EuCARD2 Magnet Objectives and Main Challenges

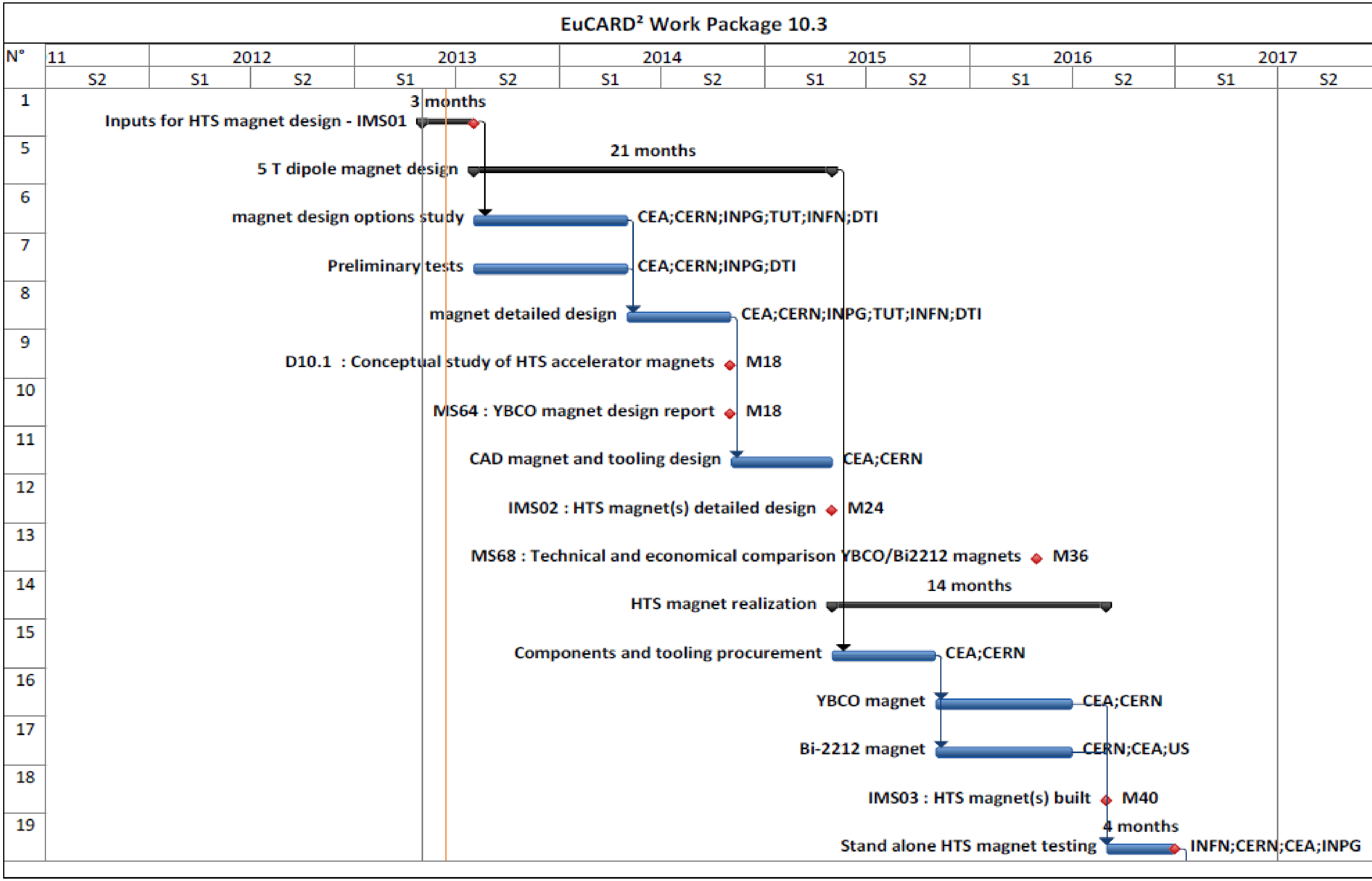
First Workshop on Accelerator Magnets in HTS (WAMHTS-1)
21/05/2014

Maria DURANTE, Glyn KIRBY
In behalf of EuCARD2 Task 10.3 members

Task 10.3 contributions

Institute	CEA	CERN	INPG	TUT	DTI	INFN
	Maria Durante Clément Lorin	Glyn Kirby Jeroen van Nugteren Nabil Chouika	Pascal Tixador Arnaud Badel John Himbele	Antti Stenvall Erkki Härö	Nikolaj Zangenberg	Giovanni Volpini Massimo Sorbi
Activities	Design and construction of YBCO made coil, development of proper technology Participation to design of Bi-2212 coil	Design and support to construction of the YBCO Design and construction of Bi-2212 coil in the collaboration with USA, development of proper technologies System for magnetic measurement evaluation	Design of HTS coils Analysis of e.m. behavior Development of technology (small coils for investigation, tests under high fields)	Modeling of HTS coils both YBCO and Bi-2212 Quench analysis and protection evaluation	Development of insulation technology for YBCO conductor Fabrication and test of samples and then of all tapes/cables Study of extension to Bi-2212	Quench computation Link to test boundary conditions

Task 10.3 SCHEDULE



Magnet specifications

	Parameter name	Symbol	Value YBCO Magnet	Value Bi-2212 Magnet	Remarks
MAGNET	**Central field**	B_0	**5 T**	Up to 5	at 4.2 K (20% margin on loadline)
	Clear bore aperture	Φ_b	**40 mm**	40	High energy LHC dipole magnet (beam size 25-28 mm)
	Operational temperature	T	4.2 K	4.2	1.9 K also possible 77 K tests during magnet realization
	Current at 20 T	I	**5 to 10 kA**	5 to 10	
	Stray magnetic field	B_{out}	≤ 0.2 T		At border of cryostat
	Magnetic multipoles at 2/3 Φ_b	b_n	$5\ 10^{-4}$	-	Geometric
	Magnetic multipoles at 2/3 Φ_b	b_n	$30\ 10^{-4}$	-	Including magnetization and persistent current (best effort)
	Magnetization	M	300 mT	300	Allowing fast ramping up
	Straight section length	L	≥200 mm	≥200	As short as possible while remaining compatible with field quality for YBCO
	Magnet length	L_M	< 1500 mm		700 mm uniform field (Fresca2) Grenoble test facility
	Magnet outer diameter	Φ_M	**< 99 mm (∅) < 140 mm x 90 mm (rect)**		Without yoke – Outsert candidates : FRESCA2 (100 mm) or EDIPO (143 mm x 93 mm)
CONDUCTOR	Engineering critical current density (20T, 4.2K)	$J_{E,\ 20T}$	600 A/mm²		In strand/tape at field perpendicular to wide face
	Available cable Engineering critical current density (20T, 4.2 K)	$J_{E,\ 20T}$	400 A/mm²		For small development magnets
	Bare cable width	w_{cbl}	10-12 mm	10-15	Provisional
	Bare cable thickness at 50 MPa	t_{cbl}	0.8-1.2 mm	1.5-2.0	Provisional

YBCO Conductor

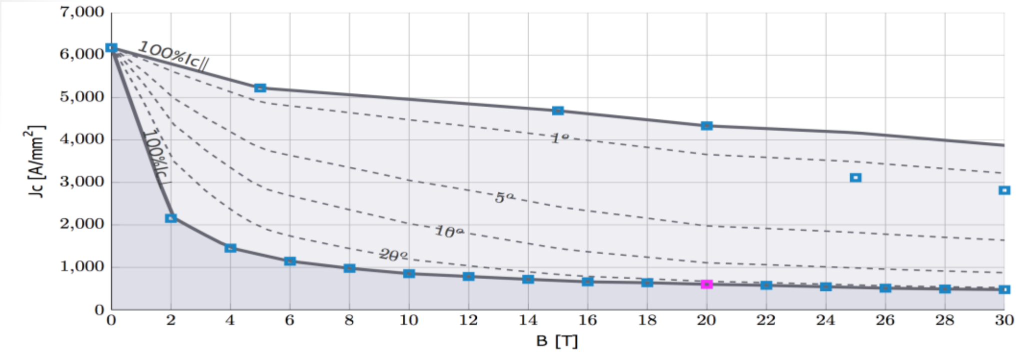
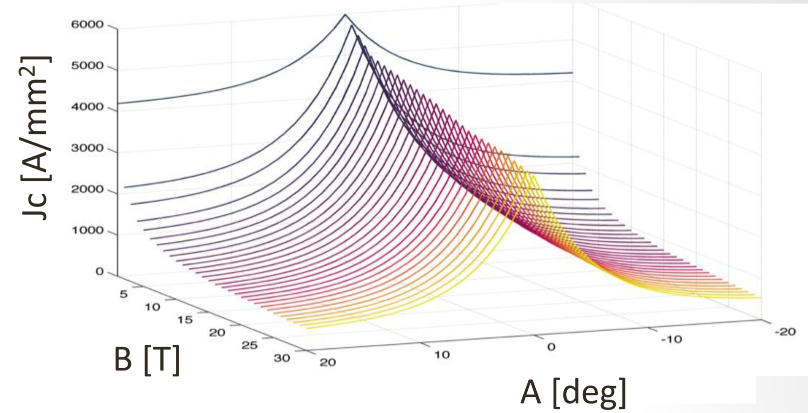


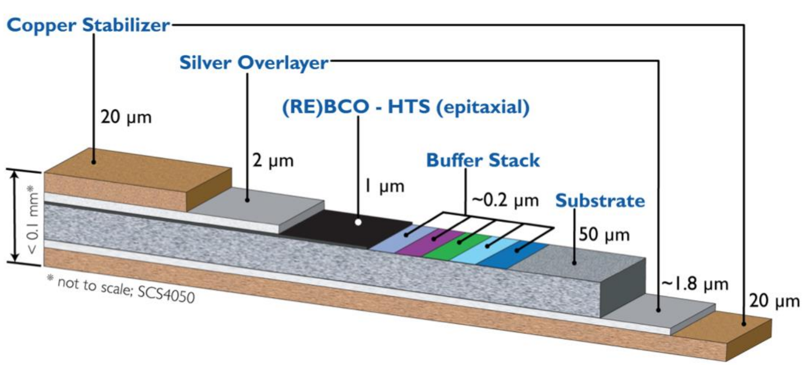
Figure 2.3: JcB plot of the used critical surface for YBCO. Also see Figure 2.2. The original experimental data on which the interpolation is based is also shown.

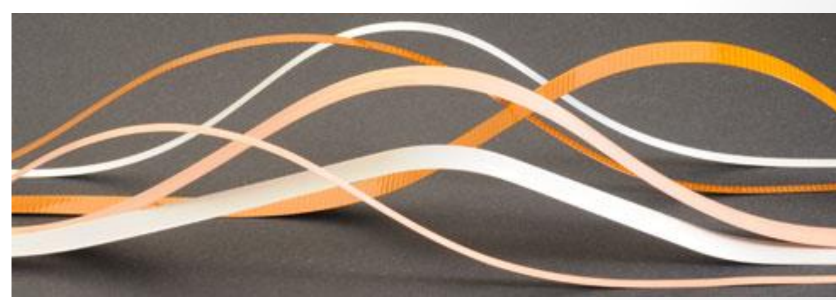
1.5 x NHFML measured data.



