IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

TOHOKU UNIVERSITY

2021 Virtual Coated Conductors for Applications (Virtual CCA 2021)
October 11-15, 2021, ONLINE

Robust REBCO Coil Structure for High Field Cryogen-free Superconducting Magnet

S. Awaji[1], A. Badel[1, 4], K. Takahashi[1], T. Abe[1], T. Okada[1], S. Fujita[2], S. Muto[2], M. Daibo[2], Y. Iijima[2], T. Uto[3], S. Hanai[3], S.Hanai[3] and S. Ioka[3]
High Field Laboratory for Superconducting Materials (HFLSM), Institute for Materials Research, Tohoku University[1]
Fujikura Ltd.[2]
Toshiba Energy System & Solutions Corporation[3]
Grenoble Electrical Engineering (G2ELAB)[4]

HFLSM Sendai

A part of project is supported by KAKENHI (18H05248) in ministry of education, Japan.

Research

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

High Field Magnet Development at HFLSM - Load map -

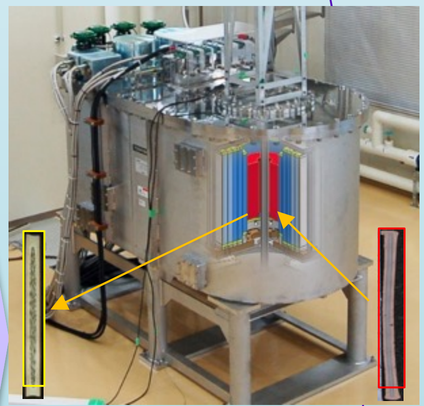
2015

25 T cryogen-free Superconducting Magnet (25T-CSM)

- 24.6 T in a 52 mm RT bore with 1 hour ramping
- Advanced high strength Nb_3Sn technologies and high strength Bi2223 (Type HT-Nx (SEI))
- World highest field in CSM
- Open for users since 2016 (250 days operation in 2018)
- 25.1 T achieved in 2020
- Long time, high precision experiments
- J_c-B-T-θ of HTS, transport, NMR, high pressure, etc.

2018-2022

Upgrade to 30T-CSM (JSPS project)



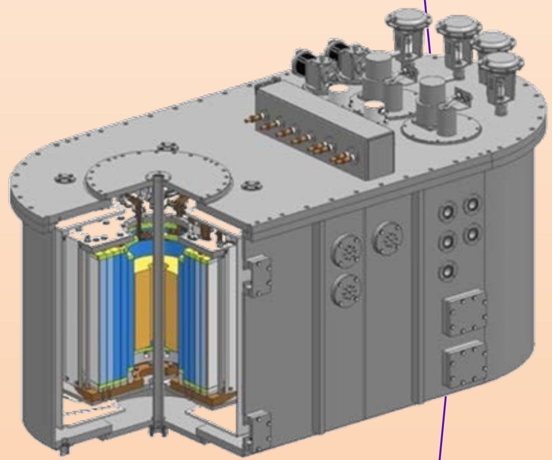
- Replace from Bi2223 insert to REBCO one.
- R&D toward to 33T

S. Awaji IEEE TAS 31 (2021) 4300105

2022-

NEW 33T-CSM

- High strength Nb_3Sn
- REBCO conductors
- Adv. HTS coil technol.



Superconducting magnet technology beyond 40 T

50T Superconducting magnet

Under "High Magnetic Field Collaboratory Japan" project

HFLSM Sendai

Summary and issues of commercial REBCO CC tapes

MT26 International Conference on Magnet Technology Vancouver, Canada | 2019

- ✓ Excellent in-field Jc and electromechanical properties.
  - ✓ Stress tolerance decreases with decreasing volume fraction of Hastelloy
- ✓ APC is effective to improve in-field Jc properties.
  - ✓ Angular dependence of Jc is not complicated below 20 K even for REBCO with APC.

Issues

- ✓ Delamination and the local degradation.
  - ✓ Current share is a key to overcome the hotspot.
- ✓ Screening current induced field and stress
- ✓ Piece length: typically 100m, 2-300m (high cost), Is 1km possible?,
- ✓ Cost: ≈ \$50/m (4mm-width), Need less than \$10/m?
- ✓ Protection from the hot-spot is critical.
  - ✓ No-insulation (self-protection)-> delay of magnetic field and heating are issues.
  - ✓ Quench heater (Active protection) -> need huge power in quench heater with short time.
  - ✓ Dump resistor (Passive protection) -> need detection and quick dump before burn-out

