Applied R&D of 1st and 2nd Generation HTS Conductors

M. J. Gouge, D. K. Christen, R. C. Duckworth,

D. F. Lee, J. W. Lue and J. R. Thompson

Oak Ridge National Laboratory

DOE 2004 Peer Review

July 27-29, Washington, DC

FY 2004 Goal and Objectives

Project Level Goal: The purpose of this R&D project is an investigation of HTS conductor design optimization with emphasis on stability and protection issues for YBCO wires and coils applied to electric power devices.

Budget: $150K

FY 2004 Objectives

- ✓ **Study the impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerances**
- ✓ **Characterization of NiW substrate as it pertains to ac losses and inductance in YBCO cables (new task)**
- ✓ **Over-current testing of single HTS tapes (BSCCO and YBCO) with stabilization (new task)**
- – **Normal zone propagation and stability margins will be measured in a series of copper-stabilized YBCO and BSCCO with different copper thicknesses and joining techniques. These tests will be performed at temperatures between 40 K and 80 K**
- – **A 1-Tesla HTS coil will be made with YBCO conductor, instrumented and tested to determine operating envelope and stability margins**
- – **Plan to make a YBCO cable with ~ 4-mm wide 2G tape.**

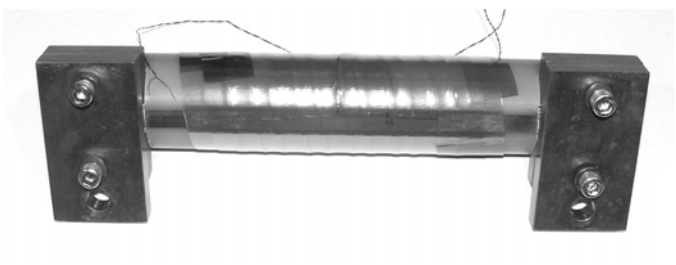
Motivation/background

- Stability and protection are crucial issues for HTS tapes and coils applied to electric power devices.
  - Both in normal operation (for example, conductor motion during a transient, conductor hot spot)
  - From an external event such as a short circuit (e. g. fault current in HTS cables) or loss of cooling
- Minimization of AC losses is a key issue for the economic argument for HTS AC applications like cables, FCLs, inductors and transformers.
- Conductor design is important to optimize several diverse parameters such as cost, performance and reliability (protection, stabilization).

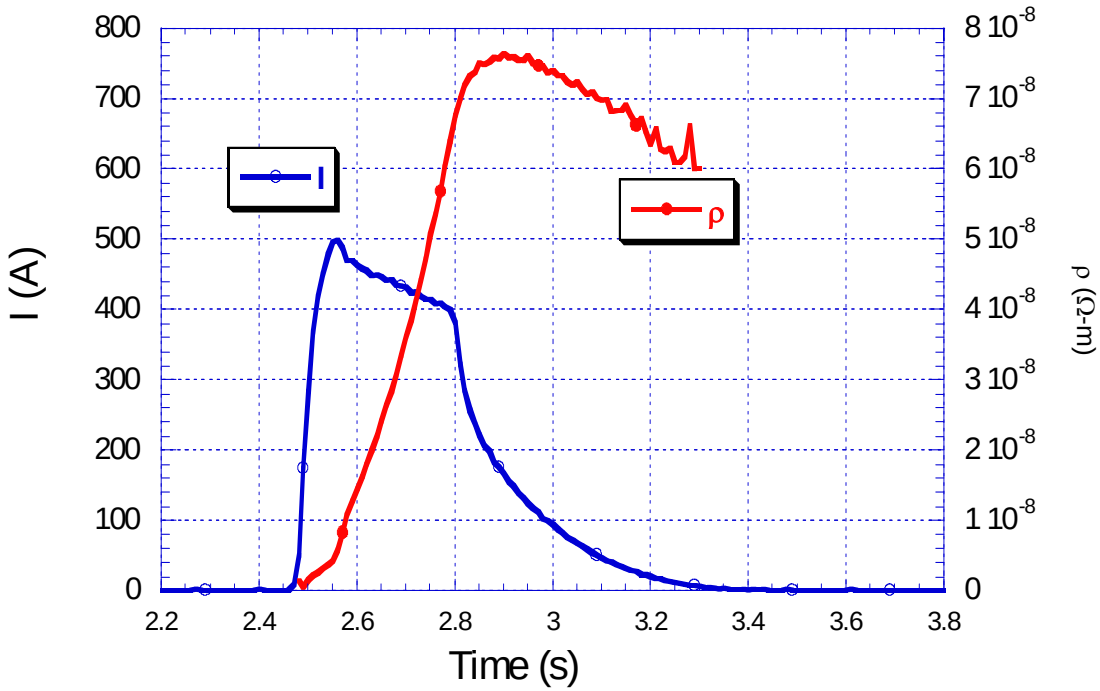
Over-current Pulse Limitation Tests of BSCCO and YBCO Tapes

- 20-cm long HTS tapes were laid straight on a G-10 cylinder and covered with layers of Cryoflex dielectric tapes to simulate HTS cable construction
- tested in liquid nitrogen bath
- To study the effect of reducing the peak conductor temperatures, samples with an extra Cu-strip (3.05 mm x 0.25 mm) laying on top of the HTS tape were also tested, electrically connected at each end

Configuration	Sample
1	Cu-plated BSCCO (15 microns of Cu, both sides)
2	Cu-plated BSCCO + 1 Cu strip
3	Stainless steel laminated BSCCO
4	1 ss-BSCCO + 1 Cu strip
5	Cu-laminated YBCO (50 microns of Cu, one side) (from AMSC)
6	Cu-laminated YBCO + 1 Cu strip
7	2 strips of Cu



