Integrated Electro-Thermal Model for Quench Simulation in YBCO Tapes.

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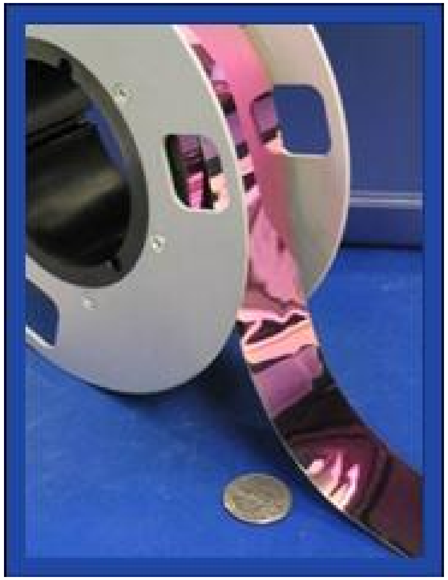
Outline

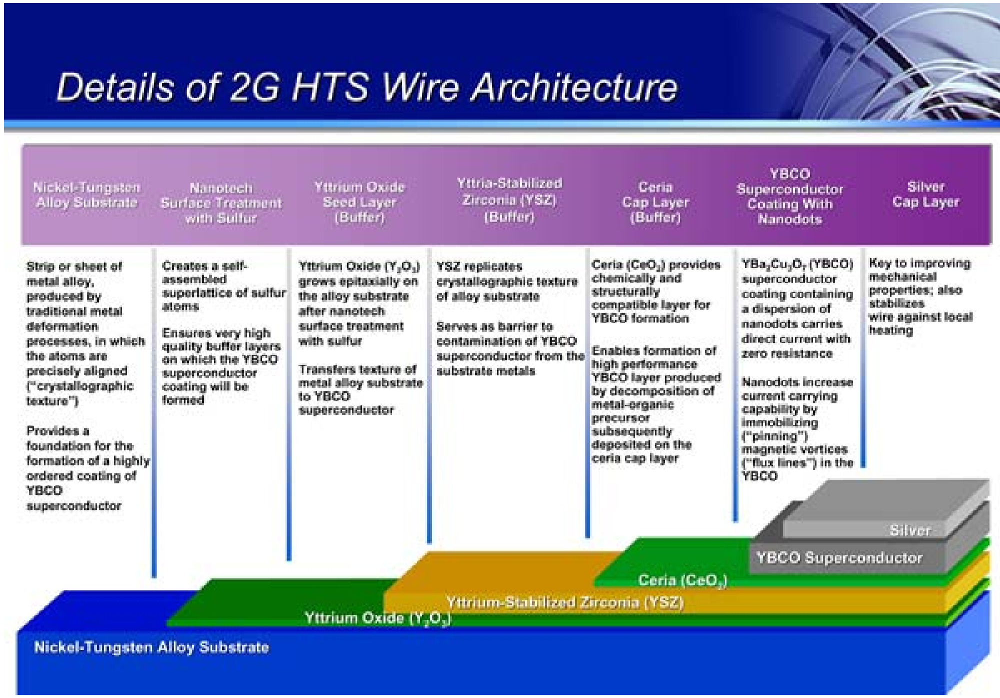
- Tape configurations and physical properties
- Problem statement
- Quench process in YBCO 2G conductors
- Existing models in the literature and their limitations
- Effect of current diffusion on quench dynamic
- From tape to device quench modelling
- Key parameters
- Proposed improved model
- Preliminary qualitative results and future work

American Superconductor - Tape Configurations

American Superconductor 344 - Copper-stabilized second generation HTS wire
0.2 mm * 4.35 mm
70 A @77K (minimum)

American Superconductor S344 - Stainless steel-stabilized second generation HTS wire
0.150 mm * 4.33 mm
60 A @77K (minimum)





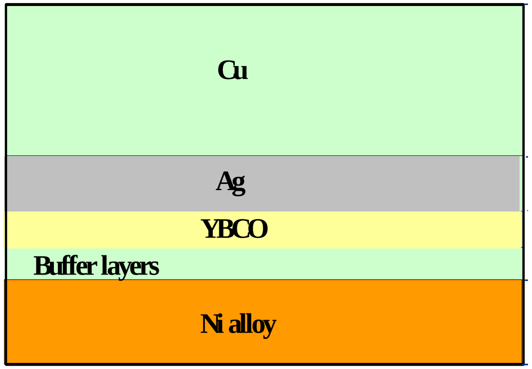
Details of 2G HTS Wire Architecture

Nickel-Tungsten Alloy Substrate	Nanotech Surface Treatment with Sulfur	Yttrium Oxide Seed Layer (Buffer)	Yttria-Stabilized Zirconia (YSZ) (Buffer)	Ceria Cap Layer (Buffer)	YBCO Superconductor Coating With Nanodots	Silver Cap Layer
Strip or sheet of metal alloy, produced by traditional metal deformation processes, in which the atoms are precisely aligned ("crystallographic texture") Provides a foundation for the formation of a highly ordered coating of YBCO superconductor	Creates a self-assembled superlattice of sulfur atoms Ensures very high quality buffer layers on which the YBCO superconductor coating will be formed	Yttrium Oxide (Y_2O_3) grows epitaxially on the alloy substrate after nanotech surface treatment with sulfur Transfers texture of metal alloy substrate to YBCO superconductor	YSZ replicates crystallographic texture of alloy substrate Serves as barrier to contamination of YBCO superconductor from the substrate metals	Ceria (CeO_2) provides chemically and structurally compatible layer for YBCO formation Enables formation of high performance YBCO layer produced by decomposition of metal-organic precursor subsequently deposited on the ceria cap layer	$YBa_2Cu_3O_7$ (YBCO) superconductor coating containing a dispersion of nanodots carries direct current with zero resistance Nanodots increase current carrying capability by immobilizing ("pinning") magnetic vortices ("flux lines") in the YBCO	Key to improving mechanical properties; also stabilizes wire against local heating

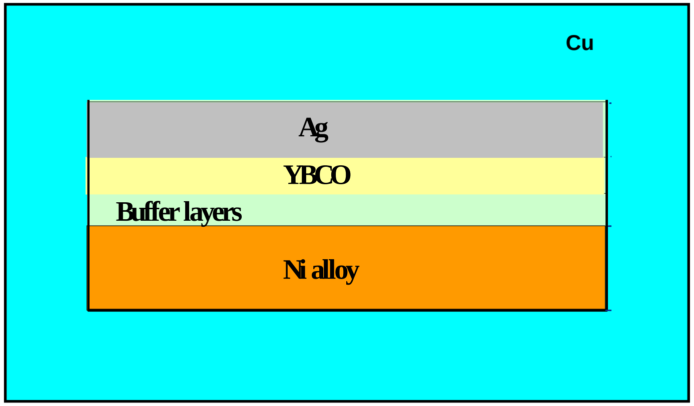
- Multi-layer configuration
- Physical properties strongly dependant on temperature

