ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Stacked tape HTS conductors for Fusion Magnets

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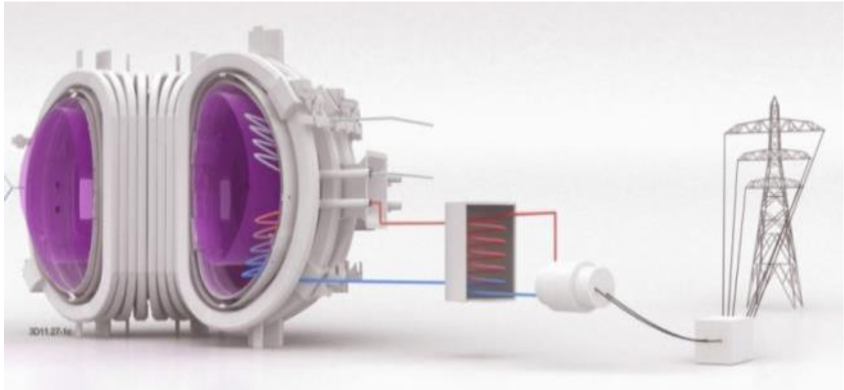
- Background
- Motivation
- Development of HTS conductor for Fusion
- Prototype test and electromagnetic cycling
- Design of HTS conductor for Central Solenoid
- Summary

Background

EU-DEMO (2020-2050)



DEMO is a power plant prototype

DEMO should produce electricity

Construction cost should compare to competitors (PV, wind, storage, gas, …). Cost is a design constrain.

"…fusion will have to demonstrate the potential for competitive cost of electricity. …, the perspective of economic electricity production from fusion has to be set as a target, e.g. minimizing the DEMO capital costs"

https://www.euro-fusion.org/wpcms/wp-content/uploads/2013/01/JG12.356-web.pdf

FCC (2020-2040)

FCC is a scientific instrument

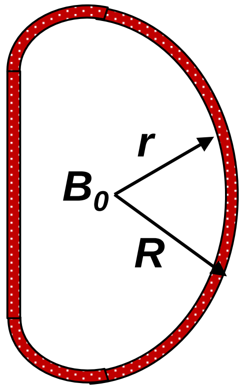
FCC should produce knowledge

Construction cost should be "affordable"?

Background

The magnet type influence the cable design.

Fusion magnets



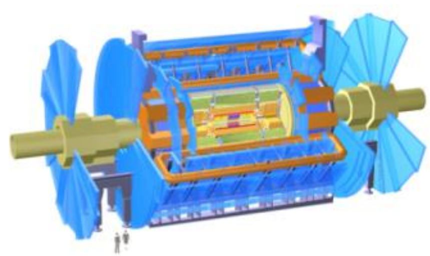
R/r ~ 1

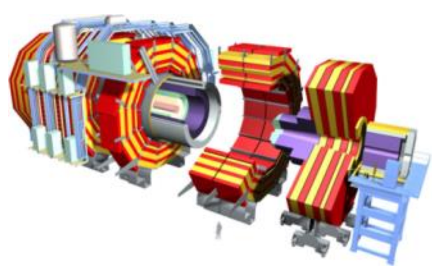
Thin winding

Large bore

B_{peak}/B_0 > 1

Superconductor is far from the center $\Rightarrow$ J_{nonCu} is not so important





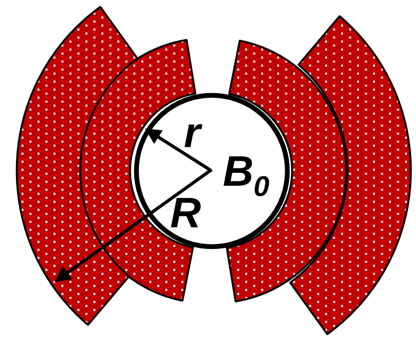
High field dipoles

R/r > 1

Thick winding

Small bore

B_{peak}/B_0 ~ 1



Superconductor is close to the center $\Rightarrow$ J_{nonCu} must be high

Motivation

Why HTS for Fusion Magnets?

OPPORTUNITIES

- **Higher operating temperatures** than LTS.
- **Higher operating field** (in the plasma) than LTS.
- **Higher temperature margin** (>10 K instead of 2-3 K) than LTS: HTS could easily sustain the large nuclear heat load in the innermost layer.
- **Cost**: today coated conductors are more expensive than LTS (next slide) but HTS are much "younger" than Nb_3Sn and have large margin for improvements.

CHALLENGES

Cost balance: cryogenic vs. conductor cost. Which coolant? LH?

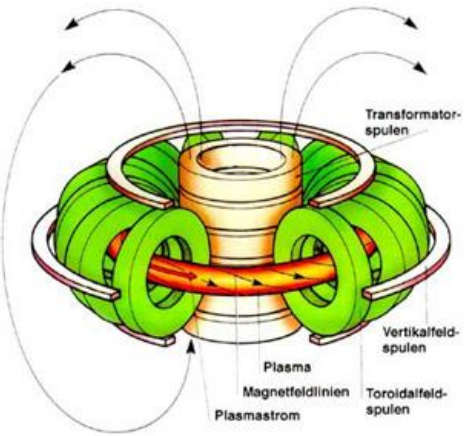
At present the divertor can not take such high heat loads. Neutron resistant structural materials.

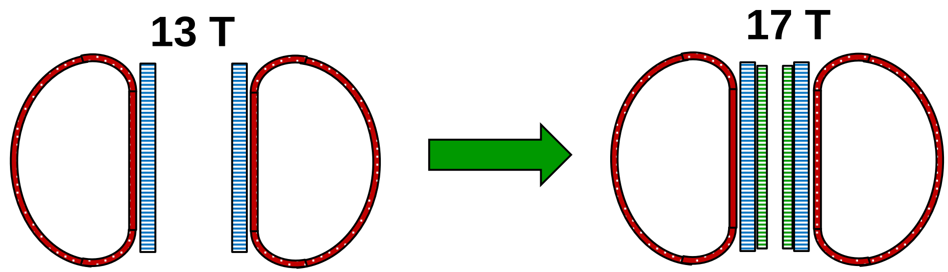
Refrigerator: cost balance.

