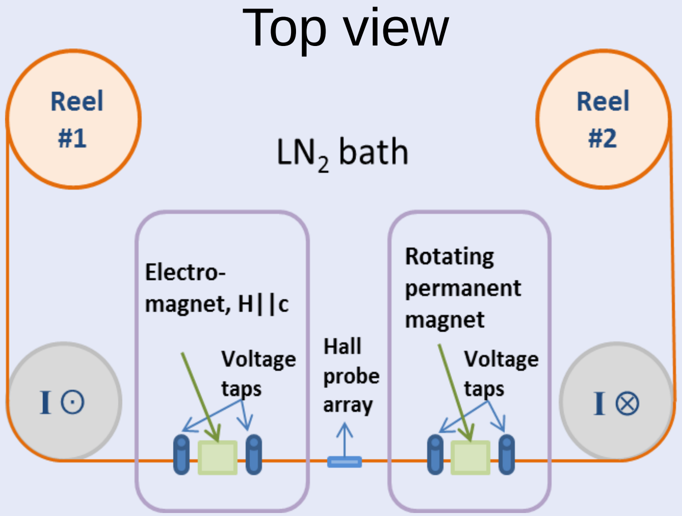
YateStar– a unique tool for lengthwise transport I_c characterizations

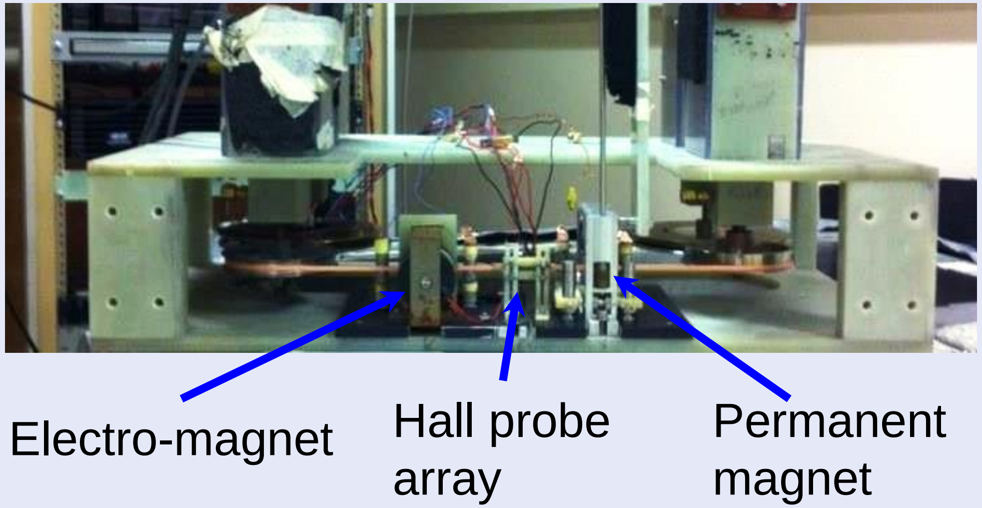
Xinbo(Paul) Hu, Griffin Bradford, Michael Small, Jan Jaroszynski, David Larbalestier

Outline

- What can YateStar tell us?
  - I_c variations, especially the vortex pinning variations
  - J_c uniformity across the tape width, and edge qualities
- How is the uniformity of tapes from different manufacturers?
  - Historical statistics of tapes from one manufacturer
  - Cross-comparison of tapes from different manufacturers

YateStar: A unique instrument for lengthwise I_c measurement in-field (0.6-1 T) with high spatial sensitivity in transport (~20 mm) and magnetization (~1 mm)





