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Industrial and Medical Applications of Superconductivity

Ziad Melhem
Oxford Instruments Omicron Nanoscience

AIME Superconductivity Event at CIEMAT
Madrid, Spain

28th May 2013

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Objective

- last year the world celebrated
  - 100 years from the discovery of superconductivity
  - 50 years from the start of applied superconductivity
  - 25 years from the discovery of high-temperature superconductors

Objective of this talk is to provide an overview on

Commercial Superconducting Technology and in particular industrial and medical applications

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Commercial Magnet Technology Started Here!

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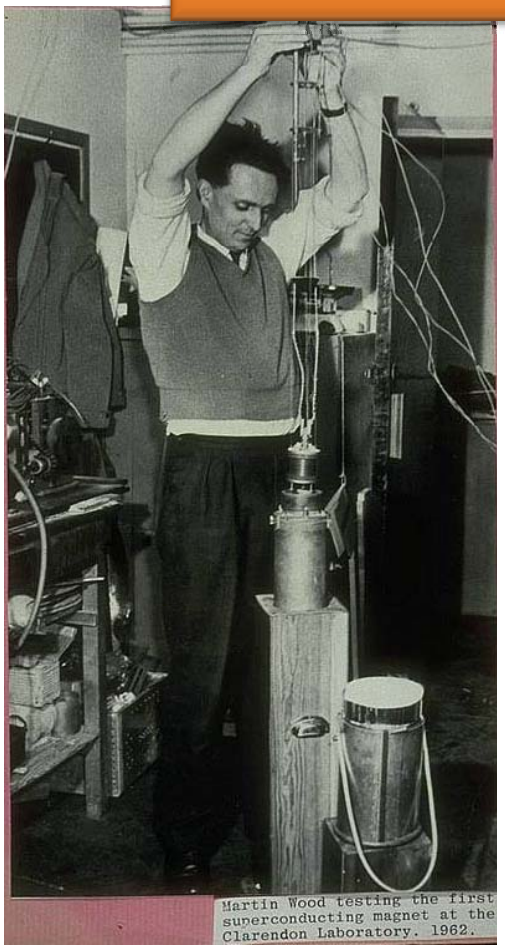
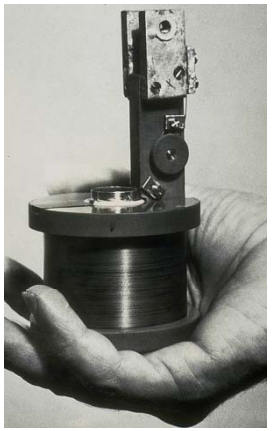
The birth of Oxford Instruments 1962



Sir Martin Wood testing the 1st Commercial Magnet (4T)



Sir Martin Wood standing in the door of the shed in his back garden – 1st OI company site!

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Outline

- Introduction and Background
- Medical applications
- Industrial applications
- Current and future trends in HTS applications
- Superconducting technology
- Superconducting economics
- Summary

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Discovery *by accident !*

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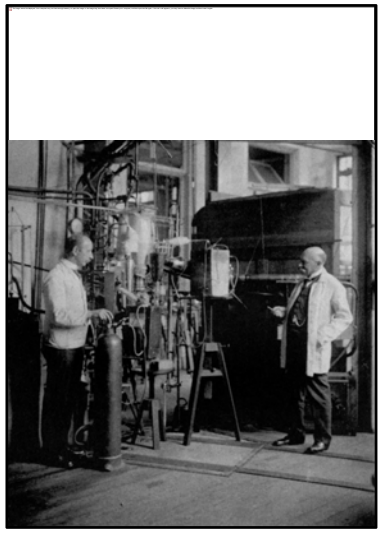
Heike Kamerlingh Onnes (1853-1926)

"Door meten tot weten" ("Through measurement to knowledge")



1908 Kamerlingh Onnes Liquefies Helium

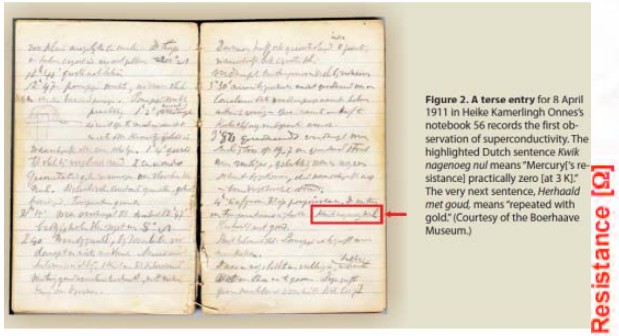
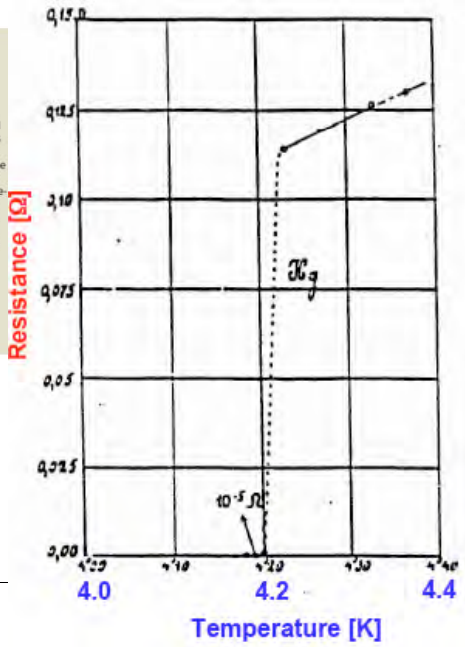


Figure 2. A terse entry for 8 April 1911 in Heike Kamerlingh Onnes's notebook 56 records the first observation of superconductivity. The highlighted Dutch sentence *Kwik nagenoeg nul* means "Mercury['s resistance] practically zero [at 3 K]." The very next sentence, *Herhaald met goud,* means "repeated with gold." (Courtesy of the Boerhaave Museum.)

8 April 1911

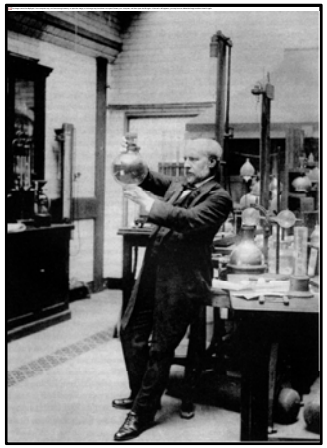
*"*The Resistance of Mercury at helium temperatures*"*

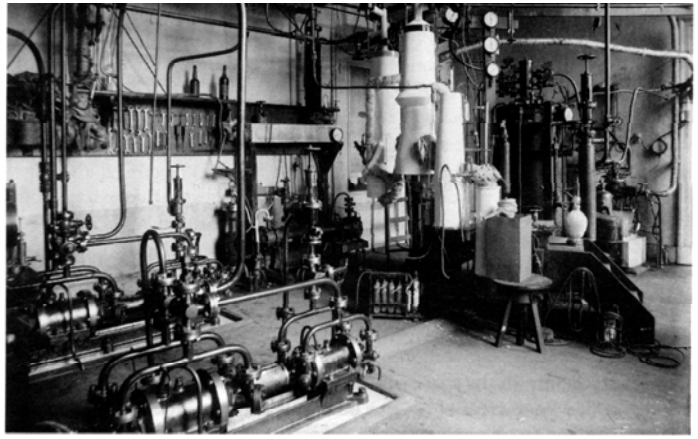
0.034 Ω at 13.9 K, 0.0013 Ω at 4.3K and less than **0.0001 Ω at 3K**



Visionary behind the 10T magnet

1892 James Dewar Invents 'Dewar Flask'





October 1911 (Reported in November 1911)

"On the sudden change in the rate at which the resistance of mercury disappears"

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Spectrum of Magnetic Field Strengths

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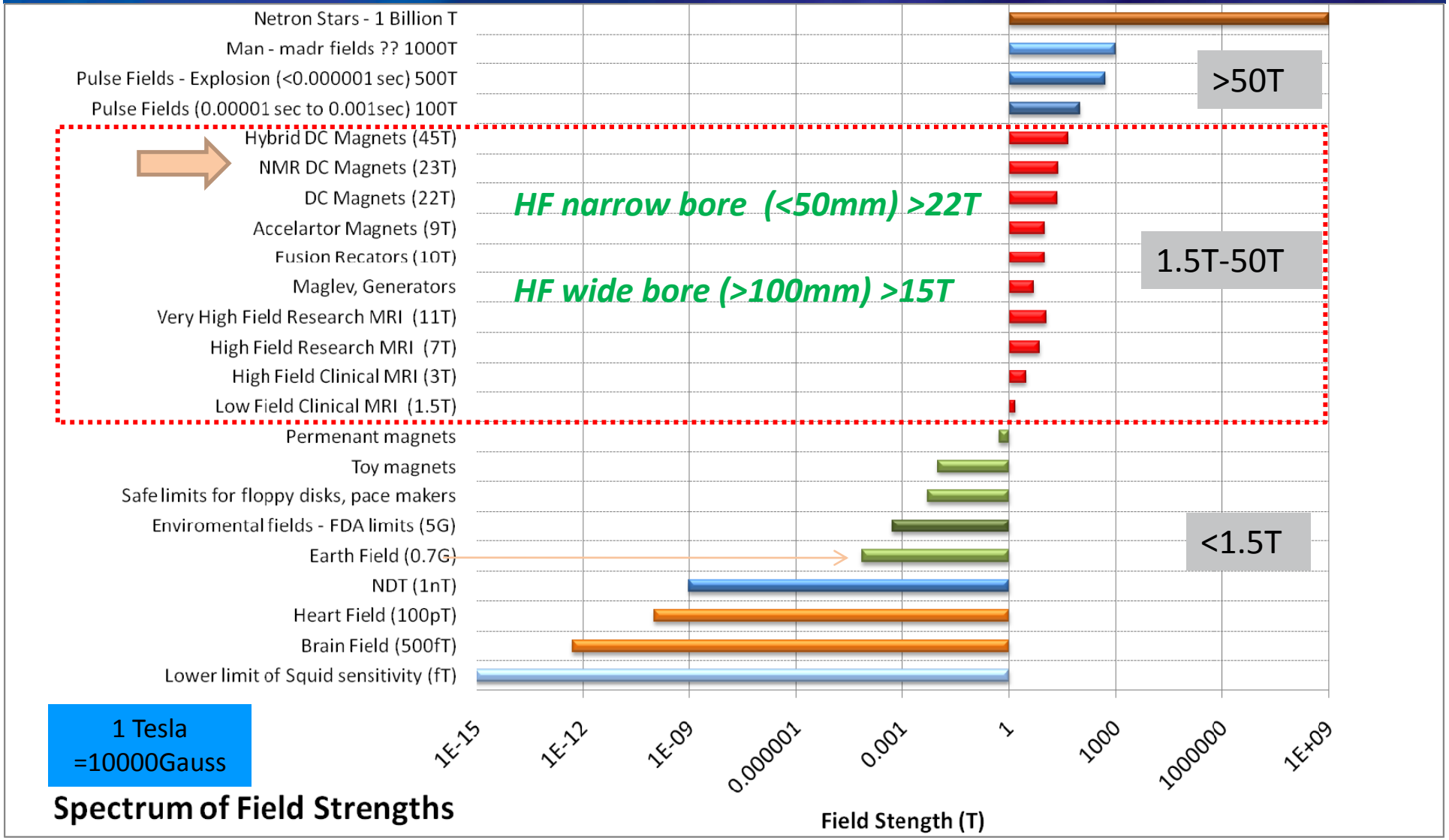

