Magnetic Vector Potential-Based Formulations for Electromagnetic Modeling of Superconductors: an Alternative to the *H* Formulation

F. Grilli, V. Zermeño, R. Brambilla, T. Benkel, A. Morandi, E. Pardo

H formulation: the de facto standard for simulating electromagnetic behavior of HTS

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Supercond. Sci. Technol. **19** (2006) 1246–1252 doi:10.1088/0953-2048/19/12/004

Numerical solution of critical state in superconductivity by finite element software

Z Hong, A M Campbell and T A Coombs

INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **20** (2007) 16–24 doi:10.1088/0953-2048/20/1/004

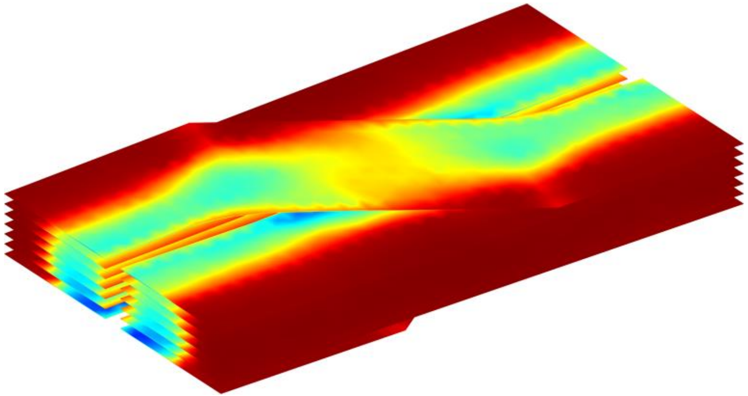
Development of an edge-element model for AC loss computation of high-temperature superconductors

Roberto Brambilla[1], Francesco Grilli[2,3] and Luciano Martini[1]

At least 45 research groups have used it since 2006!

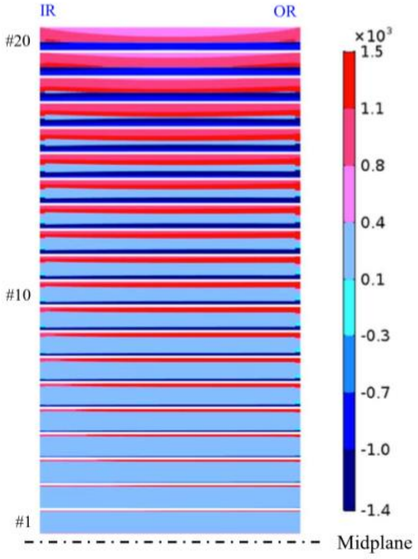
Complex HTS applications have been successfully simulated with the *H* formulation

Roebel cables



Zermeno et al. 2013 SuST **26** 052001

Large magnets



(c) J_φ (A/mm^2)

Xia et. al 2019 SuST **32** 095005

Why look for alternatives?

- Efficiently simulate HTS tapes in electrical machines

  → *T-A* formulation

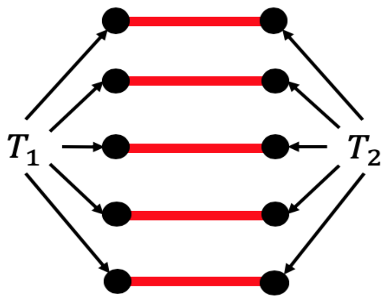
- Use different constitutive law from power-law

  → Quasi critical state model

T-*A* formulation

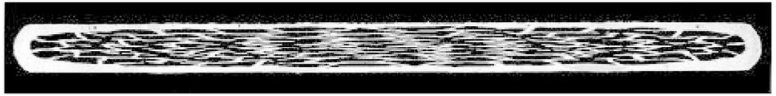
So far used to simulate thin superconductors

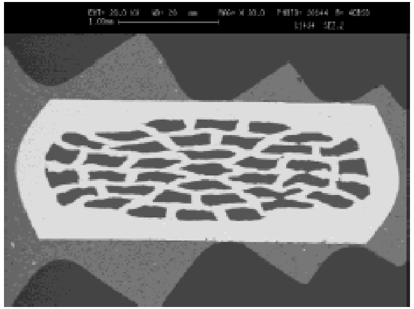
- Model proposed by Zhang et al. 2017 SuST **30** 024005
- Magnetic vector potential *A* → magnetic field (everywhere)
- Current vector potential *T* → *J* in infinitely thin superconductors
- Very easy to apply the desired current



