AC Losses of Roebel Cables with Striated 2G YBCO Strands

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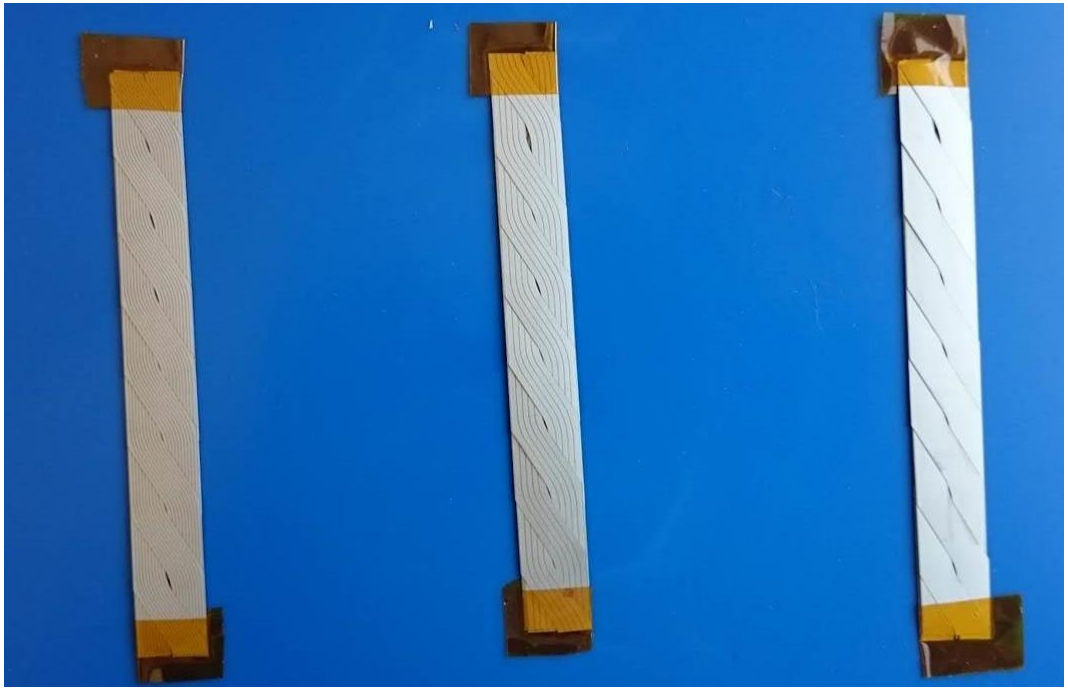
Contents

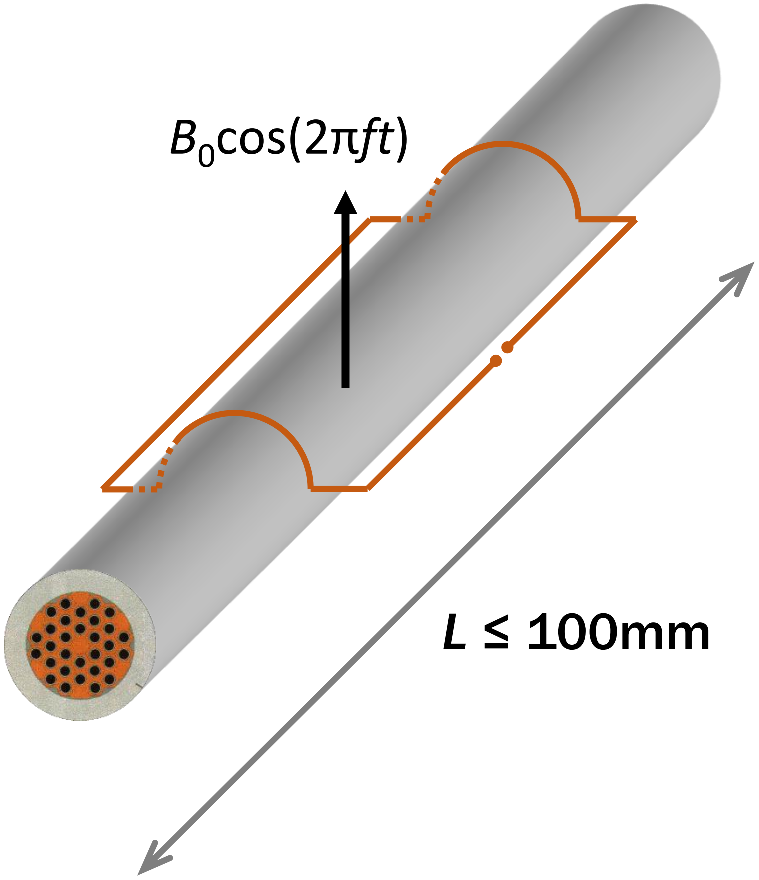
Methods: Samples by KIT

- 5.5mm wide Roebel strands formed by laser cutting
- Striation by laser scribing (5 and 10 filaments per strand)
- Post-oxidation for inter-filament resistance control



Methods: AC Loss Measurements

- ❑ <u>Applied sinusoidal field</u>
  - $B_0 \leq 0.2$ T
  - 5Hz ≤ f ≤ 2kHz
- ❑ <u>Measurements</u>
  - 3K ≤ T ≤ 100K
  - Single-turn saddle pick-up coil
  - Sample length L ≤ 100mm



