

Transport AC Loss Measurements in Bifilar Stacks Composed of YBCO Coated Conductors

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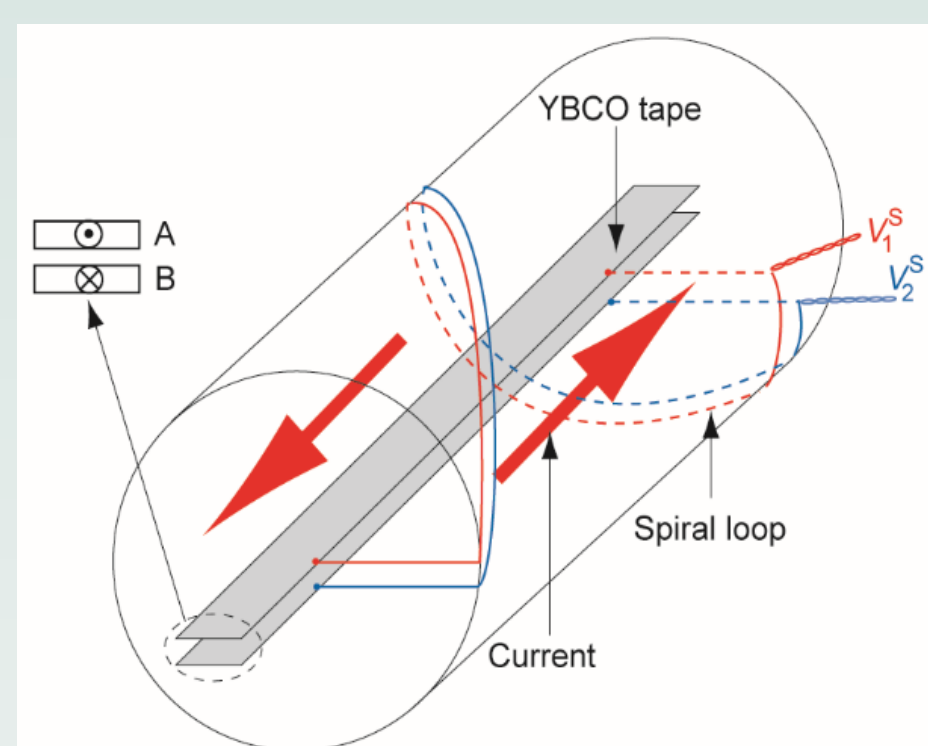
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Introduction

- Large power ratings of HTS resistive type fault current limiters (FCLs) needs to increase current-carrying capacity of wire by stacking coated conductors (CCs) [1]-[4].
- Bifilar coil design has been proven to be an effective solution for AC loss reduction in resistive type FCLs wound with HTS CCs [5]-[9].
- It is therefore important to investigate AC loss characteristics in conductor arrangements with varying conductor numbers.
- We have built three bifilar stacks with two, four, and six conductors using 4 mm-wide YBCO wires to investigate AC loss dependence of bifilar stacks on the number of conductors.
- In the three basic configurations (AB, AABB, and AAABBB), the upper half conductors carry current in one direction, and the lower half conductors carry current in the opposite direction.
- We report transport AC loss results on bifilar stacks
 - measured at three different frequencies
 - compare with those in stacks with the same conductor number and geometry but producing different degrees of field cancellation
 - explore the dependence of AC loss on a central gap in bifilar stacks
 - verify with the numerical results by FEM method

Measurement method [10]



