Karlsruher Institut für Technologie

Superconducting Transformers

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Institute for Technical Physics
EASITrain Summer School, September 3rd-7th 2018, Vienna

KIT-ENERGY CENTRE

Motivation of Superconducting Transformers

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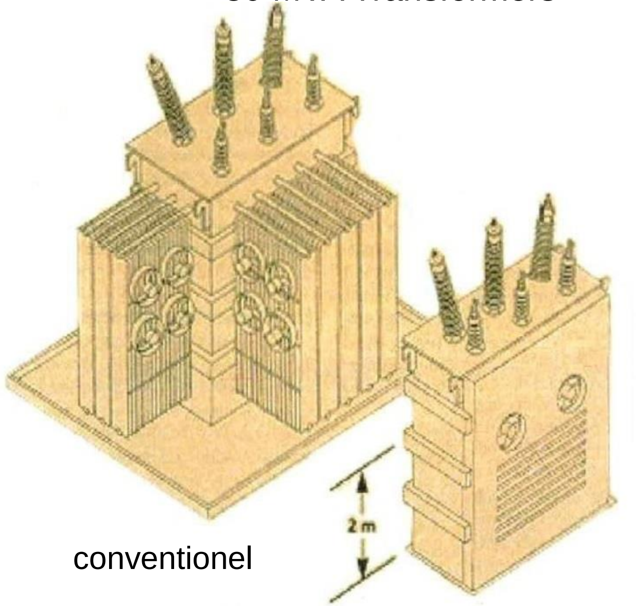
- Motivation
- Different Types
- A few Basics
- State-of-the-Art
- Applications
- Summary

Motivation of Superconducting Transformers

Manufacturing and transport

- Compact and lightweight (~50 % Reduction)

30 MVA Transformers



conventionel

superconducting

©Waukesha

Motivation of Superconducting Transformers

Manufacturing and transport

- Compact and lightweight (~50 % Reduction)

Environment and Marketing

- Energy savings (~50 % Reduction)
- Ressource savings

Conventionel 400 MVA Transformer

Motivation of Superconducting Transformers

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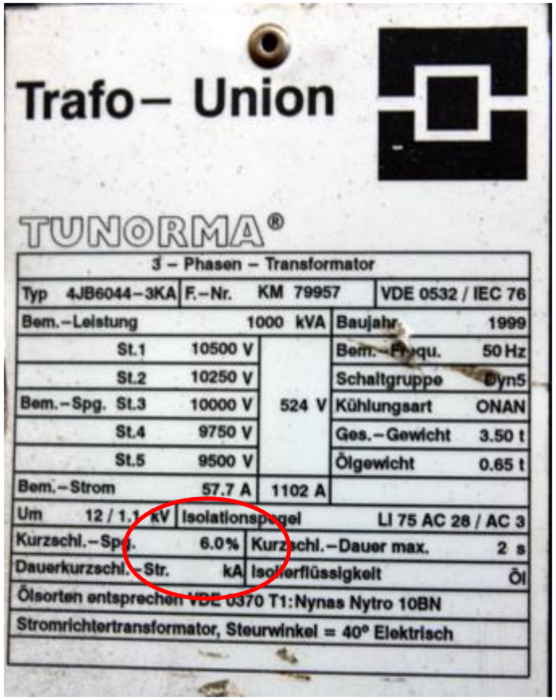
Operation

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



Motivation of Superconducting Transformers

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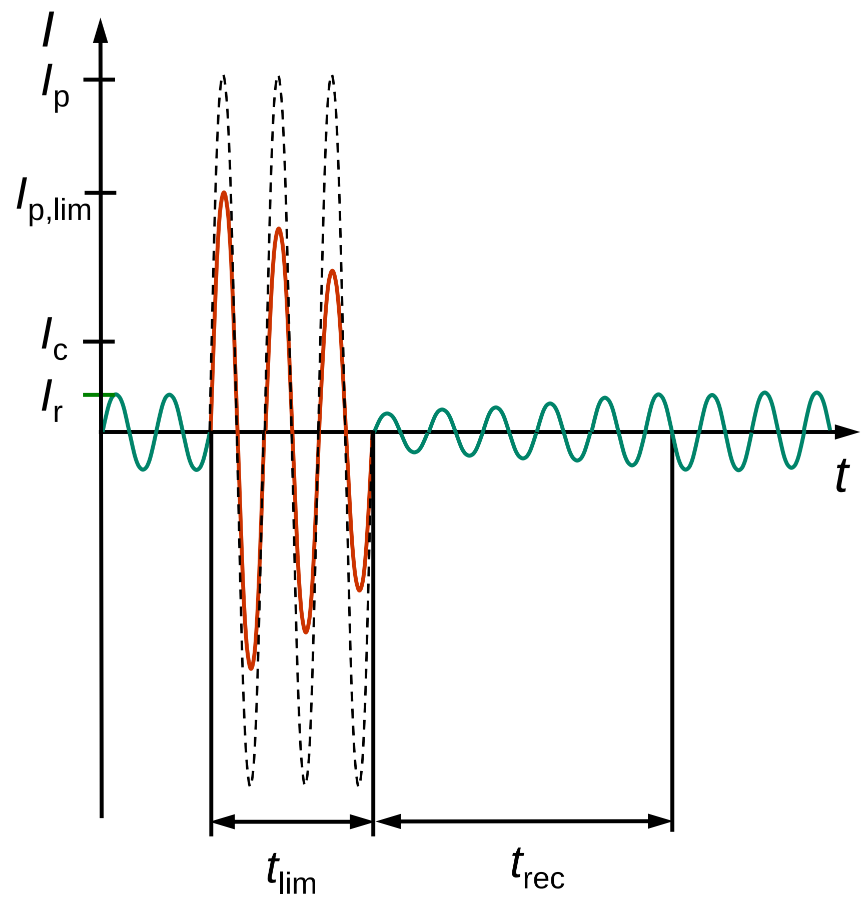

Enables a new class of transformers

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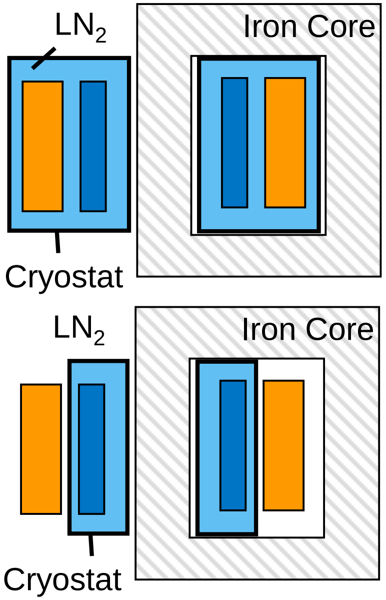
Different Types of Superconducting Transformers

