MT25 The 25th International Conference on Magnet Technology

The EuCARD2 "Future Magnets" Program for particle accelerator high field dipoles: review of results and next steps

Lucio Rossi - CERN

On behalf of the Collaboration

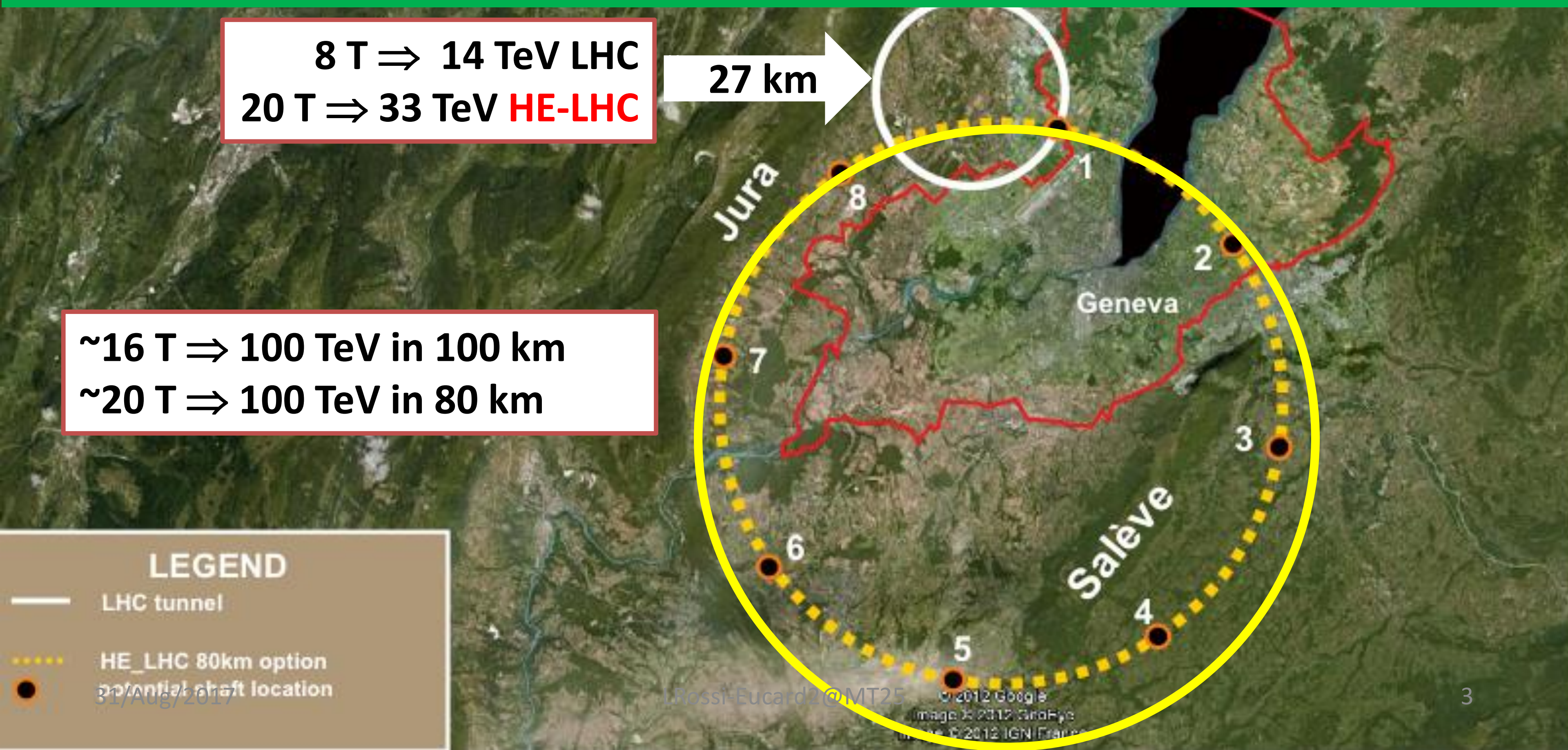
EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

The Partners

- Bruker HTS : REBCO tape
- Conductor: CERN, KIT, UniGeneve, UniTwente, UniSouthHampton
- Magnet: CEA-Saclay, CERN, INPG (Grenoble), Danish Tech. Inst.
- Test: CERN & INFN-LASA (PSI for test of a race-track coil inside Sultan)

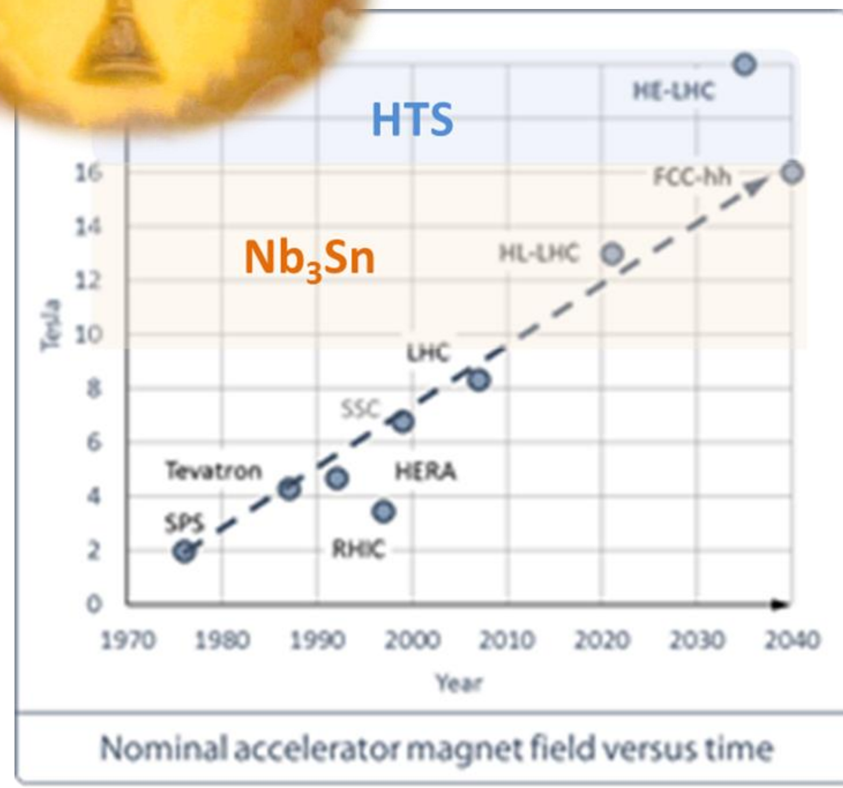
FCC Study (Future Circular Colliders)
CDR and cost review for the next ESU (2019-20)

- 80-100 km tunnel infrastructure in Geneva area
- pp-collider (VHE-LHC) defining the infrastructure requirements
- e+e- collider (TLEP) as potential intermed. step and p-e (VLHeC) option
- CERN-hosted study performed in international collaboration



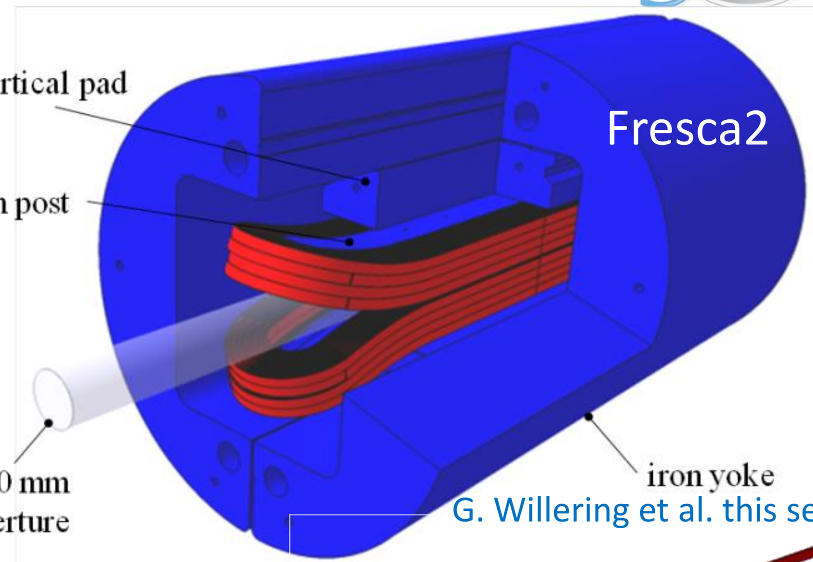
Many reasons for HTS: not only highest field

- 20+ T dipole field is the holy grail for accelerator people
- Better solution in high rad zone (triplet regions), B=10-15 T with high margin
- Pulsed magnets in the accelerator chain: 3-6 T at 20-80 K for low power consumption
- Long SC links for cold powering (s.f. 100-200 kA cable, 100-500 m long)



Framework & goals

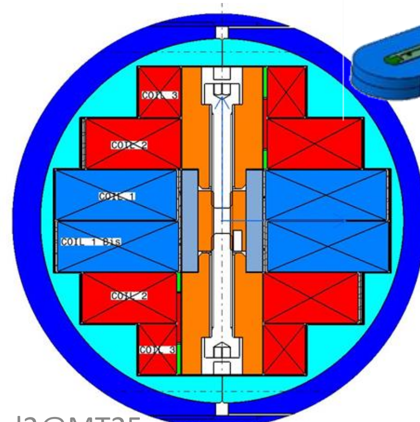
- FP7 EuCARD – WP7 technology R&D 2008-2013
  - FRESCA2 dipole
    13 T, ∅ 100 mm facility
    Tested in July 2017: **13 T!**
  - HTS insert + 6 T (no bore)
    Tested in Juy 2017: **4.52 T @4.2K**
    (power supply limit, no quench)



G. Willering et al. this session

- **In 2011** we set the goal for a new EU program FP7-EuCARD2 for enabling HTS in accelerator dipoles.
  - **Develop a CONDUCTOR of accelerator quality**
  - **Develop a Dipole demo with accelerator characteristics**

EuCARD HTS Insert



M. Durante et al. Wed-Af.P03

Program of EuCARD2-WP10 *Future Magnets:* 2013-2017

CONDUCTOR

- 5-20 kA cable @4.2K 5-20T
  ten kAmps-class cable
- For accelerator dipoles:
- $J_{overall} \geq 400$ A/mm2
  - 80-85% filling factor
  - J_{eng} strand ≥ 400 A/mm^2 min.
  - **J_{eng} strand ≥ 600 A/mm^2 enhan.**
- Field Quality
  - transposed
- Not too many joints $\Rightarrow$ high current – 100 m long tape

MAGNET DEMO

- **Aperture ~ 40 mm**
  (R_{min} cable $\Rightarrow$ 20 mm!)
- 5 T standalone with 20% margin (> 6 T ss limit)
- Insertable in High Field
  $\Rightarrow$ outer Diam < 100 mm (including mech. structure)
- Length < 1m ($L_{straight} \geq$ 200mm)
- Must reach 16-17 T in 13 T background (Fresca2)

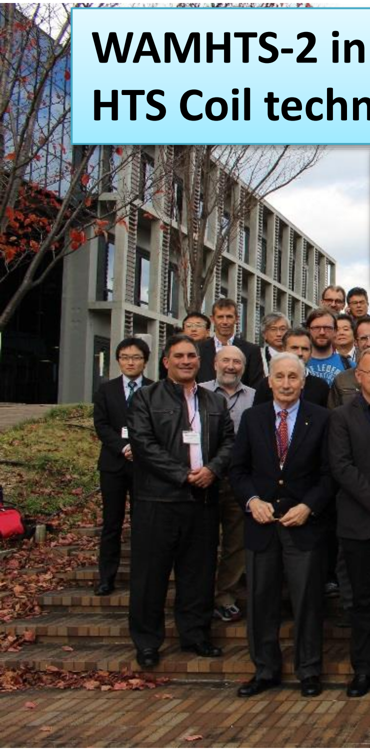
The extended collaboration and WAMHTS

- EuCARD2 has triggered a International collaboration also beyond EU labs
- Japan:
  - Kyoto Univ., KEK, RIKEN
- USA (ASC@FSU, LBNL…)
- Industry:
  - BHTS (Eucard2),
  - SuperPower,
  - Fujikura
  - Sunam,
  - SuperOx,
  - Sumitomo,
  - GCS (NZ),
  - STI

WAMHTS-1 in Hamburg 21-23 May 2014
HTS Conductor – 57 participants

WAMHTS-2-3-4-…

WAMHTS-2 in Kyoto 21-23 May 2014
HTS Coil technology – 55 participants

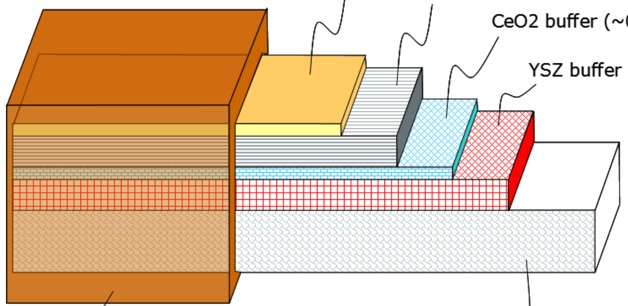


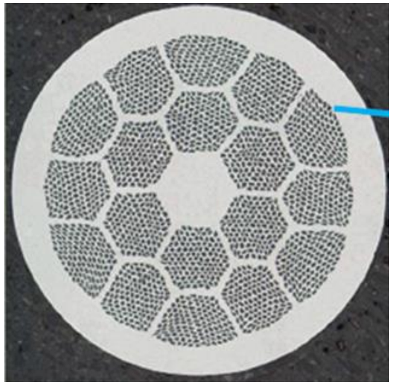
WAMHTS-3 in Lyon 10-11 September 2015
HTS Magnet protection – 66 participants

WAMHTS-4 in Barcelona 15-17 February 2017
HTS Magnet design – 87 participants

With FP7-Eurotapes

Conductor: the initial choice



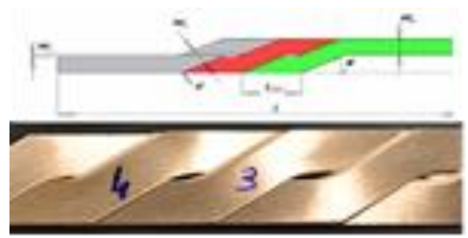


REBCO	characteristics	Bi-2212
High, steadily improving	**Critical current**	High, more stagnant
Roebel cable (waste), ready to use, 50-200 m unit length	**Cabling and general**	Easy Rutherford cable, but need special H.T., very long length possible
Very bad (tape).	**Magnetization**	Worst than NbSn but manageable
Excellent, better than Nb_3Sn	**Mechanical prop.**	Weak vs. transv. stress
Difficult bend in non-easy way, joints not easy, good insulation and handling	**Coil technology**	Very complex HT, large scale coils may be difficult. Easy joints
Various suppliers and projects everywhere	**Supply**	Limited number

Conductor cont.

- Choice in favor of REBCO tapes assembled in Roebel cable
  - REBCO: continuing the route of EuCARD
  - EU Industry. Other EU programs (FP7-Eurotapes)
  - High current density (use// orientation) & Transposition!
  - “Easy” start: conductor in final form, no need high temperature heat treatment of whole coil.

W. Goldacker et al., 2006
J Phys. Conf. Ser. 43 901

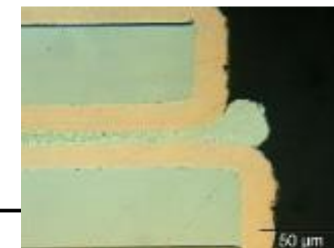


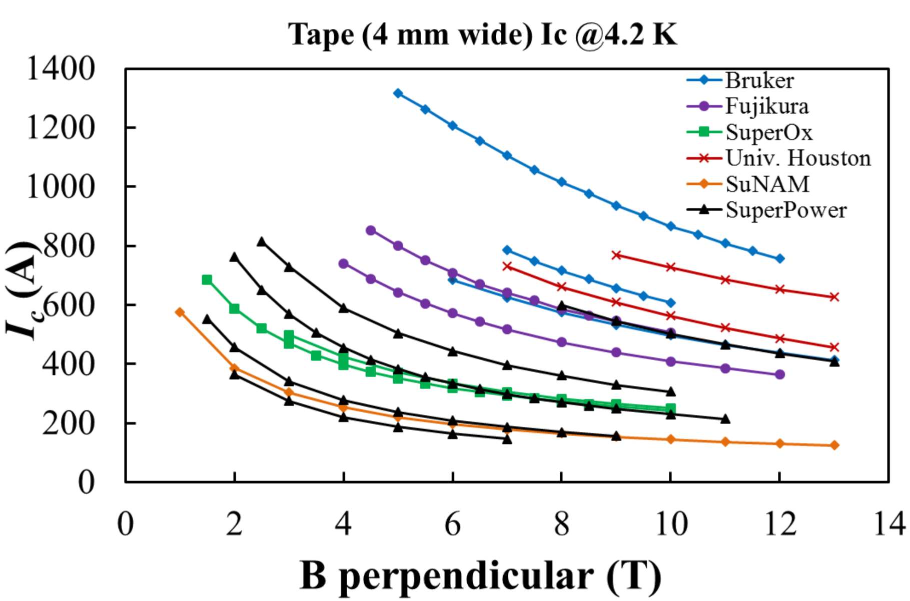
- Other types of cable like stacked tape cable with twist on the curvature ends have been investigated. Eyes on CORC®!
- Activity on Bi-2212 have been pursued in the collaboration CERN-ASC(Fl) on advanced powder from Nexans with mesurements by Univ. of Geneva on strand and in future U.Twente on cable