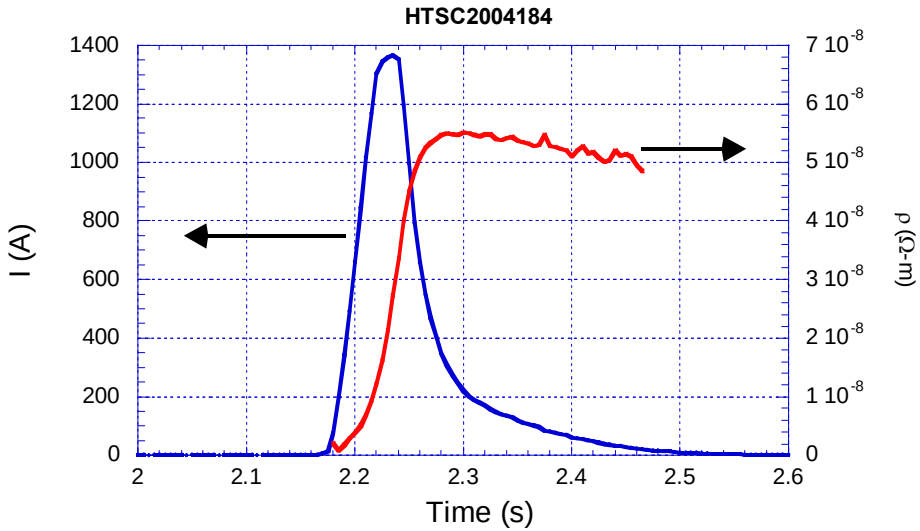
Resistivity change of the conductor is found to be the best indication of the temperature rise

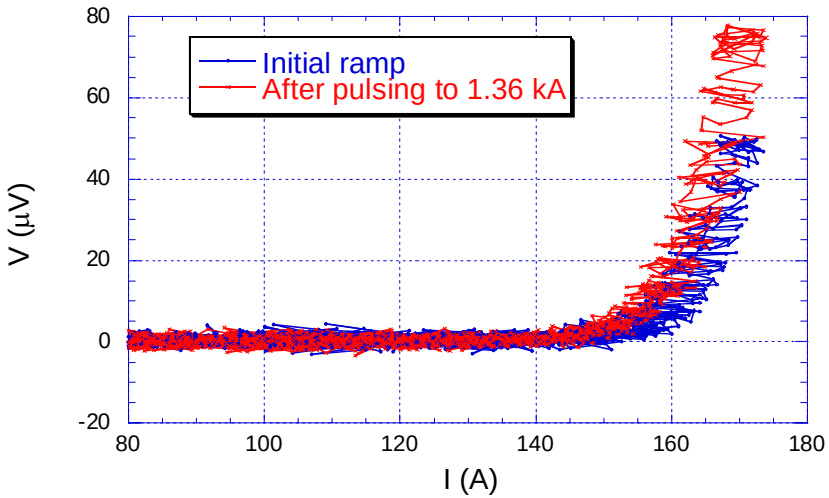


- The resistivity of the Cu-plated BSCCO tape (1) increased rapidly during an over-current pulse.
- For a 450-A, 320-ms pulse, the peak resistivity of 7.6 x 10^{-8} Ω-m corresponds to a temperature of 720 K.
- No degradation was observed until a slightly longer pulse of 450-A, 330 ms was applied, resulting in 800K peak temperature. I_c was reduced from 119 to 50 A.

BSCCO tape: 4.27 x 0.25 mm including 15 micron of Cu plating

Electro-mechanical limits of YBCO tape (Configuration 5)

