Loss measurements in superconducting magnets at CERN

Incomplete collection of data to start a discussion and direction of future research

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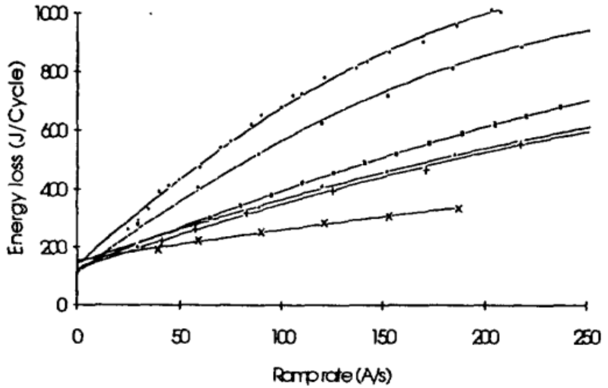
HFM QuaT meeting

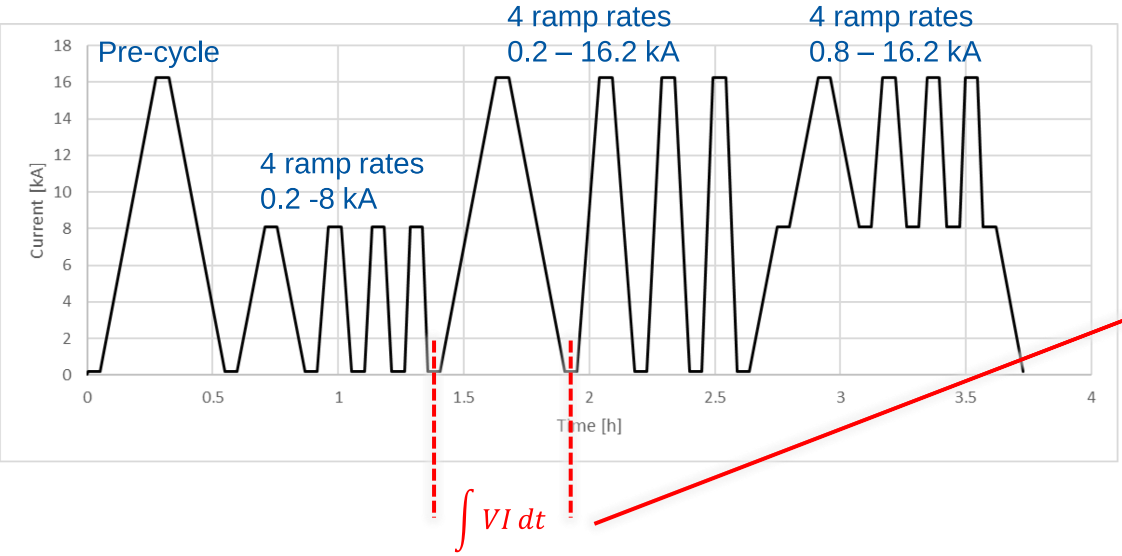
Loss measurement methods for magnets, introduction

Two methods to measure losses:
- Calorimetric
    - Requires well controlled and measured temperatures and helium liquid/gas flows. Often the cryostats are not designed to have accurate enough measurements.
- Electrical
    - Rather accurate. Methods exist to distinguish different type of losses, notably the hysteresis loss and coupling loss.
    - Method in use at CERN at least since 1994: "A. Verweij et al., *Analysis of the AC Loss Measurements on the One-Metre Dipole Model Magnets, IEEE Transactions on Magnetics, Vol 30, No 4, July 1994.*



