Numerical Modelling of Dynamic Resistance in a Parallel Connected Four-Tape Stack of YBCO Thin Films

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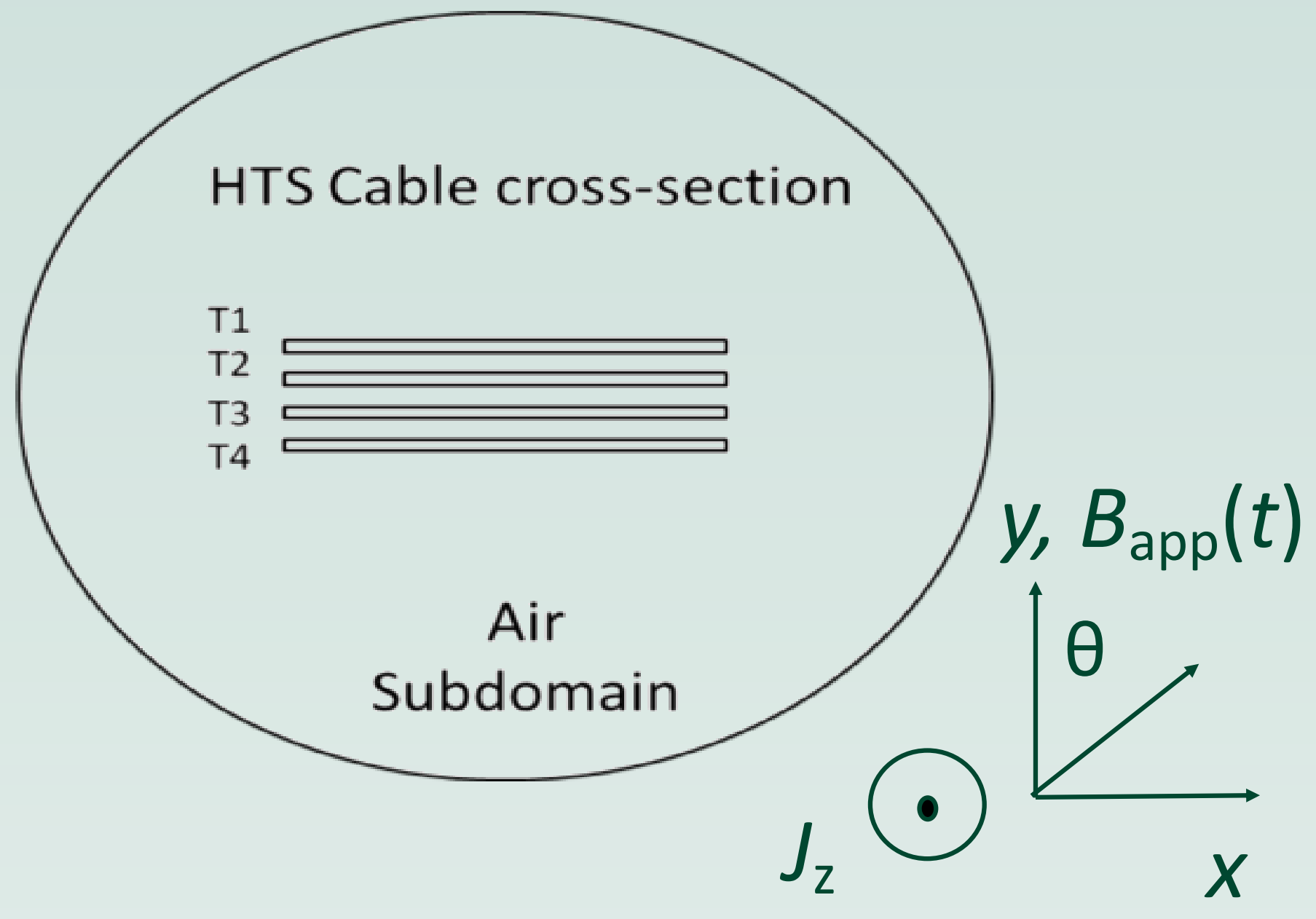
Dynamic resistance, R_{dyn}, and its importance to Devices