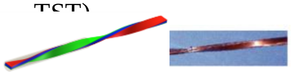
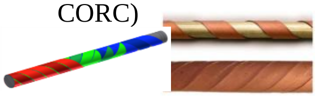
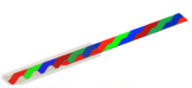
1.5 x BNL measured data

- Critical current is highly anisotropic
  - Strongly dependent on the orientation of the tapes in the applied magnetic field
  - Factor of ~5 difference between perpendicular and parallel field
  - Effect becomes stronger at high magnetic fields



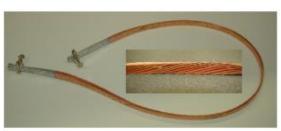


Review of YBCO cable configurations

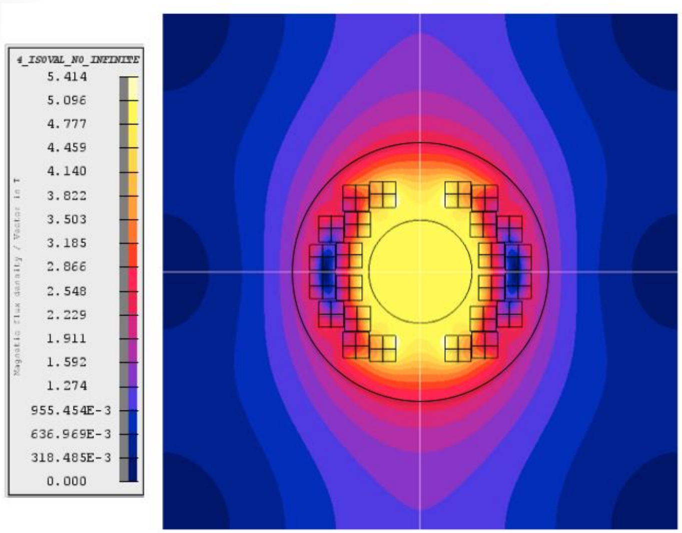
Cable concept	I_{op} (kA)	J_E (A/mm^2)	J_E^{max} (A/mm^2)	$\sigma_{transverse}$ (MPa)	$\varepsilon_{longitudinal}$ (%)	Comments
Tape stacks	5		≈ 600	As for tape		Not transposed
Twisted stacked-tape (TSTT) 	**3 (4.2 K, 12 T)** **4 (4.2 K, 19.7 T)** 8…100 (4.2 K, 16 T)	273 (4.2 K, 16 T)	300…400			Partially transposed; 140 mm bending radius: 3.6% degradation; Sensitive to transverse e.m. loads
Helically twisted stacked-tape (HTST)	 10…20	**100 (4.2 K, 12 T)**	≈ 100	< 30 [1]		Partially transposed; Sensitive to transverse e.m. loads
Cable on Round Core (CORC) 	**5**	**114 (4.2 K, 19 T)**	≈ 150		**+0.8 %**	Transposed; 40 mm bending radius: 2.5% degradation; Core deforms under e.m. load and folds tapes; joint resistance 40-200 nΩ;
Roebel 	**3…10**	**400 (4.2 K, 10 T)**	≈ 500	**> 45** [5]		Transposed e.m. loads are concentrated at cross contact surfaces

Roebel cable

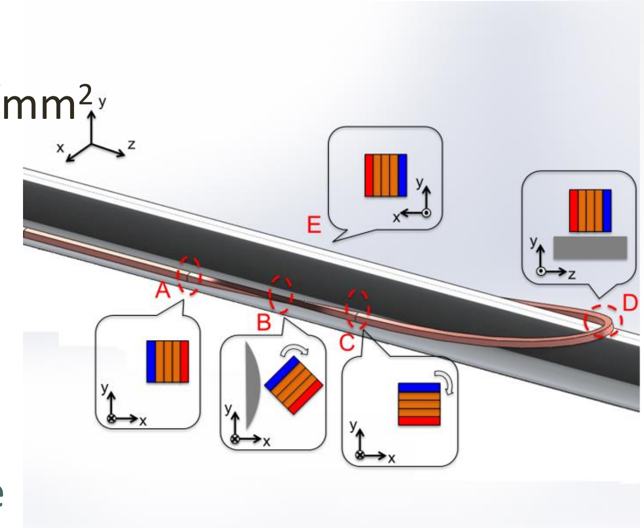
- ✓ Taken as baseline (high JE, high compaction, fully transposed)
- ✓ Old type of cabling (electrical machinery) revisited,
- ✓ Based on punched tapes,
- ✓ Produced by KIT partner of task 2 and New Research Industry –NZ



Design Study – Block with stacked tapes cable



JE = 400 A/mm²



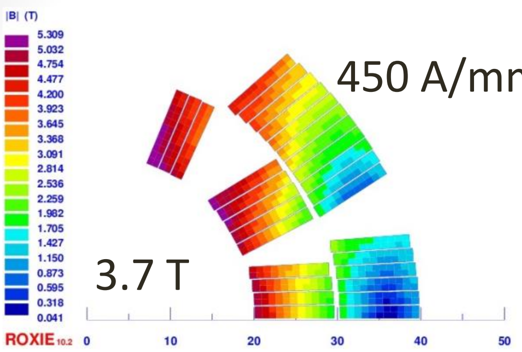
John Himbele

- Non-continuous transposition of the stacked tapes
  → cable transposition at coil ends or between coil layers
- Low cost conductor
- Cable windability : “twist and bend”
- Mechanical strength, twisted regions

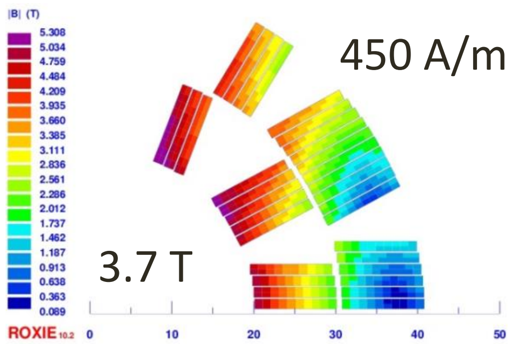
Design Study - Cosine-Theta

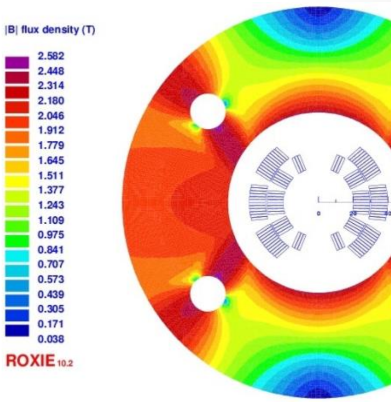
Clément Lorin (CEA)

BSCCO Rutherford cable



YBCO Roebel cable





Iron yoke 5 T

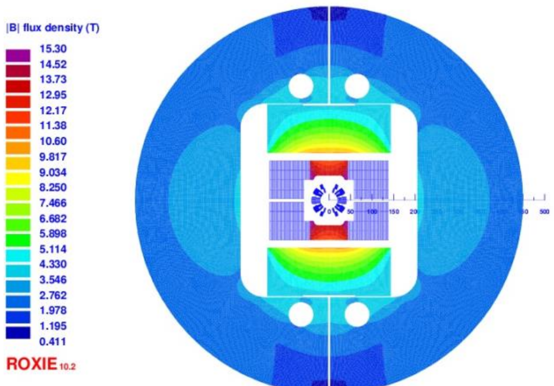
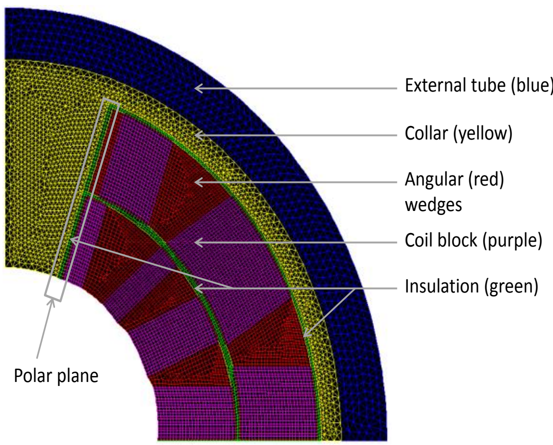


Table X1: Lorentz forces in [kN/m] on coil blocks of the HTS insert in both configurations and for a hypothetical** J_e = 600 A/mm²

HTS magnet inserted in:	the iron yoke	Fresca2	Fresca2 (J_e = 600 A/mm²)**
Block1* (Fx Fy) =	(74, -8)	(328, -8)	(458, -13)
Block2 (Fx Fy) =	(80, -9)	(333, -9)	(467, -16)
Block3 (Fx Fy) =	(45, -7)	(172, -9)	(244, -15)
Block4 (Fx Fy) =	(50, -5)	(176, -5)	(250, -9)
Block5 (Fx Fy) =	(20, -23)	(401, -23)	(525, -40)
Block6 (Fx Fy) =	(86, -74)	(721, -78)	(969, -137)
Block7 (Fx Fy) =	(85, -36)	(401, -38)	(557, -67)
	Fx_{total} = 2x49 tons/m	Fx_{total} = 2x258 tons/m	Fx_{total} = 2x354 tons/m

*Block number (see Fig. X1)

