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Presentation given at Coated Conductors for Applications Workshop, Houston, TX, USA, April 2023.

Customization of Coated Conductors to enhance the Normal Zone Propagation Velocity

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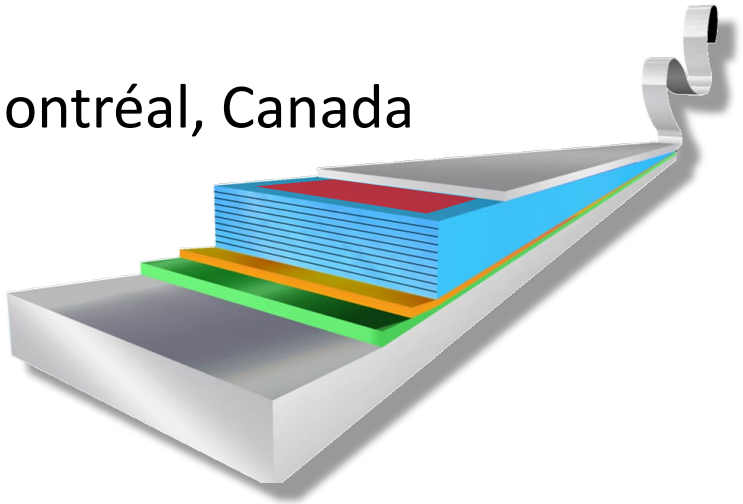
Polytechnique Montréal, Chemin de Polytechnique 2500, Montréal, Canada



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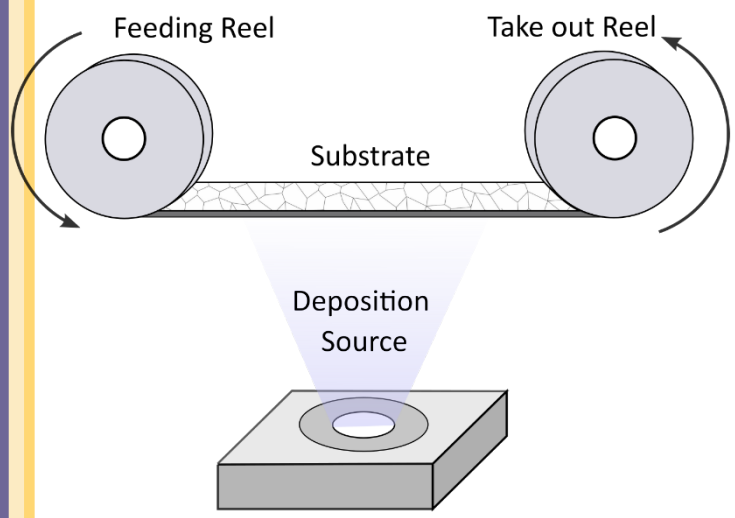
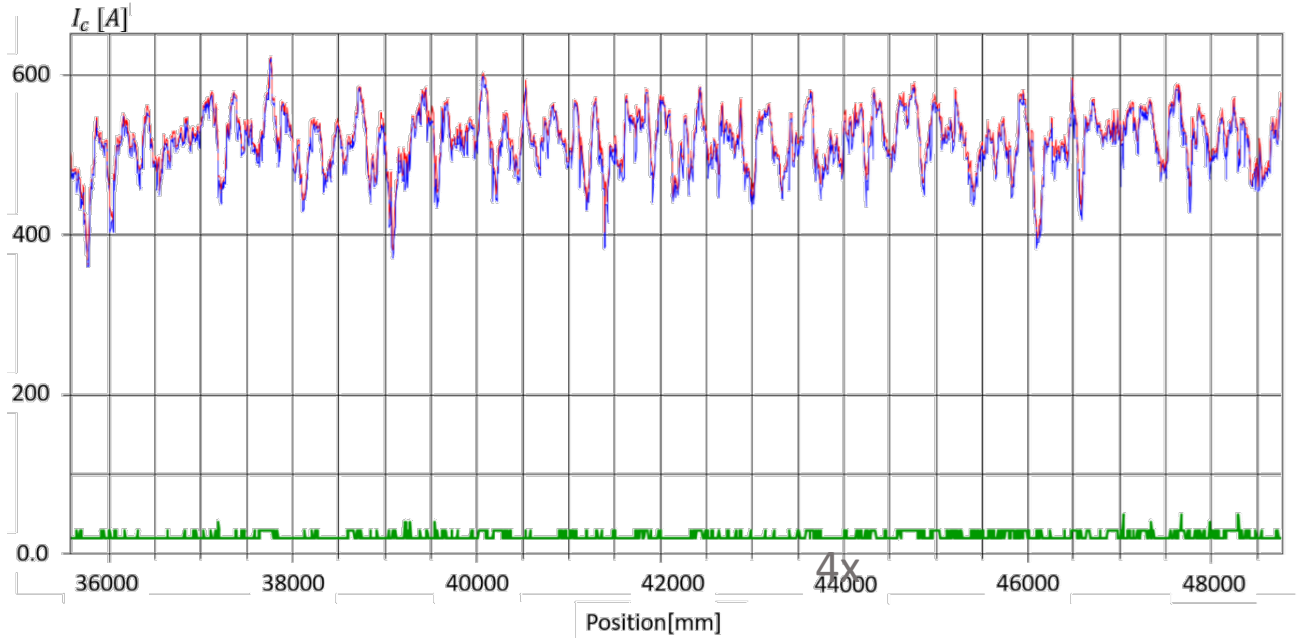
Outline

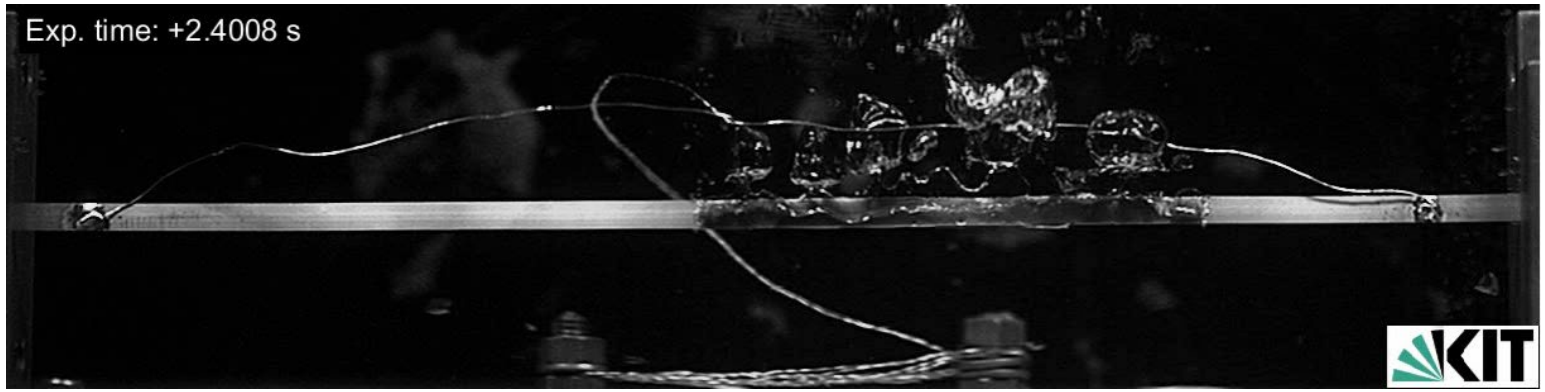
- **Motivation**
  - The hot-spot issue
  - Reasonable Current Contact size
- **CFD fabrication routes:**
  - 1st proposal: Local Annealing
  - 2nd proposal: Local hydrogen Reduction
  - 3rd proposal: Yttria CFD
  - 4rd proposal: Sulfide b-CFD
- **Conclusion & outlook**

Motivation: The *hot-spot* regime





Video from Sebastian Hellmann – 3M-LS-O2.7 – EUCAS 2015



Superconductor 4mm, Superpower ReBCO-tape 40 µm Cu-stabilization

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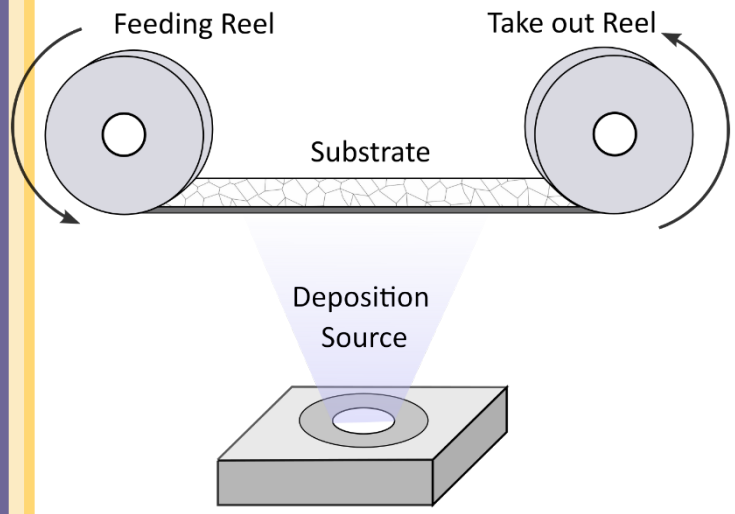
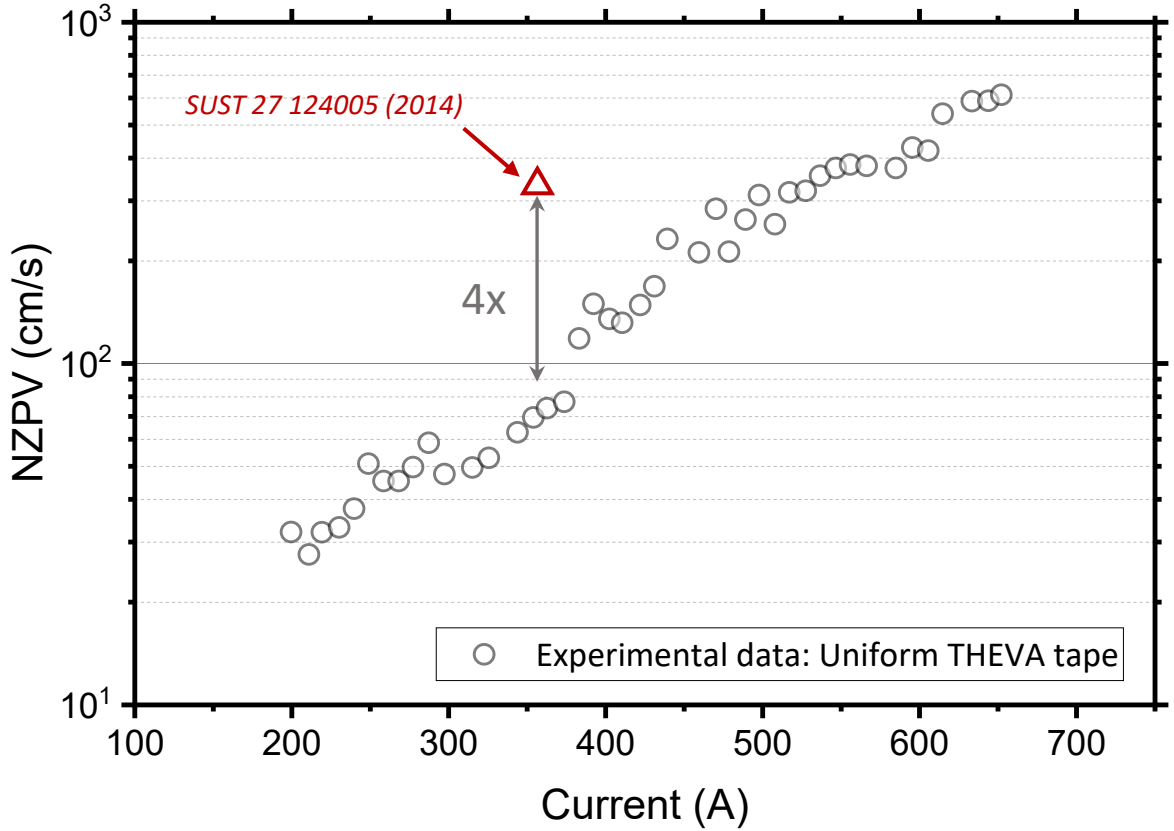
Motivation: The *hot-spot* regime



