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LANZHOU UNIVERSITY
College of Civil Engineering and Mechanics

Effect of thermal mismatch and electromagnetic force on delamination in epoxy impregnated REBCO pancake coils

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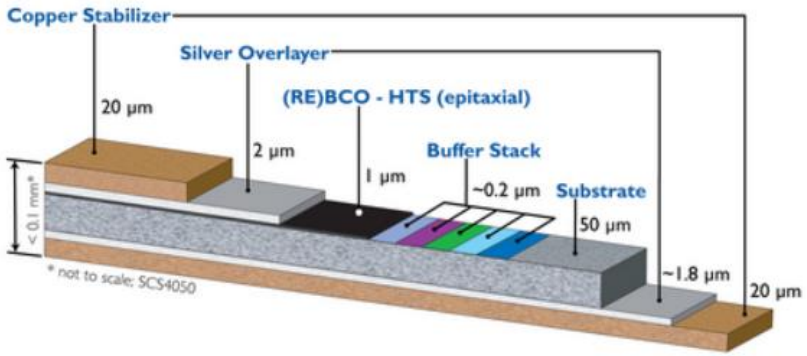
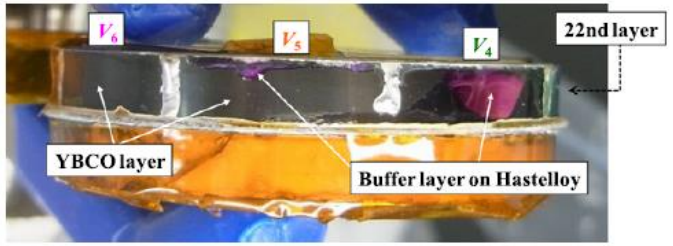
Outline

1. Motivation
2. 2D multiscale delamination model
3. Results and discussions
   a. Stress and delamination due to cooling
   b. Stress due under self-field
   c. Stress and delamination under background-field
4. Conclusion
5. Acknowledgement

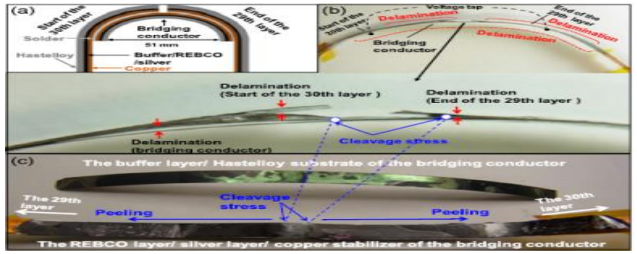
Motivation



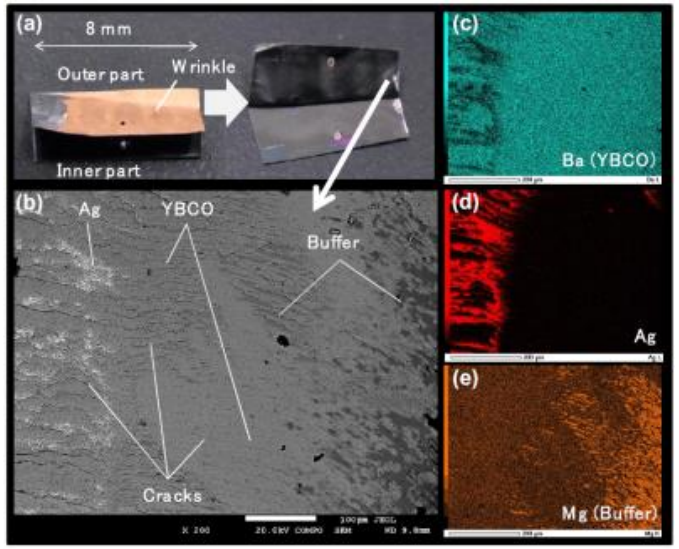
http://www.superpower-inc.com/content/2g-hts-wire



Yanagisawa Y et al. *Physica C*, 2012



Kajita K et al. *IEEE Trans Appl Super*, 2016



Takematsu T et al. *Physica C*, 2010

- Delamination is a fracture mode that seriously affects the performance of laminated composites.
- Quench, cooling, Lorentz force could induce stresses/strains to the constituent layers of REBCO CC tapes, results in delamination.
- Delamination in an epoxy impregnated REBCO pancake coil is multi-scale failure: delaminate in micrometer due to the accumulation in decimeter.
- Difficult to study experimentally deformation and stresses/strains in each turn and each constituent layer; only macroscopic experimental results.

A multiscale delamination model is necessary

1. Study the generation, propagation properties of delamination in epoxy impregnated REBCO pancake coils
2. Guide the fabrication and structure configuration

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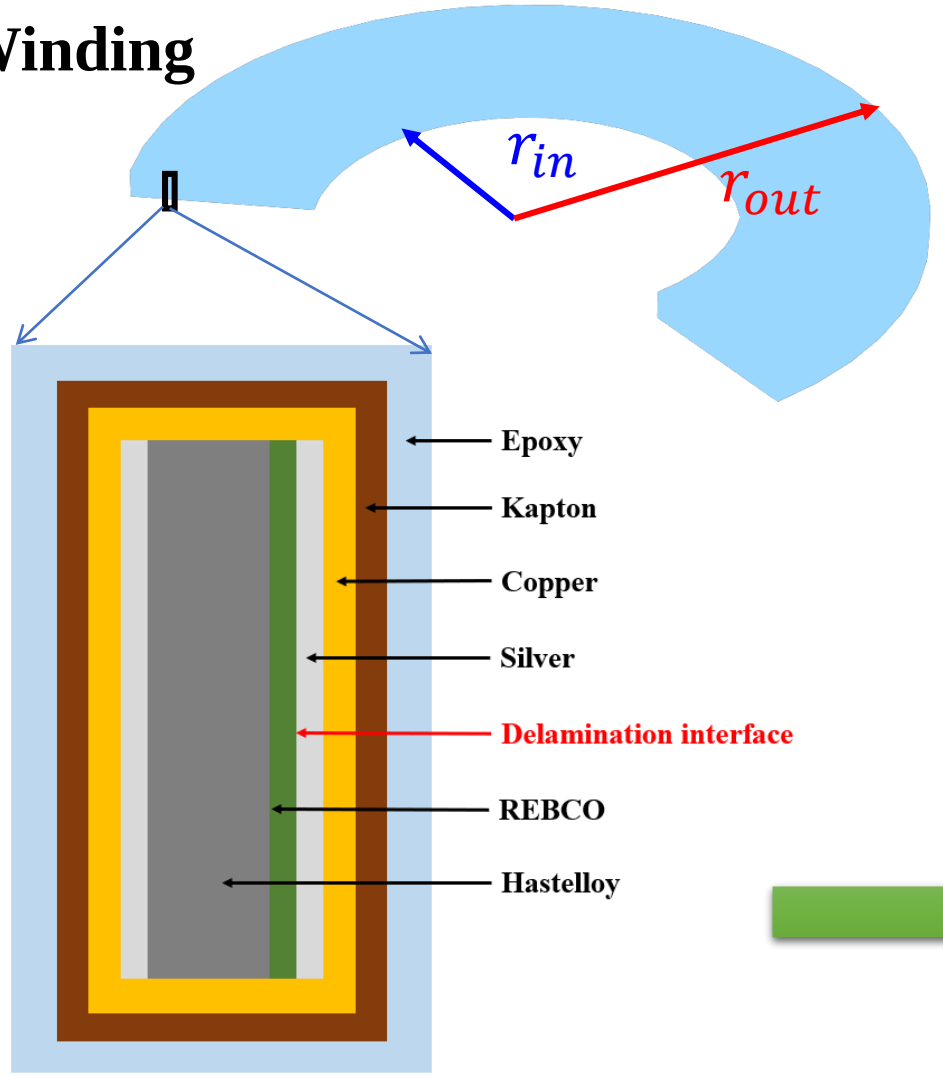
2D multiscale delamination model -Realization of multiscale

