Application of Low and High T_c Superconductors in Magnets and Power Applications

René Flükiger

Dept. Physics Condensed Matter (DPMC)

University of Geneva

Geneva, Switzerland

Outline

- HTS and LTC Materials
- Power Cables
- MRI: Magnetic Resonance Imaging
- Fault Current Limiters
- Motors, Generators, Transformers
- Very high field magnets, NMR magnets
- Summary

Present Situation of High Current Superconductor Applications

So far the applications have been concentrated on the use of Low Temperature Superconductors (LTS), both in research areas and industrial application areas:

- **magnetic resonance imaging (MRI)**
- **NMR spectrometers**
- **magnetic separators**
- **magnetic energy storage systems (SMES) with small capacity**

General prospects for the future of high current superconductor applications

Potential of HTS Superconductors will open up further application areas, e.g. **electric power engineering.**

It will probably also increase the market for already existing application areas of superconductors.

Time frame for implementation: will strongly depend on developments in the area of conductors and cryogenics

HTS Materials for Applications

Production level	Material	T_c(K)
Industrial	**Bi,Pb(2223)**	**110**
	Bi(2212)	92
Pre-industrial	Y(123), R.E.(123)	92-94

Low T_c materials

Industrial	NbTi	10
Industrial	Nb_3Sn	18
Pre-industrial	MgB_2	39

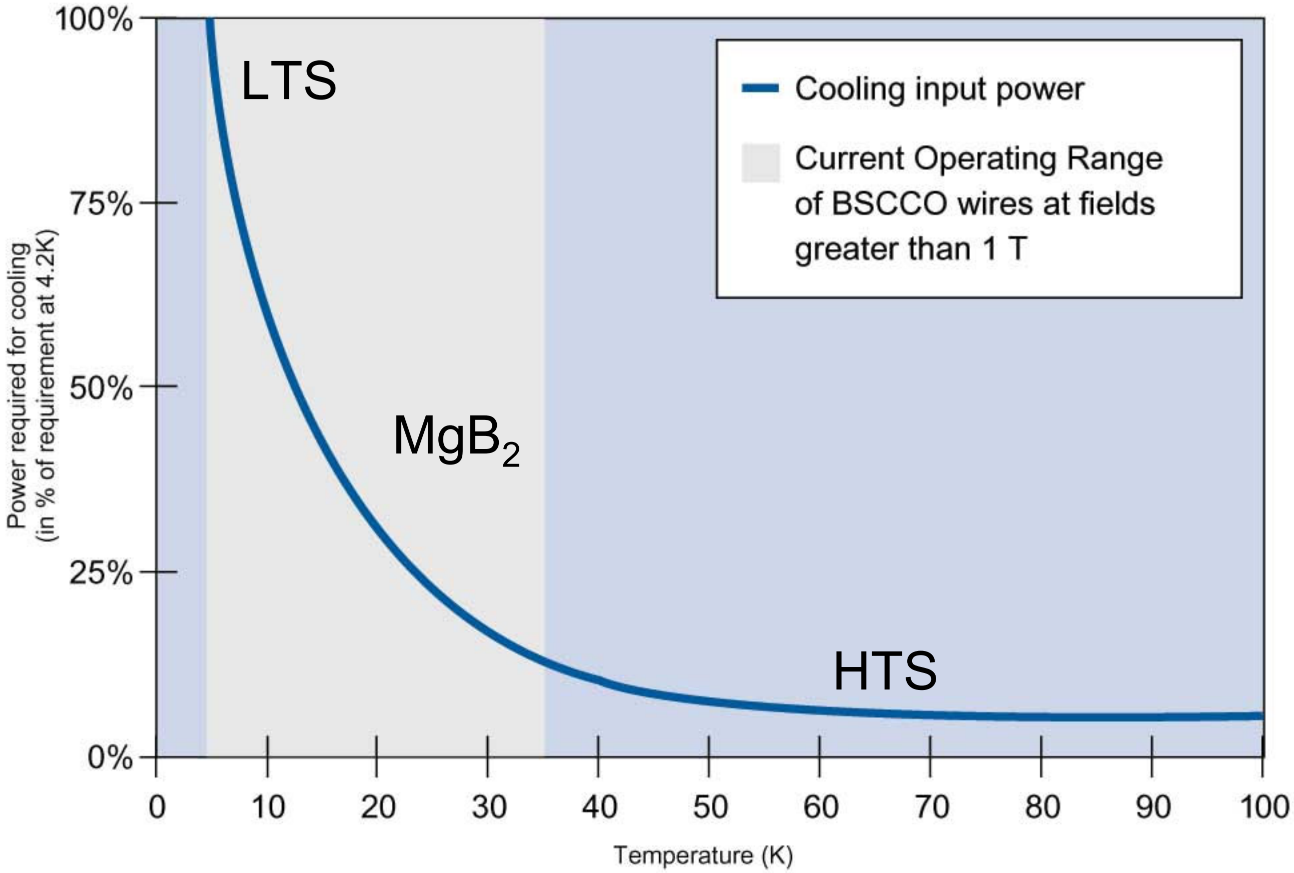
General status of HTS conductors

- **Multifilamentary tape conductors** : **Bi-Sr-Ca-Cu-O**
  developed up to industrial state. Their properties are reasonable for different use, but prizes are **still high**

- **Coated tape conductors**: **Y-Ba-Cu-O**
  offer superior properties, but **very early state of the art**, in spite of large development effort

- **Recently discovered superconductor**: **MgB_2**
  might gain **niche applications**, if further developments will be successful.

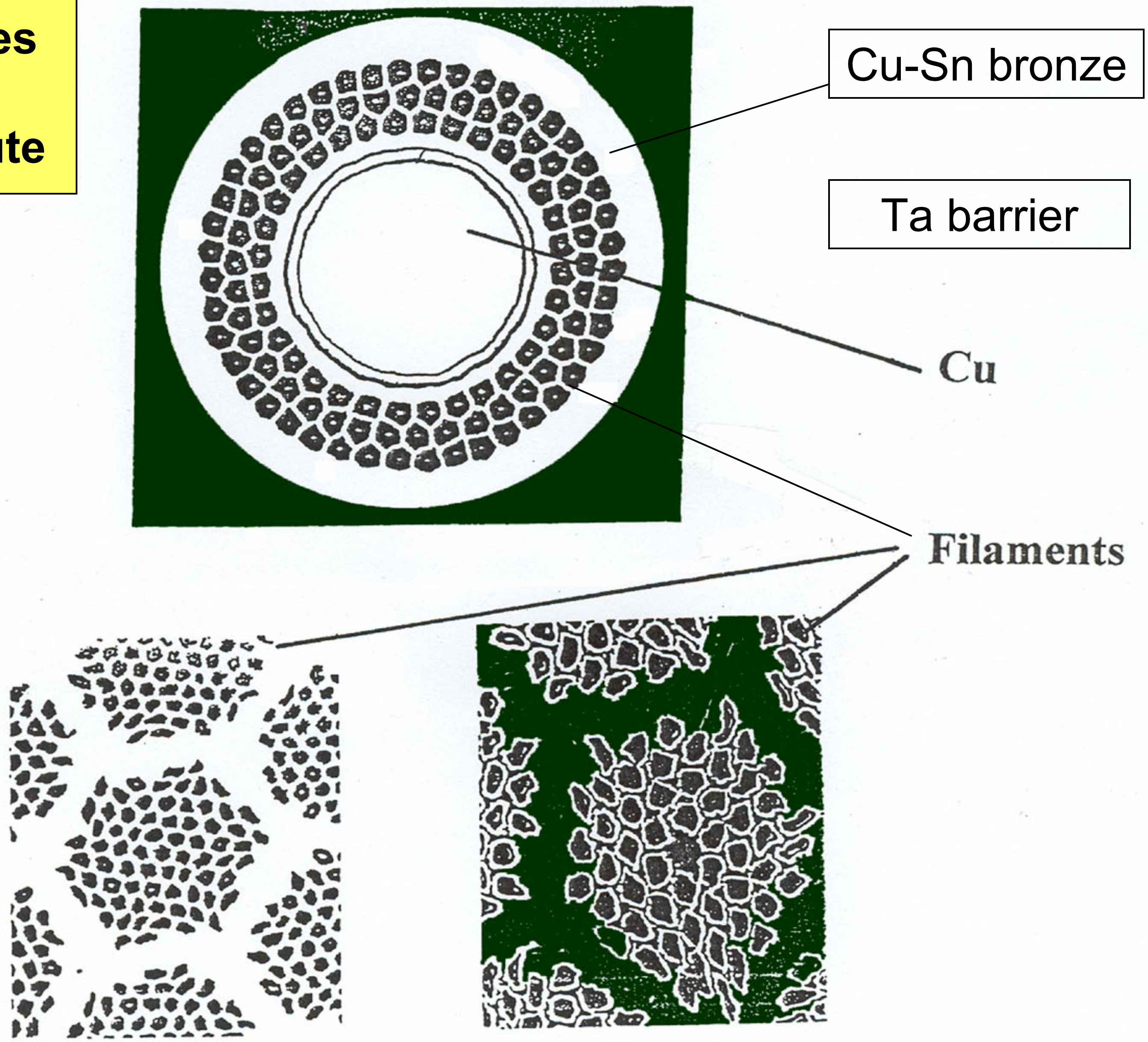
Cooling Power Required for HTS Wires



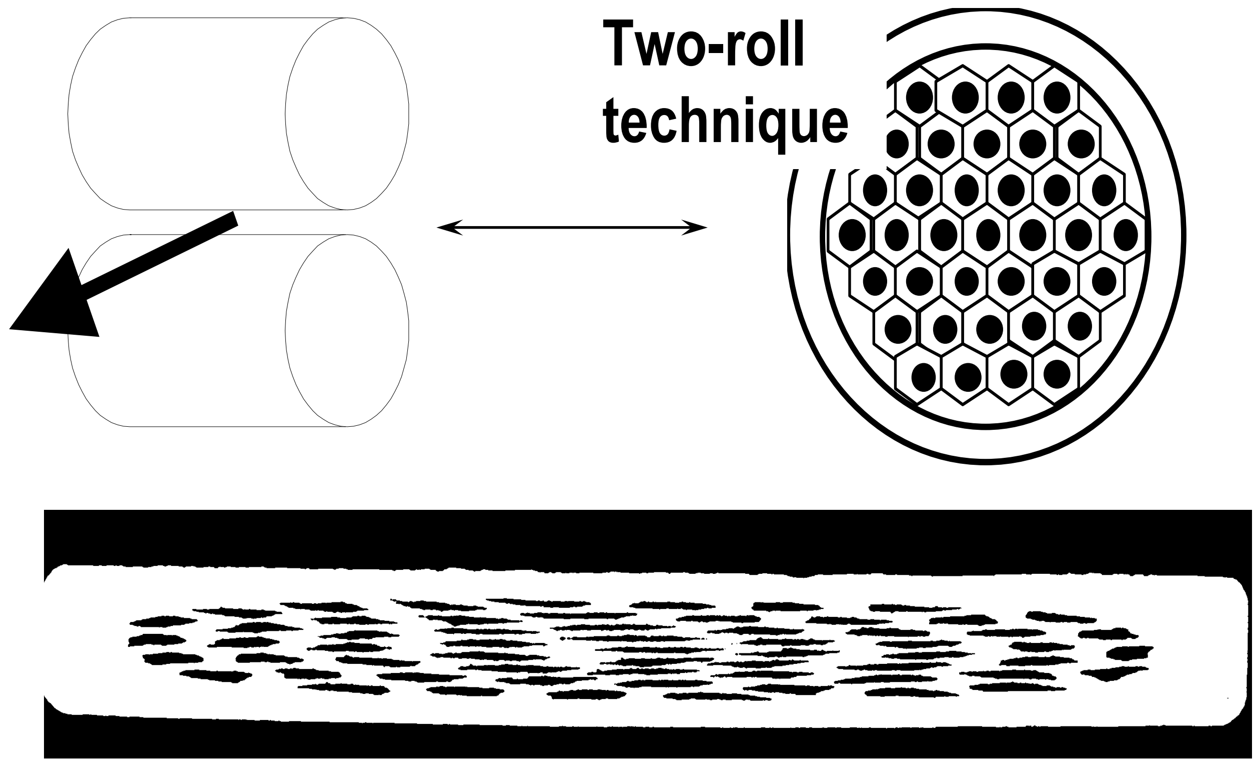
The ideal power required for refrigeration for HTS applications at 35 K is less than 10% of that required for low-temperature superconductivity applications at 4.2 K. Actual power requirements will vary depending on cooling scheme chosen and system efficiency.

