Interplay of loss scenarios and resulting temperature in the cold mass and the 11 T coil

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- Summary

Intro

- We aim to keep the new 11-T dipole cold-mass at 1.95 K
- The exceptions are short – time losses when we accept + 50 mK -> 2.0 K, as a temporary excursion

DS - cryo hardware steady-state cooling limits

The 11T dipoles and the associated collimators left and right of IP7 are part of 107 m long 1/2-cell cooling loops.

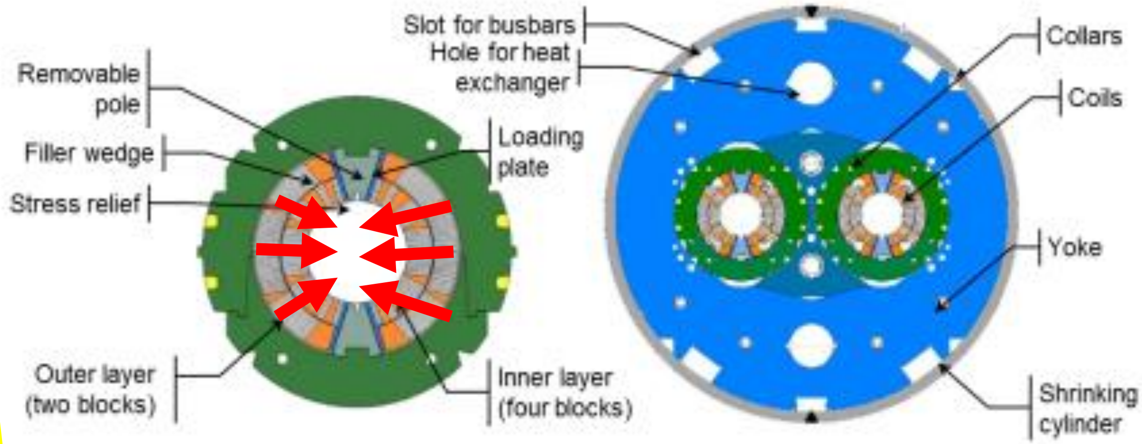
Cooling-power provided by the collective performance of:

1. Bayonet heat exchanger, *protruding through all cold masses*: design limit 7 g/s ≡140 W (at 1.9 K, pumping)
2. Very low pressure counterflow heat exchanger *installed in the QRL-service module*: limit 5 g/s ≡100 W (at 1.9 K, pumping)
3. LHC operating experience puts the cold-mass temperatures ≤ 1.95 K and static heat load ≈ 0.4 W/m.

Available cooling power for 11 T: ≈ 60 W maximum

11 T dipole steady state as function of power: 1) « static coil + beam-pipe cooling limits »

Coil-heat must go first from coil to annular space around beam-pipe and then towards the magnet ends



Updated values 17.09.2018

No radial cooling holes → ≈ 4.5 W/m per aperture

(at 1.95 K cold-mass temperature, per aperture conduction cooling)

Total continuous extraction capacity limit from the coil area is ≈ 50 W both apertures combined

(at 1.95 K cold-mass temperature)

Steady state as function of power:
2) « cold-mass cooling limits »

If we consider that the DS-bayonet heat exchanger is operated at its fullest capacity then the 11T cold-mass part will take ≈ 8-10 W under the corresponding ΔP and wetting conditions. The remainder is conducted away.