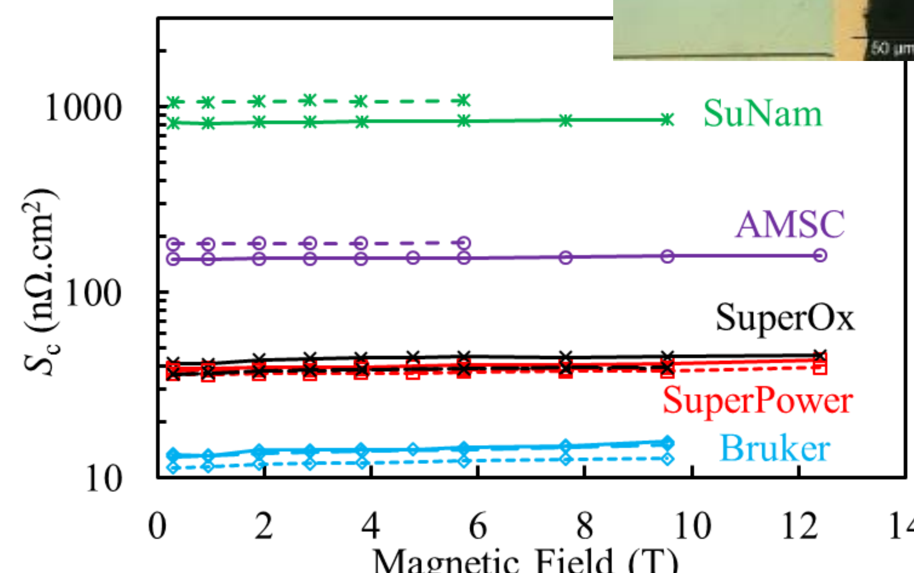
Conductor meas. @ CERN

- Elaboration of J_c(B,T,θ) scaling for REBCO materials
- Magnetization measurements with VSM +/-10.5 T, 1.9-100 K
- Residual Resistivity Ratio (RRR) measurements of the copper stabilizer
- Splice resistance measurements at 4 K in the field range 0-12 T and at 77 K
  - **Type 0:** Lowest resistance (**13-40 nΩ· cm²**)
  - **Type 1**: High resistance (**98-570 nΩ· cm²**)
  - **Type 2**: Very High resistance (**150-884 nΩ·cm²**)

J. Fleiter



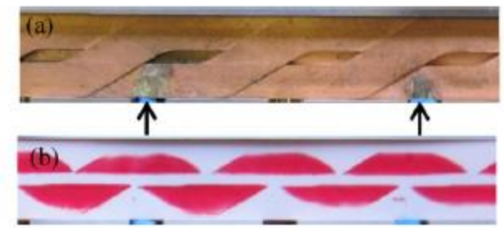




Conductor meas. @ CERN

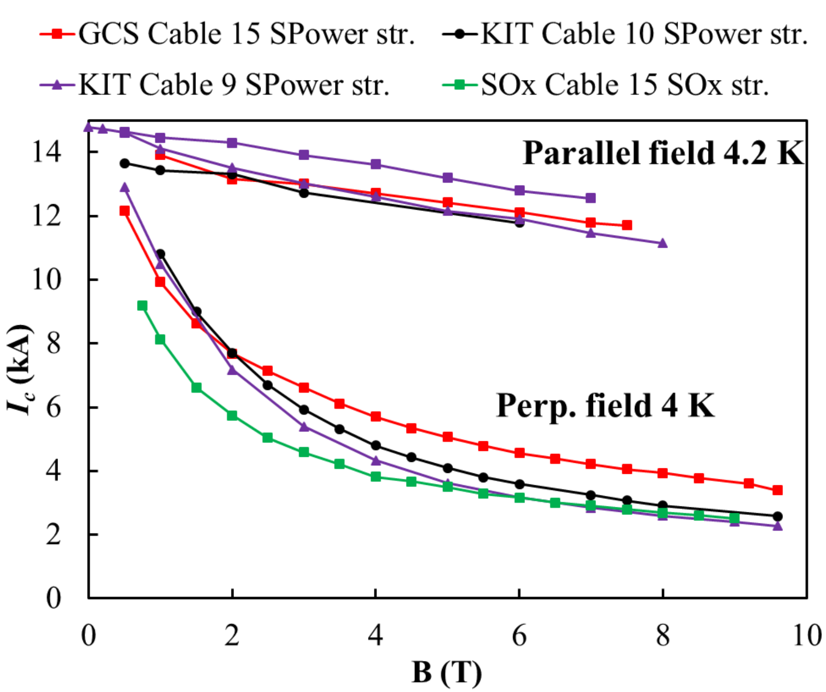
Non impregn. cable I_c measured in FRESCA in ⊥ and // fields up to 10 T

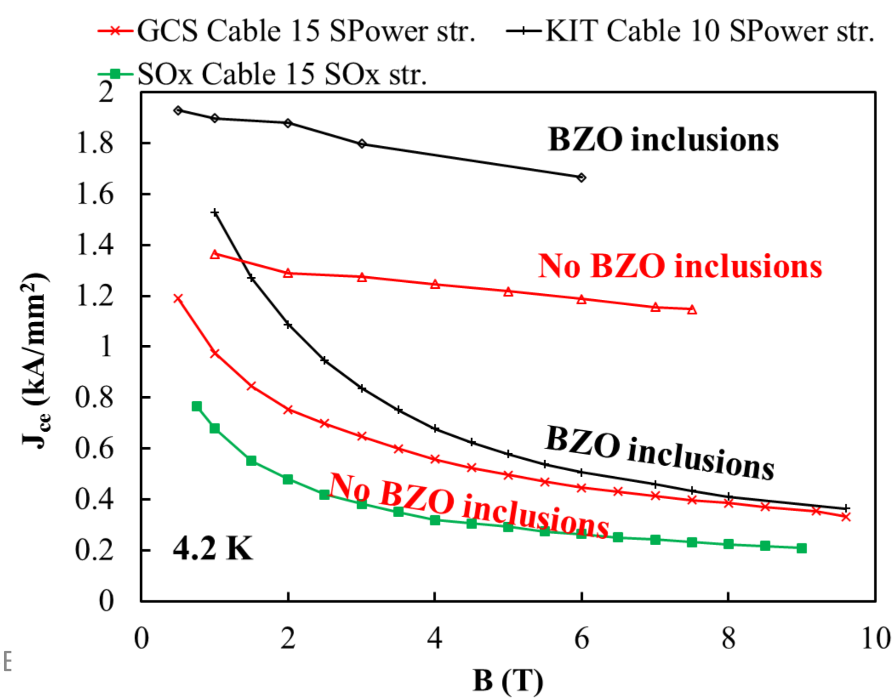
- **Low joint resistance ~1 nΩ (252-300 mm long)**
- **I_c of about 12 kA in 7 T // field with extremely high J_{ce}**



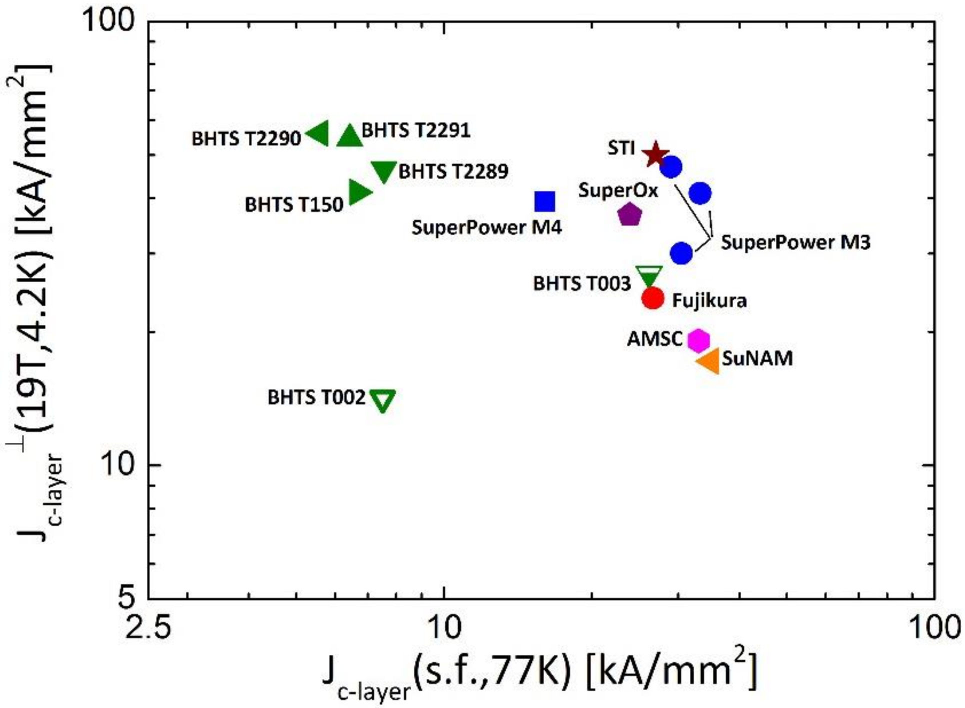
➢ **All cables reached the expected I_c**

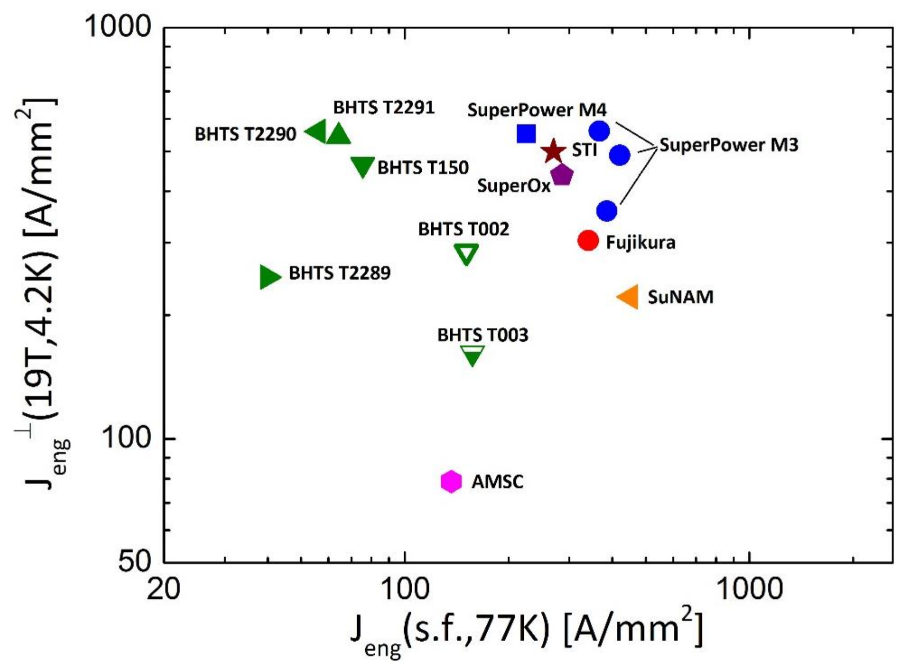
➢ **Cable I_c depends on characteristics of REBCO tapes**





Characterization: full campaign @ UniGe





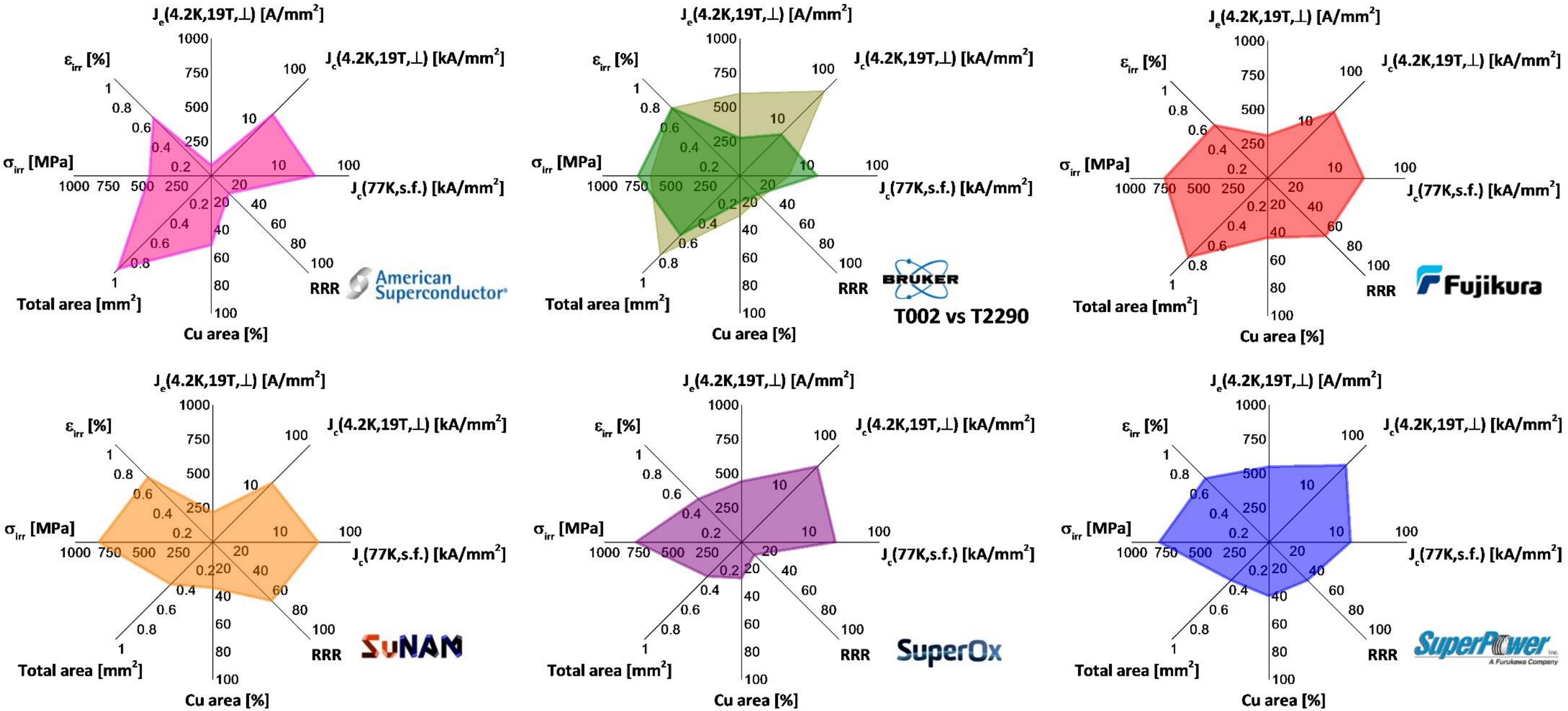
UNIVERSITÉ DE GENÈVE

C. Senatore & C.Barth

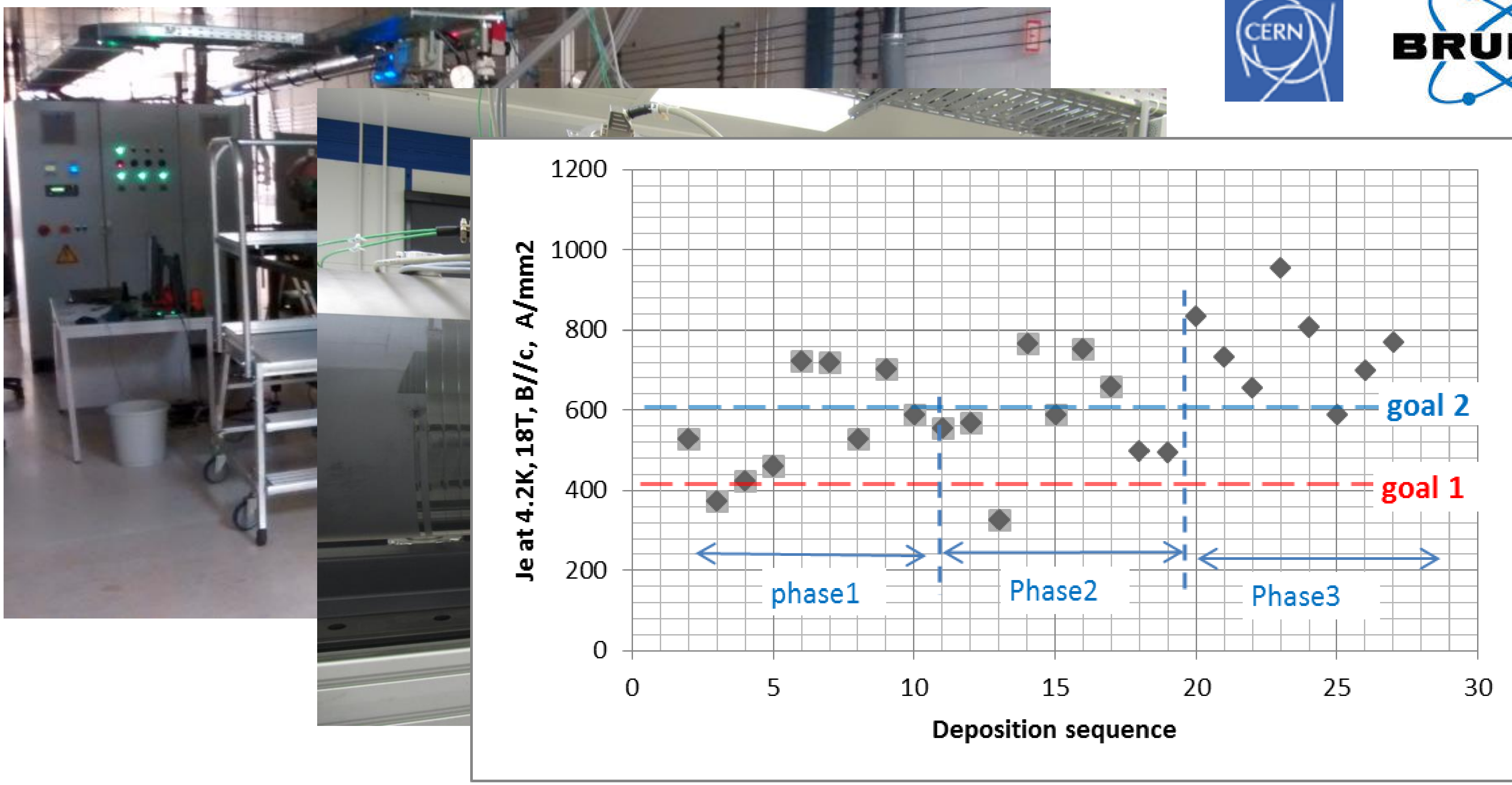
We procured and tested tapes form various suppliers

