Margin in 16 T dipole magnets

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Why do we need margin?

An amount of something included so as to be sure of success or safety

Calling it margin is CRAP. We are not capable of building SC magnets without margin. It does NOT work without it, so it is not a margin, it is a MUST for a working magnet

We need it to account for variations in production and during operation (beam losses, splice heating, ramp losses)

We should separately discuss margin for reducing training and for avoiding quenches during operation

Margin you need for reducing the training!

A point or area that represents the difference between acceptable and unacceptable technical values for a system.

Courtesy Miguel Jiminez

Outline

- Margin ‘before’ quench
  - Loadline margin
  - Temperature margin
  - Enthalpy margin
  - Current margin

This talk

- Margin ‘after’ quench
  - Hot-spot temperature margin
  - Temperature gradient margin
  - Voltage margin
- Mechanical/structural margin

See talk’s of Tampere, INFN, CEA, CIEMAT

Loadline margin

- Loadline margin is most widely used because of its simplicity and possibility of easily compare different designs to each other
- Two strategies could be selected:
  - Select a loadline margin such that the first quench is above nominal current (no training)
  - Select a loadline margin such that after training and thermal cycle the next quench is above the nominal current
- Regular re-training in the machine does not seem an option for the FCC

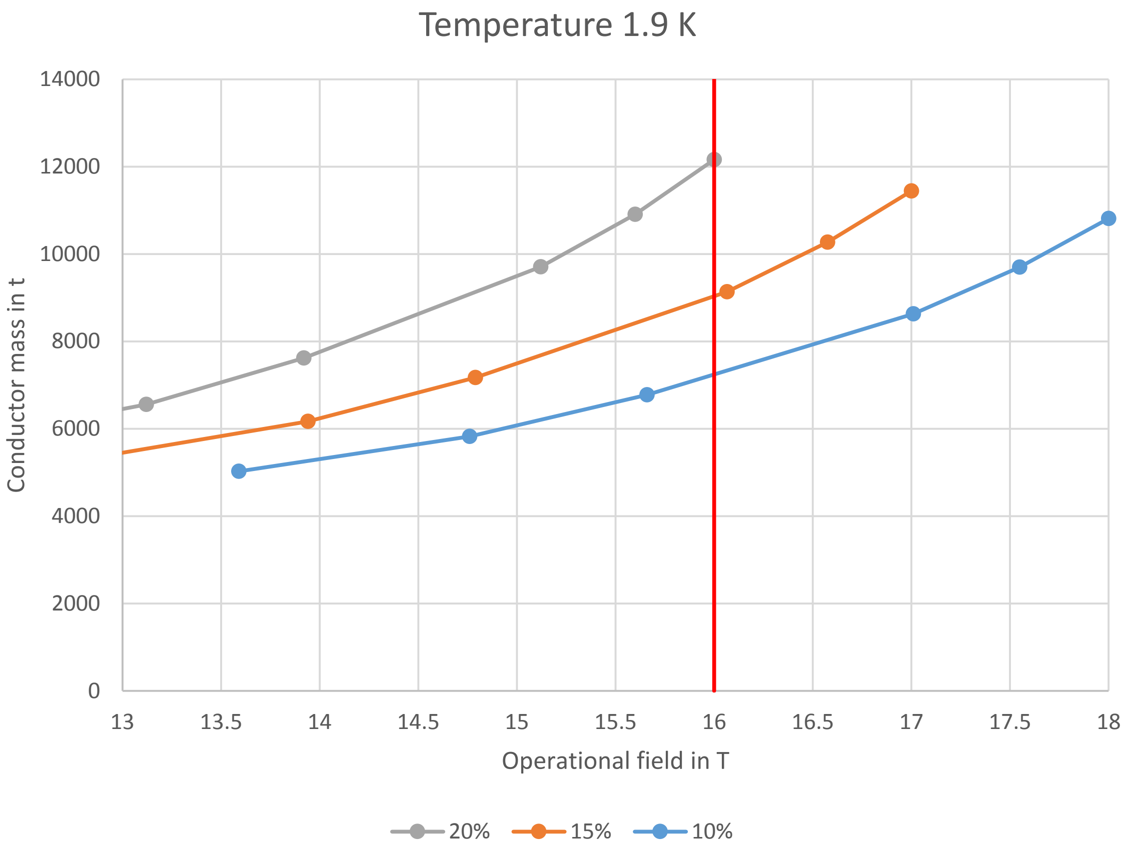
	Margin $1-B_{nom}/B_{ss}$	**Margin** $1-I_{nom}/I_{ss}$
LHC dipoles	14%	15%
MQXF	21%	23%
11 T	18%	20%
FCC	?	-