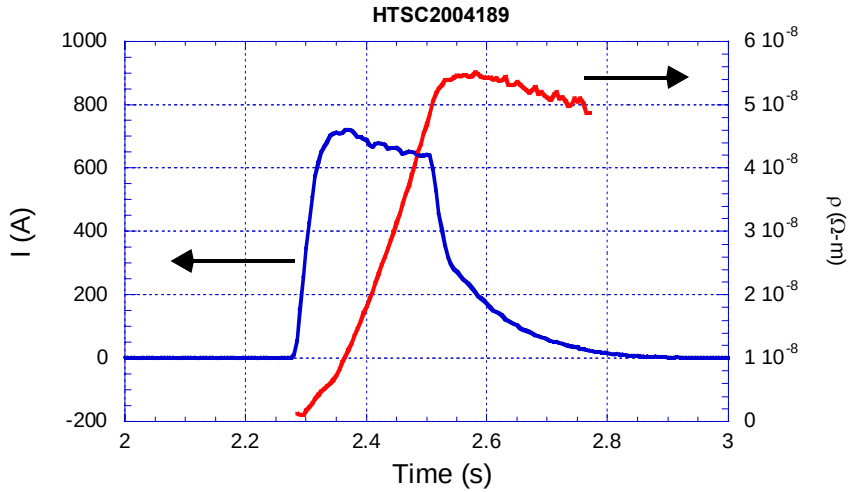


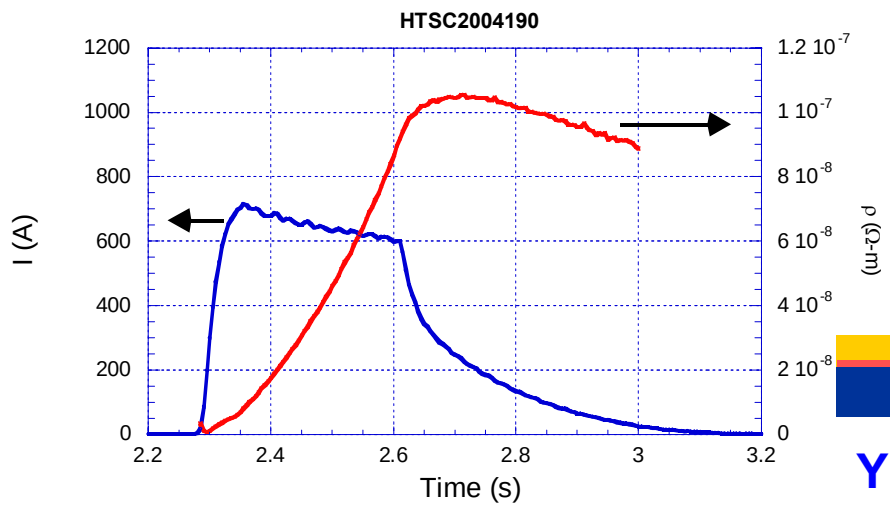


- Pulse length was reduced to 35-60 ms and as high a current as could be achieved was used in this series of tests.
  - Simulate 1st half-cycle EM forces
- No change in V-I curve was observed after pulsing to 1.23 kA (temperature transient to 335 K)
- Critical current decreased from 161 A to 157 A after a pulse to 1.36 kA (peak temp of 370 K).
- As a result of the 1.36 kA pulse, the tape was subjected to a buckling stress of 0.38 MPa (56 psi).

YBCO : 10 x 0.15 mm with 75 micron NiW substrate and 50 micron of Cu

Thermal Limitation of YBCO Tapes (Configuration 5)

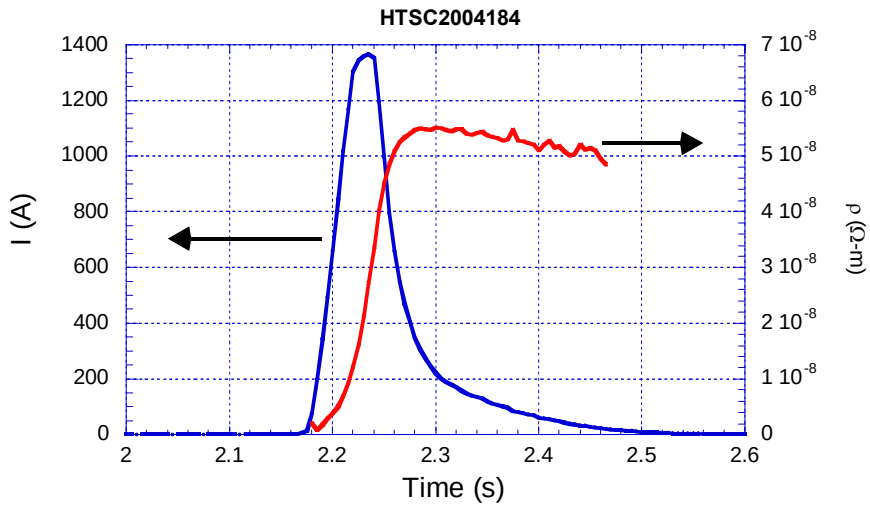


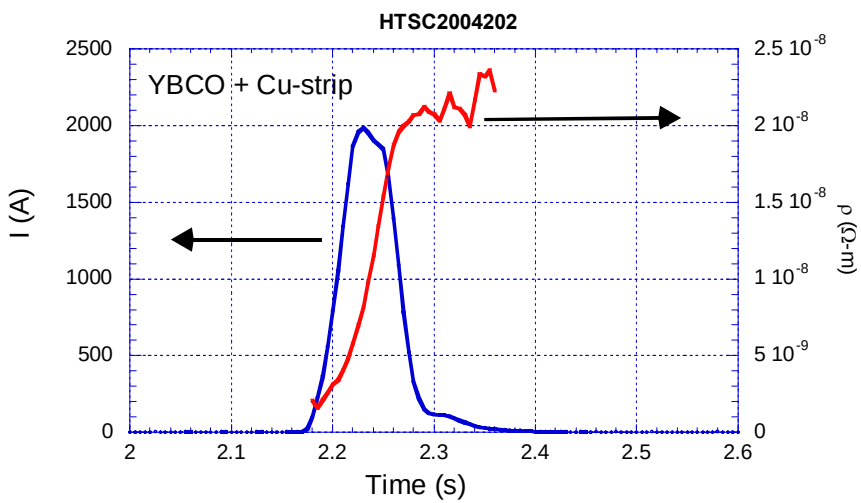


- For these tests the pulse length was extended x10 to 200-300 ms.
- The resistivity of the YBCO tape increased rapidly during an over-current pulse.
- For a 675-A, 200-ms pulse, the peak resistivity of 5.5 x 10^{-8} Ω-m corresponds to a temperature of 370 K.
- For a 655-A, 330-ms pulse, the peak resistivity of 1.05 x 10^{-7} Ω-m corresponds to a temperature of 670 K.
- After the 330-ms shot the YBCO was severely degraded – I_c decreased from 160 to 90 A.

YBCO : 10 x 0.15 mm with 75 micron NiW substrate and 50 micron of Cu

Much improved tolerance with added Cu-strip (configuration 6)



