Conductor Design for HTS Applications

S. Bhuyian, J. Demko, R. Duckworth, A. Ellis, R. James, F. List, M. Mallette, M. Paranthaman, C. Rey, S. Sathyamurthy, I. Sauers, and E. Tuncer

Oak Ridge National Laboratory

T. Kodenkandath, M. Rupich, E. Siegal, C. Thieme and D. Verebelyi

American Superconductor

V. Selvamanickam and Y. Xie

SuperPower

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OAK RIDGE National Laboratory

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Project Overview

- **Objective: Incorporate conductor design for practical, low ac-loss, stable YBCO wires.**

- **This project consists of both a collaboration between the wire development and application groups at ORNL and involvement of wire manufacturers and HTS application programs (SPI)**

- **Areas of emphasis:**
  - **AC loss**
  - **Conductor performance**
  - **Quench and Stability**
  - **Dielectrics**

Each area of emphasis addresses issues outlined in the 2003 DOE Wire Workshop roadmap.

FY 2006 Plans

- Develop a capability to fabricate and process low ac-loss coated conductors using inkjet printing of solution precursors.
- Establish and demonstrate experimental facilities to characterize rapidly the ac losses of short filamentary conductors.
- Understand the role of copper stabilization in operational stability limits and ac loss in filamentary and non-filamentary YBCO coated conductors.
- Study the impact of different techniques of copper stabilization on the high voltage properties of superconducting tapes.
- Measure stability and ac loss of prototype YBCO coils and cables to understand better the effects of splices & magnetic substrates.
- Investigate the use of polymer-based epoxy dielectrics.

Presentation Outline

- FY 2006 Results
  - Inkjet printing & processing of filamentary conductors (Fred)
  - AC losses in filamentary conductors (Fred)
  - Role of Cu stabilizer in stabilization & ac loss (Robert)
  - Stability & AC loss for coils & cables (Robert)
  - Polymer-based epoxy dielectrics (Robert)
- FY 2006 Performance and FY 2007 Plans (Robert)
- Research Integration (Robert)

Inkjet Printing & Processing of Filamentary Conductor

Motivation:

- Filamentary HTS conductors show reduced ac-loss.
- Certain applications may require low ac-loss HTS (e.g., high power 60 Hz grid applications and high frequency, portable military applications).
- Inkjet printing represents a potentially low cost method for fabricating filamentary HTS conductors.

Several fabrication methods for filamentary HTS conductors have been explored.†

- Laser scribing (AFRL/OSU)
- Photolithography (SuperPower)
- Mechanical scribing (LANL)

} Material Removal

- Ink transfer printing (SNL)
- Inkjet printing (AMSC/ORNL)

} No Material Removal

† - Interest in fabrication of filamentary HTS conductors is global.

Inkjet printing is attractive for a solution approach to filamentary conductors.

Commercial Inkjet Printhead

(cost & performance specifications)

(Dimatix, Inc.)

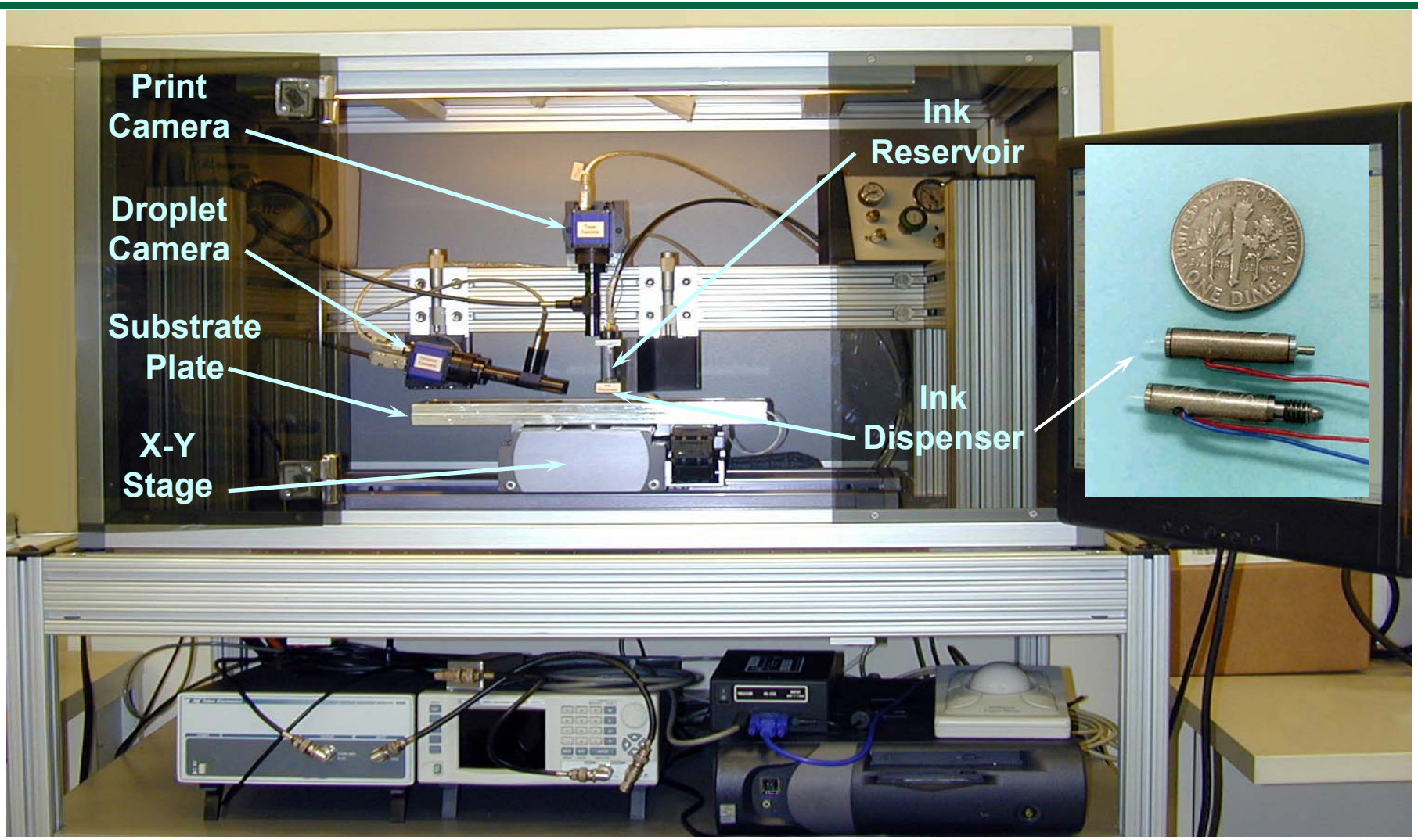
- head cost ……. $2.5k
- # of jets/head ……. 256
- drop diameter ……... 50μm
- head width …….. 6.5 cm
- max. frequency …….. 20 kHz
- max. soln. delivery rate … ~1 l/hr
- max. line speed ……. ~1 m/s
- min. head lifetime …….. 40 l
- variable head cost …..…. $0.02/m

- High rate
- Low cost
- Accurate (± 5 μm for R-2-R)
- Simple (additive process)
- Versatile (YBCO, Ag, dielectric)

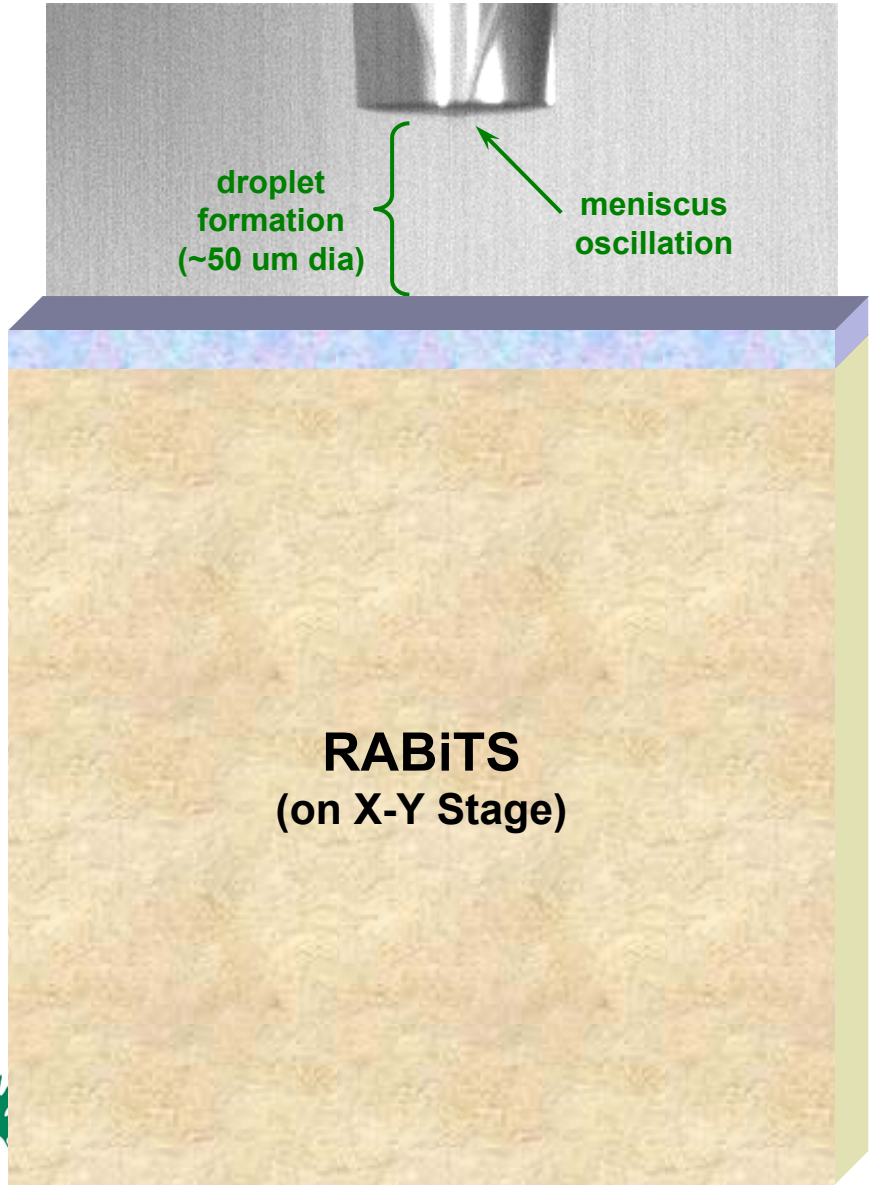
Objectives
(Inkjet Printing)

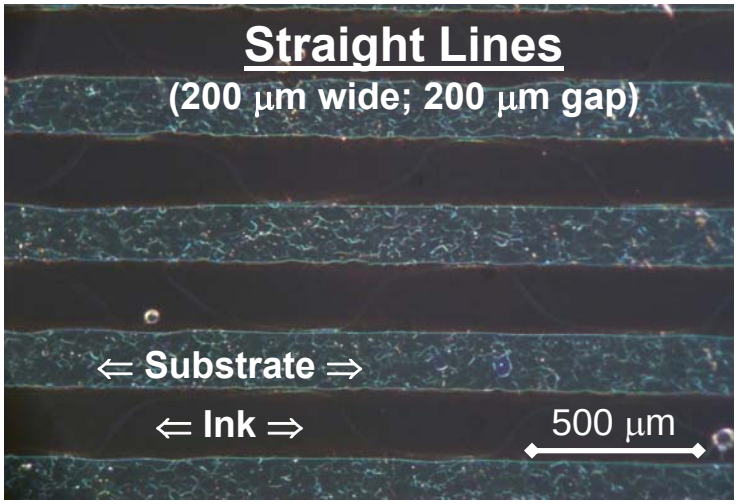
- To develop an inkjet printing system for substrates of fixed lengths
- To evaluate and optimize precursor inks (YBCO, Ag)
- To prepare filamentary coated conductors by inkjet printing
- To characterize the properties of such conductors

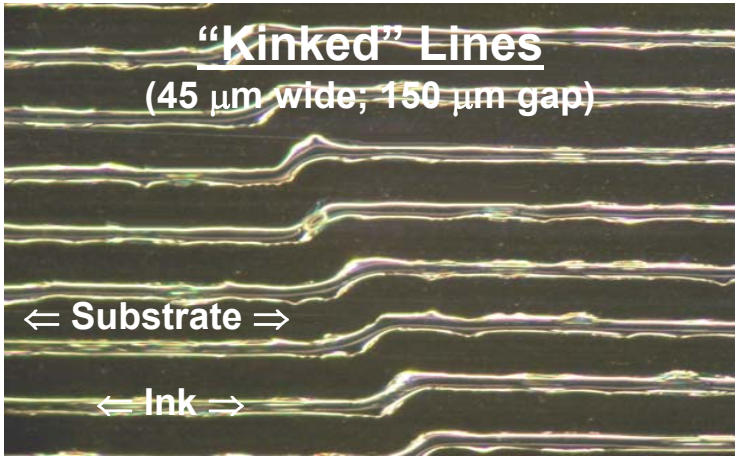
A printing system for fixed-length substrates is operating at ORNL.



Precursor inks have been successfully dispensed and printed.







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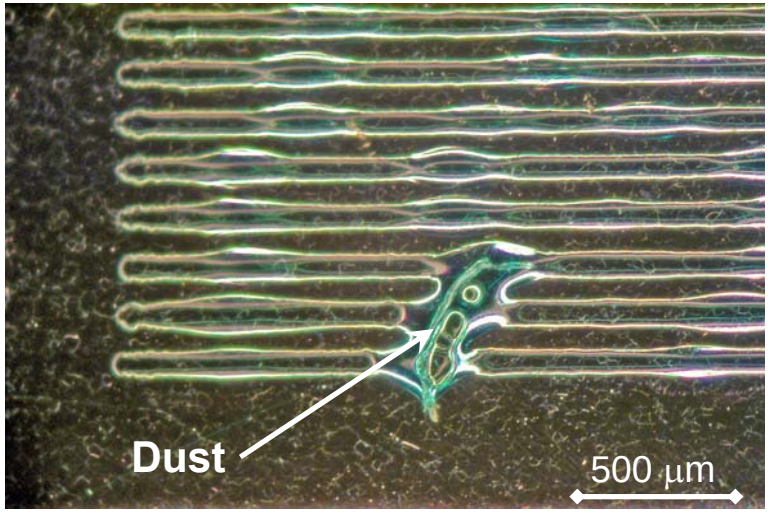
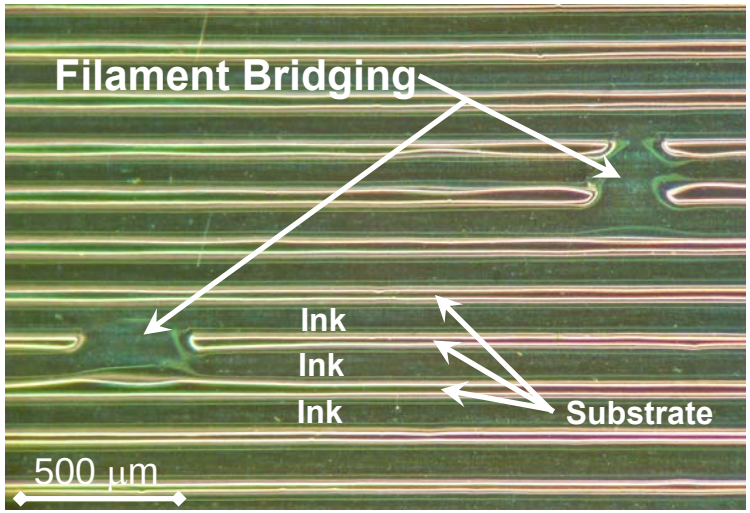
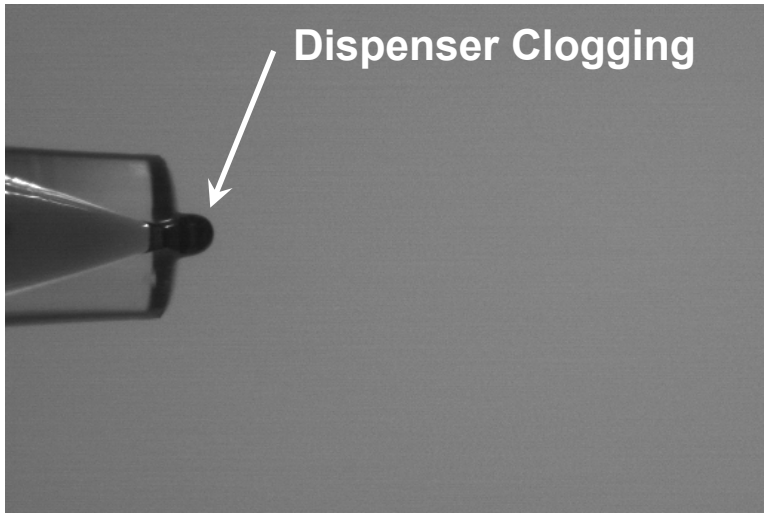
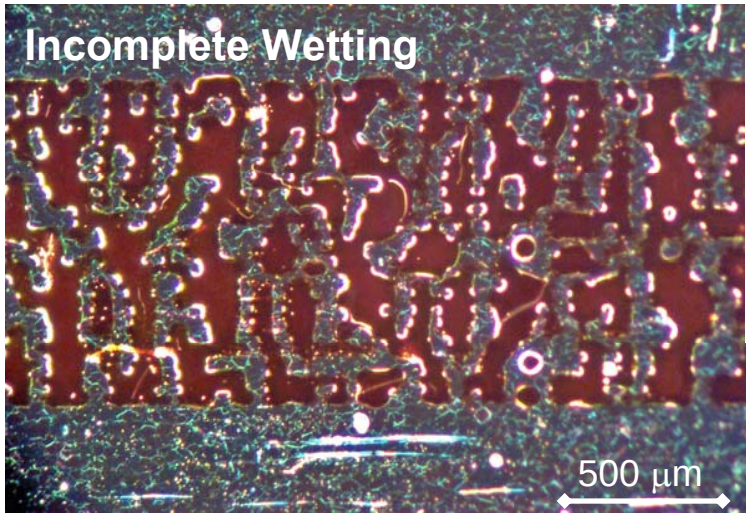
Control of printing conditions is required for successful deposition of precursors.







