Development of LTS and HTS conductors for Accelerator Magnets at EAS

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Historical Look Back

Present EAS Activities and Plans

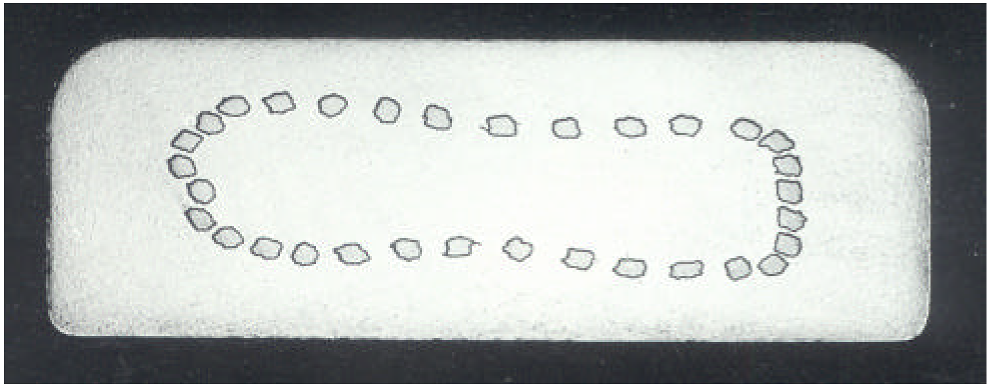
- LTS
  - NbTi : Conductors for Pulsed Magnets
  - Nb_3Sn : Conductors for Pulsed Magnets (Bronze Route) and High Field Magnets (PiT)
- HTS : for Elevated Temperature Operation and/or Very High Field Magnets
  - Bi2233 : Multifilamentary Tapes
  - YBCO : Thin Film Conductors (“Coated Conductors”)

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

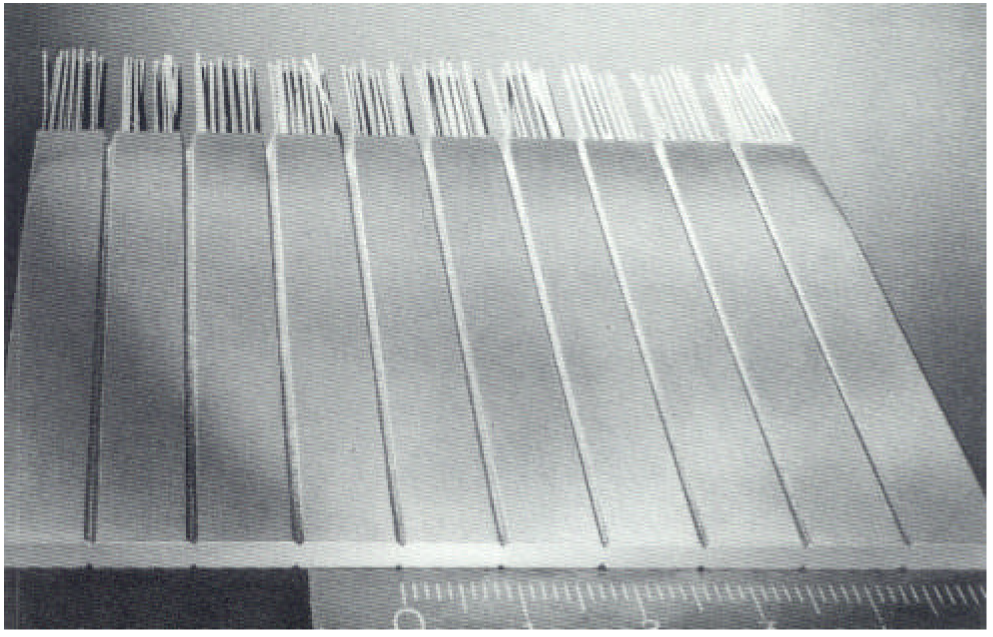
++ Magnets for high Energy Physics (Accelerator and Detector Magnets) have always been a Technology Driver for Superconductors

–- But never (or very seldom) were a Cash Generator

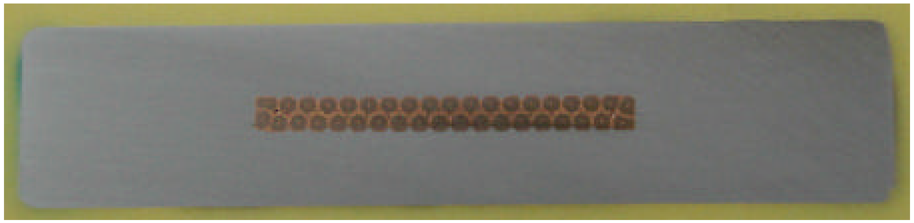
? What will be in Future?



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

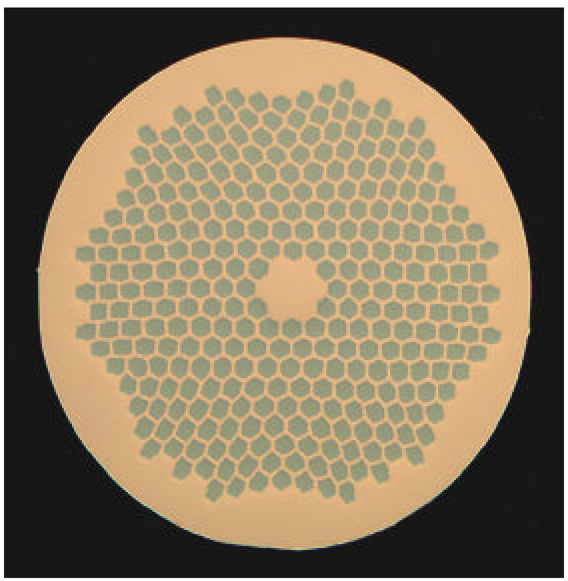


Composite Conductor
10 Strands in parallel
e-beam welded
90 x 3 mm²
$I_c \approx 8000$A @ 4.2 K, 5 T



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

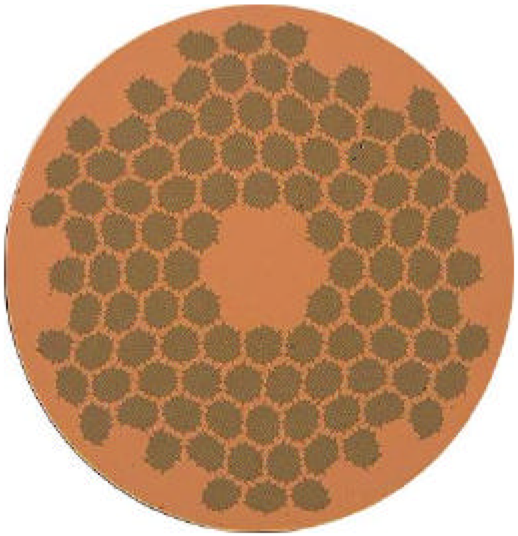


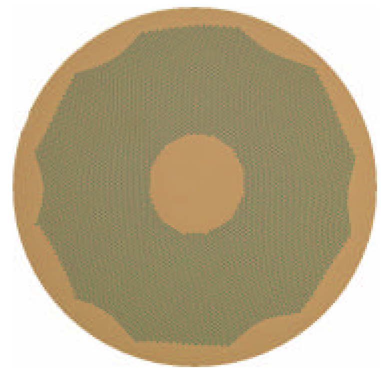
Cable

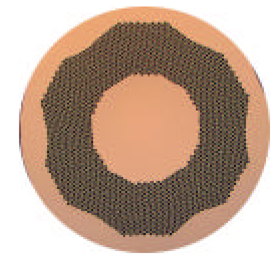
No. Of strands	38
Dimension	26 x 2.3 mm²

Strand

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







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

- Filament diameters (6 µm) of Conductors for Present Accelerator Magnets (LHC) are Based on Field Quality Considerations

