Review of I_c variation, R_c, RRR and other parameters

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Special thanks to AMSC, Fujikura, SuNAM, SuperOx for providing samples for testing

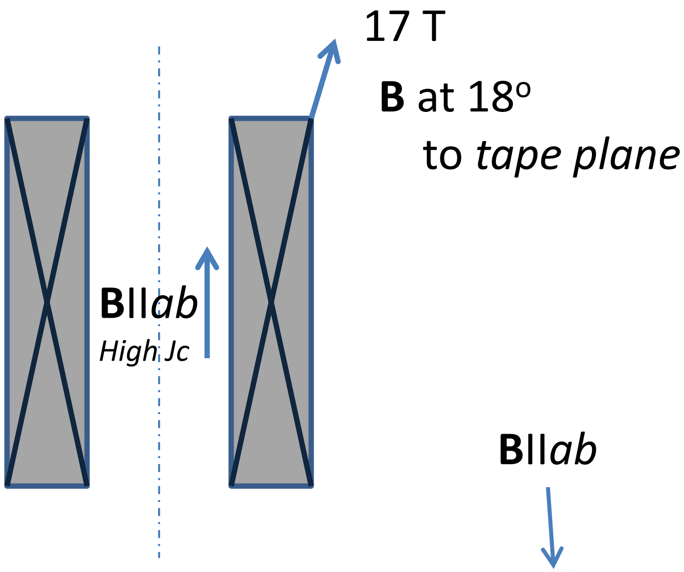
- Quality Assurance procedure for 32T project:
  - We are looking for compliance with our specification, which includes transport and geometrical properties of (Re)BCO tape using minimum set of measurements.
  - (Re)BCO coated conductor was purchased from SuperPower Inc. : 144 lengths, 60 m or 110 m each
- Comparison of 4K in- field I_c measured on short samples for conductors from different manufacturers

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.

Origins of specification for (Re)BCO conductor

Restriction on I_c :

- One of the major limiting factors of coil performance is sharp $J_c(\Theta)$ dependence in (Re)BCO
- The minimum I_c for 32 T coil design occurs at 18° critical angle between tape plane and magnetic field of 17 T

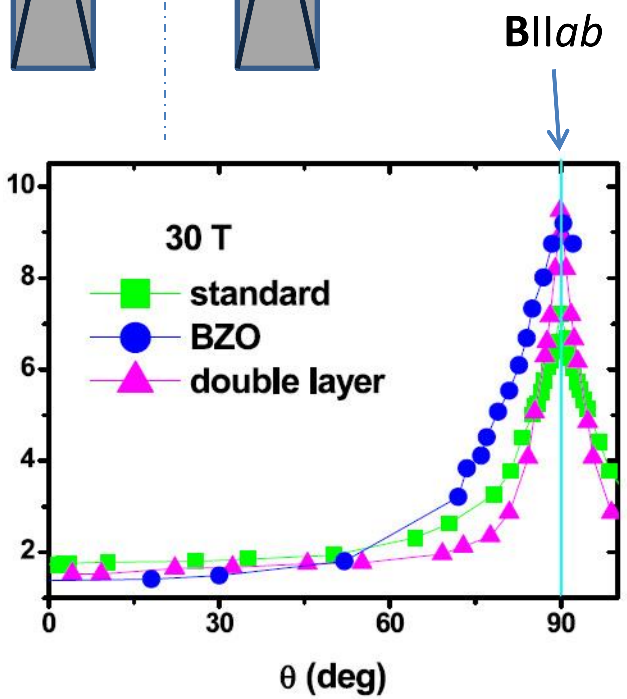


Other transport properties:

- Tape is being delivered in 110 or 60 m lengths, making joints resistance critical
- RRR>50 for low resistance of stabilizer in case of quench

Dimensions

- Cu stabilizer layer should be uniform through length and width of the tape to provide mechanical stability between pancake windings and get uniform heat propagation
- Tape width should be uniform to avoid variations in I_c and mechanical properties, difficulties in coil manufacturing



Xu A., *et al*., Superconducting Science and Technology, **23**, 014003 (2010).

(Re)BCO conductor specification
(short list)

Property of tape from the specification	Value	Units
Minimum I_c at 4.2 K, extrapolated to 17 T from $I_c(B)$ measured at 18° angle	>256	A
n from $V \sim I^n$ fit	>25	-
Joints resistance measurements	≤230	$\mu\Omega \cdot cm^2$
Residual Resistivity Ratio of Cu (4.2 to 300 K)	>50	-
Final conductor width	4.10 ± 0.05	mm
Final conductor Thickness	≤0.170	μm
Cu Stabilizer Cross-sectional Area	0.42 ± 0.01	mm^2
Substrate cross-sectional Area	0.20 ± 0.01	mm^2
Ag layer thickness	2.0 ± 0.5	μm

I_c testing system for 32 T tape characterization

Oxford Instruments
Superconducting 13.5 T (4.2K) magnet

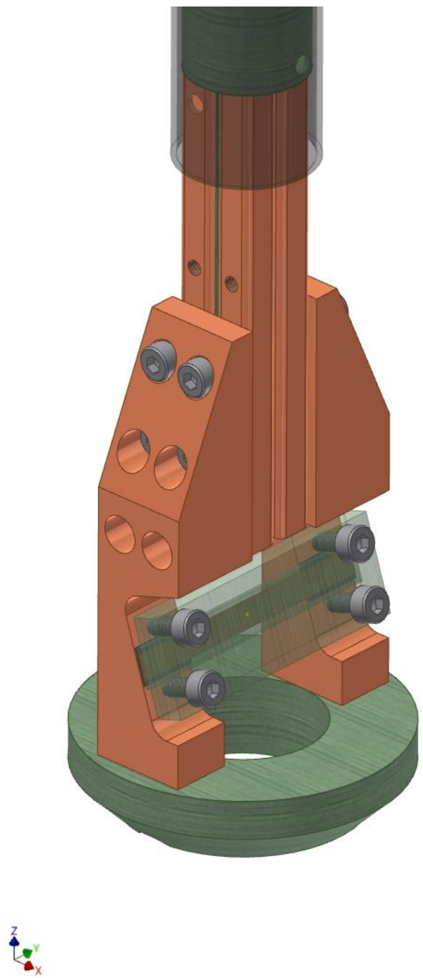
Current biasing: two Sorensen power supplies

- up to **1400 A**
- Analog connection

Current monitor: Keithley 2000
Voltage measurement: Keithley 2184A
Magnet power supply: Lake Shore LS 622

LabView based program for automatic B and I_{bias} sweeping and I_c calculation

sample holder

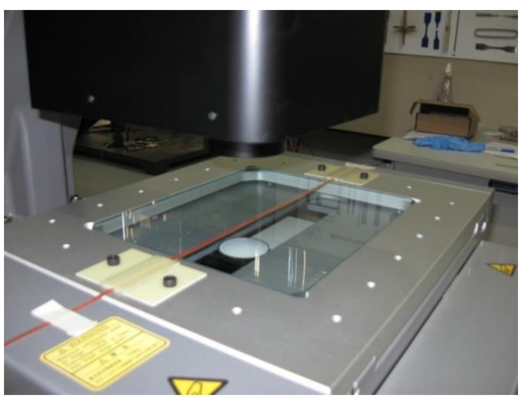


Other techniques routine QA tests

SEM visualization with Zeiss 1540 XB Cross beam

Ag thickness
ReBCO uniformity
***ab*-plane orientation**

Nikon iNexiv VMA-2520 microscope



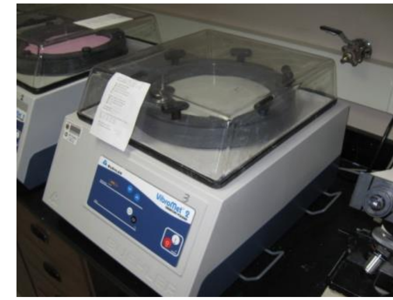
Final conductor width
Surface condition
Thickness profiles

Olympus Microscope BX41M-LED

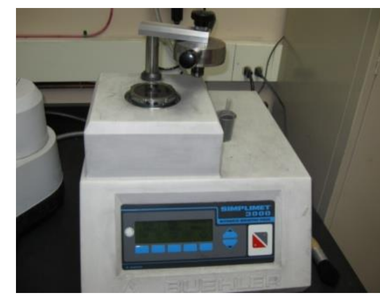
Total conductor thickness
Cu Stabilizer cross-sectional area
Substrate cross-sectional area

Transport measurements of R_c, I_c of lap joints in LN, self field

Vibromet 2



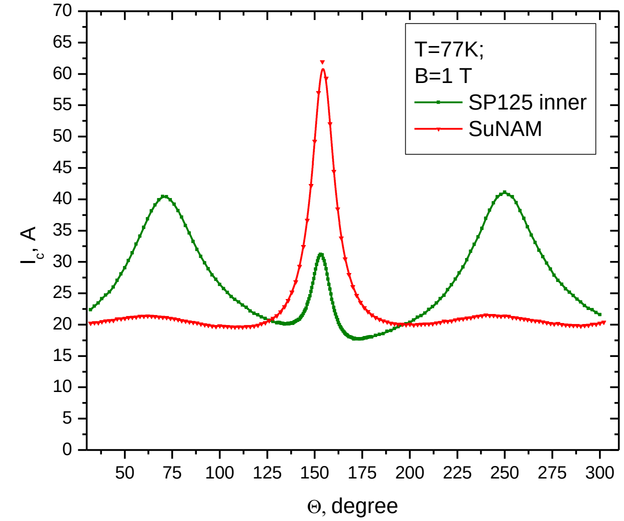
Simplimet 3000

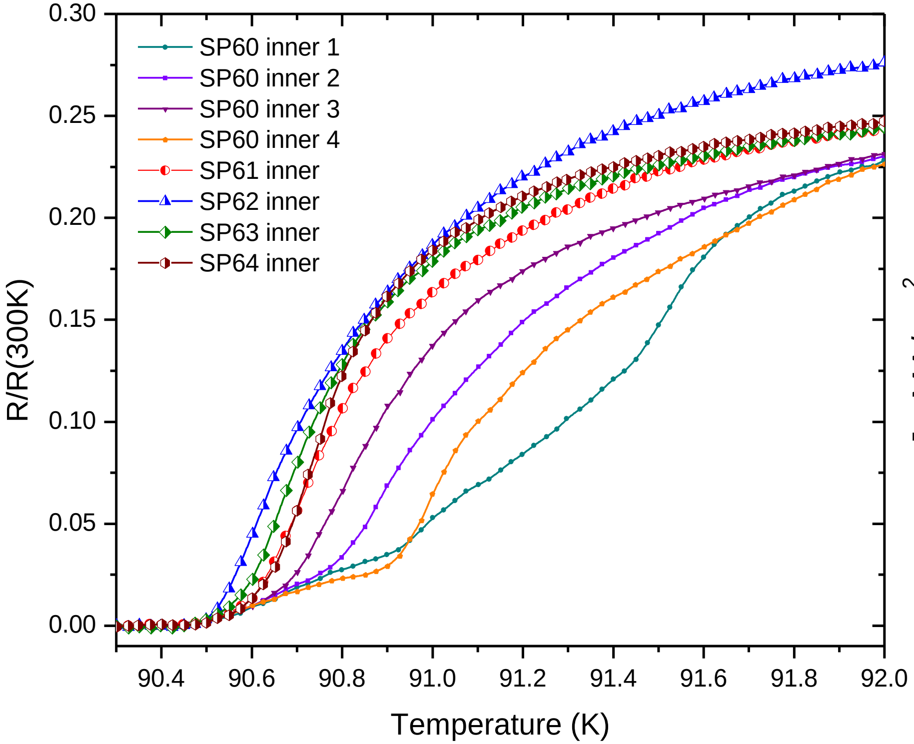


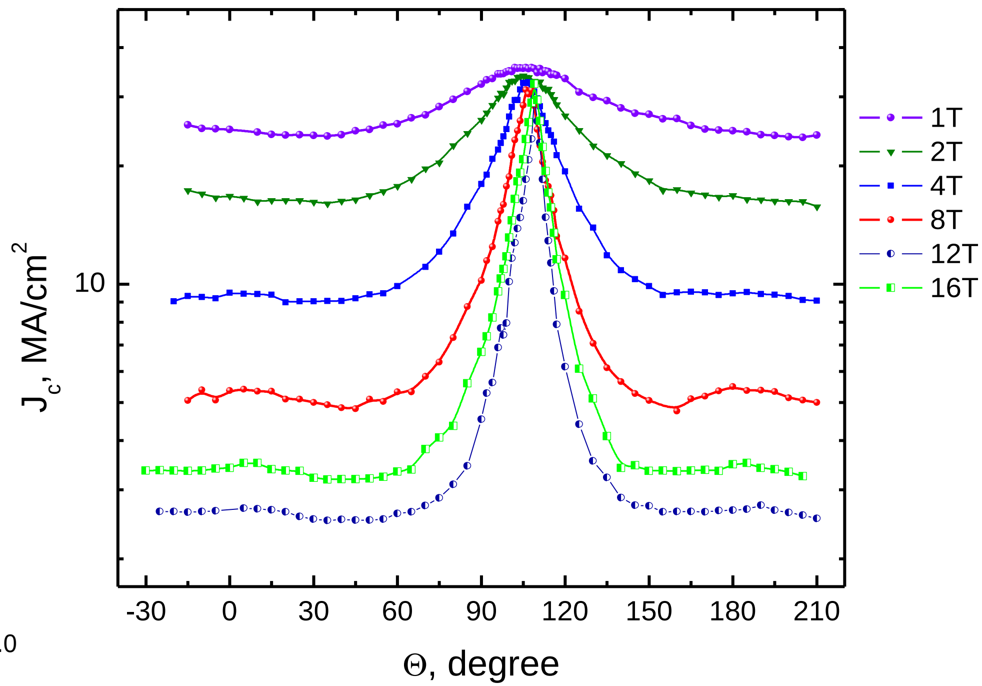
Preparation cross-sections

Additional techniques used for study properties of ReBCO tapes

- 16 T Quantum design PPMS for measuring in- field variable temperature angular dependence of I_c and R(T);
- Rotator with split coil electromagnet 1T; 77K for measuring angular dependence of I_c in full width tapes;
- YateStar system for measuring distribution of transport critical current at 77K, 0.8T





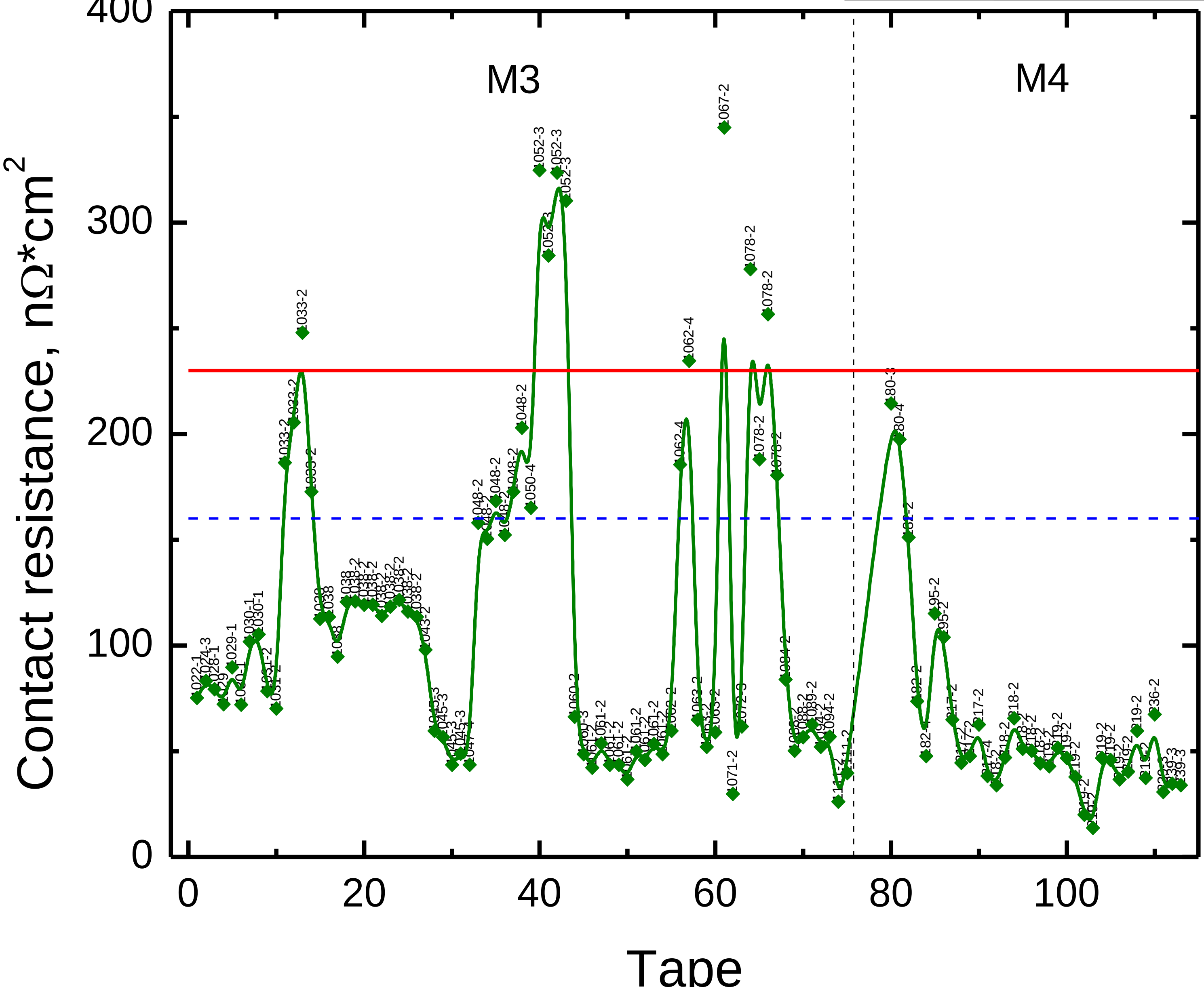


Contact resistance of lap joints

Contact resistance arranged by SP process run number

Small spread within each run, but has large difference between some runs

Measurements done on standard lap joints with 80 mm overlap



T=77K; SF

32T spec.