Warm Iron Core



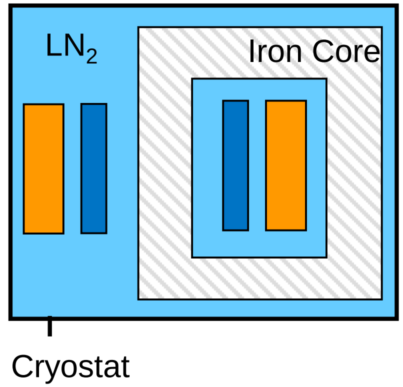
☺ Low Cooling Power

☺ Iron at Room Temperature

☹ Expensive Cryostat

☹ 3 Cryostats needed

Cold Iron Core

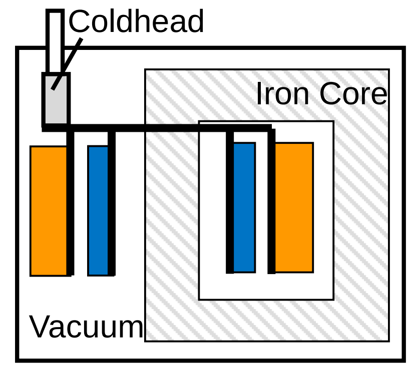


☺ Simple Cryostat

☺ 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

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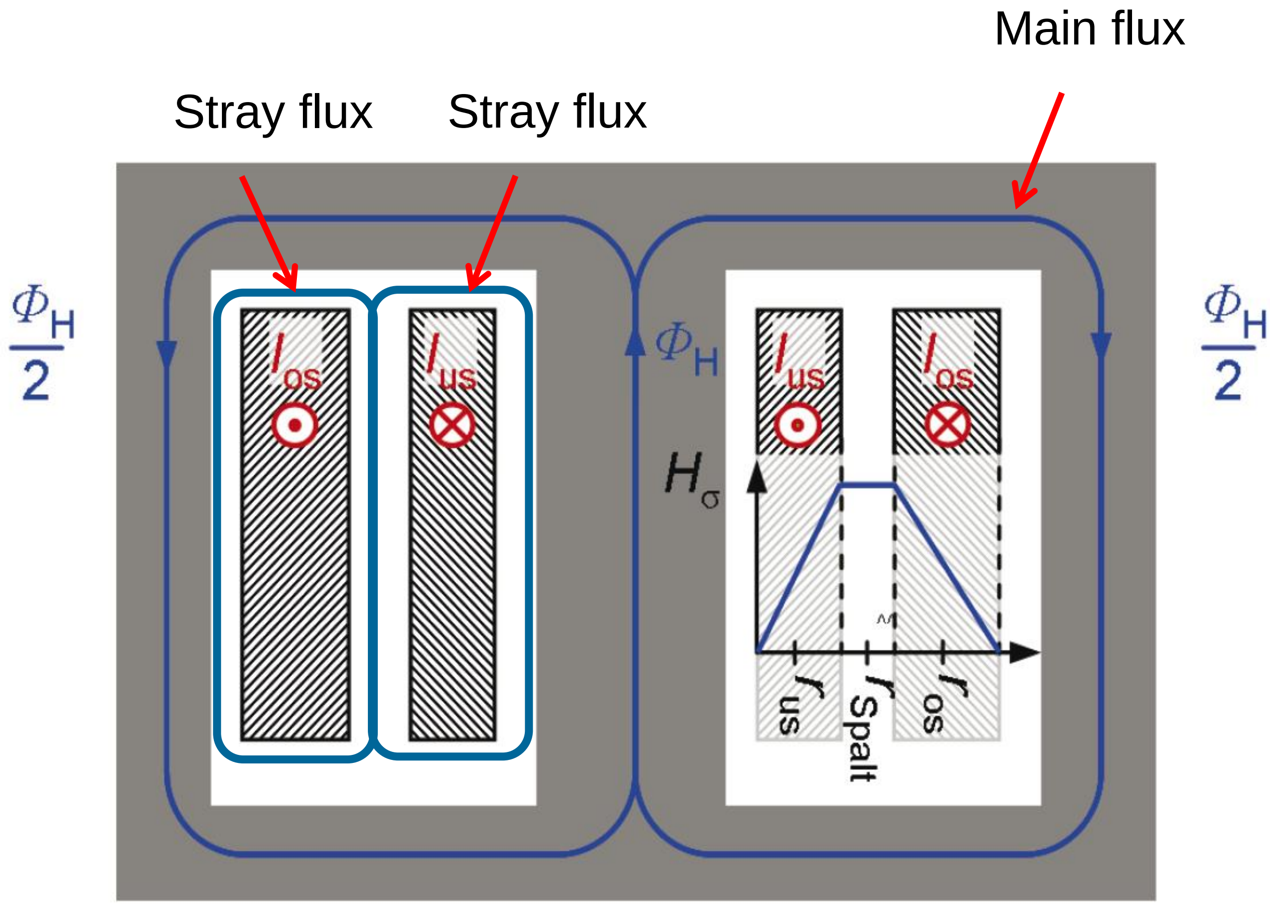
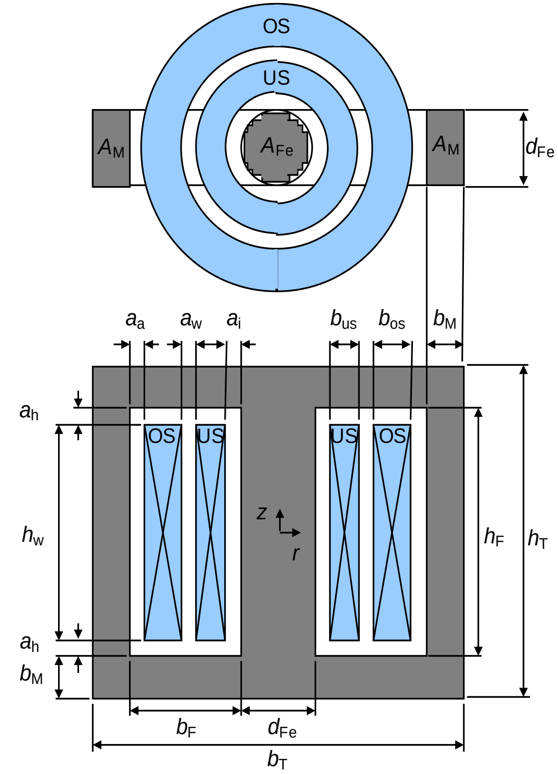
Transformer Flux Linkage



Transformer Inductances

Main Inductance

$$L_{\mathrm{H}} = \mu_0 \cdot \mu_{\mathrm{r}} \cdot w_{\mathrm{os}}^{2} \cdot \frac{A_{\mathrm{Fe,eff}}}{\ell_{\mathrm{Fe}}}$$



Stray Inductance

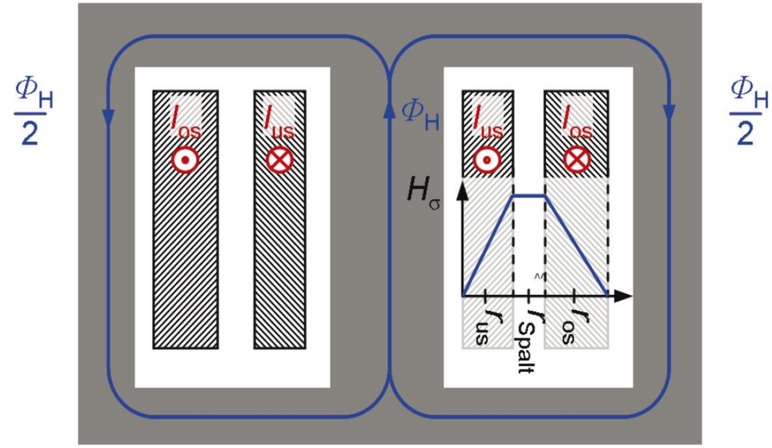
$$L_{\sigma} = \frac{2\pi \cdot \mu_0 \cdot w_{\mathrm{os}}^{2}}{h_{\mathrm{w}}} \cdot \left(\frac{r_{\mathrm{us}} \cdot b_{\mathrm{us}}}{3} + r_{\mathrm{Spalt}} \cdot a_{\mathrm{w}} + \frac{r_{\mathrm{os}} \cdot b_{\mathrm{os}}}{3} \right)$$

$$r_{\mathrm{os}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}} + \frac{b_{\mathrm{us}}}{2} + a_{\mathrm{w}} + \frac{b_{\mathrm{os}}}{2},\ r_{\mathrm{us}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}} + \frac{b_{\mathrm{us}}}{2}\ \text{und}\ r_{\mathrm{Spalt}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}} + \frac{b_{\mathrm{us}}}{2} + a_{\mathrm{w}}$$

