Beyond 20T: Tape characterization

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Plan

- Motivation
- Techniques
- Comparison I_c(B, 4K) for SuperPower R&D and production line tapes
- Comparison transport properties of ReBCO tapes from different manufacturers
- Comparison high field I_c of steel coated and Cu plated tapes from SuNAM for making no-insulation magnets
- Conclusions

This work was supported in part by the U.S. National Science Foundation under Grant No. DMR-0654118, DMR-0923070 and the State of Florida.

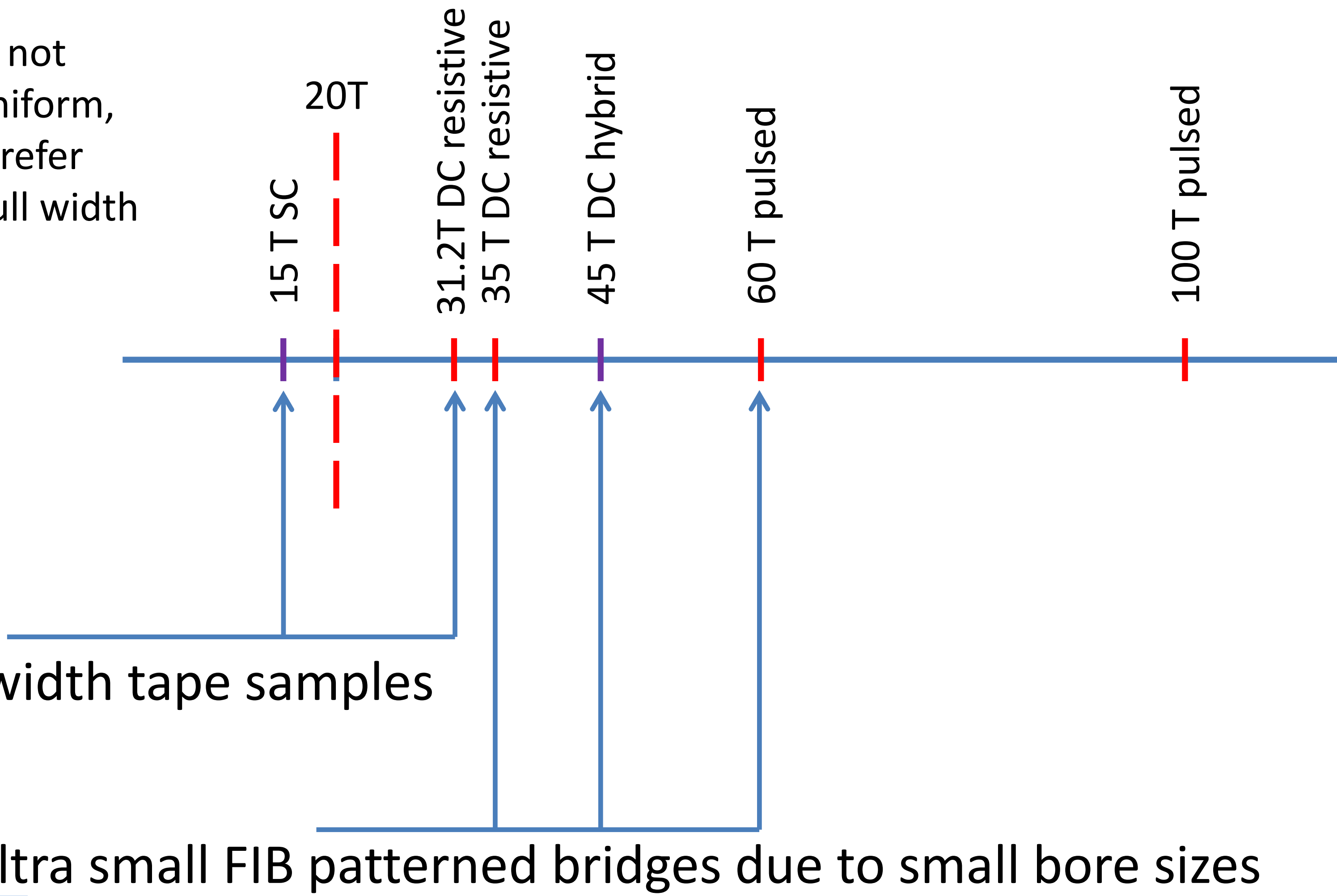
Motivation

- 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

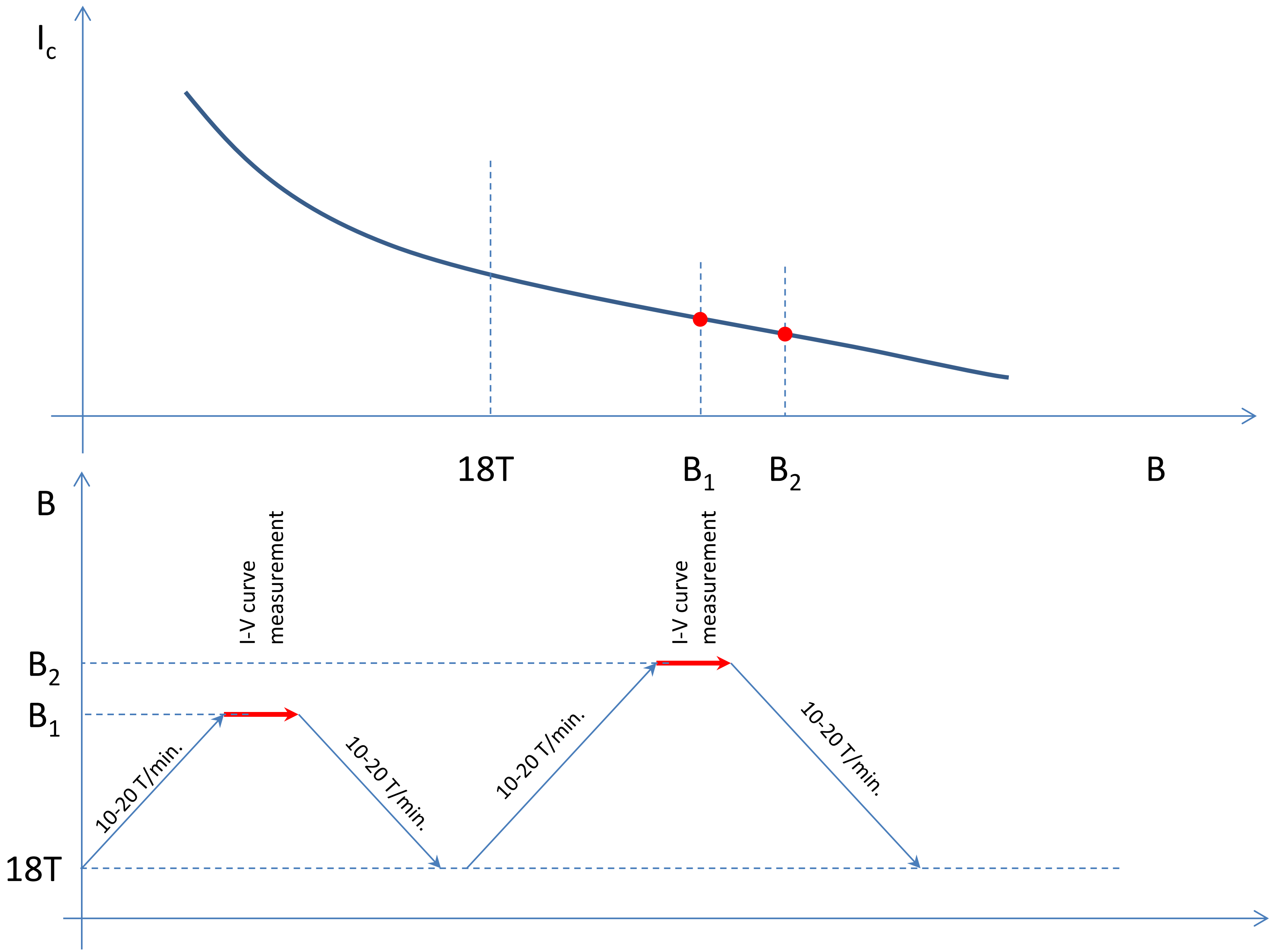
Since real tapes are not perfectly flat and uniform, magnet designers prefer measurements of full width tapes.



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

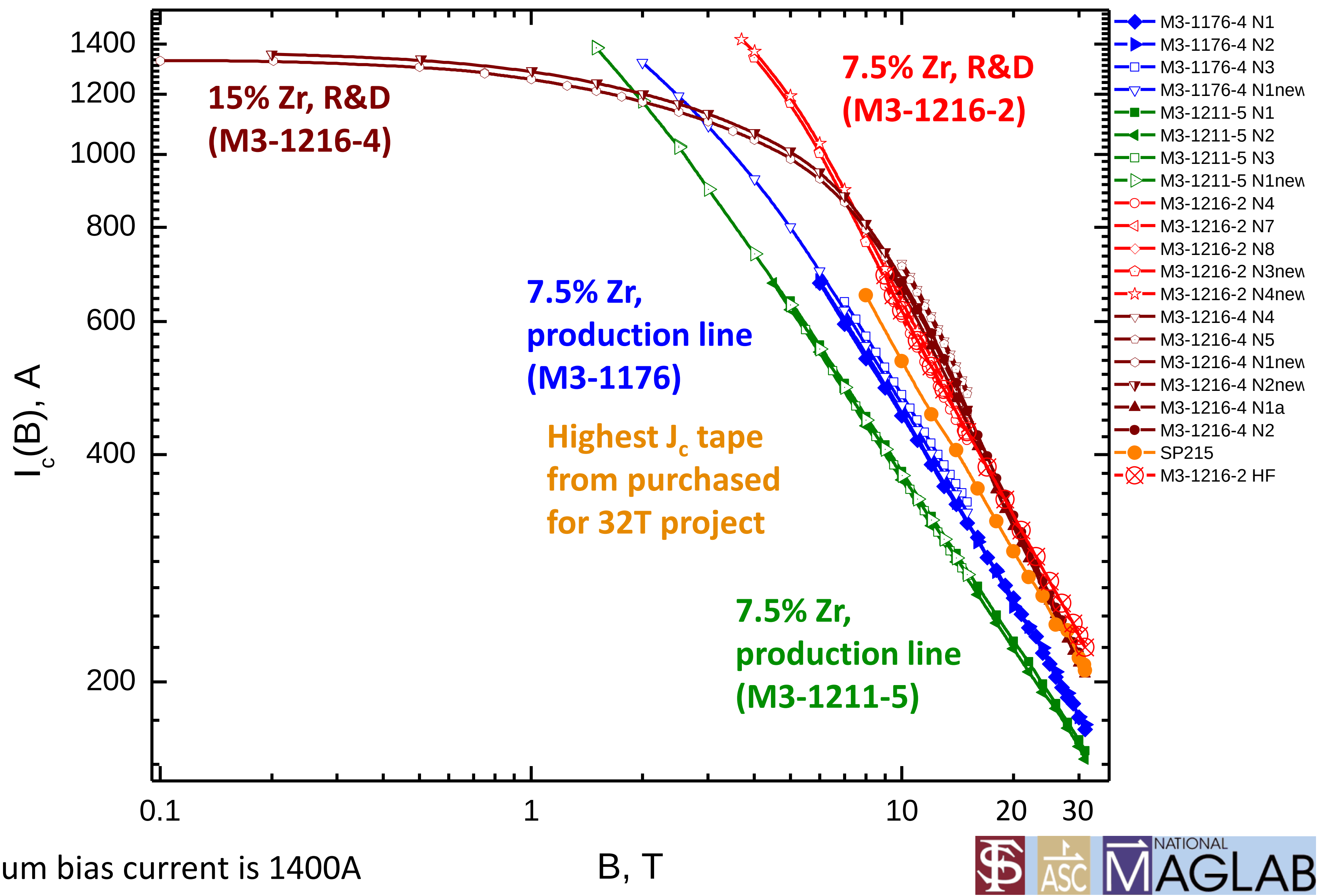
Way to mitigate helium bubble problem: measure I-V curves immediately after ramping from 18T



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

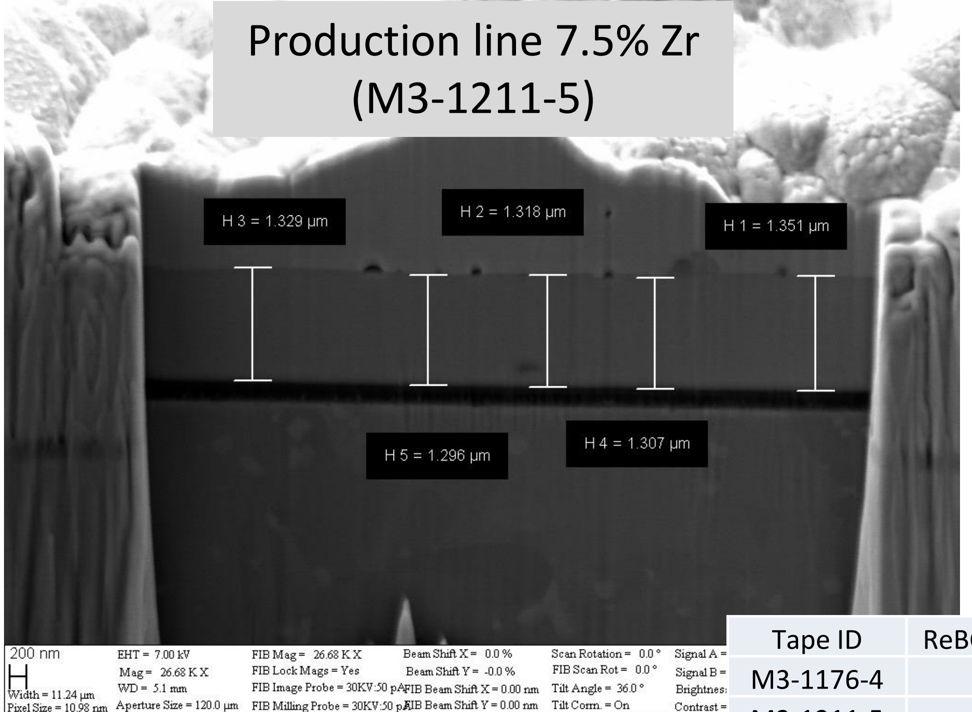
Combination of I_c(B,4K) measured in resistive and superconducting magnets

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

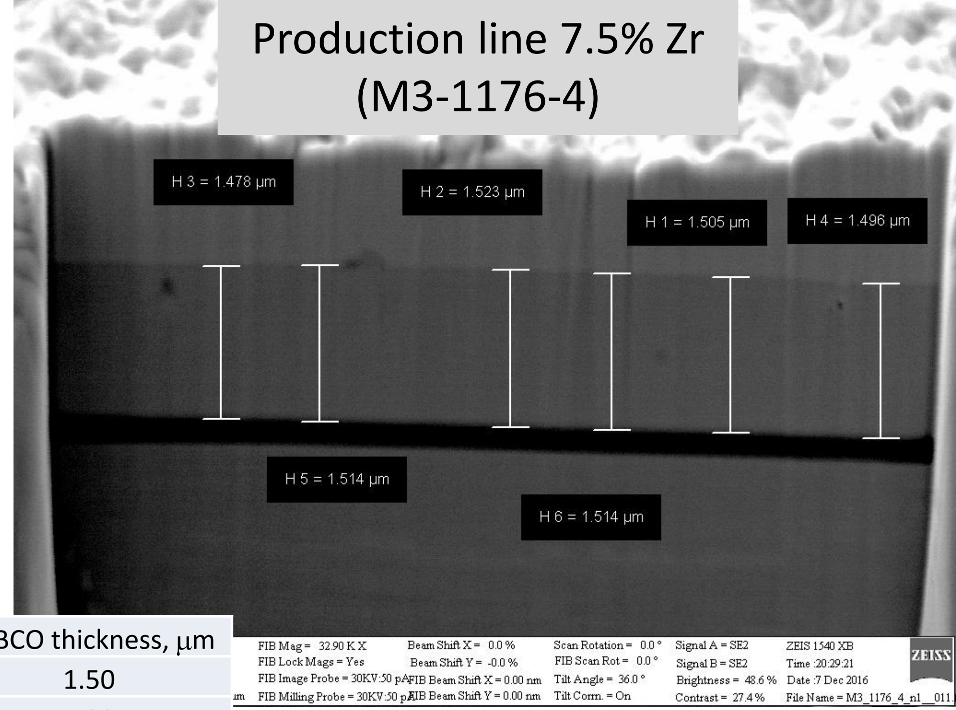


Maximum bias current is 1400A

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



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

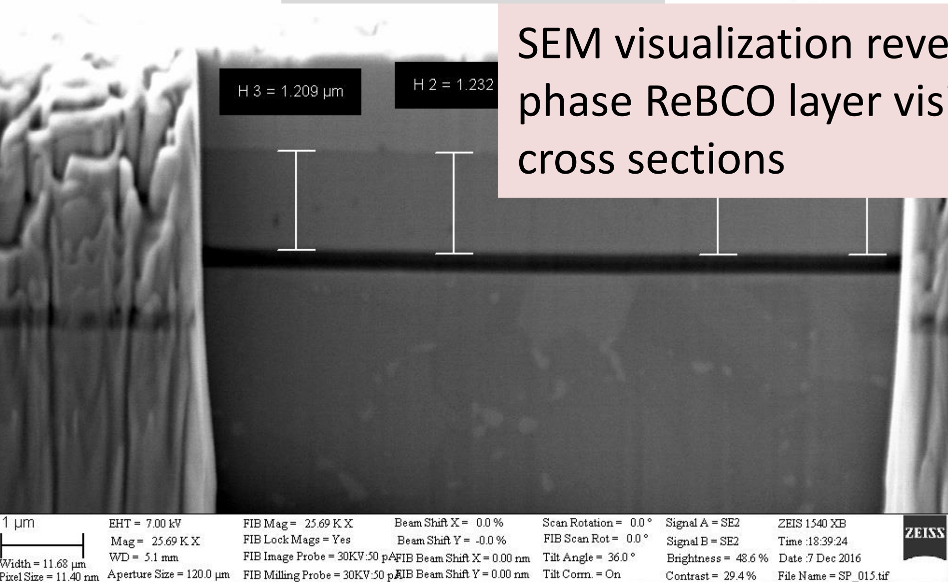


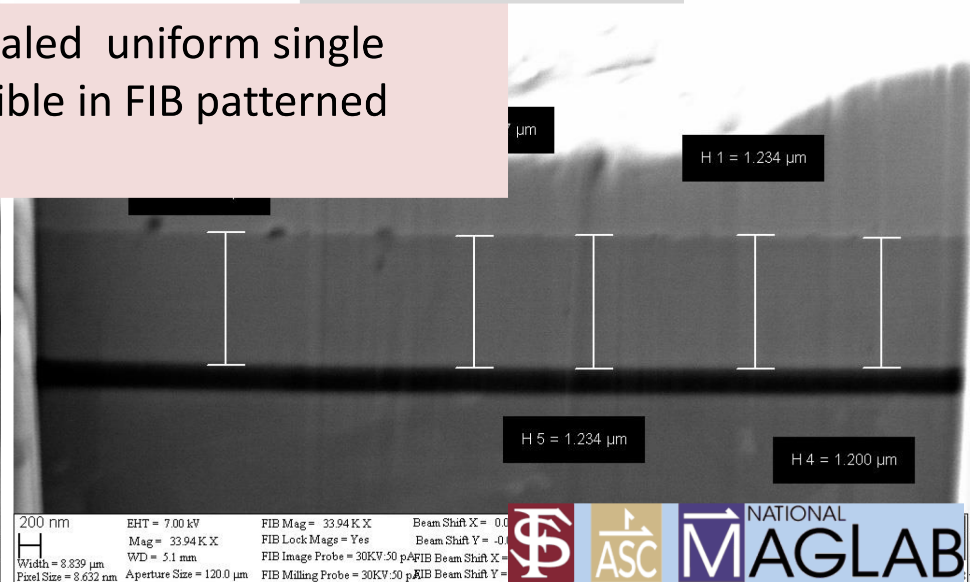
Tape ID	ReBCO thickness, µm
M3-1176-4	1.50
M3-1211-5	1.32
M3-1216-2	1.22
M3-1216-4	1.22