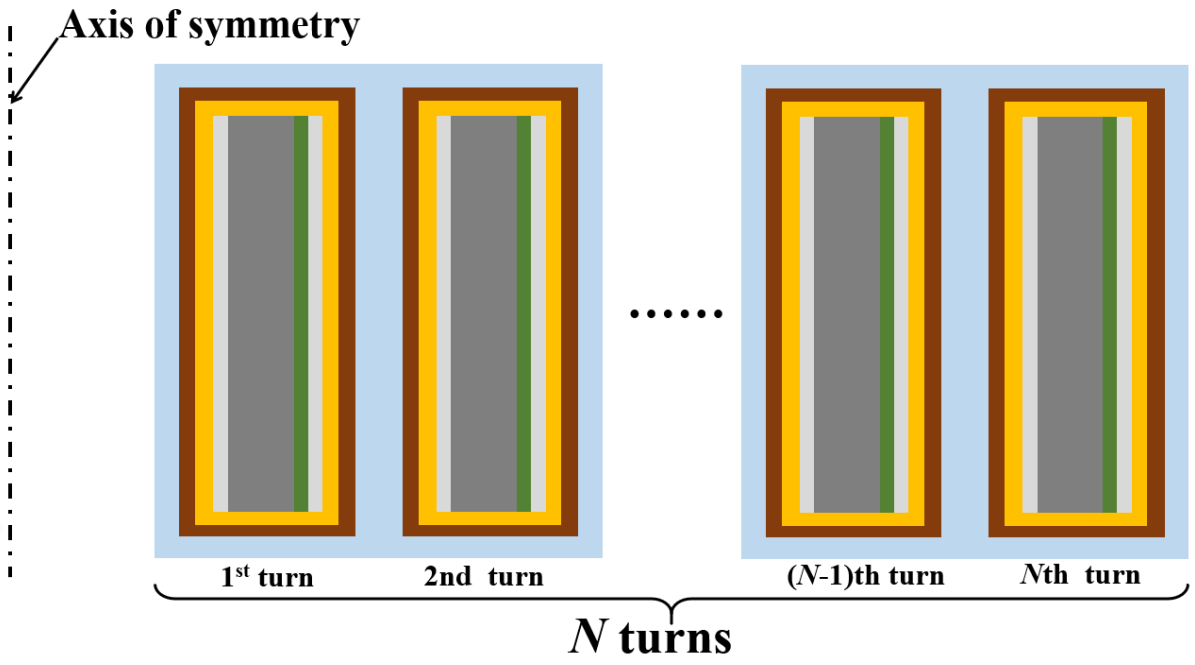
Winding



A representative volume element of epoxy impregnated REBCO pancake coil

Coil	Constituent layers
10^{-2}-10^{-1}m	10^{-6}–10^{-5}m

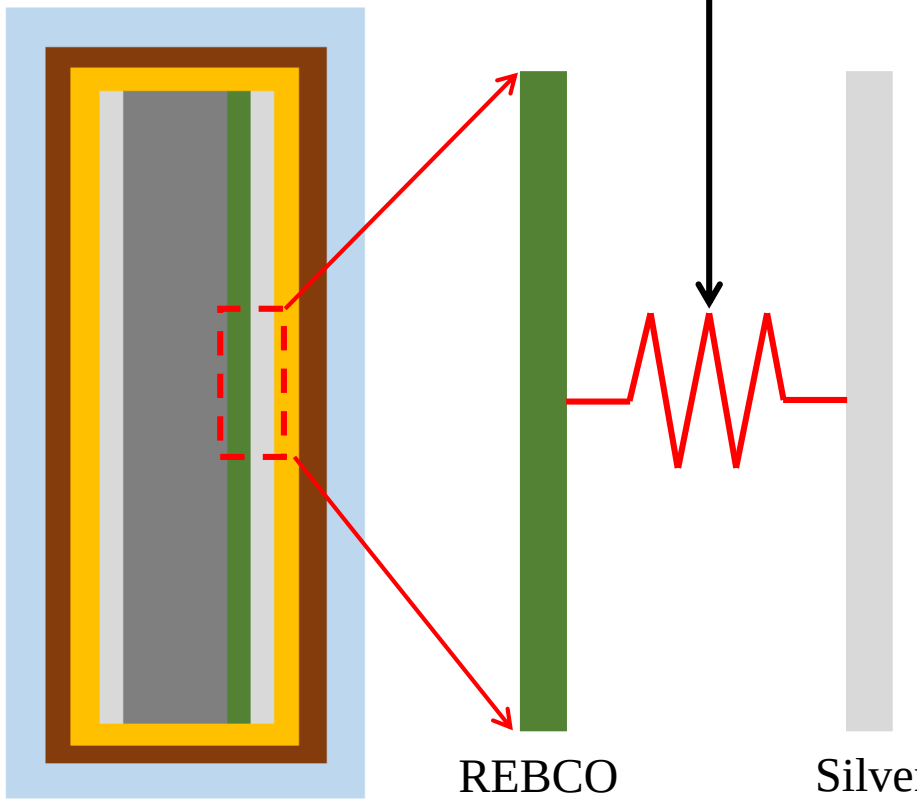
Multiscale issue



Cross-section of epoxy impregnated REBCO pancake coils

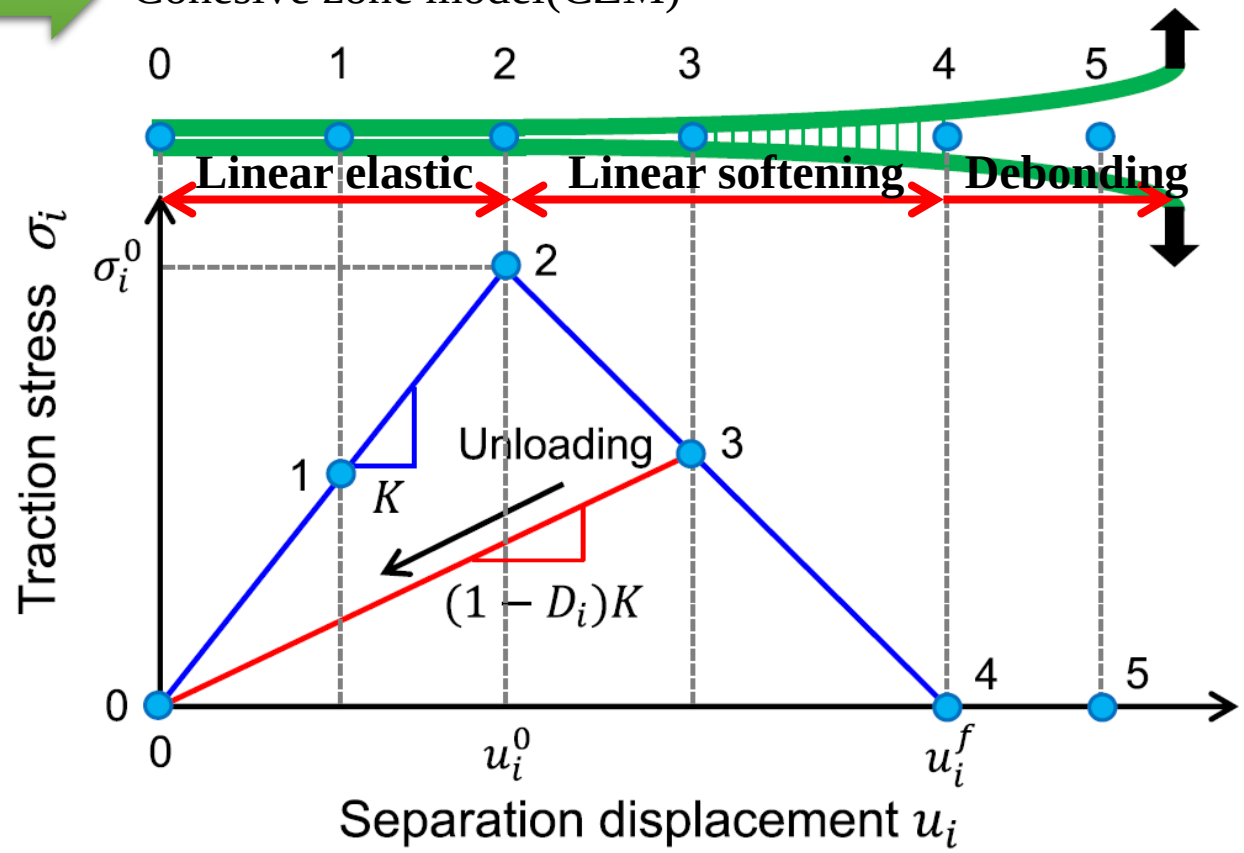
2D multiscale delamination model -Realization of delamination

