Panel 5 – Innovative Traction Systems

Superconducting traction transformer

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Energy Efficiency Days 2009

Why superconducting transformers ?

Wheel load is critical

- serious weight limits on rail vehicles
- Transformer weight is relevant
- ***Solution***: transformer with windings from High Temperature Superconductor (HTS)

Advantages:

- reduced winding loss
- 30 - 40% less weight
- 20...50% less volume

Additional benefits:

Oil free, no fire hazard

No aging of cold insulation

Disadvantages:

☹ needs cooling by liquid nitrogen at ≤-196 °C (≤77 K)

☹ Double walled, vacuum isolated cryostat („Thermo flask“)

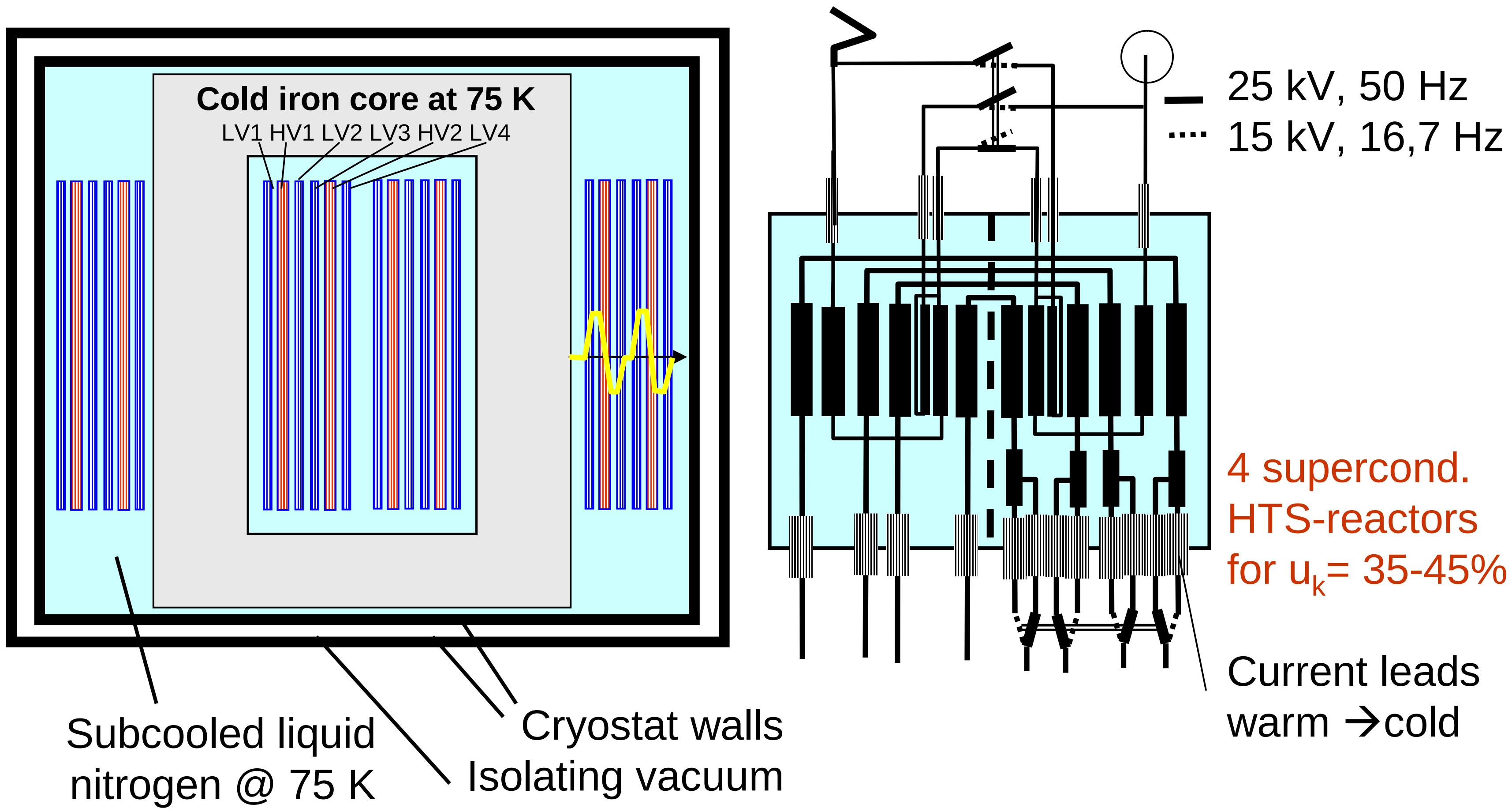
☹ Cooling by cryogenic cooler → drive power as loss