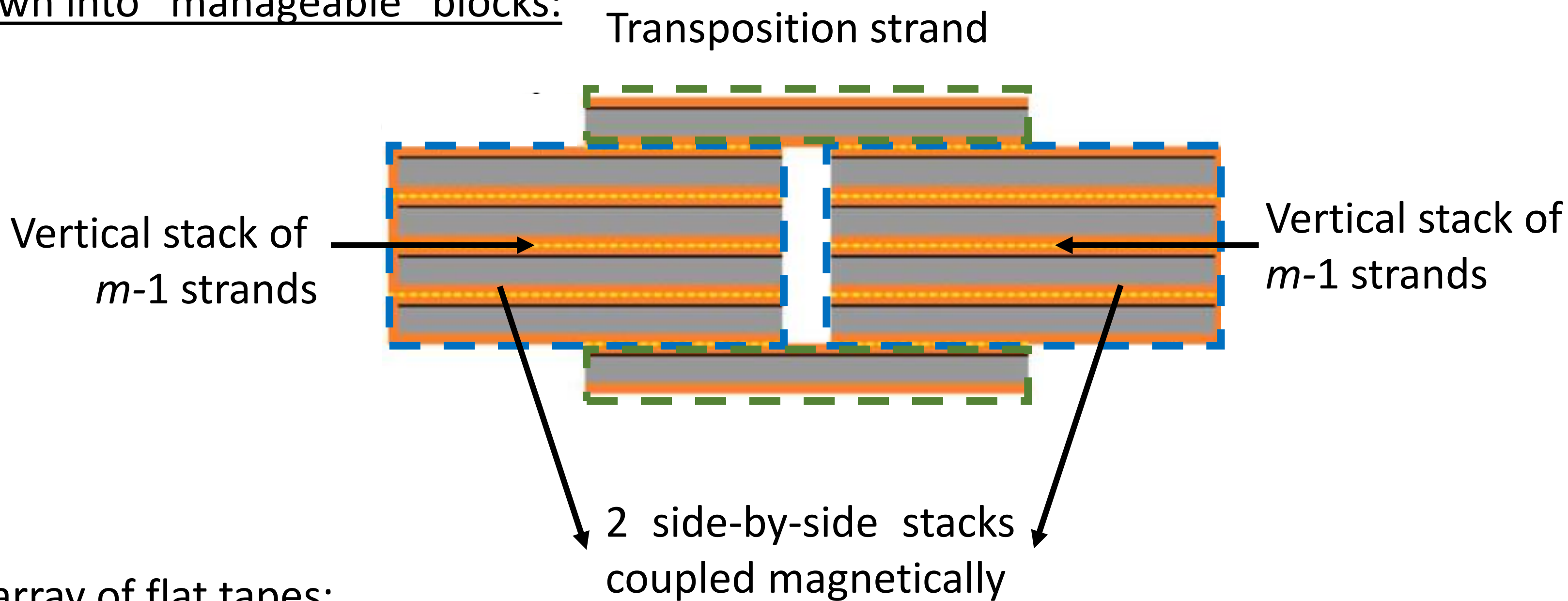
❑ **Strength**: Wide frequency range for detailed probing of the coupling current: *essential for twisted filaments.*

❑ **Limitation**: No DC field

❑ **Mitigation**: Extended range of temperature

A Semi-Quantitative Analysis of Losses in "Standard" Roebel Cables (1)

Breakdown into "manageable" blocks:



Isolated array of flat tapes:

Details modelled in 2d by Pardo, *Phys Rev B* 67 (2003)

3D necessary?

The blocks are quite simple:

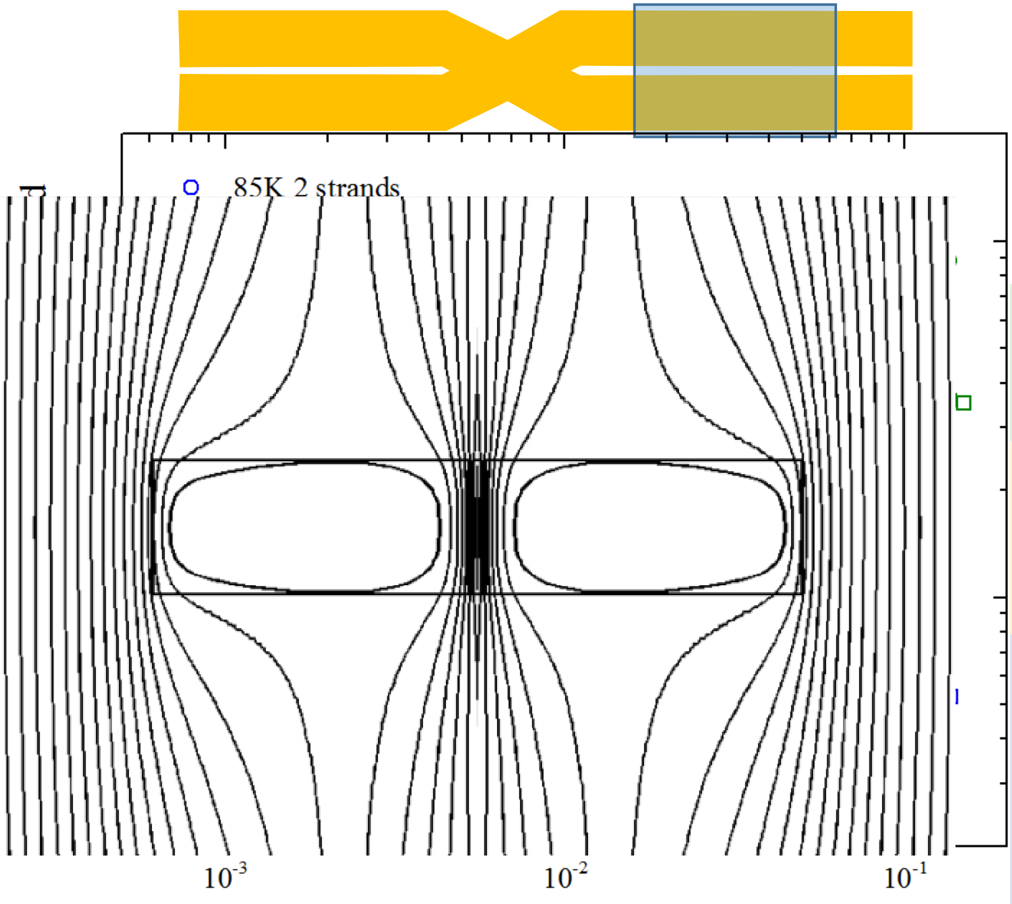
Vertical stacks are closely packed and should remain almost strip-like

