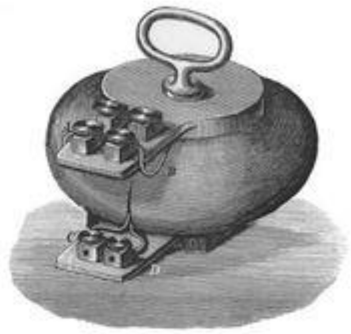
Superconducting Transformer

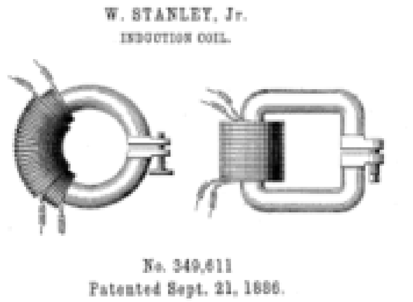
1. History and motivation
2. Different design principles
3. Equivalent circuit
4. Loss calculation
5. State of the Art and application examples

History

- 1831 Michael Faraday - Electromagnetic induction
- 1884 Károly Zipernowsky, Miksa Dén, Ottó Titusz Bláthy – Synchronous converter



- 1885 William Stanley – Further development



- 1888 Gisbert Kapp – Fundamental work on theory of transformers
- 1891 Michael von Dolivo-Dobrowolski – Delta-wye transformer
- since 1965 Resin casted transformer

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/4545 A	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

Motivation

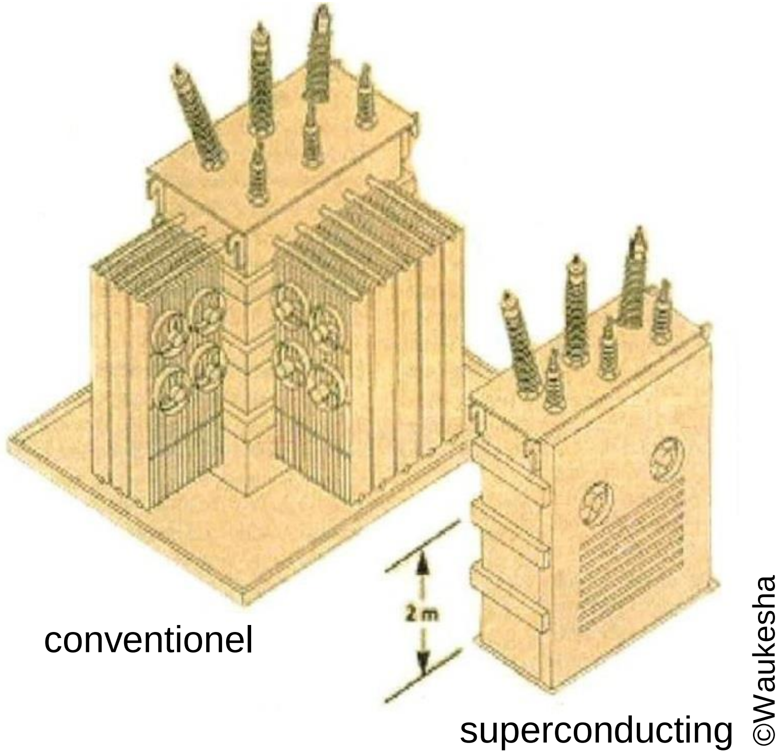
Production and Transport

- Compact and lightweight (approx. 50 %)

Trailer failure left something really big in Kendall County road

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

30 MVA Transformers



Motivation

Production and Transport

- Compact and lightweight (approx. 50 %)

Environment and Marketing

- Energy efficiency (~ 50 %)
- Resource efficiency

Conventional 400 MVA Transformer

Motivation

Production and Transport

- Compact and lightweight (approx. 50 %)

Environment and Marketing

- Energy efficiency (~ 50 %)
- Resource efficiency
- Non flammable (no oil)

Production and Transport

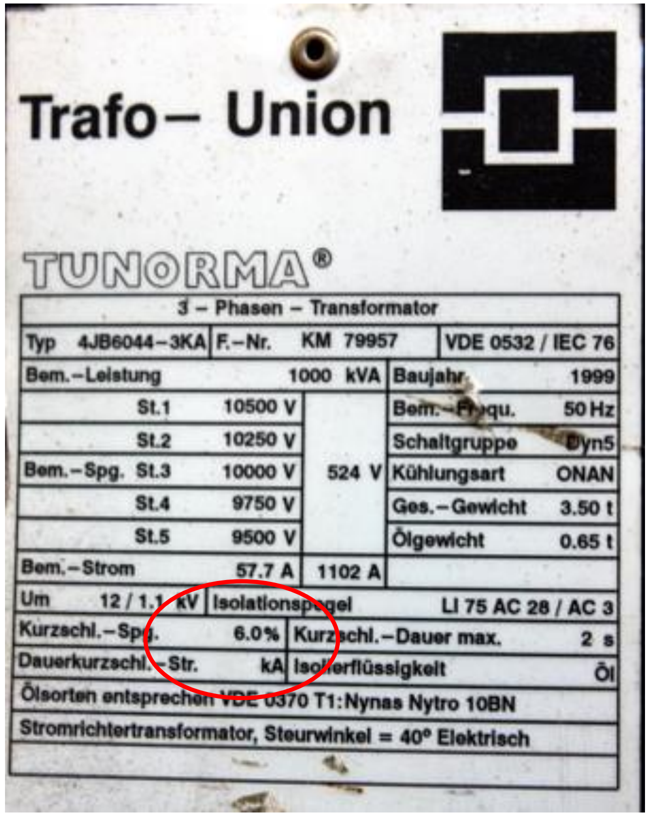
- Compact and lightweight (approx. 50 %)

Environment and Marketing

- Energy efficiency (~ 50 %)
- Resource efficiency
- Non flammable (no oil)

Operating behavior

- Low short-circuit impedance
  - High stability
  - Lower voltage drops
  - Lower reactive power



Motivation

Production and Transport

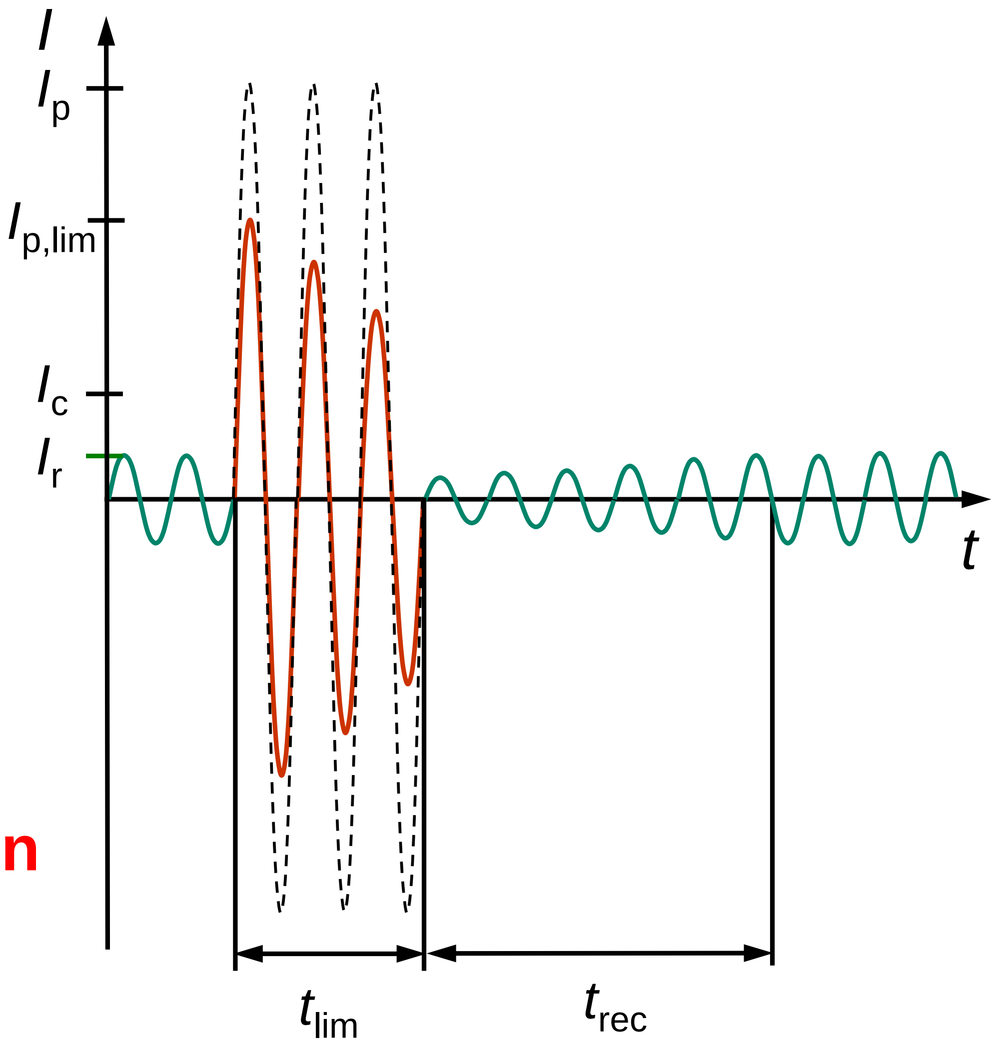
- Compact and lightweight (approx. 50 %)

Environment and Marketing

- Energy efficiency (~ 50 %)
- Resource efficiency
- Non flammable (no oil)

Operating behavior

- Low short-circuit impedance
  - Hight stability
  - Lower voltage drops
  - Lower reactive power
- **Active short-circuit current limitation**
  - Protection of equipment
  - Advantages like a current limiter



Motivation

Conventional Transformer

- ≈ 99,8 % for transformer with S_N > 10 MVA
- ≈ 99,2 % for transformer with S_N > 1 MVA
- $I_{max} \approx 20 \times I_N$ to withstand highest short-circuit currents

Advantages of railway transformer (5-10 MVA)

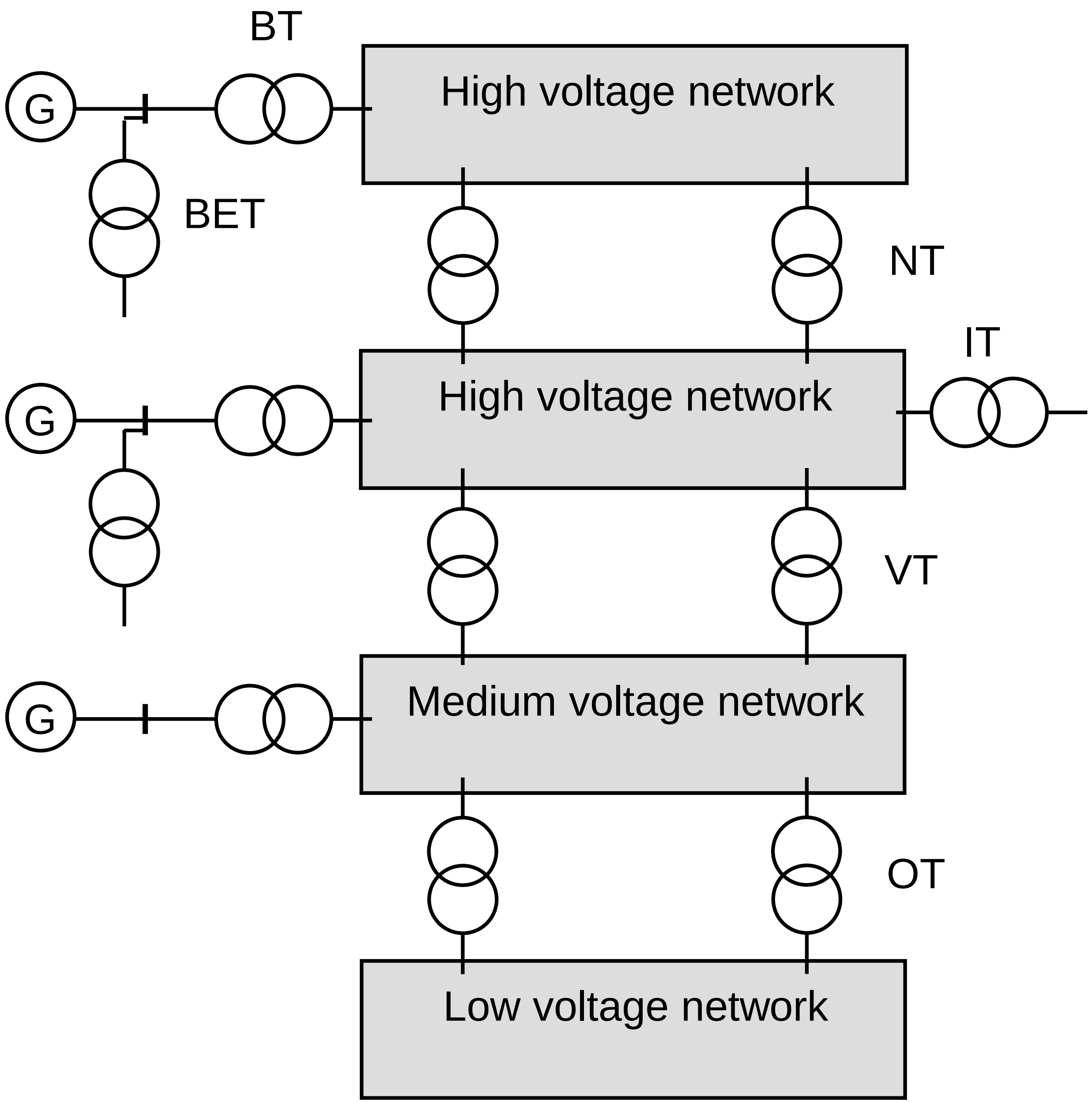
- Weight reduction from 12 t to 7,7 t for 10 MVA
- Increasing efficiency from ca. 90 % to 99 %
- CO_2 reduction of 2200t/train

Advantages of stationary transformer (> 20 MVA)

- Weight reduction > 30 %
- Volume reduction > 40 %
- Loss saving > 35 %
- Oil free transformer

Motivation

Application possibilities



Superconducting Transformer

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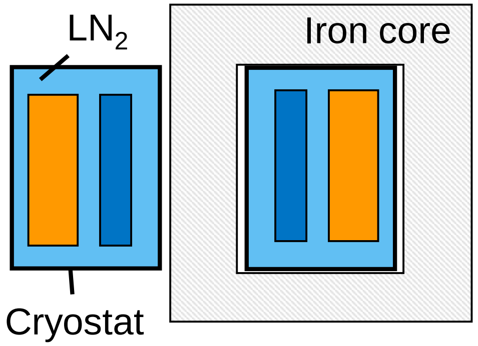
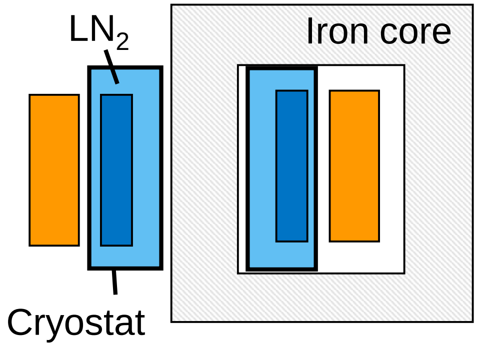
Different designs of HTS transformer

Karlsruhe Institute of Technology

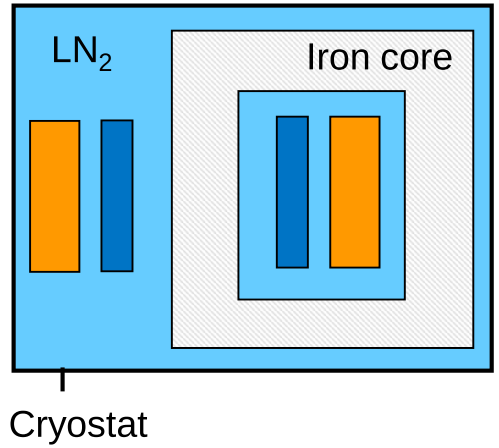
Warm iron core





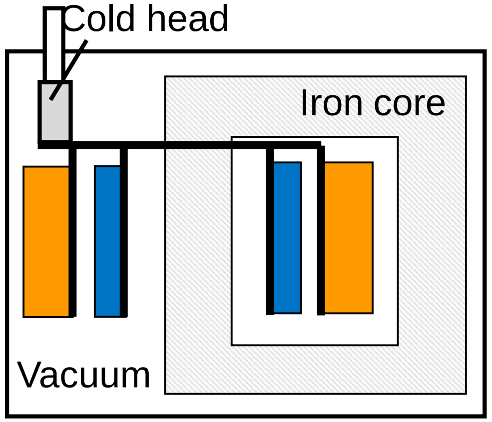
- ☺ Lowest cooling power
- ☺ Iron at RT
- ☹ Expensive cryostat (GRP)
- ☹ 3 cryostats required

Cold iron core



- ☺ Simple metal cryostat
- ☺ Simple cooling interface
- ☹ Iron losses at cryogenic temperatures

