

HTS accelerator magnets: from Eucard2 and Aries toward IFAST



Lucio Rossi (CERN, now University and INFN Milano) on behalf
EU FP7-EuCARD2 & H2020-ARIES collaborators

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M. Durante, C. Lorin, Ph. Fazilleau, Th. Leclercq (CEA), A. Kario, W. Goldacker (KIT),
A. Usoskin and U. Betz (BHTS), C. Senatore, M. Bonurs (UniGE), M. Dhallé, P. Gao (U Twente), T. Salmi (U.Tampere)

The Partners



- BHTS: A. Usoskin
- CEA: M Durante, Ph. Fazilleau, C. Lorin (F. Borgnolutti)
- CERN: A. Ballarino, M. Bajko, L. Bottura, J. Fleiter, G. Kirby, J. van Nugteren, L. Rossi
- DTI: N. Zangenberg
- INFN: G. Volpini (M. Sorbi)
- INPG: A. Badel, P. Tixador
- KIT: W. Goldacker, A. Kario
- SOTON: Y. Yang
- TUT: E. Härö, T. Salmi, A. Stenvall
- UniGE: C. Senatore
- UT: M. Dhallé

Scope of FP7-Eucard2



CONDUCTOR

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

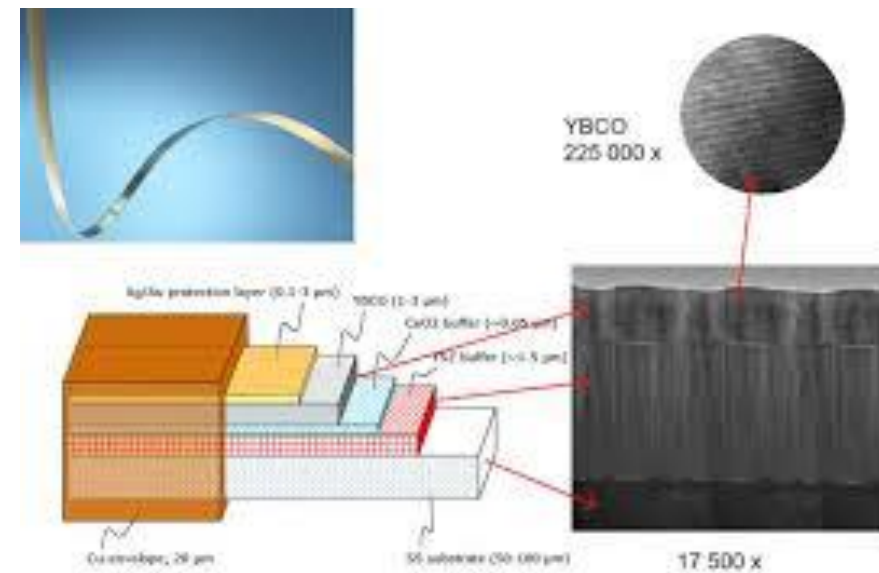
Demonstrator MAGNET – accelerator type

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

Selection HTS: REBCO → cable type: ROEBEL

- 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 coil heat treatment.**

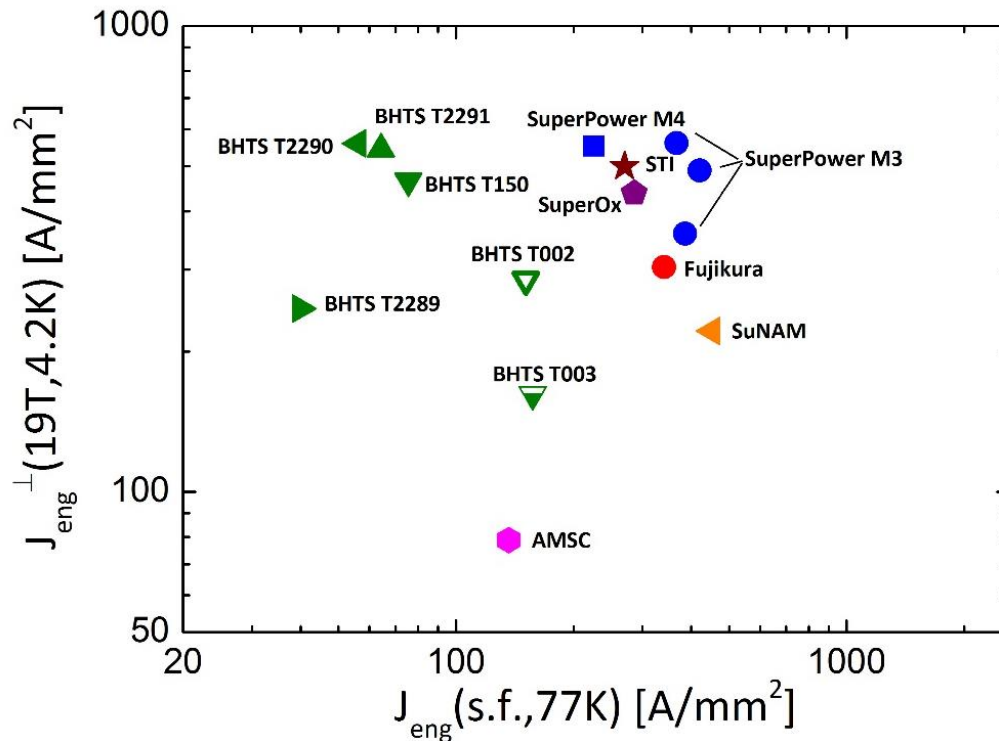
W. Goldacker et al., 2006
J Phys. Conf. Ser. 43 901



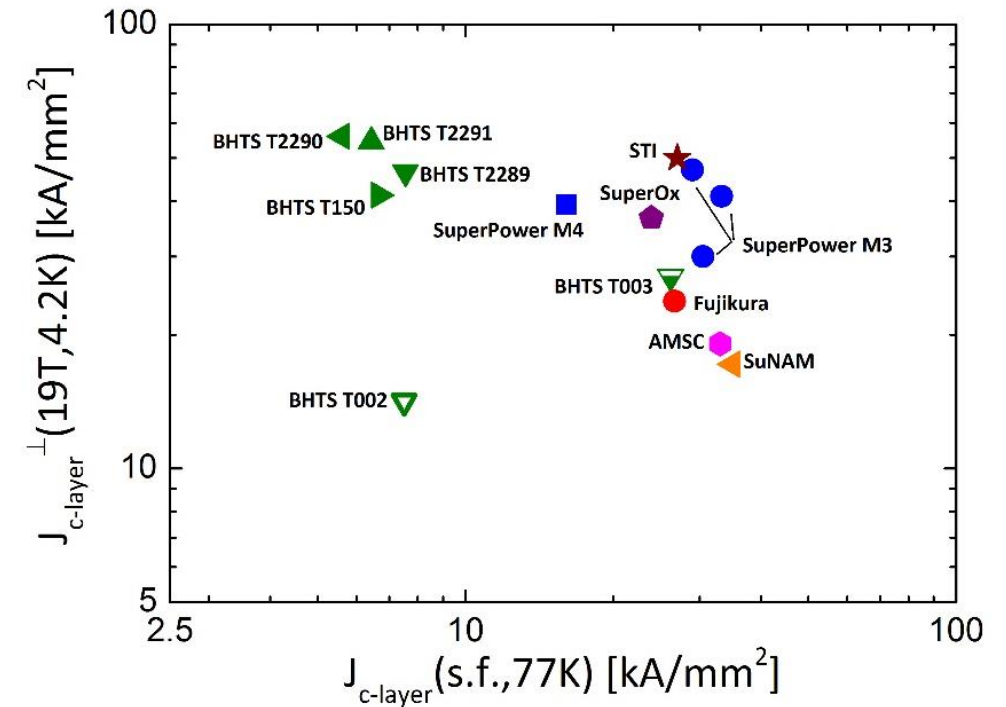
- Other types of cable like stacked tape cable with twist on the curvature ends have been investigated. Eyes on CORC®!
- Activity on Bi-2212 have been pursued in the collaboration CERN-ASC(FI) on advanced powder from Nexans with measurements by Univ. of Geneva on strand and in future U.Twente on cable

EuCARD2 conductor

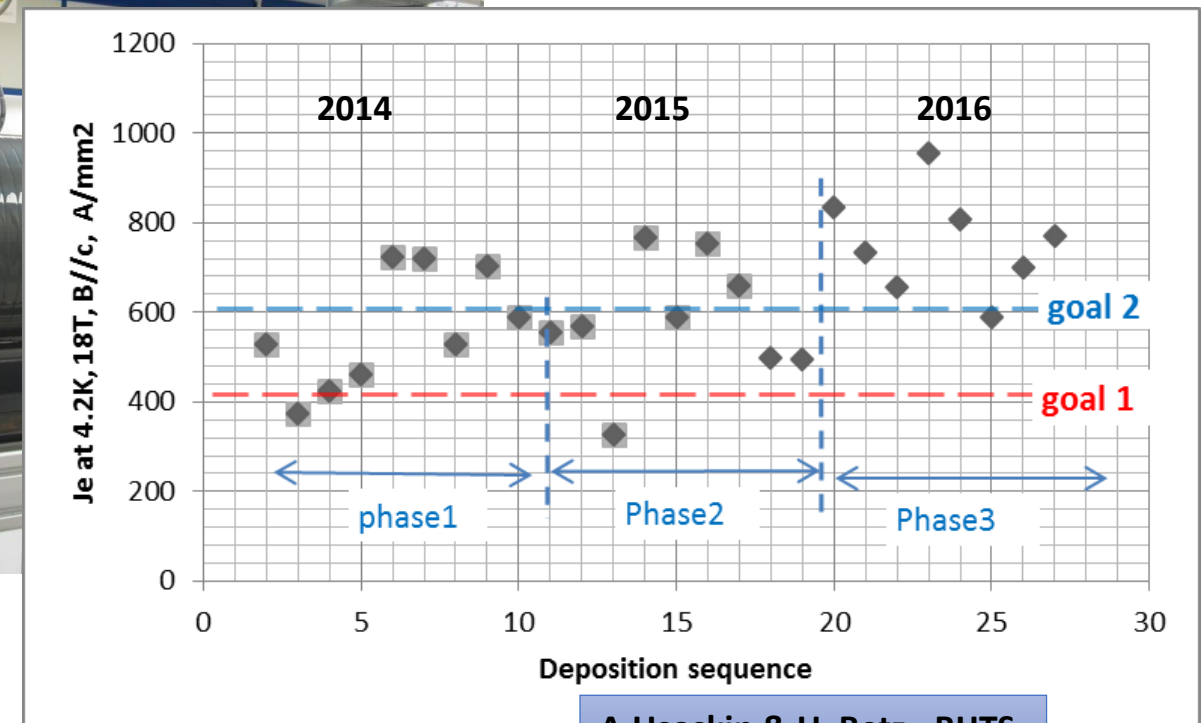
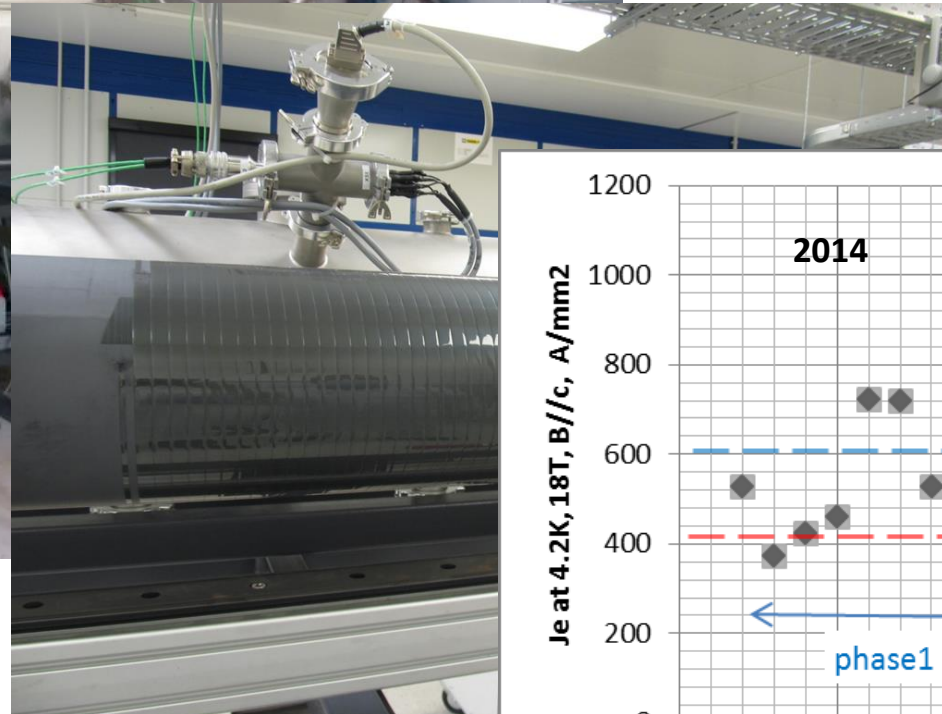
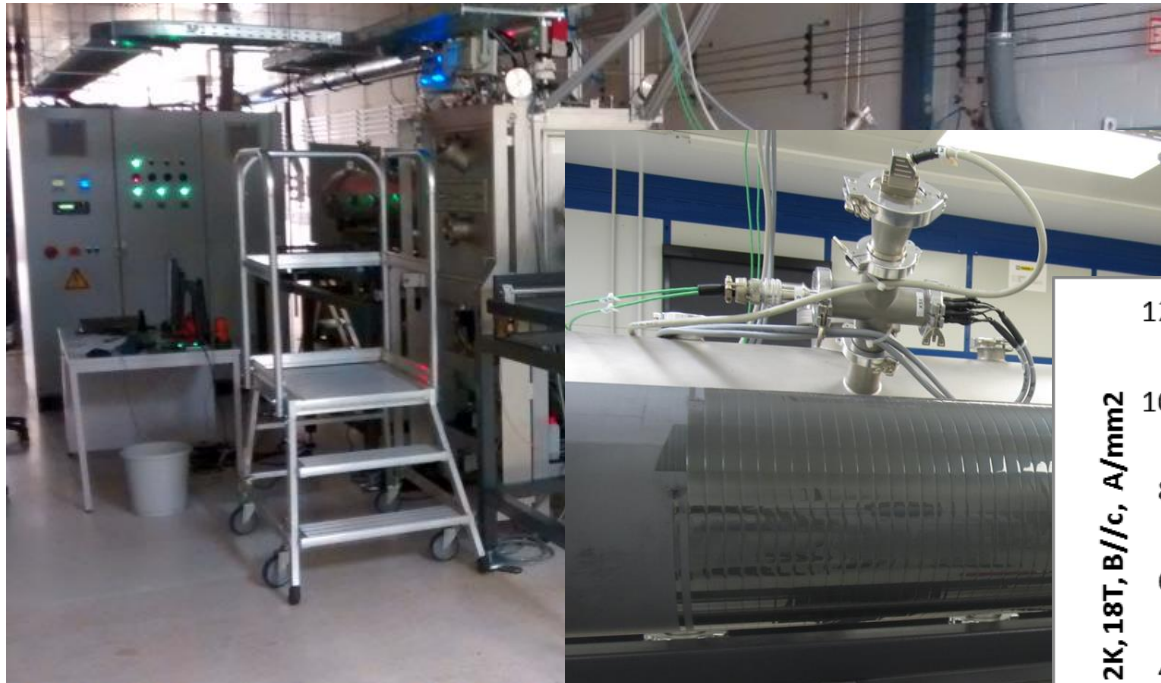
Good in term of J_e



Even better in terms of J_{layer} YBCO



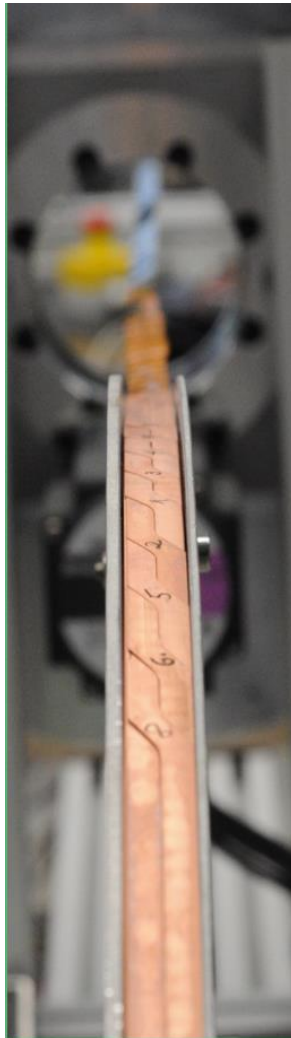
New line for CERN (w=12mm) at Bruker



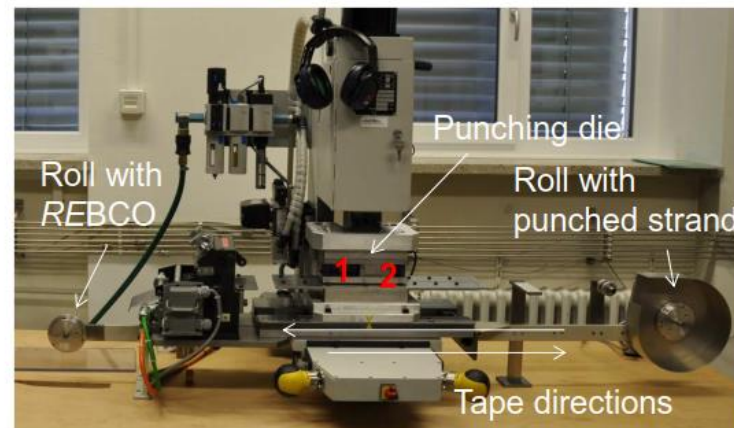
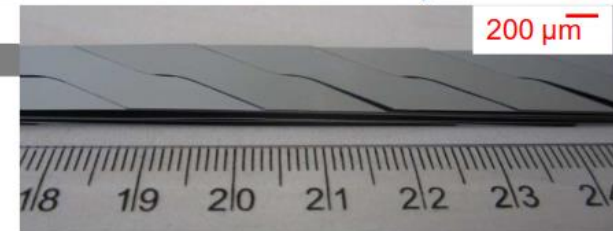
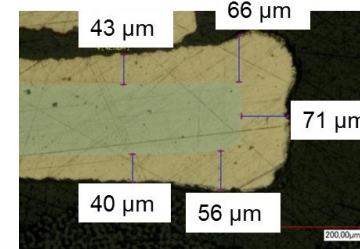
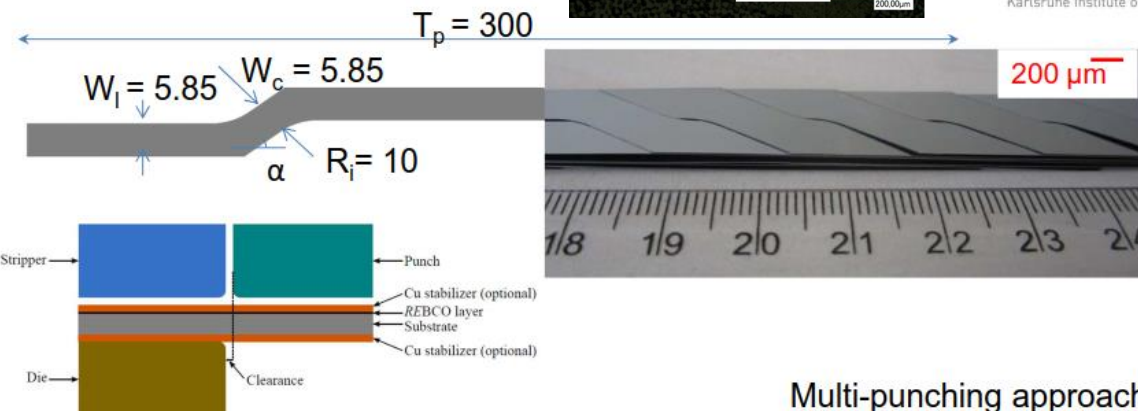
A.Usoskin & U. Betz - BHTS

Back to Eucard2 : from tape to cable

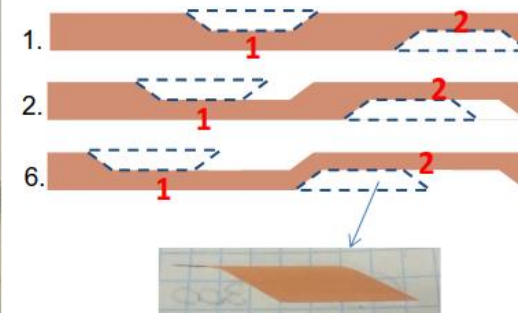
A. Kario & W. Goldacker



Punching process:



Multi-punching approach
(flexibility)



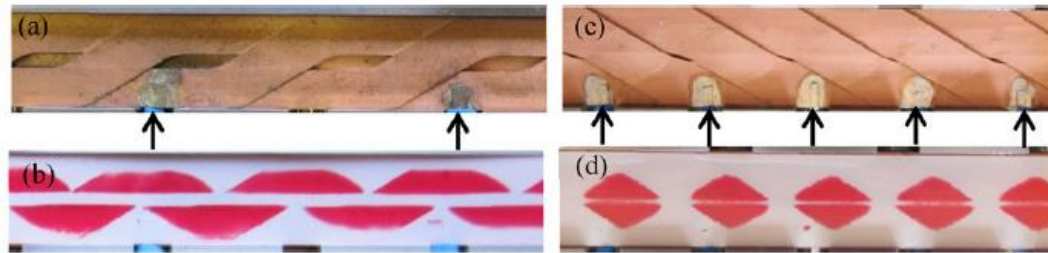
New line for the Roebel

Anna Kario, Simon Otten, Andrea Kling, et al.

