AC losses quantification in Nb_3Sn magnets

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2nd International Workshop on Superconducting Magnet Tests Stands

Outline

- Origin of the AC loss
- Measurement technique
- Experimental result
- Simulation result

References

LHC-MTA-IN-2000-131
2000-10-17

LHC - MTA

Energy loss and field advance in MBP2O1 prototype magnet at different ramp rates

A. Akhmetov, Z. Ang, I. Balaazi, L. Bottura, M. Gateau, P. Pugnat, L. Walckiers / LHC-MTA

Keywords: Dipole magnet, Energy loss, Field advance, Interstrand resistance

Distribution: LHC-MTA Scientific Staff; LHC-MMS distribution list; N. Siegel / LHC-ICP; L. Evans / DG-DI; Ph. Lebrun, T. Taylor / LHC

MTA-IN-2002-208
November 18, 2002

LHC - MTA

Analysis program LMA – Loss Measurement Analysis.

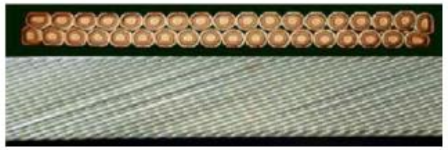
N. Ponomarev, F. Patru, L. Denia, L. Bottura, LHC/MTA

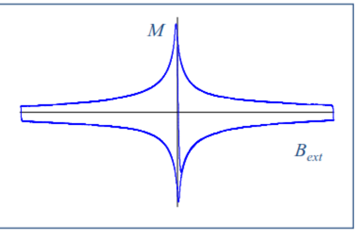
Keywords: Magnet test, field measurement analysis, loss measurement analysis, inductance, LMA library

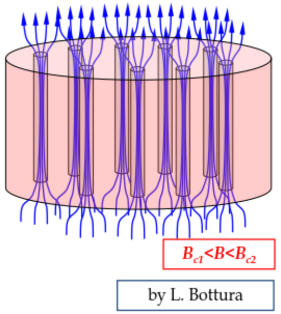
Distribution: MTA Group

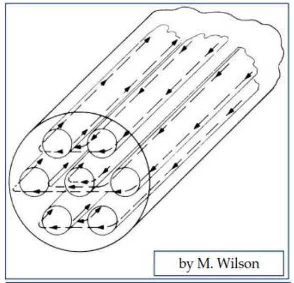
Origin of AC losses

- There are 3 main sources of loss when a transport current is ramped in a superconducting magnet.
  - **Hysteretic magnetization loss** (i.e. flux flow combined with flux pinning, results in a net energy loss when subjected to a field cycle)
    - Proportional to the superconductor Jc and filament size (Deff)
  - **Inter-strand coupling** loss (ISCC) and **Inter-filament coupling** losses (IFCC)
    - Combination of individual superconducting filaments and a separating normal-metal matrix results in a coupling Joule loss
    - Low thanks to the use of cored cable
    - Low at the typical ramp-rate of an accelerator as LHC/FCC (10 A/s)
  - **Eddy currents** in normal-metal
    - Iron yoke and saturation effect









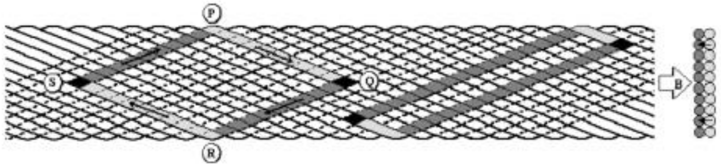


Fig. 19. Coupling currents flowing via crossover resistance R_c in transverse field (upper wires shown light grey).

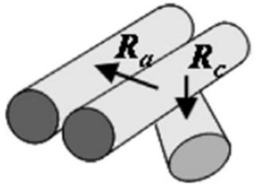
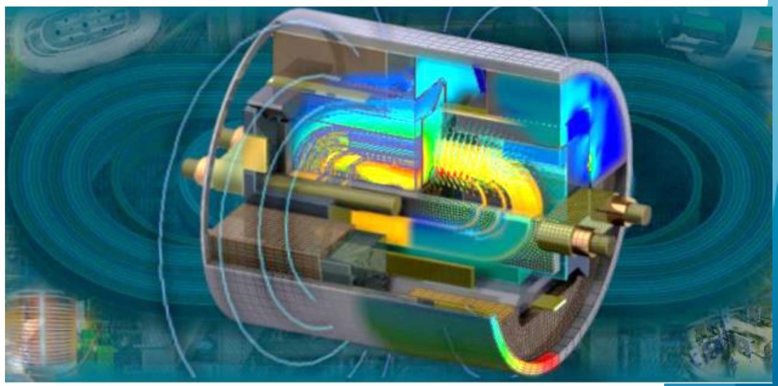


Fig. 18. Crossover resistance R_c and adjacent resistance R_a.



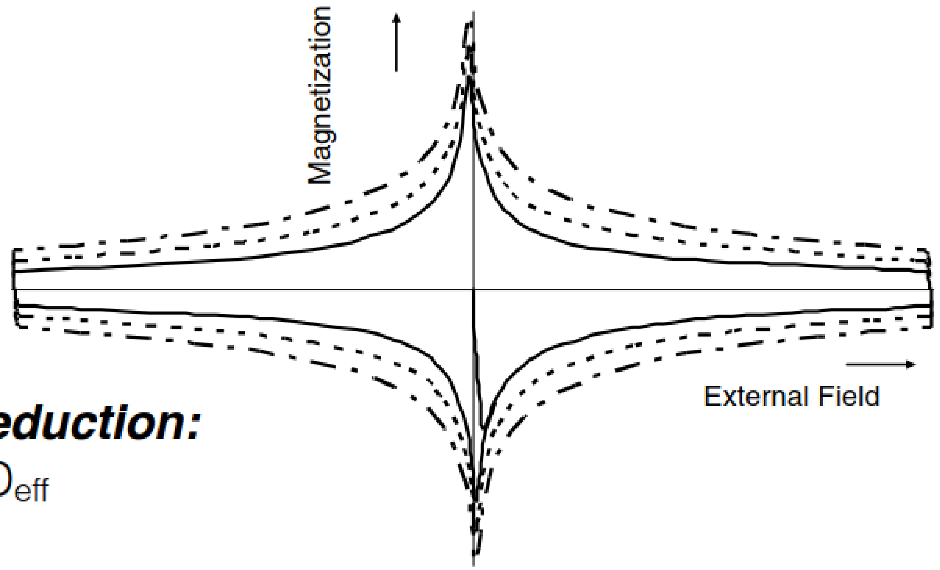
Origin of AC loss

First estimate of AC losses: Hysteresis losses

$$Q_{cyc} = \int_0^{t_0} J_c(B) \frac{2D_{eff}}{3\pi} \frac{dB}{dt} dt \qquad \text{[J/m}^3\text{, per cycle]}$$

$$Q_{hyst-tot} = Q_{cyc} * V_{sc} \qquad \text{[J, per cycle]}$$

This has motivated the quest for fine filament wire!



Hysteresis loss reduction:

- minimize D_{eff}

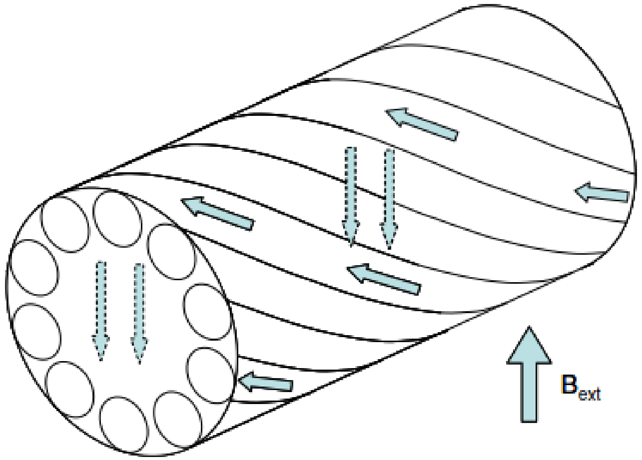
Origin of AC loss

First estimate of AC losses: Coupling losses

$$\tau = \frac{\mu_0}{2\rho_t}\left(\frac{p}{2\pi}\right)^2 \qquad q_{coupling} = \frac{(dB/dt)^2}{\mu_0}2\tau \quad [\mathrm{W/m^3}]$$

$$Q_{coupling-tot} = Q_{coupling} * V_{cond}$$

Coupling loss reduction:
- minimize twist pitch



AC losses measurement

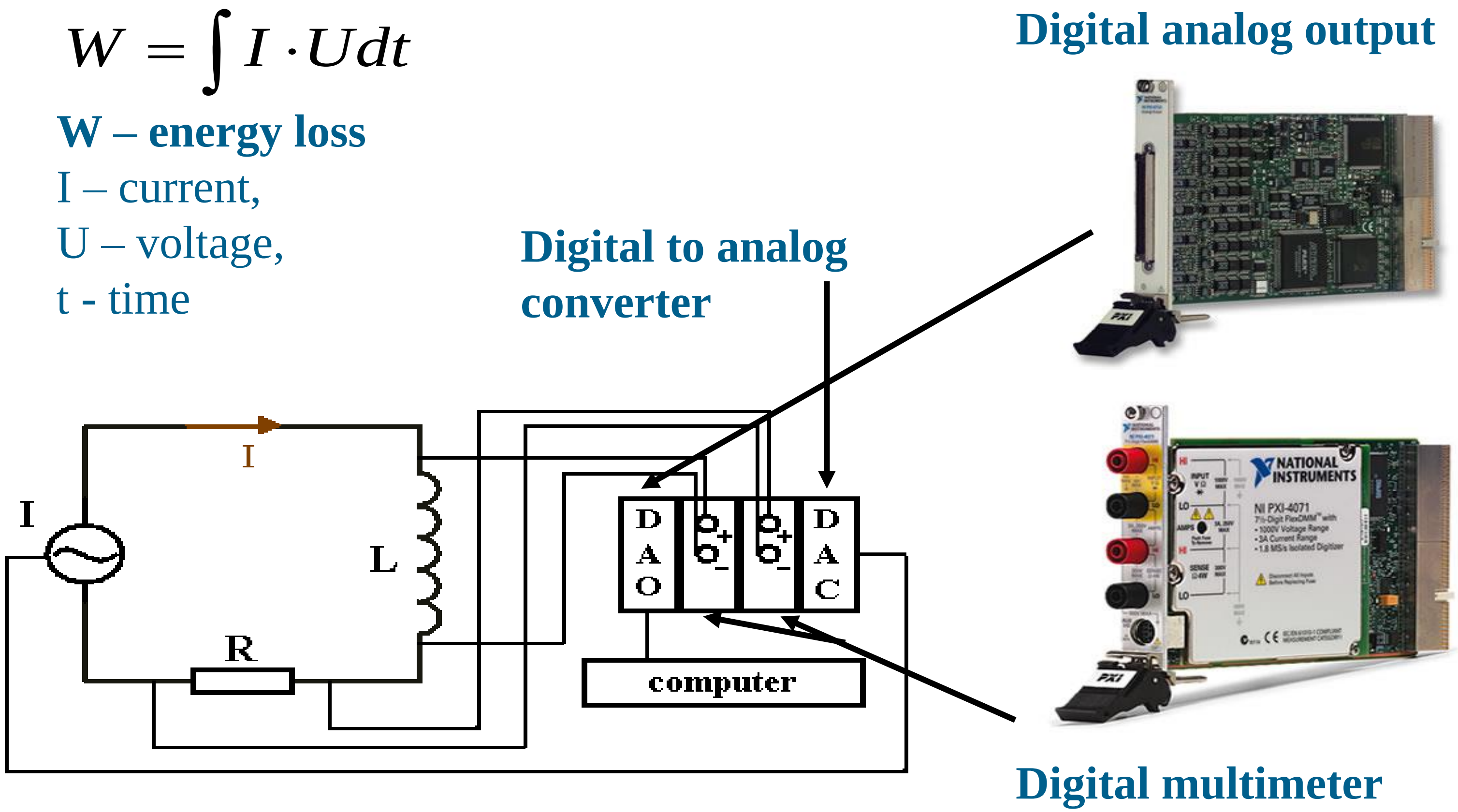
- Measurement issues in superconducting magnet
  - The AC losses are delicate measurements as one has to detect *Joules* (resistive) over *hundreds of kJ* (inductive voltage).
  - It requires **High Resolution/precision Digital MultiMeters** (DMM 1 uV ± 0.01%).
  - Measurement requires to perform a great number of cycles at different ramp rate and level of current. Those are time-consuming measurements that are not systematically done.
  - Need a performant framework for **automatic analysis** over 10^{th} of file, 100^{th} of cycle, 10^{th} of voltages.