Loss measurement methods - electrical

AC-loss cycle from Q2 MQXF test plan, EDMS 2873724



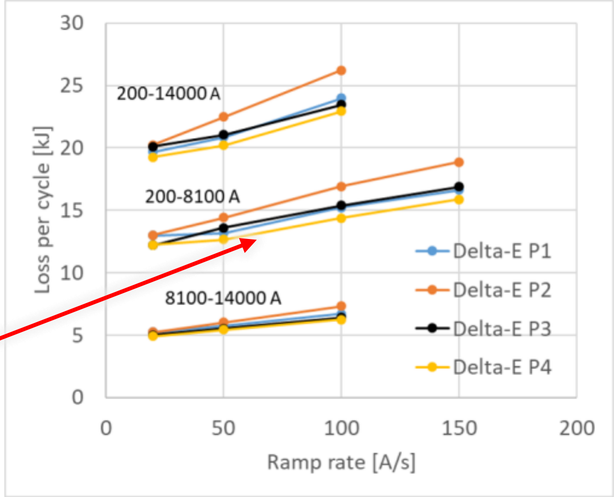


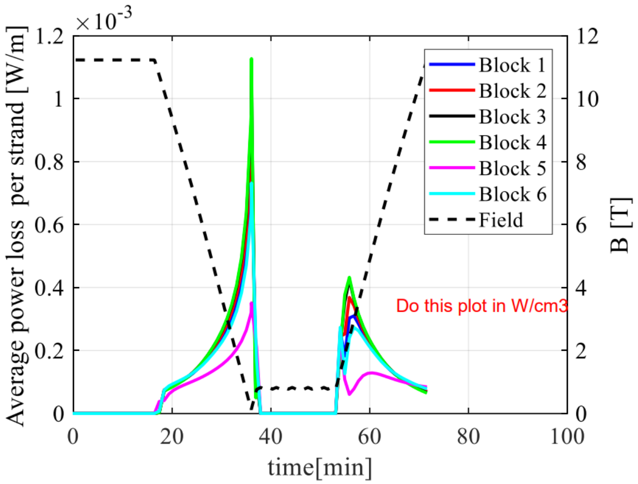
Figure 25: Energy loss during a current cycle, for each coil, as function of ramp rate. The three groups of curves correspond to the three current ranges investigated: 200-14000 A (top), 200-8100 A (middle), 8100-14000 A (bottom).

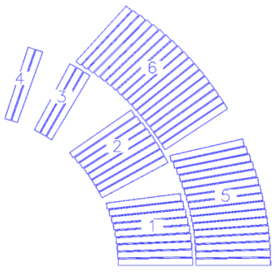
MQXFBP2 test results: EDMS 2469619
Note: values per 7 meter long coil.

Simple and clean method.
Requires: Full cycle required to remove stored magnetic energy from the integral.
Requires: Good offset compensation, no drift in voltage measurements, no splice resistance. 1 µV gives about 25 J for a 20 A/s cycle.

AC loss during magnet ramp
In the11T

- This energy is more or less uniformly deposited in the different blocks except in the outer layer mid-plane block.





$1\ mW/m/A_{strand} = 2.3\ mW/cm^3$

It is good to realize that the loss depends on current and moment in the cycle.

Typically low field (higher J_c) gives higher loss.

S. Izquierdo Bermudez – Margin on the 11T dipole
https://indico.cern.ch/event/760815/contributions/3156774/

Some historic measurements at CERN

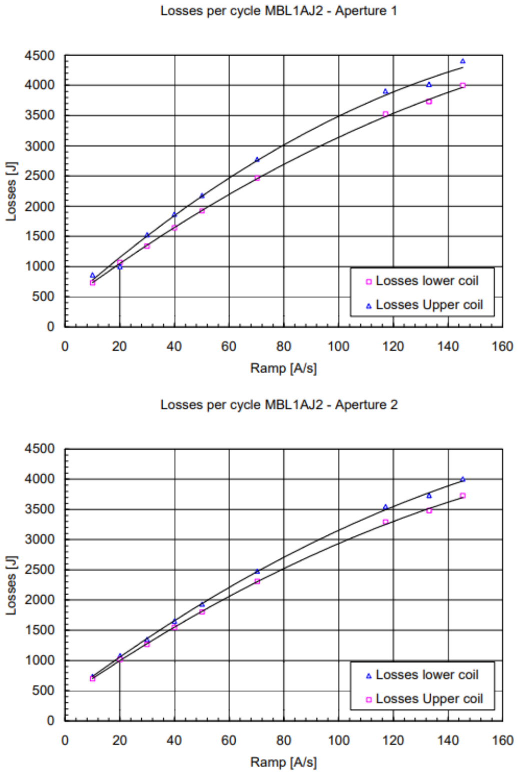


Figure 11. Loss per cycle as a function of ramp-rate in the four poles (upper and lower pole, aperture 1 at the top and 2 at bottom) of MBL1J2, measured as a function with trapezoidal current cycles between 60 A and 3 kA (corresponding to approximately 2.2 T field swing).