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

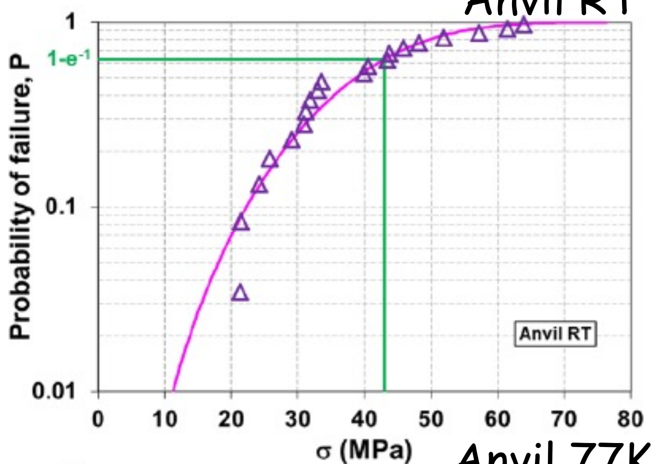
HFLSM Sendai

Issues of REBCO coated conductors for high field magnets

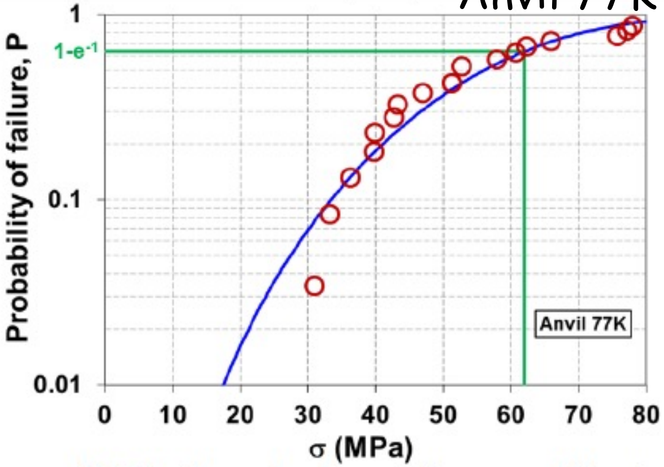
✓ Delamination and local degradation

D. Hazelton. WAMHTS-4, 2017

Anvil RT



Anvil 77K

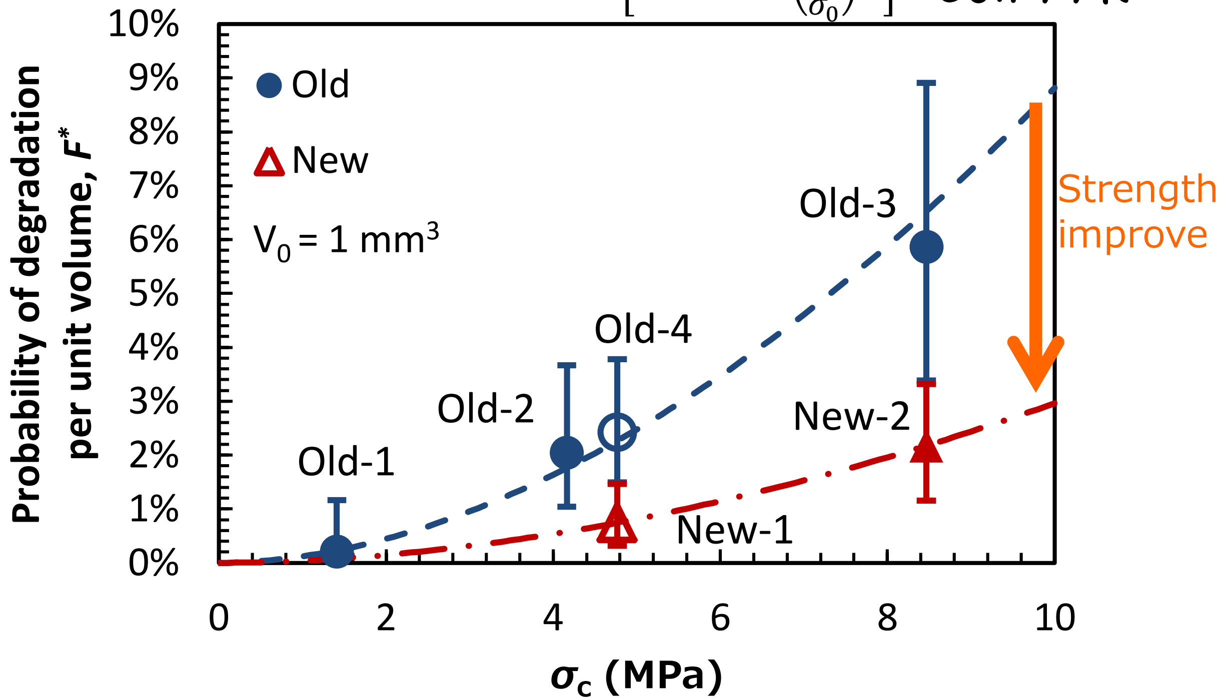


Muto et al., IEEE TAS 28 (2018) 6601004 .

Open symbol : 2.6 m
Closed symbol : 4.2 m

$$F(\sigma_c, V) = 1 - \exp\left[-V_E(m,V)\left(\frac{\sigma_c}{\sigma_0}\right)^m\right]$$

Coil 77K

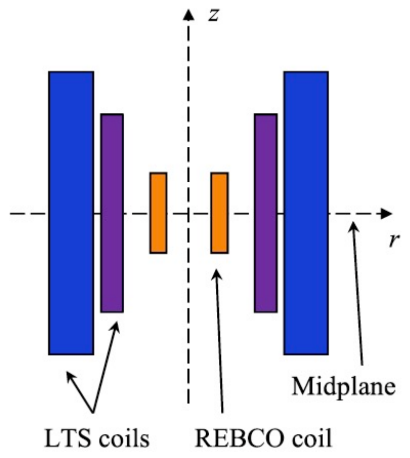


σ_c is estimated for R/in/Rout ratio.

It may be impossible to avoid the local degradation statistically, although its possibility can be reduced so much.

HFLSM Sendai

Issues of REBCO coated conductors for high field magnets



REBCO insert for 32T-SM
(B_{LTS}=15T, B_{HTS}=10.7T)

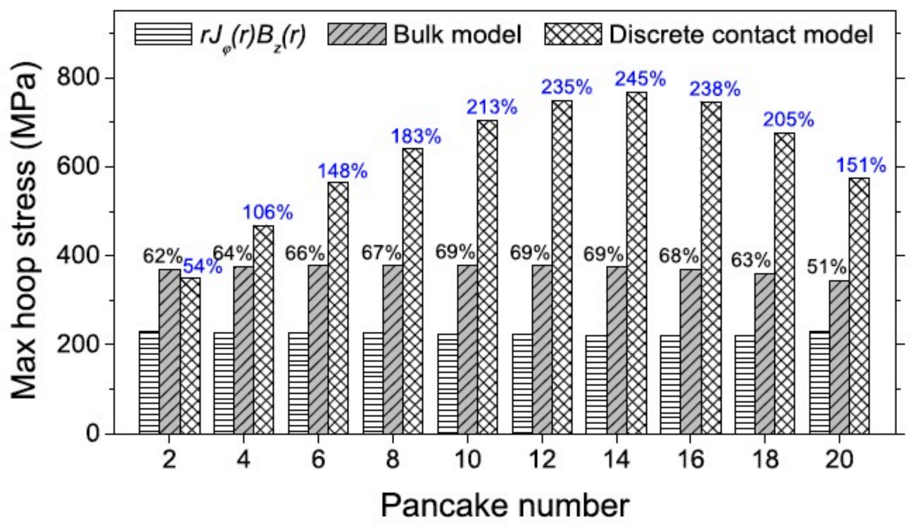
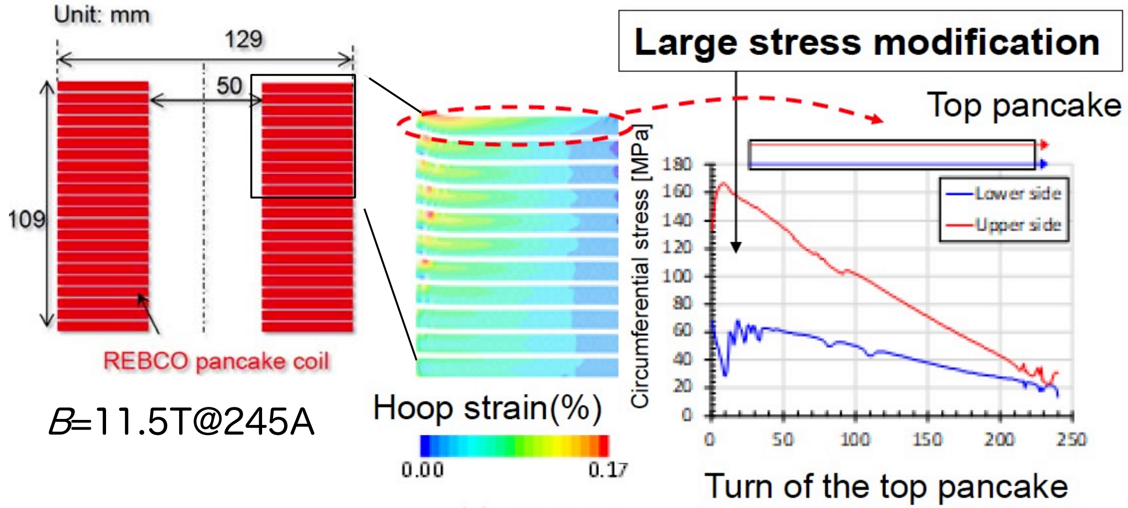
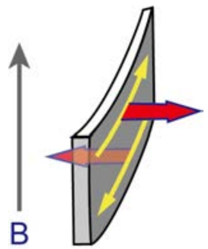


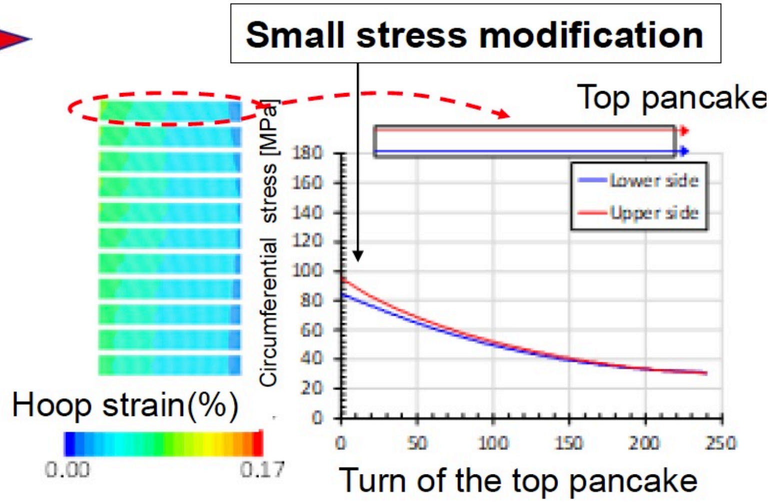
Figure 15. Maximum local hoop stresses in pancakes based on the classic formula (without SC), bulk model (with SC) and discrete contact model (with SC), respectively.