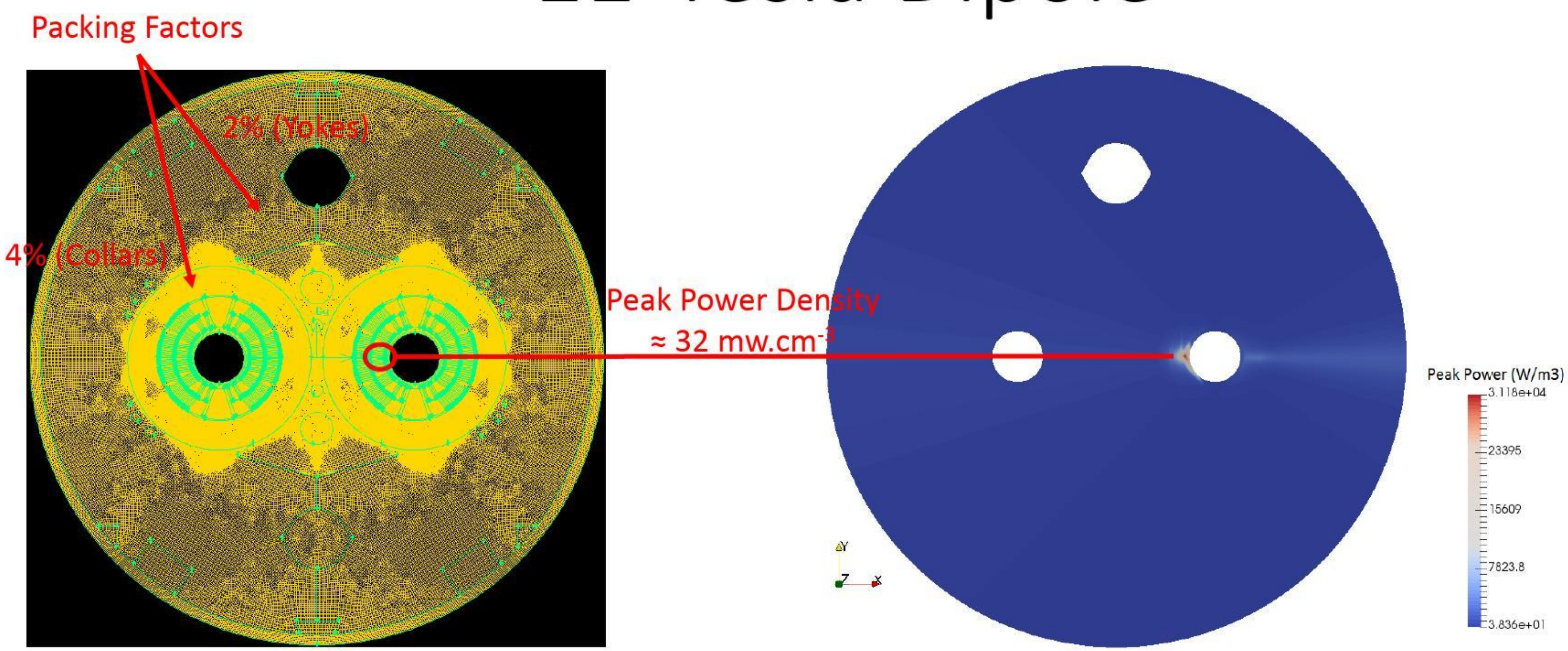
Neighbouring magnets can then take ≈ 50 W max, hardware limited by the cold-mass interconnects' free conduction area.

→ total ≈ 60 W for the full 11T cold –mass (i.e. coil + collars + yoke + beam pipe +…)

N.B. 60 W power is coherent with the estimated maximum DS cooling power that could be affected to the new magnet (slide - 4)

11 T dipole thermal quench limit
Steady state modelisation results
(by former fellow *Fouad Aabid*)

11-Tesla Dipole



<u>Mesh Quality</u>:

Numerical Mesh: 375196 cells (hexahedral)

Min. cell volume: 6.2e-12 m^3 – Max. cell volume: 8.8e-9 m^3

99% of Mesh Cells < 0.5 in Equisize Skewness, worst element at 0.83

<u>Boundary Conditions</u>:

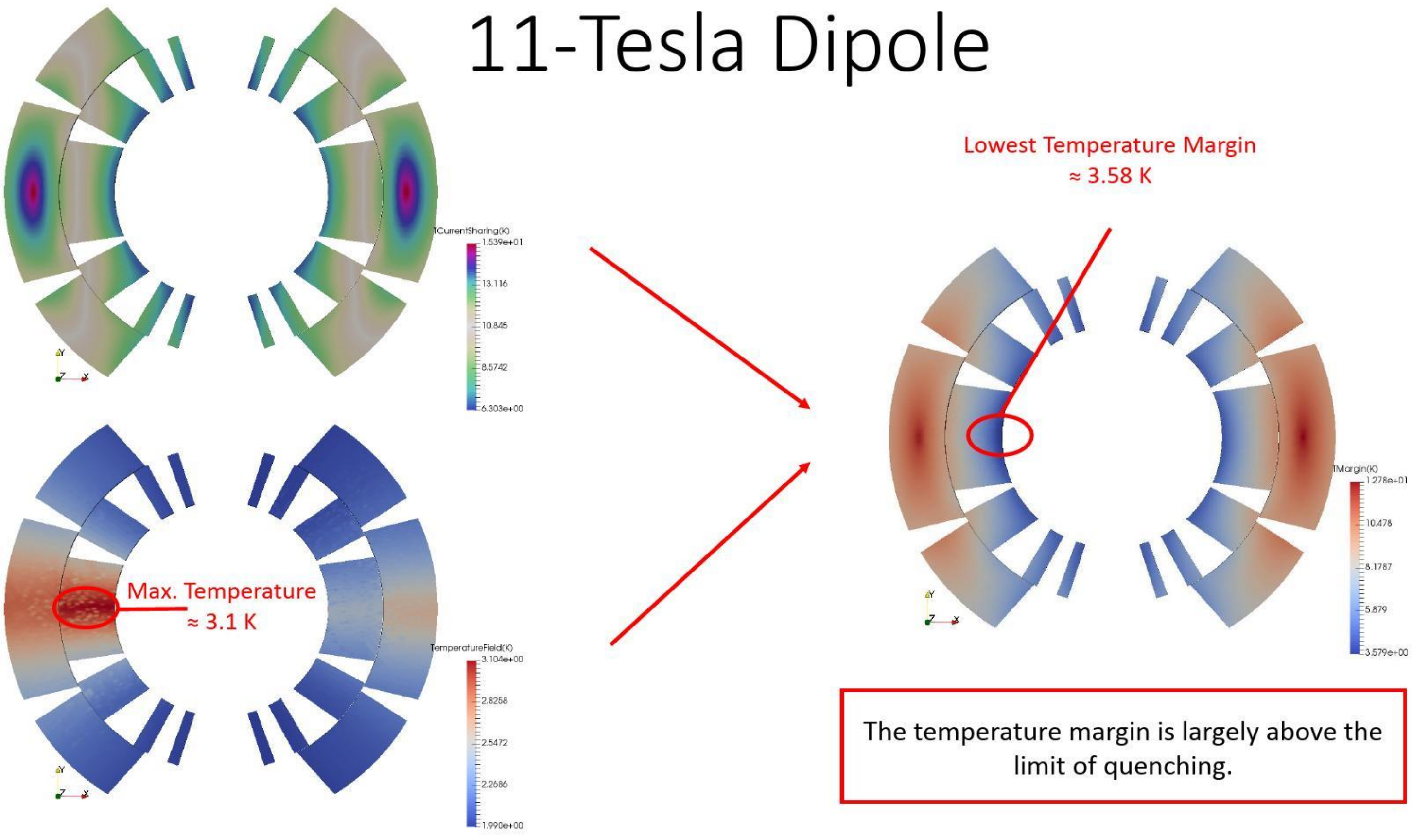
Constant Temperature T=1.9K at the Cold Source