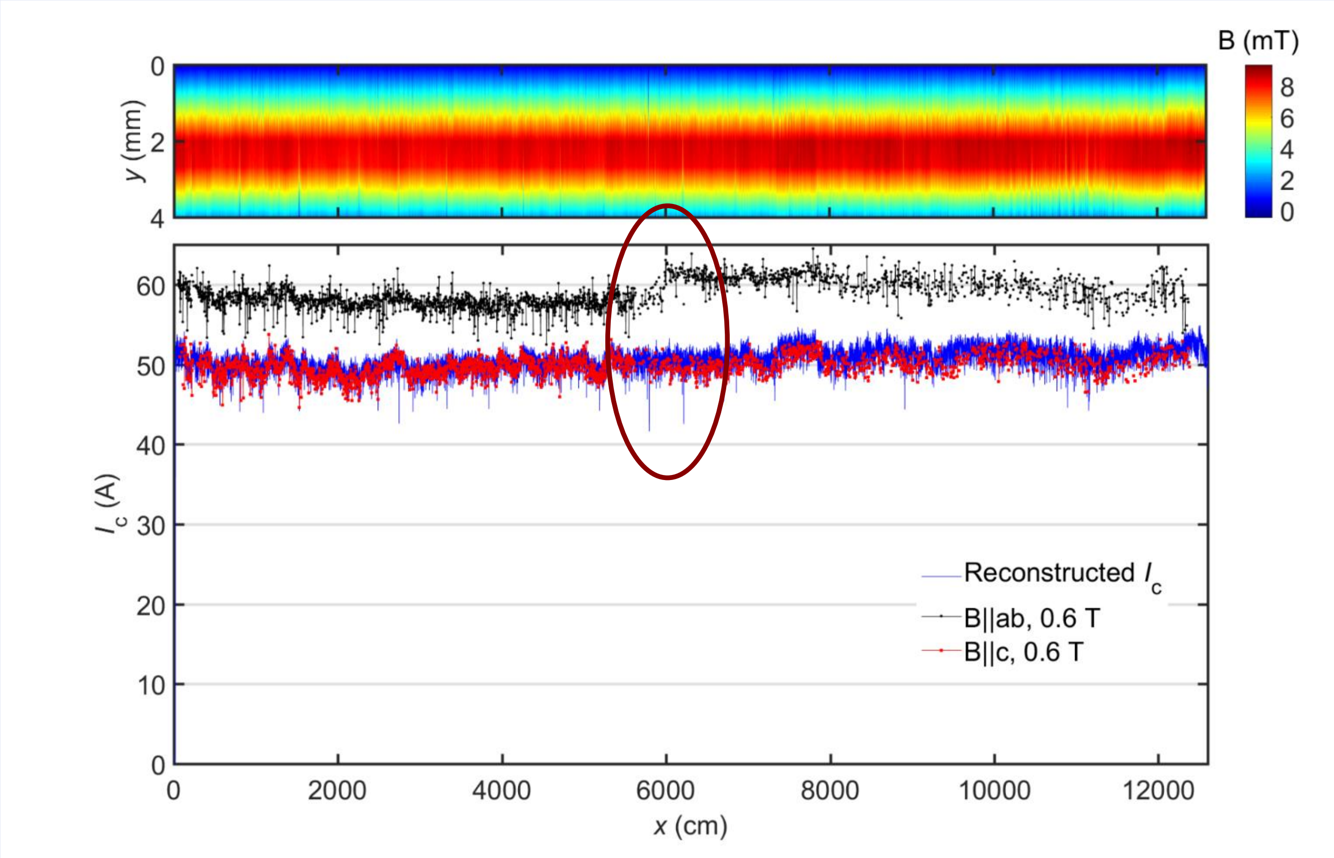
- Designed by Yates Coulter (NHMFL-LANL) and continuously innovated at ASC by improvements to indexing, increase in length capability (now 500 m) and measuring speed (now 30 m/h) and addition of Hall probe array.
- Transport measurement: I_c (x, θ, B) [resolution ~2 cm]
  - ✓ Two channels for I_c(x) [normally perpendicular and parallel field]
  - ✓ Any interesting point can have a full I_c(θ, 0.6T) evaluated
- Magnetization measurement gives fluctuations of I_c(y) as well as I_c(x)

A very valuable *post-mortem* tool:

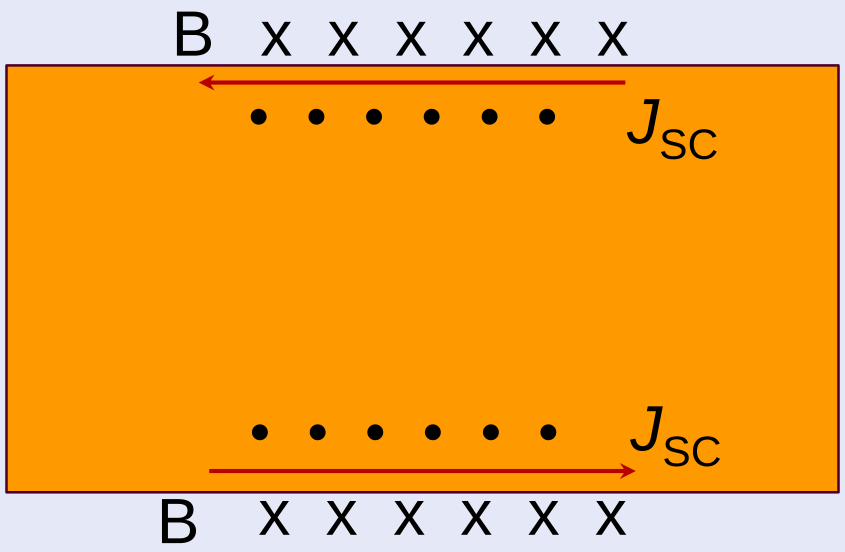
[1] S. Hahn, K. Kim, K. Kim, X. Hu, T. Painter, I. Dixon, S. Kim, K. R Bhattarai, S. Noguchi, J. Jaroszynski, D. C. Larbalestier, "45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet", *Nature*, **570**: 496-499 (2019).
[2] X. Hu, M. Small, K. Kim, K. Kim, K. Bhattarai, A. Polyanskii, K. Radcliff, J. Jaroszynski, U. Bong, J. H. Park, S. Hahn, and D. Larbalestier, "Analyses of the plastic deformation of coated conductors de-constructed from ultra-high field test coils," *Supercond. Sci. Technol.*, **33**: 095012 (2020).

