Development of 2G HTS Coated Conductors at STI

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Tenth EPRI Superconductivity Conference

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Corporate Overview and History

STI is a world leader in the development and production of High Temperature Superconducting (HTS) materials and associated technologies

1986

Discovery of High Temperature Superconducting (HTS)

Superconductor Technologies Inc. (STI) incorporated in Santa Barbara, California

1996

HTS Thin Films for Electronics

Utilizes Reactive Co-evaporation – Cyclic Deposition and Reaction (RCE-CDR) HTS deposition technology

1998

SuperLink® Product Released

High performance Radio Frequency (RF) infrastructure solution

HTS Manufacturing Ecosystem Created

Cost competitive HTS and cryogenics in full scale manufacturing production

2009

2G HTS Wire for Emerging Power Applications

Developing HTS wire to capture new market opportunities

HTS Technology in the Smart Grid

Increasing investment into Smart Grid infrastructure and alternative power generation

- HTS expected to play a crucial role in new emerging electric power generation, distribution and conversion applications
- HTS power applications expected to improve grid reliability and efficiency at a competitive cost to alternatives
- *"The global market for power generation equipment during the 2010 to 2020 period is estimated at approximately $2.35 trillion"* *(Amadee+Company Superconductivity 2011 – 2020 Analysis and Forecasts).*

GENERATION

Wind Turbines

Superconducting Wind Turbine Generator

STORAGE

Power Storage

Superconducting Magnetic Energy Storage (SMES)

DISTRIBUTION

High Voltage Cable

Superconducting Transmission Cables

CONVERSION

Substation Equipment

Superconducting Fault Current Limiter (SFCL)

END USE

Factory

Superconducting Industrial Motors

Low-Cost, High-Performance Coated Conductors

Existing price of 2G HTS wire is high

HTS wire will need to compete with copper on price per kA·m

- Copper wire is available in high volume
  - Raw materials cost is the key driver
- HTS wire is currently only available in low volume
  - Raw materials are far less of a cost driver

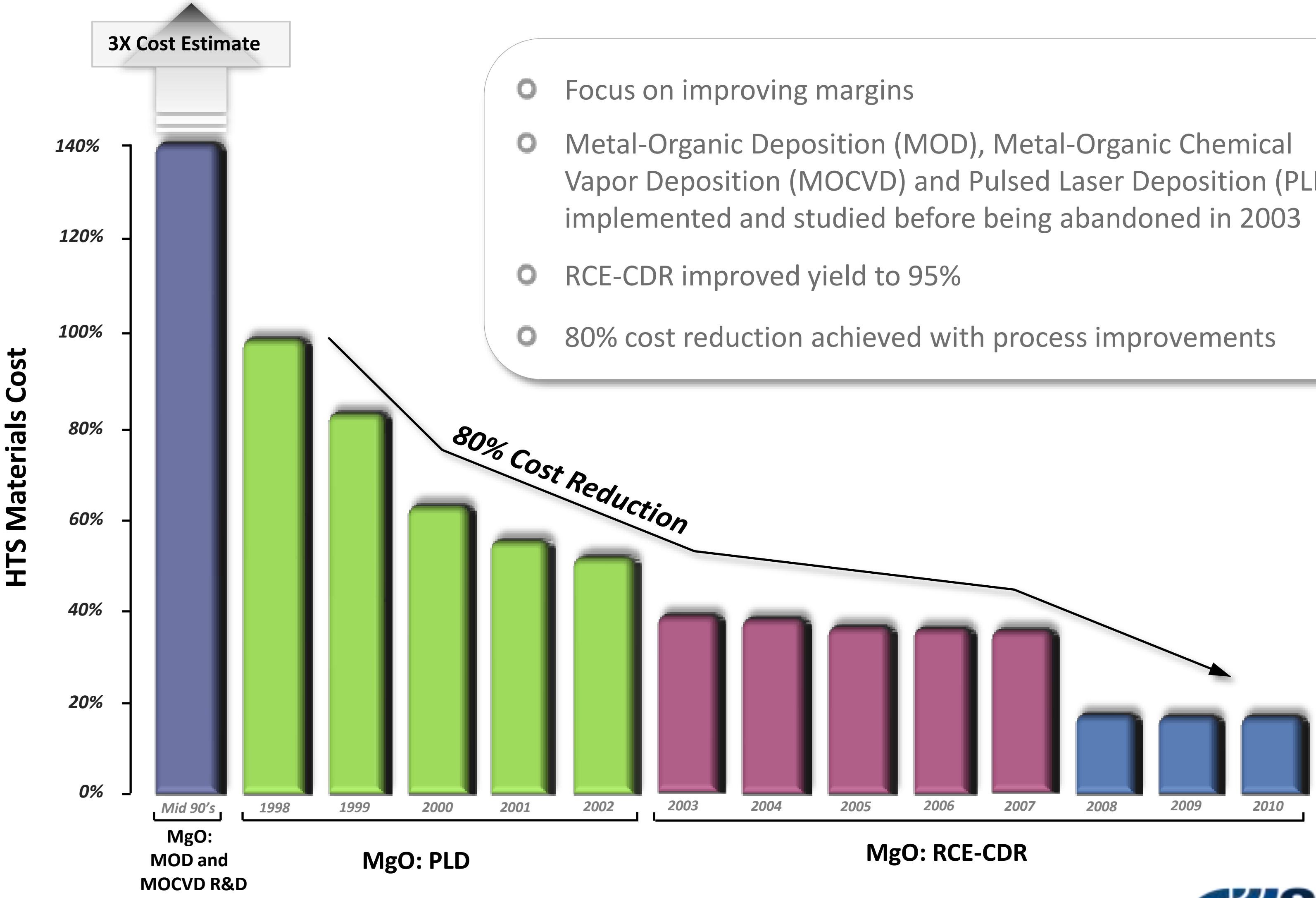
Factors driving 2G HTS wire cost today

- Wire performance – improvement can reduce cost per kA·m
- Process steps
- Capital equipment
- Facilities – power and space
- Volume – scale
- Yield

The potential for reducing HTS wire price is apparent

HTS Materials Cost Reduction Over Time

- Focus on improving margins
- Metal-Organic Deposition (MOD), Metal-Organic Chemical Vapor Deposition (MOCVD) and Pulsed Laser Deposition (PLD) implemented and studied before being abandoned in 2003
- RCE-CDR improved yield to 95%
- 80% cost reduction achieved with process improvements