- 10 meter long dipole magnet MBL1J2 – 1997
- Losses were defined as function of ramp rate
- Measurements done between 60 A and 3 kA
- Hysteresis loss small compared to coupling loss
- For LHC main dipole magnets, it seems that it was mainly used for calculating interstrand resistances, with less emphasis on energy deposited in the helium bath.

	Hysteresis (J/A)	Coupling (Js/A^2)
AP1 Lower Coil	54.05 10^{-3}	7.014 10^{-3}
AP1 Upper Coil	45.67 10^{-3}	8.22 10^{-3}
AP2 Upper Coil	53.44 10^{-3}	6.589 10^{-3}
AP2 Lower Coil	74.2 10^{-3}	5.533 10^{-3}

Table 5. Coefficients of the fits of the total hysteresis and coupling losses dependence reported in Fig. 11, as measured from the I V integrals on the four poles of the dipole magnet. The coefficients are obtained as the zero ramp-rate intercept (hysteresis) and first order (coupling currents), and they are normalised to the twice the current sweep used in the measurement (approx. 3 kA).

https://edms.cern.ch/ui/file/356495/1/mta-in-97-012.pdf
https://edms.cern.ch/ui/file/384105/1/ELFA.pdf

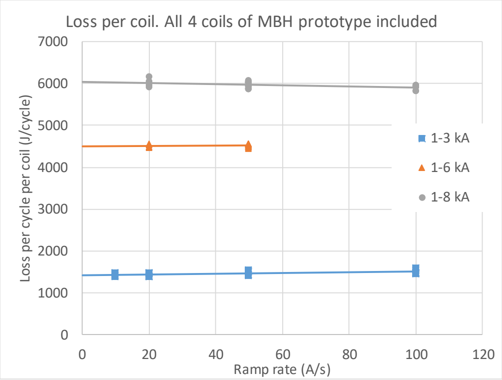
MBH 11T full length prototype AC loss measurements - 2018

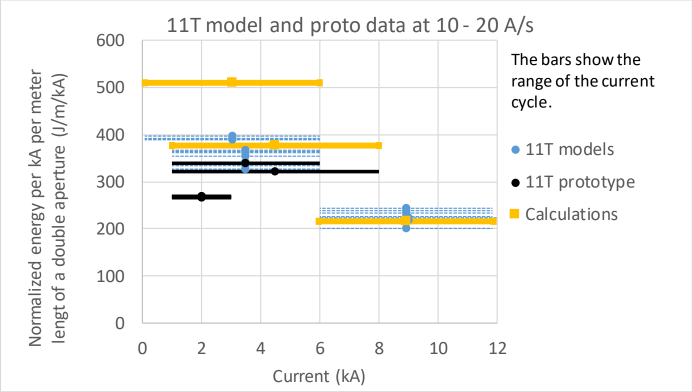
Calorimetric and electrical loss measurements

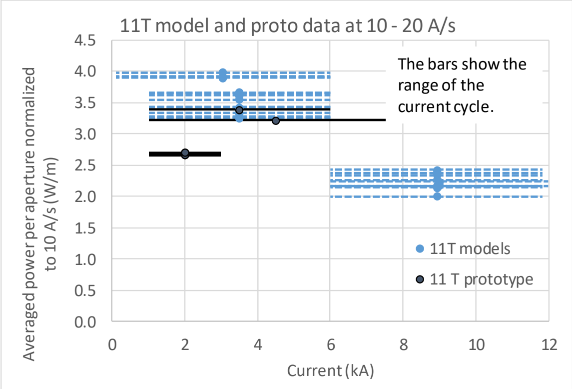
MBH 11T full length prototype - AC losses campaign - 2018

Normalize and compare to short models.

Translate to average power loss per cycle at 10 A/s







Very little variation in the loss per cycle between the 4 coils of MBH-prototype.

Ramp rate dependent loss contribution (coupling loss) is very small.

G. Willering – AC-loss measurements 11T horizontal magnet – calorimetric and electric.
https://indico.cern.ch/event/760815/contributions/3156773/

Summary plot of SP102, SP104, SP105, DP101, SP106, SP107, MBH-proto and calculations

Good correlation between all models and prototype all values within ± 10 %

Calculations higher than measurements.

