Finite element modeling of quench dynamics in 2G HTS CCs and the Current Flow Diverter (CFD) Concept

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A word about the authors

- F. Sirois
  - Full prof. at Polytechnique Montreal (Univ. of Mtl)
  - Former researcher at IREQ (Hydro-Québec res. Inst.)
  - Leader of the only research group in applied superconductivity in Canada
  - Research focused on modeling HTS power appl.
- C. Lacroix
  - PDF at Polytechnique Montréal (2010-2012)
  - Research associate since 2012
  - Realized most of the work presented here

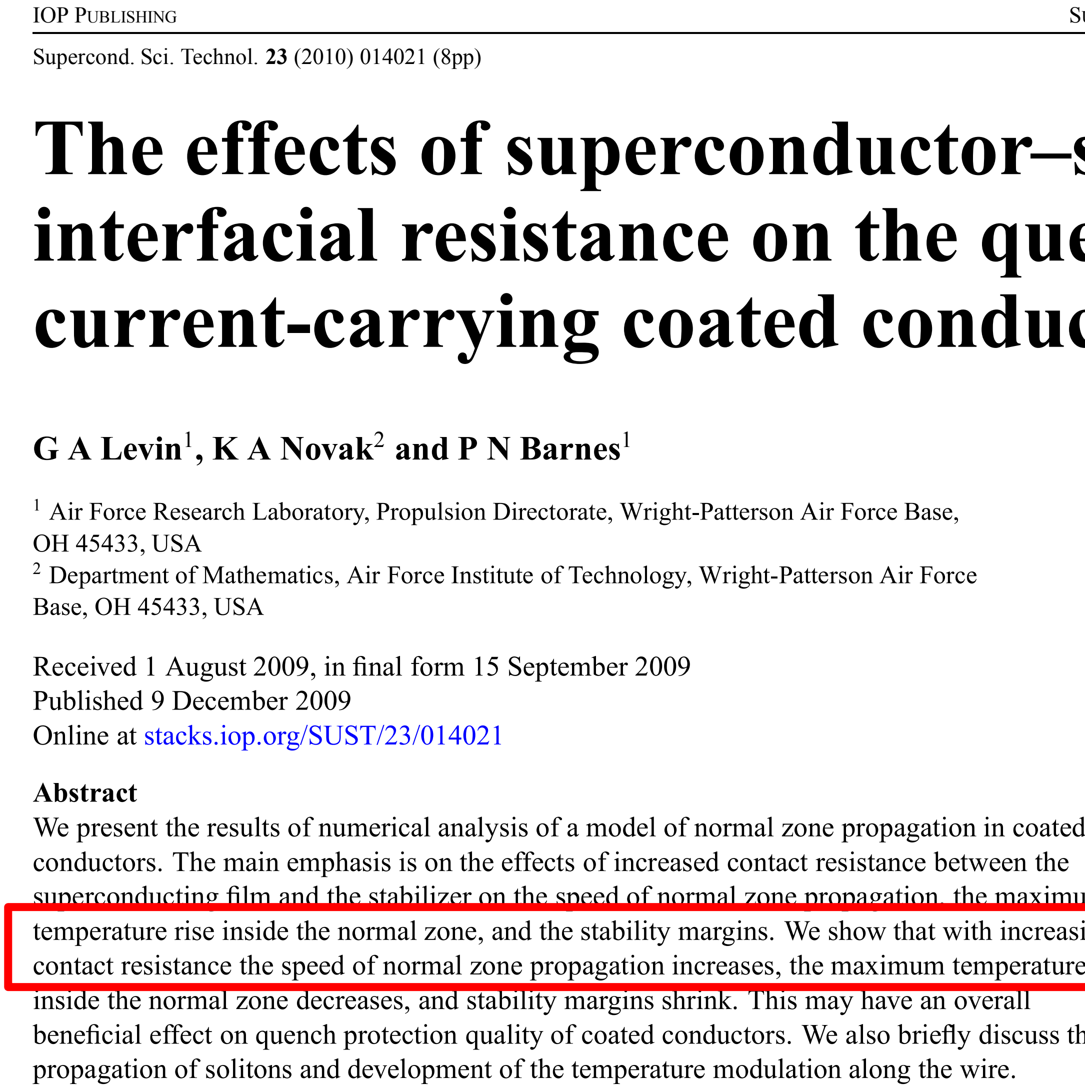
Introduction: hot spot issue

- Hot spot issue in 2G HTS CC when $I_{op} \approx I_c$
  - Local variation of I_c along tape length (≈ 10 %)
  - Low normal zone propagation velocity (NZPV)

- Solution #1 : increase stabilizer thickness
  - Reduced fault current limitation capability
  - Reduced engineering current density

- Solution #2 : accelerate NZPV

Introduction: accelerating the NZPV



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The effects of superconductor–stabilizer interfacial resistance on the quench of a current-carrying coated conductor

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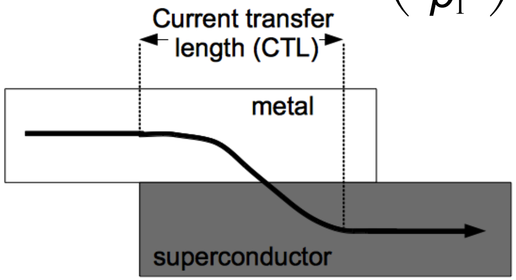
Abstract

We present the results of numerical analysis of a model of normal zone propagation in coated conductors. The main emphasis is on the effects of increased contact resistance between the superconducting film and the stabilizer on the speed of normal zone propagation, the maximum temperature rise inside the normal zone, and the stability margins. We show that with increasing contact resistance the speed of normal zone propagation increases, the maximum temperature inside the normal zone decreases, and stability margins shrink. This may have an overall beneficial effect on quench protection quality of coated conductors. We also briefly discuss the propagation of solitons and development of the temperature modulation along the wire.

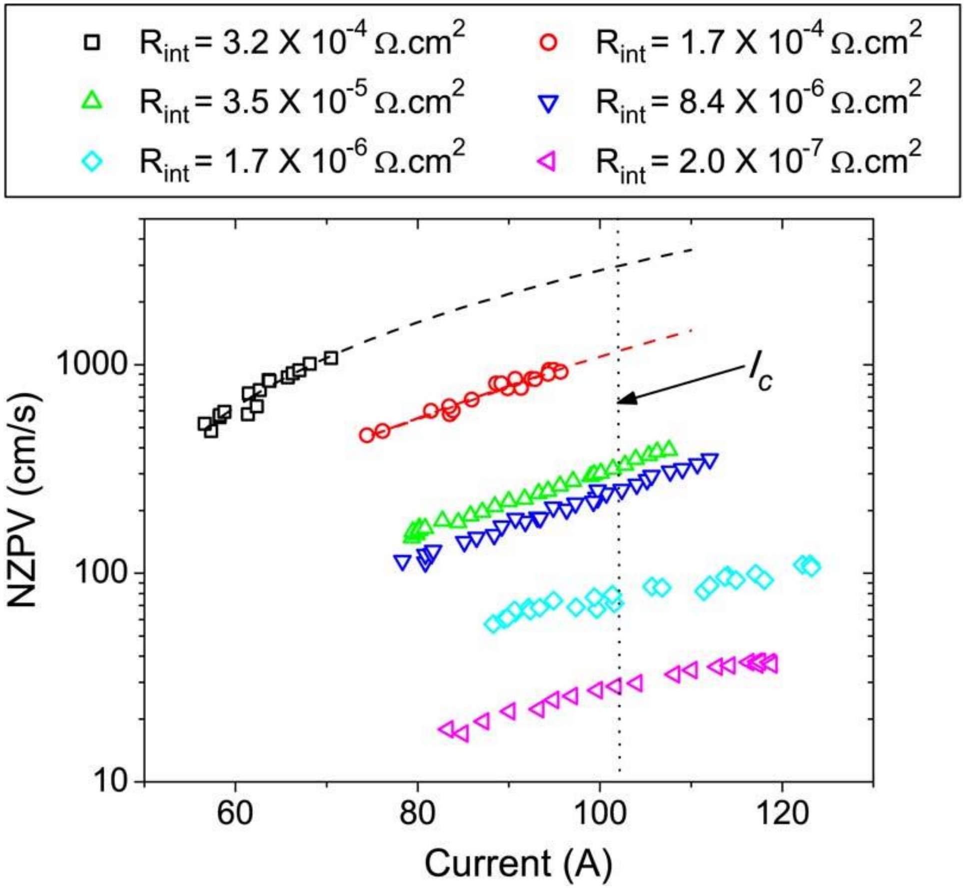
$$\lambda = \left(\frac{\bar{R}d_1}{\rho_1}\right)^{1/2}$$



NZPV approx. scales with CTL

Introduction: NZPV vs R_{int} (experimental)

SuperPower tape – 4mm wide – stabilizer free (2 μm Ag) – I_c = 102 A



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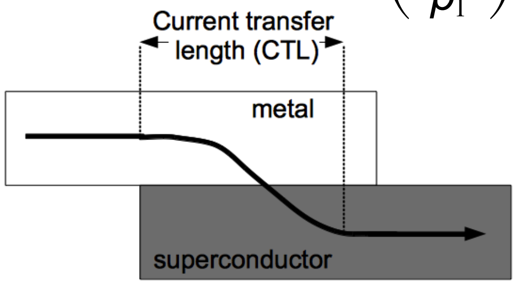

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Lacroix *et al. IEEE Trans. Appl. Supercond.* 23, 4701605 (2013)

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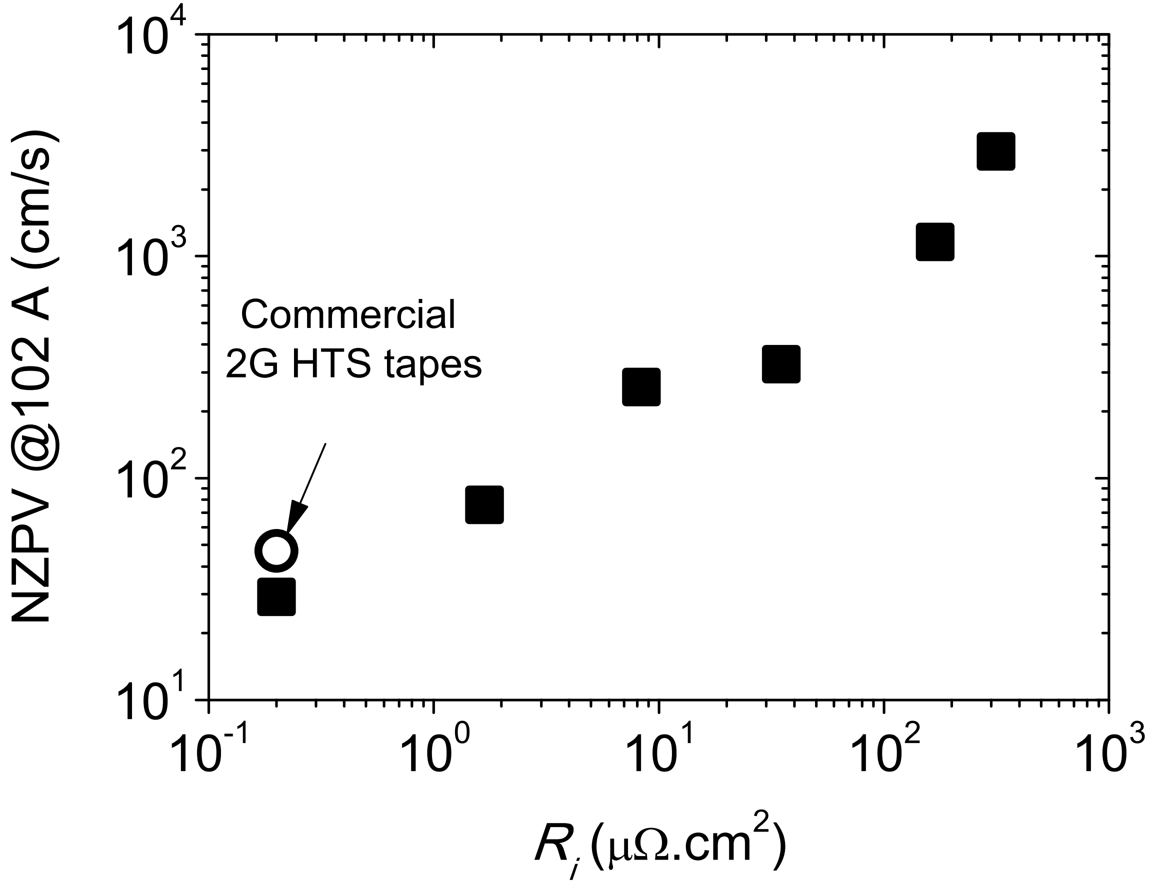
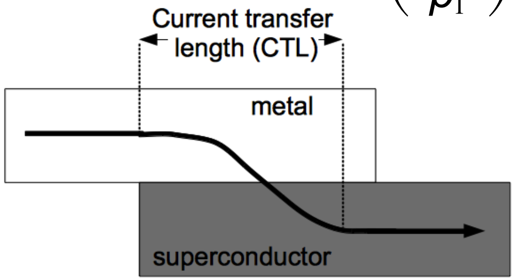


$$\lambda = \left(\frac{\overline{R}d_1}{\rho_1}\right)^{1/2}$$



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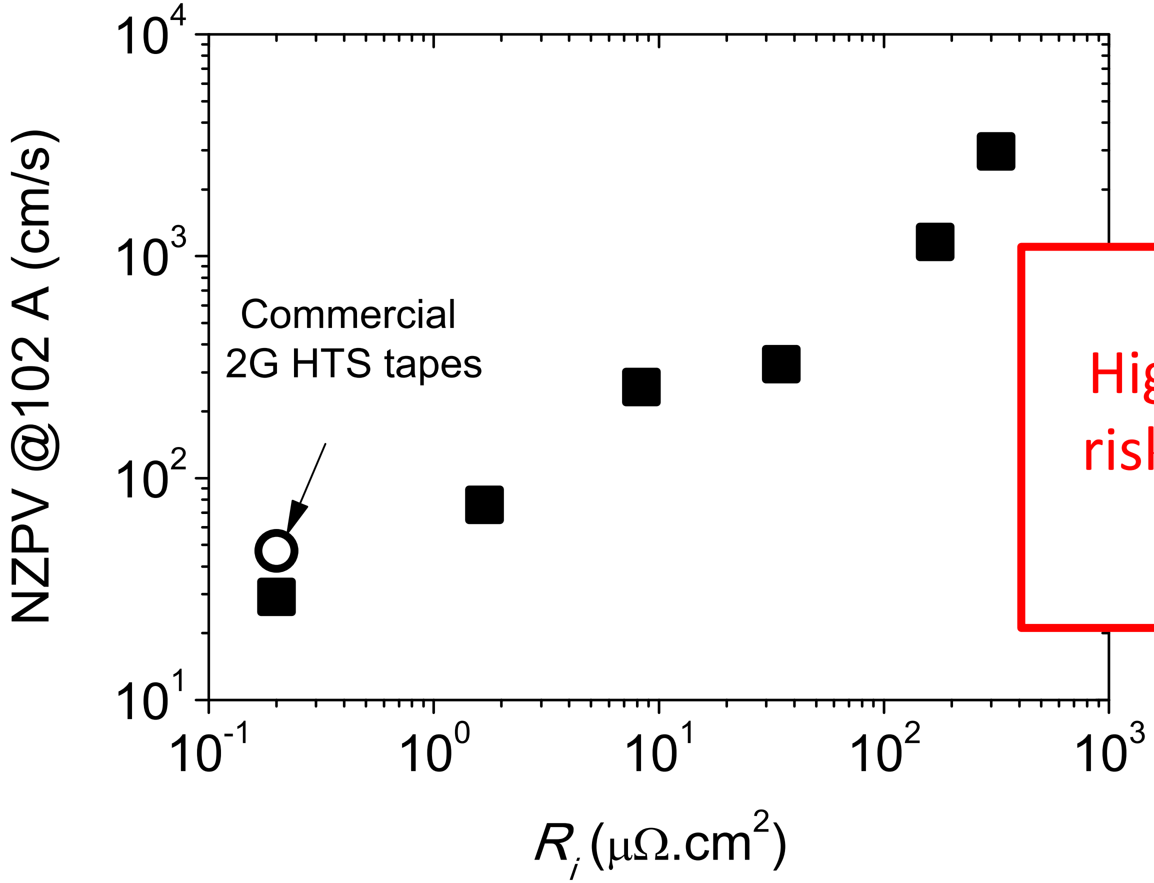