"… with an NZPV greater than 300 cm s−1, it is possible to achieve a satisfying local thermal stability with relatively short HTS-CCs …" (* at 365 A)

- Daniele Colangelo and Bertrand Dutoit Supercond. Sci. Technol. 27 124005 (2014)

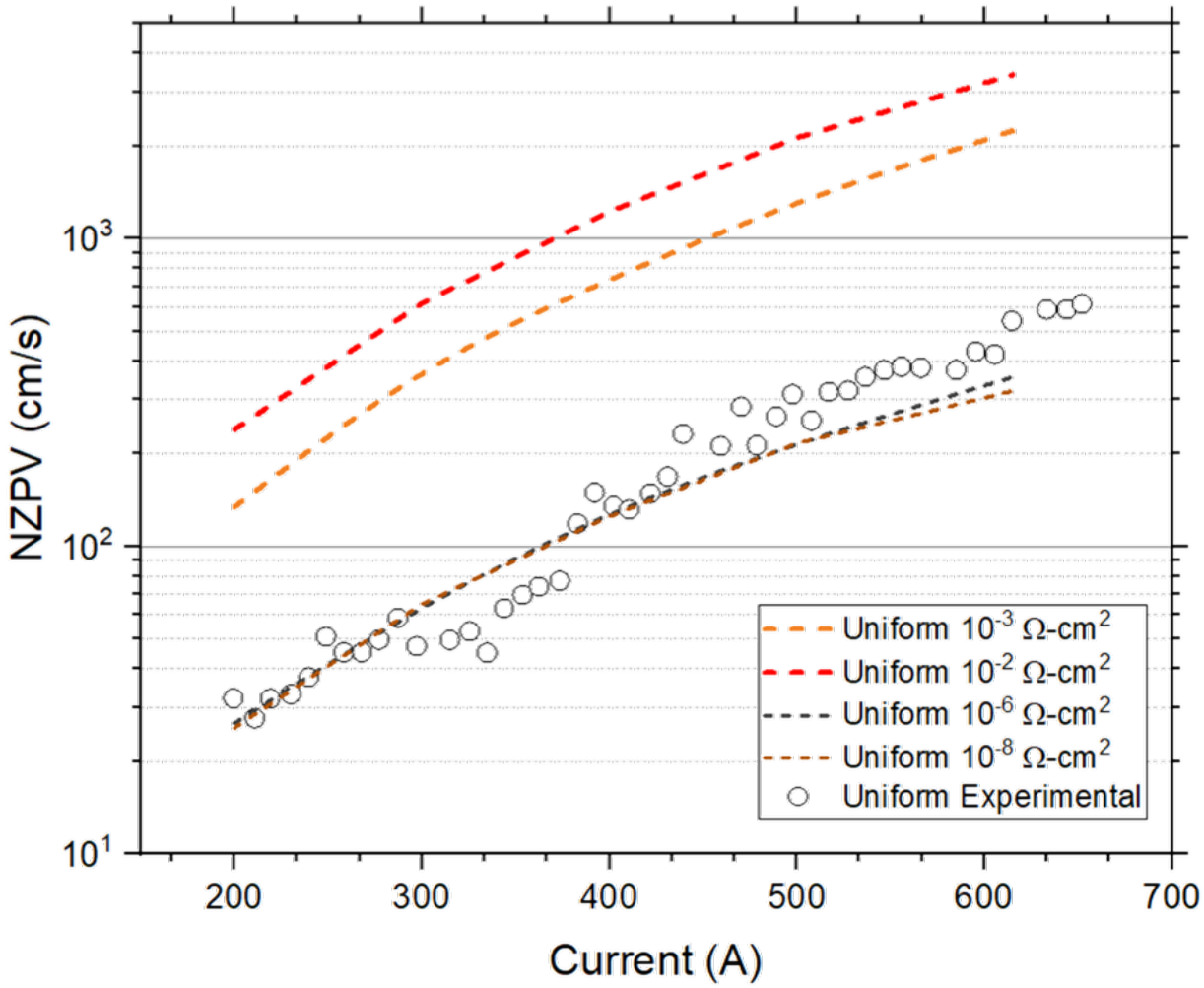


Designing the Current Contacts Size

Uniform **Low** Interfacial Resistance

Uniform **High** Interfacial Resistance

- $ReBa_2Cu_3O_{7-\delta}$
- Buffer layer
- Hastelloy
- Silver (Ag)
- Low interfacial resistance
- High Interfacial resistance



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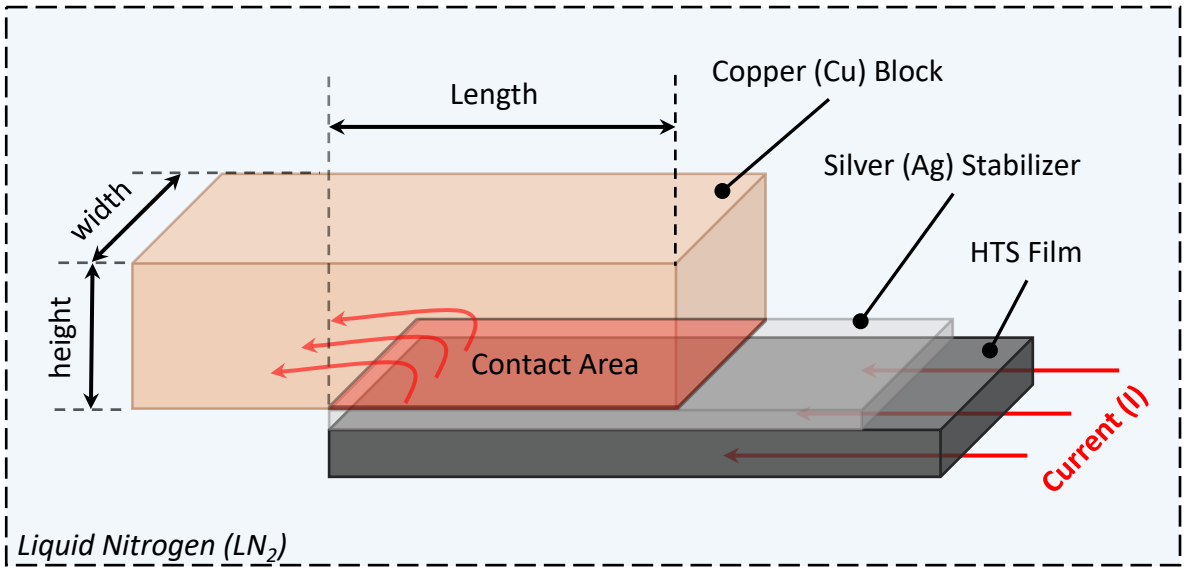
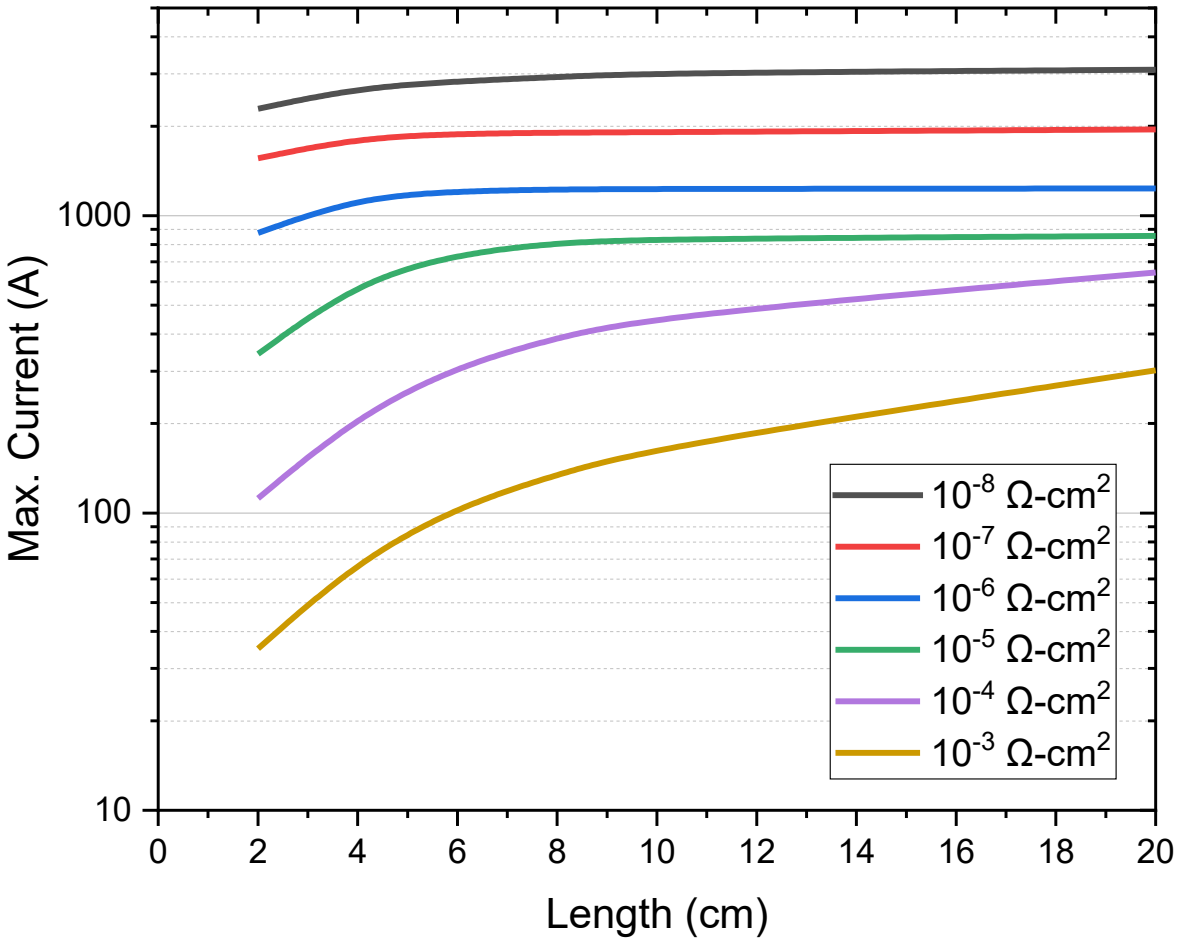
Designing the Current Contacts Size

