High temperature superconducting transformers

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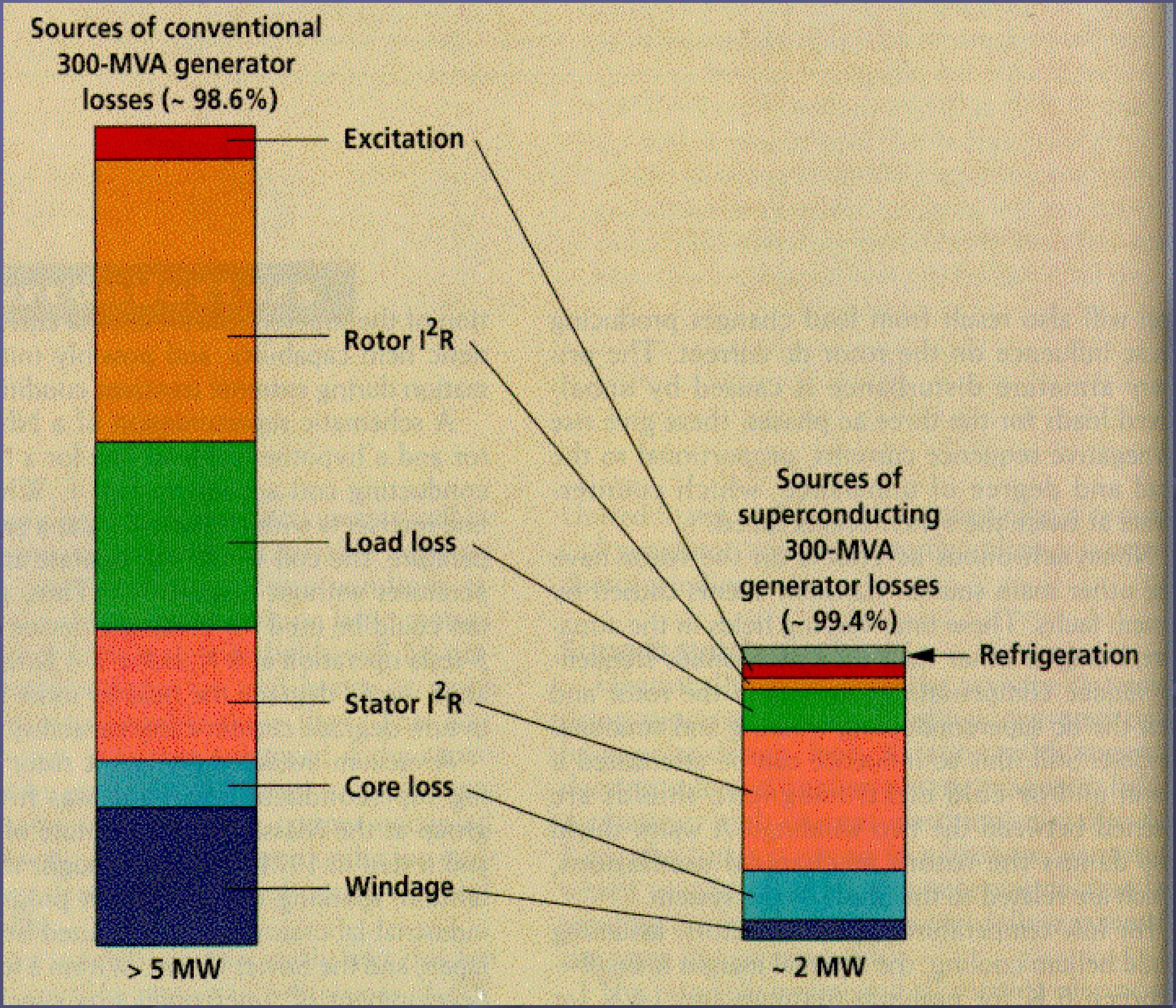
Superconducting power devices

Why ?

Superconducting power devices



Losses in conventional and superconducting designs

Superconducting power devices

Railway transformers

superconducting

conventional

and

- smaller size
- reduced weight

Superconducting power devices

LTS (Low Temperature Superconductivity) has not been successful in electric power applications

- low reliability
- high cost
- difficult technology

Impact of HTS (High Temperature Superconductivity)

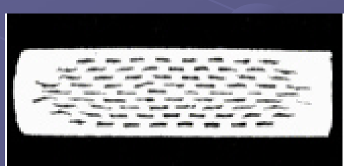
- better thermal stability
- cheaper cooling
- improved reliability

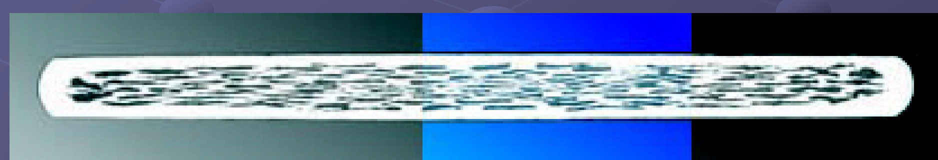
Applications of HTS
(High Temperature Superconductivity)

- ceramic materials discovered in 1986
- conductivity 10^6 better than copper
- operate at liquid nitrogen temperature (78K)
- cheap technology (often compared to water cooling)
- current density 10 times larger than in copper windings
- great potential in electric power applications (generators, motors, fault current limiters, transformers, flywheels, cables, etc.), as losses and/or size are significantly reduced
- present a modelling challenge because of very highly non-linear characteristics and anisotropic properties of materials, and due to unconventional designs

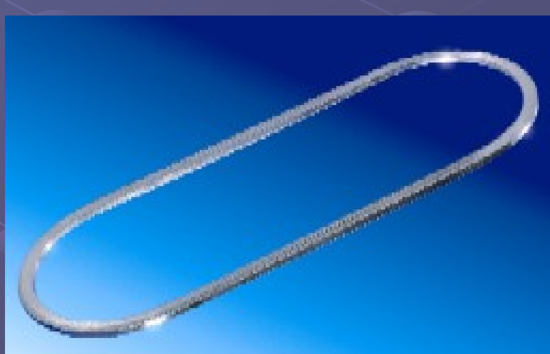
Common HTS materials:

Yttrium compounds (YBCO)		
$Y_1Ba_2Cu_3O_{7-x}$	(123)	T_c = 92 K
$Y_2Ba_4Cu_7O_{15-y}$	(247)	T_c = 95 K
Bismuth compounds (BISCCO)		
$Bi_2Sr_2Ca_1Cu_2O_y$	(2212)	T_c = 80 K
$Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_y$	(2223)	T_c = 110 K
Thallium compounds		
$(TlPb)_1Sr_2Ca_2Cu_3O_9$	(1223)	T_c = 120 K
$Tl_2Ba_2Ca_2Cu_3O_{10}$	(2223)	T_c = 125 K
Mercury compounds		
$Hg_1Ba_2Ca_2Cu_3O_{10}$	(1223)	T_c = 153 K



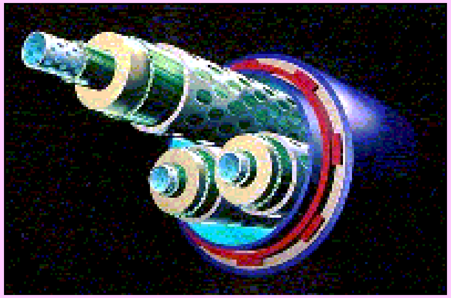


Multi-filament HTS tapes



HTS coils

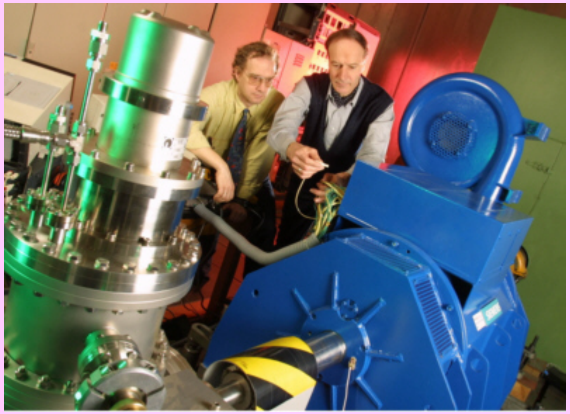
Applications of High Temperature Superconductivity (HTS)



Concept and realization of a three-phase HTS power cable

40kW 3000 rpm reluctance motor with YBCO bulk parts in the rotor

BSCCO HTS magnet for whole body open MRI



400 kW HTS synchronous motor

HTS fault current limiter based on melt-cast BSSCO

Superconducting power devices

All conceptual HTS designs and small demonstartors use BSCCO tapes at temperatures between 20K and 30K

- at 30K critical fields and currents order of magnitude better than at 78K
- it is possible to have a core-less design

But !!!