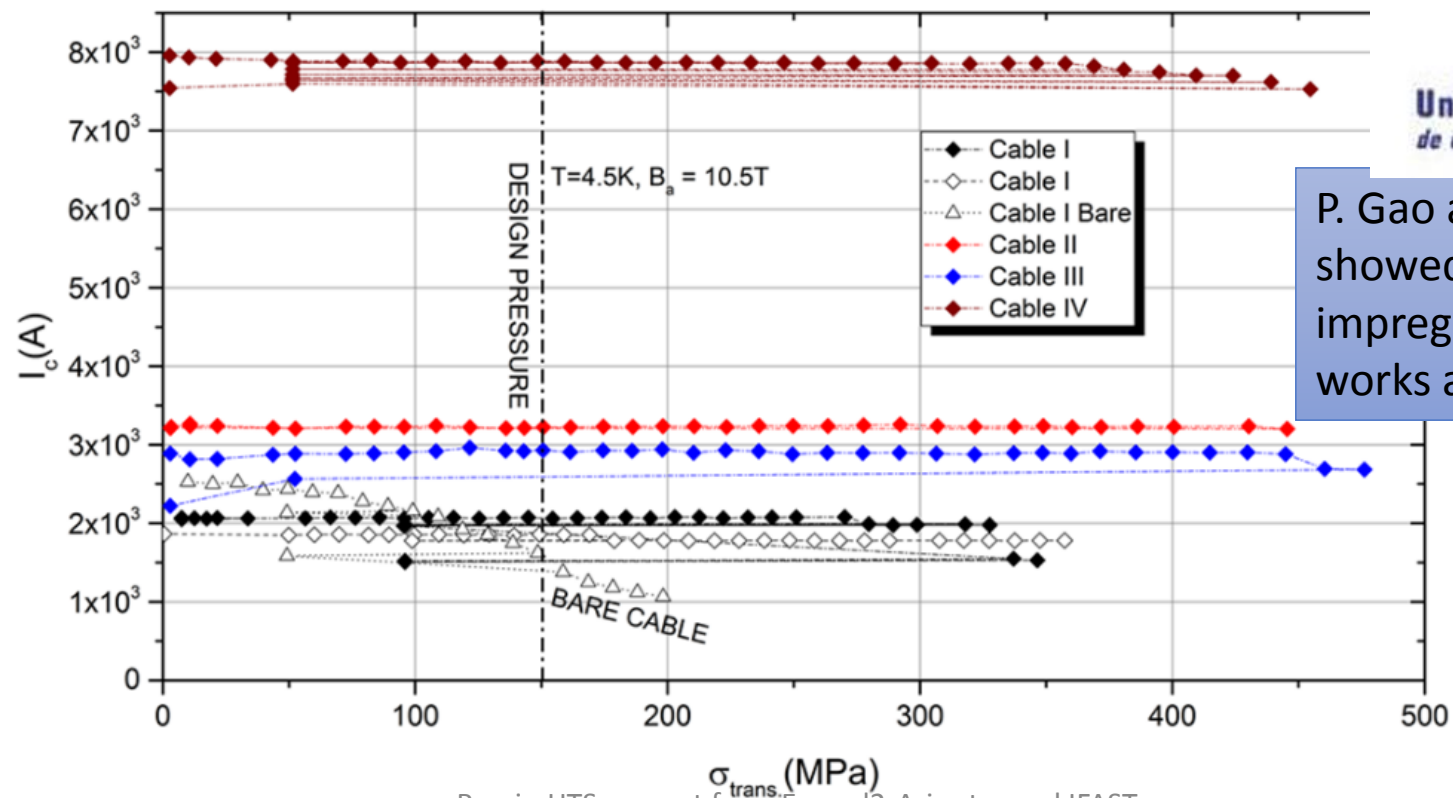
New improved punching tool: first tests



I_c vs. transv. stress

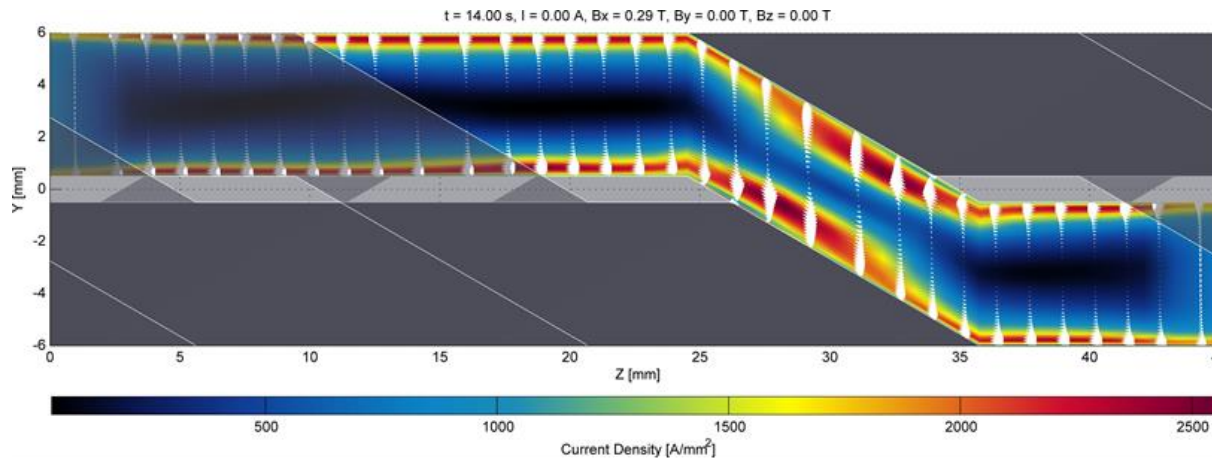


J. Fleiter et al. SUST 26.6 (2013)
Demonstrated that above 100 MPa bare cable is severely damaged: but we will work at 150-200 MPa...

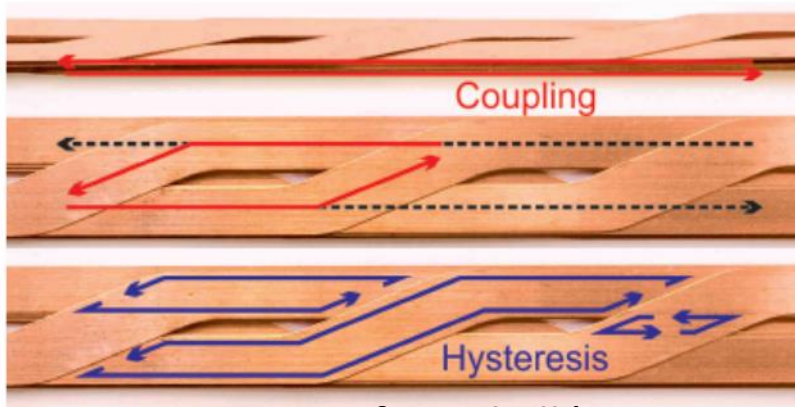


P. Gao and M. Dhallé
showed that
impregnated cable
works at 400 MPa

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



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

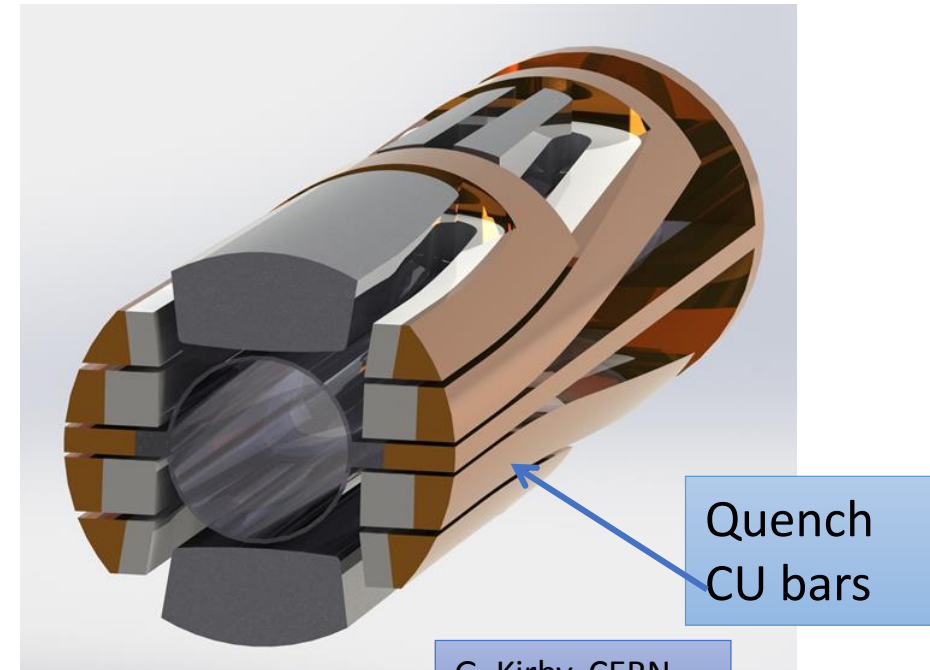
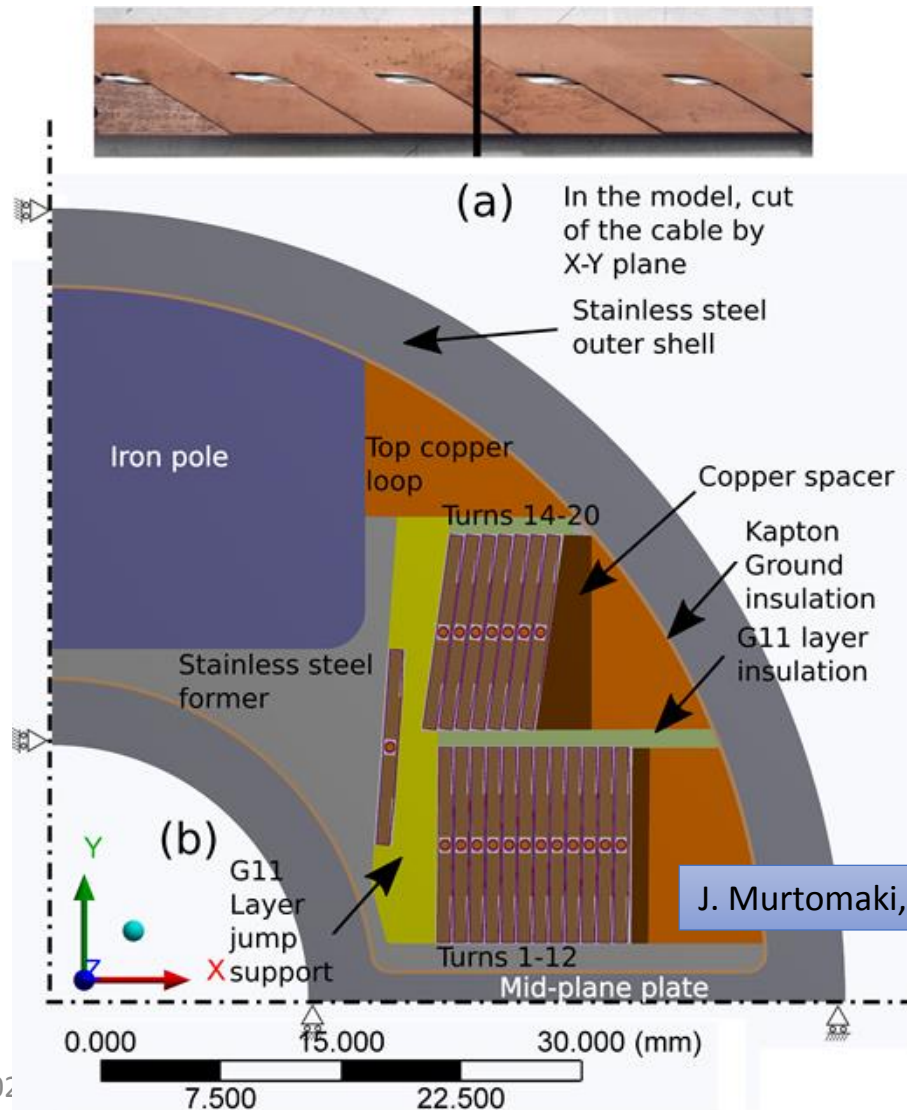


Courtesy of M. Dhallé, U.T.

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

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

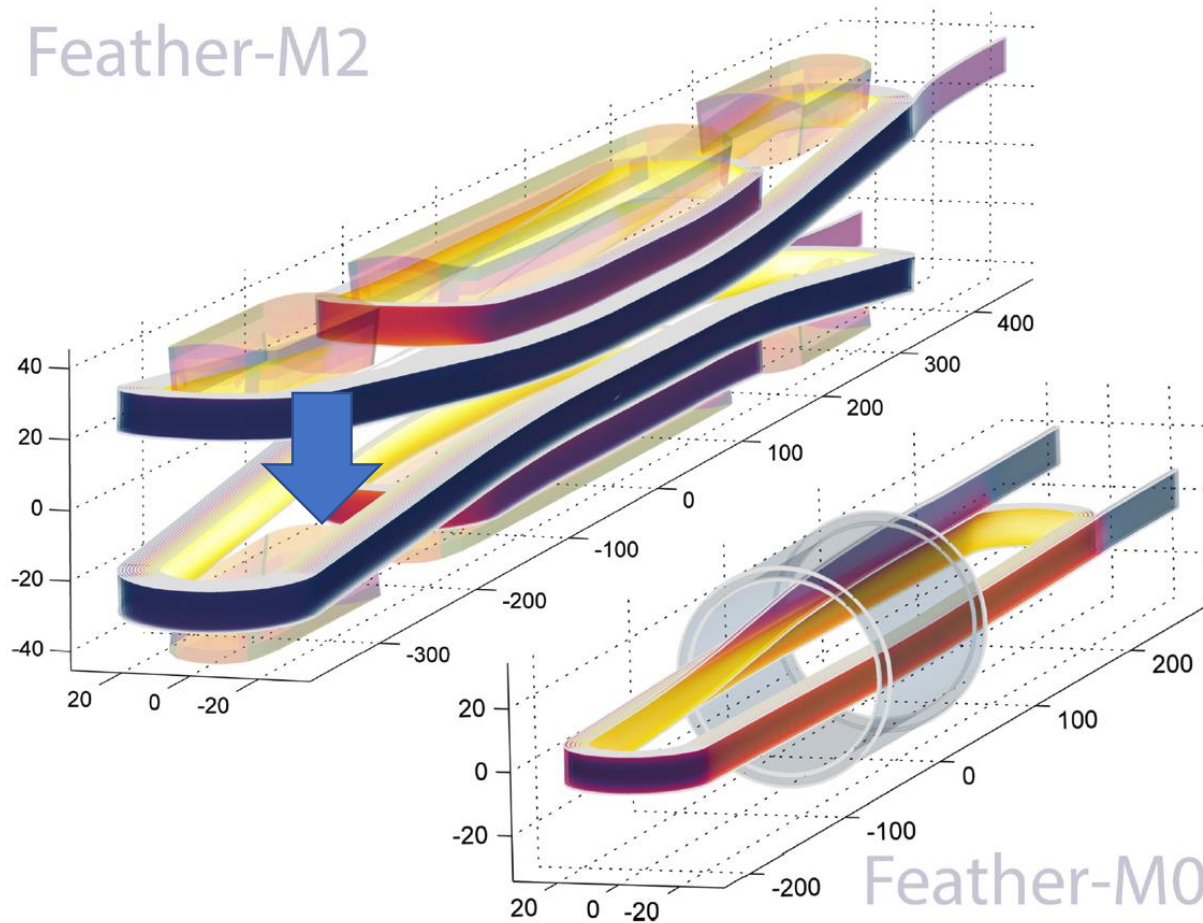
AB dipole magnet (FeatherM2)



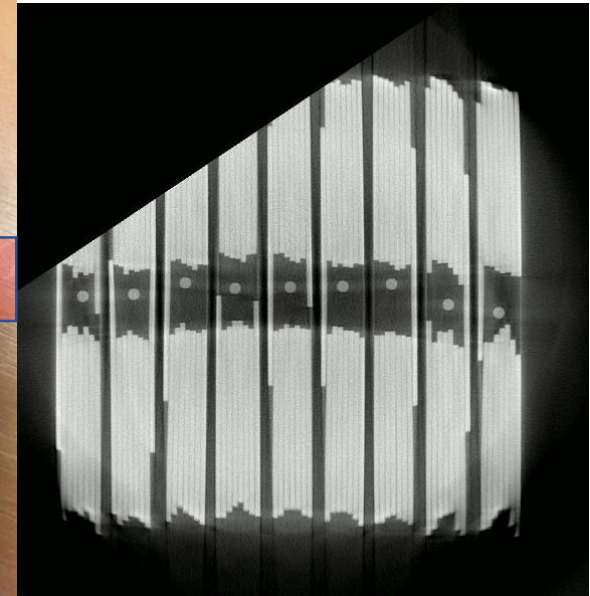
**Design: minimal precompression:
the coil are leaning against a rigid
wall**

Going in steps: FeatherM0 flat racetrack, 5 m cable

Feather-M2

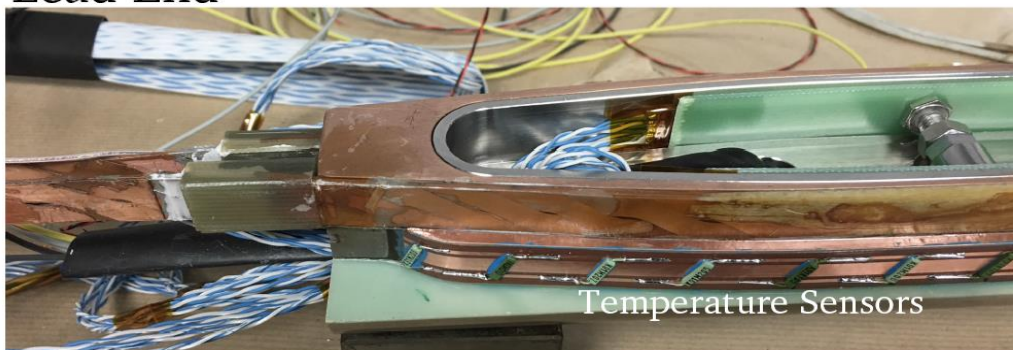


G. Kirby, J. van Nugteren, CERN

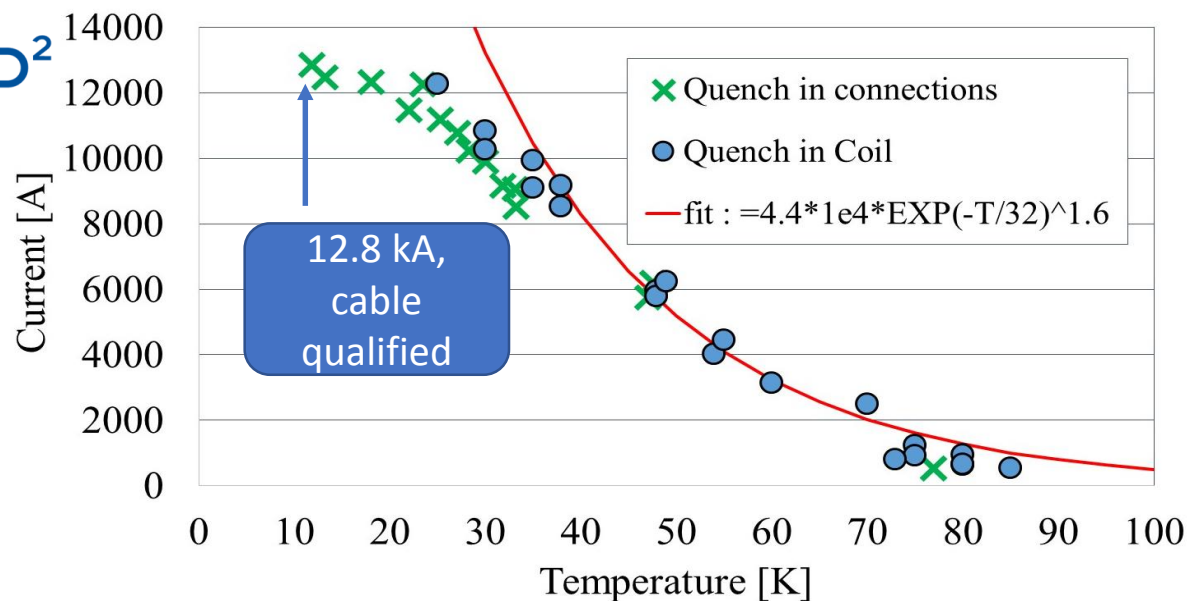


FeatherM0.4 – cable behaved as “expected”