Here extended to thick superconductors

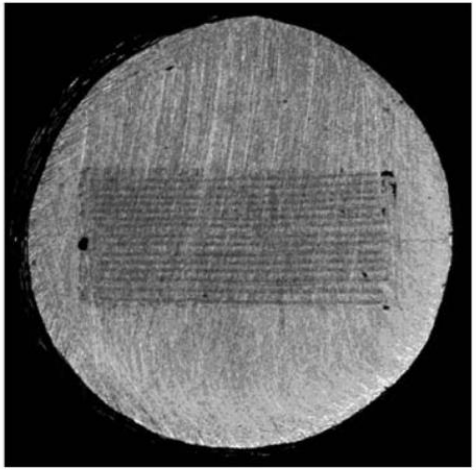
Bi-2223 or MgB_2 tapes





Sumitomo, Ansaldo Superconductors

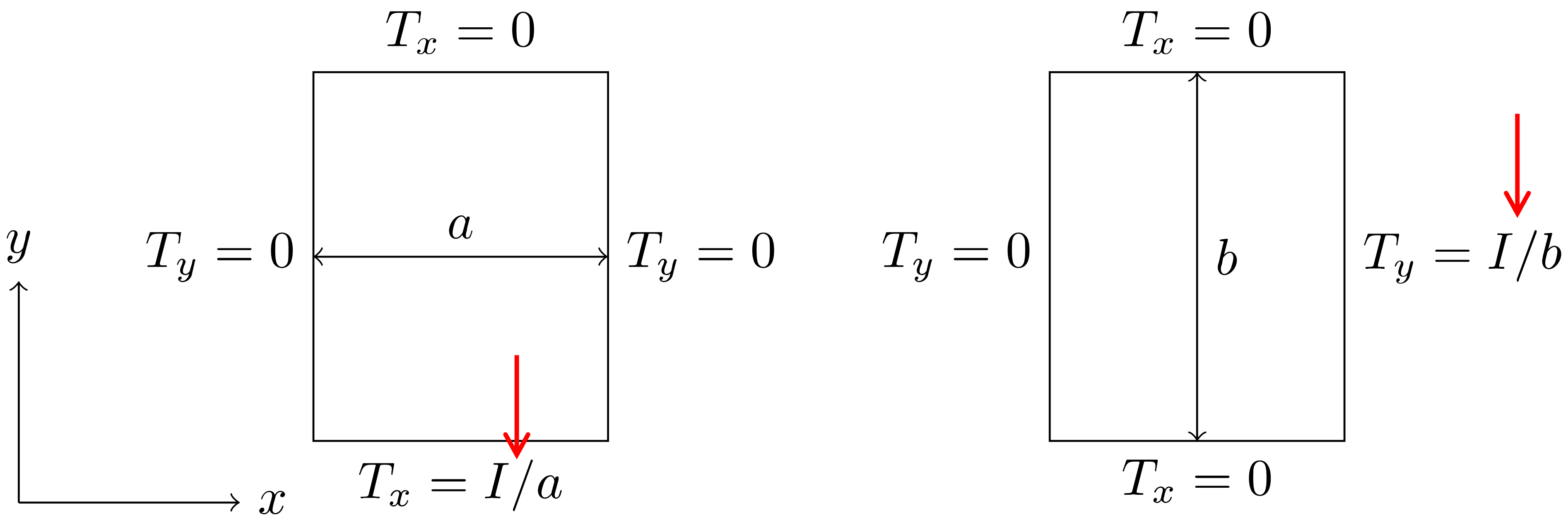
Stacks of coated conductors



Uglietti et al. 2014 IEEE TAS **24** 4800704

How do we impose the desired current?

$$I = \iint_S \mathbf{J}\,\mathrm{d}S = \iint_S \nabla \times \mathbf{T}\,\mathrm{d}S = \oint_L \mathbf{T}\,\mathrm{d}l$$

