EPFL

AC losses in superconducting magnets

D. Uglietti

The course provides:

- Concepts, definitions
- References (past courses, publications and books) for deeper studies and further reading

No need to understand and learn everything at once. When you have a problem to solve, you can start from the references in the course to find a solution.

Course Plan

Online course
4th Workshop on Superconducting Magnet Test Facility
2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

When AC losses in superconductors were first studied?

The understanding of AC losses was carried out in parallel with (or just following) superconducting magnet development, starting in the 60's and continuing during the 70's.

1963 Hysteretic losses: H. London

1968 Coupling losses: Smith

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1982 A. M. Campbell "A general treatment of losses in multifilamentary superconductors" https://doi.org/10.1016/0011-2275(82)90015-7

1983 M. Wilson, book "Superconducting magnets"

2008 M. Wilson "NbTi superconductors with low ac loss: A review" https://doi.org/10.1016/j.cryogenics.2008.04.008

2009 T. Iwasa, book "Case Studies in Superconducting Magnets"

Almost all what is needed for LTS and HTS

AC losses physics and analytical tools have been around for >40 years

Where to find information on AC losses in superconductors?

Books

M. Wilson, "*Superconducting Magnets*", chapter 8

S. Iwasa, "*Case Studies in Superconducting magnets*", chapter 7

Build your knowledge on solid foundations: <u>books</u>

Courses

M. Wilson, JUAS 2015, *Lecture 2: Magnetization, cables and ac losses*

L. Bottura, 2007 THRMOMAG, *Cable and Magnet losses* https://slideplayer.com/slide/13511852/

S. Prestemon, P. Ferracin, E. Todesco, *Unit 7 AC losses in Superconductors*, CERN, LNBL
https://indico.cern.ch/event/440690/contributions/1089769/attachments/1148950/1648370/U7-final.pdf

F. Gömöry, *AC loss – part I*

Scientific review papers

1982 A.M. Campbell *A general treatment of losses in multifilamentary superconductors*
https://doi.org/10.1016/0011-2275(82)90015-7

2008 M. Wilson, *NbTi superconductors with low ac loss: A review* https://doi.org/10.1016/j.cryogenics.2008.04.008

2014 F. Grilli, *Computation of Losses in HTS Under the Action of Varying Magnetic Fields and Currents* https://doi.org/10.1109/TASC.2013.2259827

What are AC losses in superconductors?

- Superconductors have no dissipation at constant current and magnetic field.
- Superconductors dissipate (generate heat) during I(t) and/or B(t) transient. AC loss is the energy (heat) released during transient.

Superconducting devices can be subdivided in two categories, according to the transient:

Electro-technical devices
motors, transformers, AC power cables, …
I(t) cycling operation

I(t) is usually the main loss source
(little field generation)

Losses can be an obstacle to applications.

Magnets
MRI, NMR, lab, fusion, accelerators, …
B(t) transients

B(t) is usually the main loss source
I(t) could be neglected, at least in first approximation

This course is on losses generated from magnetic field transient.

Why are AC losses important?

At least a couple of reasons:

1. **Stability** — heat dissipation leads to temperature increment. If the temperature rises too much, superconductivity is lost.

2. **Economics** — Even if the AC loss heat is removed and the device remains superconducting, heat removal costs electrical power. Superconducting magnets are usually cheaper to build and cheaper to run (lower power consumption) than resistive ones.

Losses upper limit: electricity consumption to remove losses should be lower than electricity consumption of an equivalent resistive magnet…

Of course, the lowest the AC loss, the better. But, is it worth to pay a high price for loss reduction?

Examples:

NbTi fine twisted filaments comes at little costs, and the AC loss reduction is massive

Bi2223 filament twisting has high production cost and reduces I_c, twisting was discontinued

What is the difference in AC losses between HTS and LTS?

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With the emergence of REBCO coated conductors in high field magnet applications, there is a growing interest in AC losses in REBCO magnets.

Short answer: **none**. See “Case Studies in Superconducting magnets”, p. 446:
“… the mechanisms of AC losses in HTS are the same as those of AC losses in LTS…. ”

In short:

- AC losses depends on **geometry**, **size** and electrical characteristics (**J_c, normal metal resistivity**). No dependence from T_c or chemical composition.
- All the theory and analytical formulae developed in the 60’s and 70’s work also for modern coated conductor magnets.

What is the difference in AC losses between HTS and LTS?

D. Uglietti

There is a difference between LTS and HTS: it is about the consequences of loss heating.

Examples:

NbTi magnets are operated around 4.2 K, and have a tiny temperature margin (even <1 K).

Low specific heat and small temperature margin → **even a relatively small heat dissipation may lead to a temperature increment exceeding the margin**.

REBCO magnets are operated from 4.2 K up to 20 K or more, and have huge temperature margin (several K) → **even enormous heat dissipation may not be sufficient to exceed the margin**. (see slide 17).

REBCO (and other HTS) magnets can tolerate much larger losses than NbTi and Nb_3Sn magnets

But, of course, heat removal will cost more electricity

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AC losses in magnets — magnetic field transient, B(t)

D. Uglietti

In superconducting magnets, heat is released during magnetic field transient.

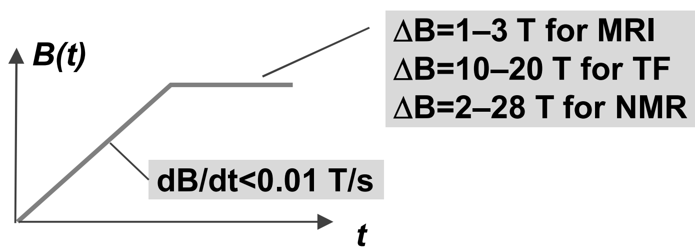
The heat, Q, depends on field amplitude and sweep rate: **Q(ΔB,dB/dt)** in J or J/m or J/m^3 (cable/strands), sometimes the power loss is used (W, W/m, W/m^3).

Let's see how much ΔB and dB/dt are in various magnet types:

NMR, MRI, some Fusion magnets (Toroidal Field and Stellarator)

STEADY STATE OPERATION

One linear ramp, then constant field for months/years.



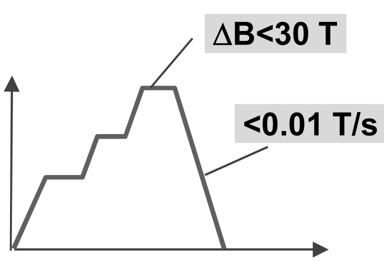
Magnetic Resonance Imaging

Nuclear Magnetic Resonance, to study structure and dynamic of complex molecules.

>90% of all sc magnets

Laboratory magnets

STEADY STATE OPERATION



Fundamental research in condensed matter physics, chemistry and biophysics.

Few % of all sc magnets

Warning: ramping faster than specified by the manufacturer may lead to quench…

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4th Workshop on Superconducting Magnet Test Facility
2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

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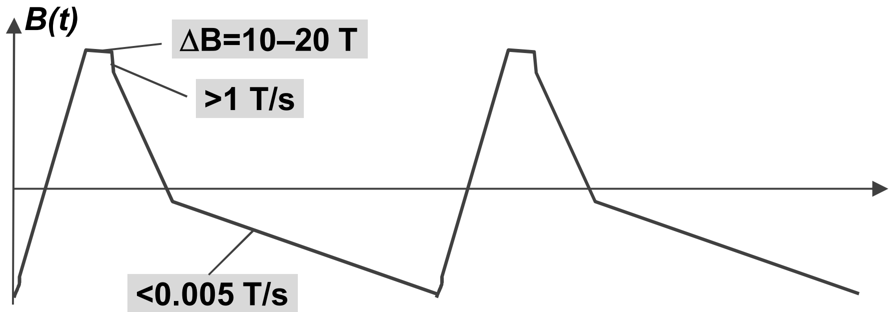
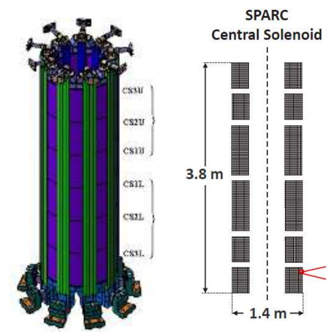
Losses in magnets — magnetic field transient, B(t)

D. Uglietti

Central Solenoid in tokamak — Complex waveform, wide range of sweep rates



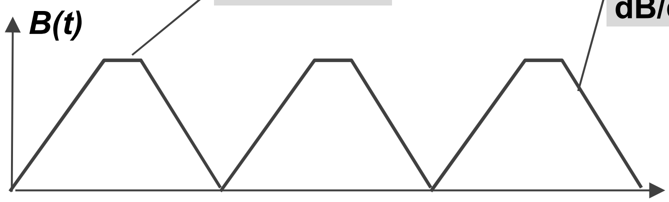


CYCLING OPERATION

Dipoles for accelerators

Slow (LHC) or fast (Dubna, SIS300) ramped.

Gantry.



CYCLING OPERATION

Few % of all sc magnets

Wide range of values for ΔB and dB/dt:

- **Field amplitude from few T to >20 T**
- **Indicative sweep rate from 5 mT/s to 5 T/s**
- **Steady state or cycling operations**

Online course
4th Workshop on Superconducting Magnet Test Facility
2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

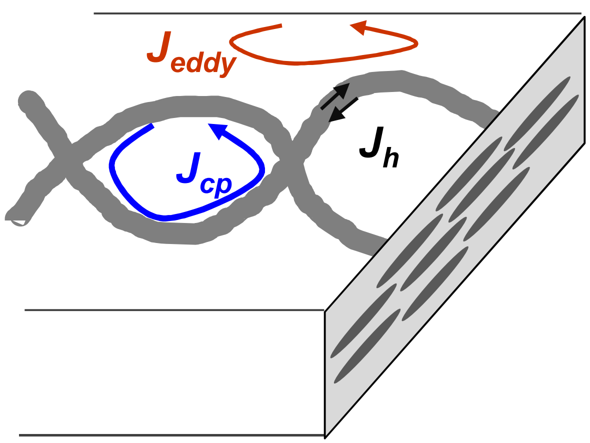
What is the physical nature of AC losses?

