Comparison of in-field transport I_c , J_c, and F_p for R&D and production ReBCO tapes

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Outline

- Motivation
- Techniques
- Comparison I_c(B, 4K) for SuperPower R&D and production line tapes
- Transport $I_c(\theta$, B, T) measured on FIB trimmed bridge in 45T hybrid magnet
- Comparison transport properties of ReBCO tapes from different manufacturers
- Conclusions

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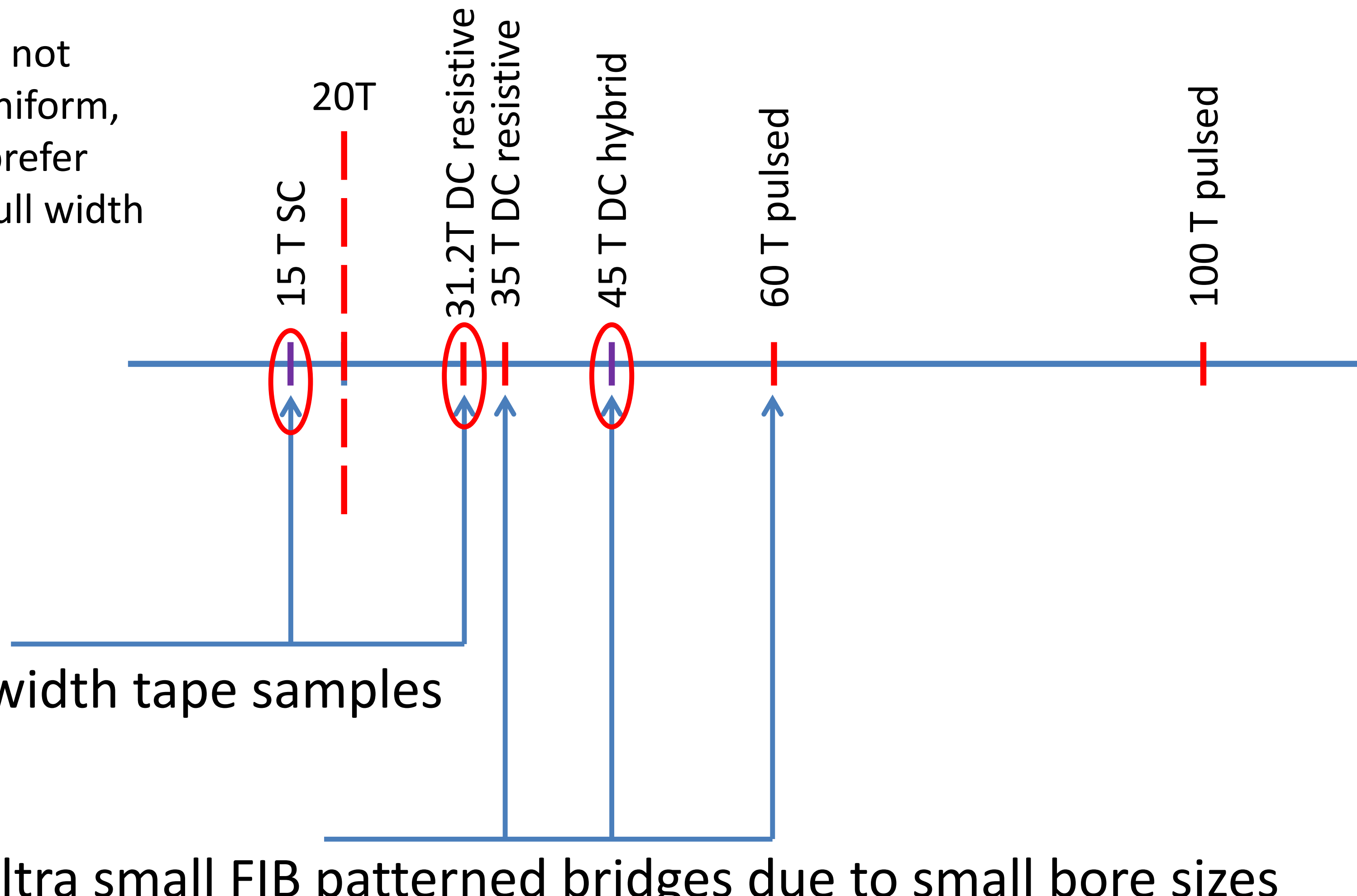
Motivation

- ReBCO superconductors become a choice material for developing all superconducting magnets capable generating ultra-high fields due to very high critical current densities in the presence of magnetic fields and high irreversibility fields
- Therefore, it is important to develop instrumentation suitable for testing I_c , J_c, F_p of ReBCO conductors in such regime
- Recent progress in introducing high concentration artificial pinning centers (APC) in ReBCO conductors makes them optimized for low-temperature high-field applications
- The understanding performance of APC at fields above 20T fields is important for solving vortex dynamics problems, conductor development, and magnet design.

Magnet systems available in NHMFL

For now resistive magnet systems available for characterization above 20T and pulsed magnets is the only choice for generating fields above 45T

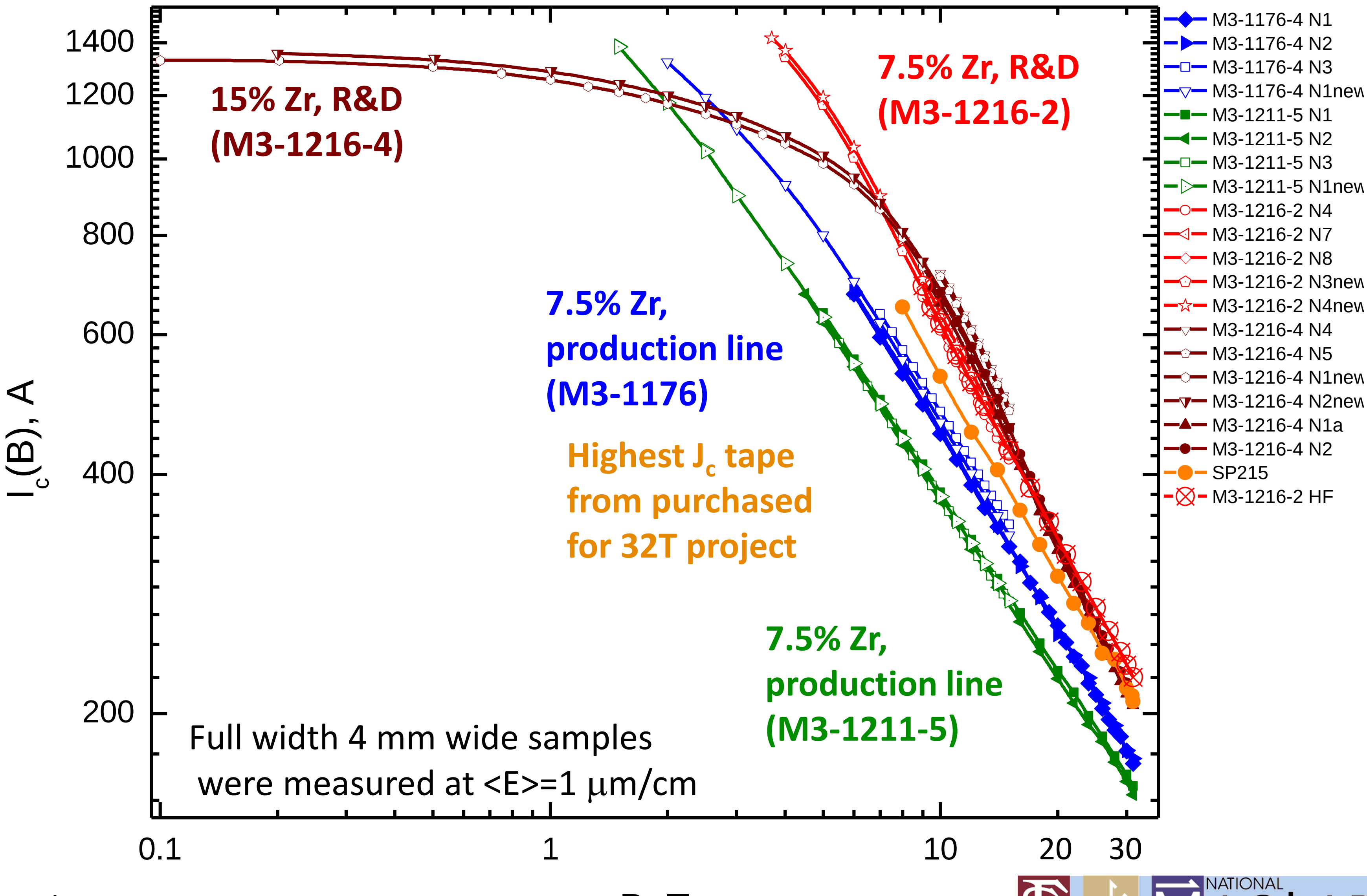
Since real tapes are not perfectly flat and uniform, magnet designers prefer measurements of full width tapes.



Comparison I_c(B, 4K) for SuperPower R&D and production line tapes

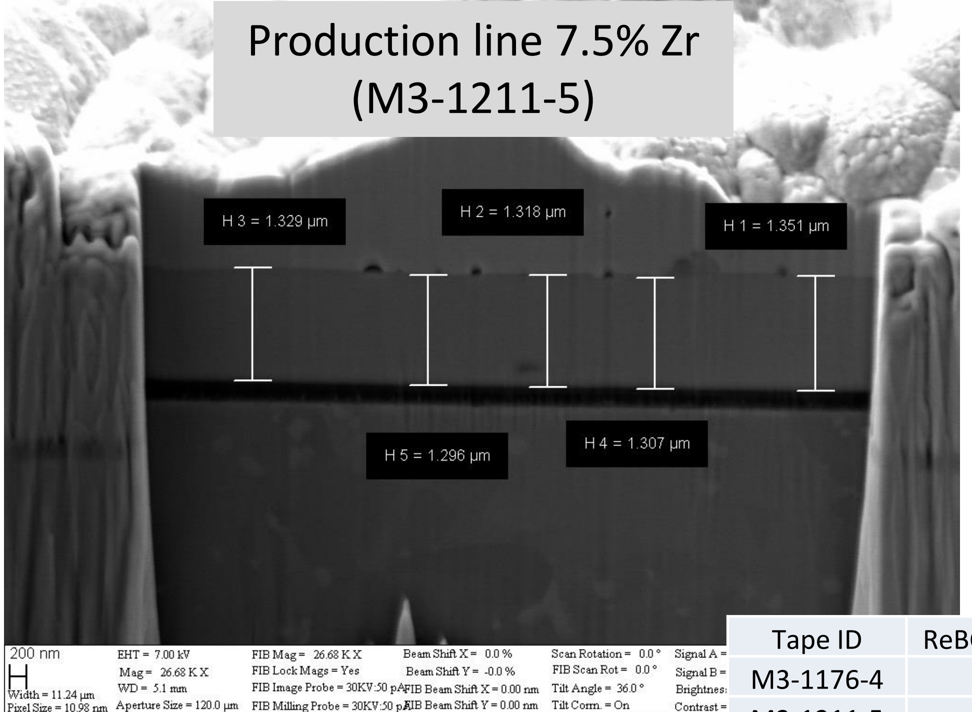
Combination of $I_c(B,4K)$ measured in resistive and superconducting magnets

Below ≈2T 15% Zr tape has lower I_c than 7.5% Zr production line tape

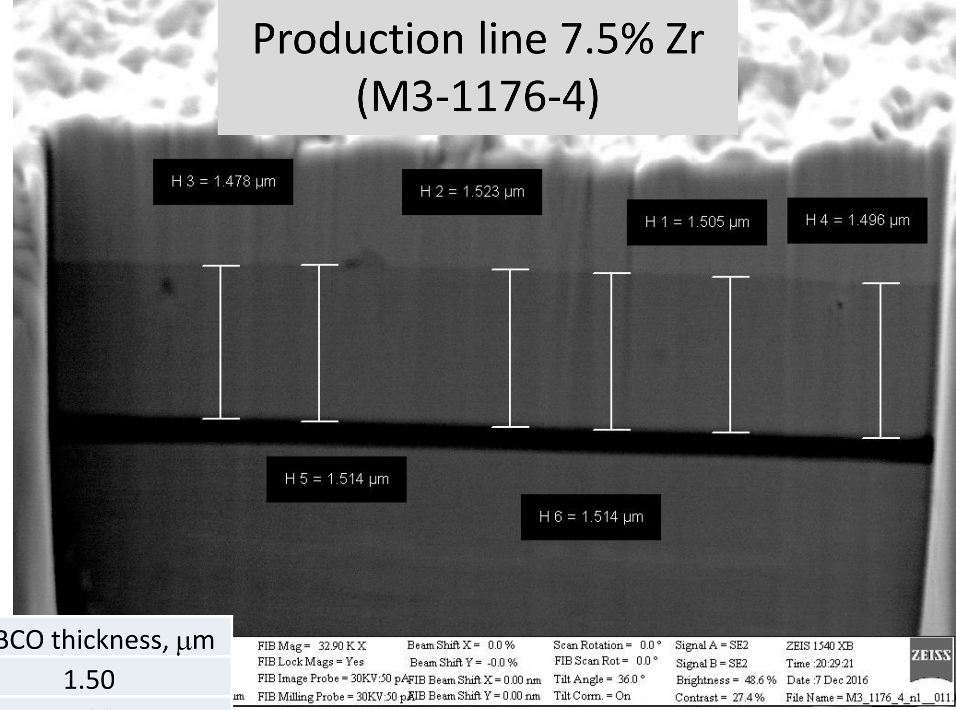


Maximum bias current is 1400A

Production line 7.5% Zr
(M3-1211-5)



Production line 7.5% Zr
(M3-1176-4)

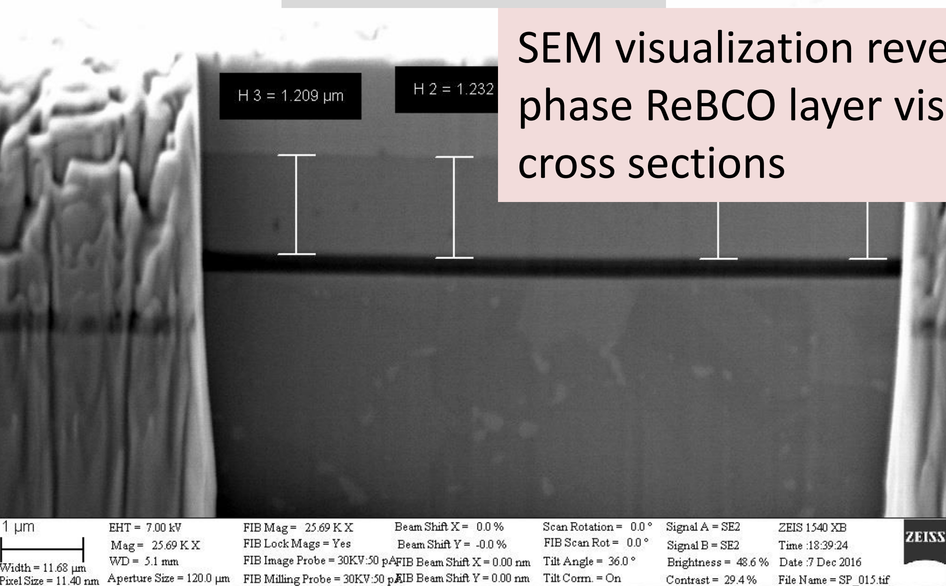


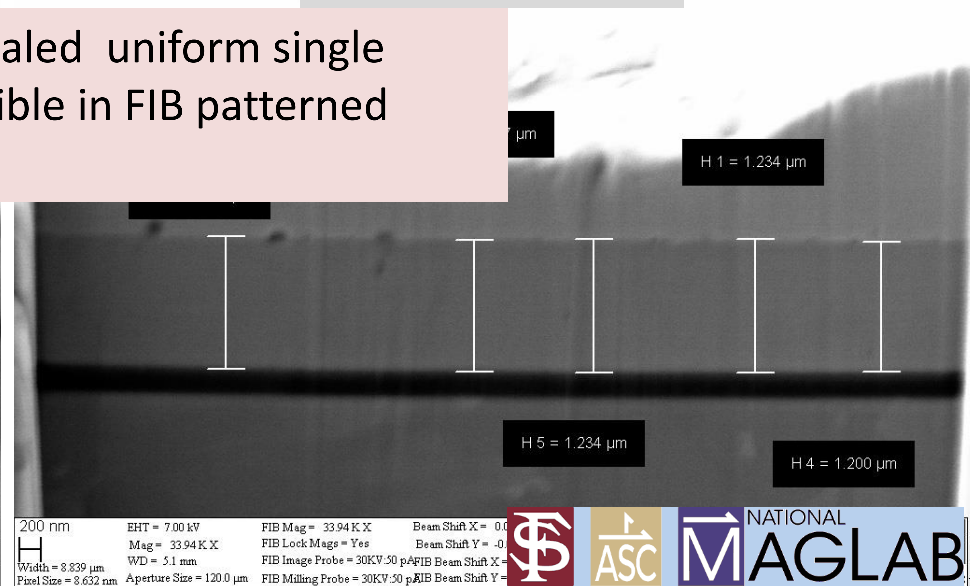
Tape ID	ReBCO thickness, µm
M3-1176-4	1.50
M3-1211-5	1.32
M3-1216-2	1.22
M3-1216-4	1.22

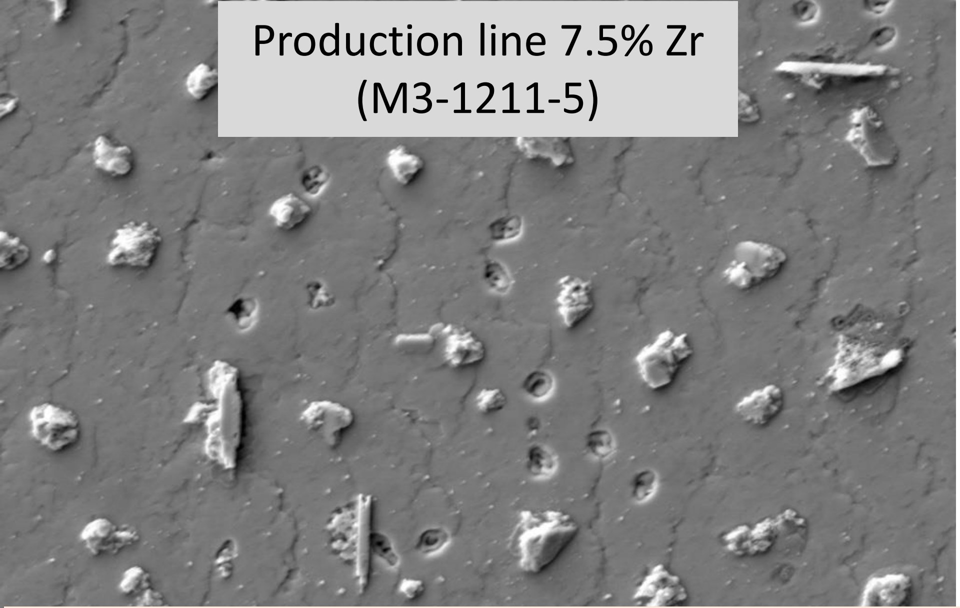
7.5% Zr R&D
(M3-1216-2)

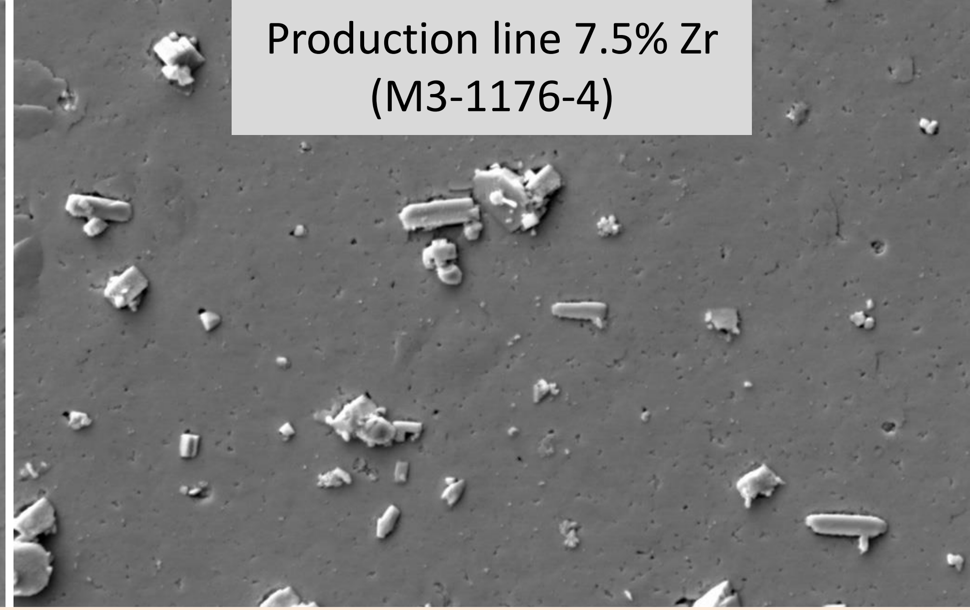
15% Zr, R&D
(M3-1216-4)

SEM visualization revealed uniform single phase ReBCO layer visible in FIB patterned cross sections