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

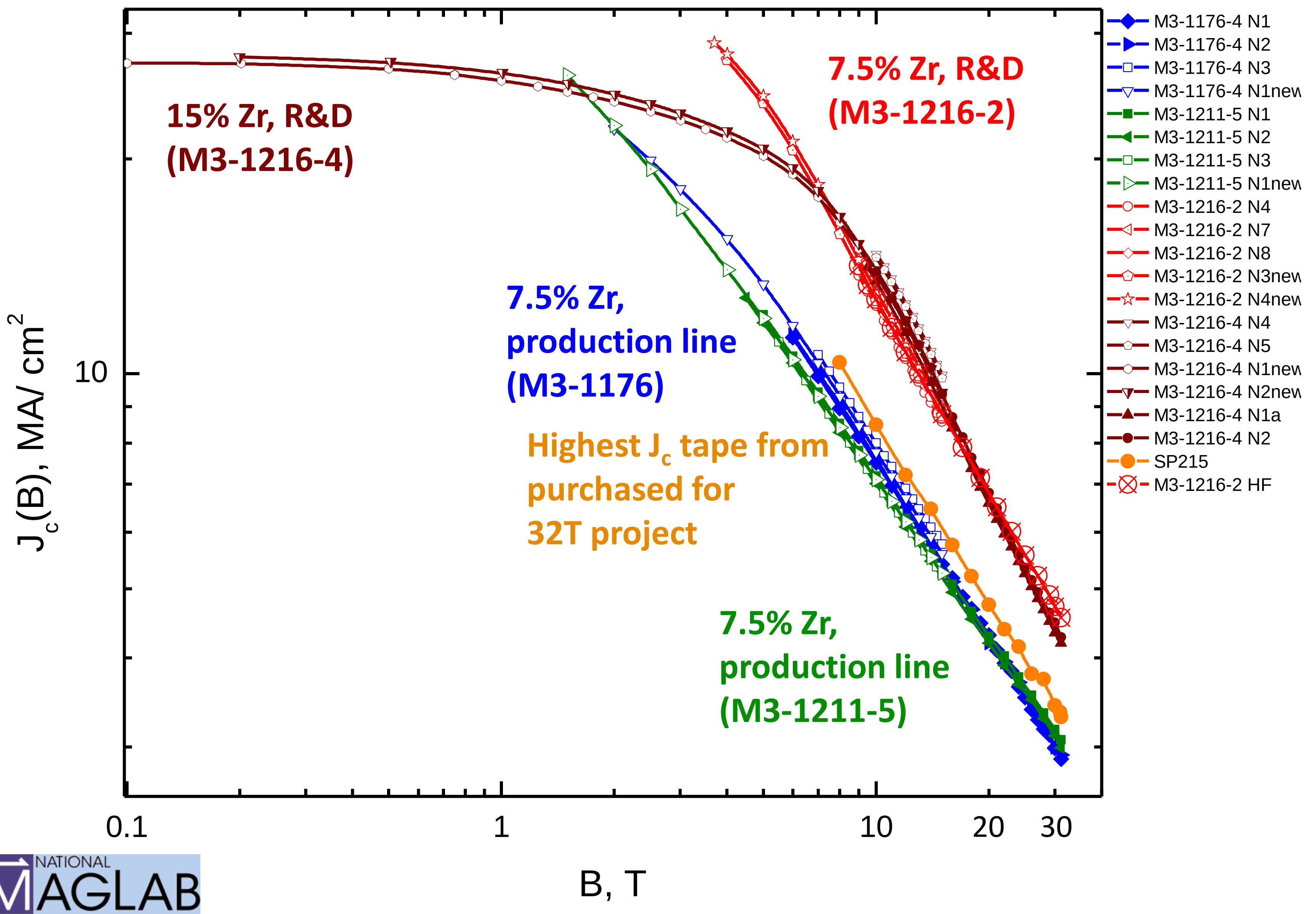
15% Zr, R&D (M3-1216-4)

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

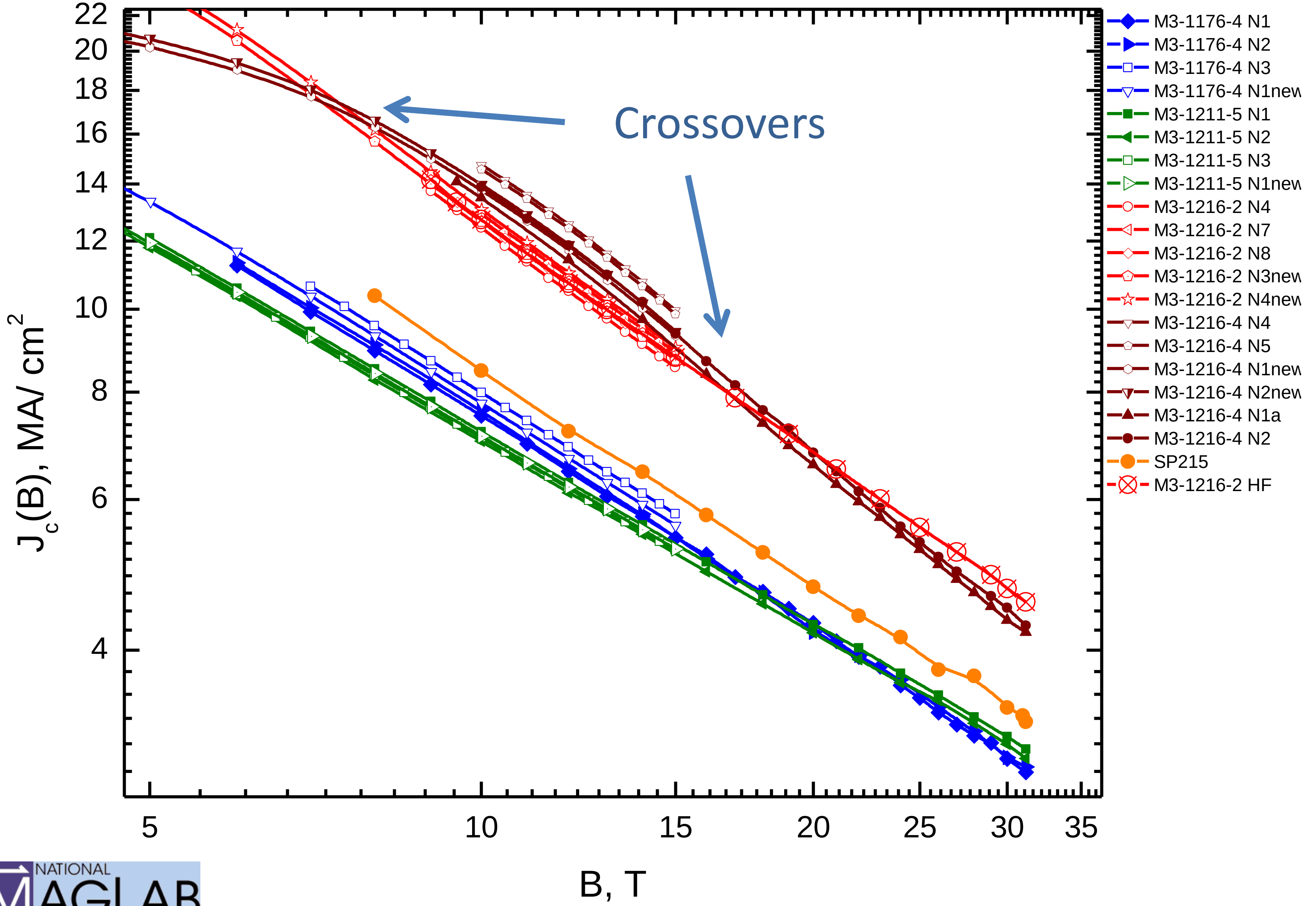




J_c(B,4K) measured in resistive and superconducting magnets



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



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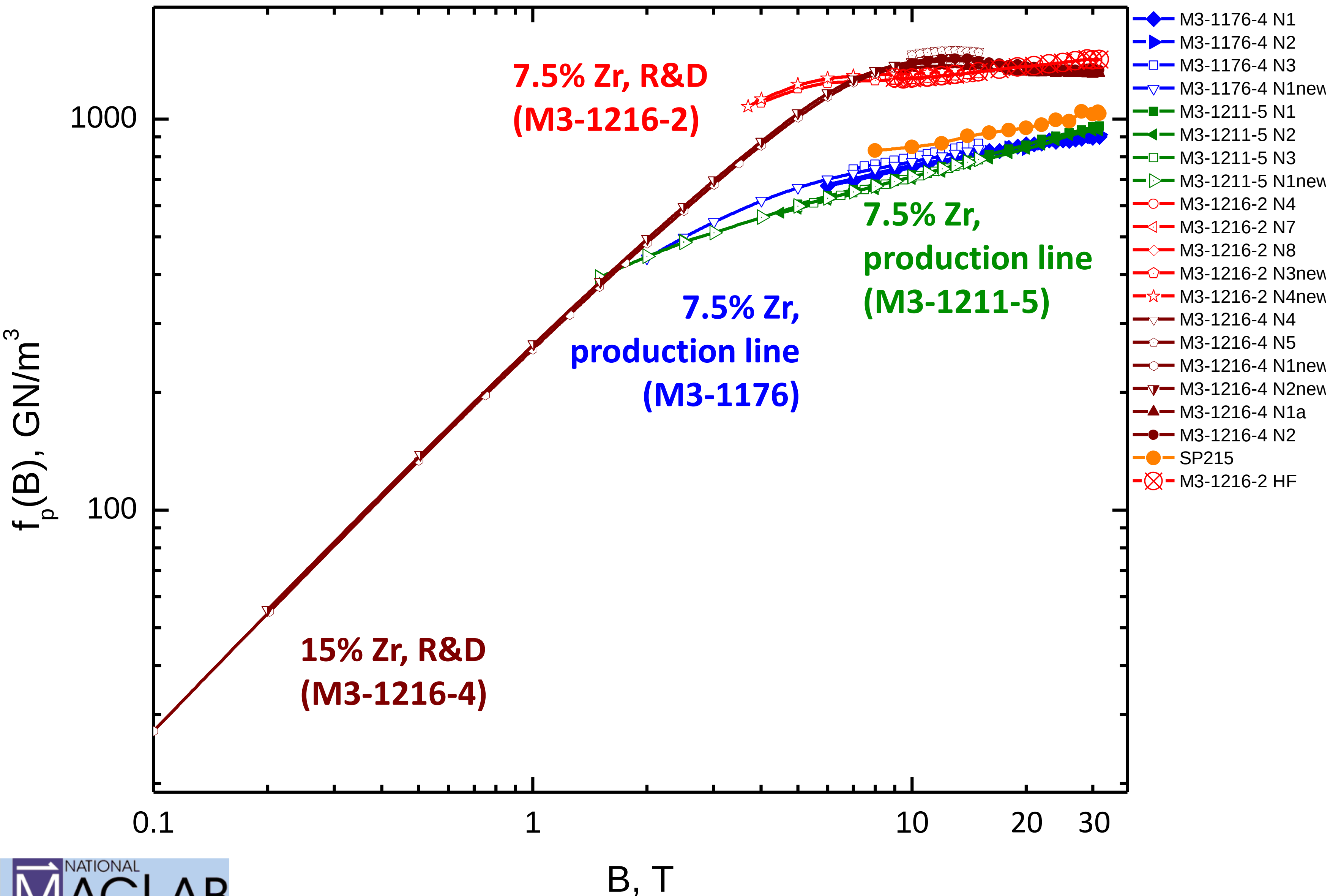
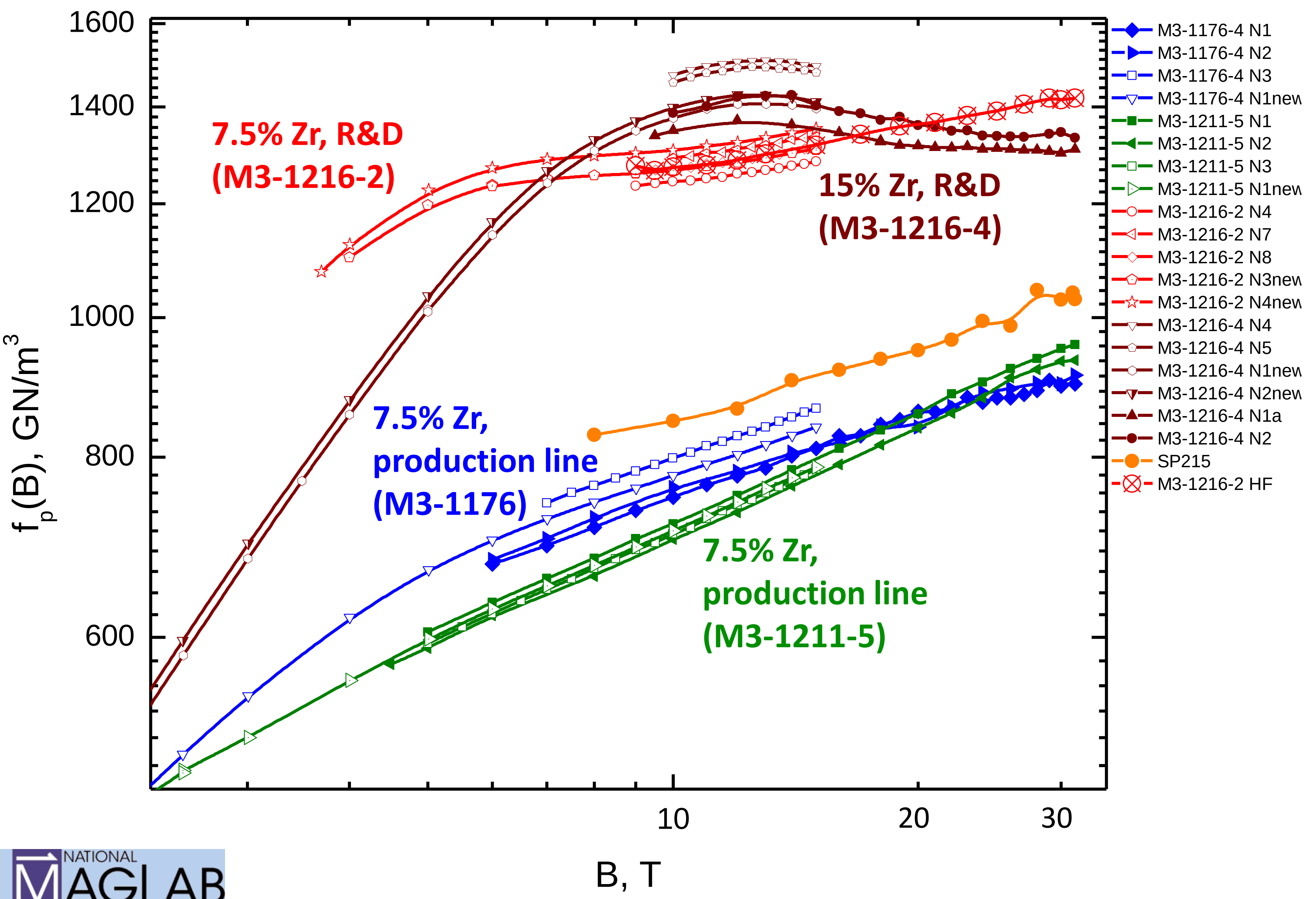
Very different values and field dependence of f_p(B, 4.2K) measured for R&D and production wires in resistive magnet up to 30T