Will ever low-cost coated conductors be produced?

Motivation – HTS in the Central Solenoid

Opportunity for high field in the CS



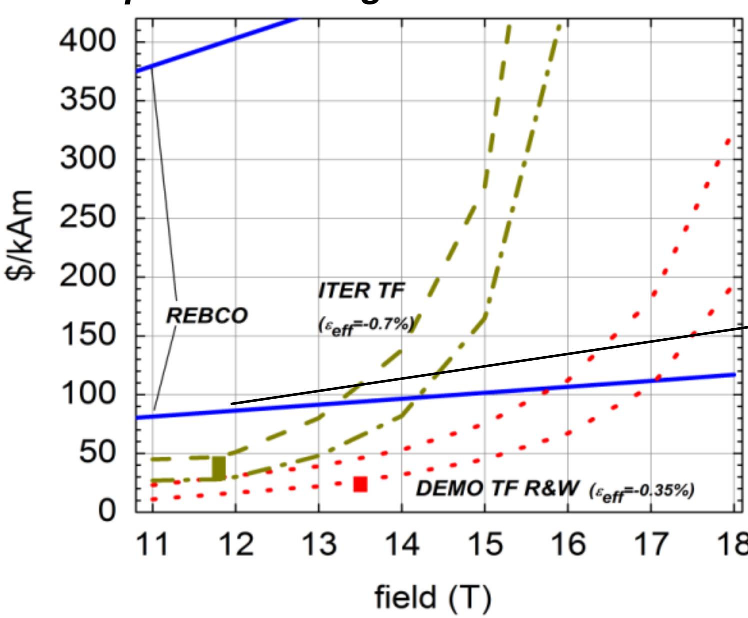


Large and expensive TF

Smaller and cheaper tokamak

<u>Same magnetic flux</u>

Superconducting cost for Fusion cable



c.c. tape cost (4.2 K, 12 T):
60~300 $/kAm

The extra cost of HTS in the Central Solenoid can save a lot on the cost of Nb_3Sn and steel on the Toroidal Field magnet.

R. Wesche et al., Winding pack proposal for the TF and CS coils of European DEMO, IEEE Trans. Appl. Supercond. 26 (3) (2016) 4200405

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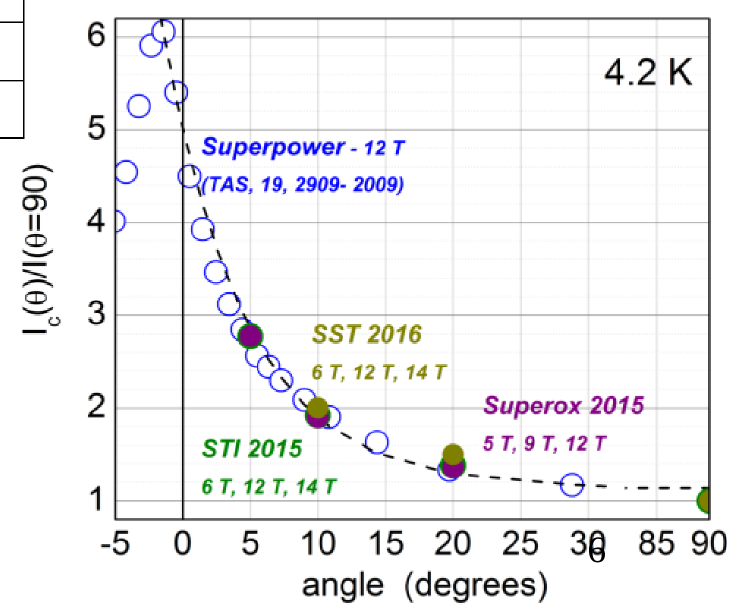
Tape Overview – $I_c(B,\theta)$

manufacturer	*I_c (77 K, s.f.) on 4 mm*	***I_c (4.2 K, 12 T) A/cm width***	***J_e(nonCu) at 4.2 K, 12 T***
STI Conductus	130-180 A	**850-1200**	**1700-2400 A/mm²**
Shanghai Sup. Tech.	>140 A	**600-1000**	**1200-2000 A/mm²**
Superpower	80-120 A	**400-1000**	**800-2000 A/mm²**
Bruker	45 A	**>1500**	**>1500 A/mm²**
Fujikura	300 A	**1200**	**1600 A/mm²**
Superox	90-150 A	**420-520**	**700-870 A/mm²**
Theva	100-200 A	**500-1000**	**500-1000 A/mm²**
AMSC		**400 (1000 irr.)**	**500 (1300 irr.) A/mm²**
SuNAM	>300 A	**400**	**400 A/mm²**
D. Nanoschicht	100 A	**350**	**350 A/mm²**
SWCC	120 A		
Sumitomo, Metox, SAMRI/CAS, Shanghai Creative Sup. Tech., Oxolutia			

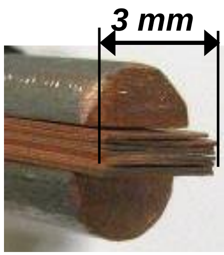
November 2016

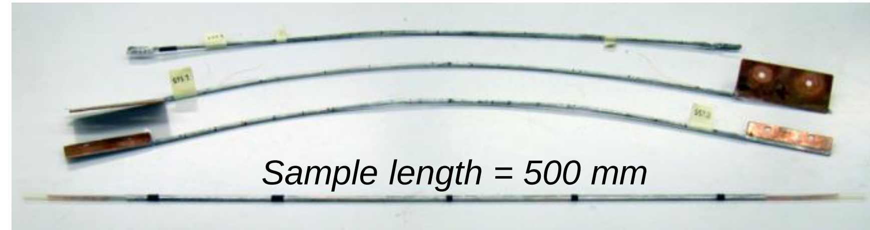
Measured at SPC-SG and from publications/presentations.



