DEVELOPMENT OF LTS AND HTS SUPERCONDUCTORS FOR ACCELERATOR MAGNETS AT EAS AND EHTS

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Abstract

The actual development of the two affiliated companies EAS and EHTS in the field of Technical Superconductors for Accelerator Magnets is described. EAS is active in the development of multifilamentary conductors by mechanical hot and cold working, based on NbTi and Nb_3Sn ("LTS") as well as BiSrCaCuOxide (Bi-2223) HTS tapes produced by the powder-in-tube (PiT) route. Nb_3Sn conductors are produced by the Bronze route and also by a PiT process. The latter is performed in a co-operation with SMI/Netherlands. EHTS is developing thin film HTS tapes based on YBaCuOxide (Y-123).

1. INTRODUCTION

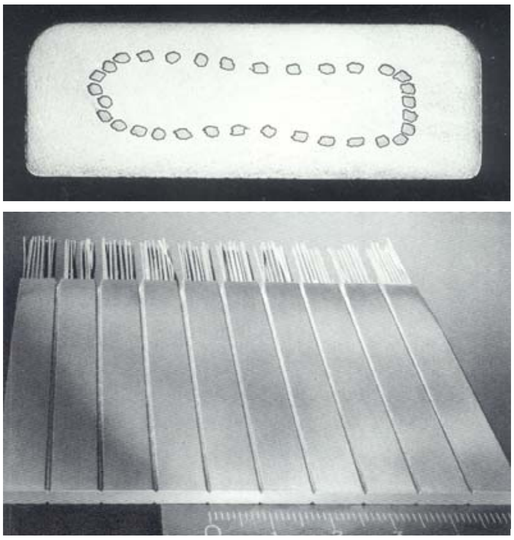
Accelerator magnets for high energy and nuclear physics have always been an important application for Technical Superconductors. EAS (until June 2003 a division of Vacuumschmelze GmbH & Co. KG, Hanau/VAC) has participated since the beginning in the development and production of conductors for both accelerators and detector magnets. Some milestones are given in Fig. 1.

1970	Big European Bubble Chamber (BEBC),CERN
1971	PLUTO Detector, DESY
1979	ISR Quadrupoles,CERN
1986	ALEPH Detector, CERN
1987	HERA Quadrupoles, DESY
1990	CLEO Detector, Cornell
1991	H1 Detector, DESY
1992	CLAS Torus, CEBAF
1997	ATLAS Detector, CERN
1998	LHC Dipoles and Quadrupoles MQM/MQY, CERN

Fig 1 Major Accelerator and Detector Magnet Projects with EAS Conductors

In many of these projects the specifications were very demanding and required significant development effort. As such accelerator applications have frequently acted as a technology driver for superconductor industry.

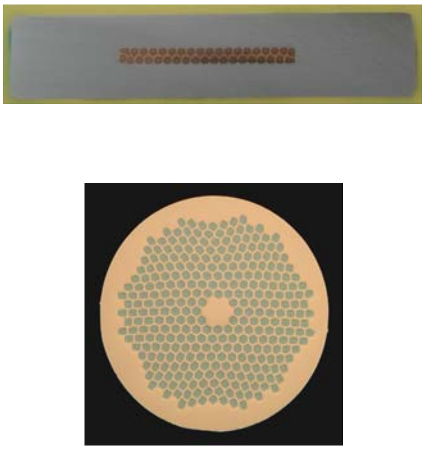
The progress in understanding technical superconductors and their production technology is visible in Fig. 2 and Fig. 3. Fig. 2 shows the conductor of the Big European Bubble Chamber (BEBC) at CERN using then advanced technologies such as continuous electron beam welding, but with on the other hand thick untwisted filaments and "strands" without transposition. Figure 3 shows the modern equivalent, the conductor for the ATLAS detector, with a fully transposed Rutherford cable of low Cu-ratio fine filament strands, co-extruded with ultra-pure aluminium for stabilization.



Multifilamentary Strand
8,8 x 3 mm²
32 Filaments, untwisted
Cu Ratio 25

Composite Conductor
10 Strands in parallel
e-beam welded
90 x 3 mm²
$I_c \approx$ 8000A @ 4.2 K, 5 T

Fig. 2 BEBC Conductor 1970



Conductor

Dimension	57 x 12 mm²
Unit length	1730 m
Total length	56 km
Critical Current	> 58 kA @ 4.2 K; 5 T
Operating Current	20.5 kA @ ~ 4.8 K; 3.8 T
RRR (ALU)	> 1000

Cable

No. Of strands	38
Dimension	26 x 2.3 mm²

Strand

Diameter	1.3 mm
Cu : NbTi	1.2
Critical Current	> 1700 A

Fig. 3 ATLAS Conductor 2000

So far virtually all accelerator and detector magnet projects have been realized with NbTi conductors. It is expected that this will change in future and that Nb_3Sn technology will play a significant role. Also, on a longer term, HTS conductors may become important. In the following the LTS development activities going on at EAS will be described [1, 2]:

- Conductors for pulsed accelerator magnets (NbTi, Nb_3Sn) [3]
- Conductors for high field (>10 T) accelerator magnets (Nb_3Sn) [4]

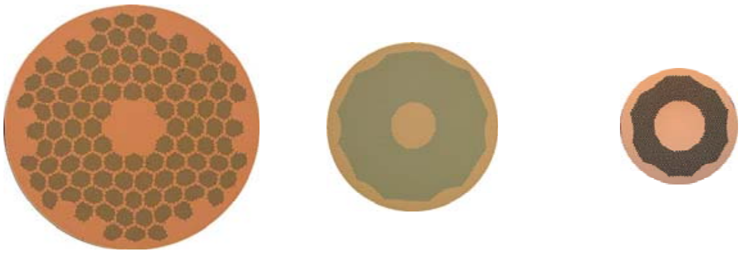
As concerns HTS, application specifications are as yet only vaguely defined, so conductor development is of a more general nature. The present status and on-going activity will be presented for

- Bi-2223 multifilamentary tapes with a silver (-alloy) matrix (EAS) [5]
- Y-123 thin film tapes ("coated conductors") on a stainless steel substrate (EHTS) [6]

European High Temperature Superconductors (EHTS) is a sister company to EAS founded in March 2004. EHTS is producing and developing Y-123 based on the IBAD/PLD technology pioneered by ZFW Göttingen.

2. DEVELOPMENT OF METALLIC SUPERCONDUCTORS FOR ACCELERATORS

The present state of the art of NbTi conductors is best represented by the conductor family of keystoned Rutherford cables presently produced in large scale for LHC. Depending on coil type the cables consist of 22 to 36 strands, coated with a thin Sn-Ag layer to control the adjacent and transverse resistance between the strands in the cable. Examples of strand cross sections are shown in Fig. 4.



diameter 1.065 mm
8670 filaments à 7 µm
double stacking

dipole cable 01 with 28 strands

diameter 0,735 mm
6264 filaments à 6 µm
single stacking

matching quadrupole
cable 06 with 22 strands

diameter 0,480 mm
2124 filaments à 6 µm
single stacking

matching quadrupole cables:
cable 04 and 07 with 36 strands
cable 05 with 34 strands

Fig. 4 LHC strands from EAS

Typical strand characteristics are:

- 2000 to 9000 filaments with 6 to 7 µm diameter in a pure Cu matrix
- Each filament protected by a Nb barrier against formation of Cu-Ti intermetallics
- Single stacking or double stacking design

The development of further advanced conductors for new projects is directed towards:

- Pulsed magnets for fast cycling accelerators (mainly NbTi)
- High field magnets for accelerator up-grades (such as LHC)
  or the next generation of circular hadron colliders (such as VLHC) making necessary Nb_3Sn (or related) technology.

3.1 Conductors for fast ramped magnets

In existing superconductor magnets for accelerators, such as LHC, the conductor design is based on field quality considerations at injection field. In fast cycling accelerators pulse field loss considerations are becoming essential [3].

An example is the planned FAIR project (Facility for Antiproton and Ion Research) at GSI/Darmstadt (Gesellschaft für SchwerIonenforschung). Two synchrotrons are foreseen:

- SIS 100 with $B_{max} = 2$ T and dB/dt = 4 T/s
- SIS 300 with $B_{max} = 6$ T and dB/dt = 1 T/s

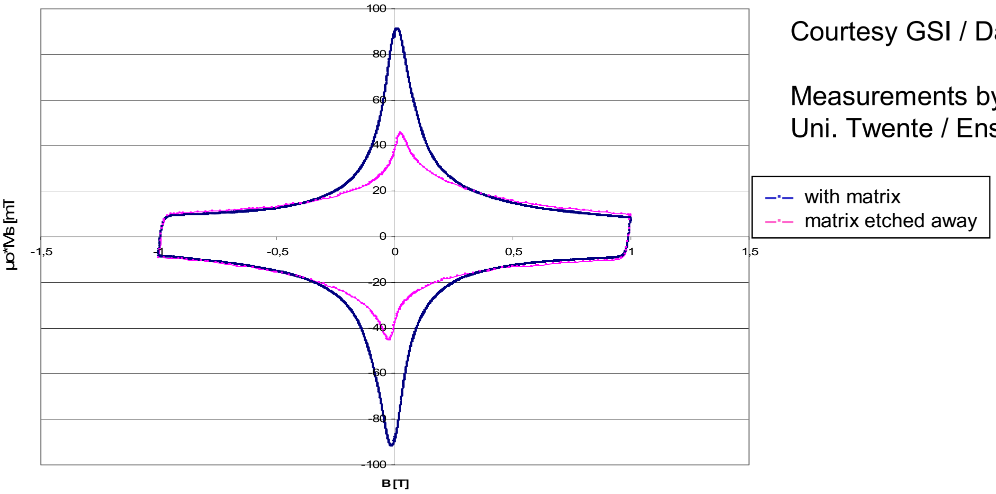
It is obvious that pulse losses have to be reduced as much as possible to operate such a machine most economically. The consequences for the conductor design are as follows

