Magnetization loss for stacks of ReBCO tapes

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HTS MODELLING 2016

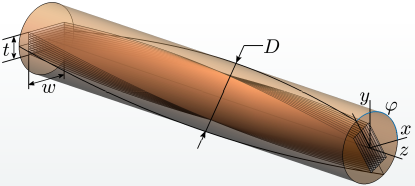
15 – 17 June, Bologna, Italy

Outline

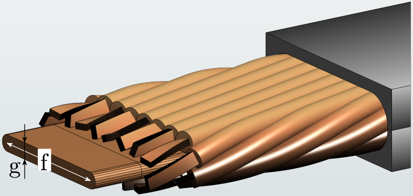
Outline

HTS fusion cable concept at SPC:

- **Strand** – stack of HTS tapes twisted and soldered between copper profiles:



- **Cable** – copper cored Rutherford design:



- **EDIPO sample** – 60 kA/12 T cable prototypes:
  2 cables made of SuperPower & SuperOx tapes
  20 strands per cable twisted at 1 m
  16 tapes per strand twisted at 320 mm

Work motivation

✓ Feasibility of the proposed HTS strand and cable designs for fusion magnets was experimentally demonstrated with the DC tests performed in EDIPO

- Improvement of the mechanical properties of the strand against the transverse Lorentz force is the ongoing task . . .
- AC loss mechanisms of the proposed cable design:
  1. Hysteresis loss in the stacked tapes
  2. Inter-tape coupling current loss
  3. Inter-strand coupling current loss (dominant one in the prototypes)
  4. Eddy current loss

➥ Study of the magnetization loss in the stacked tapes is the scope of this work:

influence of the number of tapes in the stack?

. . . width of the tapes?

. . . orientation of the applied magnetic field?

. . . manufacturer of the HTS tape?

Outline

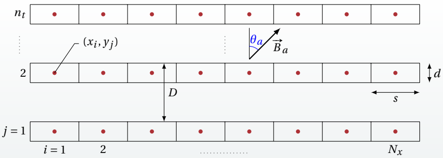
Description of the model

Parameters

n_t number of tapes
w width of the tape
d thickness of the SC layer (1 μm)
D distance between the layers

$$E = E_c \left(\frac{j}{j_c(B,\theta)} \right)^n$$ – power law relation

Sketch of the geometry



➥ 2D geometry with the uniform grid

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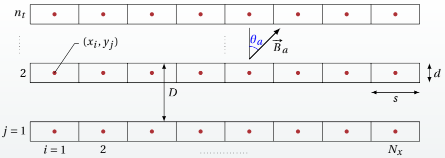


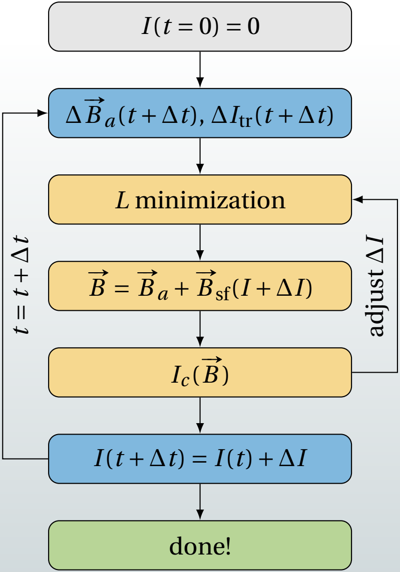
➥ 2D geometry with the uniform grid

Functional ($A - \phi$ formulation)

$$L(\Delta I) = \sum_{i=1}^{N} \left(\frac{\sum_{j=1}^{N} \frac{1}{2} C_{ij} \Delta I_j \Delta I_i + \Delta A_{a_i} \Delta I_i}{\Delta t} + \frac{E_c I_{b_i}}{n+1} \left(\frac{|I + \Delta I|}{I_b} \right)_i^{n+1} \right)$$

- Minimization of L is equivalent to solving the Maxwell equations
- C_{ij} – matrix of mutual inductances (expressed analytically)
  A_a – vector potential of the applied magnetic field
- Transport current is implemented as a constraint for ΔI