Connect REBCO and Silver layers with **Nonlinear Spring**



Other adjacent layers connected with Displacement Continuity Conditions $[\mathbf{U}]^{+} = [\mathbf{U}]^{-}$

Cohesive zone model(CZM)



- linear elastic range (Point 0-2) with high initial stiffness K
- After the interfacial tractions attain critical strength (Point 2), the stiffness gradually reduced to zero (Point 2-4).
- Stiffness reverts to zero, results in debonding (Points 4 and 5),

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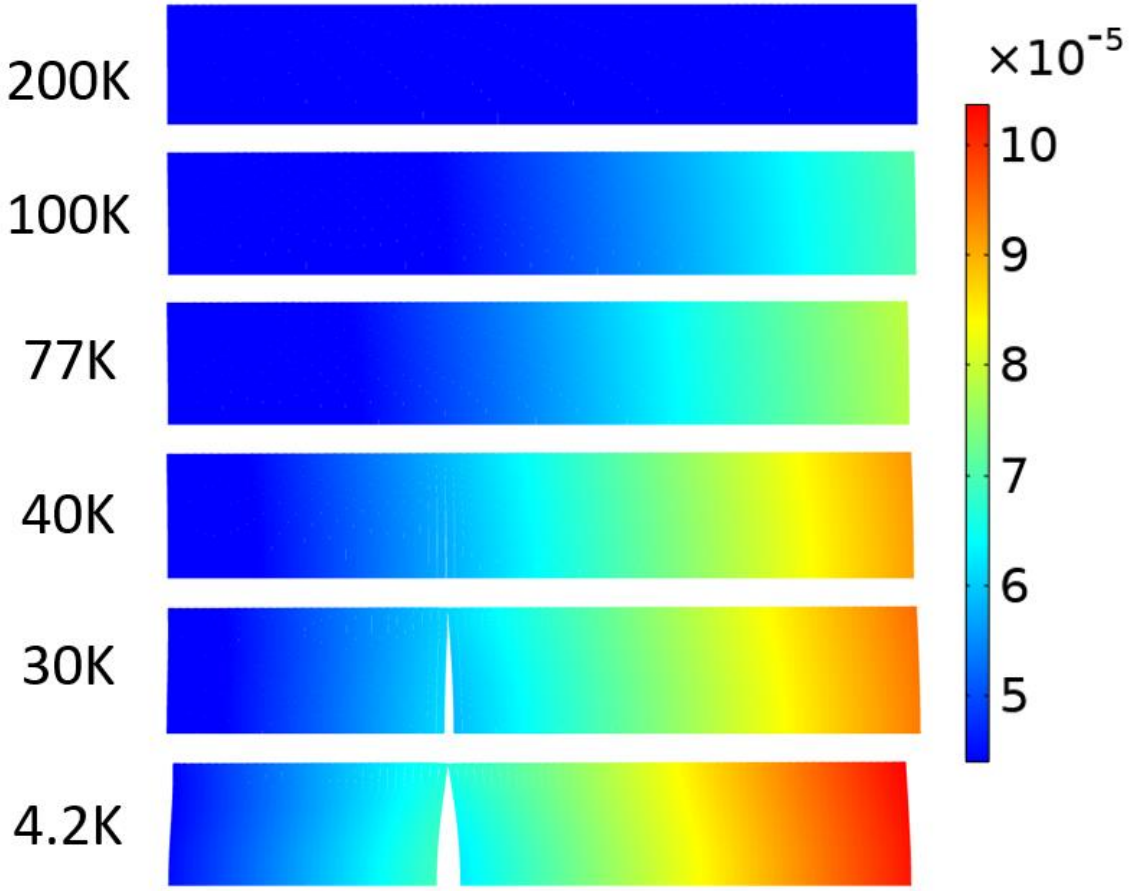
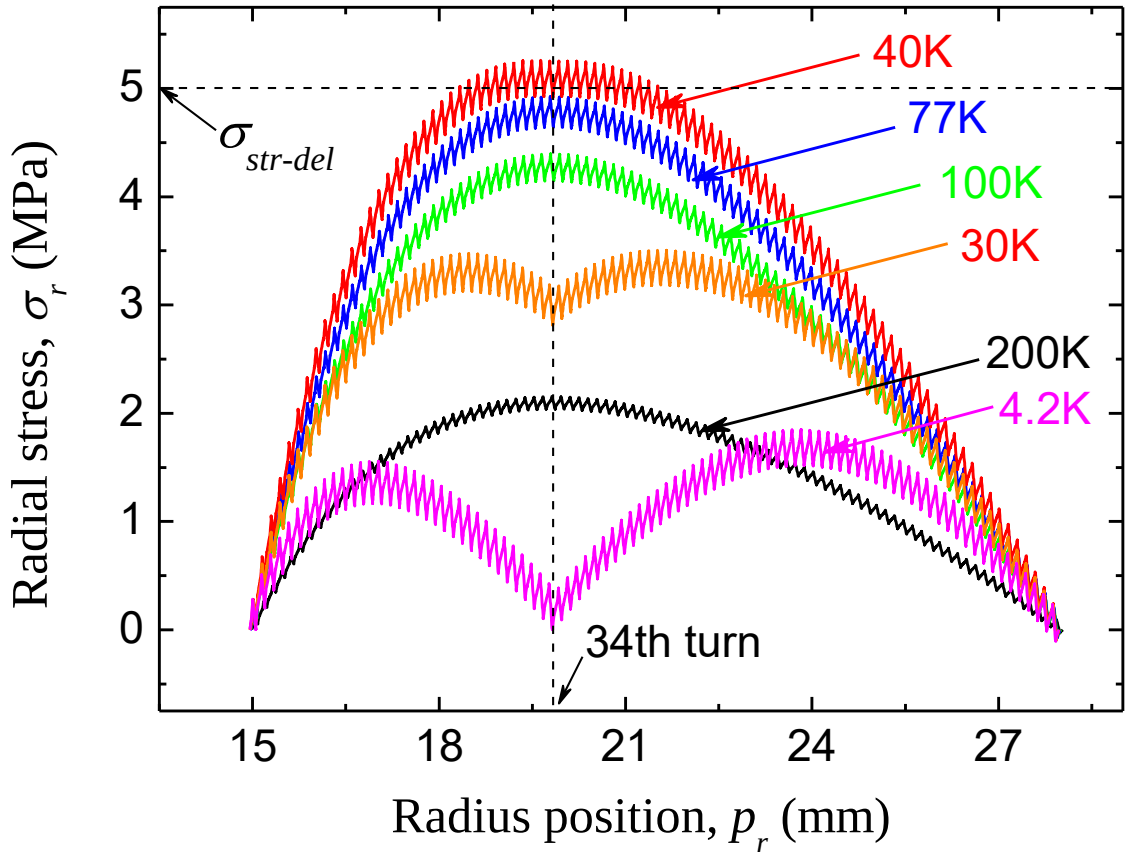
Stress and delamination due to cooling