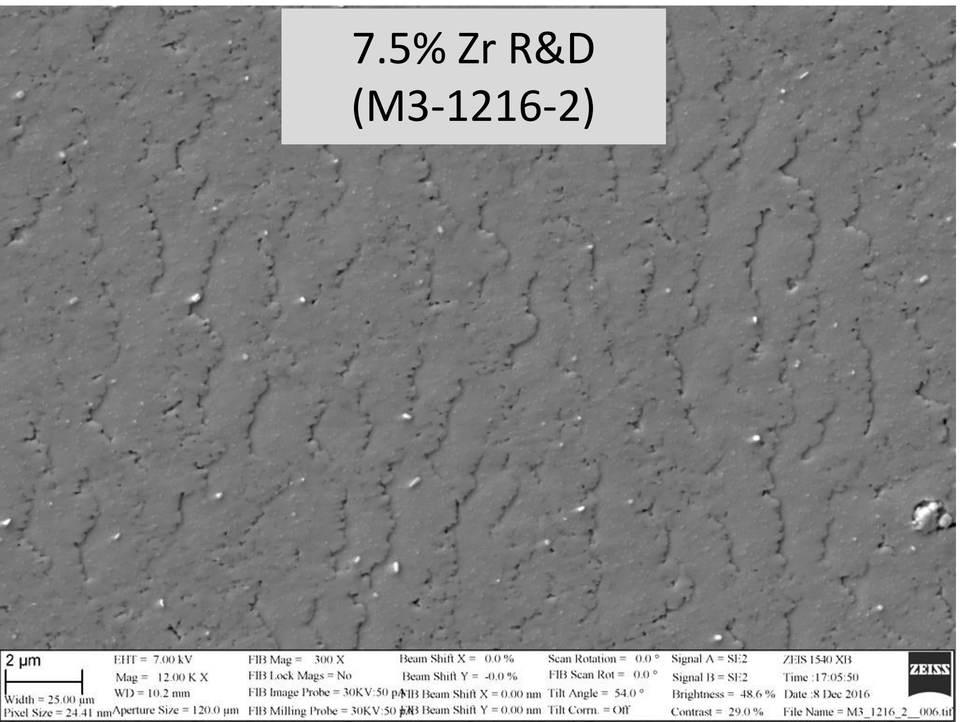


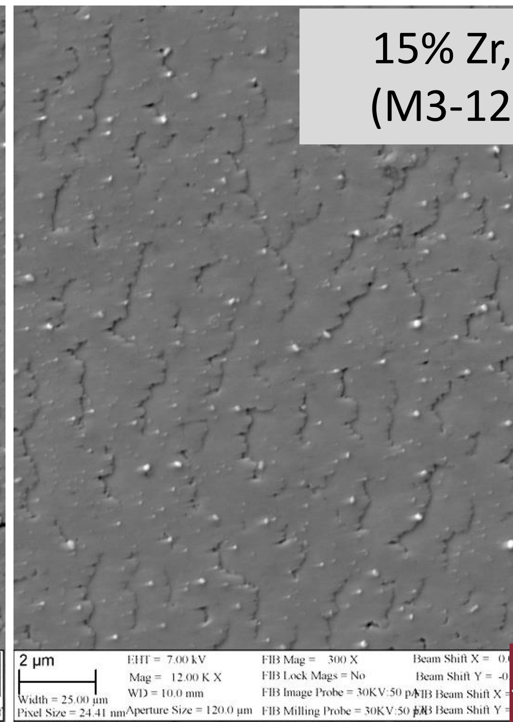




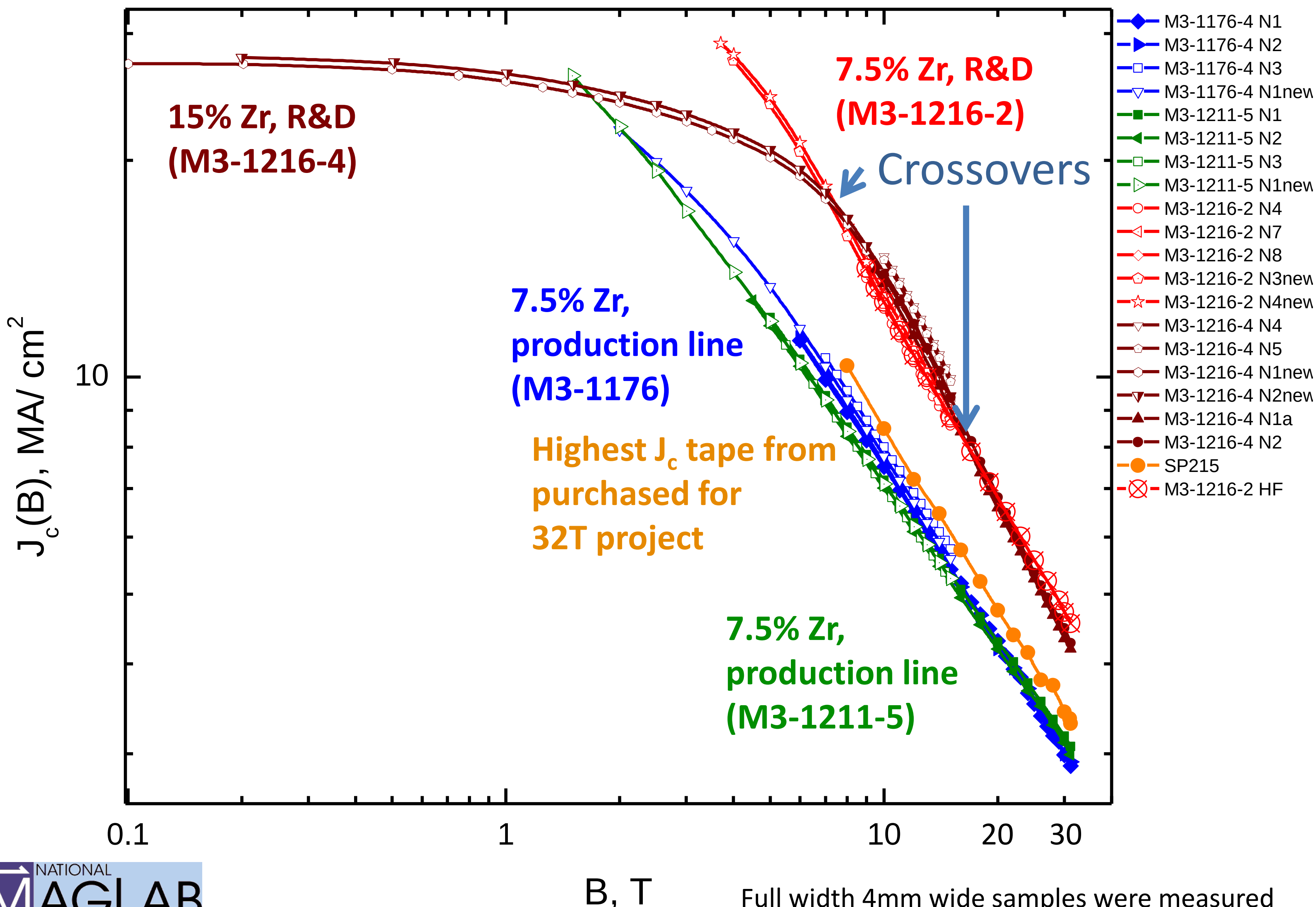


ReBCO surface of R&D tapes are free from a-axis grains and CuO grains





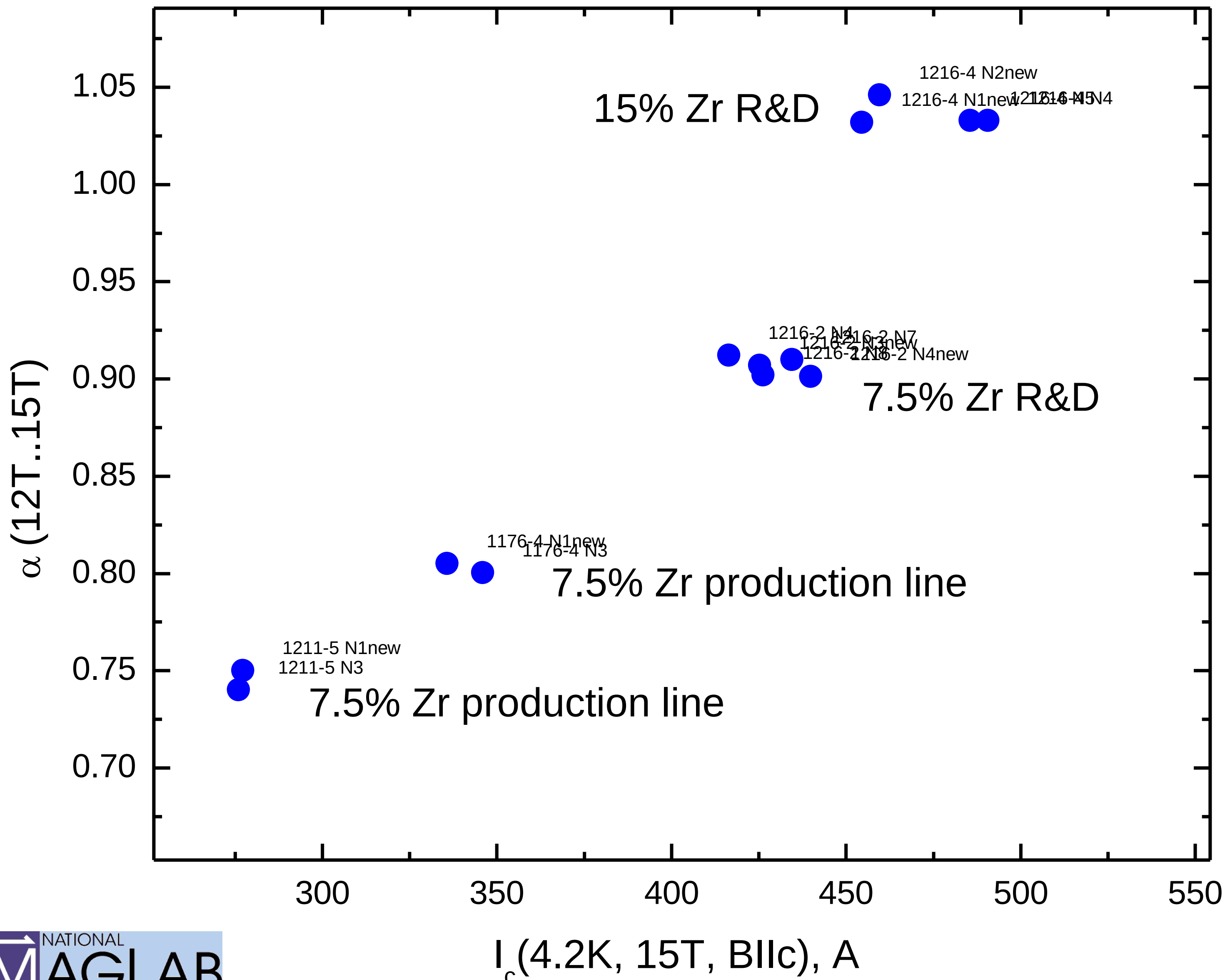
J_c(B,4K) measured in resistive and superconducting magnets



Full width 4mm wide samples were measured

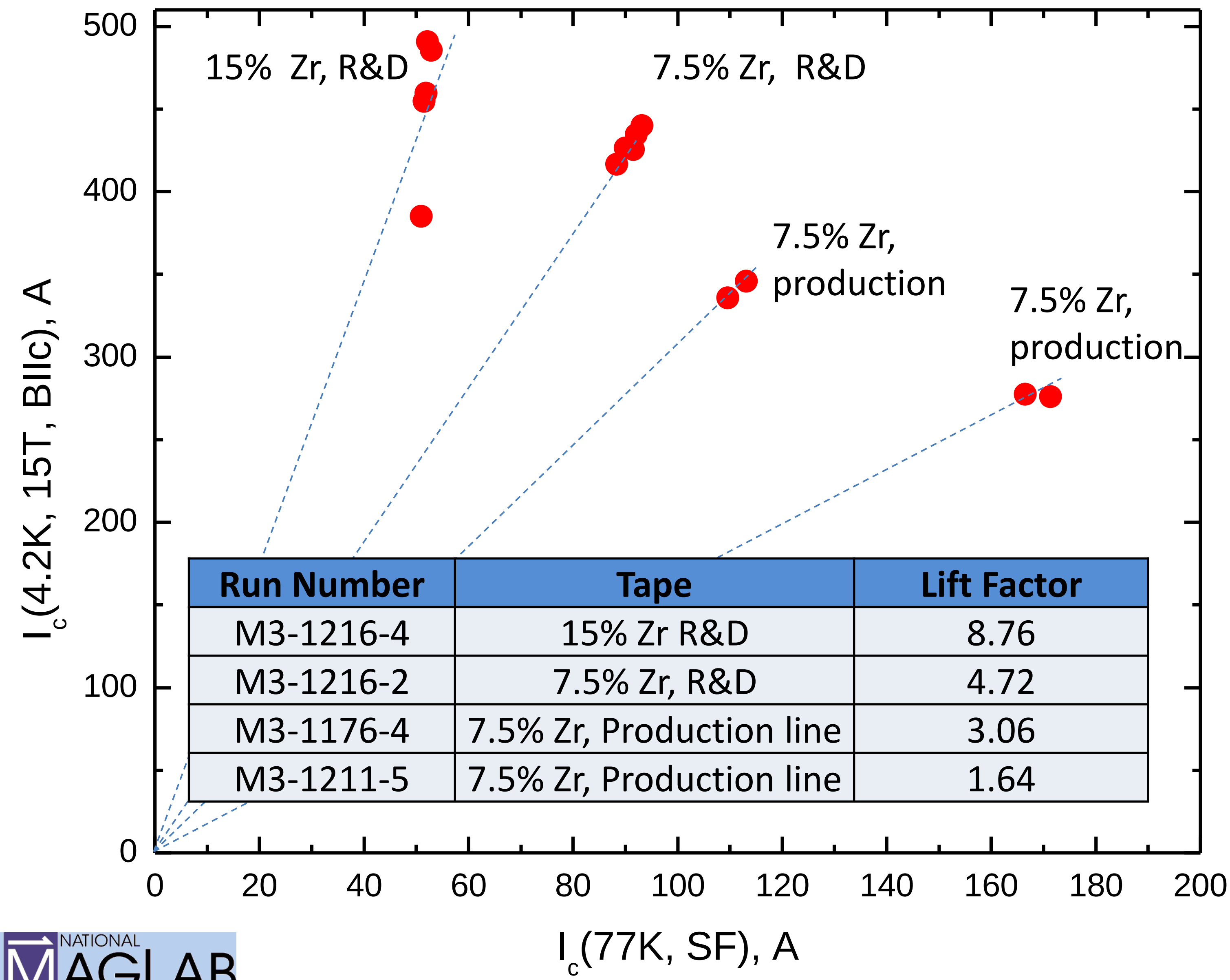
Larger α values corresponds to higher I_c(4K, 15T)

$I_c \sim B^{-\alpha}$



Very different lift factors for compared tapes

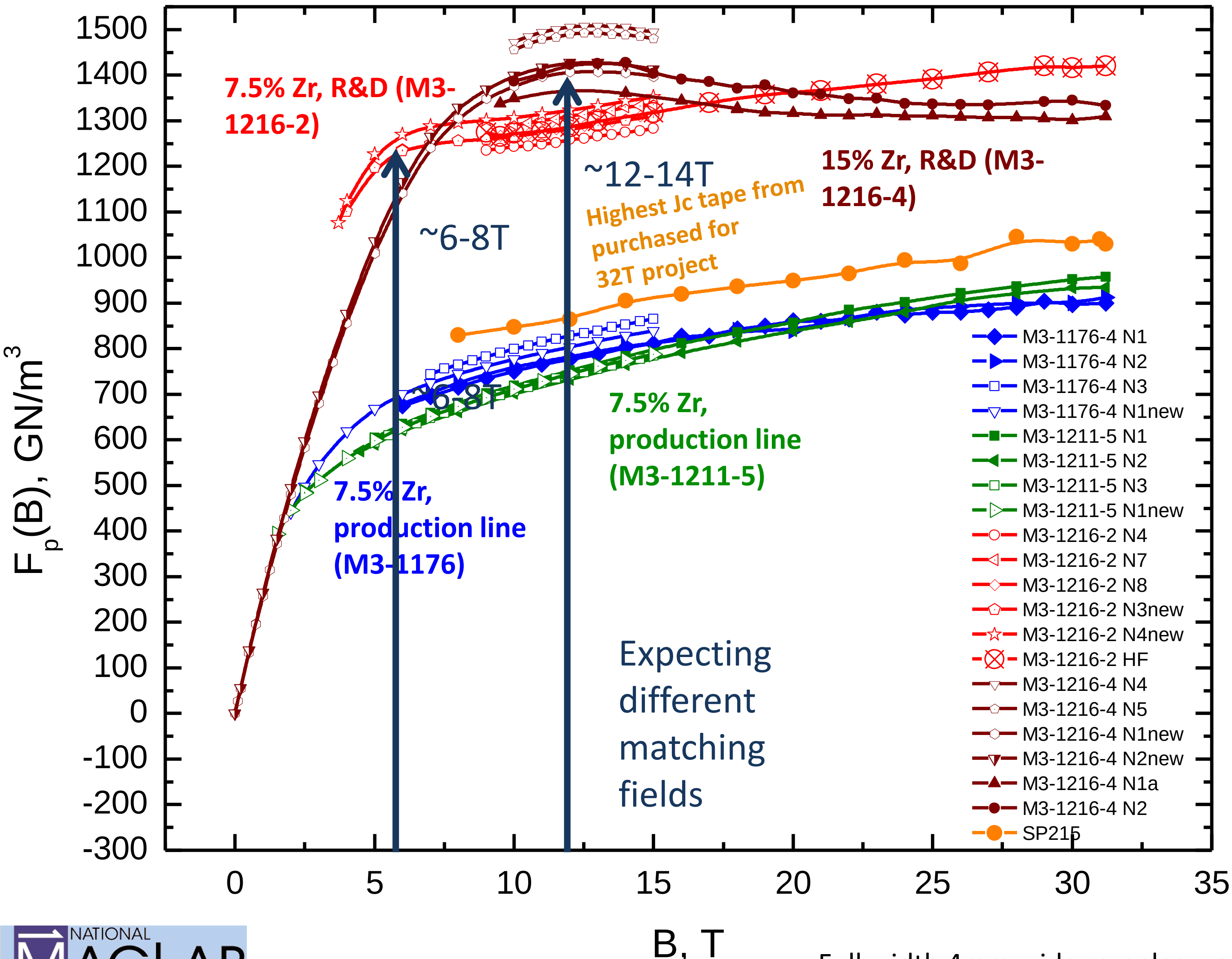
Interpretation: Additional pinning centers are not effective at 77K, SF



Run Number	Tape	Lift Factor
M3-1216-4	15% Zr R&D	8.76
M3-1216-2	7.5% Zr, R&D	4.72
M3-1176-4	7.5% Zr, Production line	3.06
M3-1211-5	7.5% Zr, Production line	1.64

Very different values and field dependence of $F_p(B, 4.2K)$ measured for R&D and production wires in resistive magnet up to 30T

Detected crossovers in $F_p(B)$ for 7.5% , 15% Zr R&D tapes at 7-8T and 17-20T



Full width 4mm wide samples were measured

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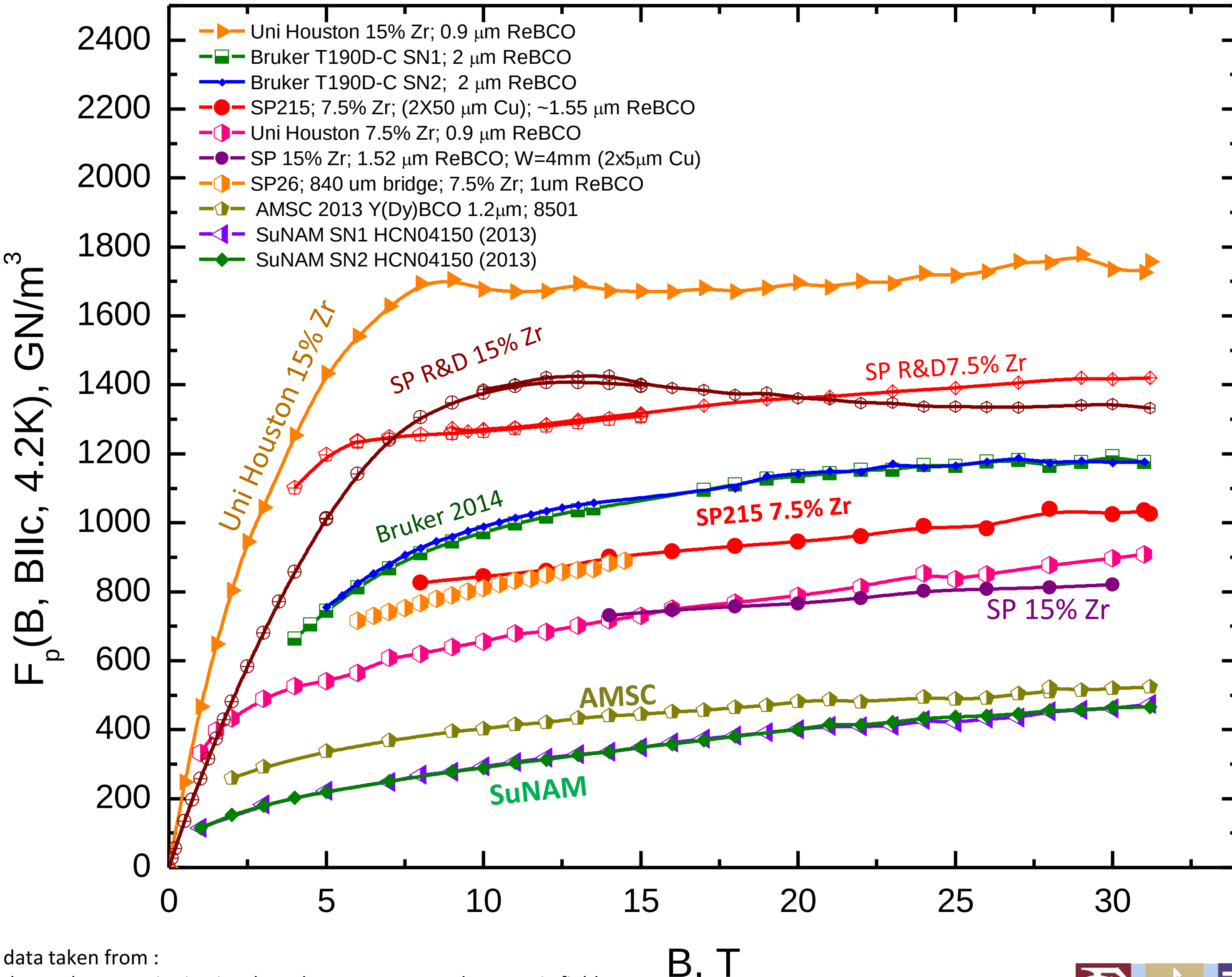
Recent SuperPower R&D tapes grown on production line are approaching Uni. Houston lab grown $F_p(B)$ values



Uni Houston data taken from :
<<Strongly enhanced vortex pinning in a broad temperature and magnetic field range of Zr-added MOCVD coated conductors>> Aixia Xu, et al.

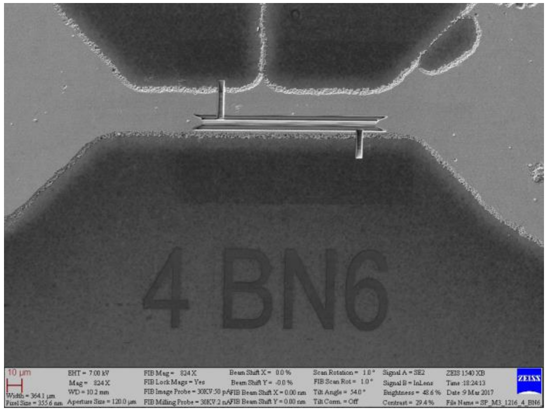
These data have just been extended to 45 T and these new data will also be reported.

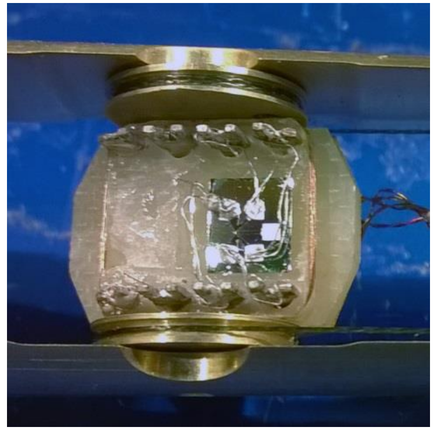
Transport $I_c(\theta, B, T)$ measured on FIB trimmed bridge in 45T hybrid magnet

- **Does I_c drop more rapidly as field exceeds 30T?**
- Does F_p reach maximum at 45T?