Activities performed & Status

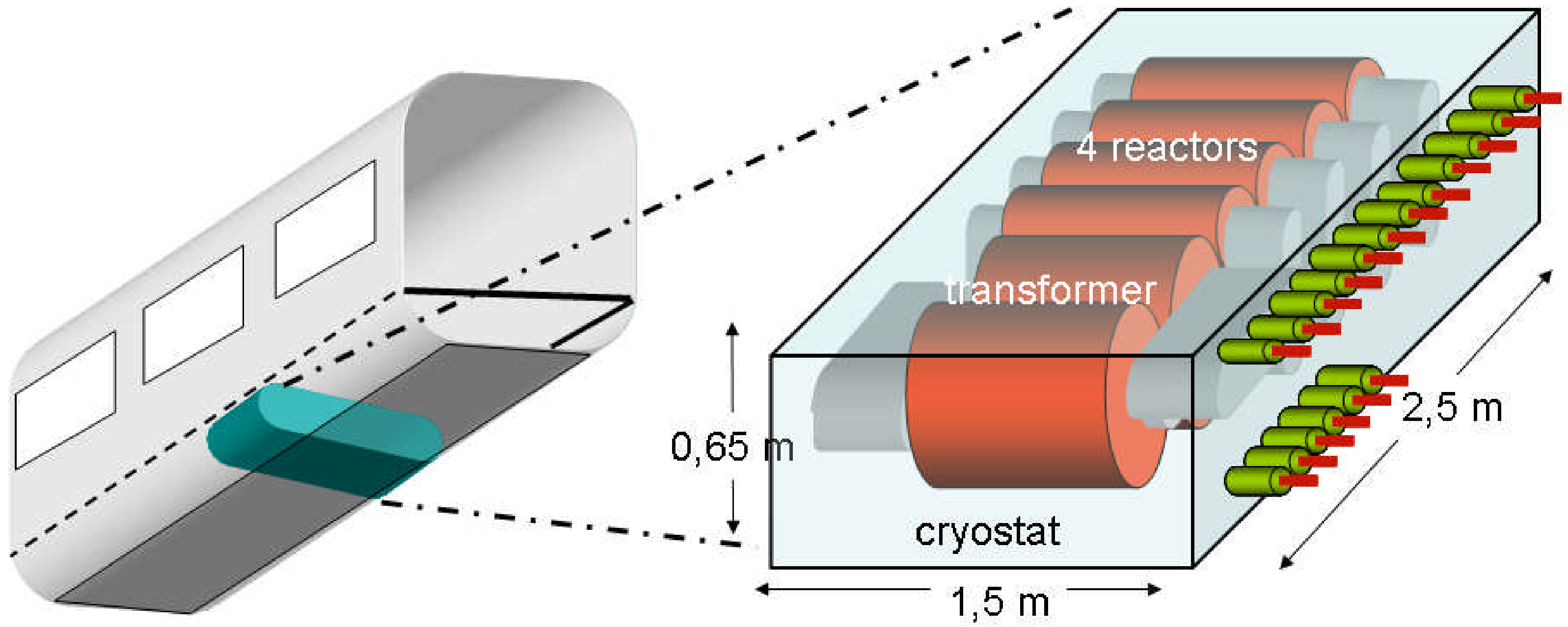
- Main specifications for ICE 3 MS transformer

2 AC-power systems:	**16,7 Hz**	**50 Hz**
primary secondary	15 kV, 4,6 MVA 4 x 2 kV, 1,15 MVA	25 kV, 4,6 MVA 4 x 2 kV, 1,15 MVA
Short circuit voltage u_k	35% - 45%	35% - 45%
Maximum dimensions including cryocooler	height < 0,65 m footprint < 2 m x 5 m	
Overall efficiency	> 99%	> 99%

