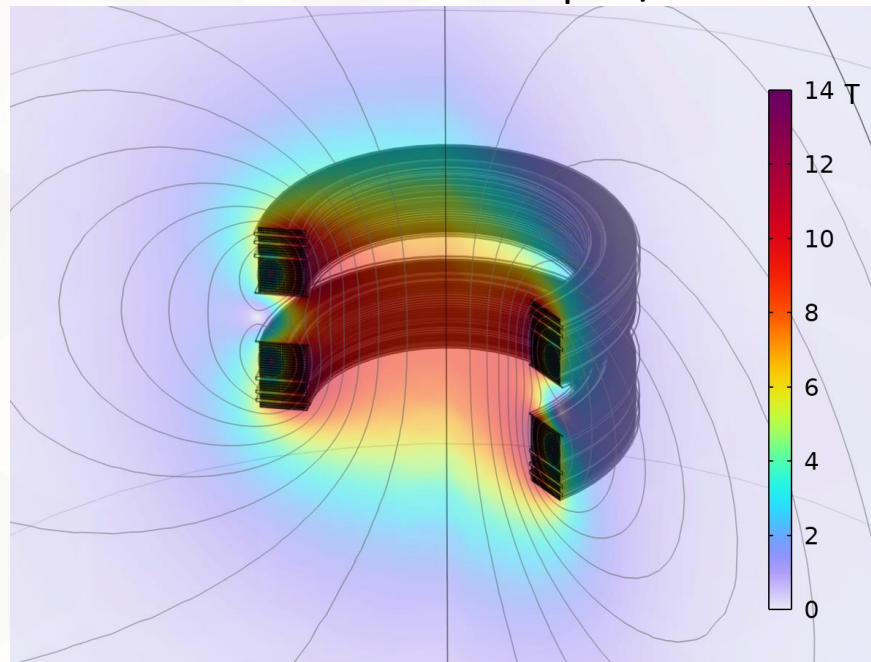


High strength (*insulated*) REBCO winding for compact large bore split coils

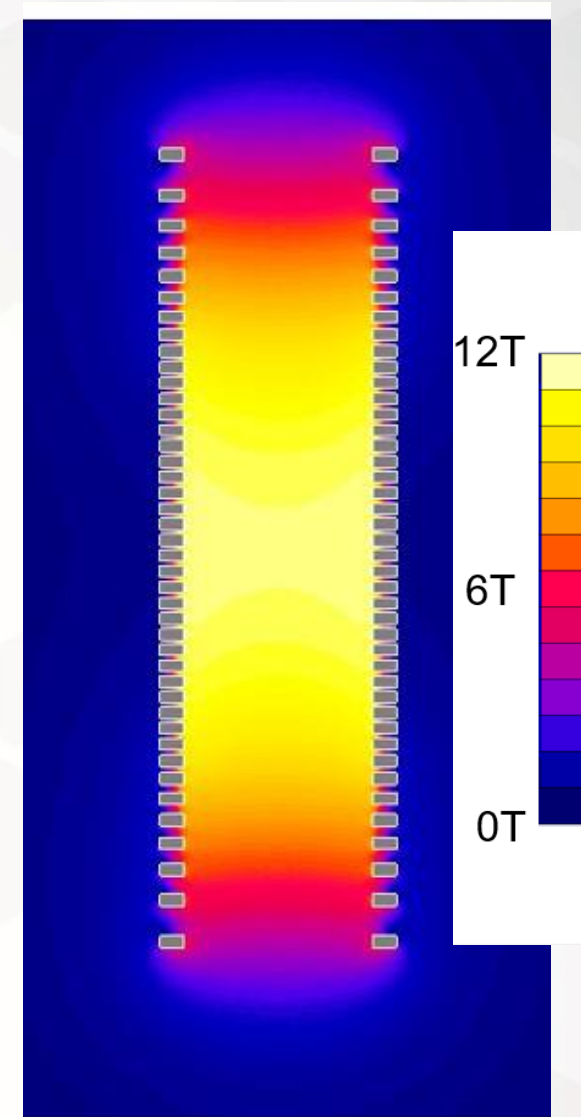
A. Badel, J. Vialle, J. Cicéron, D. Motte-Michellon, P. Tixador
Université Grenoble Alpes / CNRS



- Past experience on insulated REBCO coils
- Archymed large bore split coil project
- Conceptual design, Validation prototypes
- Design evolutions

2015 – 2020 : 1 MJ insulated solenoid based on 12 mm single tape from SuperOx

Energy	1	MJ
Height	814	mm
Inner / Outer Diameter	180 / 240	mm
B_{INT}	12	T
B_R	4.5	T
$I_{OPERATING}$	880	A
$I_{OPERATING}/I_C$	49	%
Current density (bare conductor)	772	A/mm²
Maximum hoop stress (full cond.)	421	MPa
Tape unit length	121	m
Specific energy	20	kJ/kg



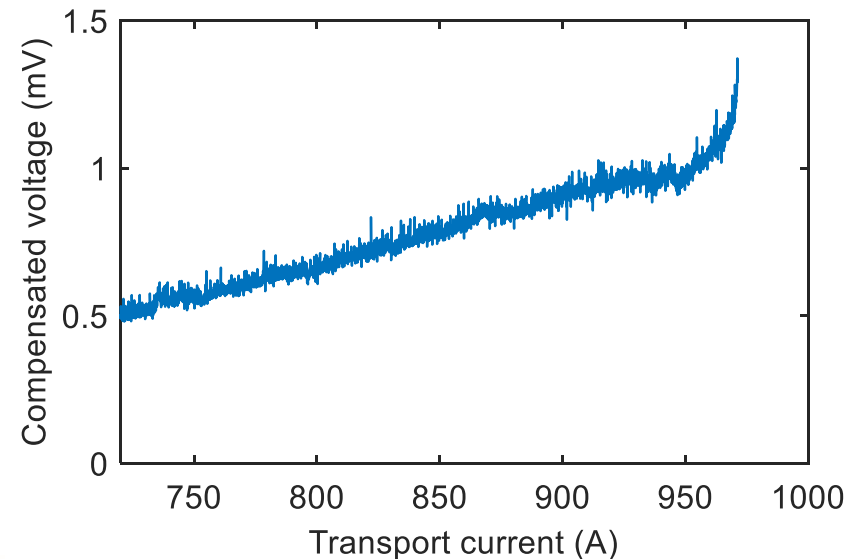
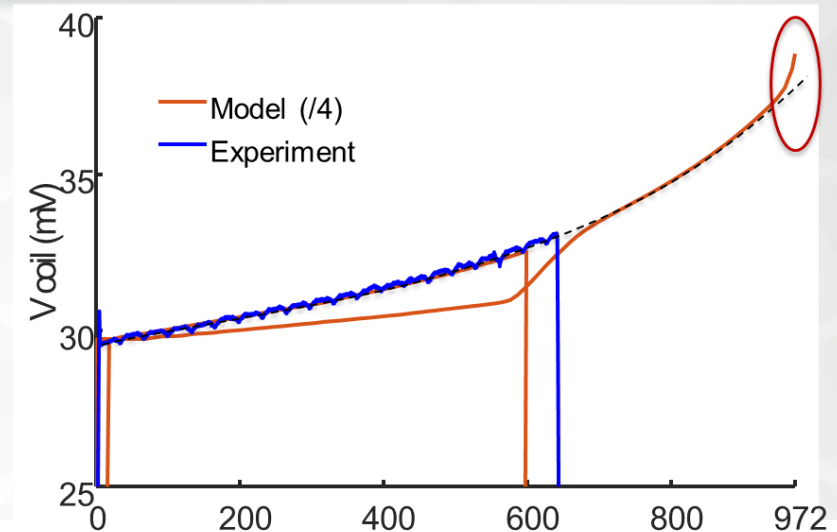
J. Ciceron TAS 2018 DOI: 10.1109/TASC.2018.2820906

2015 – 2020 : 1 MJ insulated solenoid at 4.2 K based on 12 mm single tape from SuperOx

- Insulation degrade mechanical performance
⇒ make it thinner : thin film deposition
- Single tape operation : sensitive to tape defect
⇒ Test all pancake to nominal current at 4.2 K

Preliminary results:

- Tested all 21 double-pancakes (some 2 or three times)
⇒ Practical experience (voltage drifts, noise, wire mvts)
⇒ Electromag Modelling validation
- Tests of DP in background to reach stress
- Reached « limiting » current at 973 A (850 A/mm^2)
⇒ Insulated operation possible at high J with care