Conduction cooled



- ☺ Simple metal cryostat
- ☺ Simple cooling interface
- ☺ Iron at RT
- ☹ Long recooling time after quench
- ☹ temperature gradients
- ☹ not applicable for

  high-voltage level

Superconducting Transformer

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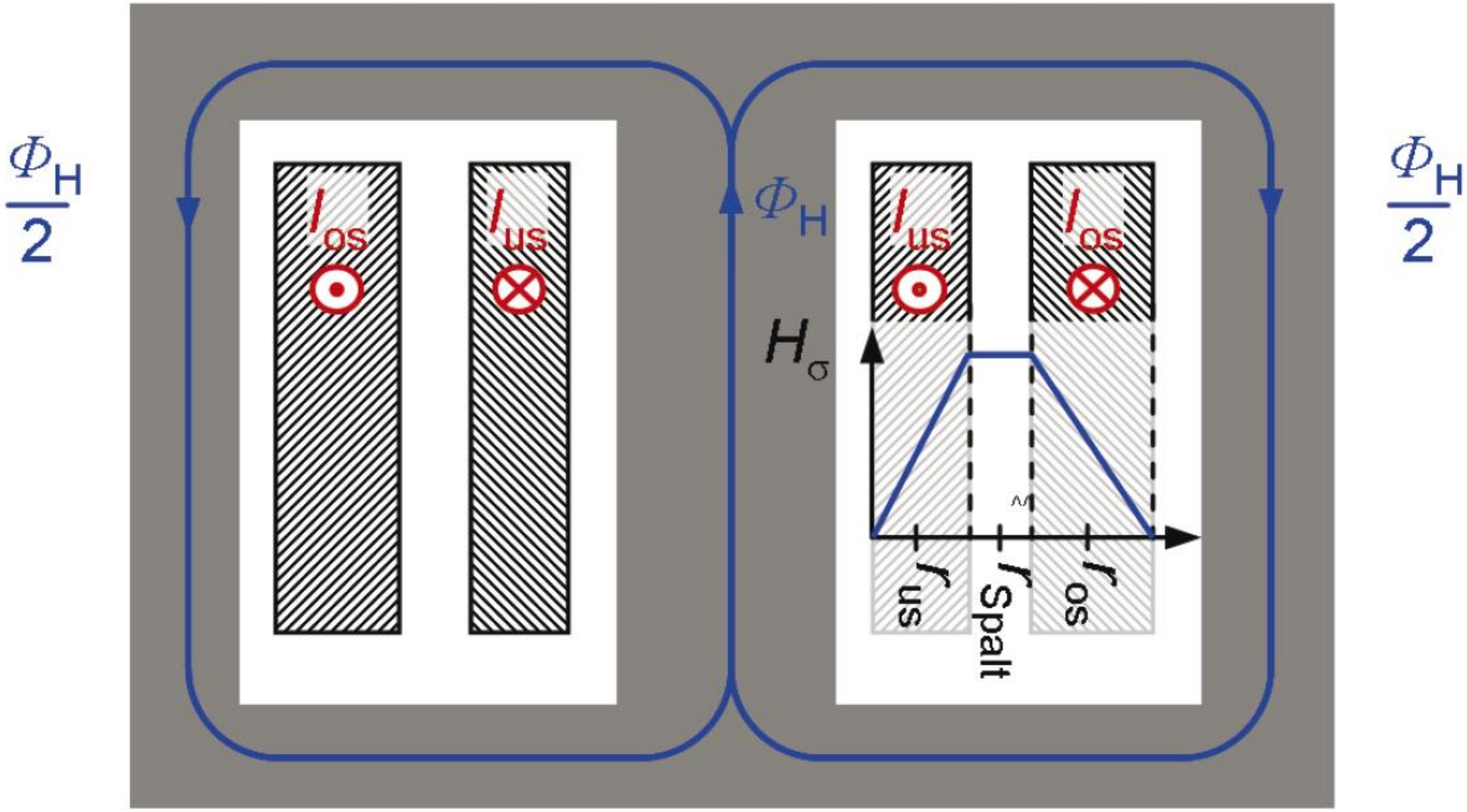
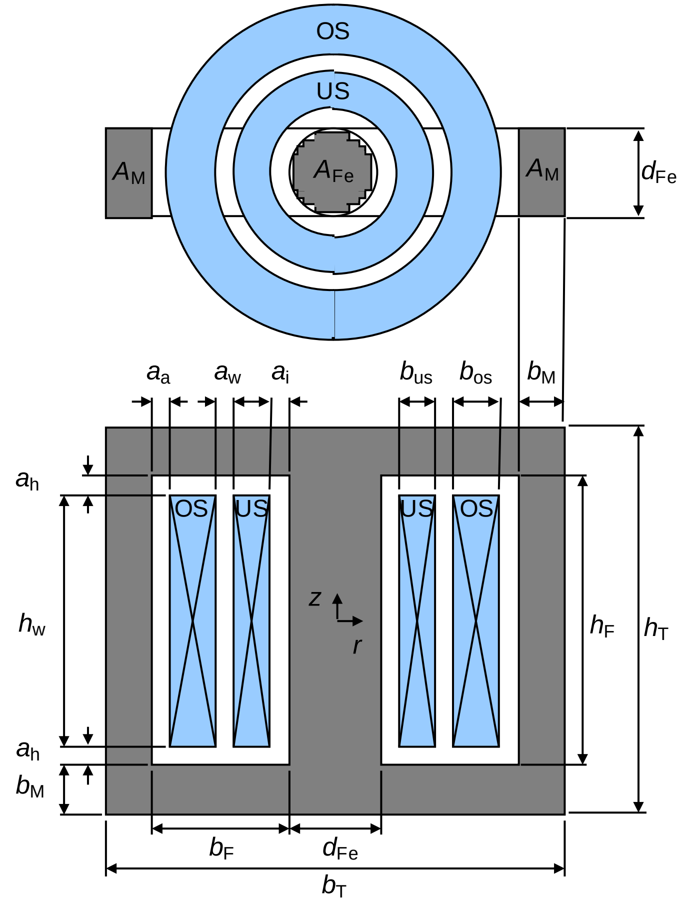
Magnetic flux in transformers



Inductivities in transformer

Mutual inductance

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

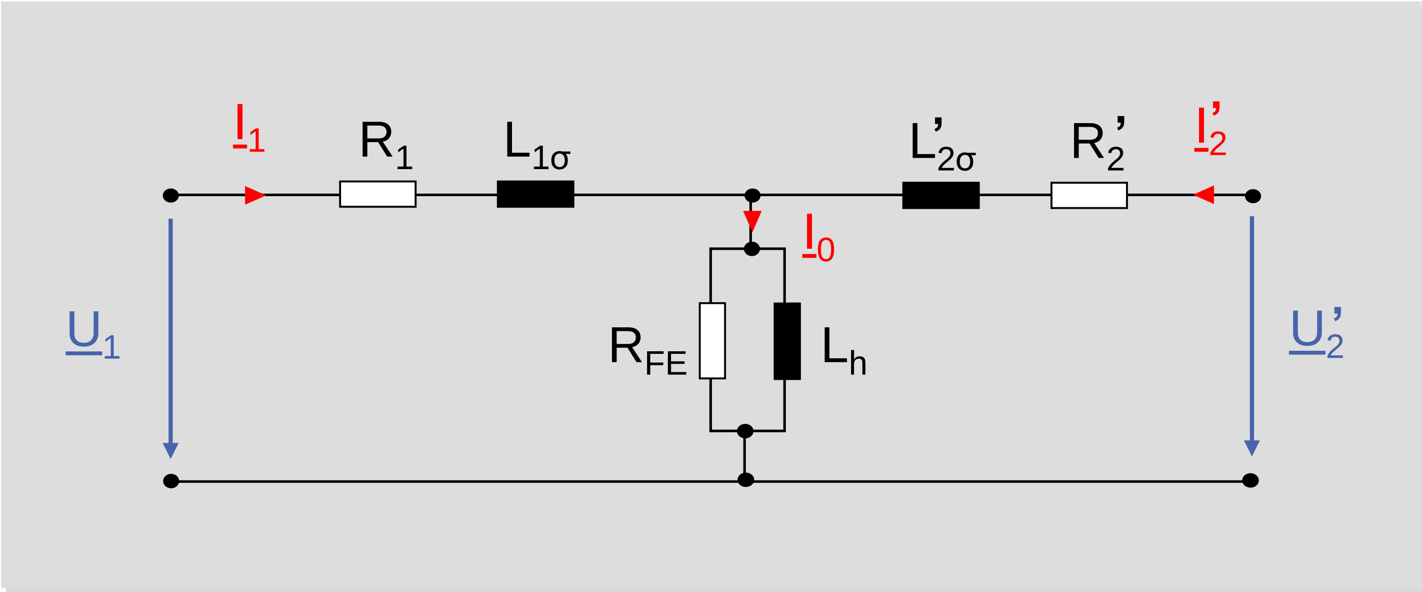


Leakage inductance

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

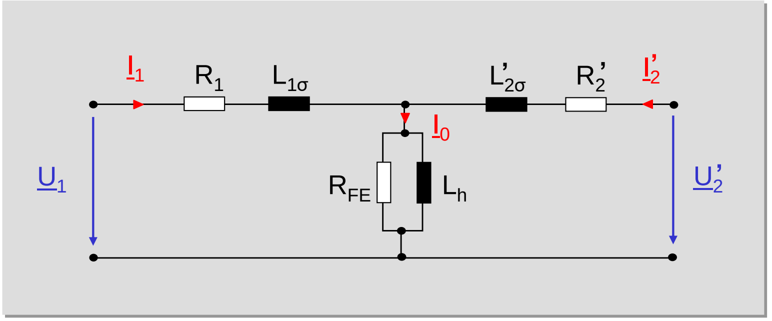
$$r_{\mathrm{os}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}} + \frac{b_{\mathrm{us}}}{2} + a_{\mathrm{w}} + \frac{b_{\mathrm{os}}}{2},\; r_{\mathrm{us}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}} + \frac{b_{\mathrm{us}}}{2} \text{ und } r_{\mathrm{Spalt}} = \frac{d_{\mathrm{Fe}}}{2} + a_{\mathrm{i}}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

Equivalent circuit



What changes in a superconducting transformer?

Power of a transformer



$$S = \frac{U_1 I_1 + U_2 I_2}{2}$$

$$U_1 = \frac{n_1 \omega}{\sqrt{2}} B_{Fe} A_{Fe}$$

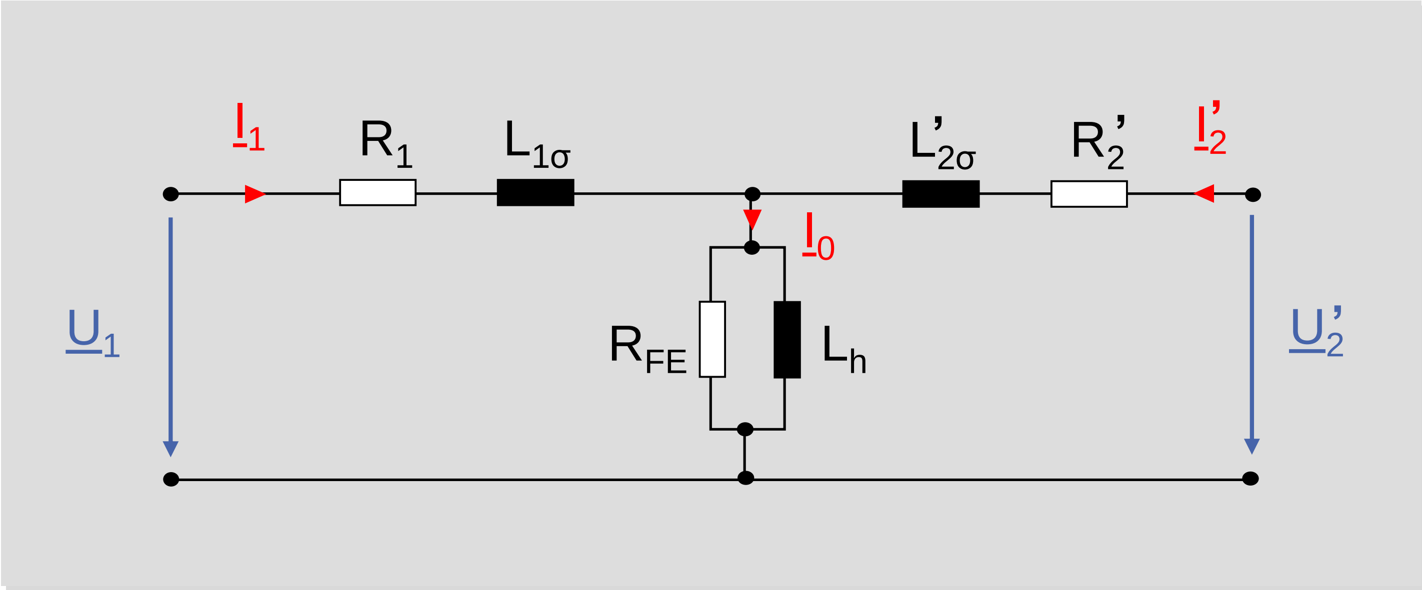
$$S = \frac{\omega B_{Fe} A_{Fe}}{\sqrt{2}} \left(\frac{n_1 I_1 + n_2 I_2}{2} \right)$$

$$n_1 I_1 = n_1 j_1 A_1$$

$$n_2 I_2 = n_2 j_2 A_2$$

$$j_1 = j_2 = j$$

HTS transformer without iron core?



Superconducting Transformer

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Losses in HTS transformer

Short-circuit losses

- P_{AC} AC losses in the superconductor (current dependent)
- P_{SZF} Current lead losses (partially current dependent)
- P_{ZUS} Additional losses (current dependent)

Open-circuit losses

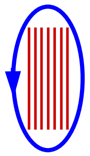
- Eddy current losses (voltage dependent) } P_{FE}
- Hysteresis losses (voltage dependent) } P_{FE}
- P_{Di} Dielectric losses (voltage dependent)
- P_{Th} Thermal losses (not voltage dependent)