Peak maximum
230 nΩ· cm^2

Maximum average
160 nΩ· cm^2

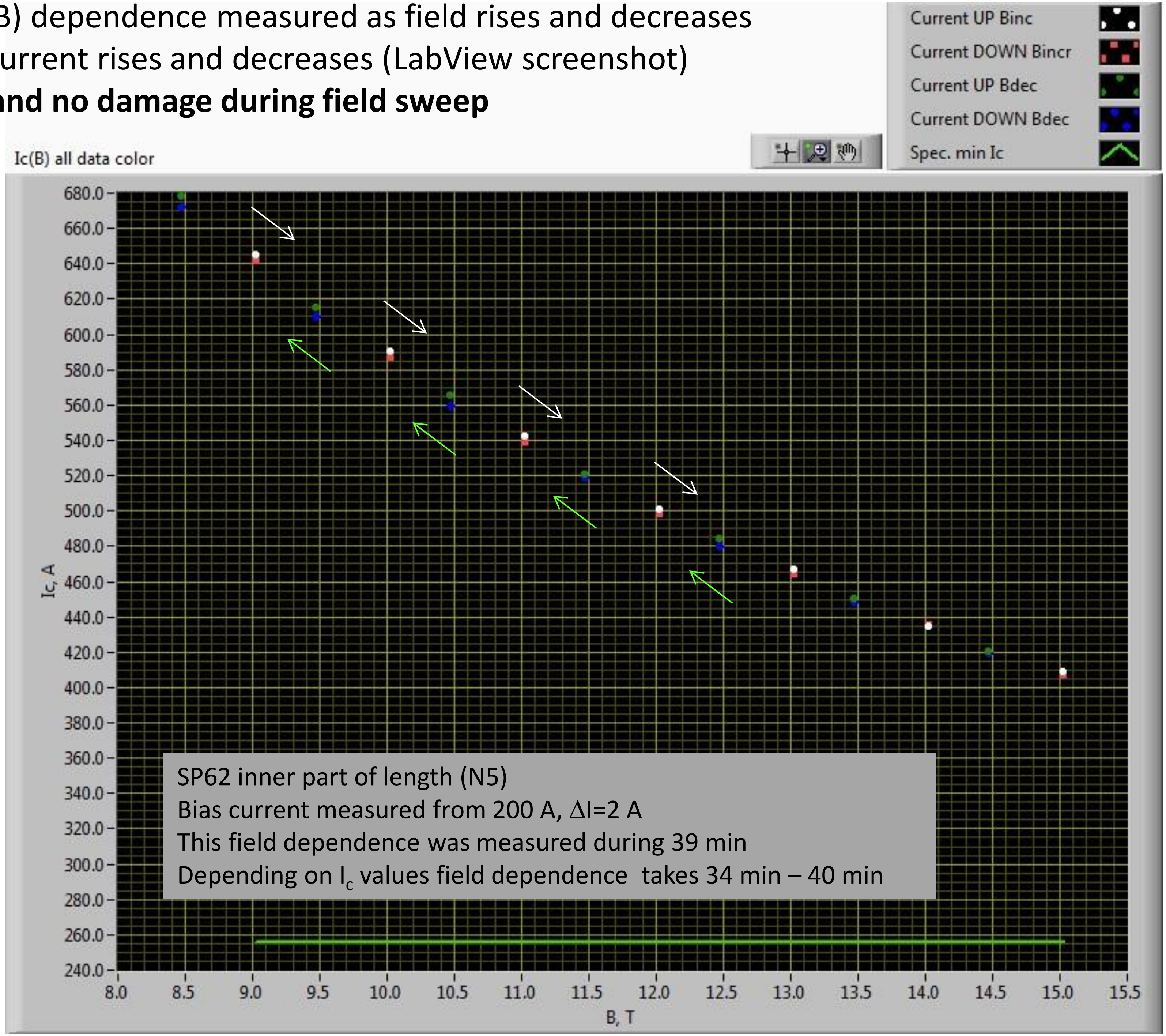
M3-1033
M3-1062
have low I_c (4K) and high joint resistance

Measurements of in-field critical currents at fixed orientation

$I_c(4.2K;18^o;B)$

Typical $I_c(B)$ dependence measured as field rises and decreases and current rises and decreases (LabView screenshot)

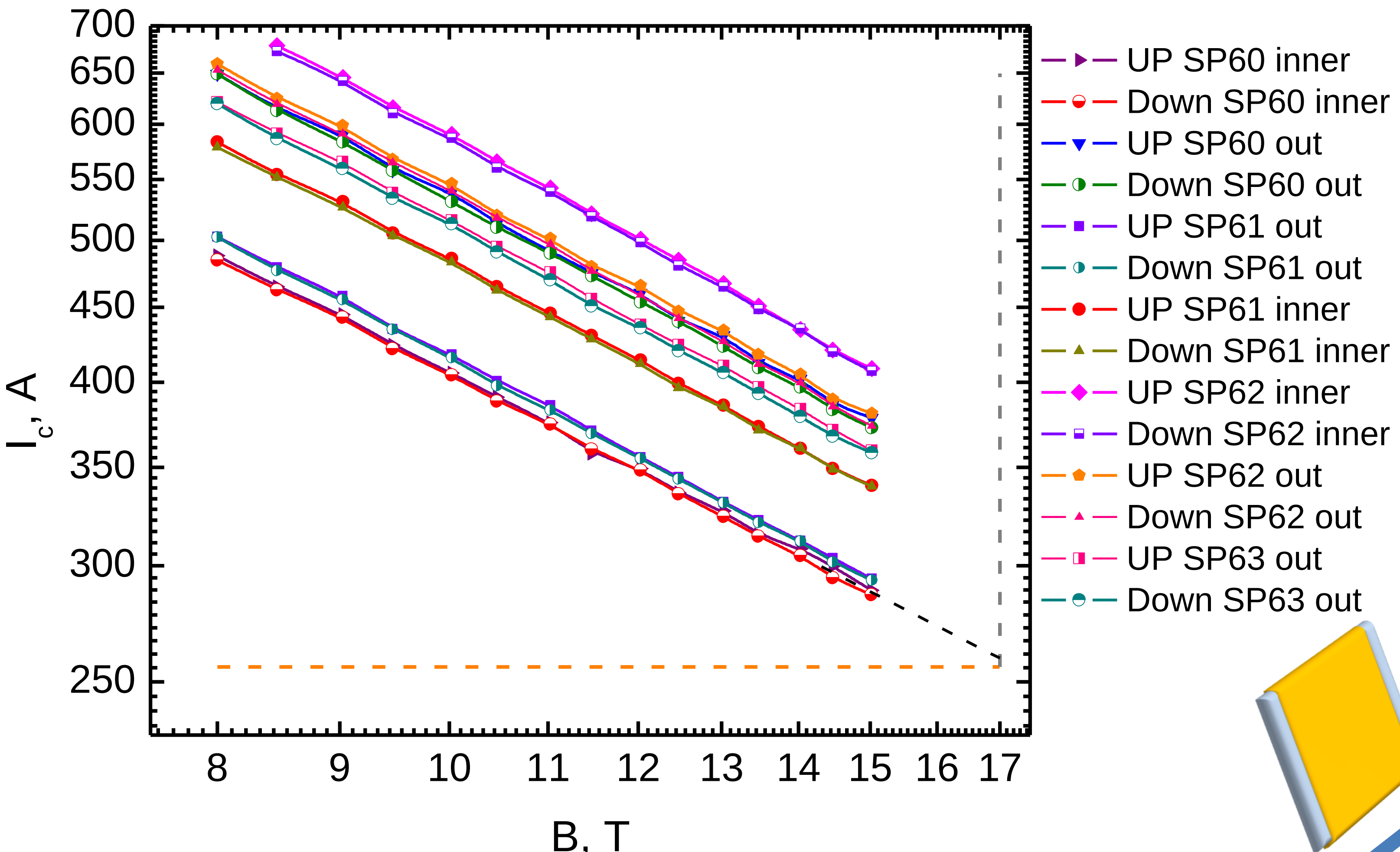
No hysteresis and no damage during field sweep

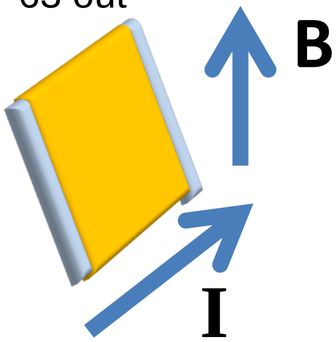


Representative selection of $I_c(B)$ curves measured at 4.2 K with 18° between sample plane and **B**.

Most of measured samples have $I_c > 256$ A;

No hysteresis in increasing and decreasing field; These data have tight fit to $I_c \sim B^{-\alpha}$

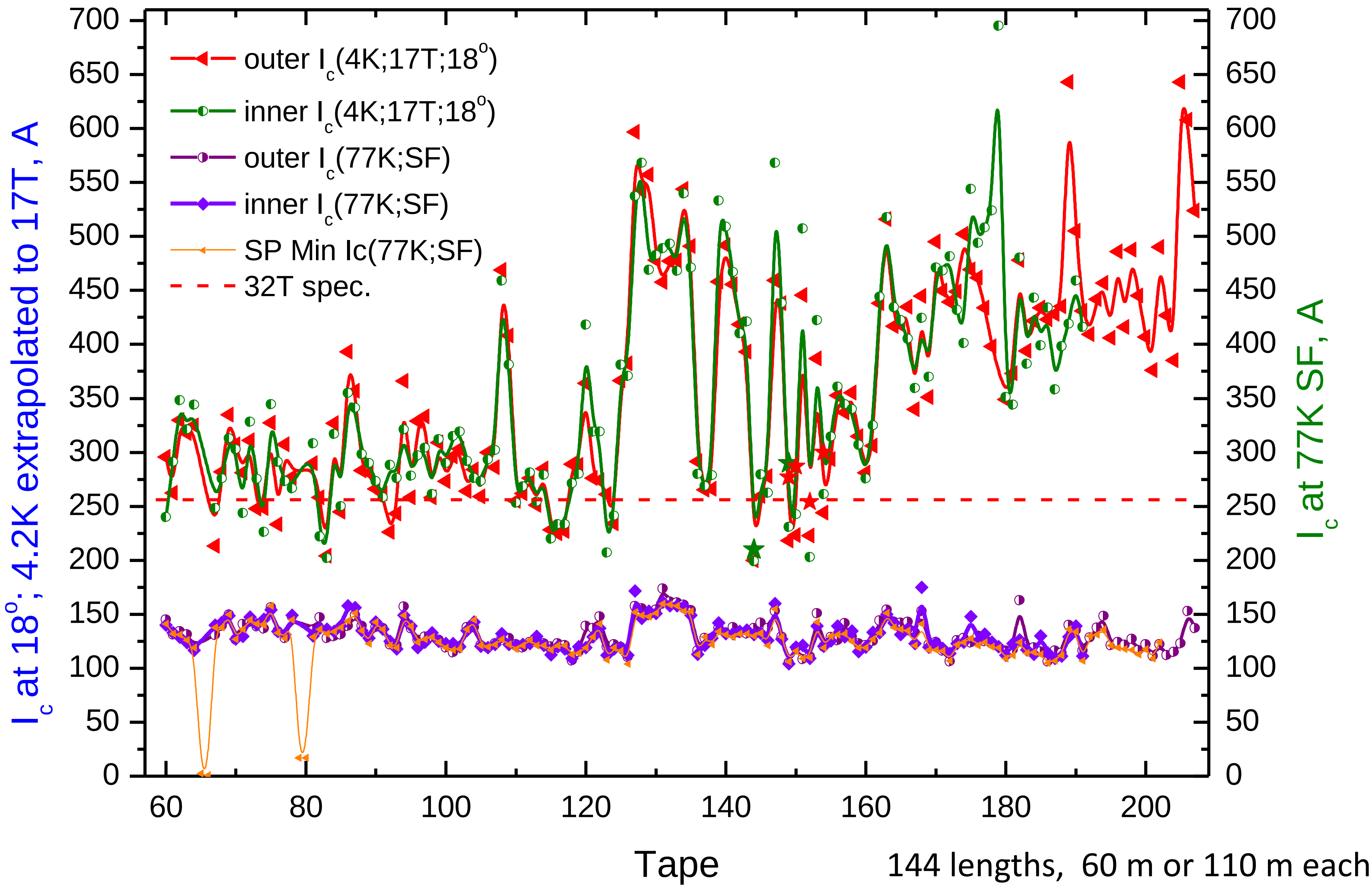




Orange horizontal line represents 256A minimum specified at 17T.

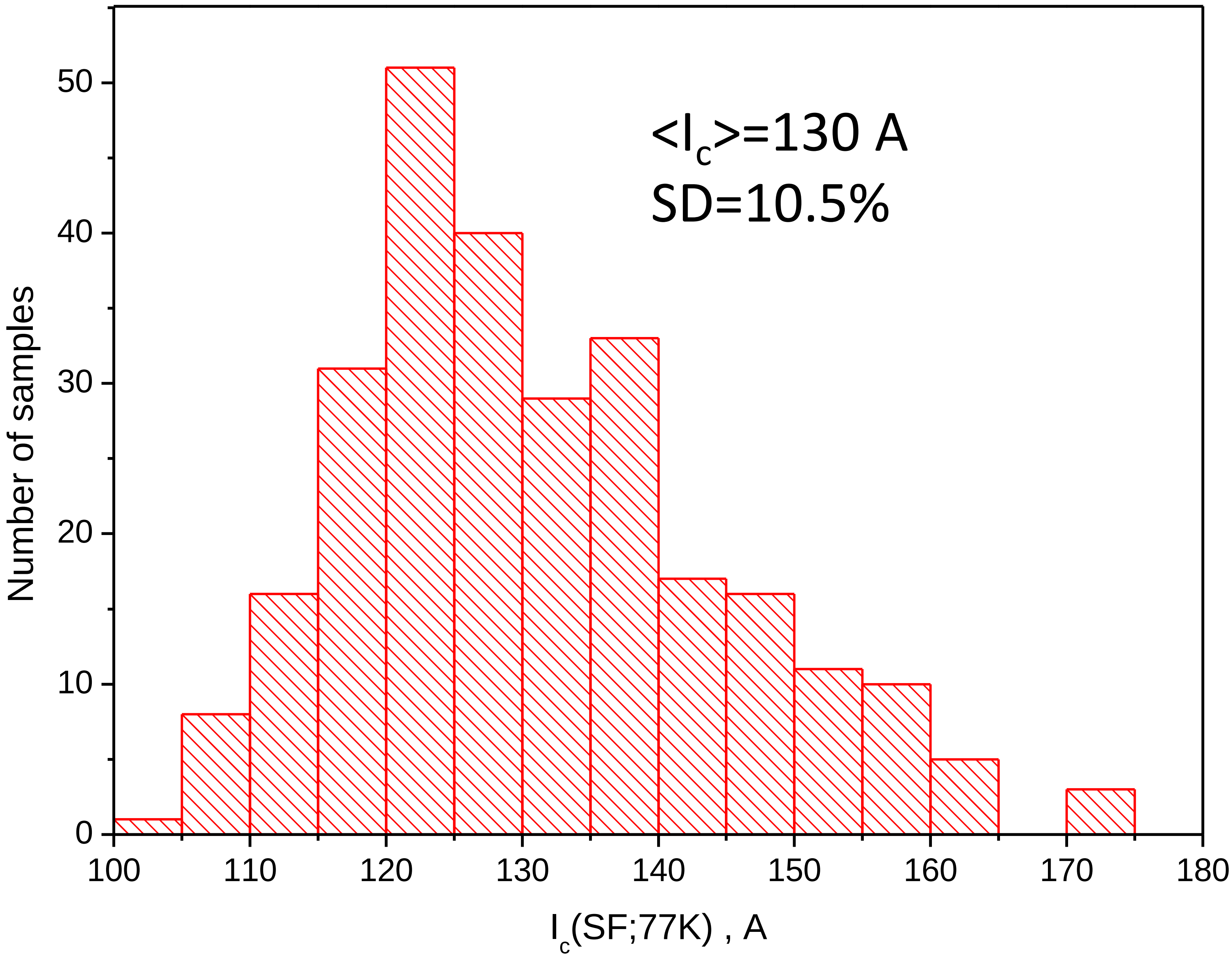
Progress in I_c measurements: SP60 – SP207

Data arranged by NHMFL numbers – delivery time line

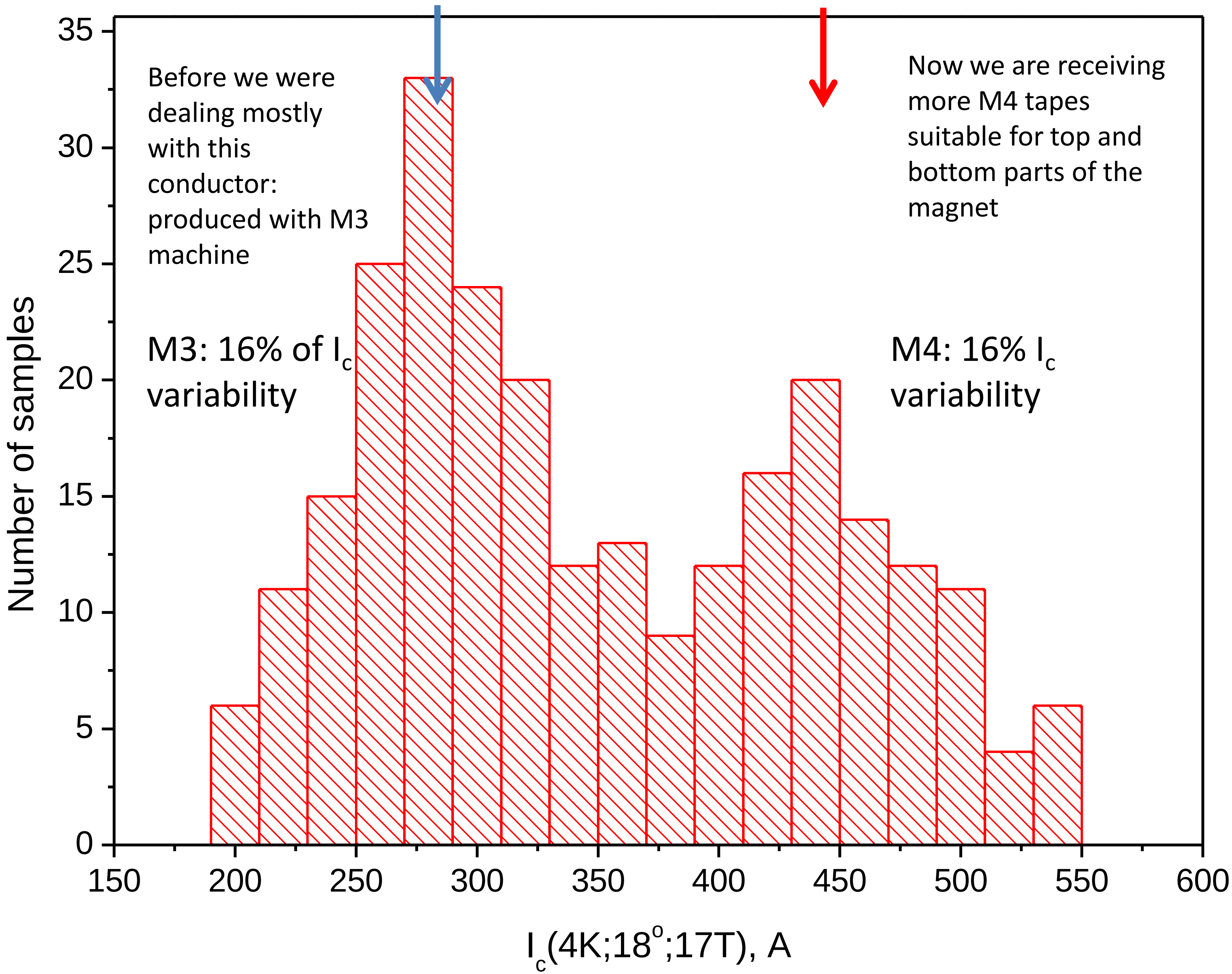


Tapes SP65, 66, 79, 80 were sent for developing winding technique

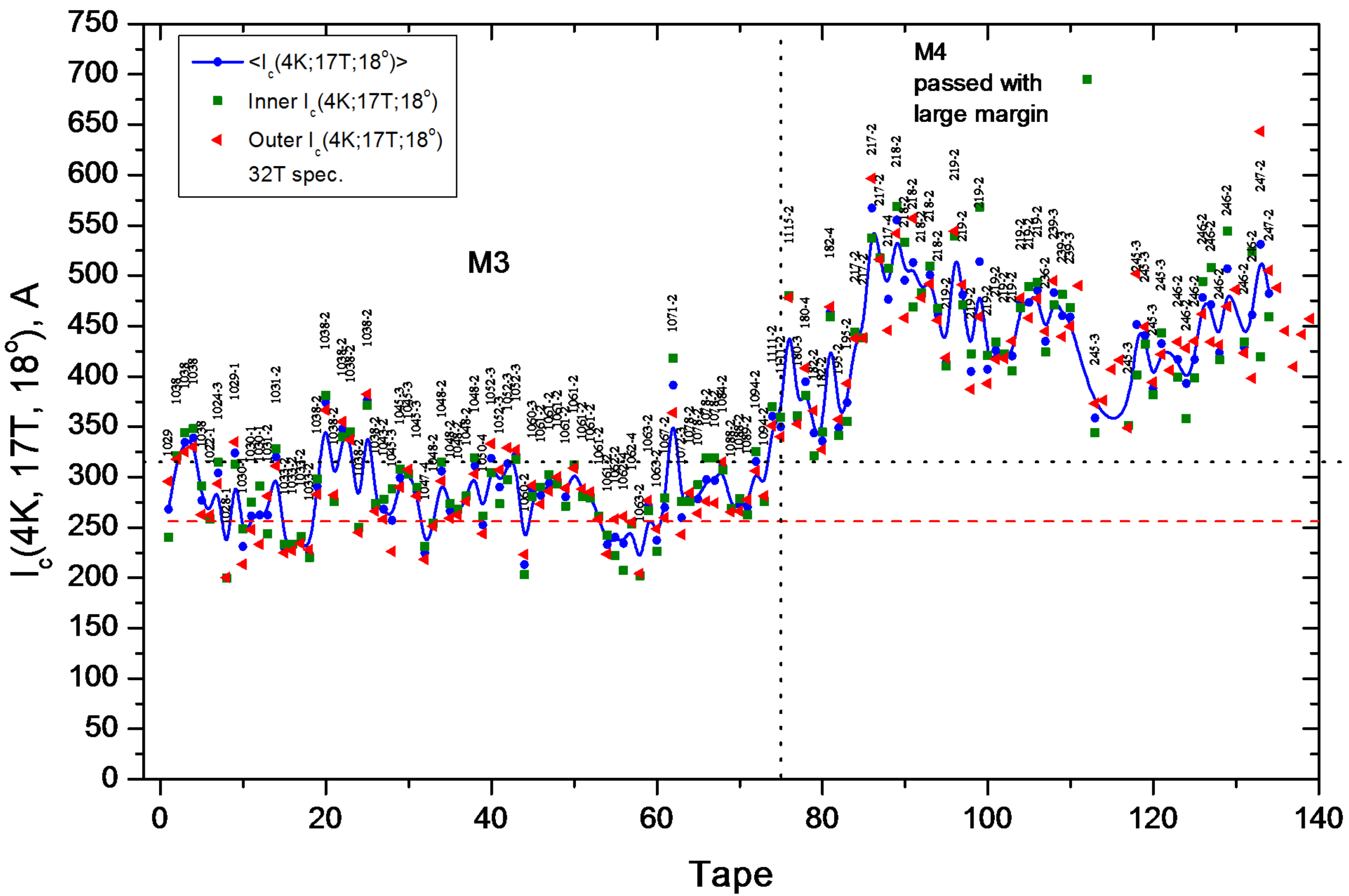
Histogram of I_c measured at 77K, SF



Histogram for I_c measured at 4.2 K, 17 T, 18deg.