Adiabatic Walls (No heat exchange) on the walls of the External Shell

Uniform heat flux from the Coldbore (where peak power density is): 3.31 $W.m^{-3}$

Steady state modelisation results 11T-dipole

(by former fellow *Fouad Aabid*)



Steady state modelisation results 11T-dipole
(by former fellow *Fouad Aabid*)

The configurations featuring peak power densities of 50mW/cm^{-3} and 100mW/cm^{-3} are also tested. The aim is to verify that the cooling is sufficient for the coils to sustain such levels of energy while maintaining their superconductivity. The results reported in Figs. 14-15 show that the temperature margin is > 3K with a peak power density of 50mW/cm^{-3}. When the energy deposited in the coils climbs up to 100mW/cm^{-3} however, the temperature margin remains positive in the coils but the helium in the annular gap largely warms up to T_λ and slightly above, which could indicate a failure in cooling.

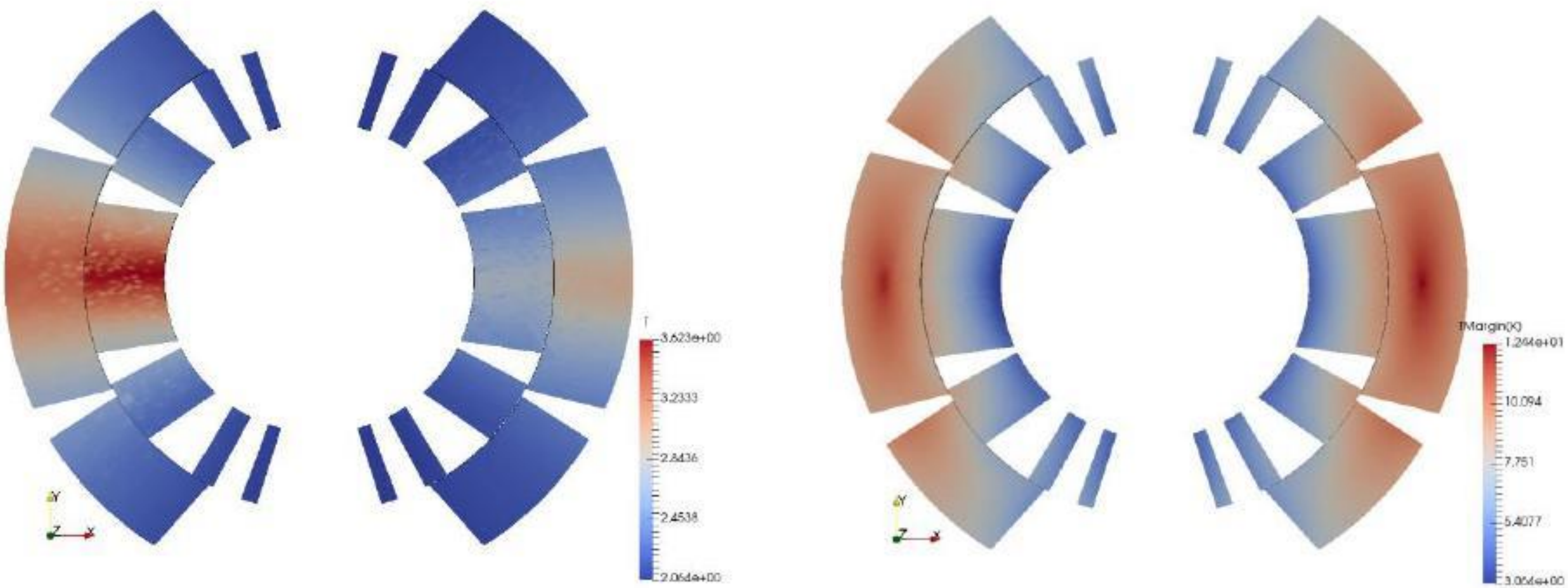


Fig. 14: The operating temperature reaches a maximum value of approximately T = 3.62K, which leads to a temperature margin T_{Margin} > 3.0K when the peak power density is of 50mW/cm^{-3}.