Loadline margin

Margin is expensive

Conductor mass in kt

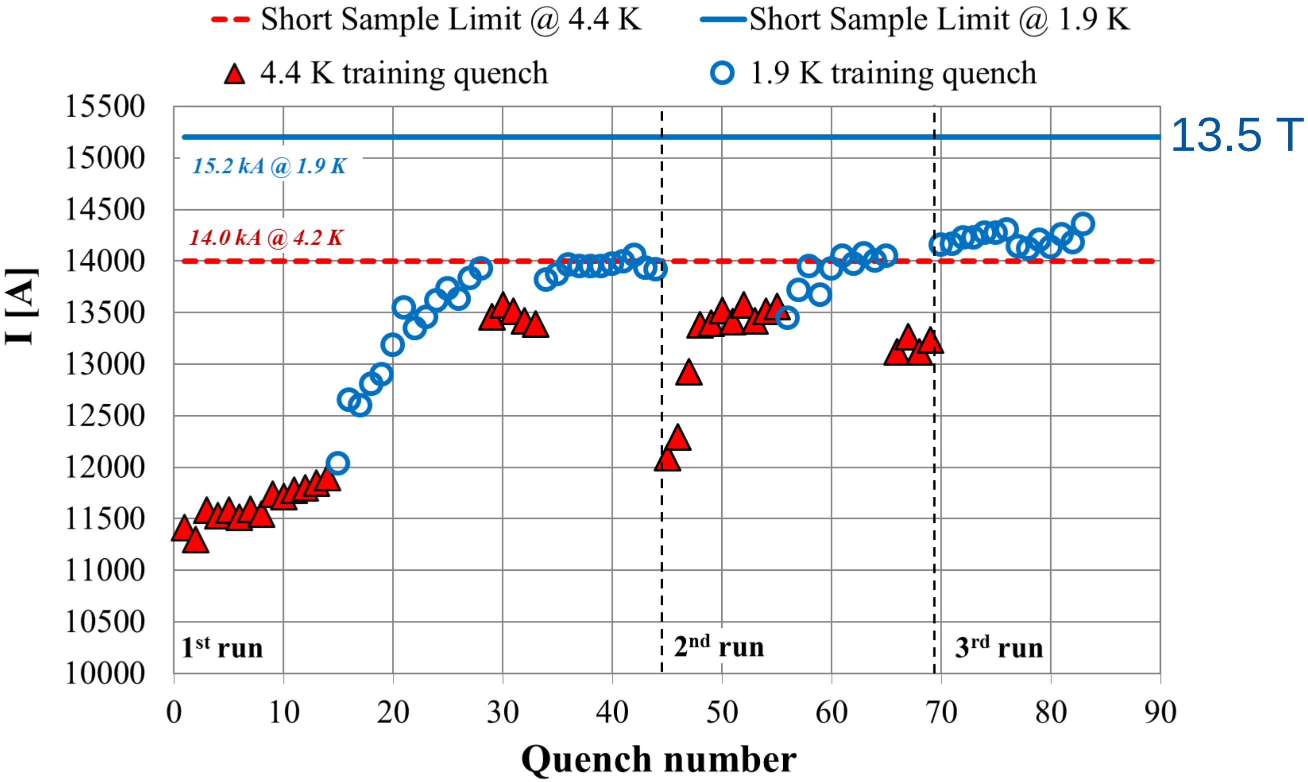
kt	15 T	16 T
10%	6	7
15%	8	9
20%	10	12



Constant integrated field

Needed margin: SMC 3a

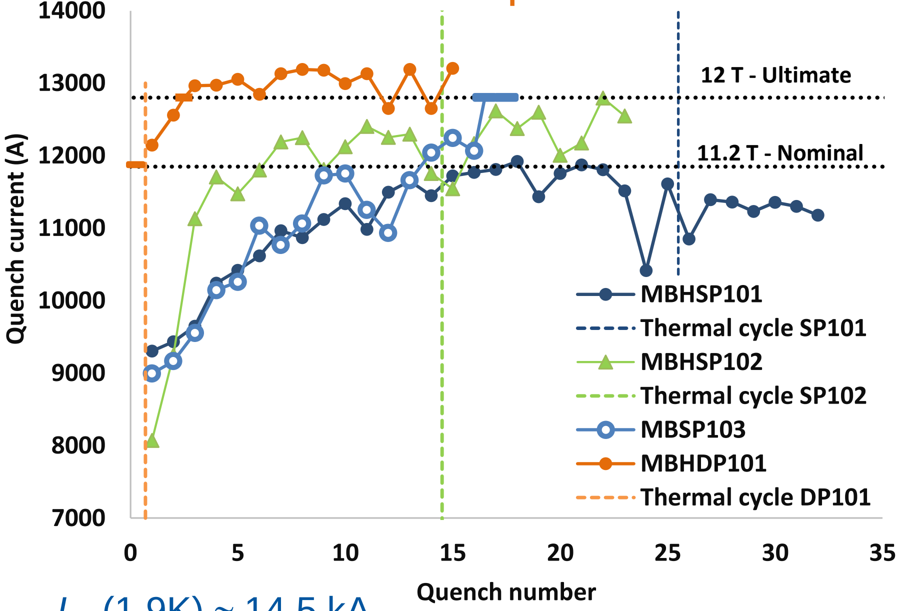
After 1st thermal cycle first quench is around at ~14% from the