COMSOL





- Heights: h_{cu}= 1 cm, h_{Ag}= 1 µm, h_{HTS} = 100 nm
- Width: $w_{cu} = w_{ag} = w_{hts} = 12$ mm
- Length sweep: $2 \leq L \leq 100\ cm$
- Transport Current sweep: $1 \leq I \leq 2000\ A$
- Interfacial Resistance : $10^{-6} \leq \rho \leq 10^{-3}$ Ω-cm^2
- Criteria for Min. Cont. Area: Maximum **decrease of 5% in I_c**

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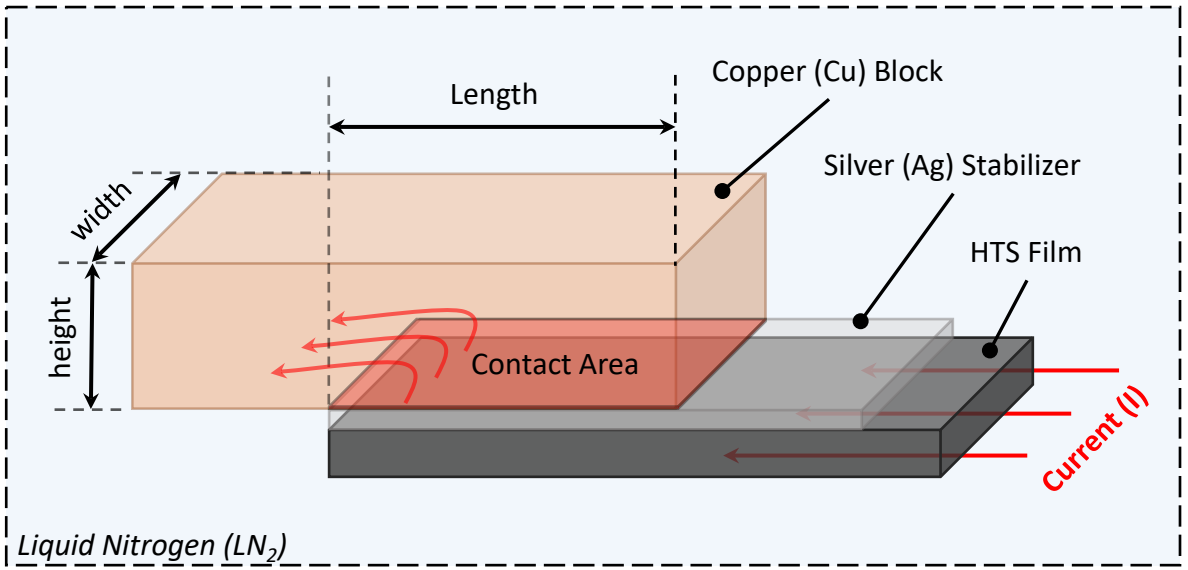
Designing the Current Contacts Size

COMSOL



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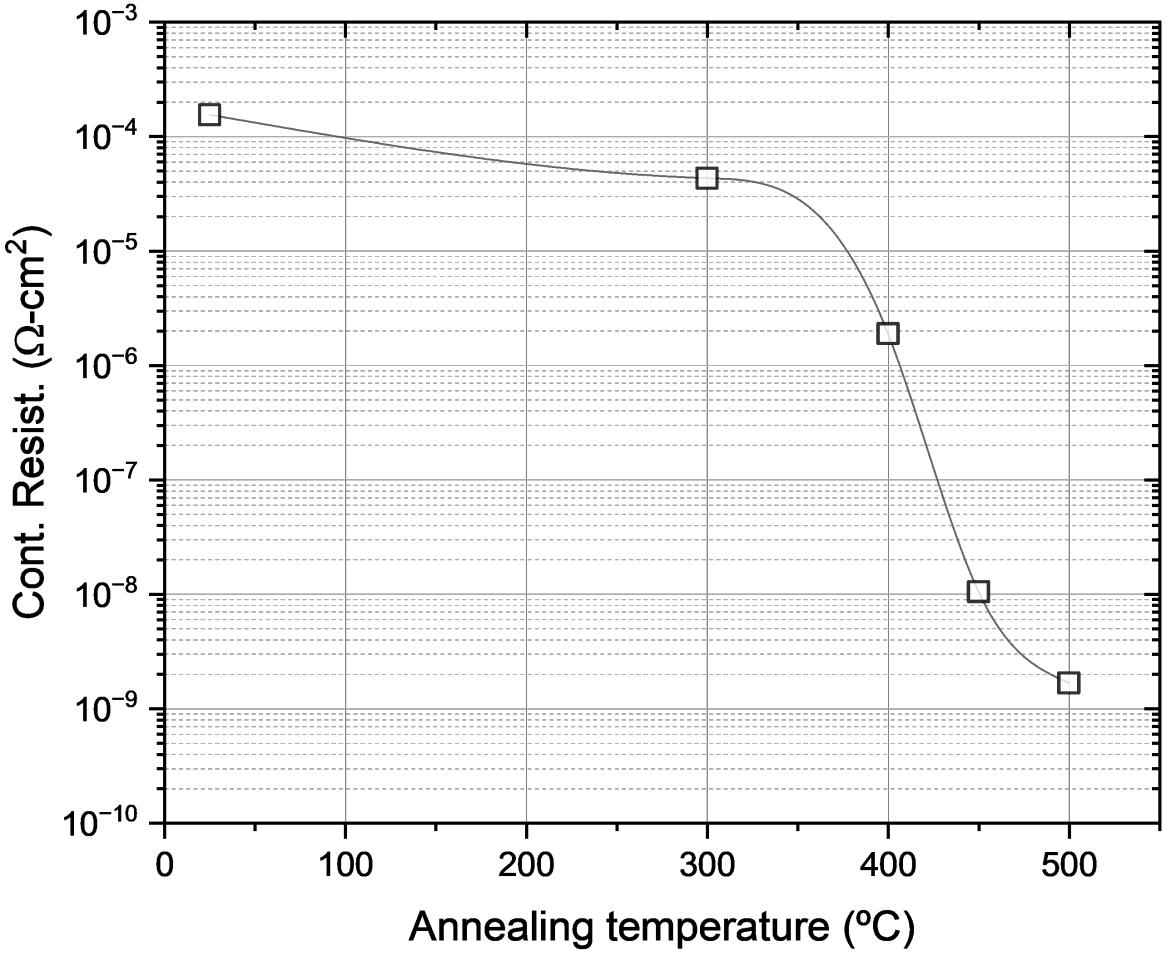
Silver-GdBCO contact resistance versus Annealing temperature (T plateaus of 2 hours)



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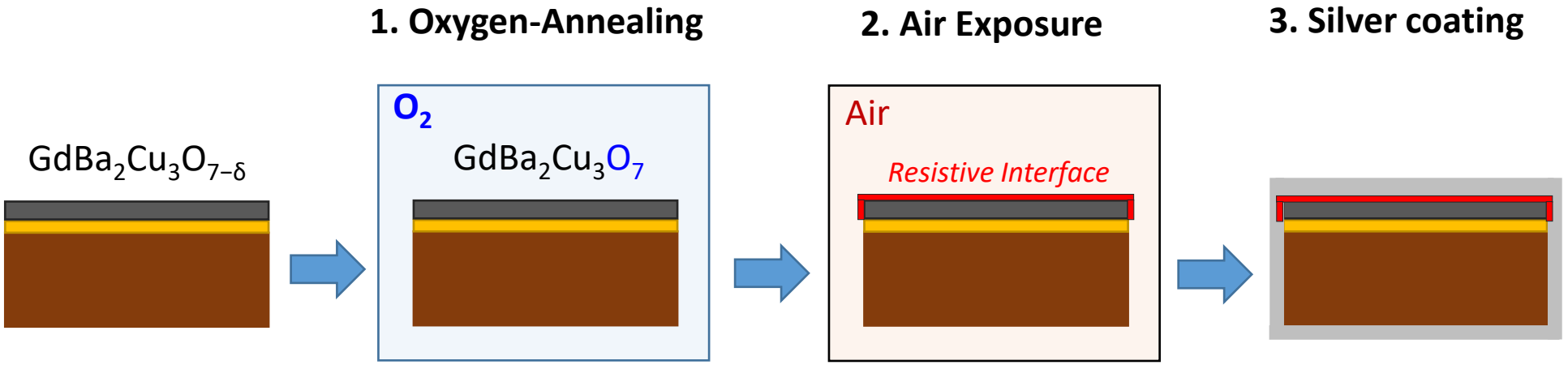
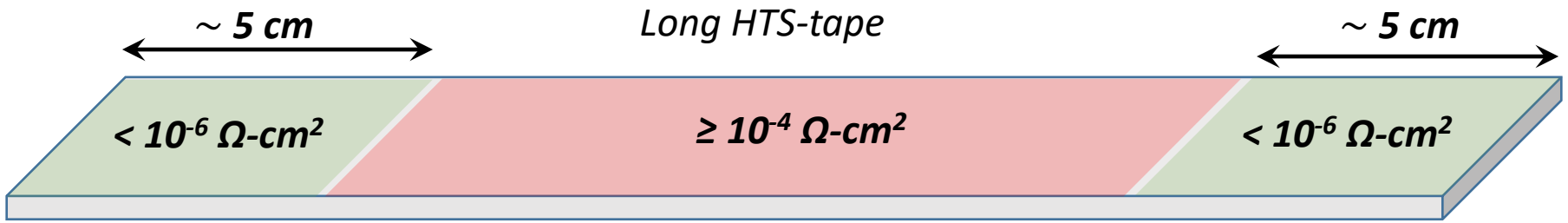
1st Proposal: Local Annealing