UNIVERSITÉ DE GENÈVE

C. Senatore

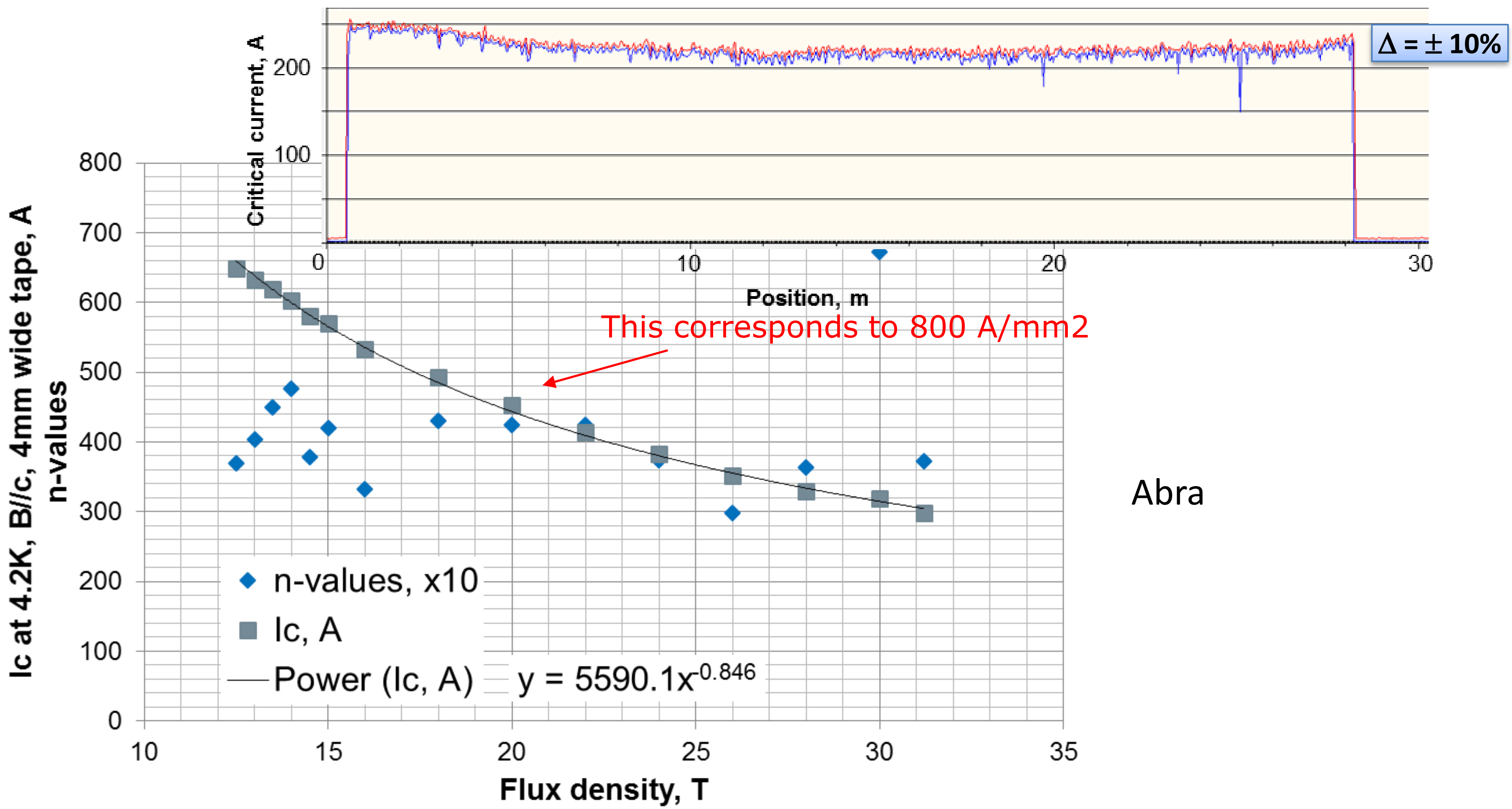


New line for CERN (w=12mm) at Bruker



A.Usoskin & U. Betz - BHTS

Confirmation of J_E on BHTS tapes at ASC-Tallahassee

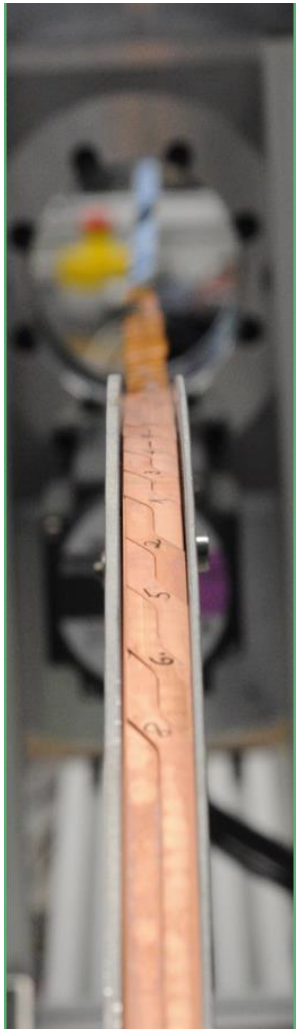


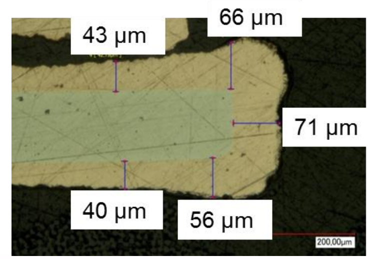
Abra

From tape to cable

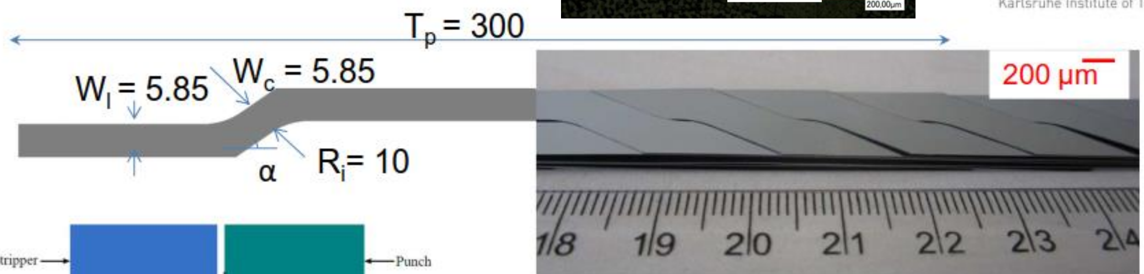
A. Kario & W. Goldacker

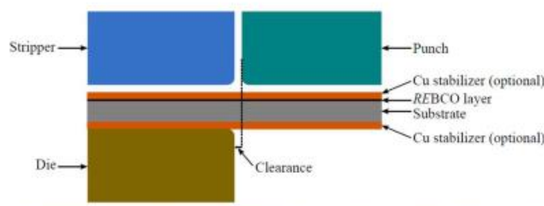
Karlsruhe Institute of Technology

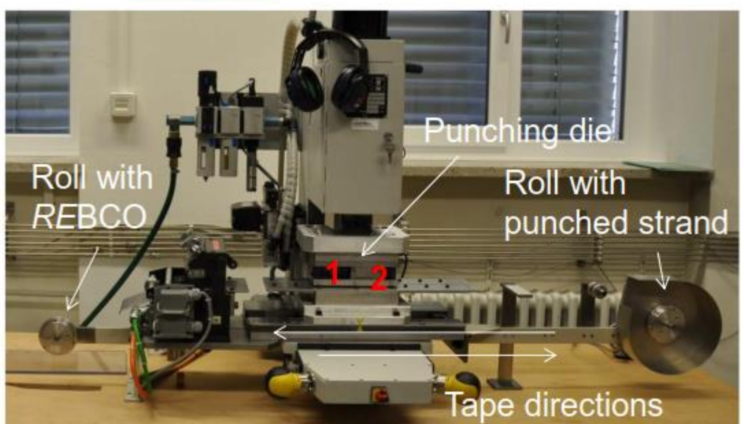




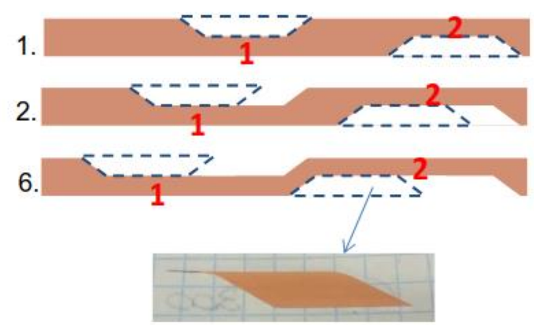
Punching process:







Multi-punching approach
(flexibility)



Roebel cable - cont.

"Punch-and-coat" method results in regular thickness of the cable:

Karlsruhe Institute of Technology

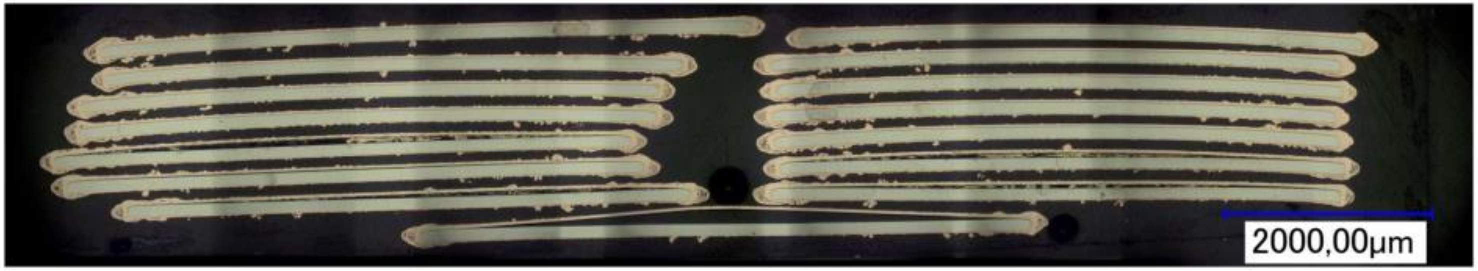
BRUKER

A. Usoskin, A. Rutt

Cu plated tape punched, strands assembled into cable.

Examples of delamination

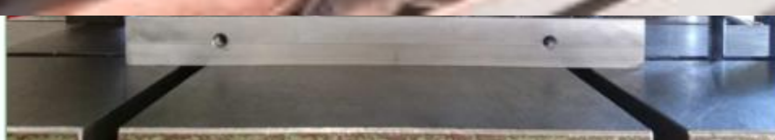
Ag coated tape punched, strands Cu plated, strands assembled into cable.



New line for the Roebel

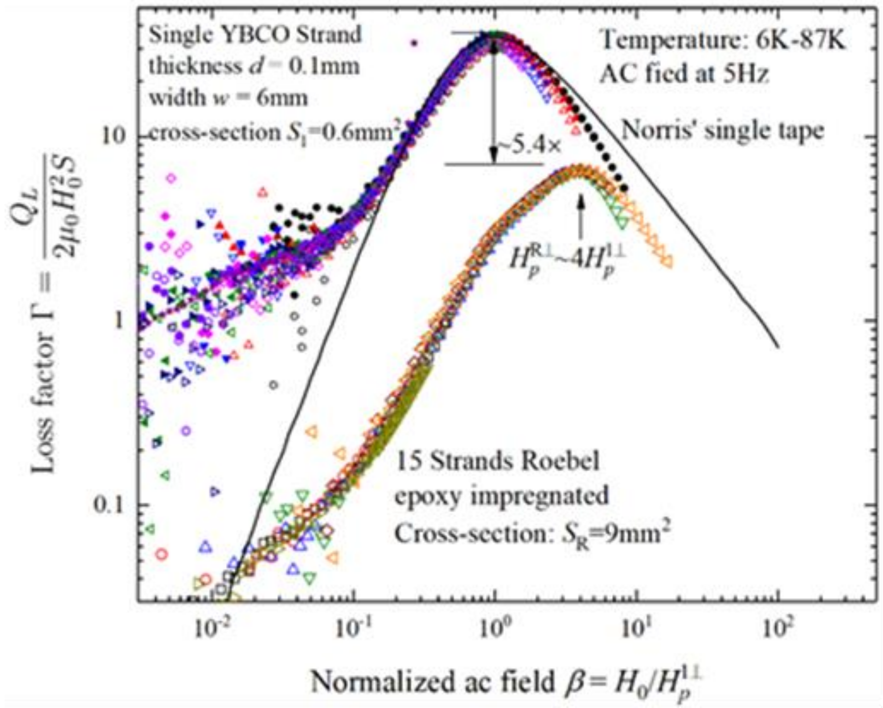
Anna Kario, Simon Otten, Andrea Kling, et al., Wed-Mo-Or21-01

New improved punching tool: first tests

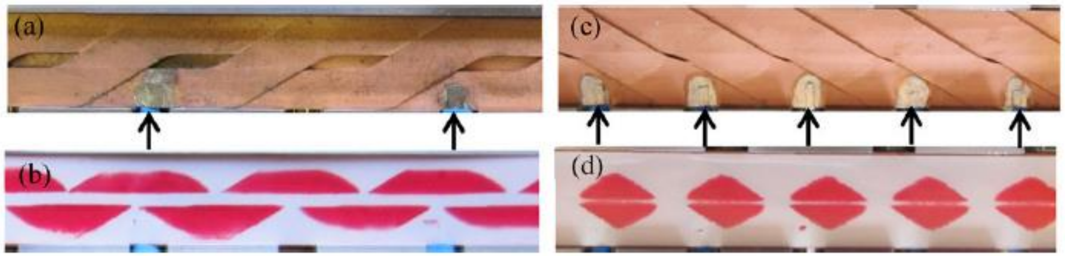


Measurements of losses in Univ. of Twente (NL) and Univ. of Southampton (UK)

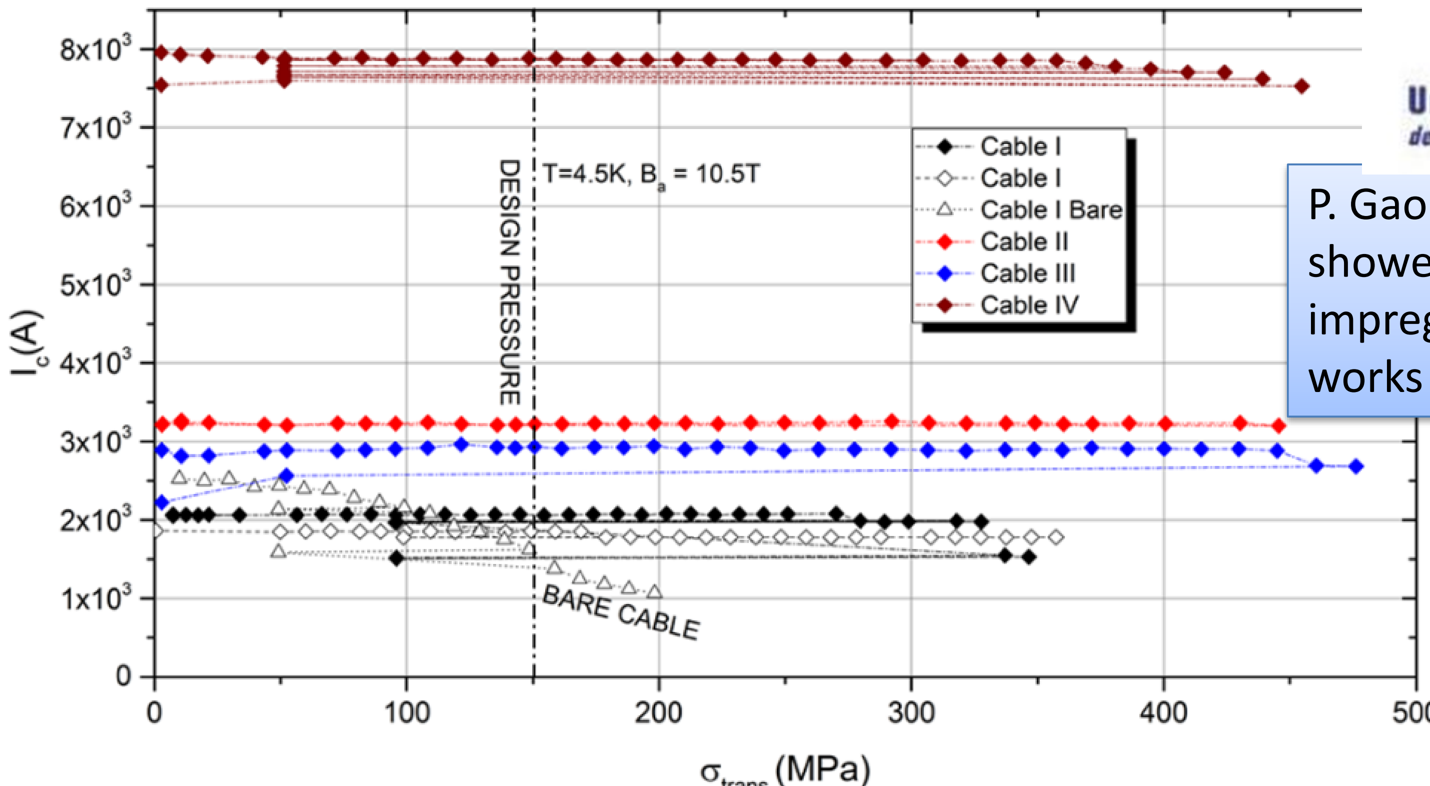
- Losses are dominated by the hysteresis of superconductor assemblies in Roebel.
- Simple assemblies of isolated tapes are coupled, i.e. as a monolithic conductor, but not quite fully.
- The 15 tape Roebel samples with/without epoxy impregnation behave as two in-line coupled stacks, each stack of 7-8 tapes. The saturation fields of the stacks increases linearly with the number of tapes, as expected.
- Epoxy impregnated Roebel is less coupled and the strand in transposition seemed uncoupled.