High R_i greatly increases risk of quench at current lead connections

Lacroix *et al. IEEE Trans. Appl. Supercond.* 23, 4701605 (2013)

Quench modeling of 2G HTS CCs

- *Analytical formulas can be used, but with some care, e.g.*

NZPV →

$$U_\ell = J\sqrt{\frac{\rho_n k_n}{C_n C_s (T_t - T_{op})}}$$

Miminum Propagation Zone (radius) →

$$R_{mz} = \sqrt{\frac{3k_{wd}(T_c - T_{op})}{\rho_m J_m^2}}$$

→ *From Iwasa's book: Studies in superconducting magnets*

Miminum quench energy →

$$\mathrm{MQE} = V_{\mathrm{MPZ}} \int_{T_{\mathrm{op}}}^{T_{\mathrm{c}}(B,J_{\mathrm{op}})} C_{\mathrm{p}}(T)\,\mathrm{d}T.$$

→ *Stenvall et al.* SUST 19, 184 (2006)

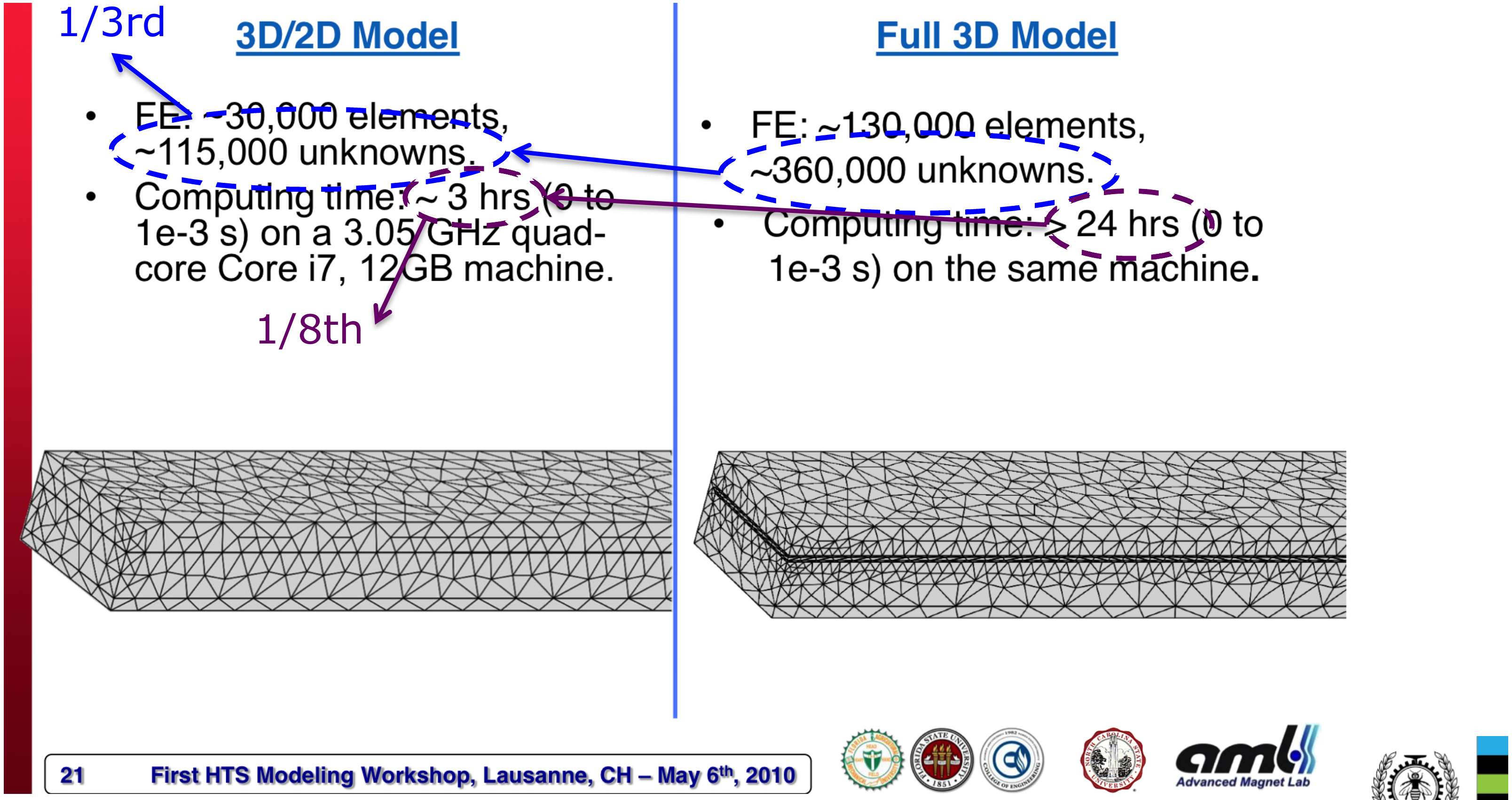
Quench modeling of 2G HTS CCs

- Only numerical modelling allows fully investigating quench dynamics under various conditions
  - time-varying current
  - type of thermal disturbance
  - **variations in tape architecture**
  - etc.

- Basic requirements:
  - Very nonlinear problem: full time-domain solution
  - 2-D or 3-D models (3-D is actually VERY important)
  - Ability to deal with thin layers

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
EXAMPLES OF "SMART" MODELLING APPROACHES

- Thin interface conditions for quench problems



1/3rd

3D/2D Model

- FE: ~30,000 elements, ~115,000 unknowns.
- Computing time: ~ 3 hrs (0 to 1e-3 s) on a 3.05 GHz quad-core Core i7, 12GB machine.

1/8th

Full 3D Model

- FE: ~130,000 elements, ~360,000 unknowns.
- Computing time: > 24 hrs (0 to 1e-3 s) on the same machine.

21 First HTS Modeling Workshop, Lausanne, CH – May 6th, 2010

16 **W.-K. Chan et al.**, 1st HTS modelling workshop, Lausanne, Switzerland, May 2010.

Chan et al. *IEEE Transactions on Applied Superconductivity* 20, 2370–2380 (2010)

Numerical modeling of 2G HTS CCs

- Finite element is the perfect tool for electro-thermal simulations
- Model developed in
  - COMSOL 4.3b (Joule heating module)
  - Equations:

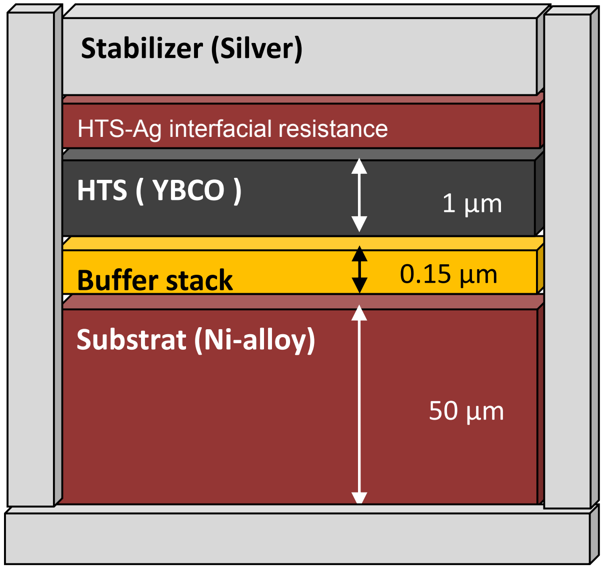
Current density (J)

$$\nabla \cdot (-\sigma(T)\nabla V) = 0,$$

$$\rho_{\mathrm{m}} C_{\mathrm{p}}(T)\frac{\partial T}{\partial t} + \nabla \cdot (-k(T)\nabla T) = Q_{\mathrm{j}},$$

$$Q_{\mathrm{j}} = \sigma(T)(-\nabla V)^2,$$

Typical 2-D/3-D model of CC architecture, including buffer layers and HTS-Ag interfacial resistance



Numerical modeling of 2G HTS CCs

- Finite element is the perfect tool for electro-thermal simulations
- Model developed in
  - COMSOL 4.3b (Joule heating module)
  - Equations:

Buffer layers and HTS-Ag contact resistance

Approximation:
- Infinitely thin layers

$$\nabla \cdot \overbrace{\left(-\sigma(T)\nabla V\right)}^{\text{Current density (J)}} = 0, \dashrightarrow J_z = \sigma(T)\frac{\partial V}{\partial z} = \sigma(T)\left(\frac{V_2 - V_1}{t}\right)$$

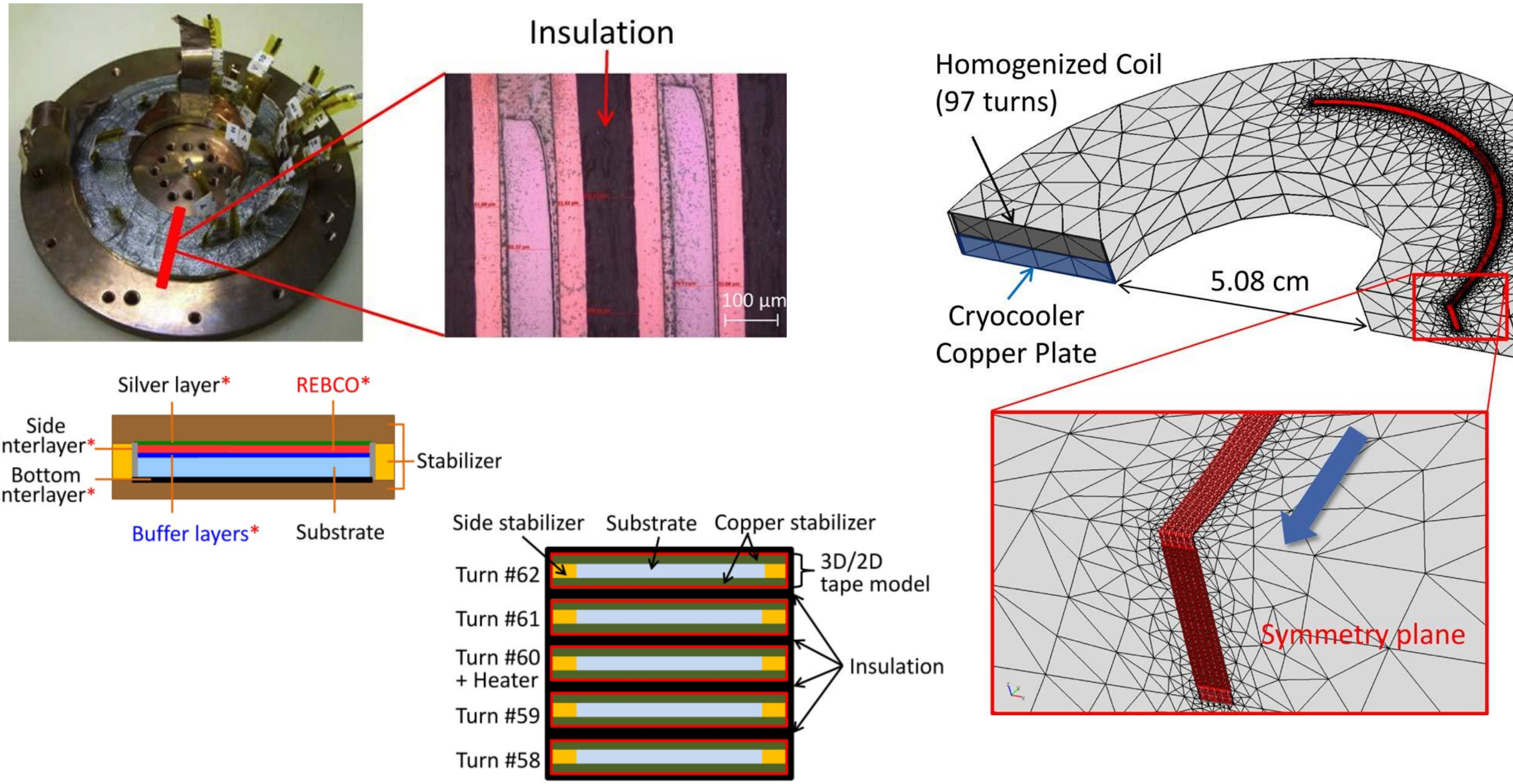
$$\rho_{\mathrm{m}} C_{\mathrm{p}}(T)\frac{\partial T}{\partial t} + \nabla \cdot \left(-k(T)\nabla T\right) = Q_{\mathrm{j}}, \dashrightarrow Q_z = k(T)\frac{\partial T_1}{\partial z} = k(T)\left(\frac{T_2 - T_1}{t}\right)$$

