# Superconducting Transformers

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**Institute for Technical Physics**
**EUCAS Short Course Power Applications, September 17th 2017., Geneva**

KIT-ENERGY CENTRE

# Motivation of Superconducting Transformers

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

# Motivation of Superconducting Transformers

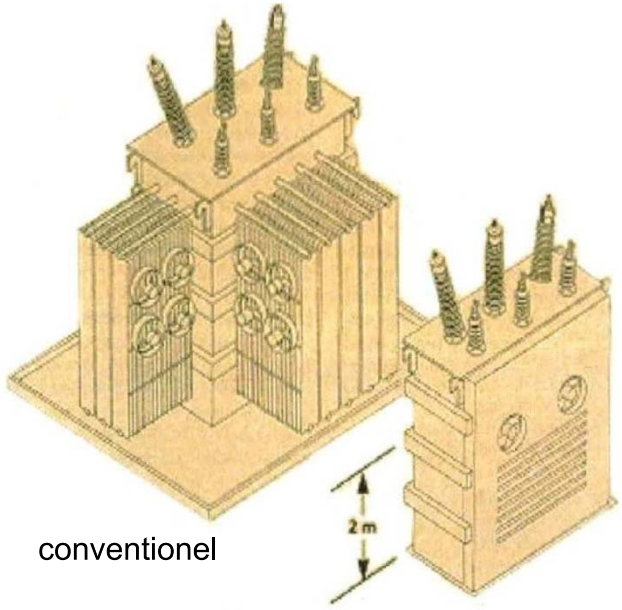
## Manufacturing and transport

- Compact and lightweight (~50 % Reduction)

Trailer failure left something really big in Kendall County road

By Zeke MacCormack Updated 9:44 pm, Monday, August 25, 2014

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

©ABB

# Motivation of Superconducting Transformers

Karlsruher Institut für Technologie

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KIT Karlsruher Institut für Technologie

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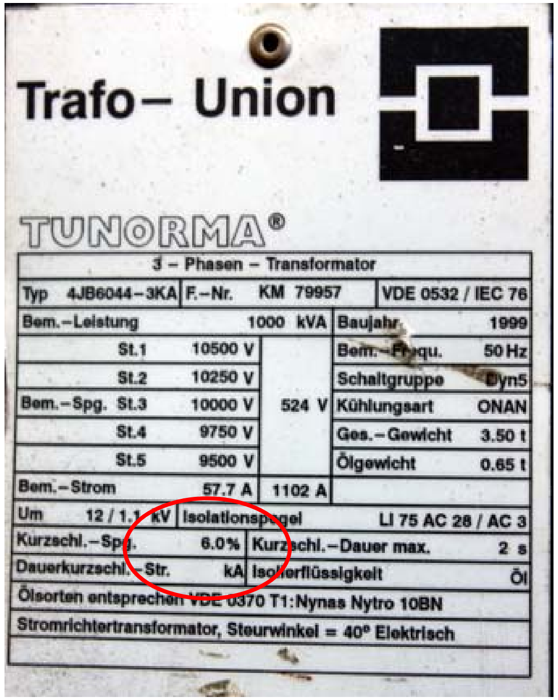
**Operation**

- 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

Karlsruher Institut für Technologie

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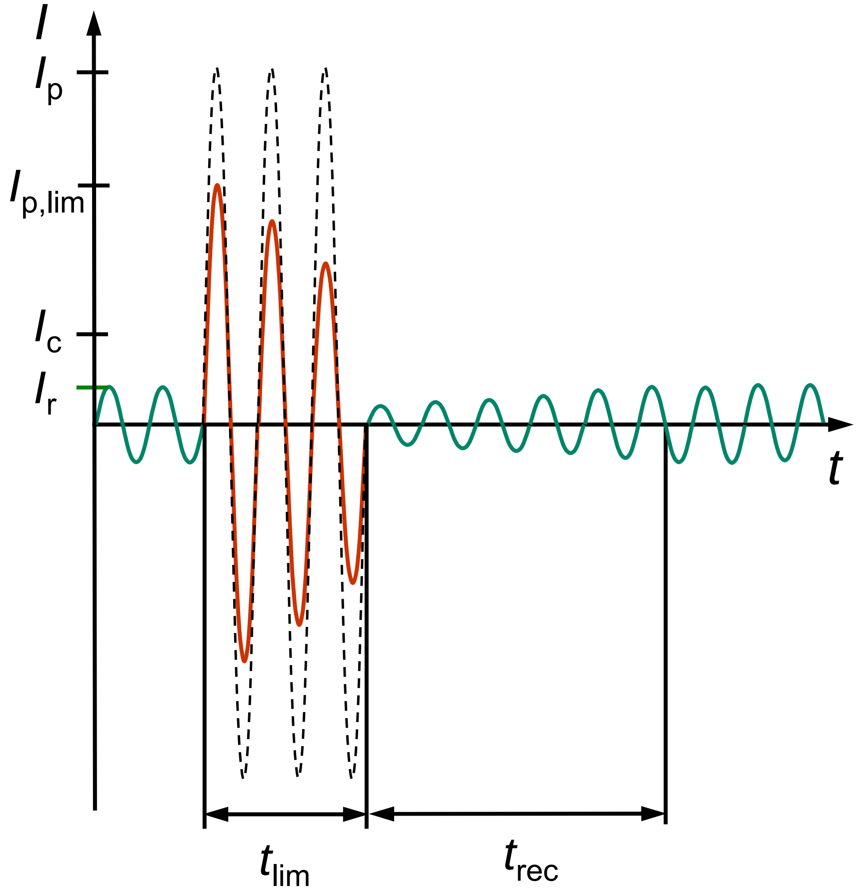


**Enables a new class of transformers**

# Motivation of Superconducting Transformers

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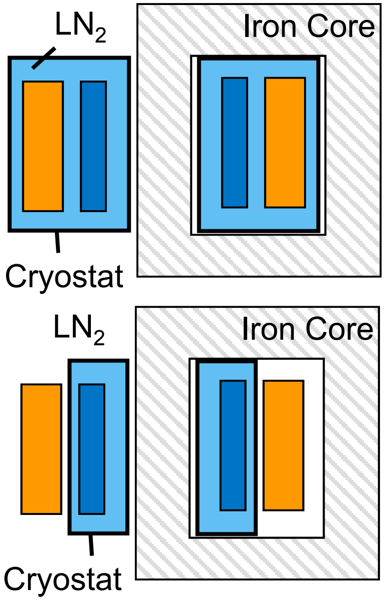
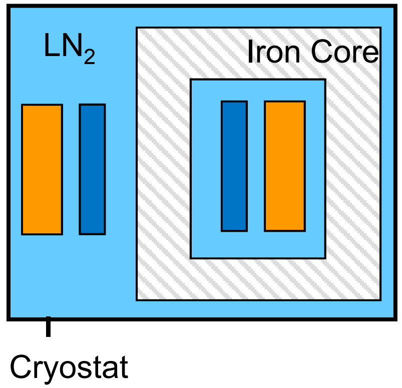
# Different Types of Superconducting Transformers

## Warm Iron Core



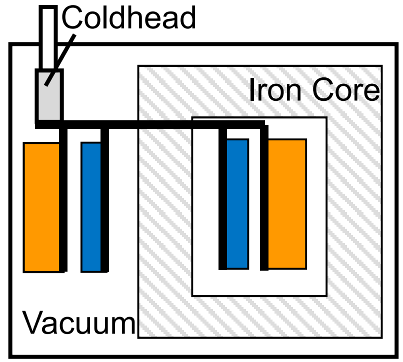

- ☺ Low Cooling Power
- ☺ Iron at Room Temperature
- ☹ Expensive Cryostat
- ☹ 3 Cryostats needed

