AC loss for EuroCirCol 16 T designs

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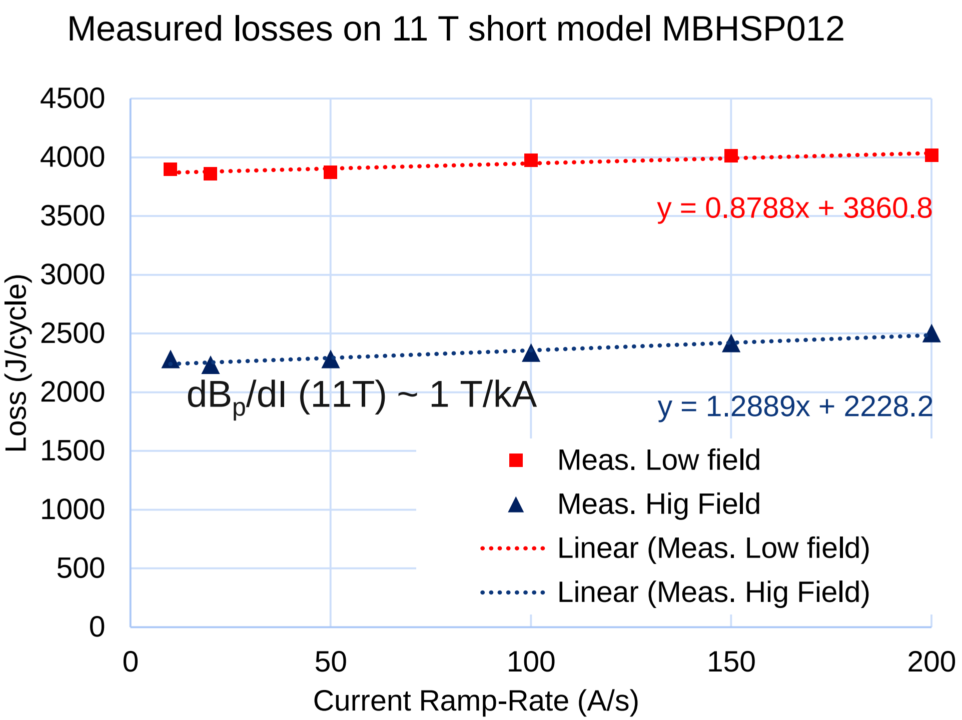
Acknowledgements: Fernando Toral, Vittorio Marinozzi, Clement Lorin

01-11-2017

Losses

- Three sources:
  - Magnetization losses
    - Proportional to the superconductor J_c and filament size (D_{eff})
  - Inter-strand coupling loss (ISCC)
    - Low thanks to the use of cored cable
  - Inter-filament coupling losses (IFCC)
    - Low at the typical ramp-rate of an accelerator as LHC/FCC (10 A/s)