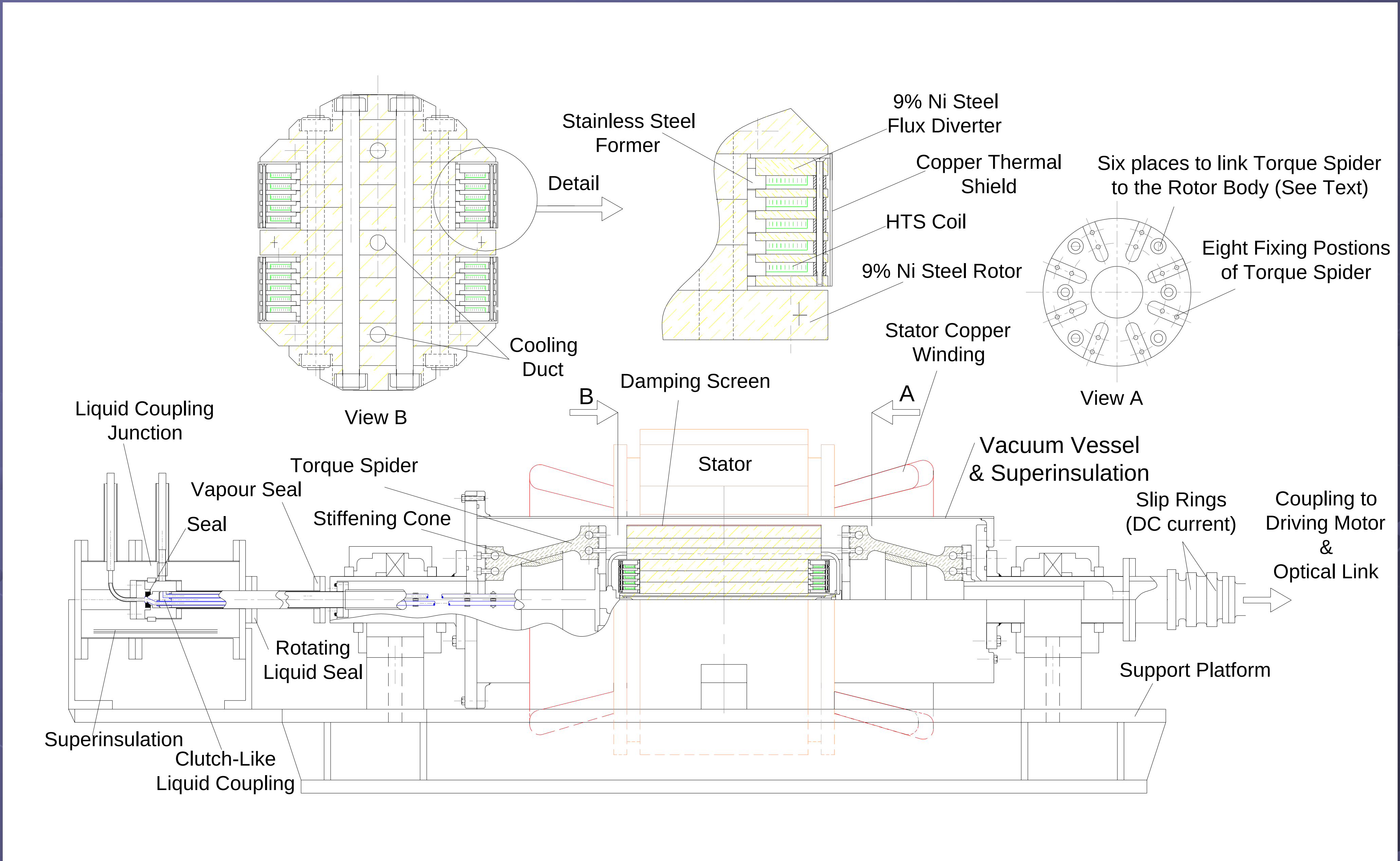
- liquid neon or helium gas needed
- increased cost and complexity of refrigeration plant
- reduced thermodynamic efficiency
- worse reliability and higher maintenance requirements

Superconducting generators and motors

Synchronous generator at Southampton

- 100 kVA, 2 pole
- cooling at 78 / 81 / 65 / 57 K
  (liquid nitrogen or air / sub-cooled nitrogen or air)
- magnetic core rotor design
  - reduces the ampere-turns required by a factor of ten
  - significantly reduces fields in the coils
- rotor made of cryogenic steel (9%)
- 10 identical pancake coils made of BSCCO
  (Ag clad Bi-2223), length of wire approx 10 x 40m