- Further reduction of filament diameter to 3.5 µm (or below)
- Tight twist pitch

- Resistive barriers in the cable (strand coating, central high resistivity tape in the cable core e.g. of stainless steel)

Based on the LHC experience 3.5 µm strand designs were developed, tested and optimized with respect to

- Avoiding filament shape distortions and related excess magnetization
- Avoiding proximity enhanced magnetization at injection conditions (see Fig. 5 for magnetization measurements of the strand and the bare filament bundle by etching the matrix)



Courtesy GSI / Darmstadt

Measurements by
Uni. Twente / Enschede

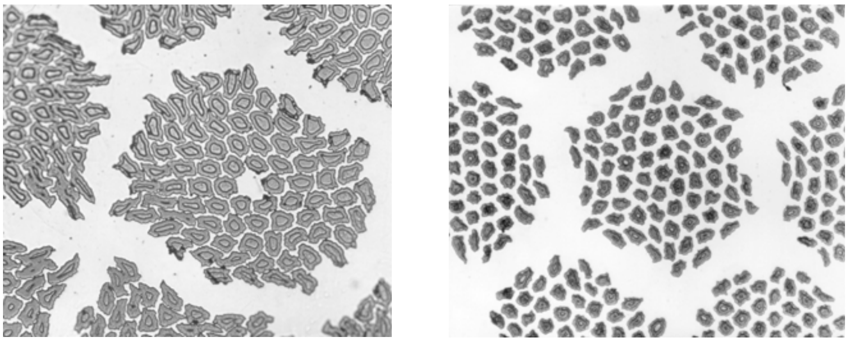
Magnetization of 3.5 µm NbTi filaments
with Cu-matrix present
with Cu-matrix etched away

⇒ Proximity coupling sets in below 0.3 T

Fig. 5 NbTi/Cu: proximity coupling

As an intermediate result, a strand with 12300 filaments and a current density of well above the specified 2750 A/mm² @ 5 T, 4.2 K, 0.1 µV/cm was successfully developed and produced.

It is important to mention that Bronze Route Nb_3Sn conductors are best suited for pulsed magnets at higher fields. Low loss Nb_3Sn strands were developed and produced as part of the ITER project for nuclear fusion. Due to the relatively large amount of bronze within a Bronze Route Nb_3Sn strand it is possible to avoid filament bridging and intergrowth during reaction treatment and the related volume growth. Fig 6 shows examples with and without filament bridging by properly choosing the local Bronze to Nb ratio [1, 2].



Filament bridging due to low local bronze ratio

→ n-value highest
→ effective filament diameter
≈ bundle diameter

Avoidance of filament bridging due to high local bronze ratio

→ reduced n-value
→ low d_{eff}, low losses

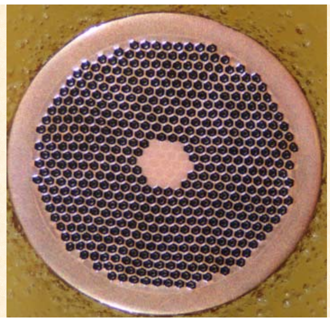
Fig. 6 Nb_3Sn : Avoidance of filament bridging in reacted Bronze Route Nb_3Sn Conductors

3.1 Nb3Sn conductor development for high field Accelerator Magnets

At magnetic fields well above the present LHC field level the capabilities of NbTi are exhausted, even with sub-cooling to 1.8 K. High field Accelerator Magnets with a field of 12 T or 15 T have therefore to be built with Nb_3Sn (or related materials) [4]. Unfortunately the presently almost exclusively used Bronze Route Nb_3Sn conductors exhibit too low a current density for Accelerator Magnets. High current density routes have to be applied instead, such as Internal Tin (IT) and Powder-in-Tube (PiT). Of these two routes the PiT approach seems to exhibit the best prospects for accelerator and other high current density applications.

EAS has therefore launched a joint development programme together with SMI/Enschede in the Netherlands to develop conductors with parameters suited also for Accelerator Magnets [2]

An example of conductor design and typical parameters of PiT Nb_3Sn strands is given in Fig. 7. Figure 8 summarizes some major achievements with PiT conductors made by SMI.