1 Tesla =10000Gauss

Spectrum of Field Strengths

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Diverse End Markets

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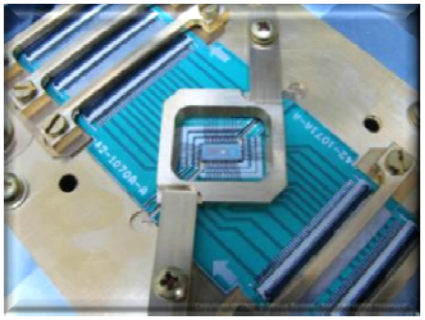
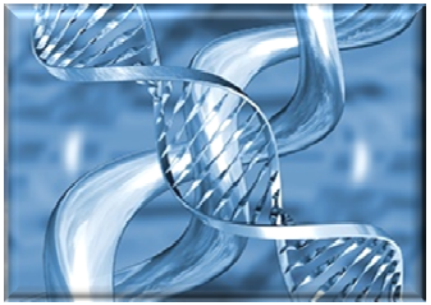
Quantum Computing

Image courtesy of D-Wave Systems Inc

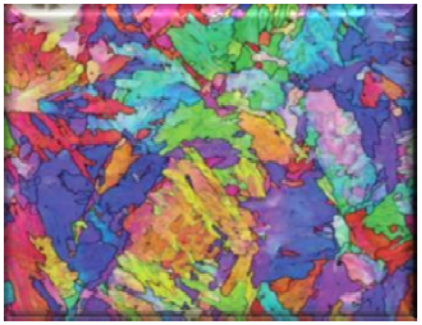


Energy Generation



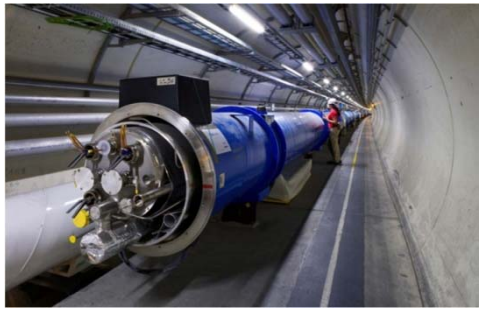
Life Sciences

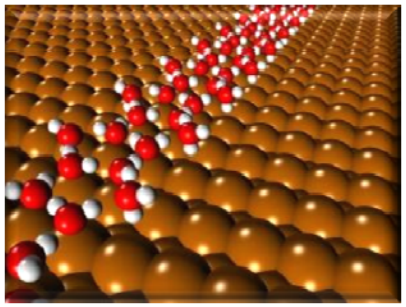
Health Care



Materials Discovery/ Characterisation

Semiconductor Research





HEP/Particle Discoveries

LHC magnet (Courtesy of CERN)

Nanotechnology/ Mesoscience

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Manufacturing Sites (~1800 Staff)

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Timeline of Discoveries!

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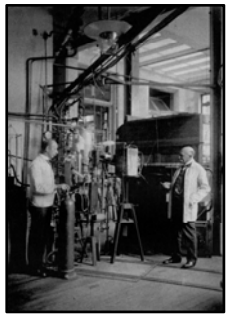
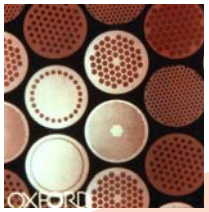


1910

The Discovery

1920 -1950

The Theory



1960 -1970 Applications

Research Magnets

NMR

Physics Magnets

1980- Volume Production

MRI

HTS (1986)

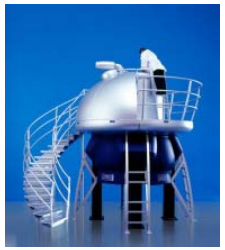
2000 - New Frontiers

High Field Magnets

Energy Applications

Transport

Large Scale



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Superconducting Applications are very diverse

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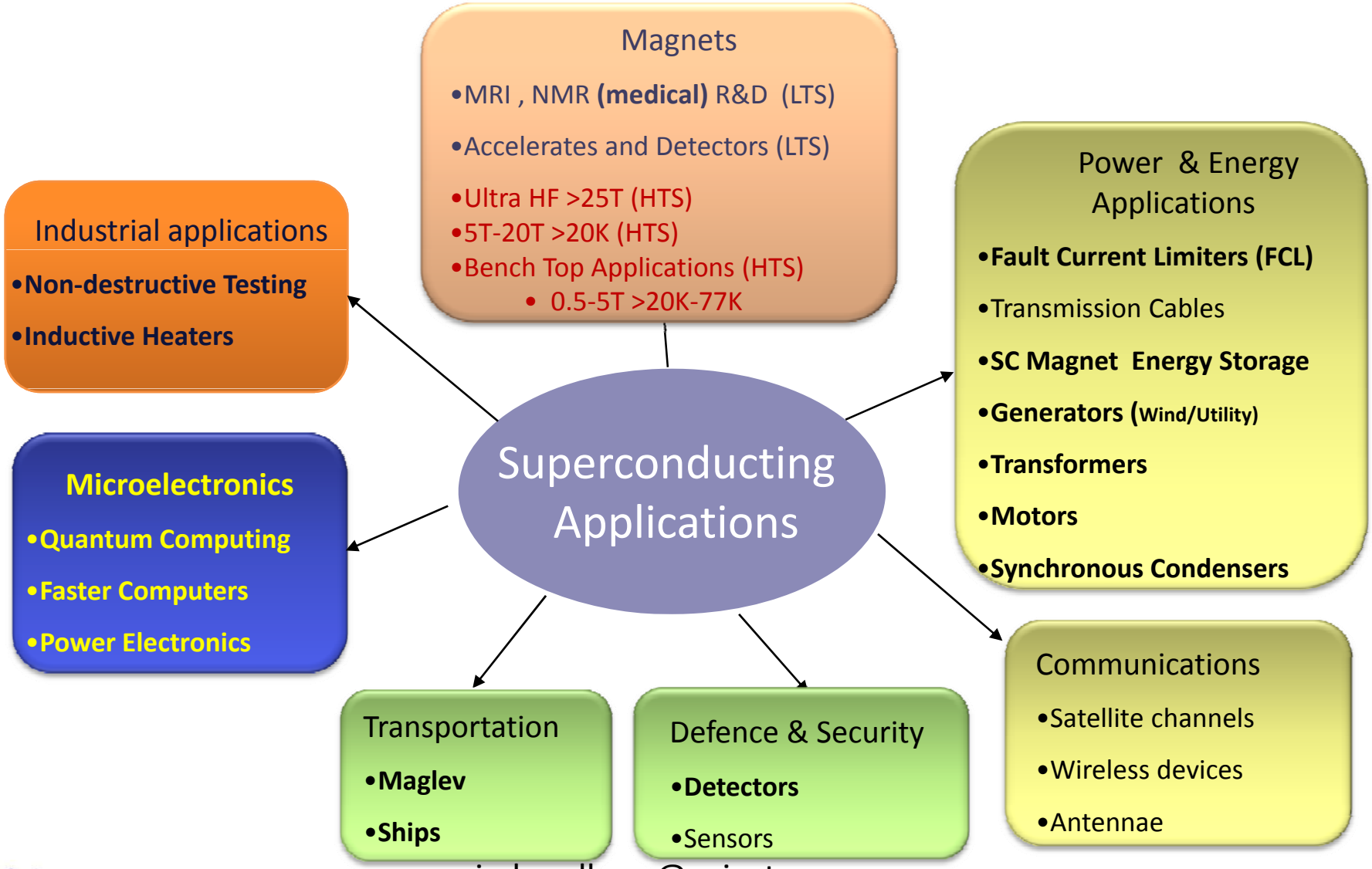

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Superconductors for Industrial Applications

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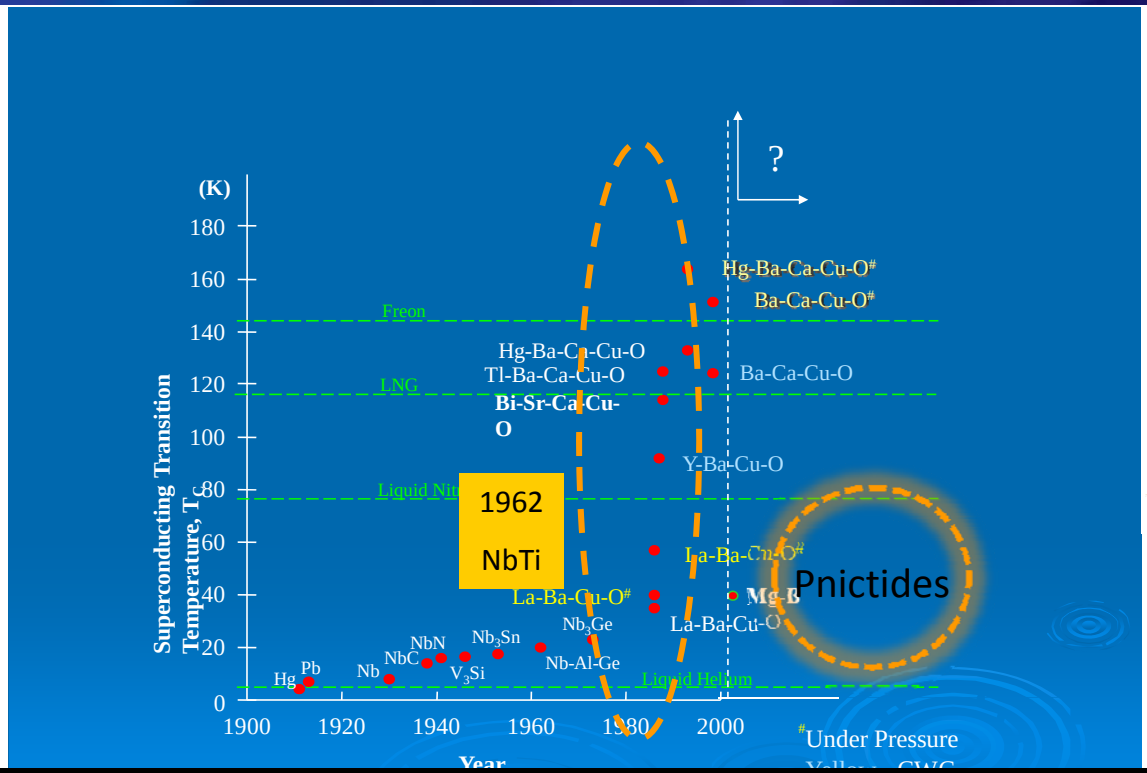
>10 winners since 1911 In superconductivity and applications



>1000 superconductors discovered so far

Only 6 useful!