4. Local Oxygen-Annealing



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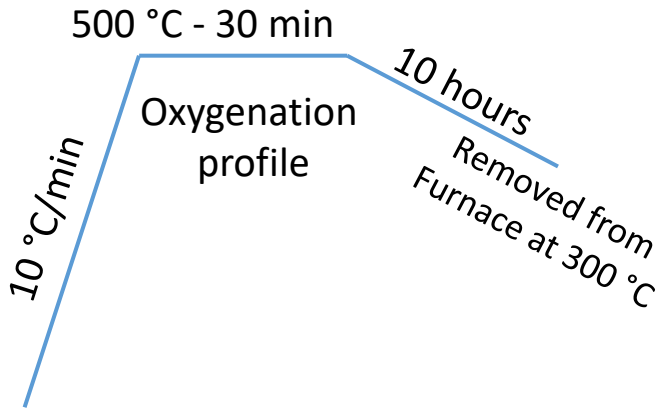
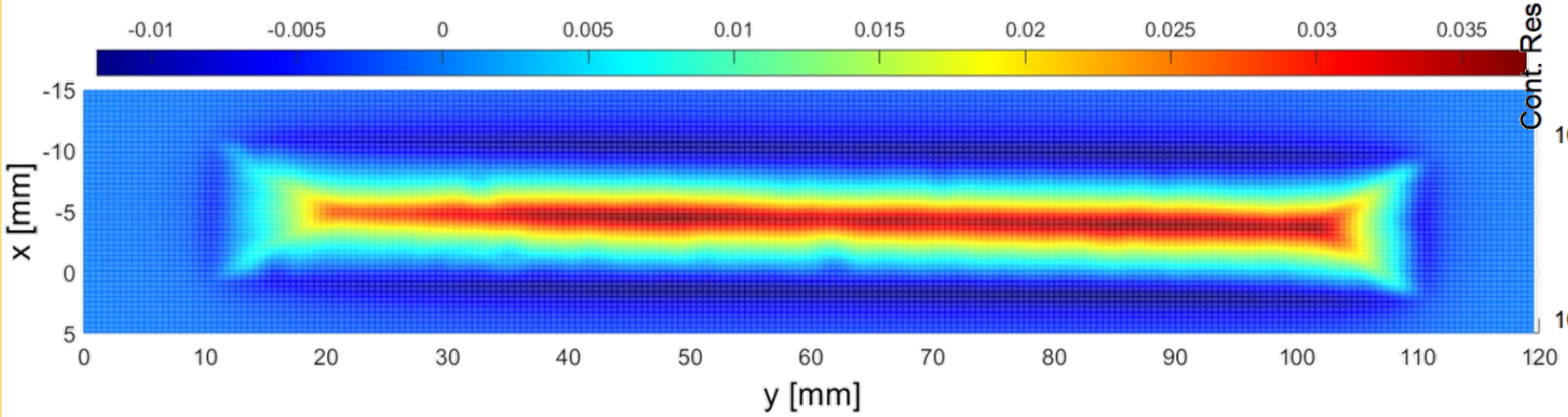
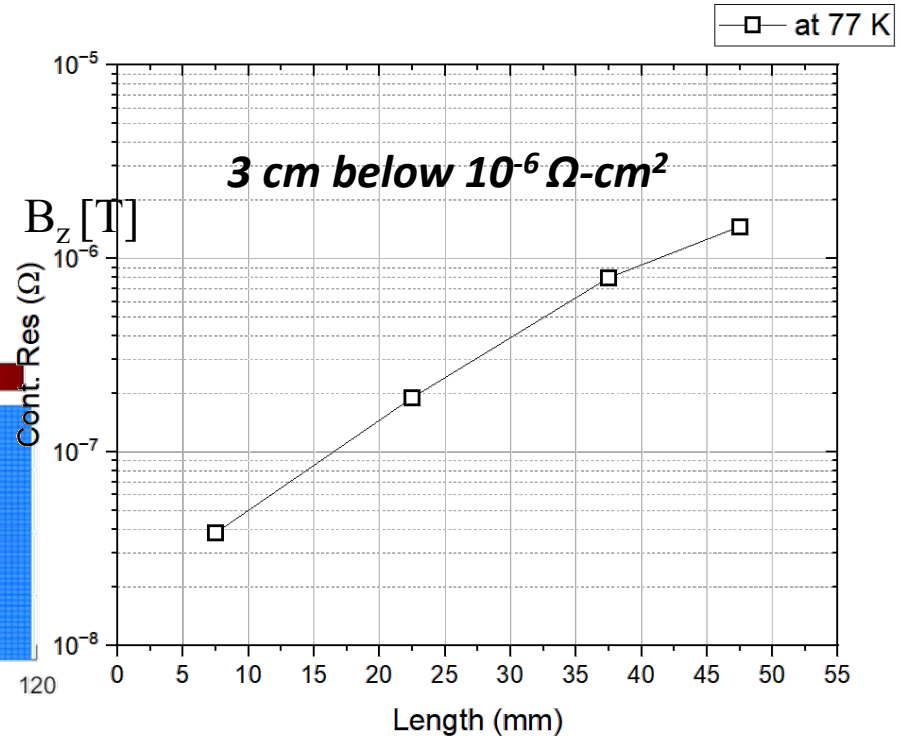
Local Annealing: Experiment



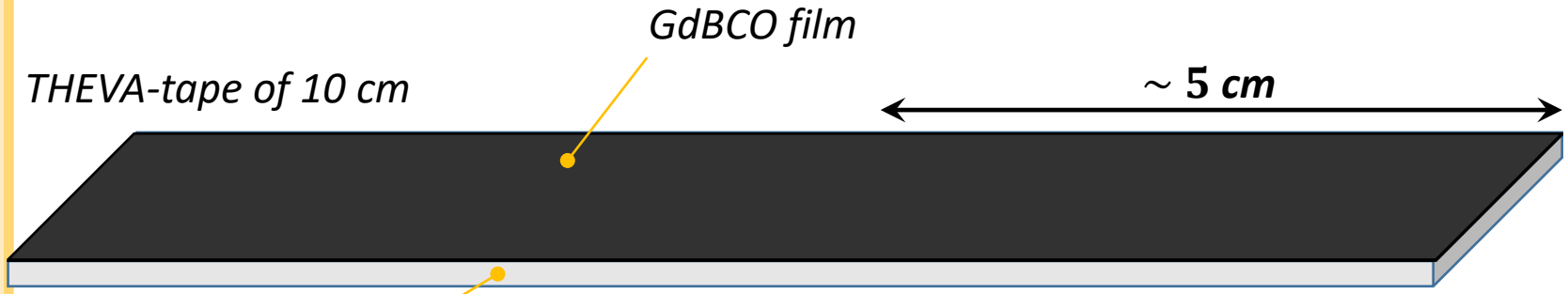
✓ Local Annealing at 500 °C for 2h in 0.6 L/min of O_2 flow

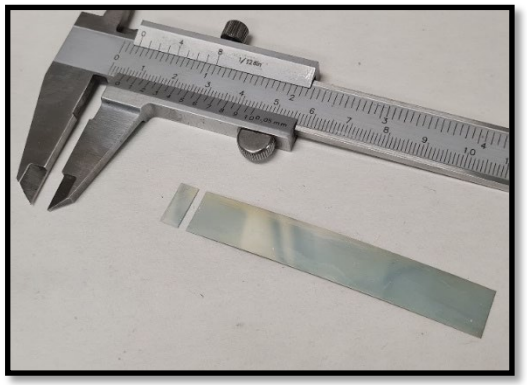
Scanning Hall Probe Microscopy THEVA-tape of 10 cm





Local Annealing: Experiment





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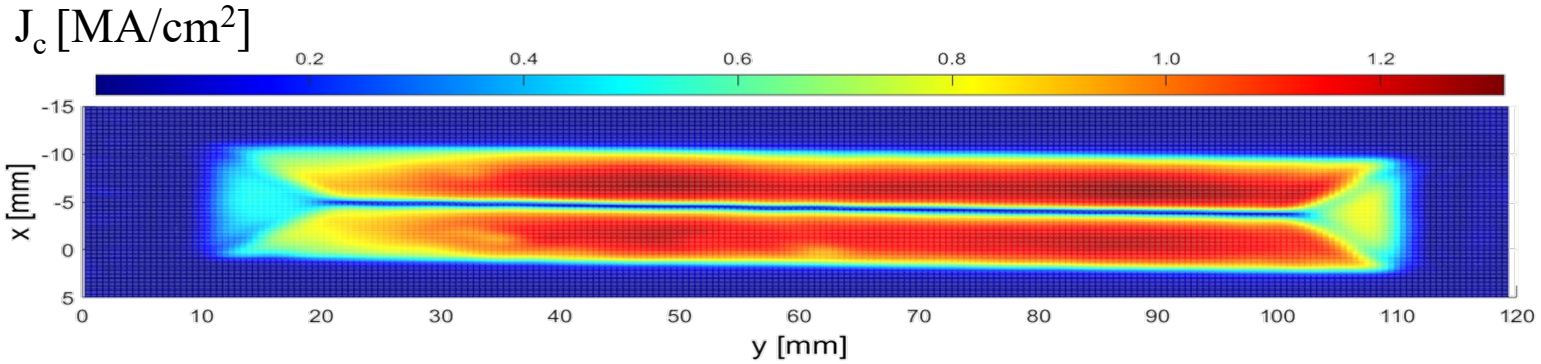
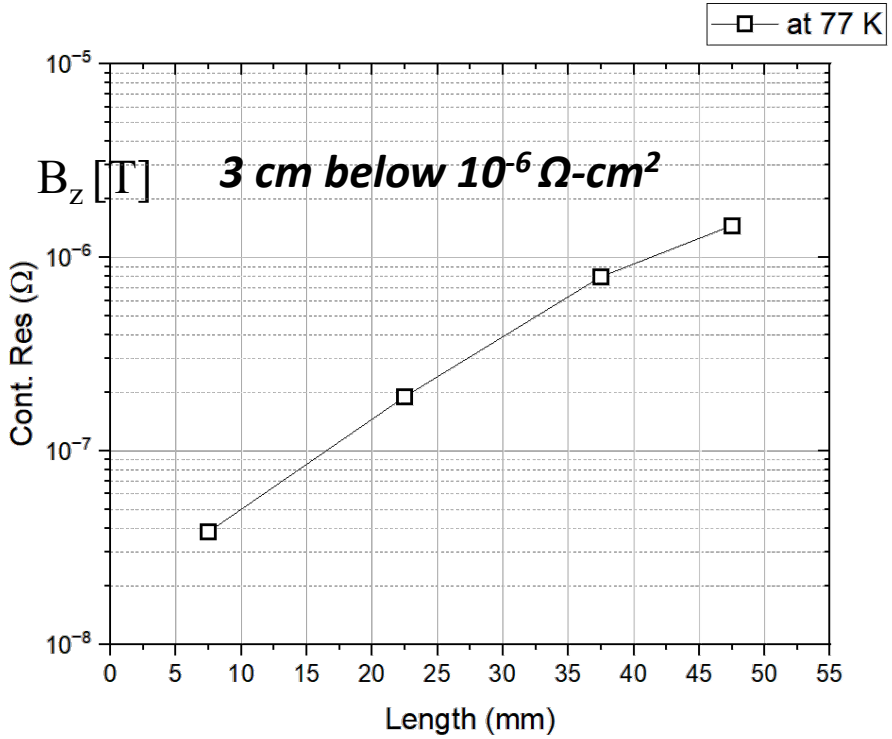