Measurement Procedure (hardware)

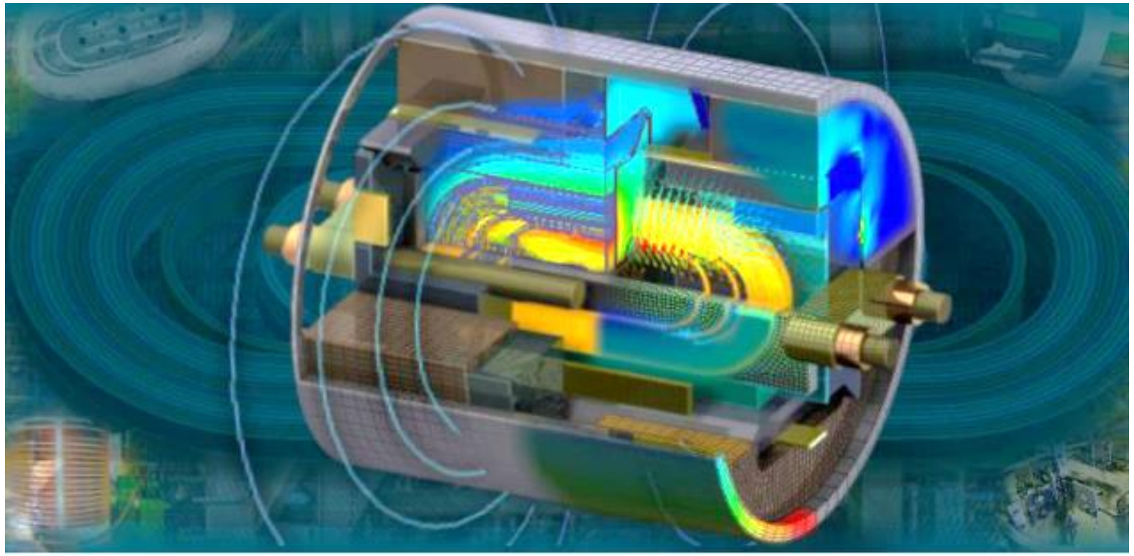
- Measurement of the voltage across the coil using the voltage taps signals acquired with high precision high resolution DMM
  Measurement of the the transport current using DCCT signals
- Numerical integration of the power over current ramp cycle.

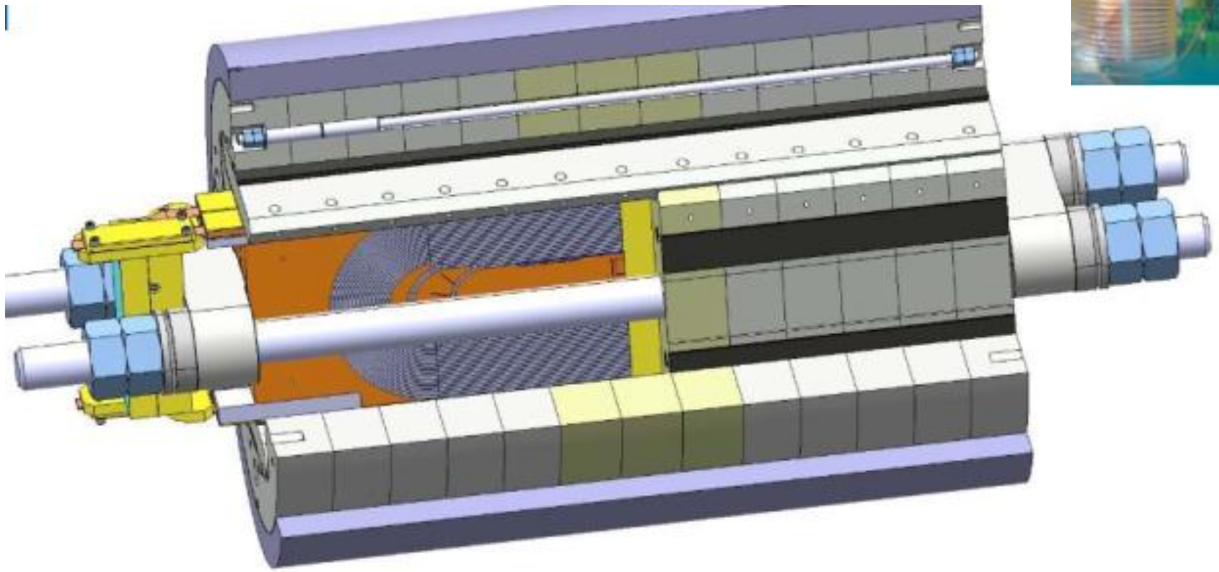
$$W = \int I \cdot U dt$$

W – energy loss
I – current,
U – voltage,
t - time



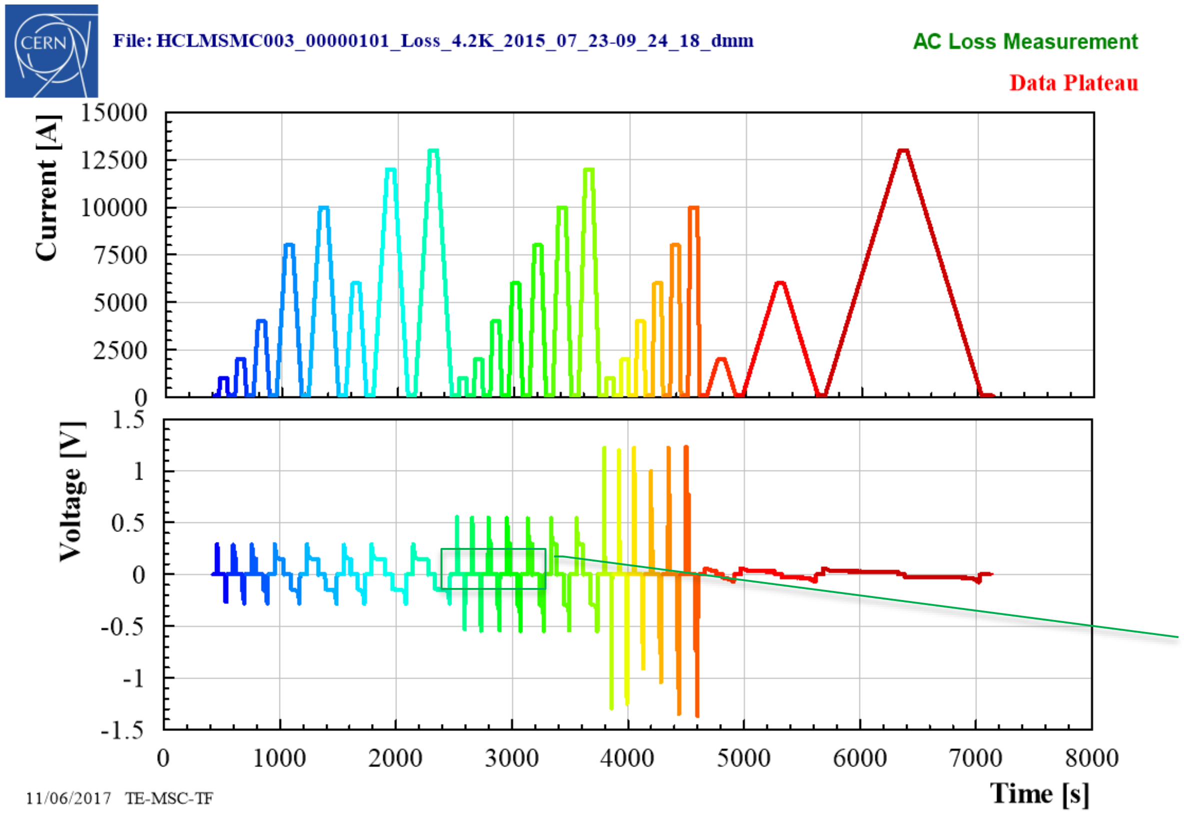
Measurement Procedure (example on SMC11T)