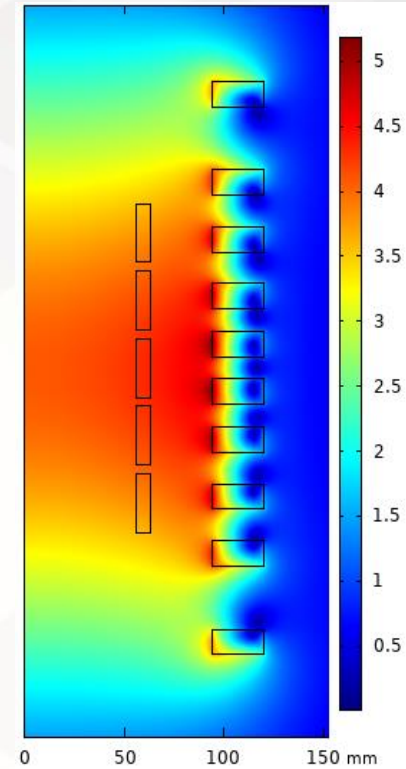
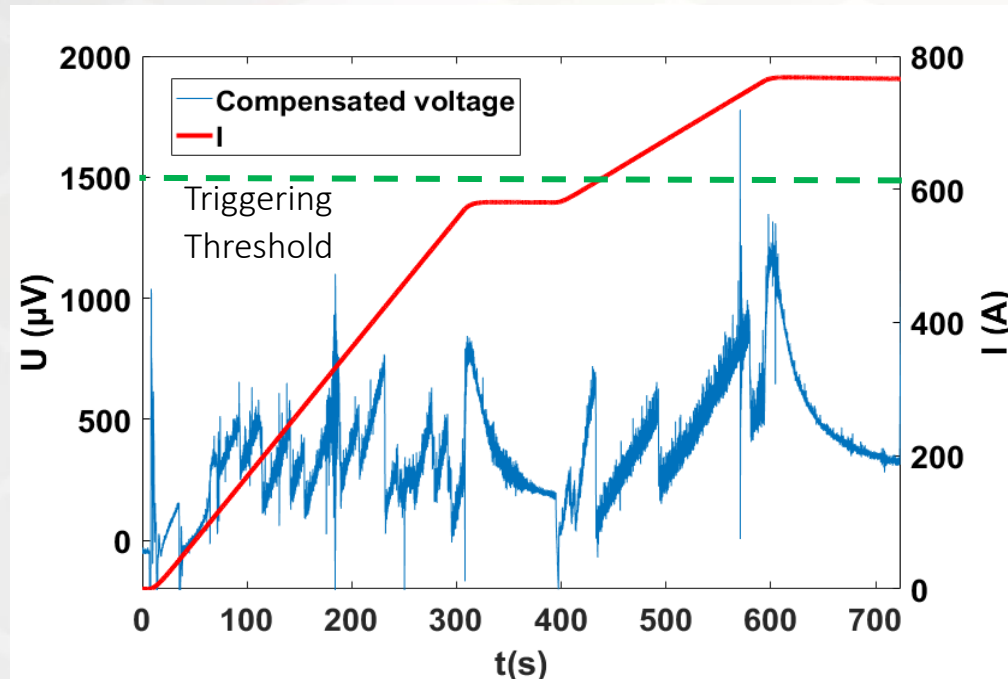
J. Ciceron TAS 2018 DOI: 10.1109/TASC.2018.2820906

2015 – 2020 : 1 MJ insulated solenoid based on 12 mm single tape from SuperOx at 4.2 K

Assembly results:

- 3 then 5 DP stack assembly tested but **no full stack test**

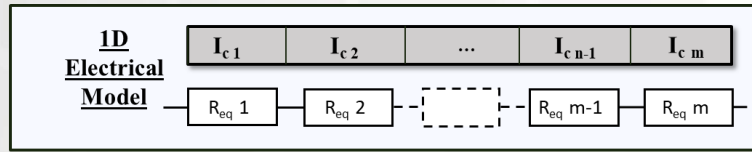
Insulation aging and copper terminal issues



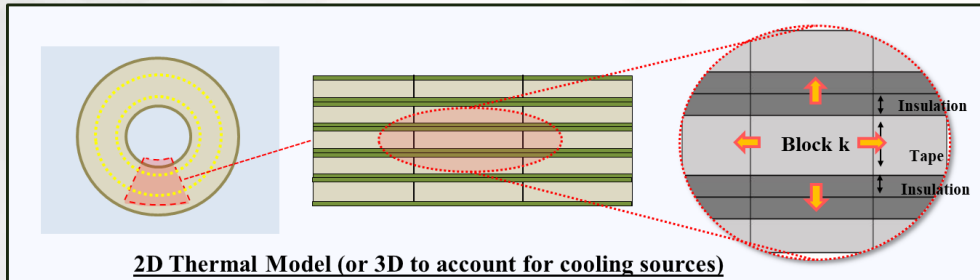
Frustrating but promising :

Insulated high current density REBCO coils can work ! (2020)

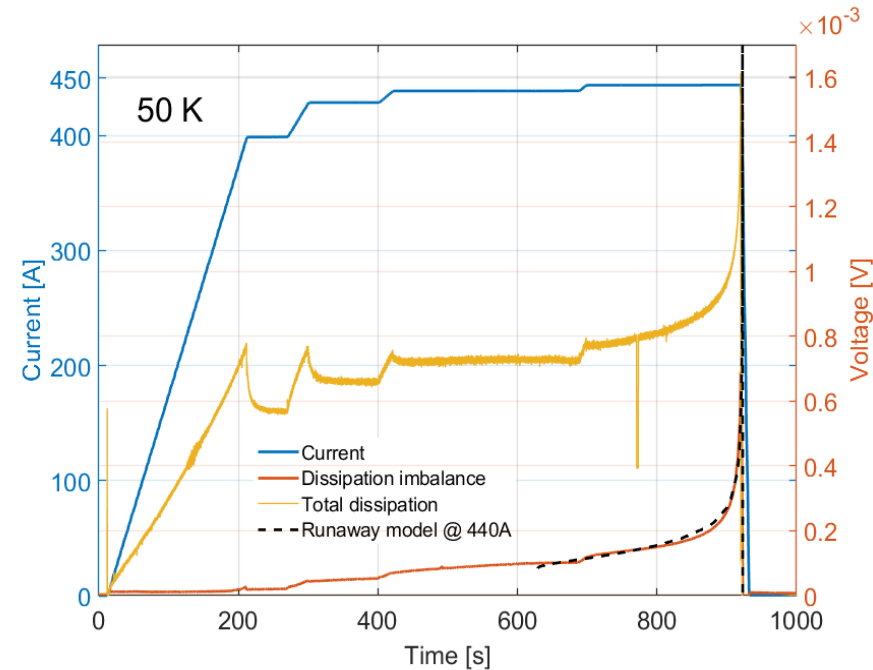
- Both « early believer » in REBCO insulated coil ... with sufficient modelling tools



Heat sources by block (Joule losses) : Q_k $t = t_n$ $t = t_{n+1}$ Average Temperature by block : T_k



Badel 2019 SuST: DOI 10.1088/1361-6668/ab181f



Abe 2022 TAS, DOI : 10.1109/TASC.2022.3163690

... and tape redundancy (2 tapes, large margin)

- Validated with large prototype from 33 T project (presentation by Pr Awaji)

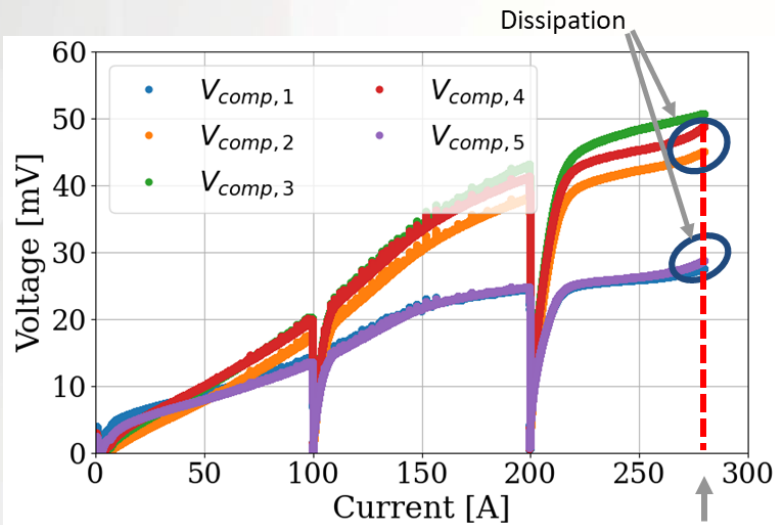
Test of 20 stack-coil using sensitive detection



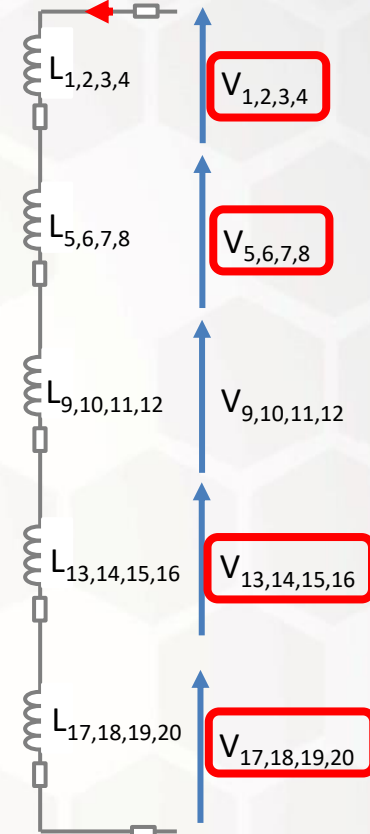
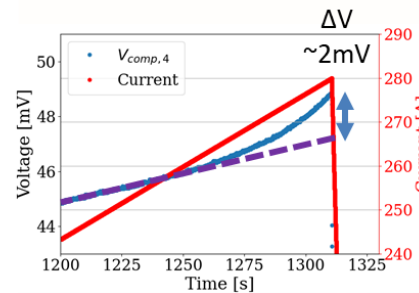
REBCO prototype insert: Characteristics	
REBCO Tape	4 mm Fujikura
Tape thickness	0.15 mm
Number of tapes per turn	2 (Face-to-back)
Number of turns per pancake	271-294
Inner diameter	68 mm
Outer Diameter	266 mm
Number of pancakes	20
Self-Inductance	2.63 H
Nominal Current	300 A
Nominal Axial Magnetic Field	11 T



$$V_{comp}(t) = V_{losses}(t) + V_{dissip\ sc}(t)$$



Limits reached safely dozens of time @ various Temp. and J_{eng} up to 250 A/mm²



Current Ramping Up (0.33 A/s) → Maximum safe Current

A. Zampa 2024 @ MT 28

- 10T, 500 mm bore split-pair magnet
 - Axial bore : Room temperature, as large as possible (no constrain)
 - Transverse bore : Room temperature, 40 mm minimum
- All-REBCO winding, closed-cycle cryogenics
.... to be built by 2028