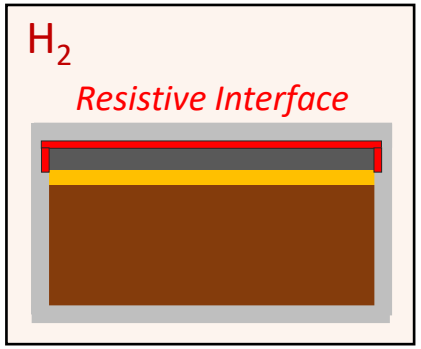
2nd Proposal: Local Hydrogen Reduction

0. Pre-Oxygenated (Commercial tape)

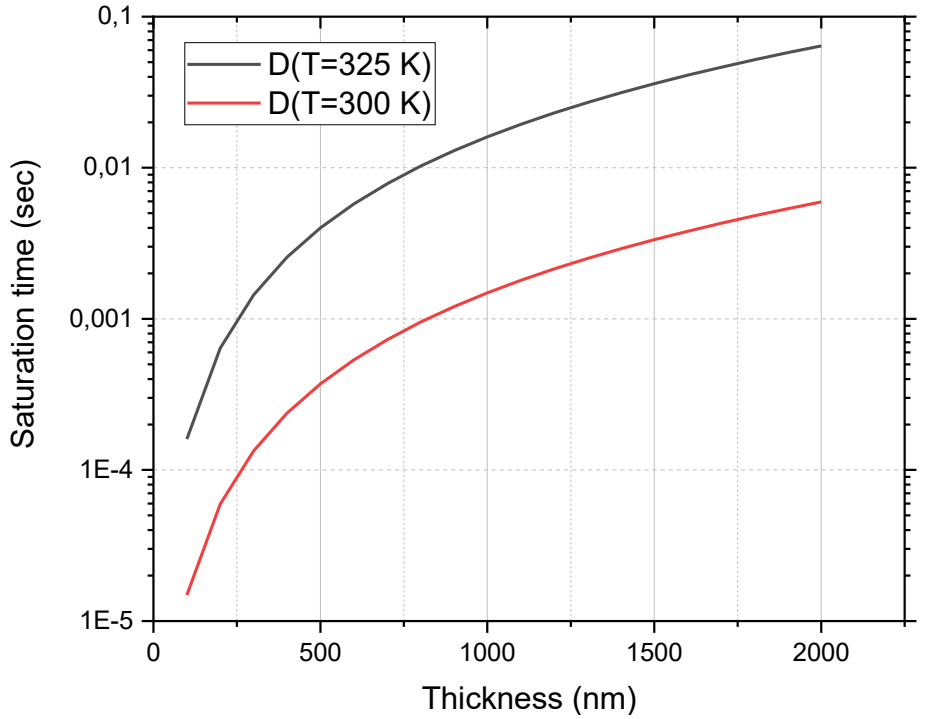
$GdBa_2Cu_3O_7$

Tape cross section

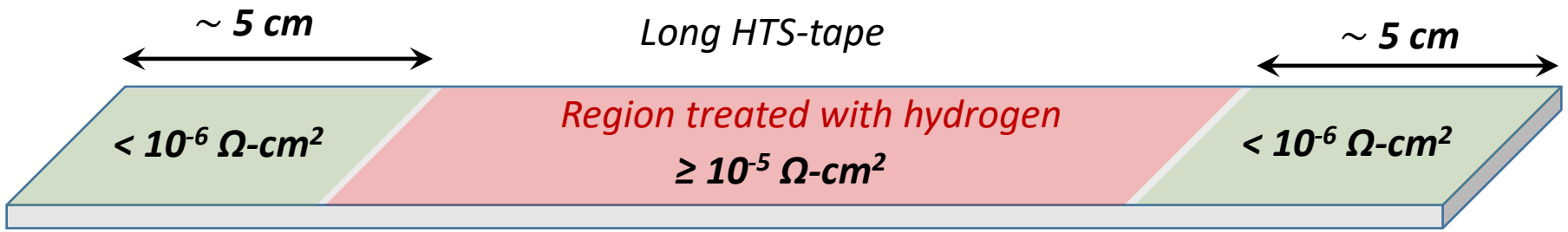
1. Hydrogen Exposure



Hydrogen Saturation time vs. Ag thickness



2. Tape with local High interfacial resistance



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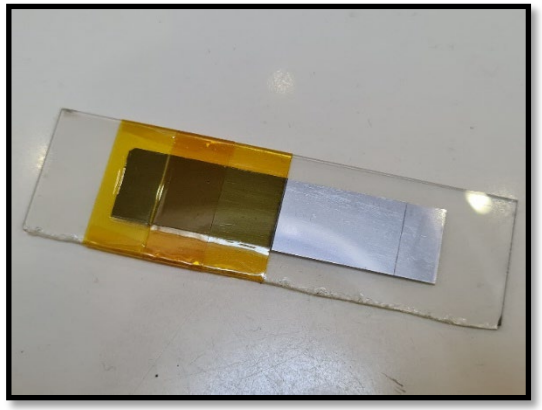
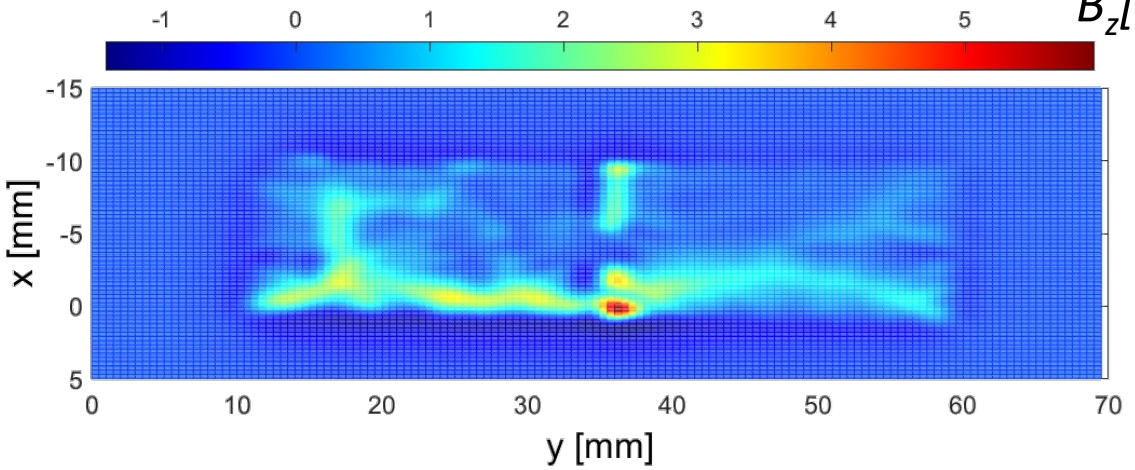
2nd Proposal: Local Hydrogen Reduction Experiment

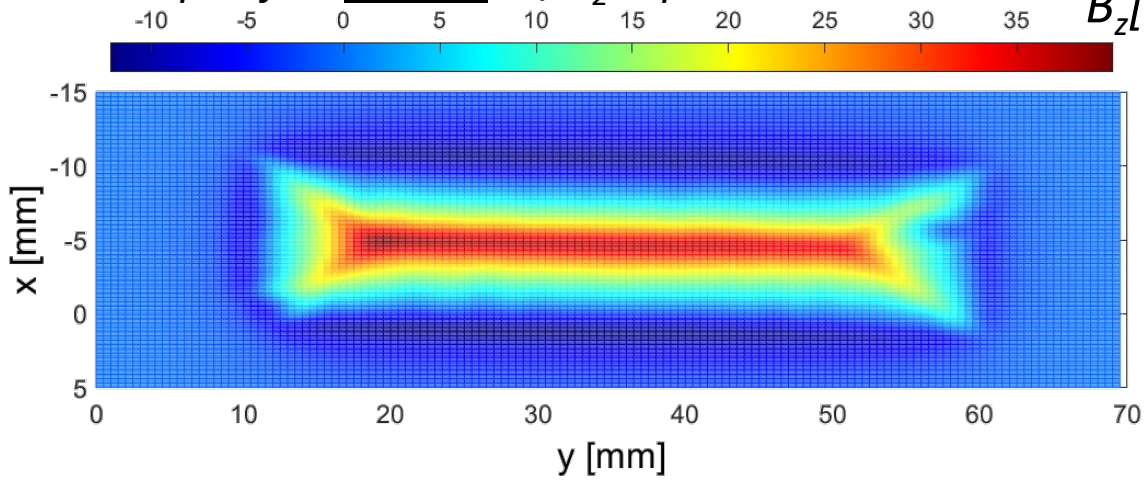
5 cm long Ag coated Gd123-tape



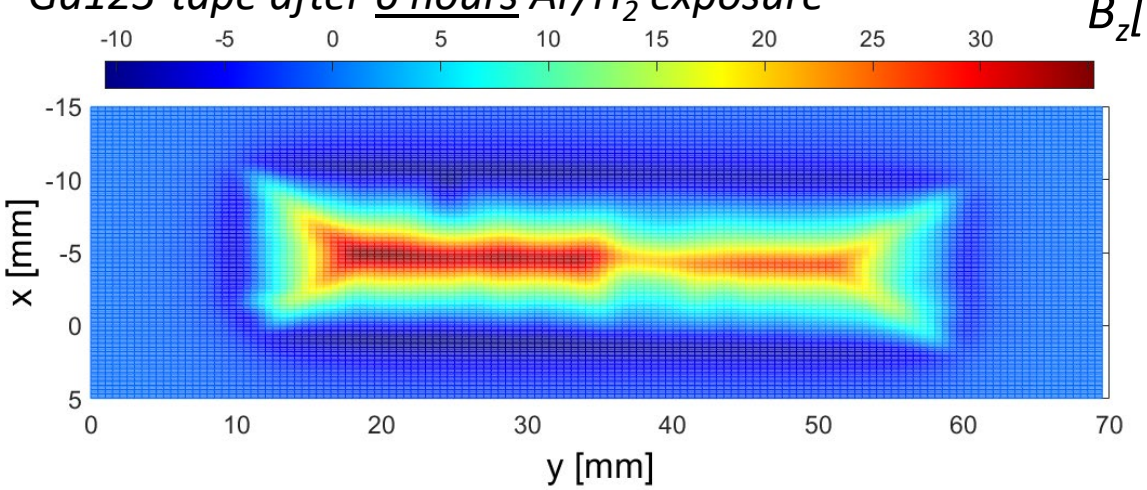
Gd123-tape after <u>20 hours</u> Ar/H_2 exposure



Gd123-tape after <u>4 hours</u> Ar/H_2 exposure at 200 °C

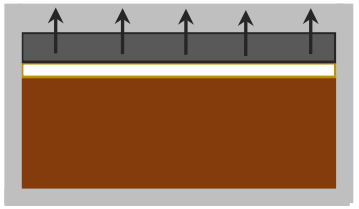


Gd123-tape after <u>6 hours</u> Ar/H_2 exposure

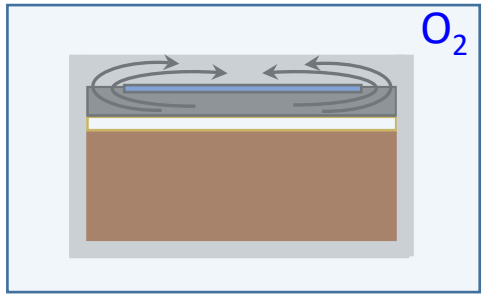


3rd Proposal: The Current Flow Diverter or CFD

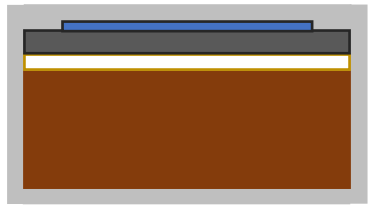
Uniform
Tape cross section



4. Final O_2 Annealing for CFD

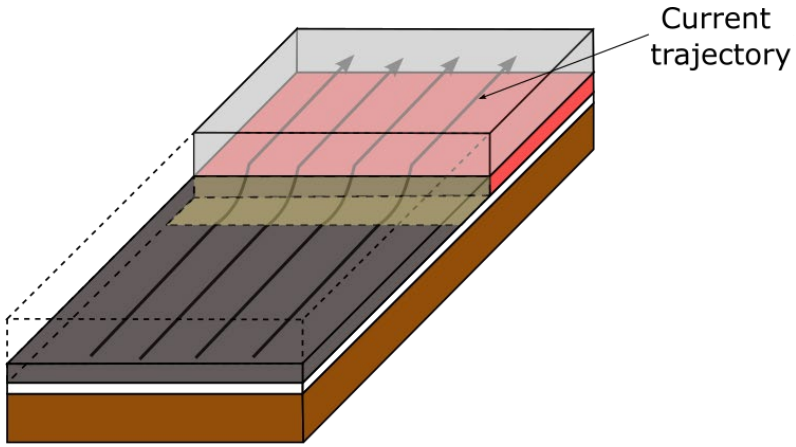


3. Silver Coating



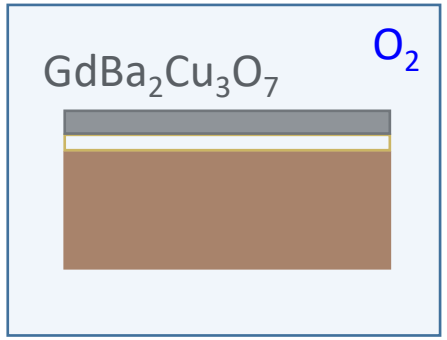
0. Grown HTS film (NOT oxygenated)

