Cooling performance of the HL-LHC cells affected by the TCLD and 11T-dipole including thermal assessment of 11T coil

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+ multiple inputs from the Fluka & Collimation teams

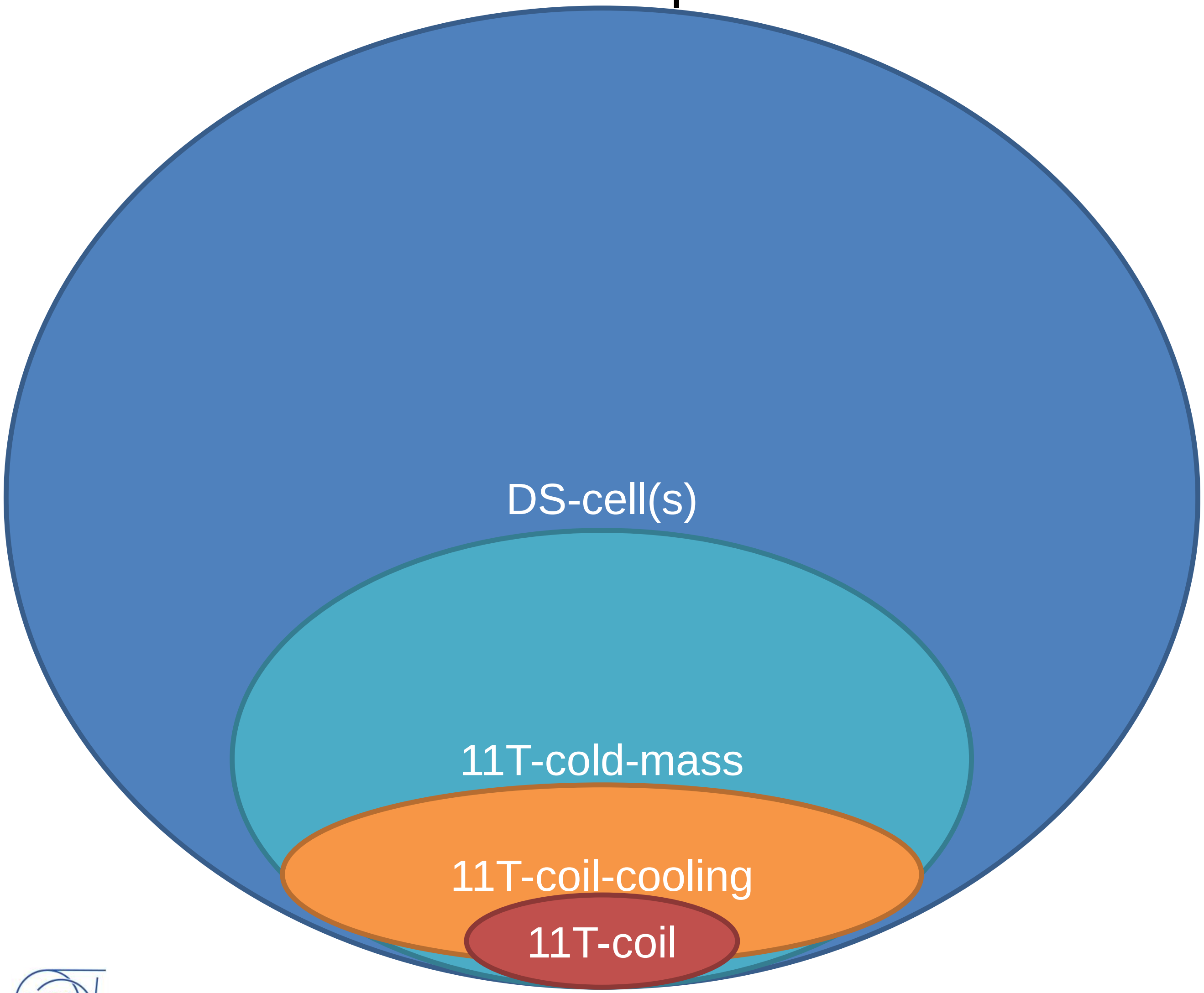
HL-LHC Collaboration Meeting 2018

Overview

- Intro
- 11 T dipole steady-state cooling limits
  - Coil + beam-pipe
  - Cold-mass
- 11 T dipole thermal quench limit
- Nb_3Sn stack measurements
- DS – cryogenic hardware steady-state cooling limits
- Implications for proposed Beam-Lifetime scenarios
- Summary of implications for proposed Beam-Lifetime scenarios

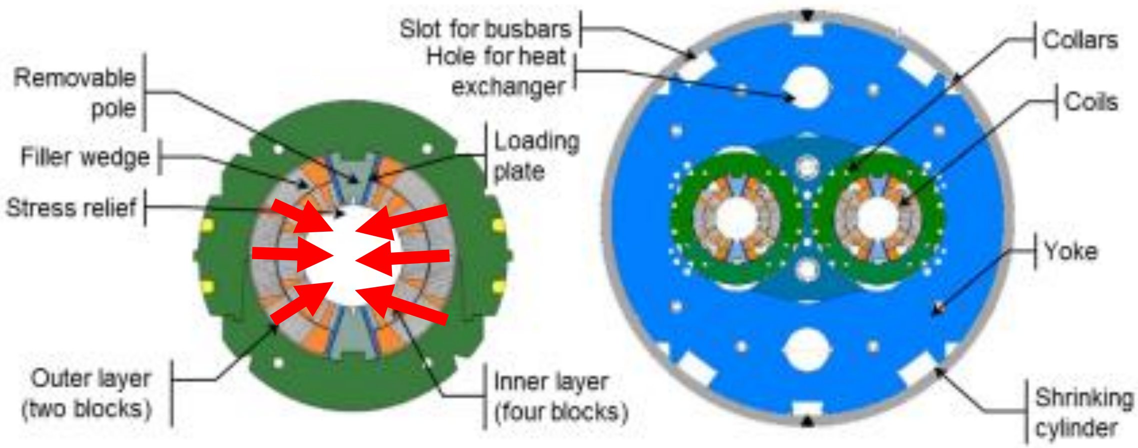
Intro

Assesment on various scales of the thermal load withstand-levels of the 11T-dipole and the DS-cells