Only 2 stacks interact magnetically side-by-side

Transposition isolated?

A Semi-Quantitative Analysis of Losses in "Standard" Roebel Cables (2)

2 strips side by side: less than full coupling?



Thin strip loss factor per unit volume:

$$\Gamma(\beta) = \frac{Q}{2\mu_0 H_0^2 S} = \frac{\pi}{5}\frac{w}{d}\beta^{-1}\left(\frac{4}{5\beta}\ln\left(\cosh\left(\frac{5\beta}{2}\right)\right) - \tanh\left(\frac{5\beta}{2}\right)\right)$$

$$\beta = \frac{H_0}{H_P}, \qquad H_P = \frac{5}{2\pi}\sigma_c = \frac{5I_c}{2\pi w}$$

A. Two strips far apart: Uncoupled (UC)

$$\Gamma_{2\times UC} = \Gamma_s, H_{P,UC} = H_{Ps}$$

B. Two side-by-side strips electrically connected: Fully coupled (FC)

$$\Gamma_{2\times FC} = 2\Gamma_s, H_{P,FC} = H_{Ps}$$

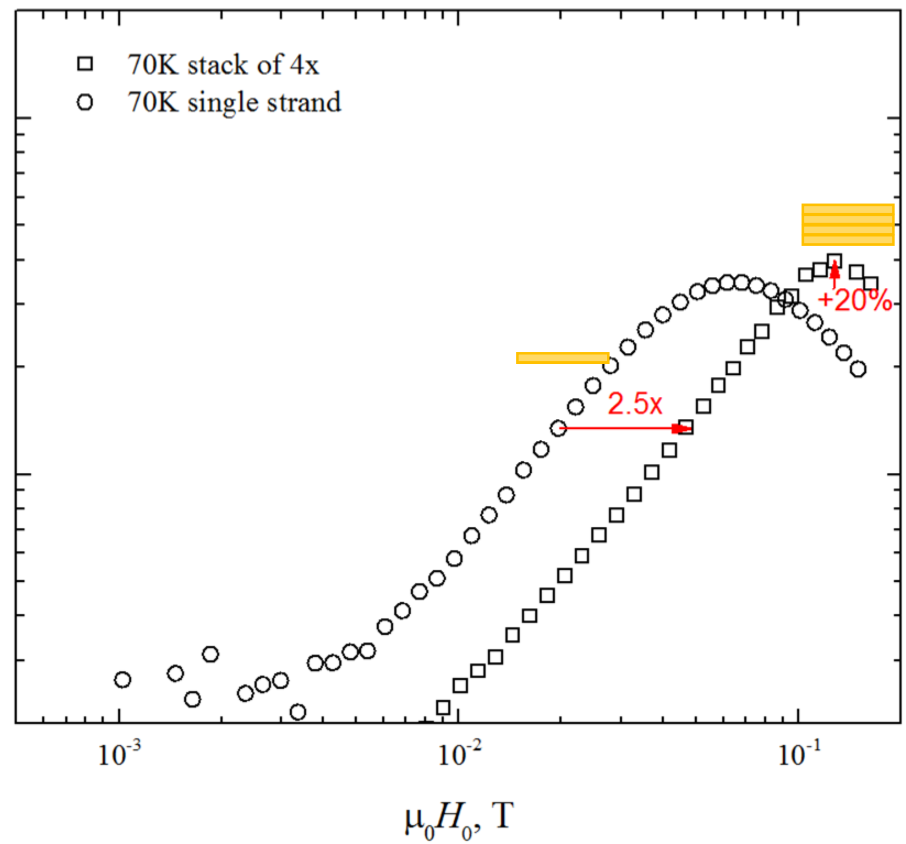
C. Two isolated side-by-side strips: magnetically coupled (MC)

$$\Gamma_{2\times MC} \sim \sqrt{2}\Gamma_s, H_{P,MC} \sim 0.75 H_{Ps}$$

Higher loss than UC and lower H_P due to flux compression in between

A Semi-Quantitative Analysis of Losses in "Standard" Roebel Cables (3)