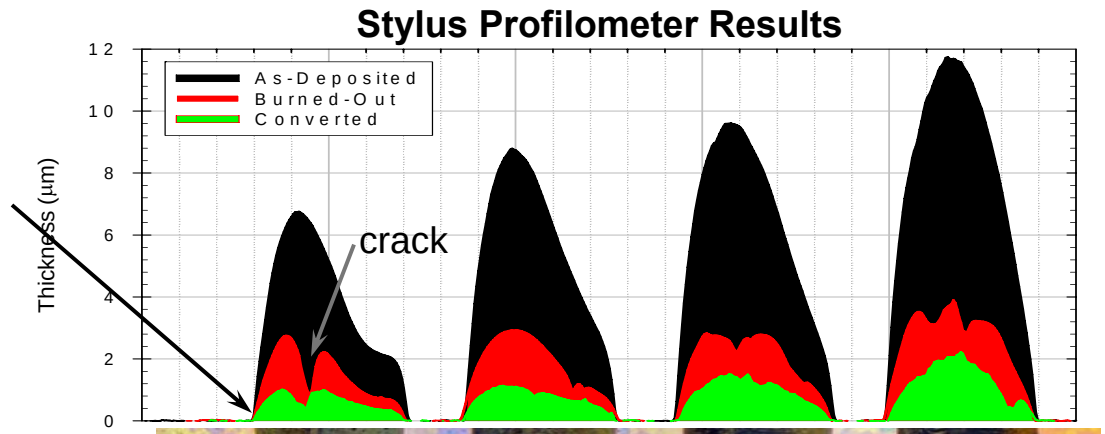


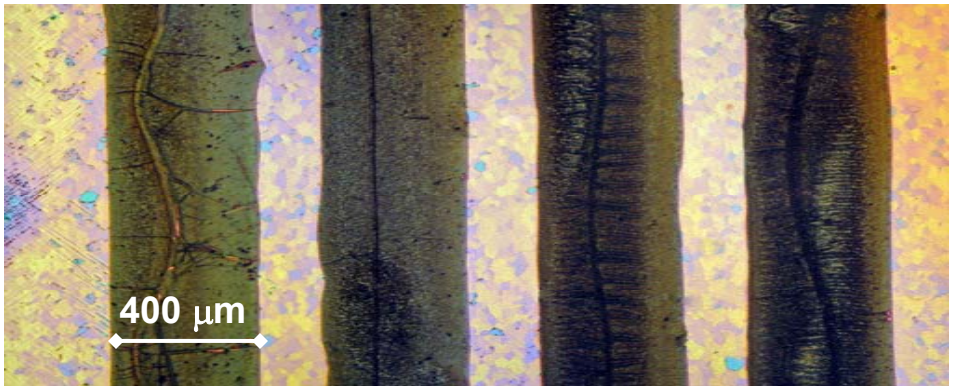
Each step in YBCO solution processing involves a large reduction in volume.

32 μm

MOD Solution

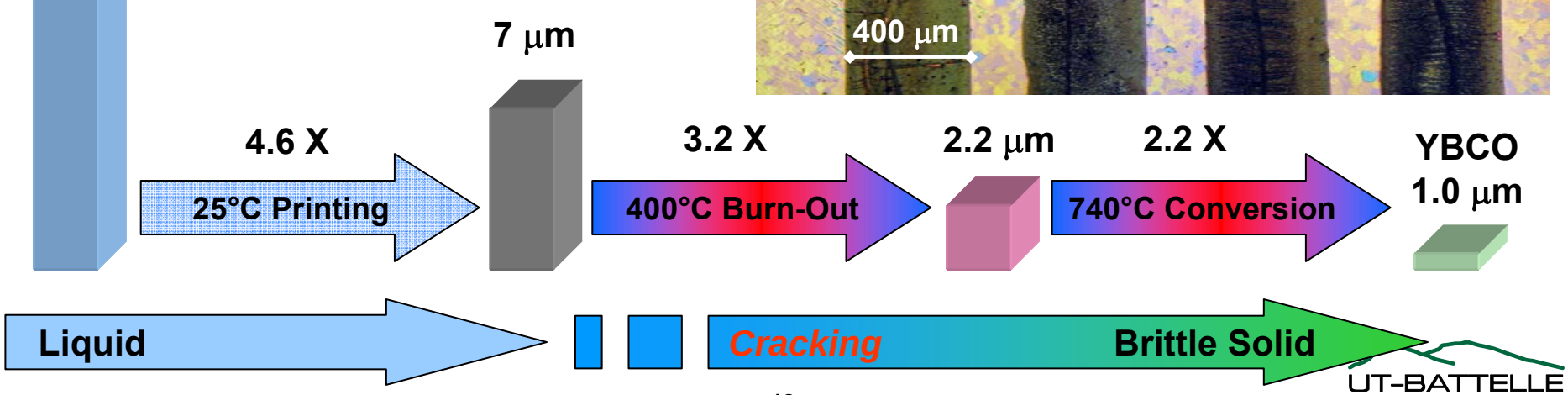
No lateral shrinkage occurs during processing





Volume reduction occurs by:

- thickness reduction
- film cracking



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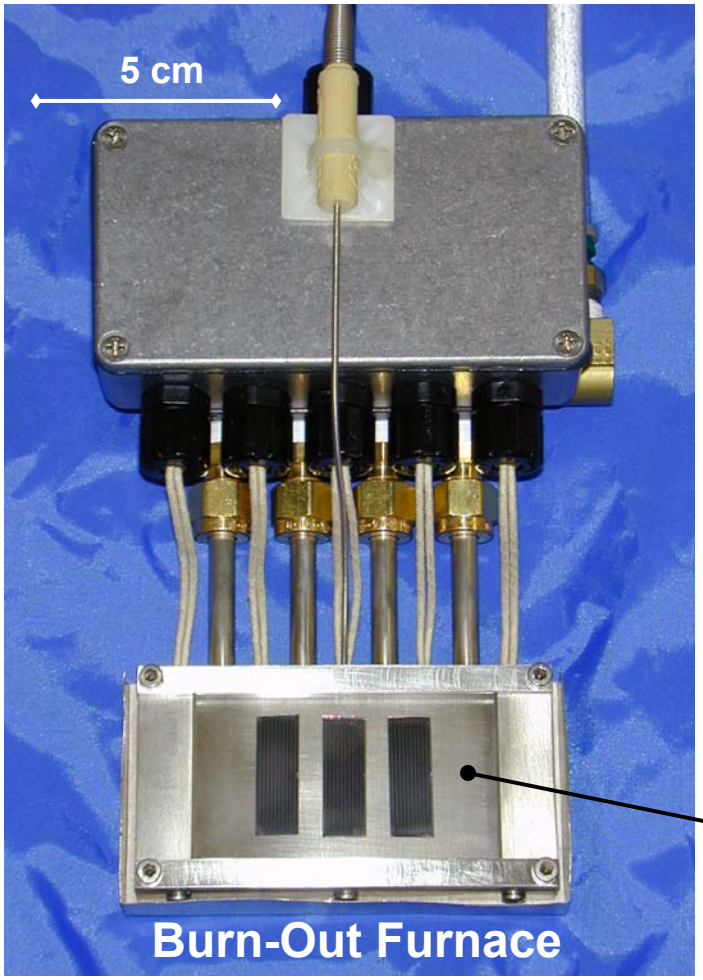
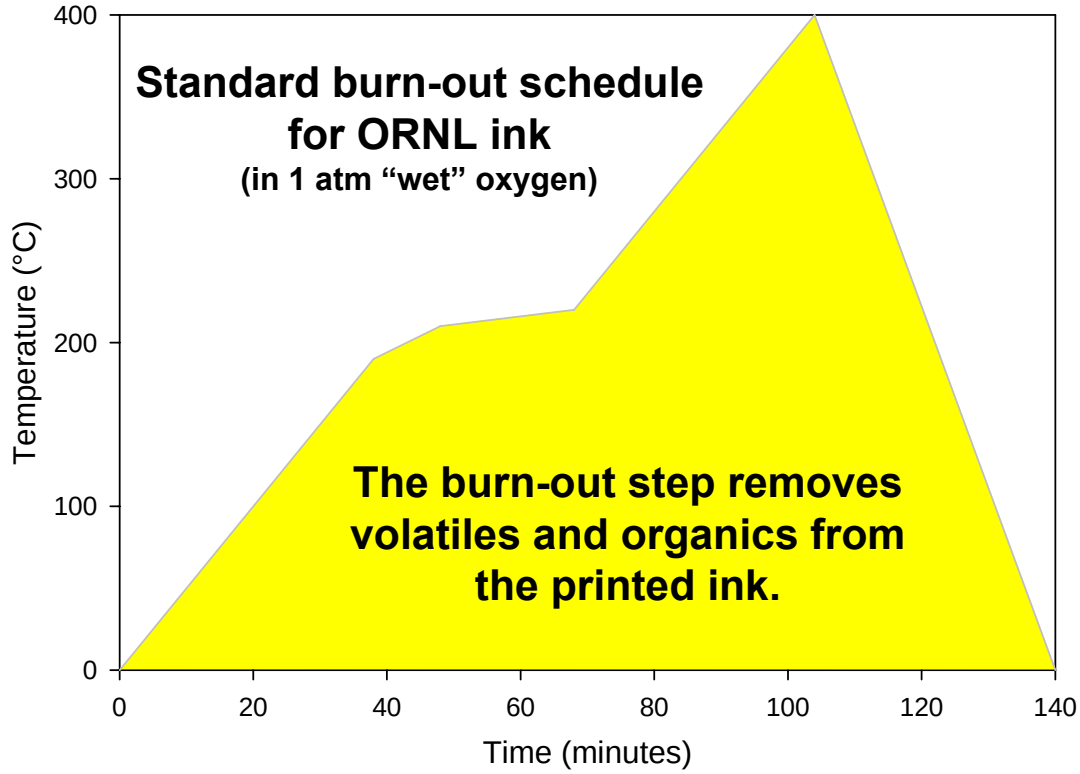
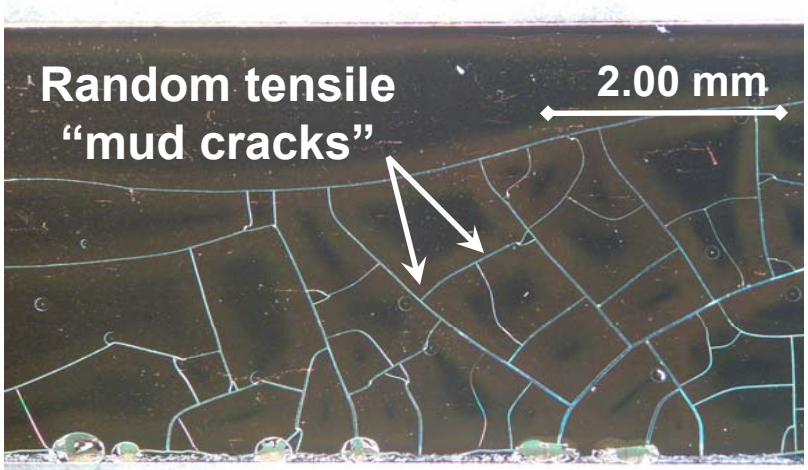
To understand better cracking during burn-out, a specialized burn-out furnace was designed.



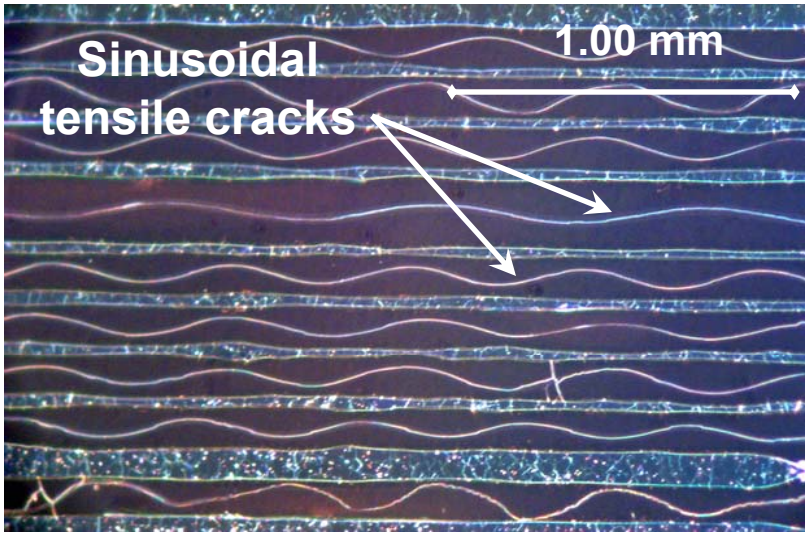


A glass window enables real-time microscopic imaging during burn-out.

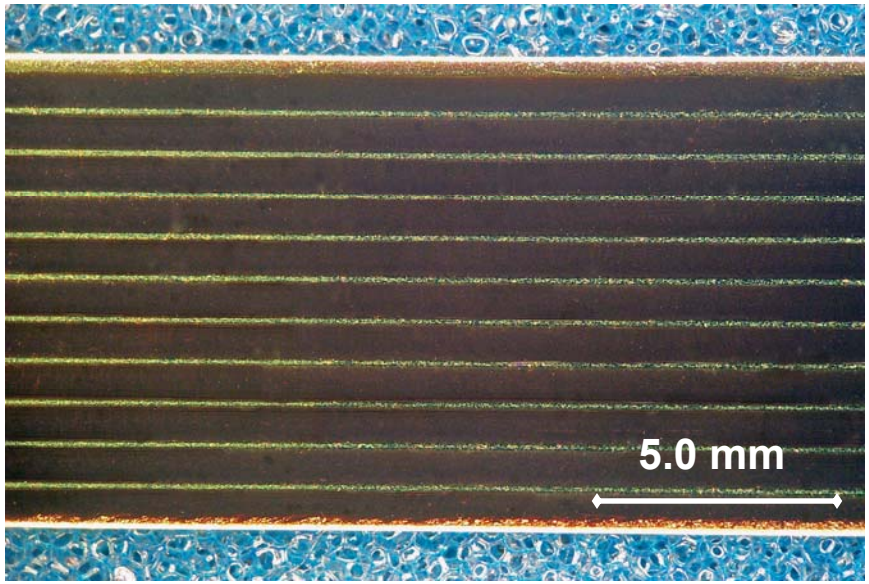
Cracking of precursor has been significantly reduced using improved burn-out.



Standard Burn-Out

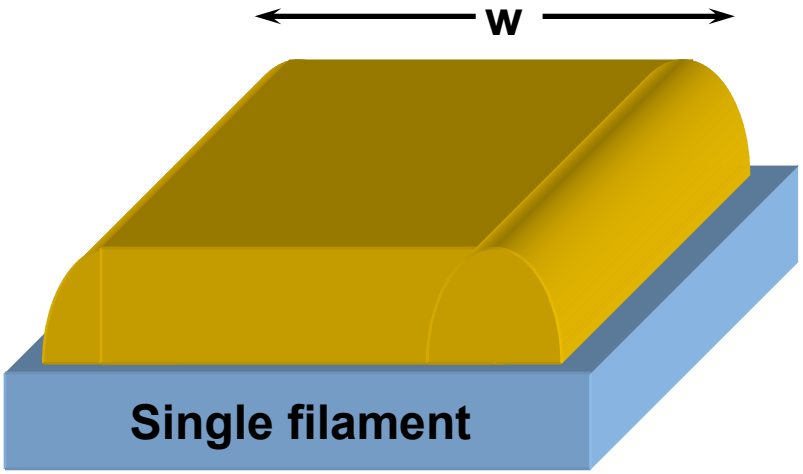


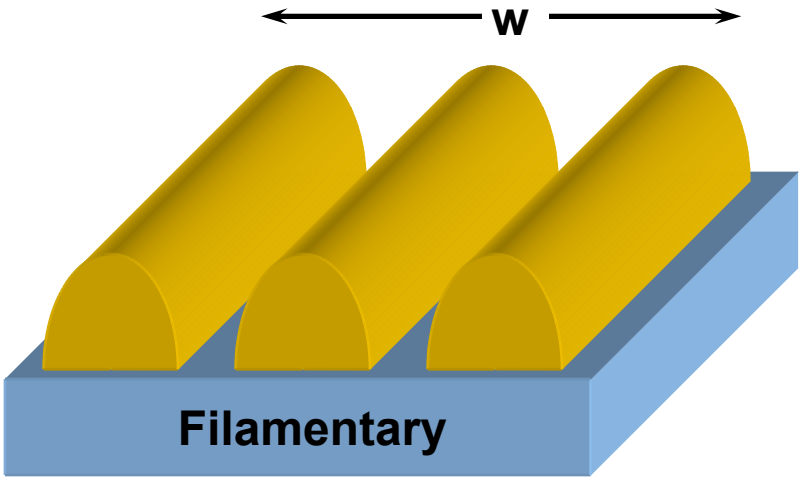
Improved Burn-Out



Following successful burn-out, precursors undergo conversion to YBCO.