Nb_3Sn wires

Bronze route

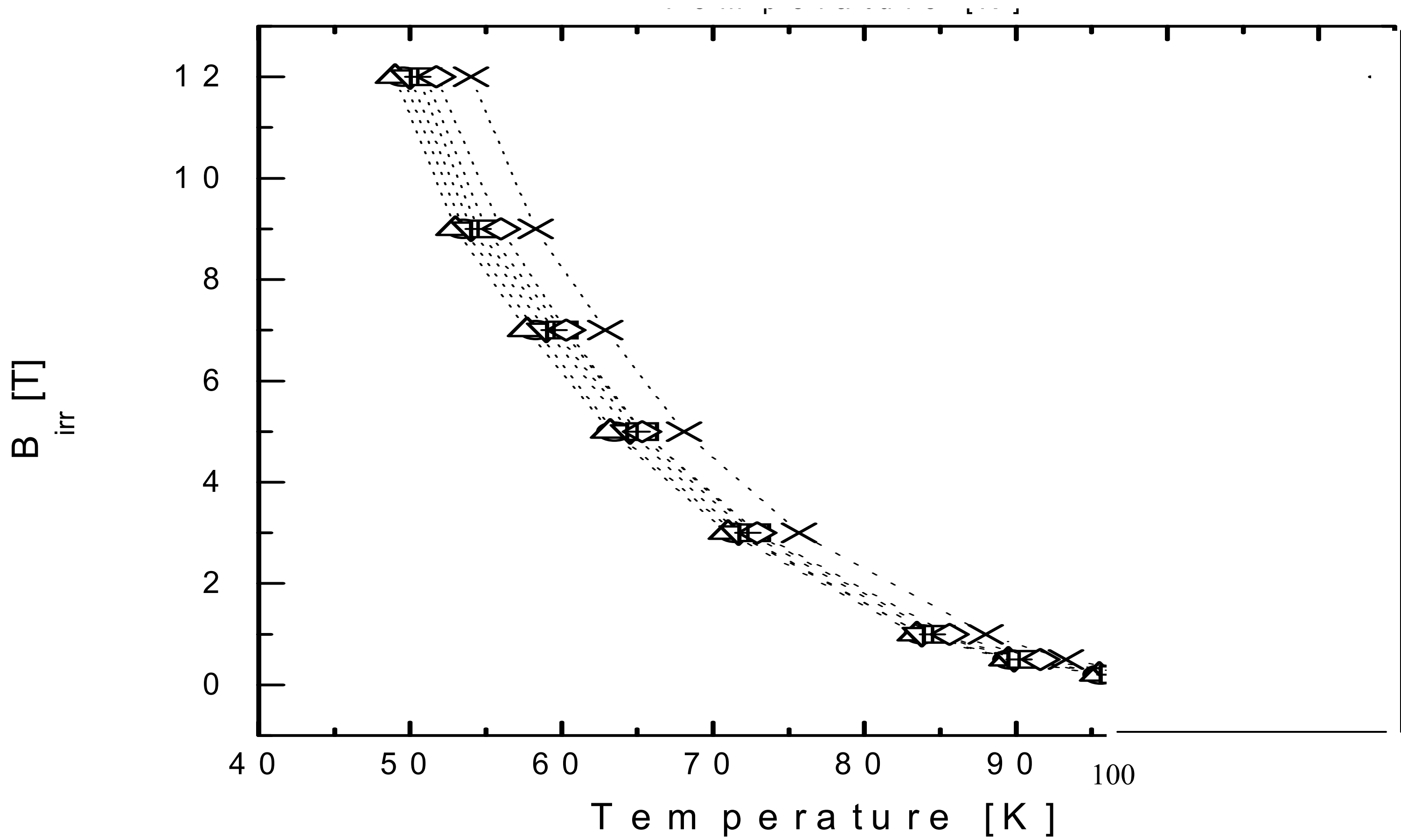


Bi,Pb(2223) multifilamentary tape

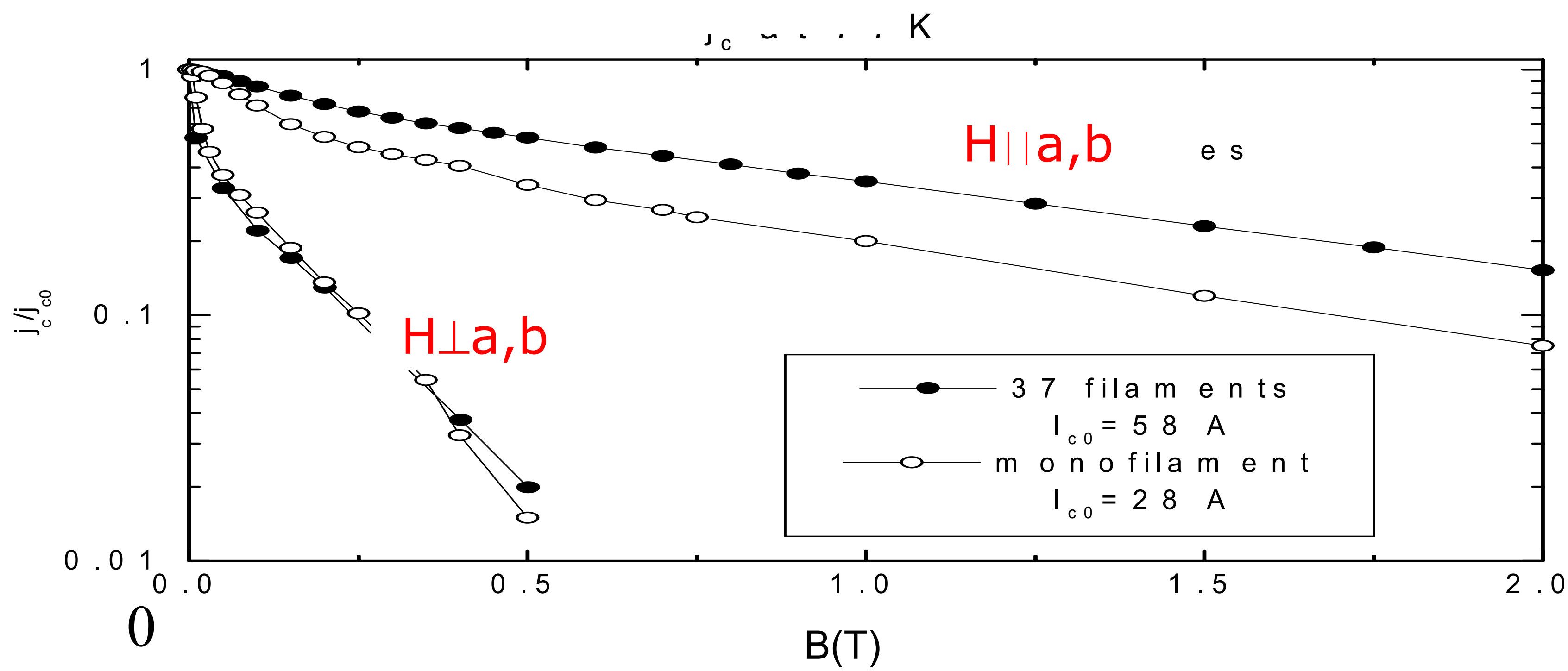


Bi,Pb(2223) Tapes

Temperature dependence of J_c

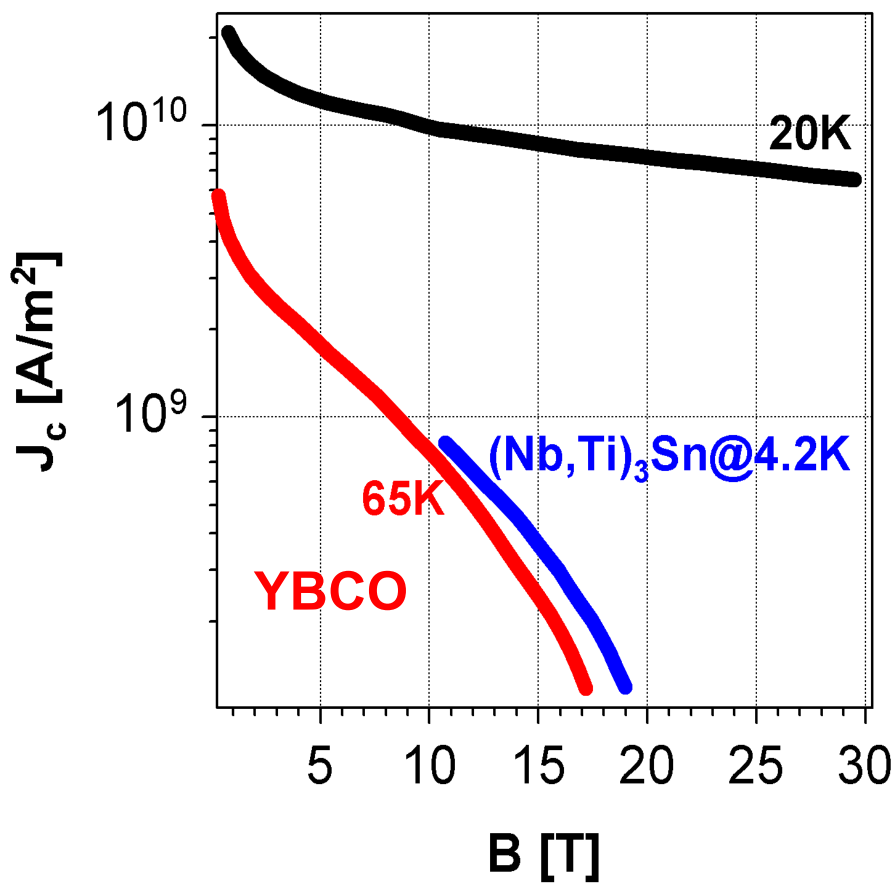


Critical current density of Bi(2223) tapes :Anisotropy



T [K]	J_c [A/cm2]	Achievable field
77	45’000	0.5–0.6 T
30	≈100’000	3–4 T
4.2	≈200’000	>25 T

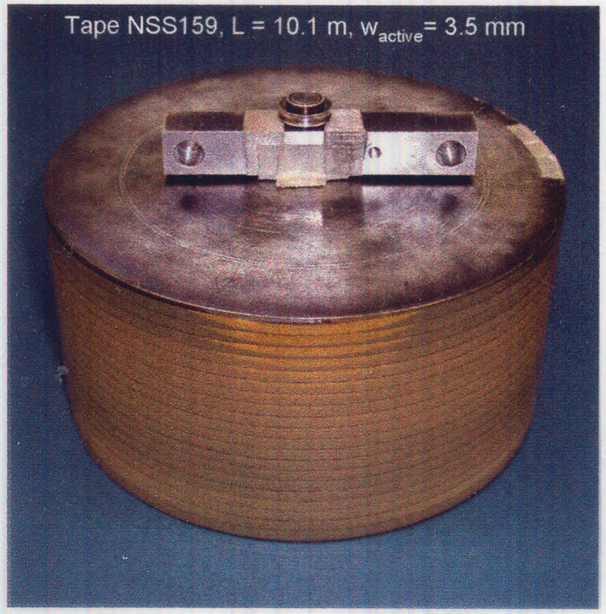
Comparison of J_c-B- I properties: YBCO, $(Nb,Ti)_3Sn$