$$Q_{\mathrm{j}} = \sigma(T)(-\nabla V)^2,$$

+ boundary conditions

2) OVERVIEW OF MODELS AND NUMERICAL METHODS
EXAMPLES OF "SMART" MODELLING APPROACHES

- Hierarchal, 3-D multi-scale tape model for magnets

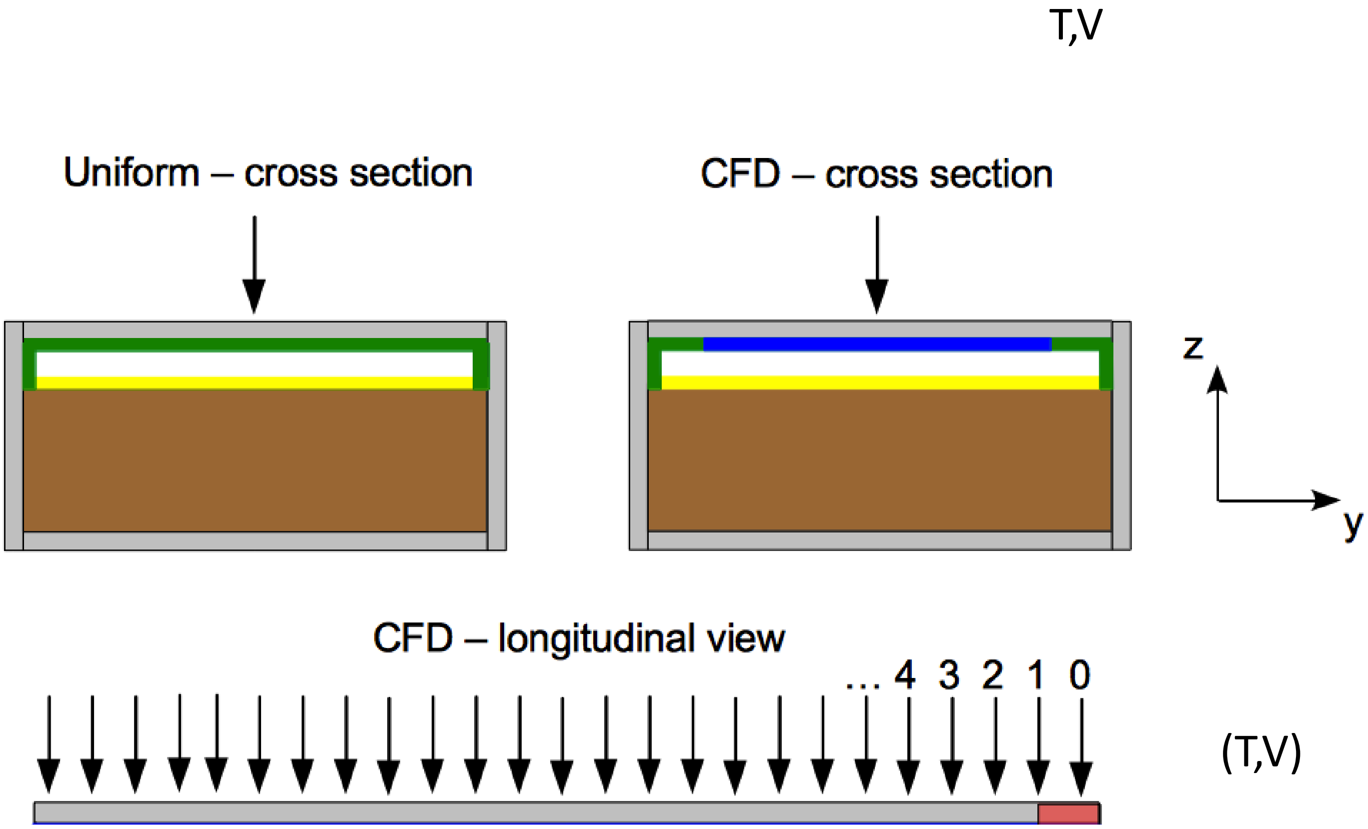


W. K. Chan and J. Schwartz, *IEEE T. Appl. Supercon.*, 22 (5), p. 4706010, 2012.

© F. Sirois et al., EUCAS 2013, Genova, Italy, Sept. 15-19, 2013

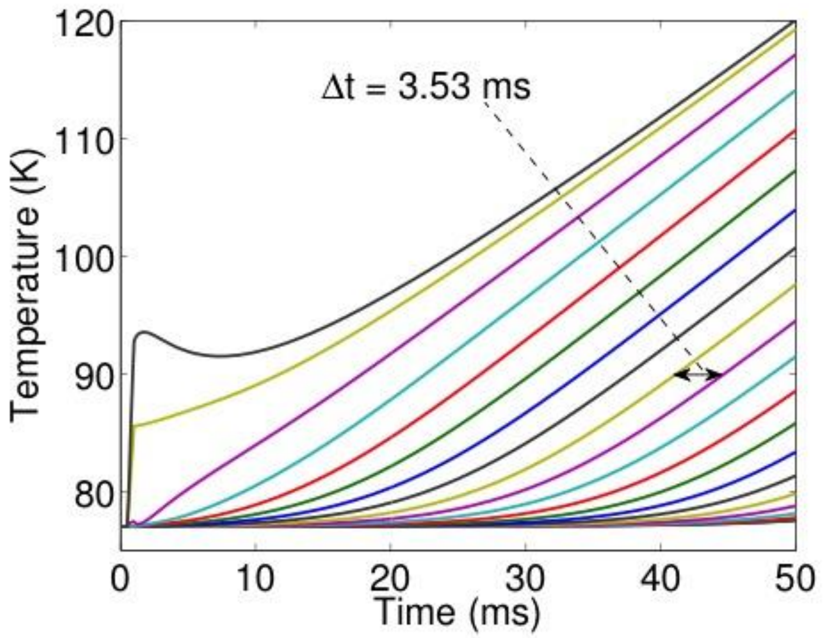
Numerical modeling of 2G HTS CCs

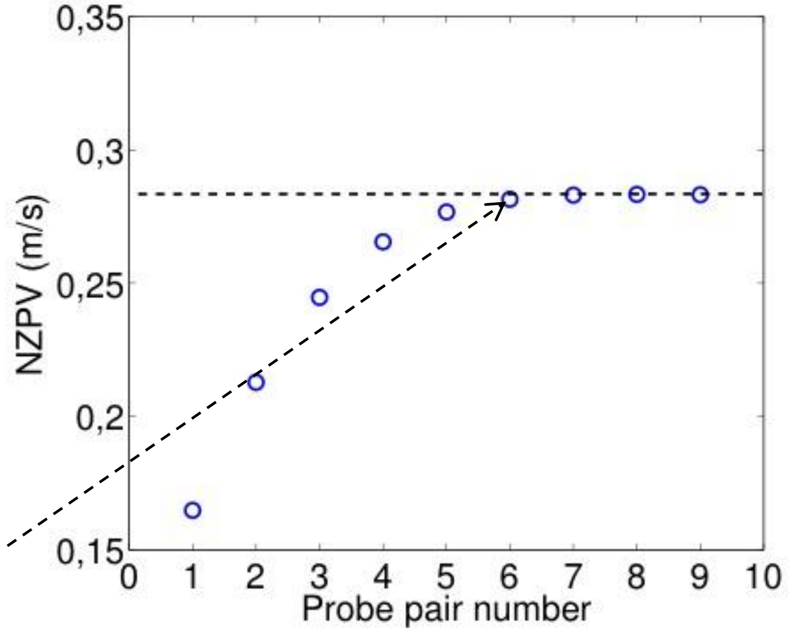
- Some delicate points to know…



Numerical modeling of 2G HTS CCs

- Some delicate points to know…
  - NZPV value must be extracted a few taps away from hot spot initiation



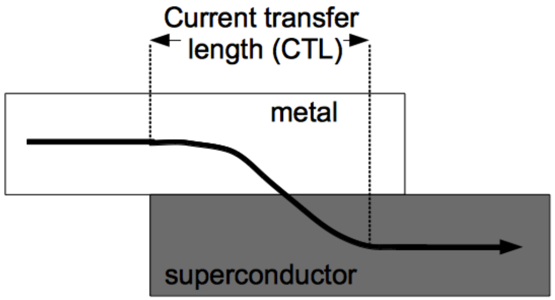


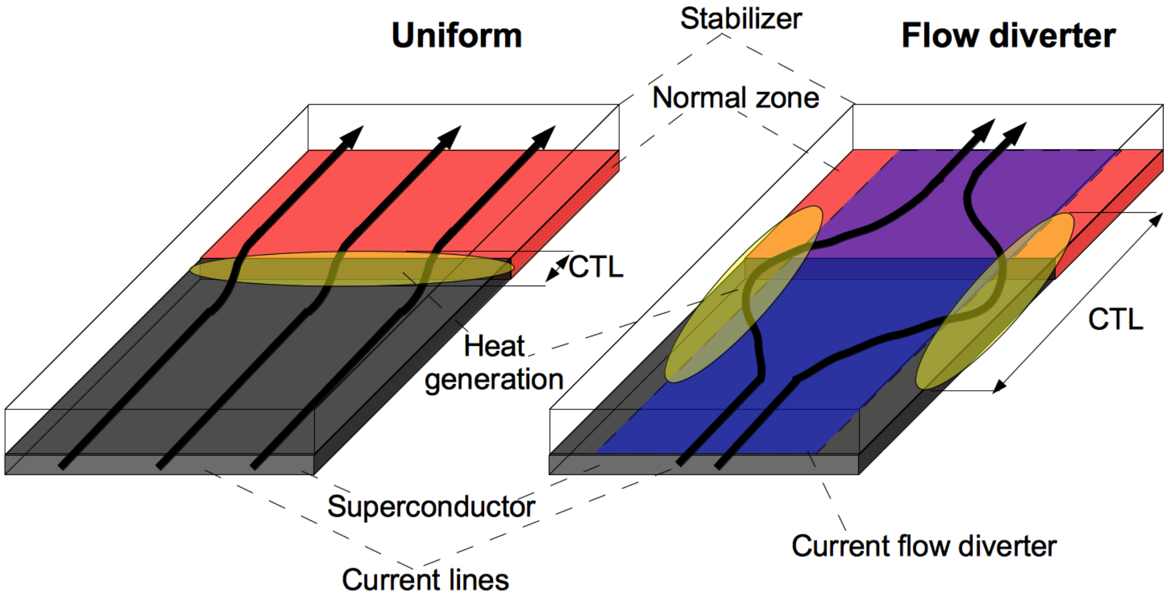
Numerical modeling of 2G HTS CCs

- Some delicate points to know…
  - NZPV value must be extracted a few taps away from hot spot initiation
  - NZPV is highly sensitive to discretization along the length of the tape
    - Rule of thumb: needs at least a few elements per unit length of CTL
    - If mesh too coarse, it **artificially increases** the CTL and thus the NZPV

Current Flow Diverter (CFD) concept[1]

- Highly resistive layer that **partially** covers the HTS-Ag interface to increase the *current transfer length* (CTL)





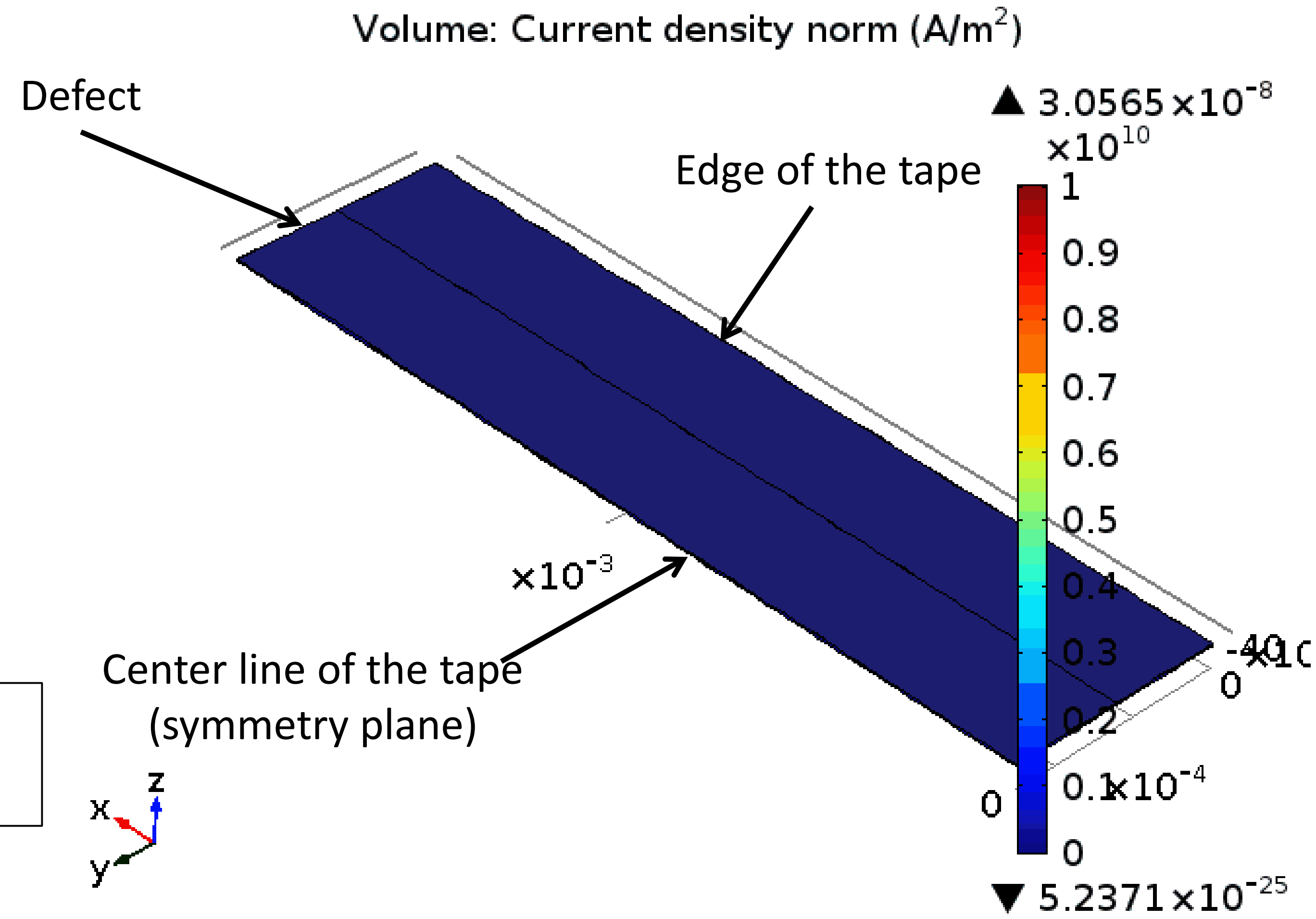
- Increases the NZPV by an order of magnitude for a given interface resistance (R_i)

[1] Lacroix *et al. SUST* 27, 035003 (2014)

Current Flow Diverter (CFD) concept[1]

- **<u>Uniform R_i</u>**
- 10 mm wide
- $I = 0.9\ I_c$
- $I_c = 160$ A
- **$T_{op} = 77$ K**
- **3 μm Ag**

UNIFORM interfacial resistance = 1 μΩ.cm²



Defect

Edge of the tape

Center line of the tape (symmetry plane)

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Current Flow Diverter (CFD) concept[1]