Field transients B(t) induces currents in:

- **Superconductor** (hysteretic, screening or magnetization currents)
- **Superconductor/metal** (coupling currents)
- **Metal** (eddy currents)

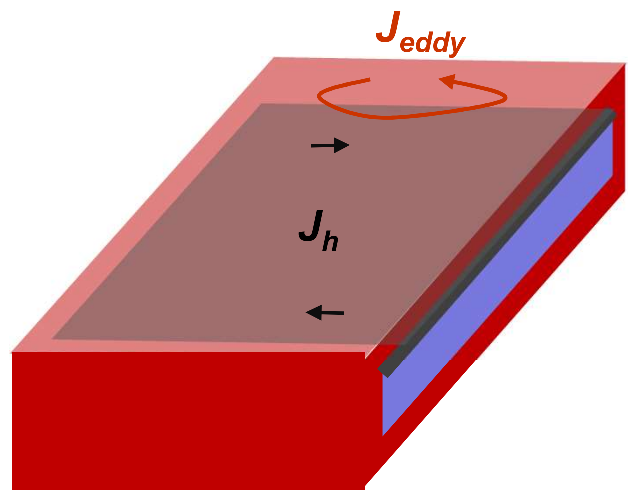
Examples:

twisted filaments Bi2223 tape (discontinued)



Same situation in a twisted, multifilamentary round wire (Nb_3Sn, NbTi).

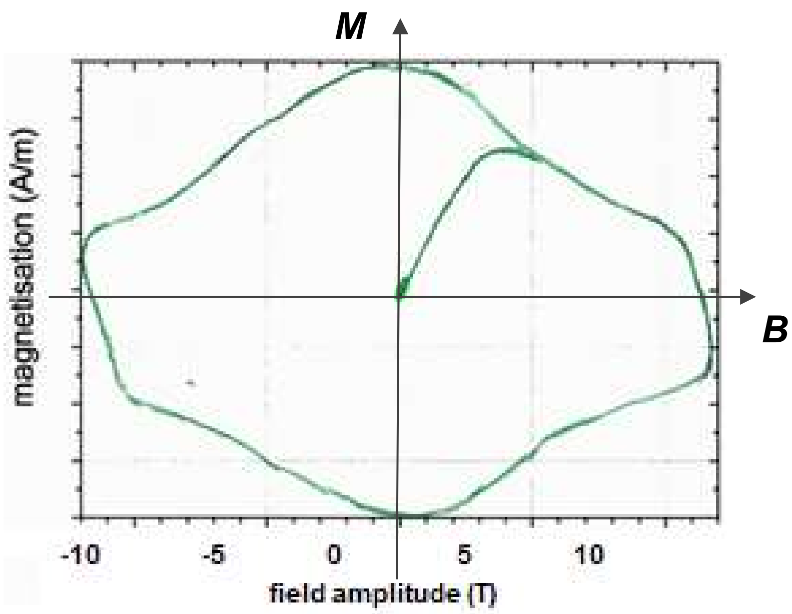
REBCO coated conductor



All induced currents generates a magnetic field (magnetization), M(t)

What is the physical nature of AC losses?

Plotting the magnetization, M, versus B:



[MxB]= T A/m =J/Am^2 A/m = **J/m^3**

The loop area is the dissipated energy per unit volume, like in magnetic materials.

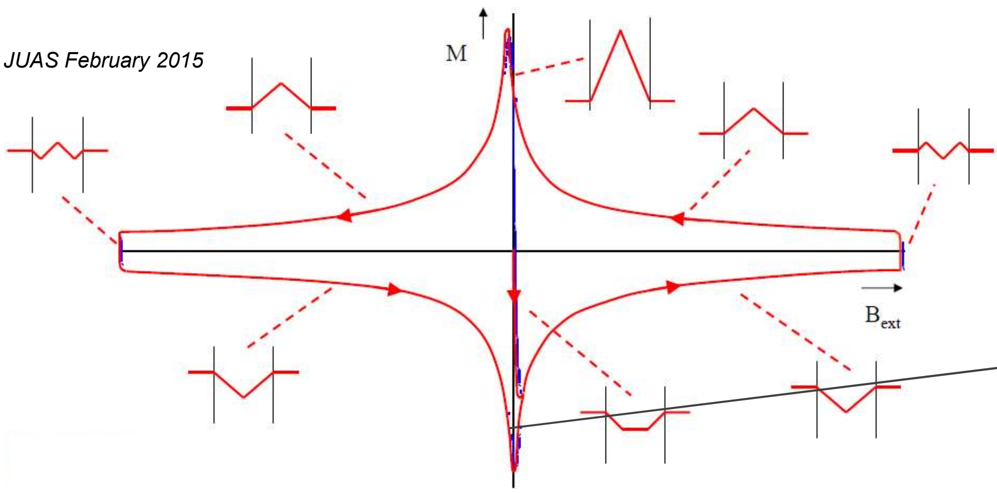
Large loops are also bad for field quality…

Then, induced currents generate losses:

- **In superconductor → hysteretic losses**
- **In superconductor/metal → coupling losses**
- **In normal metal → eddy current losses**

Hysteretic losses

Let's take just one superconducting filament.



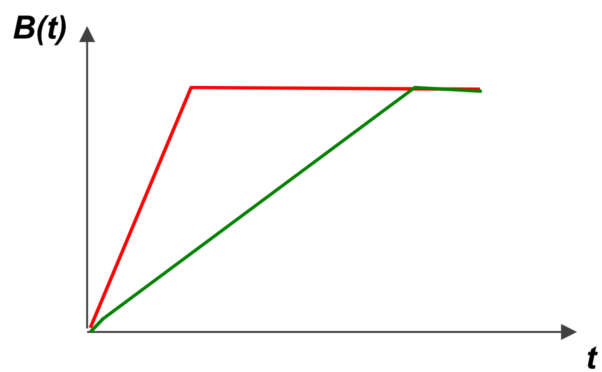
The energy is required for depinning and moving the flux lines, which is a dissipative process.

B_p, penetration field: <0.1 T for fine filaments, several T for tape stacks…

The loop area depends only on the superconductor shape, size and $J_c(B)$.

Same energy dissipation loop for slow or fast dB/dt.

Of course the slow ramp has lower power dissipation (W/m^3) than the fast one



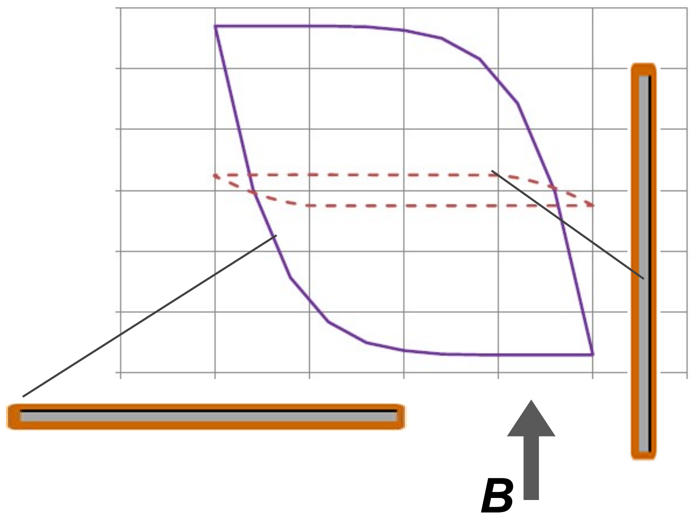
Hystertic losses — Energy dissipation does not depends on sweep rate (T/s).

Hysteretic losses

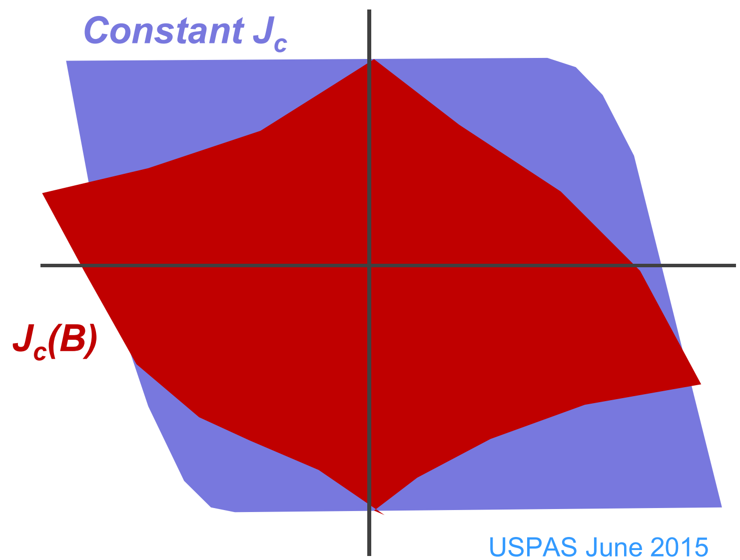
What is the effect of the superconductor size and field orientation?

