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

F. Sirois, C. Lacroix, J.-H. Fournier-Lupien

Regroupement Québécois sur les Matériaux de Pointe (RQMP)

Electrical Engineering Department, Polytechnique Montréal, Canada

F. Sirois CV at glance

- Prof. at Polytechnique Montreal (Univ. of Mtl): 2005-…
- Previous (1998-2005):
  - Researcher at IREQ (Hydro-Québec res. Inst.)
  - Ph.D. in applied physics
  - Trained as electronic engineer (undergrad)
- Leader of the only research group in applied superconductivity in Canada
- Trained a dozen of PhD and more than 30 master's students over time
- Initiator of the HTS modeling workshops series
  - 2010: Lausanne, 2011: Cambridge, …, 2016: Bologna (4th)

HTS Modelling 2016

15 - 17 June, 2016 - Bologna, Italy

We are very pleased to invite you to the 5th International Workshop on Numerical Modelling of High Temperature Superconductors, which will be held in Bologna - Italy from June 15 to 17, 2016.

The aim of the event is to stimulate discussion and collaboration among experts in order to produce advances in modelling methods and tools needed for the development of HTS technology.

The beautiful and lively city of Bologna will be the ideal frame for fruitful and pleasant discussion as it is in the tradition of the HTS modelling workshops.

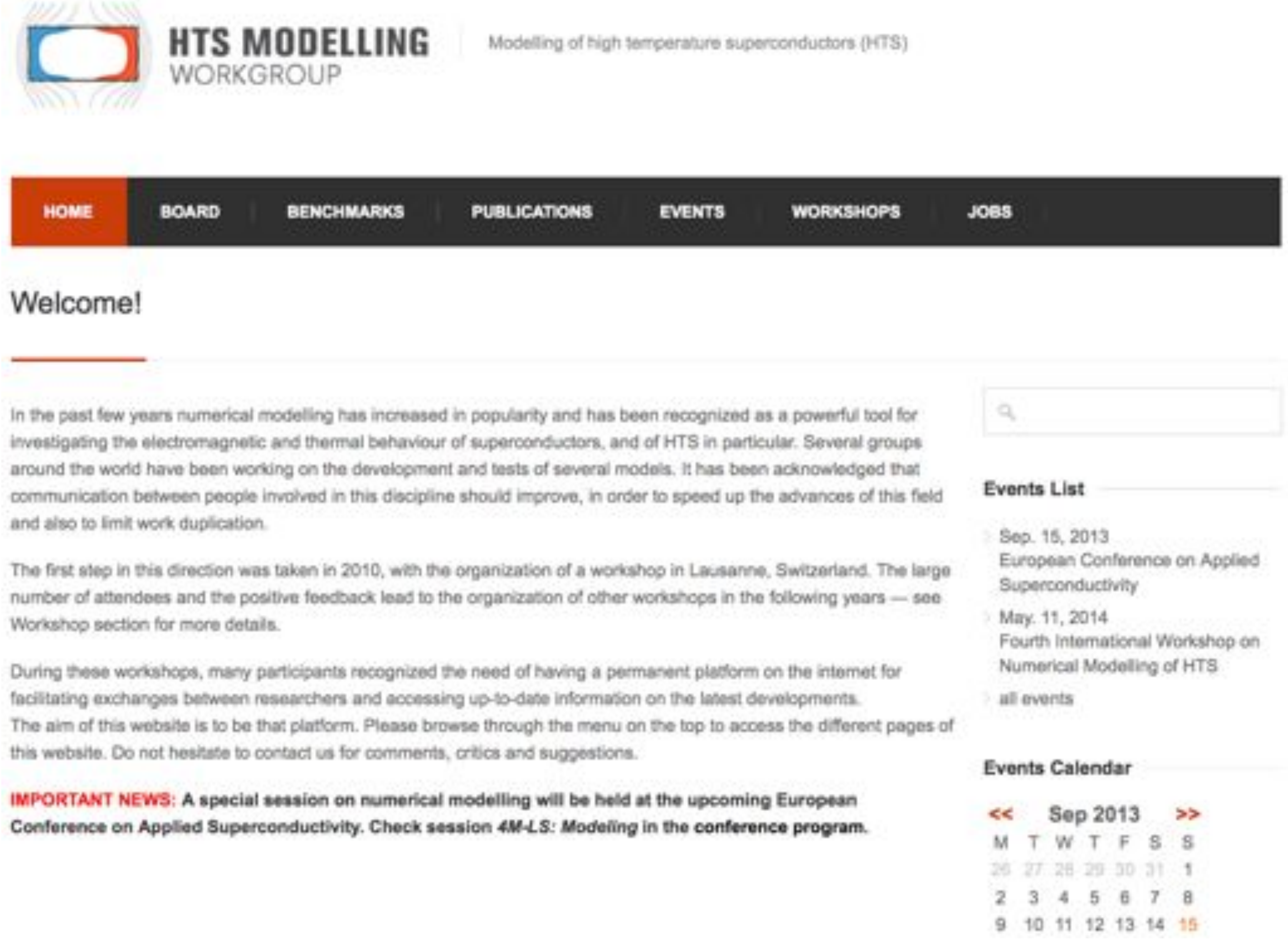
We are looking forward to meeting you at

HTS MODELLING 2016

5th International Workshop on Numerical Modelling of High Temperature Superconductors

June 15-17, 2016 Bologna – Italy

https://events.unibo.it/htsmodelling2016 http://www.htsmodelling.com



Welcome!

In the past few years numerical modelling has increased in popularity and has been recognized as a powerful tool for investigating the electromagnetic and thermal behaviour of superconductors, and of HTS in particular. Several groups around the world have been working on the development and tests of several models. It has been acknowledged that communication between people involved in this discipline should improve, in order to speed up the advances of this field and also to limit work duplication.

The first step in this direction was taken in 2010, with the organization of a workshop in Lausanne, Switzerland. The large number of attendees and the positive feedback lead to the organization of other workshops in the following years — see Workshop section for more details.

During these workshops, many participants recognized the need of having a permanent platform on the internet for facilitating exchanges between researchers and accessing up-to-date information on the latest developments.
The aim of this website is to be that platform. Please browse through the menu on the top to access the different pages of this website. Do not hesitate to contact us for comments, critics and suggestions.

IMPORTANT NEWS: A special session on numerical modelling will be held at the upcoming European Conference on Applied Superconductivity. Check session *4M-LS: Modeling* in the conference program.

Events List

- Sep. 15, 2013
  European Conference on Applied Superconductivity
- May. 11, 2014
  Fourth International Workshop on Numerical Modelling of HTS
- all events

Events Calendar

<< Sep 2013 >>

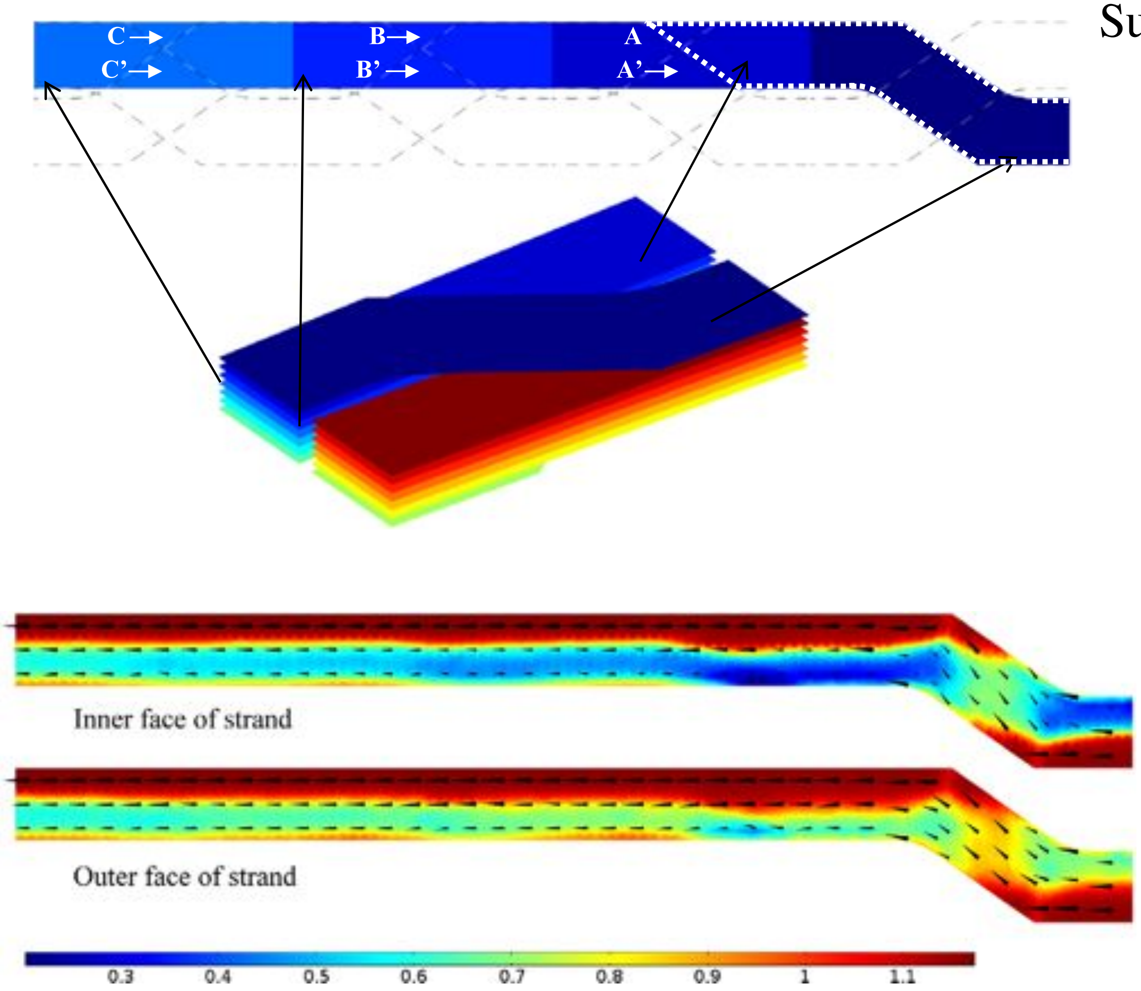
M	T	W	T	F	S	S
26	27	28	29	30	31	1
2	3	4	5	6	7	8
9	10	11	12	13	14	15

F. Sirois research activities

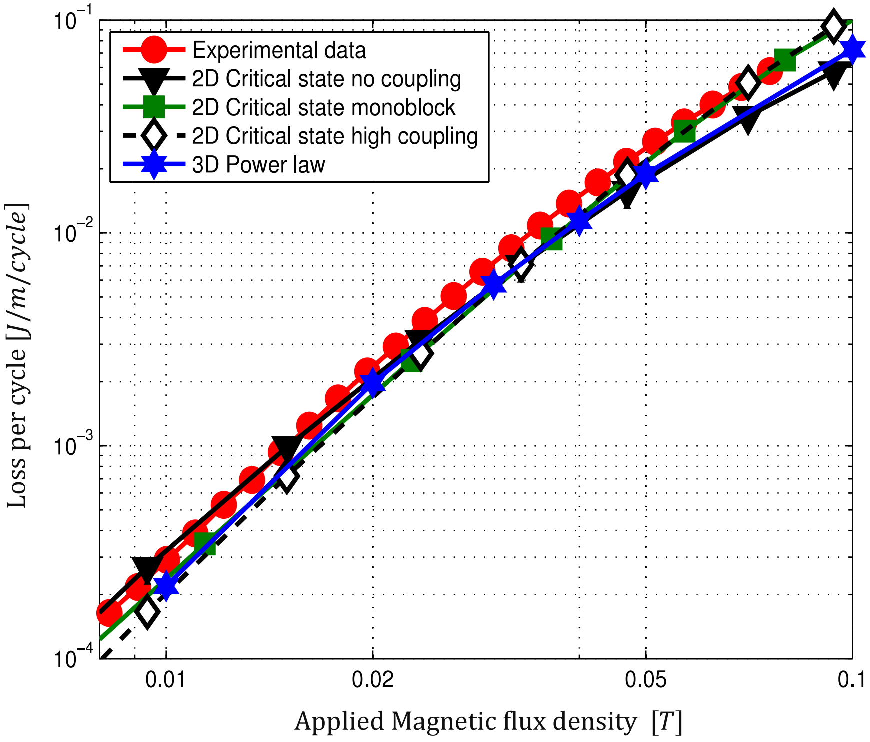
- My research activities at glance
  - Applied superconductivity
    - Modeling 2G tapes and devices
    - Numerical methods and code development
    - Custom characterization and quench experiments
  - Materials characterization (experimental)
    - Thermal and electrical characterization of Carbon Fiber Reinforced Plastic (CFRP)
    - Magnetic and thermal characterization of steels and alloys
    - Thermal/mechanical response to lightning strikes
  - Energy storage
    - Distributed thermal energy storage in power systems
    - Lumped energy storage in supercapacitors

Modeling activities

- Example: AC losses in Roebel cables

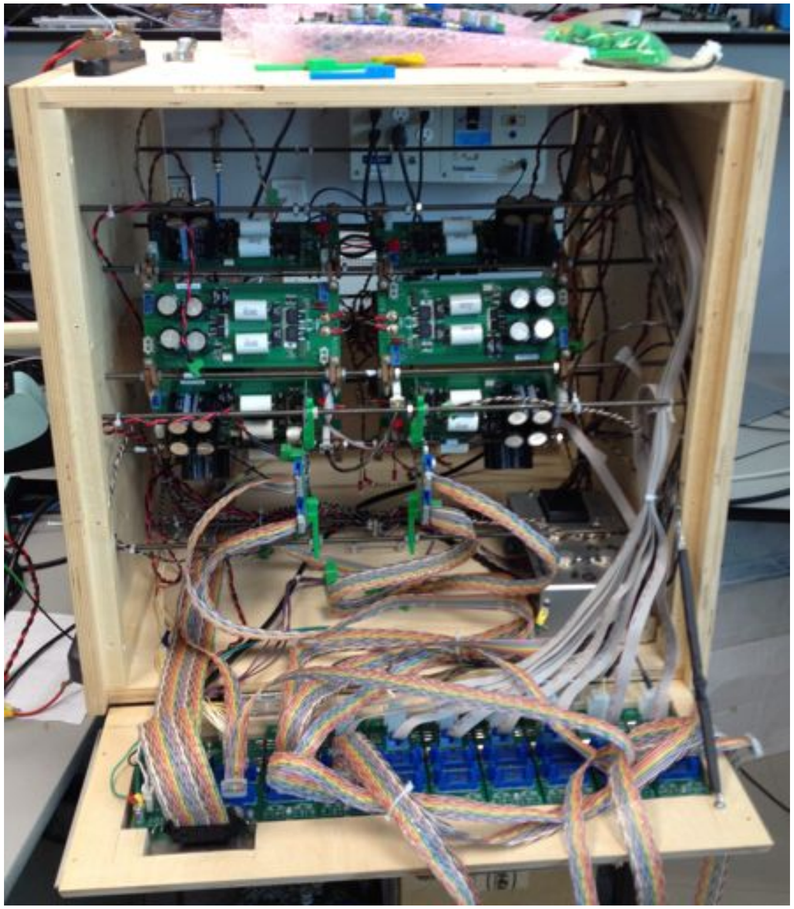


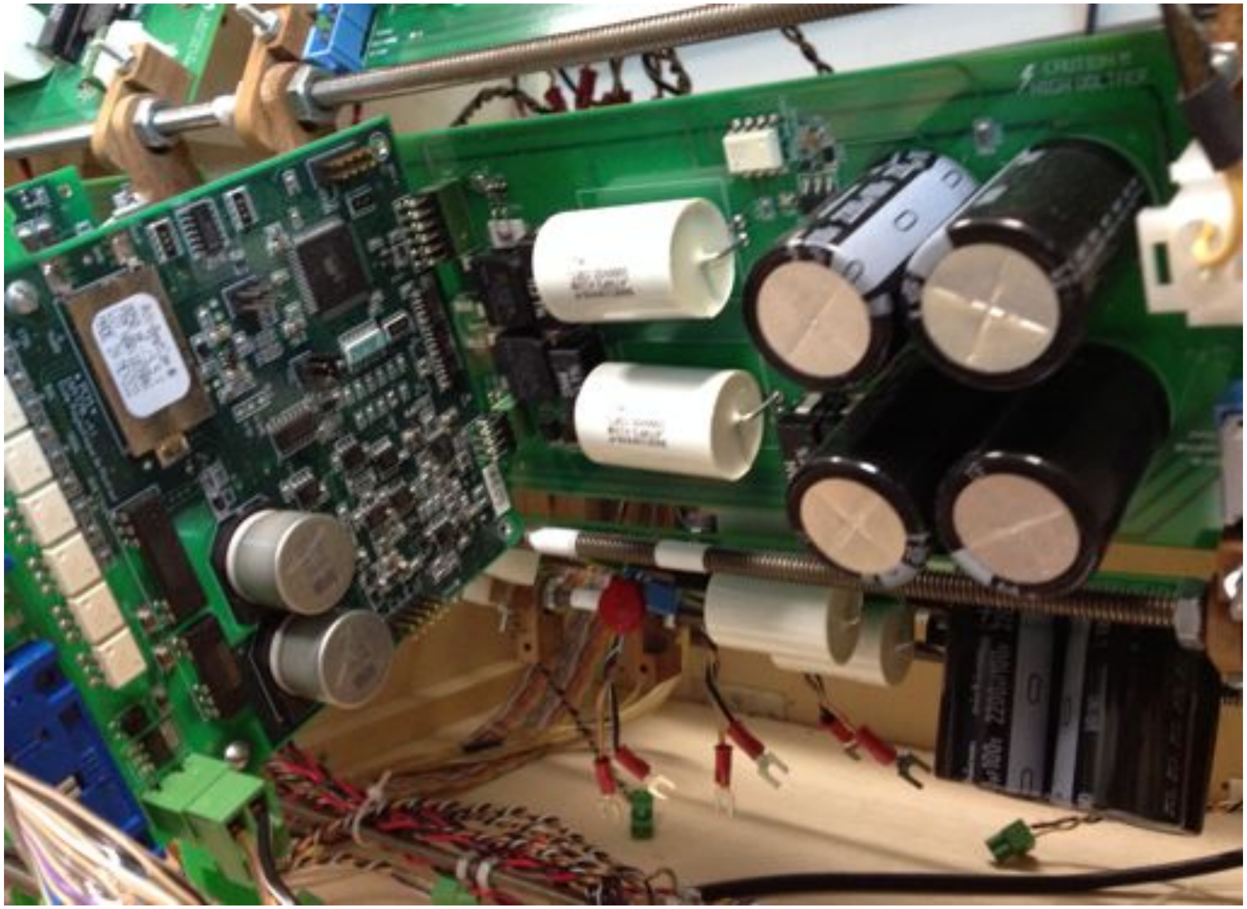
Supercond. Sci. Technol. **26** (2013) 052001 (8pp)



Custom experimental infrastructure

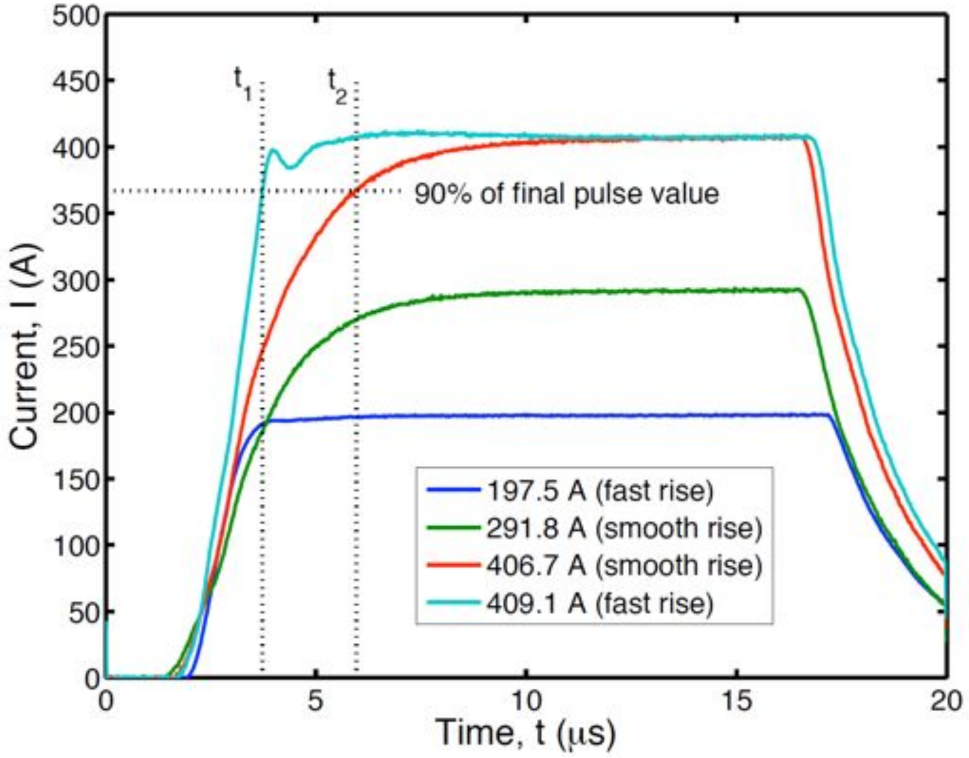
- Very fast pulsed V-I current characterization