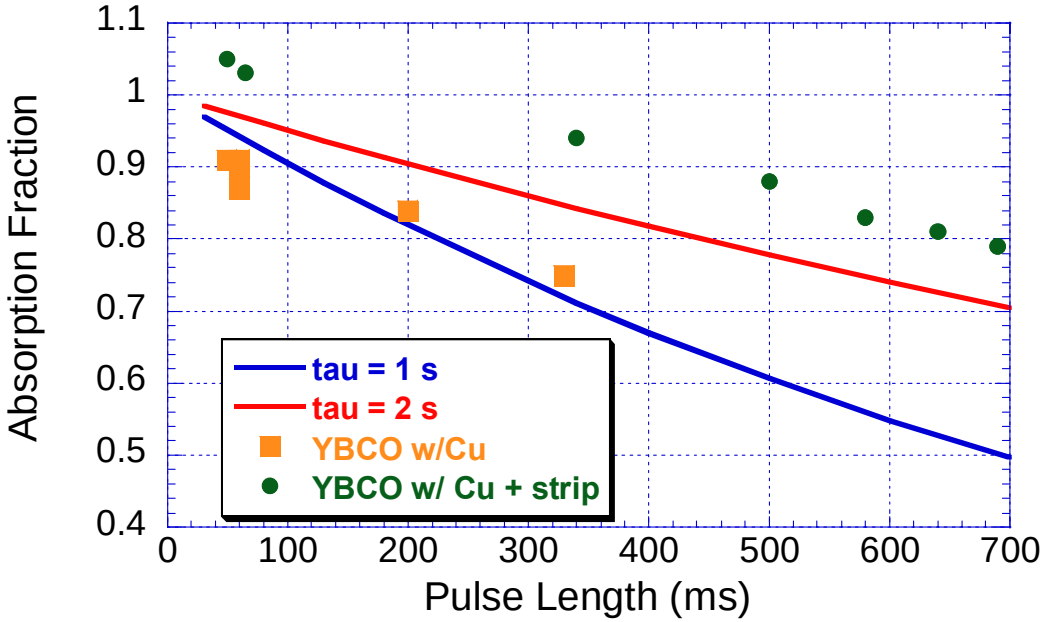


- With an added 3 mm x 0.25 mm Cu-strip the peak current was increased to 2.0 kA.
- The peak conductor temperature, however, decreased from 370 to 240 K.
- There was also no change in V-I curve after the 2-kA pulse.
- Both the over-current and pulse duration tolerances were about doubled with the added Cu-strip

YBCO : 10 x 0.15 mm with 75 micron NiW substrate and 50 micron of Cu

Near adiabatic effect for short pulses

- Ratio of heat absorbed by sample to the measured V-I product shows that the majority of the energy is absorbed by the conductor (HTS + Cu stabilizer)



Electro-mechanical and Thermal Limitations/Summary of Benefits

- **No electromechanical damage was found for short (less than 50 ms) current pulses to 1-1.3 kA for BSCCO and YBCO tapes**
- **The HTS tapes can be heated to the 500-600 K range by over-current pulses without suffering from degradation**
- **The addition of a Cu-strip can enhance the tolerance to the over-current magnitude and pulse length very significantly**
  - Both the over-current and pulse duration tolerances were about doubled with an added Cu-strip.
- **The temperature of the conductor appears to increase with over-current pulse length exponentially; it is prudent to limit the design peak temperature to 200 K or less.**

YBCO prototype applications R&D

1-T YBCO Coil

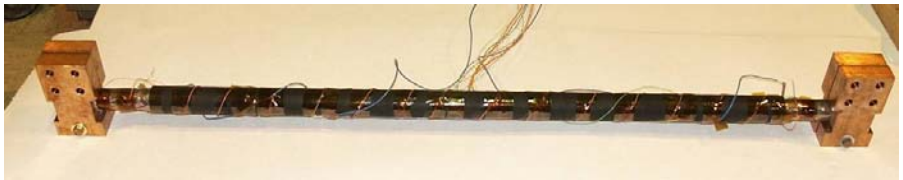
- Funding limitations resulted in only completion of coil design this year- ORNL plans to build and test the coil in FY 2005
- AMSC has improved their YBCO tape performance to a critical current of 270 A/cm-width (March 2004)
- Can a 1-T coil be made in boiling nitrogen (77 K)?

YBCO cable with ~4-mm wide tape

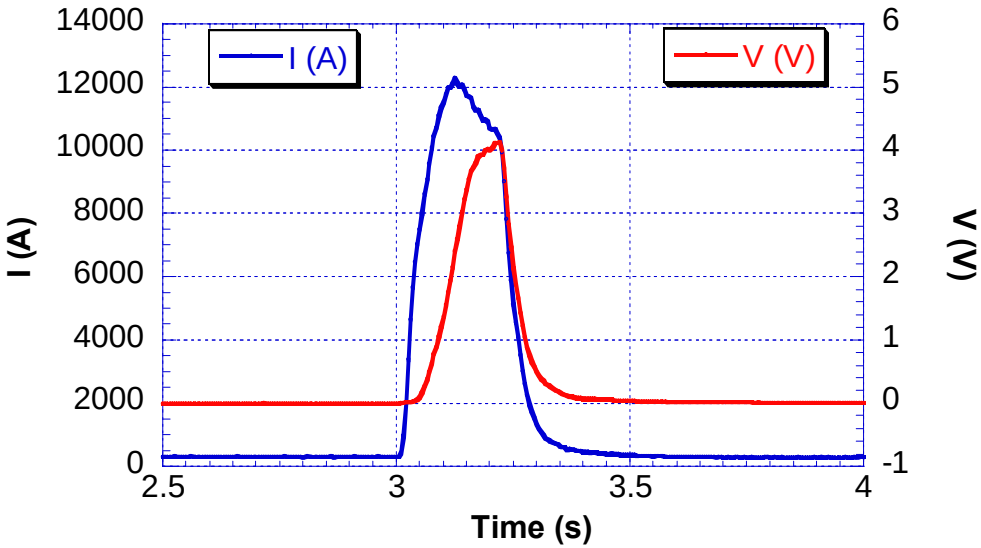
- Funding limitations and availability of 4-mm YBCO tape in sufficient length precluded cable fabrication this year
- Cable will be similar to the 1.25-m long YBCO cable built in 2003 and reported at last year's Peer Review.
  - conducted over-current testing of this cable in August 2003