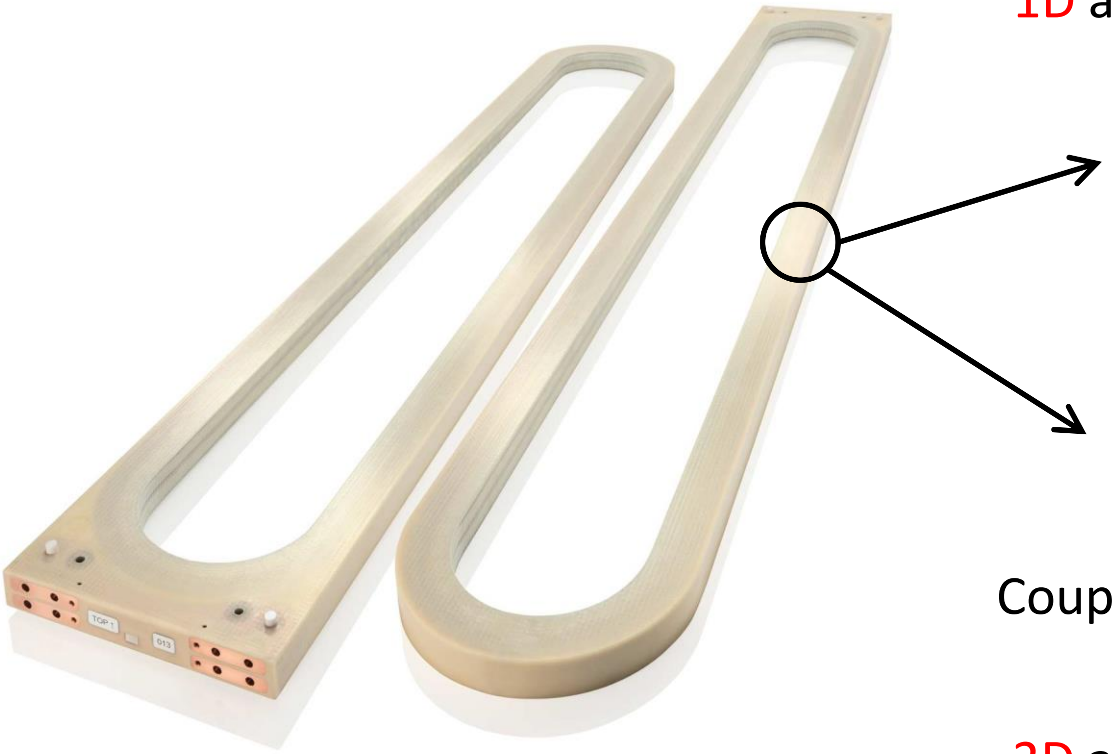


Application to HTS coils

Insulated turns

=

1D approach



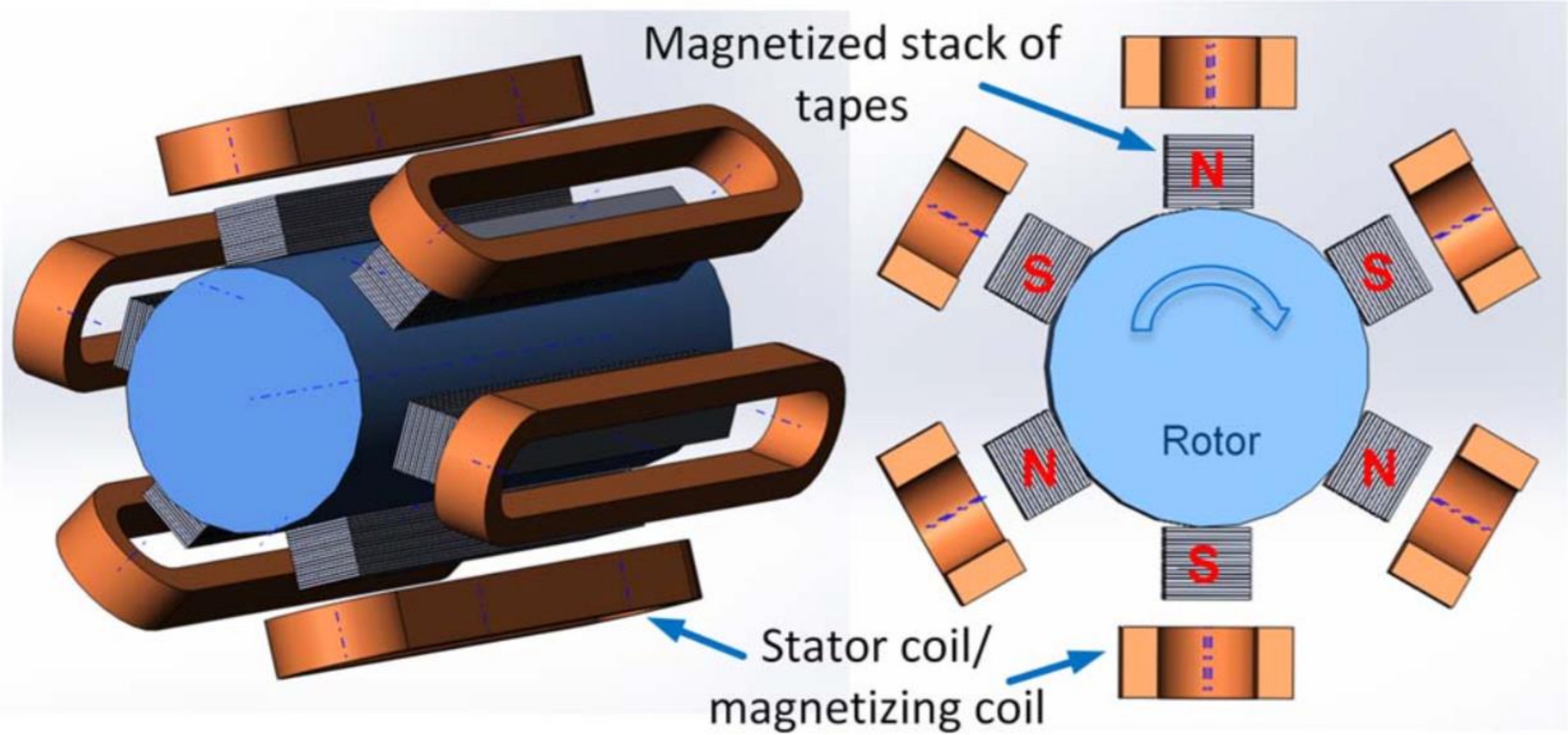
Theva GmbH