Low-Cost HTS Coated Conductor Requirements

Low number of template buffer layers

- Simple and repeatable

Low number of process steps per layer

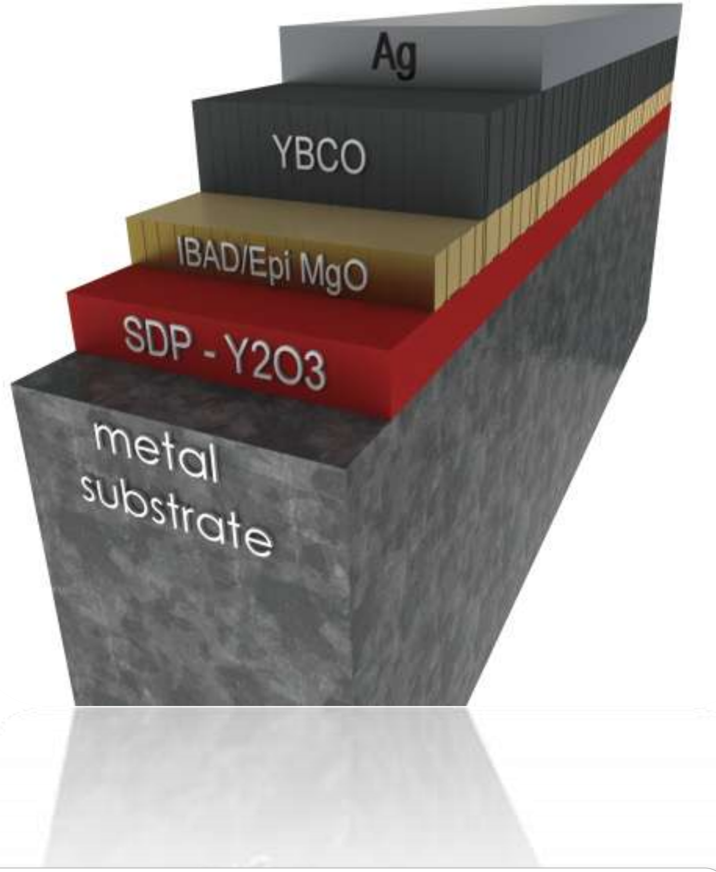
- Reduced runtime and high yield

High throughput and large HTS growth area

Low production equipment cap-ex

Low direct cost of raw materials

- Elemental source materials
- Inexpensive substrate material



Simplified structure inherently reduces cost and also increases yield

Core Processes

SDP **IBAD/epi MgO** **RCE-CDR**

Solution Deposition Planarization (SDP)

Ion Beam Assisted Deposition (IBAD)

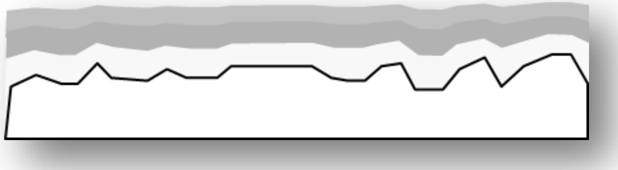
Reactive Coevaporation – Cyclic Deposition and Reaction (RCE-CDR)

Core Layer Processes:

- Y_2O_3 – Solution deposition planarization (SDP)
- MgO – Ion beam assisted deposition (IBAD)
- YBCO – Reactive coevaporation – cyclic deposition and reaction (RCE-CDR)

SDP Layer

- Process developed by Los Alamos and Sandia National Laboratories
- Solution planarization is an effective means of overcoating surface asperities with a flat surface
  - Solution deposited layer encapsulates metal tape and prevents metal interdiffusion
  - SDP combines electropolishing, barrier, and bed layer deposition into one process for IBAD CC
- No need to process or polish metal substrate tape
  - Broadens the range of substrates that can be used
  - Non-magnetic substrates can be chosen
  - Substrates with high structural integrity for high-field magnets can be used
- We are presently depositing Y_2O_3 SDP layers on Hastelloy C276 and stainless steel substrates with good results on up to 12-meter lengths
- RMS surface roughness < 2 nm (5 x 5 µm^2) obtained on all substrates
- Deposition system to scale up to long lengths is under construction



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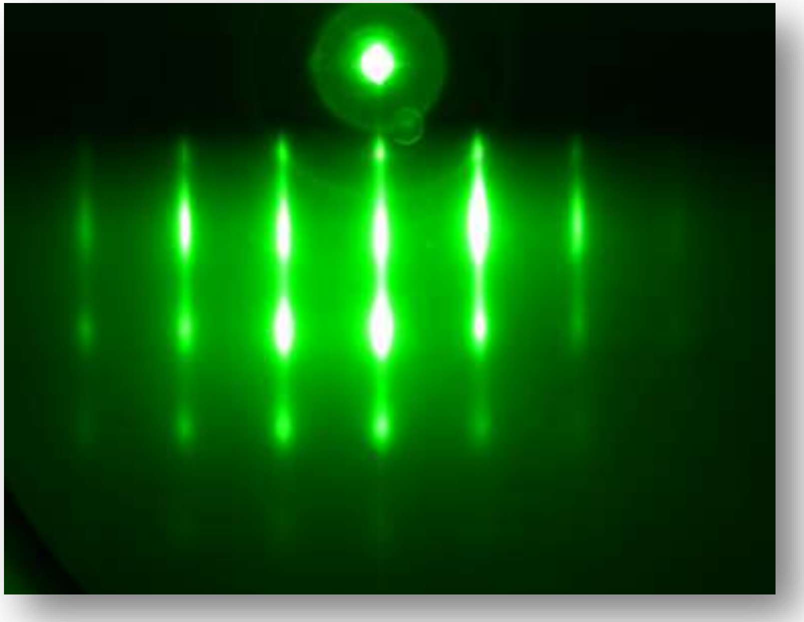
TEM: Terry Holesinger

IBAD / epi MgO Layer

- Requires only thin MgO layers for crystallinity
- Fast process
- *In situ* process in a single deposition system
- Has been proven for long-length CC
- STI IBAD system is under construction



RCE-CDR Layer

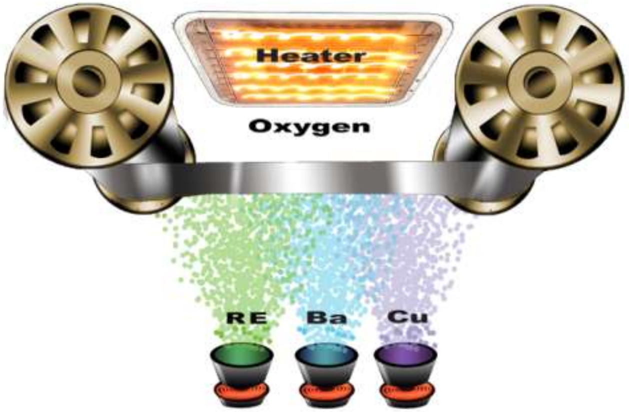
- STI has developed the RCE-CDR technique for >15 years and shown it to be a low-cost, high-yield production technique for HTS wafers
- Enables growth directly on MgO layer: eliminates need for other layers
- *In situ* process in a single deposition system
- Low materials cost – elemental sources
- Large-area deposition / scalable
- Manufacturing costs for this process are well understood
- We believe that scaling this process will result in low-cost 2G HTS wire at reasonable volumes
- Presently growing RE-BCO films on simplified IBAD templates on short lengths and meter-length scale
- Deposition system to enable scale-up to long lengths is under development