But the Quest is on for the dream SC

Low cost and high performance

NbTi LTS	Nb_3Sn/RRP LTS	MgB_2 MTS	Bi-2212/Bi-2223 HTS	YBCO HTS
Tc = 9.8 K Bmax (4.2K) 9.5T (2.2K) 11.5T	Tc = 18.1 K Bmax (4.2K) 20T (2.2K) 23.5T	Tc=39K Bmax (4k) 5T-10T ?	Tc = 90-110K Bmax > 40 T @4.2K; 8 T @20K 4 T @65K	Tc = 90-135K Bmax > 40 T @4.2K 12 T @20K 8 T @65K

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Medical Applications

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HF SC NMR Magnet Development Timeline –

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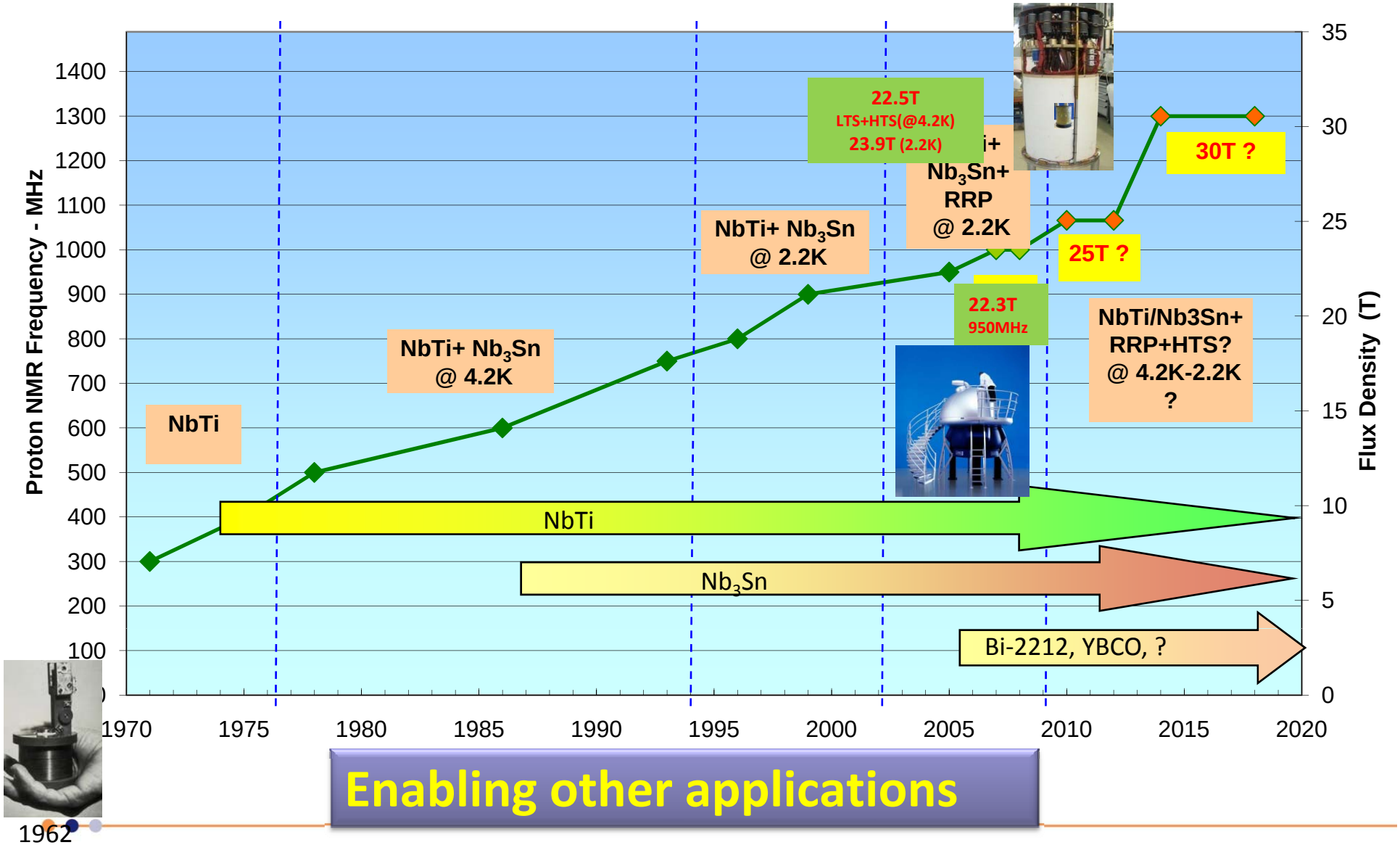

1962

Enabling other applications

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NMR Commercial systems (200Mhz to 950MHz) for Disease treatment and Drug discovery

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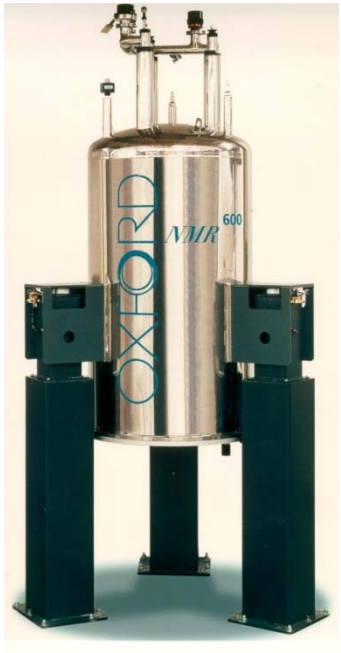

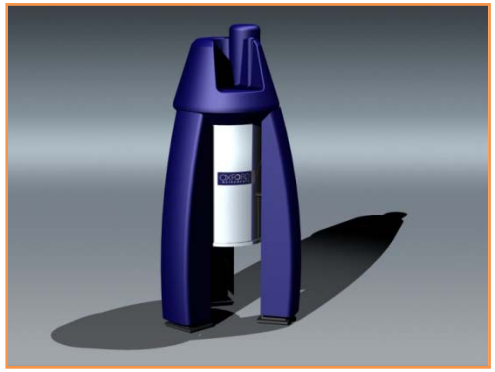

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MRI Magnets – 1st Commercial 1980

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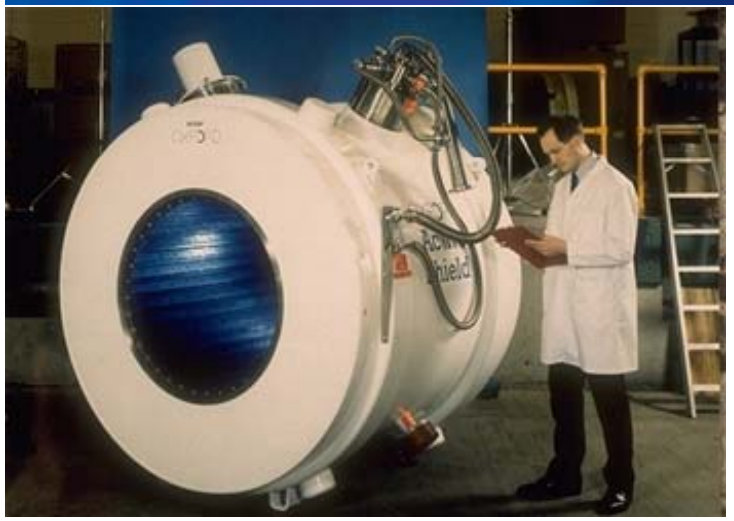

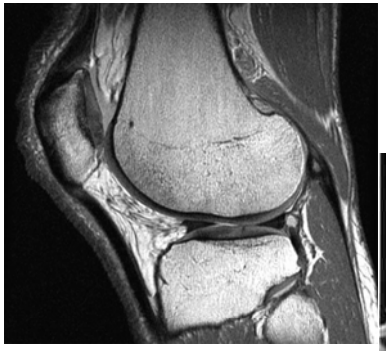

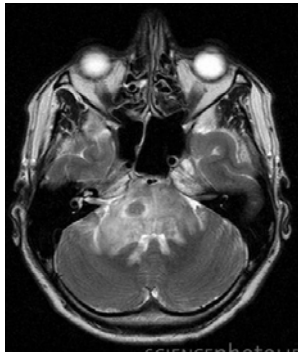

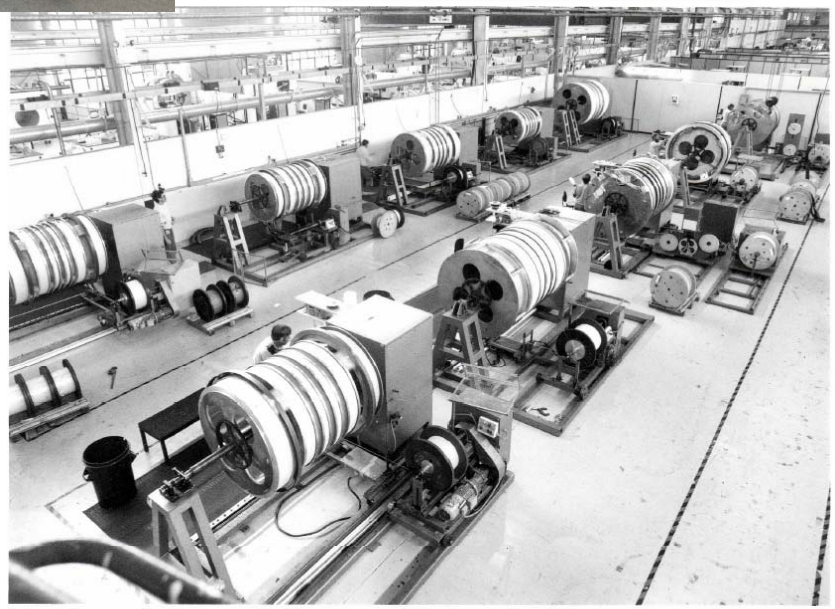

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MRI Magnets Development
Health Sector

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- All using LTS Materials
- 2500/yr production
- >3Billion Euro/yr market

1st MRI

AS 1.5T

AS 3T

1.5T Small

9.4T

1980 1986 1989 1994 1997 2000 2001 2005 2008 2011

1st Active shield (AS)

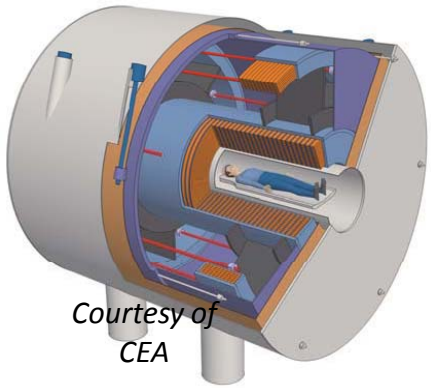
1st Open MRI Magnet

AS 4T

7T

Courtesy of Siemens

11.7T



Courtesy of CEA

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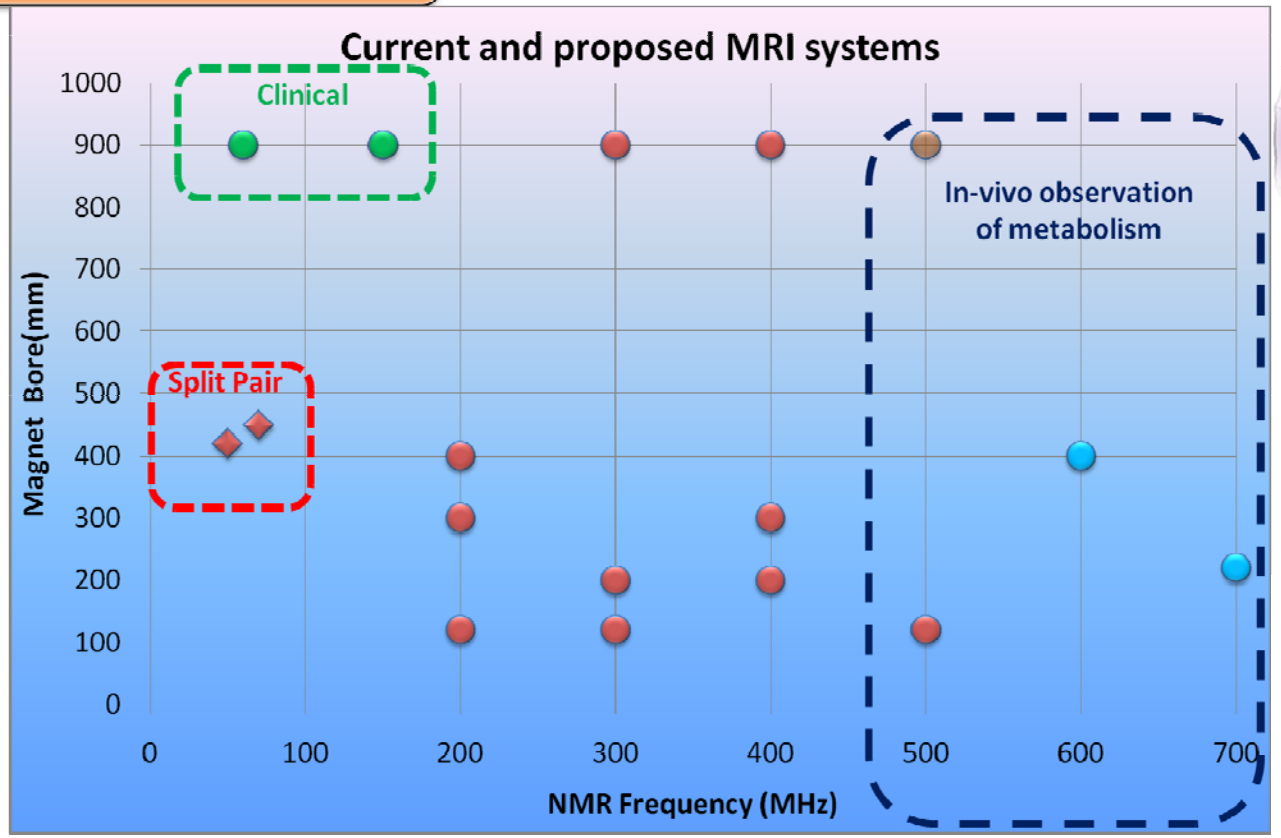
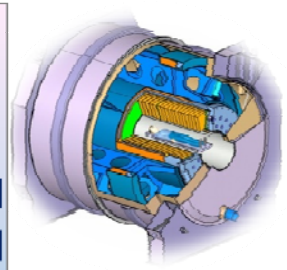
MRI coverage