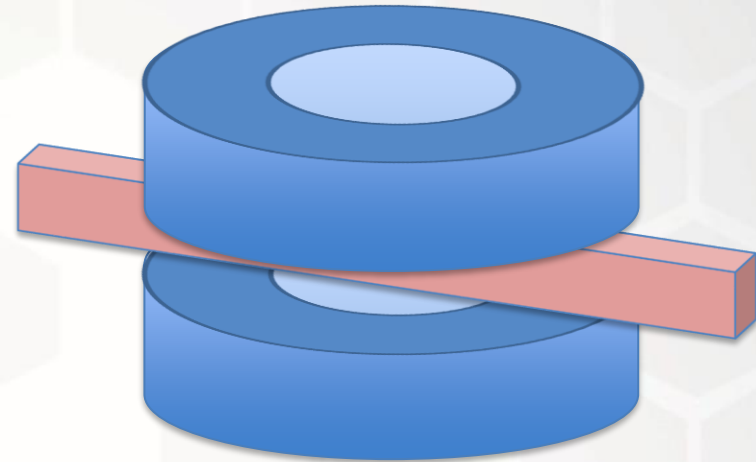
What does that mean ?

10 T in 500 mm bore, 500 mm height

- ⇒ **3.9 MJ** : Energy density at 10 kJ/kg of winding (density 9000)
- ⇒ **390 kg / 0.043 m³** : assuming 4 mm x 150 μm tape conductor
- ⇒ **72 km of tape (hopefully not all REBCO)**

- Use lesson learned from BOSSE and other Insulated REBCO coils (Tohoku univ.)

More-than-one tape co-wound conductor / thin and stiff insulation



- **Winding based on « Robust REBCO Coil » structure**

Awaji, IEEE TAS 31(5), 4300105, 2021

- Isolated winding, two-tape + insulation co-wound
- Thin FRP flange + Edge impregnation

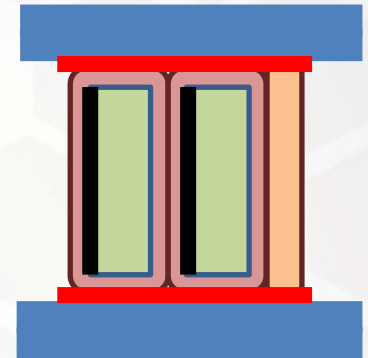
- **Winding as thin as possible**

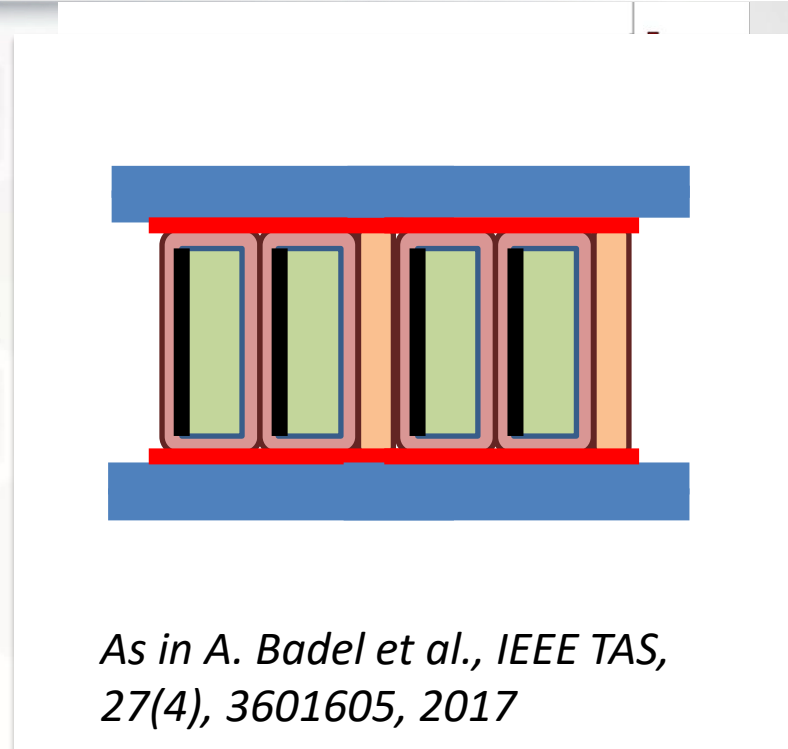
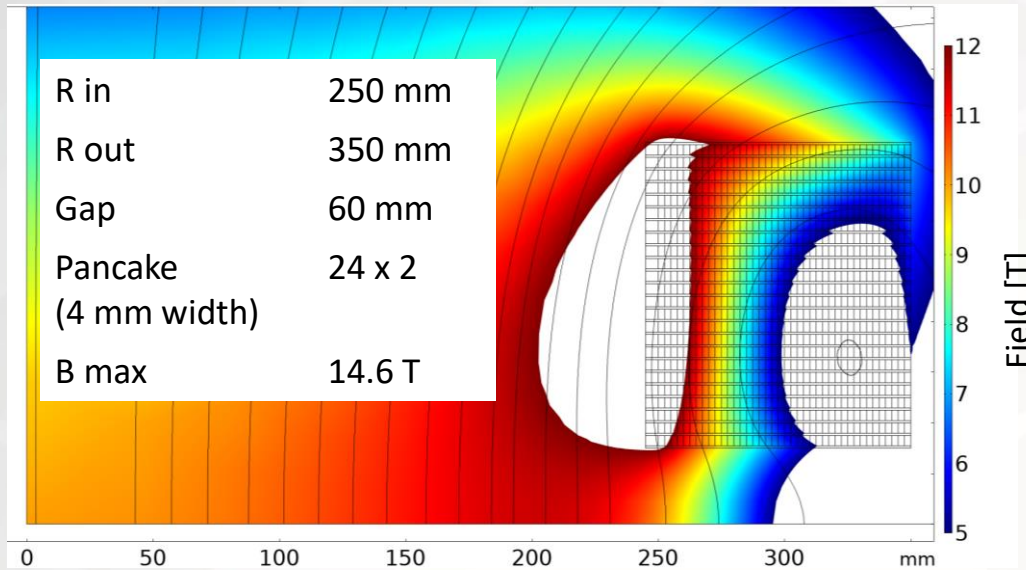
- Reduce conductor cost,
- Limit winding risk
- Contain inductance

- **Current density compatible with quench detection / fast dumping**

⇒ Ideally tape $J_e < 400 \text{ A/mm}^2$

Badel, IEEE TAS 34(5), 4301205, 2024





As in A. Badel et al., IEEE TAS, 27(4), 3601605, 2017

- **405 A** on 2 tape (expected $I_c > 1000 \text{ A @ } 4.2 \text{ K}$)
- **52 km** of 4mm-wide REBCO tape
- Hoop stress : **450 MPa**
(1500 if BJR !)
- $7.4 \text{ MJ} \Rightarrow L_{\text{total}} = \mathbf{90 \text{ H !!}}$

With 4 independent coils :
 $L_{\text{coil}} = \mathbf{22.5 \text{ H}}$

Design improvement

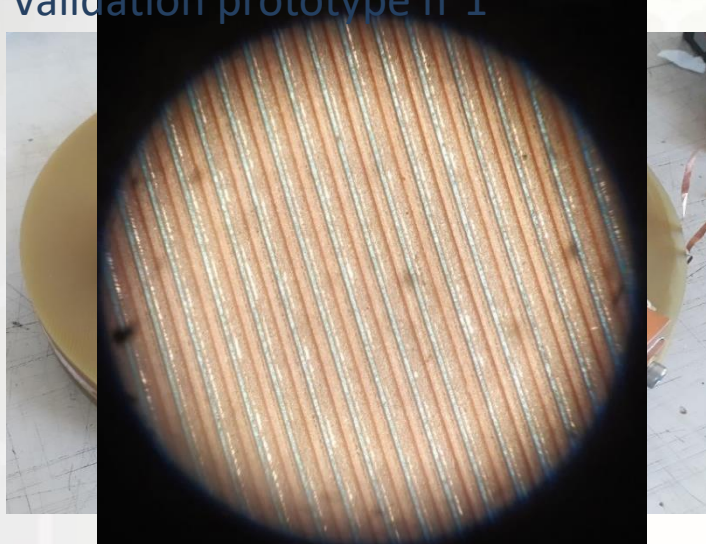
- Independent current leads for top/bottom halves
- 4 co-wound tape bundle ?
- Reinforced winding : **Less turns, less margin**