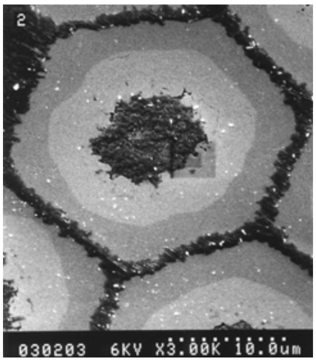


504 filament PiT
at intermediate diameter

Mono filament
- Nb or NbTa tubes
- $NbSn_2$ based powder

Multifilamentary wire
- 36 to 504 filaments in a Cu matrix
- Typical wire diameter 0.5 to 1.3 mm
- Filament diameter 20 to 60 µm
- Short heat treatment
- Well defined geometry

Fig. 7 Nb_3Sn PiT Design



Cross section of a PiT filament
after heat treatment
(typ. 64 h / 675 °C)

From outside:

- Cu matrix
- Unreacted Nb layer
- Nb_3Sn layer
- Residual powder core

Non Cu jc up to 2400 A/mm² @ 12 T, 4.2 K, 0.1 µV/cm
1300 A/mm² @ 15 T, 4.2 K, 0.1 µV/cm

Fig. 8 Nb_3Sn PiT performance

Intensive additional development is needed to further enhance the performance of the conductors and especially to scale-up the production technology. But the envisaged specifications

- 1500 A/mm² @ 15 T or 3000 A/mm² @ 12 T (4.2 K, 0.1 µV/cm)
- Effective filament diameter $d_{eff} \cong 40\text{-}50$ µm
- Wire diameter up to 1.25 mm

would seem to be well within reach of PiT Nb_3Sn.

4. CERAMIC HIGH TEMPERATURE SUPERCONDUCTORS (HTS) DEVELOPMENT

The ceramic HTS materials discovered in the late 1980s were opening up new application prospects of superconductors, especially because of their high critical temperature but also because of their extraordinary high field properties, at least at low temperature. Thus, both, operation at elevated temperature near liquid nitrogen (77 K) and high fields well above 20 T at liquid helium temperature became possible.

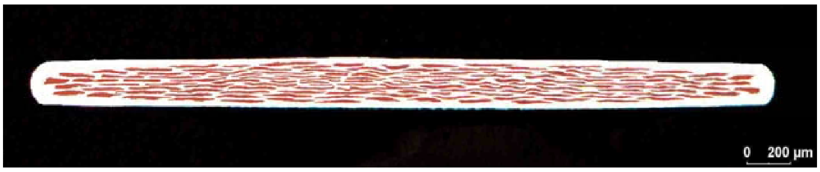
The most promising candidates for technical superconductors turned out to be the BiSrCaCuOxides $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223, $T_c \cong 110$ K) and $Bi_2Sr_2CaCu_2O_x$ (Bi-2212, $T_c = 85$ K) and $YBa_2Cu_3O_x$ (Y-123, $T_c \cong 90$ K). Except for Bi-2212 the conductor geometry has to be that of a thin flat tape in order to texture the ceramic materials such that the grains are well connected for superconducting current flow. Bi-2212 round wires with high critical current density at low temperatures around 4.2 K and at high fields were already demonstrated by EAS (VAC at that time) in 1989. This development is presently suspended at EAS because of the inferior properties of Bi-2212 as compared with Bi-2223 for most applications.

At present EAS and EHTS concentrate on the tape development for Bi-2223 and Y-123, respectively. In the course of the material research and conductor development it has been found that a mono-axial (out-of-plane) texture is sufficient to allow high currents to flow in polycrystalline Bi-2223. It is therefore possible to produce high current density Bi-tapes by a PiT route with appropriate precursor powders, cold working and final thermo-mechanical treatment. On the other hand, Y-123 has to be bi-axially textured, which is, so far, only possible via thin film processes by depositing the YBCO-layer on an appropriately textured flexible template.

4.1 Bi-2223 PiT tapes [5]

Bi-2223 tapes are produced by starting with inserting precursor powder of optimized phase composition in a silver tube. After cold working a certain number of these monofilaments are bundled in an outer silver tube and than extruded/drawn to final diameter and than flattened by rolling. After that the Bi-2223 phase is formed and textured by a sequence of heat treatment and rolling steps (Thermo mechanical treatment). The resulting typical tape geometry is shown in Fig.9.