How we use the data emerging from YateStar

- Multiple data types:
  - Transport $I_c(x)$ for H⊥ and ∥ to tape plane (or indeed any angle) – with 2 cm resolution at H ⊥ 0.6-1 T and 0.6 T for H ∥ tape plane
  - 7 array Hall probe to give an $I_c(y)$, not just $I_c(x)$ information – with ~ mm resolution
  - Cross-correlations can be specially valuable and correlations to the 4 K, high field

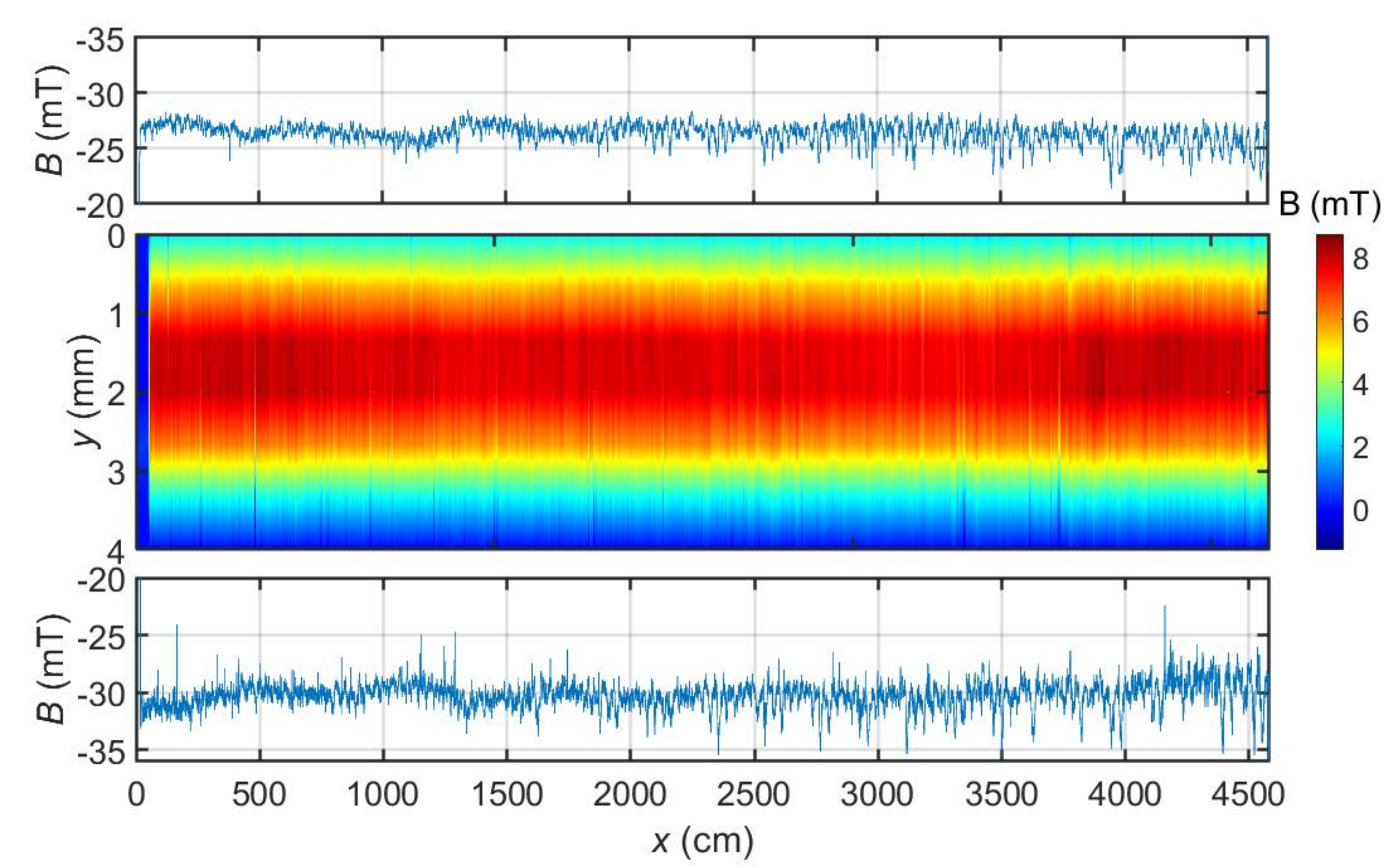


Hall probes on the 2 edges can characterize the edge qualities



- Many degradation starts from the edges due to the pre-existing defects.
- The screening current stress has drawn great attentions recently, and it is closely related to the edges as well.