Lead End



Turn End



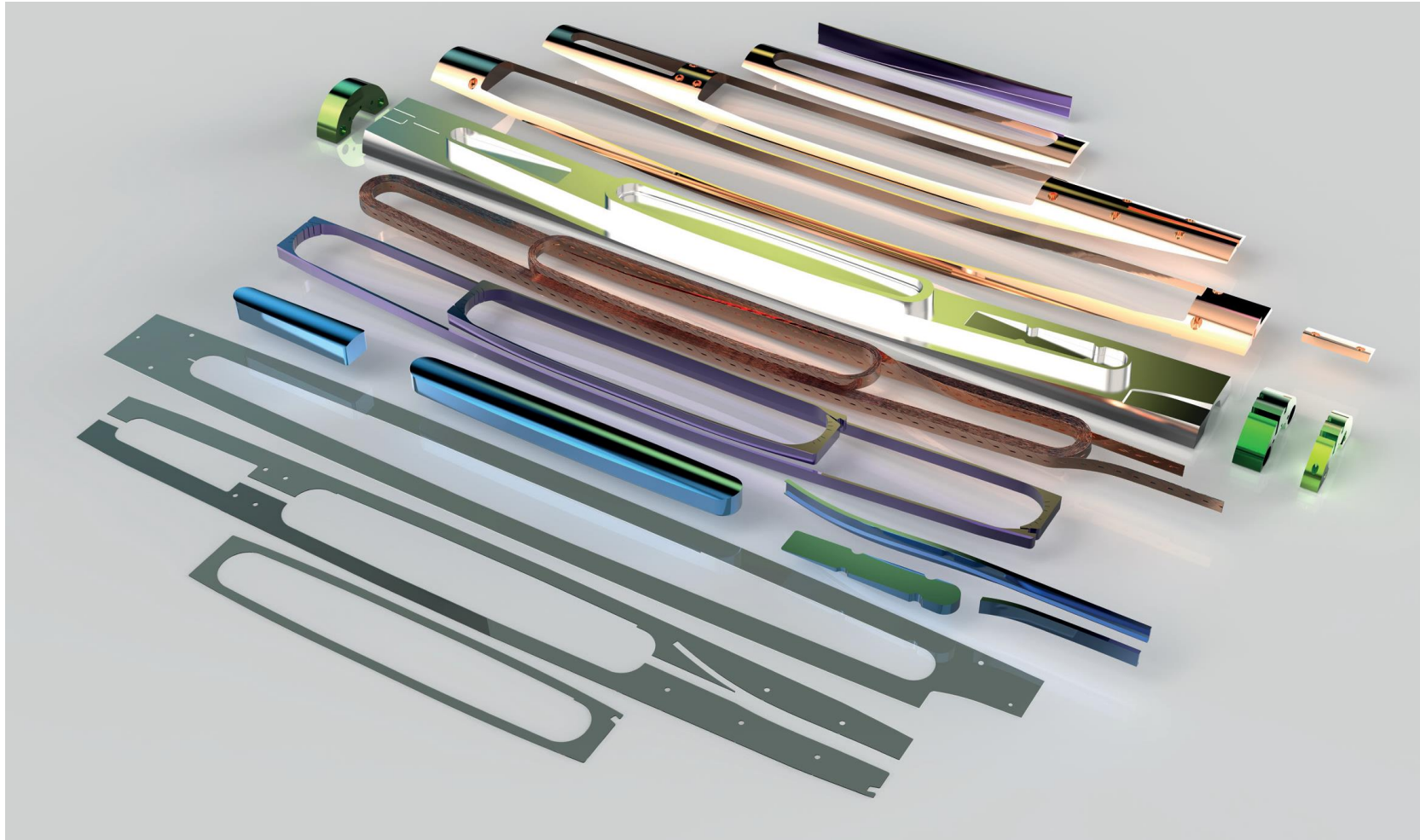
Computation showed little time to react to a quench: 20-30 ms:

Way too much diagnostics
Too many wires!

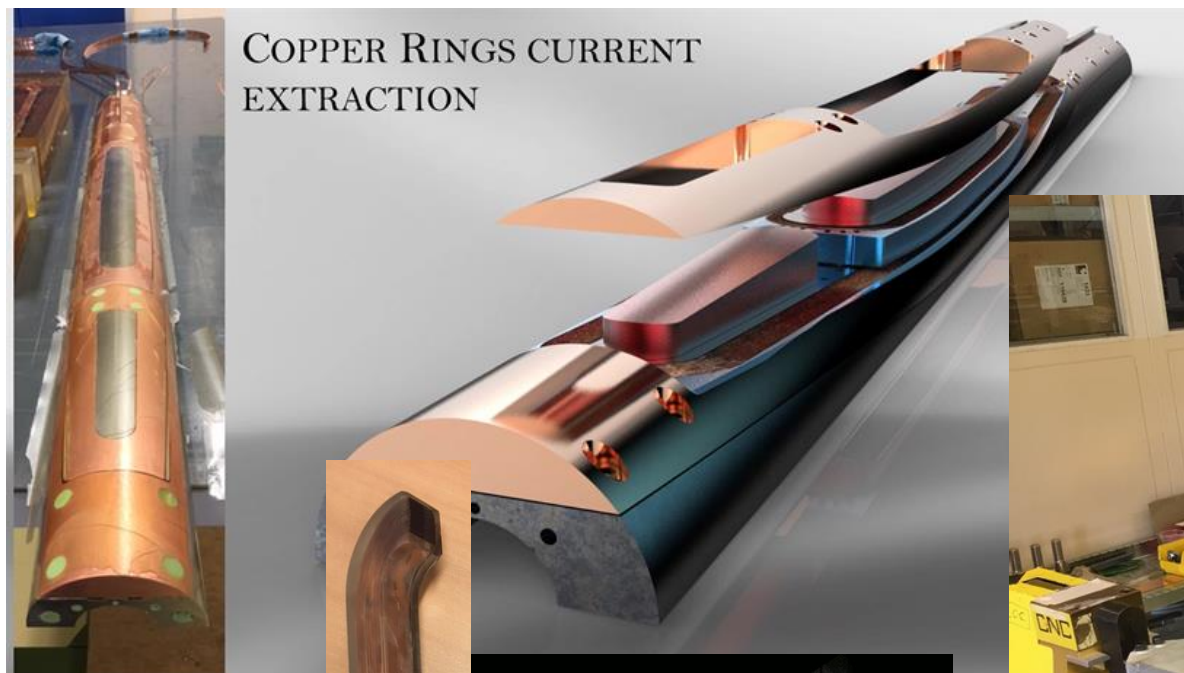
Quench detection.

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

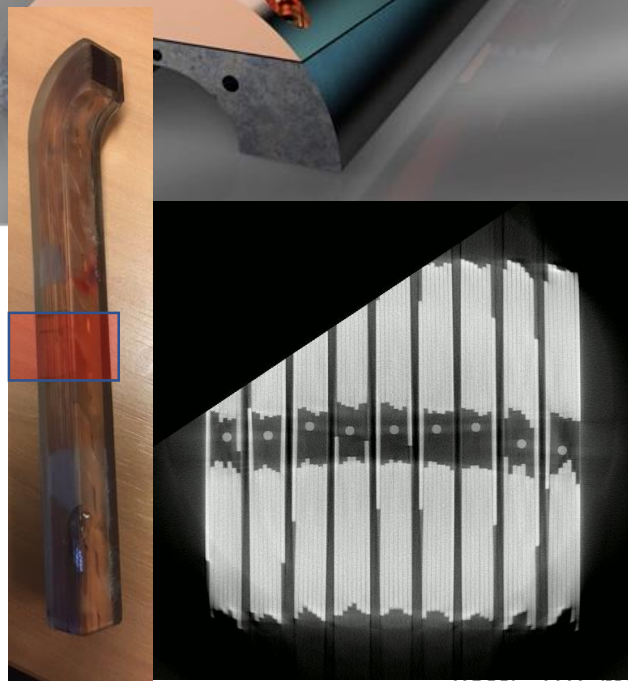
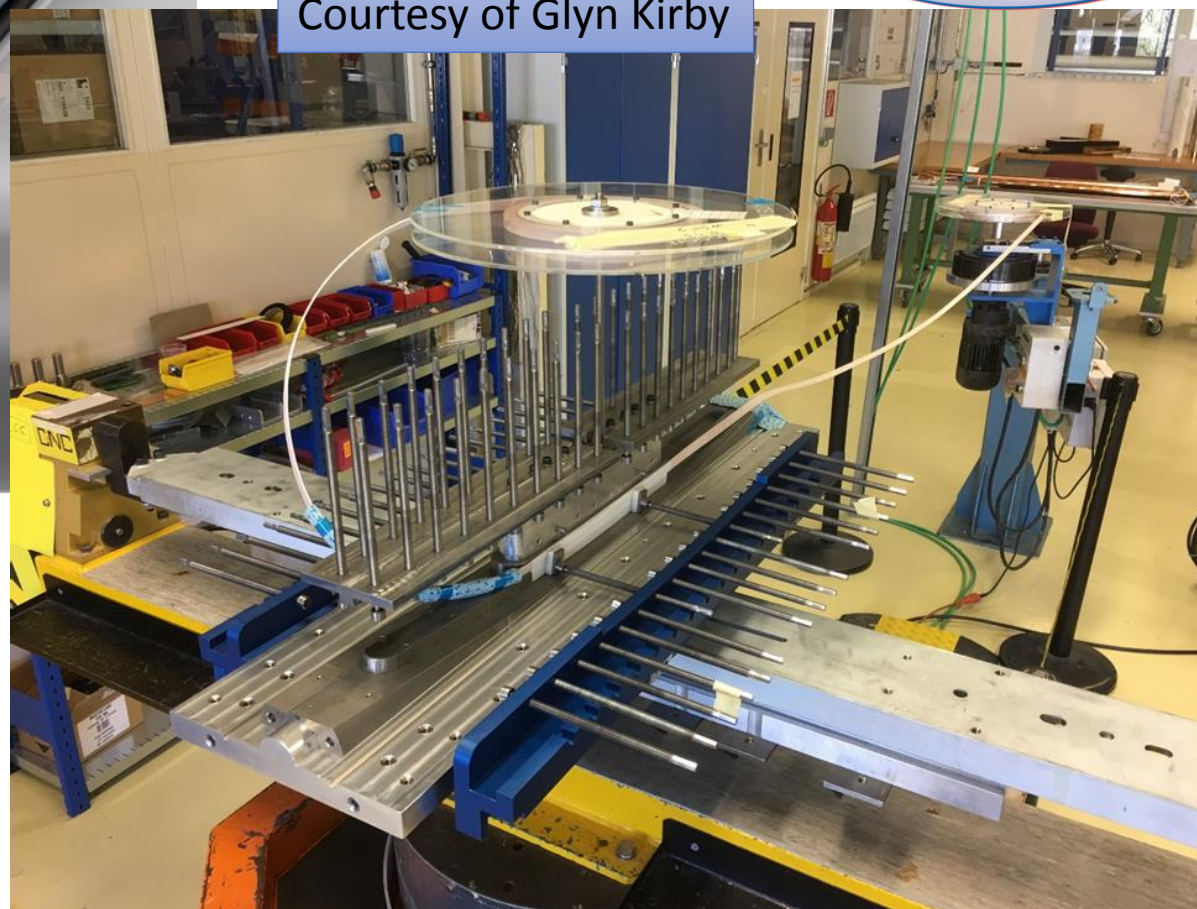
FeatherM2 construction: a complex assembly



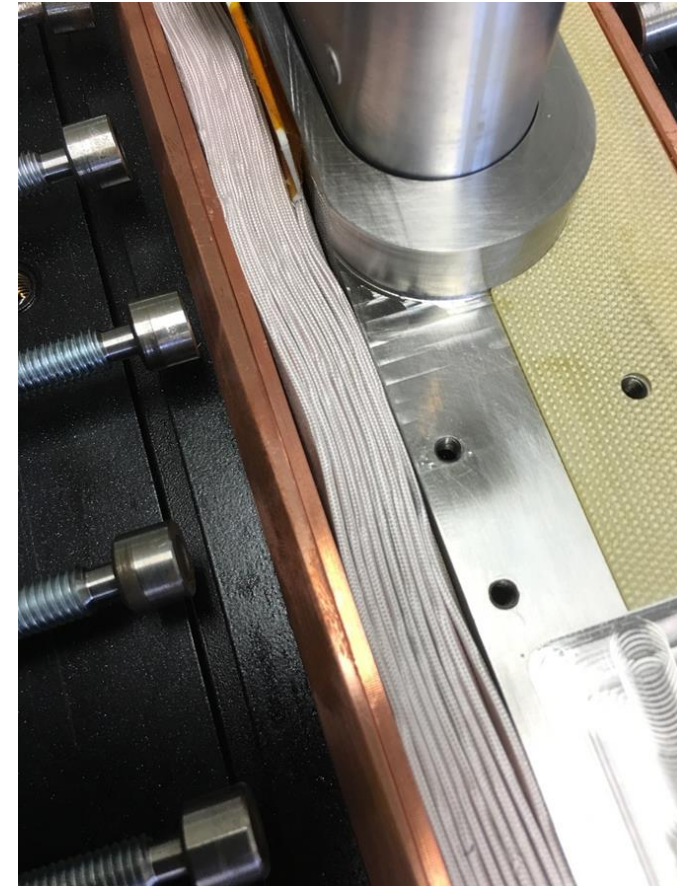
Manufacturing the Eucard2 first AB dipole FeatherM2



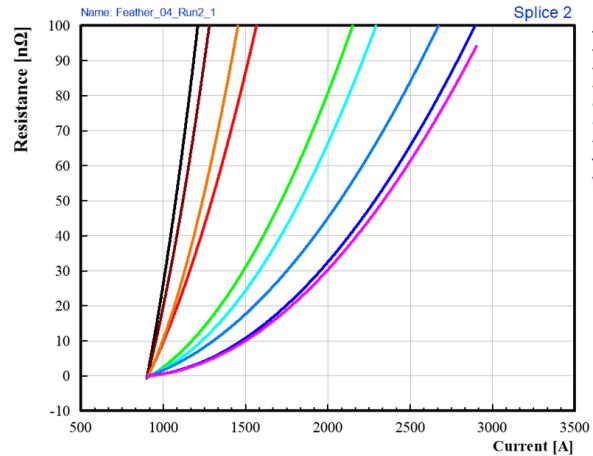
Courtesy of Glyn Kirby



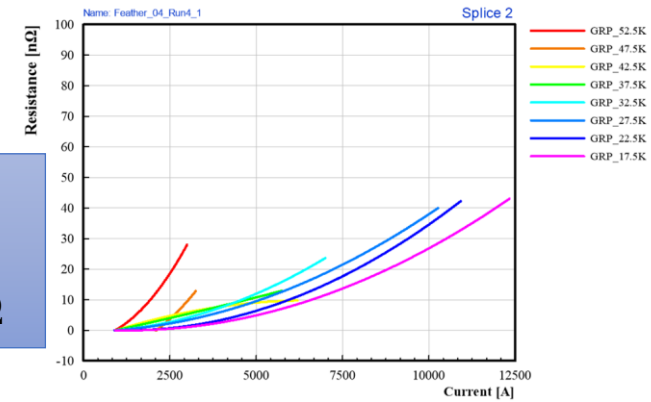
FeatherM2 AB block dipole construction



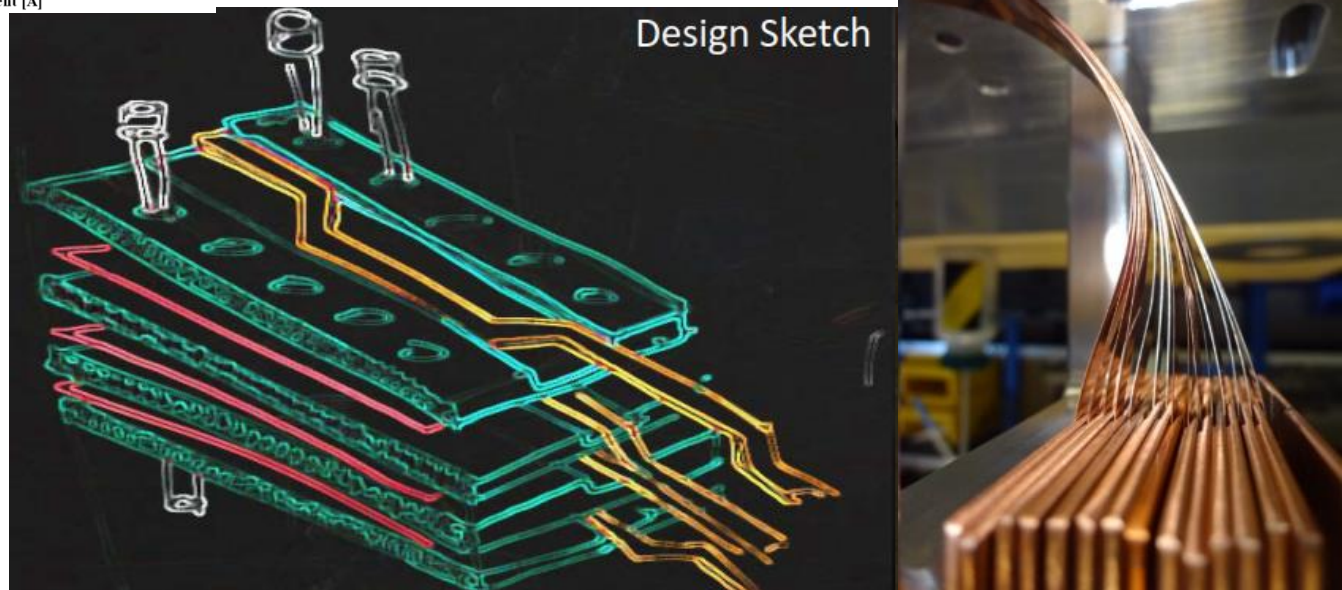
Fin Joints by G. Kirby



Classical butlap
joint in **FM0.4**:
>100 nΩ! \Rightarrow 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...



Rossi - HTS magnet from Eucard2-Aries toward IFAST

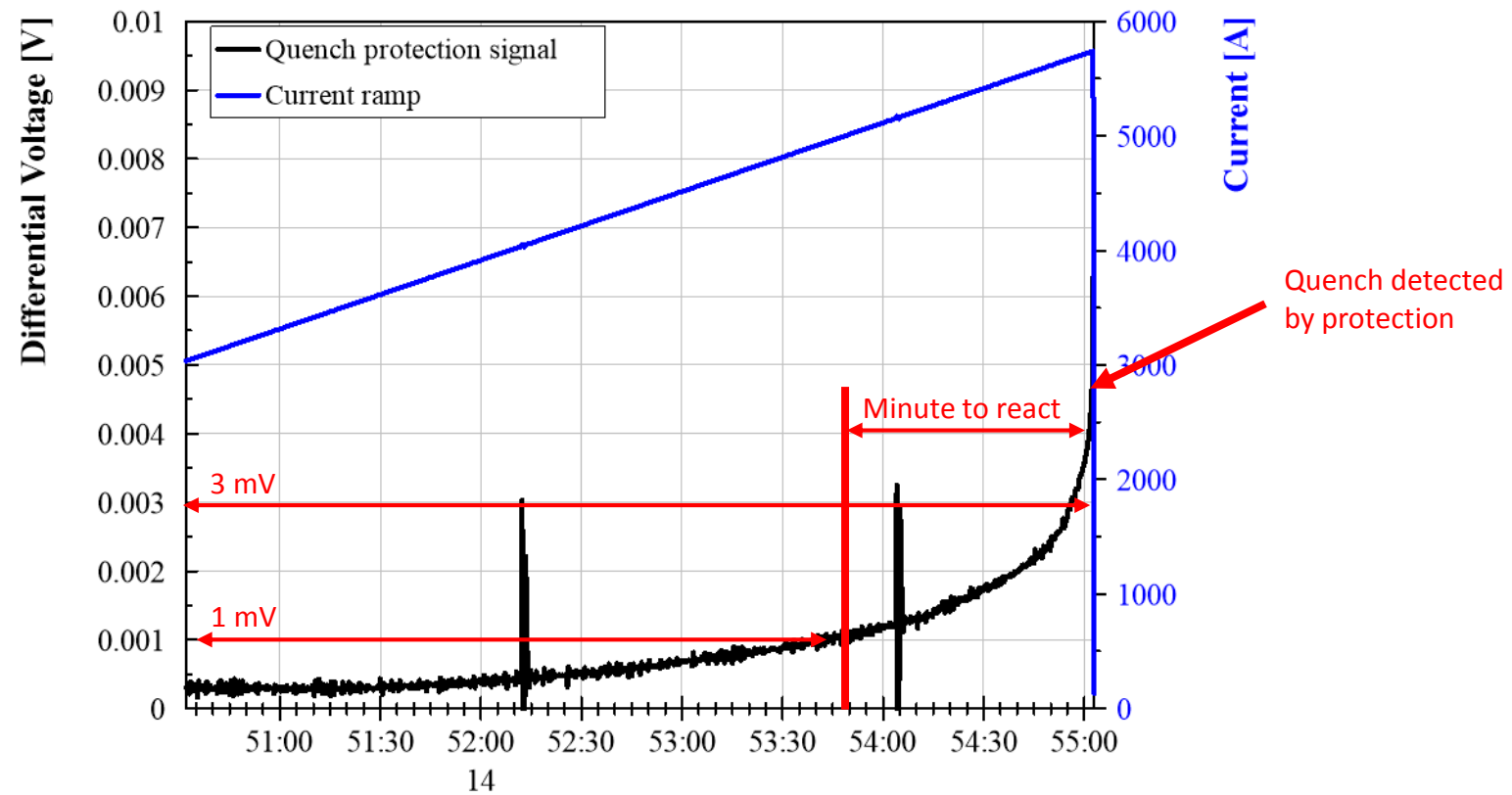


First accelerator-type magnet before going to test:
The Eucard2 FeatherM2.1-2 dipole
April 2017.