Low-Cost Raw Materials

Yttrium

Barium

Copper



Current Work

Deposit SDP layers at STI on metal substrates

Deposit IBAD layers at LANL under CRADA

Deposit HTS films by RCE-CDR at STI on

- MgO single crystals
- IBAD/SDP templates

Develop long-length SDP, IBAD MgO, and RCE-CDR

Materials optimization

Optimize materials properties for high $J_c(H, \theta)$

Composition

- RCE-CDR allows stable and reproducible compositional control

Thickness

Growth conditions

- Deposition rate
- Temperature
- Oxygen pressure

Current materials investigation

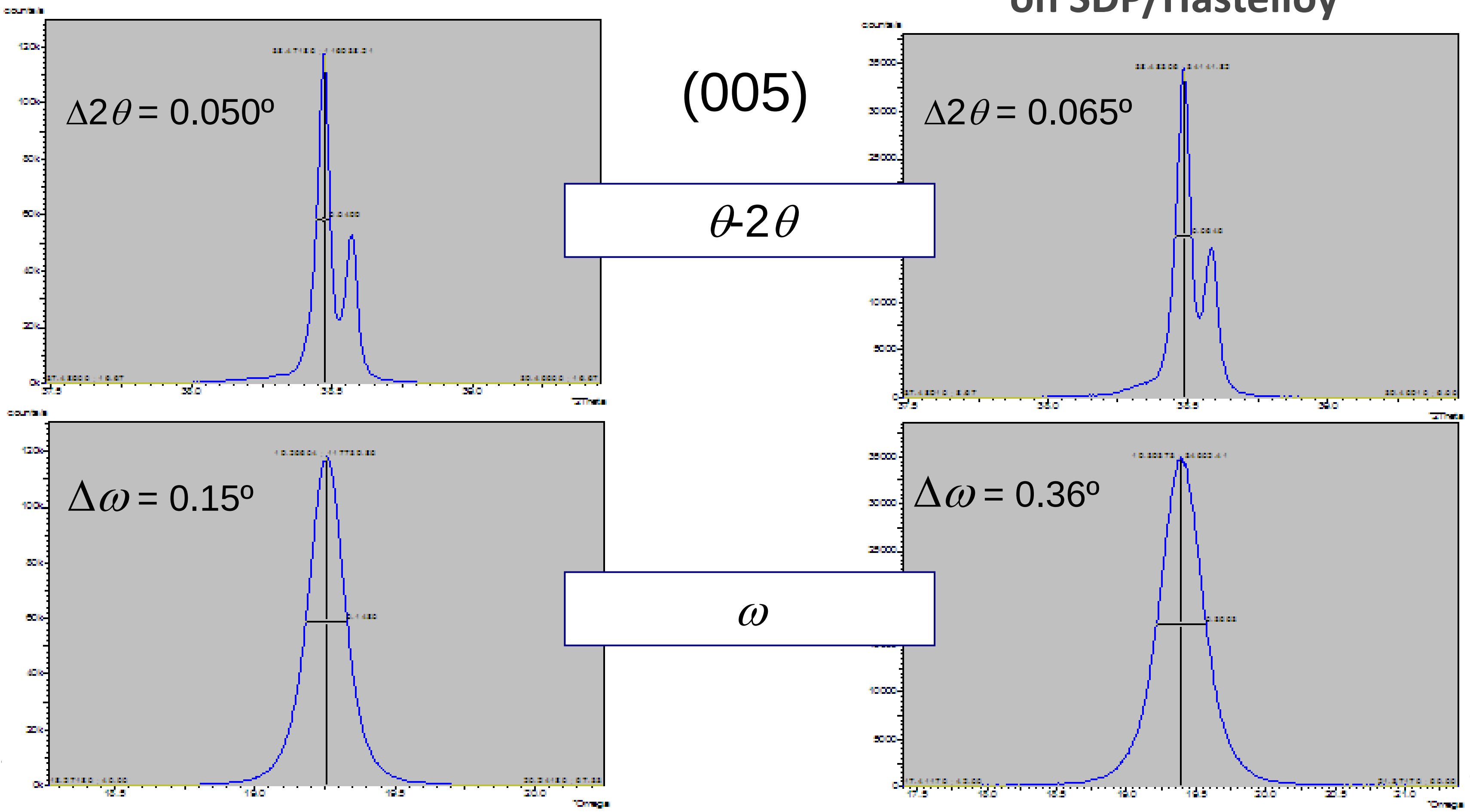
- Simple HTS compounds
- Single rare earth elements only
- No artificial pinning center additions

Crystallinity

- Excellent crystallinity
- Compares favorably to our standard HTS films on MgO
- 5.3-µm films grown in same run:

YBCO on MgO Single Crystal

YBCO on 30 nm IBAD/epi MgO on SDP/Hastelloy



(005)

θ-2θ

ω

$\Delta 2\theta = 0.050^{\circ}$

$\Delta 2\theta = 0.065^{\circ}$

$\Delta\omega = 0.15^{\circ}$

$\Delta\omega = 0.36^{\circ}$

Achieved I_c > 1000 A/cm-width on IBAD/SDP Templates for 3.3-µm Films

HTS films grown by RCE-CDR on SDP/IBAD textured templates

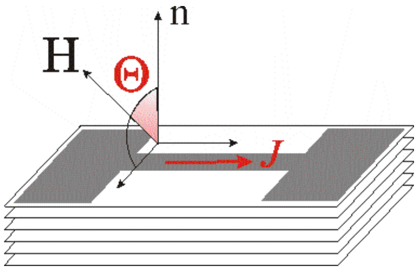
- Unpolished Hastelloy or stainless steel
- SDP Y_2O_3
- IBAD/epi MgO

>1000 A/cm-width in SF at 77 K achieved in a 3.35-μm film

- J_c ~ 3 MA/cm^2

Sample	*t* (μm)	I_c/cm-width, (A/cm) at 77 K, SF	*n* value	J_c (MA/cm^2) at 77 K, SF
X11026B/IB506-3	3.35	1015	33	3.03
X11030C/IB524D	2.8	743	31	2.66
X10048H/IB500B	2.0	556	31	2.78
X10043F/IB494D	1.5	540	46	3.60
X11025C/IB524A	0.7	335	33	4.78

