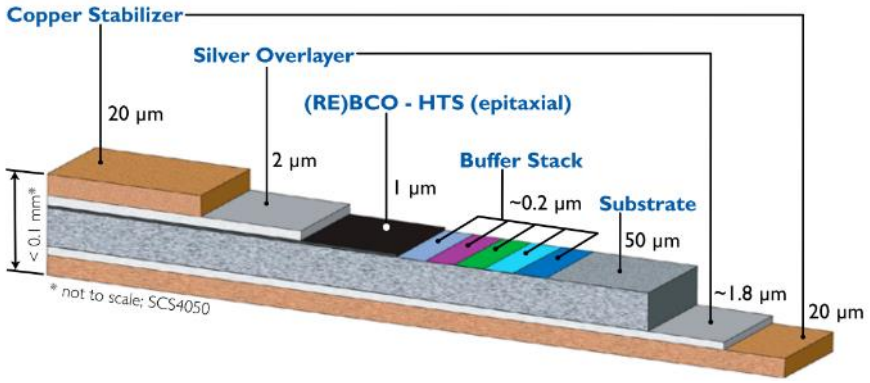
GaToroid
Demonstrator

Impregnation tests on dummy stacks

Motivation



SuperPower 2G HTS

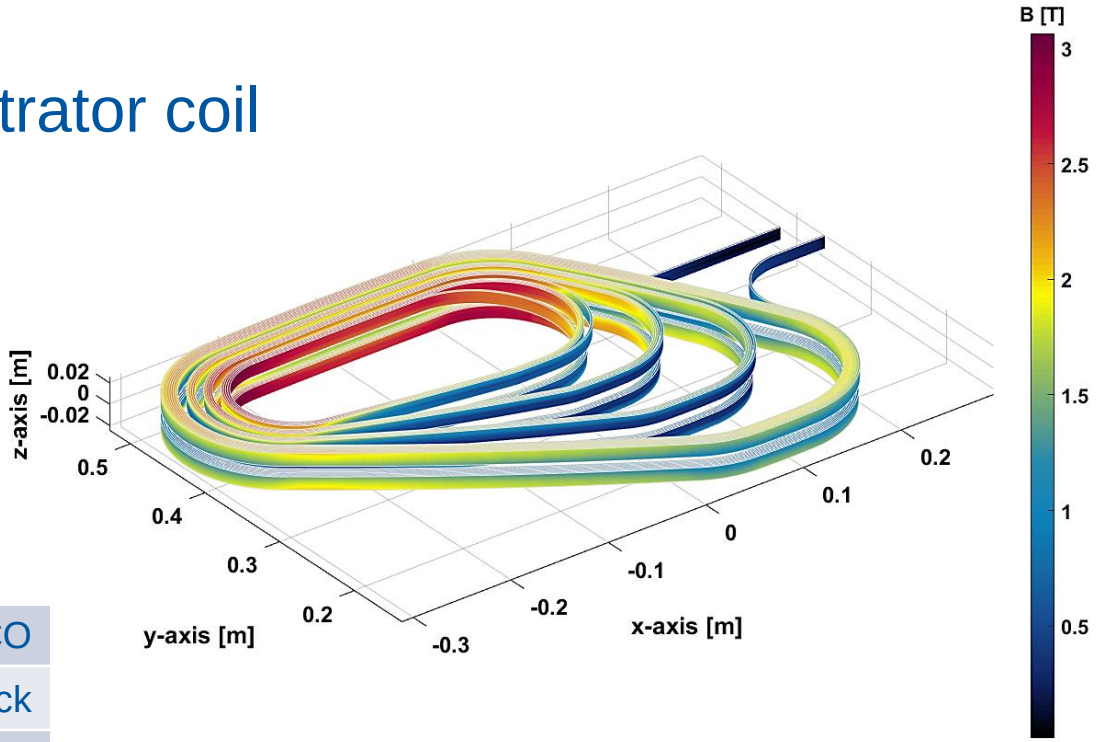
- Impregnated HTS tape coils have shown degradation after thermal cycles.
  - Feather.M0, Feather.M2
  - HTS Roebel cable (Peng Gao - Twente)

- The degradation could be caused by :
  - Delamination of the tape due to resin thermo-mechanical properties
  - Cracks in the resin causing points of defect on the tape

- We want to investigate the compatibility of the impregnation resin with the HTS tape.