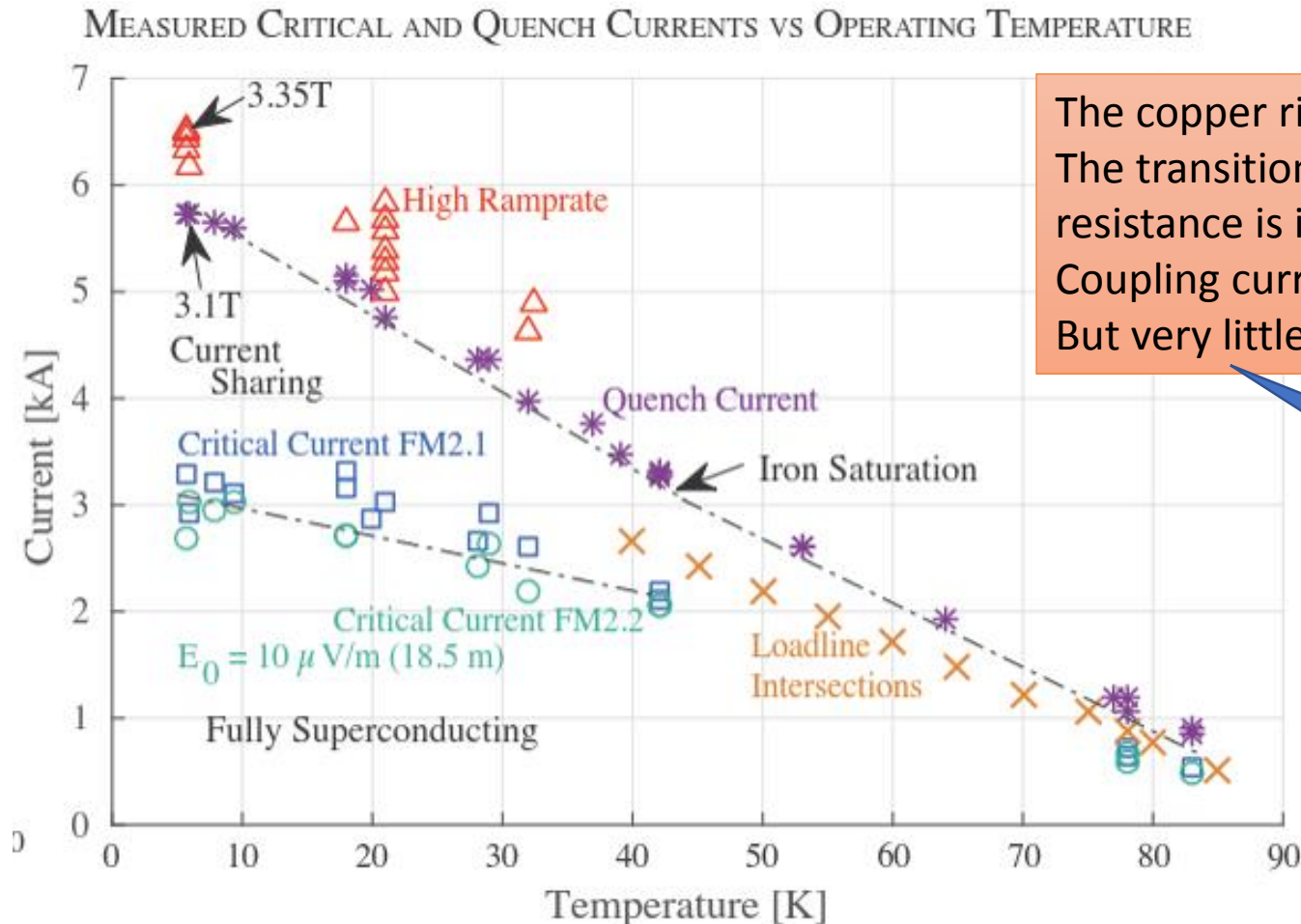
FeatherM2.1-2
Is special cable:
Tape from SUNAM
Cable by SuperOx
Low current

High resolution low frequency acquisition

Thanks to good QDS
(quench detection
system) safe protection



FeatherM2 first excitation cycle



Courtesy H.Bajas and
J. van Nugteren, CERN

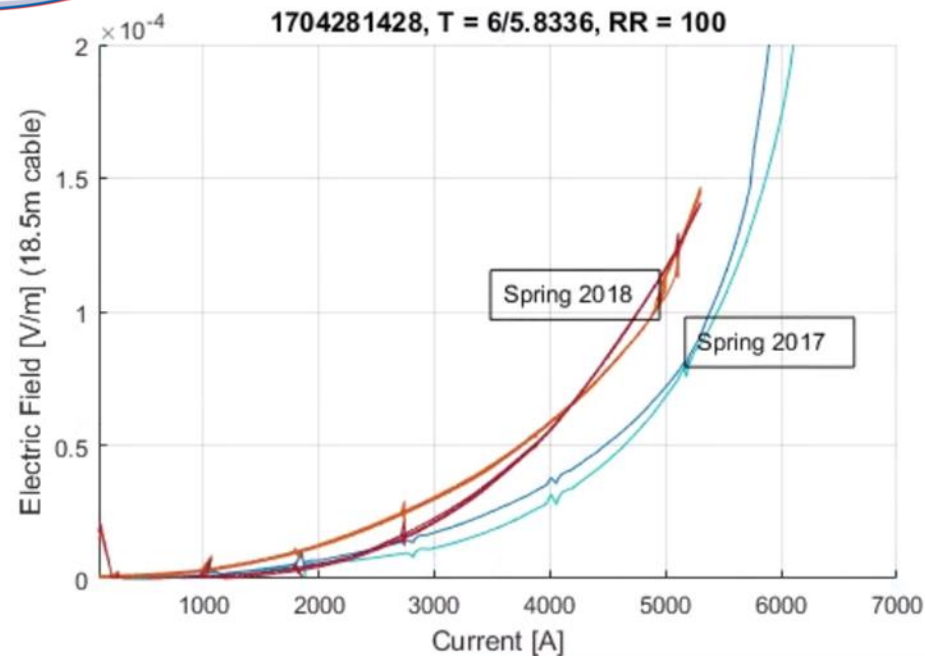
The copper ring works
The transition is soft, Contact
resistance is in the 10 μΩ range!!
Coupling current decay in 80 s
But very little persistent current!

Only 60 unit of b3
foreseen
(model with no iron).
Measured about 20 unit!
Recalculated with iron (L.
Bortot et al.): agreement
with 20 units!

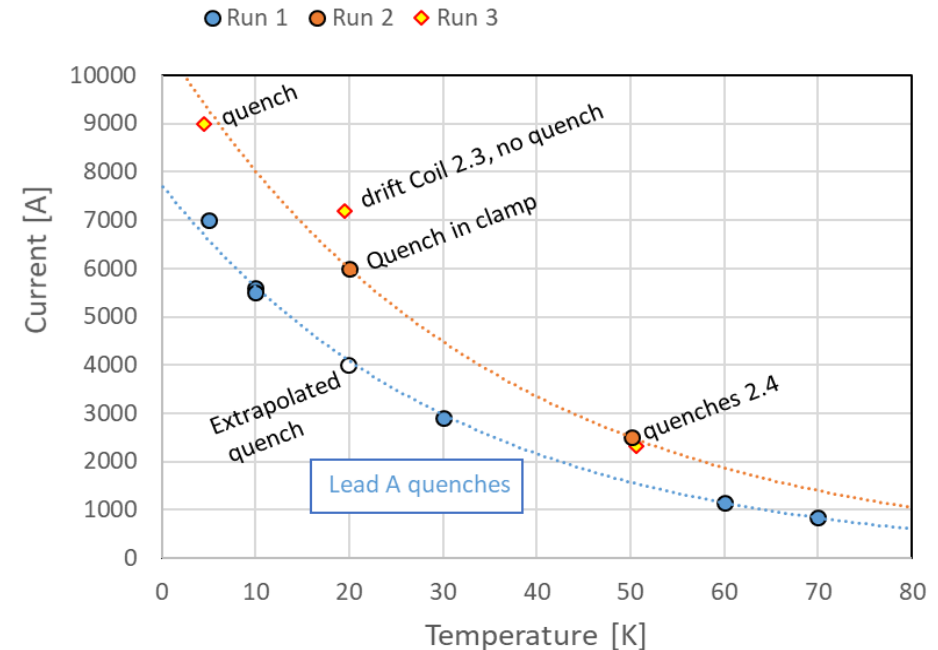
Degradation due to the cycle? Cold down also a little suspicious. But happened other times



G. Willering, CERN



FeatherM2_1-2
3.1 T



FeatherM2_3-4
(Eucard2 cable) 4.5 T
(expected > 5 T)

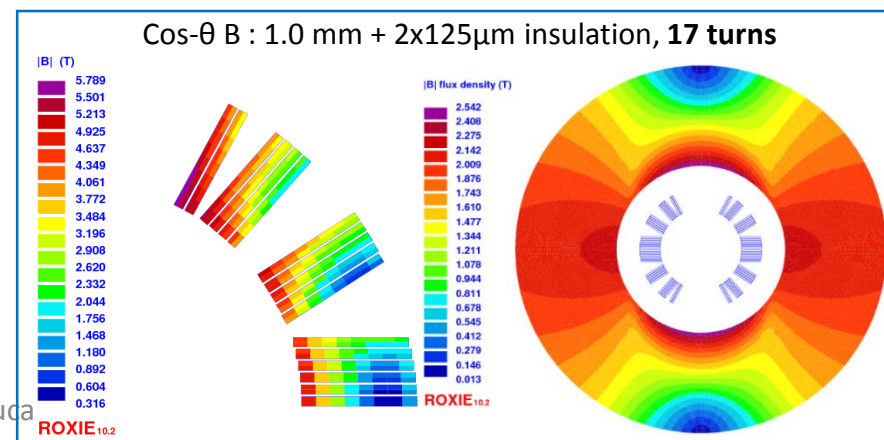
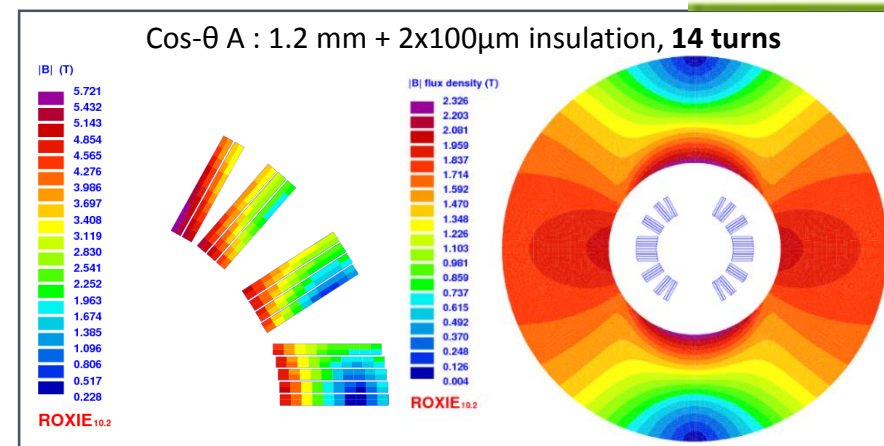
Cos θ design with Roebel at CEA-Saclay

C. Lorin, M. Durante & Ph. Fazilleau

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



Layout	Unit	Cos θ A	Cos θ 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 radius	mm	50	50
yoke outer radius	mm	112	110
Nb. of turns	-	14	17
Unit len. of cond.	m	20	24

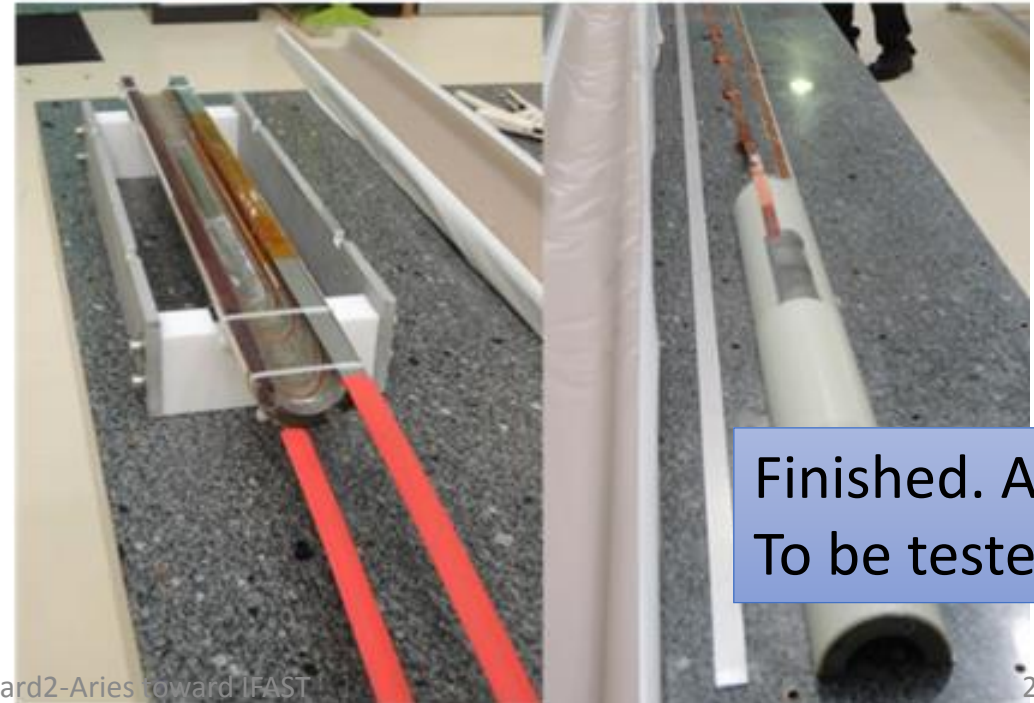
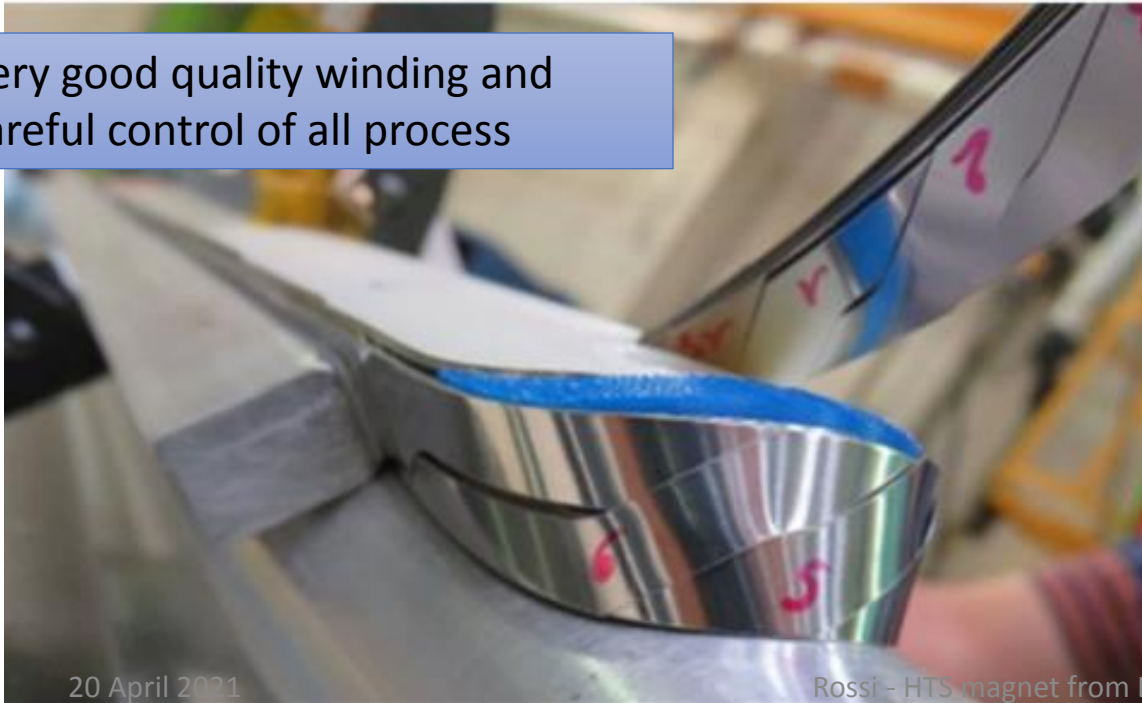


Cos Theta coil at CEA: one layer; Technological test to compare with Ruth. cable

C. Lorin, M. Durante & Ph. Fazilleau, CEA



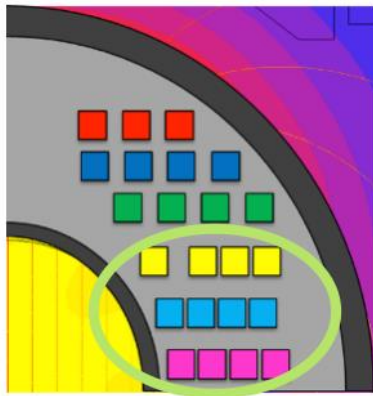
Very good quality winding and
careful control of all process



Finished. At CEA
To be tested

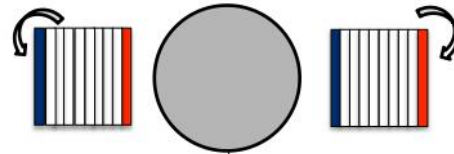
Stacked cable based magnet design (Grenoble)

Racetrack flat coils



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

90° twist + 270° twist 2 x 90° twist

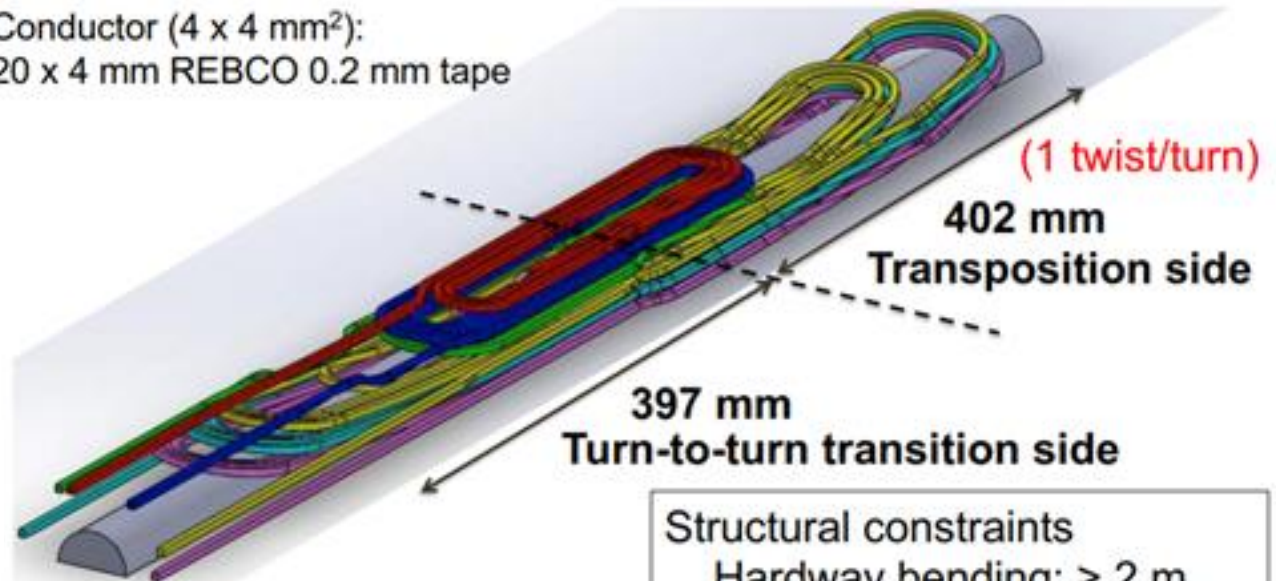


Left side: 360° twist + ew

Winding head



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 redistribution: partial insulated tape inside the cable

Structural constraints
Hardway bending: > 2 m
Easyway bending: > 10 mm
Twist pitch: 1.8 °/mm