Pinning Landscape



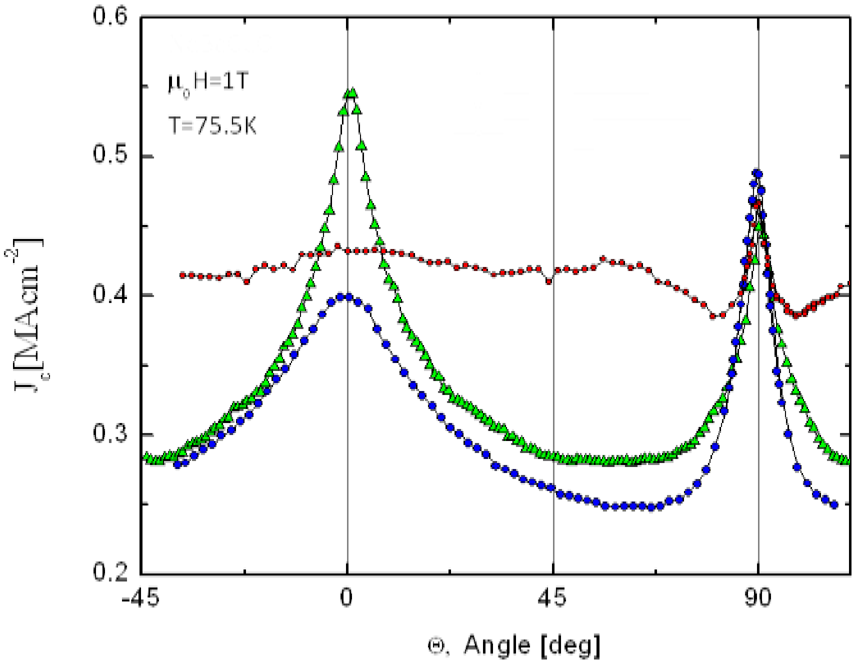
Need good in-field performance for many applications: rotating machines

Performance target

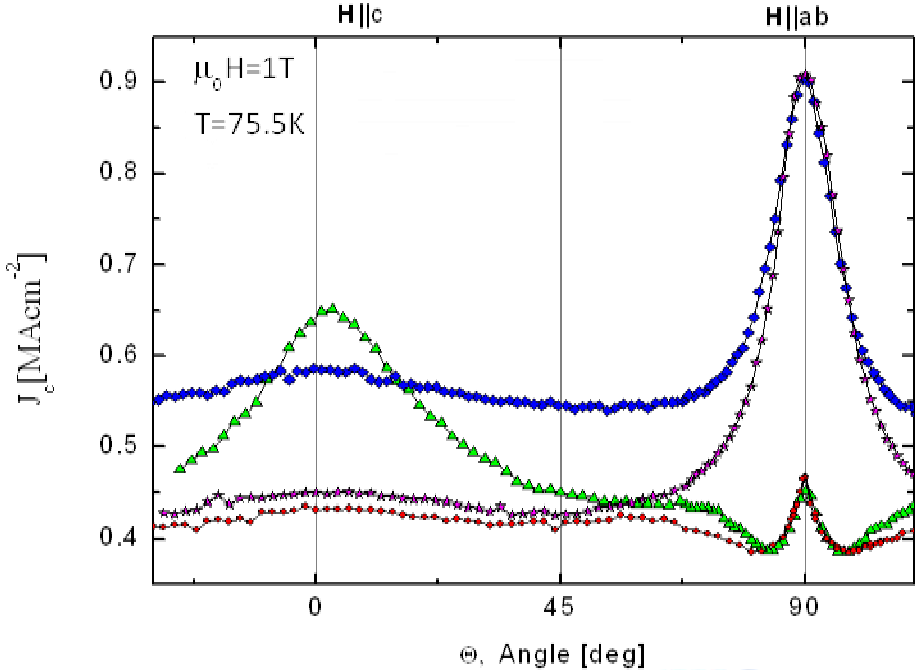
- Minimum I_c value at all angles of magnetic field: 250 A/cm-width at 65 K, 3 T