Losses scales with the width of the superconductor in the plane perpendicular to the field. 1982 A. M. Campbell “A general treatment of losses in multifilamentary superconductors” https://doi.org/10.1016/0011-2275(82)90015-7

That is why fine filaments are for good for low hysteretic losses.



What is the effect of $J_c(B)$ on losses?
In first approximation, constant J_c is fine, just slightly overestimation.



Hysteretic losses

- Modern Bi2223 tapes have non-twisted filaments (lower production cost and higher J_c).
- Non-twisted stacks of coated conductor are getting more and more used.

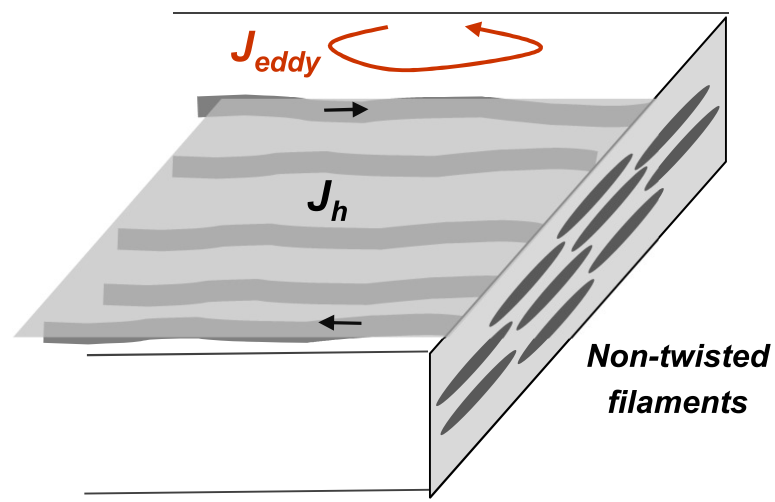
Non-twisted filaments/tapes: *the loss corresponds to that of a mono-core conductor capable to carry the same critical current.* https://doi.org/10.1016/S0921-4534(97)00119-6

"Case Studies in…" *Although Bi2223 and MgB2 tapes comprise many "filaments" to reduce their effective size (2a of Bean slab), because these filaments are not twisted, let alone transposed, AC losses remain a critical issue*

Coupling currents saturates to J_c, then the fully coupled (or saturated) loss is formally equivalent to the hysteretic losses of a monocore.

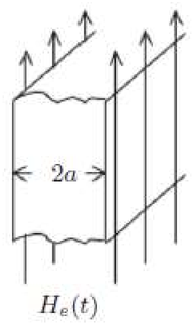
Bi2223 tape

non-twisted filaments

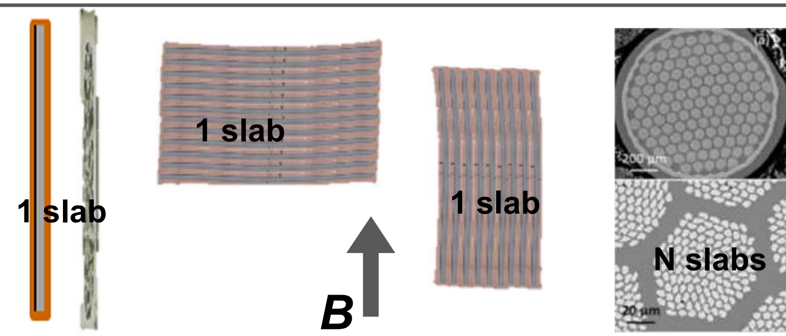


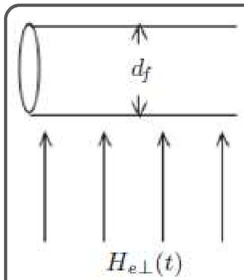
Hysteretic losses — analytical models

Several geometries can be studied analytically, see “Case Studies in Superconducting Magnets”, p.401. Three geometries are of interest for strand/conductor magnets:

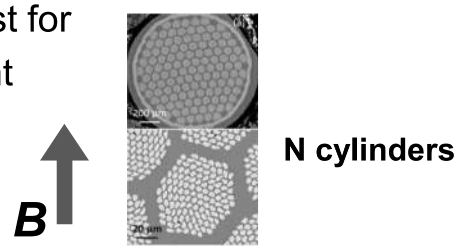


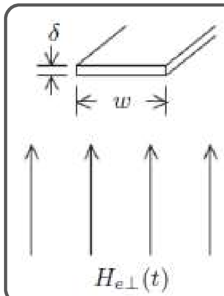
Semi-infinite **slab**, best for a high aspect ratio (tapes parallel to the field), but works also for non-twisted tape stacks or even for round filaments (at large B_{ac}).



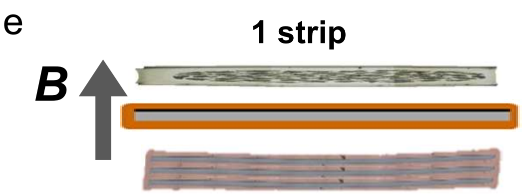


Cylinder, best for round filament





Strip for a single tape, or for a stack of few, wide tapes.



Semi-analytical formula for non-twisted stack of various aspect ratio in http://stacks.iop.org/SUST/17/537

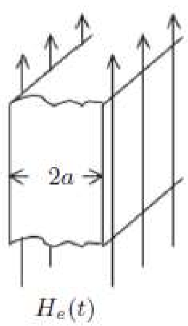
Hysteretic losses — analytical models

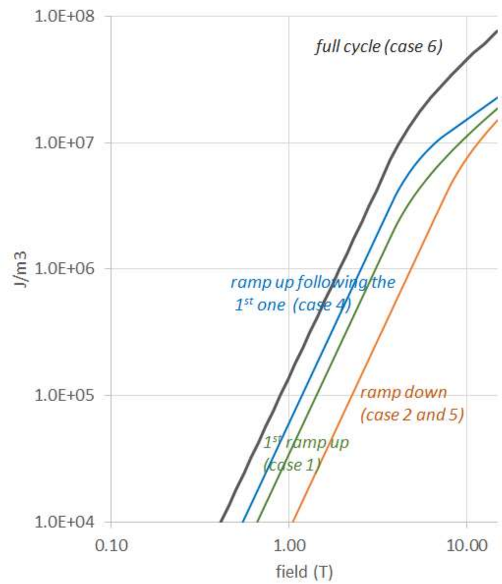
D. Uglietti

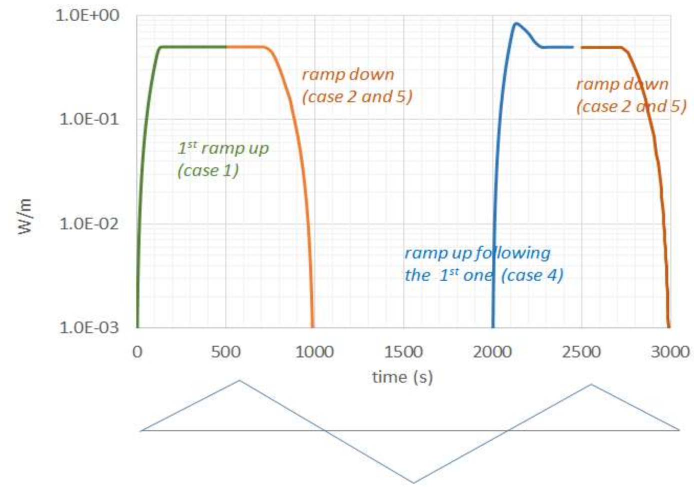
As exercise, plot the energy nad power loss for various geometries.

"Case Studies in Superconducting Magnets", p.439, **no transport current**

Semi-infinite slab





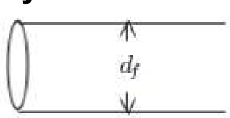


The power loss (W/m³) is obtained by differentiation, formulae can be found in:
https://doi.org/10.1109/TASC.2014.2366552
https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7429753

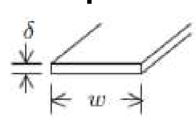
P. 440, **with transport current.** No transport current is an acceptable approximation (verify as exercise).

P. 440, **only transport current.** Not so useful for magnets.

Cylinder



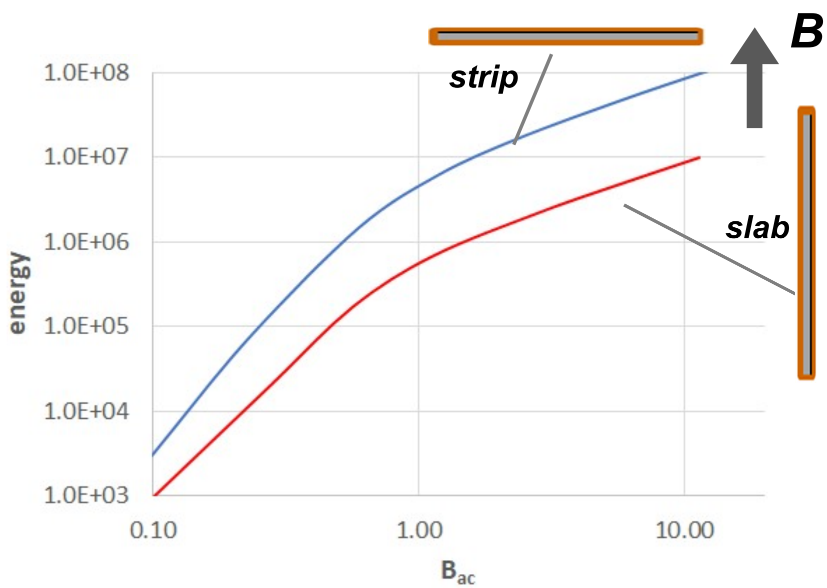
Strip



P.441, with and without transport current, perpendicular and parallel field orientations.

