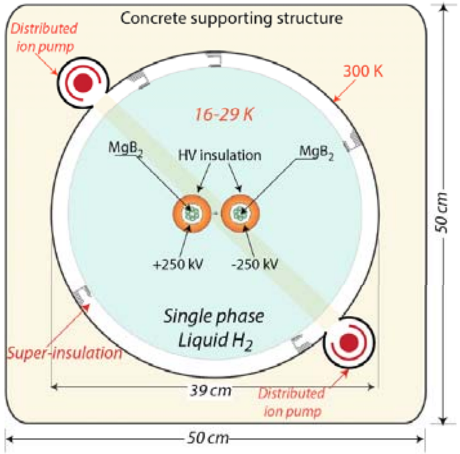


Figure: C. Rubbia, IASS

Degaussing of ships

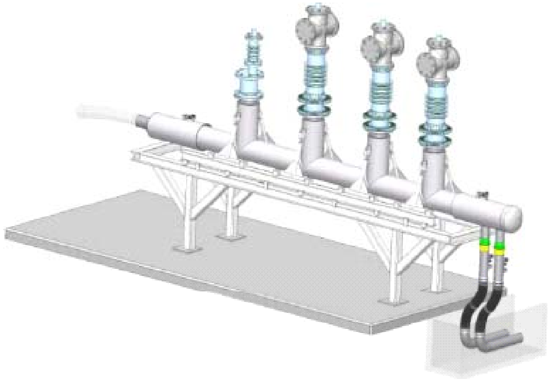


Figure: B. Fitzpatrick, HTS Peerreview2010

Superconducting DC Cables
Energy Efficiency – Comparison of Copper and HTS Cables

Specific loss

$$p_{Cu} = 1000 \frac{1 \frac{A}{mm^2}}{57 \frac{m}{\Omega mm^2}} = 17{,}54 \frac{W}{m\,kA}$$

Copper at 20 °C

$$p_{Cu} = 1000 \frac{1 \frac{A}{mm^2}}{45 \frac{m}{\Omega mm^2}} = 22{,}2 \frac{W}{m\,kA}$$

Copper at 90 °C

$$p_v = \frac{P_{Cryo} + P_{CL}}{\eta_{Cooling}} = \frac{\pi \cdot 150\,mm\, 1 \frac{W}{m^2} + 4 \cdot 20 \frac{W}{kA}}{\frac{1}{15}} = 7{,}06 \frac{W}{m} + 1200 \frac{W}{kA}$$

HTS

Assumptions	
Copper transmission line	
Current density	1.0 *A/mm²*
Specific conductivity	57 *m/Ωmm²*
Temperature value	0,0038
Max. Temperature	85-90 °*C*
HTSL DC transmission	
Cryostat diameter	150-200 *mm*
Cooling efficiency	1/15
Current lead loss	20 *W/kA*
Cryostat loss	1 *W/m²*

Example: 5 kA, 100 km

Copper (300 K) = 8770 kW

HTS = 712 kW

HTS DC cables can reduce transmission loss by more than 90 %.

High Temperature Superconductor Power Applications

Motivation

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New Power System Equipment

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Summary

Superconducting Rotating Machines

Motivation

Smaller volume and weight

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

Less resources

- Higher efficiency
- Less material

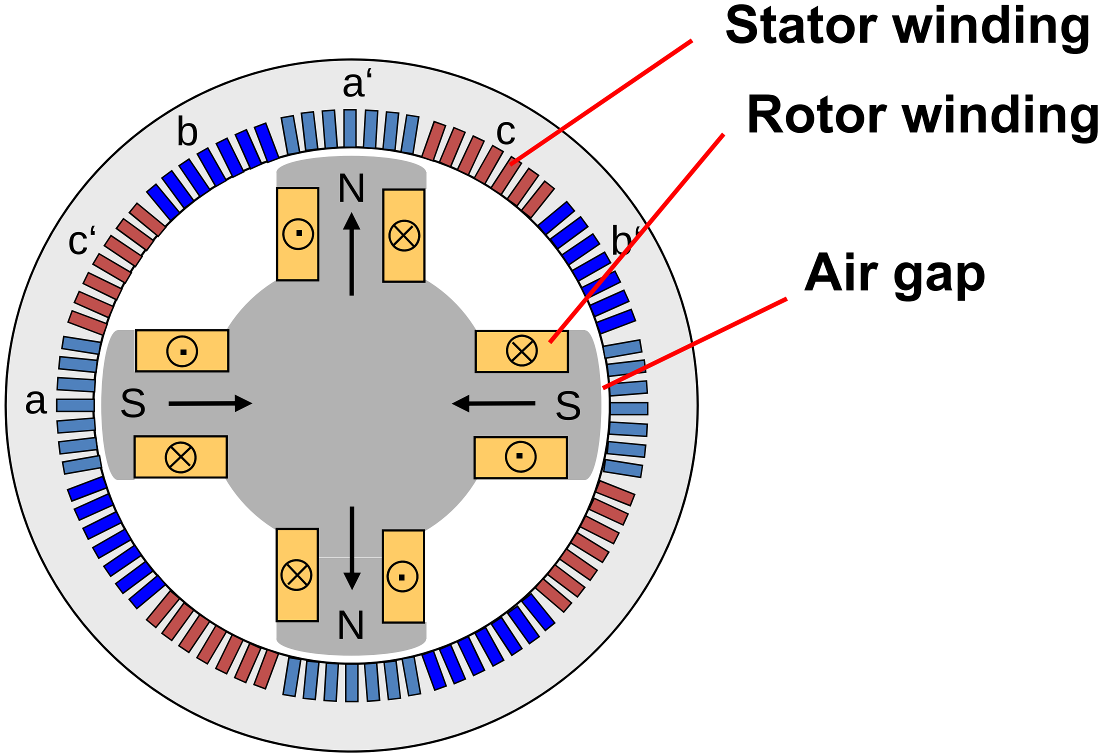
Improved operation parameters

- 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

Superconducting Rotating Machines

Conventional synchronous machine (4 poles, p=2)



Parameter

Torque/Lenght

$$\sim n \; I_{stat} \; B_r \; r$$

$$\sim A_1 \; r \; B_r \; r$$

Power

$$\sim A_1 \; B_r \; r^2 \; L \, n$$

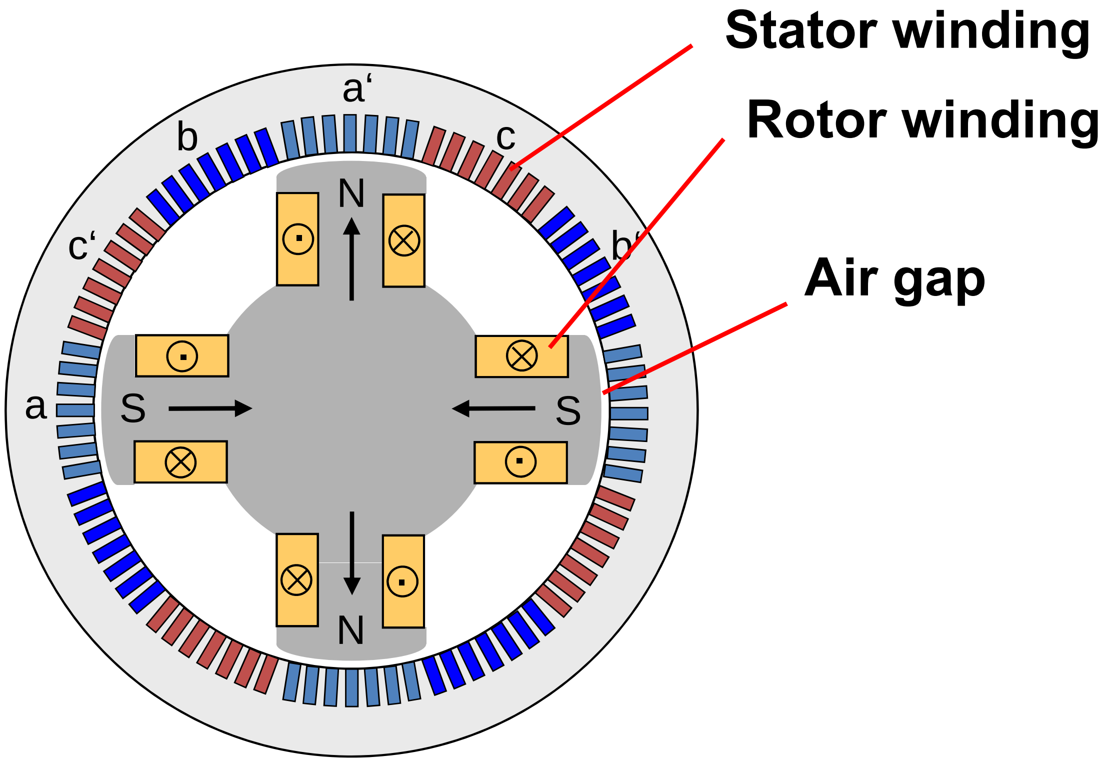
Power/Volume

$$\sim A_1 \; B_r \; n$$

- Small air gap
- Iron rotor
- Stator winding in grooves

What is the impact of superconductivity?

Superconducting Rotating Machines
Conventional synchronous machine (4 poles, p=2)



- Small air gap
- Iron rotor
- Stator winding in grooves

Conventionel

$B = 1\ T$

$A_1 = 1$ p.u.

$P = 1$ p.u.

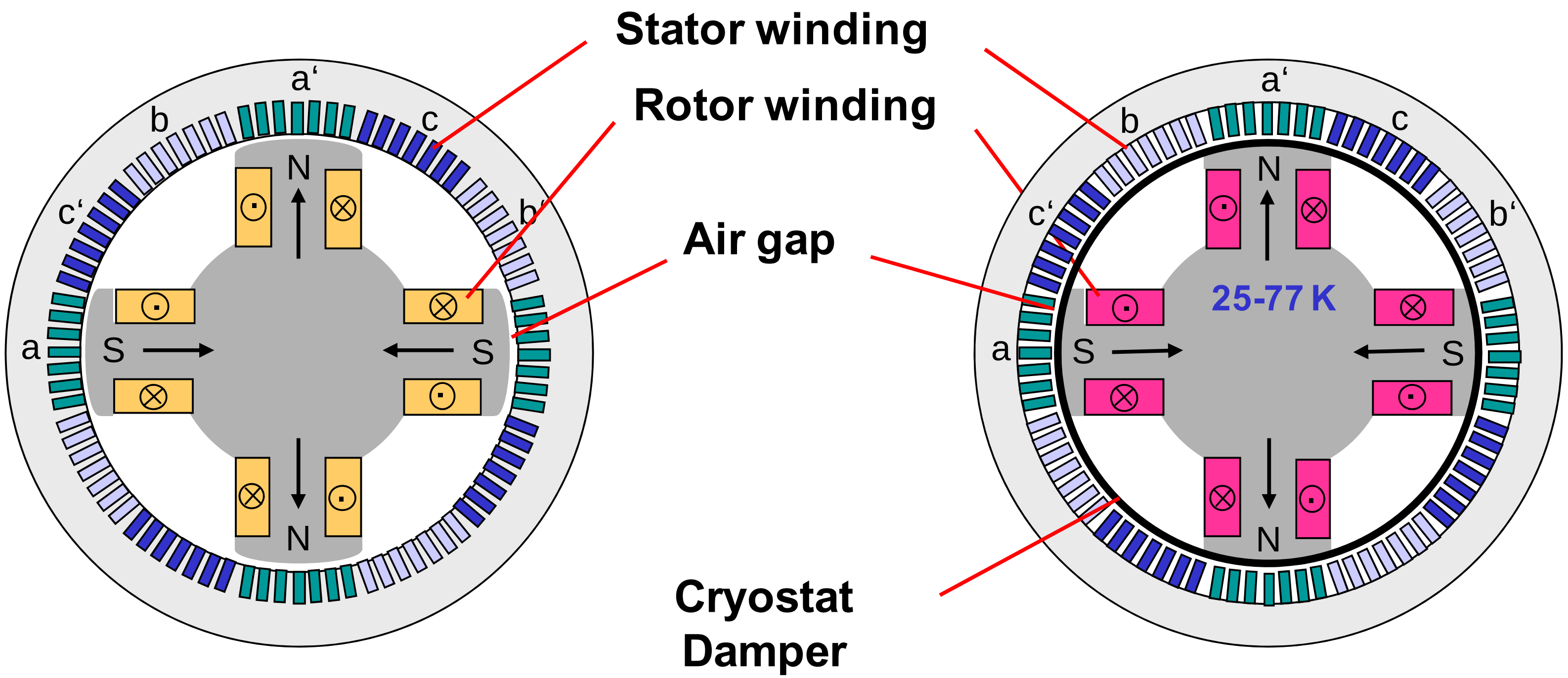
<u>Loss</u>

$P_{Cu,stat} = 1$ p.u.

$P_{Cu,rot} = 1$ p.u.

$P_{Fe} = 1$ p.u.

Superconducting Rotating Machines

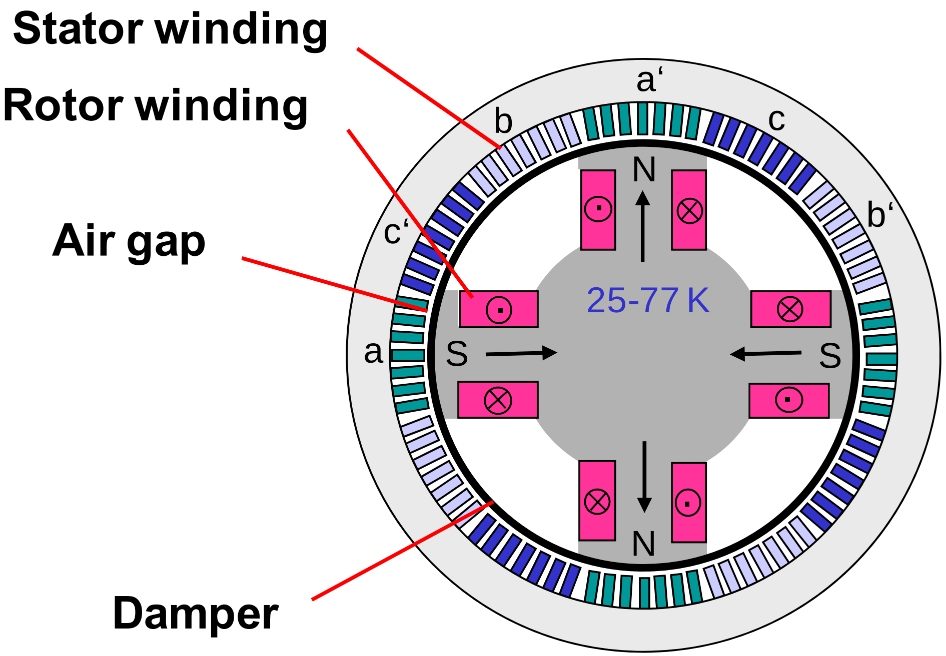


- Small air gap
- Iron rotor
- Stator winding in grooves

- Copper stator winding AC
- Superconducting rotor winding DC
- non-magnetic rotor
- Air gap stator winding
- Large air gap
- Damper

Superconducting Rotating Machines

Superconducting synchronous machine
(4 poles, p=2)



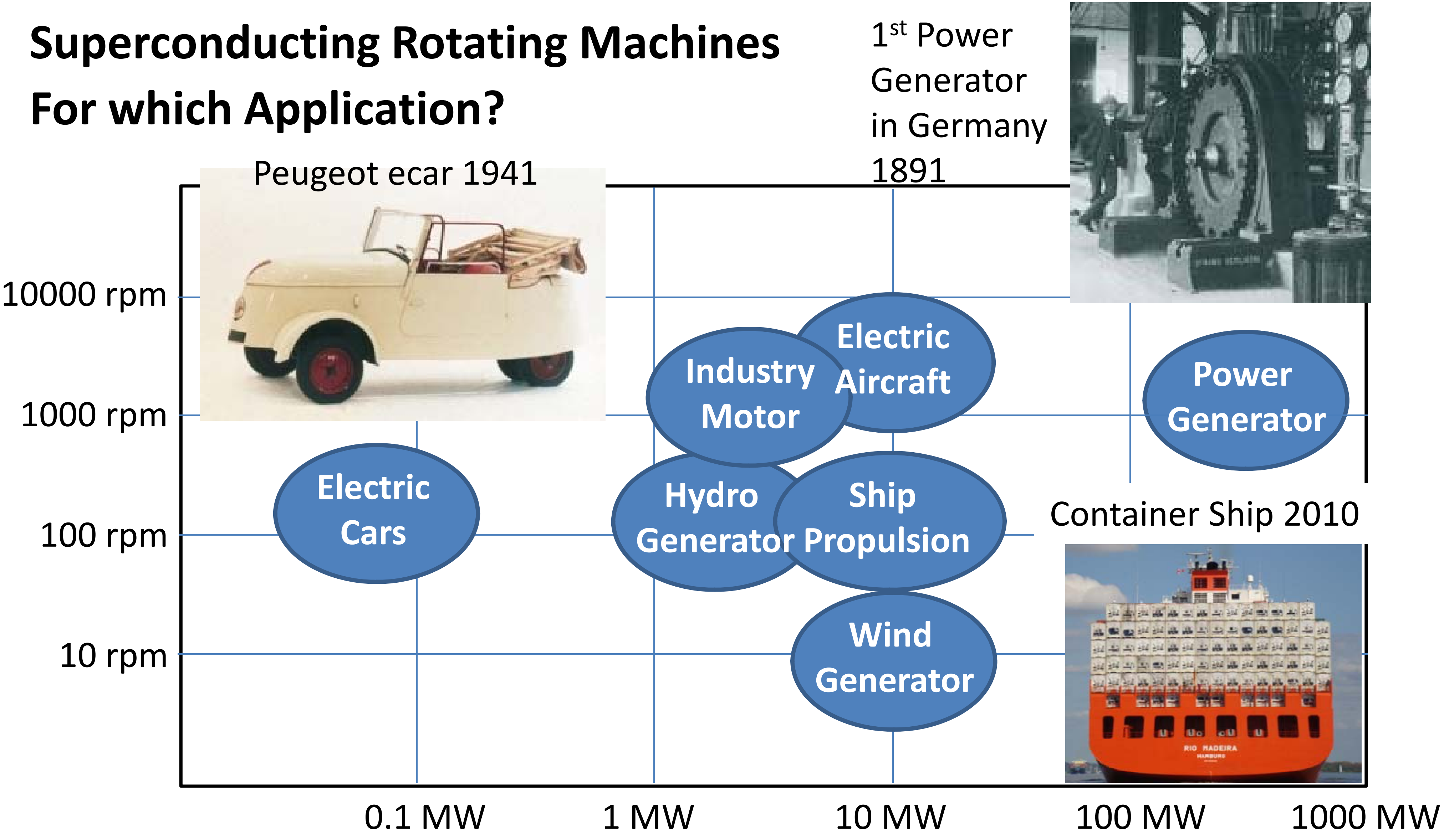
- Copper stator winding AC
- Superconducting rotor winding DC
- non-magnetic rotor
- Air gap stator winding
- Large air gap
- Damper

Superconducting	**Conventionel**
$B = 2$ T	$B = 1$ T
$A_1 = 2$ p.u.	$A_1 = 1$ p.u.
$P = 4$ p.u.	$P = 1$ p.u.
Loss	Loss
$P_{Cu,stat} = 2$ p.u.	$P_{Cu,stat} = 1$ p.u.
$P_{Cu,rot} = 0$ p.u. $+ P_{Kälte}$	$P_{Cu,rot} = 1$ p.u.
$P_{Fe} = 0{,}6$ p.u.	$P_{Fe} = 1$ p.u.