Electrical Circuit

f_H: main flux

f_σ: stray flux



R_1: resistance primary winding

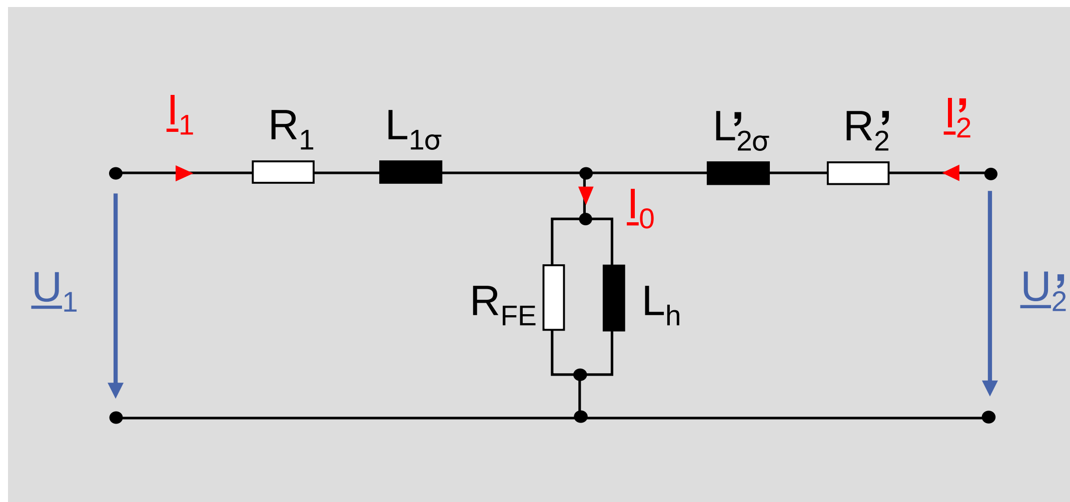
$L_{1\sigma}$: Stray inductance primary winding

R_2`: resistance secondary winding

$L_{2\sigma}$`: Stray inductance secondary winding

L_h: main inductance

R_{FE}: iron core loss



What is different between normal and superconducting transformers ?

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History of LTS Transformers

Year	Organization	Country	Power in kVA	Data	Voltage per winding	Super-cond.
1985	GEC-Alstom	F	80	660V/1040V 124A/77A	2,14 V	NbTi
1988	Kyushu University	J	72	1057V/218V 68A/332A	-	NbTi
1991	Toshiba	J	30	100V/100V 300A/300A	-	NbTi
1991	Ktio	J	100	6600V/210V 15A/476A	4,57 V	Cu/NbTi
1992	Kyushu University	J	1000	3300V/220V 303A/4545A	10 V	NbTi
1993	ABB	CH	330	6000V/400V 56A/830A	7,9 V	NbTi
1995	Osaka University	J	40	460V/150V 50A/200A	0,45 V	NbTi

Source: Technik und Einsatz von HTSL Leistungstransformatoren, Diss. E. Sissimatos 2005

630 kVA Transformer (ABB)

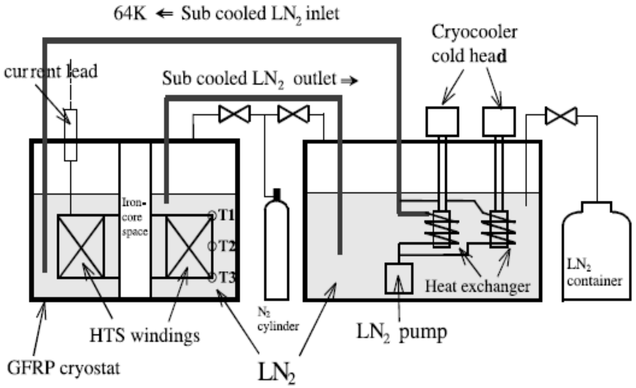
Worldwide first field test of a superconducting transformer

Power	630 kVA
Voltage	18 720 / 420 V
Group	Dyn11
Frequency	50 Hz
Short circuit impedance	4,6%
Current	11,2 / 866
Superconductor	Bi 2223
Cooling	LN_2 bei 77 K V
Losses at I_r	337 W @ 77 K

Quelle: H. Zueger et al, Cryogenics 1998 Volume 38, Number 11

1 MVA Transformers – 1996 - (Kyushu)

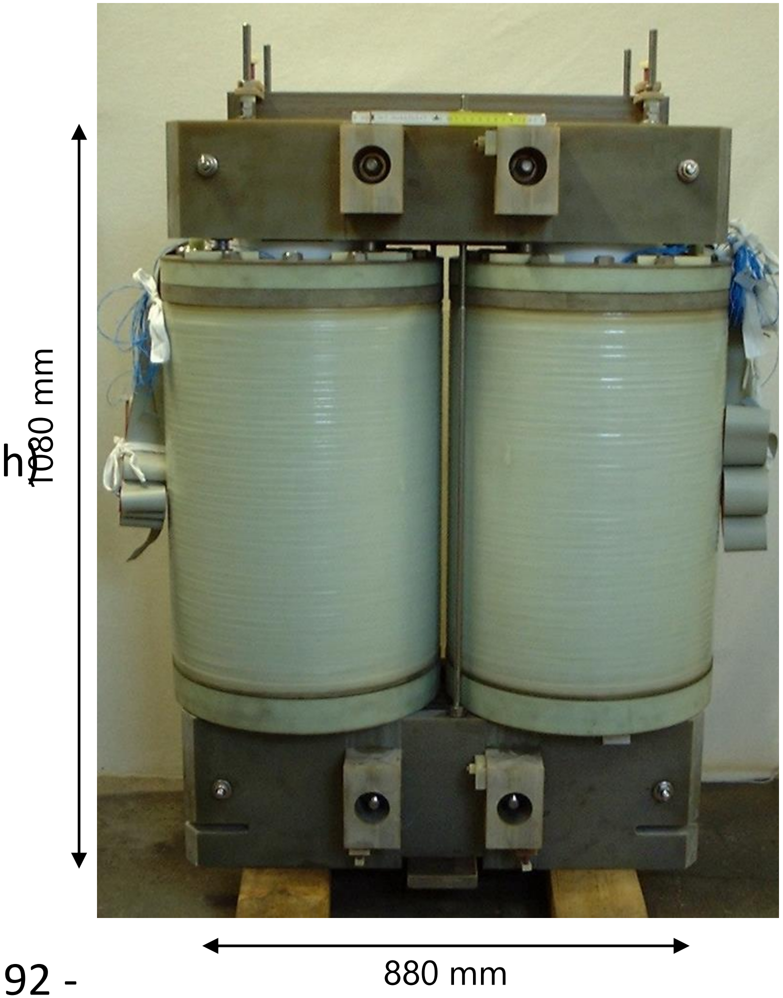
- Rated power: 1 MVA
- Rated Voltage: 22/6,9 kV
- Frequency: 60 Hz
- Short-circuit voltage: u_k = 5 %
- Cooling: subcooled LN_2 at 64 K
- Volume: 1,5 m x 1,2 m x 2,7 m (l x w x h)
- Weight: 5100 kg
- Bi-2223 Superconductor
- Losses: 160 W bei 65 K
- Successful Field Test



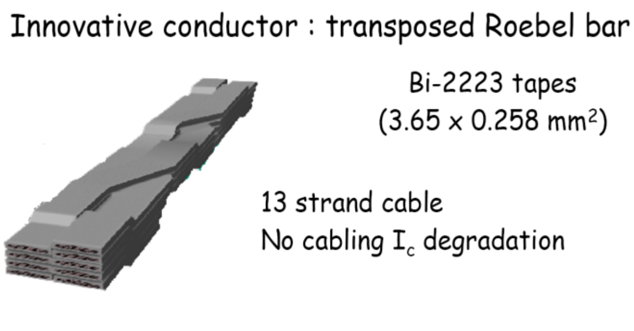
Quelle: Kimura et al Physica C 372-376, 2002-S. 1694-1697