Ic vs. transv. stress



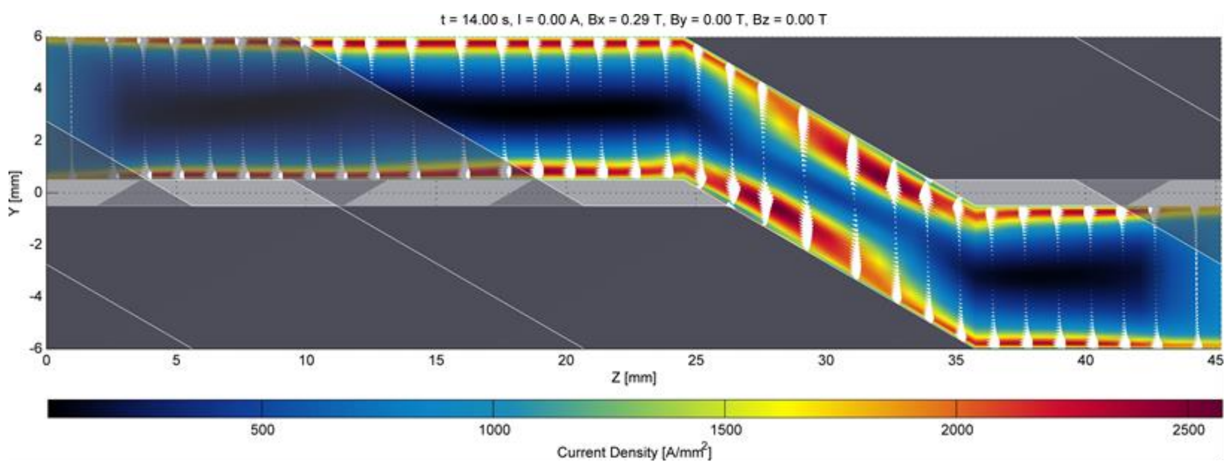
J. Fleiter et al. SUST 26.6 (2013) Demonstrated that above 100 MPa bare cable is severely damaged: but we will work at 150-200 MPa...



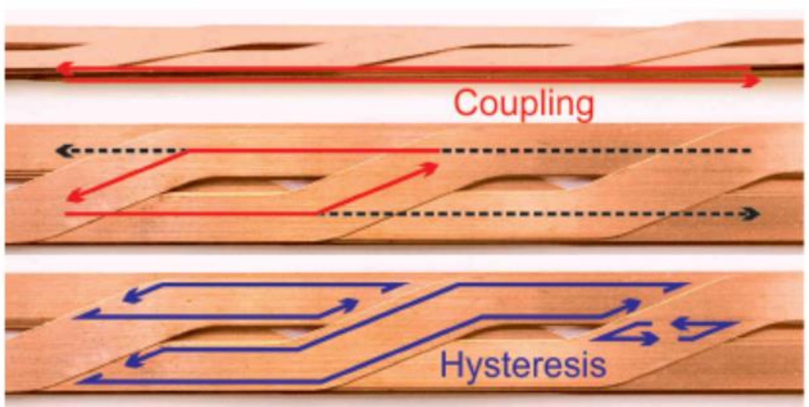
Universiteit Twente
de ondernemende universiteit

P. Gao and M. Dhallé showed that impregnated cable works at 400 MPa

e.m. model by J. van Nugteren (CERN& U.T.)



Dynamic E.M. cable model J. van Nugteren, EUCAS 2015

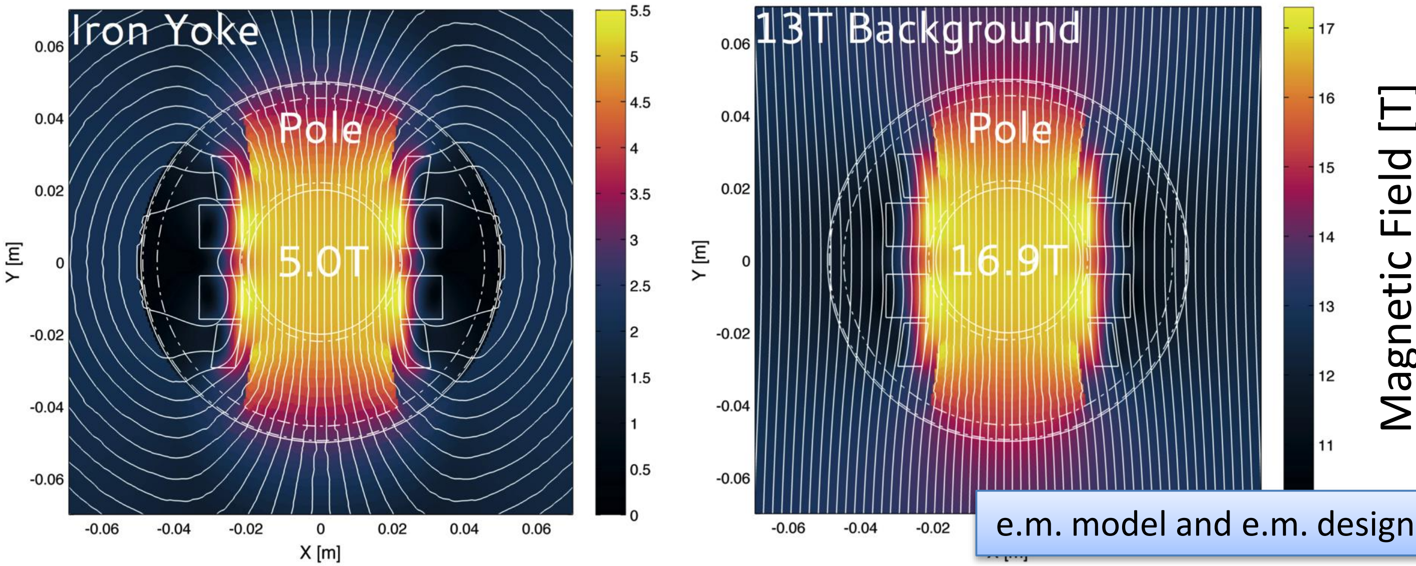


Courtesy of M. Dhallé, U.T.

Hysteretic losses are dominant but how much coupling do we have in impr. Roeble?

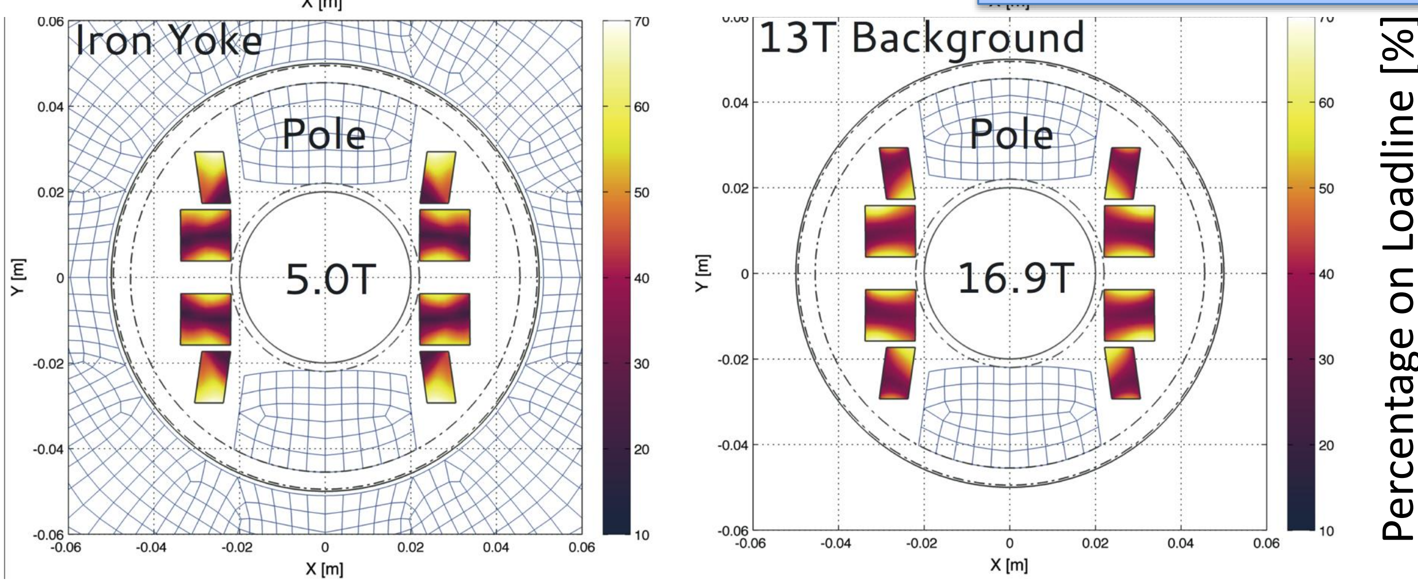
Measurements at U. Twente have validated the e.m. model with a contact resistance in the orders of 10 μΩ; These values are not too different to measurements done in KIT (A. Kario): 20-30 μΩ
Good news: we expect current sharing in our cable.

Aligned Block lay-out



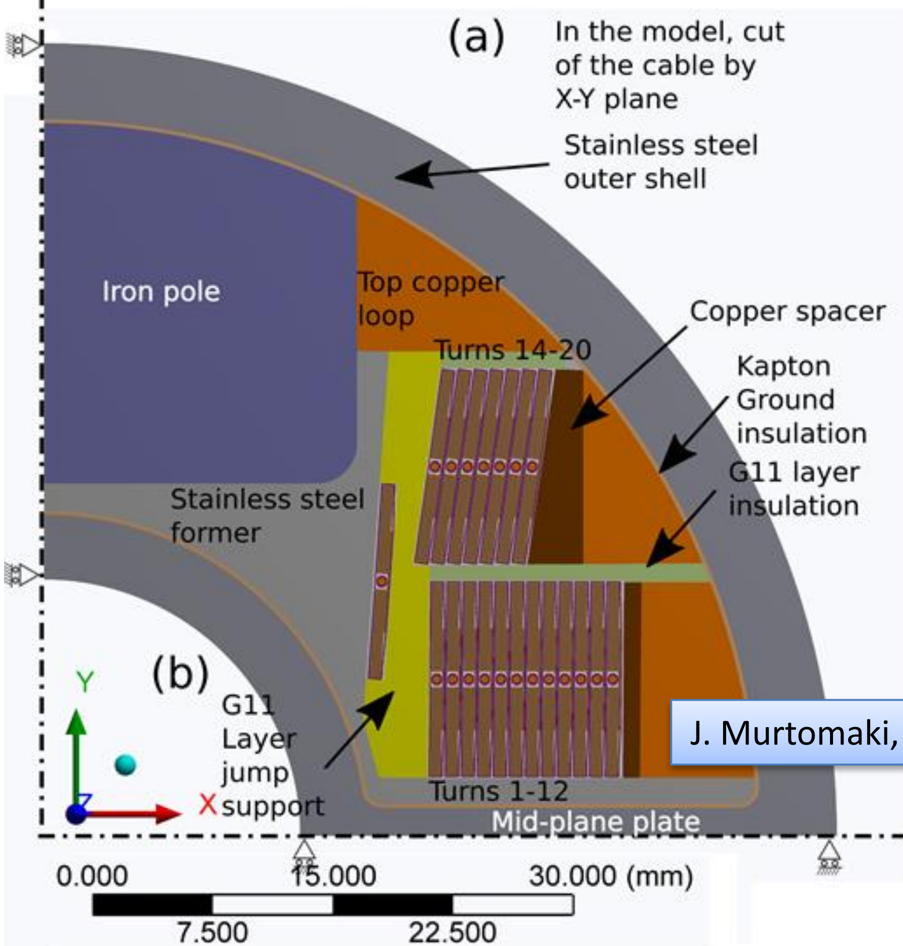
The two plots present flux path variation for insert magnet:
(left) standalone in Iron ,
(right) in 13T ideal background field

e.m. model and e.m. design by J. Van Nugteren @ CERN

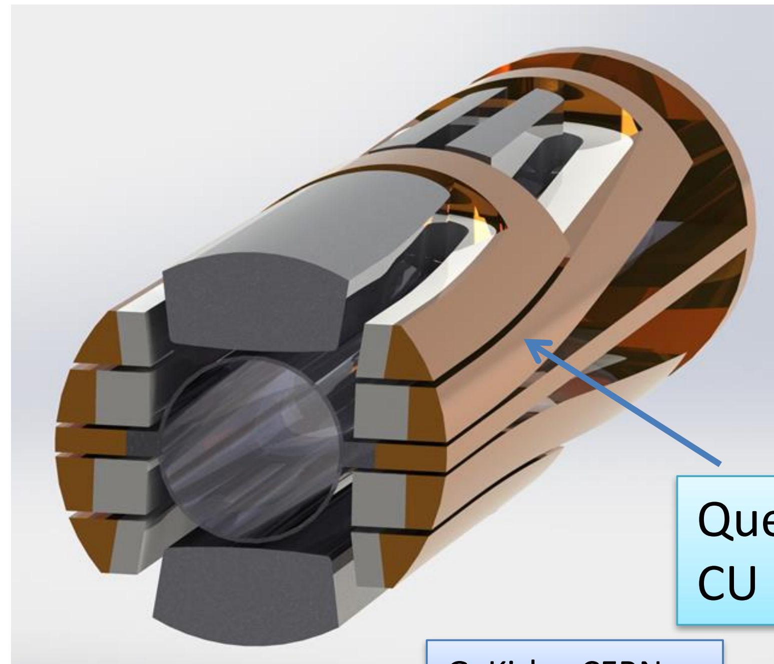


Yellow area is the region more near to short sample.
Very different from std. LTS magnets.