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

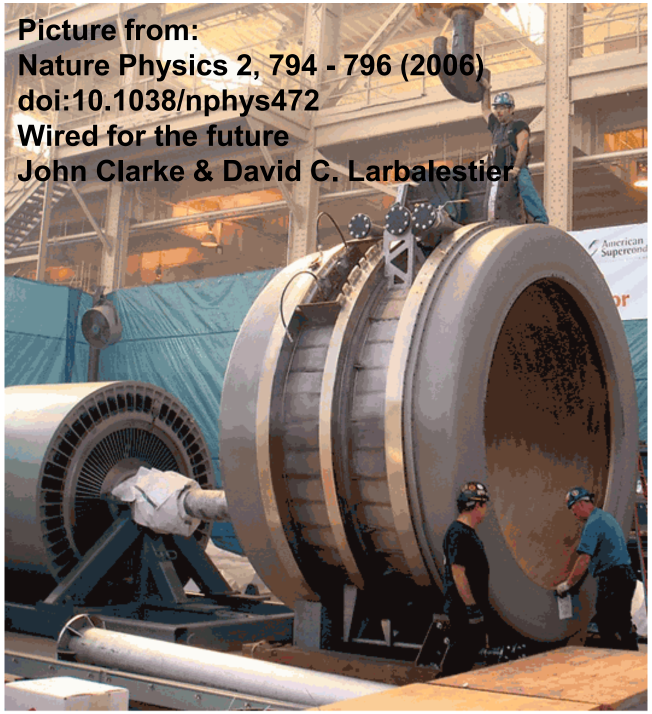
Manufacturer / Country	Machine	Timeline
AMSC (US)	5 MW demo-motor	2004
	8 MVA, 12 MVA synchronous condenser	2005/2006 (**Field test**)
	40 MVA generator design study	2006
	36 MW ship propulsion motor 8 MW wind generator design study	2008 2010
GE (US)	100 MVA utility generator	2006 (discontinued)
	5 MVA 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), now GE	1.25 MVA hydro-generator	2012
	500 kW demo-generator	2008
	8 MW wind generator design study	2010

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
36.5 MW ship propulsion


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

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

Superconducting Rotating Machines
4 MW Synchronous Generator

4 MW HTS II – Long term field test at Siemens motor factory in Nuremberg

Figure: Siemens

Test results:

- Loss reduced by 50 %
- Full capacitive power
- High overload stability
- Low voltage drop
- Low total harmonic distortion
- More than 7500 operating hours
- Safe operation

None of the shutdowns caused by HTS winding or cooling!
All operating states and shutdowns tolerated by the system!

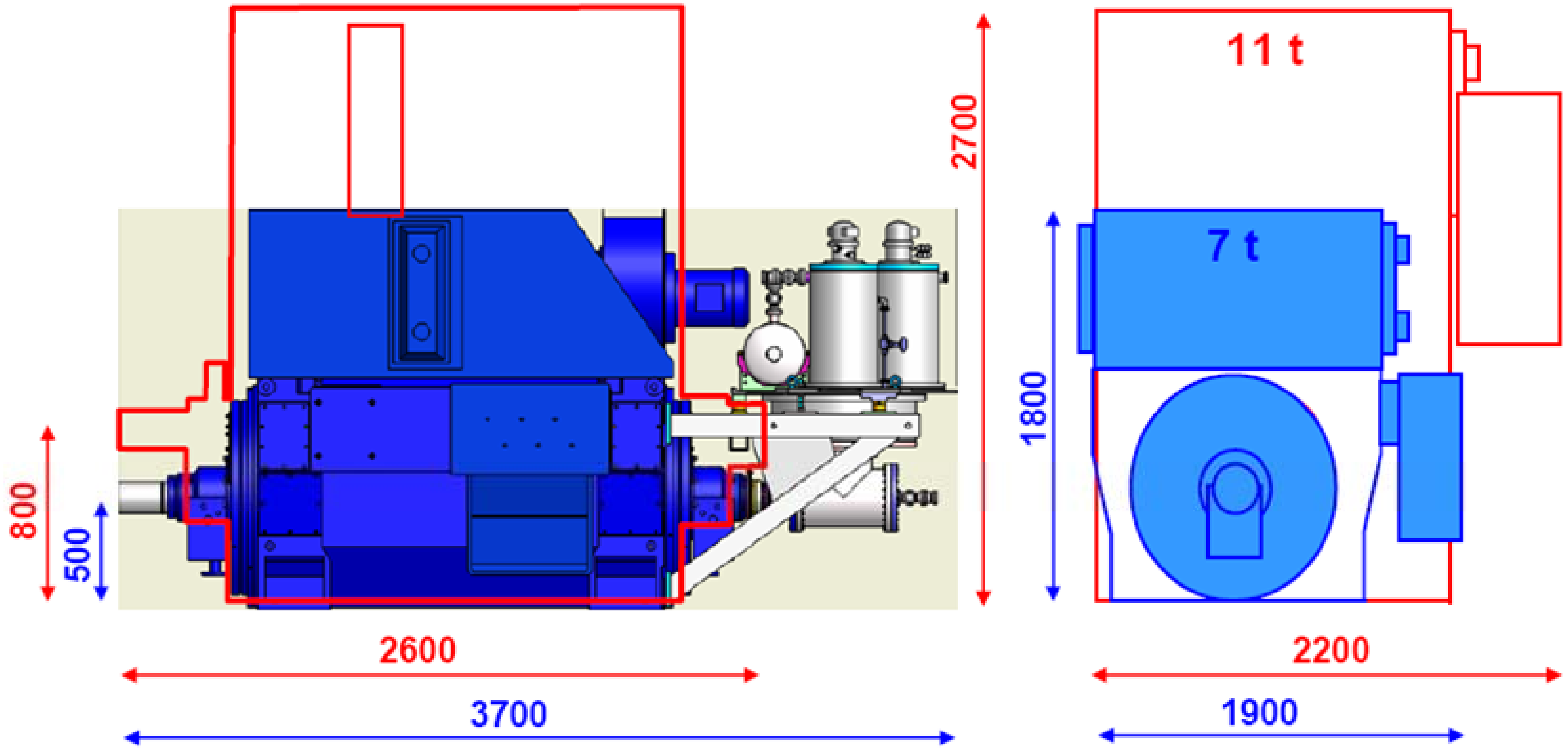
Superconducting Rotating Machines
4 MW Size and Weight Comparison (Siemens)

Conventionel Maschine

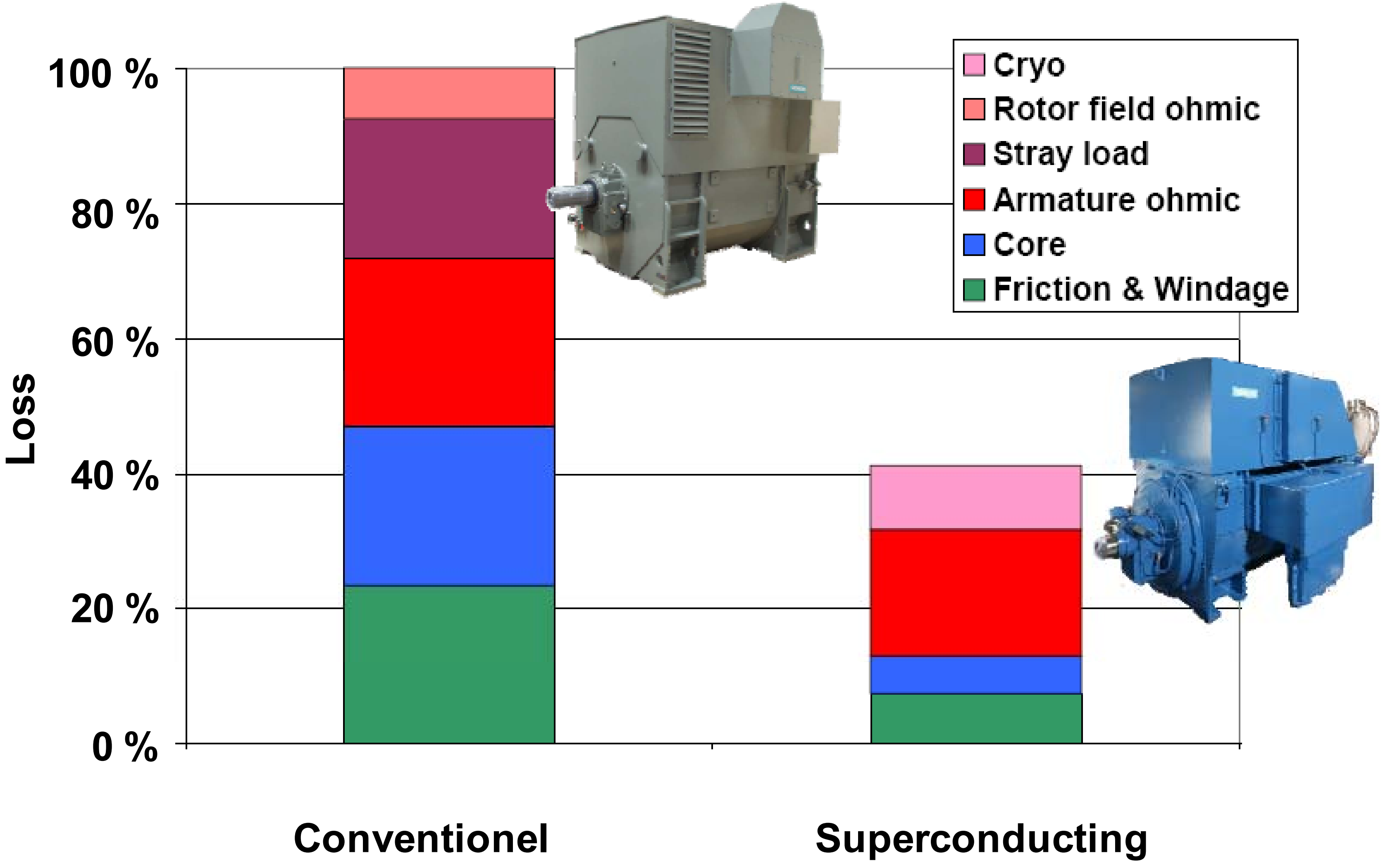
Weight 11 to

Superconducting Machine

Weight 7 to



Superconducting Rotating Machines
4 MW Energy Efficiency Comparison (Siemens)



η=96,5 % **η=98,7 %**

Superconducting Rotating Machines
1.7 MW Hydrogenerator (EU project Hydrogenie)

Objective

Develop and field test of a compact HTS hydro power generator

Partners

GE (Converteam) UK
Politechnika Slaska, Poland
Kema, Nederland
E.ON Wasserkraft, Germany
Zenergy Power, Germany
Stirling Cryogenics, Nederland
Cobham CTS, UK

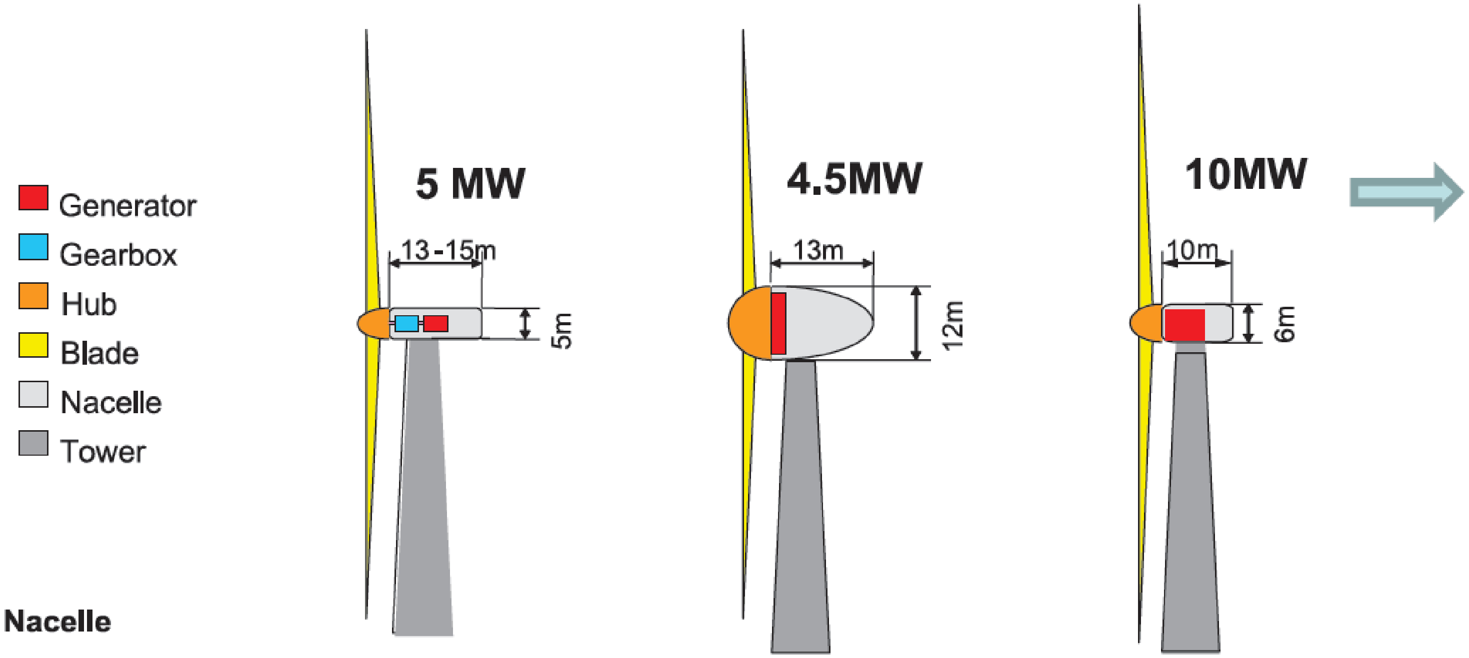
Image Courtesy of Converteam

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
Installation in 2012

Successful test in 2013

Superconducting Rotating Machines

HTS Wind Generators



Possible to go as large as 20MW with HTS

	Main Stream Geared	**Conventional Direct Drive**	**Optimized HTS Direct Drive (AMSC)**
Mass of Nacelle + Hub + Blades	m_{Top} ~310 to 430t	m_{Top} ~500t	
Extrapolated for 10 MW	m_{Top} ~750t – 850t	m_{Top} ~800t-900t	m_{Top}<500t

Picture from AMSC SeaTitan^{TM} Data Sheet

One HTS wind generator with 10 MW and 4000 full load hours earns 1.8 Mio. €1) more per year than a conventional 5 MW wind generator.