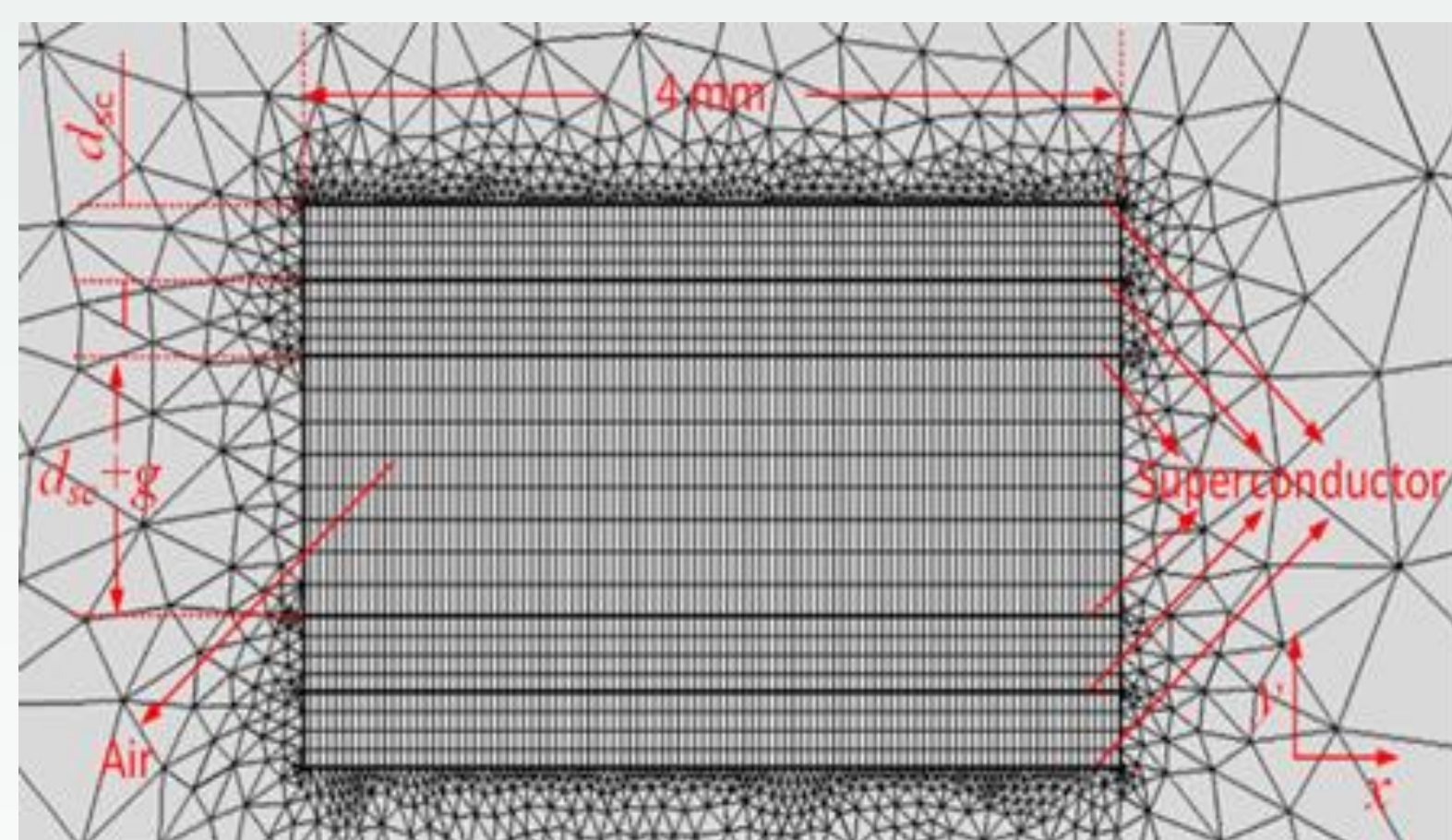
Spiral loop arrangement for stack AB

$$Q_t = \frac{I_{rms}}{dfN} \left(\sum_i V_i^s \right)$$

Geometric details of the stacks

Stack name	Conductor number	Net current (A)
AB	2	0
AABB	4	0
AAABBB	6	0
A	1	I
AA	2	≈ 2I
AAAA	4	≈ 4I
AABB-g	4	0
ABAB	4	0
AAAAA	6	≈ 6I
AAABBB-g	6	0
ABABAB	6	0

Numerical method



2D model geometry and structured mesh for the YBCO layer in six-tape stack

$$E = E_c \left(\frac{J}{J_c(B)} \right)^n \quad J_c(B) = J_{c0} \left(1 + \frac{|B_{\perp}|}{B_0} \right)^{-1}$$

- $J_c(B)$ is the critical current density dependence on magnetic field, $E_c = 10^{-4}$ V/m, and $n = 30$.
- For the $J_c(B)$ relationship, we have used a modified Kim model [11], where J_{c0} and B_0 are constants determined from the measured E - I curve of sample A under perpendicular magnetic field, B_{\perp} .