Over-current testing of 1.25-m YBCO cable

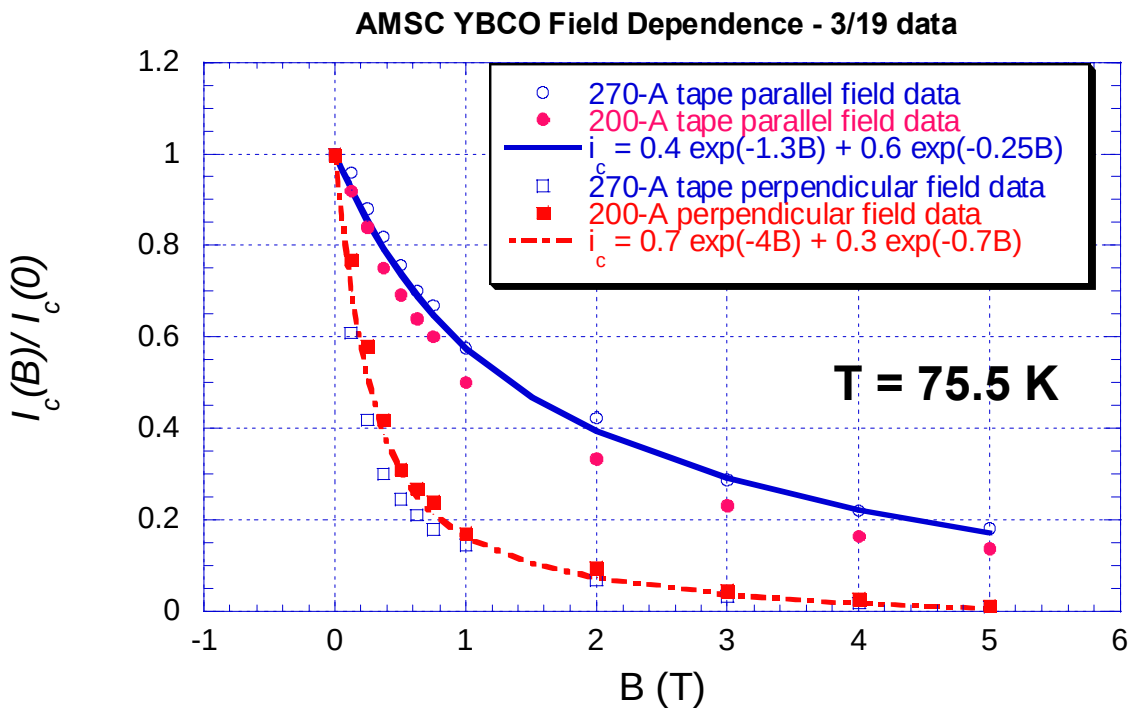
I_c = 4200 A
n = 28



- Fault currents up to 12 kA were applied to the YBCO cable.
- Pulse lengths of 0.1 and 0.2 s were used to simulate 6 and 12 cycles of short circuit faults.
- The figure shows the over-current waveform for a peak current of 12 kA for a nominal duration of 0.2 s on the YBCO cable.
- The cable survived with a temperature rise to about 105 K at the end of the pulse.
- The cable showed no degradation of critical current after the sequence of over-current pulses.



Curve Fitting of YBCO B-Field Dependence Data



- **Both the parallel and perpendicular field dependences can be fitted with the sum of two exponential functions.**
- **For a 270-A self-field tape, I_c = 155 A @ 1-T parallel field or 0.2-T perpendicular field.**

Possible 1-T YBCO Coils @ ~77 K

B_0= 1 T, I_{op}= 120 A, T_{op}= ~77 K

Bore	1” 2.54 cm	2” 5.08 cm
OD	2.38” 6.04 cm	3.62” 9.20 cm
Height	1.98” 5.03 cm	2.37” 6.03 cm
Tape length	59 m	139 m
$B_{r\text{-}max}$	0.27 T	0.39 T
I_c @ $B_{r\text{-}max}$	131 A	101 A
Inductance	3.7 mH	16 mH

- A coil current of 120 A – 77% of I_c (1 T) is used for the design
- Winding current density = 6 kA/cm^2 (includes insulation)
- For the 2”-bore design, the I_c for the coil end radial field is smaller than the design current – doubling of the YBCO tapes for the inner turns of the end pancakes is required

Coil Protection - hot spot calculation

Cu-laminate thickness	**50 μm**	
Tape normal resistivity @ 77 K	**6.9 x 10^{-7} Ω-cm**	
Conductor current density	**8,054 A/cm^2 (with stabilizer)**	
Quench detection time	**1 sec**	
Dump decay time constant	**1 sec**	**5 sec**
T-max	**126 K**	**220 K**

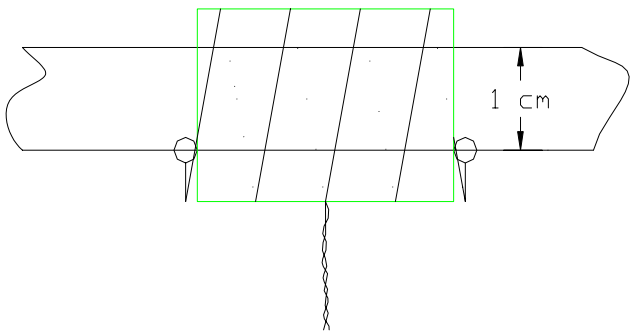
- Because of the slow normal zone propagation, a quench detection (and delay) time of ~1 sec may be required.
- Coil inductances of 3.7 and 16 mH are estimated for the present coils – a dump decay time constant of 1 sec or less can be achieved easily with external dump resistors.
- However, the hot spot temperature may be too high for a larger coil with a dump decay time constant of 5 sec or more.
- Thicker Cu layer is also required for higher conductor current densities.

