ARWtr 2004
Advanced Research Workshop on Modern Transformers
28 - 30 October, Vigo – Spain

Superconducting transformers

Professor Jan Sykulski

MSc, PhD, CEng, FIEE, SMIEEE, FInstP, HonProf

Head of Electrical Power Engineering
School of Electronics & Computer Science
University of Southampton, UK

University of Southampton

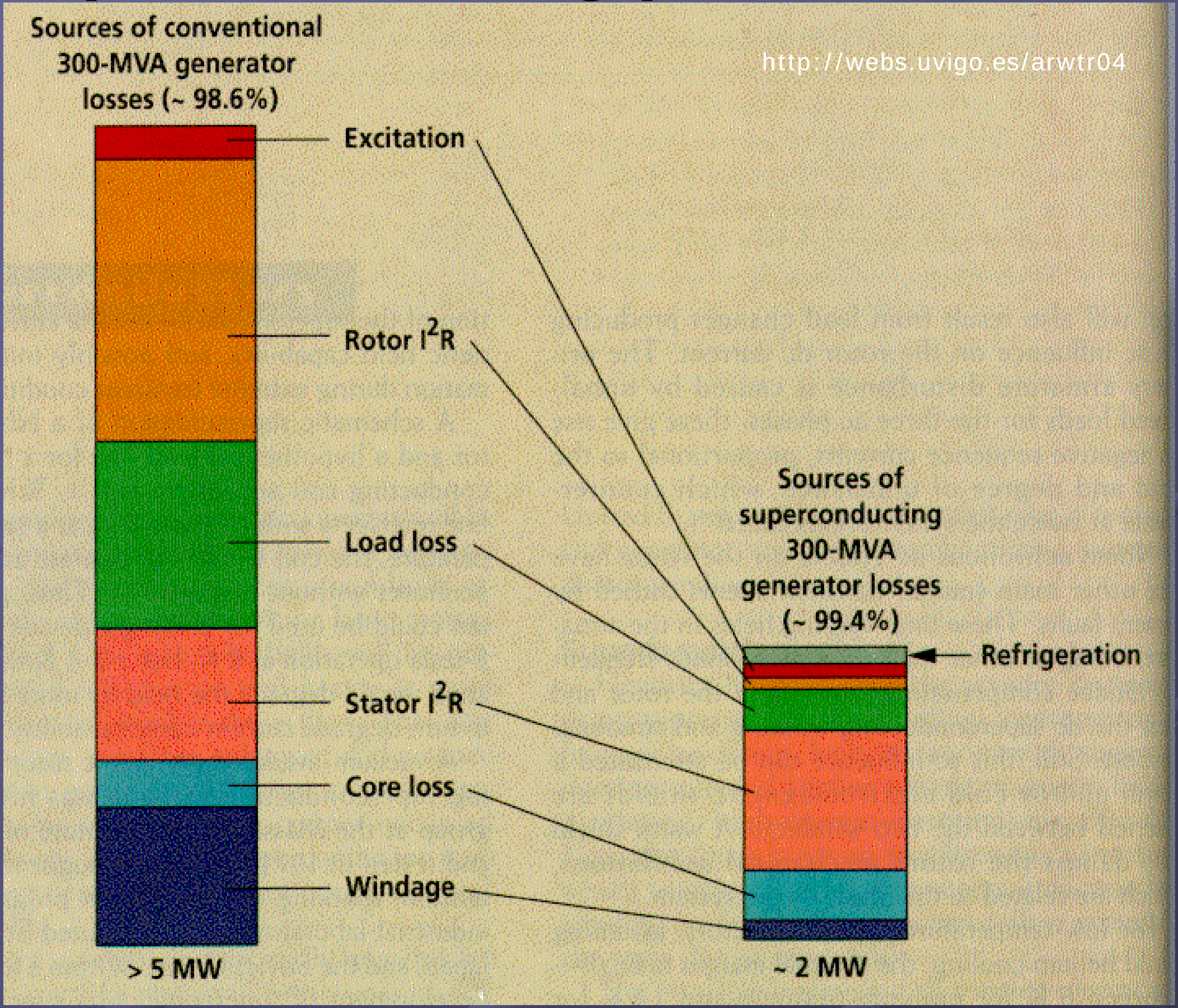
Electronics and Computer Science

ARWtr 2004 Modern Transformers 28 -30 October. Vigo – Spain http://webs.uvigo.es/arwtr04

Superconducting power devices

Why ?

Superconducting power devices



Losses in conventional and superconducting designs

Superconducting power devices

Railway transformers

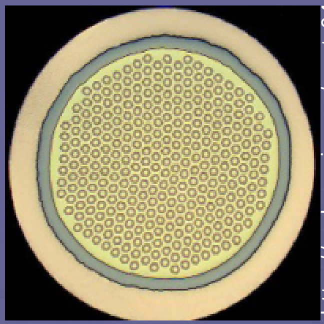
superconducting

conventional

and

- **smaller size**
- **reduced weight**

Applications of Low Temperature Superconductivity (LTS)



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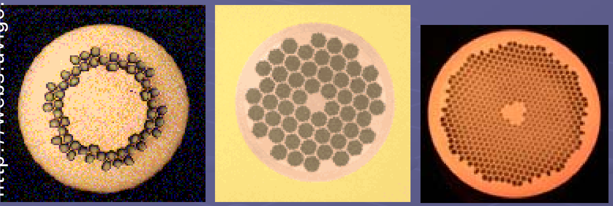
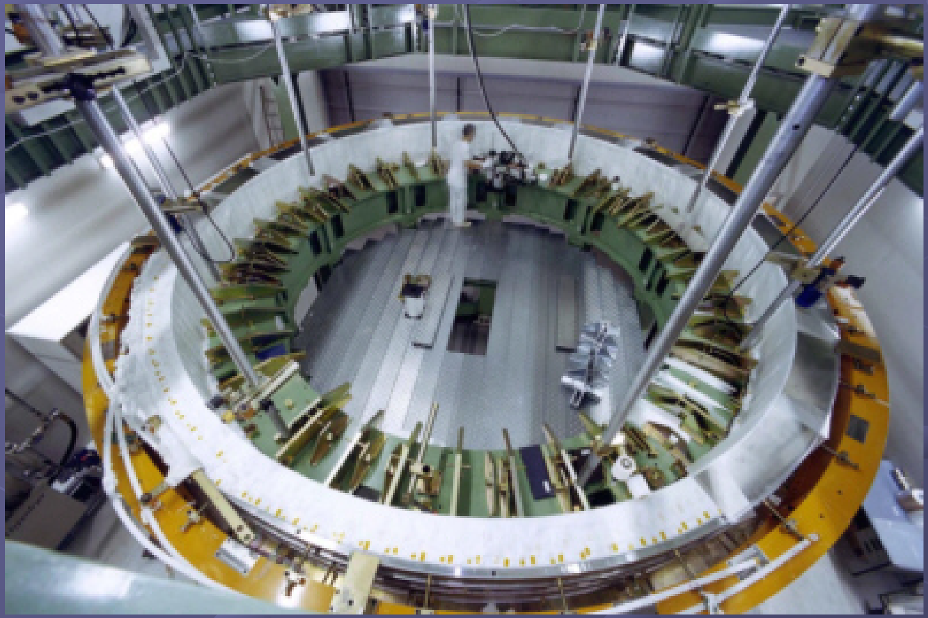
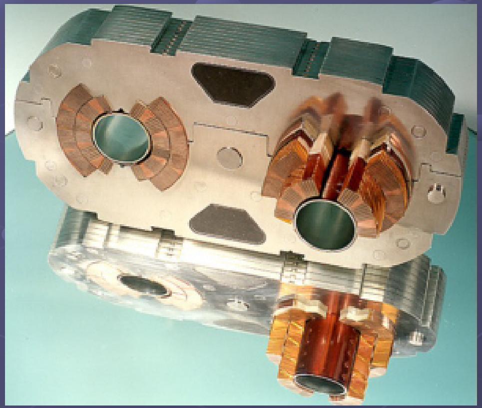
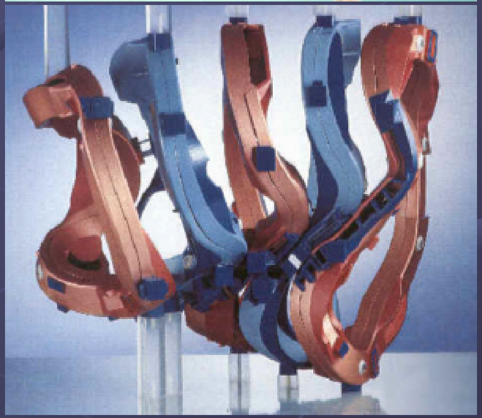


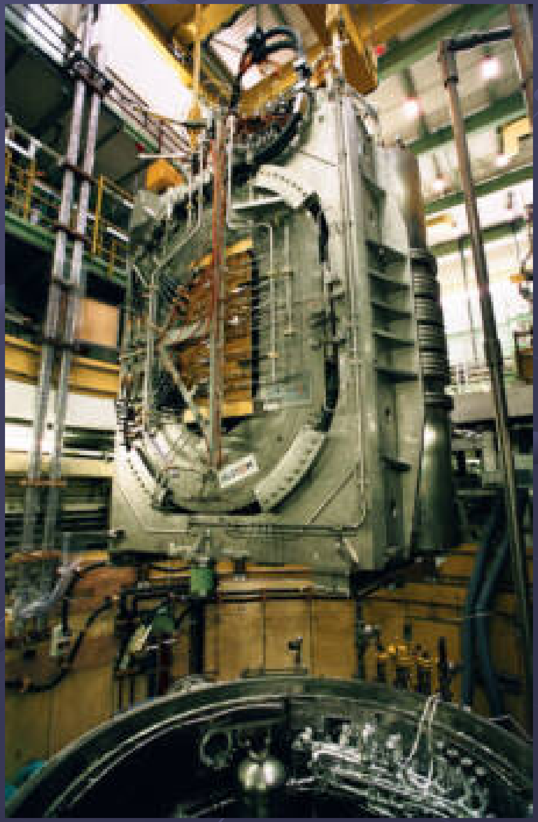
Examples of multi-filament LTS wires

Nearly all LTS applications utilize wires and cables based on NbTi, Nb3Sn or other A15 compounds.