## 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

# Motivation of Superconducting Transformers

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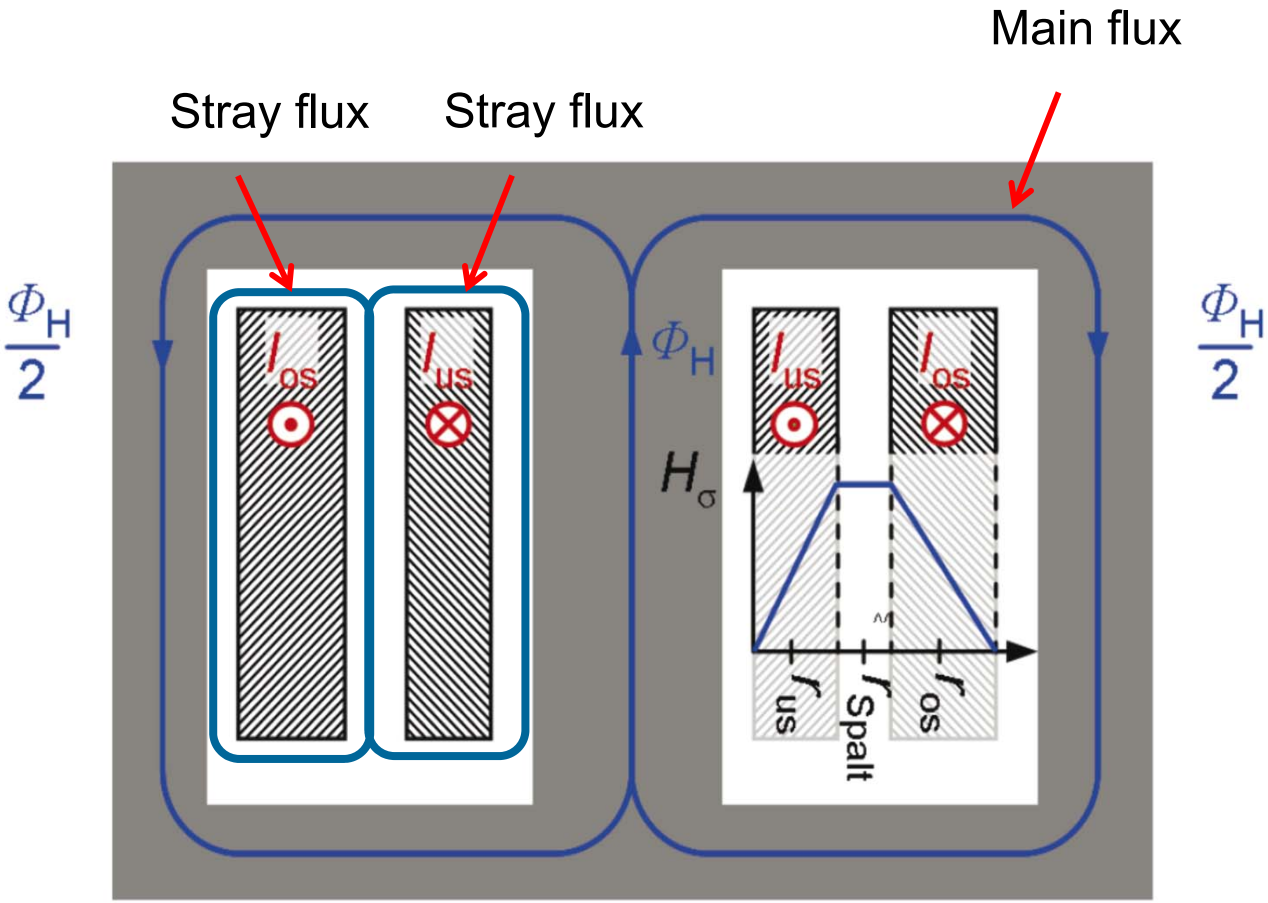
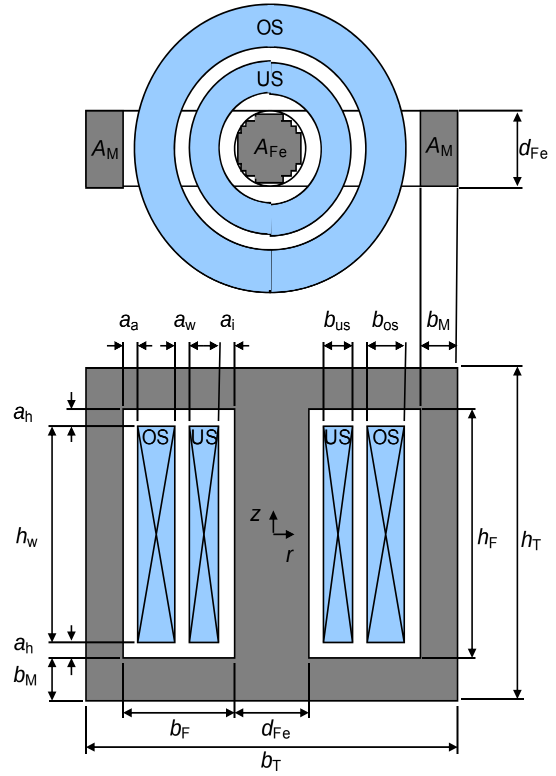
# Transformer Flux Linkage



# Transformer Inductances




## Main Inductance

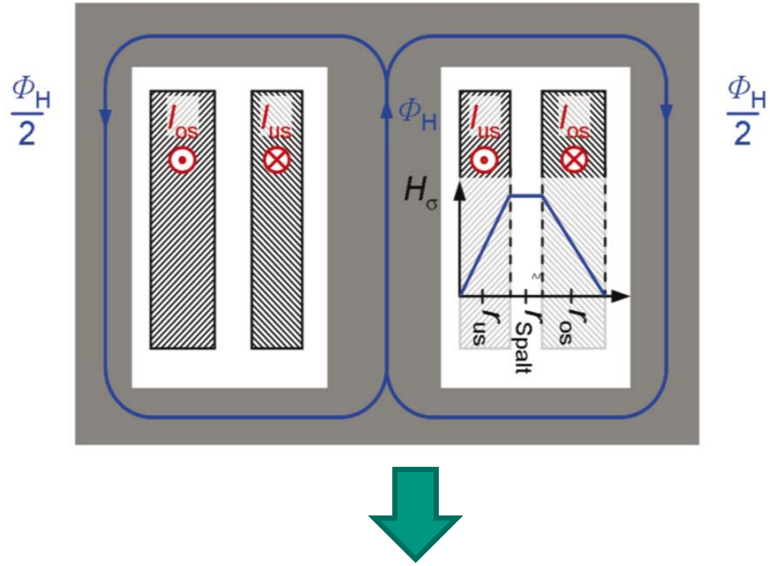
$$L_H = \mu_0 \cdot \mu_r \cdot w_{os}^{\ 2} \cdot \frac{A_{Fe,eff}}{\ell_{Fe}}$$

## Stray Inductance

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

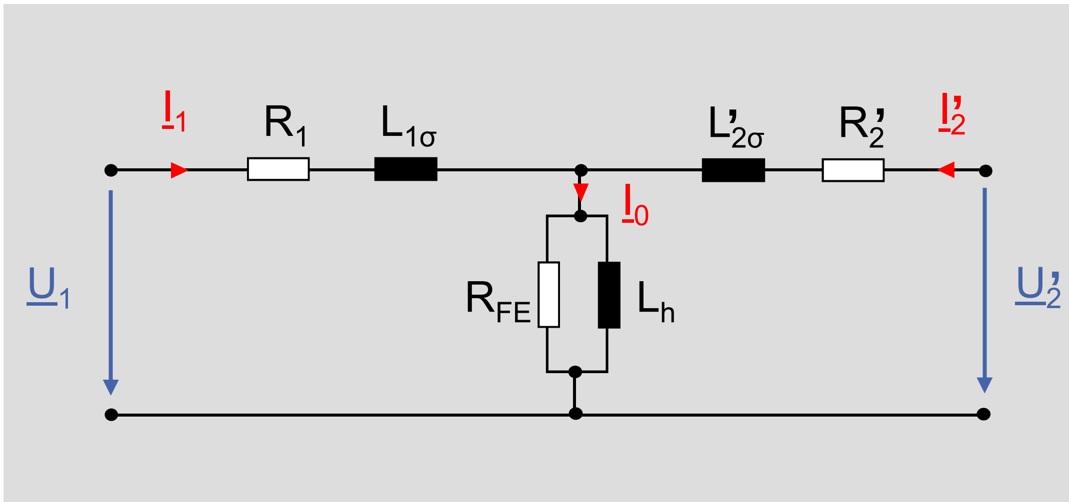
$$r_{os} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w + \frac{b_{os}}{2},\ r_{us} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} \text{ und } r_{Spalt} = \frac{d_{Fe}}{2} + a_i + \frac{b_{us}}{2} + a_w$$

# Electrical Circuit




$\varphi_H$: main flux

$\varphi_\sigma$: 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 ?