Context

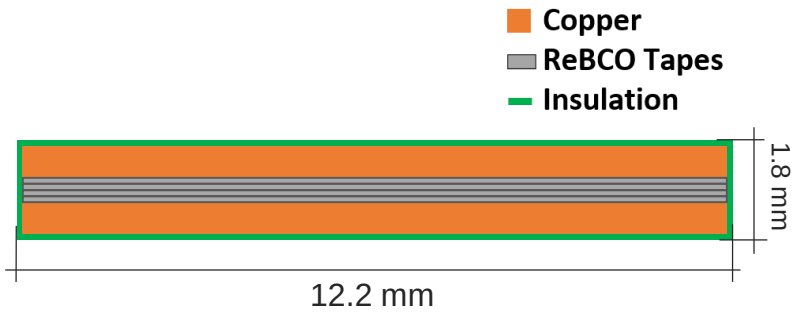
GaToroid HTS demonstrator coil



Superconductor	ReBCO
Cable topology	Stack
N of HTS tape	4 (0.1 mm)
N of Copper tape	2 (0.55 mm)

Cable width	12.2 mm
Cable thickness	1.8 mm

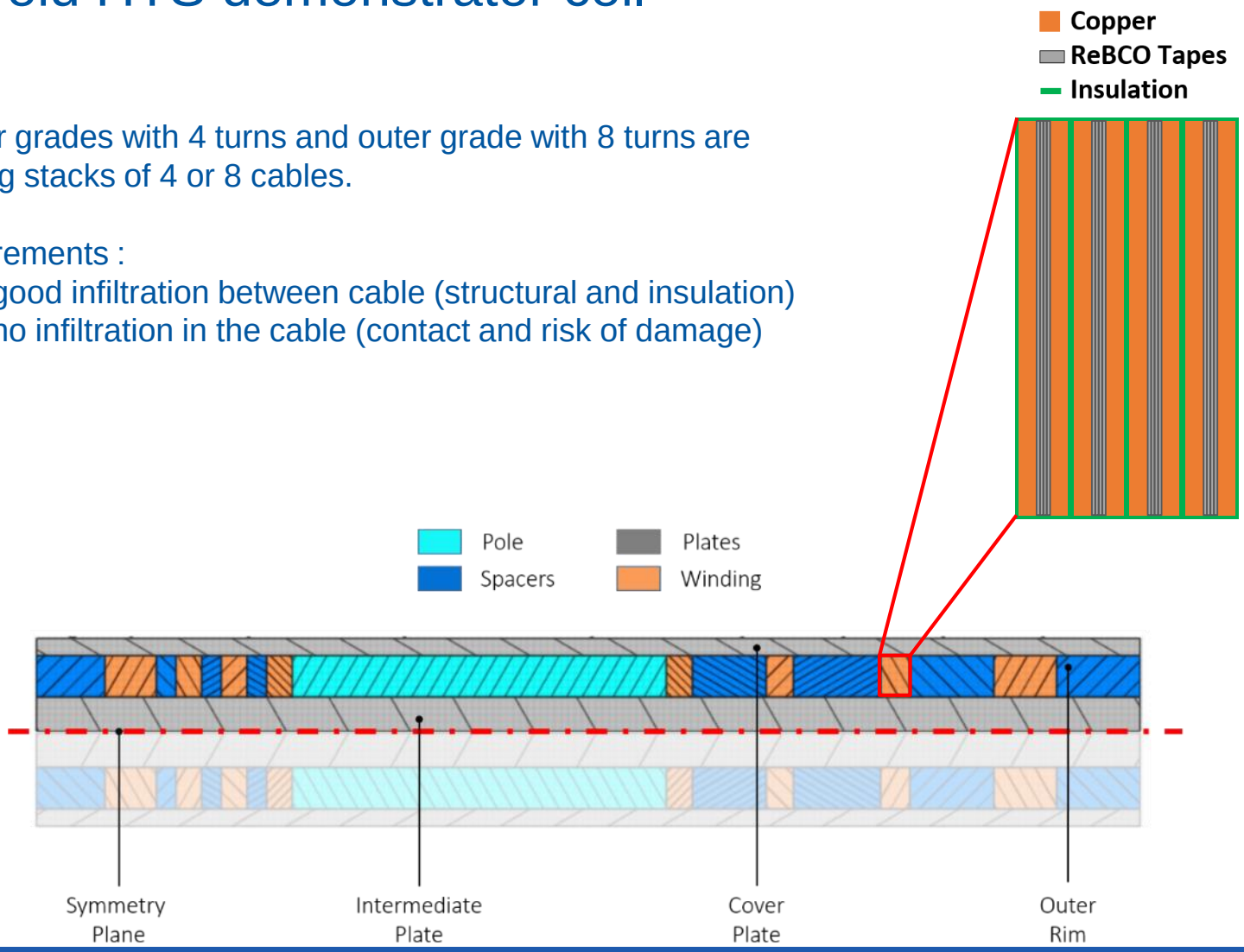
Cu: Non-Cu ratio	5.3



Context

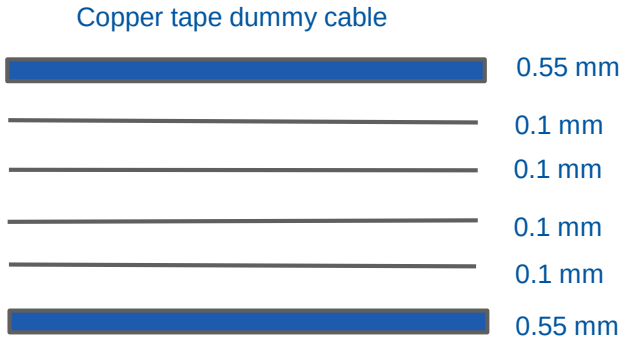
GaToroid HTS demonstrator coil

- 3 inner grades with 4 turns and outer grade with 8 turns are forming stacks of 4 or 8 cables.
- Requirements :
  - good infiltration between cable (structural and insulation)
  - no infiltration in the cable (contact and risk of damage)

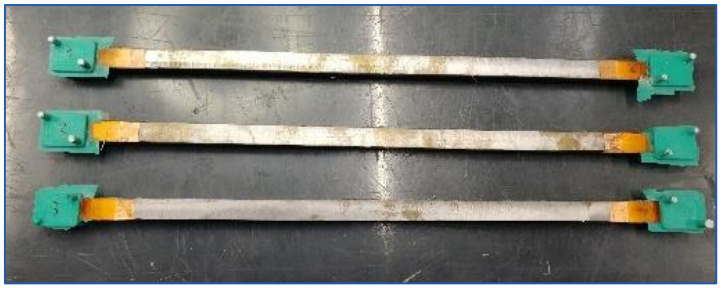


Test plan

Phase 1 - Dummy stacks