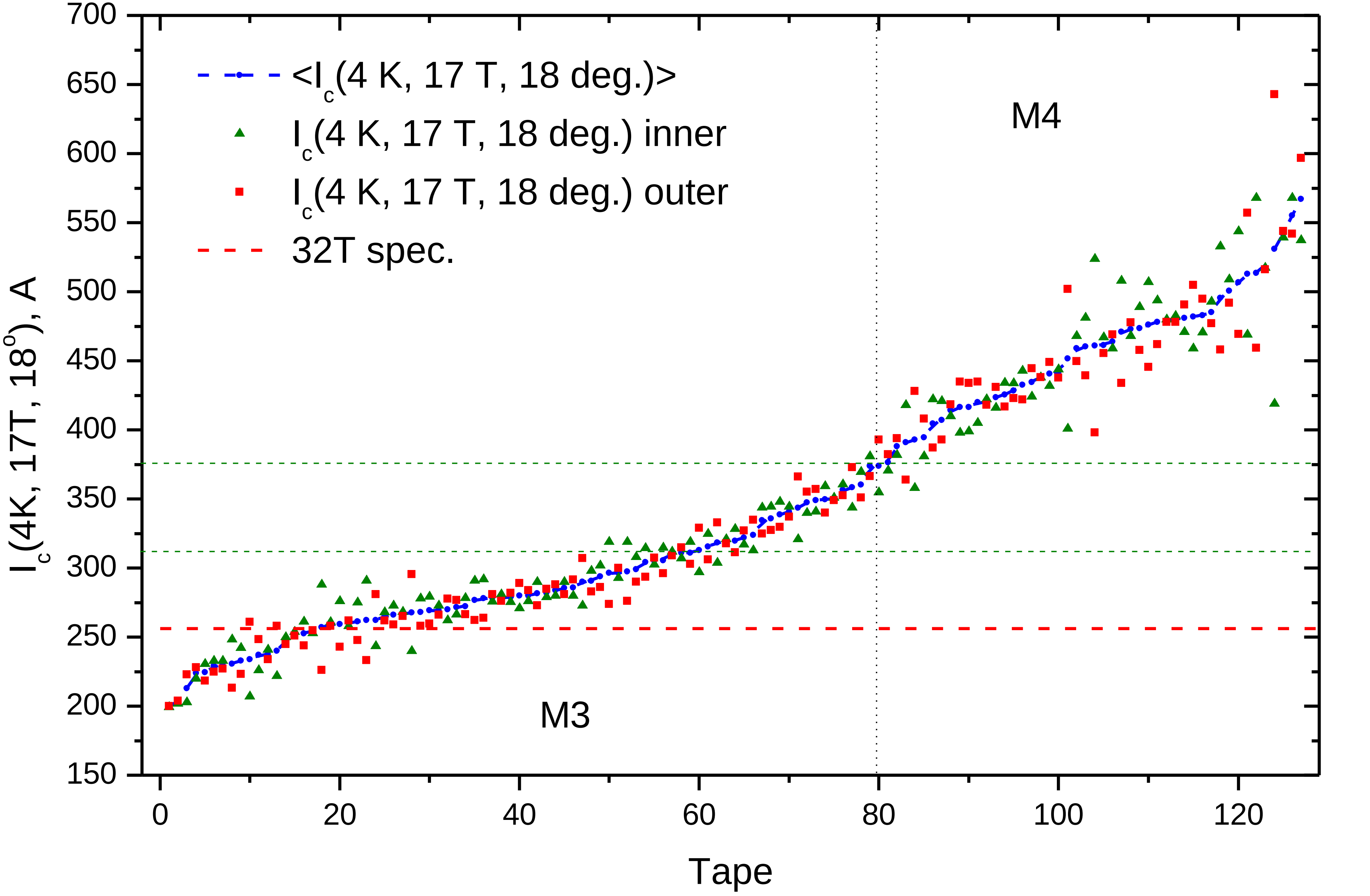


I_c(4K;17T;18°) data arranged as ascending SuperPower run number (we assume it as time line for each M3, M4 machine)

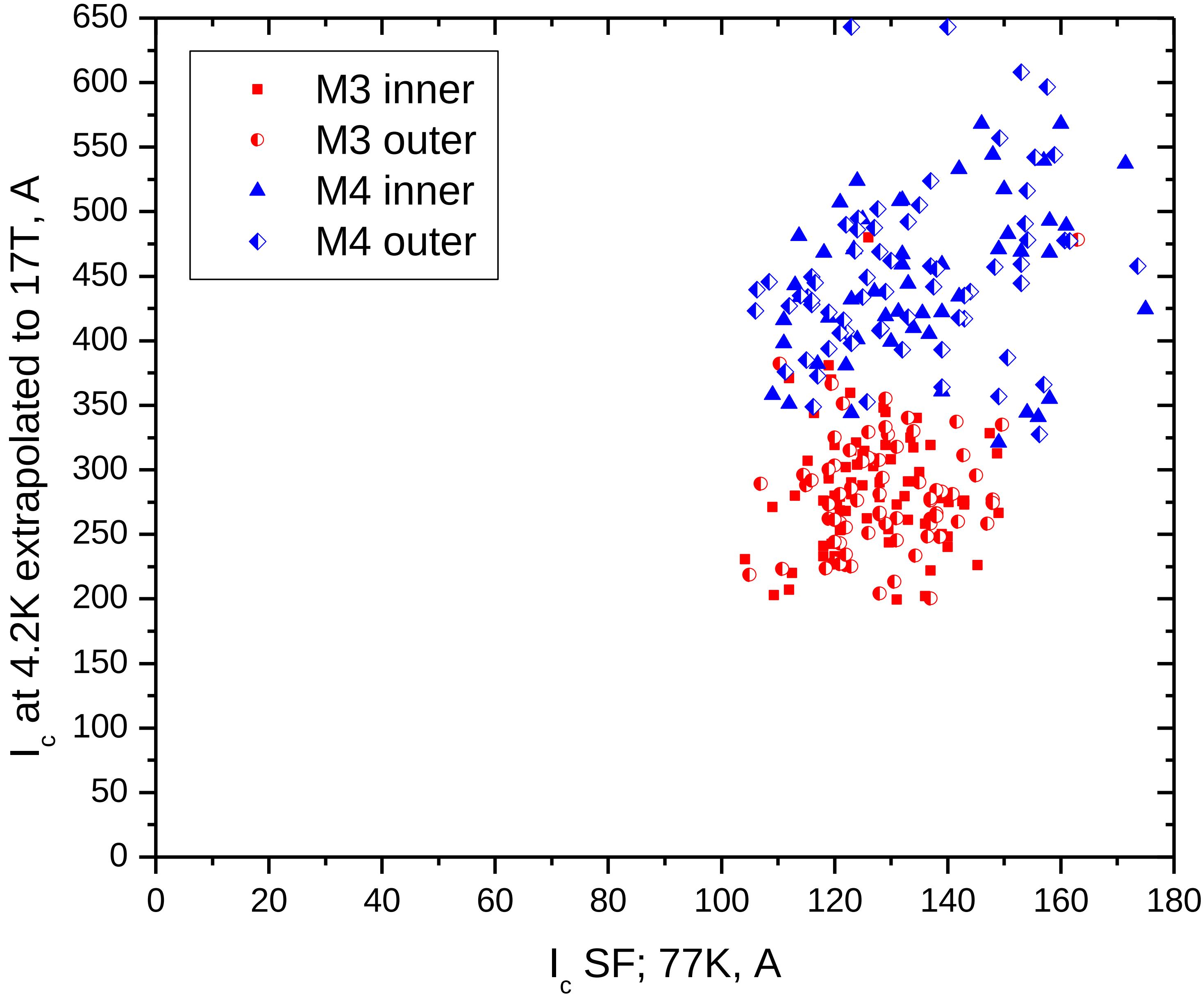


Same I_c(4K;17T;18°) data as on previous slide, but arranged as ascending < I_c(4K;17T;18°) >

Observations : small difference in I_c for samples from different ends;
Tapes within one process have similar I_c ; M4 process yields tapes with higher I_c ;
Uniform distribution with two steps at 270A and 480A



We are getting two types of conductors from different SuperPower Inc. machines with averaged lift factors **2.21** (M3) and **3.36** (M4)



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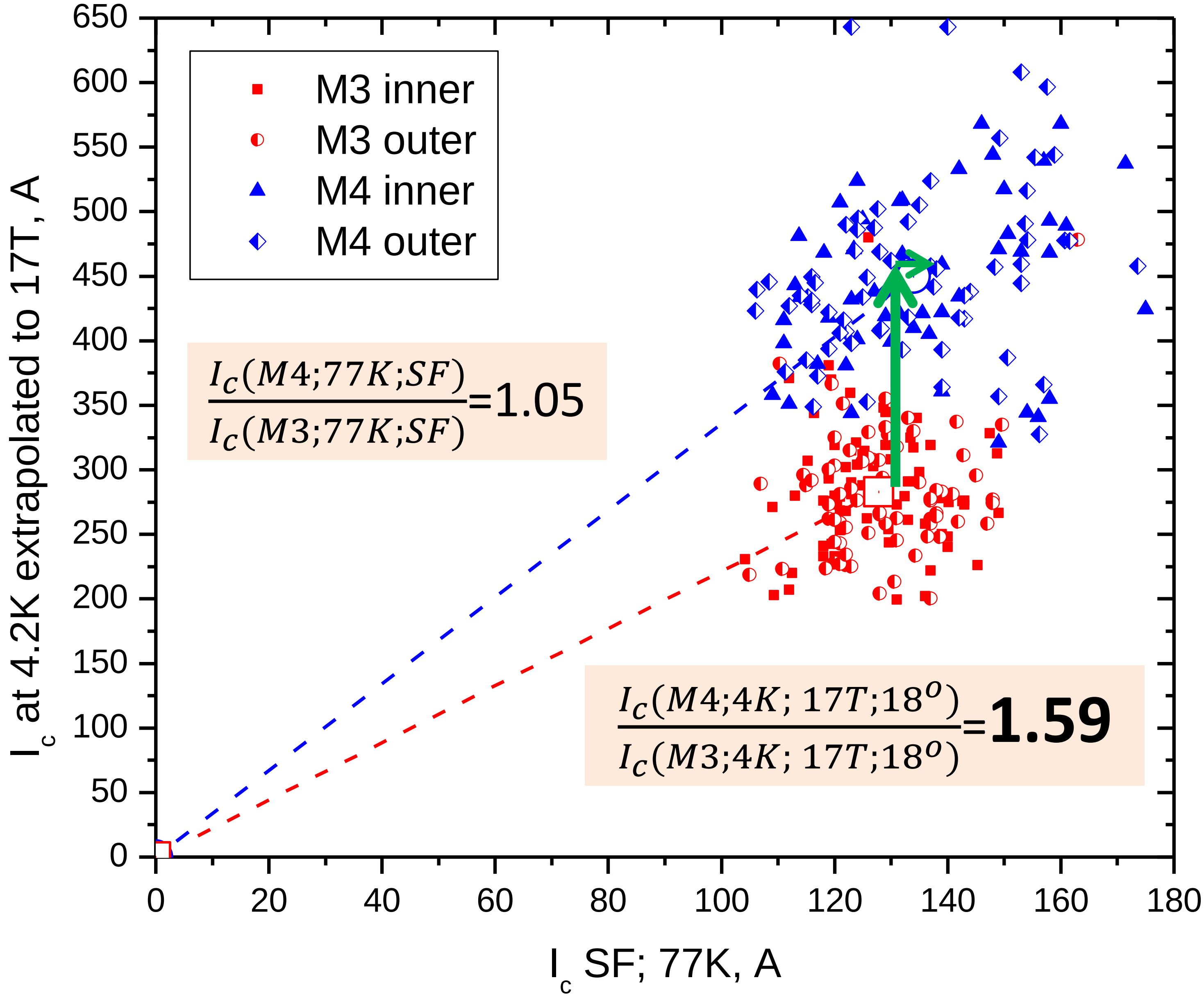
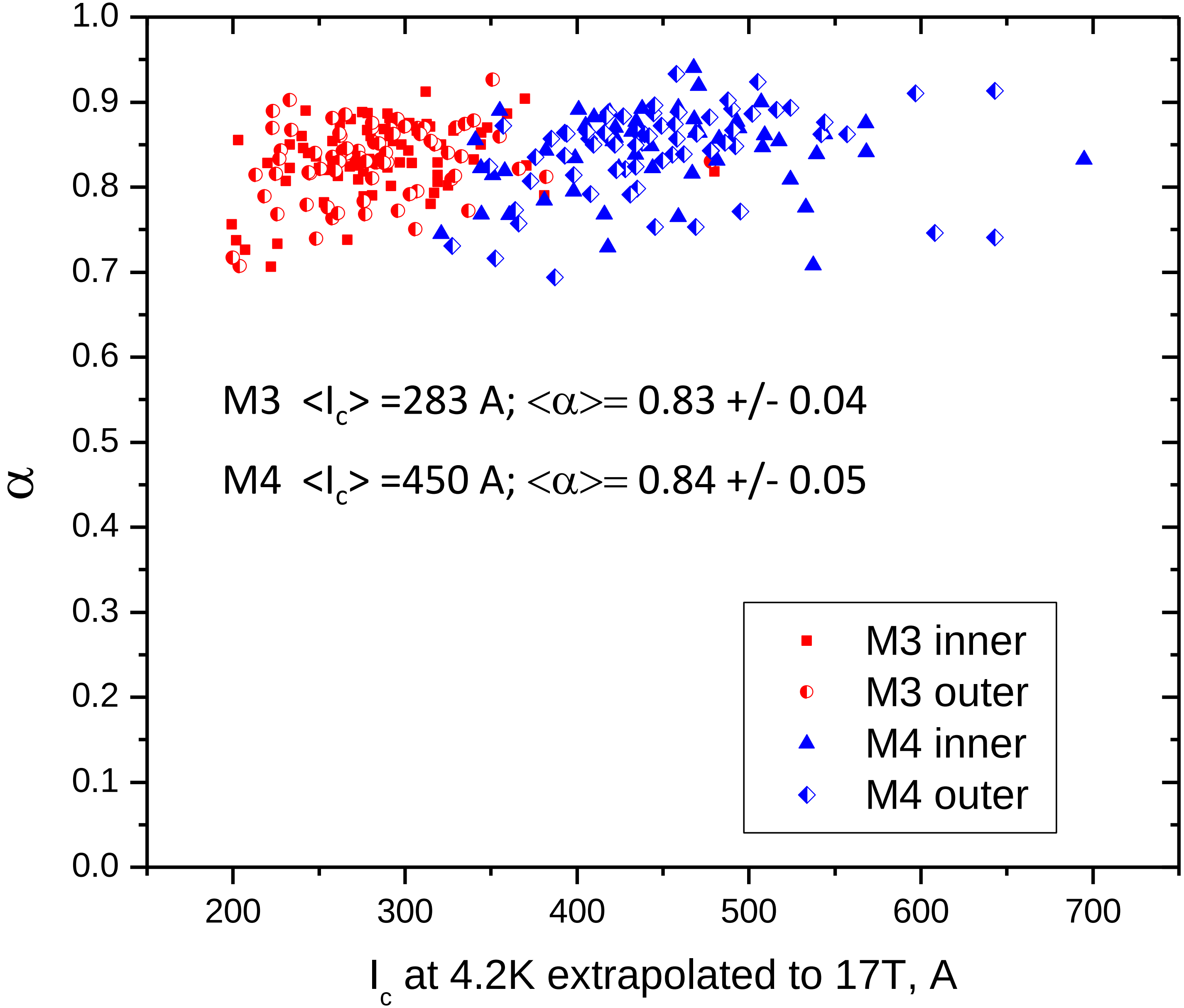


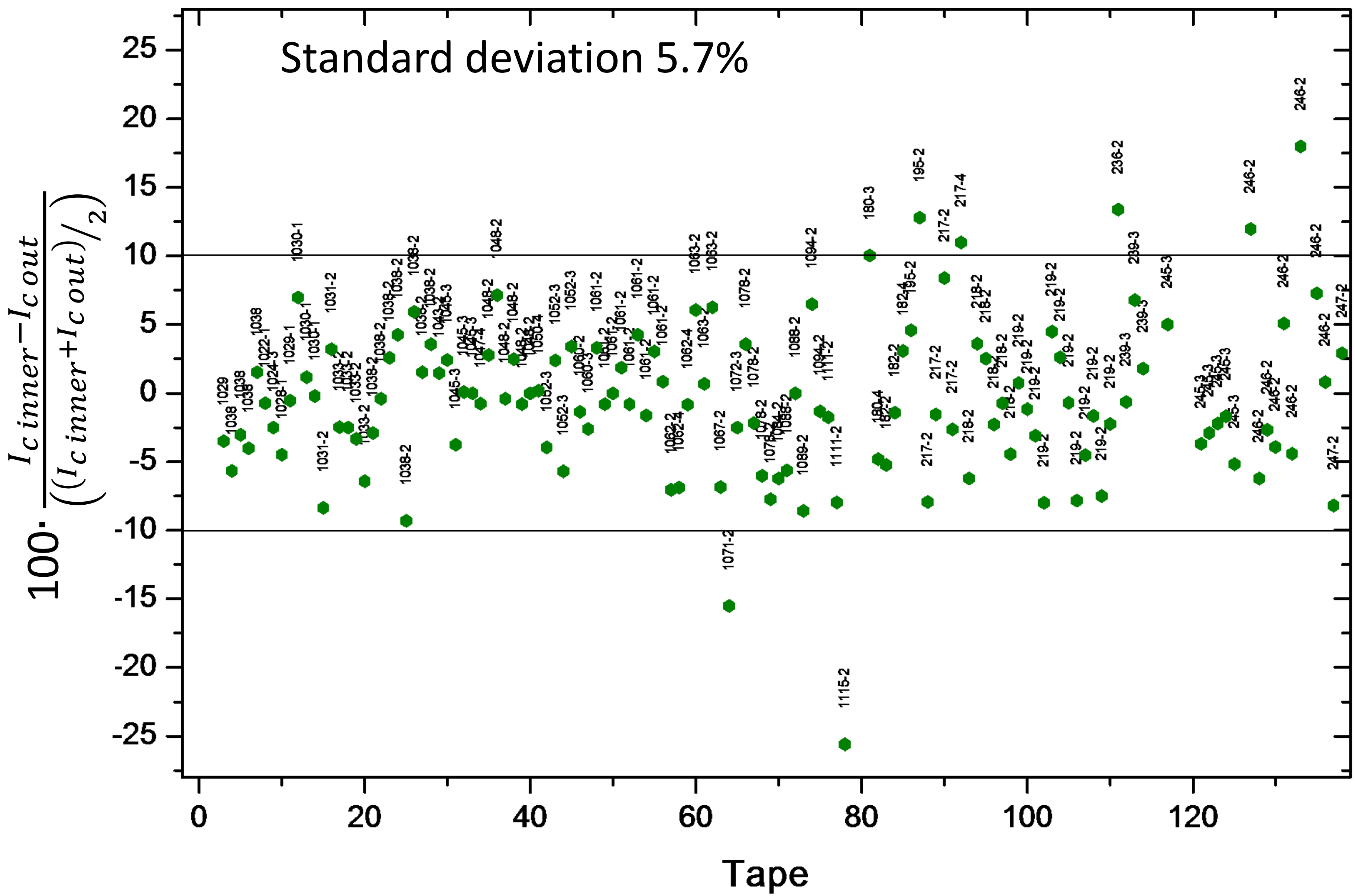
No dramatic changes in α values.