AC losses in superconductor

Single tape

- Self-field losses

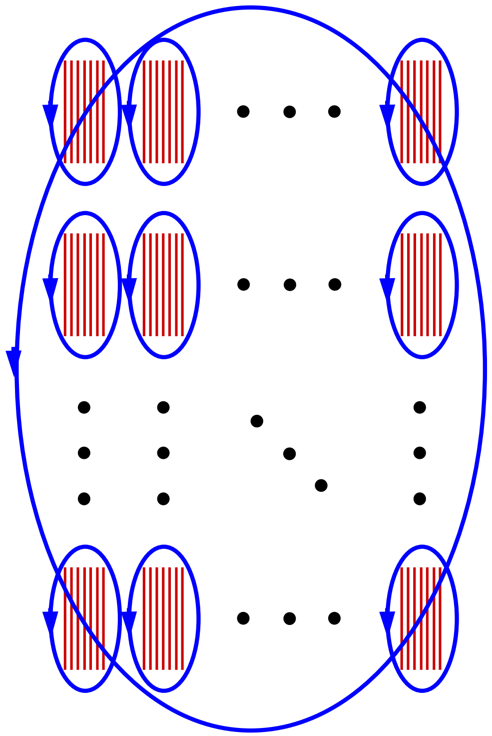
AC losses in superconductor



Tape stack

- Self-field losses
  - Stack factor

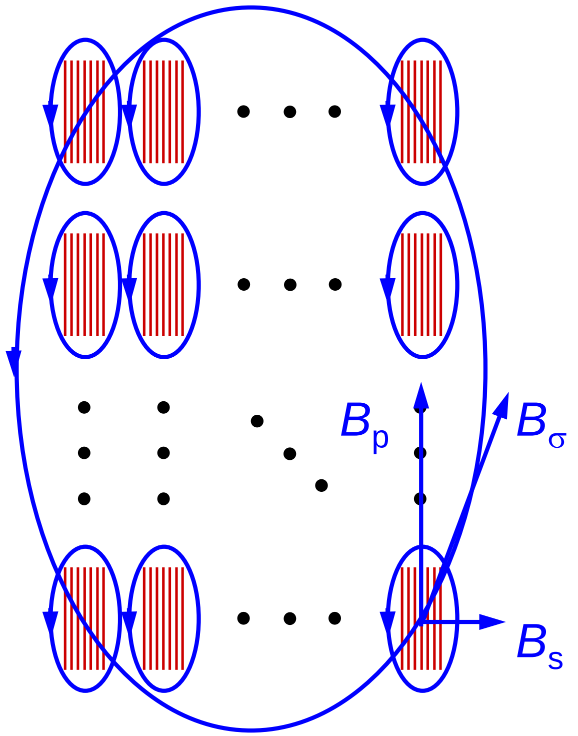
AC losses in superconductor



Winding pack

- Self-field losses
  - Stack factor
- External field losses

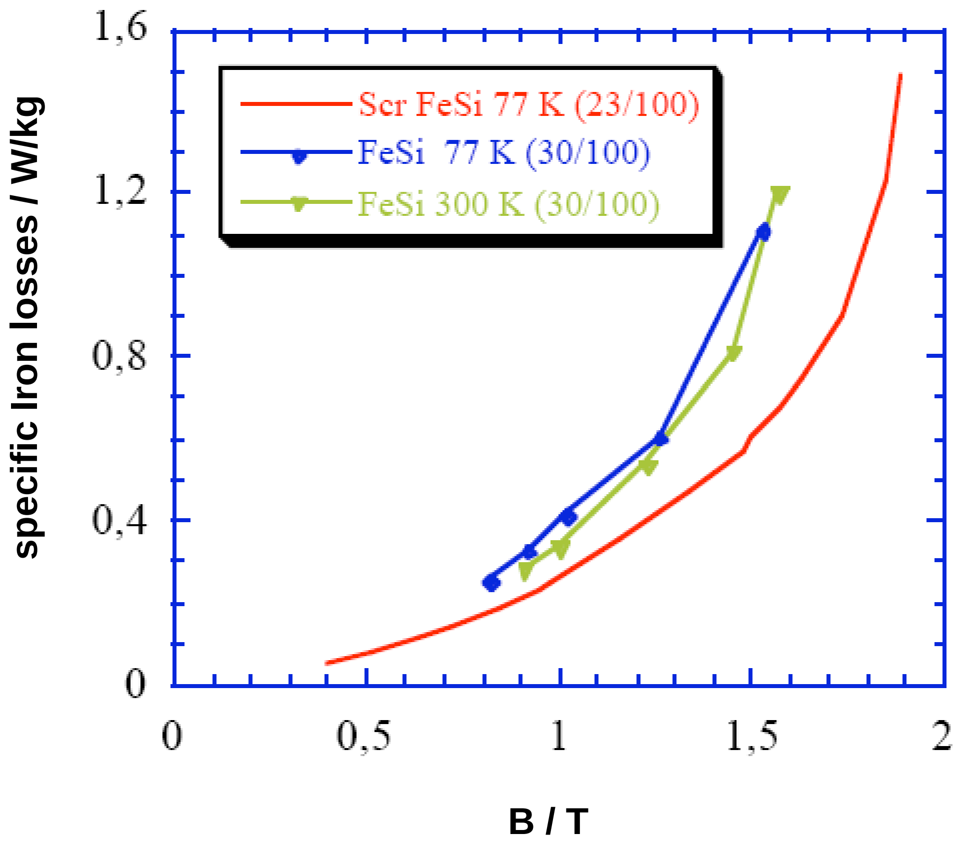
AC losses in superconductor

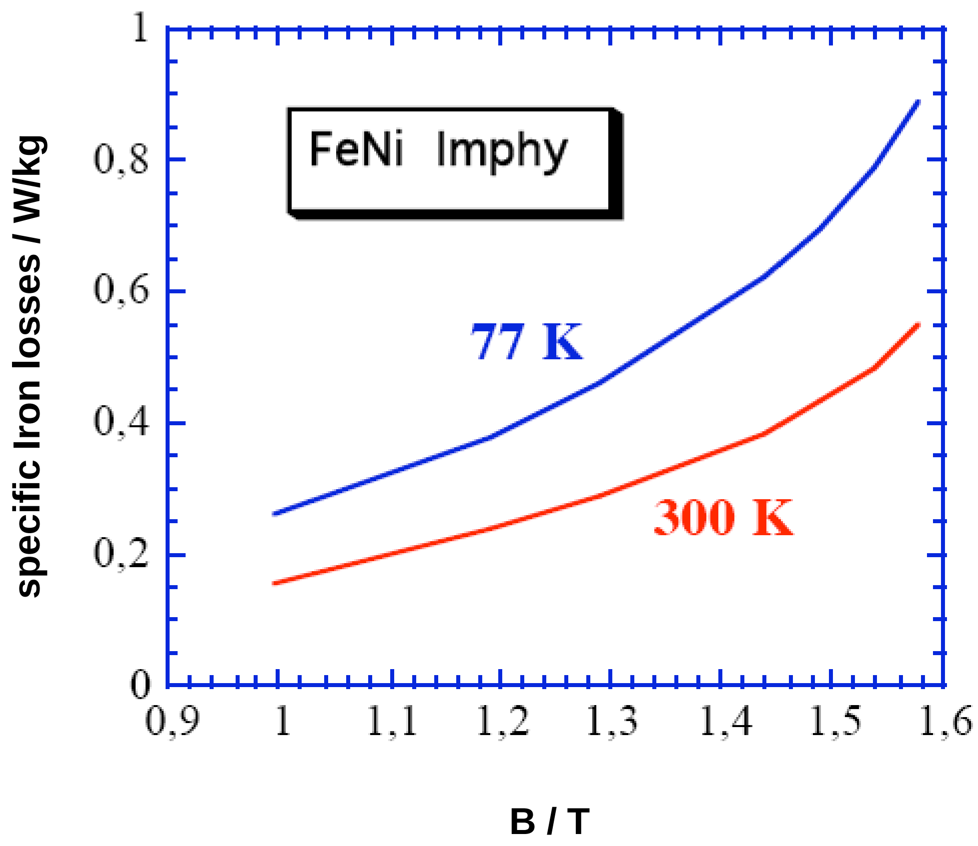


Winding pack

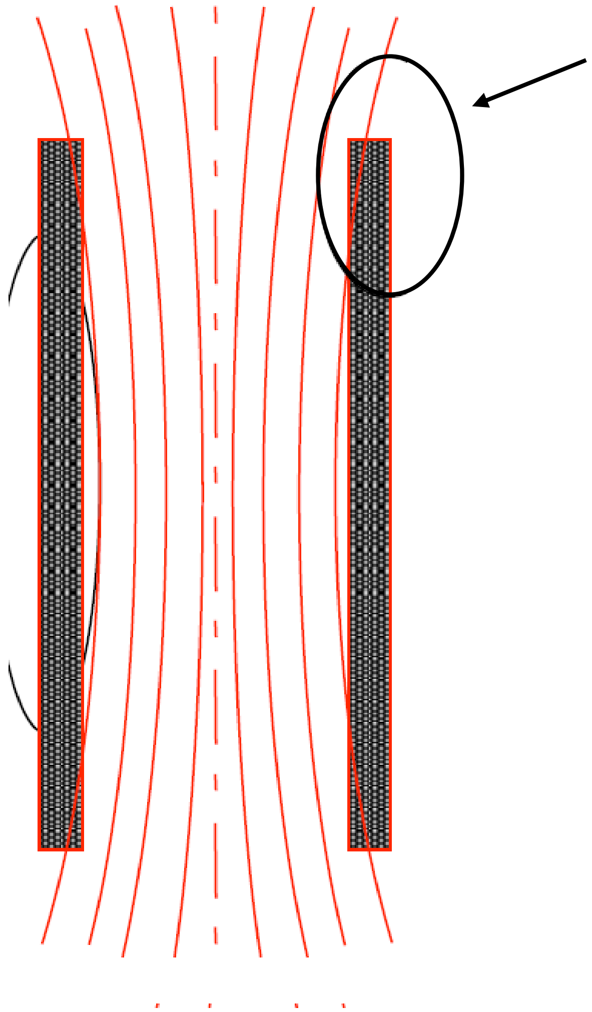
- Self-field losses
  - Stack factor
- External field losses
  - parallel magnetic field density B_p
  - perpendicular magnetic field density B_s

Iron losses at cryogenic temperatures



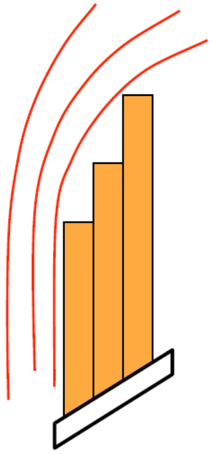


Reduction of AC losses in HTS transformer



Reduction of transversal field by:

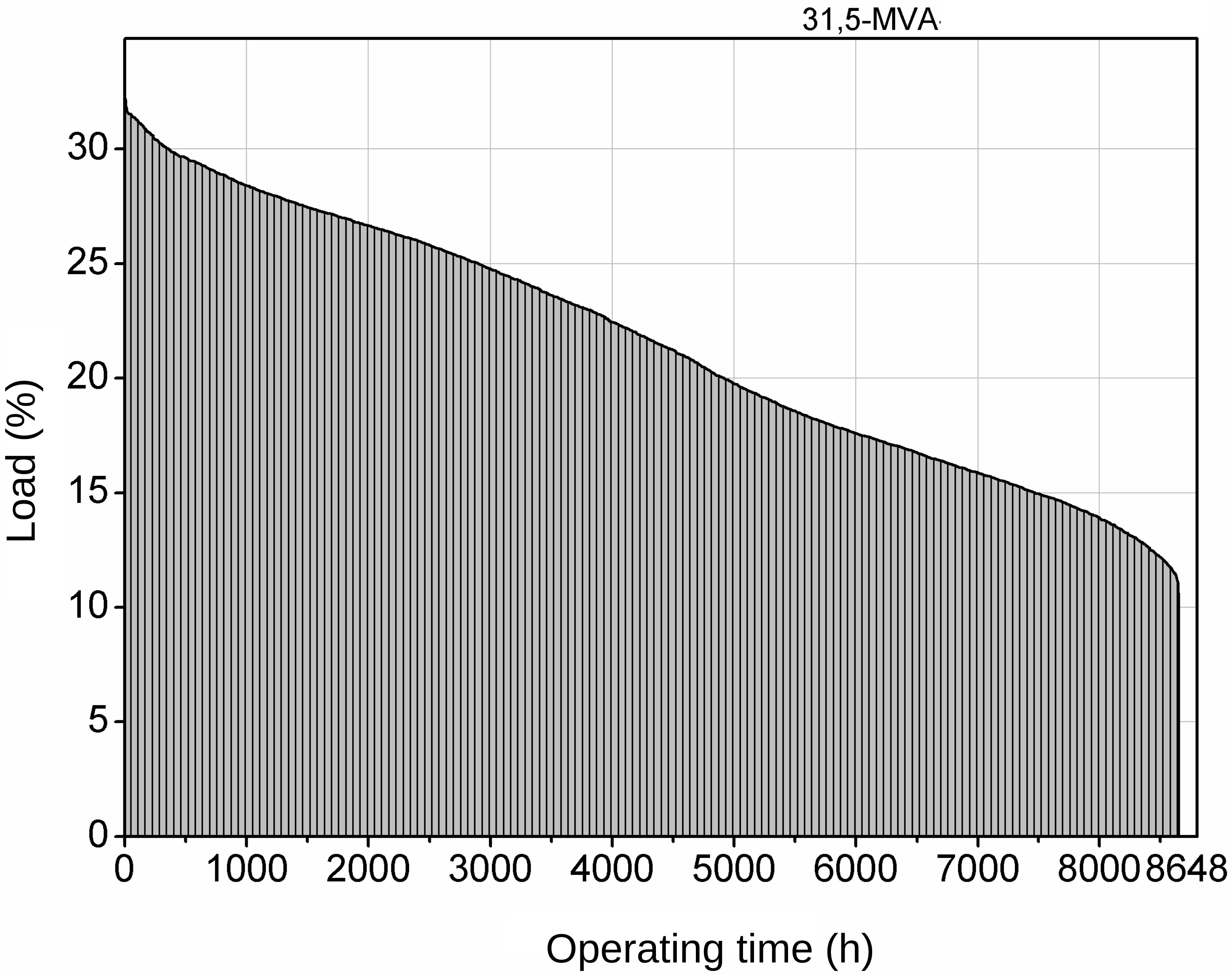
- Flux controling
- Coil geometry at end of coil



Loss calculation – Example
Network transformer

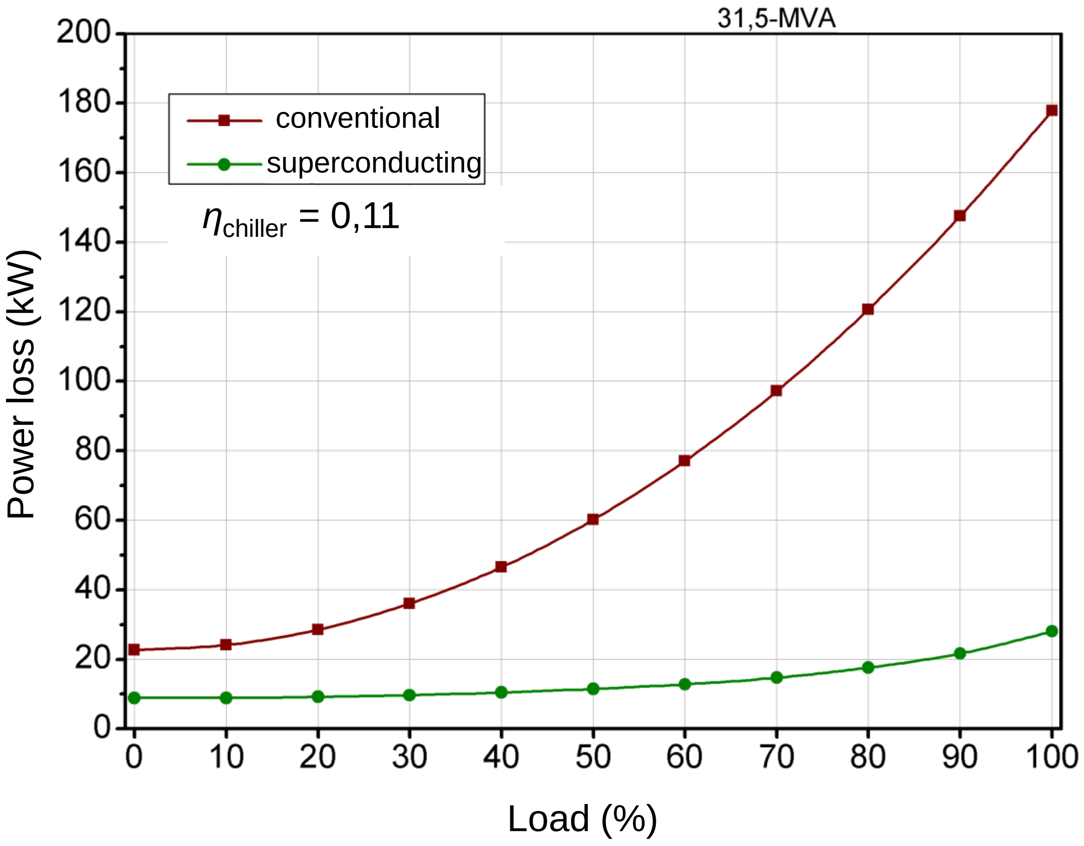
	conventional	superconducting
S_N (MVA)	31,5	
U_{pN} / U_{sN} (kV)	110 / 20 in YNd5-Vector group	
I_{pN} / I_{sN} (A)	165 / 909	
u_k (%)	12,1	7
Current density (A/mm^2)	-	54
Total mass without insulation (kg)	-	12840