- Dummies are made from Copper tapes mimicking the real HTS cable stack.
- An impregnation mold allows the preparation of 3 identical samples per batch.
- Parameters are:
  - insulation type
  - resin type
  - compression



Test Plan

Phase 1 - Overview

To check:

- Impregnation quality (voids, bubbles)
- Mechanical properties (peeling, cracking)
- Insulation between cables
- Contact between tapes in a cable

Our tools:

- Peeling and visual inspection
- Cutting and microscopic inspection

- Electrical tests at room Temp. and at 77K
- Electrical tests after 10 low Temp. cycles

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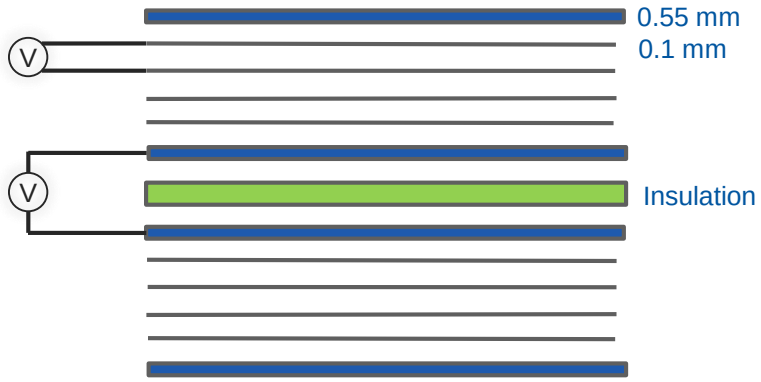
Impregnation: Sebastien Clement, Romain Gavaggio, Ahmed Benfkih