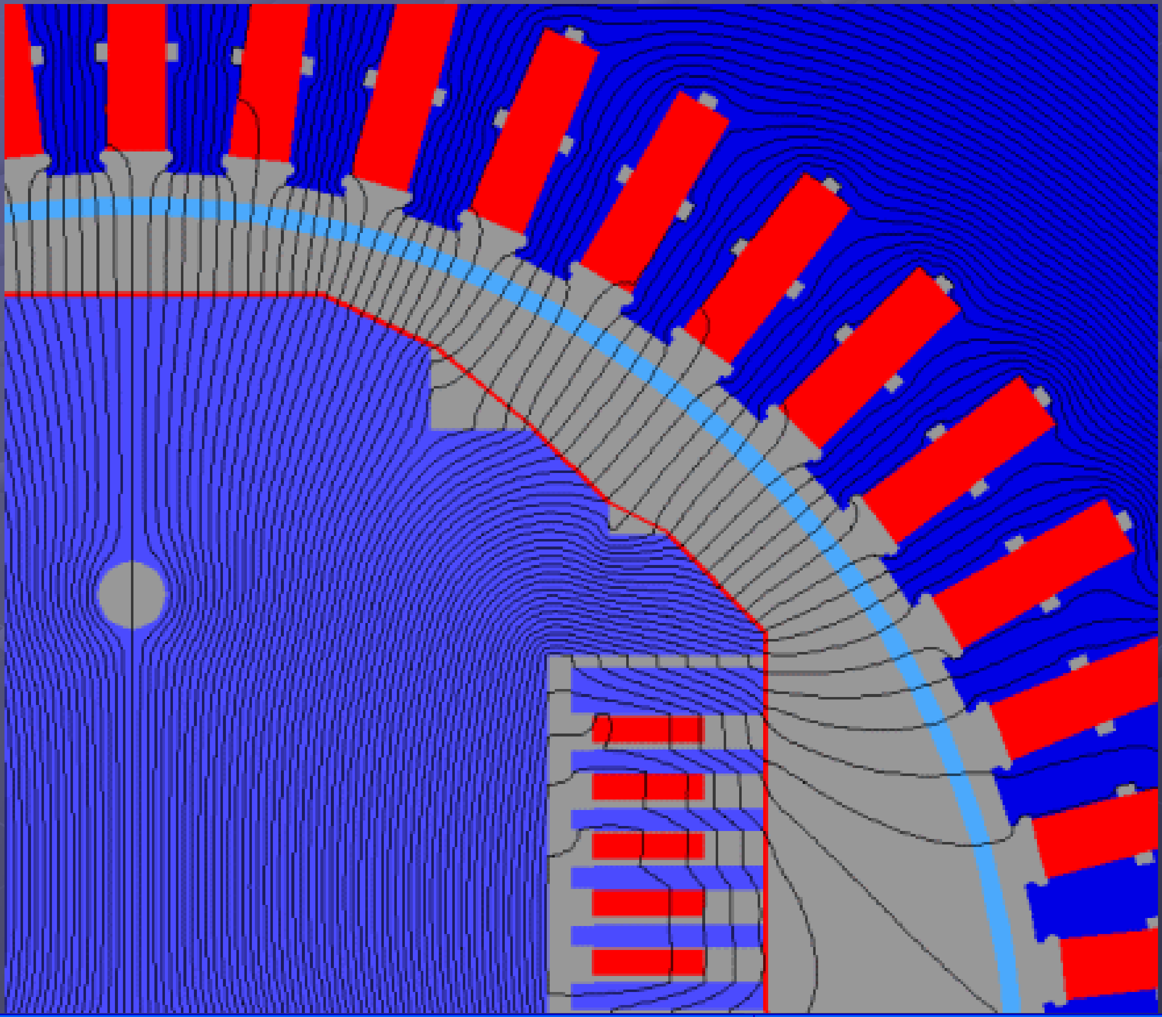
Southampton 100kVA HTS generator



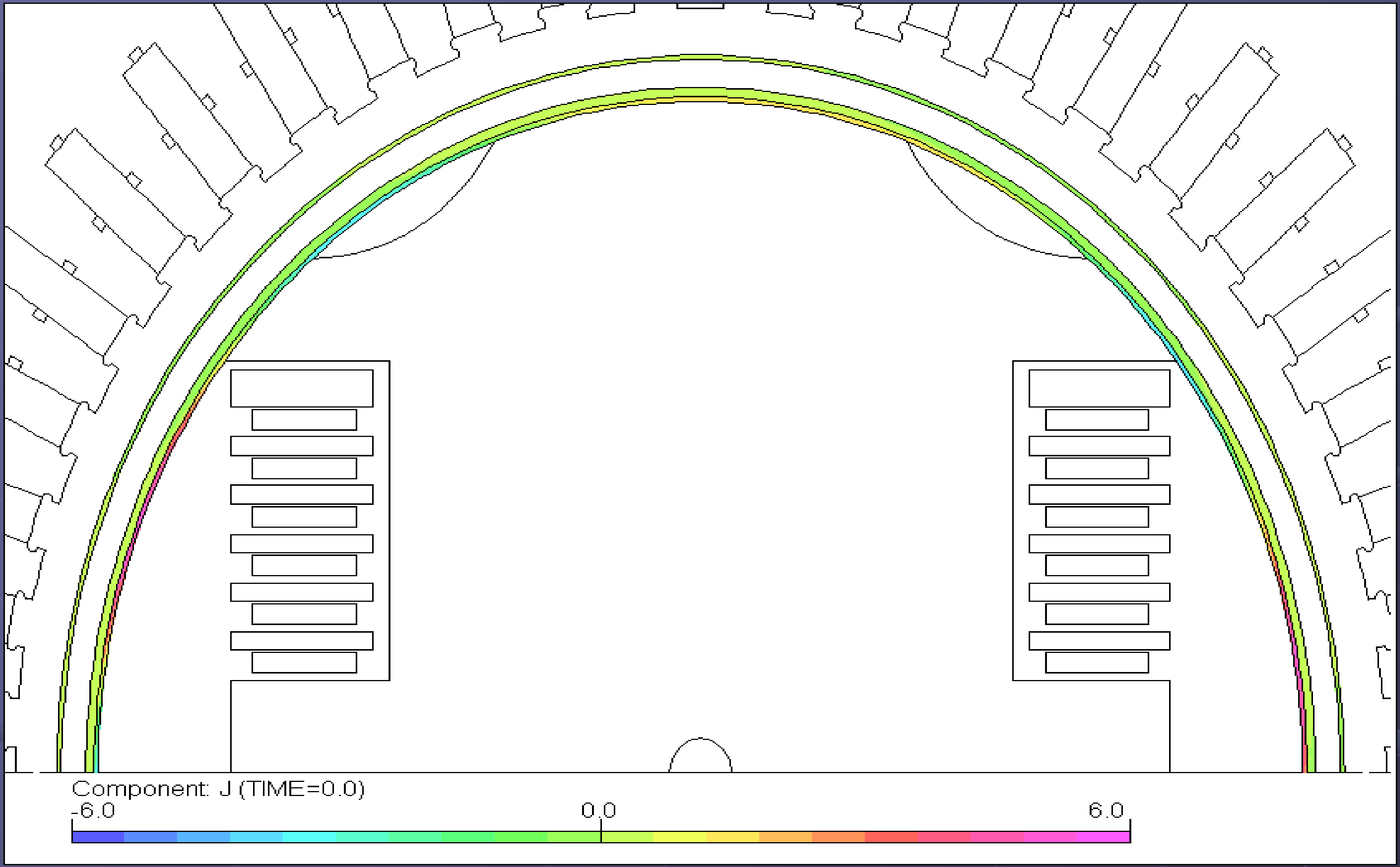
Modelling of Eddy-Current Loss

No-load losses

- Eddy currents occur as 48th time harmonic
- Transient losses were estimated and subtracted
- Total no-load loss found to be **0.264 W**