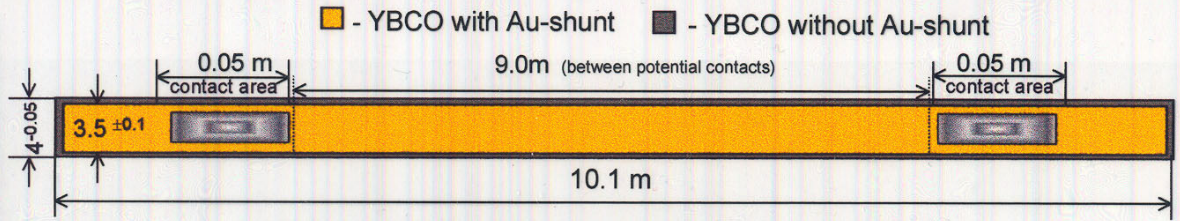


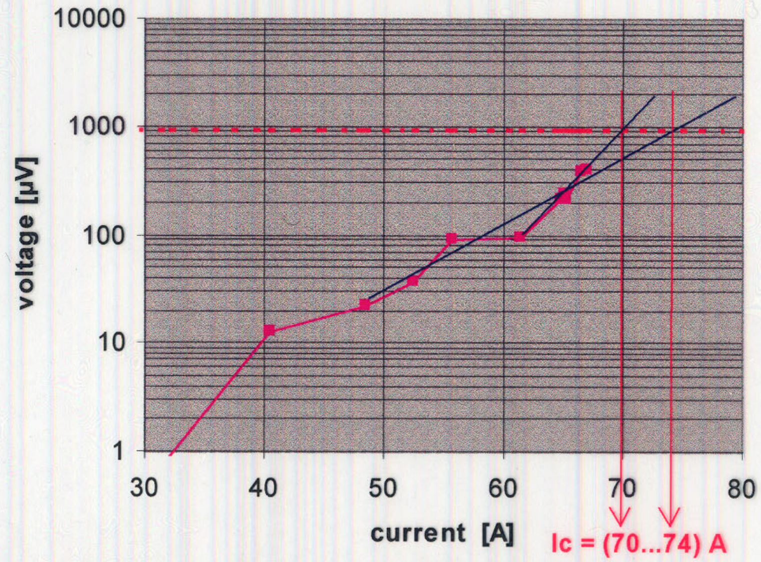
University
Göttingen
H. Freyhardt

Coated Conductors: Long YBCO coated SS tapes

March 2002





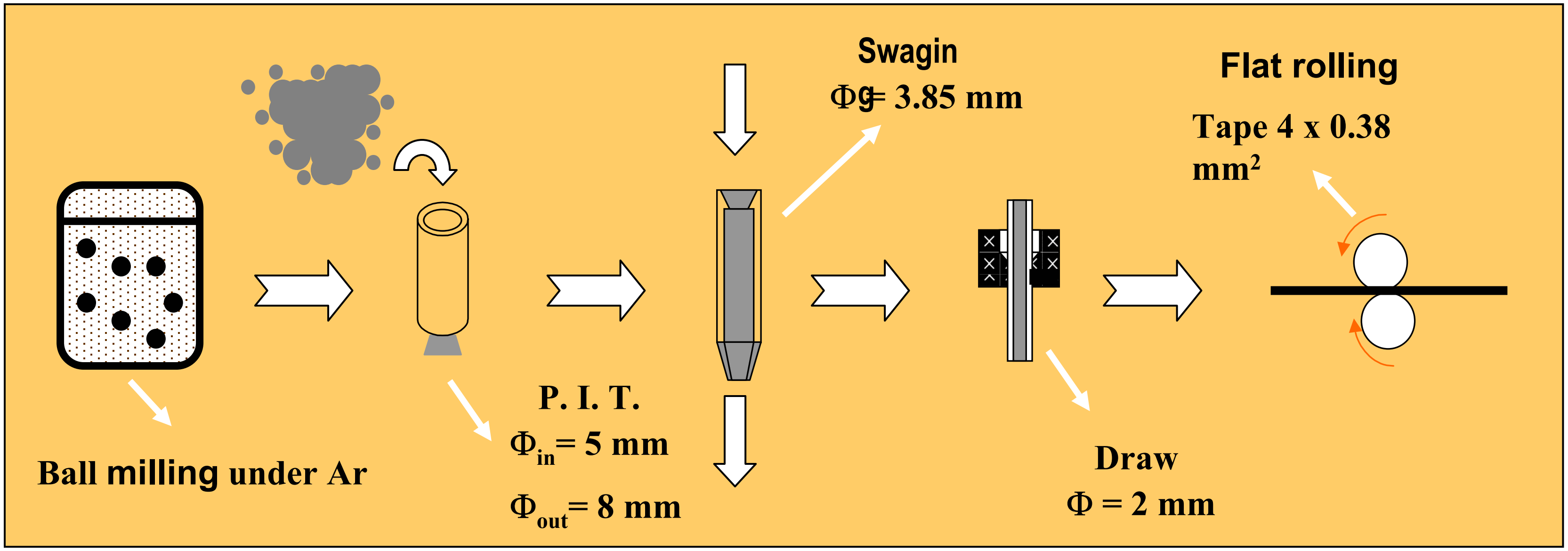


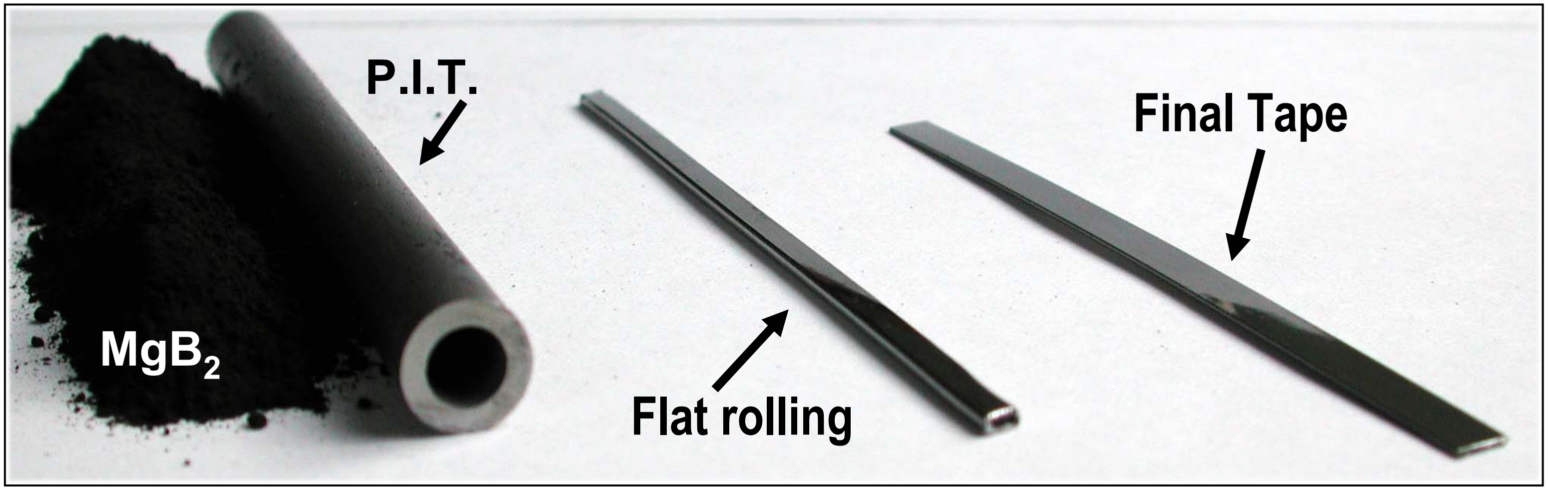
- SS tape (0.1 mm) // IBAD-YSZ (1.3 µm) // CeO_2 (<0.1 µm) // YBCO (1.1 µm)
- Coated Conductor : **10 m long, 4mm wide, with 3.5mm-wide YBCO film**
- Critical current, I_c, and current density J_c :

$I_{c,min}$ = 70 A & $J_{c,min}$ = 1.82 MA/cm², $J_{c,max}$ = 3.3 MA/cm² & Ic/w = 200 A/cm (77K, SF)