- How magnetic field dependence of fitting parameter T_o changing from 7.5% to 15% Zr in R&D tapes?
- Is sample to sample variation masking difference between 7.5% and 15% Zr?

Techniques to measure transport I_c (θ, B,T) of high J_c ReBCO





- 45T DC hybrid magnet
- Focused ion beam used to pattern ultra narrow ReBCO bridges
- Temperature stabilized actively on the rotator
- Use pick-up coil for angle measurement
- Fast reliable and simple sample mounting (5 samples measured)
- Above 4.2K I-V were measured in He gas
- I_c at <E>=10 μV/cm averaged from several I-V curves
- For highest currents I-V curves measured using pulsed technique to avoid overheating and thermal runaway.

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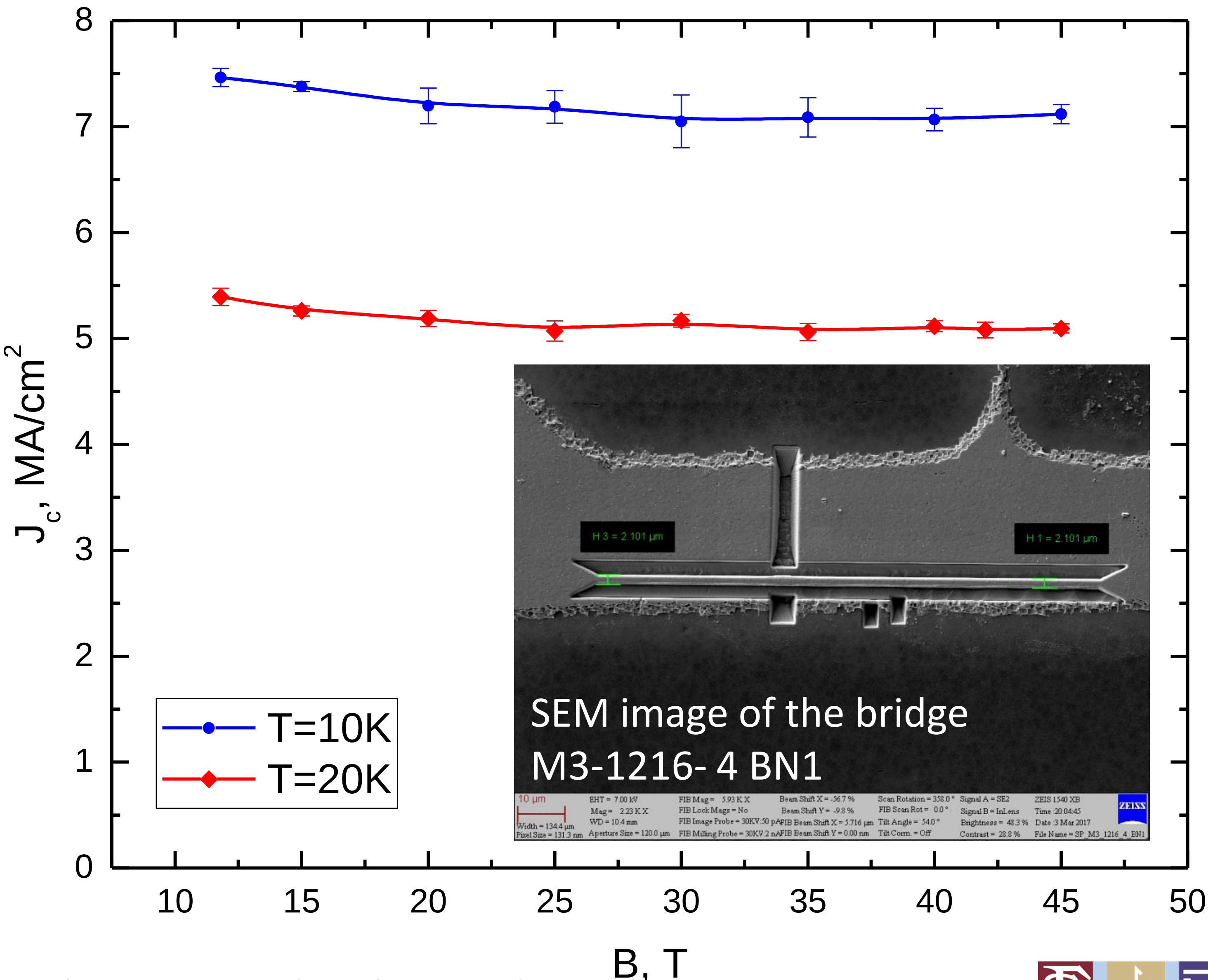
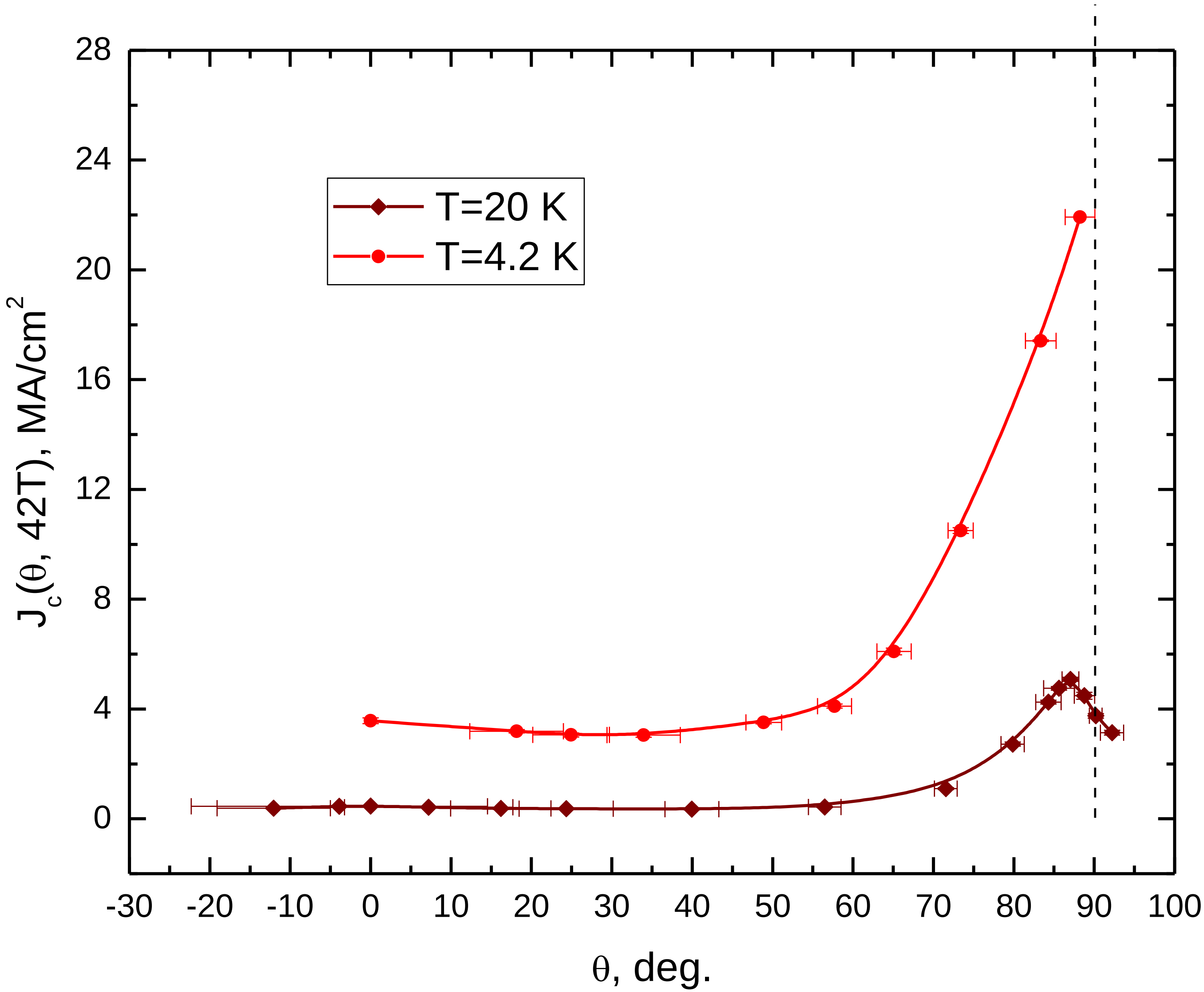
Field dependence of I_c at BIItape up to 45T at different temperatures.

Does J_c drop more rapidly as field exceeds 30T? - NO



Bridge 106 μm long, 2.1 μm wide with 15% Zr doping

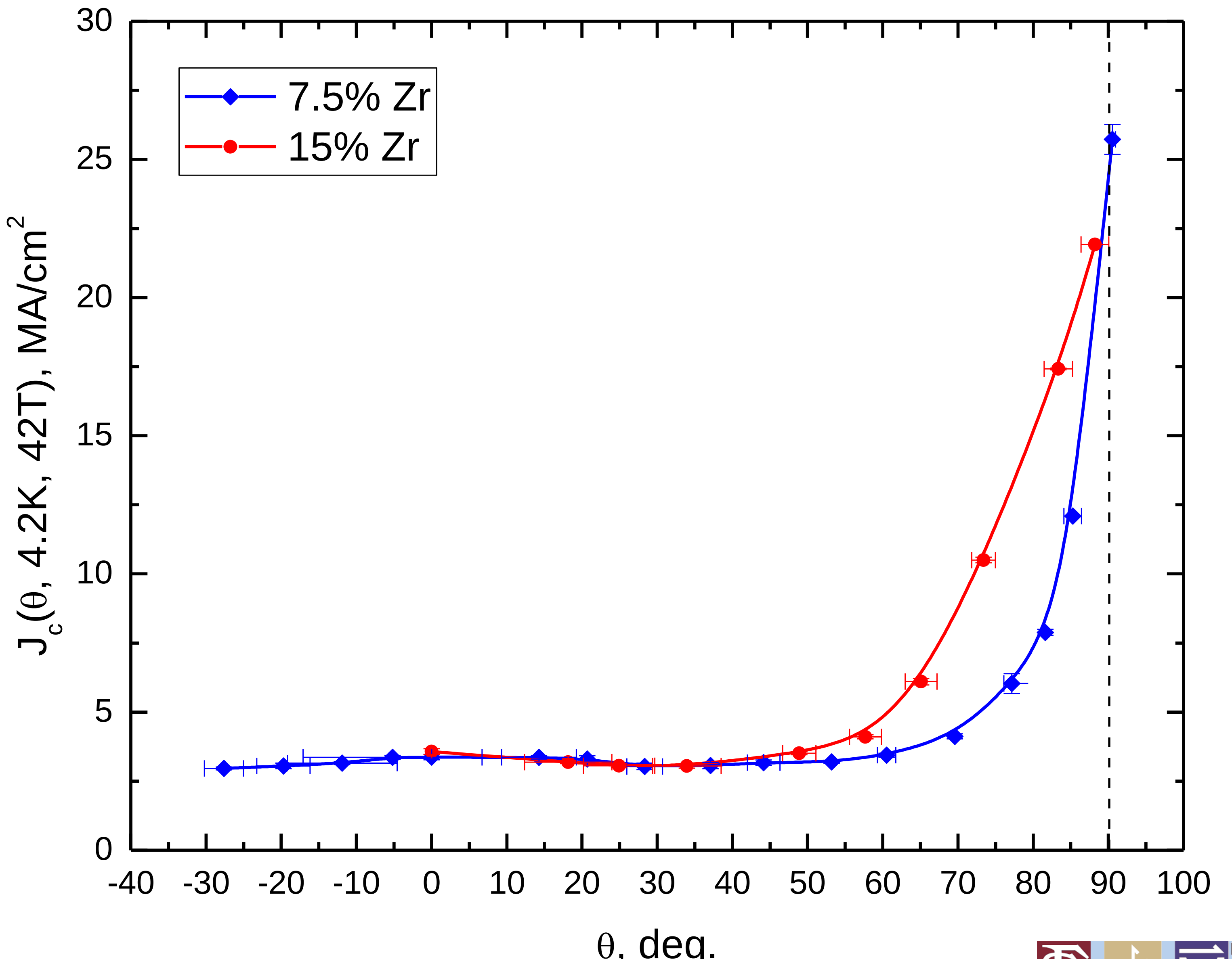
$J_c(\theta, 42T)$ measured at two temperatures for ReBCO bridge 15% Zr doping



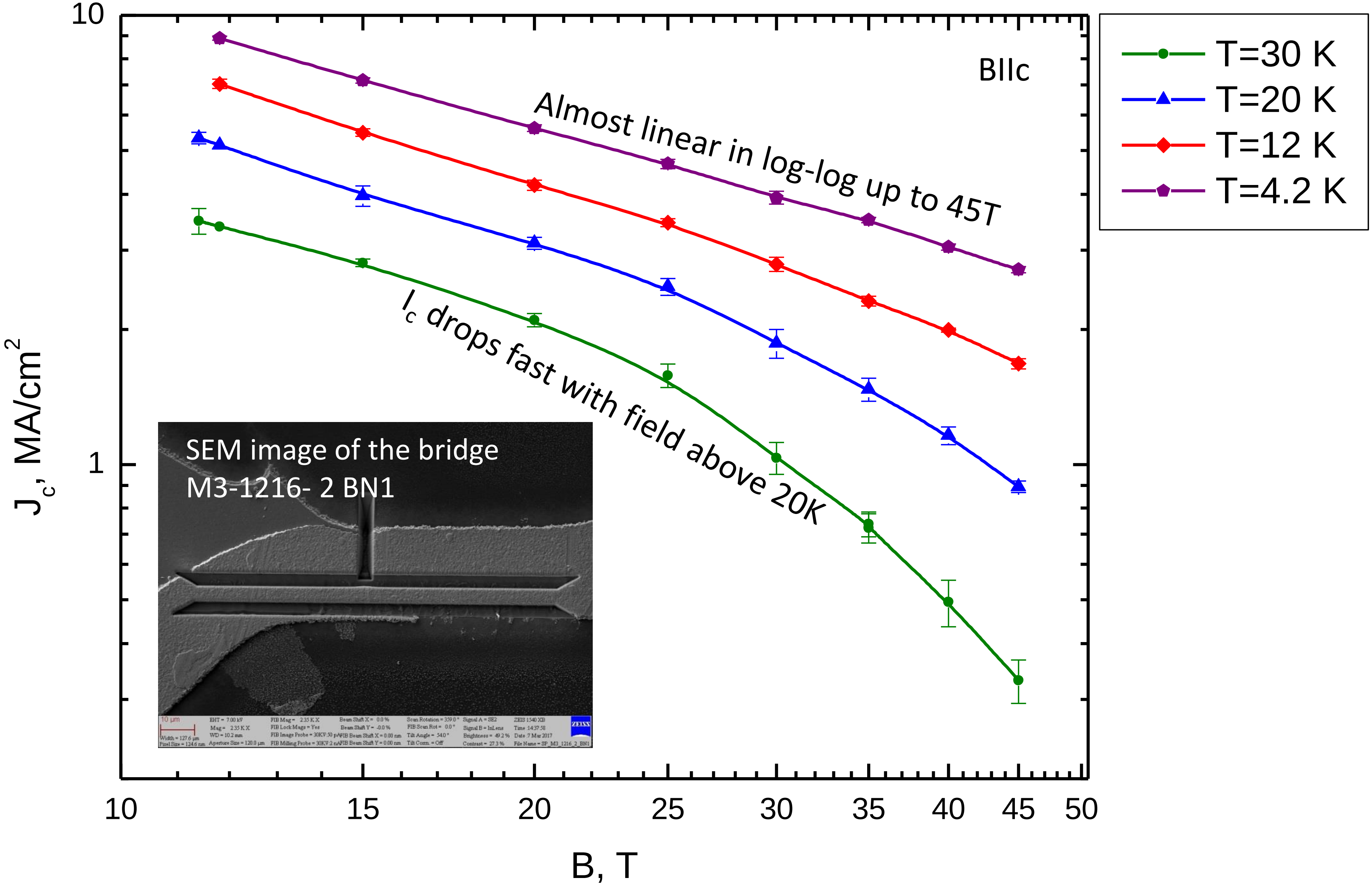
Bridge 106 μm long, 2.1 μm wide with 15% Zr doping

Comparison of $J_c(\theta$, 4.2K, 42T) for two ReBCO bridges 7.5% and 15% Zr doping

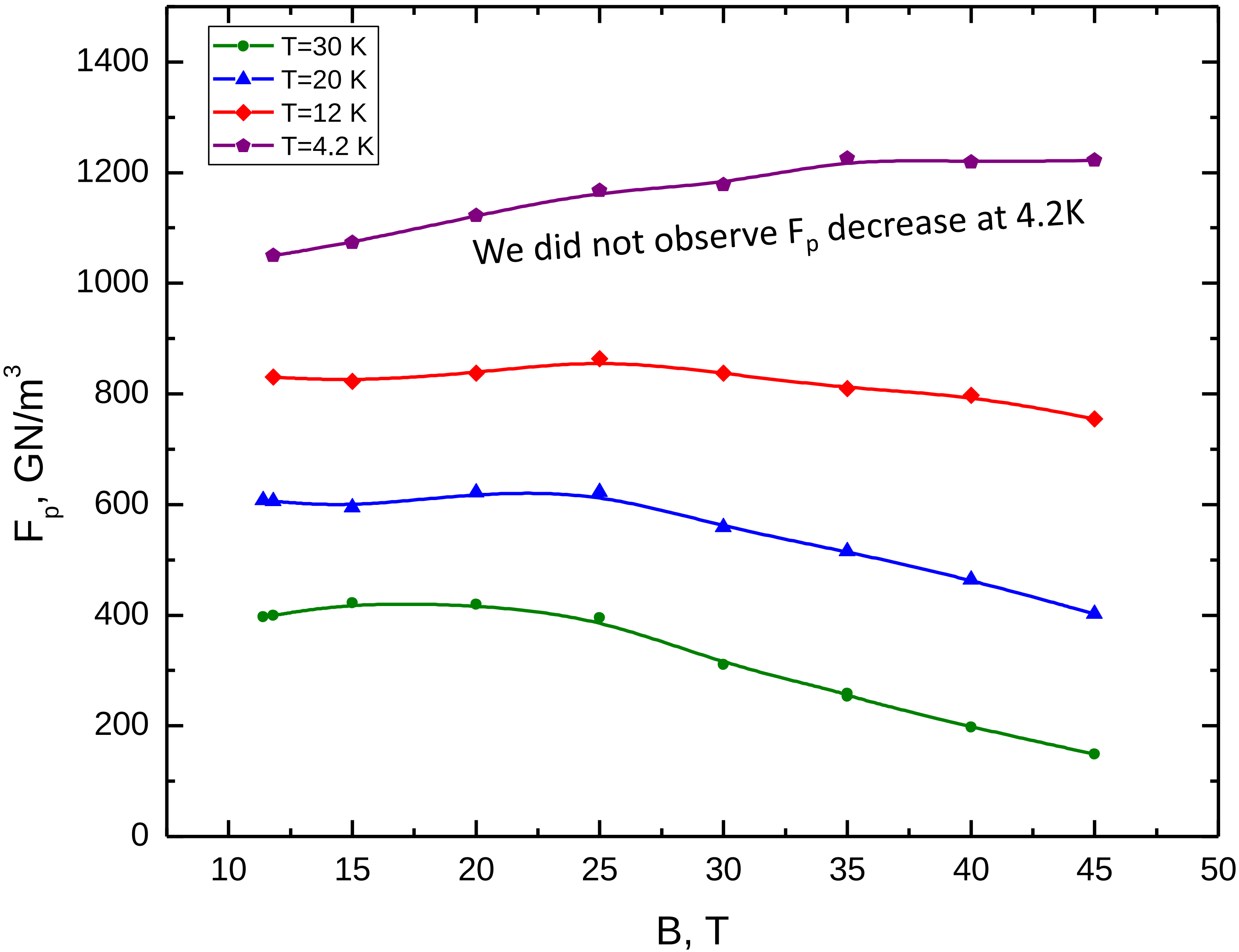
Observation: at 42T 15% Zr ReBCO has wider ab-peak, but near B_|_tape J_c coincide



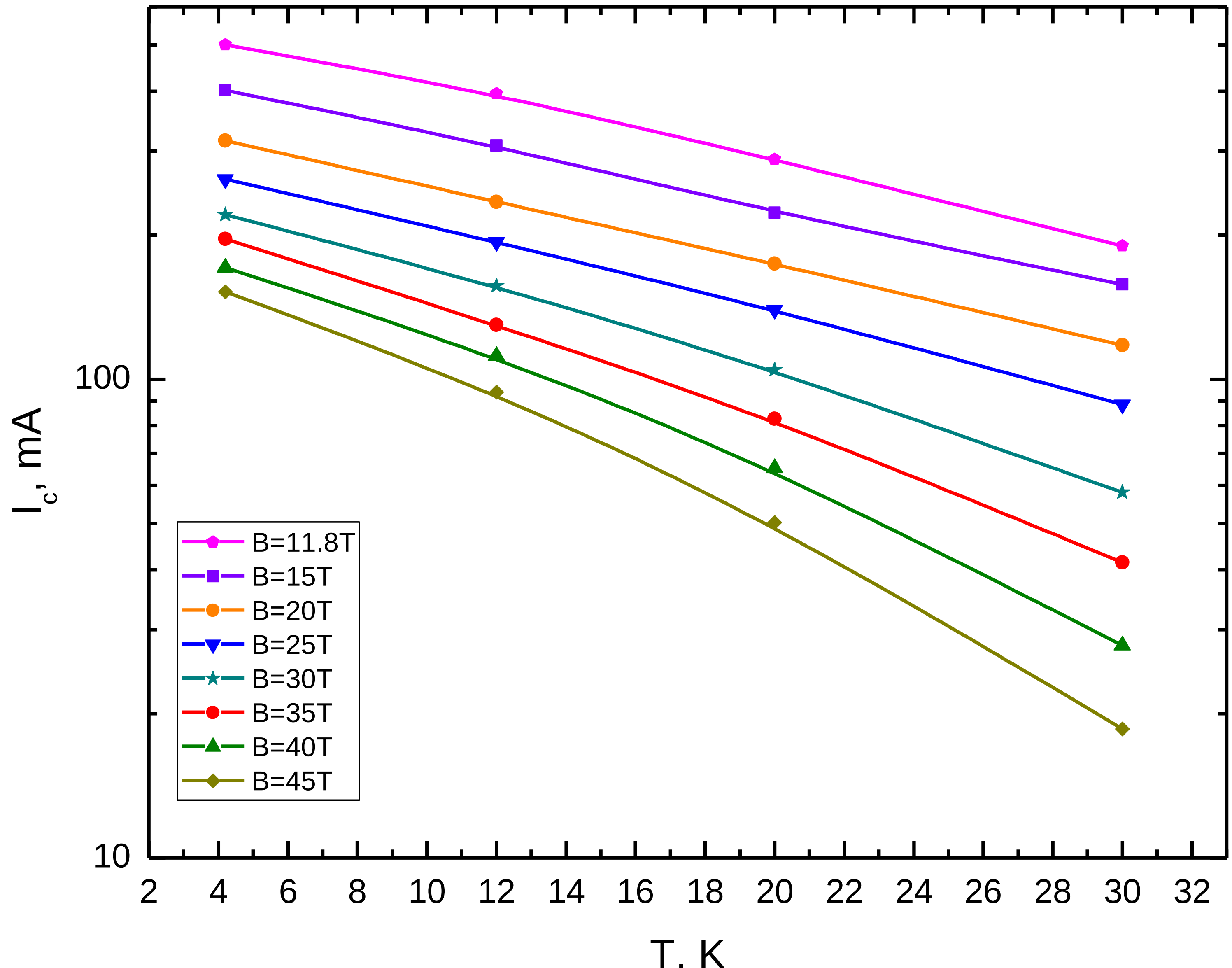
Magnetic field dependence of J_c at different temperatures for
R&D SuperPower tape M3-1216-2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag



Magnetic field dependence of F_p at different temperatures for
R&D SuperPower tape M3-1216-2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag

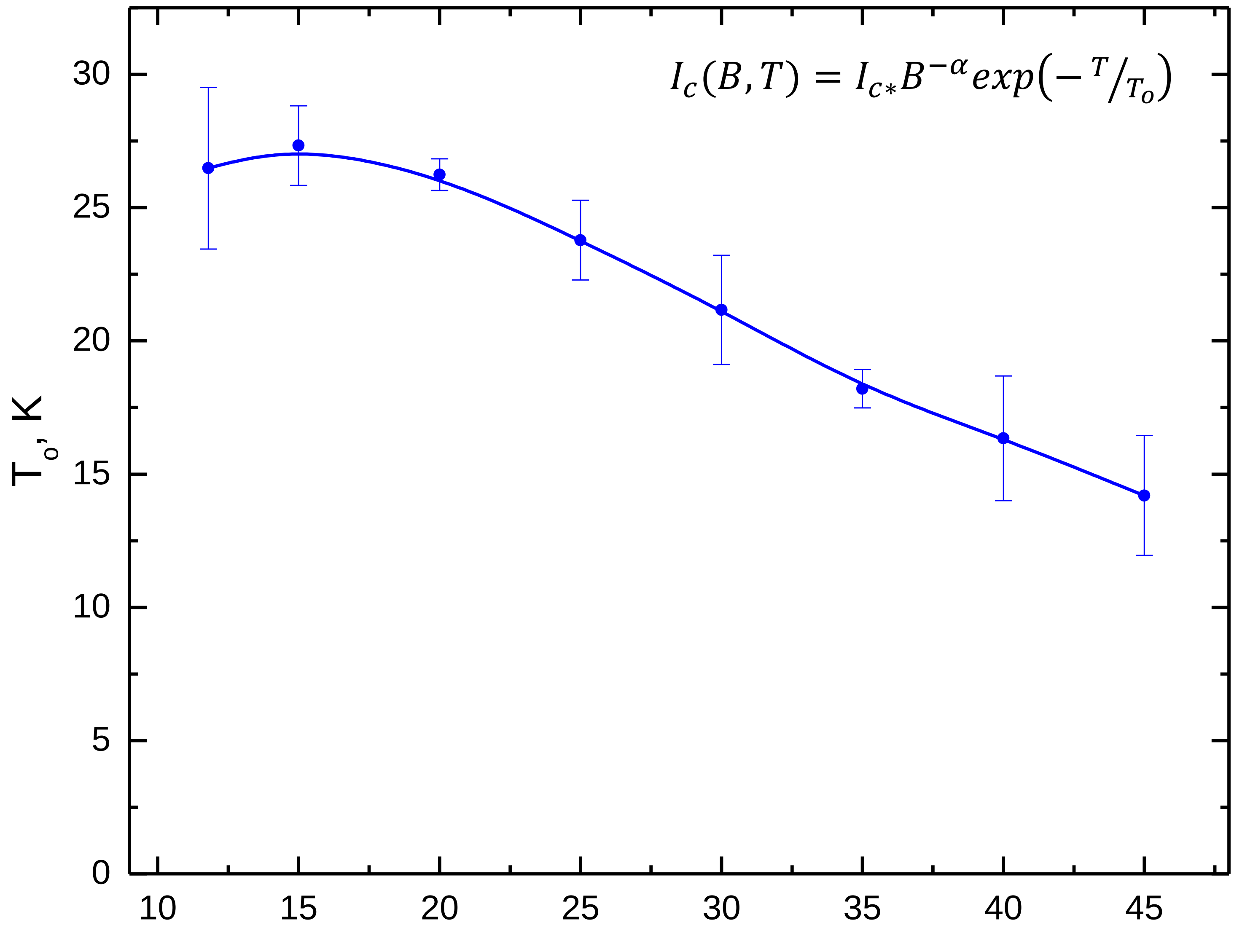


I_c (T, B) for R&D SuperPower tape M3-1216 2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag

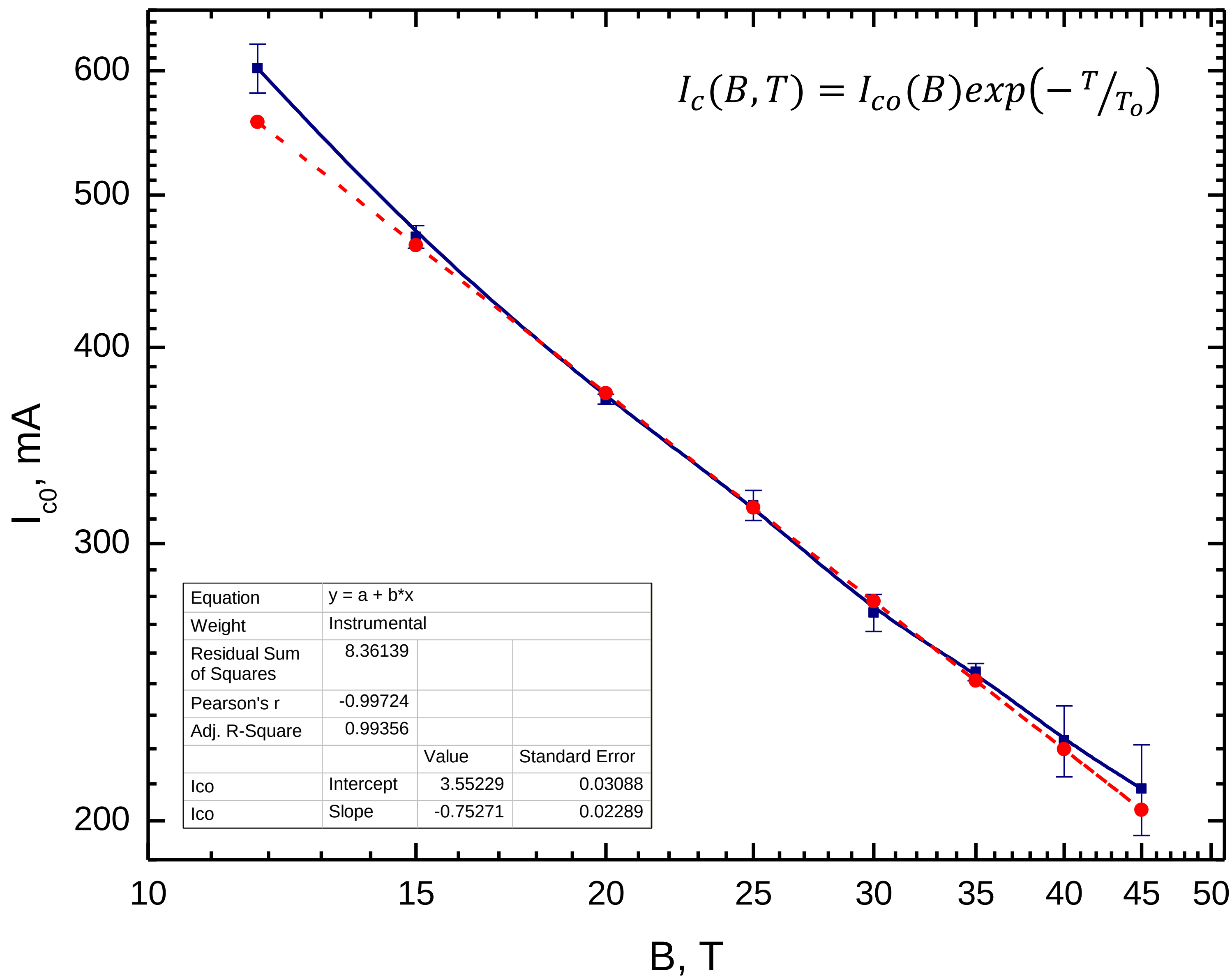


$$I_c(B,T) = I_{c*}B^{-\alpha}exp\left(-{}^{T}/_{T_o}\right)$$

Magnetic field dependence of fitting parameter $T_o(B)$

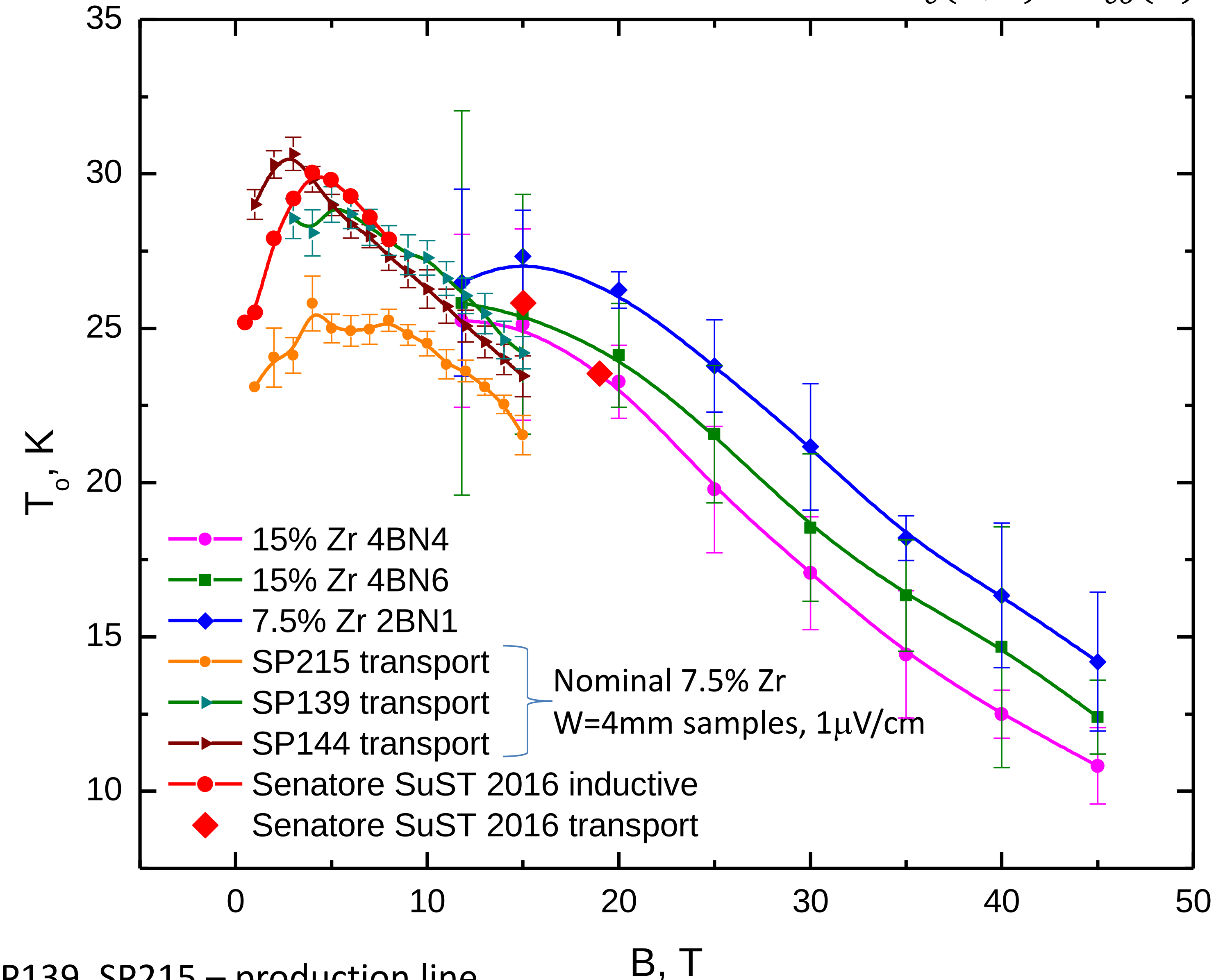


Magnetic field dependence of fitting parameter $I_{co}(B)$



Comparison of magnetic field dependencies of fitting parameter $T_o(B)$

$$I_c(B,T) = I_{co}(B)exp(-T/T_o)$$



SP144, SP139, SP215 – production line samples purchased for 32T project

Comparison transport properties of ReBCO tapes from different manufacturers

Tape	ReBCO Thickness
SP M3_1252_13	1.32
Shanghai SC	1.34
SP_42T_BottomPancake	1.42
SP_2ndFromTop	1.43
SP M4-396	1.47
SuNAM_160804_02	1.58
SuNAM_160804_01_SCN_0 4150	1.62
SuNAM 160819_08	1.65
Bruker39	1.82
Bruker37	1.97

BRUKER

上海超导
SHANGHAI SUPERCONDUCTOR

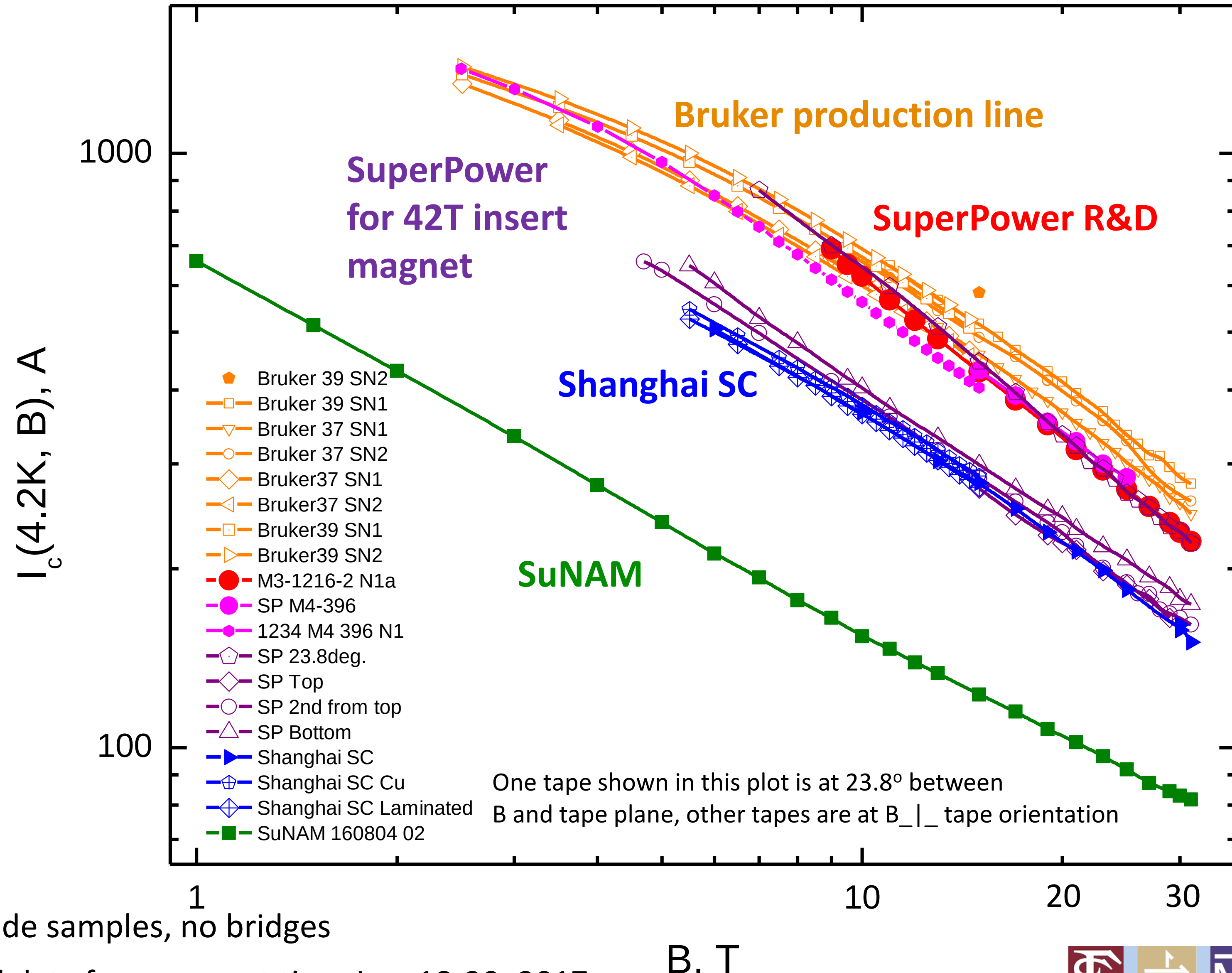
SuNAM

SuperPower Inc.
A Furukawa Company

Comparison transport I_c(4.2K, B) for ReBCO tapes from different manufacturers

Bruker production line tapes show higher I_c(4K,B) then SuperPower R&D tapes

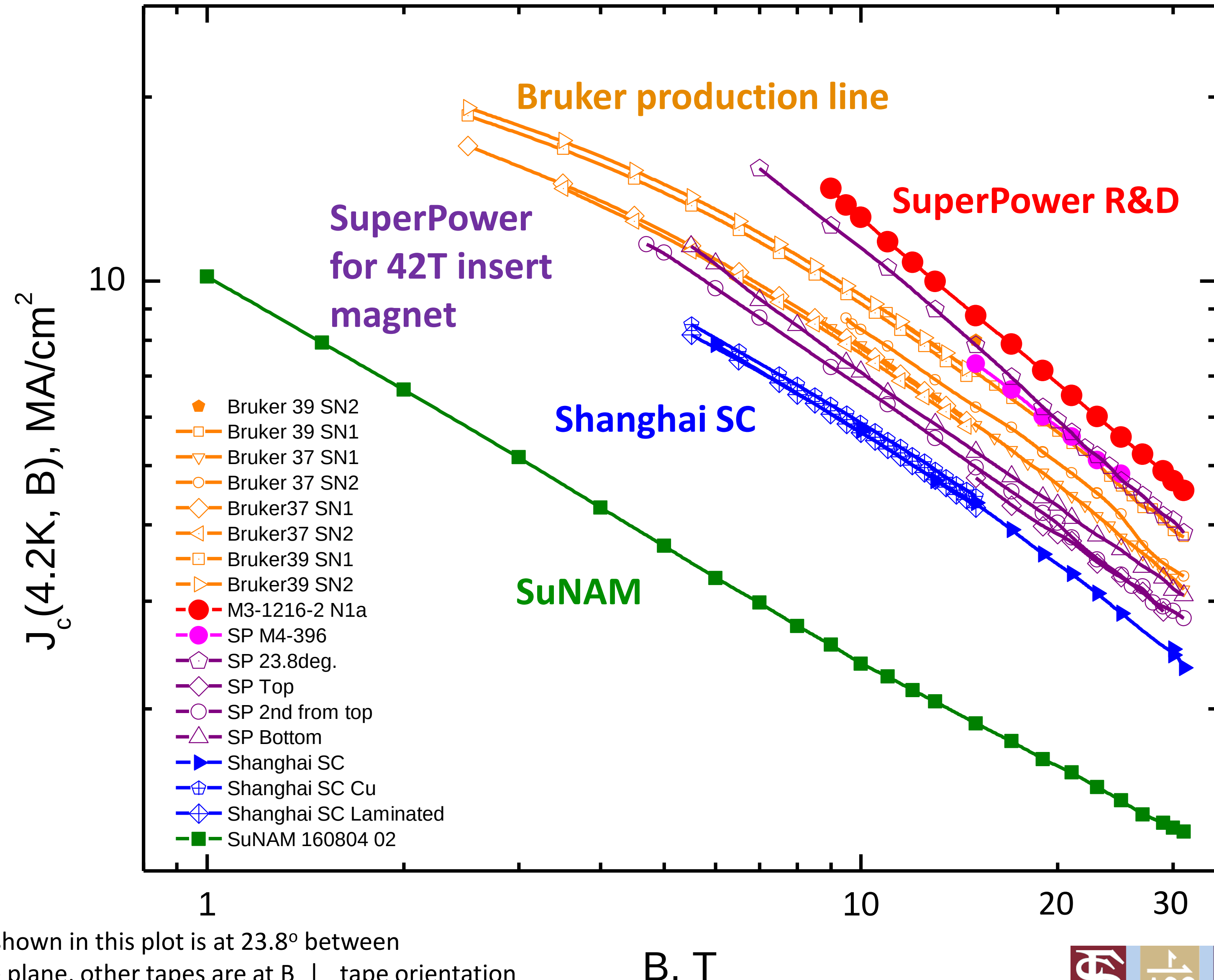
Shanghai SC tapes show I_c (4K,B) comparable to SP tapes used for 42T insert