Procedure of the calculation



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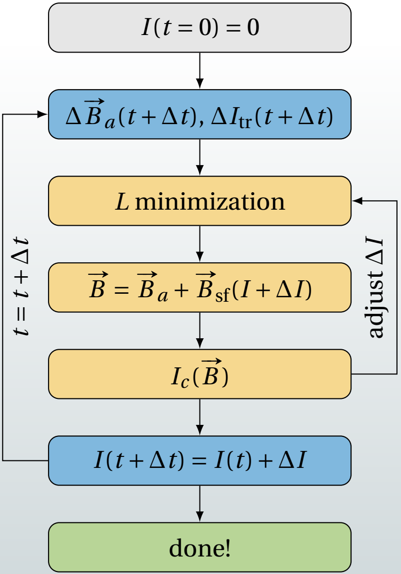


- Magnetic moment per unit length:

$$m(t)=-m_z(t)=\sum_{k=1}^{N}x_k I_k(t)$$

- Instantaneous power loss:

$$P(t)=\sum_{k=1}^{N}E_k(t)I_k(t)=\sum_{k=1}^{N}\frac{E_c}{I_{b_k}^n}|I_k(t)|^{n+1}$$

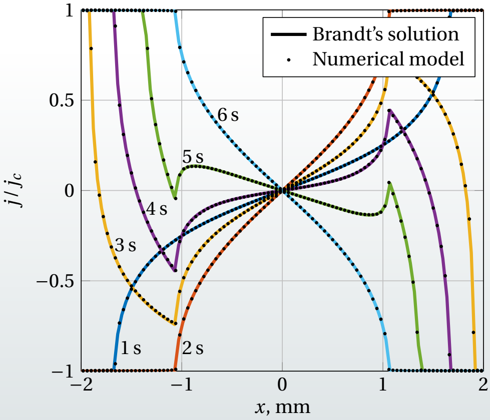
- Hysteresis loss:

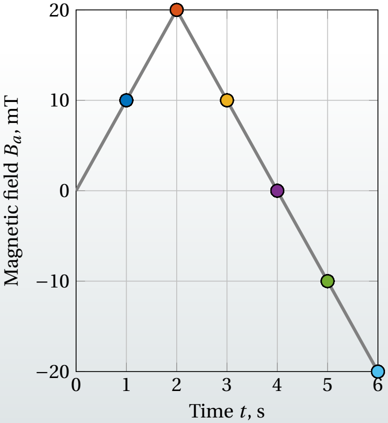
$$Q=\int P(t)\,\mathrm{d}t$$

- Magnetization loss:

$$Q=\oint m\cos\theta_a\,\mathrm{d}B_a$$

Benchmarking





- Parameters: $n_t = 1$, $w = 4\,\text{mm}$, $N_x = 100$, $n = 1000$, $j_c(B,\theta) = 40\,\text{kA/mm}^2$

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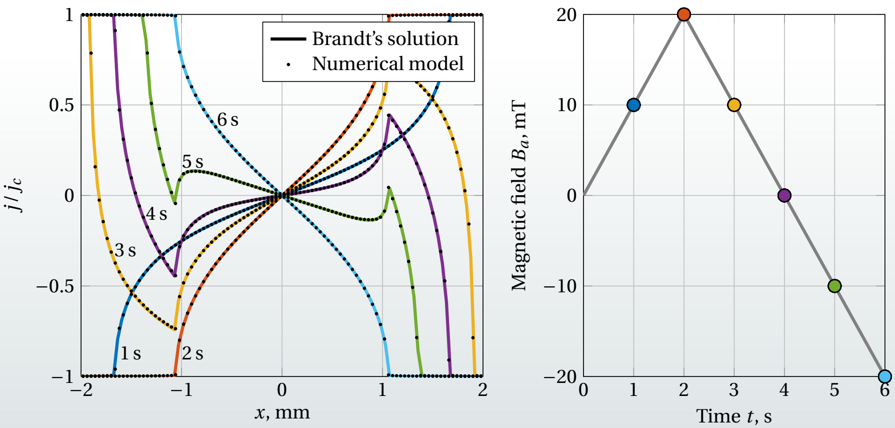