Electrical tests: Pierre-Antoine Contat, Francois-Olivier Pincot

Cut and microscope: Ana Teresa Perez Fontenla

Supervision: Ariel Haziot, Nicolas Bourcey, Juan Carlos Perez



Test Plan

Phase 1 - Status

		STACK CONFIGURATION			PROCESS				
Batch #	Stack #	Insulation	Resin	Compression	Preparation	Impregnation	Electrical test	Peel and VI	Cut and VI
1	1-3	Fiber glass	MY750	High	Done	Done	Done	Done	Done
2	4-6	Fiber glass	CTD101K	High	Done	Done	Done	Done	Done
3	7-9	Fiber glass	CTD101K	Low	Done	Done	Done	Done	Done
4	10-12	Fiber glass	MY750	Low	Done	Done	Done	Done	-
~~5~~	~~13-15~~	~~C-Shape Polyimide~~	~~CTD101K~~	~~Low~~	~~Done~~	~~Done~~	-	-	-
6	16-18	C-Shape Polyimide	MY750	Low	Done	Done	Done	Done	-
5.2	19-21	C-Shape Polyimide	CTD101K	Low	Done	Done	Done	Done	Done
7	22-24	C-Shape Polyimide	Mix61	Low	Done	Done	Done	Done	-
~~8~~	~~25-27~~	~~Fiber glass~~	~~Mix61~~	~~Low~~	~~Done~~	~~Done~~	-	~~Done~~	-
8.2	28-30	Fiber glass	Mix61	Low	Done	Done	Done	Done	-

Test Plan

About the resins

	CTD101K	MY750	NHMFL "Mix" 61
Chemistry	Liquid epoxy resin + anhydride Hardener	MY750 (Resin) + HY 5922 (Hardener)	liquid epoxy resins A + B + amine hardener + high molecular weight additive
Curing	125 °C	80 °C	100 °C
Viscosity	Low, long pot life	Higher, shorter pot life	Higher, shorter pot life
Fracture Toughness (RT/77K) [MPa$\sqrt{m}$]	0.6 / 1.4	NF / 2.4	4.6 / 4.7
Elongation at fracture	0.97 %	??	10 %
Thermal shock resistance	177 K	510 K	268 K
Thermal expansion (below Tg) [m/mK]	50 x 10-6	50 x 10-6	50 x 10-6

André Brem, Barbara Gold, Theo Tervoort, Auchmann and Davide Tommasini (ETH + CERN)
Shijian Yin, Tengming Shen (Berkeley lab)

Test Plan

About compression

Different shims of different thickness are used to modify the size of the cavity depending on the insulation type and the desired compression.

Cavity size: 12 mm
Stack with fiberglass (0.15 mm) : 7.2 mm
Stack with polyimide (0.05 mm) : 6.4 mm

The compression parameter should be understood here as the free space for the resin.

Void at low compression: 1 mm
Void at high compression: 0.2 mm

Results

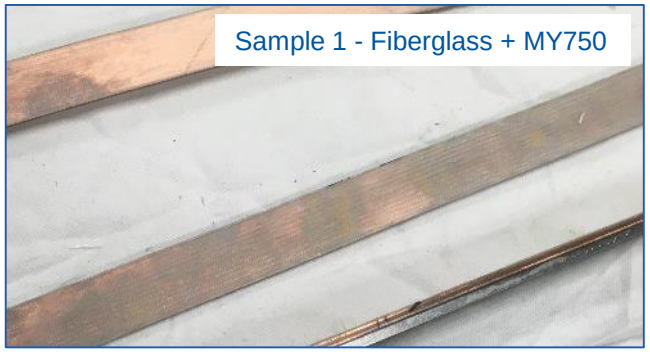
Quality of impregnation / peeling resistance

- Peeling resistance is generally higher with fiber glass than with polyimide. The structure is reinforced by the fiber.
- Peeling resistance is higher with MY750 and Mix61 (more elastic) than with CTD101K that tends to fracture and propagate a crack.
- Cracks can be observed with CTD101K after LN2 thermal cycles.

Results

Insulation between cables – Fiber glass

- Distance between cables is homogenous along the sample for both compressions.
- The impregnated fiber glass fills the gap and plays a buffer role.
  - 167 µm at high compression
  - 213 µm at low compression



- The fiber glass is impregnated for both CTD101K and MY750
- MY750 did not wet the copper while the CTD101K wet it only partially.