Other Configurations

- Major manufacturers are American Superconductor, Sumitomo, EHTS, THEVA
- All have different configurations in terms of:
  - Layer thickness
  - Stabilization layer
  - Current density
- Maximum length achieved is 322 m by Sumitomo

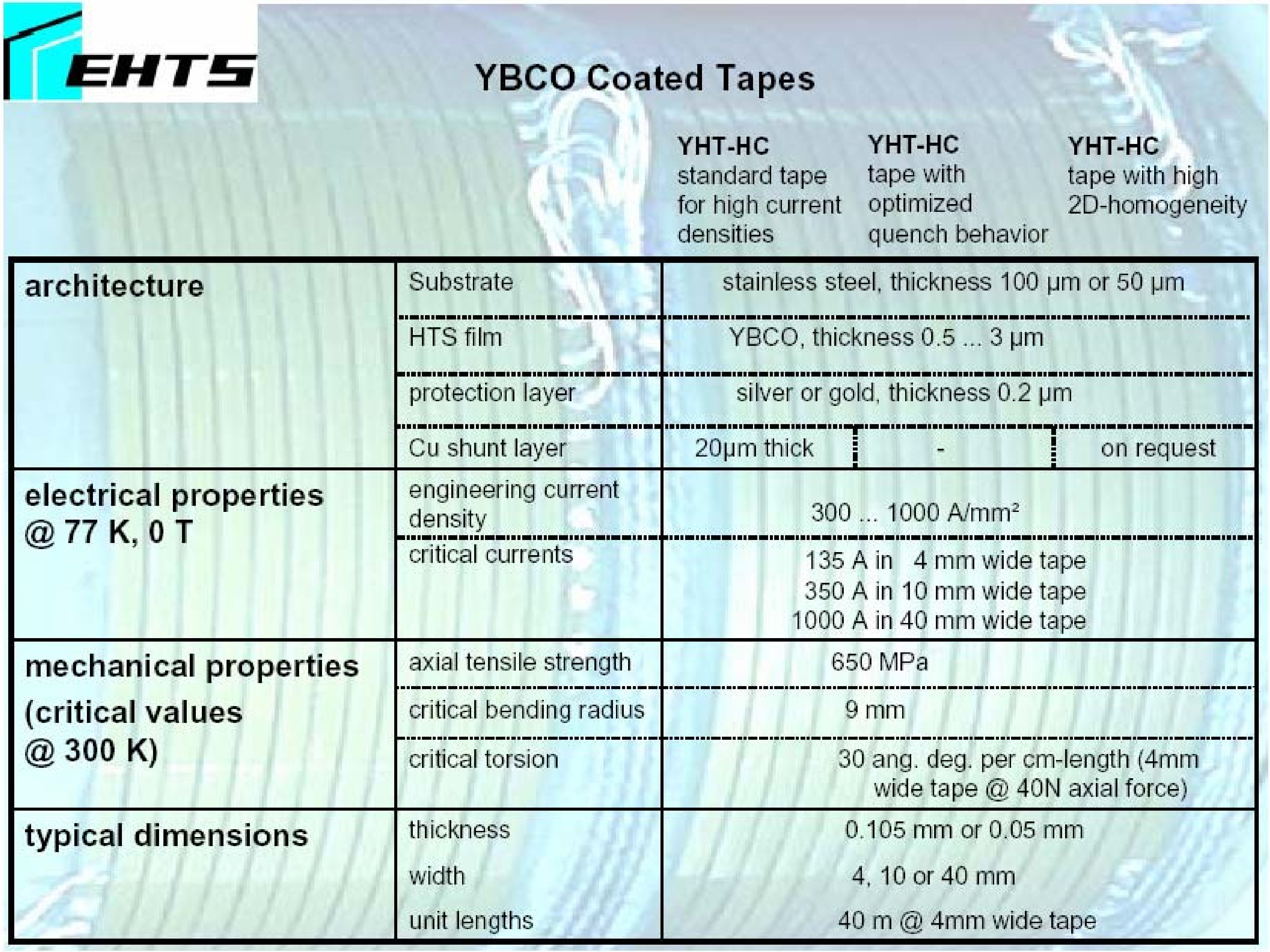


typical configuration 1



Typical configuration 2

EHTS Tapes Available



EHTS

YBCO Coated Tapes

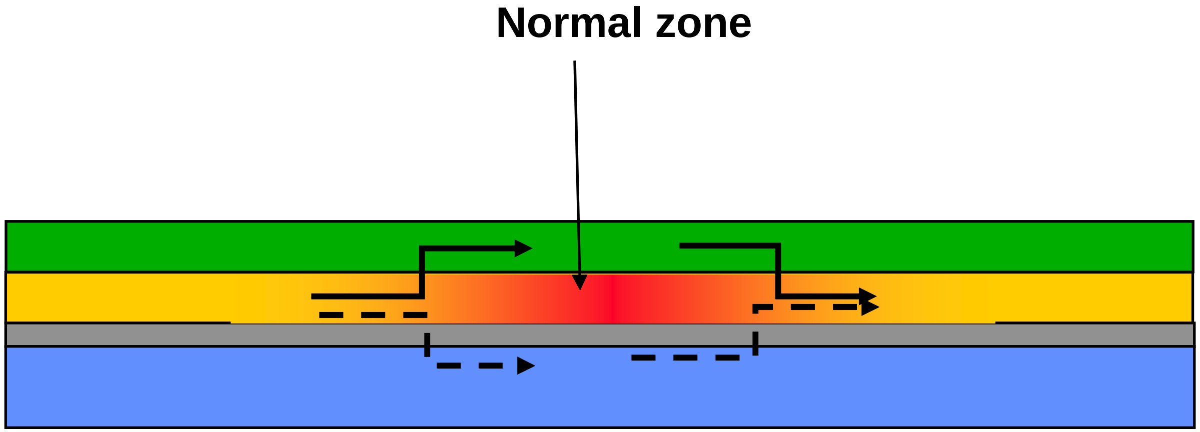
		YHT-HC standard tape for high current densities	**YHT-HC** tape with optimized quench behavior	**YHT-HC** tape with high 2D-homogeneity
architecture	Substrate	stainless steel, thickness 100 µm or 50 µm		
	HTS film	YBCO, thickness 0.5 ... 3 µm		
	protection layer	silver or gold, thickness 0.2 µm		
	Cu shunt layer	20µm thick	-	on request
electrical properties @ 77 K, 0 T	engineering current density	300 ... 1000 A/mm²		
	critical currents	135 A in 4 mm wide tape 350 A in 10 mm wide tape 1000 A in 40 mm wide tape		
mechanical properties (critical values @ 300 K)	axial tensile strength	650 MPa		
	critical bending radius	9 mm		
	critical torsion	30 ang. deg. per cm-length (4mm wide tape @ 40N axial force)		
typical dimensions	thickness	0.105 mm or 0.05 mm		
	width	4, 10 or 40 mm		
	unit lengths	40 m @ 4mm wide tape		

The Problem

- Why is quench a problem in 2G wires?
  - Normal zone propagation velocity too slow 1-10 mm/s
  - Hot spot T could be very high and destructive
  - Non uniformity of material properties
  - Not yet well understood

- Stabilization and quench protection are VERY important
  - Quench development appears to be a 3D phenomenon from experiment (because it is so slow that turn to turn diffusion matters)
  - Need 3D simulation tool to analyze quench and develop protection schemes

Problem: quench propagation in 2G tapes



Buffer is highly resistive: how much current goes into Ni layer?