1) 1 kWh=9Eurocent

Superconducting Rotating Machines
Suprapower Project (http://www.suprapower-fp7.eu/)

Weight of the nacelle

- Reduced support structures and foundations

- Reduction: SC generator and Direct Drive

SC wire: MgB_2

- based on economical and technical reasons

- demonstration of viability for WT

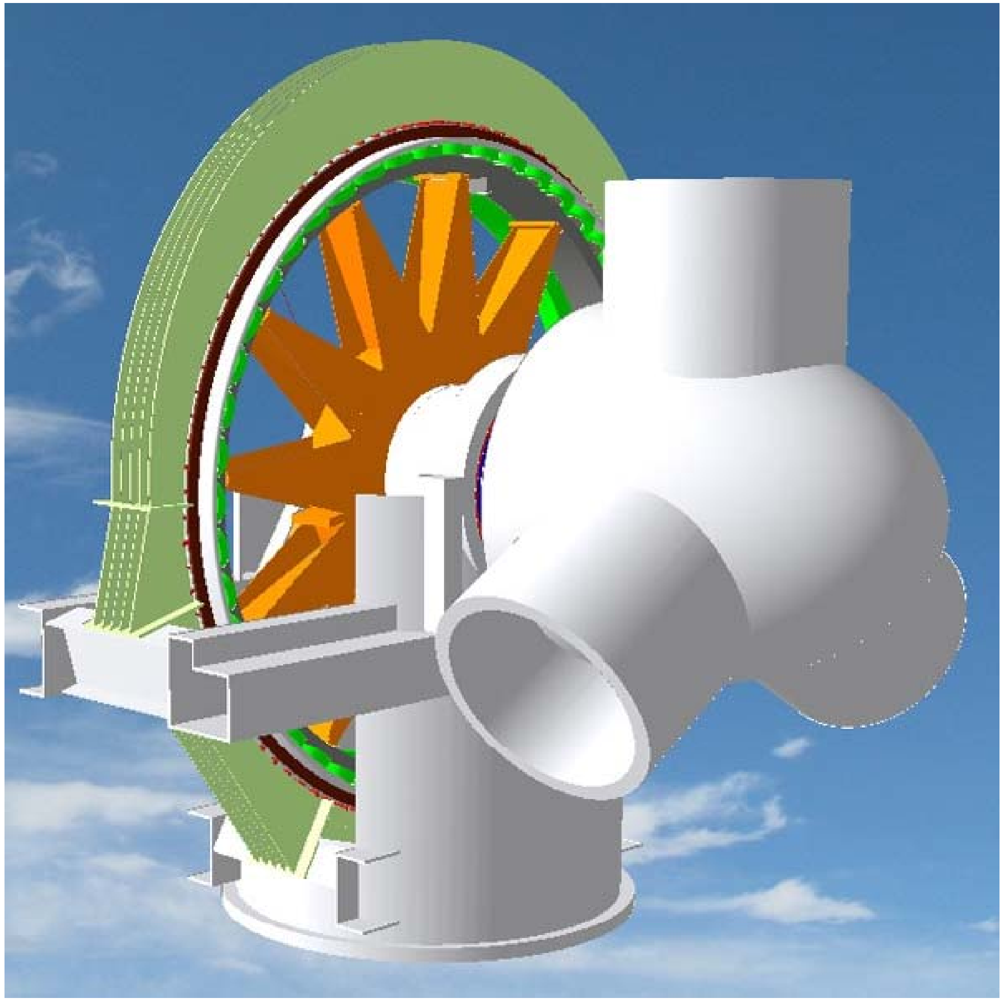
Cryogenic system: conduction-cooled (cryogen-free)

- Gifford-McMahon cryocoolers

- Heat is removed by closed contact

- Compressors cannot rotate => High-pressure
- Helium rotary feed-through

Industrially viable, installable and environmentally sustainable



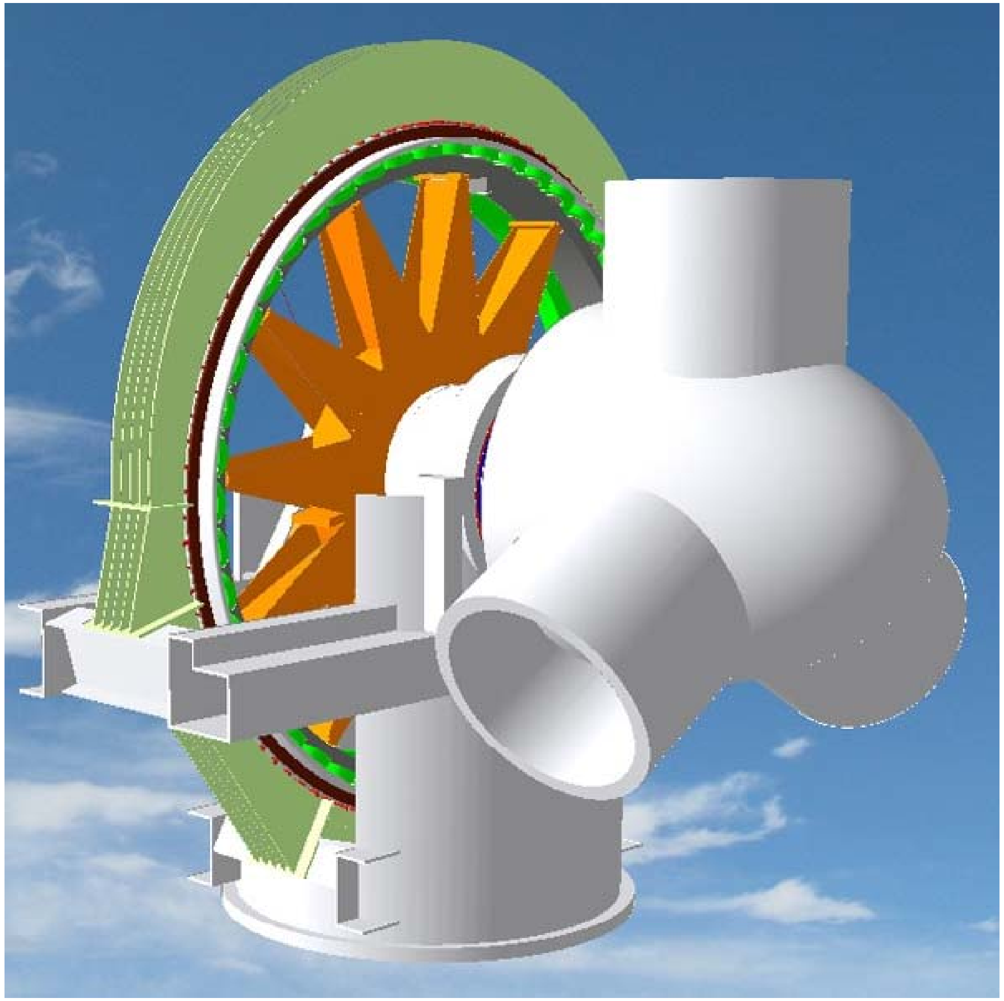
SC wind turbine according to Tecnalia concept (PTC/ES2009/070639)

Superconducting Rotating Machines

Suprapower Project (http://www.suprapower-fp7.eu/)

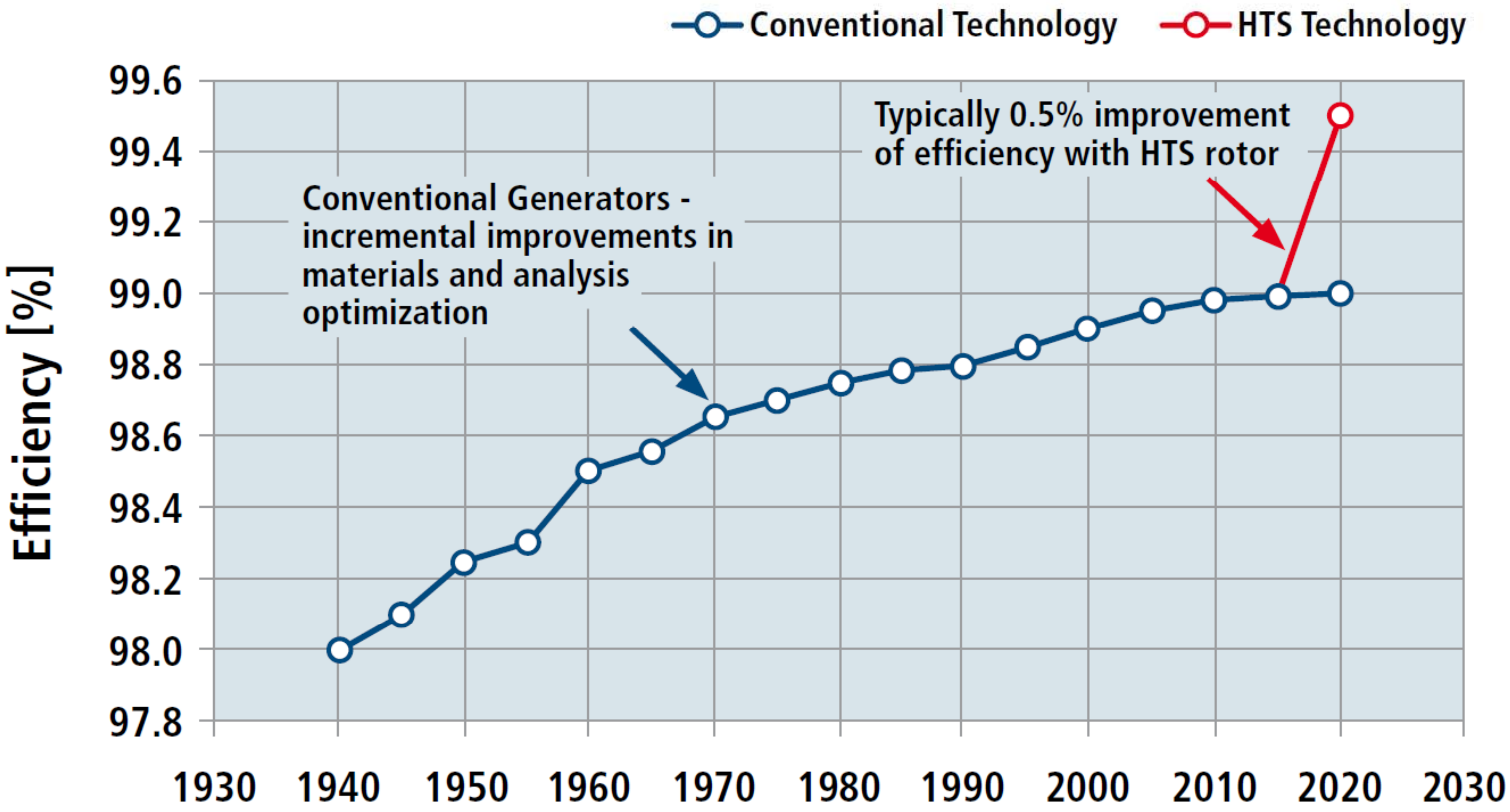
Partner

- tecnalia
- ACCIONA WindPower
- ACCIONA Energia
- Columbus Superconductors
- Oerlikon-Leybold Vacuum
- Institute of Electrical Engineering Slovak Academic of Sciences
- University of Southampton
- KIT
- d2m Engineering



SC wind turbine according to Tecnalia concept (PTC/ES2009/070639)

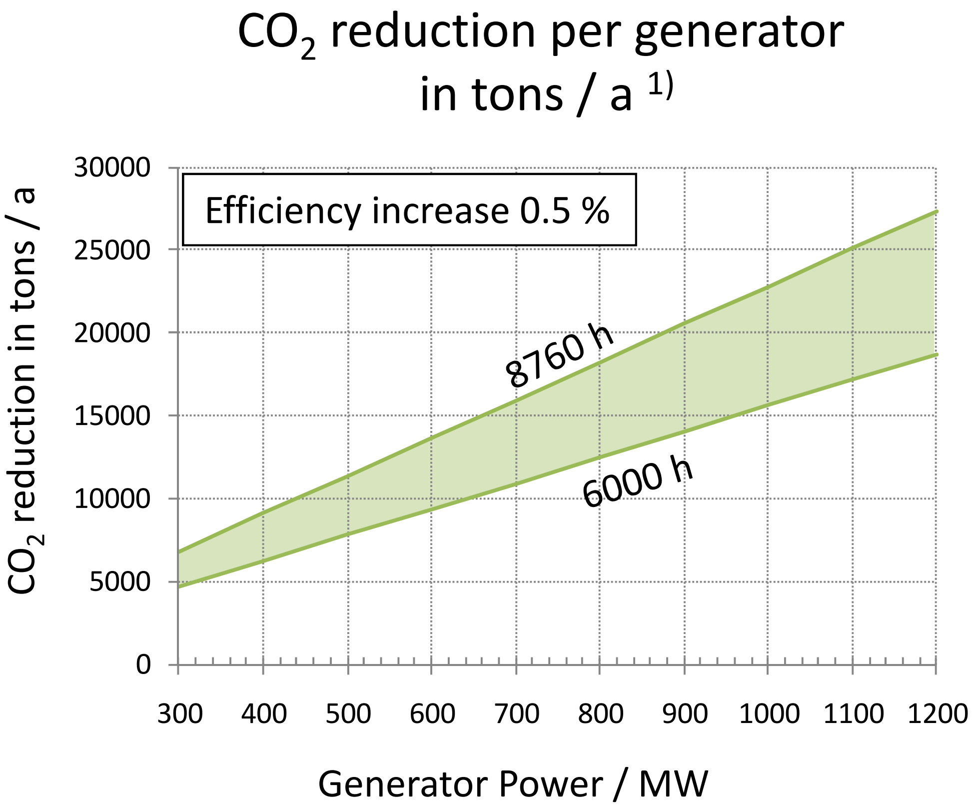
Superconducting Rotating Machines
Energy Efficiency of HTS Power Generators



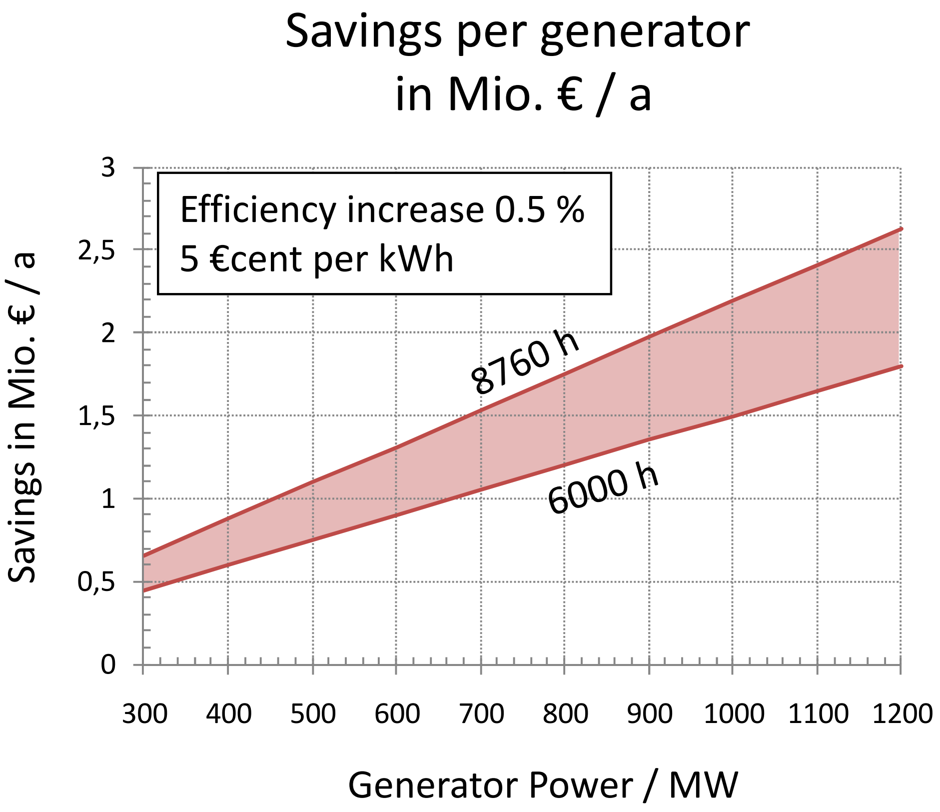
Source: High-Temperature Superconductivity for Power Engineering, Materials and Applications, Accompanying Book to the Conference ZIEHL II, Future and Innovation of Power Engineering with High-Temperature-Superconductors, 16-17 March 2010, Bonn, Germany

Superconducting Rotating Machines

Energy Efficiency of HTS Power Generators



CO_2 reduction per generator in tons / a 1)



Savings per generator in Mio. € / a

High Temperature Superconductor Power Applications

Motivation

Conventional Power System Equipment

- Cables, Rotating Machines, Transformers

New Power System Equipment

- Current Limiters, SMES

Summary

Superconducting Transformers

Motivation

Manufacturing and transport

- Compact and lightweight (~50 % Reduction)

Environment and Marketing

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

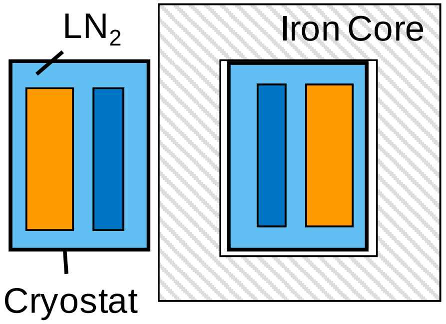
Operation

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

Superconducting Transformers

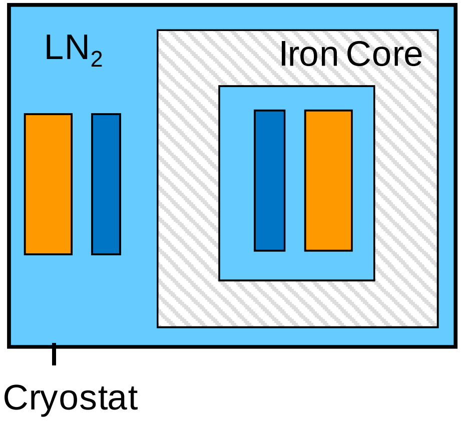
Different types

Warm Iron Core



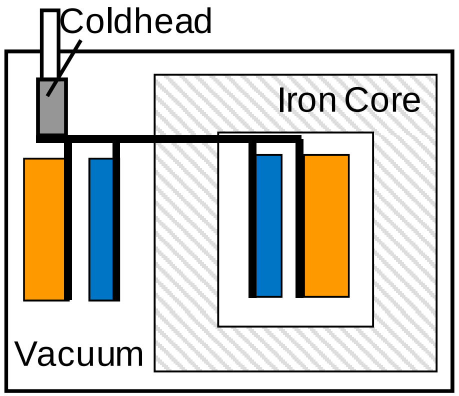
- ☺ Low Cooling Power
- ☺ Iron at Room Temperature
- ☹ Expensive Cryostat
- ☹ 3 Cryostats needed

Cold Iron Core



- ☺ Simple Cryostat
- ☺ Simple Cooling inerface
- ☹ High Cooling Power (Iron core loss at low temp.)