# Motivation of Superconducting Transformers

Karlsruher Institut für Technologie

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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<br>124A/77A | 2,14 V | NbTi |
| 1988 | Kyushu University | J | 72 | 1057V/218V<br>68A/332A | - | NbTi |
| 1991 | Toshiba | J | 30 | 100V/100V<br>300A/300A | - | NbTi |
| 1991 | Ktio | J | 100 | 6600V/210V<br>15A/476A | 4,57 V | Cu/NbTi |
| 1992 | Kyushu University | J | 1000 | 3300V/220V<br>303A/4545A | 10 V | NbTi |
| 1993 | ABB | CH | 330 | 6000V/400V<br>56A/830A | 7,9 V | NbTi |
| 1995 | Osaka University | J | 40 | 460V/150V<br>50A/200A | 0,45 V | NbTi |

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

# 630 kVA Transformer (ABB)

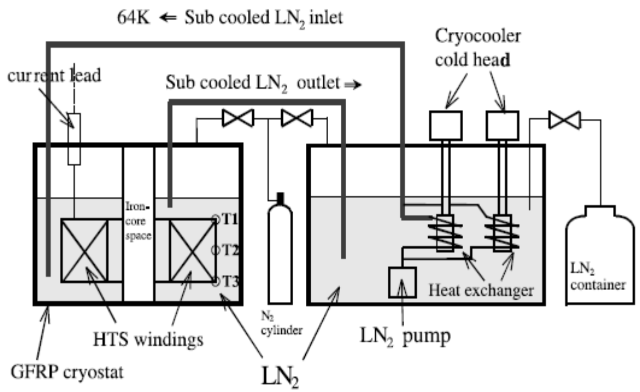
Worldwide first field test of a superconducting transformer


| | |
|---|---|
| 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

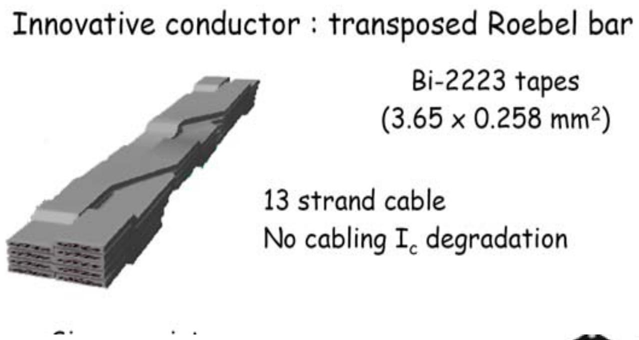



Quelle: Kimura et al Physica C 372-376, 2002-S. 1694-1697

# 1 MVA Mobile Transformer - 2001 (Siemens)

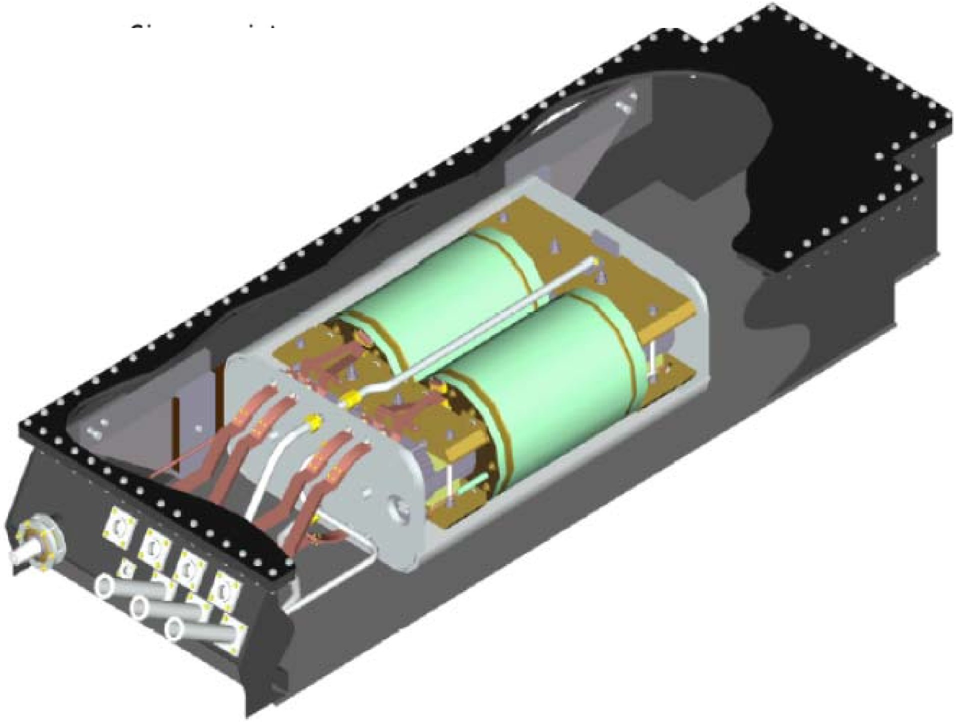
- Rated Power: 1 MVA
- Rated Voltage: 25/1,4 kV
- Frequency: 50 Hz
- SC impedance : $u_k$ = 25 %
- Cooling $LN_2$ at 67 K
- Volume: 0,88 m x 0,406 m x 1,08 m (l x w x h)
- Weight active part: 1010 kg
- Weight $LN_2$ Tank: 272 kg
- Length Bi-2223 tapes: 6,8 km
- Losses: 1960 W bei 67 K
- Efficiency: $\eta$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

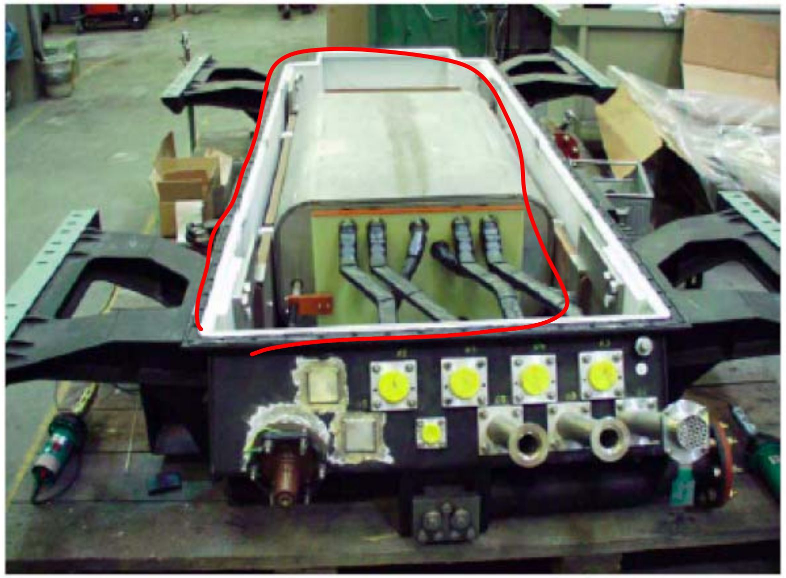
# 1 MVA Mobile Transformer – 2001 (Siemens)




**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

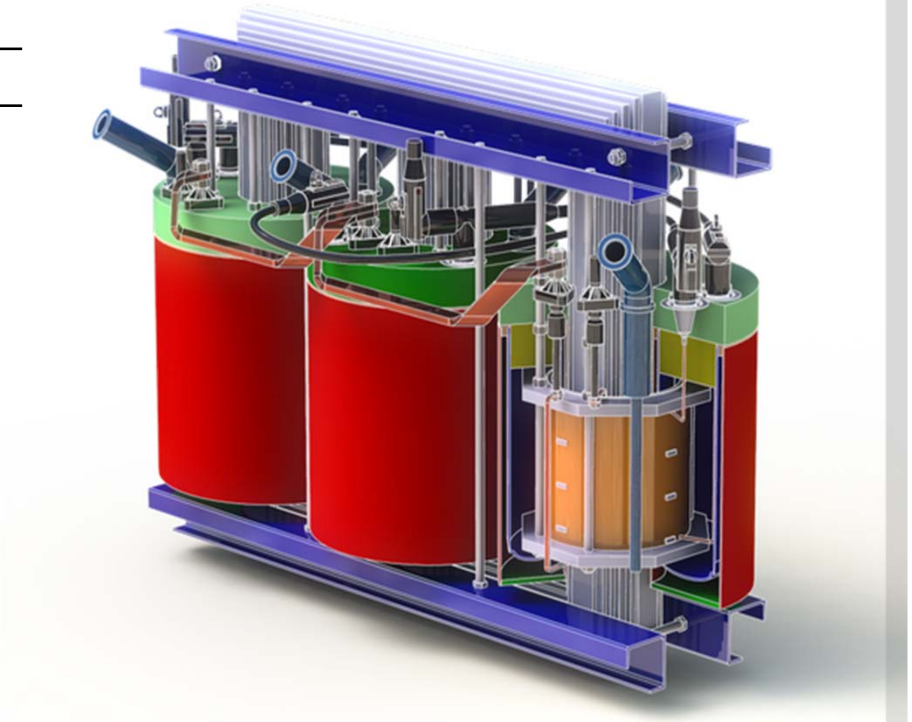
| Country | Inst. | Application | Data | Phase | Year | HTS |
|---|---|---|---|---|---|---|
| Switzerland | ABB | Distribution | 630 kVA, 18,42 kV/420V | 3 Dyn11 | 1996 | Bi 2223 |
| Japan | Fuji Electric | Demonstrator | 500 kVA, 6,6 kV/3,3 kV | 1 | 1998 | Bi 2223 |
| Germany | Siemens | Demonstrator | 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