Existing Models

- Chyu – Oberly – first study (1990)
- Iwasa – 1D steady state
- Fu – 1D lumped circuit – no magnetic coupling
- Ishiyama – 1D current sharing
- Iwasa – copper stabilized
- Vysotsky – scaling theory

Existing Models (2)

- Stadel – electrical field distribution due to hot spot
- No electrical breakdown to be expected

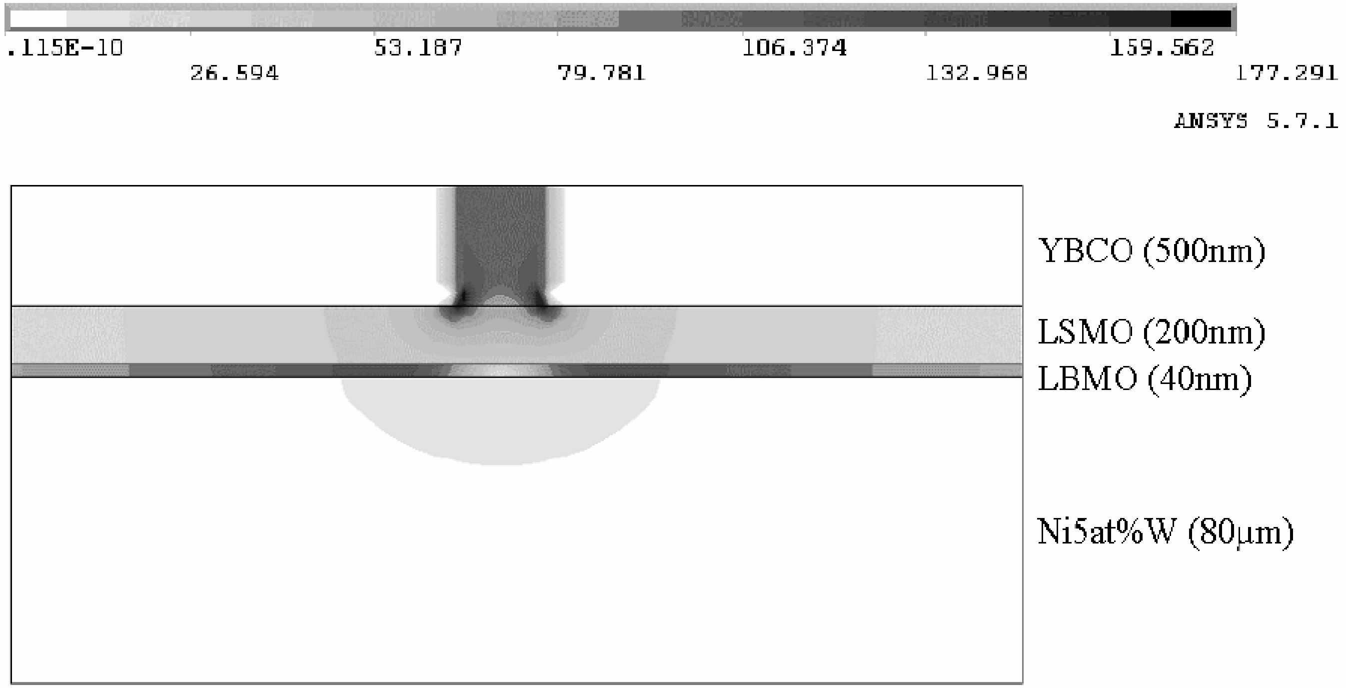


Figure 1. Cut-Out of simulated allocation of the electrical field in the model. The dimension of the electrical field is given in V/m.

Existing Models (3) : 1-D PDE

$$C_{avg}(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q_j - Q_c$$

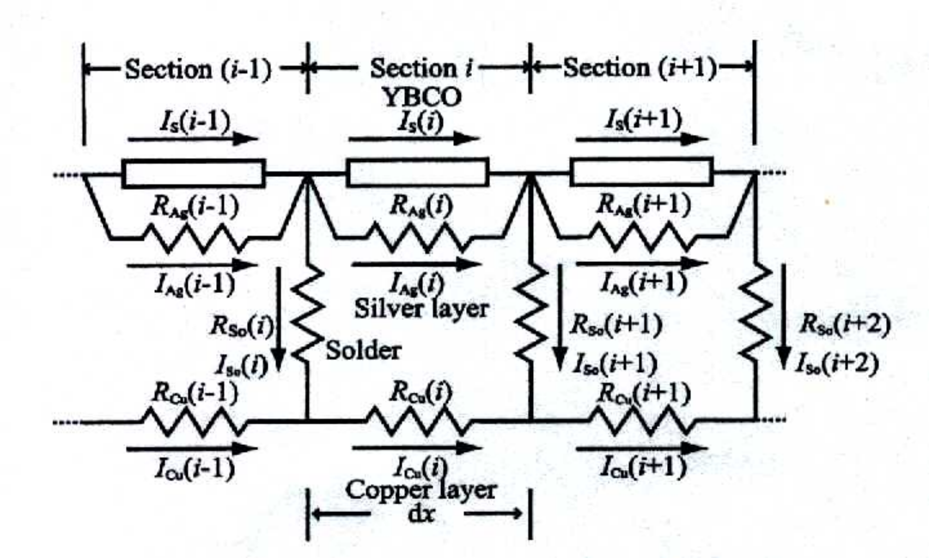
$$Q_j = \begin{cases} 0 & I < I_c \\ \left(\frac{\rho}{A}\right)_m \frac{I}{A_t} I_m(T) & T < T_c,\, I > I_c \\ \left(\frac{\rho}{A}\right)_m \frac{I^2}{A_t} & T > T_c \end{cases}$$

- One dimensional model
- Temperature uniform across the tape
- Nickel and silver in parallel
- Simple formula for the joule loss

- OR. C. Duckworth et al., “Quench dynamics in silver coated YBCO tapes”, Proc. ICMC, Vol. 48, 2002