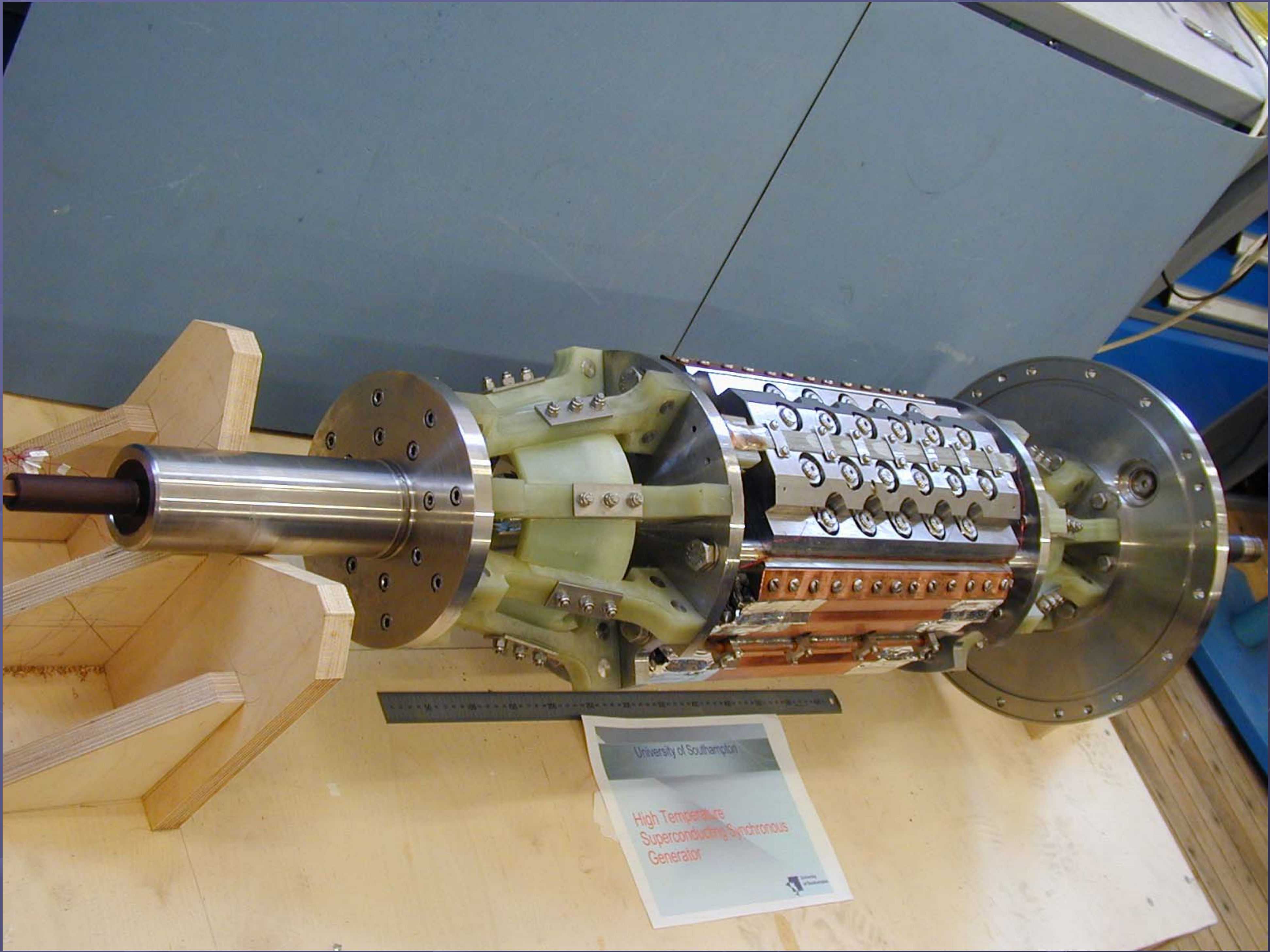
Modelling of full-load losses



Eddy currents due to MMF harmonics

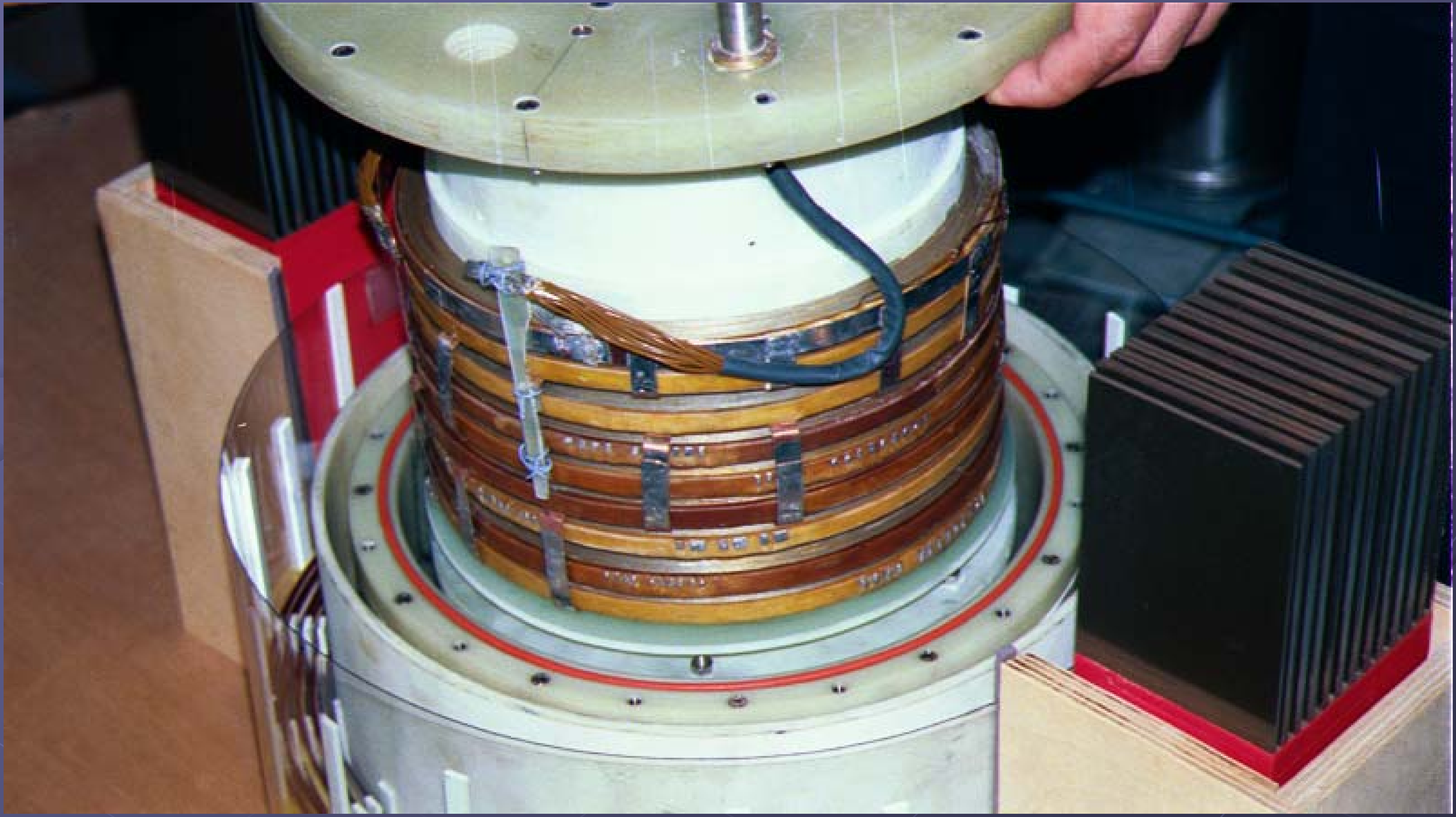
Summary of eddy current losses

- No-load losses: 0.264 W
- Full-load losses: 2.319 W
- These losses are released at liquid nitrogen temperature and have to be removed using the inefficient refrigeration system
- Each 1W of loss to be removed requires between 15 – 25 W of installed refrigeration power at 78K (a similar figure at 4K would be about 1000 W)


University of Southampton
High Temperature
Superconducting Synchronous
Generator

Superconducting generator testing

HTS transformer
built and tested at Southampton 1998/99



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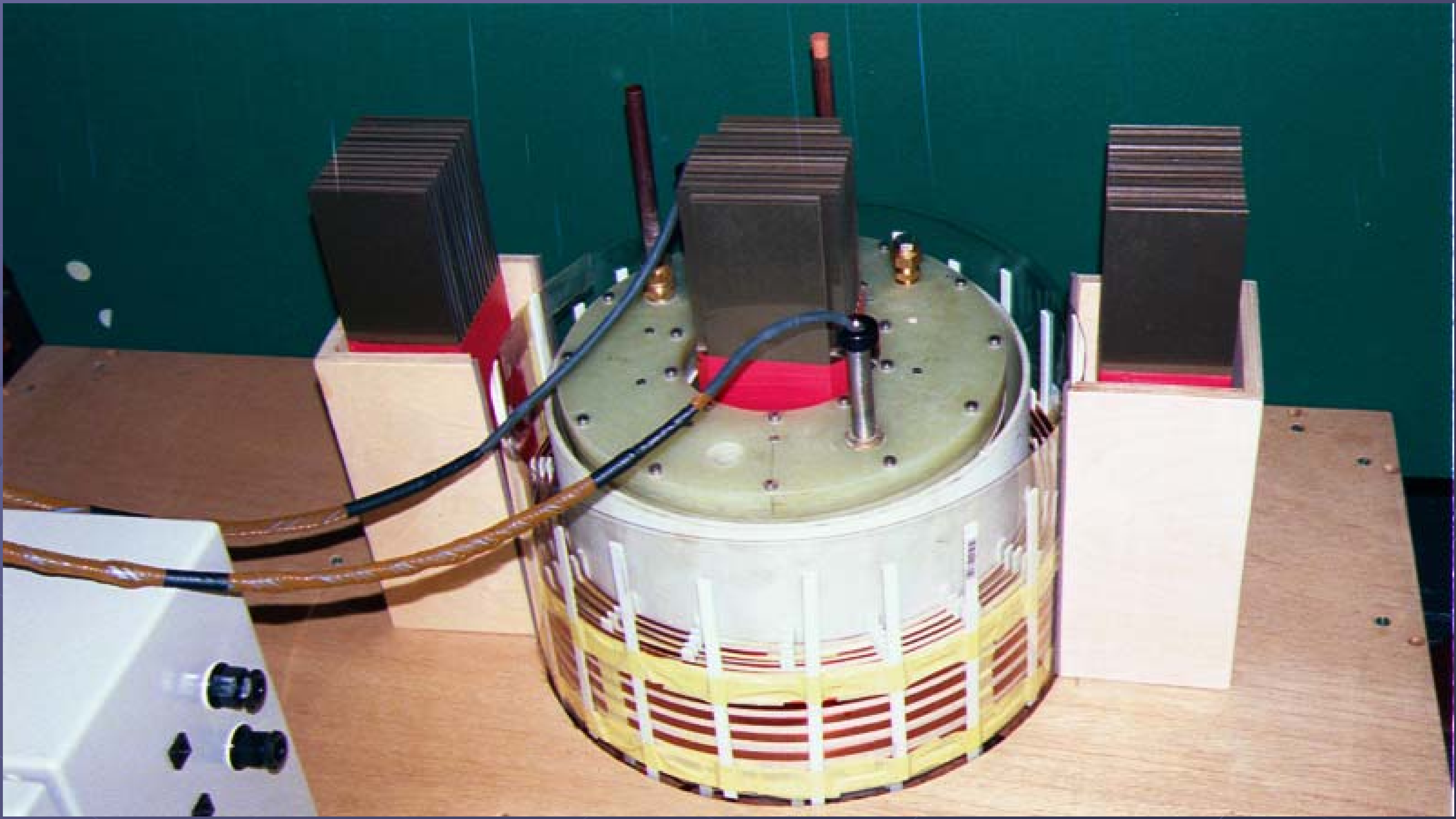