Edge Hall probes show that the edge quality can be different even for the mid-slit tapes



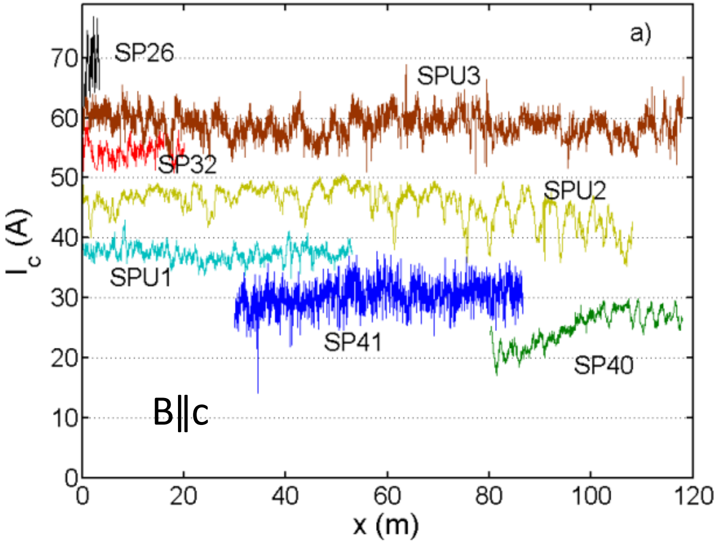
- The edge Hall probes are more sensitive than the Hall probe array to the edge defects.

Outline

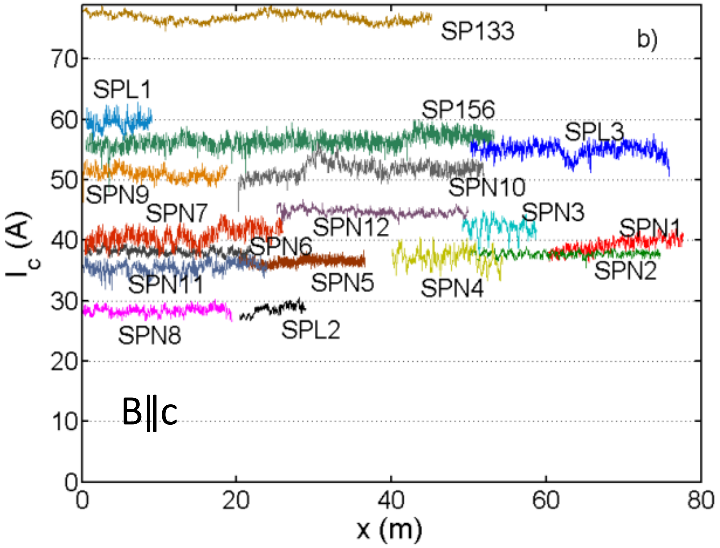
- What can YateStar tell us?
  - I_c variations, especially the vortex pinning variations
  - J_c uniformity across the tape width, and edge qualities
- How is the uniformity of tapes from different manufacturers?
  - Historical statistics of tapes from one manufacturer
  - Cross-comparison of tapes from different manufacturers