Existing Models (4) : Electrical network

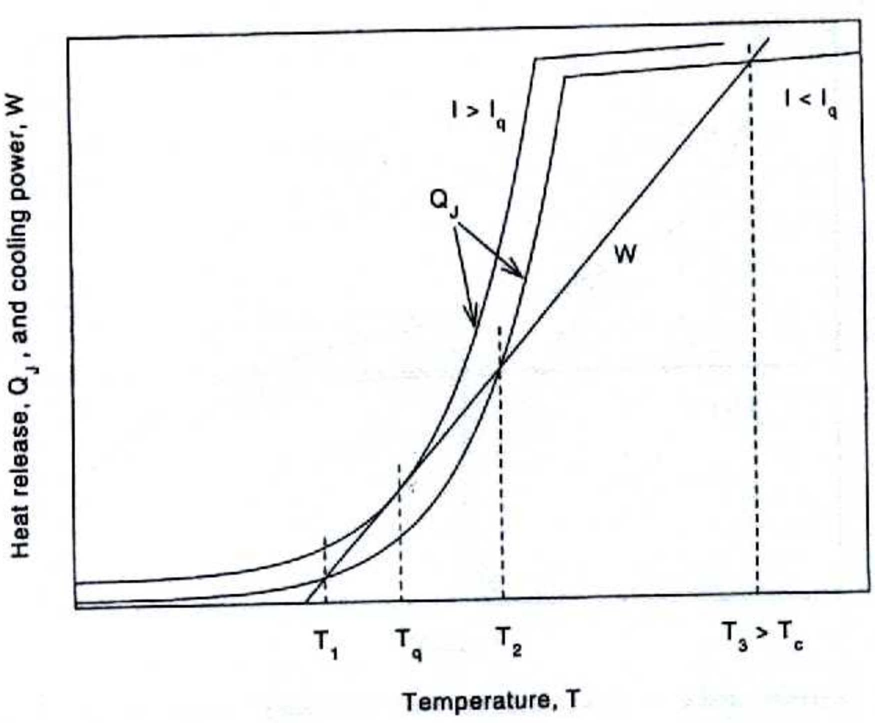
- Solder only considered for the transverse resistance
- Silver and copper not in parallel
- Inductive effects negligible



- Y. Fu, O. Tsukamoto, M. Furuse, “Copper stabilization of YBCO coated conductor for quench protection”, IEEE Trans. Appl. Supercond., 2003

Existing Models (5) : Universal scaling

- Uniform temperature along the tape
- Power law for the superconductor
- Based on equilibrium theory
- Analytical solution relative to the tape heating



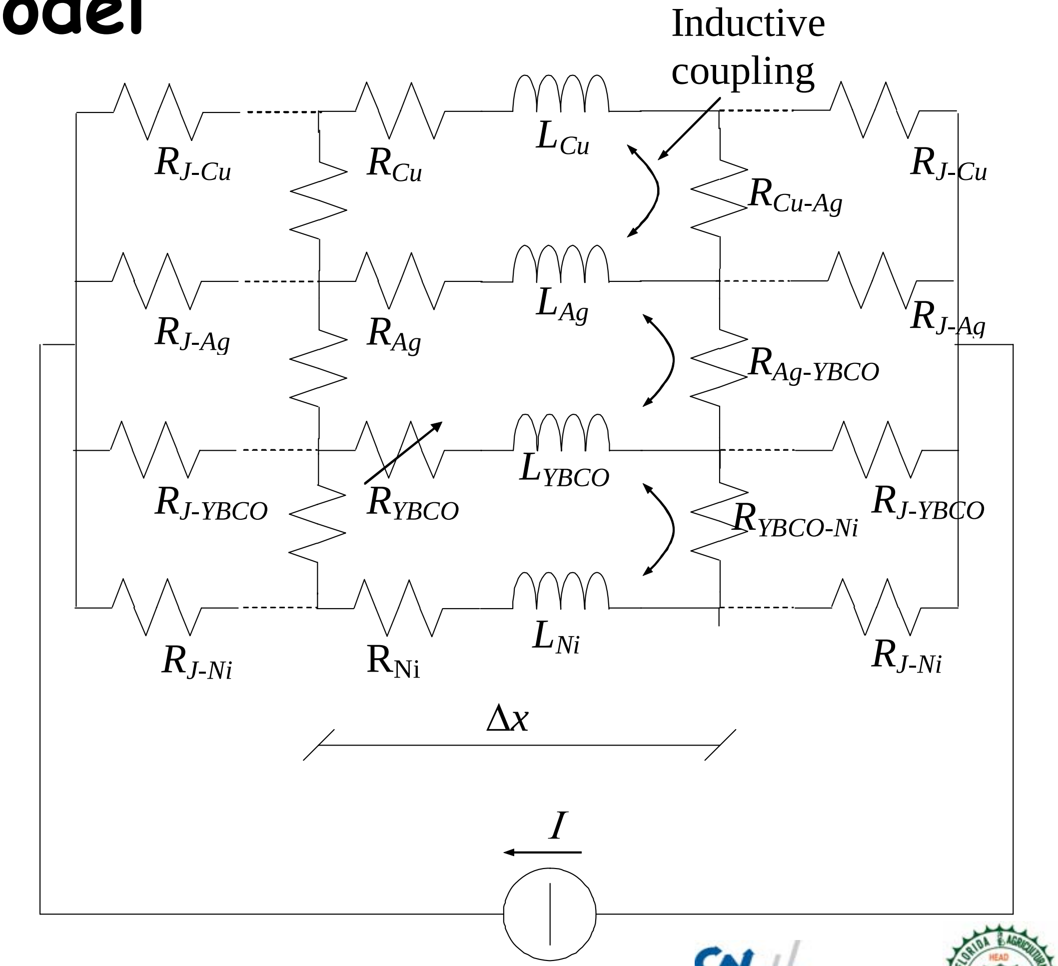
- A. L. Rakhmanov, V. S. Vysotsky, Y.A. Ilyin, T. Kiss, M. Takeo, “Universal scaling law for quench development in HTSC tapes”, Cryogenics 40, 2000

Existing Models (6) : Lumped Parameters Assumptions

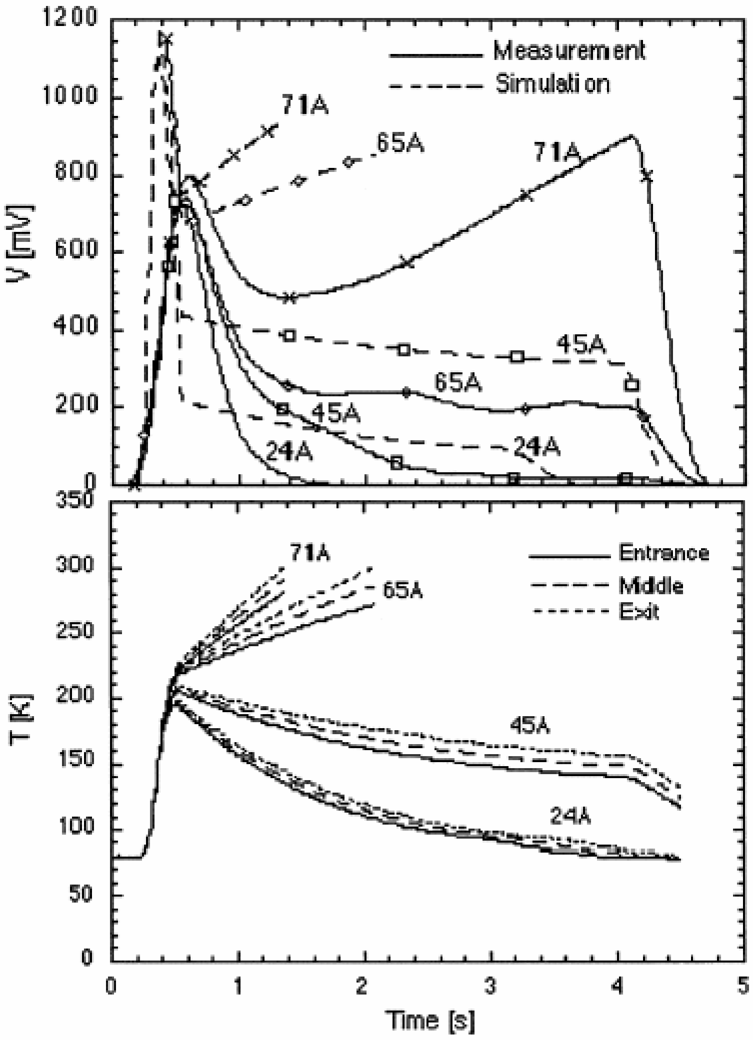
- Lumped electrical parameters model coupled with a discrete (electrical equivalent) thermal model
- Tape uniform along the length
- Tape divided into N_L layers and N_S sectors along the length
- Each layer sector has different thermal and electromagnetic properties
- Electrical coupling through electrical contact resistances and mutual induction coefficients
- Thermal coupling through thermal contact resistances
- Joule losses and temperature dependent properties link the two models