AB dipole magnet



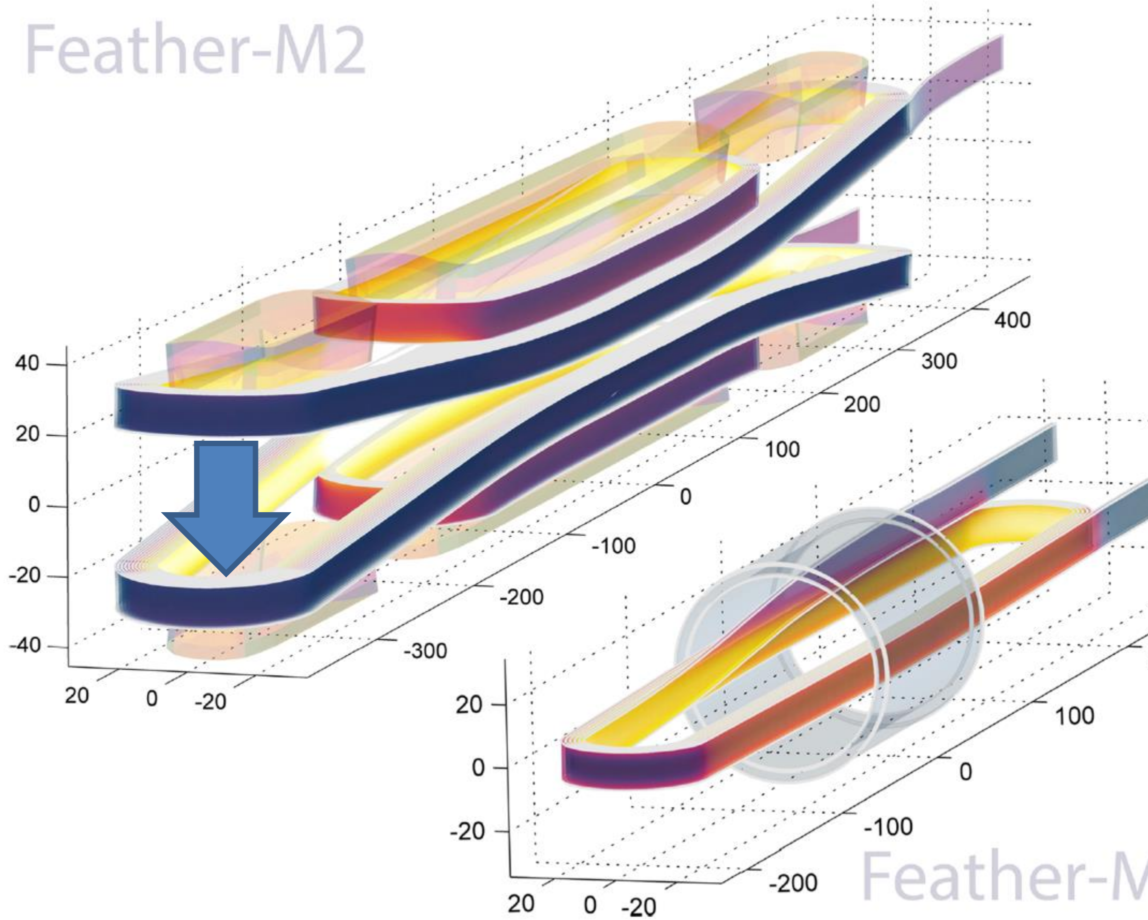
J. Murtomaki, CERN

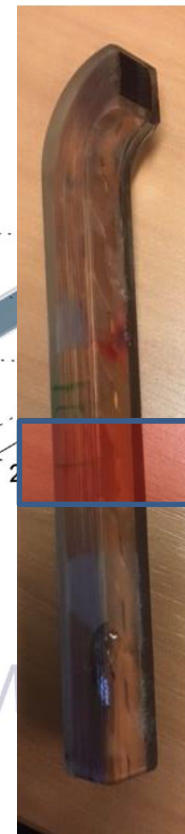


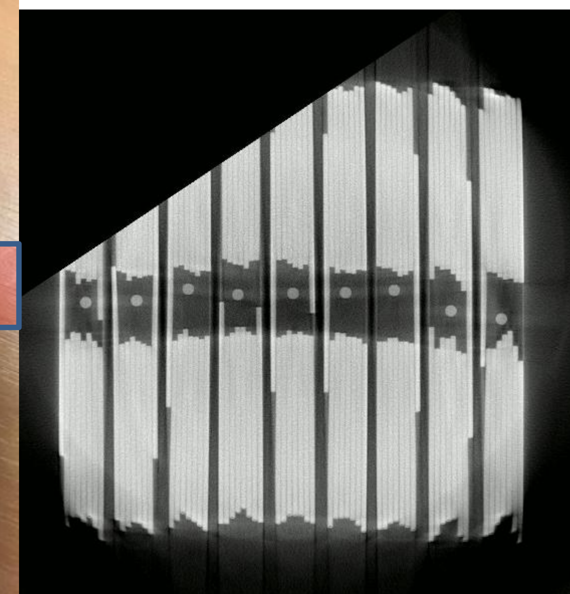
Quench CU bars

G. Kirby, CERN

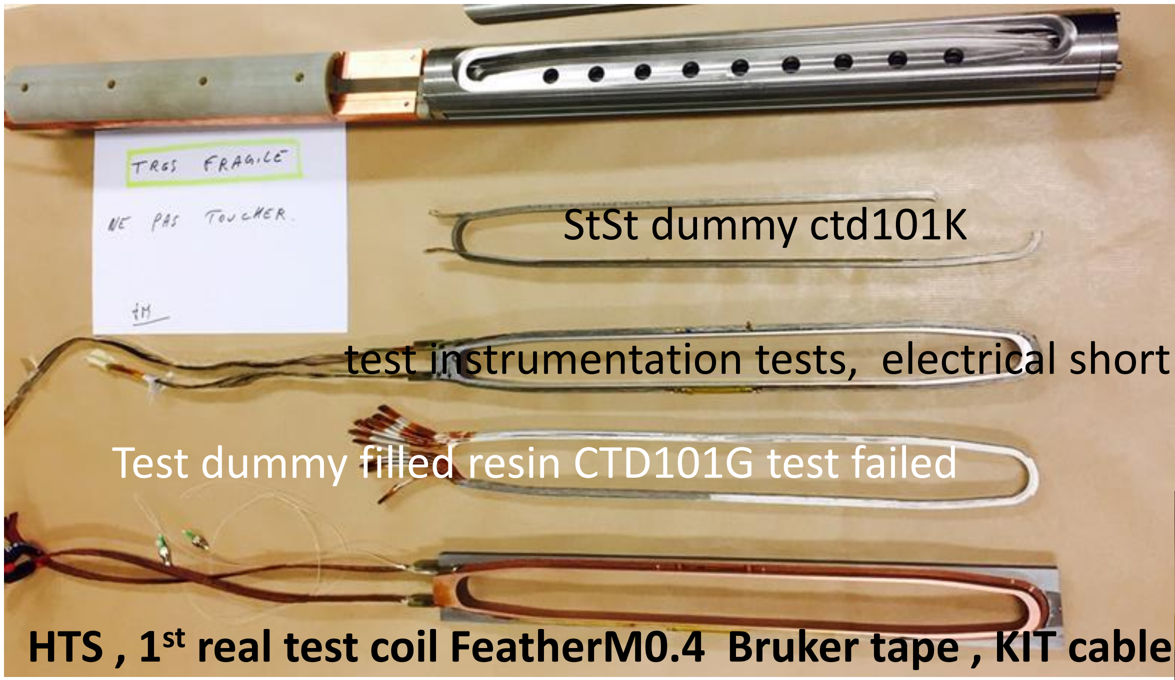
Going in steps:FeatherM0 flat racetrack, 5 m cable



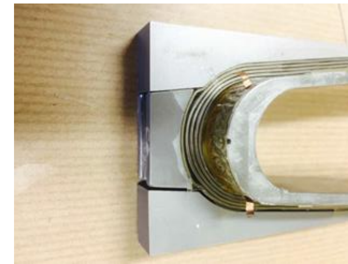


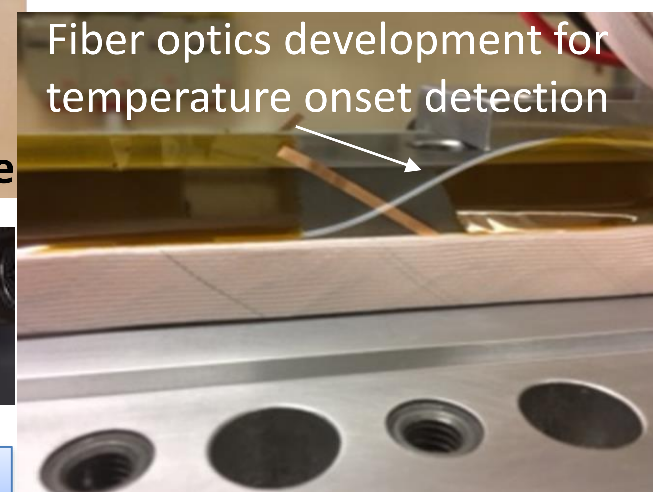


F_M0.1,2,3,4



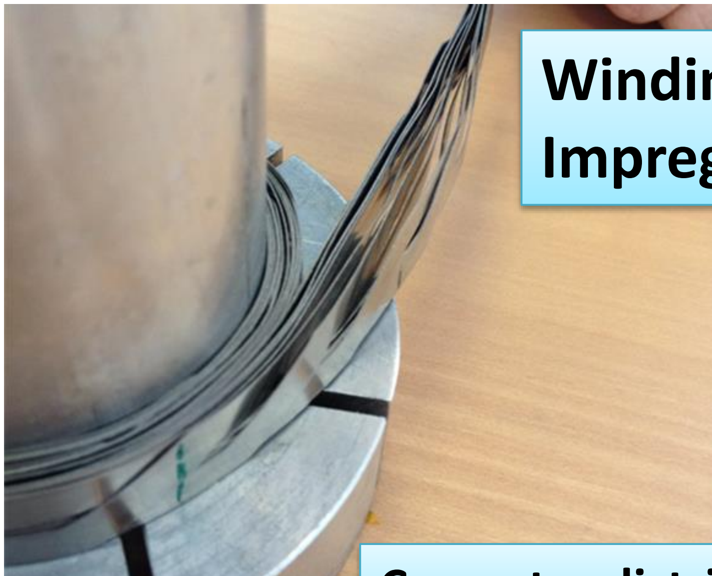
FeatherM0.5, SuperOx cable the next Feather ZERO to be tested.





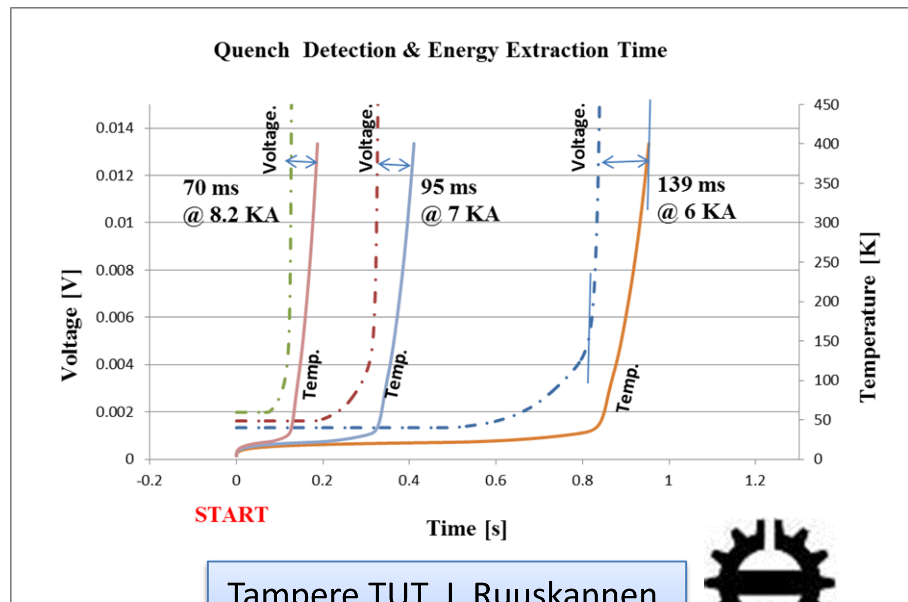
G. Kirby, CERN

Magnet technology issues… design & protection issues…



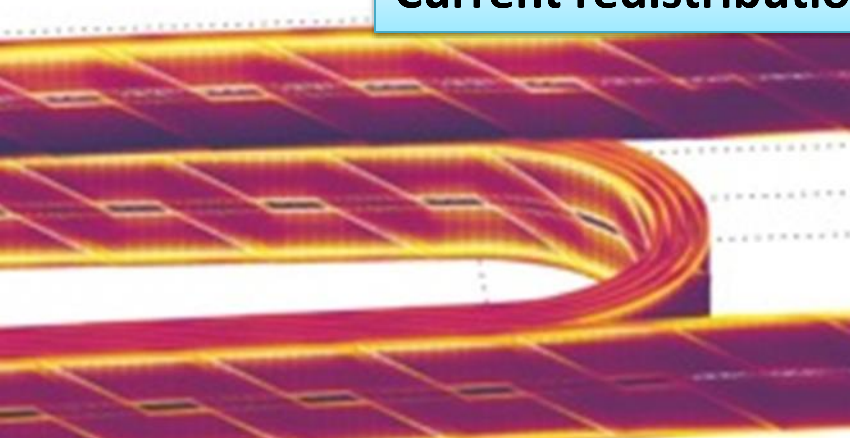
Winding (un)stability : small tension
Impregnation → delamination

QD & QP Studies with strongly anistotropic th. Cond. and with strong TCS variation inside tape/cable



Tampere TUT. J. Ruuskannen Thu-Af-Po4.09-09,

Current redistribution

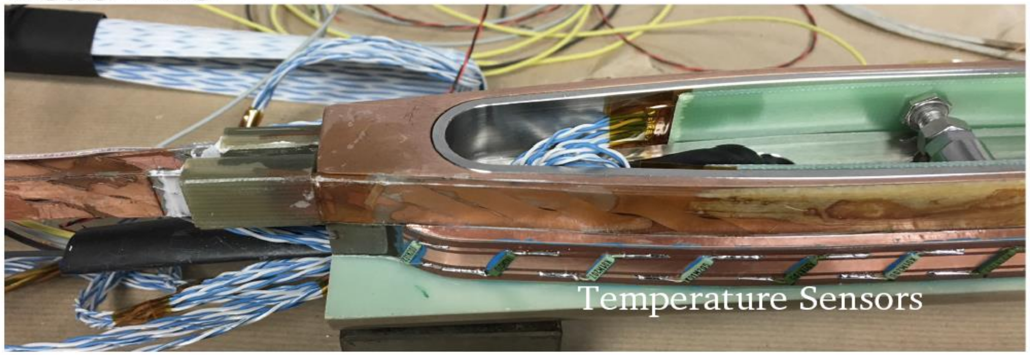


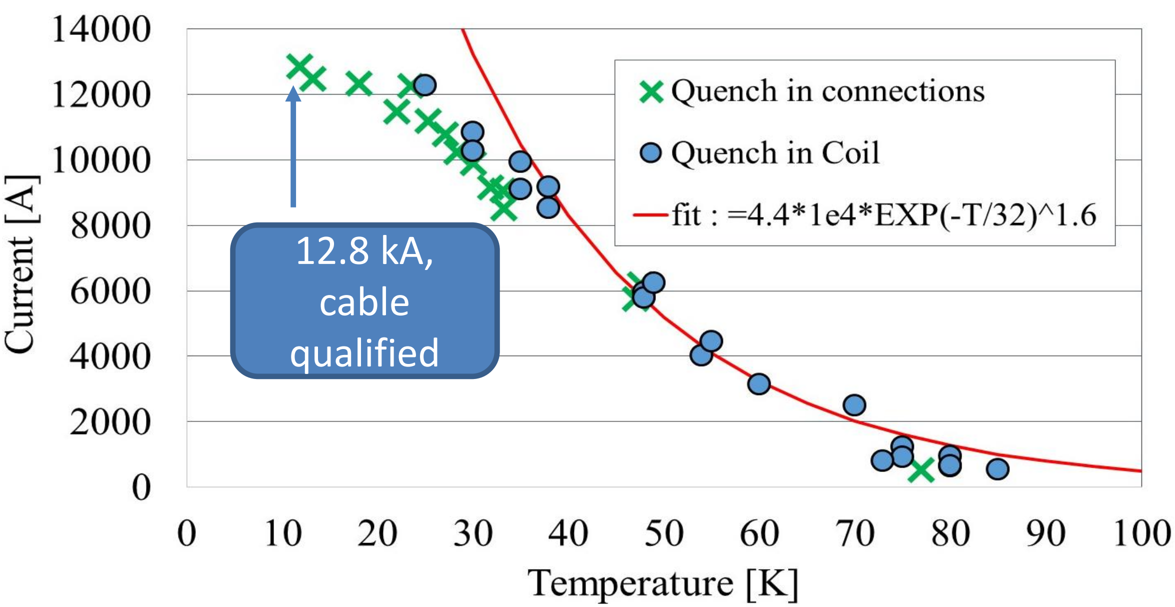
e.m. model of J. Van Nugteren, U.T. & CERN

FeatherM0.4

Lead End

Turn End





Computation showed little time to react to a quench: 20-30 ms:

Quench detection.

1. **Improved voltage taps (≈ 1 mV)**
2. Array of temp. sensors
3. Pick-up coil array
4. **Fiberglass in Bragg grating**

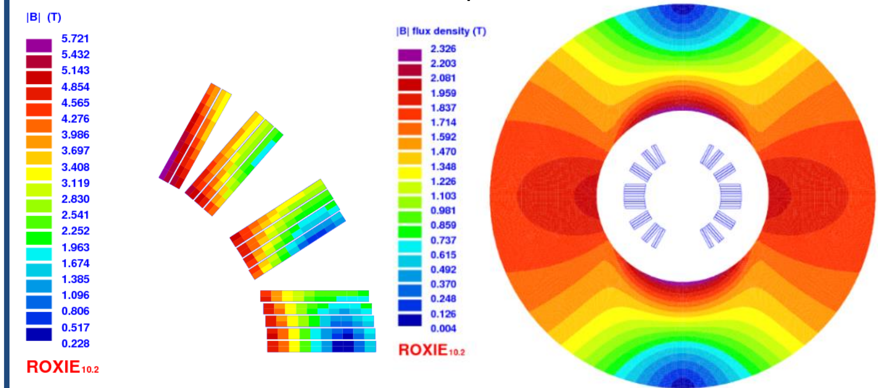
Cosϑ design with Roebel at CEA-Saclay

C. Lorin, M. Durante & Ph. Fazilleau

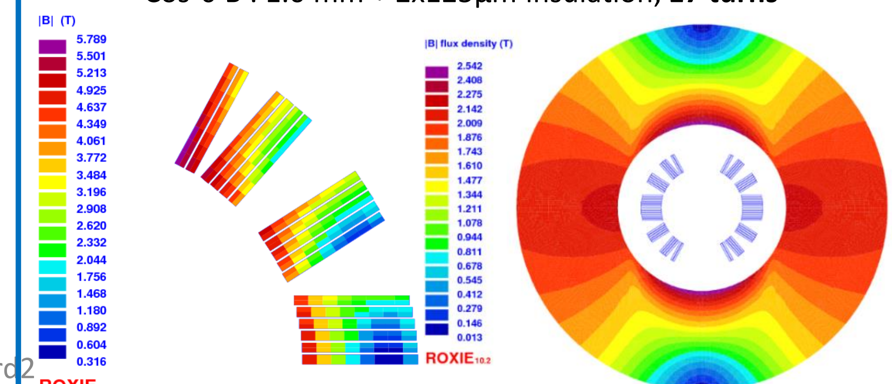
- Design A - « thick » cable : 12 x 1.2 mm² bare, 13 tapes 140-µm thick
- Design B - « thin » cable : 12 x 1.0 mm² bare, 15 tapes 100 µm-thick

Layout	Unit	Cosϑ A	Cosϑ B
Iop	kA	11.68	10.06
Bop	T	**5**	**5**
Bpeak	T	5.7	5.8
Ic	kA	14.4	15.2
LL margin	(%)	20	34
T margin	K	20	30
Sd. inductance	mH/m	0.49	0.73
coil inner radius	mm	**22**	**24**
yoke inner raidus	mm	50	50
yoke outer raidus	mm	112	110
Nb. of turns	-	14	17
Unit len. of cond.	m	20	24

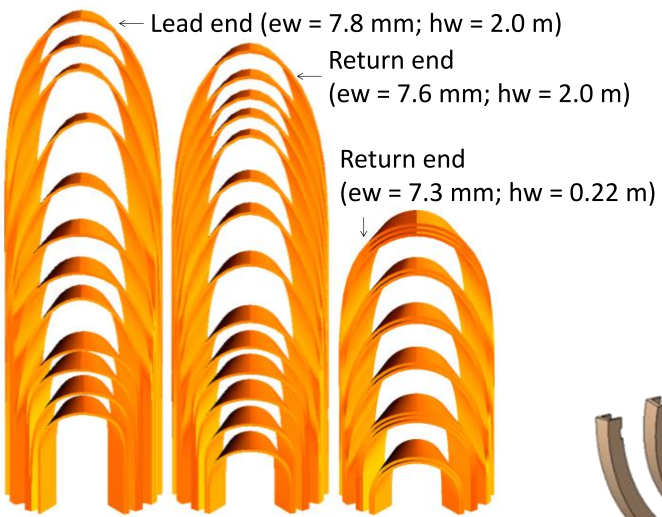
Cos-θ A : 1.2 mm + 2x100µm insulation, **14 turns**