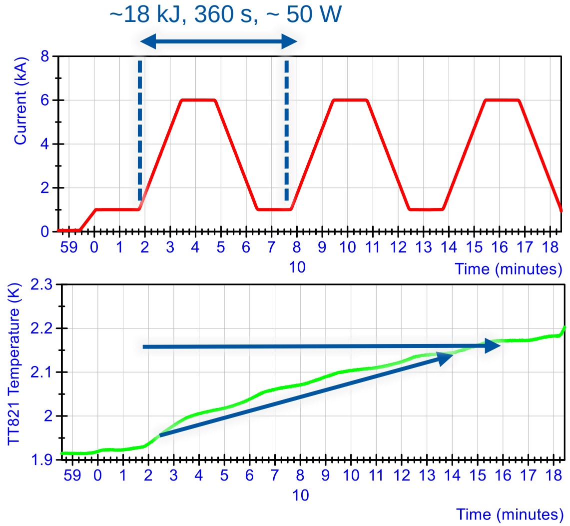
1-3 kA cycles results for MBH prototype seem an anomaly. To be verified.

Average power dissipation per double aperture varies between 2 and 4 W/m, depending on the cycle.

The 3 W/m (as has been confirmed before) during ramping will be used throughout the rest of the presentation.

MBH 11T full length prototype - AC losses campaign - 2018

This was the only (recent) measurement campaign using calorimetric loss measurements at CERN and comparing them to the electrical loss measurements.



Measurement method:

- Current cycles done in MBH-prototype with different ramp rates between 1 and 6 kA
- Fixing the pumping valve (45 % open)
- Monitoring the temperature rise in TT821 (between shell and yoke in the middle of the magnet)

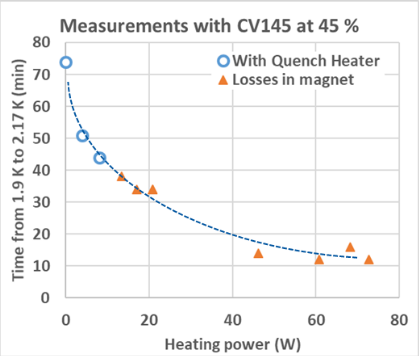
Results are summarized by :

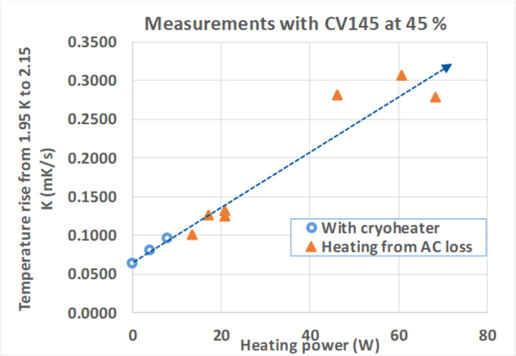
1. Calculating the average power dissipation over the cycles (Electrically measured)
2. Time to reach 2.17 K
3. Slope from 1.95 K to 2.15 K

With the cryo heater reference power losses are done at 0, 4 and 8 W.

G. Willering – AC-loss measurements 11T horizontal magnet – calorimetric and electric. https://indico.cern.ch/event/760815/contributions/3156773/

Calorimetric loss measurements MBH-proto





- Electrical AC loss measurements are consistent with cryoheater calibration measurements
- Calorimetric loss measurement could work for the horizontal benches at 1.9 K, but only when calibrated with electrical measurements.

G. Willering – AC-loss measurements 11T horizontal magnet – calorimetric and electric. https://indico.cern.ch/event/760815/contributions/3156773/

Loss measurements in HTS coils

- At CERN some loss measurements were done on Feather coils, maybe some data could be extracted for Eucard coils. This will take some time.

Literature shows more calculations than measurements, to be investigated in more detail.