1.5T-3T	• Clinical MRI
7-9.4T	• Laboratory MRI
>11.4T	• Special &Future MRI





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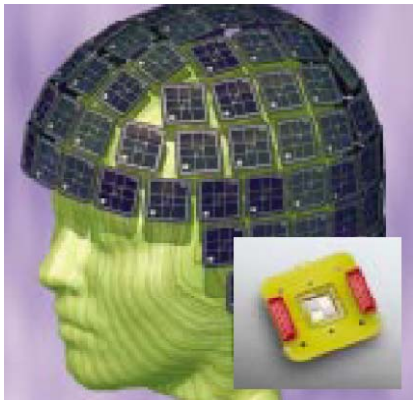
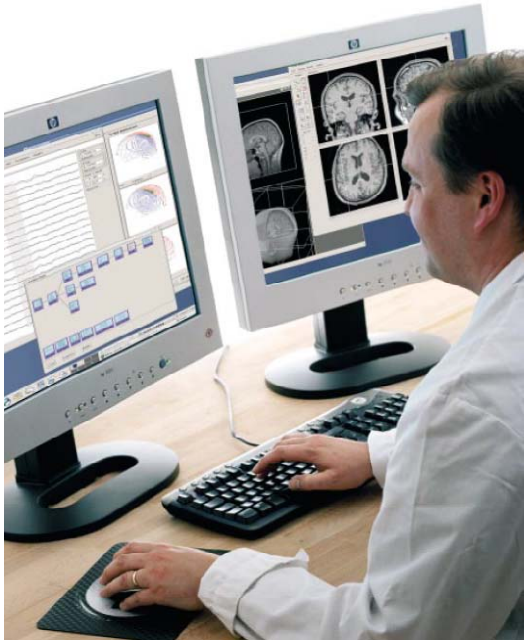
Magnetoencephalography MEG





- real time non invasive mapping of brain activity by measuring extremely small changes in magnetic field
- array of 400 LTS SQUID gradiometers

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Stereotaxis system - Medical

- **Magnetic Navigation System (MNS)**
  - Three solenoid magnets arranged along 3 perpendicular axes
- **Designed to provide catheter navigation and control anywhere in the body**
  - Help reduce complexity of critical surgical procedures
  - Optimize time and cost
  - Improve patient outcomes

System 1 installation- St Louis, MO

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Industrial Applications

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Industrial Magnets
Magnetic separation - Carpco

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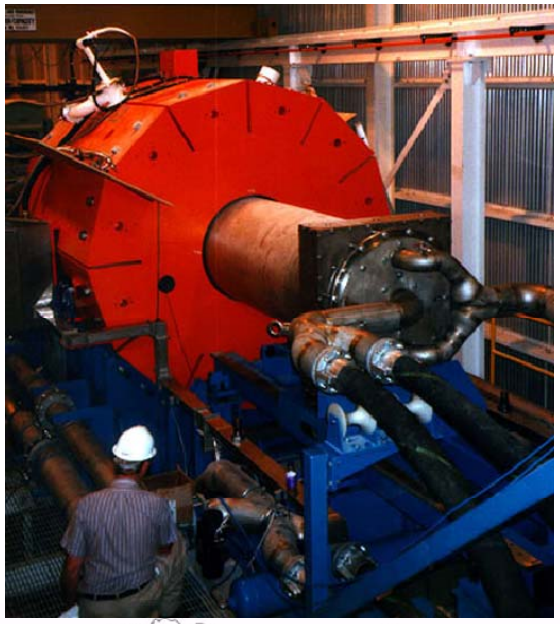
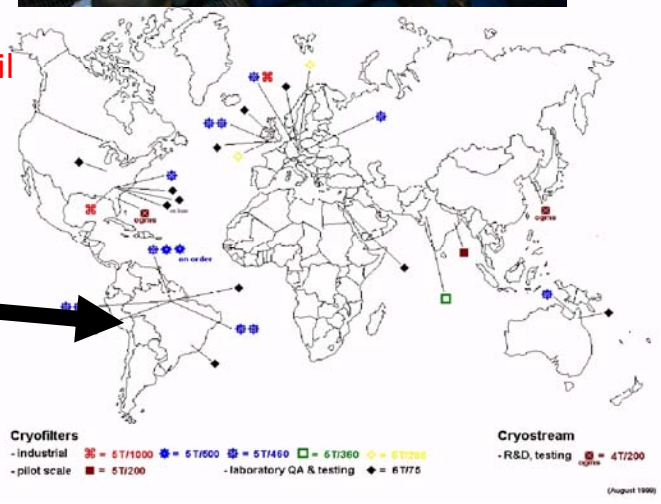
- High gradient magnetic separation (HGMS)
- Primarily for kaolin processing
  - removing weakly magnetic impurities to improve whiteness (and therefore economic value)
- **5 T** magnets, 360 mm to 1000 mm bore



operate at the mining source

- Amazon rainforest, Brazil
- Queensland, Australia
- Cornwall, UK



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Helios compact electron synchrotron X-ray source for microchip

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High field Synchrotron for X-Ray Lithography for microchips

- LTS SC
- small bending radius
- compact size

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Industrial Magnets
Gyrotrons - nuclear fusion and Radar

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- for production of high-power, high-frequency microwaves
  - up to 1 MW at 140 GHz
  - typically up to ~6 T but with complex coil geometry
- plasma heating in nuclear fusion
  - Electron Cyclotron Resonance Heating (ECRH)
- low loss cryostats, often with shield coolers

- Cryofree magnets for radars
- ~95 GHz
- For detection of small, fast-moving objects over flat surfaces

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Superconducting Magnets for Fusion (6-13T) – ITER – Energy Sector

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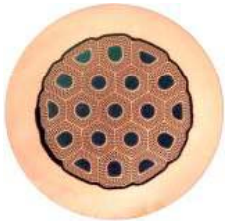
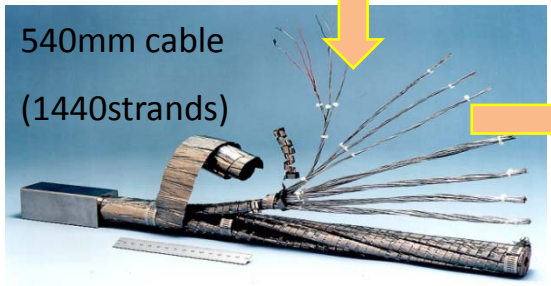
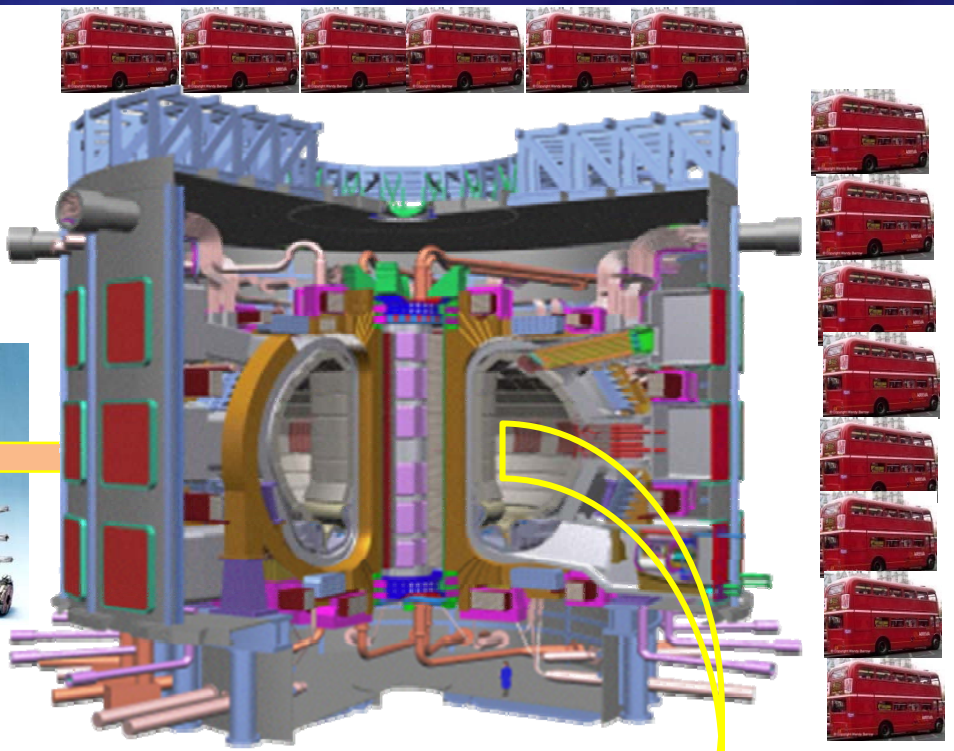
0.73mm ITER LTS strand







- **ITER strand** - new generation of LTS superconductors for energy applications
- 15B Euro development cost
- >20 yr development programme (10yr to build)
- 2020! date for 1st Plasma
- 74,000Km of superconducting wires (Almost twice around the earth!)

ITER uses 600 tonnes of Nb_3Sn

High field Superconducting magnets to contain plasma- Sun conditions 10 Million Degrees

One toroidal coil will weigh the same as a full jumbo jet at takeoff

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ST25 and HTS Coil Developments Route to HF Tokamaks for plasma physics reserach

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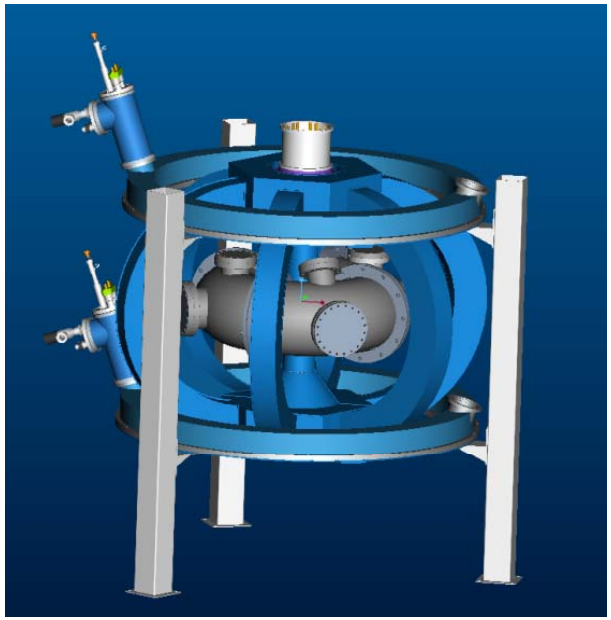
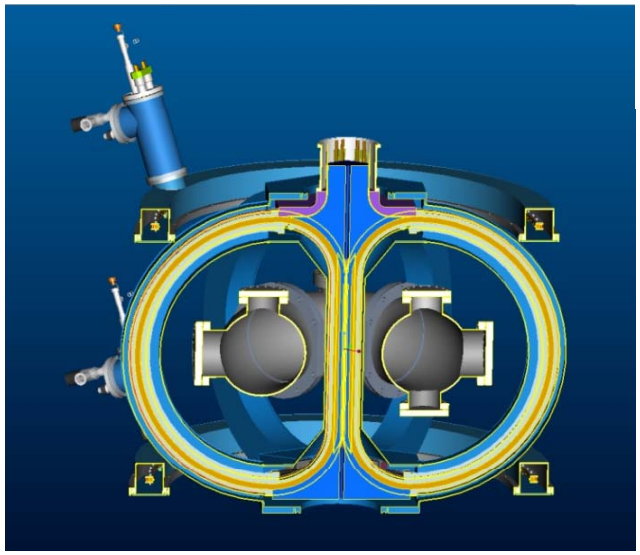
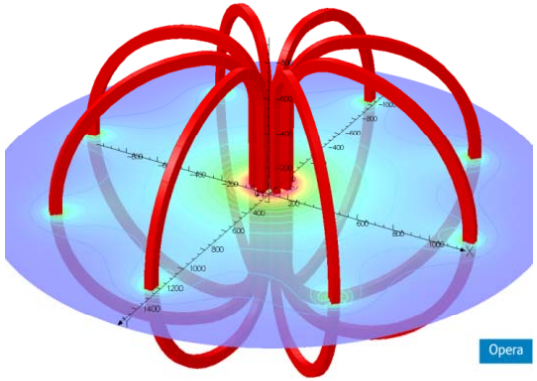
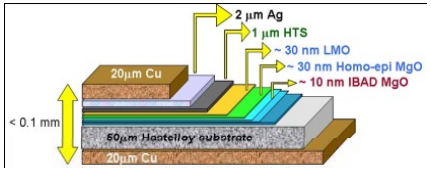