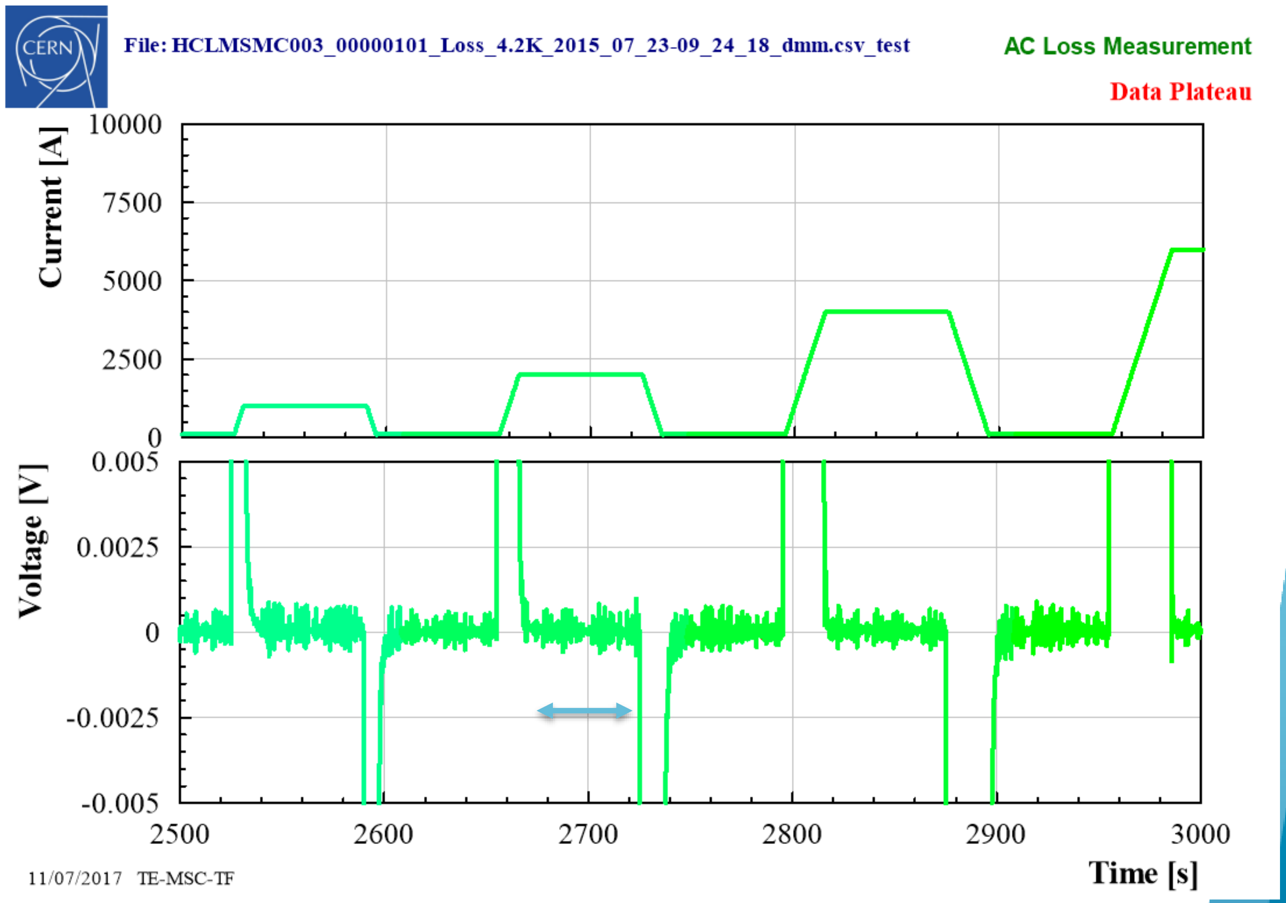




Measurement Procedure (example on SMC11T)

Current cycle between two level of current
@ different ramp rates

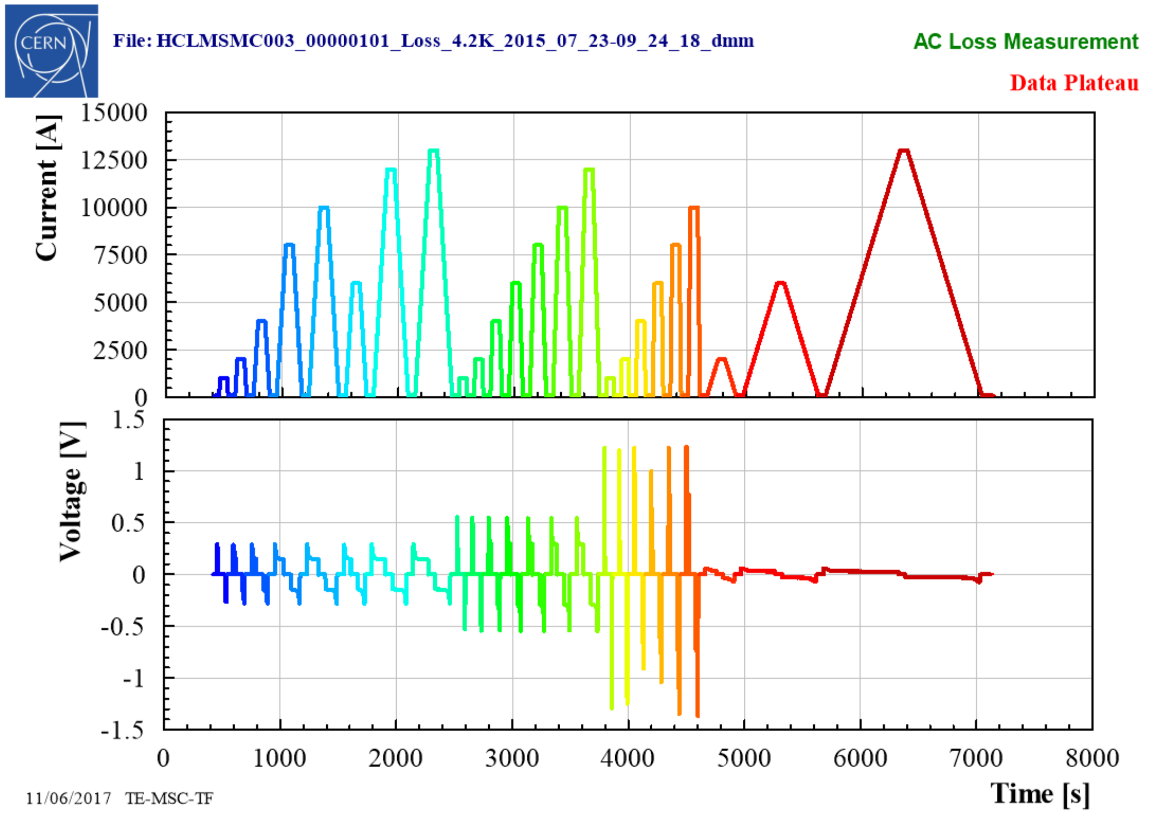


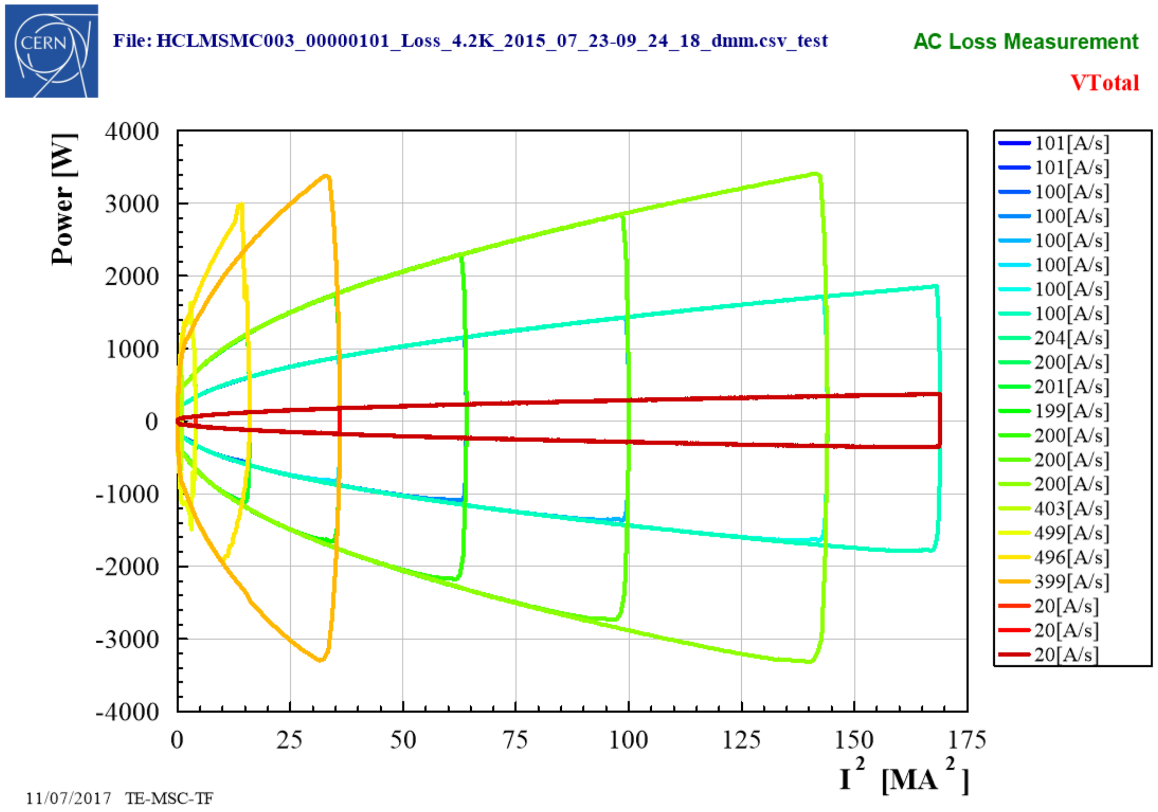


Measurement Procedure (example on SMC11T)

Current cycle between two level of current
@ different ramp rates

$$P = U.I$$



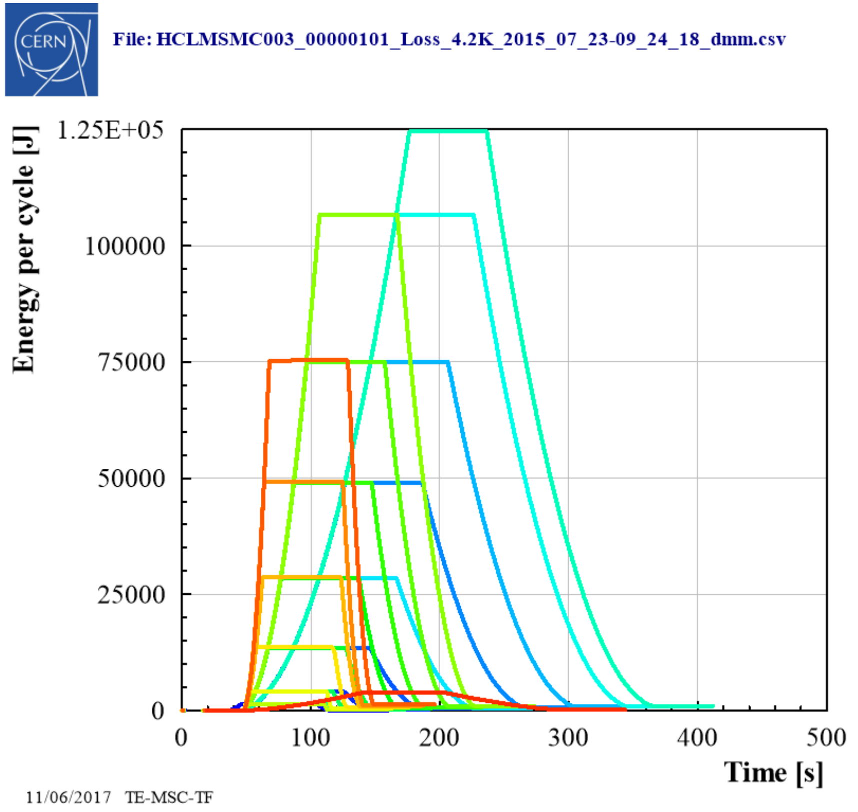


Importance of the cycle and offset definition!!