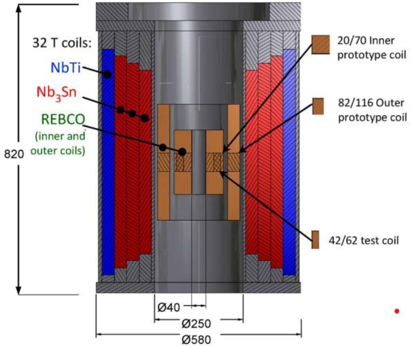


Fig. 1. Cross-section of the 32 T magnet with the LTS outsert (preliminary design concept by OI) and the HTS insert REBCO coils. REBCO test and prototype coils built in the course of HTS insert development are shown, too: "20/70", "82/116", and "42/62" denote the inner and outer radii of the prototype and test coils, respectively. All dimensions are in mm.

A. Gavrilin et al., *Observations from the analysis of magnetic field and AC loss distributions in the NHMFL 32 T all-superconducting magnet HTS insert, IEEE. Trans. Appl. Supercon., Vol 23, No 3, June 2013*

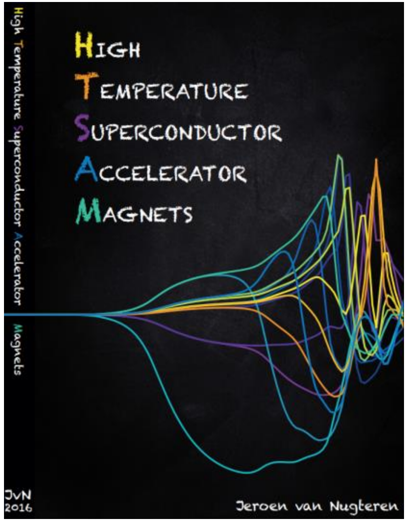
E. Berrospe-Juarez et al., *Screening currents and hysteresis losses in REBCO insert of the 32 T all-superconducting magnet using T-A homogeneous model, IEEE Trans. Appl. Supercond., Vol 30, No. 4, June 2020*

I could not find reports on measurements, to be verified.

J.Lu et al., *AC losses of REBCO pancake coils measured by a calorimetric method, IEEE Trans. Appl. Supercond. Vol 25, No 3, June 2015*

V. Conclusion

The AC losses of a set of pancake coils have been measured using a calorimetric method. The majority of the measured AC losses are from the turn-to-turn coupling loss due to the imperfections in the coil insulation. We found the AC losses are much smaller than we previously estimated. The discrepancy is attributed to the strong magnetic shielding in radial direction.



Thesis by Jeroen van Nugteren, 2016
It is worth to read chapter 4.
https://cds.cern.ch/record/2228249/files/CERN-THESIS-2016-142.pdf