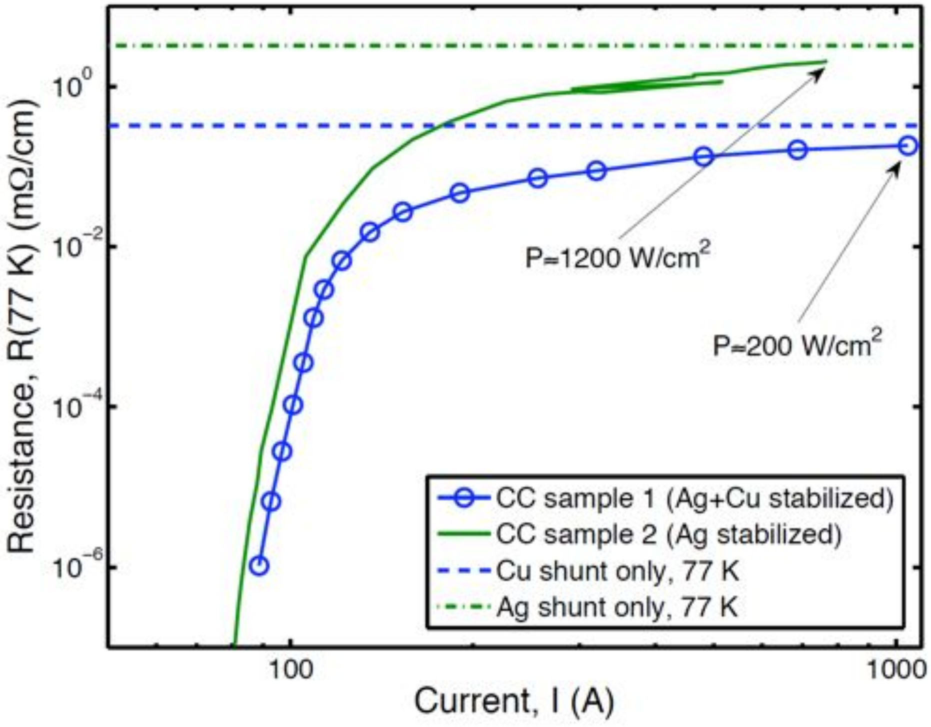




Custom experimental infrastructure

- Pulsed current characterization (fast pulses)



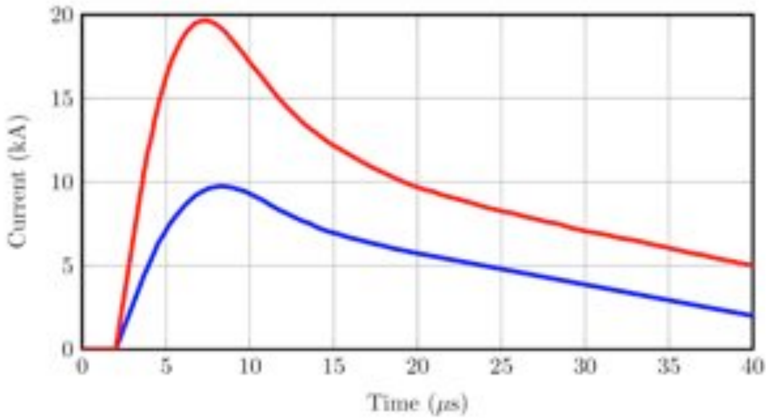


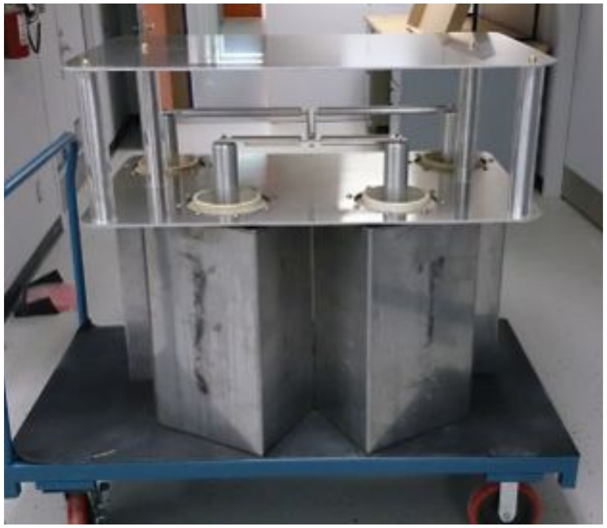
IEEE Trans. on Appl. Supercond. **19** (2009) 3585 (6pp)

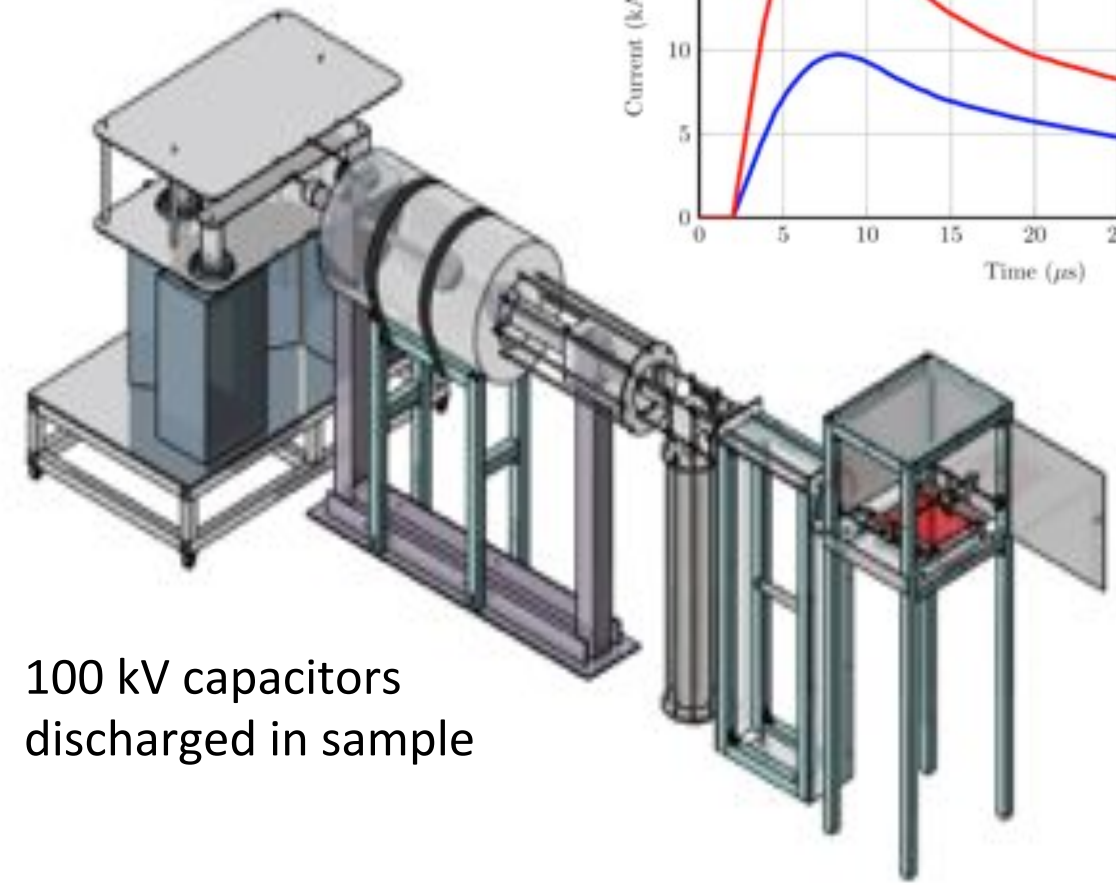
Supercond. Sci. Technol. **23** (2010) 034018 (6pp)

Custom experimental infrastructure

- Lightning strike emulation
  - 50 kA peak



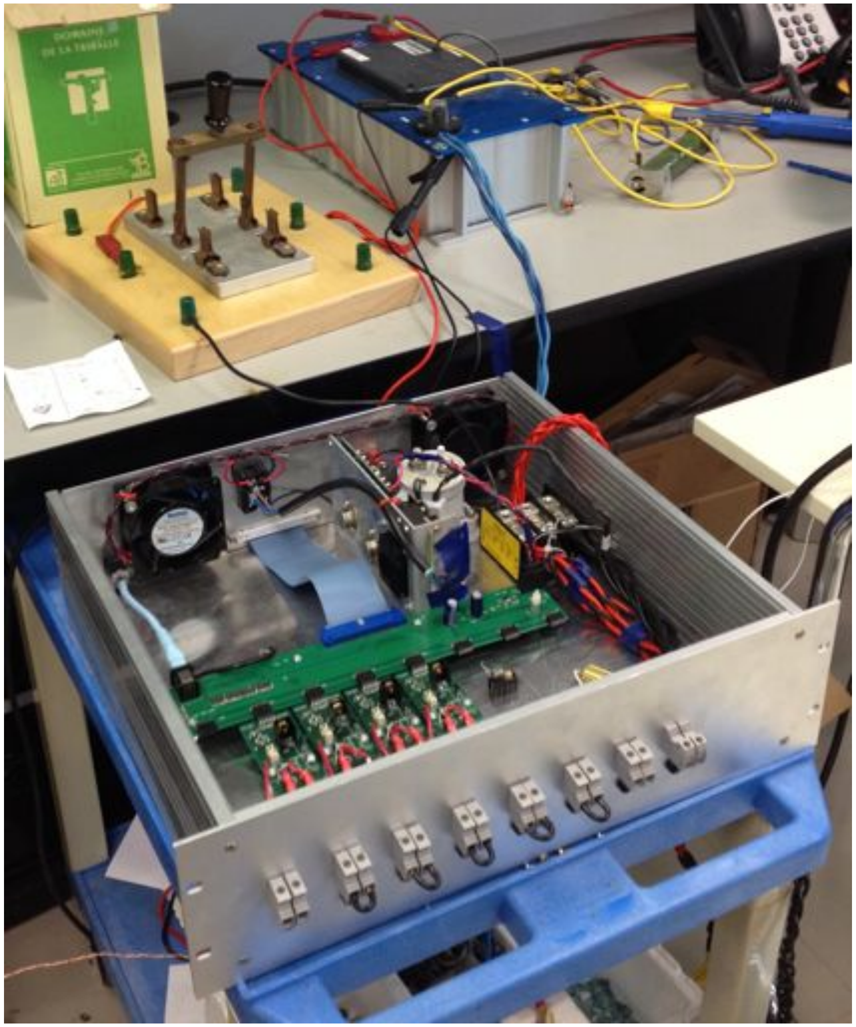


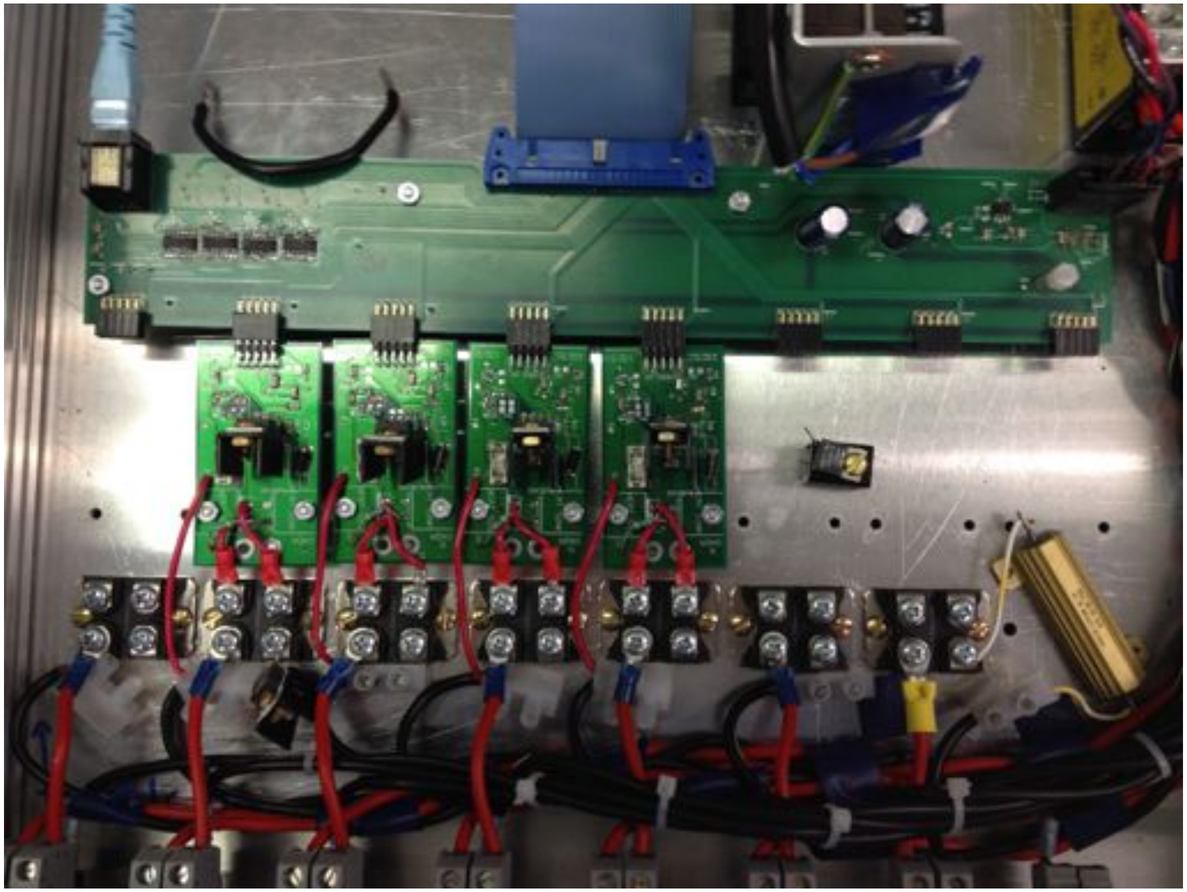


100 kV capacitors discharged in sample

Custom experimental infrastructure

- Quench measurement

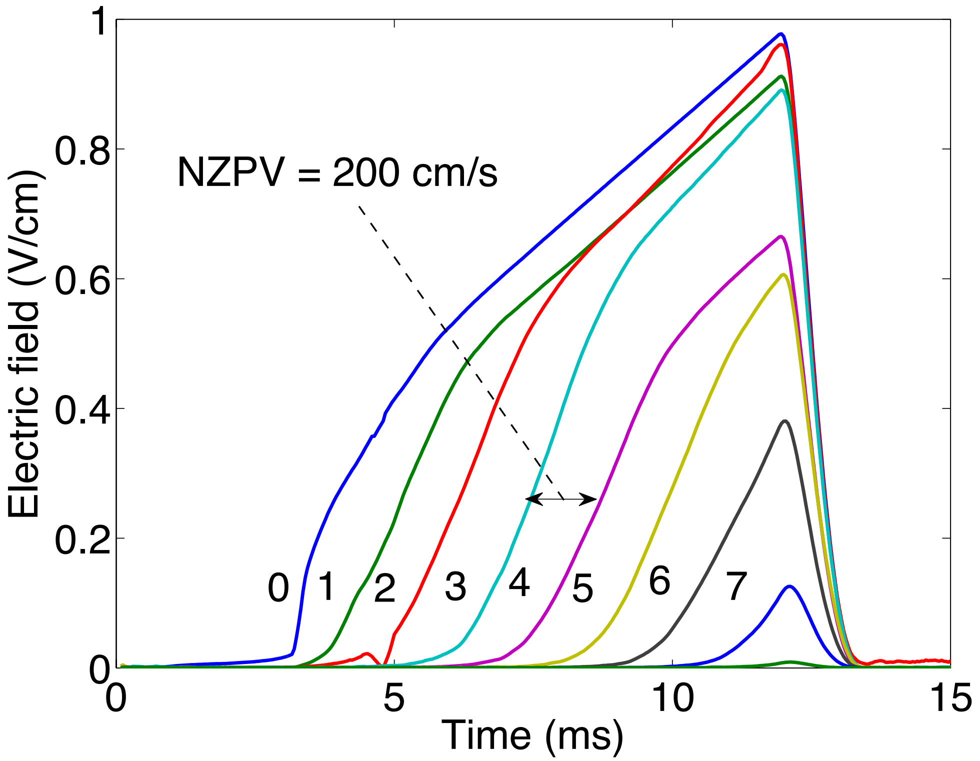




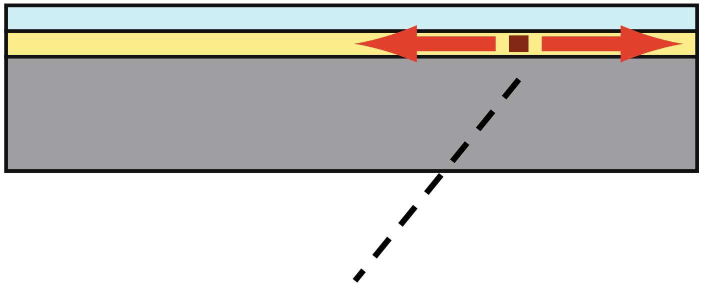
Custom experimental infrastructure

- Quench measurement

Physica C **469** (2009) 1462 (5pp)



Ruban supra 2G



Generation and propagation of hot spot

NZPV: Normal Zone Propagation Velocity

IEEE Trans. on Appl. Supercond. **23** (2013) 4701605 (5pp)

Supercond. Sci. Technol. **27** (2014) 055013 (6pp)

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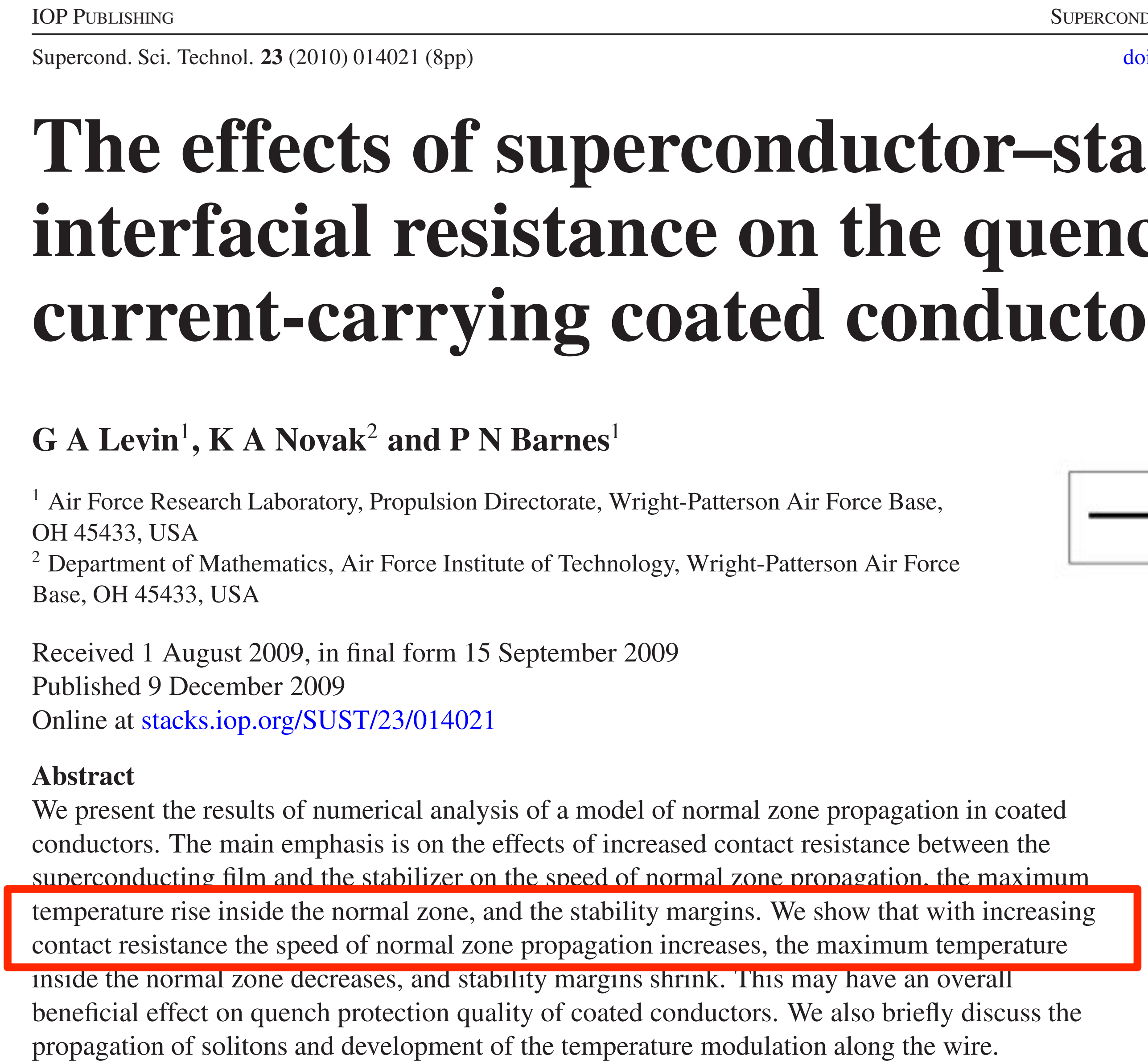
Introduction: hot spot issue

- 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



IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **23** (2010) 014021 (8pp) doi:10.1088/0953-2048/23/1/014021

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

G A Levin[1], **K A Novak**[2] **and P N Barnes**[1]

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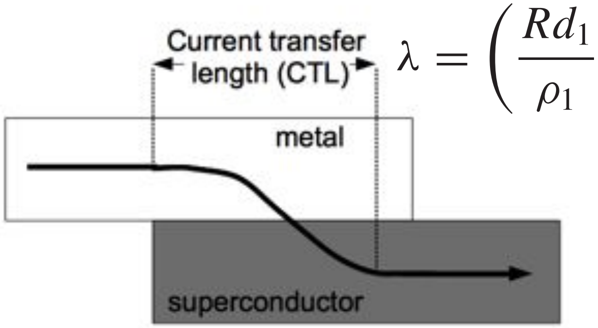
[2] Department of Mathematics, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH 45433, USA

Received 1 August 2009, in final form 15 September 2009
Published 9 December 2009
Online at stacks.iop.org/SUST/23/014021

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.