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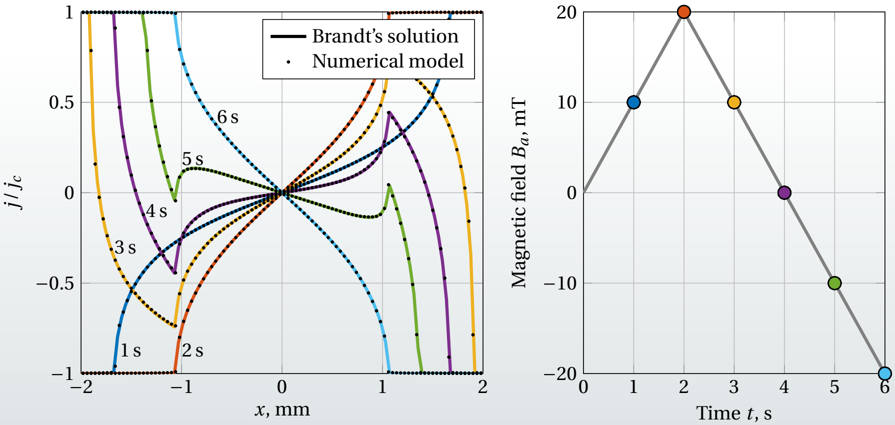

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✓ Numerical model is validated

Stack of tapes in the critical state model

- Brandt's solution ($n_t = 1$):

  $$Q_{\text{brandt}} = w j_c B_c q_1\left(B_a/B_c\right), \quad B_c = \frac{\mu_0 j_c d}{\pi}$$

  $$q_1(x) = 2\ln(\cosh x) - x\tanh x$$

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- Mawatari's solution ($n_t = \infty$):

$$Q_{\text{mawatari}} = w j_c B_c q_\infty \left(B_a / B_c, 2D/\pi w\right)$$

$$q_\infty(x, a) = a^2 \int_0^x (x - 2\xi) \ln\left(1 + \frac{\sinh^2(1/a)}{\cosh^2 \xi}\right) \mathrm{d}\xi$$

$D \gg w$: $q_\infty(x, a \gg 1) = q_1(x)$

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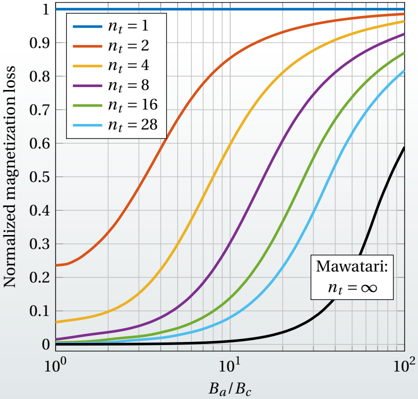

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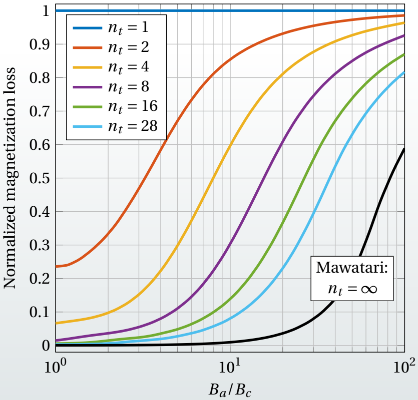

n_t-tape stack one can consider as the stack with infinite number of tapes but with some effective distance between the tapes $D_{\text{eff}}(n_t)$:

$$Q_{n_t} = w j_c B_c q_{n_t} \left(B_a / B_c, 2D/\pi w\right)$$

$$q_{n_t}(x,a) \approx q_\infty \left(x, a + \frac{0.34 a^{0.10}}{n_t^{4.44a + 0.65} - 1}\right)$$

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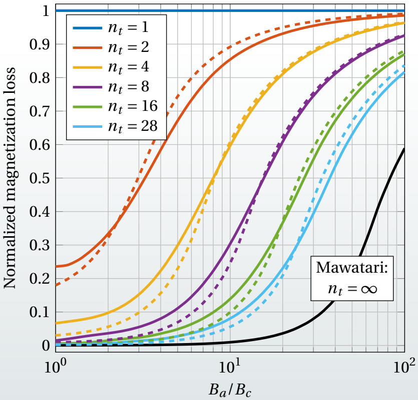