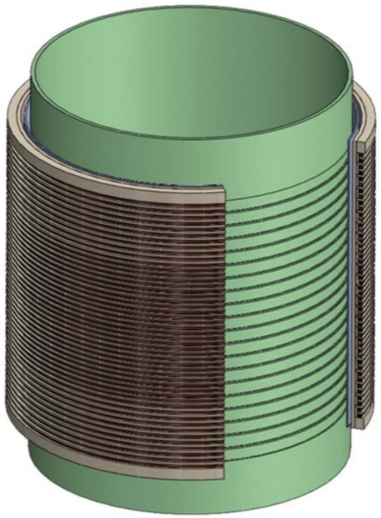
**First HTS Roebel wire in field test**

# Current Limiting Transformer - 2013

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

**Project Partners**: IRL, Wilson Transformers, General Cable …

**HV Winding**



4 mm wide YBCO

$I/I_c$ ~ 25%

Polyimide wrap insulation

24 double pancakes

**LV Winding**

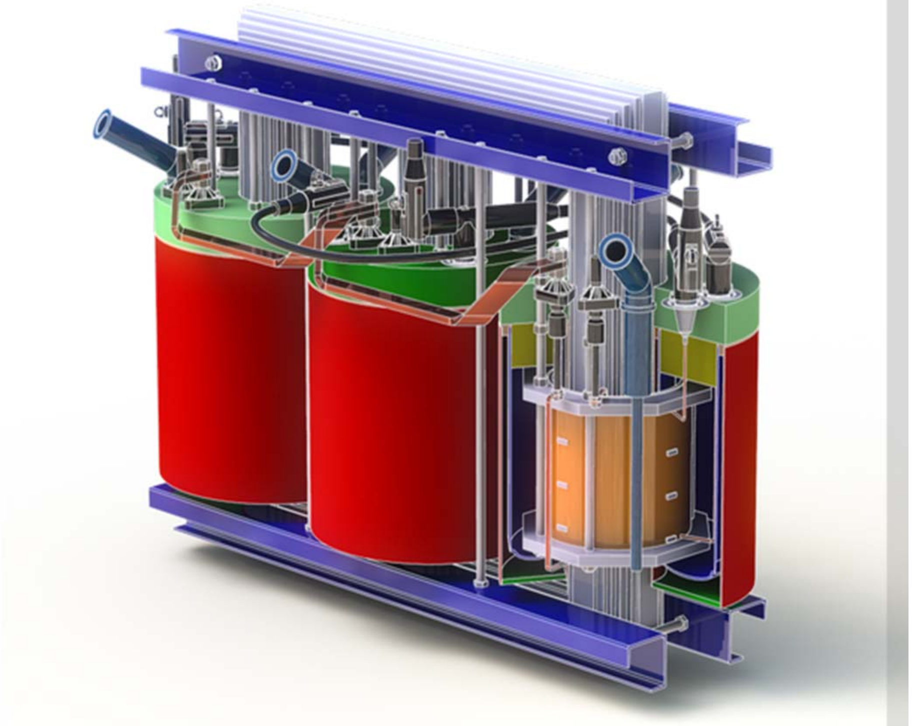
YBCO Roebel Cable

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

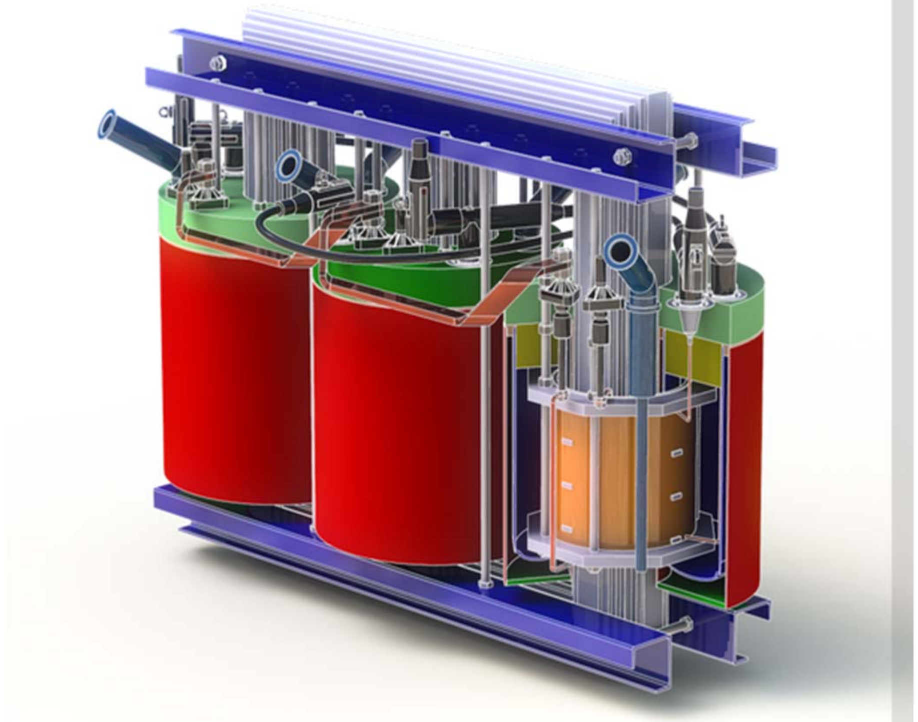
# Current Limiting Transformer - 2013

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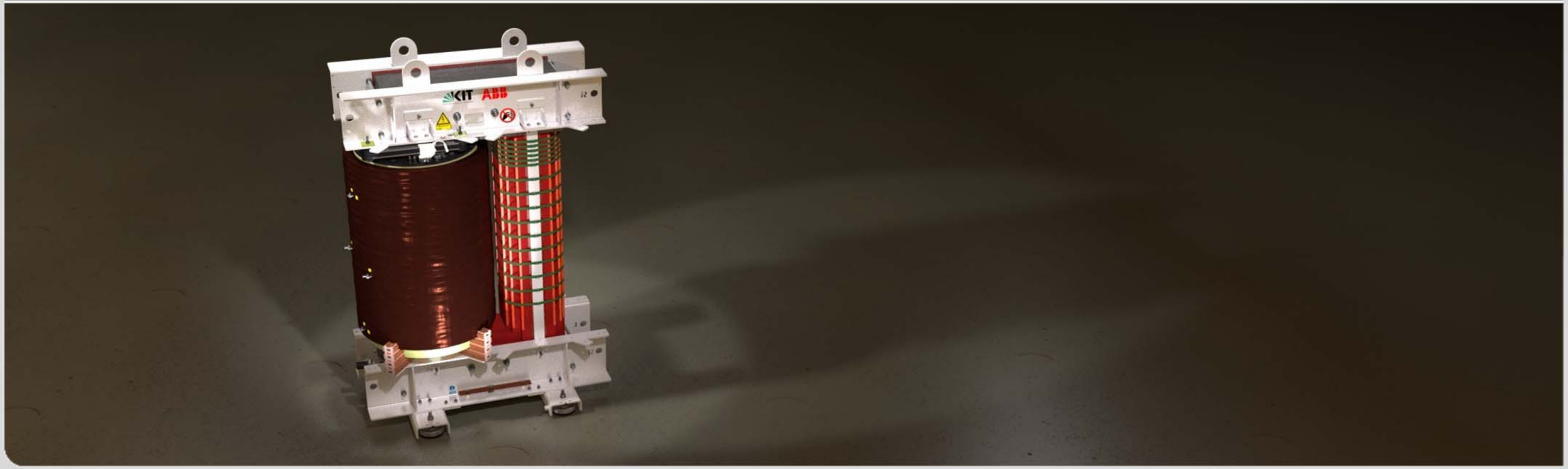
# Manufacturing and Test of a 1MVA-Class Superconducting Fault Current Limiting Transformer