Coupled turns

=

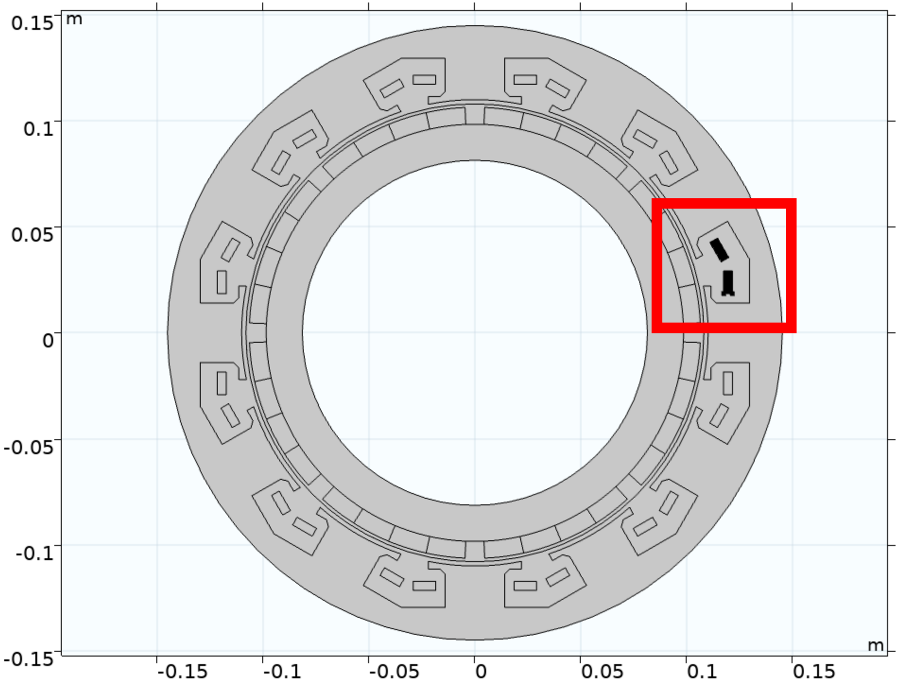
2D approach

Application to HTS machines



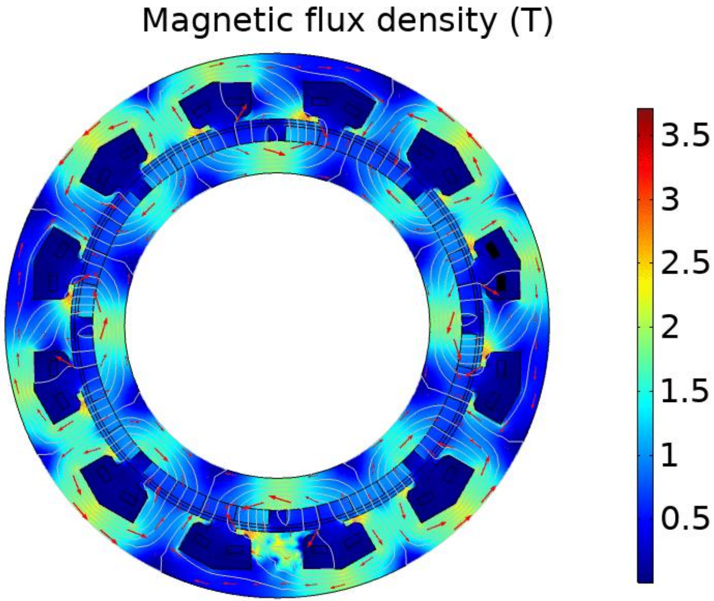