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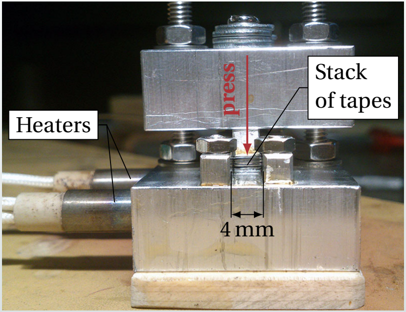
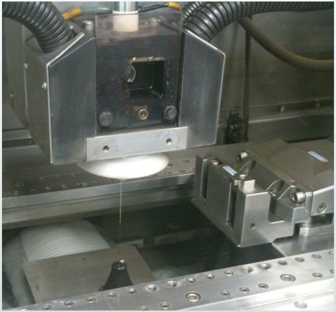
Outline

Fabrication of the samples

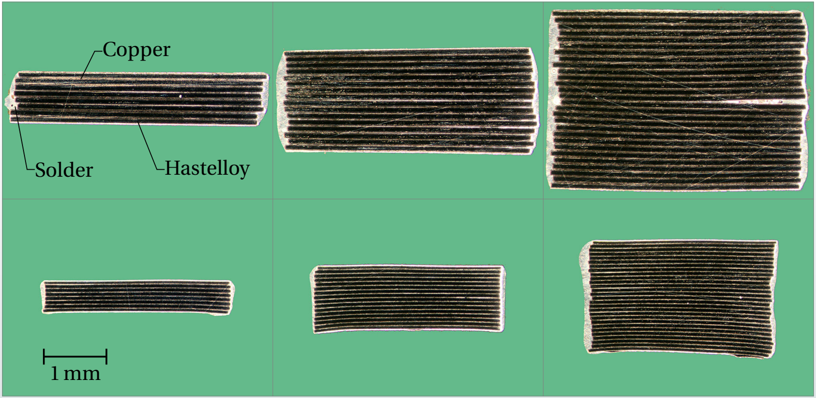
HTS tape	I_c, A	n-value
SuperPower 4 mm	155 ± 2	33
SuperPower 3 mm	70 ± 1	29
SuperOx 4 mm	164 ± 1	34





- Tapes were measured at 77 K/self-field before the stacks fabrication
- Soldering device ensures correct tapes stacking in the cross-section
- Edges of the stacks were cut by the electro-erosion process

Cross-section of the SuperPower stacks



- Top row: 4 mm wide, 100 µm thick tapes
  Bottom row: 3 mm wide, 60 µm thick tapes
- 3 mm wide stacks have slightly distorted geometry (parabolic shape)
- Thickness of the solder between tapes is negligible,
  i.e. $D = 100\,\mu\text{m} / 60\,\mu\text{m}$ for the modelling

Test program

HTS tape	Number of tapes, n_t	Orientation of the sample, θ_a
SuperPower width 4 mm length 4 mm	1	0°
SuperPower width 4 mm length 5 mm	1 8 16 28	0° / 45° 0° / 45° 0° / 45° / 90° 0° / 45°
SuperPower width 4 mm length 10 mm	1 16	0° 0°
SuperPower width 3 mm length 5 mm	1 8 16 28	0° 0° 0° 0°
SuperOx width 4 mm length 5 mm	1 16	0° 0°

VSM system at ENEA

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- Finite length effect of the samples

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VSM system at ENEA

- Finite length effect of the samples
- Geometry aspects on the magnetization behaviour (different w, D)

Test program

HTS tape	Number of tapes, n_t	Orientation of the sample, θ_a
SuperPower width 4 mm length 4 mm	1	0°
SuperPower width 4 mm length 5 mm	1	0° / 45°
	8	0° / 45°
	16	0° / 45° / 90°
	28	0° / 45°
SuperPower width 4 mm length 10 mm	1	0°
	16	0°
SuperPower width 3 mm length 5 mm	1	0°
	8	0°
	16	0°
	28	0°
SuperOx width 4 mm length 5 mm	1	0°
	16	0°

VSM system at ENEA

- Finite length effect of the samples
- Geometry aspects on the magnetization behaviour (different w, D)
- Shielding effect for the different number of tapes in the stack n_t