Xia et al, SuST, 32 (2019) 095005



(a) Dry wound coil





(b) Epoxy impregnated coil

H. Maeda, ASC2020 Wk2LOr2A-2, Ueda et al, to be published.

Impregnation −>Improve coil stiffness

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

Concept of Robust REBCO coil

- Robust against local degradation: Two bundle winding
- Robust against mechanical stress: Edge impregnation

Two tape bundle winding with a face-to-back configuration

Current share at local damaged area.

Reduce amount of insulation (Increase J_{space}).

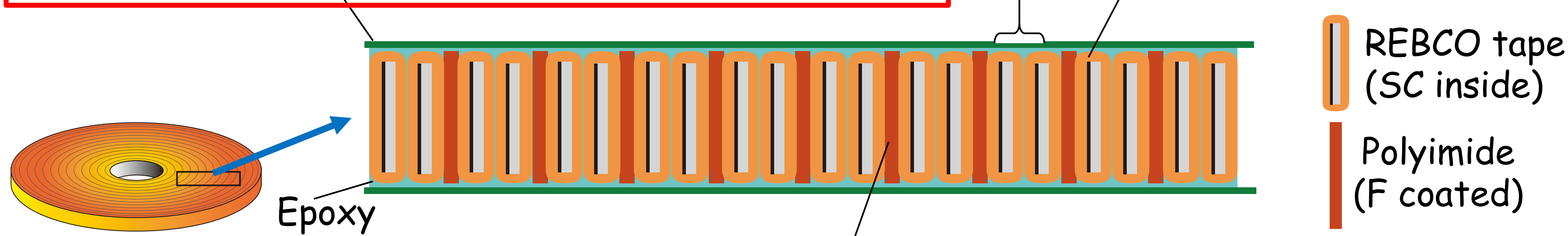
Edge impregnation

Thin FRP plate glued on coil & Impregnation

(Improve coil stiffness)

40 μm Cu stabilizer

(Reduce hot-spot temp.)



All turn separation with F-coated polyimide

(Reduce delamination force on REBCO tape)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

TOHOKU
UNIVERSITY

Robust against local degradation: Two bundle winding

HFLSM
Sendai

Research

HFLSM Sendai

Robust against local degradation:

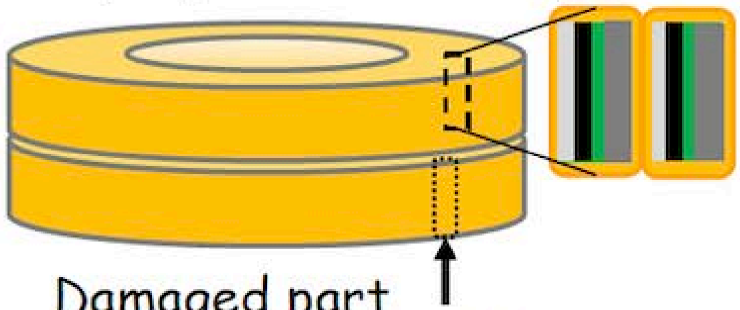
Two bundle insulated double pancake coil with a damaged area

EuBCO tape with BHO	
Width	4 mm
full thickness	0.11 mm
*RE*BCO thickness	2.5 μm
Hastelloy® thickness	50 μm
Cu thickness	20 μm
I_c (4mm, 77 K, s.f.)	213.5 A

Double pancake coil	
tape	EuBCO+BHO
Turn number	101 turn × 2 layer
Inner diameter	40.0 mm
Outer diameter	94.0 mm
Position of damage*	55 turn of bottom coil, outer tape
Coil constant	3.87×10^{-3} T/A

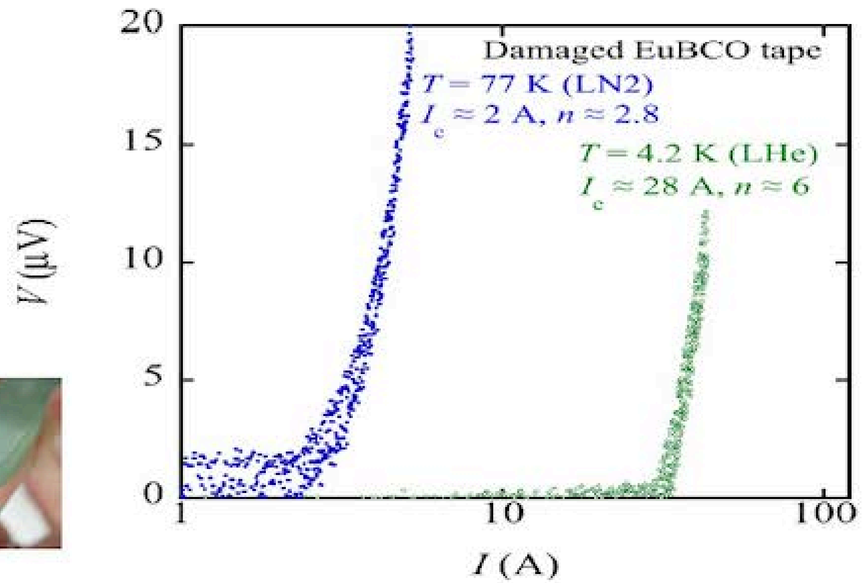
*Damage was introduced by double bending with ϕ12 mm bending dia.