Exploring simple cuprates with different rare earths

RE1-BCO



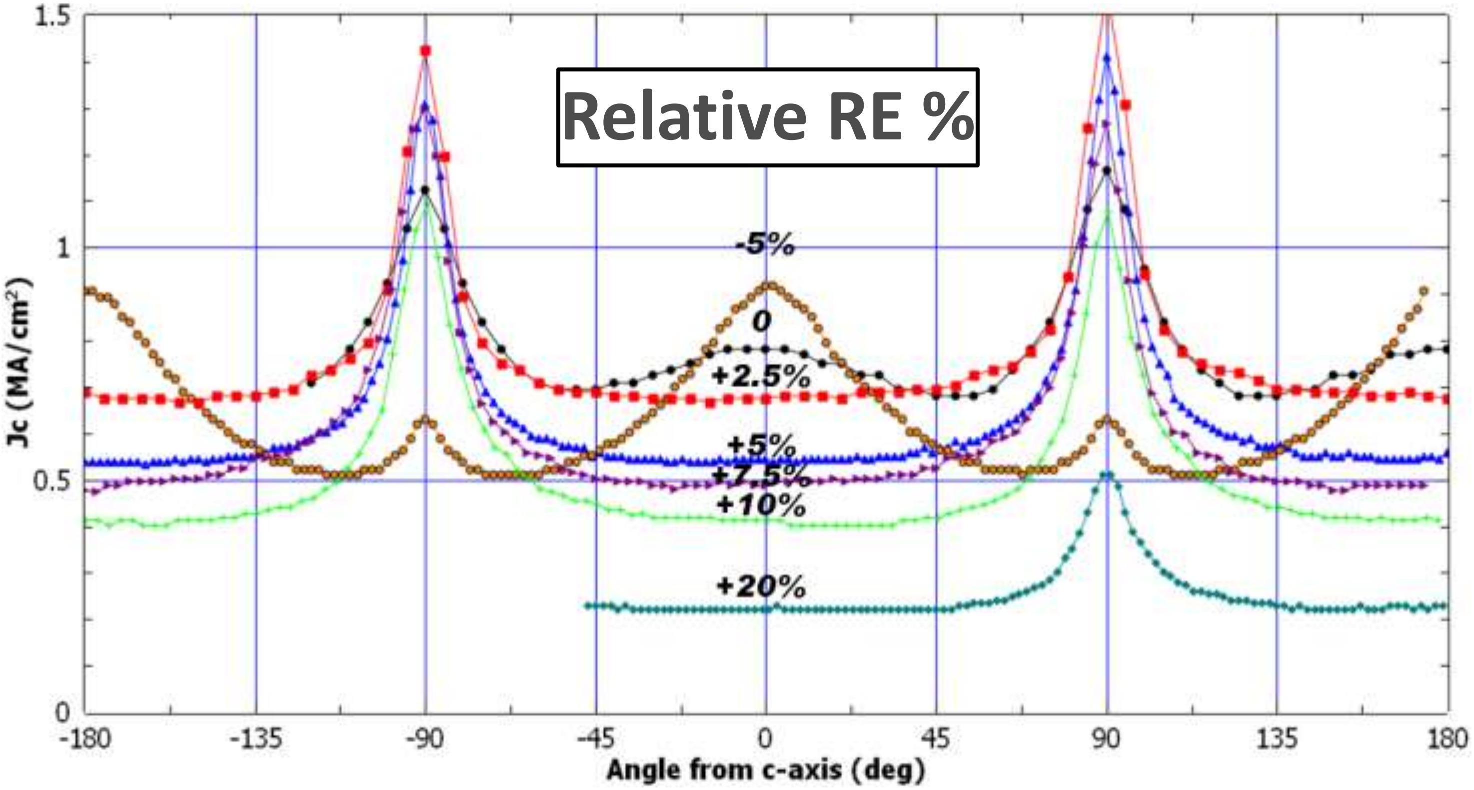
RE2-BCO



RE-BCO composition

In-field performance dependent on RE content

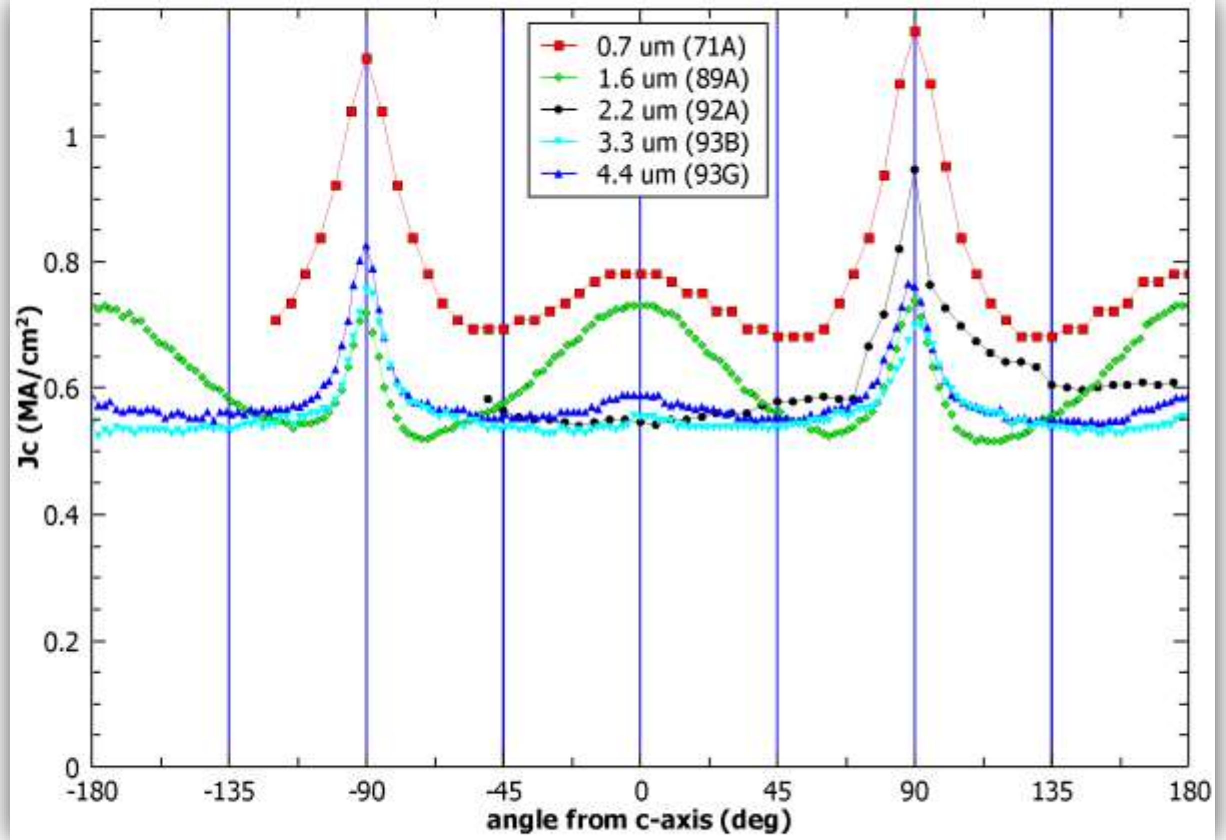
- 0.7-µm films on MgO
- 0.9 T, 77 K



RE-BCO Thickness

Minimum J_c is independent of thickness for thicker films

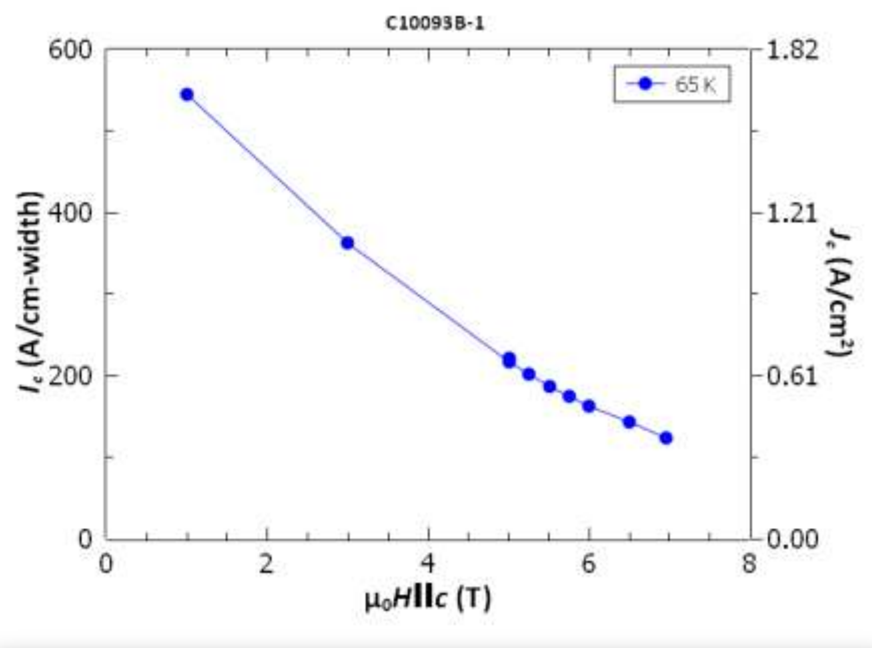
- 0.7 to 4.4 µm films on MgO
- 0.9 T, 77 K