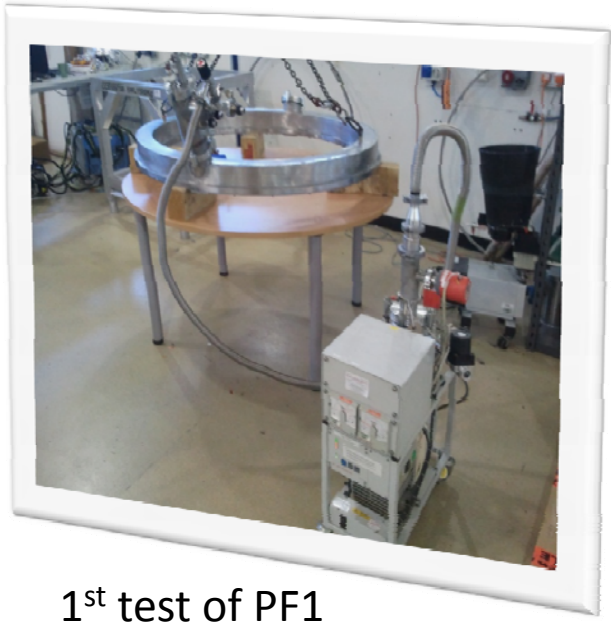


R/a	25/12.5cm
B_t	0.4T
700m HTS	12mm YBCO

Tokamak Solutions



Courtesy of SuperPower Inc



1st test of PF1
3rd May 2012

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Current and future trends in HTS applications

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Superconducting Cables

Field test of 500m long HTS cable (Furukawa Electric CRIEPI (Central Research Institute of Electric Power Industry) & Super-GM (Engineering Research Association for Superconductive Generation Equipment and Materials) 2005

Note the elevation and the corners!

Cable at Holbrook, Long Island USA, operational 2009

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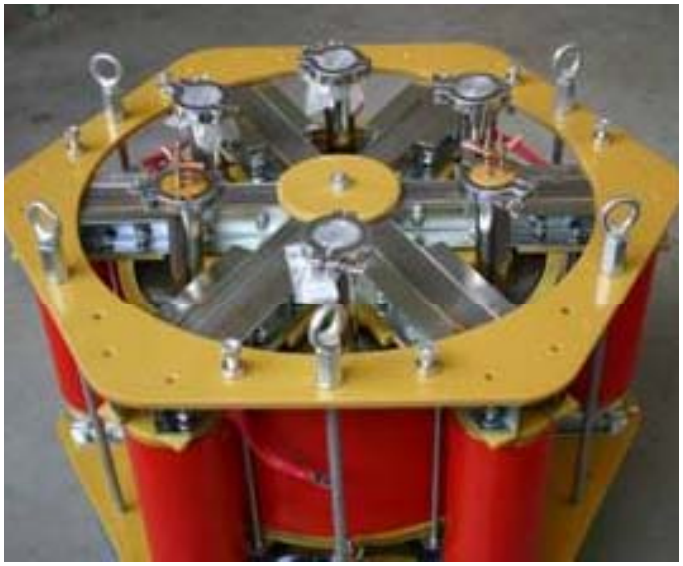
Superconducting FCL (few examples)

SIEMENS

thin film
YBCO



INNOPOWER

China

Bulk B2212

Nexans

Zenergy Power
USA

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Superconducting Magnetic Energy Storage SMES

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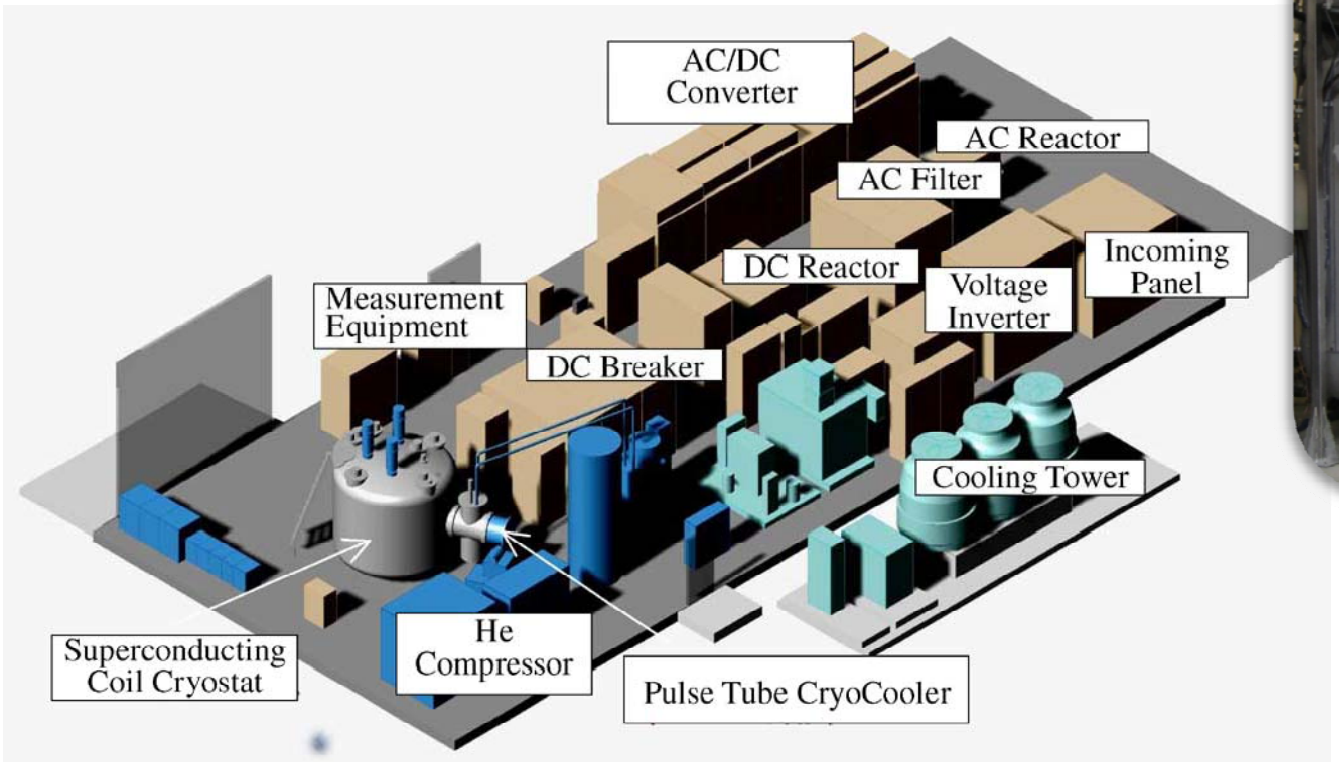
Used to smooth the power demand of a metal rolling factory in Nikko, Japan
stored energy 19.2MJ output power 1 MW



Chubu Electric Power
Mitsubishi
Toshiba
CRIEPI

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SC generator

Hydrogenie genearotor for E.On Power Station on the Main-Donau Kanal at Hirschaid, Germany

Existing 1.25 MW generator sets for hydropower

CRIEPI superconducting generator on test

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SC Transformers

1MVA prototype transformer

630kVA 3 phase transformer at Baiyin China

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Superconducting Motors

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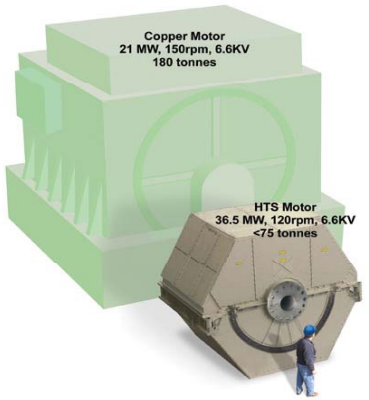
36.5MW ship propulsion motor
B2223 rotor tested Jan 2009



30kW prototype electric car
Sumitomo Electric Industries

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Levitation

18 May 2011
Japanese Government authorizes Central Japan Railway Co to proceed with high speed Maglev link from Tokyo to Osaka by 2045 speed 580 kph

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Superconducting electronics

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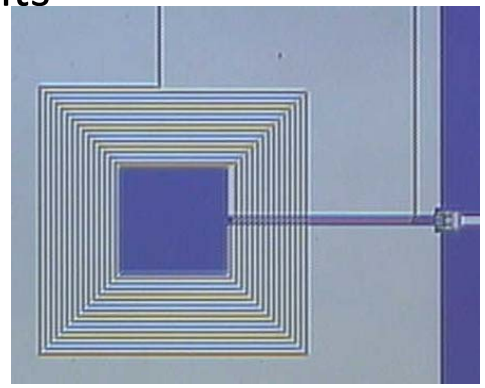
Devices using Josephson effect & flux quantization

- SQUID magnetometers - medical, geology, detection of faults
- absolute voltage standards
- single flux quantum SFQ computing
- analogue to digital convertors
- high frequency mixers