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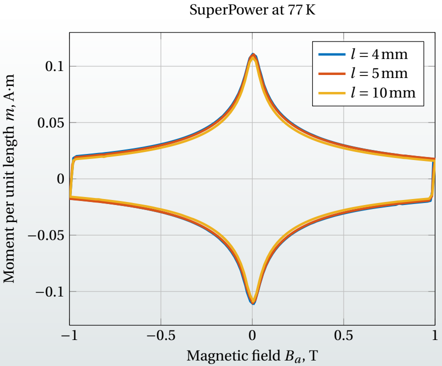
- Finite length effect of the samples
- Geometry aspects on the magnetization behaviour (different w, D)
- Shielding effect for the different number of tapes in the stack n_t
- Effect of the orientation of the magnetic field θ_a
- Magnetization loss from the area of minor magnetization loops

Outline

Magnetization loops

Finite length effect



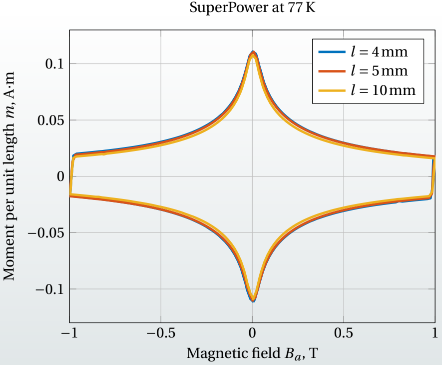
Saturated state of the finite length tape:

$$\frac{m_{\text{sat}}}{l} = \frac{1}{4} I_c w \left(1 - \frac{w}{3l}\right) \left(\frac{\dot{B} w}{2E_c}\right)^{1/n} \frac{2n}{2n+1}$$

- Moment is corrected by $(1 - w/3l)$
- $\dot{B}$–effect due to finite n-value

Magnetization loops

Finite length effect



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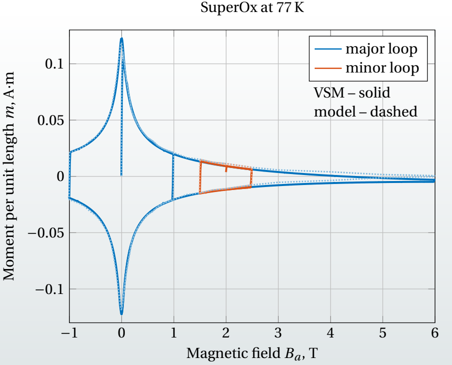
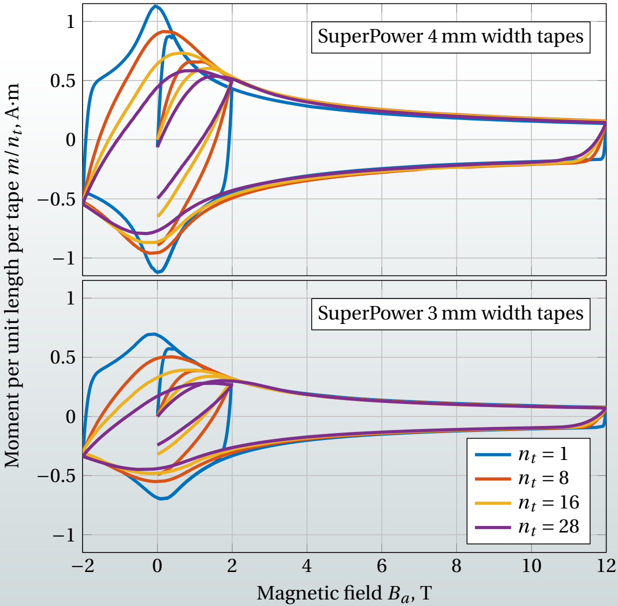
Major & minor loops



- major loops: $0 \to 6 \to -1 \to 1 \to 0$ T at 77 K; $0 \to 12 \to -2 \to 2 \to 0$ T at 5 K
- minor loops: $2 \to 2.5 \to 1.5 \to 2.5 \to 2$ T at 77 K; $10 \to 11 \to 9 \to 11 \to 10$ T at 5 K
- good agreement with the modelling, if $j_c(B,\theta)$ is well defined