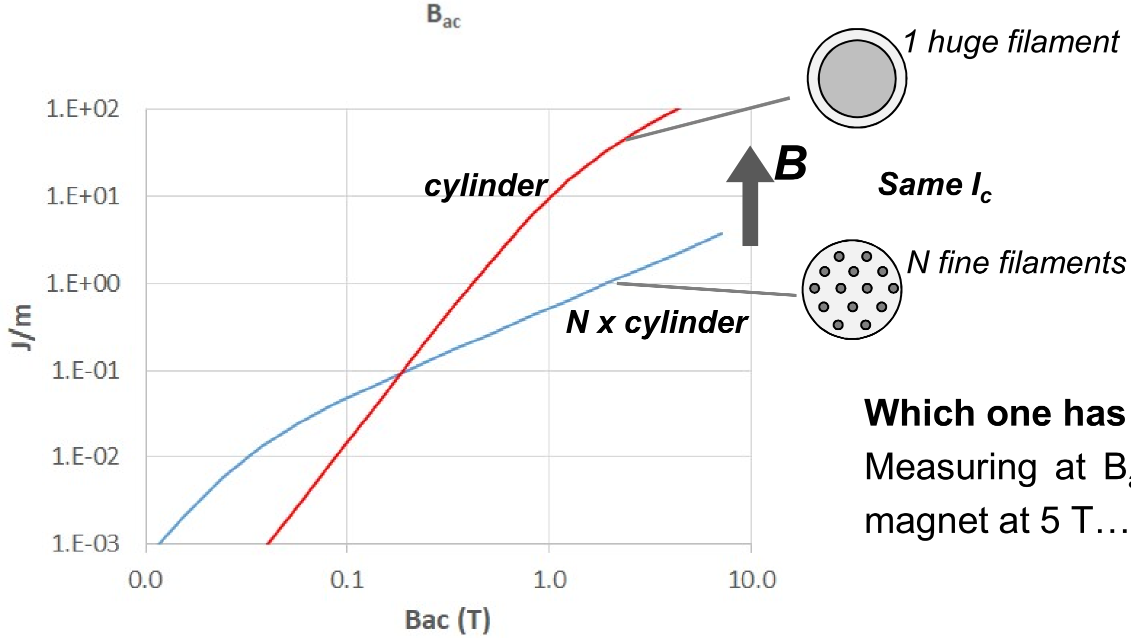
Hysteretic losses — analytical models

Few more examples (repeat calculations as exercise):



Losses scales with the width of the superconductor in plane perpendicular to the field, see slide 13.

At very slow sweep rate



See slides 24-25

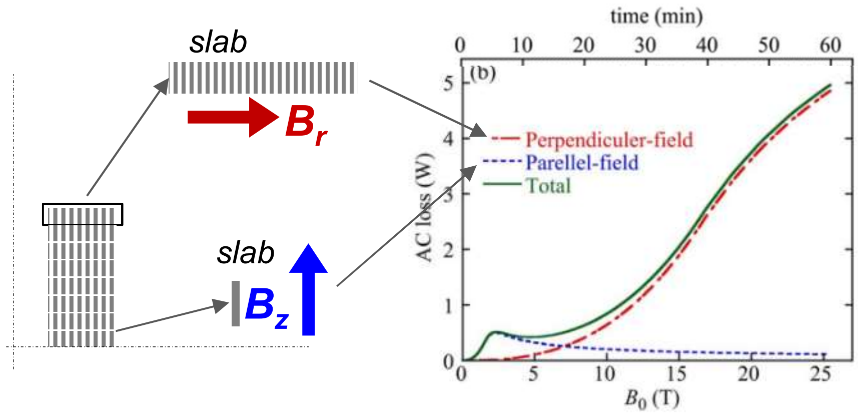
Which one has the lowest hysteretic losses?

Measuring at B_{ac}=0.1 T is different than in the magnet at 5 T…

Hysteretic losses — analytical models

EXAMPLE: 25 T cryocooled magnet at Tohoku University

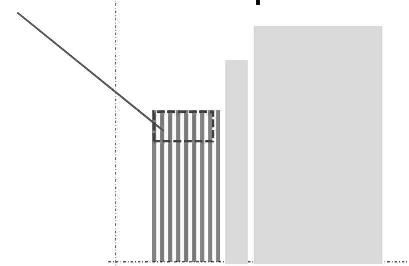
Ramping loss = axial field component loss + radial field component loss



https://doi.org/10.1109/TASC.2014.2366552

2’700 kJ/m³ for the full ramp

1’800 W/m³ in end pancakes



25 T at Tohoku	**850 kJ/m³**
32 T at NHFML	**1080 kJ/m³**

https://doi.org/10.1109/TASC.2014.2377562

Supported by measurements:

LTS 4.3 K → 5.1 K

HTS 4.3 K → 9 K

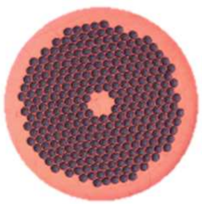
https://doi.org/10.1109/TASC.2017.2673762
https://doi.org/10.1109/TASC.2014.2368713

REBCO has much larger losses than multi-filamanetary LTS, but that’s fine (at least for stability)

Coupling losses

D. Uglietti

Instead of 1 filaments, let's measure a bundle of <u>twisted</u> filaments in conductive matrix. The losses now depends on dB/dt.



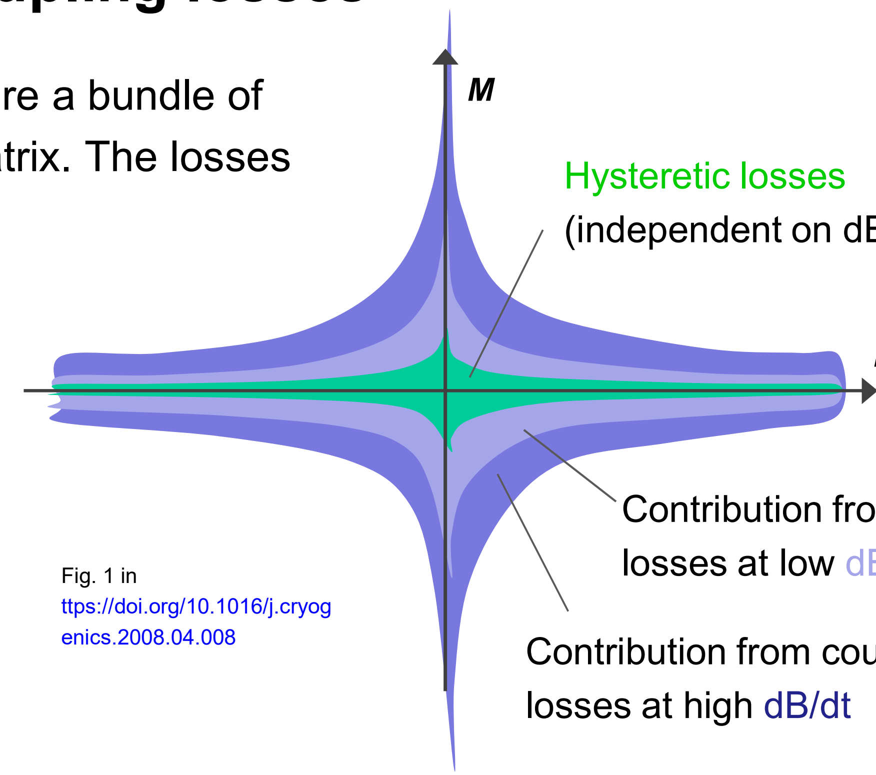
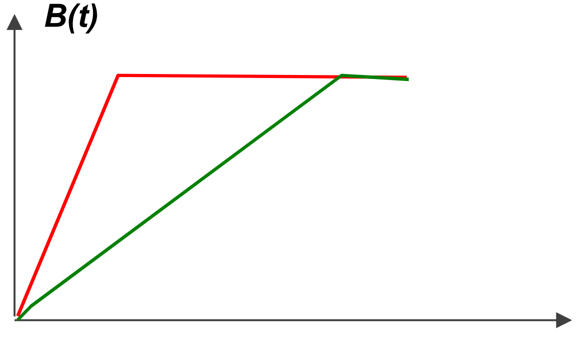


Fig. 1 in ttps://doi.org/10.1016/j.cryogenics.2008.04.008



Slow ramp: **small energy dissipation** (J/m^3)
Fast ramp: **large energy dissipation** (J/m^3).