Reinforced conductor : replace polyimide insulator

MgO-coated Hastelloy as insulating co-winding

- ✓ 20 % stress reduction on tape
- ✓ Improve radial stress transfer

Validation prototype n°1



Pancake specifications	
Tape dimension (Fujikura FESC)	4 mm wide / 150 μ m thick
No. of bundled tape	2 (face-to-back)
Tape reinforcement	50 μ m (hastelloy)
MgO insulation thickness	5 μm
No. of turns	155
Inner diameter	148 mm
Outer diameter	257 mm

Reinforcement / Insulation tape from Theva

J. Vialle et al., IEEE TAS, 33(5), 4600405, 2023

- Validated up to 500 MPa hoop stress (eq. to 600 with soft insulation) in 8T back. @ HFLSM
- Insulation appeared « sufficient » at low voltage (30 mV per turn)

With Reinforced conductor

MgO-coated Hastelloy as insulating co-winding

- ✓ 20 % stress reduction on tape
- ✓ Improve radial stress transfer

⇒ Outer diameter reduced to 328 mm : *tape length – 40 % !*

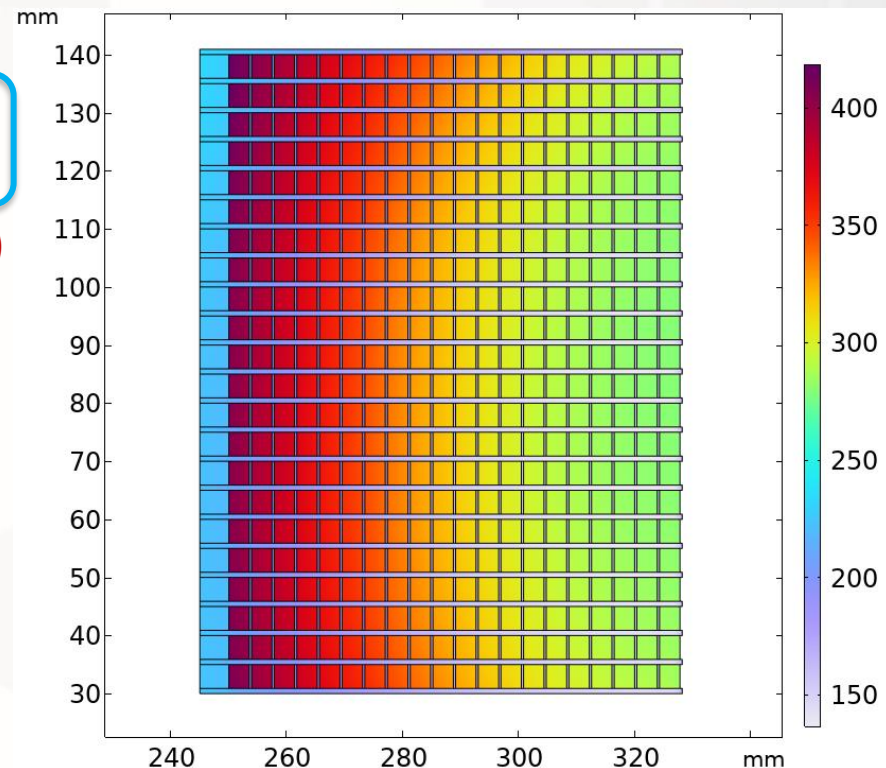
⇒ Reduce peak stress to *428 MPa*

still 1500 MPa at inner turn if unsupported

⇒ **Radial stress 100 % compressive**

⇒ *I_{nom} increased to 500 A on 2 tapes (+ 25 %)*

Full impregnation possible ?



- Reinforced conductor : replace polyimide insulator

MgO-coated Hastelloy as insulating co-winding

- ✓ 20 % stress reduction on tape
- ✓ Improve radial stress transfer

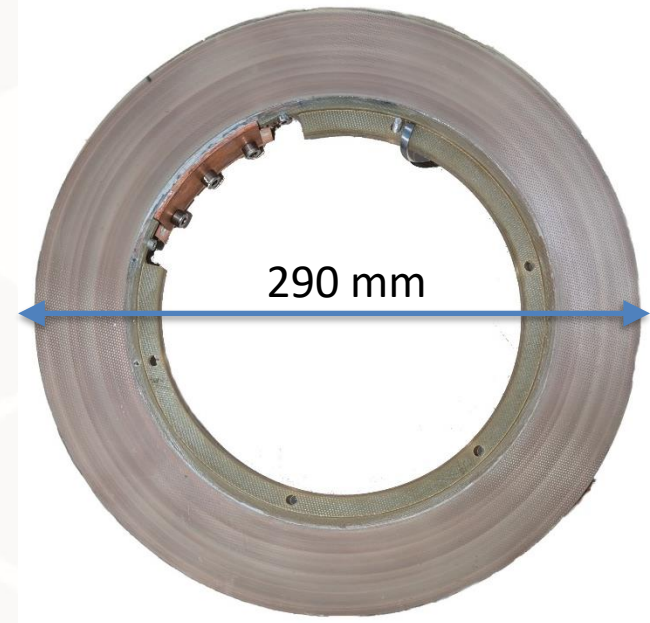
- Double pancake structure

Full epoxy impregnation

- ✓ Enhance stiffness
- ✓ Reduce risk of stress concentration @ inner contact

Validation prototype 2 : Single pancake Rout/Rin 1.45

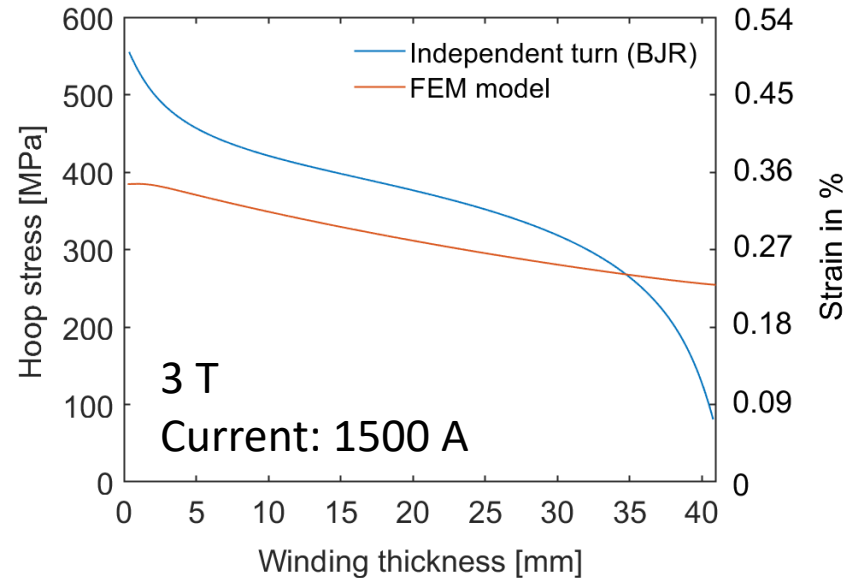
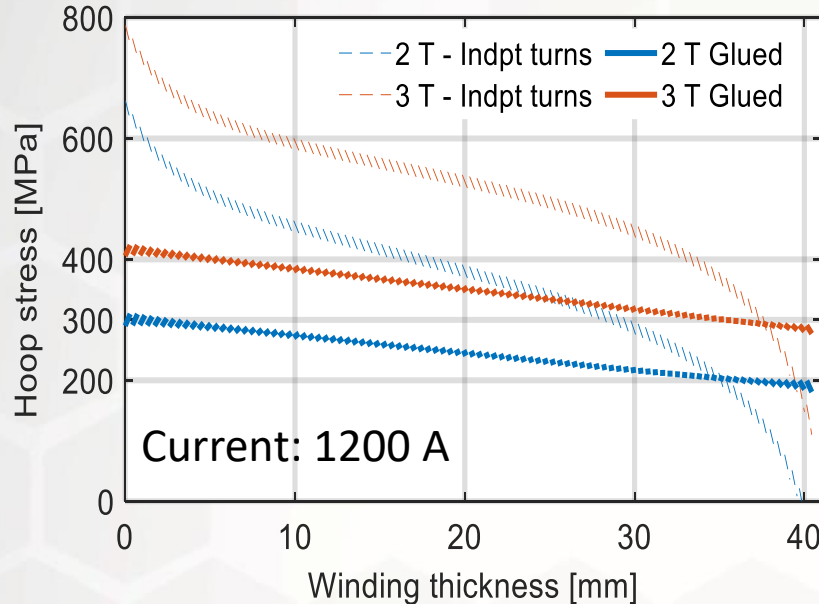
Prototype SP2 specifications	
REBCO Tape (Faraday Factory Japan)	4 mm wide / 90 µm thick
Number	2 (face-to-back)
Reinforcement / insulation tape (Theva)	4 mm wide / 50+5 µm Hastelloy + MgO
Number	2 (back-to-back)
No. of turns	140 expected
Inner / outer diameter	200 / 290 mm