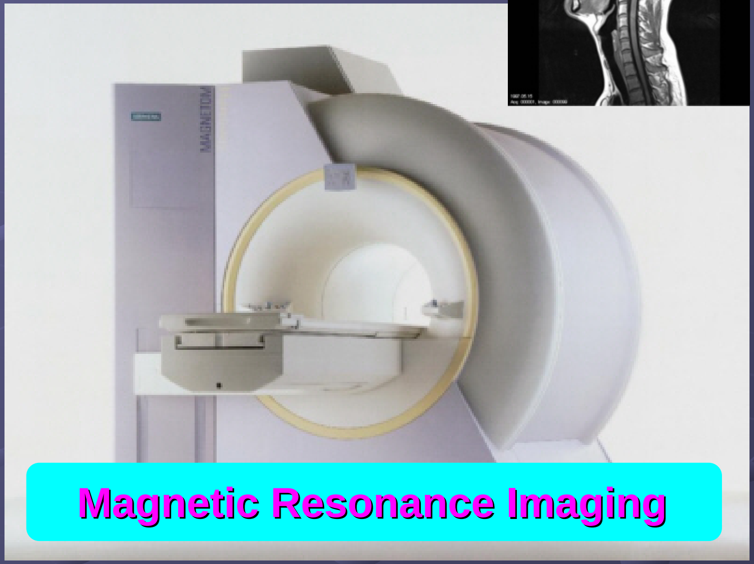




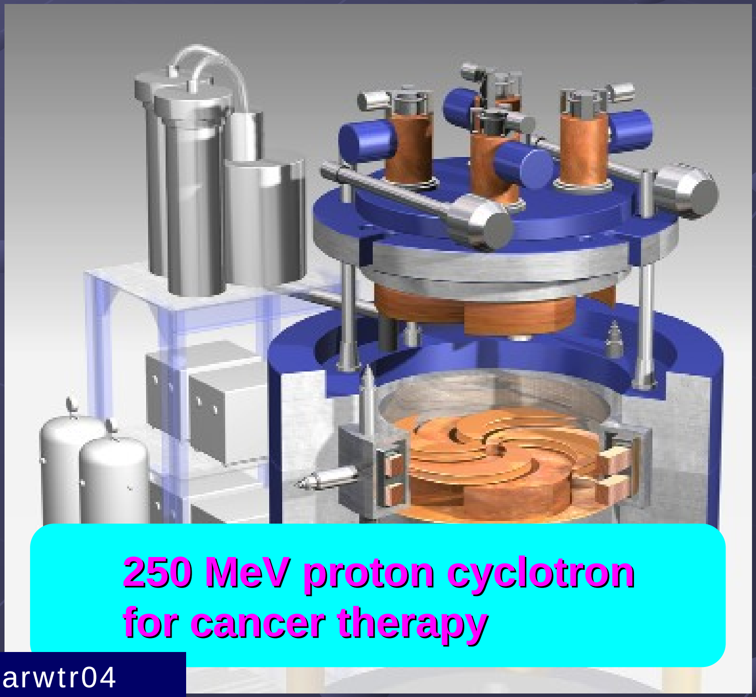
Examples for superconducting LTS coils of sometimes rather complex shape and significant size

Applications of Low Temperature Superconductivity (LTS)

900 MHz LTS superconducting Nuclear Magnetic Resonance Spectroscopy system for studies of various biological macromolecules at Yokohama City University



Magnetic Resonance Imaging



250 MeV proton cyclotron for cancer therapy

Applications of Low Temperature Superconductivity (LTS)

Superconducting cavities for accelerators:

cleanroom manufacture and assembled module for CERN / LEP

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**

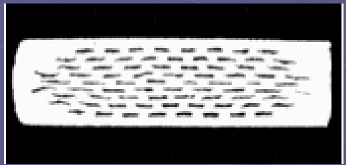
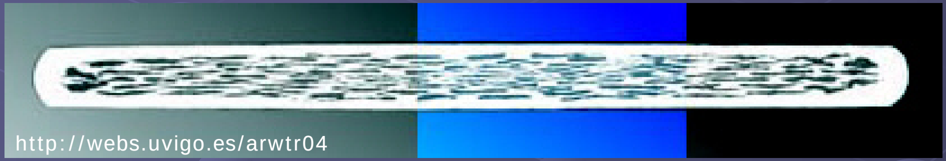
Applications of HTS

(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:

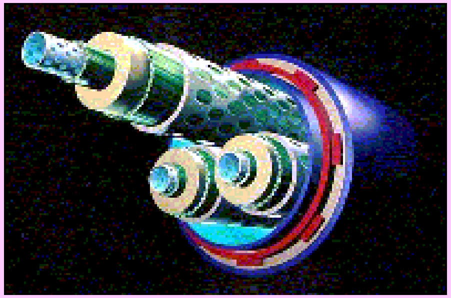
Yttrium compounds (YBCO)		
$Y_1Ba_2Cu_3O_{7-x}$	(123)	T_c = 92 K
$Y_2Ba_4Cu_7O_{15-y}$	(247)	T_c = 95 K
Bismuth compounds (BISCCO)		
$Bi_2Sr_2Ca_1Cu_2O_y$	(2212)	T_c = 80 K
$Bi_{2-x}Pb_xSr_2Ca_2Cu_3O_y$	(2223)	T_c = 110 K
Thallium compounds		
$(TlPb)_1Sr_2Ca_2Cu_3O_9$	(1223)	T_c = 120 K
$Tl_2Ba_2Ca_2Cu_3O_{10}$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

Multi-filament HTS tapes


HTS coils

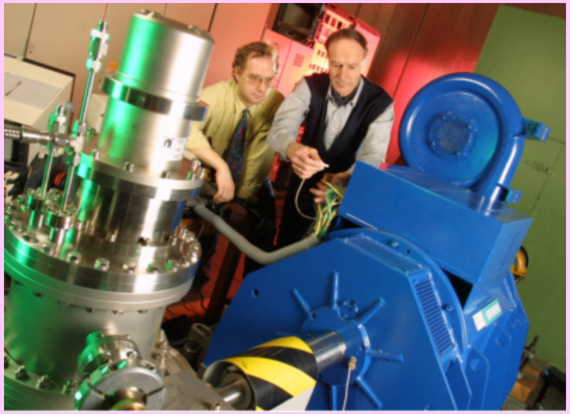
Applications of Low Temperature Superconductivity (LTS)