H2020-ARIES

Scope: reduce substrate

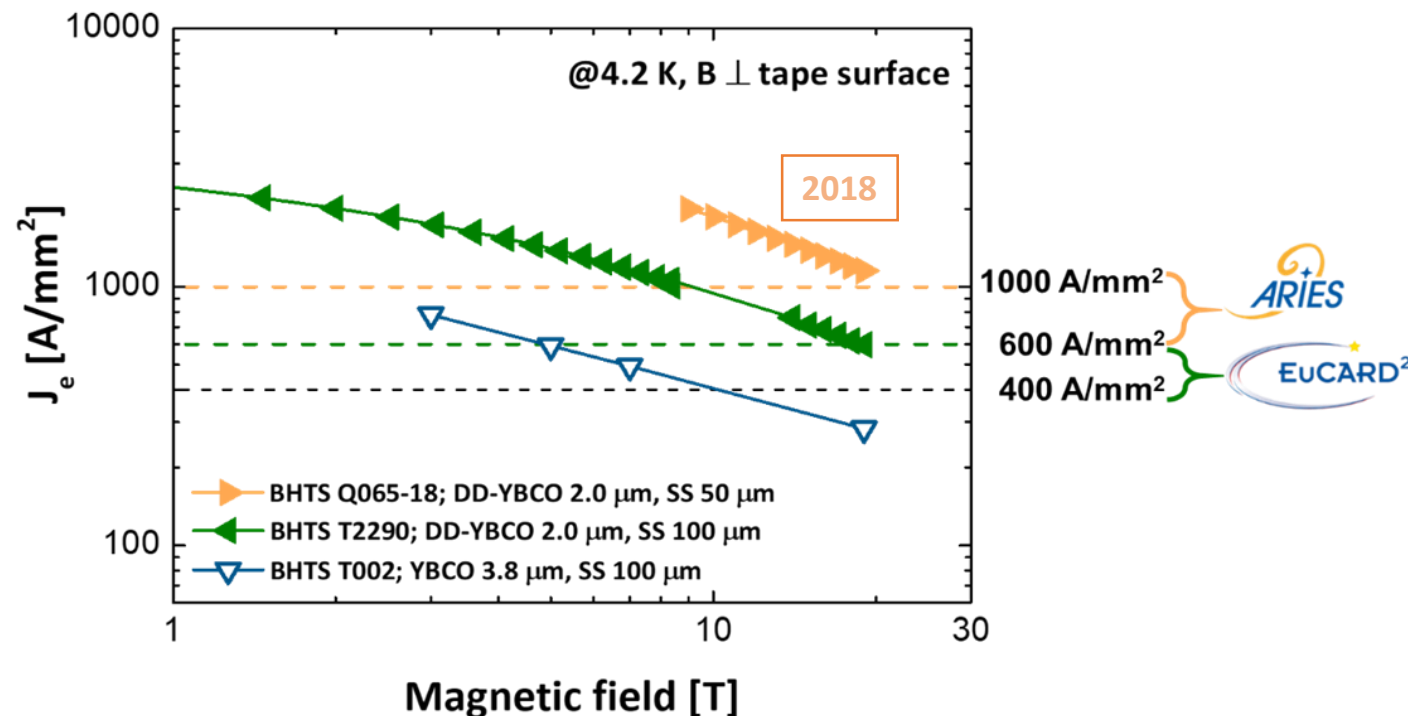
100 μm \rightarrow 50 μm

To – almost – double J_e

Idea behind:

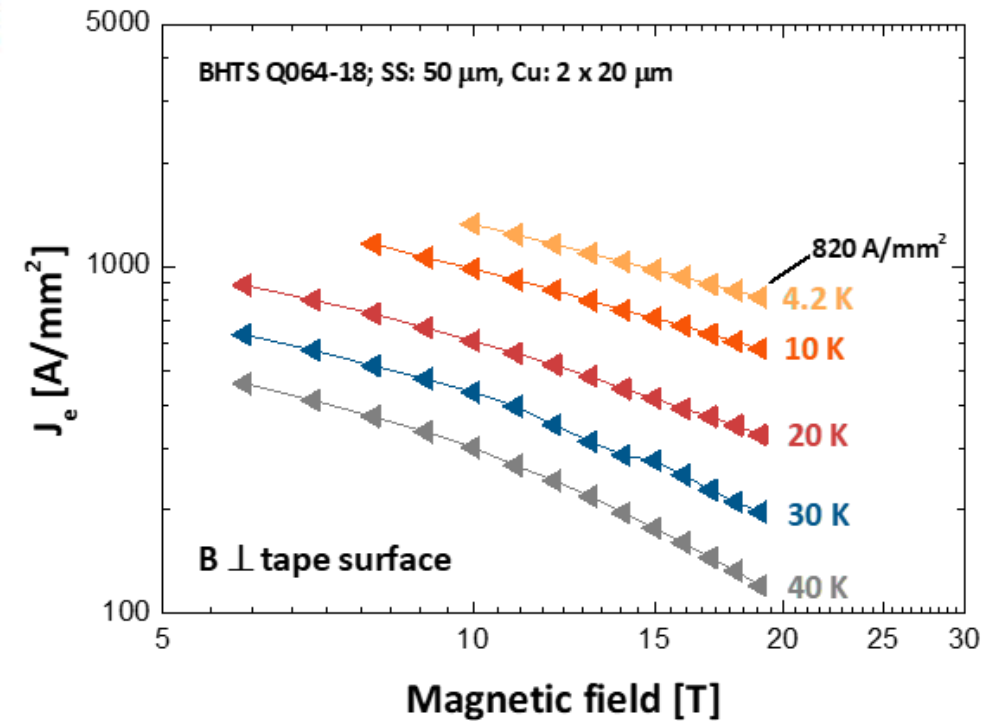
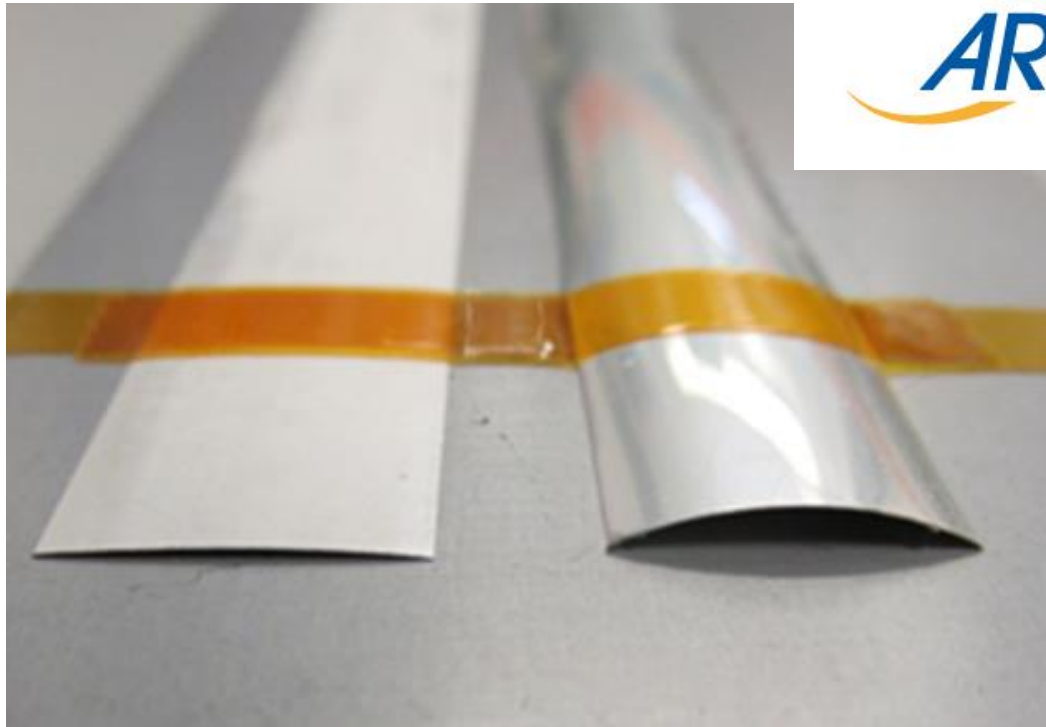
Reduce cost of kA-m

Possible use of extra current density to increase Cu stabilizer



After a successful start ... \rightarrow

...did not work at all; low yield; severe bow of the tape. Attempt to correct the bow **decreased J_e**



(some) Technical lessons

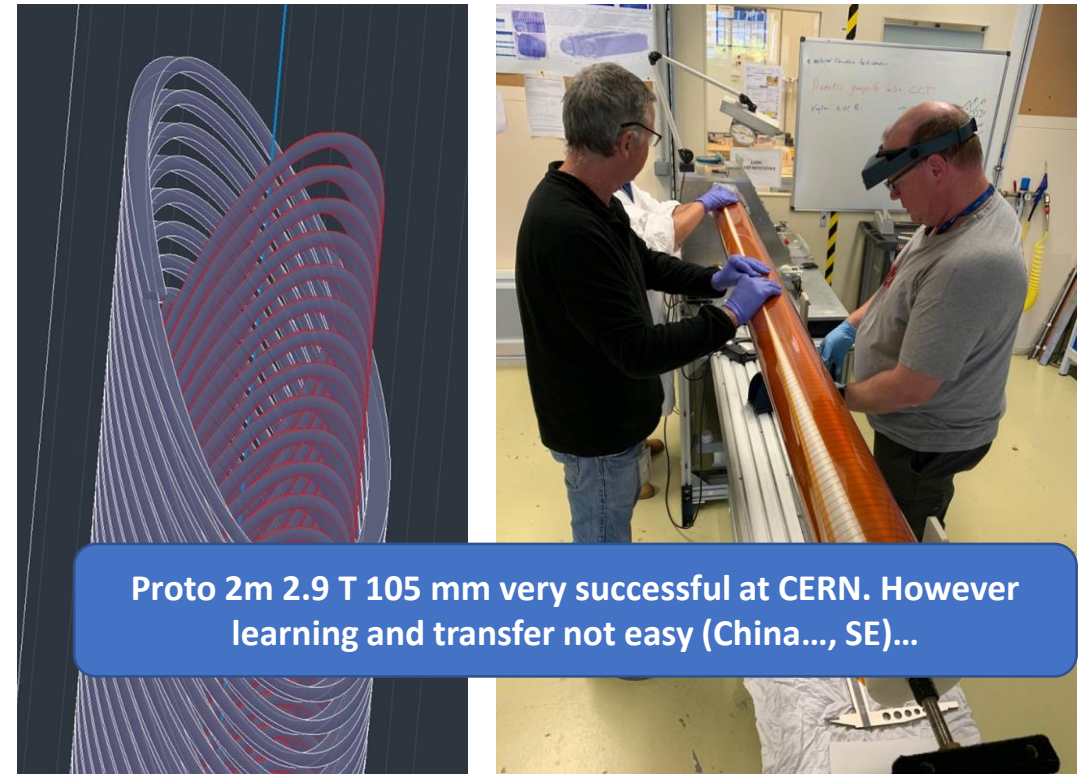
- Working with tape and Roebel is difficult but possible. **But do we need transposition?**
 - Relatively smooth process in the period when effort was sufficient
 - Too many uncertainty open. **Main is the degradation. Is it intrinsic? Due to resin-induced delamination ? (CT101K is already suspected for NbSn...). Compatibility with resin is to be assessed more systematically.**
- Persistent Currents are reasonable for FQ, not bad (**b3 about 20 units**).
 - **D. Uglietti -> we do not need transposition.** Simple stacked tape can do the job? **WHAT IS IMPORTANT IS TO HAVE GOOD CURRENT SHARING.** Roebel even impregnated shows it
- **The large enthalpy margin really pays off but must be coupled with a current sharing mechanism. Defect needs to be “bypassed”. Current sharing plays the role of “stabilizer” to shunt defects. The large enthalpy margin allows for the small inherent dissipation.**
- **We had about 3.5 km of tapes and 150 of Roebel. → Luca Bottura excel file**
Some unit lengths is still there. **It is possible to have a final FeatherM2_5-6 built in more controlled condition.**

Nb-Ti CCT: p-gantry and HiLumi LHC

LBNL: CCT coil prototype for large acceptance **proton gantry** $\varnothing = 400$ mm: Successfully tested to 3.5 T; segmented former.

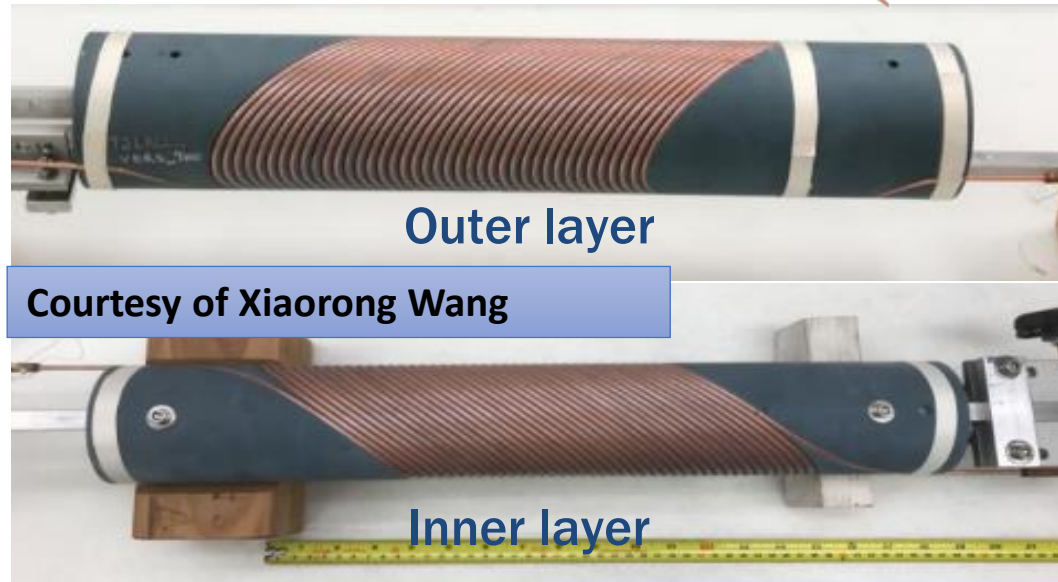


HiLumi LHC: CERN has designed, built and tested a dual 3 T, 2 m long - $\varnothing = 105$ mm, straight CCT. Now IHEP Beijing producing 2x13 units

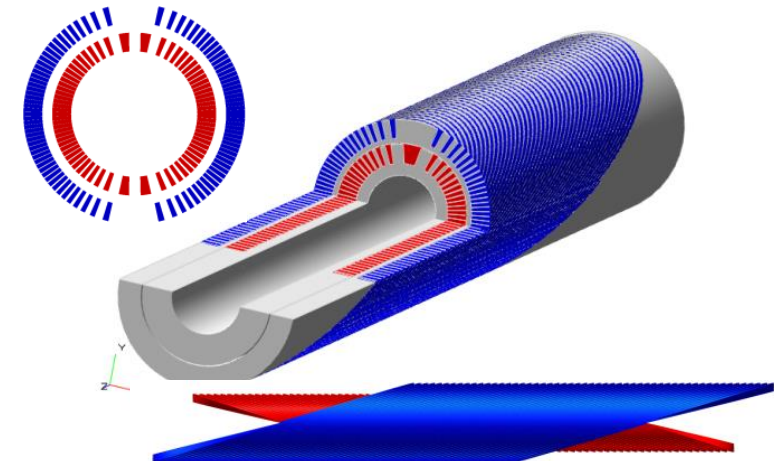
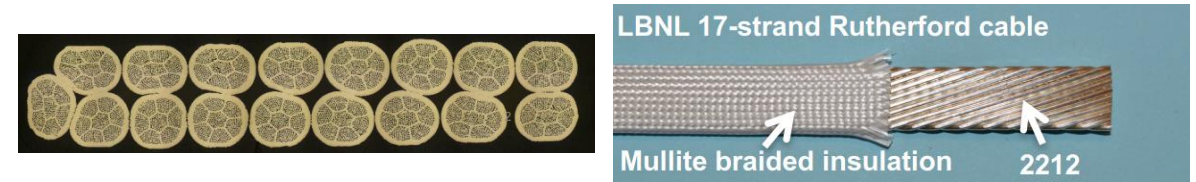


USA-LBNL effort on HTS accelerator magnets

Program based on CORC and CCT layout led by X. Wang & S. Prestemon



Program on use of Bi-2212 Rutherford cable with race track and CCT layout led by T. Shen and S. Prestemon



Courtesy of Tengming Shen

The next step

SEEIIST – First Green Infrastructure in line with Horizon Europe Cancer Mission



SC magnet based
synchrotron ?

SC magnet
based gantry

20 April 2021

Rossi - HTS magnet from Eucard2-Aries toward iFAST

The EC H2020 funded program

- HITRI presented in Nov.2019 (not funded)
 - Heavy Ion Therapy Research Infrastructure
 - Scope: design study mainly (if not purely) for SEEIST
 - Not approved (March 2020): weak in medical part and use... (Physics part OK)
- **HITRIplus (Hitri+)**
 - Medical part improved, scope expanded not only to SEEIST (still most prominent project in EU). Physics part same as HITRI
 - **WP8 on Magnet Design**
 - overview and assessment of various conductors (LTS, HTS, various types of cables) and magnet layouts (cos θ , CCT, racetracks – spit coils or flare ends – etc...). Both for Synchrotrons (main dipole and extraction channel) and Gantry
 - Design construction and test of 1 demonstrator ~500 mm long (either LTS or HTS)
 - Very much CCT oriented!
 - Applied in May 2020; assessment expected by 19th October!
- **I.FAST**
 - Is the *omnibus* program following CARE, Eucard, Eucard2, ARIES to integrate accelerator R&D across EU labs
 - **WP8 on Innovative Superconducting Magnets**
 - scope is fostering technology innovation: → exploring HTS cable and magnet layout
 - General consensus to go toward CCT: CORC[®]?, stacked tapes? Roebel? Or Bi-2212 Rutherford cable? Other magnet layout not excluded
 - The WP8 fosters also a panel among various lab to steer HTS for accelerator magnets in EU and the development of a HTS cable suitable for low losses - large size - fast cycling - synchrotrons (led by GSI)
 - Applied in May 2020; assessment expected by 19th October!

I.FAST WP8 Innovative SC Magnet HTS Demonstrator in Industry!!!

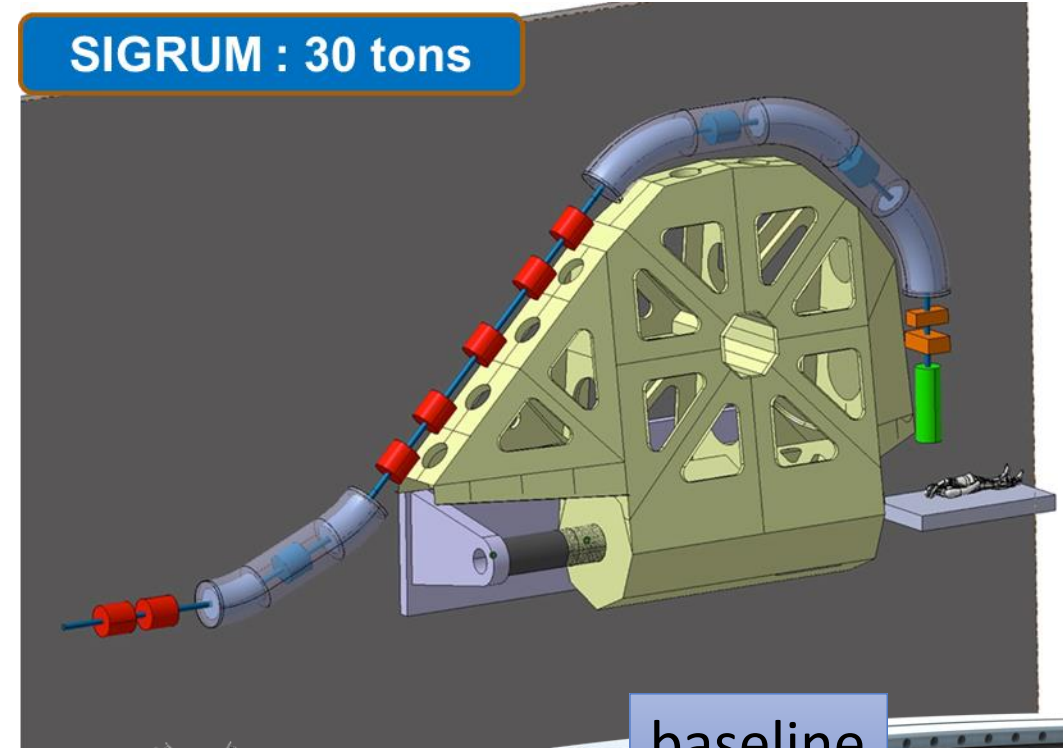
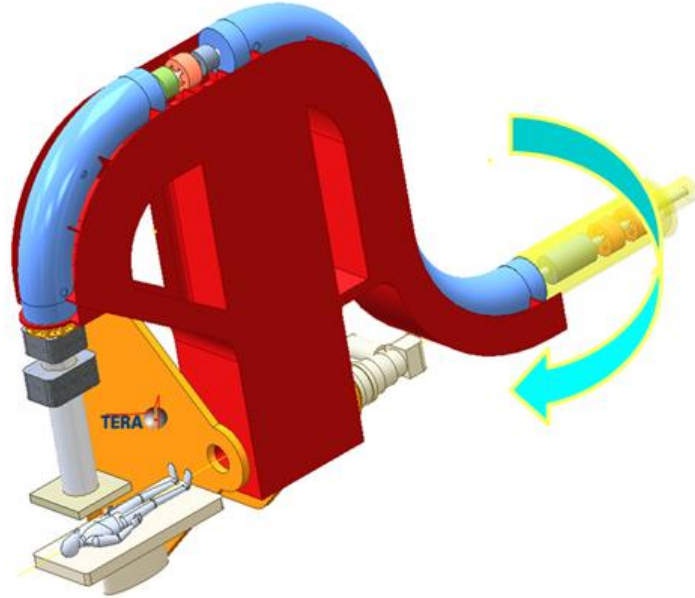
Also a research on high
current HTS Nuclotron
cable led by GSI



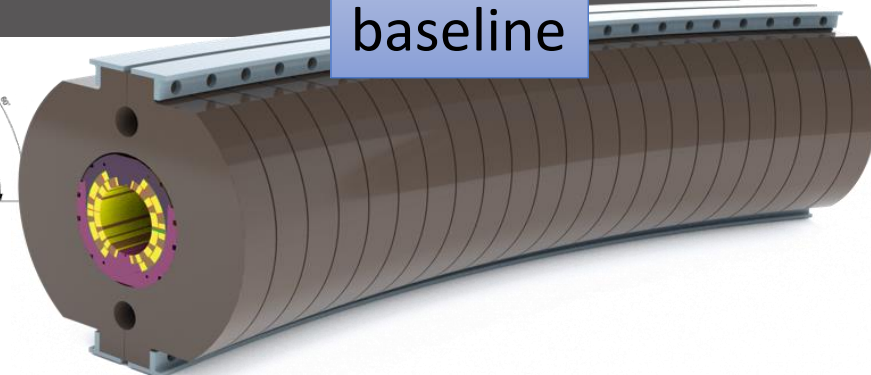
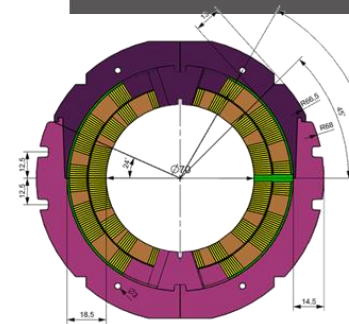
Members	Person-months	EC funding	Institute matching funds	TOTAL Funds
CEA	10	42,188	76,705	118,892
CERN	11	190,153	345,732	535,884
Wigner RCP	24	24,638	44,795	69,433
INFN	14	112,613	204,750	317,363
CIEMAT	12	26,438	48,068	74,506
UU	5	31,500	57,273	88,773
PSI	6	28,688	52,159	80,847
BNG	10	64,313	116,932	181,244
Scanditronix	10	59,938	108,977	168,915
Elytt	15	59,938	108,977	168,915
Sigmaphi	15	59,938	108,977	168,915
Grand Total	132	700,340	1,273,345	1,973,685

CERN is Project Coordinator
INFN is the WP8 – Magnet Coordinator (CEA is the deputy)
START: 1 May 2021

SIGRUM light rotatable Gantry: CERN-NIMMS-TERA Maybe a second generation in HTS after IFAST?