Steady state modelisation results 11T-dipole
(by former fellow *Fouad Aabid*)

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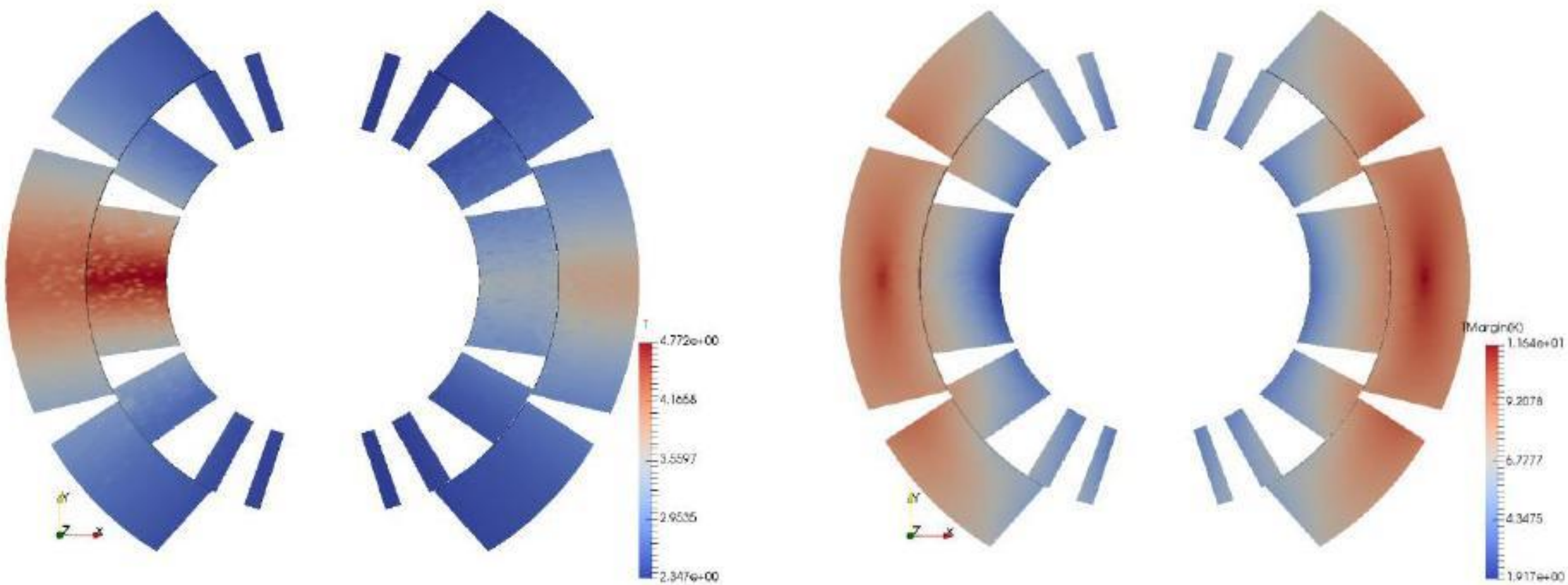


Fig. 15: The operating temperature reaches a maximum value of approximately T = 4.77K, which leads to a temperature margin $T_{Margin} \approx 1.9K$ when the peak power density is of $100mW/cm^{-3}$.

11 T dipole thermal quench limit
Steady state modelisation results 11T-dipole
(by former fellow *Fouad Aabid*)

<u>Recap:</u>

At 32 mW/cm^3 → Tmargin ~ 3.6 K
At 50 mW/cm^3 → Tmargin ~ 3.0 K
At 100 mW/cm^3 → Tmargin ~1.9 K

Locally the 11T dipole coil is highly resistant.

However these values apply only to the worst cold-mass coil-section!