Devices using zero resistance

- cavity resonators
- delay lines
- filters - communications, astronomy
- transmission lines
- bolometers
- antennas - NMR spectroscopy & MRI

low noise and sharp edge filter minimizes out-of-band interference

Geomagnetic prospecting

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Superconducting Technology

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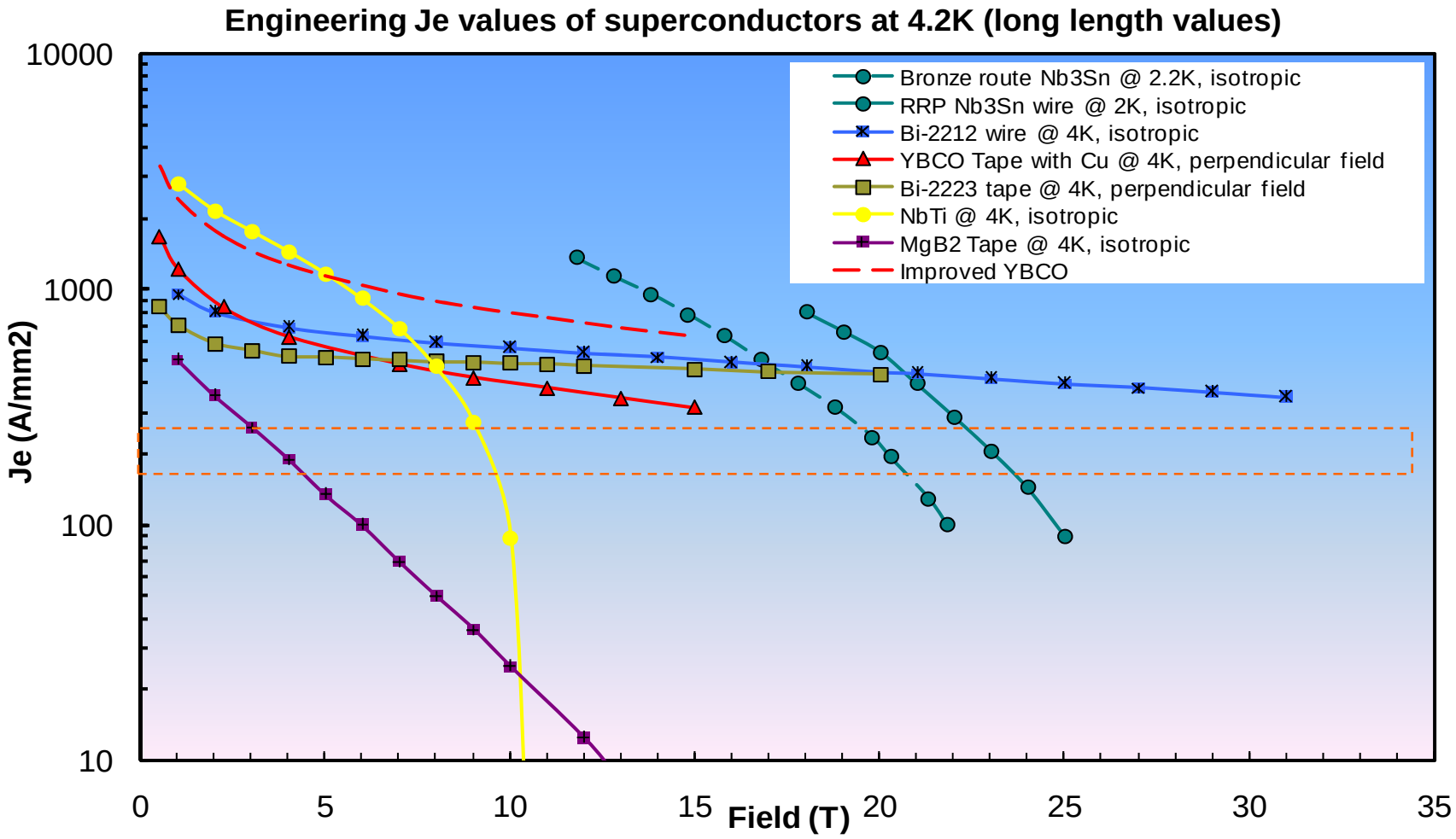
Engineering Current Density Je



LTS practical engineering limit 23-24T?

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Innovative New wires and enhanced performance of LTS and HTS

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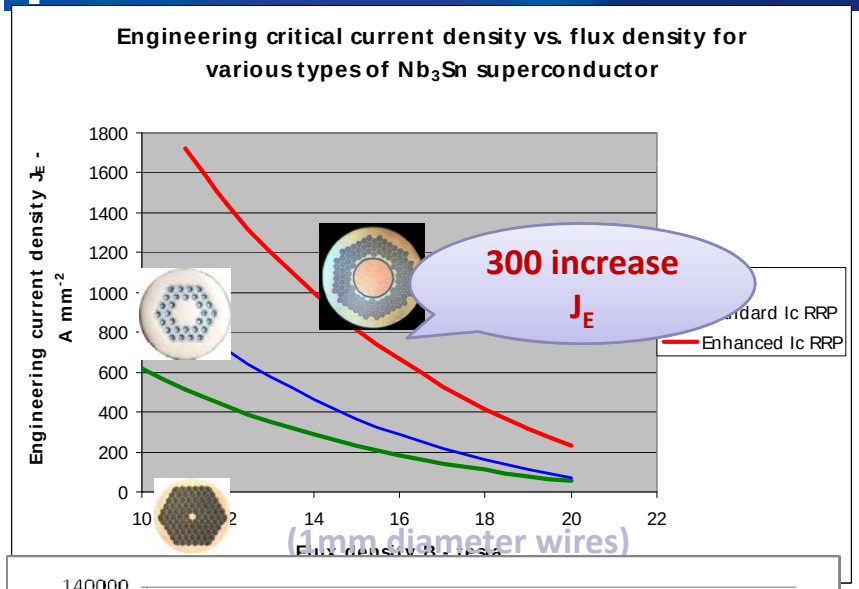
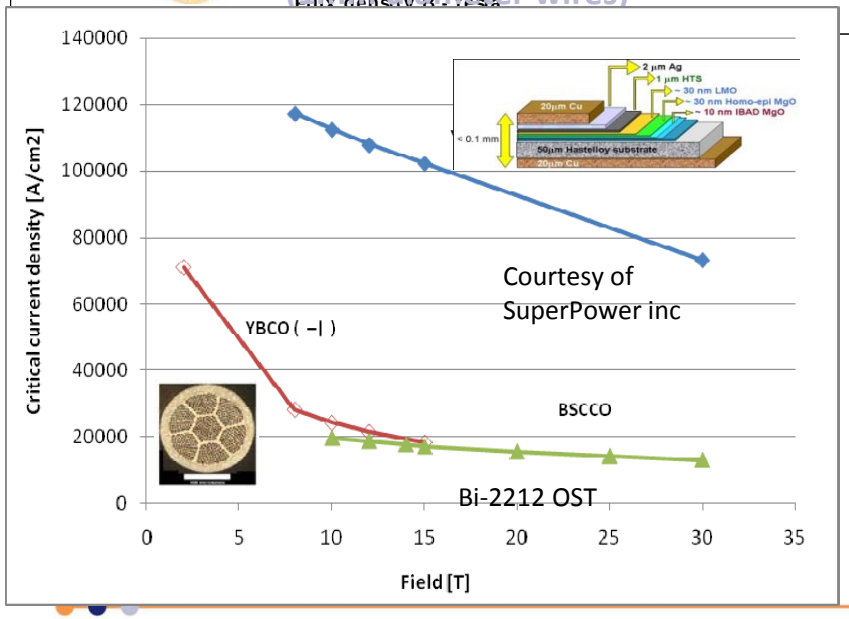
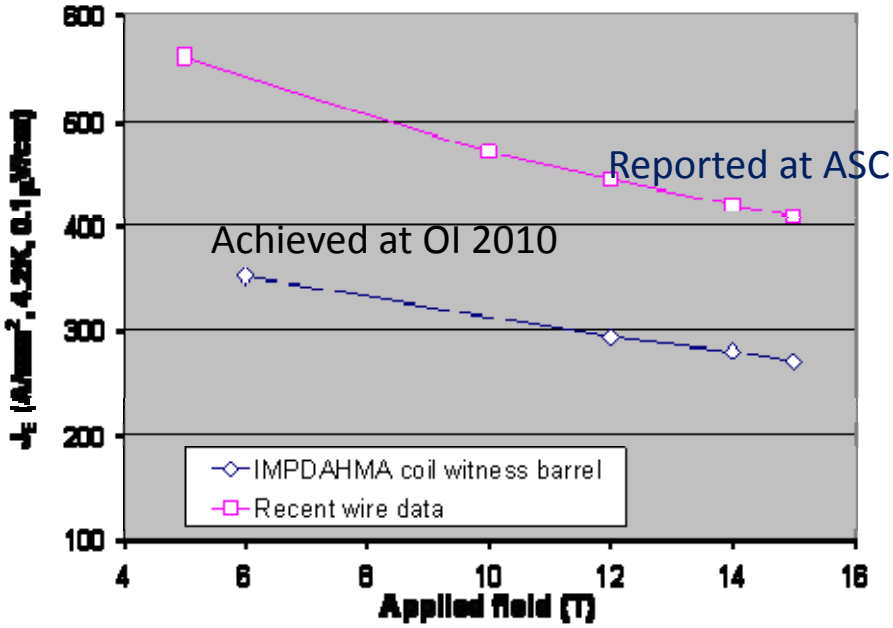




Bi-2212 Round wire



Optimised SC wire designs –

is the route to compact systems and cost effective solutions

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New generation of Superconducting magnets

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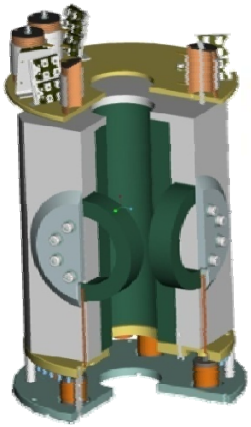
- **New compact HF products**
  - Solenoid magnets at 2.2, 4.2K and >4.2K
  - Split pair magnets
  - Vector rotate magnets
  - Dipoles, Quad, etc,
- **Specific properties for applications**
  - High homogeneity, high stability
  - Cancellation, modulation, gradient coi
  - Active shielding
- **Cooling technologies**
  - Liquid helium ('wet')
  - Recondensing
  - Cryofree®
    - 'Stand alone' cryofree magnets
    - Cryofree magnets with shared cooling



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Need for Compact High-Field Magnets

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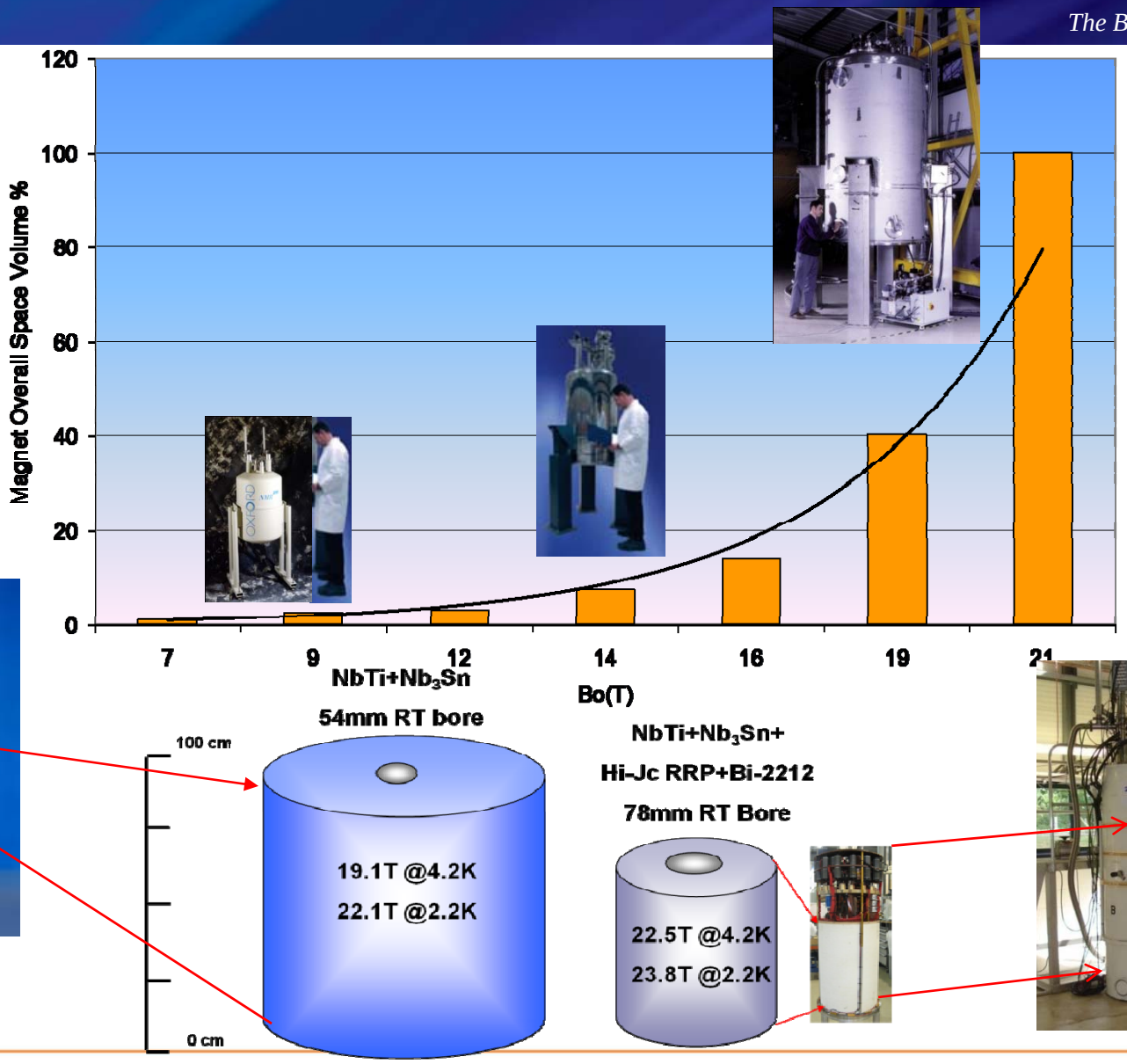