~4mm wide samples, no bridges

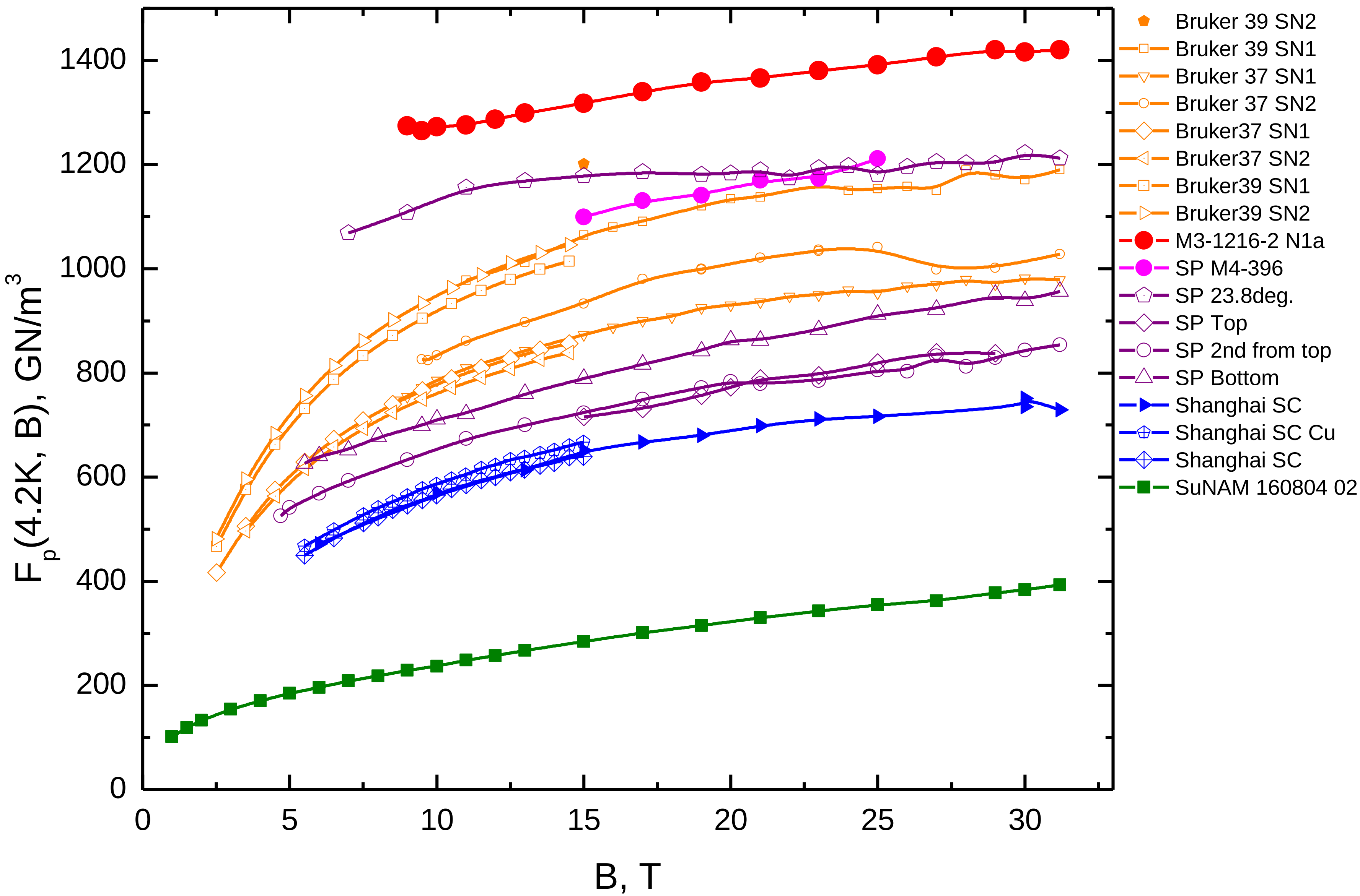
High field data from magnet time Jan. 18-20, 2017

Comparison transport J_c(4.2K, B) for ReBCO tapes from different manufacturers

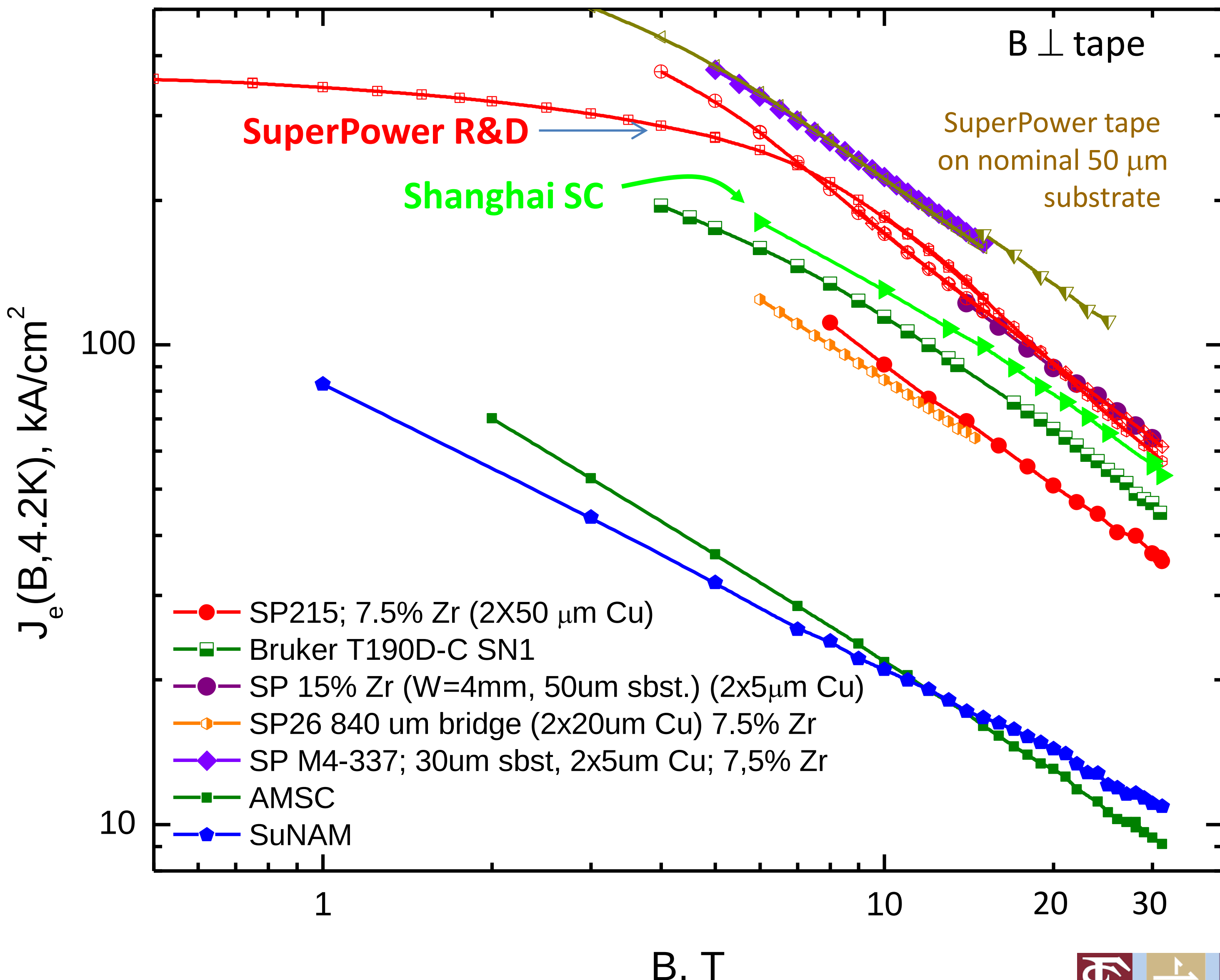


One tape shown in this plot is at 23.8° between B and tape plane, other tapes are at B_|_ tape orientation

Comparison transport f_p(4.2K, B) for ReBCO tapes from different manufacturers SuperPower R&D sample show the largest F_p(B)



SuperPower Inc. achieved record high J_e (4.2K, B) for tape with 45 μm substrate

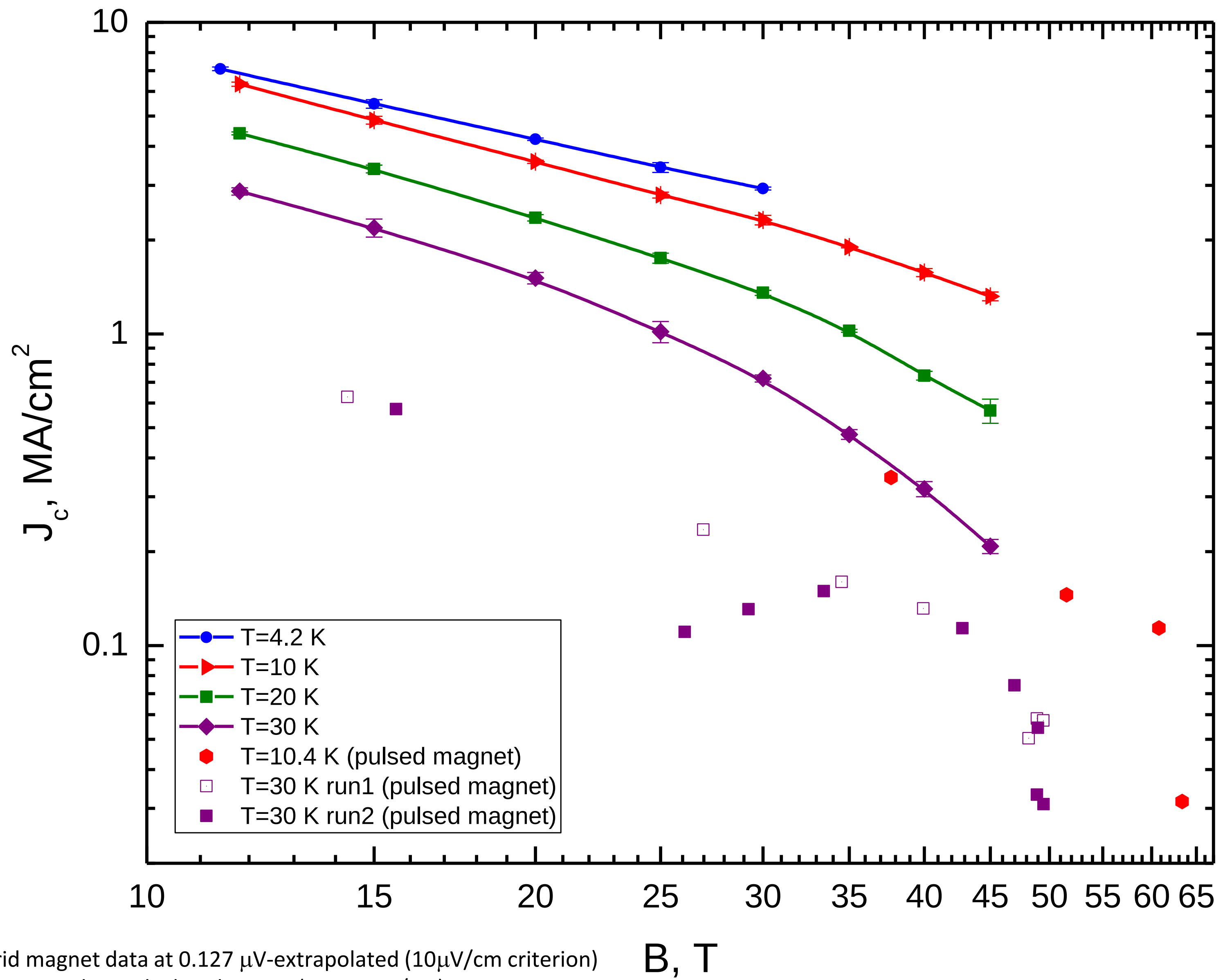


Conclusions:

1. **Comparison $I_c(B, 4K)$ for SuperPower R&D and production line tapes**
    1) Below ≈2T 15% Zr tape has lower I_c than 7.5% Zr production line tape
    2) SEM visualization suggests uniform single phase ReBCO layer visible in FIB patterned cross sections
    3) ReBCO surface of R&D tapes are free from a-axis grains and CuO grains
    4) SuperPower achieved very large values of f_p >1400 GN/m^3 in R&D 7.5%Zr tapes
    5) Very different values and field dependence of $f_p(B, 4.2K)$ measured for R&D and production wires in resistive magnet up to 30T
    6) Detected crossovers in $f_p(B)$ for 7.5% , 15% Zr R&D tapes at 7-8T and 17-20T
    7) Larger α values corresponds to higher $I_c(4K, 30T)$
    8) Lift factor grow with % of Zr doping. Additional pinning centers are not effective at 77K, SF
2. **Measurements of transport $I_c(\theta, B, T)$ on modern R&D high J_c ReBCO tapes is possible up to 45T**
    1) No J_c drop in BIItape orientation above 30T
    2) At 4.2K we detected almost linear $J_c(B)$ at B_|_tape in log-log up to 45T
3. **Comparison transport properties of ReBCO tapes from different manufacturers**
    1) Bruker production line tapes show higher $I_c(4K,B)$ than SuperPower R&D tapes, but SP R&D J_c values are higher
    2) Shanghai SC tapes show I_c (4K,B) comparable to SP tapes used for 42T insert
    3) SuperPower Inc. achieved record high J_e (4.2K, B) for tape with 45mm substrate
    4) Recent SuperPower R&D tapes grown on the production line are approaching Uni. Houston lab-grown $f_p(B)$ values

Additional slides

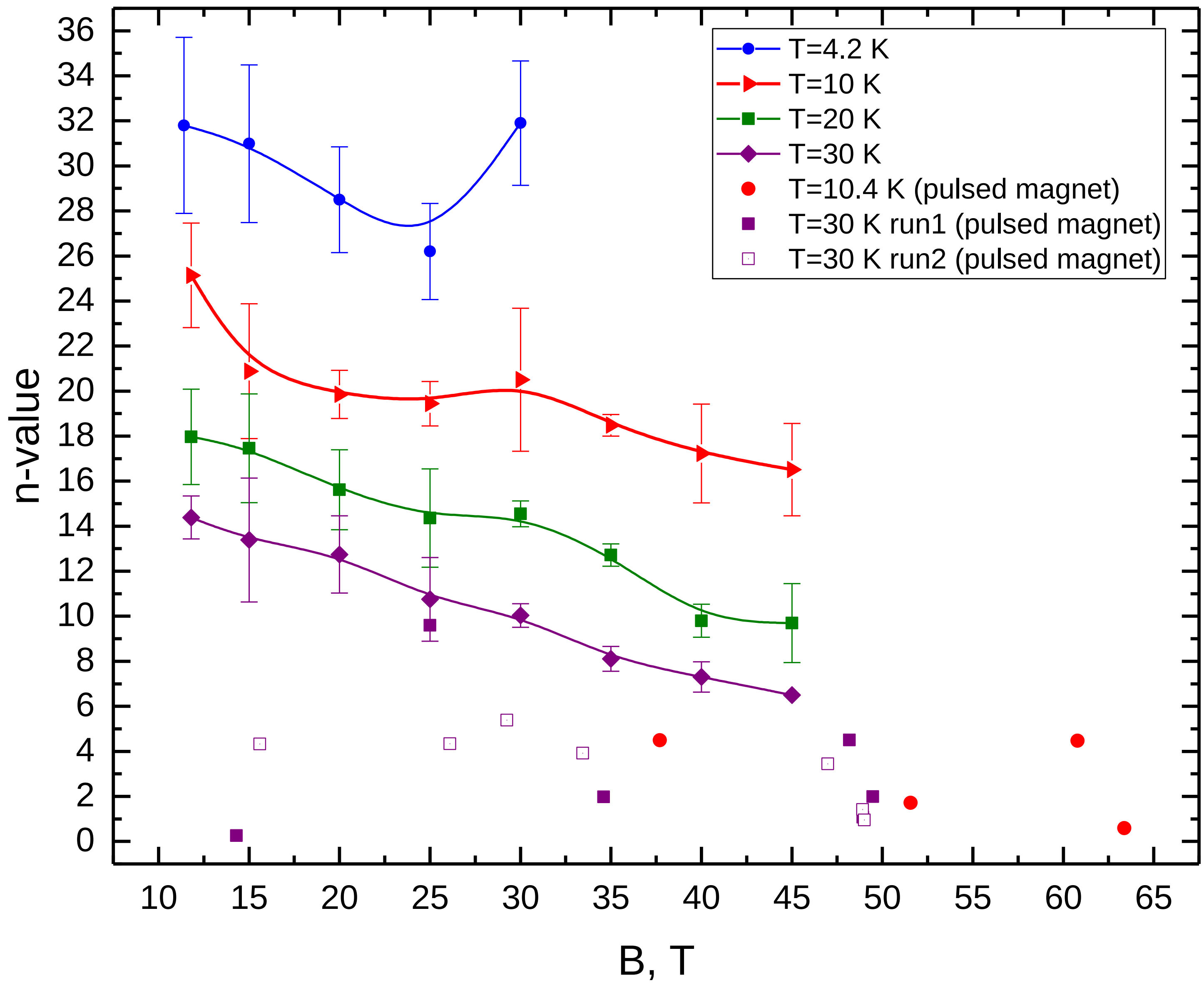
Comparison of transport J_c measured on SuperPower M3-1216-4 tape at B⊥tape; 15% Zr; Bridge #4; 1.9 μm wide in 45T DC hybrid magnet and M4-290-6 tape B at ~42°; 15% Zr, Bridge #10; 0.49 μm wide in 65T pulsed magnet



45T DC hybrid magnet data at 0.127 μV-extrapolated (10μV/cm criterion)

65T pulsed magnet data calculated at 3μV (≈3700 μV/cm)

Comparison n-values from I-V curves measured on SuperPower M3-1216-4 tape at B⊥tape; 15% Zr; Bridge#4; 1.9 μm wide in 45T DC hybrid magnet and M4-290-6 tape B at ~42°; 15% Zr, Bridge #10; 0.49 μm wide in 65T pulsed magnet

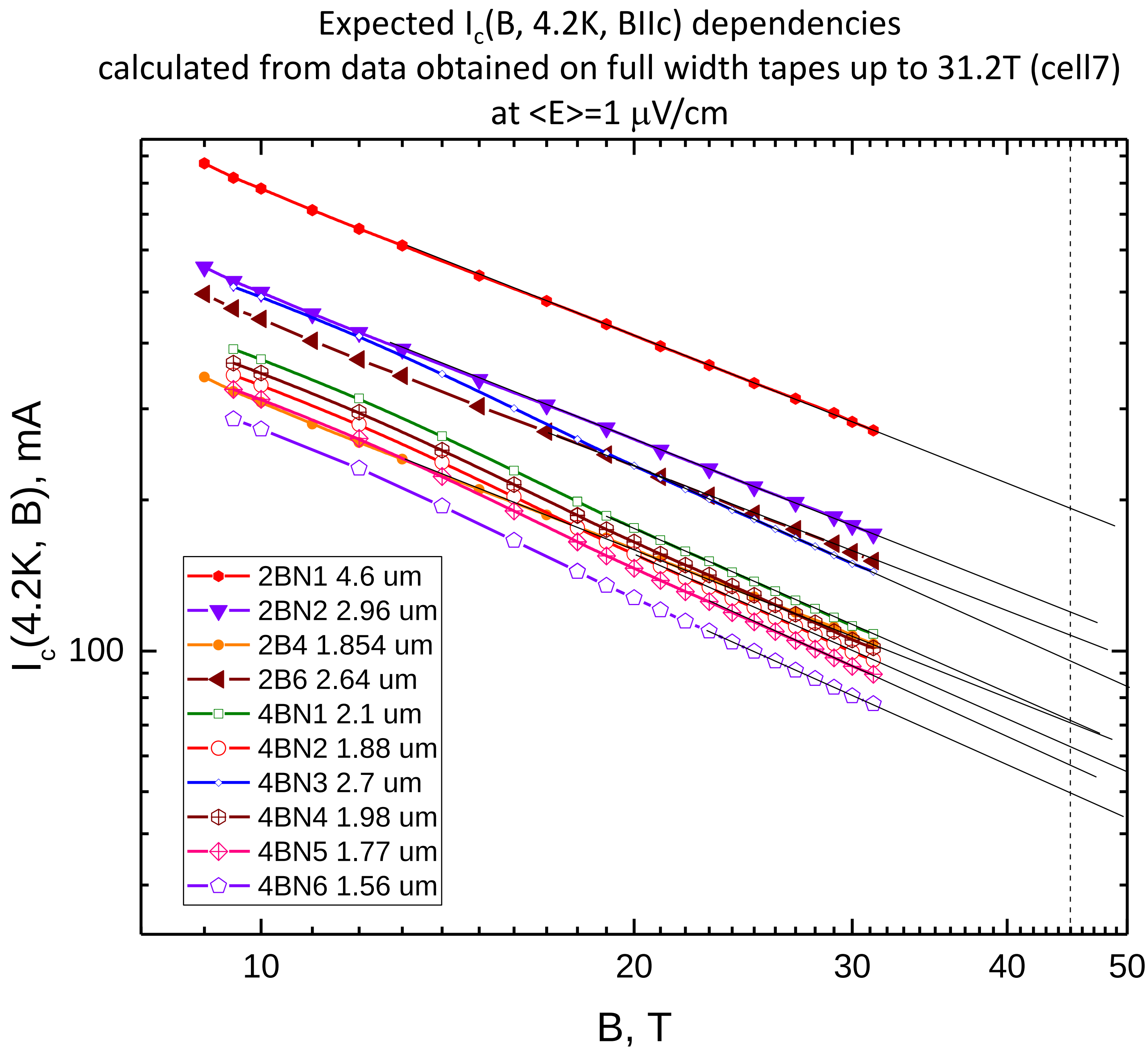


Samples:

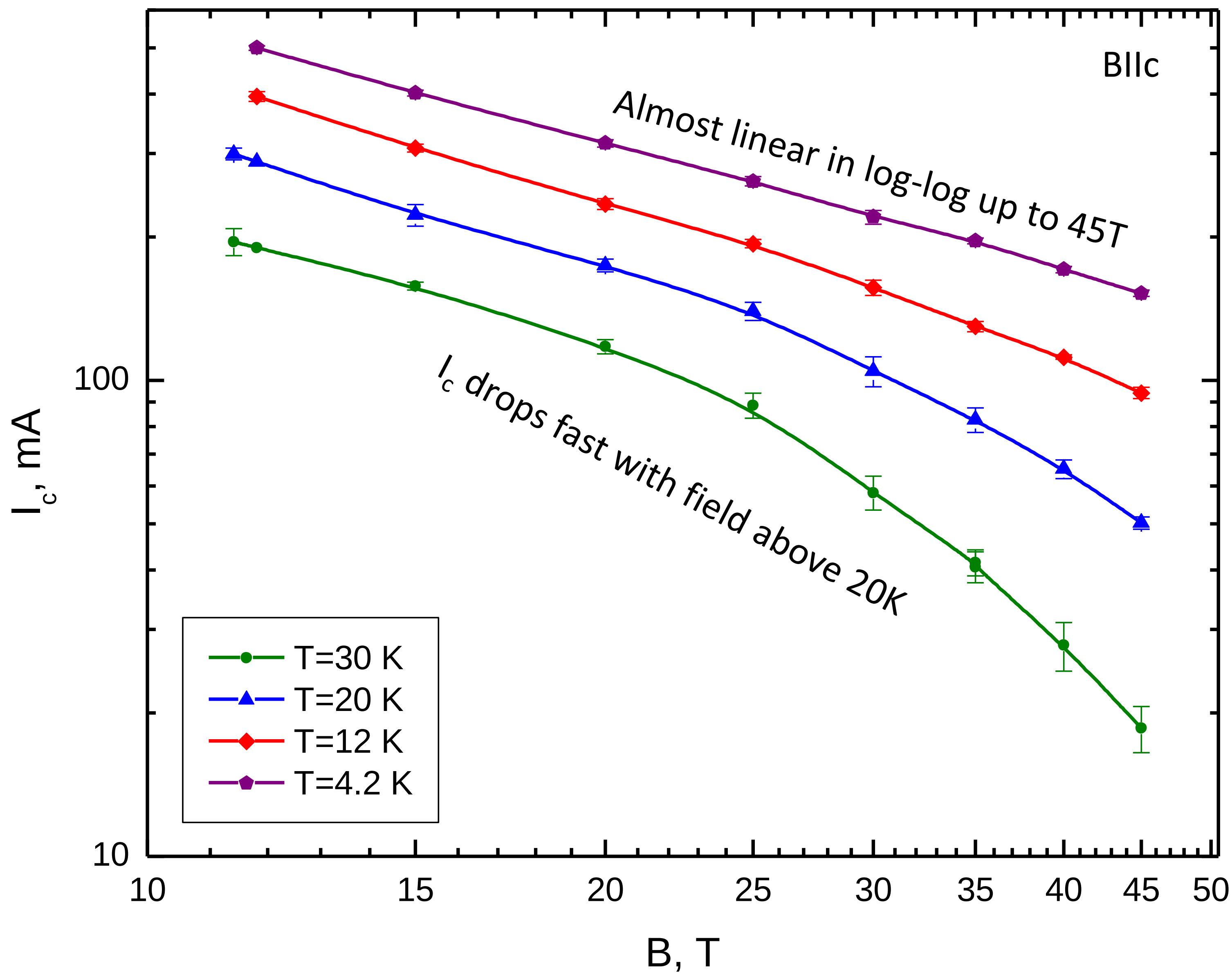
R&D SuperPower tapes were used because the amount of secondary phase was minimized
Ultra narrow bridges were patterned with photolithography and subsequently trimmed with FIB. Dimensions are full tape thickness – 1.22μm; 4.6μm – 1.6μm wide and about 100 μm long (9 bridges: 63μm-127μm most of them about 100um)