1 MVA Mobile Transformer - 2001 (Siemens)

- Rated Power: 1 MVA
- Rated Voltage: 25/1,4 kV
- Frequency: 50 Hz
- SC impedance : u_k = 25 %
- Cooling LN_2 at 67 K
- Volume: 0,88 m x 0,406 m x 1,08 m (l x w x h)
- Weight active part: 1010 kg
- Weight LN_2 Tank: 272 kg
- Length Bi-2223 tapes: 6,8 km
- Losses: 1960 W bei 67 K
- Efficiency: η = 97,75 %
- Efficiency of normal train transformers: η = 92 - 95 %

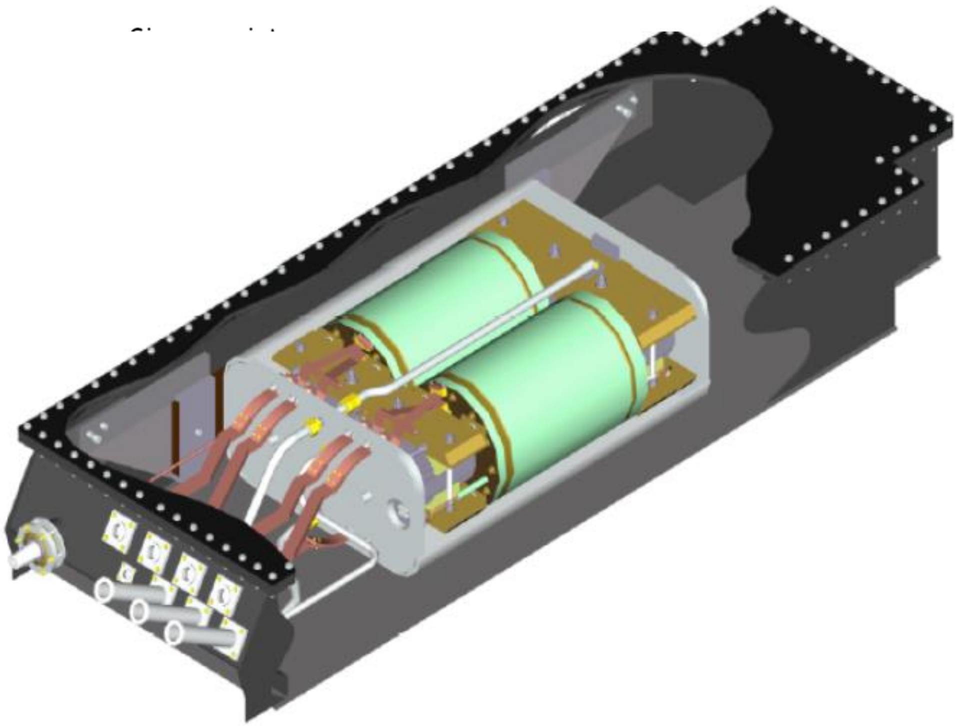


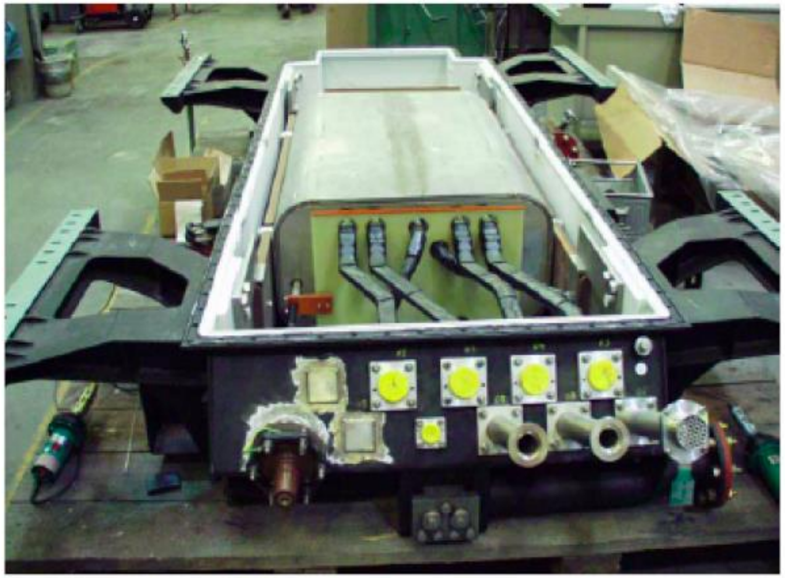
1 MVA Mobile Transformer – 2001 (Siemens)



Losses

Iron Core	700 W
Stray field (Iron)	280 W
Winding and current leads	780 W
Thermal losses	200 W
Total loss	1960 W @ 67 K
Total loss	23 kW @ RT
Efficiency supercond.	97,75%
Efficiency normal	92-95 %





Transformer installed in frame

1 MVA Mobile Transformer - 2001 (Siemens)

HTS-Train transformer left
Normal train transformer right

HTS-Transformer in test field

Major HTS Transformers Projects

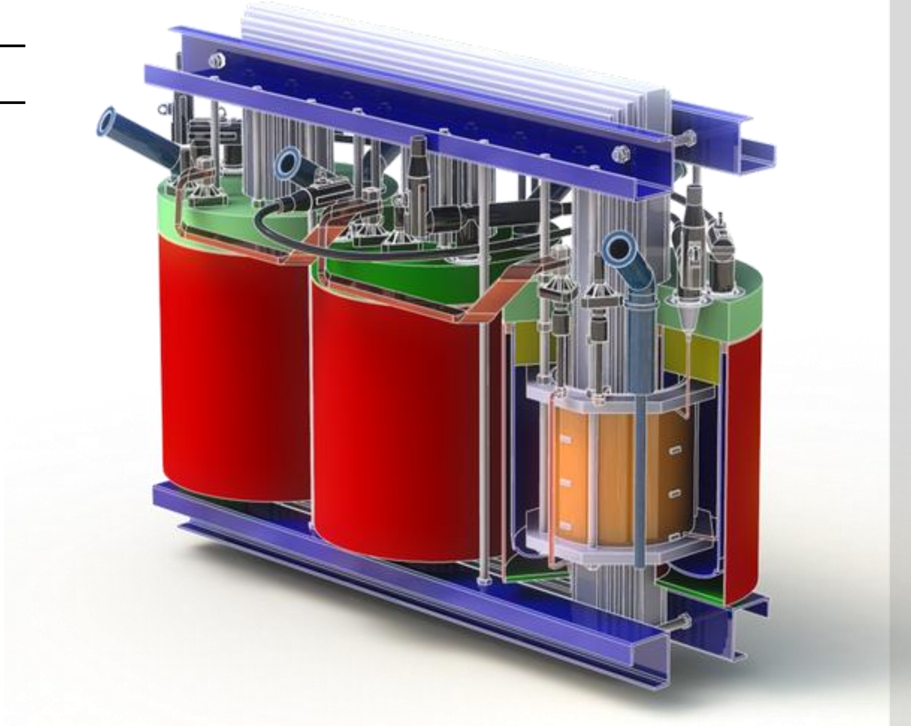
Country	Inst.	Application	Data	Phase	Year	HTS
Switzerland	ABB	Distribution	630 kVA, 18,42 kV/420V	3 Dyn11	1996	Bi 2223
Japan	Fuji Electric	Demonstrator	500 kVA, 6,6 kV/3,3 kV	1	1998	Bi 2223
Germany	Siemens	Demonstrator	100 kVA, 5,5 kV/1,1 kV	1	1999	Bi 2223
USA	Waukesha	Demonstrator	1 MVA, 13,8 kV/6,9 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

