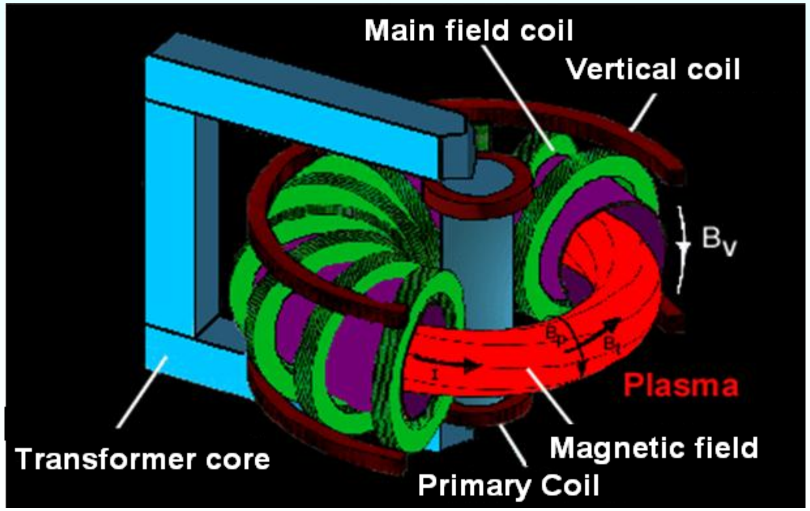
New technologies of electric energy converters and actuators

Contents



Source: Internet

New technologies of electric energy converters and actuators

2. Application of superconductors for electrical energy converters

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New technologies of electric energy converters and actuators

2. Application of superconductors for electrical energy converters

2.1 Applications of technical superconductors in research and technology

2.2 Superconductivity for electrical energy technology

Applications in systems, in which the use of superconducting windings is indispensable:

- Magnetohydrodynamic generators (MHD)
- Magnetic storage (superconducting magnetic energy storage, SMES)
- Fault current limiter, FCL
- Electrodynamic levitation (EL) (e.g. high-speed trains)
- Fusion reactor magnets
- Highest-field magnets for research and measuring purposes
- Particle accelerator (detector magnets, beam guidance magnets)
- Synchrotron radiation sources

Applications in systems, in which the use of superconductivity competes with conventional designs

- Inductive heating
- Electrical machines
- Transformers
- Power transmission cables
- Electro-magnetic levitation (ML)
- Computer NMR tomographs
  (Nuclear Magnetic Resonance, MRI)
- Magnetic separators

Conventional inductive heating

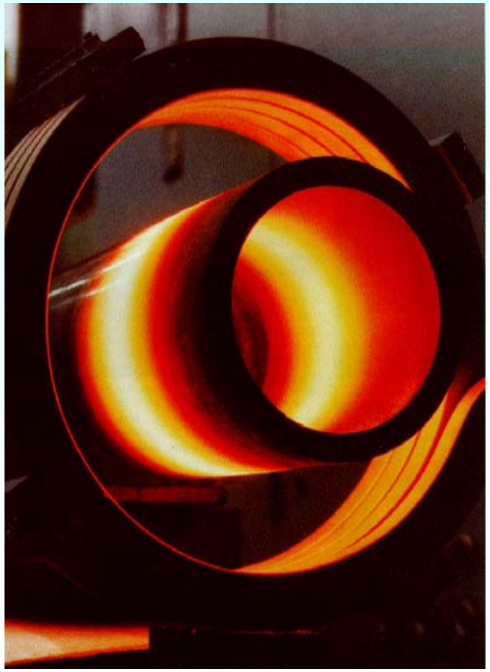
An AC fed coil (frequency in the kHz-range; power electronics feeding) excites a magnetic AC field. Into the metallic (conductive) work piece via eddy currents a heat loss P_d is injected, which heats up the metal!

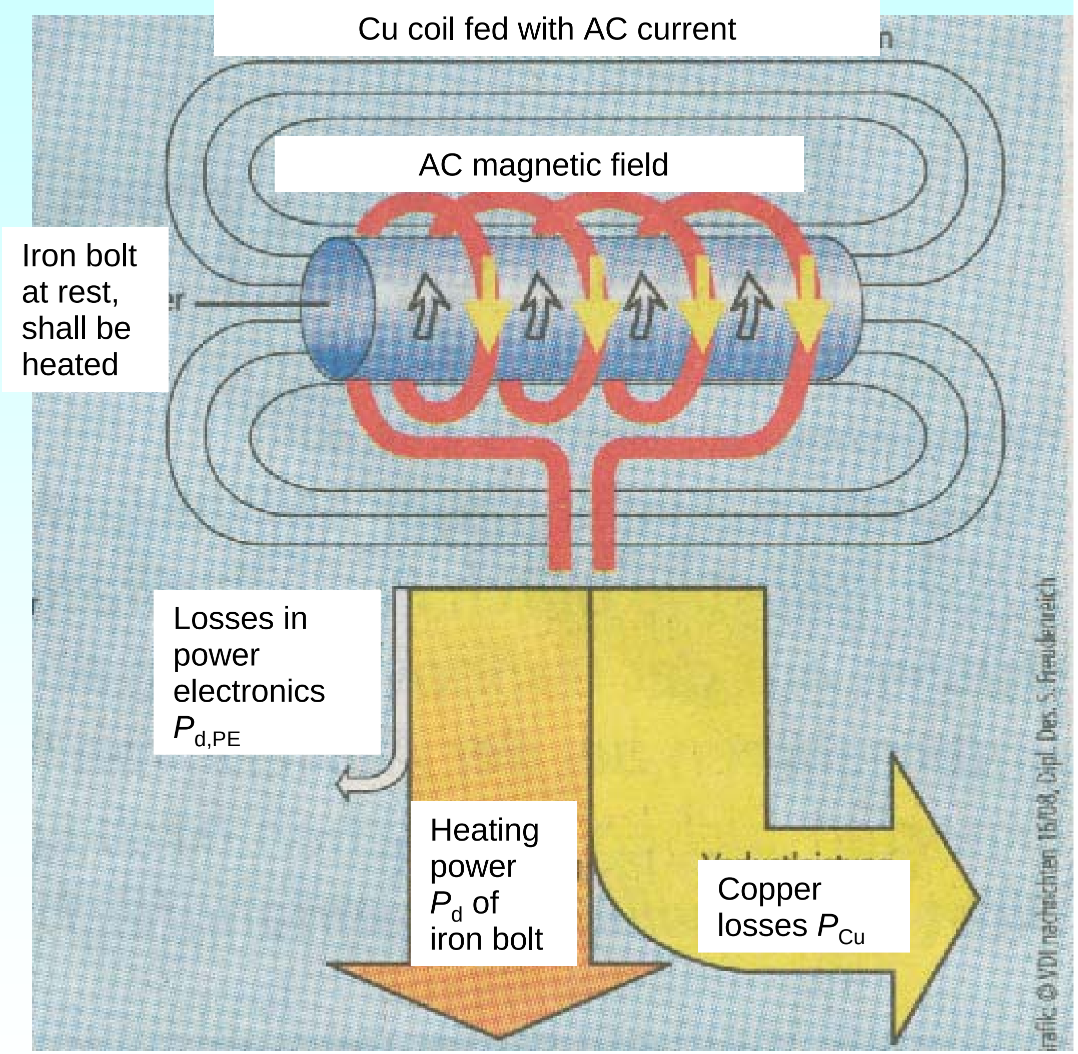
Source: VDI-nachrichten, 2008

Disadvantage:
High losses $\boldsymbol{P_{Cu}}$ in the (water-cooled) AC coil and in the power electronics $\boldsymbol{P_{d,PE}}$

Input power:
$\boldsymbol{P_{in} = P_d + P_{Cu} + P_{d,PE}}$

Efficiency:
$\boldsymbol{P_d / P_{in} \approx 50\%}$





Cu coil fed with AC current

AC magnetic field

Iron bolt at rest, shall be heated

Losses in power electronics $P_{d,PE}$

Heating power P_d of iron bolt

Copper losses P_{Cu}

Inductive heating with superconducting coils

- A DC-fed HTSC coil excites a magnetic DC field (Cooling power: P_c).

- A motor drives the metallic (conductive) work piece in this DC field. Via induction of motion a voltage and hence eddy currents are induced in the work piece, causing the heat loss P_d, which heats up the metal.

- The motor must overcome the braking torque M of the eddy currents in the DC magnetic field as the necessary driving power $P_d = 2\pi n \cdot M$ at rather low motor losses $P_{d,m}$.

Advantage: The DC magnetic field is excited at rather low excitation losses (cryogenic LN_2 cooling). The **efficiency P_d/P_{in} rises from 50% to 80%.**

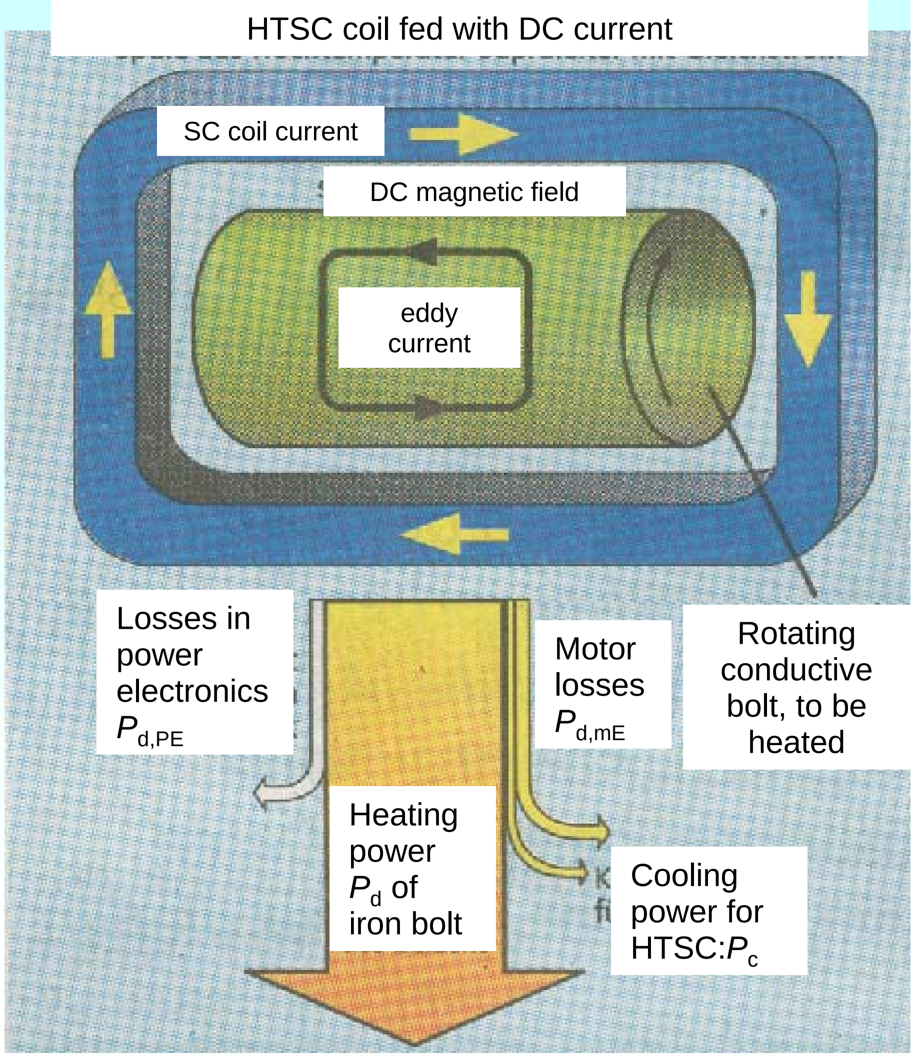
Input power:

$P_{in} = P_d + P_{d,m} + P_c + P_{d,PE}$

Efficiency:

$P_d/P_{in} \approx 80\%$

Source: VDI-nachrichten, 2008



New technologies of electric energy converters and actuators

Summary:
Applications of technical superconductors in research and technology

- Wide field of use of super-conductivity, also in electronics
 (e.g. *Josephson*-contact)
- Generation of ultra-high magnetic fields for physics experiments
- Wide commercial use of low temperature SC coils in MRI
- Slow, but steady progress for the use in power engineering

New technologies of electric energy converters and actuators

2. Application of superconductors for electrical energy converters

2.1 Applications of technical superconductors in research and technology

2.2 Superconductivity for electrical energy technology

2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

2.2.4 Superconducting power transformers

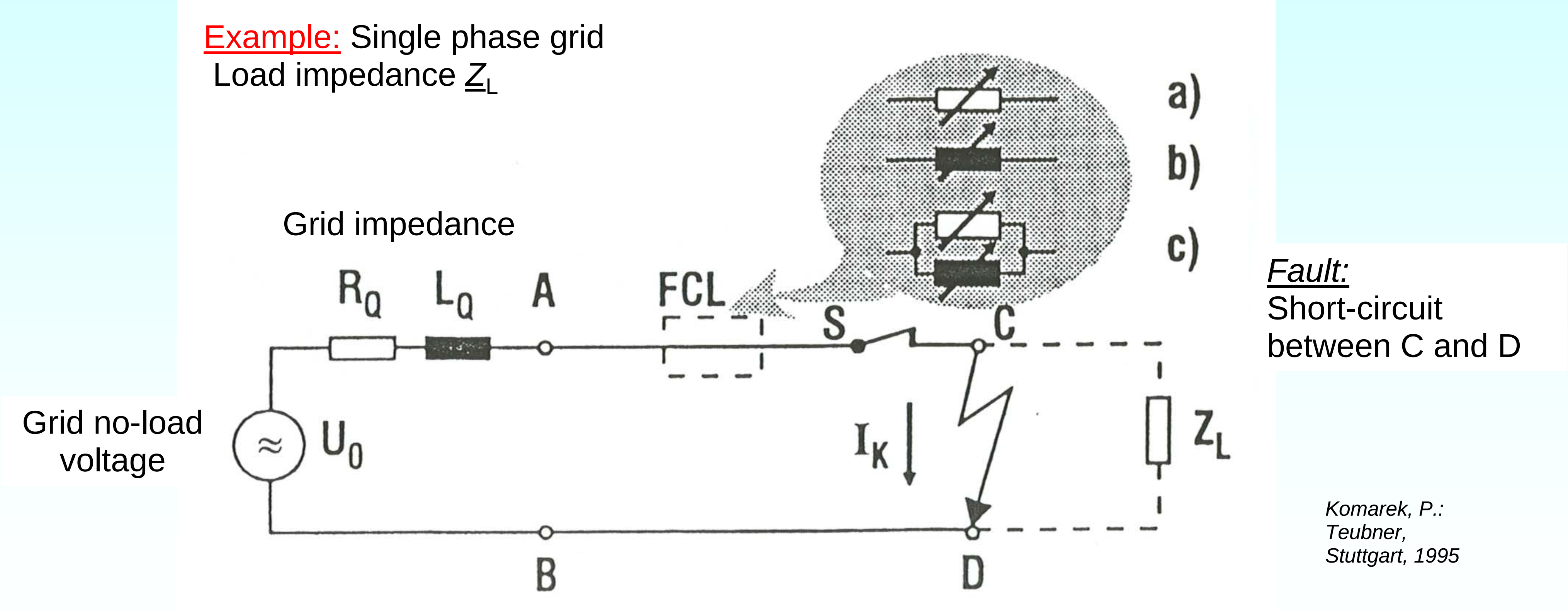
2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

2.2.1 Principle of fault current limiter (FCL)

Limitation of fault current $I_k = \frac{U_0}{\sqrt{R_Q^2 + (\omega L_Q)^2}}$ by means of a FCL as a

a) *ohmic* resistance, b) inductance, c) combination of a) + b)



Example: Single phase grid
Load impedance $\underline{Z}_L$

Grid impedance

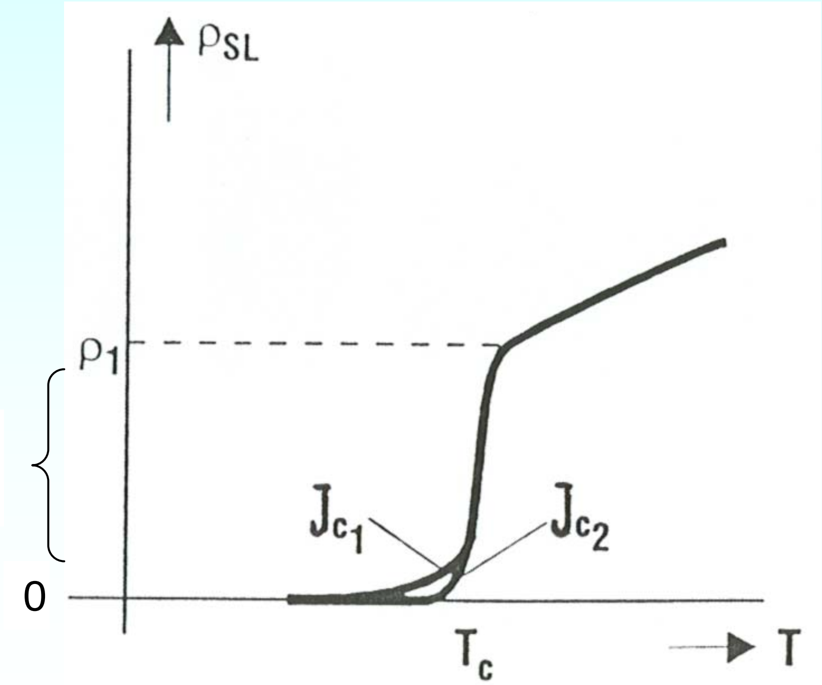
Grid no-load voltage

Fault:
Short-circuit between C and D

Komarek, P.: Teubner, Stuttgart, 1995

Quench process: Increase of ρ_{SL}

- Quenching: Transition from superconducting to normal-conducting state at $\rho_{SL} = \rho_1$
- Increase of specific electrical resistance $\rho_{SL}(T)$ is "locally" continuous
- *Example:* HTSC Bi(2223) at 77 K: At a larger critical current density $J_{c1} = 10^5$ A/cm^2 > $J_{c2} = 10^4$ A/cm^2 the quench occurs faster



Thermally activated flux creeping

Komarek, P.: Teubner, Stuttgart, 1995

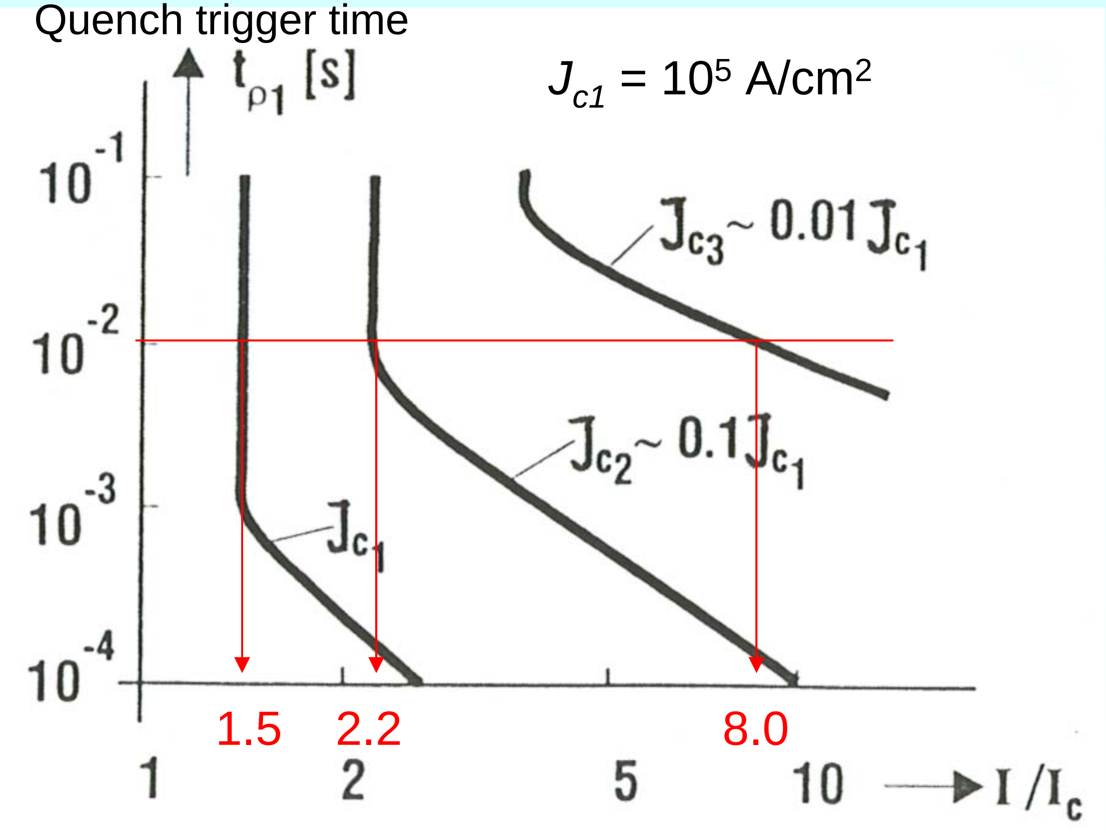
Dynamics of the quench process

Example: HTSC Bi(2223) at 77 K

Komarek, P.: Teubner, Stuttgart, 1995

I: Actual DC current
I_c: Critical DC current

Quench trigger time



For a quench trigger time of 10 ms at critical current density of 10^5 A/cm² a dynamic current overshoot of only 1.5-times the critical current is necessary.

With decreasing critical current density a much higher overshoot is necessary.

Facit:
For a fast quenching a high critical current density of at least 10^5 A/cm² is required.

Stationary voltage-current-characteristics at quench

Quench of HTSC:
„Autonomous switching“
after surpassing the critical current

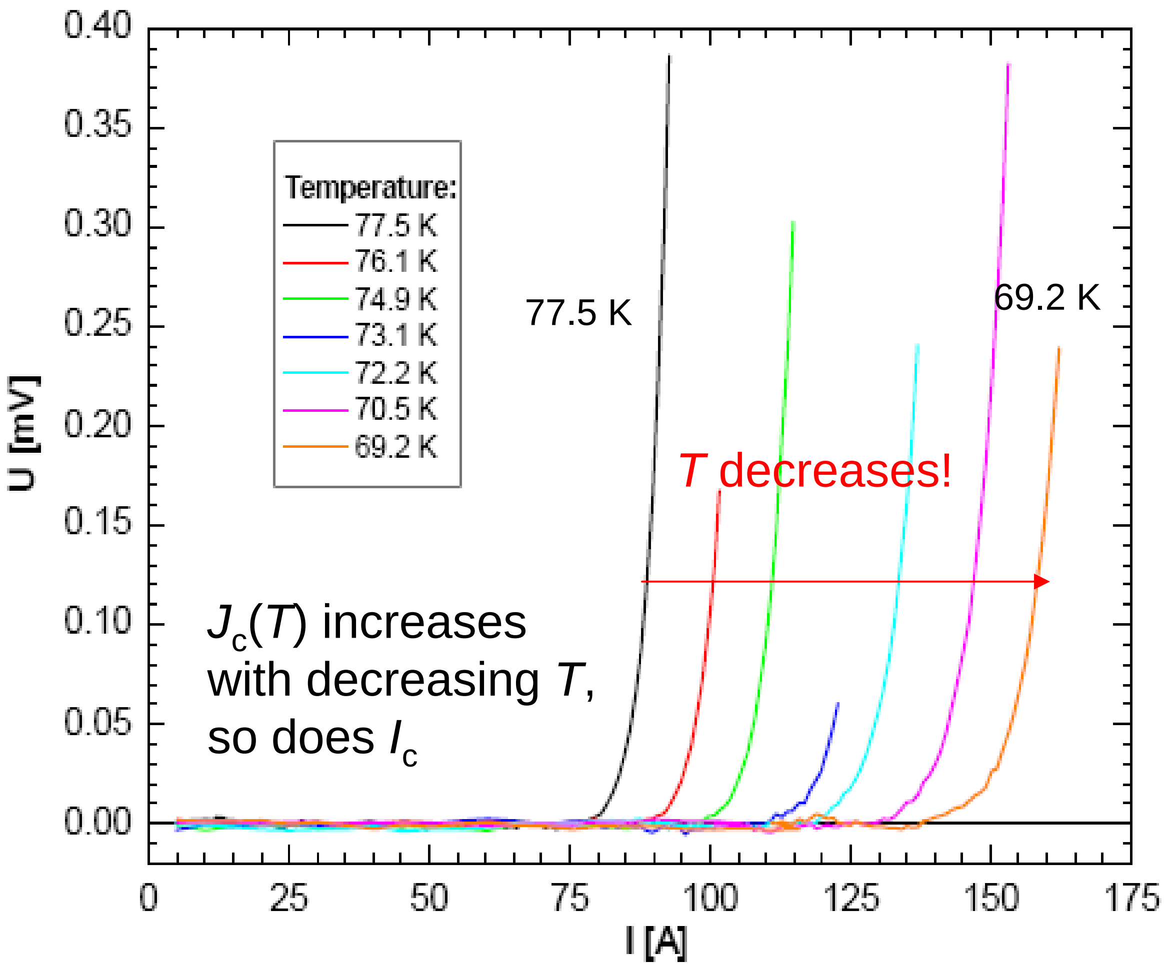
Very fast changing from SC to the resistive state needed

Heating of the FCL during the current limiting process

Therefore fast switch-off of FCL necessary

Cooling down to SC state necessary before putting FCL into grid operation again

Source: Siemens AG, Erlangen



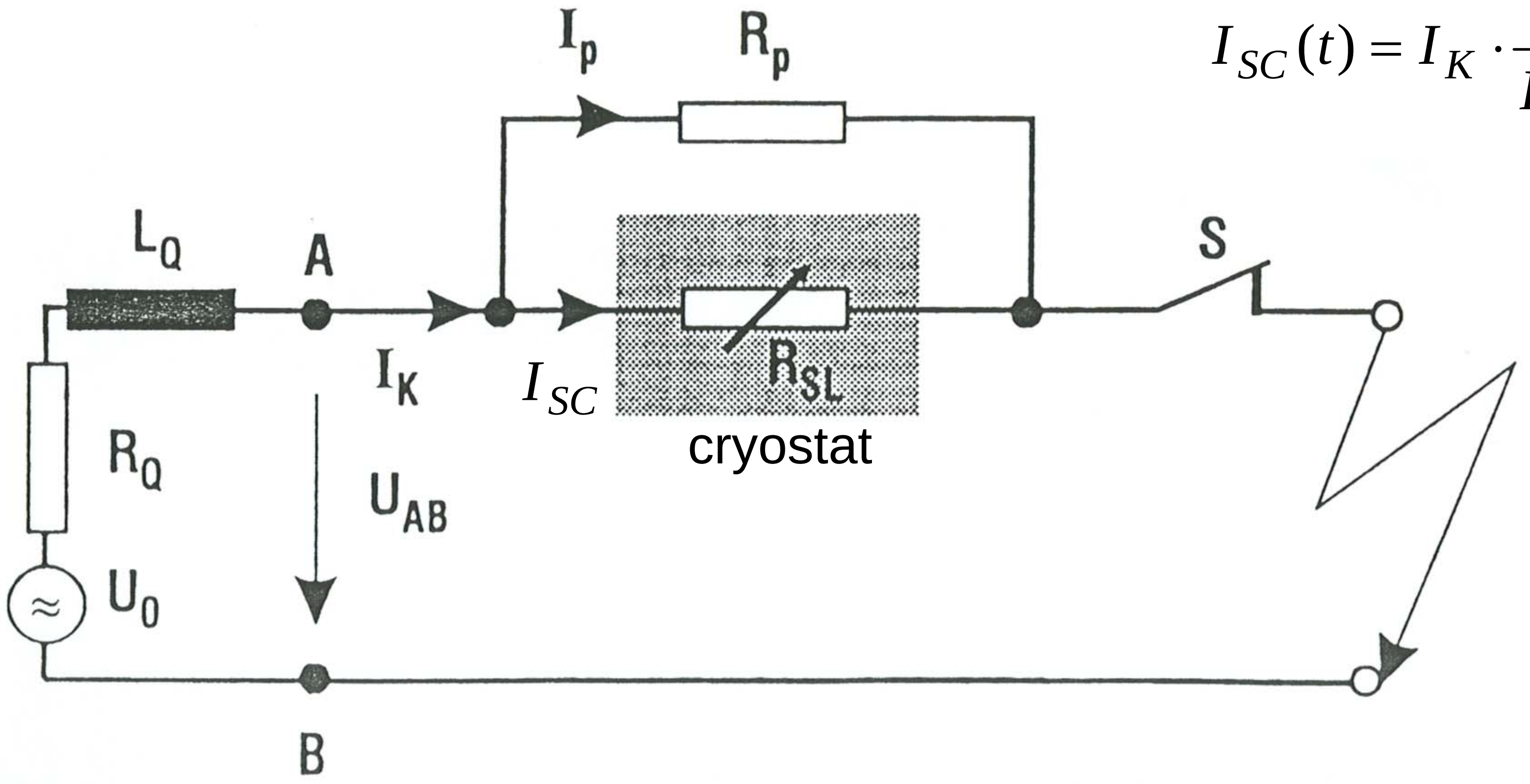
T decreases!

$J_c(T)$ increases with decreasing T, so does I_c

Resistive fault current limiters

- Limitation of current I_{SC} in the superconductor paths by a normal-conducting parallel resistance R_p located outside the shaded cryostat

$$I_{SC}(t) = I_K \cdot \frac{R_p}{R_p + R_{SL}(t)}$$



Komarek, P.: Teubner, Stuttgart, 1995

Design directives for FCL

- **Passive self-triggering:** Short-circuit current density in SC exceeds J_c, so that normal conductivity appears along the entire conductor's length L in few ms to prevent local overheating.

\- Conductor must be **homogeneous** for that along the whole length L,

\- Conductor needs a **high J_c** for a fast quench propagation rate inside the SC.

- In SC operation: low **50 Hz AC current loss demanded:**

  \- Twisting of very thin composite conductors (ca. 0.1 ... 0.3 mm).

  \- **Bifilar wiring** of the conductors (coiled up as air-core inductor): low self flux density B (typically $B < 0.3$ T)

- **Low voltage drop in SC operation = low series impedance:** $R + j \cdot \omega \cdot L$

  R low due to SC, L low (ca. 0.1-0.2 mH) due to bifilar winding

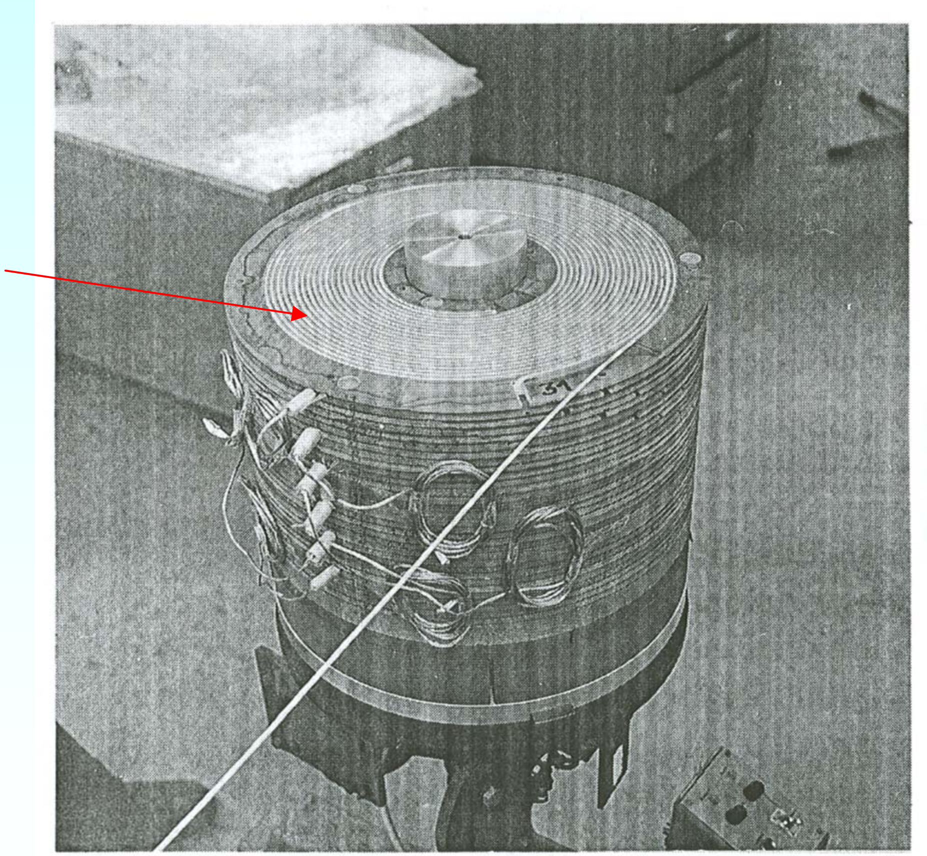
- **Losses at SC operation** are caused mainly due to heat input via the power terminals, but also due to heat inflow via the cryostat walls and due to the AC losses in the SC:

Sum loss typically 10 W to 20 W

2.2 Superconductivity for electrical energy technology

LTSC resistive fault current limiter

- Early prototype: 1000 m NbTi composite conductor in CuNi matrix triggered from a capacitor discharge, 47 kV operating voltage, 40 MVA, I_N = 900 A, I_c = 2 kA, resistance 400 Ω at normal-conducting state



Bifilar wiring of the coil

Source:

FSZ Karlsruhe, Germany

HTSC fault current limiter

- **At a total loss power of the FCL at SC operation of** 10 W, a LTSC-FCL with LHeI cooling 4.2 K needs a cooling power of 7 kW, but a HTSC-FCL (LN_2 cooling 77K) only 0.3 kW → Significant economic advantage for HTSC-FCL.

- **Resistive FCL prototype Y(123) (= YBCO) – Thin-film HTSC (250 nm thick) on substrate (*Siemens AG, 1997*):**

  J_c = 20 kA/mm^2 (77 K) in self-field, with 100 nm gold film for smoothing the quench, spiral conductor arrangement: l = 800 mm/element, b = 7 mm wide, 100 kV, 10 elements in series

  Single-phase prototype test:

  735 V, 135 A nominal data, sudden short circuit current reduction from 666 A to 108 A.

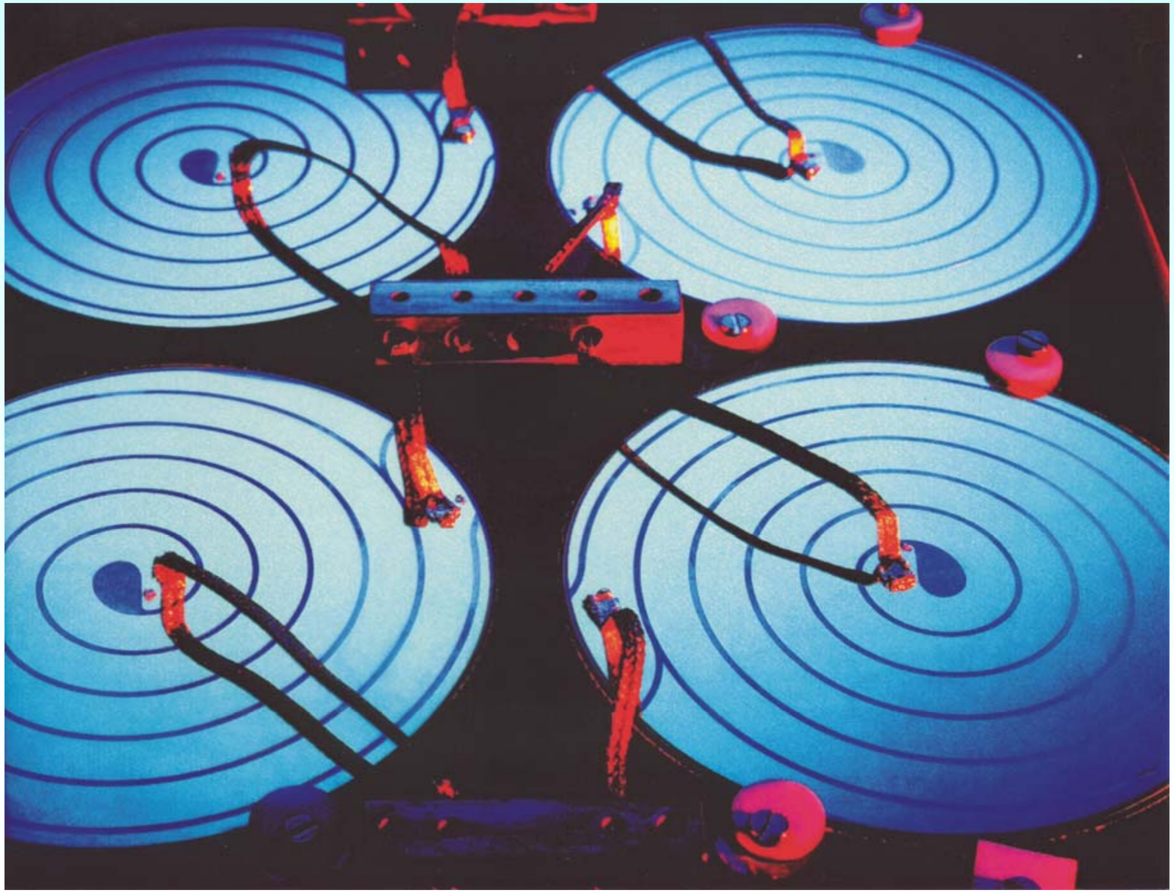
- **Resistive FCL prototype with massive Bi(2212) conductor (Lockheed Martin):**
  Put in series with a normal-conducting coil (solenoid), arranged within this coil ⇒ field B is inside homogenous ⇒ smooth quenching, B field triggers passively.

  Single-phase prototype test:

  Nominal data: 11 kV, 400 A, limits the theorically possible fault current 37 kA (peak) to 12 kA (peak).