Whether the loads can be sustained over large cold-mass volumes and as function of time depends on the previous DS cooling capacity assessment which limits the total cold-mass power to < 60 W

Complementary validation is ongoing with Cryolab stack-measurements analysis

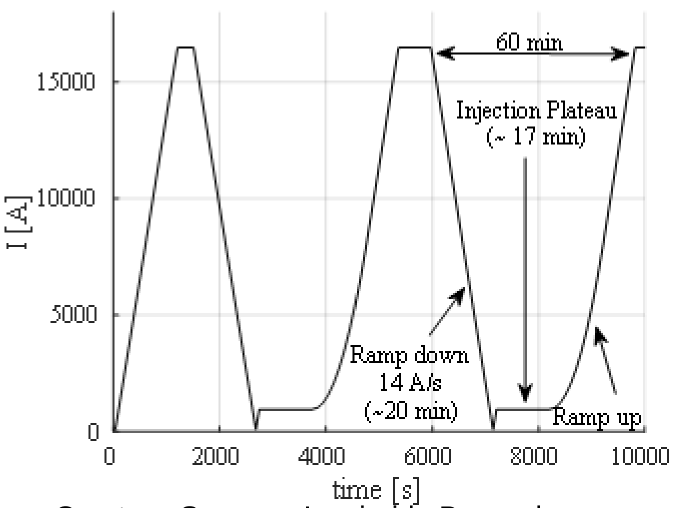
(Note: strong indications of some He presence in coil pack, to be confirmed)

Current ramps
(11T cold-mass only)

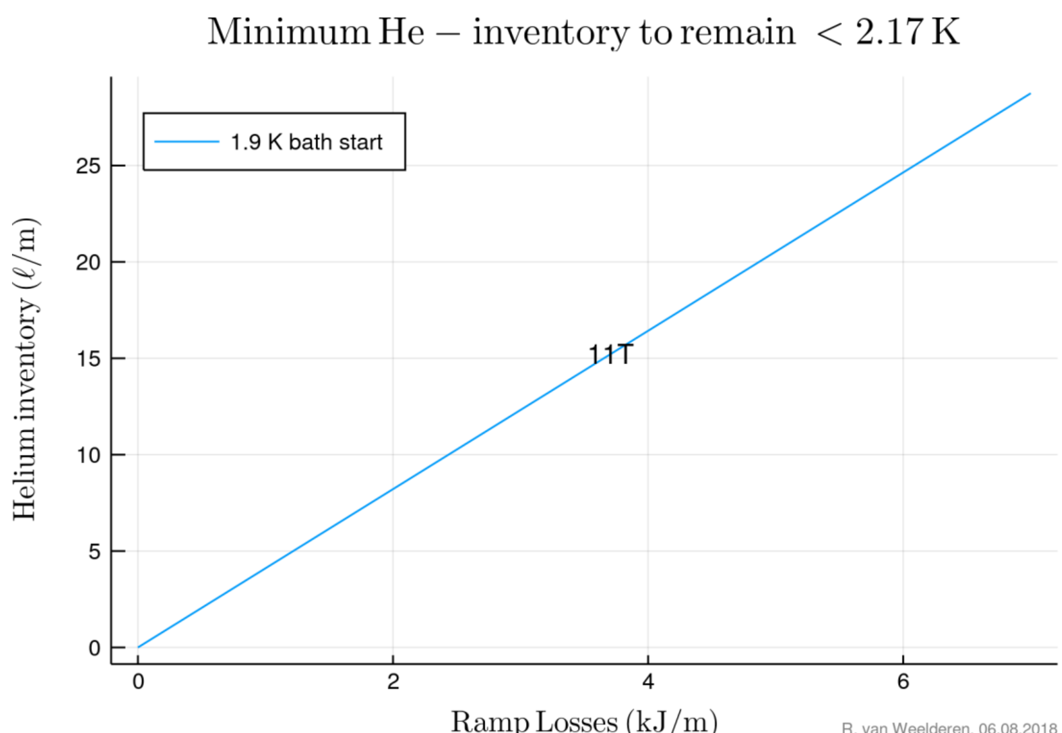
Updated graph 17.09.2018

- Current ramp is estimated to dissipate ~ 4 W/m
  (~ 2207 J/m/aperture in 20 min x 2 apertures + 0.5 W/m static losses)
- The losses would heat up the magnet to near Tλ (2.17 K) as the cold-mass inventory is ~ 27 ℓ/m

→ Ramp can be coped with by the helium buffer and whereas continuous cooling will deal with recovering to the operating temperature.



