Reference situation of cooling capabilities for 11T and implications for eventual modification (needs and impact)

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+ multiple inputs from the Fluka
& Collimation teams

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Overview

- Intro
- 11 T dipole thermal quench limit
- 11 T dipole steady-state cooling limits
  - Coil + beam-pipe
  - Cold-mass
- DS – cryogenic hardware steady-state cooling limits
- Cryogenic assessment summary
- Implications for proposed Beam-Lifetime scenarios
- Summary

Intro

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

DS-cell(s)

11T-cold-mass

11T-coil-cooling

11T-coil
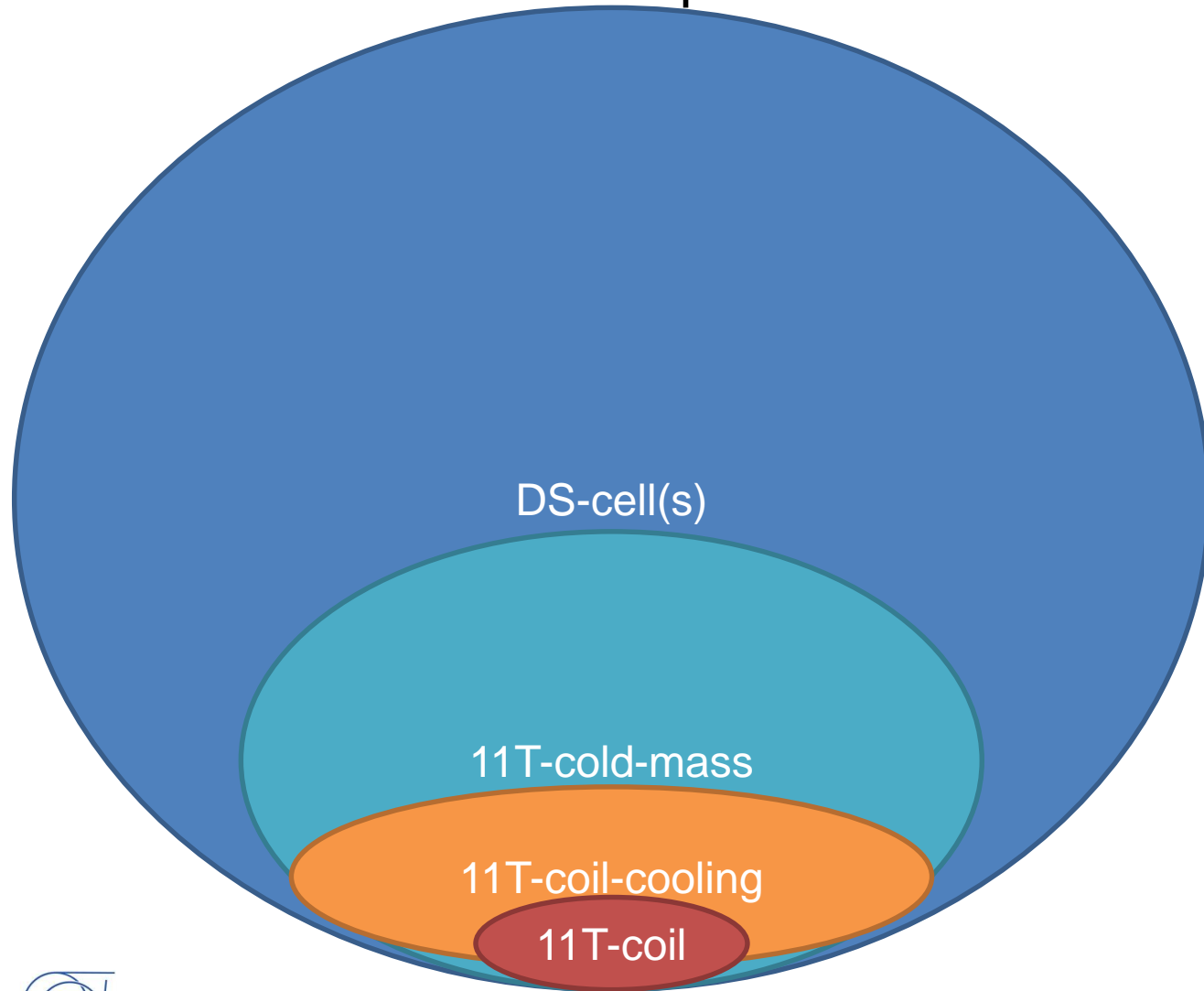
11 T dipole thermal quench limit