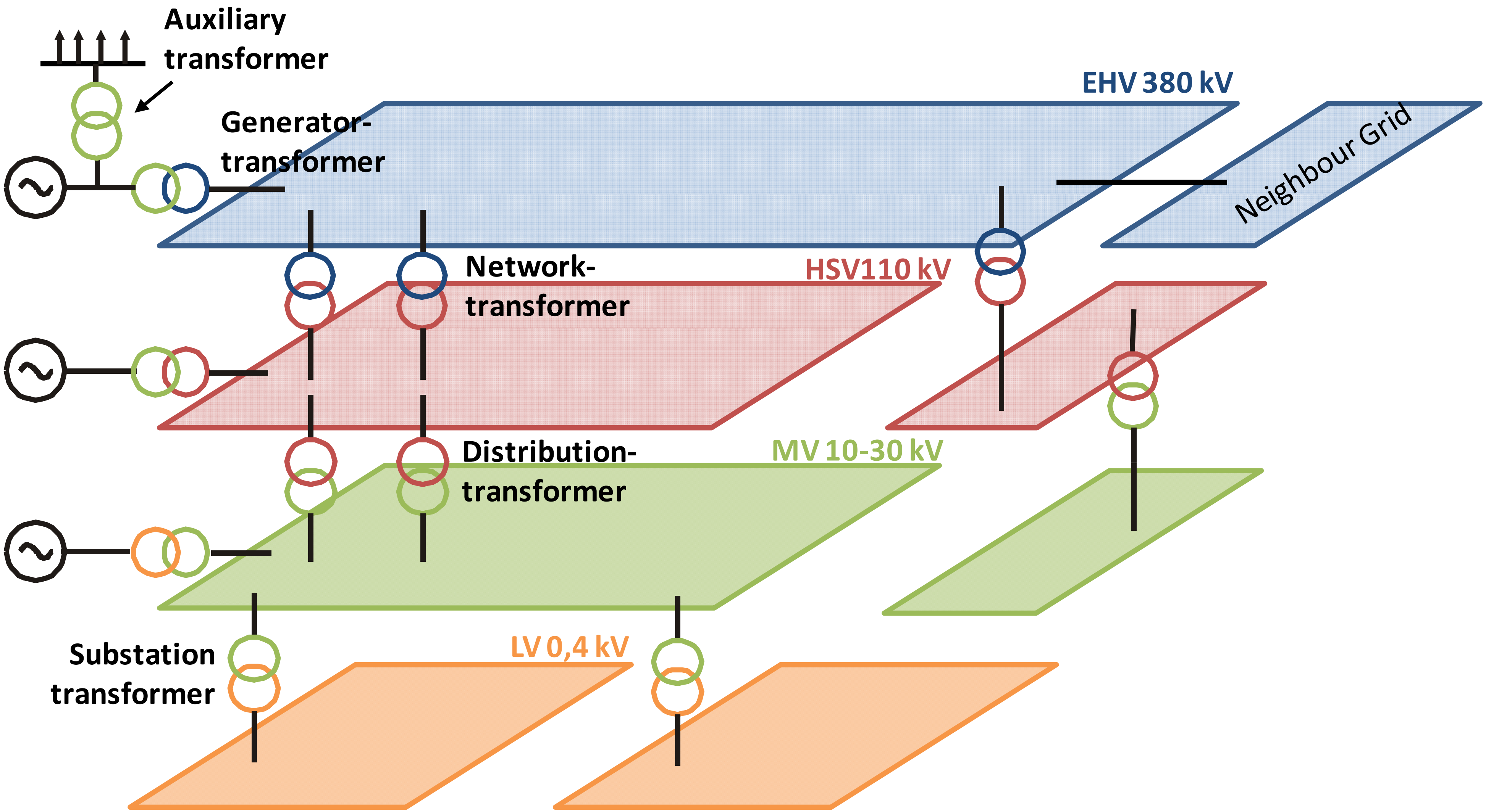
Conduction Cooled



- ☺ Simple Cryostat
- ☺ Iron at Room Temperature
- ☹ Long recooling after quench
- ☹ Temperature difference
- ☹ Not suitable for high voltage

Superconducting Transformers

Applications



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

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	400 kVA	1	2010	YBCO
Australlia	Callaghan Innovation	Demonstrator	1 MVA	3	2013	YBCO

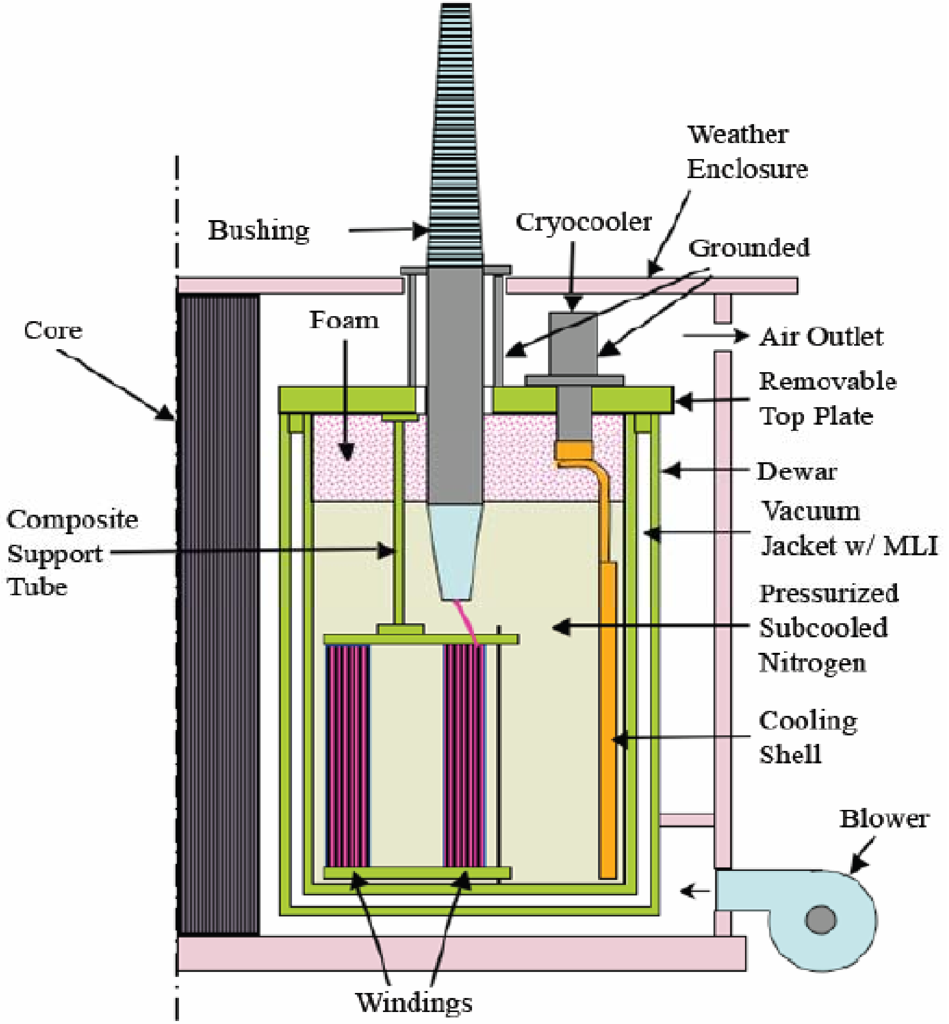
🟦 Active current limitation

Superconducting Transformers
28 MVA, 70 kA Prototype

Project Partners: SuperPower, Waukesha, SCE, ORNL, U Houston

Objective: Develop and field test a 28 MVA HTS transformer using YBCO

Parameter	Value
Primary voltage	70.5 kV
Secondary voltage	12.47 kV
Operating Temperature	~ 70 K, press. LN_2 (1.1-3 bar)
Target Rating	28 MVA
Primary Connection	Delta
Secondary connection	Wye
YBCO tape length	~ 12 km of 12 mm wide tape
HV rated current	230 A
LV rated current	1296 A



Source: F. Roy, “The 28-MVA FCL Smart Grid Demo Transformer and Modeling Concerns about its Operation under Fault Conditions,” 2nd International Workshop on Modeling HTS, April 11-13, 2011, Cambridge, United Kingdom.

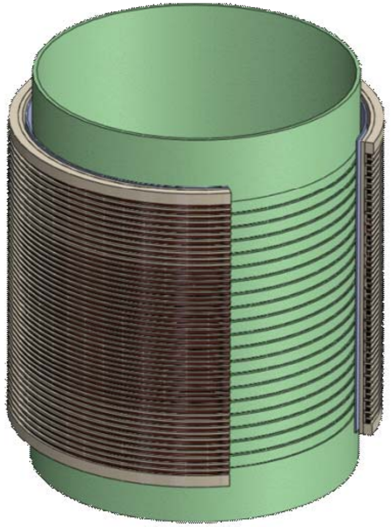
Superconducting Transformers

1 MVA Technology Demonstrator

Project Partners: Callaghan Innovation, Wilson Transformers, General Cable

Objective: Develop and field test of a 1 MVA HTS Transformer with YBCO

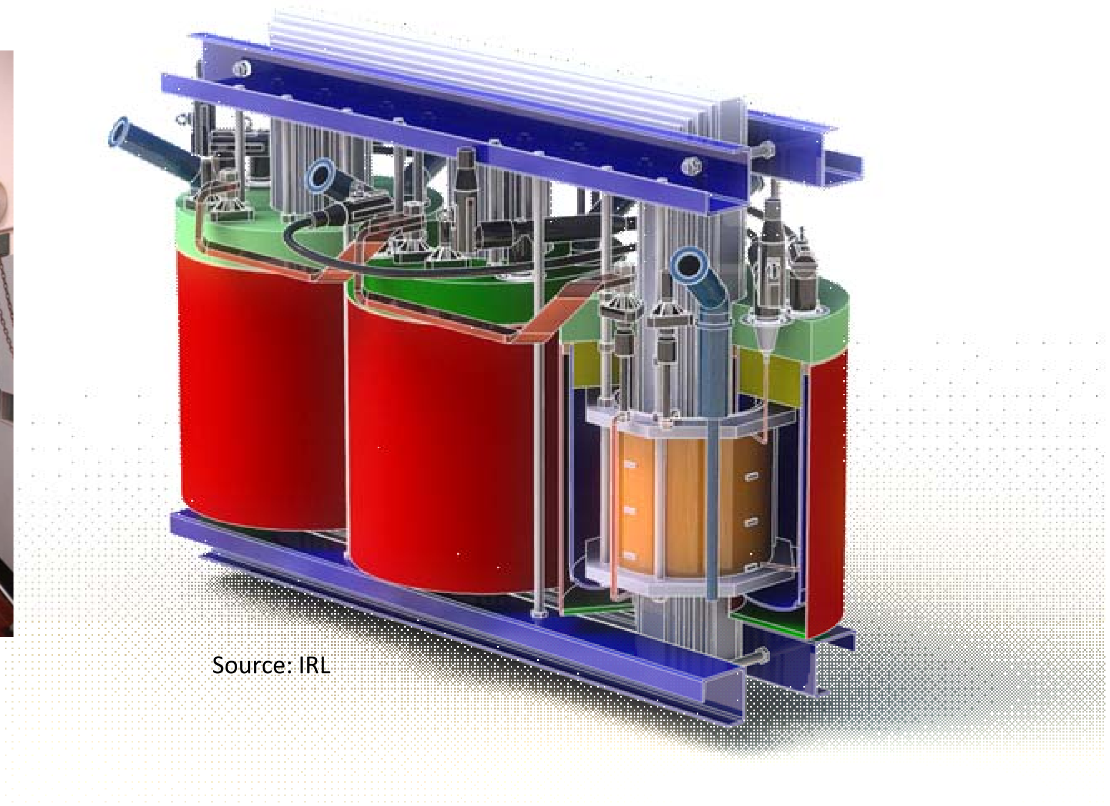
HV Winding



4 mm wide YBCO
I/I_c ~ 25%
Polyimide wrap insulation
24 double pancakes

LV Winding

YBCO Roebel Cable
L = 20 m
15 strands
5 mm width
I_c ~ 1400 A @ 77 K, sf



Source: IRL

First HTS Roebel wire in field test!

Superconducting Transformers
400 kVA Demonstrator

Project Partners: Kyushu Electric Power, Kyushu University

Objective: Develop 20 MVA transformer using YBCO

Data of 400 kVA demonstrator tested in 2010

Parameter	Value
Primary Voltage	6.9 KV
Secondary Voltage	2.3 kV
Op. Temp.	LN_2 at -207° C
Target Rating	400 kVA
LV Rated Current	174 A
HV Rated Current	58 A

Source: Superconductivity WEB21, Winter 2011, January 17 2011

D=565 mm
H=810 mm

D=738 mm
H=2300 mm

Superconducting Transformers at KIT

Test experience of recovery under load after fault limitation

Data:

S_N = 60 kVA

U_p = 1000 V

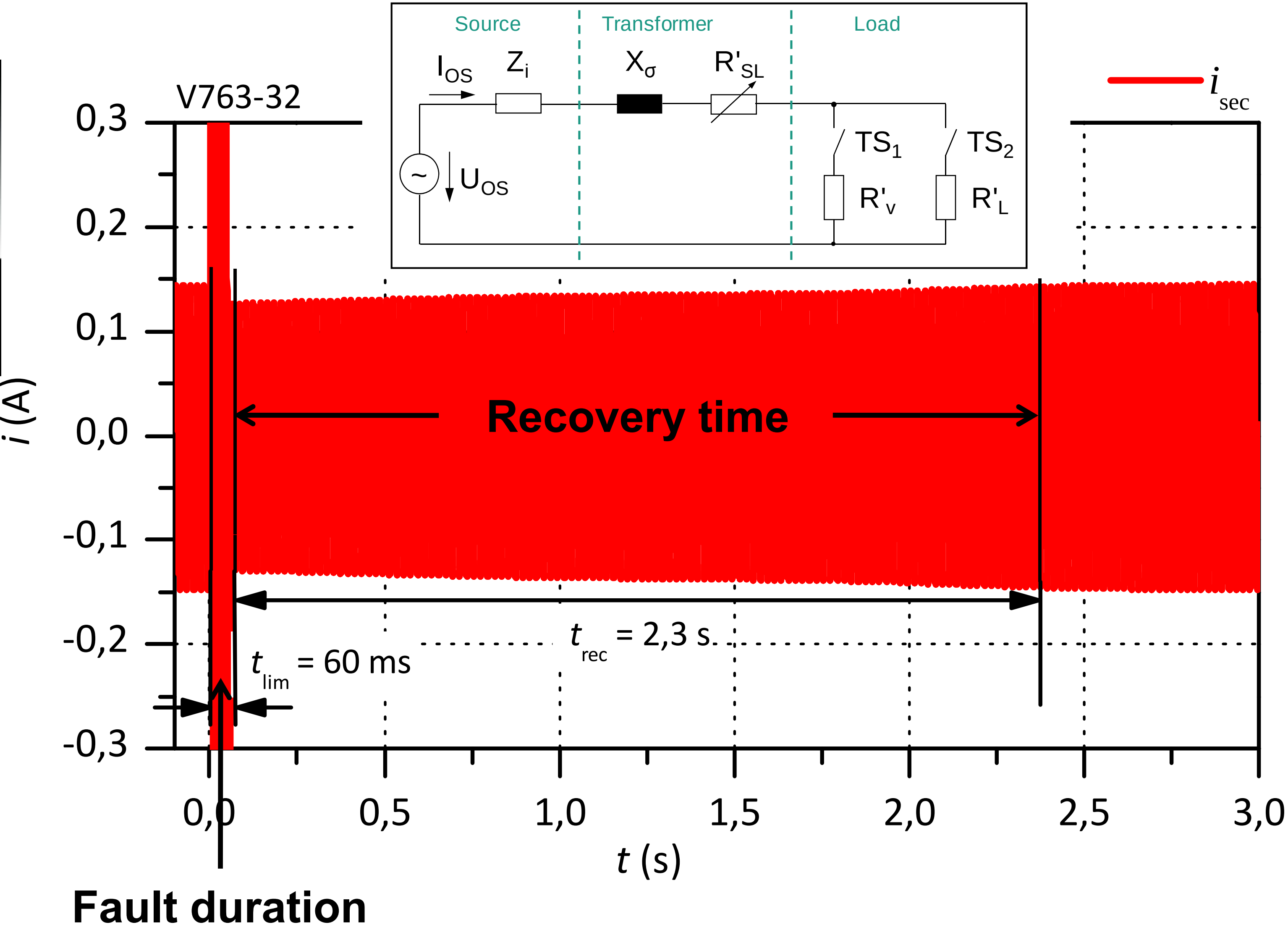
I_p = 60 A

u_k = 1,58 %

12 mm YBCO tape

48 m

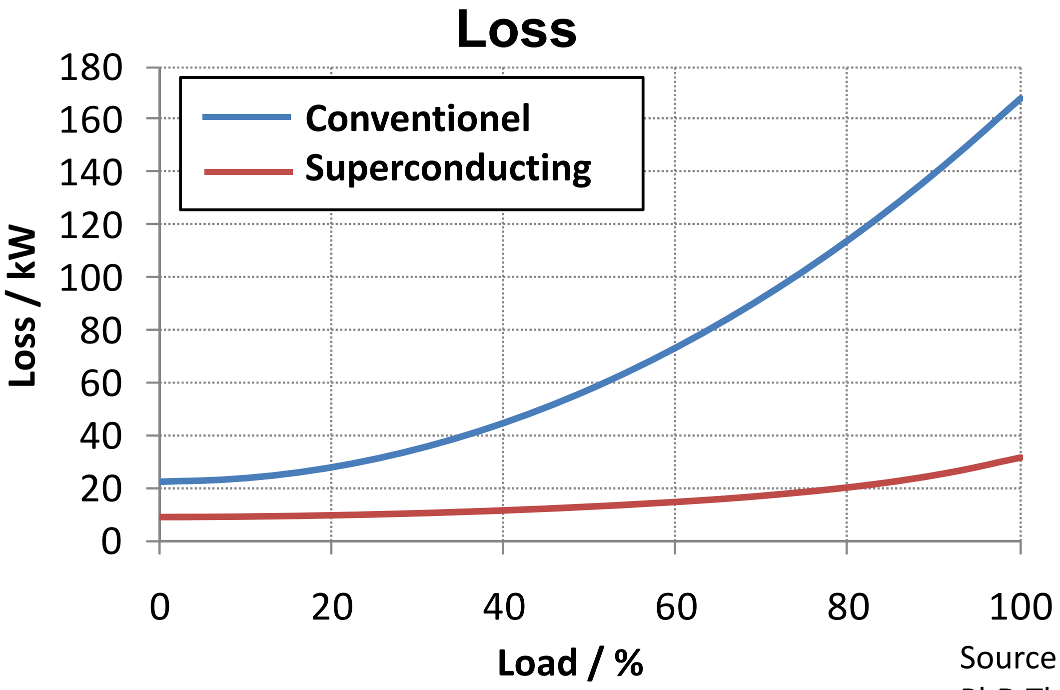
I_c= 272 A (77K, sf)