Tape Run	Bridge #	Manufacturing Date	Ag left?	Polished? (Y/N)	L (SEM)	W (SEM)	L(FIB)	W (FIB)	Vc from L SEM	Vc from L FIB	I_c(4K, 45T) expected	Thickness	Zr doping	Measured?
			y/n	y/n	um	um	um	um	nV	nV	mA	um	%	Y/N
											BIIc			
M3-1216-2	1	3/7/2017	y	n	105.6	4.6	101.4	4.635	10.56	10.14	183.6		7.5	y
M3-1216-2	2	3/7/2017	y	y			100.5	2.964	--	10.05	117.9		7.5	y/n (rotated)
M3-1216-2	3	--	--	--	--	--	--	--	--	--	--	--	7.5	--
M3-1216-2	4	3/6/2017	n	y	104.9	1.854	100.3	1.894	10.49	10.03	74.04		7.5	--
M3-1216-2	5	--	--	--	--	--	--	--	--	--	--	--	7.5	--
M3-1216-2	6	3/8/2017	n	y	63.39	2.64	60.88	2.68	6.339	6.088	108	--	7.5	y
M3-1216-4	1	3/3/2017	n	n	106.2	2.1	101	1.913	10.62	10.1	74.6		15	y
M3-1216-4	2	3/3/2017	n	n			101.8	1.878	--	10.18	66.58	1.22	15	--
M3-1216-4	3	3/6/2017	n	y	105	2.737	100.9	2.865	10.5	10.09	93.04		15	--
M3-1216-4	4	3/10/2017	n	y	127.2	1.984	121.4	1.722	12.72	12.14	74		15	y
M3-1216-4	5	3/8/2017	n	y	115.6	1.77	110.3	1.967	11.56	11.03	62		15	--
M3-1216-4	6	3/9/2017	n	y	116.8	1.56	111.4	1.426	11.68	11.14	55		15	y

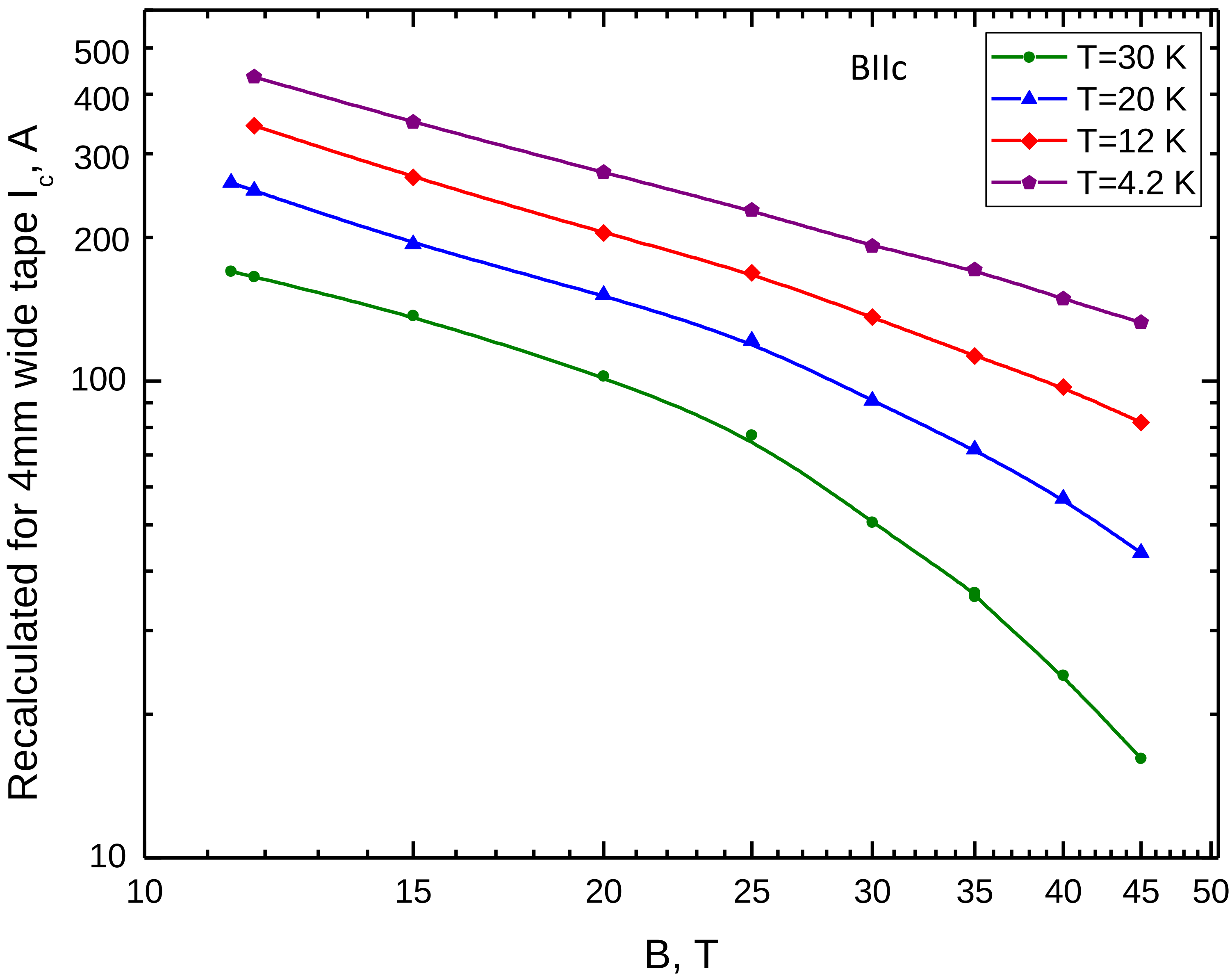
Measured in 45T magnet bridges marked red


Expected I_c(B, 4.2K, BIIc) dependencies
calculated from data obtained on full width tapes up to 31.2T (cell7)
at <E>=1 μV/cm
I_c(4.2K, B), mA
100
10
20
30
40
50
B, T
2BN1 4.6 um
2BN2 2.96 um
2B4 1.854 um
2B6 2.64 um
4BN1 2.1 um
4BN2 1.88 um
4BN3 2.7 um
4BN4 1.98 um
4BN5 1.77 um
4BN6 1.56 um

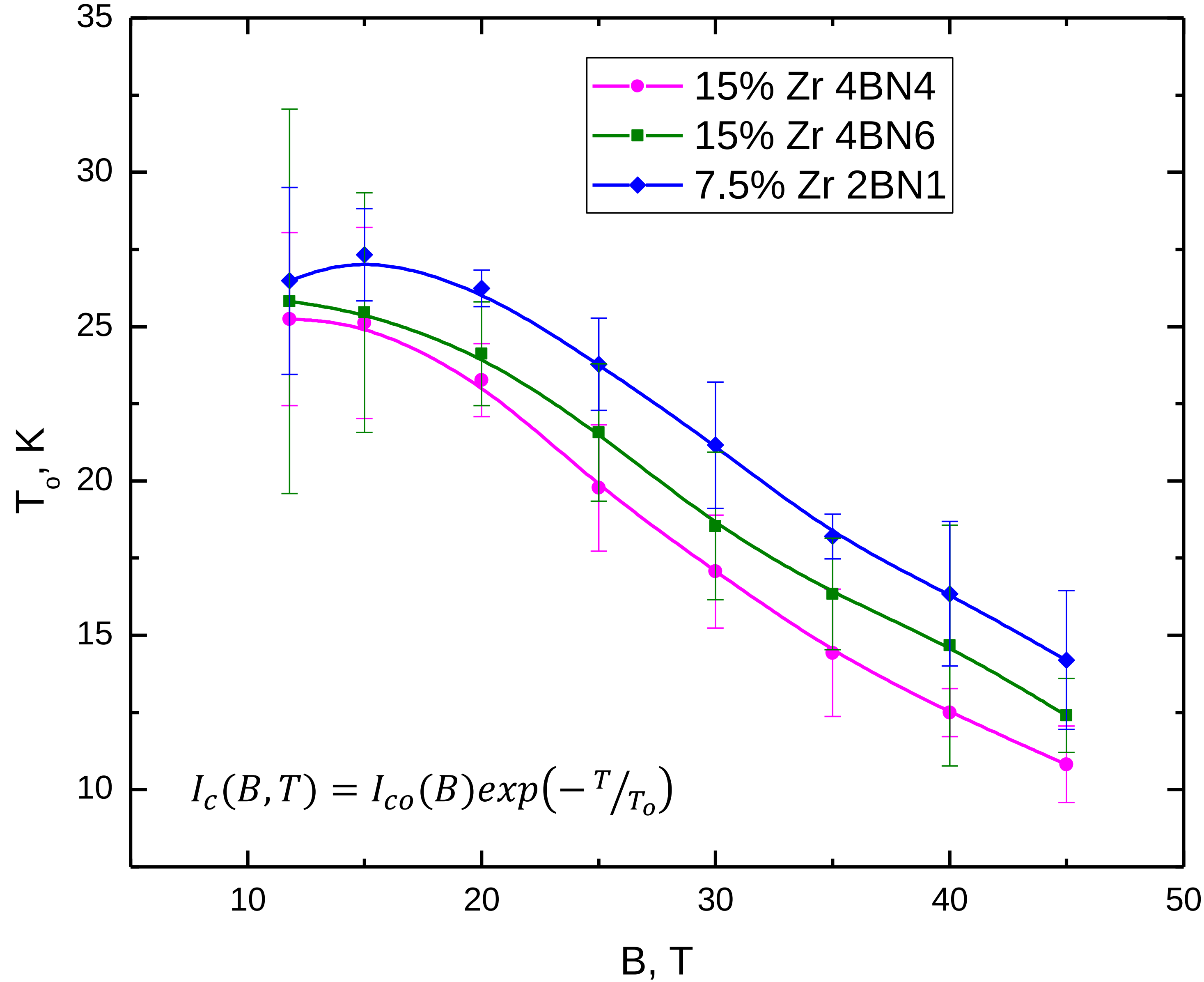
Magnetic field dependence of transport I_c at different temperatures for
R&D SuperPower tape M3-1216-2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag



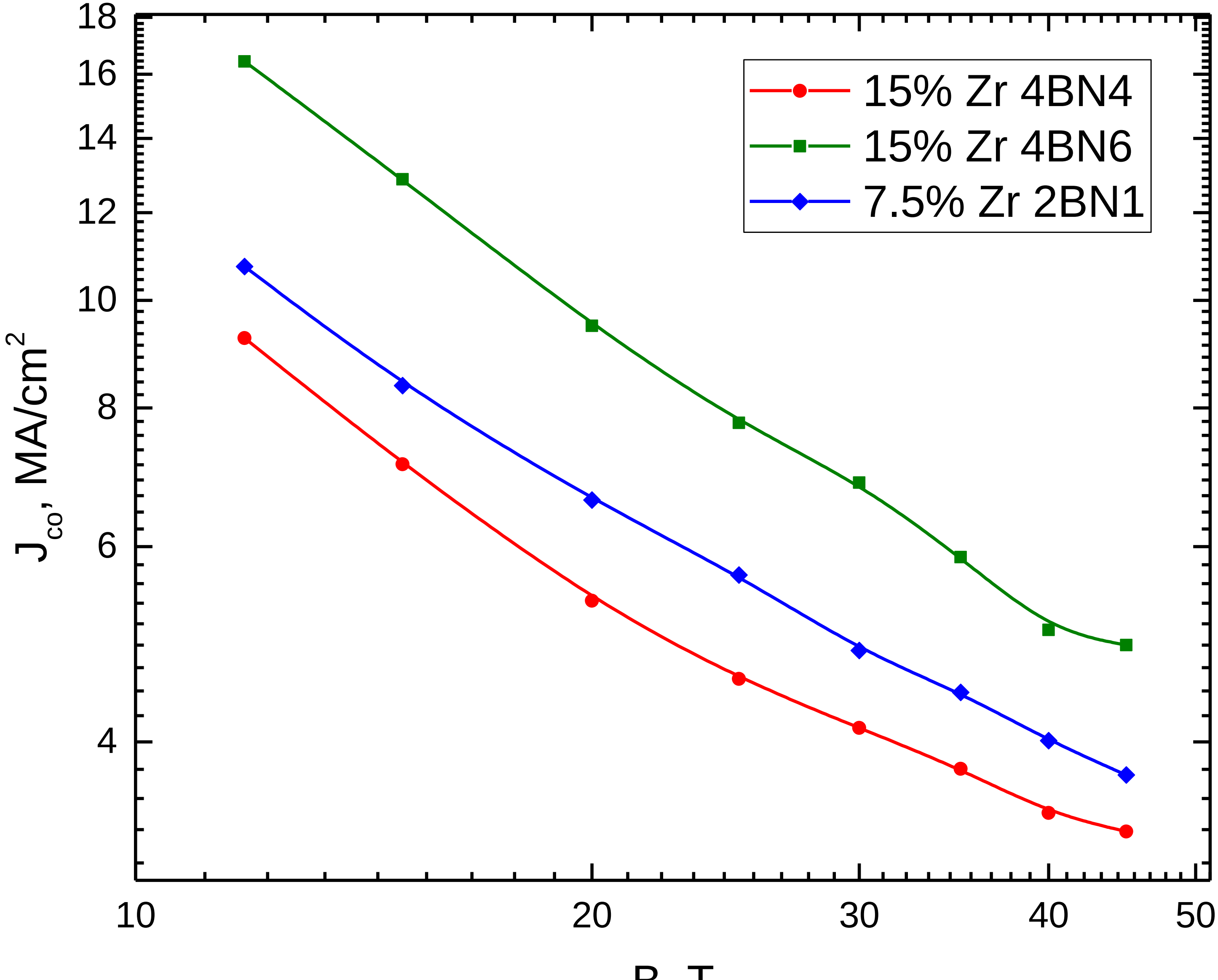
Magnetic field dependence of I_c (recalculated to 4mm wide tape) at different temperatures for R&D SuperPower tape M3-1216-2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag

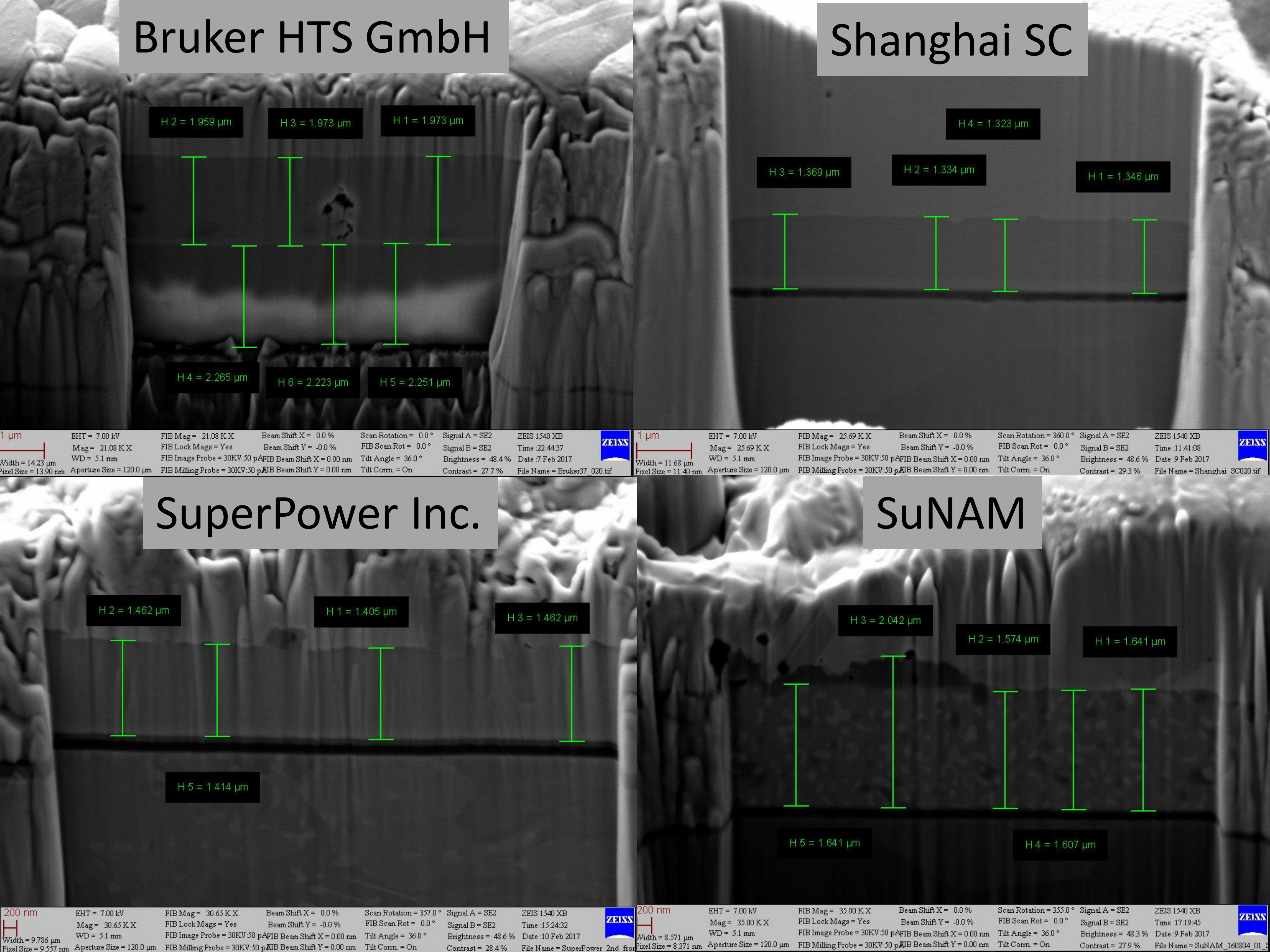


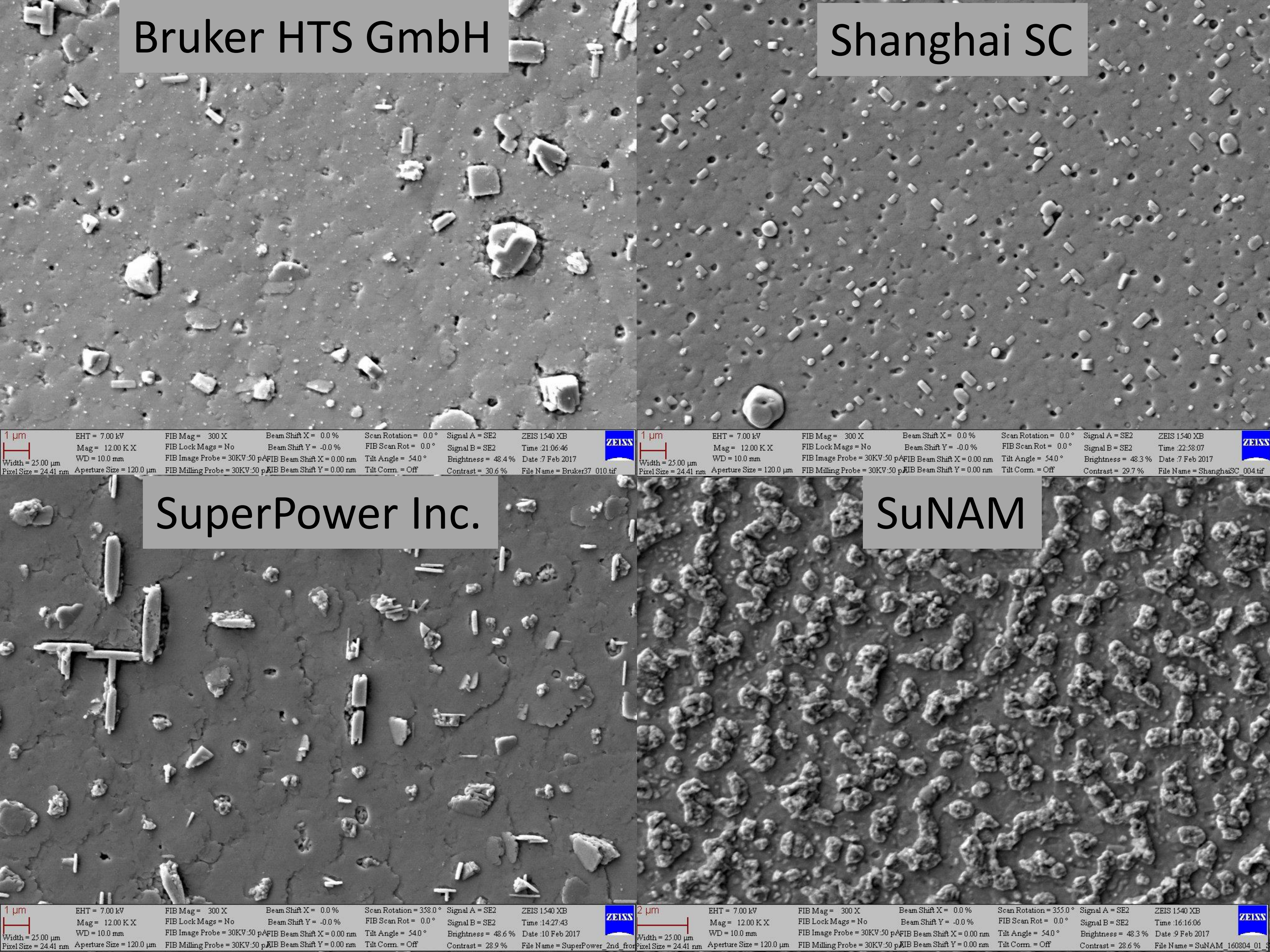
Magnetic field dependencies of fitting parameter $T_o(B)$ for 7.5% and 15% Zr