Conditions for YBCO conversion may require modification for filamentary inkjet precursors.





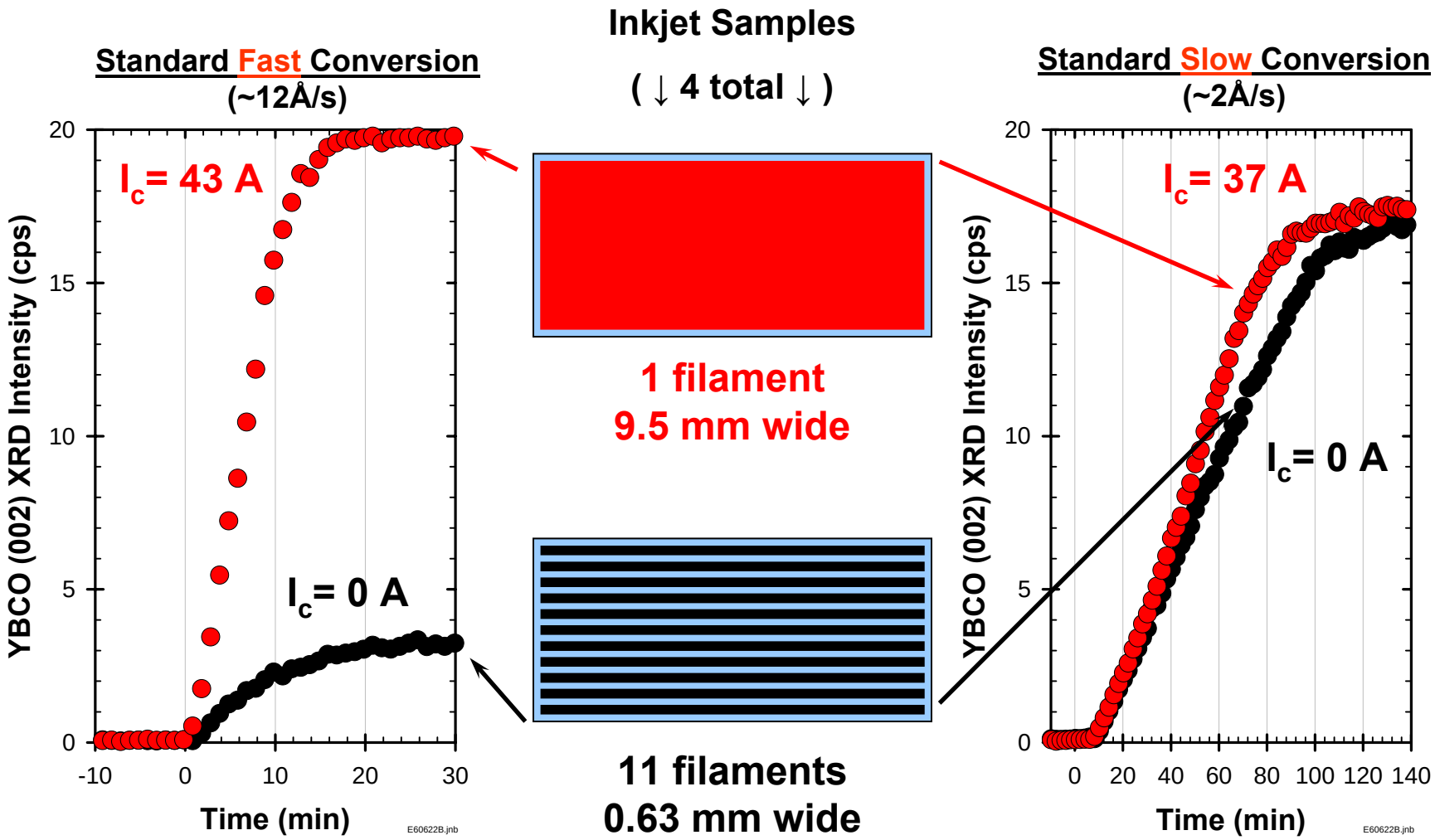
YBCO conversion requires:

- Diffusion to/from the free surface
- Adjustment for precursor thickness
- Nucleation at the substrate

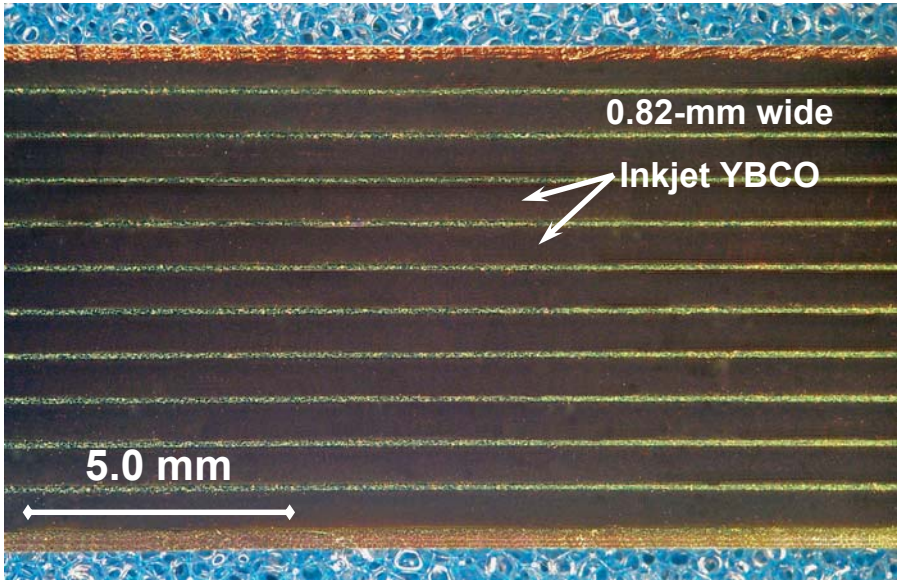
Filamentary precursor exhibits:

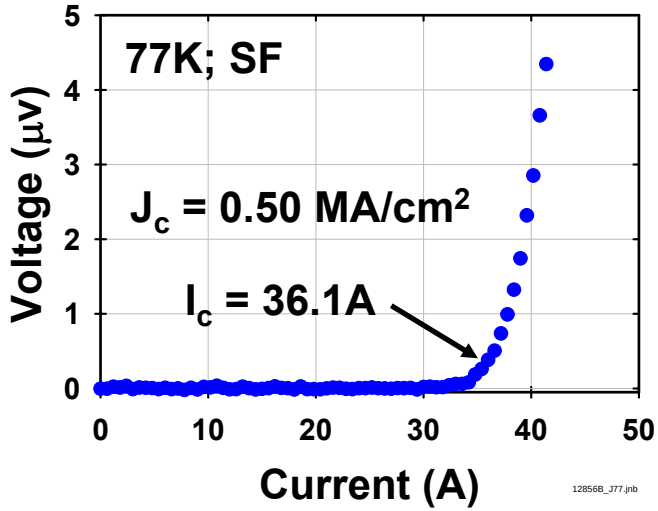
- Reduced lateral diffusion distances
- Greater variations of thickness
- Greater edge density (nucleation)

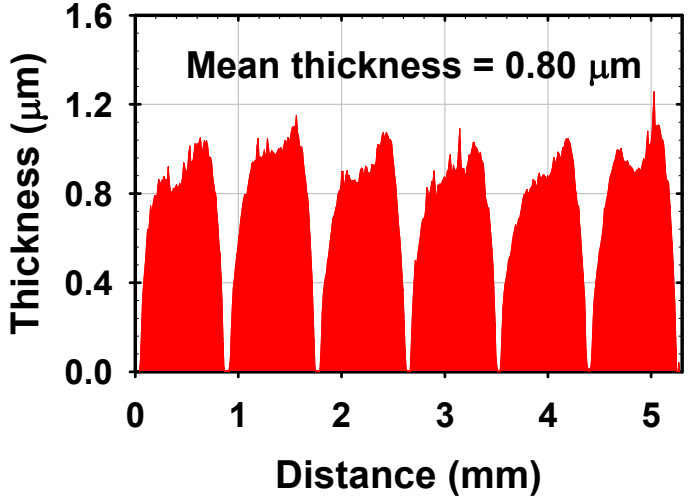
In-situ XRD shows that filament geometry strongly affects precursor conversion.



Modification to the standard conversion is required for filamentary precursors.







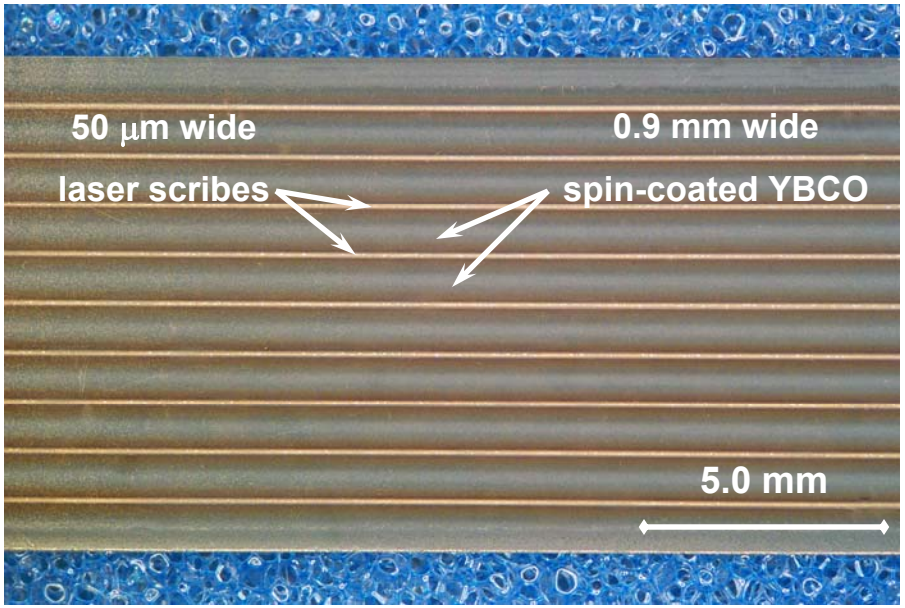
Filamentary inkjet precursor has been successfully converted to YBCO by adjusting standard slow conditions.

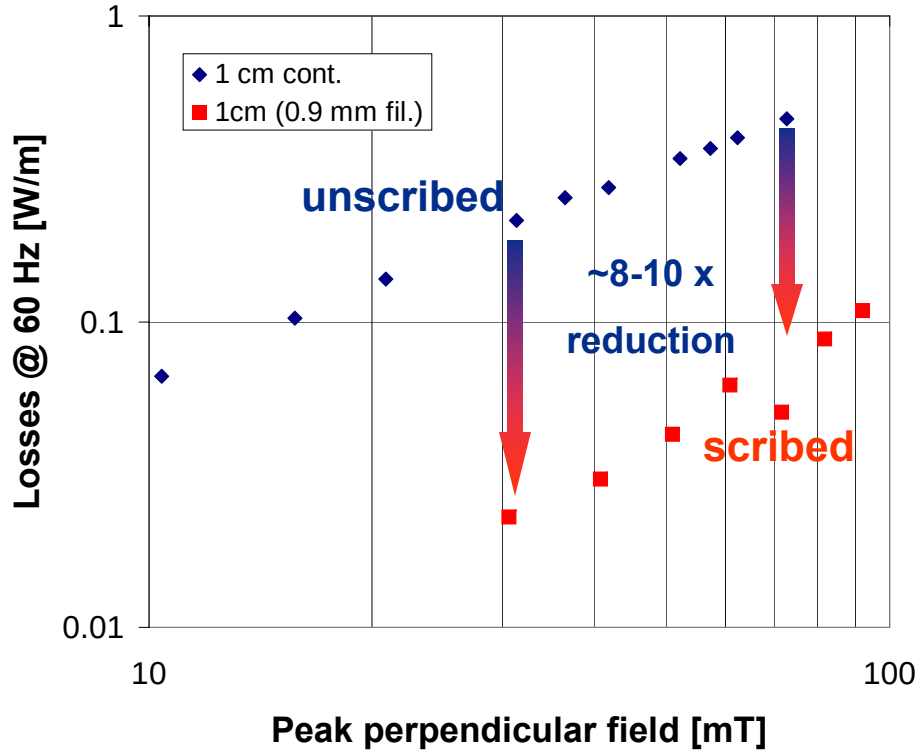
Filamentary YBCO was prepared by laser scribing to verify the test equipment.

Two 0.9 μm thick, spin-coated† samples

- **One, 1-cm wide, unscribed**
- **One, filamentary, laser scribed**

† - precursor solution same as that used for inkjet printing





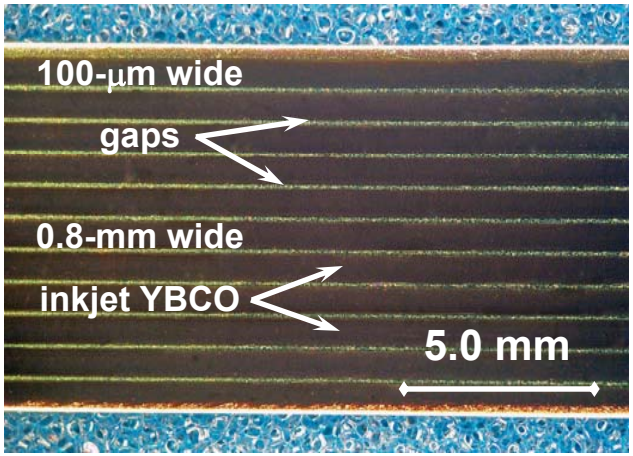
The reduction in ac loss is that expected for these filamentary conductors.

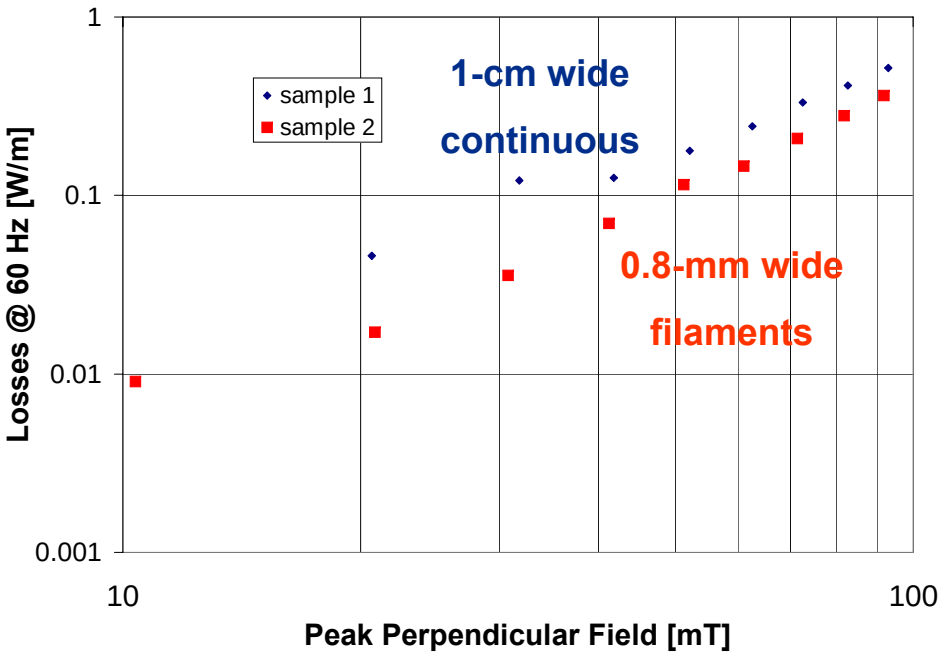
The ac losses for inkjet filaments have also been characterized.

Two 0.8 μm thick, 5-cm long inkjet samples

Each 1-cm wide, J_c ~0.4 MA/cm^2 (est.)

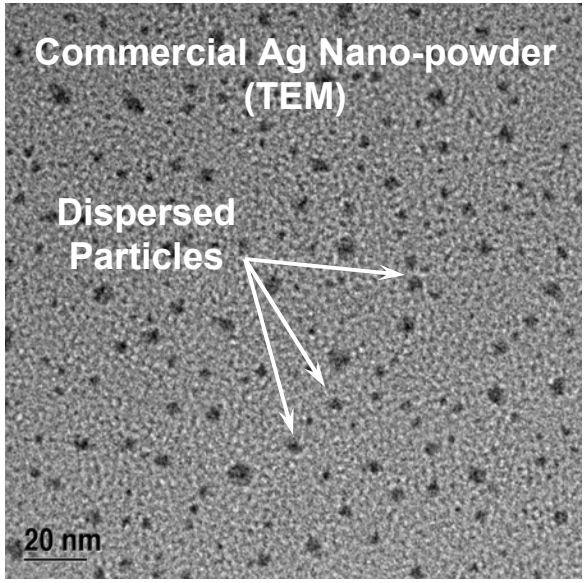
- **One, full-width, continuous (#1)**
- **One, 11 filaments, 0.8 mm wide (#2)**





The modest reduction in ac loss and the field dependence of the ac losses may suggest the presence of coupling losses.