- **CFD**
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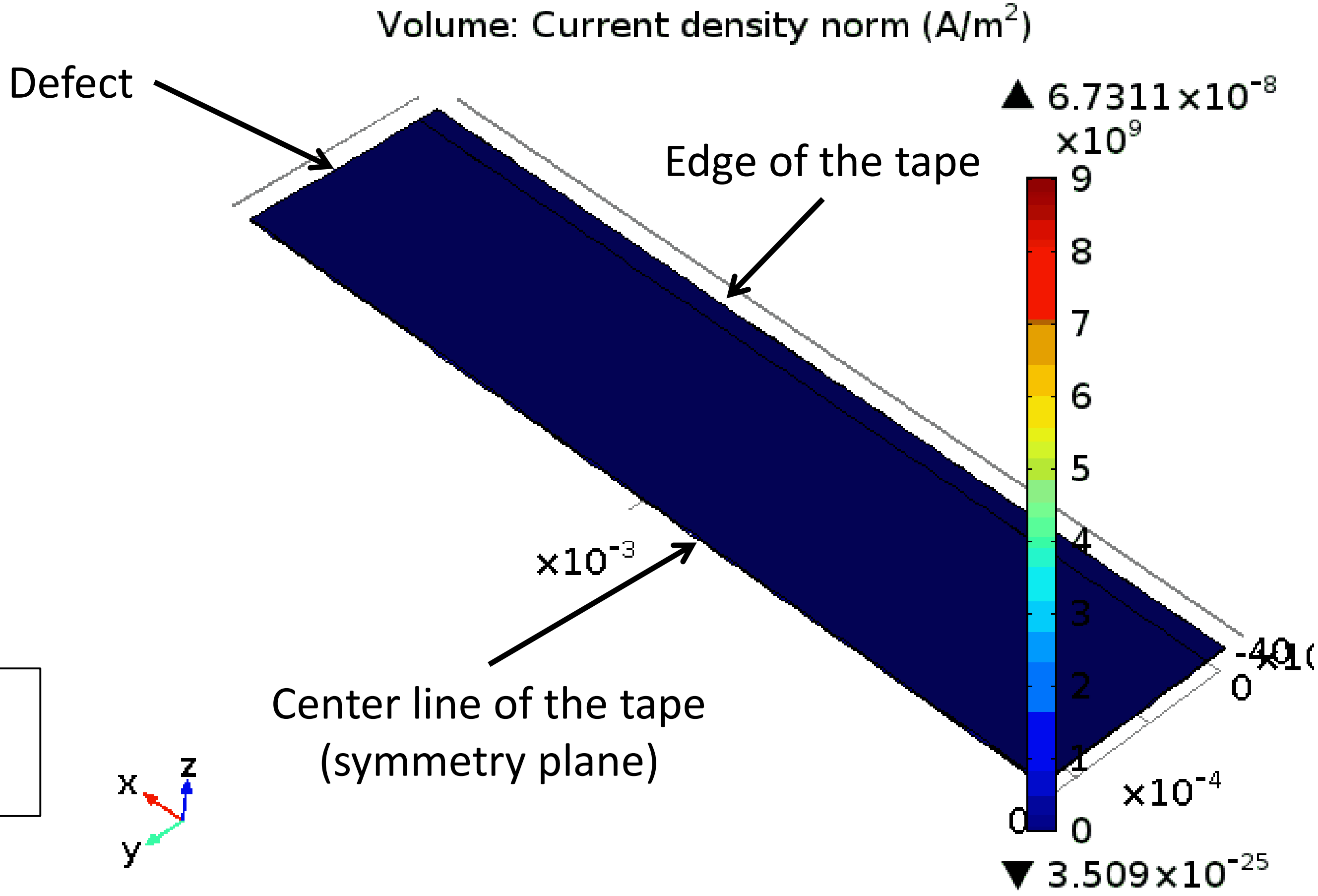

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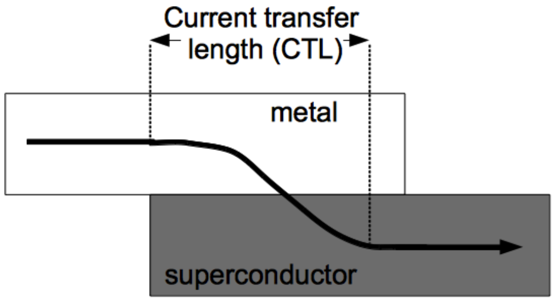

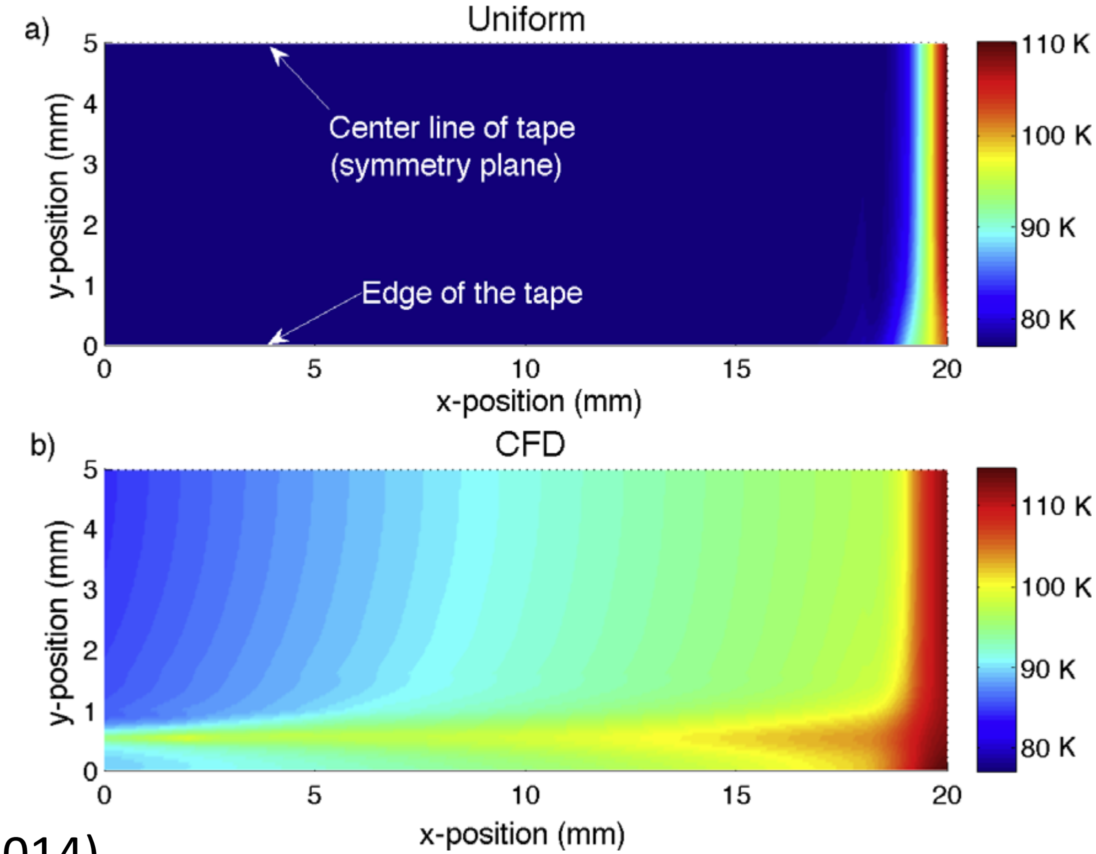

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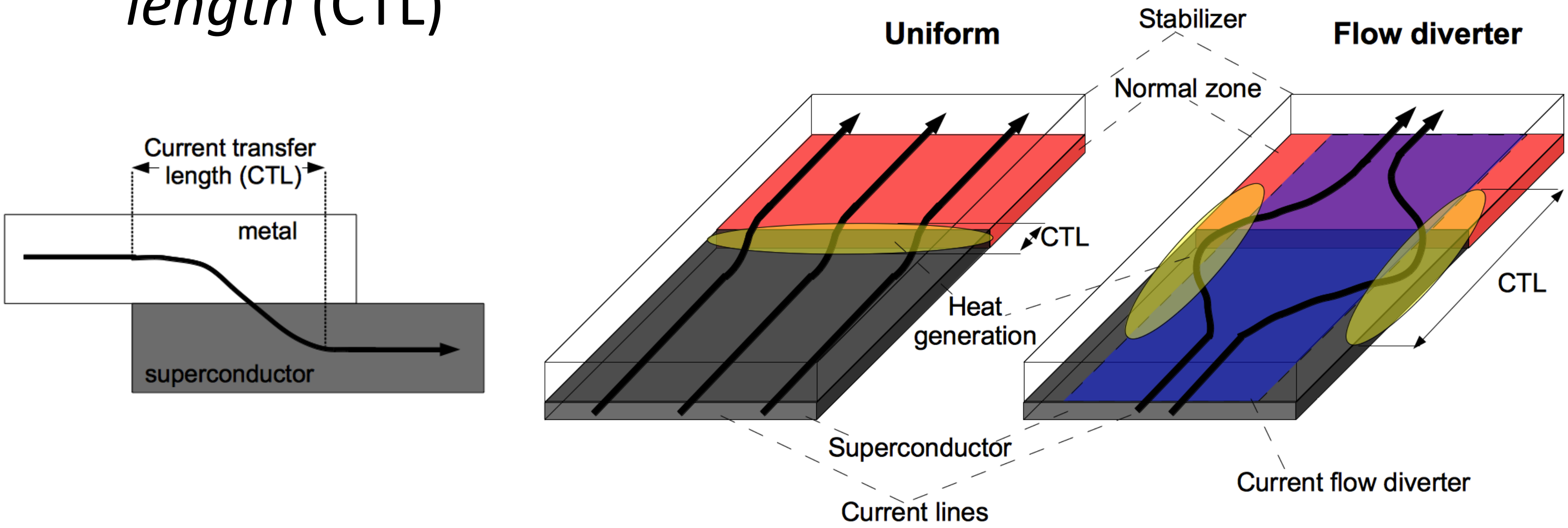

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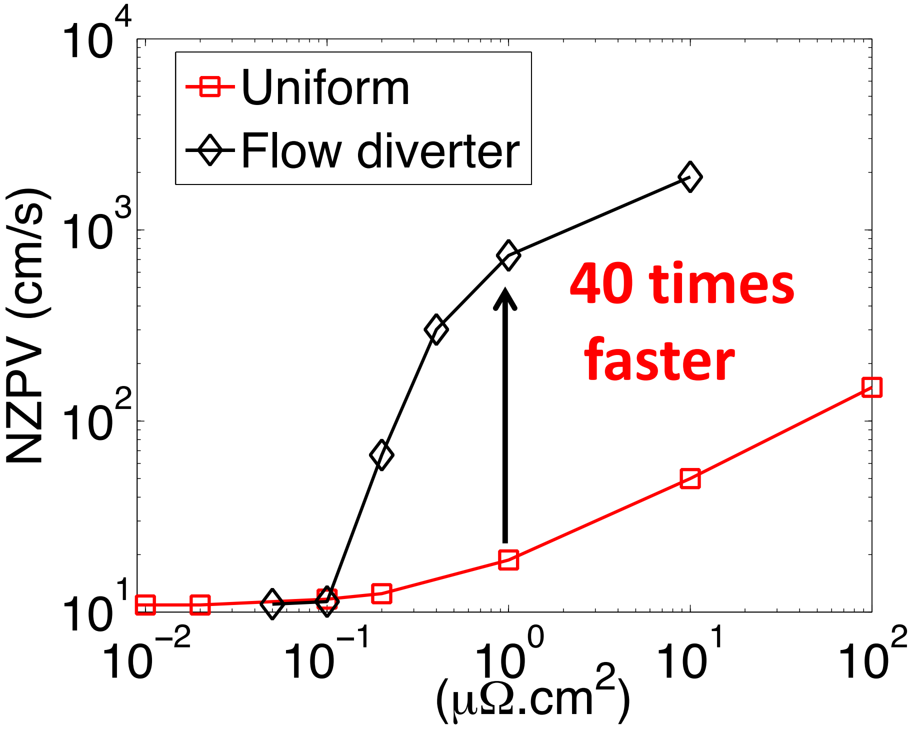
FEM Calculations: CFD vs. uniform

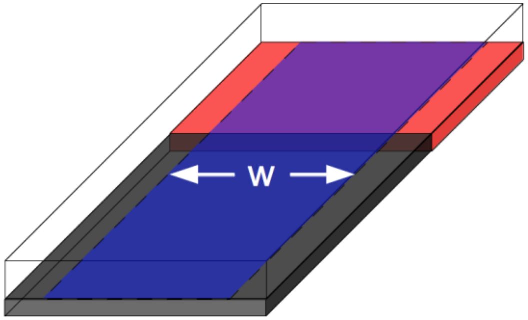
T_{op} = 77 K, I_c (77K) = 160 A, I_{op} = 0.9 I_c A, **t_{ag} = 3 µm**

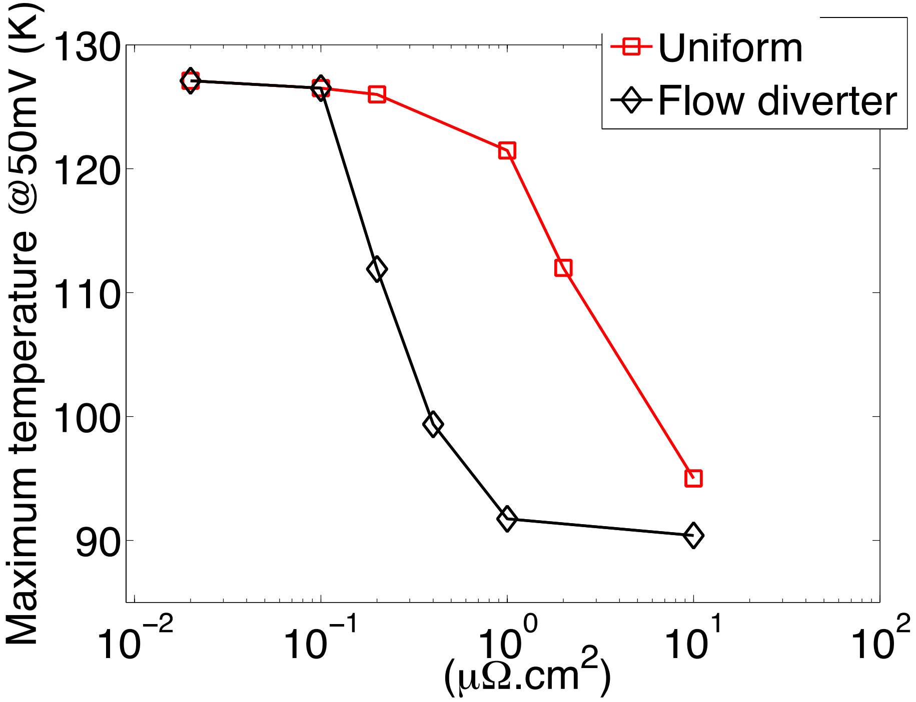


40 times faster

Low resistance part = 0.1 μΩ.cm²

CFD = 1 Ω.cm²





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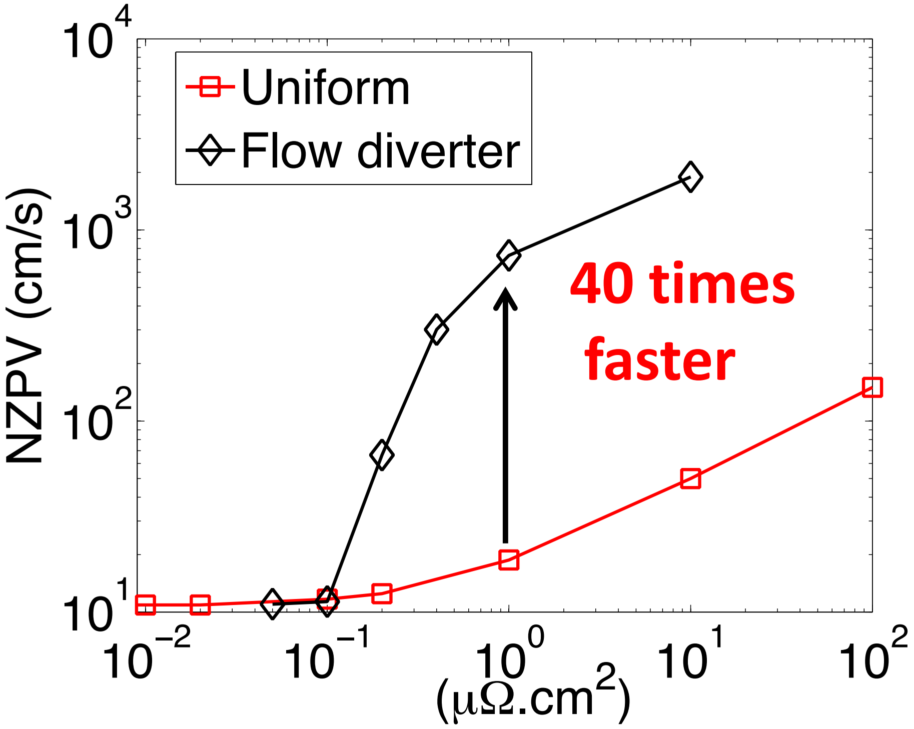