Current Limiting Transformer - 2013

Objective: Develop and field test a 1 MVA HTS transformer using YBCOa

Project Partners: Gallaghan Innovation, Wilson Transformers, General Cable …

Parameter	Value
Primary Voltage	11,000 V
Secondary Voltage	415 V
Maximum Op. Temp.	70 K, liquid nitrogen cooling
Target Rating	1 MVA
Primary Connection	Delta
Secondary Connection	Wye
LV Winding	20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)
LV Rated current	1390 A rms
HV Winding	918 turns of 4 mm YBCO wire per phase (24 double pancakes of 38.25 turns each)
HV Rated current	30 A rms



Source: Gallaghan Innovation

First HTS Roebel wire in field test

Current Limiting Transformer - 2013

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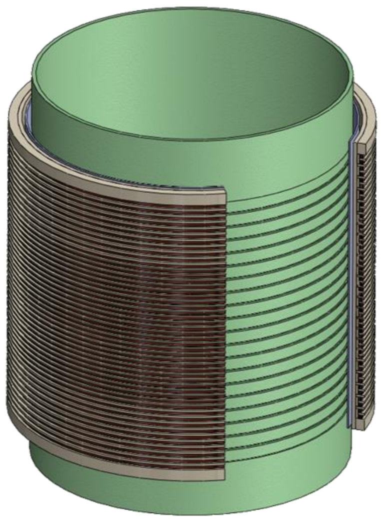
HV Winding



4 mm wide YBCO

I/I_c ~ 25%

Polyimide wrap insulation

24 double pancakes

LV Winding

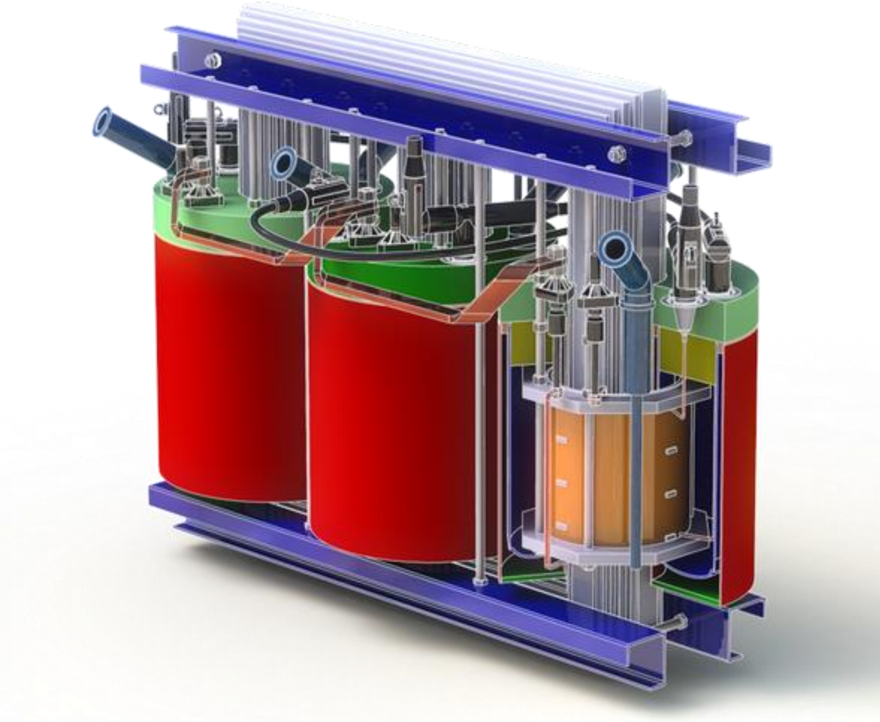
YBCO Roebel Cable

L = 20 m

15 strands

5 mm width

I_c ~ 1400 A @ 77 K, sf



Source: Igallaghan Innovation

More information: Neil D. Glasson, Mike P. Staines, Zhenan Jiang, and Nathan S. Allpress, "Verification Testing for a 1 MVA 3-Phase Demonstration Transformer Using 2G-HTS Roebel Cable", IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

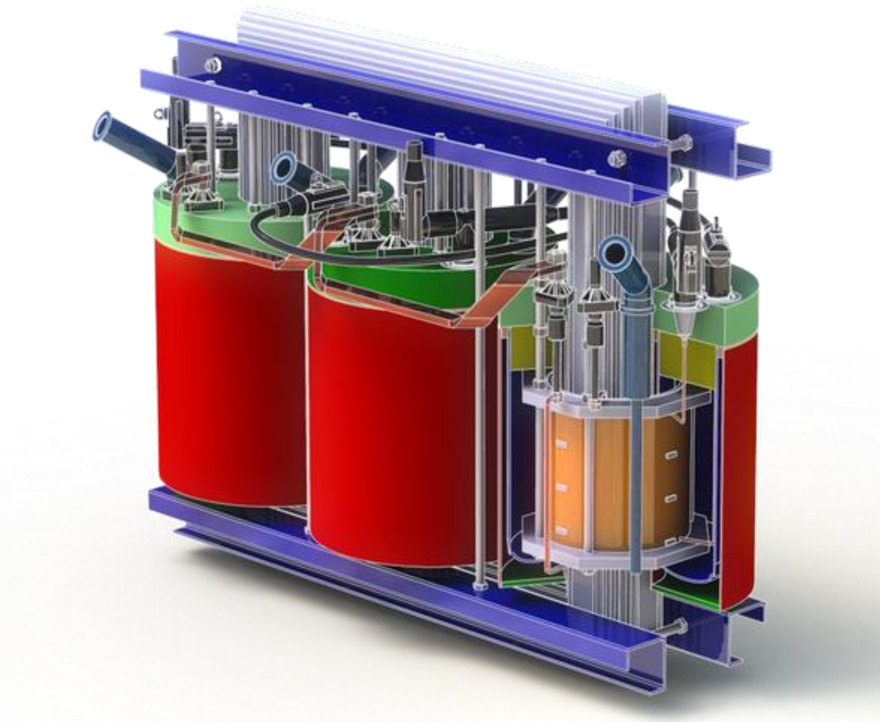
Current Limiting Transformer - 2013

Objective: Develop and field test a 1 MVA HTS transformer using YBCOa

Source	Heat load
Cryostat	113 W
Electrical bushing	343 W
AC loss in LV	390 W
AC loss in HV	90 W
Total	**936 W**