Interpretation: pinning mechanism is probably similar for low I_c and high I_c tapes



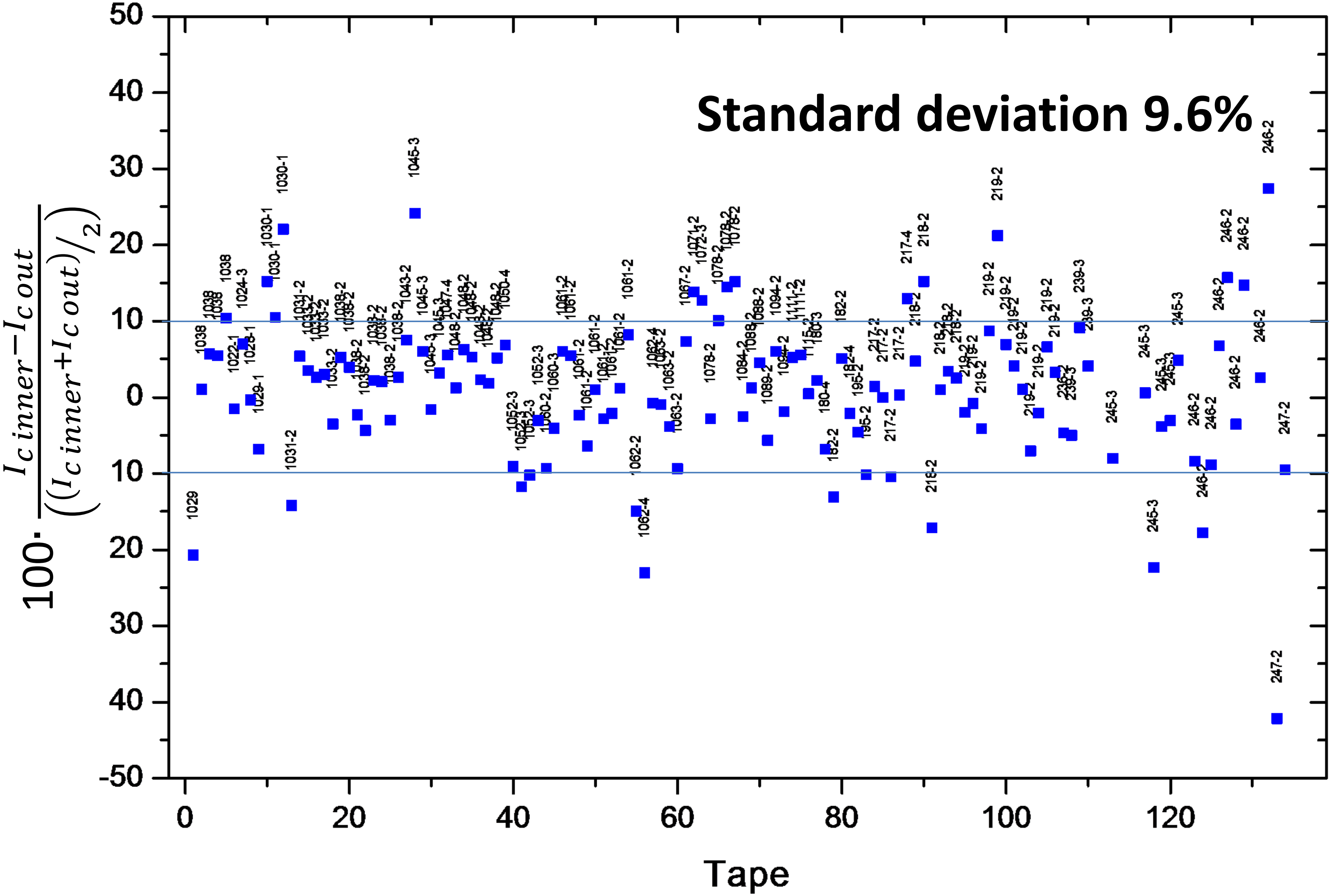
End to end relative variation of I_c(77K; SF)

At 77K; SF just few tapes have relative spread above 10%



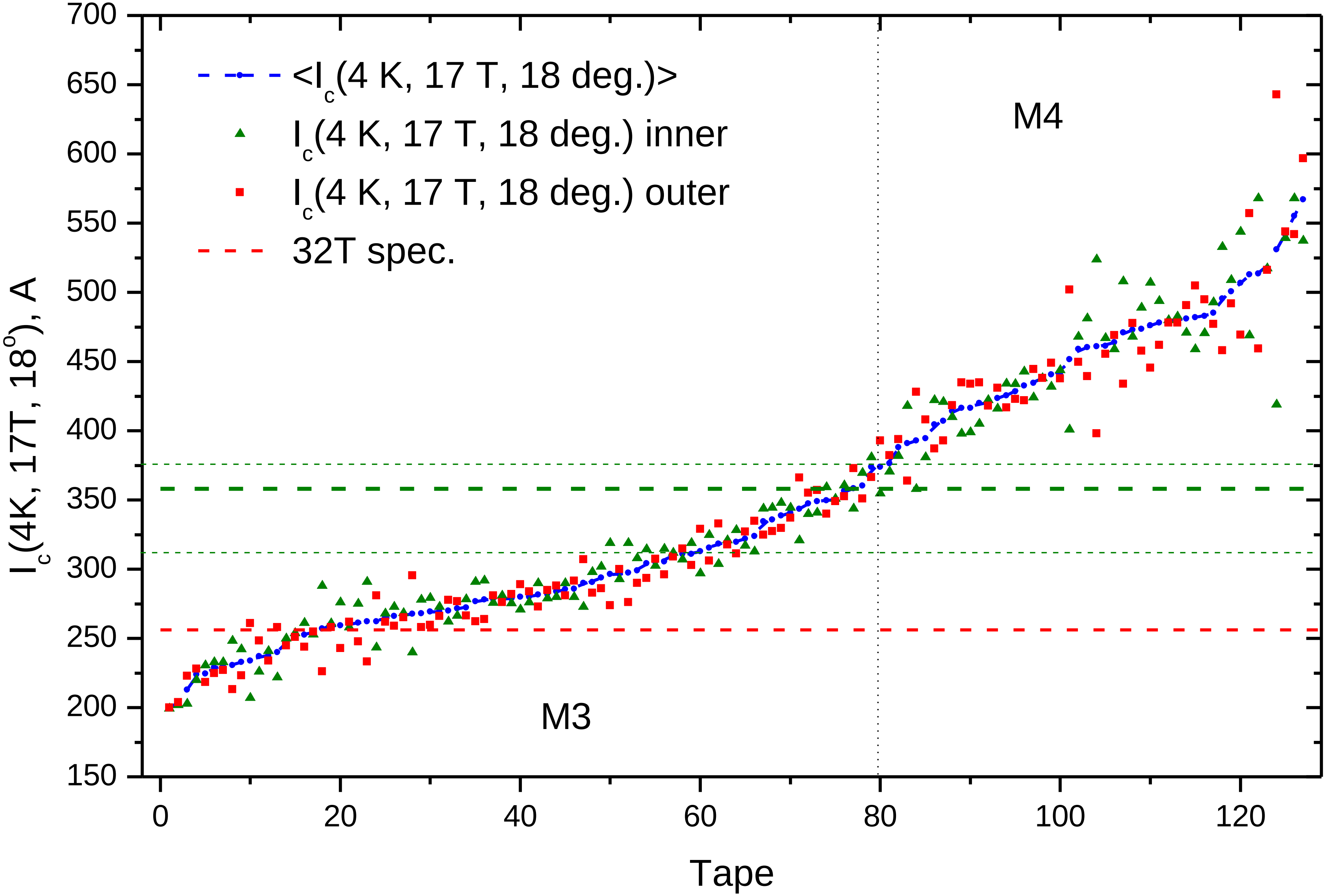
End to end relative variation of I_c(4K; 17T; 18°)

At 4.2K in-field more tapes have relative spread above 10%



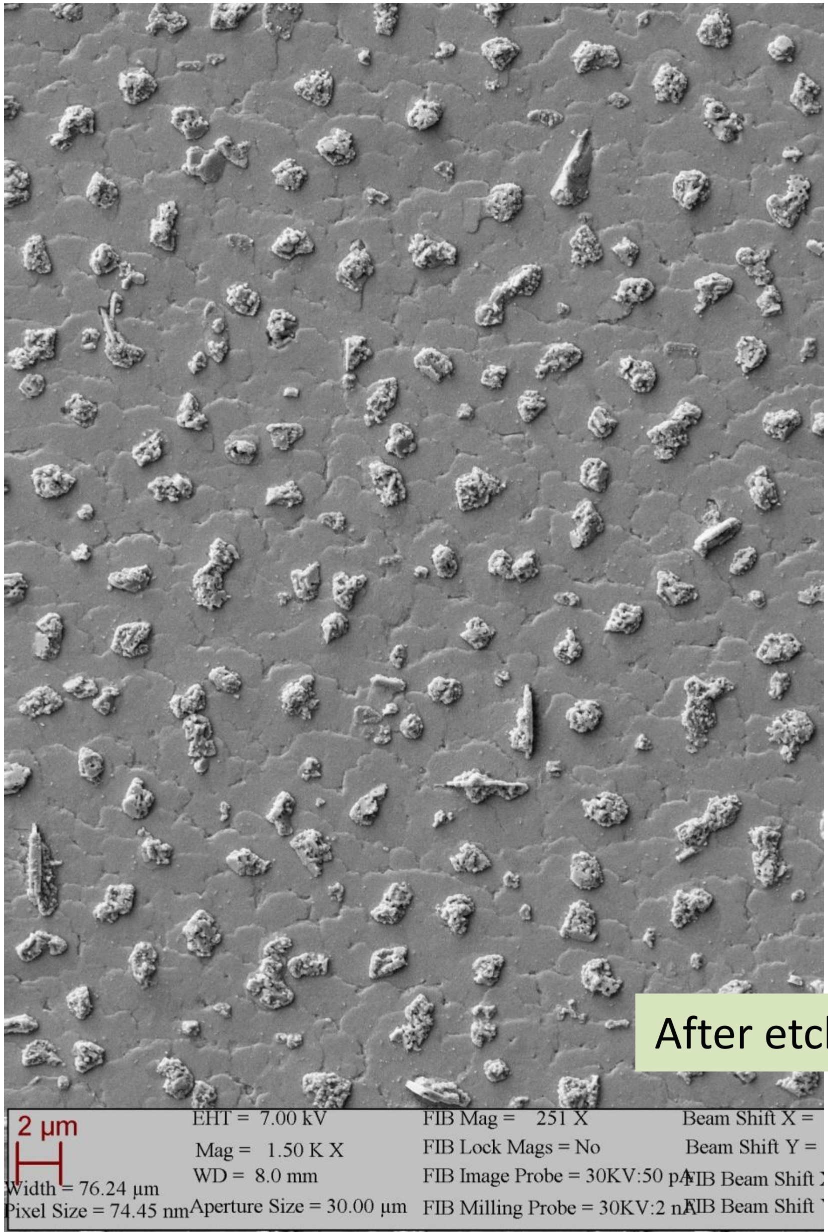
Same I_c(4K;17T;18°) data as on previous slide, but arranged as ascending < I_c(4K;17T;18°) >

Observations : small difference in I_c for samples from different ends;
Tapes within one process have similar I_c ; M4 process yields tapes with higher I_c ;
Uniform distribution with two steps at 270A and 480A

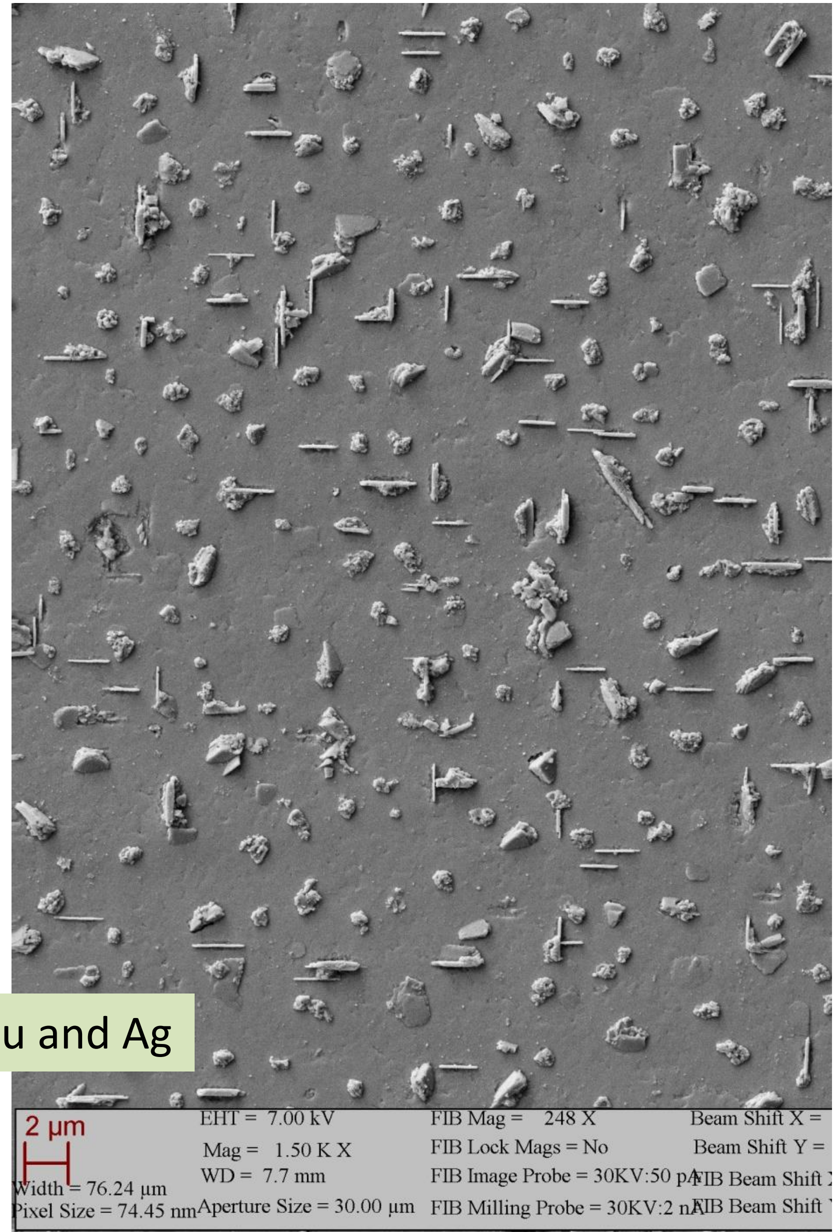


SEM images of ReBCO surface: Larger and irregularly shaped grains on SP60; more needle like grains for SP62-64; staircase like surface for SP60, but flat surface for SP61-64