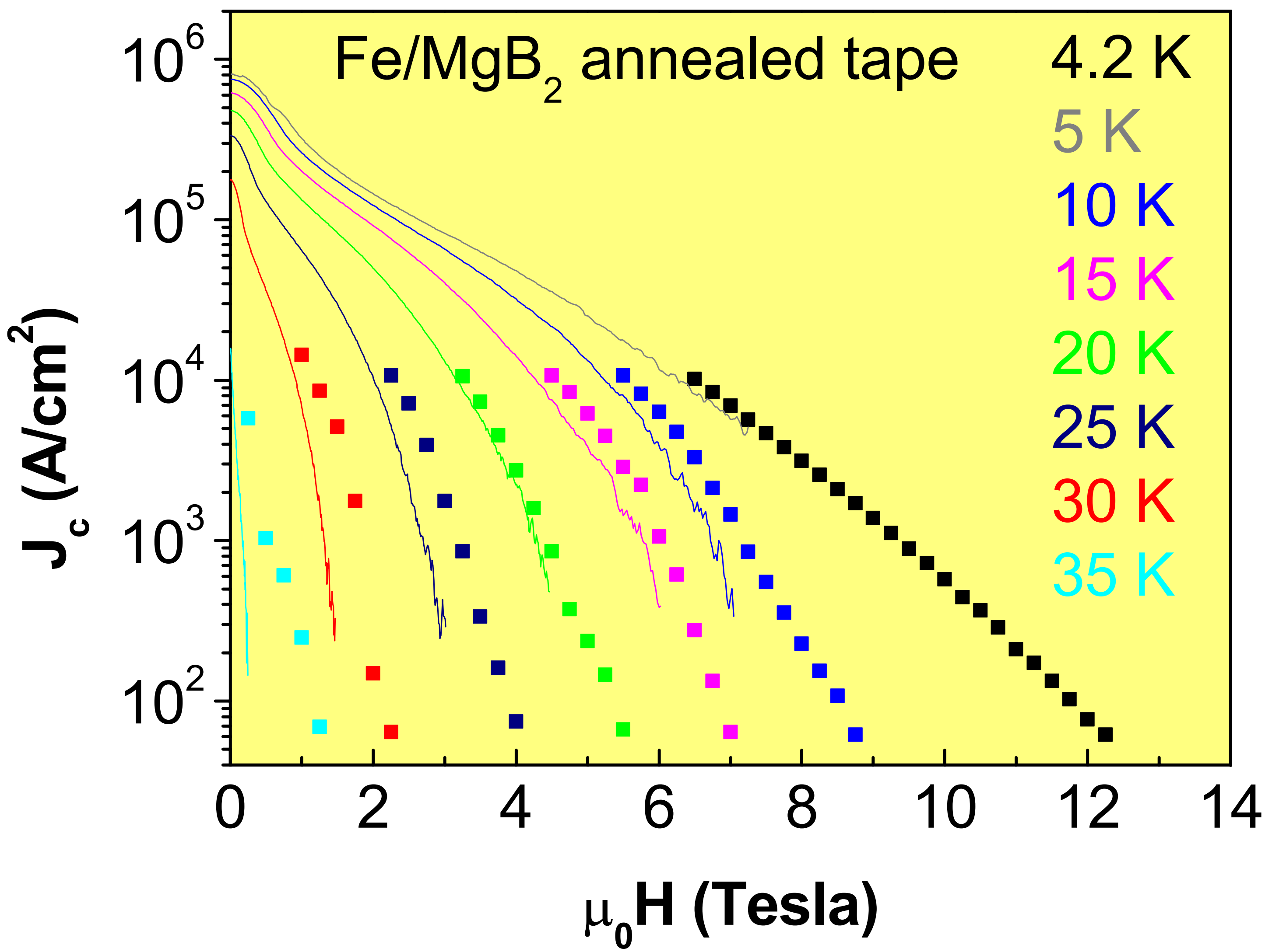
MgB_2 Tapes and Wires

Preparation of MgB_2 Tapes



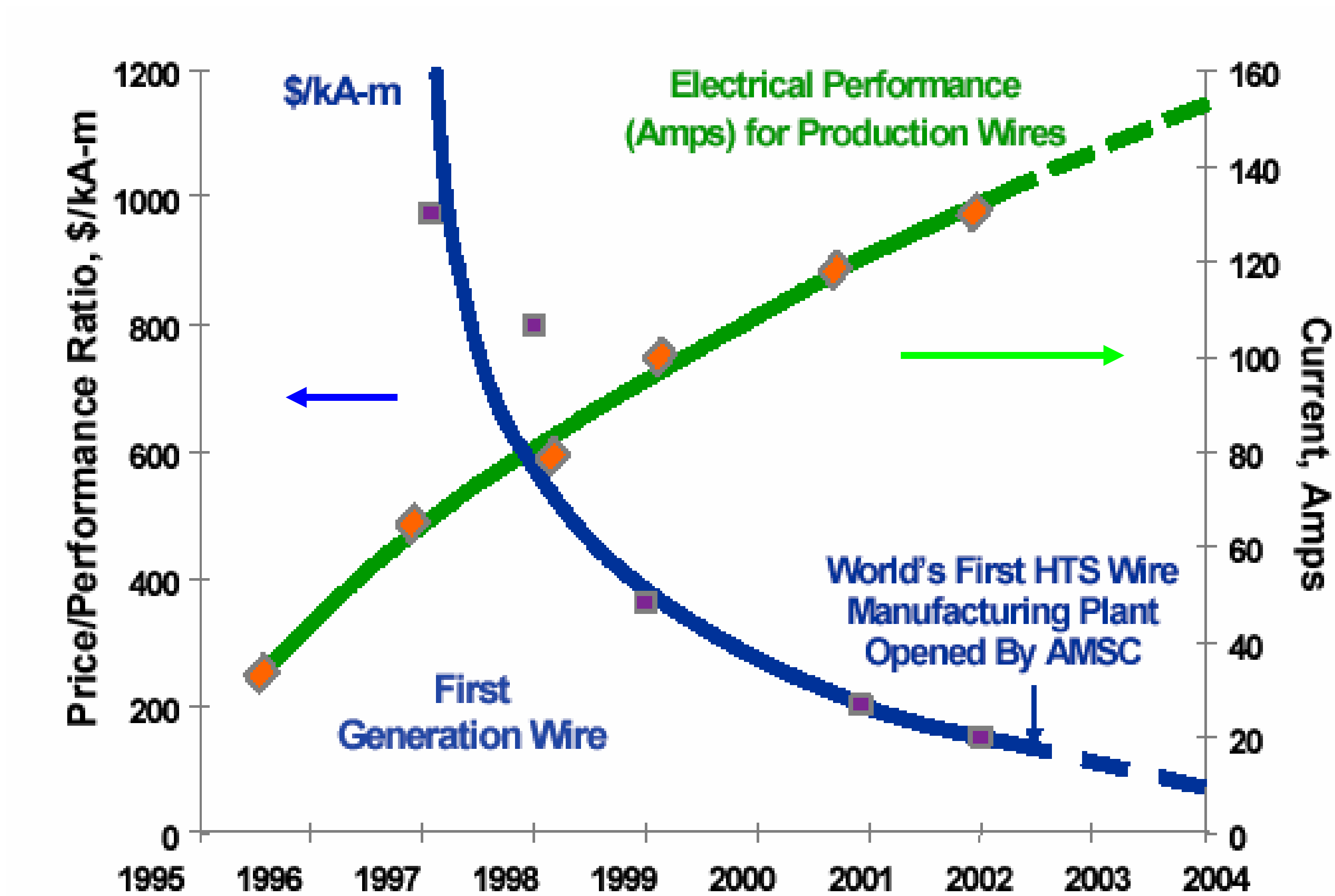


Critical current densities of Fe/MgB_2 tapes



First Generation HTS:Bi,Pb(2223)
Price/Performance ratio of multifilamentary wires

(Data from American Superconductors)



Costs of Superconducting Wires

• Bi(2223): HTS Conductors

- 200 $/kA.m at 0T/ 77 K
  - 150 $/kA.m at 25T/ 4 K
  - Goal: 30 - 50 $/kA.m at 0T/ 77 K

Conditions at 0T/ 77K correspond roughly to:
12T/ 4K, or
7T/ 20K

• LTS Conductors

- MgB2 Tapes:
  < 10 $/kA.m at 20K/2T
- NbTi - Standard:
  4 - 6 $/kA.m at 8T/ 4K
- Nb_3Sn - Standard:
  15 - 30 $/kA.m at 12T/ 4K
  75 - 150 $/kA.m at 21T/ 2 K

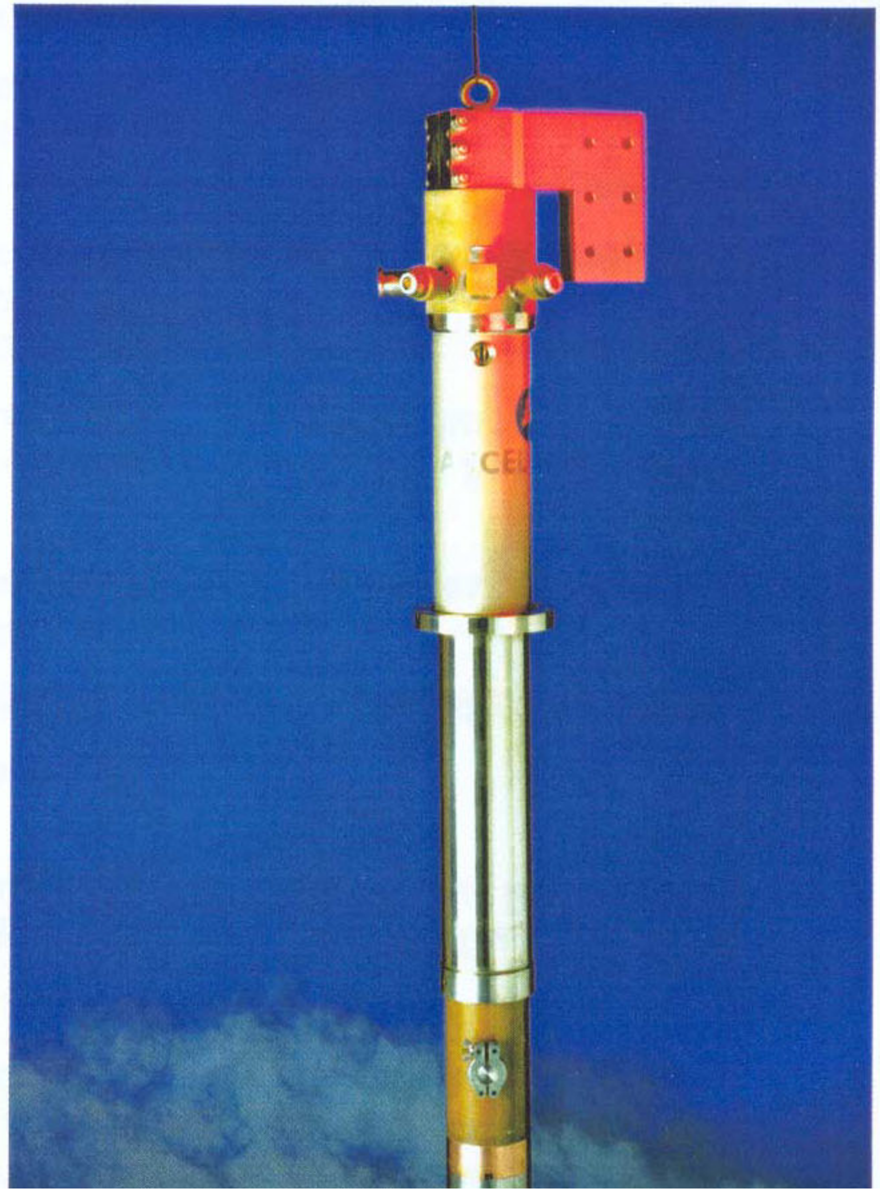
Current Leads

American Superconductors

13 kA HTS Current Leads for LHC, CERN

Features

- Bulk BSCCO material at the lower stage
- Upper stage with helium gas heat exchanger
- High thermal runaway stability after loss of coolant
- Vacuum-insulated envelope



Parameter list 13 kA Current Lead

Rated current	13 000 A
Heat load to liquid helium	1.5 W @ 13 kA 1.0 W @ 0 A
Contact resistance	2 nΩ @ 4 K 20 nΩ @ 50 K
Time constant of current decay after detection of a quench (quench stability)	120 s

Superconducting Cables

Foreseeable "near term" applications with the HTS conductors developed so far

- Power transmission cables, using Bi(2223) at ~ 65 K
- Later on, YBCO at 77 K is also envisaged

S.C. Power Transmission Cable Projects

recently completed or running

- **Sumitomo Electric + TEPCO : 66 kV/114 MVA, 3-phase cold dielectric, 100 m, One year test operation at CRIEPI, completed June 2002**

- **Southwire/USA:12,4 kV/26 MVA, 3 single phases, 30 m,cold dielelectric, in operation now since 2001, supplying the manufacturing complex in Carrolton in automated mode**

- **NKT/Denmark: 30 kV/104 MVA 3 single phases, 30 m, warm dielectric, in operation since 5/2001 supplying the Amager area of Copenhagen**

- **Pirelli/USA:24 kV/100MVA, 3 single phase, 120 m, warm dielectric, two phase have vacuum leaks, thus only one can be tested (in 2003).**

S.C. Power Transmission Cable Projects

planned or under construction

- **Super ACE/Japan: 66 kV/ ~ 100 MVA, 3 single phases, cold dielectric, 500 m, under construction for operation in 2003/04, Bi-2223**