- Pulsed Magnets will be needed for fast cycling Accelerators

- Example GSI Synchrotrons SIS 100 and SIS 300
  - SIS 100 : B_m = 2 T, $\dot{B}$ = 4 T/s
  - SIS 300 : B_m = 6 T, $\dot{B}$ = 1 T/s

$\Rightarrow$ Pulse Loss Reduction is Essential
Conductor Losses are Contributing Significantly

- Losses at Each Level have to be Reduced
  - Filaments : Diameter « 6 µm (e.g. 3.5 µm)
  - Strands : Twist pitch very tight (few mm)
  - Cable : Resistive Barriers (e.g. SS central foil)

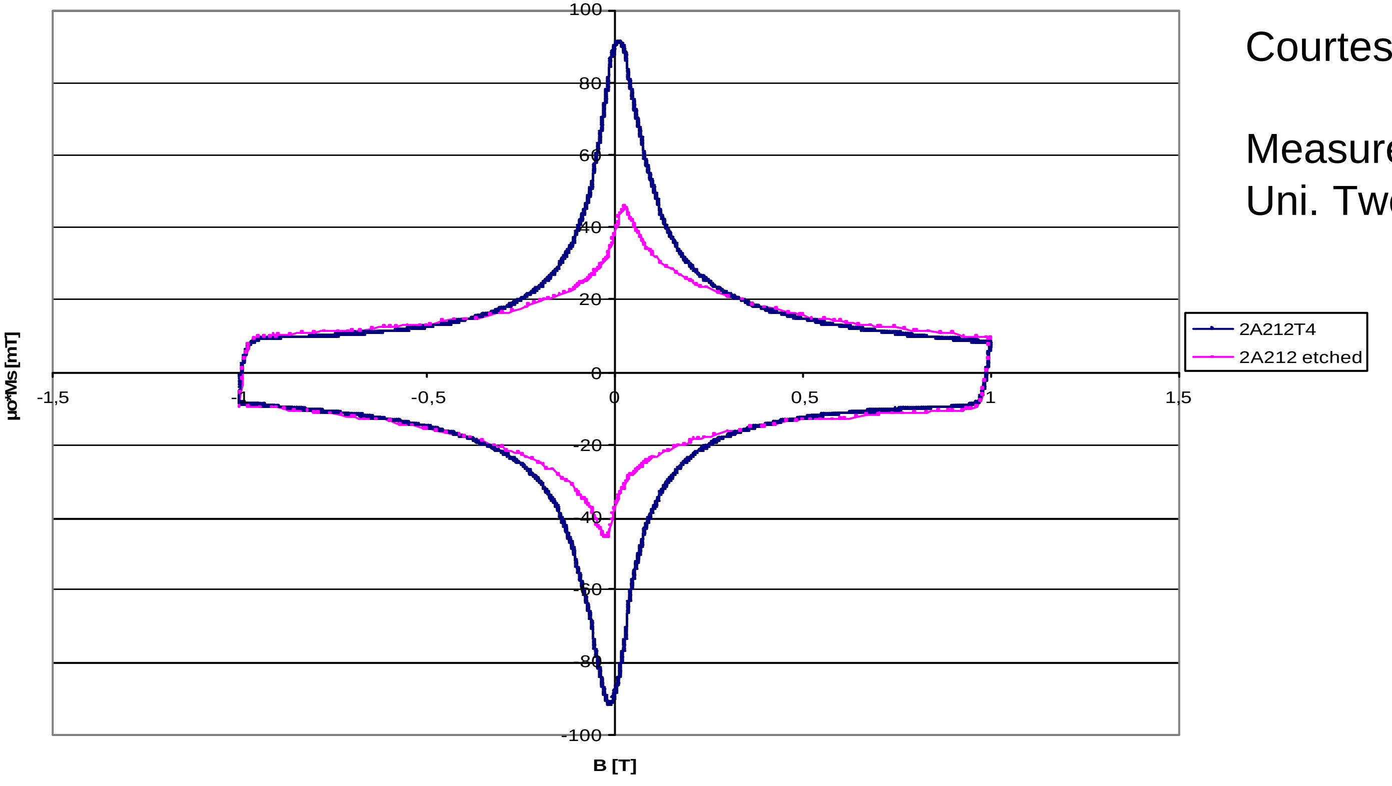
Strand Development with 3.5 µm Filaments

- Optimization of jc
  - geometrical strand design
  - thermomechanical treatment
- Reduction of excess magnetization
  - filament geometrical distortions
  - proximity coupling

Achievements with optimized Cu-Matrix Conductors

- Same jc level at 3.5 µm as with 6 µm (LHC)
- Excess magnetization can be avoided even with a Cu-Matrix except below 0.3 T

$\Rightarrow$ Ongoing Development at EAS



Courtesy GSI / Darmstadt

Measurements by
Uni. Twente / Enschede

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

$\Rightarrow$ Proximity coupling sets in below 0.3 T

Bronze Route is best suited for fine filament Nb_3Sn Conductors because of Bronze Matrix and their Properties

- Large Matrix to Filament Area Ratio (to provide enough Sn)
- High Hardness of Bronze (limited filament geometry distortions during hot and cold working)

Achievements with strands for ITER CSMC (Central Solenoid Model Coil)

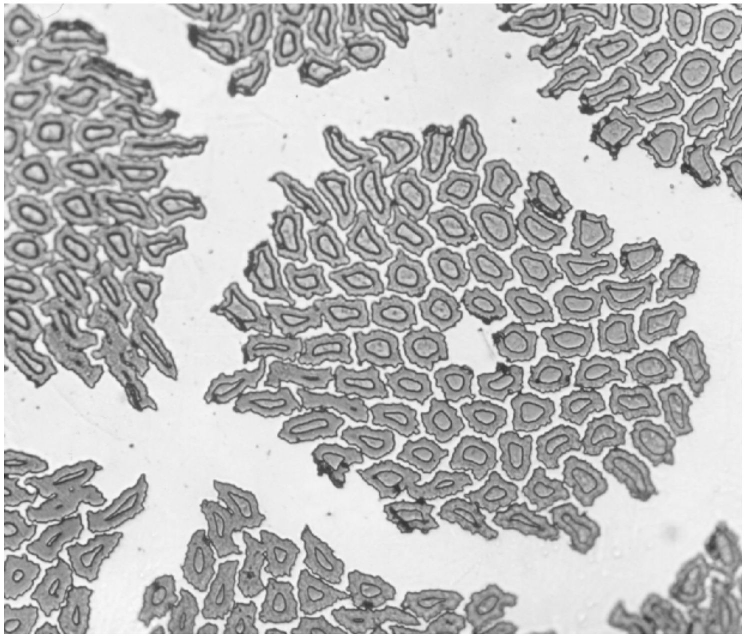
- Non Cu jc 650 A/mm² @ 4.2 K, 12 T, 0.1 µV/cm
- Hysteresis Losses $P_h \leq$ 100 mJ/cm³ per full ± 3 T cycle

$\Rightarrow$ Present contract with EFDA for ITER

- Goal jc $\geq$ 800 A/mm² @ 4.2 K, 12 T, 0.1 µV/cm

$\Rightarrow$ Best Achievement with Bronze conductors so far

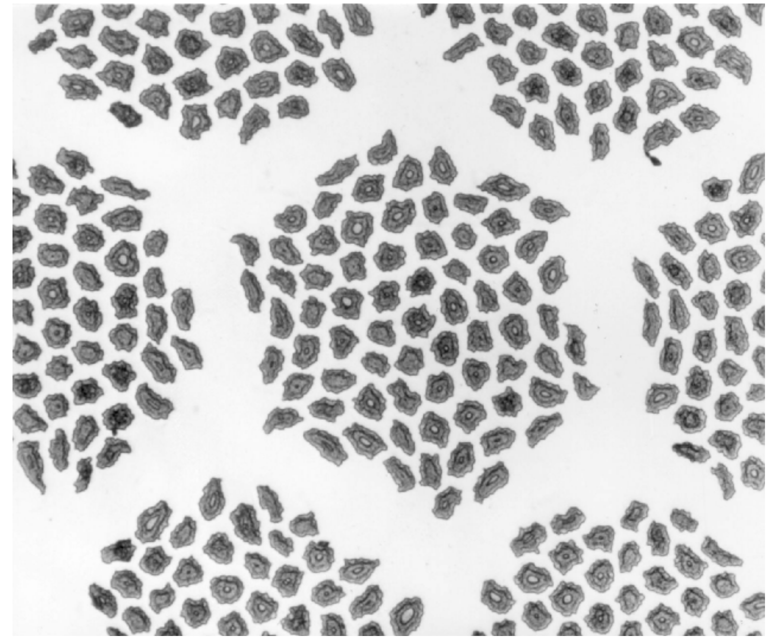
jc $\approx$ 900 A/mm² @ 4.2 K, 12 T, 0.1 µV/cm