Results

Insulation between cables - Polyimide

The impregnation is not homogenous between the cables. The resin (for all of them) fills preferentially one inter-cable space and pushes the other cables against each other.

As a result, the resin is almost not present when the cables are compacted together.

Results

Insulation between cables – Electrical tests

Fiber Glass	No T cycle	T cycled
MY750 (high)	705 GΩ	593 GΩ
MY750 (low)	2162 GΩ	882 GΩ
CTD101K (high)	1869 GΩ	1964 GΩ
CTD101K (low)	+ 2610 GΩ	1269 GΩ
Mix61 (low)	285 GΩ	633 GΩ

Polyimide		
MY750 (low)	+ 3000 GΩ	+ 2823 GΩ
CTD101K (low)	+ 3000 GΩ	2913 GΩ
Mix61 (low)	829 GΩ	536 GΩ

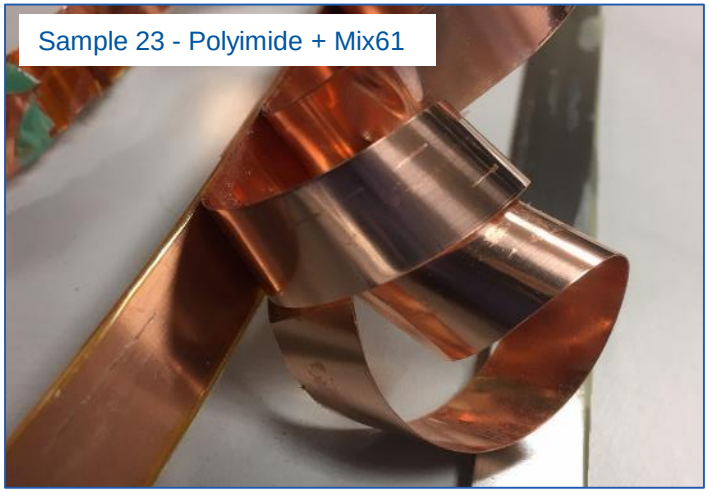
Pre-Conclusion

- With fiber glass the CTD101K shows better insulation properties between cables than the MY750 as it seems to wet better the cable.
- Low compression samples are showing better result as the inter-cable distance is larger.
- With polyimide, the insulation is very good although non-homogenous filling is observed, and more measurements are needed.
- Mix61 is showing in both cases lower insulation properties.
- In all cases insulation between cable is not an issue.

Results

Contact between tapes in a cable

- The fiber glass allows the resin to flow through and the samples are showing some traces of resin between the tapes.
- Also, it seems the MY705 is more likely to go in between than the CTD101K.

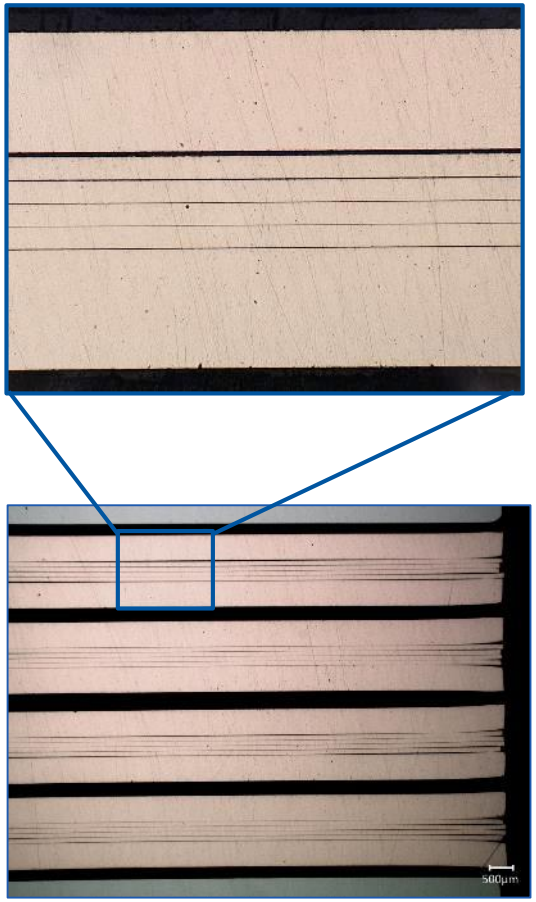


- Samples with polyimide are showing only very few resin traces between the tape with the MY750 and no signs of resin are observed nor with the CTD101K or the Mix61.