Manufacturer A: improvement of inter-tape uniformity but not intra-tape

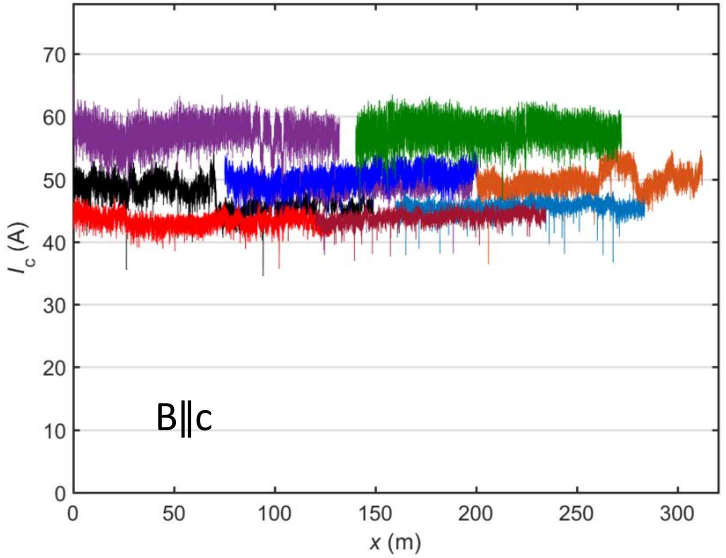
Received: 2010-2012



Received: 2013-2014



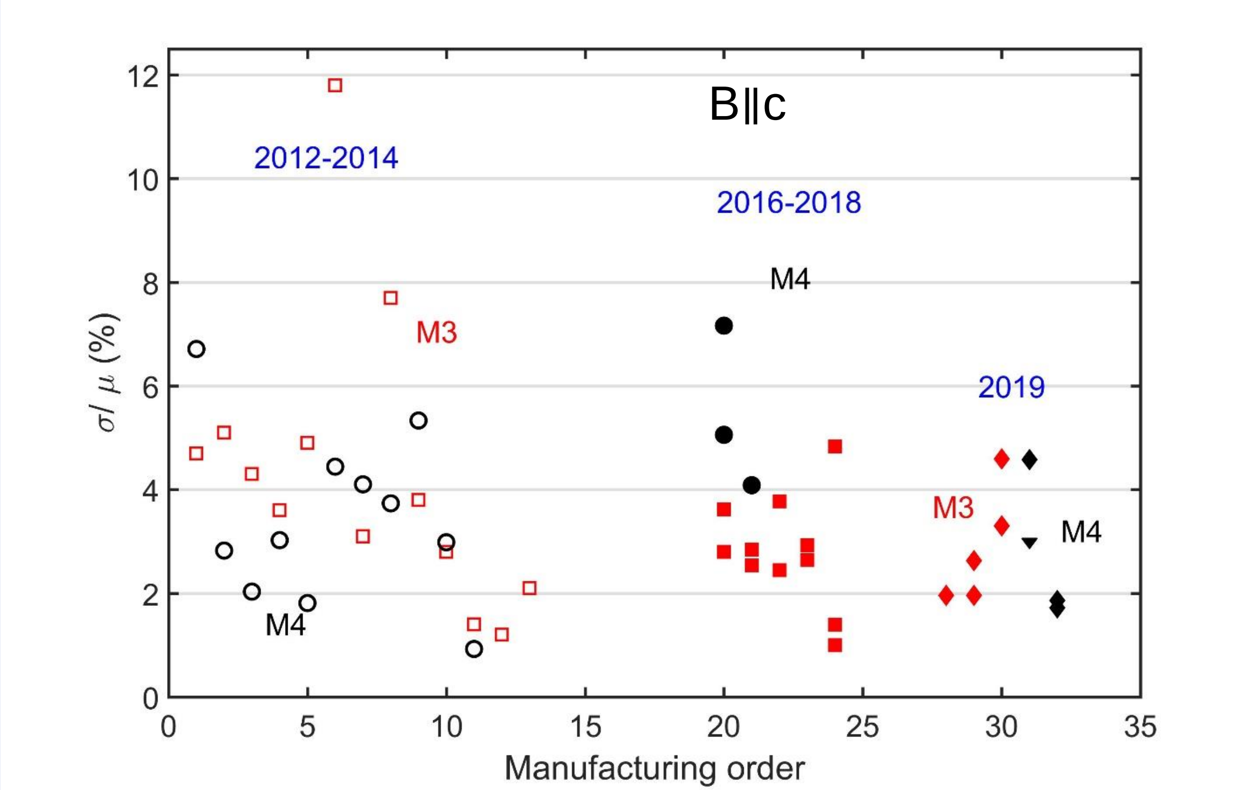
Received: 2019



- Much longer tapes are available in recent years

No obvious improvement of I_c uniformity since 2014

σ: standard deviation
μ: mean value
σ/μ: relative standard deviation of $I_c(x)$



- The relative standard deviations are calculated from the transport data.
- The I_c variations can probably arise from the intrinsic features of the manufacturing method.

Statistical analyses of I_c variations by Fourier transform

- Longer length in real space corresponds to lower frequency in Fourier transform.
- The area under the power spectrum (or power spectral density) is the variance of $I_c(x)$.

$$S(f) = \frac{|F(f)|^2}{2T}$$

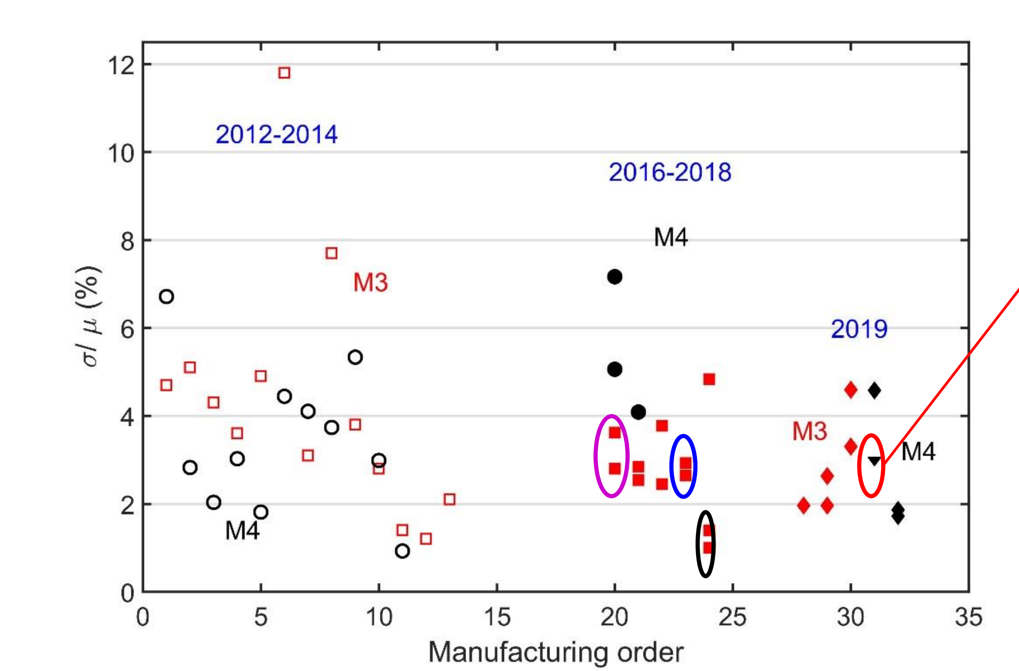
$$\sigma^2(f_1, f_2) = \int_{f_1}^{f_2} S(f)\, df = \int_{f_1}^{f_2} f S(f)\, d\log f$$