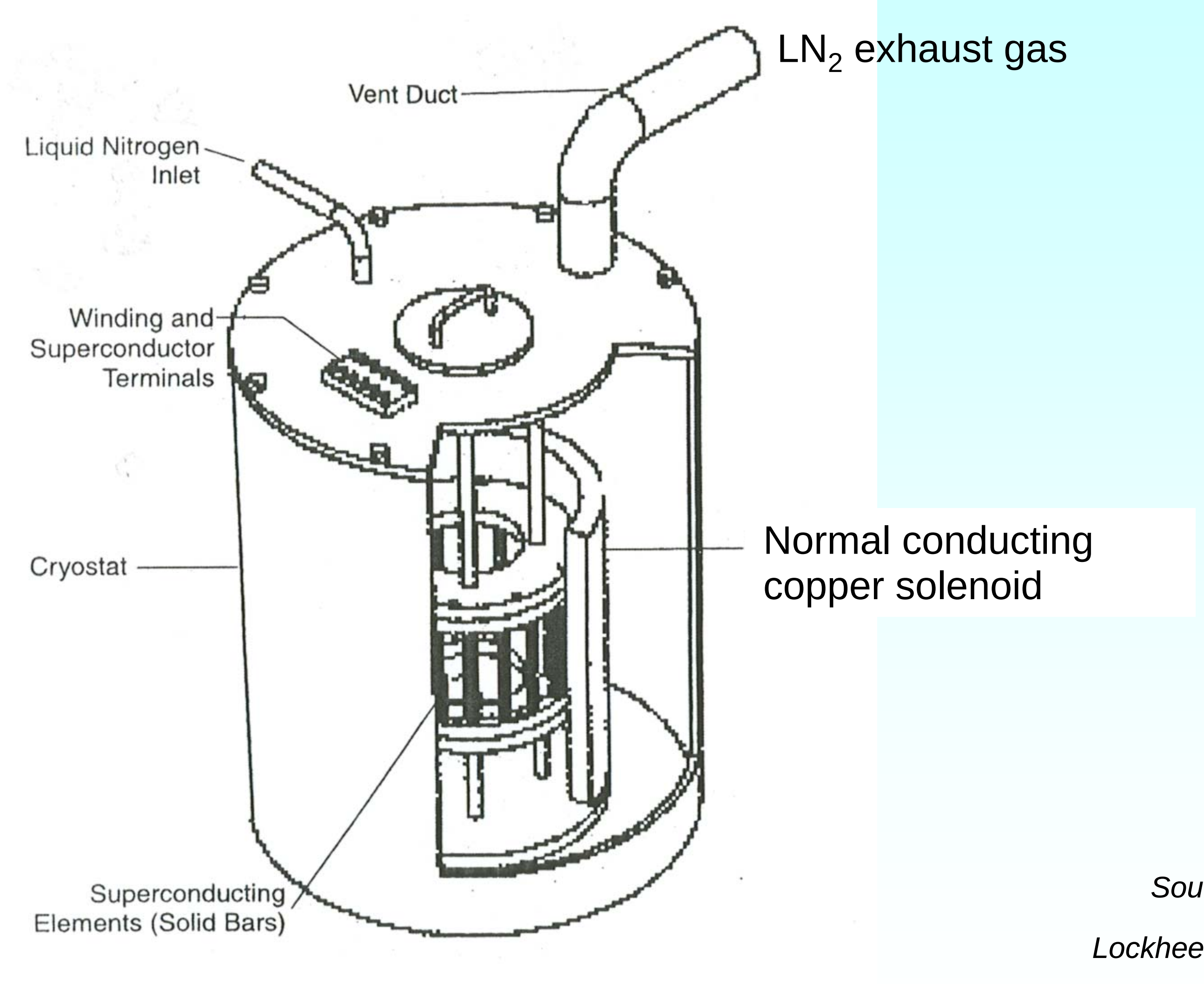
YBCO HTSC resistive fault current limiter

Y(123) thin-film spirals (1mm) at 77 K on ceramic carrier (10x20 cm^2), e.g.: 10 elements in series



Source: Siemens AG

BSCCO bar Bi(2212) resistive HTSC fault current limiter



Source:

Lockheed Martin

BSCCO Bi(2212) HTSC fault current limiter

2.4 kV, 3 kA

top: power electronics

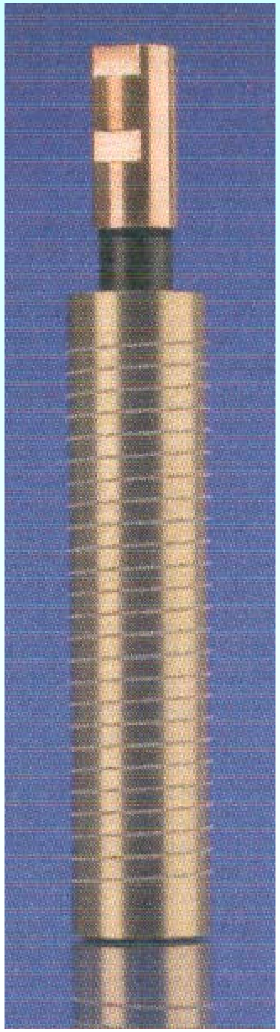
bottom: cryostate with FCL coil

Test operation at Sub-station *Norwalk, Calif*., *USA*

Source:

Lockheed Martin

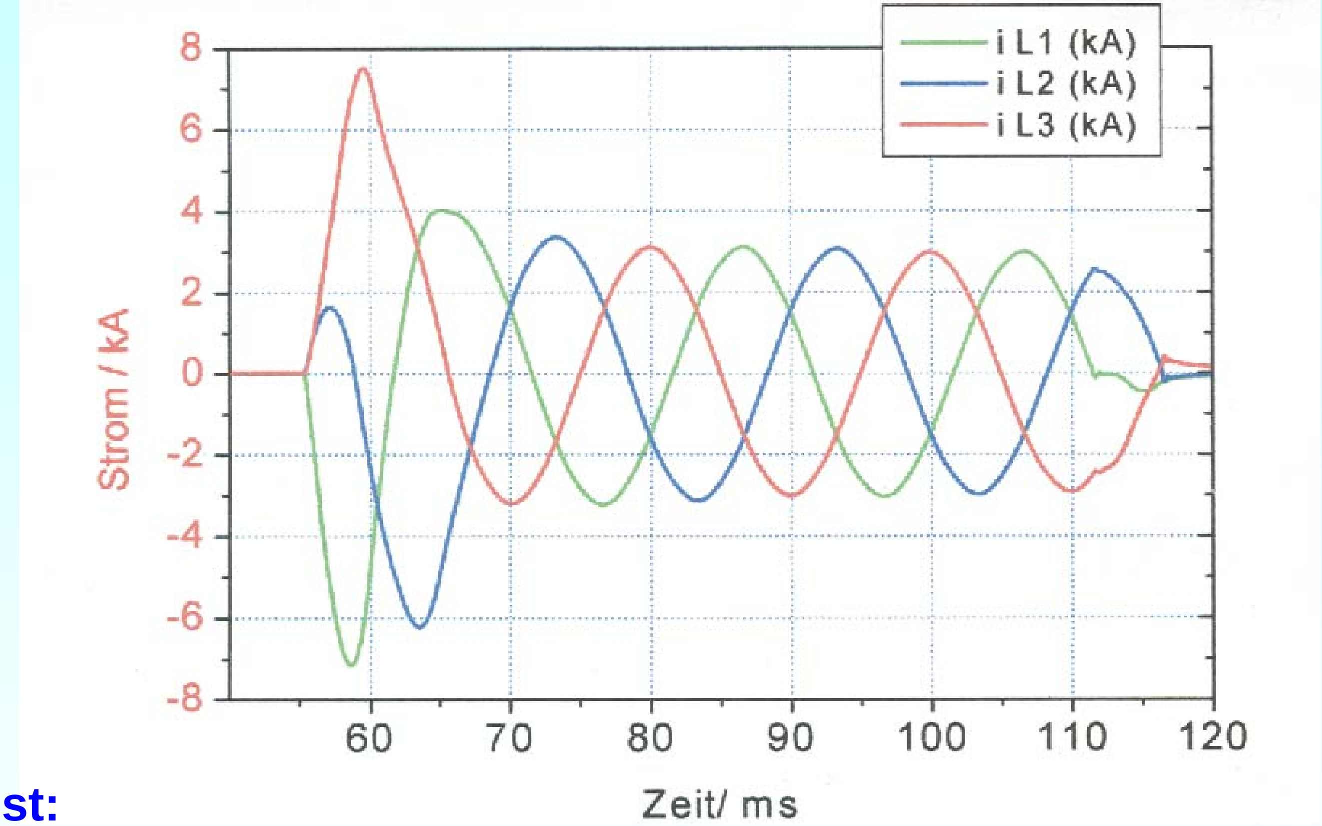
BSCCO-Bi(2212) resistive HTSC fault current limiter (1)



- Helical bifilar arranged and cut melt-textured massive BiSCCO-2212-layers on a copper cylinder as a current by-pass (Shunt)
- Operated at 66 K
- Self-triggering: Surpassing of the critical current density
- Prototype for 10 kV, 10 MVA, 600 A (r.m.s.)

Source: Nexans, Germany

BSCCO-Bi(2212) resistive HTSC-fault current limiter (2)



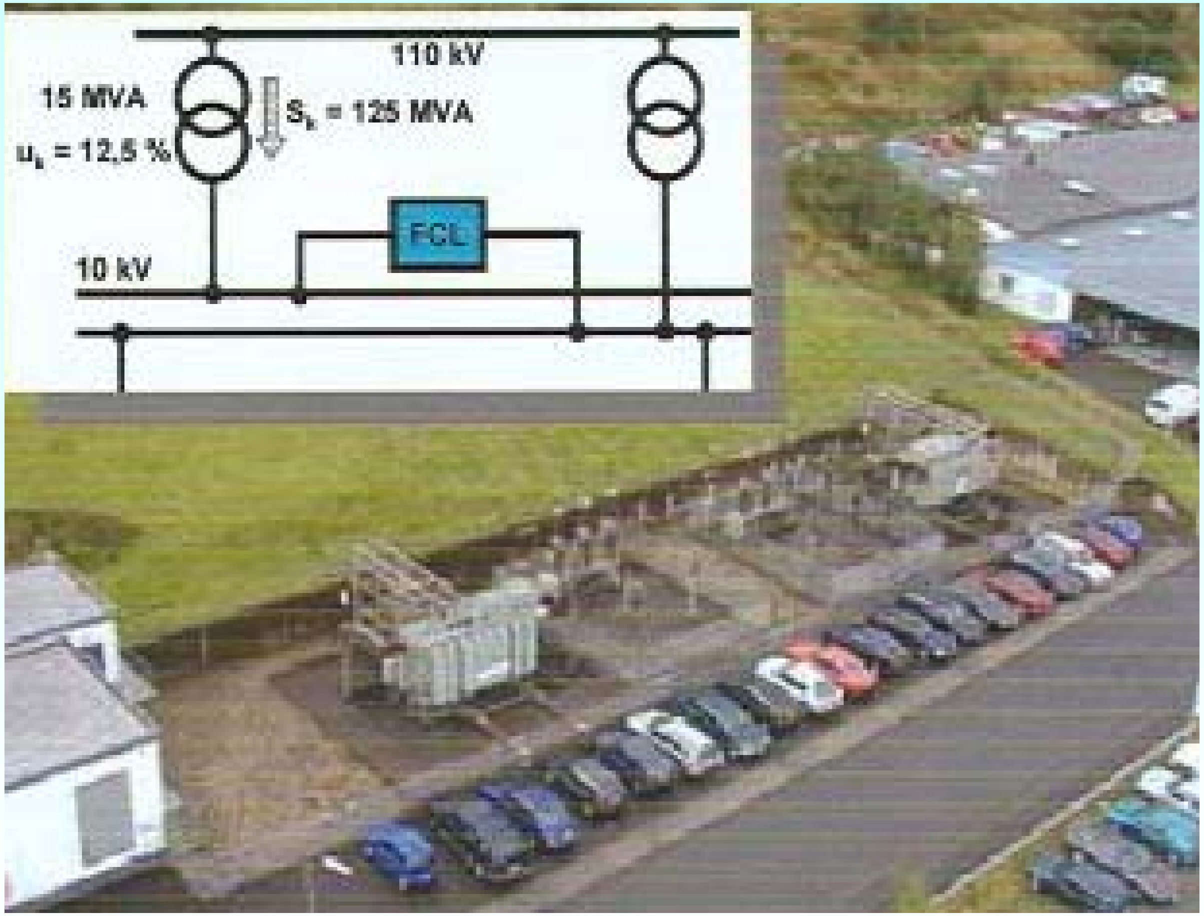
Source: Nexans, Germany

Prototype test:

Sudden short circuit current: Maximum current value 7 kA (= 39% of the short circuit current peak value 18 kA without FCL)

- After 10 ms the current is limited to 3 kA (see Figure above!).
- Current commutes from high resistive normal conducting SC to the parallel shunt resistor (copper cylinder support)

BSCCO-Bi(2212) resistive HTSL fault current limiter (3)



- Field test
- Substation *Netphen* of *RWE, Germany*
- Duration of field test: 1 year
- Two transformers: S_r = 15 MVA
- 110 kV / 10 kV
- Transformer impedance voltage u_k = 12.5%
- Peak sudden short circuit current: 18 kA
- FCL would limit to only 7 kA.

$$I_N = S_N/(\sqrt{3}\cdot U_N) = 15MVA/(\sqrt{3}\cdot 10kV) = 866A$$

$$I_k = \frac{I_N}{u_k} = 866A/0.125 = 6928A$$

$$\hat{I}_k = 2\cdot\sqrt{2}\cdot I_k = 19596\text{A with DC component}$$

$$\hat{I}_k = 2\cdot\sqrt{2}\cdot I_k = 18000A\text{ with damping}$$

Source: Nexans, Germany

$$S_k = \sqrt{3}\cdot U_N\cdot I_k = \sqrt{3}\cdot 10kV\cdot 6928A = 120MVA$$

2.2 Superconductivity for electrical energy technology

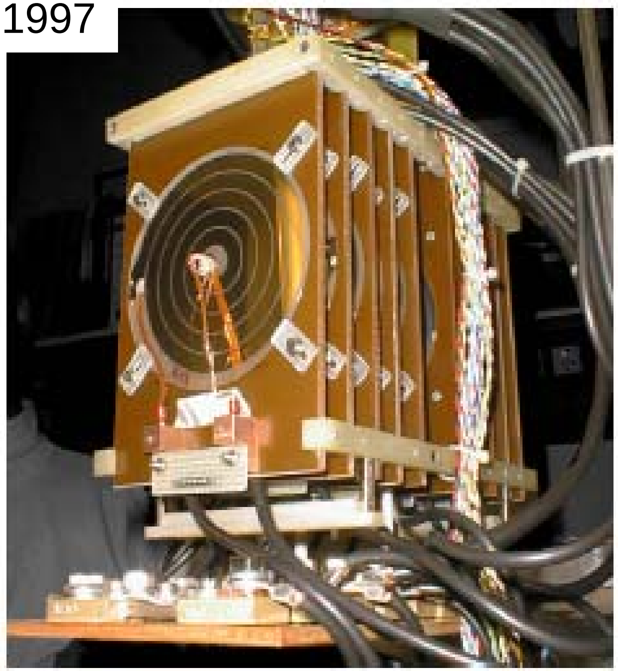
HTSC fault current limiter at *Siemens research CT*

HTSC fault current limiters, based on YBCO-plates **„1. Generation“**

- 1992: Begin of development with FCL based on YBCO thin films
- 1997: 100 kVA prototype, single phase, 135 A / 465 V, 10 plates, diameter 10 cm (Theva)
- 2001: 1.2 MVA prototype, 3-phase, 100 A / 7.2 kV, 63 plates in series, diameter 10 cm
- 2003: 900 kVA prototype, DC, 1000 A / 900 V, 14 plates in series 10 x 20 cm^2

Source: Siemens AG

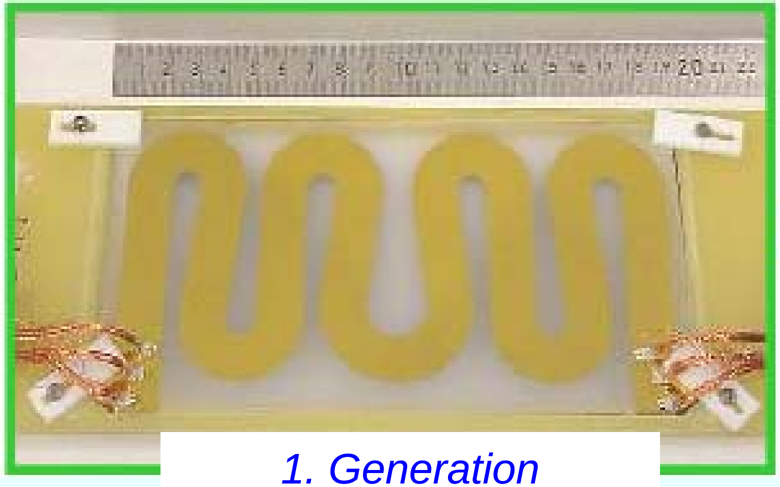
1997



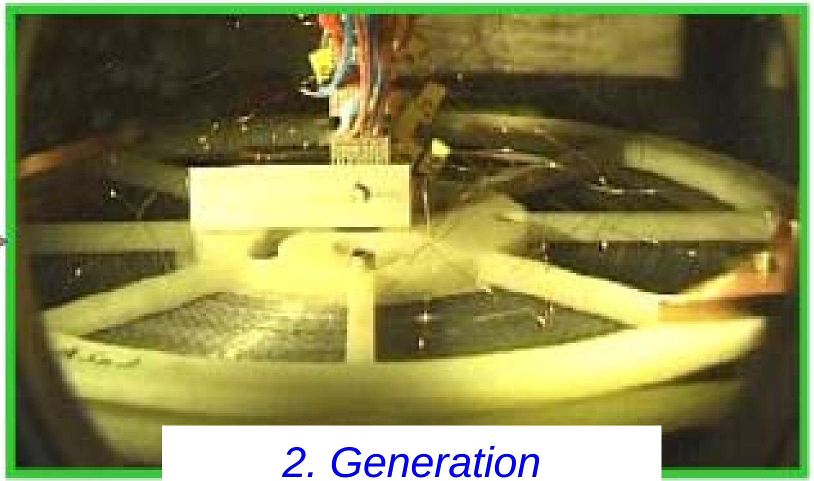
2001

2003

HTSC-YBCO tape conductors as fault current limiters at *Siemens research CT*, „2. Generation“



1. Generation



2. Generation

HTSC YBCO-film applied to expensive ceramic support plates

- Sensitive against mechanical cracks
- High cost of ca. 3 200 US$/MVA, also for series production
- Expensive vacuum depositing process for the YBCO layer

Source: Siemens AG

HTSC YBCO-tape conductors as robust and rather cheap series wound coils

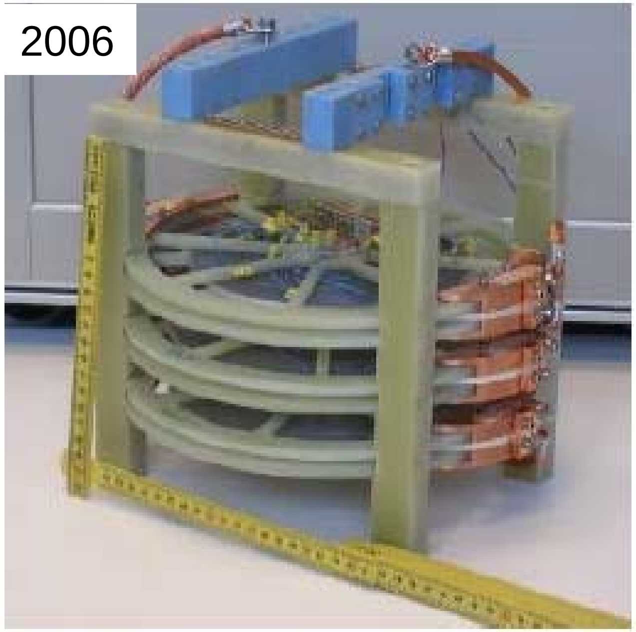
- Robust coil design with patented spacers
- With a prospective tape conductor price of 20 US$/(kA/m) the specific costs are reduced to < 500 US$/MVA.
- YBCO layer is deposited chemically with a rather cheap process on the stainless steel tape with a high deposit rate

*) 2006: 1000 US$/(kA/m), 2017: 50 US$/(kA/m) expected

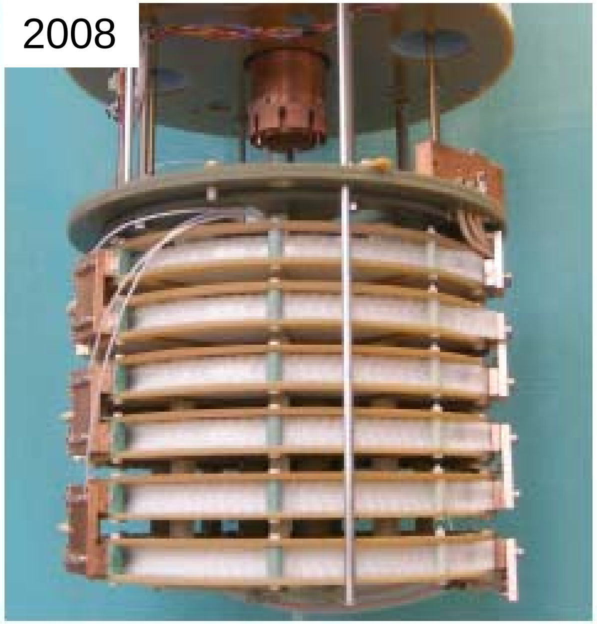
HTSC-YBCO tape conductors as fault current limiters at *Siemens research CT,* „2. Generation“

Source: Siemens AG

- 2006: 120 kVA prototype, single phase, 50 A / 2.4 kV, 3 coils with each 19 m tape conductor
- 2007: 2.2 MVA prototype, single phase, 300 A / 7.2 kV, 15 coils with each 50 m tape conductor
- 2008: 3.5 MVA prototype, single phase, 425 A / 8.4 kV, “sub-scale” module for HV-FCL of D.O.E./USA


2006

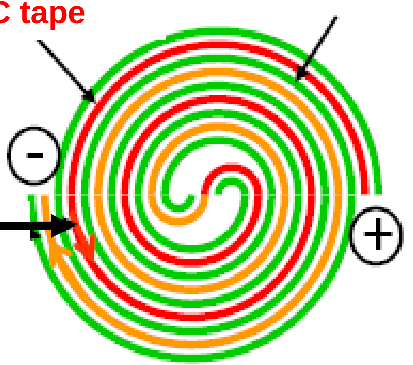

2007


2008

HTSC-YBCO tape conductor: Fault current limiter for medium voltage up to 30 kV

SC elements

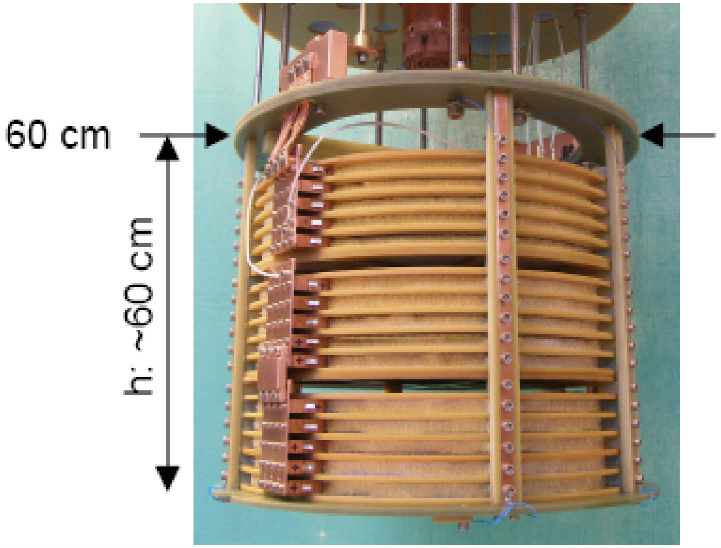
- Bi-filar wound disc coils of YBCO tape conductor with 50 m/coil, LN_2-cooling, coil diameter 50 cm
- Bi-filar: Self-inductance is (nearly) zero, SC: AC-resistance is (nearly) zero, At SC state FCL is “invisible” for the grid!



Bi-filar wound disc coils: Opposing current flow in adjacent conductors = resulting magnetic coil field is nearly zero: $L \approx 0$

FCL module

- One phase, 7.2 kV rms, 300 A rms, 15 disc coils: 5 coils in parallel each, 3 coil groups in series
- Normal conducting resistance $R_{295\ K}$ = 12 Ohm



Source: Siemens AG

FCL: Power test at medium voltage up to 30 kV

Power test with highest current

Grid voltage before short circuit:

U_0 = 7.7 kV rms

Prospective short circuit current without FCL:

$I_{sc,prosp}$ = 28 kA rms

Grid short circuit impedance:

u_k = 1 %

Short circuit occurs at a phase angle φ = 75°

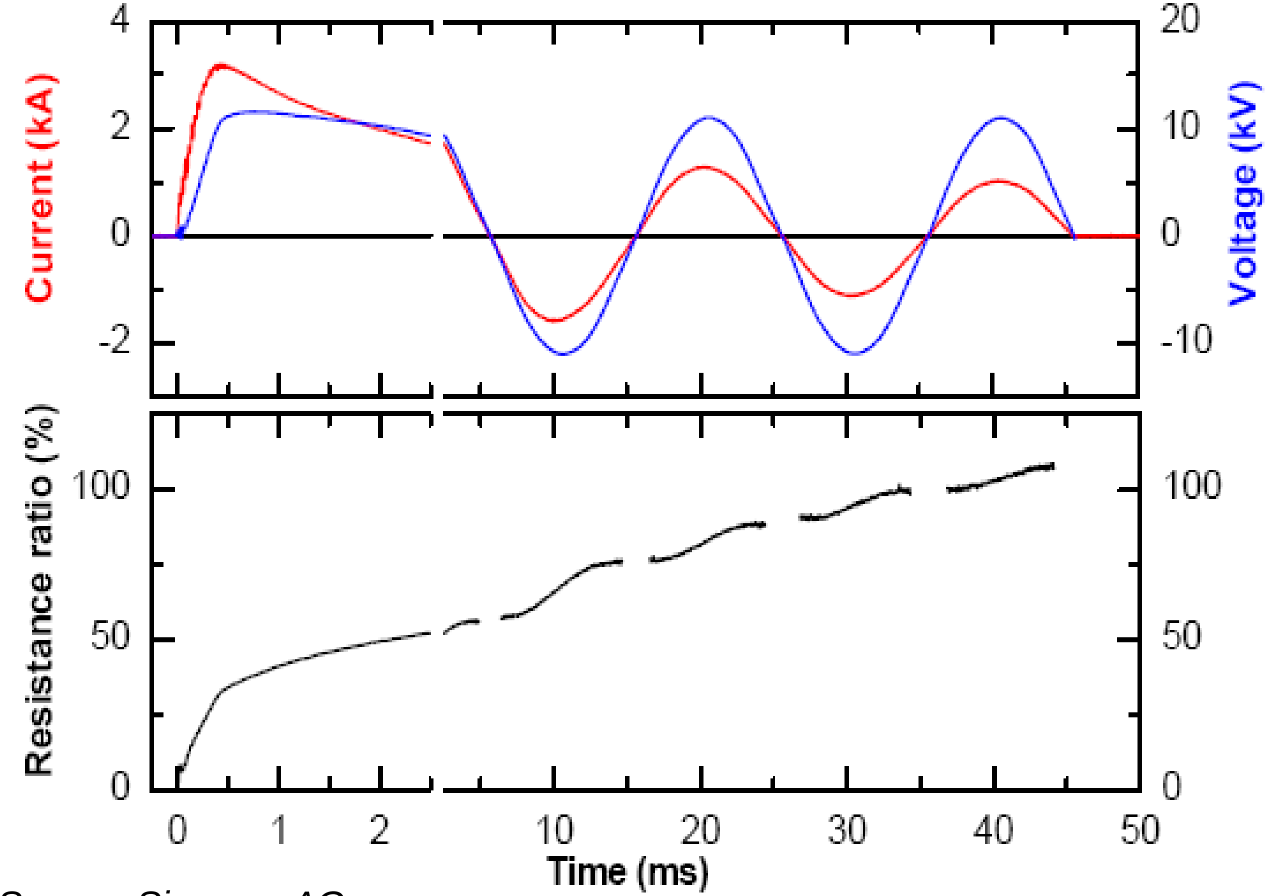
Peak short circuit current with FCL:

I_{peak} = 3.2 kA = 7.3 x I_c

Steady state limited current:

I_{lim} = 700 A rms = 2.3 x I_N

Maximum ratio $R / R_{295\ K}$: 110% due to 70°C steady state temperature



Source: Siemens AG

Resistive FCL project for *Devers* substation, *USA*

Project 2011:
Devers Substation 115 kV/500 kV, 60 Hz
(desert location), *Palm Springs, USA*

FCL on the 115 kV-side, 1200 A nominal current, voltage across the FCL per phase after tripping: 31 kV

Trip current 160% rated current

Short-circuit current without FCL: 63 kA r.m.s.

FCL in a “dead tank” arrangement (tank is grounded)

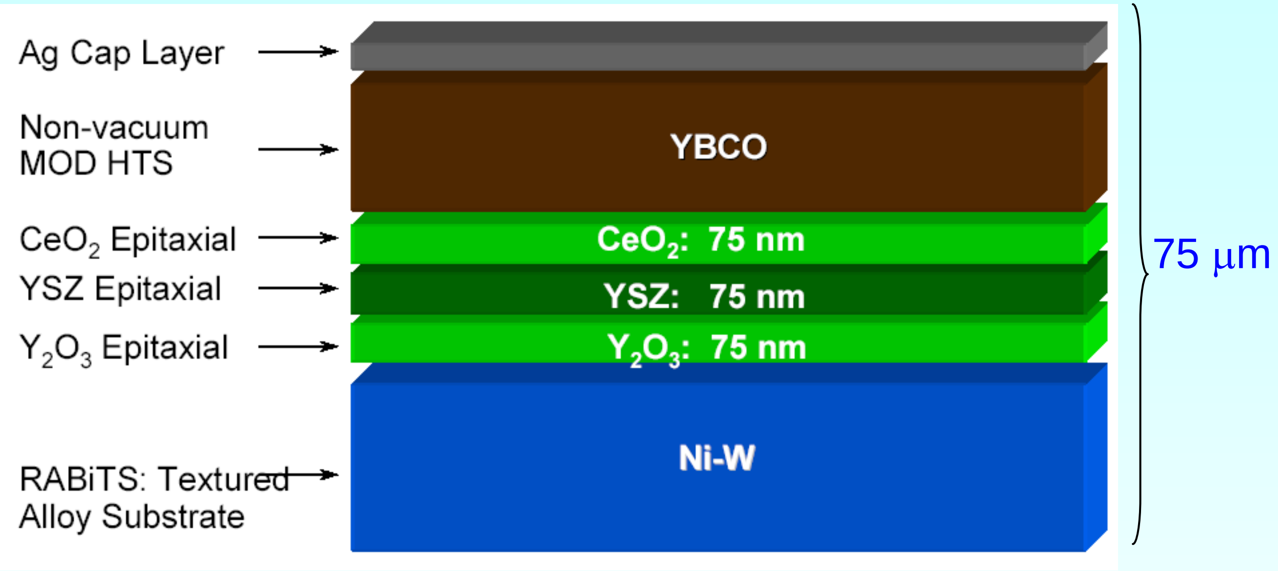
Each FCL phase in a separate tank

Cooled at 72 K, 5 bar

Prototype testing successfully completed for one phase
2012: Project cancelled by DOE/USA, due to shift in funding

Source: Siemens AG

YBCO tape for resistive FCL project *Devers, USA*



YBCO tape structure

YBCO tape: 12 x 0.28 mm^2
on stainless steel stabilizer

YBCO tape data:

Critical current 253 A at 77 K

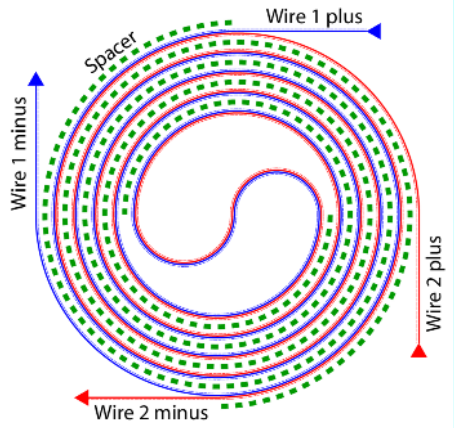
Resistance at 20°C: 0.114 Ohm/m

Voltage 54.6V/m at 67 ms fault hold time

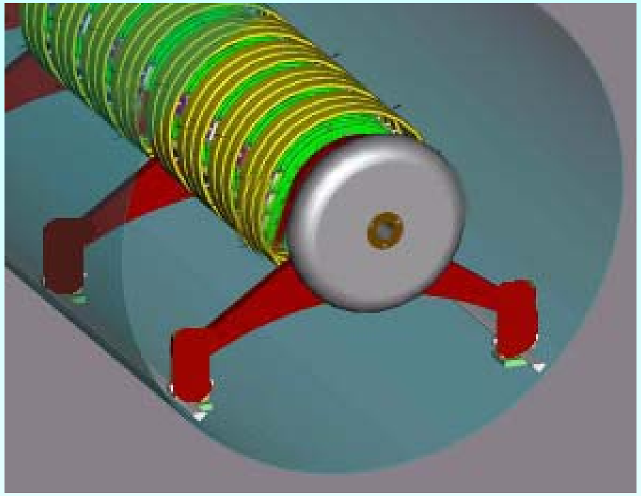
Source: ASC &Siemens AG

YBCO tape manufacturing

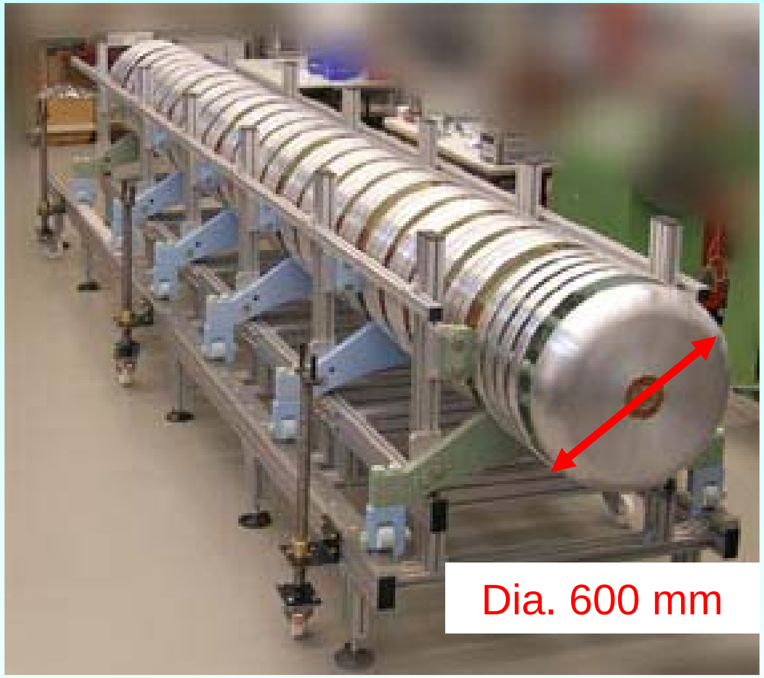
Resistive FCL project for *Devers* substation, *USA*



Bifilar YBCO tape coil



63 bifilar coils form one module



FCL module

Module data:

3 coils in parallel, 21 triplets in series = 63 coils in total

Length: 5 m, Diameter 0.6 m

Critical current 1900 A (rms) at 74 K

Rated current: 900 A, trip current 1350 A, module voltage after trip: 30.9 kV
1350 A x 30.9 kV = 42 MVA

Source: Siemens AG

Short circuit test: Instead of 60 kA peak only 10 kA peak occurred!

Resistive FCL project ECCOFLOW (EU-project)

YBCO tapes:

a) Stainless steel carrier tape: 12 mm x 0.1 mm

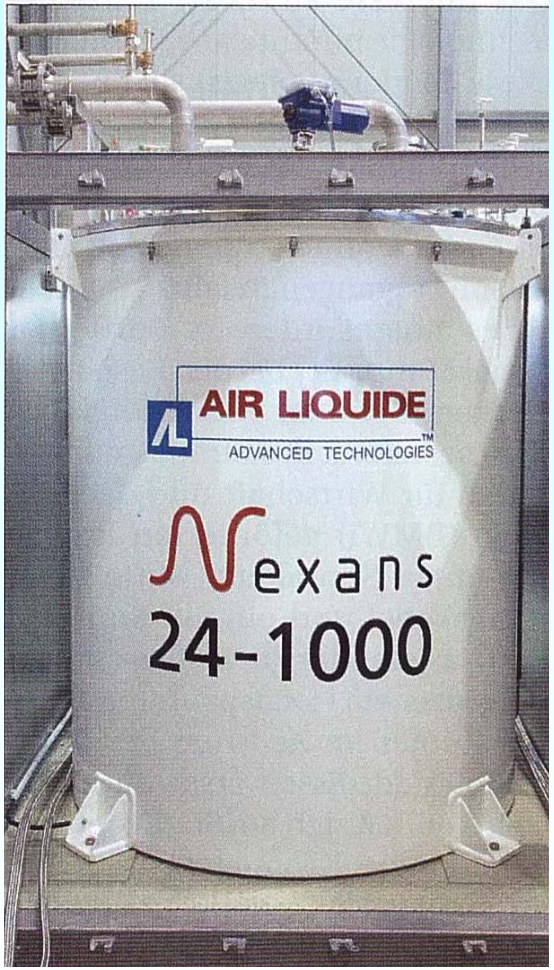
b) YBCO layer: 12 mm x 0.001 mm

FCL-Rating: 1 kA, 24 kV, 50 Hz, -180°C, LN_2 cooling

A prospective sudden short circuit current peak of 26 kA is limited to 10.8 kA during the first half wave.

Fault current clearing time max. 30 s to let the FCL operate again in “normal” (=super-conducting) condition

Installation first at *Palma de Mallorca* (*Endesa* sub-station) for 6 months field test, then at *Kosice* (*Kaschau*), *Slovakia* in the VSE national grid behind a transformer



Source: Nexans Superconductors GmBH, published in: energiewirtschaft 112, 2013, no. 6

Inductive superconducting fault current limiters (1)

a) Cross section:

1: iron core,

2: LN_2 cryostat,

3: secondary HTSC hollow cylinder,

4: LN_2 cooling

5: primary Cu coil L_1 (number of turns N)

b) $B(r)$ field profile at nominal & fault current I_N & I_k,

r_K: iron core outer radius

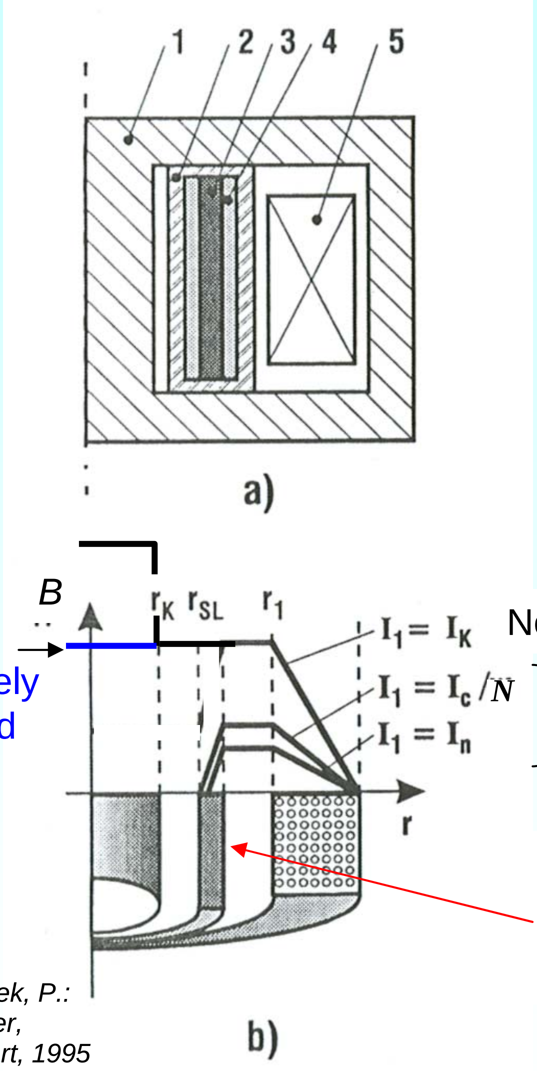
r_{SL}: SC cylinder inner radius

r_1: coil inner radius

I_1: primary coil current

I_c: critical coil current

I_k: short circuit current



If iron is completely saturated

Normal conducting state

SC state

Local quench starts here at maximum field

Komarek, P.: Teubner, Stuttgart, 1995

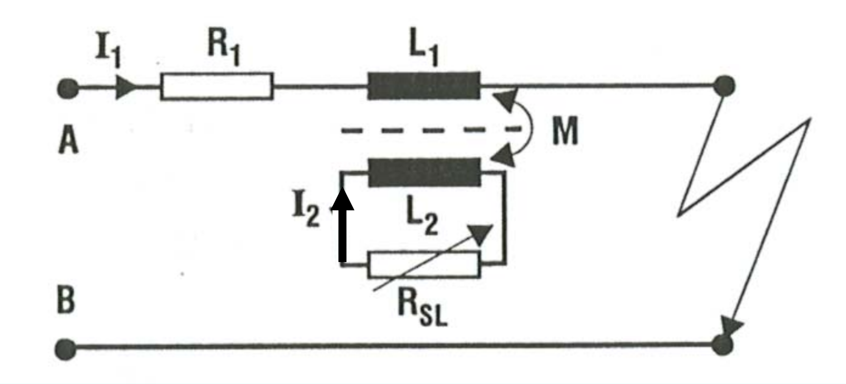
Primary coil and secondary HTSC cylinder form a shell type transformer with the voltage transfer ratio:

$$\ddot{u} = N_1 / N_2 = N / 1 = N$$

$$I_1 \ddot{u} = I_2 = I_{SC} = N \cdot I_1$$

Inductive superconducting fault current limiters (2)

Transformer equivalent circuit diagram:



Primary Cu coil: inductance L_1, resistance $R_{1,}$ leakage inductance: σL_1, leakage coefficient $\sigma \approx 0.1$

Secondary HTSC cylinder: inductance L_1, resistance R_{SL}, leakage inductance nearly zero!