Efficiency at 100% load: ~ 97%
Efficiency at 50% load 98.5 %

<u>Current standard</u>
Efficiency at 50% 99.27%



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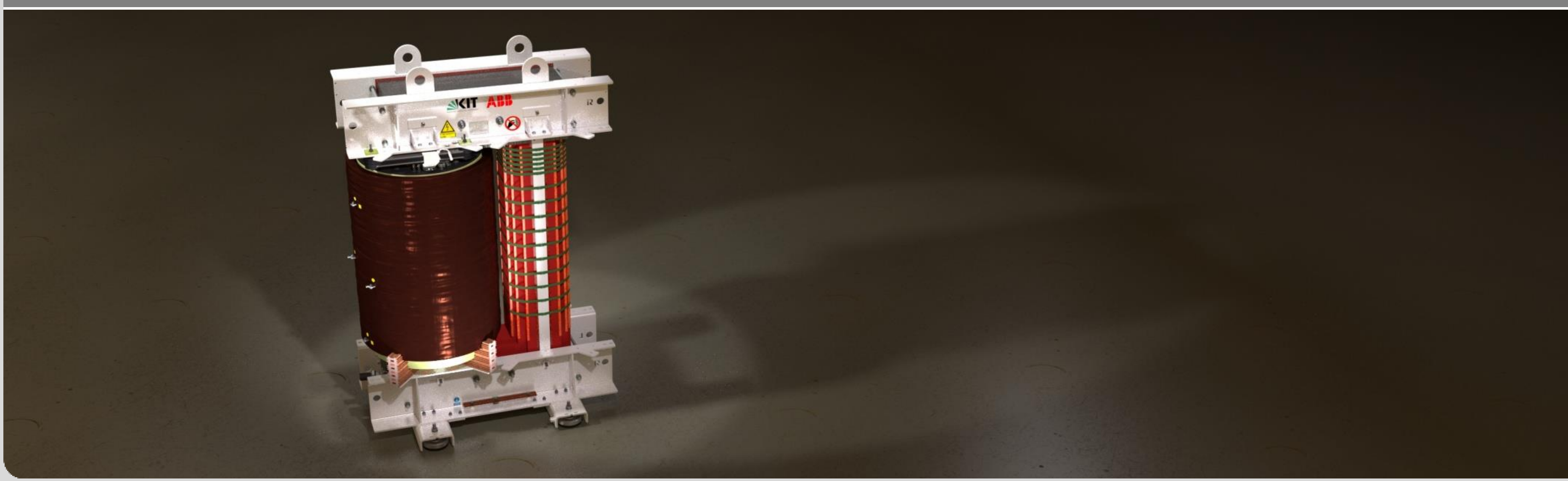
Manufacturing and Test of a 1MVA-Class Superconducting Fault Current Limiting Transformer

02.06.2017, Karlsruhe

Sebastian Hellmann (KIT) / Markus Abplanalp (ABB)

Institute for Technical Physics (ITEP)

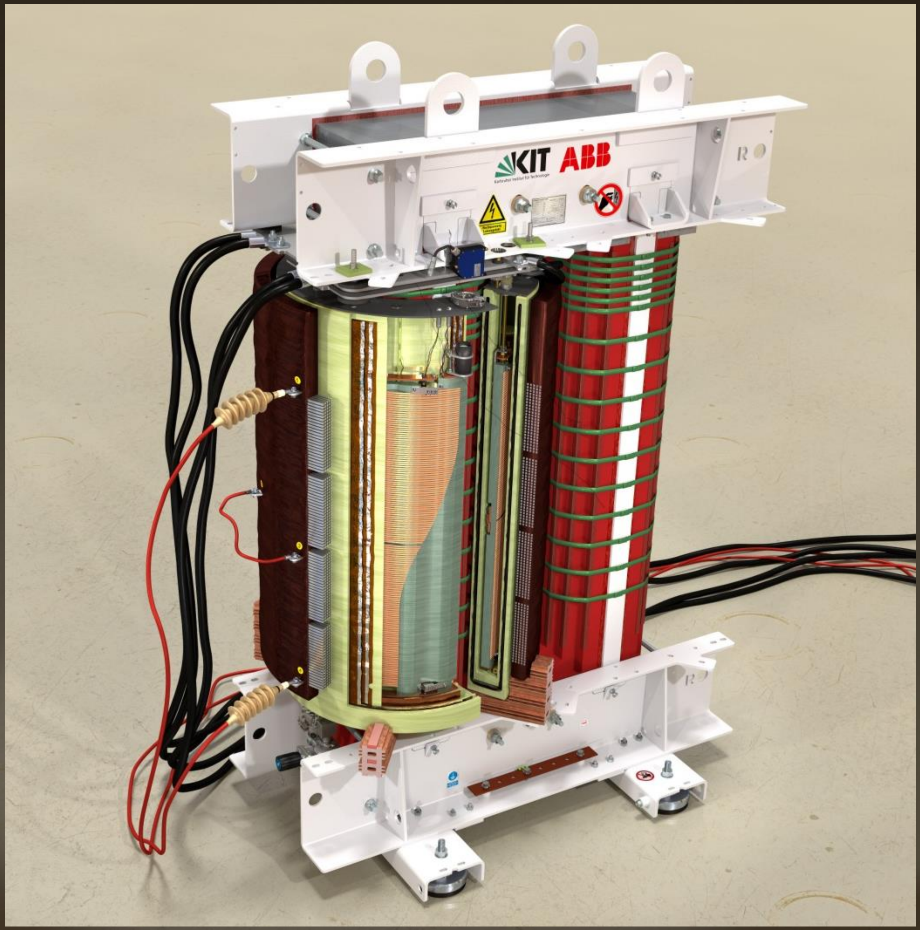


Transformer Design Fix

Main transformer parameters:

Name	Unit symbol	Value	Unit
Nominal power	P_{nom}	577.4	kVA
Primary winding (normal-conducting winding)	U_{prim}	20	kV
	I_{prim}	28.9	A
Secondary winding (superconducting winding)	U_{sec}	1	kV
	I_{sec}	577.4	A
Fault duration	t_{fault}	60	ms
Current limitation 1st HW	$I_{LIM,\ 1HW}$	13.55	kA
Limitation 1st HW in resp. to prosp. current	LIM_{1HW}	71.4	%
Current limitation 6th HW	$I_{LIM,\ 6HW}$	6.5	kA
Limitation 6th HW in resp. to prosp. current	LIM_{6HW}	35.7	%