Recent test of HTS in SM18

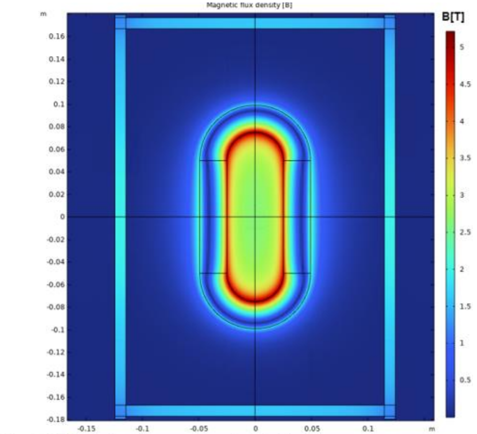
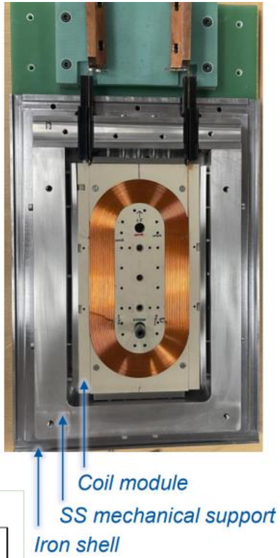
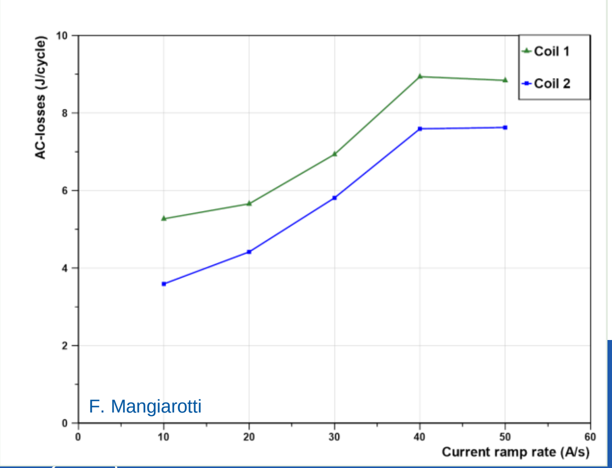
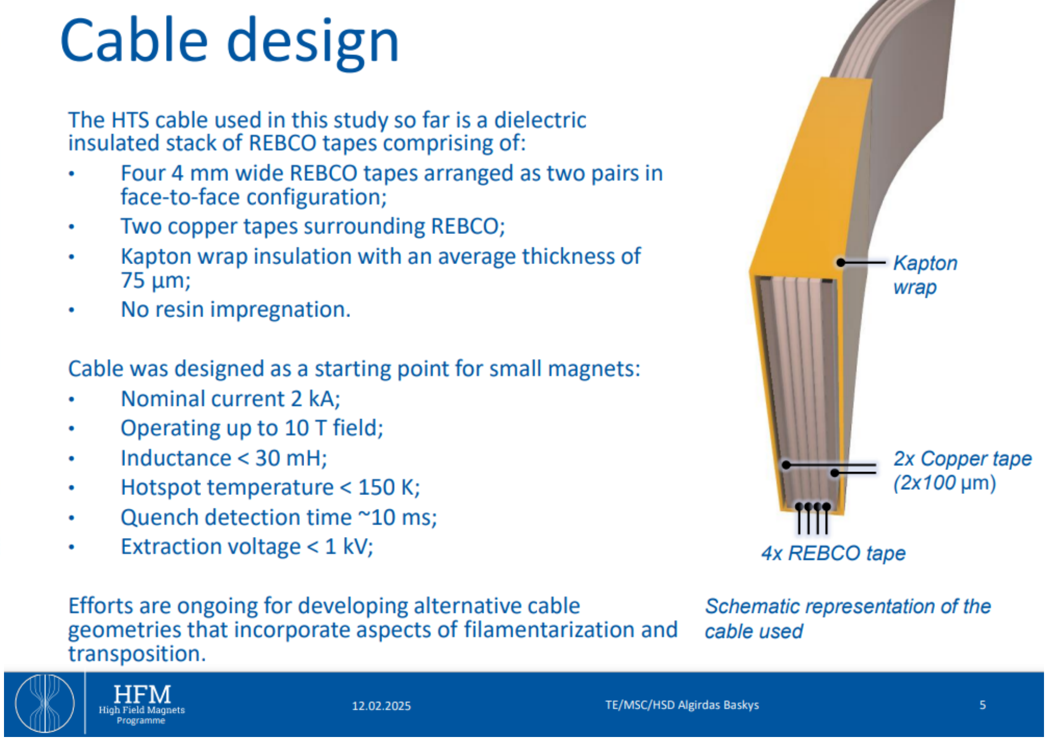


Figure 9. Field map in the coil test setup along the longitudinal axis.







Cable design

The HTS cable used in this study so far is a dielectric insulated stack of REBCO tapes comprising of:

- Four 4 mm wide REBCO tapes arranged as two pairs in face-to-face configuration;
- Two copper tapes surrounding REBCO;
- Kapton wrap insulation with an average thickness of 75 µm;
- No resin impregnation.

Cable was designed as a starting point for small magnets:

- Nominal current 2 kA;
- Operating up to 10 T field;
- Inductance < 30 mH;
- Hotspot temperature < 150 K;
- Quench detection time ~10 ms;
- Extraction voltage < 1 kV;

Efforts are ongoing for developing alternative cable geometries that incorporate aspects of filamentarization and transposition.

Schematic representation of the cable used

HFM High Field Magnets Programme   12.02.2025   TE/MSC/HSD Algirdas Baskys   5

https://indico.cern.ch/event/1471305/contributions/6260711/attachments/3013697/5314373/A_Baskys_HFM_2025Feb12.pdf

Conclusion

- Measurement method well established
- Nb_3Sn magnet loss well established and predictable. It is mostly ramp rate independent.

- For HTS the data set seems much smaller.
    - What is the impact of cable type (roebel, tape stack, CORC)
    - How does loss depend on ramp rate?
    - How important is inter-tape contact resistance?