Mutual inductance between primary Cu coil and secondary HTSC cylinder: M

$$L_1 - \sigma \cdot L_1 = N \cdot M = N^2 \cdot L_2$$

$$L_1 \sim N_1^2 = N^2 \qquad M \sim N_1 N_2 = N \qquad L_2 \sim N_2^2 = 1$$

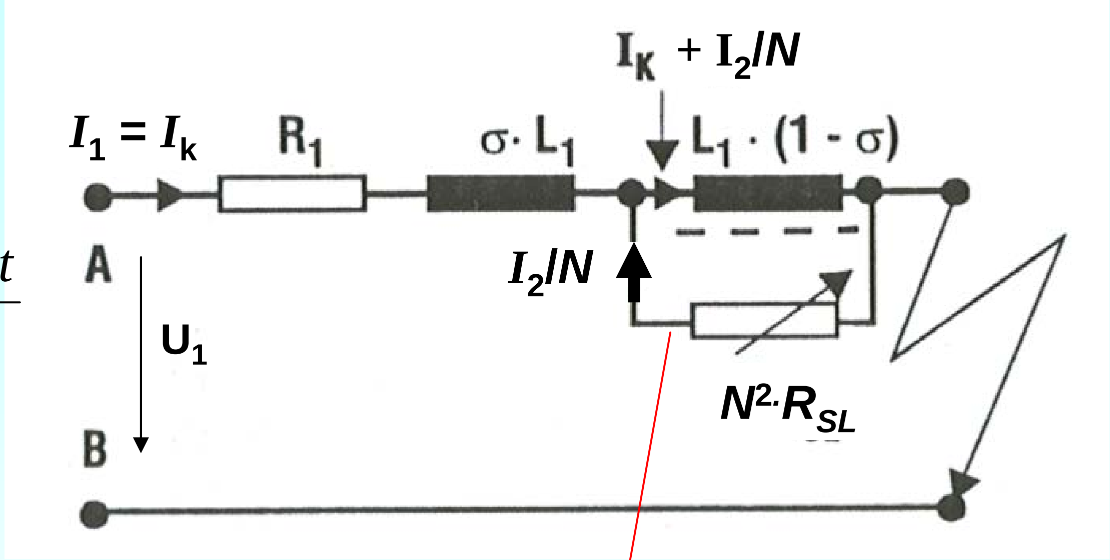
Komarek, P.: Teubner, Stuttgart, 1995

Inductive superconducting fault current limiters (3)

Transformer equivalent circuit diagram:

$$u_1 = R_1 i_1 + L_1 \cdot di_1/dt + M \cdot di_2/dt$$

$$u_2 = 0 = R_{SL} i_2 + L_2 \cdot di_2/dt + M \cdot di_1/dt$$



$$L_1 - \sigma \cdot L_1 = N \cdot M = N^2 \cdot L_2$$

$$u_1 = R_1 i_1 + L_1 \cdot di_1/dt + N \cdot M \cdot d(i_2/N)/dt$$

$$0 = N^2 R_{SL} \cdot (i_2/N) + N^2 L_2 \cdot d(i_2/N)/dt + N \cdot M \cdot di_1/dt$$

$$u_1 = R_1 i_1 + \sigma L_1 \cdot di_1/dt + (1-\sigma) L_1 \cdot d(i_1 + i_2')/dt$$

$$0 = N^2 R_{SL} \cdot i_2' + (1-\sigma) L_1 \cdot d(i_1 + i_2')/dt$$

Resulting impedance:

$$\boxed{\underline{Z} = \frac{N^2 R_{SL}}{1 + \dfrac{N^2 R_{SL}}{j\omega L_1 (1-\sigma)}}}$$

Komarek, P.: Teubner, Stuttgart, 1995

Inductive superconducting fault current limiters (4)

$$\boxed{\underline{Z} = \frac{N^2 R_{SL}}{1 + \frac{N^2 R_{SL}}{j\omega L_1 (1-\sigma)}}}$$

Resulting impedance:

a) No fault, SC state: $R_{SL} = 0$ $\boxed{\underline{Z} = 0}$

b) Fault, normal conducting state: $R_{SL} \to \infty$ $\boxed{\underline{Z} = j\omega \cdot (1-\sigma) \cdot L_1}$

a) Series impedance small: $\boxed{R_1 + j\omega \cdot \sigma \cdot L_1}$

b) Series impedance big = limits fault current: $\boxed{R_1 + j\omega \cdot L_1}$

Komarek, P.: Teubner, Stuttgart, 1995

Inductive superconducting fault current limiters (5)

- Normal-conducting Cu primary coil L_1 (number of turns N),
  HTSC hollow cylinder = shorted secondary coil: **"ampere-turns balance":**

  ***R*_SL = 0:** SC current $I_2' \approx -I_1 = -I_N \Rightarrow I_2 \approx -I_1 / \ddot{u} = -I_1 \cdot N$

- Magnetic field strength in iron core nearly zero:

  $$0 = \oint_C \vec{H}_{Fe} \bullet d\vec{s} = (NI_1 + I_2)$$

- **Resulting inductance low:** Only stray field in annular gap $\sigma \cdot L_1$.
  Small stray field = Low AC loss, dissipated via LN_2 bath cooling.
- Fault current: HTSC cylinder becomes normal-conducting.
- R_{SL} >> 0: High secondary resistance: $I_{2,k}' \approx 0 \quad \Leftrightarrow$ "no-load": I_1 excites high flux in the iron: high inductance L_1.
- **Hight current-limiting impedance:** $\boxed{R_1 + j\omega \cdot L_1}$

Inductive superconductive fault current limiters (6)

- **Cryostat** made of **non-conducting** material, otherwise it acts as short-circuit conductive turn, causing a temperature rise by eddy current losses.
- HTSC cylinder must be homogenous for simultaneous quenching at the entire perimeter. Only local quenching bad ⇒ locally high losses ⇒ local heating ⇒ local increased mechanical stress ⇒ brittle Bi(2212) cylinder breaks.
- **Advantage:** No conductor connections from HTSC to normal-conducting coils necessary: low **SC losses** **due to low heat inflow!**

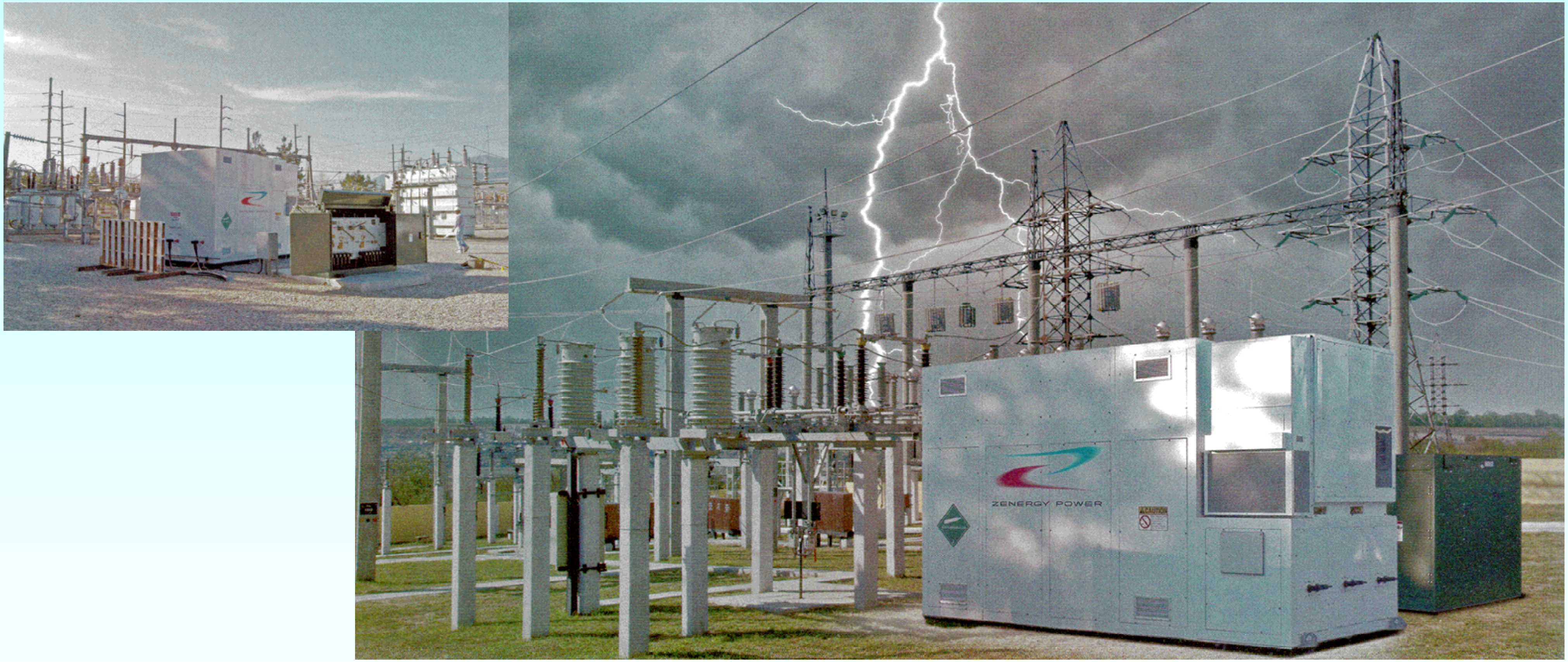
Single-phase prototype test:

I_N = 200 A, U_N = 8.3 kV, 0.5 m^3 volume of the device, fault current 13.2 kA (66 - times of rated current!).

Fault current limited to: 4.3 kA (peak) and after 20 ms to 1.4 kA (r.m.s.).

2.2 Superconductivity for electrical energy technology

Inductive superconducting fault current limiter



Use of an inductive HTSC-FCL with a DC saturation principle in the medium voltage grid of *Southern California Edison* near *Los Angeles, USA,* since spring 2009,

- Operation temperature: -240°C (33 K!), 10 W loss of power in the FCL
- Necessary cooling power: 16 kW

Source: Zenergy Power GmbH, Rheinbach, D,
BWK 62 (2010) no. 9, p. 58

Perspectives for SC fault current limiters

- Fault current limiters only possible with superconductor technology.
- They allow saving of system resources due to smaller short circuit currents (= smaller overload of devices) and are therefore **economically very appealing.**
- They can be designed in such a way that the AC loss in SC operation remains sufficiently small.
- Hence their deployment has high appeal, justifying the effort for development and, during operation, for the required cooling.

New technologies of electric energy converters and actuators

Summary:
Fault current limiter

- Competing resistive and inductive SC fault current limiter systems
- Only high temperature superconductors used
- Several long term field tests in progress
- Reduction of short circuit current allows protection of power devices
- Wider use in near future expected

2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

2.2.4 Superconducting power transformers

2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

2.2.2 Overhead line – cable – LTSC cable

- **Advantages of AC high voltage overhead lines**

  - low construction and maintenance cost,
  - low dielectric loss (air as insulation medium),
  - high transmission capacity (up to ca. 6 GVA) due to high transmission voltages (up to typically 765 kV in *USA/Canada*), several parallel lines per steel tower

⇒ Usage for about 95% of electrical energy transmission

- **Cable:** Complicated construction, buried: 5 to 10 times as expensive
  - Used, where overhead lines are not feasible (e.g. down-town)
  - Smaller dimensions than overhead lines:
    Big capacity $C_{\text{cable}} = \text{ca. } 10C_{\text{overhead line}}$ ⇒ high charging current

- **LTSC cable:** market for AC cables significantly higher than for DC cables (HVDCT):

  - AC loss and (thus increased) cooling losses with LHeI
  - losses are proportional to cable length ⇒ expensive cooling system

Therefore, in spite of extensive technical trials and good technical results, for economical reasons the LTSC cable was not introduced at the market.

HTSC cable

- **HTSC cable:** LN_2: cheaper cooling: The superconductor power cable is attractive for transmission capacities of ca. 1000 MVA, e.g. increasing the transmission capacity with unchanged transmission route

- **Magnetic advantage:** Self-field *B* is low ⇒ HTSC multifilament conductors with lower critical flux density B_{c2} (< 4 T at 77 K) do not quench

Example: Current *I* = 6 kA r.m.s., diameter of cylinder conductor: *d* = 4 cm,
self-field at the surface of the cylinder conductor: 85 mT amplitude

$$\hat{B}_e = \mu_0 \sqrt{2} \frac{I}{d\pi} = 85 mT$$

HTSC **Bi(2223):** B_{c1} (77 K) ca. 20 ... 80 mT ⇒ *Shubnikov* phase:
Field enters the superconductor.

- **Hysteresis loss P_{Hy}** in conductor volume *V* small, **must be checked by cooling technology**:

$$\boxed{P_{Hy} \sim V \cdot f \cdot B_e^2 \cdot \frac{B_e}{J_c}}$$

HTSC power cable with cold dielectric (insulation)

Prototype: 110 kV/ 1000 MVA, all three phases in one cryostat

1: HTSC strip conductor, stranded on inner tube cooled by LN_2 (77 K)

2: LN_2 cooled HV insulation (e.g. PPP)

3: HTSC outer conductor (stranded tapes) for field shielding as "return"

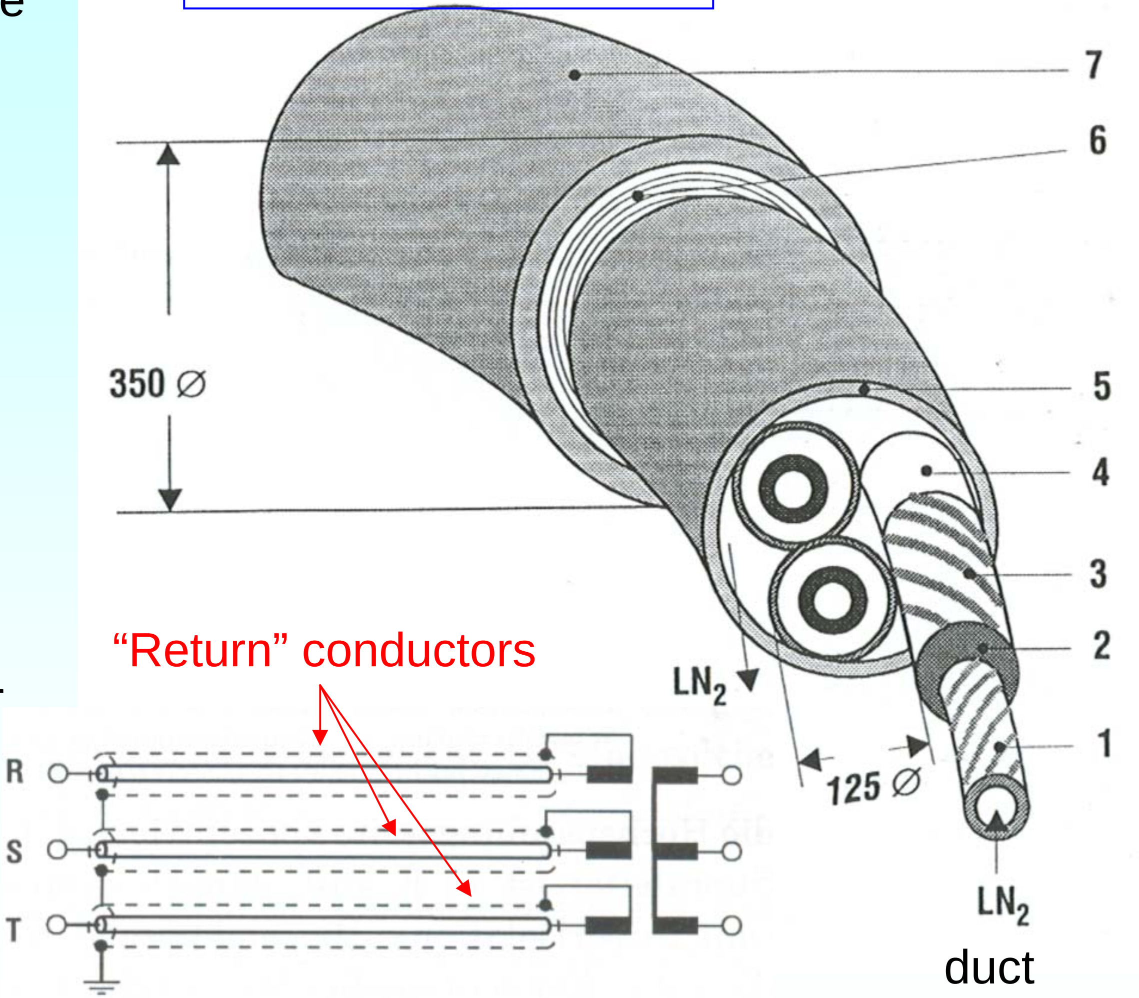
4: electrostatic shield

5: LN_2 tube container

6: Super insulation in vacuum chamber

7: Outer pipe with corrosion protection

One common cryostat



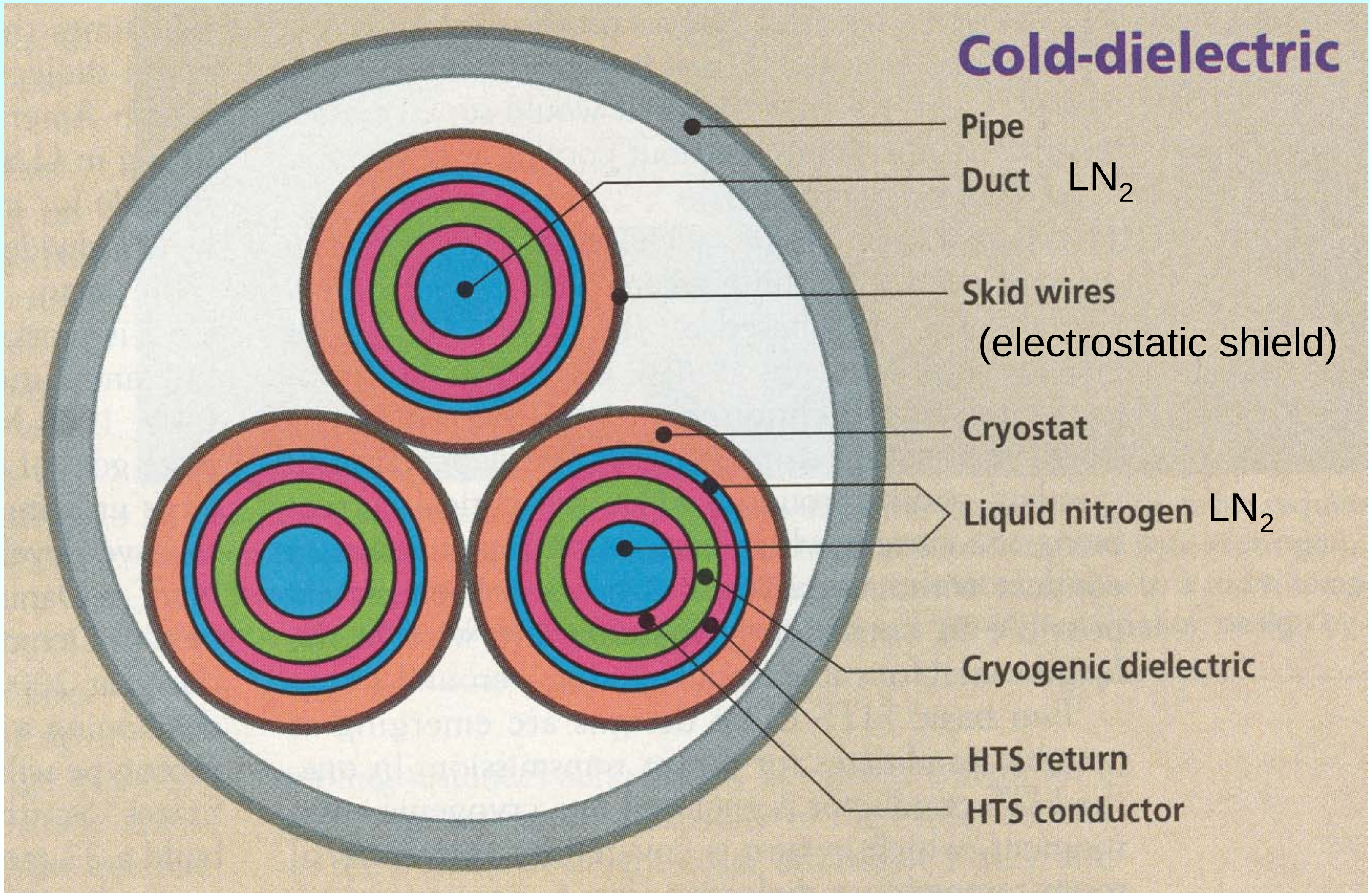
"Return" conductors

duct

Komarek, P.: Teubner, Stuttgart, 1995

2.2 Superconductivity for electrical energy technology

HTSC power cable with cold dielectric



Duct LN_2

(electrostatic shield)

Liquid nitrogen LN_2

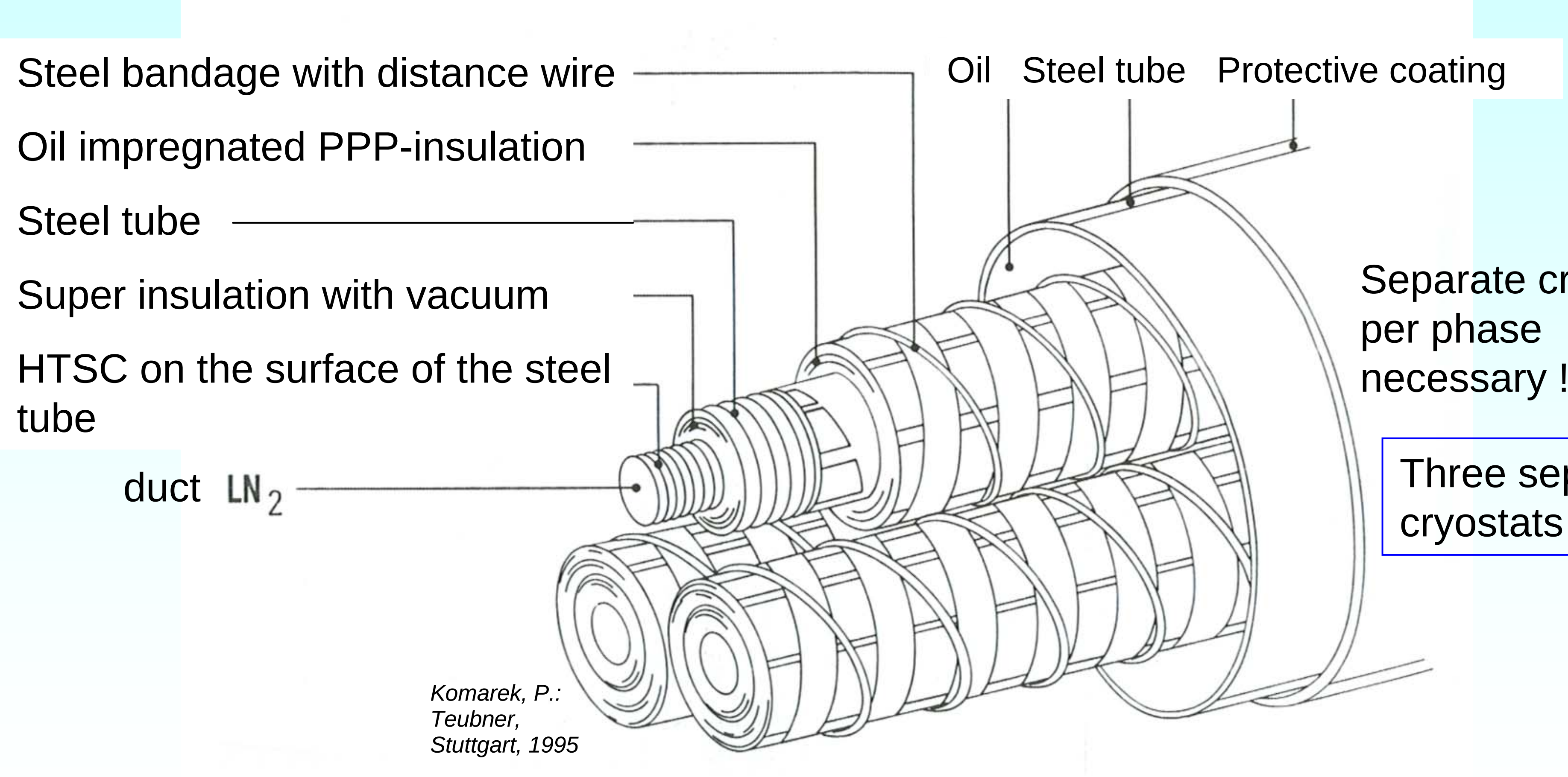
Source:
IEEE/PES Journal,
1998

Variant with each phase in a separate cryostat

Three separate cryostats

HTSC power cable with warm dielectric (insulation)

- HTSC (77 K), conventional high voltage insulation at ambient temperature



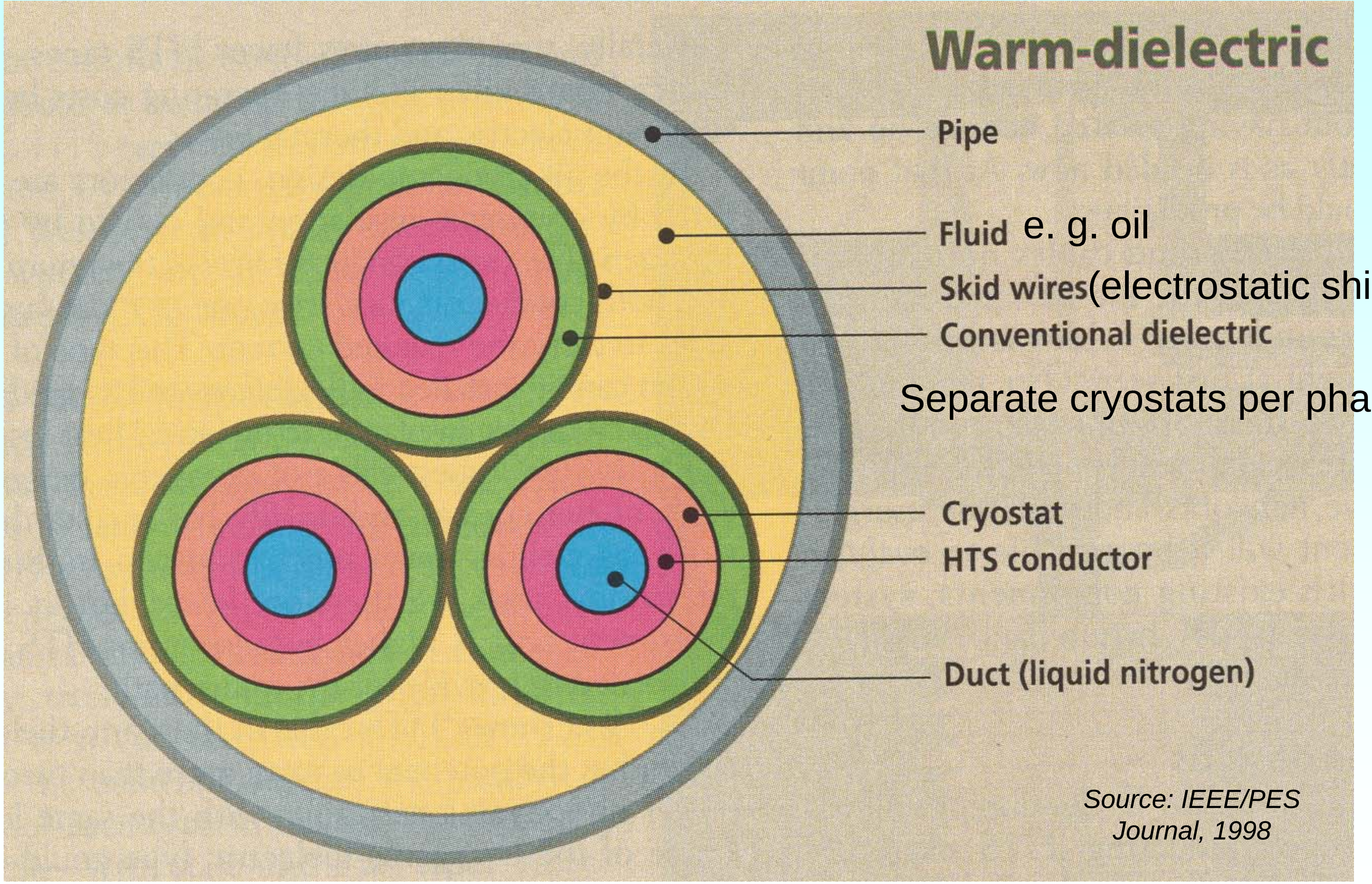
Komarek, P.: Teubner, Stuttgart, 1995

Separate cryostats per phase necessary !

Three separate cryostats

2.2 Superconductivity for electrical energy technology

HTSC power cable with warm dielectric



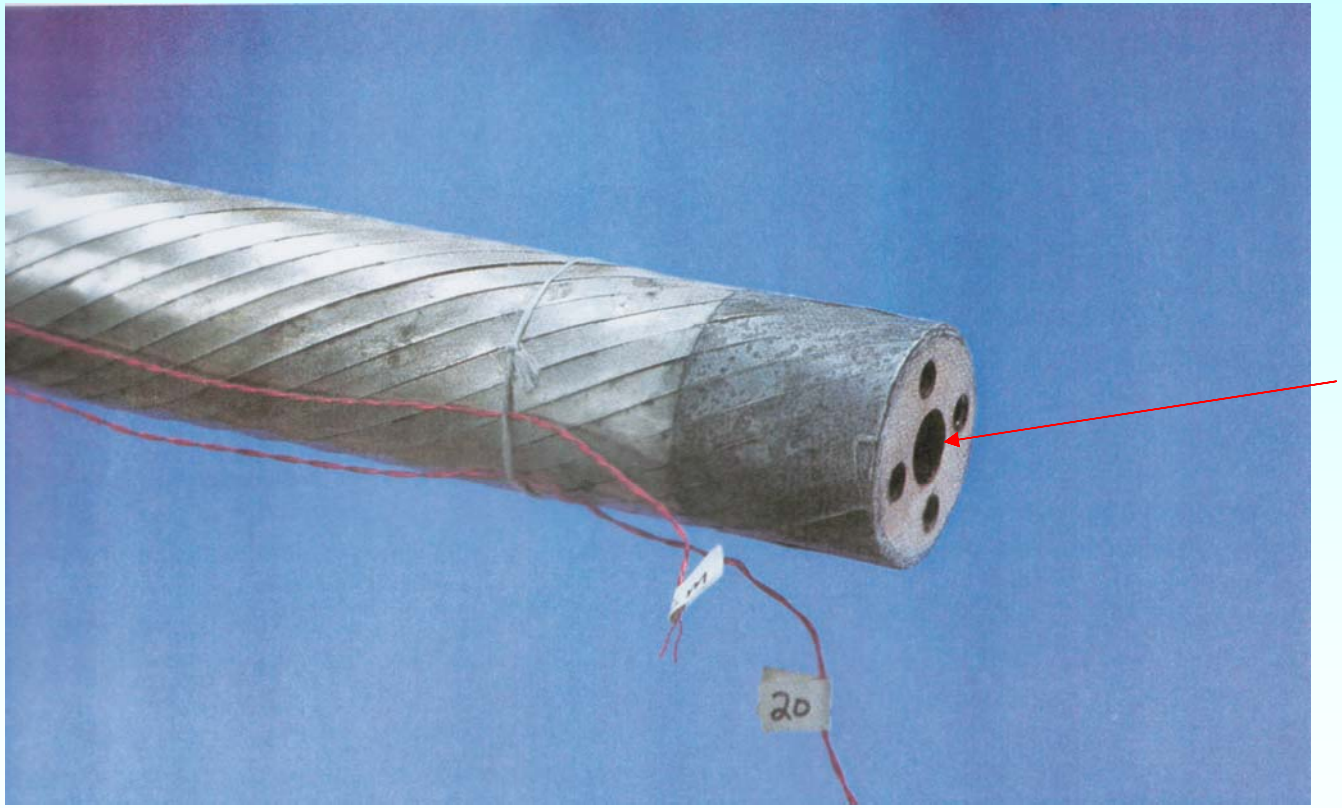
e. g. oil

(electrostatic shield)

Separate cryostats per phase

Source: IEEE/PES Journal, 1998

One phase of an HTSC power cable with warm dielectric



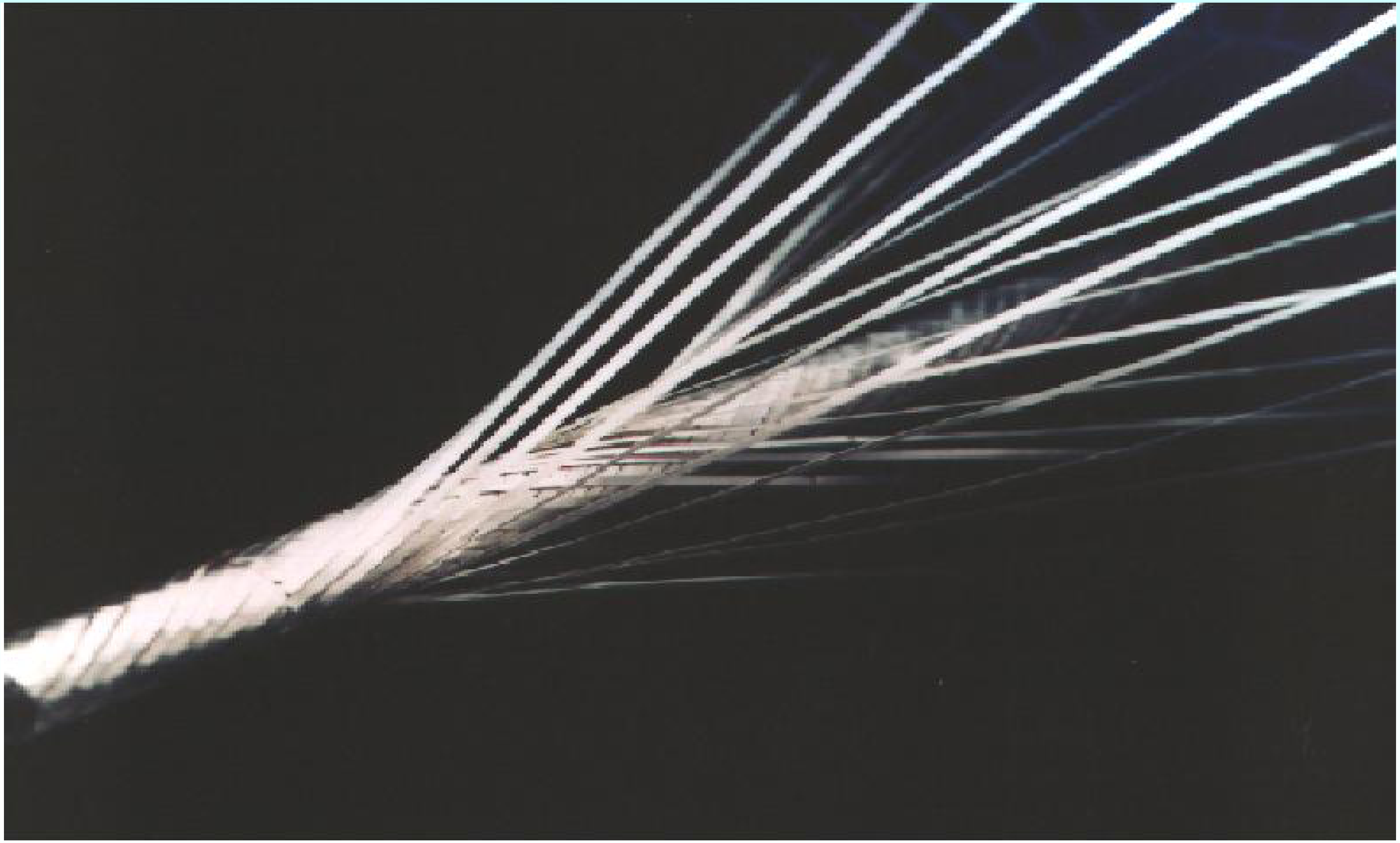
Duct LN_2

Source:

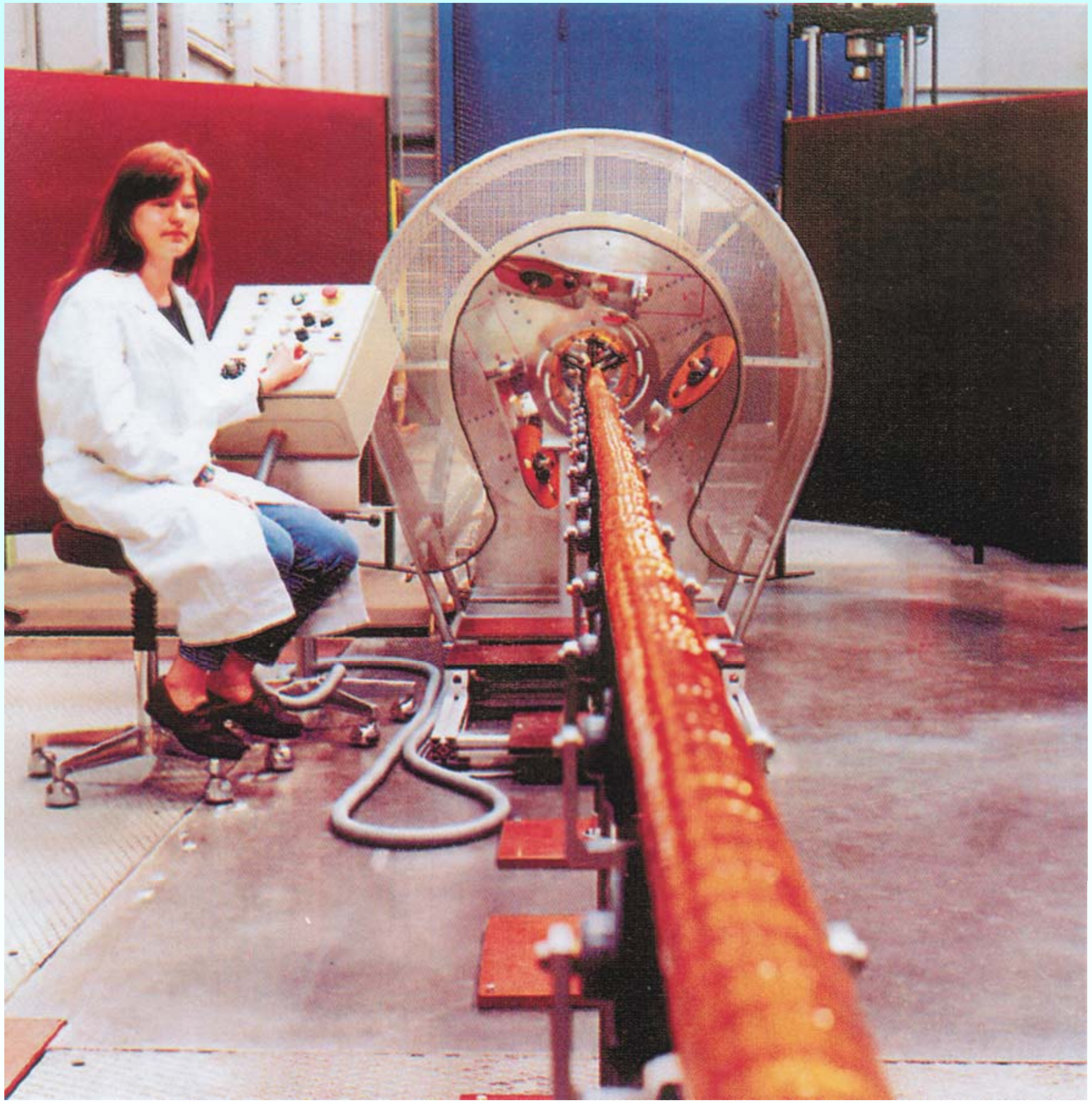
Pirelli & American Superconductor

BSCCO 2223 HTSC strip conductor on rigid carrier, 90 kV, 50 m lang, LN_2 inner cooling in a central duct

Stranding of the HTSC-BSCCO conductors of one cable phase



Source: American Superconductor, USA



Production of prototype HTSC cable

Stranding of the BSCCO strip conductors on a rigid carrier

Critical temperature of the SC cable at zero field: 110 K

LN_2 cooling

Source: Siemens AG, Germany

Cooling of HTSC power cable

- Warm dielectric: Cryogenic area restricted to the high voltage side:

  - allows less SC material, **less cryogenic requirement,**

  - **but no** magnetic field compensation: AC field induces eddy current losses in cryostat, which load thermally the cryogenic coolant.