- Dynamic resistance is a source of dissipation in type-II superconductors carrying DC transport currents while exposed to alternating magnetic fields
- Caused by flux motion over DC current region in the superconductor
- Parasitic heat load in DC / AC magnets, flux pumps and synchronous machines. Can be used to induce a resistance in short lengths of superconductor, useful for the design of a persistent current switch
- Performing measurements on short lengths of parallel connected wires is complicated by the variation in solder resistance between wires. Thus, we present finite element analysis of the dynamic resistance in a parallel connected stack of YBCO thin films carrying arbitrary DC currents I_{DC} while exposed to sinusoidal perpendicular fields $B_{app}(t) = B_{a0}\sin(\omega t)$

Modelling Methodology

- 2-D *H*-formulation model in *xy* plane
- Simulation governed by Faraday's and Ampere's laws, electrical properties of the superconductor obey an ***E J*** power law employing measured critical current $I_c(B,\theta)$, and flux creep exponent $n(B,\theta)$ data
- 2-stage model consisting of a DC ramp followed by application of a sinusoidal perpendicular field

Model Architecture



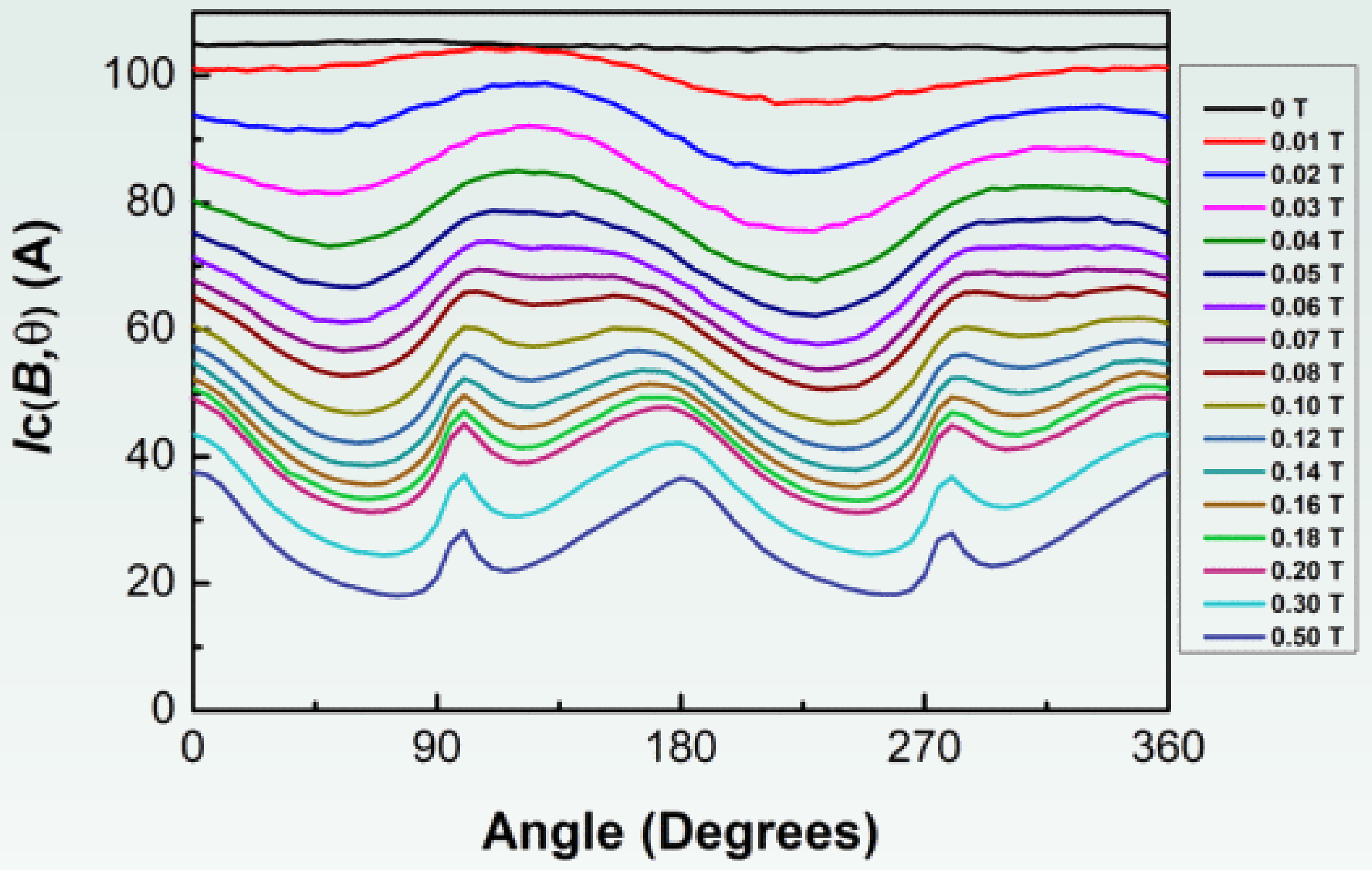
Governing equations

$$(1)\ \nabla \times \boldsymbol{E} = -\mu_0 \frac{d(\mu_r \boldsymbol{H})}{dt}$$

$$(2)\ \nabla \times \boldsymbol{H} = \boldsymbol{J}$$

$$(3)\ \boldsymbol{E} = \frac{E_0}{J_c(B,\theta)} \left|\frac{J}{J_c(B,\theta)}\right|^{n(B,\theta)-1} \boldsymbol{J}$$