ϕ40 × ϕ94, 101 × 2 turns/pc



Damaged part
in 55th/101 turn of bottom PC

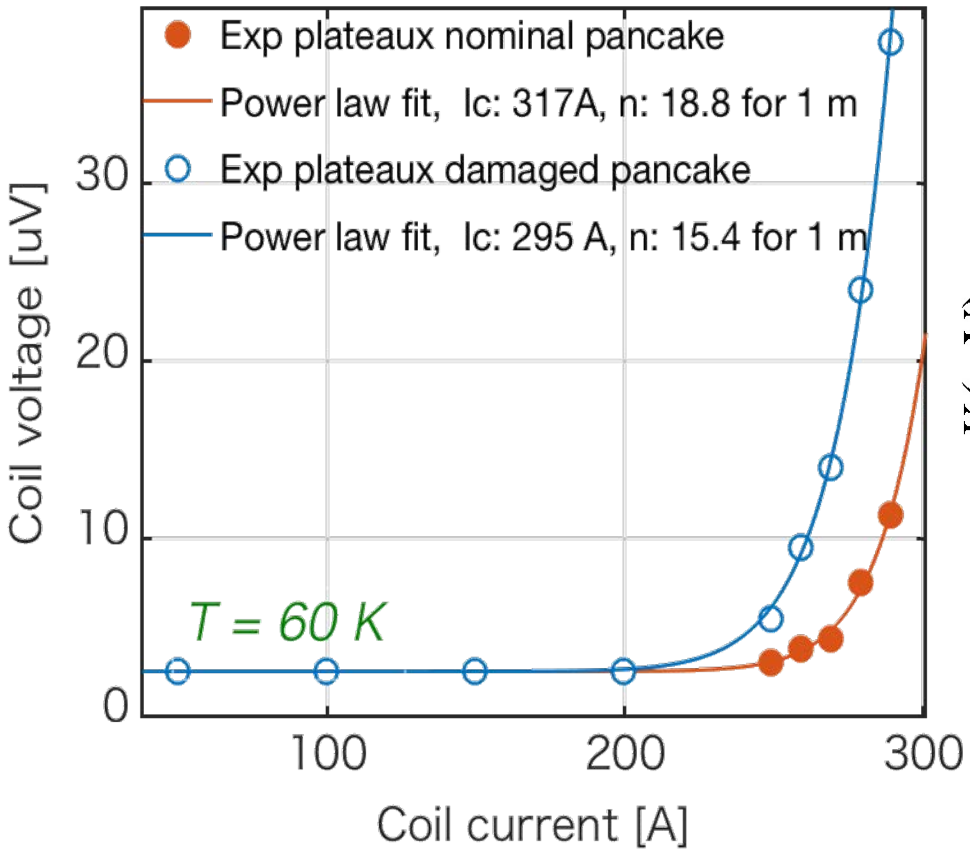
IV property of damaged EuBCO

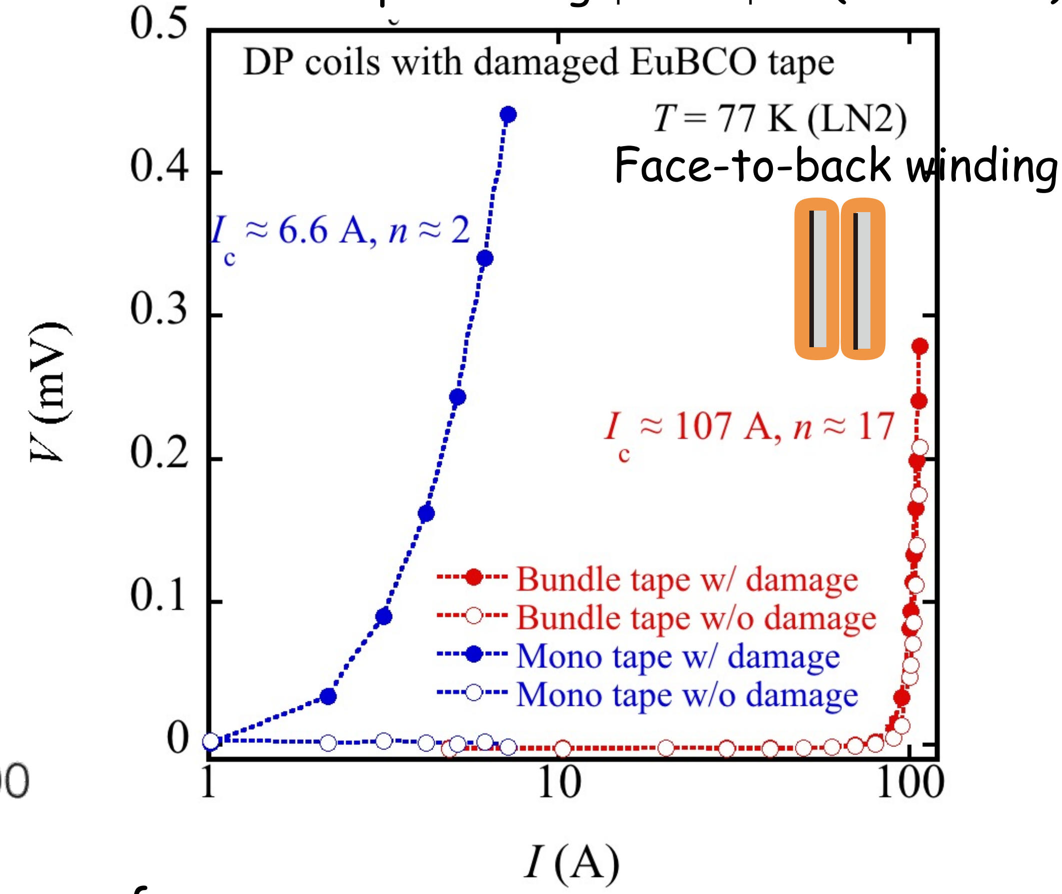


Robust against local degradation:

Two bundle insulated double pancake coil with a damaged area

Bundle winding ϕ40 x ϕ94 (101 turns x 2)
Mono tape winding ϕ40 x ϕ99 (198 turns)





- Monotape coil with a damage shows low performance.
- Bundle tale coil with damage shows similar performance to that without a damage at 77K and slightly lower with decreasing temperature.
- Ic difference may be related to Ic distribution in the coil.

⇨ Bundle winding is effective!

Abe *et al*, MT27 (TUE-PO1-722-06)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

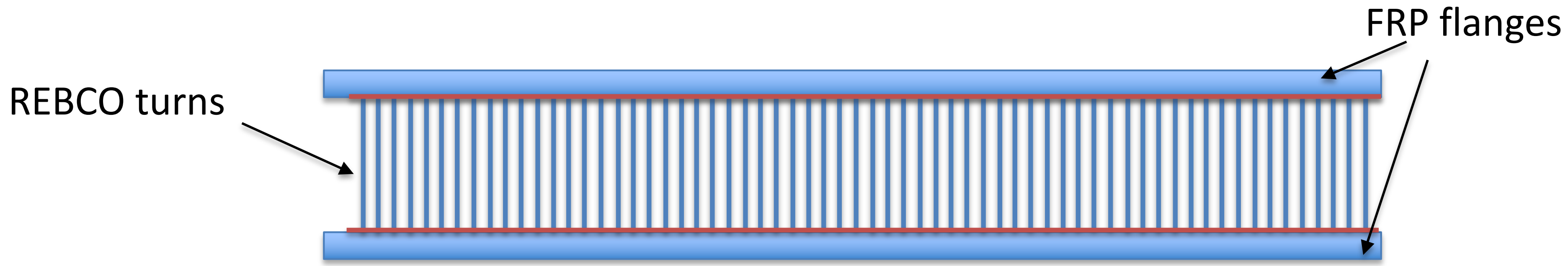
TOHOKU UNIVERSITY

Robust against mechanical stress: Edge impregnation

HFLSM Sendai

Research

Robust against mechanical stress: Edge impregnation



Turns are not glued only to the flanges (in red), not to each other

Radial stiffness is defined by ratio between flange thickness and tape width : can be made very low