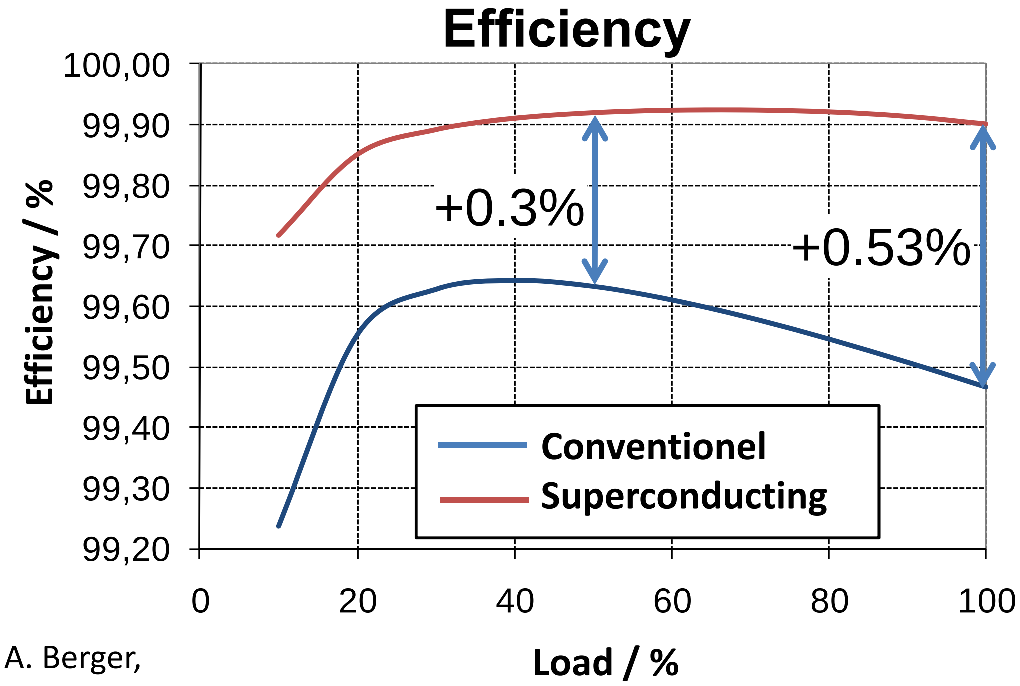


Full recovery under nominal load was demonstrated with 2G HTS wire!

Superconducting Transformers

Energy Efficiency (Example 31,5 MVA Transformer)





Source: A. Berger,
PhD Thesis to be published 2010
KIT Scientific Publishing

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 TWh1).
- 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

High Temperature Superconductor Power Applications

Motivation

Conventional Power System Equipment

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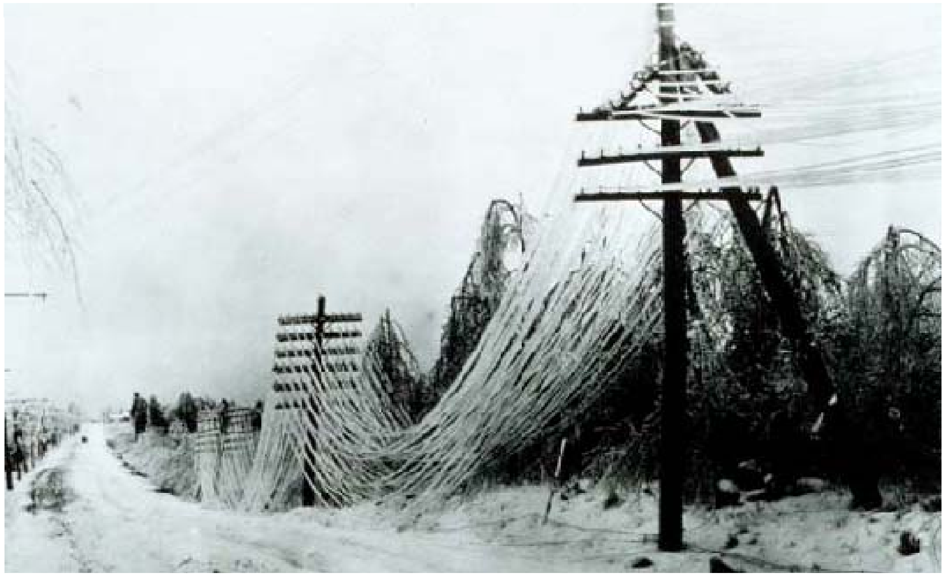
New Power System Equipment

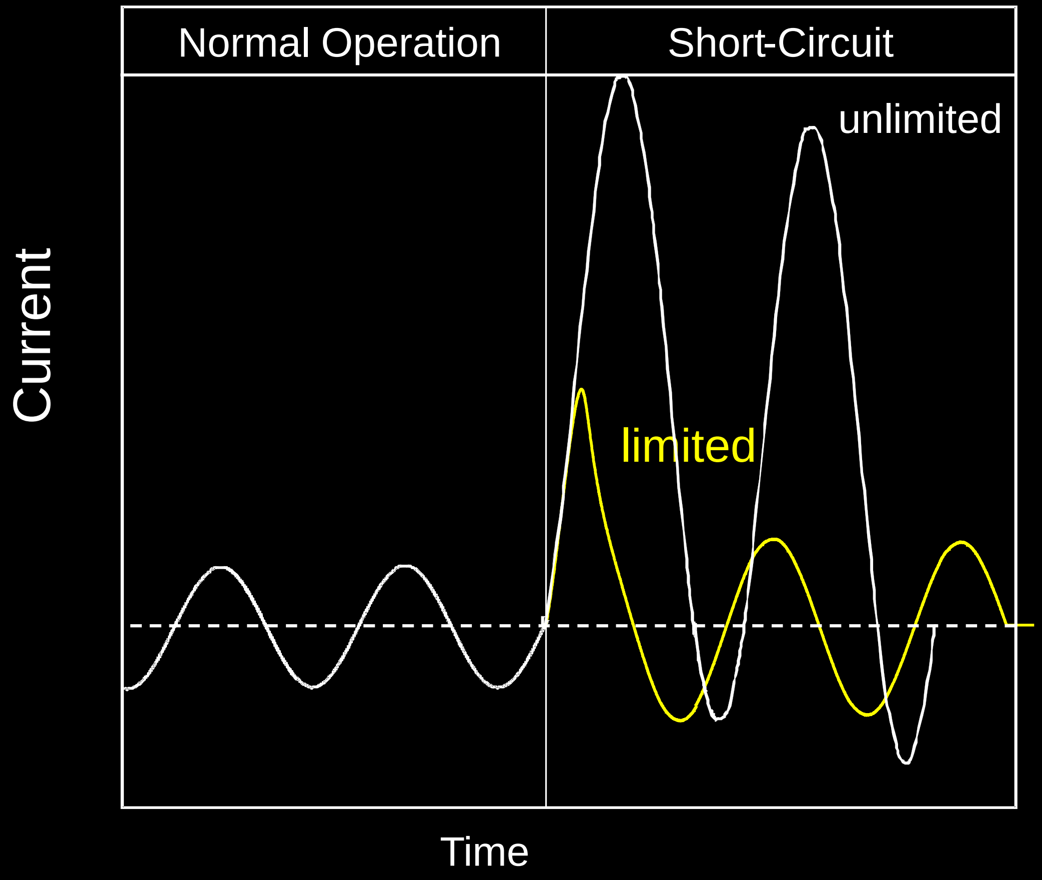
- Current Limiters, SMES

Summary

Superconducting Fault Current Limiters

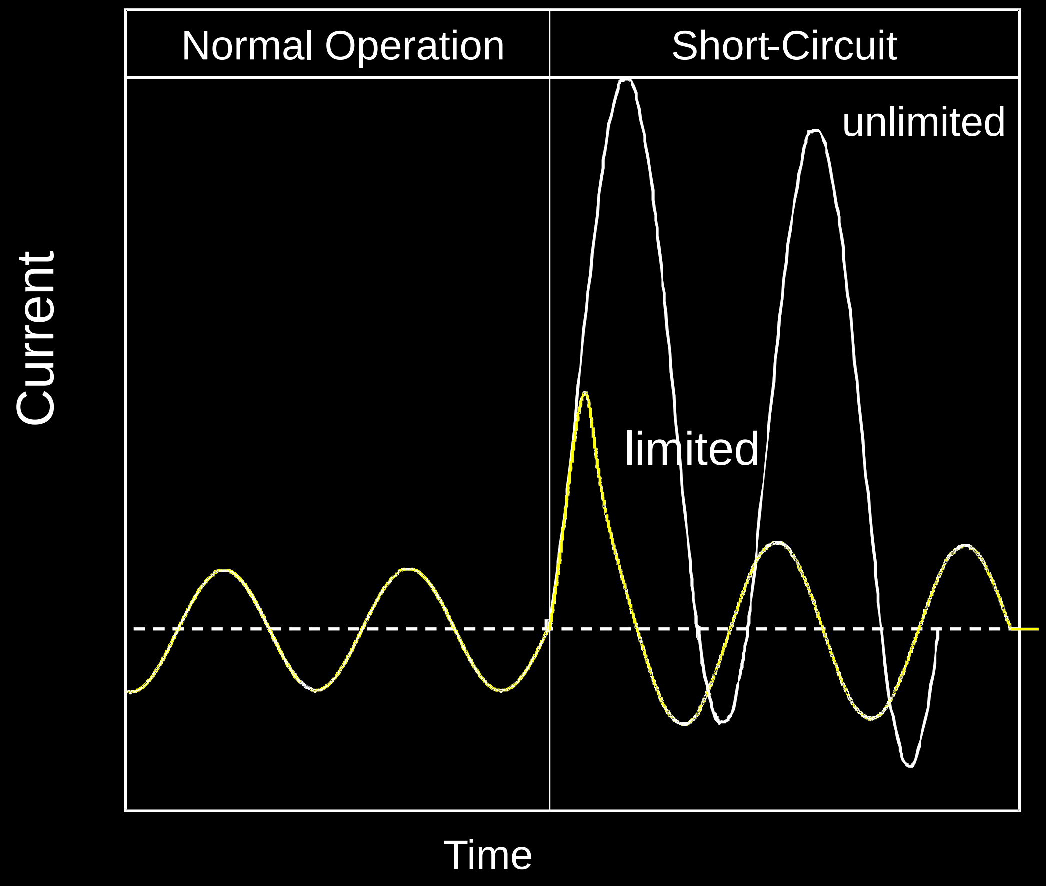


It is impossible to avoit short-circuits!



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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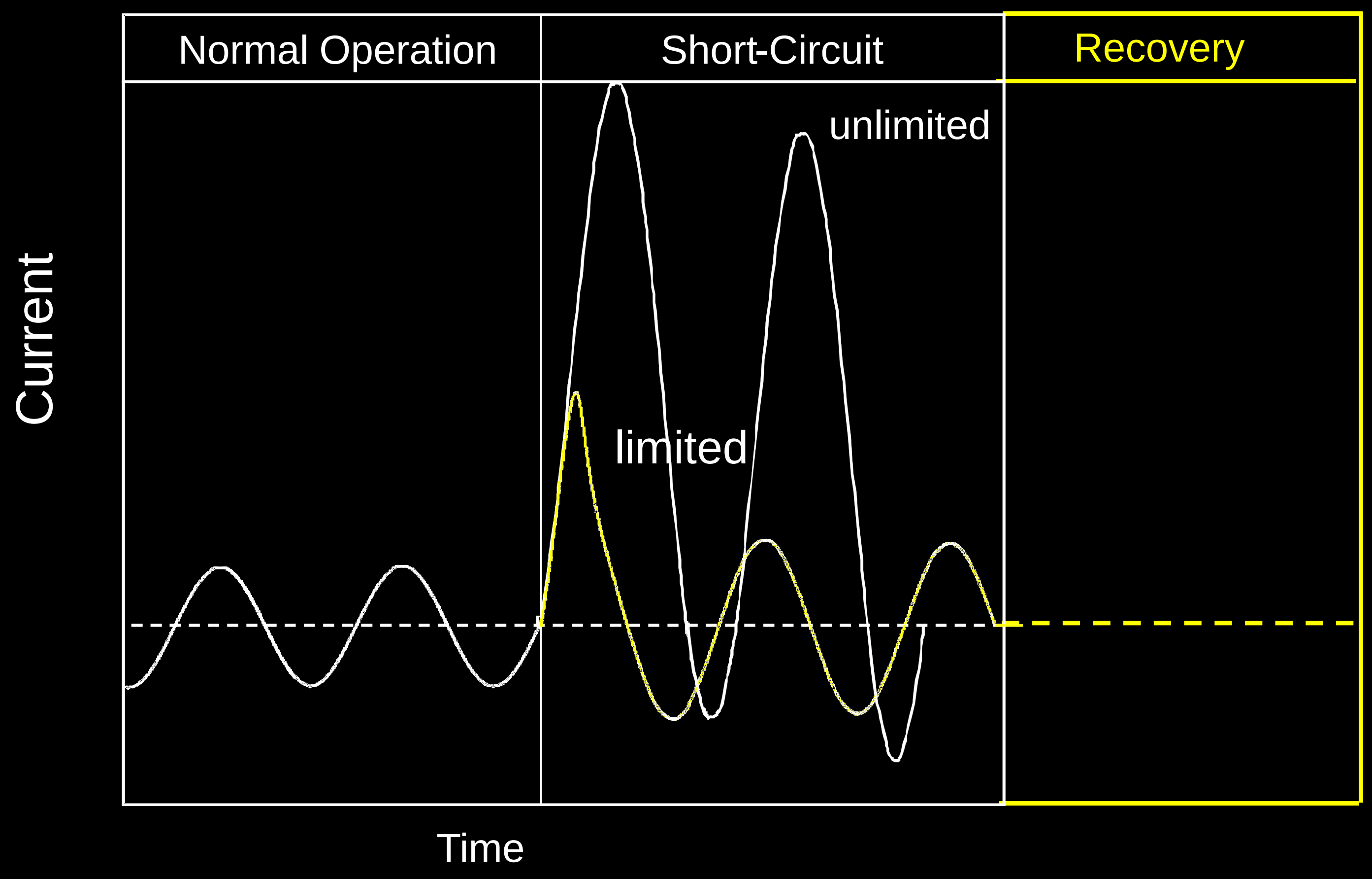
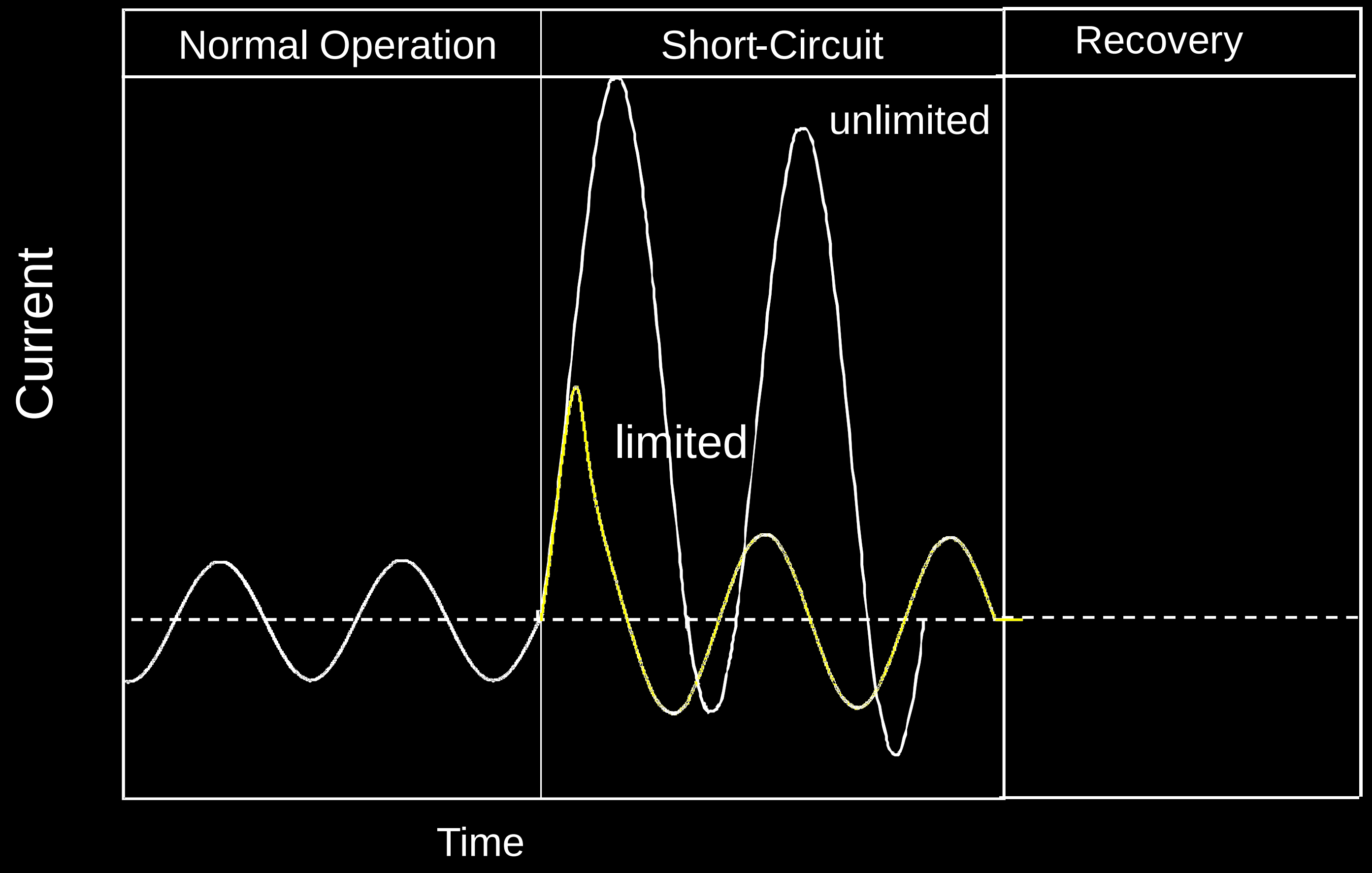