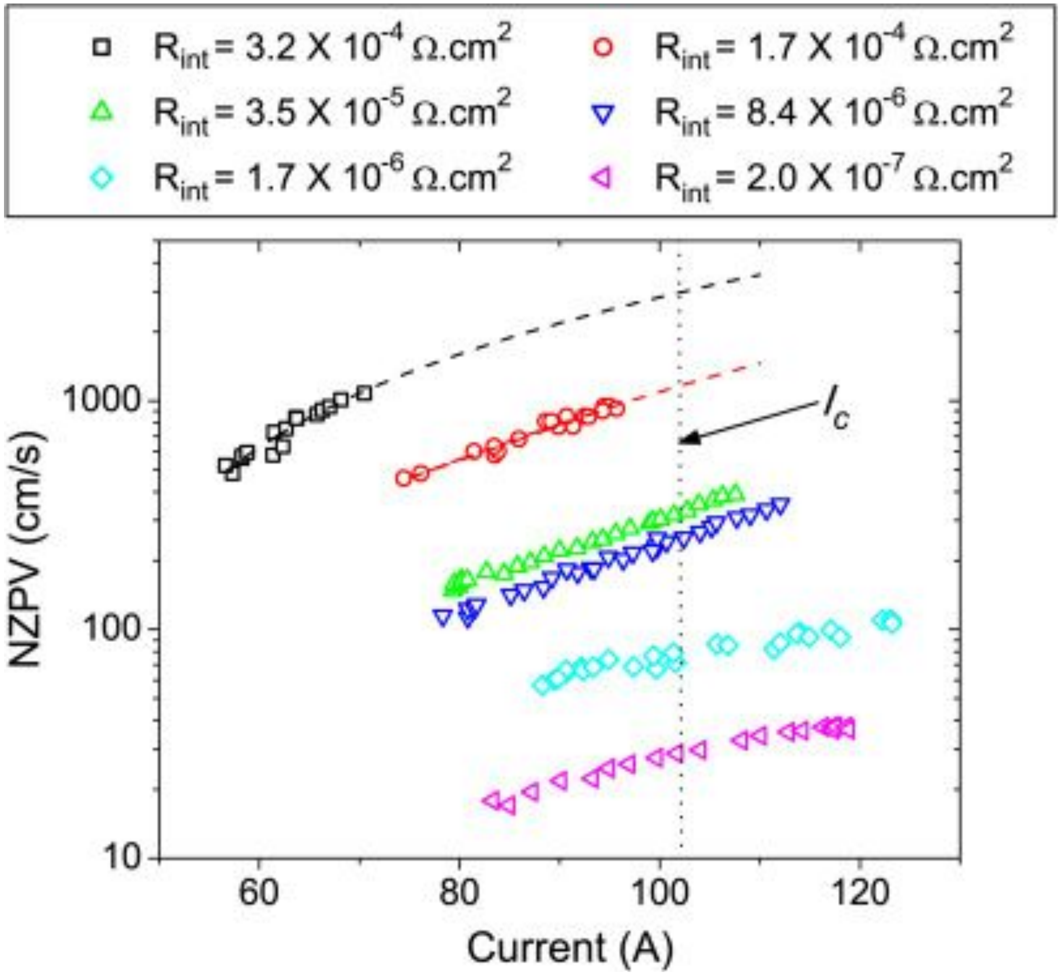


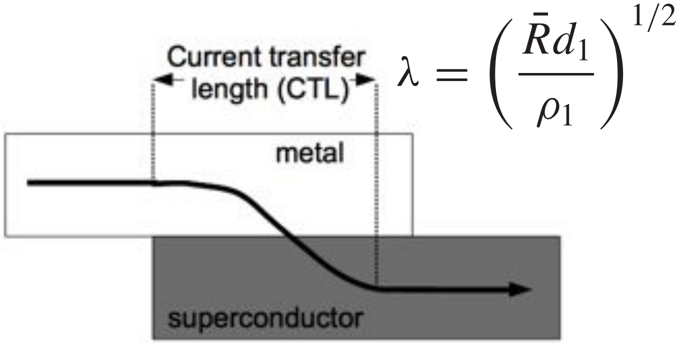
$$\lambda = \left(\frac{\bar{R} d_1}{\rho_1}\right)^{1/2}$$

NZPV approx. scales with CTL

Introduction: NZPV vs R_{int} (experimental)

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





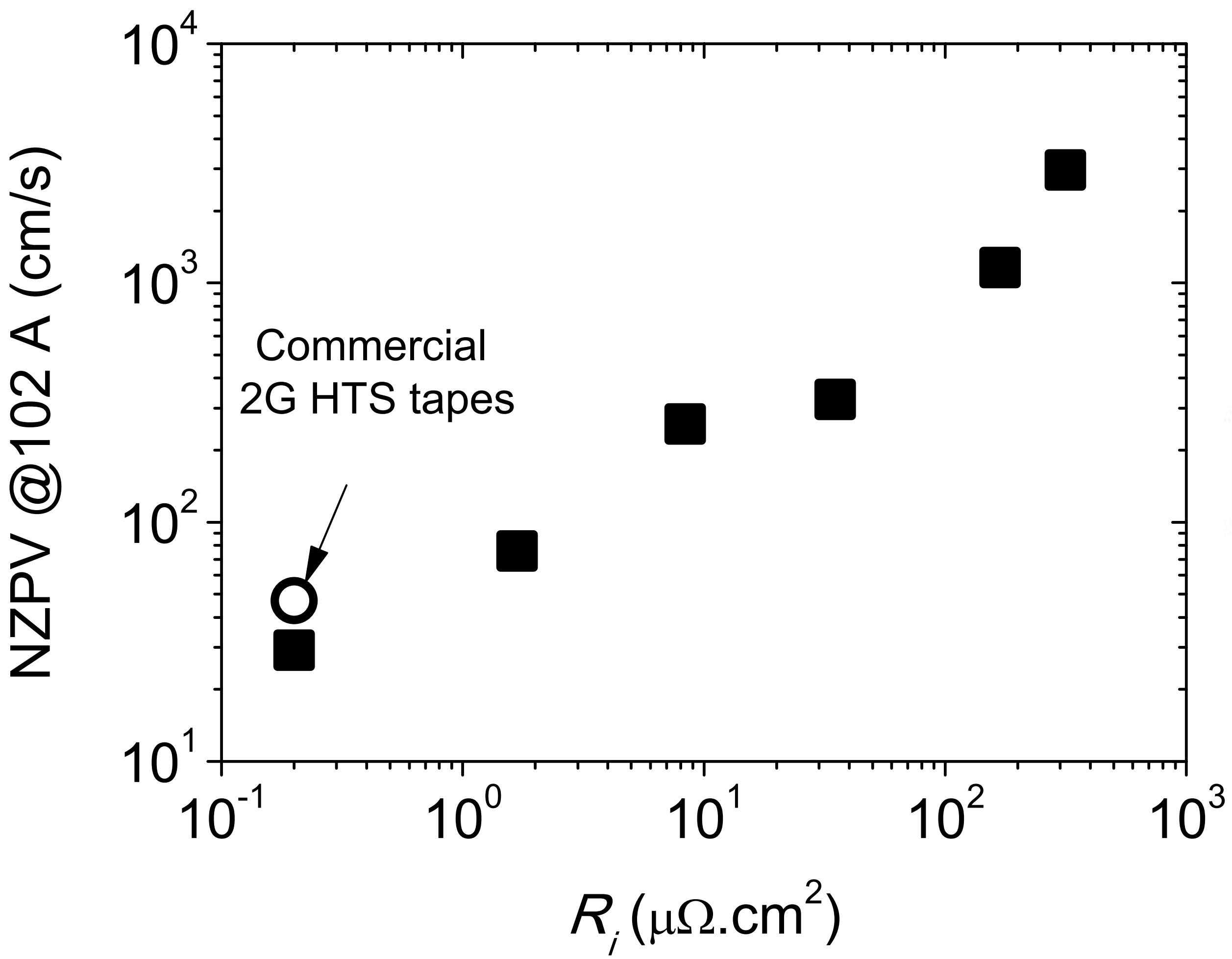
$$\lambda = \left(\frac{\bar{R} d_1}{\rho_1}\right)^{1/2}$$

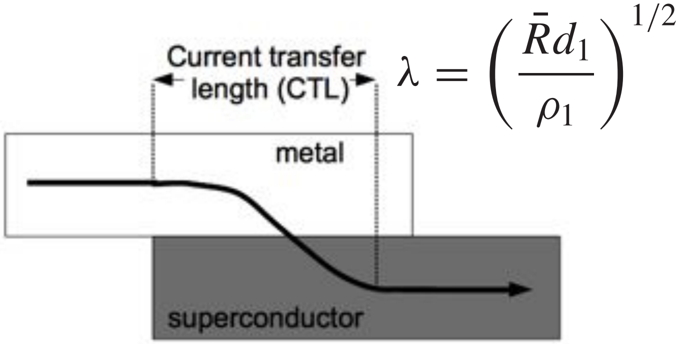
NZPV approx. scales with CTL

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

Introduction: NZPV vs R_{int} (experimental)

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





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

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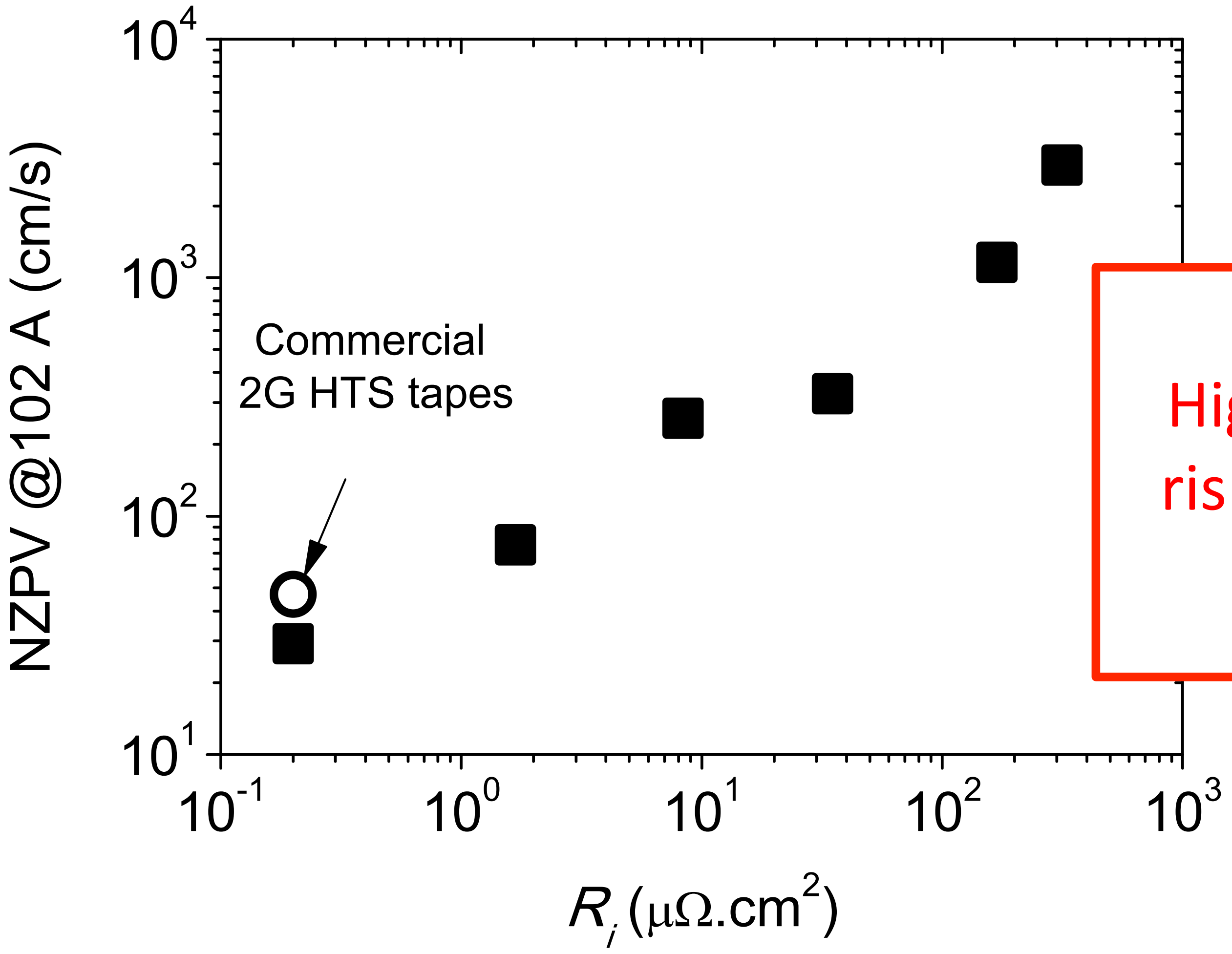


High R_i greatly increases risk of quench at current lead connections

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

Quench modeling of 2G HTS CCs

- 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**

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:

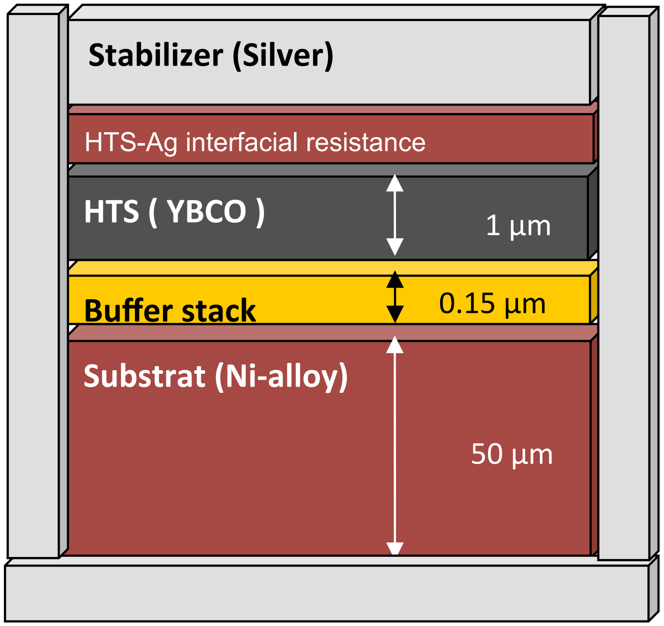
Current density (J)

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

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

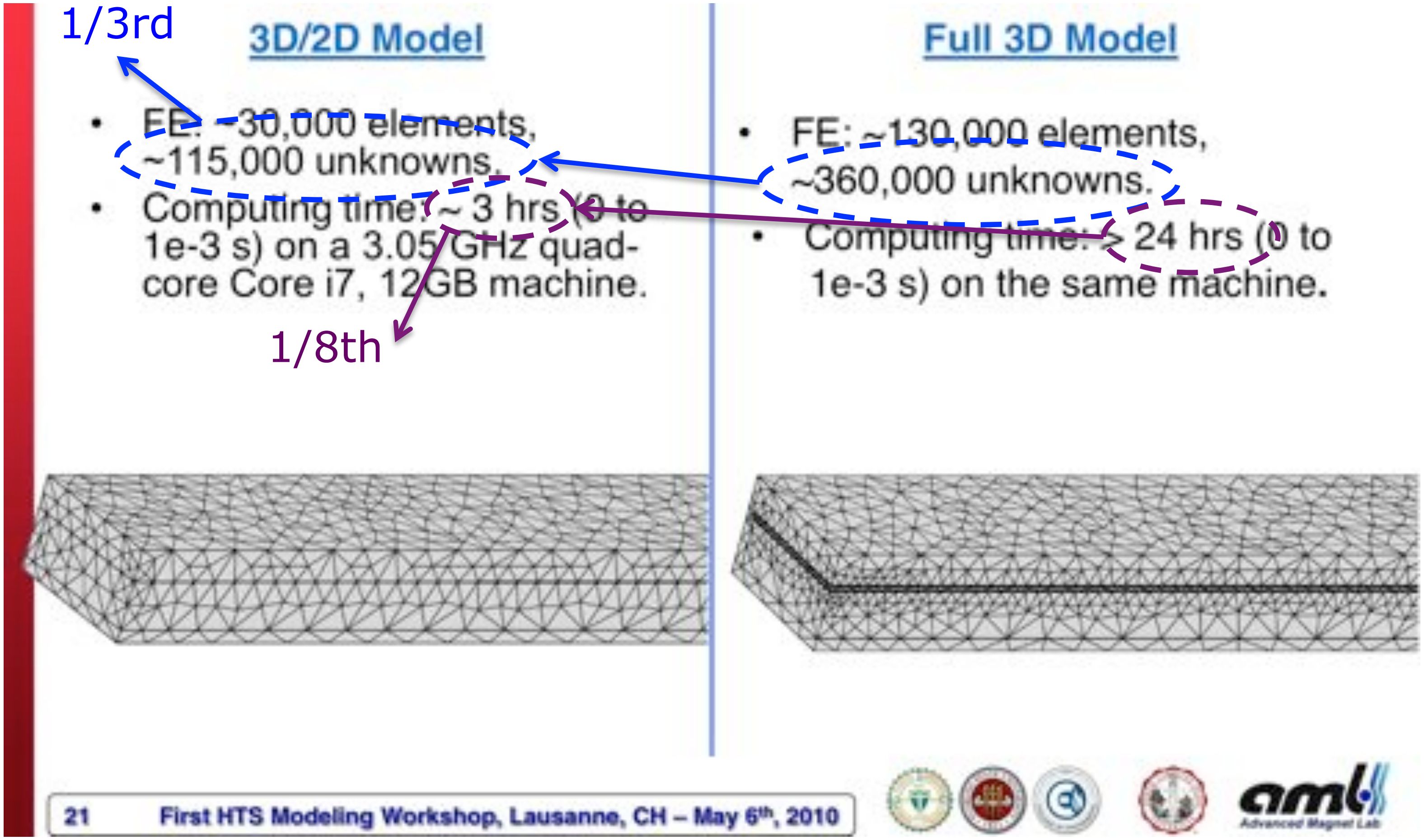
$$Q_{\mathrm{j}} = \sigma(T)(-\nabla V)^2,$$

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



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)

$$\nabla \cdot (-\sigma(T)\nabla V) = 0,$$ → $$J_z = \sigma(T)\frac{\partial V}{\partial z} = \sigma(T)\left(\frac{V_2 - V_1}{t}\right)$$

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

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

+ boundary conditions

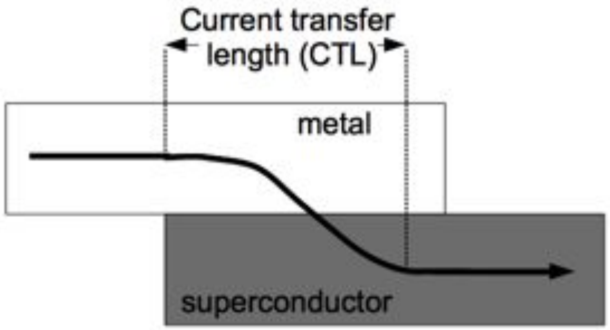
Buffer layers and HTS-Ag contact resistance