⇒Radial tensile stress only in the flange : no delamination risk

⇒Hoop stress profile can be adjusted to be more homogenous

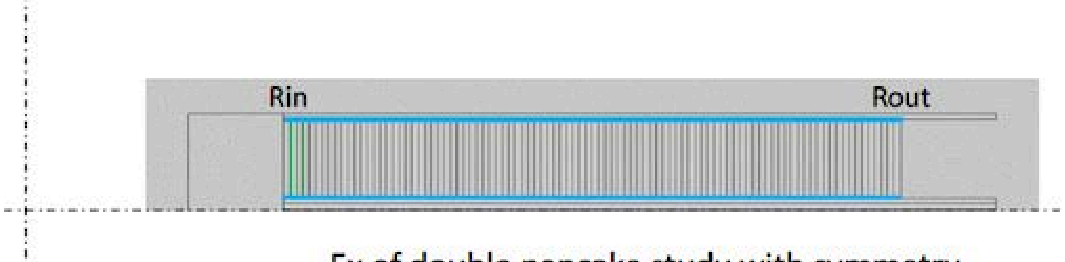
Edge impregnation can be obtained :

- Impregnation + non-stick material for isolation between turns (fluorine-coated polyimide)
- Only gluing the flanges on the pancake after winding

A. Badel presented at CEC/ICMC 2021

Edge impregnation modelling approach

- 2D axisymmetrical Magnetostatic / Mechanics coupled using Comsol®



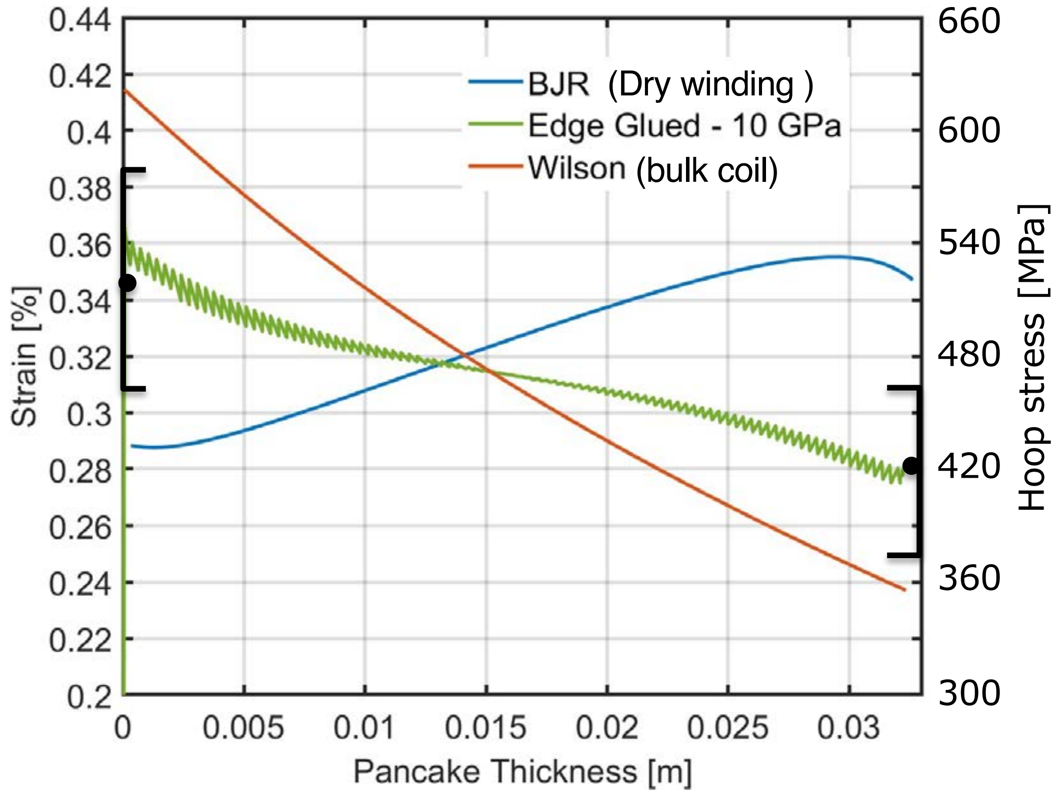
Ex of double pancake study with symmetry

- Mechanics: Solid deformation, no friction/dry contact → not valid with radial compression
- Whole conductor is averaged :
  Young Modulus : 150 GPa for 2 x 150 µm REBCO
- Polyimide + Fluorine Insulation represented by elastic interface (in green)
  Very low Young Modulus (1 MPa) represent non-stick behavior
- Epoxy between conductor – FRP flanges : elastic interface (in blue)
  Young Modulus : 10 GPa
- Every turns represented independently or groups of several: save computing time, similar results)

A. Badel presented at CEC/ICMC 2021

Mechanical study : 2 tape co-wound pancake by Toshiba

Basic studies : "Wilson" hypothesis (all turns glued strongly together) or "BJR" (all turns acting independently)

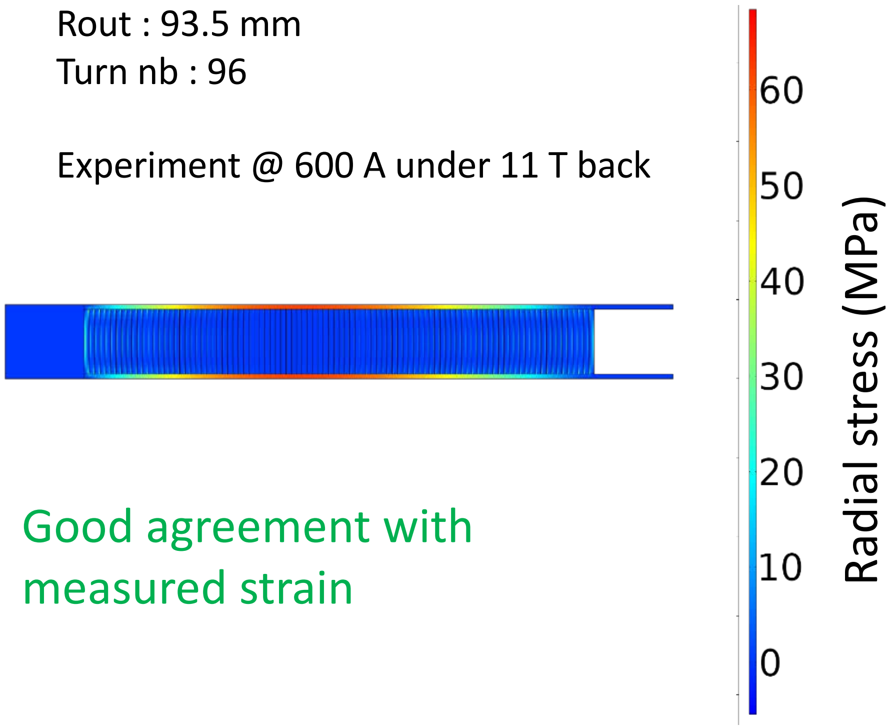


K. Takahashi, IEEE TAS, 2021

30 T project sub-scale test pancake

Conductor : 4mm wide, 2 x 150 um Fujikura tape
Rin : 60 mm
Rout : 93.5 mm
Turn nb : 96

Experiment @ 600 A under 11 T back



Good agreement with measured strain

Question: How's screening current induced stress?