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



Close view: 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

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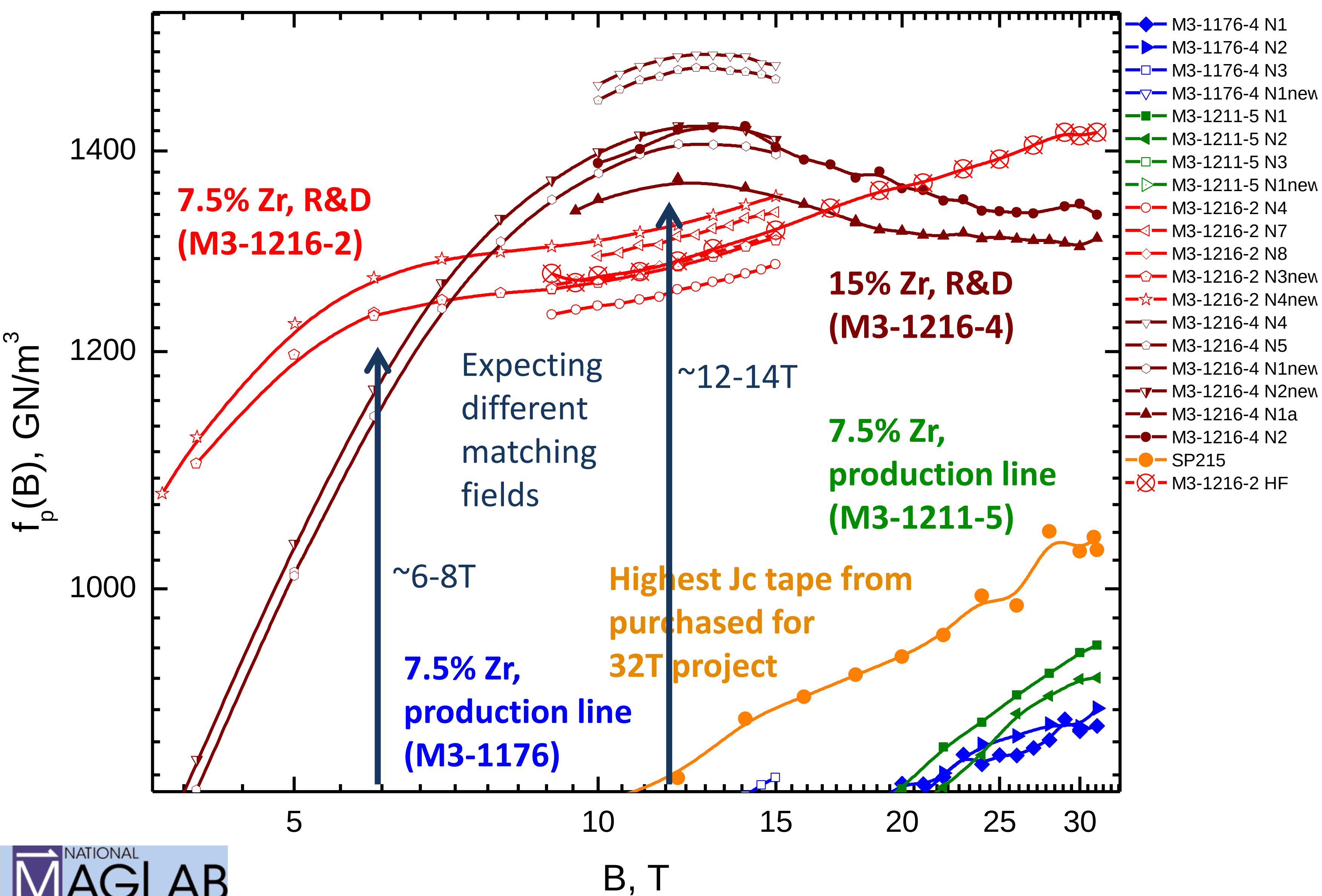
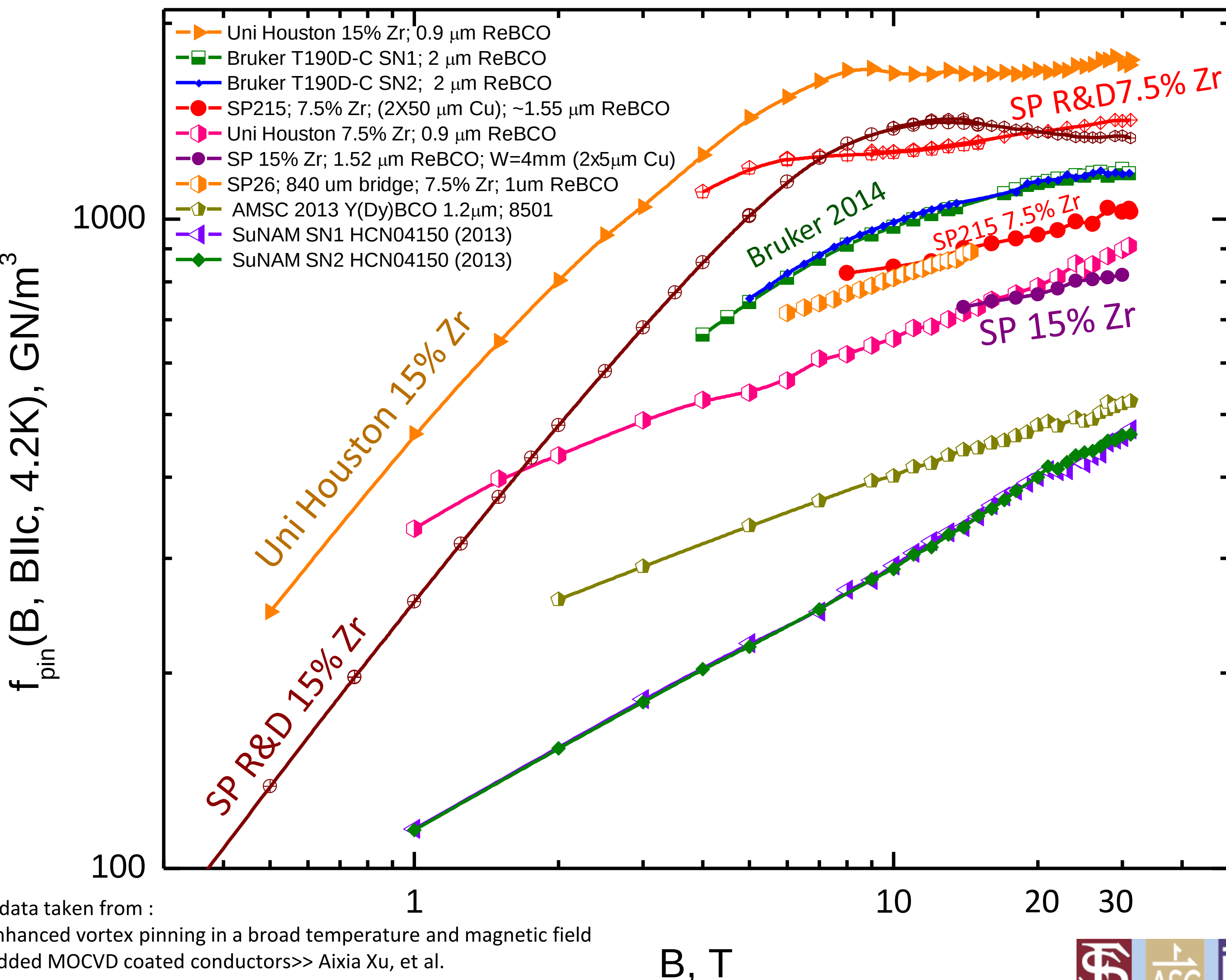
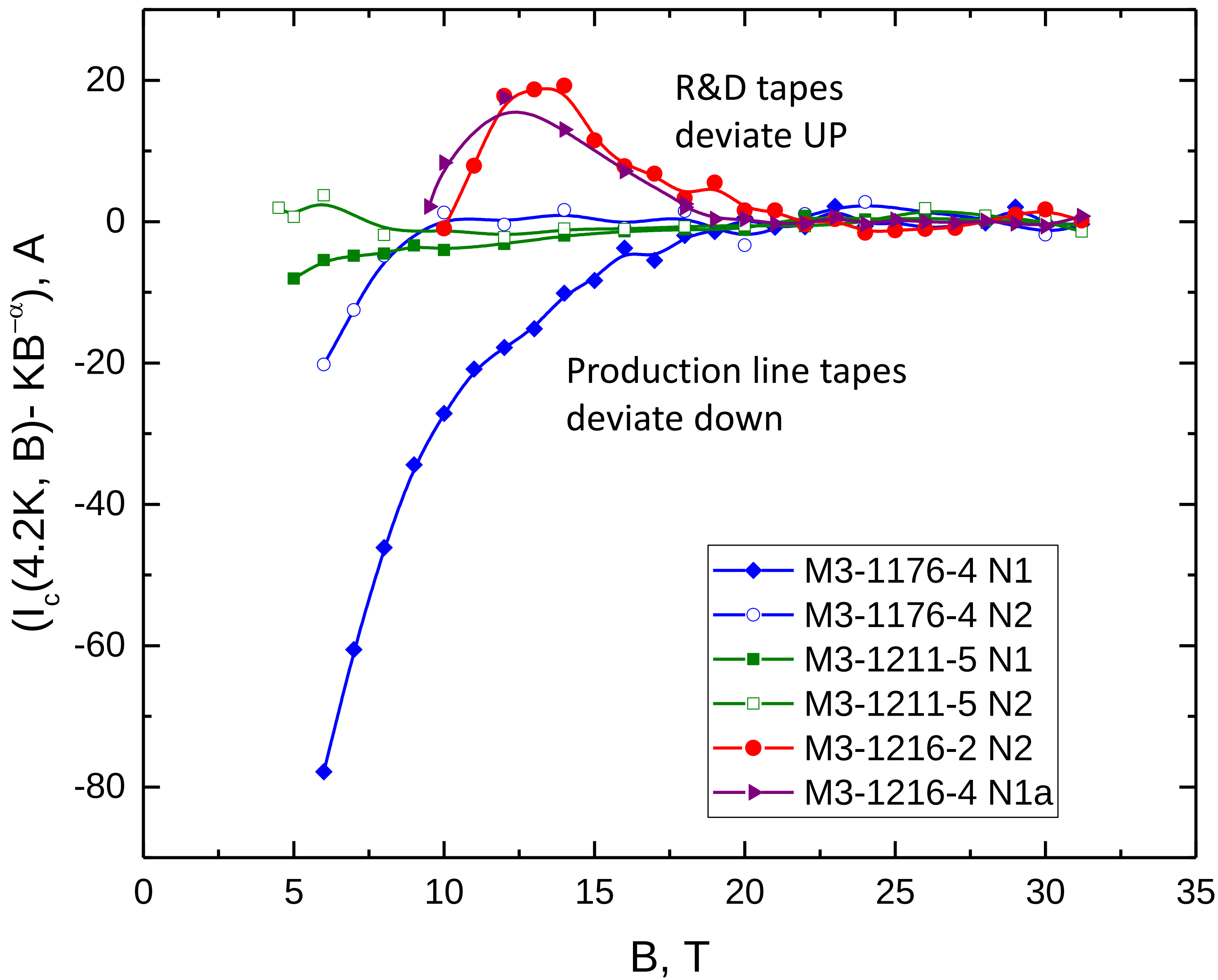


Recent SuperPower R&D tapes grown on production line are approaching Uni. Houston lab grown $f_p(B)$ values



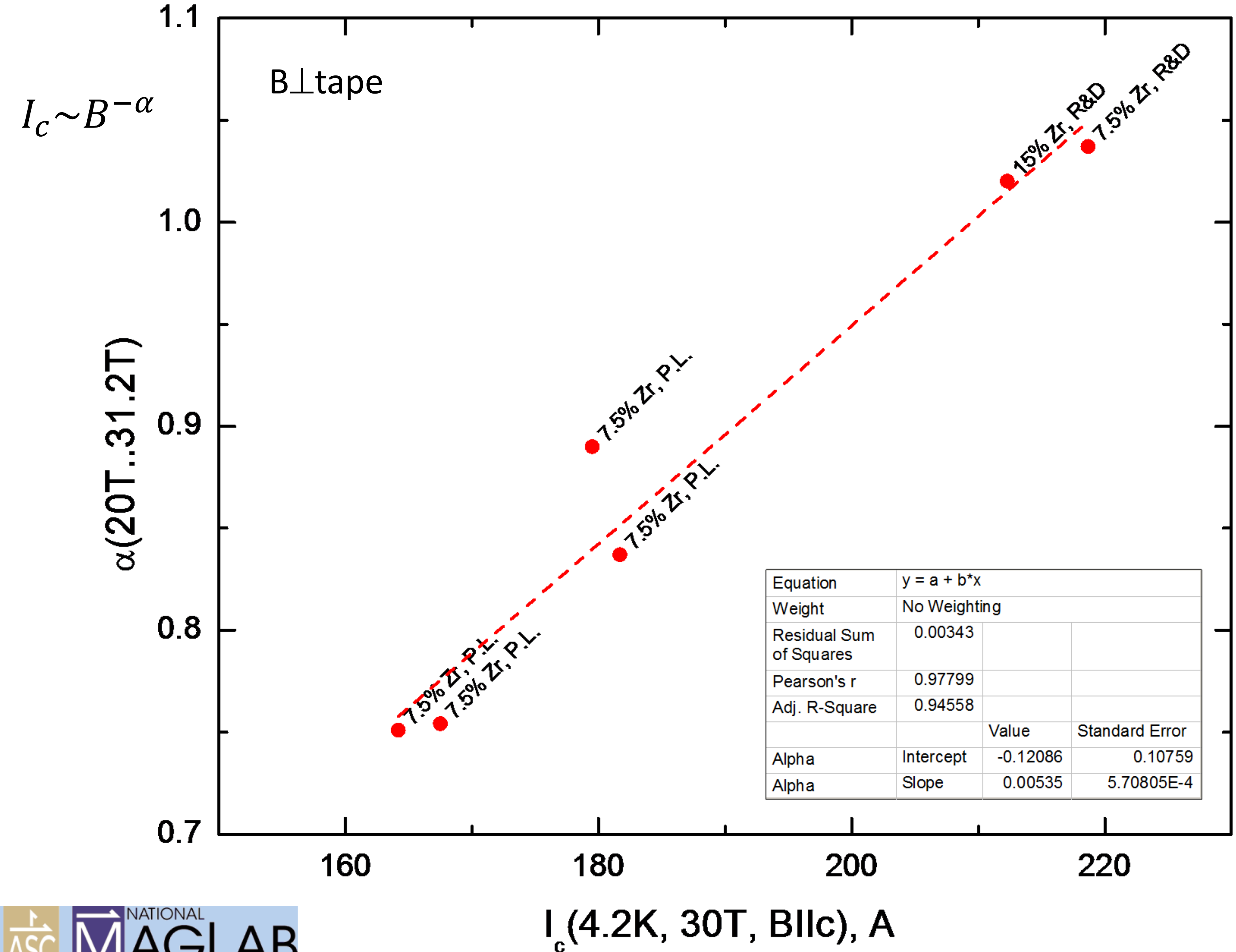
Uni Houston data taken from :
<<Strongly enhanced vortex pinning in a broad temperature and magnetic field range of Zr-added MOCVD coated conductors>> Aixia Xu, et al.

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



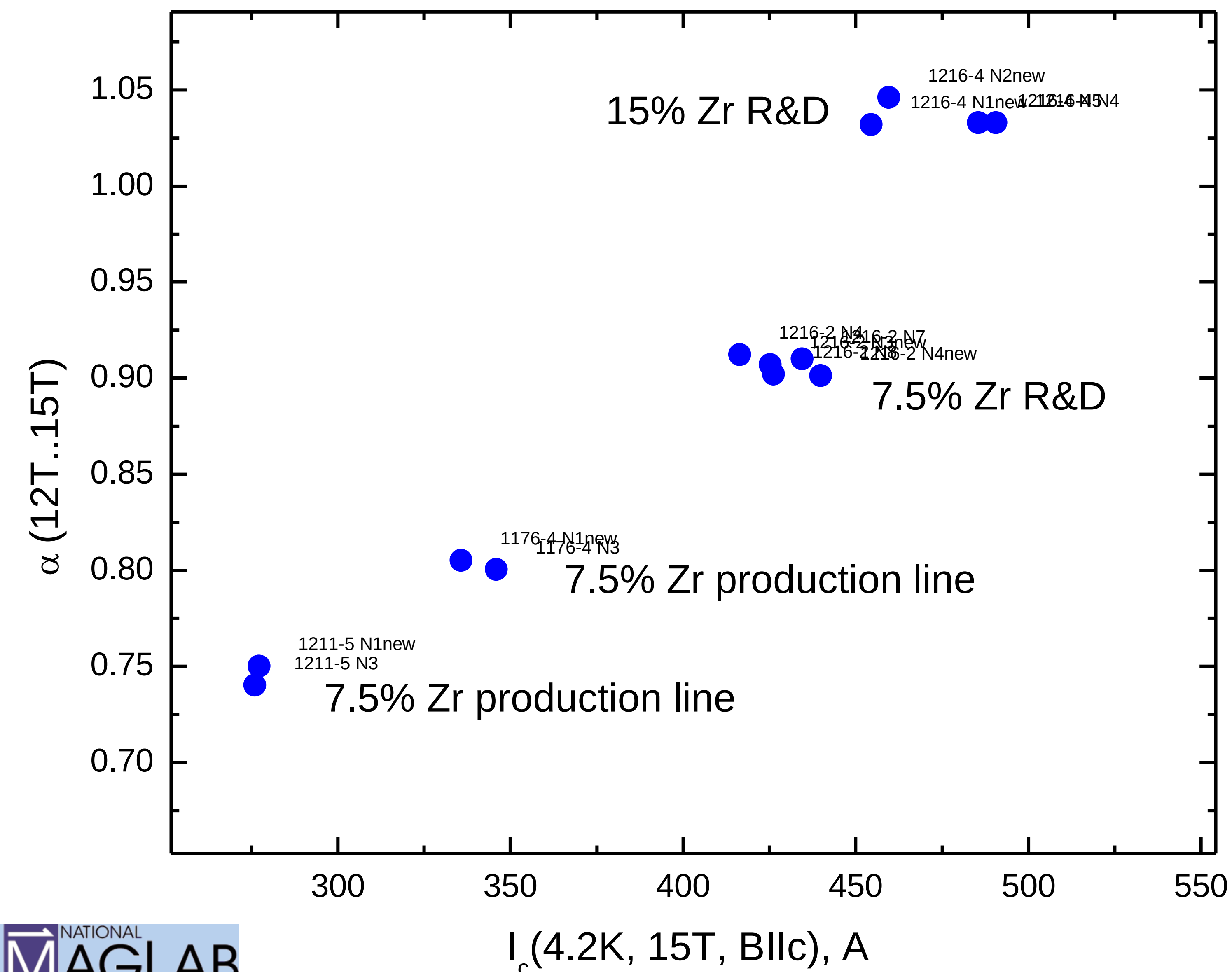
Larger α values corresponds to higher I_c(4K, 30T)

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



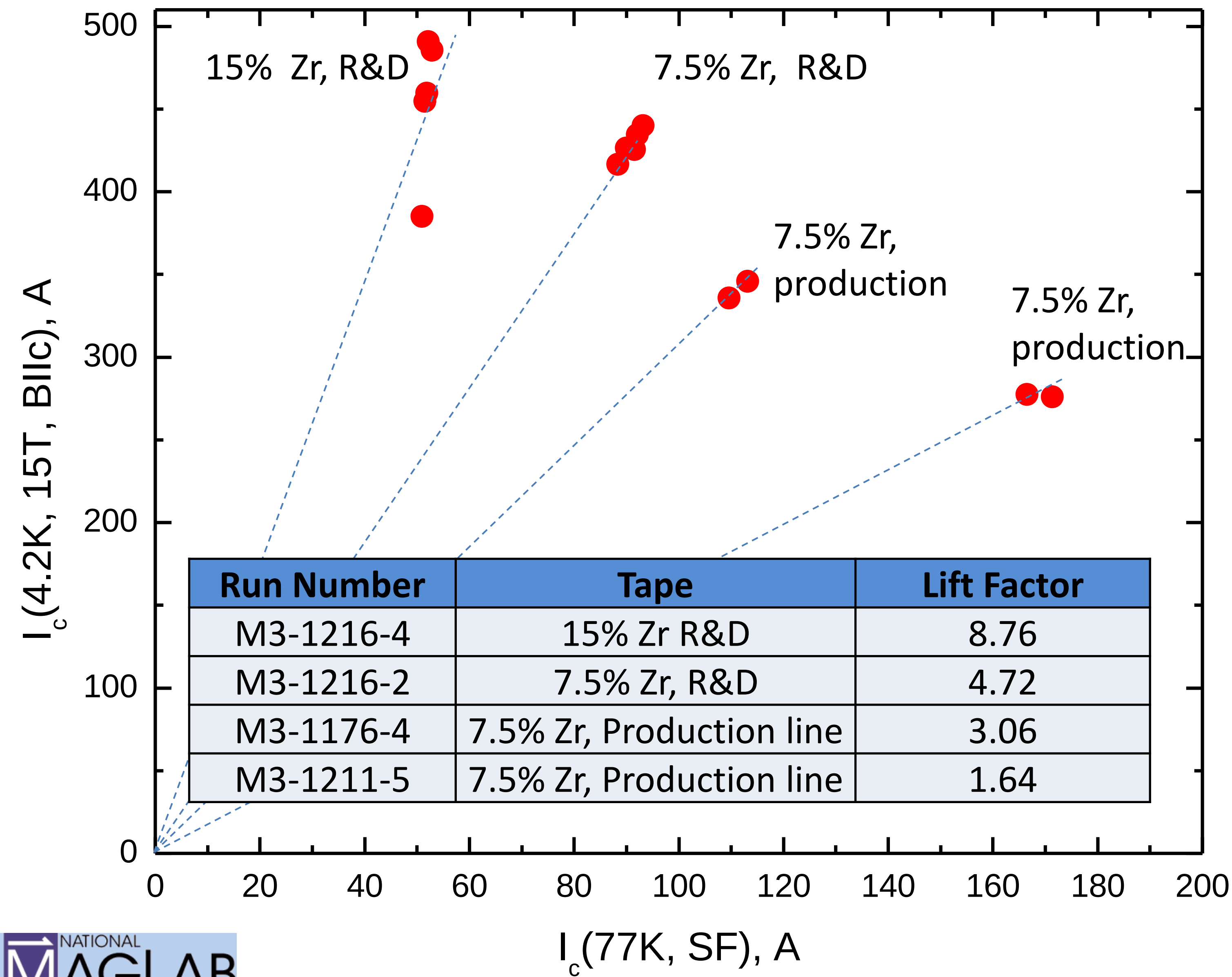
Larger α values corresponds to higher J_c(4K, 15T)