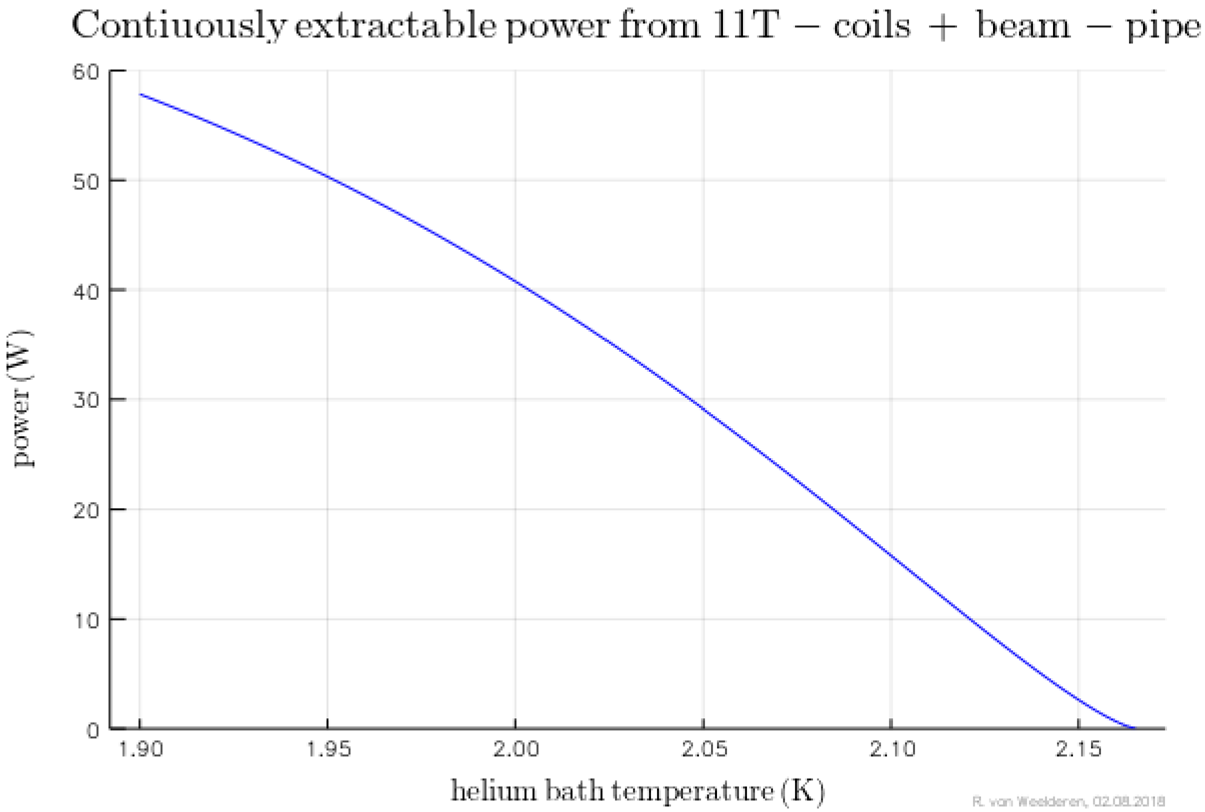


11 T dipole steady state as function of power: 1) « static coil + beam-pipe cooling limits »

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



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



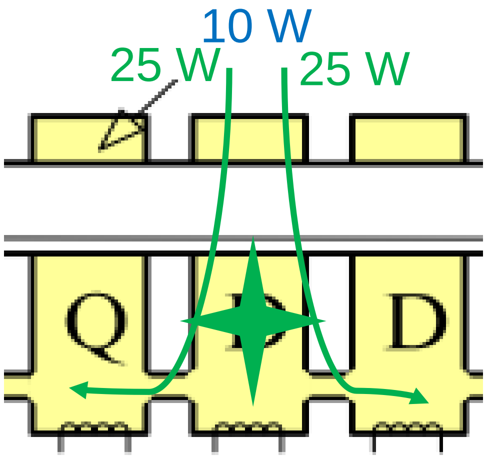
Without radial cooling channels the total continuous extraction capacity limit from the coil area ranges from ≈ [50 W @1.95 K -15 W @2.10 K]

(both apertures combined)

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 within limited ΔT.



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

Precise profile to be evaluated with detailed model

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

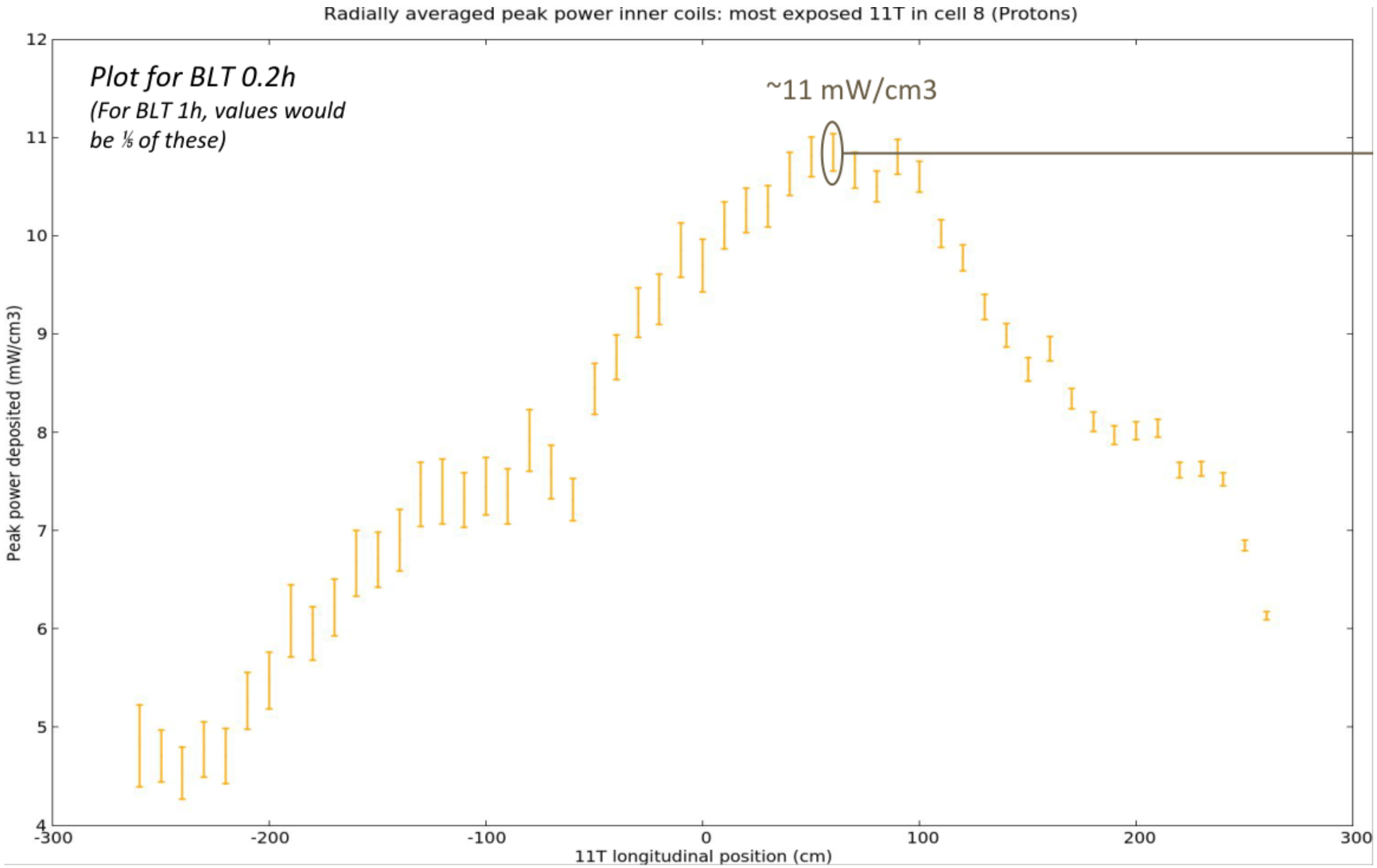
Beam LifeTime (BLT) of 1 h is just a rescaling of the 0.2h BLT results (0.2h results divided by 5).

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**.

