AC loss – part I

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Outline of Part I:

1. What is AC loss

2. Dissipation mechanisms: Resistive, Eddy currents, Flux pinning, Coupling currents

3. Possibilities for AC loss reduction

4. Methods to measure AC loss
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What is understood under AC loss

= amount of heat released during operation in cyclic (or transient) regime

it does not appear in DC regime

is not a property of material but of a (superconducting) object operating in well defined conditions (temperature, transported current, applied magnetic field)
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Resistive AC loss

does not fall under the definition of AC loss because it is due to static $E(j)$ relation

can be calculated from $E(j)$

should be marginal in nominal operating regime
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Eddy current loss

*induced currents in metallic parts*  
*treated in textbooks of electromagnetism (skin effect, inductive heating)*

penetration depth  
$$\delta = \sqrt{\frac{2\rho}{\mu_0\omega}}$$  
metal resistivity  
frequency (angular)  
magnetic permeability of vacuum

shielding of magnetic field if  \(\delta \ll\) wall thickness

negligible if  \(\delta \gg\) thickness of metallic object

should be marginal in nominal operating regime
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Hysteresis loss in superconductor

because of magnetic flux pinning in superconductor
(the mechanism securing high current transport capacity i.e. large
critical current density in magnetic fields \( \gg 1 \ T \) )

“hard” = type II superconductor with flux pinning

critical state model – Ch. P. Bean 1962:

\[
|j| = \begin{cases} 
0 & \text{in the places that never experienced electrical field} \\
 j_c & \text{elsewhere} 
\end{cases}
\]

simplest version: \( j_c \) independent of \( E, B \)

\( j_c = \text{const.} \) sometimes call “the Bean model”
Transport of electrical current

e.g. the critical current measurement
Transport of electrical current

AC cycle with $I_a$ less than $I_c$ : *neutral zone*
AC transport in hard superconductor: is it still without dissipation?

\[ Q = \int_{T} I Ud\, dt = -\int I d\Phi \]

neutral zone:
\[ j = 0, \ E = 0 \]

check for hysteresis in \( I \) vs. \( \Phi \) plot

\[ U = -\frac{\partial \Phi}{\partial t} \]
AC transport loss in hard superconductor

![Graph showing AC transport loss with hysteresis leading to dissipation and then AC loss]

hysteresis $\rightarrow$ dissipation $\rightarrow$ AC loss
AC transport loss in hard superconductor

hysteresis $\rightarrow$ dissipation $\rightarrow$ AC loss
Hard superconductor in changing magnetic field

0 $\rightarrow$ 30 $\rightarrow$ 50 $\rightarrow$ 40 mT

$\rightarrow$ 0 $\rightarrow$ -50 $\rightarrow$ -40 $\rightarrow$ 0 $\rightarrow$ 50 mT
Hard superconductor in changing magnetic field

dissipation because of flux pinning

volume loss density $Q$ [J/m$^3$]

$$\frac{Q}{V} = \int B_a \, dM$$

magnetization:

$$M = \int_S -x \cdot j(x, y) \, dx \, dy$$
Round wire from hard superconductor in changing magnetic field

- $M_s$ saturation magnetization, $B_p$ penetration field
Round wire from hard superconductor in changing magnetic field

estimation of AC loss at \( B_a >> B_p \)

\[
\frac{Q}{V} \approx 4B_a M_s
\]
Slab in parallel magnetic field – analytical solution

\[ B_p = \mu_0 j_c \frac{w}{2} \]

\[ M_s = j_c \frac{w}{4} = \frac{B_p}{2\mu_0} \]

\[ \frac{Q}{V} = \frac{1}{\mu_0} \left\{ \frac{2}{3} \frac{B^3_a}{B_p} \right\} \]

\[ 2B_p B_a - \frac{4}{3} B_p^2 \]

\[ Q \approx 4B_a M_s \]
Slab in parallel magnetic field – analytical solution

\[ Q \approx 4B_a M_s \]
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Coupling loss - two parallel superconducting wires in metallic matrix

in the case of a perfect coupling:

\[ B_a \]

 Coupling currents

\[
\begin{align*}
0 & \rightarrow 20 & \rightarrow 80 & \rightarrow 60 \text{ mT}
\end{align*}
\]
Magnetization of two parallel wires

how to reduce the coupling currents?
Composite wires – twisted filaments

\[ \rho_t = \rho_m \frac{1 - \lambda}{1 + \lambda} \quad \text{good interfaces} \]

\[ \rho_t = \rho_m \frac{1 + \lambda}{1 - \lambda} \quad \text{bad interfaces} \]

\[ \lambda = \frac{S_{SC}}{S_m} \]

\[ j_\perp = \frac{l_p \dot{B}}{2\pi \rho_t} \]
Composite wires – twisted filaments

coupling currents (partially) screen the applied field

\[ B_i = B - \tau \dot{B} \quad \tau - \text{time constant of magnetic flux diffusion} \]

\[ \tau = \frac{\mu_0}{2 \rho_t} \left( \frac{l_p}{2\pi} \right)^2 \]