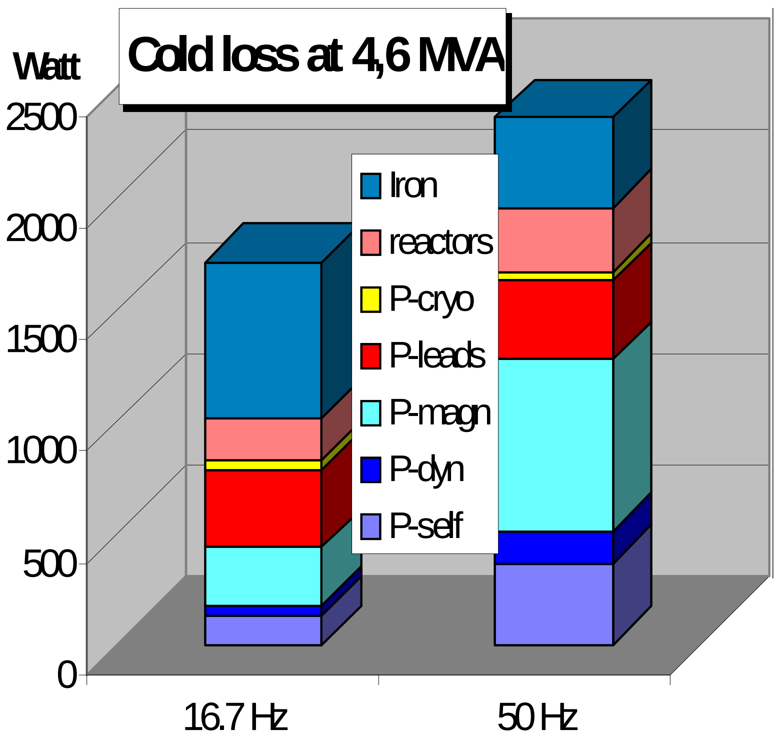
Setup of ICE3 MS HTS-traction transformer