A. Patel et al. 2015 IEEE TAS **25** (3) 5203405

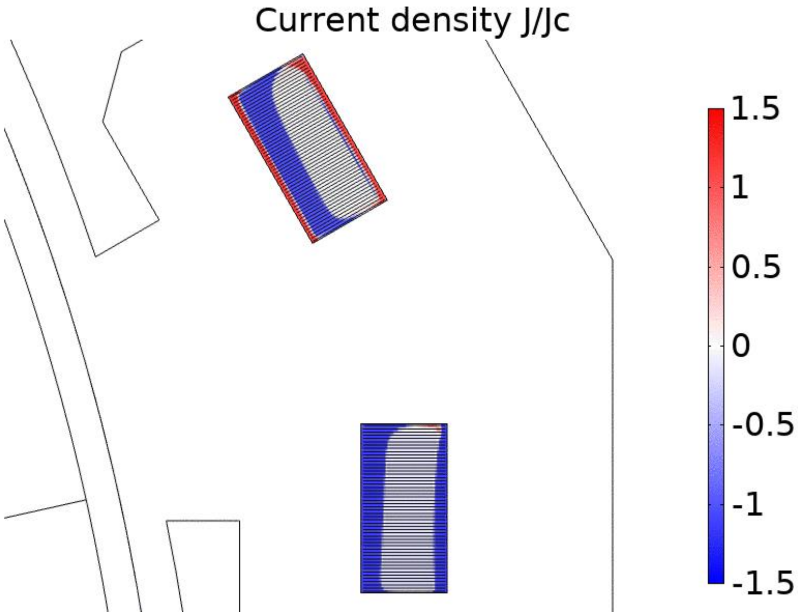
We can now simulate superconducting turns in HTS machines!