Courtesy Cristina Bahamonde Castro

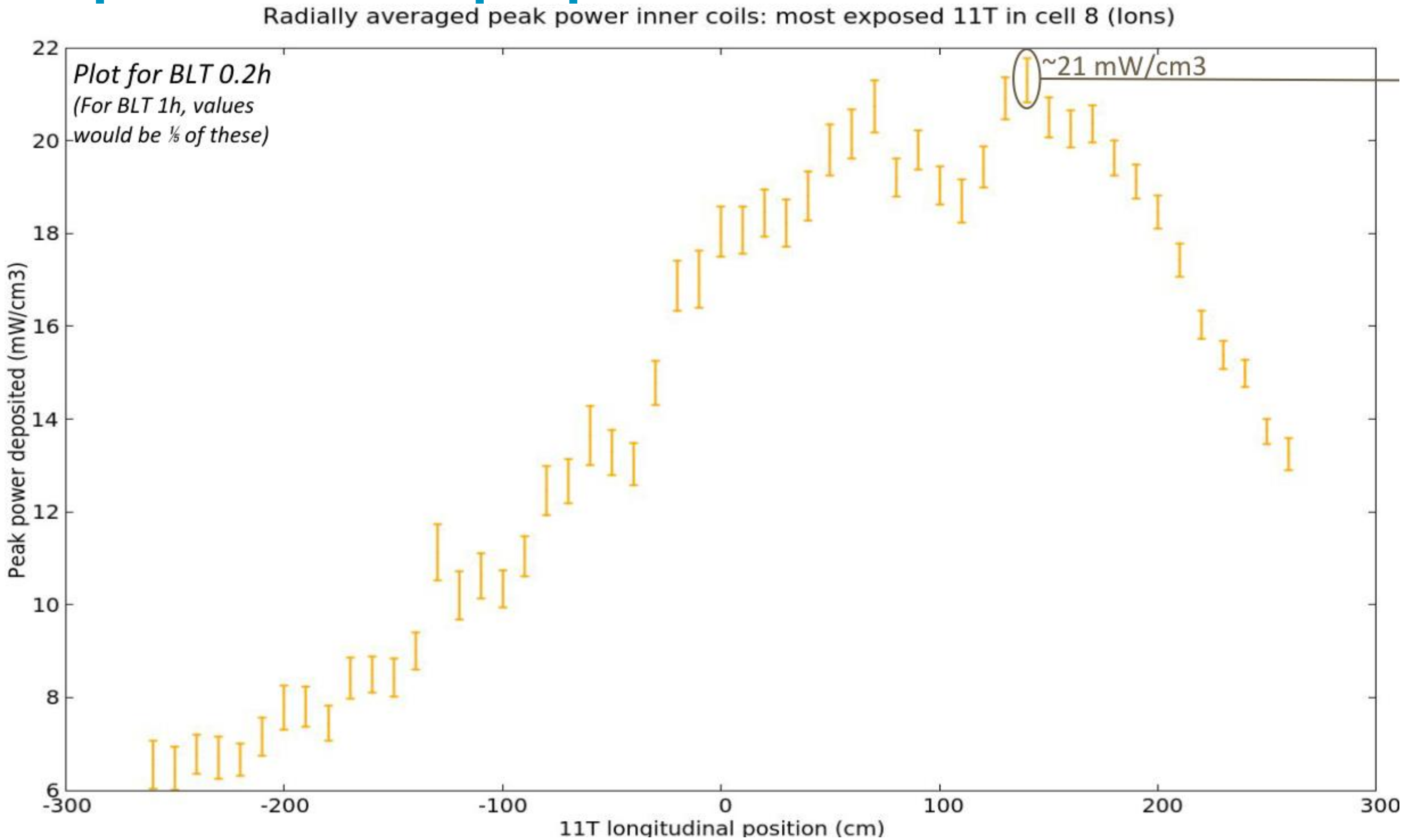
Implications for proposed Beam-Lifetime scenarios



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**

C. Bahamonde - WP 11 Technical machine interfaces working group 2

Courtesy Cristina Bahamonde Castro

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

11T dipole specific summary for proposed beam-Lifetime scenarios (MBB.B8)

Continuous cooling ←→ Blt 1h

	Peak power (mW/cm³)	11T: coil + beam-pipe (W)	11T total (W)	comment
Protons	2	12	34	& (< 50 mW/cm³ and < 41 W, total < 60 W)
Ions	4	21	66	& (< 50 mW/cm³ and < 41 W total close to 60 W)

For the 1h Blt the 11T dipole thermal design is sufficient

11T dipole specific summary for proposed beam-Lifetime scenarios (MBB.B8)

Transient cooling ←→ Blt 12min

	Peak power (mW/cm^3)	**11T: coil + beam-pipe (W)**	**11T total (W)**	**10 s Energy (kJ)/(kJ/m)**	**comment**
Protons	11	58	170	1.7/0.3	< 50 mW/cm^3 **coil > 40 W, total > 60 W**
Ions	21	105	330	3.3/0.6	< 50 mW/cm^3 **coil > 40 W, total > 60 W**

For the 12min Blt the 11T dipole thermal design is ok for peak power on coil - but overall temperature will drift during transient (slide 31)

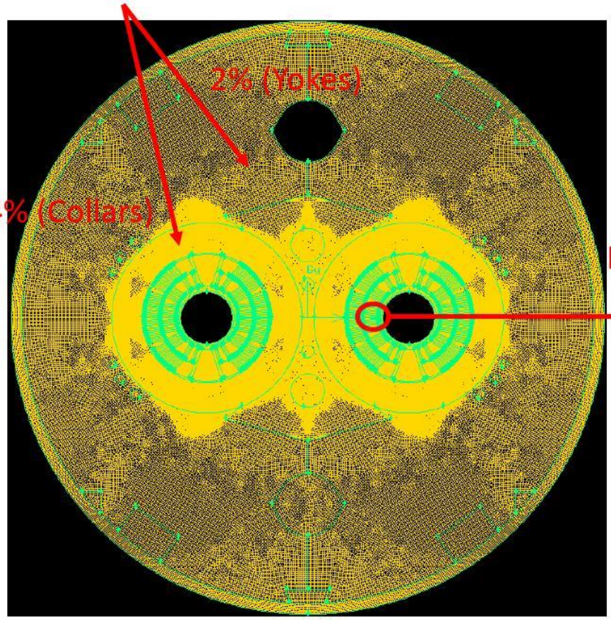
11 T dipole thermal quench limit

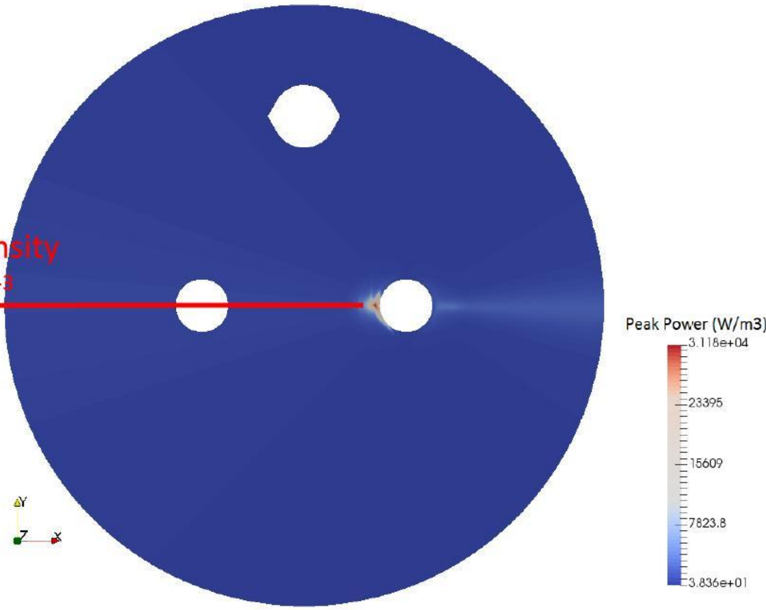
The thermal quench limits as function of locally deposited power are assessed via:

1) Computational Fluid Dynamics of coil-section using inputs from (2) + material data
2) Thermal characterization of cut-out coil stack-sample in cryolab-test stand

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

11-Tesla Dipole





Mesh Quality:

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

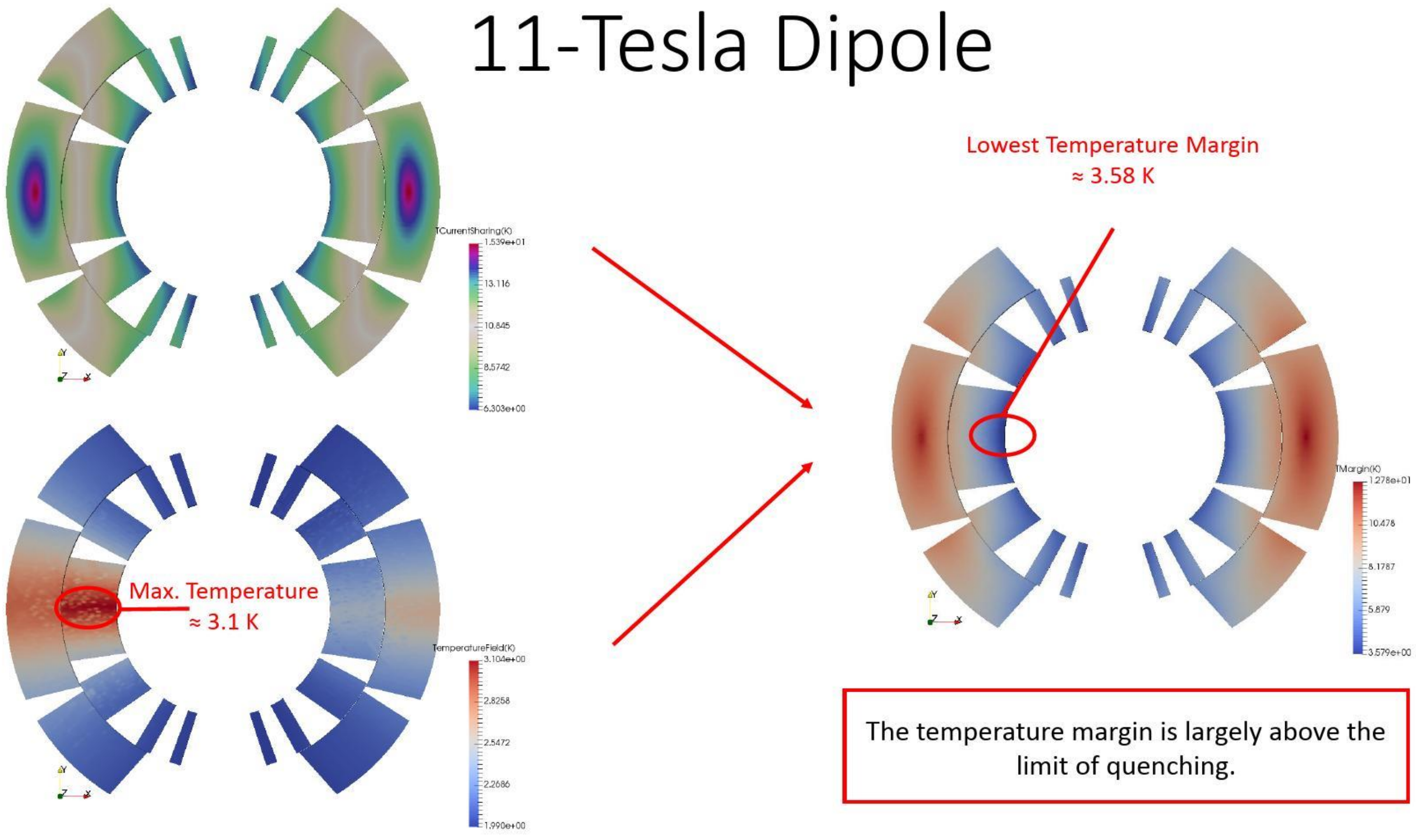
Boundary Conditions:

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*)



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 can take high heating loads.

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

Whether the loads can be sustained over large cold-mass volumes and multiple magnets and as function of time depends on the previous DS cooling capacity assessment for Proton and Ion runs respectively

Complementary validation is ongoing with Cryolab stack-measurements analysis

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

Nb_3Sn stack measurements

Experimental setup

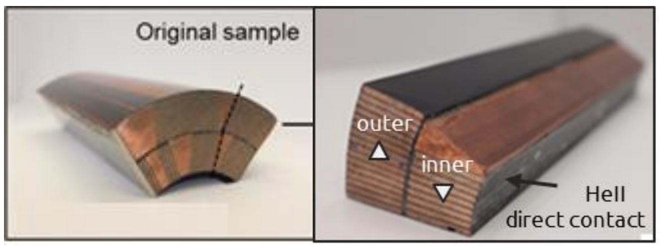
Exploiting different AC loss mechanisms the sample is heated and the temperature evolution in sample and bath is measured.

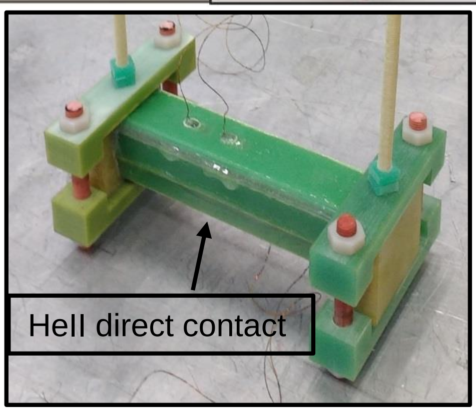
The generated power can be varied by changing the combination of the resistor box.

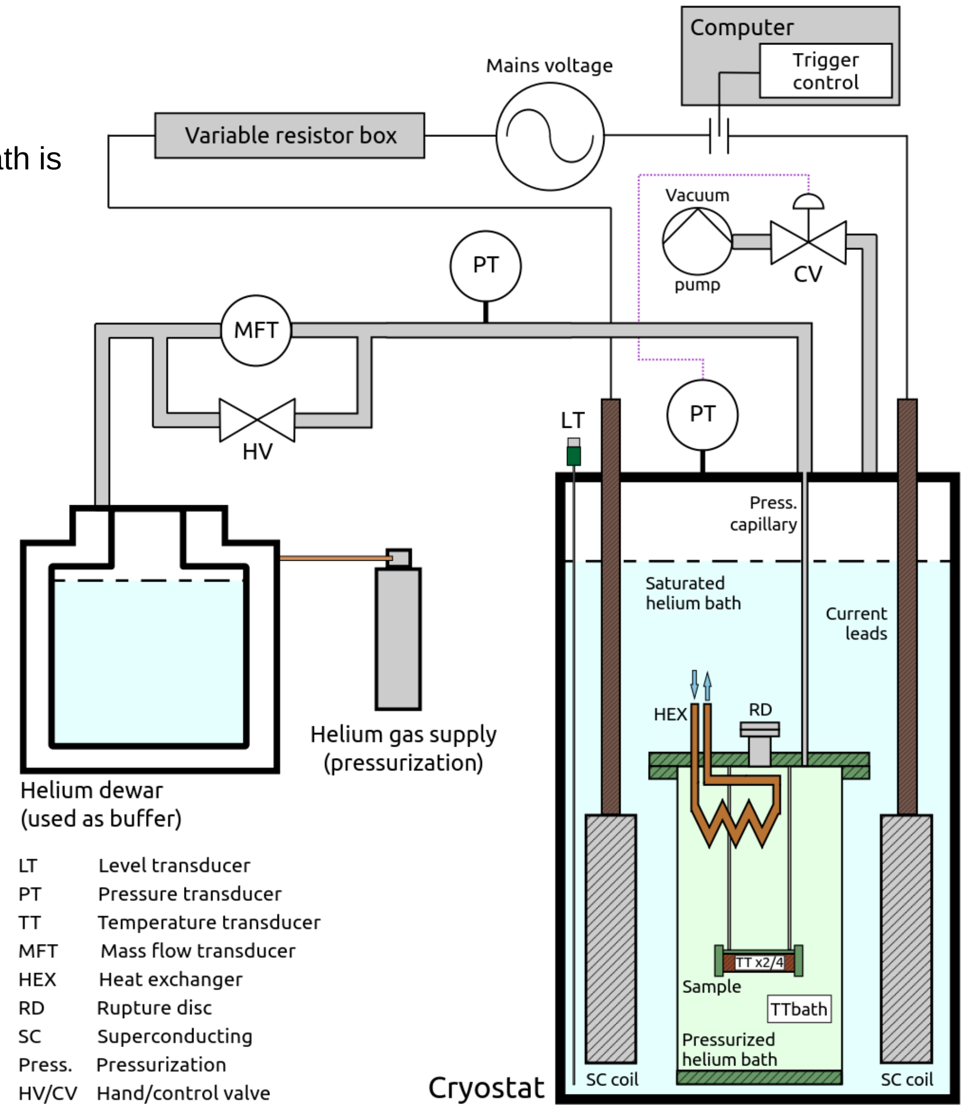
Important parameters:

T_{eq} : equilibrium temperature

τ : time constant (time to reach 63.2 % of peak temperature)

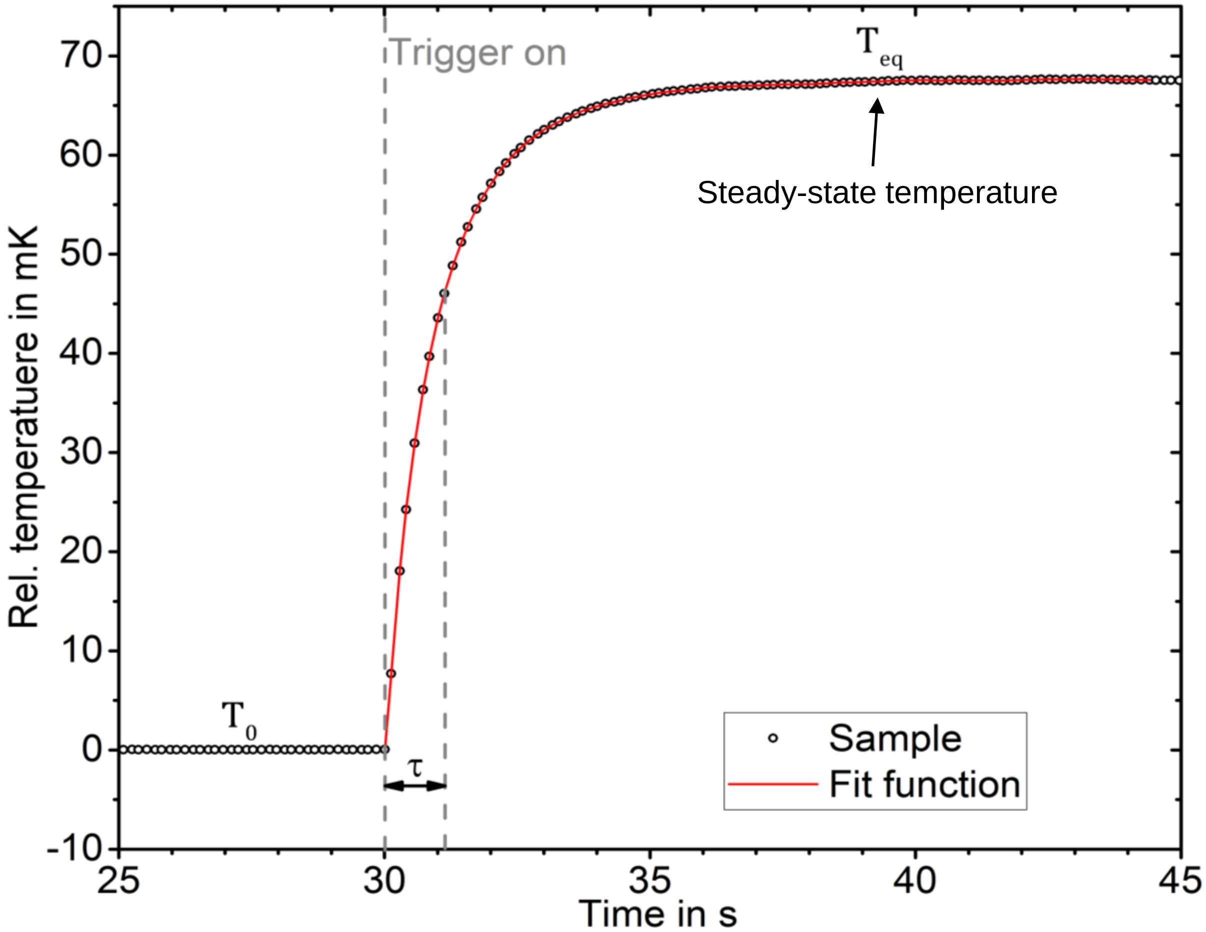




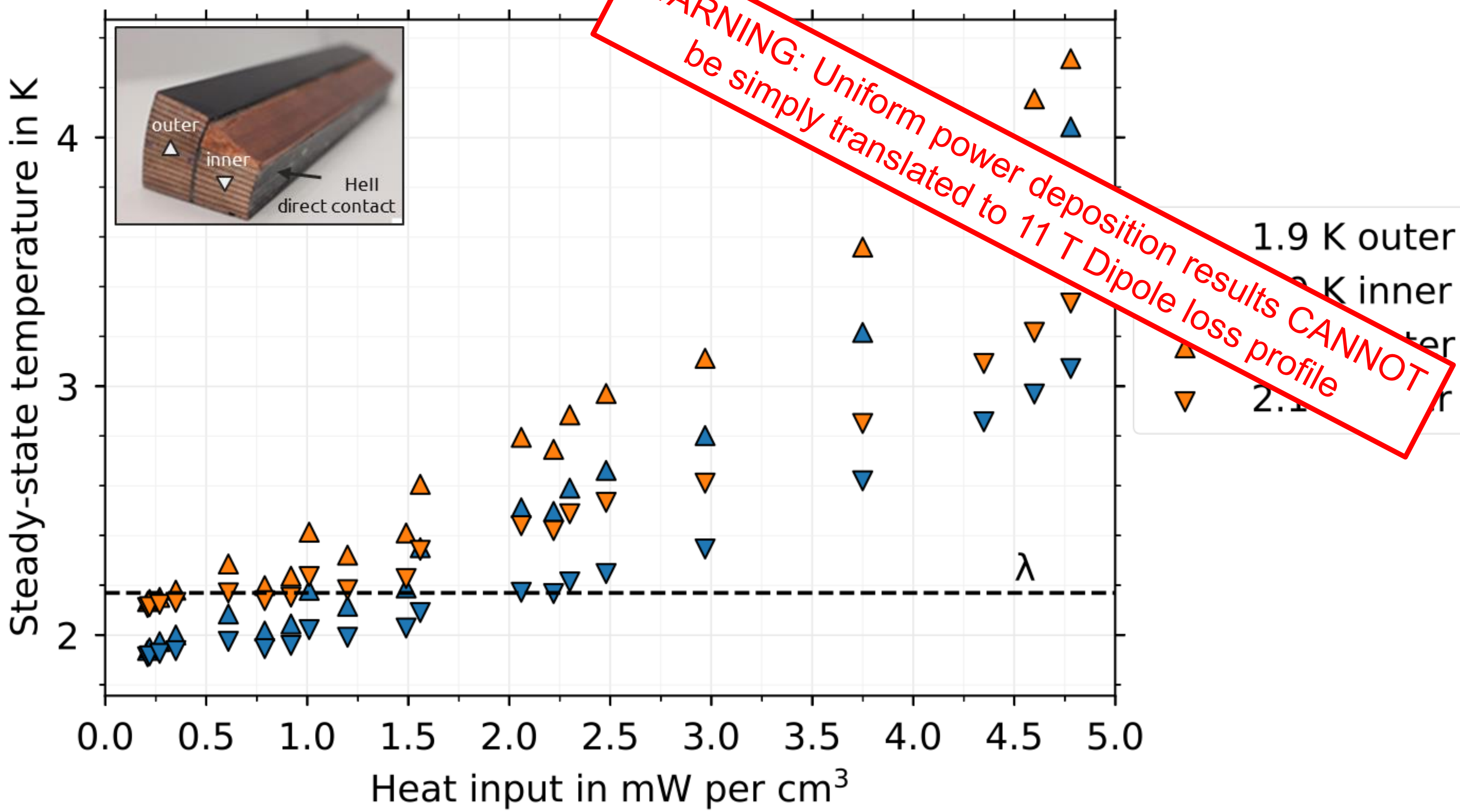


Nb_3Sn stack measurements

Typical measurement curve



Nb_3Sn stack measurements

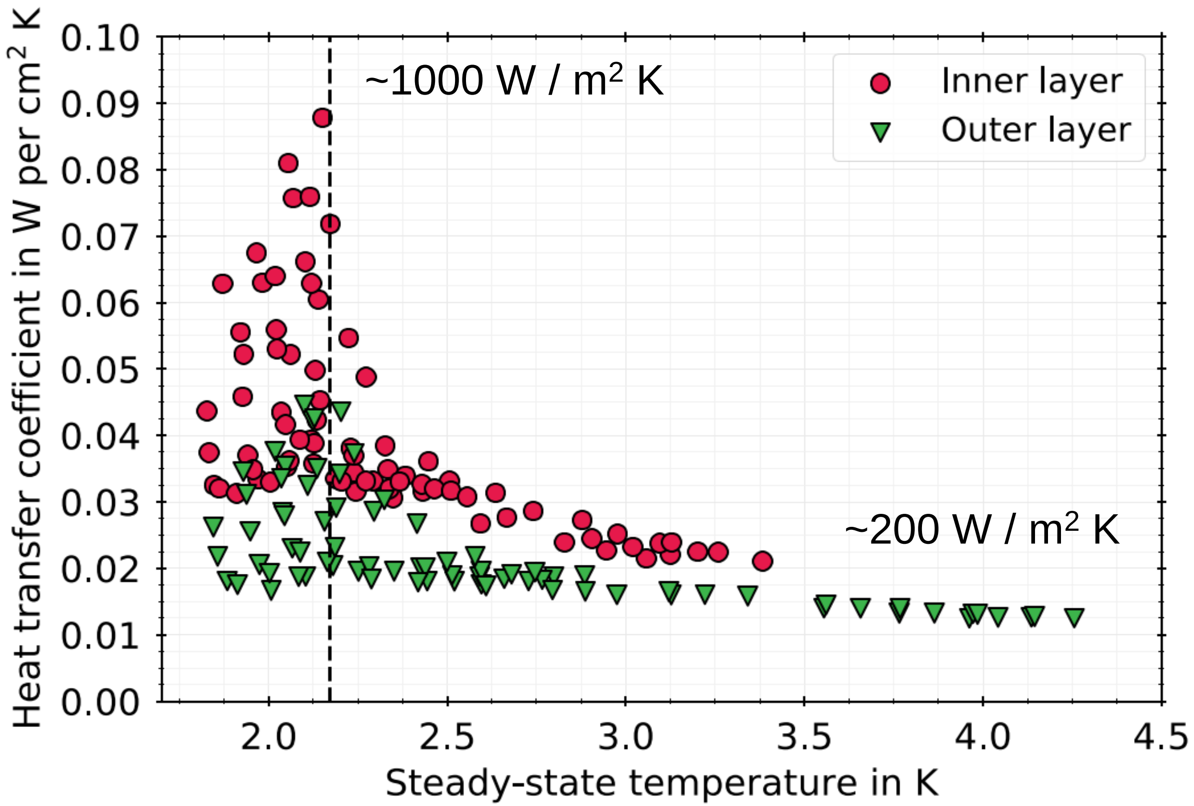


WARNING: Uniform power deposition results CANNOT be simply translated to 11 T Dipole loss profile

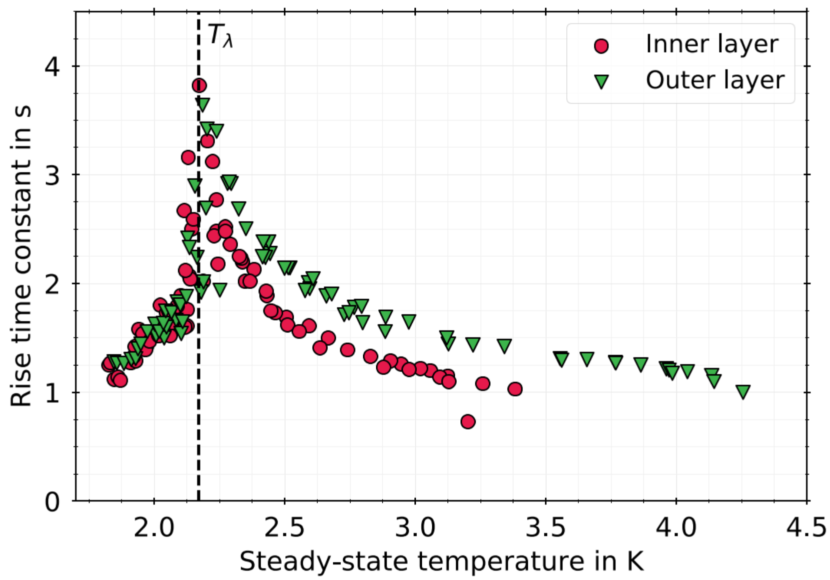