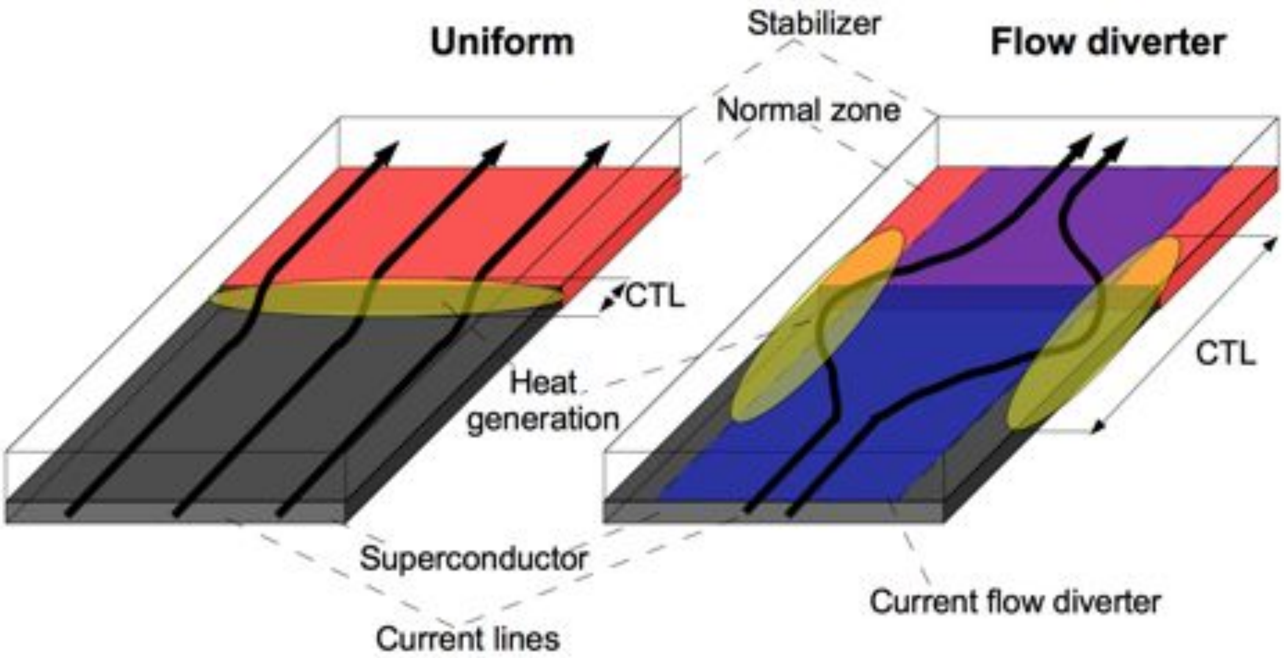
Approximation:

- Infinitely thin layers

Current Flow Diverter (CFD) concept[1]

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





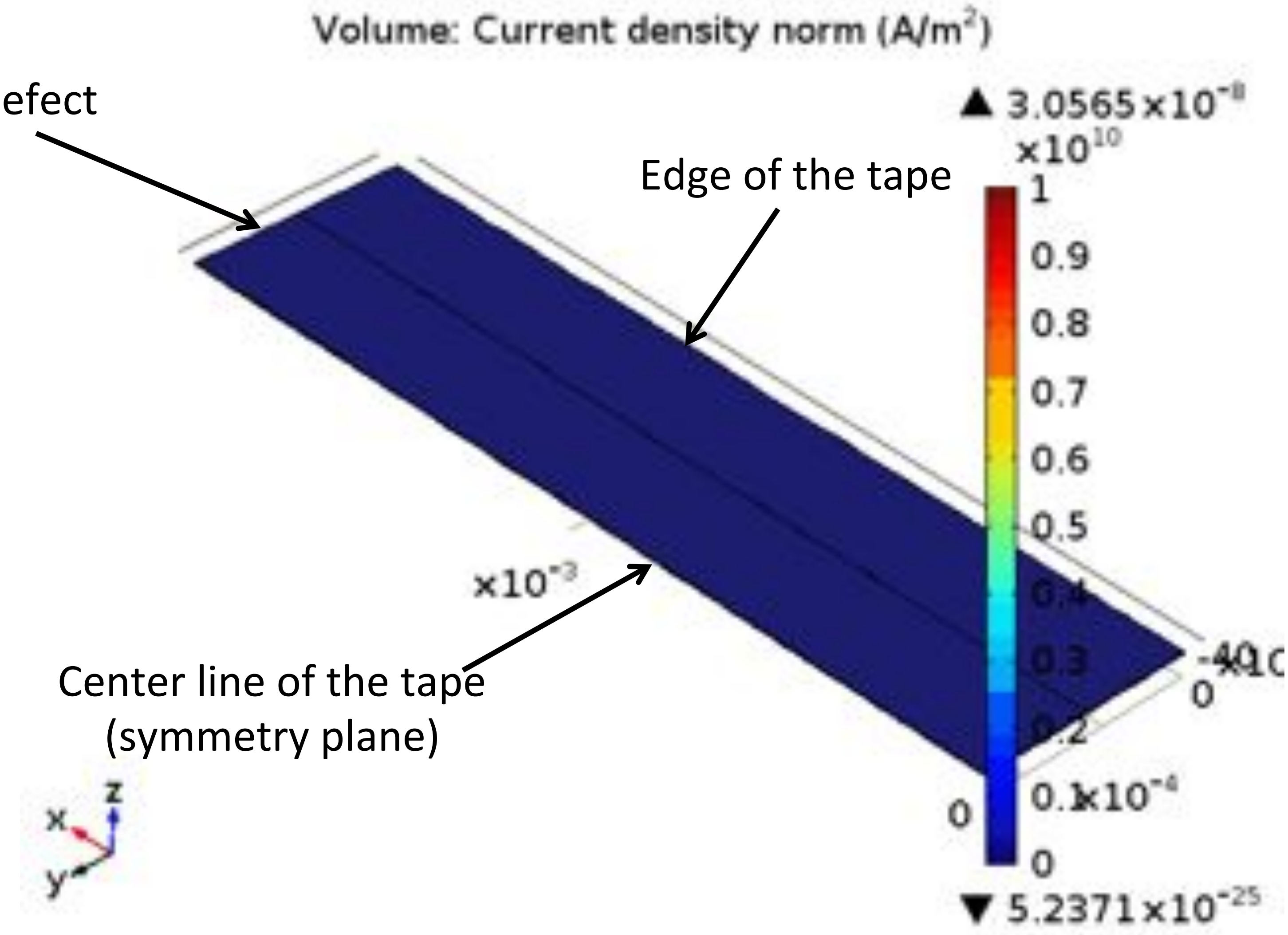
- Increases the NZPV by an order of magnitude for a given interface resistance (R_i)

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

Current Flow Diverter (CFD) concept[1]

- **Uniform *R*$_i$**
- 10 mm wide
- I = 0.9 I_c
- I_c = 160 A
- **T_{op} = 77 K**
- **3 μm Ag**

UNIFORM interfacial resistance = 1 μΩ.cm^2



Defect

Edge of the tape

Center line of the tape (symmetry plane)

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

Current Flow Diverter (CFD) concept[1]

- **<u>CFD</u>**
- 10 mm wide
- $I = 0.9\ I_c$
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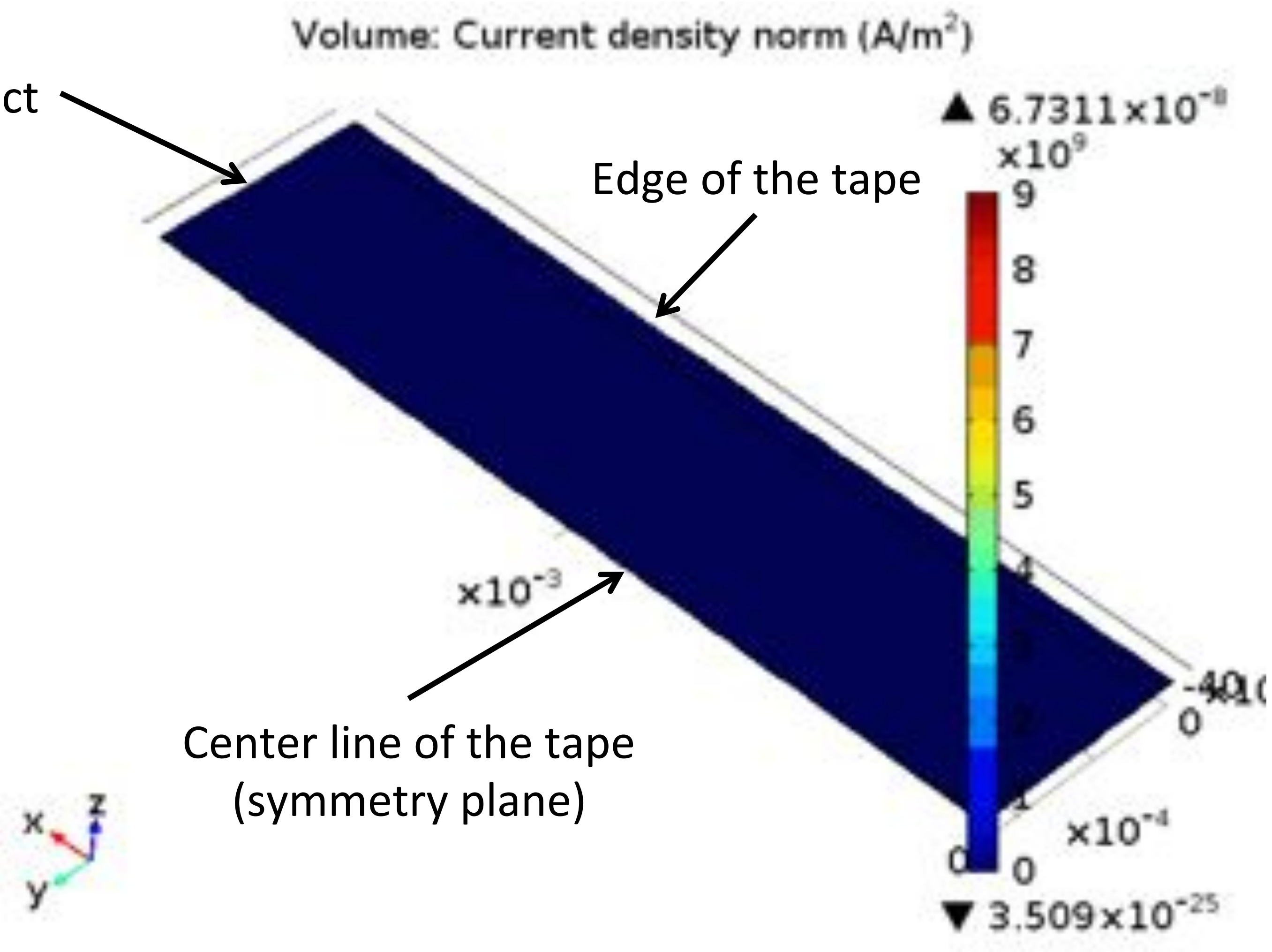
- **3 µm Ag**

CFD interfacial resistance = 1 µΩ.cm²



Defect

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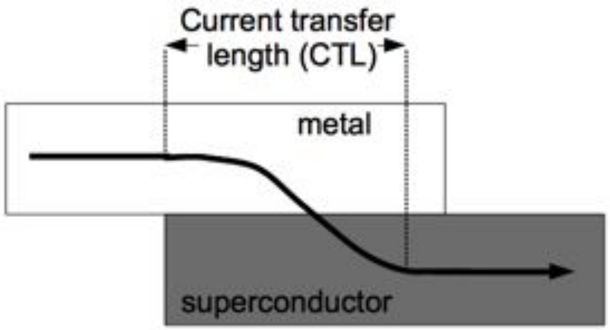
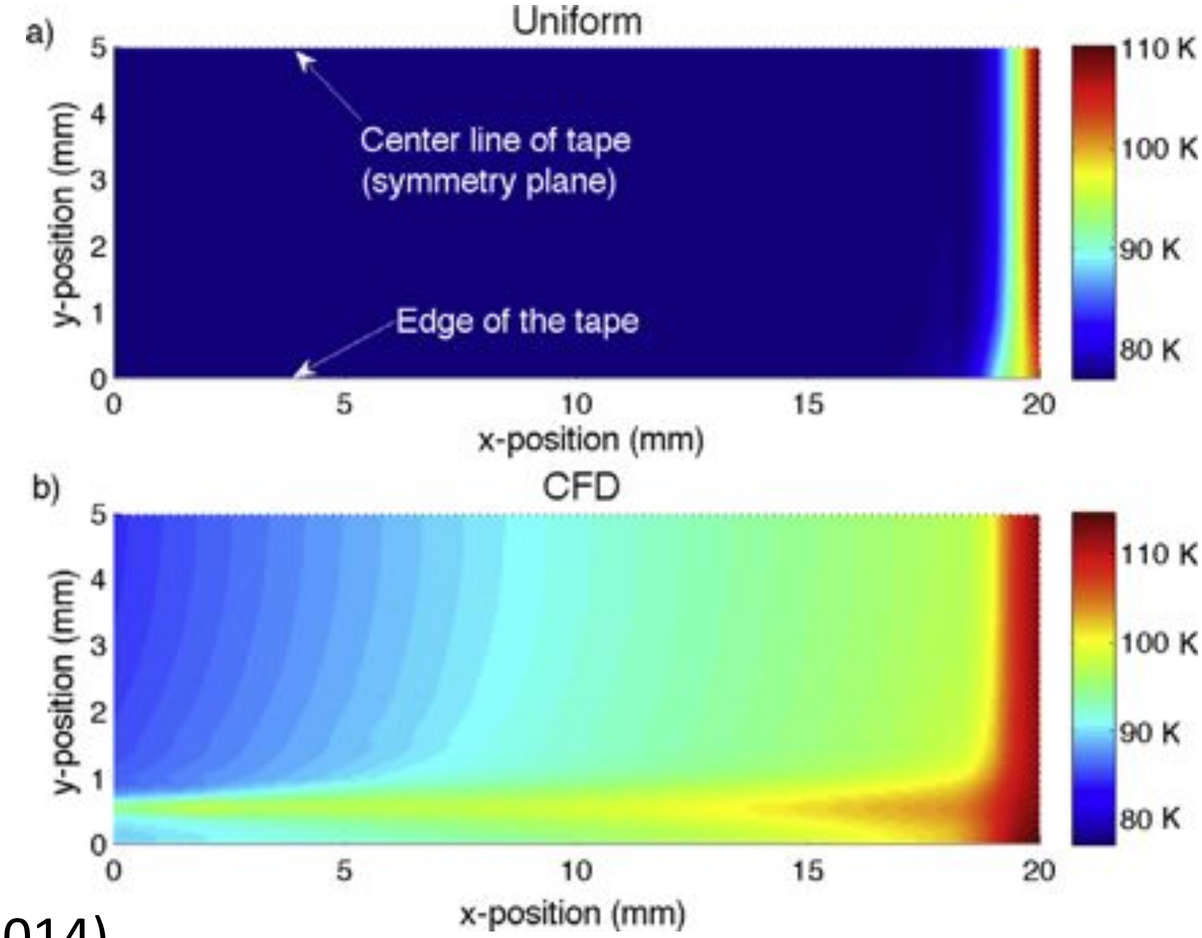
[1] Lacroix *et al. SUST* 27, 035003 (2014)

Current Flow Diverter (CFD) concept[1]

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

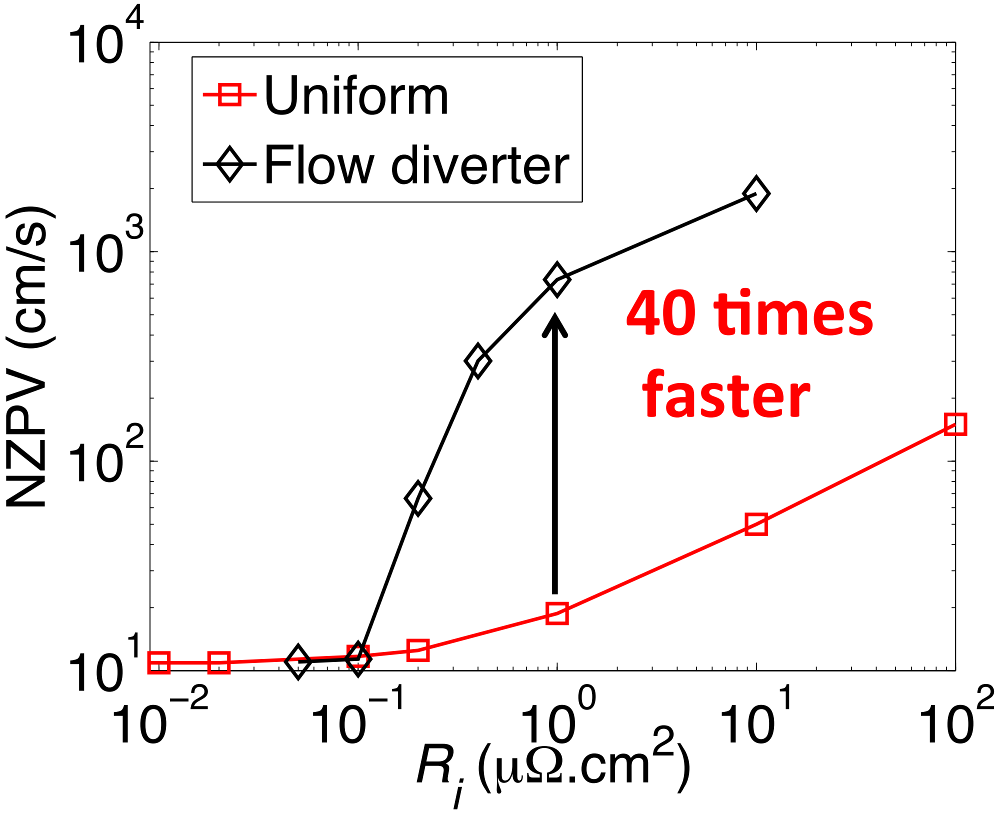




[1] Lacroix *et al. SUST* 27, 035003 (2014)

FEM Calculations: CFD vs. uniform

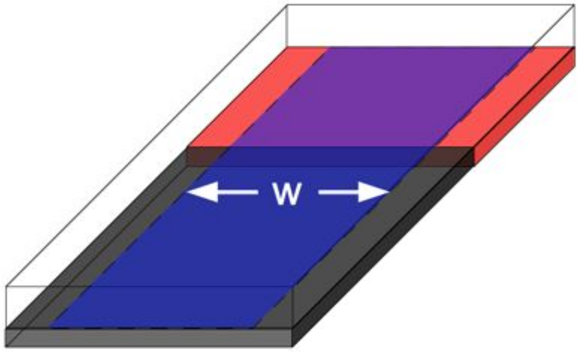
$\mathbf{T_{op} = 77\ K}$, I_c (77K) = 160 A, $I_{op} = 0.9\ I_c$ A, $\mathbf{t_{ag} = 3\ \mu m}$