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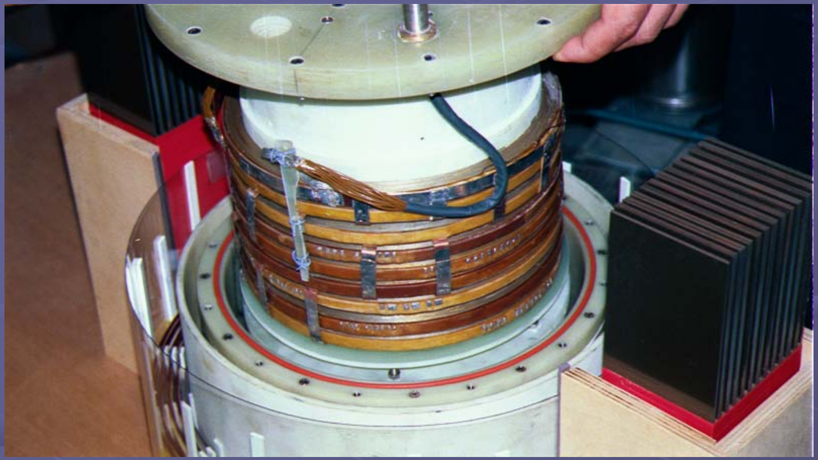