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**

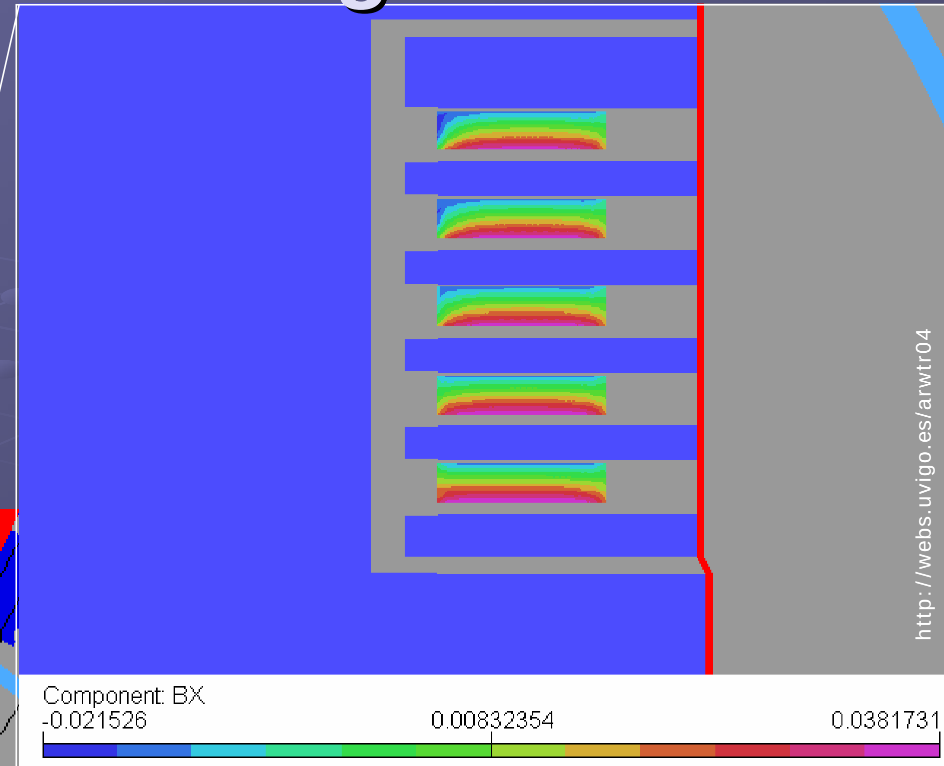
Superconducting generators and motors

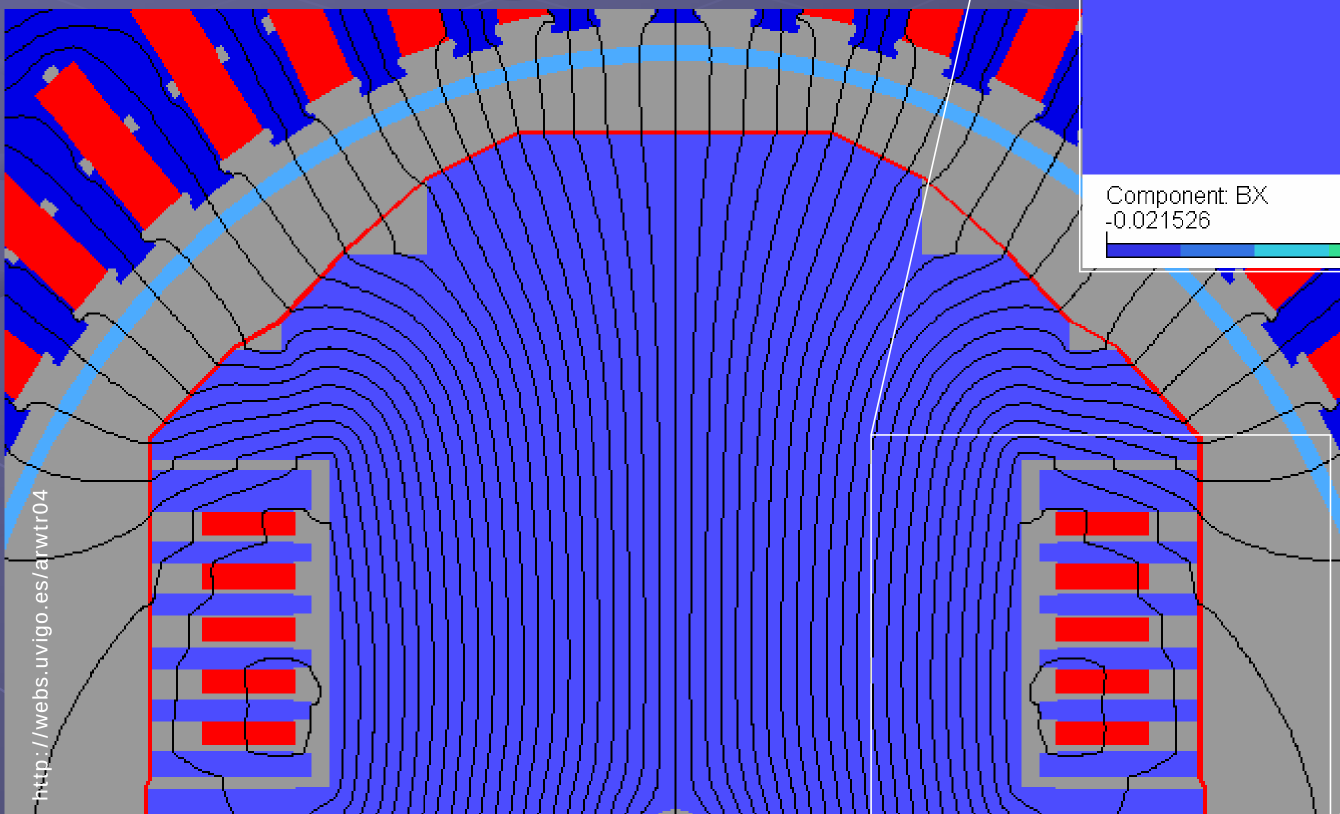
Southampton design

- 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

- The distribution of the normal field in the HTS coils and the flux potential plot. The flux diverters successfully reduced the normal field to only 0.038T with the air-gap flux at 0.66T.

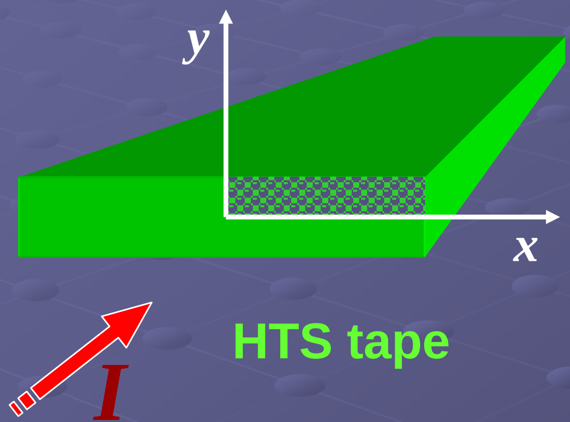




Summary of eddy current losses

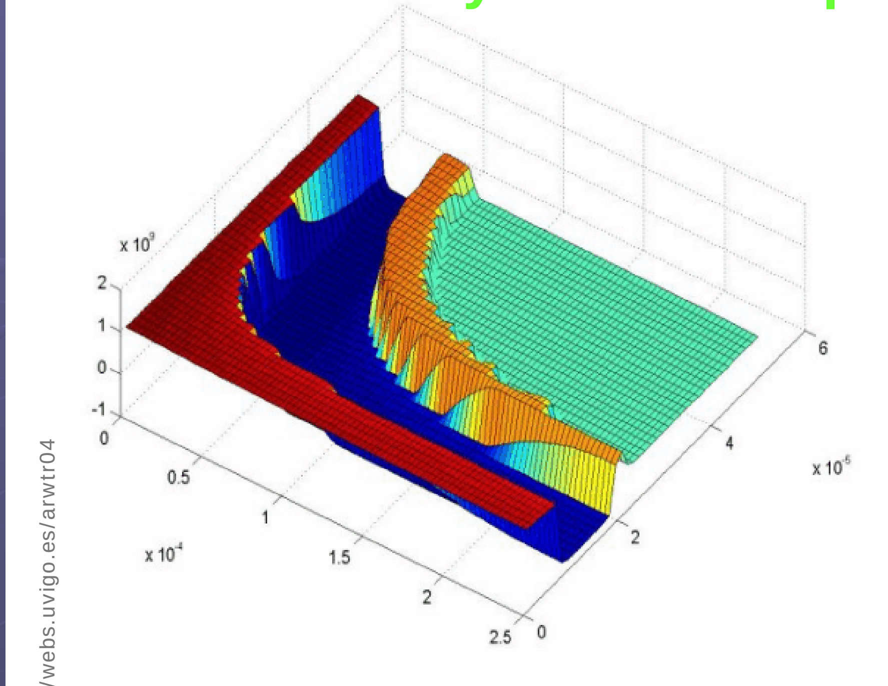
- **No-load losses: 0.264 W**
- **Full-load losses: 2.319 W**
- **These losses are released at liquid nitrogen temperature and have to be removed using the inefficient refrigeration system**
- **Each 1W of loss to be removed requires between 15 – 25 W of installed refrigeration power at 78K (a similar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