critical surface and is even only 7% after the 2nd thermal cycle



Needed margin: HiLumi Nb_3Sn magnets

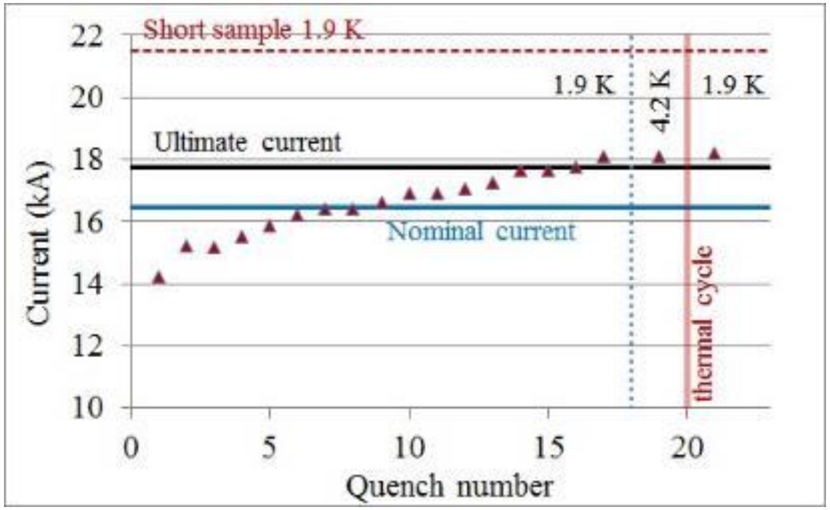
- 11 T dipole after assembly in 2-1 quenched at 17%, no data after thermal cycle available
- MQXF kept its training after a TC (~16% on the load line)