**R&D target value [cf. intermediate report on Task 10.2] leading to a central field of 18 T instead of 16.75 T

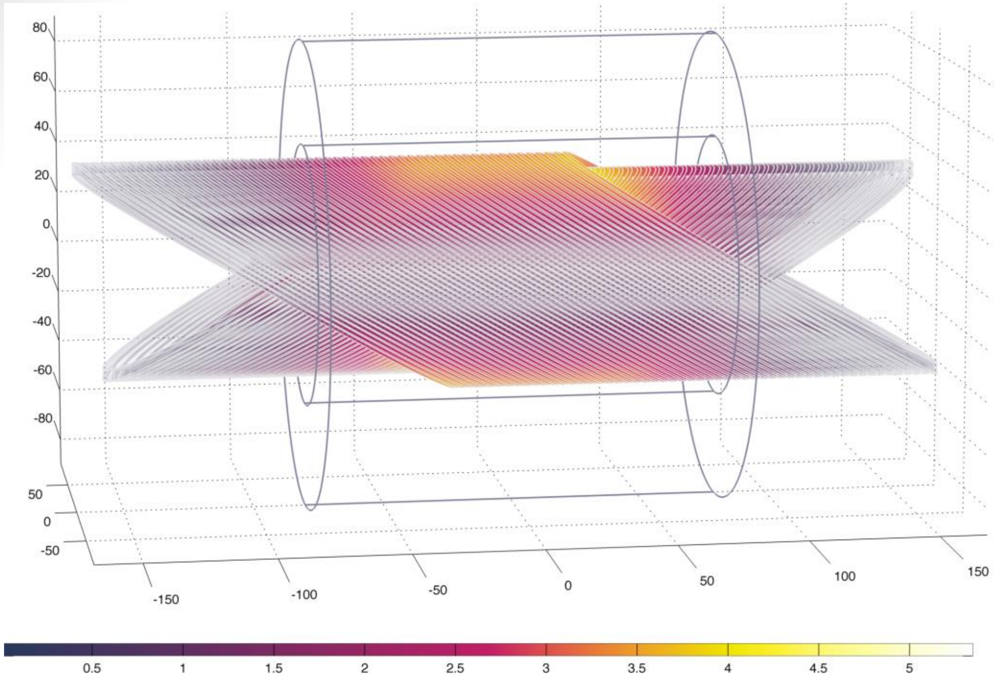


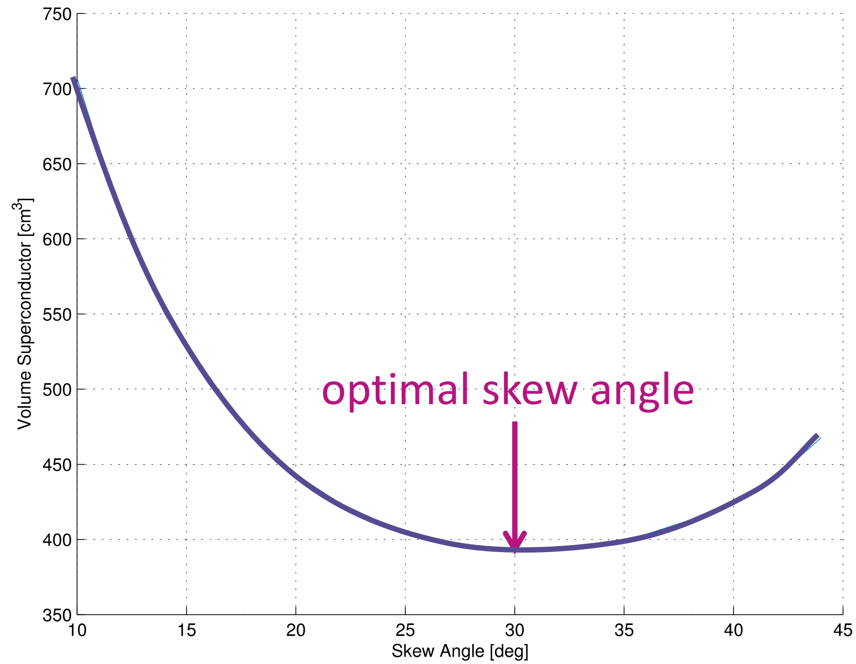
Mechanical model

End optimization

HTS dipole inside FRESCA2 magnet - Lorentz forces

Design Study - Canted Cosine Theta



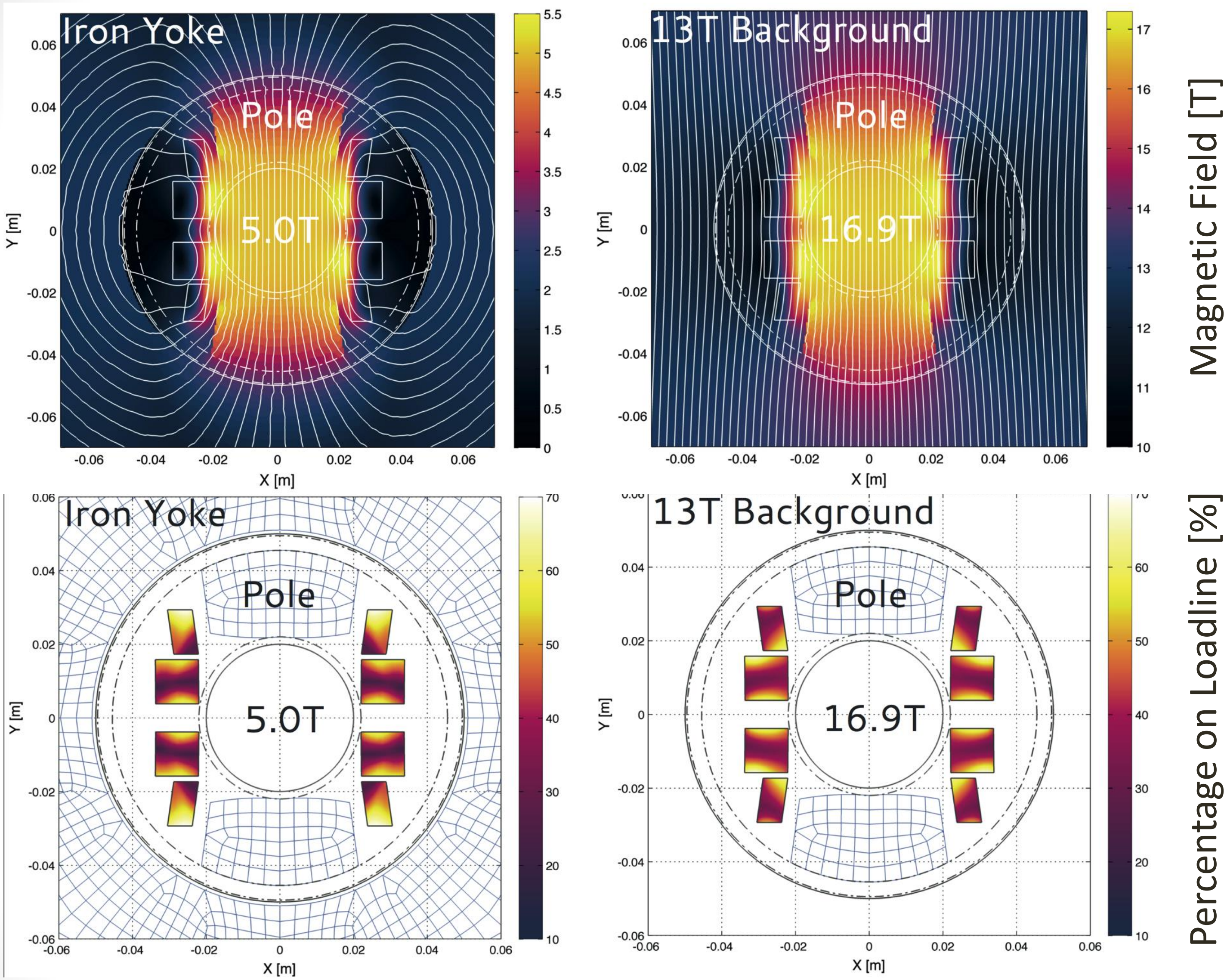


- Developed in collaboration with S. Caspi LBNL

Specifications:

- 30 deg skew angle
- 5 T central field in iron yoke
- 1.4X4.2 mm cable (2X6 strands)
- 3304 A = 562 A/mm^2 operating current (80%Ic)
- 64.7 m cable length
- 0.38 mm midplane (smallest) rib thickness

Design Study – Aligned Block



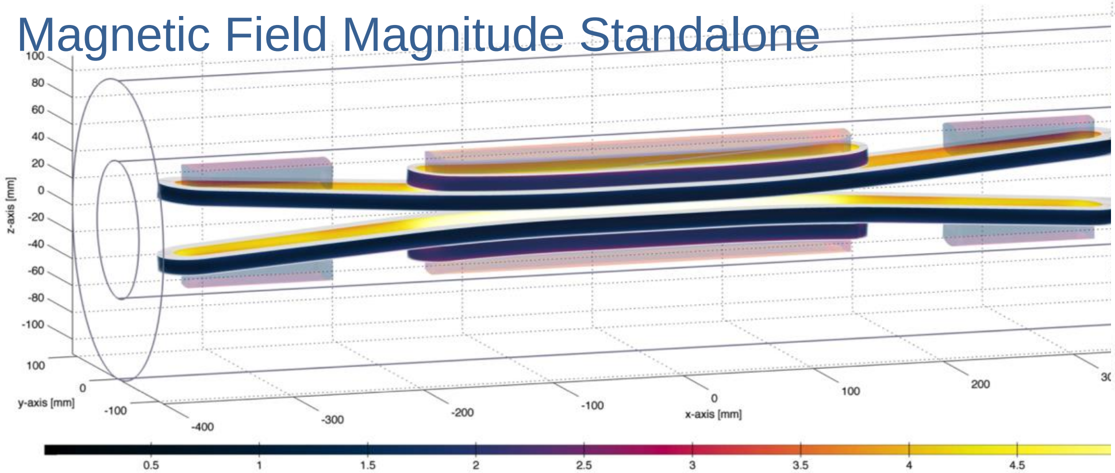
The two plots present flux path variation for insert magnet:
(left) standalone in Iron ,
(right) in 13T ideal background field

Note! Yellow area is the high short sample position.

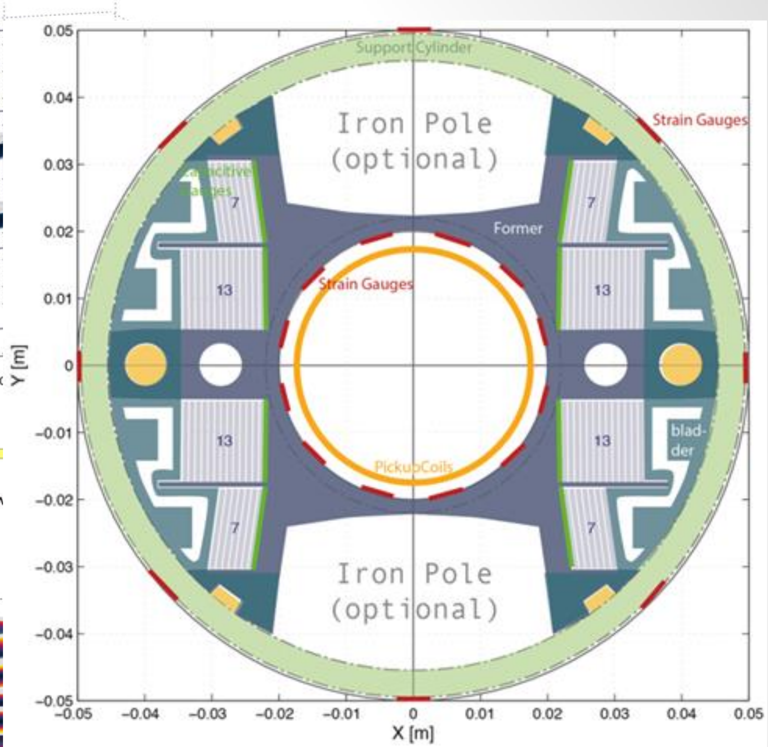
Very different from std. LTS magnets.