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

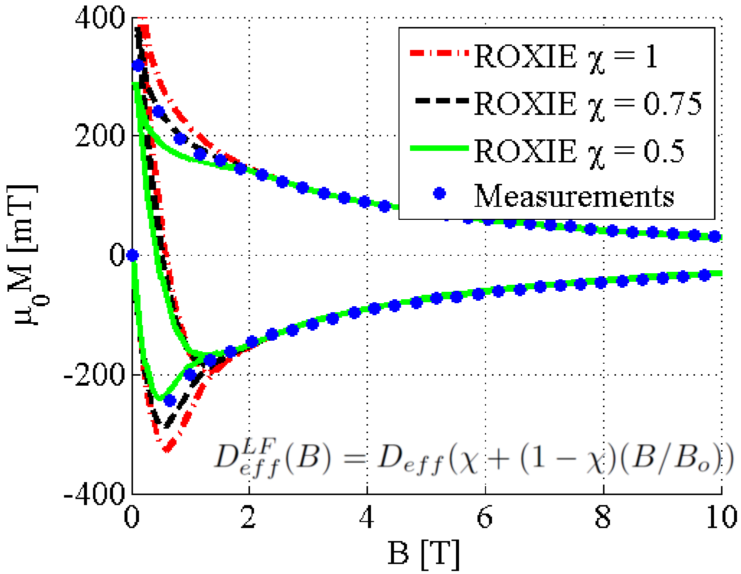


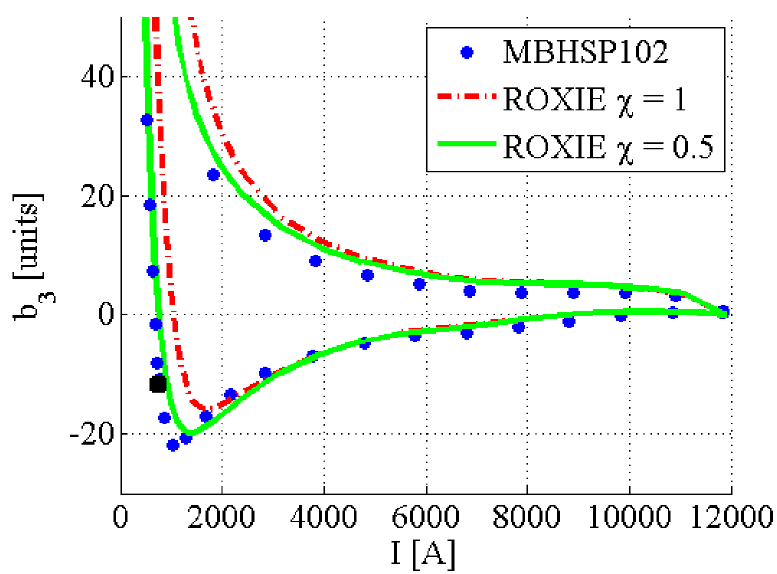
Low field: from 0.1 to 6 kA
High field: From 6 kA to 11.85 kA

Measurements:
Gerard Willering & Hugo Bajas

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





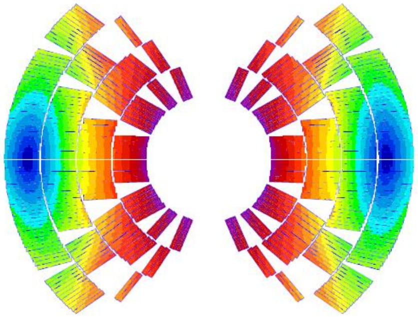
[1] C. Vollinger, Superconductor magnetization modelling for the numerical calculation of field errors in accelerator magnets. PhD thesis, 202
[2] S. Izquierdo Bermudez, et.al, Persistent Current Magnetization effects in High-Field Superconducting Accelerator magnets, IEEE 2016
[3] S. Izquierdo Bermudez,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

AC Losses – Parameter dependence

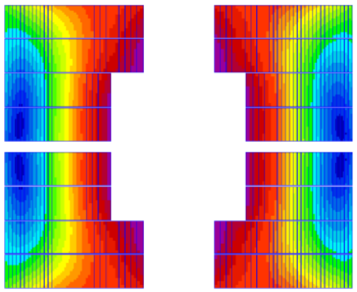
- Strand magnetization, which depends on
  - Sub-element diameter (d_{sub})
  - Critical current density (non-Cu) (J_c)
  - Cu/non-Cu ratio (λ)

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

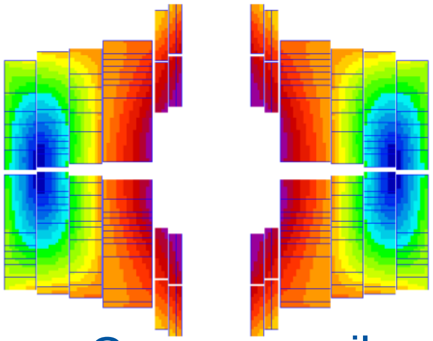
- Magnet powering cycle
- Coil geometry
  - Here we study the cos-theta, block and common coil EuroCirCol coil configurations.