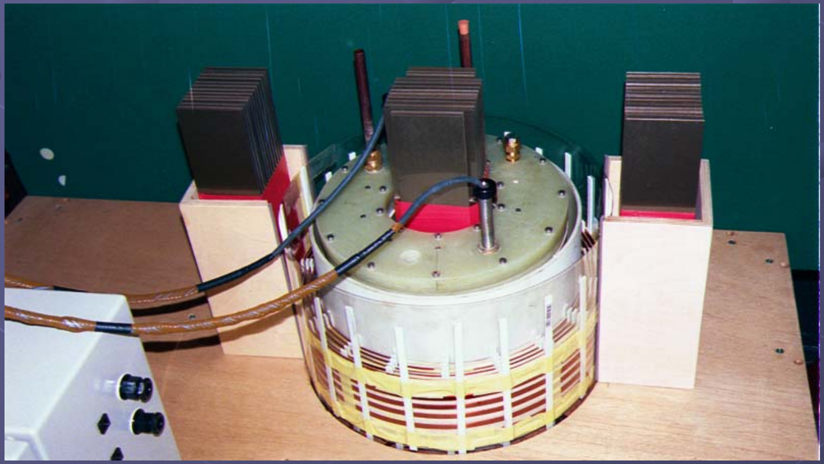

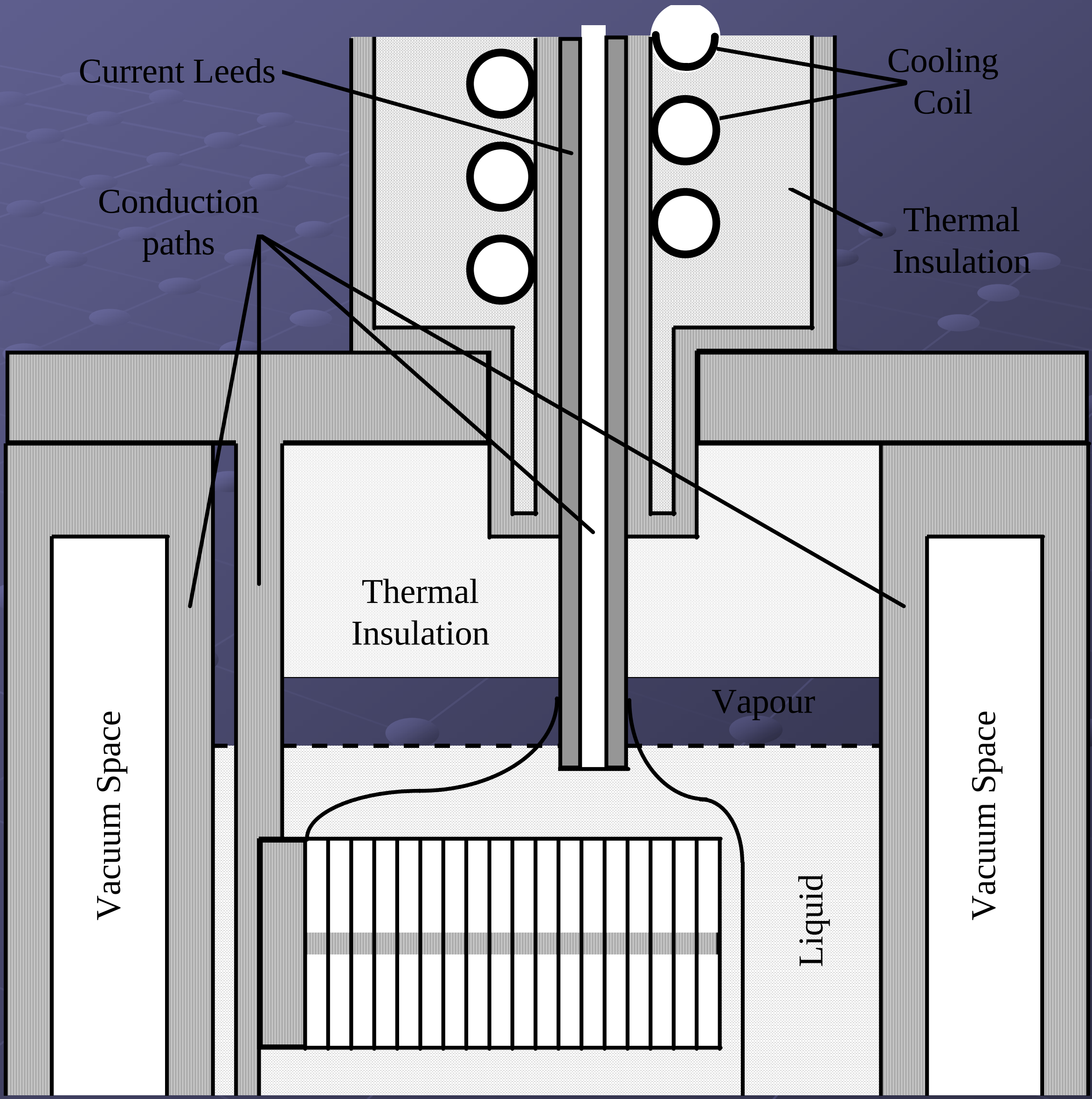

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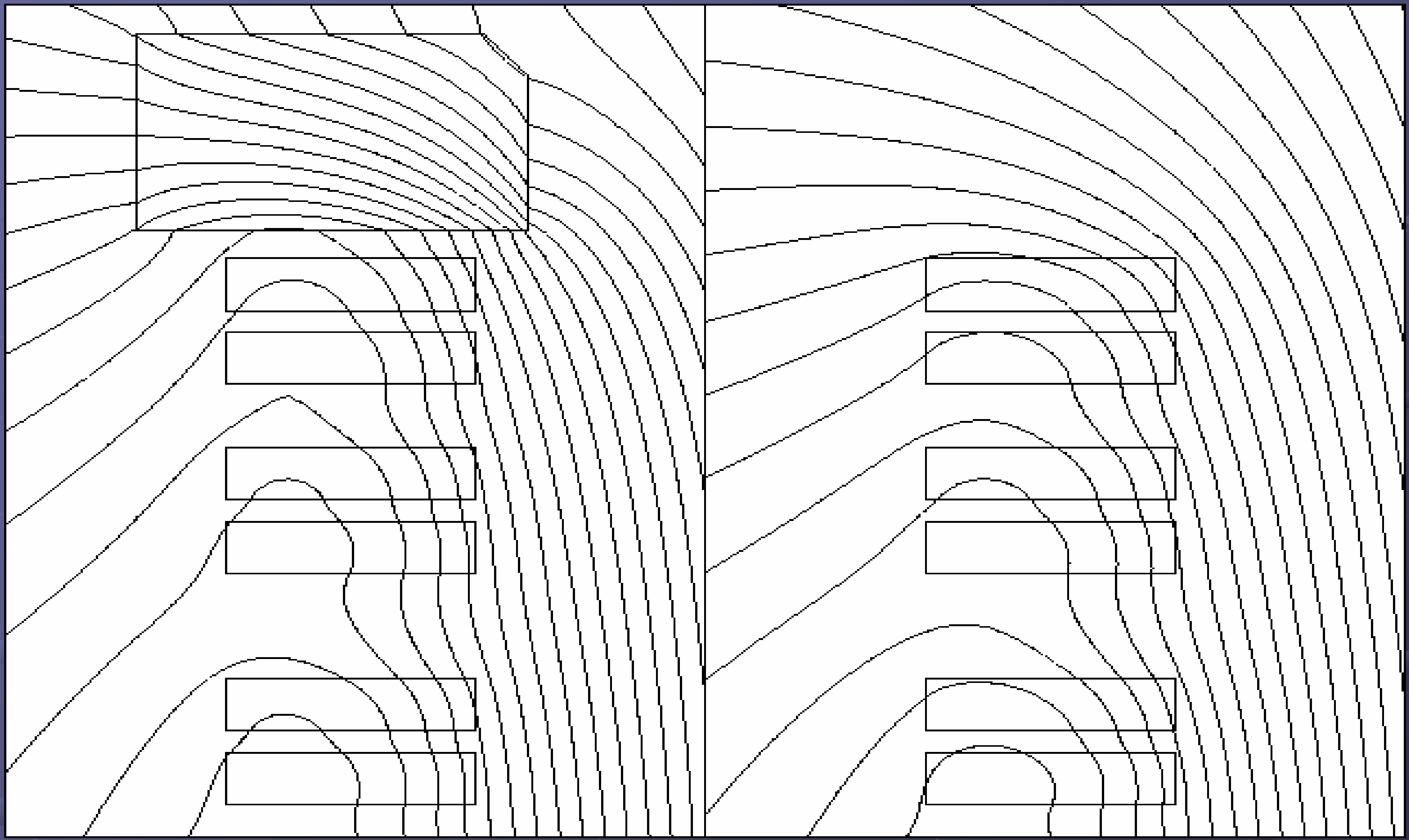

Field plots with and without flux diverters

HTS transformer
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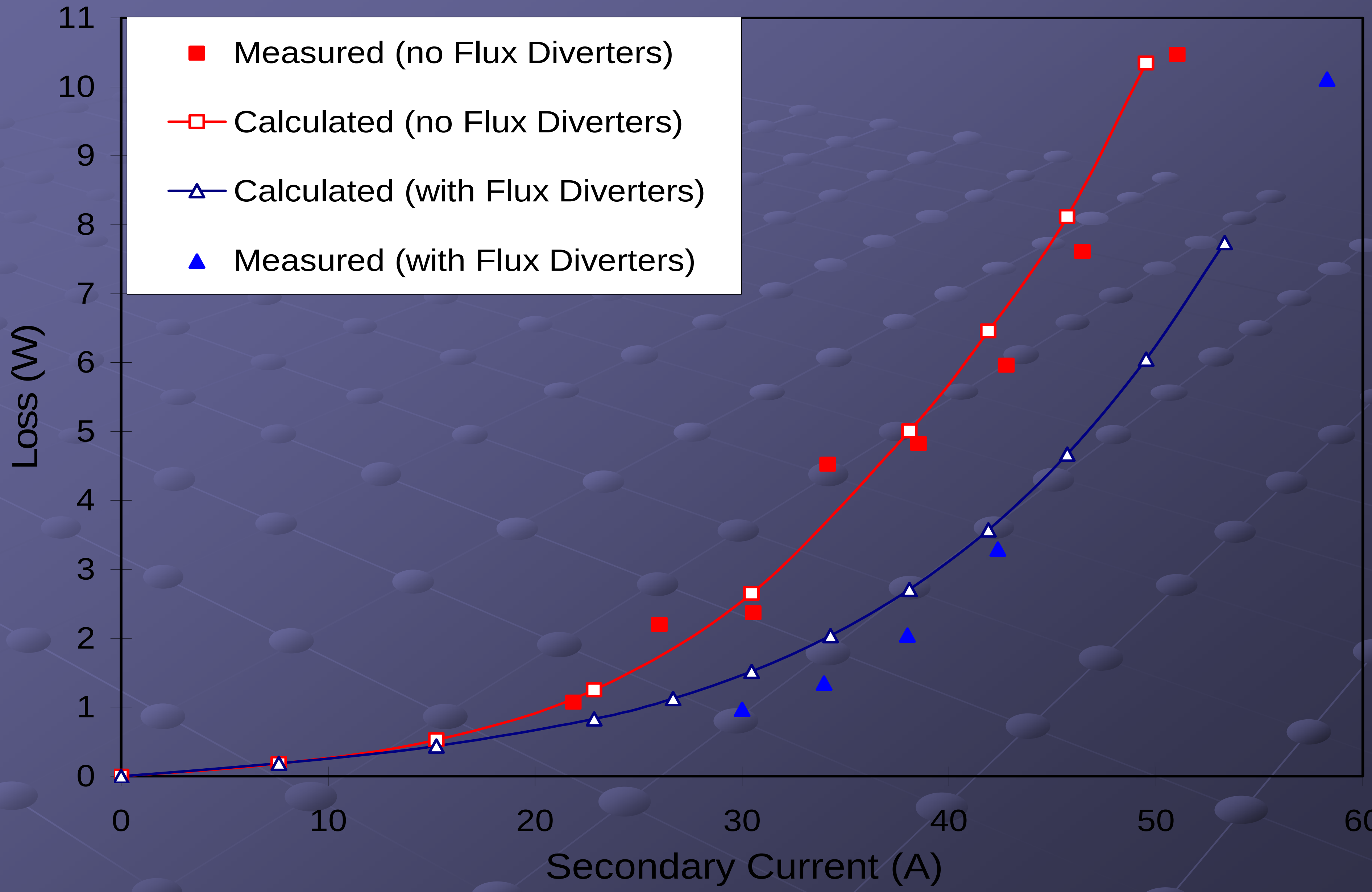

Design feasibility study for a 240MVA HTS grid auto-transformer

Principal parameters:

kVA:	240,000
Normal Volts:	400/132 kV
Tappings:	132 kV + 15% - 5% in 14 steps
Line current:	346/1054 A
Diagram No:	Yy0 Auto
Reactance:	20%

Rated current densities:

series winding* = 39.1 A/mm^2

common winding* = 36.9 A/mm^2

tap winding = 3.0 A/mm^2 (conventional)

(average over composite conductor section, comprising both superconducting and matrix materials).*

Design feasibility study for a 240MVA HTS grid auto-transformer

Loss analysis

	HTS	Conventional
Core loss	8	9
Clamp stray loss	5	5
Tank loss	-	7
Total copper loss	<1 (tap)	79
Refrigeration power	7	-
Gas-cooling fan loss	2	-
Estimated total loss	23	100 *

* Total loss of conventional design = 100%

Comparison of technical features ... 1

Parameter	HTS	Conventional
Core length *	88.5	100
height *	82.4	100
thickness *	100	100
Window, height * × width *	70 × 78.5	100 × 100
Core weight *	80	100
Winding weight *	6.3	100
Tap winding weight *	100	100
Cooling of core and tap winding	Forced N2 gas	ONAN/OFAF
Cooling of common and series winding	Liquid N2 (with refrigeration)	ONAN/OFAF

* shown as percentage of the appropriate value for a conventional transformer

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Comparison of technical features ... 2

Parameter	HTS	Conventional
Guaranteed % reactance B in core, T J rated, rms, A/mm^2	20 1.67 38	20 1.67 2.83
Rated loss, total *	23	100
Overload capability Through fault capability, pu (+ doublingh transient), recoveruy time without disconnection Survival time at 5 pu (+ doubling transient)	2 pu, many hours 2 pu, 64 ms 166 ms	1.3 pu, 6 hrs 1.5 pu, 30 min 5 pu, 3 s seconds (> 3)

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Design feasibility study for a 240MVA HTS grid auto-transformer

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Cost savings on continuous full load

Savings/expenditure	%
Saving on core plate	1
Saving on continuously transposed copper	7
Saving on copper losses, discount over 10 years	65
Cost of refrigeration plant	–21
First-cost equivalent expenditure on refrigeration drive power, discount over 10 years	–6
Cost of AC conductor, total of 7371 amp-kilometres	–10
Total equivalent first-cost saving	36

But !!!