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



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

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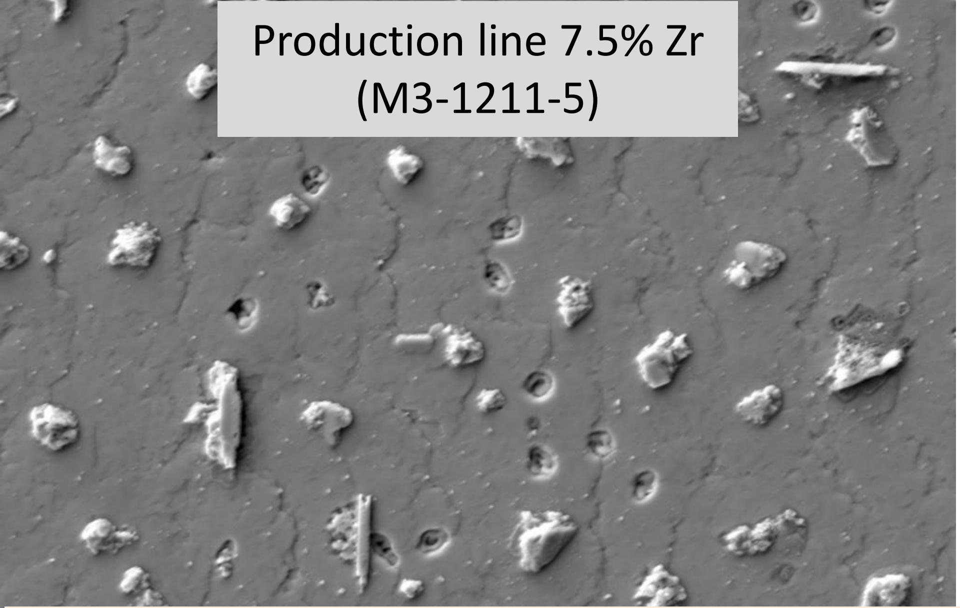
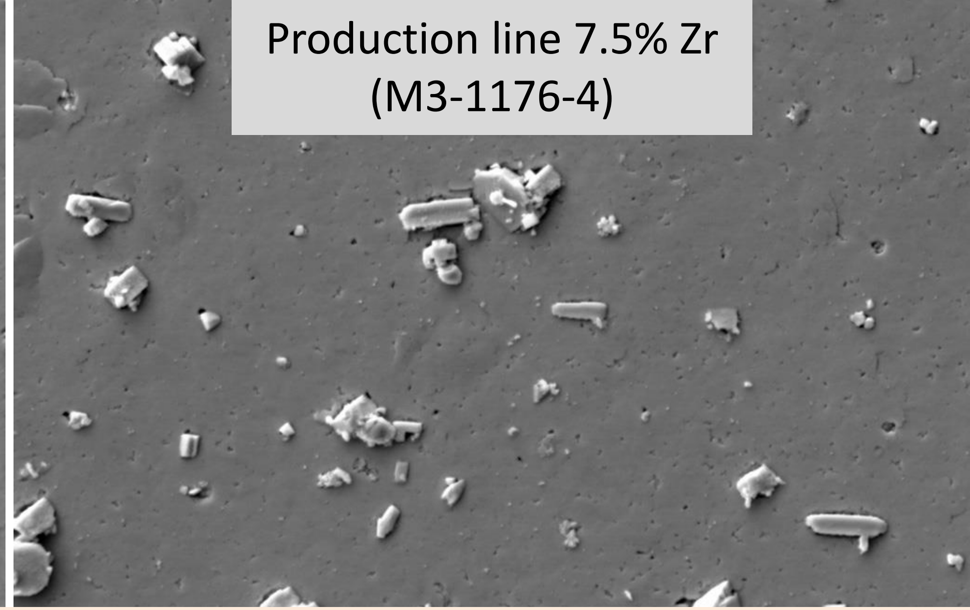
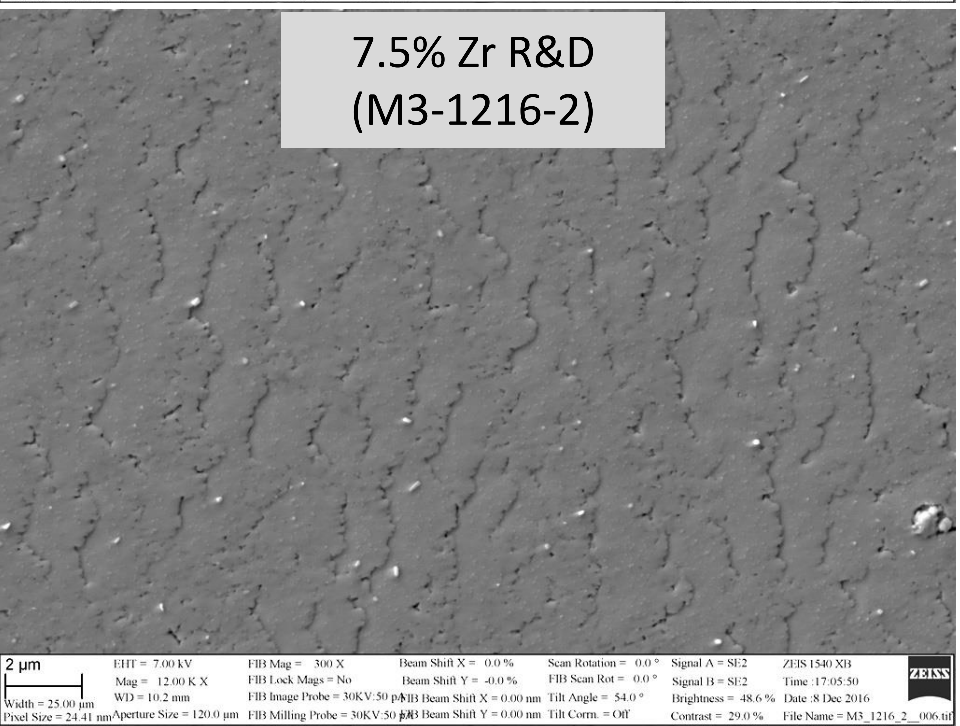
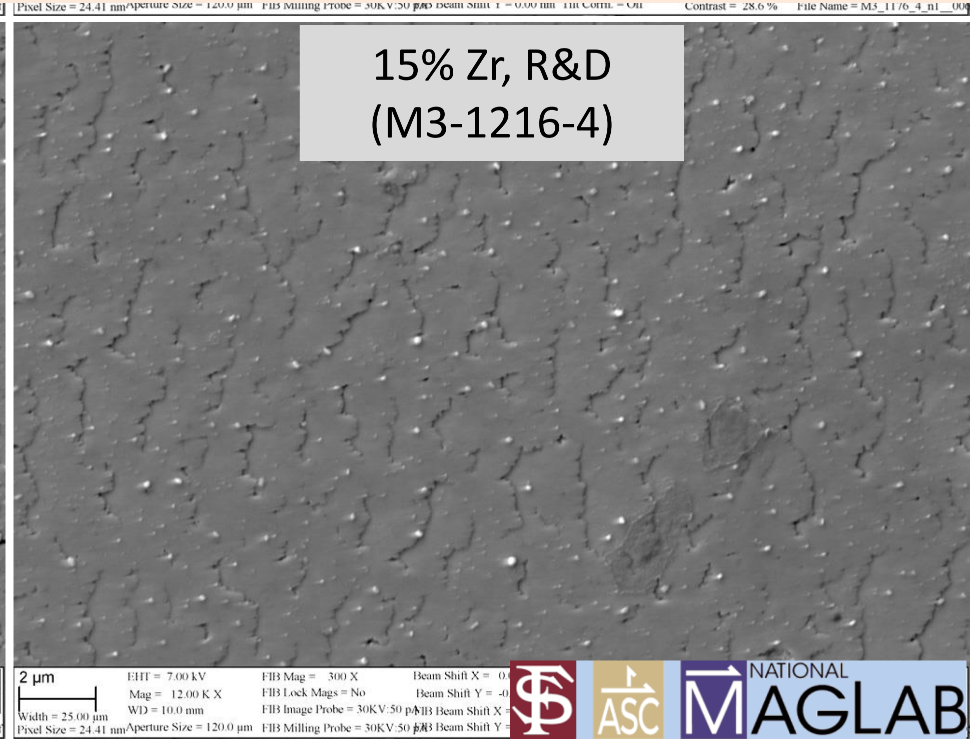




ReBCO surface of R&D tapes are free from a-axis grains and CuO grains





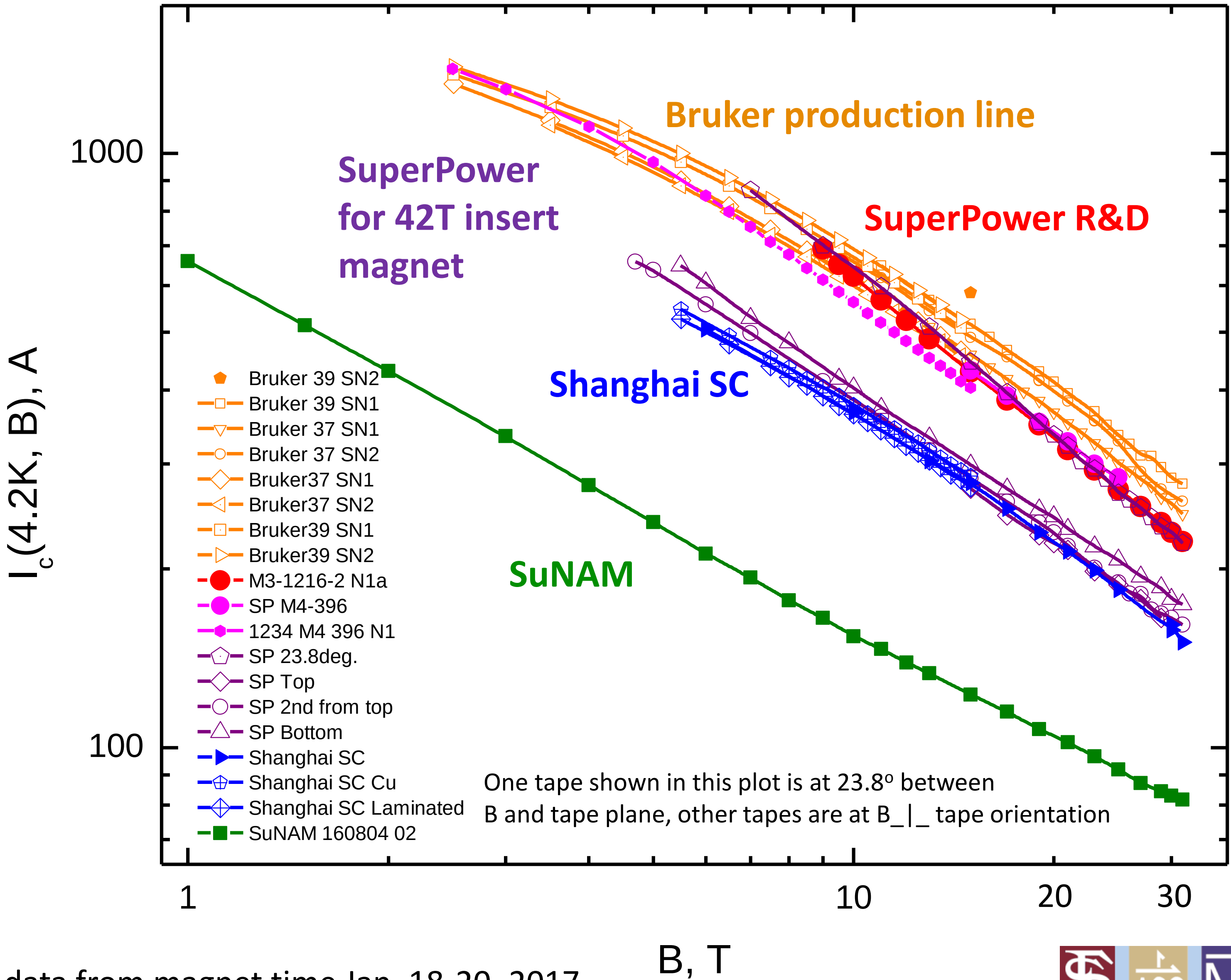
Comparison transport properties of ReBCO tapes from different manufacturers

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

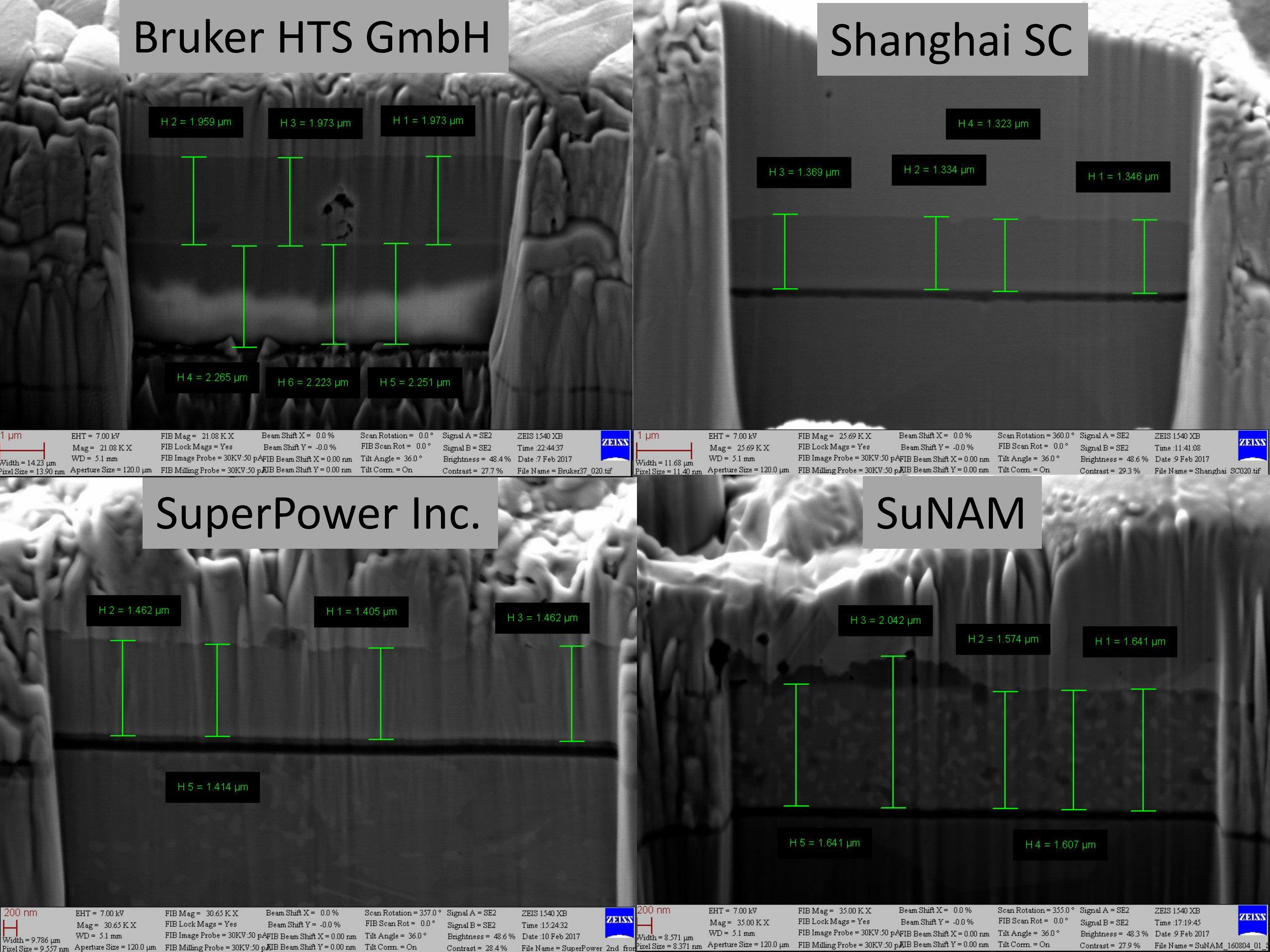
Comparison transport I_c(4.2K, B) for ReBCO tapes from different manufacturers

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

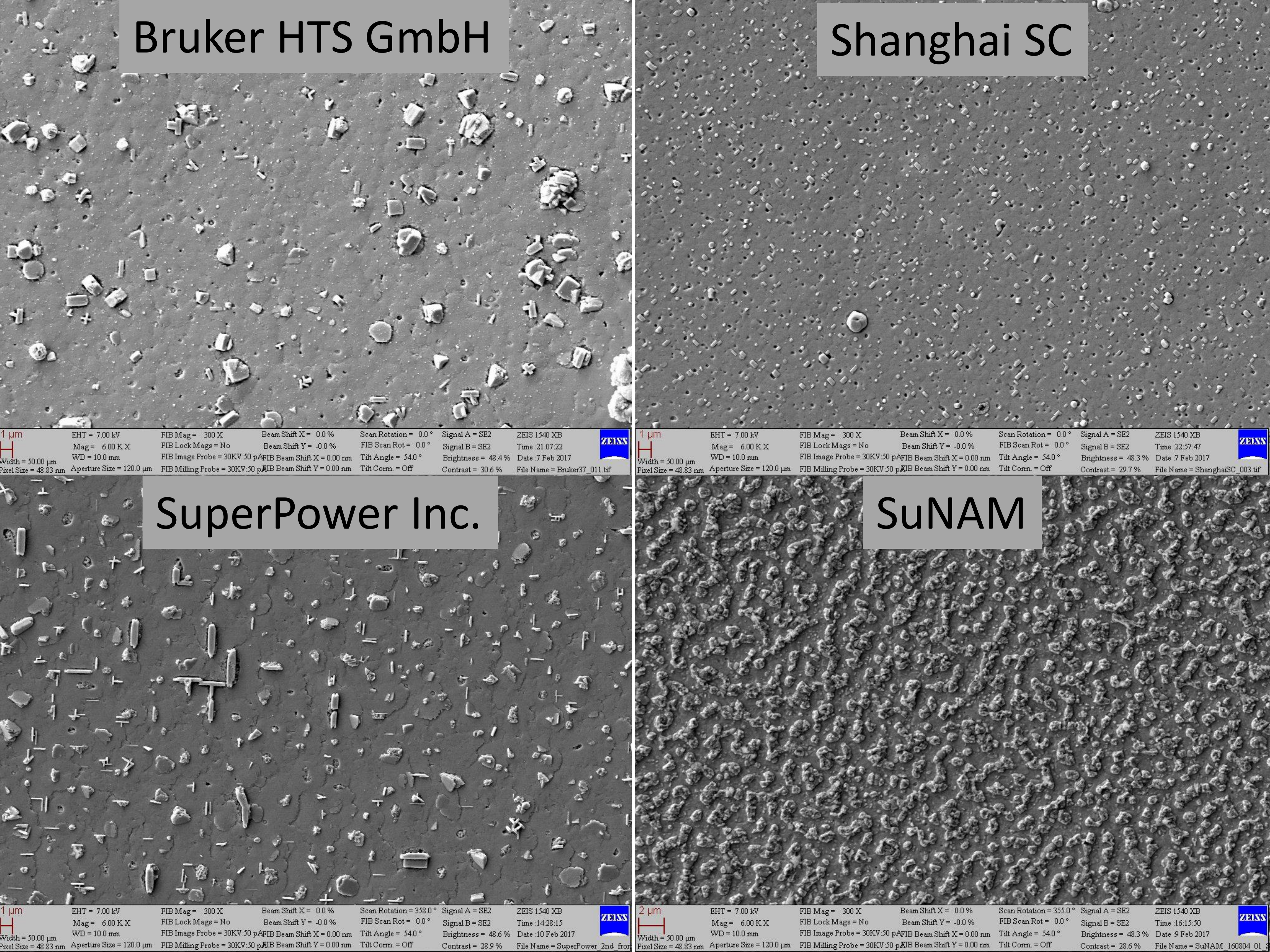
Shanghai SC tapes show I_c (4K,B) comparable to SP tapes used for 42T insert