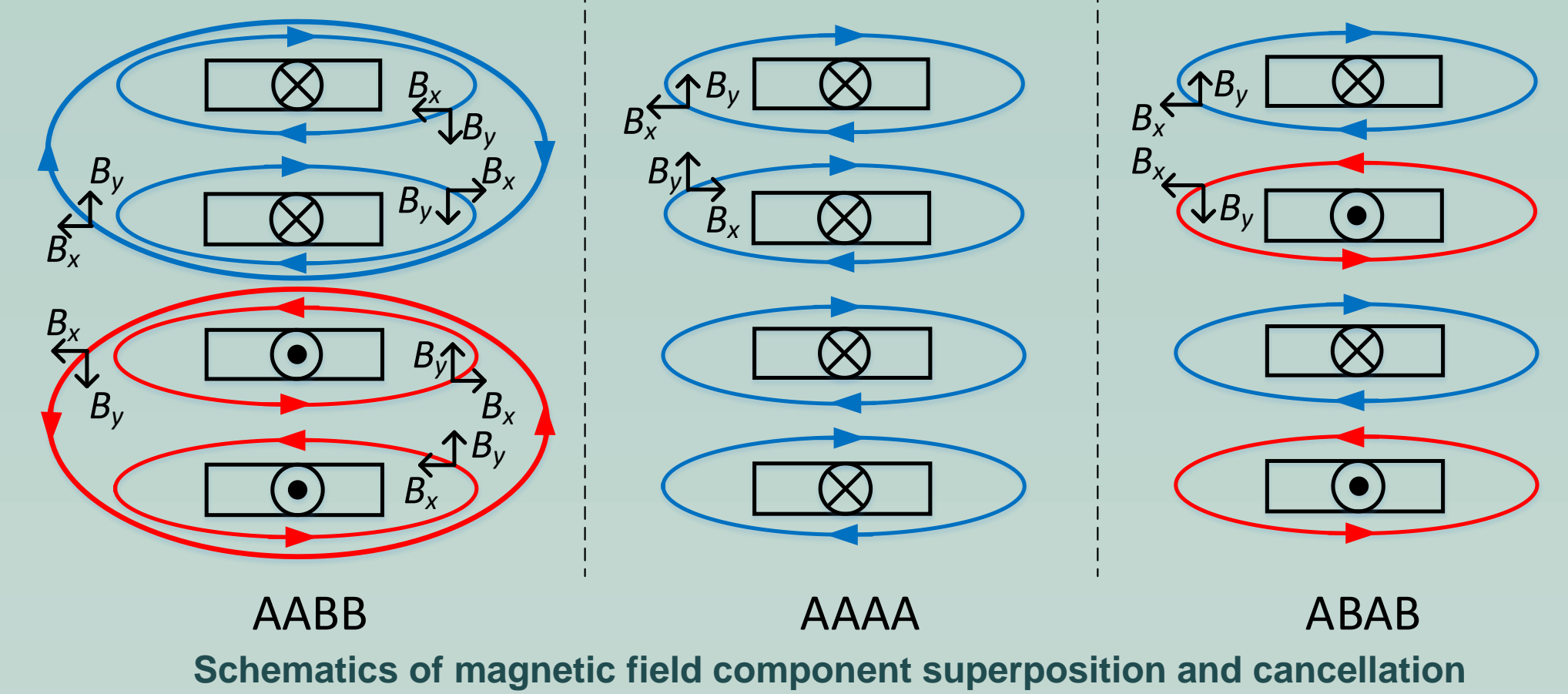
Reference

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Results- I_c measurement

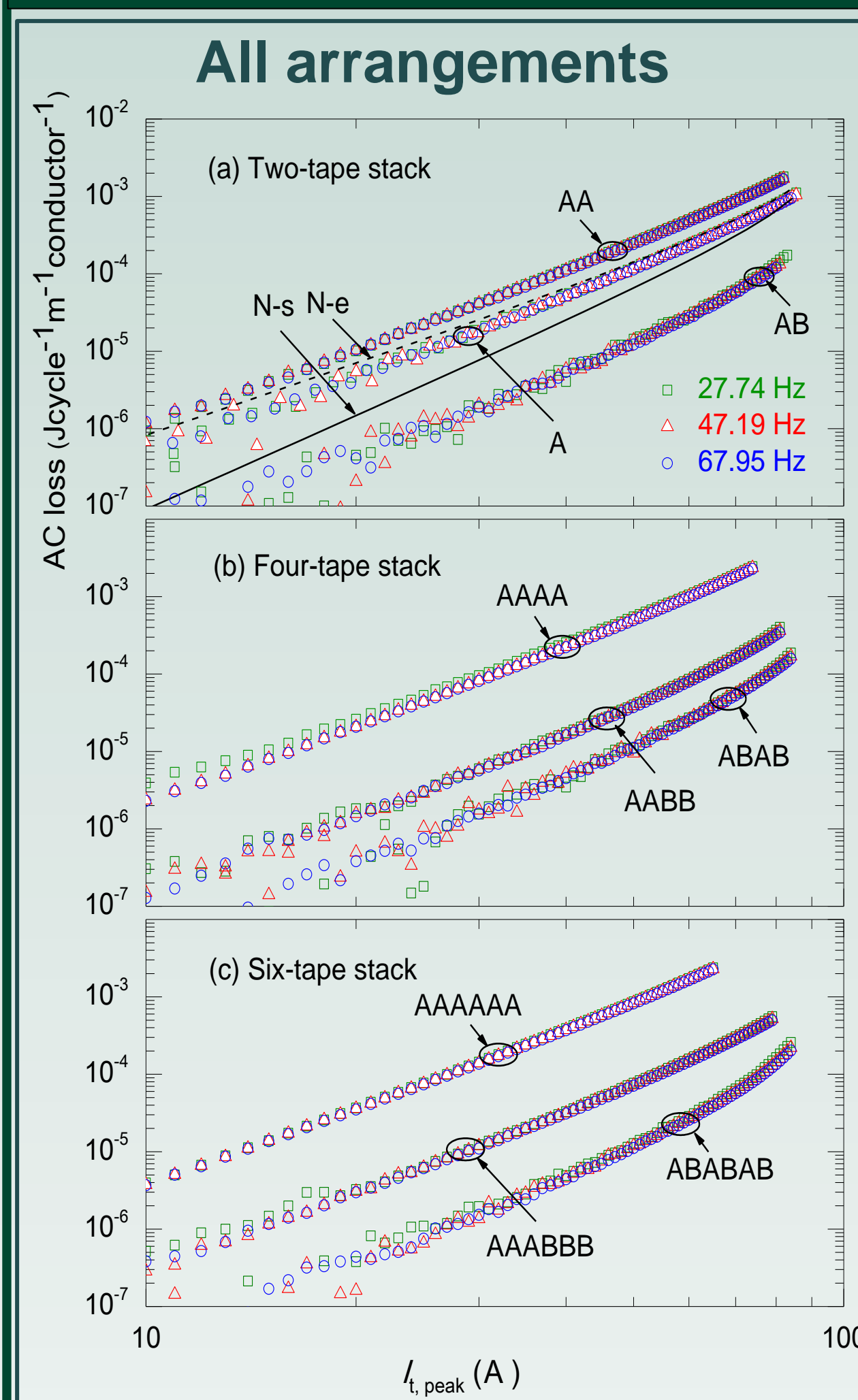
Critical current measurements in stack assemblies						
	T-1	T-2	T-3	T-4	T-5	T-6
Self-field I_c (A)	87.67	87.49	87.11	87.72	87.73	87.03
I_c in AB (A)	86.74	86.92				
I_c in AA (A)	84.32	86.86				
I_c in AABB (A)	87.30	86.00	82.19	87.36		
I_c in AAAA (A)	78.88	78.90	81.11	81.86		
I_c in AABB-g (A)	85.23	82.25	81.92	85.52		
I_c in ABAB (A)	88.20	88.22	88.65	88.13		
I_c in AAABBB (A)	88.22	85.09	82.41	79.13	82.87	87.47
I_c in AAAAAA (A)	72.99	72.60	74.73	76.02	74.94	75.04
I_c in AAABBB-g (A)	86.52	84.26	82.84	79.43	82.73	85.26
I_c in ABABAB (A)	89.35	85.91	88.05	88.47	89.47	87.37