Cos-theta



Block



Common-coil

Superconductor parameters

- Superconductor current density as specified for EuroCirCol
  - $T_{c0} = 16\ K$
  - $B_{c20} = 29.38\ T$
  - $\alpha = 0.96$
  - $C_0 = 275880\ A/mm^2\ T$
  - 3 % cabling degradation

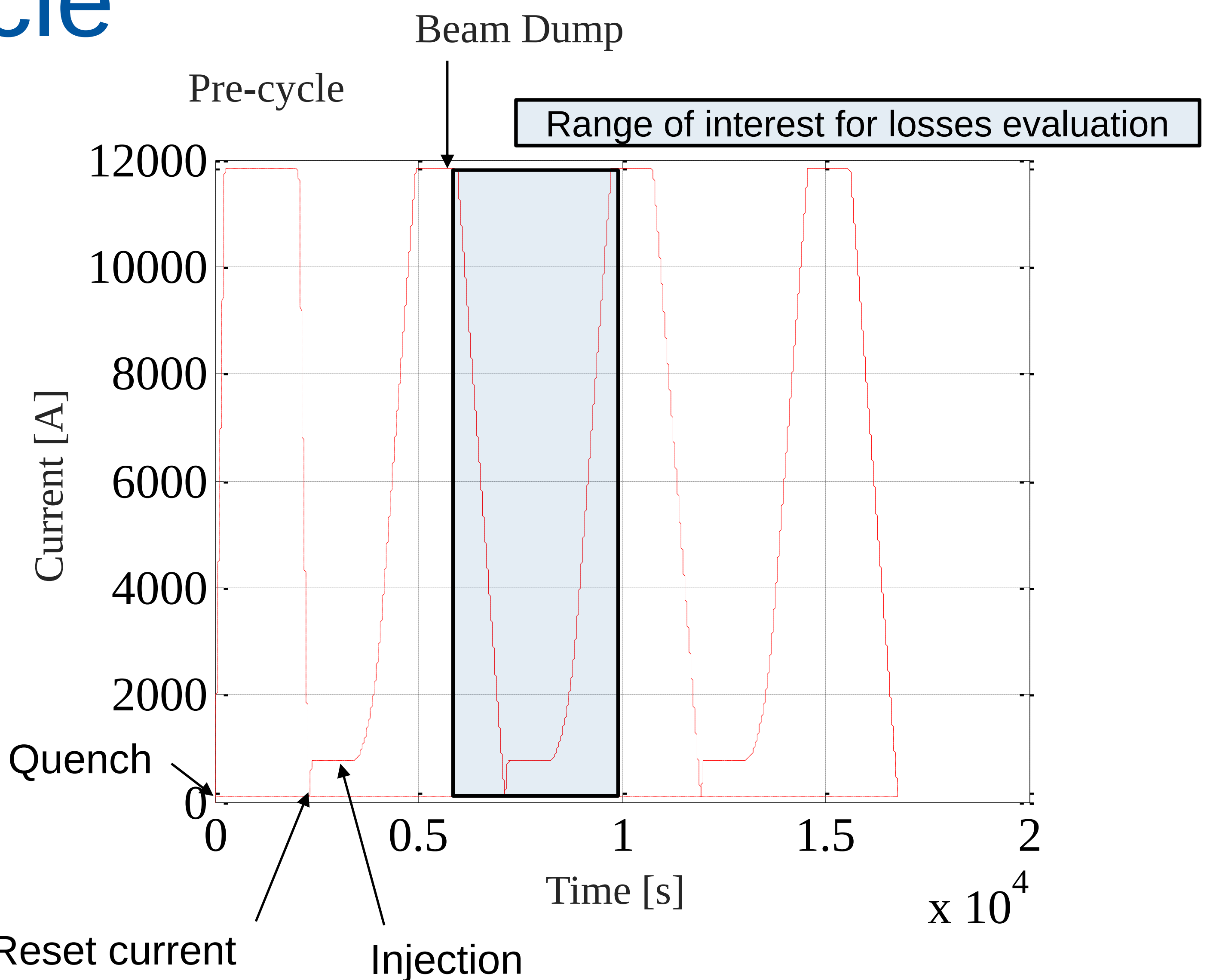
$$B_{c2}(T) = B_{c20} \cdot (1 - t^{1.52})$$