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

Conductor Specifications

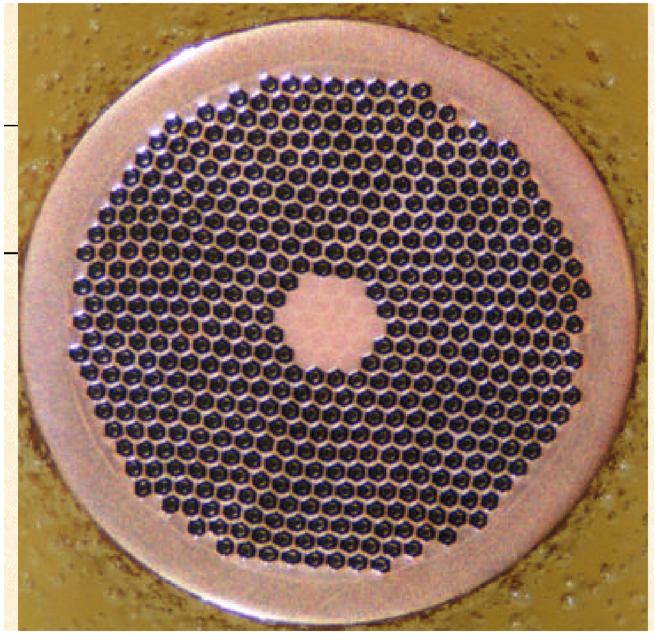
EU (NED)		US
1500 A/mm² @ 15 T, 4.2 K, 0.1 µV/cm	Non Cu j_c	3000 A/mm² @ 12 T,4.2K
£ 50 µm	d_{eff}	<40µm
1.25mm	D	0.3-1.0mm
50 – 55 %	Cu fraction	~50 %

Contractual Co-operation EAS / SMI

- Scale-up of PiT process
  - Production units / Unit lengths
  - Production capacity
- Further Enhancement of Properties
- Cost Reduction

Main Targets

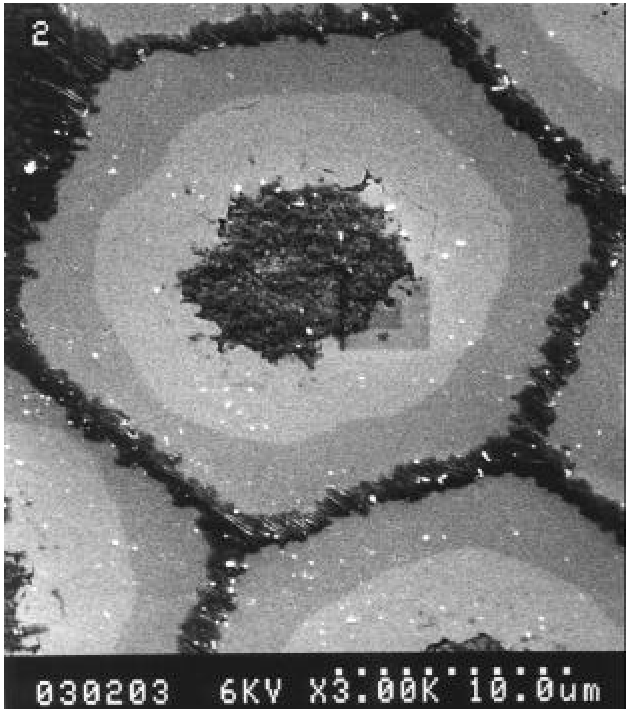
- Accelerator Magnets
- ITER Coils
- High Field magnets



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



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 2450 A/mm² @ 12 T, 4.2 K, 0.1 µV/cm
1400 A/mm² @ 15 T, 4.2 K, 0.1 µV/cm

Details see contribution of Jan Lindenhovius / SMI

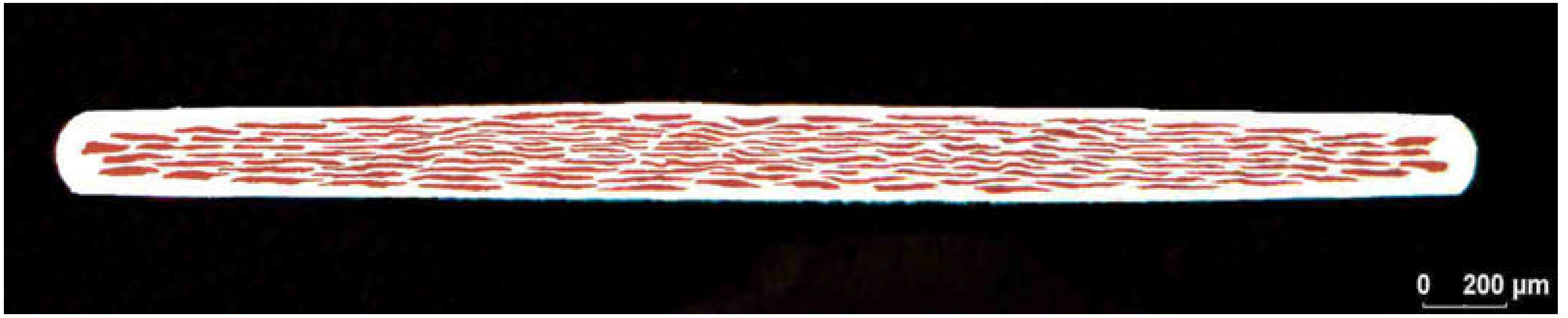
Bi-2223 ($Bi(Pb)_2Sr_2Ca_2Cu_3Oxide$) Tape Conductors

- Under development at EAS since more than 10 years
  (Initially EAS concentrated on round Bi-2212 conductors)

YBCO ($Y_1Ba_2Cu_3Oxide$) Tape Conductors

- Joint development of EAS together with the recently founded
  affiliate EHTS (European High Temperature Superconductors)
  Company, Hanau + Göttingen in co-operation with University
  Göttingen (Prof. H.C. Freyhardt)

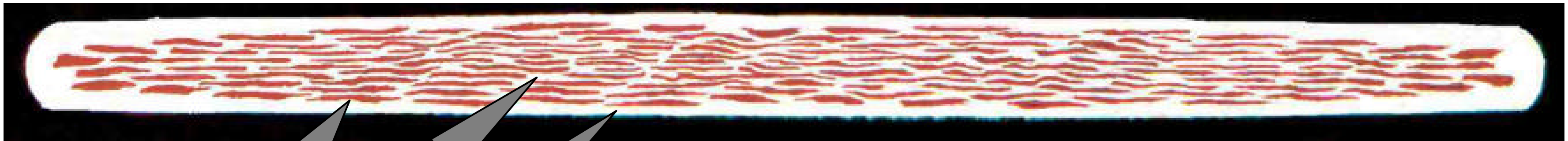
cross section of a multifilamentary Bi-2223-tape (approx. 4 mm x 0.21 mm):



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

typical I_c: $\approx$ 100 A @ 77 K, self field

Tape design options



actual:

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

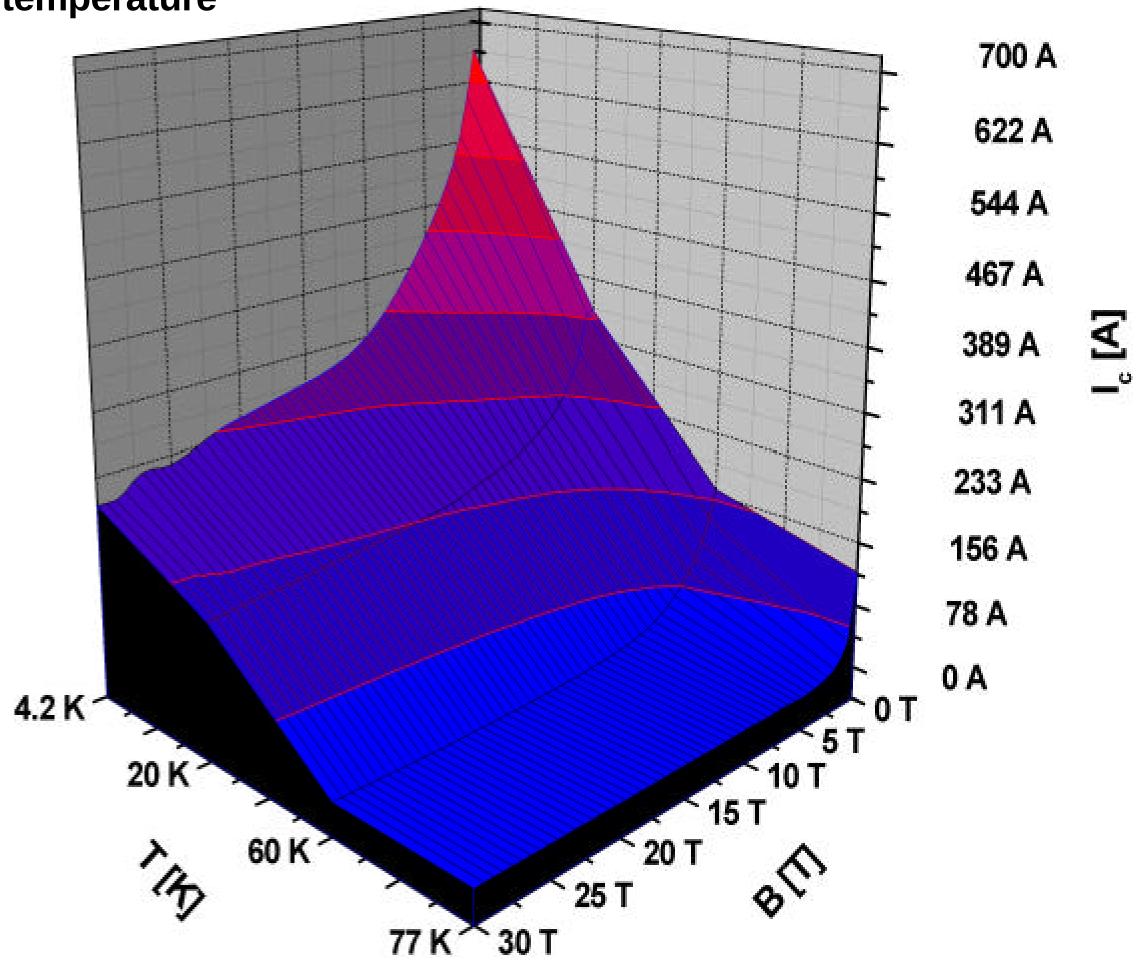
options:

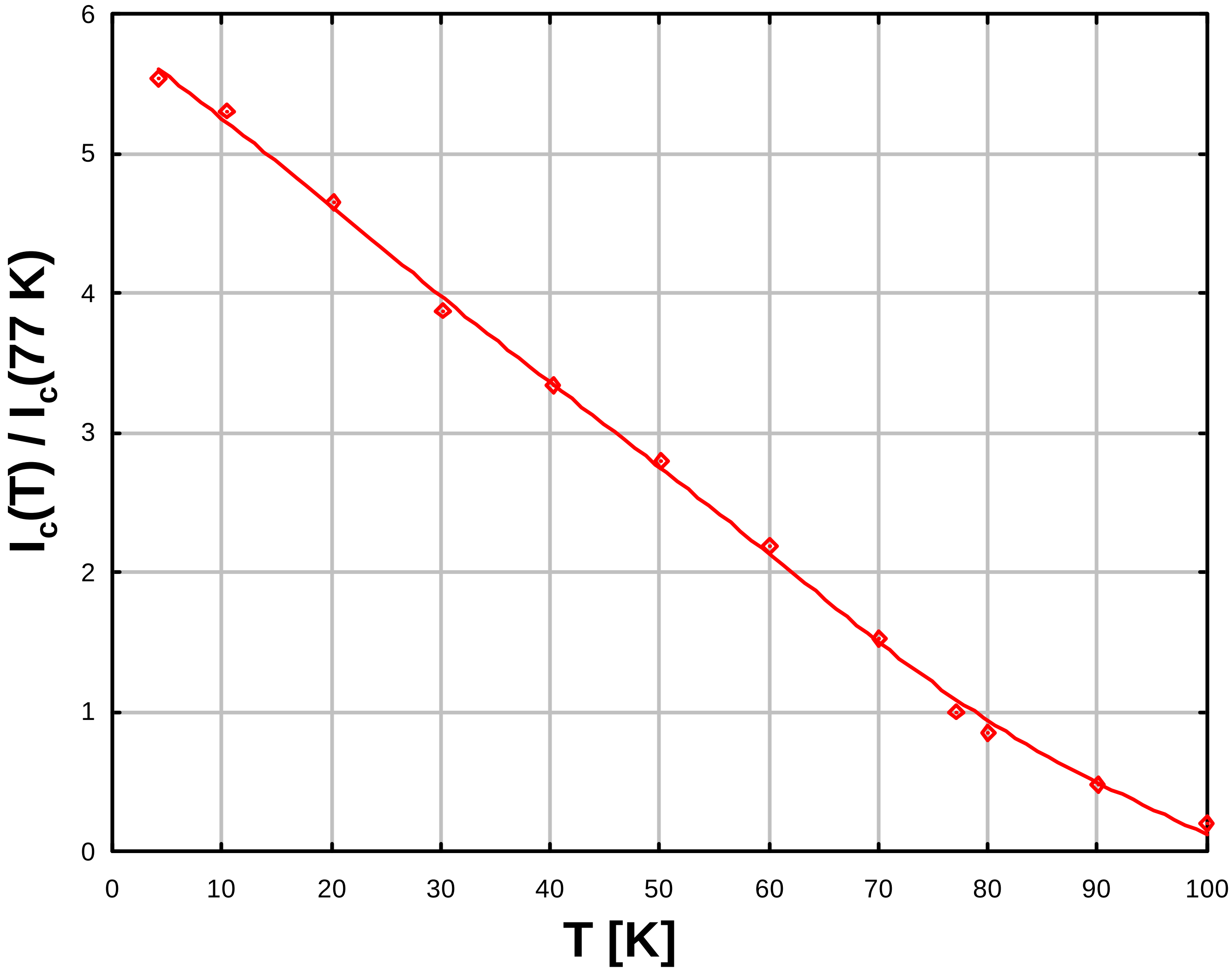
- **number of filaments:** **37, 55, 85, 121, 253 or more**
- **filling factor:** **(26-33) %**
- **matrix:** **AgAu (up to 8at.-% Au)**