SP60 inner



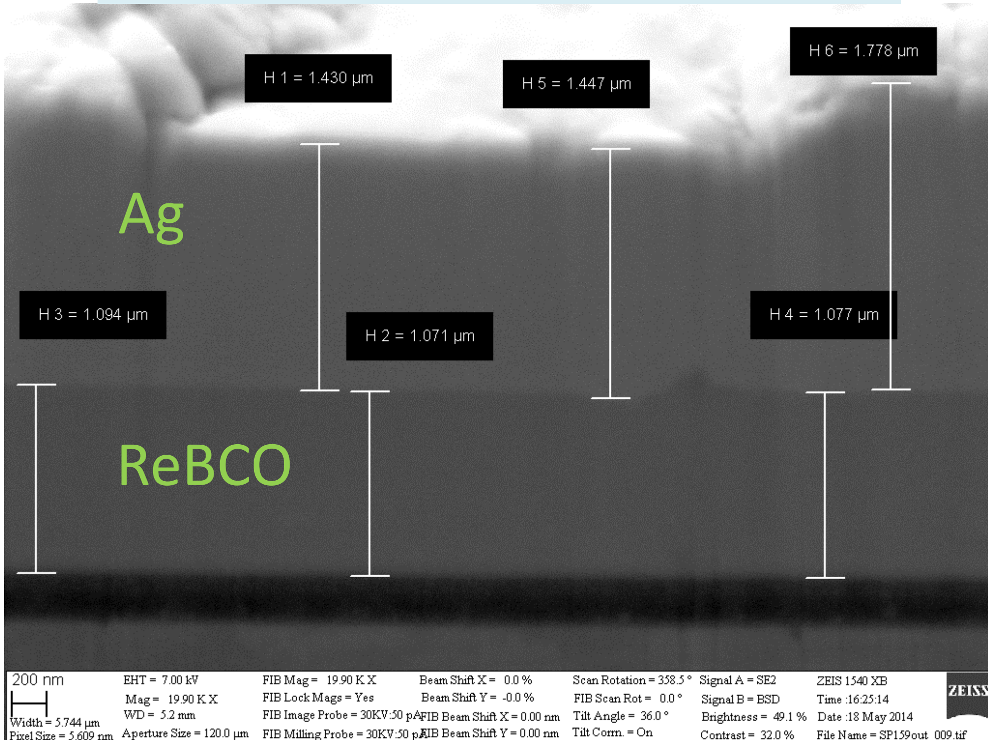
SP64 inner



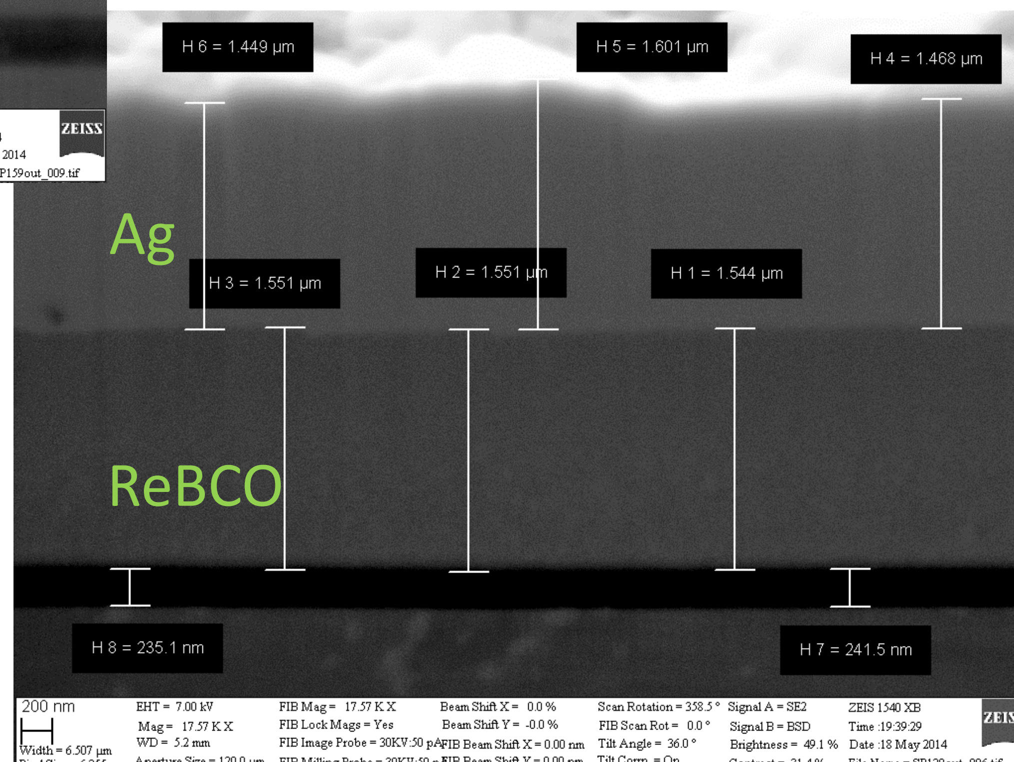
After etching Cu and Ag

Different thickness for M3 and M4 machines

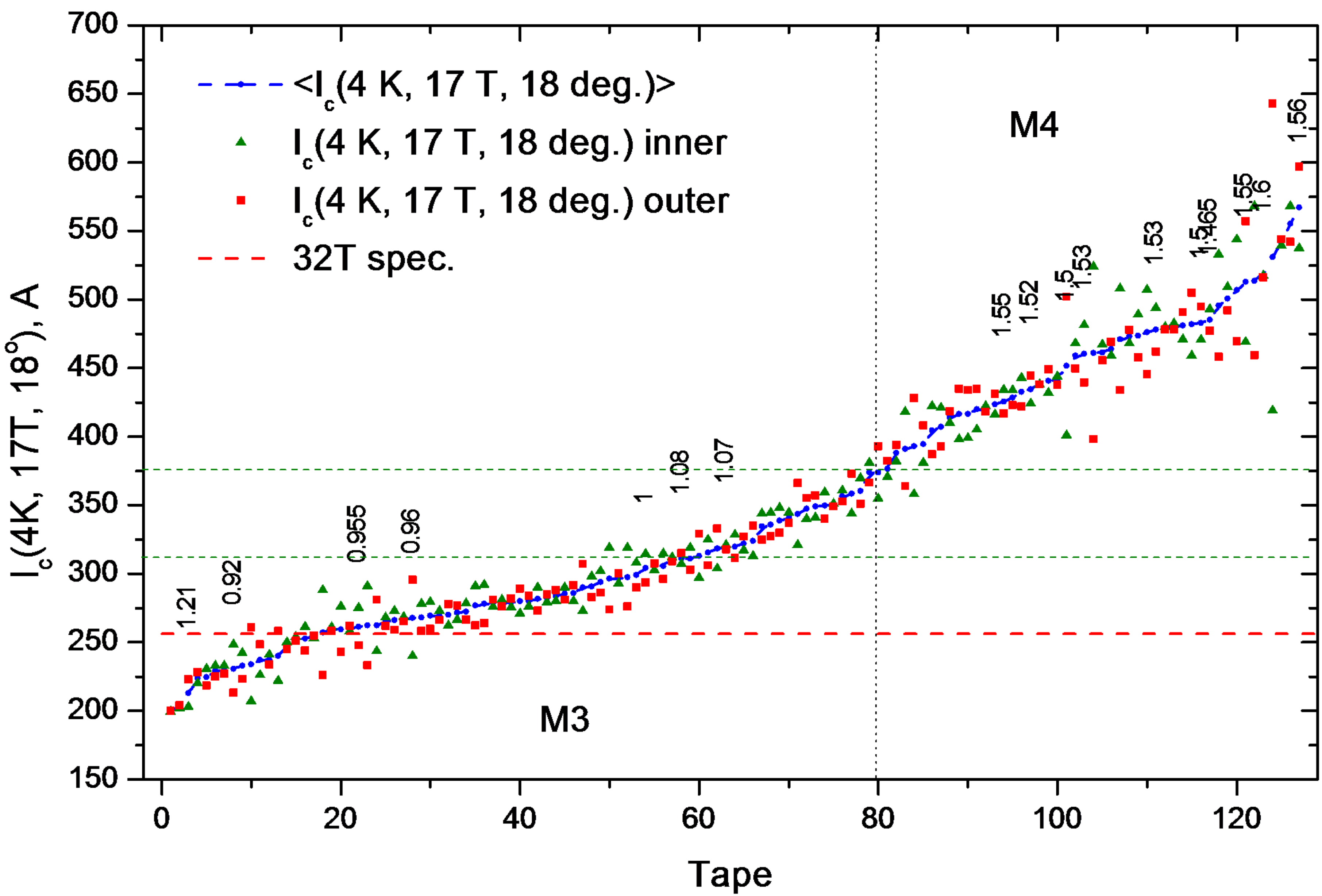
SEM cross-section of M3 SP159



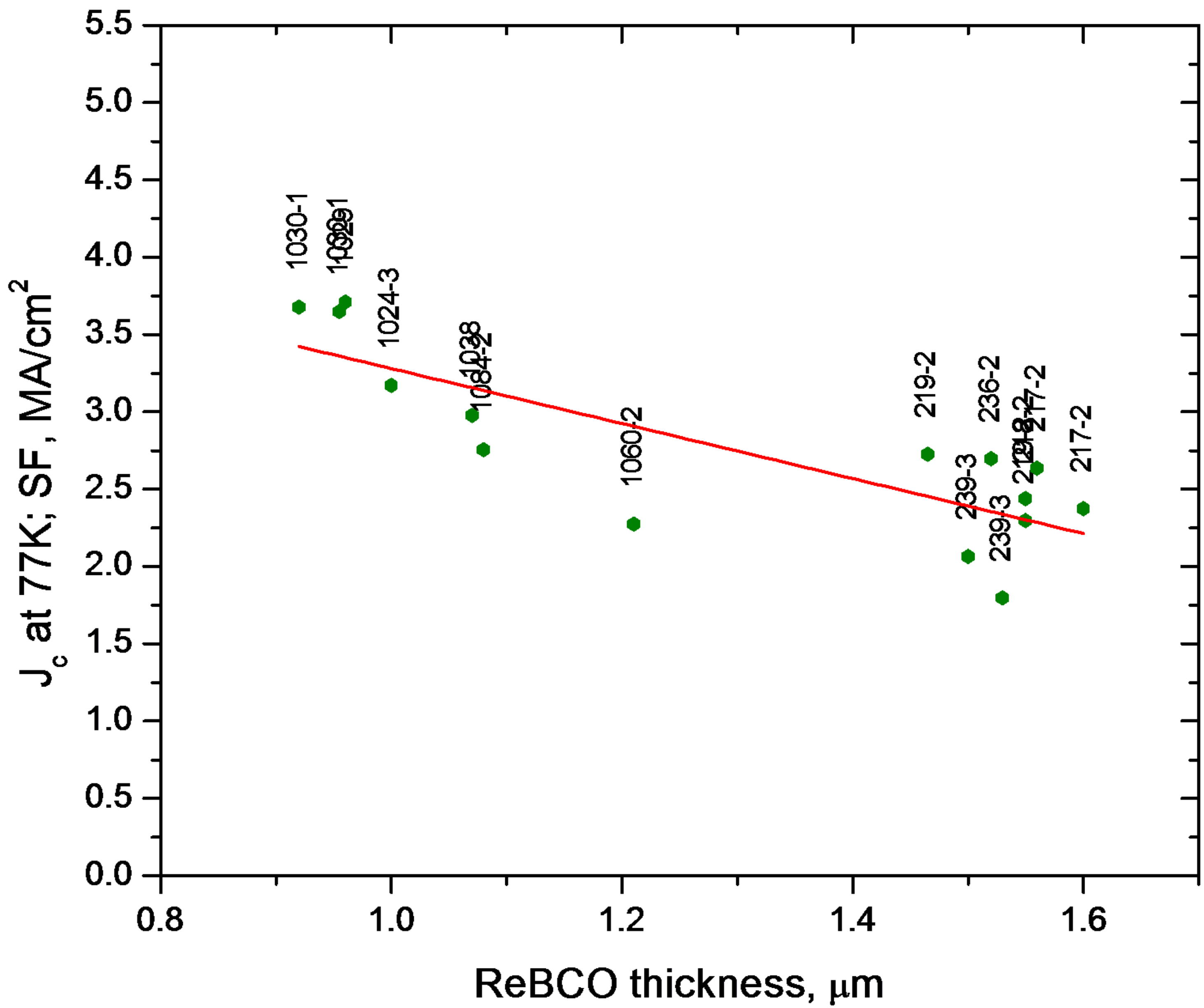
SEM cross-section of M4 SP129



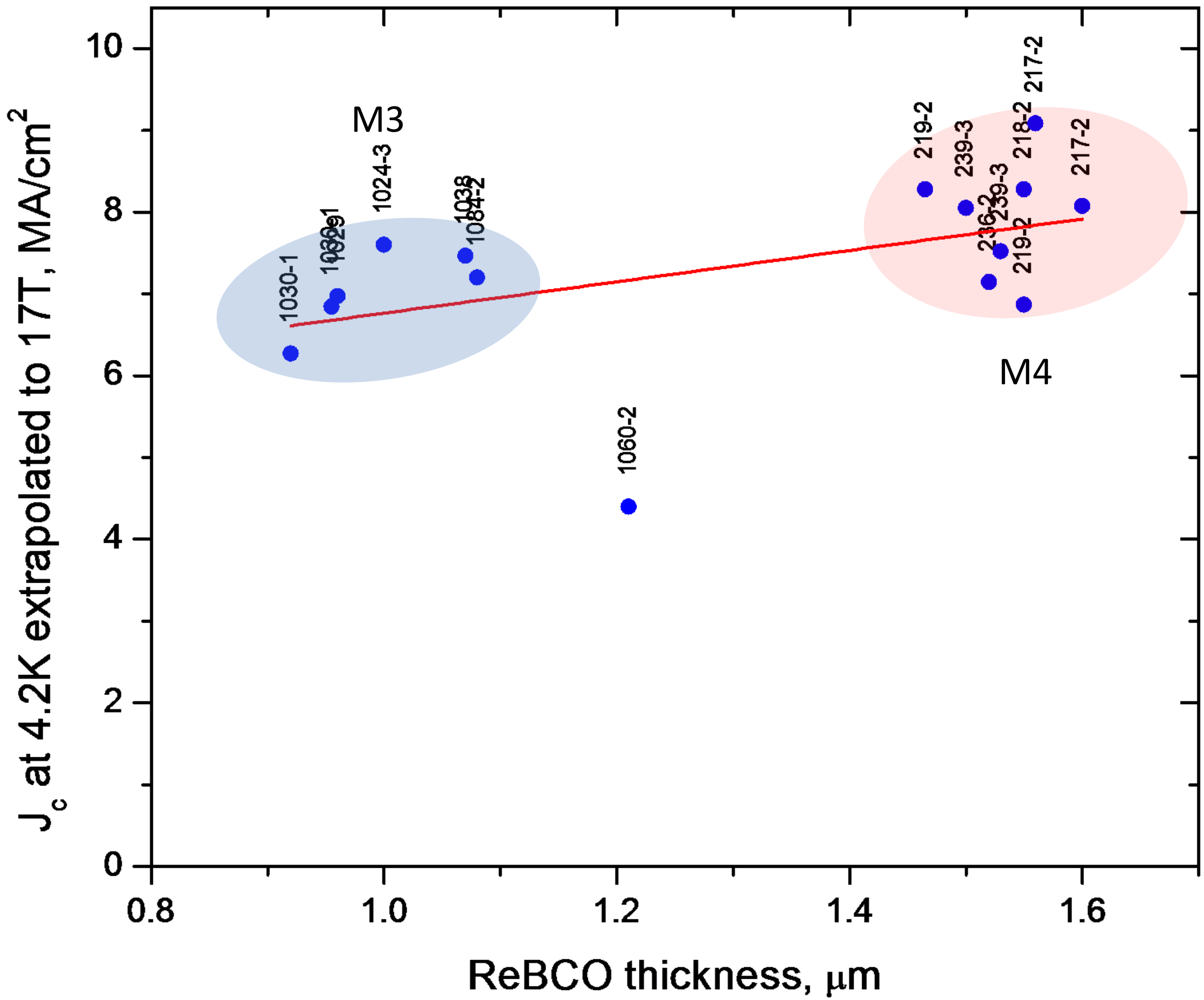
Ascending < I_c(4K;17T;18°) > plot with ReBCO thicknesses



77K self-field critical current vs. ReBCO thickness dependence



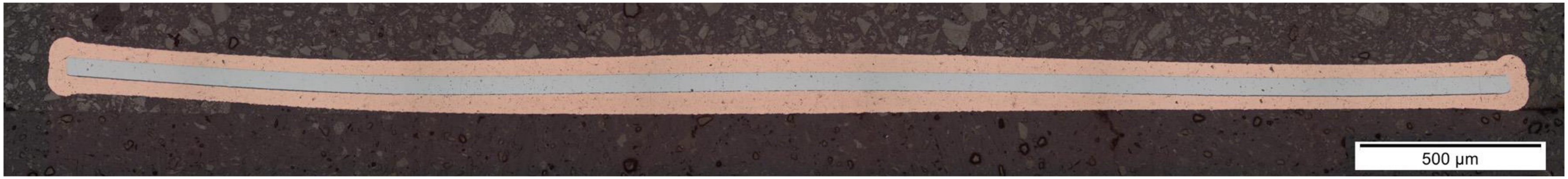
4K in-field critical current density vs. ReBCO thickness dependence

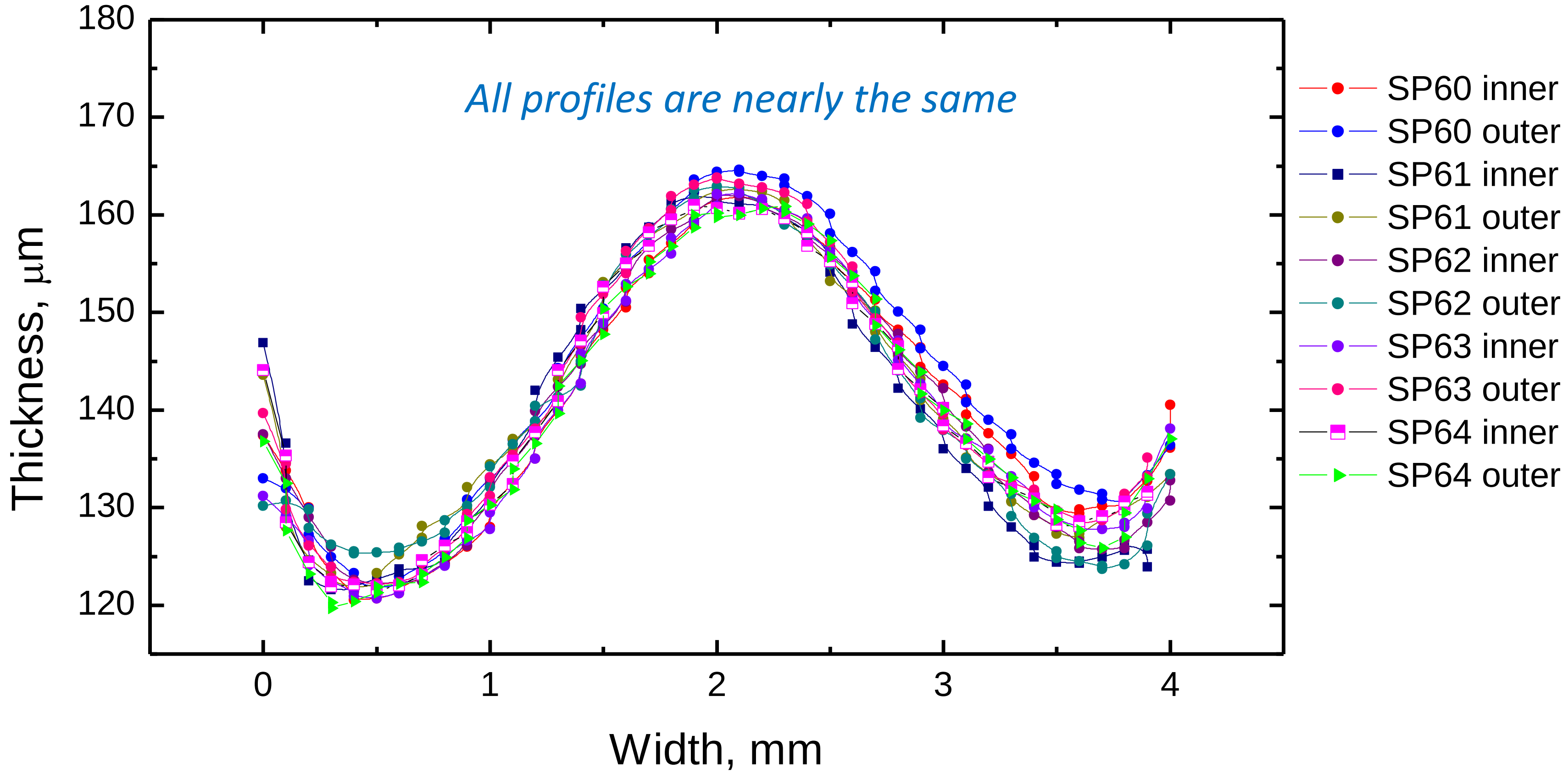


Testing geometrical tolerances

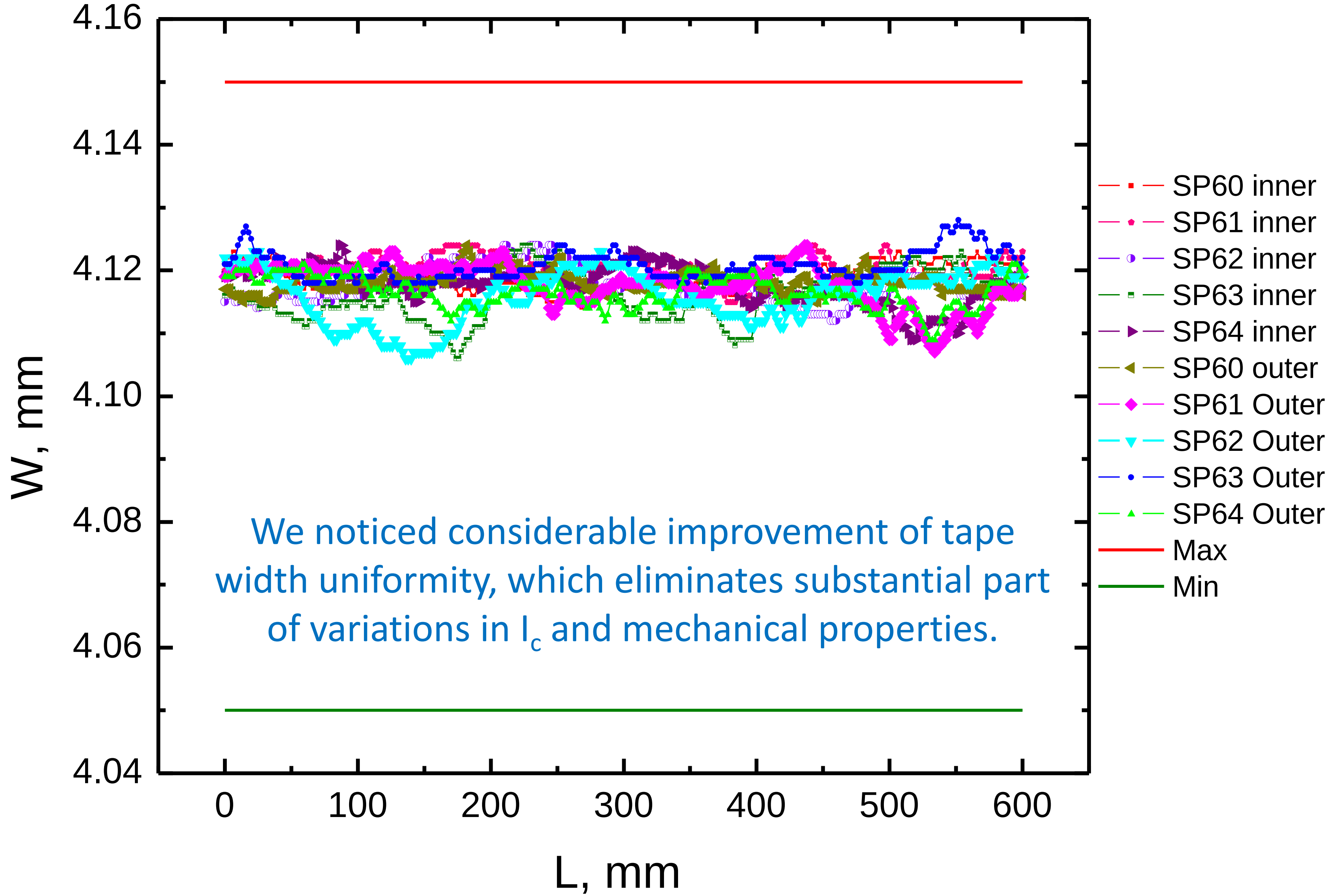
Thickness profiles measured with Nikon microscope

Optical image of typical cross section (SP 60 inner)