Superconducting motor SUTOR: Oswald et al. 2012 Physics Procedia **36** 765

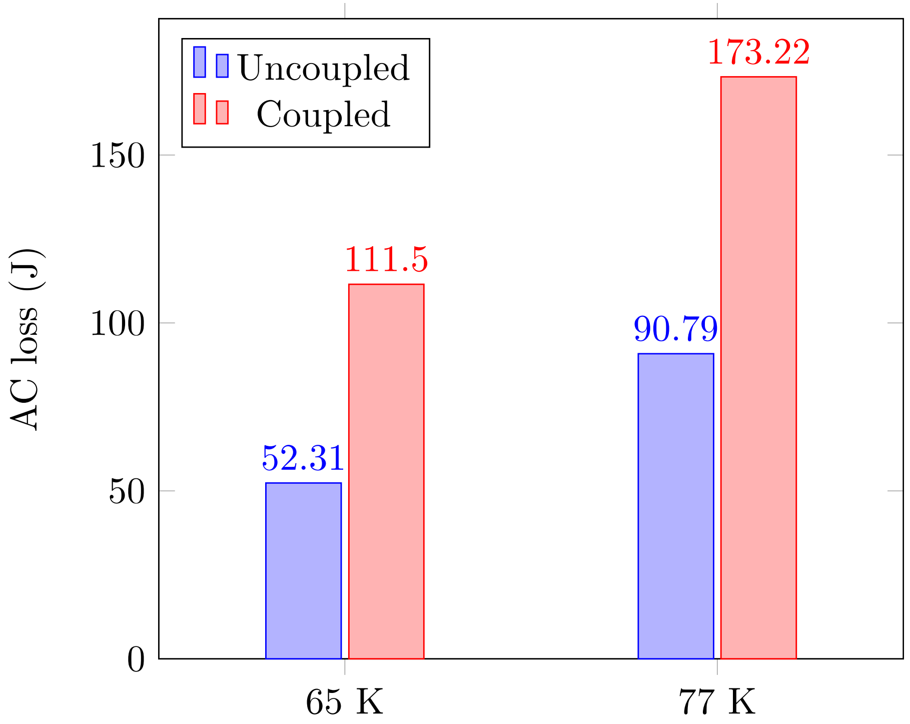
Everything done in the same model





Superconducting motor SUTOR: Oswald et al. 2012 Physics Procedia **36** 765

The coupling scenario strongly influences the AC losses of the stator's coils



Quasi critical state model

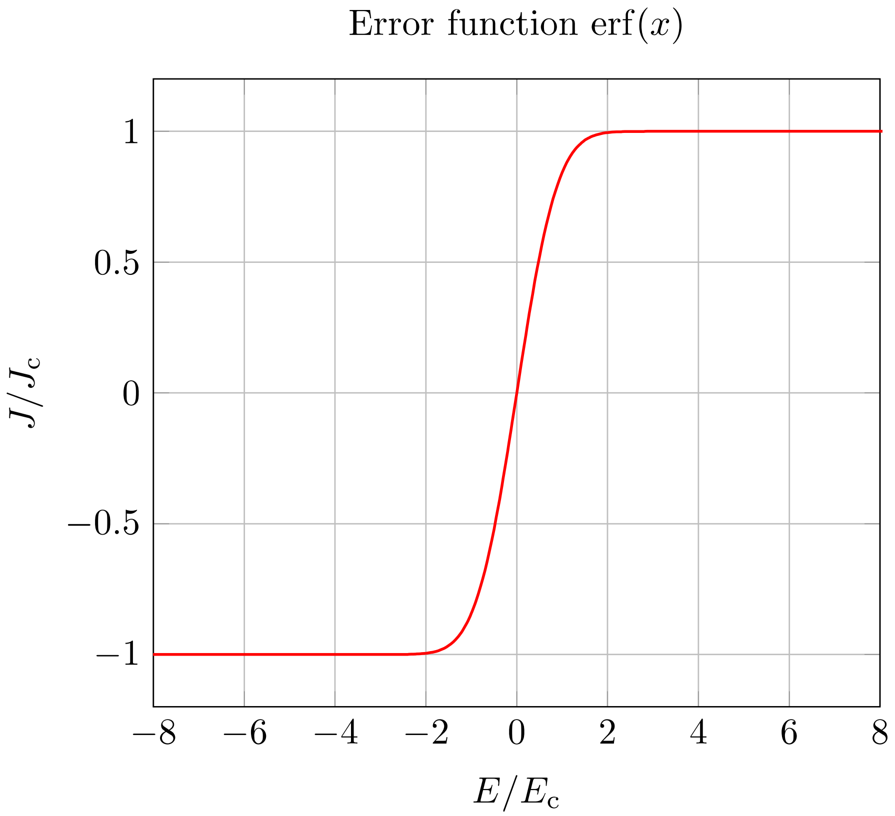
Parametric solution of magnetostatic problem with time as parameter