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

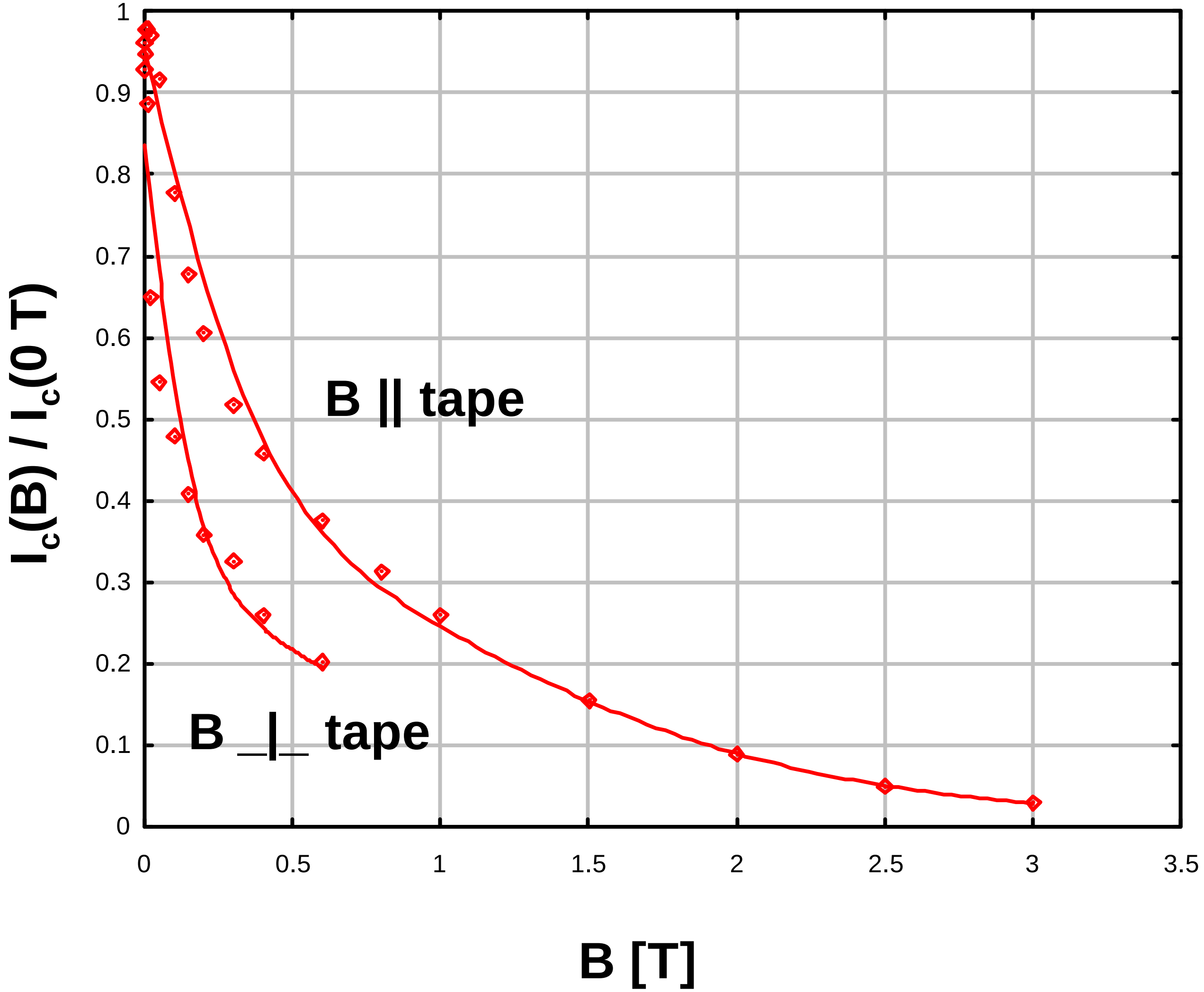
usual production lengths: **>1300 m**

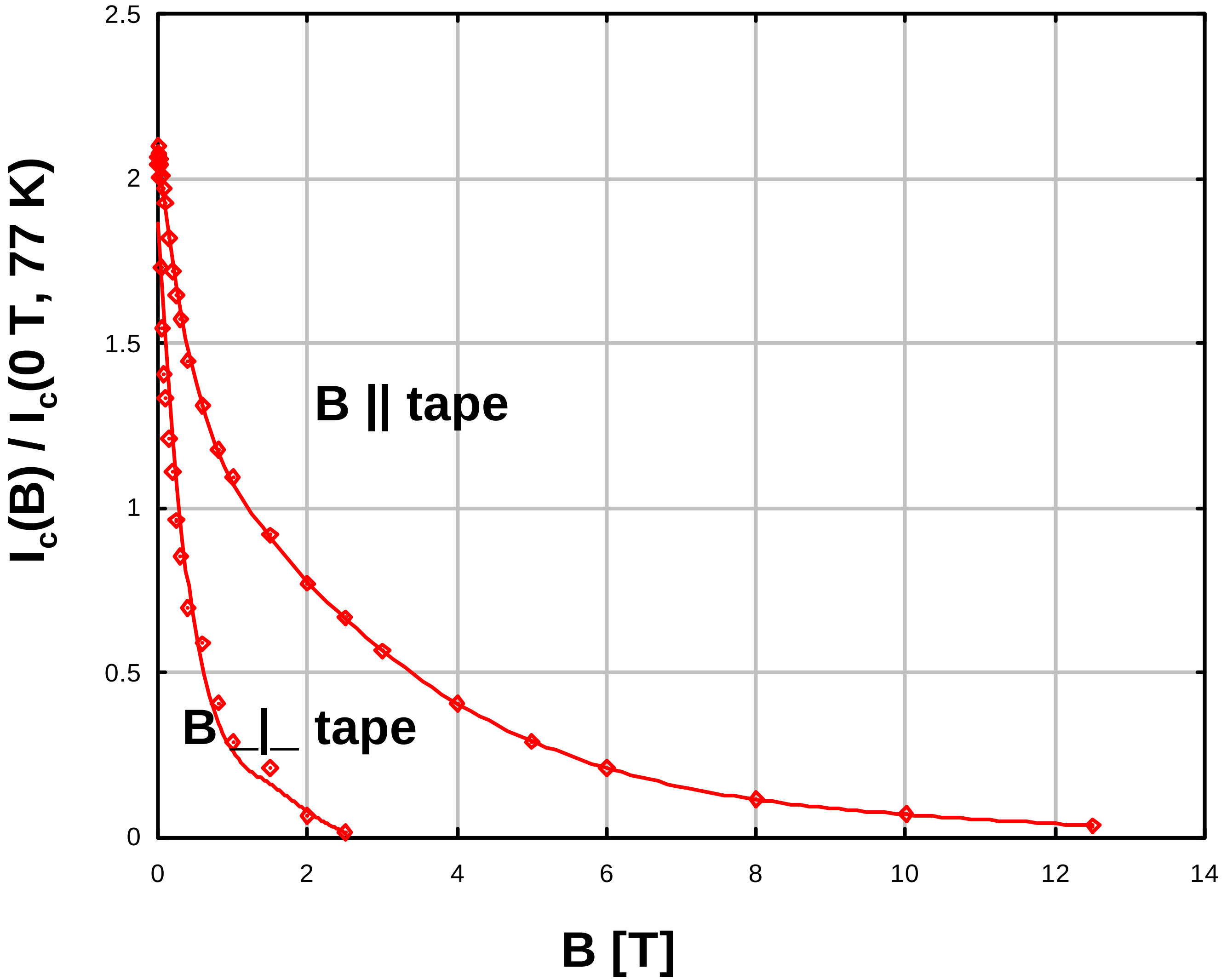
typical surface of critical current over magnetic field and temperature