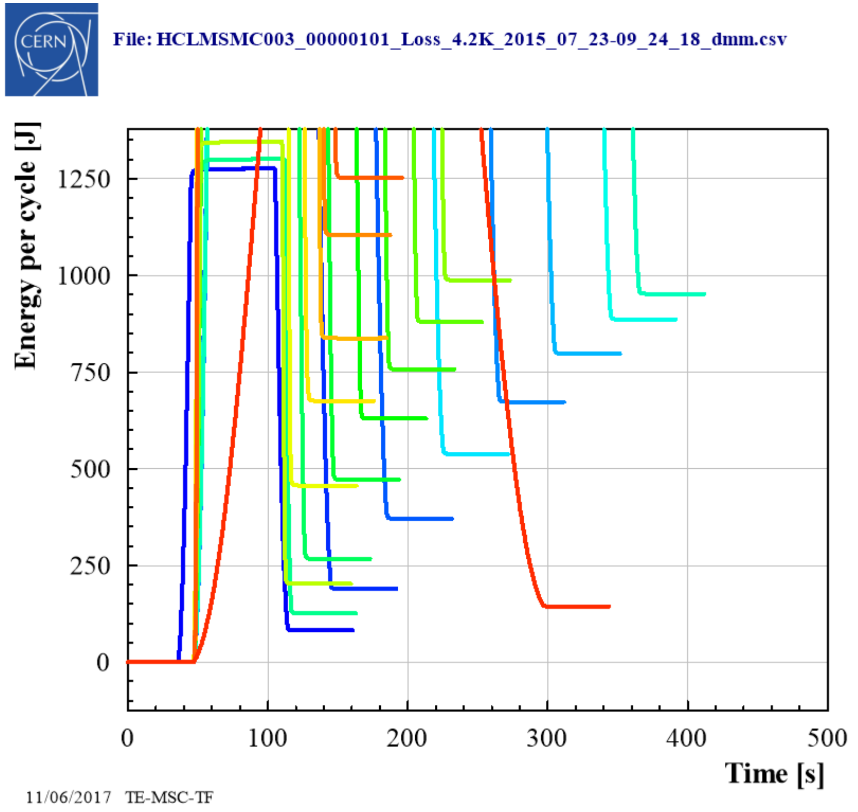
Measurement Procedure (example on SMC11T)

$$E=\int_{t_i}^{t_f} U.I\ dt$$

$$\text{Loss/cycle}=E_f - E_i$$



Loss [J]	σ(Loss) [J]	dI/dt [A/s]	I_max [A]
81.7	0.00	101	1001
202.4	0.01	403	1001
126.0	0.01	204	1001
144.1	0.02	20	2001
266.9	0.02	200	2001
189.5	0.02	101	2001
456.6	0.01	499	2001
472.1	0.01	201	4001
675.4	0.02	496	4001
371.1	0.01	100	4001
472.4	0.02	20	6000
629.6	0.01	199	6001
837.6	0.02	399	6001
538.4	0.02	100	6001
757.3	0.02	200	8001
1104.1	0.02	500	8001
672.9	0.01	100	8001
879.2	0.02	200	10001
1252.3	0.02	499	10001
797.6	0.02	100	10001
987.7	0.03	200	12000
886.2	0.02	100	12000
933.3	0.01	20	13000
952.3	0.01	100	13000



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189.5	0.02	101	2001
456.6	0.01	499	2001
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675.4	0.02	496	4001
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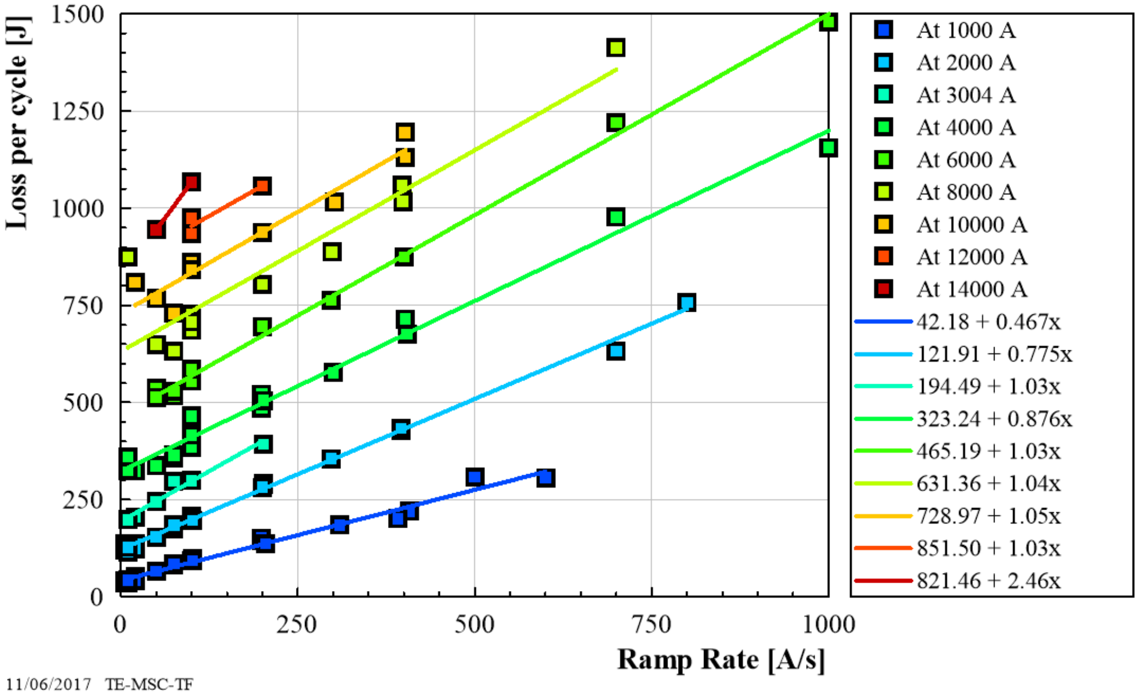
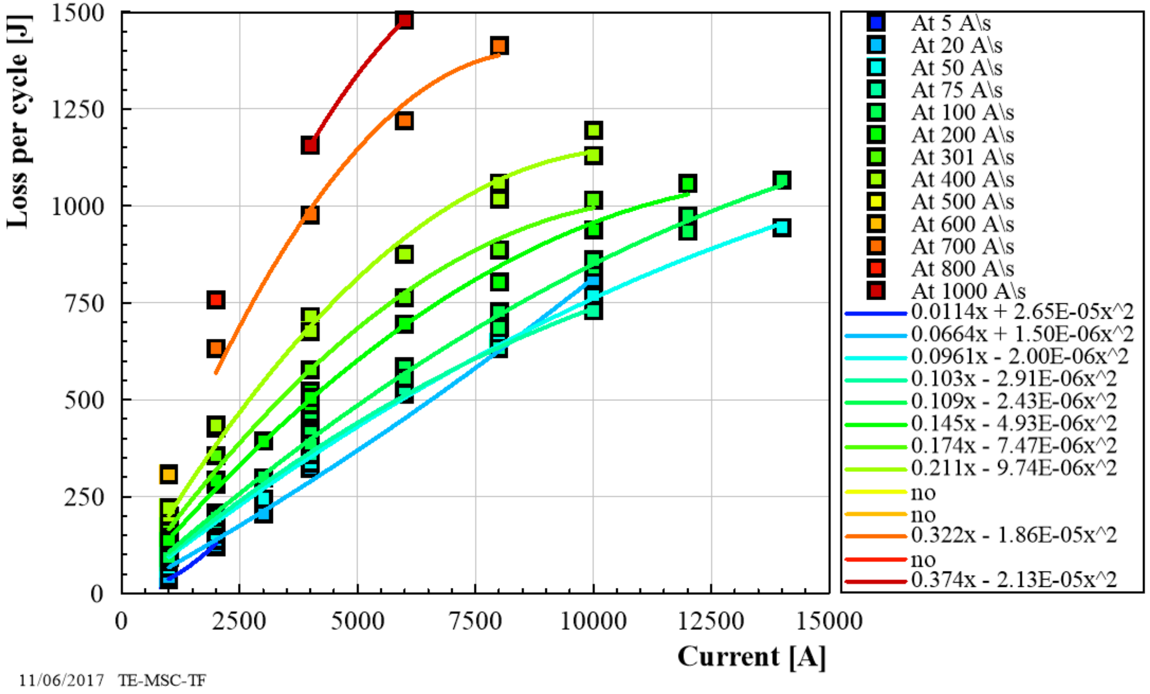
797.6	0.02	100	10001
987.7	0.03	200	12000
886.2	0.02	100	12000
933.3	0.01	20	13000
952.3	0.01	100	13000

Measurement final result (example on SMC11T - RRP)

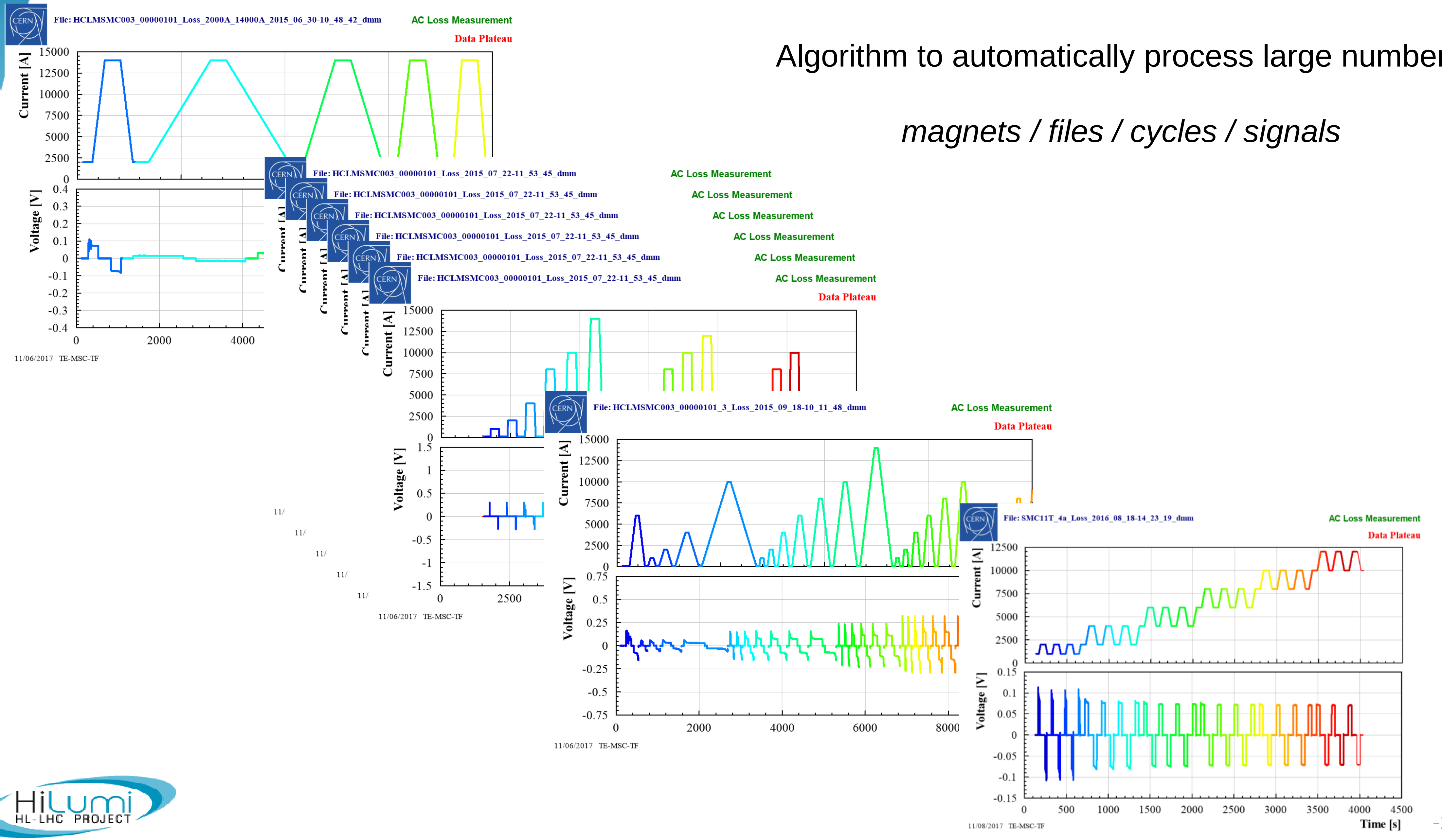
AC loss as function of the ramp rate (linear fit)