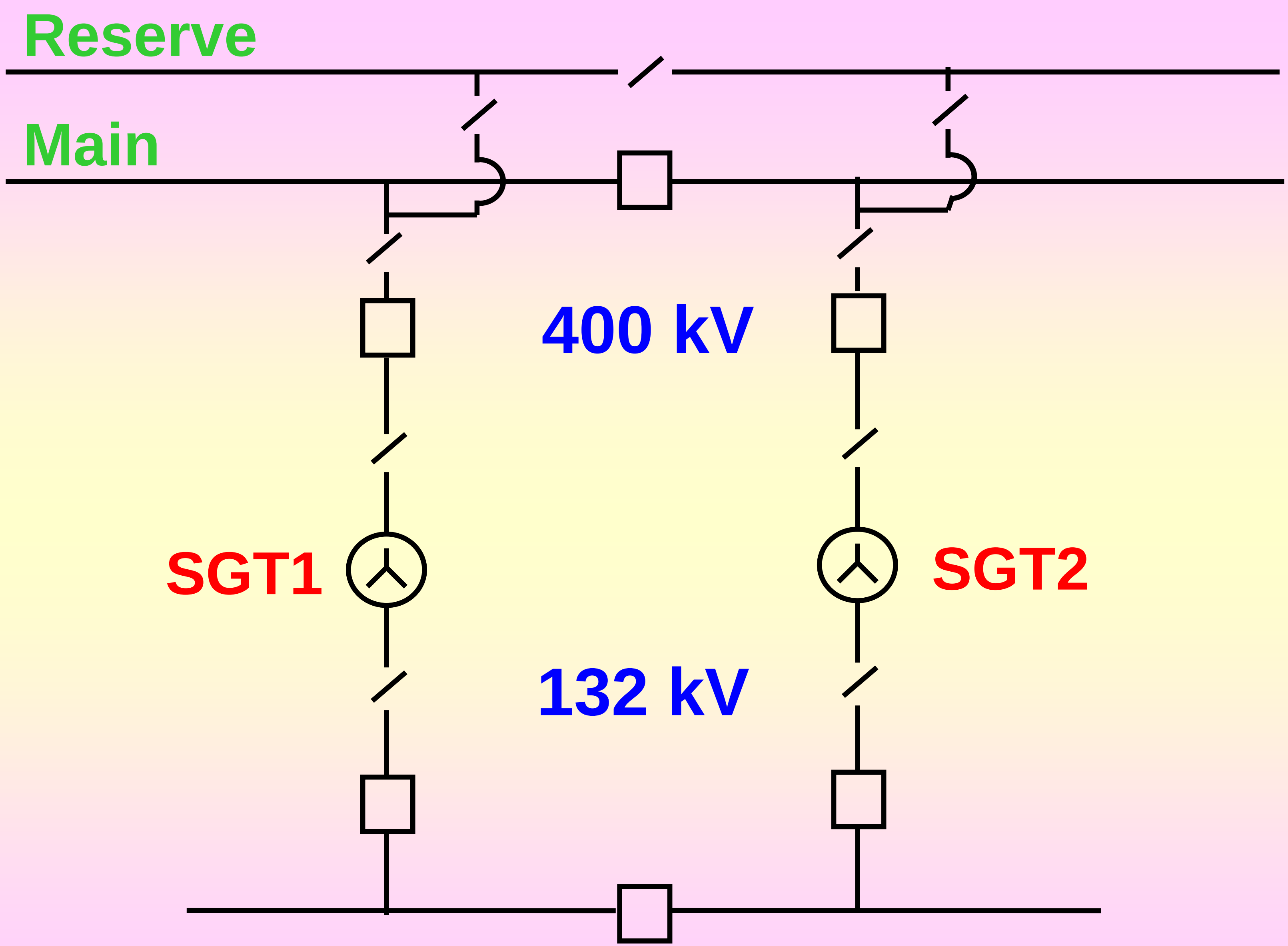
- The load factor for a grid transformer is very low,

  e.g. in the UK it is 0.23 average or 0.26 rms.

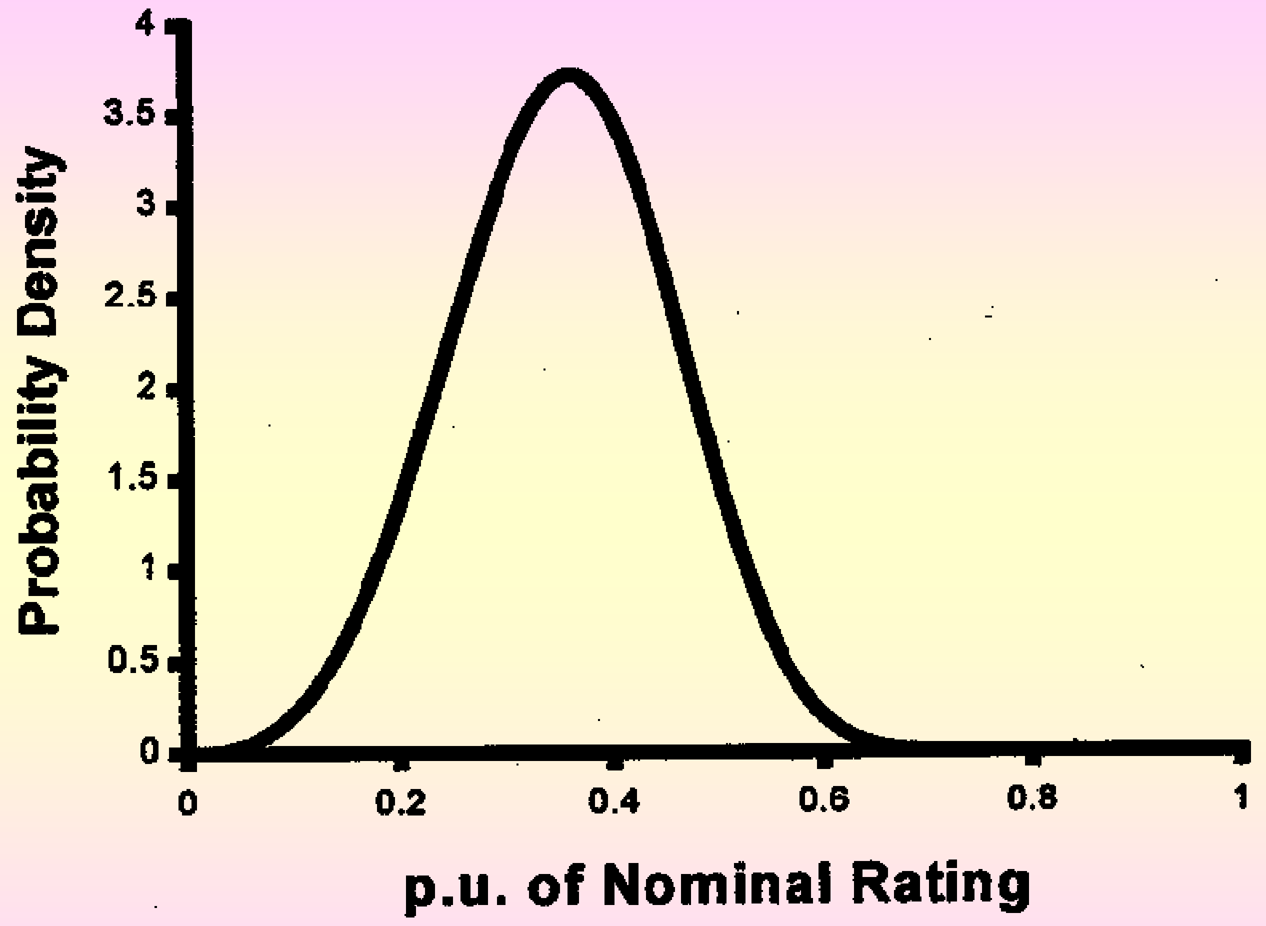
- Thus the savings may not actually happen !