Shielding effect of the stacked tapes



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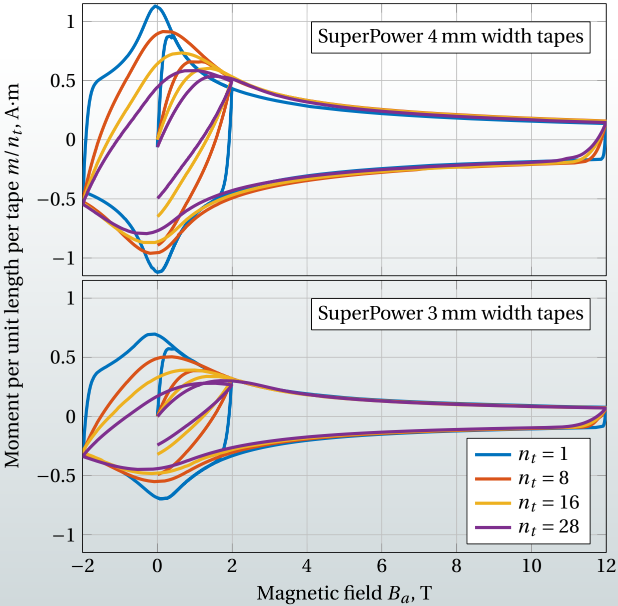

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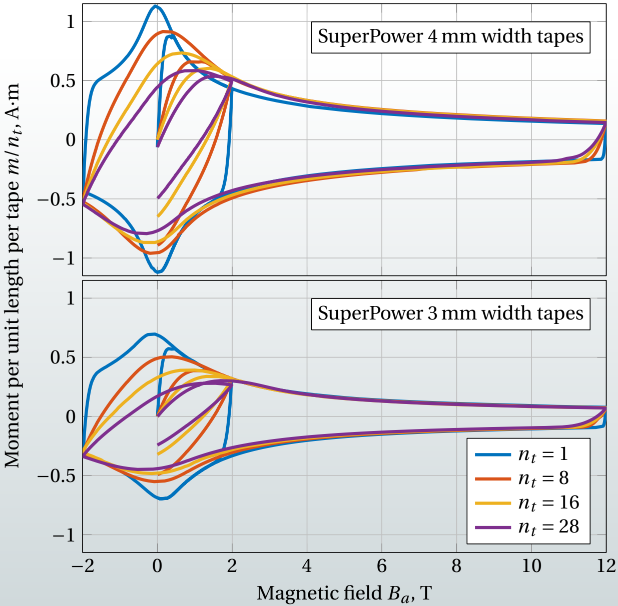

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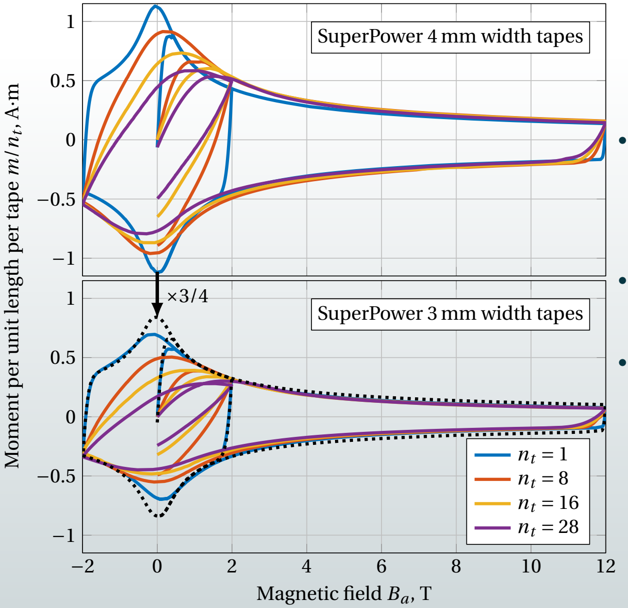
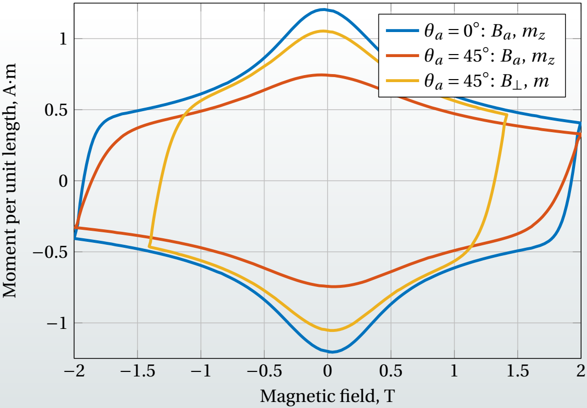