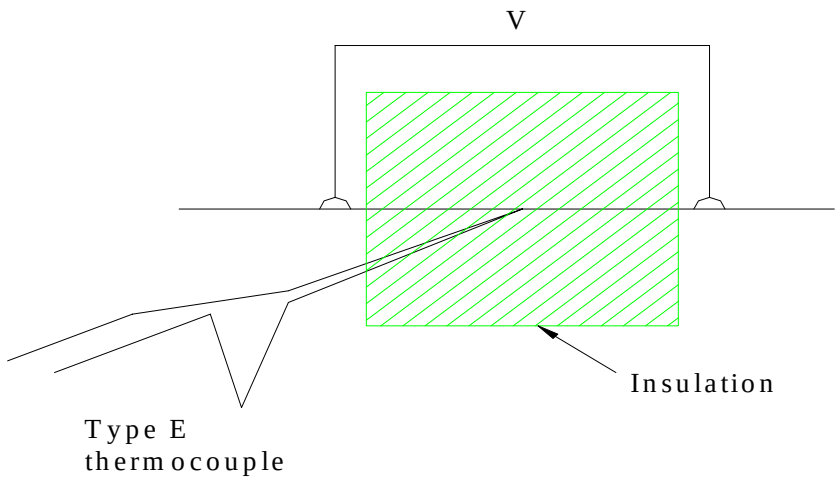
Summary - 1 T coil design

- 1-T coil can be made with the improved 2nd generation tape in boiling nitrogen (75-77 K)
- About 60 m of tape is required for a 1”-bore coil and 140 m for a 2”-bore coil
- These coils can be protected with a reasonable dump resistor, but a thicker Cu stabilization layer is required for larger coils or higher conductor current densities

AC Losses-Technical Approach

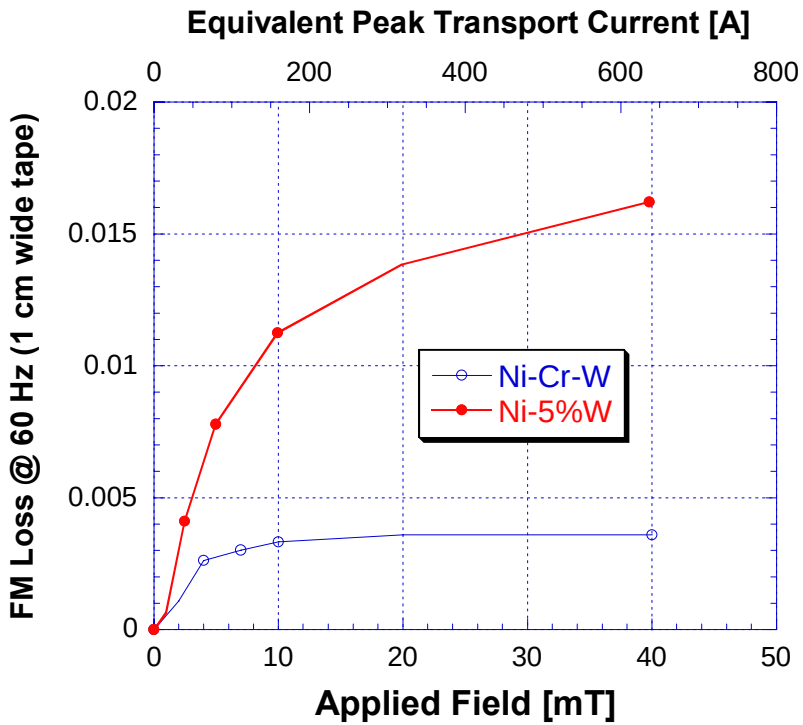
- AC loss measurements
  - Thermal and electrical measurements of YBCO samples under ac transport currents:
    - Different substrates (Ni-5at%W, Ni-Cr-W, with and without 2 micron Ni overlayer)
    - With and without copper stabilization (50 microns)
    - Different sample widths (1 cm, 4 mm)