02.06.2017, Karlsruhe

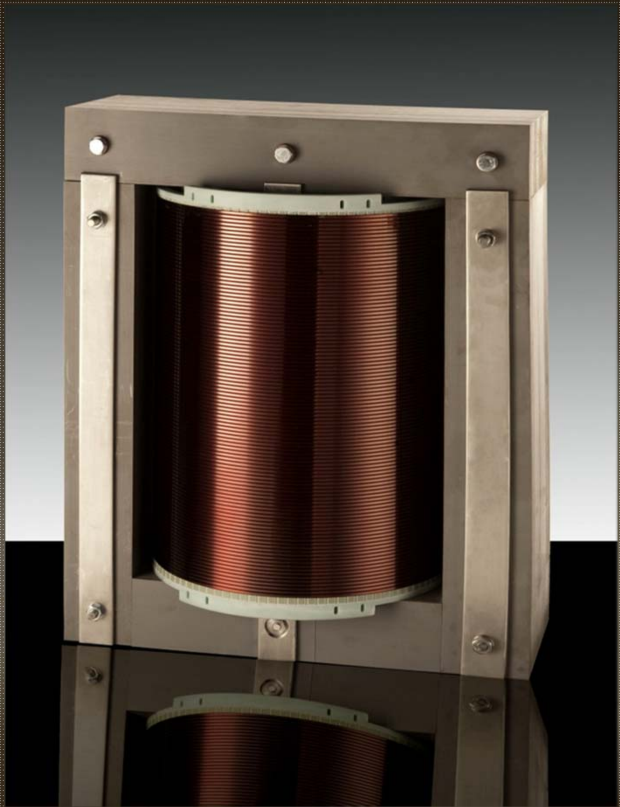
Sebastian Hellmann (KIT) / Markus Abplanalp (ABB)

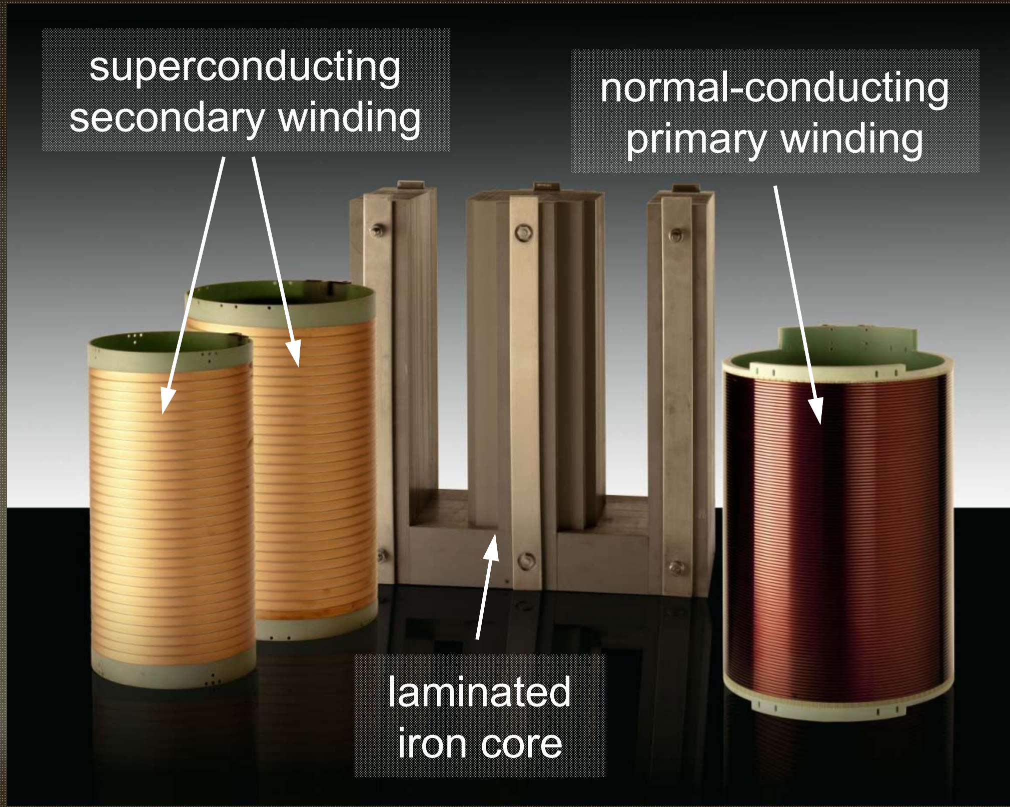
Institute for Technical Physics (ITEP)



# Introduction – 60kVA Transformer

KIT developed