21T
@2.2K

22.5T
@
4.2K

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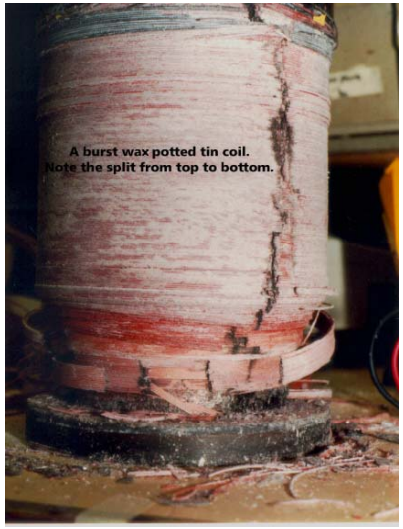
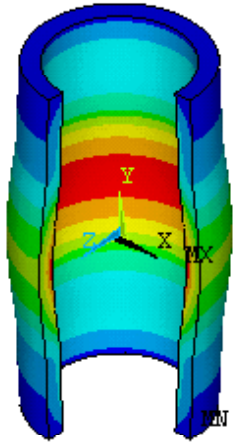
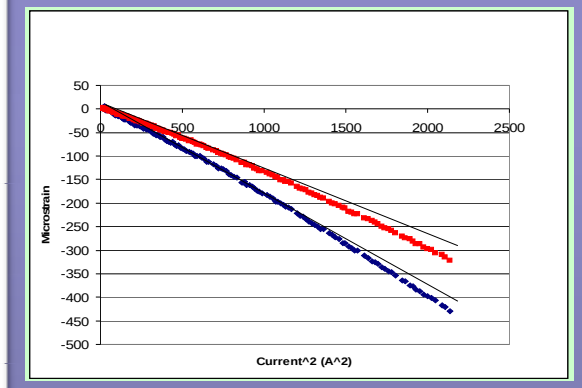
Coil Structure

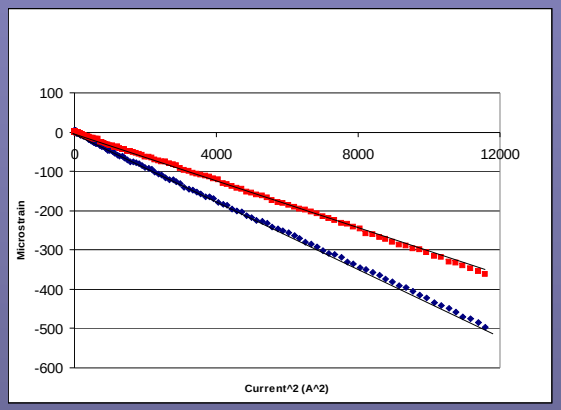
•Operating forces are trying to burst the coil outwards





High stress-strain





Early test coil deflection is non-linear,plastic deformation can be seen.

New Coil\Structure Techniques at OI led to

Coil at full operating stress levels, showing linear, elastic deformation.

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Stored Energy and Quench of HF magnets

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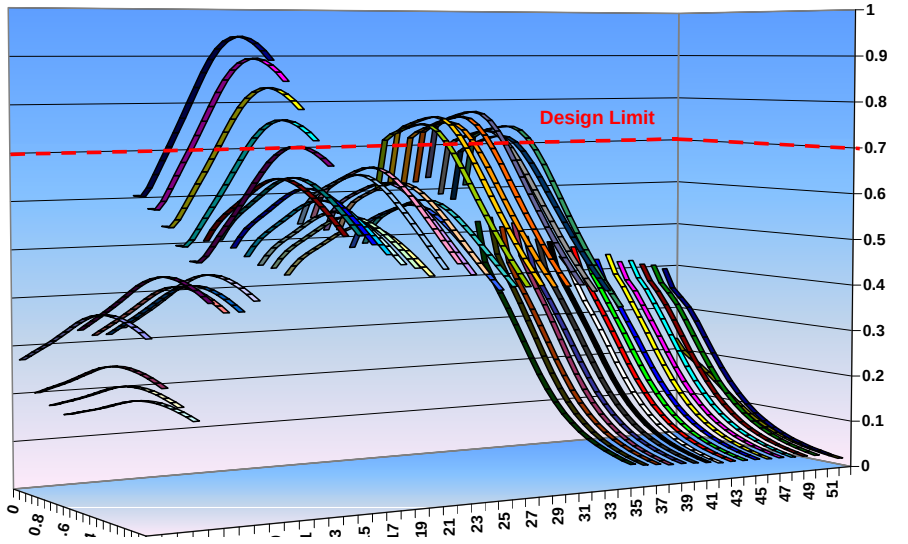
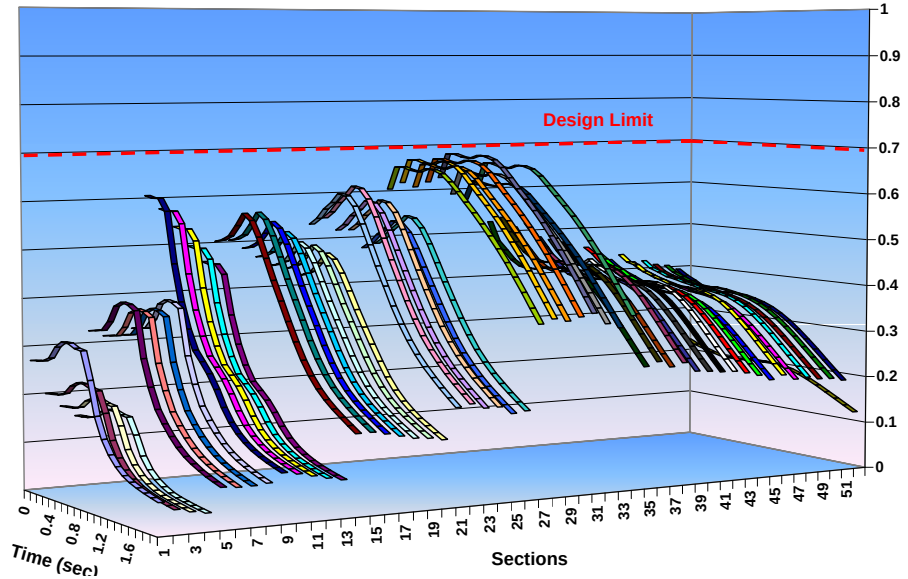
Mack Truck 8.6 Tonnes

60 Mph, 3.05 MJ

900 MHz Magnet
21 Tesla, 30 MJ





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LTS and HTS Integration

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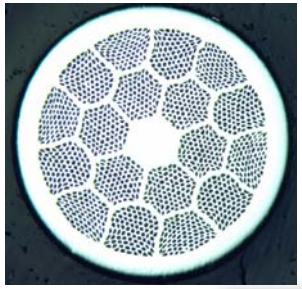
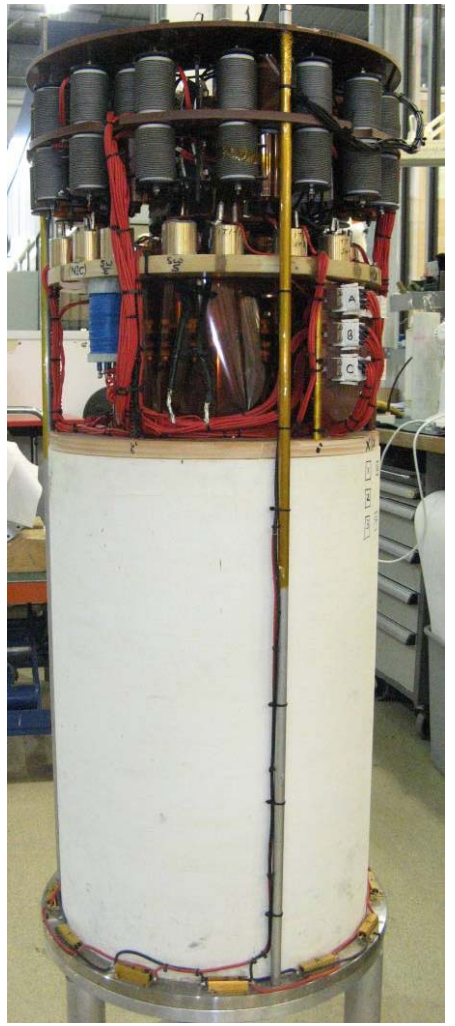
Different HTS inserts developed from Bi-2212 wind & react coils and tested in a 20T LTS magnet

- Set 1, pair of 6 layer coils 100mm long
- Set 2, single 14 layer coil 100mm long
- Set 3, pair of 6 layer coils is 300mm long



1.5mm round wire
(15x85 fil.)



22T (2.2K) 20T @4.2K,
78 mm cold bore solenoid

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The Future in Product delivery -
Solution and services provider for Industry

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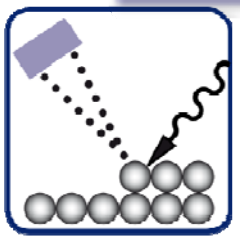
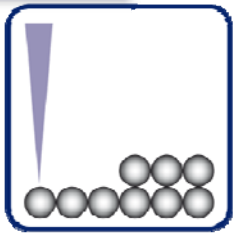
Cooling | **Application** | **HF**