Development of printable stabilizer is necessary for inkjet filaments

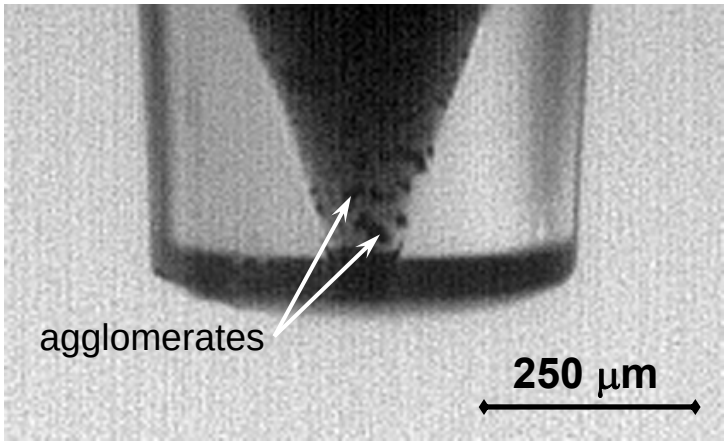


Question: Why develop silver ink?

Answer: Commercial Ag inks have “issues”.

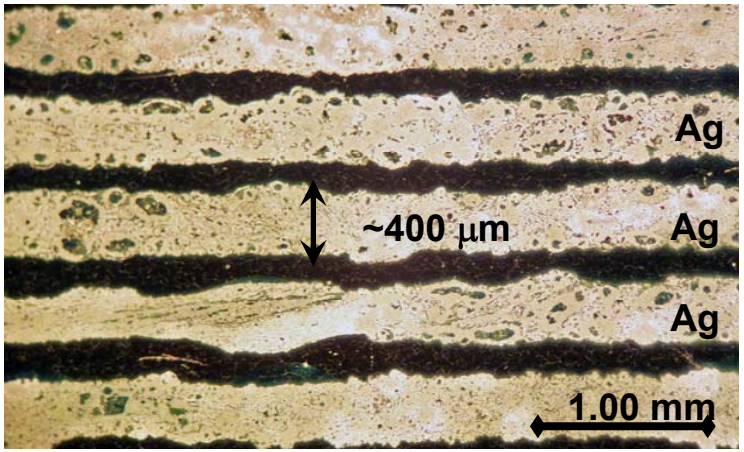
Ag Ink requirements

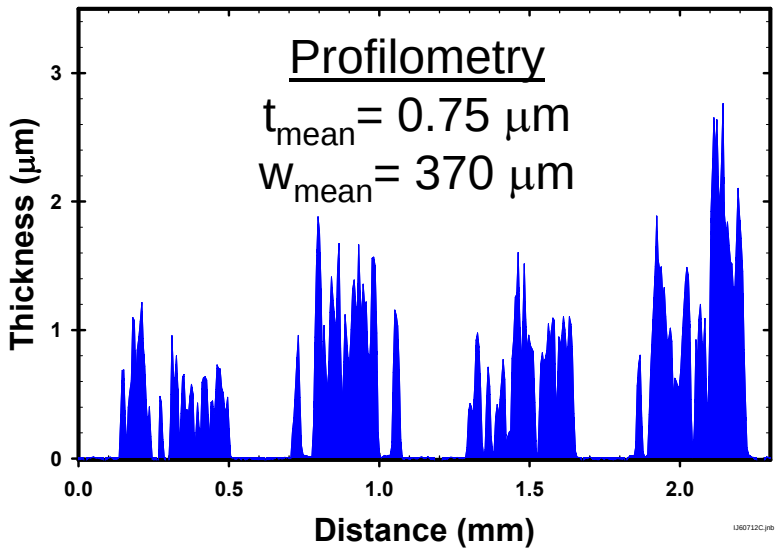
- Printable with inkjet
- Chemically compatible with YBCO
- Competitive with sputtered Ag
  - Cost & Performance

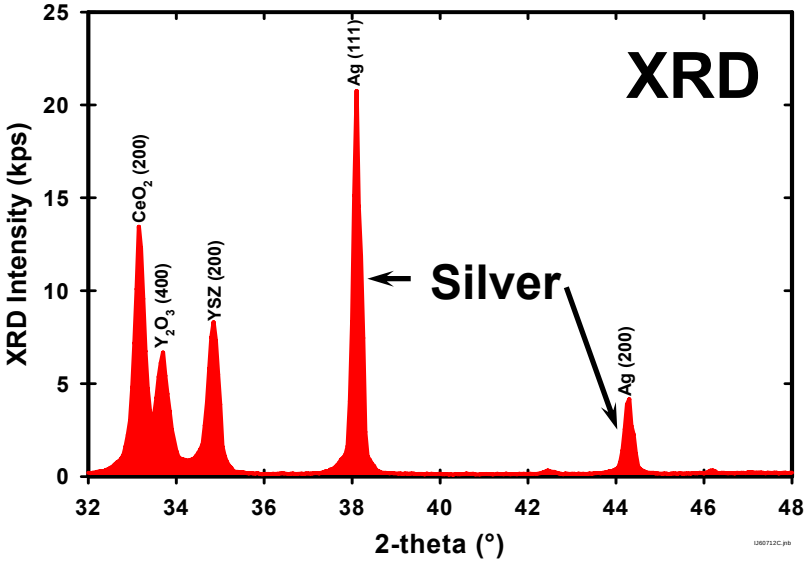


An early attempt to print a silver nanoparticle ink led to particle agglomeration in the dispenser.

Results for recent silver ink are promising.







The chemical compatibility of the Ag inks with YBCO is now being addressed.

Summary of Accomplishments

Inkjet Printing & Processing

- A single-nozzle inkjet system was designed & is operating at ORNL.
- Printing & processing of precursor inks (YBCO and Ag) have been demonstrated.
- Experimental facilities to characterize rapidly the ac losses of short filamentary conductors have been established and tested.
- AC losses for several filamentary YBCO conductors have been measured.

Presentation Outline

- FY 2006 Results
  - Inkjet printing & processing of filamentary conductors (Fred)
  - AC losses in filamentary conductors (Fred)
  - Role of Cu stabilizer in stabilization & ac loss (Robert)
  - Stability & AC loss for coils & cables (Robert)
  - Polymer-based epoxy dielectrics (Robert)
- FY 2006 Performance and FY 2007 Plans (Robert)
- Research Integration (Robert)

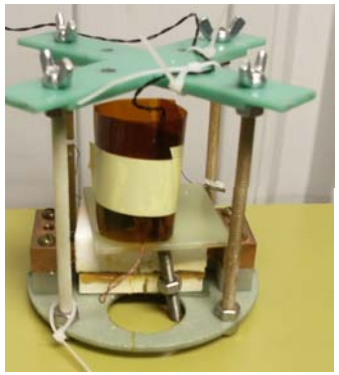
ORNL research on single tapes allows for immediate characterization/feedback

- **Motivation: In order to investigate fundamental tape properties, short lengths can be utilized to vary different factors without costly investment in time and money for HTS tapes with lengths > 10-100 m**

- **AC loss**
  - Filamentization (inkjet/laser scribed)
  - Role of stabilization/Tape qualification
  - Assembled conductors
- **Stability**
  - Role of copper stabilization
  - Cooling conditions with respect to length
- **Dielectrics**
  - Conductor geometries
  - Alternative dielectric materials

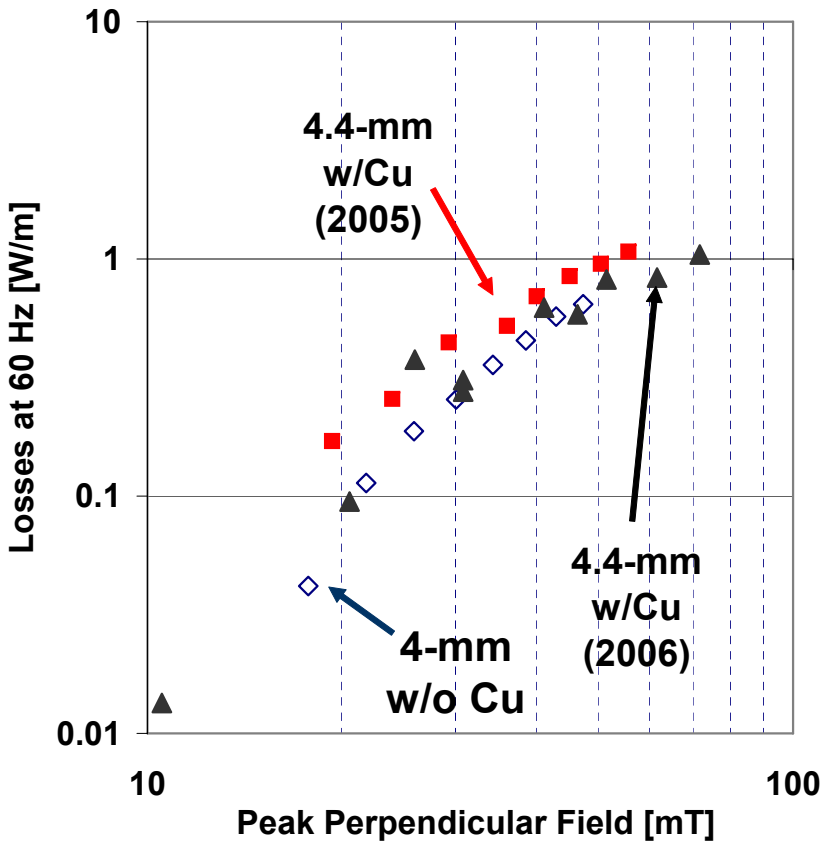
AC losses characterized on commercially available YBCO to benchmark tape performance

- **Characterization of laminated and non-laminated 344-superconductors**
- **AC loss test setup**



Thermal test setup

Solenoid, 0.1 T 6-7 cm sample area

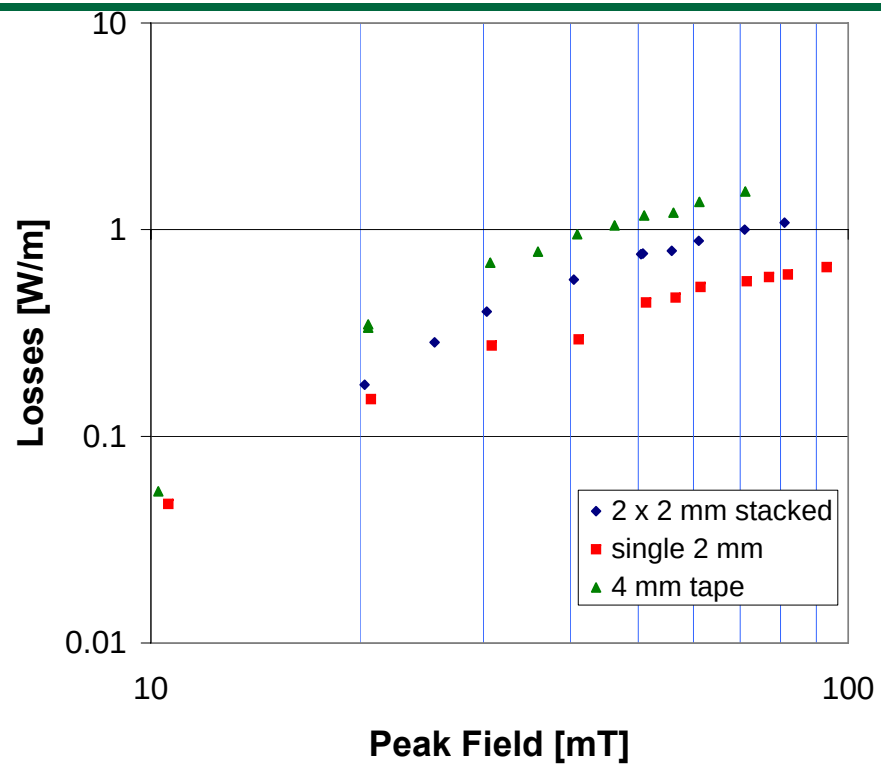


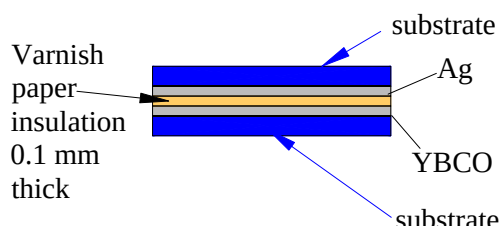
Improvement shown in effect of copper lamination on ac loss from 2005 to 2006

Copper lamination does not produce additional ac loss in this configuration

Stacks of narrow width conductors show reduced ac loss

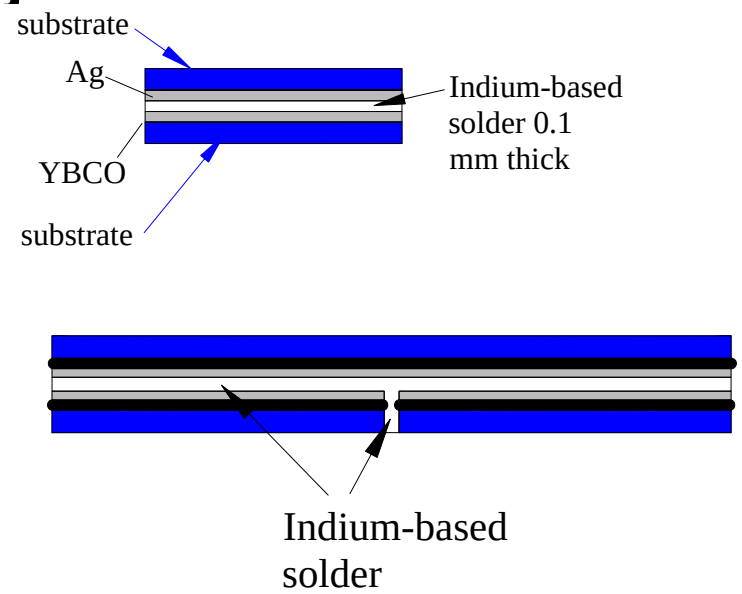
- **Motivation – Explore alternative methods to reduce ac loss not associated with filamentization**
- **YBCO tape specifications provided by Superpower**
  - **2 mm and 4 mm wide**
  - **I_c (2 mm, 77 K) 30 A**
  - **I_c (4 mm, 77 K) 60 A**
  - **No Cu-surround stabilizer**
- **Limited study to stacks of two, 2-mm wide tape due to potential current transfer issues**

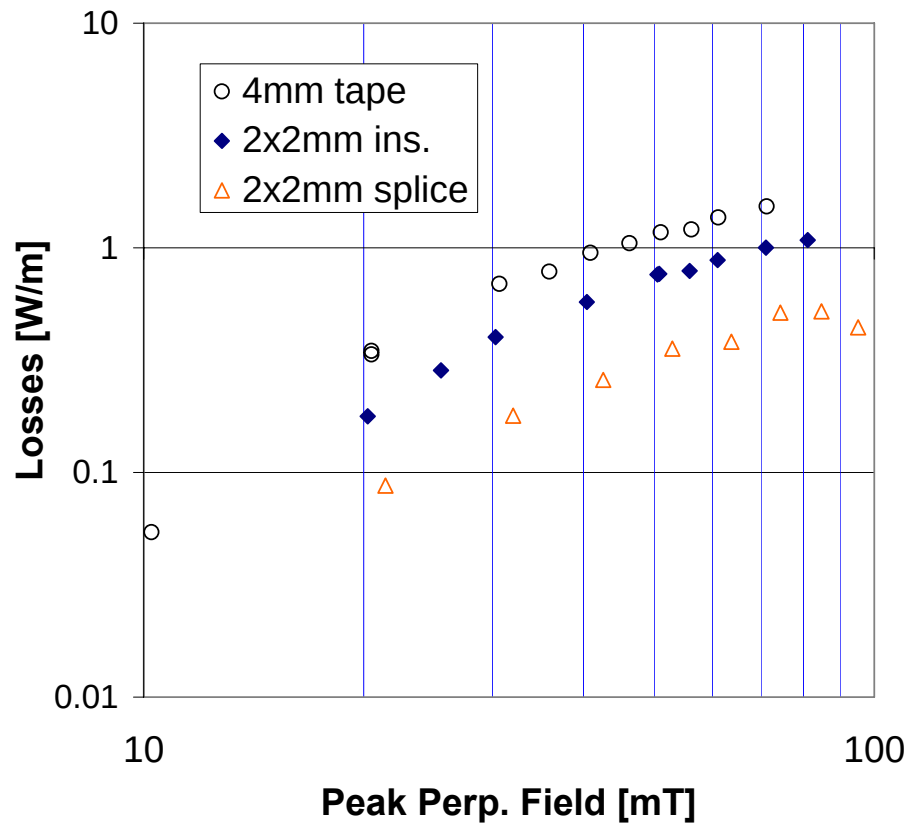




Spliced 2-mm wide tapes demonstrate lower ac loss

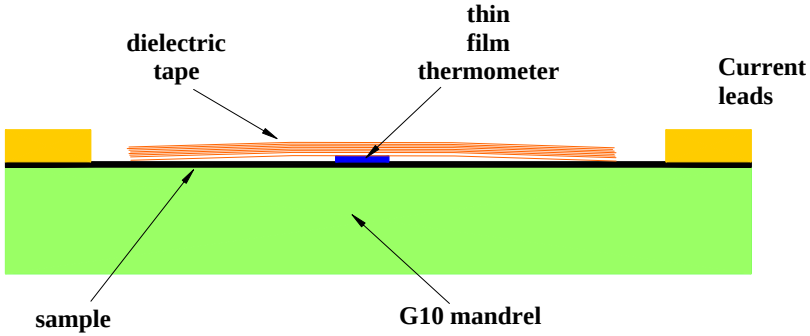
- **In a stack of two, 2-mm wide tapes, one tape was cut in two and the tapes were soldered to create low resistance joint**