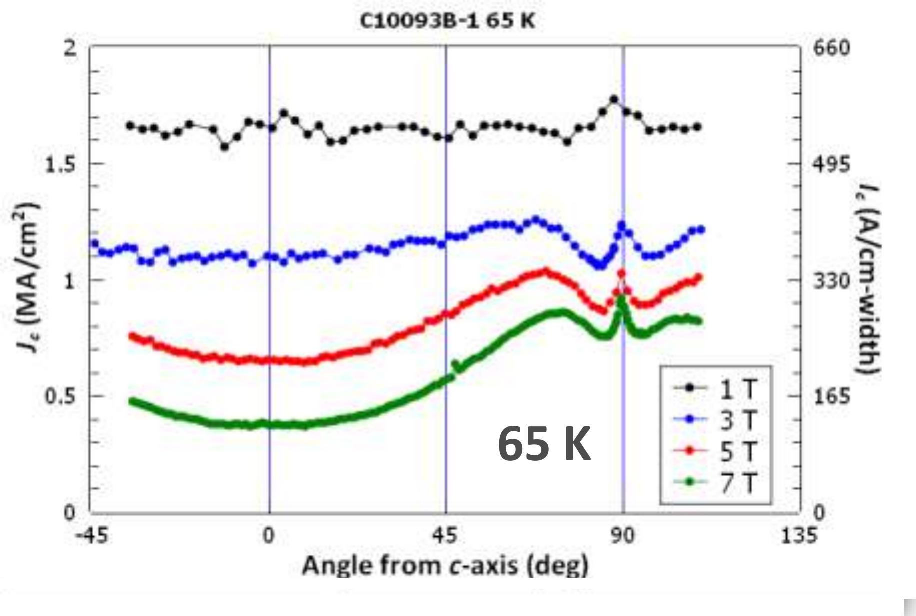


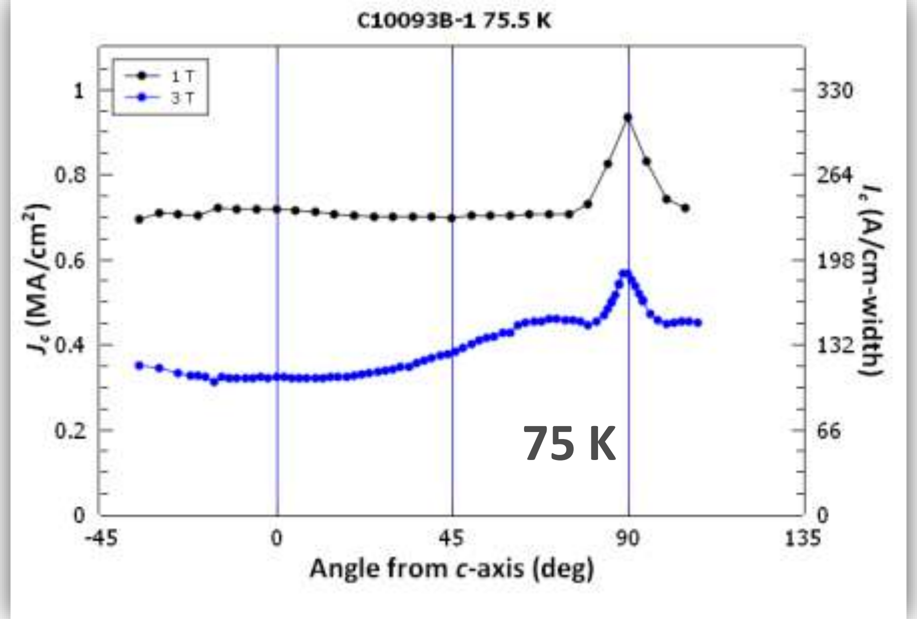
3.3-µm RE-BCO Films on MgO

- Pure RE-BCO film
- Measured on a 200-µm bridge

Field	Minimum I_c (A/cm-width)	
	65 K	75 K
1 T	518	230
3 T	**353**	105
5 T	213	-
7 T	122	-