\[ \frac{Q}{V} = \frac{B_{\text{max}}^2}{\mu_0} \frac{2\pi \omega \tau}{1 + \omega^2 \tau^2} \]

round wire

K. Kwasnitza, S. Clerc (1994) Physica C 233 423

\[ \frac{Q}{V} = \frac{B_{\text{max}}^2}{\mu_0} \frac{\chi_0 \pi \omega \tau}{1 + \omega^2 \tau^2} \]

flat wire

\[ \tau = \tau_{\text{round}} \frac{\chi_0}{2} A \]
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Hysteresis loss:

at large fields proportional to $B_p \sim j_c w$

$= \text{loss reduction by either lower } j_c \text{ or reduced } w$

lowering of $j_c$ would mean more superconducting material required to transport the same current

thus only plausible way is the reduction of $w$
effect of the field orientation

\[
\frac{Q}{V} \approx 4B_a M_s
\]
Magnetization loss in strip with aspect ratio 1:1000

\[ \frac{Q}{V} \approx 4B_a M_s \]
in the case the tape orientation is not a free parameter

= reduction of the tape width

striation of CC tapes

~ 6 times lower hysteresis loss
striation of CC tapes

but in operation the filaments are connected at magnet terminations

coupling loss will be the main issue
Coupling loss:

at low frequencies proportional to

\[
\tau = \frac{\mu_0}{2\rho_i} \left( \frac{l_p}{2\pi} \right)^2
\]

= filaments (in single tape) or tapes (in a cable) should be transposed

= low loss requires high inter-filament or inter-tape resistivity

*but good stability needs the opposite*
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Experimental methods for AC loss determination

- Tape
- Cable
- Magnet
Experimental methods for AC loss determination

Shape of the excitation field (current) pulse

transition  unipolar  harmonic

relevant information can be achieved in harmonic regime

final testing necessary in actual regime
Experimental methods for AC loss determination

1. Thermal
   a) cooling power (large devices)
   b) boil-off
   c) temperature profile

2. Electrical
   - lock-in technique
   - $\Psi(I)$ hysteresis loop registration
temperature profile method

\[ y = 0.1677x + 0.1452 \]

\[ P = \frac{(U_{tc} - 0.145)}{0.168} \]

\[ P \sim \Delta T \]
Electrical method

\[ Q = \int Power \cdot dt \]

1 AC cycle

\[ Q = \int_{t}^{t+T} U(t)I(t) \cdot dt \]

"Power meter"
Lock-in amplifier
Electrical method

Lock-in amplifier
(phase sensitive detection at fundamental component)
so called in-phase and out-of-phase signals

\[ U_S = \frac{1}{\pi} \int_{0}^{2\pi} u_m(t) \sin \omega t \, dt \]

\[ U_C = \frac{1}{\pi} \int_{0}^{2\pi} u_m(t) \cos \omega t \, dt \]

\[ u_m \] - measured voltage

reference signal necessary to set the frequency
phase
taken from AC current
Fundamental problem of electrical methods for AC loss determination

AC power supply

AC power flow

AC loss in SC object

AC power flow
Solution 1 - detection of power flow to the sample

AC power supply

AC power flow

AC loss in SC object

AC power flow

AC power flow
Solution 2 - elimination of parasitic power flows

AC power supply \rightarrow AC power flow \rightarrow AC loss in SC object
ideal magnetization loss measurement:

\[ B_{\text{ext}} = B_a \cos \omega t \]

pick-up coil wrapped around the sample

induced voltage \( u_m(t) \)

\[
u_m(t) = -\frac{d\phi_m(t)}{dt} = -A \frac{dB(t)}{dt}
\]

\[
\bar{B}(t) = \frac{1}{A} \int_A B_{\text{int}}(t) \, dA = B_{\text{ext}}(t) + M(t)
\]

\[
u_m(t) = -A \left[ \frac{dB_{\text{ext}}(t)}{dt} + \frac{dM(t)}{dt} \right]
\]

macroscopic magnetization of the sample

\[
M(t) = B_a \sum_{n=1}^{\infty} \left( \chi_n' \cos n\omega t + \chi_n'' \sin n\omega t \right)
\]

contains higher harmonics

\[
Q = \frac{1}{\mu_0} \int B \, dM = \frac{1}{\mu_0} \int B(t) \frac{dM}{dt} \, dt = -\frac{B_a^2}{\mu_0} \int_0^T \cos(\omega t) \chi'' \cos(\omega t) \, d\omega t
\]

Lock-in amplifier

\[
Q = -\frac{B_a^2}{\mu_0} \pi \chi''
\]
Real magnetization loss measurement:

\[ M = C \int u \, dt \]

by means of:

- measurement on a sample with known properties
- calibration coil
- numerical calculation

Calibration necessary
Loss measurement from the side of AC power supply:

\[ P_{\text{sample}} = I_m U_B \]
Loss measurement from the side of AC power supply:

Ψ(I) hysteresis loop registration for superconducting magnet (Wilson 1969)