Superpower SCS4050-AP $I_c(B,\theta)$ data

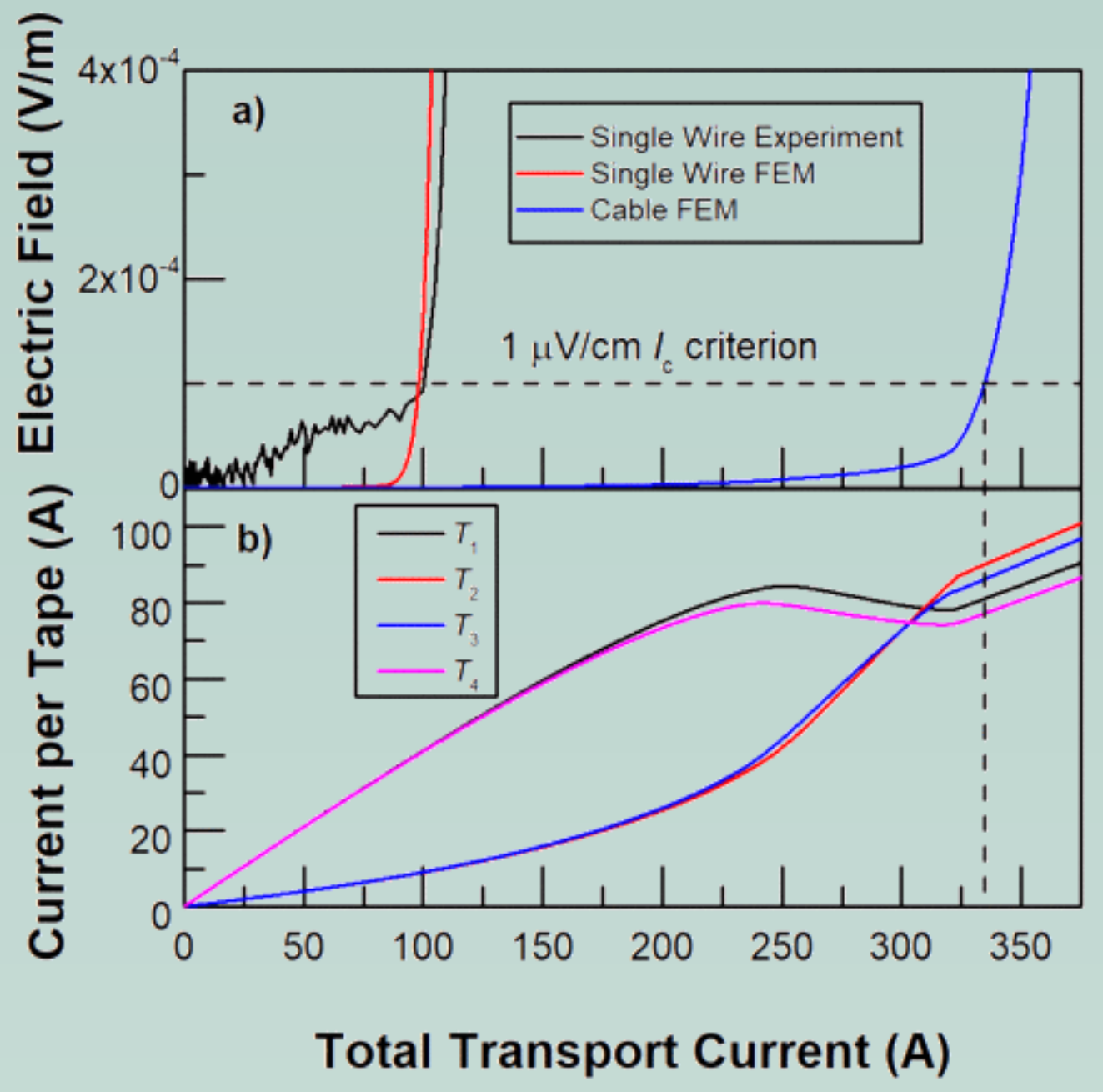


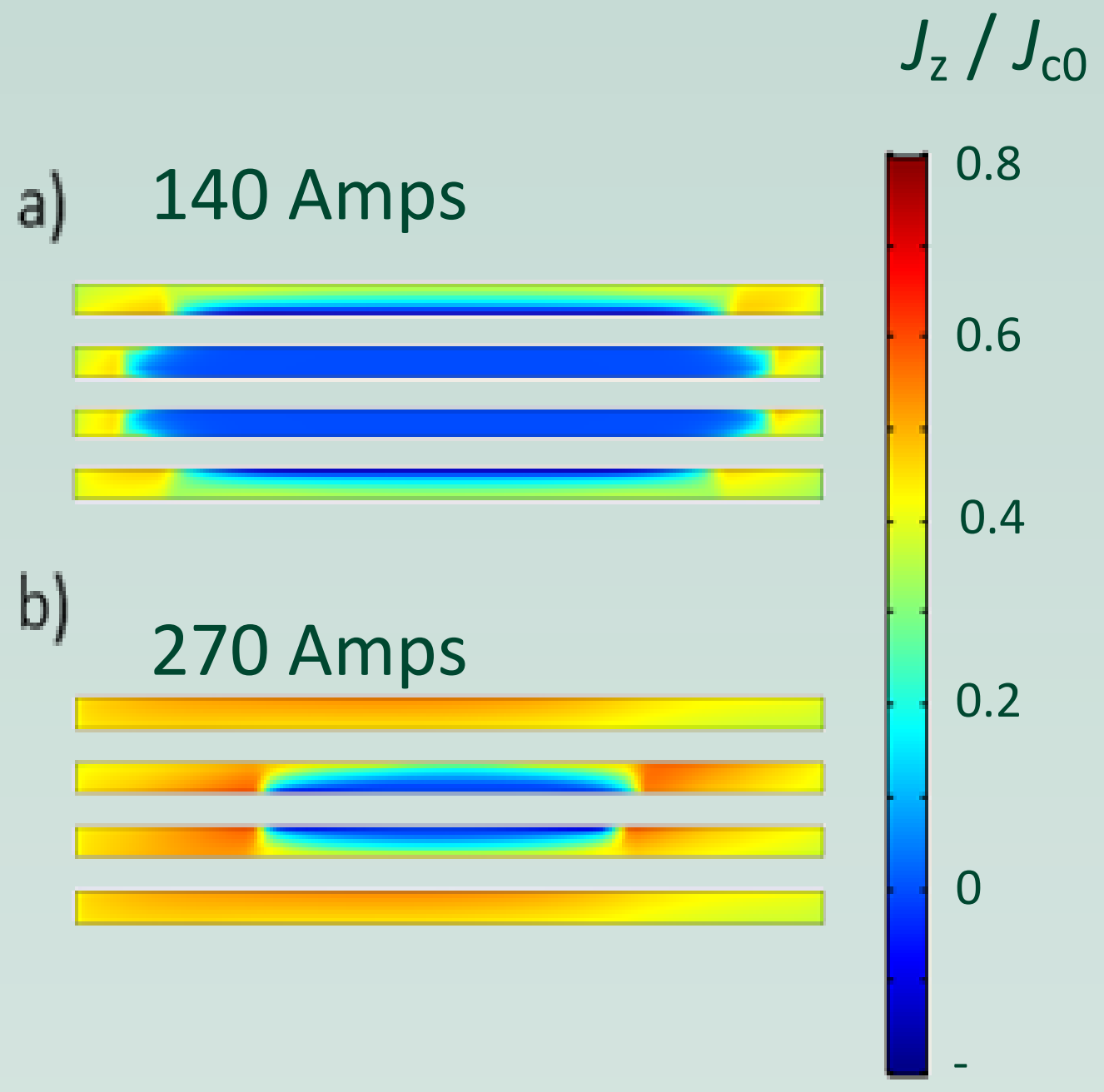
References

1) M. D. Ainslie, C. W. Bumby, Z. Jiang, R. Toyomoto, and N. Amemiya, "Numerical modelling of dynamic resistance in high-temperature su- perconducting coated-conductor wires," *Superconductor Science and Technology*, vol. 31, no. 7, p. 074003, 2018.
2) Z. Jiang, W. Zhou, C. Bumby, M. Staines, Q. Li, R. Badcock, N. Long, and J. Fang, "Dynamic resistance measurement of a four-tape ybco stack in a perpendicular magnetic field," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1–5, 2017.
3) G. P. Mikitik and E. H. Brandt, "Generation of a dc voltage by an ac magnetic field in type-ii superconductors," *Physical Review B*, vol. 64, no. 9, p. 092502, 2001.
4) C. Li, J. Geng, J. Gawith, B. Shen, X. Zhang, H. Zhang, J. Ma, and T. A. Coombs, "Design for a persistent current switch controlled by alternating current magnetic field," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1–5, 2018.