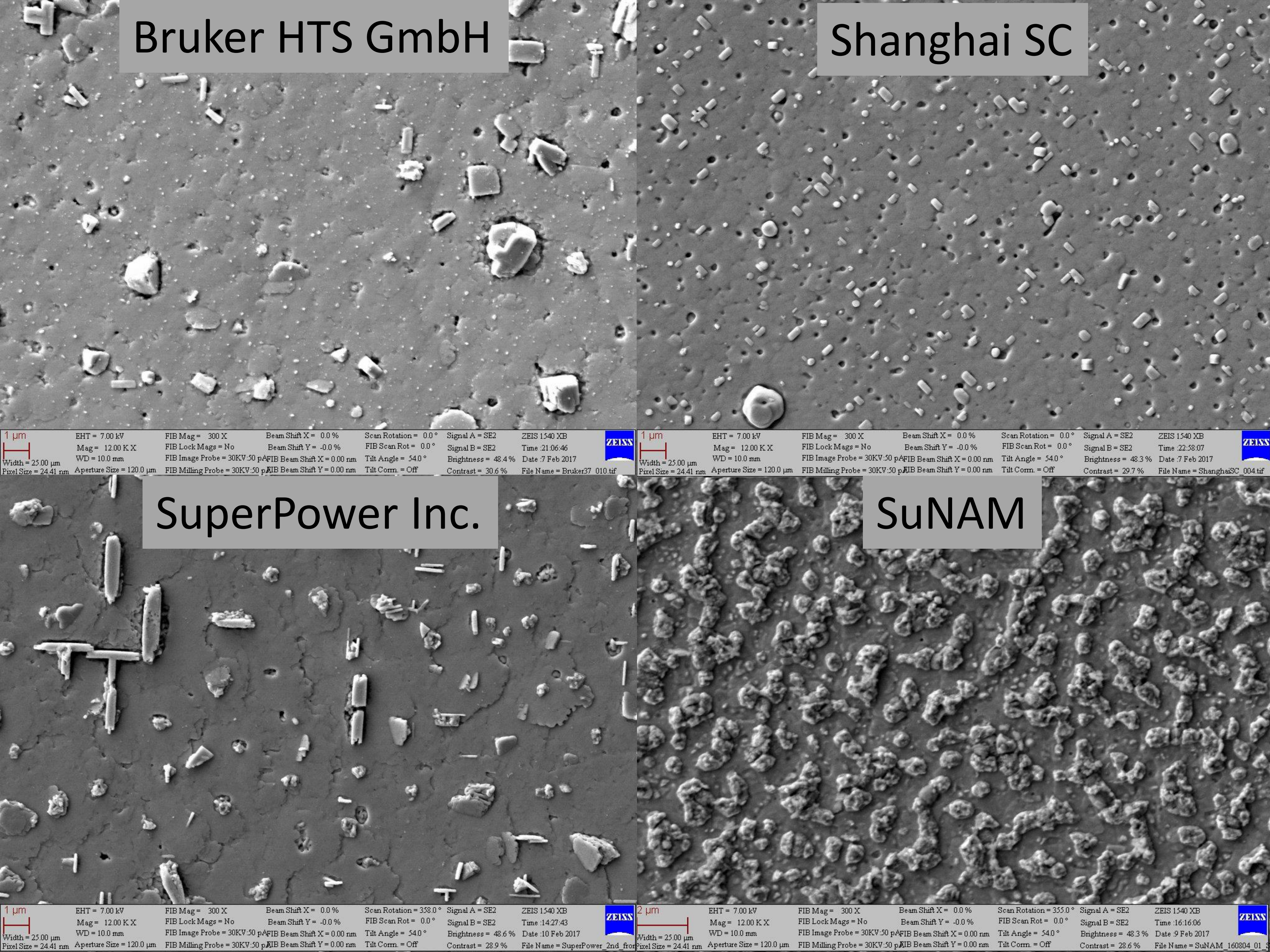


High field data from magnet time Jan. 18-20, 2017



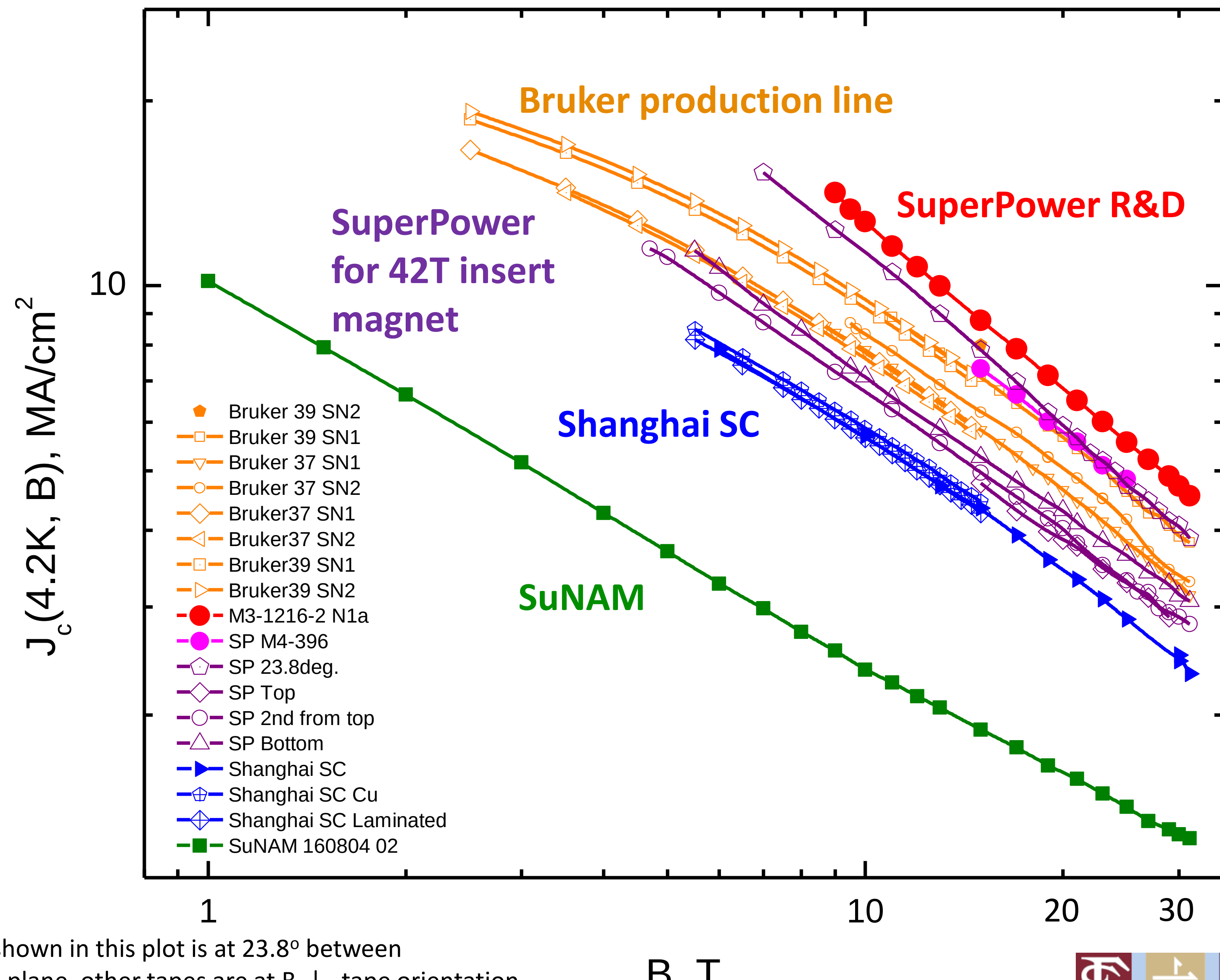
Bruker HTS GmbH
H 2 = 1.959 µm
H 3 = 1.973 µm
H 1 = 1.973 µm
H 4 = 2.265 µm
H 6 = 2.223 µm
H 5 = 2.251 µm
1 µm
Shanghai SC
H 4 = 1.323 µm
H 3 = 1.369 µm
H 2 = 1.334 µm
H 1 = 1.346 µm
1 µm
SuperPower Inc.
H 2 = 1.462 µm
H 1 = 1.405 µm
H 3 = 1.462 µm
H 5 = 1.414 µm
200 nm
SuNAM
H 3 = 2.042 µm
H 2 = 1.574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



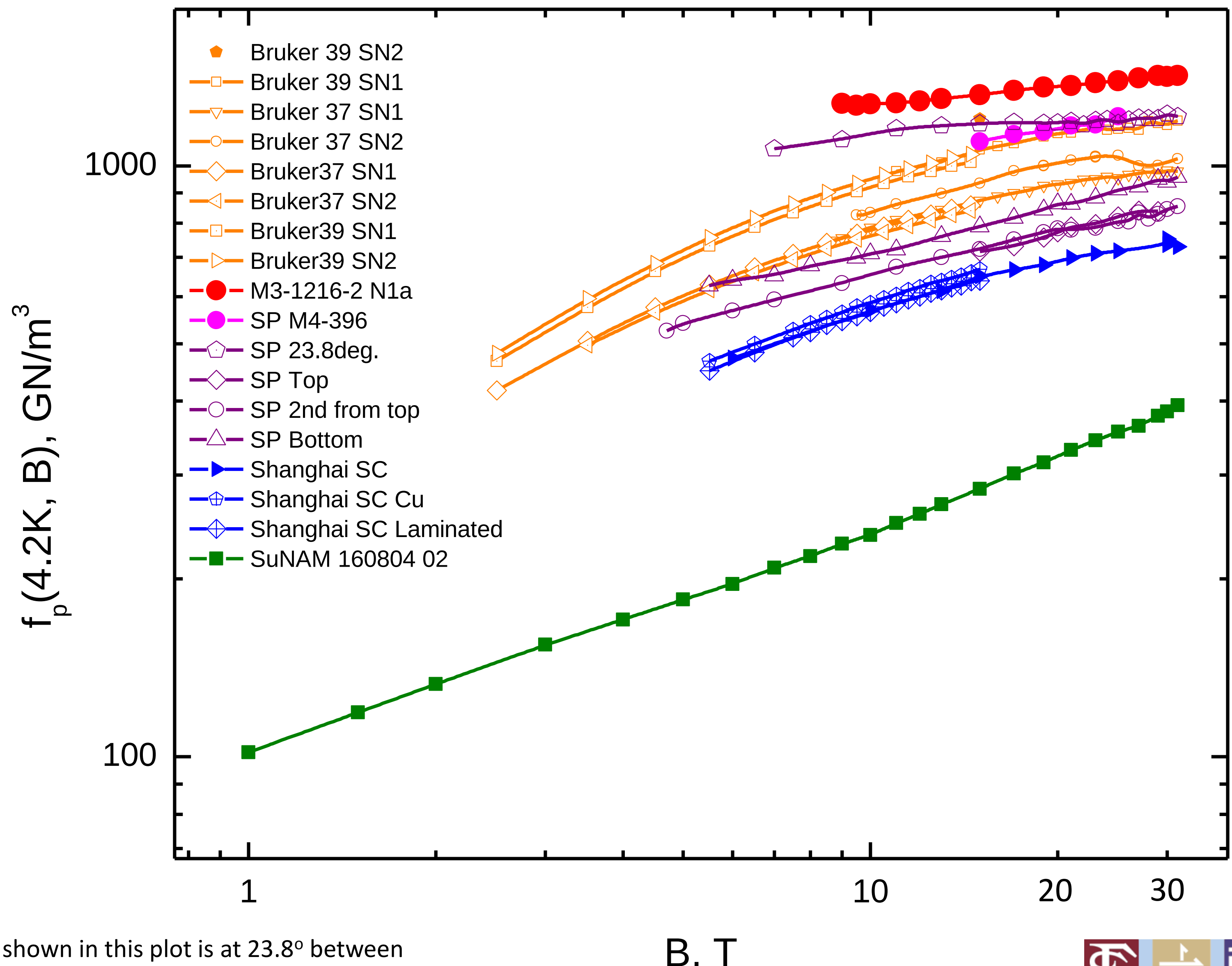
Bruker HTS GmbH
Shanghai SC
SuperPower Inc.
SuNAM
1 µm
1 µm
1 µm
2 µm

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



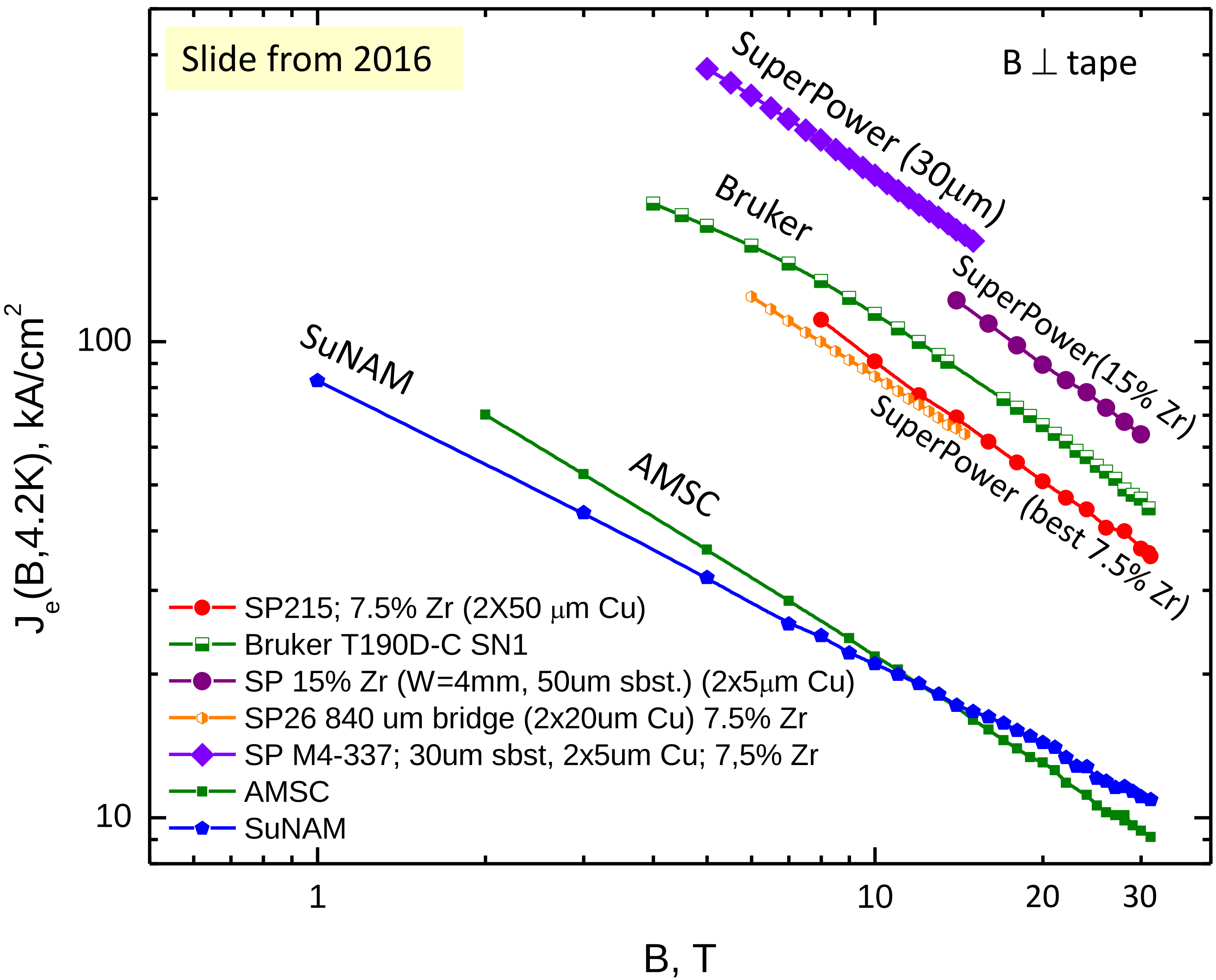
One tape shown in this plot is at 23.8° between
B and tape plane, other tapes are at B_|_ tape orientation

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

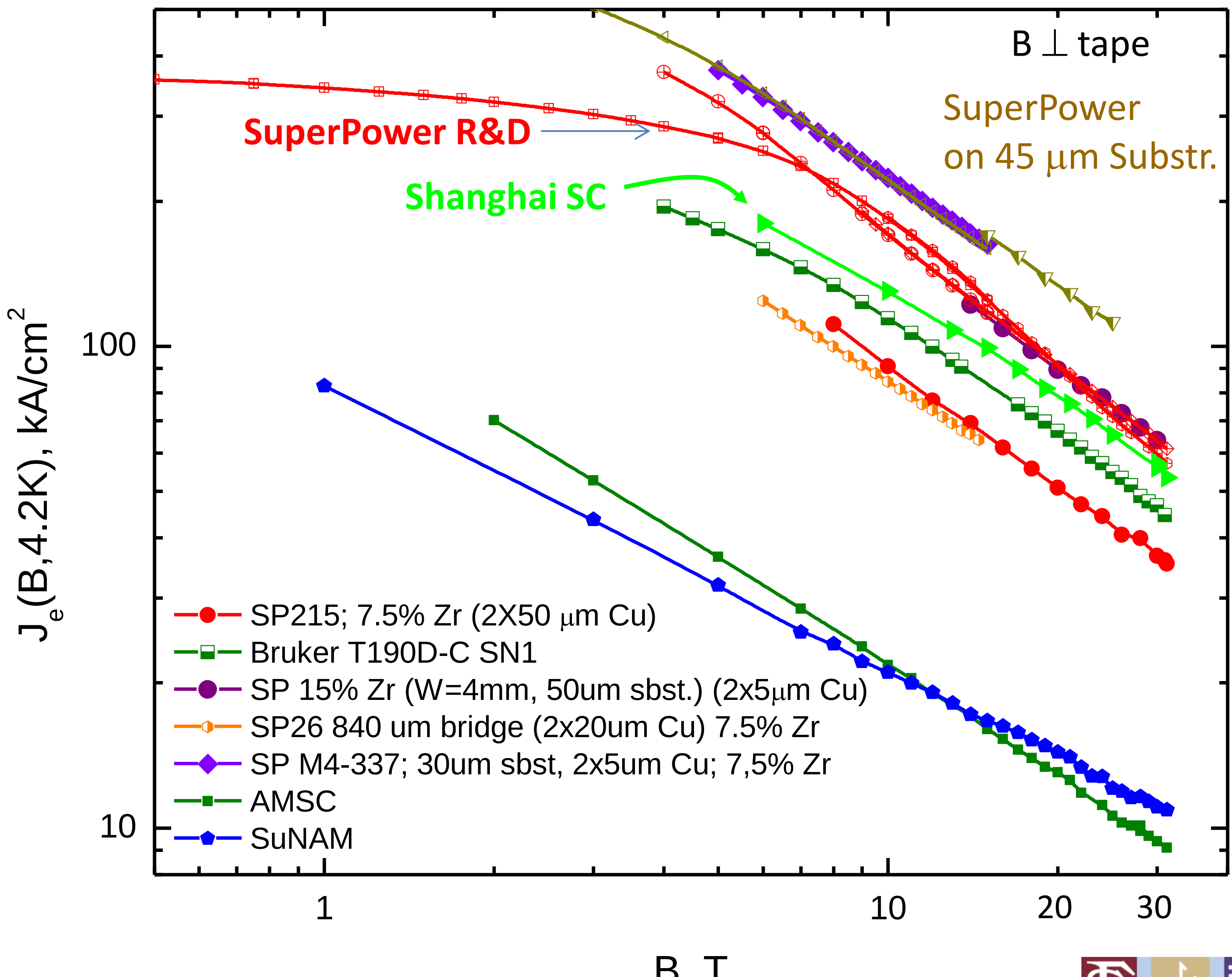


One tape shown in this plot is at 23.8° between B and tape plane, other tapes are at B_|_ tape orientation

Highest J_e detected for SuperPower Inc. ReBCO tape with 7.5% Zr 4 mm wide, with 30 μm substrate with 2x5 um thick stabilizer layer Cu

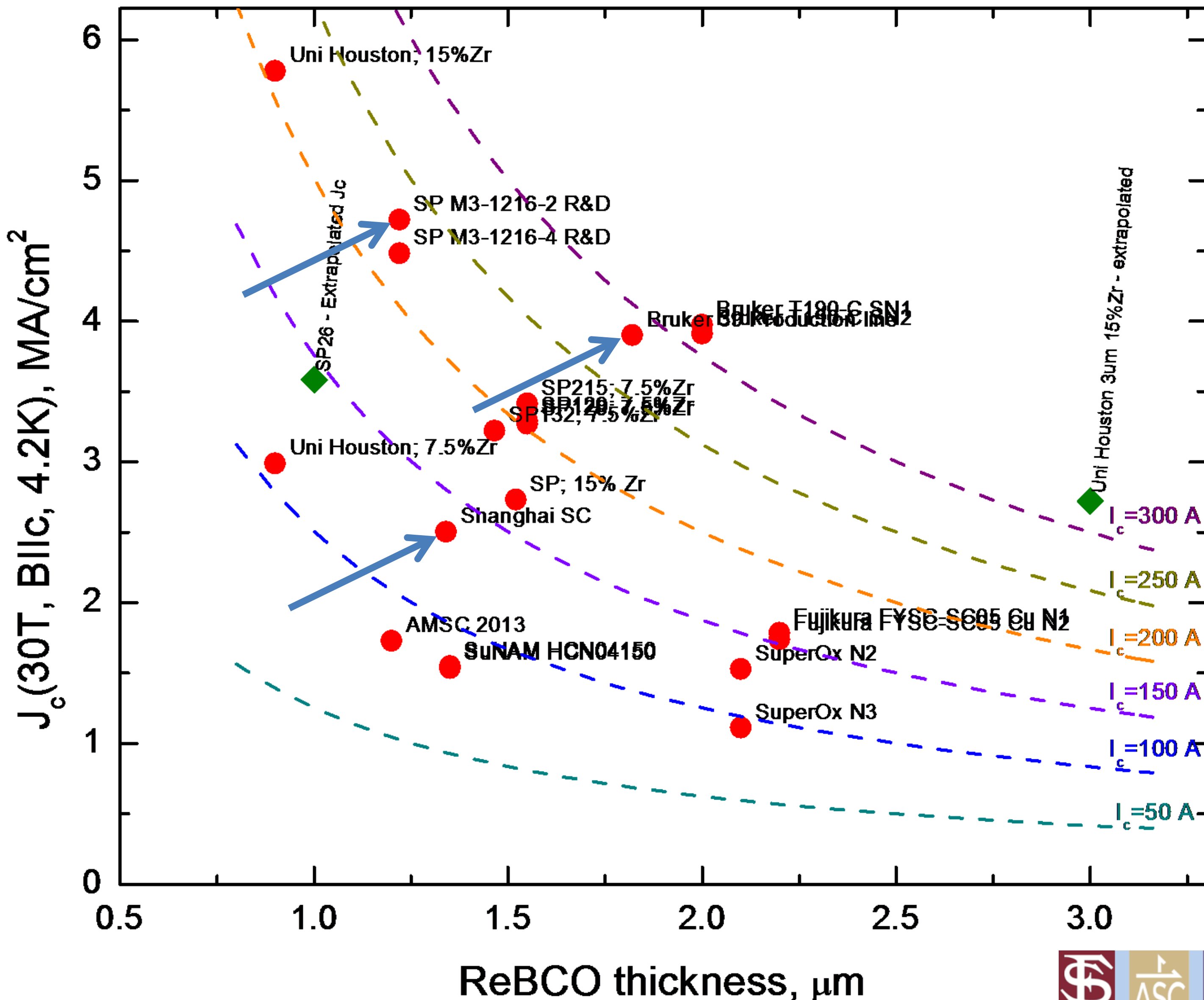


SuperPower Inc. achieved record high J_e (4.2K, B) for tape with 45 μm substrate



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

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



Critical current of Cu and Steel coated SuNAM tapes measured in magnetic fields up to 31.2 T at 4.2K