Stack of 4 strands: less than expected H_p



A. Stack of *m* **zero** thickness strips should increase $\sigma_{cm} = m\sigma_c$ and $H_{Pm} = mH_{Ps}$ so that $\Gamma_m(\beta) = m^{-1}\Gamma_s(m^{-1}\beta_s)$

B. Finite thickness appears to reduce the saturation field

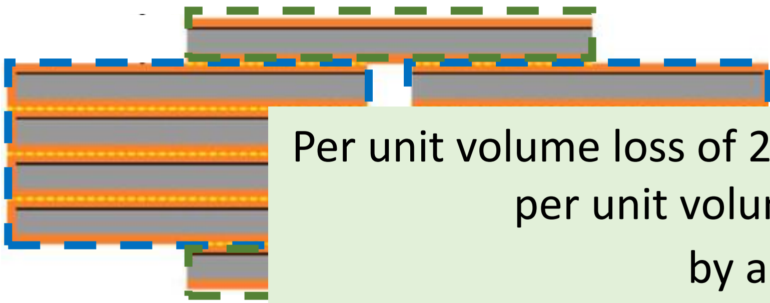
$$H_{Pm} = \frac{m}{1.6} H_{Ps}$$

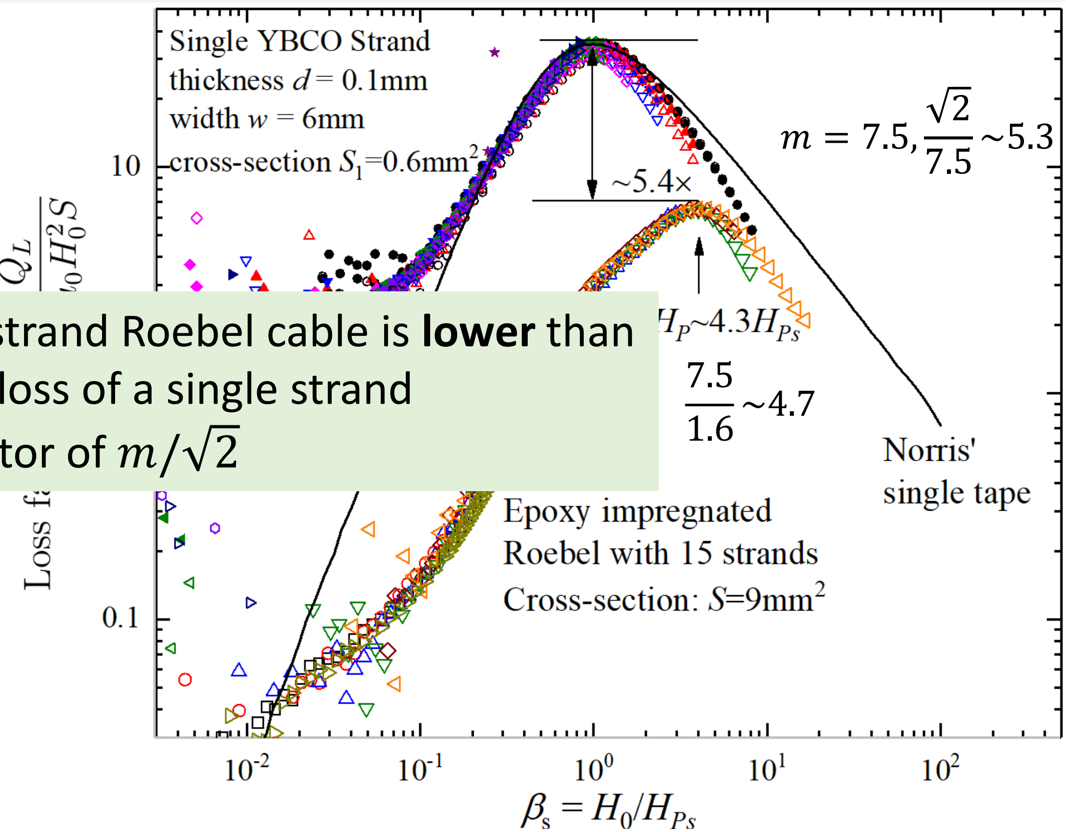
C. The loss factor of a finite thickness stack

$$\Gamma_m(\beta) \sim m^{-1}\Gamma_s(1.6m^{-1}\beta_s)$$

A Semi-Quantitative Analysis of Losses in "Standard" Roebel Cables (4)