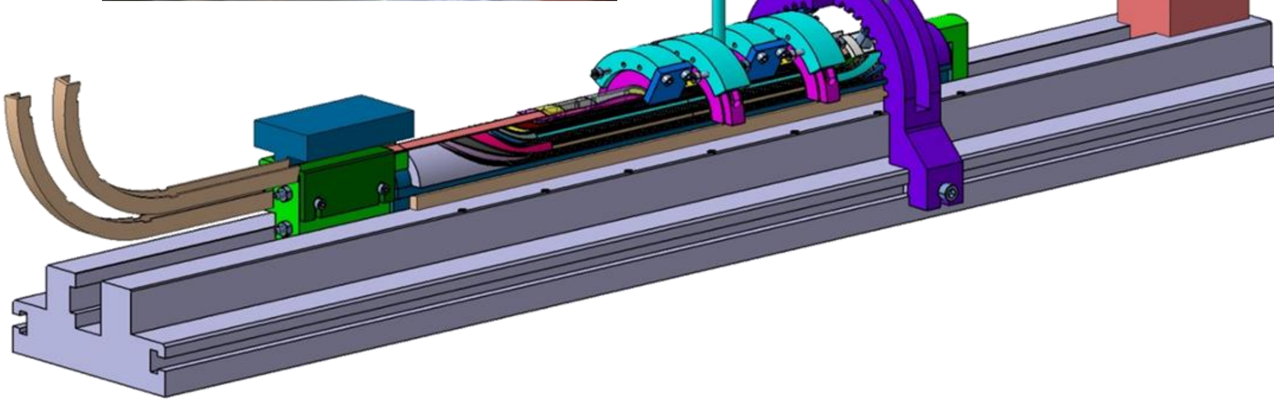


Cos-θ B : 1.0 mm + 2x125µm insulation, **17 turns**



Not so easy but almost ready to wind (Nov 2018)

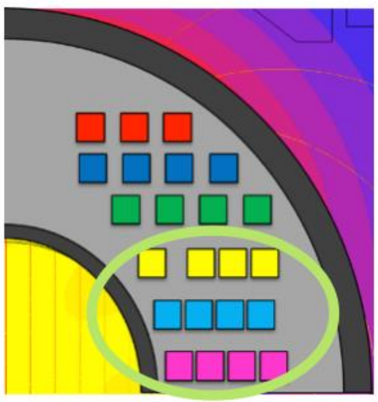


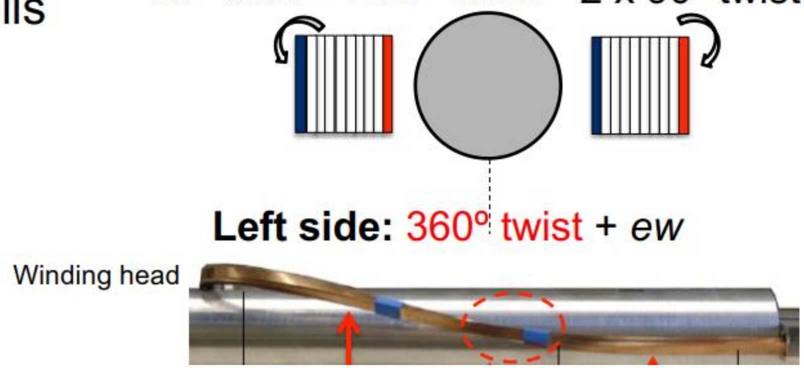


Courtesy of C. Lorin

Stacked cable based magnet design (Grenoble)

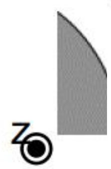
Racetrack flat coils

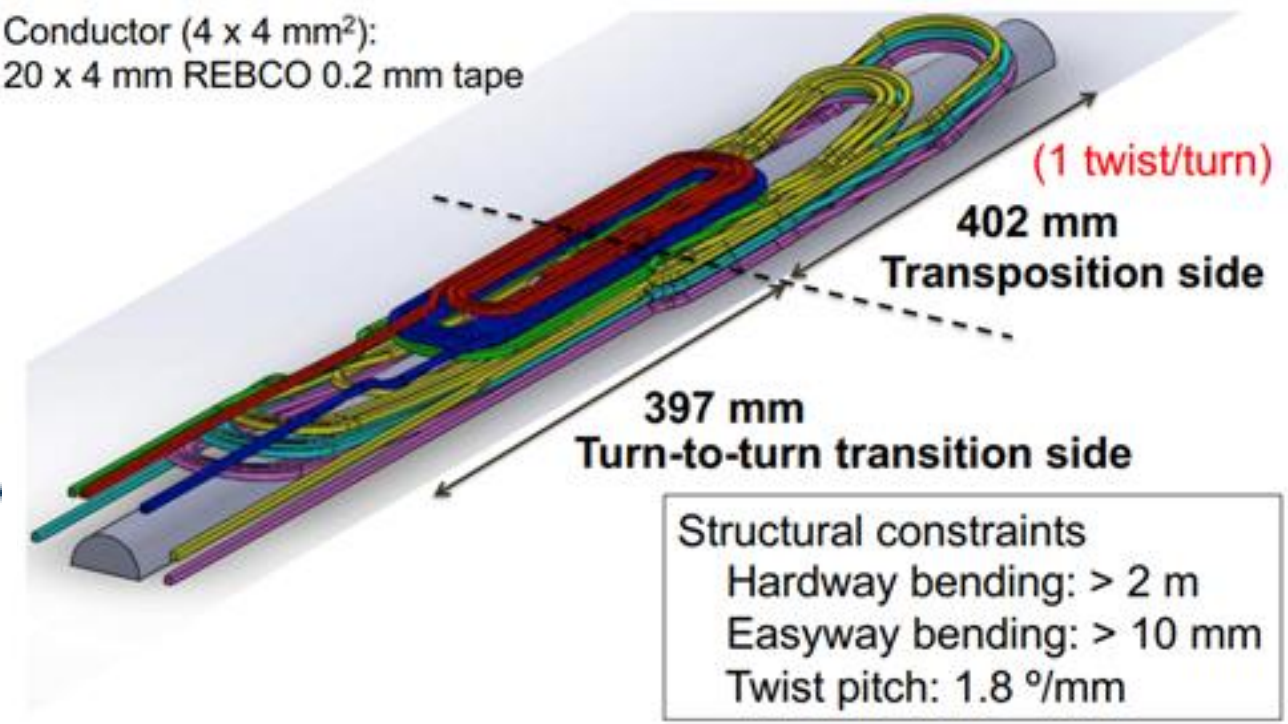




Conductor (4 x 4 mm²):
20 x 4 mm REBCO 0.2 mm tape

Mechanics at the ends is difficult but probably manageable….
To avoid huge redistribuition: partial insulated tape inside the cable

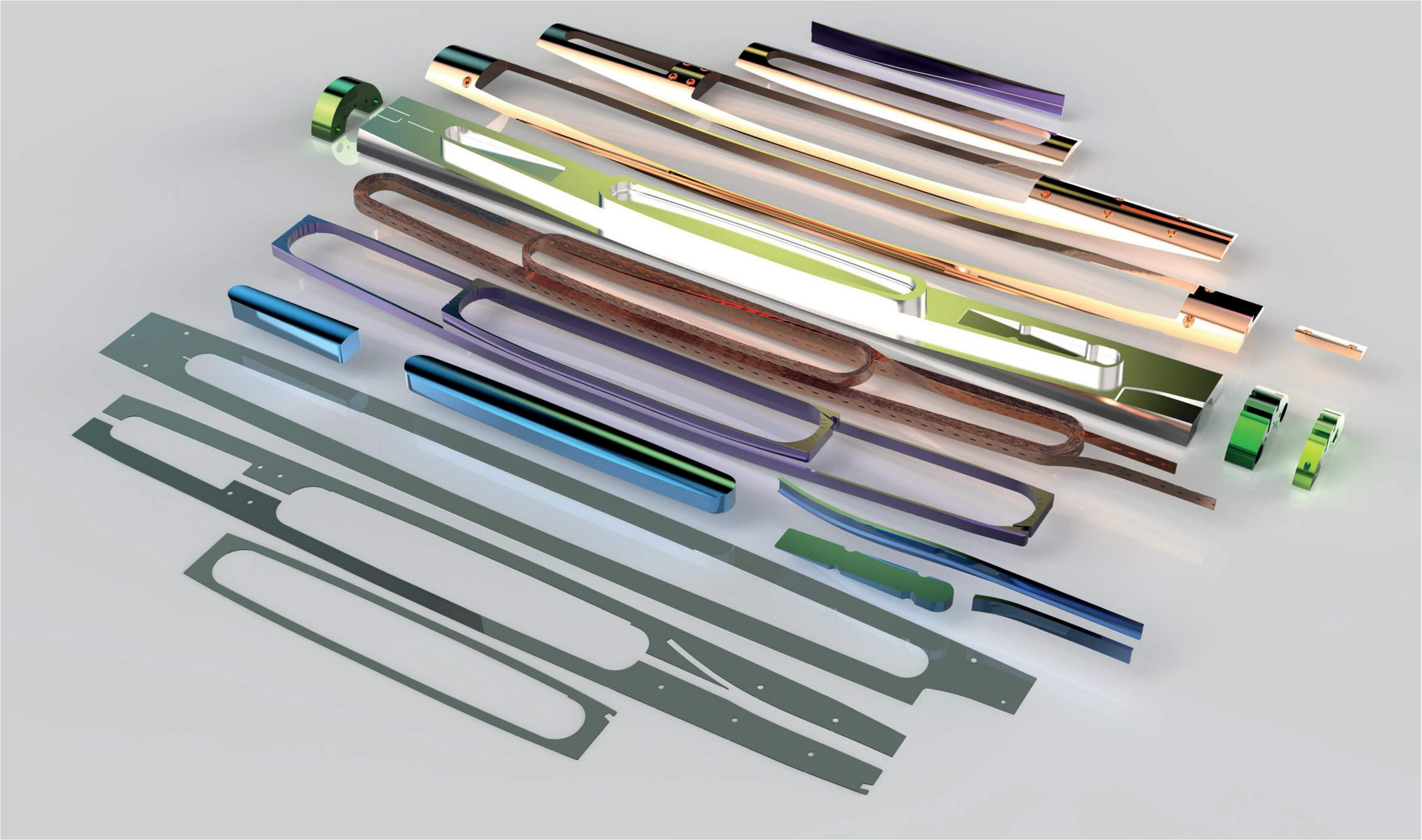




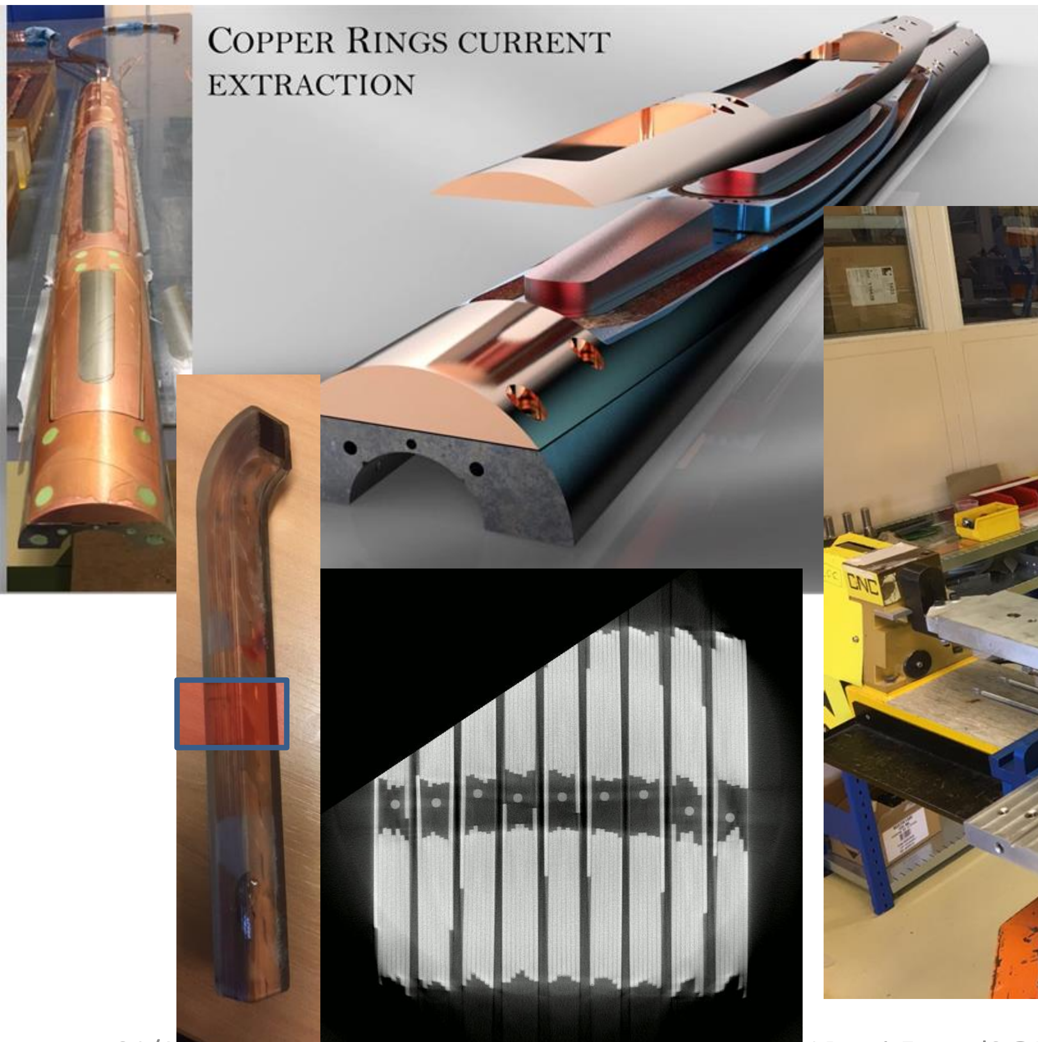
But very high Filling factor easy cable to do, no waste…

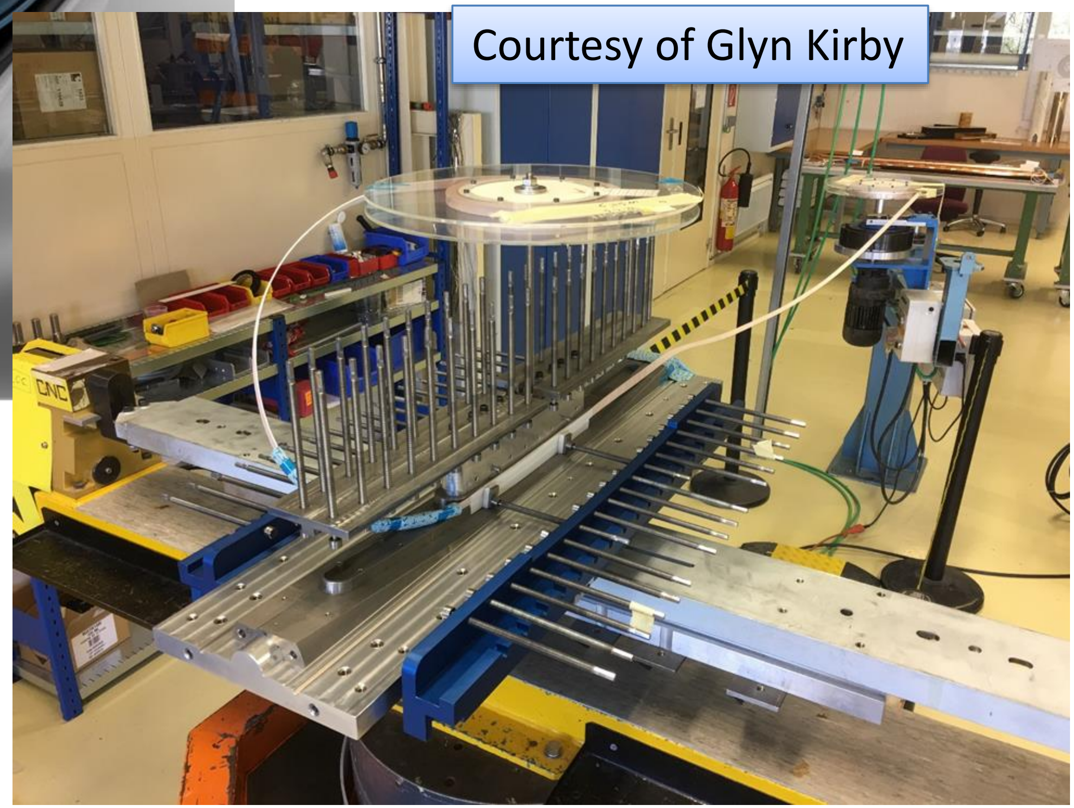
P. Tixador, A. Badel & J. Himbele

FeatherM2 construction: a complex assembly



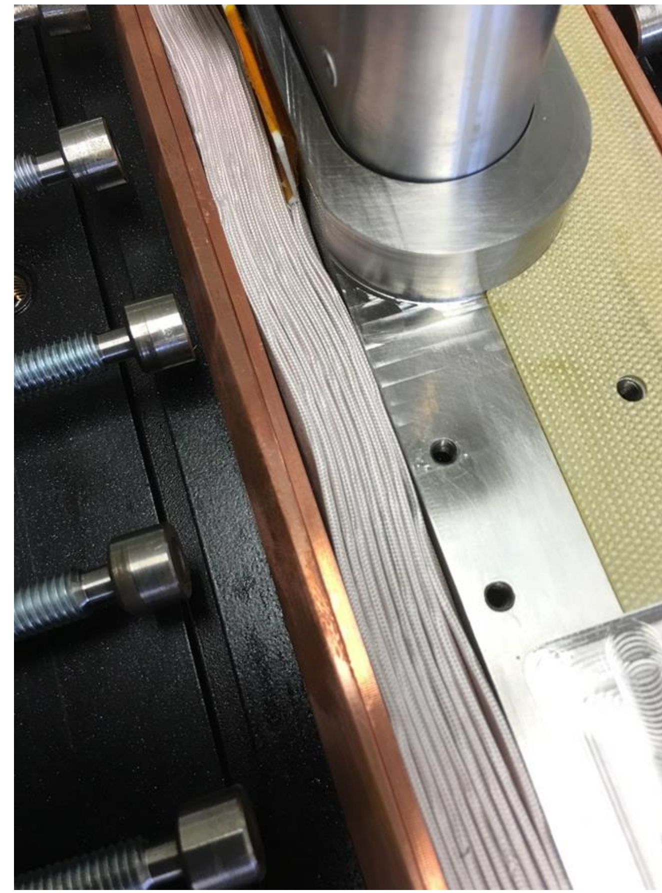
Manufacturing the Eucard2 first dipole FeatherM2