11 T dipole



I_{ss} (1.9K) ≈ 14.5 kA

MQXF



I_{ss} (1.9K)≈ 21.5 kA

Target loadline margin

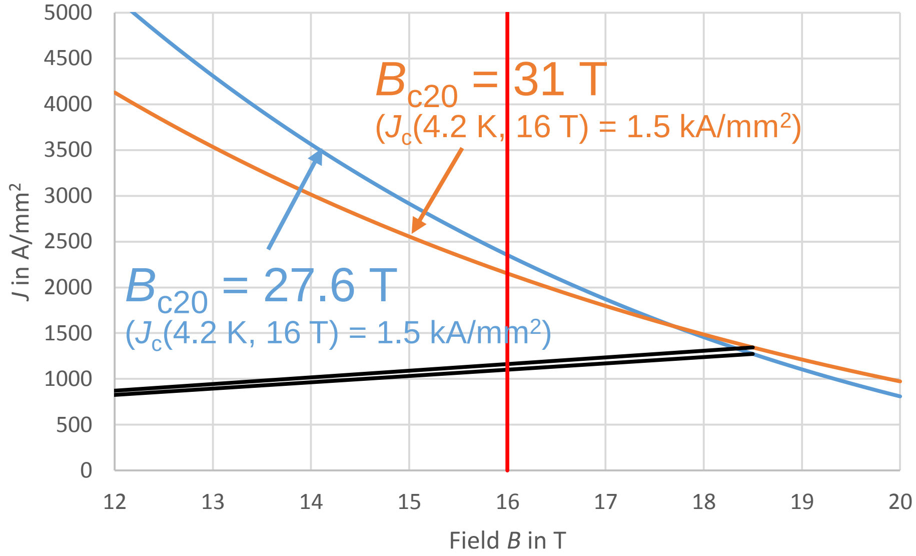
- From the experience of SMC, 11 T and MQXF it seems that a value of 14%, if an appropriate companion R&D program is established, may be on reach for the FCC. This would require testing all magnets with thermal cycle to ensure memory is kept
- Long magnets and long-term quench behaviour still need to be tested
- Most quenches occur at discontinuities of the coil (layer jumps, ends, heads), can we use the margin better?
- ERMC, RMM and Demonstrator may be used to prove that:
  - The amount of training quenches for the specified margin is reasonable.
  - A thermal cycle is sufficient to eliminate quenches below nominal field.

Temperature margin at 1.9 K

The temperature margin (assumption magnet is adapted to the available conductor):

$T_c(B_{op}, B_{op}/B_{ss} \times J_c\,(B_{ss}, T_{op})\,) - T_{op},$

with $(B_{op}, T_{op}) = (16\text{ T}, 1.9\text{ K})$



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

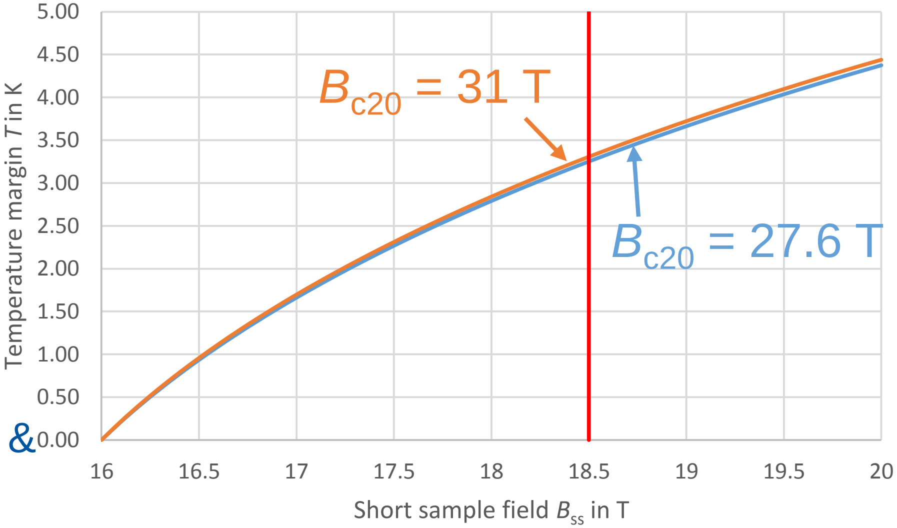
$$J_c = \frac{C(t)}{B_p}\cdot b^{0.5}\cdot(1-b)^2$$

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

Where: $t = \frac{T}{T_{c0}}$; $b = \frac{B_p}{B_{c2}(t)}$

with B_p peak field on the conductor

$J_c(4.2\text{ K}, 16\text{ T}) = 1.5$ kA/mm^2, $B_{c2}(T = 4.2\text{ K}) = 24$ T & 27 T, $T_{c0} = 16$ K, $\alpha = 0.96$, $T = 1.9$ K