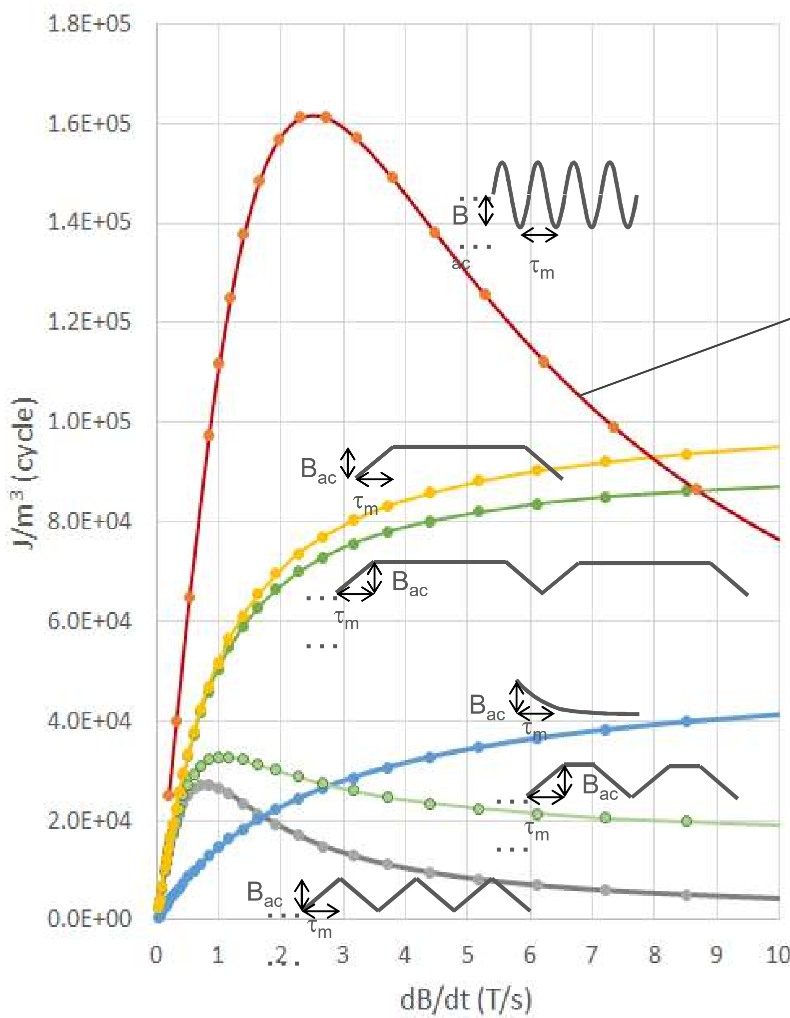
Wilson, https://doi.org/10.1016/j.cryogenics.2008.04.008
… the loss mechanism is just like an eddy current in the resistive matrix, with the superconducting filaments serving to increase the flux linkage of the eddy current paths

Coupling losses — Energy dissipation is proportional to the sweep rate (T/s)

Coupling losses — analytical models

Analytical expressions for several **B(t) waveforms**,
"Case Studies …", Table 7.8, pag. 443

Valid for wire with twisted filaments



How is the sweep rate defined?

Sinusoidal $\frac{dB}{dt}(t=0) = 2\pi \frac{B_{ac}}{\tau_m}$

All others $\frac{dB}{dt} = \frac{B_{ac}}{\tau_m}$

is equivalent to dB/dt

$$Q(f) = \sim \frac{2\pi f \cdot \tau}{(2\pi f \cdot \tau)^2 + 1}$$

What's the point in measuring coupling losses with a sinusoidal field, if magnet ramps are usually linear?

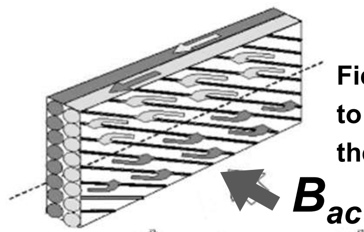
Measuring parameters (for example conductor time constant) **that are used for linear ramp or any ramp.**

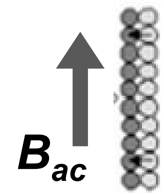
Any waveform is good for that, not just the sinusoidal.

Measuring with different waveform is useful as verification

Coupling losses – Rutherford cable

Coupling losses in Rutherford cables are similar to coupling losses in a single strand, the difference is a geometric factor.





Wilson

https://doi.org/10.1016/j.cryogenics.2008.04.008

$$\dot{Q}_{tc} = \frac{1}{60}\frac{\dot{B}_t^2}{r_c}p^2\frac{c^2}{b} = \frac{1}{120}\frac{\dot{B}_t^2}{R_c}N(N-1)p\frac{c}{b}$$

$$\dot{Q}_{ta} = \frac{1}{12}\frac{\dot{B}_t^2}{r_a}p^2\frac{c}{N\cos\theta} = \frac{1}{6}\frac{\dot{B}_t^2}{R_a}p\frac{c}{b}$$

$$\dot{Q}_{pa} = \frac{1}{16}\frac{\dot{B}_p^2}{r_a}p^2\frac{b^2}{cN\cos\theta} = \frac{1}{8}\frac{\dot{B}_p^2}{R_a}p\frac{b}{c}$$

from coupling currents across the layers

from coupling currents in the layer

Sytnikov

https://link.springer.com/chapter/10.1007/978-1-4757-9053-5_69

$$W^{\perp} = W^{\perp}_{R_\perp} + W^{\perp}_{r_\parallel} = \frac{H^2L}{3}\left(\frac{N^2}{20R_\perp} + \frac{1}{r_\parallel}\right)\left(\frac{dB}{dt}\right)^2$$

$$W^{\parallel} = \left(\frac{La^2}{r_\parallel}\right)\left(\frac{dB}{dt}\right)^2$$

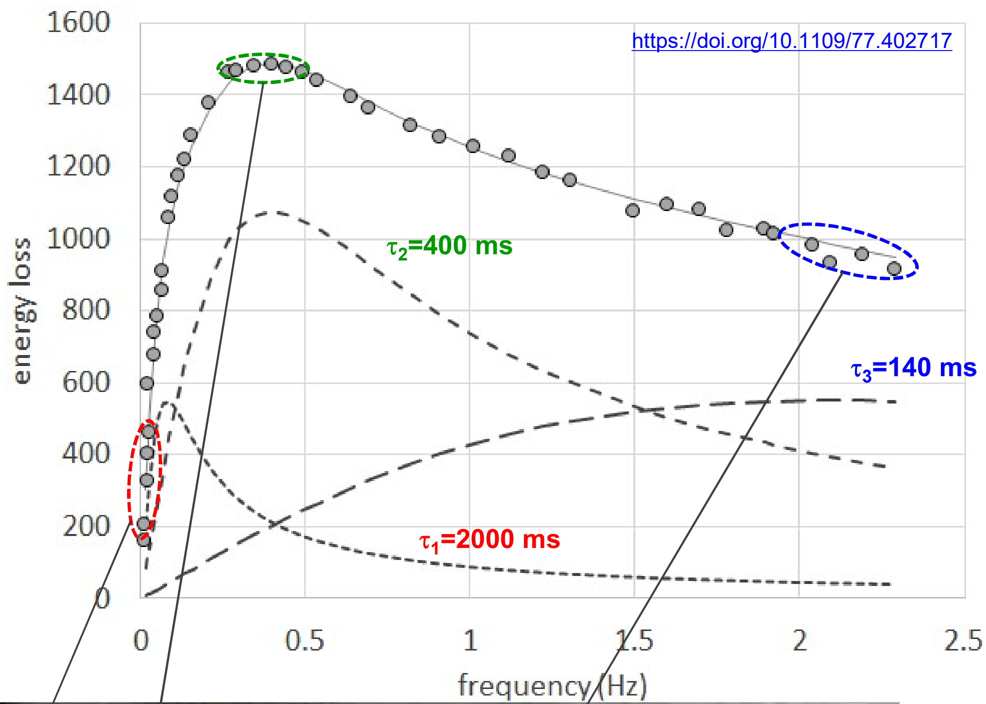
Resistances are selected to be large enough for loss reduction but low enough to allow current redistribution

Coupling losses — multistage cables

D. Uglietti

In multistage cables the transverse resistance varies greatly along the length. Strands follow complex patterns. Then:

In this example, the total loss is the sum of three different losses (three tau), instead of one tau (single strand)



Current loops change with frequency

Tau are not set by the number of stages, but rather by the number of loops, then

$\tau_1, .., \tau_N$ https://doi.org/10.1016/j.cryogenics.2010.05.001
https://link.springer.com/chapter/10.1007/978-1-4757-9059-7_166

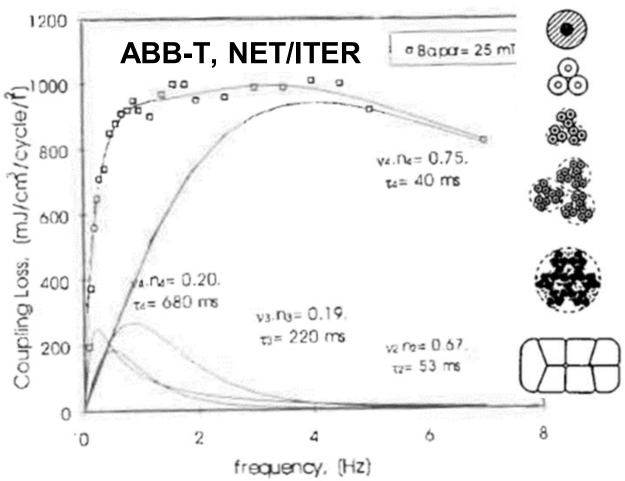
or

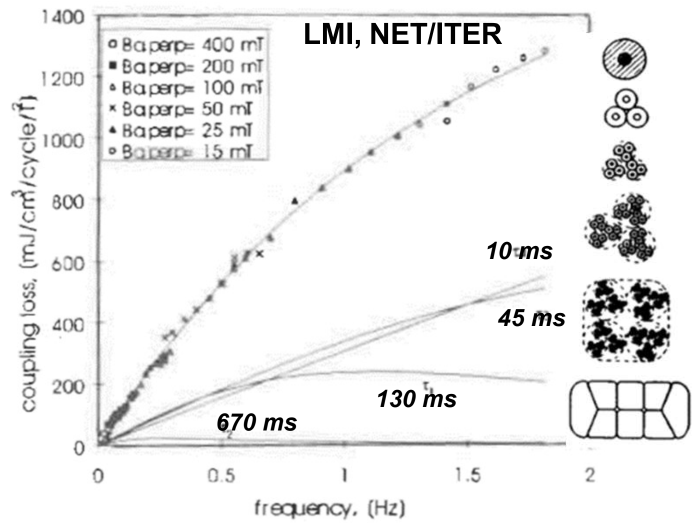
$\tau(f)$ https://doi.org/10.1016/j.fusengdes.2019.01.116