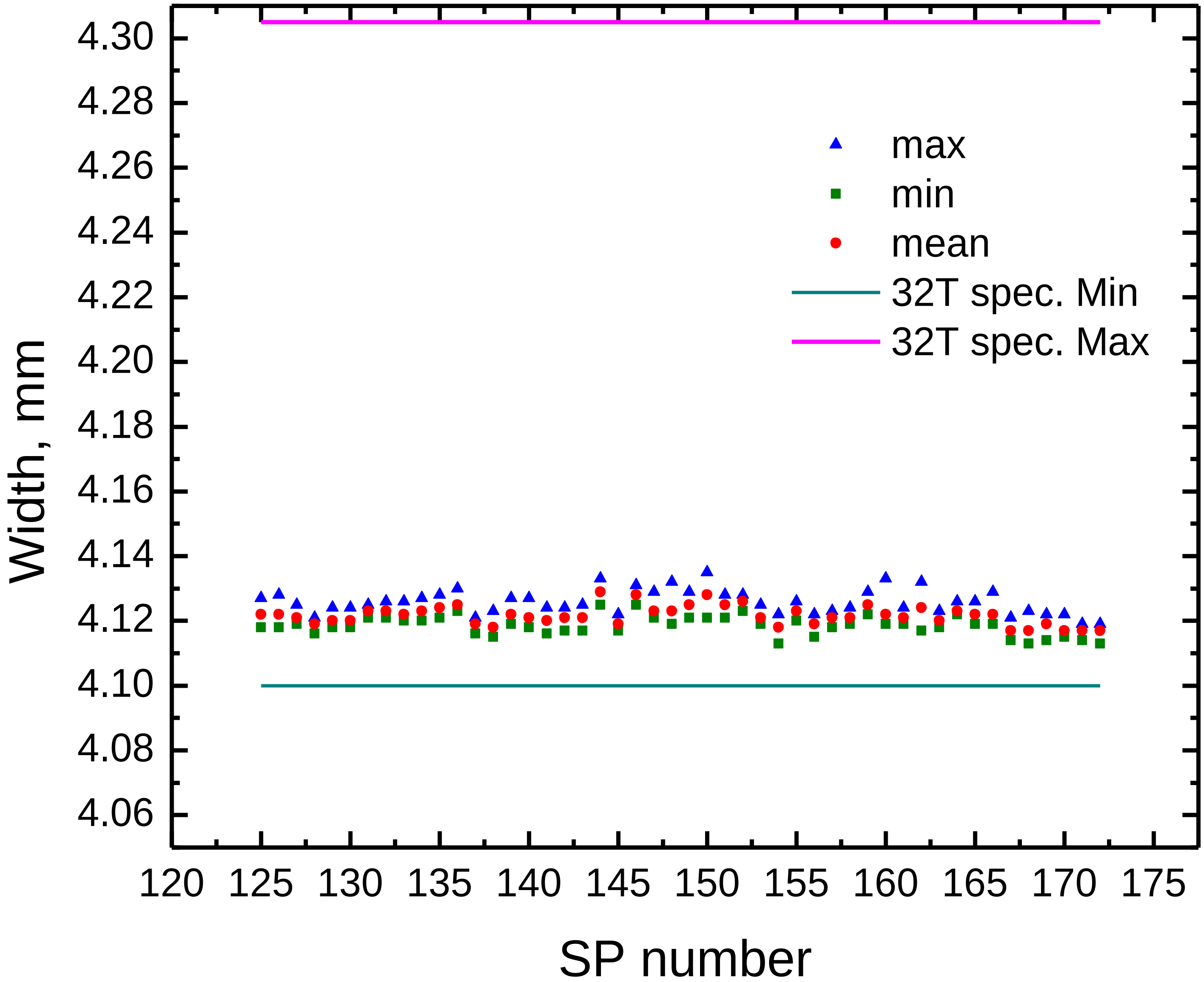




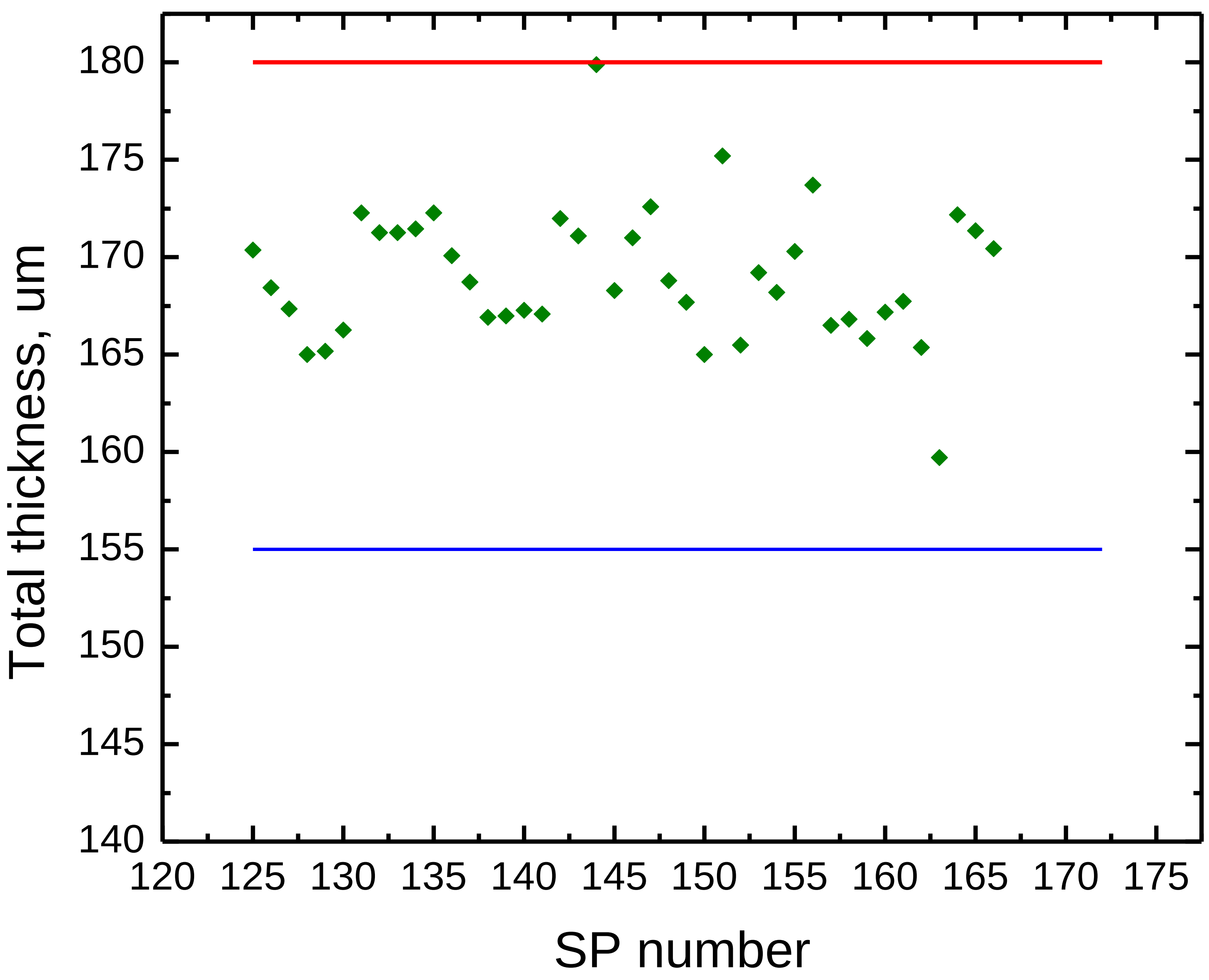
Width distributions for SP60 – SP64 tapes are within specification



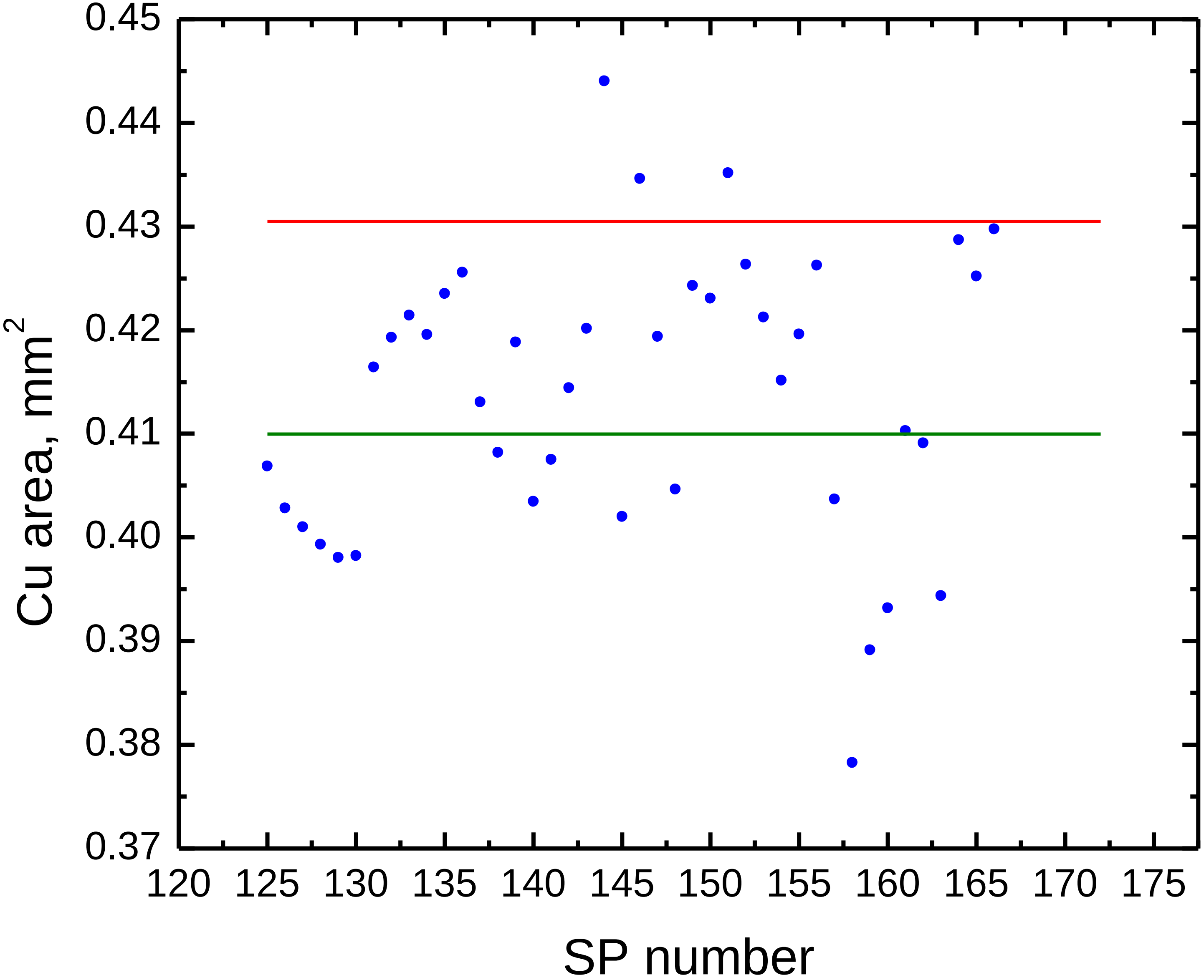
Conductor width variation



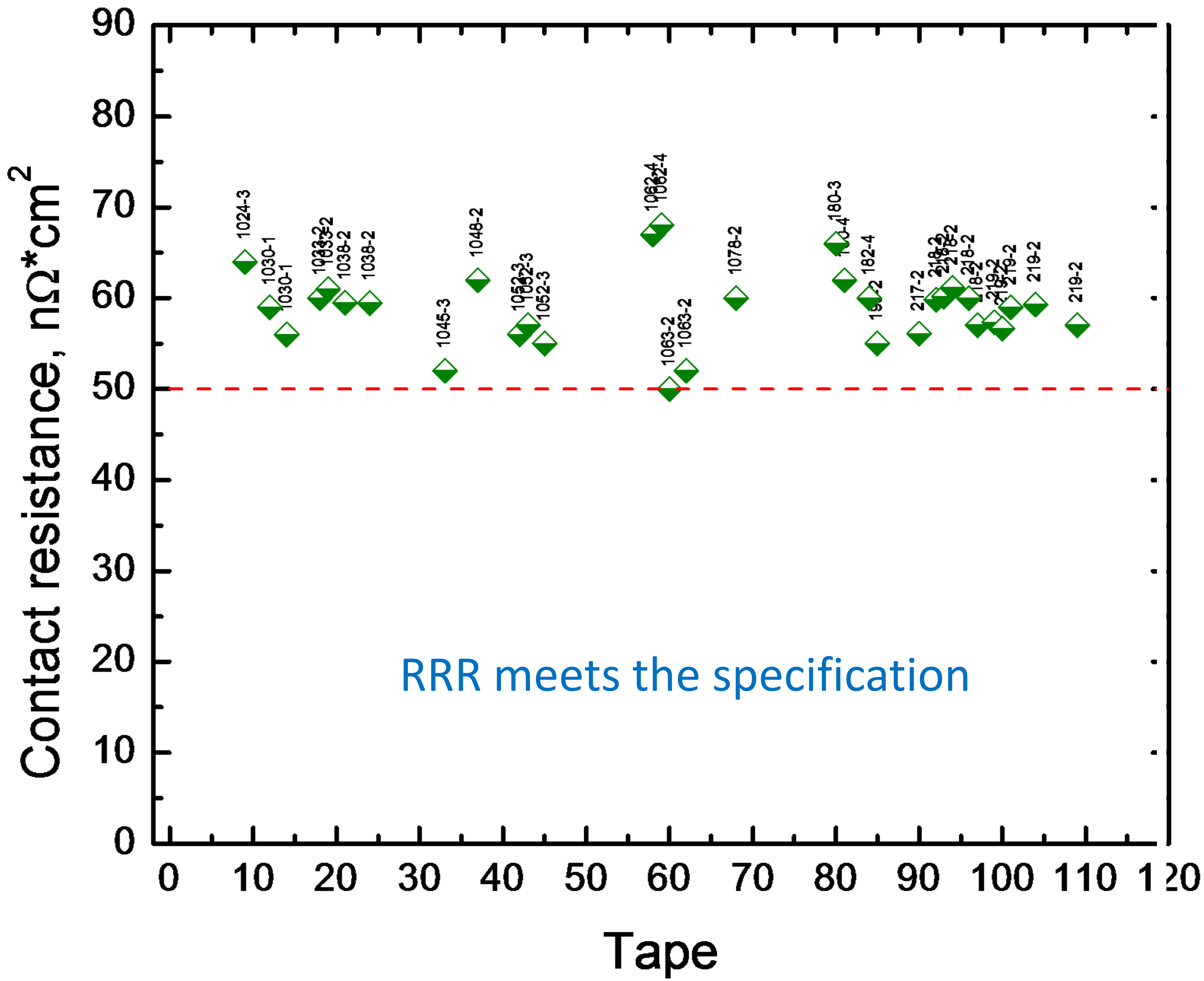
Total thickness measured with micrometer



Cu area for SP125- 166 tapes



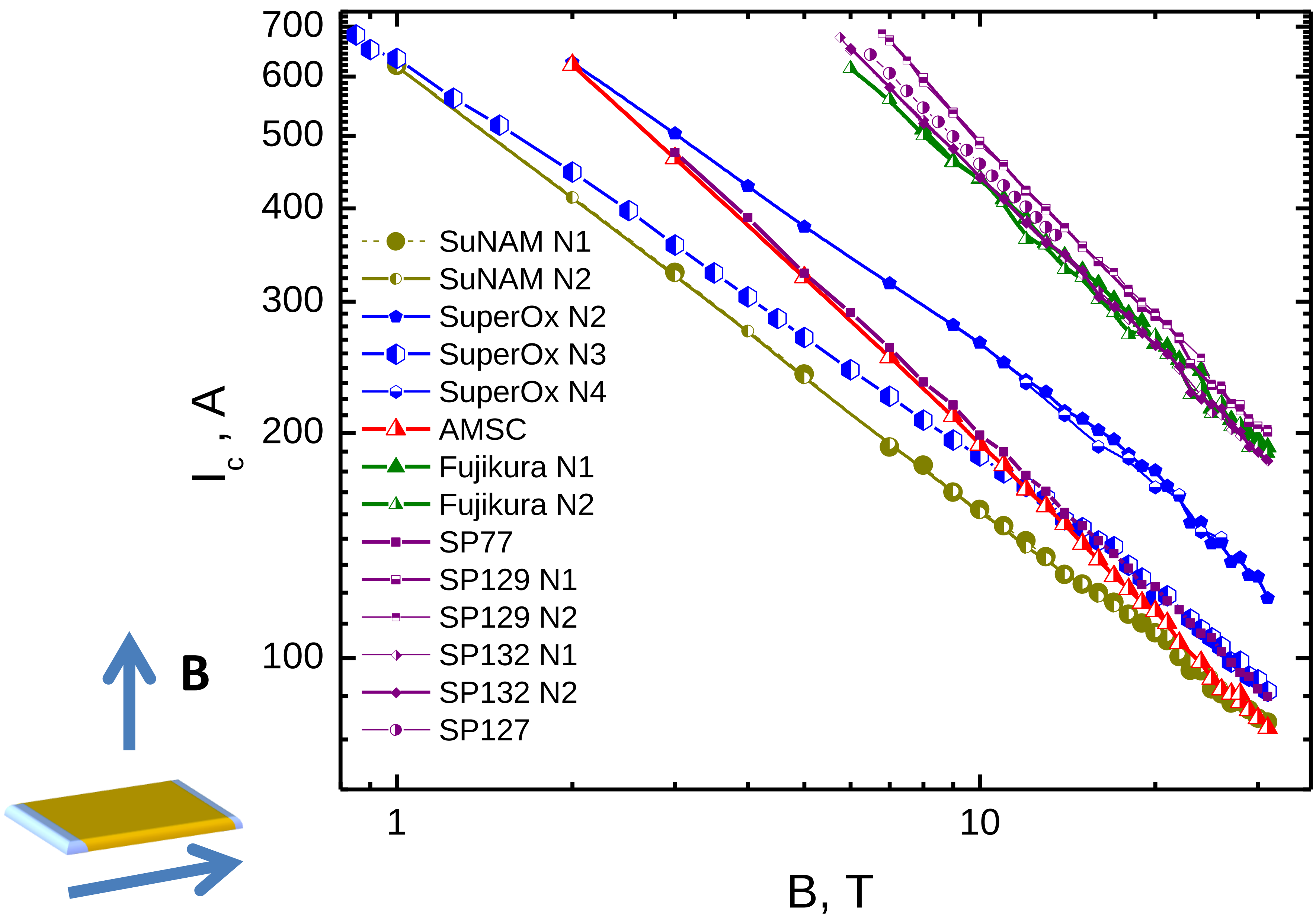
RRR of stabilizer – parallel connection of Ag and Cu layers



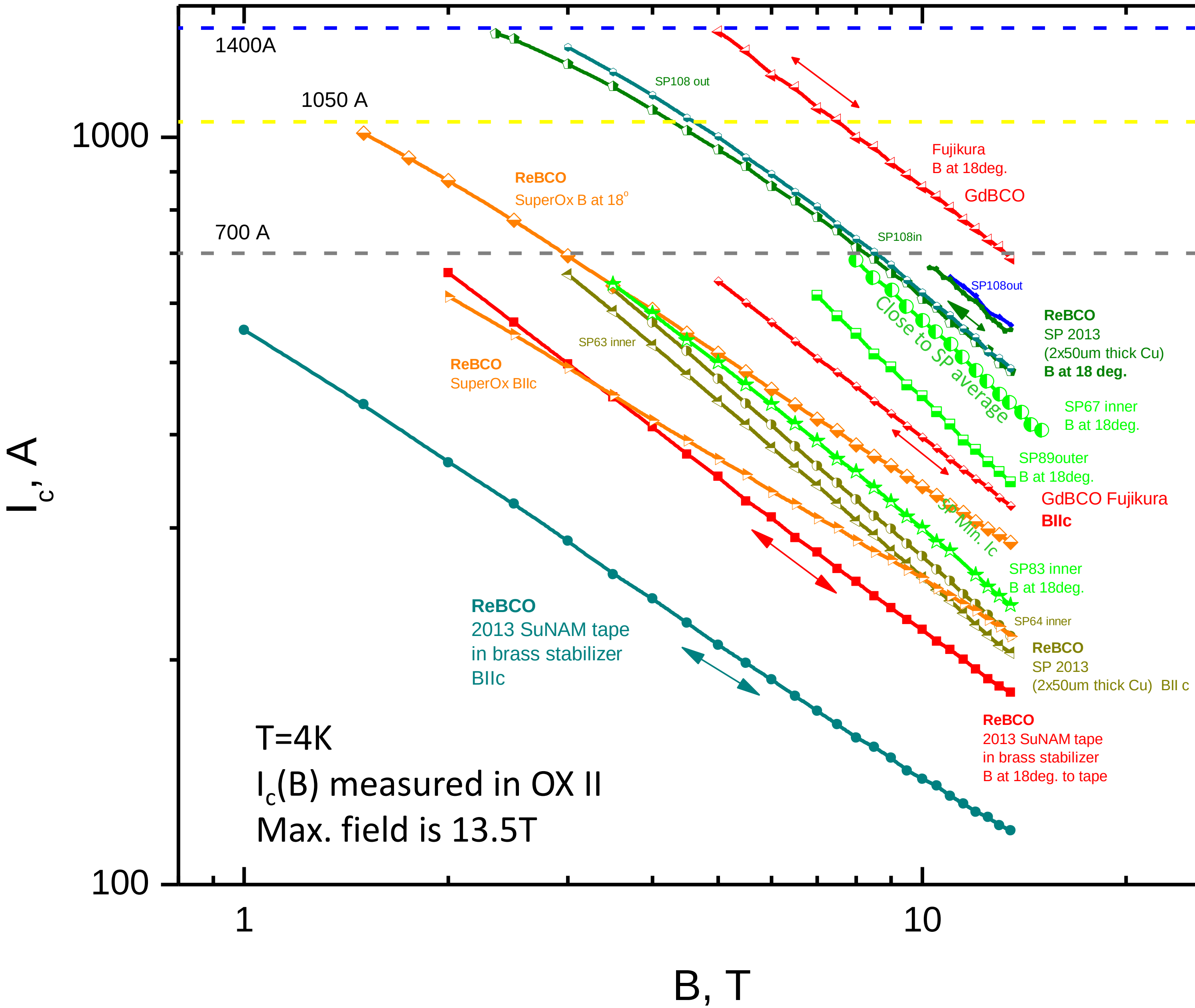
Comparison of 4K in- field I_c for conductors from different manufacturers