Ideal Fault Current Limiter

- 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

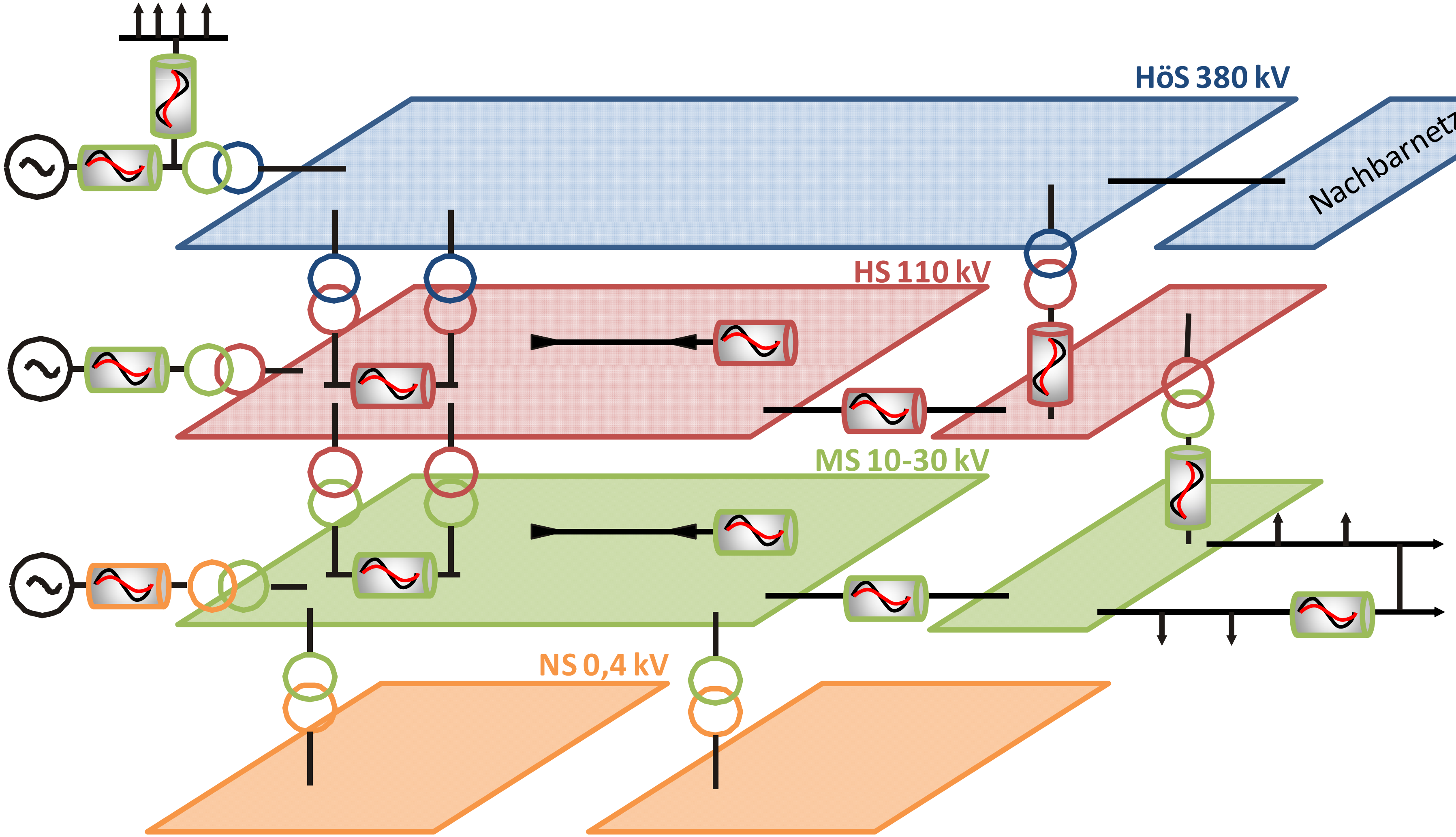
e.g. by coupling power systems

Reduce losses and CO_2 emissions

e.g. equal load distribution with parallel transformers

Superconducting Fault Current Limiters

Applications



There are many applications for SCFCLs at different voltage levels.

Superconducting Fault Current Limiters
State-of-the-Art

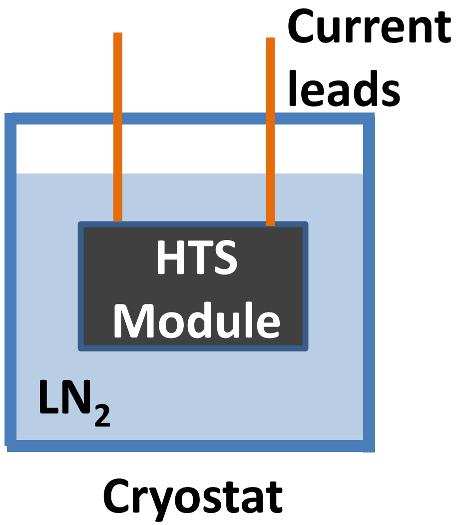
1) Year of test
2) 3-Ph. : Phase-phase voltage
   1-Ph. : Phase-ground voltage

Lead Company	Country/Year 1)	Type	Data 2)	Phase	Superconductor
ACCEL/NexansSC	D / 2004	Resistive	12 kV, 600 A	3-ph.✓	Bi 2212 bulk
CAS	China / 2005	Diode bridge	10.5 kV, 1.5 kA	3-ph.✓	Bi 2223 tape
CESI RICERCA	Italy / 2005	Resistive	3.2 kV, 220 A	3-ph.	Bi 2223 tape
Siemens / AMSC	D / USA / 2007	Resistive	7.5 kV, 300 A	1-ph.	YBCO tape
LSIS	Korea / 2007	Hybrid	24 kV, 630A	3-ph.	YBCO tape
Hyundai / AMSC	Korea / 2007	Resistive	13.2 kV, 630 A	1-ph.	YBCO tape
KEPRI	Korea / 2007	Res.-hybrid	22.9 kV, 630 A	3-ph.	Bi 2212 bulk
Innopower	China / 2008	DC biased iron core	35 kV, 90 MVA	3-ph.✓	Bi 2223 tape
Toshiba	Japan / 2008	Resistive	6.6 kV, 72 A	3-ph.✓	YBCO tape
Nexans SC	D / 2009	Resistive	12 kV, 100 A	3-ph.✓	Bi 2212 bulk
Zenergy Power	USA / 2009	DC biased iron core	12 kV, 1.2 kA	3-ph.✓	Bi 2223 tape
Zenergy Power	USA / 2010	DC biased iron core	12 kV, 1.2 kA	3-ph.✓	Bi 2223 tape
Nexans SC	D / 2009	Resistive	12 kV, 800 A	3-ph.✓	Bi 2212 bulk
Nexans SC	D / 2011	Resistive	12 kV, 800 A	3-ph.✓	YBCO tape
Innopower	China / 2010	DC biased iron core	220 kV,300 MVA	3-ph.✓	Bi 2223 tape
ERSE	I / 2010	Resistive	9 kV, 250 A	3-ph.✓	Bi 2223 tape
ERSE	I / 2010	Resistive	9 kV, 1 kA	3-ph.✓	YBCO tape
KEPRI	Korea / 2010	Resistive	22.9 kV, 3 kA	3-ph.✓	YBCO tape
AMSC / Siemens	USA / D / 2012	Resistive	66 kV, 1.2 kA	1-ph.	YBCO tape
Innopower	China / 2012	DC biased iron core	220 kV, 800 A	3-ph. ✓	Bi 2223 tape
Nexans SC	EU / 2012	Resistive	24 kV, 1005 A	3-ph. ✓	YBCO tape

Superconducting Fault Current Limiters

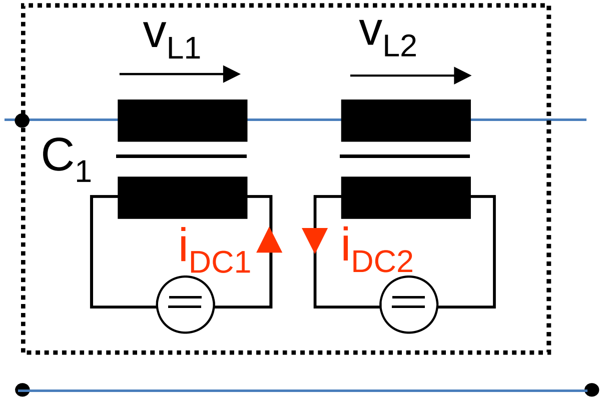
Different types

Resistive type



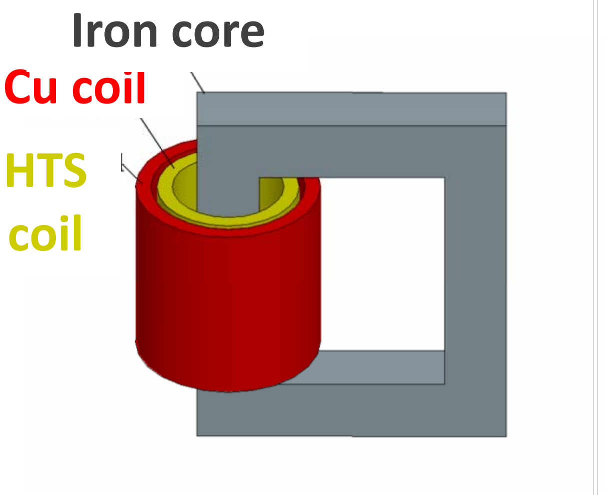
- ☺ Simple concept
- ☺ fail safe
- ☺ compact, low weight
- ☹ Current leads to low temp.

DC biased iron core „saturated iron core“



- ☺ no SC quench
- ☺ immediate recovery
- ☺ adjustable trigger current
- ☹ High volume and weight
- ☹ High impedance at normal op.

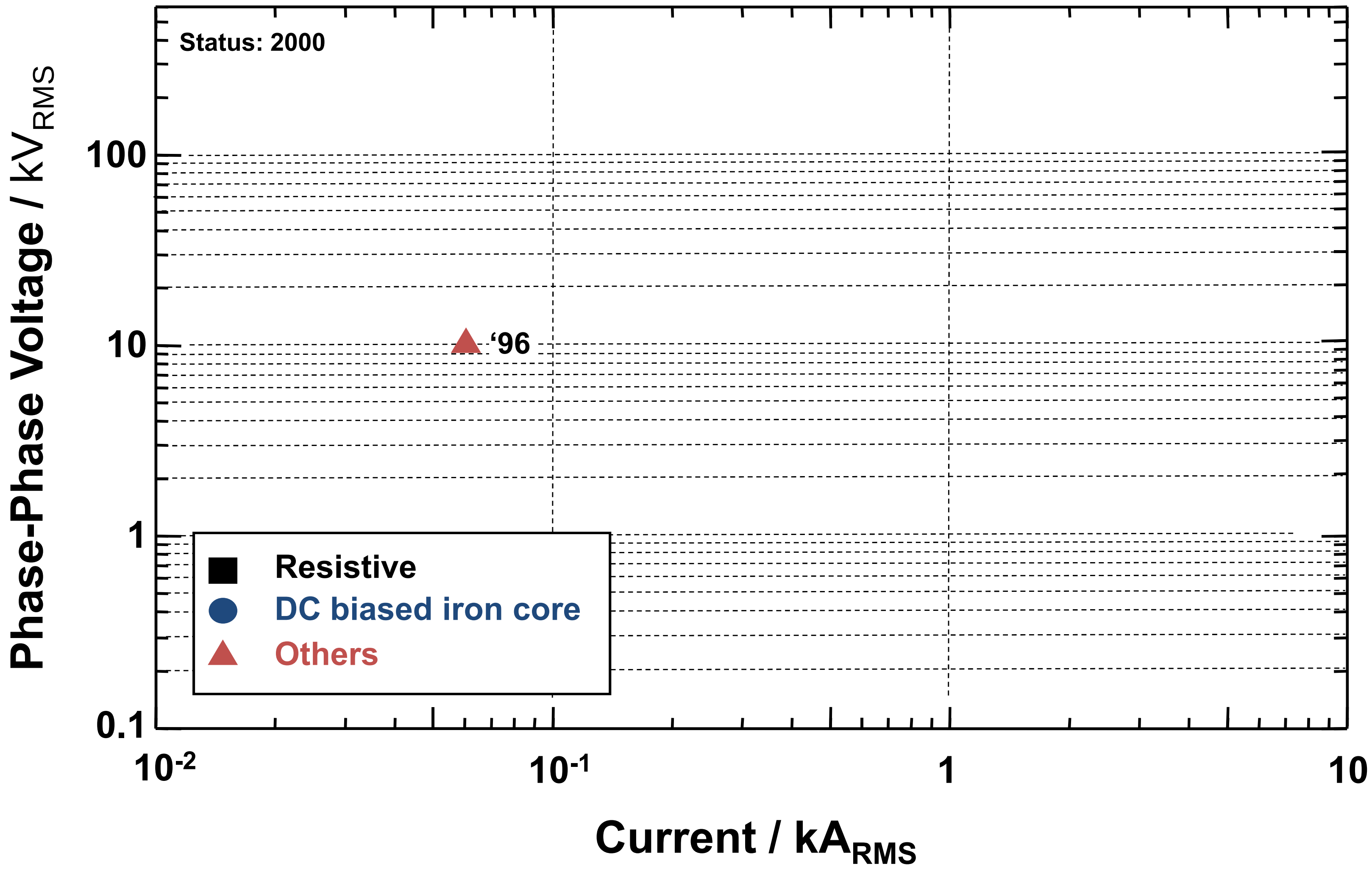
Shielded iron core „Inductive“



- ☺ No current leads to low temp.
- ☺ Fail safe
- ☹ High volume
- ☹ High weight

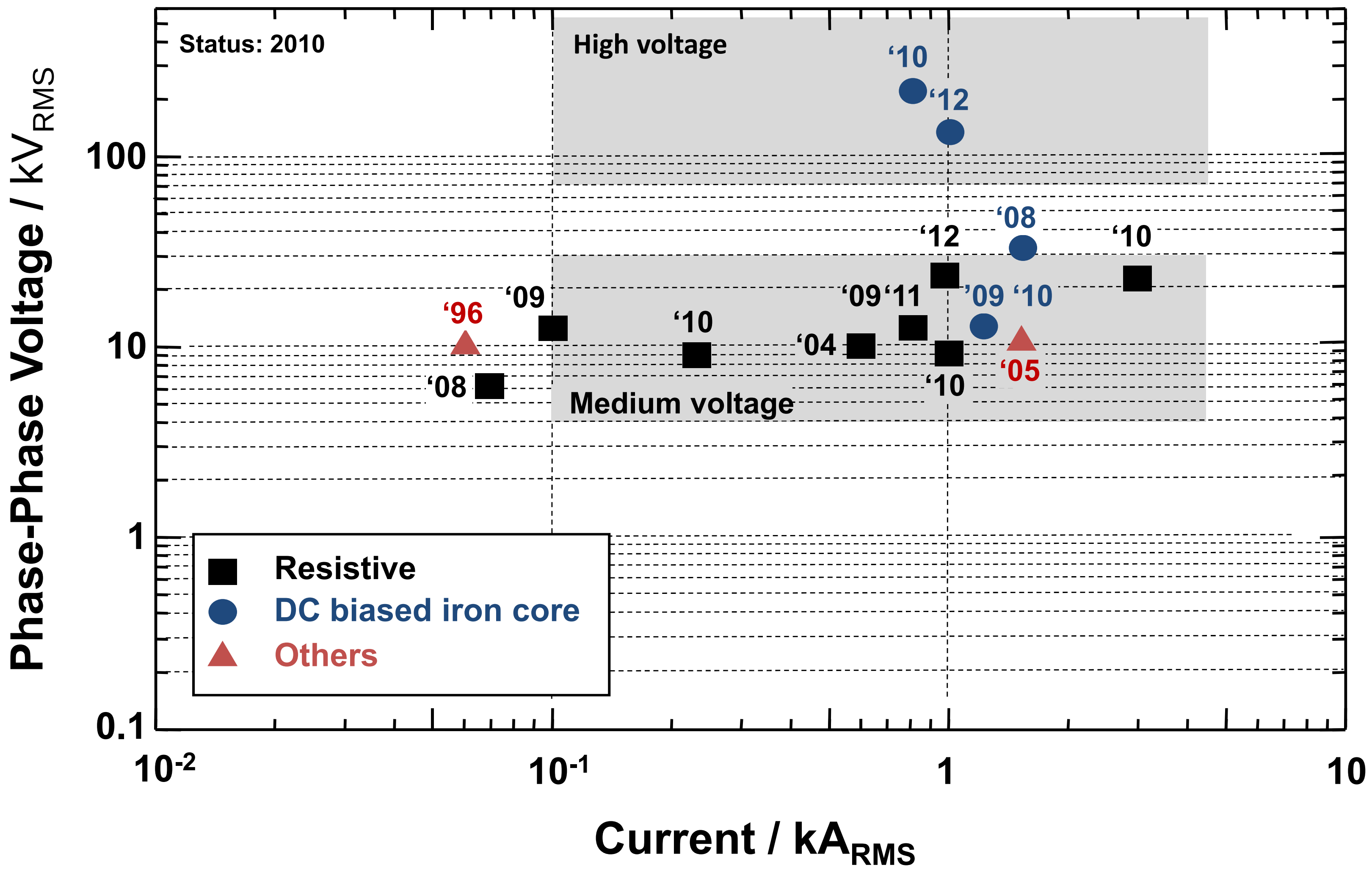
Superconducting Fault Current Limiters

Successful SCFCL Field Tests until 2000



Superconducting Fault Current Limiters

Successful and planned SCFCL Field Tests - Status 2010



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

Superconducting Fault Current Limiters
220 kV, 800 A DC biased iron core

Loose coupling, hexagonal

In grid operation since 2012

A design and manufacturing for a 500 kV prototype is ongoing.