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

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

- 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

Cycle


Beam Dump
Pre-cycle
Range of interest for losses evaluation
12000
10000
8000
6000
4000
2000
0
Current [A]
Quench
0
0.5
1
1.5
2
Time [s]
x 10^4
Reset current
Injection

Cycle - Parameters

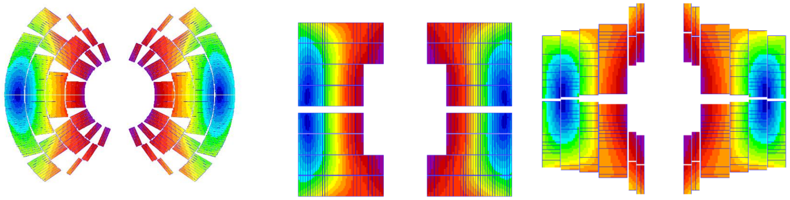
- INJECTION: For FCC (collision energy 100 TeV)
  ([1] D. Shuttle FCC week 2017) :
  - Baseline: 3.3 TeV from LHC (acceleration ratio = 15.2)

- RESET CURRENT:
  - Compromise between field quality and magnetization loss during operation
    - Reference value: 100 A
    - Sensitivity study of the AC loss as a function of the reset current, with a maximum reset current = injection current

[1]https://indico.cern.ch/event/556692/contributions/2483405/attachments/1466498/2267552/Berlin_wide2.pdf

Sensitivity to coil geometry

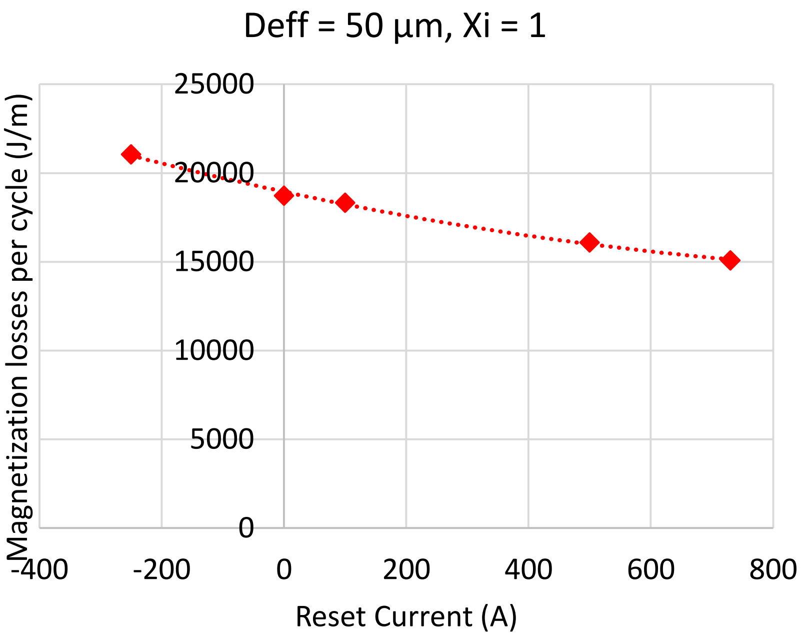
- When normalizing the to the area of superconductor, the AC loss for the 3 designs is within 3 %
- Small room of optimization of the AC-loss with an optimization of the turns location



Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
Xi	--	1	1	1
I1	Inom (50 TeV)	11060	10465	16100
I2	Ireset	100	100	100
I3	Iinj (3.3 TeV)	729.96	690.69	1062.6
I4	Inom (50 TeV)	11060	10465	16100
AC-loss (2 Ap)	J/m	18330	19603	23489
AC-loss/Asc	J/m$_3$	4728455	4633384	4776274