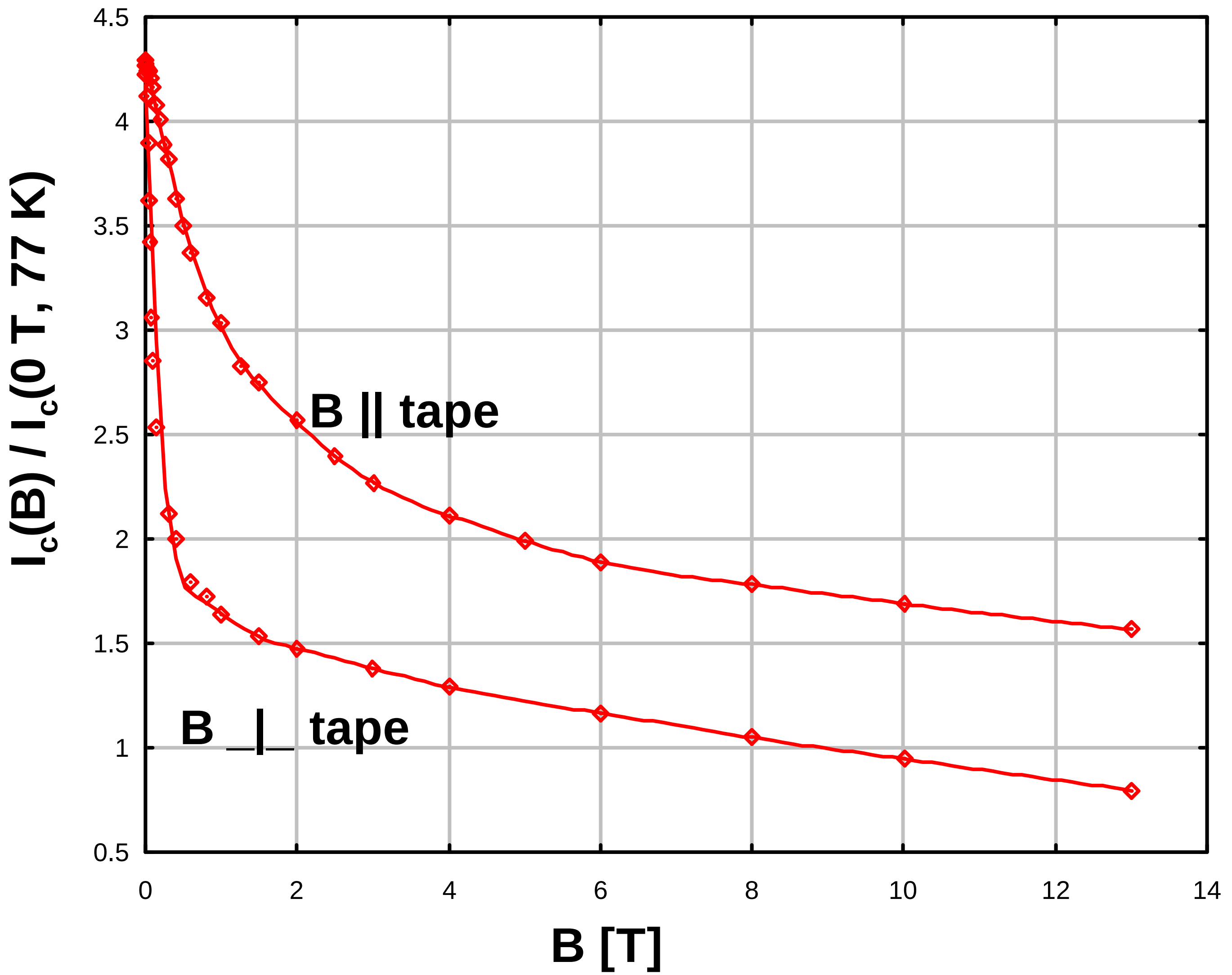



6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
$I_c(T) / I_c(77\ K)$
T [K]

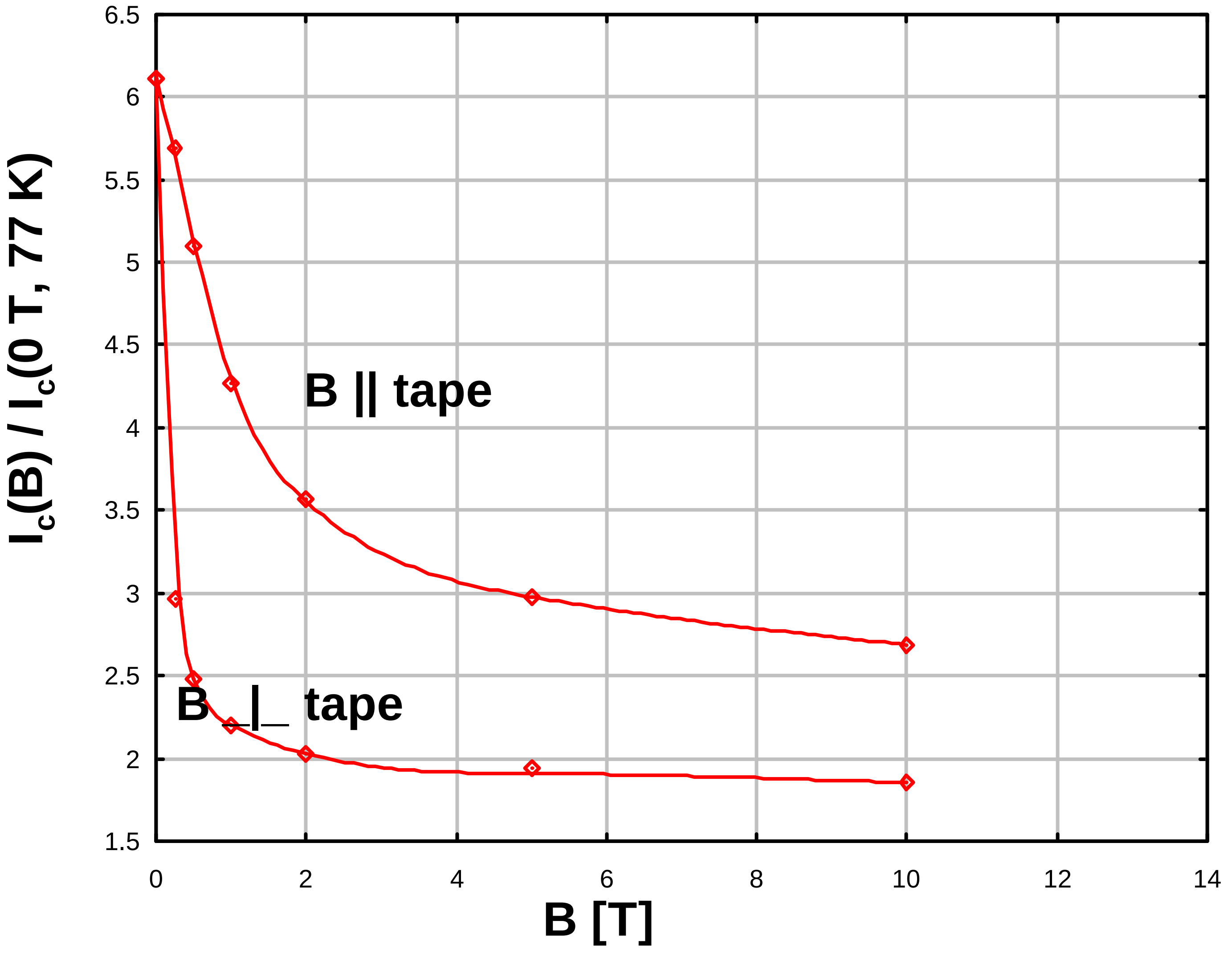
Field dependence of critical current at 77 K