Quench and stability measurements on short samples can help understand several issues

- **Role of copper thickness**
  - **Implications**
    - **Decrease in J_e**
    - **Eddy current losses from ac fields**
    - **Improves stability**
- **Sample length**
- **Splices**
  - **Impact on stability**
  - **Best practices**



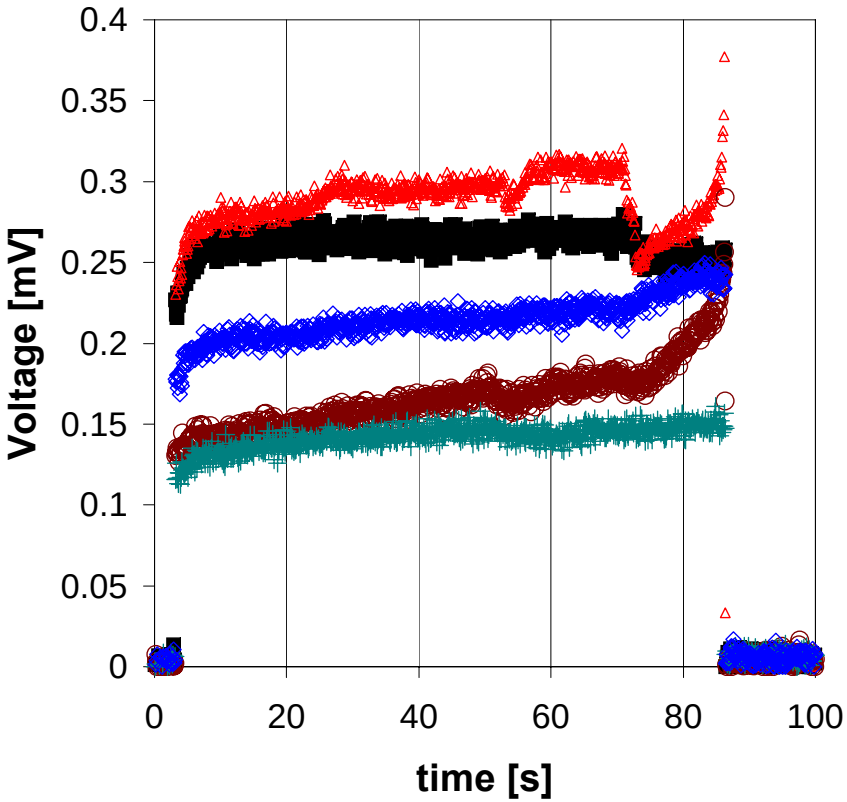
Insulated 77 K bath

Testing specifications

- **Sample**
  - **4-mm wide from Superpower**
  - **Length vary between 30 cm to 2 m**
  - **Copper thickness between 0 and 76 μm**
- **Currents**
  - **Steady state operation (I=const)**
  - **Fault current simulation ($I_{pulse} > I_c$)**

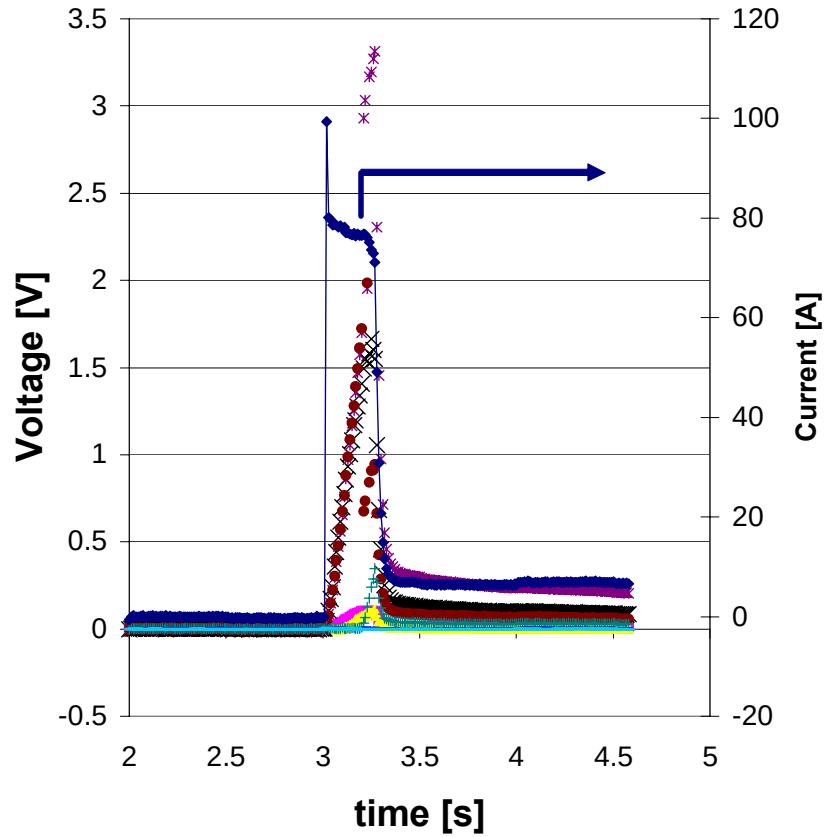
Examples of voltages for constant currents and impulse currents

I = constant ; thermal runaway



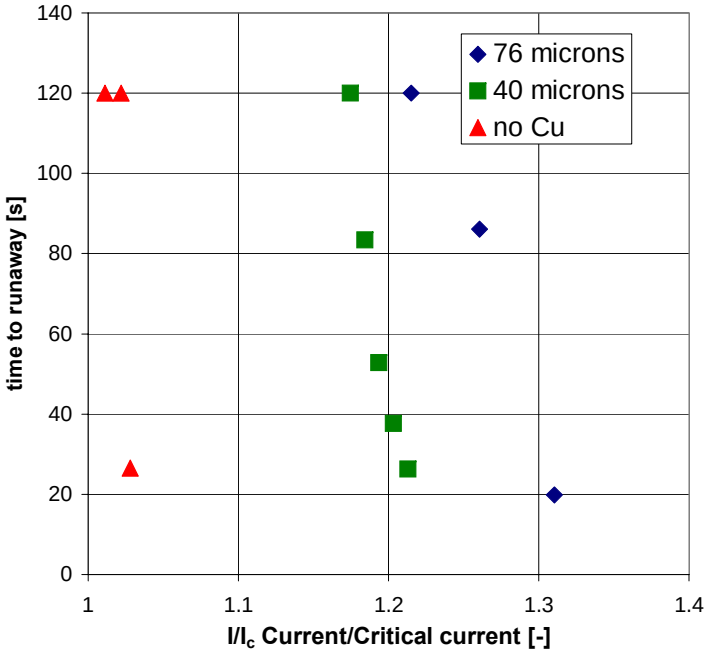
Voltage distribution for 4-mm wide sample with no Cu stabilization

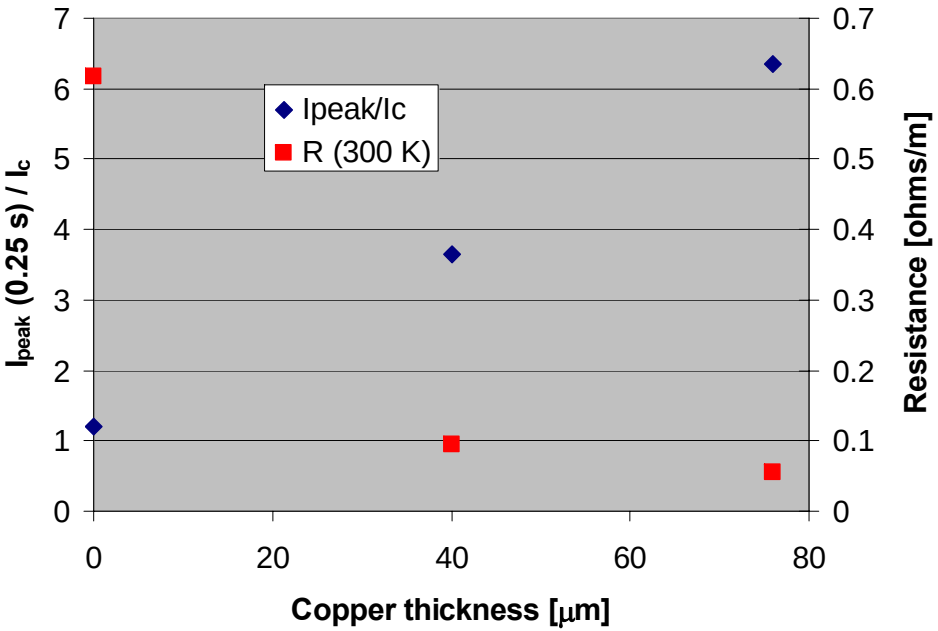
Impulse waveform



Over-current pulse 0.25 s long with operating current at 10% I_c

Nature of applied current determines impact of copper stabilization





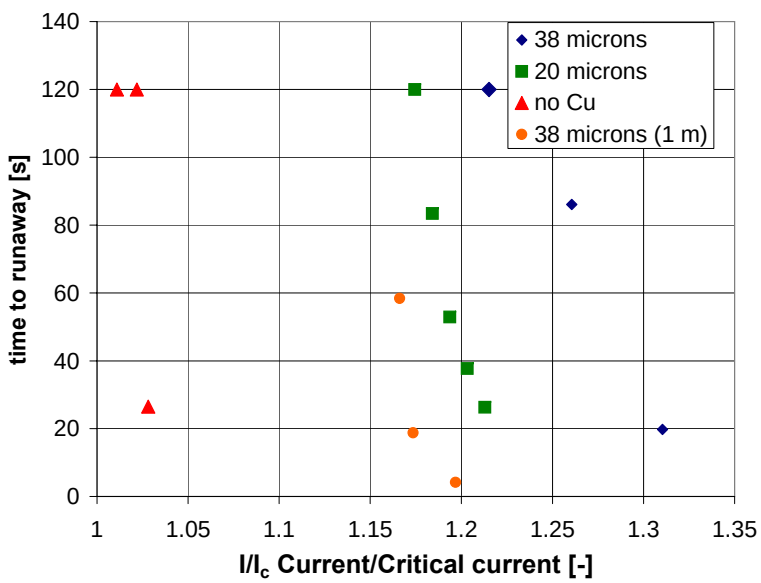
For constant currents, stability is more driven by thermal properties

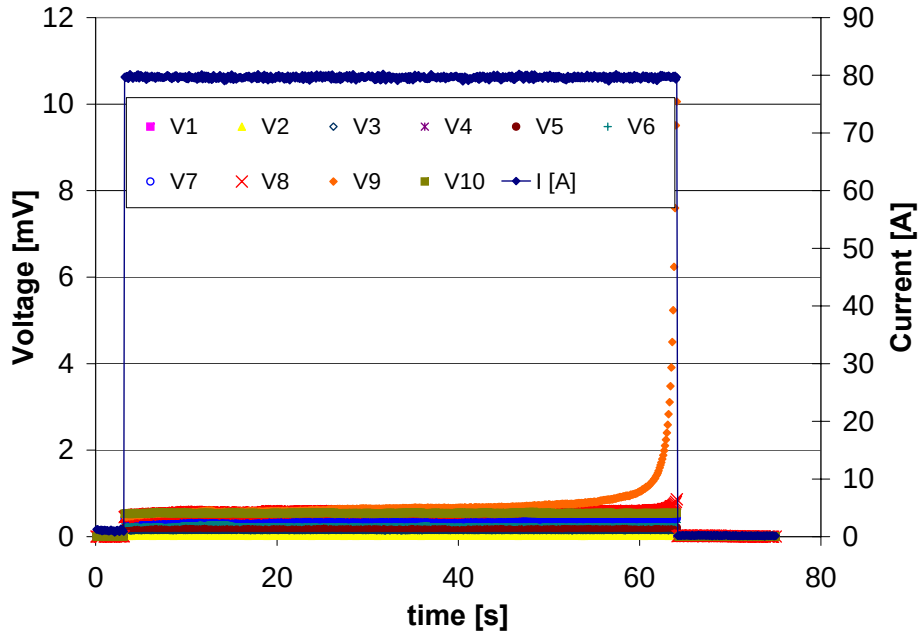
Transients are highly dominated by copper thickness

k(40 μm) – k(0 μm) > k(76 μm) – k(40 μm)

Thermal runaway current drops for longer lengths

- **Long length tapes (1 m) with 38 μm Cu surround stabilized YBCO tapes were insulated and the thermal runaway experiments repeated**
- **Less of conductor length exhibited runaway for longer length case**



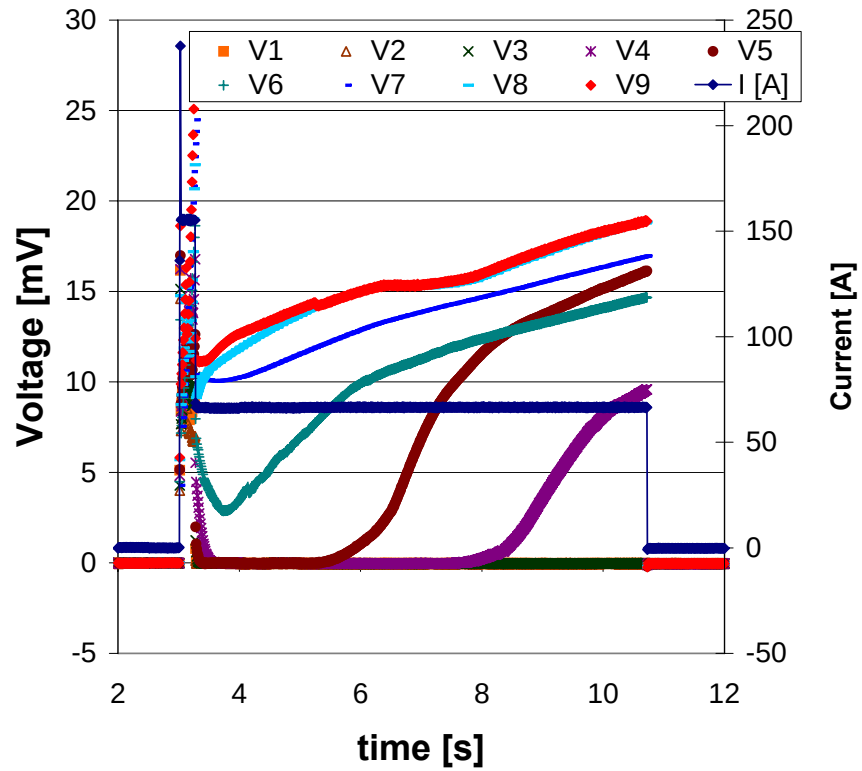


Thermal runaway in continuous piece of 1 m long

$$\frac{L(run.)}{L(30\ \ cm)} > \frac{L(run.)}{L(1\ \ m)}$$

Normal zone propagation speeds less than 1 cm/s observed for 38 μm case

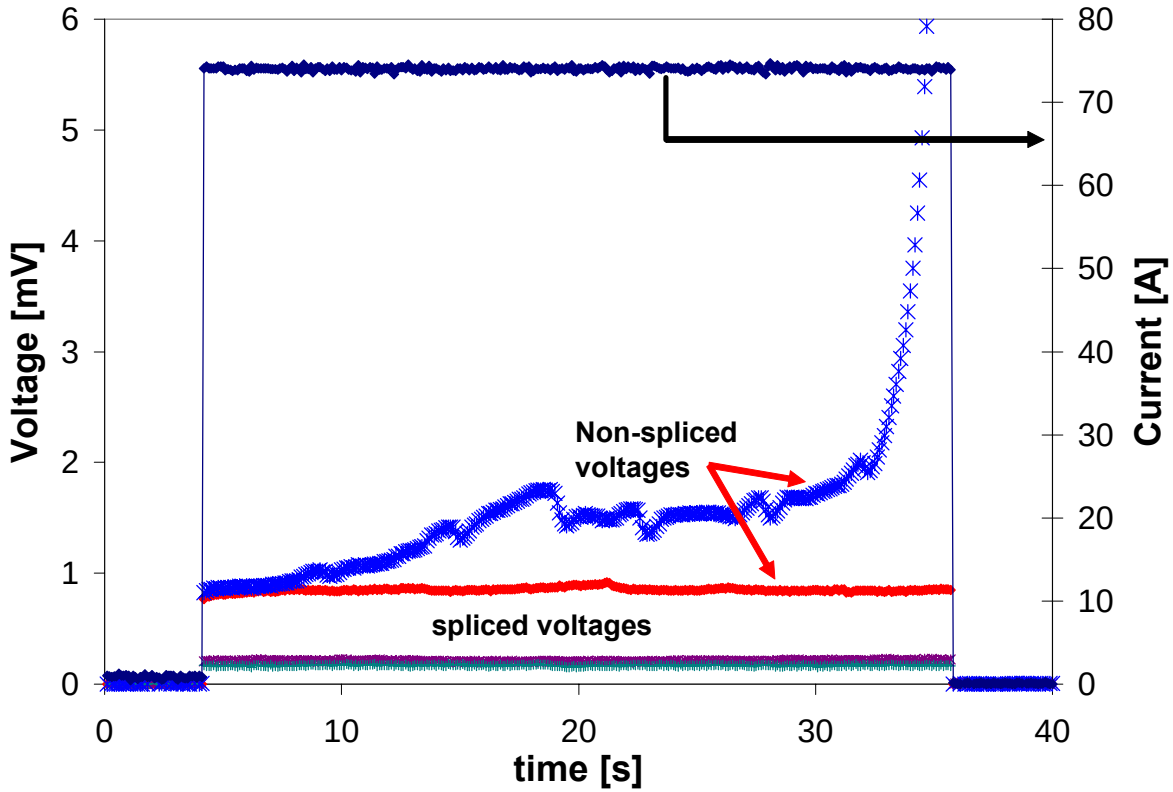
- Manipulation of the pulse current and the operating current that follows can produce propagation
- Non-uniformity of critical current over 2 cm had to be greater than 10% to localize heating in sample
- Operating current more of factor in propagation speeds than impulse current



I_{pulse} [A]	I_{pulse}/I_c [-]	I_{op} [A]	I_{op}/I_c [-]	Propagation speed [cm/s]
155.2	2.28	66.6	0.98	0.58
157.1	2.30	66.6	0.98	0.70
165.0	2.43	59.8	0.87	0.46
165.0	2.43	56.4	0.82	0.27
165.0	2.43	53.2	0.78	0.19

Splice did not affect the thermal runaway characteristics.