Loss calculation – Example network transformer
Annual load profile

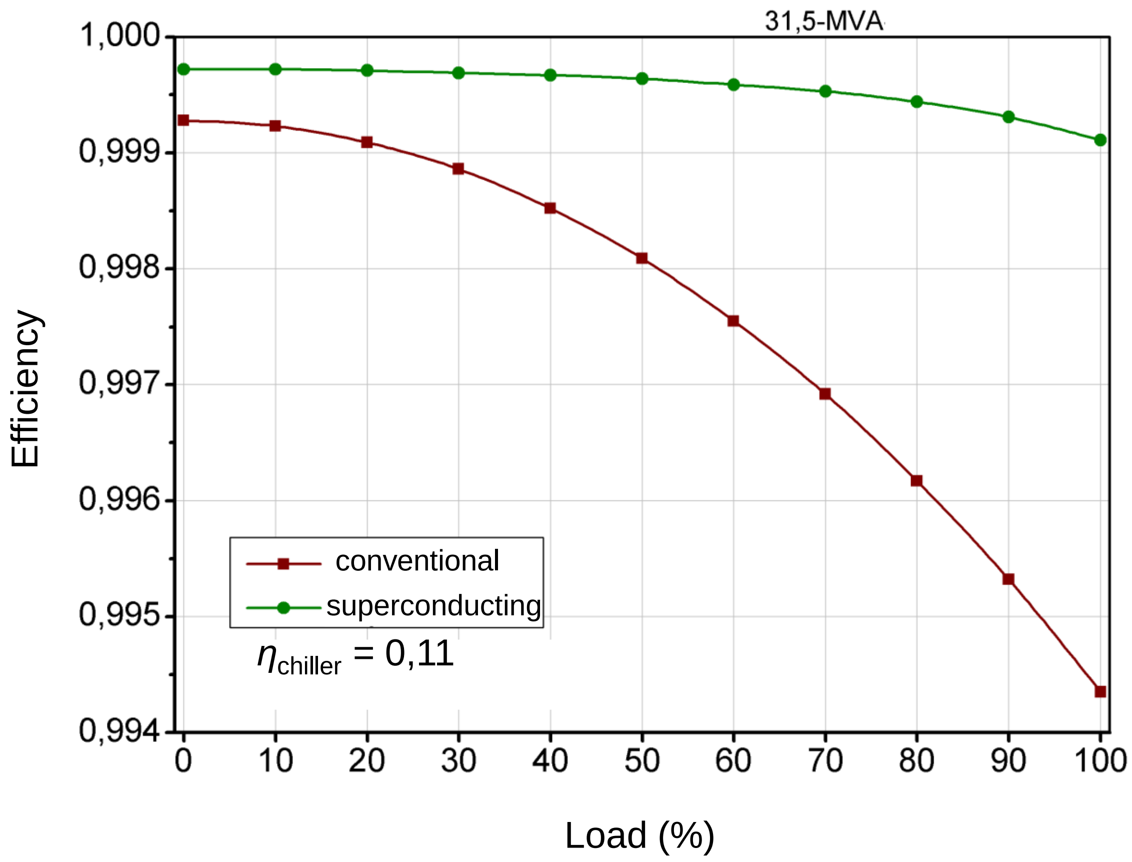


Loss calculation – Example network transformer
Losses and efficiency

Losses

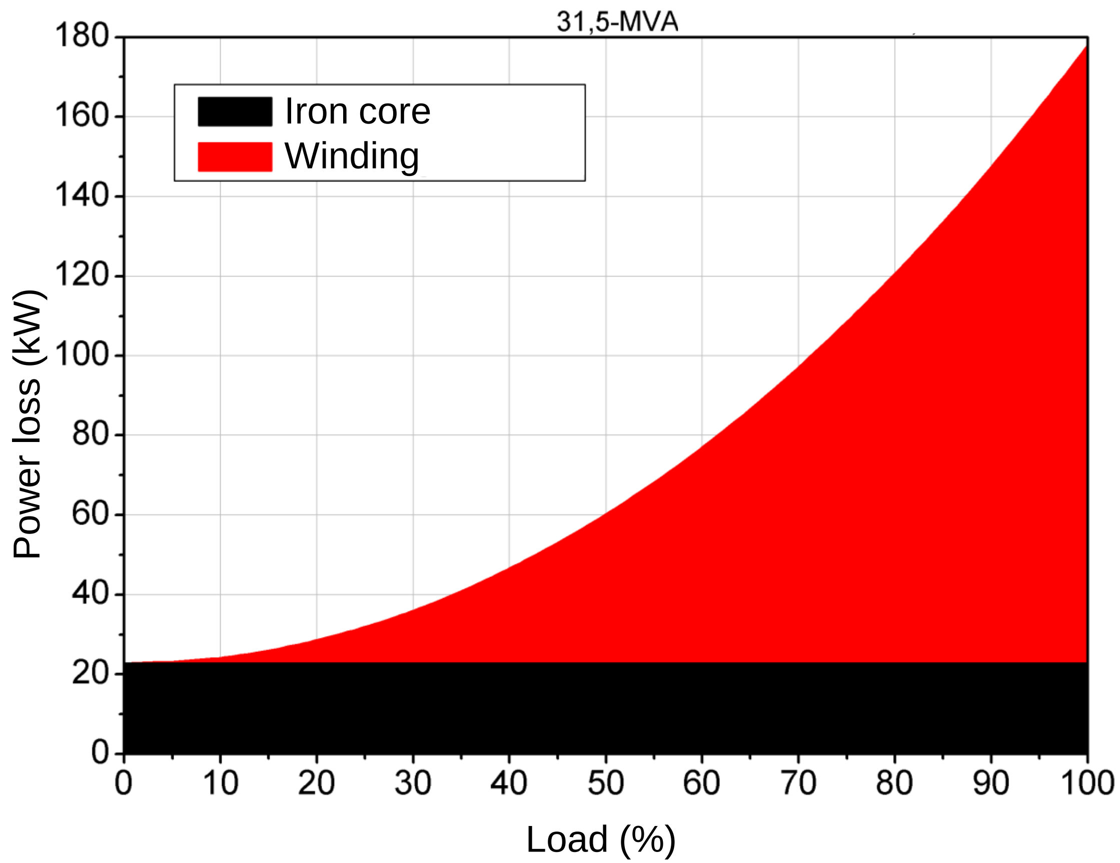


Efficiency

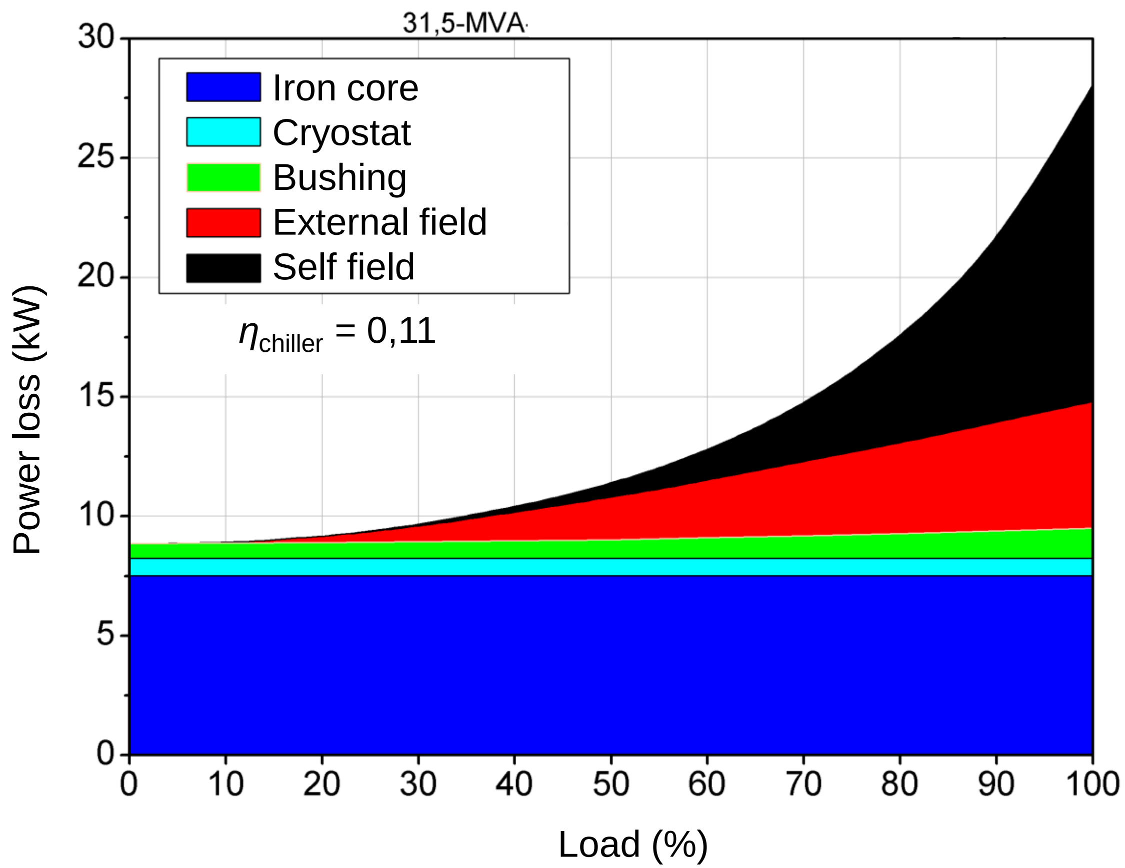


Loss calculation – Example network transformer losses

conventional

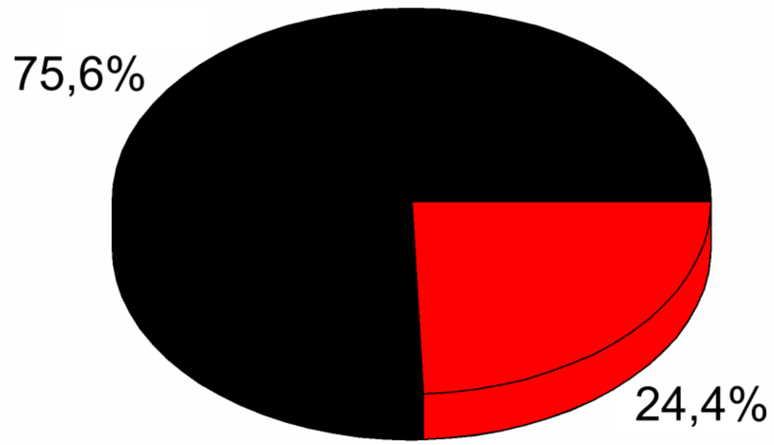


superconducting



Loss calculation – Example network transformer
Annual loss energy shares

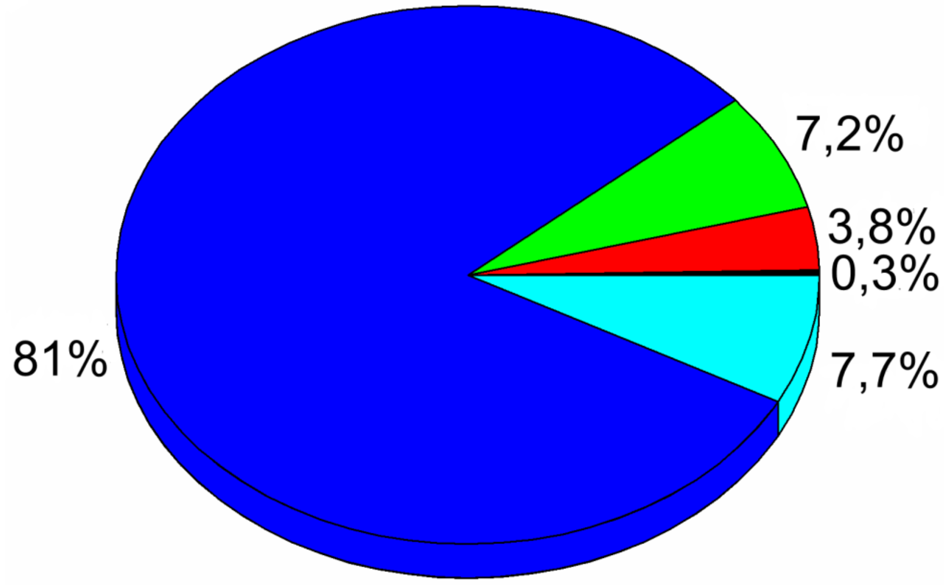
conventional



$$W_{v,tot,conv} = 259{,}4\ \text{MWh}$$
$$\eta_{tot,conv} = 99{,}56\ \%$$

- Iron core losses
- Winding losses

superconducting



$$W_{v,tot,sc} = 80{,}2\ \text{MWh}$$
$$\eta_{tot,sc} = 99{,}86\ \%$$

- Bushing losses
- Iron core losses
- Cryostat losses
- Self field losses
- External field losses

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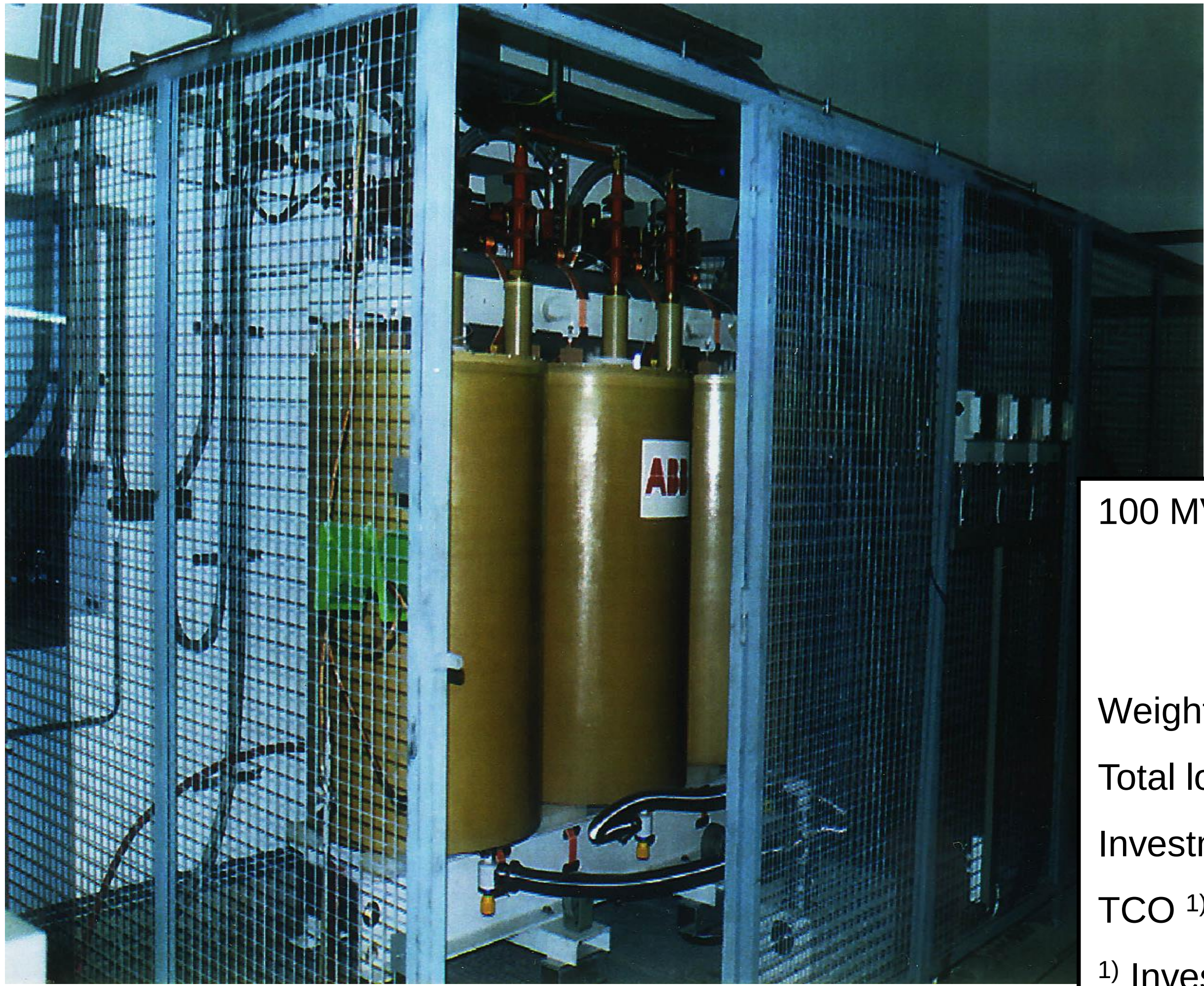
630 kVA Transformer (ABB)

Worldwide first field test of a HTS transformer

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



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

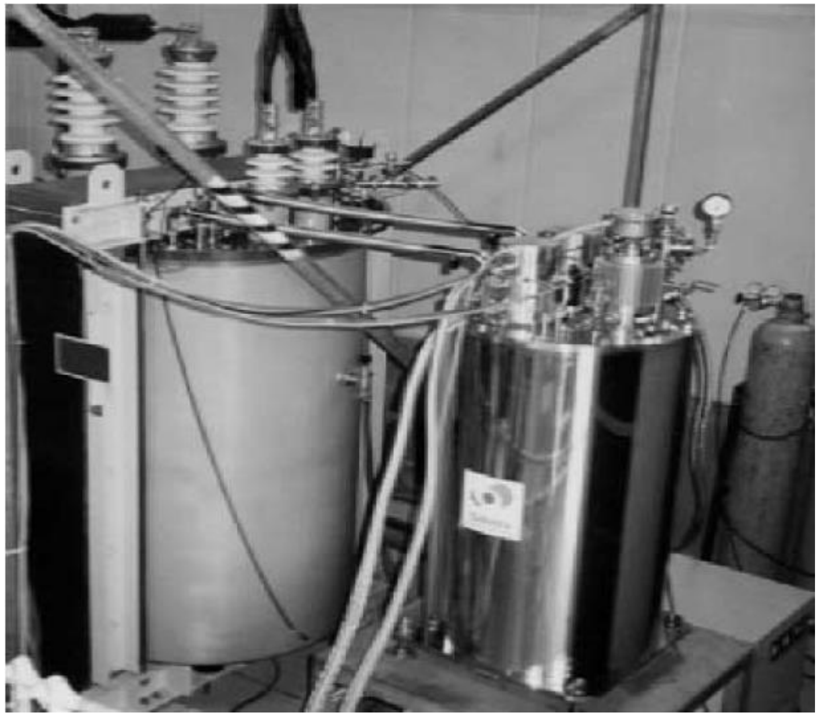
100 MVA – 220/20 kV Transformer

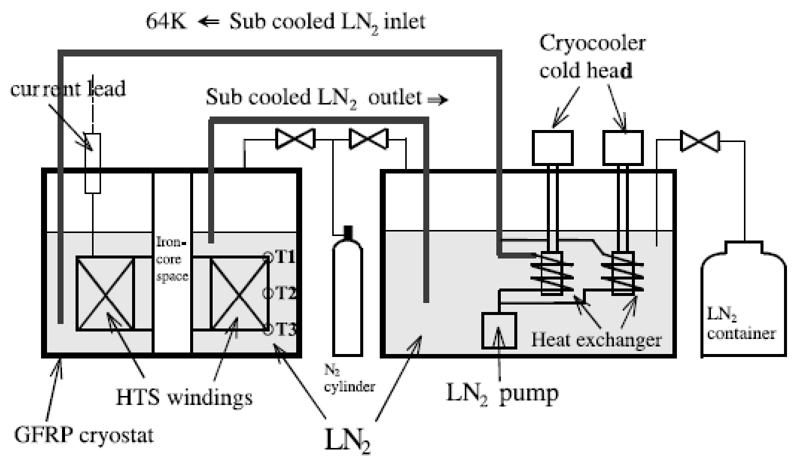
	Conv. (%)	HTS (%)	Saving (%)
Weight	100	46	53
Total losses	100	31	69
Investment	100	100	0
TCO [1)]	100	78	22

[1)] Investment and losses over 20 years

1 MVA Transformer (Kyushu Electric)

- Nominal power: 1 MVA
- Nominal voltage: 22/6,9 kV
- Frequency: 60 Hz
- Short-circuit voltage: $u_k = 5$ %
- Cooling: sub cooled LN_2 at 64 K
- Volume: 1,5 m x 1,2 m x 2,7 m (b x t x h)
- Weight active parts: 5100 kg
- Bi-2223 Superconductor
- Losses: 160 W at 65 K
- Successful field test





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

1 MVA Railway transformer (Siemens)

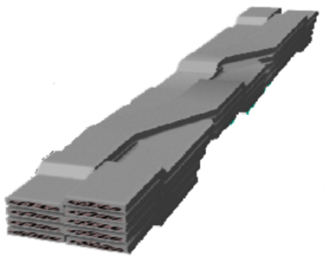
- Rated power: 1 MVA
- Rated voltage: 25/1,4 kV
- Frequency: 50 Hz
- Short-circuit voltage: $u_k = 25$ %
- Cooling: LN_2 at 67 K
- Volume: 0,88 m x 0,406 m x 1,08 m (b x t x h)
- Weight active parts: 1010 kg
- Weight LN_2 tank: 272 kg
- Length of Bi-2223 tape: 6,8 km
- Losses: 1960 W at 67 K
- Efficiency: $\eta = 97,75$ %
- Efficiency of conventional
  railway transformer: $\eta = 92 - 95$ %