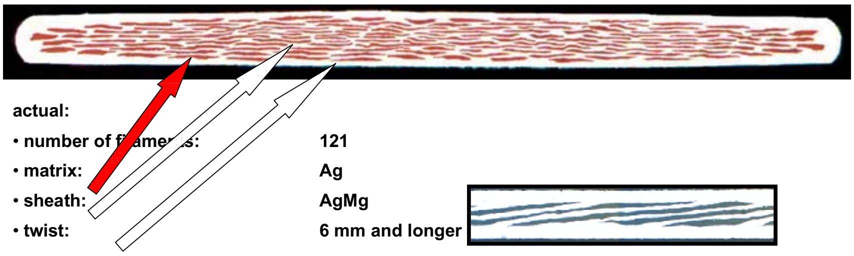
cross section of a multifilamentary Bi-2223-tape (approx. 4 mm x 0.21 mm):



width:	approx. 4 mm
thickness:	approx. 0.21 mm
number of filaments:	121
filling factor:	approx. 30 %
material of matrix:	Ag
material of sheath:	AgMg
I_c long lengths (up to 1000 m)	≈ 100 A @ 77 K, self field

Fig. 9 Bi-2223/Ag Tape geometry and performance

In order to intrinsically strengthen an AgMg alloy is used for part of the matrix of the conductor. Depending on the application, geometry and design can be varied. Some options are given in Fig. 10.



actual:

• number of filaments:	**121**
• matrix:	**Ag**
• sheath:	**AgMg**
• twist:	**6 mm and longer**

options:

• number of filaments:	**37, 55, 85, 121, 253 or more**
• filling factor:	**(26-33) %**
• matrix:	**AgAu (up to 8at.-% Au)**

usual unit lengths:	**500 m or more/ less (depends on order, up to 1300 m)**
usual production lengths:	**>1300 m**

Fig. 10 Bi-tape design options

Ag-Au alloy is used for current leads of LTS magnet systems for example, because of the low thermal conductivity of this alloy in the relevant temperature range. Presently EAS is delivering such tapes for the leads of the magnet systems of LHC.

The current carrying capability of Ag/AgMg tapes at “standard HTS-conditions” i.e. 77 K, self field is presently about 100 A, corresponding to 120 A/mm². The temperature dependence is given in Fig. 11.

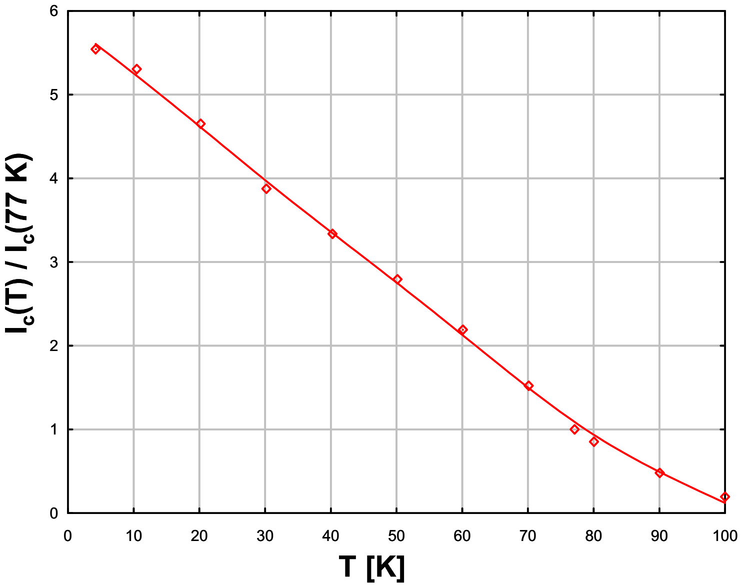


Fig. 11 Temperature dependence of critical current in self field

Unfortunately the field dependence at 77 K is very steep and strongly dependent on field direction, as can be seen in Fig. 12.

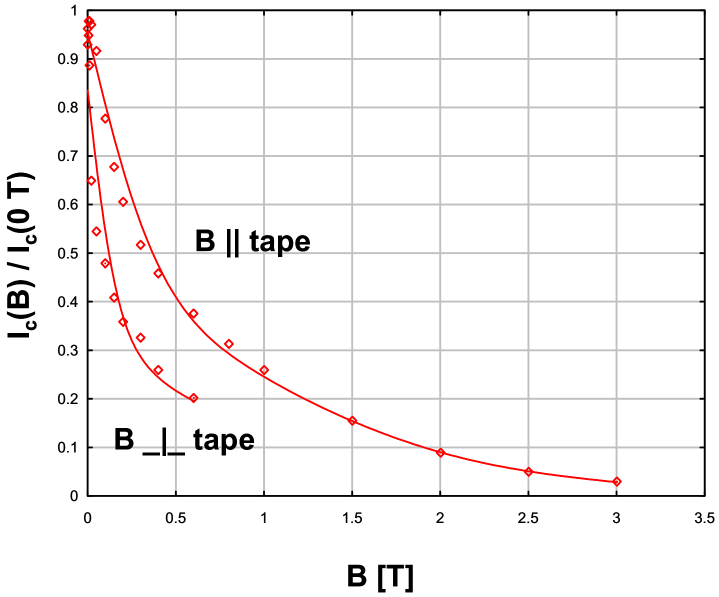


Fig. 12 Field dependence of critical current at 77 K

The Bi-based tapes are therefore limited to low field applications at 77 K. This situation improves significantly however at lower temperatures: this is already appreciable at 65 K, and below 20 K high field magnets become possible. Figures 12 and 13 show the field dependence at 20 K and 4.2 K, respectively.