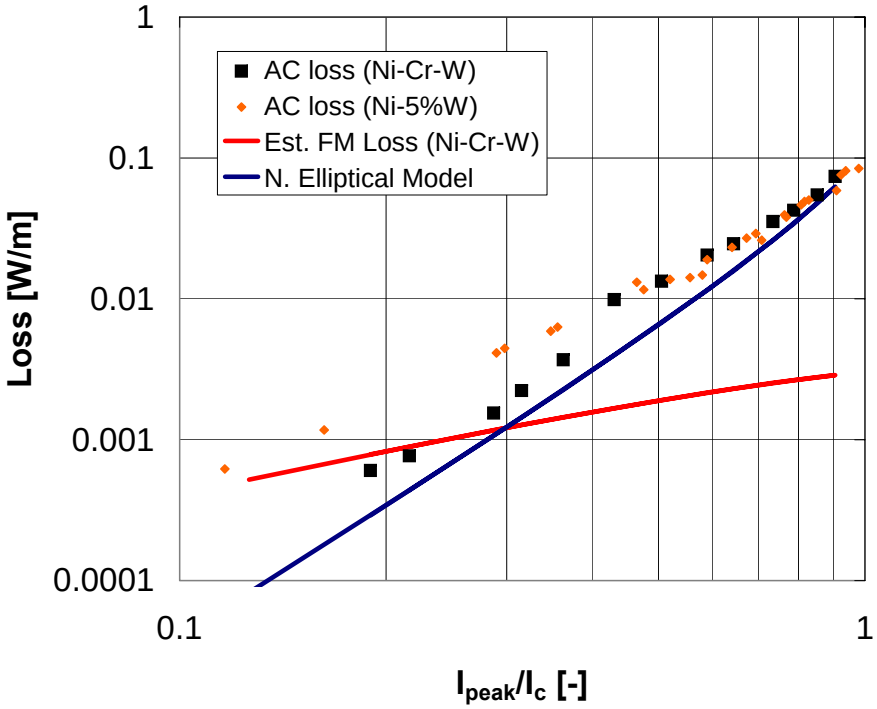


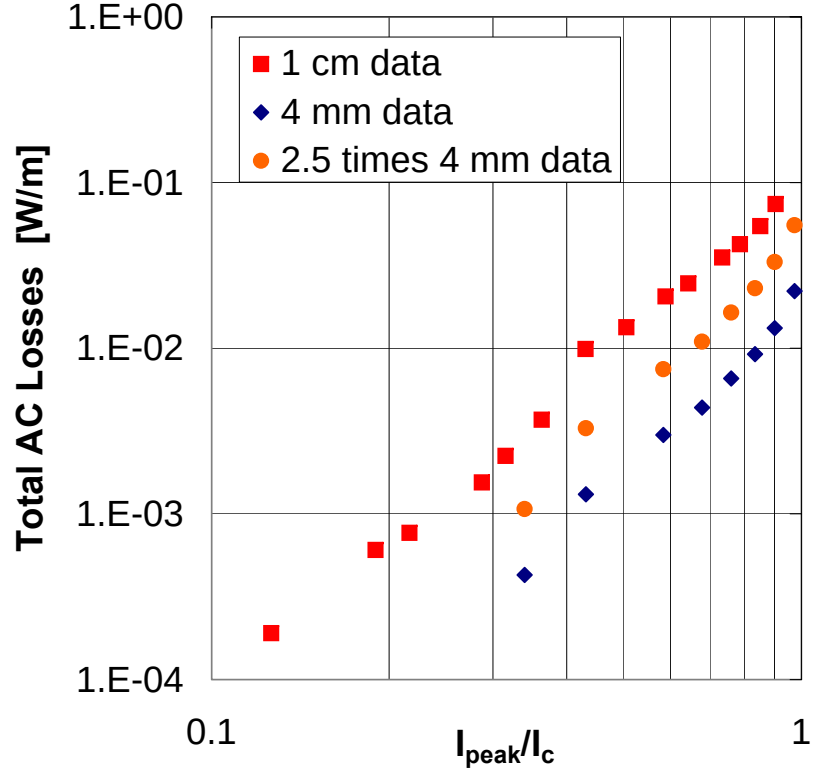
Transport AC loss of AMSC 2G tape with two different substrates

- Motivation: Previous measurement of ac losses of YBCO coated conductors on Ni-5at%W substrate with 2 micron nickel overlayer showed additional ferromagnetic loss mechanism
- Sample characteristics
  - 75 micron Ni-10%Cr-2%W with ~2 micron Ni overlayer
  - 4 mm and 1 cm sample widths
  - $I_c \approx 100$ A/cm-width
- FM loss at $I_{peak} \approx I_c$ reduced by a factor of 2-3 with Ni-Cr-W substrate



FM loss from Ni-Cr-W significantly lower than hysteretic loss of YBCO



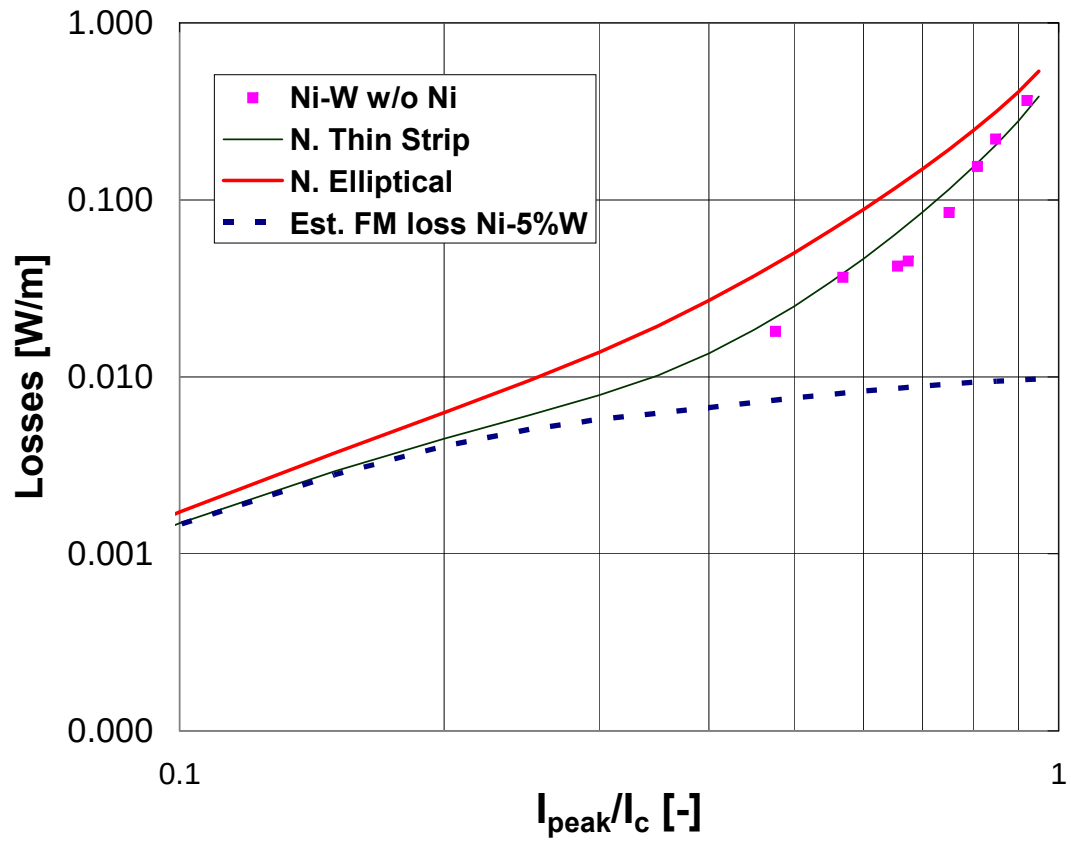


- **Total losses for Ni-W and Ni-Cr-W substrates comparable for $I_{peak}/I_c > 0.4$**
- **Reduction of tape width provides ac loss reduction in single tape experiments**

Transport AC losses scale with Norris thin strip model in Cu-laminated, YBCO tape

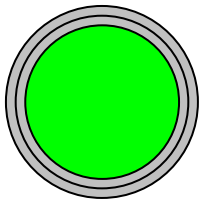
- Sample properties
  - 75 micron Ni-5at%W substrate (no Ni overlayer)
  - 50 micron Cu lamination on 3 micron silver cap layer
  - 1 cm wide
  - I_c(77 K,sf) = 260 A