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

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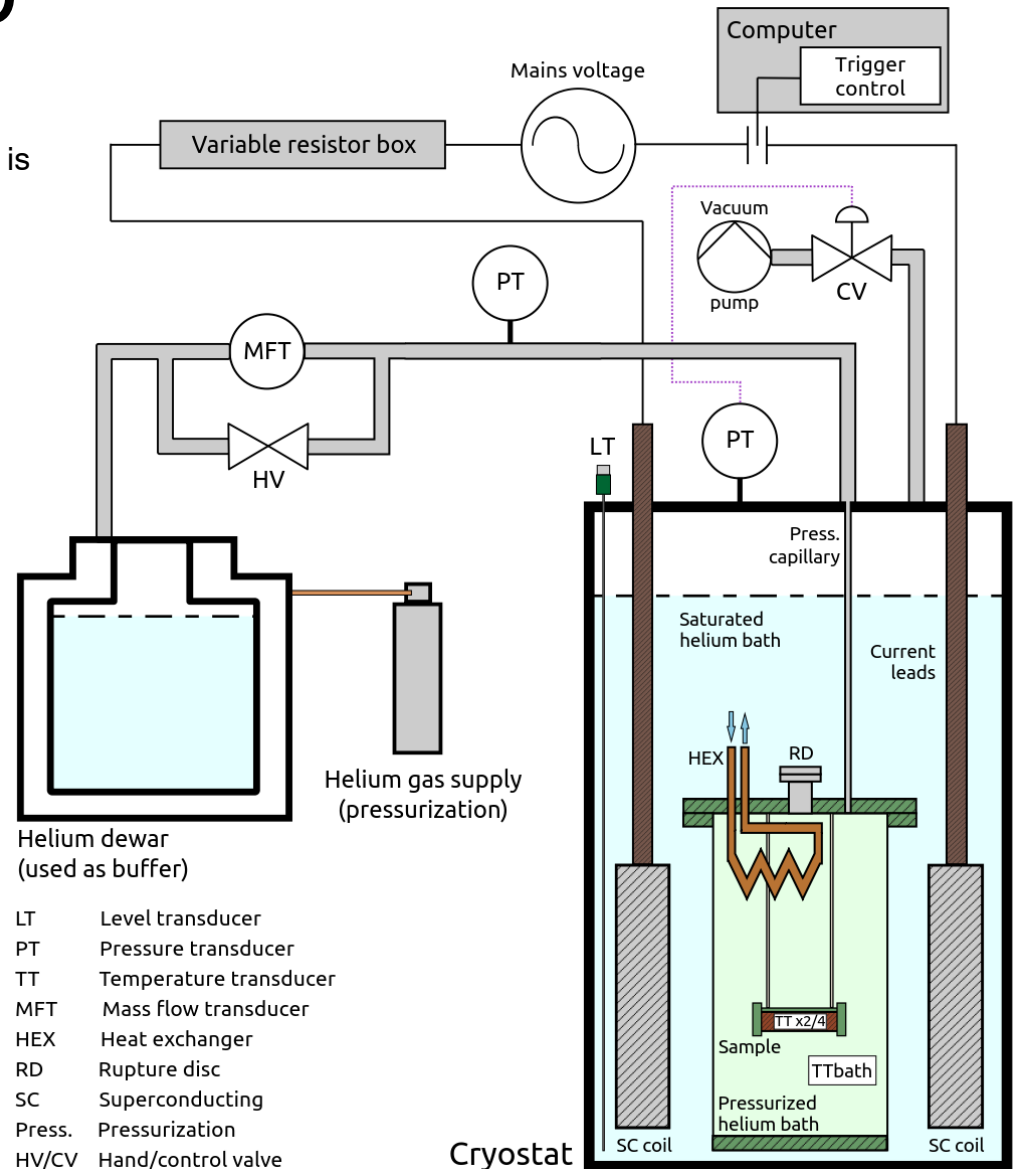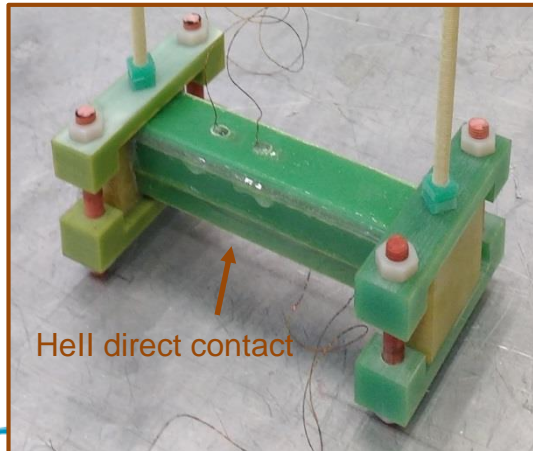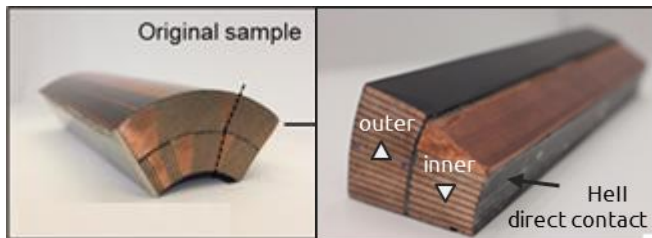
Experimental setup

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.