AC loss as function of the current (quadratic fit)



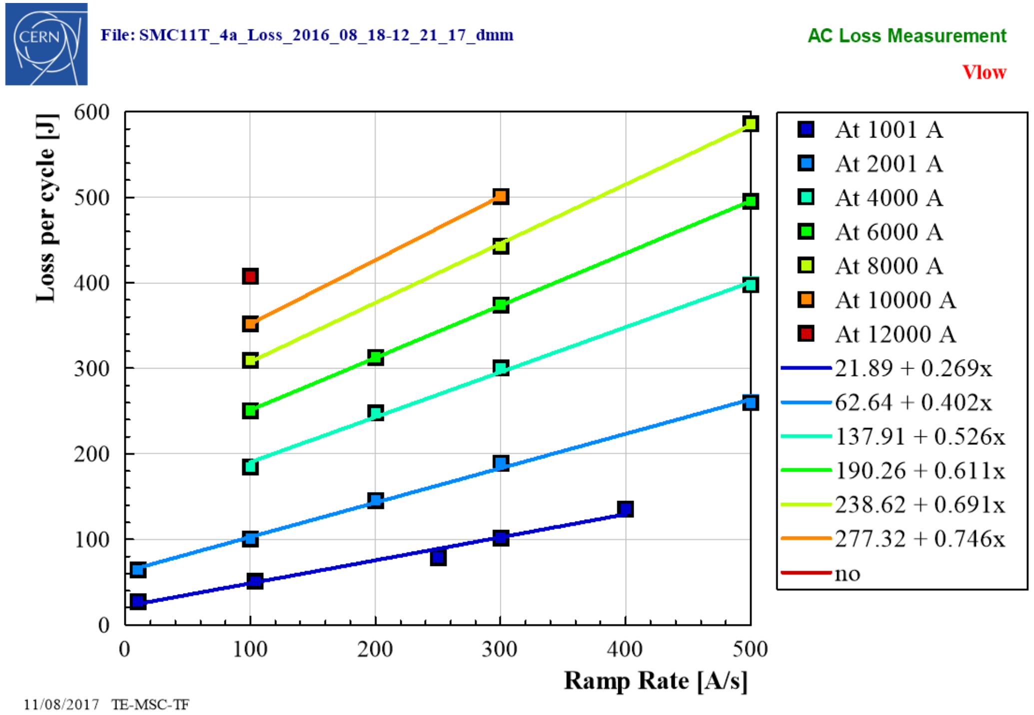
Measurement Procedure (example on SMC11T)

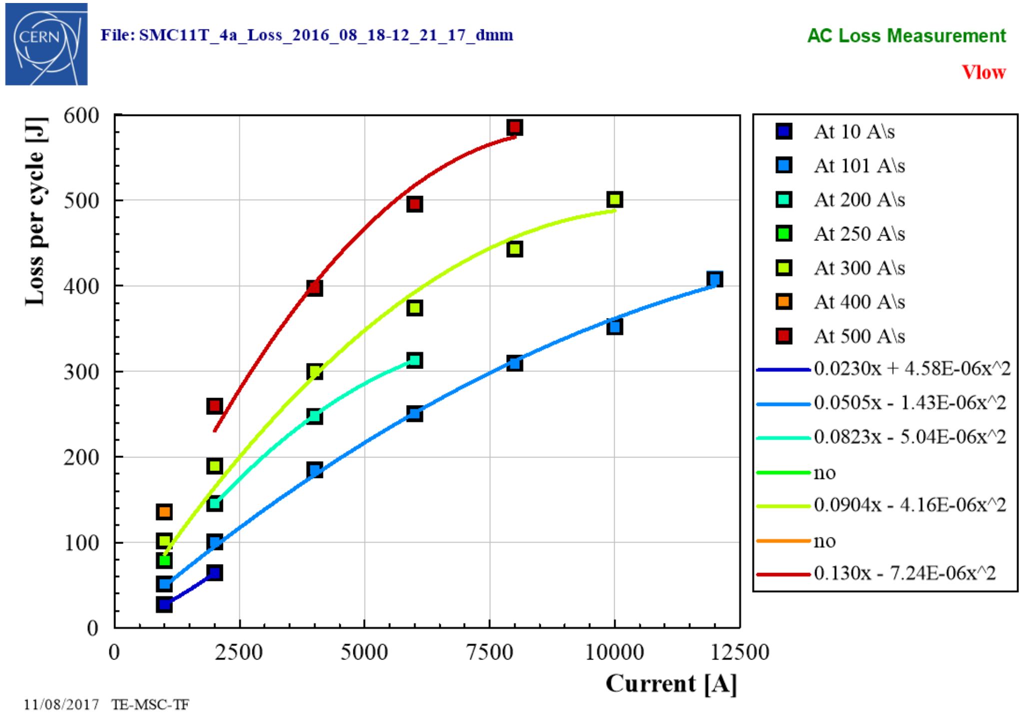


Algorithm to automatically process large number of:

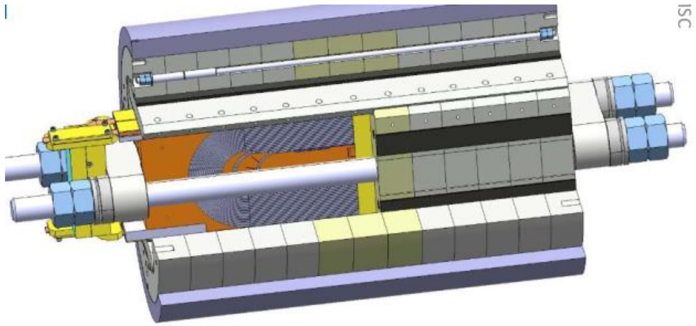
magnets / files / cycles / signals

Measurement final result (example on SMC11T4 - PIT)