Field and current penetration in HTS tape

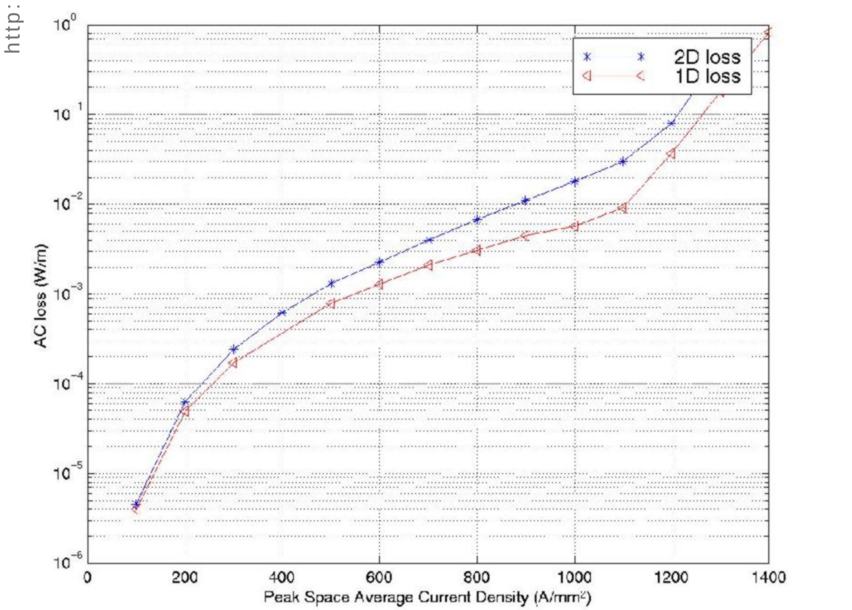


HTS tape

Diffusion of current density into HTS tape

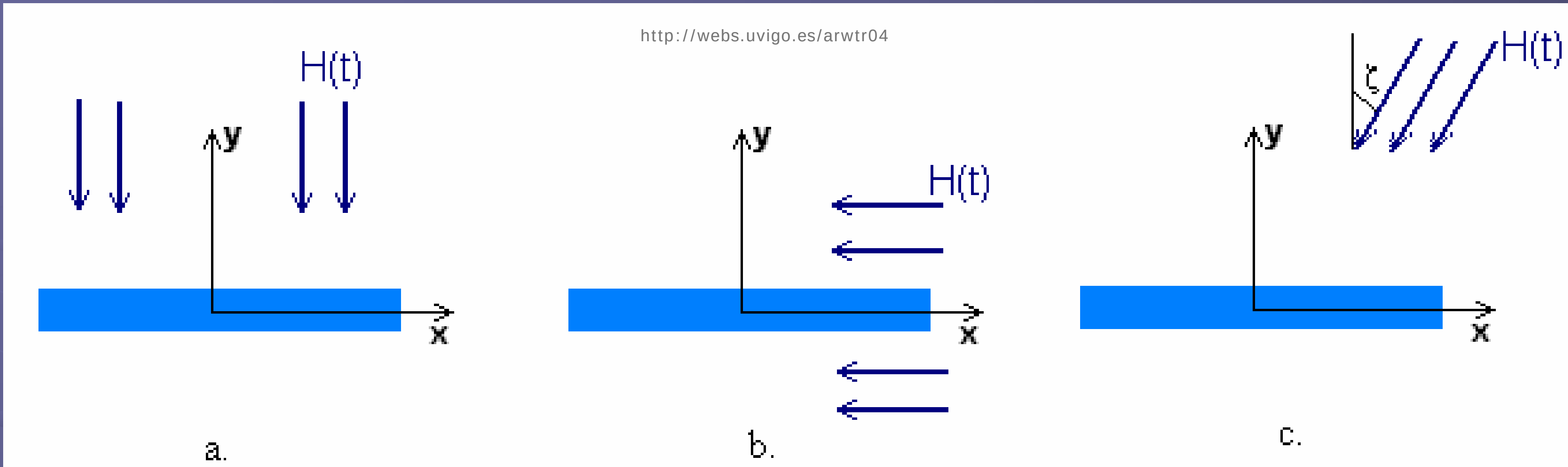


Flow of transport current through an HTS tape



AC loss as a function of average current density

HTS tape subjected to an external magnetic field



Rhyner model:

$$E = E_c \left(J / J_c \right)^{\alpha} \quad , \quad \rho = \rho_c \left(J / J_c \right)^{\alpha - 1}.$$

The critical current density J_c corresponds to an electric field E_c of $100\ \mu\mathrm{V m}^{-1}$, and $\rho_c = E_c / J_c$.

The power law contains the linear and critical state extremes ($\alpha = 1$ and $\alpha \to \infty$ respectively).

In practice $\alpha \approx 10 - 20$ and thus the system is very non-linear.

HTS tape subjected to an external magnetic field

The governing equation:

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} = \mu_0 \frac{\partial}{\partial t}\left\{\sigma_c \left|E\right|^{\frac{1}{\alpha}-1} E\right\} \quad ,$$

The FD scheme:

$$\left|E_{ij}^{(k+1)}\right|^{\frac{1}{\alpha}-1} E_{ij}^{(k+1)} = \left|E_{ij}^{(k)}\right|^{\frac{1}{\alpha}-1} E_{ij}^{(k)} + \Delta t \cdot C_{ij} = K_{ij} \quad ,$$

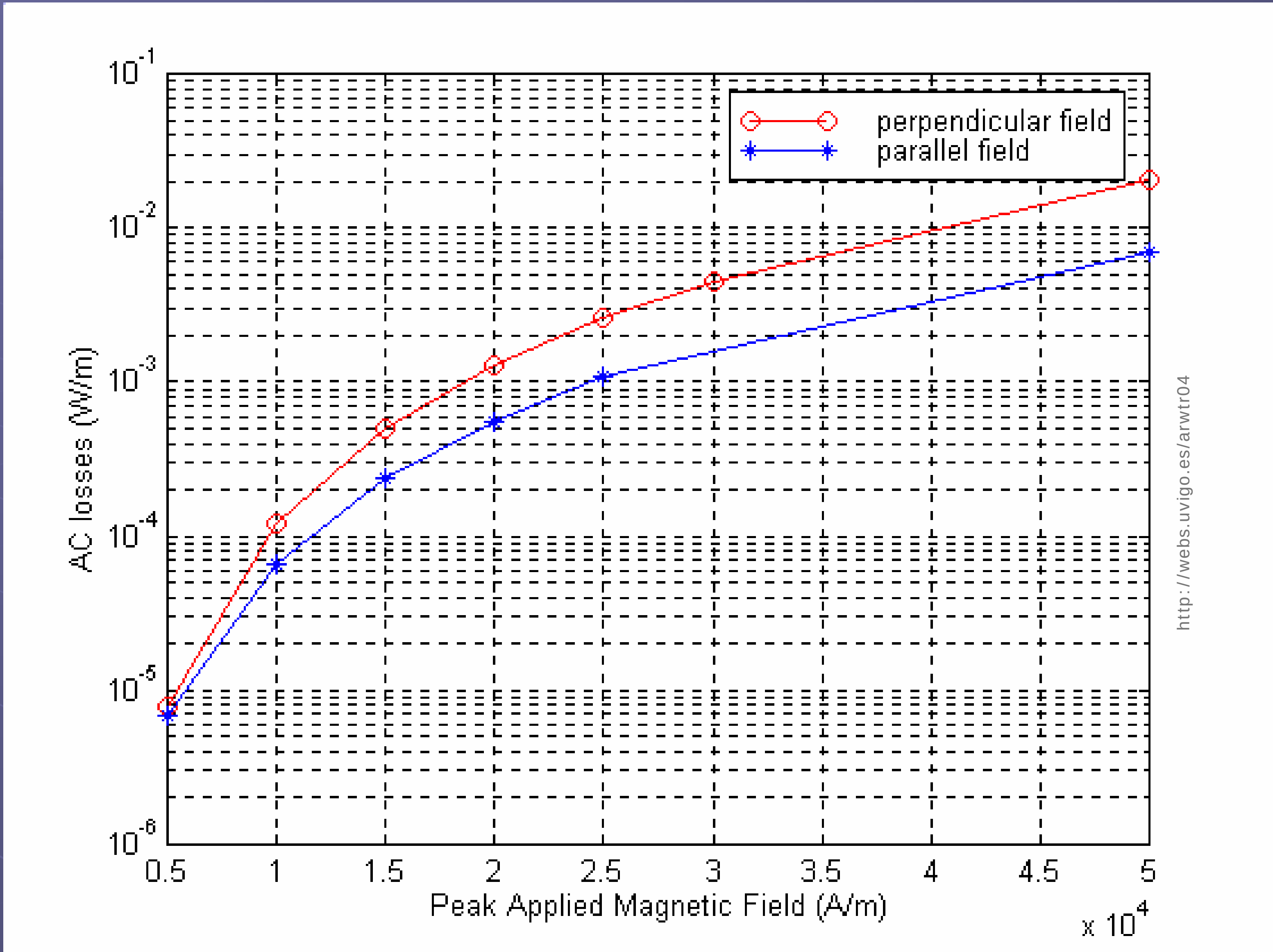
$$E_{ij}^{(k+1)} = \left|K_{ij}\right|^{\alpha-1} K_{ij} \quad .$$

where

$$C_{ij} = \left\{\mu_0 \sigma_c (\Delta x)^2\right\}^{-1} \left\{\left(E_{i+1,j}^{k} + E_{i-1,j}^{k}\right) + R^2 \left(E_{i,j+1}^{k} + E_{i,j-1}^{k}\right) - 2\left(R^2 + 1\right) E_{i,j}^{k}\right\}$$

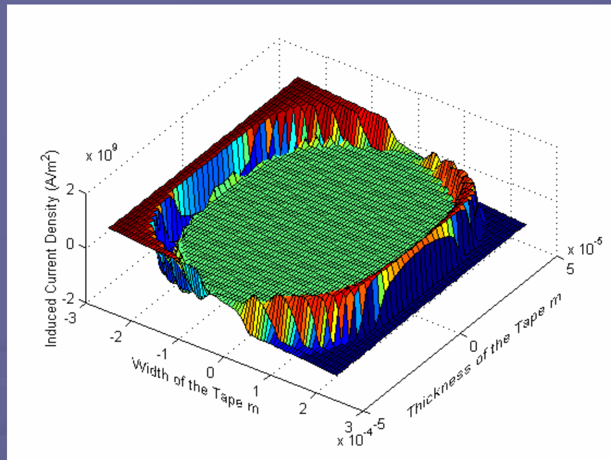
and $R = \Delta x / \Delta y$

HTS tape subjected to an external magnetic field

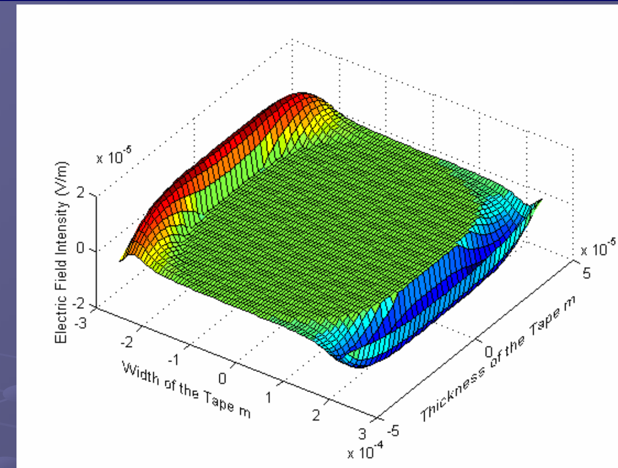


AC loss as a function of H_m (applied peak magnetic field strength)