Superconducting Fault Current Limiters

Resistive Type SCFCL Nexans

Commercial Projects

Bi 2212 bulk

12 kV, 100 A
Bi 2212 bulk

10/2009

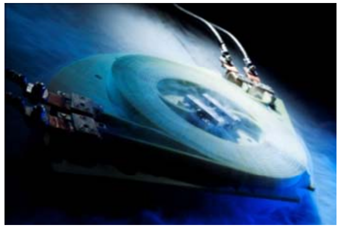
12 kV, 800 A
Bi 2212 bulk

11/2009

12 kV, 400 A
Bi 2212 bulk

2011

YBCO tapes



10 kV, 600 A
YBCO tapes

10/2011

20 kV, 1 kA
YBCO tapes

www.eccoflow.org

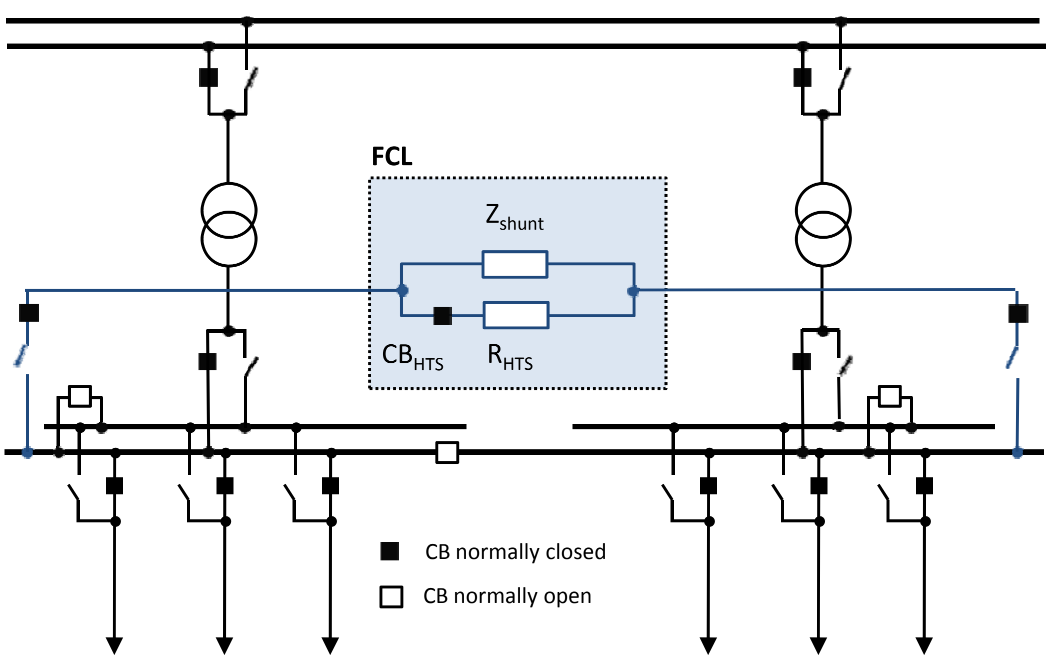
2012

10 kV, 2.3 kA
YBCO tapes

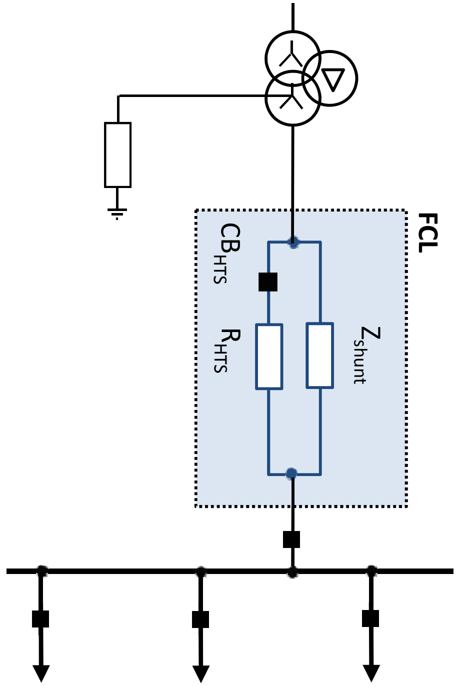
2013

Superconducting Fault Current Limiters
Application Example (FP7 Project Eccoflow: www.eccoflow.org)

Busbar Coupling



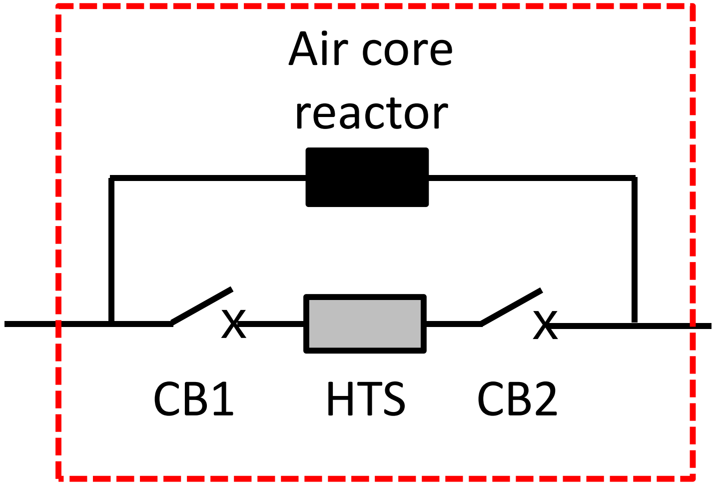
Transformer Feeder



Unique features of Eccoflow (1005A,24kV):

- One resistive SCFCL design fits two different applications
- Two field tests with the same FCL will be performed in different applications
- Five utilities participate in this project
- A permanent installation is planned

Superconducting Fault Current Limiters
Application Example (FP7 Project Eccoflow: www.eccoflow.org)



SFCL System

Arrangement

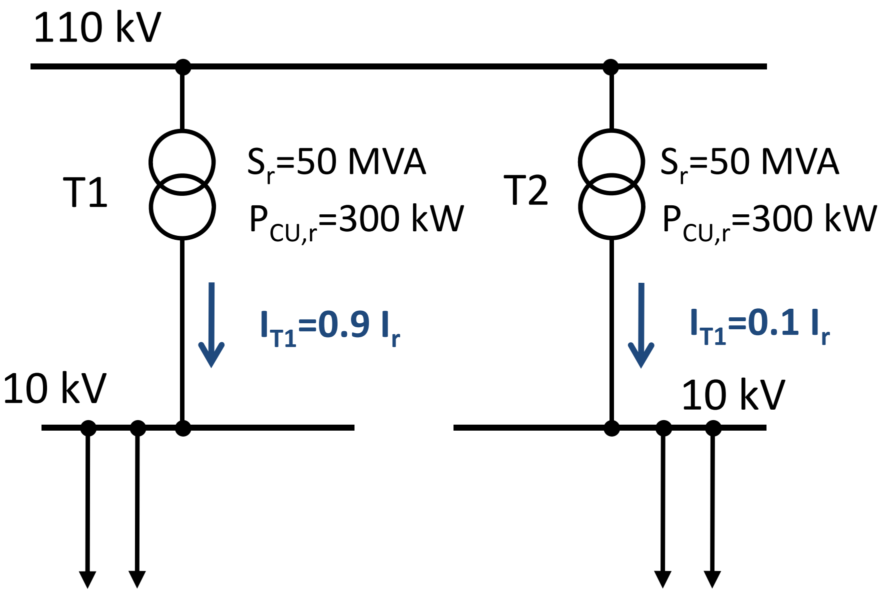
- Container with HTS-SFCL
- Standard MV Switchgear
- Air core reactors

First Field Installation in early 2013 at Endesa Grid in Majorca

Source: J. Schramm et. al. „Design and Production of the ECCOFLOW resistive Superconducting Fault Current Limiter “, ASC Conference 2012, Portland USA

Superconducting Fault Current Limiters

Impact of Energy Efficiency of SCFCLs



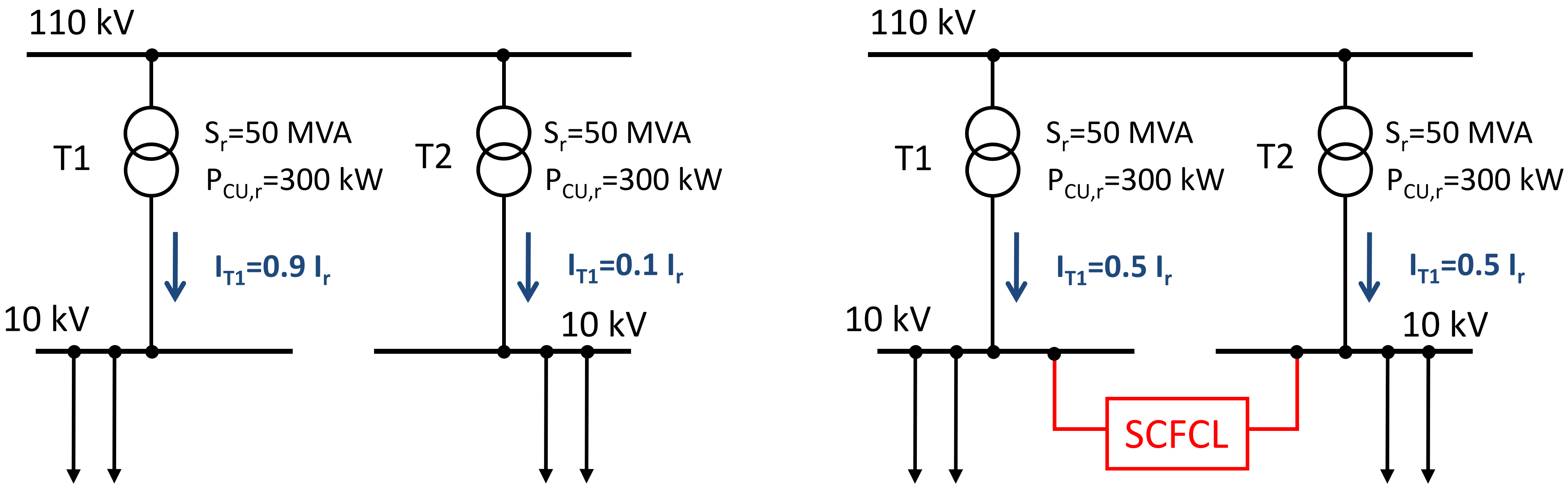
Type	**Without SCFCL**
Loss T1	243 kW
Loss T2	3 kW
Total Loss	246 kW
Energy loss /a	2154 MWh
CO_2 emission [1) /a]	1120.6 to

Source: Karl-Heinz Hartung, CIGRE WG A3.23

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

Superconducting Fault Current Limiters

Impact of Energy Efficiency of SCFCLs



Type	Without SCFCL	With SCFCL	Difference
Loss T1	243 kW	75 kW	**- 168 kW**
Loss T2	3 kW	75 kW	**+72 kW**
Total Loss	246 kW	150 kW	**- 96 kW**
Energy loss /a	2154 MWh	1314 MWh	**- 840 MWh**
CO_2 emission 1) /a	1120.6 to	683.2 to	**- 437.4 to**

Source: Karl-Heinz Hartung, CIGRE WG A3.23

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

Energy efficiency of SCFCLs has to be investigated on a case to case basis.