- Splice made at center of 1-m piece with 38 μm of Cu surround stabilizer shown in previous slide.
- R(77 K) < 1 μΩ with Sn-Bi solder.
- Thermal runaway current 74.3 A at time of 32 s. Previously this current was 74.8 A.
- Runaway occurs in non-spliced regions of the tape.

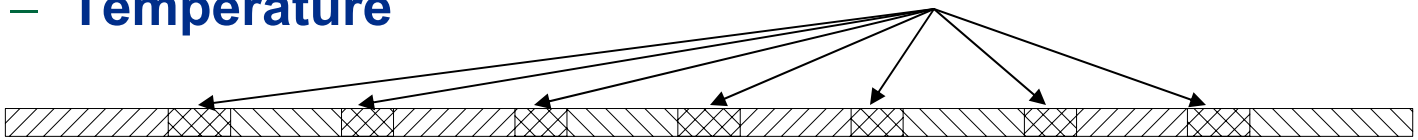


Database needed to determine best splice methods for given application

- **Motivation: Lack of non-proprietary information on best practices to produce low resistance solder joints/splice**

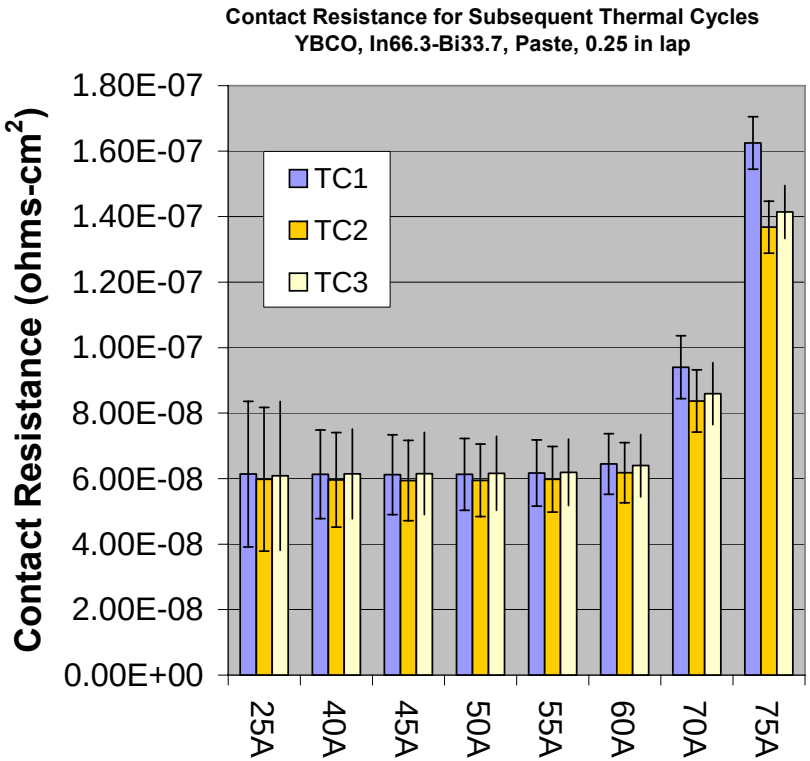
- **Parameters examined:**
  - **Tape type (BSCCO/YBCO)**
  - **Surface preparation**
  - **Surface area**
  - **Solder material**
  - **Temperature**

Measurements made over multiple joints at currents below I_c to generate statistics



Several different splice geometries have been examined

- **HTS tapes (4.4-mm wide)**
  - BSCCO
  - Brass-laminated BSCCO
  - Copper-laminated YBCO
- **Surface treatment**
  - Ruby Fluid
  - Solder Paste
  - Ethyl Alcohol
- **Solder**
  - Pb(60)/Sn(40)
  - In(66.3)/Bi(33.7)
- **Thermal cycles**

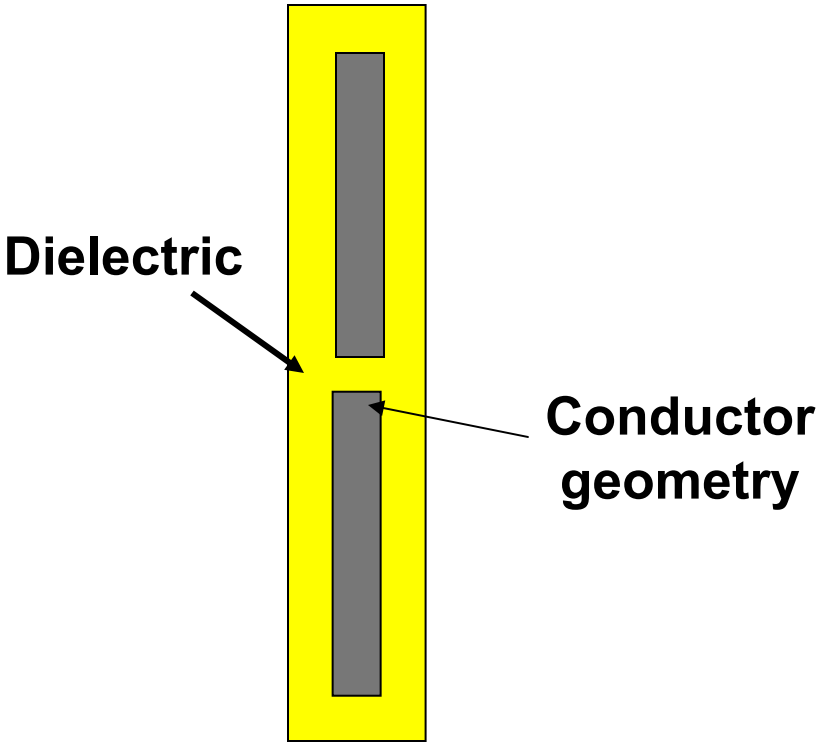


- YBCO splices 20% less than BSCCO splices for similar conditions
- Contact resistance between 3 x 10^{-8} Ω–cm^2 to 2 x 10^{-7} Ω–cm^2 measured
- Lowest resistance 3 x 10^{-8} Ω–cm^2 for 5 mm overlap with Pb(60)/Sn(40) solder

Dielectrics are a vital component in conductor integration into cryogenic applications

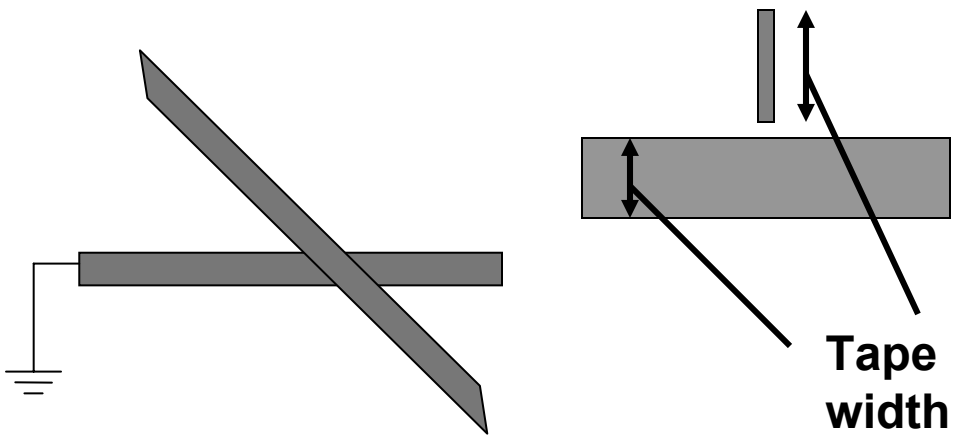
- **Motivation: Current dielectric materials use in cryogenic applications are conventional room temperature materials; more alternatives are needed**

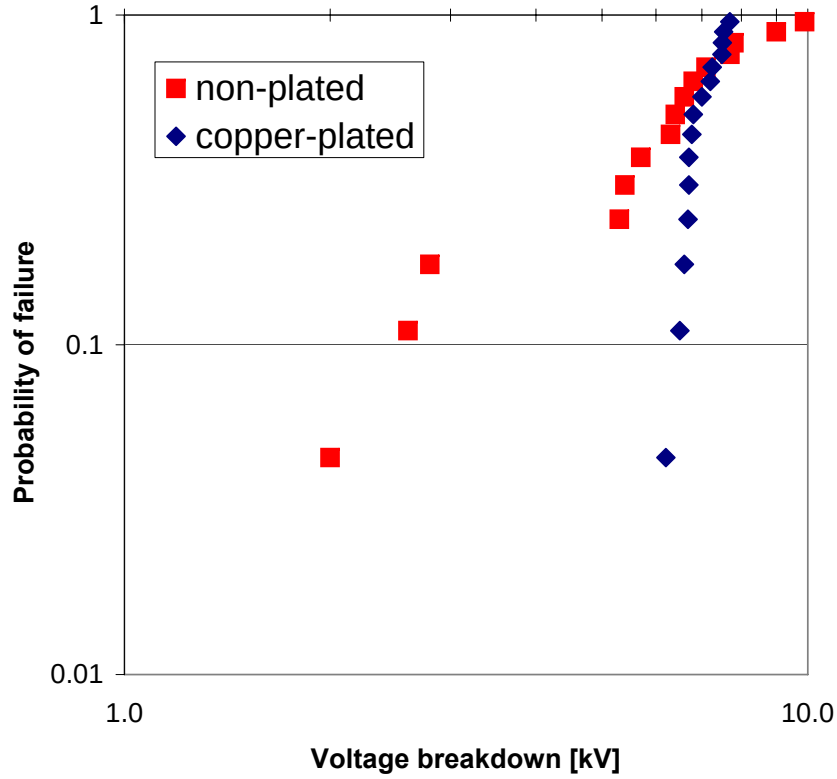
- **Desirable properties**
  - **Dielectric strength**
  - **Permittivity**
  - **Mechanical strength**
  - **Thermal conductivity**



Can breakdown initiation between two tapes be dependent on copper stabilization?

- **YES!**
- **In edge-to edge geometry, Cu-surround stabilizer in SuperPower YBCO tapes improved the characteristic breakdown when compared to as-slit YBCO tapes**

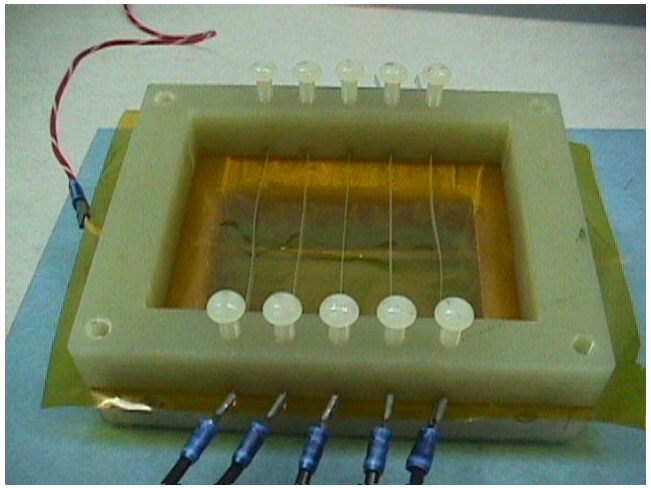




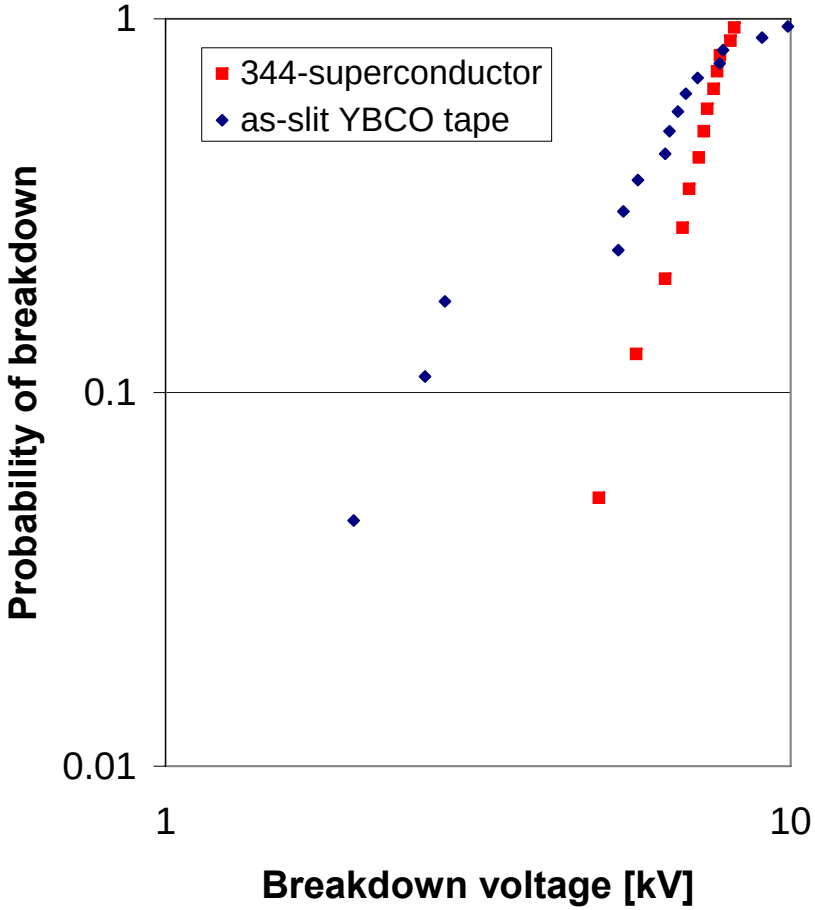
Is this effect prevalent in other copper stabilizations?

Cu-laminated YBCO tapes show improved breakdown voltages when compared to non-stabilized tapes

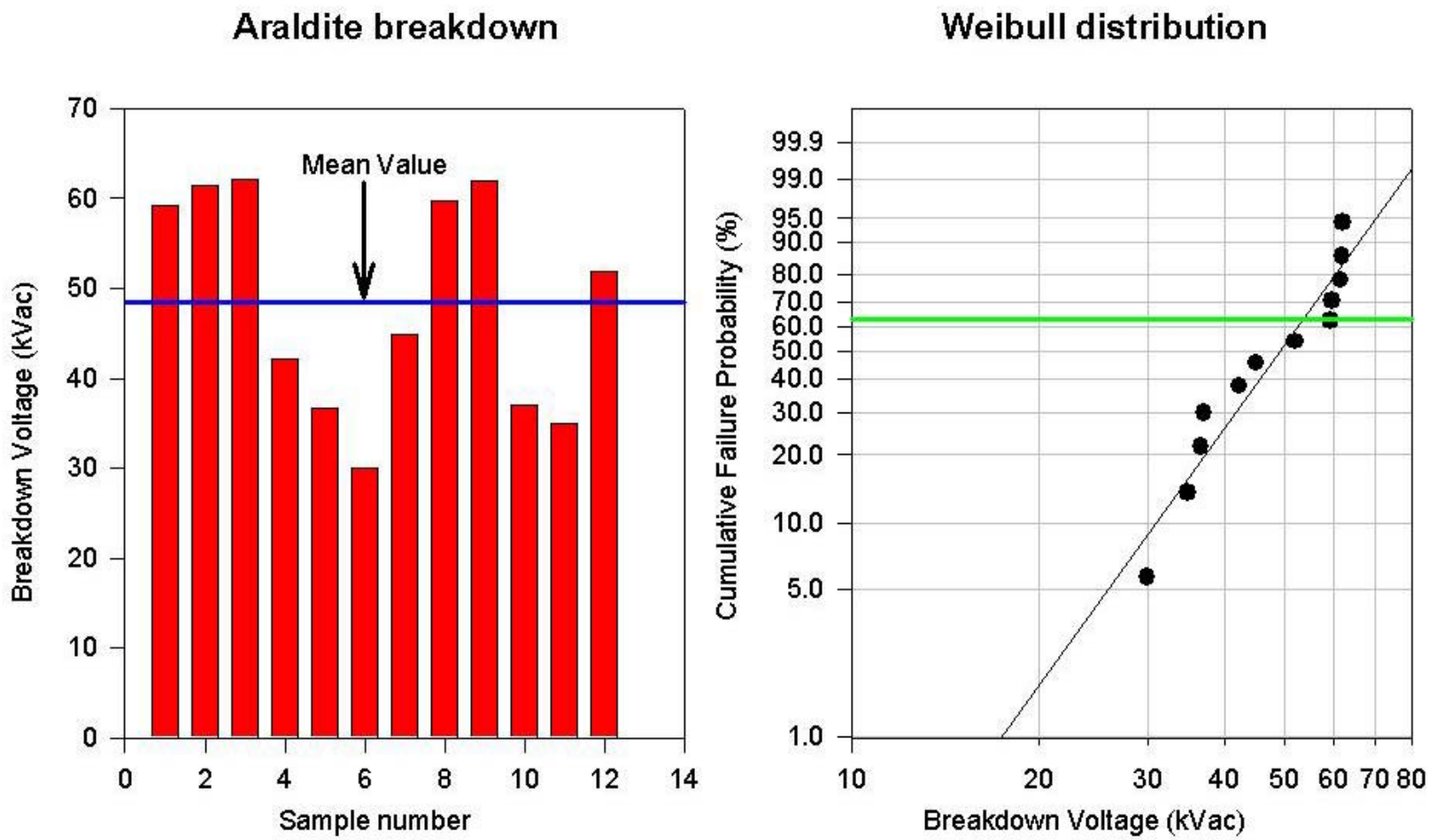
- **A set of 344-superconductor wires with 50 μm of copper lamination were placed in a cross configuration separated by 25 μm of Kapton**