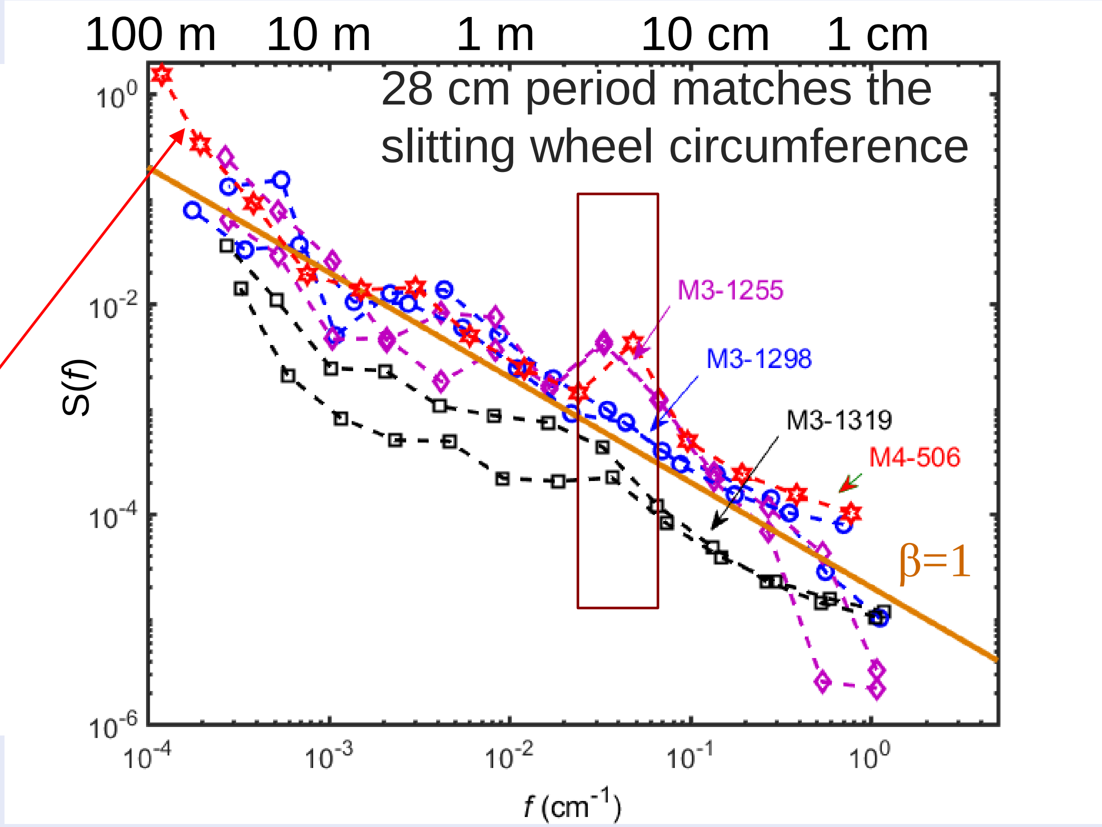
In log-log scale, the I_c variation (noise) can be depicted by a slope index β:

$$S(f) \propto f^{-\beta}$$

NATIONAL MAGLAB

Recent tapes (2016-2018) with σ/μ 2-4% have β values ~1 (Pink noise)