a 60 kVA laboratory demonstrator facilitating a superconducting secondary winding to limit fault currents





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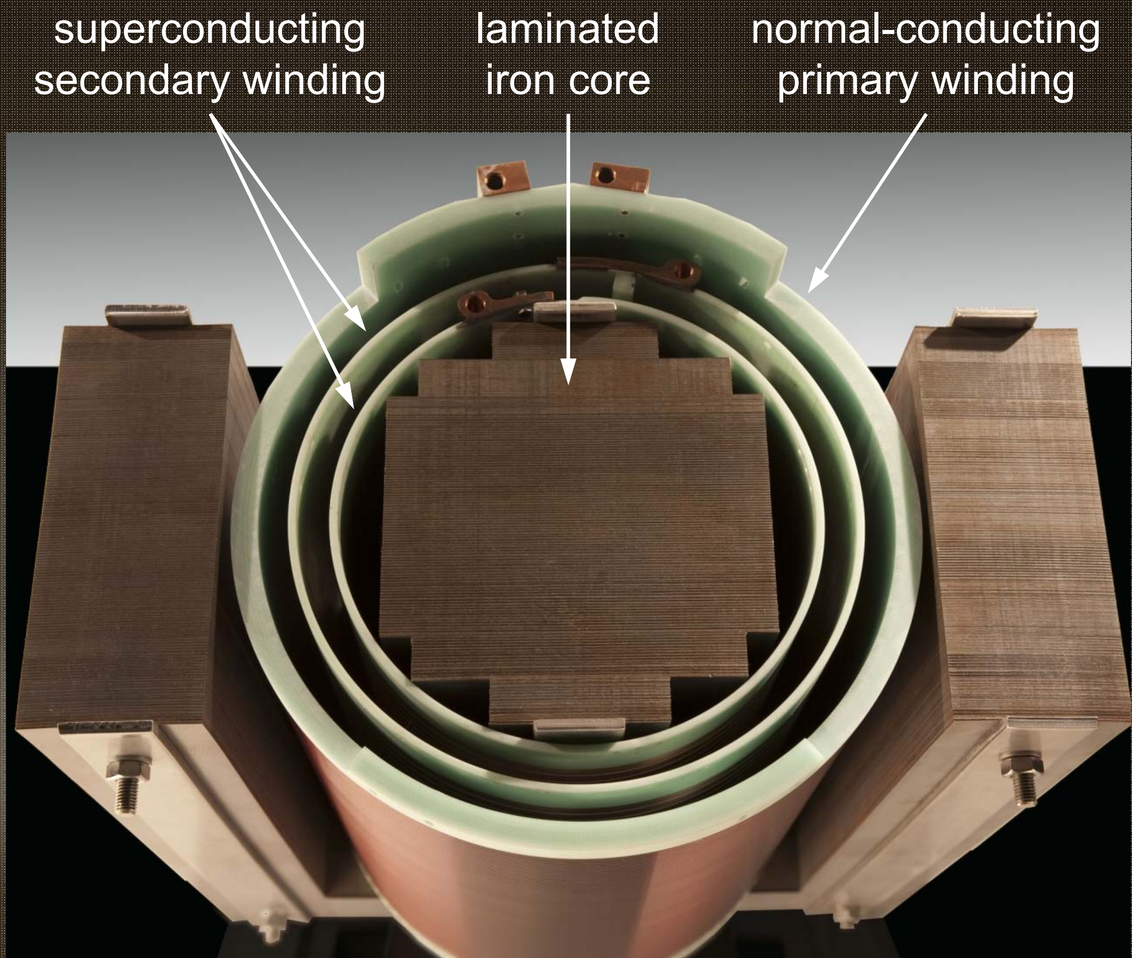
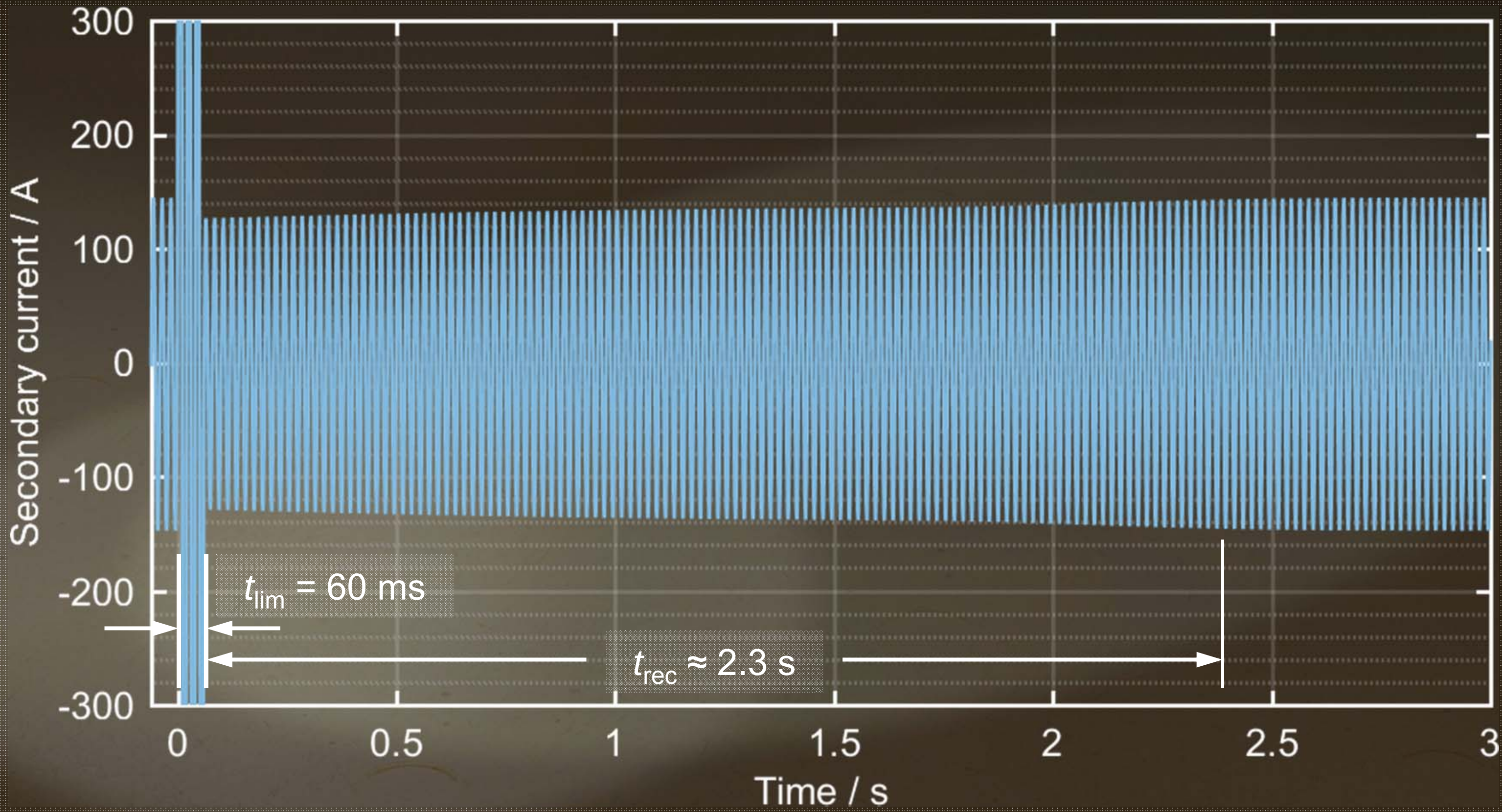