However …

Parallel operation

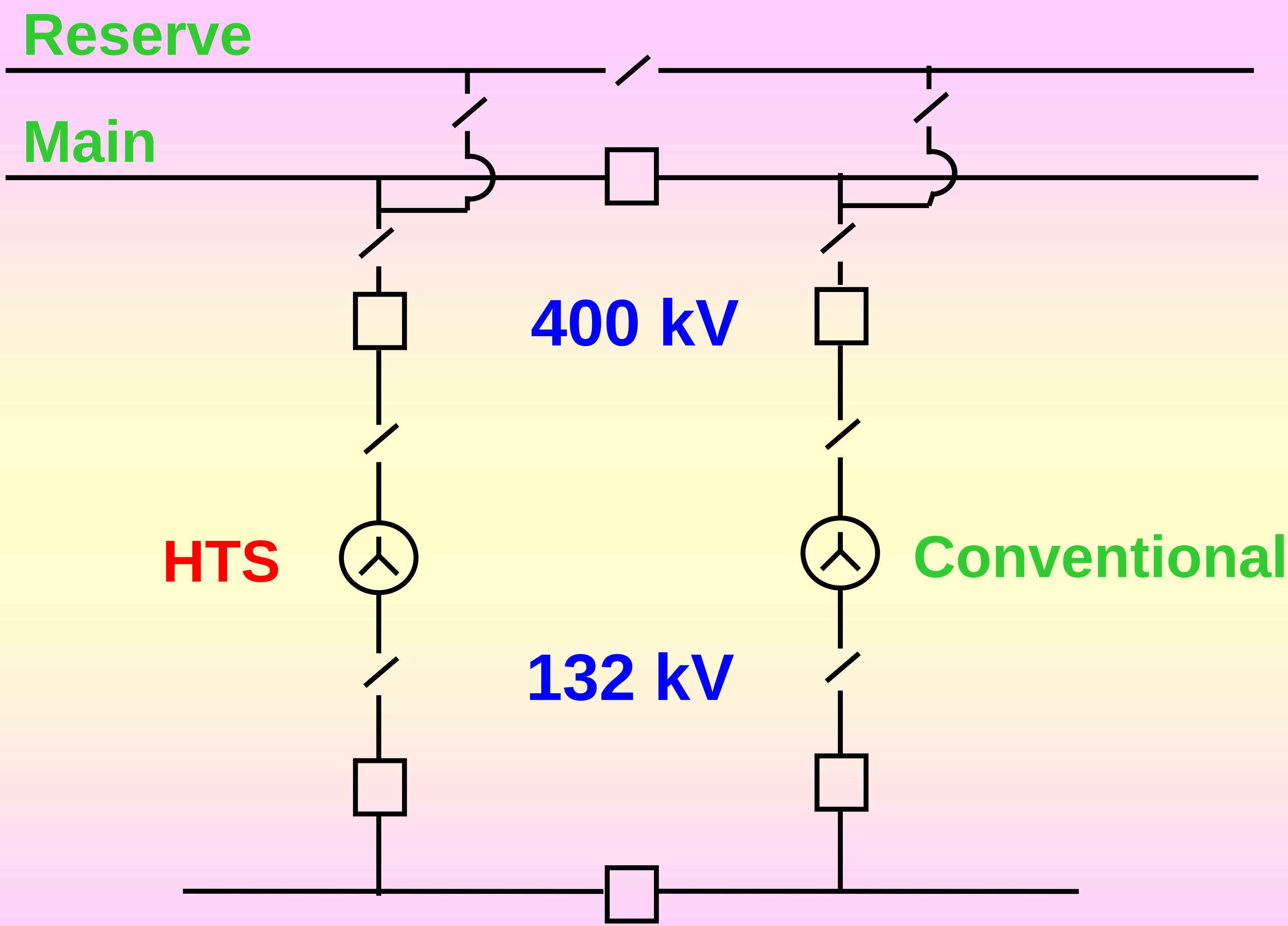


Parallel operation



Probability density of load for a typical grid transformer

Parallel operation



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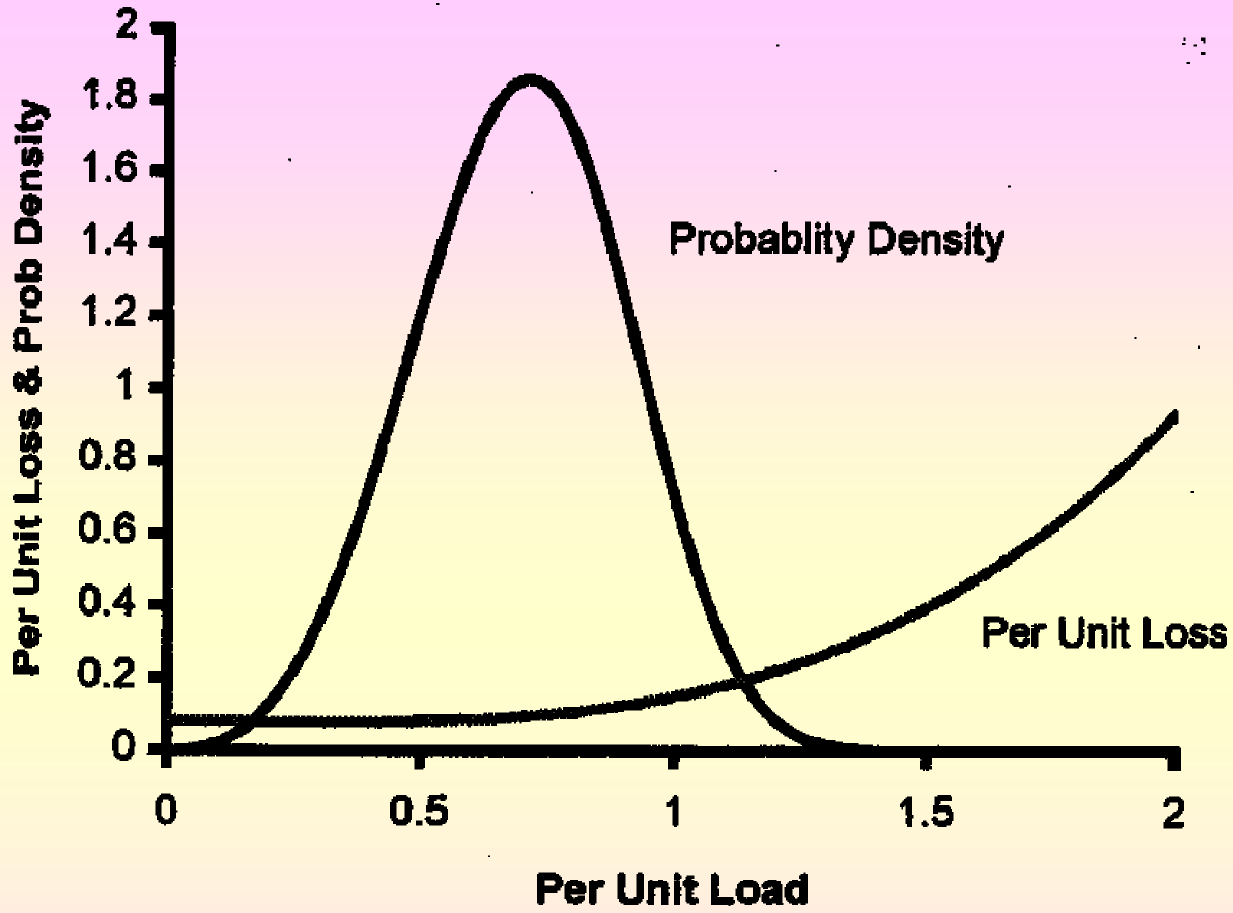

Load probability density and loss as a function of load for a HTS transformer in parallel with a (normally) unconnected conventional unit.

The mean load is around 0.7 p.u.

Parallel operation

Costs (£k)	Superconducting + conventional	2 × conventional
Transformer capital	1,000 + 1,230	2,000
Losses	0.105 × 600 × 3	0.426 × 600 × 3
Total	2,419	2,768

Cost analysis

Conclusions … 1

- Increasing activity around the world in HTS applications for power devices
- All existing demonstrators use HTS tapes at temperatures 20 to 30 K (helium or neon gas)
- Southampton designs for 78K
- Parameters of new tapes improved dramatically
- Ability to predict and reduce all ‘cold’ losses of paramount importance to show economic advantages of HTS designs

Conclusions … 2

- HTS power devices are

  technically viable

- HTS power devices may also be

  economically competitive


Thank you