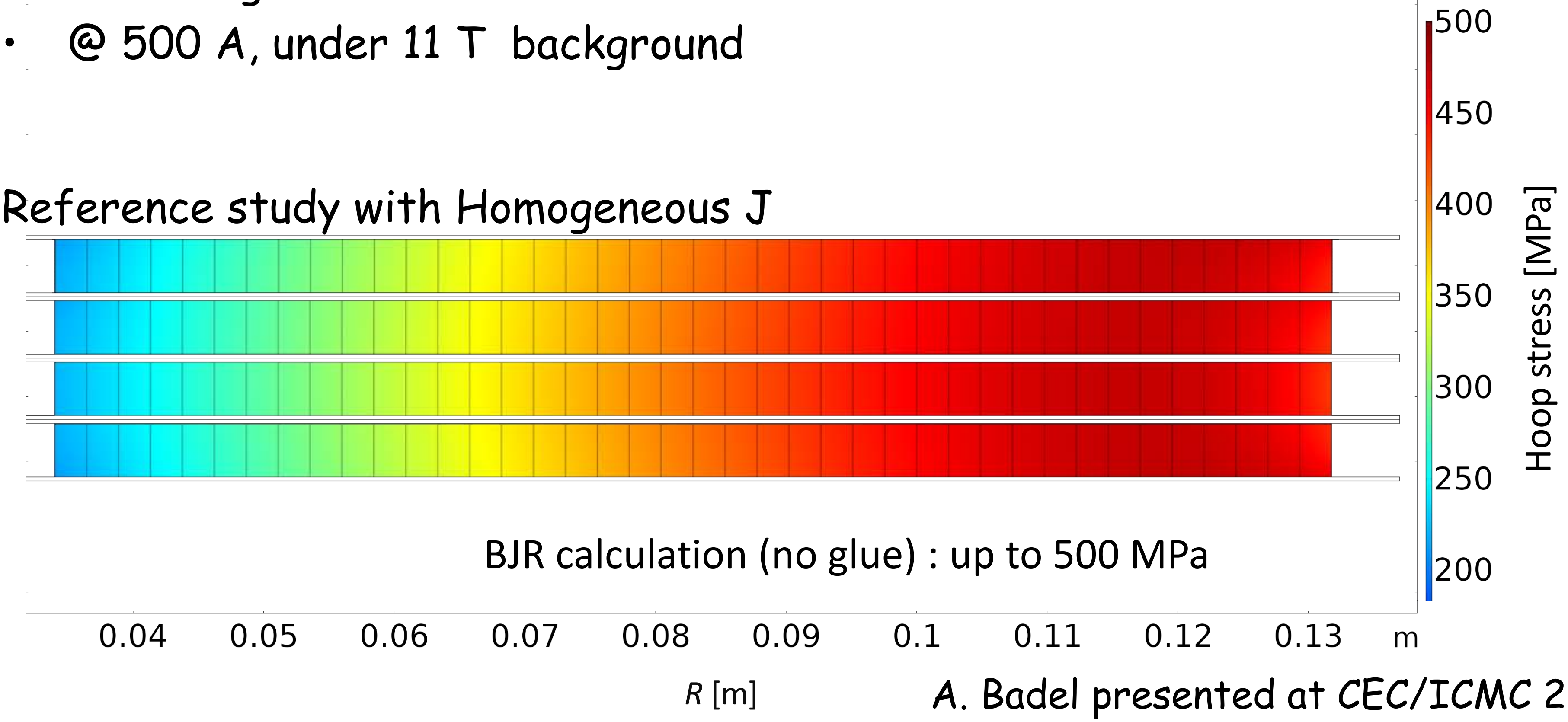
HFLSM Sendai

Effect of inhomogeneous J on stress distribution - Reference

Modelled case : stack of 4 full-scale pancakes from 30 T project insert

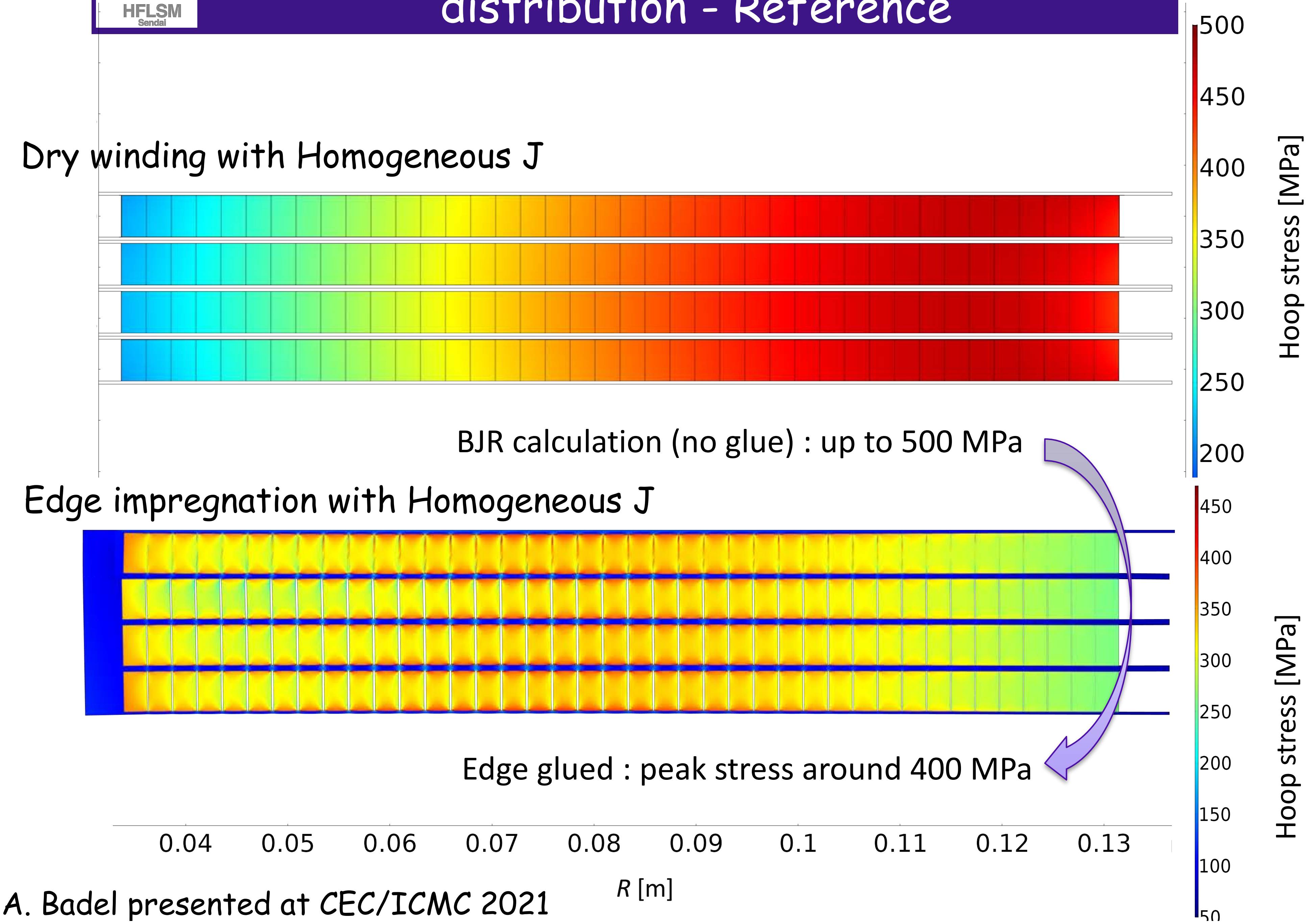
- Conductor : 4mm wide, 2 x 150 um Fujikura tape
- Rin : 34 mm
- Rout : 132 mm
- Turn nb : 300
- FRP Flange thickness : 0.34 mm
- @ 500 A, under 11 T background