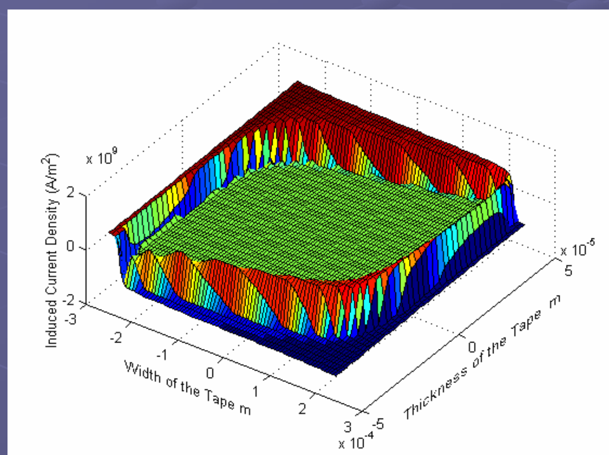
Field angle



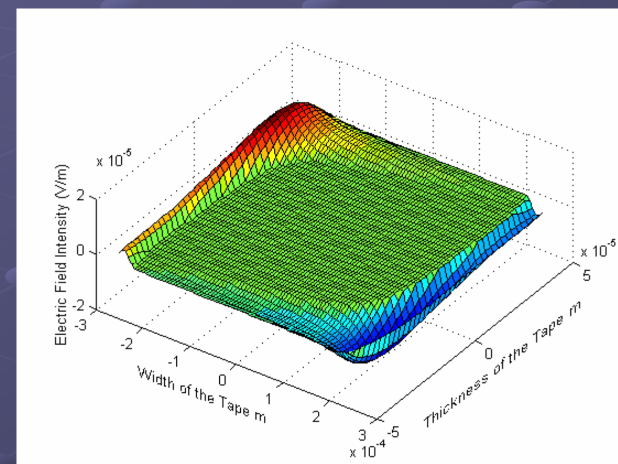
0^o



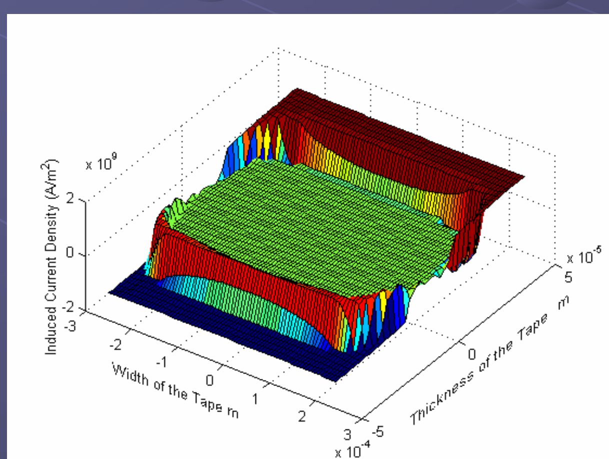
Current



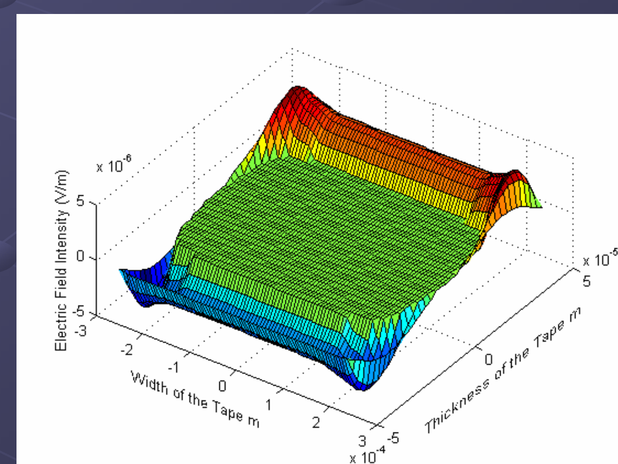
45^o



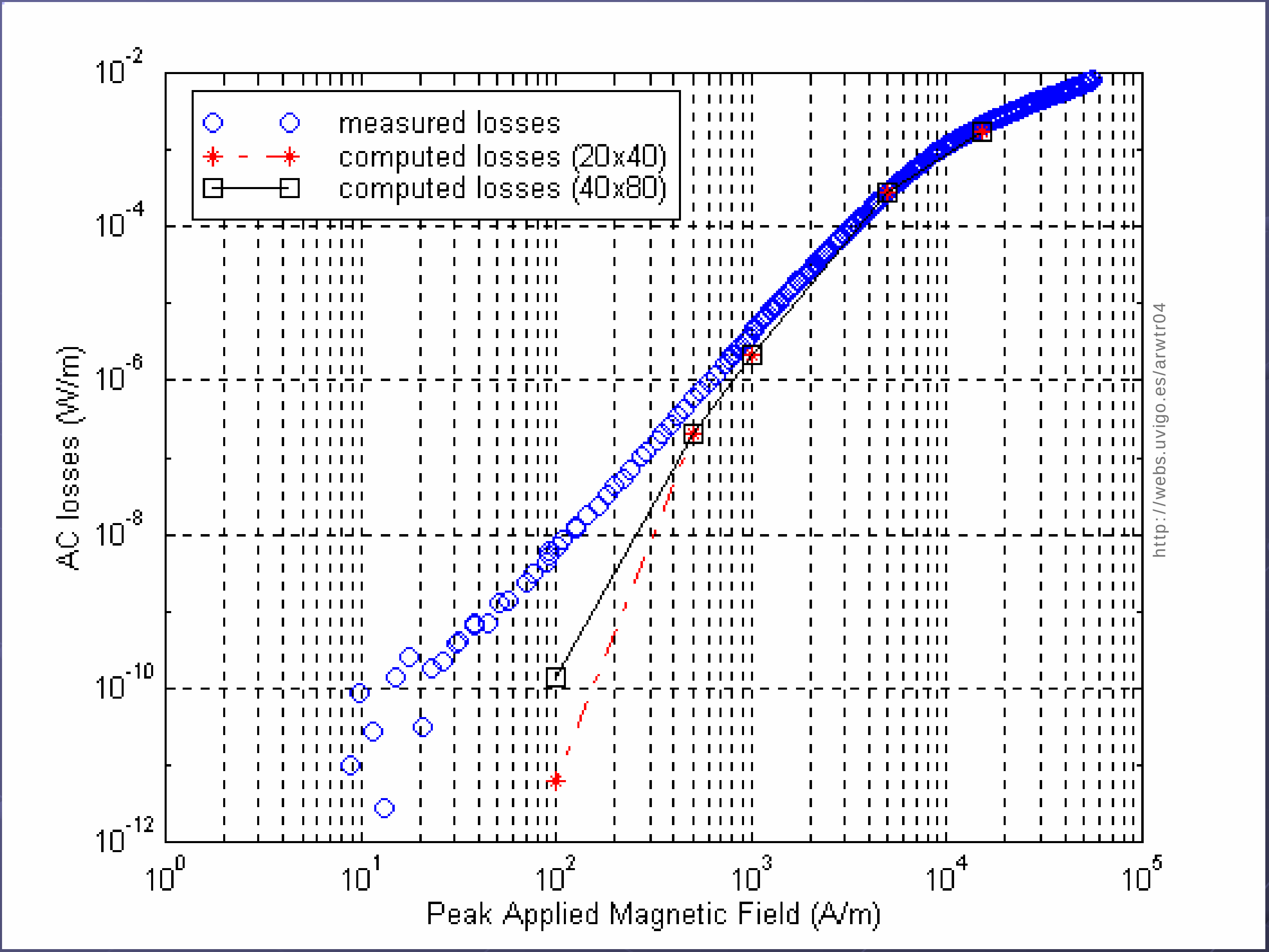
Electric field



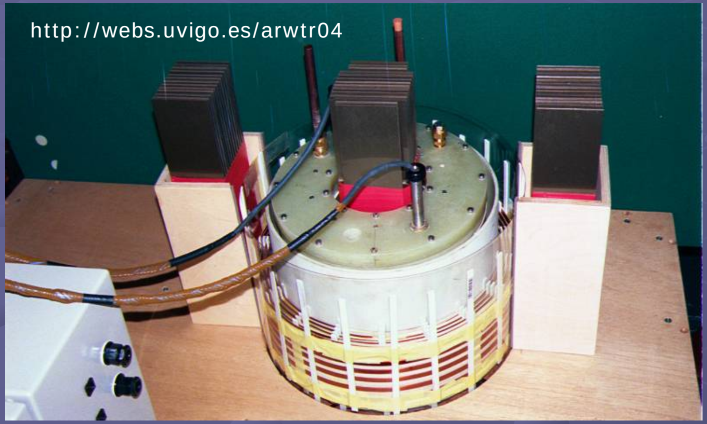