DC Ramp

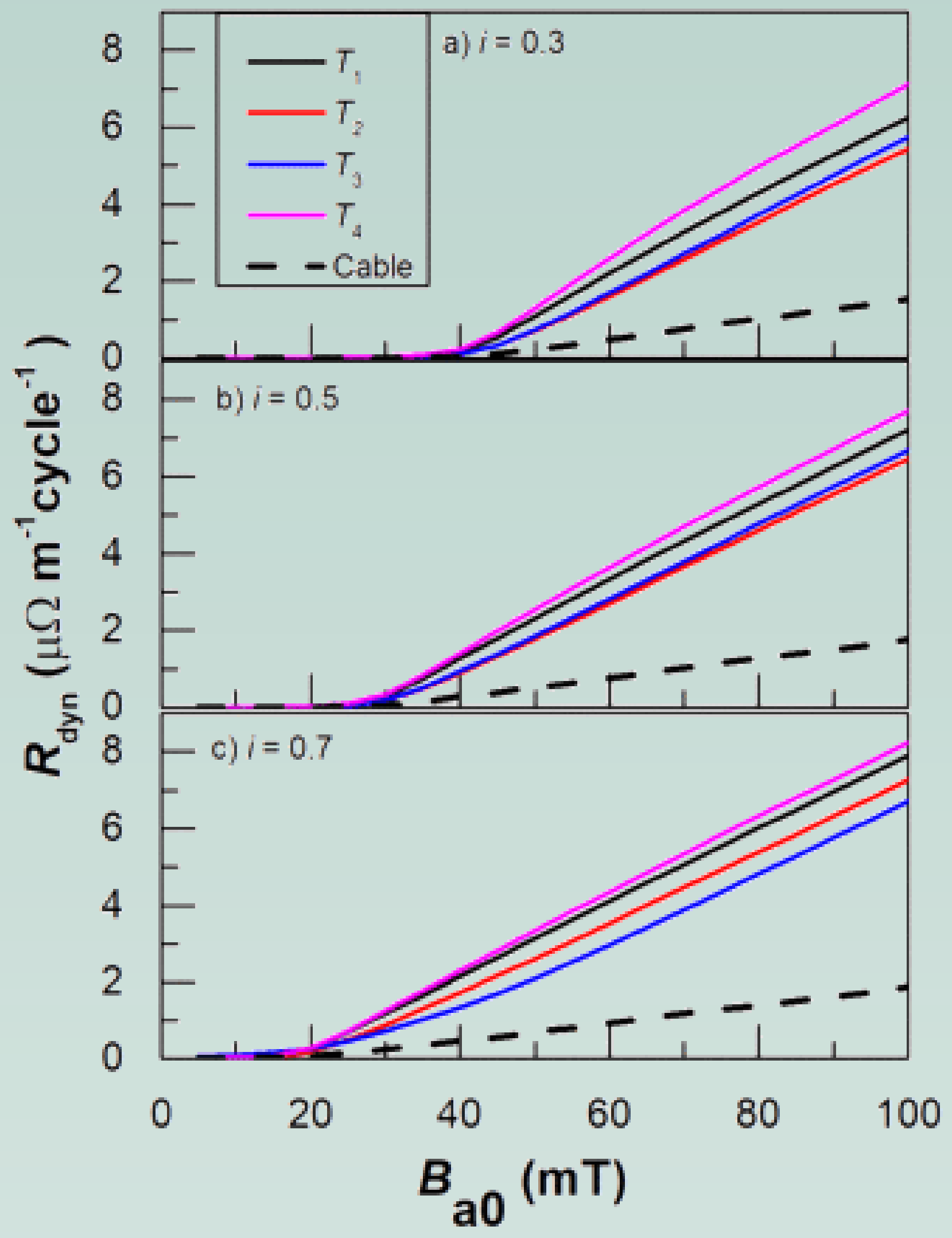
- Shown are FE results for a single wire and cable architecture alongside experimental data for a single wire
- FE analysis of single wire shows excellent agreement with experimental data
- Cable $I_{c,\,cable}$ ~ 80% of four isolated wires at 334.6 Amps.
- Outer wires in cable house the initial DC transport current
- Eventual crossover at 90% $I_{c,\,cable}$ with more current contained in inner tapes, attributed to self field suppression of J_c in the outer tapes