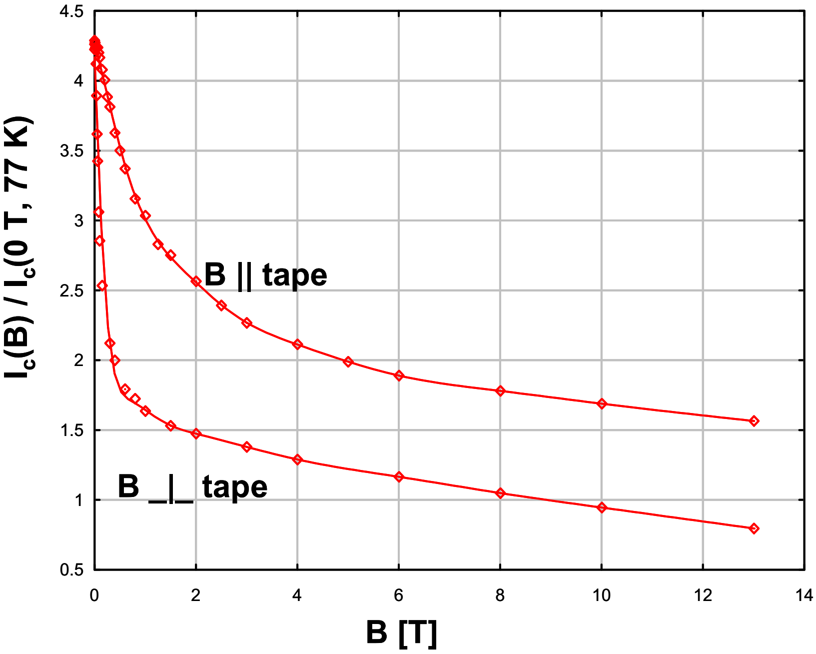


Fig. 13 Field dependence of critical current at 20 K

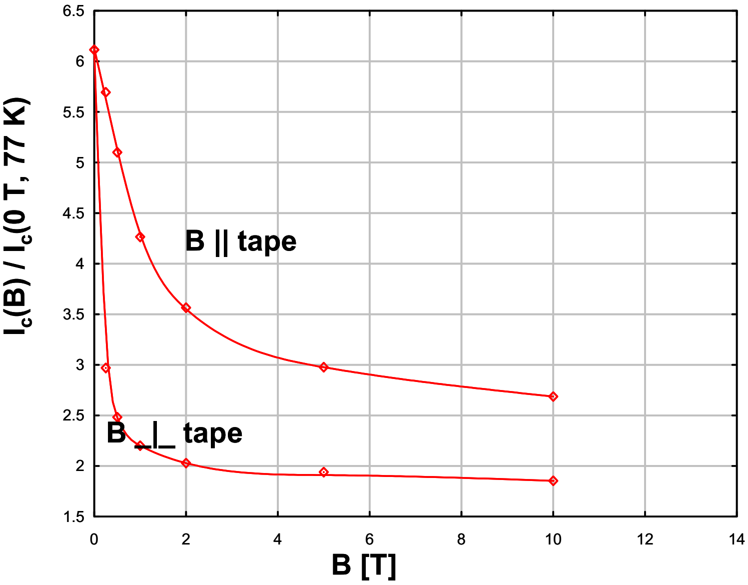


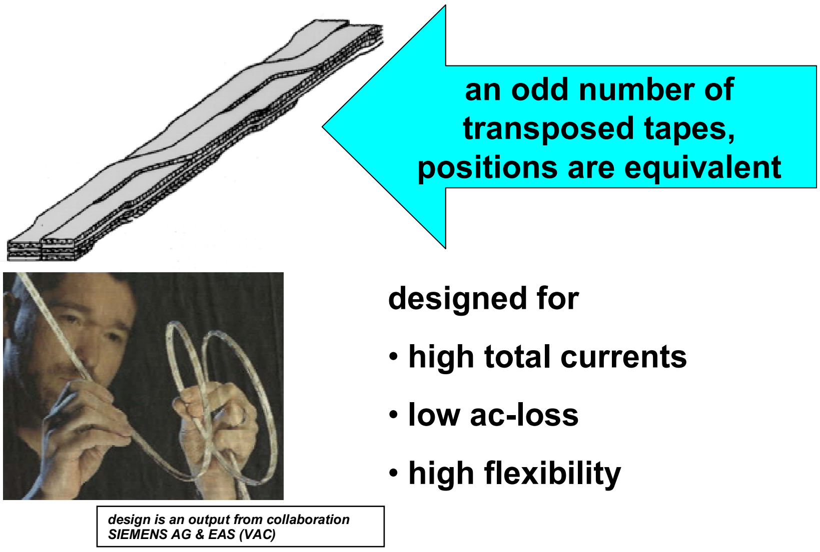
Fig. 14 Field dependence of critical current at 4 K

The multifilamentary nature of Bi-tapes allows twisting of the wire (prior to flattening) similar to metallic superconductors, and thereby the reduction of ac losses (at least for the field components parallel to the tape).