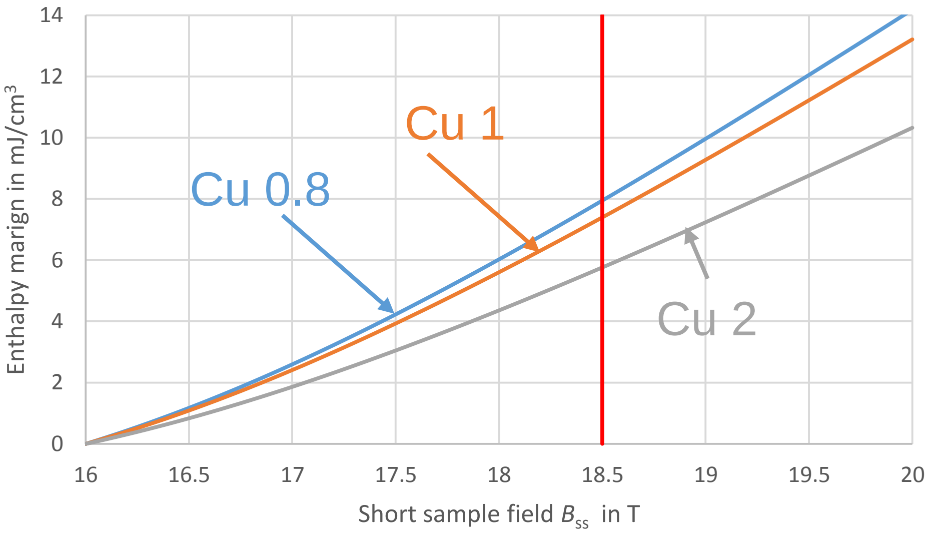
Temperature & Enthalpy margin at 1.9 K

- The temperature margin can be used to calculate the enthalpy margin

$$\Delta h = \int_{1.9\mathrm{K}}^{Tc} \rho c_p(T)\mathrm{d}T$$

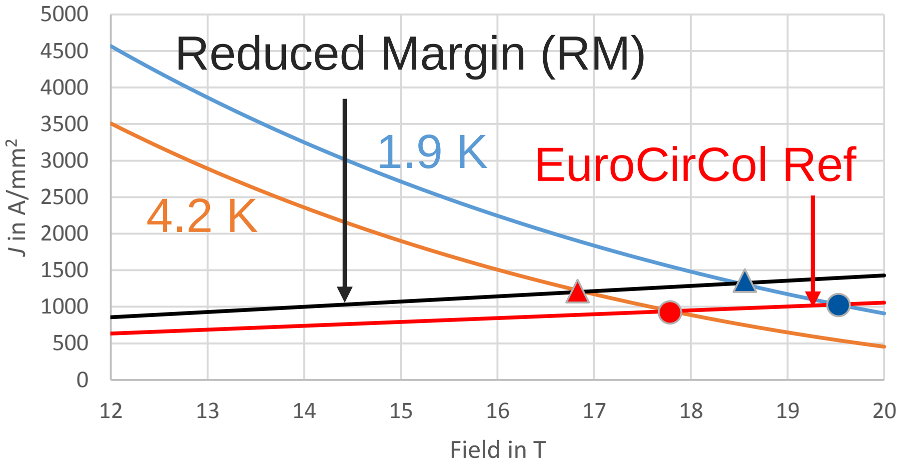
- A smaller copper fraction in the conductor is favourable for having a larger enthalpy margin. However, reducing the amount of Cu may have a negative impact on stability.