1080 mm

880 mm

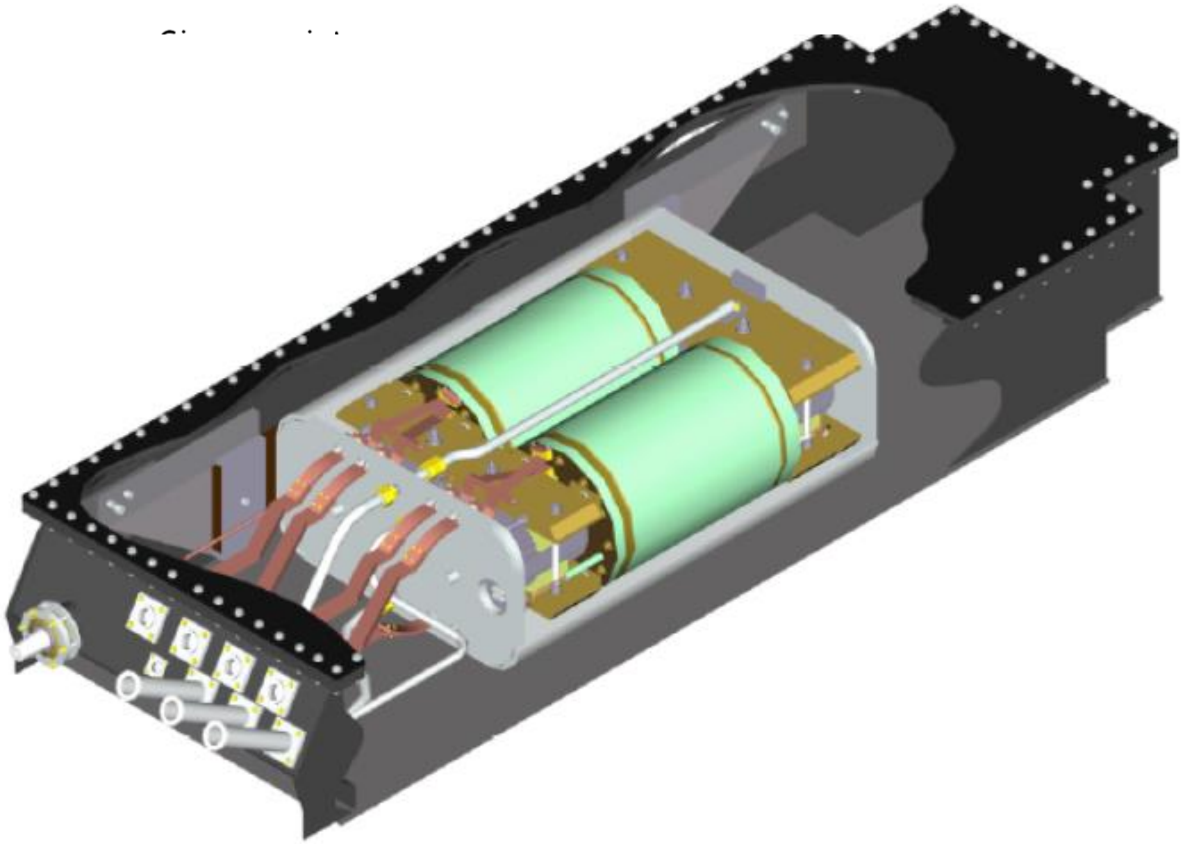
1 MVA Railway transformer (Siemens)

Innovative conductor : transposed Roebel bar

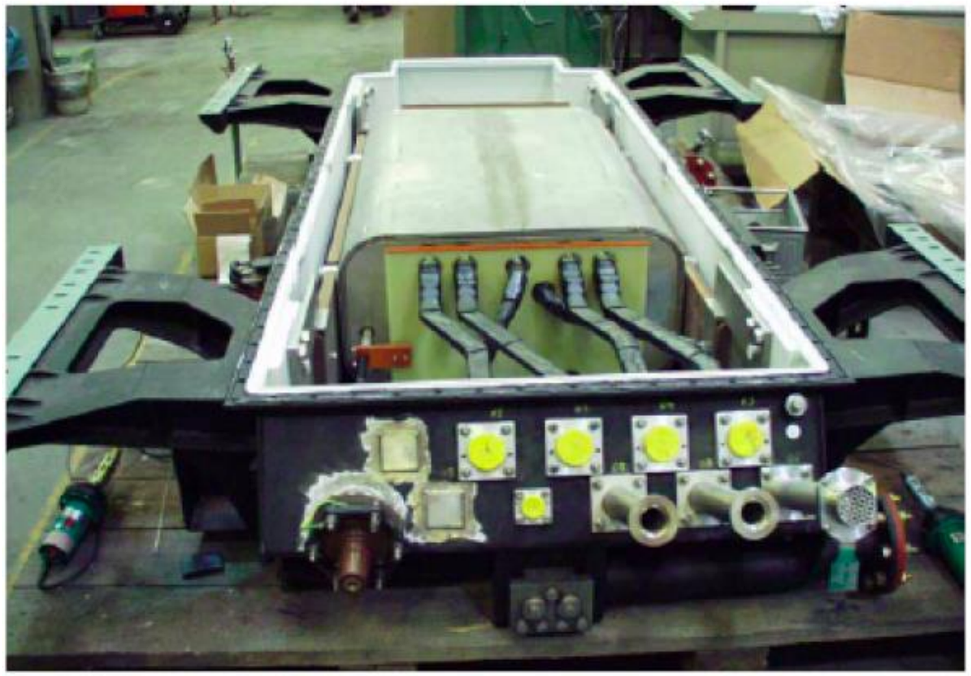


Bi-2223 tapes
(3.65 x 0.258 mm²)

13 strand cable
No cabling I_c degradation



Losses	
Iron losses	700 W
Leakage(Iron)	280 W
Winding and connection	780 W
Thermal losses	200 W
Total losses	1960 W @ 67 K
Total losses	23 kW @ RT
Efficiency	97,75%
Conv. Railway transformer	92-95 %



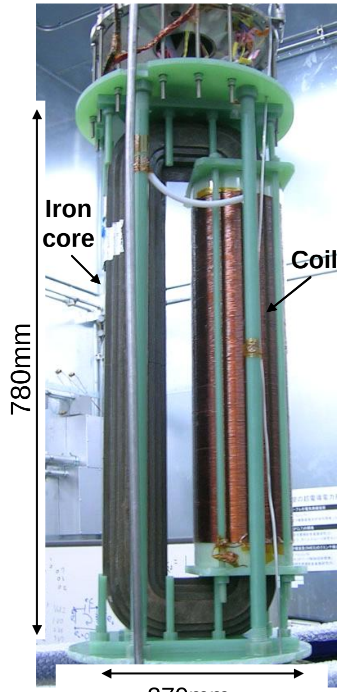
Transformer built into the carrier frame

1 MVA Railway transformer (Siemens)

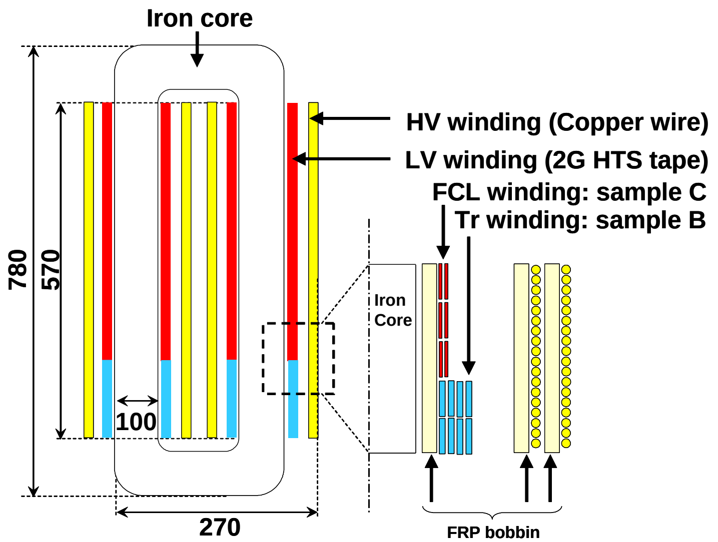
Left: HTS railway transformer
Right: conventional railway transformer

HTS transformer in test rig

Current limiting transformer (U Nagoya)



Power	100 kVA
Voltage	6,6 kV/210 V
Current	8,7 A/275 A
Ratio	1344/74
relative uk	4,6 %
Max. B-Field	1,7 T
Secondary winding	YBCO
Primary winding	Copper



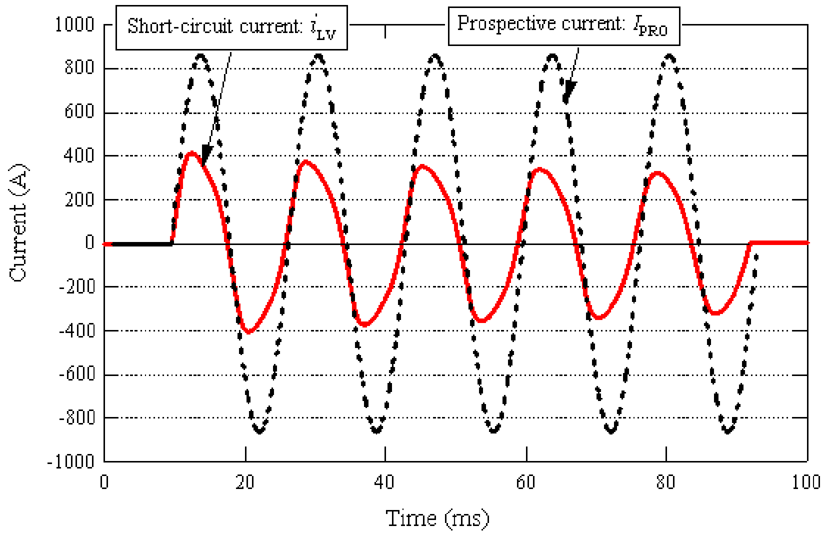


Fig. 5. Current limiting test result at I_{PRO} = 862 A_{peak}.

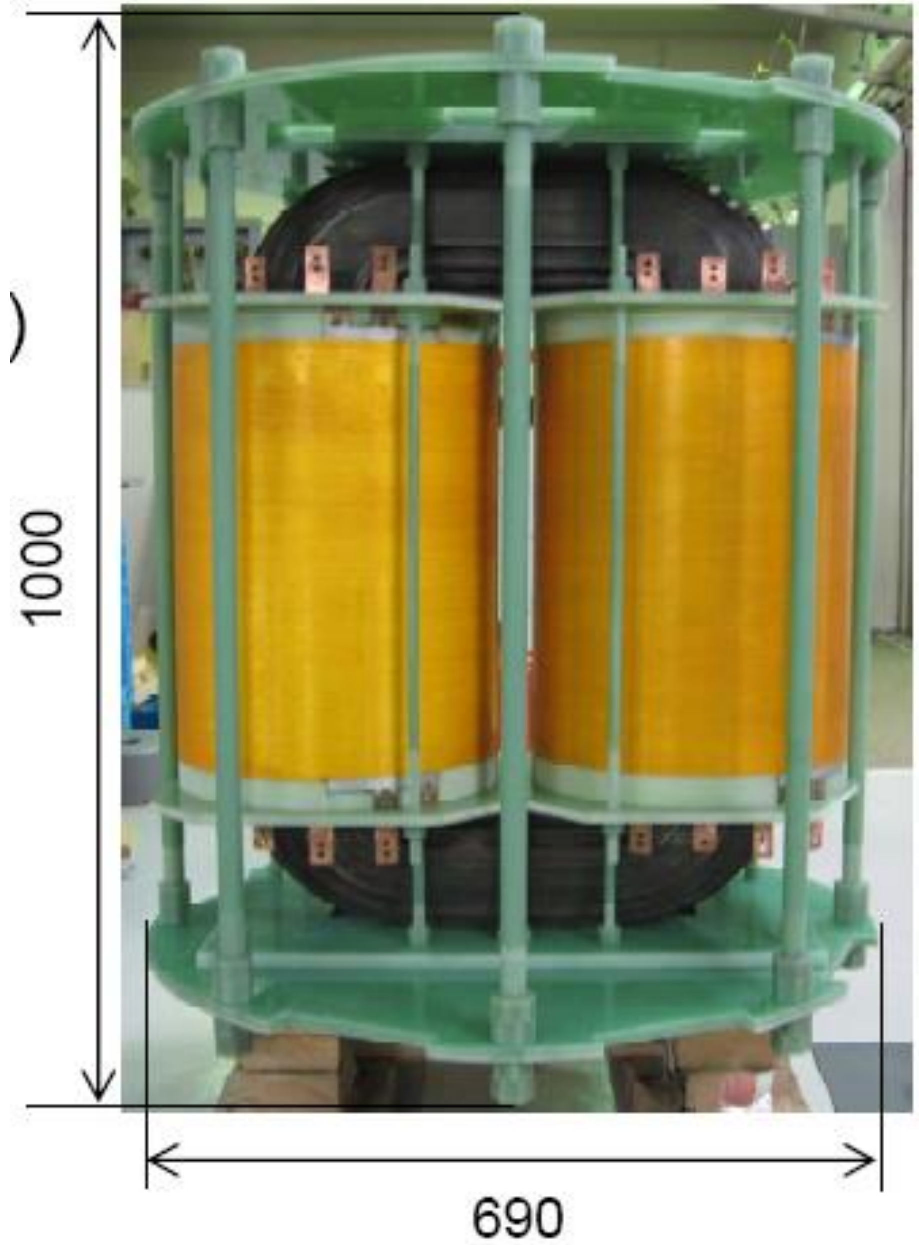
Current limiting transformer (U Nagoya)