An important aspect of ceramic superconductors is their mechanical properties. For handling at room temperature the critical limits of the AgMg strengthened tape for tensile loading are 100 MPa, and for bending 60 mm diameter. At low temperature the critical tensile stress increases to 150 MPa.

The production of Bi-2223/AgMg tapes with above parameters is very advanced and unit lengths of 1000 m and more are produced and delivered routinely.

In addition high current conductors can be produced as fully transposed cables by the Roebel technique, as shown in Fig. 15.



an odd number of transposed tapes, positions are equivalent

designed for

- **high total currents**
- **low ac-loss**
- **high flexibility**

design is an output from collaboration SIEMENS AG & EAS (VAC)

Fig. 15 Bi-2223 tape Roebel conductors with high critical current suitable for ac applications

4.2 Y-123 Thin Film tapes [6]

Due to the even more pronounced grain connectivity problem Y-123 tapes have to be produced by thin film techniques in order to achieve the bi-axially textured structure needed. The basic architecture is as follows: flexible metallic tape, ceramic buffer layer to isolate substrate and superconductor from each other and providing/transferring the texture for the superconductor layer, and environmental protection layer. There is a relatively large diversity of methods to produce such tapes. The route followed presently by EHTS is based on:

- Stainless steel tape (50-100 µm
- Ion Beam Assisted Deposition (IBAD) of Yttrium Stabilized Zirconia (YSZ) buffer and, optionally, texture improving CeO_2-layer deposition (1 to several µm)
- Pulsed Laser Deposition (PLD) of Y-123 layer (1-3 µm)
- Sputtered Au or Ag layer (< 1 µm)

Fig. 16 gives an impression of the architecture (not to scale)

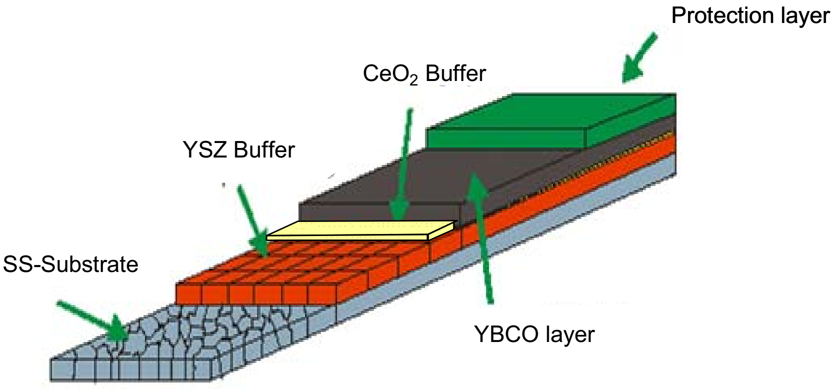
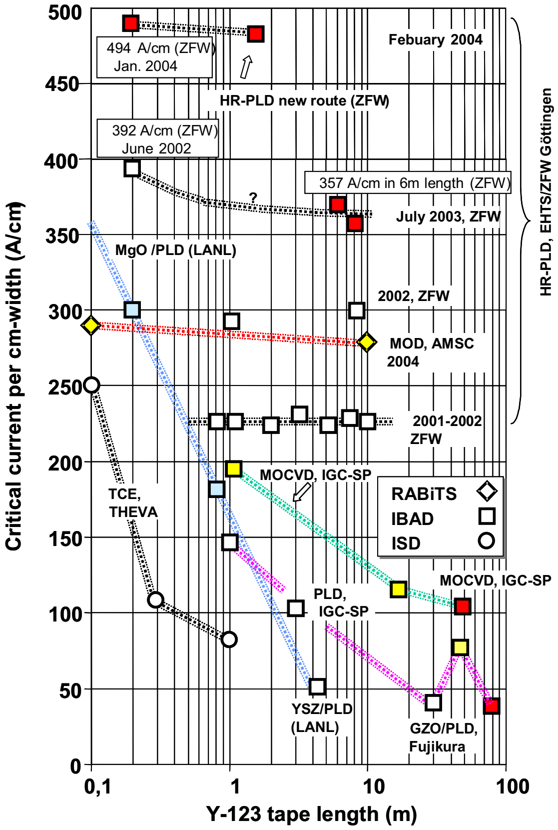


Fig. 16 Y-123 tape architecture

The chosen route was based on the excellent results of ZFW Göttingen achieved with this process. Figure 17 gives a survey of worldwide achieved performance in terms of I_c per tape width (A/cm) and tape length (m).