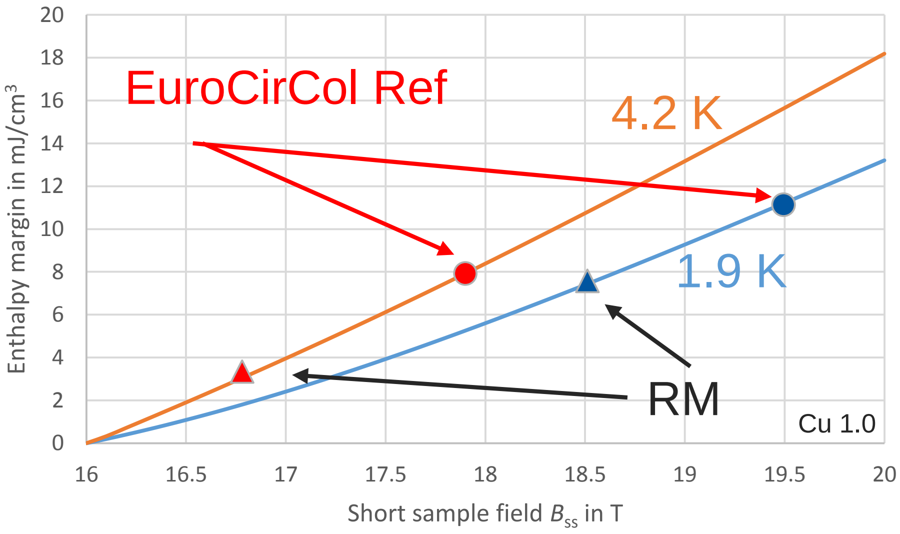
	T-Margin @ 1.9 K [K]	E-Margin @ 1.9 K [mJ/cm^3]
LHC dipoles	1.6	2.5 (70.6)
MQXF	5.2	17.4
11 T	4.4	11.9
FCC (18% LM)	4.0	11.1
FCC (14% LM)	3.3	7.8

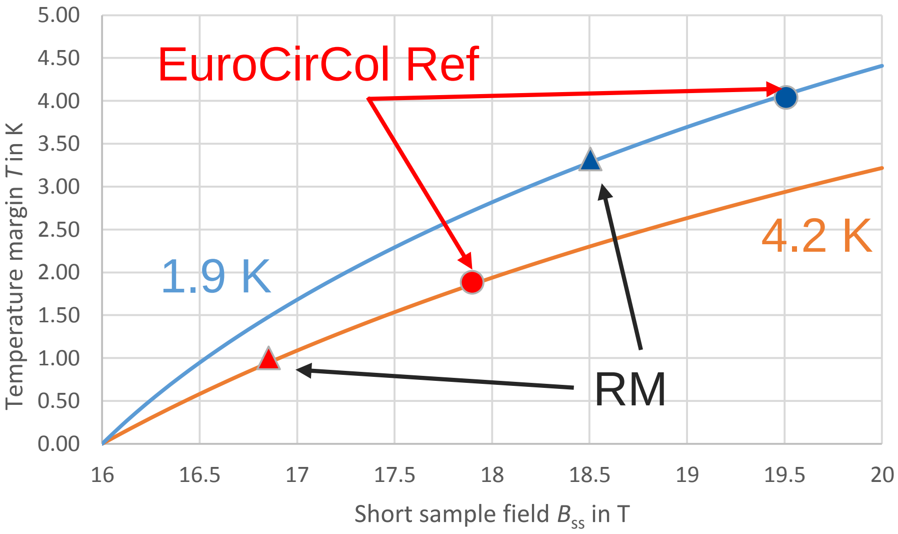


Enthalpy margin at 4.2 K vs 1.9 K

- The smaller temperature margin at 4.2 K is largely overcompensated by the cubic increase with temperature of the enthalpy
- The enthalpy margin between the two options is similar