- At longer cable lengths: 5 W/m loss in cable: **coolant** has to be fed with overpressure (e.g. 5 bar, 2 l/s coolant flow) due to pressure drops in the tube track system. Arranged in cooling sections, if necessary!

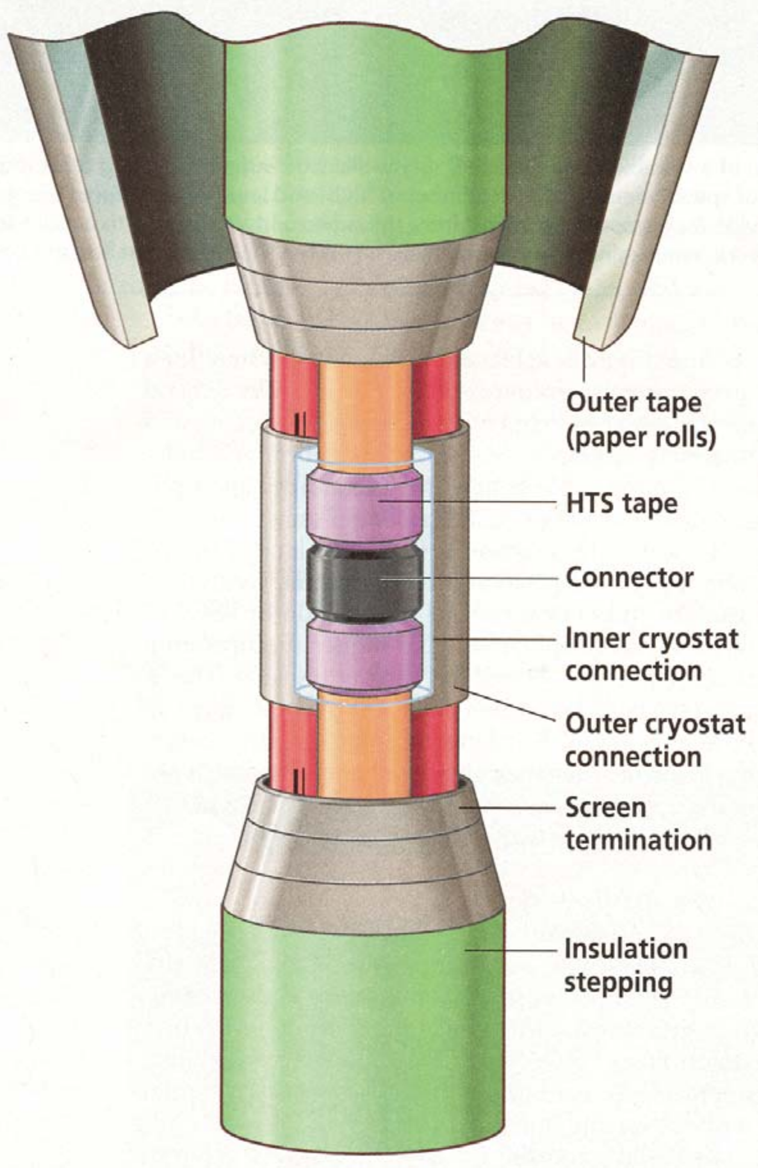
- Production length of Bi HTSC stranded conductors ca. 1 km.

  - Cable sections connected by cable joints (point-to-point soldered wiring).

- Cable sealing ends: - controlled reduction of electric field strength,
  - with low loss and LN_2 waste-gas-cooled,

- **Fault treatment:** high fault current: danger of quenching: Combination of SC cable with FCL recommended.

Cable joint (junction box) between two HTSC cables (per phase)



- nominal voltage 115 kV, 60 Hz
- warm dielectric
- LN_2 cooling
- insulation "stepping" for smoothed reduction of electric field strength = homogenization of the electric potential

Source: IEEE/PES Journal, 1998

HTSC cable for retrofit

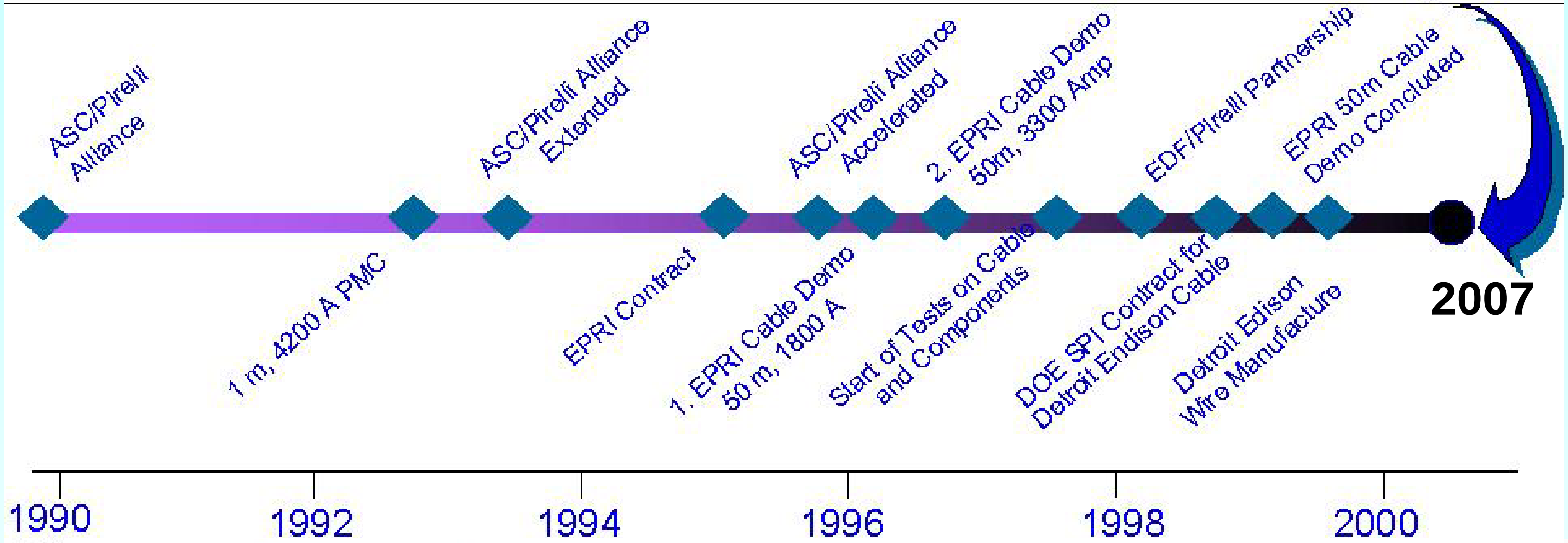
- Cost for HTSC cables sufficiently low only, if amount of HTSC material is sufficiently low: Material with $J_c > 1200$ A/mm^2 (77 K) necessary.

  At 2010: for BSCCO-wires: available: J_c ca. 500 A/mm^2
- As losses in HTSC cable are only about 1/5 of the one for the conventional cable: At equal losses: 5 times the transmission capacity.
- Retrofit plants: Old cable route used in down-town: e.g. in case of space limitation. SC cable is in that case today already economically feasible
- *Example:* ***Detroit, Michigan, USA,*** "downtown": Field test

  HTSC warm dielectric cable replaces conventional cable

  Data: $S_N = \sqrt{3} U_N I_N = 100 MVA$
  $U_N = 24$ kV, $I_N = 2.4$ kA (eff.), Bi(2223); 120 m length: connection between 120kV/24 kV transformer and the 24 kV switching station

HTSC-cable for downtown retrofit use



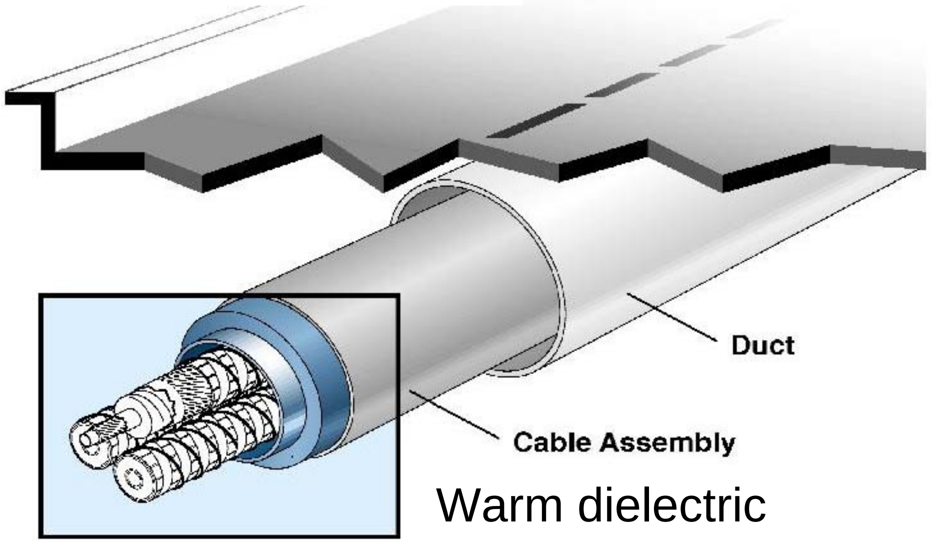
***Albany* HTSC-Cable project:**

a) BSCCO-stranded flat conductors

b) YBCO-tape conductor

Source:

ASC / Pirelli



Long Island HTSC cable application for retrofit

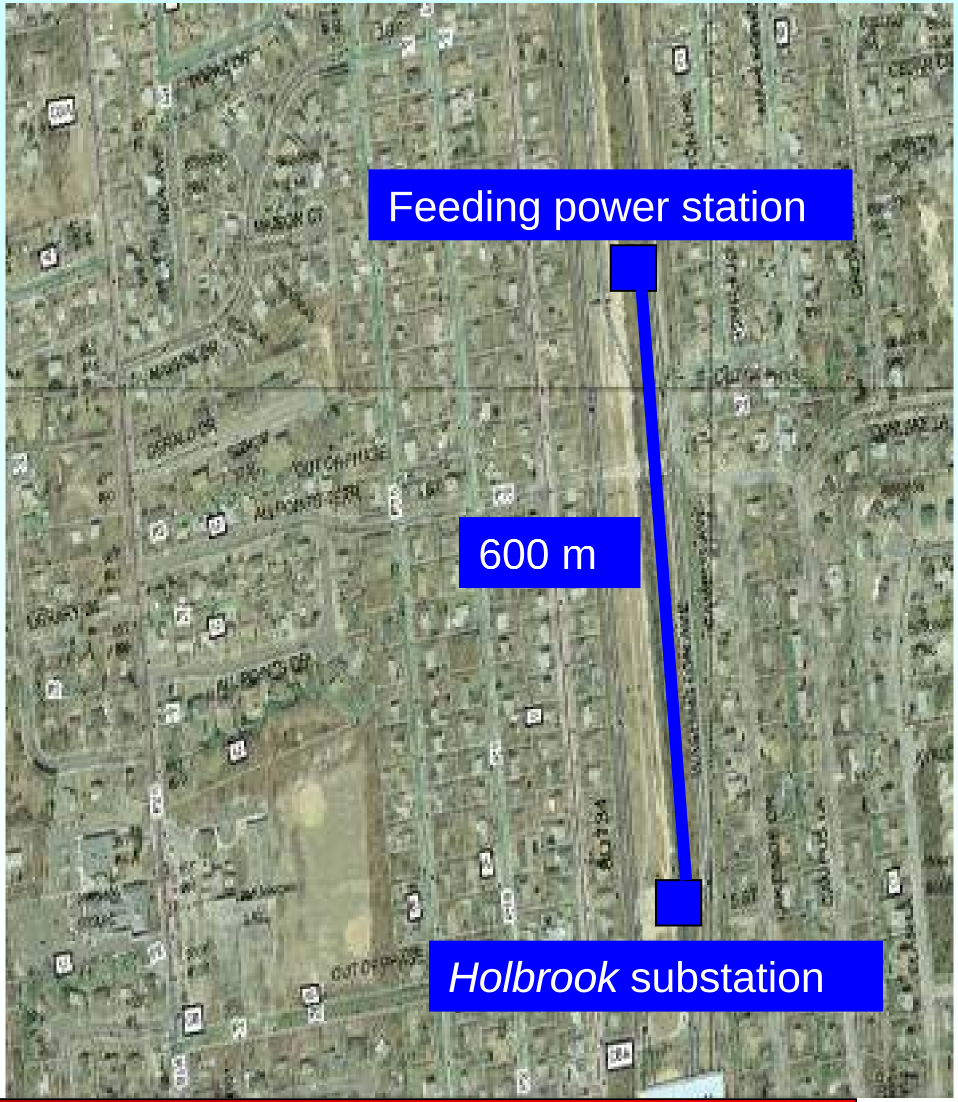
- High voltage cable connection between *Holbrook* substation and the feeding power station (600 m distance), *Long Island Power Authority, USA,* in 2008

- *Data:* 138 kV line-to-line voltage, 2400 A phase current, 574 MVA apparent transmission power, 60 Hz, short circuit current capability: 51 kA for 0.2 s

- Three single-phase cables with cold dielectric, one LN_2-cooling system, 12 bar pressure, 65 K, 155 km of BSCCO tapes used

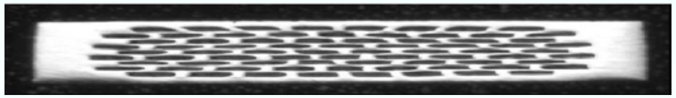
- 2 x 3 cable terminals at both ends for 138 kV into open air.

Source: Nexans, Germany



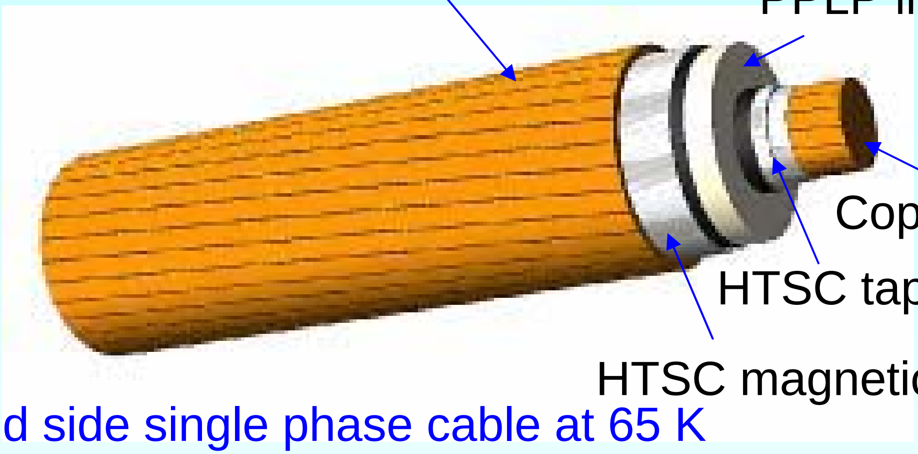
Long Island HTSC cable application for retrofit

Cable manufacturing

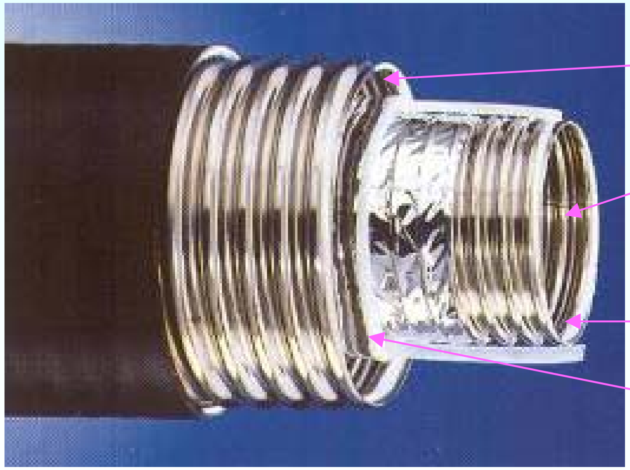


BSCCO 2223 tape structure
4.3 x 0.4 mm^2 for I_c = 200 A

Source: Nexans, Germany



Cold side single phase cable at 65 K



Single phase cable cryostat

2.2 Superconductivity for electrical energy technology

Long Island HTSC cable terminal 136 kV

Vertical part:

a) HV insulator between 136 kV and ground

b) Temperature gradient between 65 K and 300 K

Horizontal part:

a) Length equalization during cooling process

b) Connection to HTSC cable

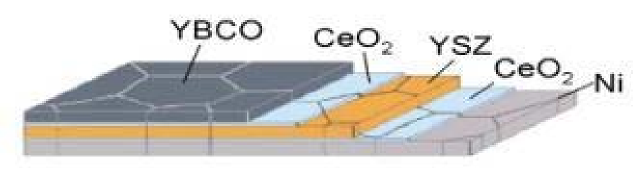
Source: Nexans, Germany

German HTSC cable project "*Ampacity*" (*Essen*)

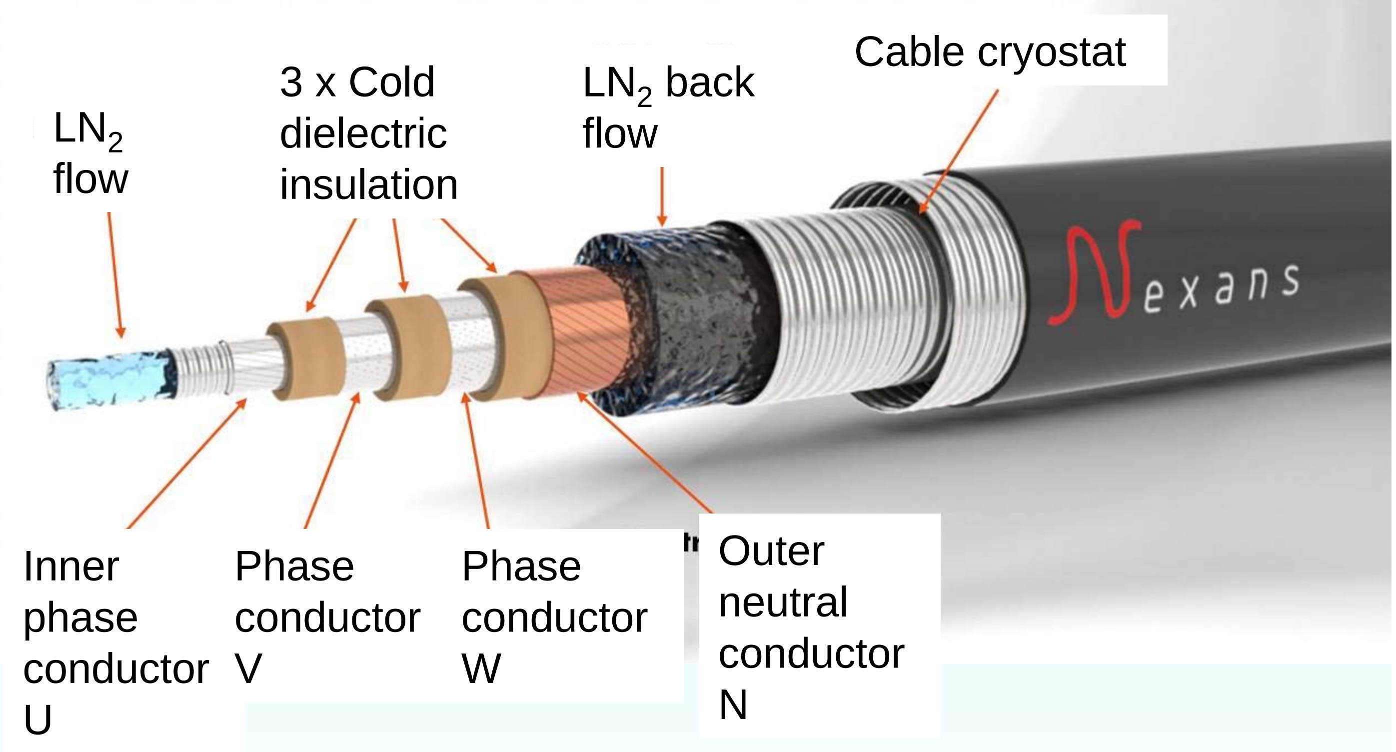
- *Essen* downtown, connecting two substations *Dellbrügge* and *Herkules* with HTSC-cable and resistive FCL as protection between HTSC-cable and transformer
- Start: May 2014; test duration: 2 years; project partners: *Nexans*, *RWE*, *KIT*
- Retrofit: 1 km = 2 x 0.5 km HTSC-cable 10 kV, 3 phases, 50 Hz, with a cable joint. It replaces an existing 110 kV normal conducting Cu-cable to increase transmission power without digging a new cable tunnel. The 110 kV/10 kV-substation is removed.
- 40 MVA power transmission: $S_N = \sqrt{3} \cdot U_N I_N = \sqrt{3} \cdot 10\mathrm{kV} \cdot 2.31\mathrm{kA} = 40\mathrm{MVA}$
  New/old: 10 kV/110 kV = 0.1, hence 2310 A / 231 A: 10-times higher current rating of the HTSC-cable via reduced rated voltage
- 3-phase concentric YBCO-tape HTSC cable, 1 km LN_2 cooling-tube, -196°C (77 K), 4 kW cooling power
- Costs = 6-times of conventional cable; total 13.5 Mio. € (5.9 Mio. € public funding)

Source: VDI Nachrichten, no.19, 9. May 2014

Concentric three-phase HTSC cables for medium voltage < 30 kV



YBCO 2223 tape structure
4.4 x 0.4 mm^2 for I_c = 90 A



Concentric 3-phase HTSC cable for 10 kV with YBCO tape conductors, cold dielectric, 65 K

Source: Nexans, Germany

Data: *Essen* down-town

10 kV line-to-line voltage

2398 A phase current

40 MVA apparent transmitted power

2 x 0.5 km length
(0.5 km transport limit)

Per 1 km: 184 km of YBCO tapes are needed.

German HTSC cable project *“Ampacity”*

Test of the 10 kV-HTSC-cable in the *Hannover* manufacturing plant of *Nexans, Germany*
- Impulse voltage test at 7-times rated voltage to withstand lightning strokes
- Steady state test at 3-times rated voltage 50 Hz, and rated current

Source: Nexans, Germany, published in: energiewirtschaft 112, 2013, no.6

Perspectives for HTSC cables

- The low self-fields together with BSCCO-HTSC allow for 77 K operation. In the future: Only YBCO-tapes in use!
- Progress of the HTSC development (higher J_c, higher conductor lengths) decreases investment cost, but still expensive
- For Retrofit plants (conurbation, space limitation), HTSC cables are already economically feasible today due to the ca. 5 times higher transmission capacity.
- The deployment of HTSC power cables competes with conventional high-power cables (e.g. oil-filled cables with water cooling), therefore large-scale deployment in the near future is uncertain.

New technologies of electric energy converters and actuators

Summary:
Superconducting power cables

- Cold and hot dielectric systems developed
- Only high temperature superconductors used
- Only short cable distances feasible for short cryostats
- Retrofit applications for increased transmission power in crowded areas
- Up to now only prototype field testing

2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

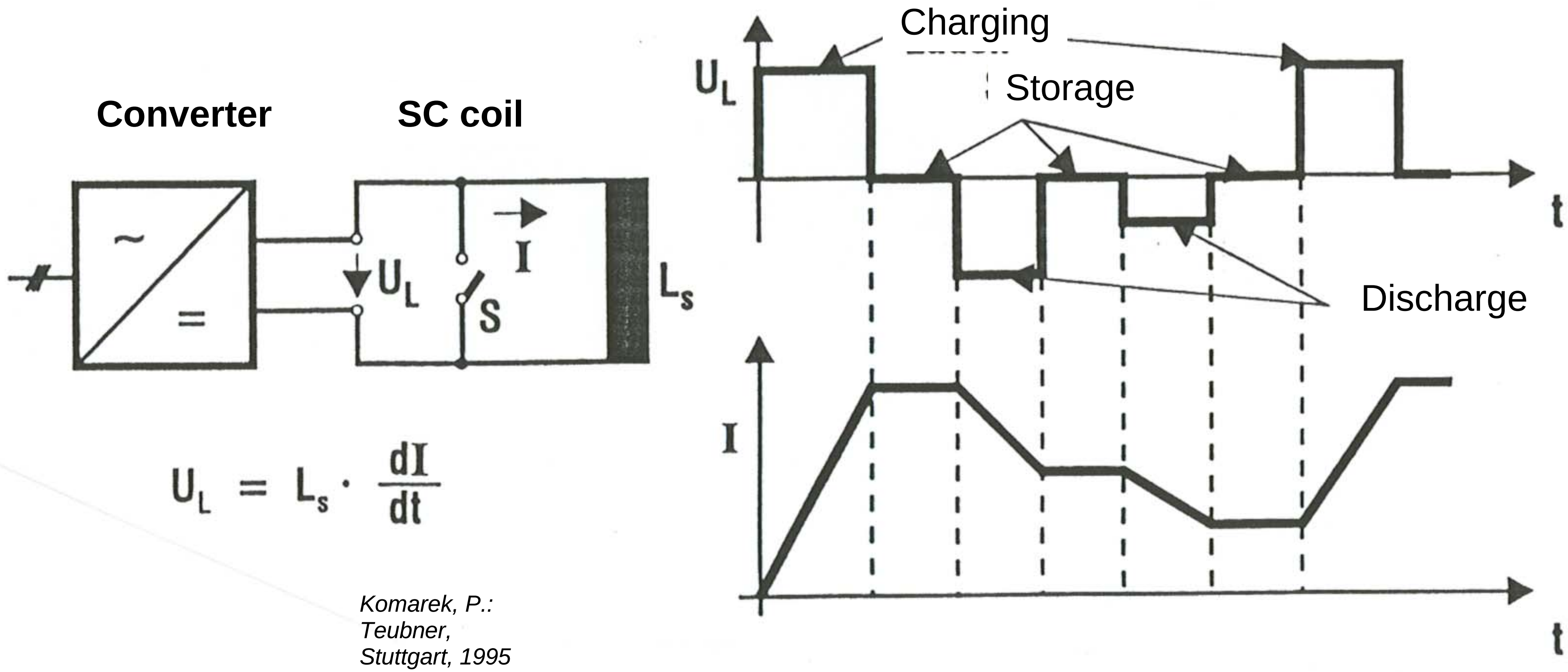
2.2.4 Superconducting power transformers

2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

2.2.3 Superconducting magnetic energy storage (SMES)

- At B = 8T: stored energy density $W/V = \dfrac{B^2}{2\mu_0} = \dfrac{8^2}{2\cdot 4\pi\cdot 10^{-7}} = 25\dfrac{MJ}{m^3}$
- L_s: superconductor coil, S: short-circuit switch



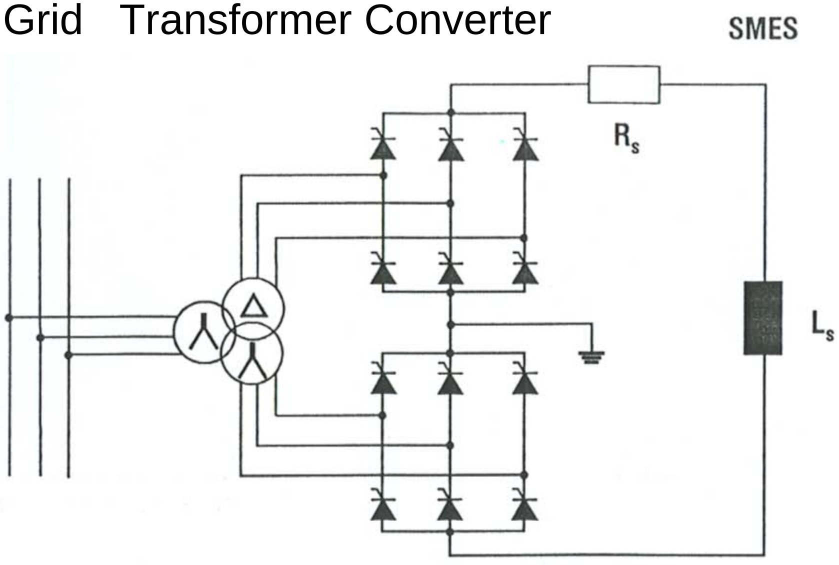
Komarek, P.:
Teubner,
Stuttgart, 1995

Uninterruptible Power Supply (UPS)

a) Connecting the SMES to the grid via a twelve-pulse converter and a 3-winding transformer

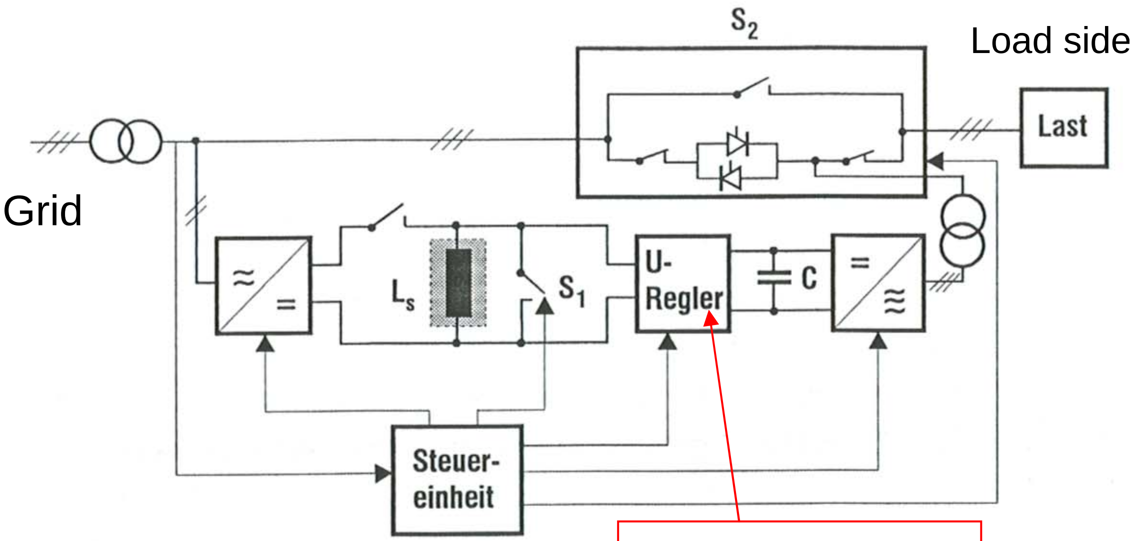
b) Block diagram for an UPS

Grid Transformer Converter



a)

Komarek, P.: Teubner, Stuttgart, 1995



Grid

Load side

Control

Voltage control

b)

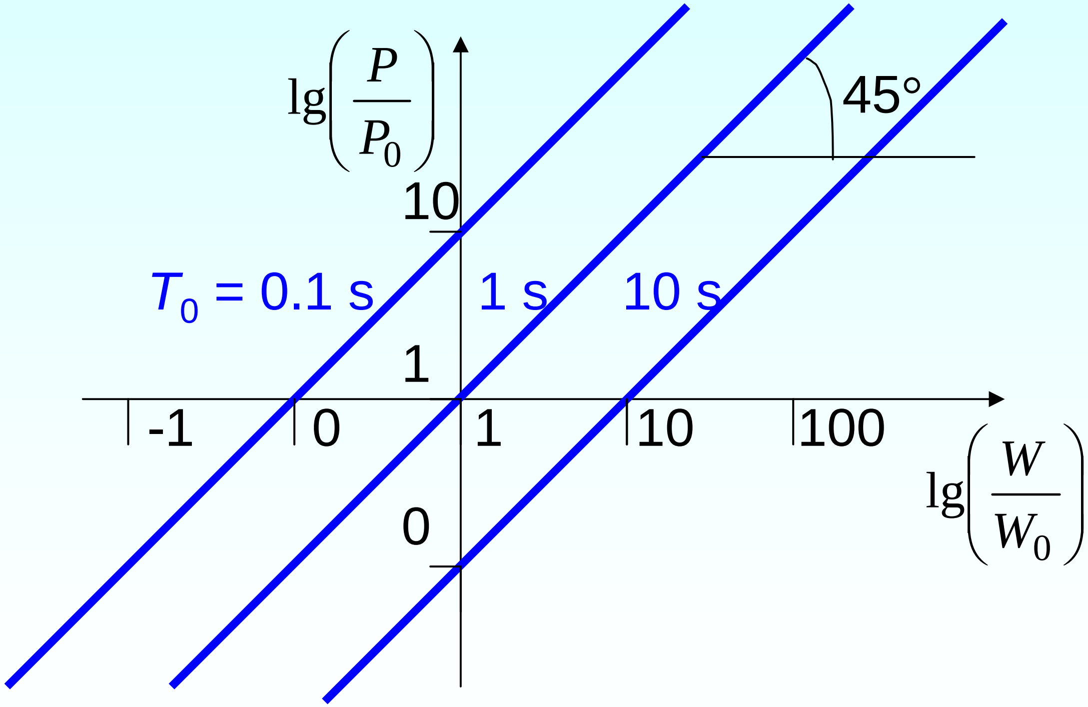
Sequence of function of a SMES

- System disturbance is detected ⇒ input capacitor *C* at converter charged with current from the storage coil
- Desired value for voltage reached: Switch S_1 closes, switch S_2 disconnects load from system. *C* feeds the load via load side converter and step-up transformer.
- Voltage drops to defined minimum value at *C*, S_1 disconnects again: Process is repeated.
- Recharging of *C* takes longer now, because the current in the superconductor L_s has become lower due to energy withdrawal from the storage.
- When the fault is cleared, the grid-side converter is synchronised to the grid. S_2 connects load to the system and disconnects from SMES.
- SMES is recharged again. The load takeover by the SMES is possible in 2..4 ms due to the fast power electronics.

RAGONE diagram

$$P = W/T \quad \Rightarrow \quad \frac{P}{P_0} = \frac{W}{W_0} \cdot \frac{T_0}{T} \quad \Rightarrow \quad \lg\left(\frac{P}{P_0}\right) = \lg\left(\frac{W}{W_0}\right) - \lg\left(\frac{T}{T_0}\right)$$

P: Discharged power, *W*: Stored energy, *T*: Discharge time at constant power, Per-unit values: P_0 = 1 kW, W_0 = 1 kWs, T_0 = 1 s



Example for
Discharge time scale:

scale	time
1	10 h
0.1	1 h
0.01	0.1 h = 6 min
0.001	0.01 h = 36 s
0.0001	0.001 h = 3.6 s

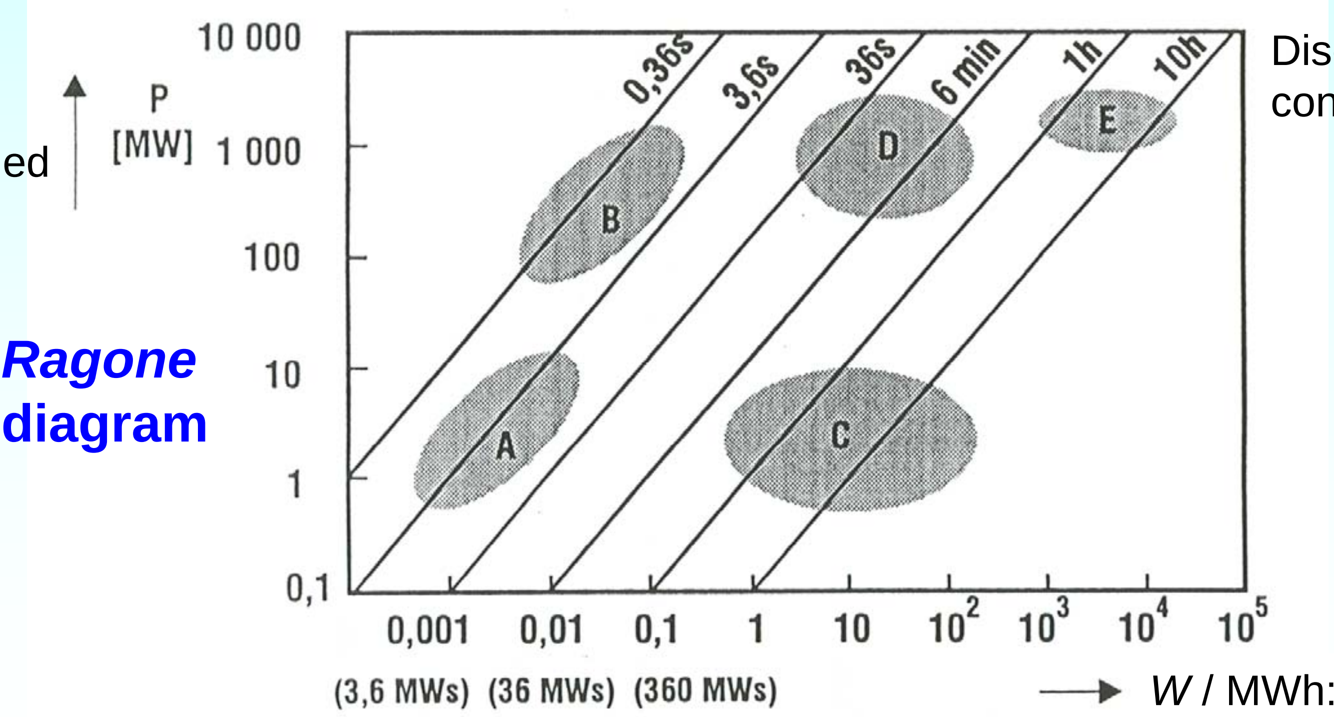
See next slide!