Design Study – Aligned Block 3D

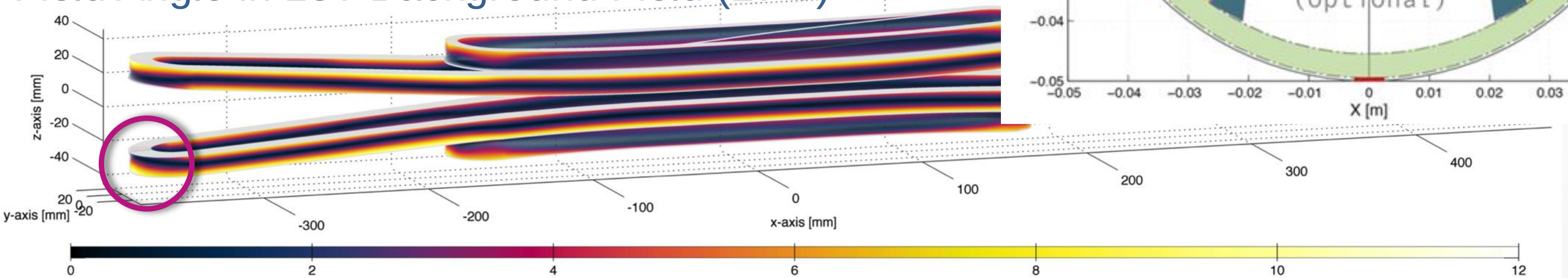
Magnetic Field Magnitude Standalone



(a) Operating at $5.0\ T$ (7915 A cable current, 649 A/mm^2 coil block current density) in an iron yoke, which is represented by the grey lines for view



Field Angle in 13T Background Field (17 T)

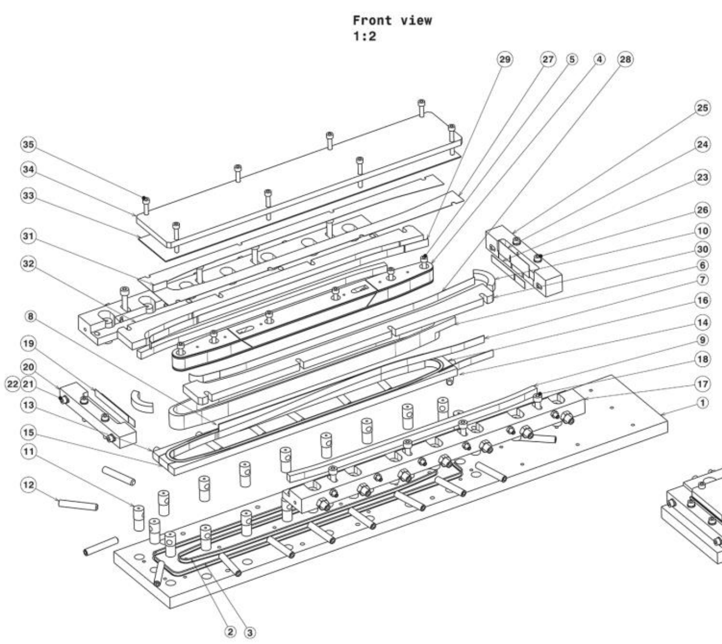


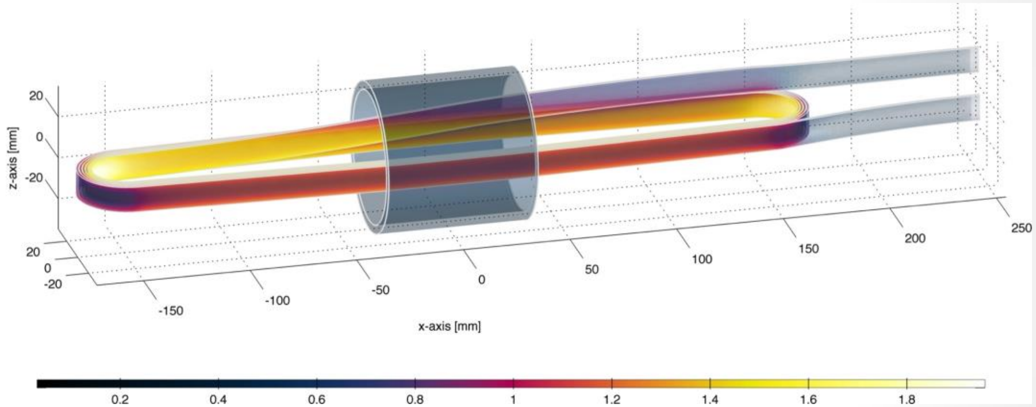
(b) Operating at $16.9\ T$ (8135 A cable current, 667 A/mm^2 coil block current density) in a background field of $13\ T$. It can be seen that everywhere along the conductor there is a band, which has a low incident magnetic field angle. On the sides of the conductor the field angle becomes larger due to the local curvature of the magnetic field.

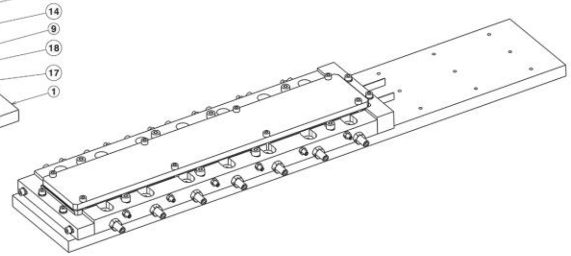
- Tracking along each strand there is always a low angle, high Jc volume.
- Lower limit expected on coil ends due to angle

Design Study – Feather-M0

- Intermediate Development Step Feather-M0
- Flat racetrack coil testing
  - Cable winding and other mechanical issues (see presentation Glyn)
  - Quench detection/protection system (working on NI fpga-cpu system).
- Can be tested standalone in an iron yoke or in Fresca-I for background field
- Aiming for first tests end of this summer (2014)







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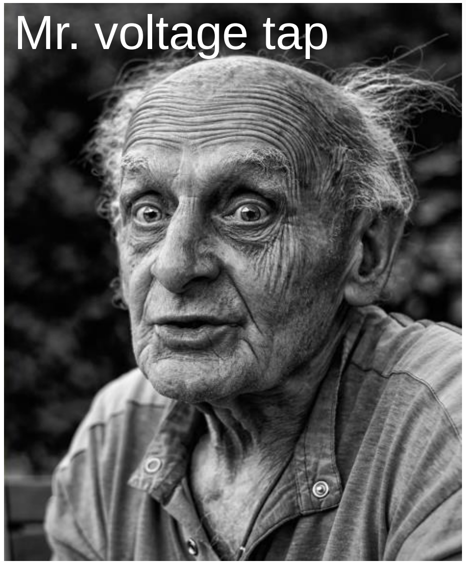
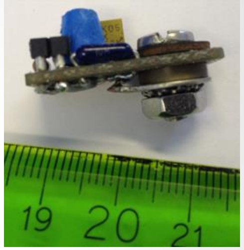
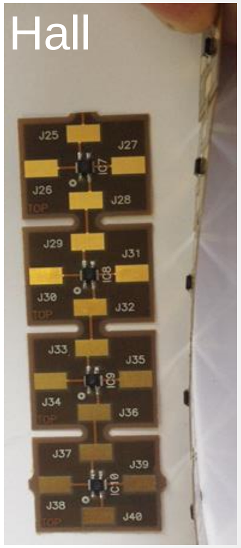
Design Study – Quench Detection

- HTS is very different to LTS when it comes to quench behavior
  - Minimal Quench Energy is high (stable)
  - Normal Zone Propagation Velocity is low (hard to detect)
- Also due to the alignment of the blocks the operating current density can be very high
- All available options for quench detection need to be re-evaluated:
  - Voltage taps
  - Pickup-coils
  - Hall probes
  - Accoustics
  - Optics

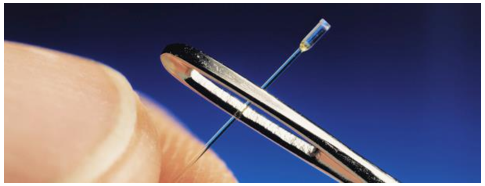


Accoustic

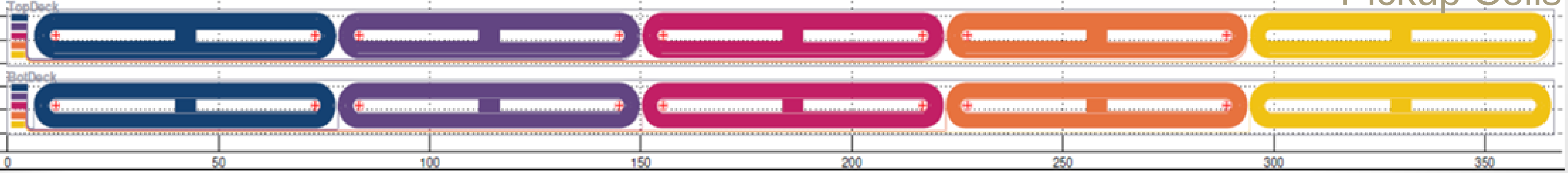




Optics



Pickup Coils

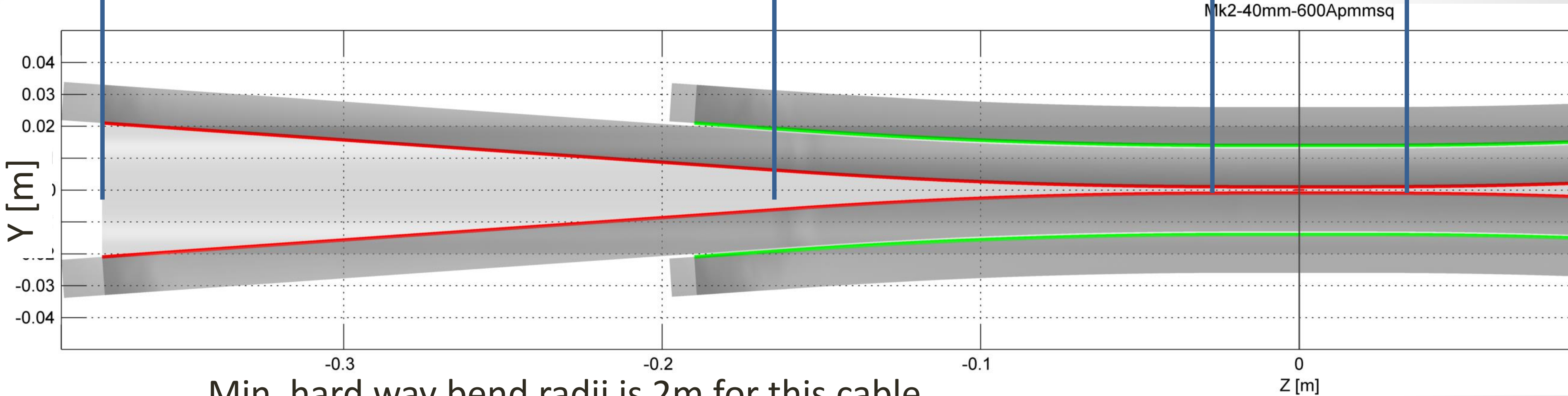


Experiments – Hardway Bend Test

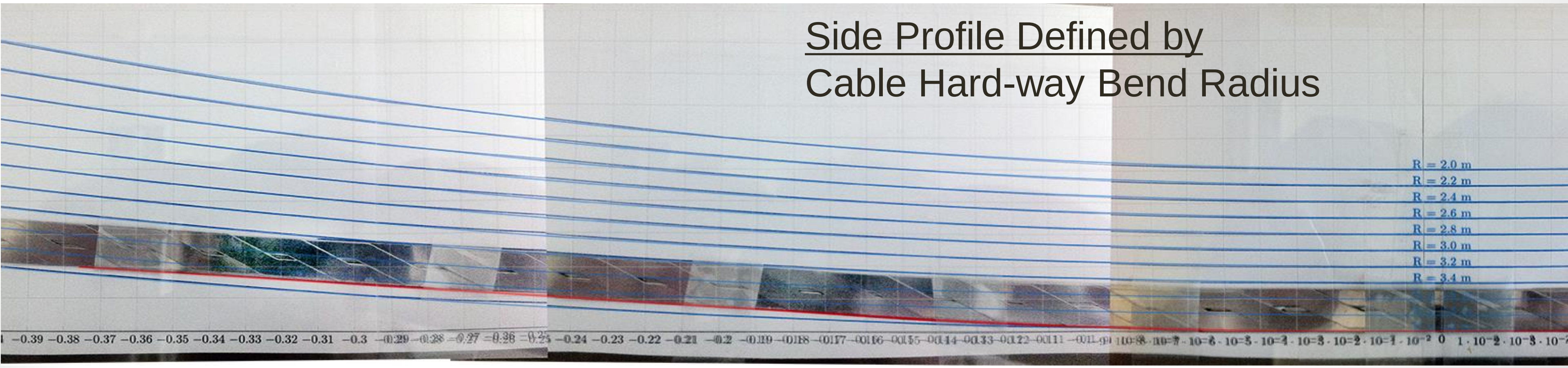
Sloped section
aslope = 4 deg max
(determines field angle at ends)