Single pancake Rout/Rin 1.45

Full epoxy impregnation

- ✓ Enhance stiffness
- ✓ Reduce risk of stress concentration @ inner contact

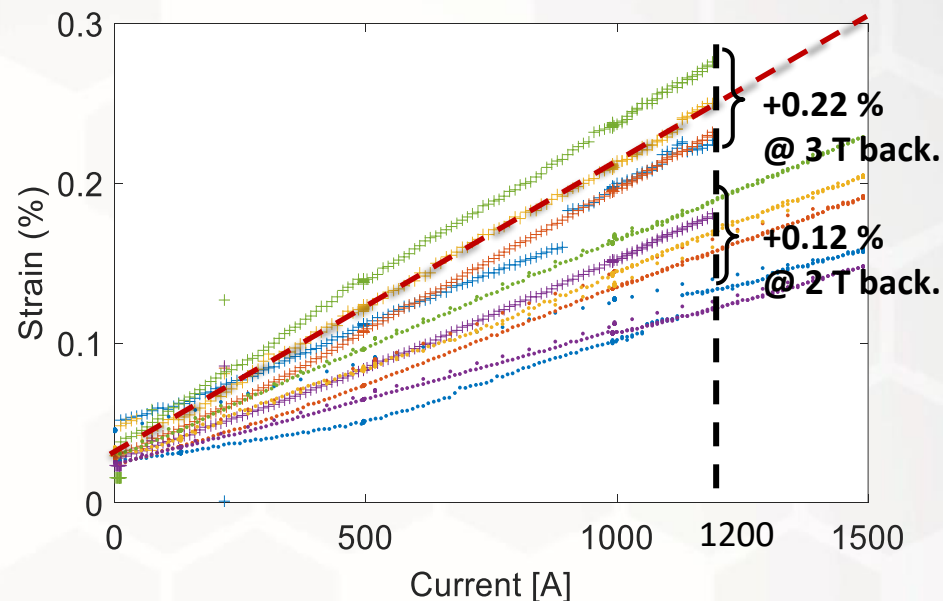
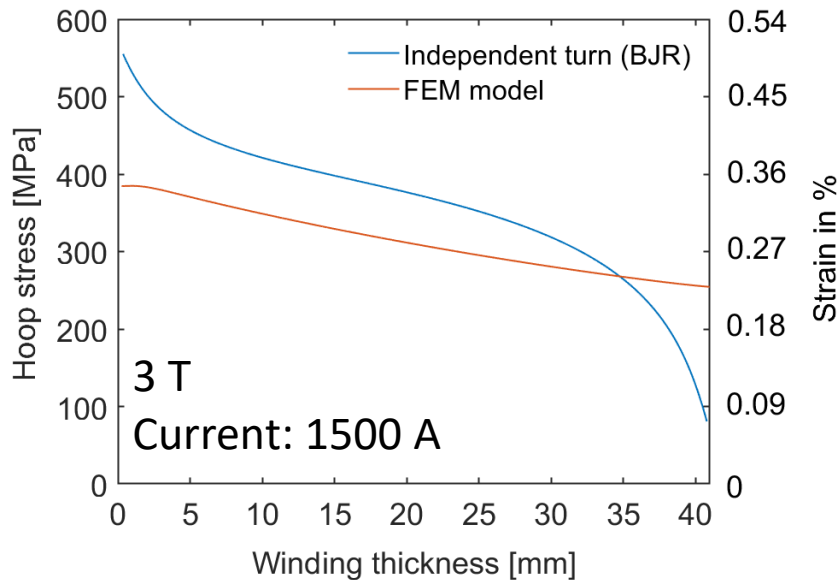


- The turn number is 2/3 of expected value
⇒ too much epoxy, stiffness is reduced

Single pancake Rout/Rin 1.45

Full epoxy impregnation

- ✓ Enhance stiffness
- ✓ Reduce risk of stress concentration @ inner contact

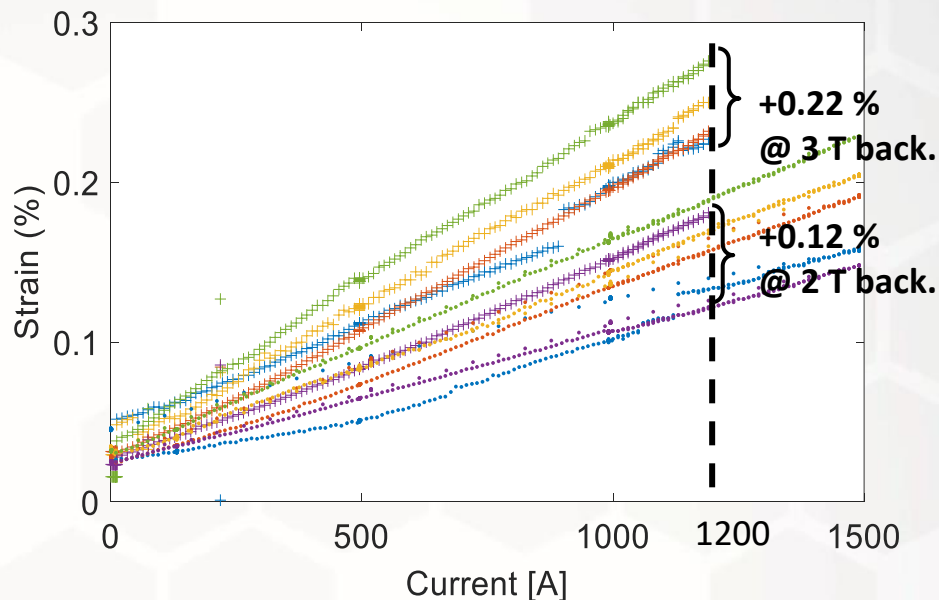
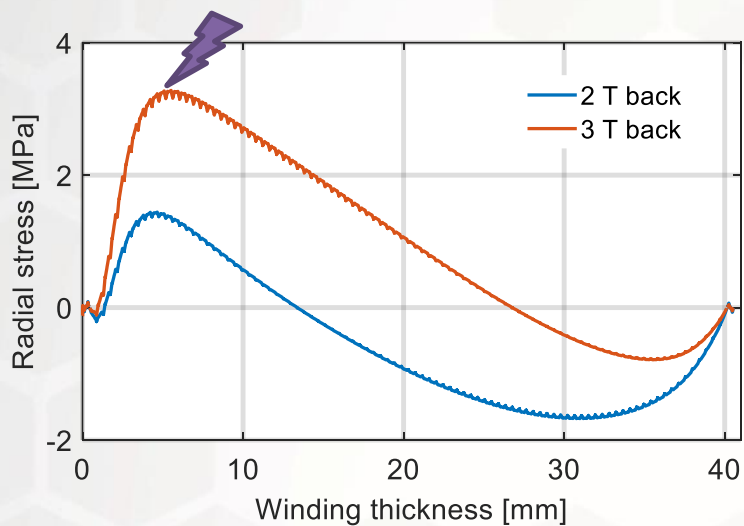


- Survive cooling, effective stress redistribution **Destroyed at 1200 A (3 MPa radial stress)**
- Hoop stress up to 300 MPa @ 1200 A under 3 T background field

Single pancake Rout/Rin 1.45

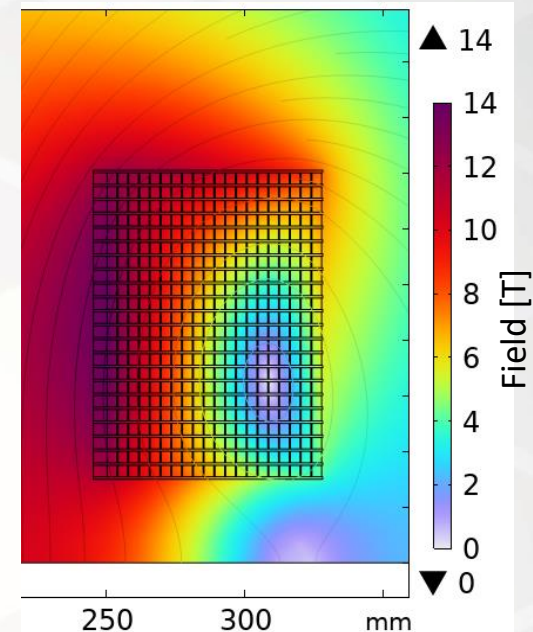
Full epoxy impregnation

- ✓ Enhance stiffness
- ✓ Reduce risk of stress concentration @ inner contact



- Survive cooling, effective stress redistribution
 - Hoop stress up to 400 MPa @ 1200 A under 3 T background field
- Destroyed at 1200 A (3 MPa radial stress)