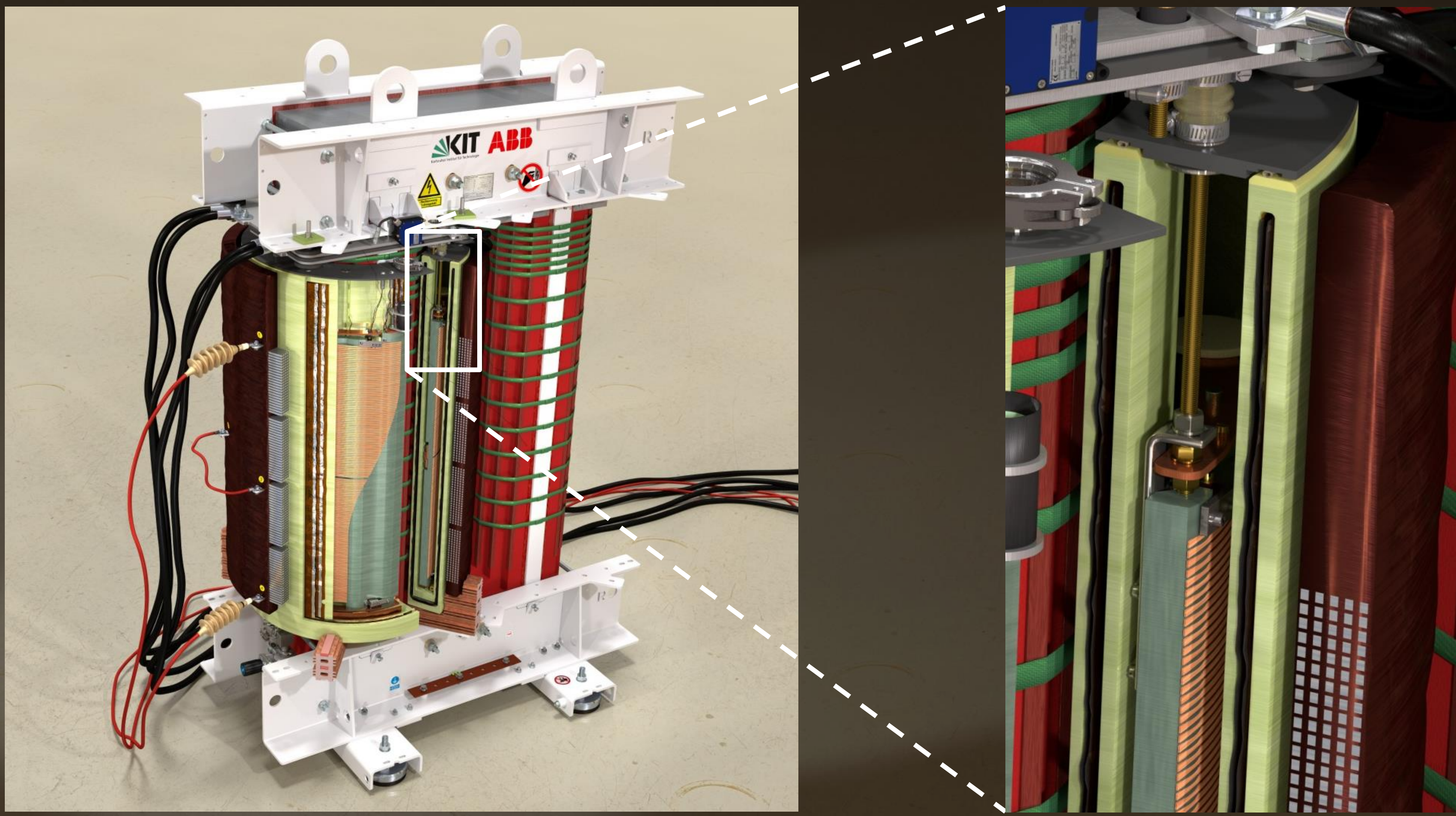
Transformer Design Fix



The design of the transformer is focusing on technology demonstration and includes practical compromises such as:

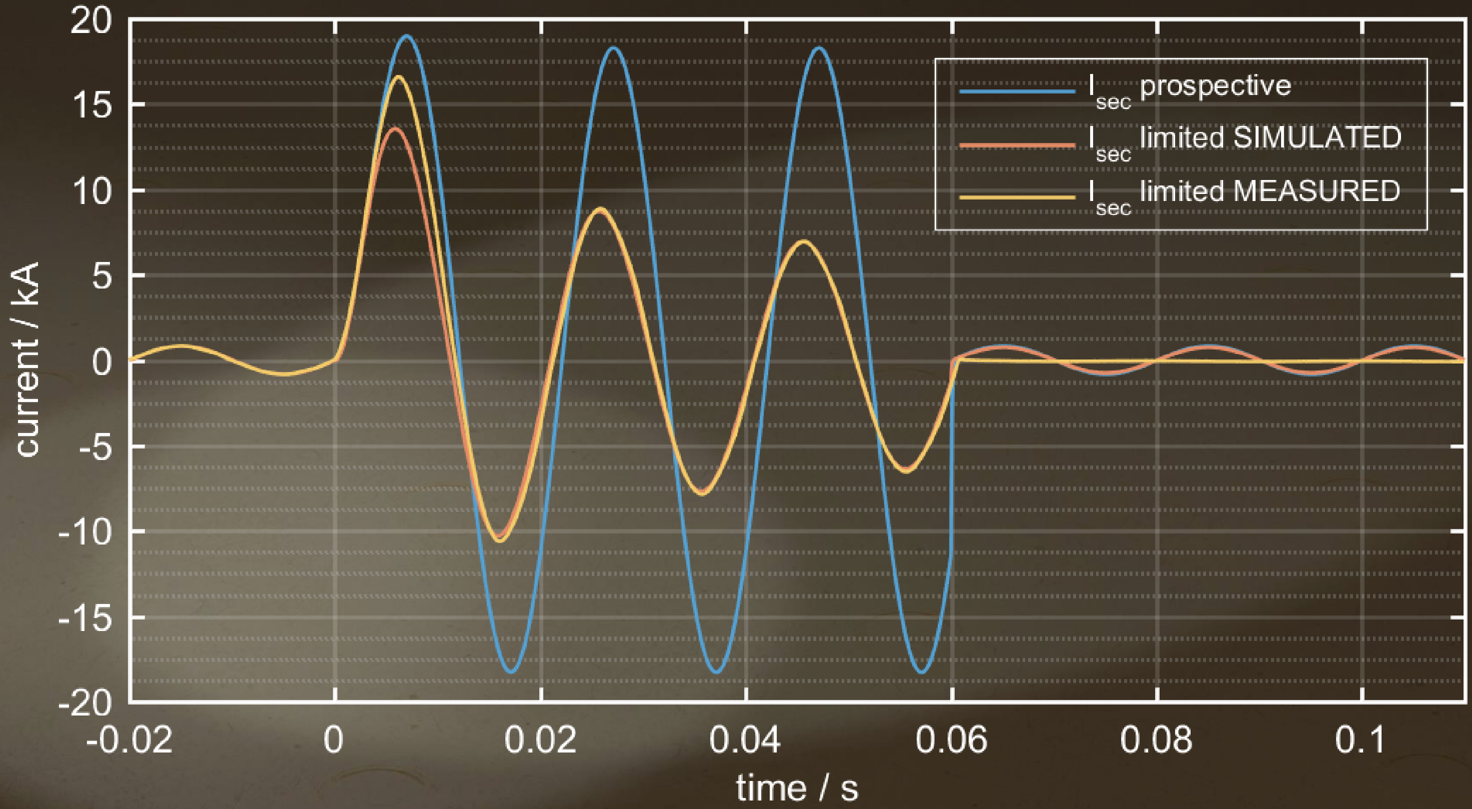
- Non-optimal cryogenic design
- Relatively short current leads
- Non-sealed cryogenic environment
- No automatic LN_2 level control