Existing Models (6) : Lumped Parameters Model

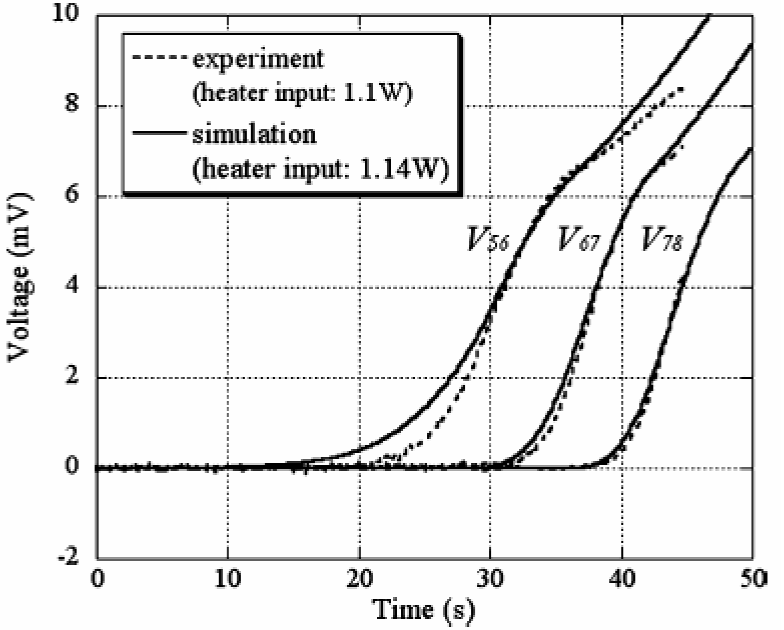
N-layer tape: lumped parameters electrical circuit model



Models Comparison with Experiments



Iwasa et Al.

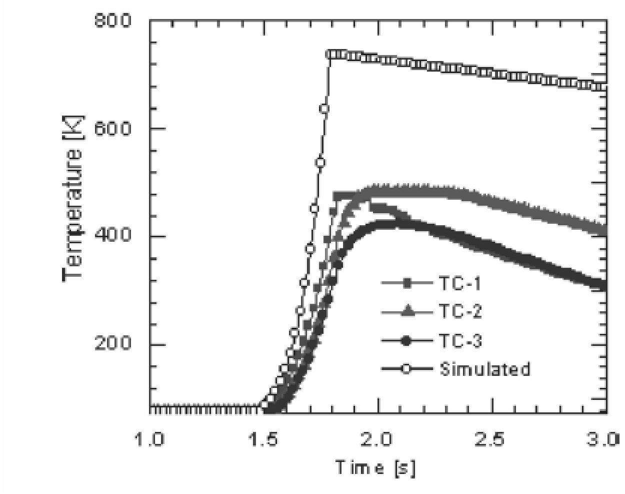


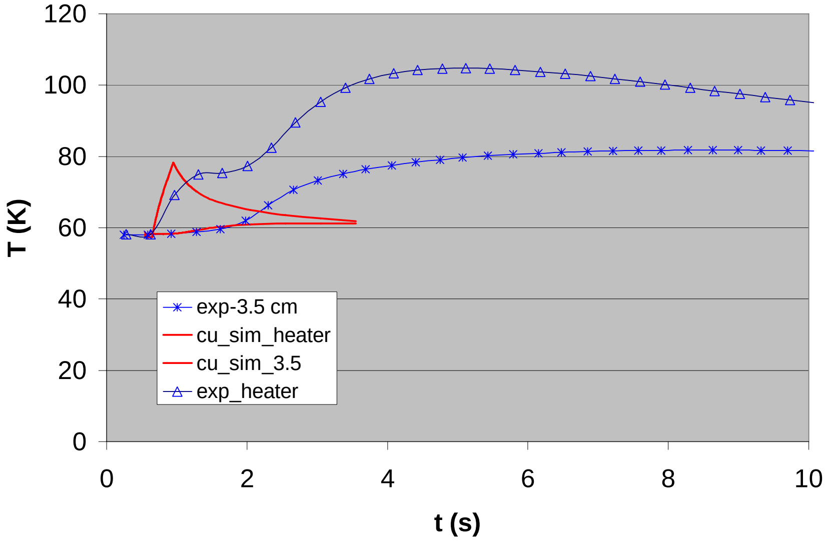
Ishiyama, et Al.

- Temperature simulations are accurate
- Large discrepancies for voltage

Conclusion on Models

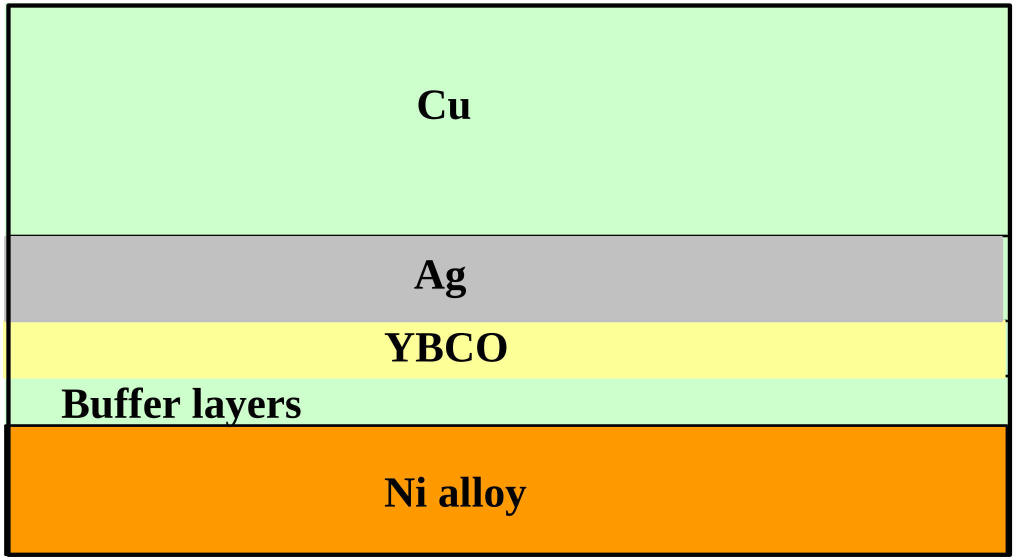
- Presented models have been validated on dedicated experiments
- Current models cannot predict quench or recovery
- Tape is considered equipotential which is not the case in reality
- Models are limited to single tape





- Need to do better.