Bend section
Rbend >= 2000 mm

Straight
Section



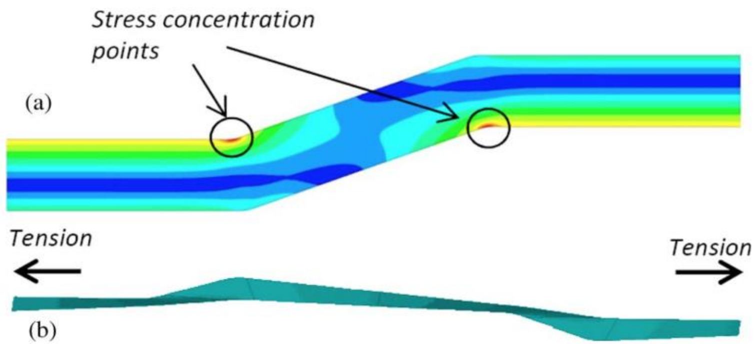
Min hard way bend radii is 2m for this cable



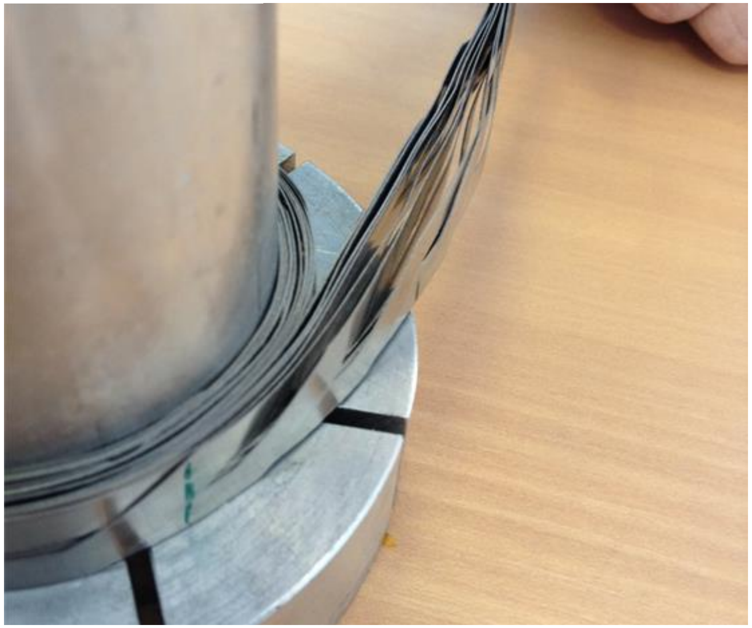
Side Profile Defined by
Cable Hard-way Bend Radius

Experiments - Impregnation Test

Experiments – Winding Tests



The dog-leg shape of each tape will limit actual tension during winding and implies control of actual coil stress.



Conclusion: During winding differential longitudinal slippage between tapes will be important to control, through design and specialist tooling. Has a serious impact on cable design.

Experiments – Coil end cable twist pitch

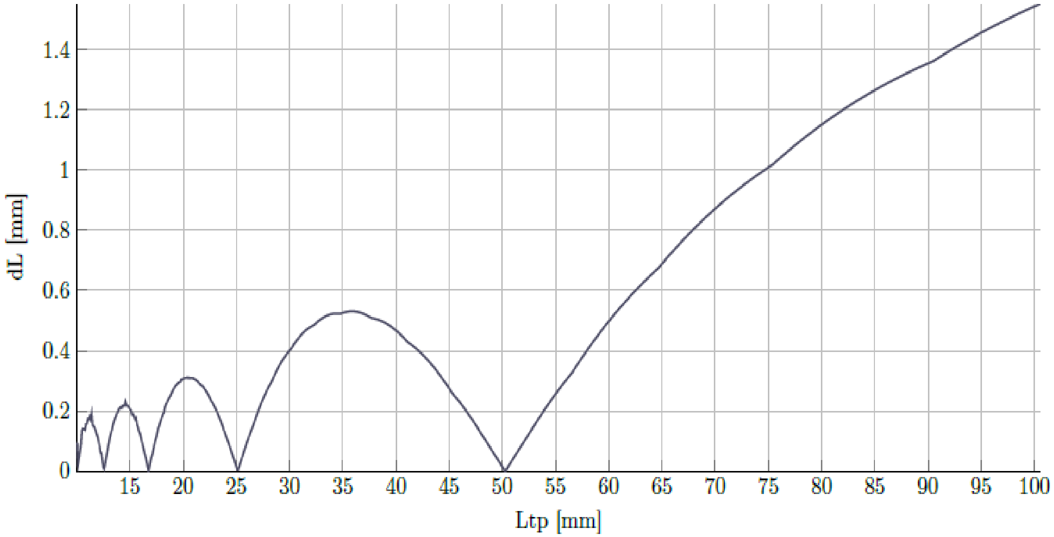


Figure 5: Strand length difference as function of twist pitch for a fixed coil end radius of 16 *mm*.

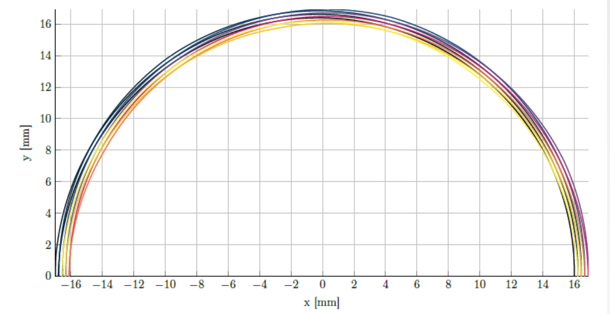
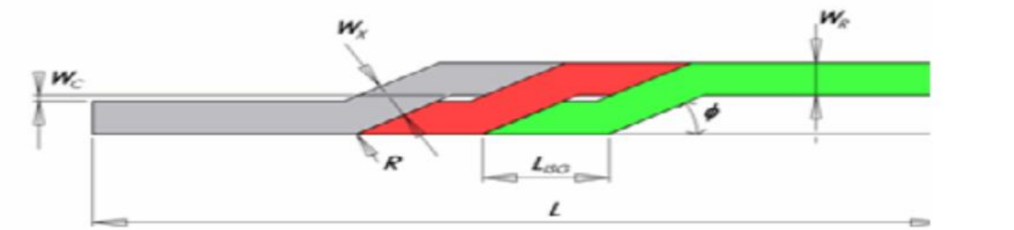


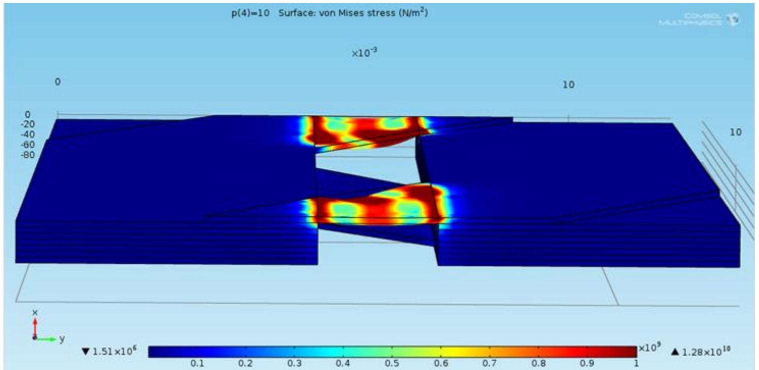
Figure 3: Strand Trajectories in cartesian coordinates for a twist pitch of 126 mm and a coil radius of 16 *mm*.



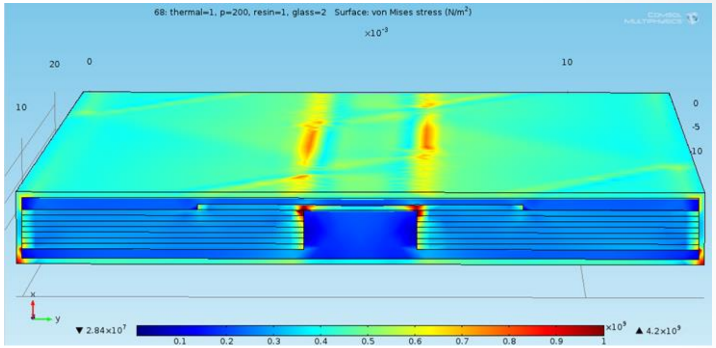
Conclusion: longitudinal slip between tapes in the cable can be corrected by matching the twist pitch of the cable to the coil end arc length of the coil end.

Twist pitches that are longer than the arc length have no solution. The tapes must be able to slip axially.

Modeling - Cable mechanical model

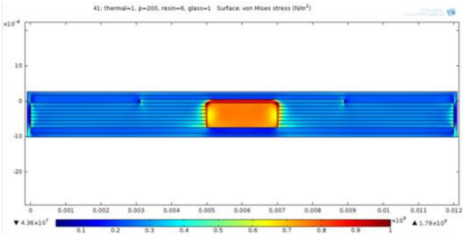


Pressure on top surface Not impregnated

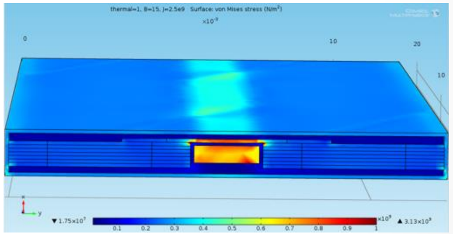


Cooled to 4K + Pressure applied on top surface (cable impregnated with epoxy & class sock around cable)

Mechanical studies are on-going
We are finding very high values due to cool down , and concentration of stress at tape edges, all needs more work.
This problem has to be addressed !