Underfloor HTS-transformer with 4 reactors



Results / loss balance in HTS-transformer

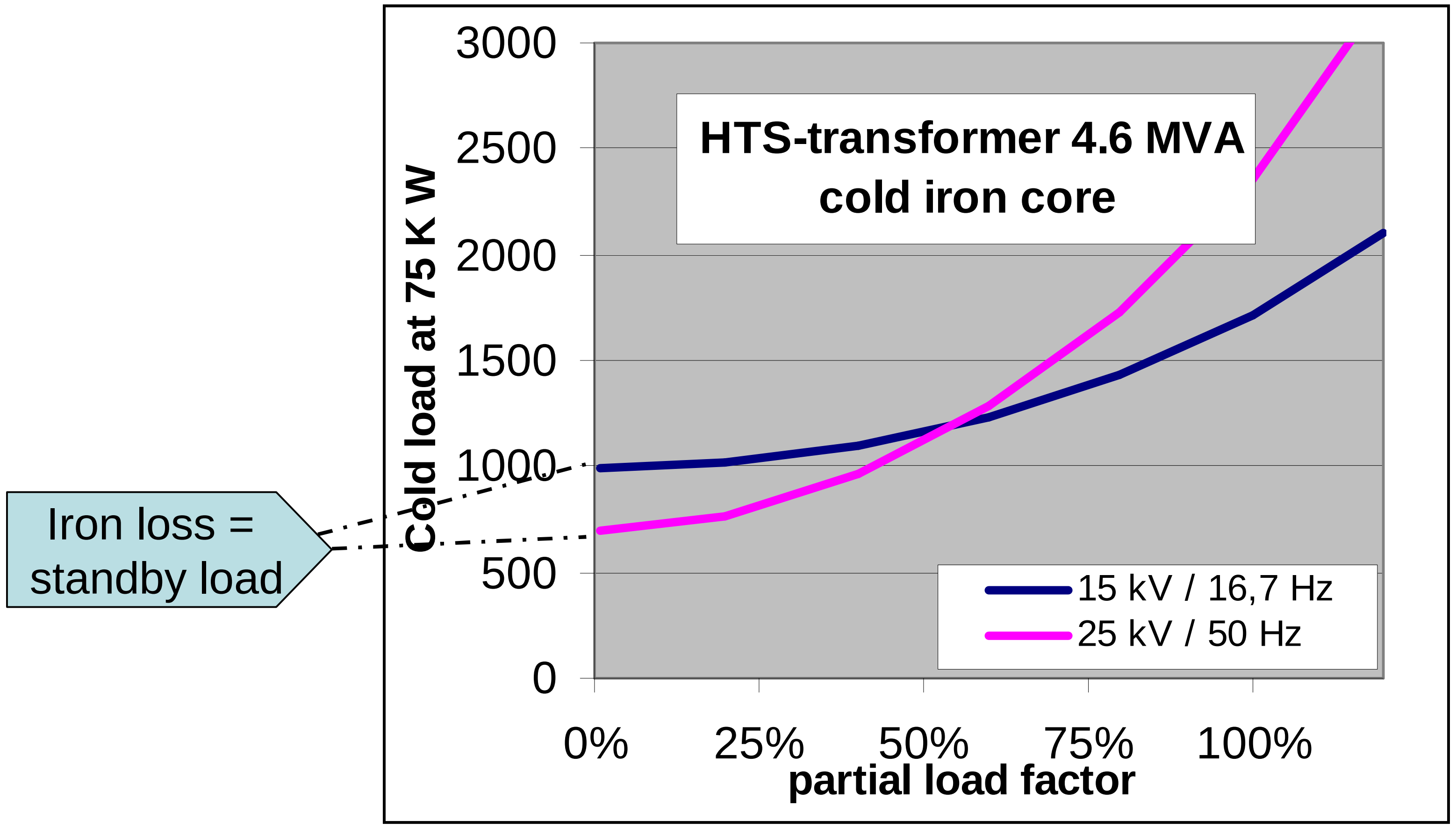


Cold loss at low temperature:

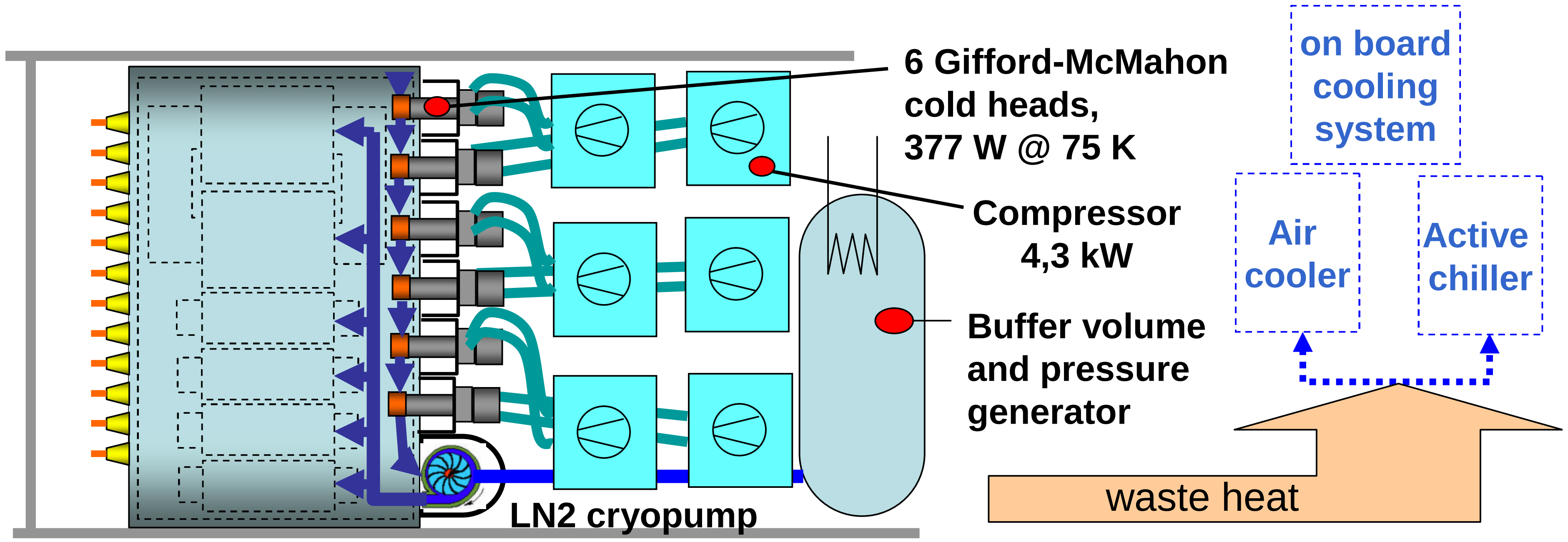
- : heat flux via cryostat walls
- : loss in cold iron
- : heat flux via current leads
- : magnetic AC-losses in HTS-wire

Loss at nominal 4.6 MVA	**16.7 Hz**	**50 Hz**
Cold loss transf. + 4 reactors	**1,7 kW**	**2,4 kW**
Cryocooler power = warm loss	**26 kW**	**36 kW**
Efficiency HTS-transformer	**99,4%**	**99,2%**
Transformer weight	5,6 t	
Efficiency Cu-oil transformer	~92% / 9,6 t	