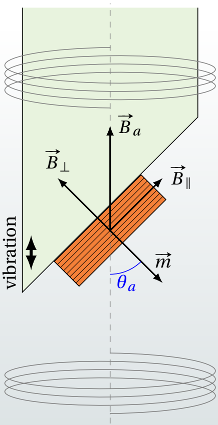
- Tapes were not damaged during the stacks fabrication (curves overlap in the high-field zone)
- ’Smoothing’ of the curves is due to the self-field effect
- Tapes of different widths have comparable I_c field dependence

Orientation of the magnetic field

SuperPower single tape at 5 K



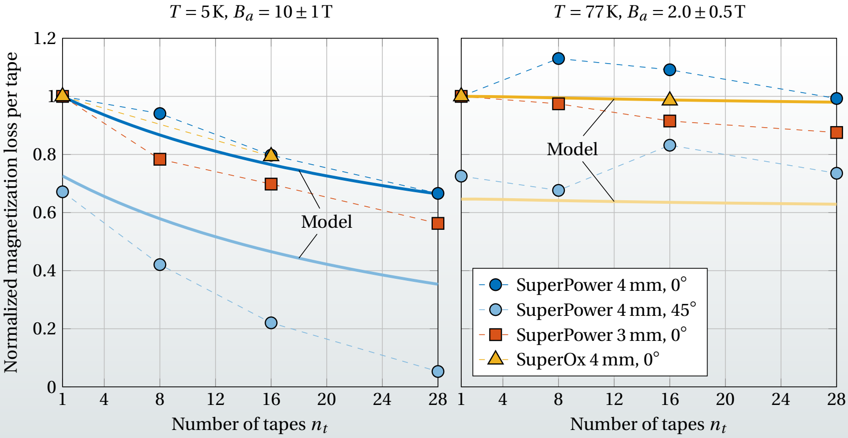
VSM sample holder



- Magnetization of the tapes correspond mainly to $\vec{B}_\perp$ component, with a slightly reduced j_c due to $\vec{B}_\parallel$ component
- One should take into account the torque acting on the sample $\vec{\tau} = \vec{m} \times \vec{B}_a$ in the measurements (possible mechanical issue)

Outline

VSM vs modelling



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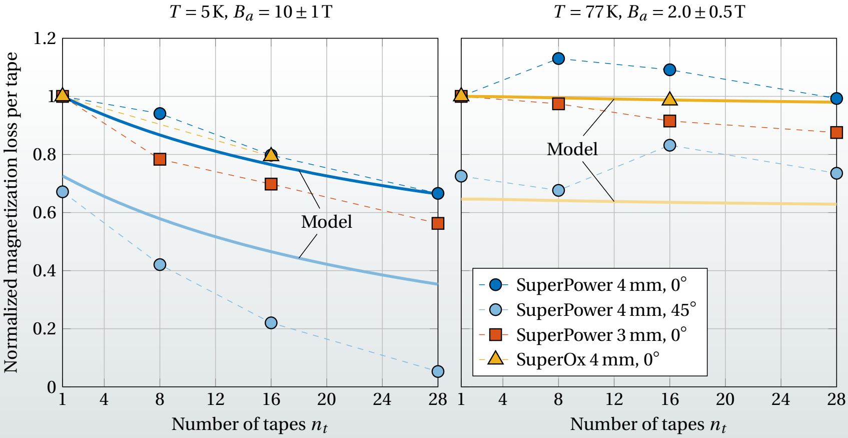