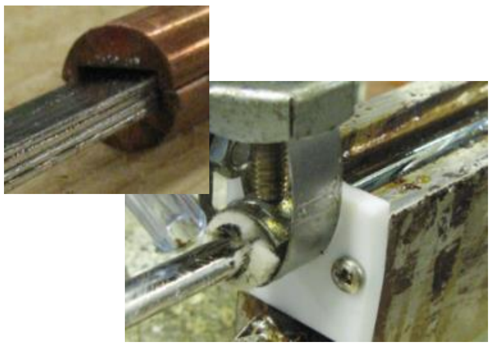
Development at SPC-SG

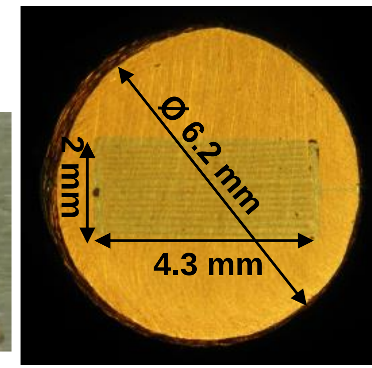
2012



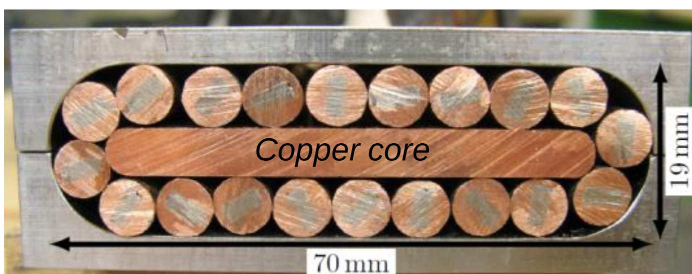


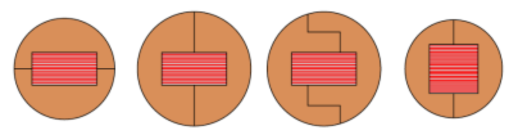
2013

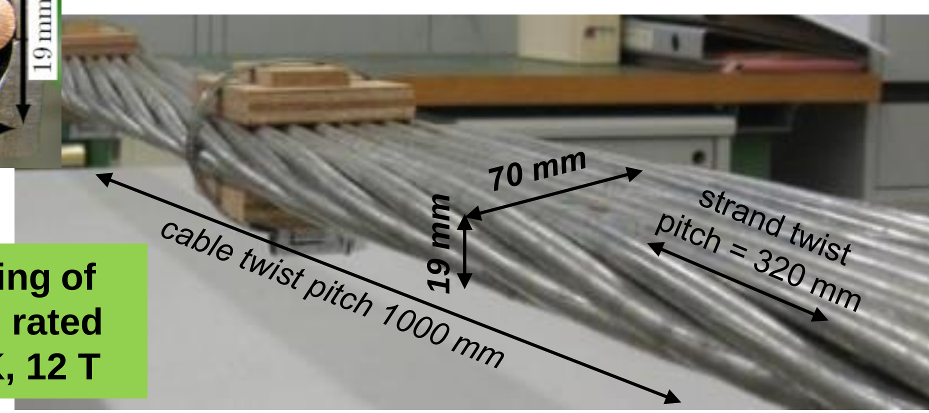


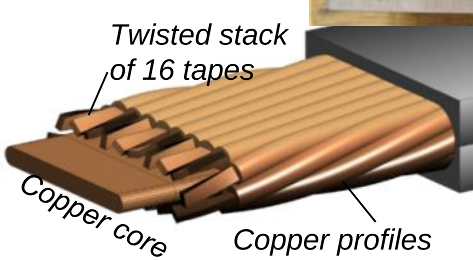


2014









In house manufacturing of two short prototypes, rated for about 60 kA at 5 K, 12 T

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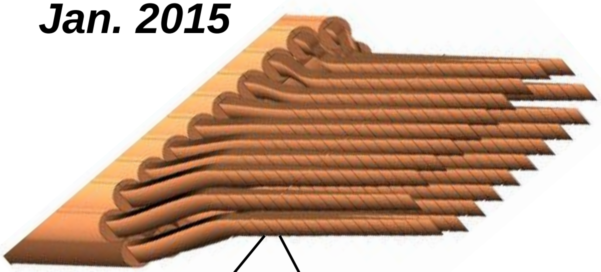
Development at SPC-SG - Terminations and jacket

Jan. 2015



Staggered tapes (15 mm)

Staggered ends soldered in grooves machined in copper blocks

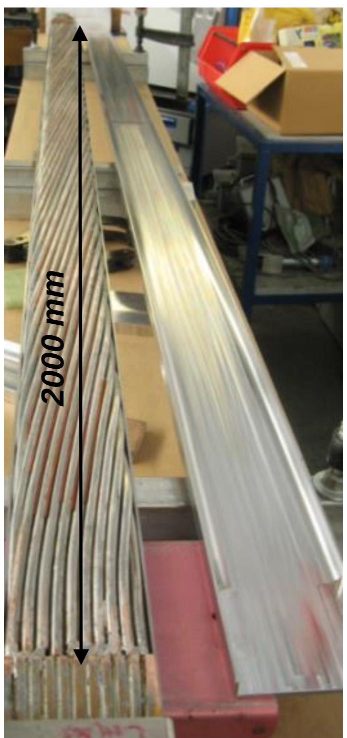
Measured resistance of each termination: < 1 nΩ