90^o

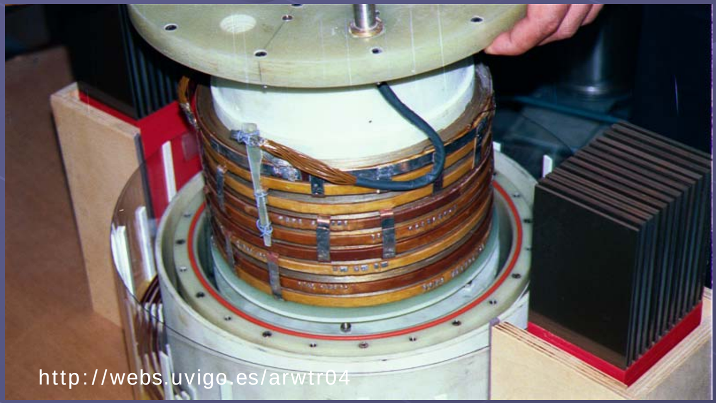


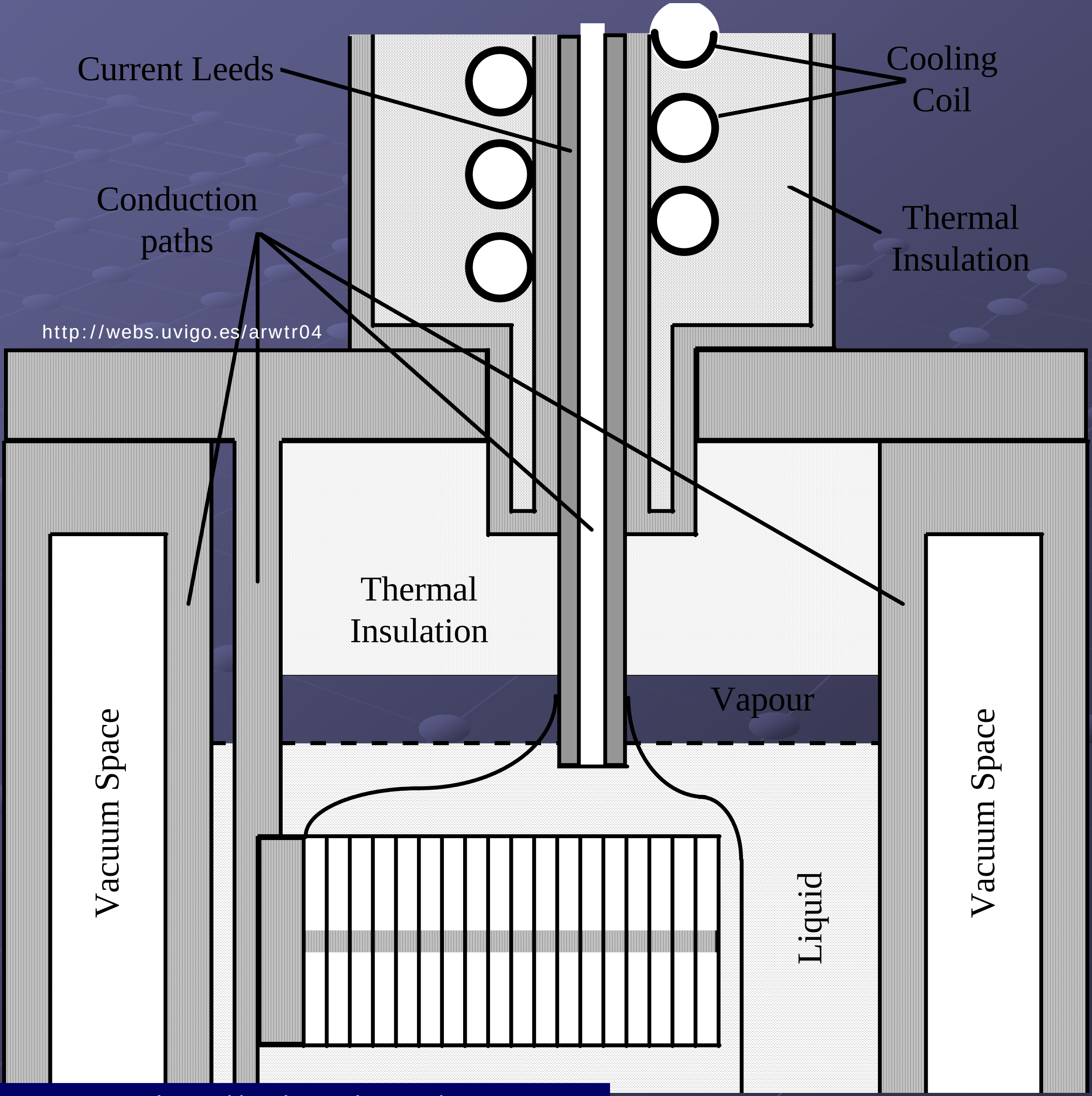
Experimental verification



HTS transformer
built and tested at Southampton 1998/99







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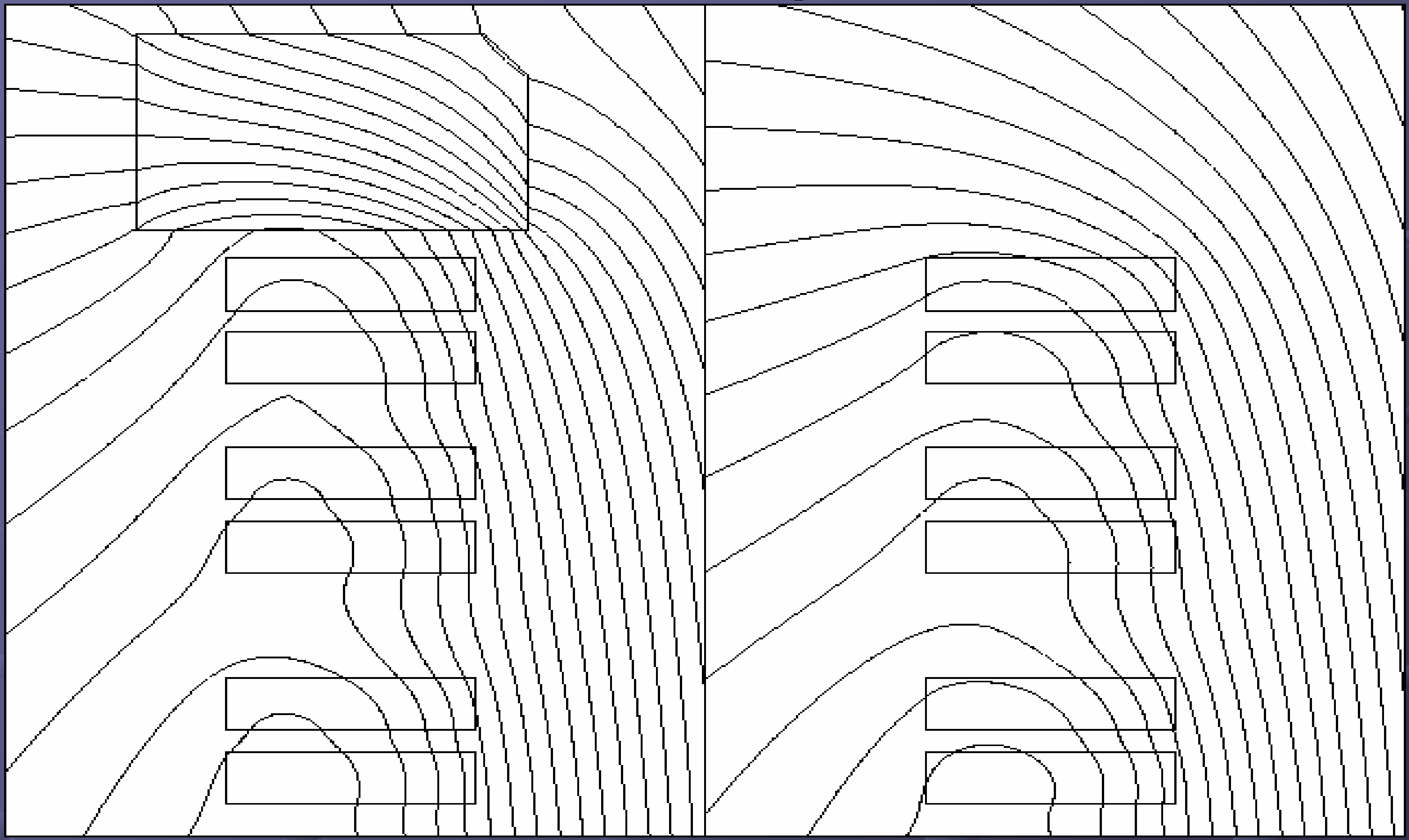