- **Average breakdown voltage of 7.0 kV**
- **Improvement in breakdown comparable to copper plated YBCO tapes**



For those materials available only average values are available



Araldite samples are 0.5 mm thick; multiply breakdown voltage by x2 for Field strength

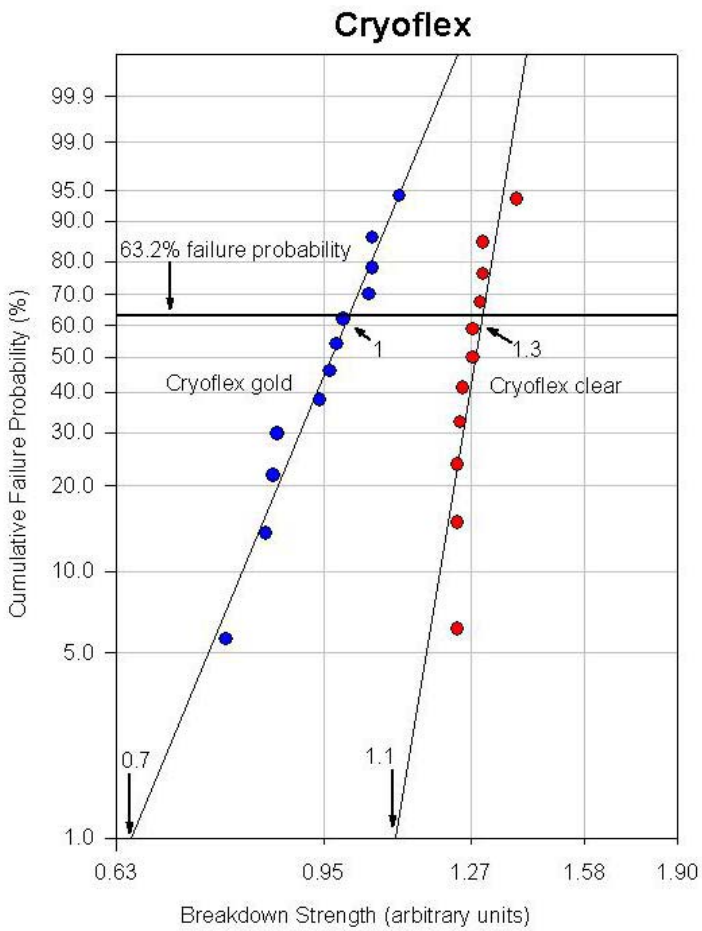
Experiment set up for multiple BD measurements

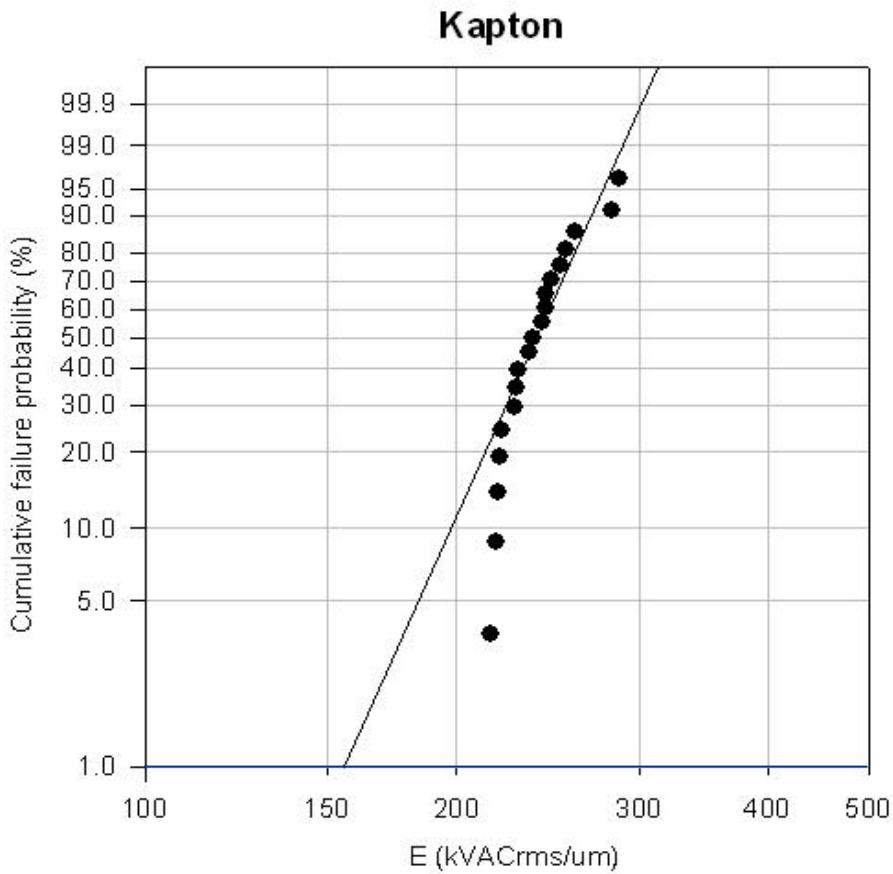
- **Multiple electrodes evaporated on polymer film permits multiple breakdown measurements**
- **Permits measurements without removing sample from LN2**
- **Statistical data allows assessment of data spread and resulting safety factor using, e.g. 1% breakdown probability or 0.1% or some other criteria**

Kapton film with 19 silver electrodes.

multiple electrode system in LN2

Breakdown data on dielectric tapes



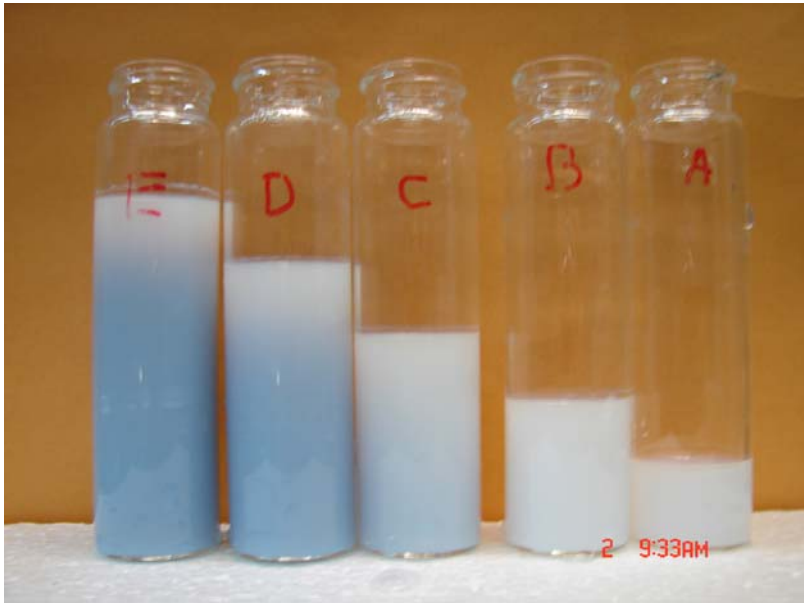


Nano-composites can benefit both dielectrics and quench and stability

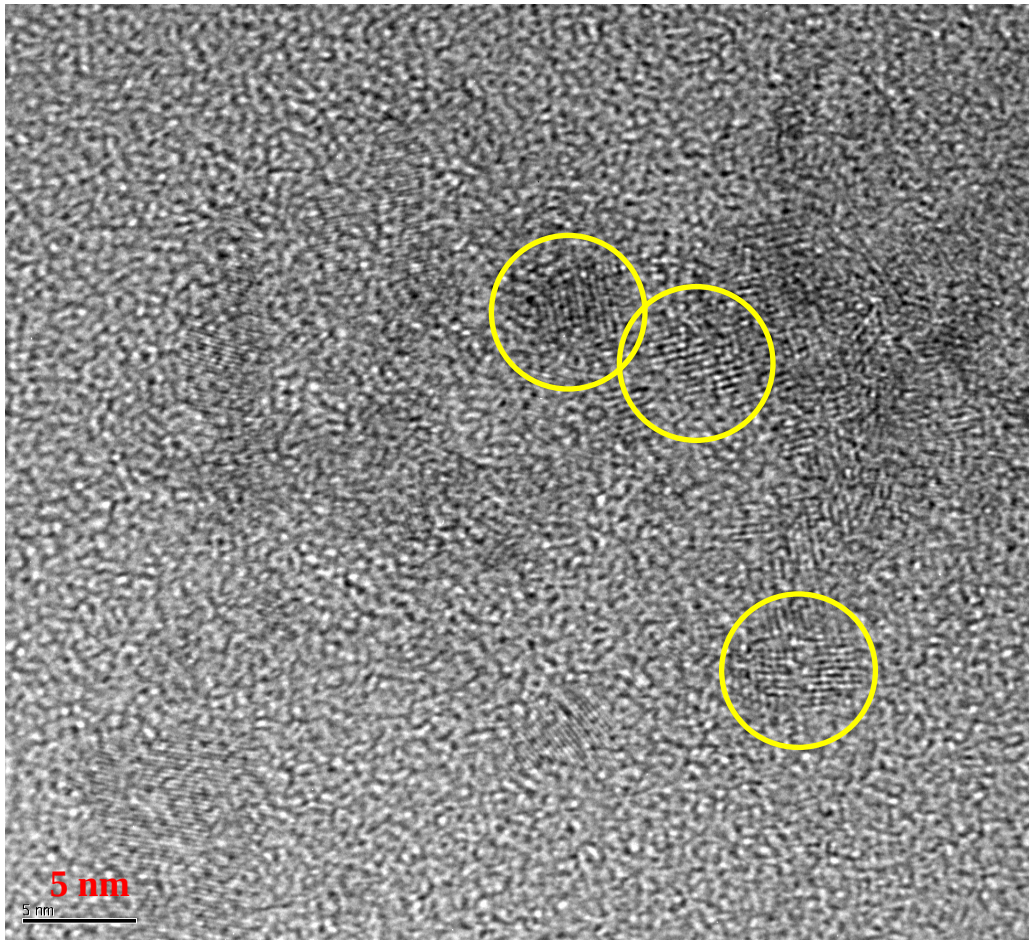
- **Challenge: To improve composite properties, additional materials are added to epoxies. However while improving some properties, these materials, micron size particles, can create sites/defects to initiate breakdowns**

- **Polymeric candidate material selected for which the breakdown strength increases with decreasing temperature.**

- **Nanoparticle filler at cryogenic temperature (open bath LN2 at 77K).**



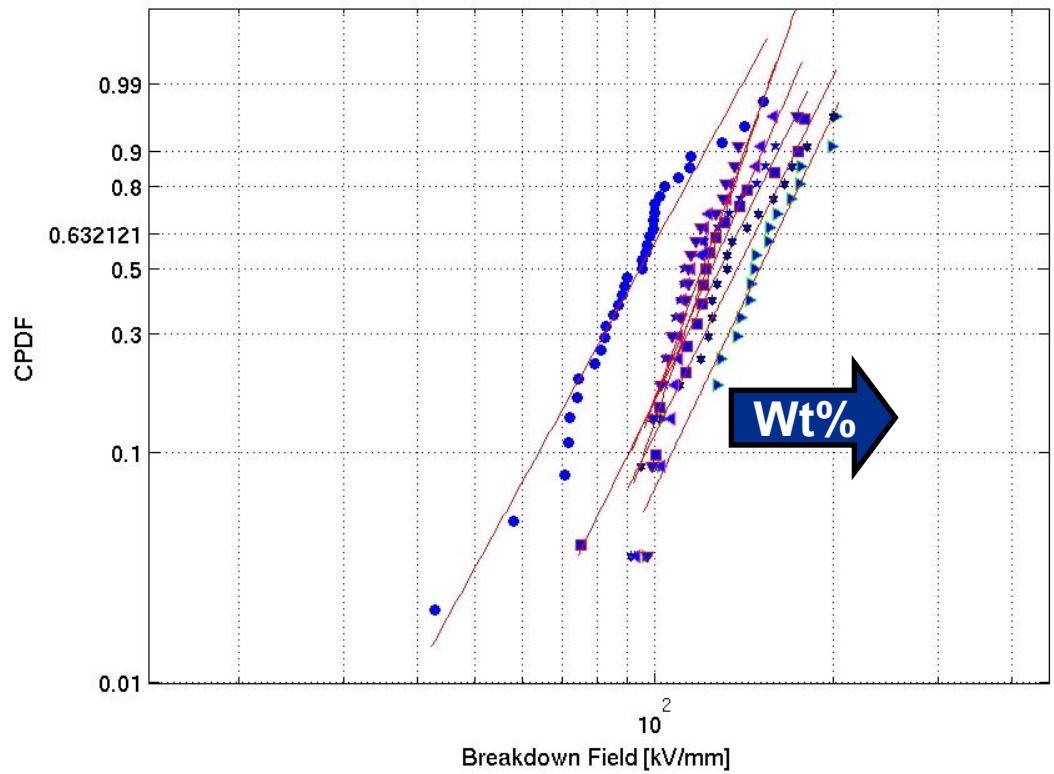
This work has utilized existing materials expertise at ORNL to understand nanoparticle inclusion



Dispersion of 5 nm nano- particles looks good and image consistent with improved breakdown results

Improved performance demonstrated

- Large filler lowers breakdown strength
- However nanoparticle composite increased in strength over the pure polymer.
- Increase in breakdown strength of polymer from approximately 95 kV/mm for the unfilled polymer film, to approximately 135 kV/mm for the nanoparticle composite, at a weight fraction of 0.08.
- Potential for improved thermal properties at cryogenic temperature



Short samples can only go so far..

- **Prototype devices can help see how short samples results can translate to applications:**
  - **Quench and Stability**
  - **AC loss (FM loss)**

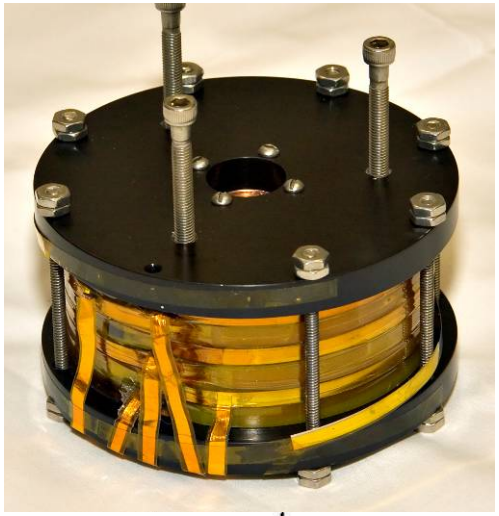
- **YBCO coil stability**
  - **Temperature**
  - **Cooling conditions**
- **HTS cables**

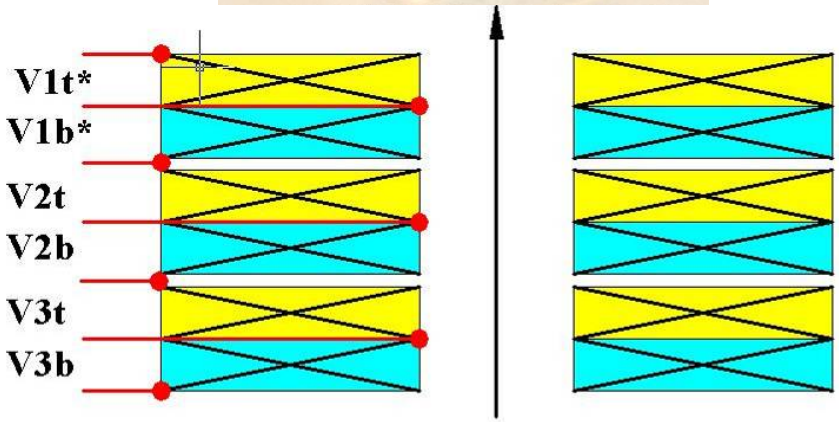
Stability study of YBCO coil carried out

Motivation: To determine if quench dynamics in YBCO coils similar to BSCCO coils

Magnet specifications

- Conductor type
  - 3-ply copper stabilized YBCO, 4.4 mm wide (344-2G, 2005)
  - 50 μm of Cu-lamination
- Magnet dimensions
  - 3 double pancakes
  - 120-m of 344 conductor
  - Ic(77 K) = 25 A*, Ic(30 K) = 100 A
  - Central field (z=0)
    - 0.32 T @77 K
    - 1.0 T @ 30 K