Interesting publications:

Rossi, L.; Senatore, C. HTS Accelerator Magnet and Conductor Development in Europe. *Instruments* **2021**, *5*, 8.
https://doi.org/10.3390/instruments5010008

Presentations of interest:

G. Willering – AC-loss measurements 11T horizontal magnet – calorimetric and electric. https://indico.cern.ch/event/760815/contributions/3156773/

H. Bajas – AC losses quantification in Nb_3Sn magnets. https://indico.cern.ch/event/704235/contributions/2932038/

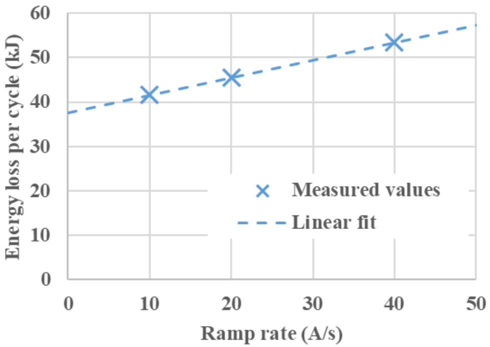
S. Izquierdo Bermudez - Hysteresis losses in Eurocircle: model and measurements https://indico.cern.ch/event/1449701/contributions/6112671/

S. Izquierdo Bermudez – Margin on the 11T dipole *https://indico.cern.ch/event/760815/contributions/3156774/*

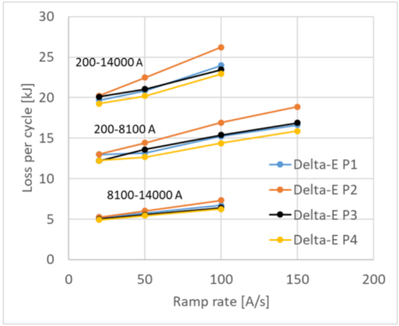
CERN

Collection of loss measurements.

- The measurement is rather standard and done for most magnet types.
- There may be much more data available that has not been reported on, since there was no real focus on it in the last decade.



FRESCA2 magnet from 0.1 to 10.6 kA (13T)



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MQXFBP2: EDMS 2469619
Note: values per 7 meter long coil.

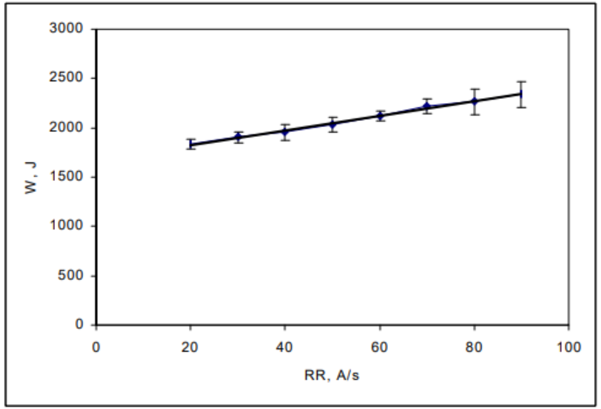

Fig. 1: The loss in the MBB-A001 dipole as a function of ramp rate.

MBB-A001 pre-series dipole from 1 to 4 kA:
https://edms.cern.ch/document/357352/1

Collection of loss measurements.

TABLE III
RESULTS OF THE AC ENERGY LOSS MEASUREMENTS PERFORMED ON THREE MAIN QUADRUPOLES

SSS	k Ap.1 [μJs/A²]	k Ap.2 [μJs/A²]	Rc Ap.1 [μΩ]	Rc Ap.1 corrected [μΩ]	Rc Ap.2 [μΩ]	Rc Ap.2 corrected [μΩ]
361	92.9	87.1	163	169	174	181
374	98.9	79.5	154	159	189	198
529	91.1	91.8	167	173	165	171

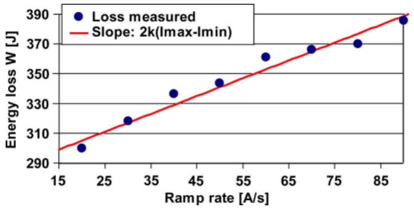

Fig. 4. The $W = W(dI/dt)$ dependence for the SSS529, aperture #1.

AC loss measurements used to calculate Rc in LHC main quadrupoles
https://edms.cern.ch/document/866619/1