Sizes of energy storage systems and fields of application

A, B: Smallest/small storages: fast energy feeding for UPS (*T*: ms range)

C, D: Medium storages for energy feeding in the seconds/minutes range (Used for primary grid control – "seconds reserve")

E: Large storages for 24-hour energy feeding to the grid



P: Discharged power

Ragone diagram

Discharge time at constant power

W / MWh: Stored energy

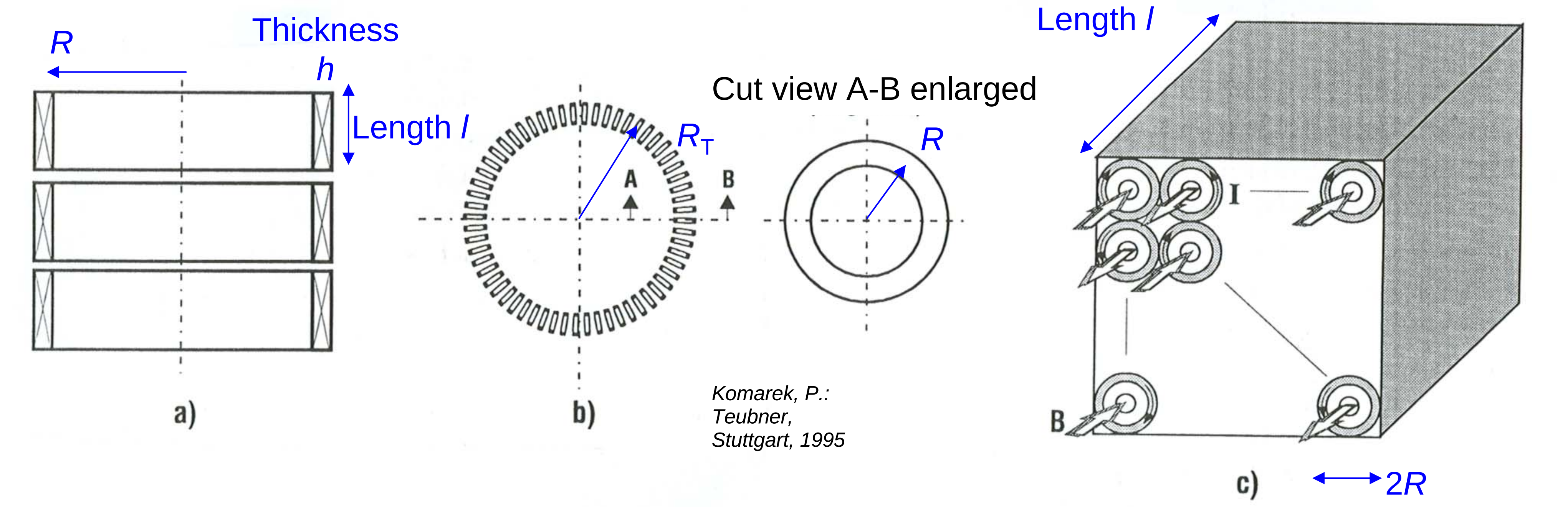
Komarek, P.: Teubner, Stuttgart, 1995

Design principles for storage coils

a) Segmented solenoid: large inner coil radius *R*, low coil thickness *h*, moderate coil height *l*

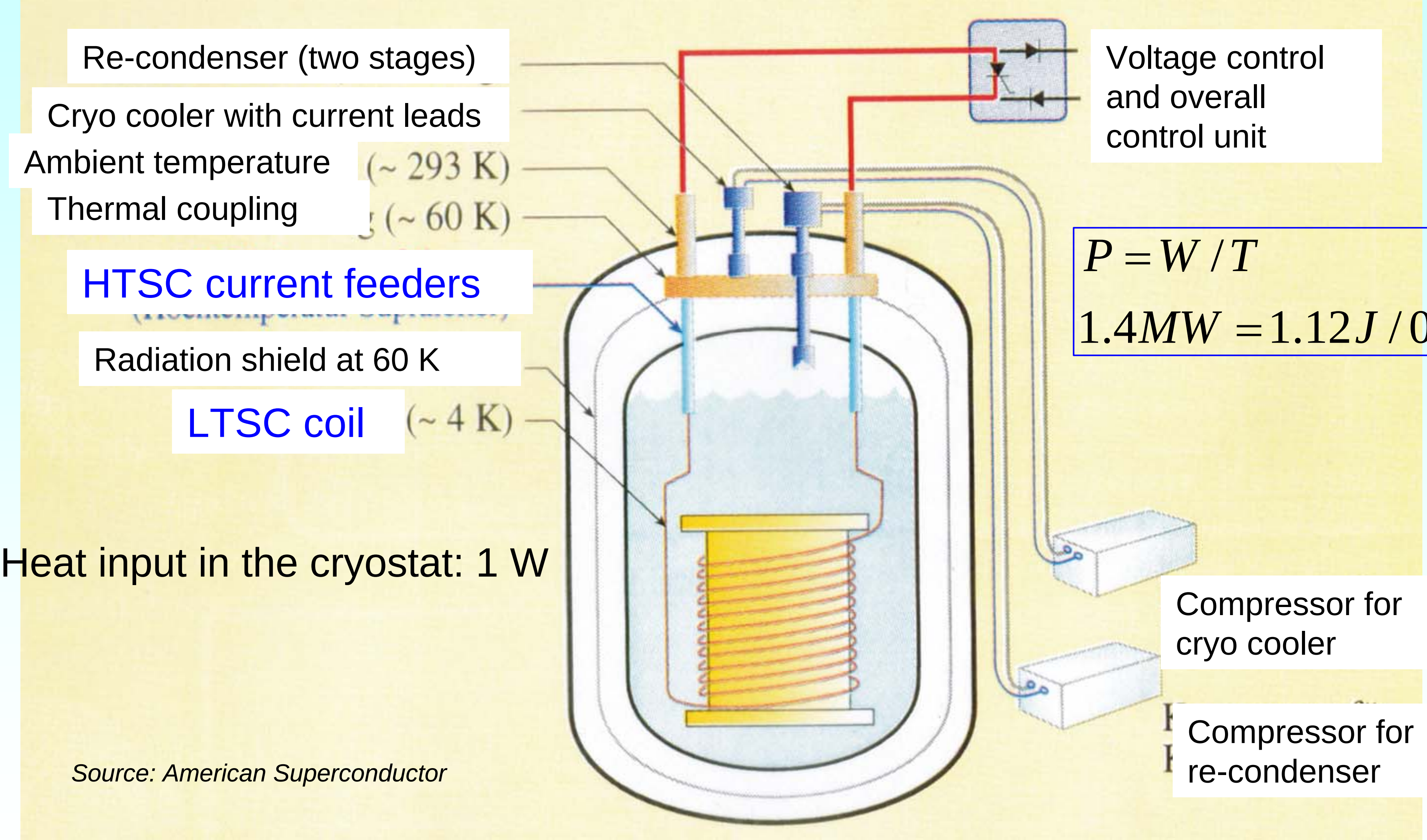
b) Torus (ring coil) of many separate coils, high ratio of mean torus radius/coil radius R_T/R

c) Bundle of single solenoids with high ratio *l*/*R* and alternating directions of current feed for minimising the outside stray field



Komarek, P.: Teubner, Stuttgart, 1995

SMES for 1.4 MW during 0.8 s as a "power storage"



Re-condenser (two stages)

Cryo cooler with current leads

Ambient temperature

Thermal coupling

HTSC current feeders

Radiation shield at 60 K

LTSC coil

Voltage control
and overall
control unit

$$P = W / T$$

$$1.4MW = 1.12J / 0.8s$$

Compressor for
cryo cooler

Compressor for
re-condenser

Heat input in the cryostat: 1 W

Source: American Superconductor

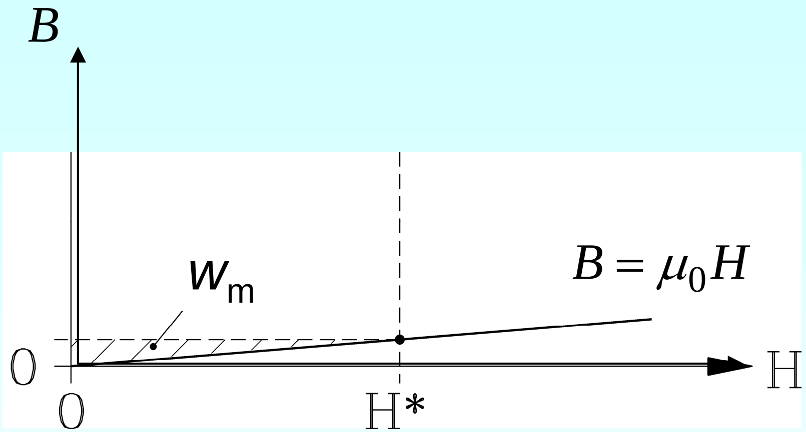
Magnetic energy density w_m in magnetic field in air

- Magnetic field in air: $\vec{B} = \mu_0 \vec{H}$

- Magnetic energy density: $w_m = \int_0^B \vec{H} \cdot d\vec{B} = \int_0^B H \cdot dB$

$$w_m = \int_0^B H \cdot dB = \int_0^B (B/\mu_0) \cdot dB = B^2/(2\mu_0) = \mu_0 H^2/2$$

- Magnetic energy in a volume *V*: $W_m = \int_V w_m \cdot dV$

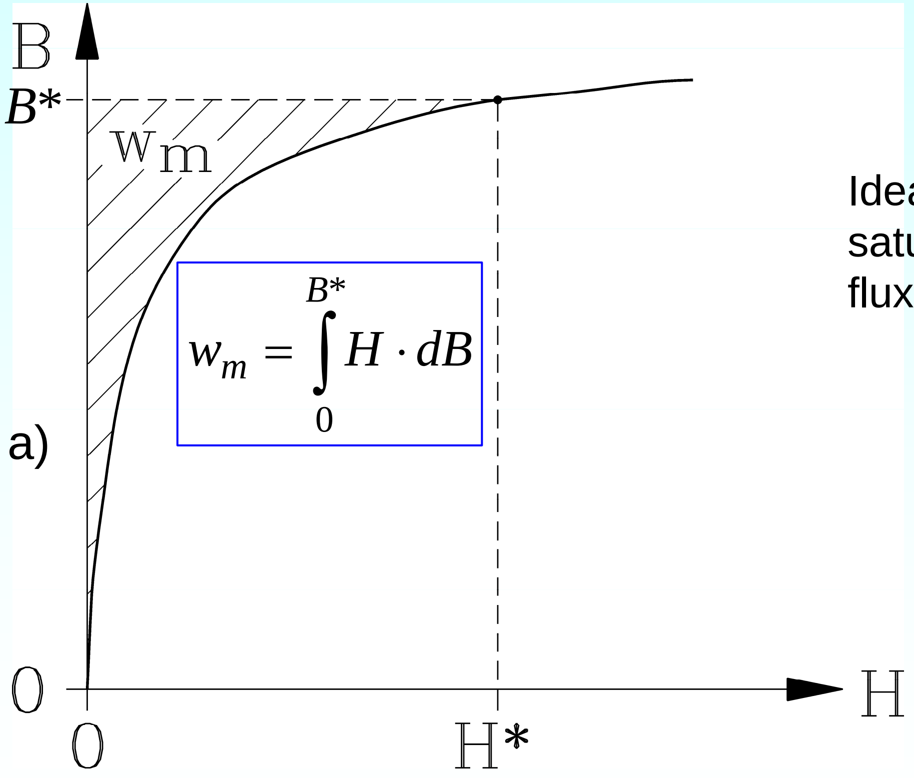


Stored energy density w_m in magnetic field H^*

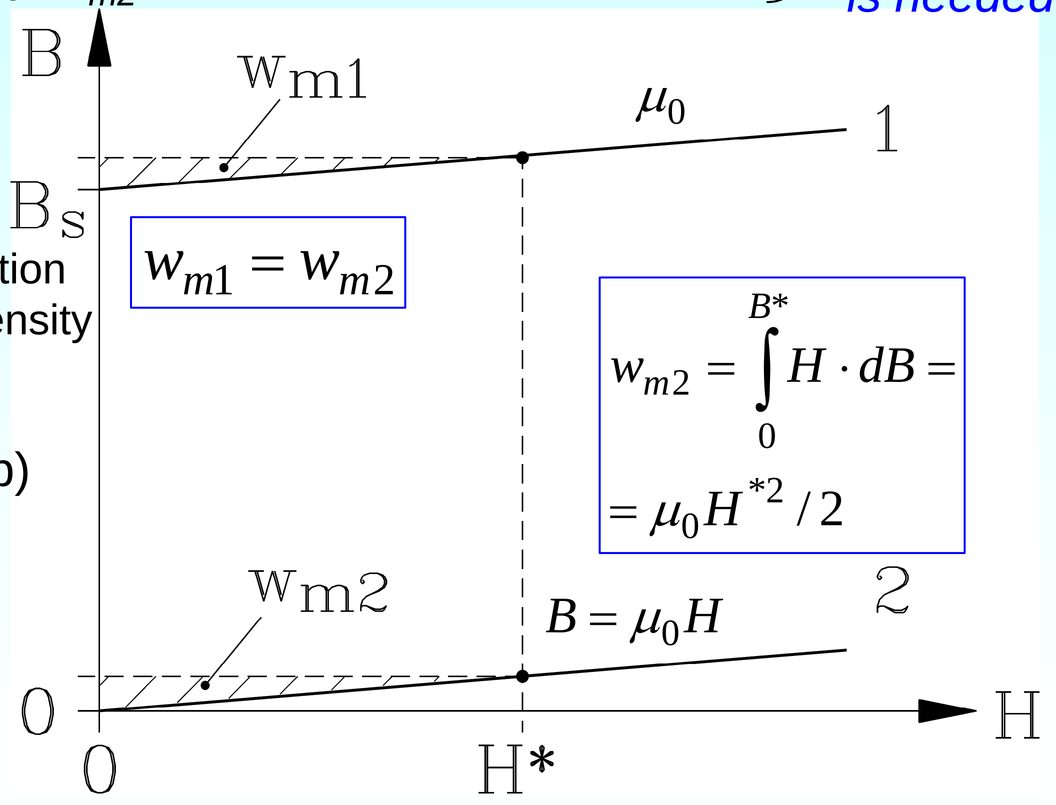
a) Energy density w_m in magnetised iron,

b) Energy density w_{m1}: 1: Coil with ideally magnetisable iron
2: Energy density w_{m2} for an air-core inductor

Result: No iron is needed!



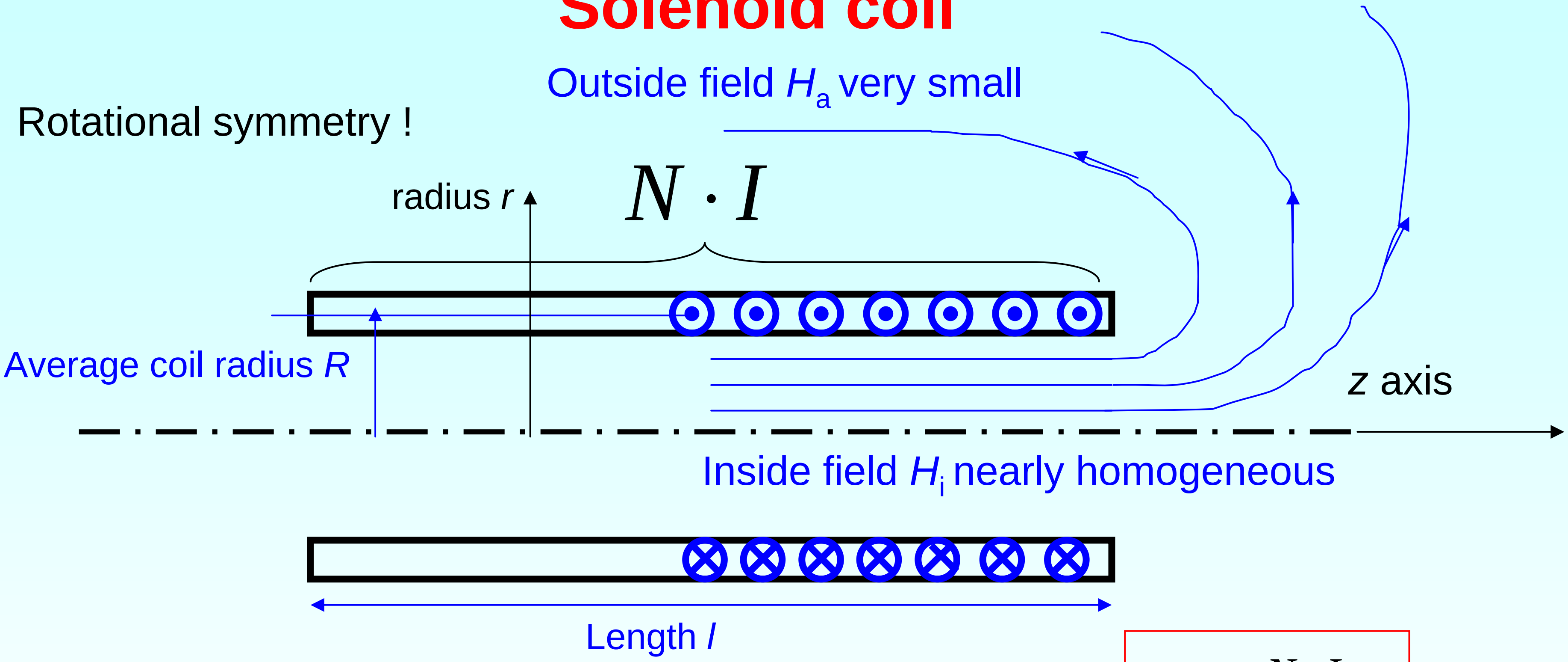
$$w_m = \int_0^{B^*} H \cdot dB$$



$$w_{m1} = w_{m2}$$

$$w_{m2} = \int_0^{B^*} H \cdot dB = \mu_0 H^{*2} / 2$$

Solenoid coil



Ampere´s law: $\oint_C \vec{H} \cdot d\vec{s} \approx H_i \cdot l + \int_{C_a} \vec{H}_a \cdot d\vec{s} \approx H_i \cdot l = N \cdot I \quad \Rightarrow \quad \boxed{H_i \approx \frac{N \cdot I}{l}}$

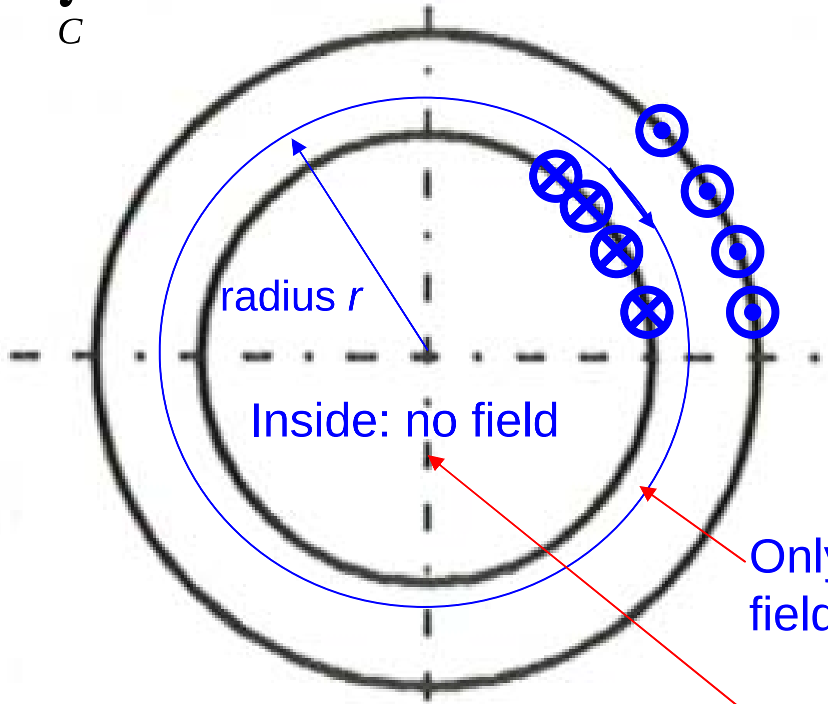
Stored magnetic energy:

$$W_m = W_{m,i} + W_{m,a} \approx W_{m,i} \approx \frac{B_i^2}{2\mu_0} \cdot R^2 \pi \cdot l = \mu_0 \frac{(N \cdot I)^2}{2l} \cdot R^2 \pi$$

Torus coil

Outside: no field

$$\oint_C \vec{H}\cdot d\vec{s} = \Theta - \Theta = 0 \Rightarrow H = 0$$



Inside: no field

Only within coil a field exists!

$$\oint_C \vec{H}\cdot d\vec{s} = H\cdot 2\pi\cdot r = \Theta = 0 \Rightarrow H = 0$$

Ampere´s law: Only azimuth field component H_φ exists!

$$\oint_C \vec{H}\cdot d\vec{s} = H_\varphi(r)\cdot 2\pi\cdot r = \Theta = N\cdot I$$

$$\Rightarrow \boxed{H_\varphi(r) = \frac{N\cdot I}{2\pi\cdot r}}$$

Stored magnetic energy: Torus volume V

$$V \approx 2\pi\cdot R_T\cdot R^2\pi$$

$$W_m \approx \frac{B(R_T)^2}{2\mu_0}\cdot 2\pi R_T\cdot R^2\pi$$

$$W_m \approx \mu_0\frac{(N\cdot I)^2}{2\cdot(2\pi R_T)^2}\cdot 2\pi R_T\cdot R^2\pi$$

$$W_m \approx \mu_0\frac{(N\cdot I)^2}{2\cdot 2\pi R_T}\cdot R^2\pi$$

Coil geometry: Solenoid or torus coil?

- For equal "length dimensions" ($l = 2\pi R_T$), the stored magnetic energy is higher in the solenoid, because the field also fills the outer space around the coil (although with lower density).

$$W_{m,Solenoid} = \mu_0 \frac{(N \cdot I)^2}{2l} \cdot R^2 \pi + W_{m,a} > \mu_0 \frac{(N \cdot I)^2}{2 \cdot 2\pi R_T} \cdot R^2 \pi = W_{m,Torus}$$

- With an equal amount of SC material used, the solenoid is cheaper, because of higher amount of stored energy at same Ampere turns!

- Disadvantage of solenoid: Stray field reaches far outside
  Demand acc. to VDE 0848/A2: publicly accessible ranges: $B < 1.25$ mT d.c.

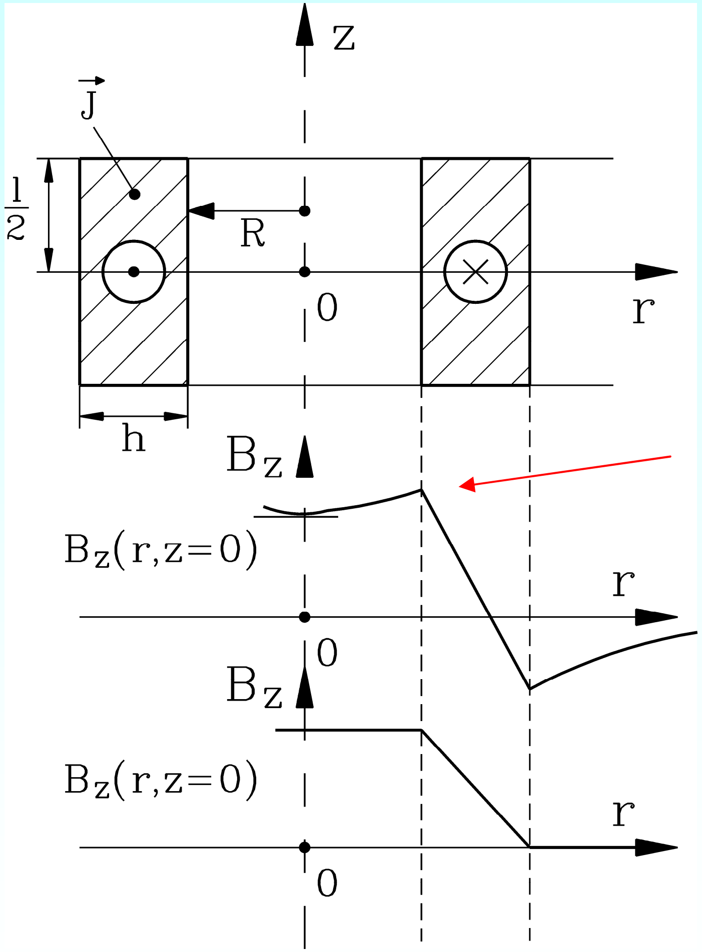
Example: Solenoid storage for 5 GWh: 0.5mT limit at a radius 2.5 km

2.2 Superconductivity for electrical energy technology

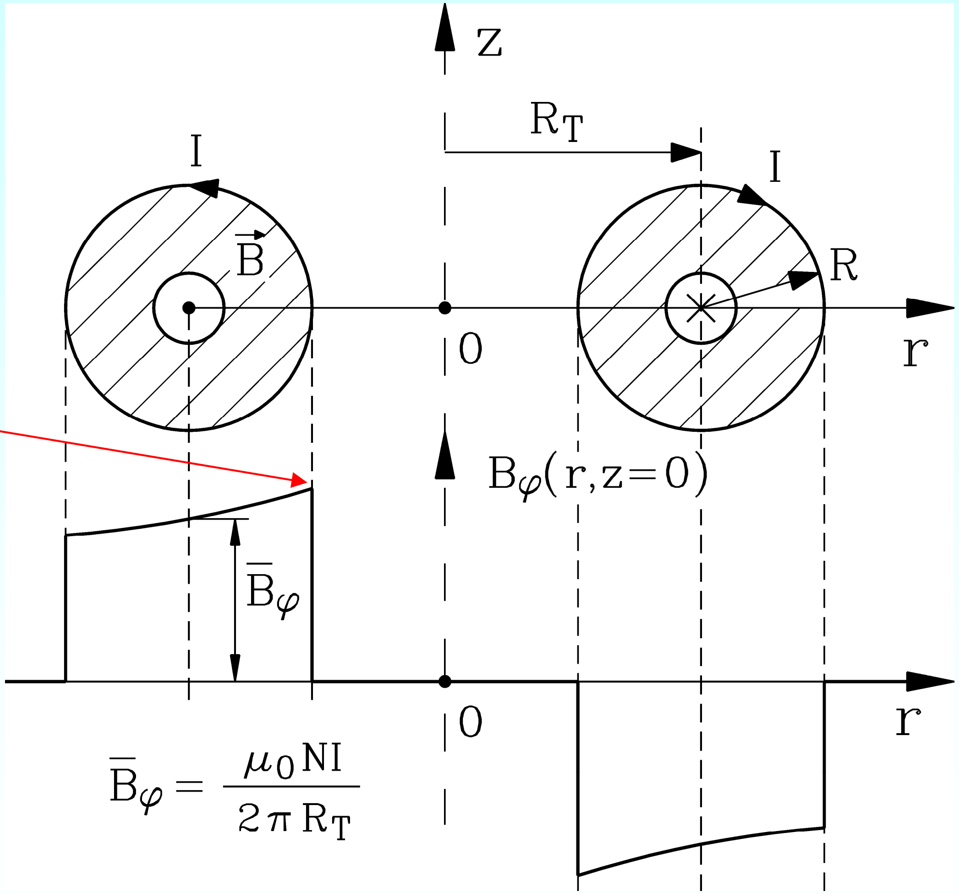
Coil parameters

a) Solenoid

b) Torus



B_{max}



$$\bar{B}_\varphi = \frac{\mu_0 NI}{2\pi R_T}$$

Coil design to avoid quenching

- Solenoid: Coil thickness h is limited by B_{max} at the coils inner side: $B_{max} < B_{c2}$ (J: current density)

$$B_{\max} \approx \mu_0 \frac{NI}{l} = \mu_0 \frac{J \cdot h \cdot l}{l} = \mu_0 \cdot J \cdot h$$

- *Solenoid: Coil thickness h must be dimensioned sufficiently low, the coil radius R must be for large W_m rather high.*

- Torus coils: Flux density B_{max} at interior highest ⇒ big ratio between „mean torus radius/coil radius“ R_T/R should be chosen to get $B(R_T) \approx B_{\max}$

$$B_\varphi(r) = \mu_0 \frac{NI}{2\pi r}$$ mean value: $$\overline{B}_\varphi = \mu_0 \frac{NI}{2\pi R_T}$$

- Design rule for torus coils: *Make the **"aspect ratio"** "mean torus radius/coil r radius" R_T/R sufficiently high.*

Aspect ratio R_T/R of torus coils

- Minimum field at outer side of torus volume: $B_{\min} \approx \mu_0 \frac{NI}{2\pi \cdot (R_T + R)}$

- Maximum field at inner side of torus volume: $B_{\max} \approx \mu_0 \frac{NI}{2\pi \cdot (R_T - R)}$

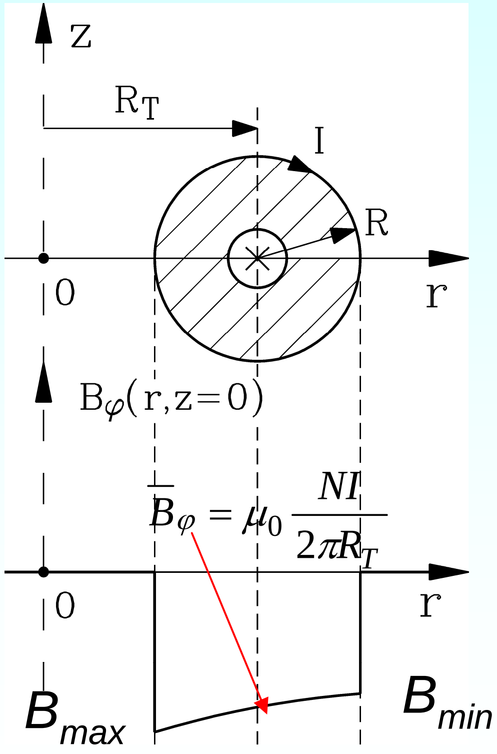
- Field at average radius of torus volume:

$$\overline{B}_\varphi(r) = B(R_T) = \mu_0 \frac{NI}{2\pi R_T}$$

- Condition for getting $B(R_T) \approx B_{\max}$:

$$\frac{(B_{\max} - B_{\min})/2}{B(R_T)} \approx \frac{(B_{\max} - B_{\min})/2}{(B_{\max} + B_{\min})/2} \to Minimum$$

$$\frac{B_{\max} - B_{\min}}{B_{\max} + B_{\min}} = \frac{\frac{1}{R_T - R} - \frac{1}{R_T + R}}{\frac{1}{R_T - R} + \frac{1}{R_T + R}} = \frac{R}{R_T} \to Minimum$$



Use of solenoid and torus coils

- Solenoids: Higher ratio of stored magnetic energy vs. used SC material, but high stray fields ⇒ Solenoid coils used for small SMES (= Uninterruptible power supply UPS), where stray field limit radius is small.

- Torus coils: Lower ratio of stored magnetic energy vs. used SC material, but no stray fields ⇒ Torus coils may be used for large SMES (= big energy storage, in order to have no additional safety zone outside coils (waste land!)

2.2 Superconductivity for electrical energy technology

Large SMES projects with torus coils

Stored energy	5000 MWh	5.7 MWh
Torus radius R_T	260 m	26 m
Mean coil radius R	13 m	1.56 m
Number of coils	360	60
Max. flux density B_{max}	9 T	8.3 T
SC material	Nb_3Sn (4.2 K)	NbTi (4.2 K)
Coil's nominal current	150 kA	50 kA

- Disadvantages: Large dimensions, large forces occurring between the individual coils $\Rightarrow$ extensive supporting elements for the stores.
- **Usage of large SMES will be a long time coming.**

Komarek, P.:
Teubner,
Stuttgart, 1995

Built SMES for commercial use

Solenoid SMES: UPS, system support in grid nodes e .g. in USA

a) *Example:* 3 MJ, 2.5 MW (1.2 s support time). IGBT - 4Q converter: 2.8 MVA, LTSC-NbTi coil, LHeI bath cooling, 4.2 K, HTSC-Bi(2223) current feed (cooled at 60 K at intermediate radiation shield), *Gifford-McMahon*-He condenser.

LN_2-cooled radiation shield reduces heat inflow via radiation. Hence the heat input into the cold area is only ca. 1 W.

b) *Example:* 1 MWs, 1MW, 1 s support time, NbTi coil, nominal current 1 kA, LHeI bath cooling in cryostat, 1 MVA converter, coil length l = 900 mm, external diameter 450 mm, B = 5 T.

HTSC solenoids: BiSCCO HTSC coils are more expensive than NbTi. They have a low critical flux density at 77 K, so due to low B the energy density is low. Construction of compact SMES not possible at 77 K (LN_2 cooling). Coils must be operated at lower temperatures, which needs higher amount of cooling .

Example of a built SMES for commercial use

Solenoid SMES: 1 MWs, 1MW, 1 s support time, NbTi coil, I_N = 1 kA, coil length l = 900 mm, outer/inner coil diameter 450 mm / 380 mm, B = 5 T.

$$W = \frac{B^2}{2\mu_0}\cdot d_{ci}^2\frac{\pi}{4}l = \frac{5^2}{2\cdot 4\pi\cdot 10^{-7}}\cdot 0.38^2\cdot\frac{\pi}{4}\cdot 0.9 = 1\mathrm{MJ}$$

$$N = \frac{(B/\mu_0)\cdot l}{I_N} = \frac{(5/(4\pi\cdot 10^{-7}))\cdot 0.9}{1000} = 3580$$

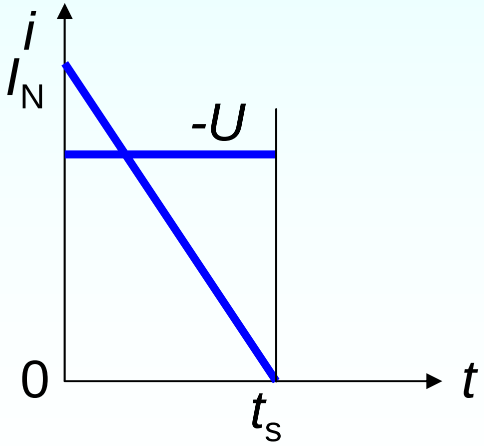
$$L = \frac{W}{I_N^2/2} = \frac{1000000}{1000^2/2} = 2\mathrm{H}$$

$$J_N = \frac{N\cdot I_N}{k_{Fill}\cdot l\cdot(d_{ca}-d_{ci})/2} = \frac{3580\cdot 1000}{0.6\cdot 900\cdot(450-380)/2} = 190\mathrm{A/mm^2}$$

$$t_s = \frac{W}{P} = \frac{1\mathrm{MWs}}{1\mathrm{MW}} = 1\mathrm{s}$$

$$U = L\cdot\frac{di}{dt} = -L\cdot\frac{I_N}{t_s} = -2\cdot\frac{1000}{1} = -2000\mathrm{V}$$

$$P = p_{av} = i_{av}\cdot U = 500\cdot(-2000) = -1\mathrm{MW}$$



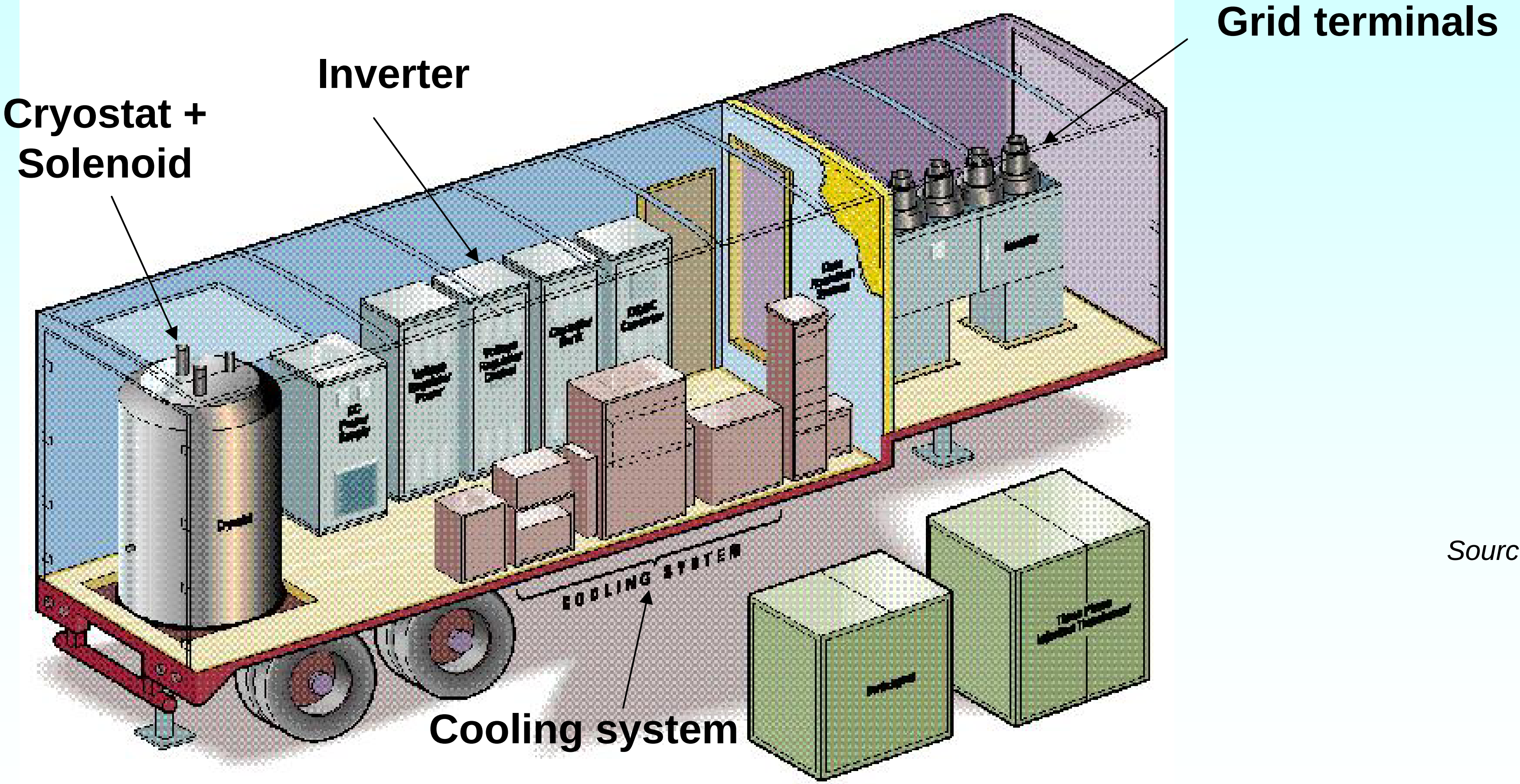
SMES with solenoid coil

Cryostat with SC coil

Installation of the complete SMES system (Superconducting magnetic energy storage) built in a container

Source: ASC

Container arrangement of a SMES for operation in the range of seconds

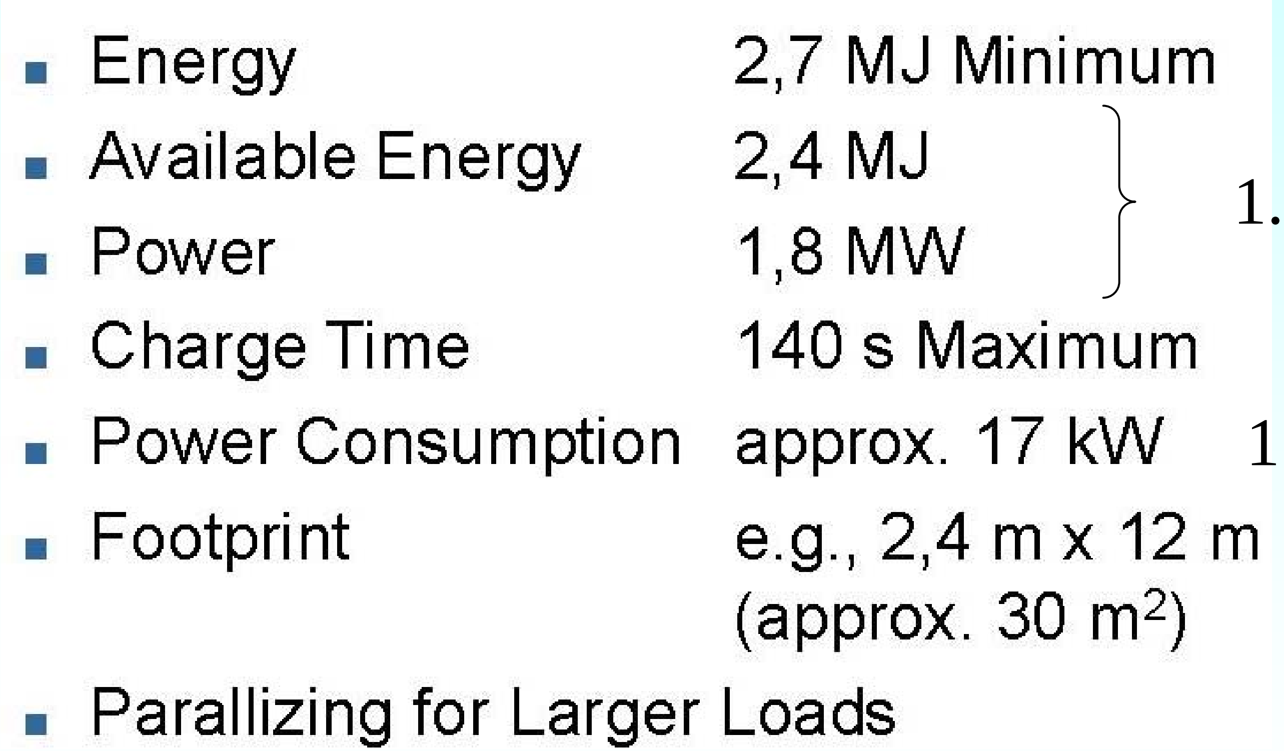


Source: ASC

2.2 Superconductivity for electrical energy technology

SMES with solenoid coil at the grid

- Increasing the grid stability with a SMES with inverter connection to the grid – additional power for 1.3 s



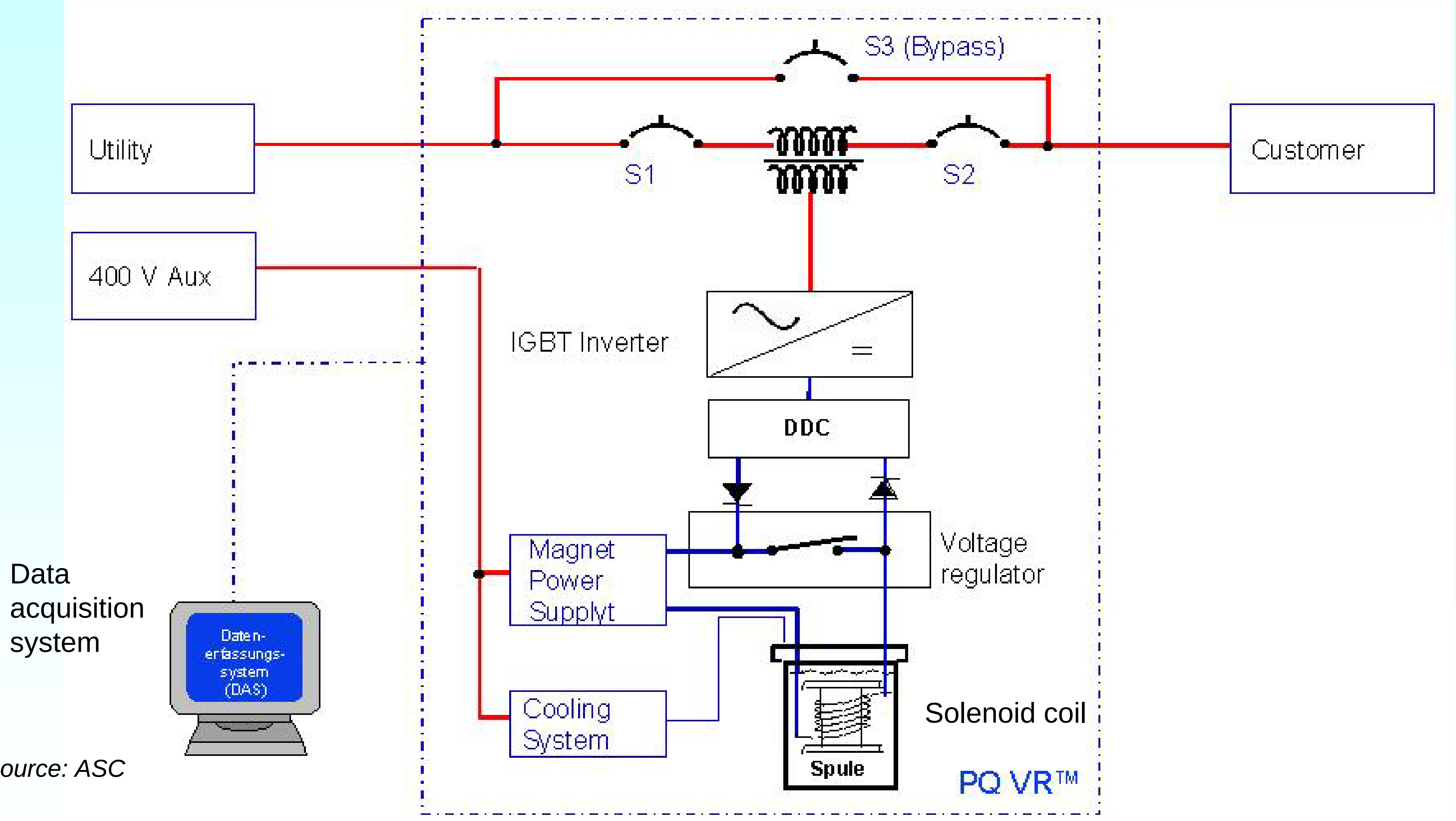
Energy	2,7 MJ Minimum
Available Energy	2,4 MJ
Power	1,8 MW
Charge Time	140 s Maximum
Power Consumption	approx. 17 kW
Footprint	e.g., 2,4 m x 12 m (approx. 30 m²)
Parallizing for Larger Loads	

$$1.8MW \cdot 1.3s \cong 2.4MJ$$

$$17kW = 2.4MWs/140s$$

Source: ASC

Serial connection of a SMES to the grid for enhancing grid stability



Source: ASC

SMES with solenoid coil at the grid

PQ VR™ 1 MVA 75 %
SAPPI Stanger, Republic South Africa

Source: ASC

New technologies of electric energy converters and actuators

Summary:
Superconducting magnetic energy storage (SMES)

- Commercial use as very fast small uninterruptible power supply units
- Low temperature superconductors used to get high field amplitudes
- Ironless solenoids at 4 K operation with inverter to the grid
- Large SC toroid stores for grid stability basically possible, but: too expensive

2. Application of superconductors for electrical energy converters

2.2 Superconductivity for electrical energy technology

2.2.1 Fault current limiter

2.2.2 Superconducting power cables

2.2.3 Superconducting magnetic energy storage (SMES)

2.2.4 Superconducting power transformers

2.2.5 Rotating electrical machines with superconductor winding

2.2.6 Cryo-machines and rotating electrical machines with massive superconductors

2.2.4 Superconducting transformers

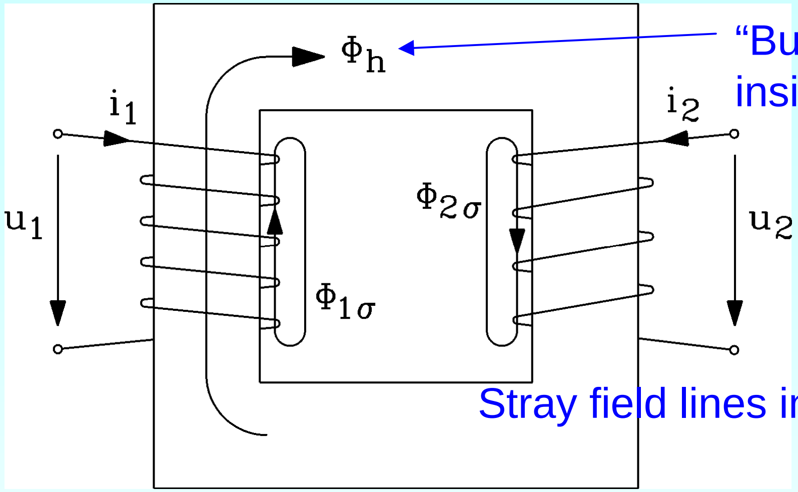
- **SC windings**: Current density dramatically increased ⇒ coil height & thickness decrease strongly ⇒ shrinking iron core (leg height, yoke length) possible
- Iron cross-section remains unchanged, so that flux density < 1.8 T, otherwise iron saturation.
- Lower iron masses (decreased iron volume V_K) ⇒
  - reduced mass of transformer (typically 50% weight saving, advantage for locomotive transformers) and
  - lower iron losses P_{Fe}.