specific contact resistance at 4.2 K (tape to Cu): 10^{-11} Ω·m^2

Supercond. Sci. Technol. 28 (2015) 124005

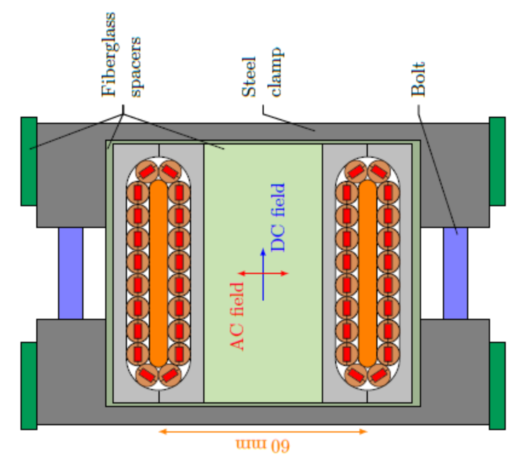
doi:10.1088/0953-2048/28/12/124005

Also non-staggered ends may work on 30-40 cm.

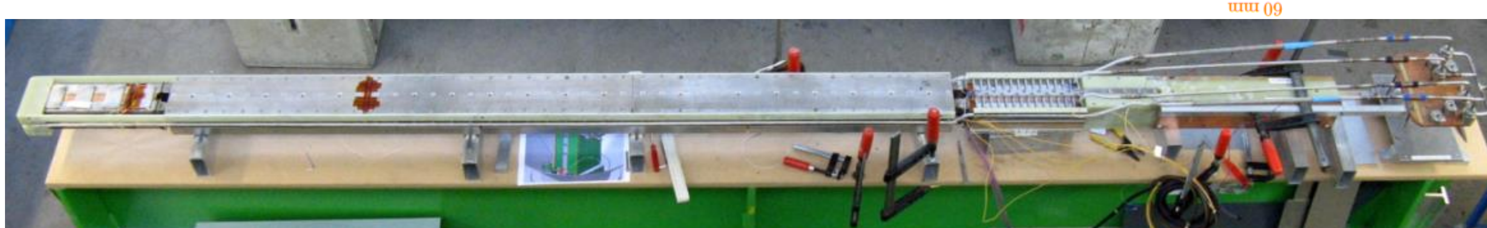


The jacket is composed of two machined profiles, welded around the cable.

During welding the strand temperature did not exceed 90°C.



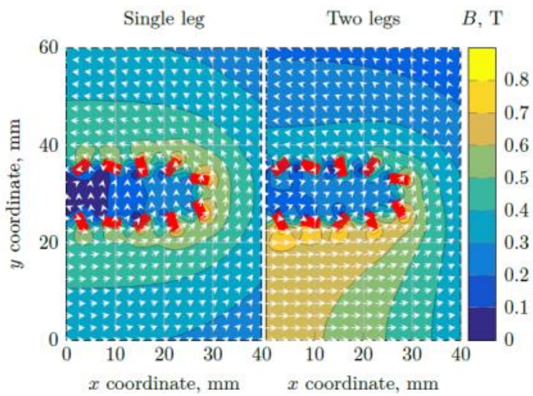
April 2015



Test – assessment

I_c(77 K) is not reliable to assess performances at 4.2 K in field.

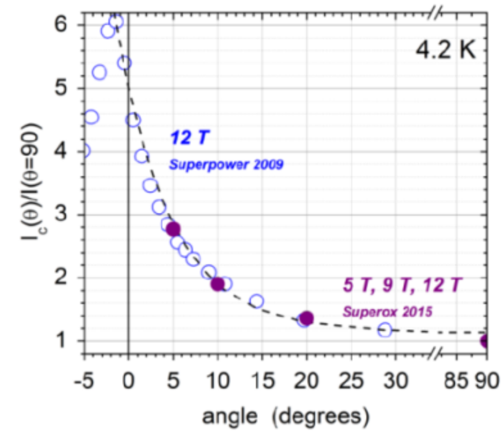
Tapes from Superpower and Superox were measured at 4.2 K, 12 T, 1 μV/cm



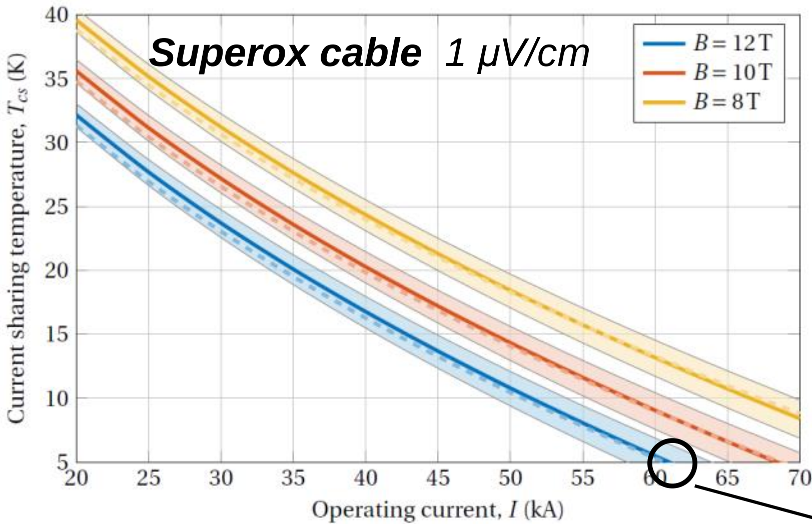
Contributions from the self field and from the return conductor.