- I_c (AAAA) < I_c (AABB) < I_c (ABAB)
- I_c (AABB-g) < I_c (AABB)

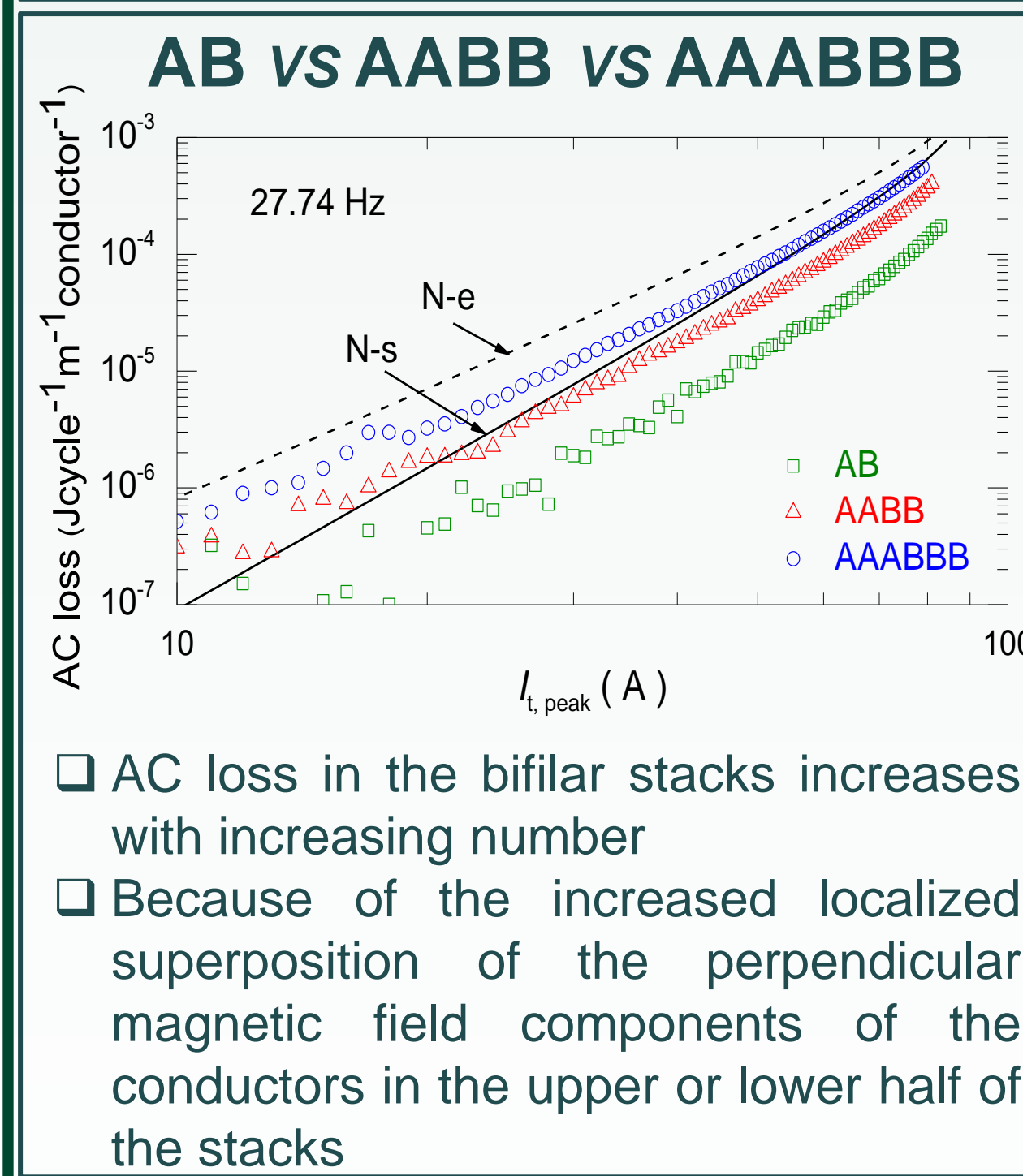


- AAAA, strong superposition of perpendicular magnetic field
- ABAB, fine cancellation of perpendicular magnetic field
- AABB, combination of both superposition and cancellation