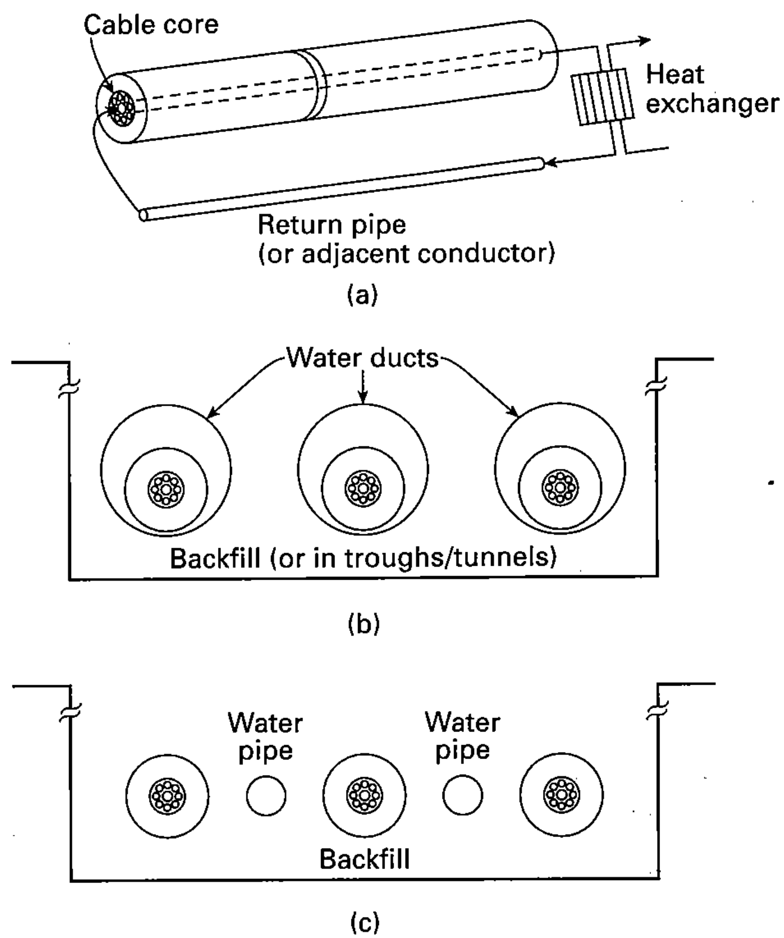
- **El./Japan: 34,5 kV, 3-phases, cold dielectric, 350 m, for Niagara Mohawk**
  distribution system in Albany, Bi-2223
  30 m YBCO cable sections are planned
  Project has started (25 Mio. $), operation is scheduled for 2005

- **ULTERA (NKT + Southwire): for American Electric Power Company at**
  Ohio, design started, completion of construction planned for 2005

- **InnoPower/Yunnan/China: 30m demonstrator scheduled for 2002-2004.**
- **Condumex/Mexico: 30m demonstrator for 2003-2005.**
- **KEPCO/Korea: 100m demonstrator, planned.**

Retrofit:

CONVENTIONAL UNDERGROUND CABLE REQUIRES SPACE UNDER THE STREET



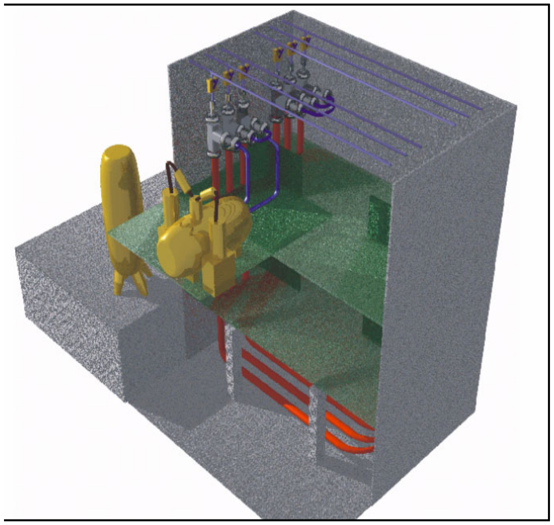
some cables
are on trays
in tunnels

<--- 1 meter --->

some cables are in trenches
cooling may be required

Engineers want FLEXIBLE CABLES

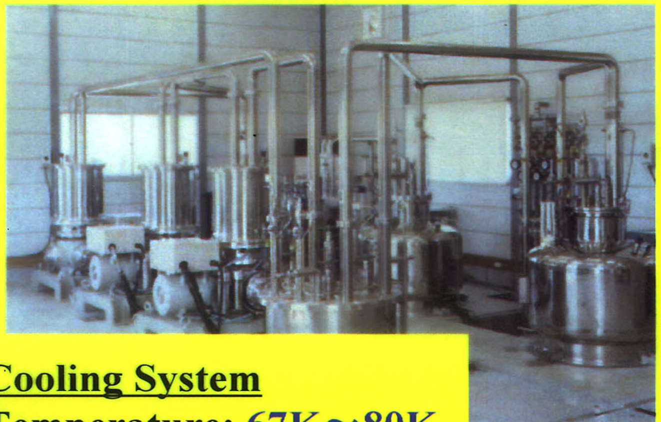
- Enables transport on cable drums
- Enables installation in cramped places

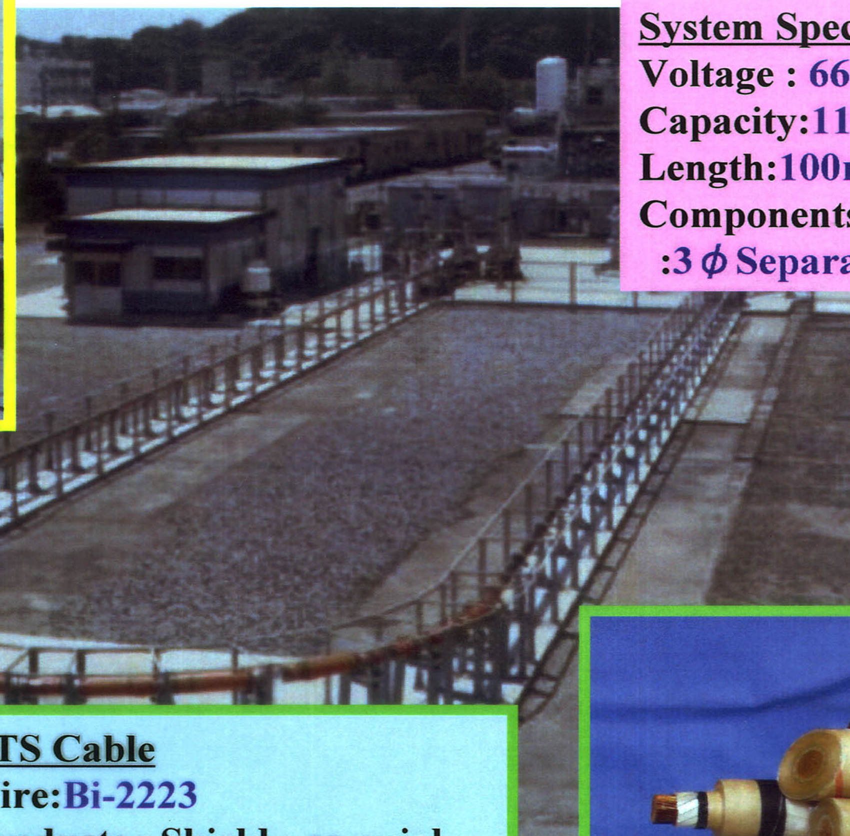


DTU-NST cable installed at Copenhagen Light & Power's Lyngby Station

Field Test of Commercial Model HTS Cable System (TEPCO, CRIEPI, SEI)

2001/6~2002/6 at Yokosuka Laboratory of CRIEPI





System Specifications

Voltage : 66kV

Capacity:114MVA

Length:100m

Components

:3 ϕ Separator, Termination

Cooling System

Temperature: 67K～80K

Pressure: ～0.5MPa

Refrigerator :1kW × 3

Cryo-pump : 2

HTS Cable

Wire:Bi-2223

Conductor,Shield : co-axial

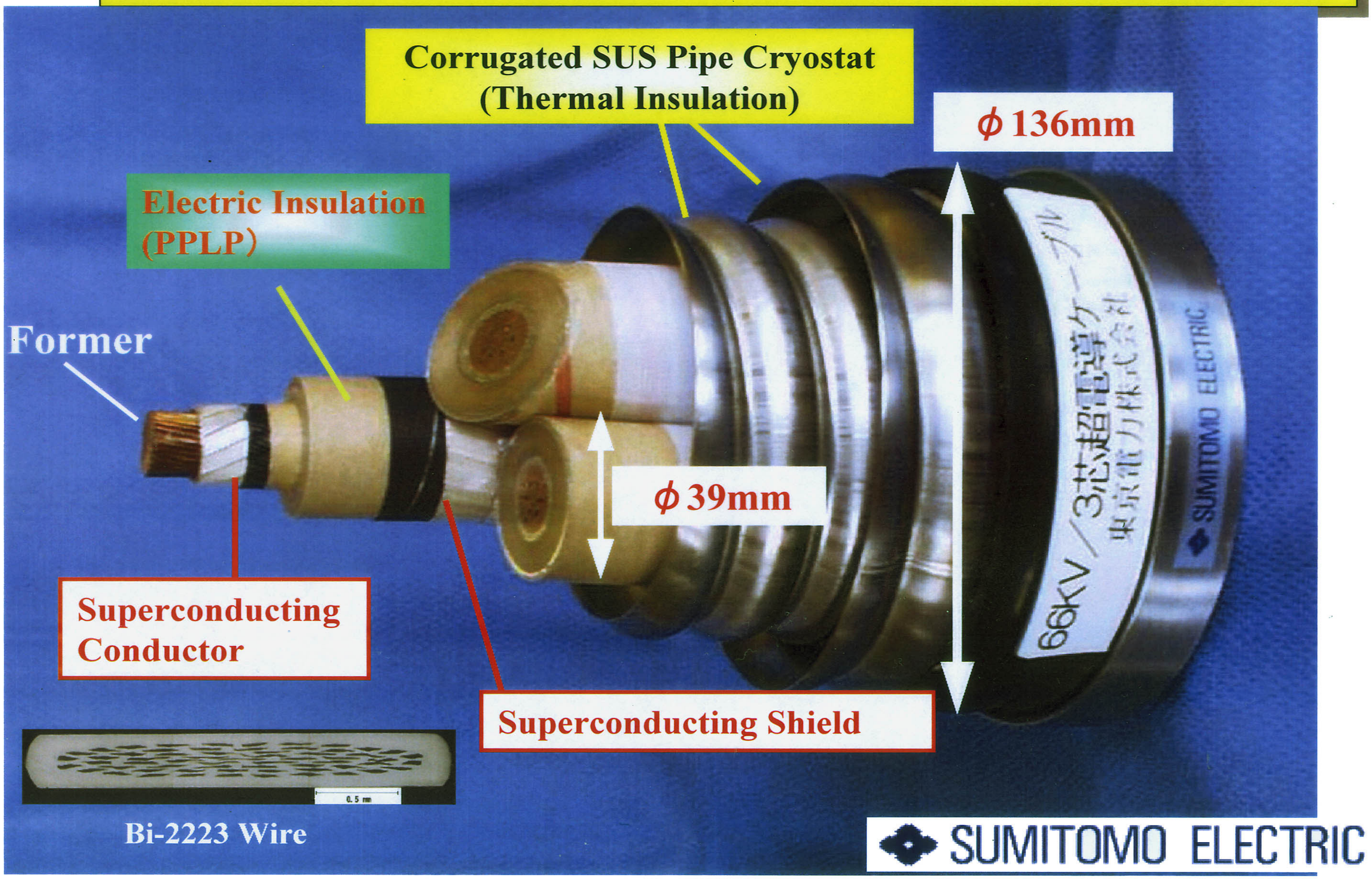
Dielectric :PPLP in LN2 (CD)

Diameter : 136mm

SUMITOMO ELECTRIC

100m-114MVA-1000A / C3-PO Cable

Cold Dielectric Designed 3-Core in a Cryostat Power Cable



Magnetic Resonance Imaging

Benefits of MRI

MRI largest existing application of superconductors

* Increase in medical diagnostic ability
* Elimination of harmful X-ray examinations
* Greatly reduced need for exploratory surgery