Typical Tape Configuration



Tape length	(cm)	14
Tape width	(cm)	1
d_cu	(μm)	50
d_ag	(μm)	3
d_YBCO	(μm)	1
d_Ni	(μm)	75
Ic (77 K)	(A)	146
n (77 K)		21

30 K

Material	Cp (J/m^3.K)	K (W/K)	ρ (kg/m^3)	μ/μ_0	σ (Ω.m)
Copper	65	1.5 e+6	8960	1	7.8 e-9
Silver	80	0.7 e+6	10490	1	7.55 e-9
Ni	30	0.4 e+6	8880	1240	2.5 e-8

77 K

Material	Cp (J/m^3.K)	K (W/K)	ρ (kg/m^3)	μ/μ_0	σ (Ω.m)
Copper	230	0.6 e+6	8960	1	8.6 e-9
Silver	170	0.45 e+6	10490	1	8.31 e-9
Ni	150	0.2 e+6	8880	1240	2.8 e-8

Diffusivity and Time Constants

- If homogeneous material considered for each layer
  - Thermal:

$$\alpha\left[\frac{m^2}{s}\right]=\frac{k}{\rho C_p} \quad\Longrightarrow\quad \frac{L^2}{\alpha}=\frac{\rho C_p L^2}{k}$$

  - Magnetic:

$$K=\frac{\sigma}{\mu} \quad\Longrightarrow\quad \frac{L^2}{K}=\frac{L^2\mu}{\sigma}$$

- How do they compare?

Effect of Current diffusion

- Diffusion time constants

30 K

Material	Thermal diffusivity	Electromagnetic diffusivity	Thermal time constant	Electromagnetic time constant
Copper	2.58	6.21 e-3	9.71 E-10	4.03 E-7
Silver	0.834	6.01 e-3	1.08 E-11	1.5 E-9
Nickel	1.5	1.6 E-5	3.75 E-9	3.51 E-4

77 K

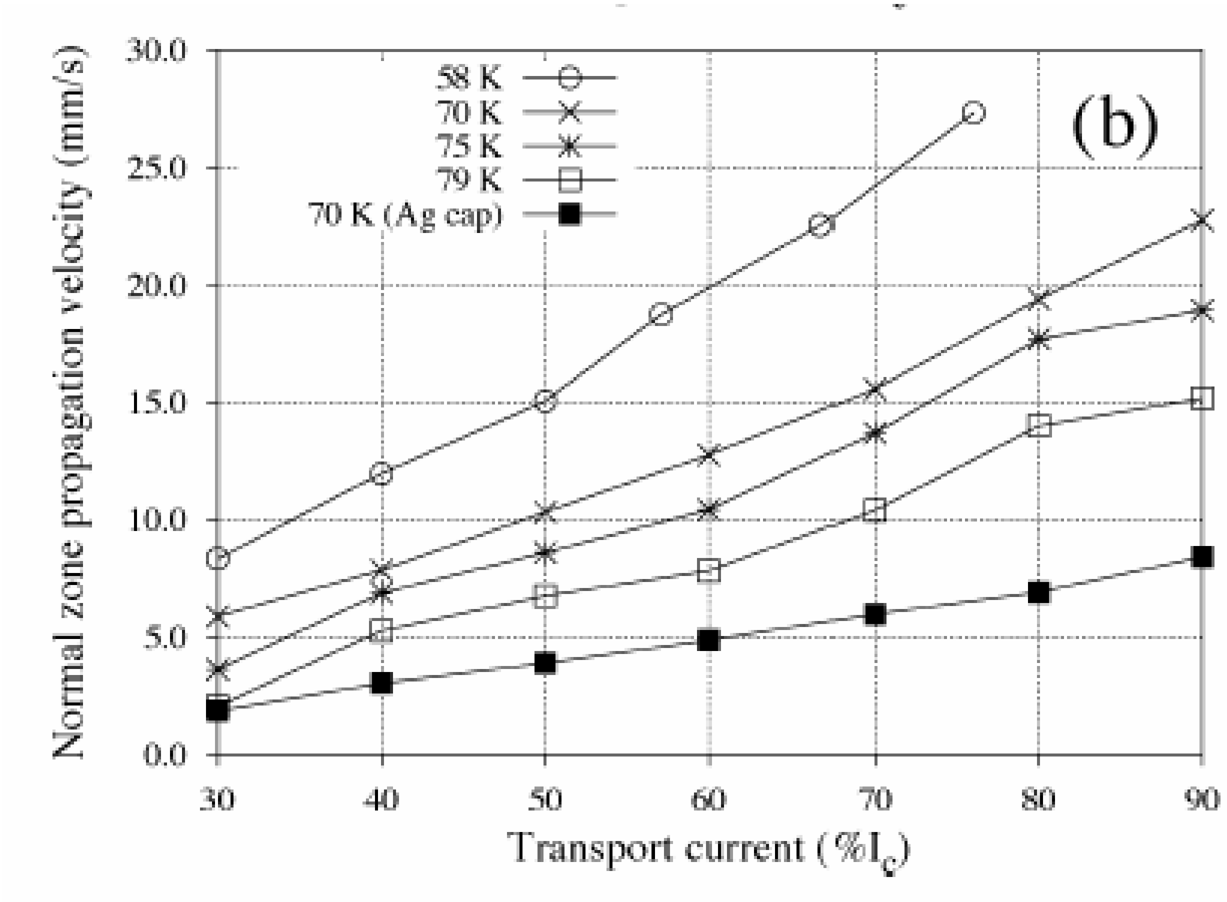
Material	Thermal diffusivity	Electromagnetic diffusivity	Thermal time constant	Electromagnetic time constant
Copper	0.291	6.84 E-3	8.59 E-9	3.65 E-7
Silver	0.252	6.61 E-3	3.57 E-11	1.36 E-9
Nickel	0.15	1.8 E-5	3.75 E-8	3.13 E-4