Cold loss in HTS-transformer & reactors



Transformer today's cooling system



- Cooling by forced flow sub-cooled liquid nitrogen at 75 K = -198 °C
- 6 commercial cryo-coolers required for full load at 50Hz
- Control of variable refrigeration demand by on/off switching

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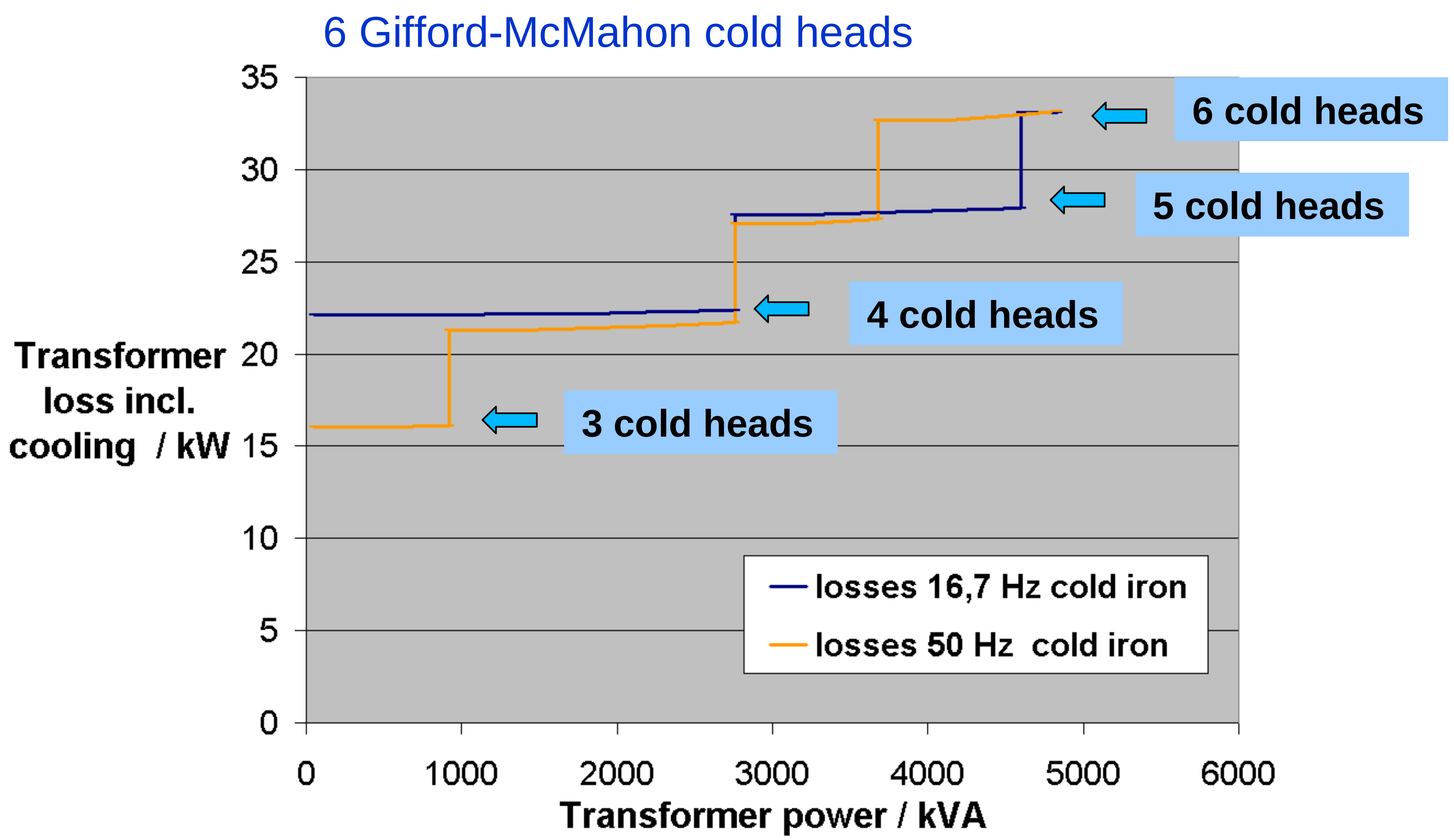
Power consumption in dependence of load