2D study : Cooled to 4K +Pressure applied on top (cable impregnated with epoxy and with copper insert)

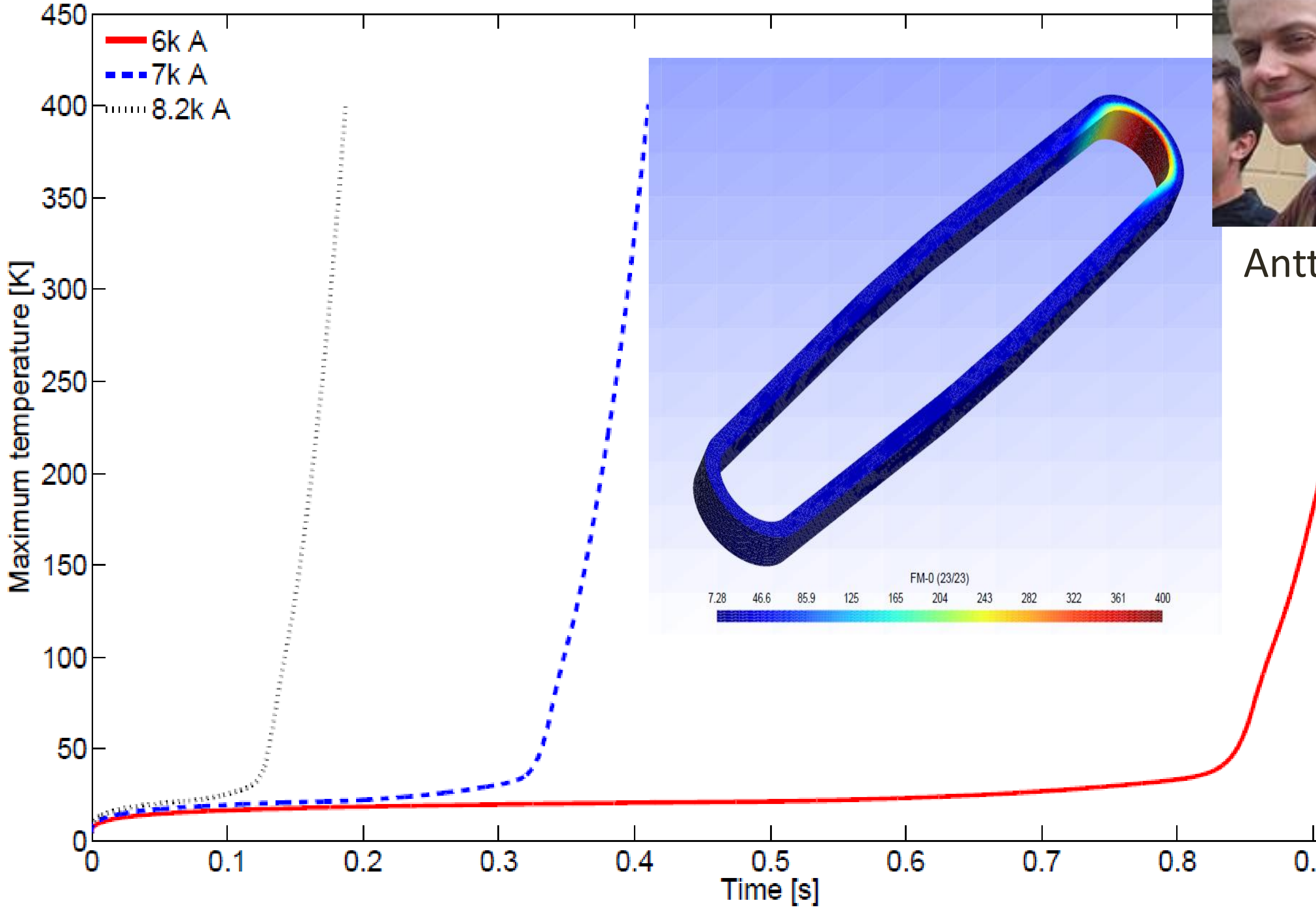


Cooled to 4K +Magnetic forces on the edges of the tapes (cable impregnated with epoxy and with copper insert)

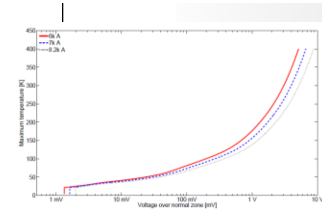
Work in progress by Nabil Chouika

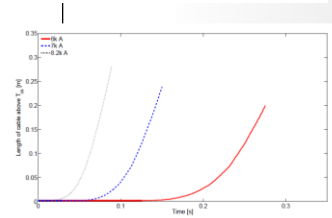
Modeling - Quench Analysis

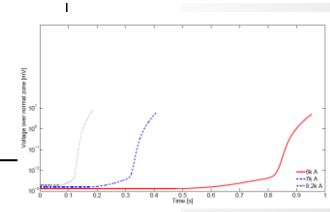
Finite Element model using anisotropic thermal conductivities



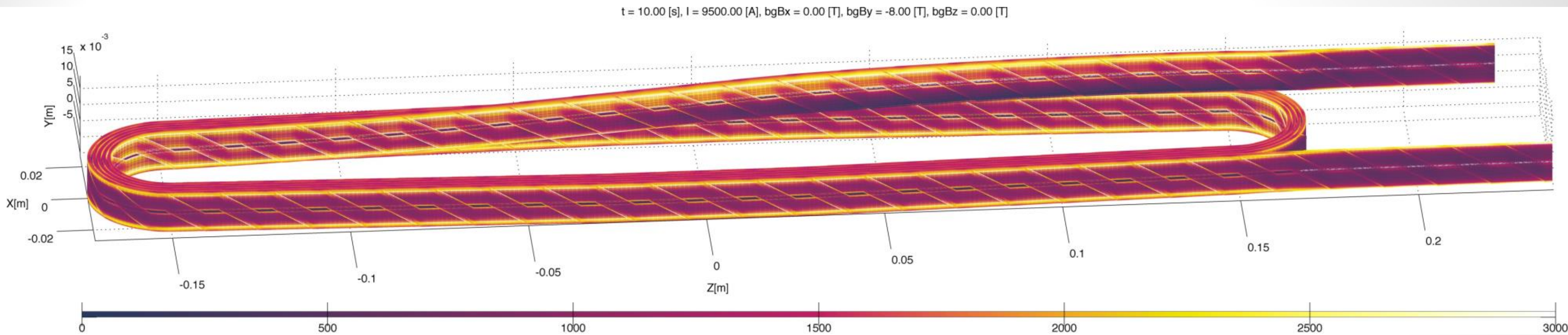
Antti Stenvall, Erkki Härö







Modeling - Current distribution in Roebel cable



Cable model developed by Jeroen Van Nugteren to predict the current distribution through the width of the tapes and between tapes in the Roebel cable, including the angular dependence of the tape.
Look for ASC 2014 paper this summer.

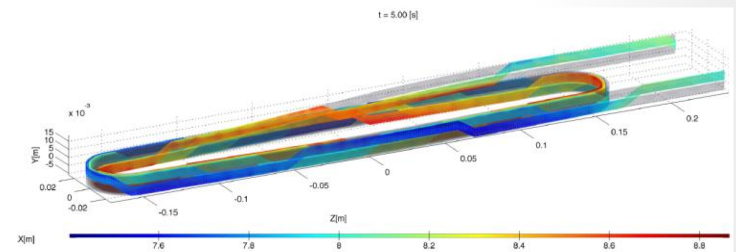
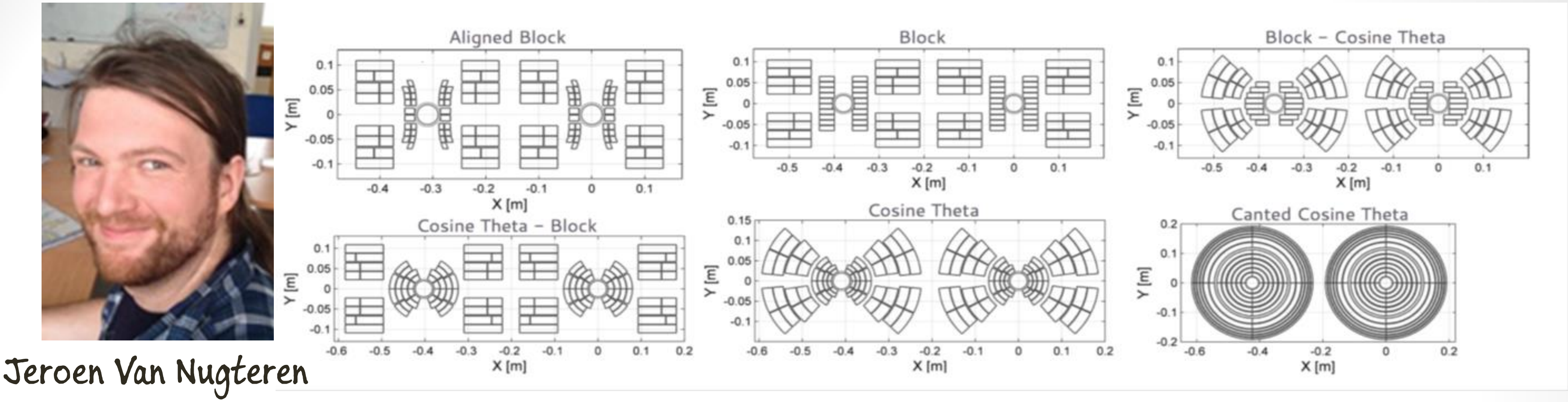


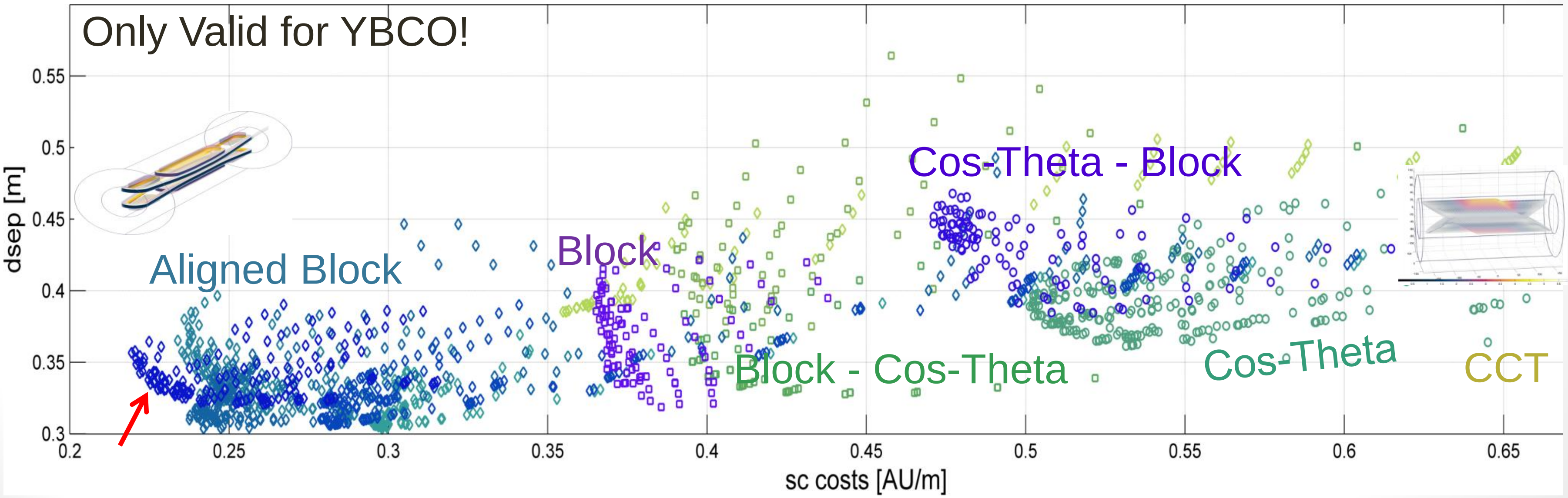
Figure 5: Magnetic Field in coil

Due to the inductive coupling, the current runs through the edges of the tapes and, as current increases, it moves to fill to the tape centre.