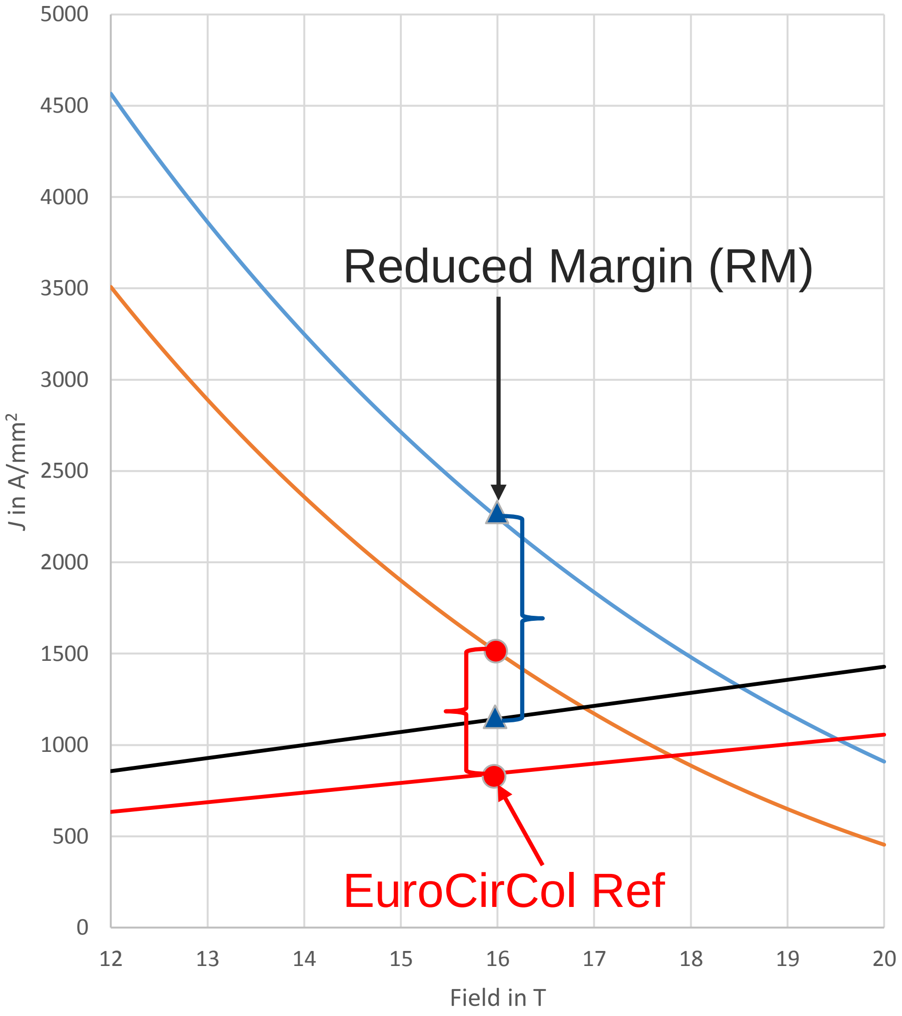




Current margin

- FCC designs have ~50% current margin. Current margin may help for:
  - current (re-)distribution in the cable
  - variation in the strand production
  - local strain
  - performance variations

A small change in the loadline margin does not seem to considerably modify the current margin



Conclusion

- At 4.2 K, 10% loadline margin the enthalpy margin is about 8 mJ/cm^3. The same enthalpy margin (about 8 mJ/cm^3) can be achieved at a loadline margin of 14% at 1.9 K
- These magnets have a 4% difference in loadline margin at 1.9 K corresponding to about 20% conductor difference
- A larger copper fraction in the conductor, as required for protection in the outer layer, results in a smaller enthalpy margin. Therefore, it could be advisable to increase the margin in the outer layers. This margin is also much cheaper, because the peak field is at around 12 T
- Considering the given target of conductor performance J_c(4.2 K, 16 T) = 1.5 kA/mm^2, a slight variation of B_{c2} has a modest influence on the temperature margin, if the magnet design is adapted