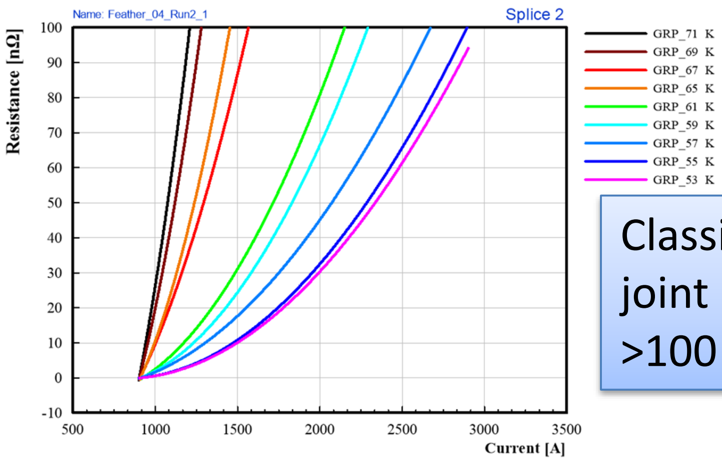


Courtesy of Glyn Kirby

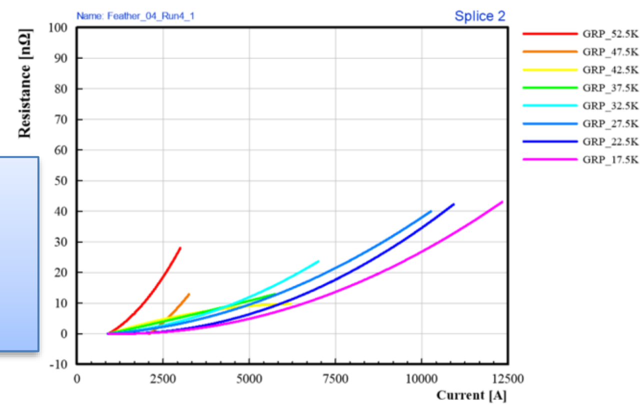
FeatherM2 AB block dipole construction



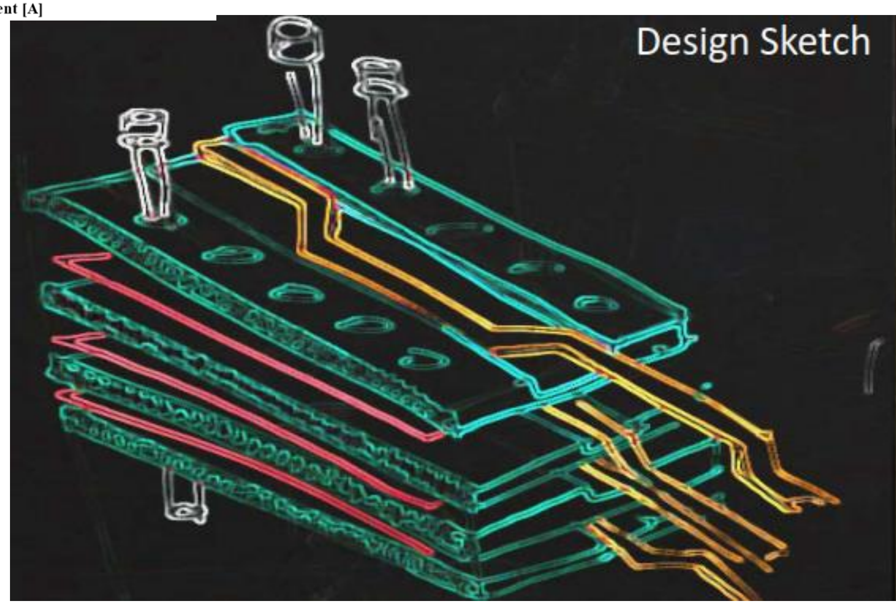
Joints



Classical butlap joint in **FM0.4**: >100 nΩ! ⇒ 40 nΩ

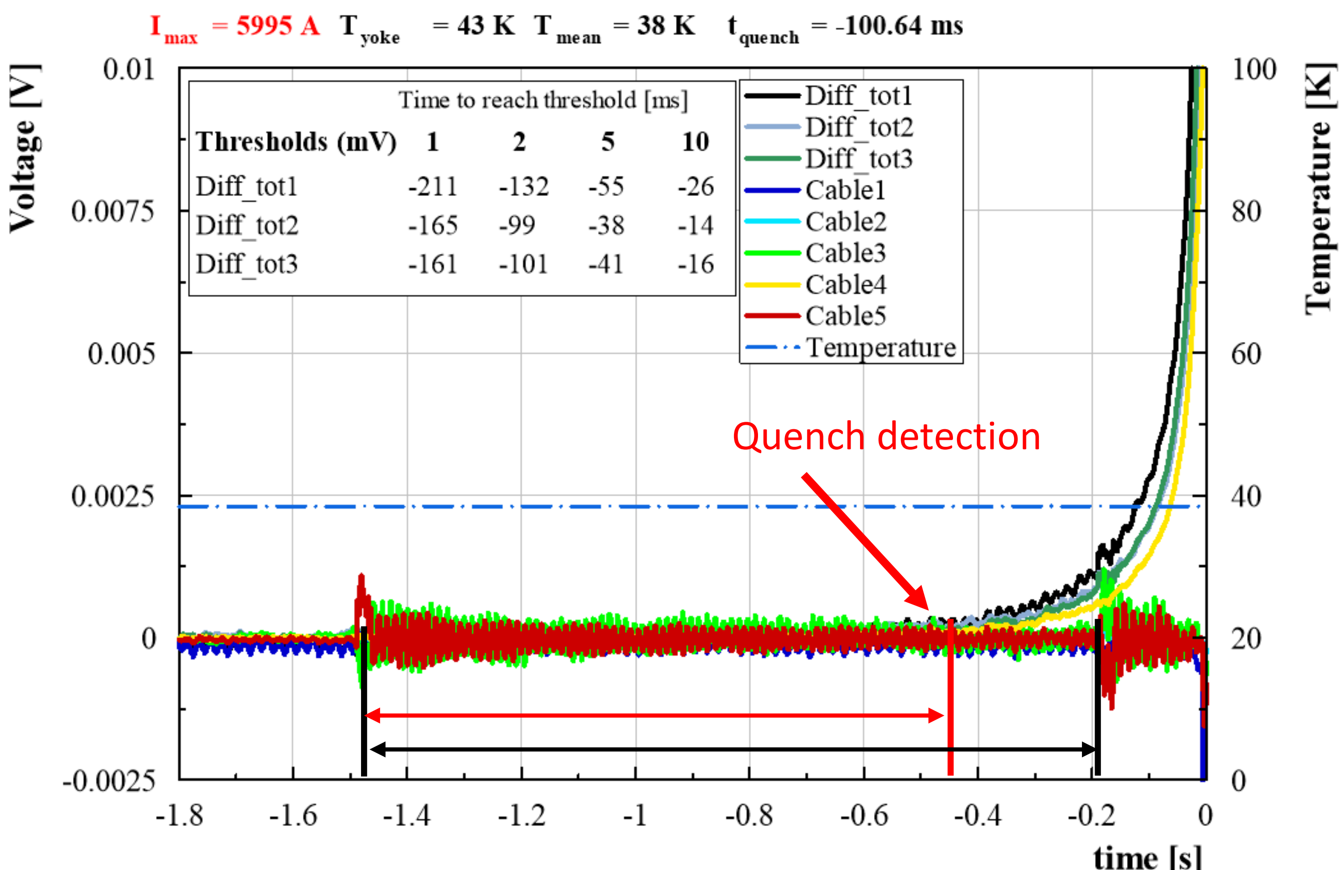


New design, called **Fin block joint** (G. Kirby). Improvement by a factor 2, no need of overcooling: do we need it? Certainly it helps to transfer current more uniformly…



First accelerator-class magnet before going to test:
The Eucard2 FeatherM2.1-2 dipole
April 2017.

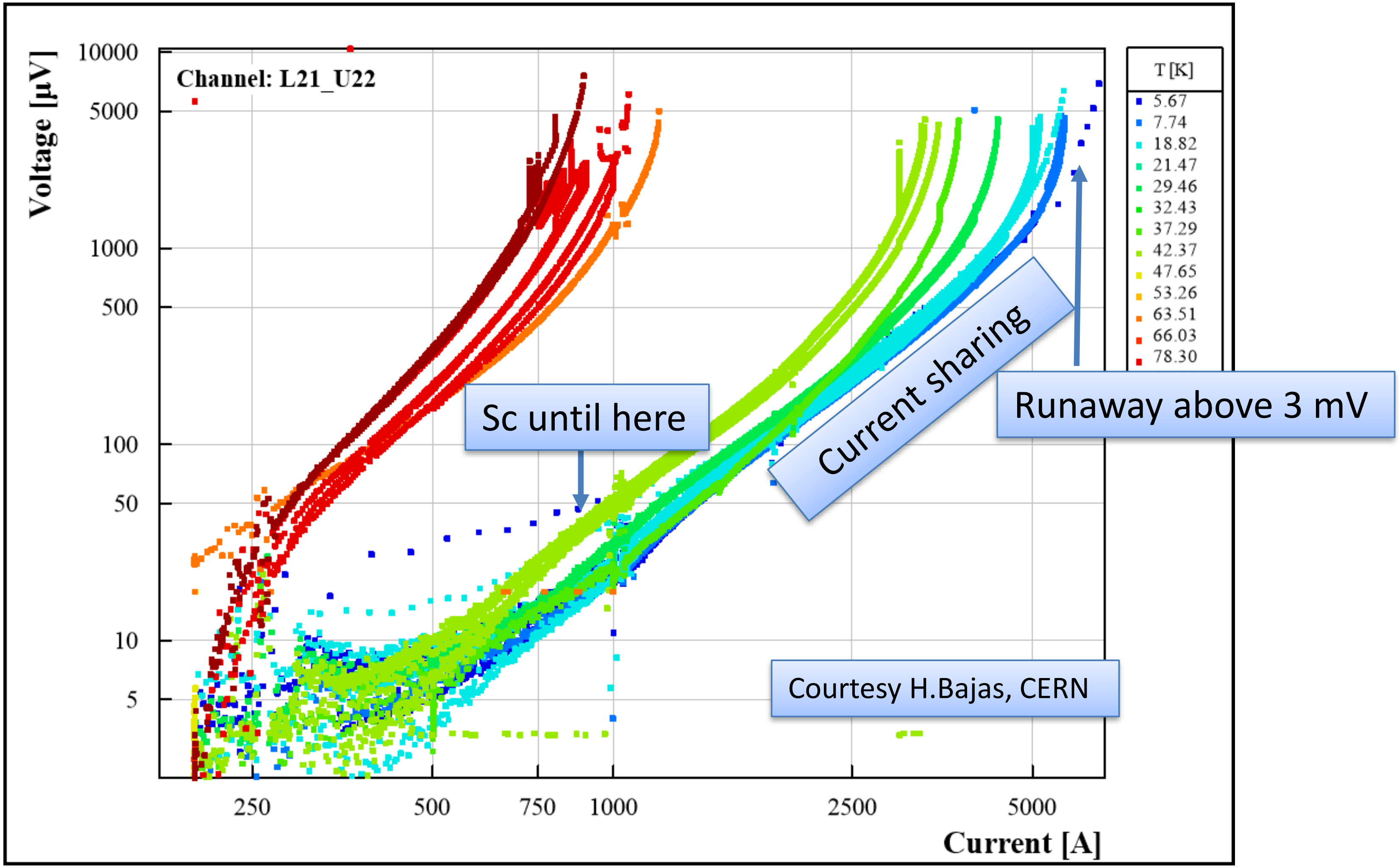
Soft transition and easy detection: FeatherM0.4 coil



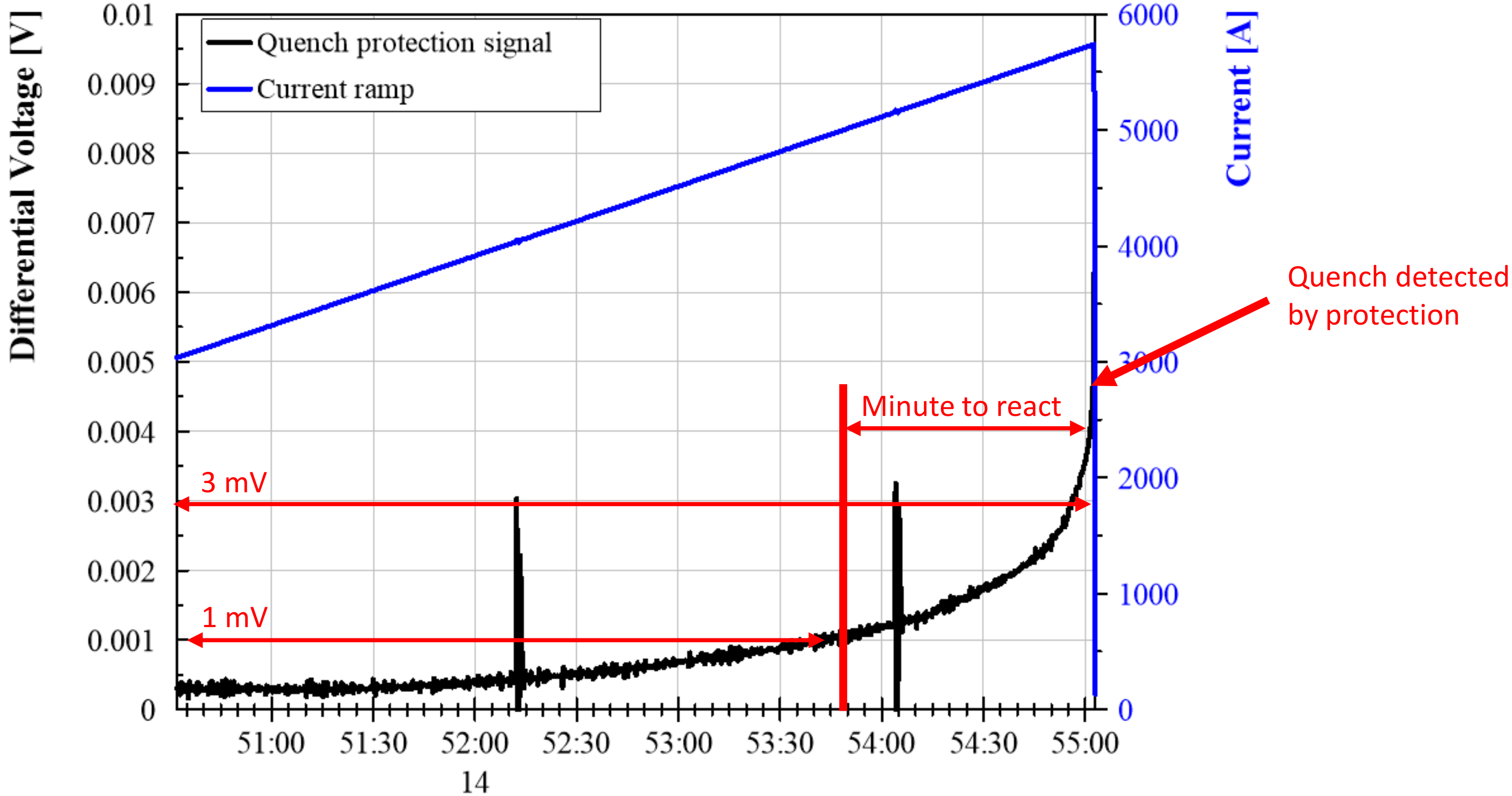
Heater pulse:
I_SH=30 A, U_SH= 40 V, t_pulse= 1.3 s

Stability is huge: hundred of Joules to quench

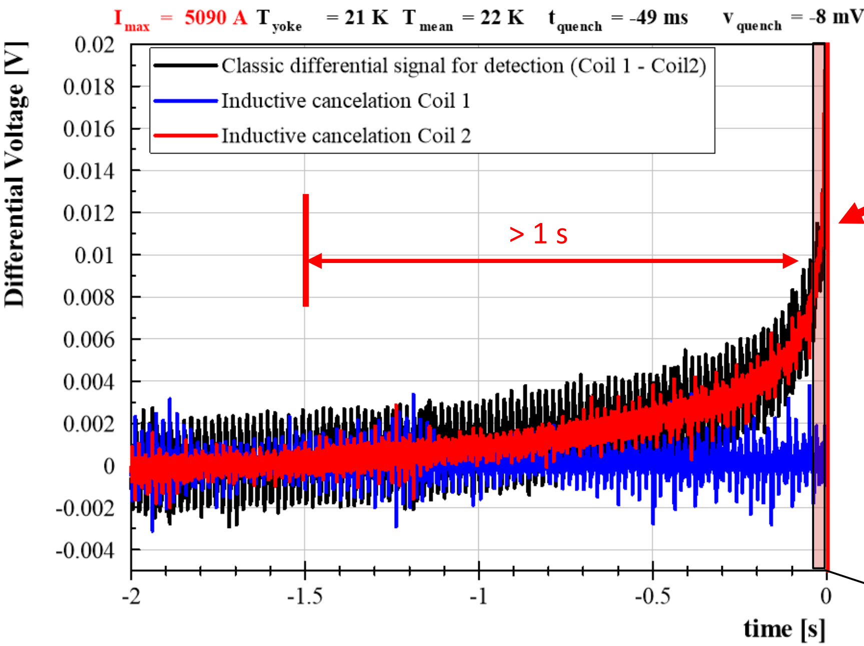
FeatherM2.1-2



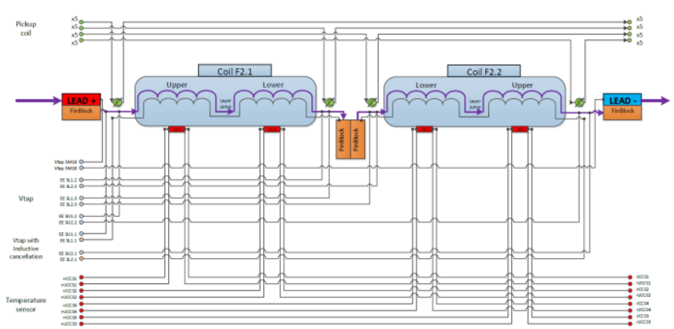
High resolution low frequency acquisition