Sensitivity to the reset current

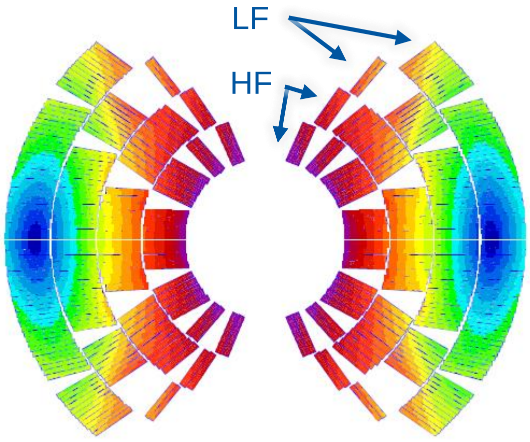
- Non-negligible reduction of the loss when increasing the reset current (we gain 17 % going from I_{reset} = 100 A to $I_{reset} = I_{inj}$)
- The impact on field dynamics needs to be evaluated, since the change on b_3 from injection to nominal will be very large.



Coil geometry		Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta
Deff	µm	50 (HF)	50 (HF)	50 (HF)	50 (HF)	50 (HF)
Xi	--	1	1	1	1	1
I1	Inom (50 TeV)	11060	11060	11060	11060	11060
I2	Ireset	100	0	-250	500	729.96
I3	Iinj (3.3 TeV)	729.96	729.96	729.96	729.96	729.96
I4	Inom (50 TeV)	11060	11060	11060	11060	11060
AC-loss (2 Ap)	J/m	18330	18739	21058	16104	15079

Sensitivity to filament size

- The larger contribution to the losses is coming from the high field layers.
- A reduction of D_{eff} from 50 μm to 20 μm in the low field cable decrease the magnetization losses by 20 %
- A reduction of D_{eff} from 50 μm to 20 μm in the low and high field cable decrease the magnetization losses by 57 %



Coil geometry		Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta	Cos-theta
Deff	**μm**	**50 (HF)**	**50 (HF)**	**50 (HF)/20 (LF)**	**50 (HF)/20 (LF)**	**20 (HF)/20 (LF)**	**20 (HF)/20 (LF)**
Xi	**--**	**1**	**0.5**	**1**	**0.5**	**1**	**0.5**
I1	**Inom (50 TeV)**	11060	11060	11060	11060	11060	11060
I2	**Ireset**	100	100	100	100	100	100
I3	**Iinj (3.3 TeV)**	729.96	729.96	729.96	729.96	729.96	729.96
I4	**Inom (50 TeV)**	11060	11060	11060	11060	11060	11060
AC-loss (2 Ap)	**J/m**	18330	16685	14340	12980	8026	7127

Our thoughts

- 15 kJ/m is what we would expect with today's target specification (focusing on J_c, not on small filaments)
- 10 kJ/m is a reasonable target, since we are already close to achieve a good low field conductor with D_{eff} = 20 µm
  - We recommend to take this as the baseline
- 5 kJ/m could be achieved by a successful implementation of new concepts (artificial pinning)