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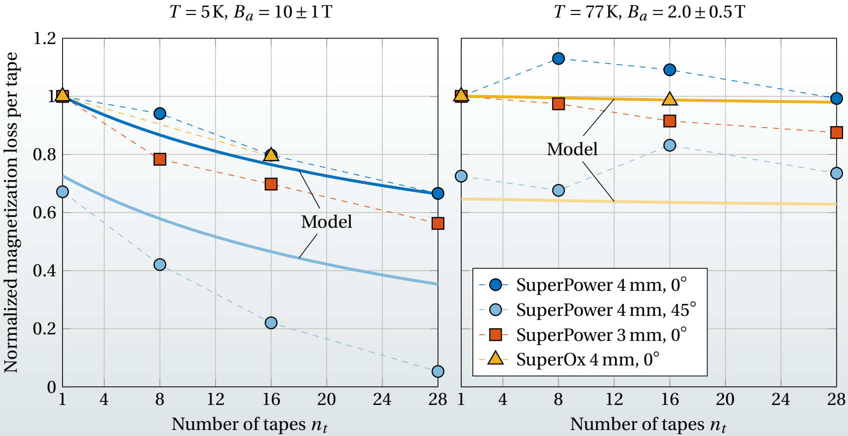

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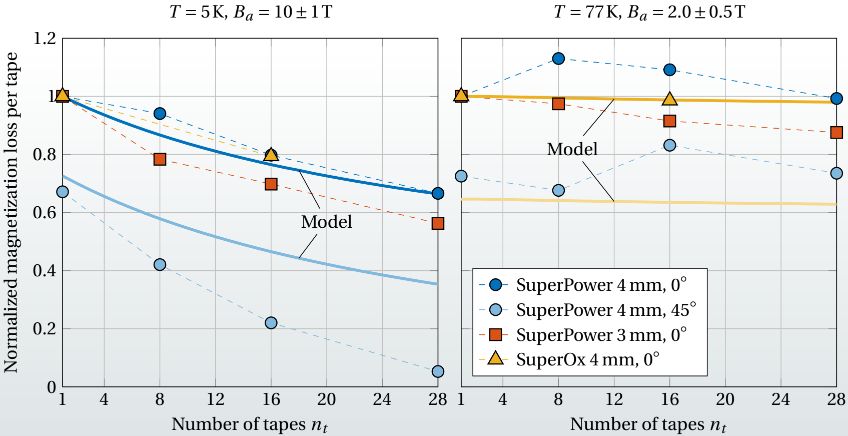

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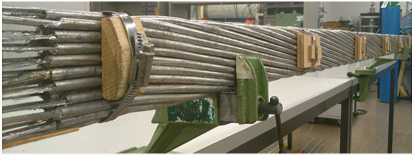
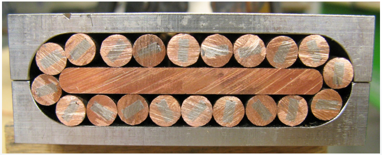
- 3 mm wide stacks have stronger demagnetization effect (ratio D/w is smaller)
- Presumably, less regular results at 77 K is due to small absolute values of the loss (~30 times smaller than the values at 5 K)

Comparison with the EDIPO test results





Magnetization loss per strand Q $\left[\mathrm{J/(m \cdot cycle)}\right]$
for $B_{\mathrm{dc}} = 2\,\mathrm{T}$ and $B_{\mathrm{ac}} = 0.3\,\mathrm{T}$ at 5 K:

	SP	SO
HTS cables in the EDIPO test	0.2 – 0.5	
Numerical model	0.21	0.22
Analytical approach	0.20	0.18

- Frequency range of the applied AC field in the EDIPO test is $\approx 0.1 - 2\,\mathrm{Hz}$. Magnetization loss was extracted by the data extrapolation to 0 Hz.
- Twisting of the strand has been considered by varying θ_a in the calculation
- Conclusions from the VSM study of the field's orientation effect on the magnetization loss were used in the analytical approach

Outline

- Using the numerical modelling, analytical approach for the magnetization loss of the stack with arbitrary number of tapes is proposed.
- Various effects of the stack on its magnetization behavior have been figured out using the VSM measurements.
- Developed numerical tools are well agreed with the different experimental results and will be used further for assessment of the stack magnetization.
- Next modelling tasks – to validate the transport current term and to improve the optimization algorithms.

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