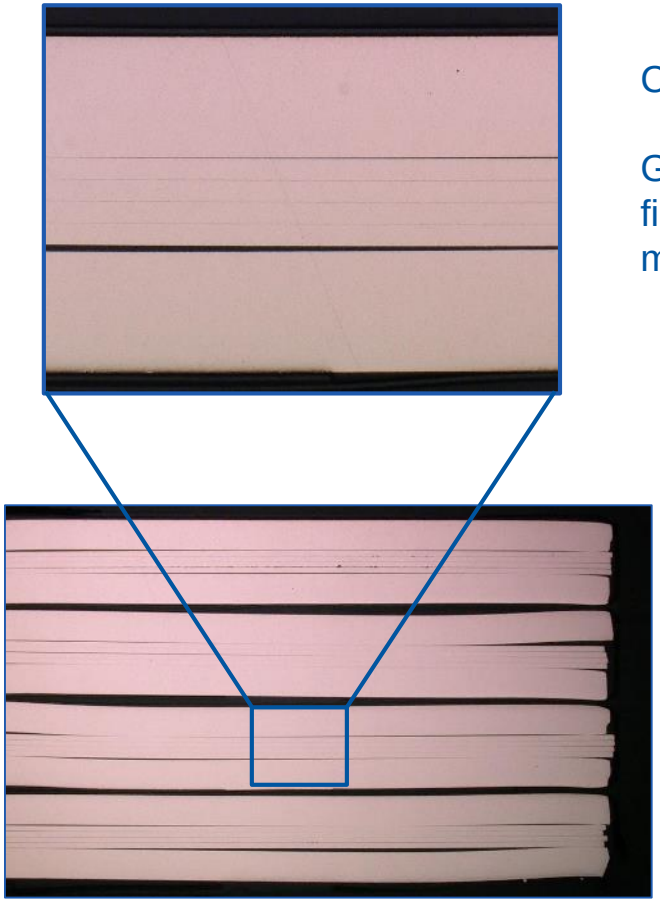
Results

Contact between tapes in a cable

Sample 1 - Fiberglass + MY750



Sample 20 - Polyimide + CTD101K



Confirmed by microscopic views.

Gaps are few microns with the fiber glass and are not measurable with the polyimide

Results

Contact between tapes in a cable

Fiber Glass	No T cycle	T cycled	At 77 K
MY750 (high)	3.0 mΩ	3.2 mΩ	0.52 mΩ
MY750 (low)	2.3 mΩ	2.2 mΩ	0.33 mΩ
CTD101K (high)	2.2 mΩ	2.3 mΩ	0.36 mΩ
CTD101K (low)	2.5 mΩ	1.7 mΩ	0.35 mΩ
Mix61 (low)	1.9 mΩ	1.9 mΩ	0.24 mΩ

Polyimide			
MY750 (low)	1.4 mΩ	1.4 mΩ	0.21 mΩ
CTD101K (low)	1.9 mΩ	1.7 mΩ	0.17 mΩ
Mix61 (low)	1.5 mΩ	1.6 mΩ	0.23 mΩ

Calculated value considering perfect contact in cable:
~1 mΩ @ 300K
~0.1 mΩ @ 77k

Pre-Conclusion

- No big differences are seen between the 3 resins with fiber glass.
- As for the visual observations, one could observe a better contact with the polyimide, but more measurements are needed.

Results

Complete table

Stack samples			Fiberglass sleeve					Polymide C-shape		
			High compression		Low compression			Low compression		
			MY750	CTD101K	MY750	CTD101K	Mix61	MY750	CTD101K	Mix61
Peeling observations			Hard to peel. A fair continuous pull is necessary	Easy to peel after a first crack	Hard to peel. A fair continuous pull is necessary	Easy to peel after a first crack	Hard to peel. A fair continuous pull is necessary	Very easy once the polyimide removed	Very easy, don't even need to remove polyimide	Very easy to peel no adhesion. Resin is pretty flexible
Visual observation	Impregnation between cables		FB is impregnated but it did not wet the cable	FB is impregnated and it partially wet the cable	FB is impregnated but it did not wet the cable at all	FB is impregnated and it partially wet the cable	FB is impregnated but it did not wet the cable very well	Not Homogeneous some resin under the polymide on both side of the "C"	Not homogeneous. No resin under the polyimide.	Not homogeneous
	Resin between tapes		several traces	very few traces	several traces	very few traces	few traces	very few traces	almost none	almost none
	Gap between cables		329 µm	334 µm	-	426 µm	-	Not homogeneous	Not homogeneous	Not homogeneous
Electrical test	Resistance between cables [GΩ]	Before thermal cycles	705	1869	2162	> 2610	285	> 3000	> 3000	829
		After thermal cycles	593	1964	882	1269	633	> 2823	2913	536
	Resistance between tapes [mΩ]	Before thermal cycles	3.012	2.222	2.323	2.491	1.882	1.403	1.944	1.535
		After thermal cycles	3.205	2.263	2.198	1.748	1.890	1.370	1.682	1.608
		At 77K	0.520	0.362	0.333	0.349	0.242	0.212	0.165	0.234