Putting two stacks side-by-side





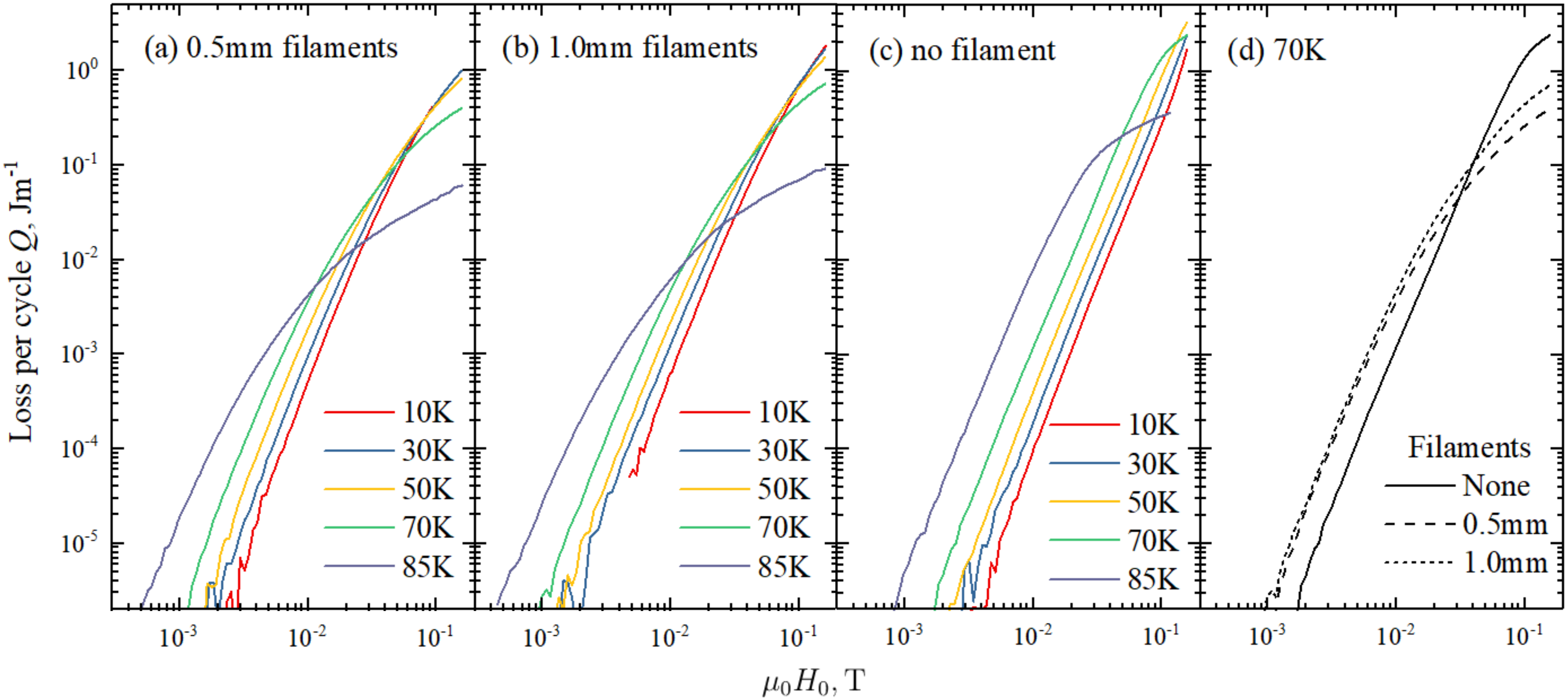
Per unit volume loss of 2m-strand Roebel cable is **lower** than per unit volume loss of a single strand by a factor of $m/\sqrt{2}$

The combined loss:

$$\Gamma_m(\beta) \sim \frac{\sqrt{2}}{m} \Gamma_S \left(\frac{1.6}{m} \beta_S \right)$$

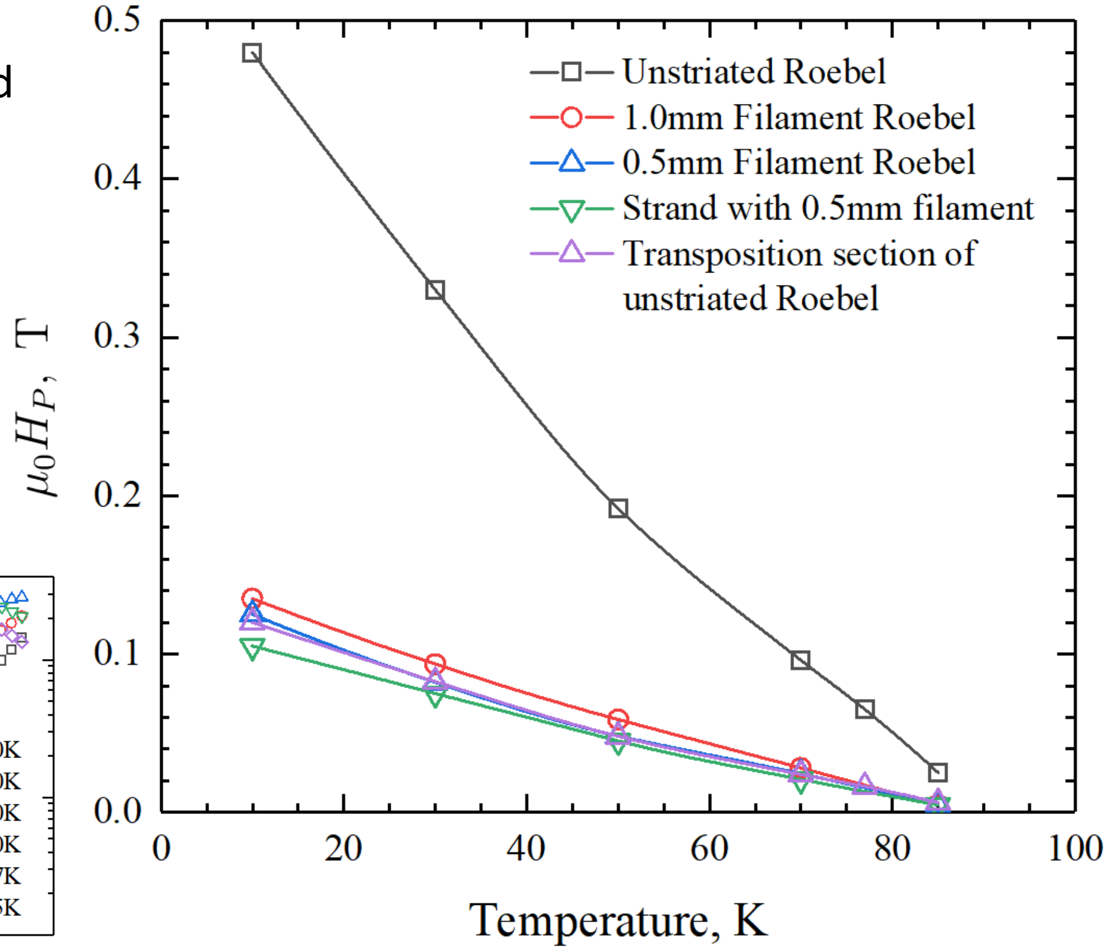
Magnetisation Loss in Striated Roebel Cable (1)