Thermal mismatch stress distribution in radial direction

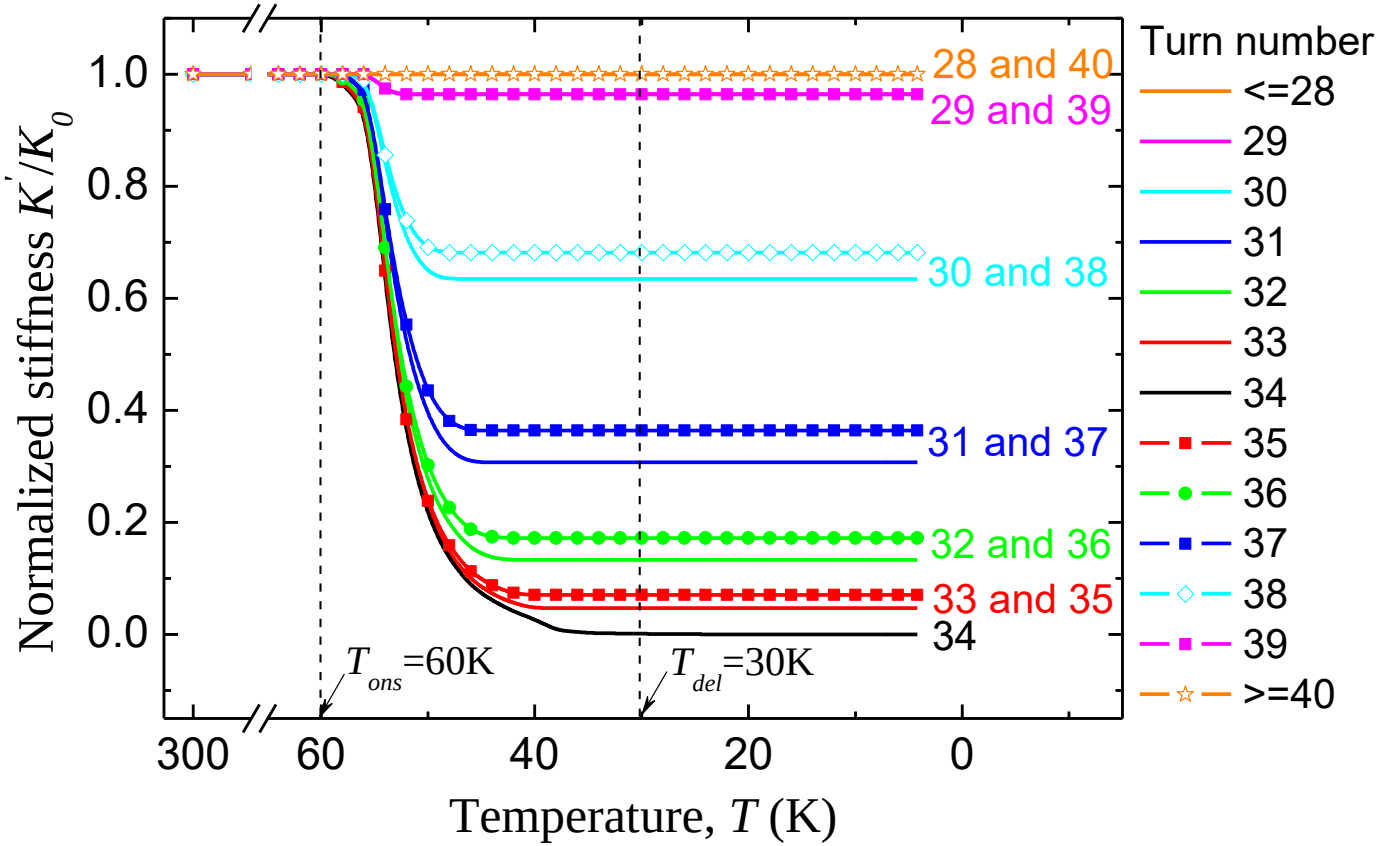


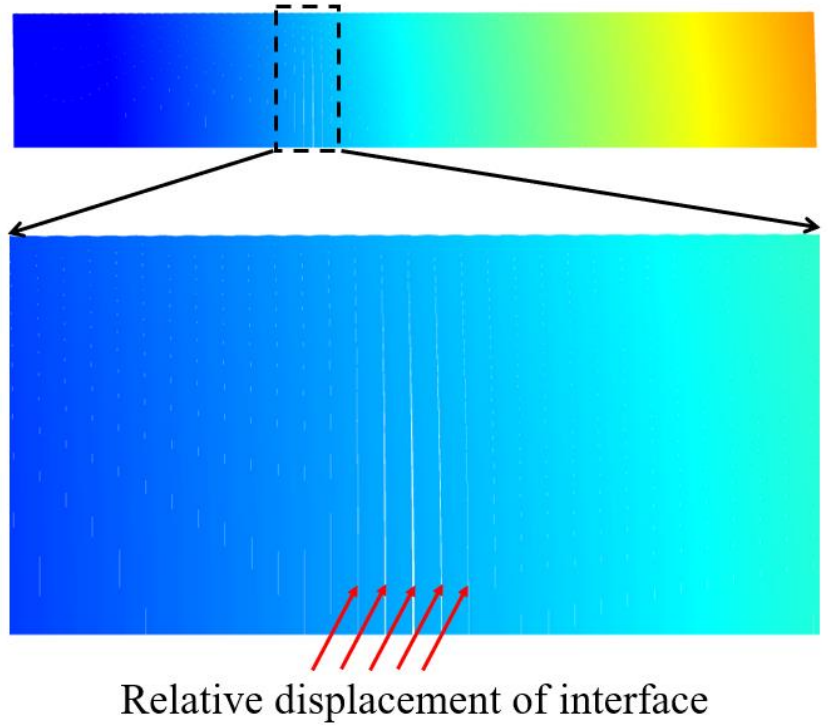


- As the temperature decreases, the winding is contracted.
- Radial stress due to thermal mismatch increases before reaching $\sigma_{str-del}$
- Delamination occurs at the 34th turn of the coil (total of 90 turns)
- Radial stress of each turn decreases after delamination

Stress and delamination due to cooling

Stiffness of the delamination interfaces varying with cooling process



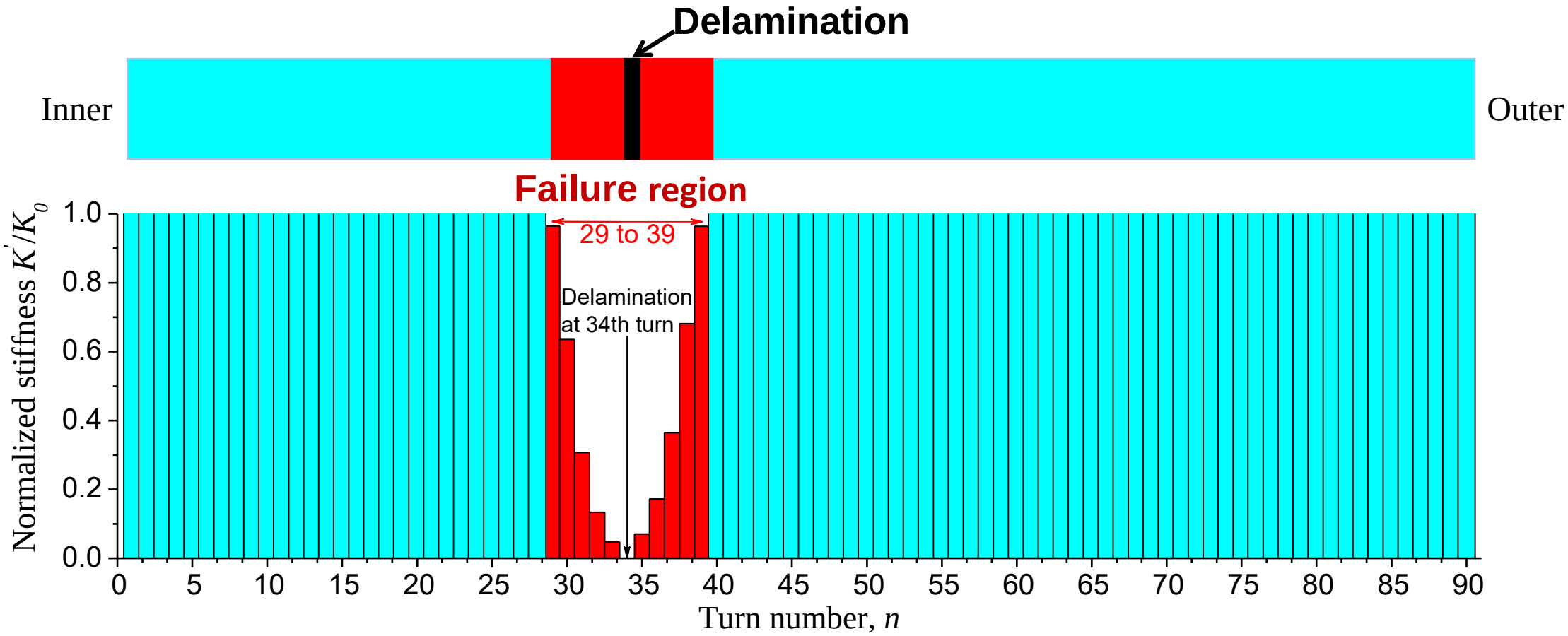


Deformation of the coil at 40K

- As the temperature decreases, the degeneration of the stiffness on CZM interfaces occur in turns 29-39.
- Only the stiffness in 34th turn completely failure.
- Onset temperature for the interfaces degradation is 60K, delamination occurrence temperature is 30 K.