Conclusion

Fiber glass

+ Better distribution of the cable stack
+ Better structural resistance

- Let some resin flow in between the tapes, less electrical contact

Polyimide

- Does not keep the cables away from each other
- Less resistance to peeling

+ Very good insulation between cables
+ Prevent the resin from flowing in the cable, better electrical contact

MY750

+ Not too brittle
- Does not wet too much

- Can be found between tapes

CTD101K

- Brittle, it cracks
+ Good wetting properties

+ Flows less between tapes

Mix61

+ Not too brittle

Conclusion

For Gatoroid

An insulation with fiber glass seems preferable.

For their mechanical resistance MY750 and Mix61 are preferred (I am going toward Mix61).

Next phase:
Ic degradation tests on real HTS stacks.

In general

A more exhaustive study is needed.

Explore other resins and fillers.

Advantages of polyimide are appealing. One could fix the lack of mechanical resistance coupling it with fiber glass.

Mechanical models could be used to simulate the peeling stress caused by the resins on tape stacks.

Test Plan

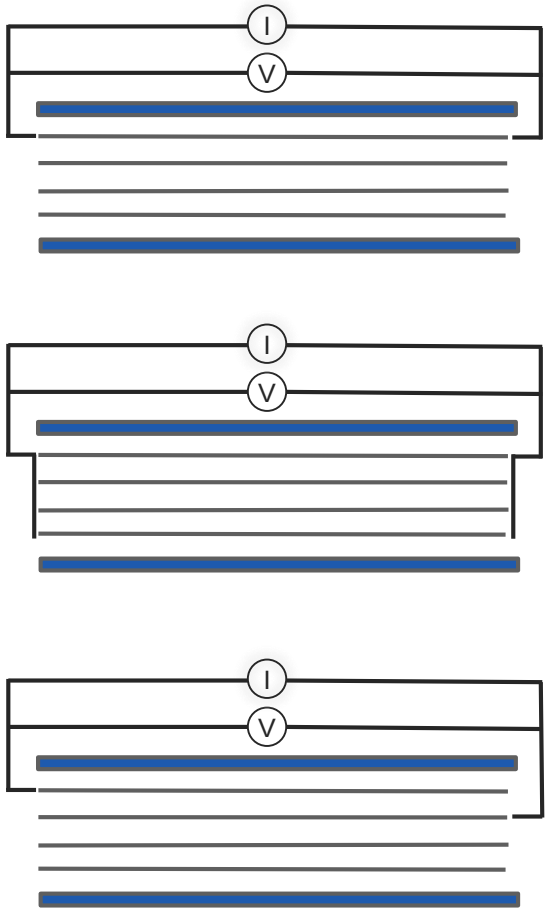
Phase 2 - Overview

To check:

- Ic measurement from 1 tape multiple times
  - Before impregnation
  - After impregnation
  - After 5 thermal cycles

- Ic measurement of 4 tapes clamped together to measure the Ic of the cable.
  - Before impregnation
  - After impregnation
  - After 5 thermal cycles

- Resistance measurements between 2 tapes at 77K, to check contact resistance.