$$\nabla \times (\nabla \times \mathbf{A}) = \mu_0 \mathbf{J}$$

$$J = J_{\mathrm{c}}\ \mathrm{erf}\left(\frac{E}{E_{\mathrm{c}}}\right)$$

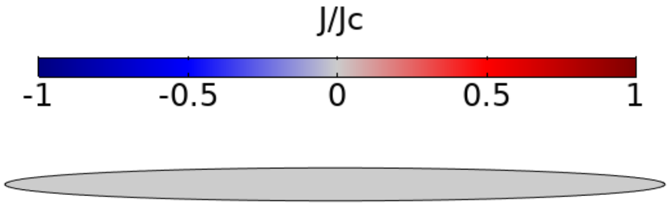
$$E = -\frac{\partial A}{\partial t} - \nabla \phi$$

$$\frac{\partial A}{\partial t} \approx \frac{A_{t+\Delta t} - A_t}{\Delta t}$$

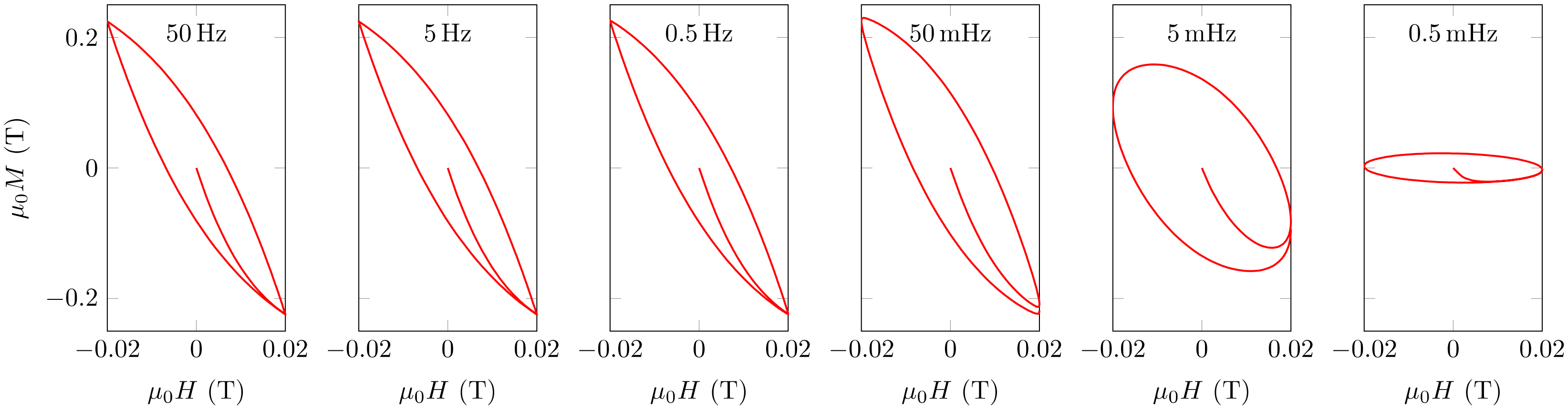


Campbell 2007 SuST **20** 292
Gömöry & Inanir 2012 IEEE TAS **22** 4704704
Gömöry & Shen 2017 SuST **30** 064005