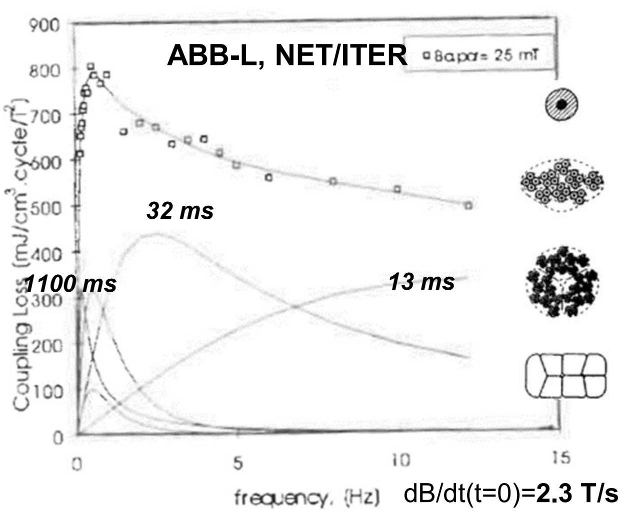
Coupling losses — multistage cables

D. Uglietti

Few more examples. Variety of shapes, depending on cable design







dB/dt(t=0)=**2.3 T/s**

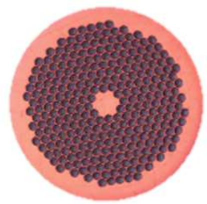
1996 Coupling loss time constants in full-size Nb3Sn CIC model conductors for fusion magnets
https://link.springer.com/chapter/10.1007/978-1-4757-9059-7_166

No model can predict the different time constant and thus the AC losses for a given cable design.

Measurements are necessary to extract the time constants.

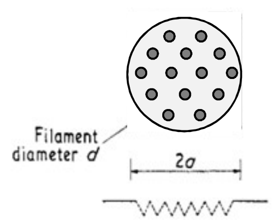
Hysteretic and coupling losses in strands

Wilson, Superconducting Magnets, p. 181 ***"As dB/dt, twist pitch is increased or rho is reduced, … the penetration loss in a twisted multifilamentary composite may be approximated by the hysteresis loss in a solid wire of the same diameter"***



The advantage of filamentisation is lost if the sweep rate is too fast.

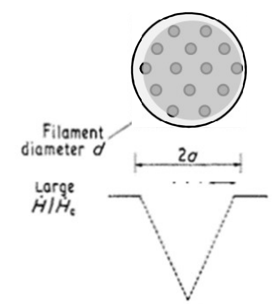
At very low dB/dt, say 0.01 T/s



Only hysteretic loss
Coupling losses are negligeable

https://doi.org/10.1088/0022-3727/3/11/304

At very fast dB/dt, say, 1 T/s



Only saturated coupling loss,
formally equivalent to hysteretic loss

Also in twisted, striated coated conductors: *Multi-filamentarization is ineffective for reducing the power loss at high frequencies.*
https://doi.org/10.1088/1361-6668/ab0d63

EPFL

Hysteretic and coupling losses in strands

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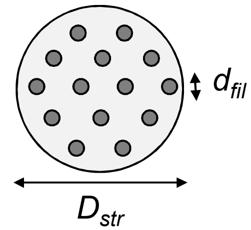
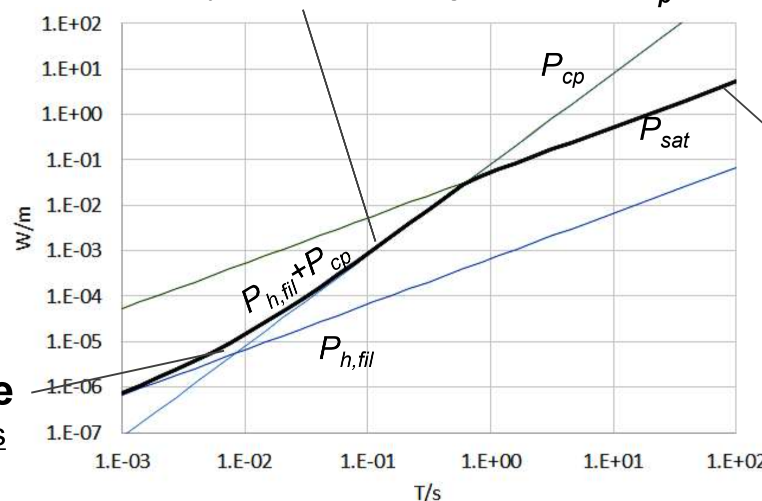
Example:
D_{str}= 1 mm
$J_{e,str}$= $4 \cdot 10^8$ A/mm^2
d_{fil}= 10 micron
N_{fil}= 2000
J_c= $2 \cdot 10^9$ A/mm^2



$B_{p,fil}$= 13 mT, $B_{p,str}$= 250 mT

Intermediate ramp rate
Hysteretic+coupling

$B>B_p$

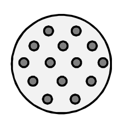


Slow ramp rate
Uncoupled filaments

Fast ramp rate
Fully coupled filaments

Hysteretic loss in filaments

$$P_{h,fil} = \frac{4}{3\pi}\frac{1}{\mu_0}\dot{B}B_{p,fil}, \quad B > B_{p,fil} = \mu_0 \frac{1}{2} J_c d_{fil}$$



+

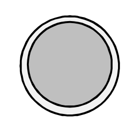
Coupling loss between filaments

$$P_{cp} = \frac{n\tau}{\mu_0}\dot{B}^2$$

Saturated loss in the strand

$$P_{sat} = \frac{4}{3\pi}\frac{1}{\mu_0}\dot{B}B_{p,str}, \quad B > B_{p,str} = \mu_0 \frac{1}{2} J_{e,str} D_{str}$$

like hysteretic loss in a monolithic wire



Similar plot in: https://doi.org/10.1088/1361-6668/ab0d63

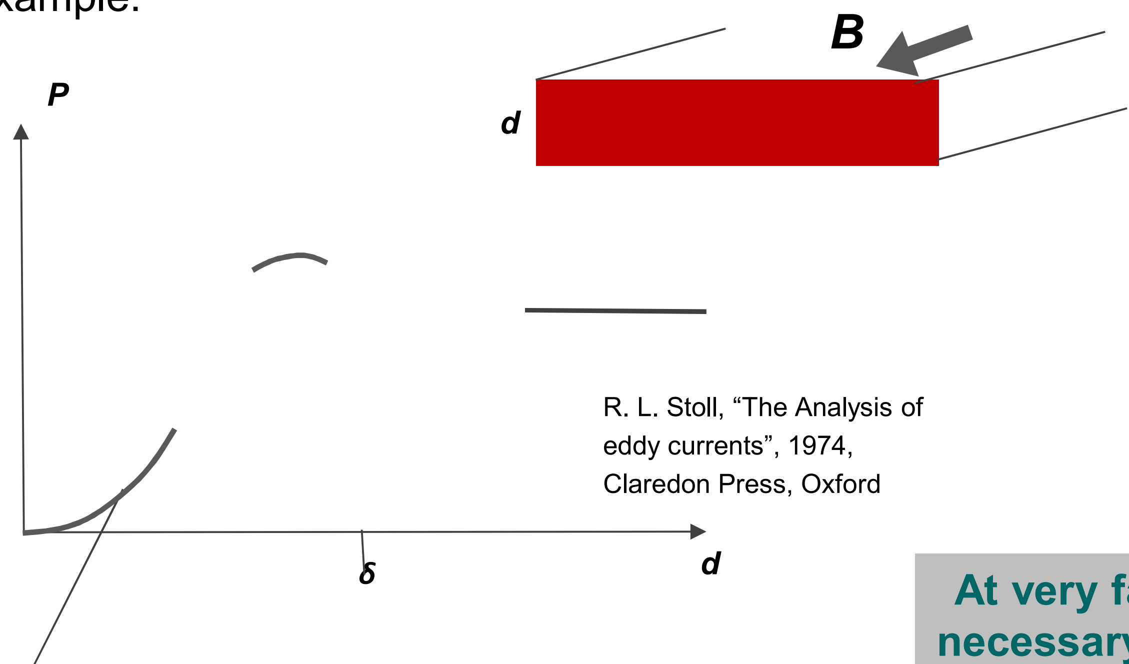
Online course
4th Workshop on Superconducting Magnet Test Facility
2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

Eddy losses

Eddy losses are studied, for example in transformers or induction heating systems. Superconducting strands and cables may need large cross section of metal (Cu or Al) for protection. In fast ramped magnets, the protection material generates eddy current losses.

Some analytical expressions in "Case Studies …", Table 7.9, pag. 443, energy density (J/m3) for wire or flat rectangular section, for various waveform.