- Possible nickel overlayer effect (further investigation is need)



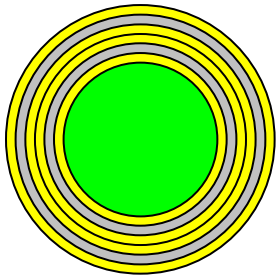
Influence of Ni-5at%W on ac loss and inductance of HTS cables

- Evaluate influence of NiW substrate on inductance and ac losses in HTS cables
- Two test cables (1.2-m long)
  - Cable A: two layers of stainless steel laminated BSCCO on 1” former
  - Cable B: two layers of stainless steel BSCCO wound on 1” former with 50 micron thick Ni-5at%W tapes (no YBCO)
  - Cables delivered in July. Will test in August
- Characterizations
  - AC loss
  - Inductance determined by decay time constant and rf measurements

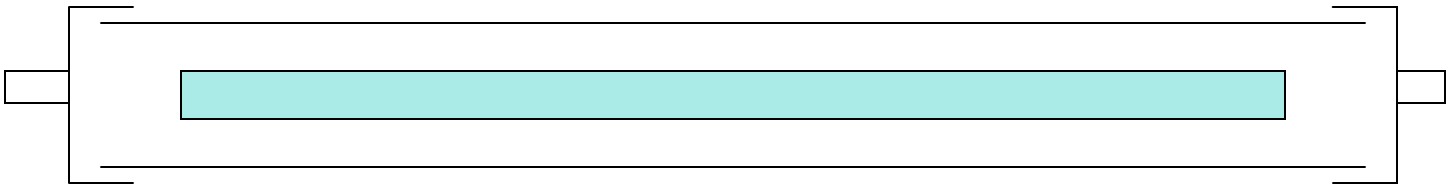


Cable A

Cable B



(not to scale)



ORNL FY 2004 Performance

FY 2004 Plan

- Study the impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerances
- Normal zone propagation and stability margins will be measured in a series of copper-stabilized YBCO and BSCCO with different copper thicknesses and joining techniques.
- A 1-Tesla HTS coil will be made with YBCO conductor, instrumented and tested to determine operating envelope and stability margins
- Over-current testing of single HTS tapes (BSCCO and YBCO) with stabilization (new task)
- Plan to make a YBCO cable with ~ 4-mm wide 2G tape.
- Characterization of NiW substrate as it pertains to ac losses and inductance in YBCO cables (new task)

FY 2004 Performance

✓ Characterized ac loss on YBCO conductor with Ni-Cr-W and Ni-5at%W substrates and with copper stabilization

✗ Task not completed due to use of equipment on SPI project. Sent sample of copper laminated YBCO to NHMFL for characterization.

✓ Design of 1 T YBCO conductor completed. Fabrication delayed to FY 2005 due to budgetary constraints.

✓ Found electromechanical and thermal limits for series of BSCCO and YBCO with additional copper stabilization

✗ Task not completed due to budget constraints and availability of sufficient 4-mm wide 2G tape.

- Model cables to be tested in August 2004

FY 2005 plans

- Impact of various YBCO conductor substrates and stabilization layers on ac losses and over-current tolerance will continue to be studied (in collaboration with AMSC).
- In addition, normal zone propagation and stability margins will be measured in a series of copper-stabilized, YBCO coated conductors
  - with different copper thicknesses and joining techniques.
- A 1-Tesla HTS coil will be made with YBCO conductor and tested to determine operating envelope and stability margins.
  - similar to a study with a BSCCO coil in 1994: “Stability measurements of a 1-T HTS magnet,” J. W. Lue, R. E. Schwall, et al.
- Plan to make a YBCO cable with ~ 4-mm wide 2G tape.

Research integration

- There is a close interaction with the 2nd generation HTS wire developers, especially AMSC.
- ORNL is working to communicate the relevant YBCO results to the SPI teams interested in YBCO replacement of BSCCO:
  - HTS cable projects
  - HTS transformer project
  - HTS generator/motor projects
- Southwire Company is making the 1.2-m cables that will be used to quantify the cable inductance effects of YBCO substrate materials.
- ORNL is part of a AMSC/NRL/LANL team addressing military applications of 2G HTS funded by DARPA/ONR.
- University of Tennessee MS student – tape burnout experiments

Publications since the last Peer Review

- **AC losses**
  - "Transport ac losses of YBCO coated conductors with Ni alloy substrates," R. C. Duckworth et al., Superconductor Science and Technology, **16**, 1294-1298, (2003)
  - "Substrate and stabilization effect on the transport ac losses in YBCO coated conductors," R.C. Duckworth, M.J. Gouge, J.W. Lue, C. Thieme and D.T. Verebelyi, to be presented at ASC 2004, Jacksonville, FL, Oct 2004**.**
- **YBCO cable including over-currents and ac losses**
  - "Testing of a 1.25-m HTS cable made from YBCO tapes," M. J. Gouge, J. W. Lue, J. A. Demko, R. C. Duckworth, P. W. Fisher, M. Daumling, D. T. Lindsay, M. L. Roden and J. C. Tolbert, *Advances in Cryogenic Engineering*, **49**, (2004).
- **BSCCO/YBCO tape over-current testing**
  - "Over-current tests of 1st and 2nd generation HTS tapes in liquid nitrogen bath cooling," M. A. Young, J. W. Lue, J. A. Demko, R. C. Duckworth and M. J. Gouge, *Advances in Cryogenic Engineering*, **49**, (2004).
  - "Short-circuit, over-current limitation of HTS tapes," J. W. Lue, R. C. Duckworth and M. J. Gouge, to be presented at ASC 2004, Jacksonville, FL, Oct 2004**.**