Time constants almost independent from temperature

Normal zone propagates at a few mm/s

⇒ **Diffusion occurs in Ni layer and has to be taken into account**

NZP Velocity

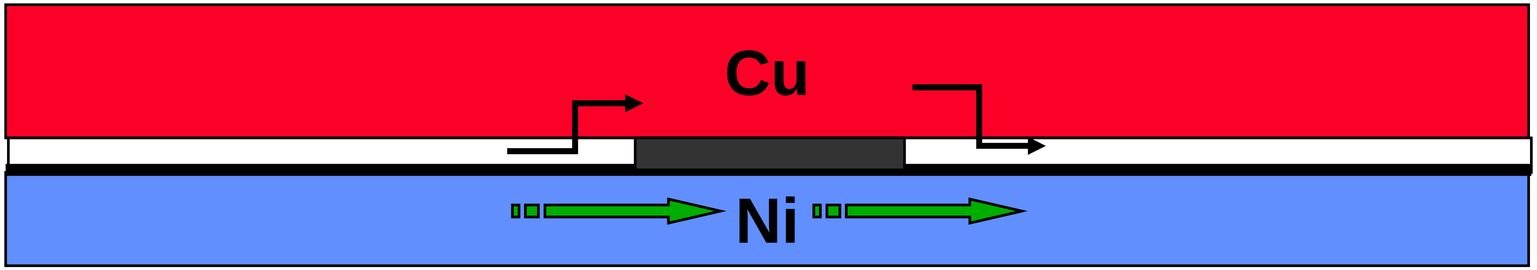


NHMFL

- Normal zone velocity in the same order of magnitude as current diffusion in Nickel layer !

Effect of Current diffusion (3)

- If model is 2D and tape considered infinite, how does current go into the Ni layer?



Current diffused in Ni layer much slower than in copper

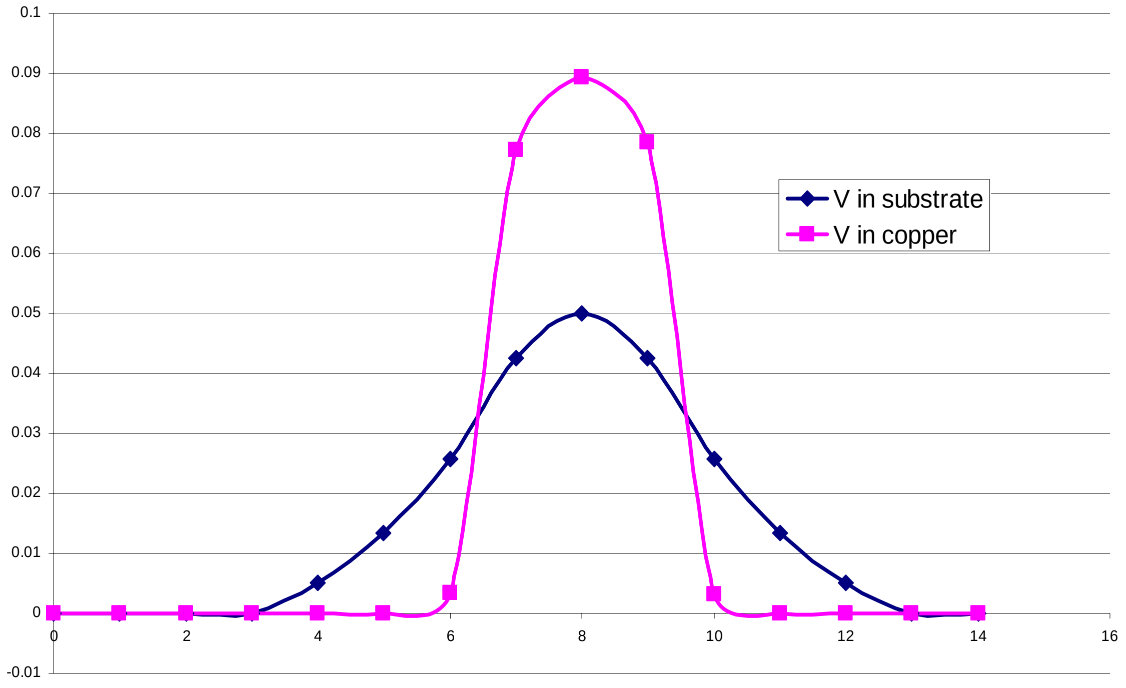
- Current diffusion in Nickel has to be taken into account
- At beginning of quench, current can not develop in Ni and dissipates more losses than expected

Proposed Model for FEA Simulations

- FEA simulation
  - YBCO layer considered as a boundary condition
  - YBCO layer considered to have infinite resistance when T increases
  - Current diffusion in Ag and Cu neglected
  - Current diffusion in Nickel taken into account

Preliminary Qualitative Results

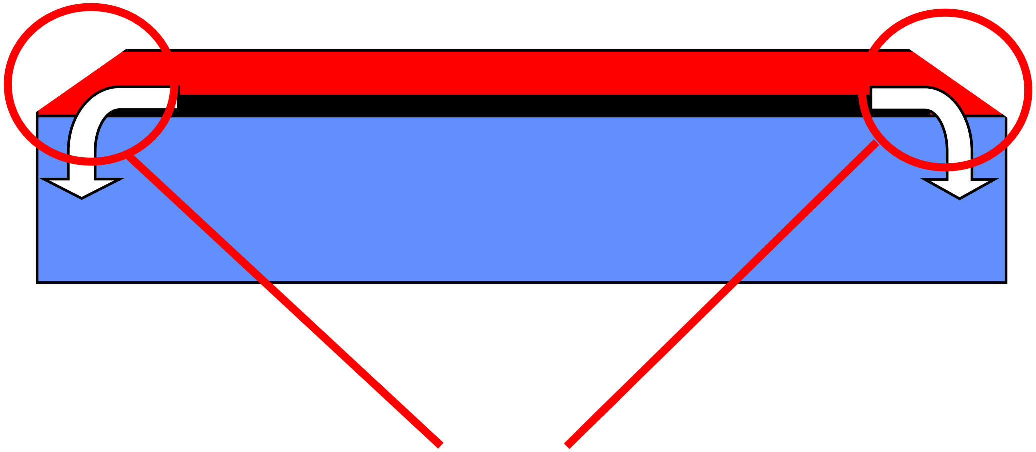
- Experiments show that current transfers on longer lengths into substrate
- This can only be explained by diffusion



• Typical sampling time in experiment around 1 ms
• Snapshot at t=1ms shows that current redistribution has already happened
• What happens before?
• What is driving the quench?