Magnetic field dependence of fitting parameter $J_{co}(B)$ for 7.5% and 15% Zr

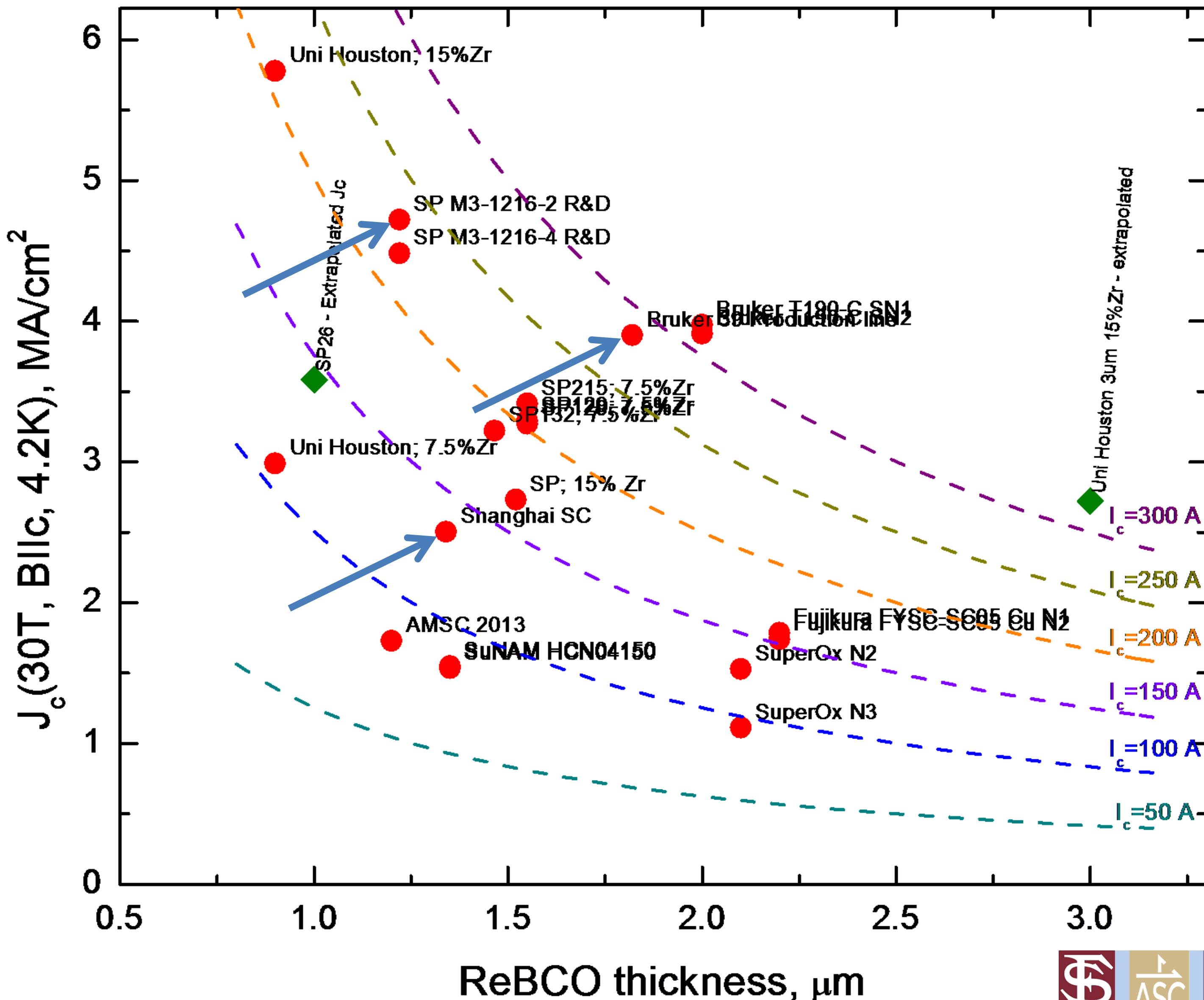



Bruker HTS GmbH
H 2 = 1.959 µm
H 3 = 1.973 µm
H 1 = 1.973 µm
H 4 = 2.265 µm
H 6 = 2.223 µm
H 5 = 2.251 µm
1 µm
Shanghai SC
H 4 = 1.323 µm
H 3 = 1.369 µm
H 2 = 1.334 µm
H 1 = 1.346 µm
1 µm
SuperPower Inc.
H 2 = 1.462 µm
H 1 = 1.405 µm
H 3 = 1.462 µm
H 5 = 1.414 µm
200 nm
SuNAM
H 3 = 2.042 µm
H 2 = 1.574 µm
H 1 = 1.641 µm
H 5 = 1.641 µm
H 4 = 1.607 µm
200 nm


Bruker HTS GmbH
Shanghai SC
SuperPower Inc.
SuNAM
1 µm
1 µm
1 µm
2 µm

Transport J_c(30T, 4K, B||c) vs. ReBCO thickness

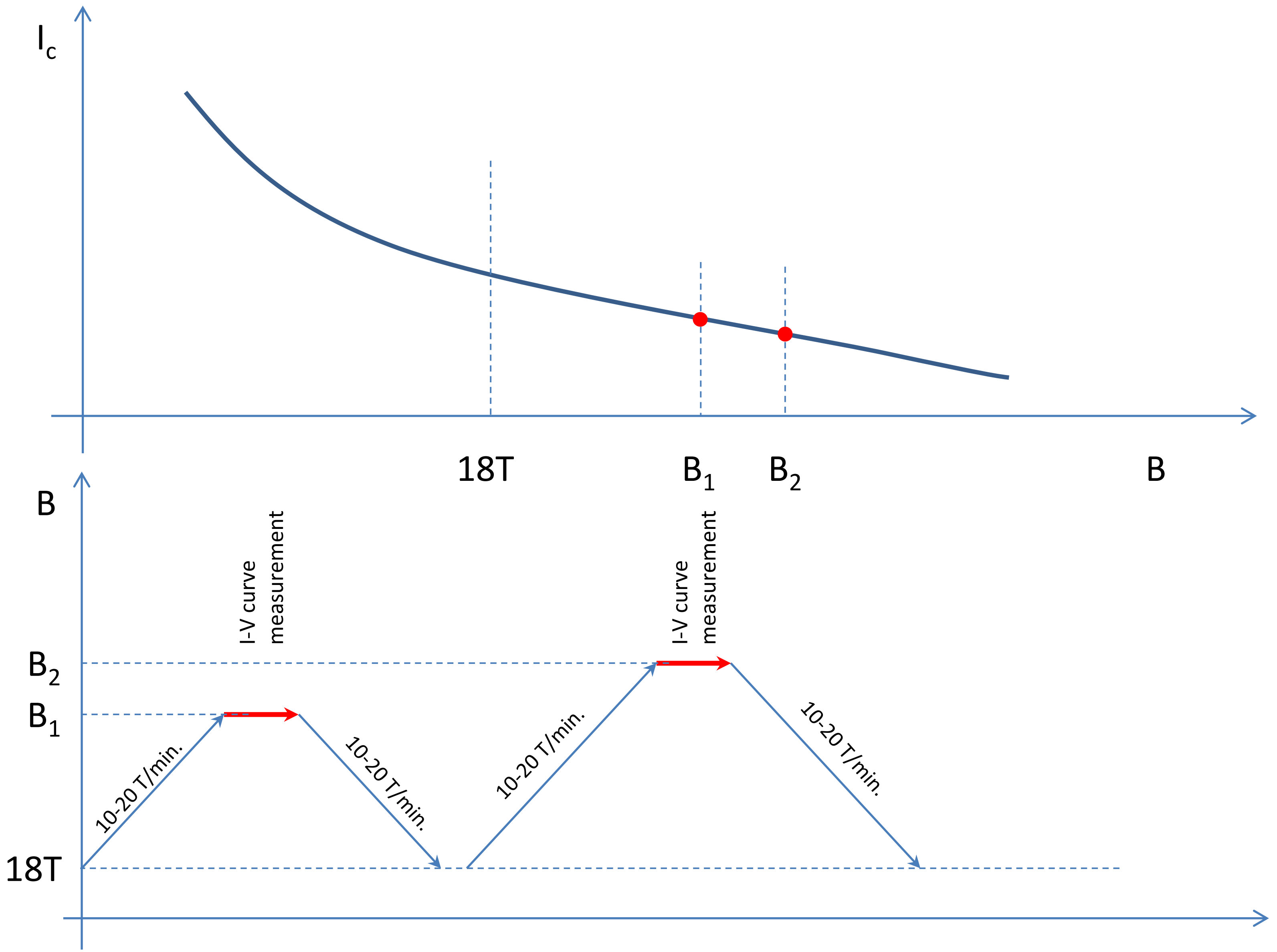
Bruker production line tape has highest I_c(30T, 4K) among commercially available

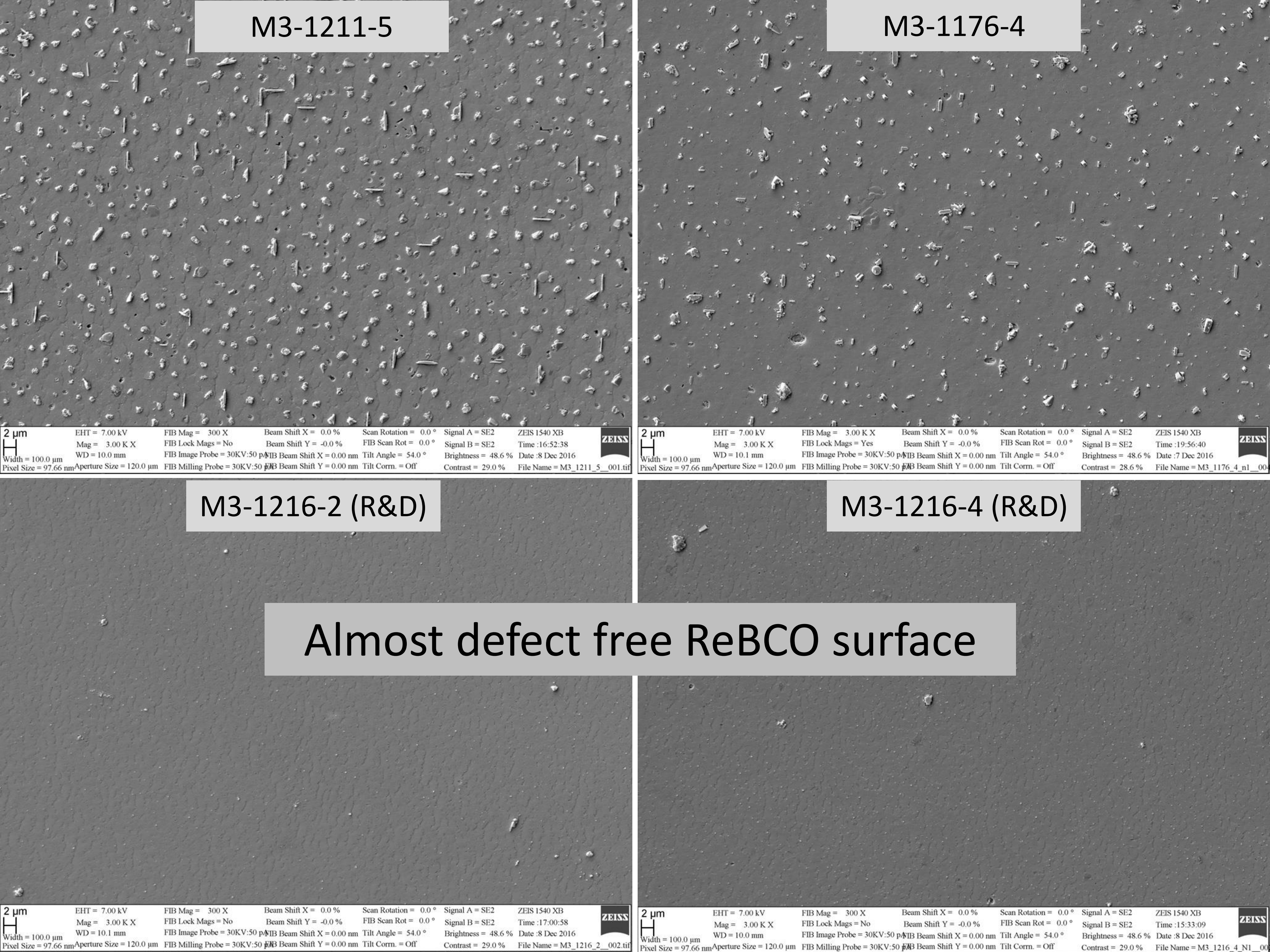


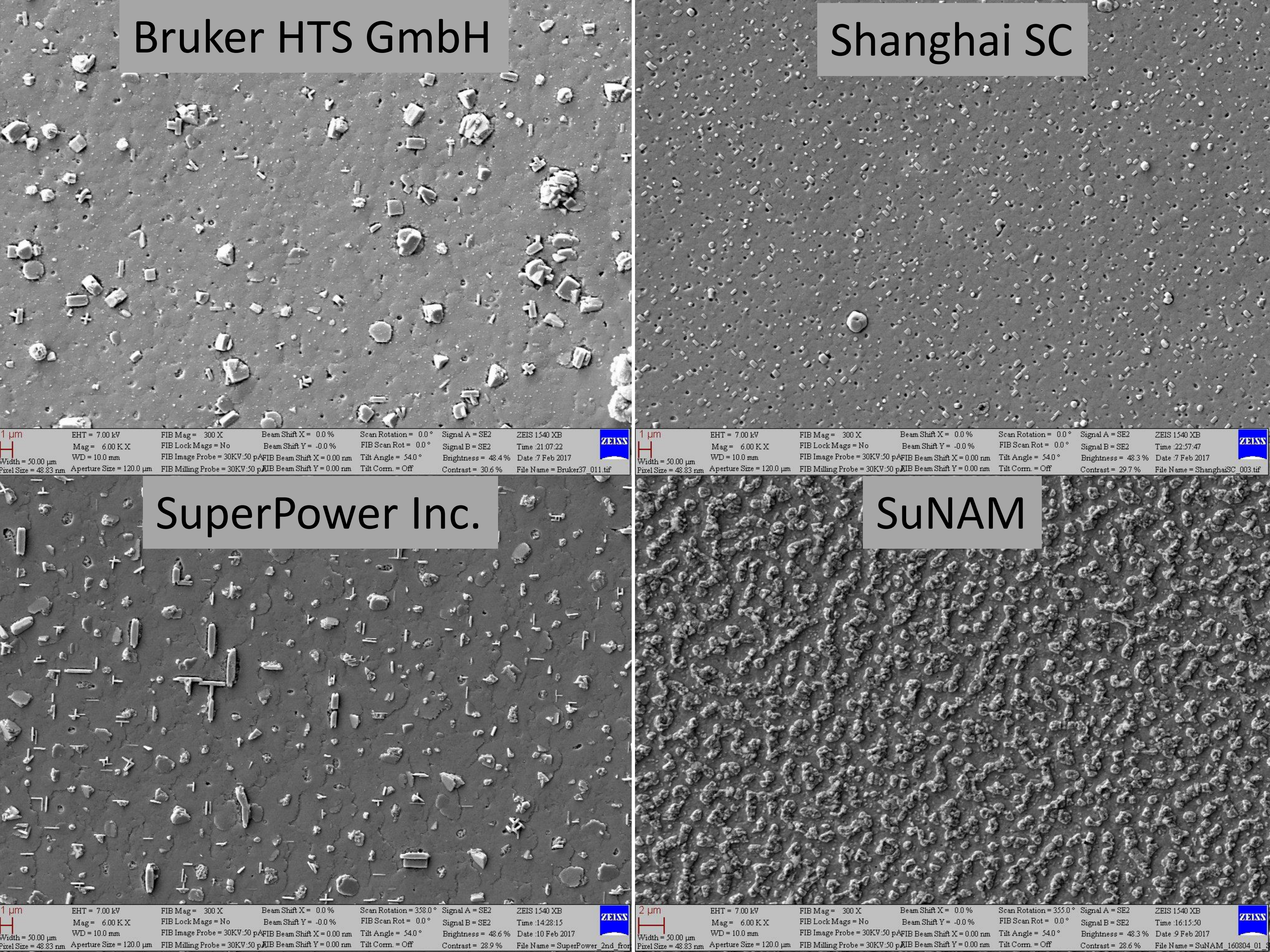
Main difficulties of I_c measurements above 20T

- Magnet time is seldom available since measurements in resistive magnets are more expensive than in SC ones
- In resistive magnets field is less stable as compared to SC magnets
- Due to smaller bore diameters in available resistive magnet systems sample are shorter, which mean smaller current contacts and smaller distances between current and voltage contacts, and smaller voltage criteria
- Sample heating is possible due to helium bubble problem above 20T. Mitigation this problem for full width tape samples (4mm) extends measurement time

Way to mitigate helium bubble problem: measure I-V curves immediately after ramping from 18T

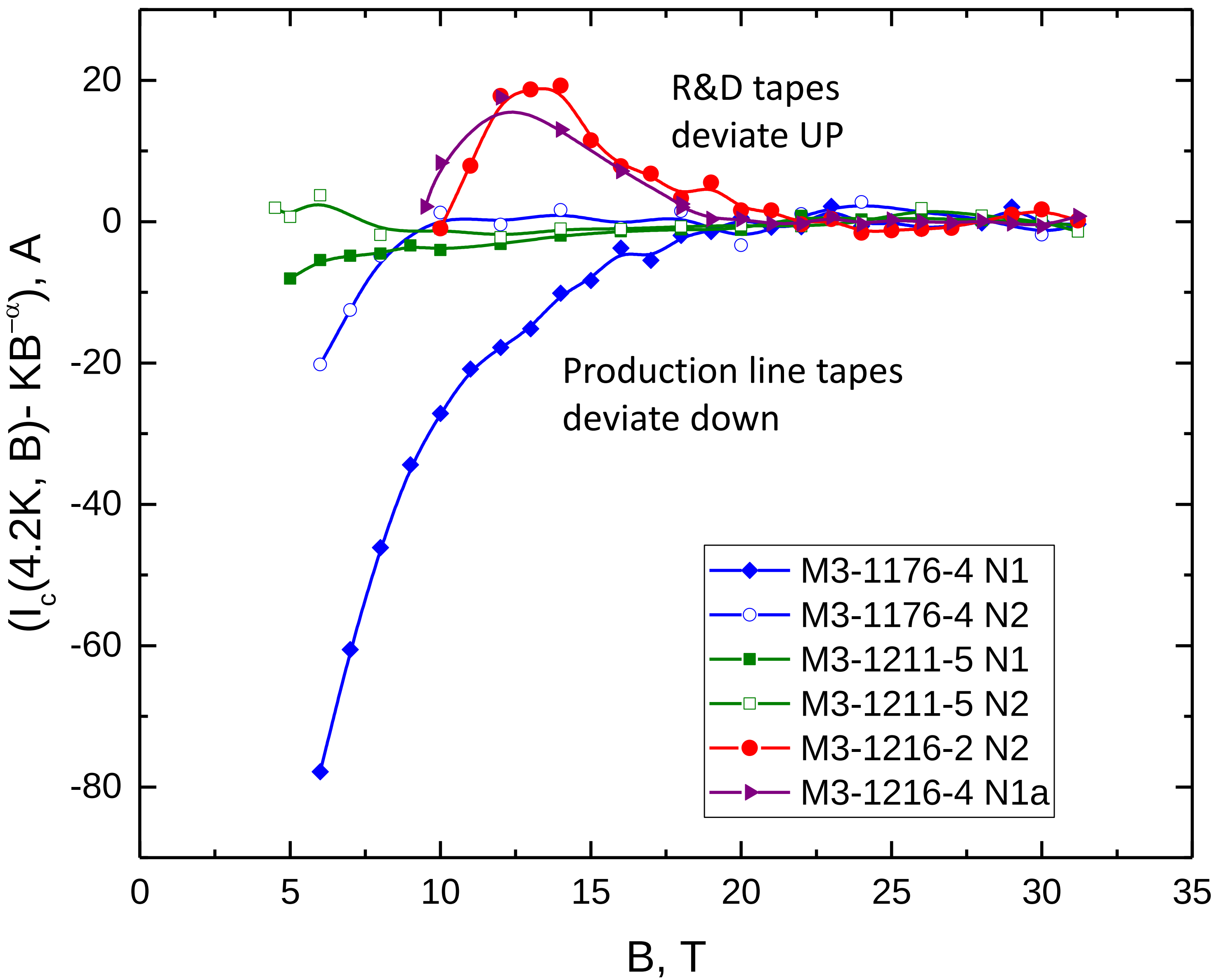



M3-1211-5
M3-1176-4
M3-1216-2 (R&D)
M3-1216-4 (R&D)
Almost defect free ReBCO surface