Short samples for in-field I_c measurements with fixed probe

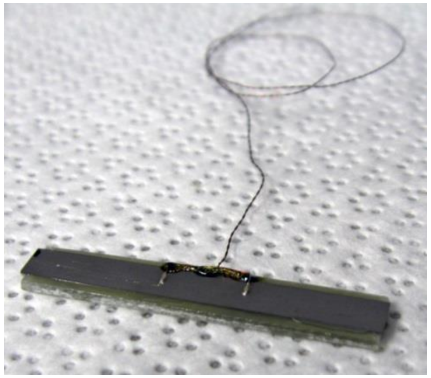
Samples SuNAM 2016 production line tapes:
35 mm long for resistive magnet,
45 mm long for superconducting magnet

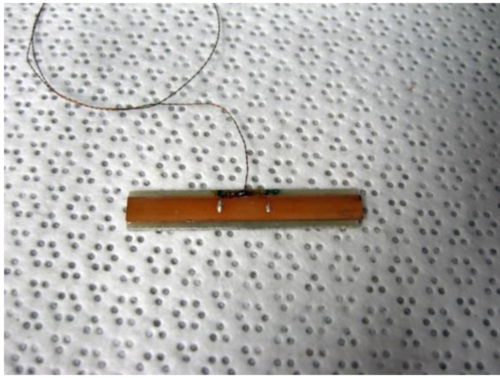
4 mm wide tapes glued on G-10 substrate

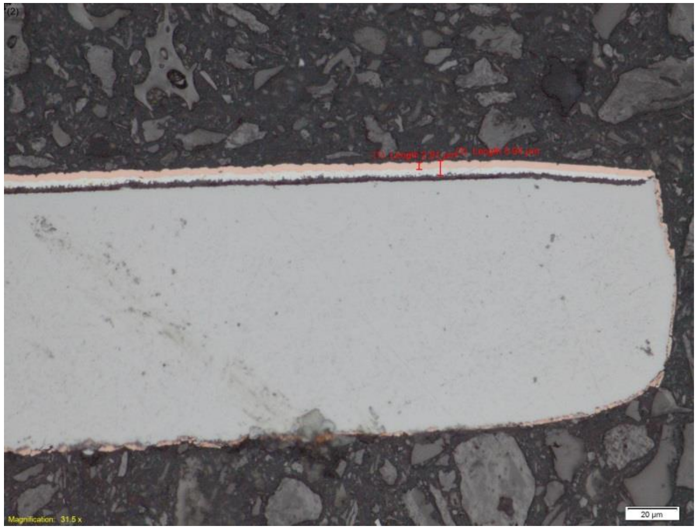
I_c(77K; SF)>150 A
STS coated - <5 μm on top of <5 μm Cu

I_c(77K;SF)>200A
Cu coating <5 μm on each side

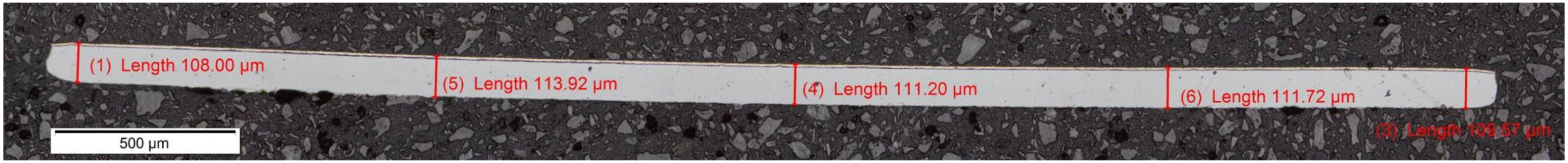
About 100 μm thick substrate



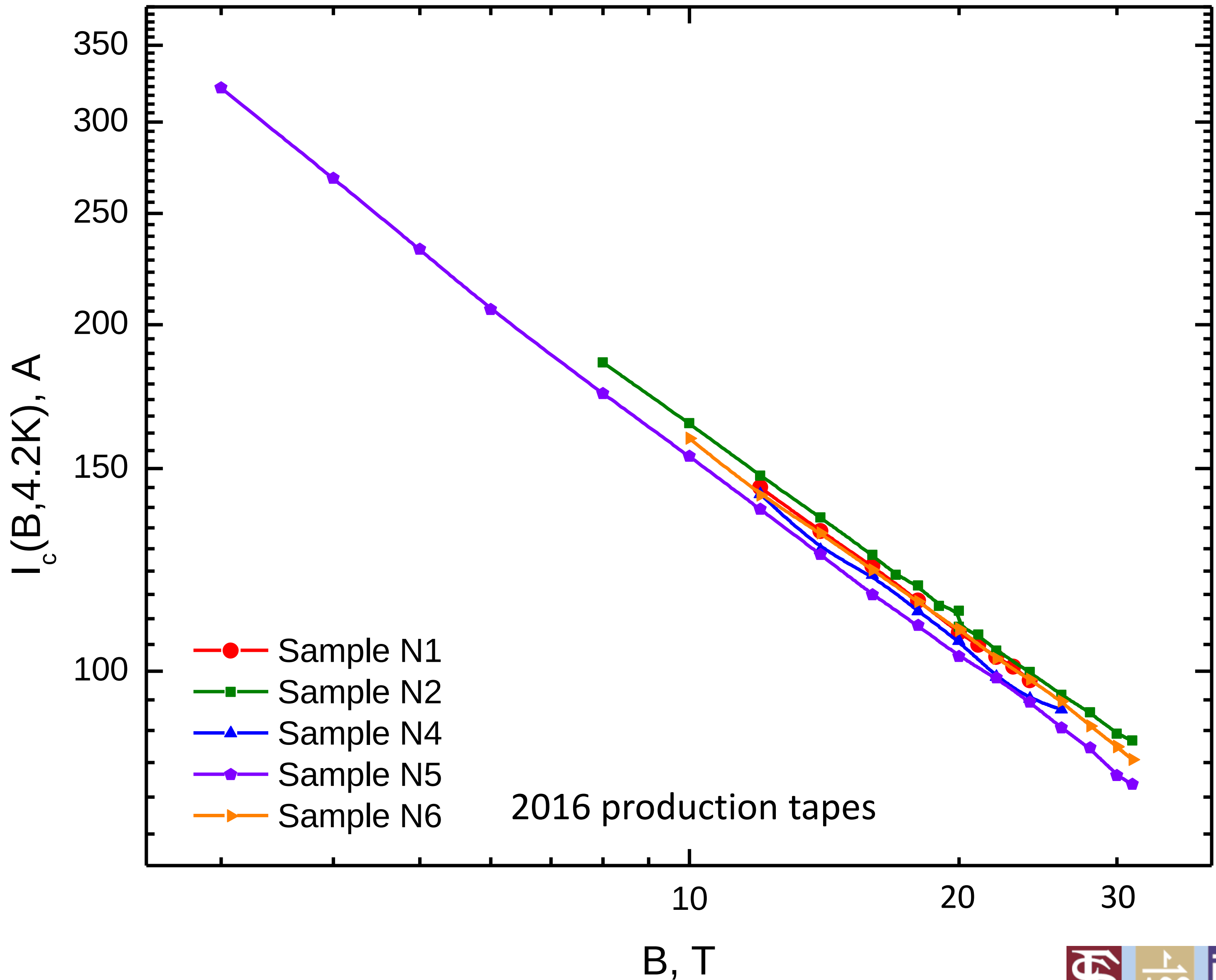




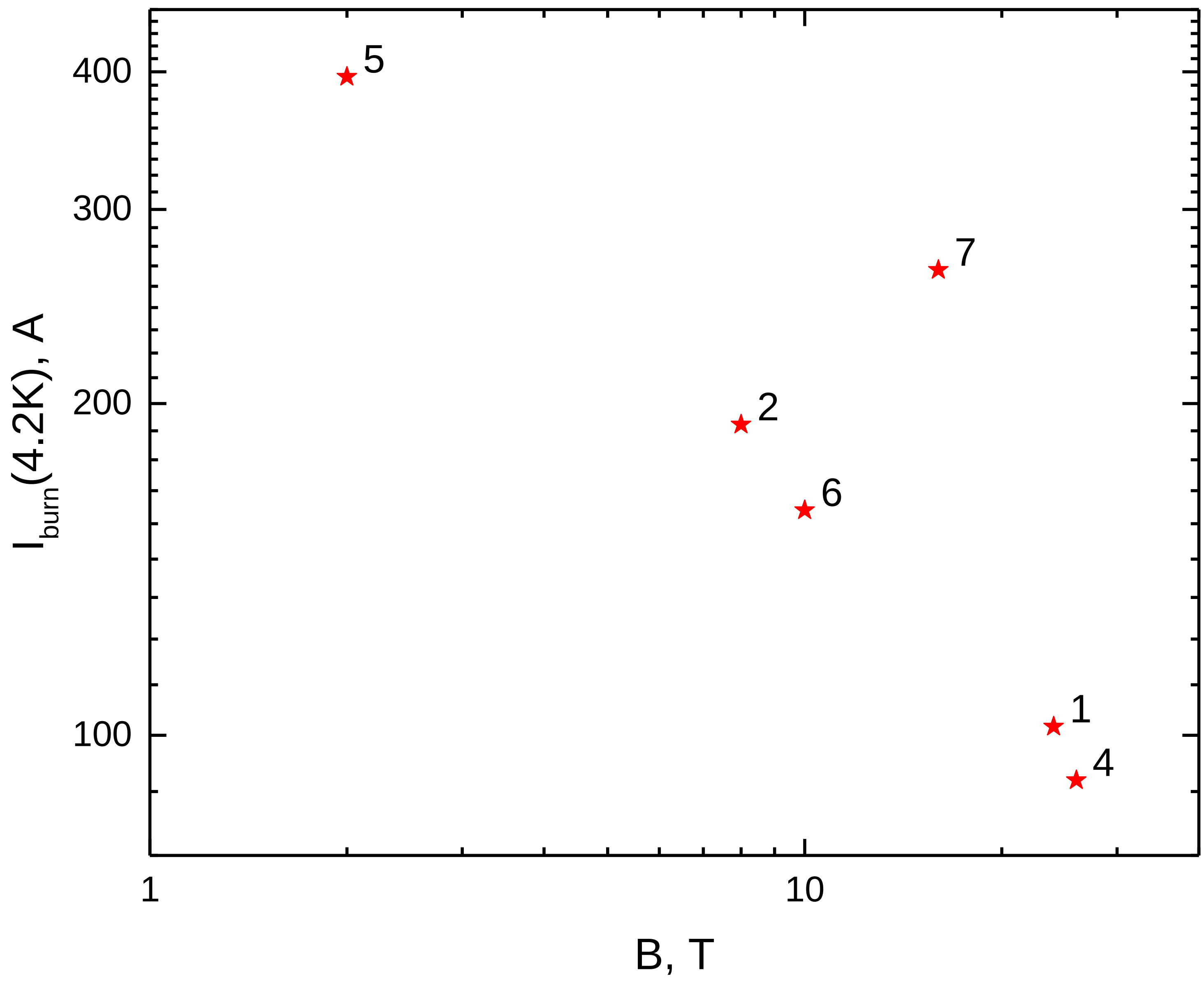
Polished cross section of steel coated tape



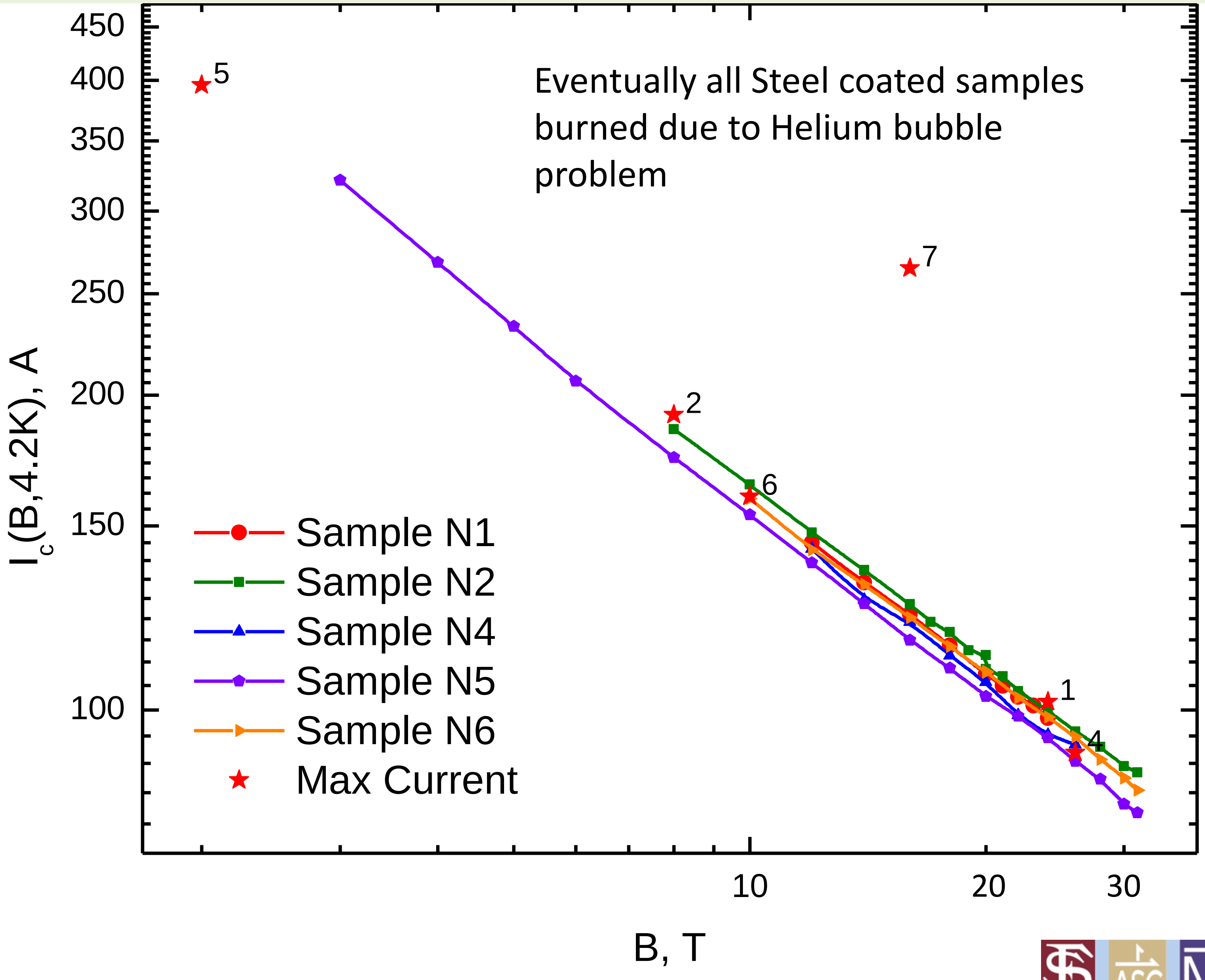
$I_c(B)$ for Steel Coated SuNAM 4 mm wide tapes at 4.2 K measured in resistive magnet (cell 7)



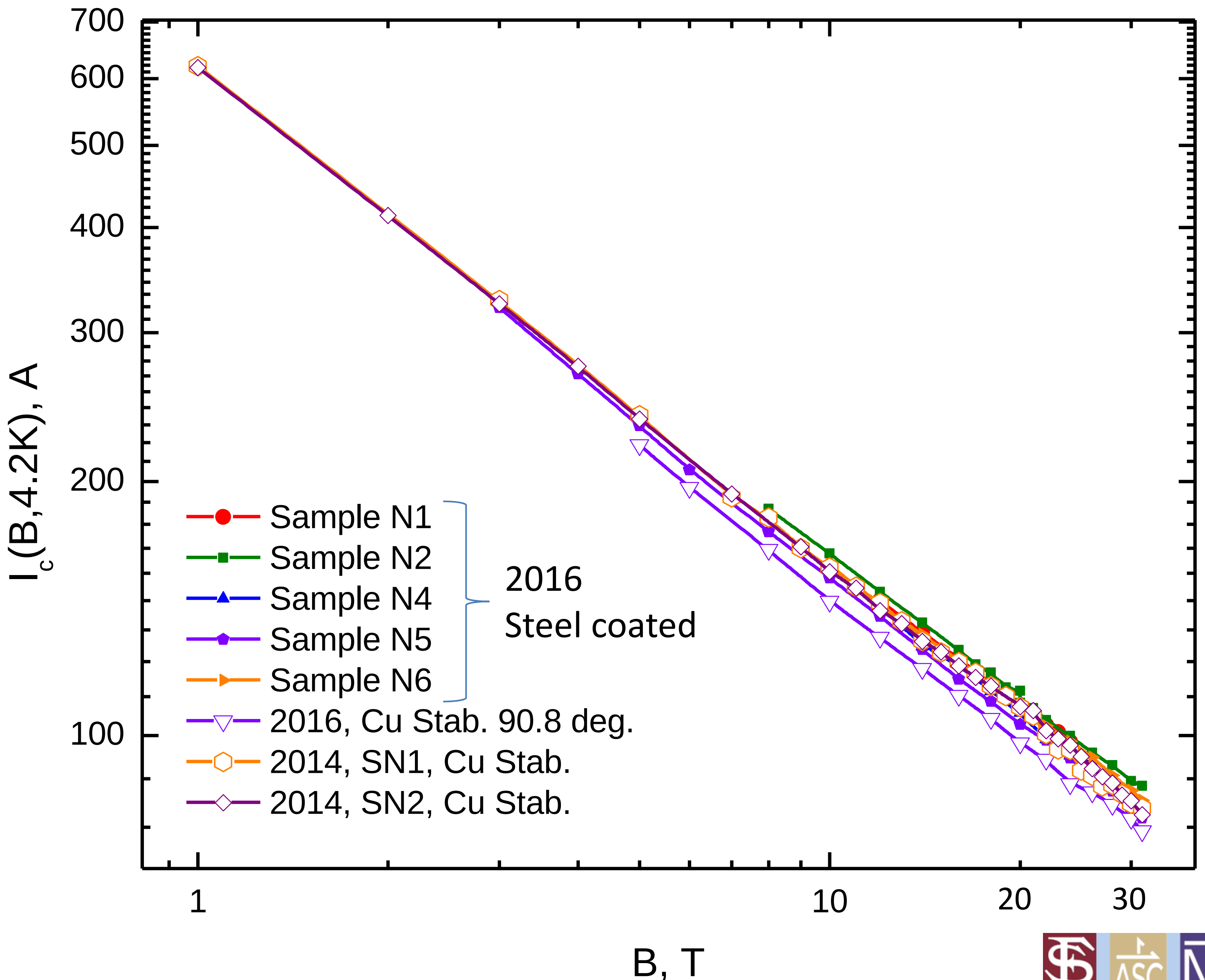
Current and magnetic field values at which samples were burned