Comparison I_c(4K; B) for tapes from different manufacturers measured up to 31.2T

Orientation : field perpendicular to tape plane

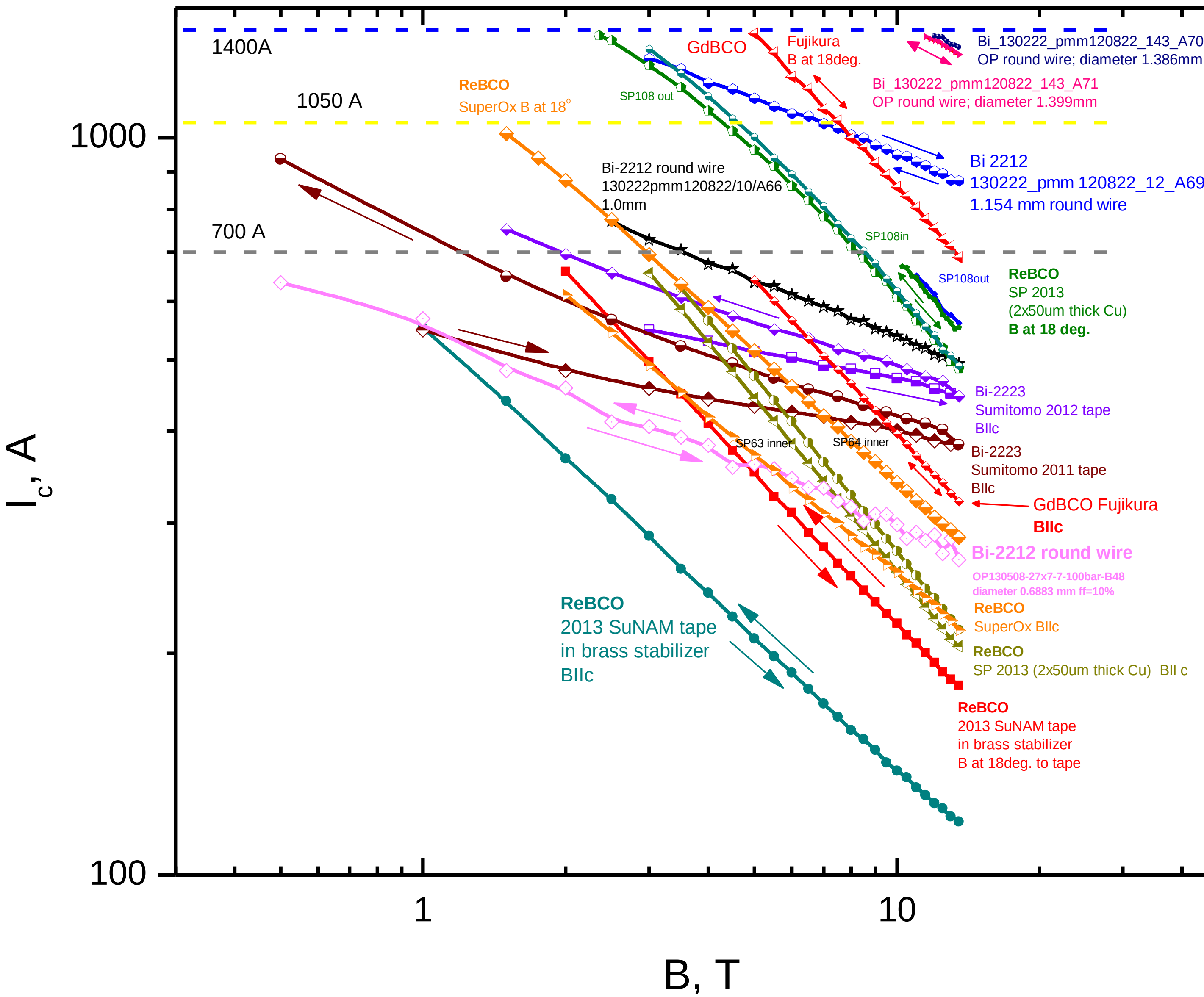


Comparison of I_c(4K;B) in ReBCO conductors in-field up to 13.5T



Comparison of conductor performances at 4.2K up to 13.5T

Measured in OX II using up to 4 Sorensen DSC8-350E

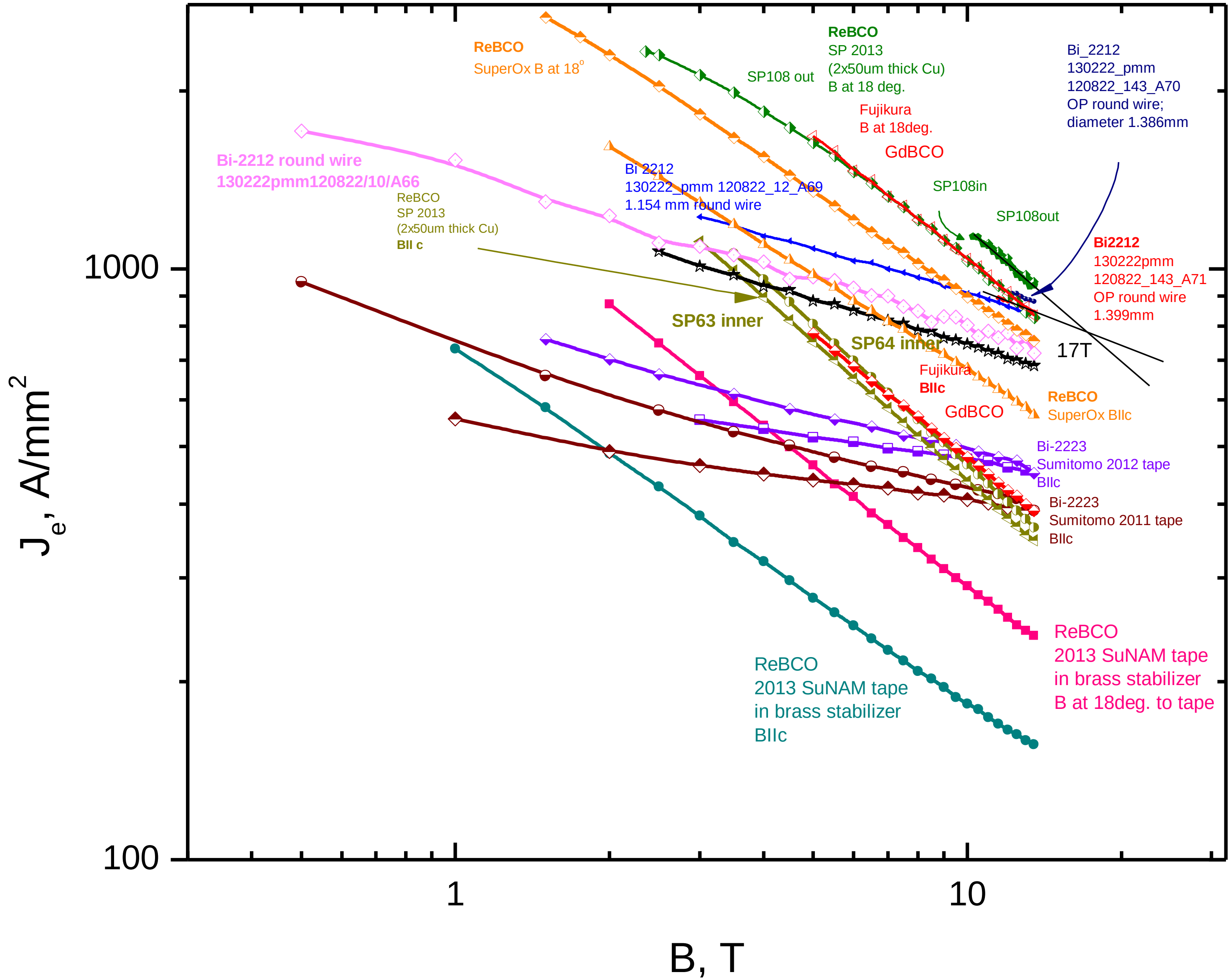


Comparison of α values

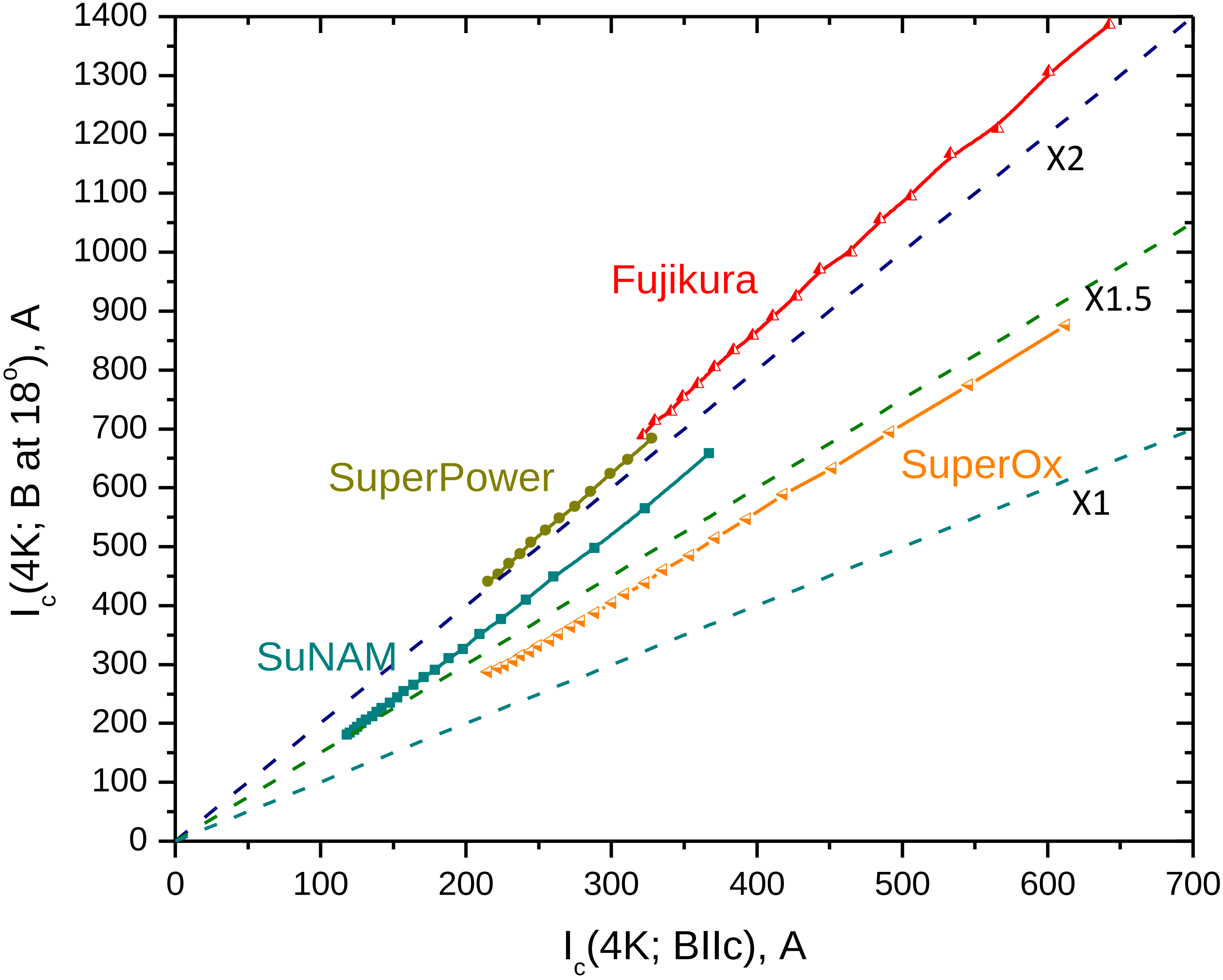
Manufacturer	Material	α at BIIc	α at 18deg.
SuperPower	ReBCO	0.67-0.76	0.7-0.9
SuNAM	ReBCO	0.6; 0.6	0.69; 0.68
SuperOx	ReBCO	0.54; 0.54	0.588; 0.59
Fujikura	ReBCO	0.641; 0.69	0.70
AMSC	ReBCO	0.74	
Sumitomo	Bi-2223	0.18; 0.164	
OP processed	Bi-2212- round d=1.38mm	0.33	
OP processed	Bi-2212 d=1.154 mm	0.27; 0.26; 0.238	
OP processed	Bi-2212 d=0.688 mm	0.27	

Comparison of conductor performances at 4.2K

Measured in OX II using up to 4 Sorensen DSC8-350E



Difference in anisotropy



Conclusions:

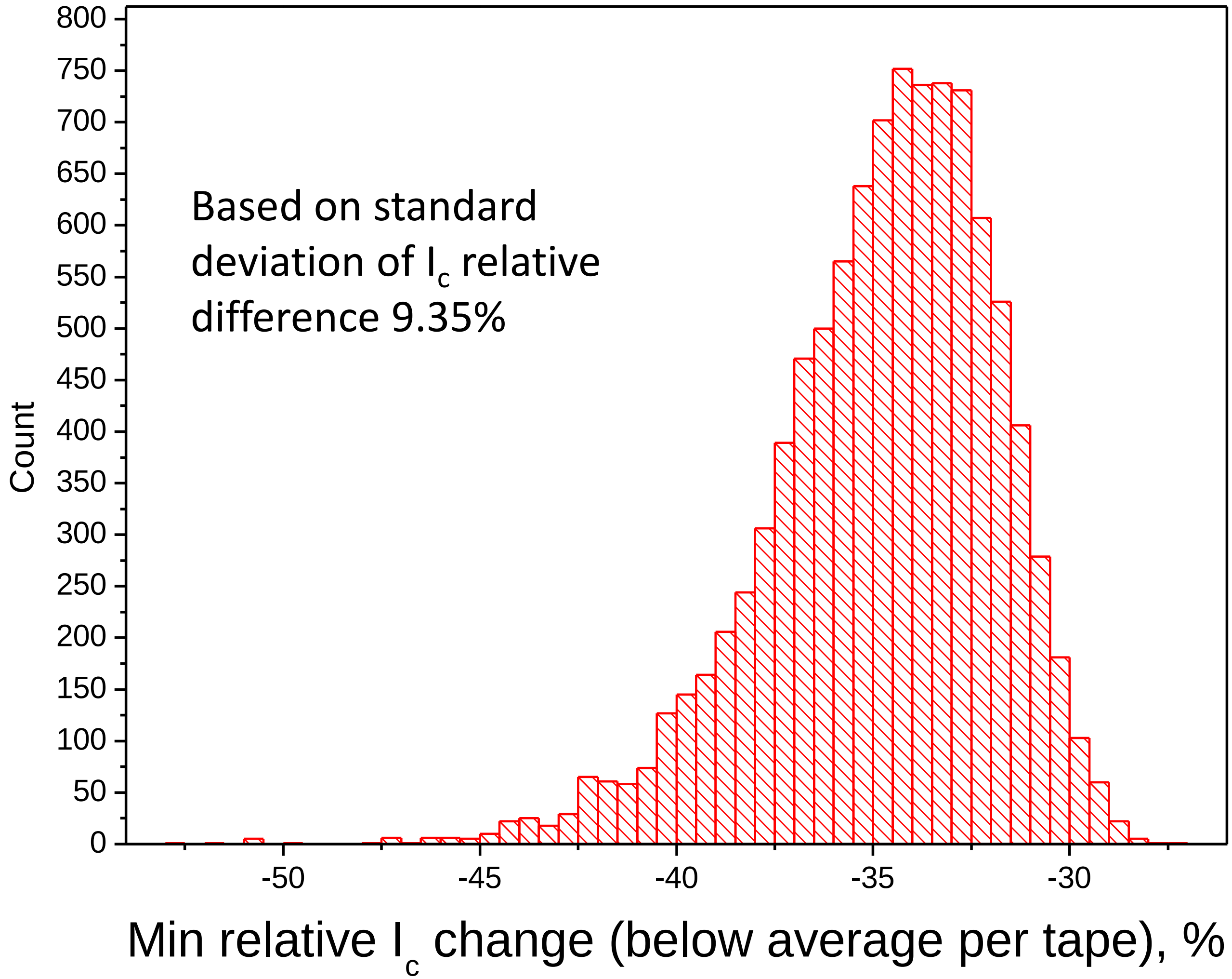
- Comprehensive analysis of various tape properties is necessary for building reliable magnet.
- I_c measured in specific field orientation at 4.2K is important for predicting coil performance, not testing at self-field 77 K;
- J_c(B, 4K, 18^o) did not dropped as ReBCO thickness got 60% increase in M4 tapes;
- Transport and geometrical properties of commercially available (Re)BCO conductor from SuperPower Inc. are not perfect but sufficient for making 32 T user magnet;
- Among ReBCO conductors SuperPower Inc. and Fujikura have largest I_c(4K, B);
- Tapes from SuperOx show smallest among ReBCO CC α and smallest I_c anisotropy;

How to choose operating current after measuring I_c in about 0.03% - 0.018% of the conductor at 4K in-field?

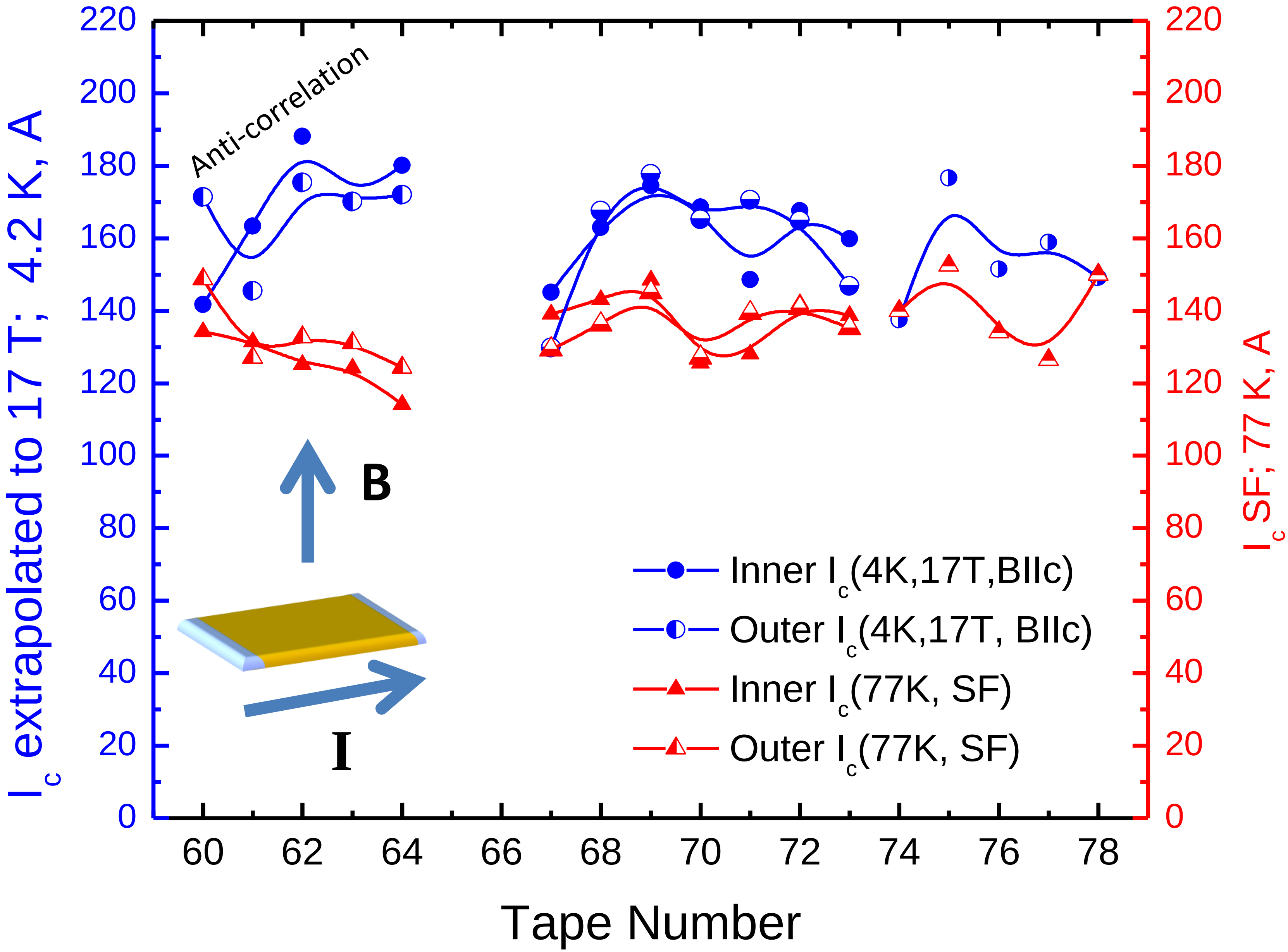
Assume that the distribution shown in experimental histogram is “universal” through every tape from the set SP60-SP124.