The above plot shows a high current density positioned in the top of the layer jump. Part way through ramping the coil. From this we can calculate dynamic field harmonics.

Modeling – Magnet Concepts Survey



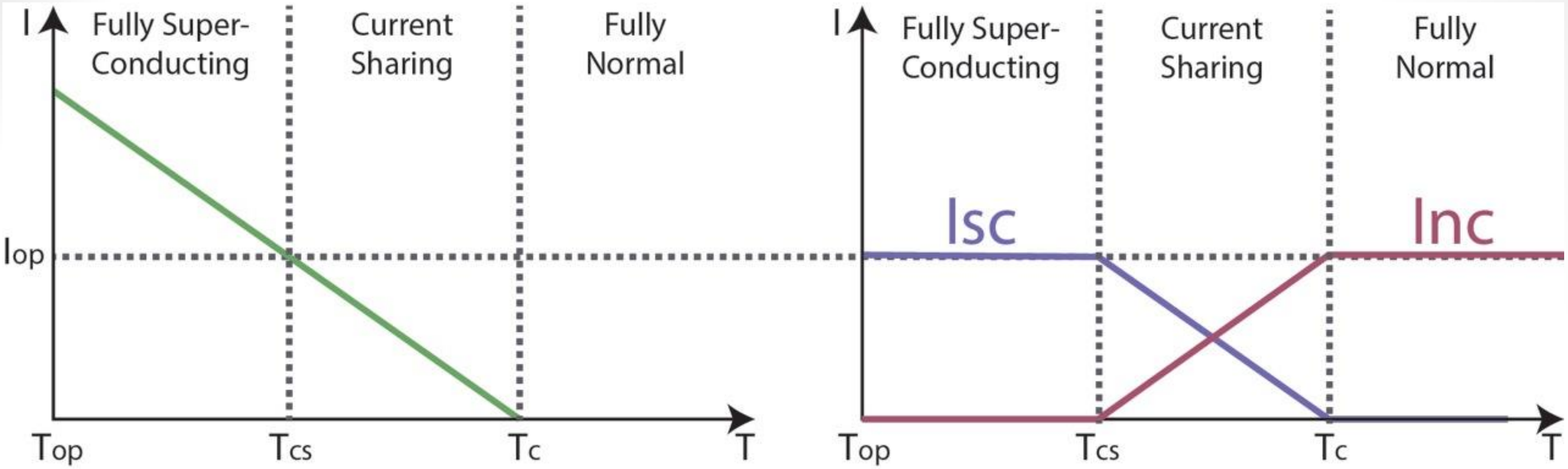


Conclusions

Thank you for your attention

Spares

Current Sharing in HTS

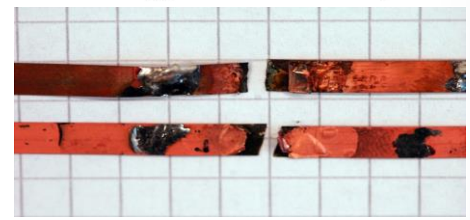


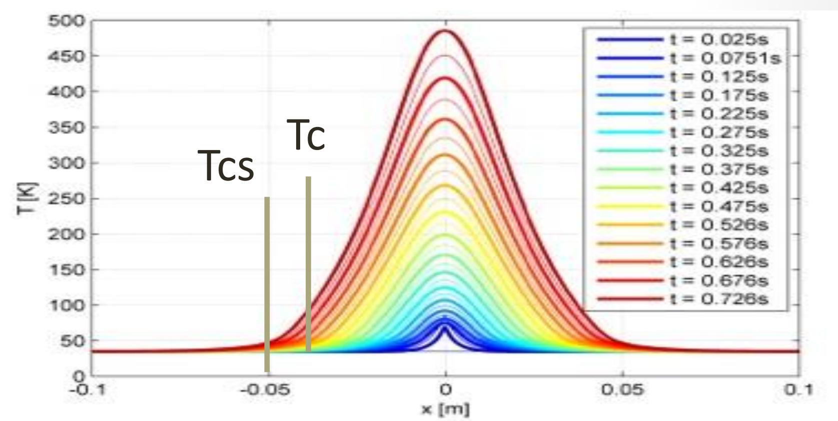
YBCO has very slow quench velocity ~ cm/s due to a much larger energy needed to take the conductor over Tc and a gradual transition between Tcs and Tc.

This makes it harder to detect, potentially leading to an unacceptably high peak temperatures.

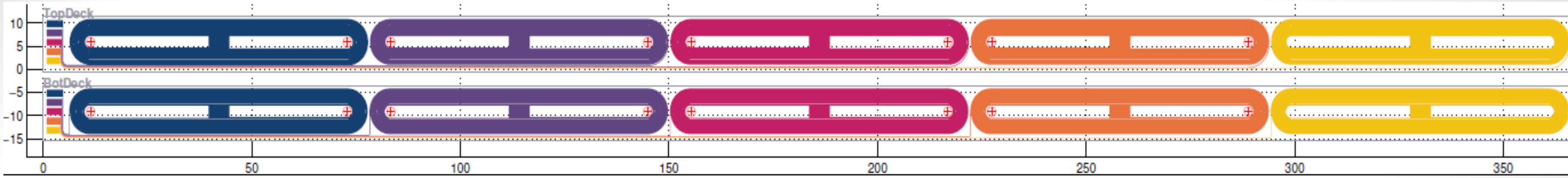
We plan to test multiple detection methods.

Burnt samples.