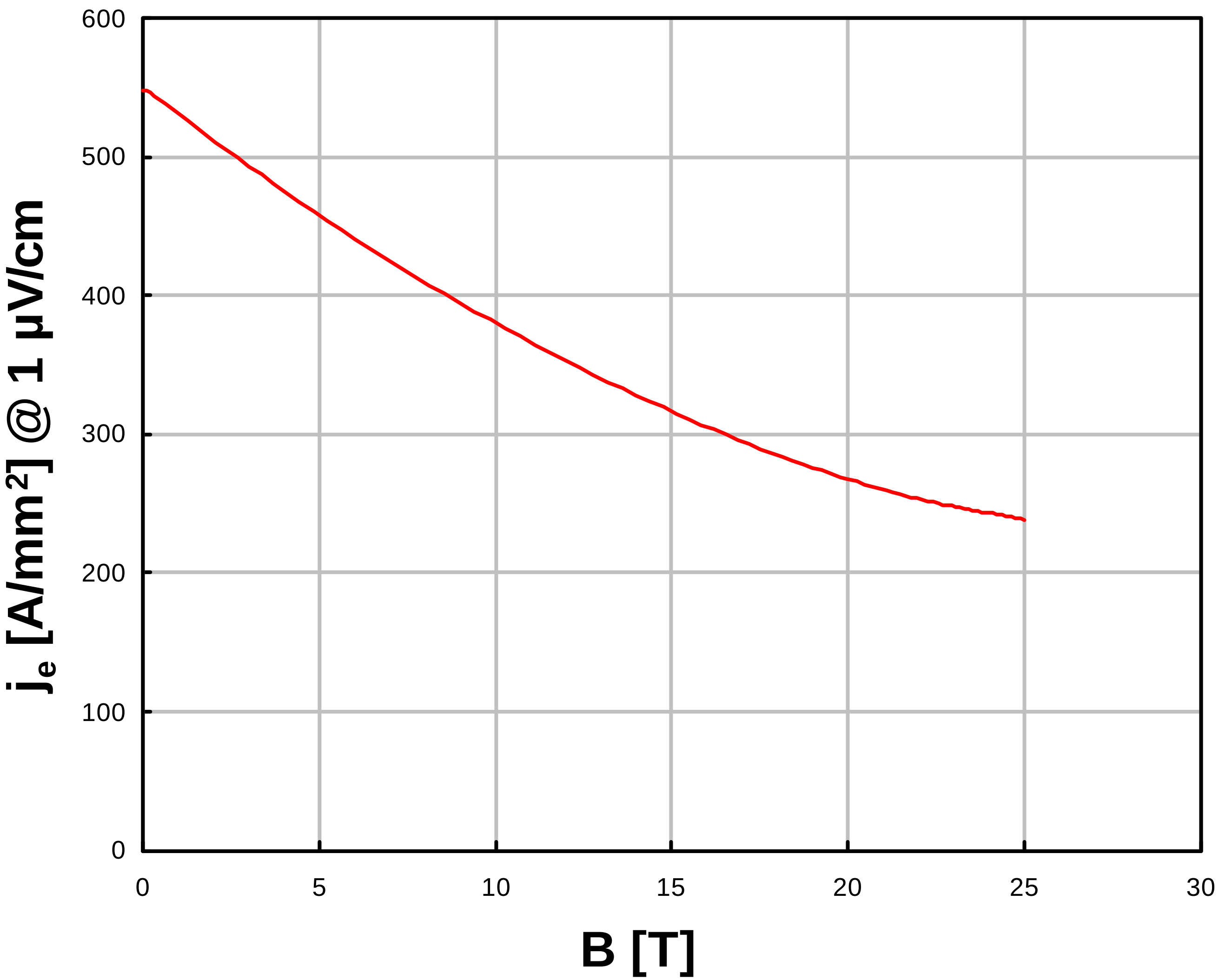

2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
B || tape
B _|_ tape
$I_c(B) / I_c(0\ T,\ 77\ K)$
B [T]



$I_c(B) / I_c(0\ T, 77\ K)$
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
14
B || tape
B _|_ tape
B [T]

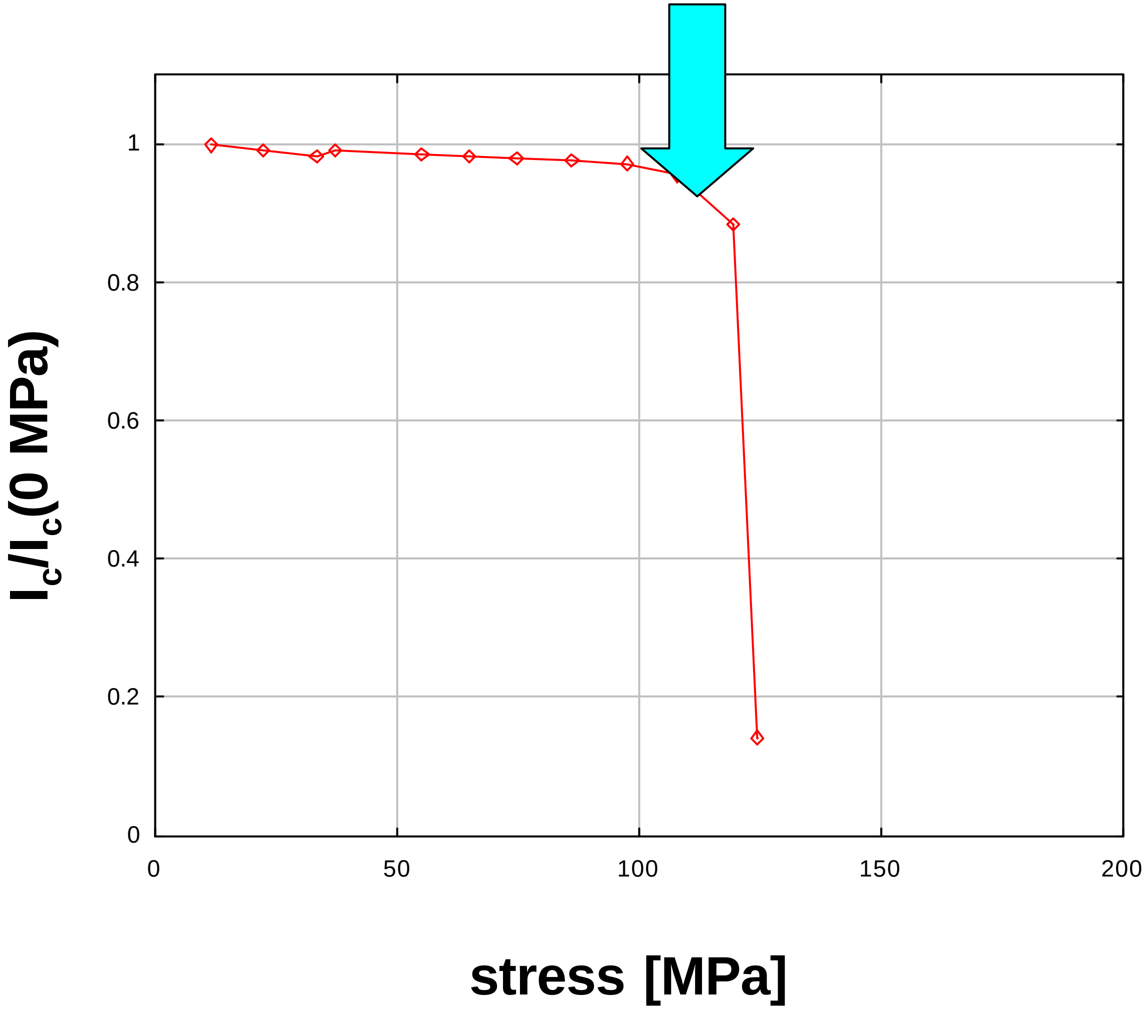


6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
0
2
4
6
8
10
12
14
B [T]
I_c(B) / I_c(0 T, 77 K)
B || tape
B _|_ tape



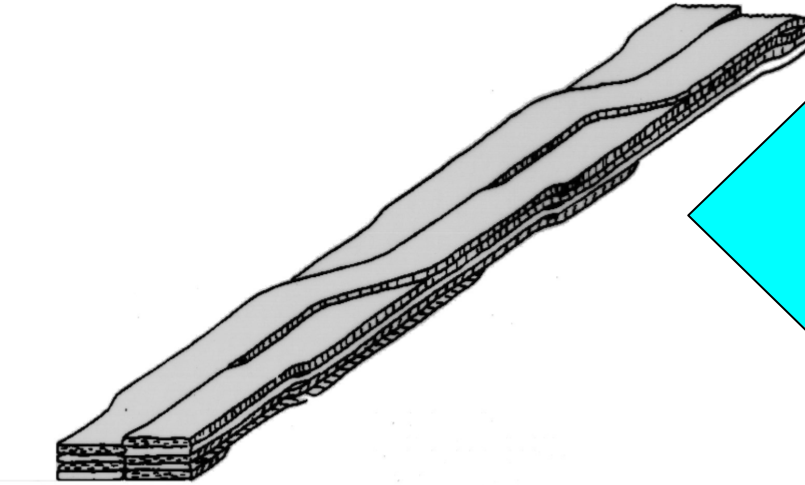
sample: helix Ø30 mm

Overall critical current density of Bi-2223-HTSL/AgAgMg at T=4.2 K. The distance of voltage taps is >1 m