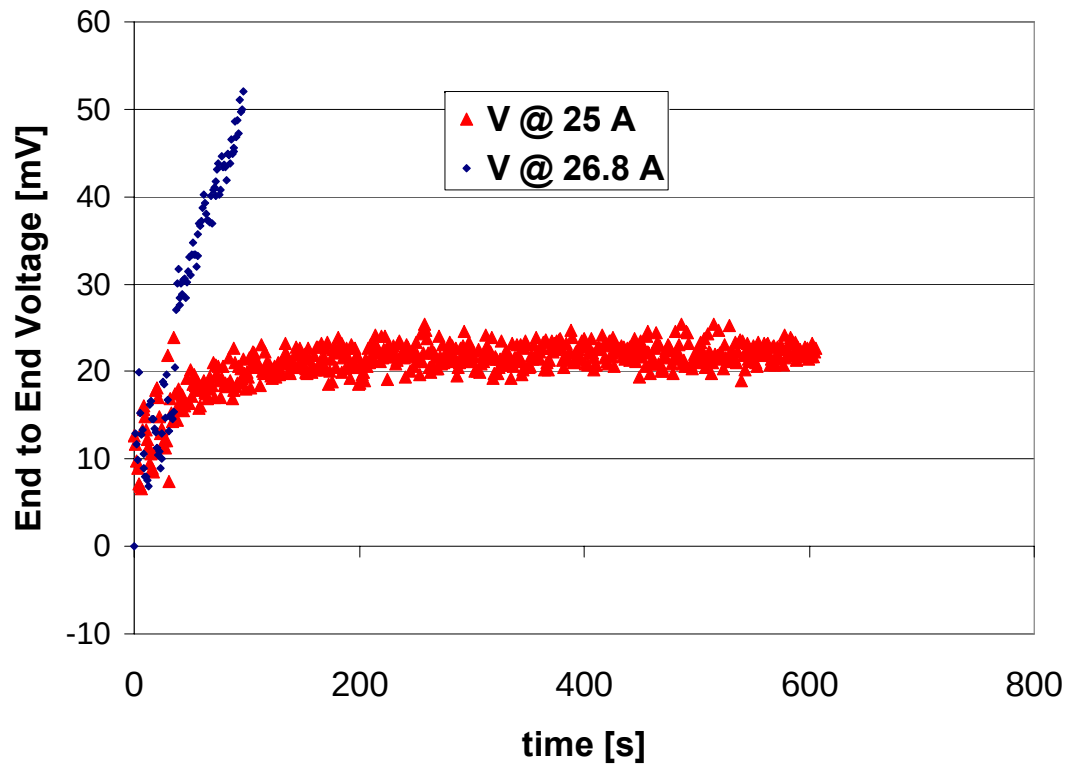




* Indicates splice within pancake

Stability of YBCO coil measured at liquid nitrogen and cryocooled conditions

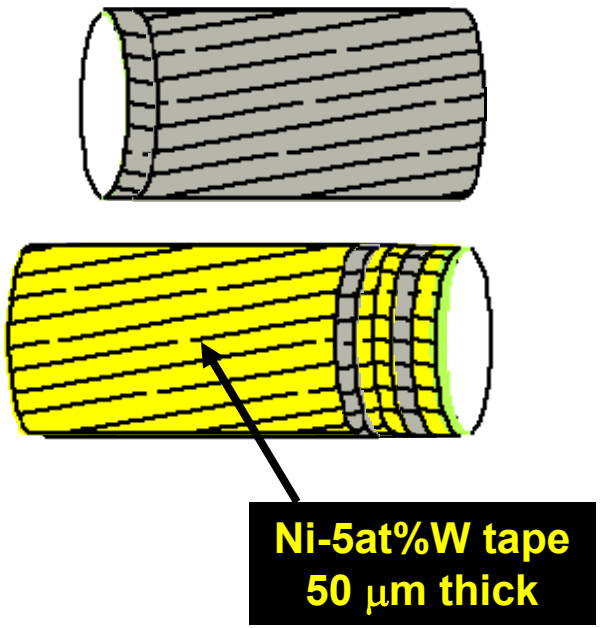
- No observable period before thermal runaway occurs
- Runaway current near I_c at 77 K. Much less than I_c for cryocooled conditions. Single tape result at 77 K was greater than $1.20*I_c$.
- When compared to thermal runaway in BSCCO coils, the sensitivity between runaway and stability is smaller for YBCO

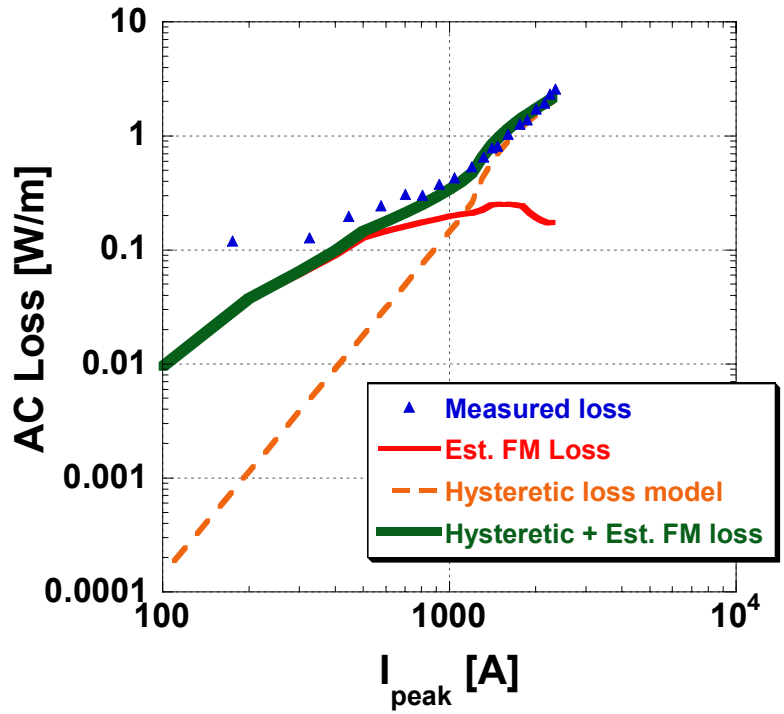


Comparison of voltages for coil in LN2 bath

Influence of Ni-5at%W examined in prototype BSCCO cables

- Two 1.25-m prototype cables in 2004
  - One cable made from two layers of 4.4-mm wide SS-BSCCO on 25.4 mm former (I_c= 3200)
  - Second cable made from two layers of 4.4-mm wide SS-BSCCO interwoven with 4.4 mm wide, 50 μm thick Ni-5at%W tape (I_c= 2200)



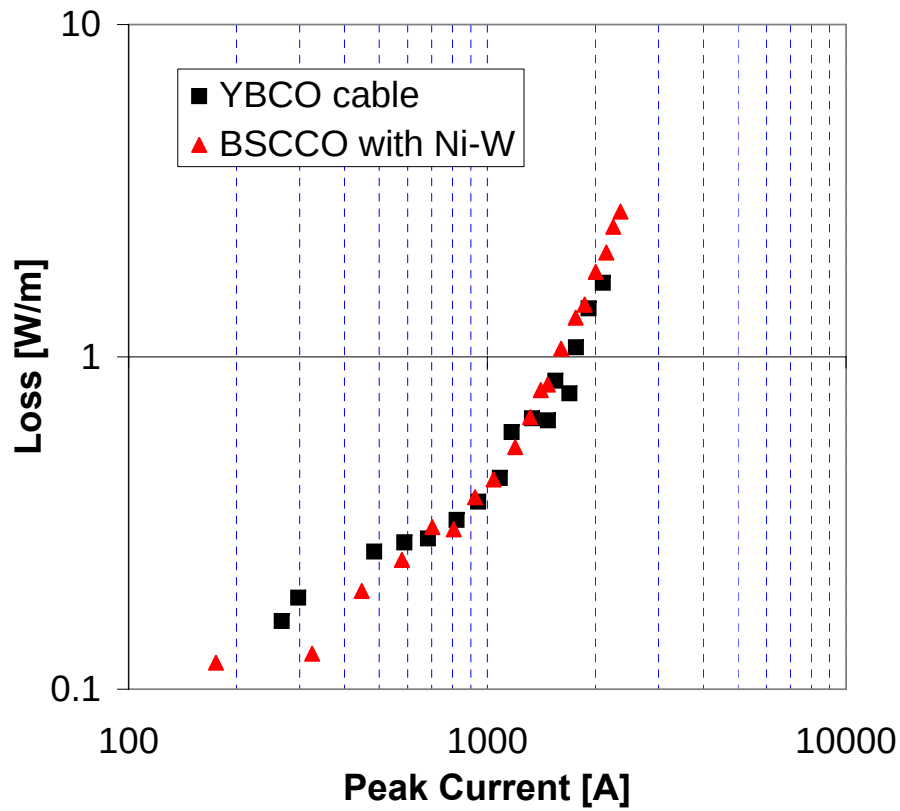


AC loss in cable with Ni-5at%W

- At operating currents, FM loss 10% or less of total ac loss
- With improvement in conductor performance, the FM contribution to ac loss and inductance should be less significant

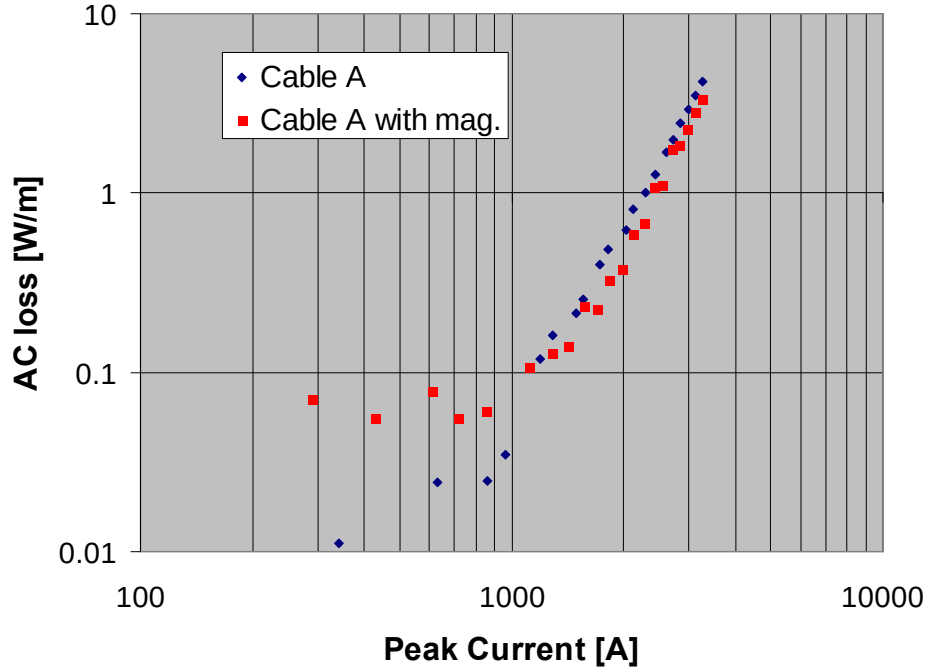
In new YBCO cable, dependence of ac loss on Ni-5at%W confirmed, slightly lower ac loss

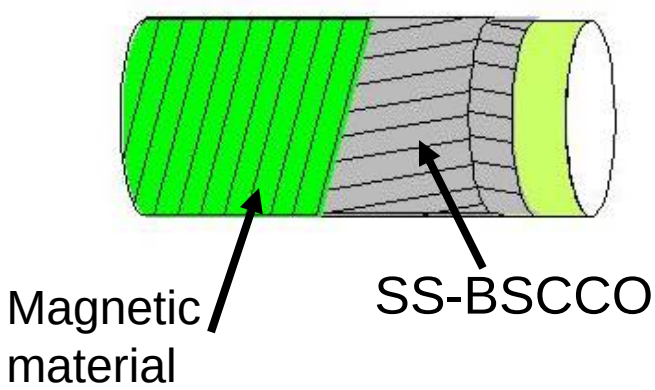
- **Cable specifications**
  - Two layers of 16 344-superconductor wires (I_c = 60-68 A per wire)
  - Former diameter of 25.4 mm (same as previous tests)
  - Projected I_c between 1920 A and 2116 A
- **Cable performance**
  - Critical current : 2100 A
  - AC losses were lower at higher operating currents
    - At a peak current of 1750 A, ac loss dropped from 1.4 W/m to 1.1 W/m



Alternative reduction of cable losses

- **Preliminary results indicate that the presence of magnetic material can reduce the ac loss in cables**
- **A thin magnetic tape was wound around the exterior of cable A to help direct fields between butt gaps in outer most layer**





- ***AC losses at higher peak currents reduced by 10-20%***
- ***At 2000 A_{rms} (2800 A_{peak}), Q/l reduced from 2.4 W/m to 1.8 W/m***

ORNL FY2006 Performance

FY 2006 Plan

- Understand the role of copper stabilization in operational limits and ac loss on non-filamentary and filamentary conductors
- Study how different techniques of Cu stabilization impact high voltage properties of superconducting tapes

FY 2006 Performance

- ✓ AC loss measured as a function of copper lamination for as-manufactured AMSC tapes
- ✓ Operation limits of SP tape as a function of copper thickness found for thermal runaway and impulse conditions
- ✓ Fundamental high voltage characterization of copper laminated tapes completed
- ✓ Characterization of copper surround stabilizer in turn-to-turn epoxy-potted conductors done

ORNL FY2006 Performance

FY 2006 Plan

- Establish experimental facilities to characterize reduction of ac losses of conductors made using both inkjet printing and laser scribing
- Develop and evaluate inkjet printing of YBCO and silver precursors for fabrication of low ac loss filamentary coated conductors

FY 2006 Performance

- ✓ Test facilities measure reduced ac losses in a series of YBCO solution samples with different filament widths produced via inkjet and laser scribing losses measured on a series of
- ✓ Inkjet equipment is operating.
- ✓ Filamentary YBCO and silver have been demonstrated.
- ✓ Progress on inkjet printing and processing is ongoing.

ORNL FY2006 Performance

FY 2006 Plan

- Measurement of stability and ac loss of YBCO coils and cables to better understand how tape properties impact applications
- Investigate the use of polymer-based epoxies with and without nano-composite materials with improved breakdown strength and electrical properties

FY 2006 Performance

- ✓ Stability of YBCO coil measured as a function of cooling conditions, temperature, and ramp rate
- ✓ AC losses and inductance measured in YBCO prototype cable
- ✓ **AC losses measured in cable with magnetic materials**
- ✓ Polymer-based composites found that have improved dielectric strength with the addition of increasing weight % of nanoparticles

FY 2007 Plans

1. Fabricate a pair of YBCO coils to serve as a test bed for advanced concepts in conductor stability, ac loss, and dielectrics.
   - Each coil will be dedicated to study ac loss and conductor stability separately and will be made of nominal 4-mm wide YBCO conductor with the ability to replace either a coil section or coil set to study how filamentization, tape splices, and thermal insulation improve the coil properties. Coil testing effort will be coupled with modeling to reduce testing and fabrication costs.

2. With existing equipment, expand ac loss measurement capability to lengths greater than 15 cm and fields of 200 mT and address the dependence of ac loss with respect to filamentization, conductor twisting, and assembled conductor geometries

3. Determine optimum bridge spacing and bridge resistance in SuperPower filamentary YBCO conductors with respect to quench and stability at 77 K and cryocooled conditions.

4. Examine different magnetic materials integrated into HTS cables for reduced ac loss

5. Evaluate thermal properties of nano-composite dielectrics with improved dielectric strength and determine impact on quench and stability in HTS devices

6. Demonstrate high rate conversion (~10Å/s) for filamentary inkjet YBCO with a J_c equivalent to that of a 1-cm width inkjet YBCO.

7. Identify a printable silver ink that is chemically compatible with YBCO with at least 80% retention of critical current.

Research integration

- YBCO conductor of lengths greater than 10 m have been provided through by AMSC and SuperPower via the working CRADA with ORNL to explore issues in conductor stability, ac loss, and dielectrics with respect to different substrates, stabilization, and width
- Results have been communicated to peers working on DOE SPI projects so conductor optimization can occur
  - Rockwell Automation sees property information on conductor performance as essential in the design process for future HTS motors
- Papers to be presented at 2006 Applied Superconductivity Conference on ac loss in filament conductors, YBCO cables, and YBCO coil performance

- This work has lead to producing additional collaborations
  - KEPRI: Examination of issues associated with the use of YBCO tape in large diameter cables. Testing with KEPRI staff on site will occur this August
  - AMSC/NRL DARPA project: Characterization of ac losses in low loss YBCO wires
  - AMSC/ORNL STTR Phase II project: Low cost inkjet fabrication of 2G wires for ac applications

Publications from this project

- **Rey, C.M. and Duckworth, R.C., *Critical Current Measurements of a 2G YBCO Coil –* IEEE Trans. Appl. Supercond. 2007**
- **Gouge, M.J., Demko, J.A., Duckworth, R.C., Rey, C.M., Lindsay, D.T., Roden, M.L., and Tolbert, J.C., *Testing of an HTS Power Cable Made from YBCO Tapes* - IEEE Trans. Appl. Supercond. 2007**
- **Duckworth, R.C., Paranthaman, P.M., List, F.A., Gouge, M.J., *AC losses in YBCO coated conductors with inkjet filaments -* IEEE Trans. Appl. Supercond. 2007**
- **List, F.A., Kodenkandath, T., Rupich, M., *Fabrication of Filamentary YBCO Coated Conductor by MOD Inkjet Printing* - IEEE Trans. Appl. Supercond. 2007**
- **Tuncer, E., Sauers, I, James, D.R, and Pace M.O., *Breakdown statistics of polyimide at low temperatures,* to be presented at the 2006 CEIDP in Kansas City**