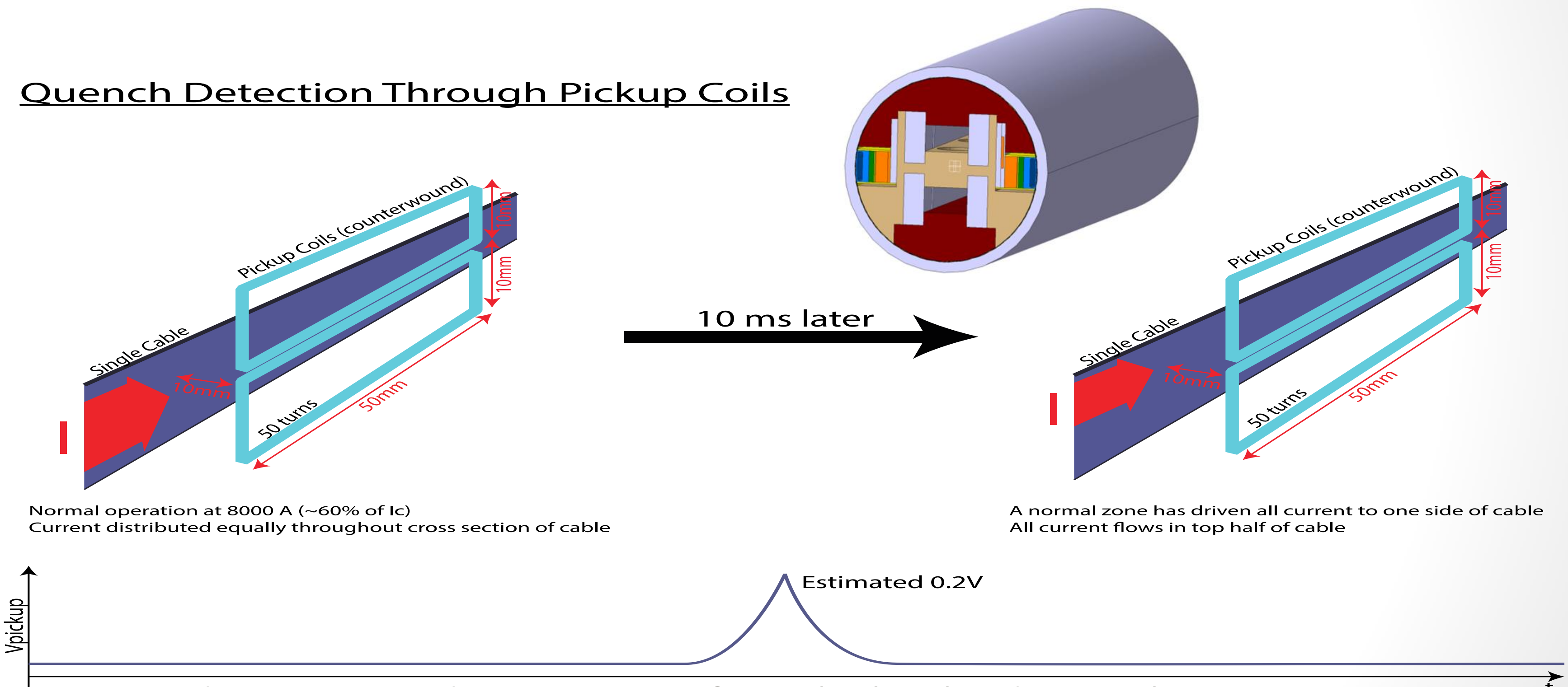




Quench Detection - Pickup Coils

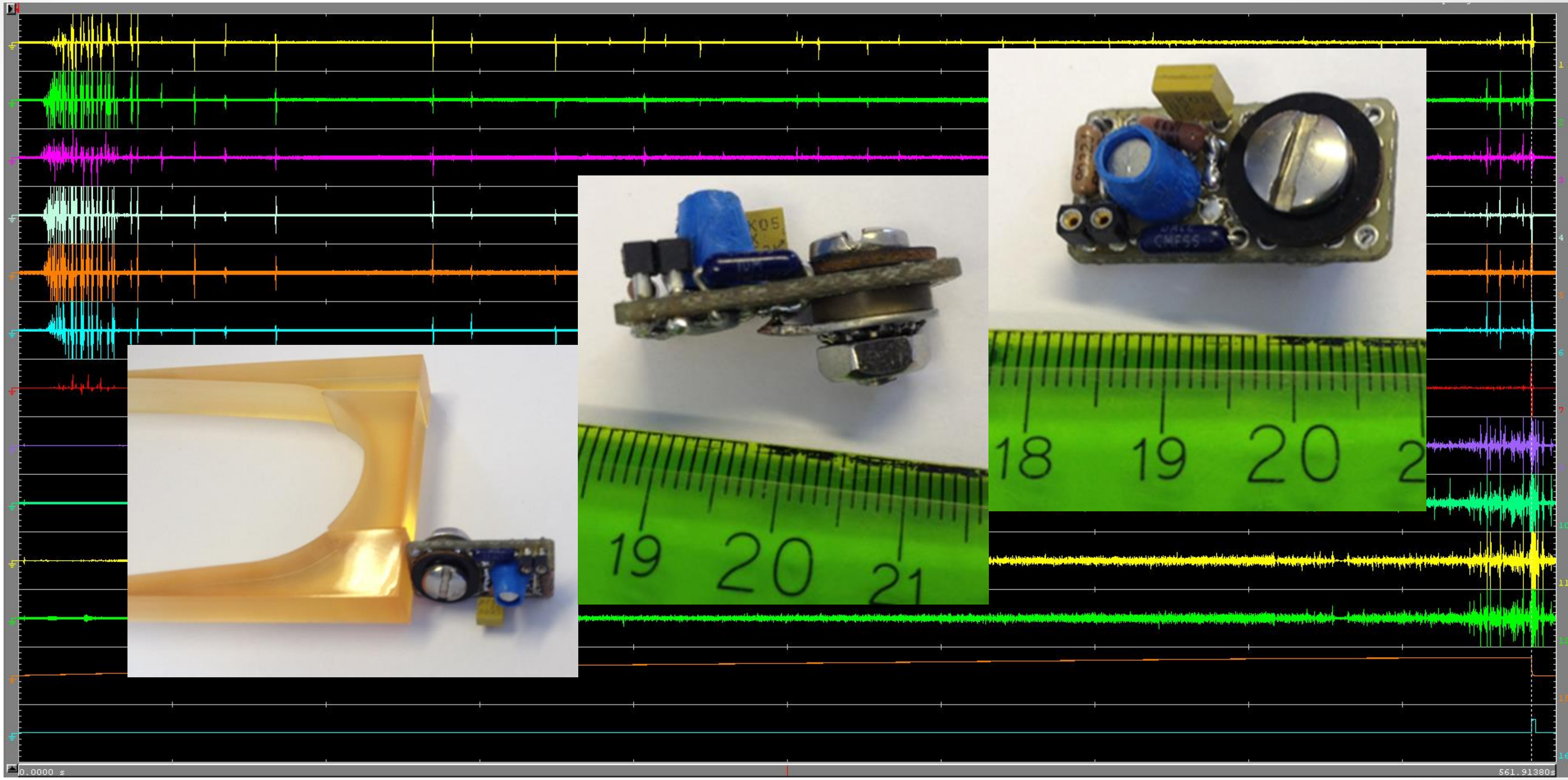


50 turns, 250 turns/coil, 0.05mm track, PCB printed on 0.05mm Kapton foil, multi-layer



We predict a current diversion away form the localized normal zone.

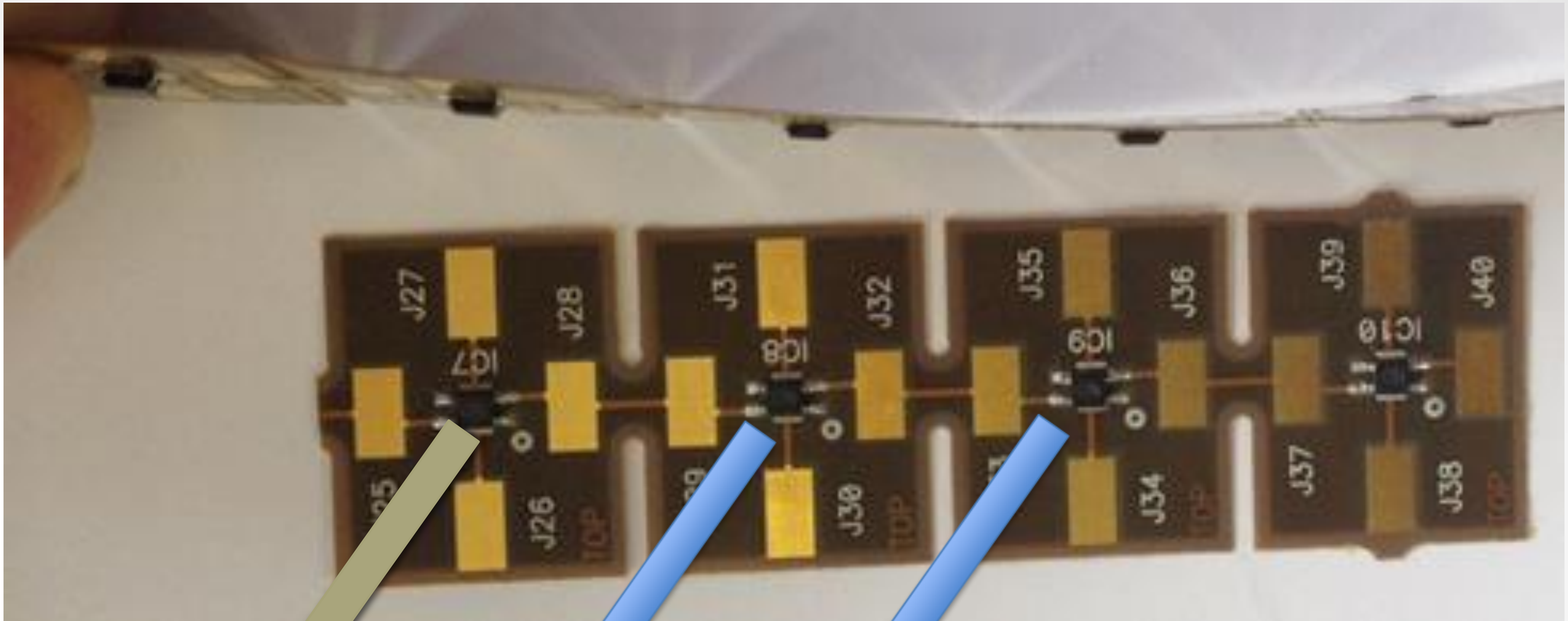
Quench Detection - Acoustics



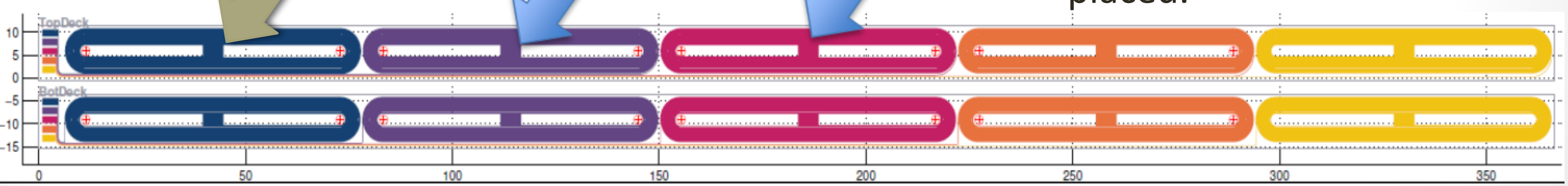
- At LBNL quench acoustic signals were detected seconds before the LTS conductor quenched.
- For HTS investigation this system will be included in the tests

Thanks to Maxim Marchevsky LBNL

Hall Probe array



At the center of the pick-up coils a hall probe will be placed.



NI-CompactRIO

Processor:
- 667 MHz dual-core ARM
- 512 MB RAM
- 1 external GB storage
- + Additional 3 TB Ext.Storage
- NI Linux Real-Time OS

FPGA:
- Xilinx Artix-7
- 2 M cells

Channels 224 total

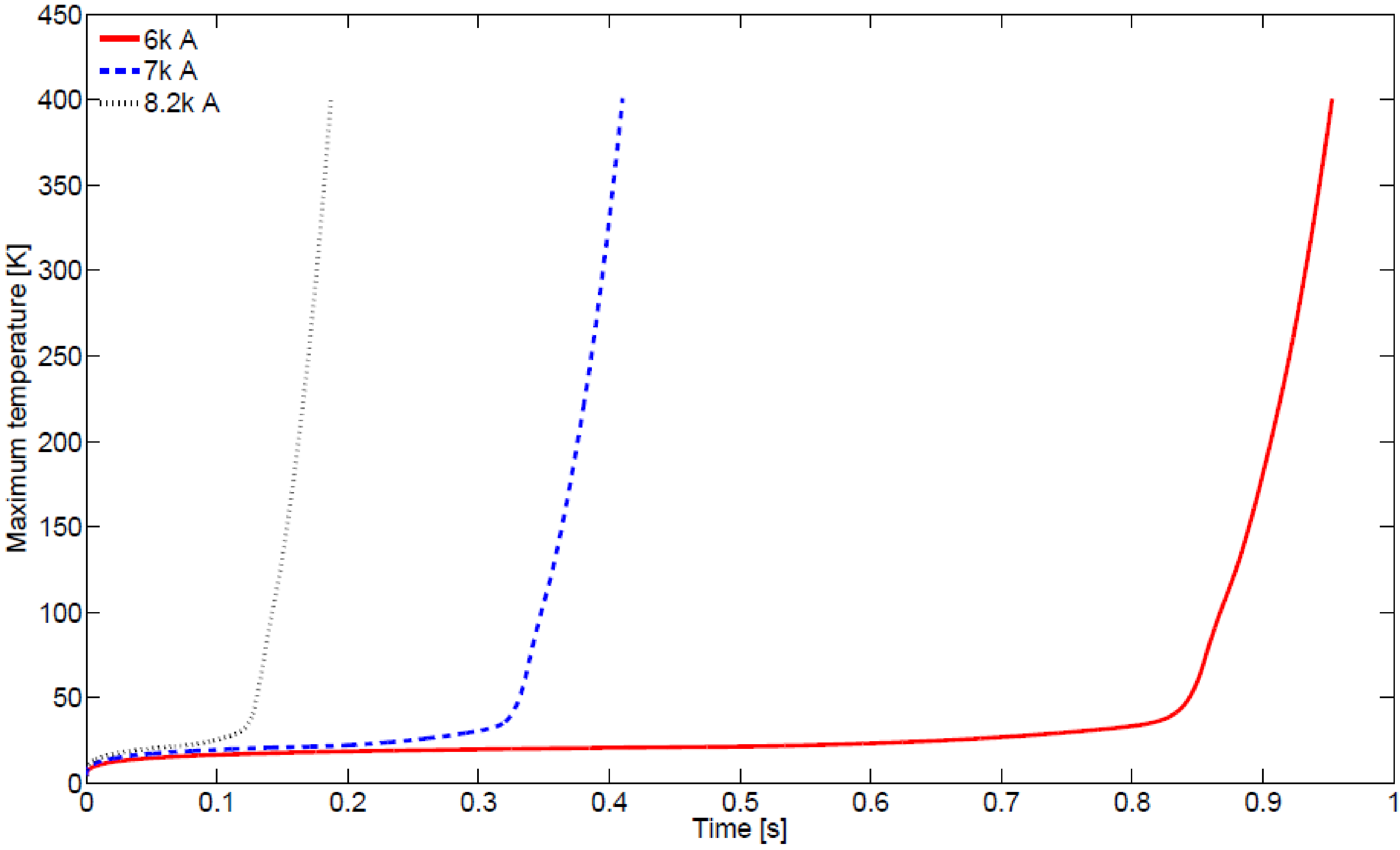
7 modules: 16 differential analogue inputs each
- +/- 200 mV till +/- 10 V input range
- 16 bits
- 7.8 kS/s per channel

1 module: 32 digital outputs
- 5 V TTL
- 7 µs response time

Also available: **high speed module**
- 4 differential analogue inputs
- 16 bits
- 1 MS/s, simultaneous sampling

A similar system is used by the EL group to capture voltage transients on the electrical network caused by EDF switching, thunderstorms and internal load changes.

Quench detection



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