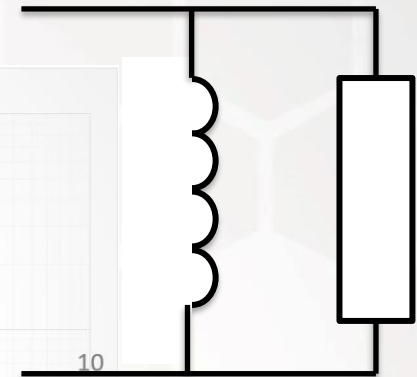
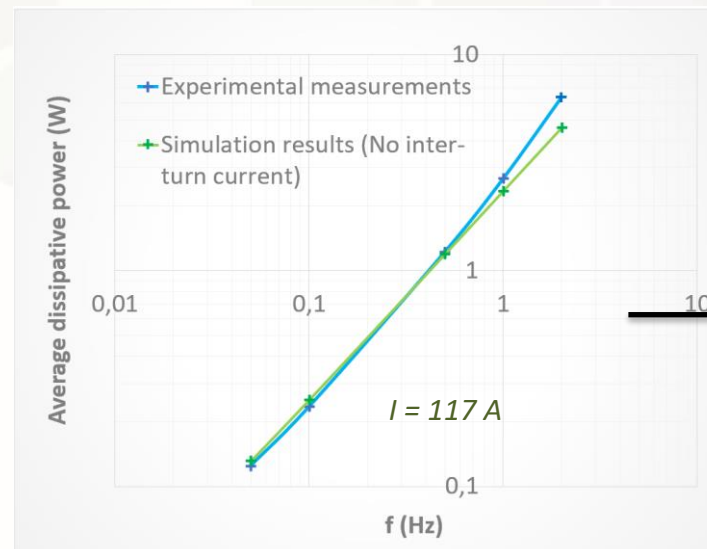
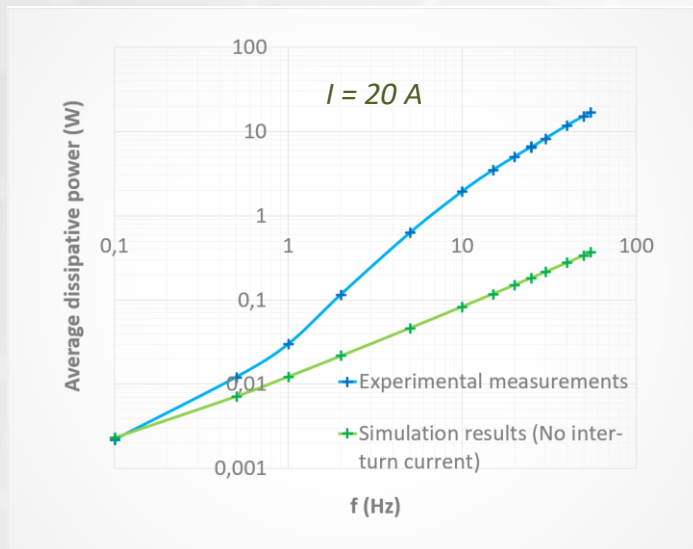
- 2 x 11 Double Pancakes : 6 tape co-wound bundle
4 REBCO + 2 Hastelloy / MgO
- Inner / outer radius : 250 / 328 mm
- Tape unit lengths per DP : 400 m – **total length 35 km**
- I_{nom} : 1000 A, on 4 tapes : 50 % margin @ 20 K
- Max stress : **420 MPa**
- $E_{mag} = 6$ MJ in 2 independent coils
 $L_{coil} = 12$ H $\Rightarrow V_{discharge} = 1$ kV for $L/R=6s$ (400 mV/turn)



Validation prototype 3 : Insulation evaluation using AC tests:

How to validate turn-to-turn insulation/contact resistance on small prototype ?

L/R ratio of prototype very low in any case... hard to be sensitive

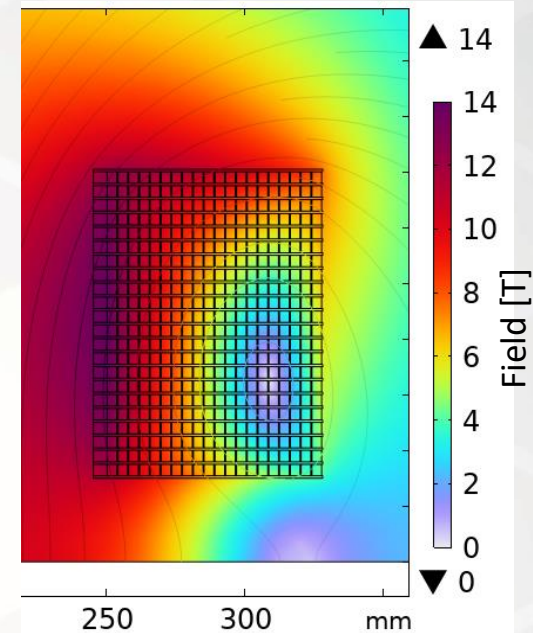


- Model w/ insulated turns : losses underestimation at higher voltages
- Influence of measurement conditions (cryostat, current leads, etc....)

Is the insulation « good enough » for full scale ? Still ongoing

Archymed re-design (2)

- 2 x 11 Double Pancakes : 6 tape co-wound bundle
4 REBCO + 2 Hastelloy / MgO
- Inner / outer radius : 250 / 328 mm
- Tape unit lengths per DP : 400 m – **total length 35 km**
- I_{nom} : 1000 A, on 4 tapes : 50 % margin @ 20 K
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Validation prototype 3 : Insulation evaluation using AC tests:

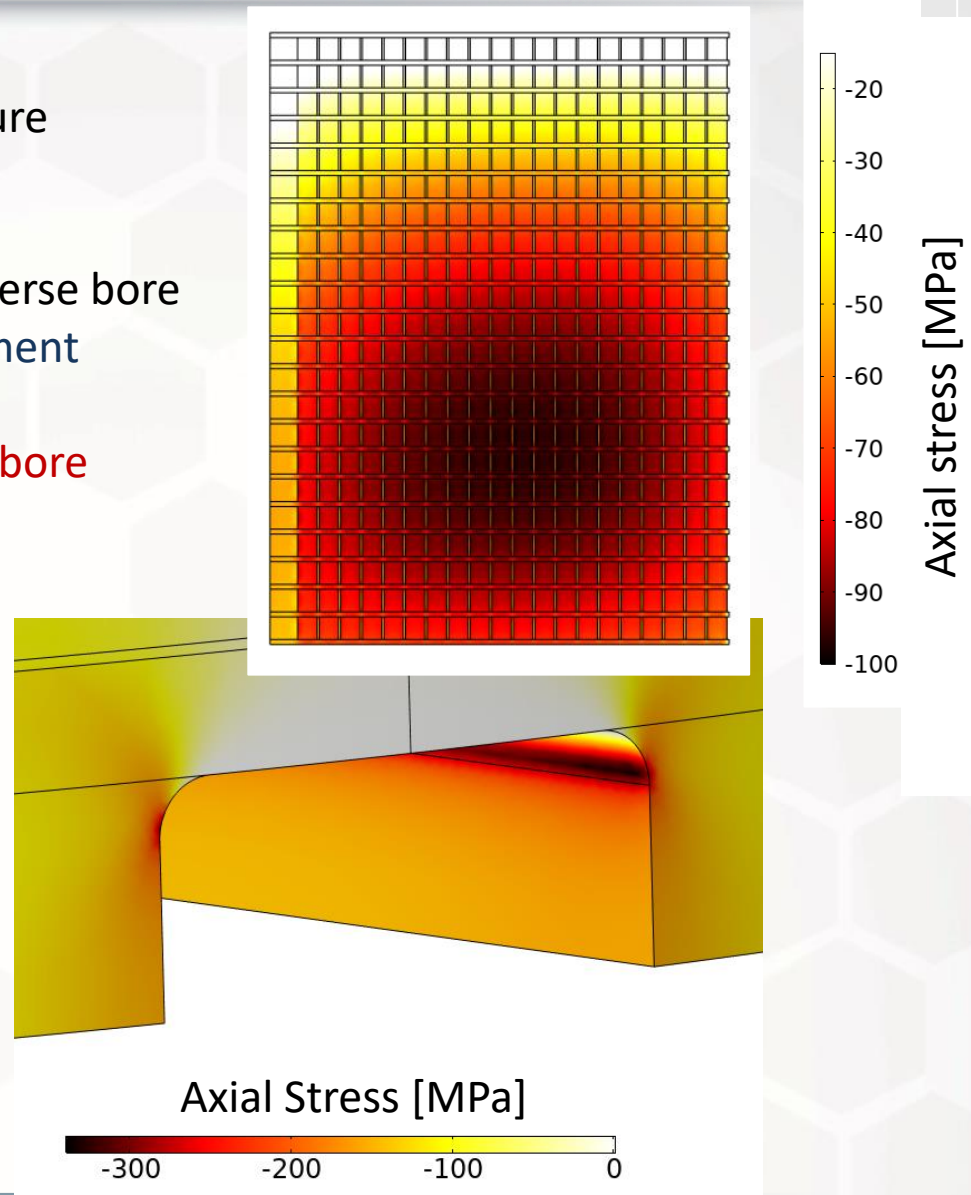
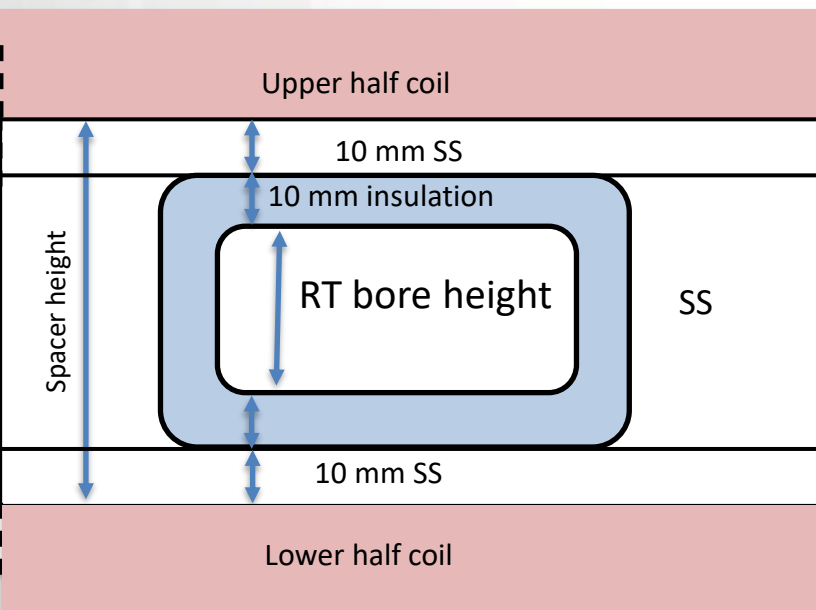
Insulation tested up to 340 mV / turn ... to be continued