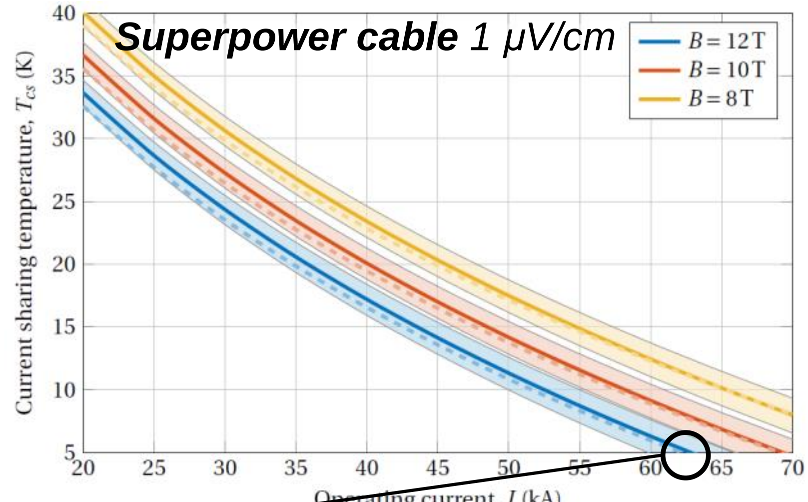
$I_c(B,T)$ scaling law (literature)

Angular dependence (measured)



Assessments of T_{cs} for both conductors





measured

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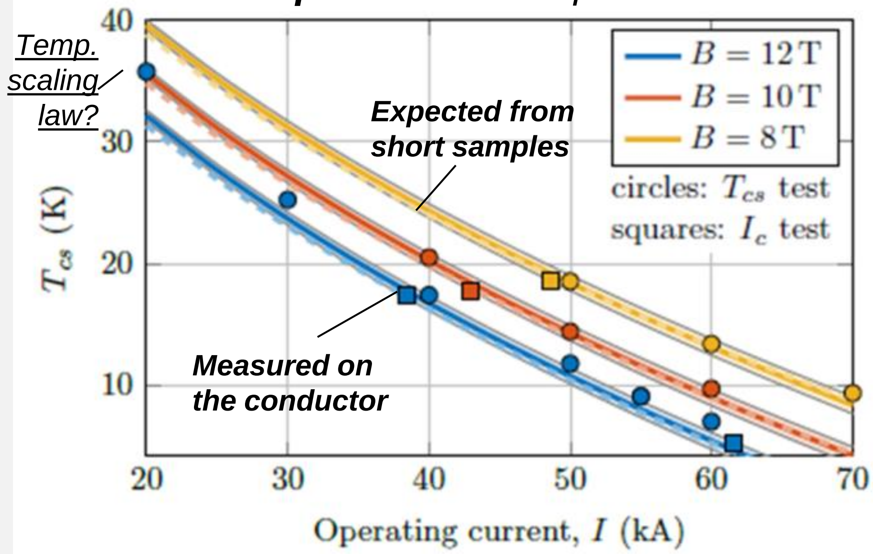
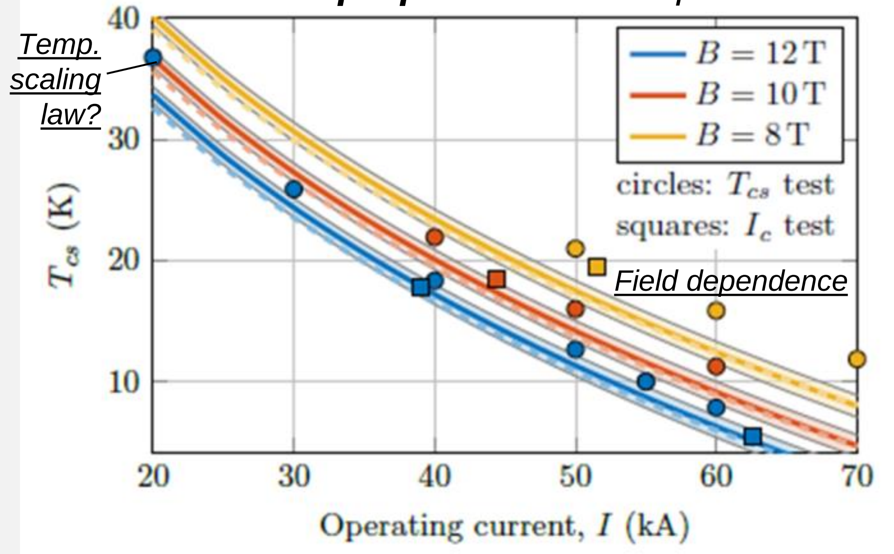
Test - DC

Superox cable *1 μV/cm*



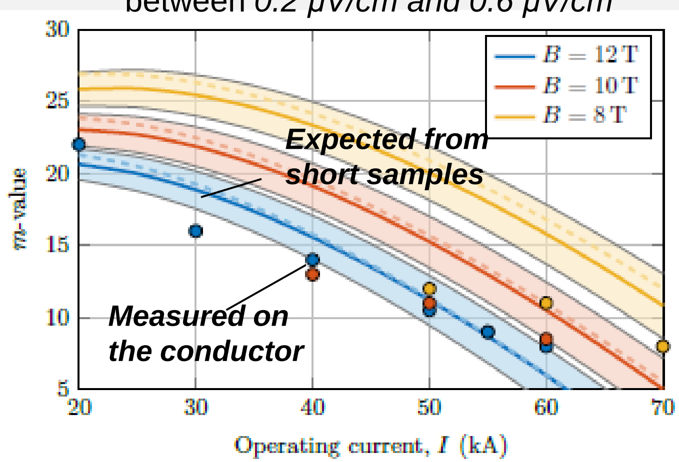
Superpower cable *1 μV/cm*



About 100% of the performances of short samples were retained in the conductors

Superox – *m* values

between *0.2 μV/cm and 0.6 μV/cm*



In ITER conductors (Nb_3Sn) 20<*m*<30 at 6 K,10.8 T.