Reference study with Homogeneous J



A. Badel presented at CEC/ICMC 2021

Effect of inhomogeneous J on stress distribution - Reference



A. Badel presented at CEC/ICMC 2021

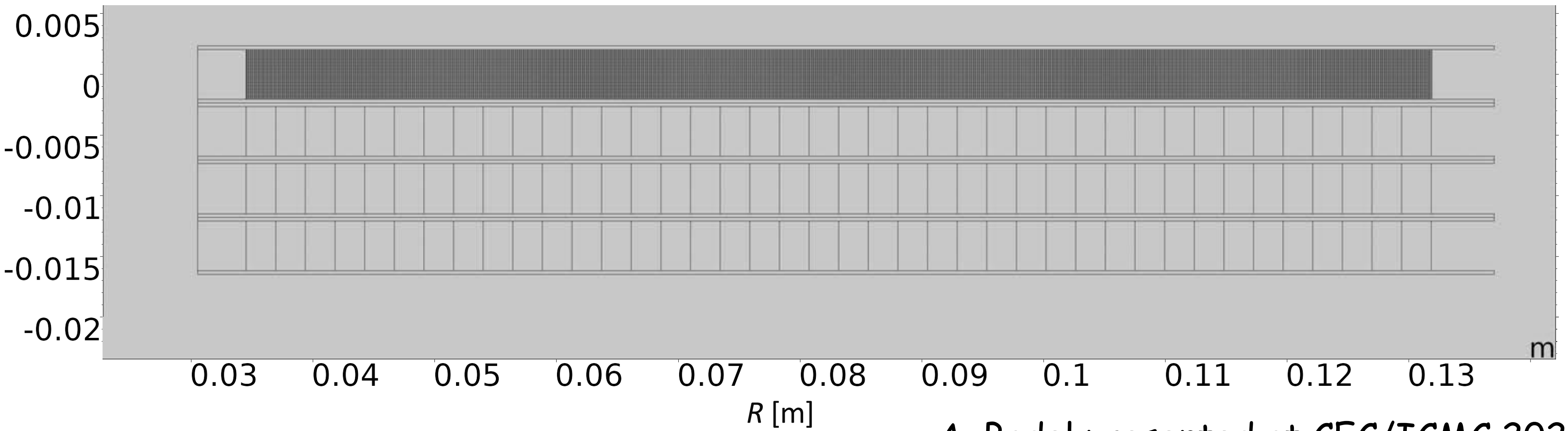
Effect of inhomogeneous J on stress distribution – model

- Input: Current density distribution @ 500A including transport, shielding and coupling currents

Obtained from detailed transient ElectroMag model (static background of 11 T added)

- In static magneto-mechanical model, top pancake modelled tape by tape: detailed local J and resulting Lorentz force Fv = J x B applied

- Other three pancakes simplified and considered with homogeneous J (as before) to include their field contribution, background field also added



A. Badel presented at CEC/ICMC 2021

Effect of inhomogeneous J on stress distribution – model

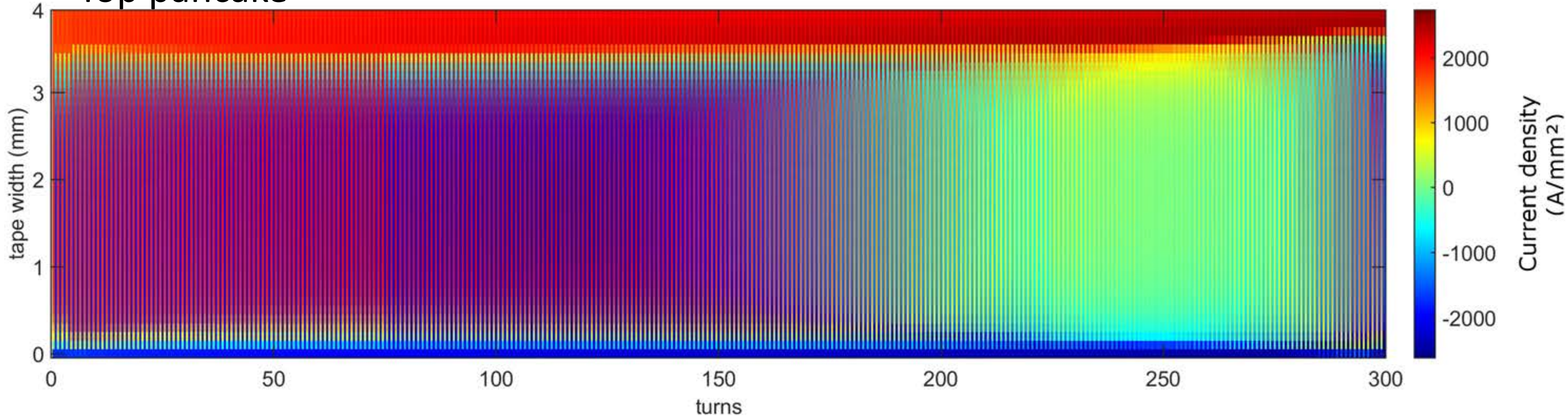
- Input: Current density distribution @ 500A including transport, shielding and coupling currents

Obtained from detailed transient ElectroMag model (static background of 11 T added)

- In mechanical model, top pancake modelled tape by tape: detailed local Lorentz force Fv = J x B applied