2 MVA, 60 Hz

22kV/6,6 kV

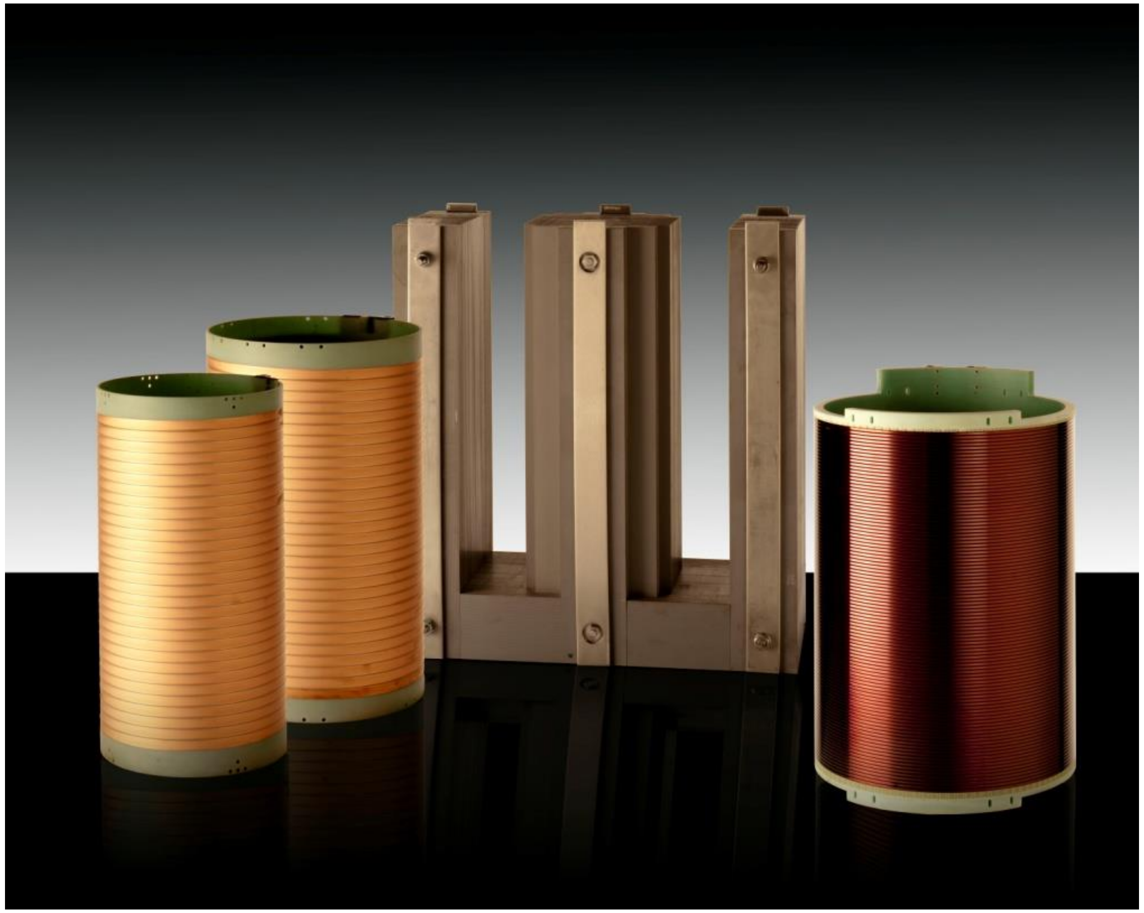
Primary winding Bi 2223

Secondary winding YBCO

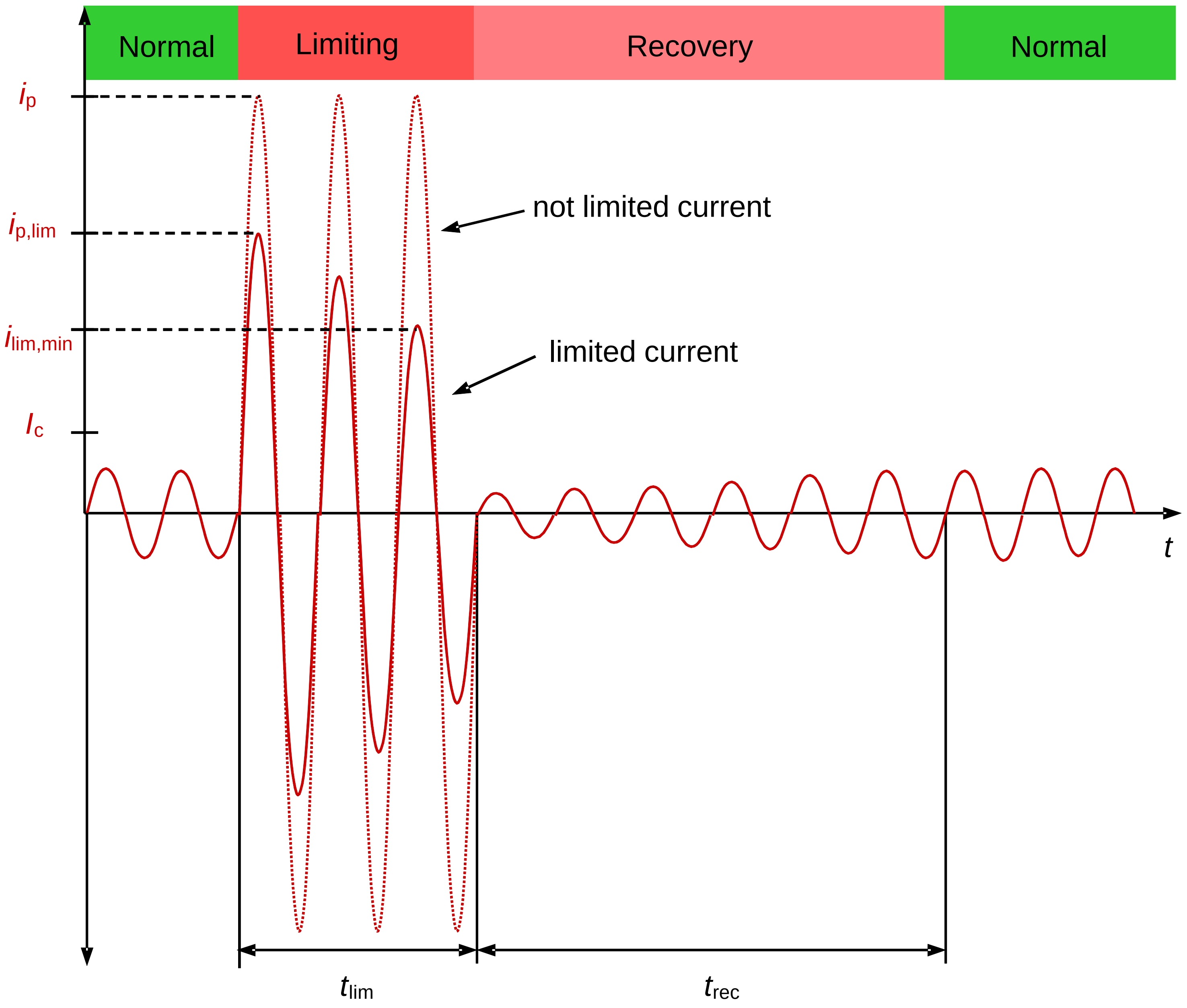


Current limiting transformer (KIT)

60 kVA demonstrator with complete recovery under load

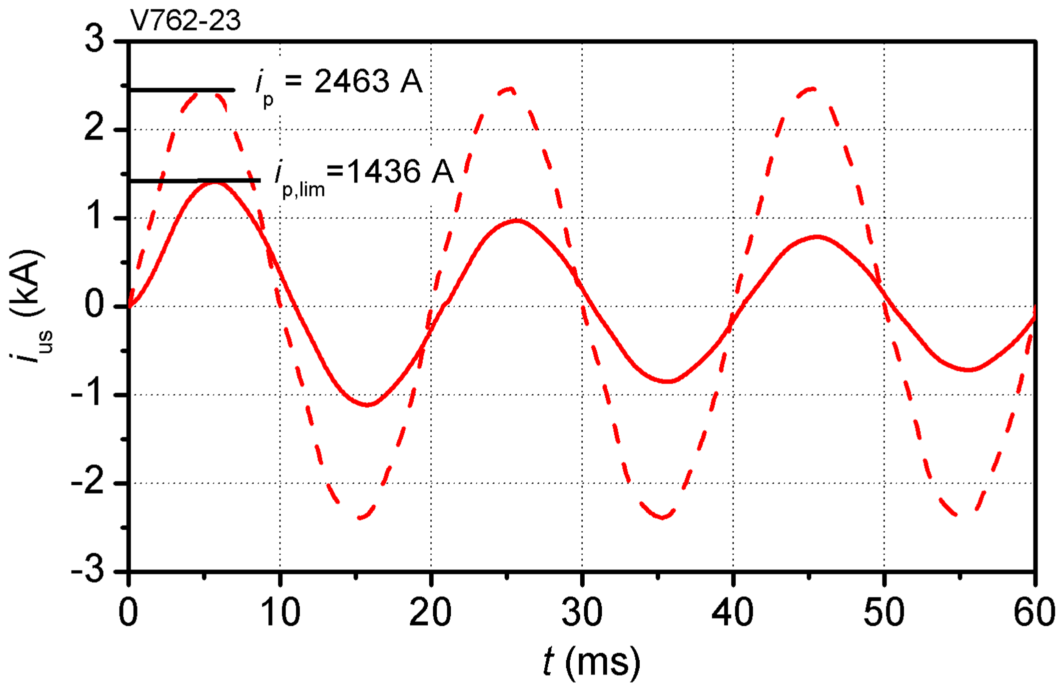


Operating behavior current limiting transformer



Current limiting transformer

60 kVA demonstrator with complete recovery under load



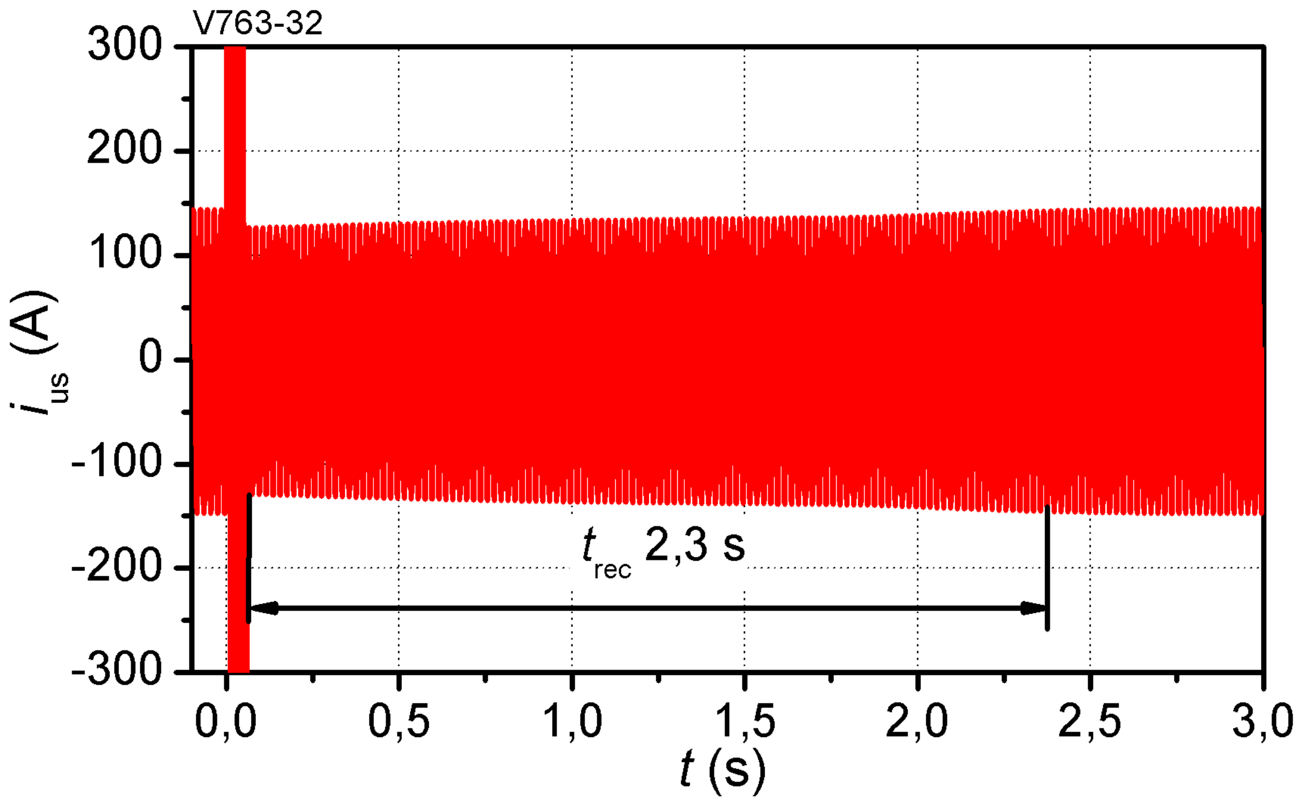
- Highest short-circuit current i_p = 2463 A (17-times rated current)
- Limited short-circuit current $i_{p,lim}$ = 1436 A (10-times rated current)

  ➔ Reduction of short-circuit current to 58 %

- Maximum temperature of superconductor after 60 ms current limiting T_{max} = 186 K

Current limiting transformer

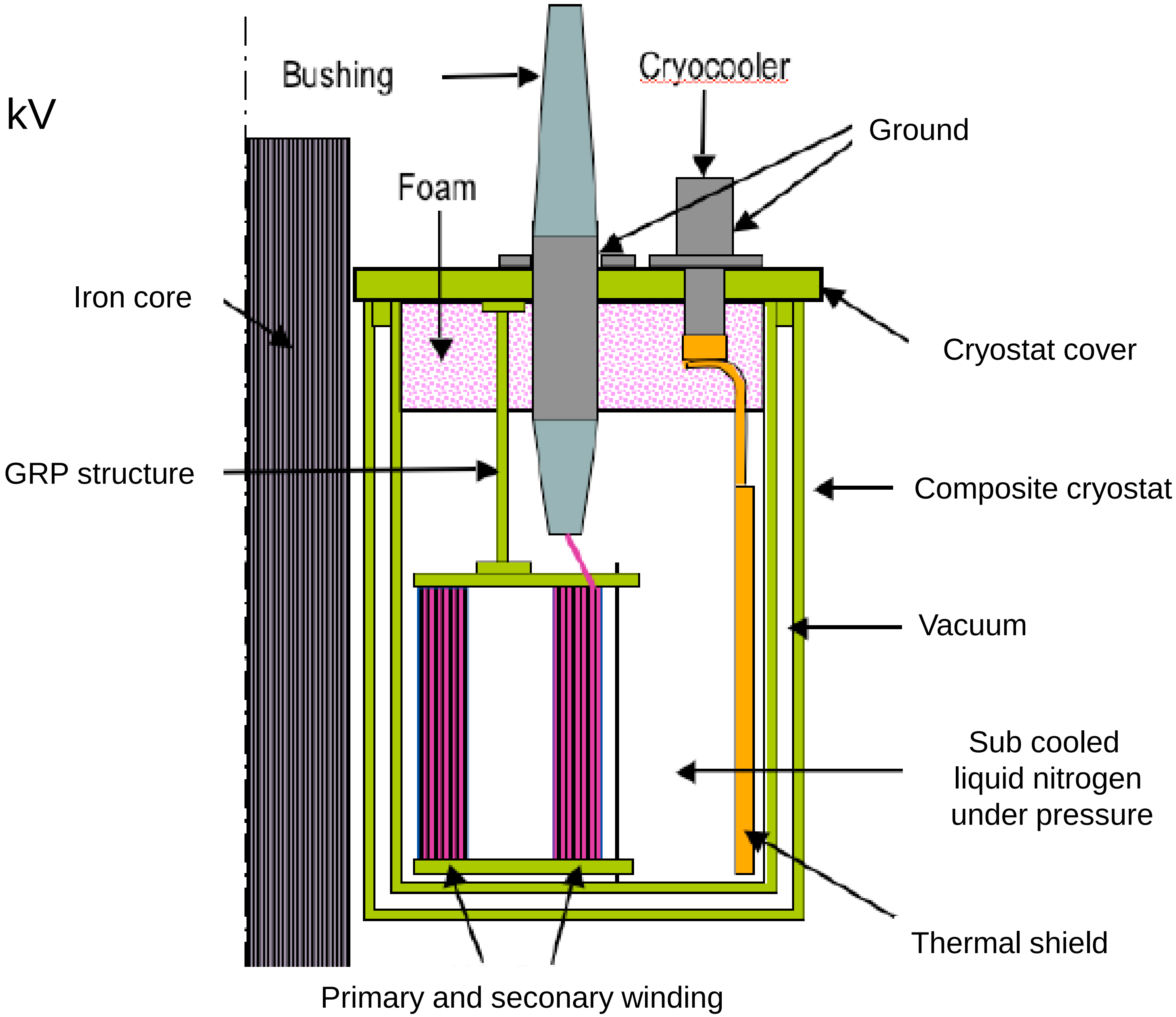
60 kVA demonstrator with complete recovery under load



- Recovery time under rated load t_{rec}(102 A) = 2,30 s

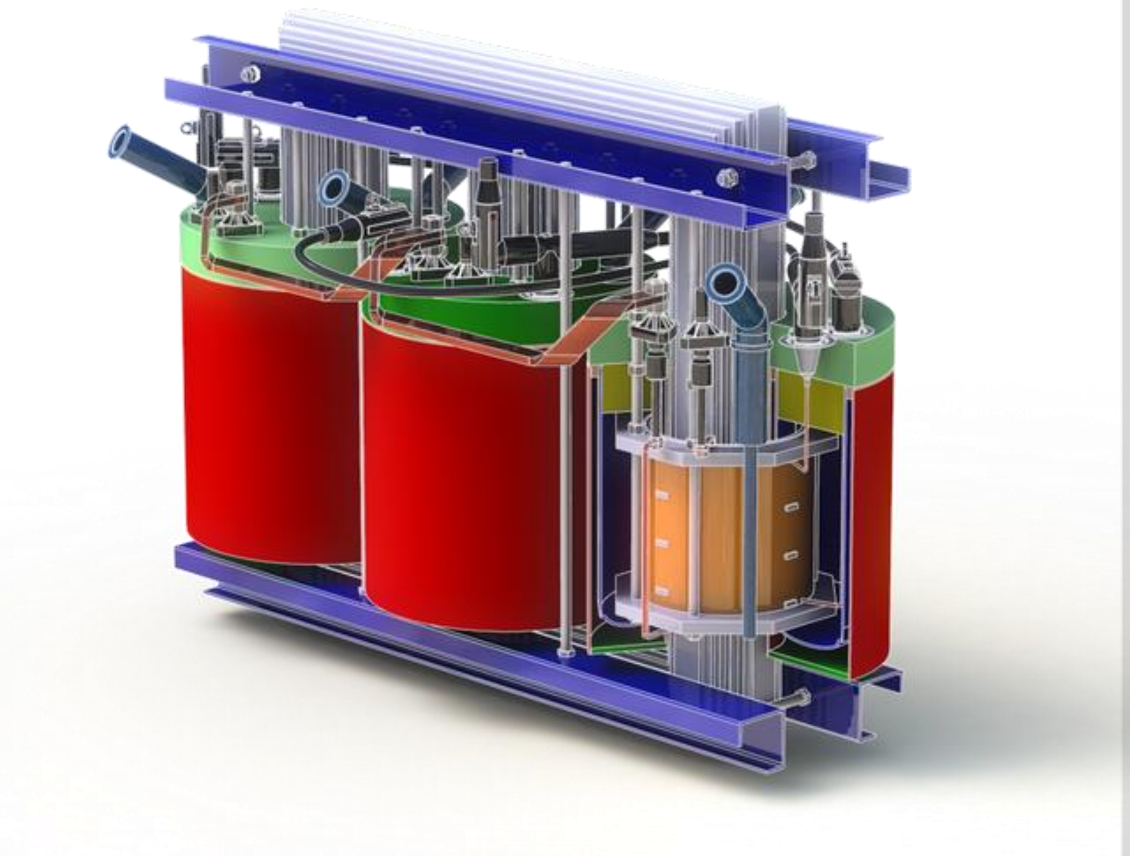
Current limiting transformer (Waukesha, SuperPower)

25 MVA
115 kV / 13,09 kV
72 A / 1103 A



Current limiting transformer (IGC u.a.)