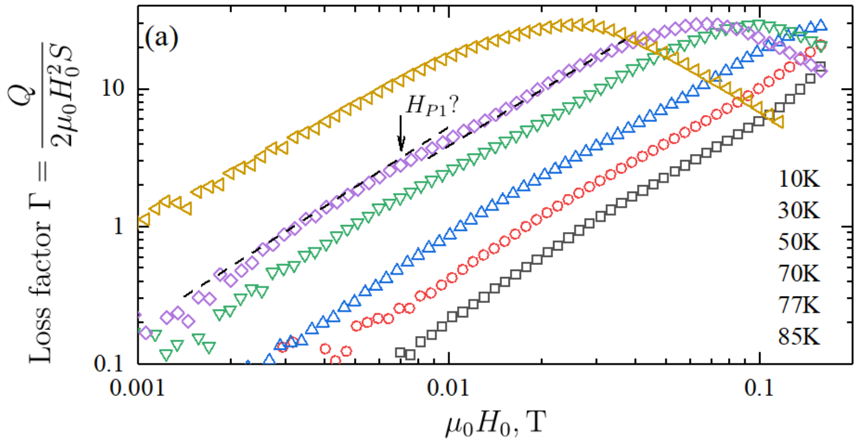
Losses of striated Roebel are lower at high fields



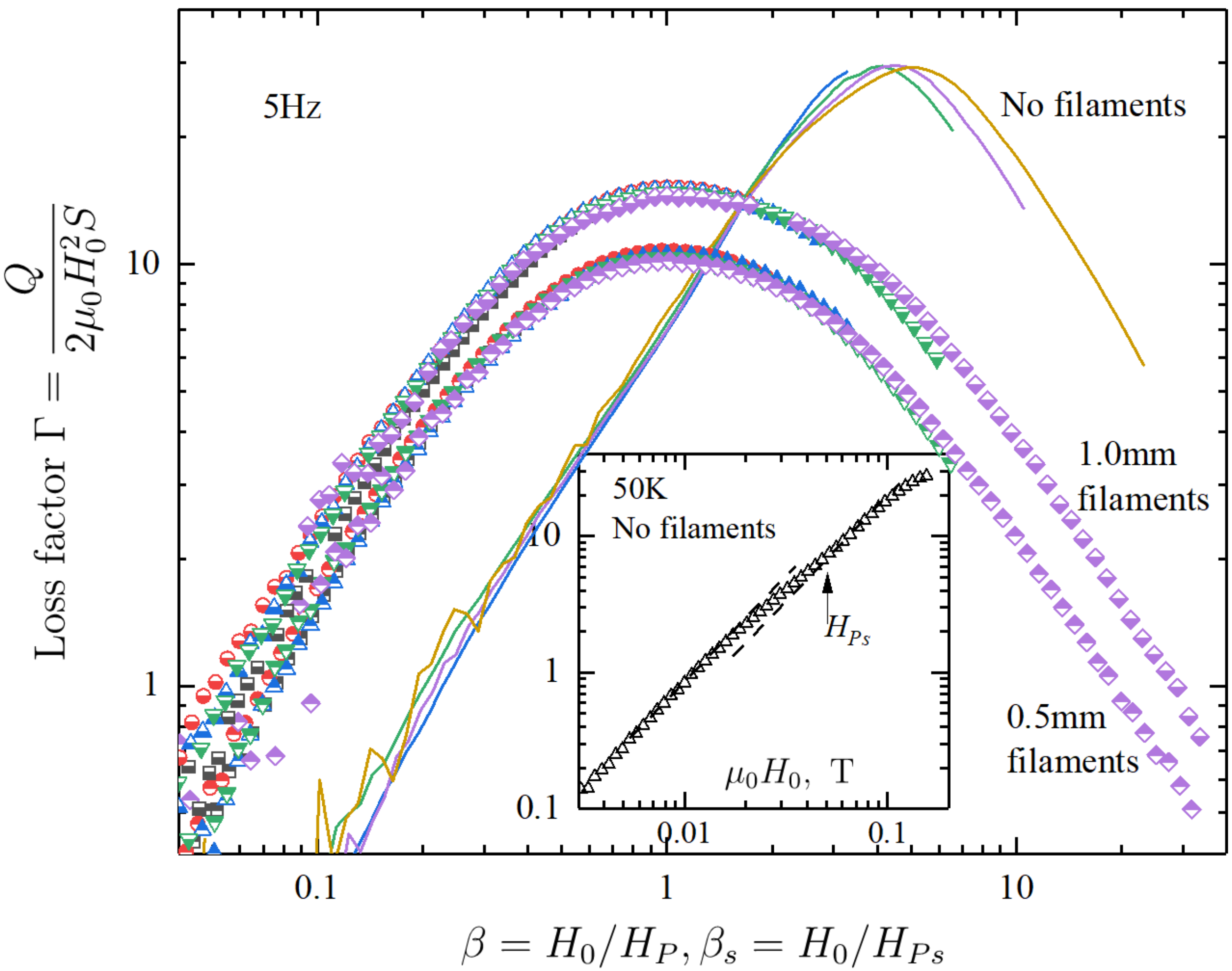
Saturation Fields of Striated Roebel Cable