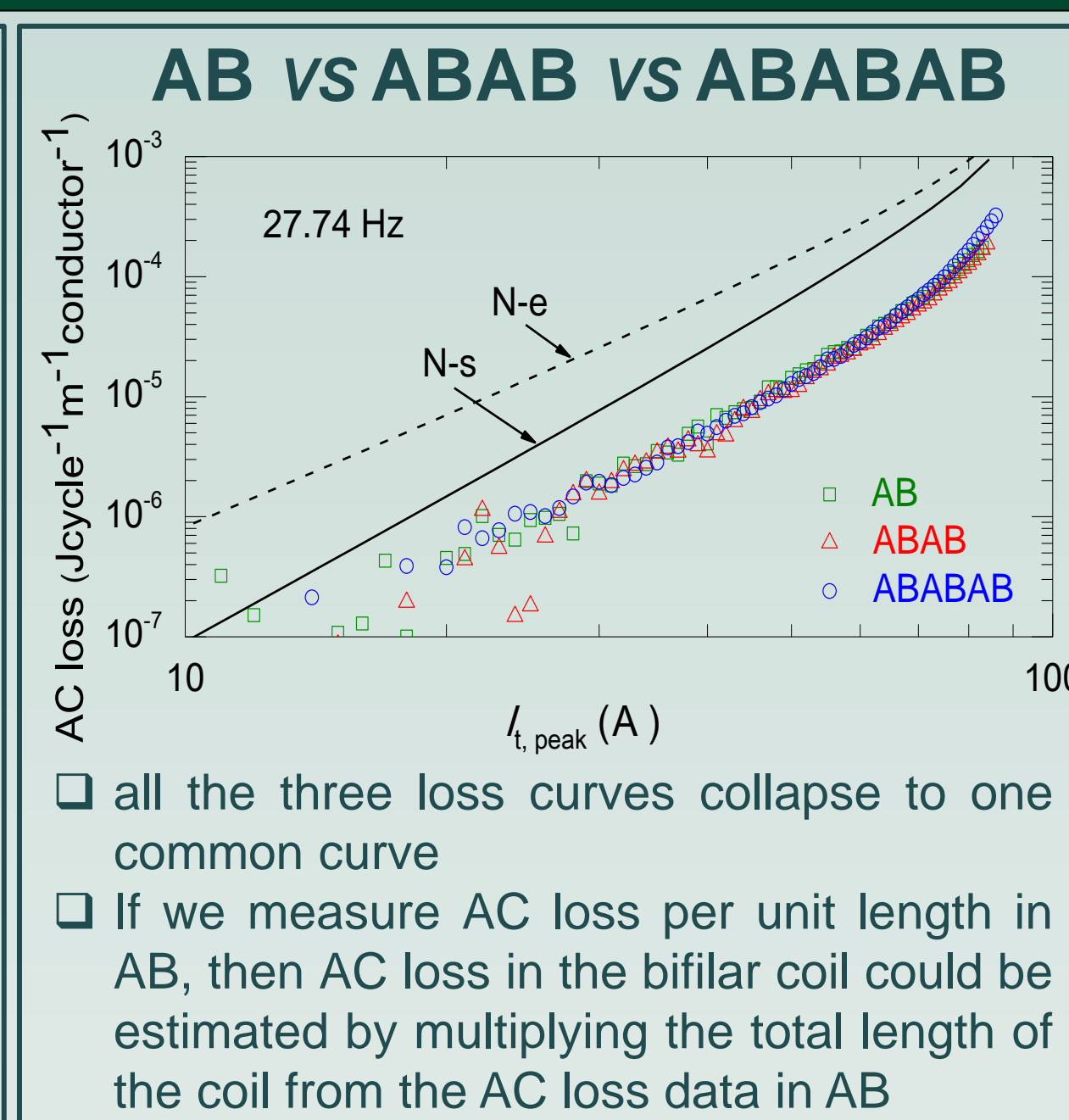
Results-AC loss measurement



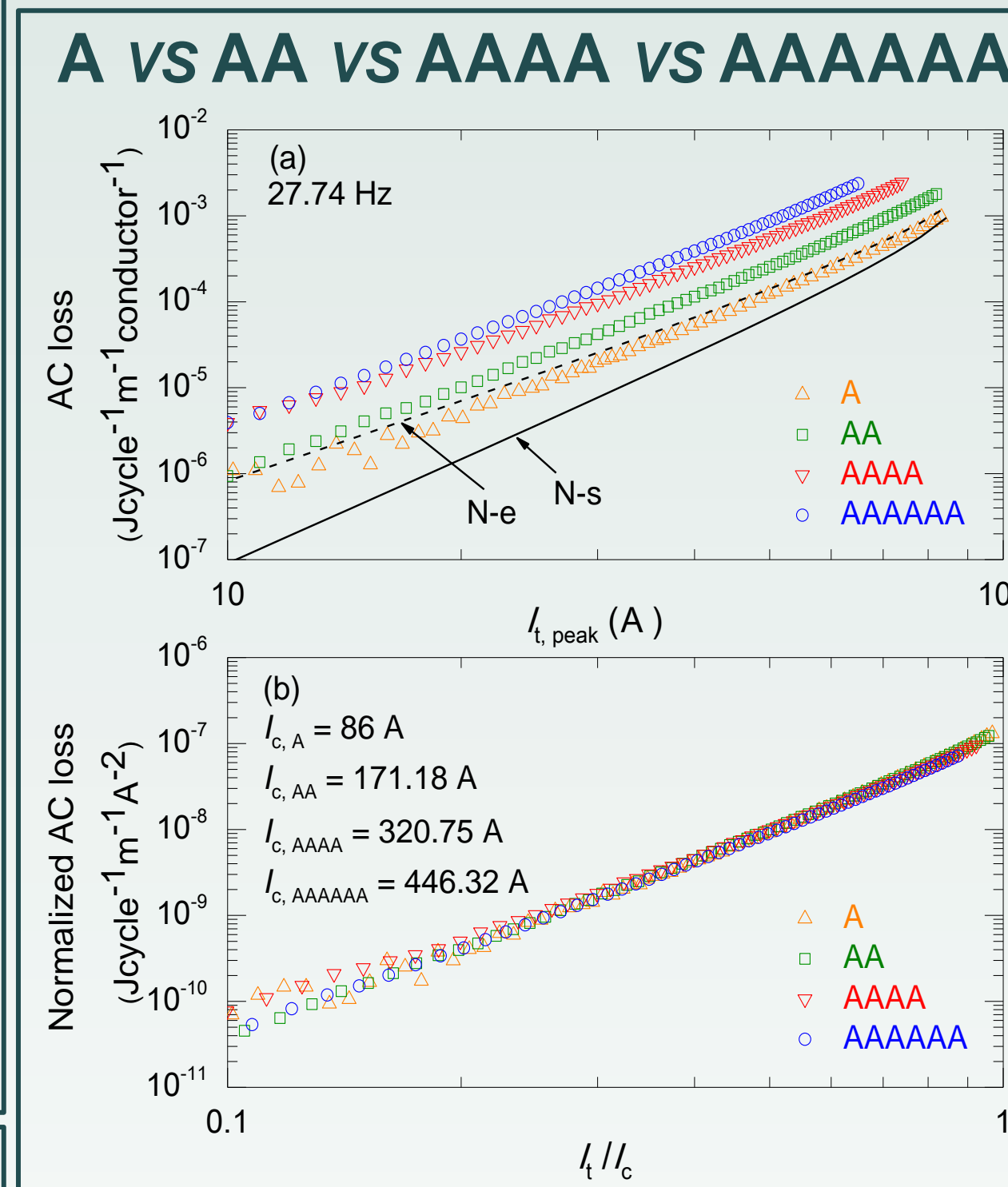
- AC loss in AA, AAAA, AAAAAA are more than one order of magnitude larger than those in AB, AABB, and AAABBB throughout the current amplitude range
- AC loss in AABB and AAABBB are larger than those in ABAB and ABABAB
- Q_{AABB}/Q_{ABAB} and Q_{AAABBB}/Q_{ABABAB} are markedly smaller than Q_{AAAA}/Q_{AABB} and Q_{AAAAAA}/Q_{AAABBB} , respectively



- AC loss in the bifilar stacks increases with increasing number
- Because of the increased localized superposition of the perpendicular magnetic field components of the conductors in the upper or lower half of the stacks