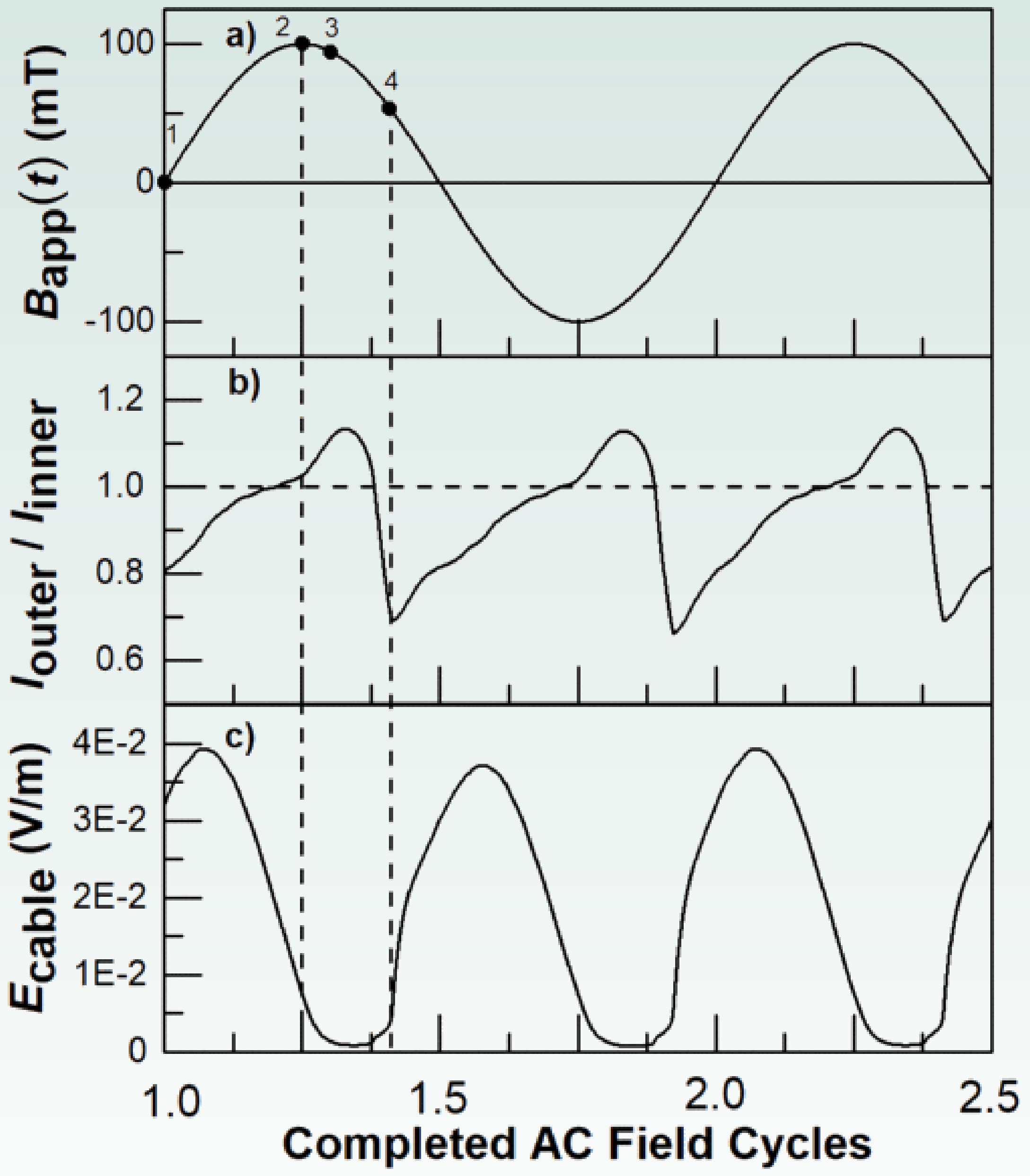


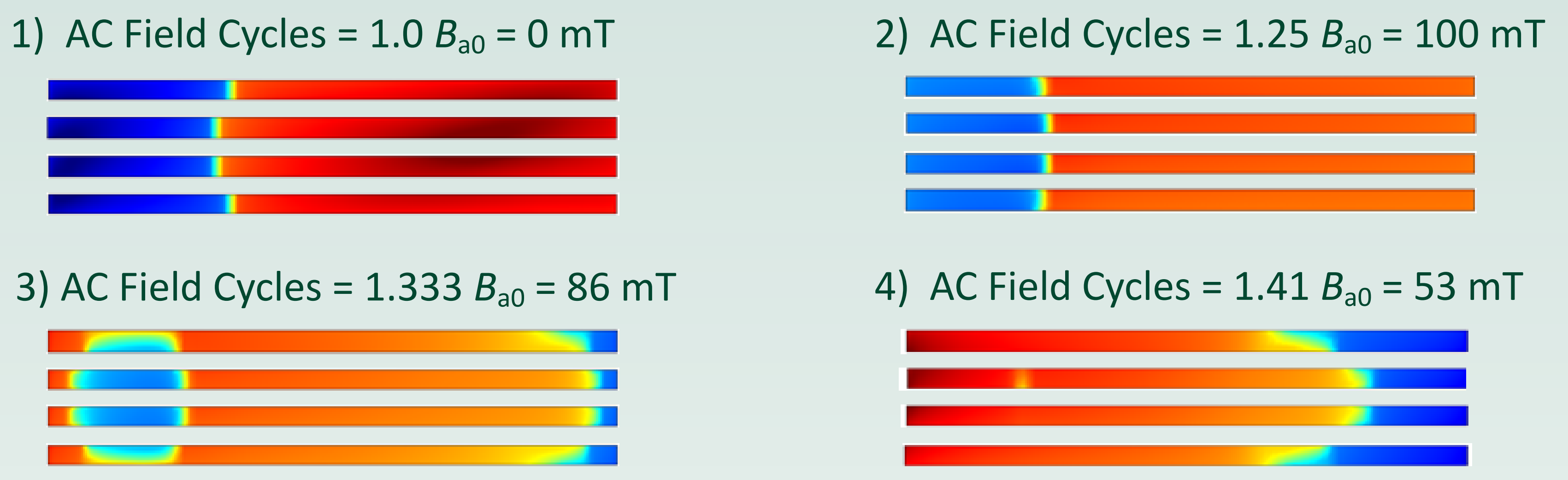
Time averaged R_{dyn}

- DC values for R_{dyn} shown for three values of the reduced current $i = I_{DC} / I_{c0}$ = 0.3, 0.5, 0.7
- For all *i*, there is a single threshold field B_{th}, above which the $R_{dyn} > 0$ for all tapes
- Outer tapes carry less of the transport current thus exhibiting larger resistances. This effect is reduced for increasing *I* as the cable is less capable of supporting screening currents



AC Field - Transient Behaviour




1) AC Field Cycles = 1.0 B_{a0} = 0 mT
2) AC Field Cycles = 1.25 B_{a0} = 100 mT
3) AC Field Cycles = 1.333 B_{a0} = 86 mT
4) AC Field Cycles = 1.41 B_{a0} = 53 mT

- The redistribution of screening currents causes the DC transport current to oscillate between the interior and exterior tapes
- As $B_{app}(t)$ varies by $2B_{th}$ from its peak values, E_{cable} undergoes a minimum while the DC current component in the outer tapes goes through a maximum. After this, E_{cable} rises sharply as screening currents flow primarily in the exterior tapes, driving DC current into the interior

Conclusions

- During the DC ramp, the transport current fills the exterior tapes first, with more current in the interior tapes by ~ 90% $I_{c,\,cable}$
- With constant I_{DC} and in an AC field, a single B_{th} is observed, below which R_{dyn} is zero
- During the AC field, the majority of DC current oscillates between the exterior and interior tapes due to the redistribution of screening currents
- The *H*-formulation is useful to explore the complex behaviour in short parallel cable configurations, otherwise inaccessible by experiment