We expected shallow transitions because of the much higher T_{cs}

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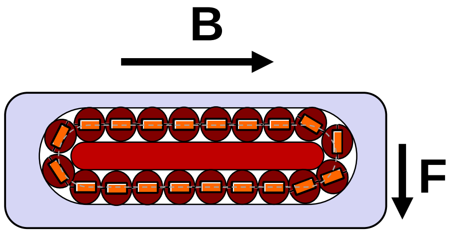
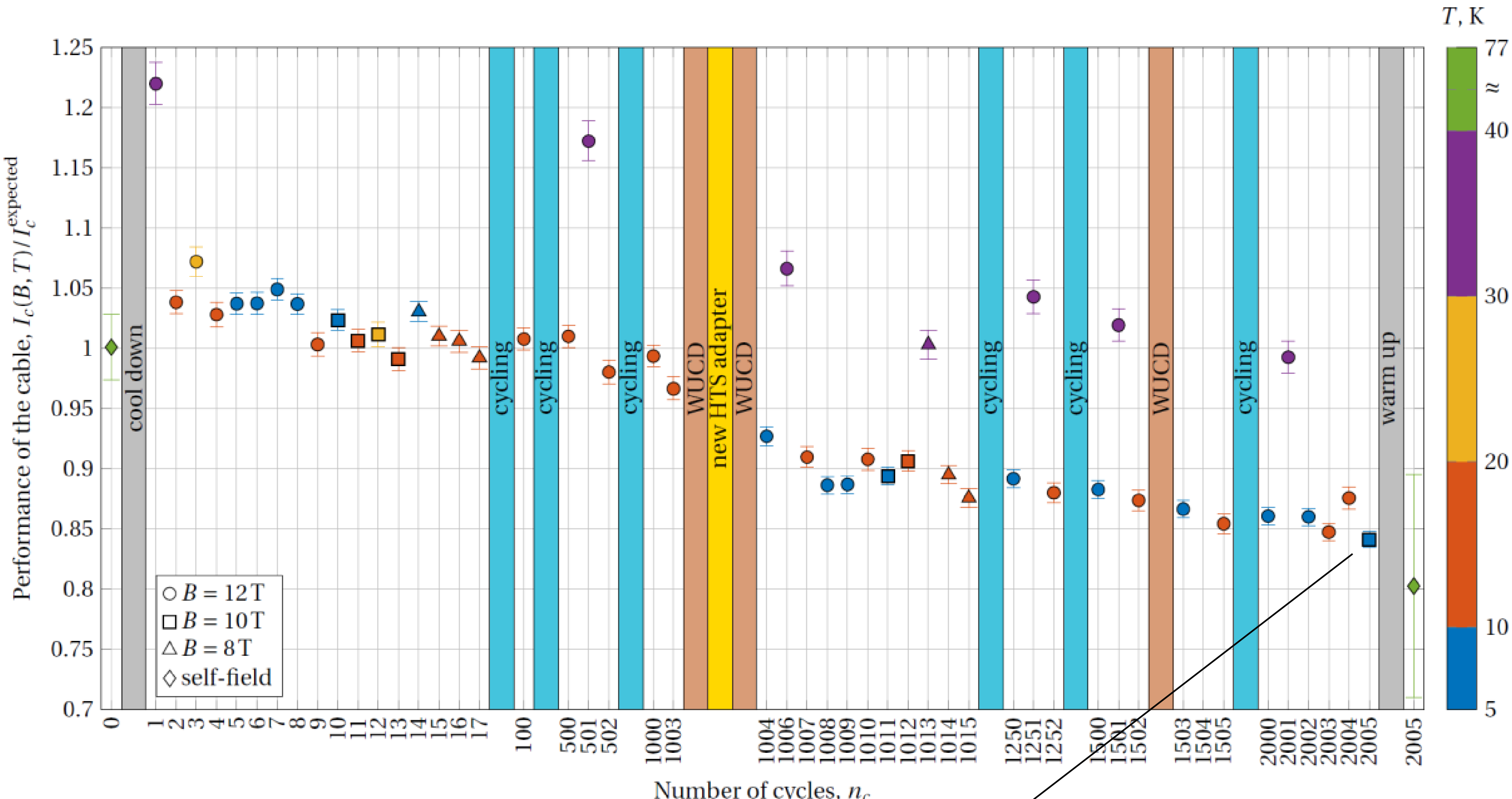
doi:10.1088/0953-2048/28/12/124005

Test - cycling



Electromagnetic cycling: in background field of 12 T the current in the sample is ramped up and down.

Large transverse e.m. forces are applied to the cable.



Supercond. Sci. Technol. 29 (2016) 084002
doi:10.1088/0953-2048/29/8/084002

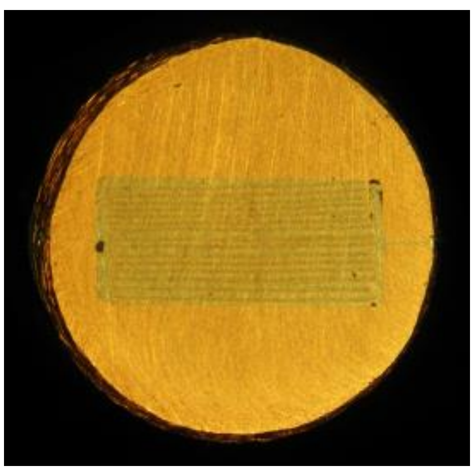
After cycling the reduction on I_c reached 15%

Visual inspection and I_c at 77 K

Jacket and terminations were removed.

Solder between copper profiles failed in few locations, mainly located at the cable edges.

Such fractures could extend into the stack of tapes, causing the delamination of the superconducting layer and a drop in I_c.