Source: Meinert, M., Siemens AG

Transformer mass	*Conventional oil loco transformer*	*HTSC loco transformer*
Regional train	4.8 tons	2.5 tons
ICE3	9.3 tons	5.4 tons
Locomotive BR152	14.5 tons	8.7 tons

Transformer principle

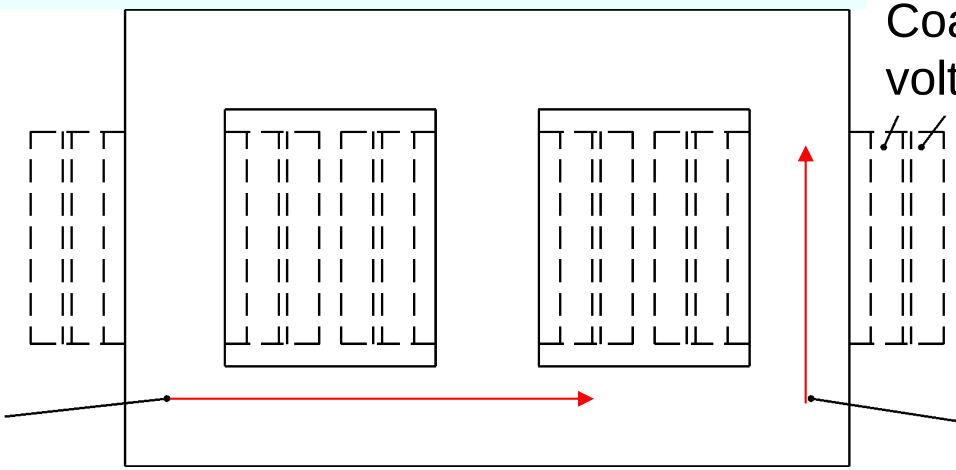
Single phase transformer in principle



"Bundled" field lines of main flux inside of the iron core

Stray field lines in air outside the core

Real coaxial coil arrangement in a three-phase transformer



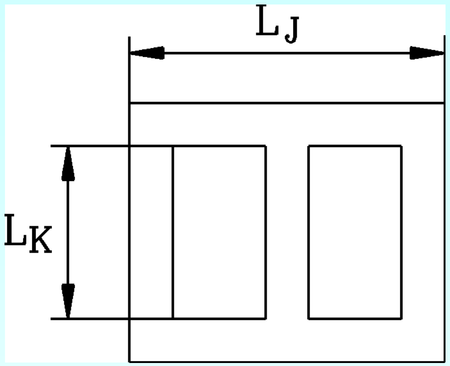
Coaxial lower & upper voltage coil per phase

Lower yoke

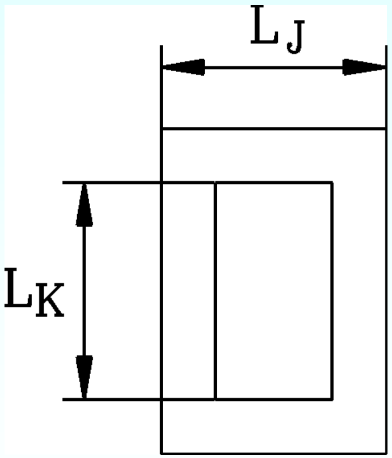
Leg

Main core dimensions of a transformer

Three-phase
transformer core with
three legs

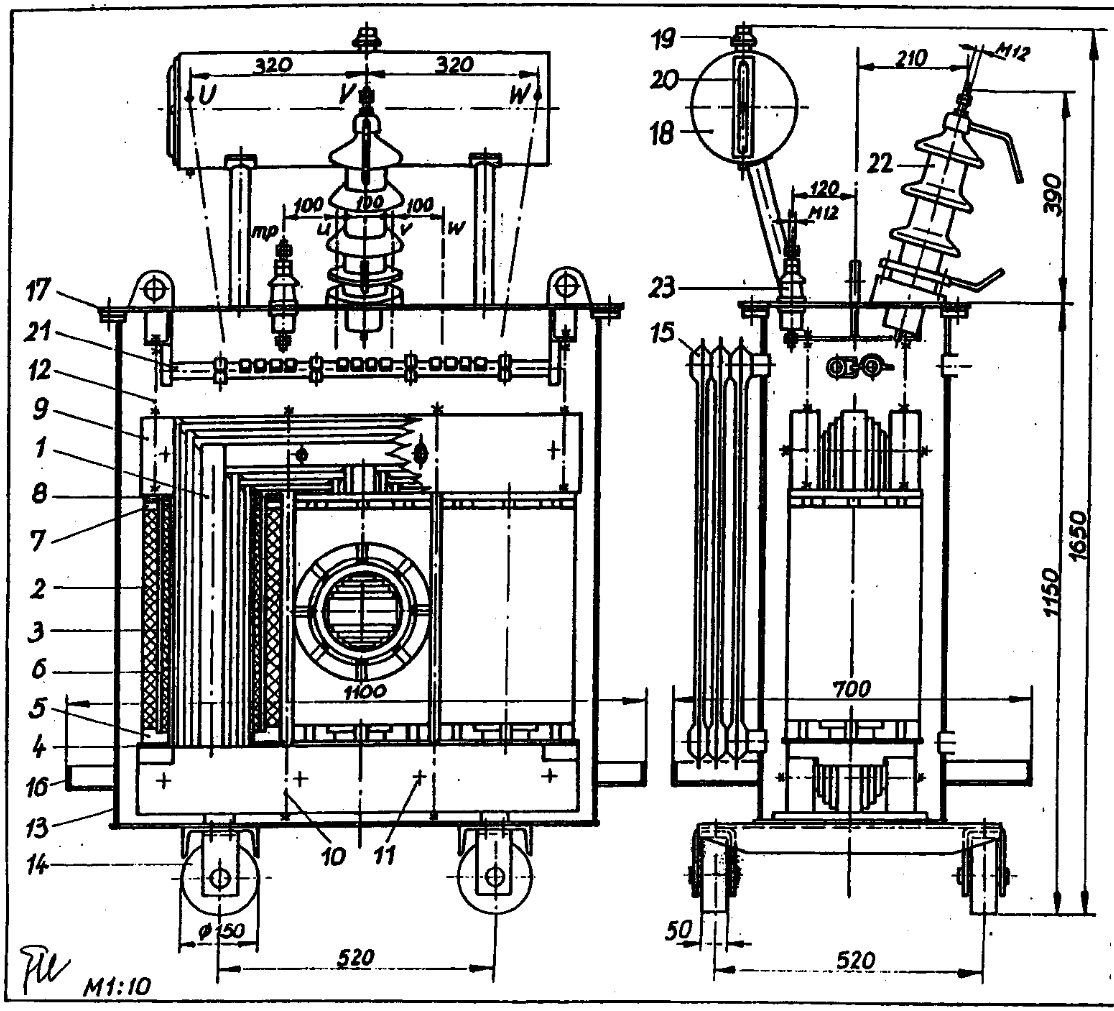


Single-phase
transformer core with
two legs



2.2 Superconductivity for electrical energy technology

Three-phase oil transformer in an oil tank



3-phase transformer

160KVA, 20.000V ± 4%
400V
u_k=4%, 50Hz, Yzn5

1 iron core
2 HV winding
3 LV winding
4 adapter ring
5 adapter part
6 oil channel spacer
7 spacer
8 press ring
9 press rod
10 strain bolt
11 press bolt
12 support bolt
13 oil tank
14 rolls
15 coolers
16 protective frame
17 lid
18 oil expansion vessel
19 oil fill inlet
20 oil level indicator
21 tap changer
22 bushing 20 kV
23 bushing 1 kV

Source:
Florian Gregori,
TU Wien, 1981

Losses in SC transformers

- Losses in SC winding (AC losses) are significantly smaller than the ohmic and eddy current losses in conventional copper coils.
- The entire savings are partially wasted by the power of the cooling unit
  ⇒ for LHe transformers with LTSC, the efficiency advantage is only low.
- **HTSC** transformers are more economical than LTSC transformers, since the power for cooling is reduced by a factor 40.
- *Only the HTSC transformer stands the change to be economically competitive to the conventional oil-immersed transformer, because the efficiencies of conventional transformers with oil cooling are typically*
  at 99.4% (1..10MVA) ... 99.8% (>100MVA)
  and are already very high.

Warm or cold iron-core ?

- **Warm iron-core:** Only the winding is in the cryostat; low cooling cost. Cryostat must be non-conductive (glass fibre composite materials, …)
- **Cold iron-core:** Entire transformer is inside the cryostat's steel plate tank. Long cooling duration (days), but "cooling storage" helps in case of disturbance of the cooling system to reduce the rate of temperature rise.
  Iron losses: Iron resistance $R_{Fe} \sim \rho_{Fe}$ drops with reduced temperature T:

$$P_{Fe,Ft} \sim \frac{\omega^2 B_K^2}{\rho_{Fe}} V_K$$

$P_{\mathrm{Fe,Ft}}$ increases at constant V_K (Volume of the iron core)

Eddy-current part of iron losses increases with reduced iron core temperature!

Choice of core induction $B_K <$ ca. 1.8 T to avoid significant iron saturation!
The SC is subjected only to the rather low transformer stray field – Hence BSCCO wires can be used!

Iron-core or ironless transformer?

- **Ironless transformer:**
  B_K > ca. 1.8 T possible, because no saturation limit, BUT then a high magnetising current is necessary. This is possible, because the low loss SC windings are used.

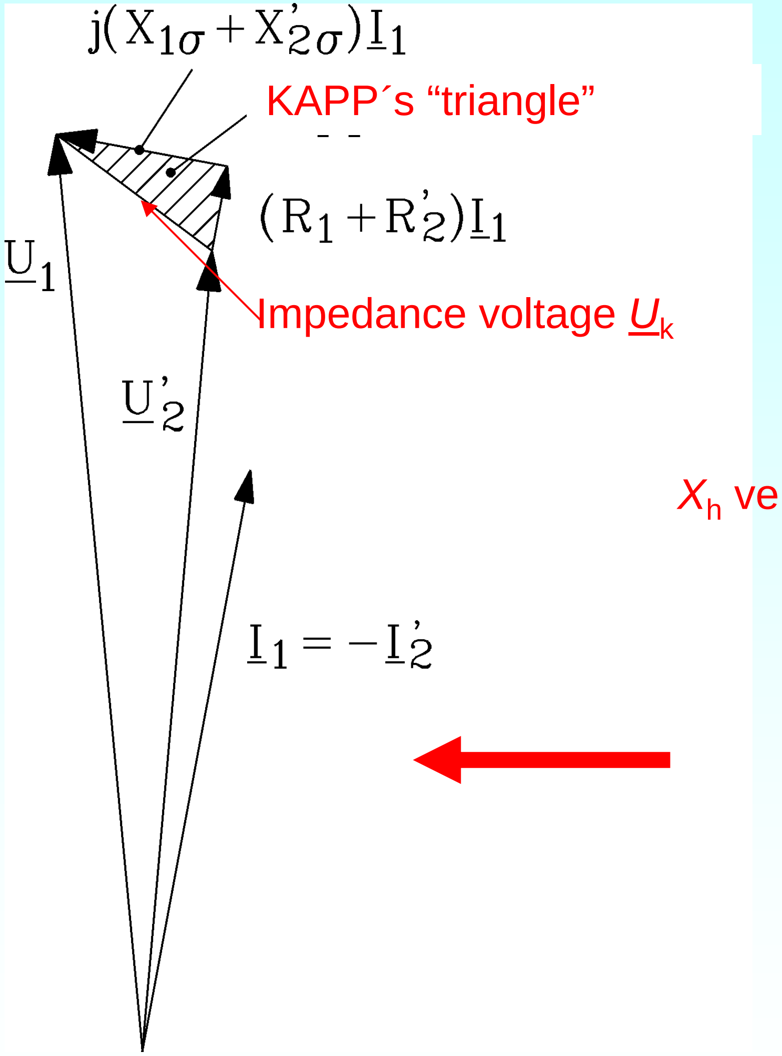
  - But flux lines are not bundled, as there is no iron core!
  - So the condition $B < B_{c2}$ **within SC is more difficult to be obeyed, as the magnetic flux lines are more difficult to** be guided in air.

  - Hence the AC losses, which increase with B^2, will be higher in air cored transformers!

  - So ironless transformers are only in an experimental stage.

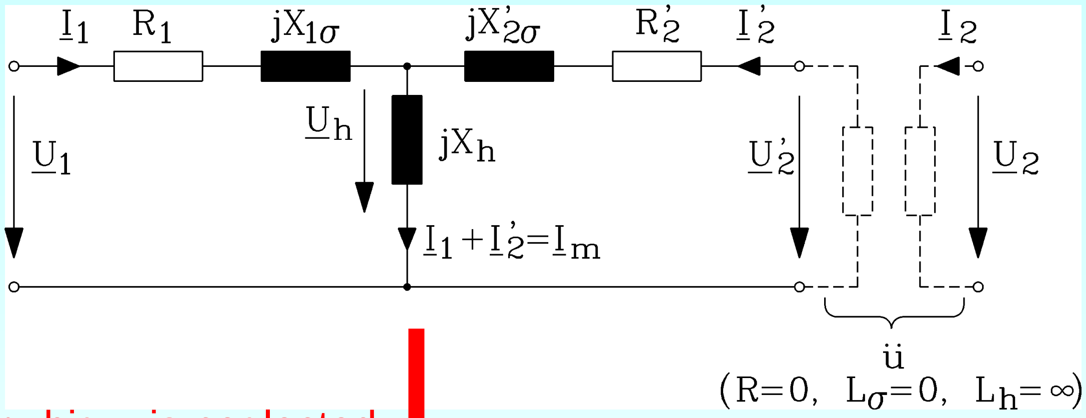
2.2 Superconductivity for electrical energy technology

Impedance voltage $u_k = U_k / U_N$

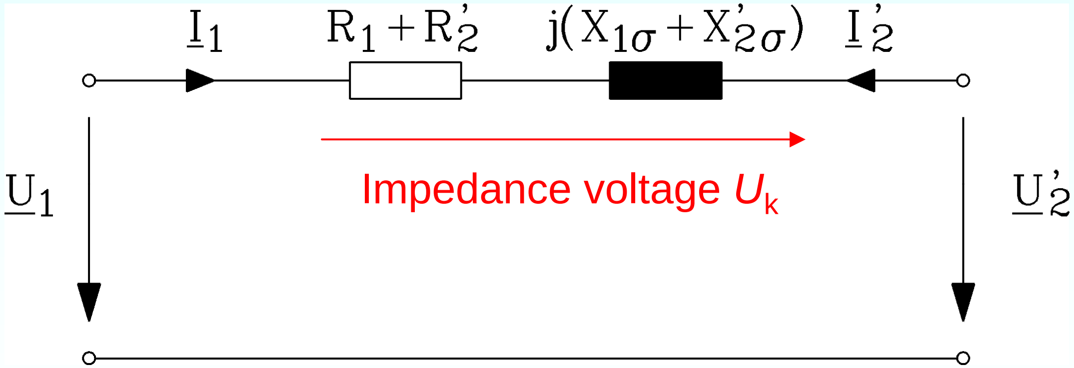


KAPP´s “triangle”

Impedance voltage $\underline{U}_k$

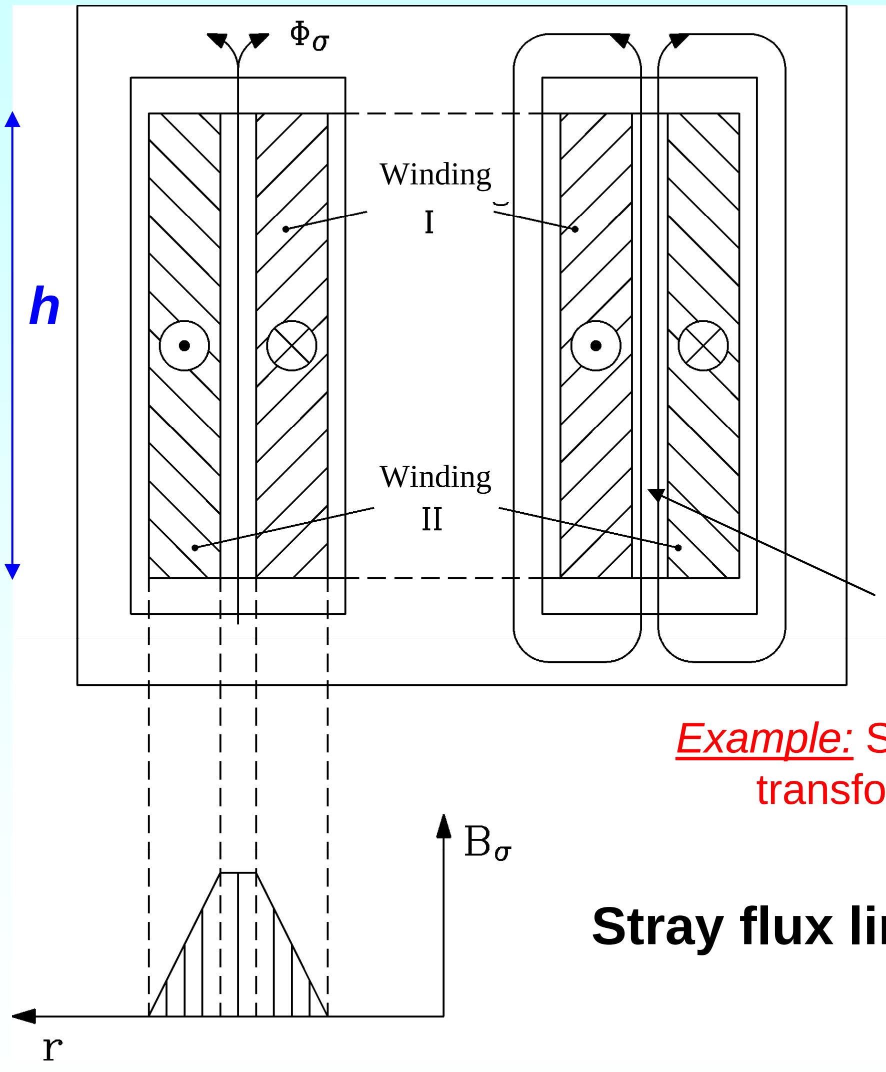


X_h very big = is neglected

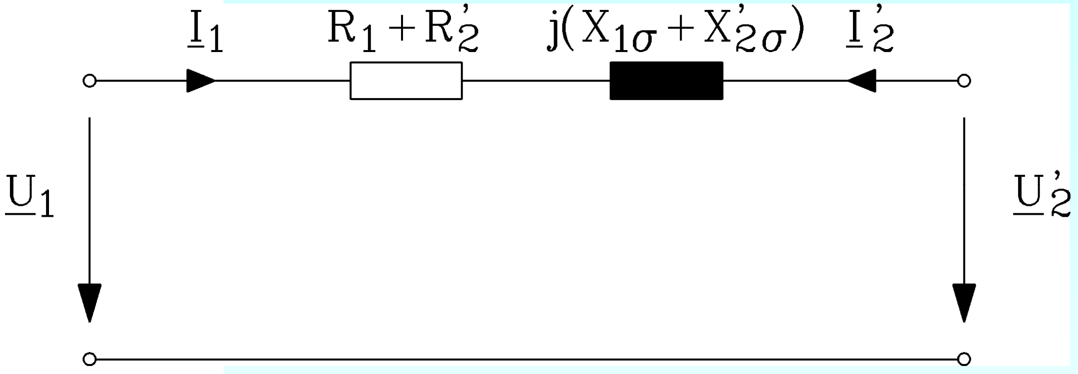


Impedance voltage U_k

Stray flux in transformers



Stray flux gap

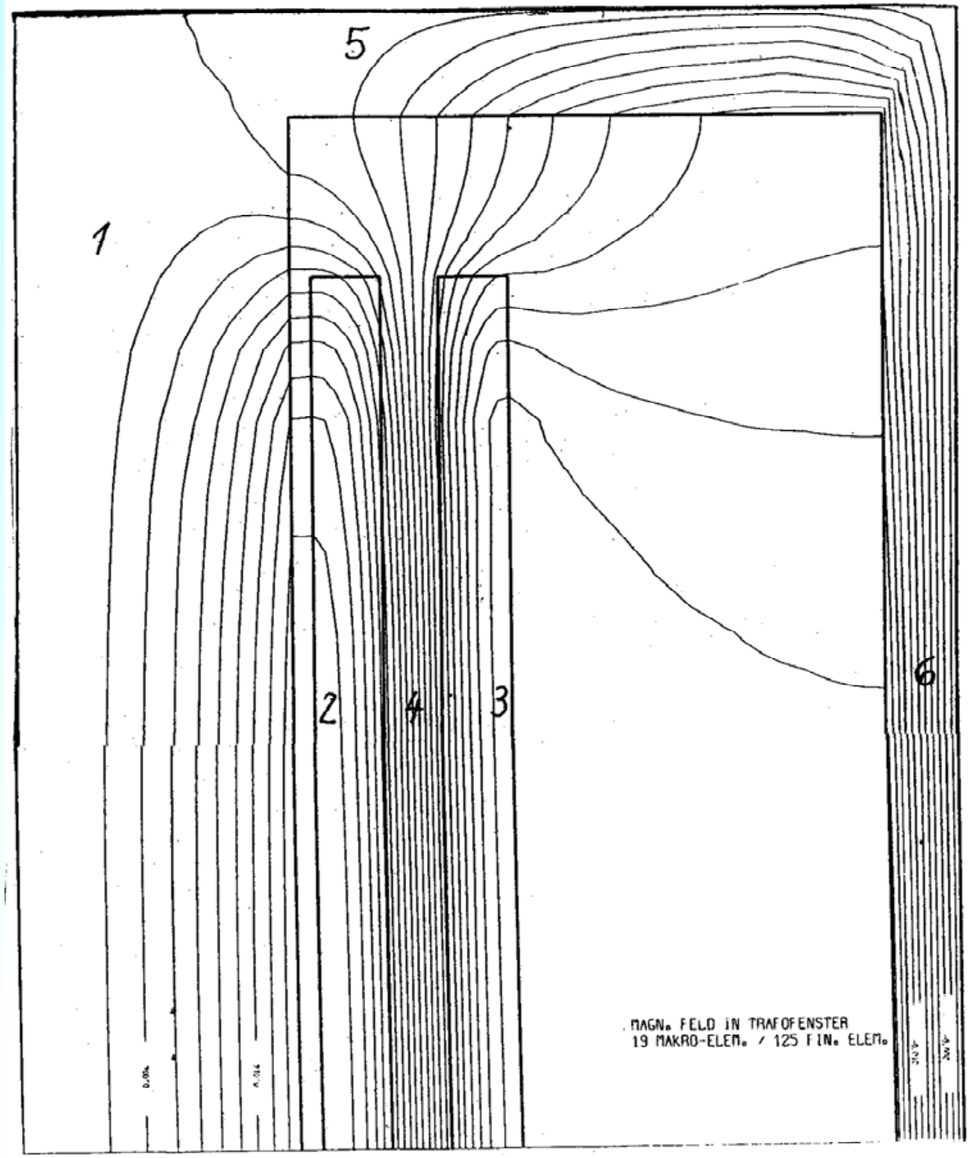


$$\underline{I}_1 = -\underline{I}'_2$$

Example: Shell-type transformer

Stray flux line distribution

Calculated flux line distribution in shell type transformer with rotational symmetry



1: iron core

2: LV winding

3: HV winding

4: Stray flux gap

5: Yoke

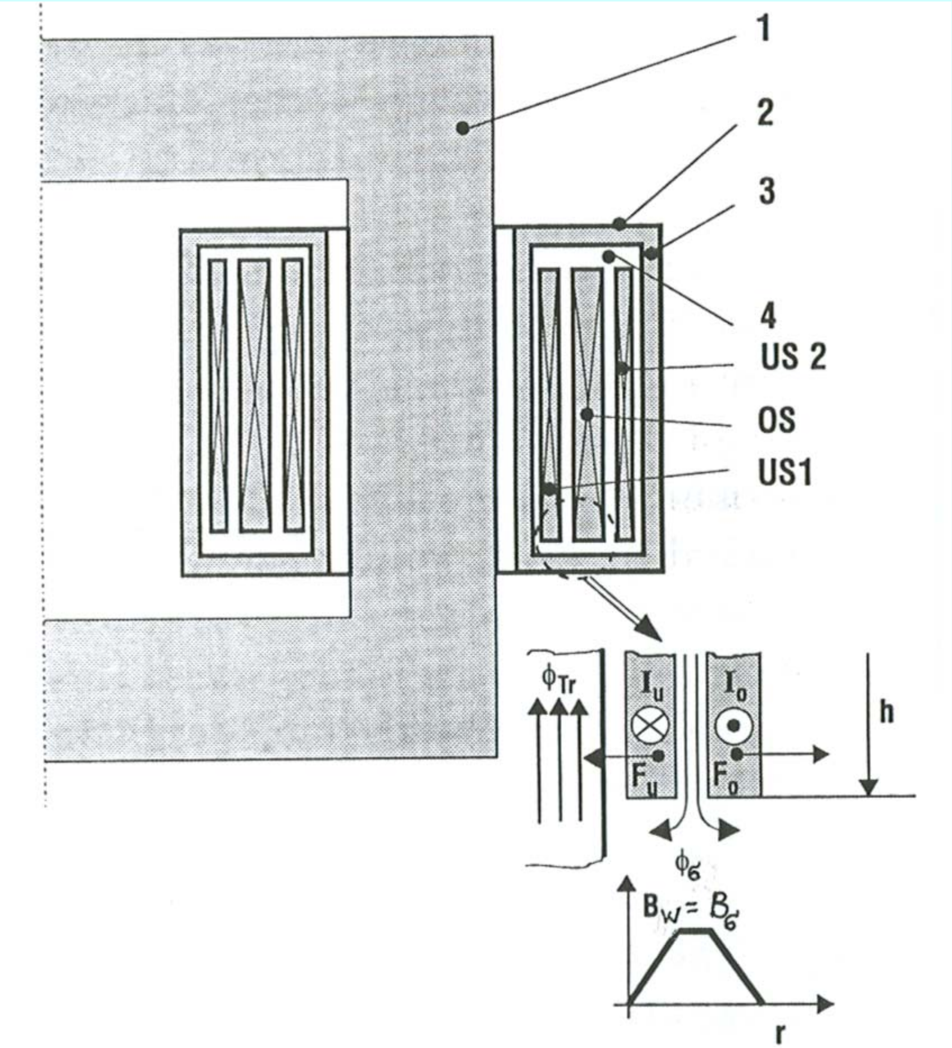
6: Outer core shell

$$\underline{I}_1 = -\underline{I}'_2$$

Primary and secondary current are nearly in phase opposition! Here: Assumed exact 180° phase shift!

Source: J. Hipfl, ELIN-UNION, Austria, 1981

Design of the SC transformer with warm iron-core



1: Iron-core (laminated),

2: Cryostat container (non-conductive)

3: Vacuum chamber,

4: LHe or LN_2 container (non-conductive),

OS/US: High-/Low-voltage winding

US1/US2: Split low-voltage winding

Φ_{Tr}: transformer core flux
Φ_σ: transformer resulting stray flux
$B_w = B_\sigma$: maximum flux density in the winding is stray flux density!
h: winding height
I_o / I_u: r.m.s. current in HV /LV winding

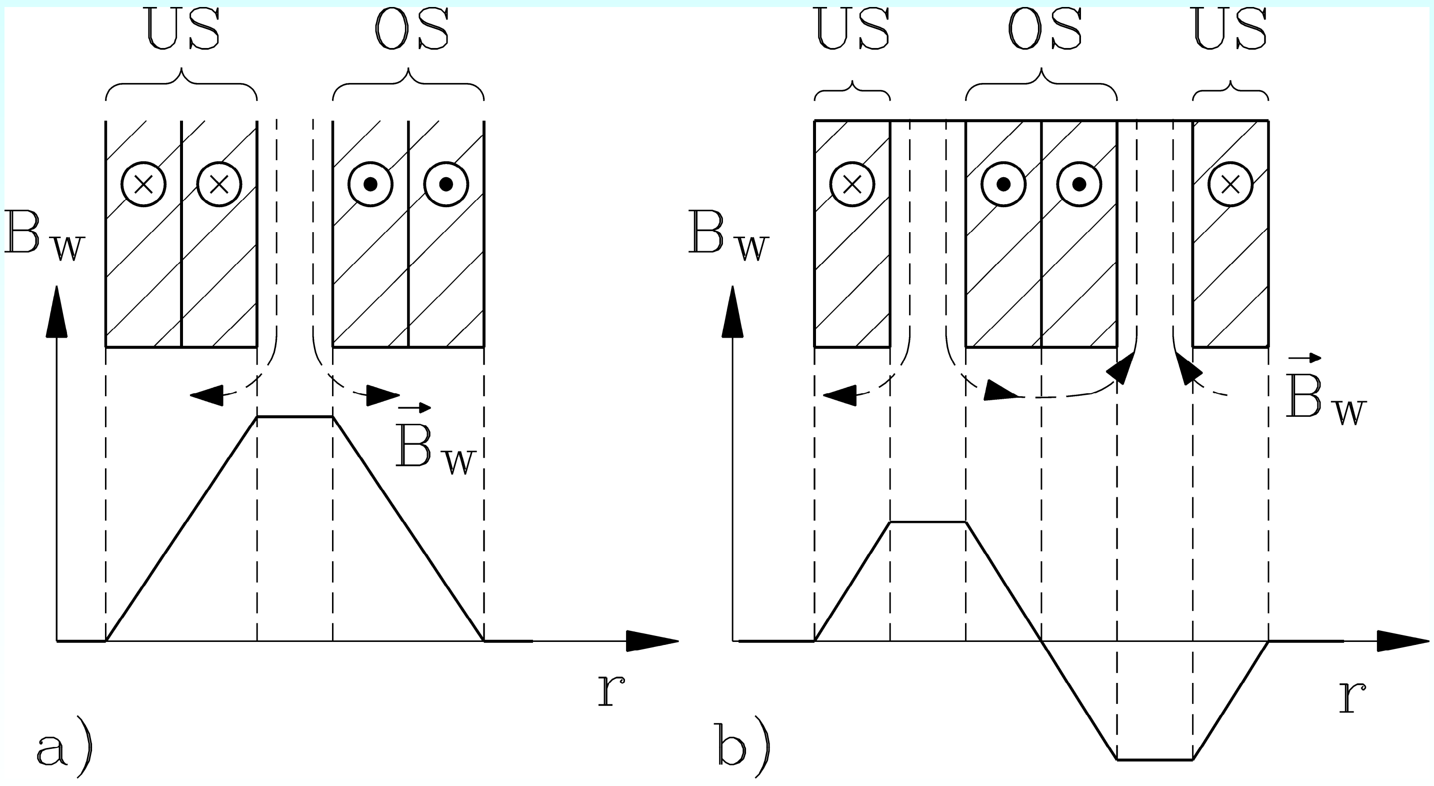
F_o / F_u: LORENTZ forces in HV /LV winding

Komarek, P.:
Teubner,
Stuttgart, 1995

Design of the transformer winding

a) Single concentric coils (unfavourable due to high stray flux),

b) Double concentric coils (favourable, as maximum alternating flux density in the winding $B_w = B_\sigma$ is reduced by 50%)



OS/US: High-/Low-voltage winding

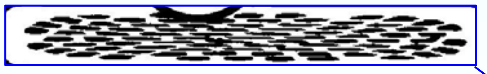
SC conductor material for transformers

- Low AC losses < 0.1 mW/(A·m): *B* within the SC winding must be max. 0.15 T.
- Only stray field B_σ within the SC winding:

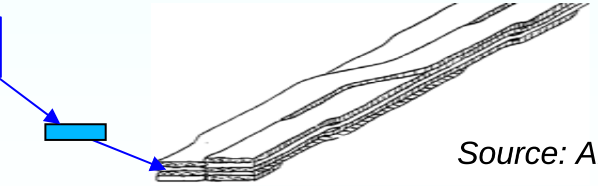
$$\oint_C \vec{H}\bullet d\vec{s} \cong \int_0^h H_\sigma ds = H_\sigma h = \Theta = N_u I_u = N_o I_o \quad \Rightarrow \quad \boxed{B_\sigma = \mu_0 \frac{N_u I_u}{h}}$$

- Multi-filamentary conductor built up with low litz wire diameter, stranded litz wires, high-resistance matrix: e.g. LTSC with CuNi matrix or Bi(2223)-HTSC in Ag matrix with Mg additive

Flat litz wire with twisted filaments

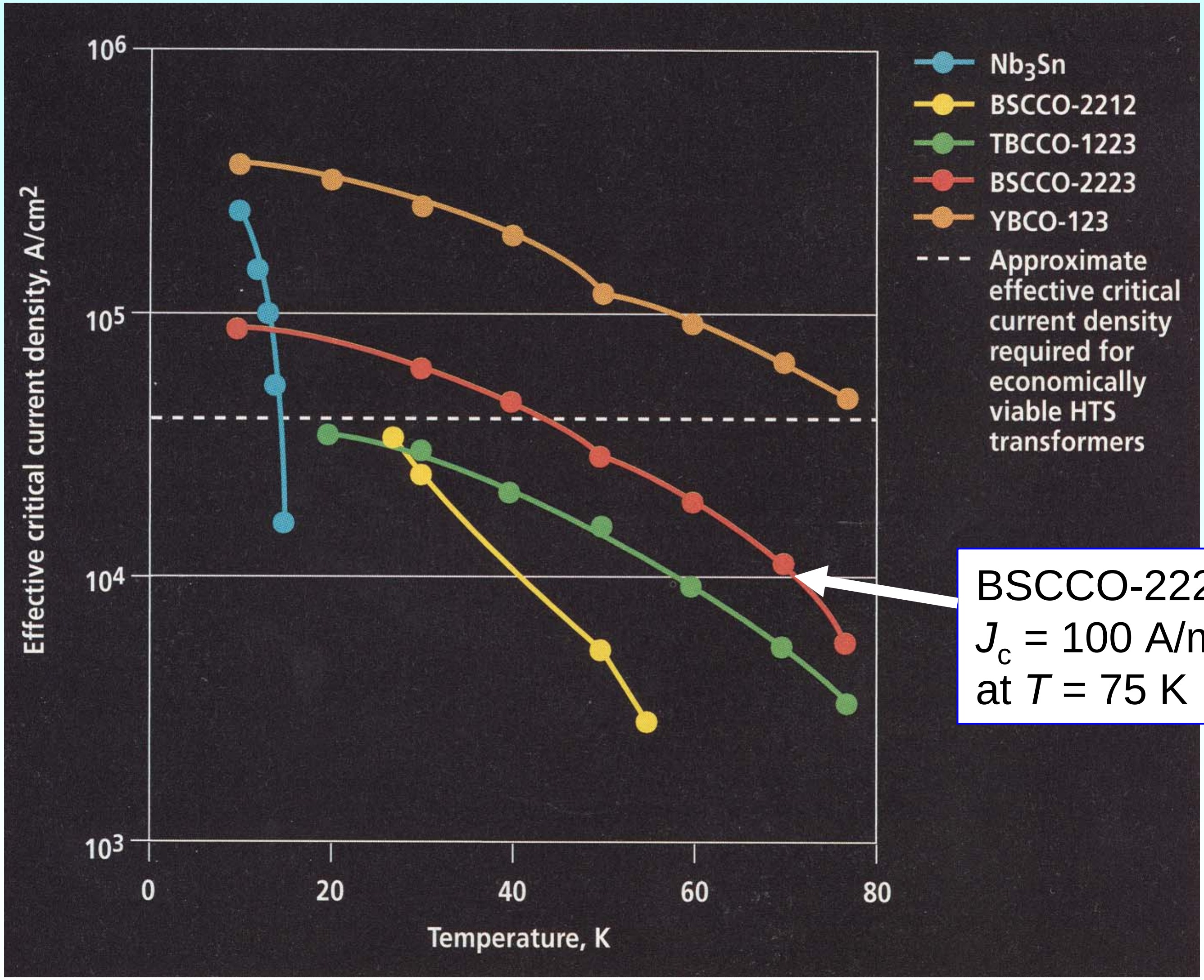


Transposed flat litz wires (ROEBEL-bar)



Source: American Superconductor, Inc.