A “quasi” critical state model



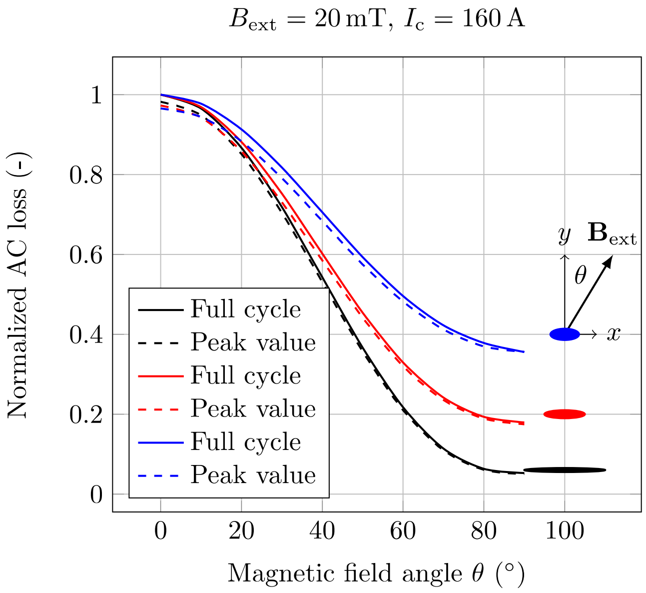
- AC magnetization of an elliptical conductor
- Magnetization loops change with frequency
- Due to smooth *E-J* relationship



Can a single static calculation predict the cyclic AC losses of an HTS tape?

Yes, if we know the field distribution at the peak*

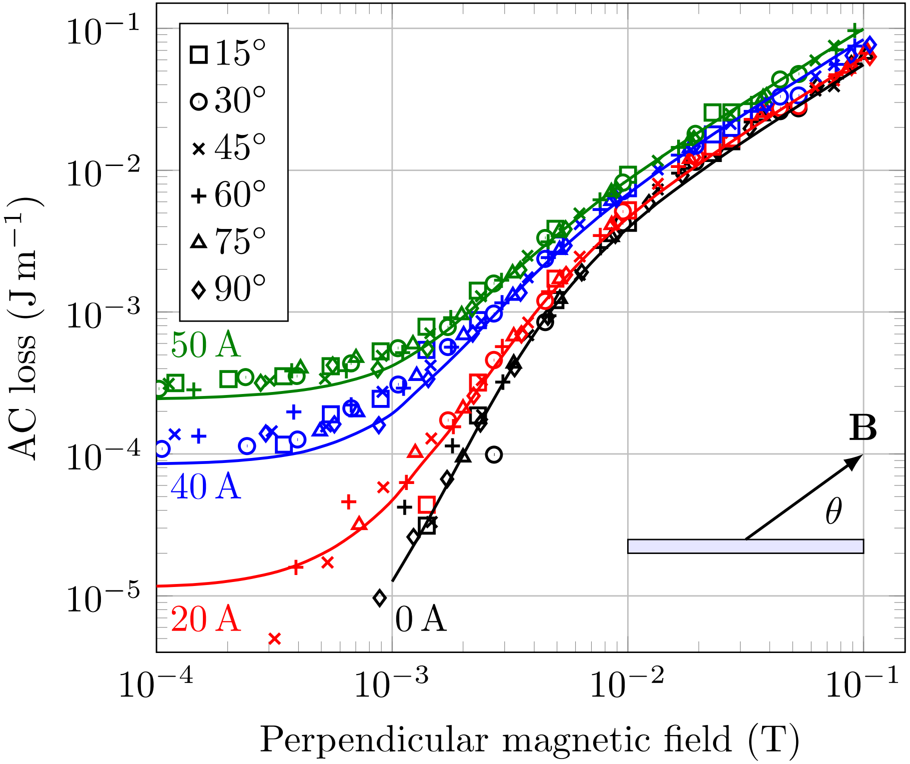
$$Q = 4J_c \int_{\Omega} |A_p| d\Omega$$



*Claassen 2006 APL **88** 122512
*Campbell 2007 SuST **20** 292
*Pardo et al. 2007 SuST **20** 351

The static model satisfactorily predicts the total losses of an HTS coated conductor

- In-phase AC current and AC field
- Various field orientations
- Perpendicular field component dominates



About one second per simulation!

Ogawa et al. 2005 Cryogenics **45** 23

Conclusions

T-A formulation

- Efficient tool for modeling HTS in electrical machines
- Different coupling scenarios considered

Quasi critical state model

- Departure from CSM behavior at low frequency
- Promising for quick one-step calculation of AC losses (single tapes)

Thank you very much

for your attention!