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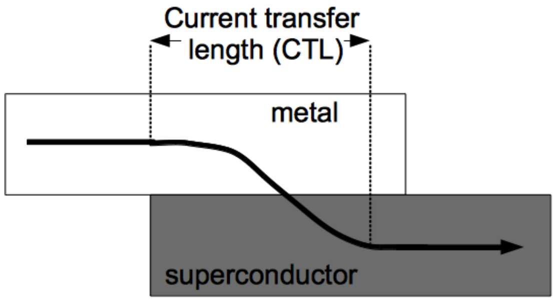
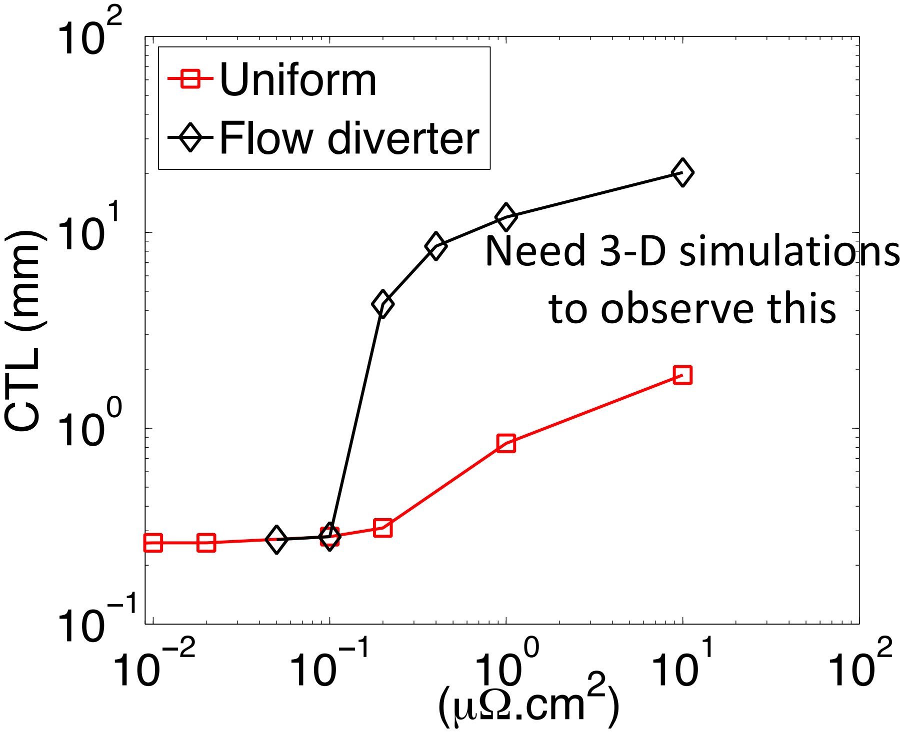
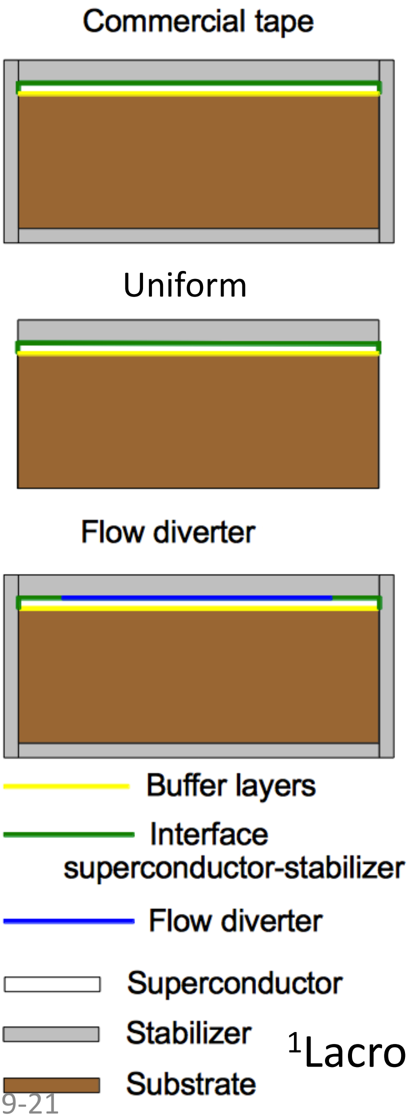




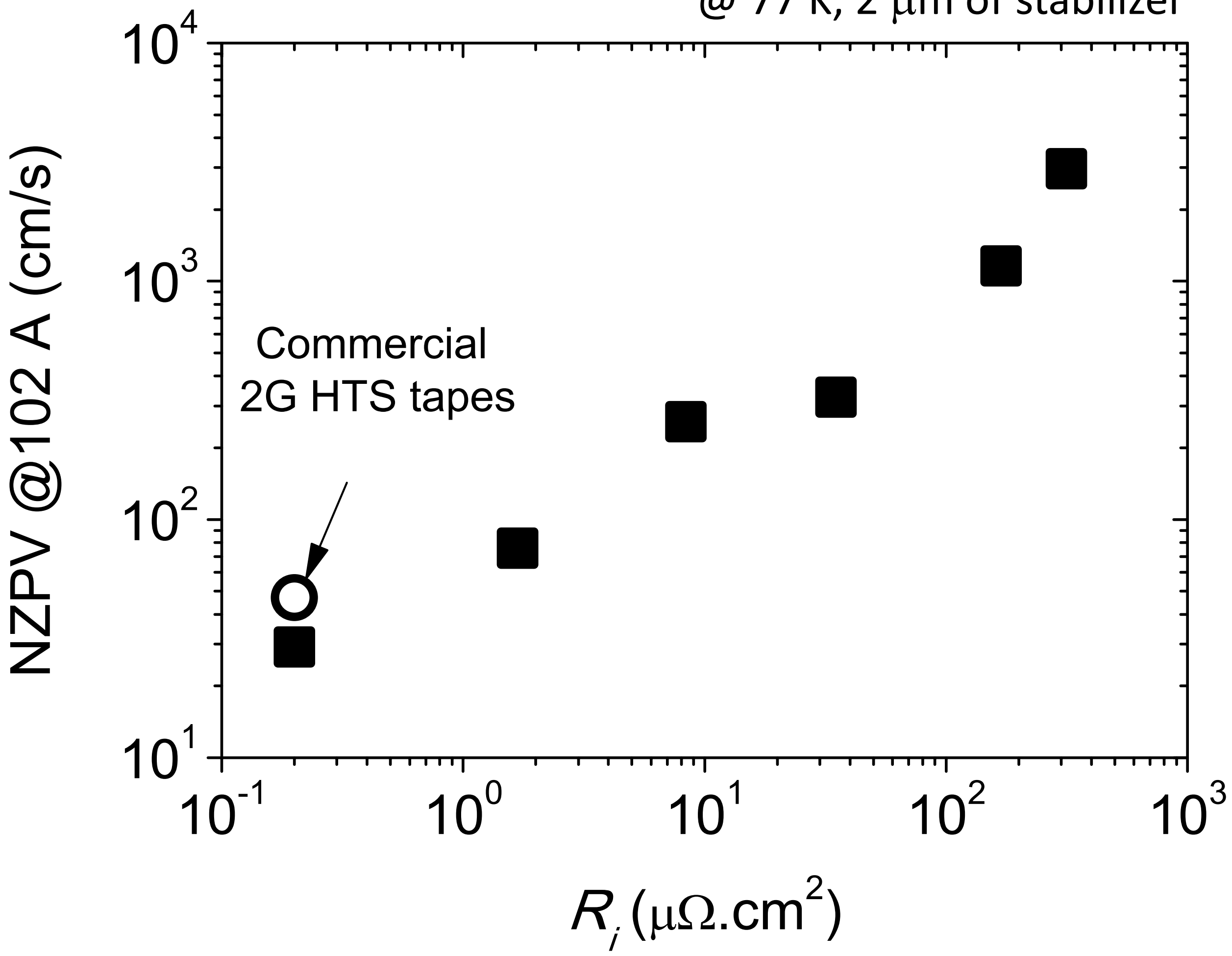
Need 3-D simulations to observe this

Low resistance part = 0.1 µΩ.cm^2
CFD = 1 Ω.cm^2

NZPV vs R_i ($I_{op} = I_c = 102$ A)[1]

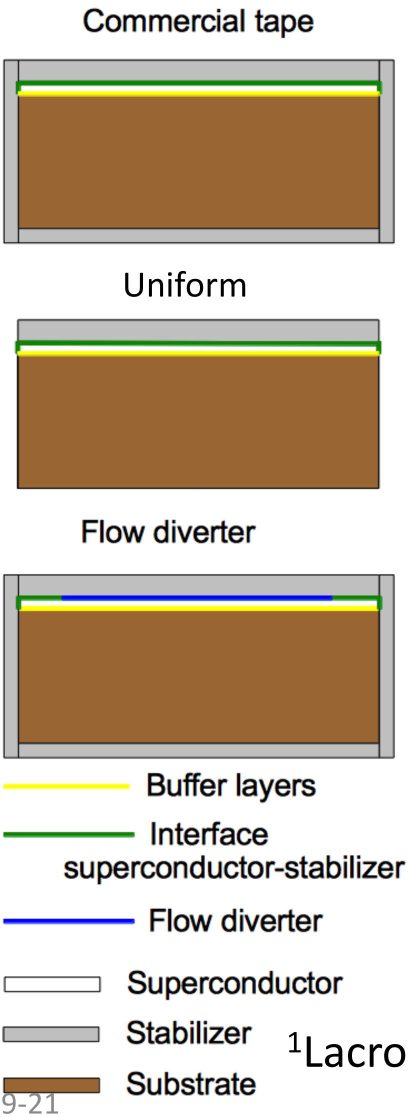


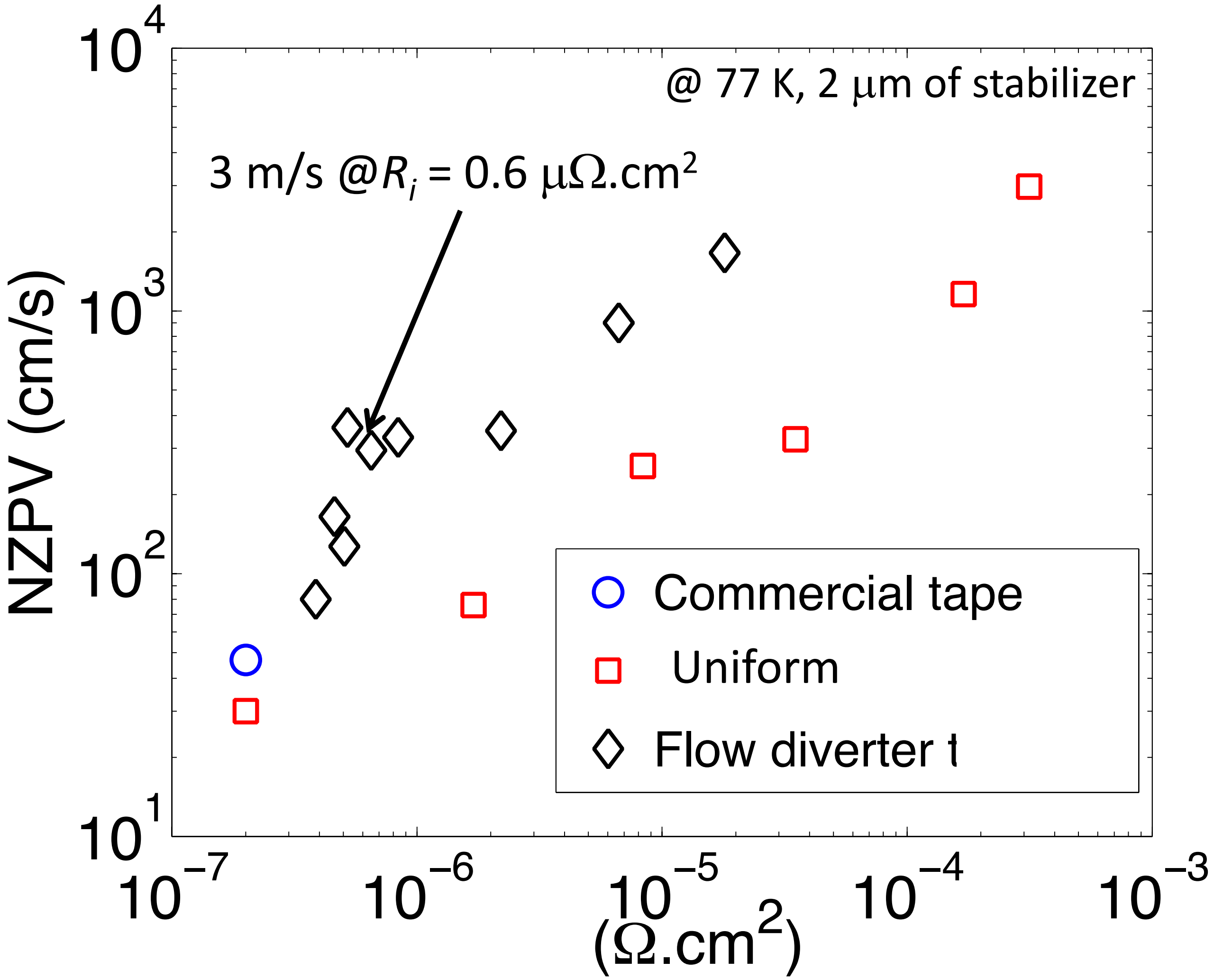
@ 77 K, 2 μm of stabilizer



[1] Lacroix *et al. SUST* 27, 055013 (2014)

NZPV vs R_i ($I_{op} = I_c = 102$ A)[1]





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[1] Lacroix *et al.* *SUST* 27, 055013 (2014)

Questions about CFD

- What is the stability of CFD tapes ?

- What is the NZPV enhancement of CFD tapes
  - at different operating currents ?
  - at lower temperatures ?
  - for thicker stabilizer ?
  - for higher critical current ?