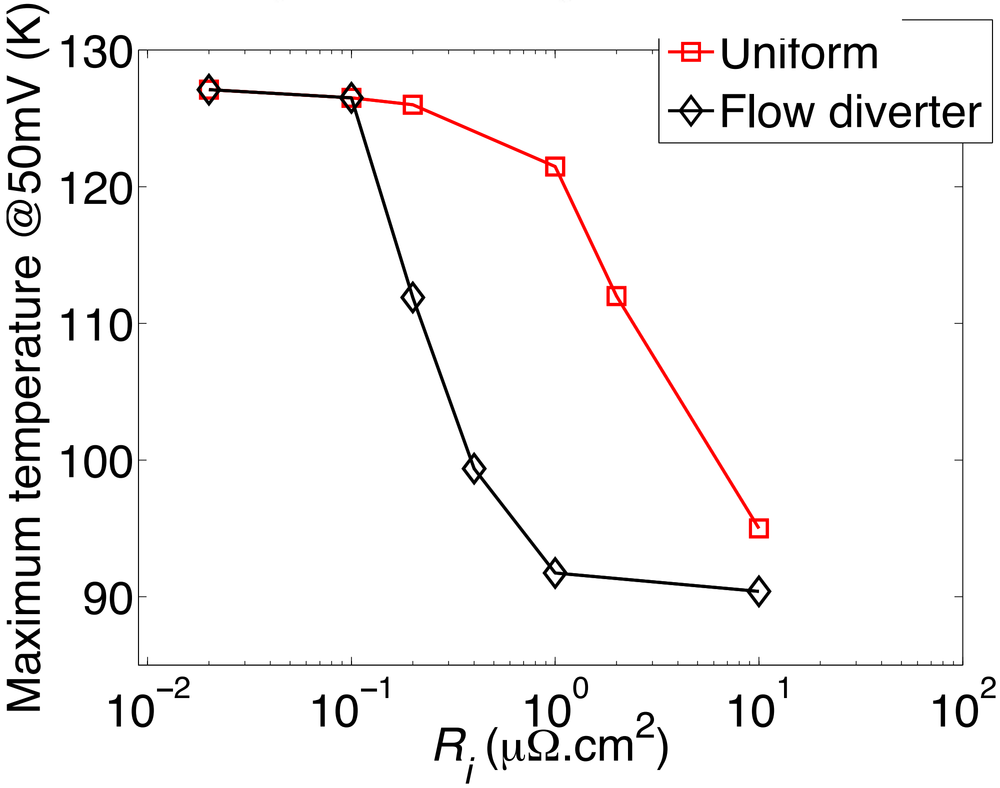


40 times faster

Low resistance part = 0.1 μΩ.cm^2

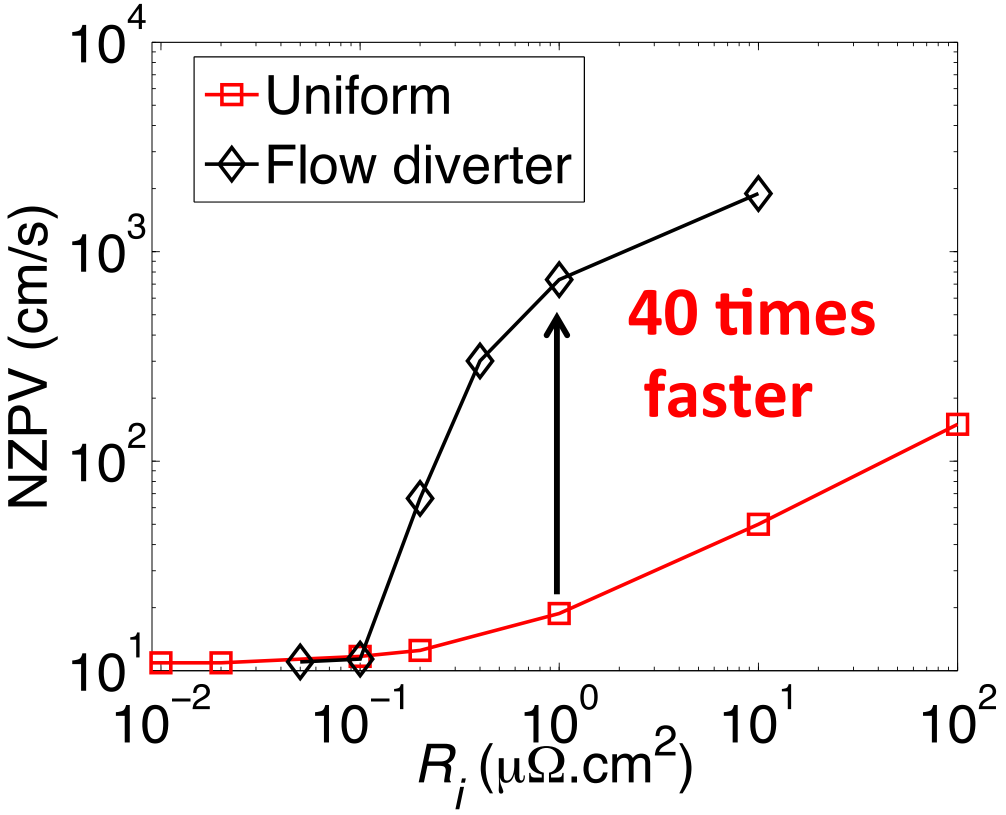
CFD = 1 Ω.cm^2





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**



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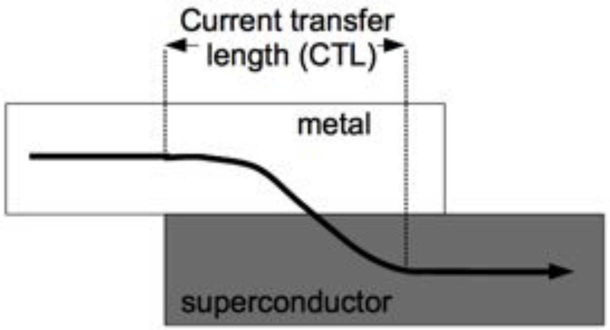
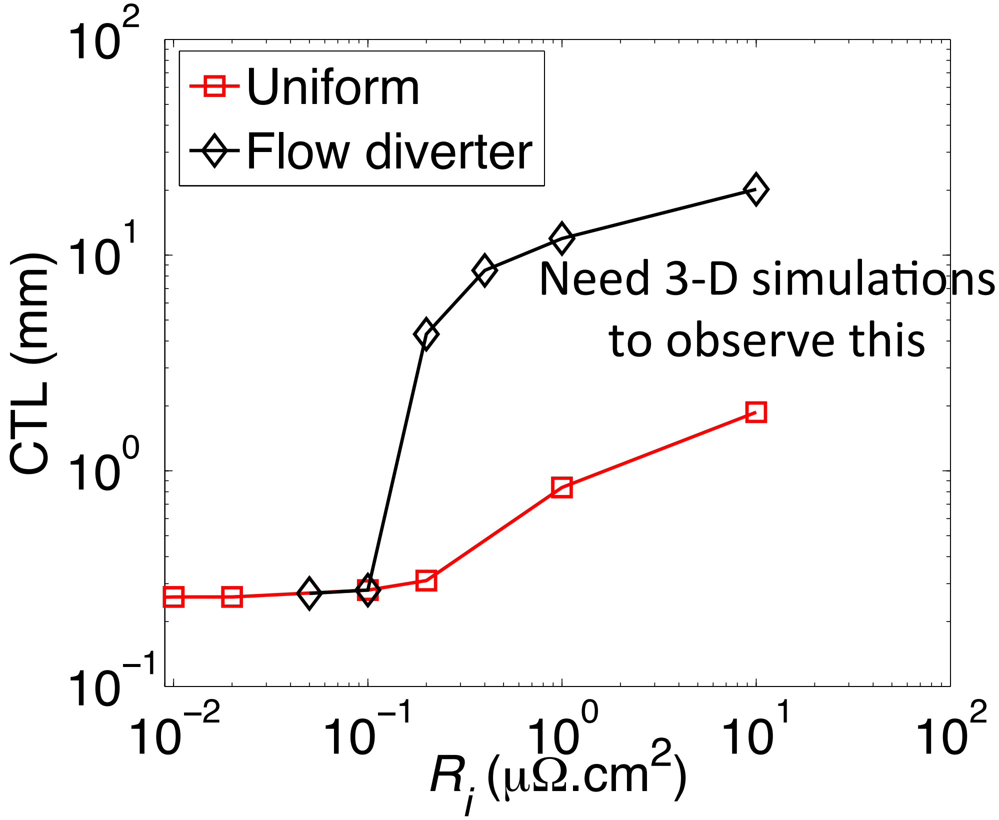
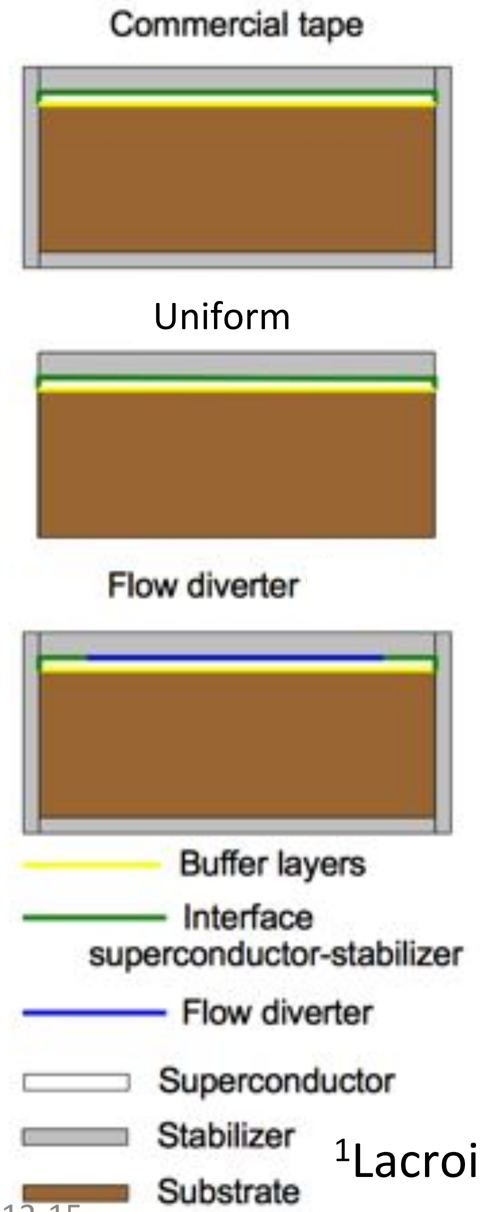


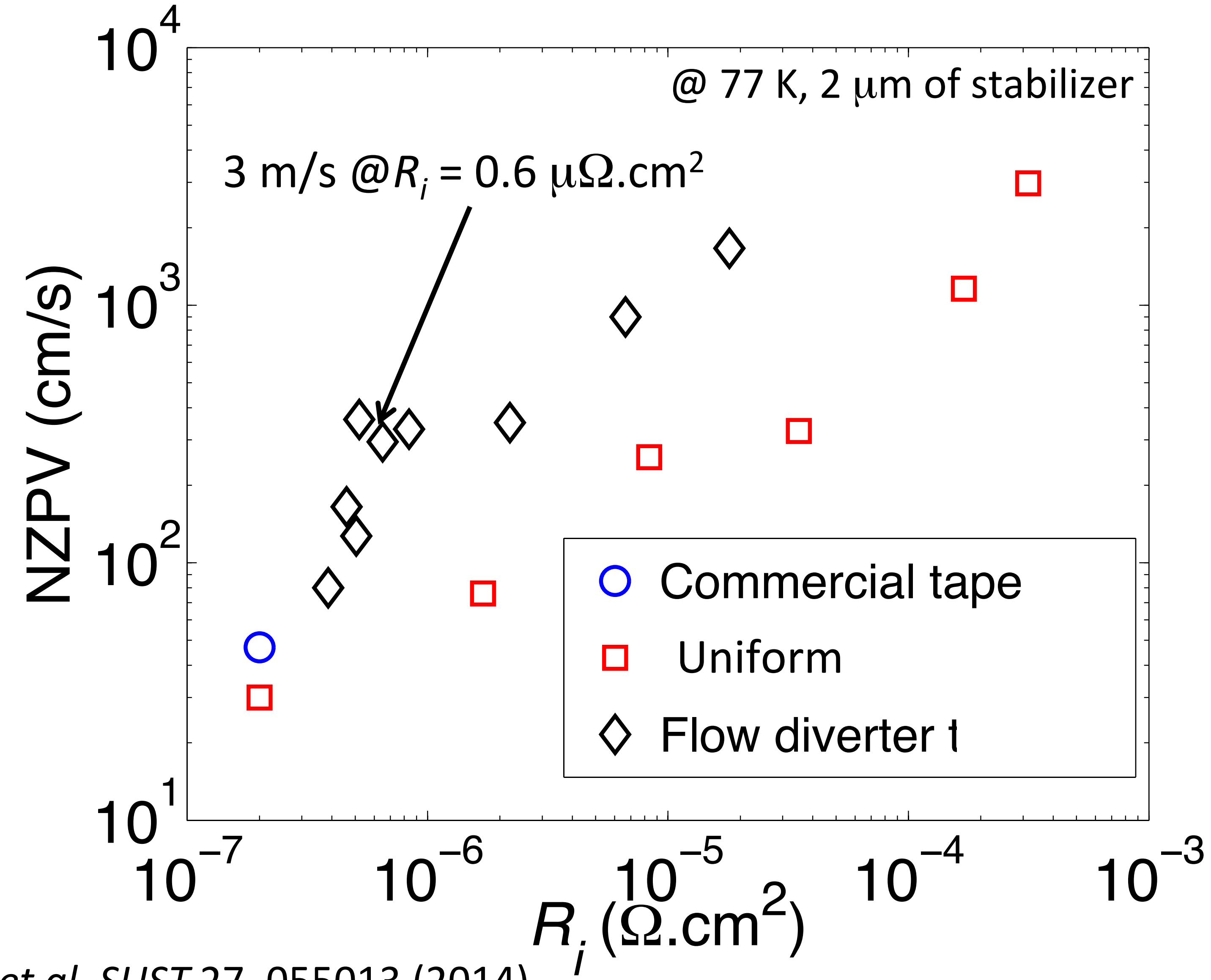


Need 3-D simulations
to observe this

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

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





@ 77 K, 2 μm of stabilizer

3 m/s @R_i = 0.6 μΩ.cm^2

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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 ?

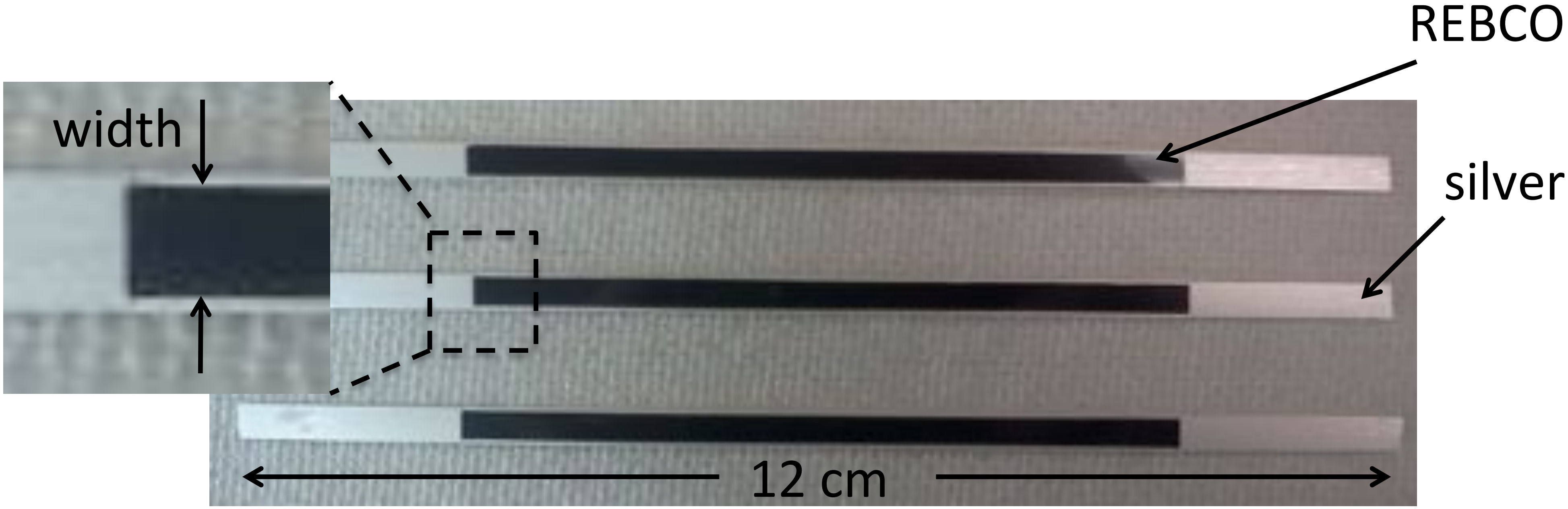
Questions about CFD

- **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 ?

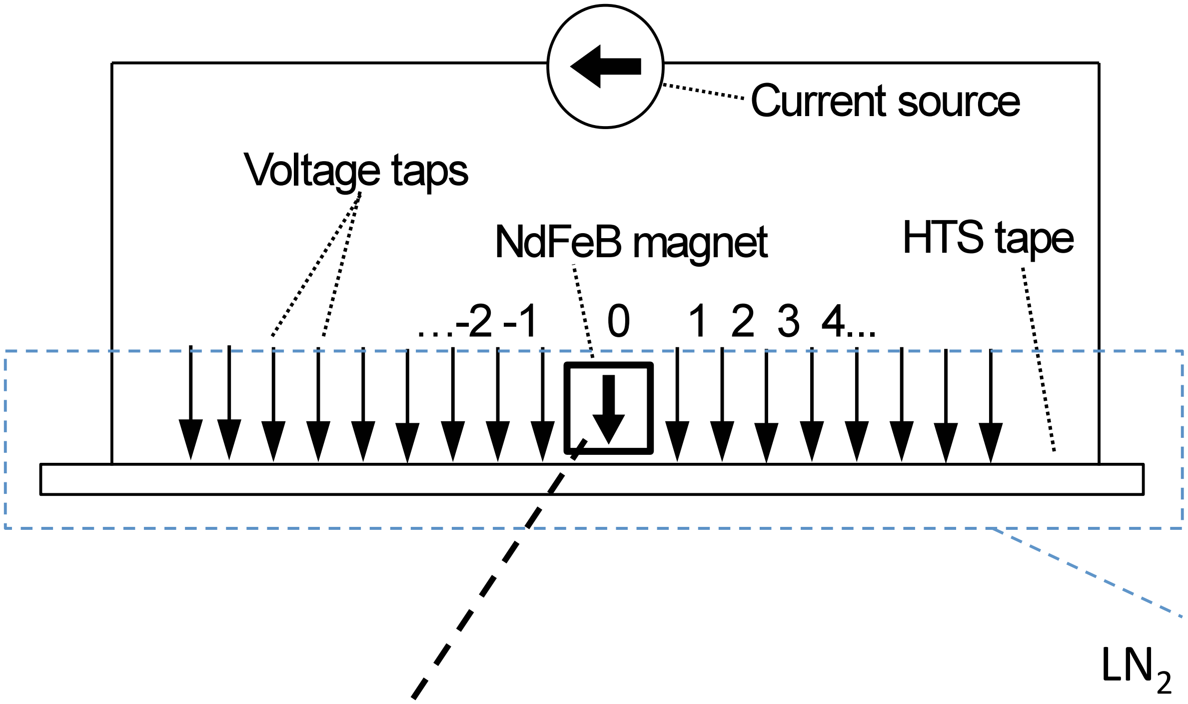
CFD tape fabrication

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



MQE measurements

- 4 mm wide 2G HTS CCs, I_c = 102 A @ 77K, 2 μm Ag
- Tapes 12 cm long with 2.8 mm (70 %) and 3.8 mm (95 %) wide CFDs were fabricated

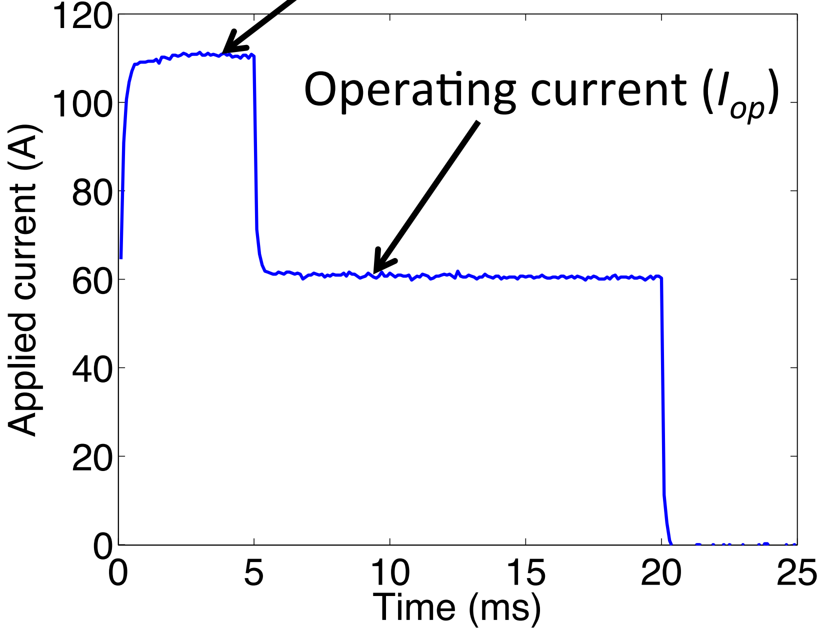


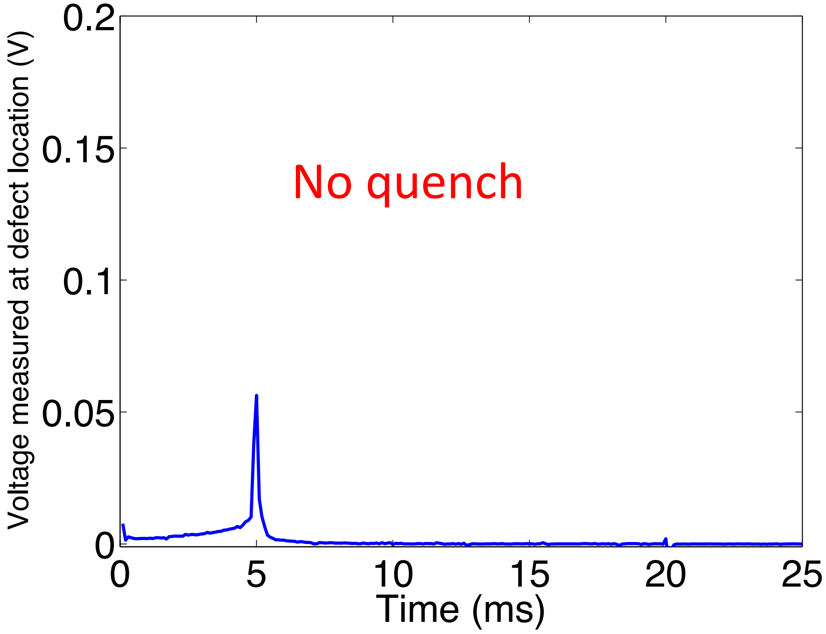
LN$_2$ bath

Magnet creates defect

MQE measurements

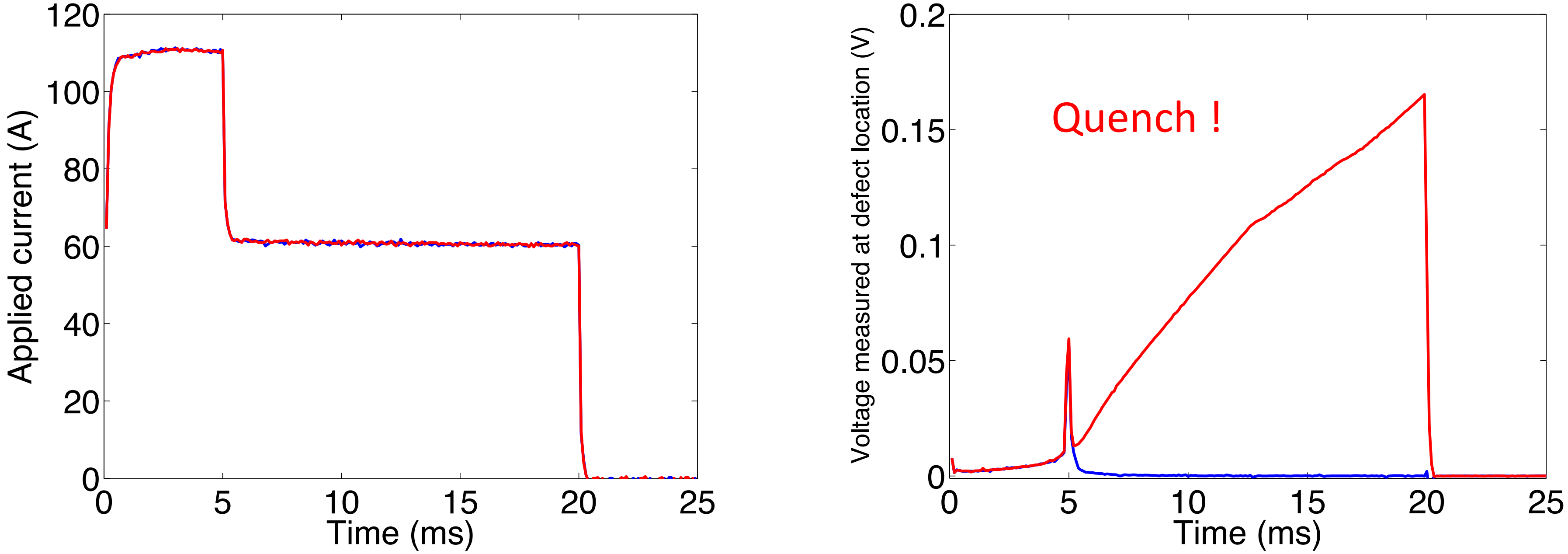
Overcurrent pulse generates heat at defect location