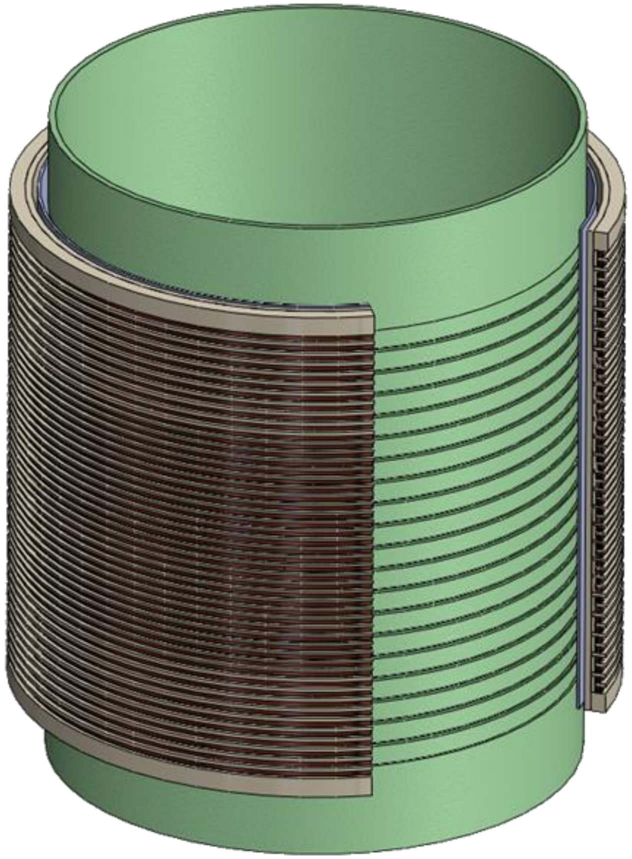
Parameter	Value
Primary Voltage	11,000 V
Secondary Voltage	415 V
Maximum Operating Temperature	70 K, liquid nitrogen cooling
Target Rating	1 MVA
Primary Connection	Delta
Secondary Connection	Wye
LV Winding	20 turns 15/5 Roebel cable per phase (20 turn single layer solenoid winding)
LV Rated current	1390 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



Current limiting transformer (IGC u.a.)

High voltage winding

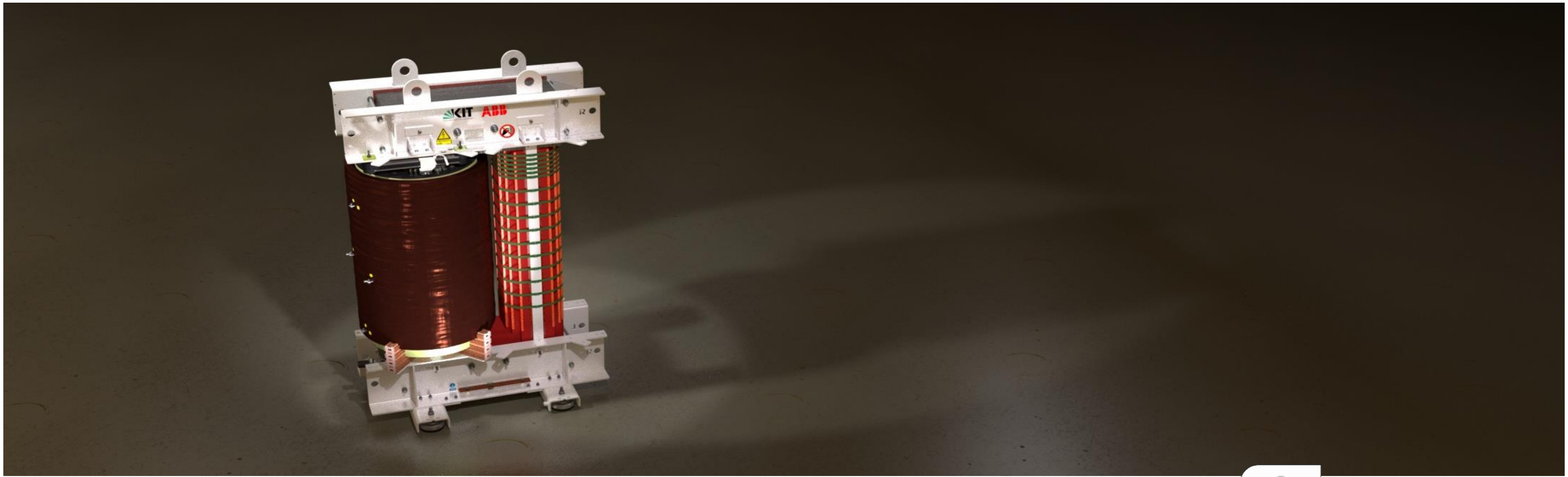
4 mm YBCO
24 double pancakes



Low voltage winding

15/5 YBCO Roebel cable
20 m length

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



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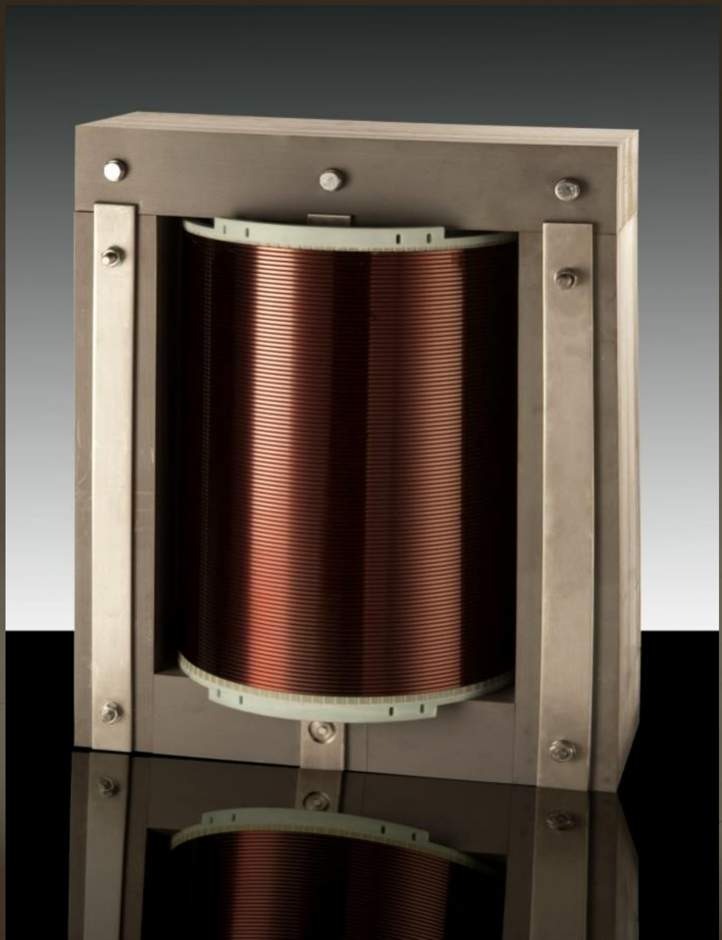
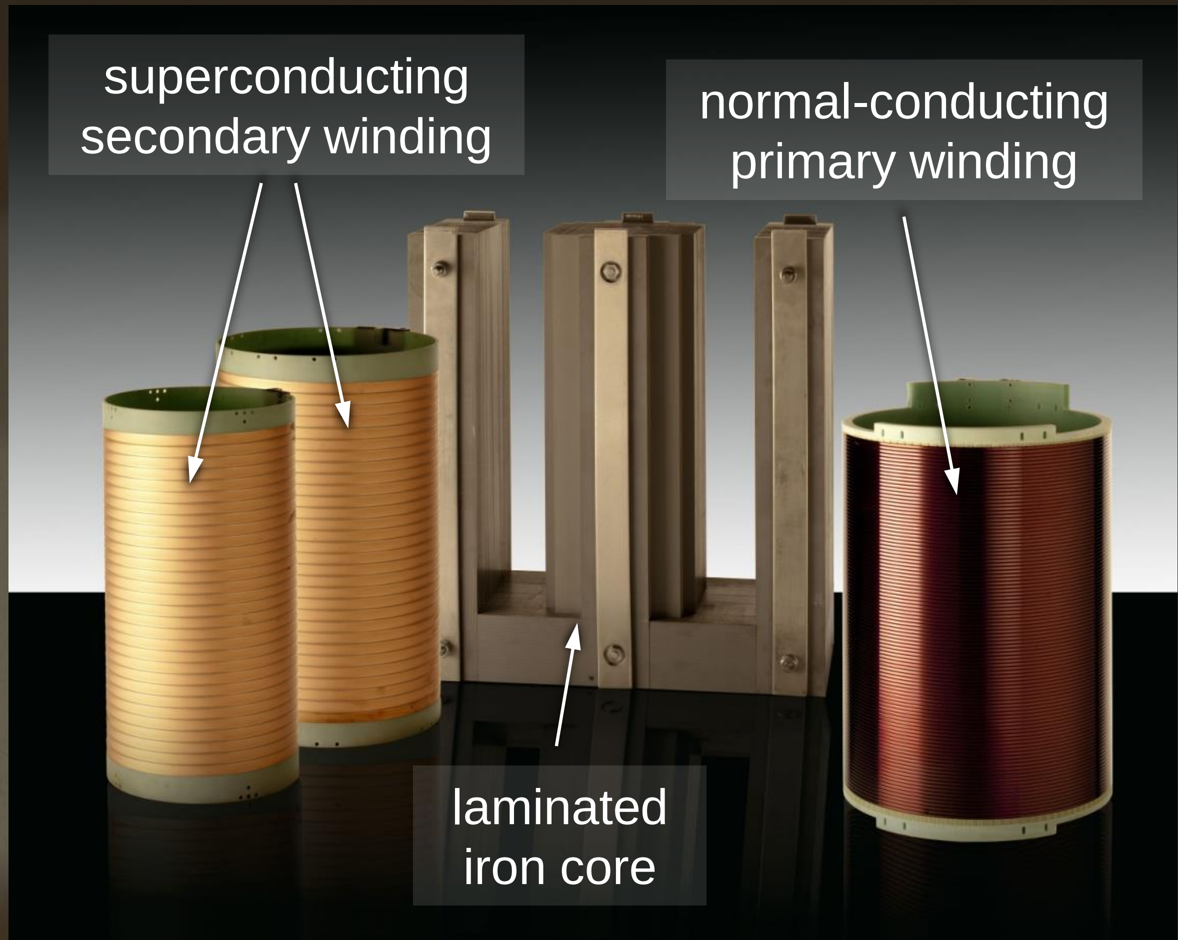
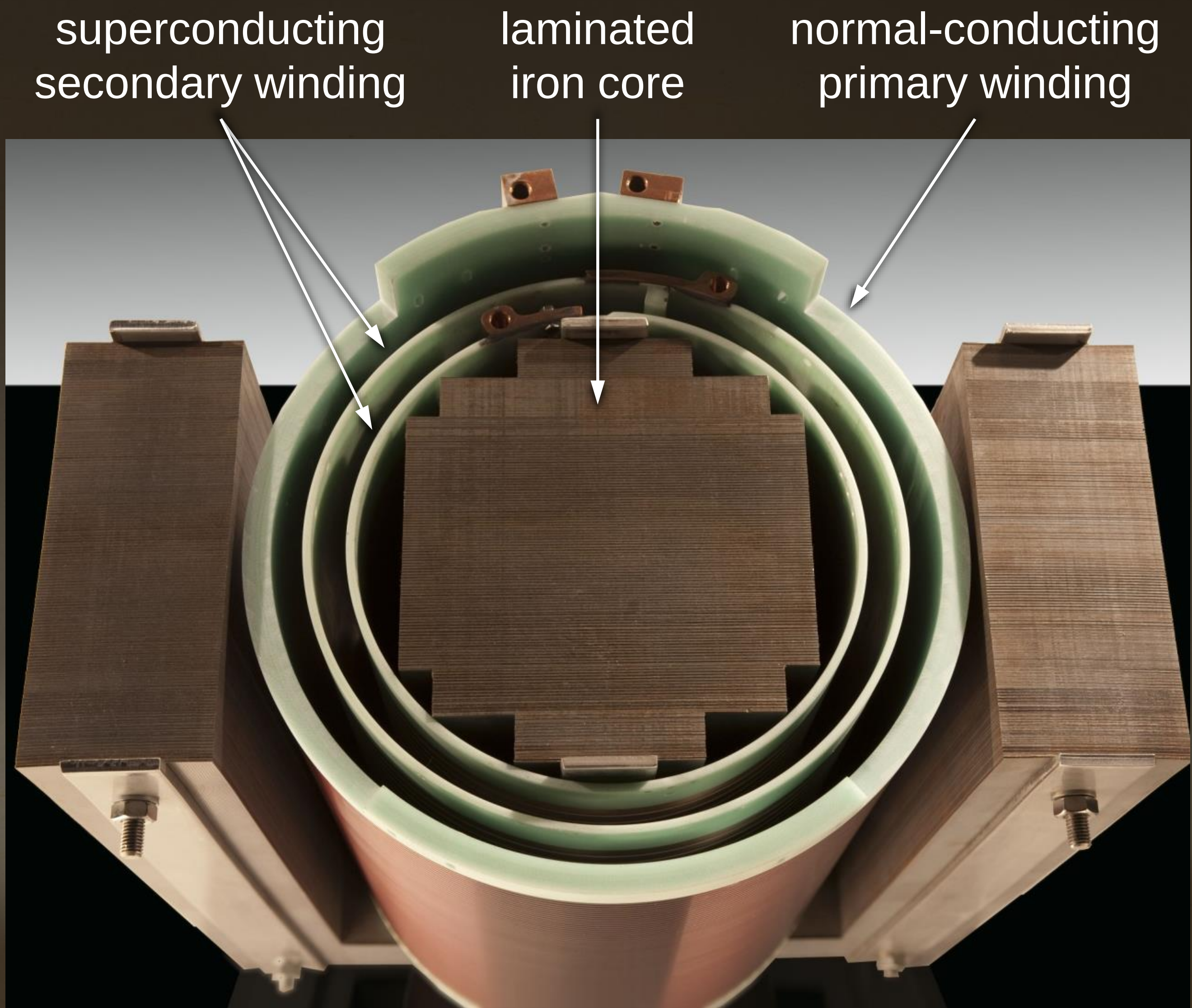
Introduction – 60kVA Transformer