Field plots with and without flux diverters

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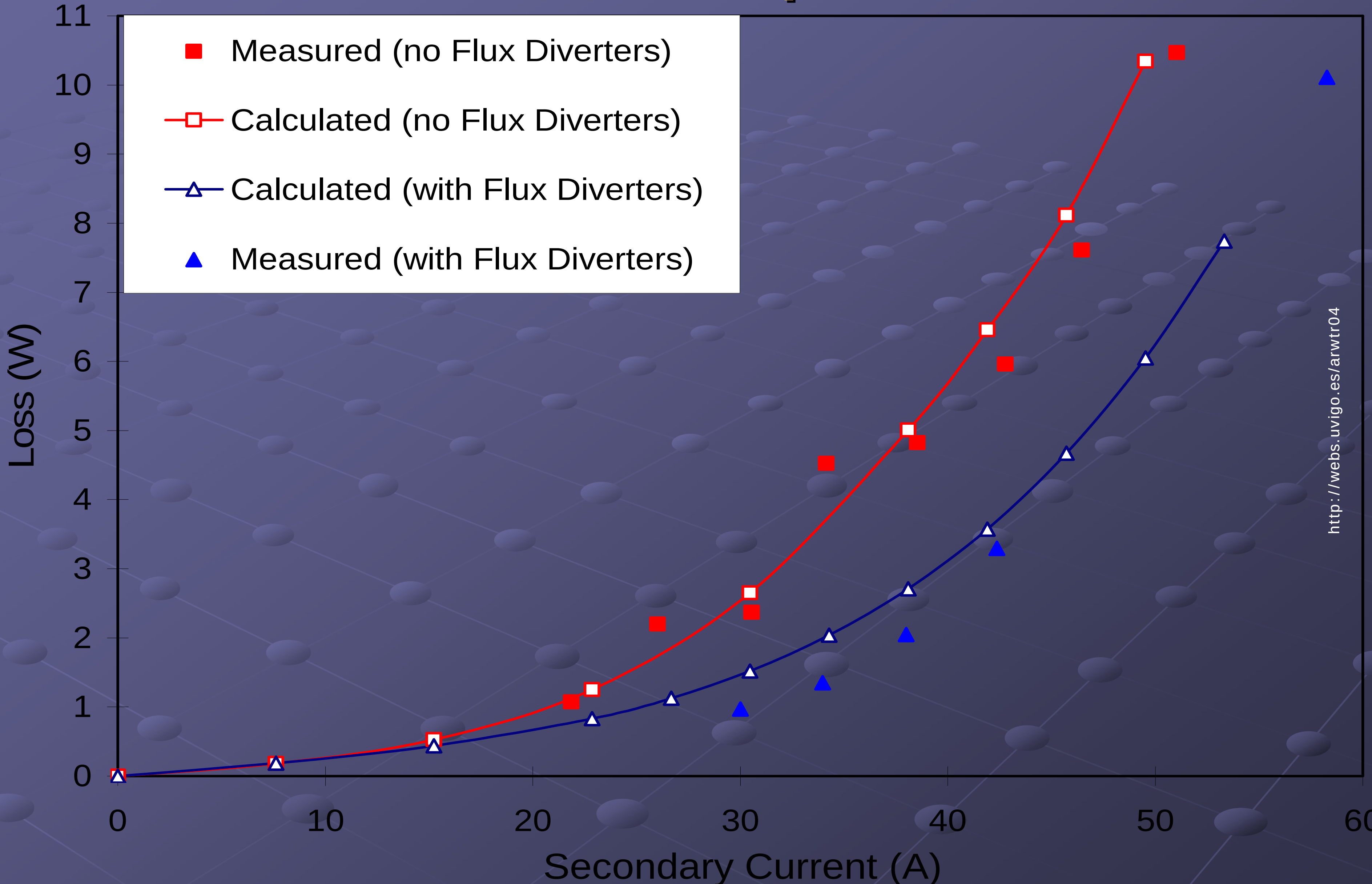

Design feasibility study for a 240MVA HTS grid auto-transformer

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%

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

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

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)

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

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

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

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B in core, T	1.67	1.67
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Through fault capability, pu (+ doublingh transient), recoveruy time without disconnection	2 pu, 64 ms	5 pu, 3 s
Survival time at 5 pu (+ doubling transient)	166 ms	seconds (> 3)

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

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

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

But !!!

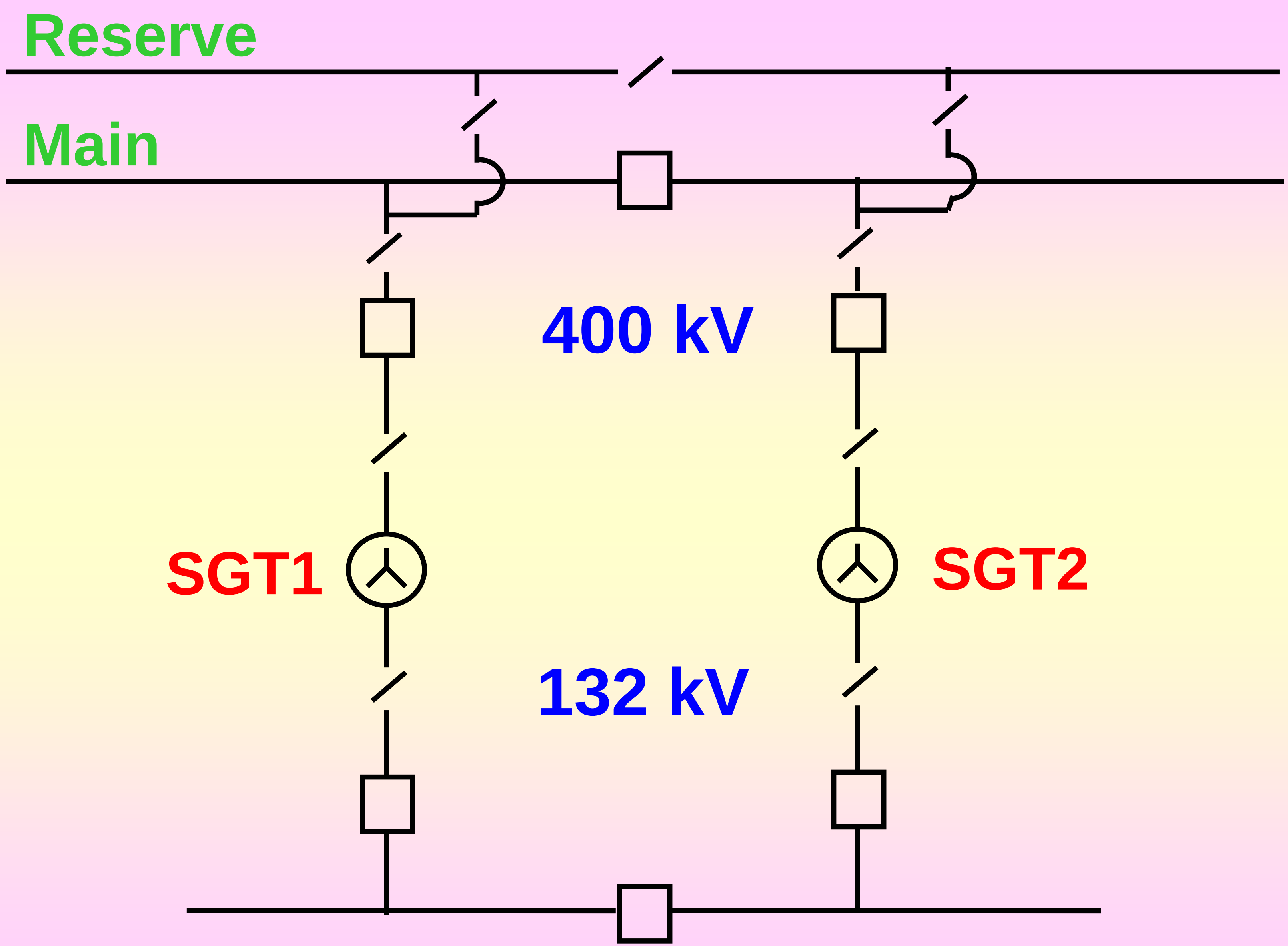
- The load factor for a grid transformer is very low,

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

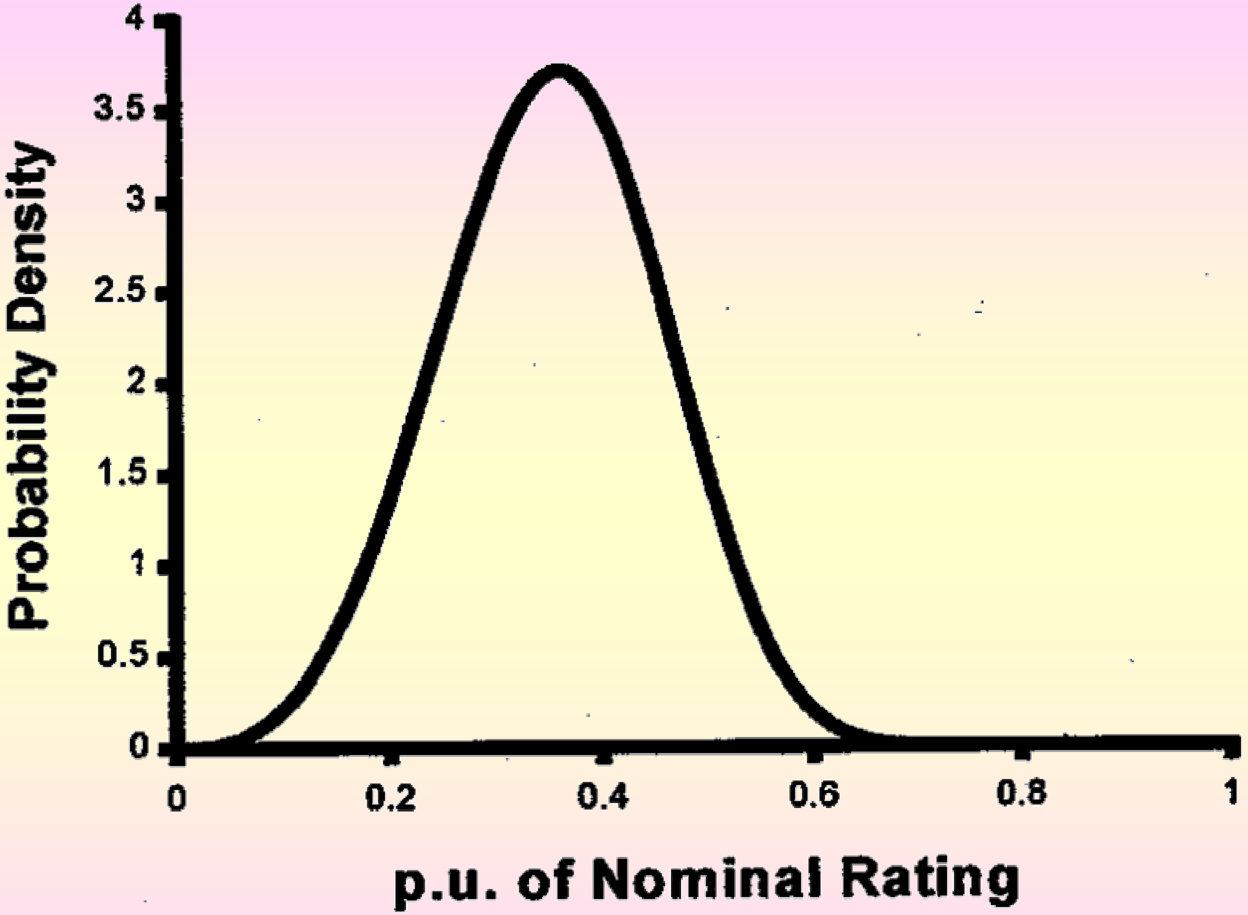
- Thus the savings may not actually happen !