MQE measurements

A slight increase in overcurrent pulse induces the quench



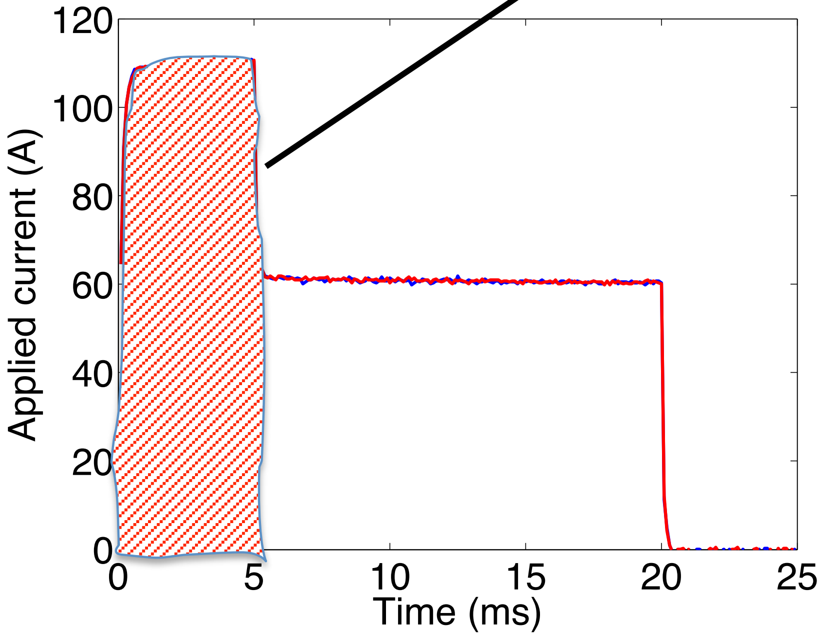
Quench !

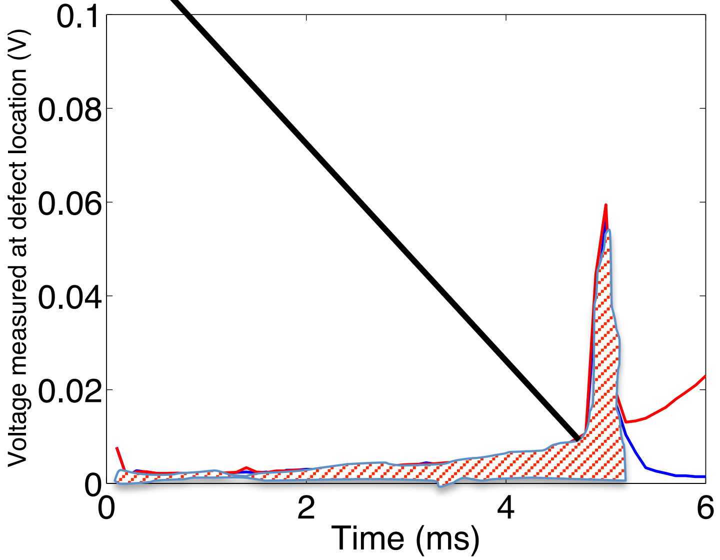
Several measurements back and forth across quench threshold were realized to determine the MQE[1]

[1] Jarvela *et al. IEEE Trans. Appl. Supercond.* 19, 3511 (2009)

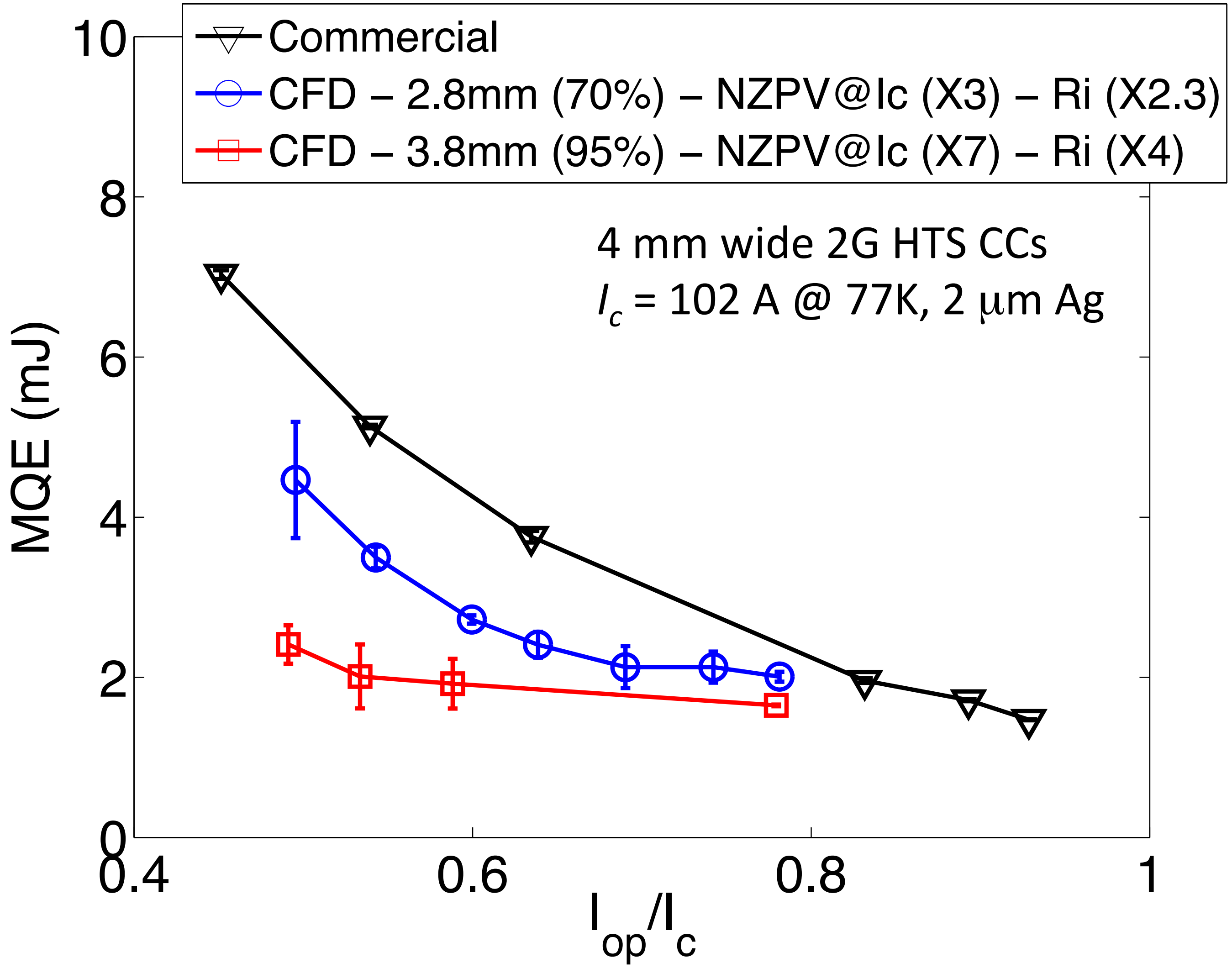
MQE measurements

Current x Voltage integrated over time = MQE (J)





Measurements of MQE vs I_{op}



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**

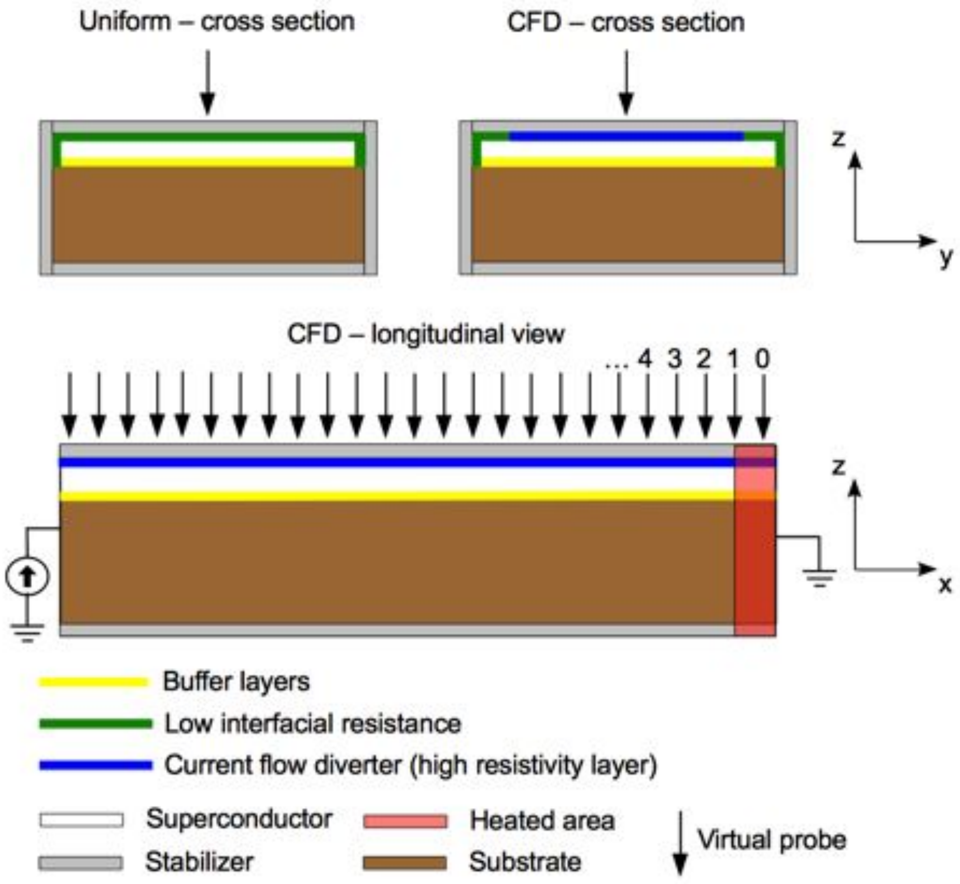
Finite element calculations[1]

- 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

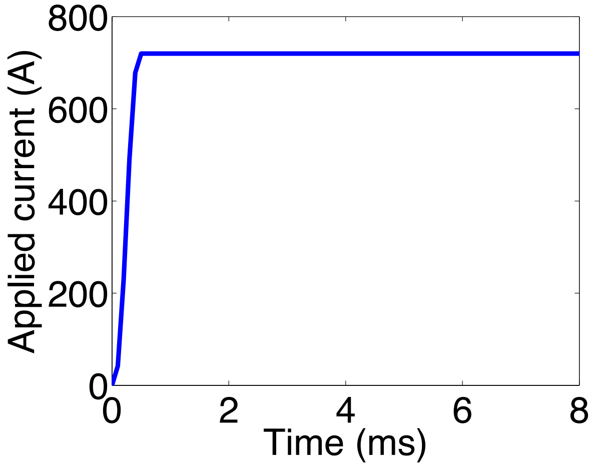
- Intrinsic HTS-Ag interfacial resistance = 100 nΩ.cm^2
- CFD interfacial resistance = 1 Ω.cm^2
- CFD coverage = 90% HTS-Ag interface

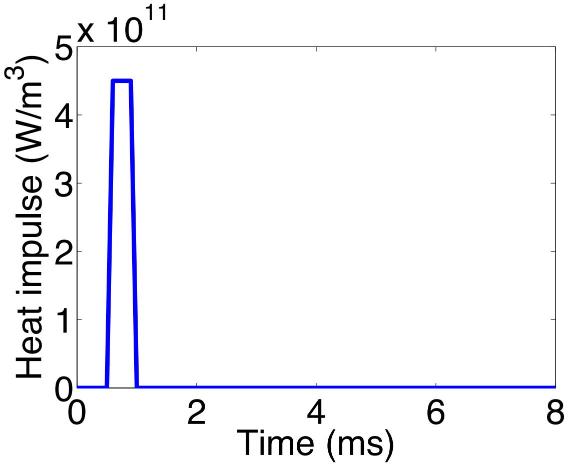


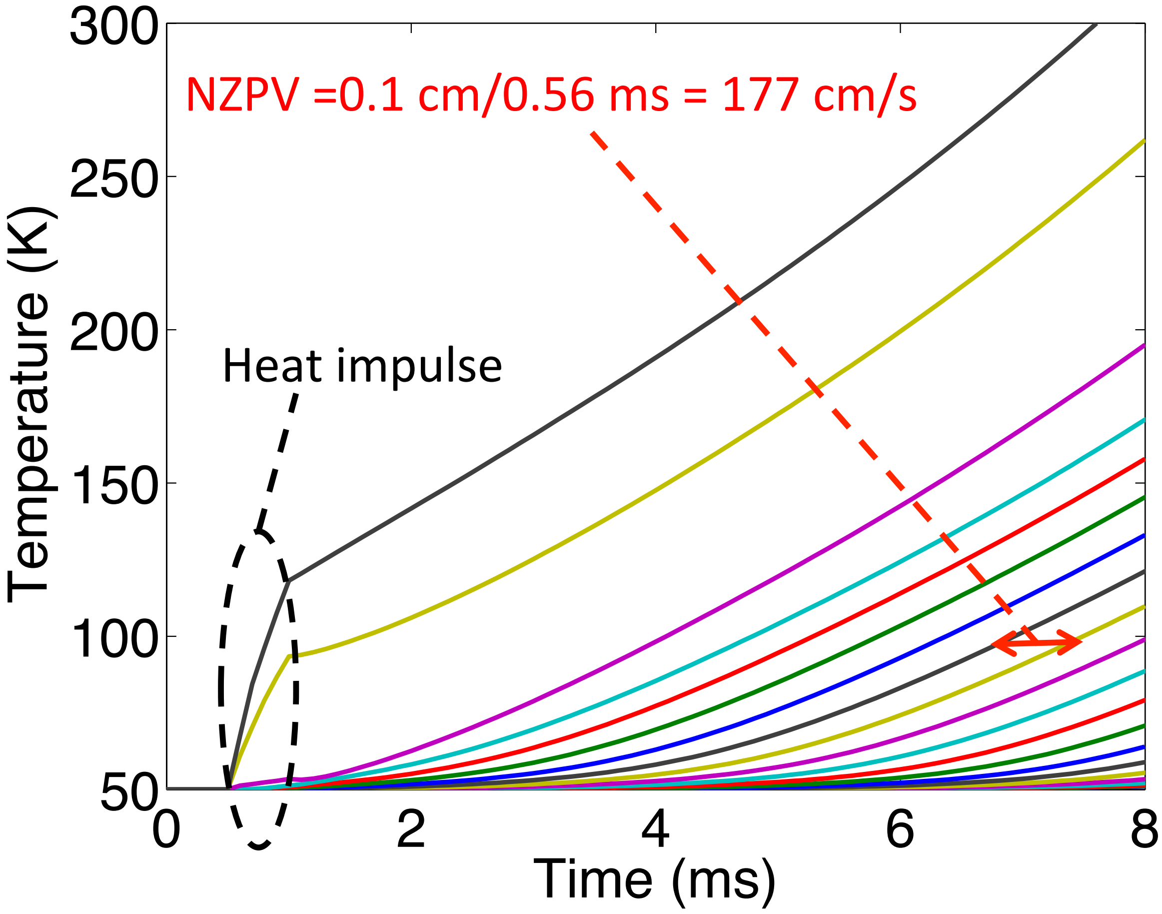
[1] Lacroix *et al.* *SUST* 27, 035003 (2014)