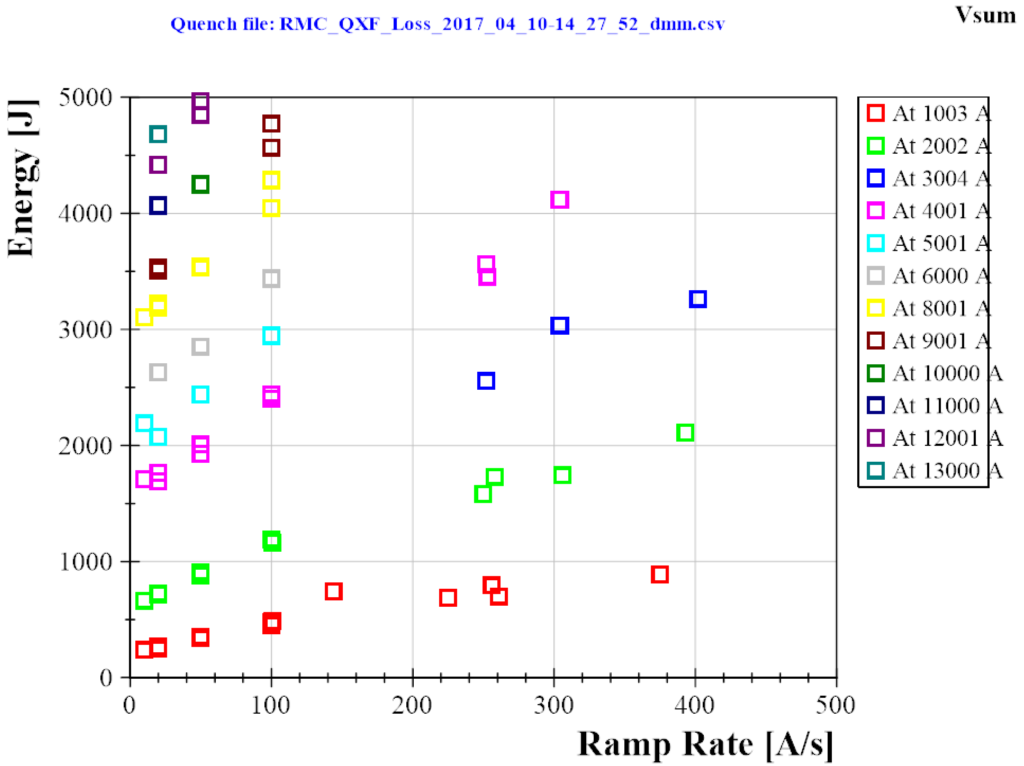


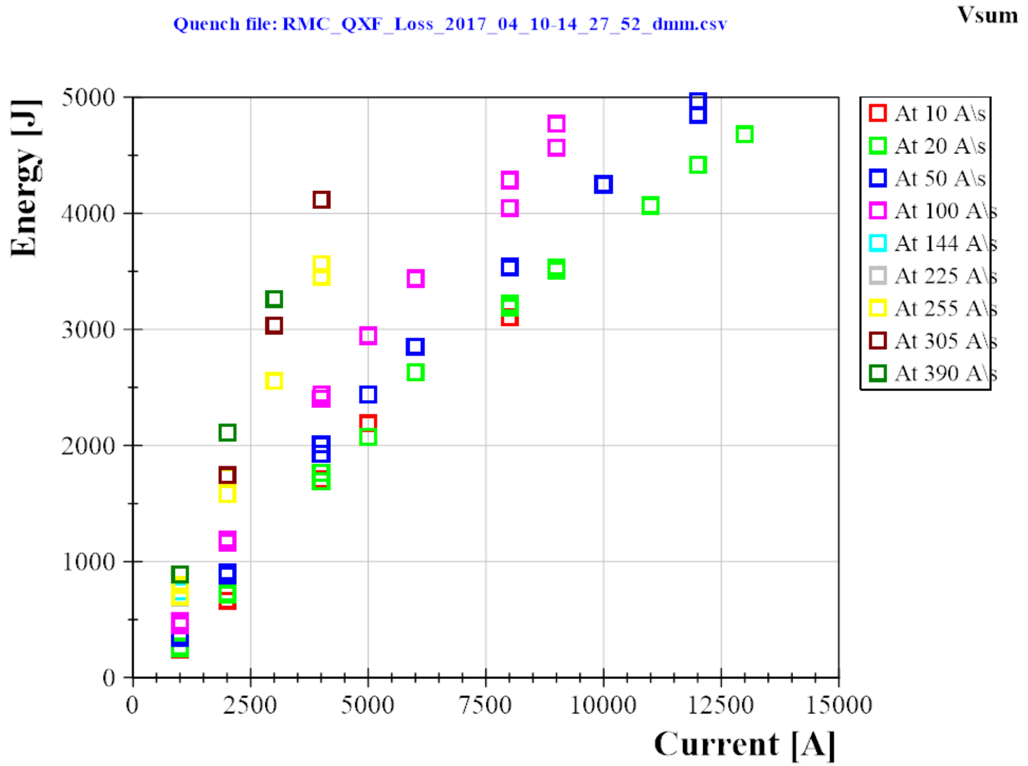


Another example of RMC…



Result for RMC_QXF



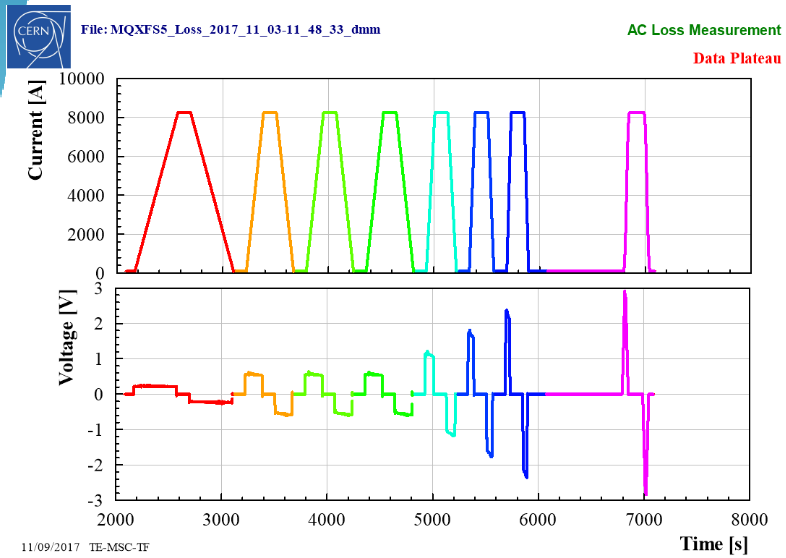


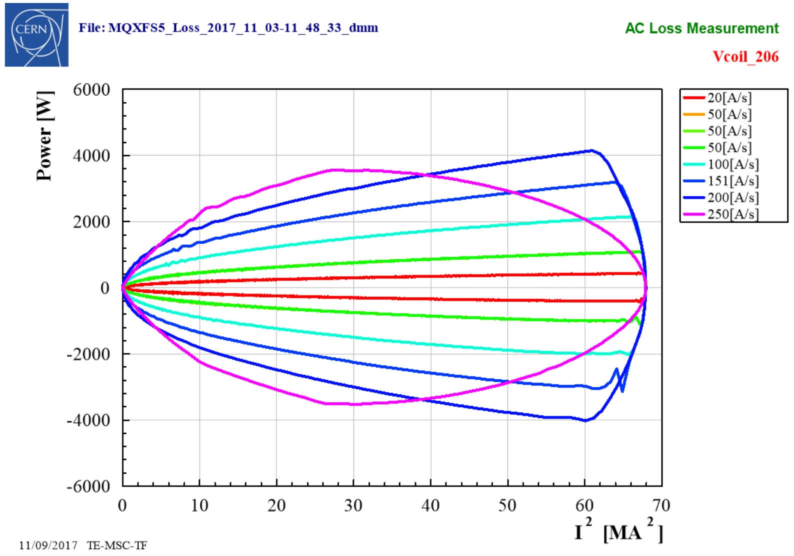
Example of analysis on MQXFS5

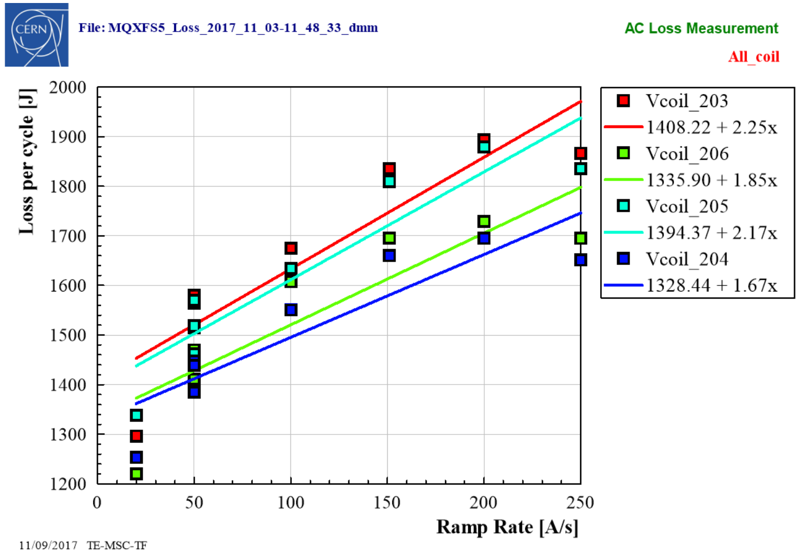
Current/voltage (0-50 % Inom & 50 -100 % I nom)

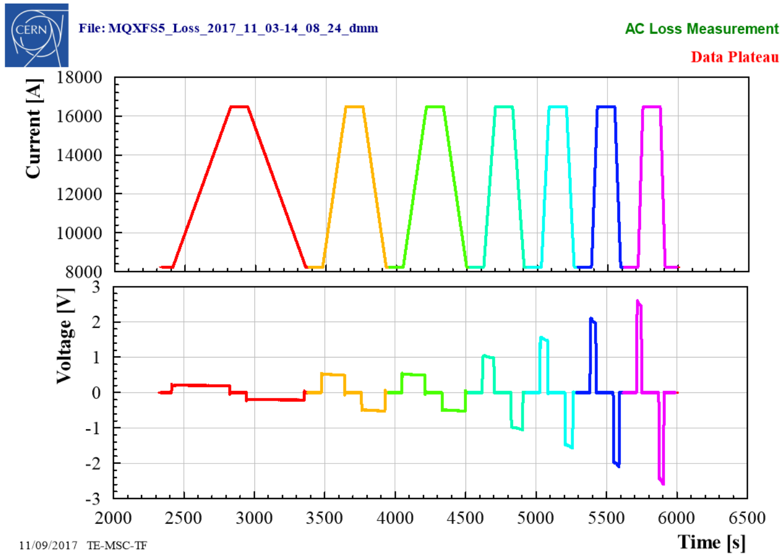
Power over cycle (1 coil)

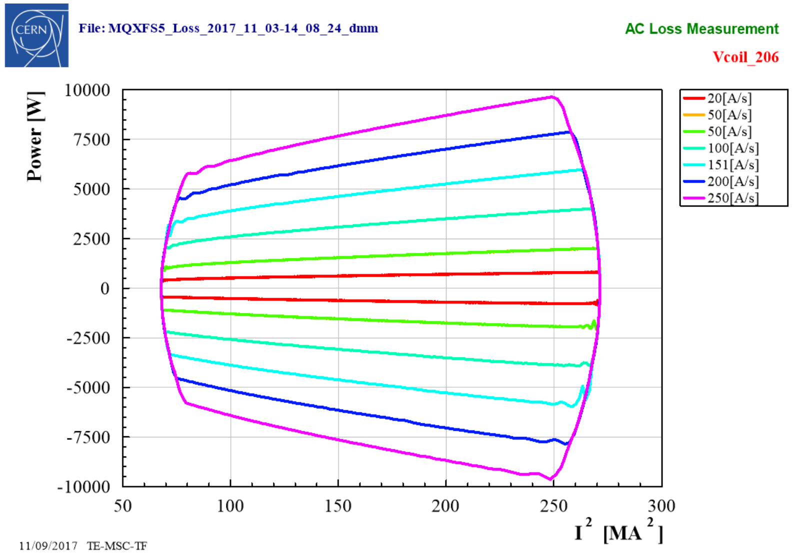
Loss per cycle function of ramp rate (4 coils)

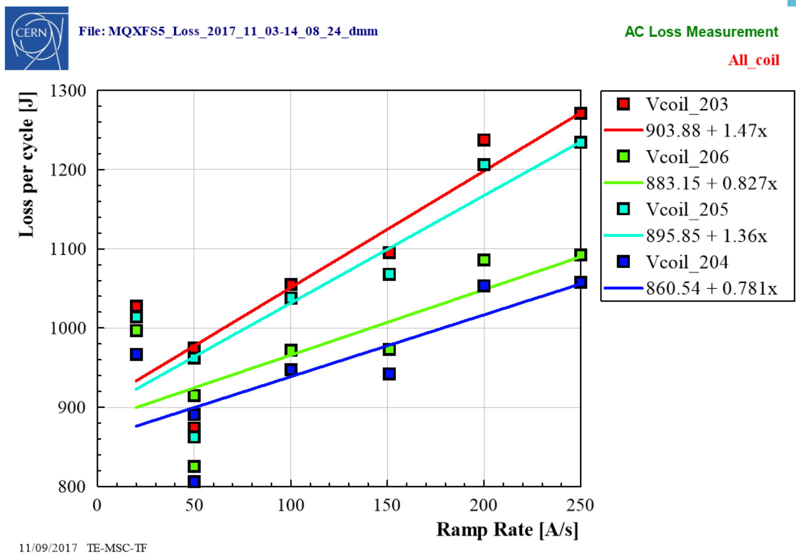








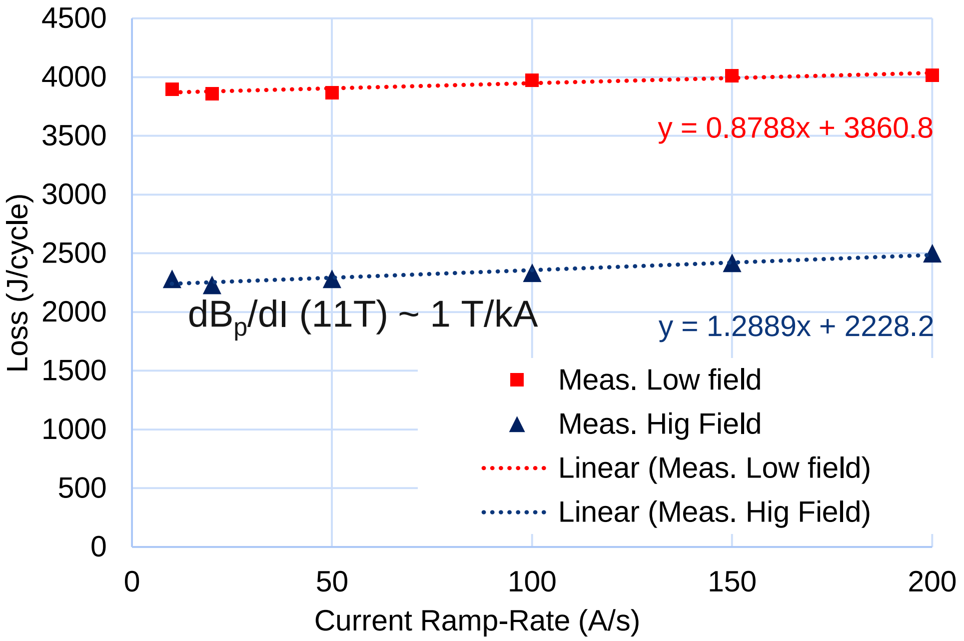




Simulation with Roxie (11T dipole)