What is left ? Axial pressure ! Hard to validate with prototypes

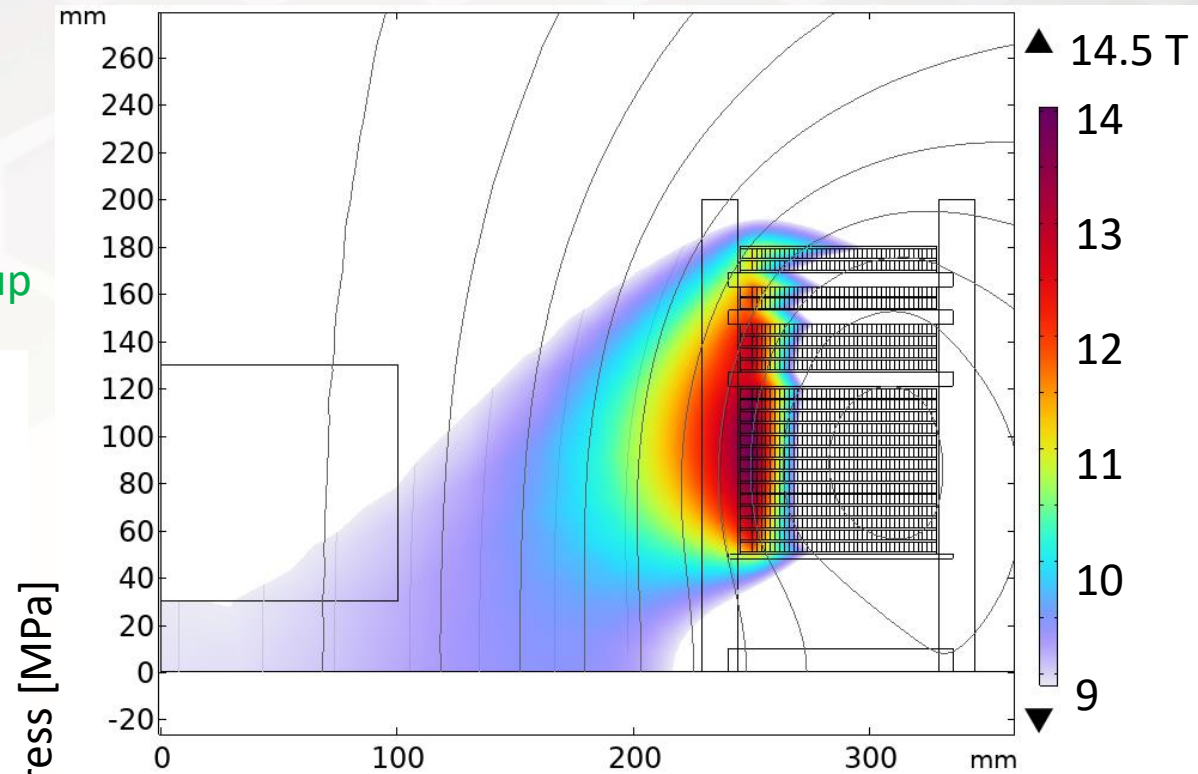
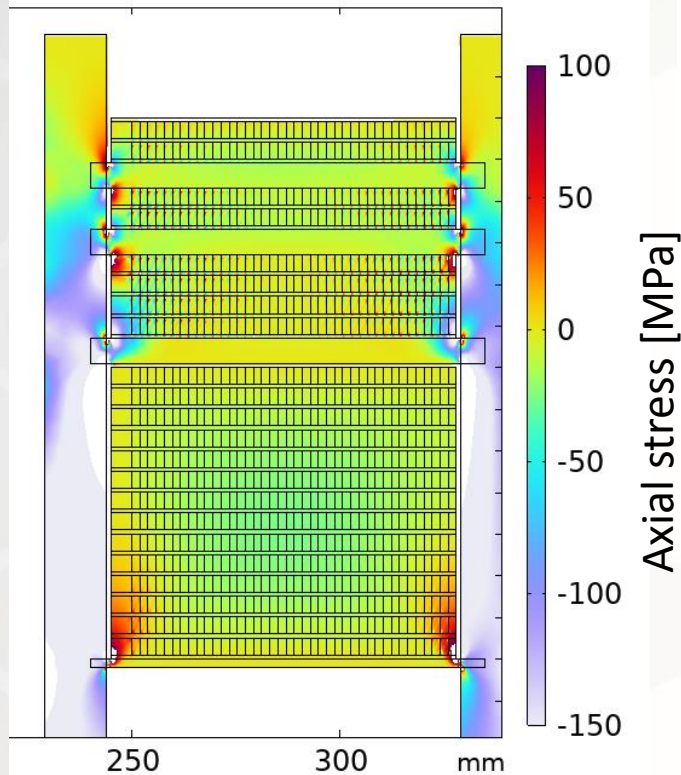
Axial pressure and transverse bore

- Severe risk above 50 MPa of axial pressure (from literature)
- Significant deformation on top of transverse bore need 10 mm steel plate reinforcement

⇒ Impossible to obtain 40 mm RT bore



- Stored energy 6 MJ
 - 2 x 11 DP
 - Intermediate flanges and support tubes
- ⇒ Reduce axial pressure build up

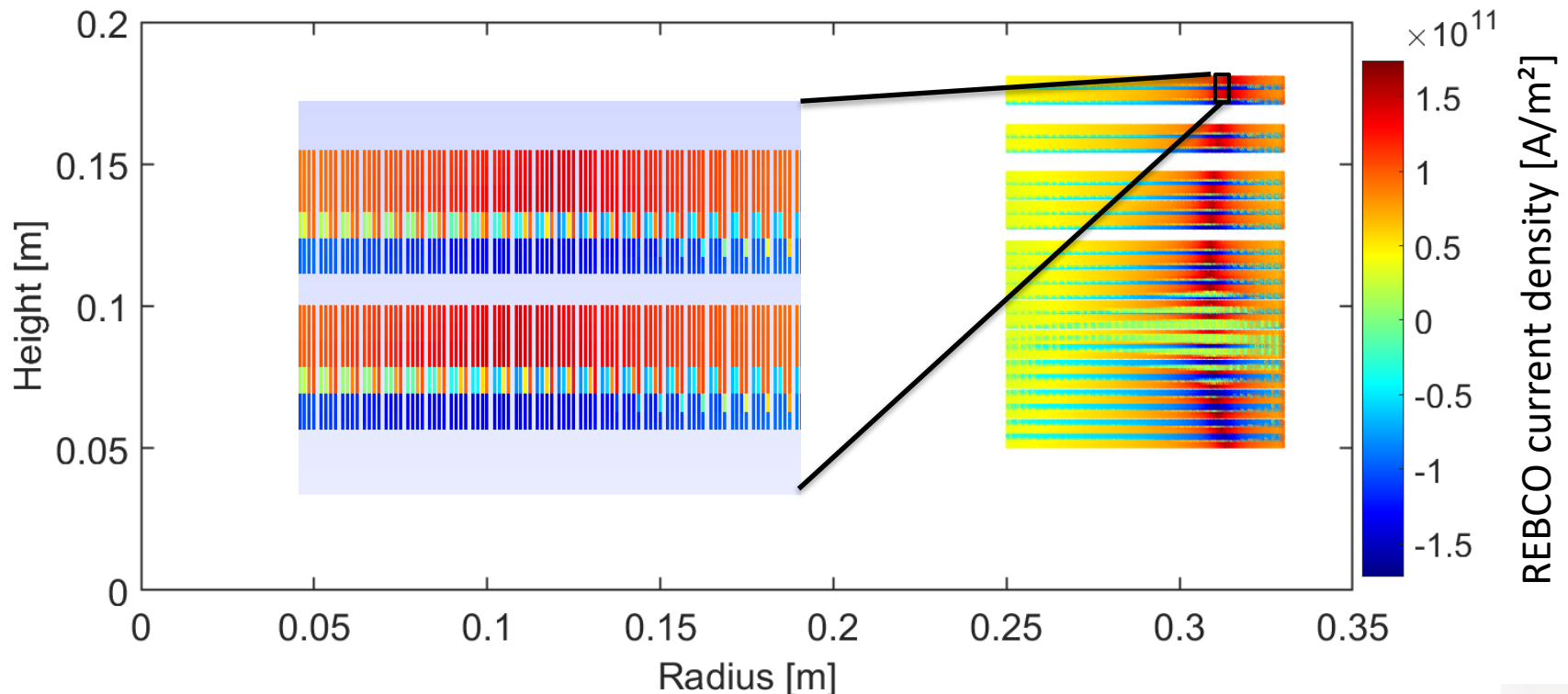


Almost no pressure on midplane spacer
⇒ increase transverse RT bore height ?