Textured Template:

RABiTS:	Buffer on textured metal substrate
IBAD:	Buffer texturing by assisting ion beam
ISD:	Buffer texturing by selecting optimum deposition angle

Y-123 Deposition:

PLD:	Pulsed Laser Deposition
TCE:	Thermal Co-Evaporation
MOD:	Metal-Organic solution Deposition
MOCVD:	Metal-Organic Chemical Vapor Deposition

Fig. 17 Worldwide achieved performance of Y-123 tape conductors in terms of critical current per width vs. length (10 cm to 100 m) as of May 2004

Presently EHTS is engaged in scaling up the developed ZFW technology, with the following

- Production of long lengths (10 m → 100 m → » 100 m)
- Continuous process and product control

- Addition of electrical stabilizer and protection material
- Application related characterization and development

4.3 Status and Prospects of HTS Conductor Application

The discovery of the Cu-oxide based HTS technical superconductors gave rise to great expectations concerning their application. Now more 15 years later, more realistic assessments can and must be made.

Genuine large scale applications have yet to become reality. Only in a niche application, current leads of LTS magnet systems, are Bi-tapes routinely used. In other fields Bi-tapes were very successfully used in demonstration models and prototypes e.g. power-cables, motors, transformers and magnets. Bi-tapes can be produced in length ≥ 1000 m and having good homogeneity, sufficient for most envisaged applications, but there are still hurdles to be overcome, both technical and economical. The brittleness of the ceramic material, and the associated cryogenics add complexity. In addition, the cost of the superconductor and the cryogenic system are still prohibitive for large scale applications if economic considerations are predominant, at least where more conventional solutions are feasible.

As regards the superconductor, the figure of merit is the cost per kAm, i.e. the production cost per length (incl. materials) versus performance as determined by the critical current at HTS standard conditions (77 K, self field). For Bi-conductors the cost per kAm are at 150-200 €/kAm and can still be reduced by increasing performance and by streamlining production. One penalty of Bi-tapes is of course the price of silver, setting an expected lower limit of tape cost at 20-30 €/kAm.

Compared to Bi-tapes, Y-123 tapes are manufactured starting with much cheaper materials (except for some chemical routes) such that Y-123 tape costs are dominated by the processing costs. At present processing and related costs per kAm are much higher than 1000 €/kAm but it can be estimated that, by process scaling-up and for very large quantities, costs of Y-123 tapes may be very much be reduced, possibly below Bi-2223 tape cost.

Another incentive to develop Y-123 tapes in addition to optimizing Bi-2223 tapes is the fact that at elevated temperature the critical current density in Y-123 is less field dependent than in Bi-2223. At a given temperature Y-123 therefore allows to generate a higher field than Bi-2223. A synopsis of the status and the prospects of applications of Y-123 in comparison to Bi-2223 are given in Fig. 18.

	Bi-2223 multifilamentary			Y-123 thin film		
	77 K	20 K	4 K	77 K	20 K	4 K
Current Leads	+++	→	+++	0	→	0
Power Cables / Bus Bars	++	÷	÷	+	÷	÷
FCL	0	÷	÷	+	÷	÷
Transformer	++	÷	÷	0	÷	÷
Motor / Generator	0	++	÷	(+)	(+)	÷
Magnets	÷	++*)	++*)	(+)*)	(+)*)	(+)*)

+++	Product
++	Tested successfully in demonstrators
+	Tested in laboratory scale
(+)	Promising
0	Questionable
÷	Not interesting and/or not possible

*) strongly dependent on magnetic field

Fig. 18 Synopsis of status and prospects of Bi-2223 and Y-123 tape application

5. CONCLUSION

NbTi-based technical superconductors and superconducting magnet technology for particle accelerators, and high energy and nuclear physics have been pushed forward in a symbiotic manner over more than 35 years now. It is expected that this development will continue by virtue of a number of ongoing projects. Besides that, the use of Nb_3Sn also in accelerator magnets will become more important, e.g. for upgrades or even more for a future large circular hadron collider. As high current density Nb_3Sn composites are mechanically much more sensitive than NbTi composites, magnet designs have to become more conductor friendly, in addition to conductor manufacturers' endeavour to reduce the consequences of this sensitivity. This requires also in future a very tight cooperation between all parties involved.

The situation is even more complex concerning applications of HTS conductors. Whereas for Nb_3Sn both, the wind-and-react and the react-and-wind technique, may be applied, for HTS the brittle ceramic conductor has to be handled during the complete magnet fabrication process. It is nevertheless expected that HTS will find its place also in accelerator and detector magnets beyond its already established use in current leads of LTS systems, because HTS offer new opportunities ranging from special magnets operating at elevated temperature to very high field magnets at low temperature.

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