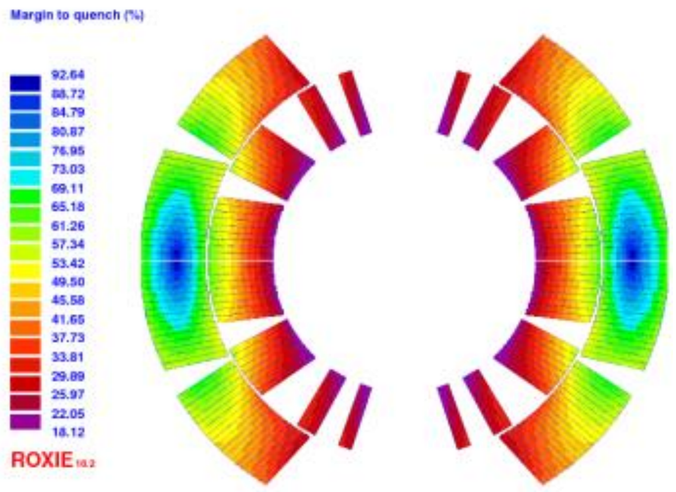
11 T (2 apertures) loss per cycle (up+down) ≈ 7 kJ/m

Measured losses on 11 T short model MBHSP012



Low field: from 0.1 to 6 kA
High field: From 6 kA to 11.85 kA

Courtesy of S.I. Bermudez and G. Willering



Margin on the loadline

Our assumption: ISCC and IFCC are negligible, only strand magnetization losses are considered

Strand magnetization, which depends on

- Sub-element diameter (d_{sub})
- Critical current density (non-Cu) (J_c)
- Cu/non-Cu ratio (λ)

$$M(B) \propto d_{sub} \cdot J_c\,(B) \cdot \frac{1}{\lambda + 1}$$

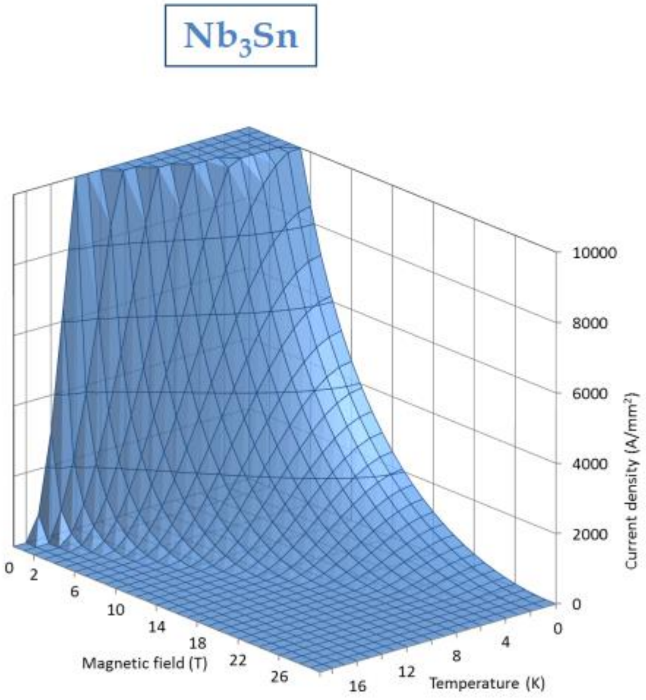
Roxie Model Input

- Superconductor current density as specified for HiLumi
  - $T_{c0} = 16$ K
  - $B_{c20} = 29.38$ T
  - $\alpha = 0.96$
  - $C_0 = 188870$ A/mm^2 T
  - 3 % cabling degradation

$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1 - b)^2$$

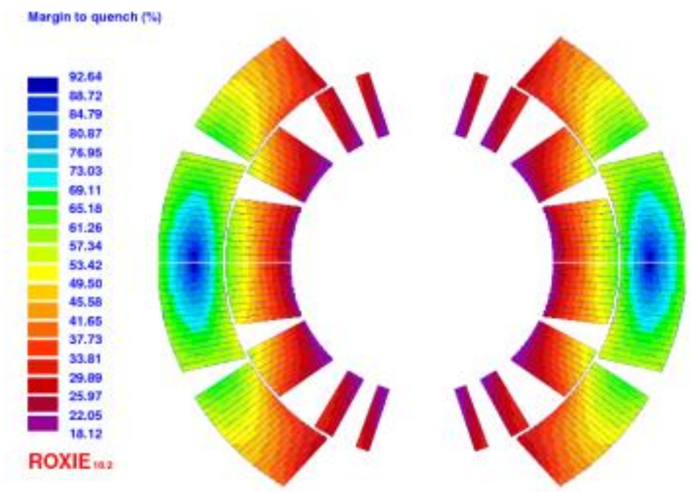
$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$



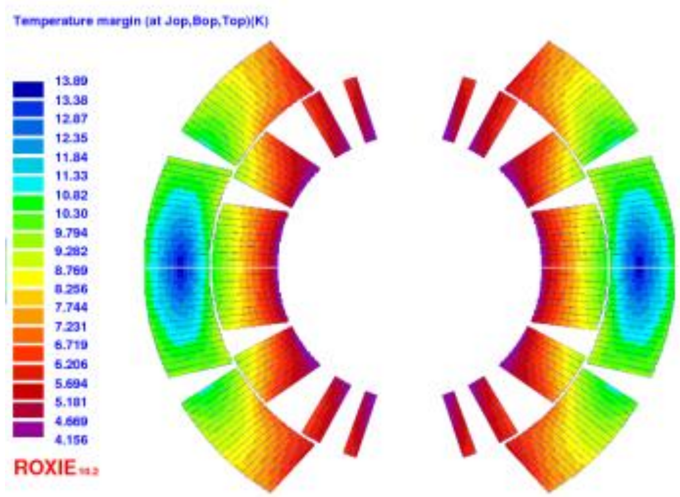
- Reference: D_{eff} = 50 µm, no reduction due to flux jumps
- Sensitivity analysis to:
  - Effective filament size D_{eff} = 20 µm, D_{eff} = 50 µm
  - Reduction of strand magnetization at low field due to flux jumps χ= 0.5-1

Courtesy of P. Ferracin

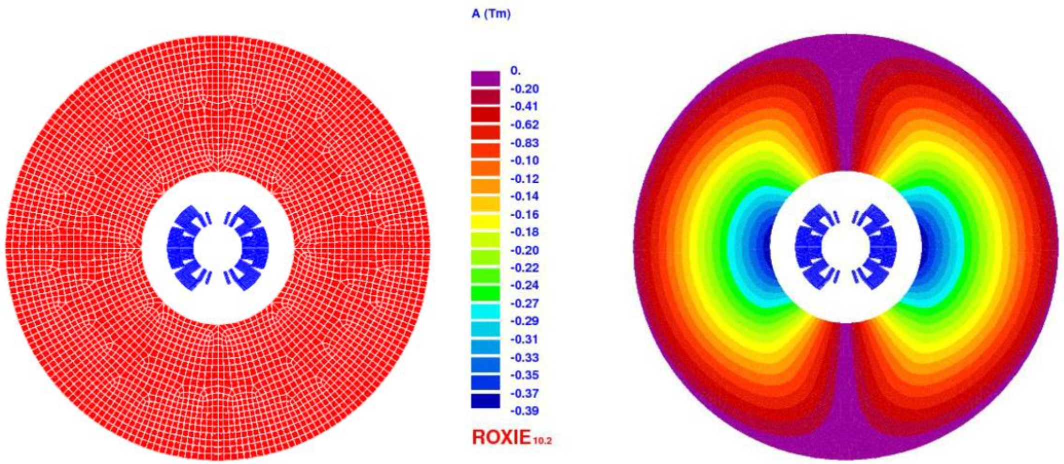
Roxie Model Input



Margin on the loadline



Temperature margin at nominal current

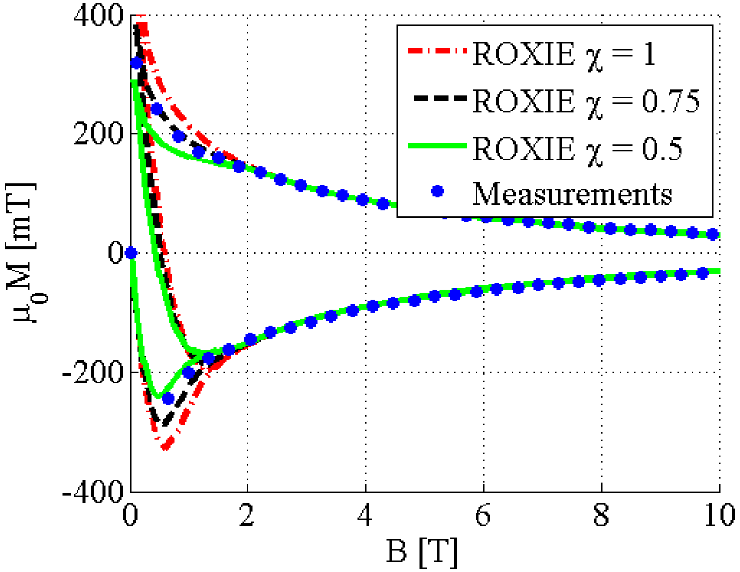


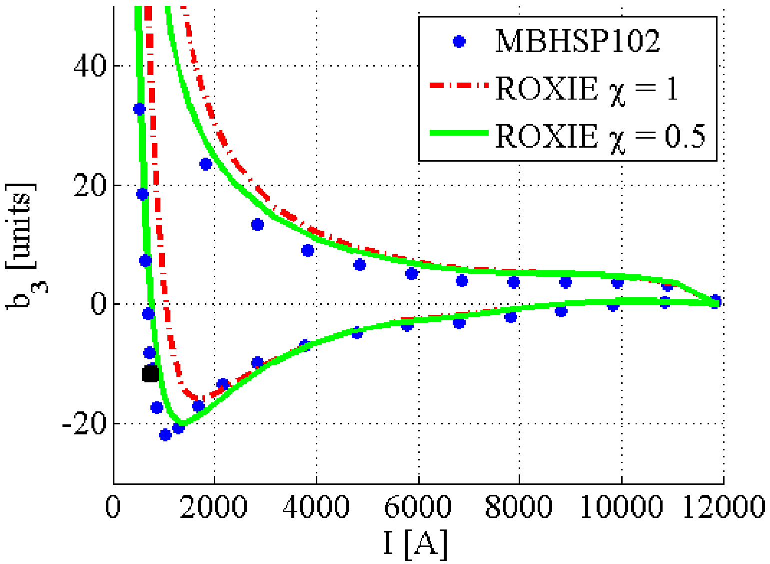
Iron mesh and vector potential

Courtesy of S.I. Bermudez and F. Murgia

Modelling SC magnetization

- Semi-analytical hysteresis model for the superconductor, developed in [1], and implemented in ROXIE [1].
- Limited accuracy at low field, partially due the reduction on magnetization observed in Nb_3Sn due to flux jumps [2], which can be overcome by introducing a reduction on the strand magnetization below a given field level.
- Model has been validated in 11 T [2] and MQXF [3] magnets