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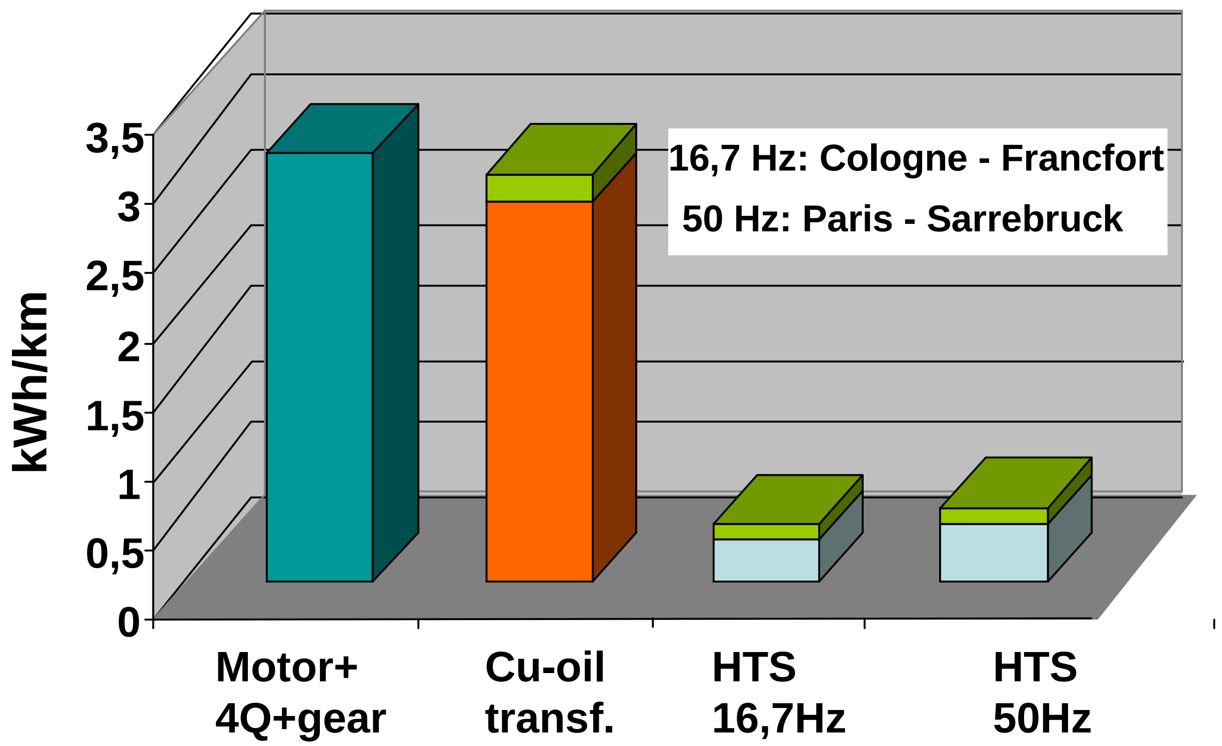
Loss/km for typical ICE3 drive cycles