Example:



Penetration depth

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \sqrt{\frac{2\rho}{\mu_0 \omega}}$$

R. L. Stoll, "The Analysis of eddy currents", 1974, Claredon Press, Oxford

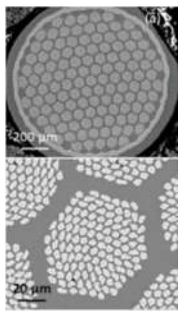
Small for thin layers and low sweep rate

At very fast sweep rate could be necessary (especially for low loss LTS conductors) to subdivide the protection material

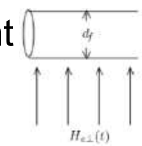
Total losses — examples

Lets's put all three losses together:

Fine twisted multifilamentary



At very height sweep rates:

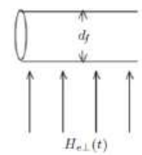


$Q_{hystertic}$ x N filaments **+ $Q_{coupling}$** **Q_{eddy}** can be neglected

At very height sweep rates:

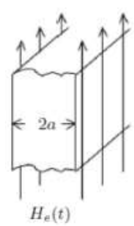
$Q_{hysteretic}$ = $Q_{fully\ coupled}$

1 large filament



Q_{eddy}

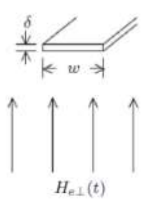
Non-twisted stack



$Q_{hysteretic}$ = $Q_{fully\ coupled}$

1 large slab

Twisted stack



$Q_{hystertic}$ x n.tapes **+ $Q_{coupling}$**

Numerical Methods

"Case Studies in Superconducting Magnets":

…a complex "real-world" case may have to be either simplified to an analytically solvable model — a recommended approach for every problem — or computed head-on with a code at the outset, an unattractive and <u>much less revealing</u> approach.

For a review of finite element (and analytical) computational methods, see:

2014 F. Grilli, *Computation of Losses in HTS Under the Action of Varying Magnetic Fields and Currents* https://doi.org/10.1109/TASC.2013.2259827

Probably, the best strategy is:

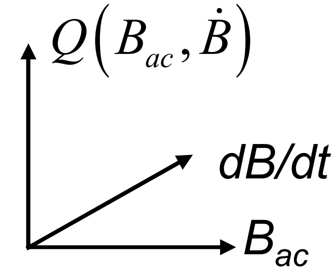
- **first analytic model, to understand the physics**
- then numerical model, to work out the details.

Loss Map

We saw (slides 25,27) the different regimes for a given strand/conductor.

How to get a comprehensive overview?

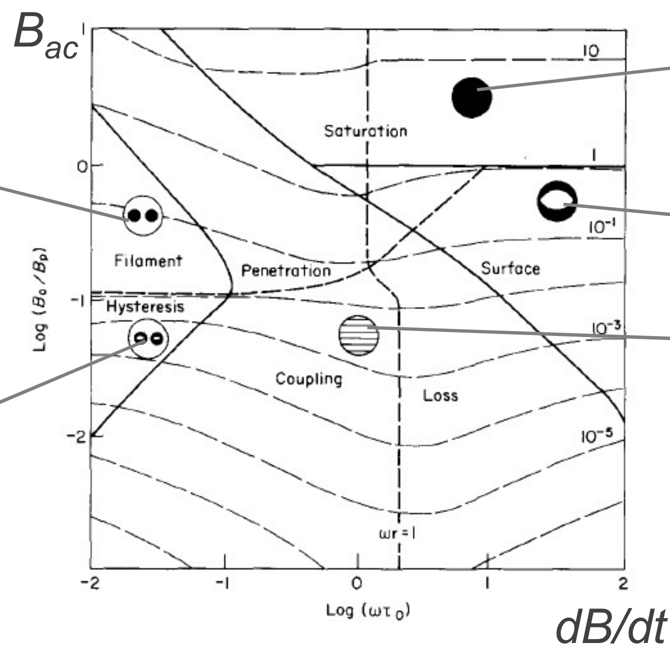
AC loss is a function of two variables, B and dB/dt.



Let's look just at the contour lines in the domain (B_{ac}, dB/dt plane) for a twisted multifilamentary wire:

Only hystertic loss, filaments are fully penetrated

Only hystertic loss, filaments are partially penetrated



Fully coupled filaments (behaves like a mono-core), fully penetrated

Fully coupled filaments (behaves like a mono-core), partially penetrated

Hystertic (in filaments) + coupling losses

1982 Campbell, A general treatment of losses in multifilamentary superconductors
https://doi.org/10.1016/0011-2275(82)90015-7

Similar analysis in Carr: https://doi.org/10.1109/TMAG.1974.1058408

Loss Map

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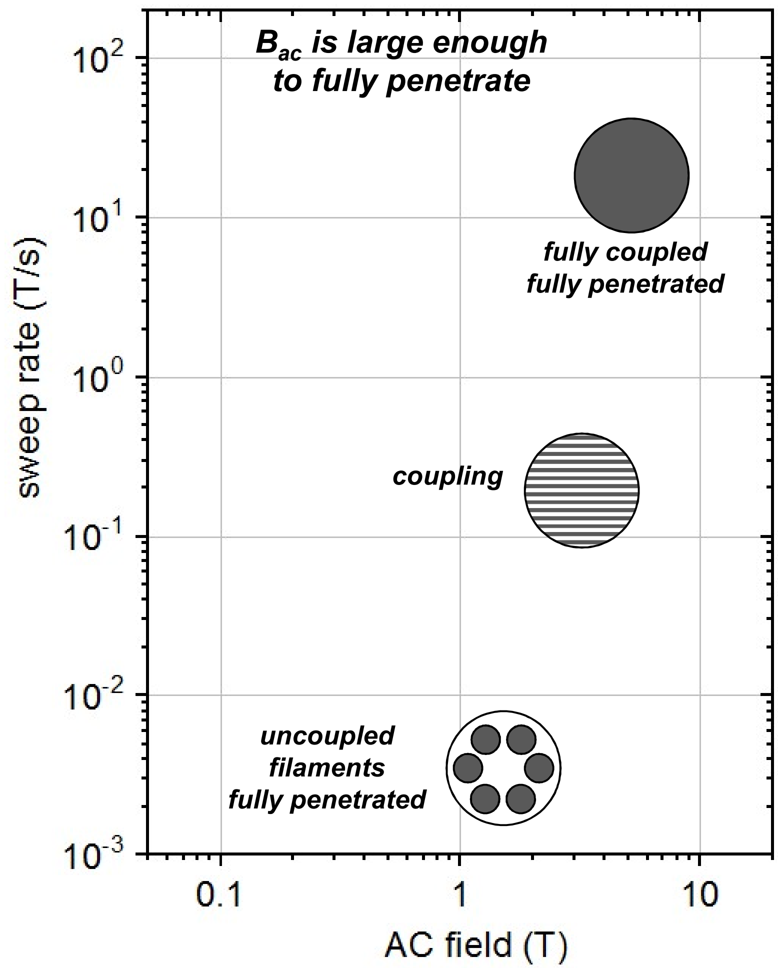
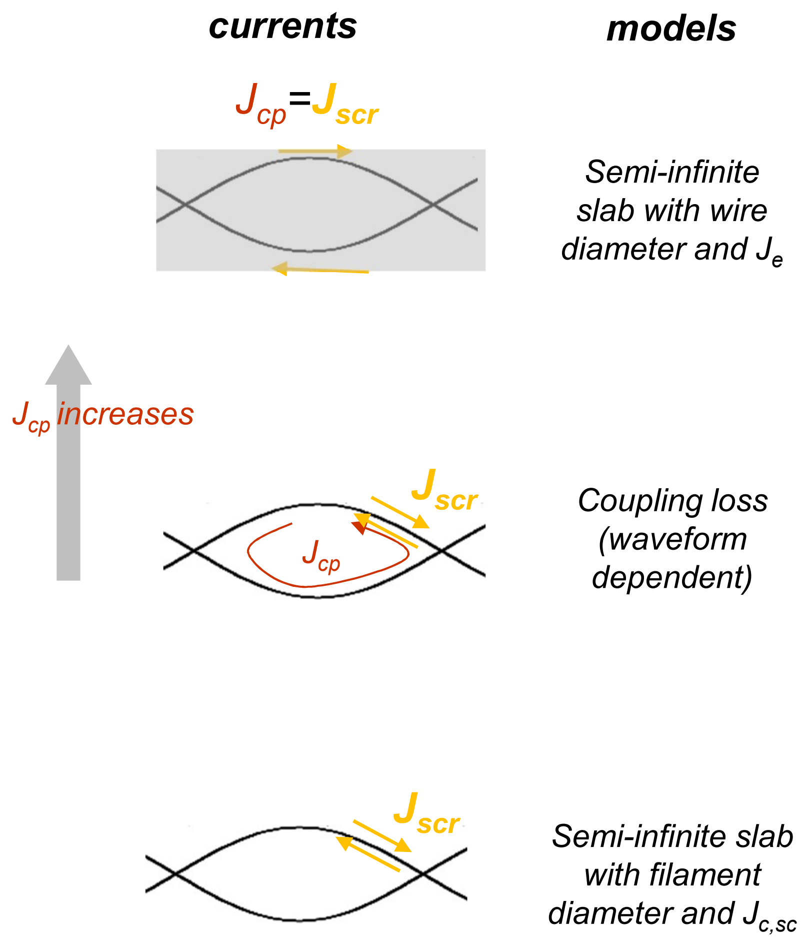
The same, with induced currents and models

1985 Superconducting Magnets: "*As dB/dt, is increased … the penetration loss in a twisted multifilamentary composite may be approximated by the hysteresis loss in a solid wire of the same diameter*"