Assume that minimum size of I_c non-uniformity is about 1 cm for 60m long tape

Here is simple statistical model: $I_c(x)$ generated with Gaussian distribution in 6000 point; min I_c taken for 10000 virtual tapes



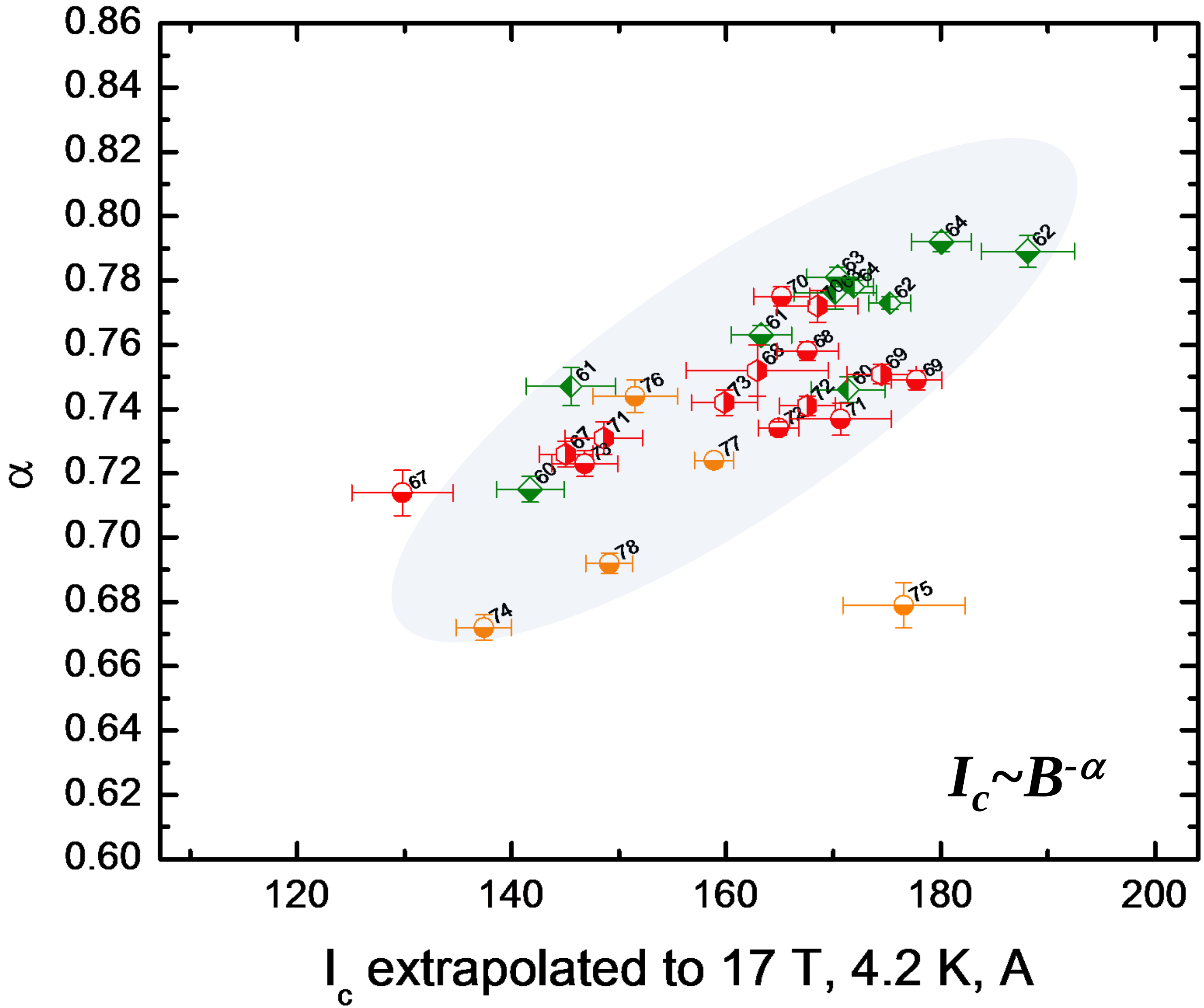
I_c(4K, 17T, BIIc) with I_c(77K, SF) for selected tapes



All tapes from M3 machine

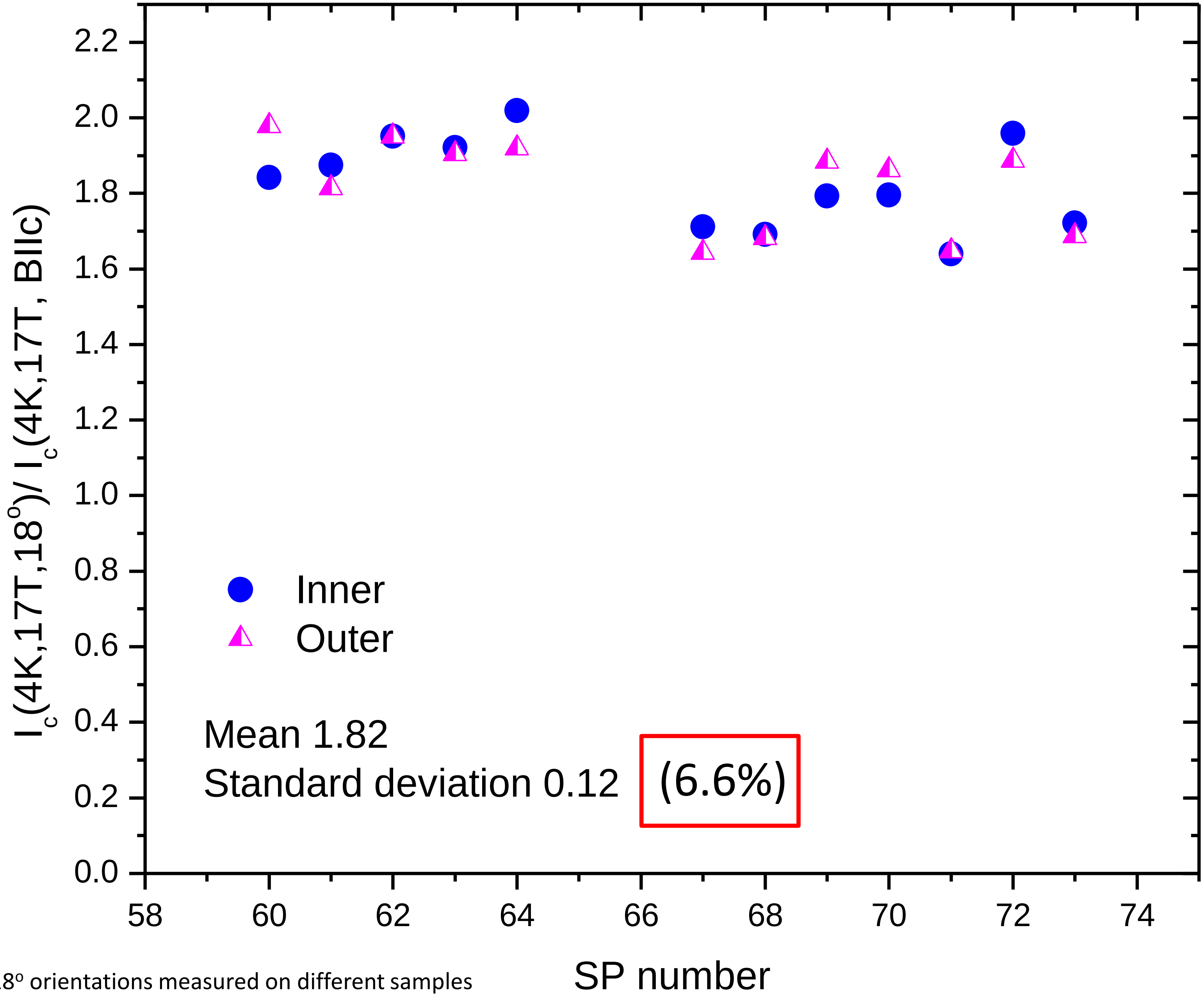
Relation between α values and I_c (4K, 17T, B||c)

For tapes with higher I_c we observe larger α values



Ratio I_c(4K, 17T, 18°) / I_c(4K, 17T, BIIc) has low spread from tape to tape

Interpretation: Angular dependence of I_c has small variation

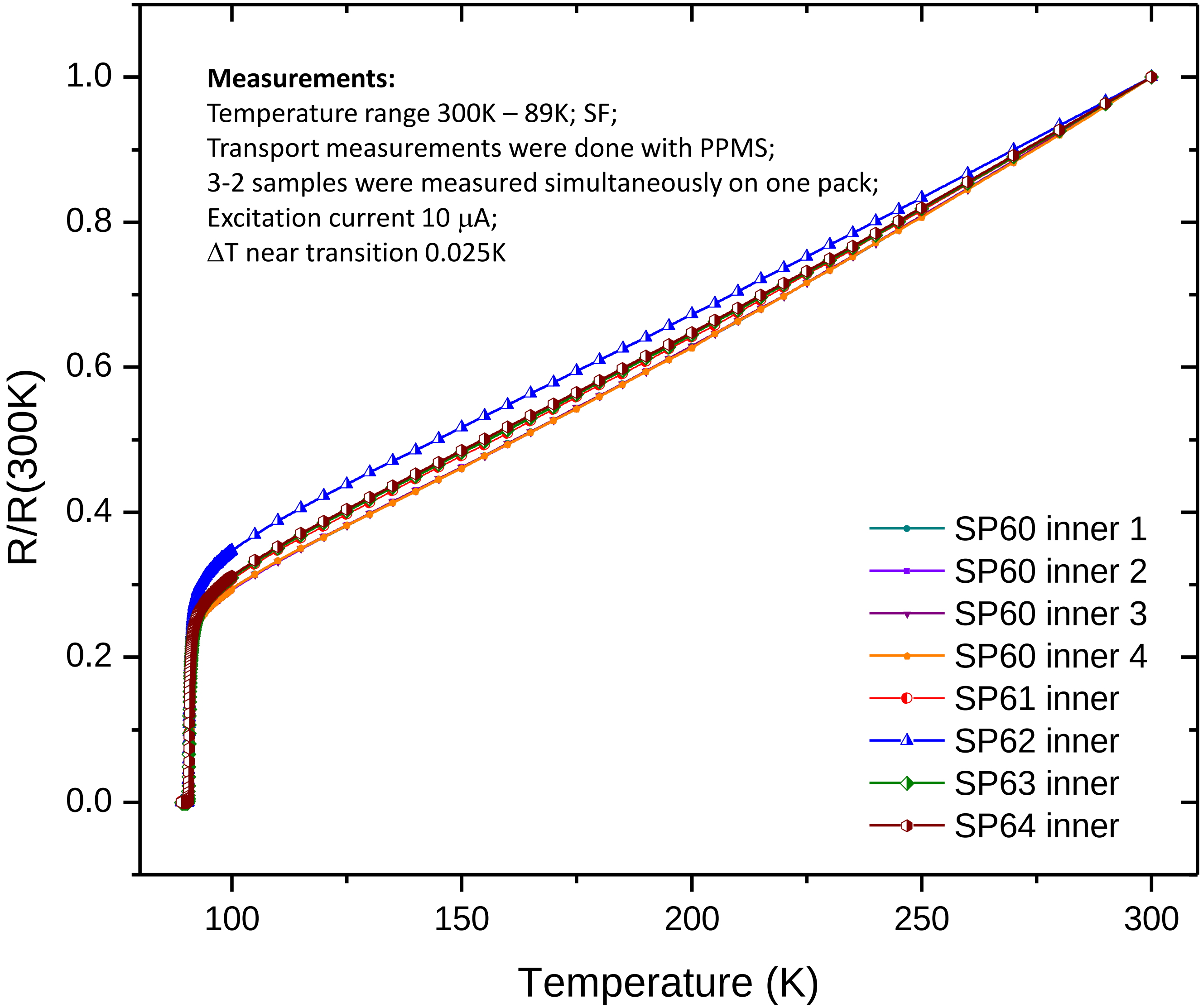


BIIc and 18° orientations measured on different samples

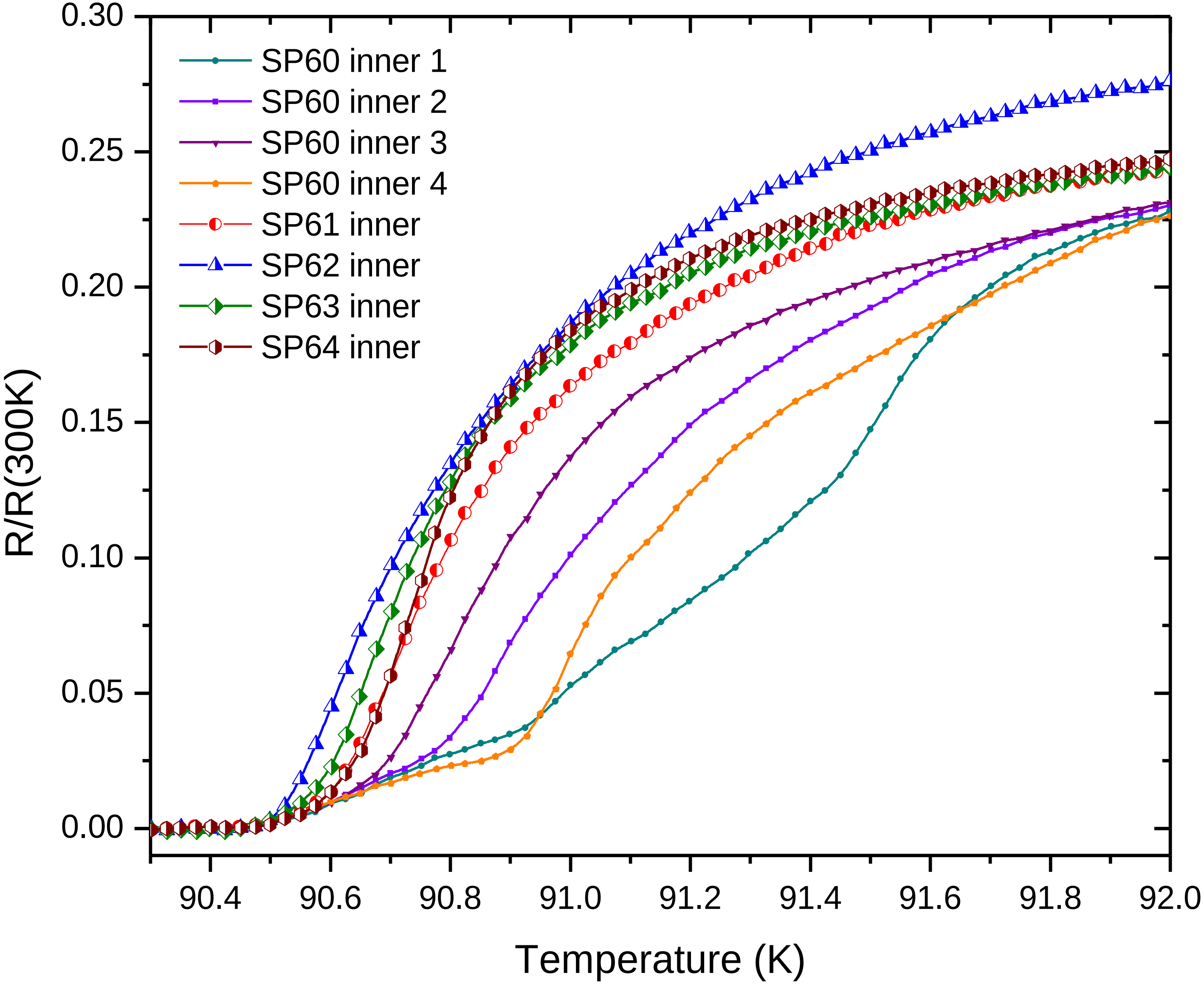
Normalized R vs. T for samples from "inner" part of spools

Aim:

By calculating T_c from electric resistivity measurements find why I_c at SF; 77K for SP60 differs from one for SP61-64



R vs. T for samples from “inner” part of spools



For inner region:

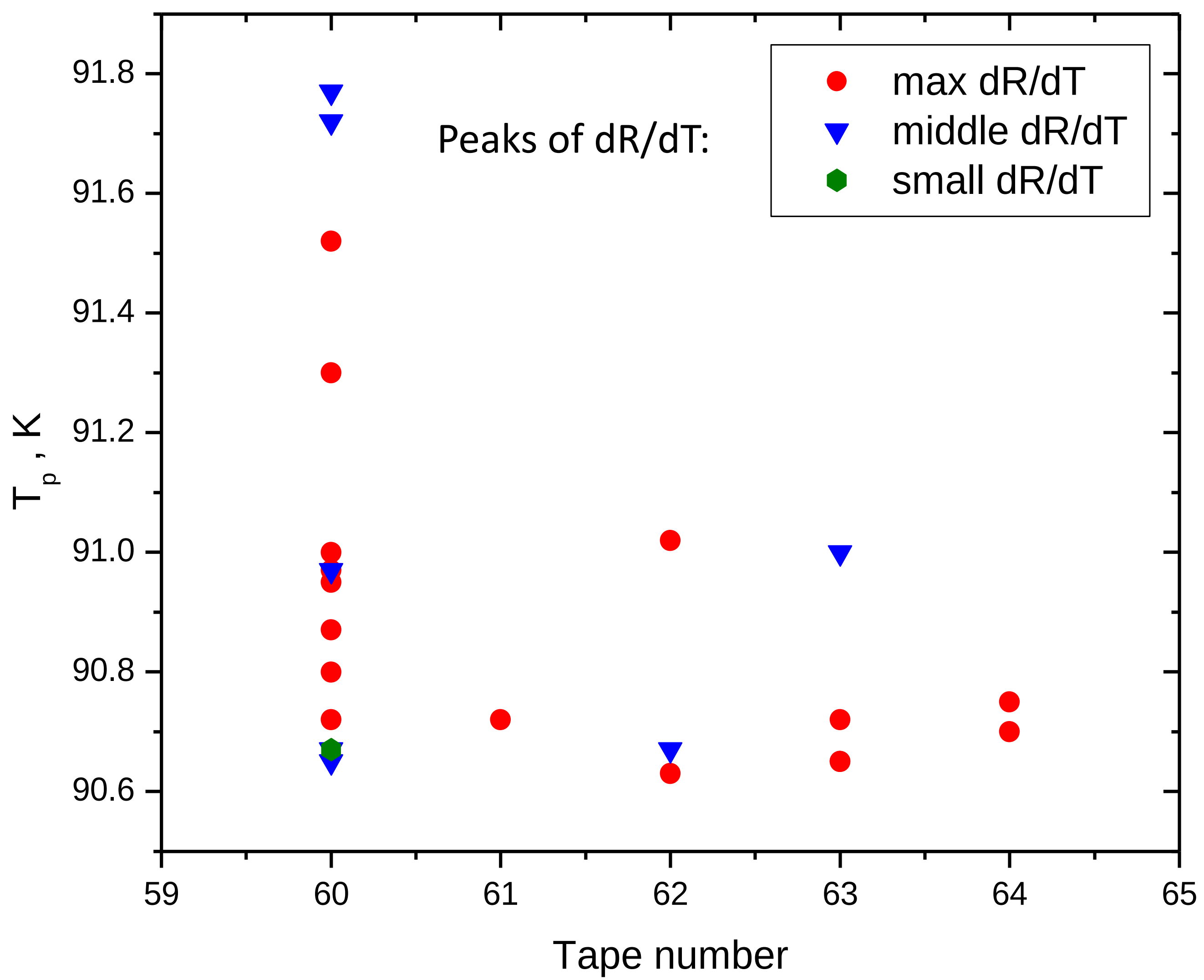
Very narrow T_c spread and sharp transition for SP61-64;

Samples from SP60 have wider and variable transition region.
Some SP60 samples have up to 3 “knee”

“inner” means that sample was cut from inner part of spool arrived from SP

Striking difference between SP60 and SP61-64

SP60 contains several phases with different T_c ranging from 90.7K to 91.8K



Interpretation:

- SP60 has non-uniform composition with multiple (Re)BCO phases;
- SP 61-64 have variable through length oxygen doping

bulk critical temperature T_c defined as maximum of dR/dT