$GdBa_2Cu_3O_{7-\delta}$



2. Yttria Chemical Solution Disposition

1. Oxygen Annealing



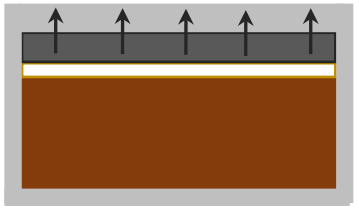
Hastelloy Substrate
REBCO film
Buffer layer
Silver stabilizer
Normal zone
Joule heating concentration
High interfacial resistance layer

Lacroix et al., SUST 27 035003 (2014)
Lacroix et al., SUST 27 055013 (2014)
Lacroix et al., SUST 30 064004 (2017)

Barusco et al., ACS Omega 7, 15315–15325 (2022)
Lacroix et al., SUST 35, 055009 (2022)

3rd Proposal: The Current Flow Diverter or CFD

Uniform
Tape cross section



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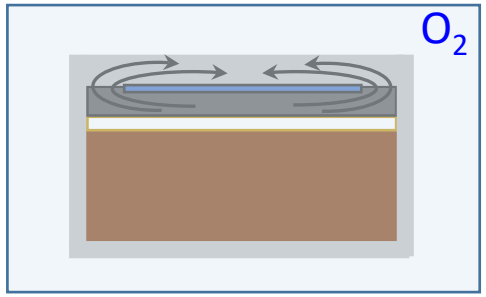

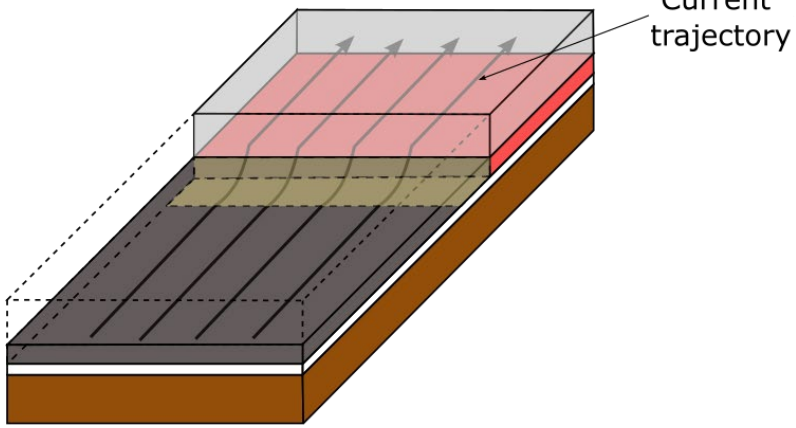

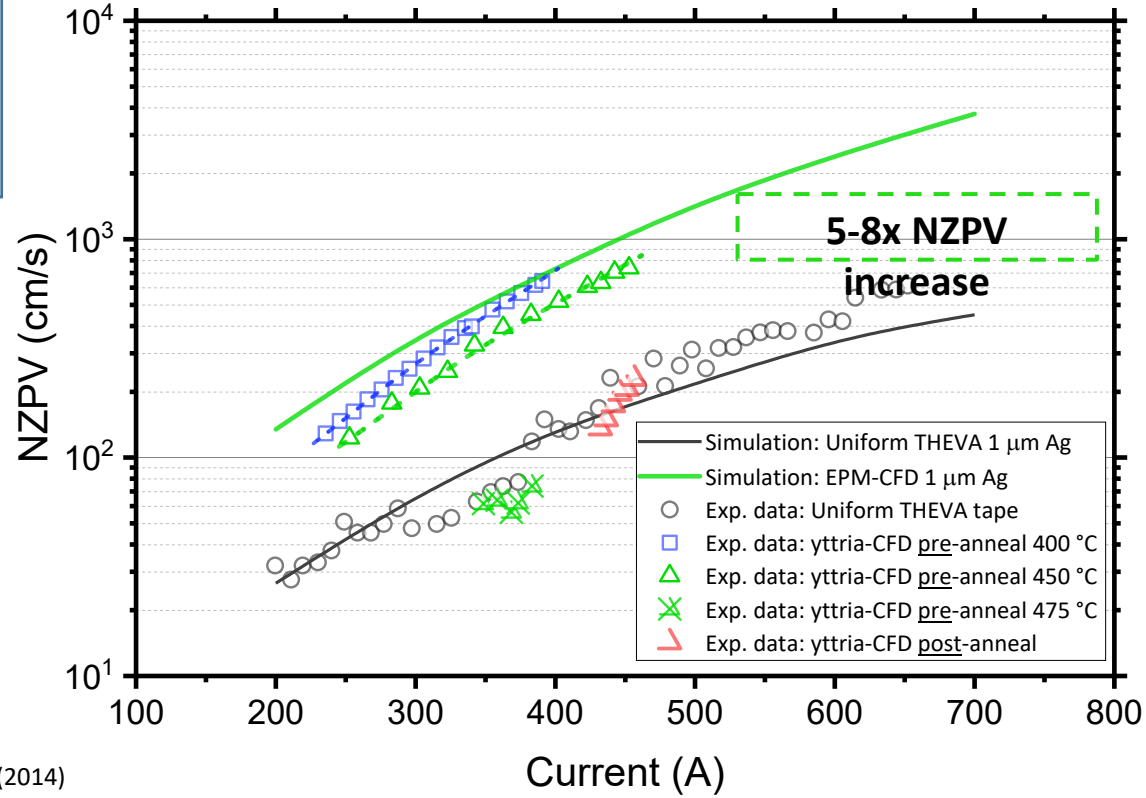

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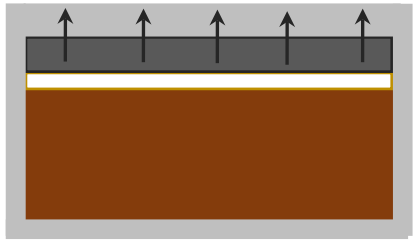
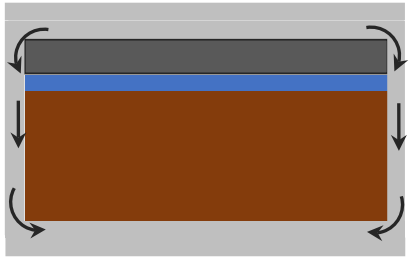
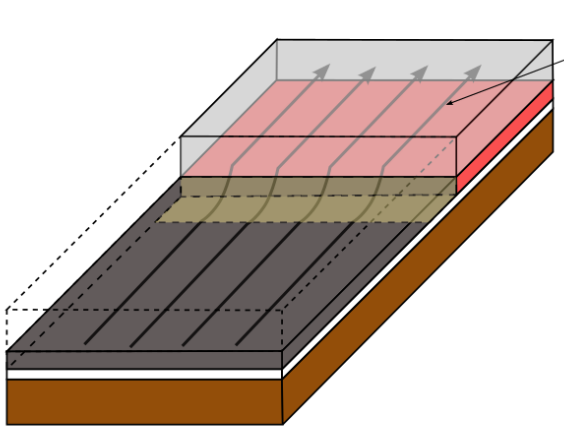
Barusco et al., ACS Omega 7, 15315–15325 (2022)
Lacroix et al., SUST 35, 055009 (2022)

4rd Proposal: b-CFD via silver sulfidation

Tape cross section







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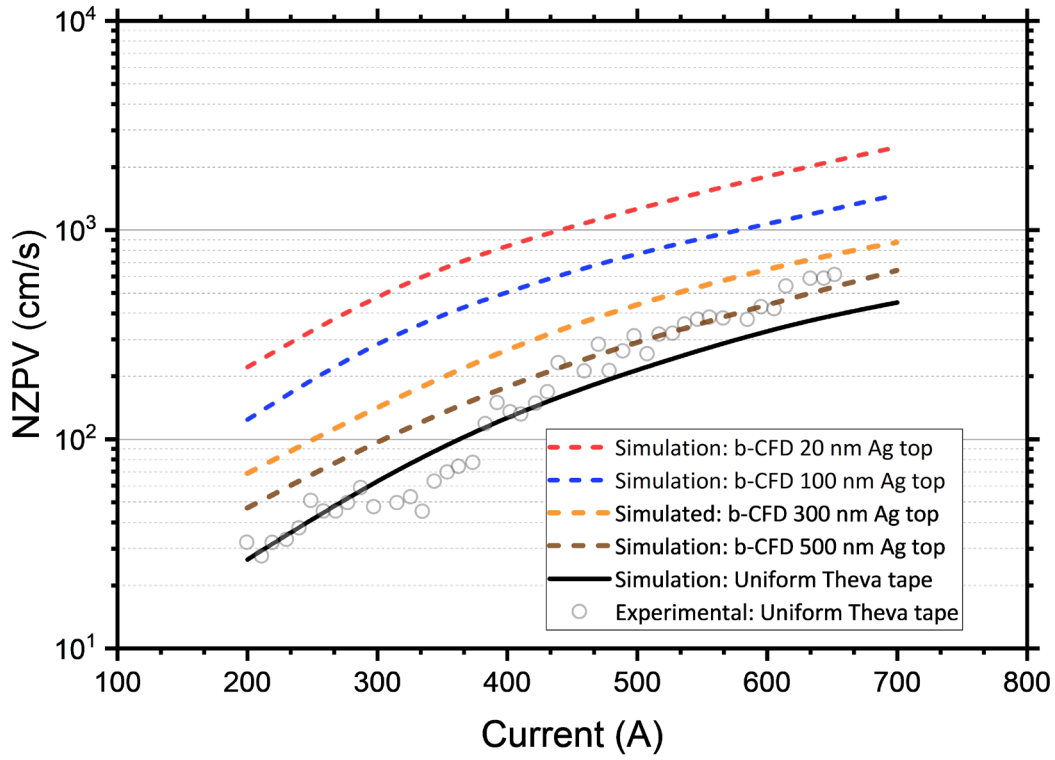

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4th Proposal: Sulfidation of the silver for the CFD