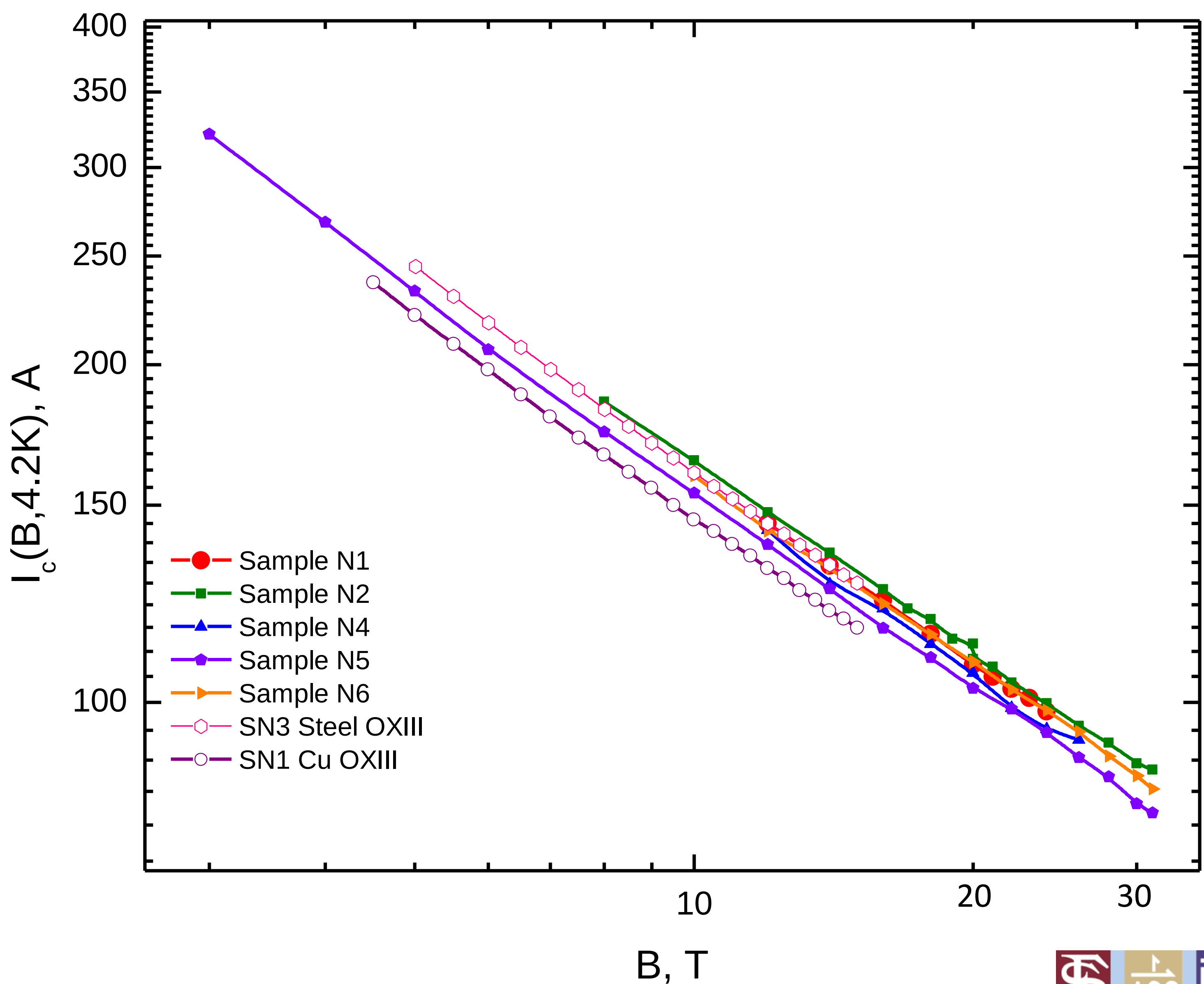
For steel coated samples burning currents coincides with critical currents



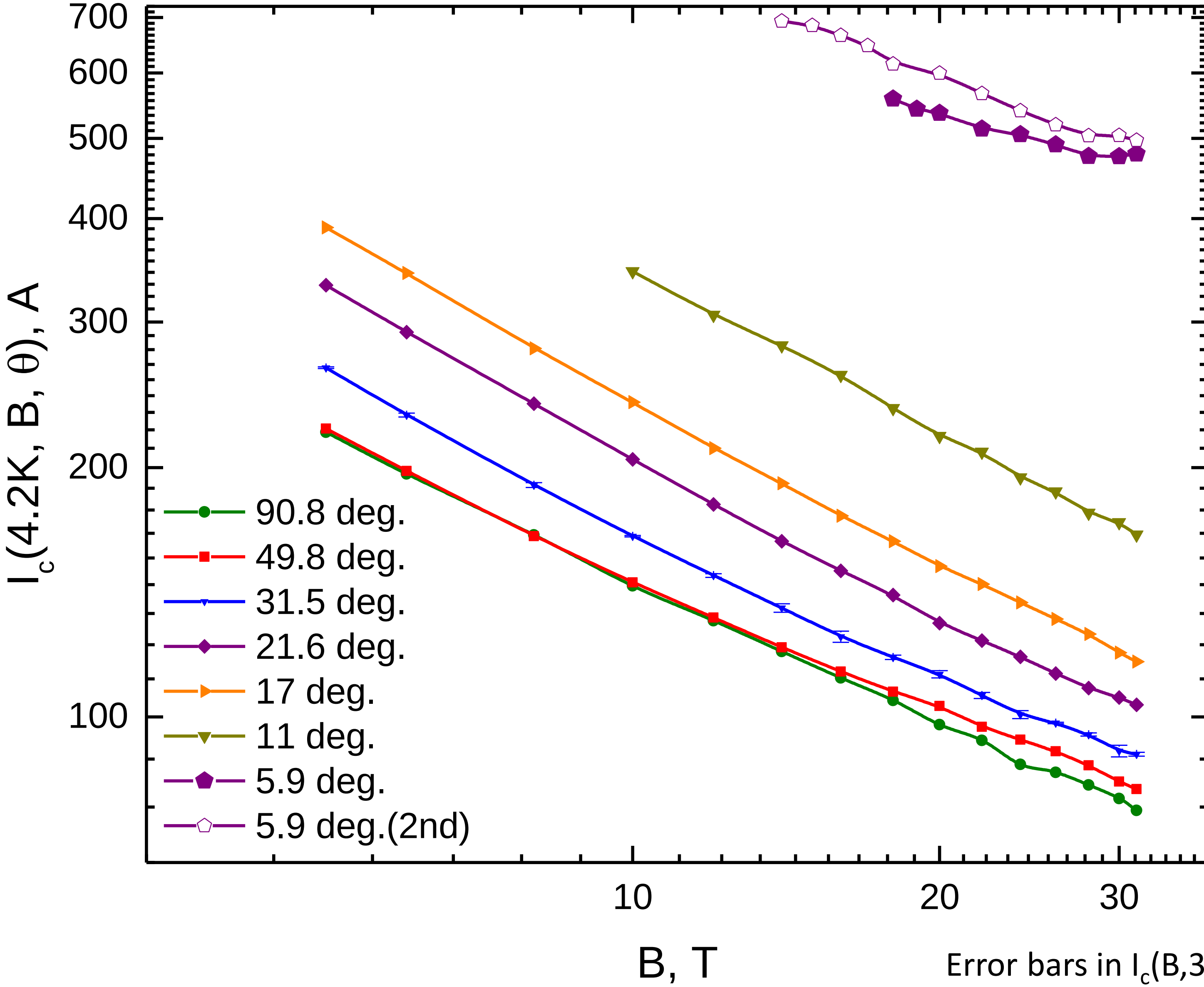
Good match of I_c values for Cu coated and Steel coated tapes measured in resistive magnets

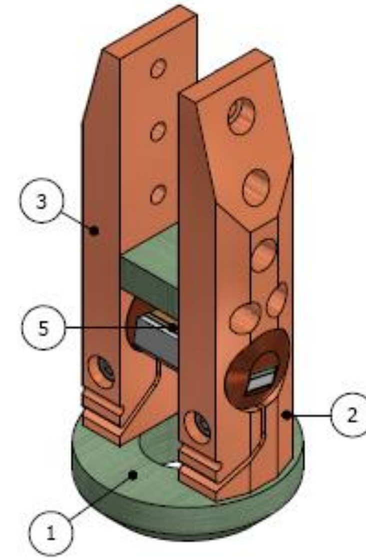


Good match of data measured in superconducting (OXIII) and resistive (cell 7) magnets



I_c(4.2K, B) of SuNAM Cu coated tape measured for several angles up to 31.2T in cell 7

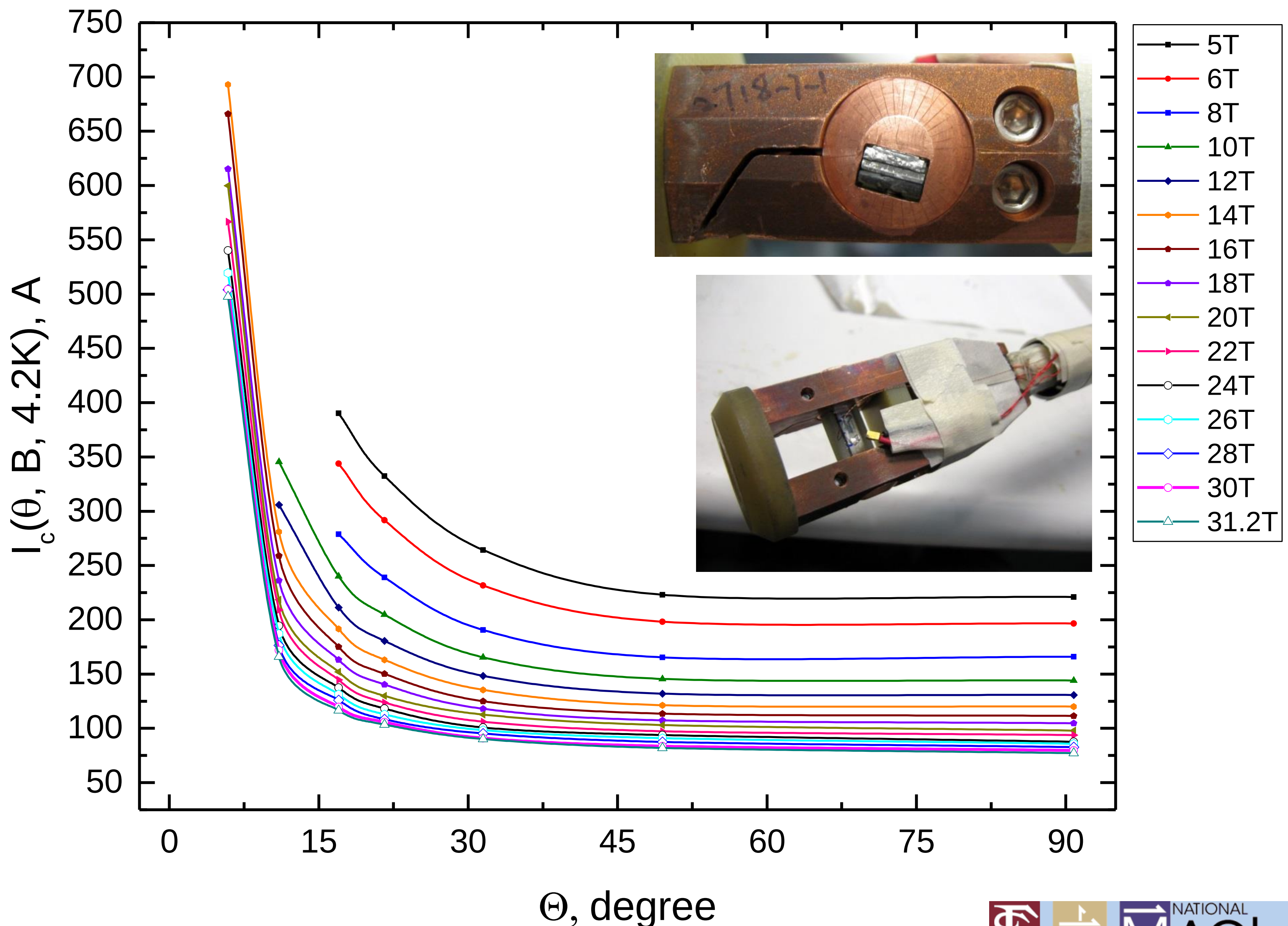




Error bars in I_c(B,31.5°) are standard deviation

All curves plotted on this graph were measured on one sample (N3) – 4mm wide

I_c(4.2K, θ,B) of SuNAM Cu coated tape measured up to 31.2T in cell 7



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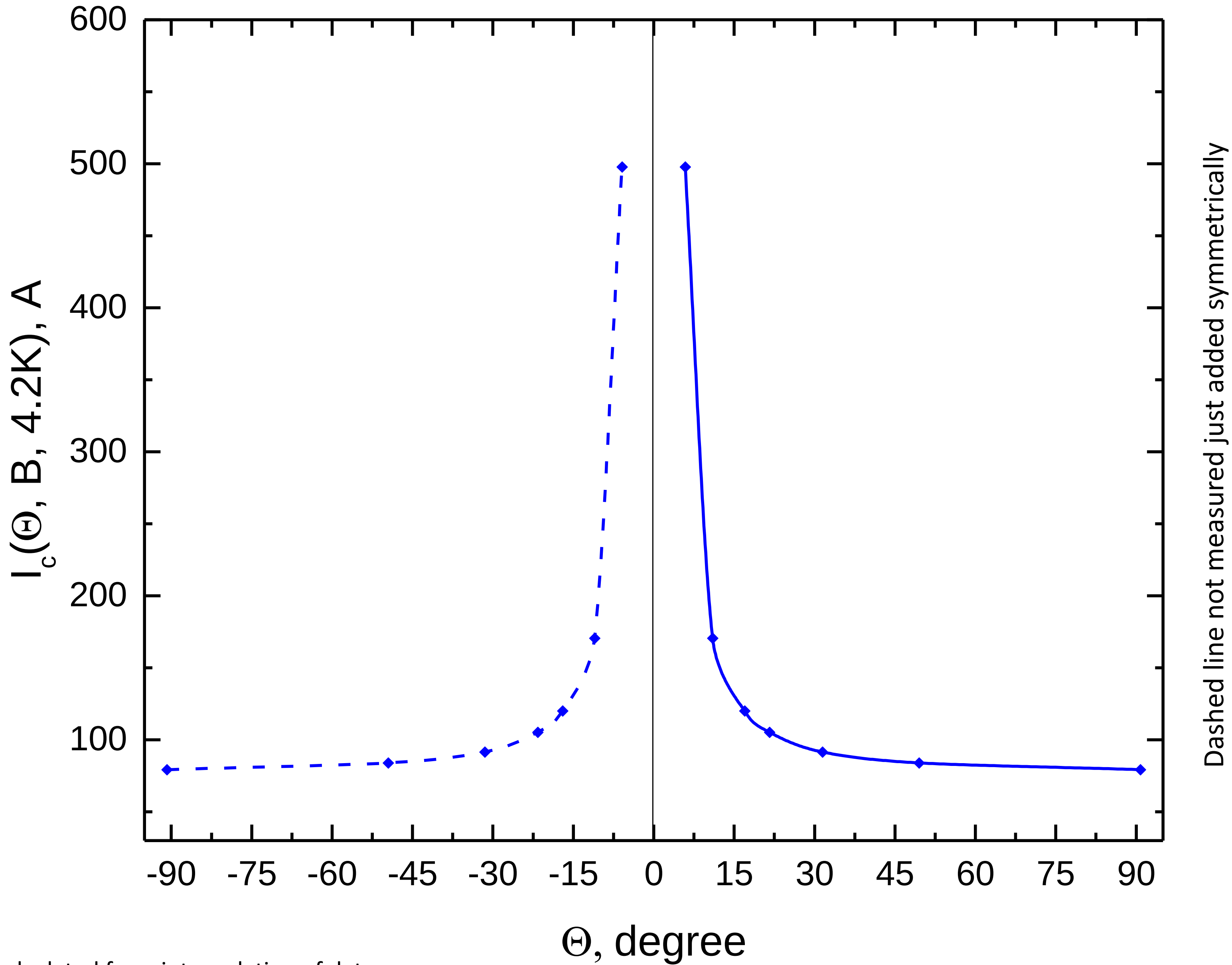
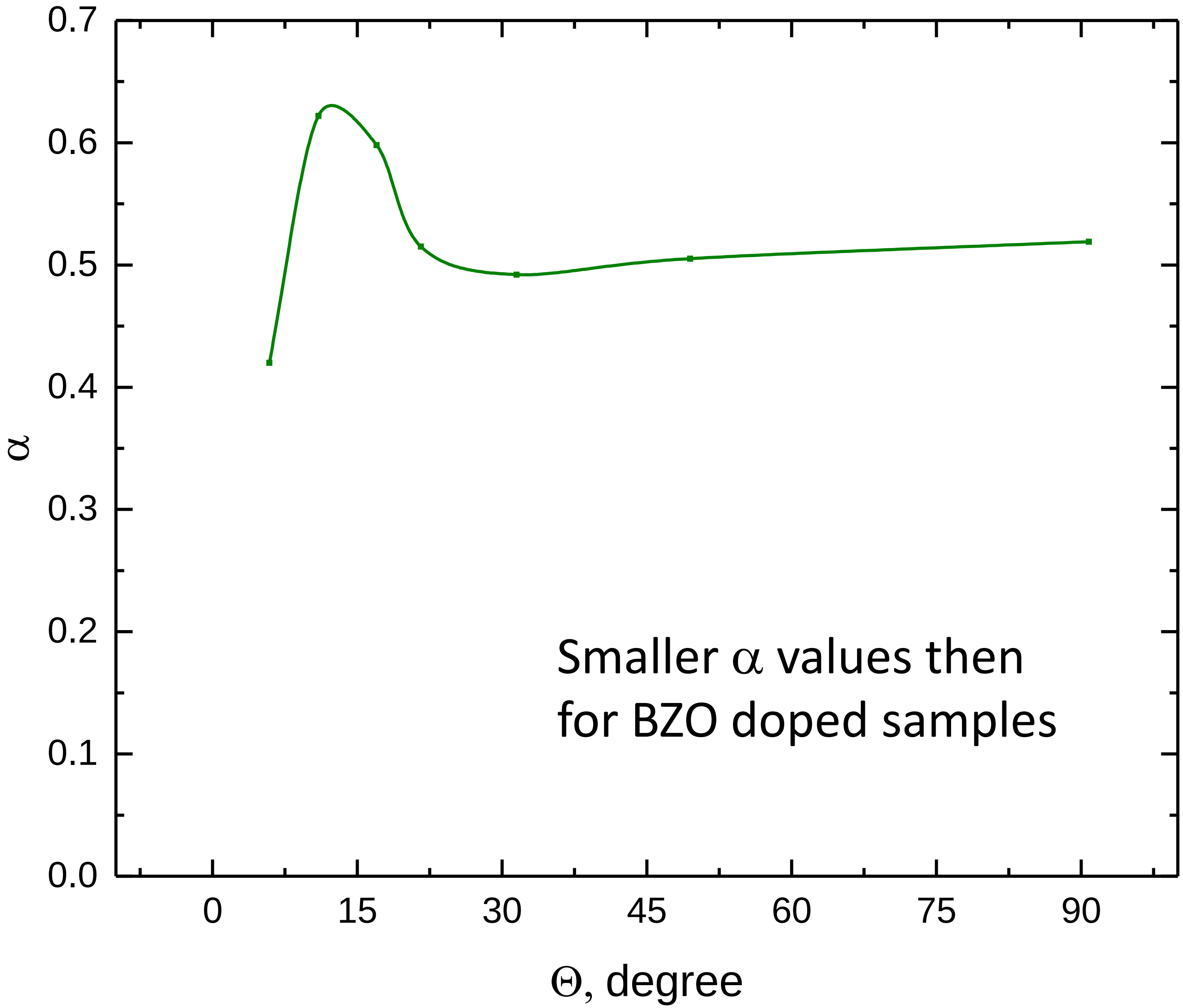
I_c(4.2K, θ, 30T) with symmetrically added data points for negative θ



I_c at 30T calculated from interpolation of data between 20t and 31.2T

Slopes of I_c vs. B in log-log scale of SuNAM Cu coated tape calculated by fitting $I_c \sim B^{-\alpha}$ to 20T .. 31.2T data



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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. **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