Current densities in HTSC transformers – comparison with LTSC

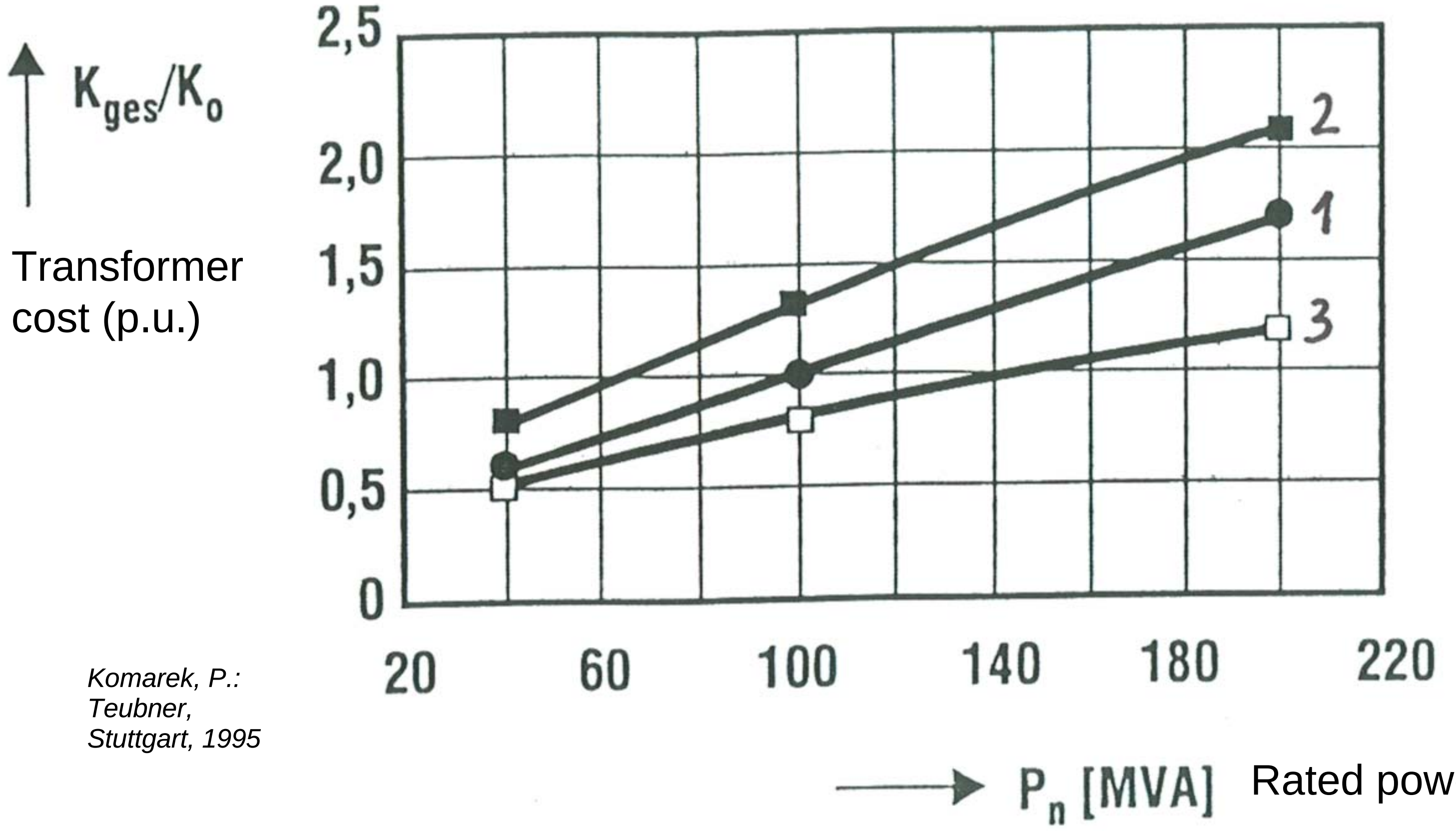


BSCCO-2223:
J_c = 100 A/mm^2
at T = 75 K

Source: IEEE/PES Journal, 1998

Total cost K_{ges}: HTSC transformers comparison

- Oil-filled transformer (1) : Reference value: Cost K_o of a 100 MVA grid transformer
- HTSC transformer: expensive/cheap HTSC acquisition price: (2 / 3)



Komarek, P.:
Teubner,
Stuttgart, 1995

Bi(2223) strip conductor:
ca. 3000 Euro/kg (2002):
too expensive),
future (expected):
700 Euro/kg

Silver matrix:
ca. 250 Euro/kg

Cu: 10 Euro/kg
(typical value for **crude** copper)

Prospects for superconductive transformers

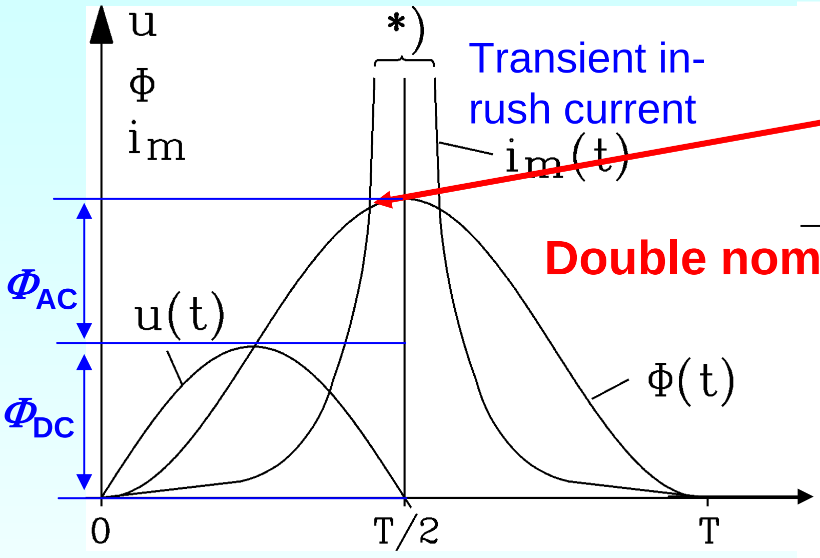
- Cost: Power transformers with 40 ... 200 MVA nominal apparent power: Investment cost + cost for power losses, capitalised during lifespan
- LTSC transformers: high cooling power needed ⇒ high capitalised cost for losses
- Only HTSC transformers have the prospect of being economically competitive to the conventional oil-cooled transformers.
- HTSC loco transformers have additional advantages, compared to HTSC power transformers: Conventional loco transformers have bad efficiency and are heavier
- Ecological aspect: Lower total losses of the HTSC power transformer:

Example: *Switzerland:*
All conventional transformers replaced by HTSC: mean power loss saving 170 MW.
Transformers 24 h online: annual energy saving:
170 MW x 8760 h = 1500 GWh: This corresponds to 750 (!) 1-MW-wind turbines with 2000 h full load hours p.a.

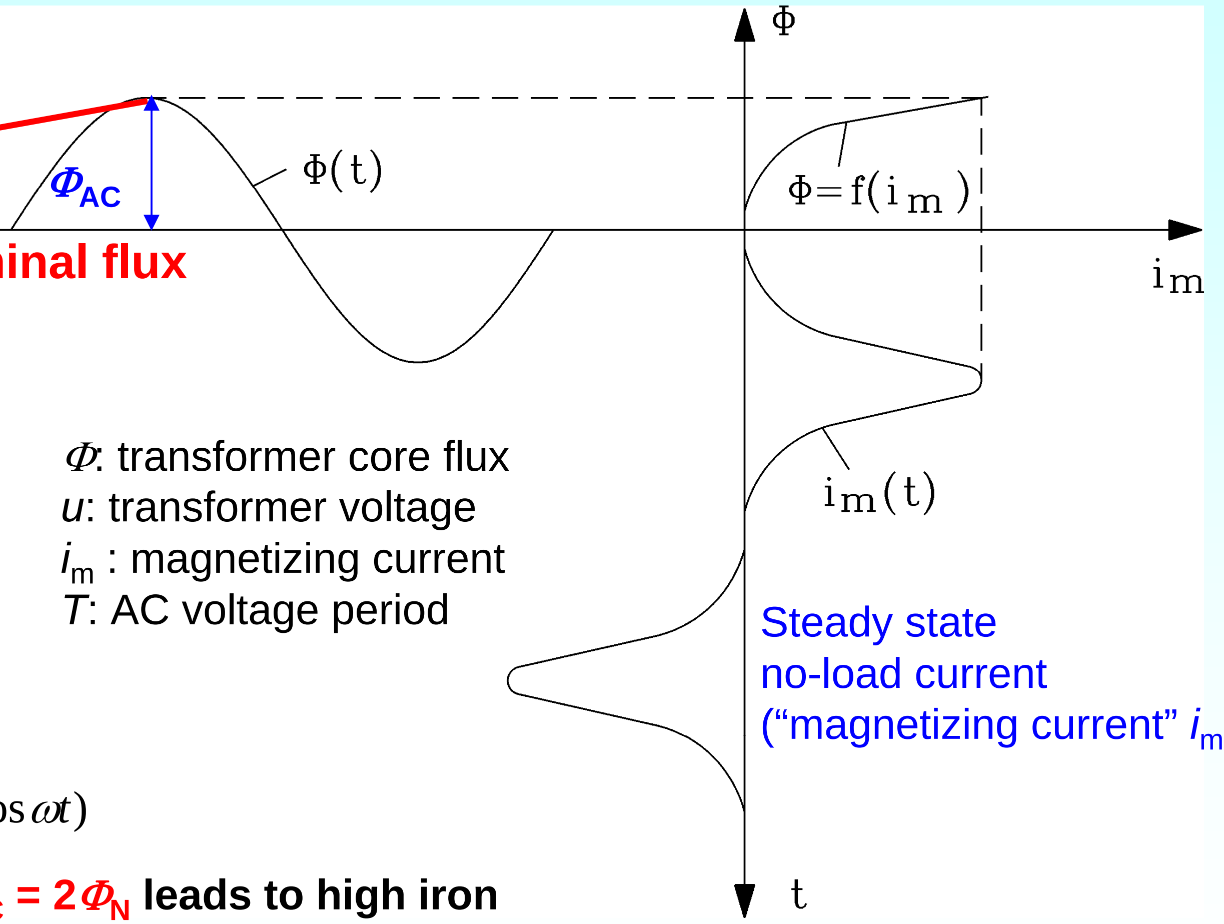
Komarek, P.: Teubner, Stuttgart, 1995

In-rush current of transformers

Peak current: 10 to 15 times nominal current



Double nominal flux



Φ: transformer core flux
u: transformer voltage
i_m : magnetizing current
T: AC voltage period

Steady state no-load current ("magnetizing current" i_m)

Worst-case: **Switching on the transformer** at zero voltage

$$R \approx 0 : u(t) \cong N \cdot d\Phi / dt = \hat{U} \sin \omega t$$

$$\Phi(t) = \int_0^t (\hat{U}/N) \cdot \sin \omega t \cdot dt = \frac{\hat{U}}{\omega \cdot N} \cdot (1 - \cos \omega t)$$

***) Double nominal flux $\Phi = \Phi_{AC} + \Phi_{DC} = 2\Phi_N$ leads to high iron saturation: $i_{m,peak}$ is very big: up to $15 x I_N$**

Transient behaviour of HTSC transformers (1)

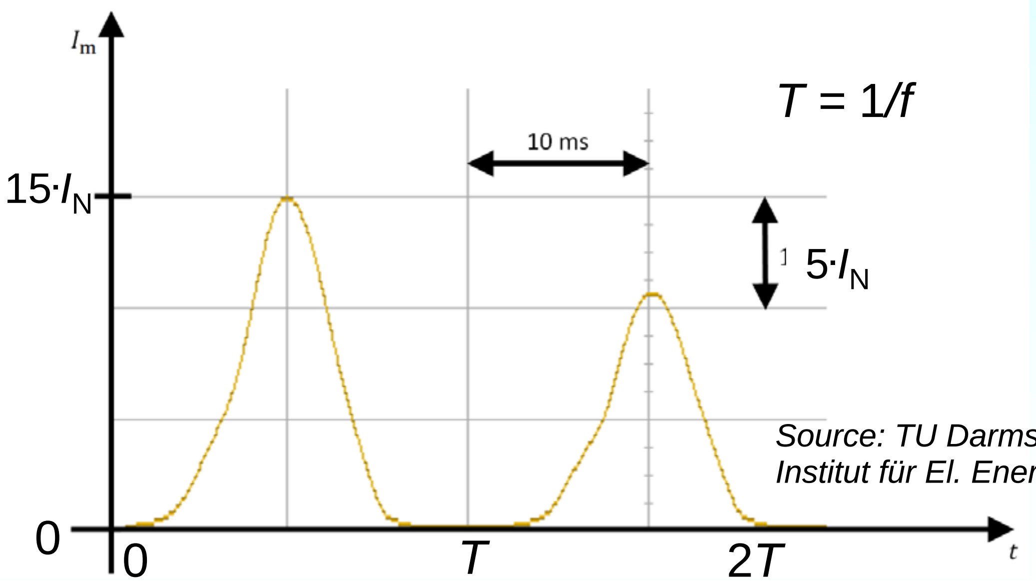
- **Switching on the transformer** **(worst-case:** at zero voltage crossing):

  High starting current in-rush occurs: 10 to 15 times nominal current ⇒ high current density $J > J_c$ ⇒ HTSC is normal-conducting ⇒ limits the in-rush ⇒ decaying current ⇒ falls below “quench” limit $J < J_c$ ⇒ superconductive again.

- **In-rush current has** DC and AC part ⇒ residual DC part flows on without losses in the SC winding ⇒ BUT it pre-magnetises the iron, which is not desired.

Potential remedy:
Damping resistors.

Example:
Measured in-rush current during the first two periods (40 ms) of a conventional air-cooled transformer witch copper winding



Source: TU Darmstadt, Institut für El. Energiewandlung

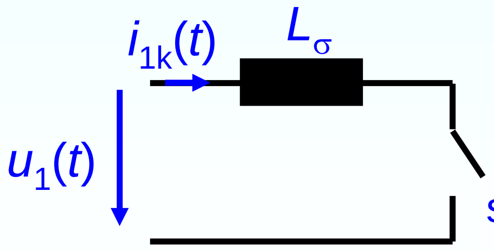
Transient behaviour of HTSC transformers (2)

- **Sudden short circuit current:** Maximum short circuit current occurs, when the sudden short circuit happens at zero voltage crossing.

  The short circuit current is limited by the stray inductance and by the resistance, if the SC winding is quenching.

  The big forces on the coils are limited by the quench, but they need a strong mechanical support. The support of the windings can be minimised, if the HTSC transformer is operated in combination with a FCL.

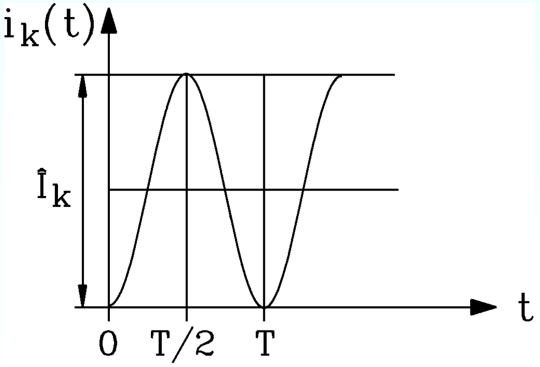
- The **short –circuit current has** DC and AC part ⇒ residual DC part flows on without losses in the SC winding ⇒ BUT it pre-magnetises the iron, which is not desired. ***Potential remedy:*** Damping resistors.



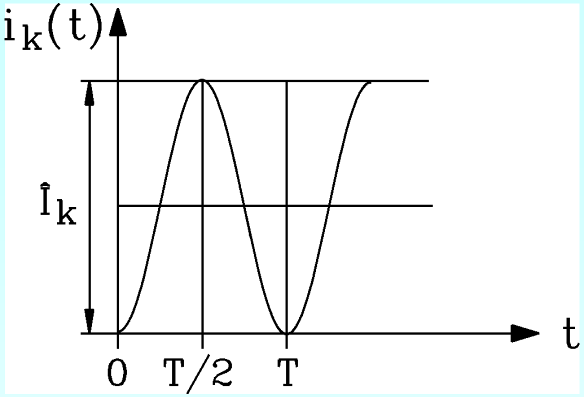
$$R \approx 0: u_1(t) = \hat{U}_1 \sin \omega t \cong L_\sigma \cdot di_{1k}/dt$$

$$i_{1k}(t) = \frac{\hat{U}}{\omega \cdot L_\sigma} \cdot (1 - \cos \omega t)$$

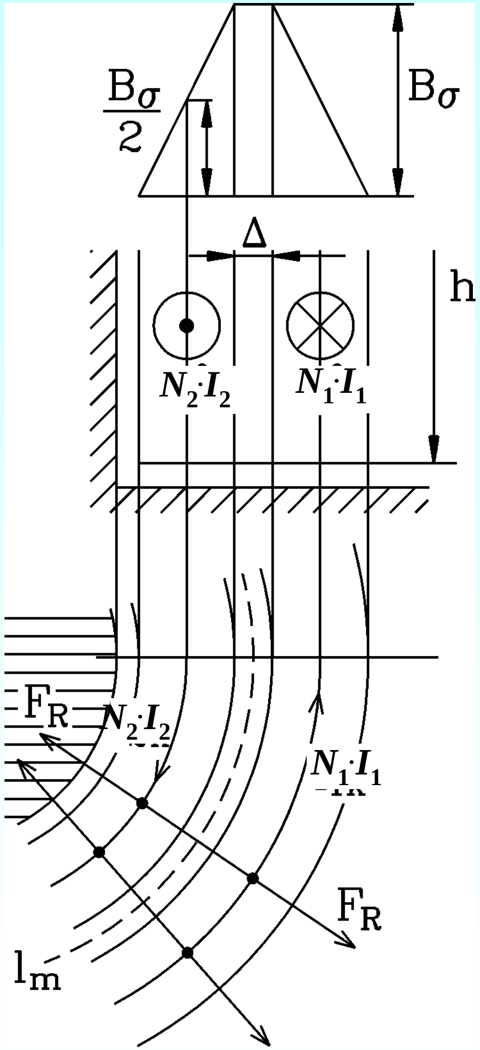
$$L_\sigma = L_{1\sigma} + L'_{2\sigma}$$



Short circuit LORENTZ forces



i_k: short circuit current
B_σ : stray flux density
I_{1k}, I_{2k}: AC HV/LV short circuit current
Δ: stray channel width
h: winding height
N_1, N_2: number of turns of HV/LV winding
l_m: average circumference length
F_R: radial LORENTZ force
T: AC current period
U_1: HV winding phase voltage
$X_{1\sigma}$, $X'_{2\sigma}$: HV/LV winding stray reactances per phase

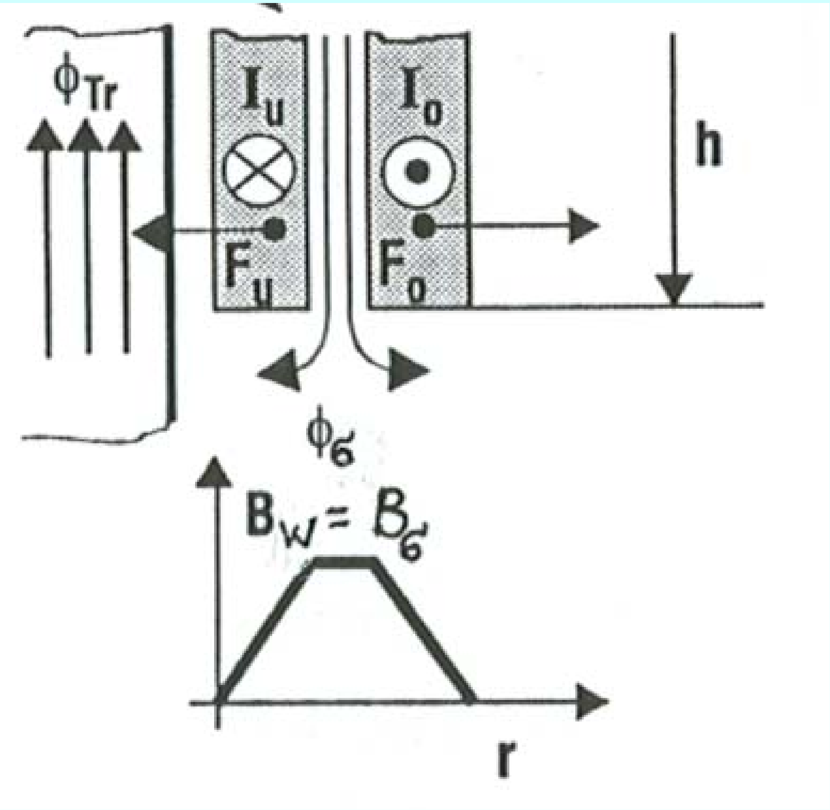


HV peak short circuit current :
(resistive damping neglected)

$$\boxed{\hat{I}_k \approx 2\frac{\hat{U}_1}{X_{1\sigma} + X'_{2\sigma}}}$$

- Sudden short circuit: resistance neglected, stray inductances limit the short circuit current i_k
- Worst-case: Short-circuit at zero voltage: i_k contains AC and DC component of same amplitude
- Opposite currents in LV and HV winding: “Exploding” force on HV winding
- Strong mechanical support needed for the windings

Forces on SC windings



Φ_{Tr}: transformer core flux
Φ_{σ}: transformer resulting stray flux
$B_w = B_{\sigma}$: maximum flux density in the winding is stray flux density!
h: winding height
I_o / I_u: r.m.s. current in HV /LV winding

F_o / F_u: LORENTZ forces in HV /LV winding

$$\hat{F}_u = N_u \hat{I}_u \cdot \frac{\hat{B}_{\sigma,u}}{2} \cdot d_u \pi \qquad d_u = d_{av} - \Delta - b_2$$

$$B_{\sigma,u} = \mu_0 \frac{N_u I_u}{h}$$

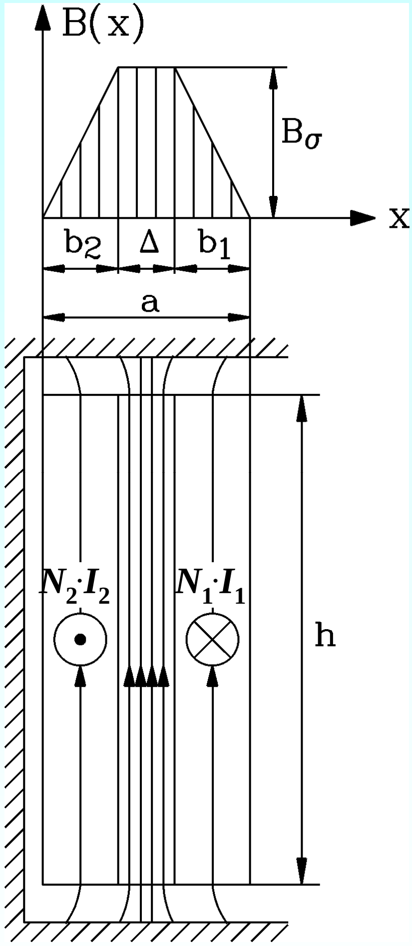
$$\boxed{\hat{F}_u = \mu_0 (N_u \hat{I}_u)^2 \cdot \frac{d_u \pi}{2h} = -\hat{F}_o}$$

Komarek, P.: Teubner, Stuttgart, 1995

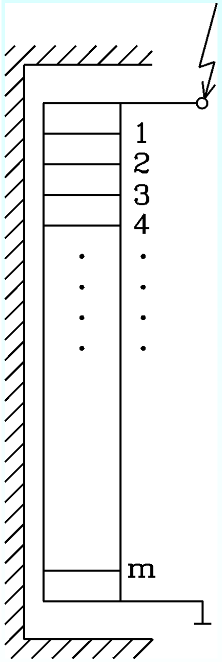
2.2 Superconductivity for electrical energy technology

Eddy currents in LV conductors due to stray flux in transformers

B: winding flux density
B_σ: stray flux density
b_1, b_2: coil breadth
Δ: stray channel width
a: overall winding width
N_1, N_2: number of turns of HV/LV winding
I_1, I_2: AC current of HV/LV winding

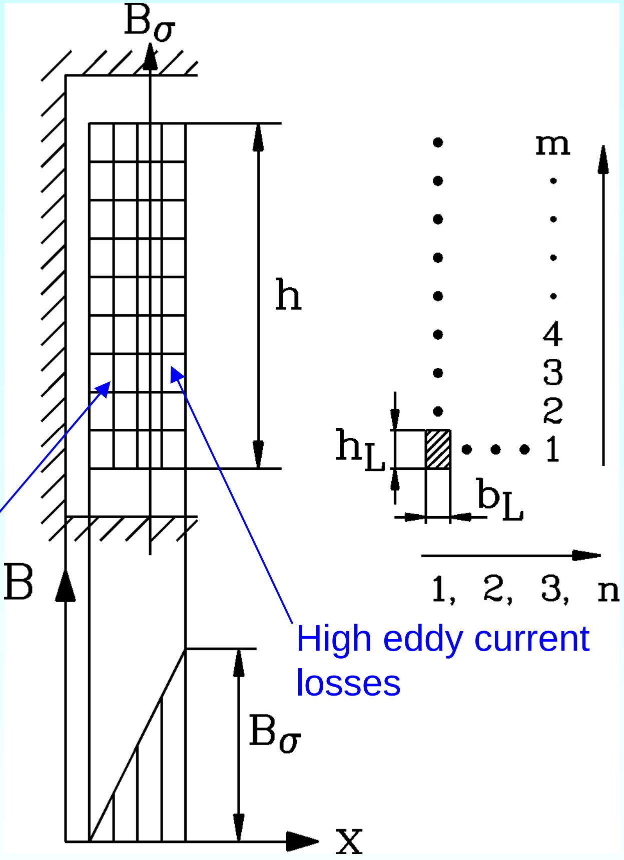


Stray flux lines



Conductor arrangement

h: winding height
m: number of coil layers
n: number of turns/layer
h_L, b_L: height/width per conductor

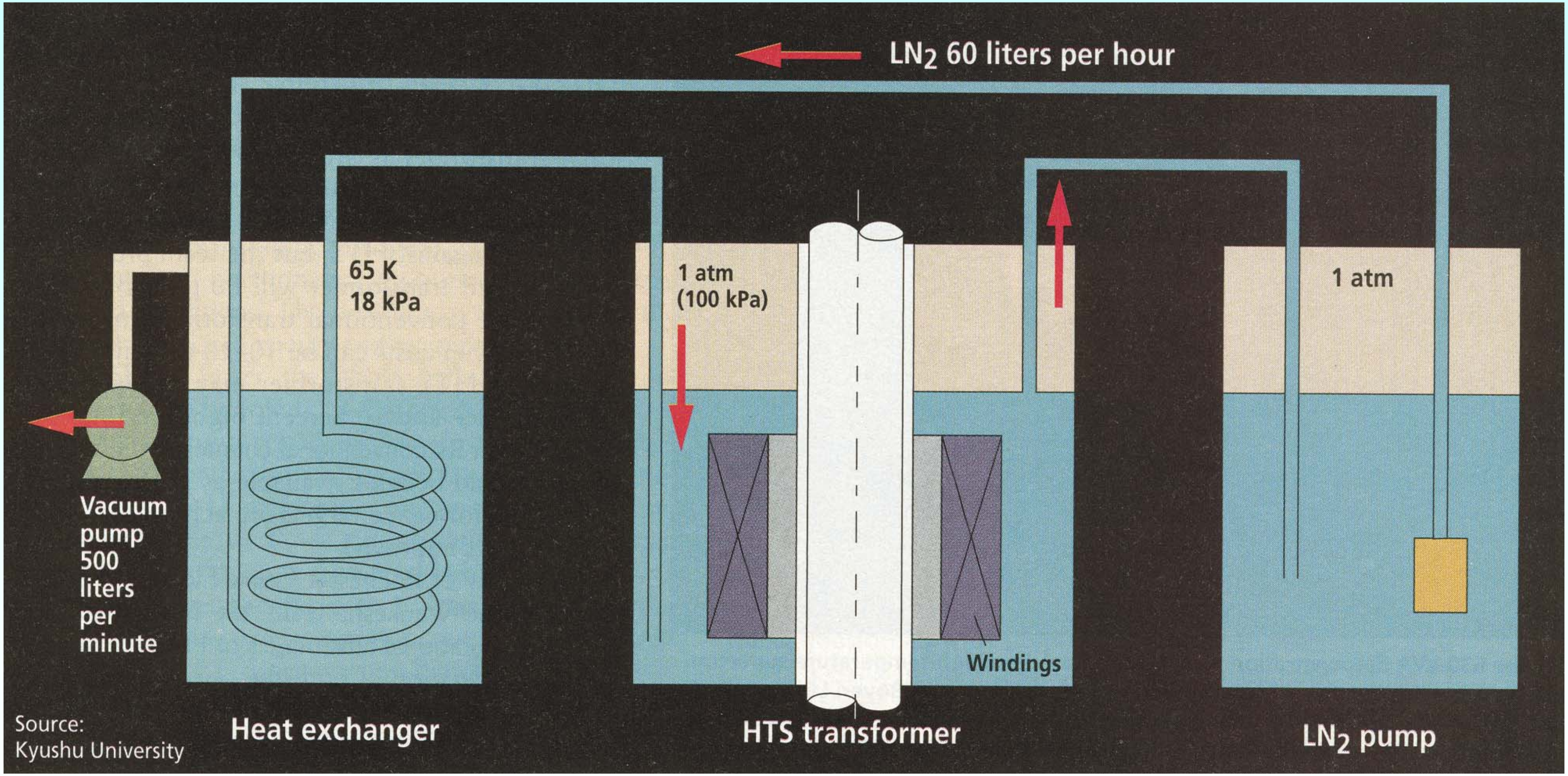


Low eddy current losses

High eddy current losses

Stray flux lines penetrate conductors: Conductors must be made of twisted strands to suppress eddy currents

Single-phase HTSC transformer (prototype, warm core)



Source: Kyushu University

500 kVA prototype with LN_2 cooling circuit *(Source: Sumitomo / Kyushu Univ., Japan)*

60 Hz-single phase-loco-HTSC-transformer (*Japan*, 2006)

Primary winding 60 Hz	3.5 MVA, 25 kV, 1 x 140 A, a_a = 2-fold parallel
Secondary winding 60 Hz	4x875 kW = 3.5 MVA, 1.2 kV, 4 x 730 A, a_a = 1
Third winding 60 Hz	0.4 MVA, 440 V, 909 A, a_a = 2-fold parallel
Impedance voltage Mass / Dimensions (without cooling system)	16.2% 1.7 t / $h \times b \times t = 1.9 \times 1.2 \times 0.7$ m
Cooling Cryostat	LN_2 66 K, warm iron core glass fiber composite
Losses at Sinus: Total / No-load	6200 W *) / 710 W
High Voltage Test	a) 42 kV AC, 10 min. b) 150 kV impulse voltage

***) 6200 W: too high losses, because the secondary parallel strands were not twisted (no ROEBEL bar technology used!)**

(Source: Railway Research Center, Japan)

Conductors for 60 Hz-single phase-Loco-HTSC-Transformer

- Bi-2223-Multi-filamentary wire, Ag-Matrix, 4.5 x 0.27 mm^2, $q = 1.215\ \text{mm}^2$
- Technical critical current density $J_{C2} = 90\ \text{A/mm}^2$ at 77 K
- Spilt secondary winding for reduction of stray field amplitude by 50%
- Voltage per turn 12.5 V
- Number of turns: primary $N_1 = 2000$, 16 layers = 16 x 125
  No parallel wires per turn: $a_i = 1$, but two parallel branches: $a_a = 2$
  Current density: $J_1 = I_1/(a_a \cdot a_i \cdot q) = 140/(2x1x1.215) = 57.6\ \text{A/mm}^2$

(Source: Railway Research Center, Japan)

- Secondary: $a_i = 8$, $J_2 = 75.6\ \text{A/mm}^2$, third winding: $a_i = 6$, $J_2 = 62.3\ \text{A/mm}^2$

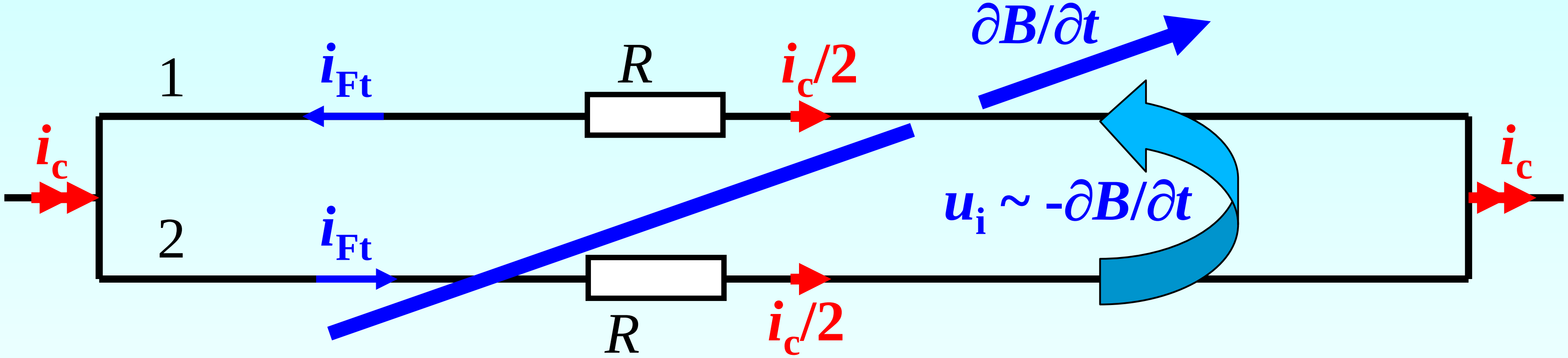
Result:

As no twisting of the strands at the low voltage side (secondary and third winding) was done, the additional losses in the winding due to non-uniform current distribution on parallel strands (8 resp. 6 strands) is already at sine wave operation much too high!

The impedance voltage is too low for inverter operation (Aim is: 50%).

Uneven current distribution in parallel strands leads to increased losses

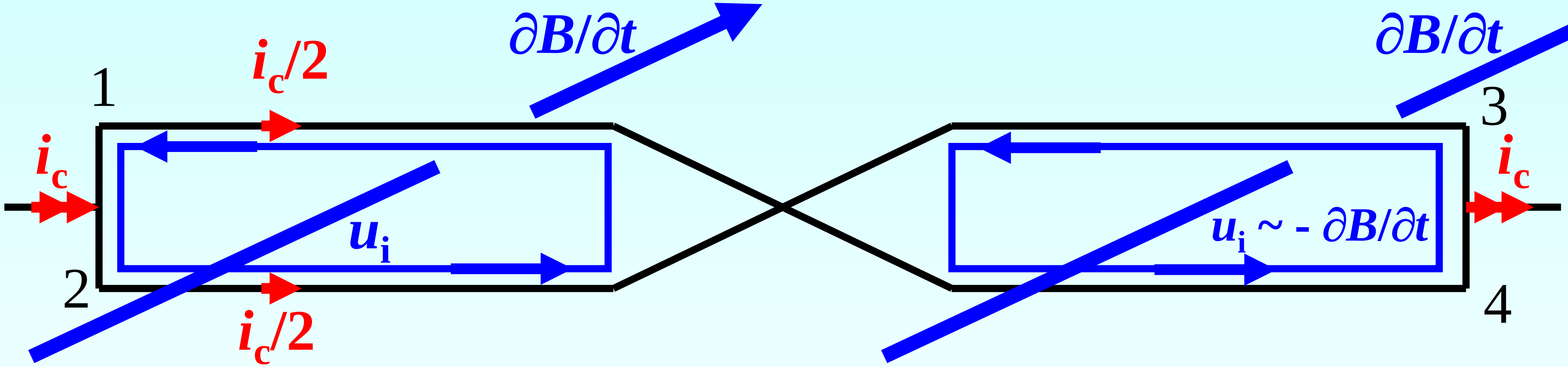
Example: $a_i = 2$ parallel strands per conductor, exposed to changing magnetic field



- Conductor current i_c flows as $i_c/2$ in each of the two parallel strands
- Changing flux density $\partial B/\partial t$ induces voltage u_i, which causes eddy current i_{Ft}
- Uneven current share per strand: $i_1 = i_c/2 - i_{Ft}$, $i_2 = i_c/2 + i_{Ft}$!
- Losses without eddy current: $i_1 = i_2 = i_c/2 : P_{d0} = 2R\cdot(i_c/2)^2 = R\cdot i_c^2/2$
- Losses with eddy current: $P_d = R\cdot(i_1^2 + i_2^2) = R\cdot i_c^2/2 + 2R\cdot i_{Ft}^2 > P_{d0}$

Twisting of strands to equalize current share in parallel strands

Example: a_i = 2 parallel strands per conductor, exposed to changing magnetic field



- The two strands are crossed ("twisted"): The induced voltage differences between points 1-4 and 2-3 are each zero = no eddy current may flow: $i_{Ft} = 0$.

- No unequal current share: $i_1 = i_c/2 = i_2$!

- No increased losses! $i_1 = i_2 = i_c/2 : P_d = P_{d0} = R \cdot i_c^2/2$

Twisted strands at big total conductor cross section

- Low voltage winding: Low voltage leads to high current = big conductor cross section = many parallel strands ($a_i > 1$)

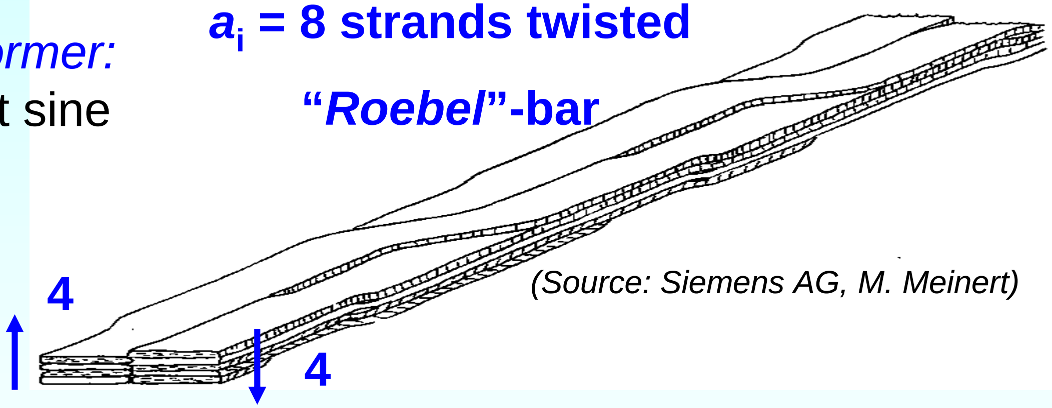
- Twisting of strands necessary to get a uniform current sharing in the parallel strands (= no circulating current component!)