Nb_3Sn stack measurements

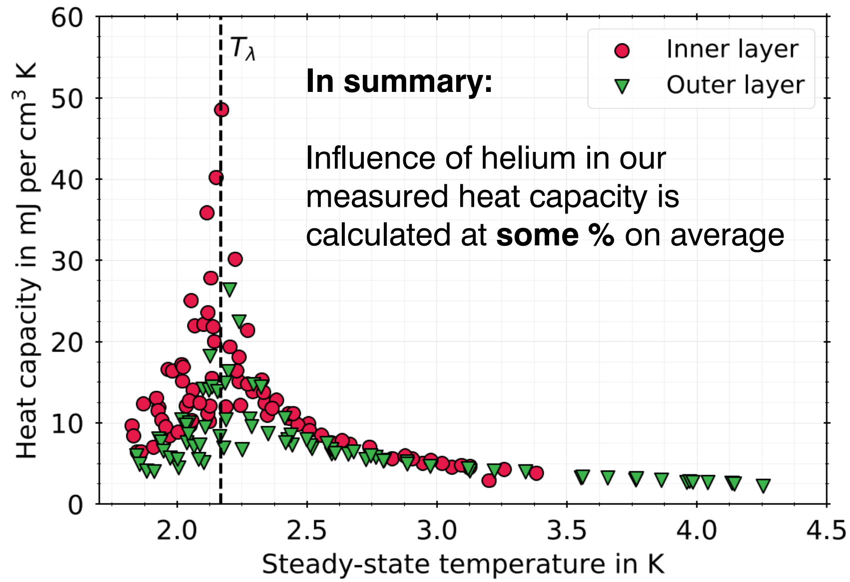
Converted into a classical heat transfer coefficient by taking the inner layer surface area exposed to He II.

- Above T_λ, it relaxes to ~200 W / m^2 K.
- Below, heat transfer is enhanced by presence of He II: calculated to the order of **some %**



Nb_3Sn stack measurements





In summary:

Influence of helium in our measured heat capacity is calculated at **some %** on average