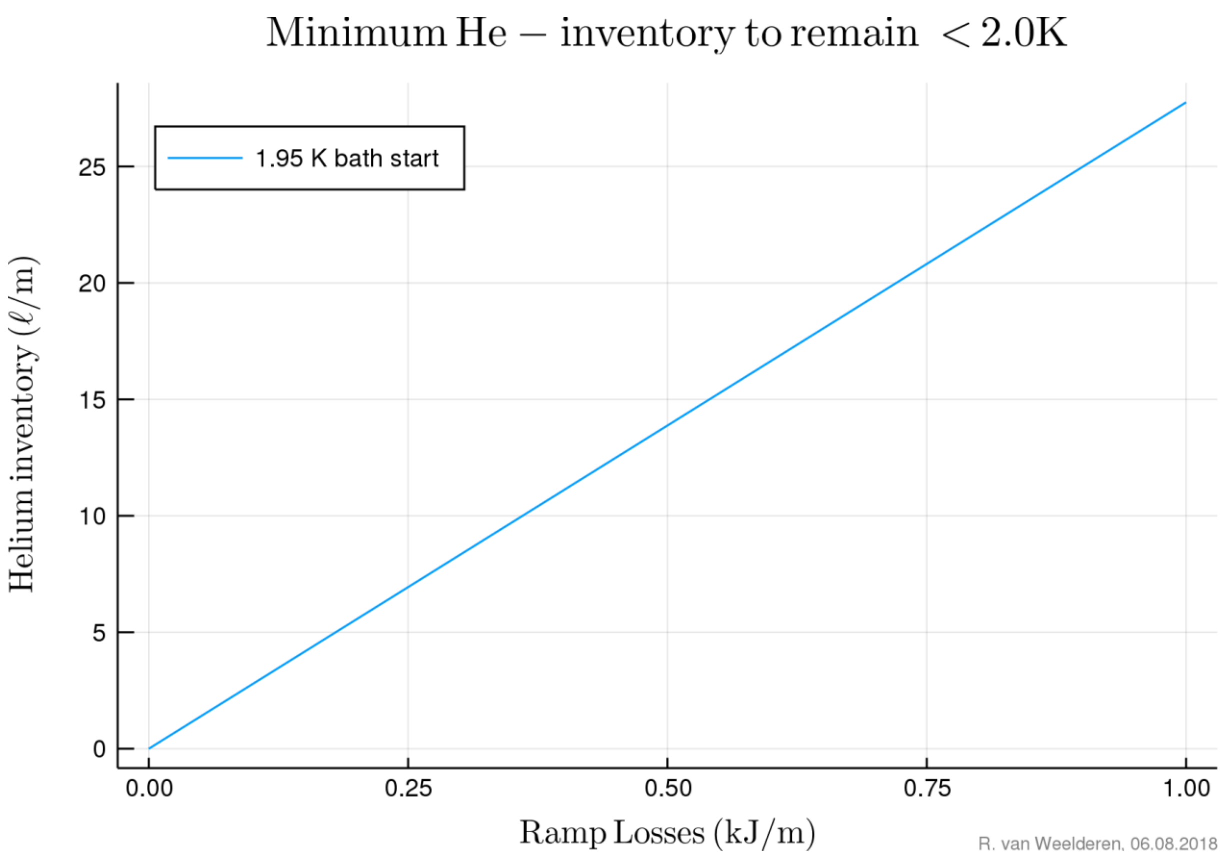
Courtesy Susanna Izquierido Bermudez



Cryogenic assessment summary

Continuous cooling power available for 11 T – dipole: 60 W
Heat extraction limit from coil area : 50 W
CFD assessment of T_{margin} at 50 mW/cm^3 : 3.0 K
50 mK temporary heat absorbtion (1.95 -> 2.0 K) for : < 0.8 kJ/m (at 25 ℓ/m helium)

Updated graph 17.09.2018



Implications for proposed Beam-Lifetime scenarios

Detailed data for cryogenics analysis

All the following plots and provided data are for:

- TCLD and 11T replacing **MBB.B8** (IR7)
- The **most exposed 11T** out of the two modules: downstream from TCLD

Beam LifeTime (BLT) of 1 h is just a rescaling of the 0.2h BLT results (0.2h results divided by 5).