However …

Parallel operation

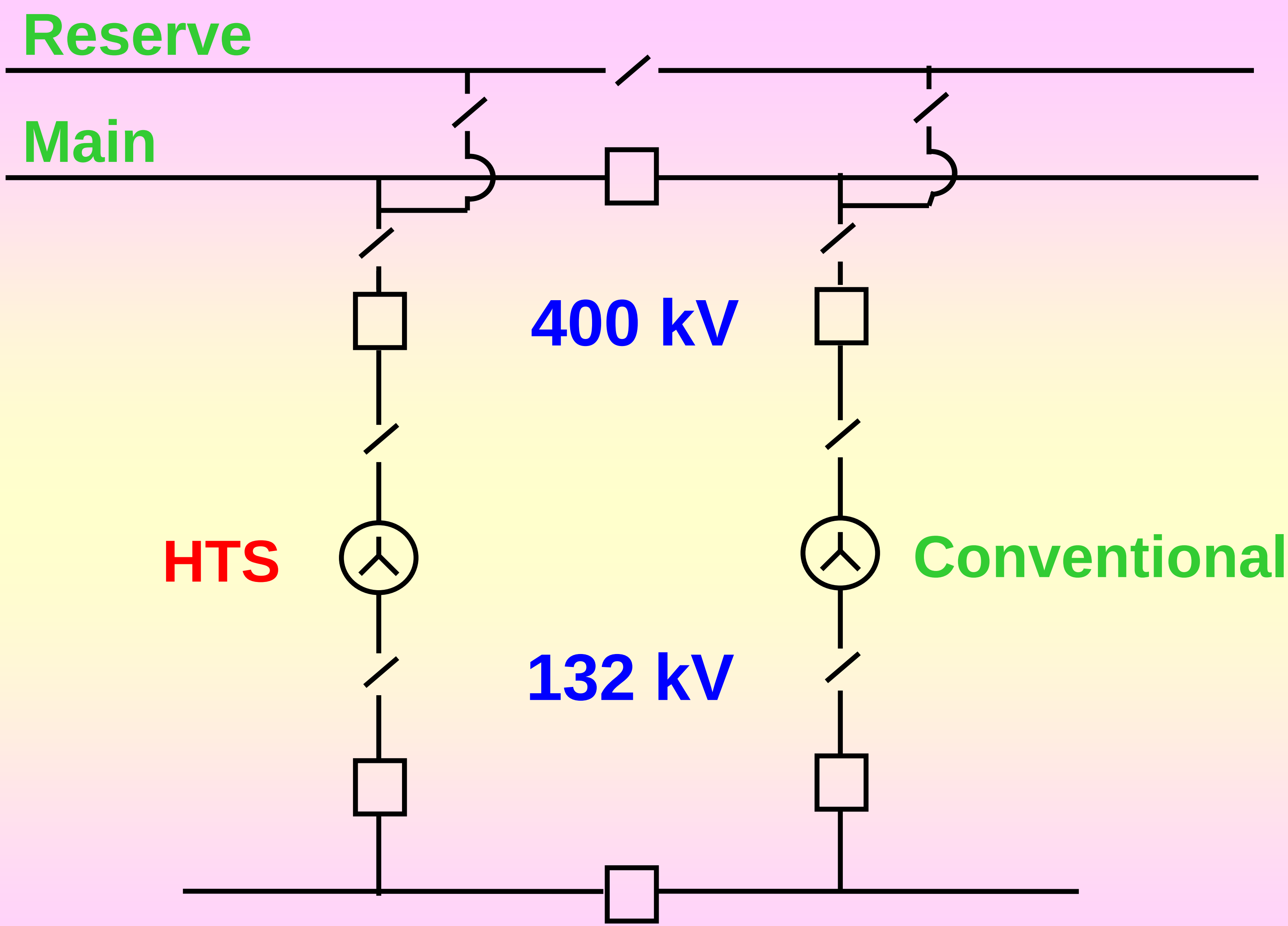


Parallel operation



Probability density of load for a typical grid transformer

Parallel operation



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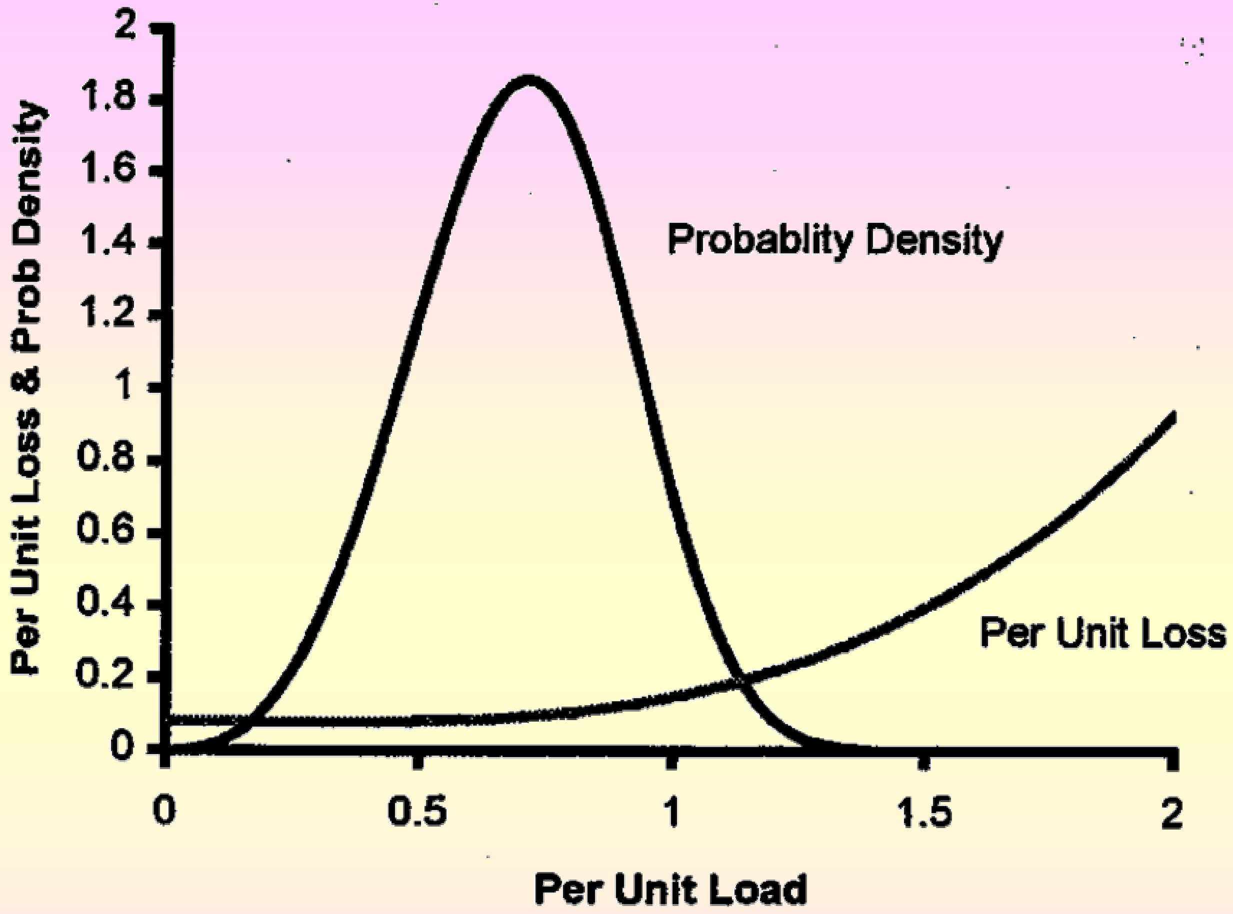

Load probability density and loss as a function of load for a HTS transformer in parallel with a (normally) unconnected conventional unit.

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 design 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


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Thank you


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