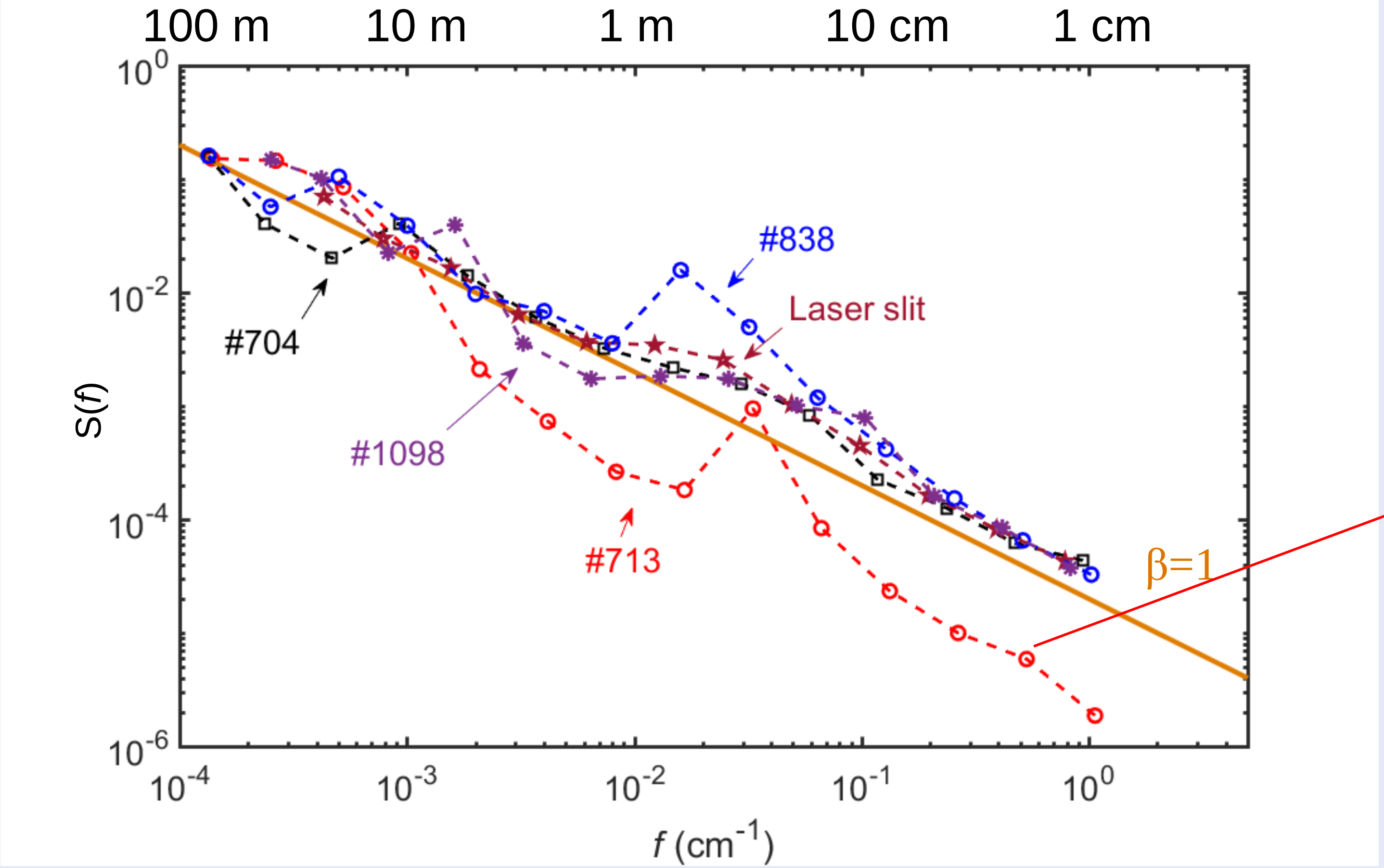


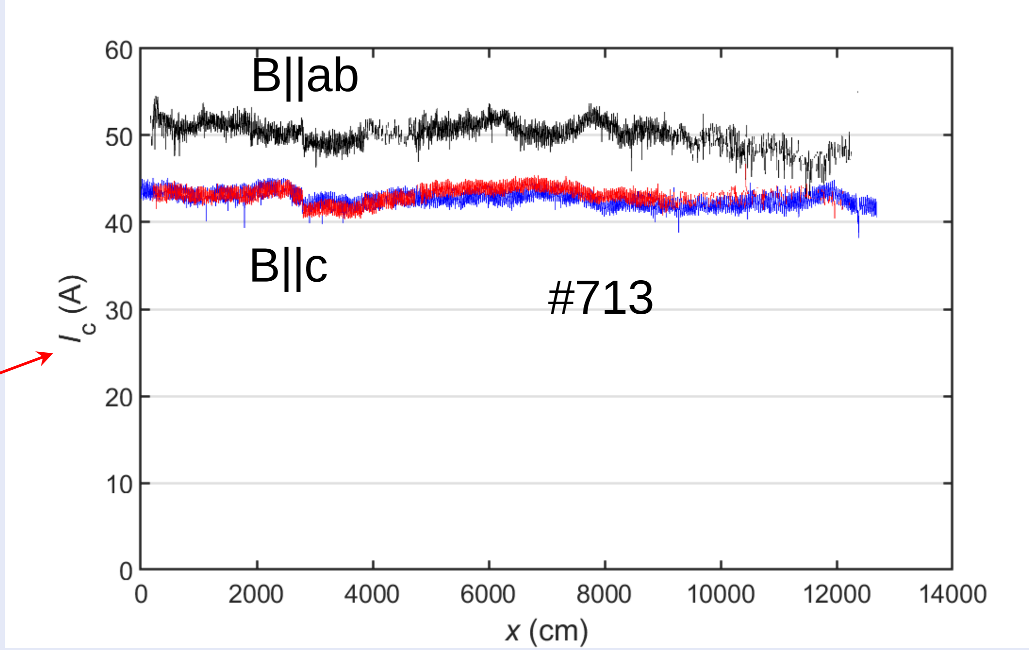


- Most points fall on the line $S(f) \propto f^{-1}$, the deviation mainly occurs in the region corresponding to the slitting wheel. Artificial effects may also come from the slitting cracks, which can be revealed in the high frequencies.
- The Fourier transform peak caused by the slitting wheel is still there and appears in tapes randomly.