Stress and delamination due to cooling

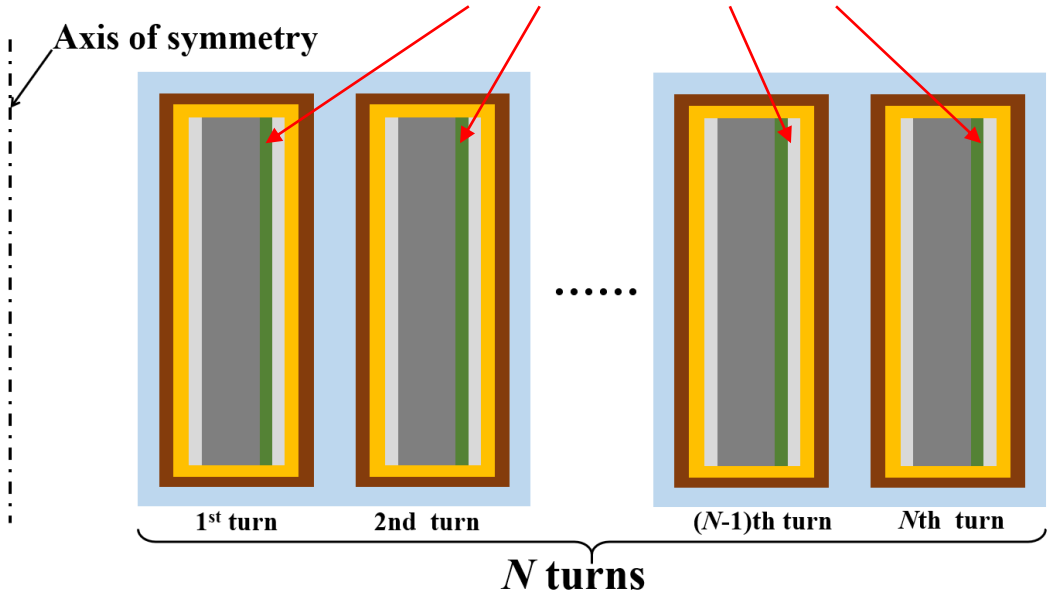
Stiffness of the delamination interfaces at T_{del} (30K)



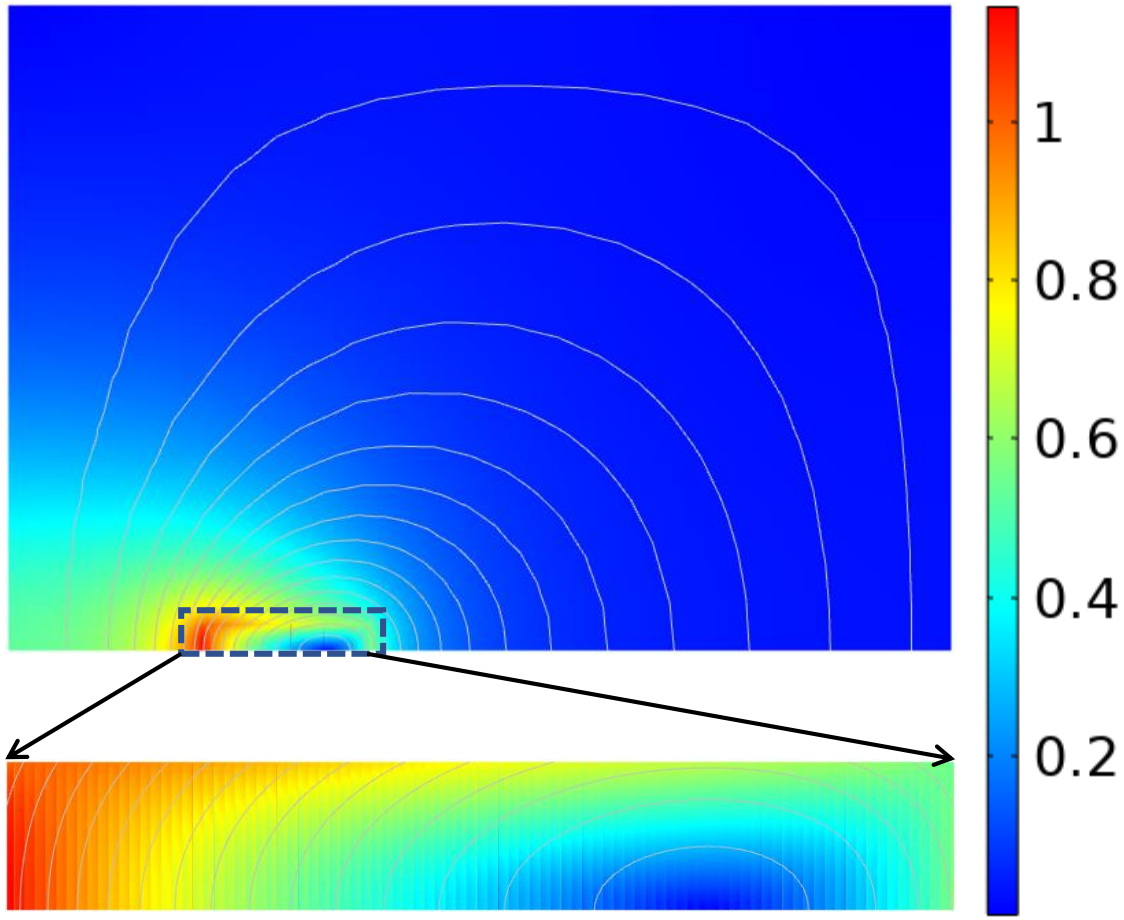
- Failure occurs in turns 29-39 ($0.322 \leq n/N \leq 0.433$).
- Delamination (completely failure) occurs at 34th turn (n/N=0.378).