* Very precise diagnostics and location information

$\rightarrow$ reduced number of interventions

$\rightarrow$ reducing the length of hospital stays

$\rightarrow$ reduced degree of discomfort suffered by patients

Largest obstacle for MRI: capital cost of equipment

Open MRI using Bi(2223) Tape

- **Oxford Instruments / Siemens**

- **HTS pancake coils can be manufactured at a size suitable for MRI**
- **MRI suitable magnetic field:**
  0.2 T, +/- 20ppm over a 36 cm sphere

- **Direct cooling by refrigerator,**
  - without the use of cryogens,

Fault Current Limiters

Superconducting Fault Current Limiters

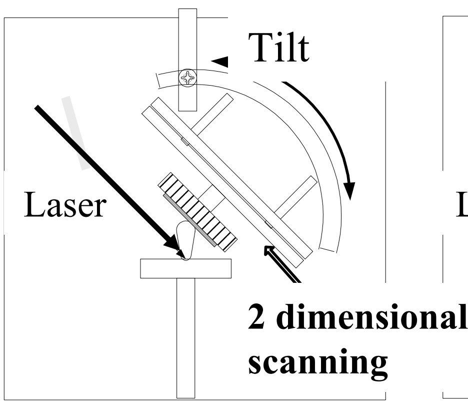
European Development

Company	Country	Type	Data	Material	Remarks
Siemens	Germany	Resistive	100 kVA / 97 1 MVA / 00	YBCO film	tested tested
ABB	Switzerland	Resistive	1.6 MVA / 00 6.4 MVA / 01 10 MVA / 03	Bi(2212) thick film	tested tested ?
Schneider 1)	France	Resistive Hybrid	400 kVA / 00 17 MVA / 02	YBCO bulk	EU -project „BYFAULT" terminated 2002
Alcatel 2)	France	Resistive	400 kVA / 01	Bi(2212) bulk & YBCO tape conductor	Brite EuRam project „SUPERPOLI" completed 2002
ACCEL 3)	Germany	Resistive	90 kVA /01 0.4 MVA /02 10 MVA / 03	Bi(2212) bulk YBCO bulk	tested tested under construction

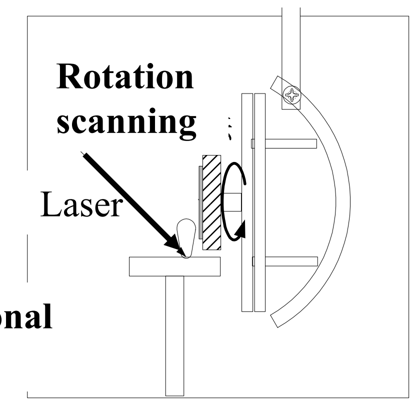
1) Diopma, REE, ANTEC, HITEC, CNRS Grenoble, ICMAB Barcelona, CIEMAT, Forschungszentrum Karlsruhe, Iberdrola
2) Nexans SuperConductors, Laborelec, ZFW Göttingen, TUT Tampere
3) ACCEL; RWE, E.ON, NexansSC, ATZ, EUS, ACCESS, FZK

Large-area SC thin film for FCL
Uniformity of Jc distribution

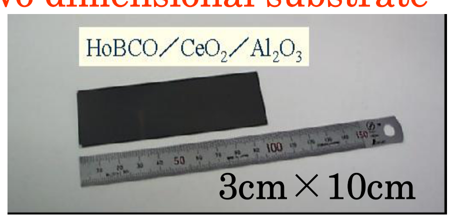
Two dimensional scanning mechanism



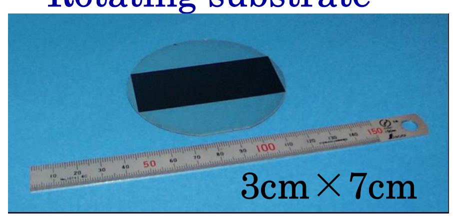
Rotation scanning mechanism



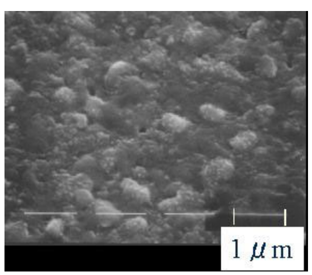
Two dimensional substrate

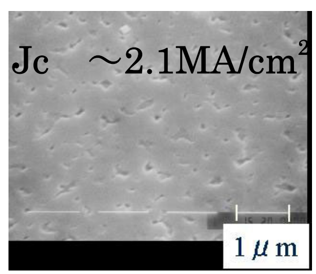


Rotating substrate



SEM photo (×20000)





Fabrication of the 3cm×10cm size HoBCo Film for FCL by using two PLD Methods.

Sumitomo Elec. Inc.

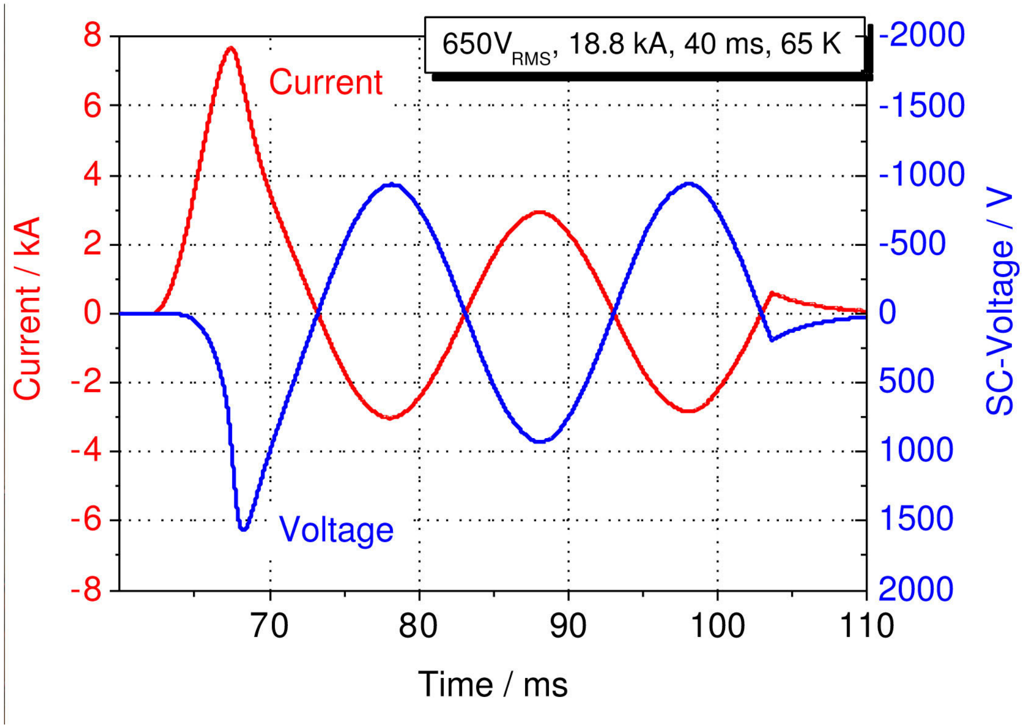
Thin films based FCL

Siemens
YBCO/Au on 4” Al_2O_3 wafer
1MW
(330kVA per phase)

Bulk HTS modules of the 10 kV/10 MVA FCL

- MCP-BSCCO2212 bifilar coil
  - Outer diameter:
    - ~ 50 mm
  - SC length:
    - 5.4 m
  - SC cross section:
    - 0.24 cm2
  - Critical current (65K):
    - 850 A
      - » Nexans SuperConductors

- Melt-textured polycrystalline YBCO meander
  - SC cross section:
    - 1.1 m
  - SC length:
    - 0.48 cm2
      - » Adelwitz Technologiezentrum



Results of three module test

- Fault current of 10 kA reduced to 6.6 kA
- Voltage 650 VRMS
- Current 600ARMS
- Fault limitation 40 ms
- Temperature 65 K
- RT-resistance 360 mW
- Electrical field 0.56 V/cm
- Ip/In ~ 9.

Superconducting Motors

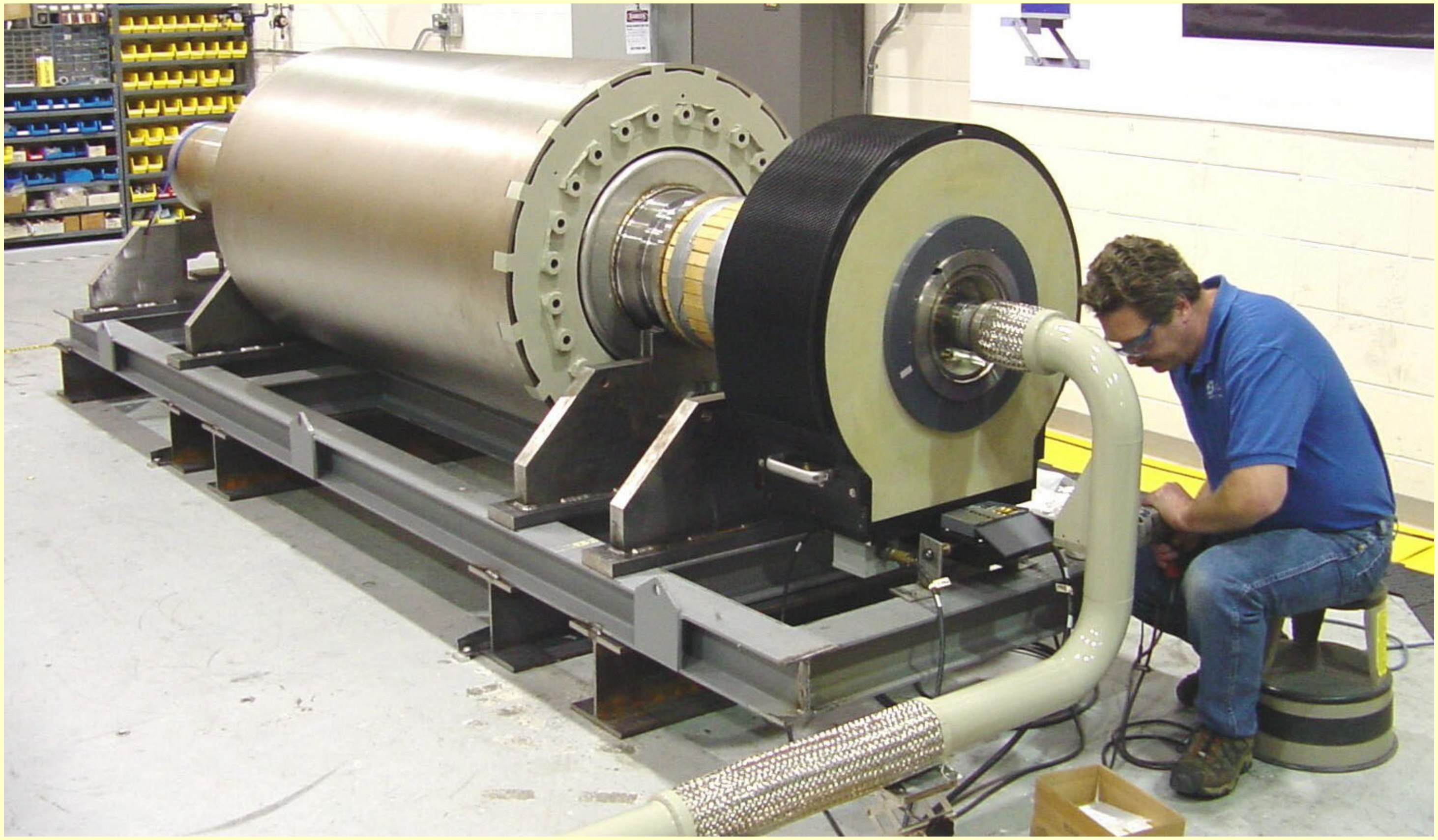
USA:

- **DOE / SPI**
  AMSC and Reliance Electric / Rockwell:
  1000 & 5000 PS motor

- **US Navy**
  AMSC: 5 MW propulsion motor
  Alsthow Power /UK: stator

- **USA test system for ship propulsion motor**

AMSC's 5MW/230rpm HTS Ship Propulsion Motor on Schedule for Summer 2003 Testing



5MW Rotor Assembly with Exciter

5MW Design Supports Commercial Motor Requirements

Courtesy: American Superconductors

5 MW, 230 RPM HTS Ship Propulsion Motor

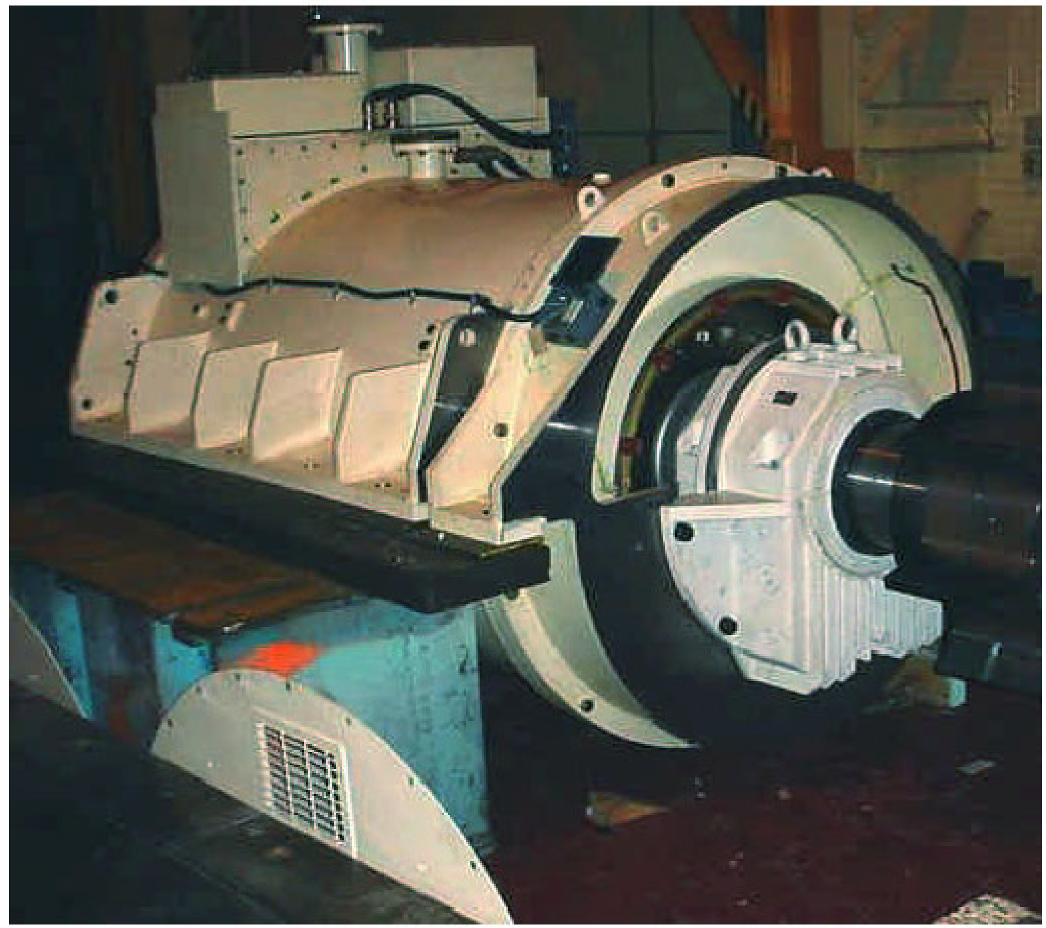
Factory Testing Undergoing

Designed and built under
Naval Research (ONR) contract

AMSC SuperMachines will deliver the
5 MW, 230 rpm motor
Integrated with a commercial Variable
Frequency Drive (ALSTOM VDM 5000

Component test bed for the ONR
36.5MW ship propulsion motor

Motor is undergoing factory testing in
ALSTOM, Rugby
Will be delivered to ONR by July 2003



Courtesy: American Superconductors

36.5 MW, 120 RPM HTS Ship Propulsion Motor

Scheduled for delivery in early 2006

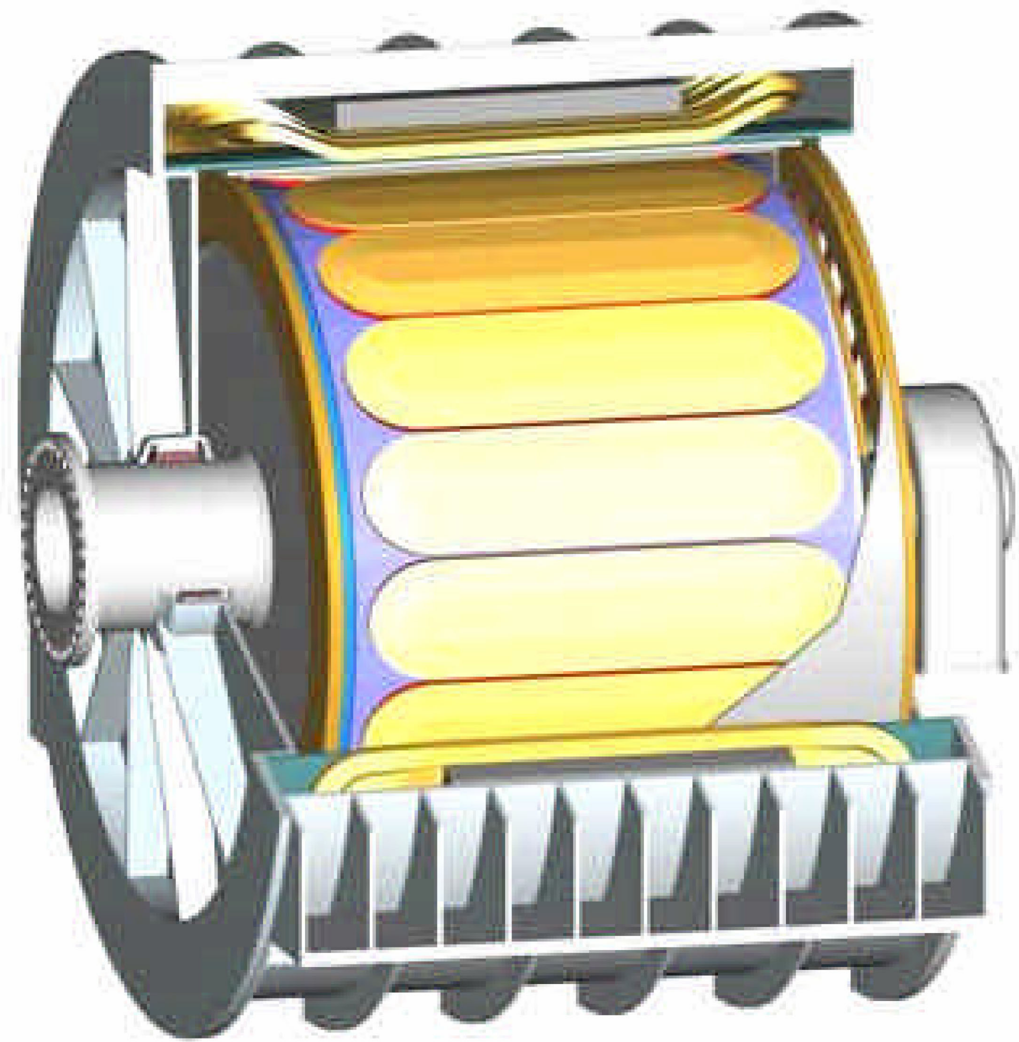
Designed and built under ONR contract

AMSC SuperMachines will deliver the 36.5 MW, 120 rpm motor (integrated with a commercial Variable Frequency Drive)

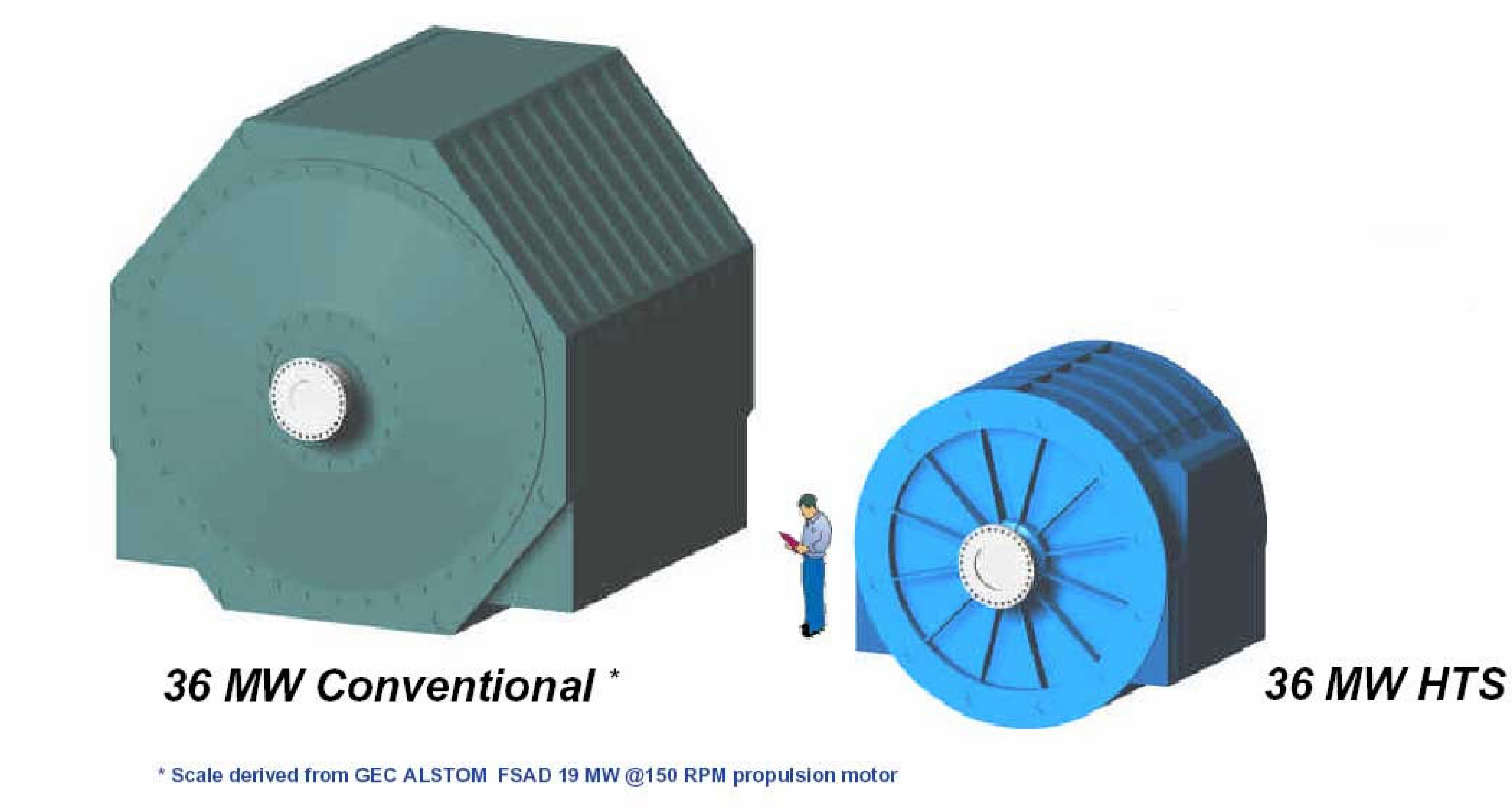
Motor is designed to power the next generation of Navy warships