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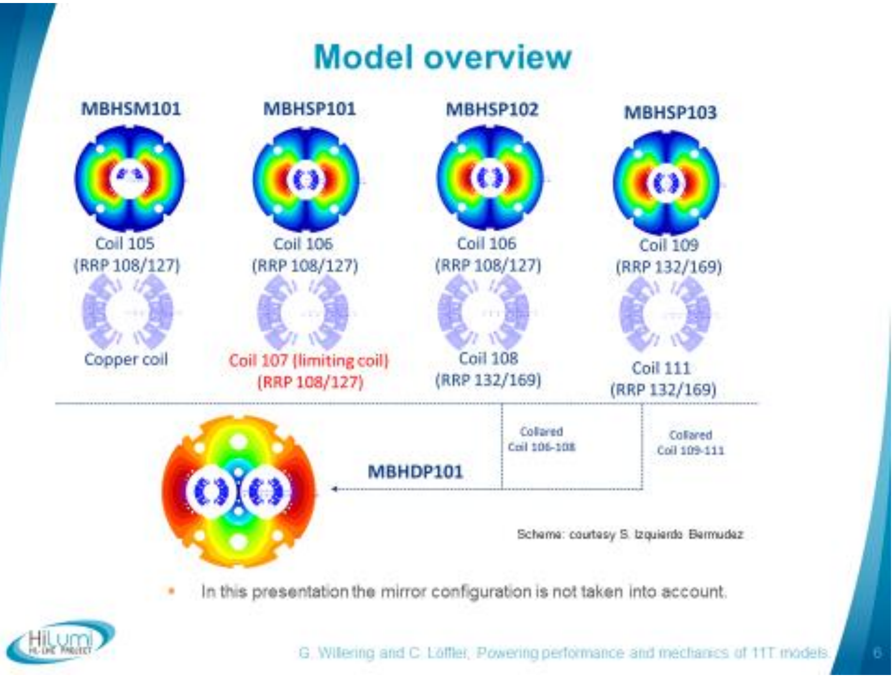
Needed margin: 11 T dipole

11 T dipole after assembly in 2-1 quenched at 17%, no data after thermal cycle available



Model overview

MBHSM101
Coil 105
(RRP 108/127)
Copper coil

MBHSP101
Coil 106
(RRP 108/127)
Coil 107 (limiting coil)
(RRP 108/127)

MBHSP102
Coil 106
(RRP 108/127)
Coil 108
(RRP 132/169)

MBHSP103
Coil 109
(RRP 132/169)
Coil 111
(RRP 132/169)

Collared
Coil 106-108

Collared
Coil 109-111

MBHDP101

Scheme: courtesy S. Izquierdo Bermudez

- In this presentation the mirror configuration is not taken into account.

G. Willering and C. Löffler, Powering performance and mechanics of 11T models

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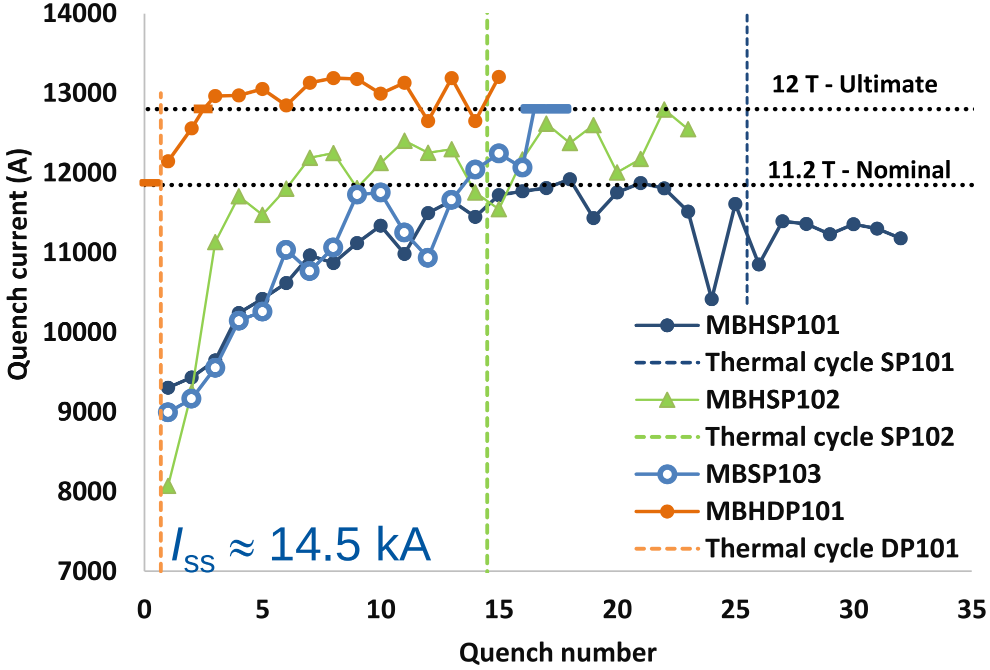

Courtesy G. Willering