Low resolution high frequency acquisition

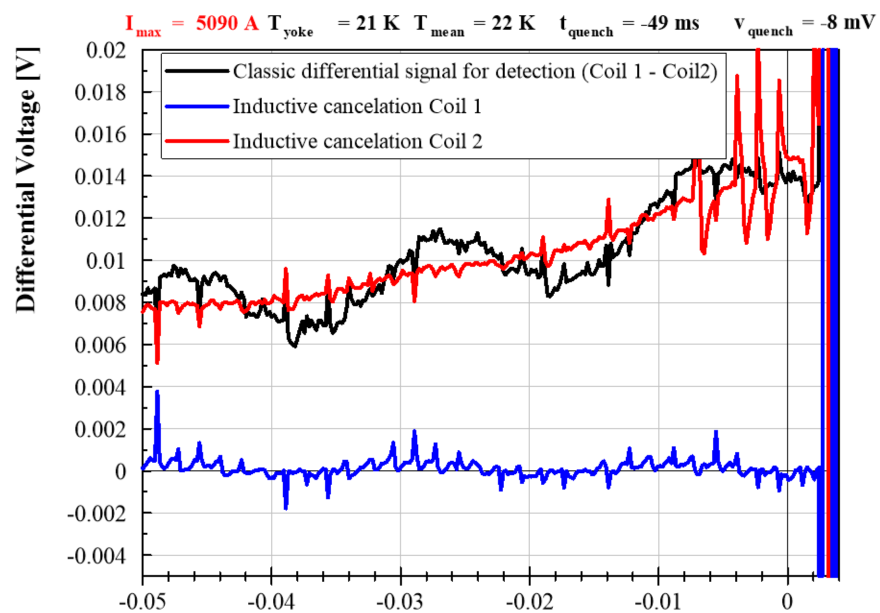


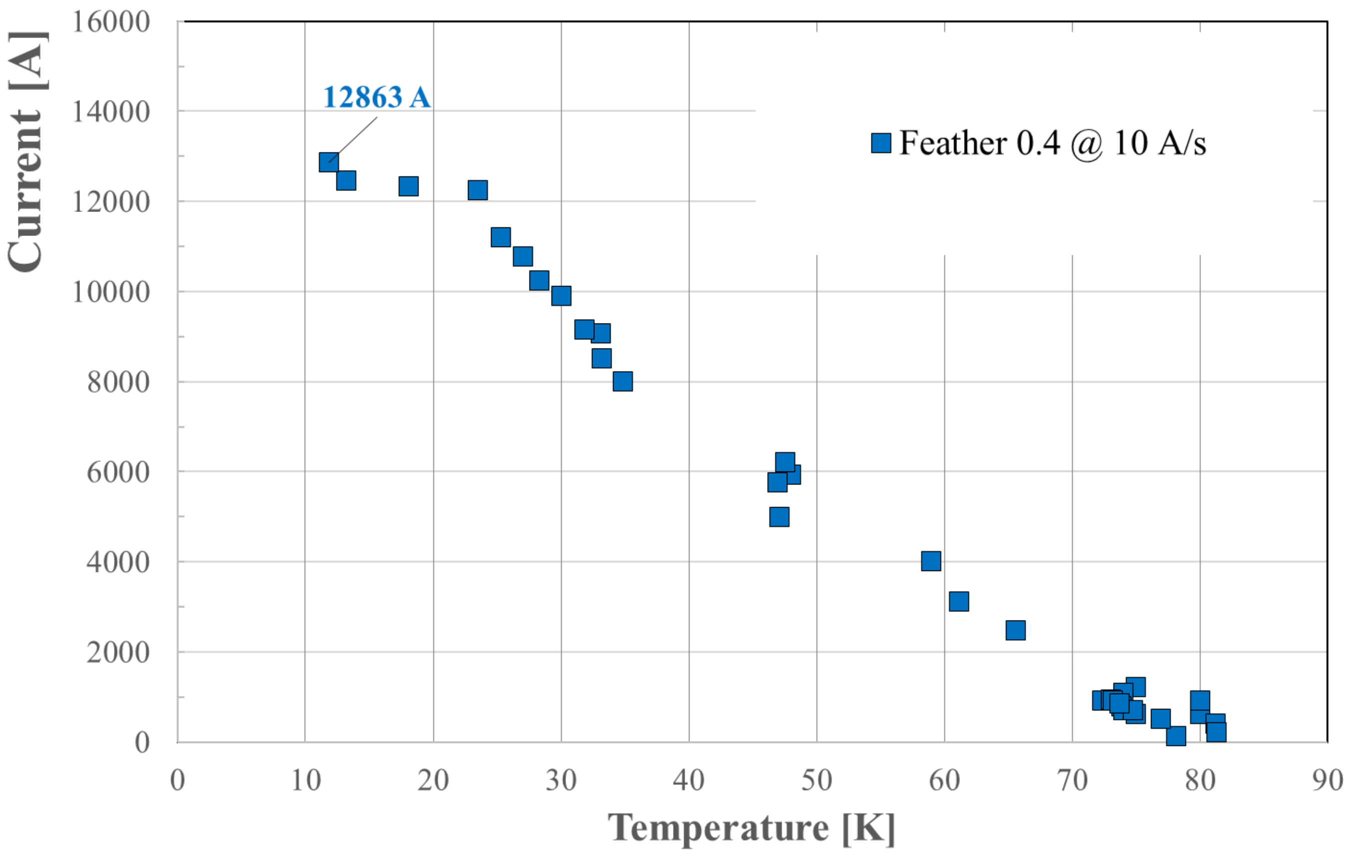
Quench detection



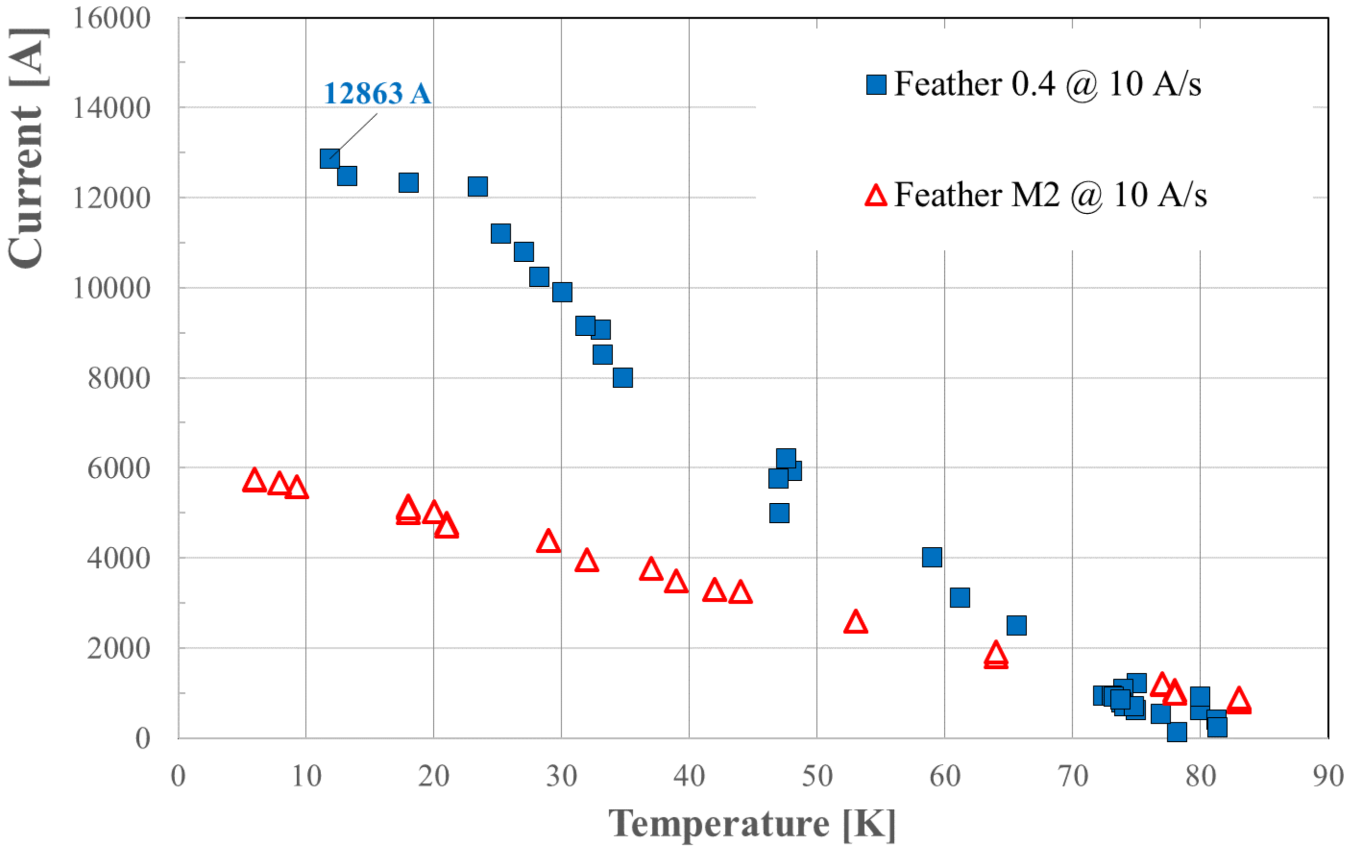
Zoom of the last 50 ms

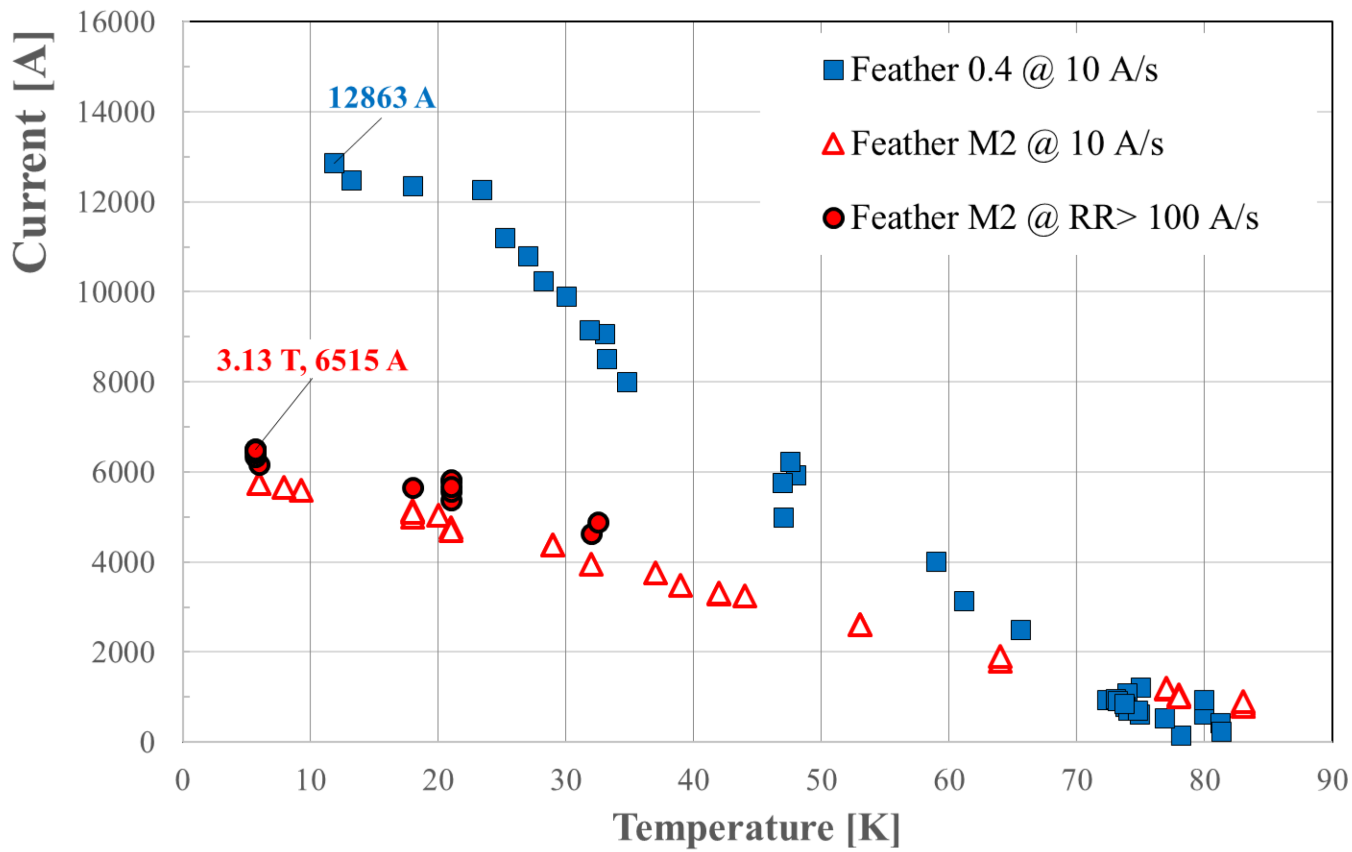
Protection 10 mV, 20 ms





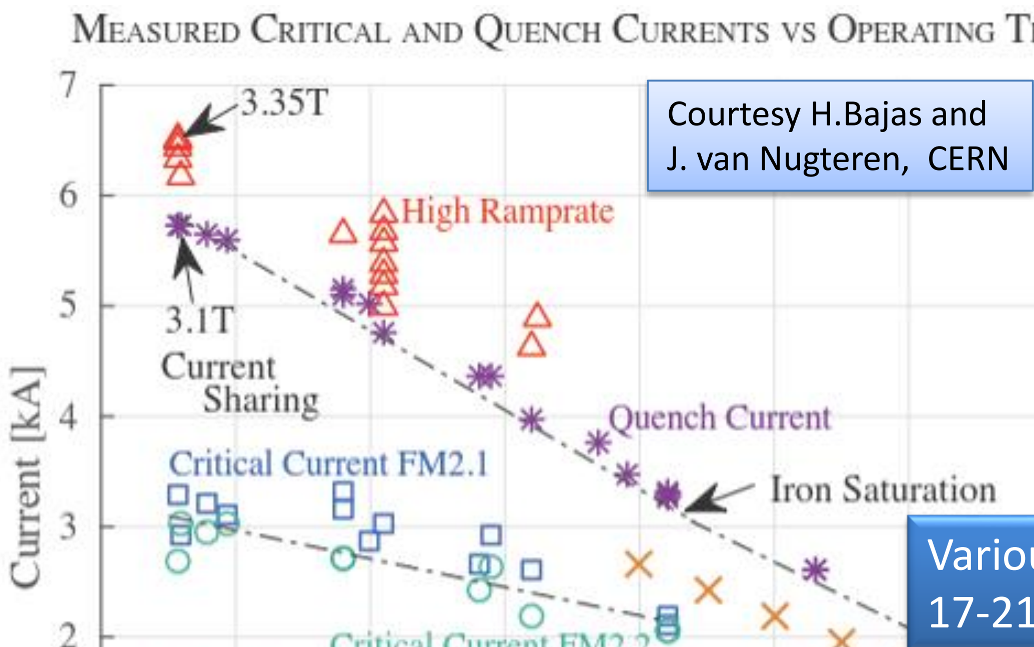
Current [A]
16000
14000
12000
10000
8000
6000
4000
2000
0
12863 A
Feather 0.4 @ 10 A/s
0
10
20
30
40
50
60
70
80
90
Temperature [K]


Current [A]
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
80
90
Temperature [K]
12863 A
Feather 0.4 @ 10 A/s
Feather M2 @ 10 A/s



Current [A]
16000
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
50
60
70
80
90
Temperature [K]
12863 A
3.13 T, 6515 A
Feather 0.4 @ 10 A/s
Feather M2 @ 10 A/s
Feather M2 @ RR> 100 A/s

FeatherM2 temporary analysis



Courtesy H.Bajas and J. van Nugteren, CERN

What else?:
The copper ring works
Pick-up coils and Fibers glass better than in F-M0.4
Coupling current decay in 80 s
But very little persistent current! To be verified!

Various talks to EUCAS2017 in Geneva!
17-21 September 2017

Next year steps

Conductor

- 600 m 12 mm tape high grade (BHTS) 600-800 A/mm^2 @20T (50 m of Roebel)
- 600 m 12 mm tape from other producer for 50 m Roebel
- 600-700 of super-high grade - >1000 A/mm2 by BHTS through H2020.Aries

Magnets & Coils

- Test FeatherM0.4 in Sultan
- FeatherM2.1-2 re-test (MM, LHe)
- Test FeatherM0.5
- More FeatherM0.X for assessing new high and superhigh grade
- Assemble high grade FeatherM2.3-4 (6+ T) & Cosϑ
- New FeatherM2.5-6 ARIES cable
- Test FM2 inside Fresca!!!

HTS are demonstrating capability to generate fields with not impossible field quality: the routes is still long and not only for cost reason. **But is worth to try!**
Nb_3Sn took 50 years before being used in accelerator magnets: HTS are not far…