Courtesy of S.I. Bermudez

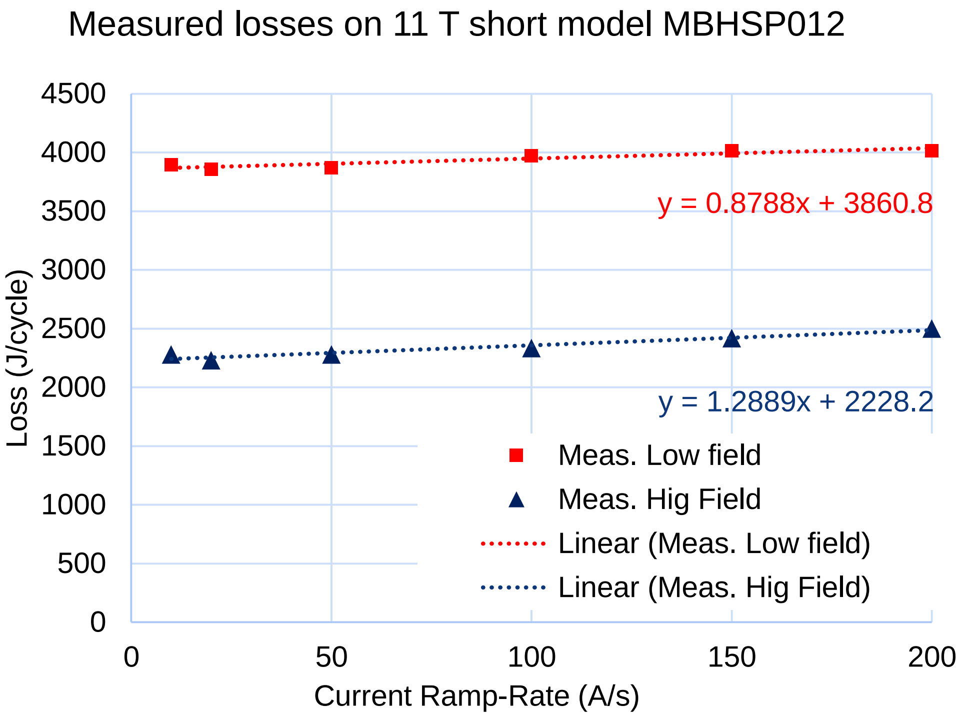
$$D_{eff}^{LF}(B) = D_{eff}(\chi + (1-\chi)(B/B_o))$$

[1] C. Vollinger, Superconductor magnetization modelling for the numerical calculation of field errors in accelerator magnets. PhD thesis, 202
[2] S. Izquierdo Bermudez, et.al, Persistent Current Magnetization effects in High-Field Superconducting Accelerator magnets, IEEE 2016
[3] S. Izquierdo Bermudez, et.al, Magnetic Analysis of the Nb3Sn low-beta Quadrupole for the High Luminosity LHC, IEEE 2017

ROXIE vs AC loss measurement: 11T

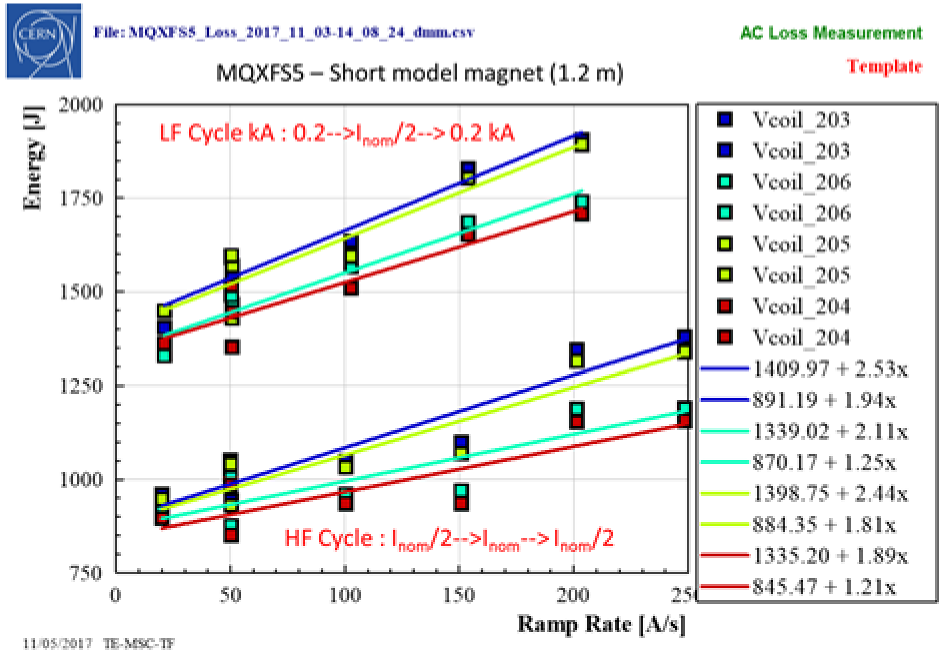
- Measured ramp up + ramp down around 6 kJ, 6/1.7= 3.6 kJ/m for a single aperture (ROXIE gives 4 kJ/m, a bit conservative, but good enough for a first approximation).

11 T - Magnetization loss per aperture (Deff = 0.046 mm, RRP 108/127)	ROXIE	
	J/m	J/m3
Pre-Cycle (0- 11.85 kA-0.1 kA)	4133	8.139E+05
Ramp up (0.1 kA -11.85 kA)	1853	3.650E+05
Ramp down (11.85 kA - 0.1 kA)	2207	4.346E+05
Ramp down + Ramp up (11.85 kA-0.1 kA-11.85 kA)	4060	7.996E+05



ROXIE vs AC loss measurement: MQXFS

- Measurements: 7.5 kJ/m, so reasonably close to the 8.3 kJ/m predicted by ROXIE (actually Jc is 5 % lower than the spec in MQXFS5, so the difference is explained with that)

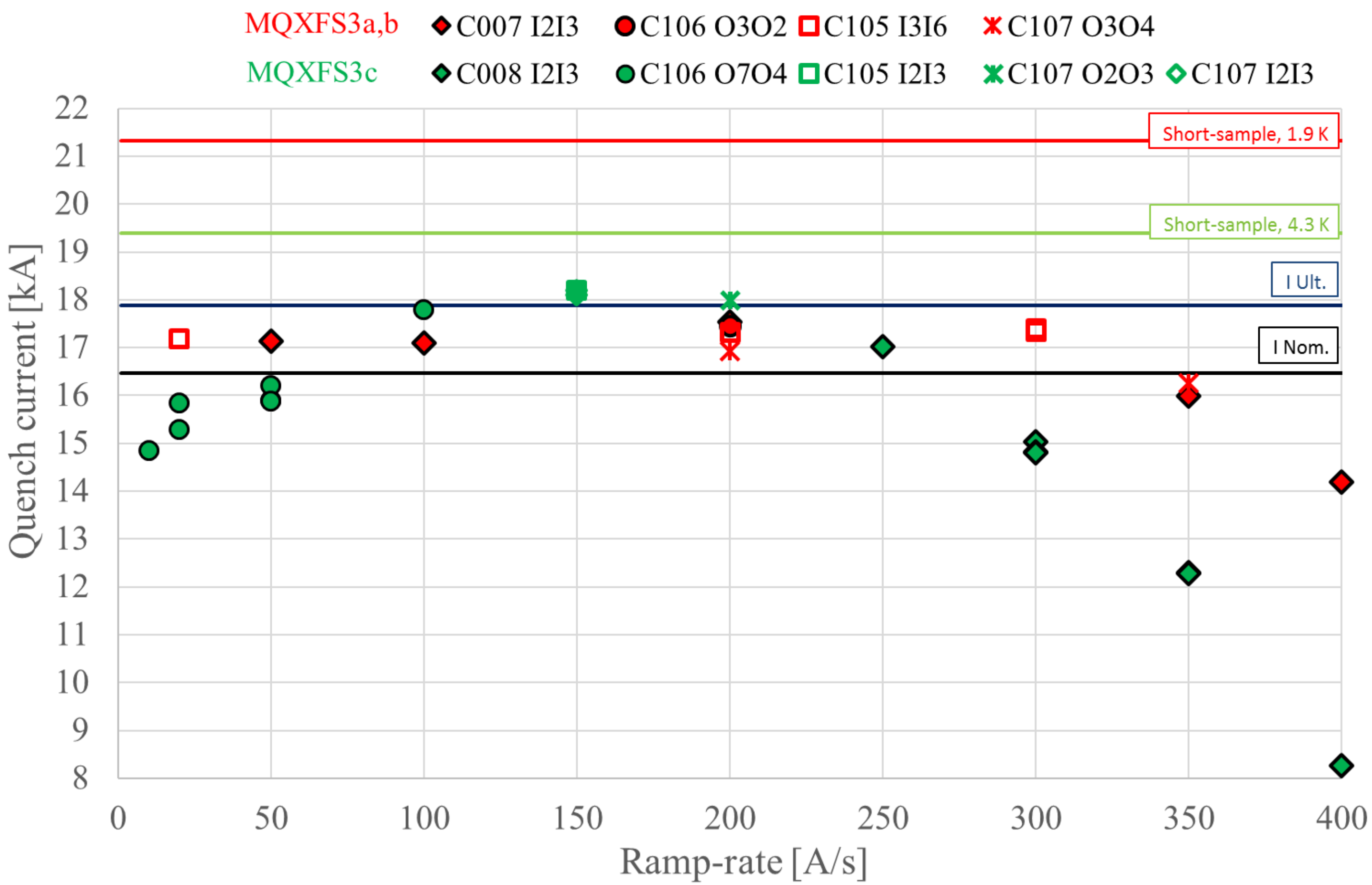


Total magnetization loss for HF + LF (i.e., ramp up and ramp down to nominal current)≅ (5.5 + 3.5)/1.2 = 7.5 kJ/m

MQXF - Magnetization loss (Deff = 0.039 mm, PIT bundle)	ROXIE	
	J/m	J/m3
Pre-Cycle (0-16.47 kA-0.1 kA)	8474	5.994E+05
Ramp up (0.1 kA -16.47 kA)	3782	2.675E+05
Ramp down (16.47 kA -0.1 kA)	4503	3.186E+05
Ramp down + Ramp up (16.47 kA-0.1 kA-16.47 kA)	8286	5.861E+05

Conclusion

- If the theory behind AC loss is well understood, the **literature** about Nb_3Sn magnet is **rather limited** and mainly referring to ITER magnet (central solenoid pulse mode).
- Experimental results on recent Nb_3Sn magnet shows values **one order of magnitude higher** than NbTi (0.5 kJ/m vs. 8 kJ/m)
- A large amount of **experimental data is now available** from (SMC, RMC, 11T, MQXF) with a defined procedure for AC loss quantification.
- A **new framework of analysis** has been developed following literature procedure to process a large number of files (including old file with different format) can now be treated massively.
- So far only **electrical method** has been used. Next would be to perform **calorimetric method**.
- Simulation work is just recently started at CERN…
- Subsidiary goal… can we simulate **quench current versus ramp rate using AC loss measurement**?


MQXFS3a,b
C007 I2I3
C106 O3O2
C105 I3I6
C107 O3O4
MQXFS3c
C008 I2I3
C106 O7O4
C105 I2I3
C107 O2O3
C107 I2I3
Short-sample, 1.9 K
Short-sample, 4.3 K
I Ult.
I Nom.
Quench current [kA]
Ramp-rate [A/s]
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
0
50
100
150
200
250
300
350
400

Thank you for your attention!