Test Plan

HTS Tape

Gatoroid tape:

Theva TPL 5121, HTS tape (pos 4)

12 x 0.1 mm

10 μm Cu, PbSn

Ic (77K) = 380 A (manufacturer)

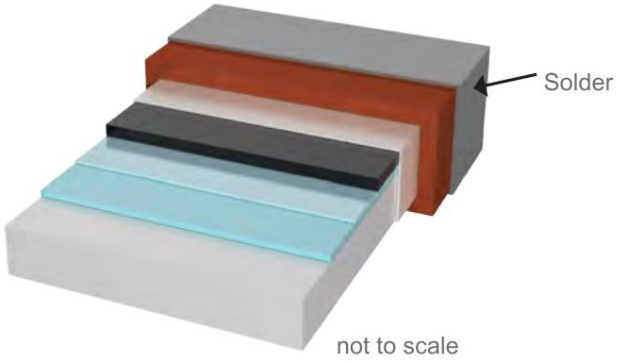
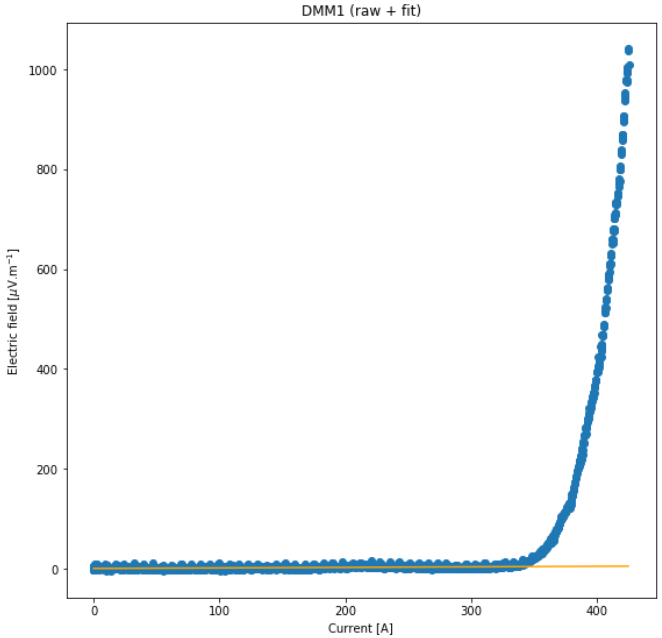
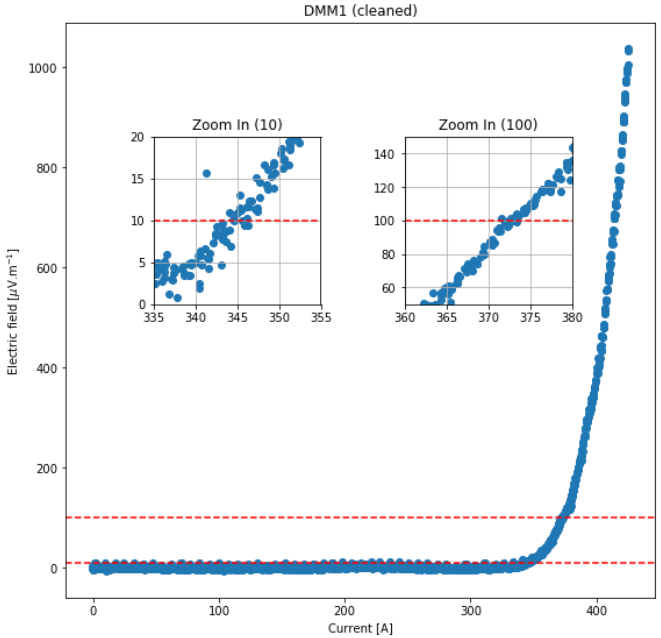


Fig. 6: Architecture of the TPL5000-series





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Thank you

Conclusion

About the resins

Viscosity:	CTD101K << Mix61 ~ MY750
Young Modulus	MY750 ~ CTD101K ~ Mix61
Yield strength	CTD101K < MY750 < Mix61
Fracture toughness	CTD101K << Mix 61 ~ MY750
Thermal shock resistance	CTD101K << Mix61 ~ MY750

Test Plan

About compression

Different shims of 1.6 mm, 2.0 mm, and 2.6 mm thick are used to modify the size of the cavity depending on the insulation type and the desired compression.

Cavity size: 12 mm
Stack without insulation : 6 mm

Fiber Glass

- Low compression: 2 + 1.6 mm (void: ~1 mm)
- High compression: 2 + 2.6 mm (void: ~0 mm)

Polyimide

- Low compression: 2 + 2.6 mm (void: ~1 mm)
- High compression: ??

Example (polyimide, low): 12 - 4 * (1.5 + 2 * 0.05) - 2 – 2.6 = 1 mm