Transformer Design Fix



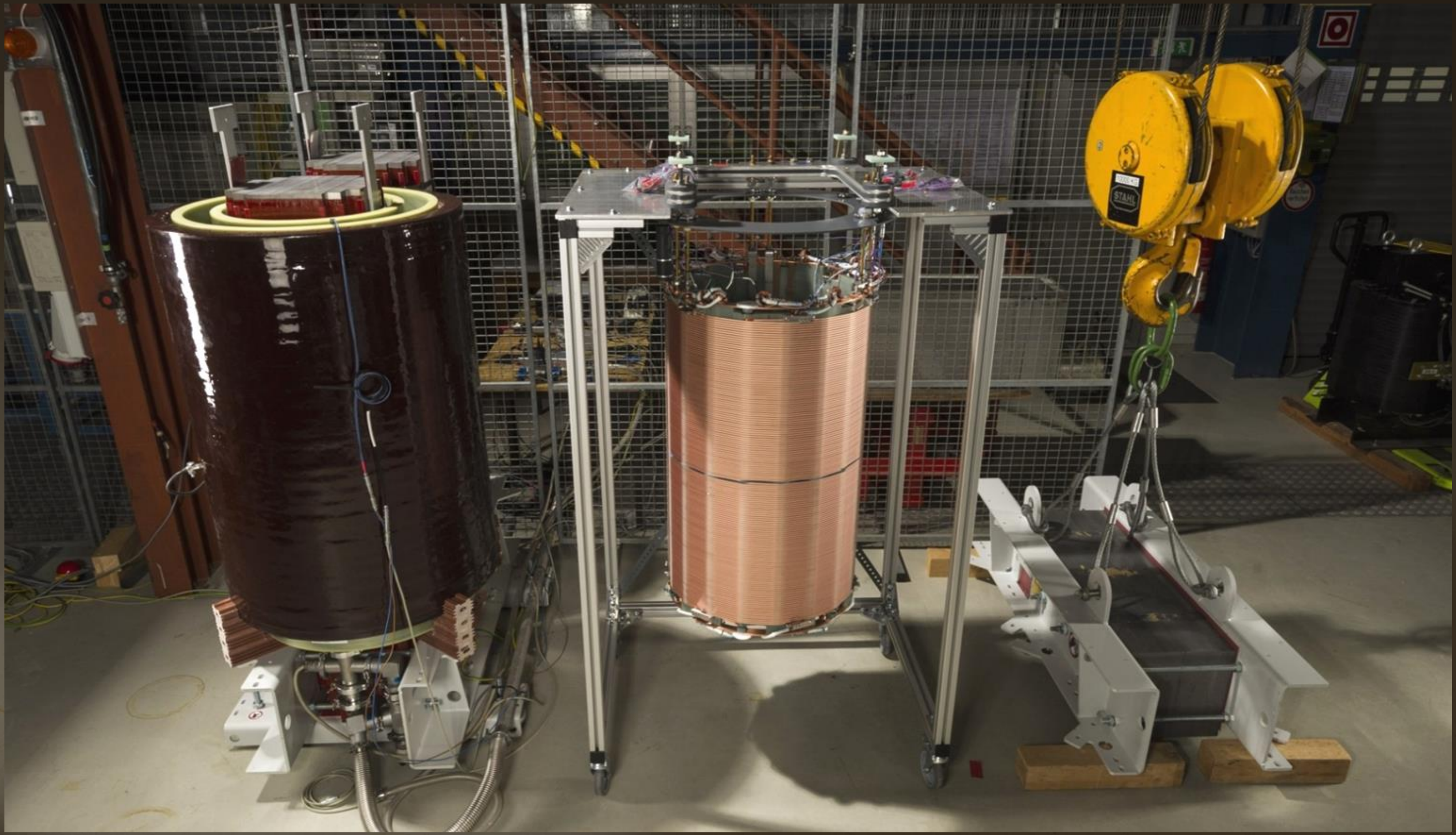
Measurements – Current limitation

Prospective current and limited current (simulated and measured) with 25.3 mΩ short-circuit:



- Thank you for your Attention -

ABB KIT Karlsruhe Institute of Technology



Sebastian Hellmann / KIT / sebastian.hellmann@kit.edu

One slide about economics of transformers

Karlsruhe Institute of Technology

Cost range of conventional transfomers

1 MVA ~ 30.000 US$

50 MVA ~ 730.000 US$

Voltage Rating (Primary-Secondary)	Capability MVA Rating	Approximate Price ($)	Approximate Weight & Dimensions
Transmission Transformer			
Three Phase			
230–115kV	300	$2,000,000	170 tons (340,000 lb) 21ft W–27ft L–25ft H
345–138kV	500	$4,000,000	335 tons (670,000 lb) 45ft W–25ft L–30ft H
765–138kV	750	$7,500,000	410 tons (820,000 lb) 56ft W–40ft L–45ft H
Single Phase			
765–345kV	500	$4,500,000	235 tons (470,000 lb) 40ft W–30ft L–40ft H
Generator Step-Up Transformer			
Three Phase			
115–13.8kV	75	$1,000,000	110 tons (220,000 lb) 16ft W–25ft L–20ft H
345-–13.8kV	300	$2,500,000	185 tons (370,000 lb) 21ft W–40ft L–27ft H
Single Phase			
345–22kV	300	$3,000,000	225 tons (450,000 lb) 35ft W–20ft L–30ft H
765–26kV	500	$5,000,000	325 tons (650,000 lb) 33ft W–25ft L–40ft H

Prices are FOB factory and do not include taxes, transportation, special features and accessories, special testing (short-circuit, etc.)

Source: Large power transformers and the U.S. electric grid, Infrastructure Security and Energy Restoration Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, June 2012

Assumption:

300 m HTS per MVA and phase

30 €/m HTS wire, 4 mm wide

30 k€ for a km

10 MVA → 9 km, 4 mm wide

270 k€ for HTS wire

100 MVA → 90 km , 4 mm wide

2.7 Mio.€ for HTS wire

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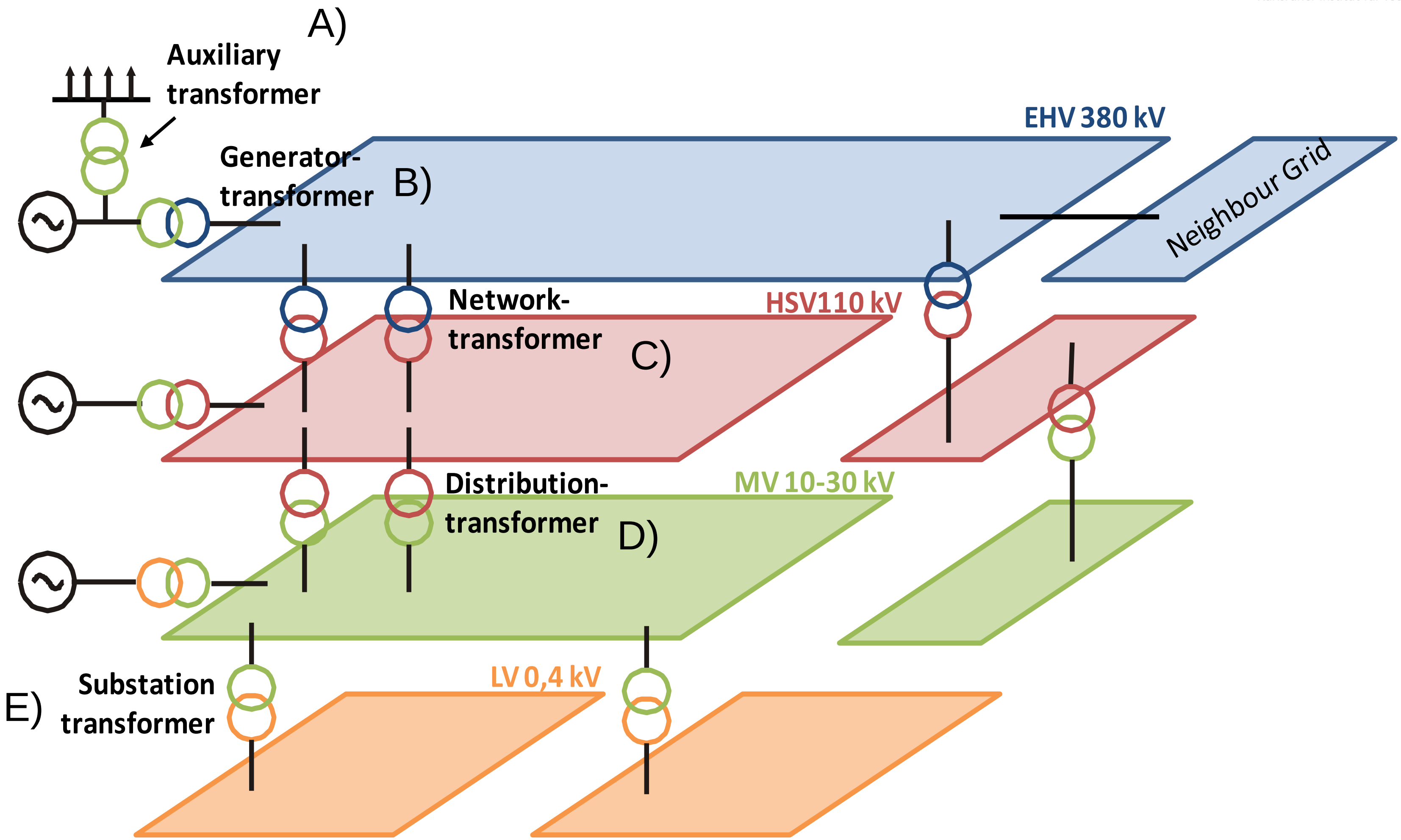
Application of Transformers?



Many potential applications but which one is attractive enough?

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Status of Superconducting Transformers

- Successful technology development in recent years mainly with YBCO wires
- Successful demonstrator development with a rating up to 4 MVA and medium voltages
- Only a few grid tests have been taken place
- Time seems ready for more 3-phase medium voltage demonstrators and prototypes for long-term field tests

A final remark

Superconducting transformers are attractive but do not solve all transformer challenges!