REBCO round flexible cables



The EU roadmap for enabling a full SC C-ion facility: synchrotron + gantry (with HTS)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
CERN-CNAO-INFN-MedAustron collab. for Gantry													
SEEIIST									this timeline is personal opinion				
Basic R&D: H2020-HITRI+ and I.FAST R&D for HTS in new HE			LTS										
			HTS										
			HTS			?	?	?	?	?	?		
	Conceptual study		Proto & Design		Construction		Installation & Commissioning						

Disclaimer: roadmap to be reviewed with stakeholders

Thanks!

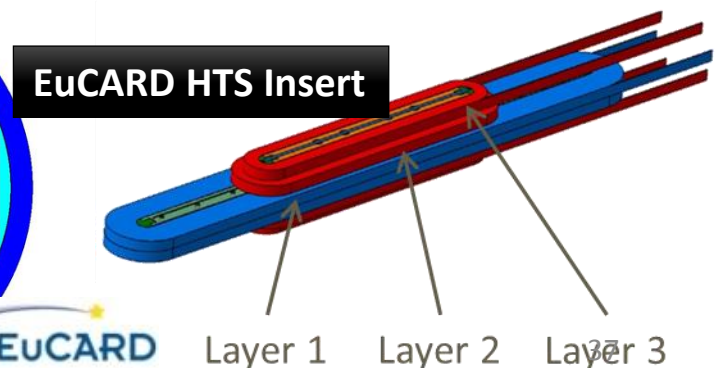
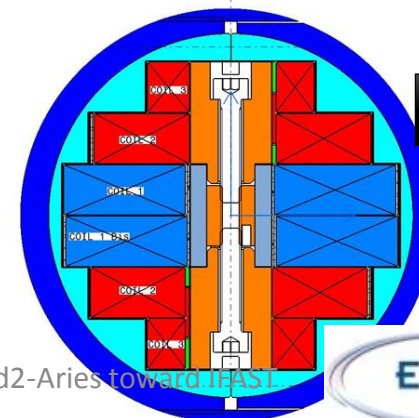
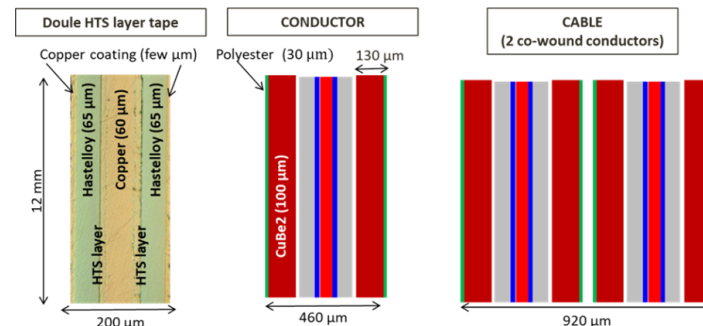
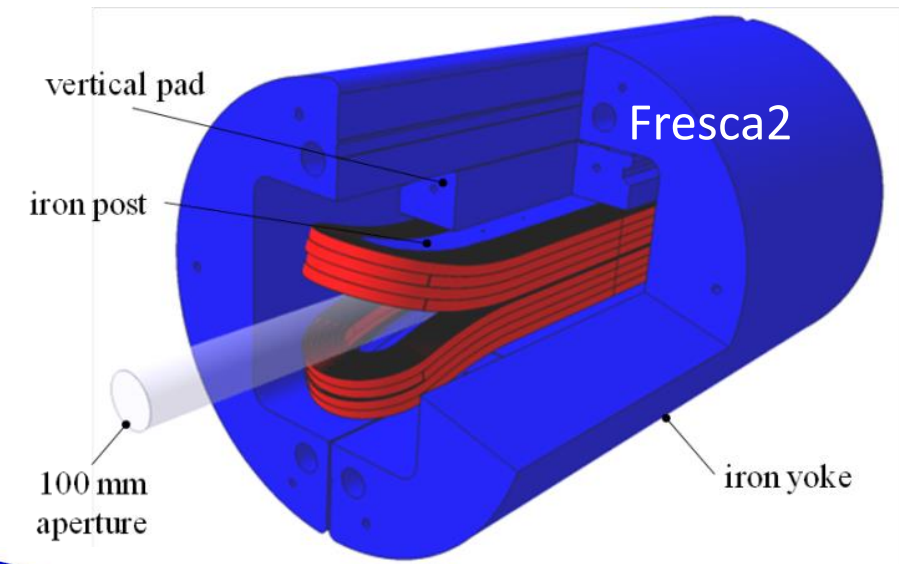
Spares

Situation in 2011-12

- Forming the EU strategy aiming at 80-100 km VLHC, then FCC.
- Dipoles of 15-16 T, ultimate 20T
- Noticing the activity in USA (stimulus program, NHMFL/ASC Bi-2212 performance jump)
- Decision to use EuCARD2 (2013-2017) to **explore accelerator quality HTS.**
- Application aimed at Bi-2212 Rutherford, but open to consider also YBCO based conductor(s)

- FP7 EuCARD – WP7 technology R&D 2008-2013

- FRESCA2 dipole
13 T, \varnothing 100 mm facility
Tested in July 2017: **13 T!**
- HTS insert + 6 T (no bore)
Tested in July 2017: **4.52 T @4.2K** (power supply limit, no quench)



Conductor procured by CERN

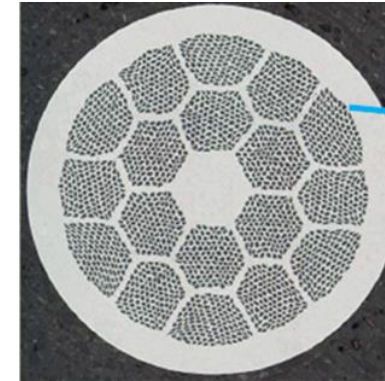
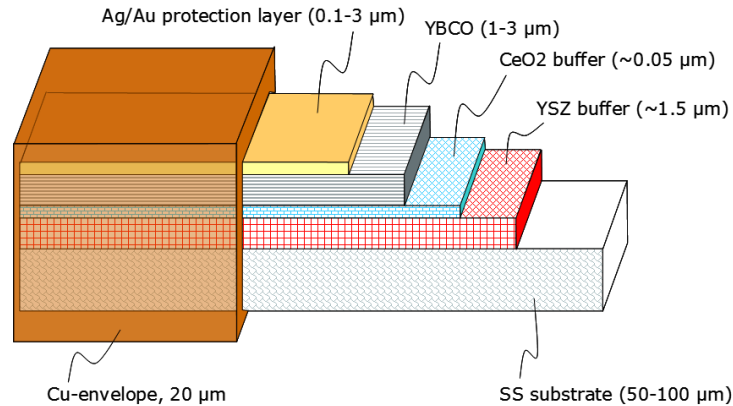
Magnet designed and manufactured by CEA

Rossi - HTS magnet from Eucard2-Aries toward IPST

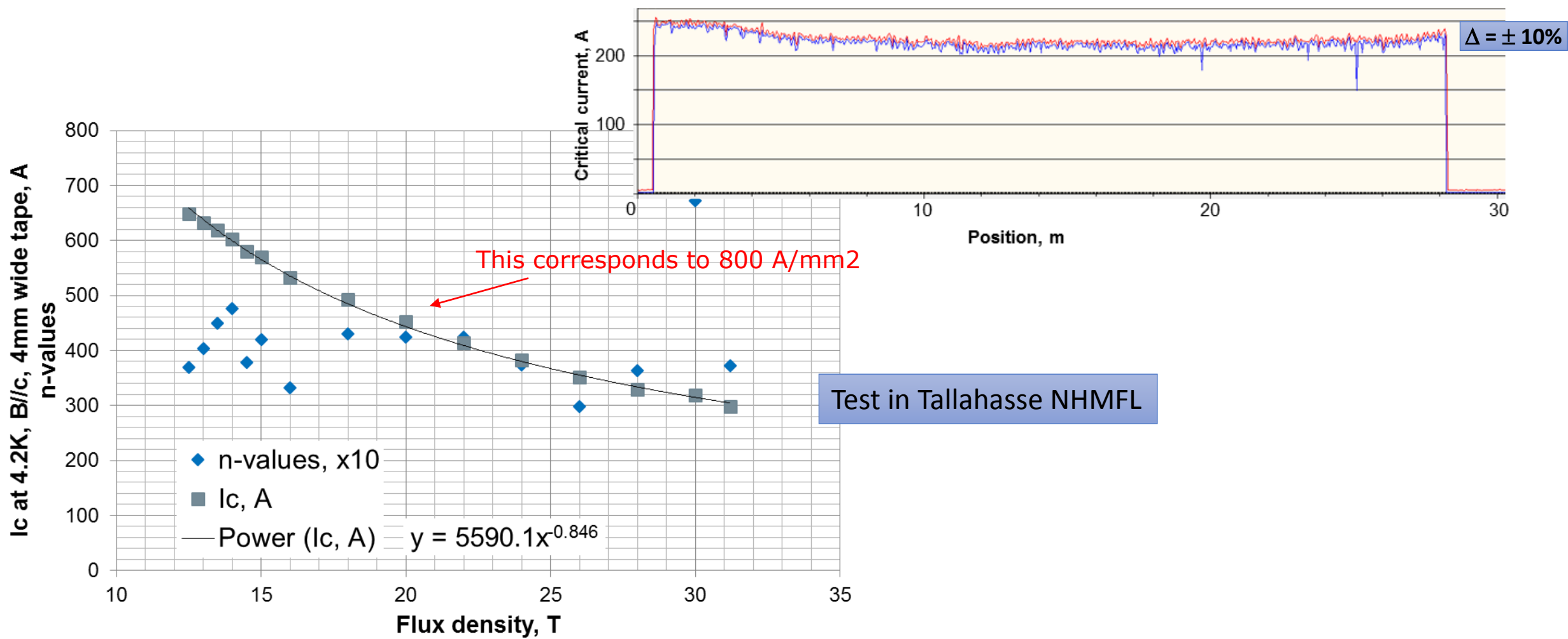


20 April 2021

Choice of Superconductor: REBCO



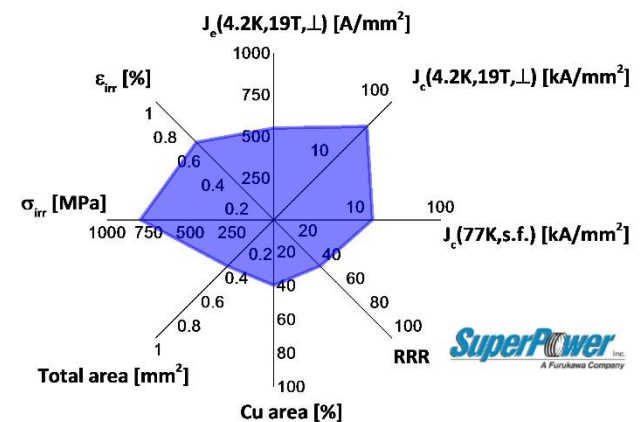
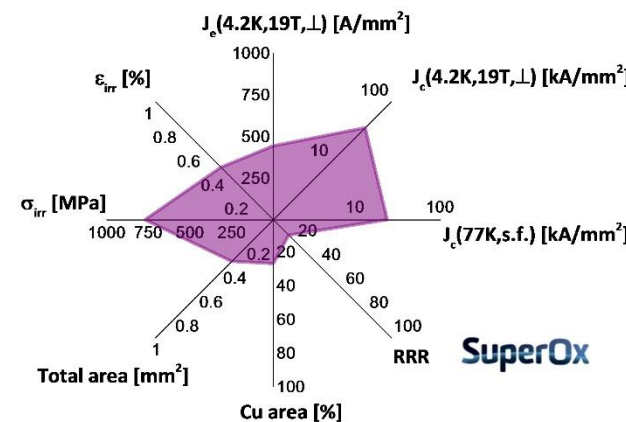
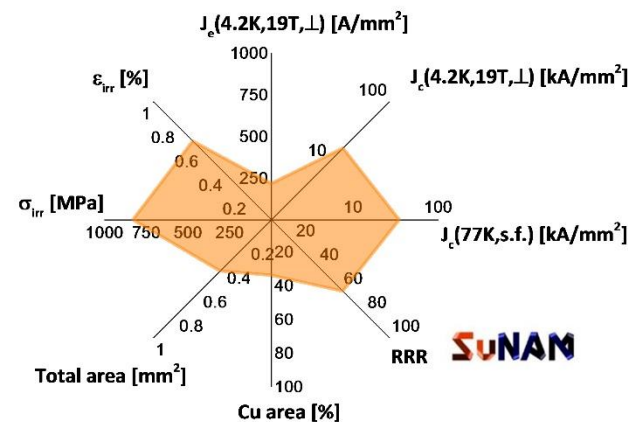
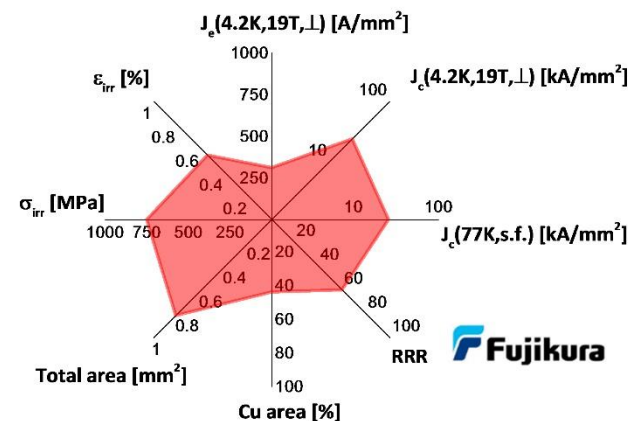
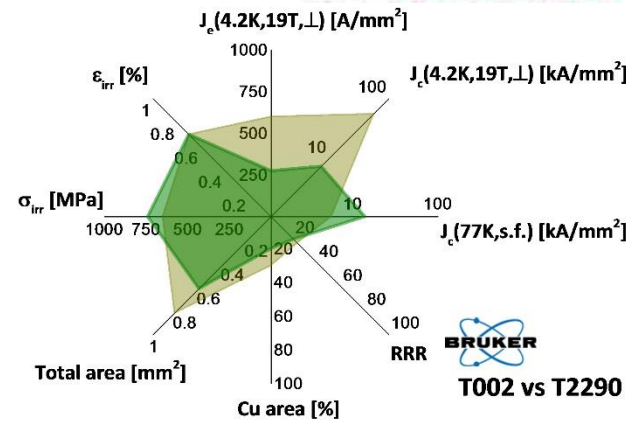
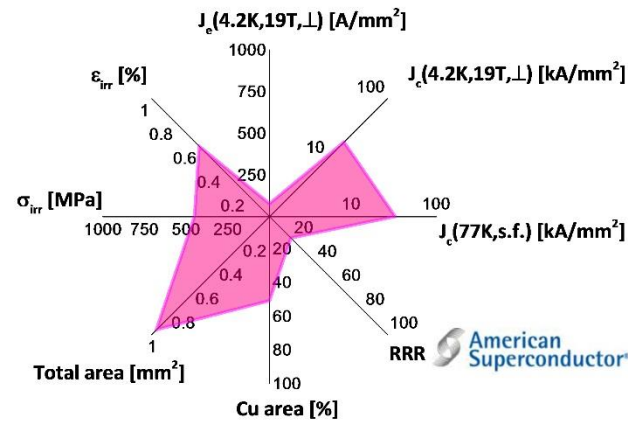
REBCO	characteristics	Bi-2212
High, steadily improving	Critical current	High, more stagnant
Roebel cable (waste), ready to use, 50-200 m unit length	Cabling and general	Easy Rutherford cable, but need special H.T., very long length possible
Very bad (tape).	Magnetization	Worst than NbSn but manageable
Excellent, better than Nb ₃ Sn	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



We procured and tested tapes from various suppliers



C. Senatore



Roebel cable - cont.

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



A. Usoskin, A. Rutt

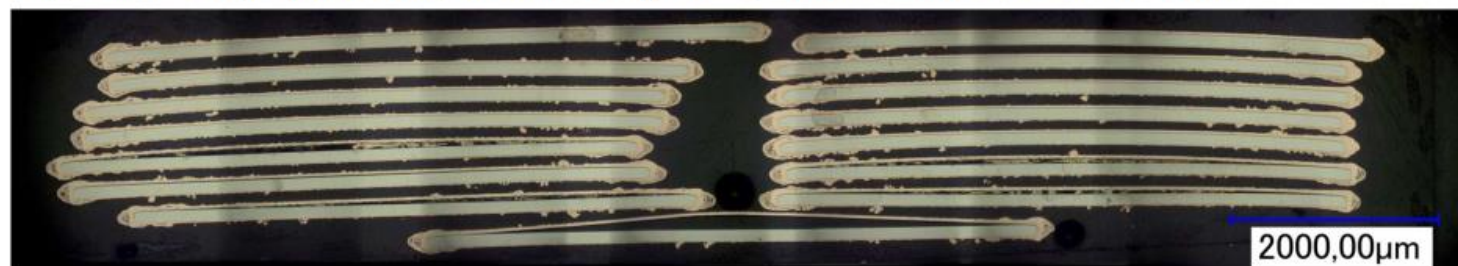
Cu plated tape punched, strands assembled into cable.



Examples of delamination



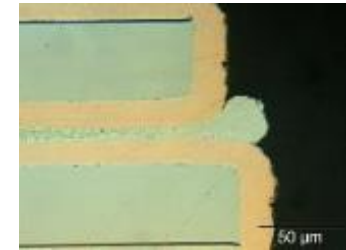
Ag coated tape punched, strands Cu plated, strands assembled into cable.