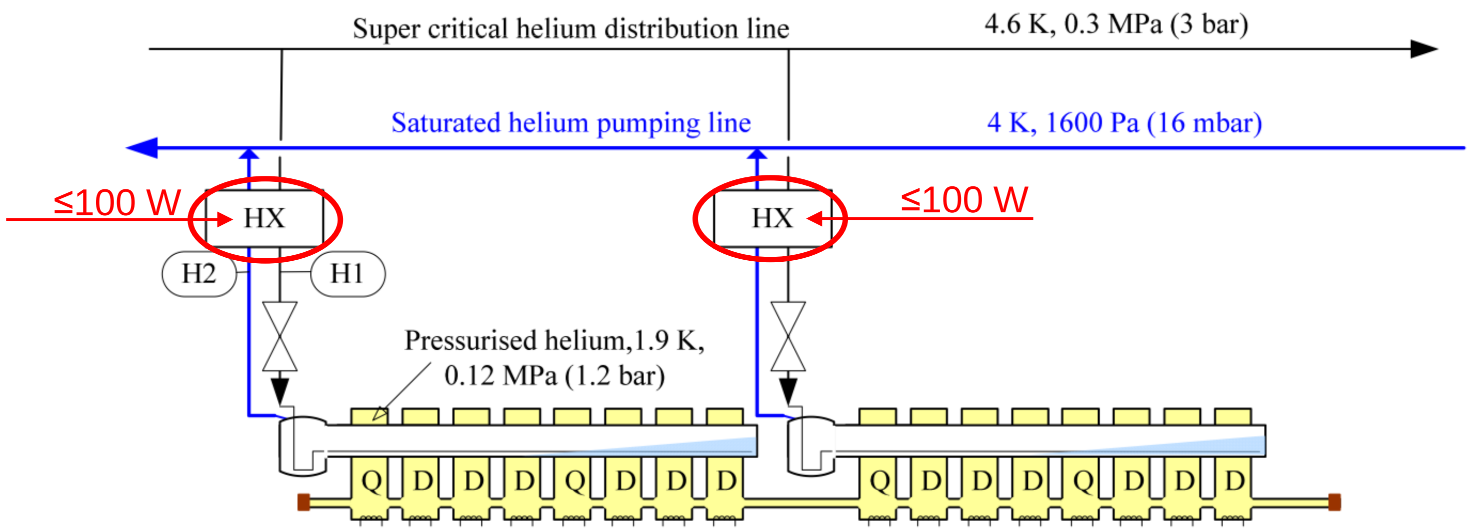
- τ seems to have a lower boundary at ~ 1 second
- Very strong peak at the λ temperature
- τ can be related to heat capacity by: $$\tau = RC = \frac{C}{\Lambda} = C_v \frac{\Delta T}{\dot{q}}$$
- τ is then proportional to volumetric heat capacity
- What volume fraction of helium is needed in the sample to have this heat capacity? (note: it is an approximation)

Nb_3Sn stack measurements

Conclusions and outlook

- Measurements of superconducting cable stacks directly from MSC production are possible
  - Absolute values shown cannot simply be translated to the 11 T collimation loss profile
  - Steady-state temperatures, as well as response times, are measured up to a UNIFORM power deposition of 5 mW per cm^3, whereas collimation-induced power distribution is a narrow cone, within a limited area.
- Steady-state results are consistent with other assessments (see L. Bottura's talk)
- Possible indication of small LHe presence in the cable
- Experiment currently being used to validate details of the 11 T Dipole magnet simulation model (Kirtana Puthran, ongoing work)

DS - cryo hardware steady-state cooling limits

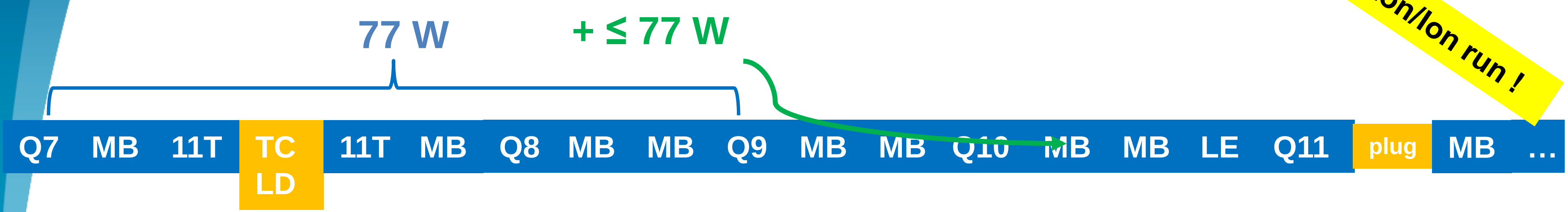


Generically LHC-cell (107 m) cooling-power provided by the collective performance of:

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. Every 2nd LHC-cell, cooling echange between cells is blocked by hydraulic restrictions → *214 m collective cooling*

DS - cryo hardware steady-state cooling limits

Proton/Ion run !



Proton & Ion runs	**½-Cell 8+9 (W)**	**Redundancy - ½ -Cells 10+11 (W)**
static + splices (0.25 W/m *)	23	23
beam-gas (0.0 W/m *)	0	0
Total (0.25 W/m)	23	23
Available for collimation	**77**	**≤ 77** (some loss due to conduction to be expected)

- *Loss data from CERN-ATS-2010-016*
- *considering beam-gas based on present LHC vacuum (factor 200 lower than TDR)*

→ Cells 8&9 have **77 W** available for collimation loads, *all magnets combined!*
→ Some extra load **≤ 77 W** could be taken via conduction through the neighbouring cell-10&11 cooling, if all loads would be < 200 W total (see later on).

DS - cryo hardware steady-state cooling limits

- LHC operating experience puts the DS-helium temperatures ≤ 1.95 K

- → *We aim to keep the 11T helium at 1.95 K*
- → *This is only possible for total loads not exceeding the 2x100 W limit of neighbouring cooling-loops*
- →The exceptions are high short – time losses when the helium temperature will drift as the heat gets absorbed.

DS - cryo hardware steady-state cooling limits

Proton run !

*Loss data (in red) Fluka team, **1h** beam life time*

23 W + 42 W + 20 W = 85 W

23 W + 2 W + (63-70) W = 88 – 95 W

Q7	MB	11T	TC LD	11T	MB	Q8	MB	MB	Q9	MB	MB	Q10	MB	MB	LE	Q11	plug	MB	…
	4W	1.4W		34W	1W	1.4W	<----- 20W ---->			<------- 2W -------->			12W	31W	17W	3-10W			

Total loads are < 200 W →
Cryo-infrastructure can maintain this in steady state!

DS - cryo hardware steady-state cooling limits

Proton run !