- Other three pancakes simplified and considered with homogeneous J (as

Top pancake

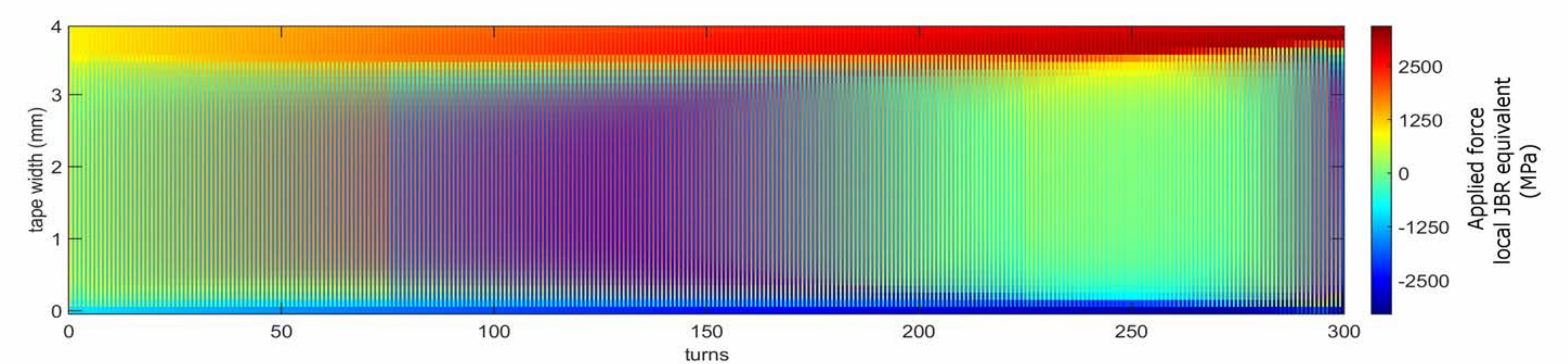


A. Badel presented at CEC/ICMC 2021

Effect of inhomogeneous J on stress distribution

With J and B, we have the applied Lorentz force *Fv*, but not the stress σ

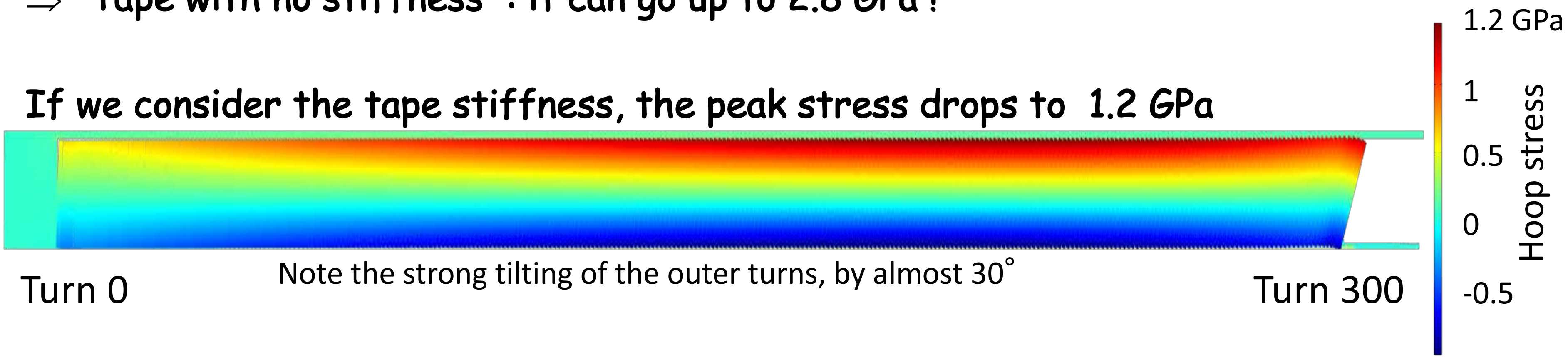
Indeed σ = B J R not valid locally, only when integrated over the conductor



Local BJR equivalent: What local stress would be if **every element** of each tape acted **independently**

⇒ **Tape with no stiffness : it can go up to 2.8 GPa !**

If we consider the tape stiffness, the peak stress drops to 1.2 GPa

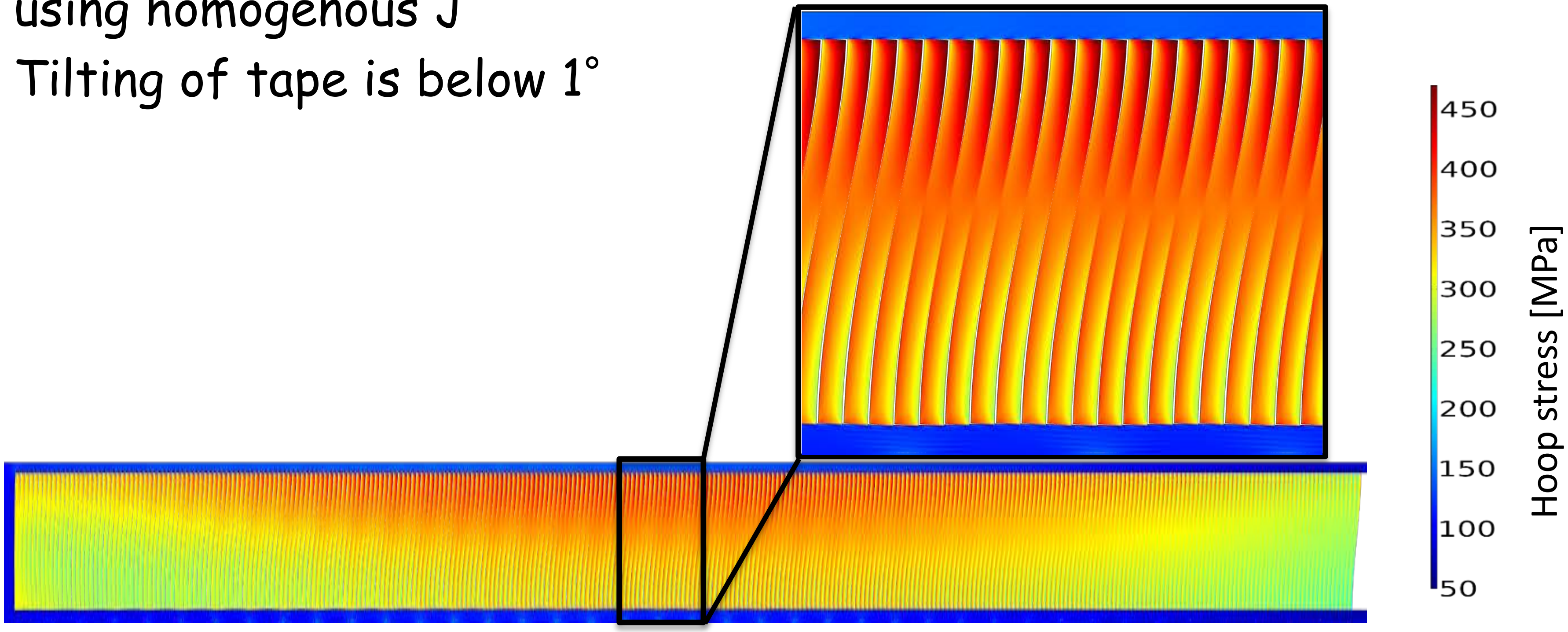


A. Badel presented at CEC/ICMC 2021

Effect of inhomogeneous J on stress distribution

We must also consider the interactions of the turns, **with each other** and **with the flanges**

- Glued edge (10 GPa) and turn to turn separation
  - Peak stress is reduced to 455 MPa, about 10 % than estimation using homogenous J
  - Tilting of tape is below 1°



*Deformations x 10

⇒ Edge impregnation concept: effectively reduce damage risks due to shielding currents without the drawbacks of full impregnation

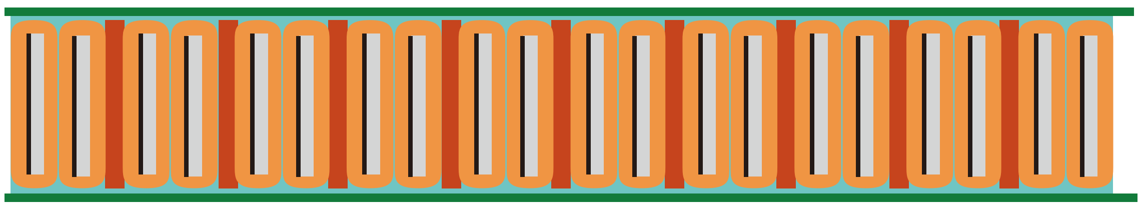
A. Badel presented at CEC/ICMC 2021

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), December 2021.
Invited presentation HF-2 given at CCA 2021, October 11 – 15, 2021, Virtual.

Conclusion

- We propose the "robust" coil concept for REBCO coated conductor.
- Robust against local degradation
  - The effectiveness of two tape co-winging is confirmed by damaged coil.
- Robust against mechanical stress
  - Edge impregnation: Thin flange helps containing the turns while keeping radial stress low on the tape
    - Turn to turn separation to limit the risk of delamination
    - Adjust the hoop stress profile
    - Reduce the screening current induced stress drastically

- Further studies are needed to check the performances of tape – flange bonding
  but experimental results so far are reassuring, even under high stress



Thank you !