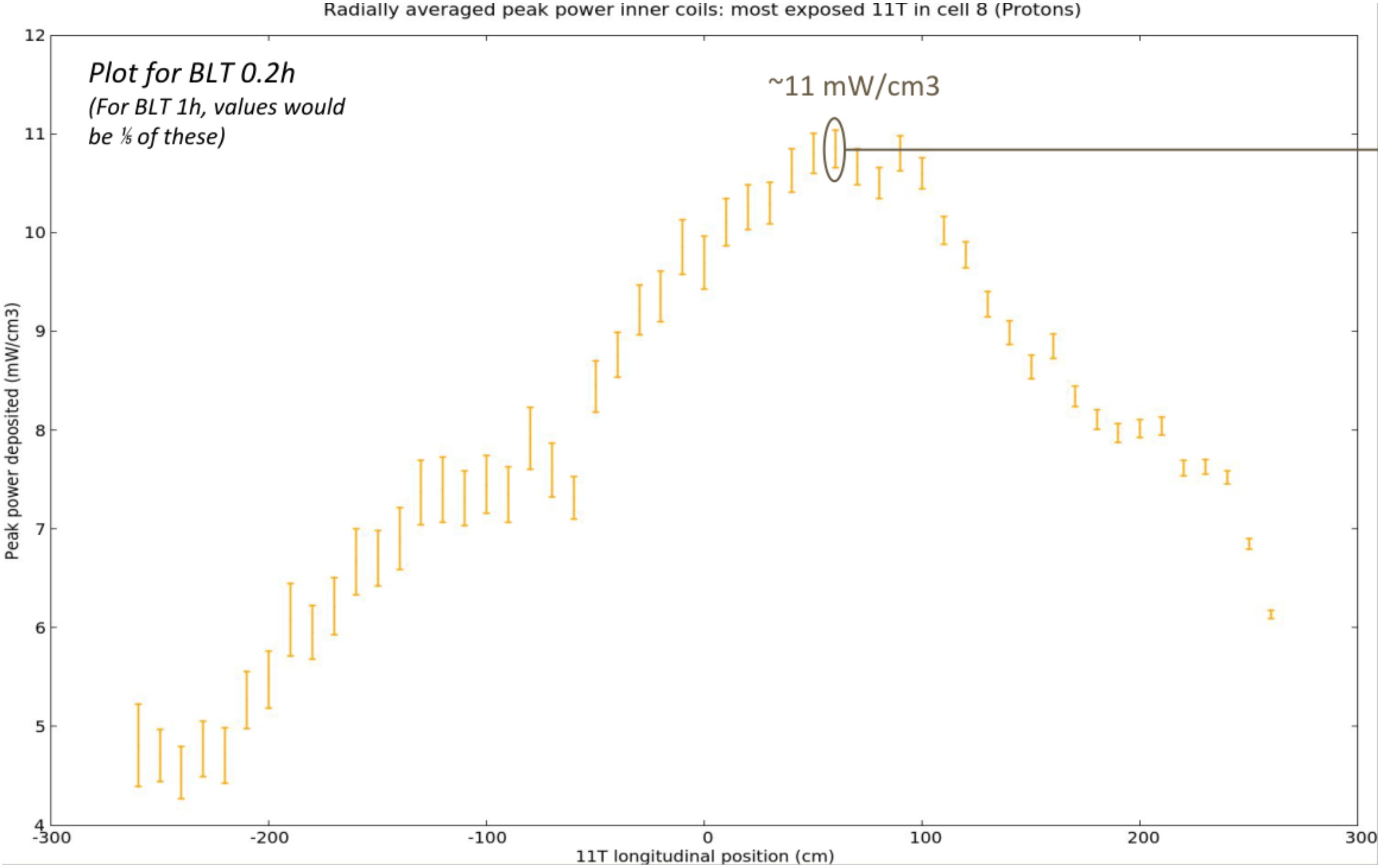
BLT of 0.2 hours, considers: Ions: 1248 bunches 2.1e8 ions/bunch. **Protons**: 2760b 2.3e11 p / bunch

Previous benchmarks showed a **factor 3** underestimation in DS with respect to BLM measurements: **this factor is already accounted for in the data**.

21/06/18 C. Bahamonde - WP 11 Technical machine interfaces working group 1

Courtesy Cristina Bahamonde Castro

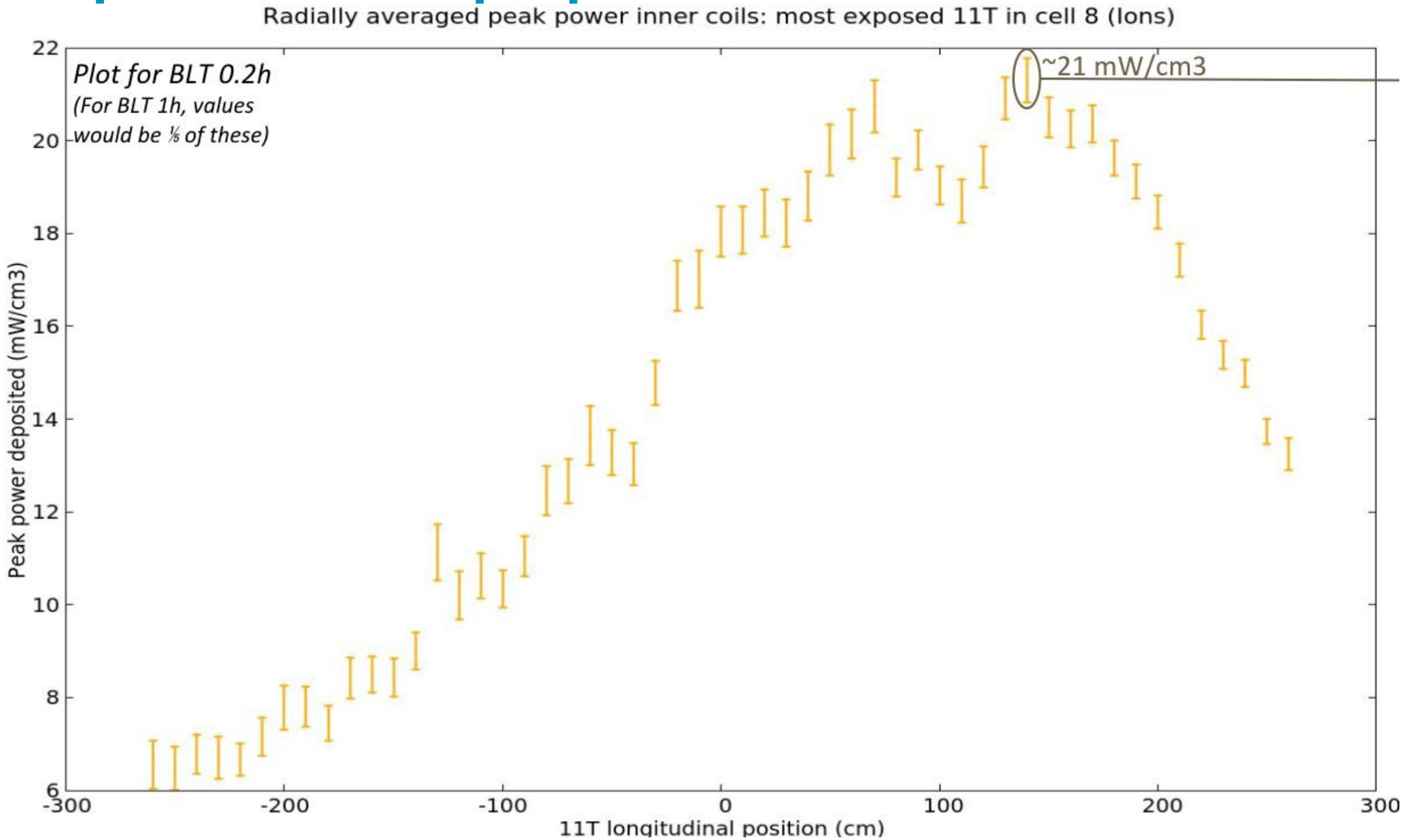
Implications for proposed Beam-Lifetime scenarios