- *Twisting of strands in the Japanese transformer:* Reduction of losses from 6.2 kW to 1 kW at sine wave operation:

- AC losses in the conductor: P_{Fe} = 710 W
  6200 – 710 = 5490 W ⇒ reduced to:
  ca. 1000 W (total: 1710 W)

a_i = 8 strands twisted

"*Roebel*"-bar



(Source: Siemens AG, M. Meinert)

- Cooling system for 1 kW dissipated power:
  Mass of cooling system: ca. 600 kg
  Electrical power: ca. 20 kW

Result: **Total mass: 1700 + 600 = 2300 kg** $\cos\varphi = 1 : \eta = 3.5/(3.5 + 0.0217) = 0.9938$

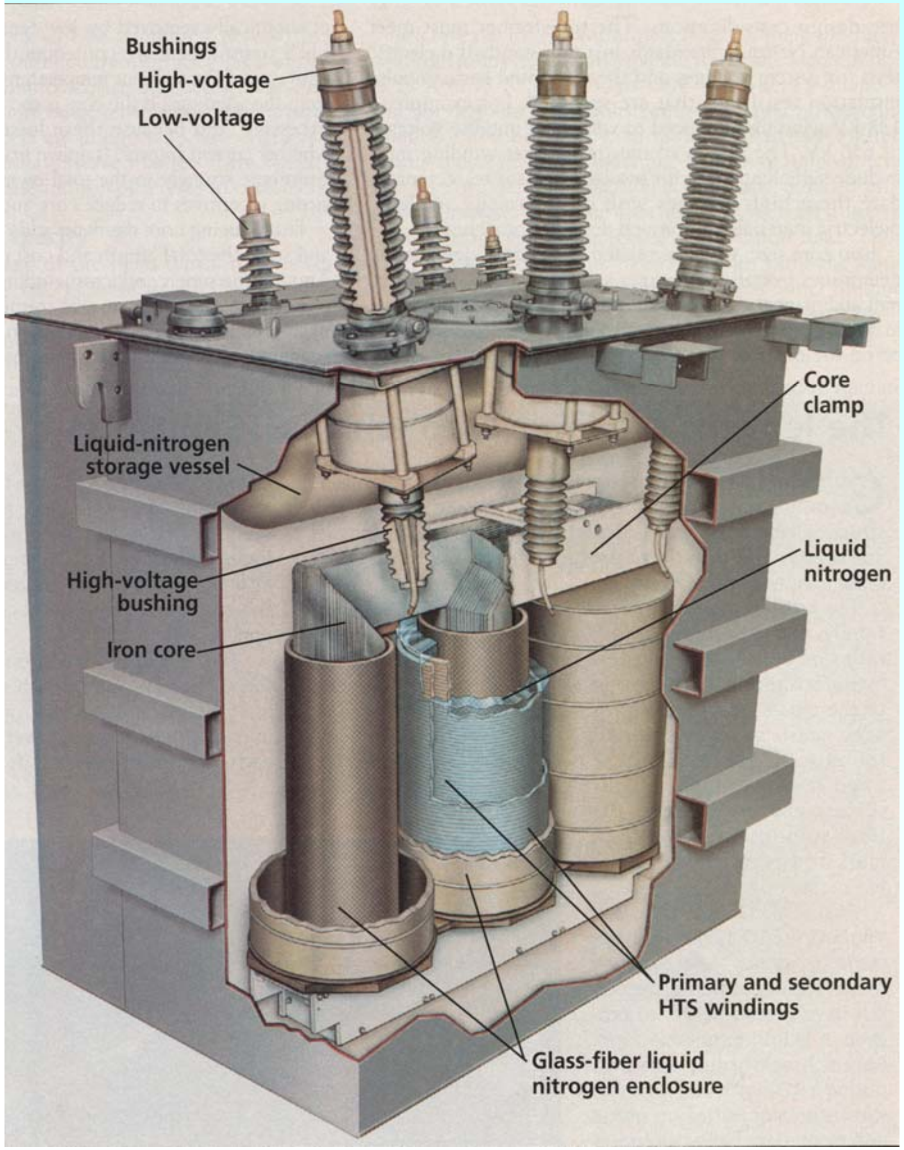
Total losses (at sine wave): 1.71 + 20 = 21.7 kW; efficiency: 99.4%

Mass: 60 Hz-single phase-Loco-HTSC-Transformer

Iron core (warm)	830 kg
Cooling system (Compressor & Refrigerator)	600 kg
Cryostat (Glass fiber composite)	210 kg
Coil and terminal wires (BSCCO)	250 kg
Liquid nitrogen	180 kg
Coolant pump, pipes, bushings	230 kg
Sum	2300 kg

(Source: Railway Research Center, Japan)

Three-phase HTSC power transformer



- Warm iron-core, LN_2 cooling

For grid operation: **Tested: One single-phase** unit: 1 MVA, 60 Hz, 1.8 kV/ 6.9 kV,

Warm iron-core: heated up to 350 K = 80°C by the core losses

- HTSC is operated at 25 K

- LN_2 tank: aluminised Mylar fabric,

- Strip conductor: Bi(2212)

- Lab test operation:
  pure reactive power 0.64 MVA

Source: IEEE/PES Journal, 1998, Waukesha/USA

Three-phase HTSC power transformer in field test

630 kVA

20 kV/400 V

Distribution transformer

Warm core

Field test in a substation in *Geneva/Switzerland*

Source: ABB/EDF

Three-phase HTSC power transformer in field test

Source: ABB/EDF

630 kVA, 20 kV/400 V, distribution transformer

warm iron core

Field test in a substation in *Geneva/Switzerland*

For grid operation:
Three-phase: 630 kVA, 50 Hz, 18.7 kV/420 V, Bi(2223) strip conductor, LN_2 cooling, 77 K, per phase: non-conductive composite cryostat, warm iron core

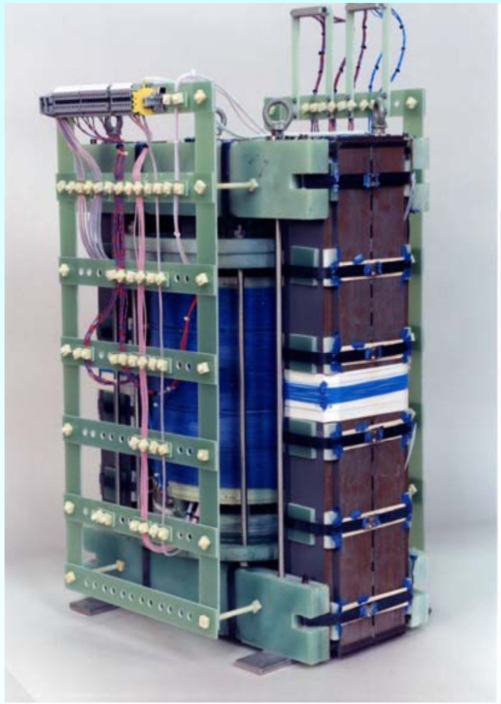
system test operation in *Geneva/Switzerland*

(ABB Switzerland / EDF, France)

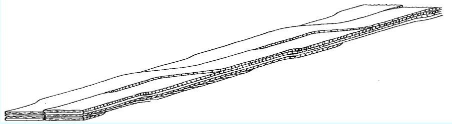
2.2 Superconductivity for electrical energy technology

Stages of development for an HTSC railway transformer

100 kVA model transformer (shell type)

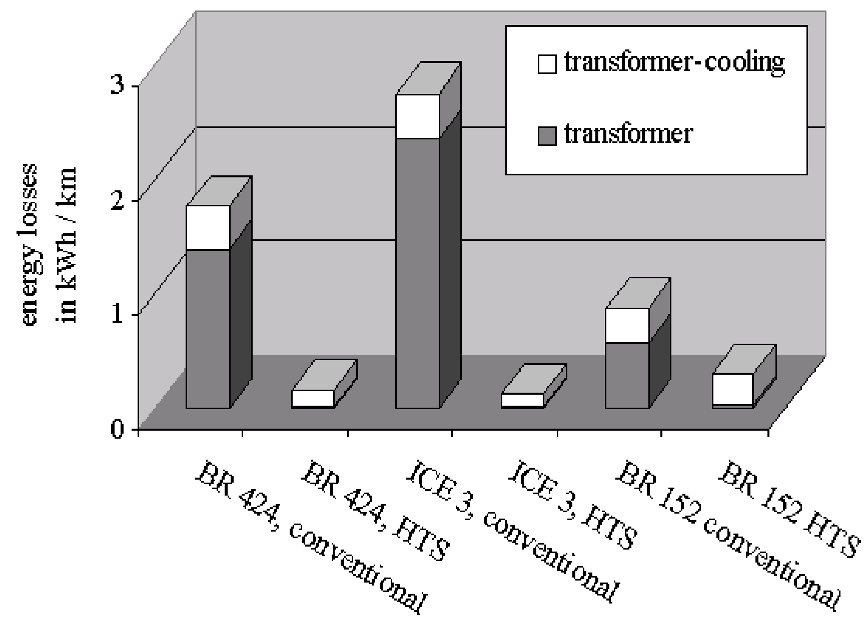


AC ROEBEL-bar conductor



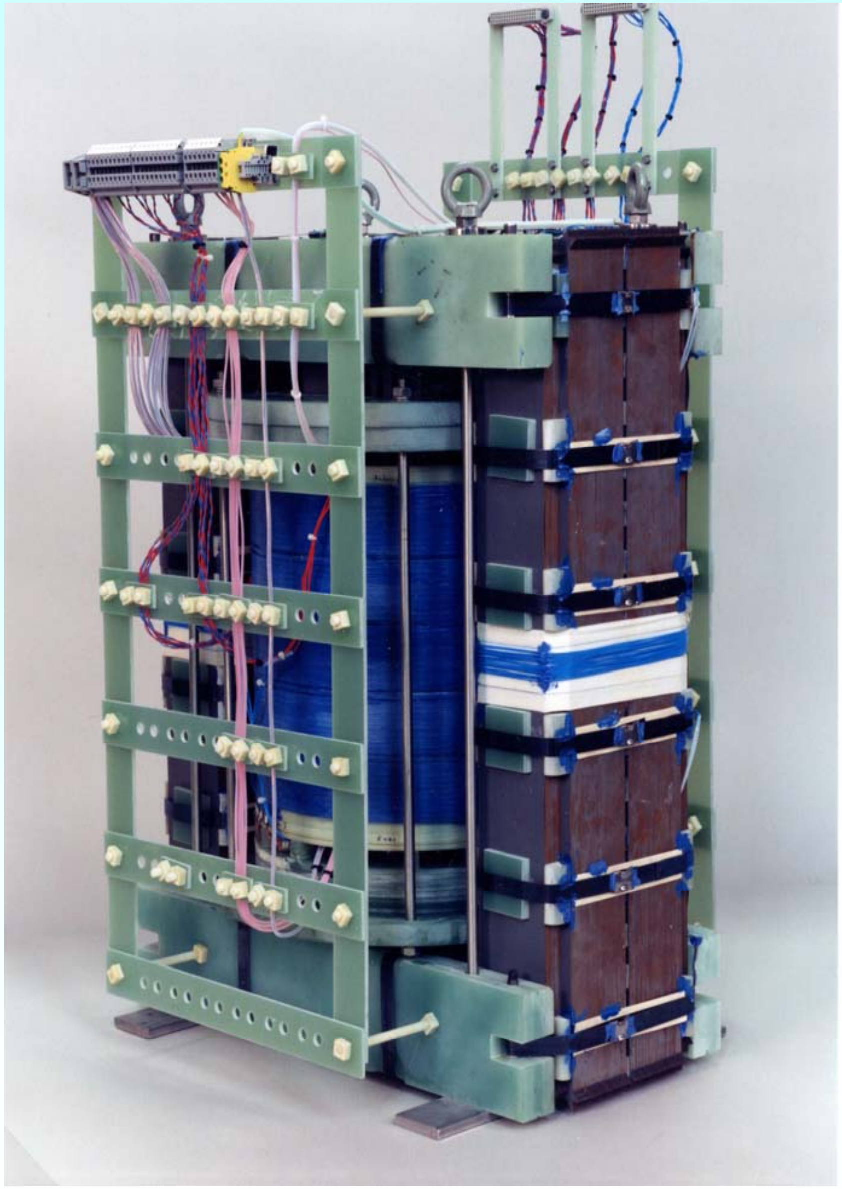
On-board prototype?

Potential energy saving



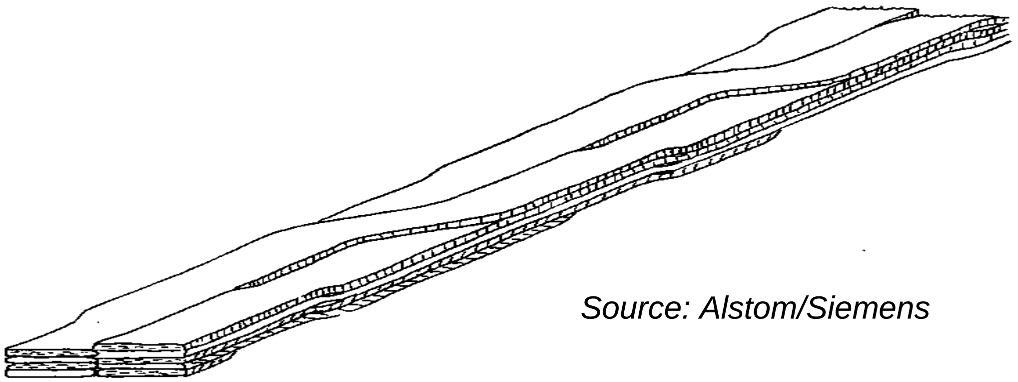
(Source: Siemens AG, M. Meinert)

1 MVA demonstrator (leg type)



100 kVA prototype HTSC railway transformer

- Cold iron-core, LN_2 bath cooling 77 K
- Shell-type transformer
- Low-voltage side: high current = high conductor cross-section: Conductors twisted BSCCO sub-conductors to reduce eddy currents (ROEBEL bar)
- Critical current density 80 A/mm^2



Source: Alstom/Siemens

Locomotive transformer, prototype 1 MVA

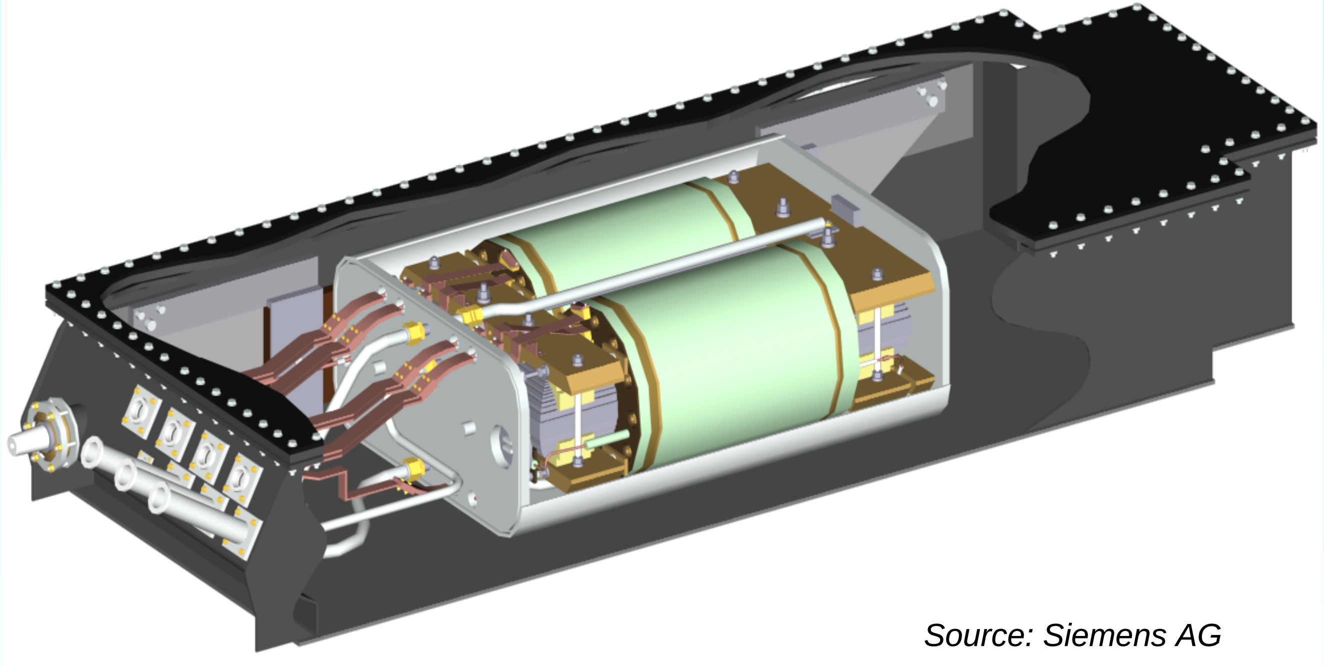
- Loco transformer: **Single-phase:** **1 MVA,**
  16.7 Hz, 25 kV / 2x1.4 kV, 40 A / 2x360 A,
  u_k = 25 %, Bi(2223) strip conductor, LN_2 cooling, forced circulation flow,
  67 K, cold iron-core, core induction 1.7 T, iron core: 1080 mm,
  Coils diameters: split LV: Ø 228mm / Ø 382mm, HV: Ø 304mm, height: 500mm
  Conductors: LV: solenoid with 13 ROEBEL bars, HV: 9 disc coils,
  Cryostat in vacuum-tight tank: L x B x H = 1140 x 832 x 420 mm

- Conductor Bi(2223)-HTSC, LV: Big cross section needed: Multi-filament conductor ($3.2 \times 0.3\ mm^2$), 55 filaments in silver matrix with magnesium additive.
  HTSC share of strip conductor cross-section: 25%.

- Nominal current density 30 A/mm^2 in strip conductor
  current density in HTSC: 120 A/mm^2 (at DC operation 250 A/mm^2 are possible).
- J_c (77 K) = 60 A/mm^2 for AC operation (1998). State in 2002: 100 A/mm^2

(Source: Siemens AG, Germany)

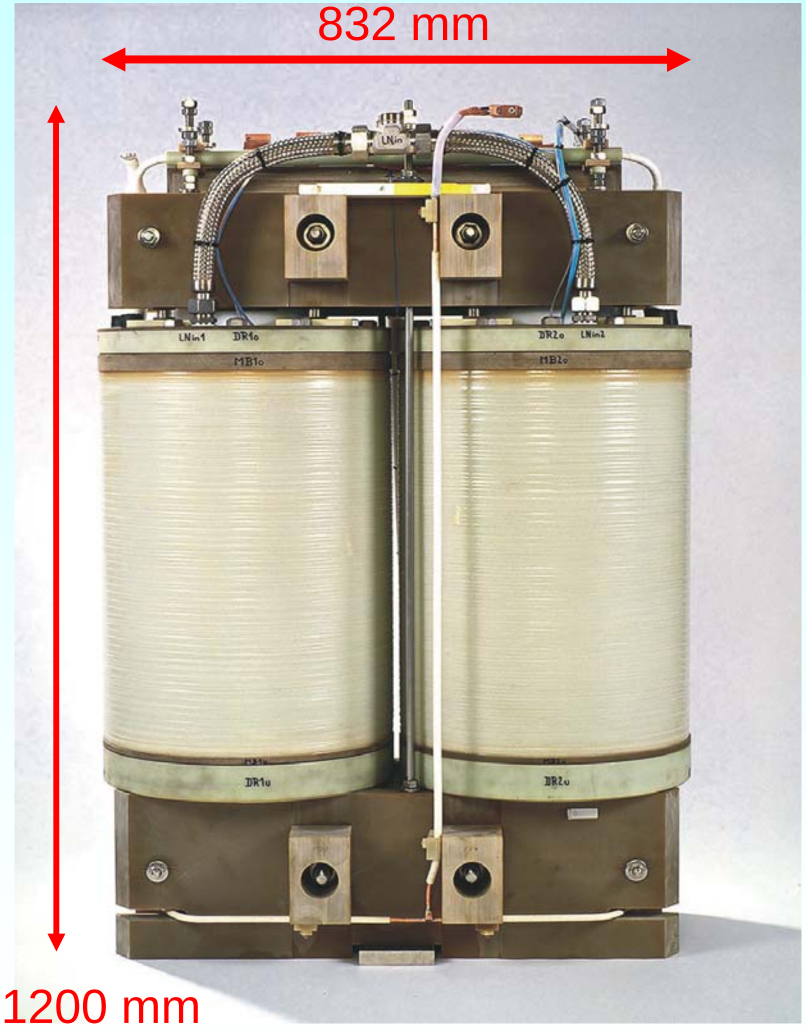
1 MW prototype of a railway transformer



Source: Siemens AG

- Single-phase leg transformer, cold iron core, LN_2 forced circulation cooling
- Installation of the active part (in cold container) into a vacuum-tight tank of the transformer of the type series BR 424/425. Together with the stainless-steel container for the LN_2 it serves as cryostat.

Data of the 1 MW HTSC railway transformer



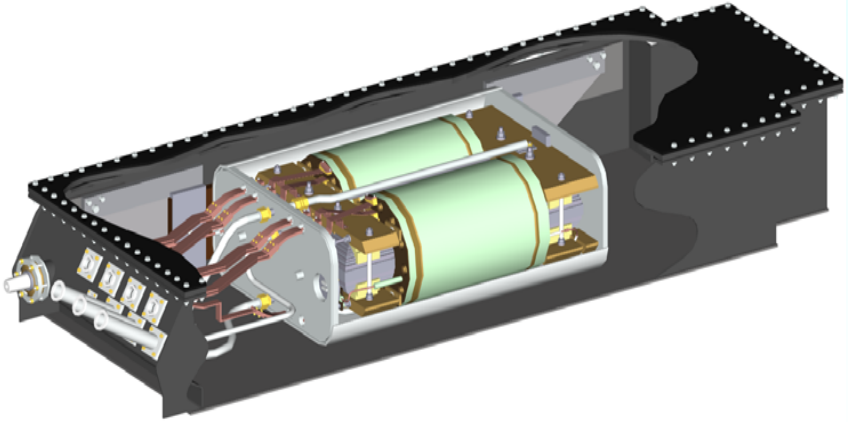
Siemens AG, Germany

- 1 MVA, 50 Hz, 25 kV / 1389 V
- Currents: 40 A / 2 x 360 A (= two low-voltage windings for two converters)
- Impedance voltage 25%
- Core induction 1.7 T
- Current density 30 A/mm^2 at 67 K = -206°C
- Total conductor length HTSC: 8.2 km, 66 kg
- Stainless-steel cryostat (thus eddy current losses occur due to the AC stray field)

Source: Siemens AG

Comparison: 1 MVA HTSC single-phase railway transformer

16.7 Hz	1.1 MVA: Copper winding, oil-cooled	1.0 MVA: HTSC winding, LN_2-cooled
	15 kV/ 816 V, $u_k = 50$ %	25 kV/2 x 1.4 kV, $u_k = 25\%$
Total losses	92 kW, inverter operation	7.8 kW, sine operation *)
Mass / efficiency	4800 kg / 92.28%	2200 kg / 99.23%
Volume (core + coils)	690 dm^3	360 dm^3



Source: Siemens AG, M. Meinert

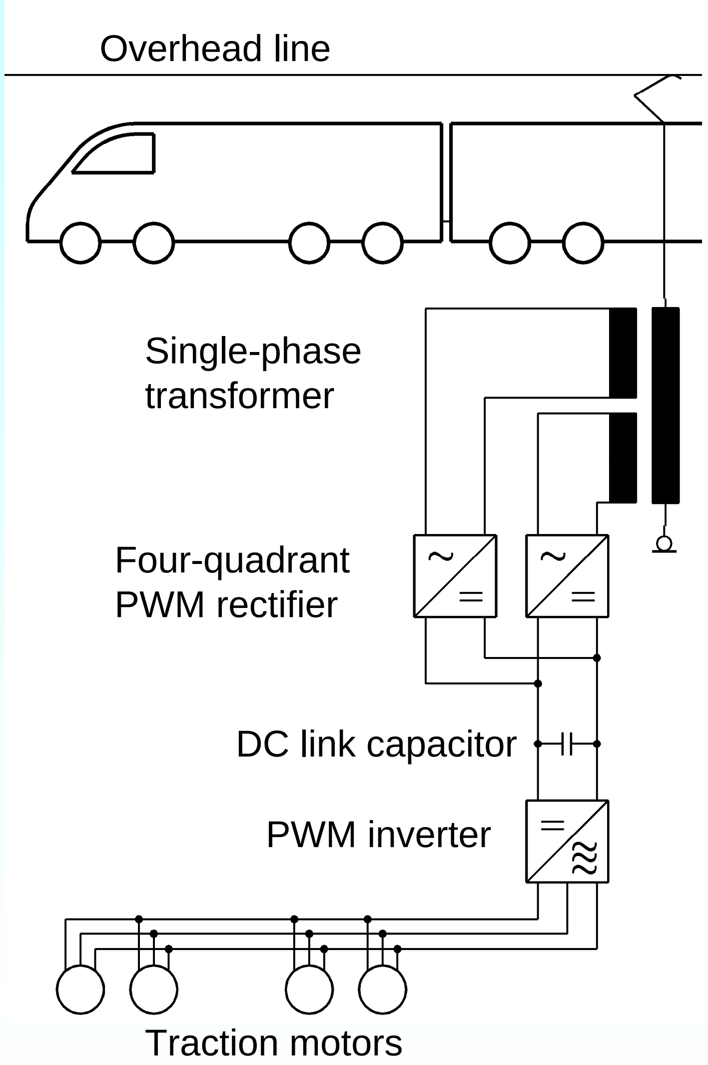
Losses during sine operation:

AC loss in the HTSC material,	
Specific total losses in the iron core *):	550 W
Cooling power:	7250 W
Total loss:	**7800 W**

***) small losses**

2.2 Superconductivity for electrical energy technology

Loco transformer for inverter-fed induction motors



Overhead line

Single-phase transformer

Four-quadrant PWM rectifier

DC link capacitor

PWM inverter

Traction motors

Single-phase AC voltage

1~, 15000 V

$16\frac{2}{3}$ Hz

Single-phase AC voltage

1~, 2x1100 V

$16\frac{2}{3}$ Hz

DC voltage

2800 V

Three-phase AC voltage

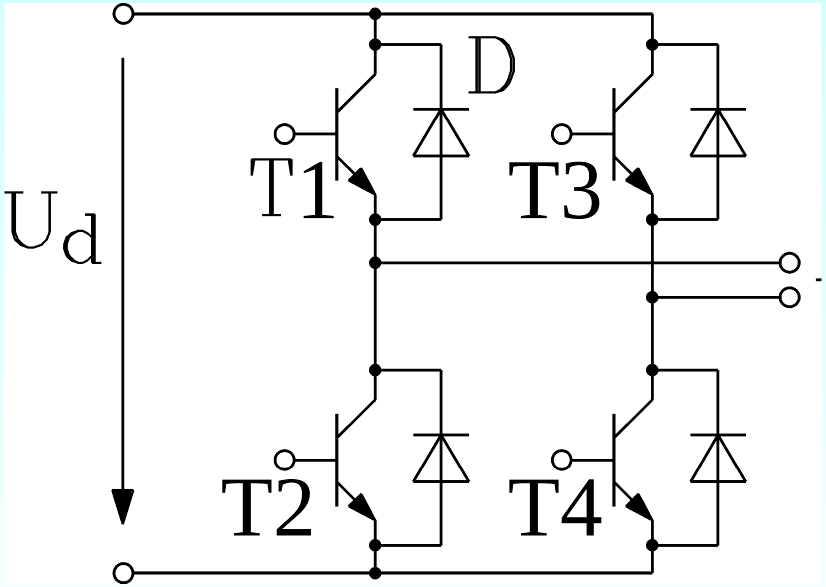
3~, 0…2000 V

0…200 Hz

Four-quadrant PWM rectifier

D: Free-wheeling diodes, T: Insulated Gate Bipolar Transistor IGBT

DC voltage for
DC link
capacitor



Single-phase AC voltage =
Transformer secondary voltage

↓ T1 & T4 are conducting

↑ T2 & T3 are conducting

PWM: e.g. T1 is opened and closed acc.
to sinusoidally varying switching times

System test of the inverter-operated HTSC-loco transformer

System test with IGBT-voltage source inverter

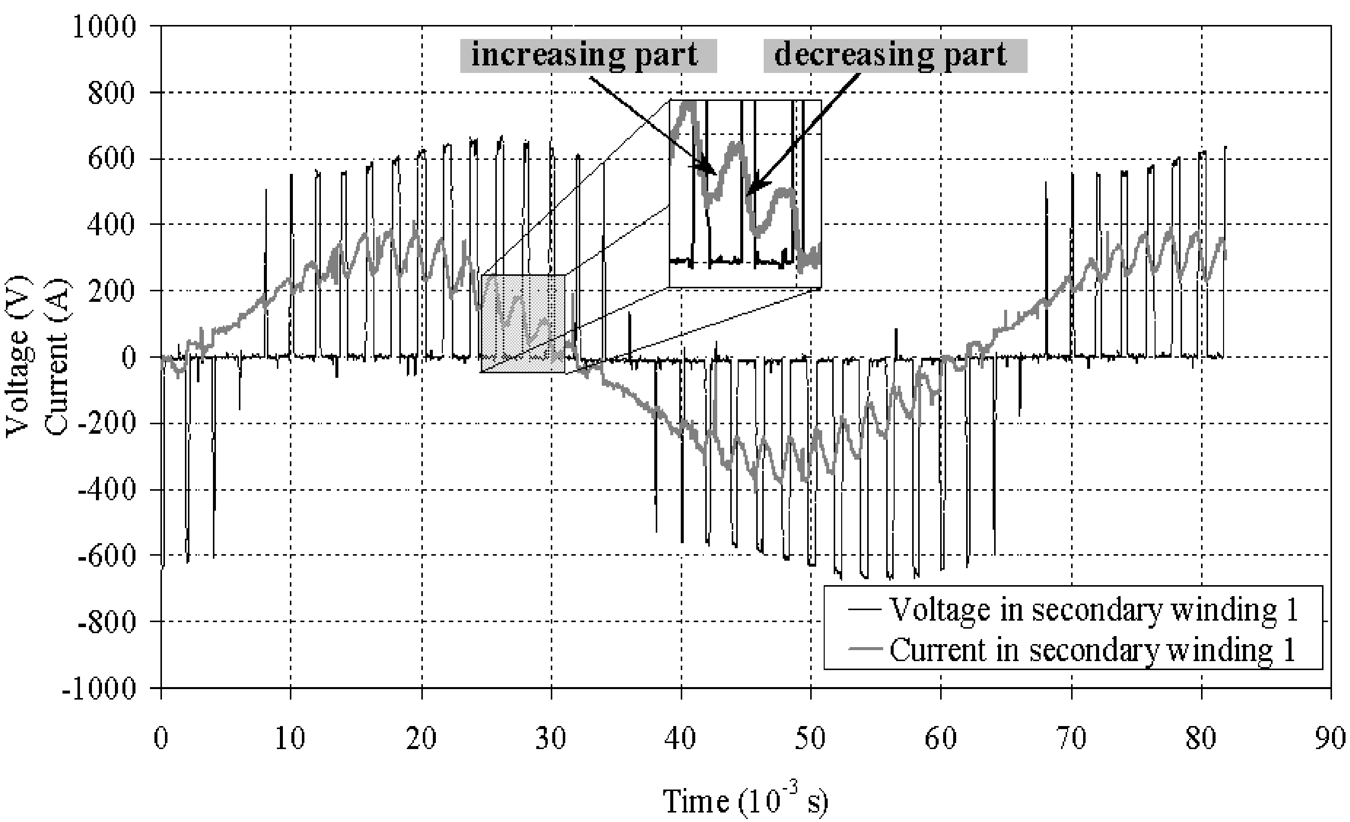
(Source: Siemens AG, Nuremberg)

2.2 Superconductivity for electrical energy technology

System test of the converter-fed HTSC railway transformer

Test-bay Nuremberg, Siemens AG

System test with IGBT inverter



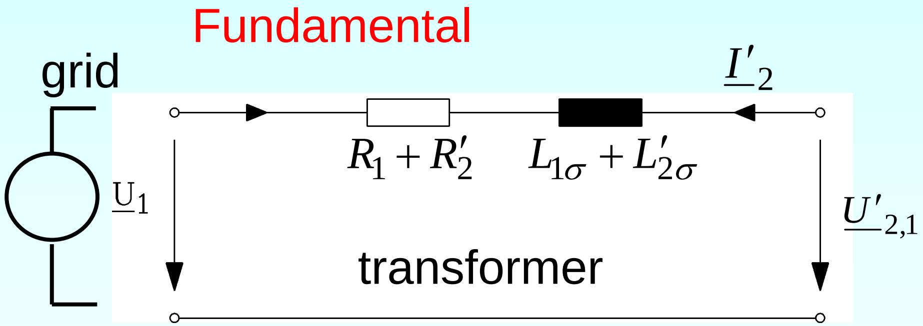
Operation of the 1-MVA-HTS transformer with an IGBT railway converter, synchronous PWM switching $f_T = 15f_s$, DC link voltage 600 V

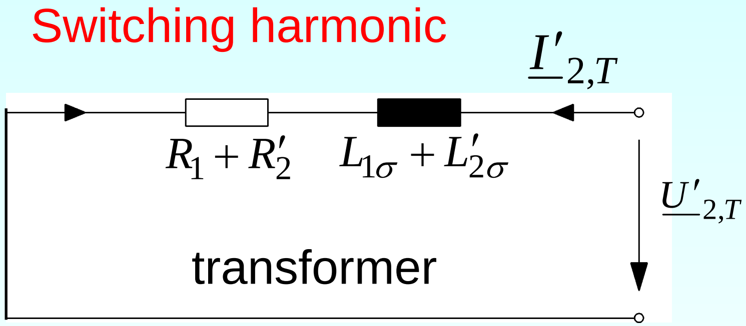
Source: Siemens AG, M. Meinert

Losses 1400 W (inverter operation) instead of 550 W (sine operation)!

Limitation of current ripple by increased impedance voltage

- **Inverter PWM output voltage = transformer secondary voltage:**
  expanded as FOURIER series: $u(t) \approx \hat{U}_{2,1} \cdot \sin(2\pi f \cdot t) + \hat{U}_{2,T} \cdot \sin(2\pi f_T \cdot t)$
  Fundamental Switching harmonic





$$R_1 + R'_2 \ll \omega \cdot (L_{1\sigma} + L'_{2\sigma}) \quad :$$

$$\underline{I}'_2 \approx \frac{\underline{U}'_{2,1} - \underline{U}_1}{j\omega \cdot (L_{1\sigma} + L'_{2\sigma})}$$

$$\underline{I}'_2 \approx \frac{\underline{U}'_{2,1}}{j\omega_T \cdot (L_{1\sigma} + L'_{2\sigma})}$$

For the high frequency switching harmonic the grid has no voltage component.
As the (ideal) grid has no internal impedance, only the transformer leakage inductance limits the current ripple $I_{2,T}$. Hence a high impedance voltage u_k is needed.

Cooling concept of the 1 MVA HTSC single-phase railway transformer

- **Cooling:** Circulation pump: 75 W, four-cylinder *Stirling* machine (10 % efficiency), it cools (at 20 °C) 2 kW transformer losses at 67 K;

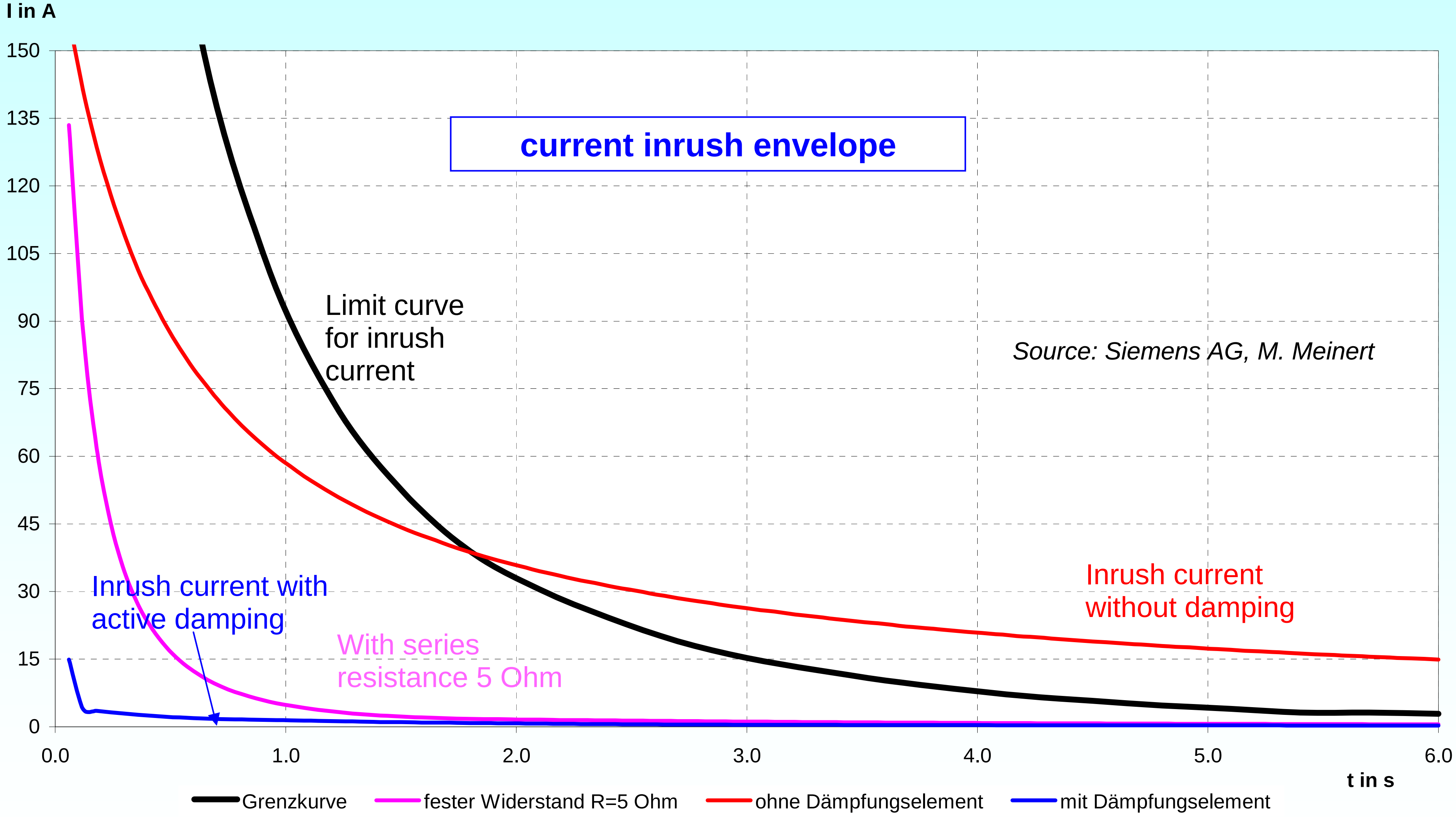
  23 kW electric connected load (maximum value).

  Above 20°C: Additional re-cooling unit used up to max. 50°C ambient temperature with 33% efficiency.

- Failure of the overhead catenary voltage ⇒ cooling unit is turned off ⇒ LN_2 circulation pump fed from on-board battery.

- Cold iron-core: During 6 h until the winding heats up from 67 K to 77 K. In case of failure of the pump this heat-up takes only 3 h. So the “limp-home” time is limited to between 3 … 6 hours.

Inrush-current of tested 1 MVA HTSC-transformer



Source: Siemens AG, M. Meinert

New technologies of electric energy converters and actuators

Summary:
Superconducting power transformers

- No commercial use until now, only prototypes for (field) tests
- High temperature superconductors at 77 K possible due to low stray field
- Reduction of mass and increase of efficiency possible
- Especially interesting for electric traction
- Reliability issue of on-board cryostat system for traction is crucial
- Transformer dynamics (e.g. inrush) badly damped with SC windings