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Loss Map

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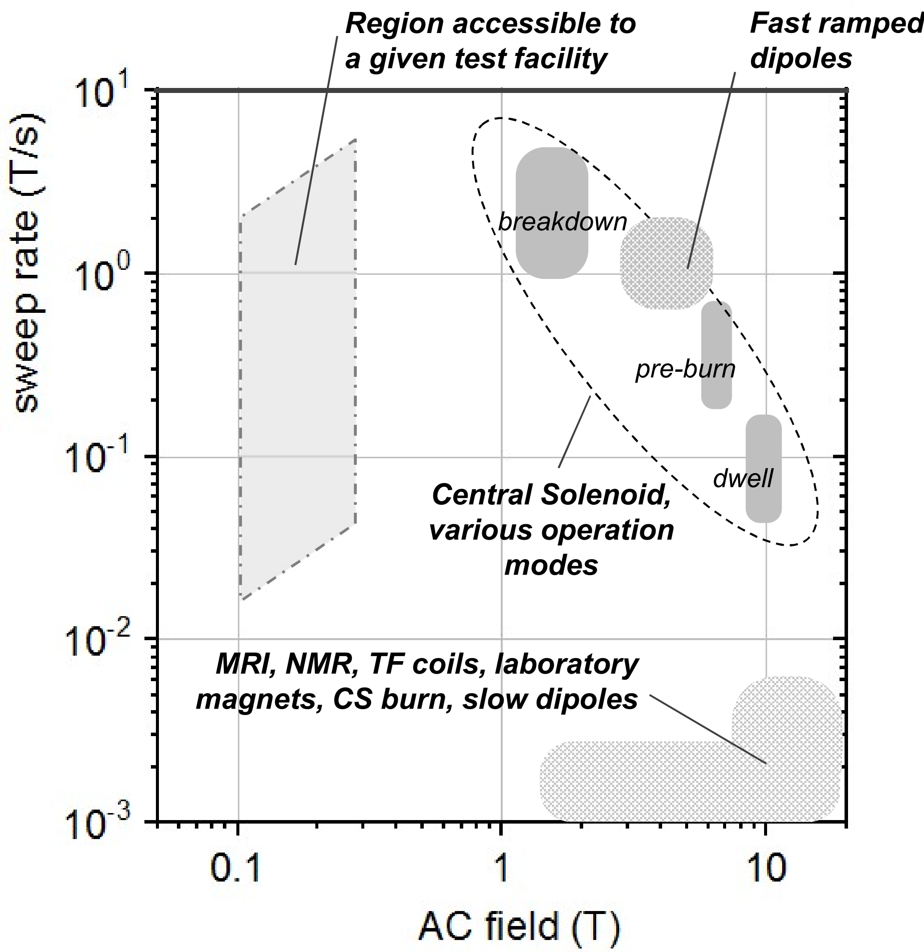
Let's put the sweep rate and field amplitudes from slides 9 and 10 on the map.



The operating magnet conditions could differ from the strand test conditions. How to go from measurements to magnet operation? **Physical model.** See slide 17.

Measuring AC losses is not always sufficient. A full understanding of loss mechanisms for a particular conductor is necessary.

Losses in magnets

Magnets are wound with strands or with cables (large magnets).
Are the losses measured on one strand or in the cable the same as in the magnet? **In general, no:**

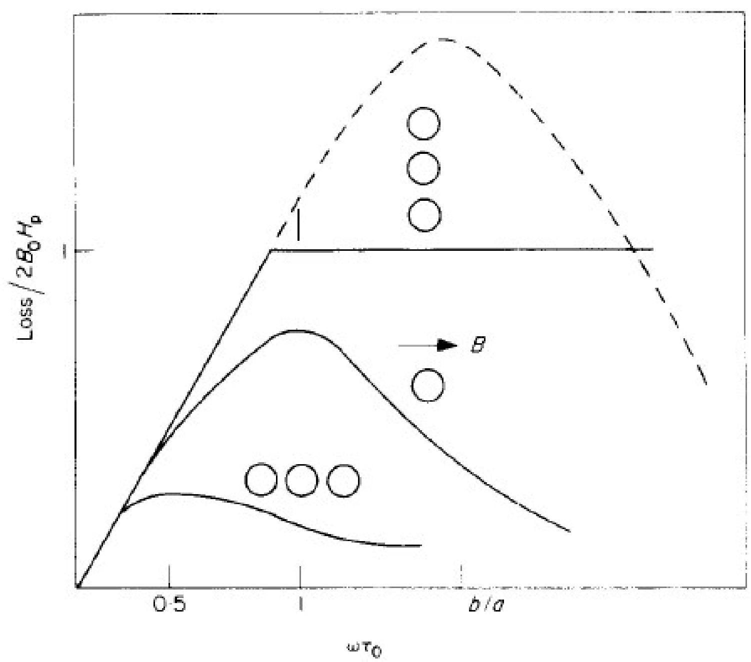


Fig. 9 The effect of winding a round wire onto a solenoid, and pancake coil of aspect ratio a/b. τ_0 is the time constant of an isolated wire and the amplitude assumed is such that the pancake coil saturates, but the isolated wire does not

1982 Campbell, A general treatment of losses in multifilamentary superconductors https://doi.org/10.1016/0011-2275(82)90015-7

Example: strip model for a single tape in perpendicular field, but slab in pancake, see slide 18

Loss reduction

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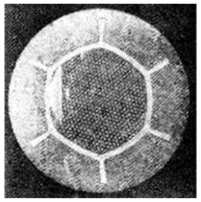
"Case Studies in Superconducting magnets", pag. 446: loss mechanism in LTS and HTS is the same, then **loss reduction strategies are the same for LTS and HTS**:

Hysteresis loss — reduce superconductor element size (in the plane perpendicular to the magnetic field).

Coupling loss — superconducting filaments magnetically and electrically decoupled (short twist pitches, increase transverse resistivity).

Eddy-current loss — conductive matrix added sparingly in the superconductor, then subdivide the matrix with high resistive metals.

Example of eddy current loss reduction in strand:



https://doi.org/10.1109/TMAG.1981.1060977

Loss reduction

D. Uglietti

NbTi, Nb_3Sn

Hysteretic: fine effective filaments (2–20 microns diameter), lead to small Q_h.

Coupling: short twist pitch for low Q_{cp}.

Bi2212

Hysteretic: twisted filaments, but bridging among filaments lead to large effective diameter.

Coupling: twisted filaments in low resistivity matrix leads to low coupling losses only at very low sweep rate.

Bi2223

Non-twisted filaments → only saturated coupling loss (equivalent to **hysteric losses of a very large filament).**

Twisting filaments (and even more resistive barrier around filaments) reduces I_c and increase fabrication costs: abandoned.

REBCO

Single layer ceramic → large hysteretic losses, similar to Bi2223, unless the field is perfectly parallel to the wide face of the tape, impossible in practical magnets.

EPFL

How to measure AC losses?

Three methods: magnetic, electrical, thermal.

MAGNETIC METHODS — measuring the whole M-B curve, the area is the dissipated energy.

SQUID or VSM magnetometer

- Small samples (wires or tapes)
- large field amplitude (10 T), low sweep rates <0.1 T/s

Susceptometer

- Small samples (wires or tapes)
- Small field amplitude (0.1 T), fast sweep rates >0.1 T/s

ELECTRICAL METHOD for coils, Wilson “superconducting Magnets”, sect. 10.6 and https://doi.org/10.1016/0011-2275(73)90063-5

- The dissipated energy is the total energy fed in the coil minus the inductive stored energy.
- Improvements in https://doi.org/10.1016/0011-2275(80)90003-X https://doi.org/10.1016/0011-2275(85)90004-9
- Application to a large cable-in-conduit coil: https://doi.org/10.1016/S0921-4534(98)00472-9

How to measure AC losses?

THERMAL METHODS — measuring temperature increment due to AC loss dissipation.

Boil-off calorimetry

- Works at best at with LHe, small sensitivity with LN
- Small samples (wires or strand) or coils ("Superconducting Magnets", sect. 10.6 and https://doi.org/10.1016/0011-2275(73)90063-5)

Adiabatic calorimetry

- The sample is insulated from the environment. AC loss will produce a temperature rise.
- Small samples (wires or strand) but can works also for coil (cryocooler)

Enthalpy or flow calorimetry

A cryogenic fluid (usually supercritical helium) cool the sample, the fluid temperature rise and the mass flow rate. Often used for cable in conduit conductors (short samples or even the whole coil)**.**
See: https://doi.org/10.1016/S0011-2275(99)00045-4 https://doi.org/10.1109/TASC.2022.3170291 https://doi.org/10.1109/TASC.2022.3170291

There is no best method.
Any method has limitations and/or disadvantages.
Understand the limitations and error sources.
It is good to have both electrical and calorimetric ones, as verification

Summary

- **Learn from books, past courses, review papers.** Fresh publications comes at the last place.
- AC losses comes in three types: **hysteretic, coupling, eddy.** The largest contribution depends on conductor, field amplitude and dB/dt. The largest contribution could be any of the three types.
- Complex variation of the three contributions at different amplitudes and dB/dt.
- **Any statement/formula on losses should include the limit of validity. There are no statements with general validity**.
- Any measuring systems have disadvantages and weak points. **Understand the limitaions of the measuring system**. **Physics is necessary to understand the measurement**.

Summary

D. Uglietti

MODELS AND MEASUREMENTS

- **Analytical models** for hysteretic losses (slab, cylinder, strip) and for coupling losses in wires **work quite well.**
- **In Rutherford and multi-stage cables**, time constants can not be predicted, and **measurements are then necessary to extract these parameters**.

MATERIALS

- **Same AC loss physics in LTS and HTS.**
- **NbTi and Nb_3Sn wires have low stability. Decades of developments have led to low losses.**
- **Bi2212 wires, Bi2223 and REBCO tapes are super stable, have been designed for maximum J_c, and losses can be quite high.** Magnets work, but may need more electricity for removing losses.