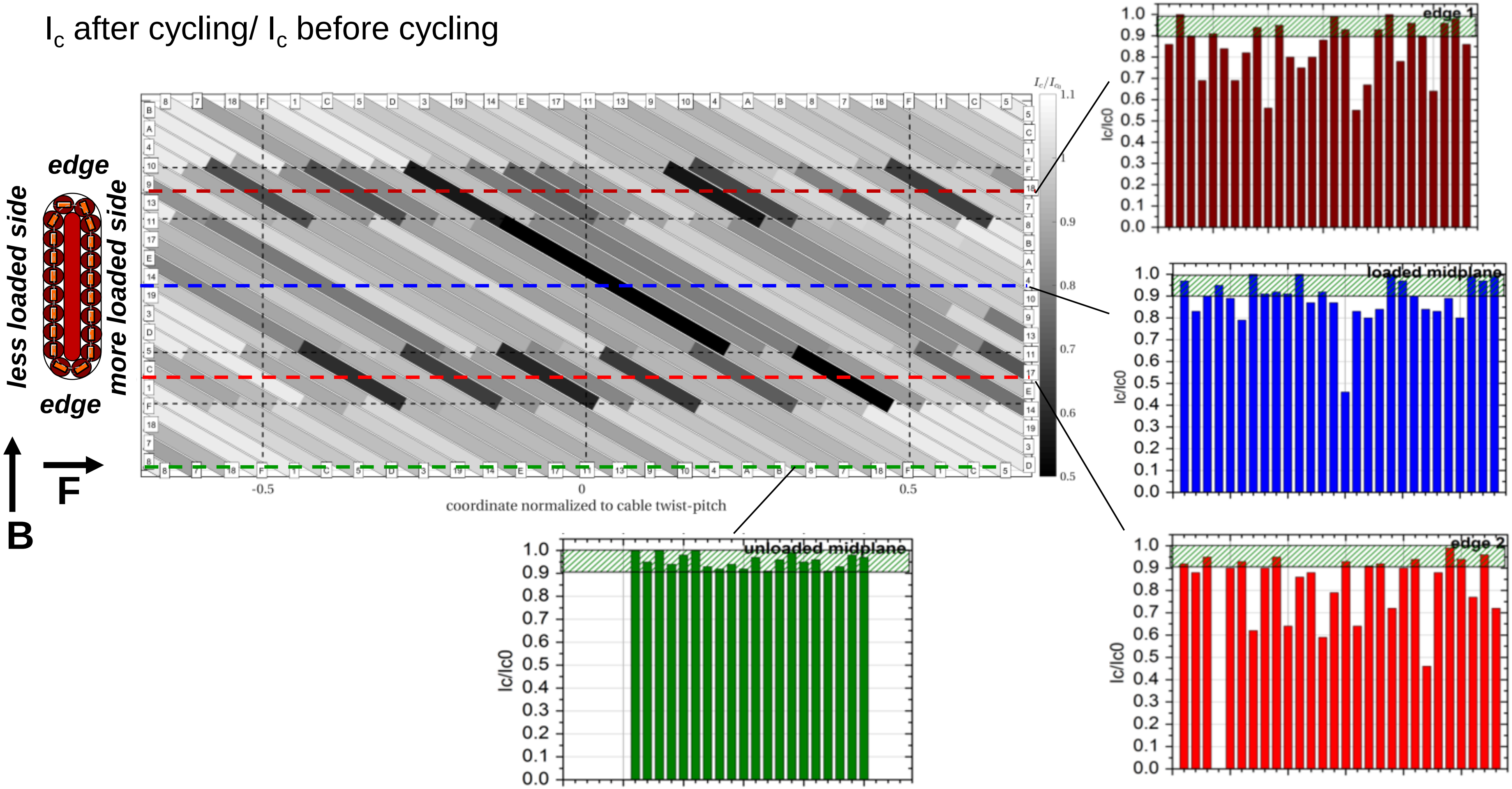


Cable was disassembled.

Strands I_c was measured at 77 K.