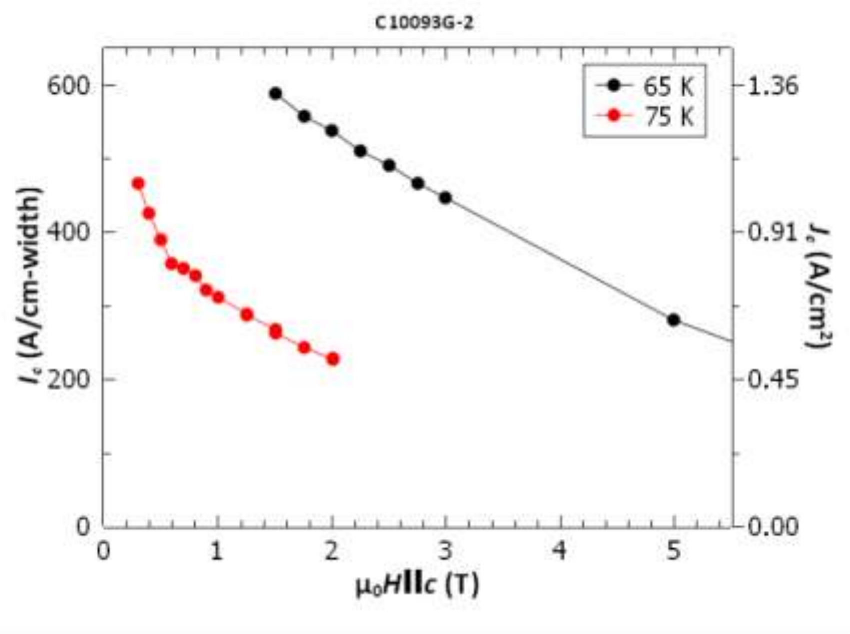


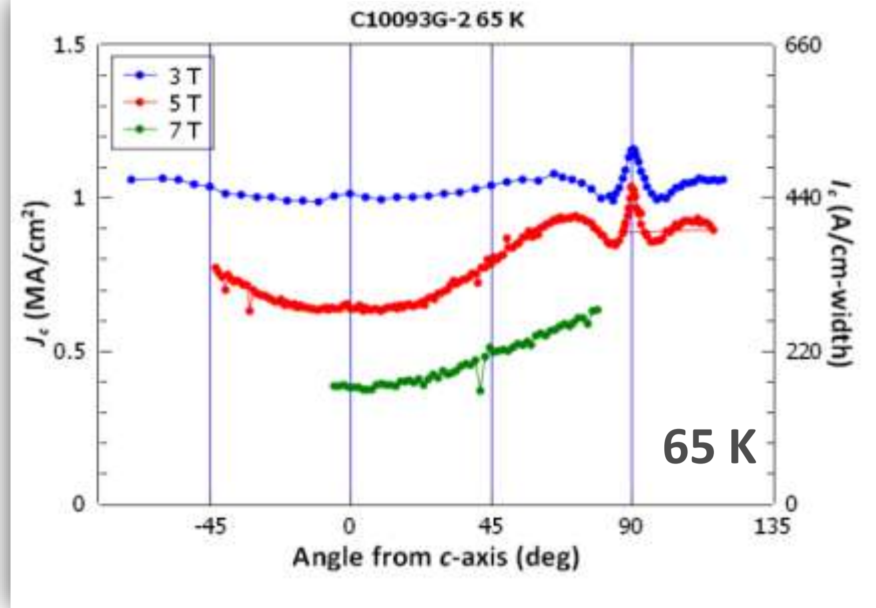


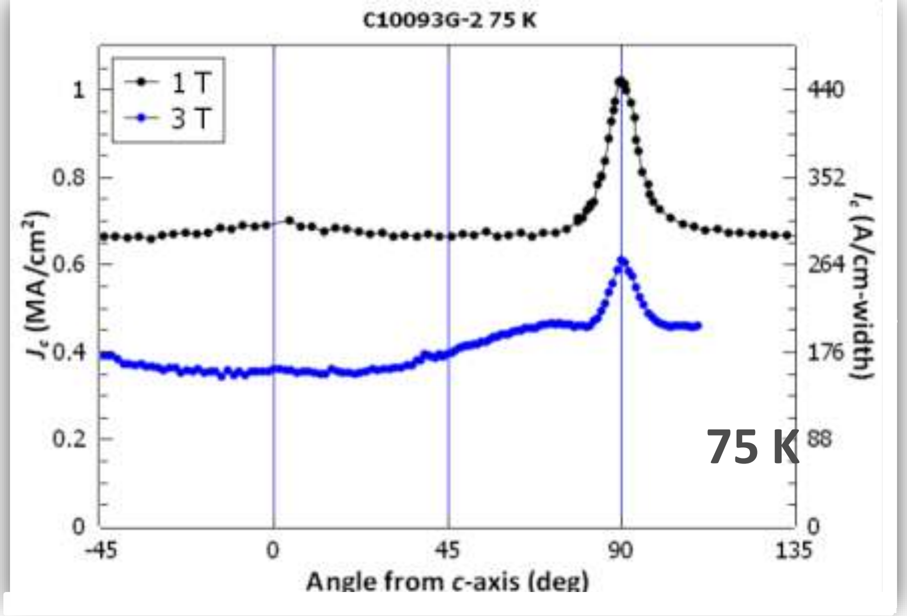
4.4-μm RE-BCO Films on MgO

- Pure RE-BCO film
- Measured on a 200-μm bridge

Field	Minimum I_c (A/cm-width)	
	65 K	75 K
1 T	-	290
3 T	**435**	155
5 T	277	-
7 T	164	-



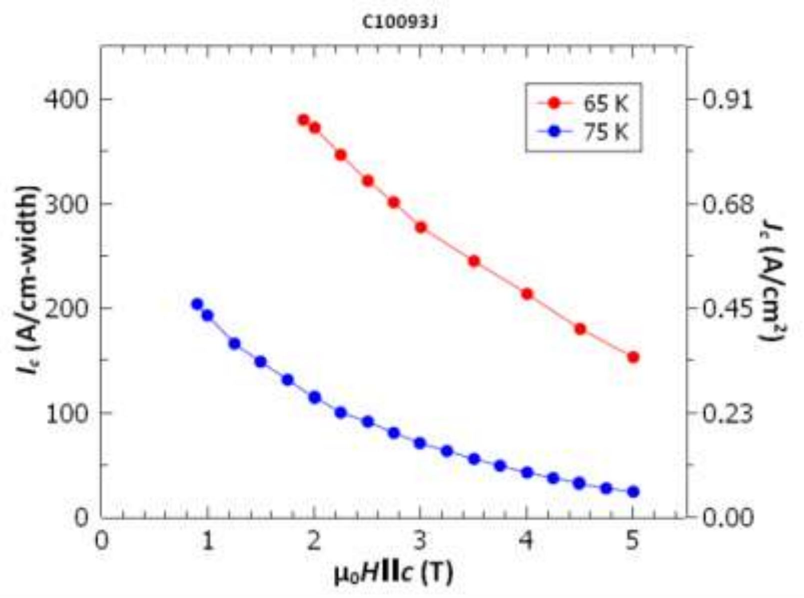


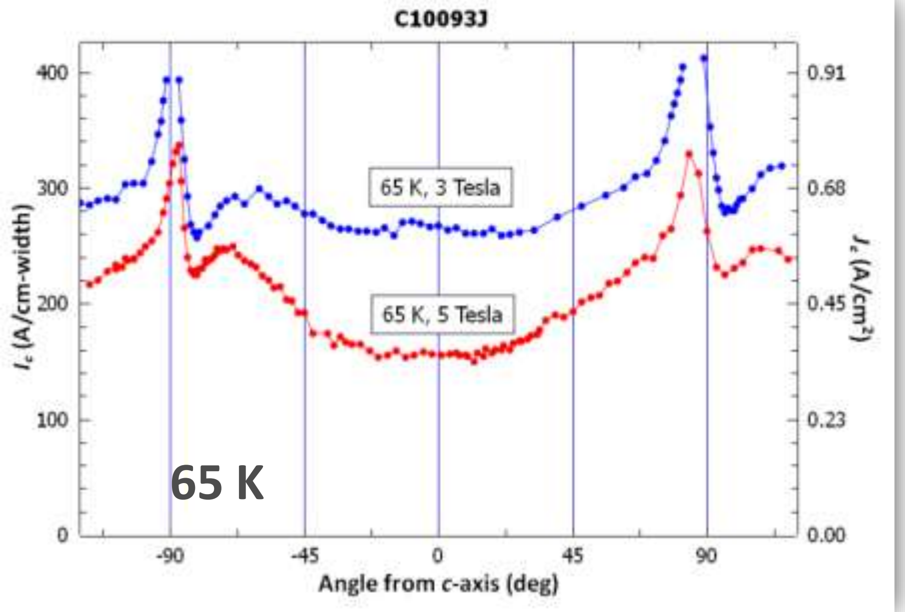


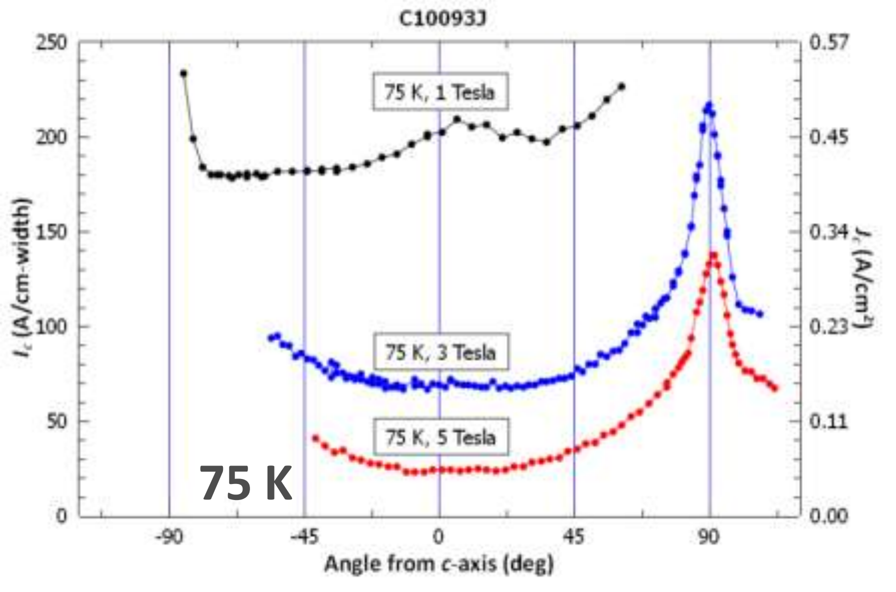
4.4-µm RE-BCO Films on Simplified IBAD Template

- Pure RE-BCO film
- Grown on a simplified IBAD template: 1 cm x 4 cm
- Measured across full tape width (8.9 mm)