**Main transformer parameters**

| | |
|---|---|
| power | 60 kVA |
| ratio | 100 / 60 (turns) |
| voltage | 1 kV / 600 V |
| currents | 60 A / 100 A |
| $j_{prim}$ | 5 A / mm$^2$ |
| $j_{sec}$ | 83.3 A / mm$^2$ |
| $u_k$ | 1.58% |

# Introduction – 60kVA Transformer

Recovery-under-Load (*RuL*) measurement for $I_{rec} = I_{nom} = 100$ A



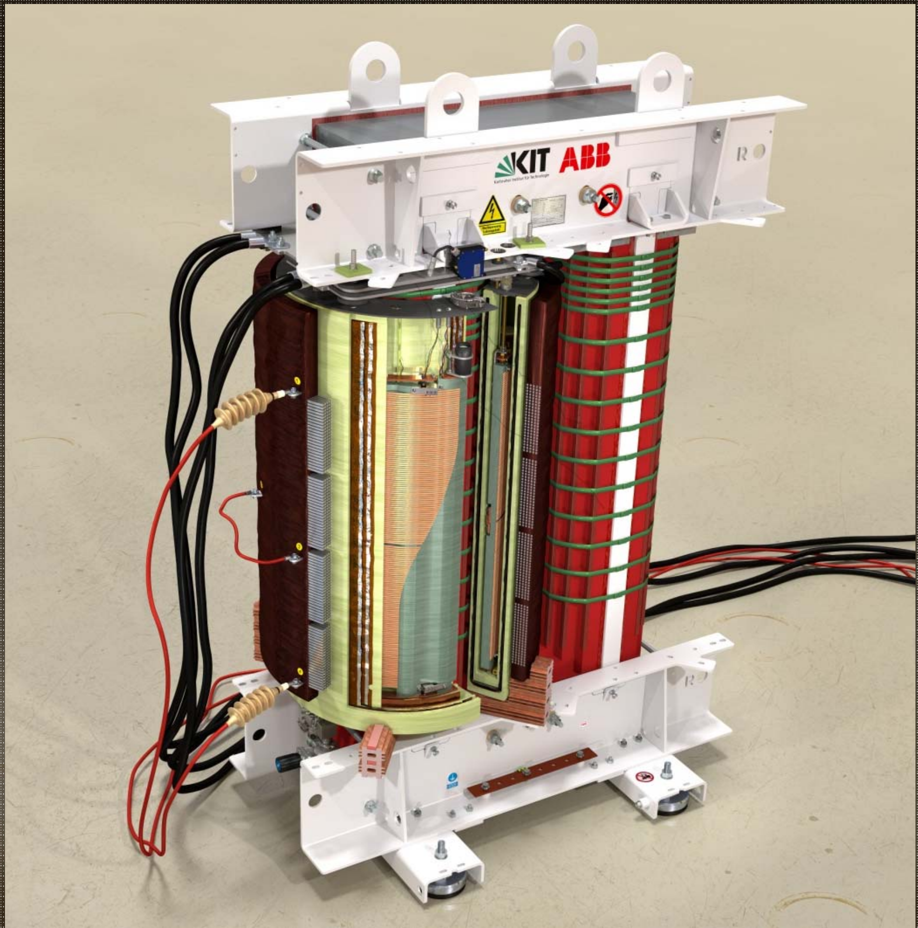
# Transformer Design Fix

ABB KIT Karlsruhe Institute of Technology

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 | % |

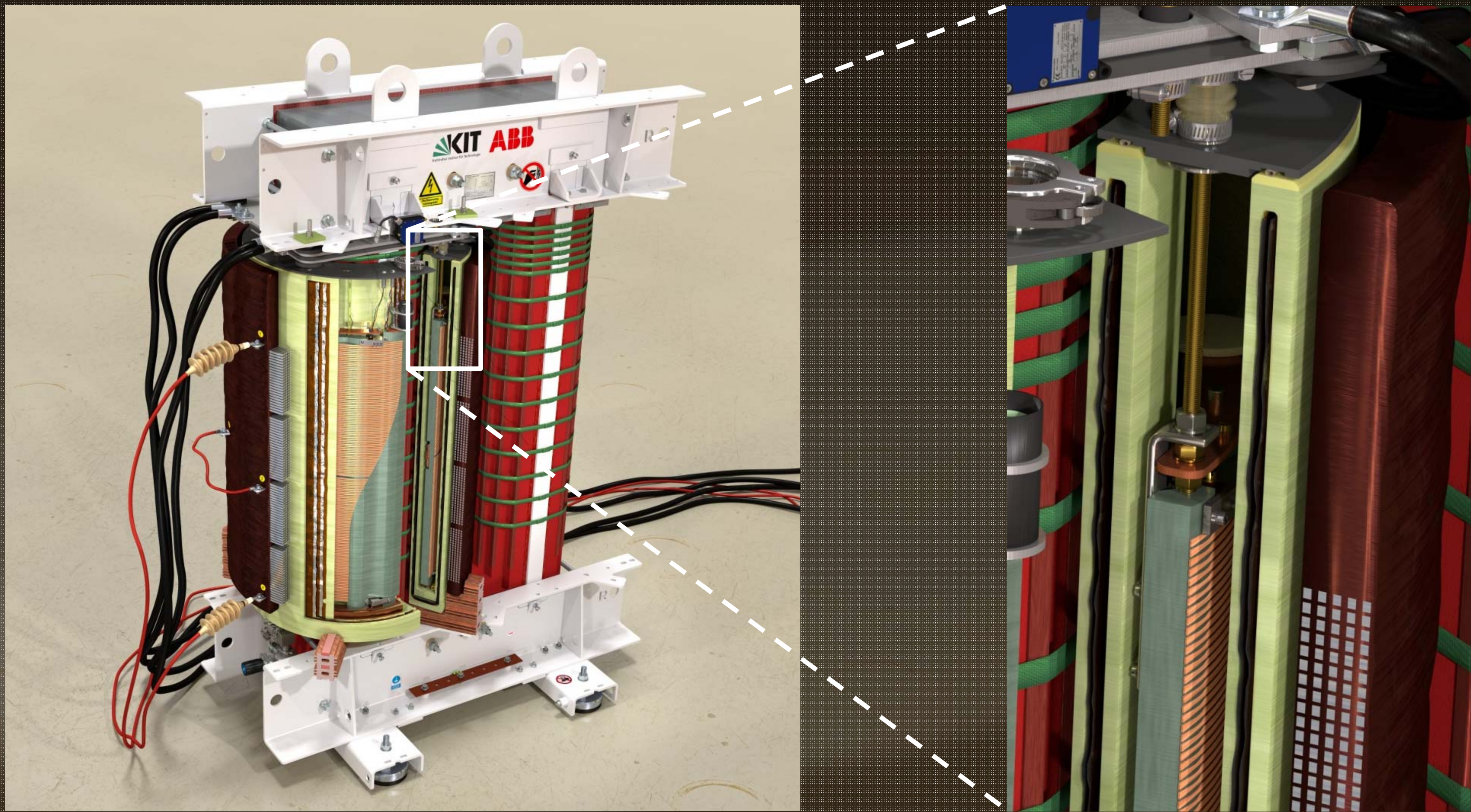
# Transformer Design Fix




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

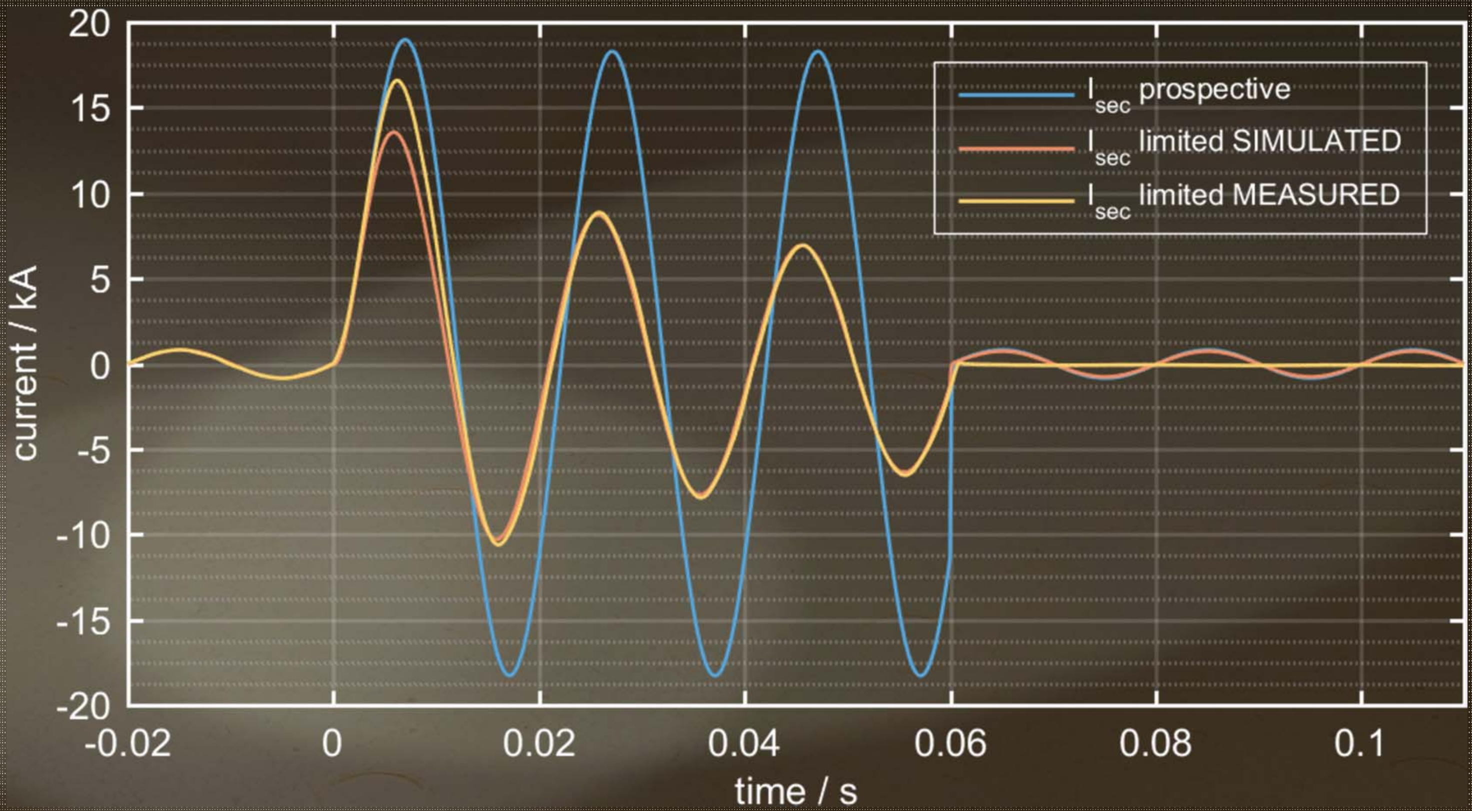
- Non-optimal cryogenic design
- Relatively short current leads
- Non-sealed cryogenic environment
- No automatic $LN_2$ level control