Courtesy Cristina Bahamonde Castro

Protons: 11 mW/cm^3 keeps > 3.6 K temperature margin according to CFD-model

Implications for proposed Beam-Lifetime scenarios



Courtesy Cristina Bahamonde Castro

Ions: 21 mW/cm^3 keeps > 3.6 K temperature margin according to CFD-model

Implications for proposed Beam-Lifetime scenarios

Heat load to the cold mass part by part

Heat load to the cold mass for HL-LHC most exposed 11T of cell 8 (W)				
	PROTONS		IONS	
	BLT (12 min)	*BLT (1 h)*	*BLT (12 min)*	*BLT (1 h)*
Coils (return coils included)	54	11	98	20
Yoke	44	9	85	17
Collars	32	6	62	12
Spacers (between coils)	11	2	23	5
Vacuum vessel	4	1	7	1
Beam pipe	4	1	7	1
Shrinking cylinder	2	0.4	4	1
Other parts	19	4	44	9
TOTAL	**170**	**34**	**330**	**66**

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→ Protons: coil + beam-pipe 12 W (BLT 1h) , total 34 W
Ions…..: coil + beam-pipe 21 W (BLT 1h), total 66 W

Implications for proposed Beam-Lifetime scenarios (MBB.B8)

Baseline

Continuous cooling ←→ Blt 1h

	Peak power (mW/cm³)	coil + beam-pipe (W)	Total (W)	comment
Protons	2	12	34	&
Ions	4	21	66	Total power ~ 60 W, doable

Helium buffer ←→ Blt 12 min

	Peak power (mW/cm³)	coil + beam-pipe (W)	Total (W)	10 s Energy (kJ)/(kJ/m)	comment
Protons	11	58	170	1.7 / 0.3	Power to coil > 50 W, T-drift
Ions	21	105	330	3.3 / 0.6	Power to coil >> 50 W, T-drift

Implications for proposed Beam-Lifetime scenarios (MBA.9)

Non-Baseline!

Continuous cooling ←→ Blt 1h

	Peak power (mW/cm^3)	coil + beam-pipe (W)	Total (W)	comment
Protons	10	≈ 20	60	& - but on the limit
Ions	7	≈ 43	130	X - Total power >> 60 W

Helium buffer ←→ Blt 12 min

	Peak power (mW/cm^3)	coil + beam-pipe (W)	Total (W)	10 s Energy (kJ)/(kJ/m)	comment
Protons	48	≈ 100	300	3.0 / 0.5	Power to coil >> 50 W, Critical
Ions	33	≈ 210	630	6.3 / 1.1	Power to coil >> 50 W, Critical

Summary

Cryogenics:

Continuous cooling power available for 11 T – dipole: 60 W
Heat extraction limit from coil area : 50 W
CFD assessment of T_{margin} at 50 mW/cm^3 : 3.0 K
50 mK temporary heat absorbtion (1.95 -> 2.0 K) for : < 0.8 kJ/m (at 25 ℓ/m helium)

Baseline beam-loss scenario (MBB.B8):

Proton run: &, but to limit T-runaway for 12 min BLT, consider dump at t < 5 s instead of 10 s
ION run…: 1h BLT (66 W) doable, 12 min BLT, T runaway expected (to be quantified), consider dump at t < 5 s instead of 10 s

→propose power limit test in LHC

Extra:

Non-baseline beam-loss scenario (MBA.9):

Proton run: & 1h BLT, but on the limit of 60 W, Critical12 min BLT T runaway expected (to be quantified)
Total power for ION run/ 1h BLT (130 W) **X**, largely above power limit