electric losses,
2 transformers per train

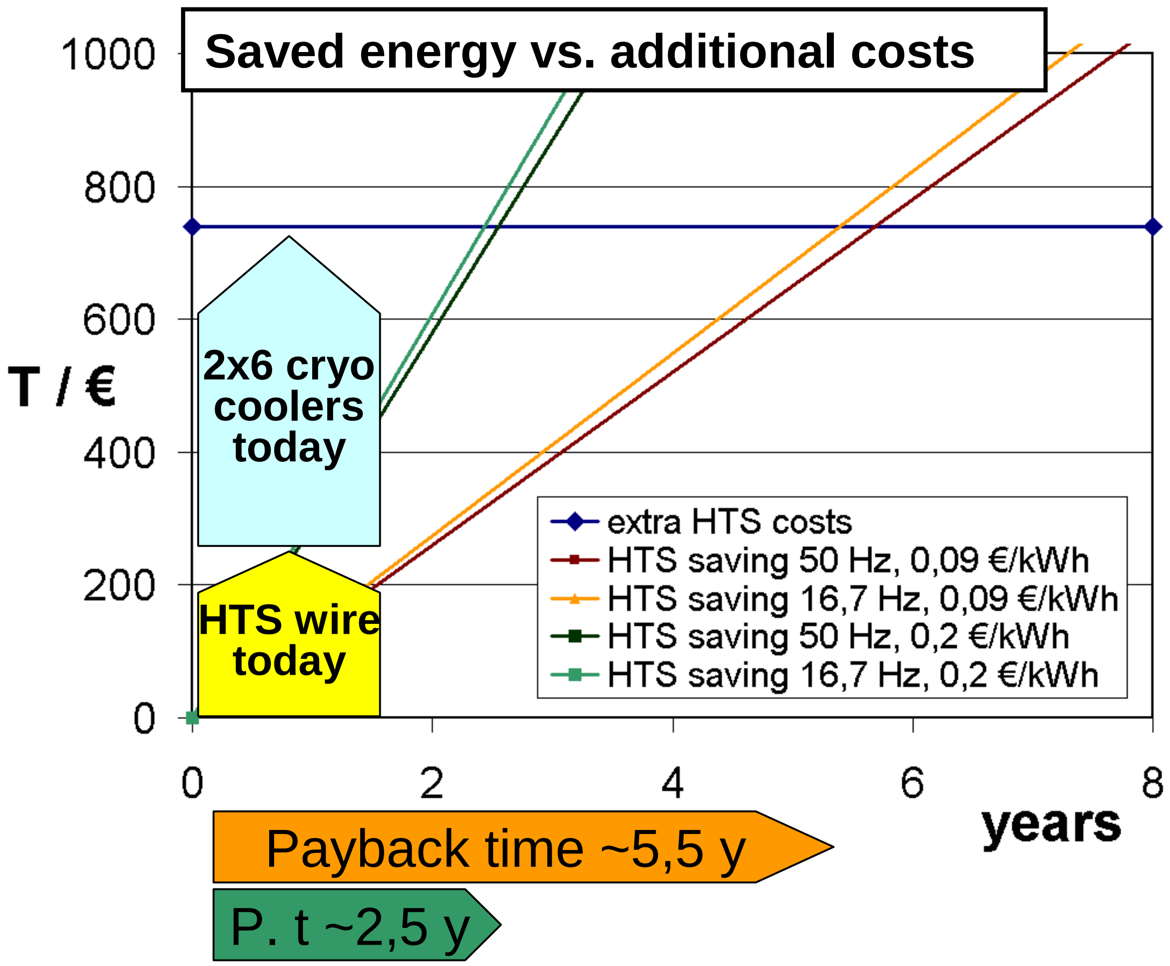
energy penalty by transformer weight
estimate 6,4 kWh/kg*yr.,
weight: Cu-oil 2x9,6 t,
weight: HTS 2x5,6 t

Annual savings by HTS-transformer in ICE3

- 600.000 km/year, typical drive cycles

Drive cycle	Paris - Sarrebruck 25 kV/50 Hz		Cologne - Francfort 15 kV/16.7 Hz	
2 transformers	convent.	HTS	convent.	HTS
Electrical loss/year	1650 MWh	250 MWh	1650 MWh	180 MWh
Weight penalty	120 MWh	70 MWh	120 MWh	70 MWh
Transformer consumption	1770 MWh	320 MWh	1770 MWh	250 MWh
Energy saved by HTS		1450 MWh		1520 MWh
Estimated savings/year per train at 9 ct/kWh**		**130 T€/y**		**137 T€/y**

Amortization of HTS-technology in ICE3



- **2 transformers per train 600.000 km/year**
- **Today's additional cost of HTS-technology is estimated ~740 T€/train**
- **Cost of future HTS technology will drop with growing markets**
- **Growing energy price reduces significantly the payback time**

Next Steps

- Data of HTS transformer as input into the global model.
- Market observation of the development of HTS conductors and suitable cooling systems.
- Further discussion on operational aspects of HTS traction transformer with operators.

Outlook

- HTS transformers can be built.
- HTS transformers will be economic viable by increasing energy prices in the next decades.

First 1MVA-HTS transformer at SIEMENS in 2001.
Function & low loss was demonstrated.

Thank you for your attention !!!!!!

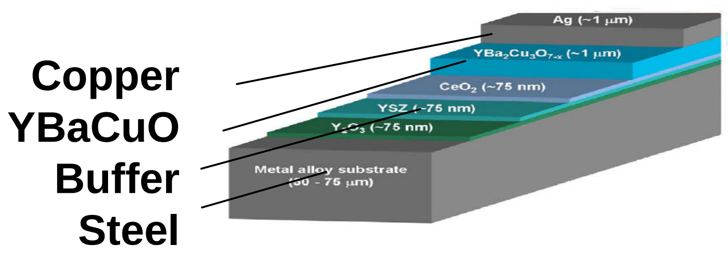
Questions ???