# Transformer Design Fix



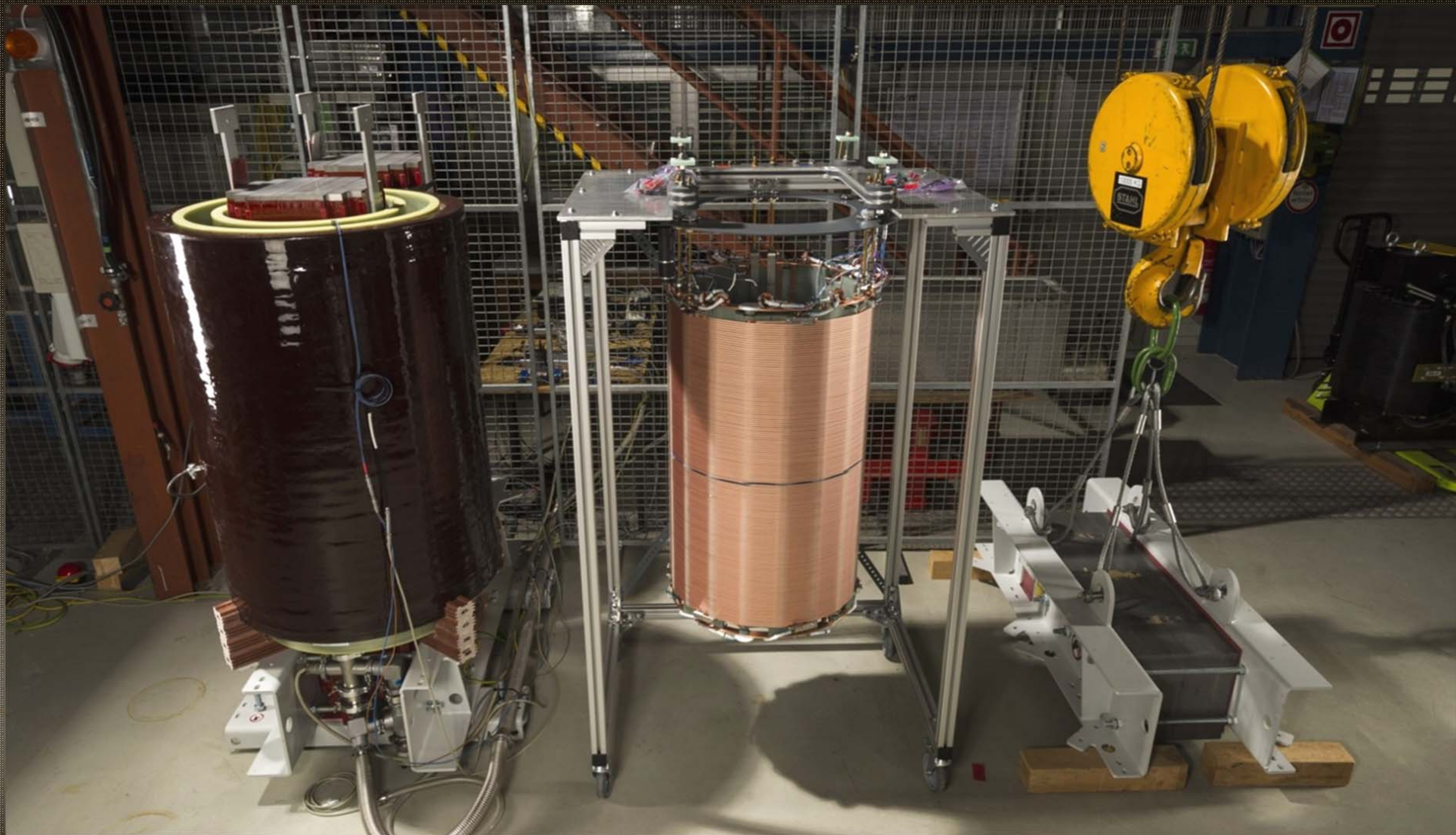
# Measurements – Current limitation

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

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)<br>21ft W–27ft L–25ft H |
| 345–138kV | 500 | $4,000,000 | 335 tons (670,000 lb)<br>45ft W–25ft L–30ft H |
| 765–138kV | 750 | $7,500,000 | 410 tons (820,000 lb)<br>56ft W–40ft L–45ft H |
| **Single Phase** | | | |
| 765–345kV | 500 | $4,500,000 | 235 tons (470,000 lb)<br>40ft W–30ft L–40ft H |
| **Generator Step-Up Transformer** | | | |
| **Three Phase** | | | |
| 115–13.8kV | 75 | $1,000,000 | 110 tons (220,000 lb)<br>16ft W–25ft L–20ft H |
| 345-–13.8kV | 300 | $2,500,000 | 185 tons (370,000 lb)<br>21ft W–40ft L–27ft H |
| **Single Phase** | | | |
| 345–22kV | 300 | $3,000,000 | 225 tons (450,000 lb)<br>35ft W–20ft L–30ft H |
| 765–26kV | 500 | $5,000,000 | 325 tons (650,000 lb)<br>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

<u>Assumption:</u>

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

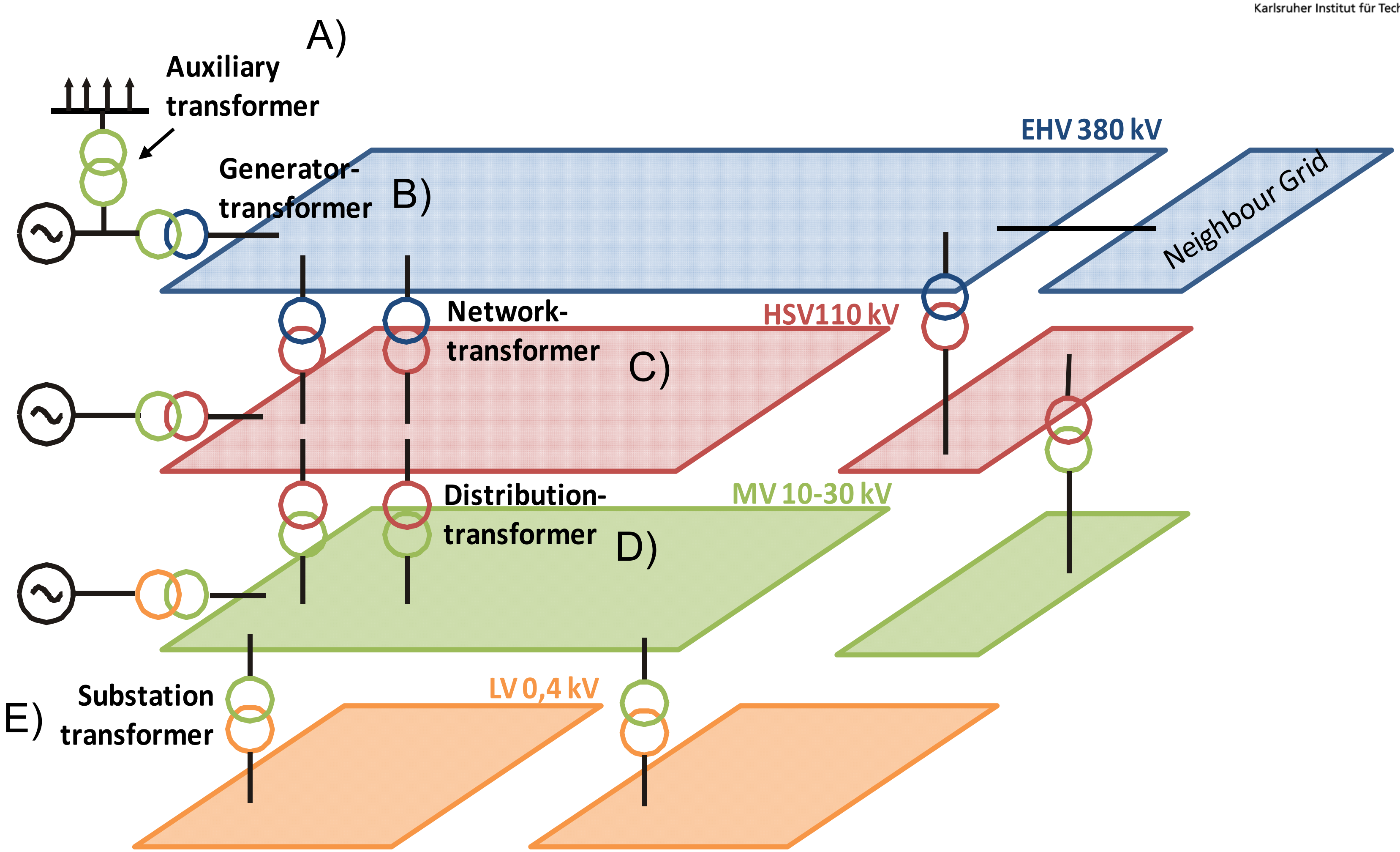
100 MVA → 90 km , 4 mm wide

2.7 Mio.€ for HTS wire

# Motivation of Superconducting Transformers

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

# Application of Transformers?

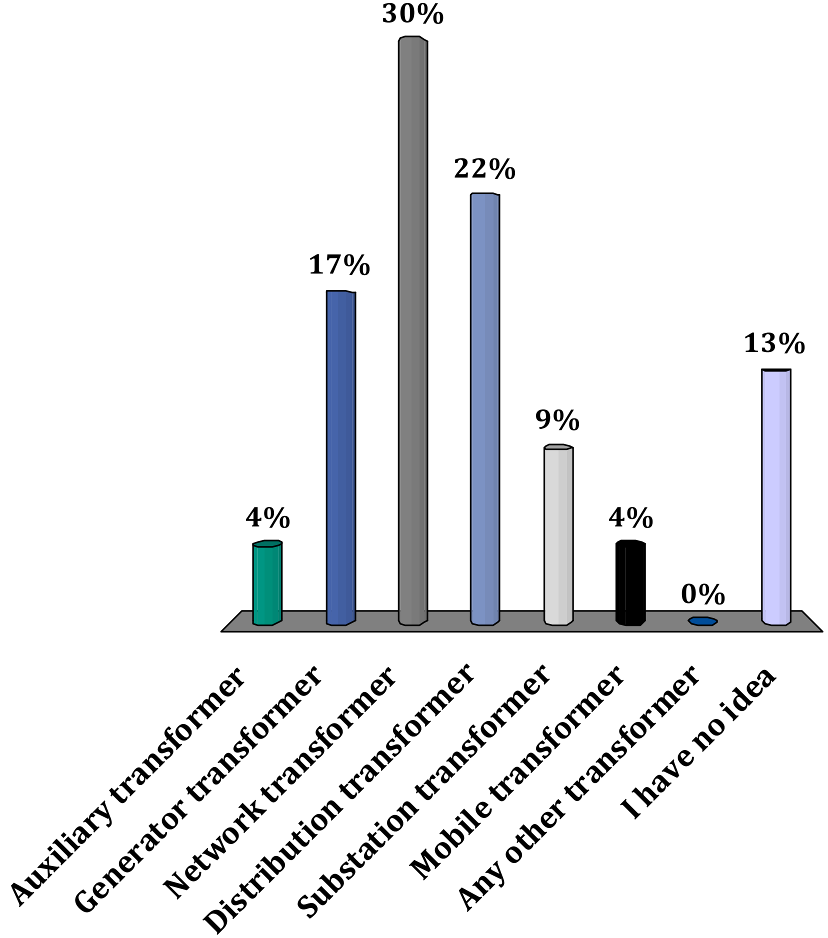



Many potential applications but which one is attractive enough?

## Application of Transformers?

**You are lucky and you can choose any application for a superconducting transformer. With which application would you start?**

A. Auxiliary transformer
B. Generator transformer
C. Network transformer
D. Distribution transformer
E. Substation transformer
F. Mobile transformer
G. Any other transformer
H. I have no idea



# Motivation of Superconducting Transformers

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

# 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!