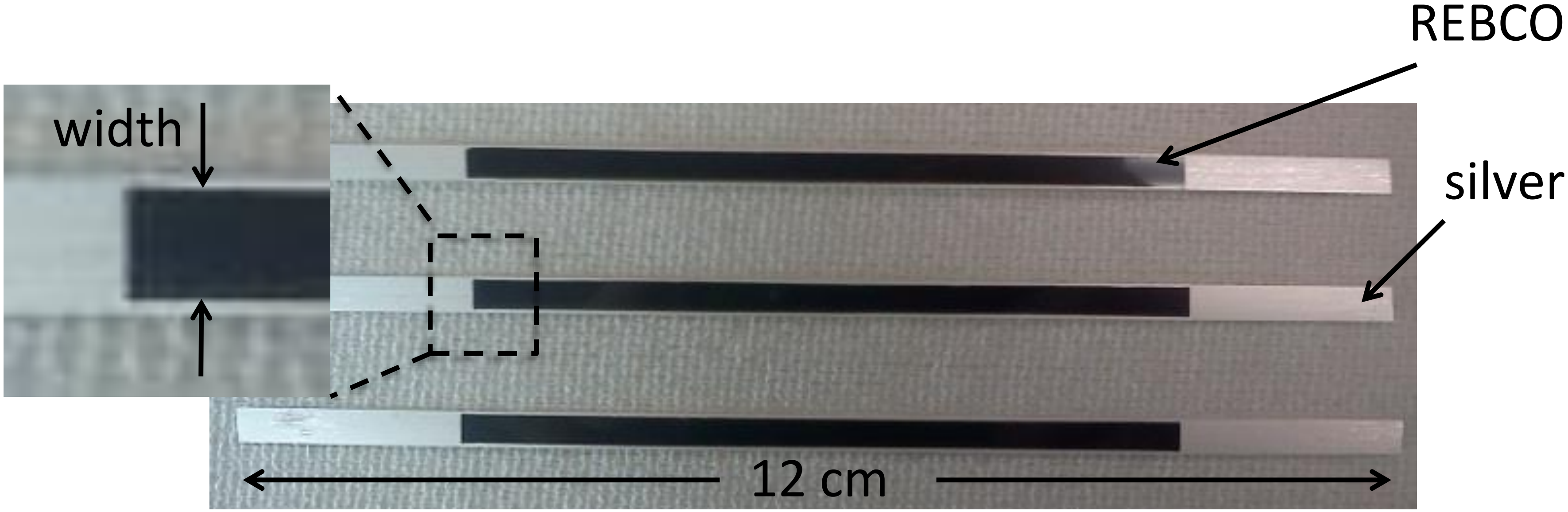
Questions about CFD

- **What is the stability of CFD tapes ?**
  - **➔ Measure the Minimum Quench Energy (MQE)**

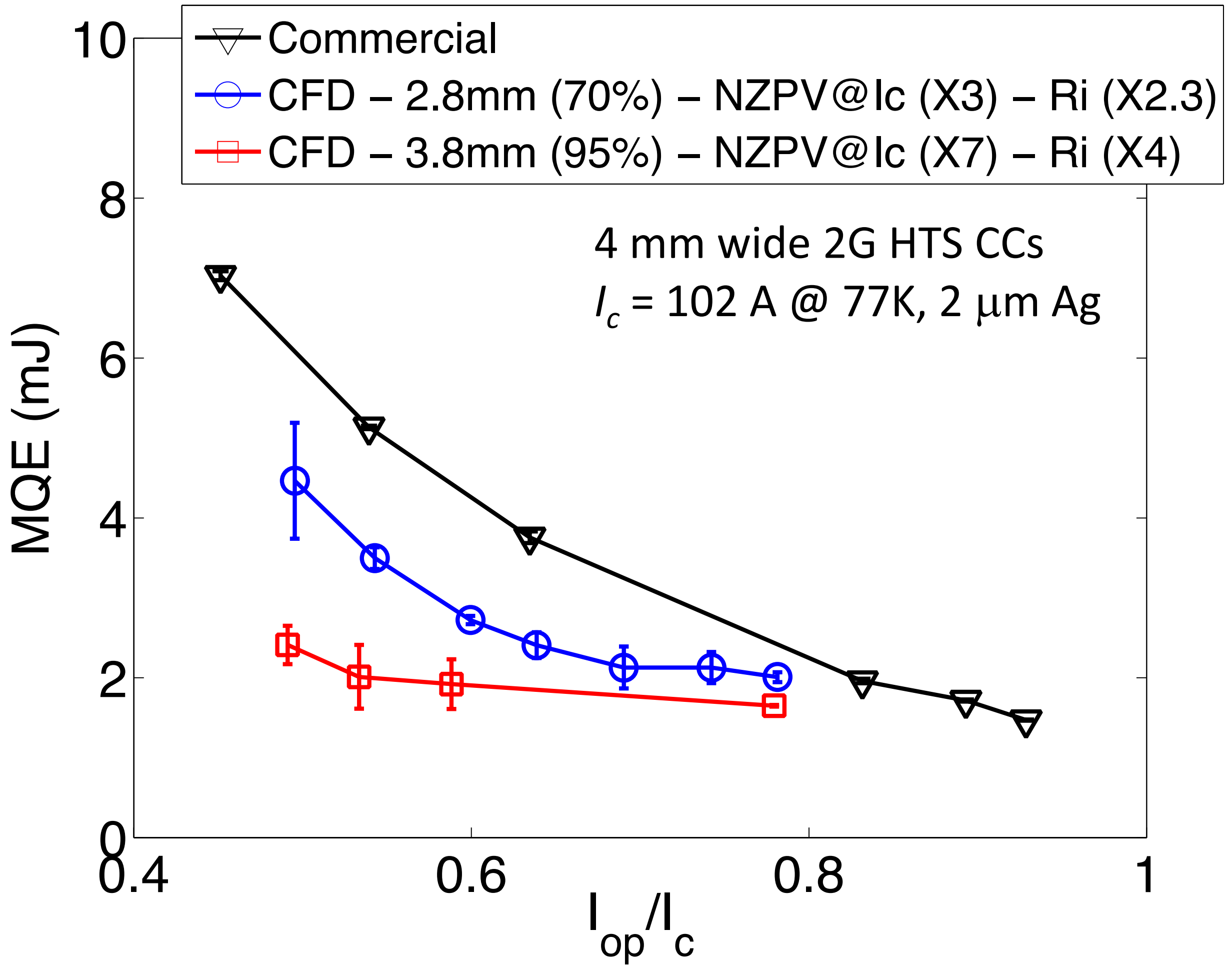
- What is the NZPV enhancement of CFD tapes
  - at different operating currents ?
  - at lower temperatures ?
  - for thicker stabilizer ?
  - for higher critical current ?

CFD tape fabrication

- Fabrication steps
  - Ag etching / degraded REBCO layer as flow diverter
  - Deposition of 1.5-2 μm of Ag
  - No degradation of I_c



MQE vs I_{op}


Commercial
CFD – 2.8mm (70%) – NZPV@Ic (X3) – Ri (X2.3)
CFD – 3.8mm (95%) – NZPV@Ic (X7) – Ri (X4)
4 mm wide 2G HTS CCs
I_c = 102 A @ 77K, 2 μm Ag
MQE (mJ)
I_{op}/I_c
0
2
4
6
8
10
0.4
0.6
0.8
1

Questions about CFD

- What is the stability of CFD tapes ?

- **What is the NZPV enhancement of CFD tapes**
  - at different operating currents ?
  - at lower temperatures ?
  - for thicker stabilizer ?
  - for higher critical current ?

  ➔**Perform finite element calculations**

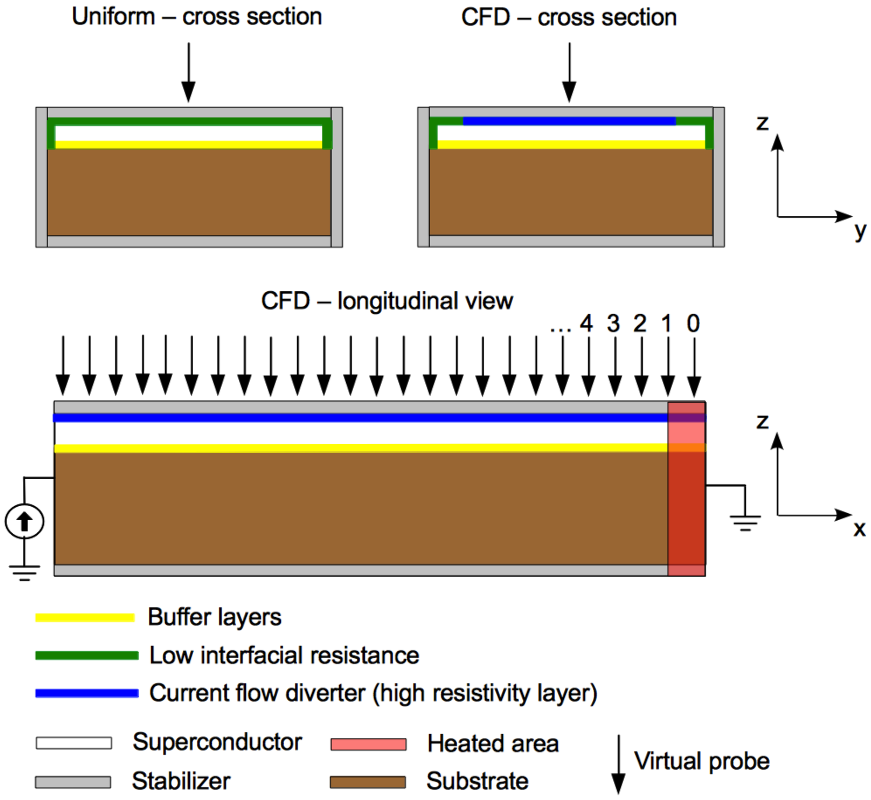
Finite element calculations[1]

- 3D electro-thermal model developed in COMSOL 4.3b

- A power-law with $J_c(T)$ and $n(T)$ was used to model the E-J curve of REBCO

- Tape length = 5 cm
- Tape width = 10 mm
- Substrate thickness (Hastelloy) = 50 µm
- Buffer layers thickness (MgO) = 150 nm
- HTS thickness ((RE)BCO) = 1 µm

- Intrinsic HTS-Ag interfacial resistance = 100 nΩ.cm^2
- CFD interfacial resistance = 1 Ω.cm^2
- CFD coverage = 90% HTS-Ag interface



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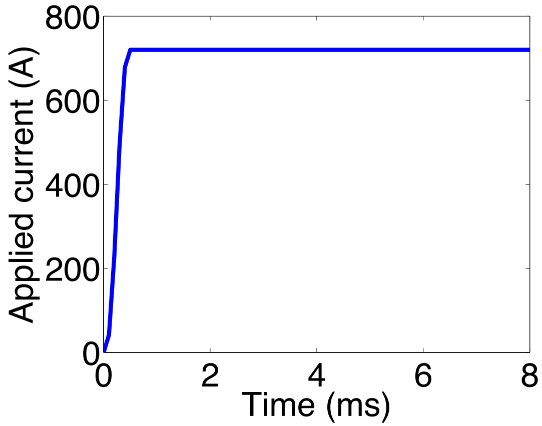
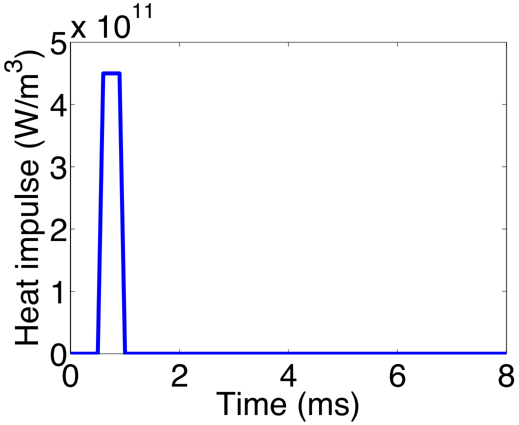
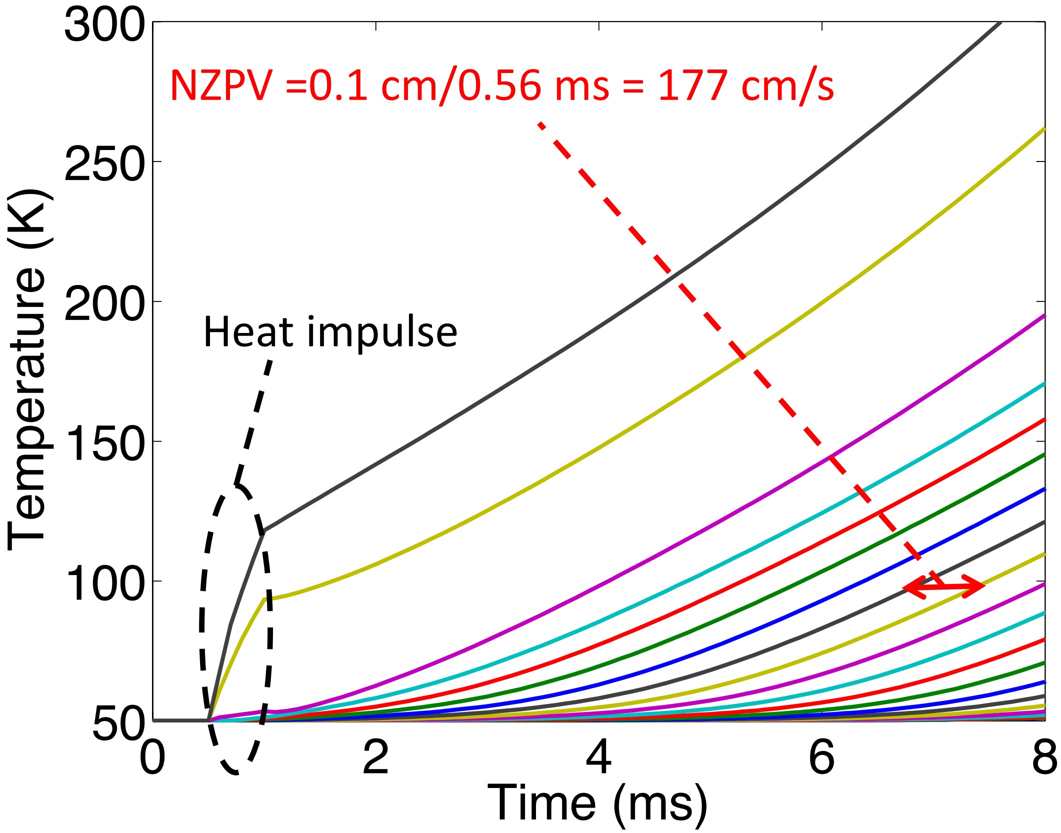
[1] Lacroix *et al.* *SUST* 27, 035003 (2014)