*Loss data (in red) Fluka team, **12min** life time*

23 W + 210 W + 100 W = 333 W

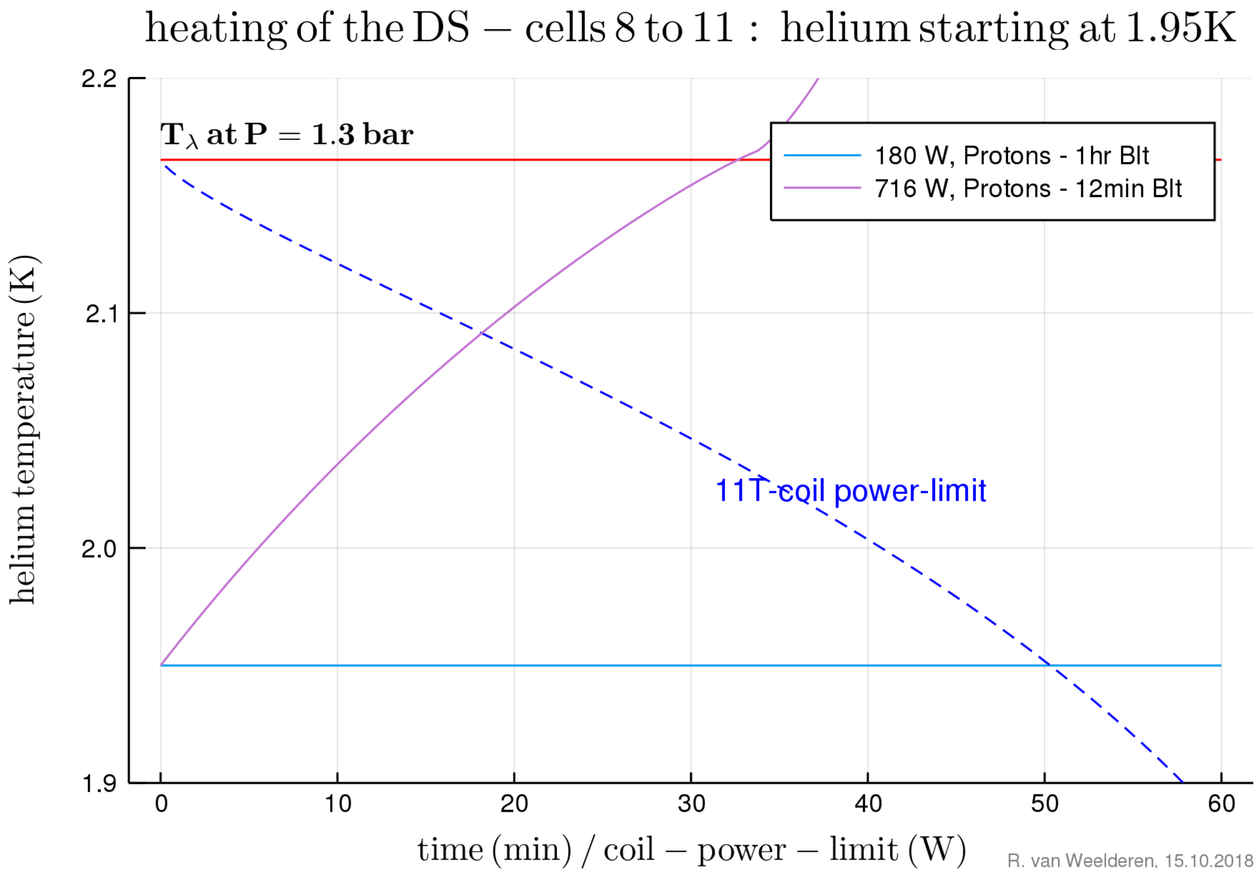
23 W + 10 W + (315-350) W = 348 – 383 W

Q7	MB	11T	TC LD	11T	MB	Q8	MB	MB	Q9	MB	MB	Q10	MB	MB	LE	Q11	plug	MB	…
	21W	7W		170W	5W	2.4W	<----- 20W ---->			<------- 2W -------->			12W	31W	17W	3-10W			

Total loads are >> 200 W →
Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!

DS - cryo hardware steady-state cooling limits



Protons (1hr Blt) : The **12 W** which need to be extracted from the coil+beam-pipe area can be sustained continuously

Protons (12min Blt) : The **58 W** which need to be extracted from the coil+beam-pipe area **cannot be taken by the helium at 1.95 K → Adiabatic T-rise of coil** (to be evaluated), The DS cooling would fail after ~ 33 min (power considered constant)

DS - cryo hardware steady-state cooling limits

Ion run !

*Loss data Fluka team, **1h** life-time*

23 W + 70 W + 27 W = 120 W

23 W + 4 W + (135-150) W = 162 – 177 W

Q7 MB 11T TCLD 11T MB Q8 MB MB Q9 MB MB Q10 MB MB LE Q11 plug MB …

0.16W 0.4W 65W 1.6W 3W <----- 27W ----> <------- 4W --------> 32W 72W 23W 8-24W

Total loads are > 200 W →
Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!

DS - cryo hardware steady-state cooling limits

Ion run !

*Loss data Fluka team, **12min** life-time*

23 W + 350 W + 135 W = 508 W

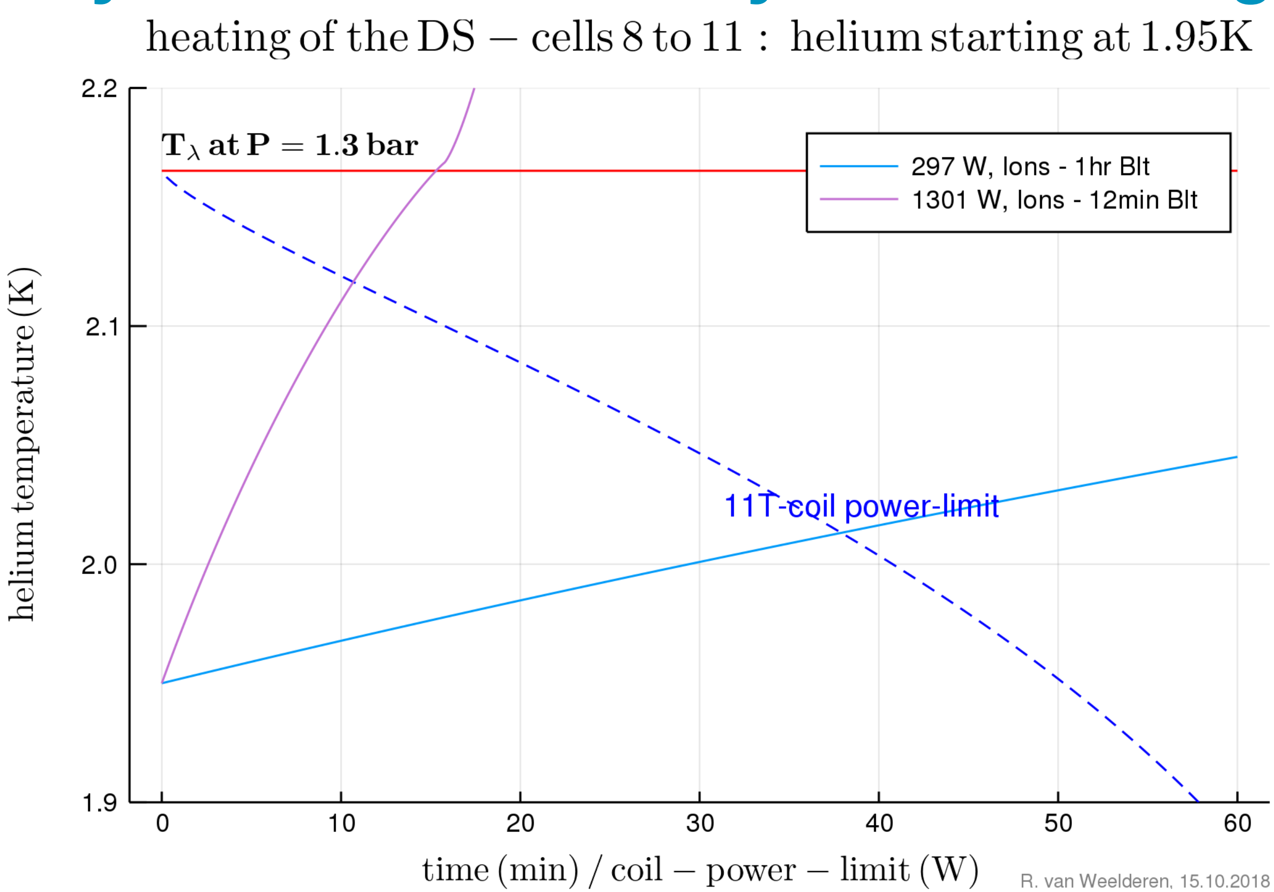
23 W + 20 W + (675-750) W = 718 – 793 W

Q7	MB	11T	TC LD	11T	MB	Q8	MB	MB	Q9	MB	MB	Q10	MB	MB	LE	Q11	plug	MB	…
	0.8W	2W		325W	8W	15W	<----- 135W ---->			<------- 20W ------->			160W	360W	115W	40-120W			

Total loads are >> 200 W →
Cryo-infrastructure cannot maintain this in steady state!

The heat capacity of the DS-helium content will be engaged!

DS - cryo hardware steady-state cooling limits



Ions (1hr Blt): The **21 W** which need to be extracted from the coil+beam-pipe area is reached after ~ 90 min (power considered constant)

Ions (12min Blt): The **105 W** which need to be extracted from the coil+beam-pipe area **cannot be taken by the helium at 1.95 K → Adiabatic T-rise of coil** (to be evaluated), The DS cooling would fail after ~ 16 min (power considered constant)

Summary of implications for proposed Beam-Lifetime scenarios

<u>Cryogenic-limitations of DS cells cooling:</u>

1hr *Blt:* ***cooling of 11-T-dipole ok for Protons and for Ions***
1hr *Blt:* ***cooling of cells 8, 9, 10 & 11 ok for Protons***

12min *Blt: helium cooling not sufficient in the long term*
→ adiabatic T-rise of 11-T-dipole coil (to be evaluated)

<u>Thermal assessment of 11T-dipole T-margin:</u>

CFD assessment indicates that locally the 11T dipole coil is can take high heating loads.

Thermal measurements of production-source Nb_3Sn coil-stacks are giving consistent results (see Luca Bottura's talk), but reveal a possible presence of helium inside the coil-stack.