A. The saturation field of unstriated Roebel is about 4x of that for striated
B. The saturation field of the striated Roebel are similar for different filament size
C. The kink at H_{Ps} still visible in the unsaturated and very similar to the H_p of the striated. (could be by chance)



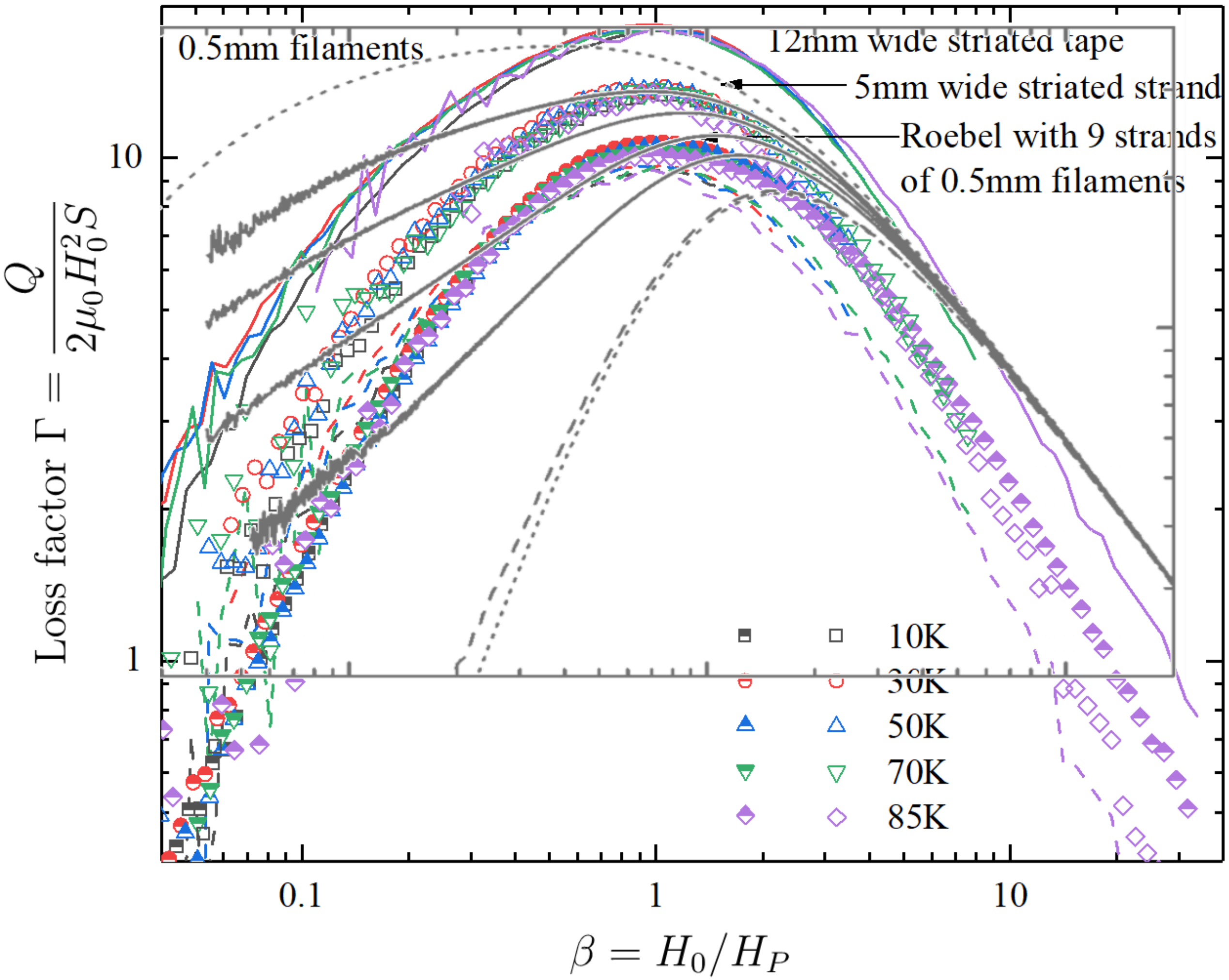


Magnetisation Loss in Striated Roebel Cable reduced by a factor of the filament number