Example of results

- T_{op} = 50 K, I_c (50K) = 800 A, $I_{op} = 0.9 I_c$, t_{ag} = 10 μm







CFD vs. uniform tapes

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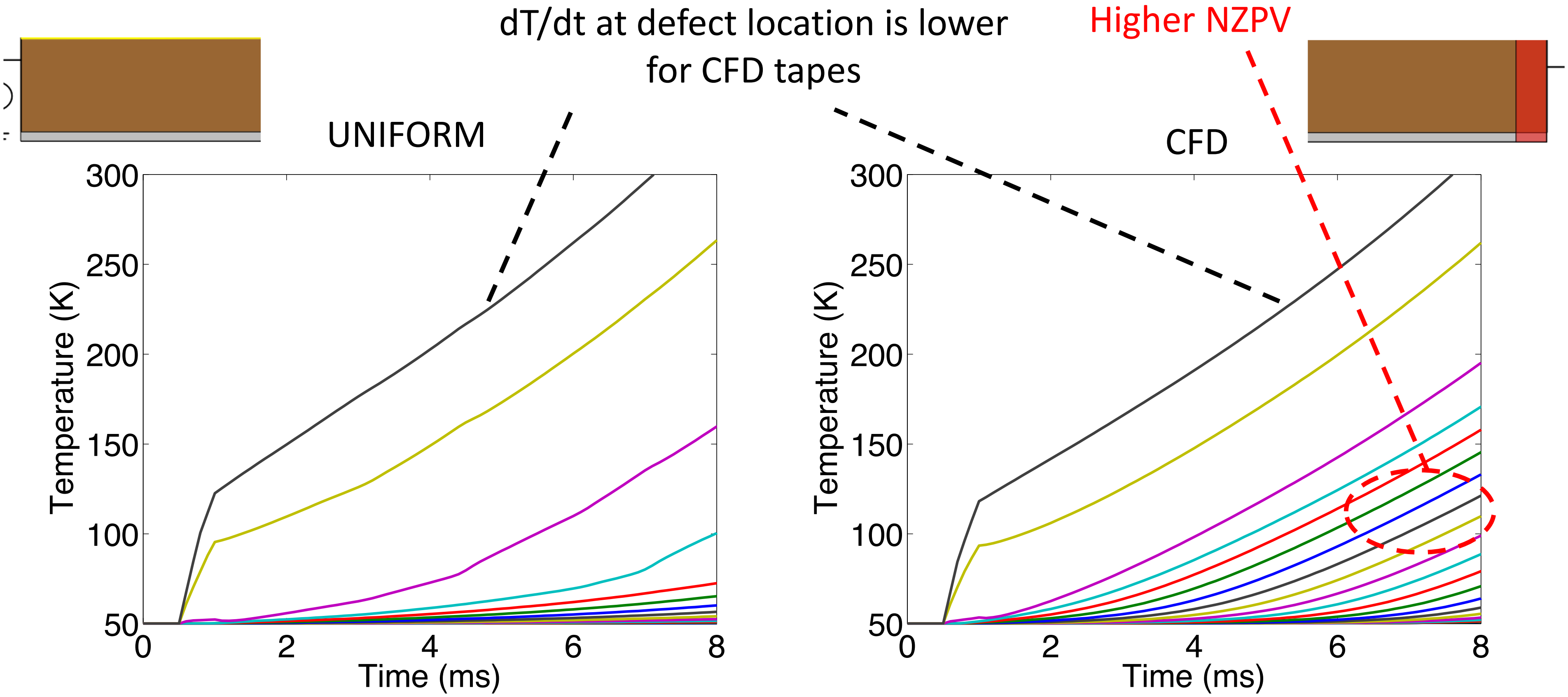


dT/dt at defect location is lower for CFD tapes

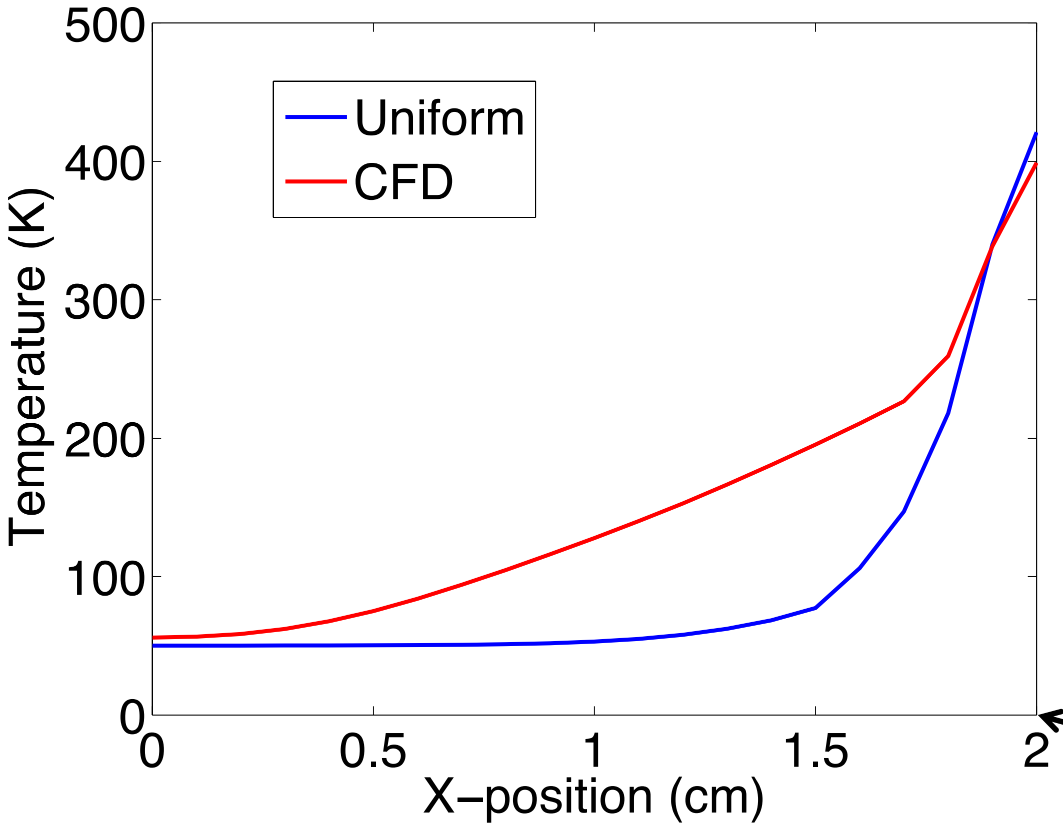
Higher NZPV

UNIFORM

CFD

Temperature along length

- T_{op} = 50 K, I_c (50K) = 800 A, $I_{op} = 0.9I_c$, t_{ag} = 10 μm, time = 10 ms



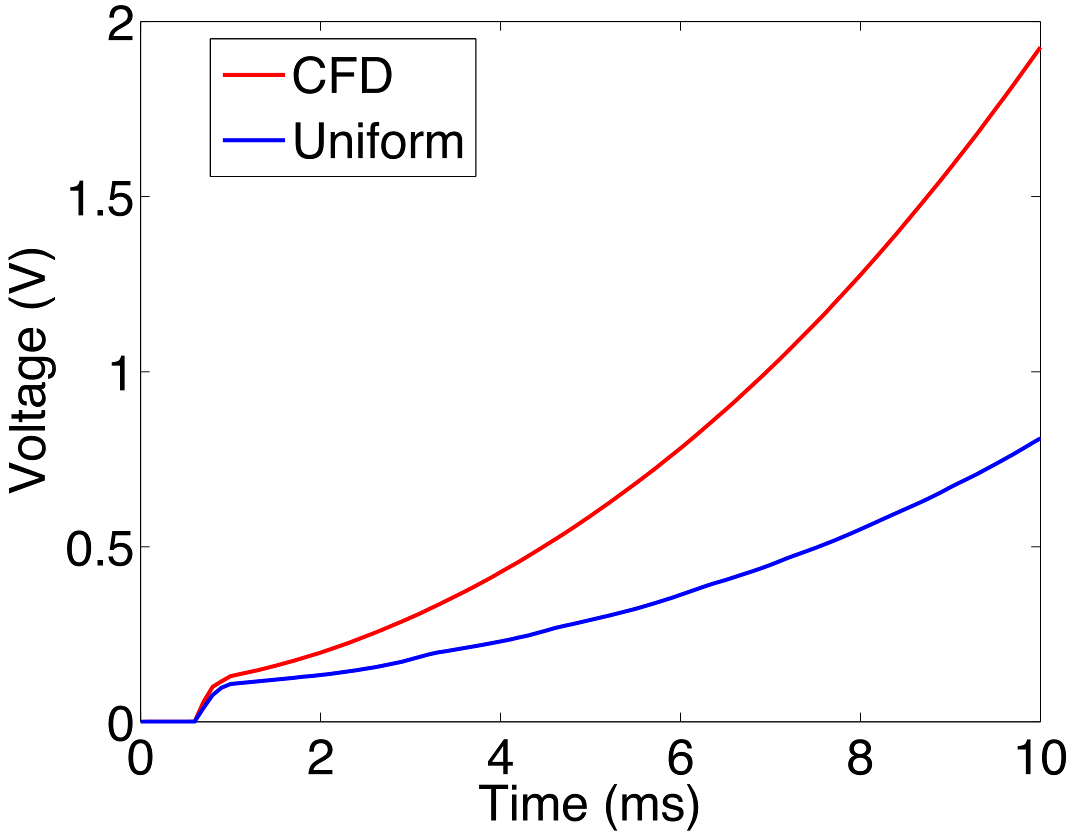
Peak temperature and temperature gradient are lower in CFD tape

Reduces thermal stress

Heat deposited at this location

Total voltage in tape

- T_{op} = 50 K, I_c (50K) = 800 A, $I_{op} = 0.9I_c$, t_{ag} = 10 μm



Voltage peak and dV/dt are higher in CFD tape

Very good for quench detection

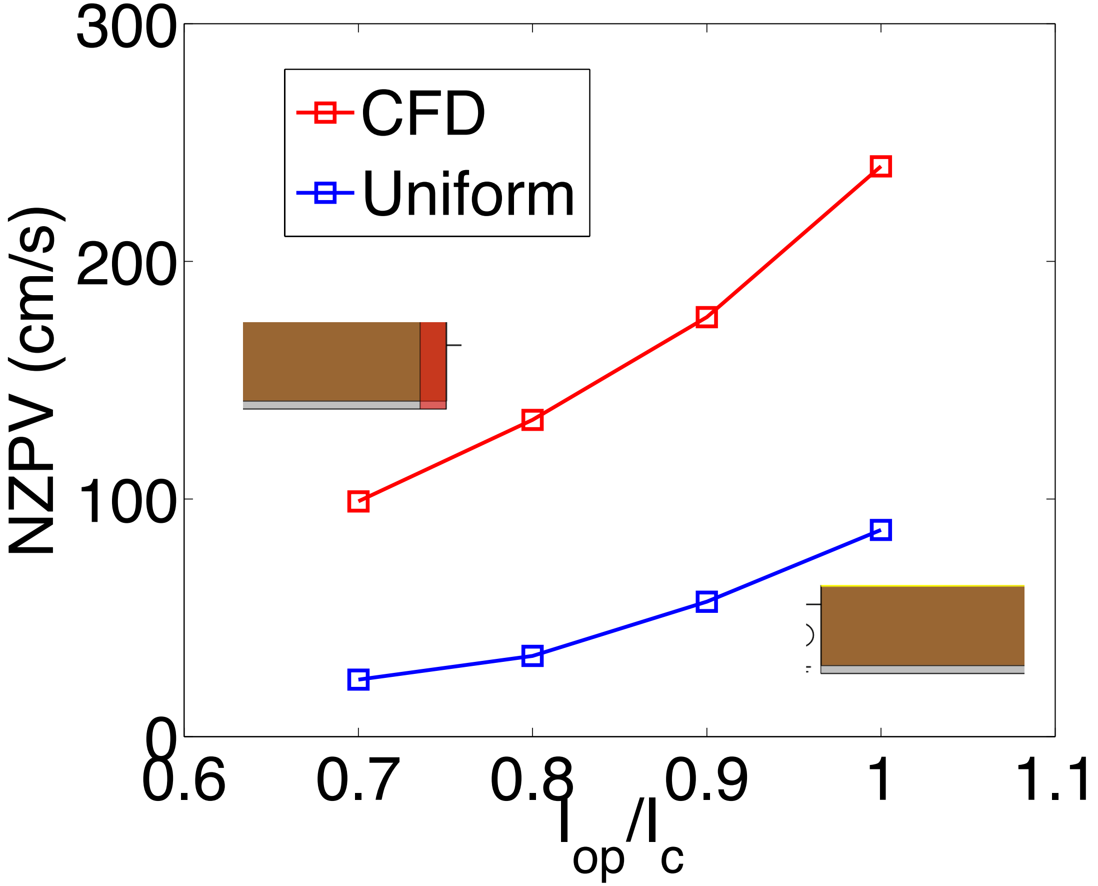
Questions about CFD

- What is the stability of CFD tapes ?

- **What is the NZPV enhancement of CFD tapes**
  - *at different operating currents ?*
  - *at lower temperatures ?*
  - *for thicker stabilizer ?*
  - *for higher critical current ?*