Example of results

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

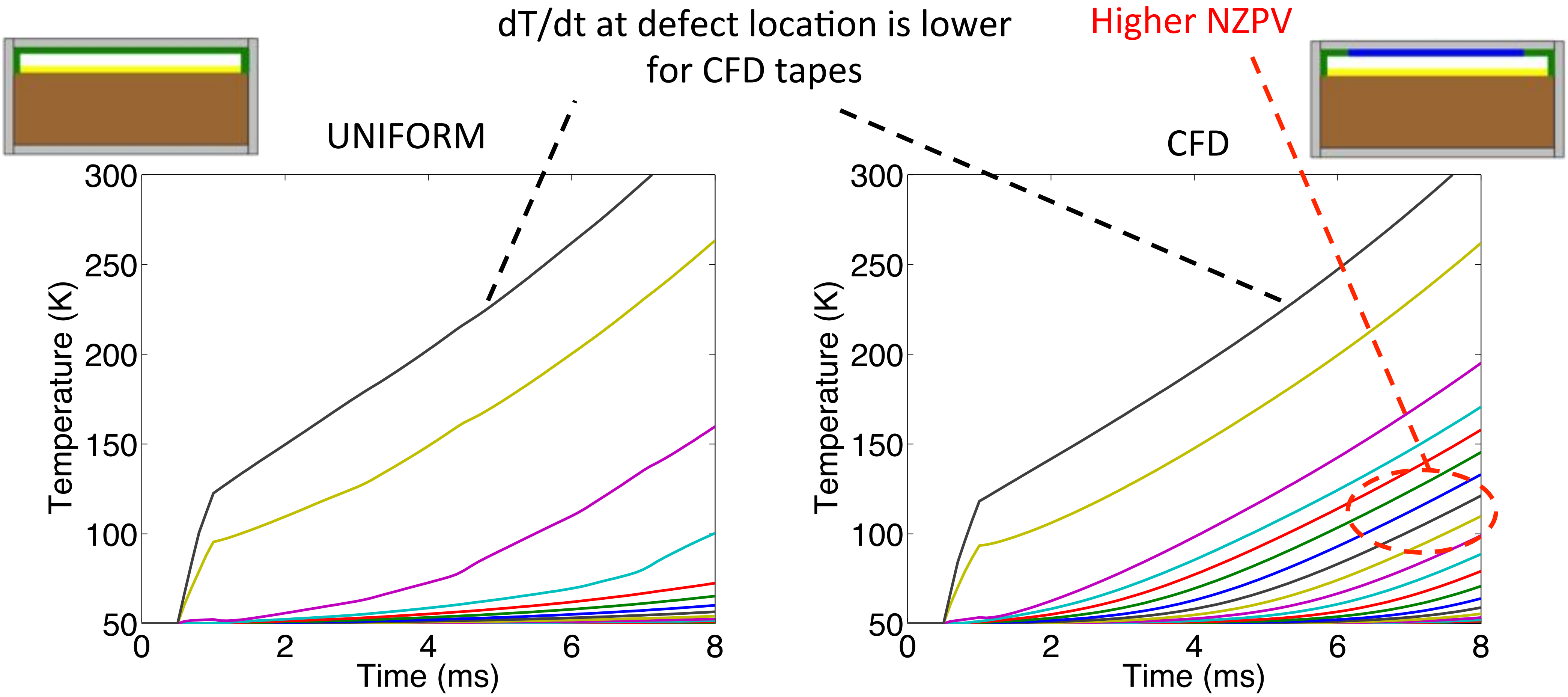






CFD vs. uniform tapes

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


dT/dt at defect location is lower for CFD tapes

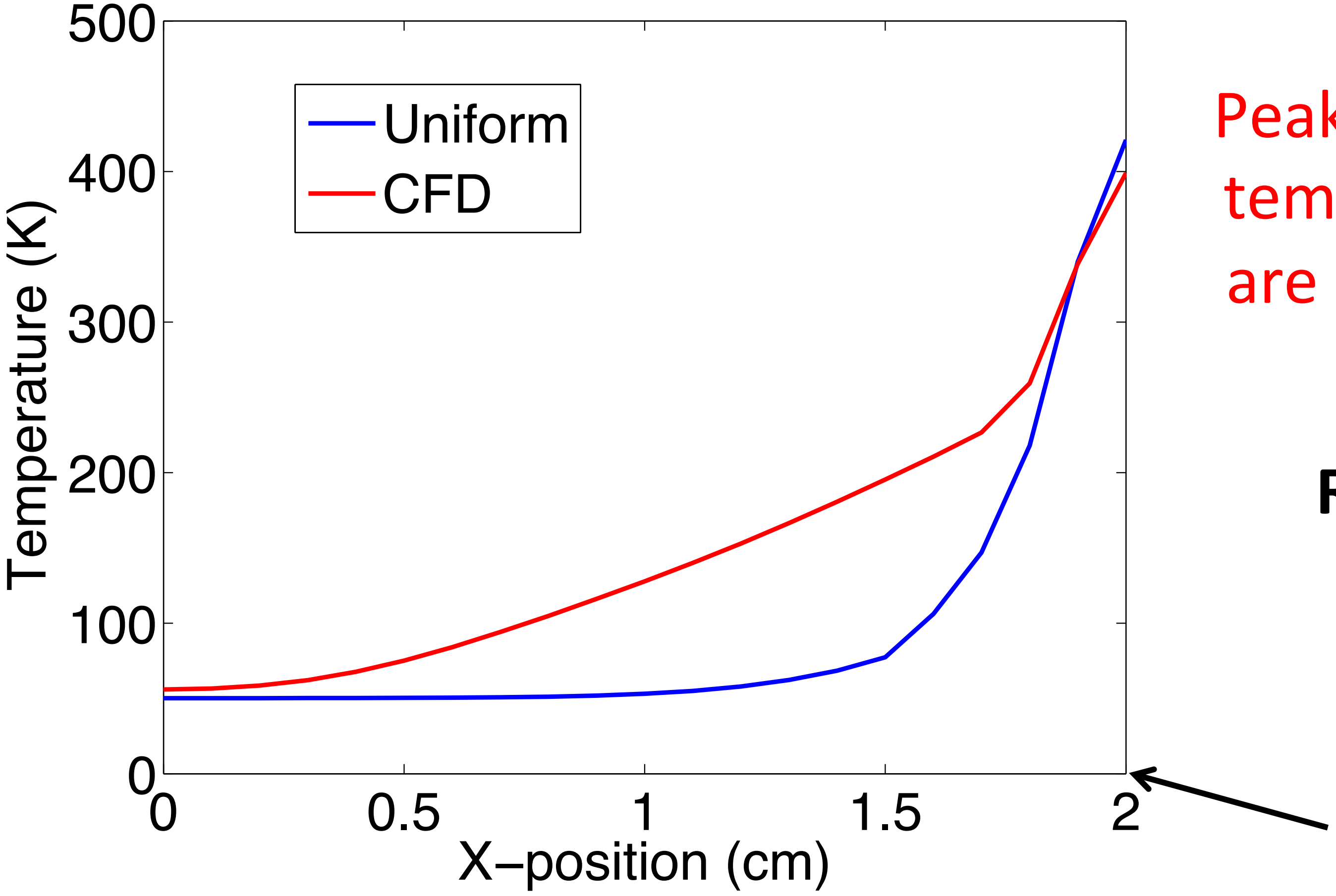
Higher NZPV

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



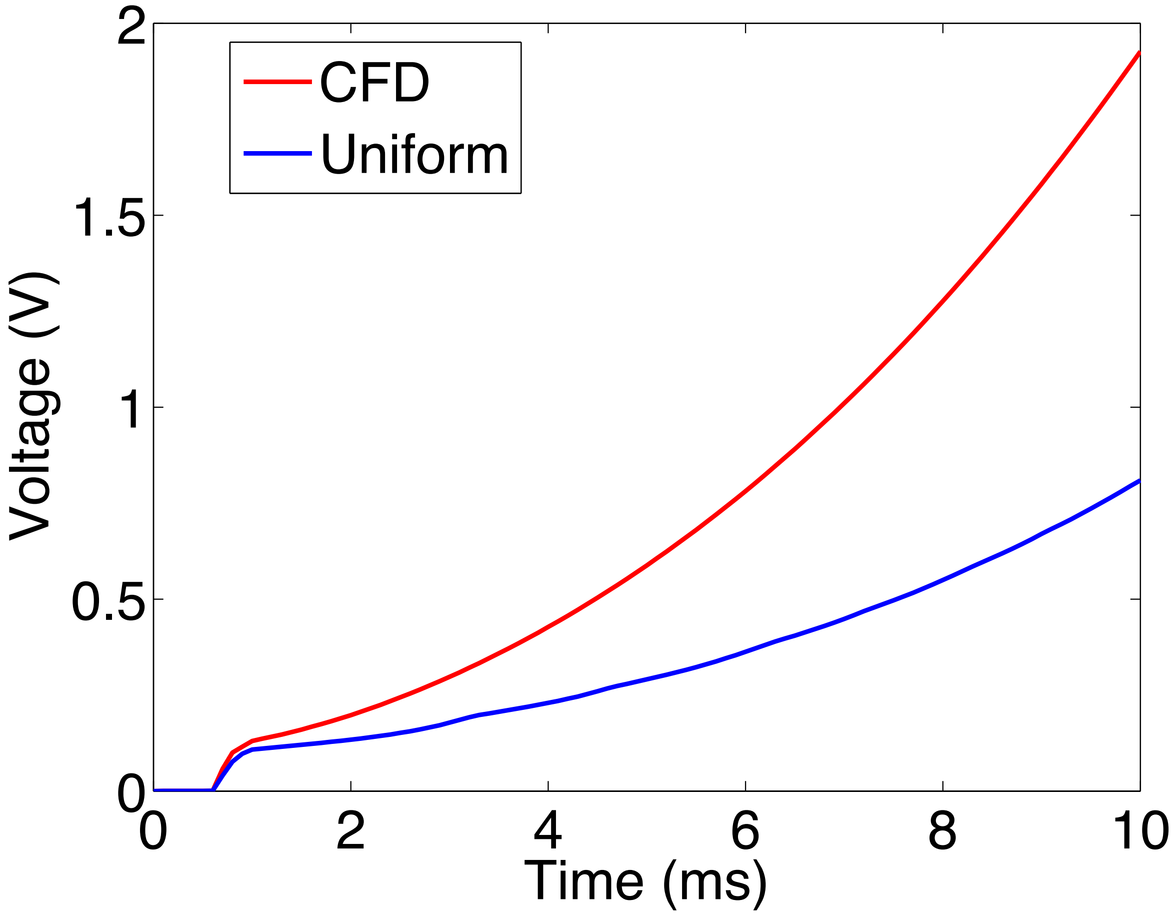
Peak temperature and temperature gradient are lower in CFD tape

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

Important for quench detection

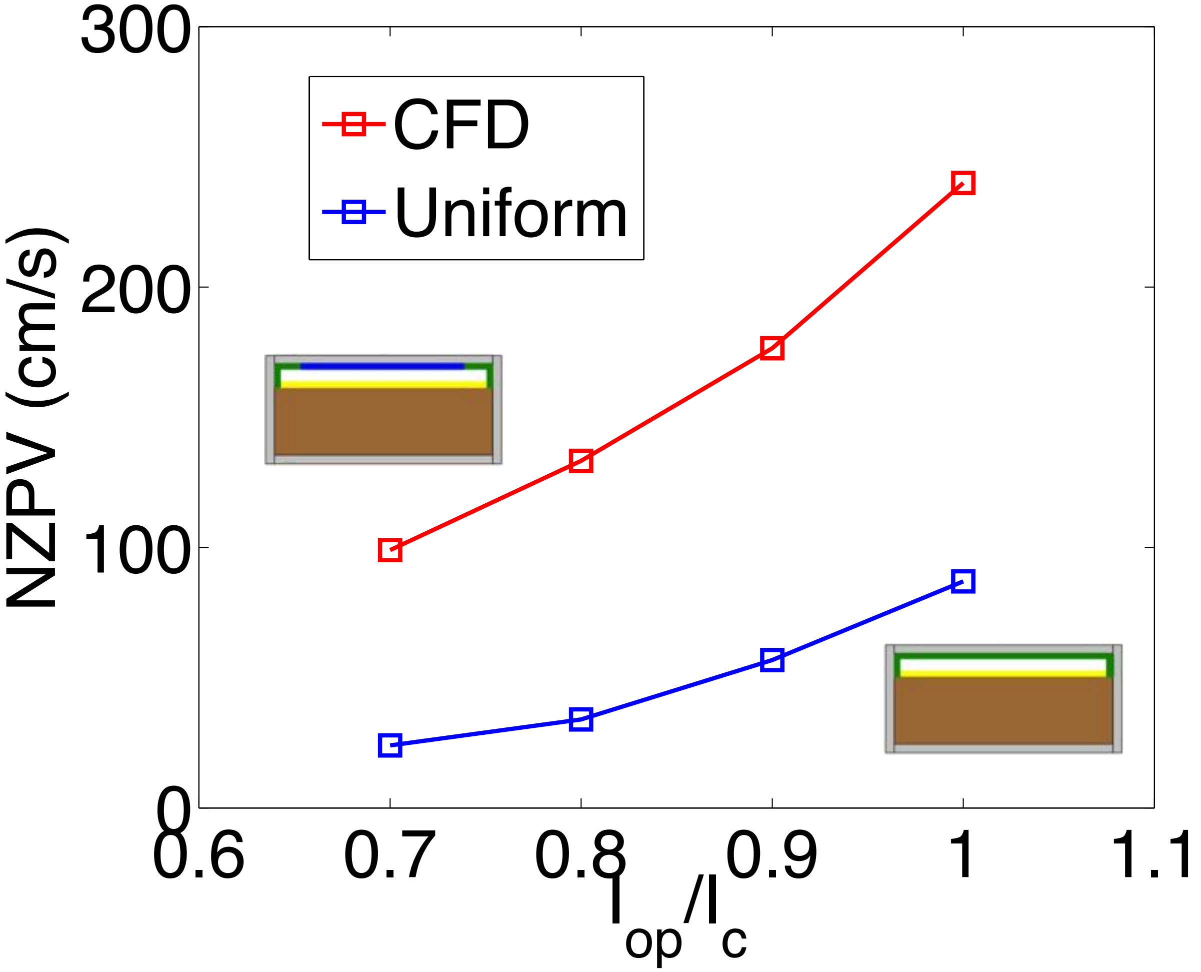
Questions about CFD

- 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 ?*

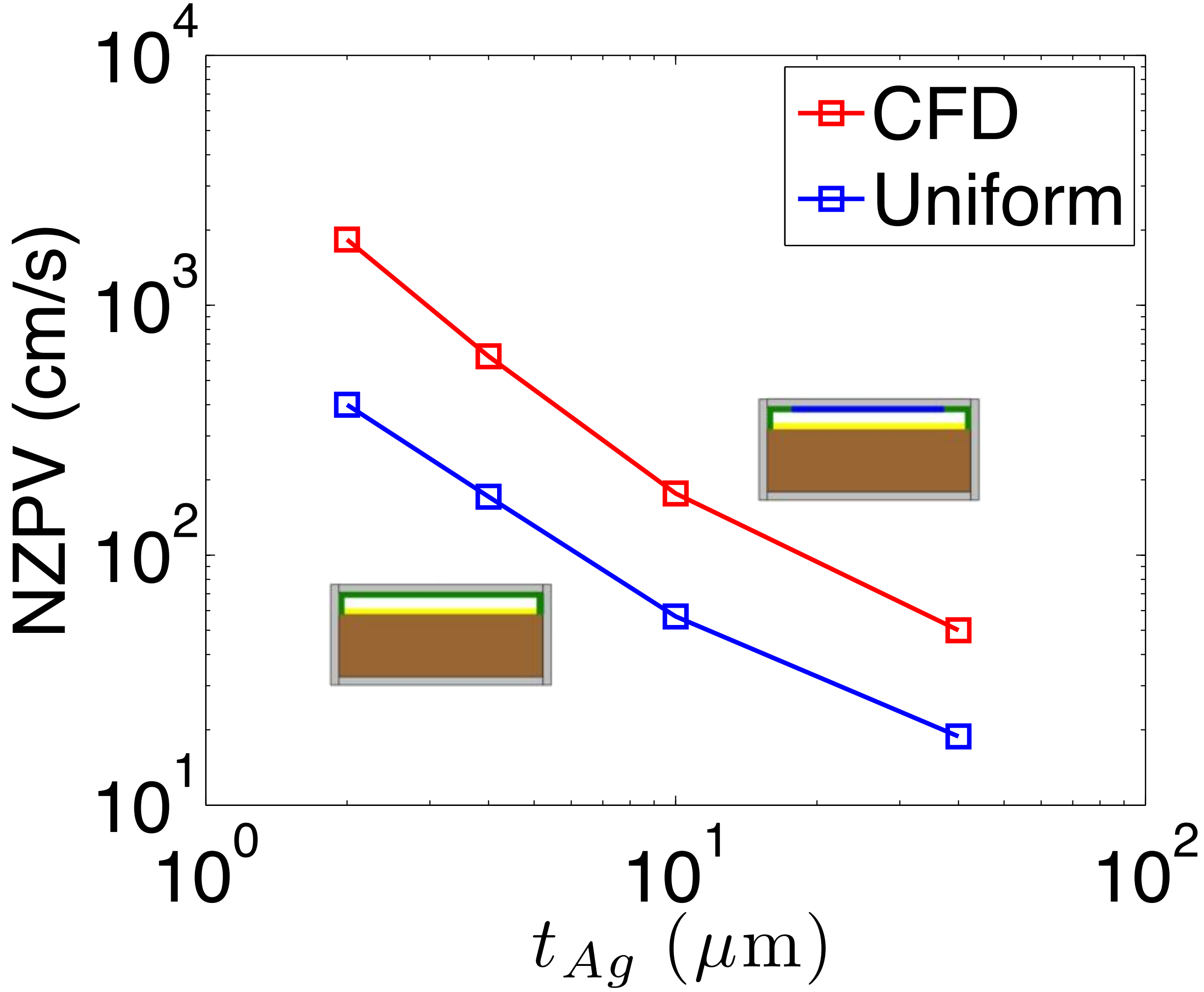
NZPV vs. operating current

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



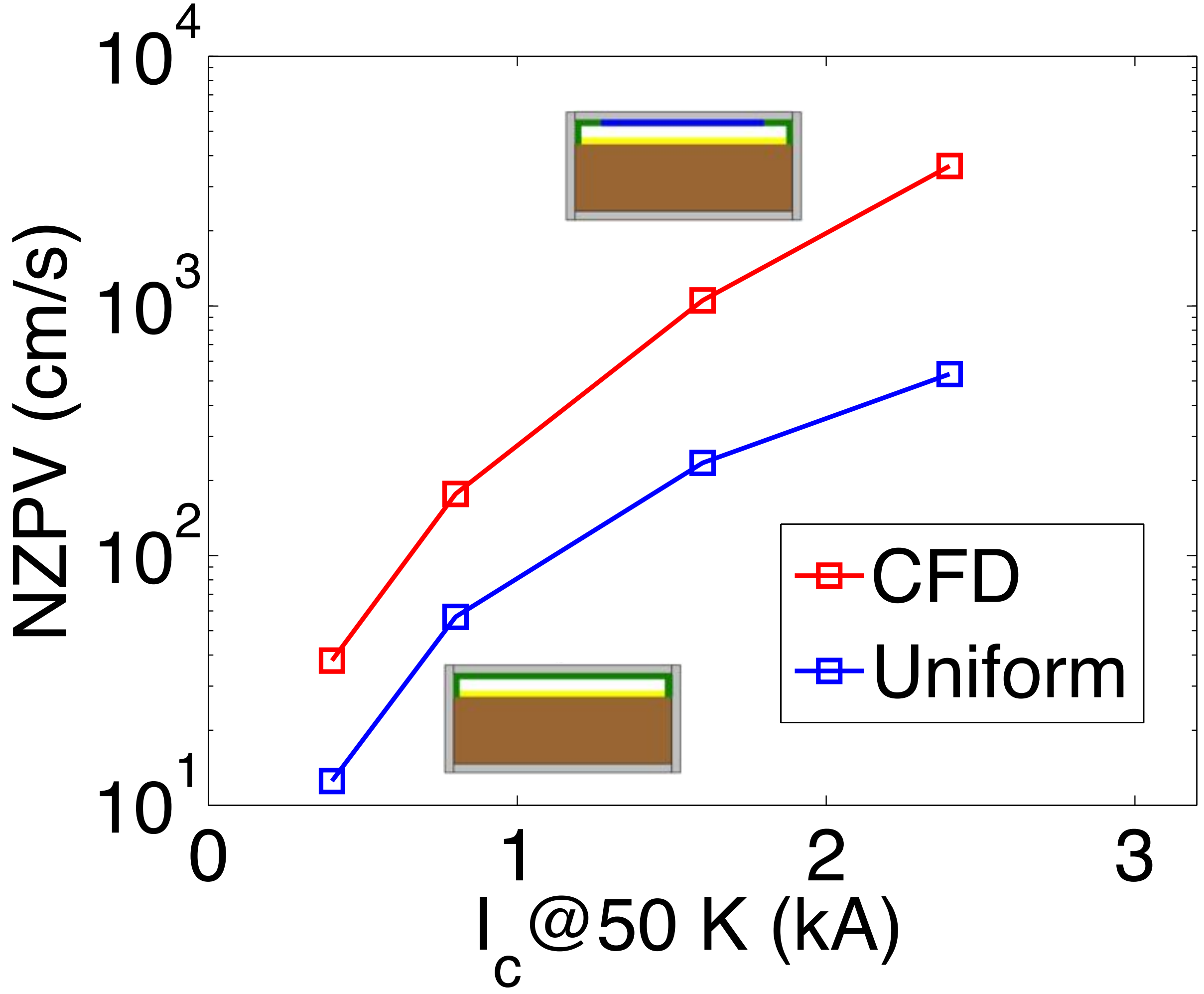
NZPV vs. stabilizer thickness

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



NZPV vs. critical current

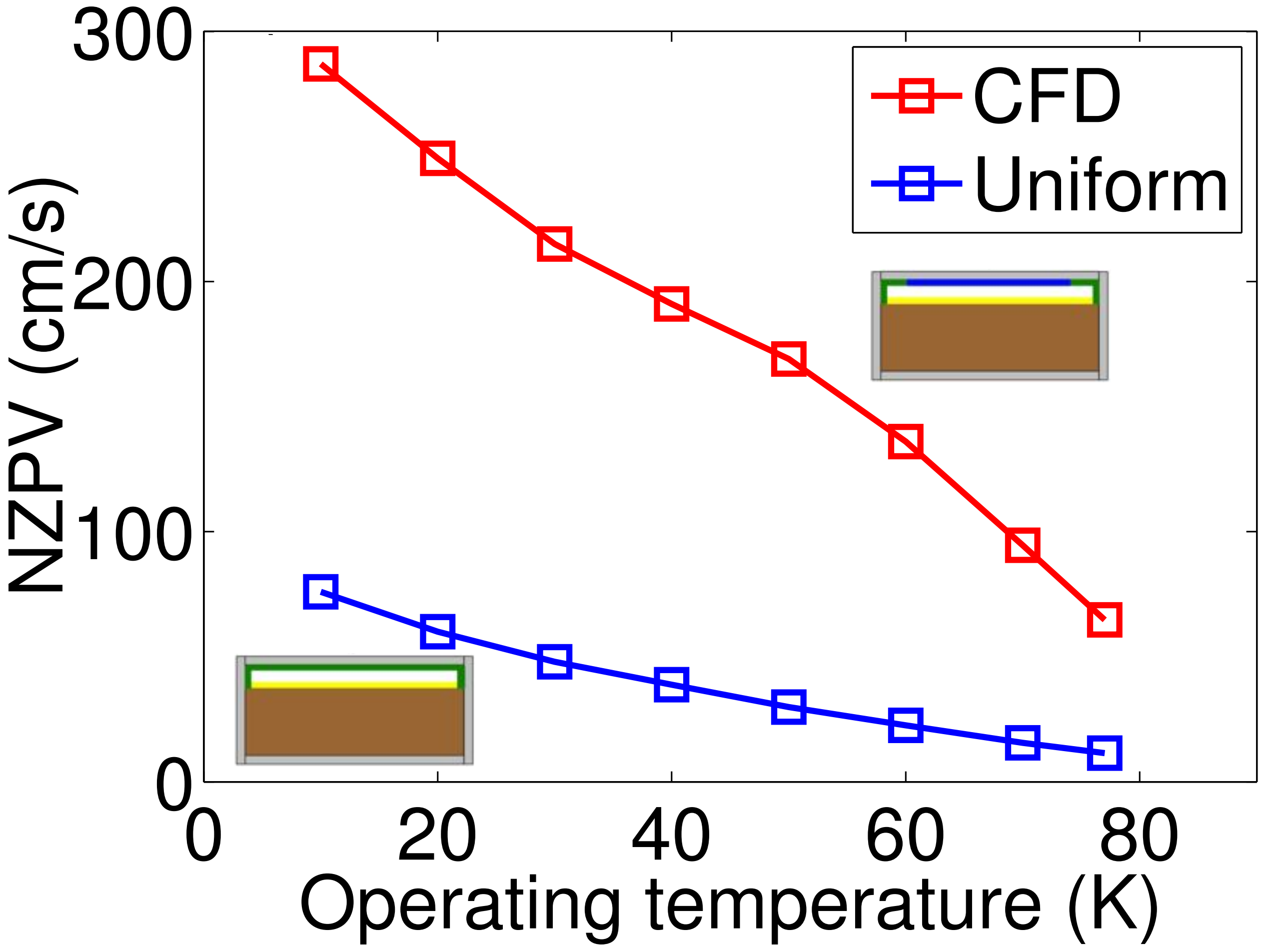
- $I_{op} = 0.9I_{c}$, $T_{op} = 50$ K, $t_{Ag} = 10$ μm