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





Introduction – 60kVA Transformer

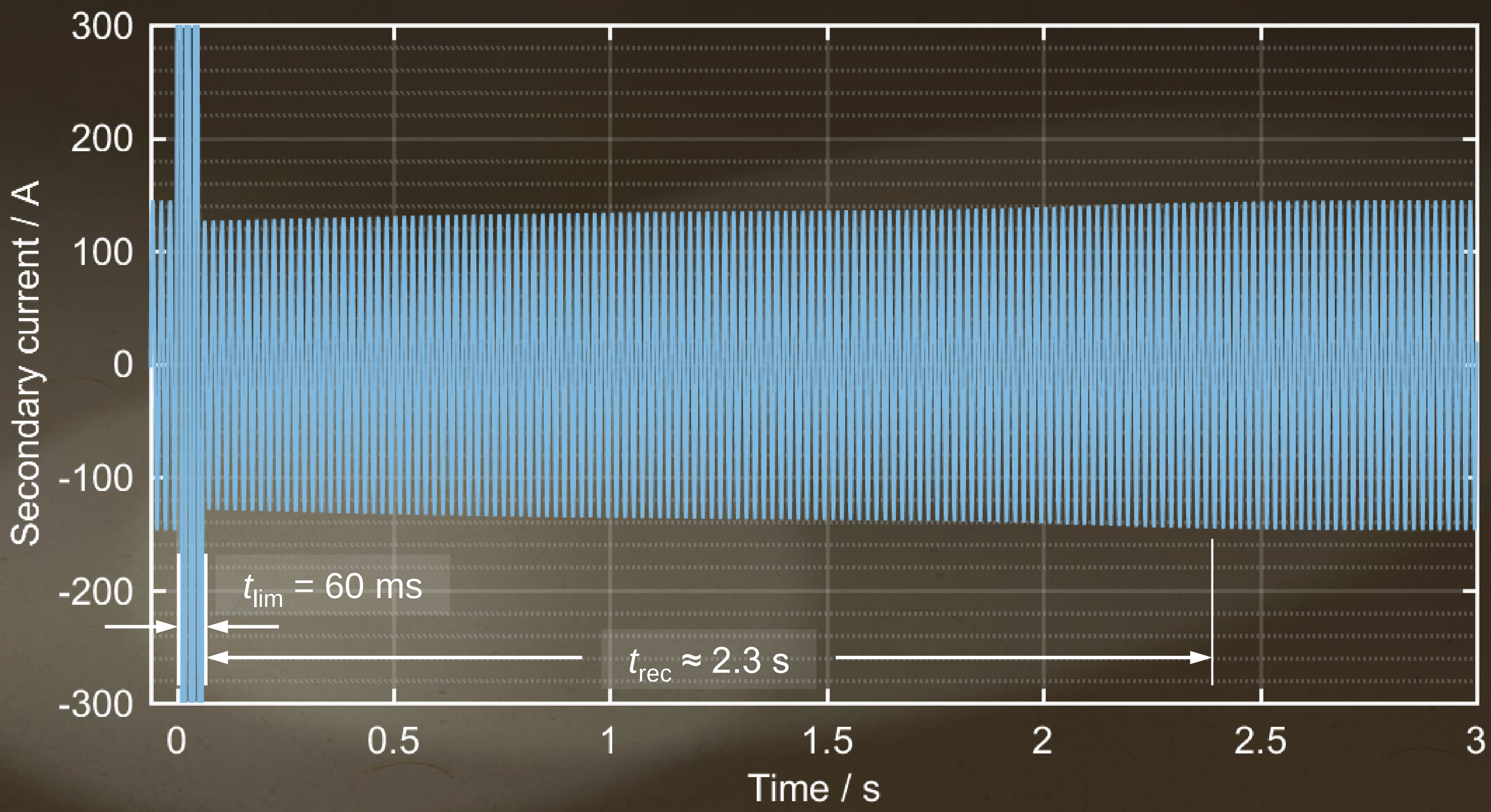


Main transformer parameters

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

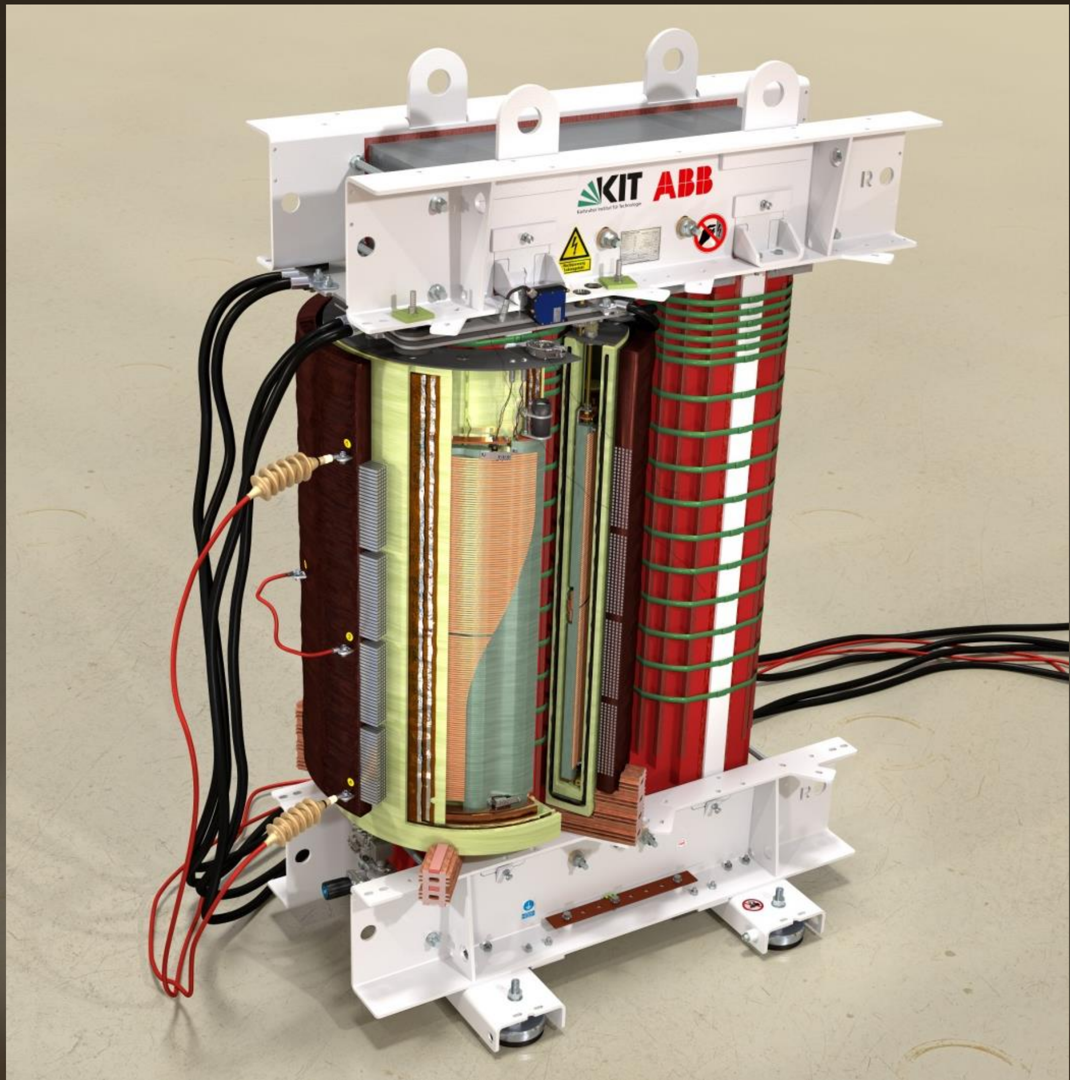


Transformer Design Fix

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	%

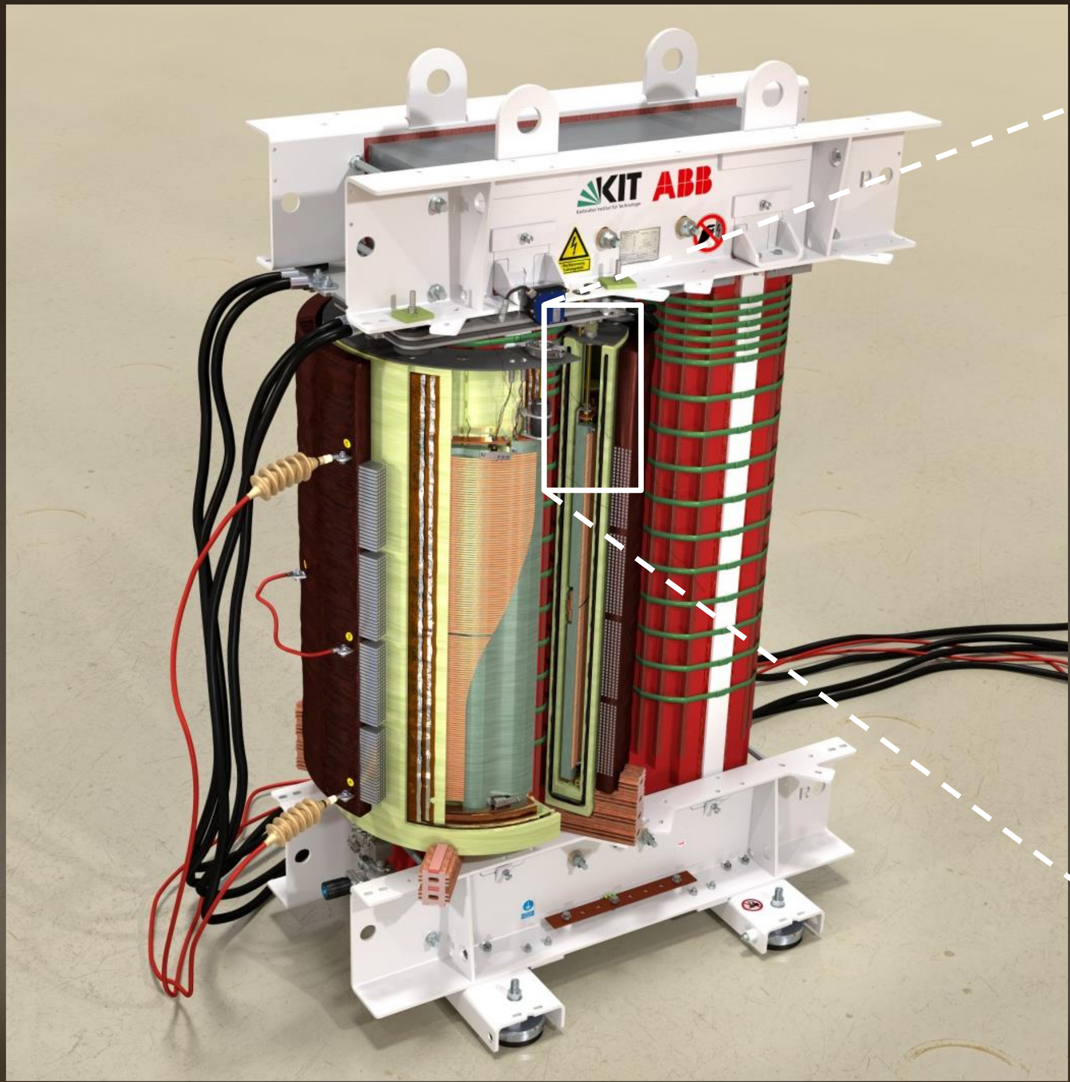
Transformer Design Fix

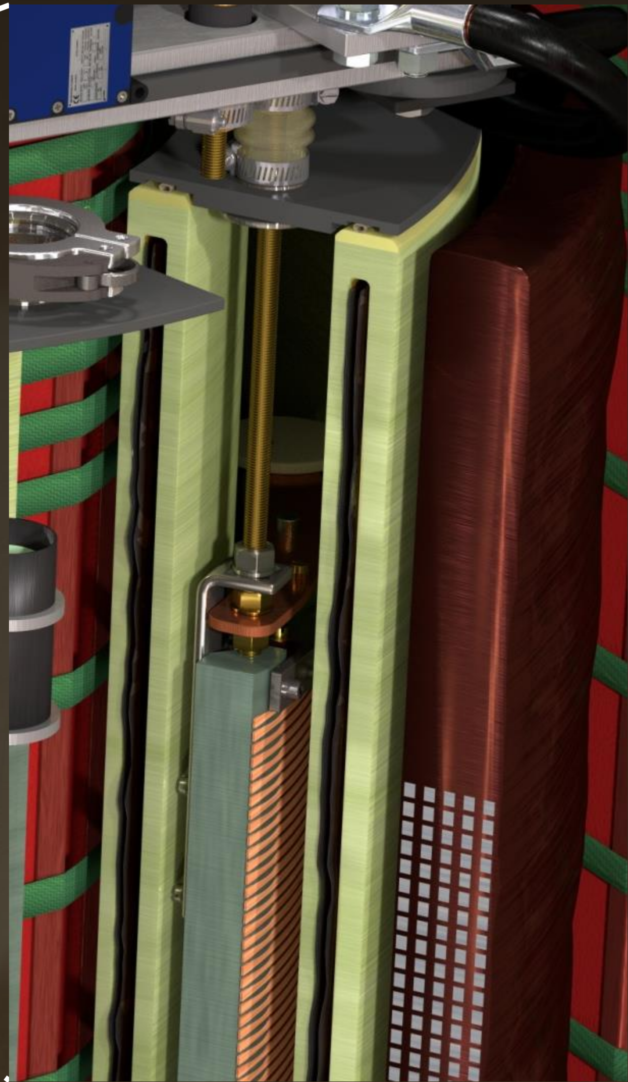


The design of the transformer is focusing on technology demonstration and includes practical compromises such as:

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

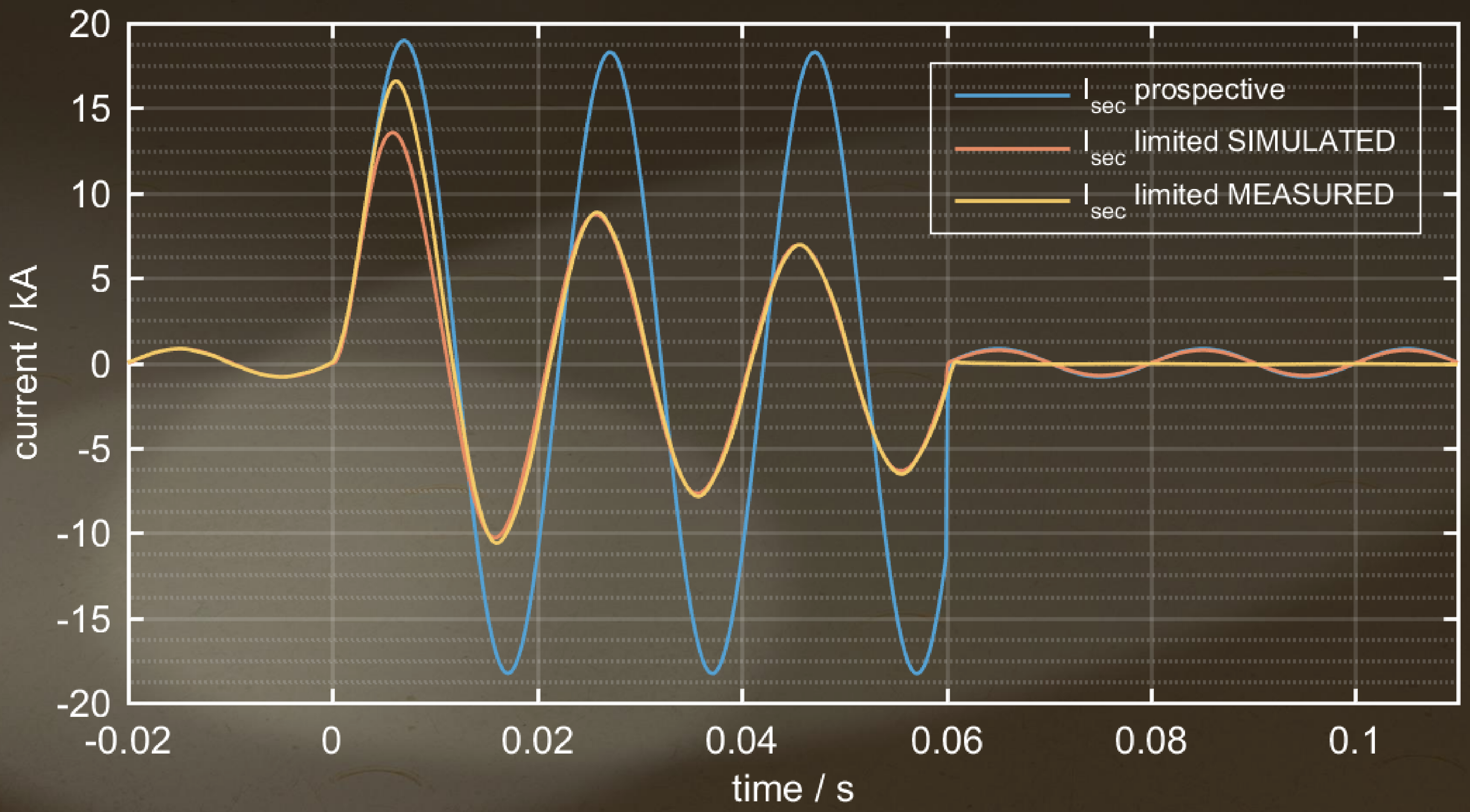
Transformer Design Fix



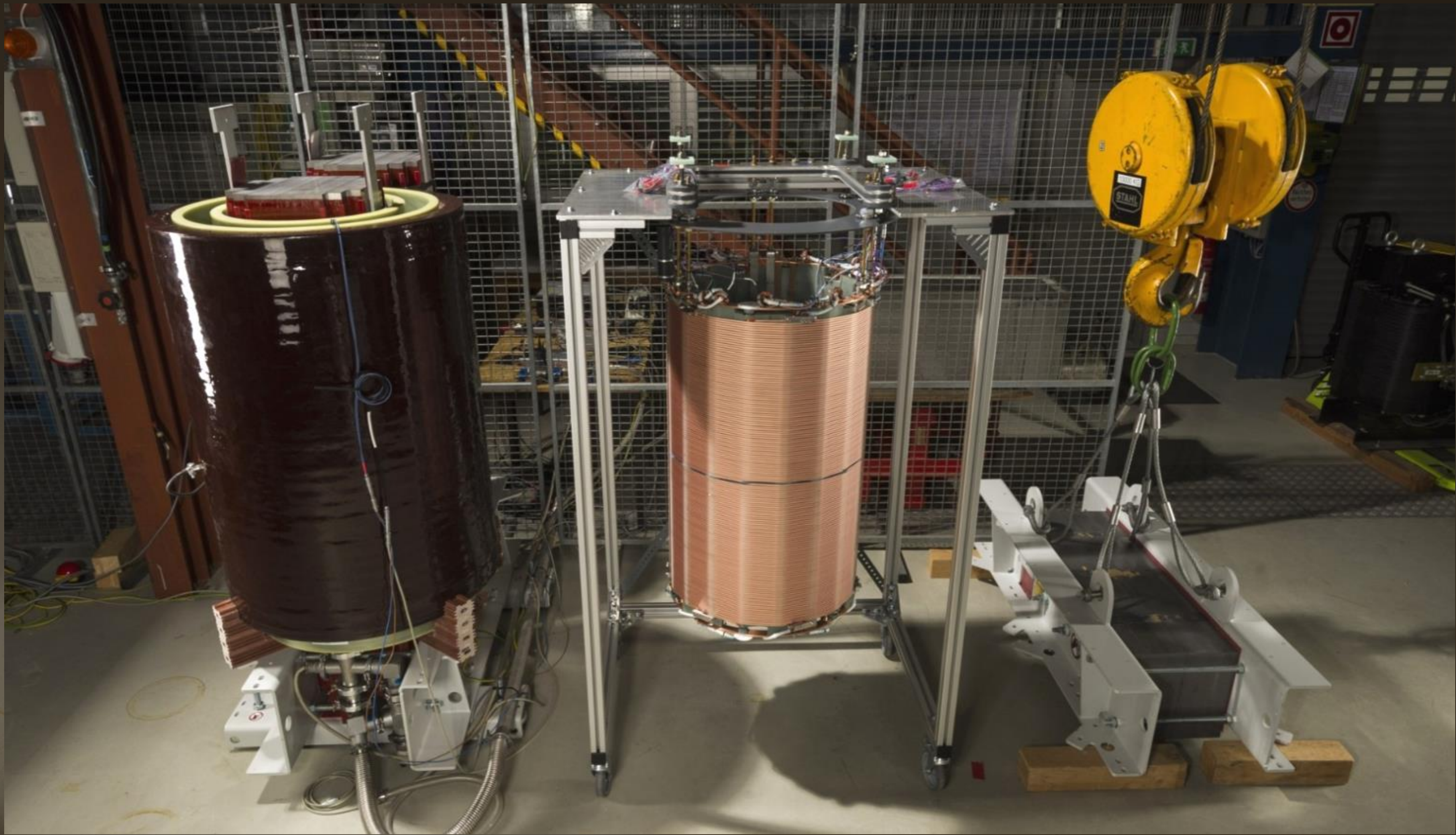


Measurements – Current limitation

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



- Thank you for your Attention -



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) 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

<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

State of development

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 complete	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

Learning objectives

- Main advantages of superconducting transformer
- Different designs of superconducting transformer and their pros and cons
- Operating parameters of superconducting transformers compared to conventional transformers
- State of the Art

Literature

Peter Komarek, Hochstromanwendungen der Supraleitung, Stuttgart Teubner 1995

Bernd Seeber, Handbook of Applied Superconductivity, Vol. 1 und 2, IOP 1998

Peter J Lee, Engineering Superconductivity, Wiley Interscience 2001