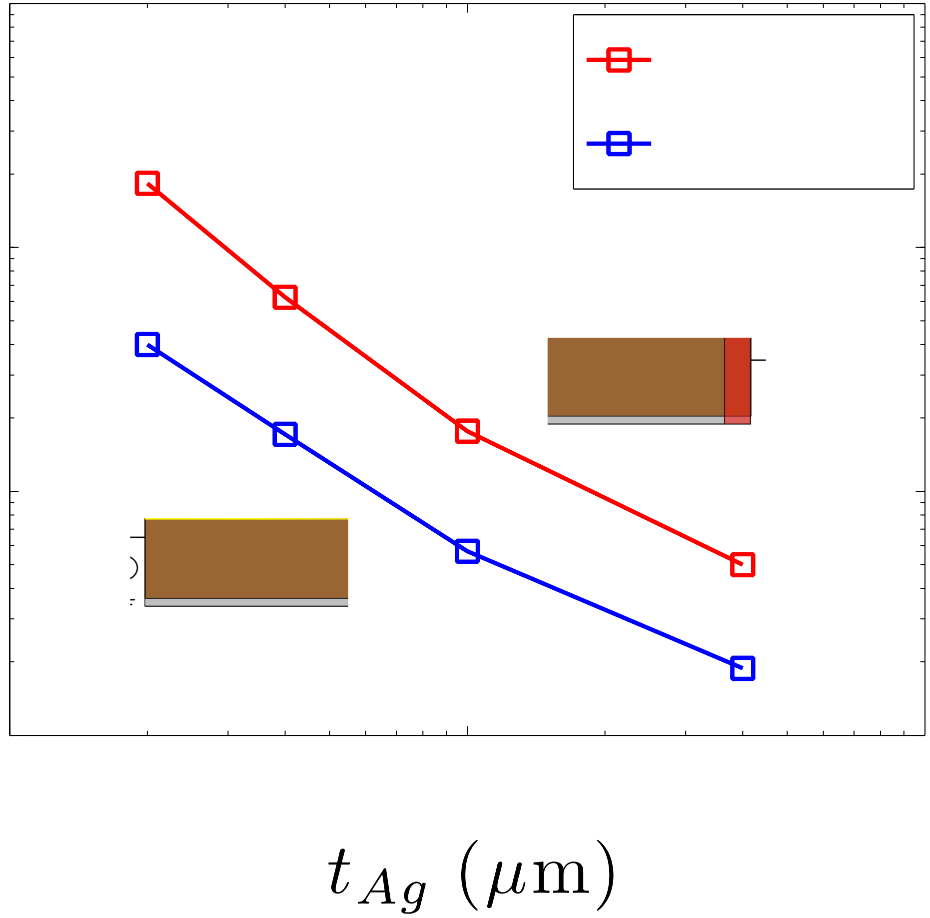
NZPV vs. operating current

- T_{op} = 50 K, I_c (50K) = 800 A , t_{Ag} = 10 μm



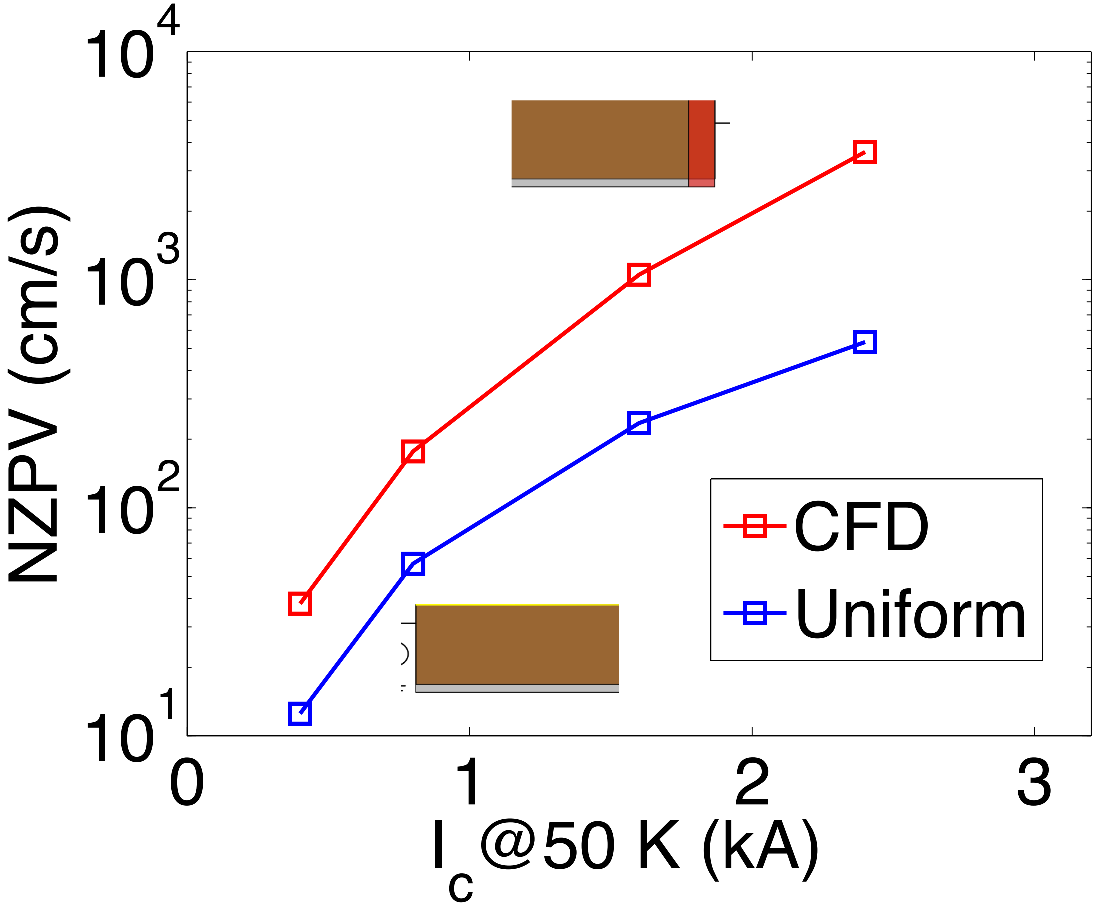
NZPV vs. stabilizer thickness

- $I_{op} = 0.9I_{c}$, $T_{op} = 50$ K, I_c (50K) = 800 A



NZPV vs. critical current

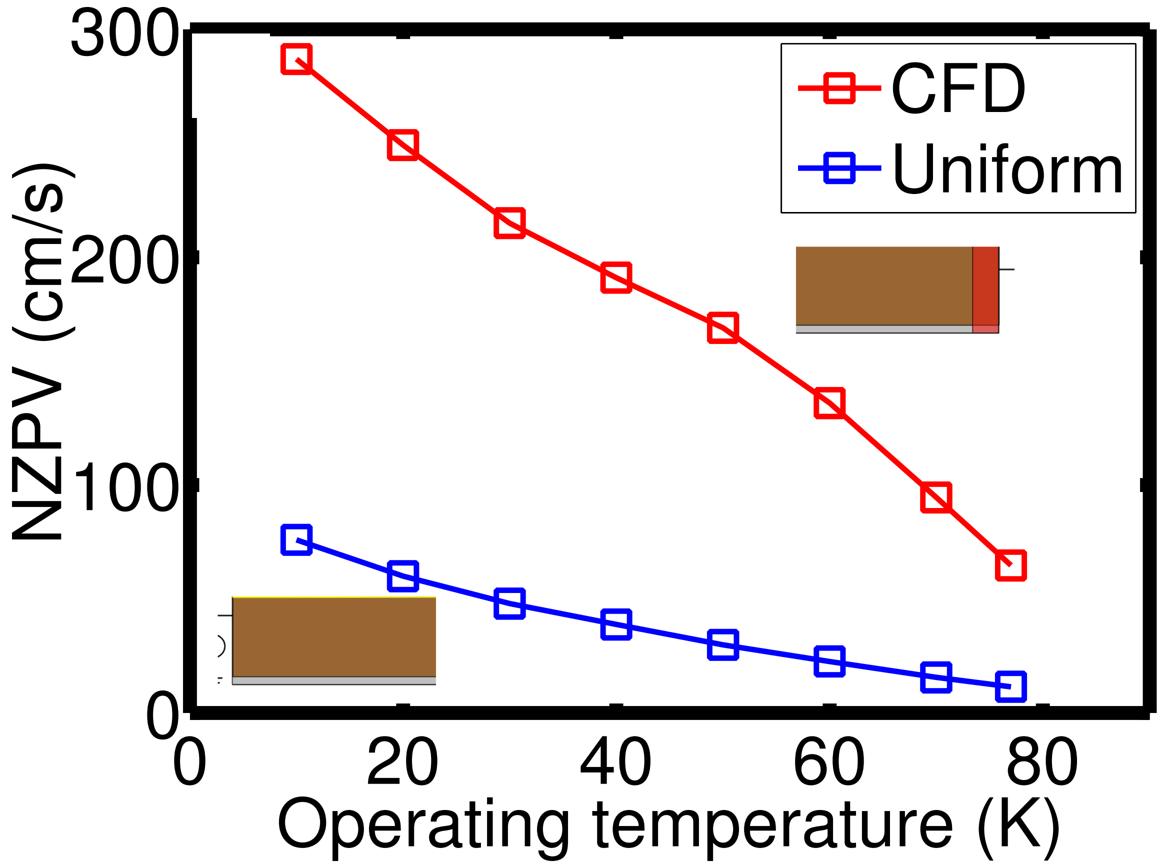
- $I_{op} = 0.9I_{c}$, T_{op} = 50 K, t_{Ag} = 10 μm



CFD architecture gets more efficient as I_c increases

NZPV vs. operating temperature

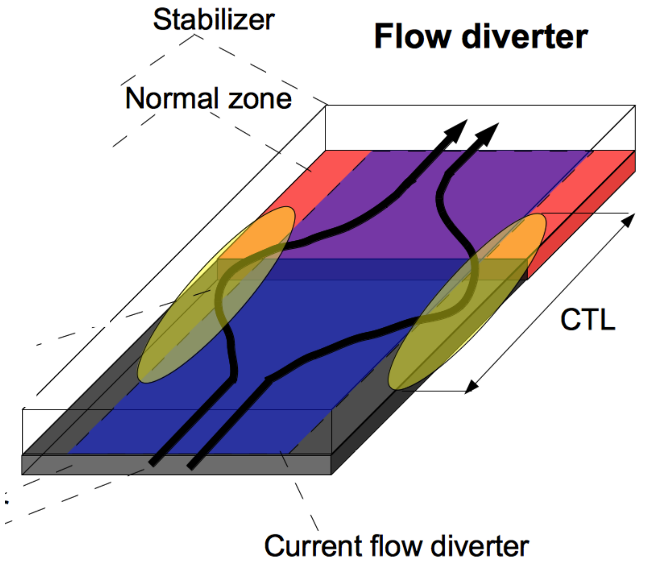
- $I_{op} = 0.9I_c$, I_c (50K) = 800 A, $t_{Ag} = 10$ μm



Processing feasibility of CFD tapes

- **In few word: not so obvious!**
  - Patterning not easy to integrate in current processes
  - Uniform architecture much easier, but less effective
  - Needs further discussions with tape manufacturers
  - But in the short term…

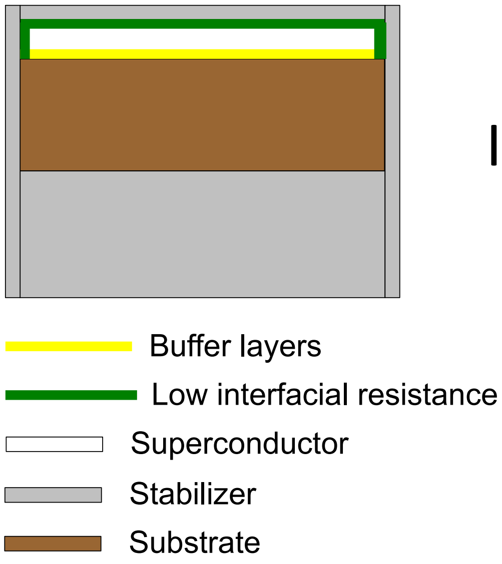
(see next slide)



Alternative CFD architecture

- **Buffer layers are electrical insulators: <u>can act as CFD</u>**
- HTS-Ag interfacial resistance is kept **low**
- Stabilizer is kept **very thin** on the HTS side but **thick** on the substrate side

Cross section

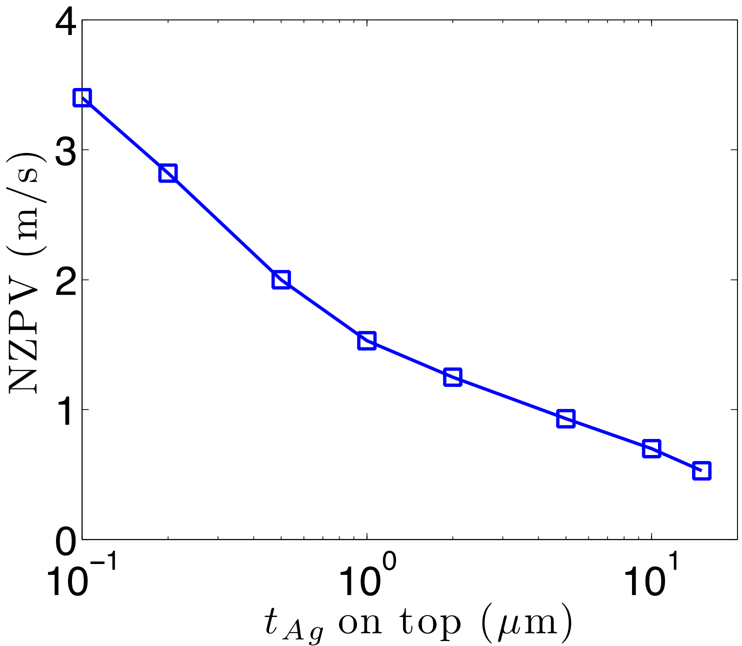


T_{op} = 10 K

I_c (10K) = 1.6 kA

$I_{op} = 0.9 I_c$

t_{ag} = 20 µm (total)



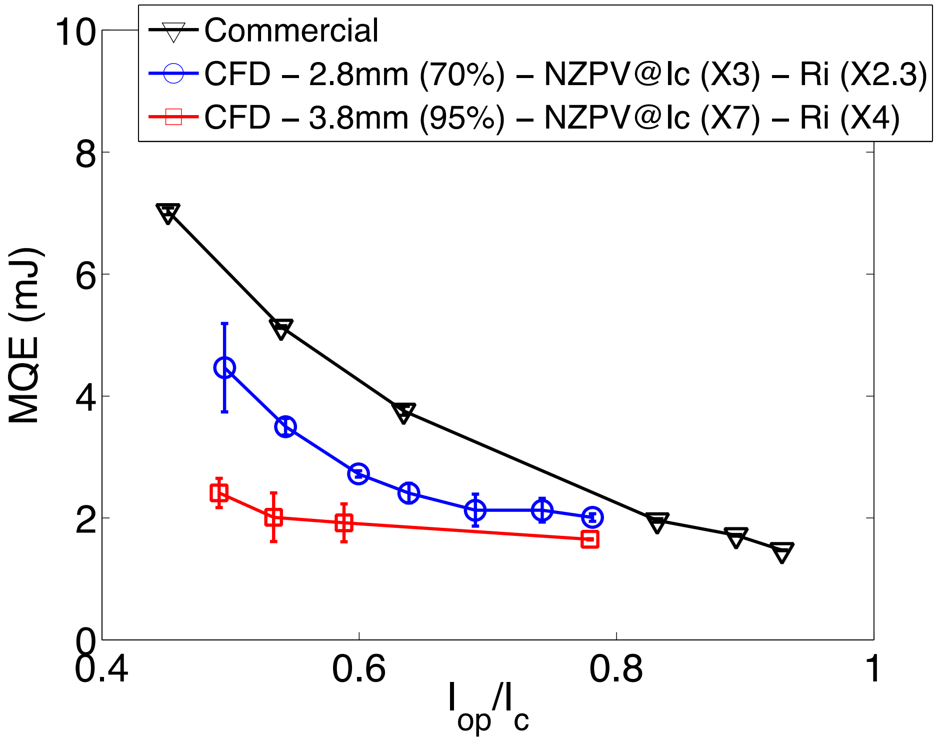
Summary

- What is the stability of CFD tapes ?

- What is the NZPV enhancement of CFD tapes
  - *at different operating currents ?*
  - *at lower temperatures ?*
  - *for thicker stabilizer ?*
  - *for higher critical current ?*

Summary

- **What is the stability of CFD tapes ?**
  - Reduced MQE in CFD tapes (tradeoff between NZPV and MQE)
  - Reduction less pronounced as we increase I_{op}



(experimental measurements)

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[1] Also observed by Wang *et al. JAP* 101, 053904 (2007)

Summary

- **What is the NZPV enhancement of CFD tapes at different I_{op}, lower T, thicker stabilizer, higher I_c ?**

(FEM calculations + experiments)

- Increases NZPV (dV/dt) and V_{peak} : **good for quench detection**
- Decreases dT/dx : **good for reducing thermal stress**

(FEM calculations)

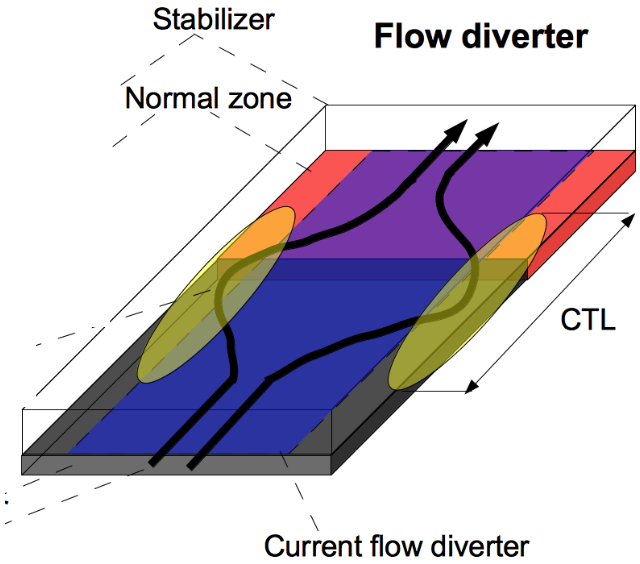
…including low temperature

- CFD effective for all operating conditions and parameters
  - Acceleration of NZPV by a factor 10 and beyond
- **Effectiveness increases as I_c of CCs increases** : follows industry trend

Conclusion

- **Current Flow Diverter (CFD) concept:**
  - might be the right approach to make quench detection easier
  - applicable to a broad range of applications (SFLCs, **magnets**, …)
  - promising for making more robust HTS devices based on CCs

Benefits seems independent from magnet quench protection strategies



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