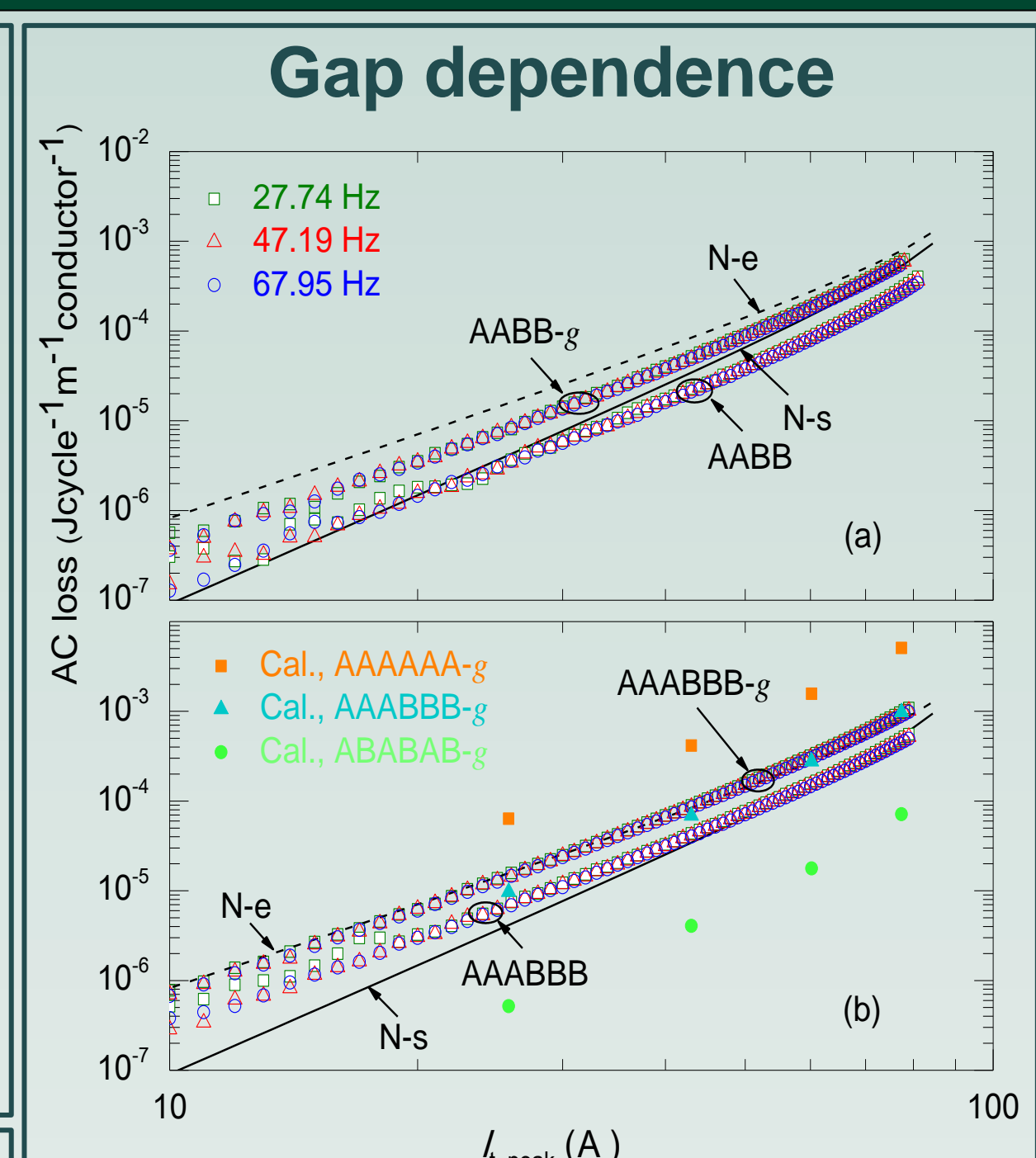


- all the three loss curves collapse to one common curve
- If we measure AC loss per unit length in AB, then AC loss in the bifilar coil could be estimated by multiplying the total length of the coil from the AC loss data in AB