CFD architecture gets more efficient as I_c increases

NZPV vs. operating temperature

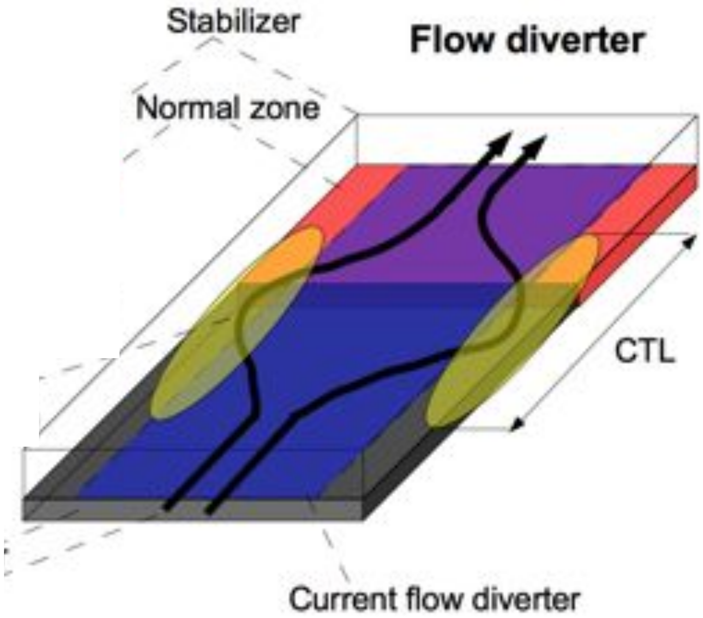
- $I_{op} = 0.9I_c$, I_c (50K) = 800 A, t_{Ag} = 10 μm



Processing feasibility of CFD tapes

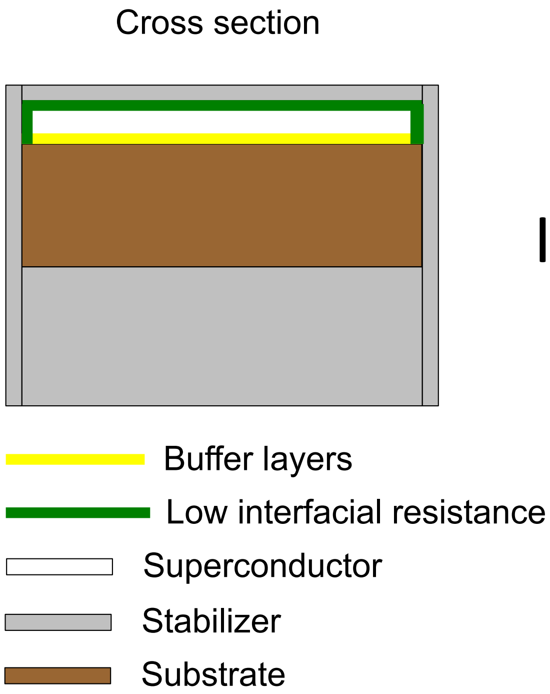
- **In few word: not so obvious!**
  - Patterning not easy to integrate in current processes
  - Uniform architecture much easier, but less effective
  - Needs further discussions with tape manufacturers
  - But in the short term…

(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 ➔ **<u>b-CFD architecture</u>**

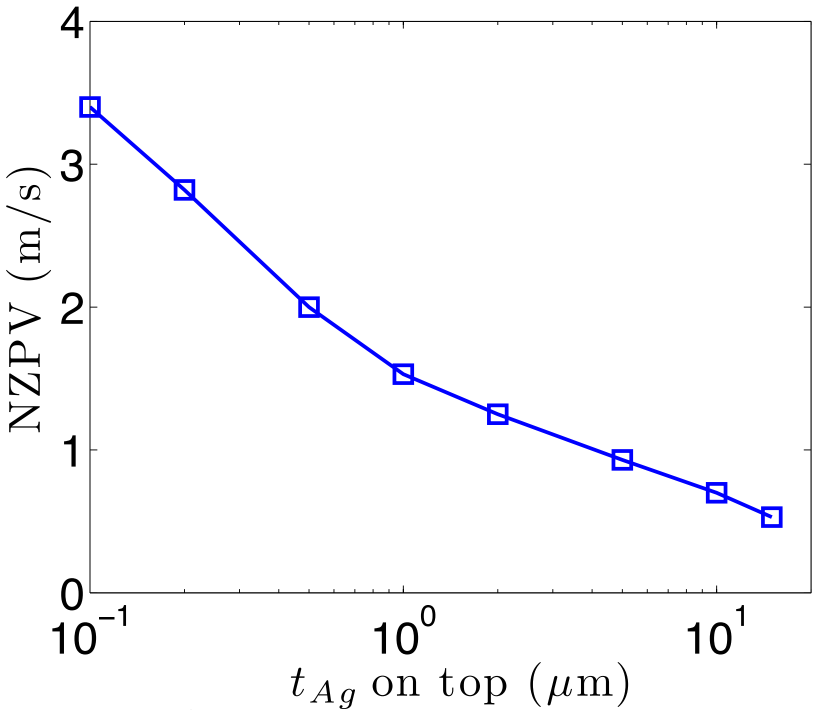


T_{op} = 10 K

I_c (10K) = 1.6 kA

$I_{op} = 0.9 I_c$

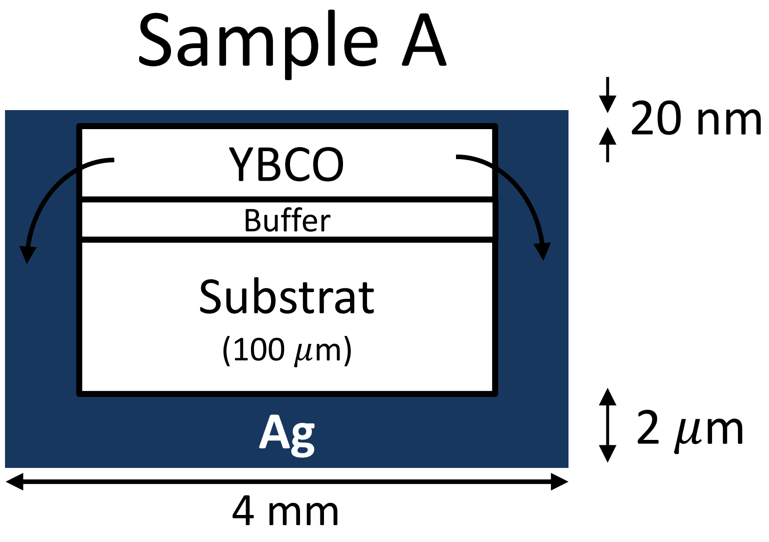
t_{ag} = 20 µm (total)

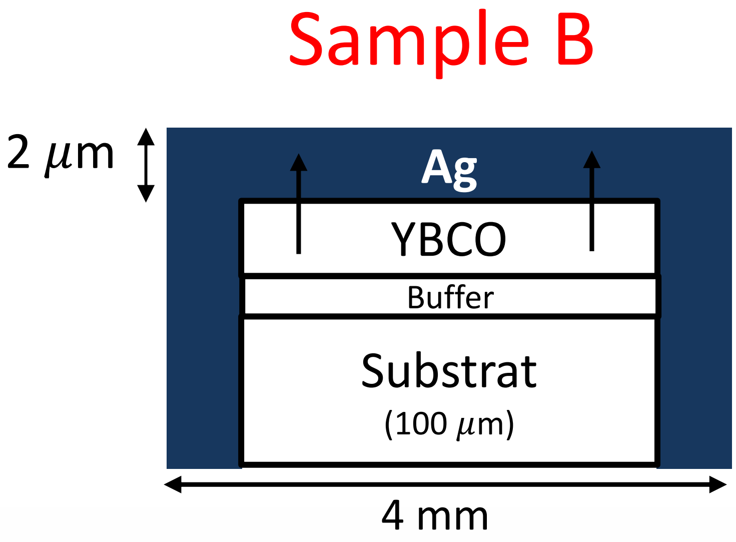


b-CFD architecture

- **First experiment on 4-mm modified STI tapes:**

T_{op} = 77 K, I_c (77 K) = 50-60 A, t_{ag} = 2 µm (total)





b-CFD architecture

Modified STI tapes:

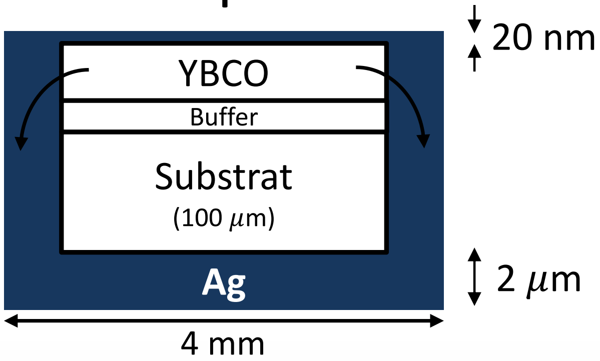
width = 4 mm

T_{op} = 77 K

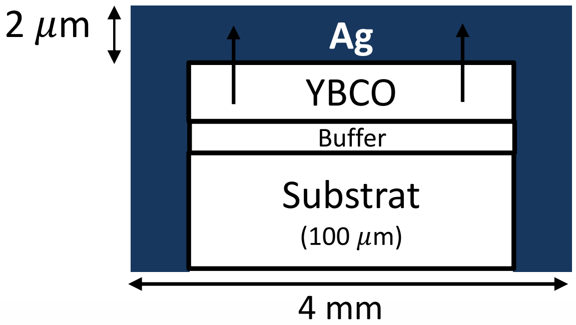
I_c (77 K) = 50-60 A

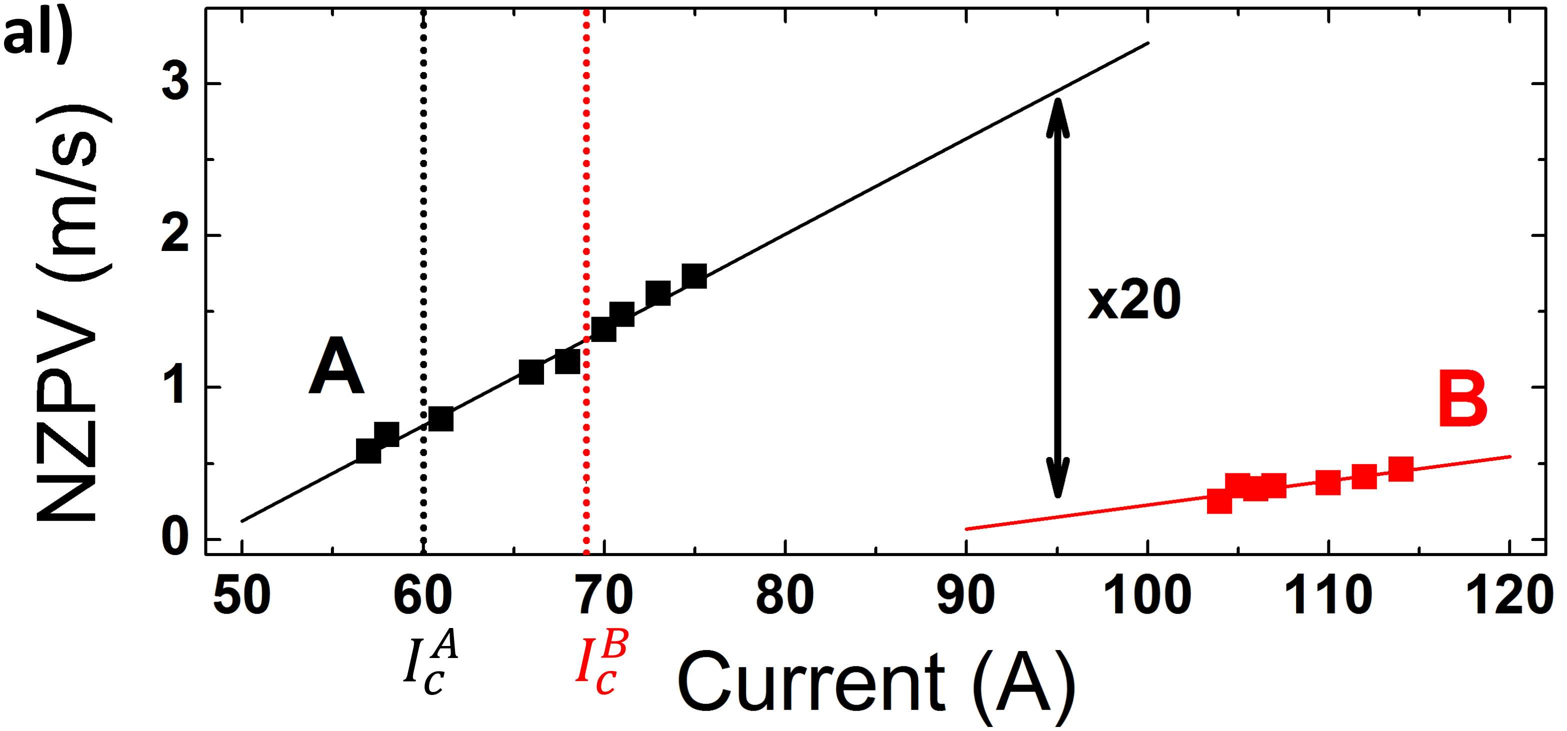
t_{ag} = 2 μm (total)

Sample A



Sample B

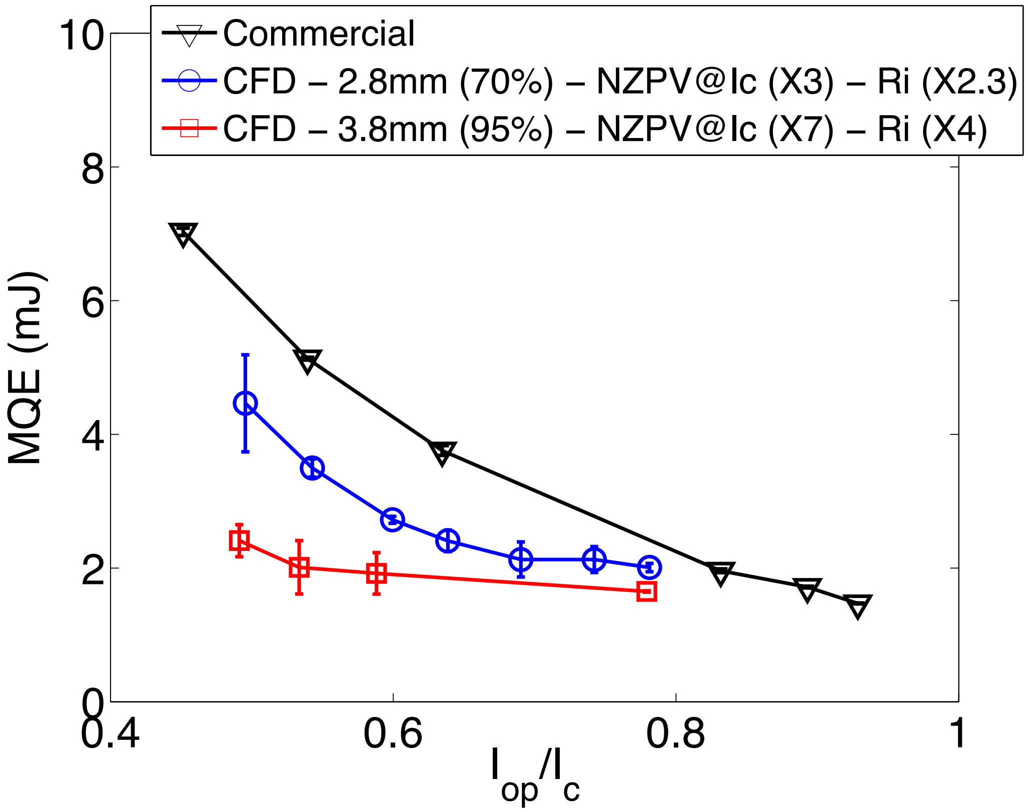




Summary

- **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)

[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} : **important for quench detection**
- Decreases dT/dx : **good for reducing thermal stress**

(FEM calculations)

…including low temperature

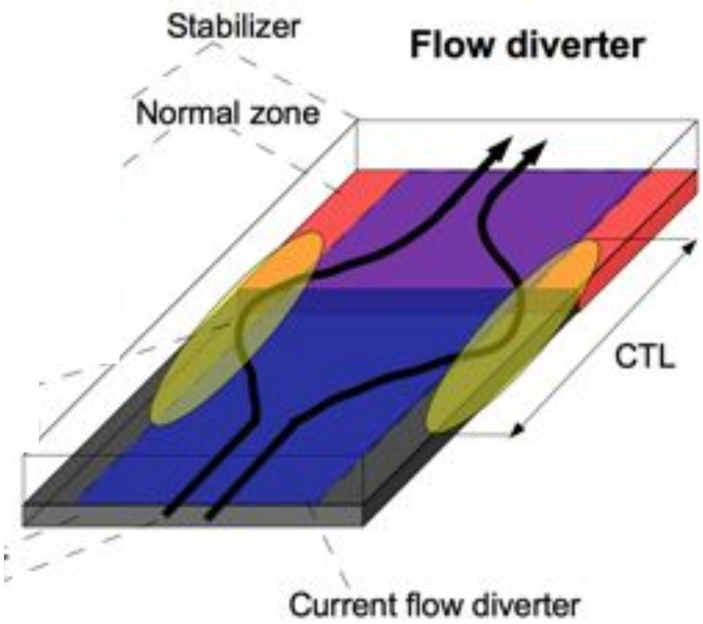
- CFD effective for all operating conditions and parameters
  - Acceleration of NZPV by a factor 10 and beyond
- **Effectiveness increases as I_c of CCs increases** : follows industry trend

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

Proved experimentally on small tape lengths

Benefits come in addition to progress in magnet quench protection strategies



Acknowledgments

Fonds de recherche
sur la nature
et les technologies
Québec

CRSNG
NSERC

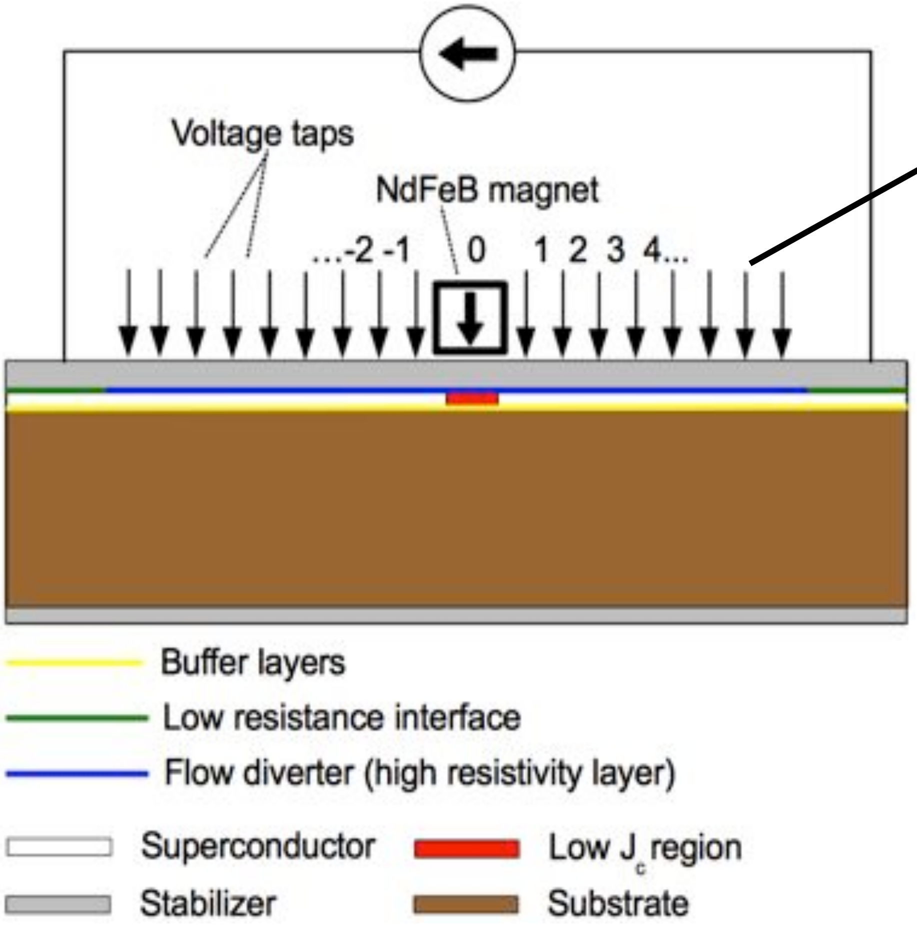
N. Veerabadren

M. R. Wertheimer

POLYTECHNIQUE
MONTRÉAL

WORLD-CLASS
ENGINEERING

Appendix: NZPV measurements



Distance
between taps =
2.5 mm