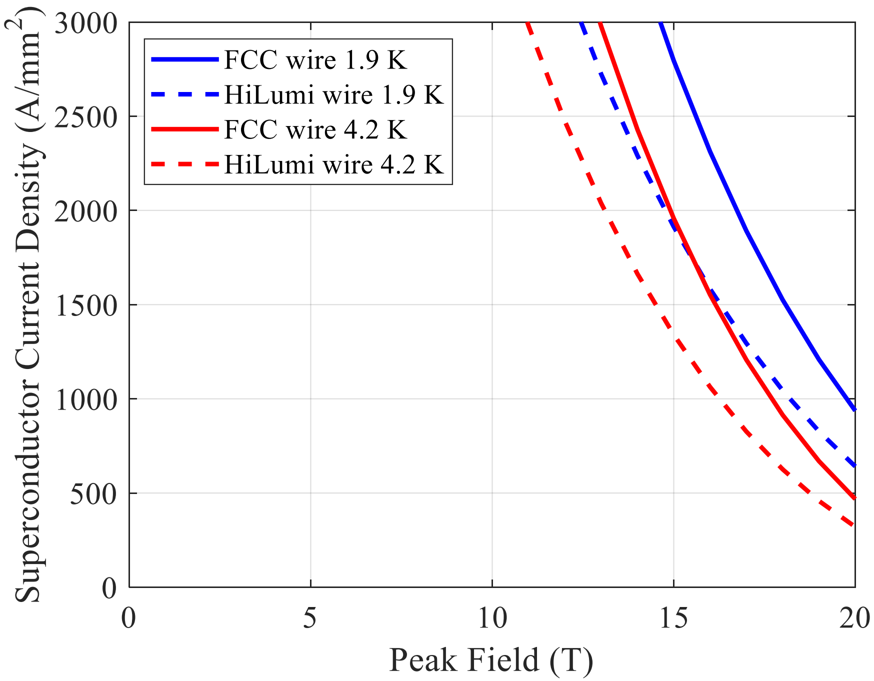
Additional slides

Superconductor parametrization

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

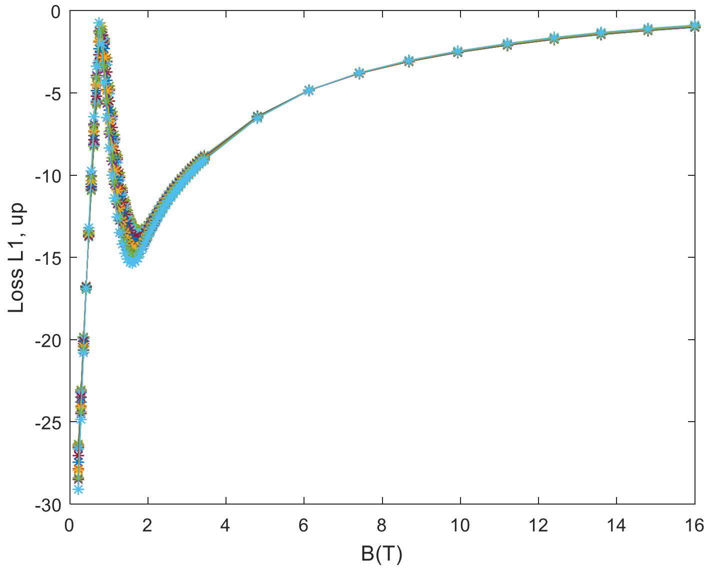
$$J_C = \frac{C(t)}{B_p} \cdot b^{0.5} \cdot (1 - b)^2$$

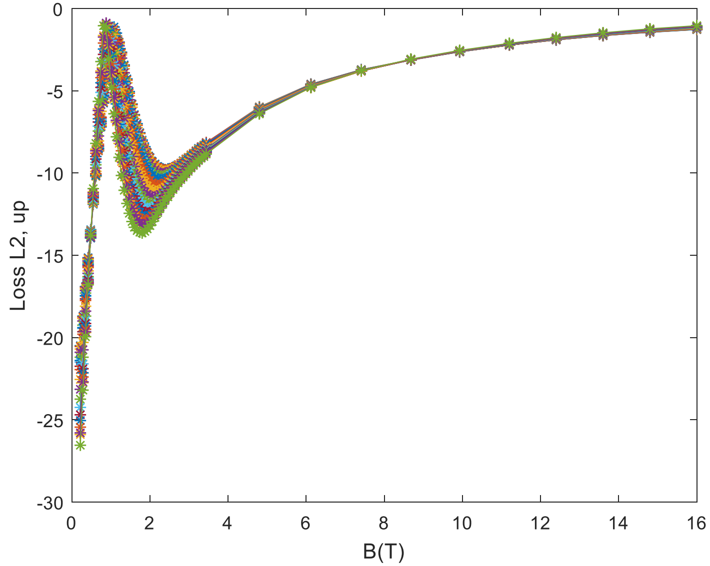
$$C(t) = C_0 \cdot (1 - t^{1.52})^{\alpha} \cdot (1 - t^2)^{\alpha}$$