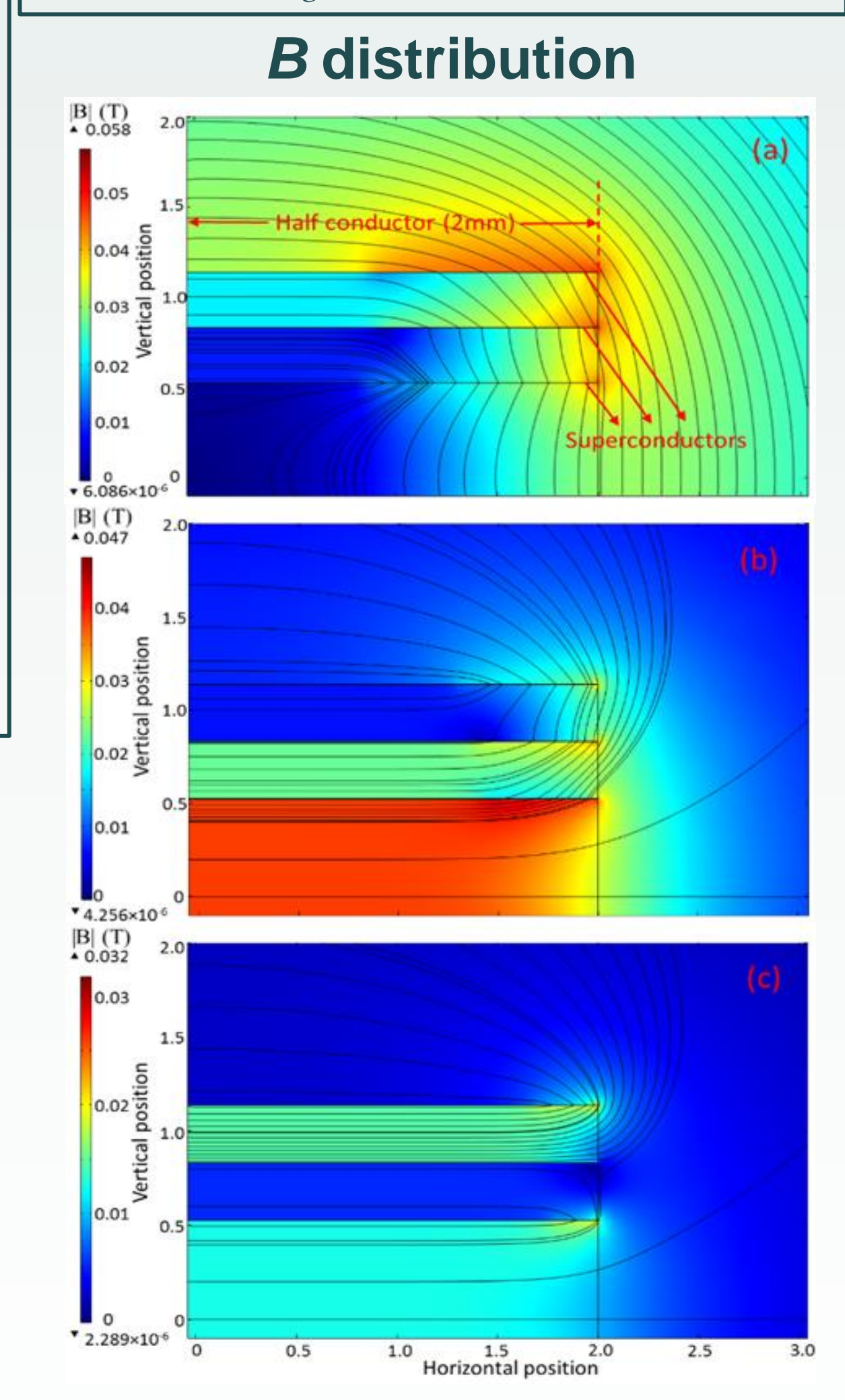


- AC loss increases with increasing the conductor number
- The normalized AC loss values for different stacks collapse to a common curve

- All three conductors in AAAAAA-g are exposed to strong perpendicular magnetic field components
- The two upper conductors in AAABBB-g are exposed to perpendicular magnetic fields while the innermost conductor is mostly exposed to parallel field or weakened perpendicular magnetic field
- All three conductors in ABABAB-g are mostly exposed to parallel fields or weakened perpendicular magnet field.
- The magnetic field range in the figures is different.



- AC loss increases due to the spacing, g
- $Q_{AABB-g}/Q_{AABB} \approx 2.5$ and $Q_{AAABBB-g}/Q_{AAABBB} \approx 2.0$ throughout the current range
- The calculated AC loss values in AAABBB-g agree with the measured ones, especially at high current amplitude
- The agreement verifies numerical model
- AC loss in AAABBB-g are smaller than those in AAAAAA-g but larger than those in ABABAB-g



Conclusion

- AC losses in bifilar stacks AB, AABB, and AAABBB were measured and compared with those in other reference stacks.
- The measured AC loss values in AAABBB-g were compared with the numerical results obtained from a 2D FEM model.
- The measured AC loss values in the bifilar stacks, AABB and AAABBB are much smaller than those in inductive stacks, AAAA and AAAAAA while larger than the values in ABAB and ABABAB, respectively.
 - The bifilar stacks where each turn is stacked with multiple wires is a promising option which compromise both high current-carrying capacity and lower AC loss for HTS FCL application.
- The AC loss in the bifilar stacks increases with increasing the number of conductors for each half of the stacks or the spacing between the two halves of the stacks.
- AC loss in the stacks scales with the macroscopic stack critical current.
- AC loss in an AB-type bifilar coil could be estimated by multiplying the total length of the coil from the loss data in AB.