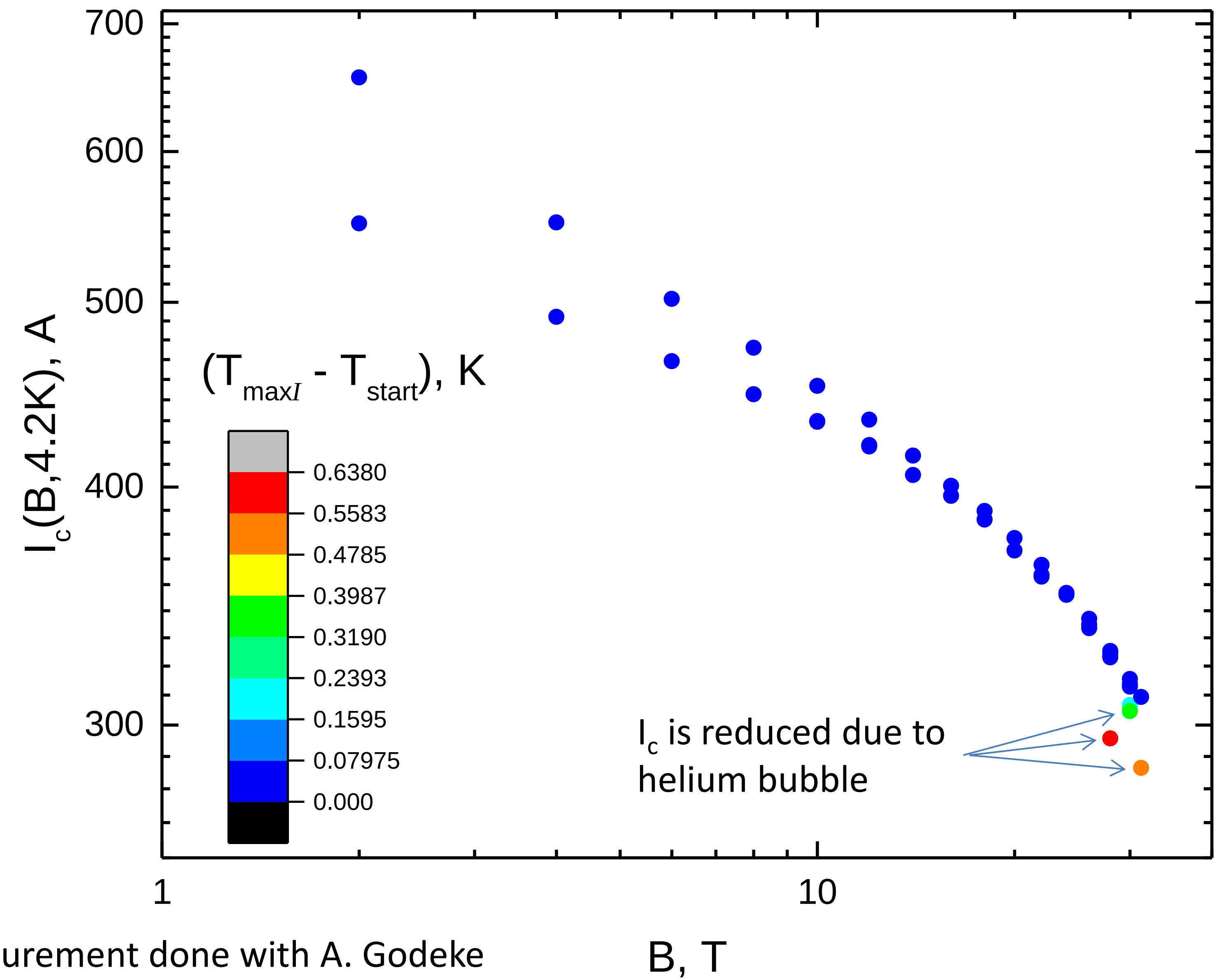
Conclusions continuing:

3. **I_c of steel coated and Cu plated tapes from SuNAM for making no-insulation magnets**

1) Above 20T we have to mitigate helium bubble problem (in current setup) for I_c characterization of steel coated samples
2) For steel coated samples burning currents coincides with I_c
3) **We observed a good match of I_c values for Cu coated and Steel coated tapes measured in SC and resistive magnets**
4) Suggestion: improve uniformity of Cu of back side and edges to let current shearing during quench
5) Field dependence of $\alpha(B)$ of SuNAM tape qualitatively similar to measured in SuperPower tapes

Additional slides

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

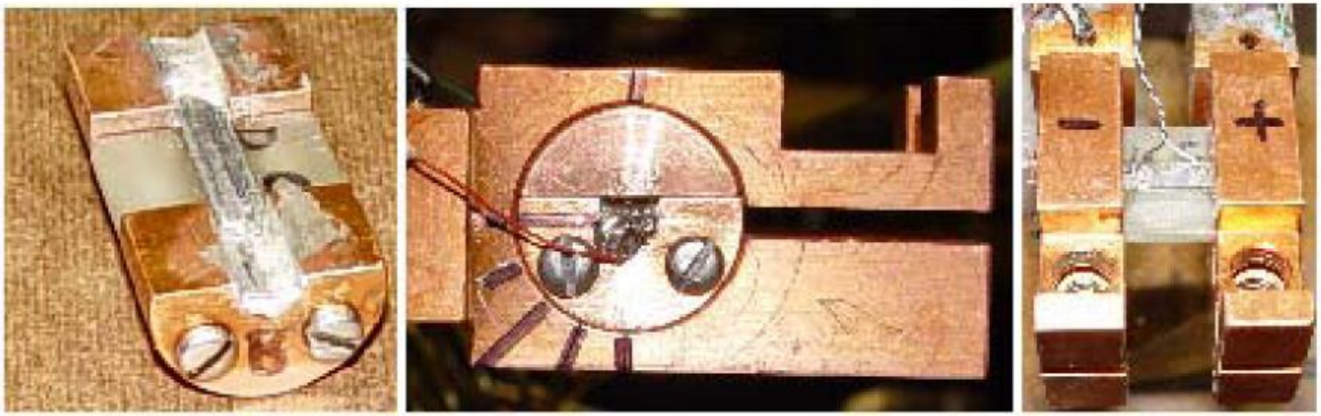
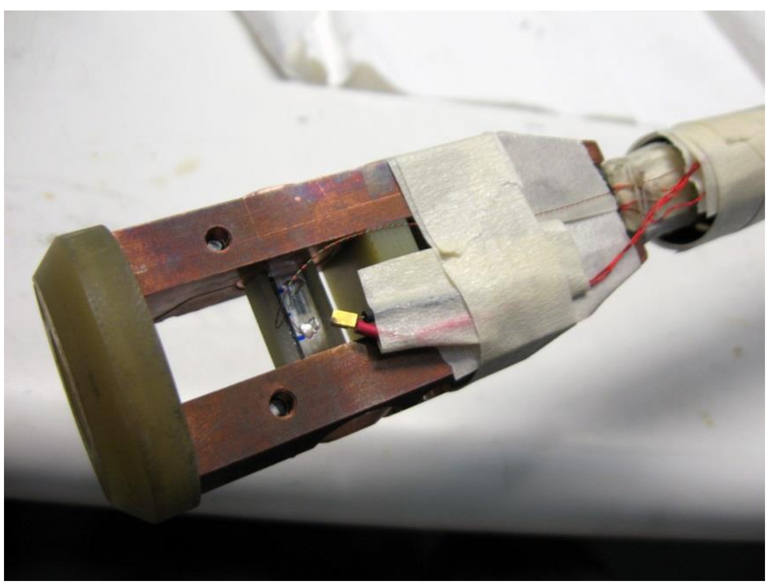


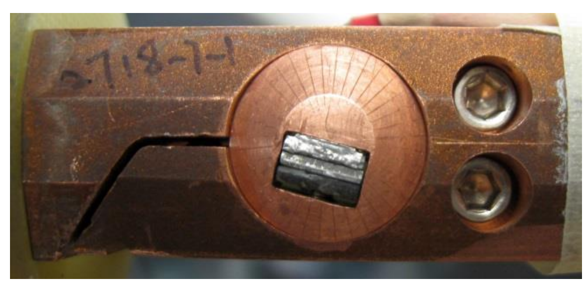
FIGURE 4. Sample holder (left), sample holder within the probe copper lugs (center), and instrumented sample (right).

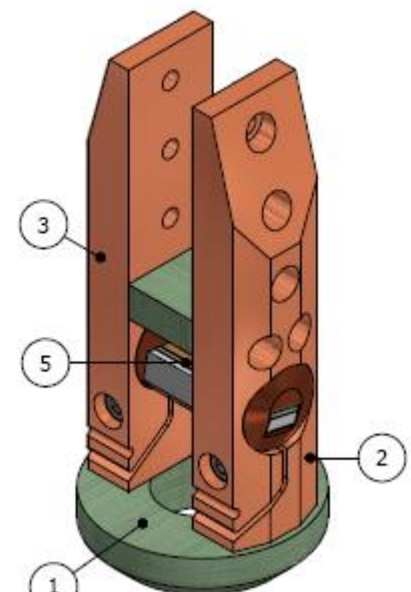
"Angular Measurements of HTS Critical Current for High Field Solenoids", D. Turrioni et al.. Advances in Cryogenic Engineering, V. 54, AIP, V. 986, pp. 451-458 (2008).

I_c measured with rotator



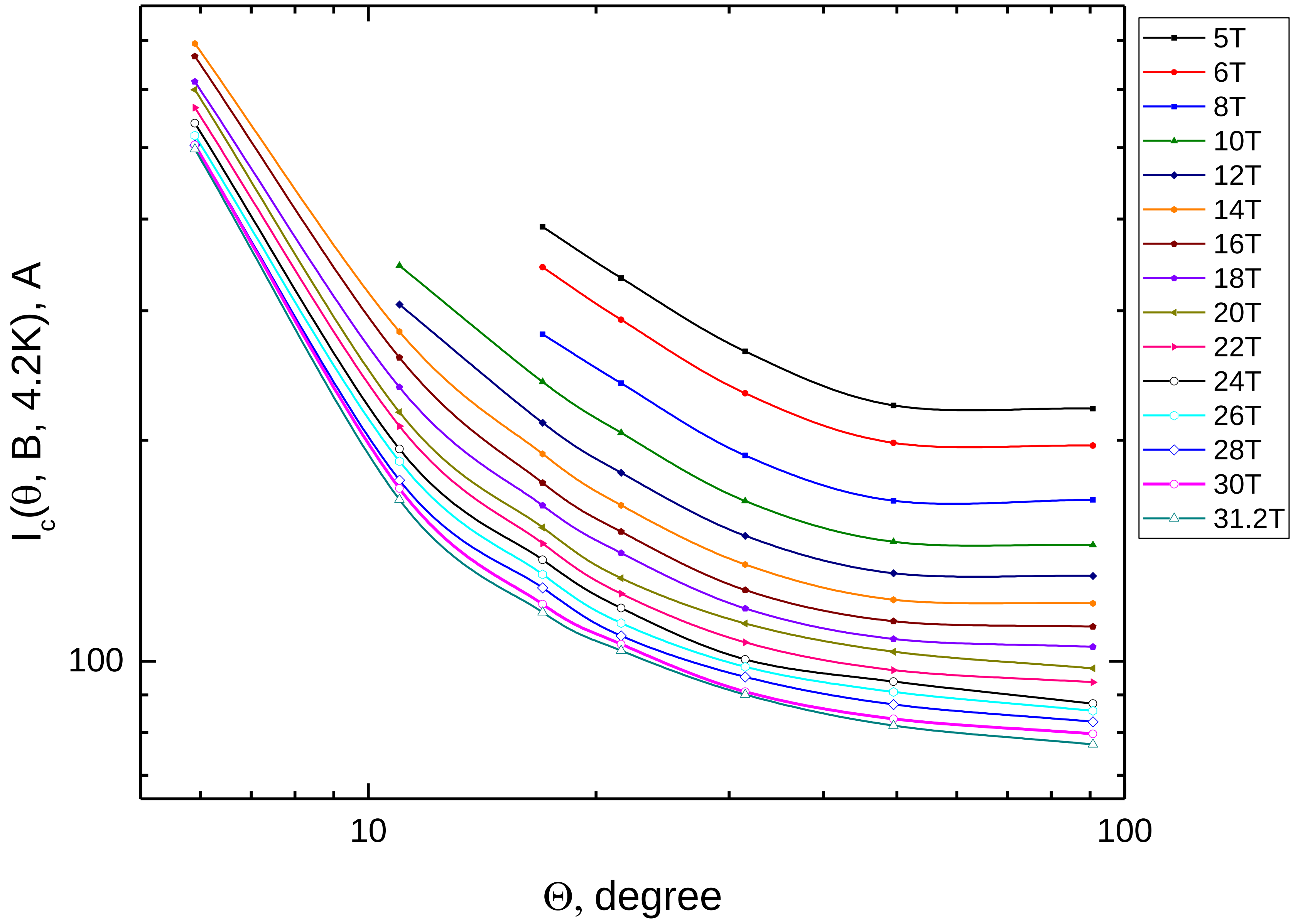
14.8 deg.

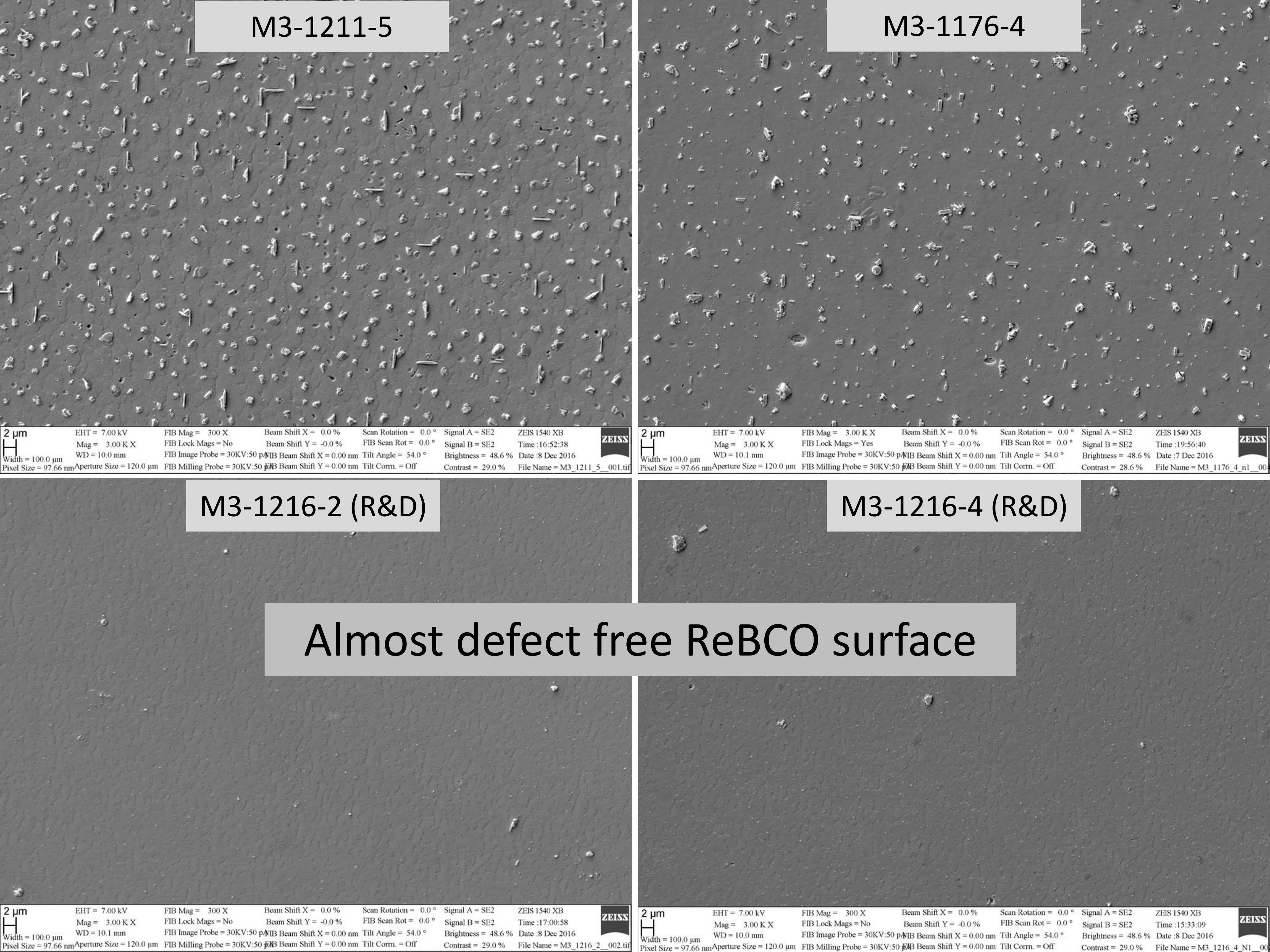




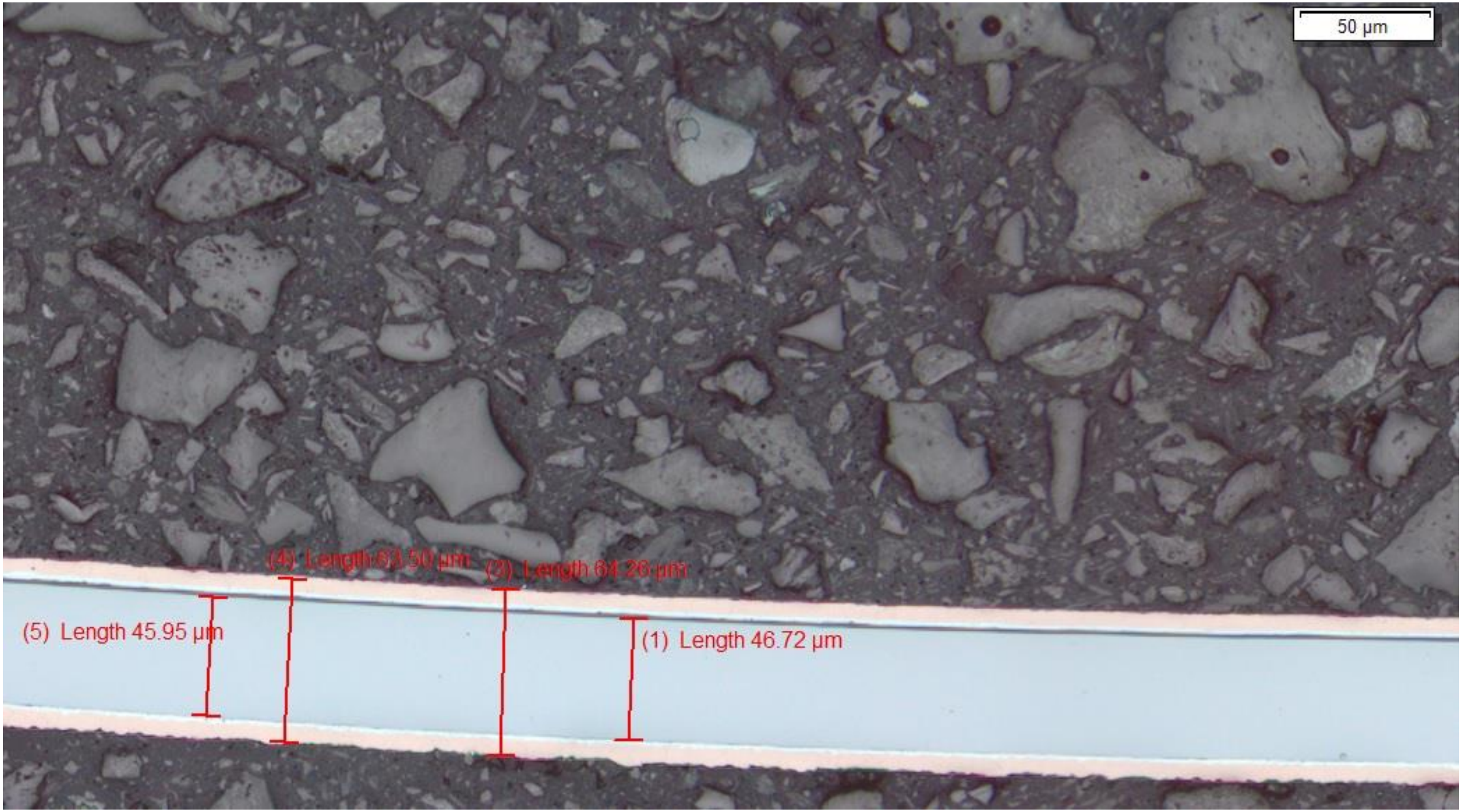
I_c(4.2K, θ, B) of SuNAM Cu coated tape measured up to 31.2T in cell 7

Graph in Log-log scale for data from the previous plot




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

M4-396- 0508



50 µm
(4) Length 63.50 µm
(3) Length 64.26 µm
(5) Length 45.95 µm
(1) Length 46.72 µm