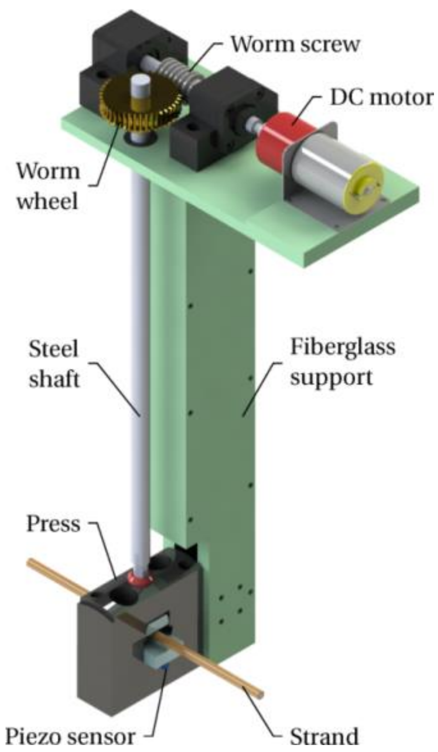
Visual inspection and I_c at 77 K

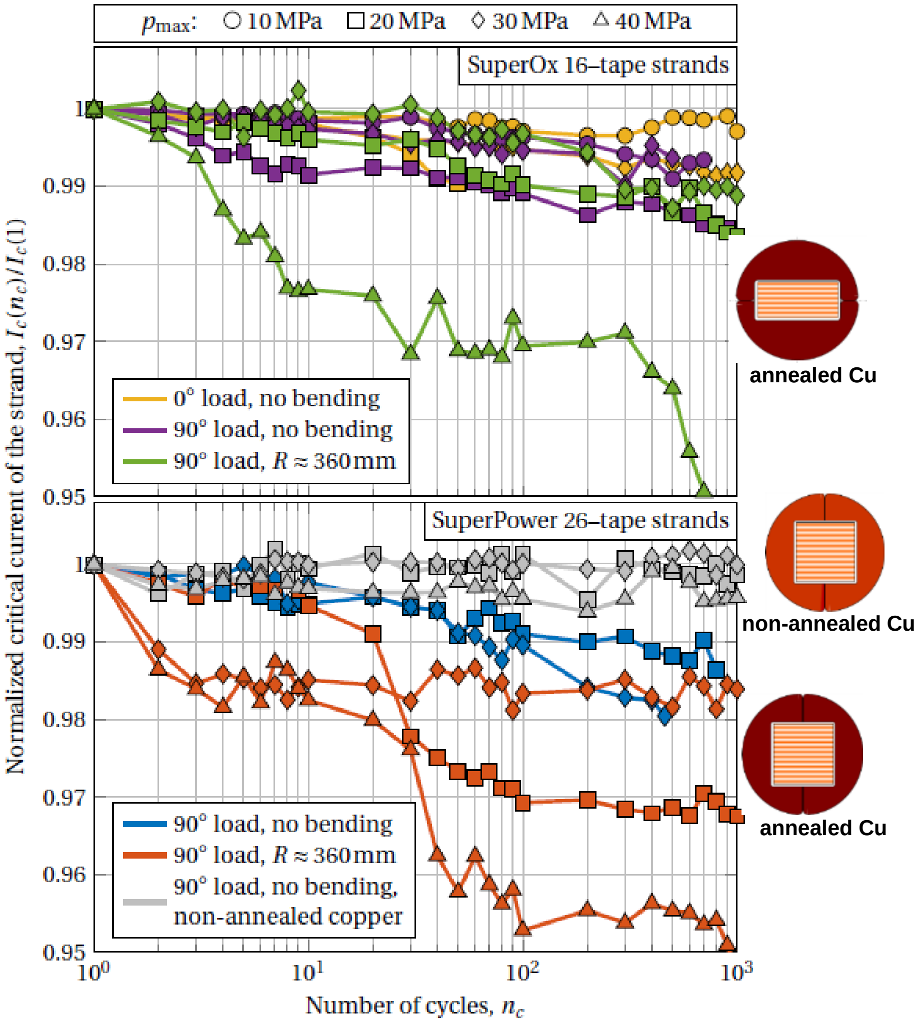
I_c after cycling/ I_c before cycling



- **The largest reduction is located at the cable edges.**
- **The heavy loaded flat side shows also some degradation.**
- **The less loaded flat side shows almost no degradation.**

Transverse pressure fatigue test

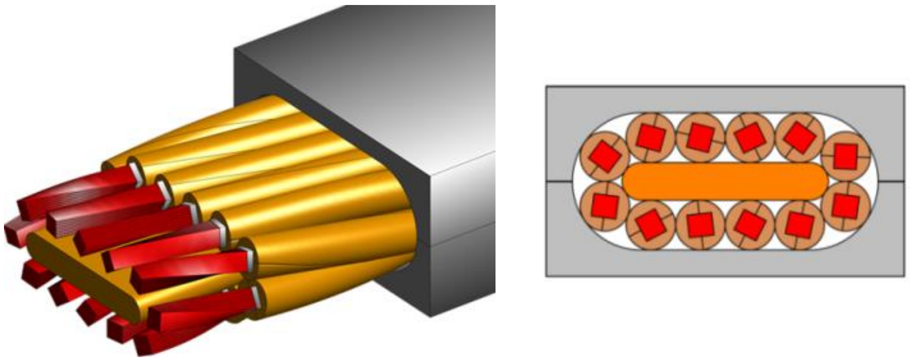


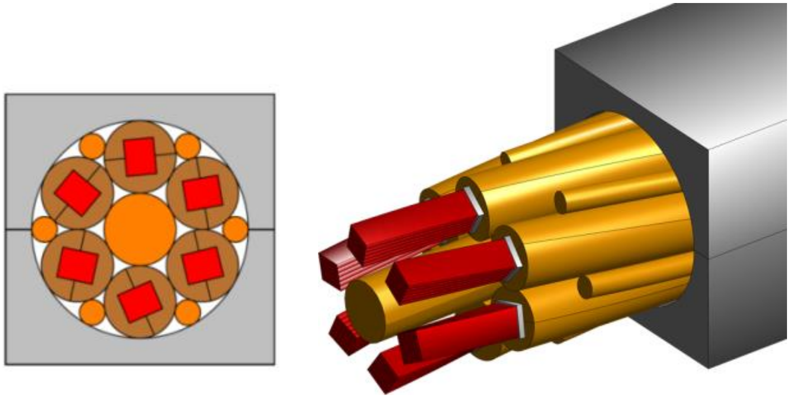


- Large degradation observed in the cable edges was not replicated in the press test.
- Only the non-annealed strand shows no degradation.
- Bent samples tend to show more degradation than the straight samples.

Design of an HTS conductor for CS

MOTIVATION - Increasing the field in the CS coil would allow to reduce the size of the CS and in turn the size (and cost) of the TF magnet system. **The cable should be operated at 51 kA (5 K, 17 T).**
Two designs will be tested:





Flat cable, annealed copper: soft Cu but lower transverse stress than in round cable.

Round cable, non-annealed copper: stronger against compression, but higher transverse stress.

Improvements:

- **Strand bending radius is increased (>4 times longer than in the first prototype).**
- **Stronger profile soldering because of the larger area (2 to 3 times).**
- **Larger strand Ø: less deformation when pressed.**

Shanghai Superconducting Technology was selected as supplier:

- **Narrow (3.3 mm) and wide tapes (4.8 mm) are available**
- **Fast delivery time**
- **Competitive high I_c over price ratio**
- **Curiosity to test one more supplier.**

Summary

- Two cable prototypes (60 kA at 5 K and 12 T) were manufactured and tested in fields up to 12 T in the EDIPO facility. The superconducting transport properties of the tapes were fully retained.
- During e.m. cycling a reduction of T_{cs} and I_c was observed.
- Measurements of I_c at 77 K on extracted strands showed that most of the degradation took place at the cable edges.
- Two prototypes for the high field CS have been designed taking into account these results: bending radius of the strand will be maximised and the strands will be made more resilient to transverse compression.