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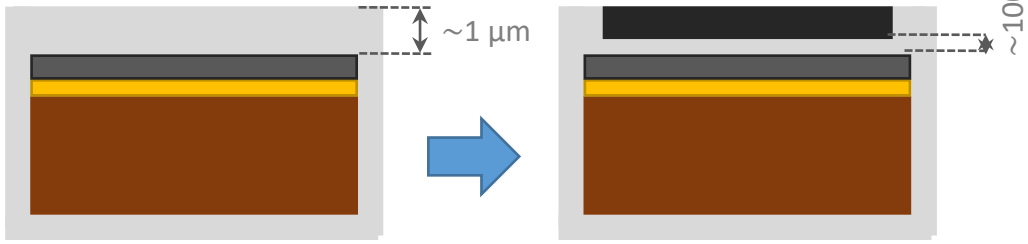
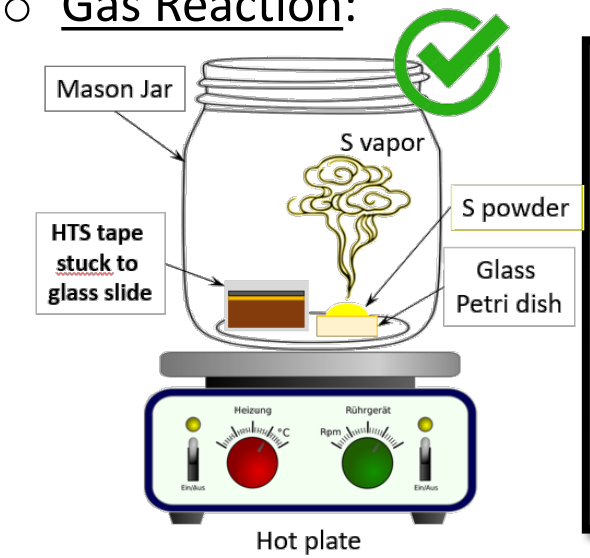
- **Partial Sulfidation of the Ag shunt:**

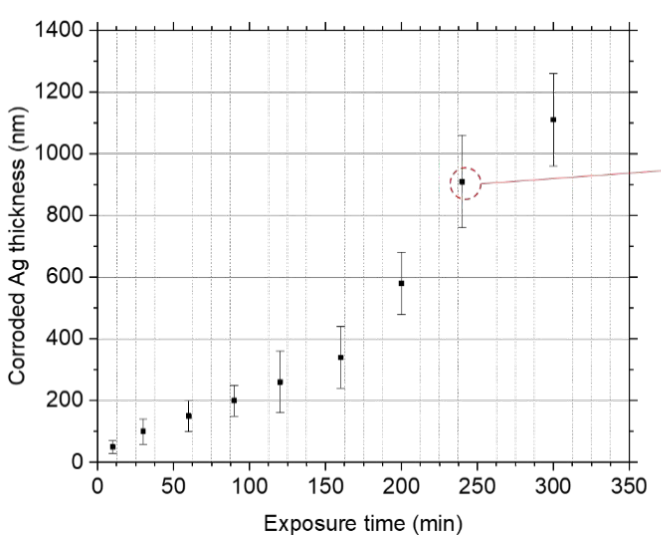
$$2Ag(s) + S\,(g) \longrightarrow Ag_2S\,(s)$$

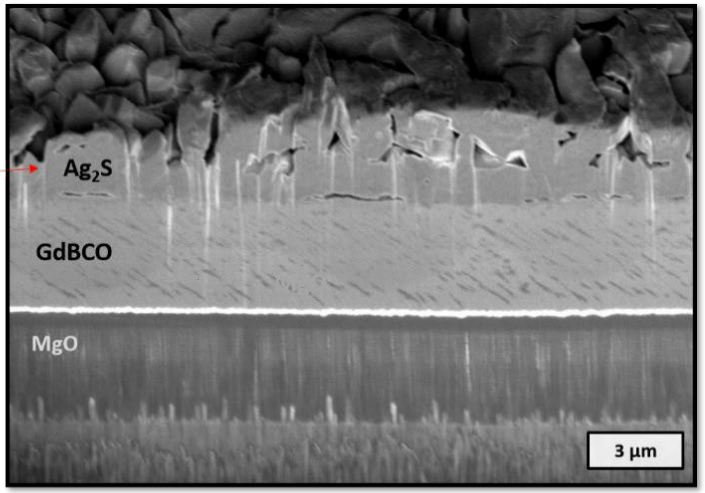


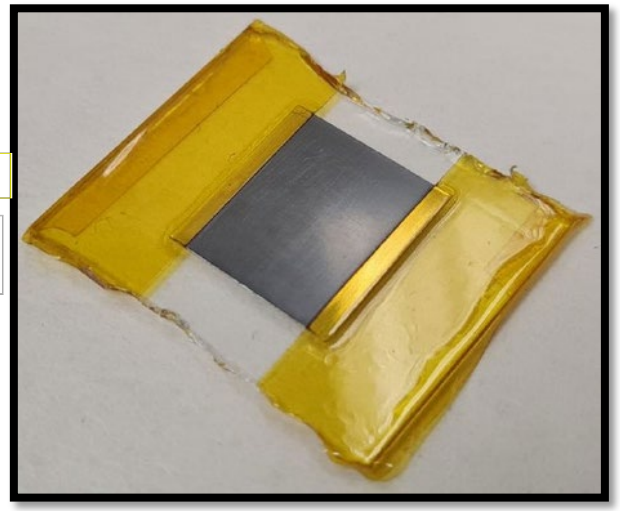
- $GdBa_2Cu_3O_7$
- MgO
- Hastelloy
- Silver (Ag)
- High resistance
- Silver Sulfide (Ag_2S)

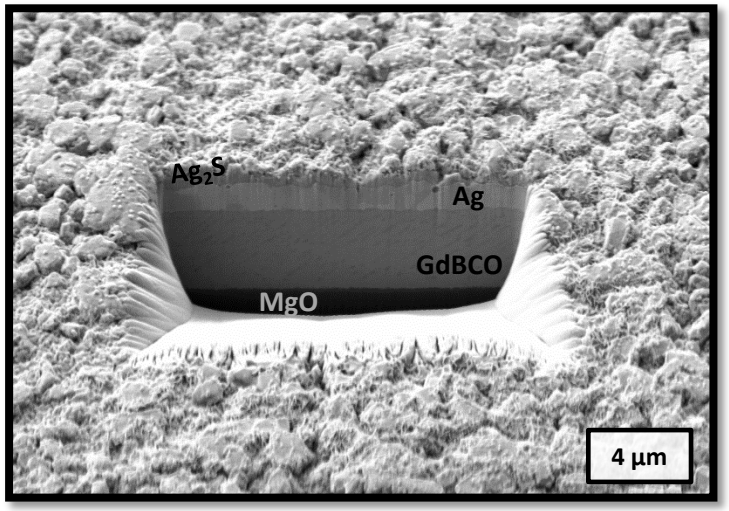
- Gas Reaction:







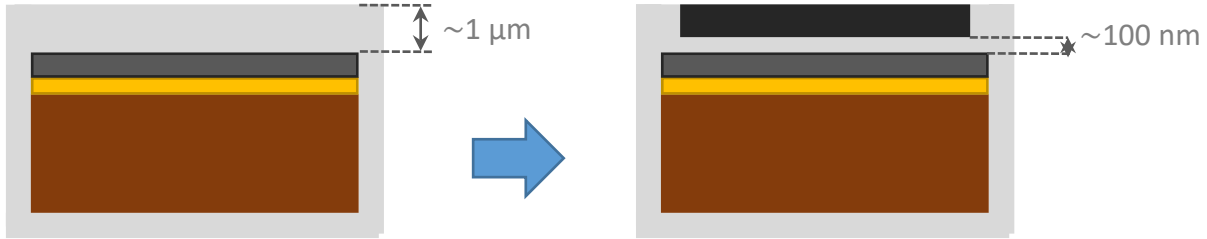




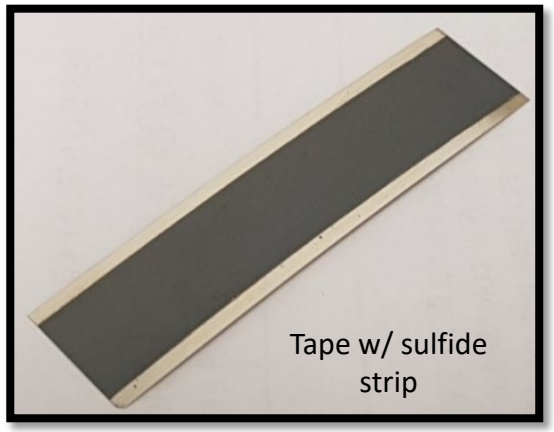
4th Proposal: The b-CFD architecture with sulfidation

- **Partial Sulfidation of the Ag shunt:**

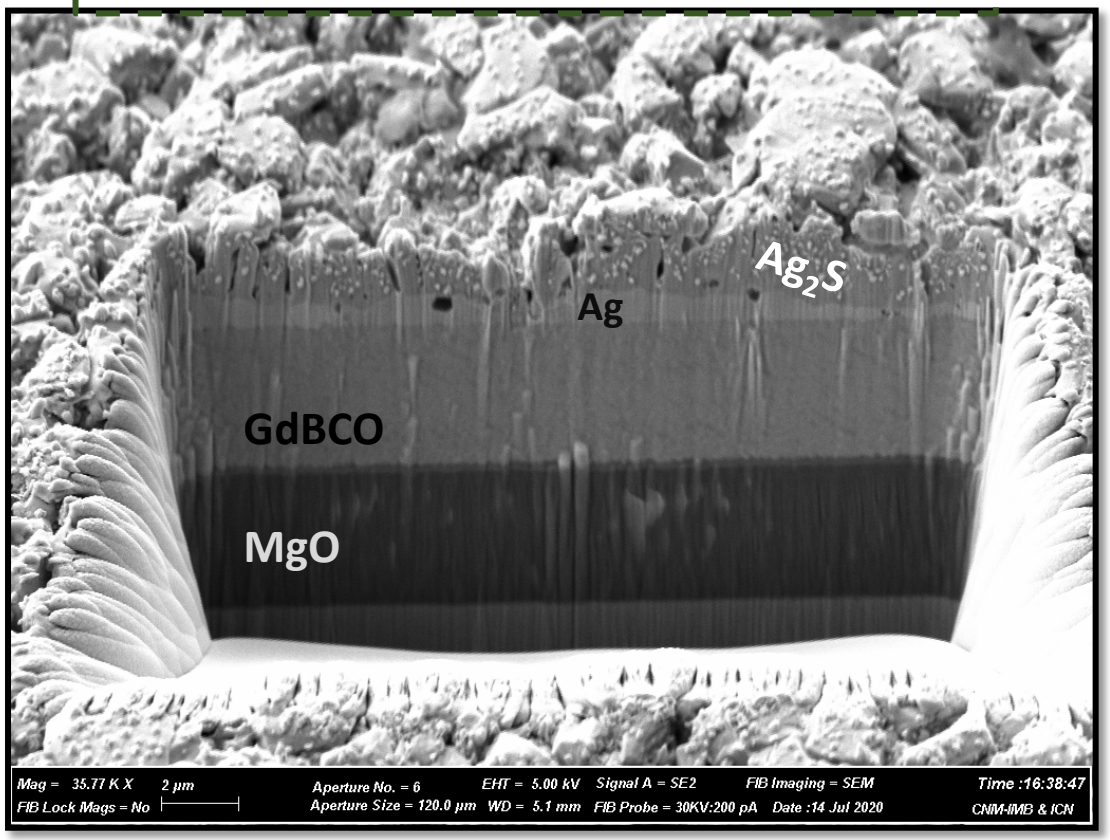
$$2Ag(s) + S\,(g) \longrightarrow Ag_2S\,(s)$$



- $GdBa_2Cu_3O_7$
- MgO
- Hastelloy
- Silver (Ag)
- Silver sulfide (Ag_2S)