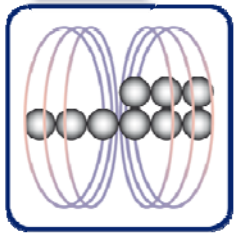
Cryogenic Systems



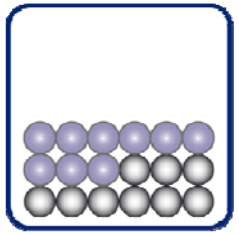
Electron Spectroscopy



Scanning Probe Microscopy

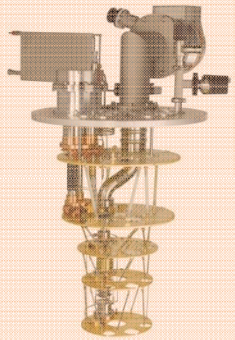


Superconducting Magnets

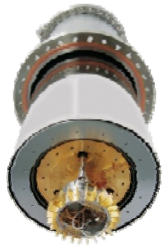


Thin Film & Tailored Systems

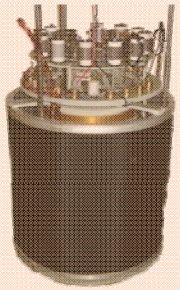
Service and Engineering



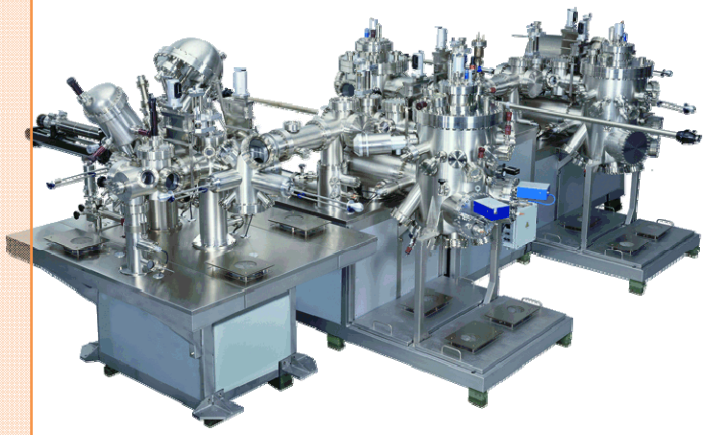
Expertise in cryogenics



Advance performance and reduce cost



Expertise in magnetic fields



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Superconducting Economics

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Market survey by Conectus*

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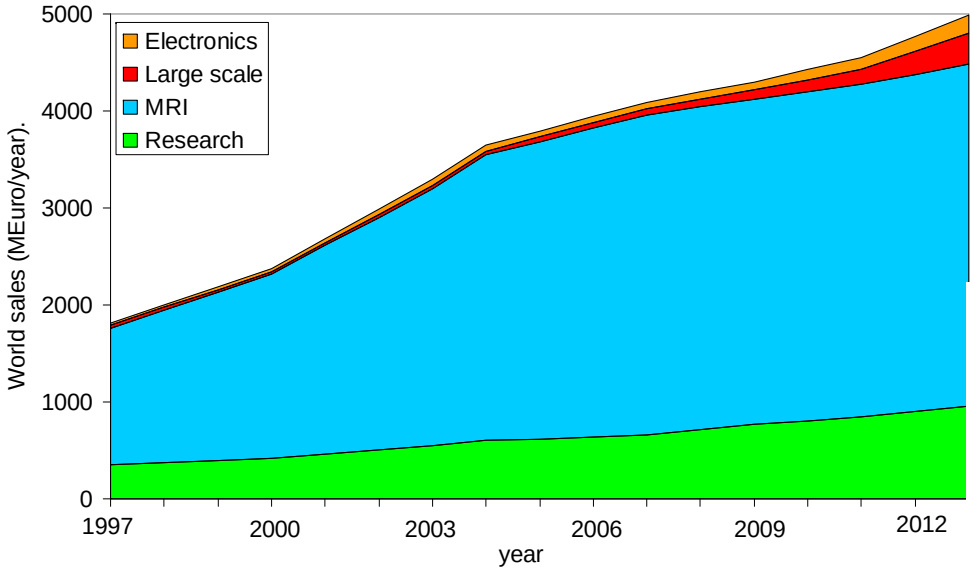
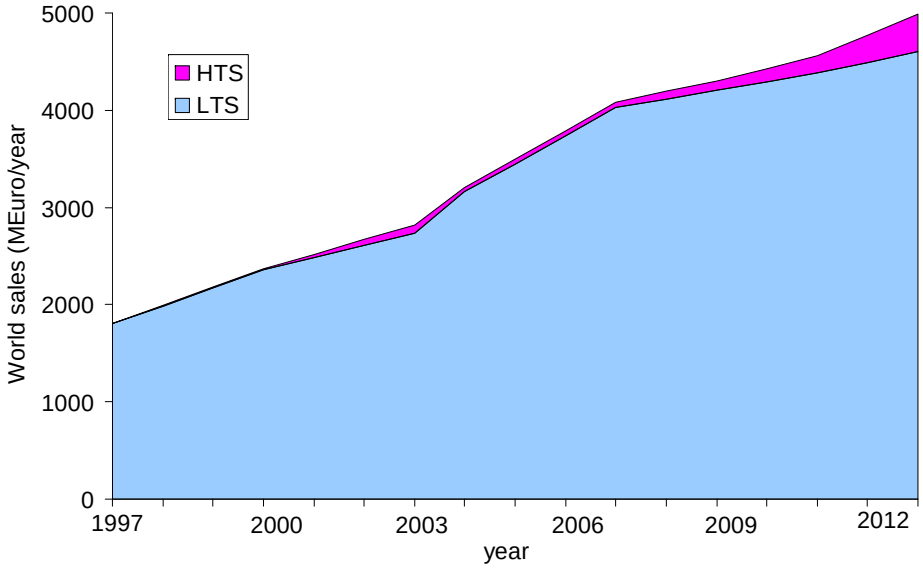
CONsortium of European Companies (determined) To Use Superconductivity



HTS

A lot of promise slow to deliver



Source: www.conectus.org *Dec 2009*

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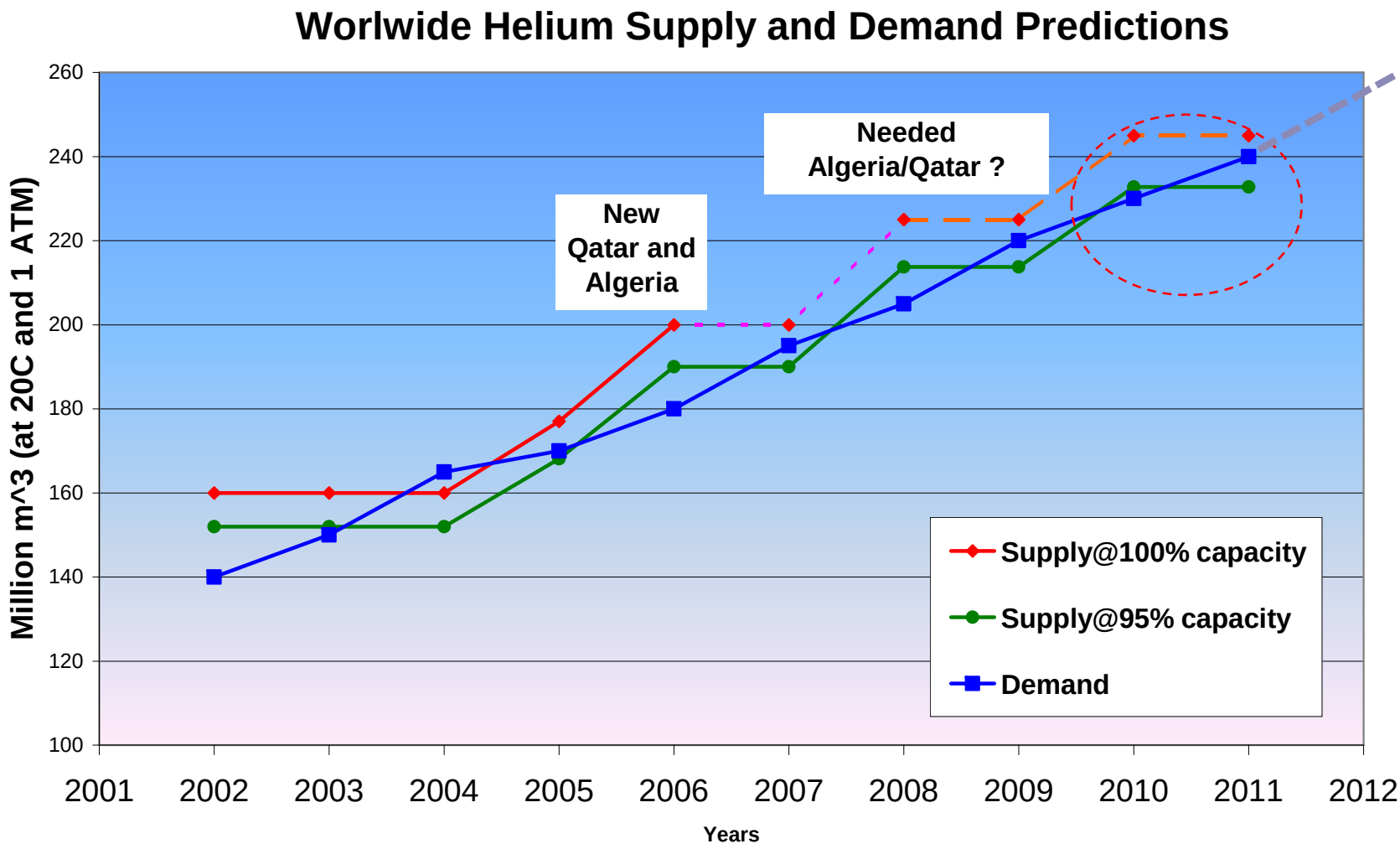
Worldwide Helium Supply and Demand Predictions



Increased demand on Helium will lead to rise in cost !

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Summary

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- ✓ SC using LTS material is a mature technology
  - ✓ small science ⇒ big science ⇒ NMR spectroscopy ⇒ (N)MRI - **all LTS**
- ✓ **MRI** applications dominate the SC market
- ✓ All commercial application of SC is dominated by **magnets**
- ✓ No electrical engineering application has been **economic** with LTS
- ✓ HTS current leads are **economic right now**!
- ✓ HTS magnets & electrical engineering applications will **only be economic** after a 10? fold reduction in the price (per Amp metre) of HTS conductors
- ✓ **Electronic applications** show lots of promise but are **not making any money yet**

Challenge going forward - build on the strengths of superconductivity – and minimize the weaknesses

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Superconducting Magnets are Impacting our Life and our Future

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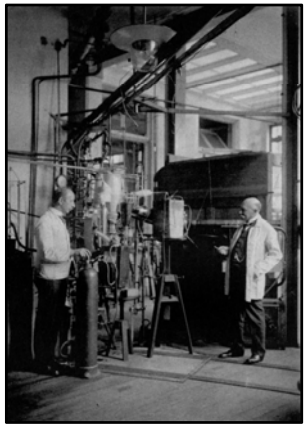
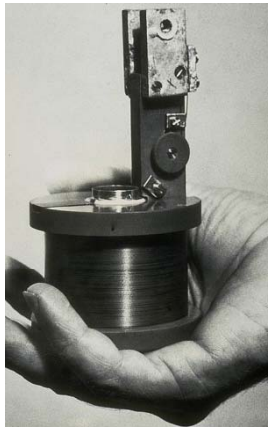
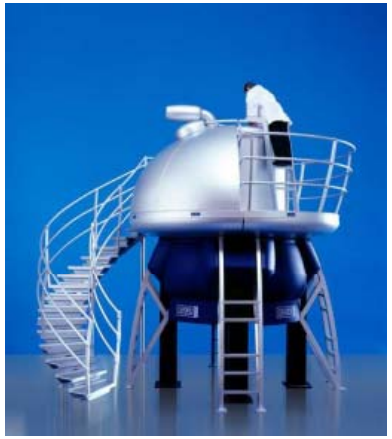
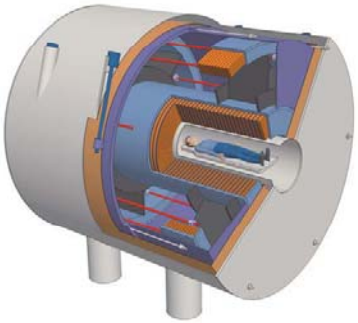
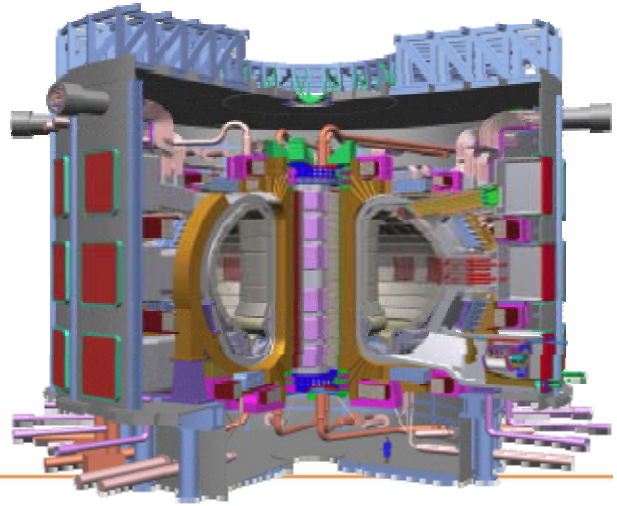





Thank you



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