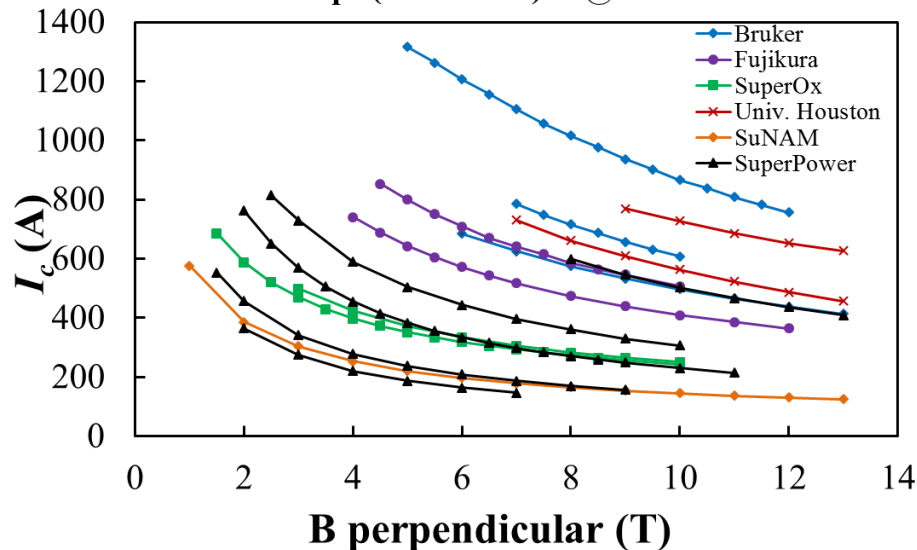
Conductor characterization at CERN (MSC-SCD)

- Elaboration of $J_c(B, T, \theta)$ 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)

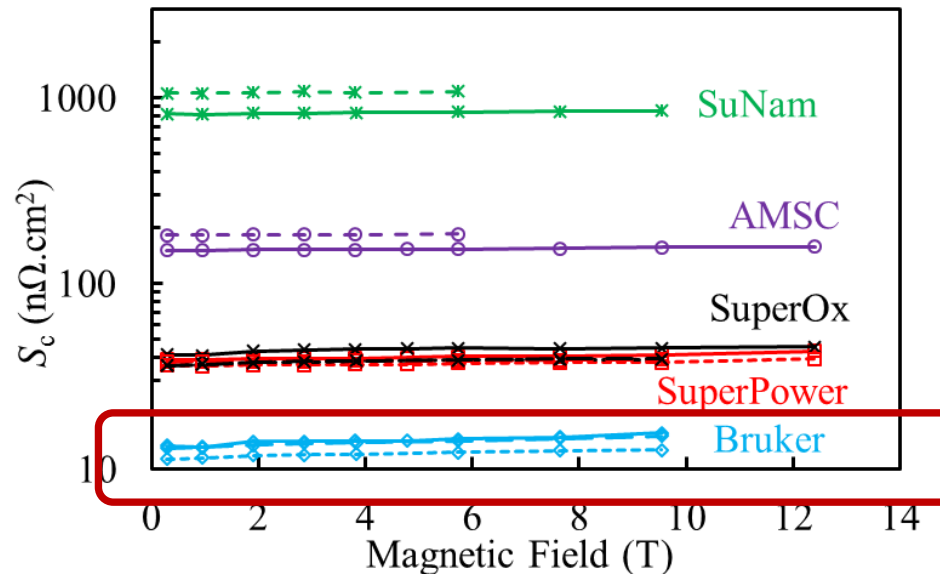
J. Fleiter



Tape (4 mm wide) I_c @4.2 K



20 April 2021



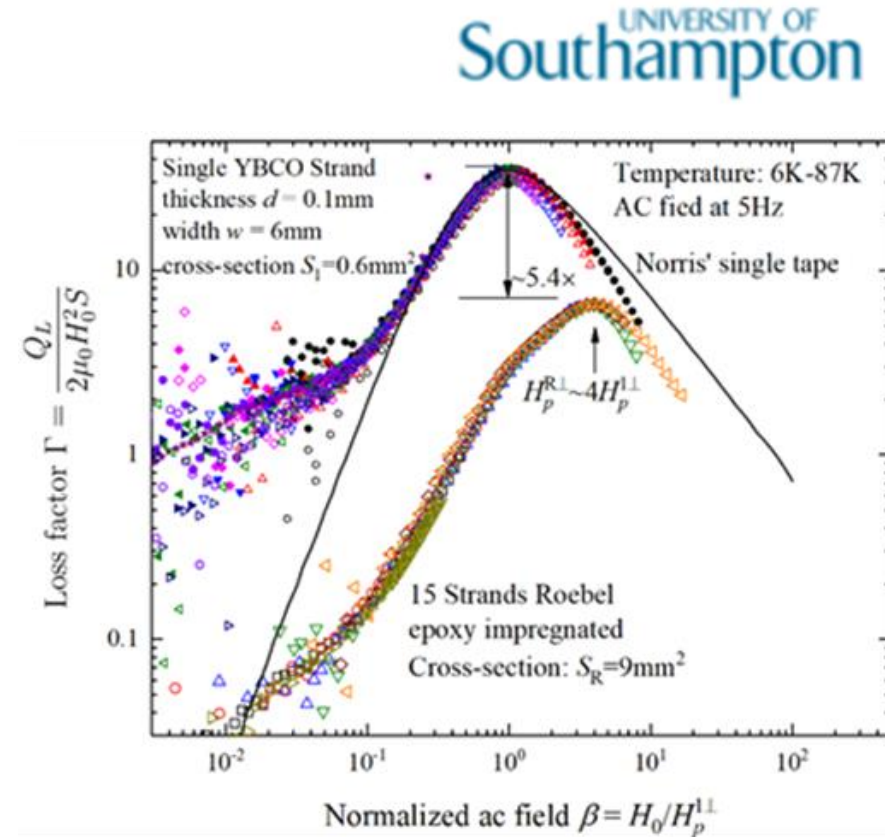
Rossi - HTS magnet from Eucard2-Aries toward IFAST

Geometrical rules for Roebel; stacking factor important



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.



Achievements (closing on 31 April 2017)

L. Bottura, CERN

Tape

parameter	units	target
J_E (20 T, 4.2 K)	(A/mm ²)	600
σ (I_C) within a unit length	(%)	10
M (1.5 T, 10 mT/s)	(mT)	300
Range of $\sigma_{\text{transverse}}$	(MPa)	100
Range of $\varepsilon_{\text{longitudinal}}$	(%)	± 0.3
Unit length	(m)	100

Cable

parameter	units	target
I_C (20T, 4.2 K)	(kA)	10
Width	(mm)	12 ± 0.1
Thickness	(mm)	1.0 ± 0.1
Effective contact resistance	($\mu\Omega$)	5

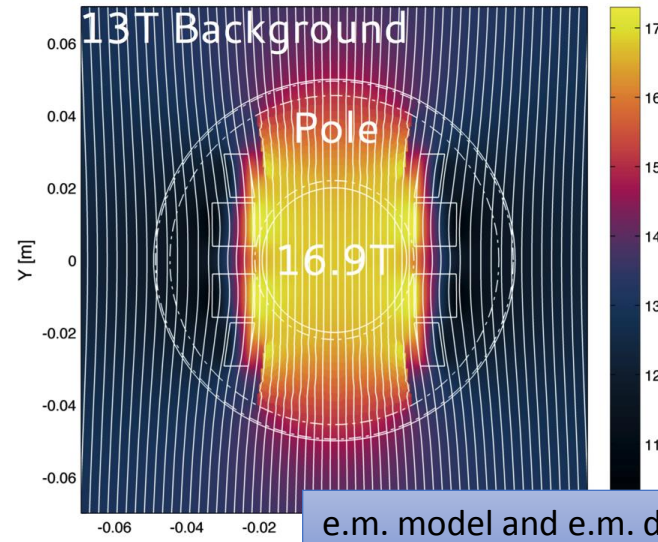
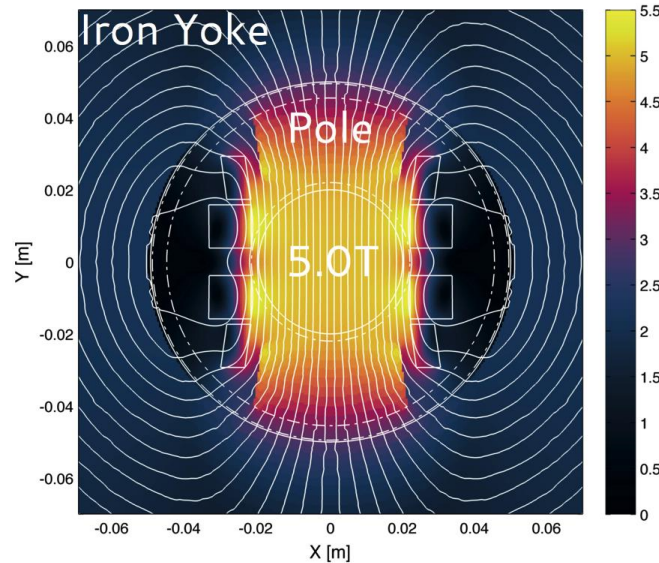
 EuCARD²

20 April 2021

Plus direct order form CERN (about 500 k€) doubling the Eucard financing to BHTS and other purchase

Rossi - HTS magnet from Eucard2-Aries toward IFAST

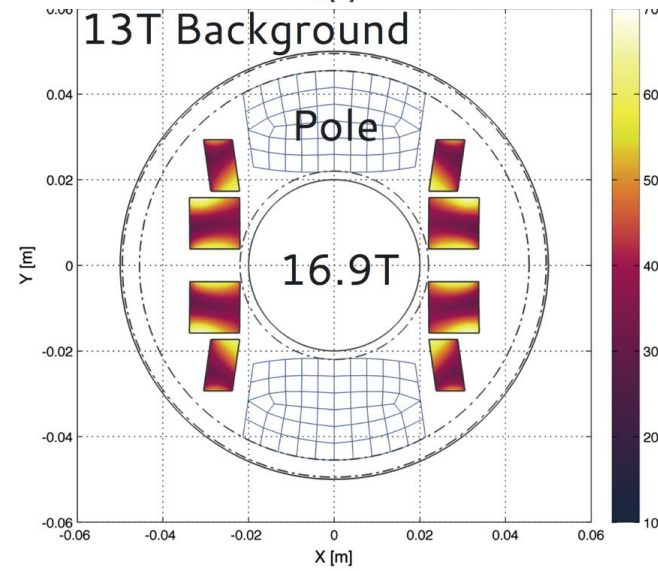
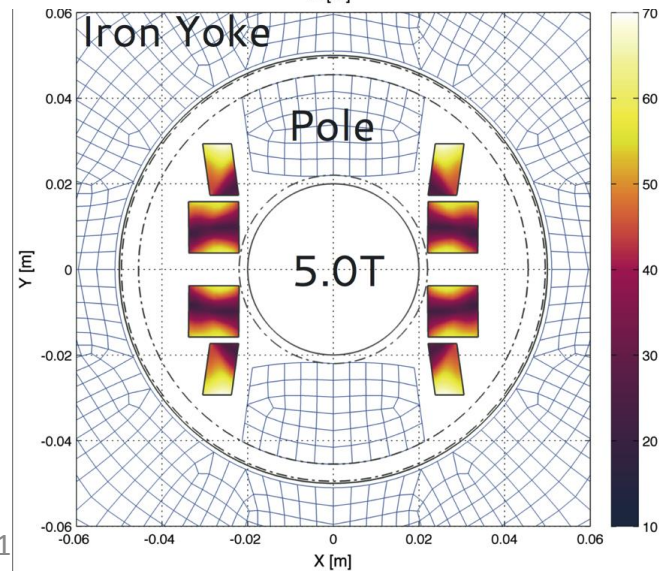
Aligned Block lay-out by J. van Nugteren



Magnetic Field [T]

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



Percentage on Loadline [%]

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

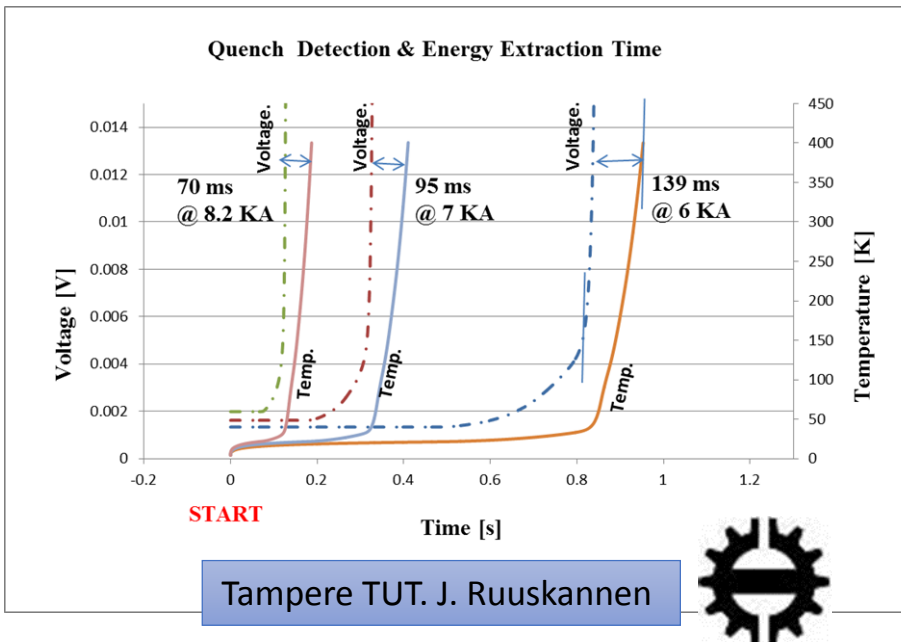
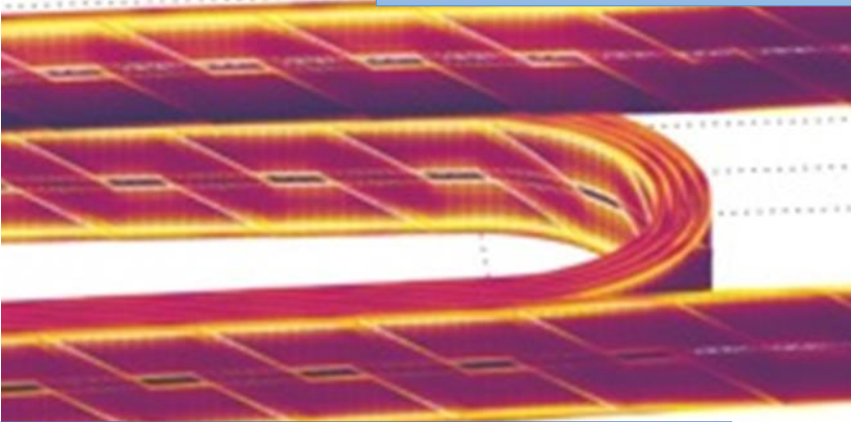
Magnet technology issues... design & protection issues...



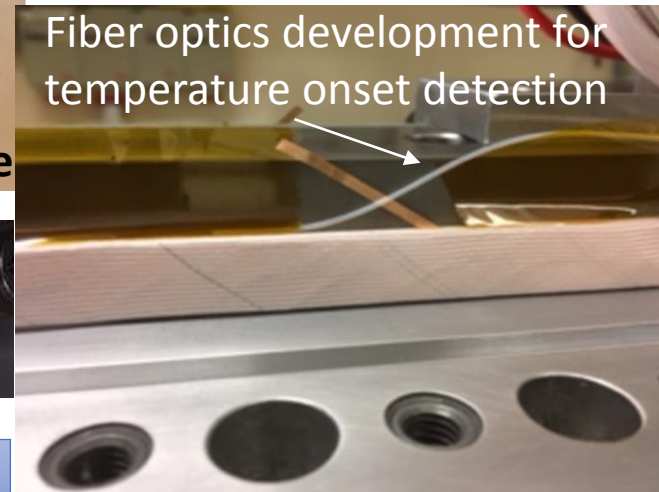
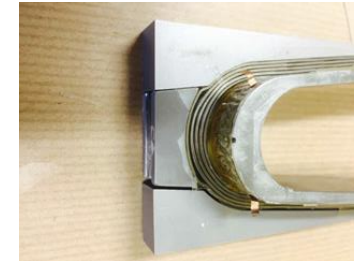
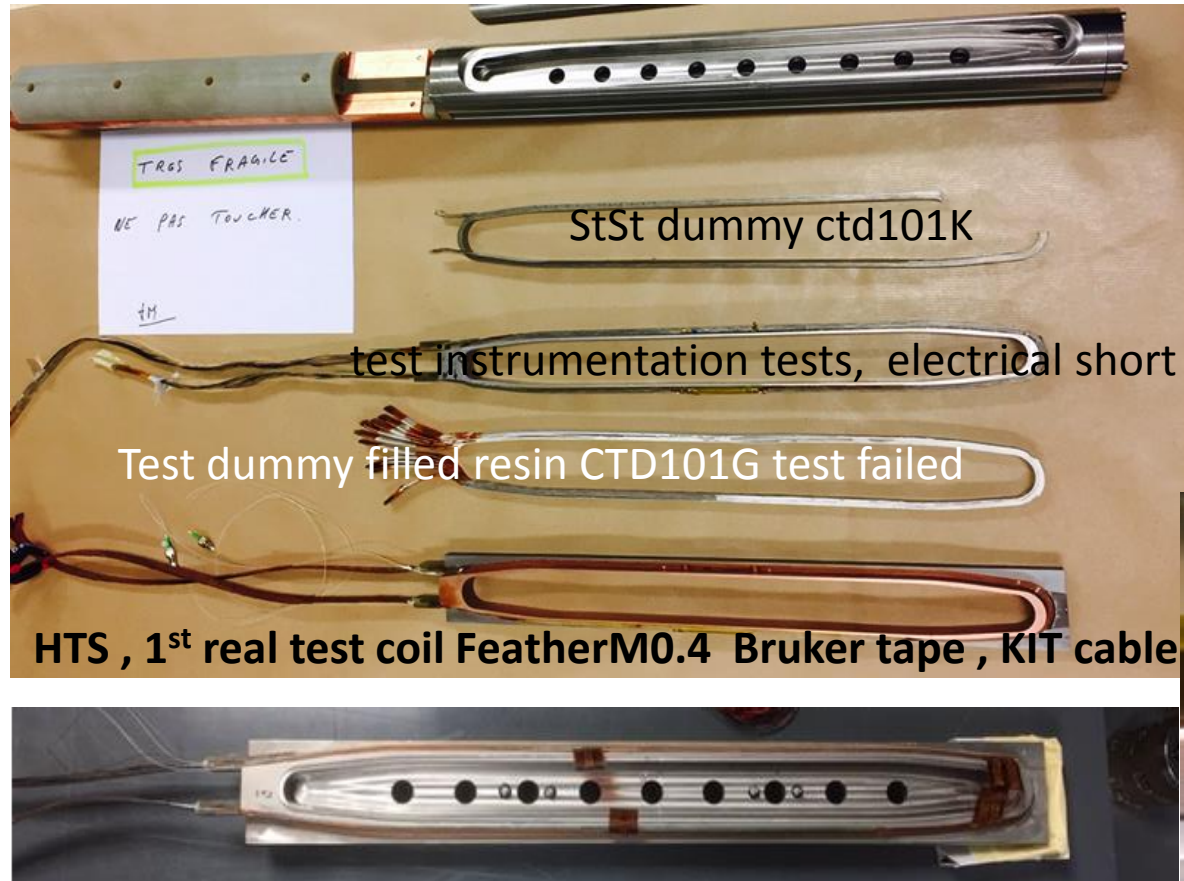
**Winding (un)stability : small tension
Impregnation → delamination**

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

Current redistribution

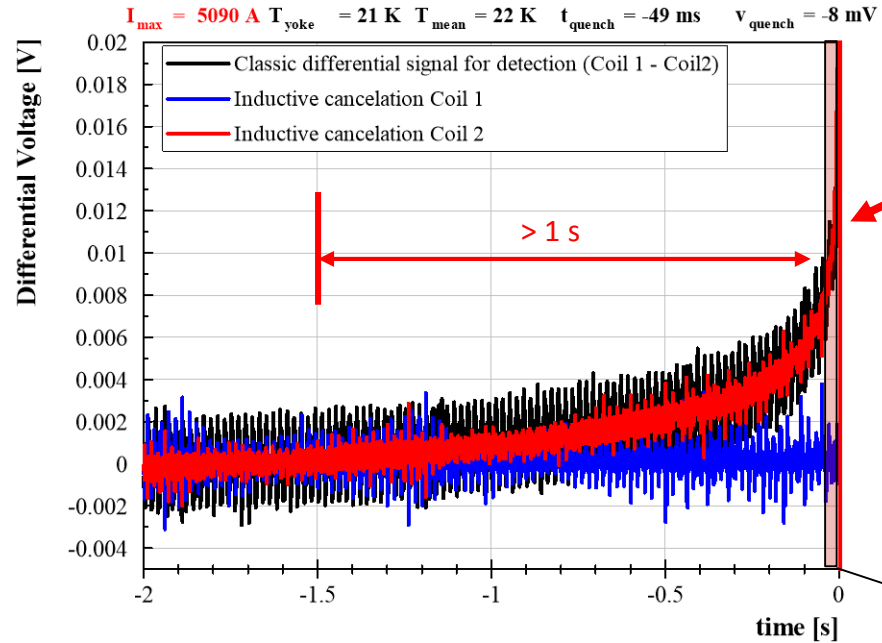


F_M0.1,2,3,4



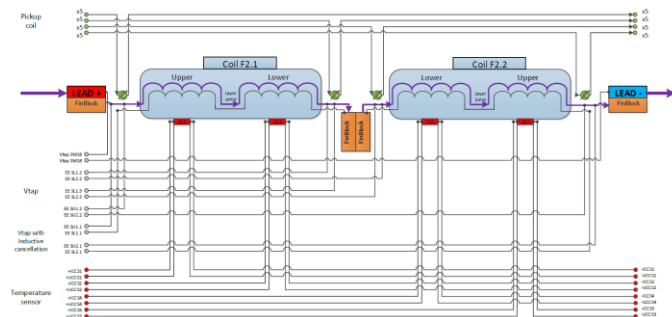
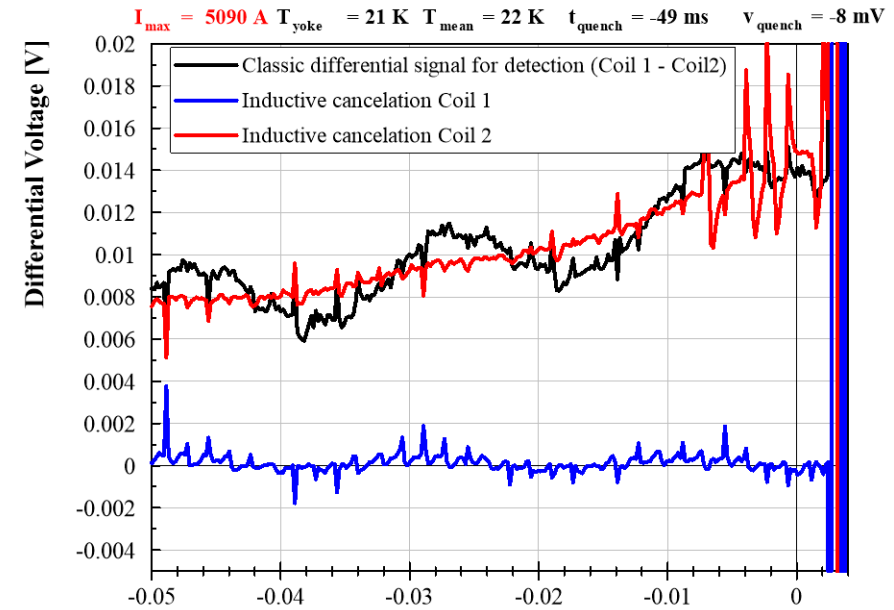
G. Kirby, CERN