Stress due to self-field

Current applied only to the superconducting layer



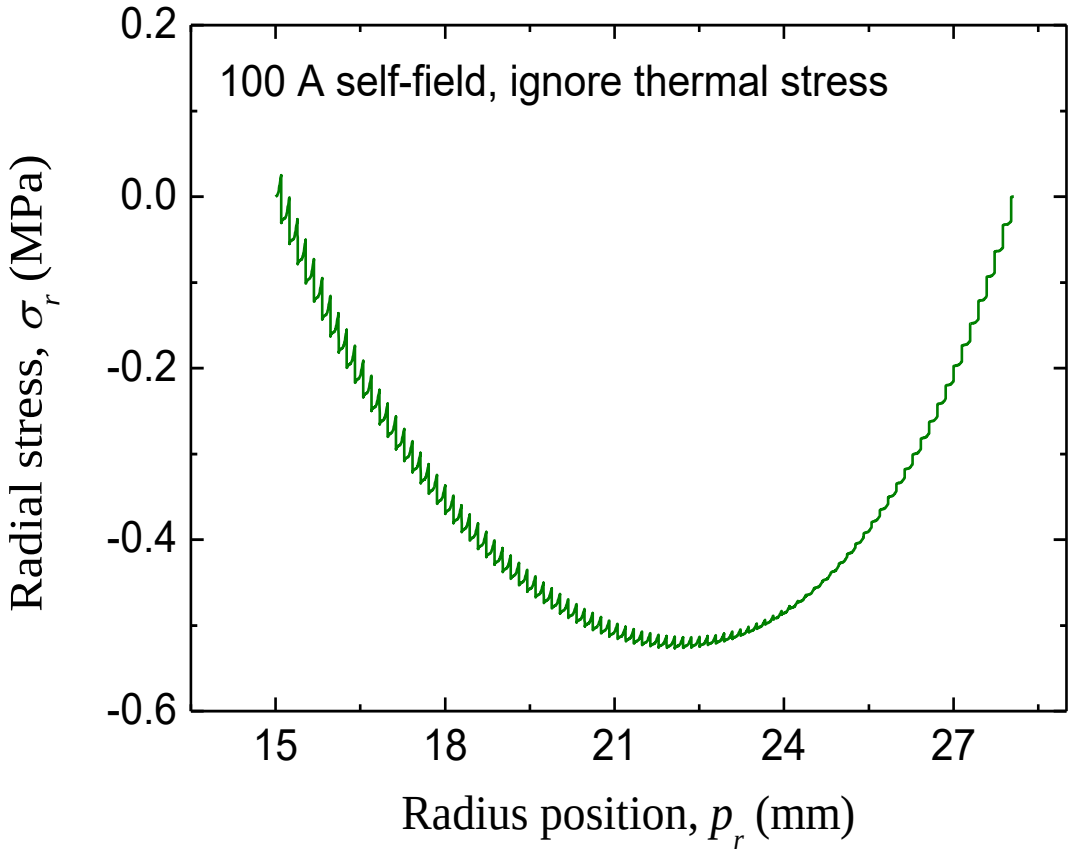
Magnetic flux density at 77K, 100A



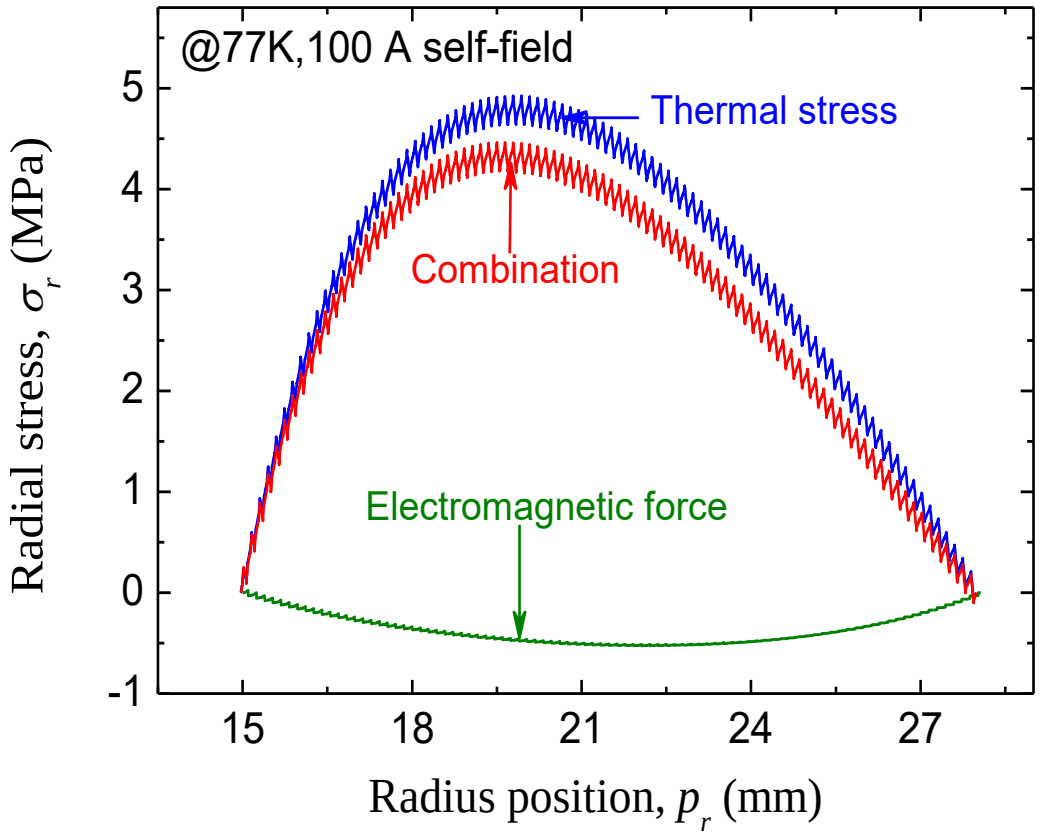
- Inhomogeneous magnetic flux density distribution is along radial direction.