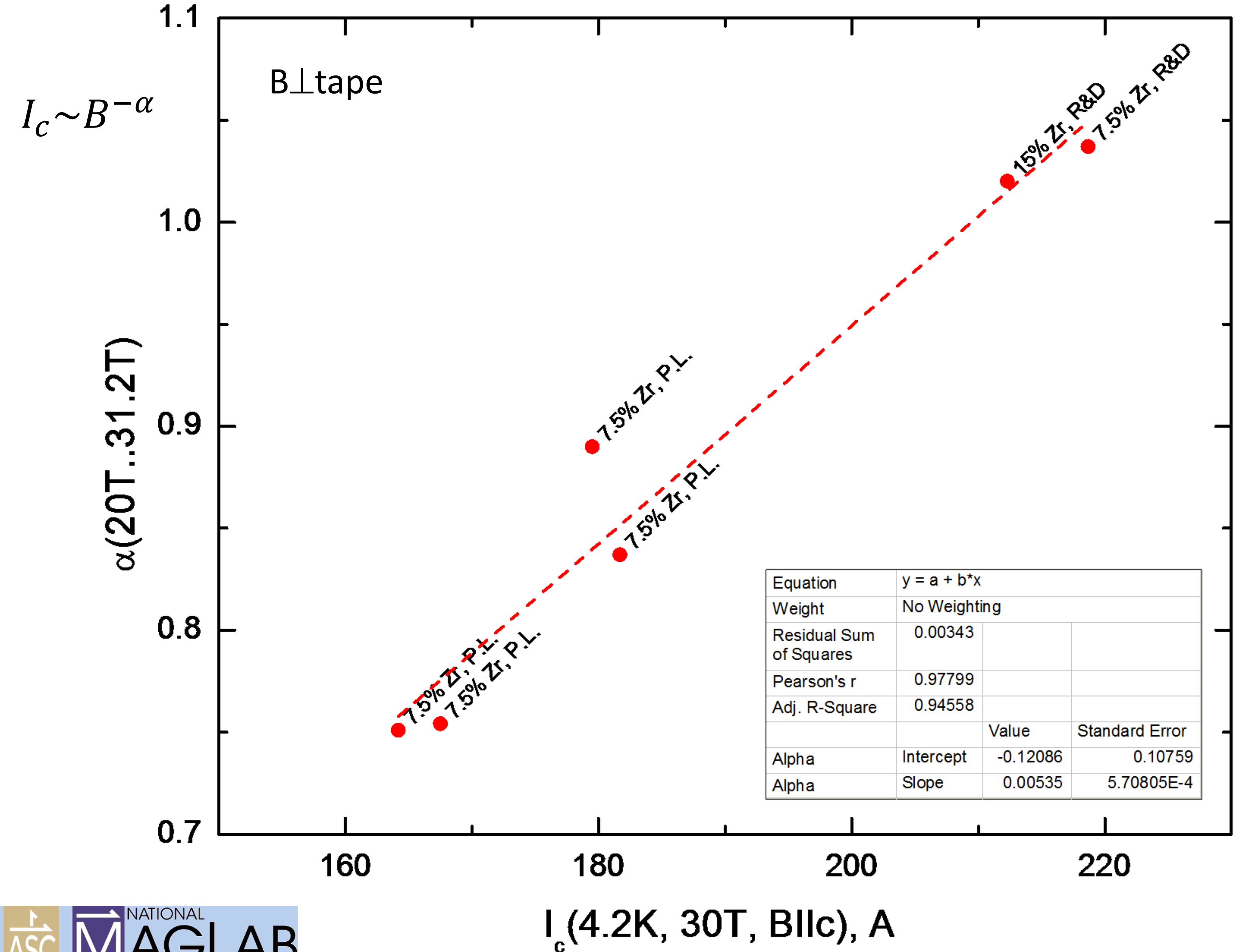
Bruker HTS GmbH
Shanghai SC
SuperPower Inc.
SuNAM
1 µm
1 µm
1 µm
2 µm

Deviation I_c(B) dependence from the fit $I_c \propto B^{-\alpha}$



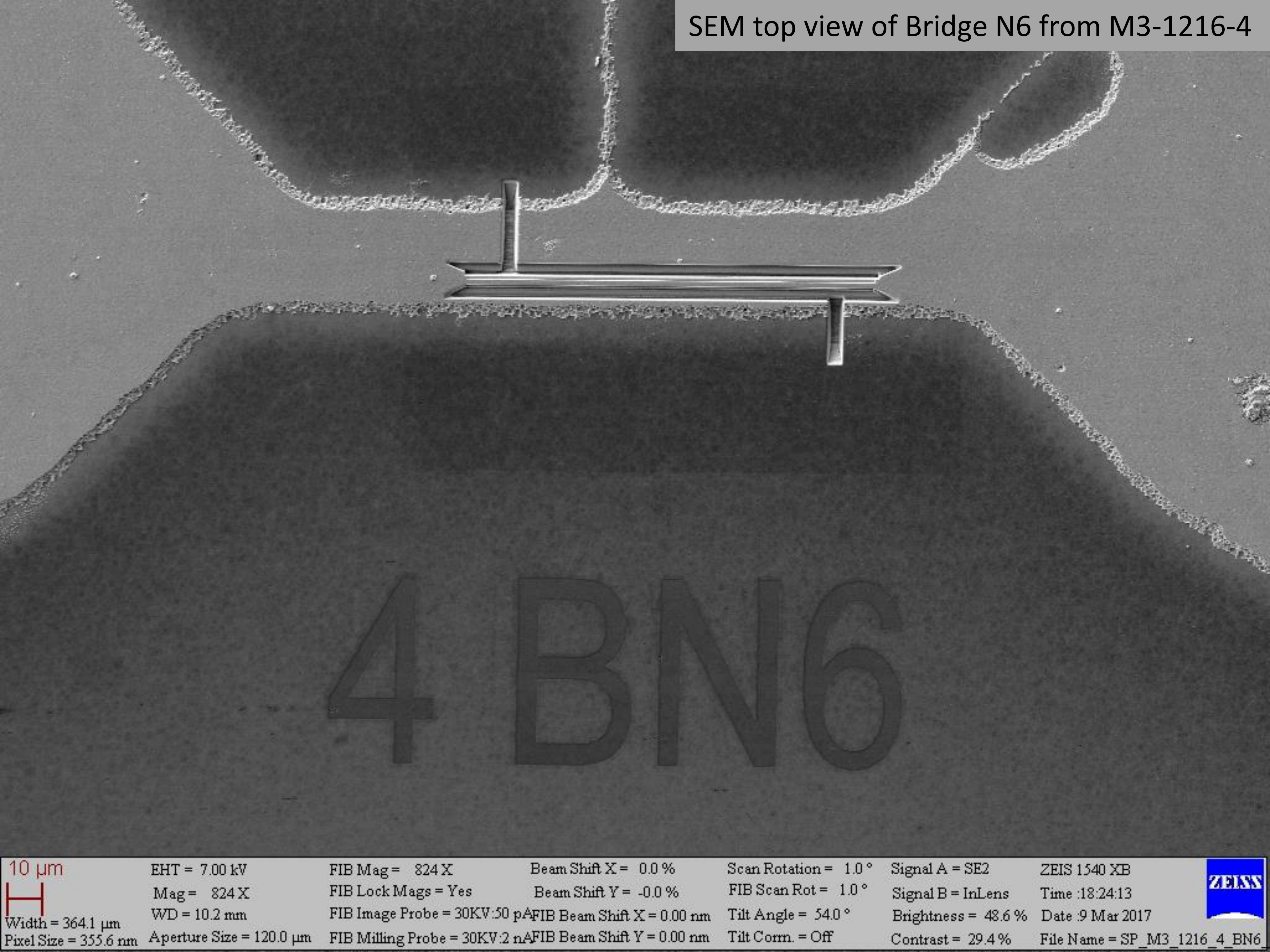
Larger α values corresponds to higher I_c(4K, 30T)

Interpretation: in BIIc orientation larger α values correspond to larger concentration of pinning centers.



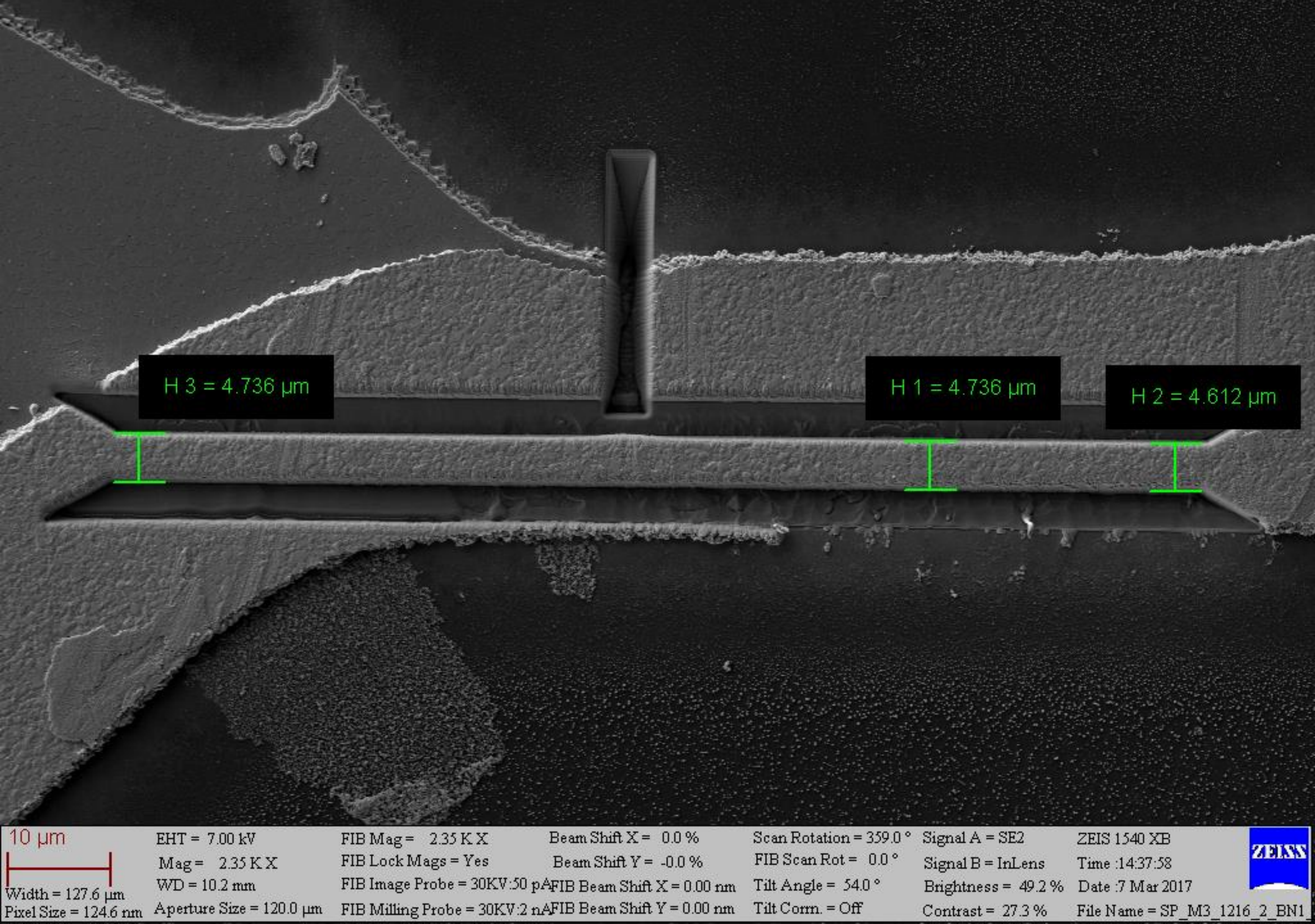
Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	0.00343		
Pearson's r	0.97799		
Adj. R-Square	0.94558		
		Value	Standard Error
Alpha	Intercept	-0.12086	0.10759
Alpha	Slope	0.00535	5.70805E-4

SEM top view of Bridge N6 from M3-1216-4



SEM top view of Bridge N6 from M3-1216-4

SEM image of the bridge M3-1216- 2 BN1



Motivation

List of questions, which can be answered by detecting transport $I_c(T, B, \theta)$ up to 45T (DC)

Information useful for ReBCO application

- **Does I_c drop more rapidly as field exceeds 30T?**
- Field dependence of I_c in B II tape orientation up to 45T at different temperatures.
- Can we predict J_c values for field orientations occurring in applications up to 45T?

ReBCO material development

How magnetic field dependence of pinning force changes at different temperatures and field orientation?

Property of SC with artificial pinning

How magnetic field dependence of fitting parameter T_o changing from 7.5% to 15% Zr in R&D tapes?

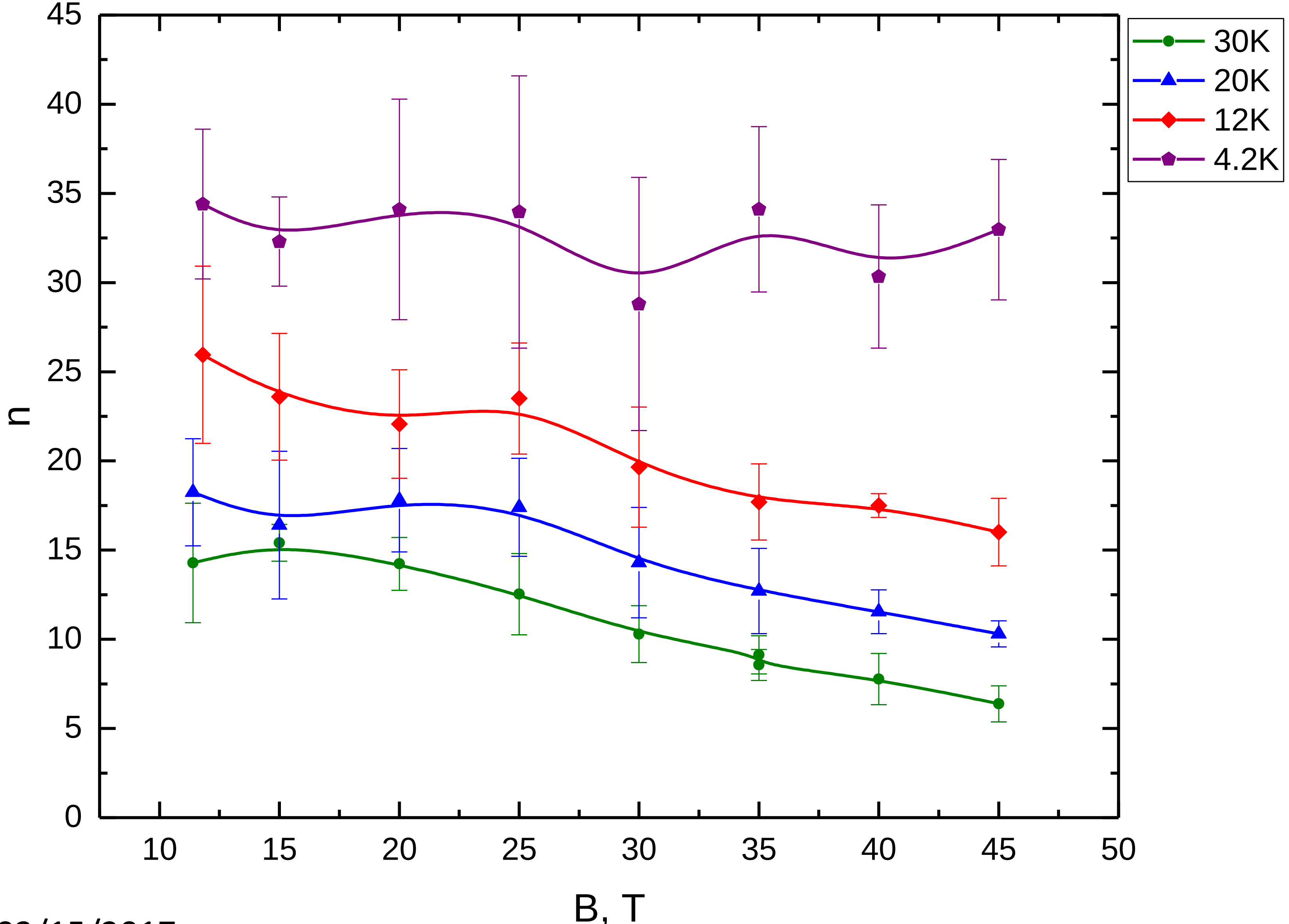
Are there any correlations between matching field (calculated from pinning center densities) and position of maximums (or variations) of $f_p(B)$ and $T_o(B)$?

Is sample to sample variation masking difference between 7.5% and 15% Zr?

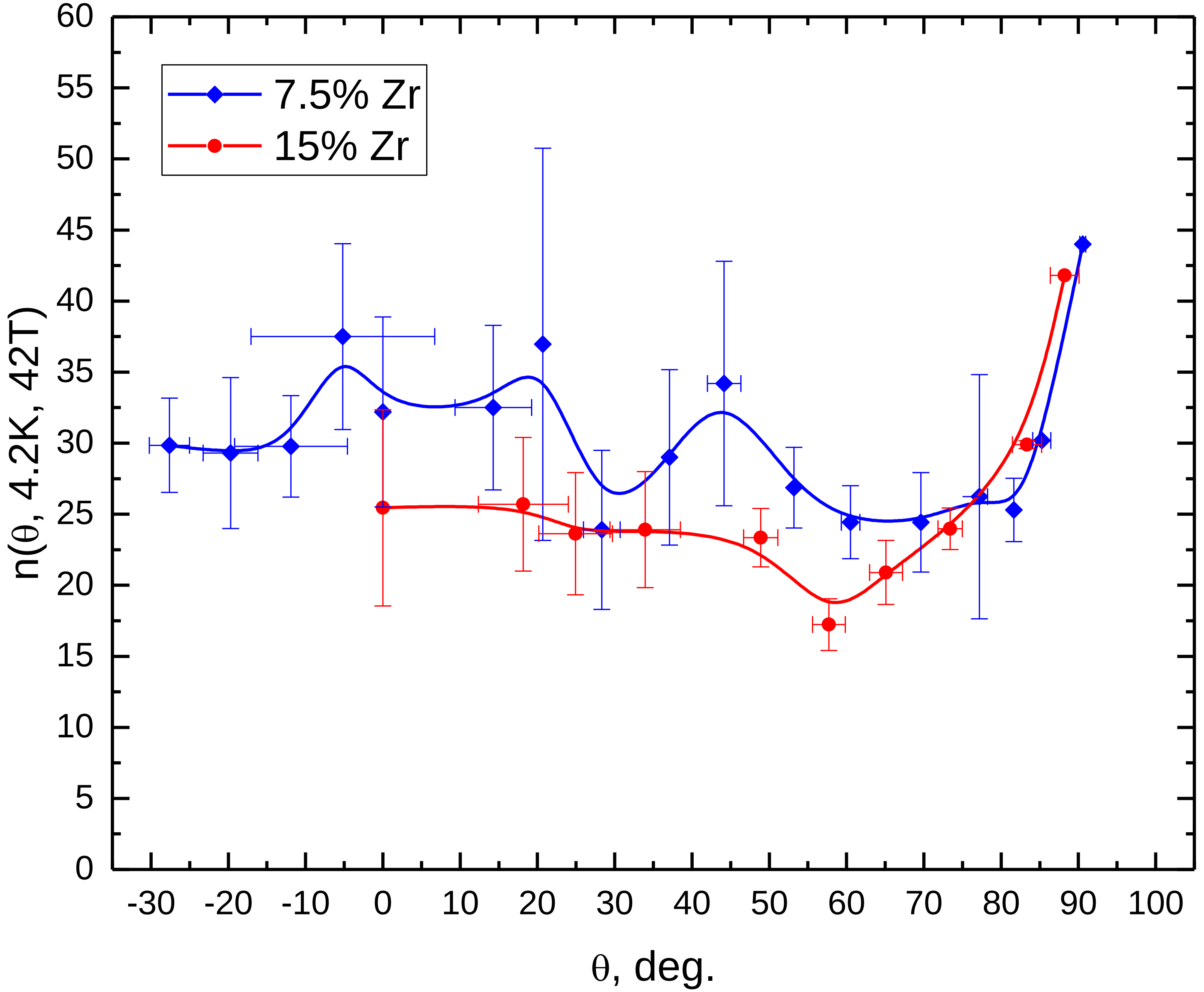
Does F_p reach maximum at 45T?

Magnetic field dependence of n-value at different temperatures for

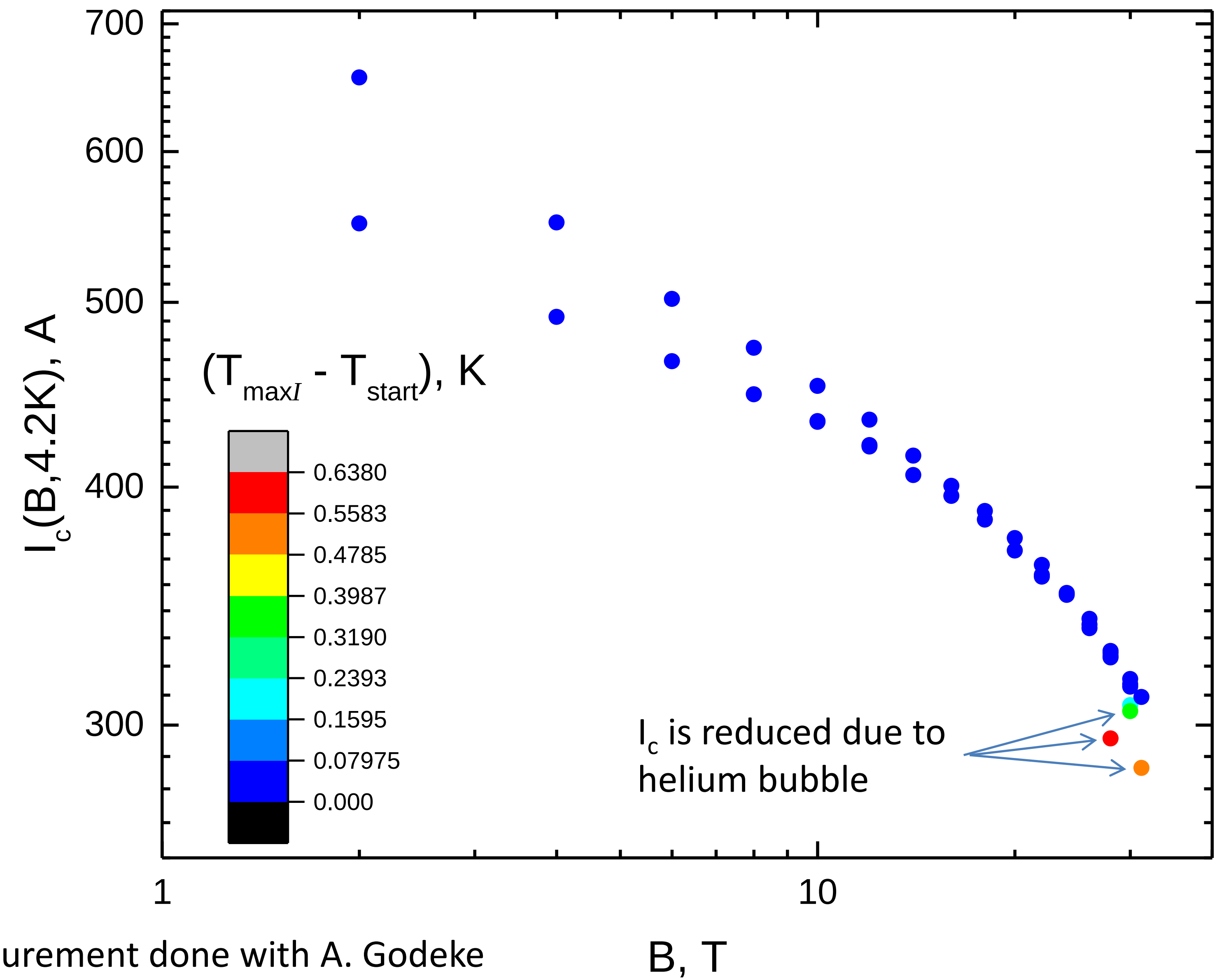
R&D SuperPower tape M3-1216 2 BN1 (W=4.6μm,L=105.6μm) 7.5% Zr, bridge covered with original Ag



Data 03/15/2017


7.5% Zr
15% Zr
n(θ, 4.2K, 42T)
θ, deg.
0
5
10
15
20
25
30
35
40
45
50
55
60
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100

Example of helium bubble problem:
Transport I_c(B, 4.2K) for short Bi-2223 Sumitomo sample N2, B _|_tape orientation



Measurement done with A. Godeke

M4-396- 0508