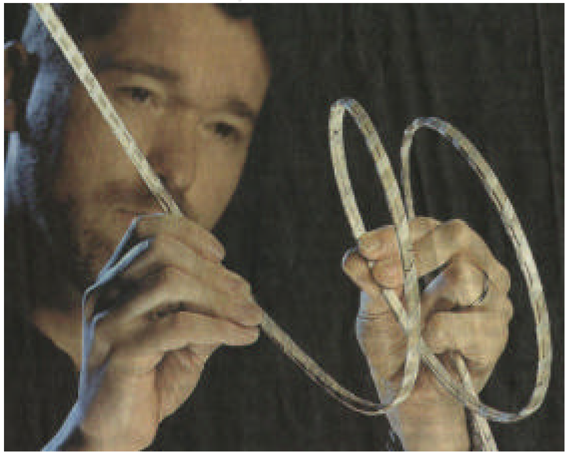


tapes with AgMg-sheath show robust mechanical properties

σ_c > 100 MPa



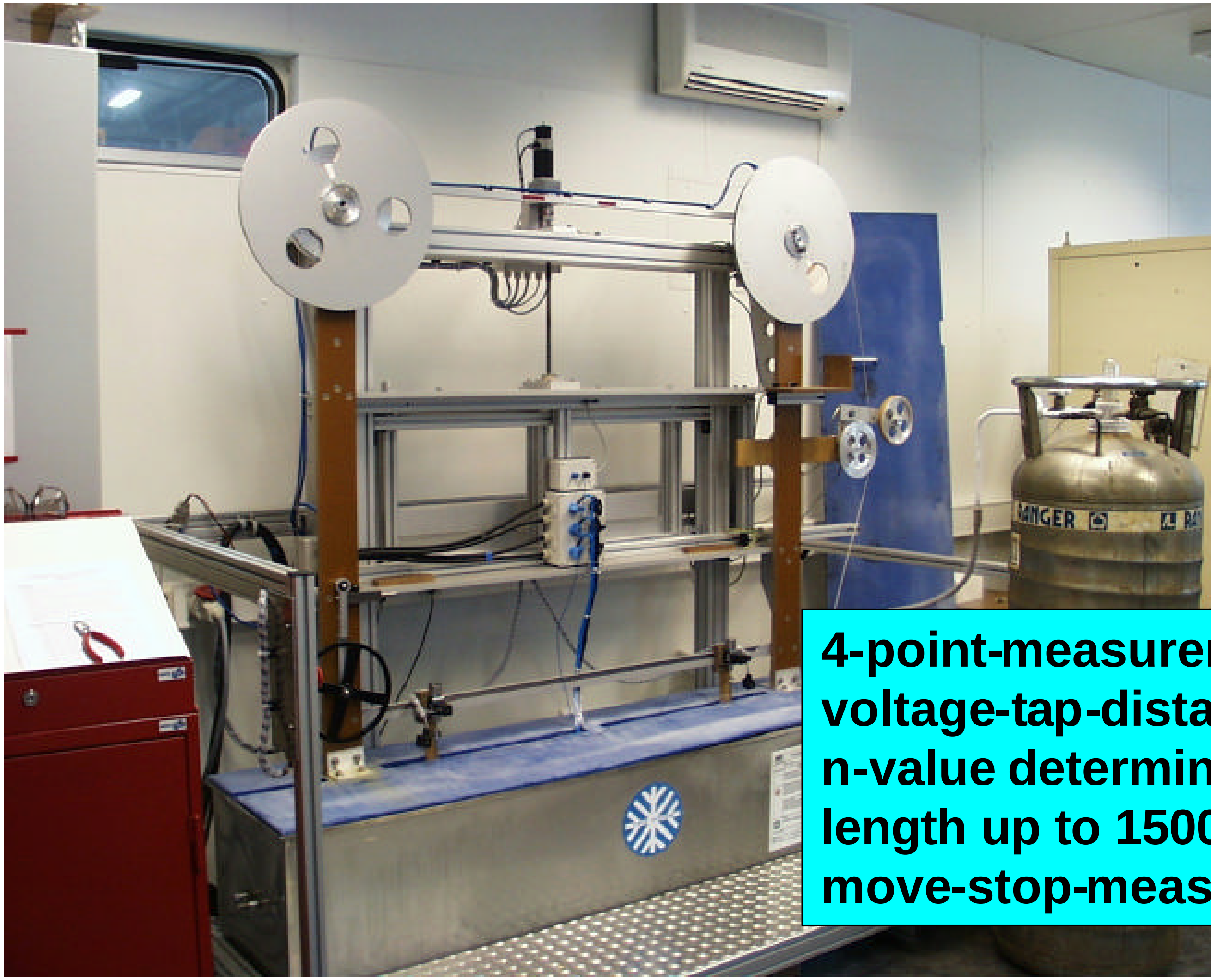
an odd number of transposed tapes, positions are equivalent



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

designed for

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



4-point-measurement
voltage-tap-distance (0.15-1.00) m
n-value determination
length up to 1500 m
move-stop-measure-move-...-mode

- During the last 2 years YBCO based, biaxially textured thin film conductors ("Coated Conductors") were proven to exhibit substantial potential for applications, based on their high current carrying capacity
- For Technical Superconductors functionalities other than jc are mandatory e.g. protection by sufficient amount of normal conducting material and mechanical strengthening
- It was therefore decided to combine the expertise of EAS on Technical Superconductors with that of ZfW Göttingen on YBCO Coated Conductors
- The newly founded EHTS (European High Temperature Superconductors) company, an affiliate to EAS, together with EAS is aiming at developing Technical YBCO conductors based on the technology developed by ZfW
- The co-operation with Prof. H.C. Freyhardt and his Group will be continued

The basic thin film composite consists of

- A high strength substrate, typically stainless steel about 100 µm thick, depending on strength requirements
- The active layer and auxiliary layers (each 1 to few µm thick)
  - Buffer layer, preferentially YSZ (Yttrium Stabilized Zirkonia) produced by IBAD (Ion Beam Assisted Deposition
  - YBaCuOxide layer, preferentially produced by PLD (Pulsed Laser Deposition)
  - Conductive protection layer, e.g. made of gold

A Technical Conductor requires

- Additional normal conducting material for protection, preferentially of Cu (100 µm to few 100 µm thick)

- No final conductor geometry defined

- Much less characterized compared with Bi-2223

Achieved performance

- Up to 40 A per mm width of conductor @ 77 K, self field
- Typ. 120 A per mm width of conductor @ 4.2 K, 20 T

In a “virtual conductor” with 100 µm SS and 100 µm Cu this corresponds to

- jc ≈ 200 A/mm² @ 77 K, self field
- jc ≈ 600 A/mm² @ 4.2 K, 20 T (!)

- This makes YBCO - in terms of jc - very competitive to Bi-2223

- Increase production unit lengths from present 10 m to 100 m to ≥ 1000 m
- Demonstrate homogeneity and reproducibility of long lengths
- Further increase performance
- Produce and test Technical Conductors with adequate protection and mechanical properties
- Build end test demonstrators for applications
- Increase production speed
- Decrease production cost

	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

- EAS is actively pursuing research and development
    - on all major LTS and HTS materials
    - for all important applications

- Accelerator applications remain a focus of our development

- Strategic acquisitions and partnerships help to speed up development and to increase efficiency