Stress due to self-field

Stress induced by electromagnetic force



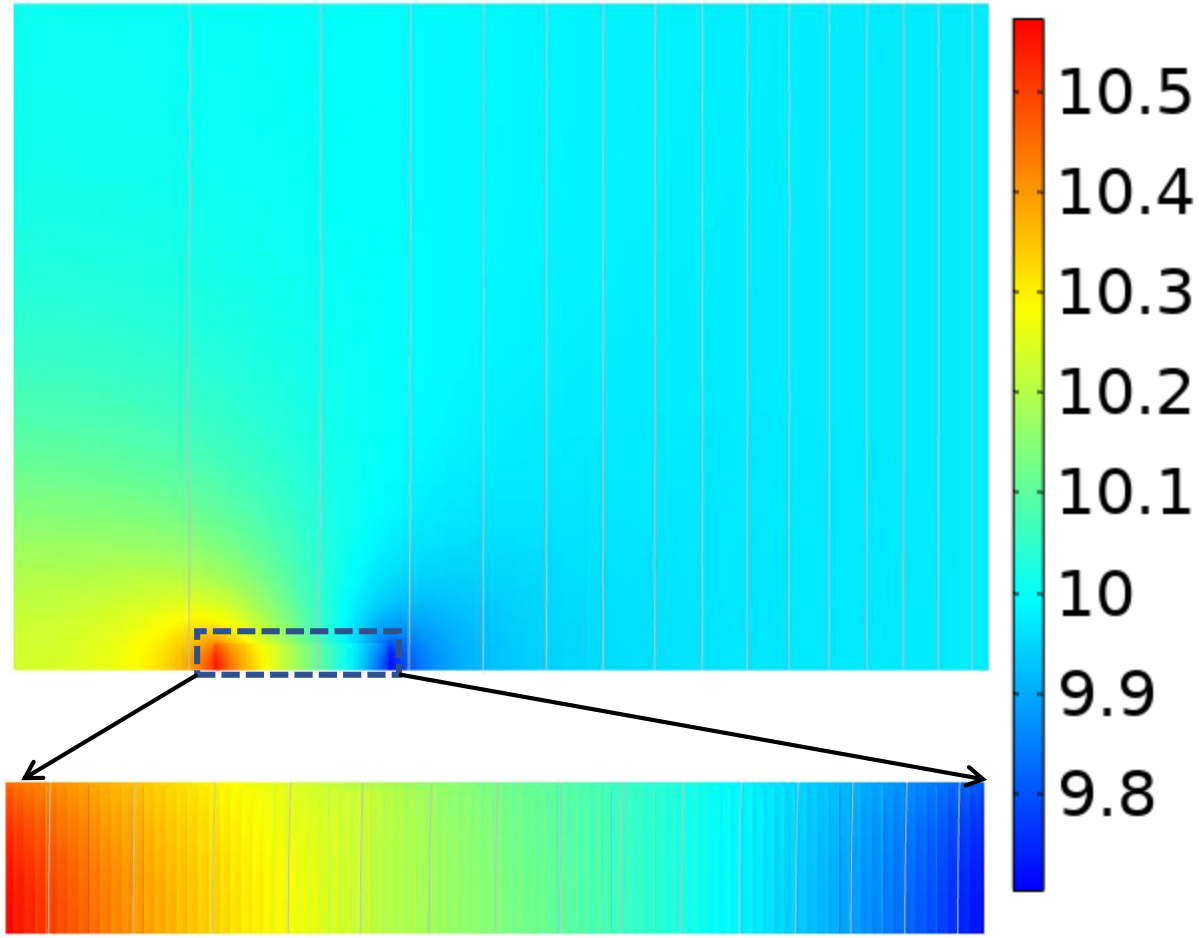
Stress components



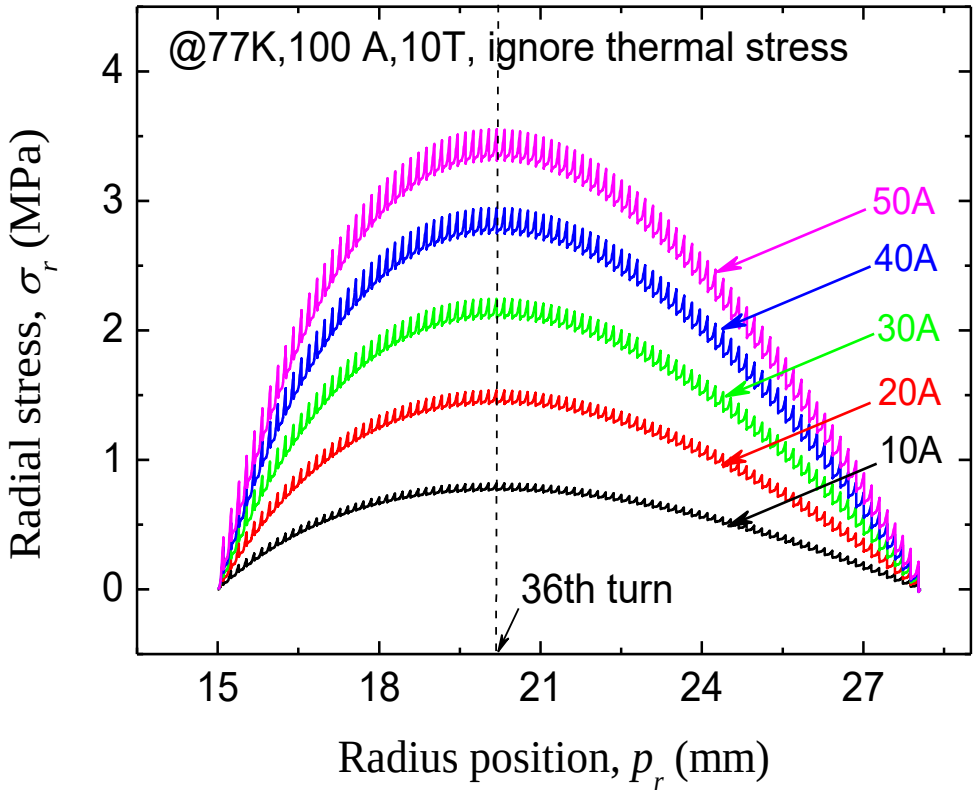
- Electromagnetic force under self-field causes the winding to be contracted.
- Cannot lead to a delamination as if cooling is safe.

Stress and delamination under background-field

Magnetic flux density and at radial stress 77K, 10T, 50A, ignore thermal stress



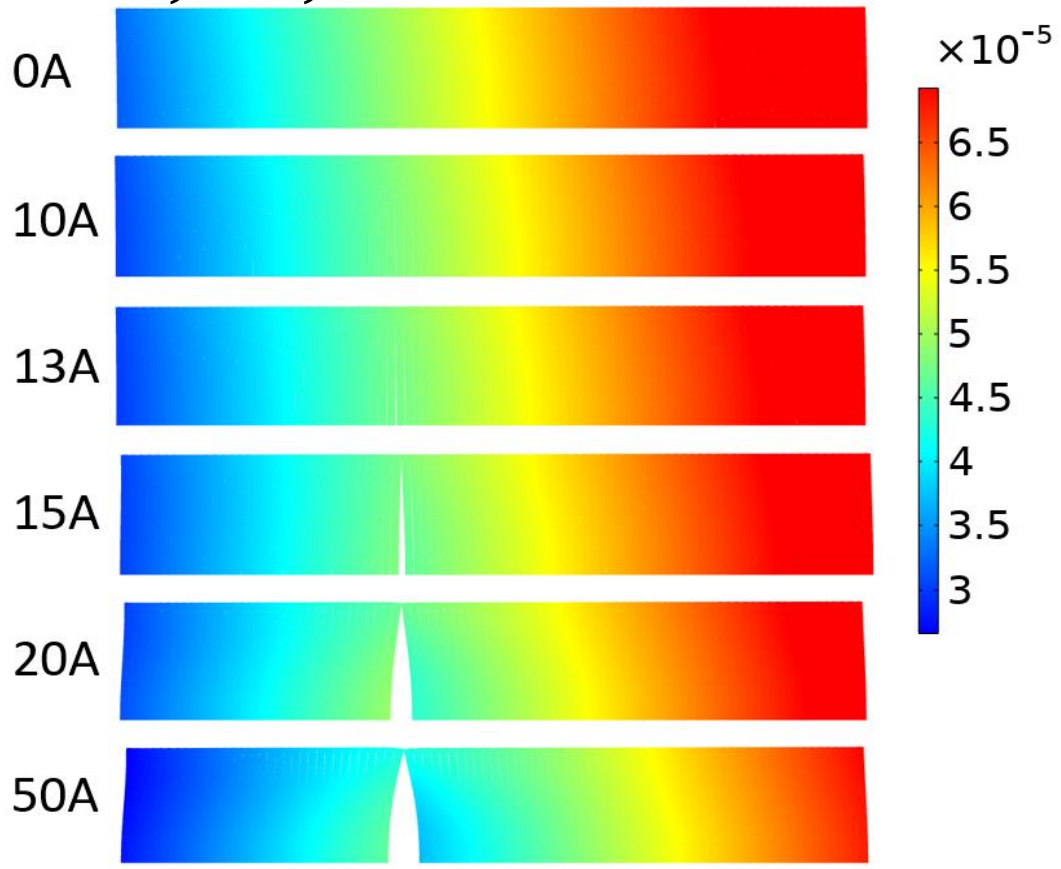
Stress distribution due to electromagnetic force

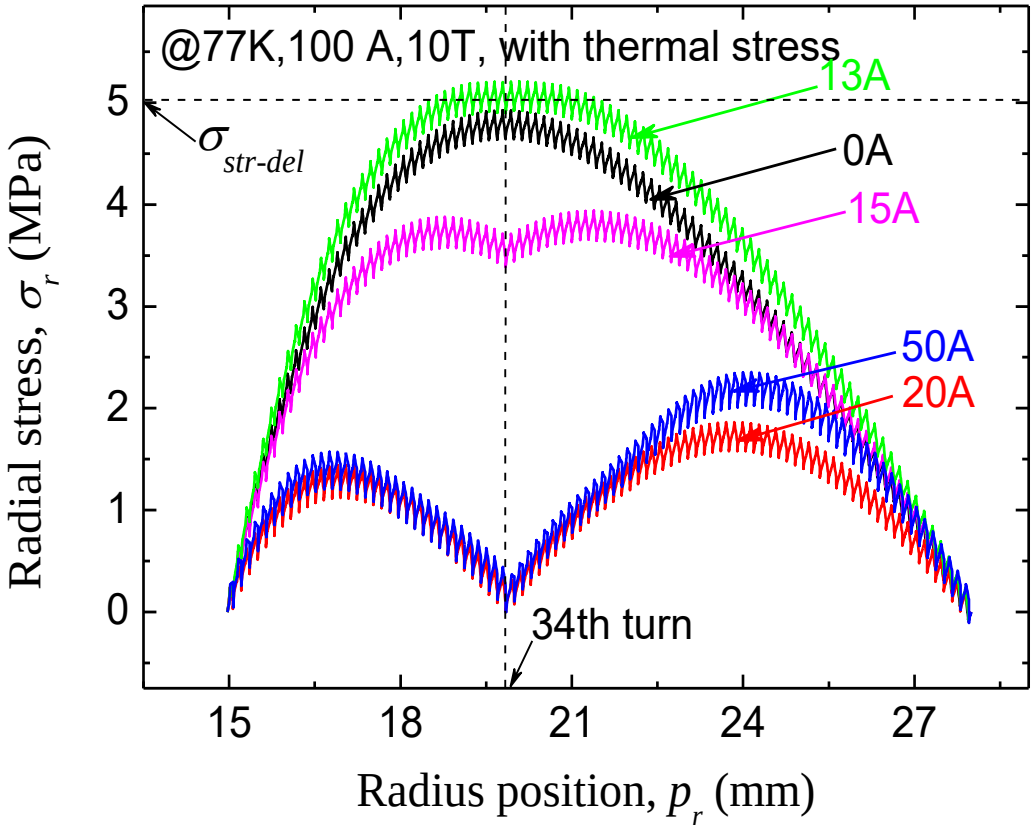


- Homogeneous magnetic flux density distribute along axial direction, gradient change along radial direction.
- Electromagnetic force under background-field causes the winding to be contracted, can lead to delamination.
- The maximum value occurs at the 36th turn

Stress and delamination under background-field

Radial stress distribution due to thermal mismatch and electromagnetic force at 77K, 10T, 0-50A