Low resolution high frequency acquisition

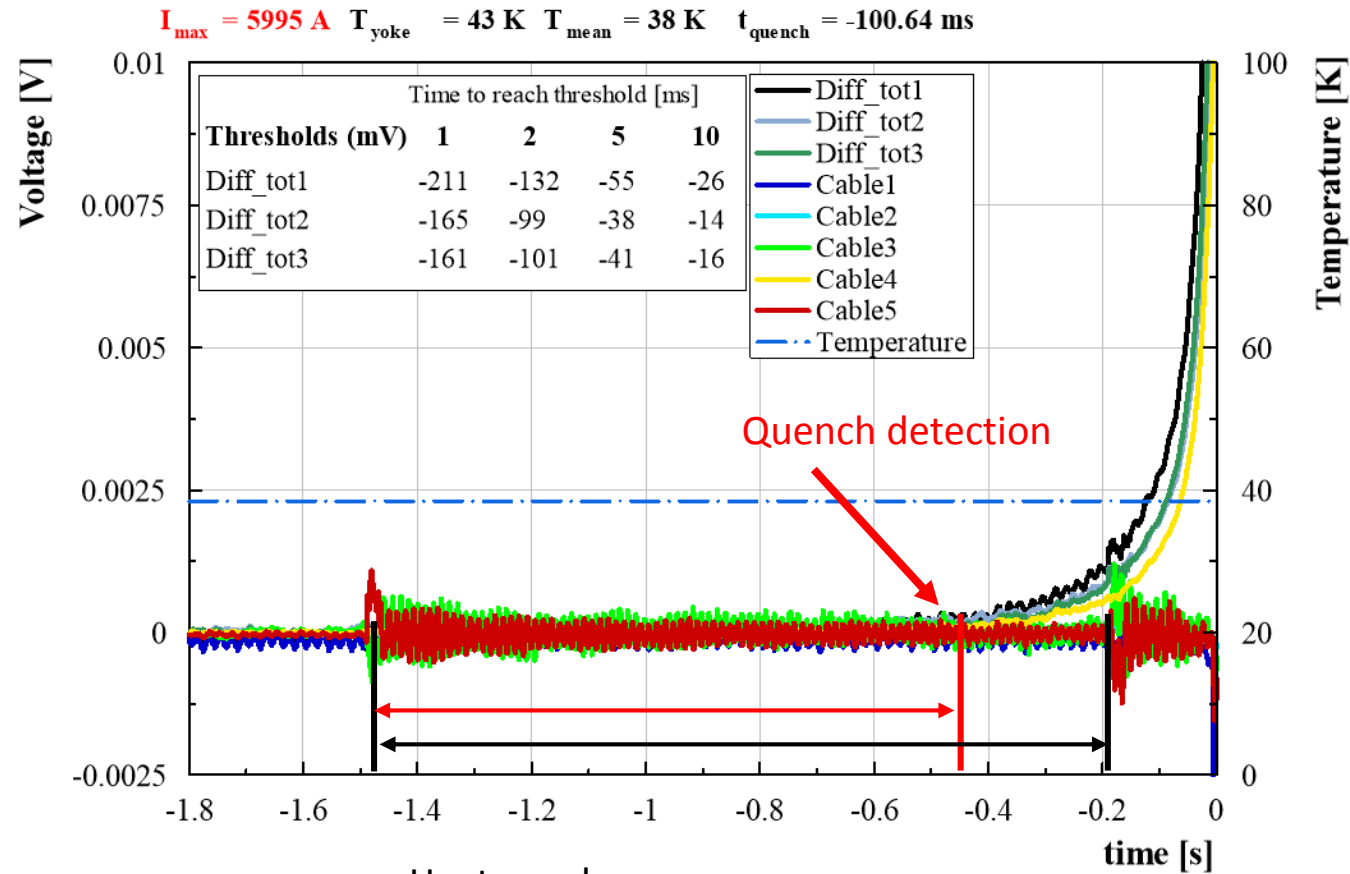


Quench detection

Zoom of the last 50 ms
Protection 10 mV, 20 ms

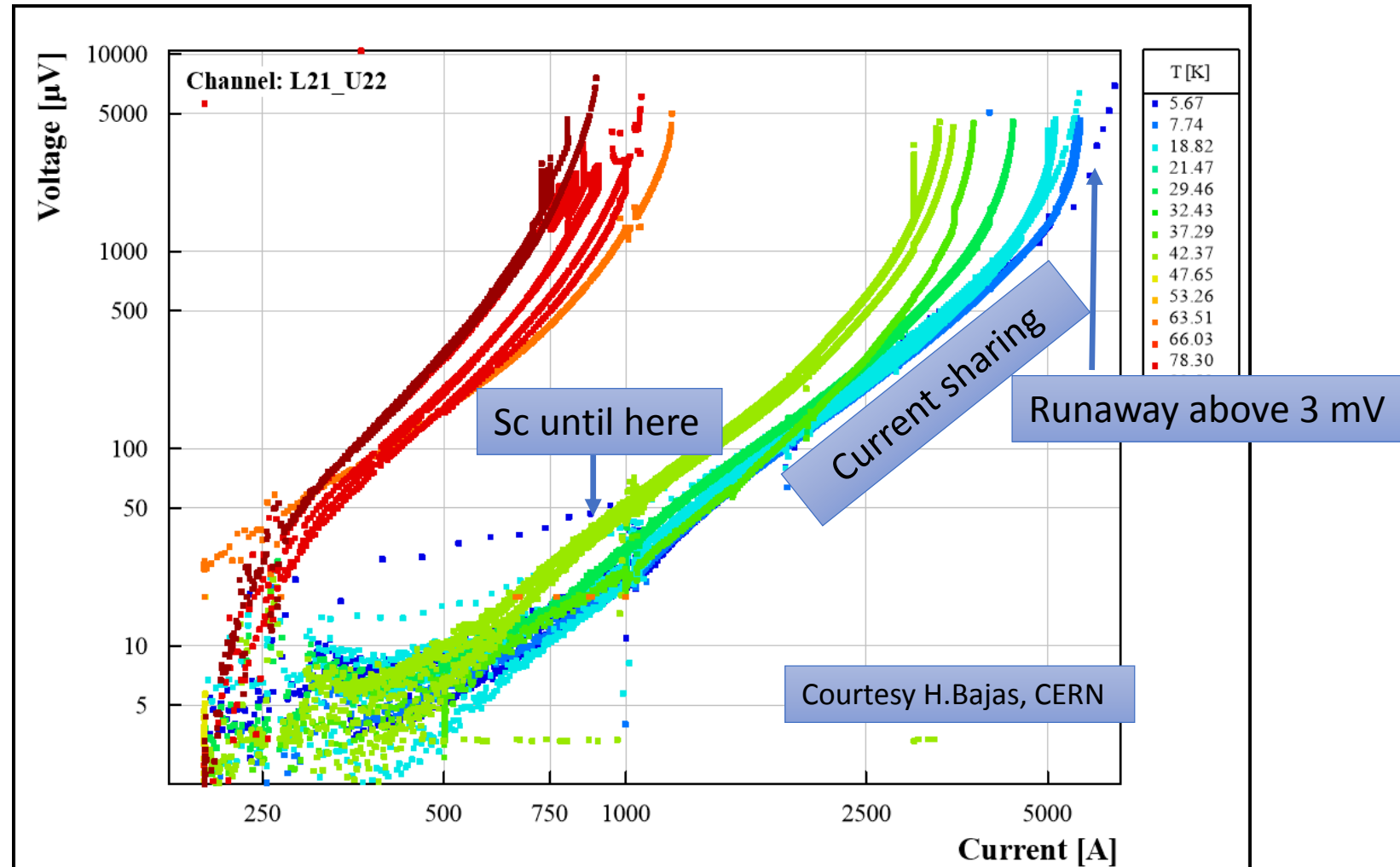


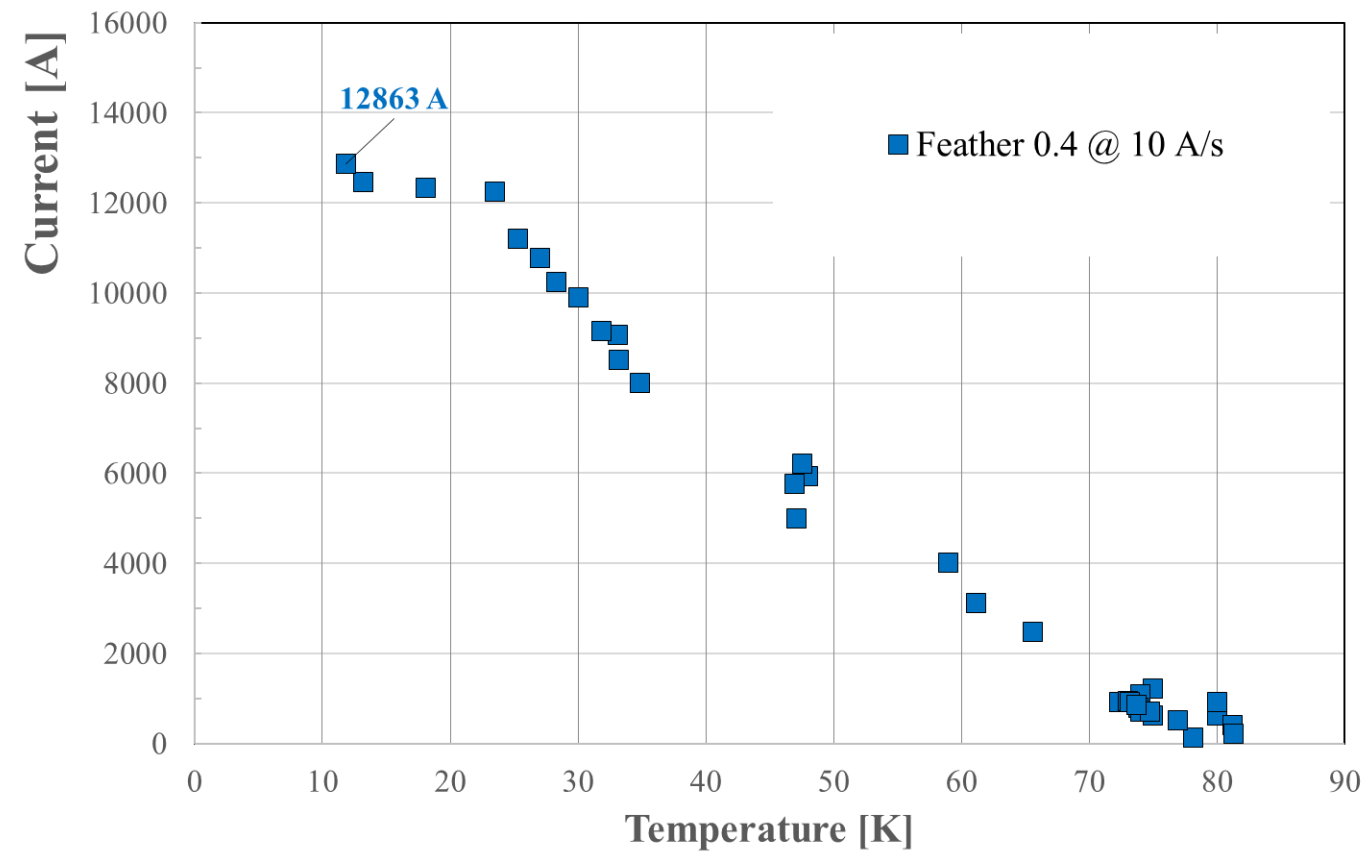
Soft transition and easy detection: FeatherM0.4 coil

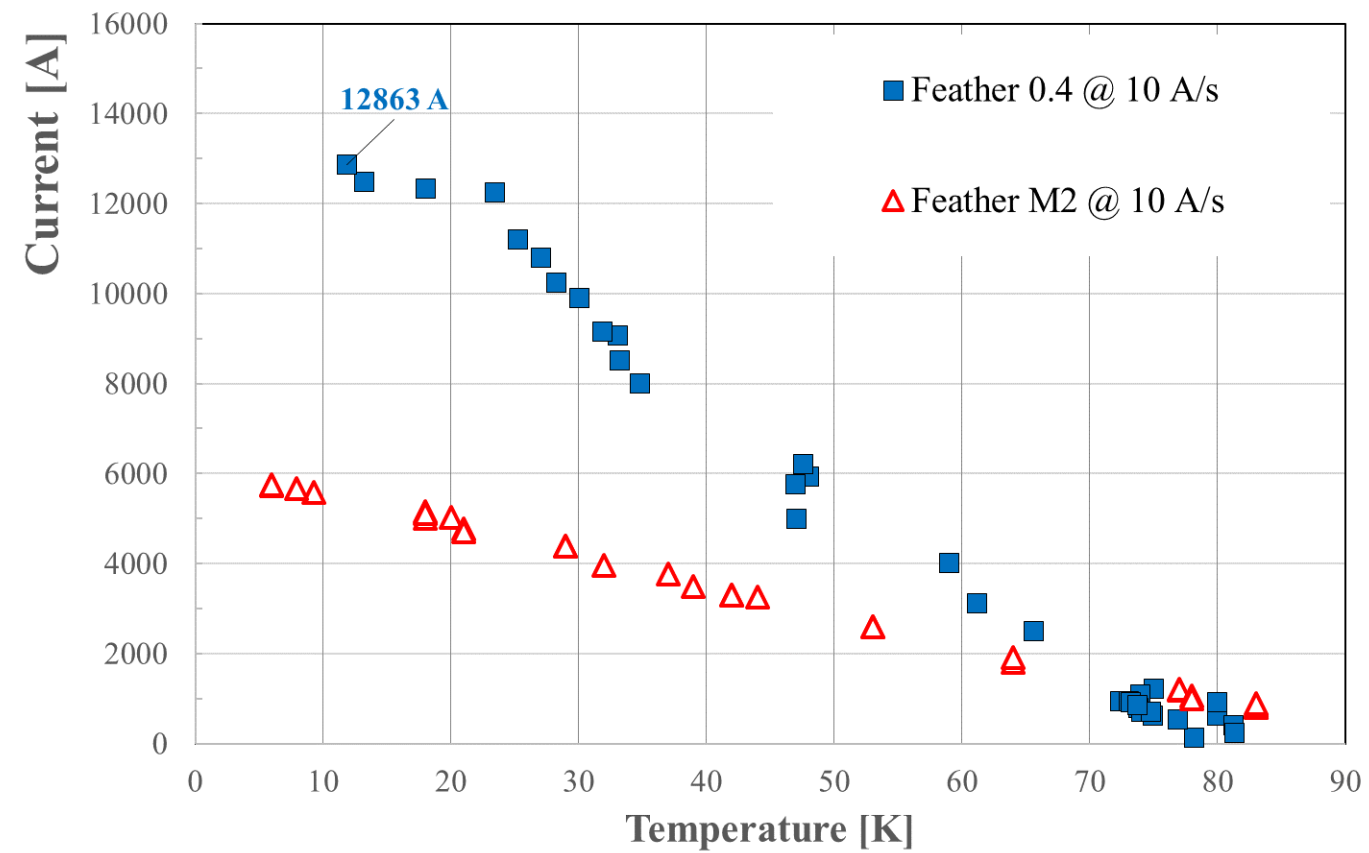


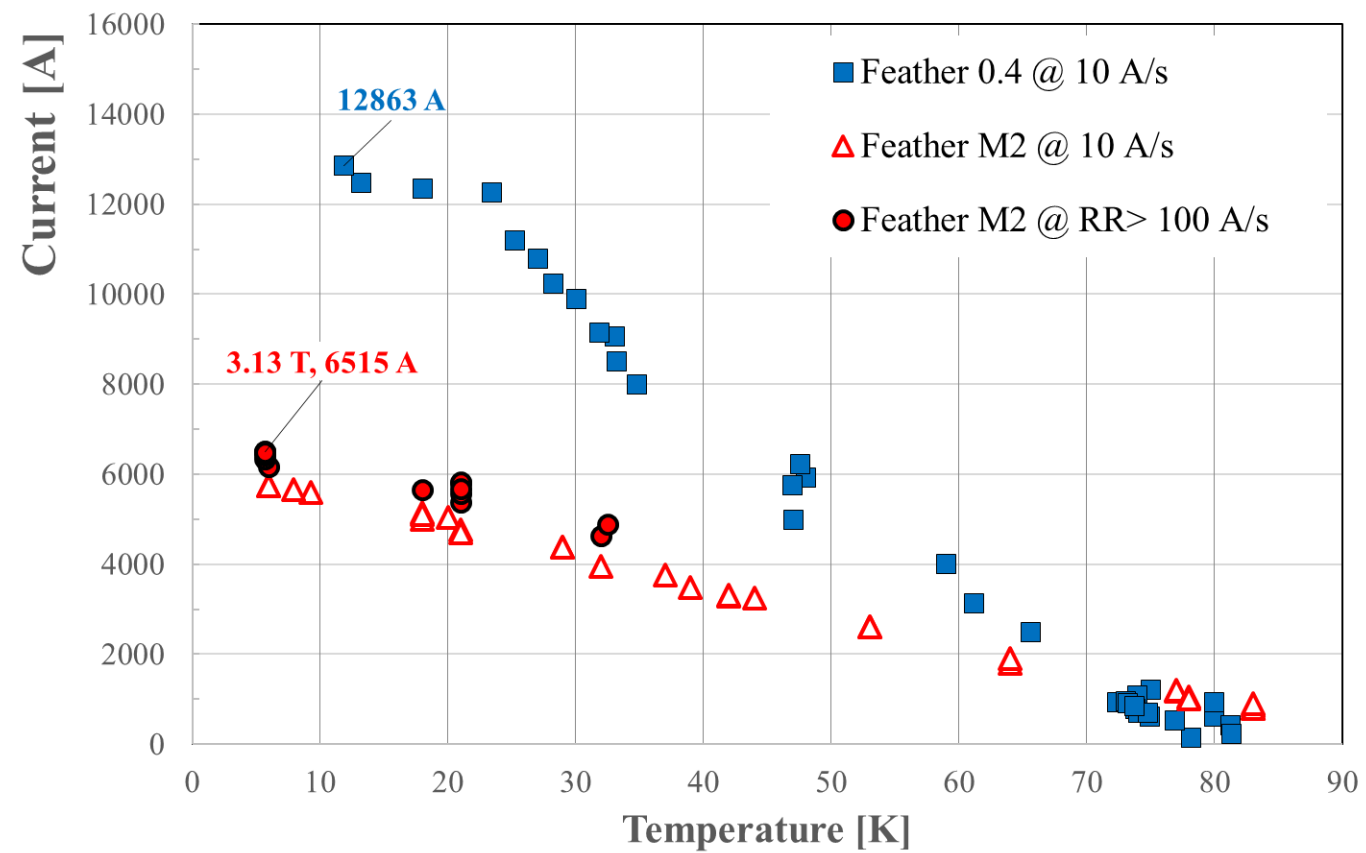
Stability is huge:
hundred of Joules to quench

FeatherM2.1-2

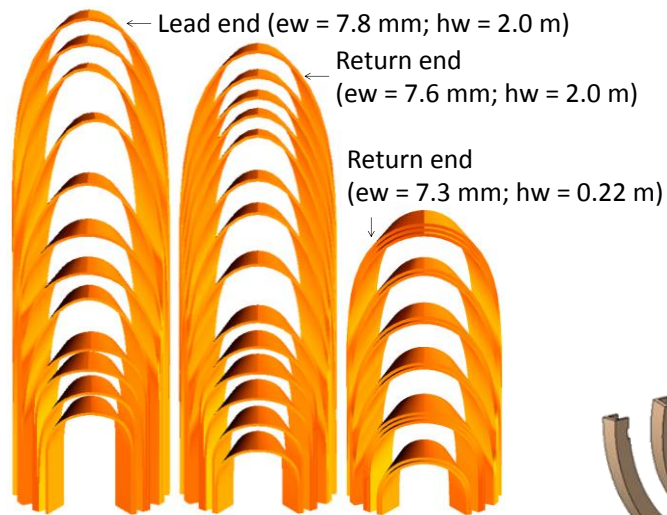








Not so easy but almost ready to wind (Nov 2018)



Courtesy of C. Lorin