The sulfurization process can be controlled to avoid damaging the HTS



4th Proposal: The b-CFD architecture with sulfidation

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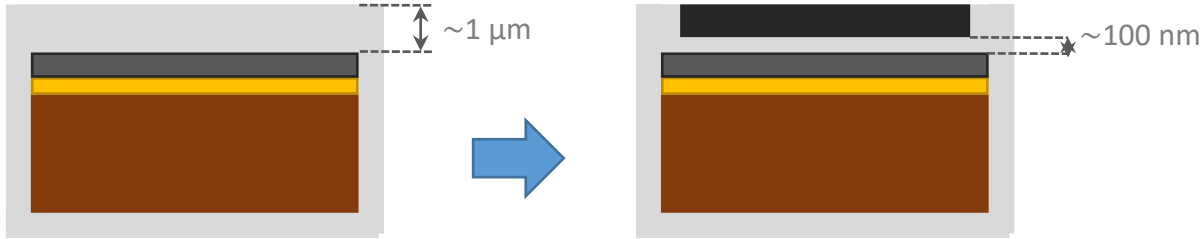

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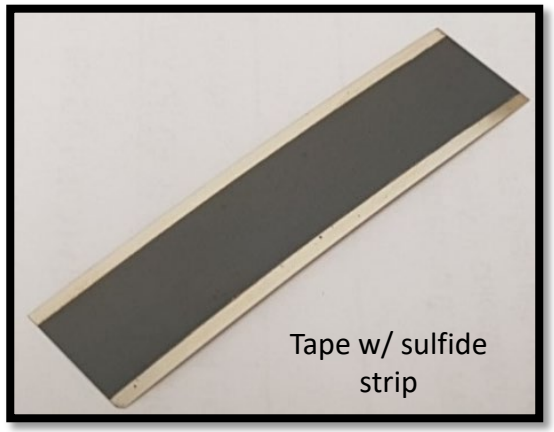

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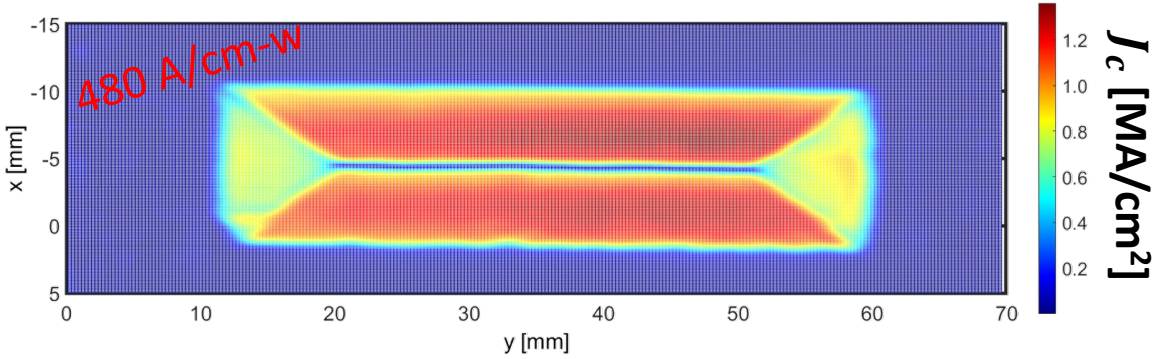

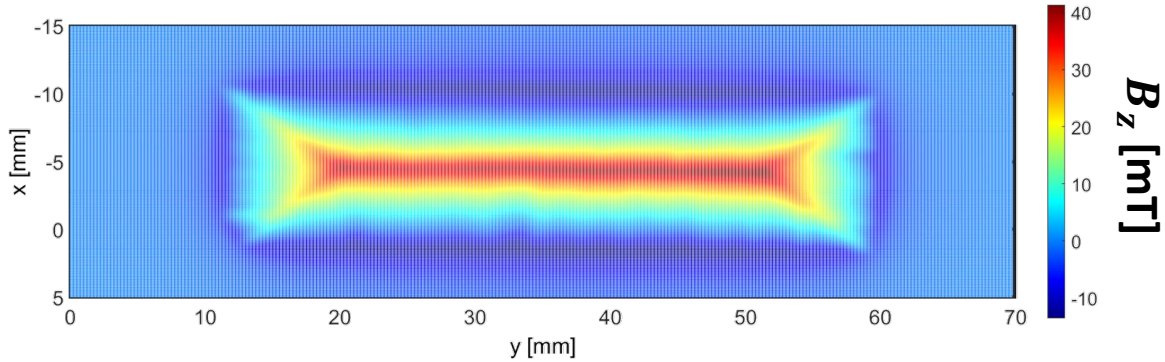

4th Proposal: The b-CFD architecture with sulfidation

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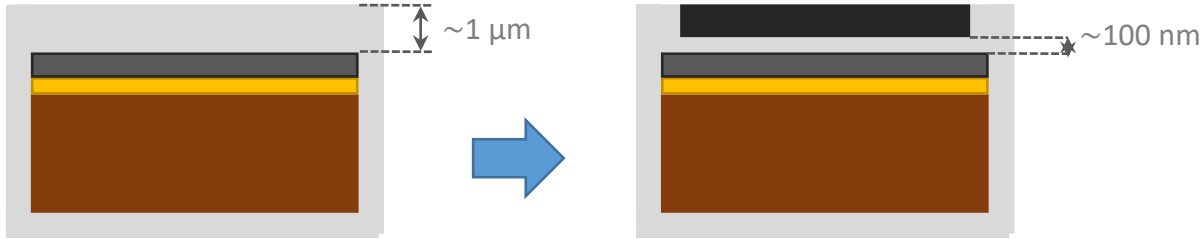

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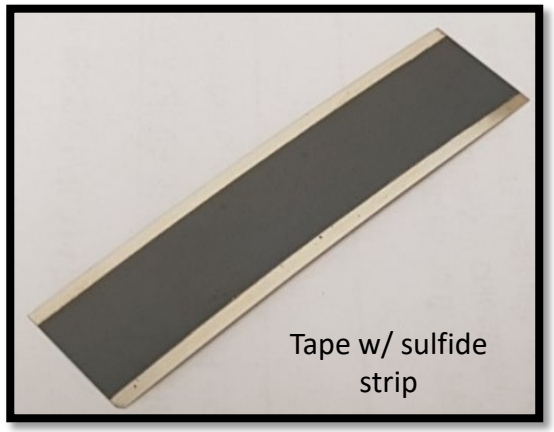

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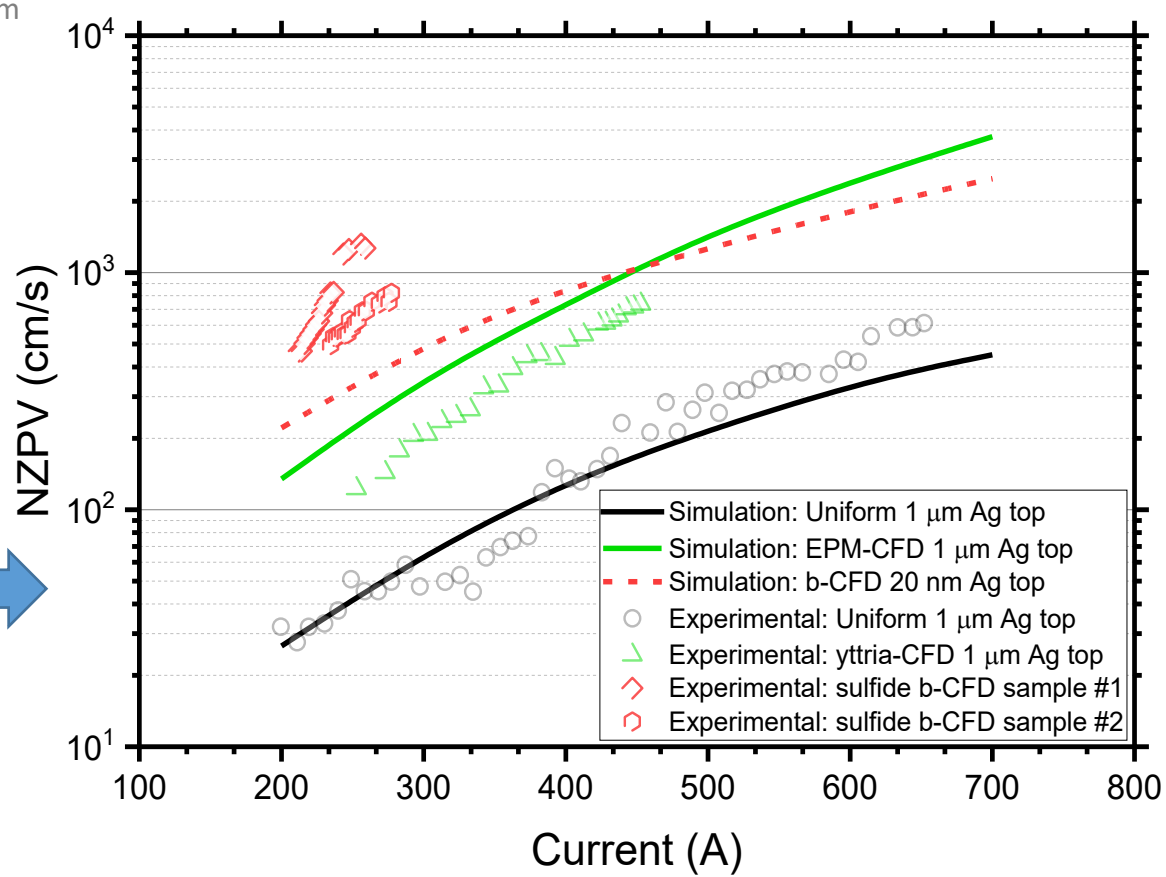

Conclusions and Outlook

- In order to safely operate it in the 1000 A range, the highest interfacial resistance in a 12 mm HTS tape, with reasonable current contact size is close to 10^{-6} Ω-cm^2 .
- The interfacial resistance threshold for substantially increasing the NZPV in a 12 mm HTS-tape is 10^{-6} Ω-cm^2
- Annealing the HTS film without silver + locally annealing the tape at the current contacts is a viable way to enhance the NZPV
  - Two extra steps are required to manufacture these tapes
  - Oxygenating the HTS-film without silver takes considerably longer annealing times (*not a problem for batch furnaces)
- The interfacial resistance silver/HTS can be increased considerably without removing the silver coating via Hydrogen reduction.
  - The diffusion of hydrogen through the HTS-film is a major challenge for using H_2 as a reducing agent
- Sulfidation of the silver stabilizer for the **b-CFD** architecture
  - The process can be done with any commercial silver coated tape
  - The NZPV gains are comparable to the classic EPM-CFD for currents below 400 A
  - ✓ The sulfidation process still needs to be tuned for long length tapes above 10 cm

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Discussion topics

- High J_c (I_c) coated conductors: key point for all power applications. Proper CC protection against quenching required (I_c fluctuations)
- Issue particularly relevant in Fault Current Limiters and high field magnets: hot spots may degrade or destroy the conductors and limit the maximum current
- Intrinsic quench protection of CCs: consider seriously (NZPV of CCs too low) so they are prone of being destroyed by local heating
- Current Flow Diversion architecture in CCs: a very effective solution to the quench protection problem
- Several approaches being tested to facilitate integration of the CFD architecture to the manufacturing approaches of industrial partners.
- ICMAB and UP Montreal are committed to transfer the process to industry