NATIONAL MAGLAB NSF ASC

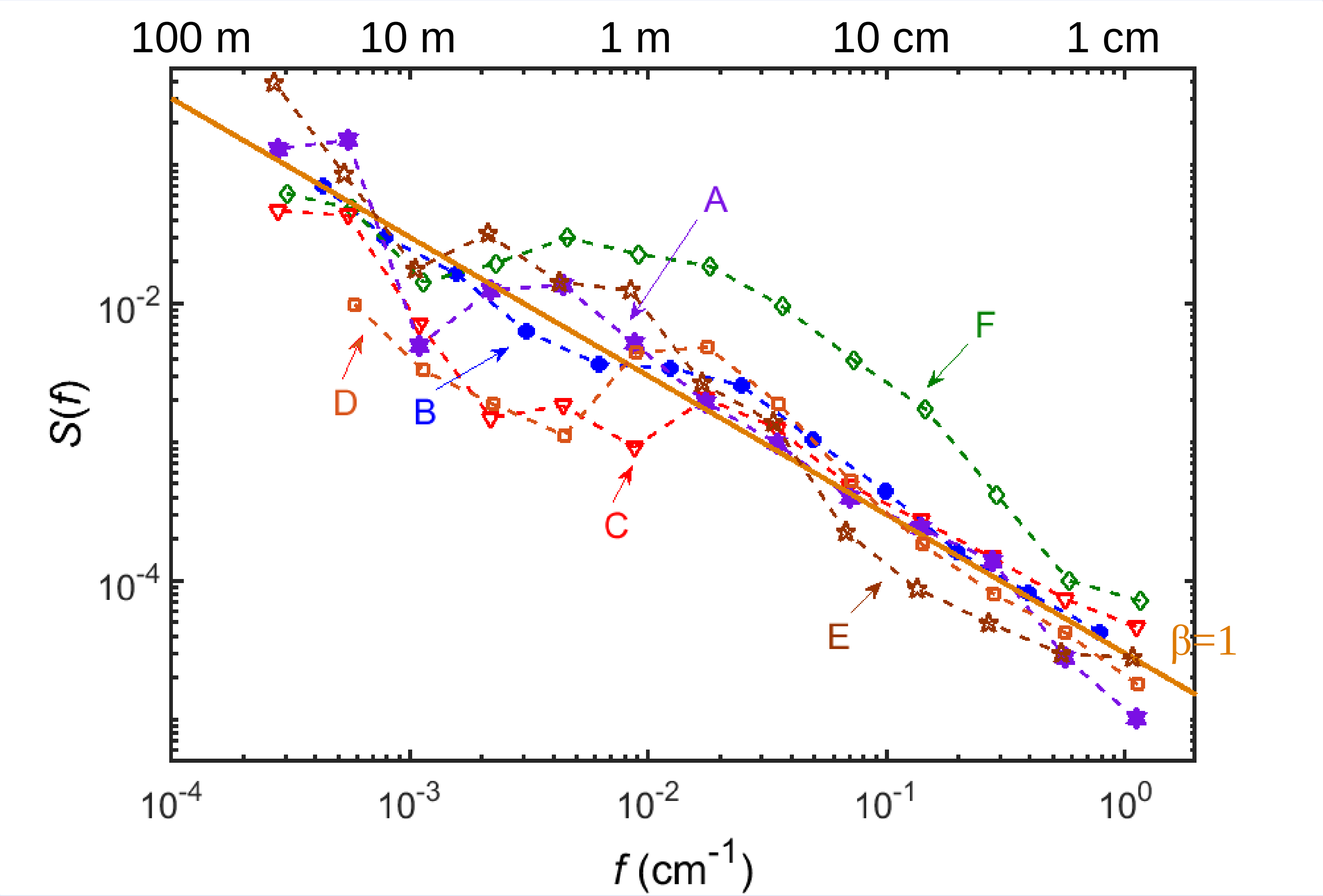
Manufacturer B: relatively better uniformity in the range of 1-10 m





- In general, good uniformity in long length scale.

Cross-comparison: a global β =1 still holds for most tapes – but with huge fluctuations depending on the length scale



Manufacturer C and D have better uniformity in the scale between 1- 10 m.

Summary

- What can YateStar tell us?
  - The vortex pinning variations exists and can only be characterized by transport measurements
  - Edge quality has been overlooked before, but now can be carefully examined
- How is the uniformity of tapes from different manufacturers?
  - The uniformity of tapes has plateaued for many manufacturers, further improvement may come from the slitting
  - Some manufactures have better control of I_c uniformity than others in the length scale of 1-10 meters.