Edge Effects in Quench Development

- Layers may be in contact on the side

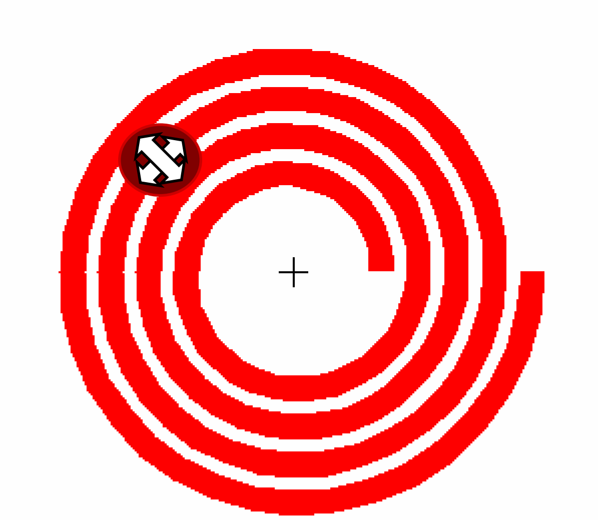


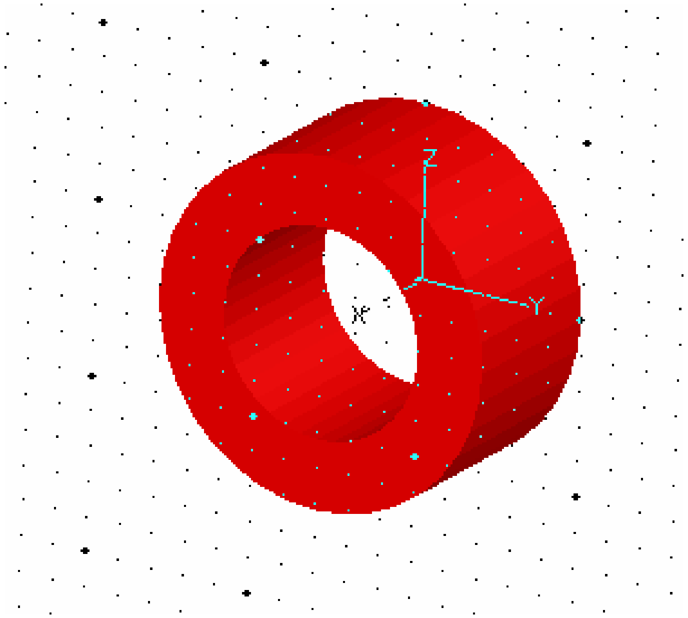
Current is forced in to Cu and Ni layers
Current cannot diffuse fast into Ni
More heat generated in copper while current goes “slowly” in buffer

Problem is not 2d but 3d (even for single tape)

From Tape to Device

- Quench in a coil will be different than in an isolated tape sample:
  - Magnetic coupling between winding layers
  - Heat transfer from one layer to another
- Quench simulation in coils is required to develop protection systems

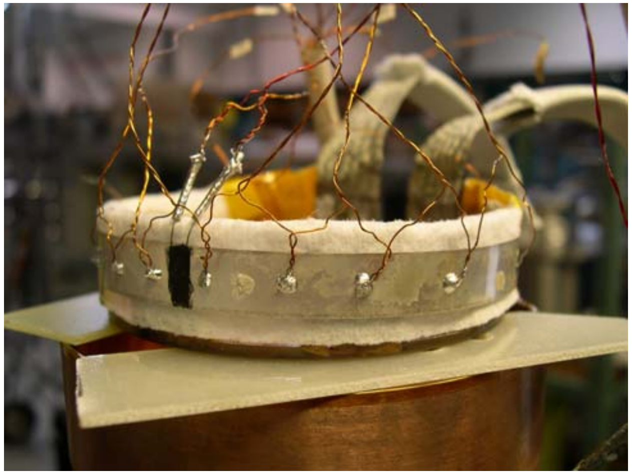


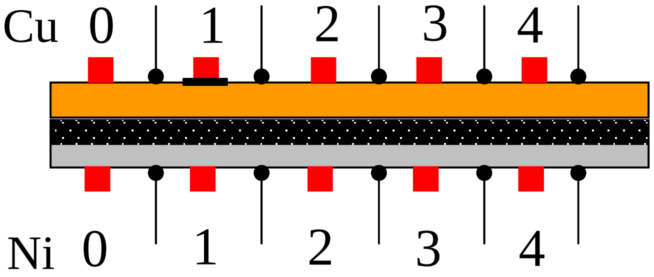


Quench propagates in 3D by heat transfer and magnetic coupling between layers

Key Parameters

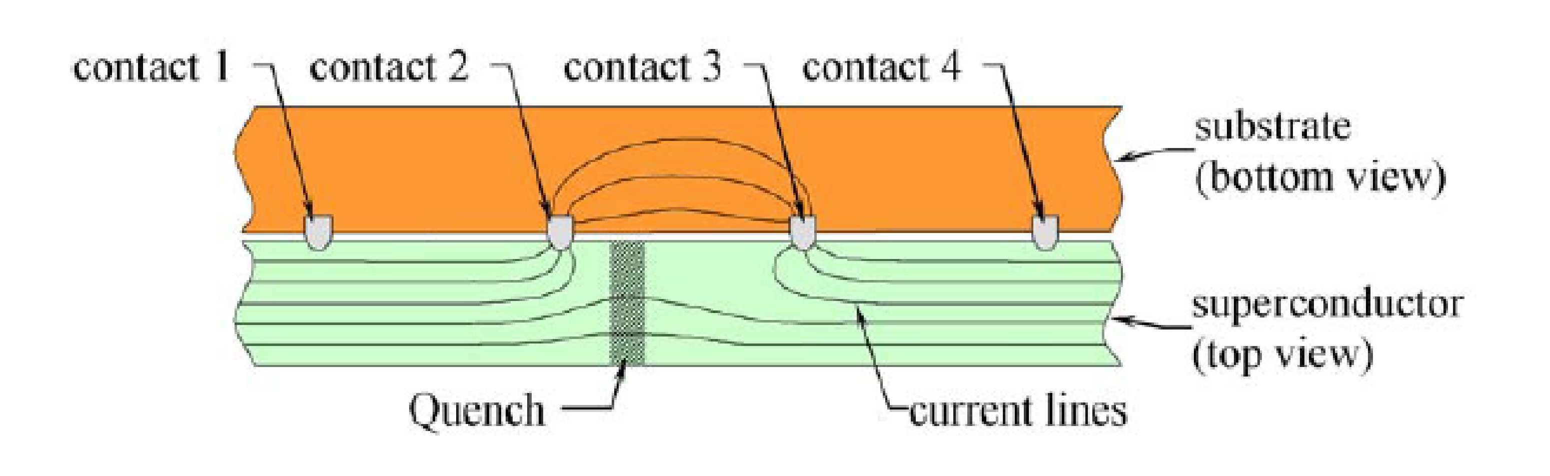
- Thermal and electrical characteristics of each of the materials forming layers
- Electrical contact resistance between layers
- Thermal contact resistance between layers
- Thermal and electrical diffusivity vs. temperature





- This implies to develop model with the help of experimental data

Promising Techniques to Speed Up Quench Propagation



- Implement contacts to force current to go into substrate
- Current density is increased at contacts thus generating more heating

Switching and quench propagation in coated conductors for fault current limiters,
W. Prusseita, H. Kindera, J. Handkea, M. Noeb, A. Kudymowb, W. Goldackerb,
Presented at ISS 2005,Tsukuba, Japan, 24.-26.10.2005

Conclusion and Future Work

- LTS protection techniques do not work. Need 3D model to develop transition protection
- Current diffusion in the substrate may have an important role in quench dynamics
- Contacts on side between layers have to be taken into account and require a 3D model
- Model development needs to be closely linked to experimental testing
- Tape model cannot be applied to quench propagation in devices. 3D approach is required to simulate interaction between layers