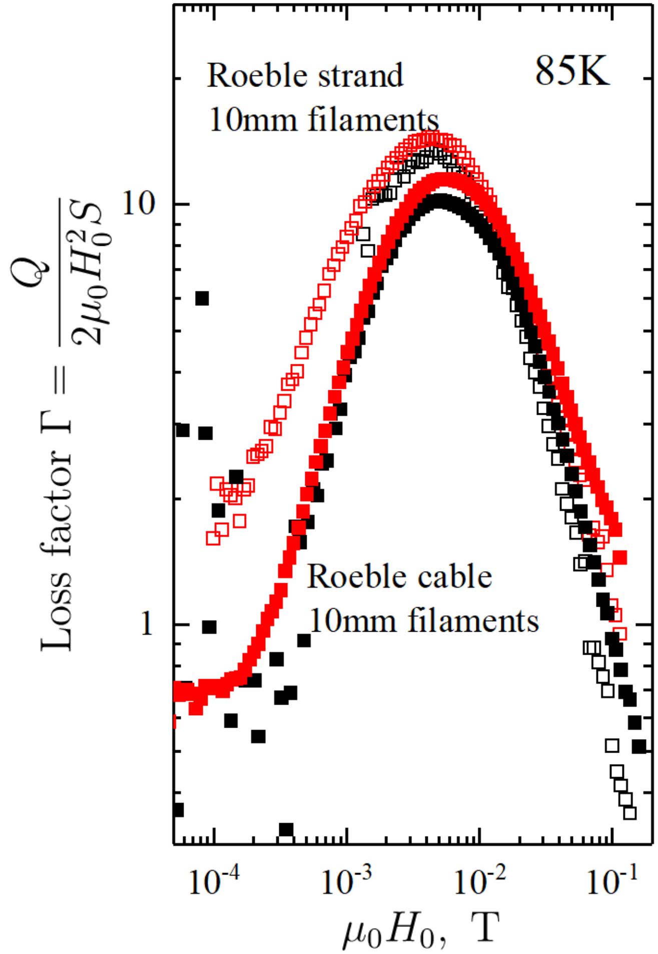
Flux penetration and $\Gamma(\beta)$ of the striated strand and Roebel

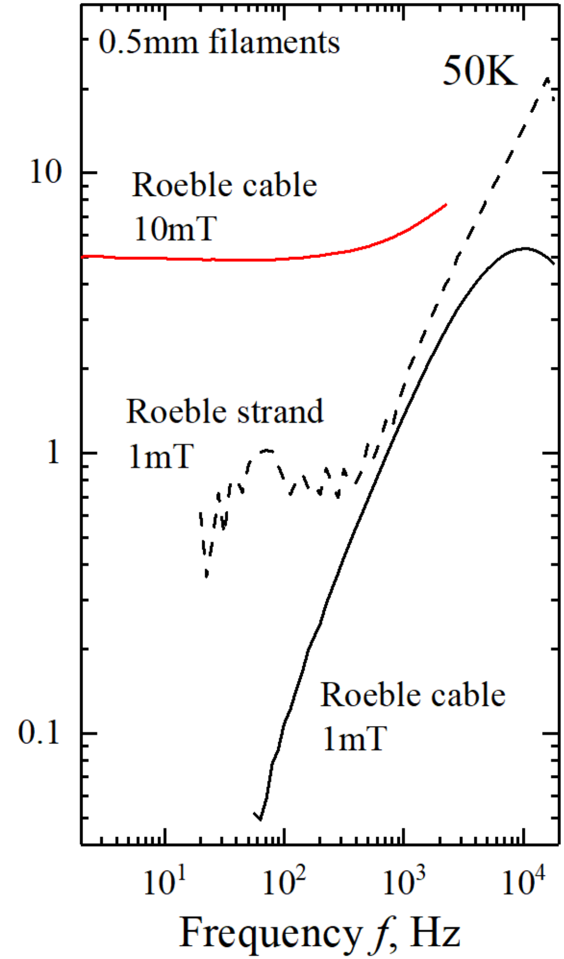
A. Similar $\Gamma(\beta)$ for striated strand and Roebel cable
B. Although $\Gamma(\beta)$ is broader than that of a single trip, it's not as much as predicted.
C. More understanding required



Coupling current Losses

A. Coupling current is present but small.
B. Dominates mostly at low fields when the magnetisation loss is small
C. Time constant in Roebel cable is about 0.1ms
D. High inter-filament resistance due to improved oxidation after laser scribing





Conclusions

1. A semi-quantitative analysis of unstriated Roebel seems to work reasonable well:
    - Simply 2 sidewise *magnetically coupled* stacks of strip-like strands
    - Isolated penetration of the transposition strand
    - loss per unit volume of 2*m*-strand Roebel lowered by a factor $m/\sqrt{2}$ from that of a single strand
2. Striated Roebel has a lower loss than that of unstriated by a factor of the filament number per strand
3. Coupling current loss is low with a very short time constant of 0.1ms
4. More understanding required for the losses of striated Roebel as a function of field