Support structure implementation to be defined

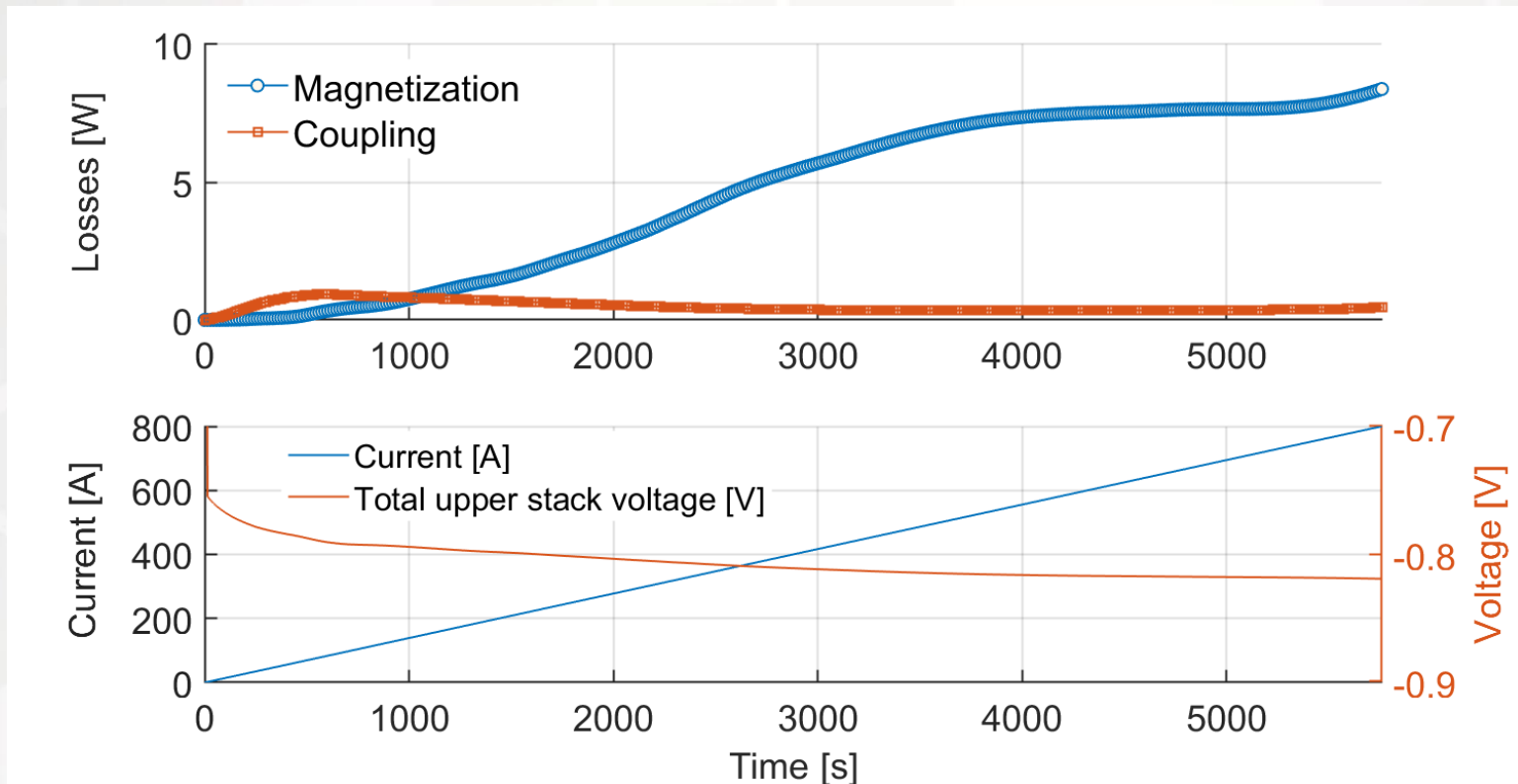
- Required to adapt detection scheme (from past experience)
- Ongoing Electromag model development using Integral formulation

2D axisymmetrical, circuit coupling account for tape-to-tape contact resistance
- in co-wound stack - in between turns if needed



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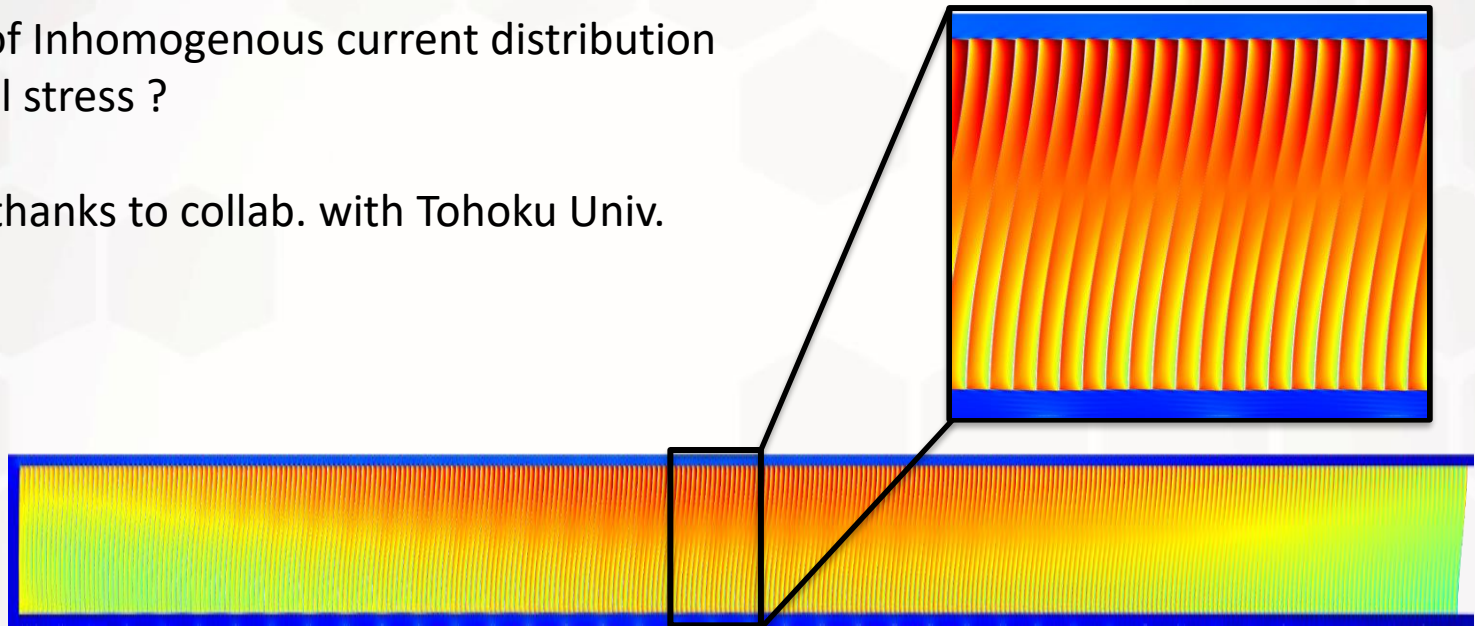


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- Ongoing Electromag model development using Integral formulation

2D axisymmetrical, circuit coupling account for tape-to-tape contact resistance
- in co-wound stack - in between turns if needed

- Effect of Inhomogenous current distribution on local stress ?

Ongoing, thanks to collab. with Tohoku Univ.



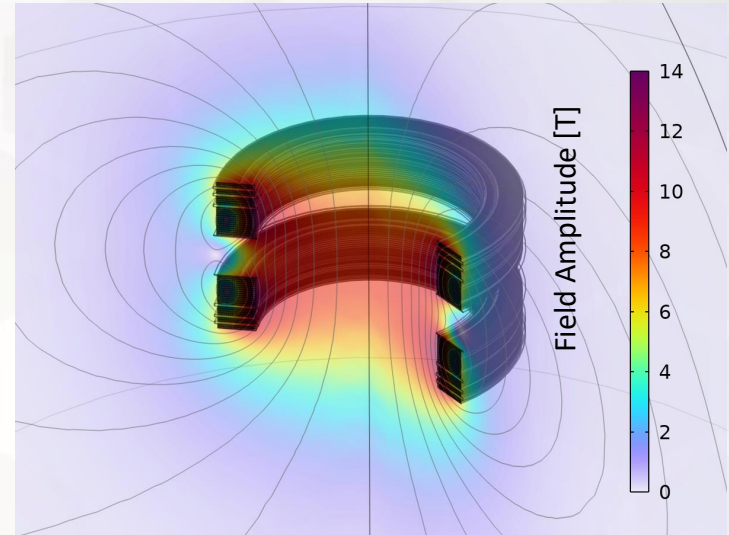
Past results from 33 T project test pancake (presented at ICMC 2021)

Archymed goal are very ambitious:

All REBCO,
conduction-cooled,
10 T / 500 mm split-pair magnet

+ RT transverse bore

+ tight (!) budget constrains



- Previous works and collaborations show narrow path of feasibility :
stress management, thermal runaway protection, etc
- Prototypes push the limits of safe operation for insulated REBCO magnets
Je up to **500 A/mm²** , **500 MPa** averaged hoop stress, dB/dT up to **2.5 T/s**
- Cryogenic design and cold mass support detailed design to be completed

*Acknowledgment: French DGA funding, Tohoku Univ. HFLSM and GIMRT program,
LNCFMI Grenoble*