High Temperature Superconductor Power Applications

Motivation

Conventional Power System Equipment

- Cables, Rotating Machines, Transformers

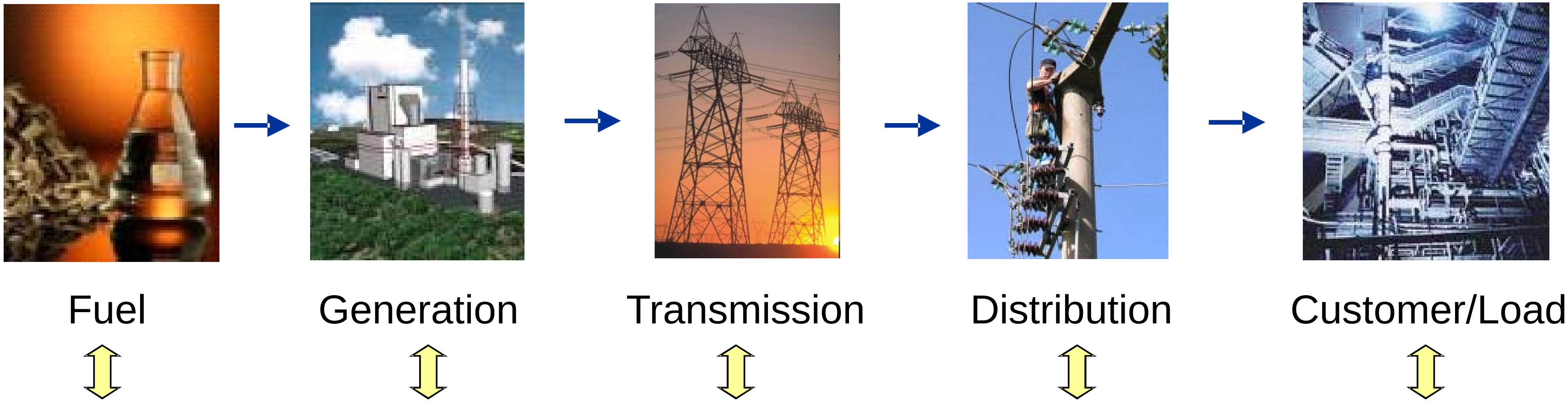
New Power System Equipment

- Current Limiters, SMES

Summary

Superconducting Magnetic Energy Storage

Motivation



Fuel → Generation → Transmission → Distribution → Customer/Load

Large scale **Energy Storage** **Small scale**

Store Renewables

Load Balance

Higher Utilization

Stability

Power Quality

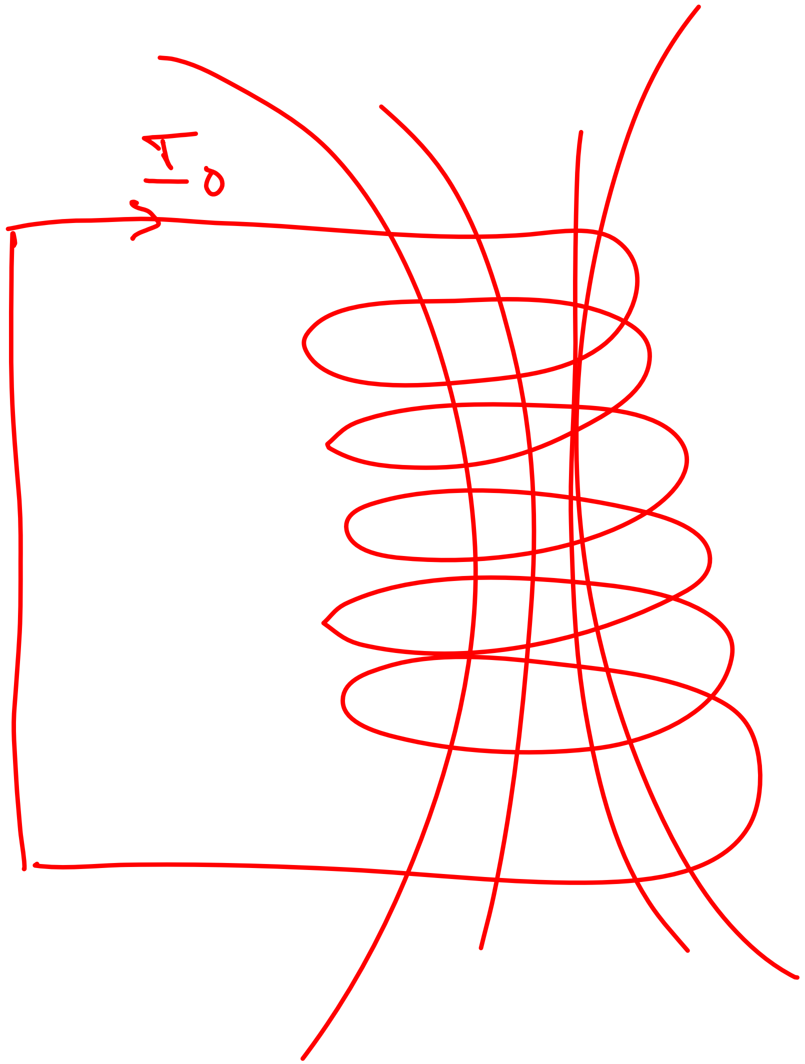
Benefits

Superconducting Magnetic Energy Storage
Benefits

- 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

Superconducting Magnetic Energy Storage

Concept



Stored Energy $$Q = \frac{1}{2} L\, I^2$$

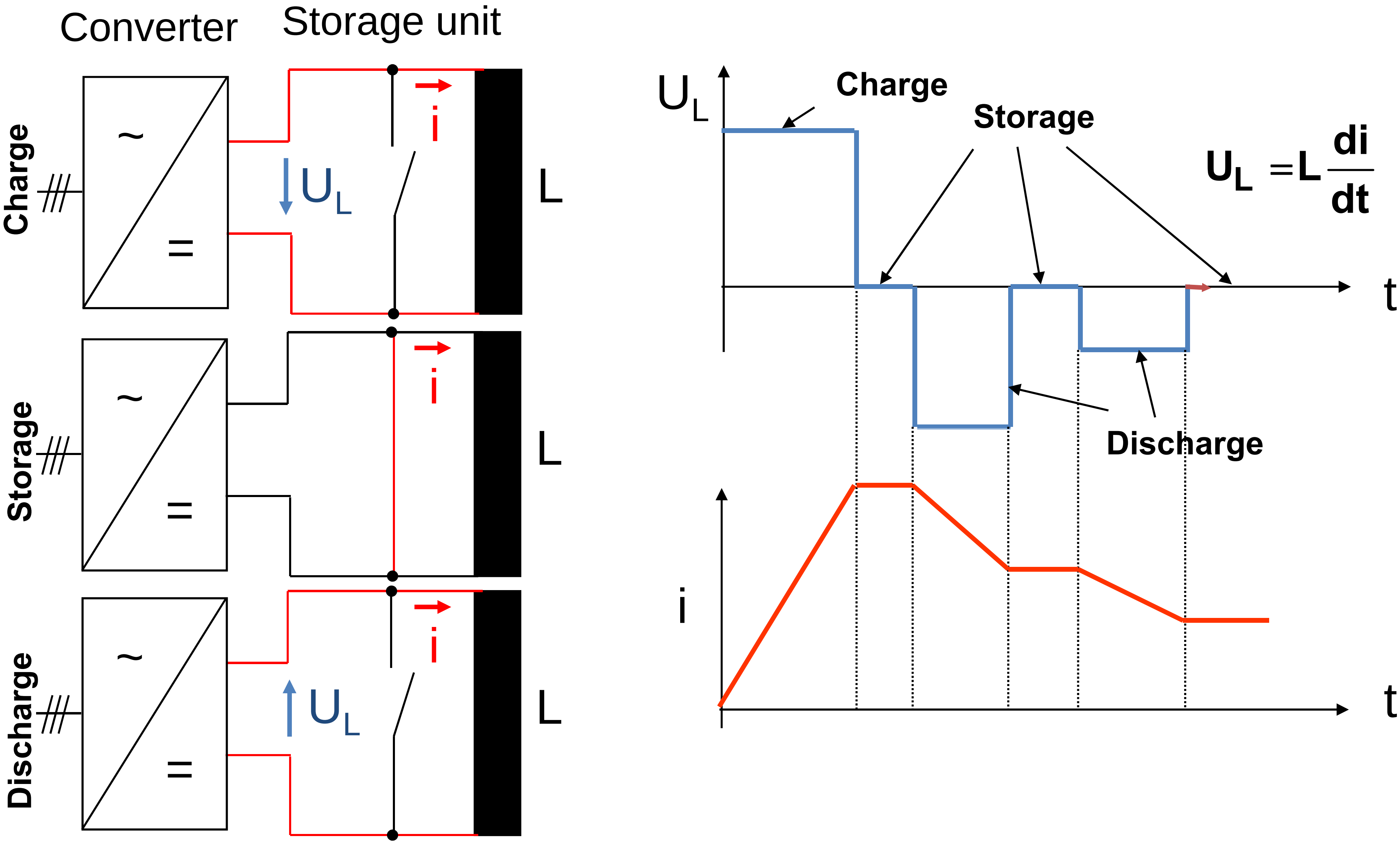
Power $$P = U_L\, I$$

SMES Energy density $$\frac{Q_{max}}{V} = \frac{B^2}{2\,\mu_0}$$

$5\,T \approx 2{,}7\ \frac{kWh}{m^3}$

Superconducting Magnetic Energy Storage

Concept



$$U_L = L \frac{di}{dt}$$

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

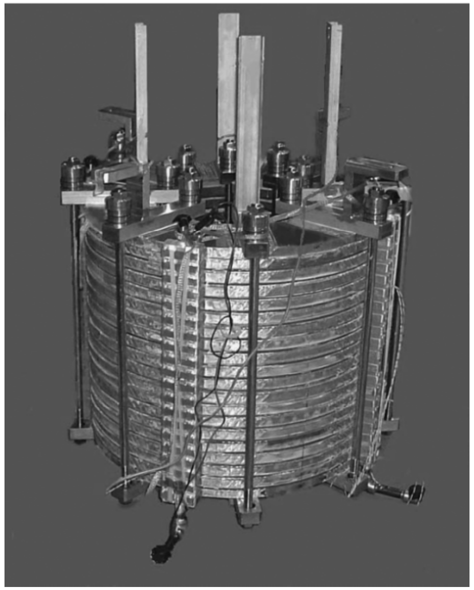


Figure: Chubu Electric

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

KERI, Korea
Power quality

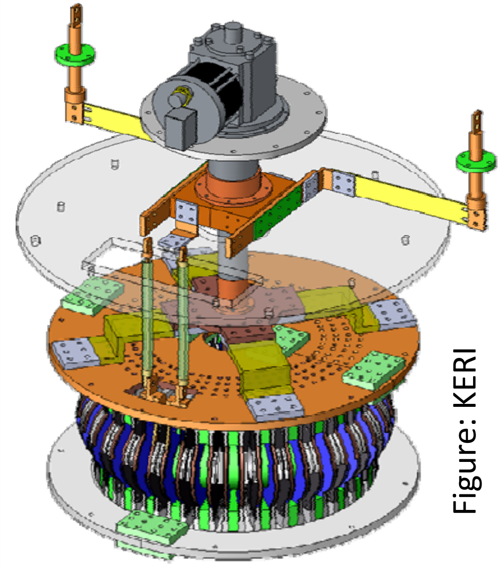


Figure: KERI

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

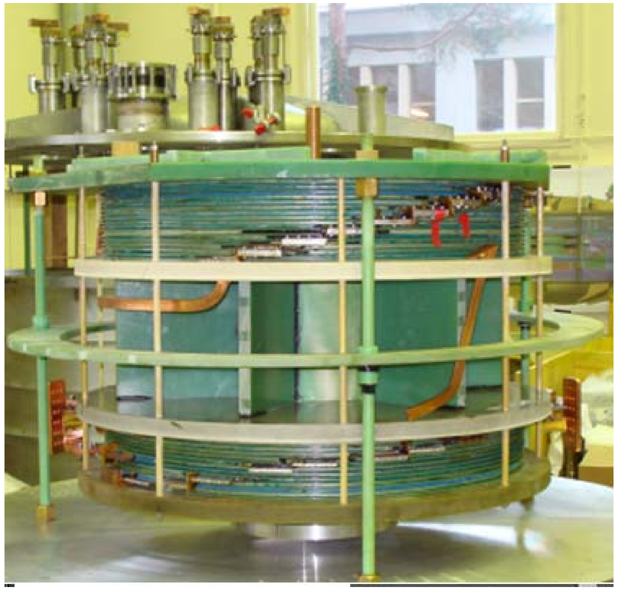


Figure: CNRS

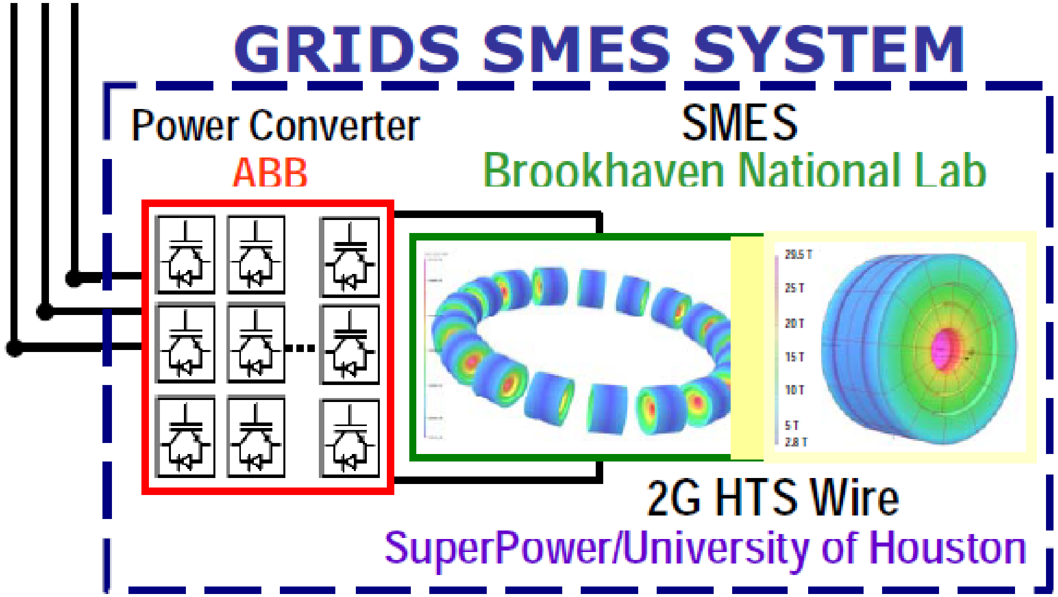
814 kJ
Bi 2212 tape
315 A
20 K conduction cooled
Diameter : 300/814 mm
Height: 222 mm

Superconducting Magnetic Energy Storage
25 T, 20 kW, 3 MJ HTS prototype (2010-2013)

Project Partners: SuperPower, ABB, Brookhaven National Lab., U Houston

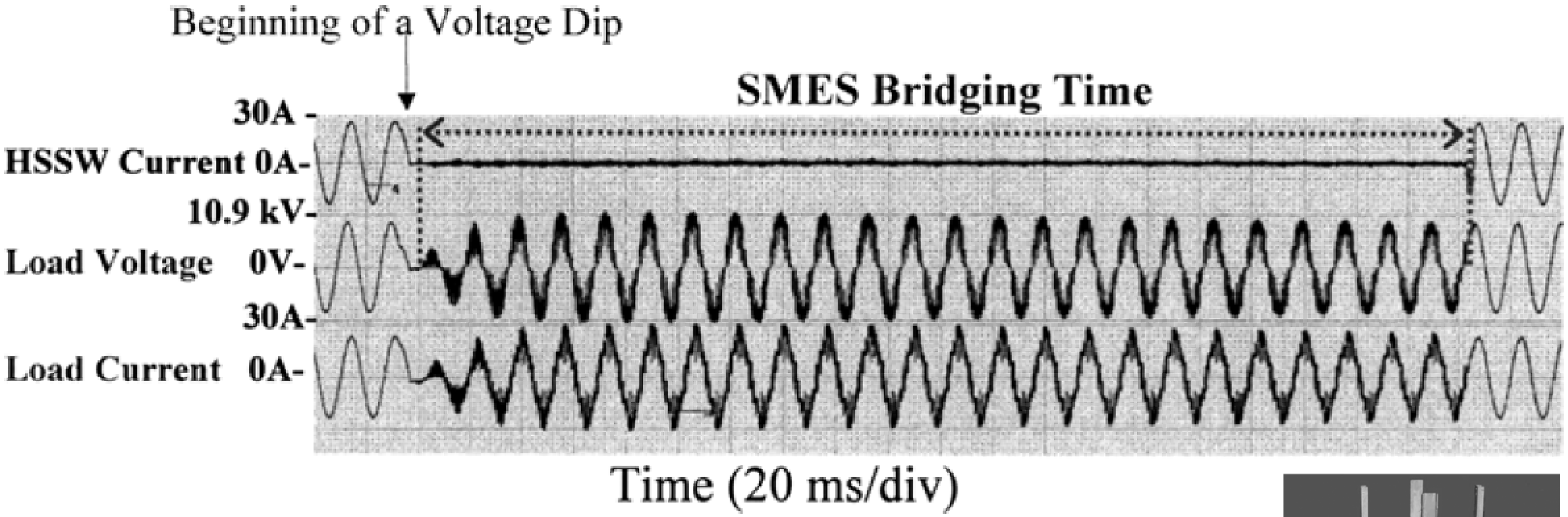
Objective: Develop and field test a HTS SMES for integrating renewables

Parameter	Value
Energy storage	3 MJ
Power	20 kW
Magnetic field	25 T
Superconductor	YBCO tape
Wire length	7 km
Tape width	12 mm
Minimum I_c	600 A

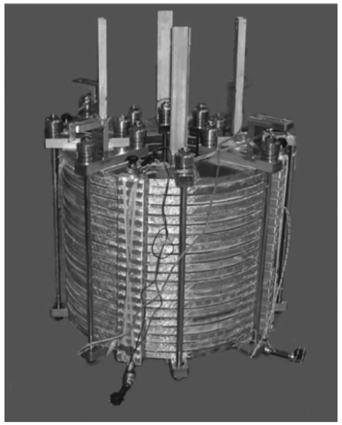


Source: Superconducting Magnetic Energy Storage (SMES) Systems for GRIDS
Qiang Li, Drew W. Hazelton, Venkat Selvamanickam, Presented by Traute Lehner,
Tenth EPRI Superconductivity Conference, Tallahassee, FL, Oct. 12, 2011

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.

High Temperature Superconductor Power Applications

Motivation

Conventional Power System Equipment

- Cables, Rotating Machines, Transformers

New Power System Equipment

- Current Limiters, SMES

Summary

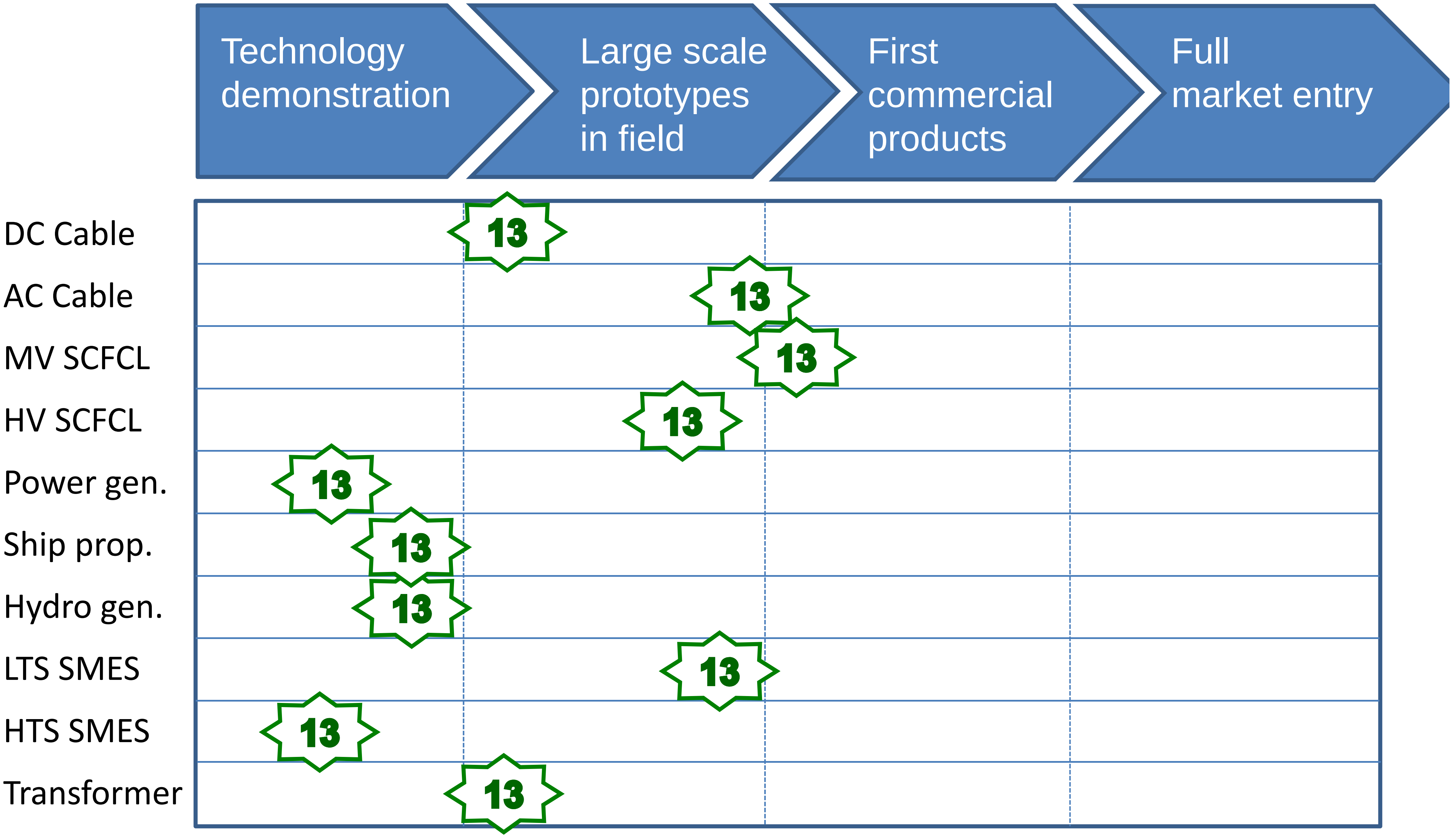
Conclusions

- HTS cables and SCFCL are very close to commercialization.
- HTS transformers, SMES and rotating machines will enter the market in the next decade.

HTS Material Research Directions for Power Applications

- Higher production (Today a few 100 km/a for 2G)
- Lower cost (Less than 10 €/kA m)
- Stability of 2G wire
- Higher critical currents in low and high magnetic fields

Status of HTS Power Applications



Technology demonstration

Large scale prototypes in field

First commercial products

Full market entry

DC Cable

AC Cable

MV SCFCL

HV SCFCL

Power gen.

Ship prop.

Hydro gen.

LTS SMES

HTS SMES

Transformer