Field	Minimum I_c (A/cm-width)	
	65 K	75 K
1 T	--	178
3 T	**257**	66
5 T	153	24



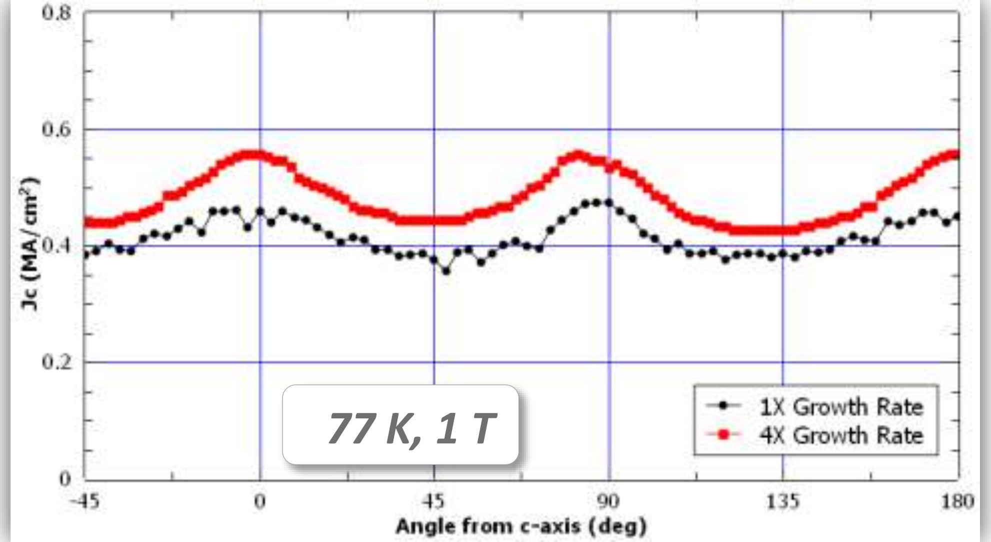




Increased Growth Rate

- HTS growth rate increased by a factor of 4
- I_c values maintained at SF and at 1 T

Sample	***t*** **(µm)**	**J_c at 1x rate (MA/cm^2) at 77 K, SF**	**J_c at 4x rate (MA/cm^2) at 77 K, SF**
D11059G	2.1	1.98	-
D11109A	2.1	-	2.14
D11076A	0.7	3.2	-
D11092A	0.7	-	3.5

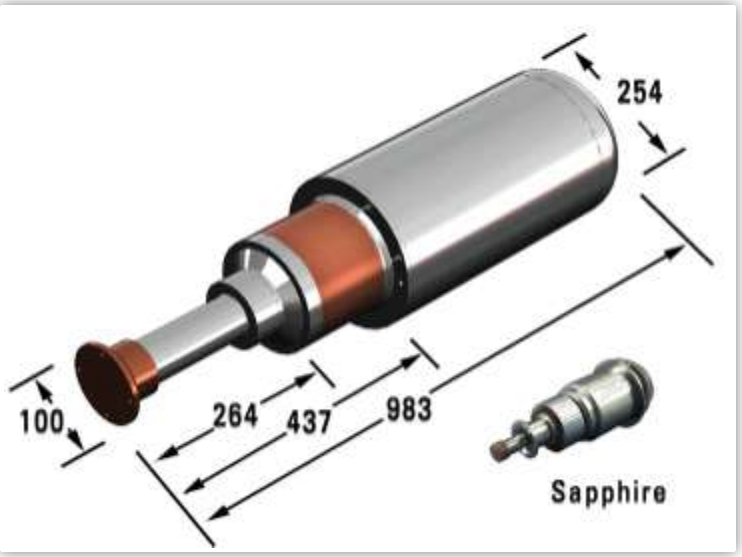


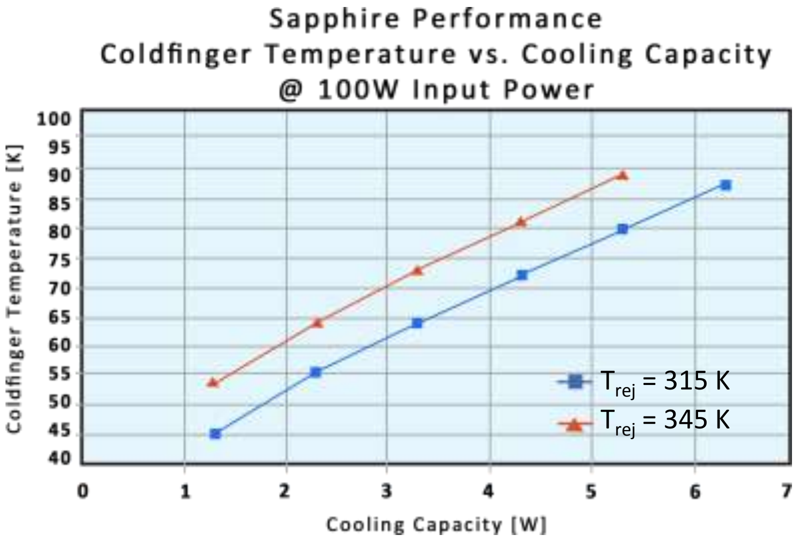
Cryocooler Expertise

- 17 years cryocooling and cryopackaging experience
- Free-piston integral Stirling cycle cryocooler technology
- Proven high-volume, low-cost manufacturability
- Scalable to larger or smaller sizes
- High reliability, long life, and high performance
  - Zero maintenance required
  - Over 6,000 cryocoolers deployed
  - Many cryocoolers have been in continuous 24/7 operation without maintenance in remote sites for > 9 years
  - No signs of wear-out mechanisms
  - Run-time > 200 Million hours
  - MTBF >> 1 Million hours
  - High efficiency - Typically achieves over 15% Carnot efficiency at 77 K in the field

Scaling Sapphire to 100 Watts

- Feasibility study suggests that our Sapphire cryocooler is scalable to much greater than 100 Watts
- Design and investigation phase of development
- Maintain key attributes of Sapphire
  - Cost-effective
  - Reliable
  - Highly efficient





Summary

- **RCE-CDR is inexpensive, high-yield, and scalable**
- **Our approach and HTS manufacturing experience can potentially meet the demand for coated conductors and beat the industry cost targets**
- **Achieved results on a simplified IBAD template process requiring only Y_2O_3 and MgO layers**
- **SF performance**
  - 1015 A/cm at 77 K, SF for a 3.35-μm film on IBAD templates; J_c = 3 MA/cm^2
- **In-field performance**
  - Minimum $I_c(\Theta)$ of 435 A/cm-width at 65 K, 3 T on MgO
  - Minimum $I_c(\Theta)$ of 257 A/cm-width at 65 K, 3 T on MgO/Y_2O_3/Hastelloy
  - Simple RE-BCO compound
  - No artificial pinning centers
- **Highly reliable and scalable Stirling cryocooler technology**

Thank You

STI
SUPERCONDUCTOR TECHNOLOGIES INC.