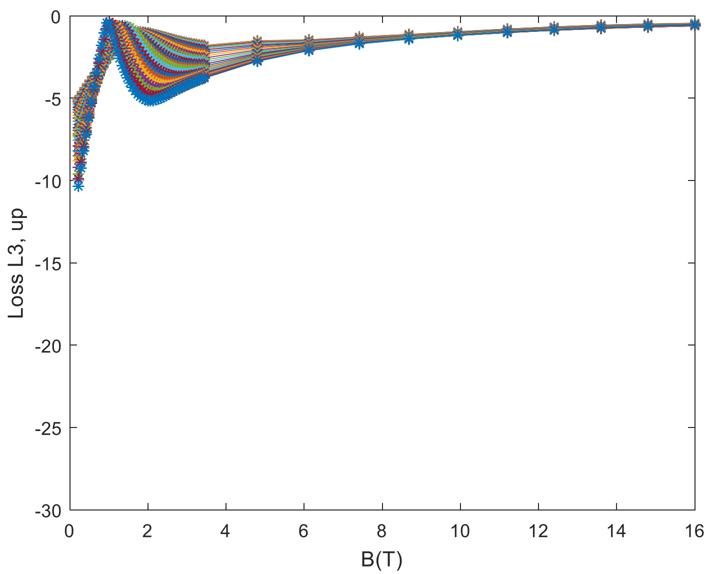


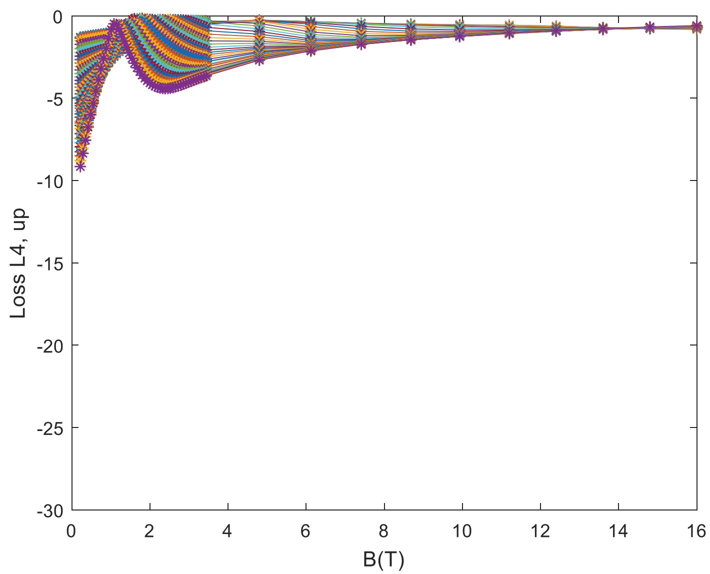
	Hi-Lumi	**FCC**
T_{c0} **(K)**	16	16
B_{c20} **(T)**	29.38	29.38
α	0.96	0.96
$C_0(A/mm^2T)$	188870	275880

J_c at 4.2 K	**Hi-Lumi**	**FCC**
12 T	2500	3610
15 T	1340	1960
18 T	625	915


Loss L1, up
0
-5
-10
-15
-20
-25
-30
0 2 4 6 8 10 12 14 16
B(T)


Loss L2, up
0
-5
-10
-15
-20
-25
-30
0 2 4 6 8 10 12 14 16
B(T)


Loss L3, up
0
-5
-10
-15
-20
-25
-30
0 2 4 6 8 10 12 14 16
B(T)


Loss L4, up
0
-5
-10
-15
-20
-25
-30
0 2 4 6 8 10 12 14 16
B(T)

Notes

- In the LHC:
  - Losses during ramp = 0.5 kJ/m
  - Fast discharge = 3 kJ/m
  - Still, what is defining the size of the cryogenic system is the loss during ramp since after the fast discharge there is no beam
- The maximum allowable dT:
  - 50 mK for the LHC
  - 2.1 K for FCC, which means 2.15 K in the coil. If we want to keep the 50 mK in the FCC we would need 300 l/m of Helium, which is too much!