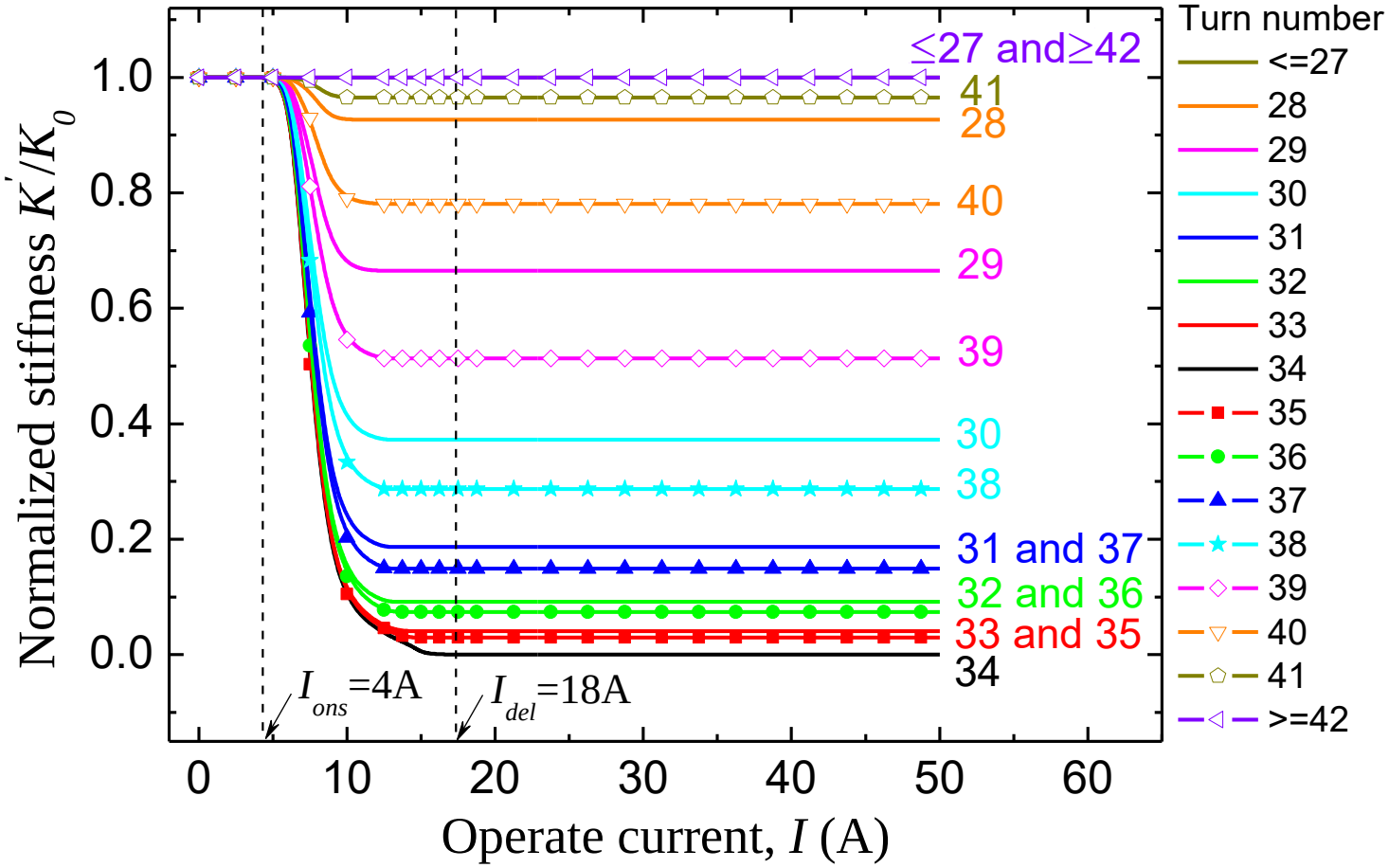




- As current increases, the winding is contracted.
- Radial stress due to electromagnetic force increases as current increases before reaching $\sigma_{str-del}$
- Delamination still occurs at the 34th turn of the coil (total of 90 turns)

Stress and delamination under background-field

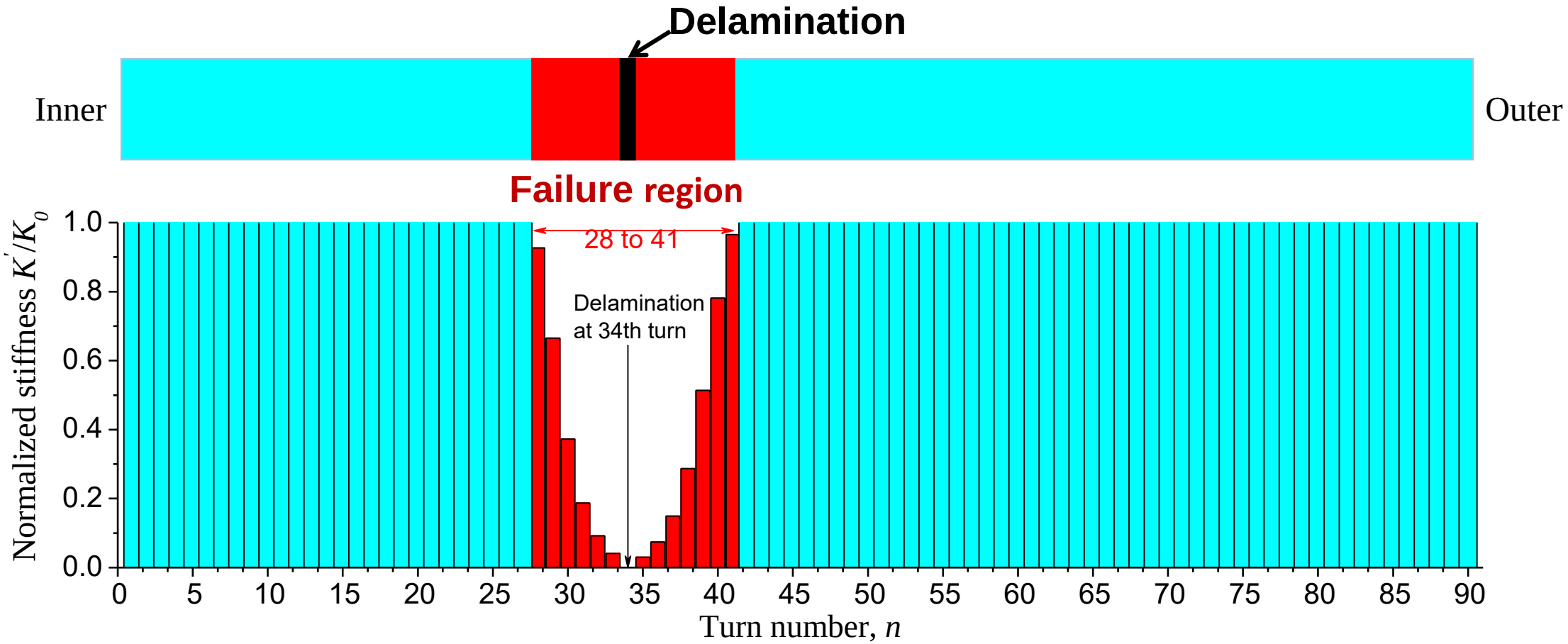
Stiffness of the delamination interfaces varying with operating current at 77K, 10T



- As temperature decreases, degeneration in stiffness of CZM interfaces occur in turns 28-41.
- Only stiffness in 34th turn completely failure.
- Onset current for interfaces degradation is 4A, delamination occurrence current is a18A.

Stress and delamination under background-field

Stiffness of the delamination interfaces at 77K, 10T, I_{del} (18A)



- Failure occurs in turns 28-41 ($0.311 \leq n/N \leq 0.456$).
- Delamination (completely failure) occurs at 34th turn (n/N=0.378).

Conclusion

A 2D axisymmetric multi-scale delamination FE model is developed to study the delamination behaviors induced by thermal mismatch and electromagnetic force in epoxy impregnated REBCO pancake coils.

1. Multi-scale model contains all the constituent layers and realizes delamination by CZM
2. Thermal mismatch stress causes the winding to be contracted, can lead to a delamination.
3. Electromagnetic force under self-field causes the winding to be squeezed, cannot lead to a delamination as if cooling is safe
4. Electromagnetic force under background-field causes winding to be contracted further, can lead to a delamination even if cooling is safe.
5. Interface failure occurs in a region after reaching $\sigma_{str-del}$, complete delamination appears on one of the failure interfaces.

Acknowledgement

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Thanks for patience

Look forward to suggestions

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