Superconducting motor:	**69 tons**
Advanced normal induction motors of similar torque:	**> 200 tons**

World's largest HTS motor for ship propulsion



Ship Propulsion Motors



- Inherently quieter
- Lower operating cost
- Equivalent prices

25% of the volume
30% of the weight
Higher net efficiency

Superconducting Transformers

Switzerland

- **ABB**
  630 kVA / 3 phases:

  successful operation: 1 year at the grid in Geneva

Japan

- **Fuji Electric**
  1 MVA / 1 phase transformer

USA

- **ABB / DOE**
  10MVA / 3 phases: discontinued (costs)

Superconducting Storage Systems

AMSC (USA)

ACCEL (Germany)

- **Small storage systems (NbTi)**

  already on the market

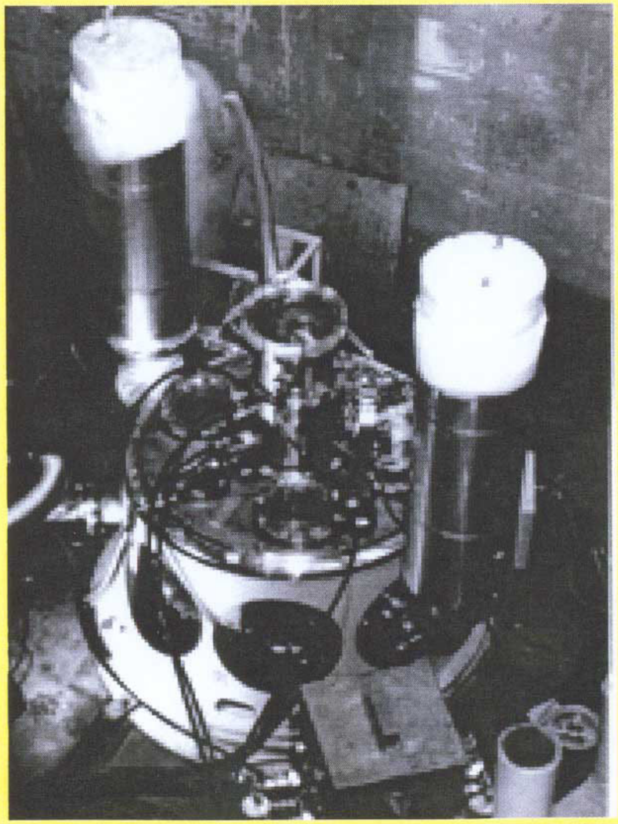
Korea

Under Development

Development of Superconducting Flywheel Energy Storage System

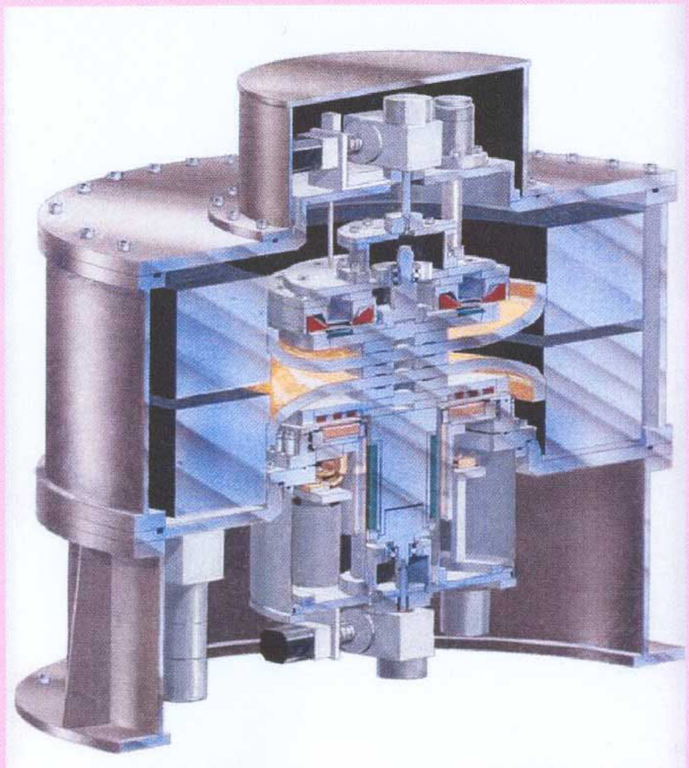
1. 4kWh FESS（developed in 1998）

Max. capacity	1.4 kWh
Rotor	ϕ 600 × 70 × 2disks
Max. rotation speed	20,000rpm
Rotor weight	65kg



17.5 kWh FESS（developing

Max. capacity	17.5kWh
Rotor	ϕ 1,200 × 200 × 2disks
Max. rotation speed	10,000rpm
Rotor weight	700kg



Applications where LTS materials are still preferred

- High field magnets (NMR)
- Magnets for Accelerators
- Fusion Magnets

Nuclear Magnetic Resonance (NMR): Nb_3Sn

Europe:

Bruker BioSpin
Oxford → **900 MHz** **1GHz** **ø 50 mm**

USA: NHMFL → **900 MHz** **wide bore: ø108 mm**

Japan: NRIM → **920 MHz** **1GHz**

Japan:

NMR User Center RIKEN, Yokohama **≈ 50 NMR magnets** **> 200 M EURO**

NMR magnet

900 MHz

21 T

BRUKER BIOSPIN

Very high field magnets at 4.2 K

Fields > 21 T

Materials:	**Nb_3Sn**	**22 T**	↗
	Bi,Pb(2223)	**24 T**	↗
	Bi(2212)	**25.4 T**	↗

Large Magnets for Accelerators and Detectors

Europe: LHC (CERN), NbTi technology

Beam Magnet : 1.8 K

Detector Magnet (ATLAS) : 4.2 K

Costs > 1 Billion EURO

USA: High Field Accelerators , Nb_3Sn

Berkeley: First experiment with HTS

Magnets for Thermonuclear Fusion

Actual State: HTS only envisaged for current leads

Tokamak KSTAR (South Korea),ITER Technology **100 M Euro**

ITER (?) Nb_3Sn Magnet Technology **50 M Euro**

Fusion Magnets : **> 1B Euro**

The ITER TF Model Coil

40 mm ø in 1.5 mm steel conduit rated current: 70 kA/11.8 T/4,6 K, ~ 1028 strands, Nb_3Sn + 1/3 Cu

ANSALDO - DP4- transfer of 2nd pancake completed .
Genova, 19 - 10 - 98

The ITER Machine (Tokamak)

LTS conductors

Fusion Power: 500 MW

Plasma Current: 15 MA

Plasma Volume: 837 m³

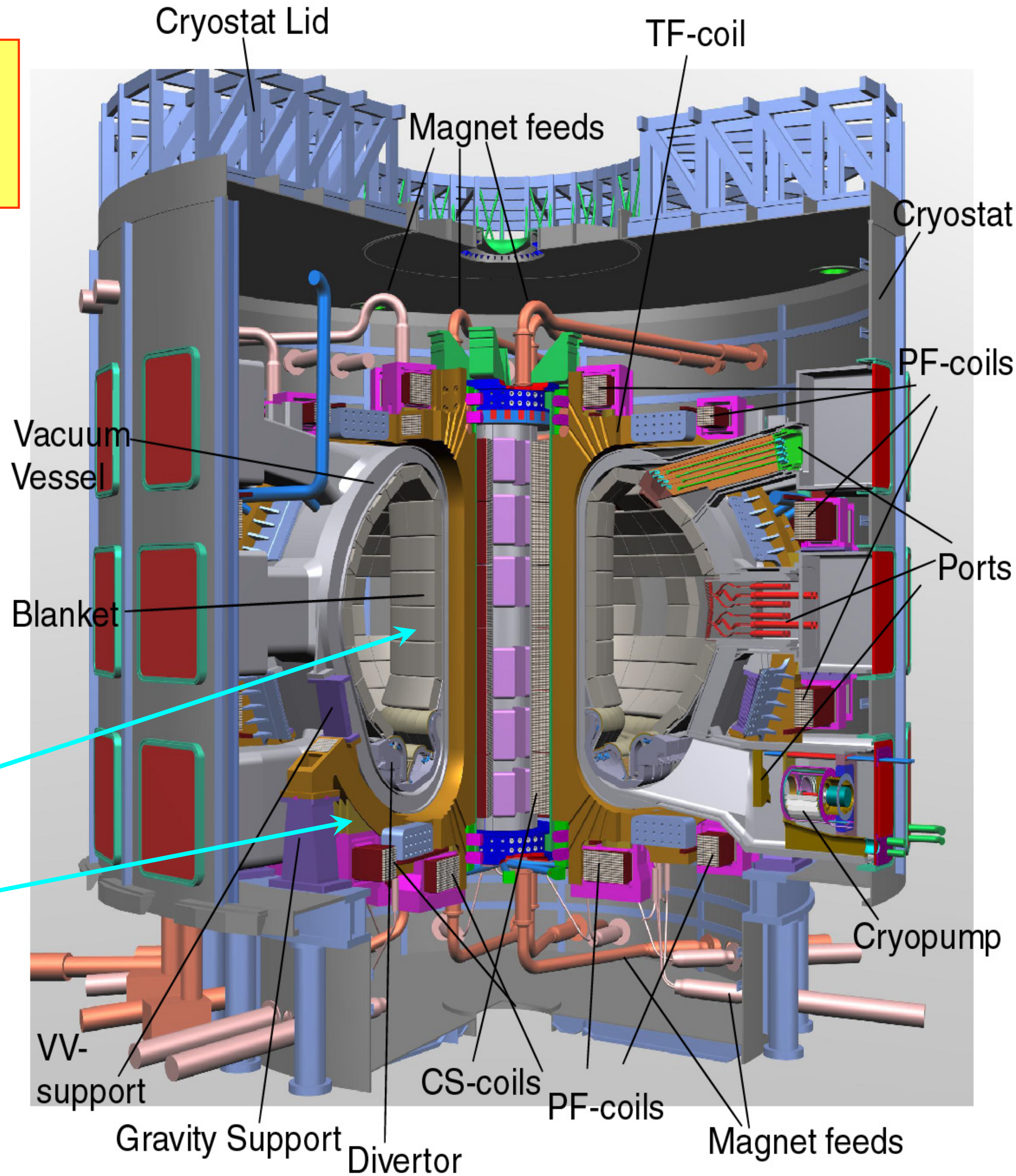
Torus Radius: 6.2 m

Plasma Radius: 2.0 m

Energy Amplification: Q=10

+ 13,5 T ⇔ - 12 T

12 T



Summary

- Present applications of high current superconductors: LTS
- Main obstacle for large market penetration of HTS: costs
- Only the first generation of HTS (Bi based) has been developed up to industrial scale
- Major effort for such near term applications can be seen mainly for power transmission cables, FCL, large motors and NMR spectrometers
- Second generation of HTS (YBCO) with superior properties still need strong development effort. Time frame: several years

Thanks to:

Prof. P. Komarek	ITP Karlsruhe, Germany
Dr. C. M. Rey	Dupont, USA
Dr. J.W. Bray	General Electric
Prof. O. Tsukamoto	Super GM, Japan
Dr. D. Eckert	Bruker Biospin, Switzerland
Dr. W. Paul	ABB, Switzerland
Dr. A. Malozemoff	American Superconductors (AMSC)
Dr. K. Marken	Oxford Instruments
Dr. Alan Wolski	Argonne Natl. Laboratory, USA
and many others	