- Back-up

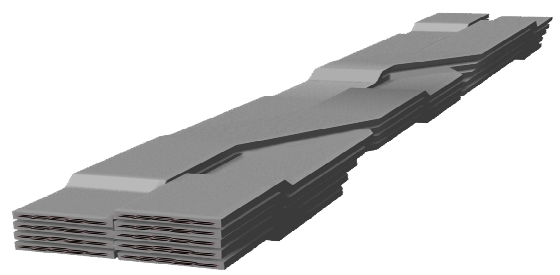
High Temperature Superconductor HTS

- New superconducting material class was detected 1987
- HTS wire has been developed, is commercially available
- Carries large currents ~30-100*jCu with zero DC-resistance
- AC-fields generate cold loss at ~77 K
- Know-how on loss mechanisms → dedicated winding design

2G_HTS: 1 µm-HTS film on support tape



High current Roebel conductor



1 MVA Transformer

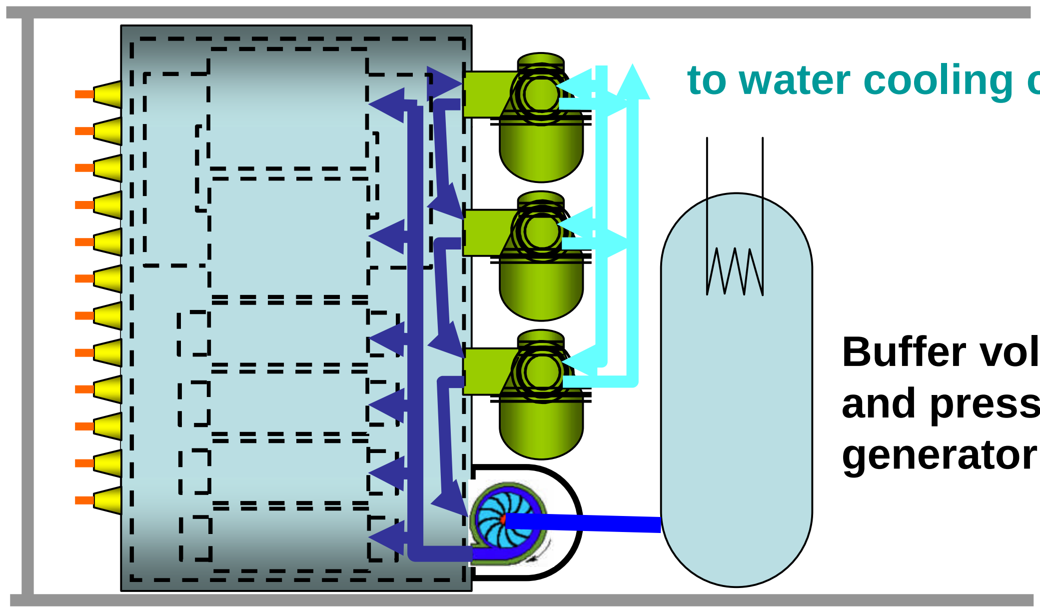
First HTS transformer at SIEMENS

Rated Power	1000 kVA
Frequency	50 Hz
Voltage	25 kV / 1.4 kV
Short Circuit Voltage	25 %
Temperature	65 K = -208°C
Cold loss at 65 K	2700 W
Stirling cryocooler power	~30 kW
Efficiency	97,4%

Function & low loss was demonstrated

Near term cryotechnology

- **Under development:** **Stirling cryocooler „Sunmachine“**
  (a modification of domestic heat and power cogeneration unit)
  Expected: 3x900 W @ 75 K, 3x5 kW drive power
  weight ~700 kg, efficiency □99,6%



Operational aspects of HTS-traction transformers in ICE 3 / Cooling

Cooling

○ Closed cryogenic cooling system:	no LN2-supply in normal operation
○ Cooldown to 75 K by cryocooler:	~12 days*
○ Cooldown to 75 K from LN2-tank:	several h – 1 day
○ Train operation at loss of cooling:	~1,4 h at 4,6 MVA, ~3h at 2,3 MVA*
○ No catenary (LN2-pump by battery):	~9 h* until 77 K
○ Standby loss at RT (iron and leads)	16 kW @ 50 Hz, 22 kW @ 16,7 Hz
○ Service of GM-cryocoolers (today)	2 years or 6000 operating hours

* source: M. Meinert (Siemens), doctor thesis TU Darmstadt 2006

Operational aspects of HTS-traction transformers in ICE 3 / Inrush current

Inrush current (zero winding resistance!)

- some damping by nonlinear V-I-curve of HTS
- actively maintaining magnetization from the secondary*
- forced secondary short circuit to drive HTS resistive*

* source: M. Meinert (Siemens), doctor thesis TU Darmstadt 2006