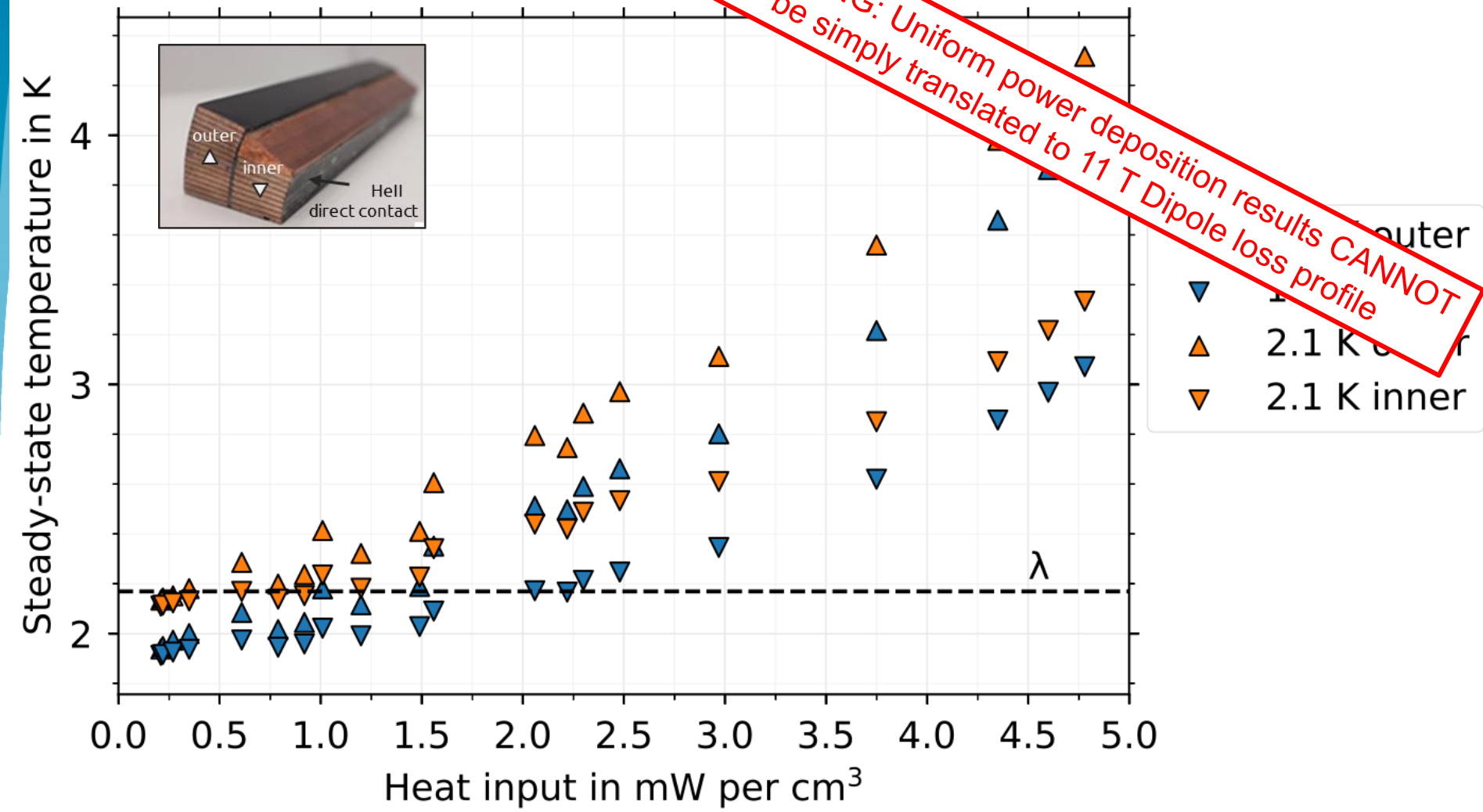**Important parameters:**

T_{eq} : equilibrium temperature

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

Original sample

outer
inner

HeII direct contact

HeII direct contact

Computer
Trigger control

Mains voltage

Variable resistor box

Vacuum pump

CV

PT

MFT

HV

LT

PT

Press. capillary

Saturated helium bath

Current leads

HEX   RD

Helium gas supply (pressurization)

TT x2/4

Sample

TTbath

Pressurized helium bath

SC coil   SC coil

Cryostat

Helium dewar (used as buffer)

LT	Level transducer
PT	Pressure transducer
TT	Temperature transducer
MFT	Mass flow transducer
HEX	Heat exchanger
RD	Rupture disc
SC	Superconducting
Press.	Pressurization
HV/CV	Hand/control valve

2) Thermal relaxation times

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

11-Tesla Dipole

Packing Factors

2% (Yokes)

4% (Collars)

Peak Power Density
≈ 32 mw.cm⁻³

Peak Power (W/m3)
3.118e+04
23395
15609
7823.8
3.836e+01

Y
Z — X
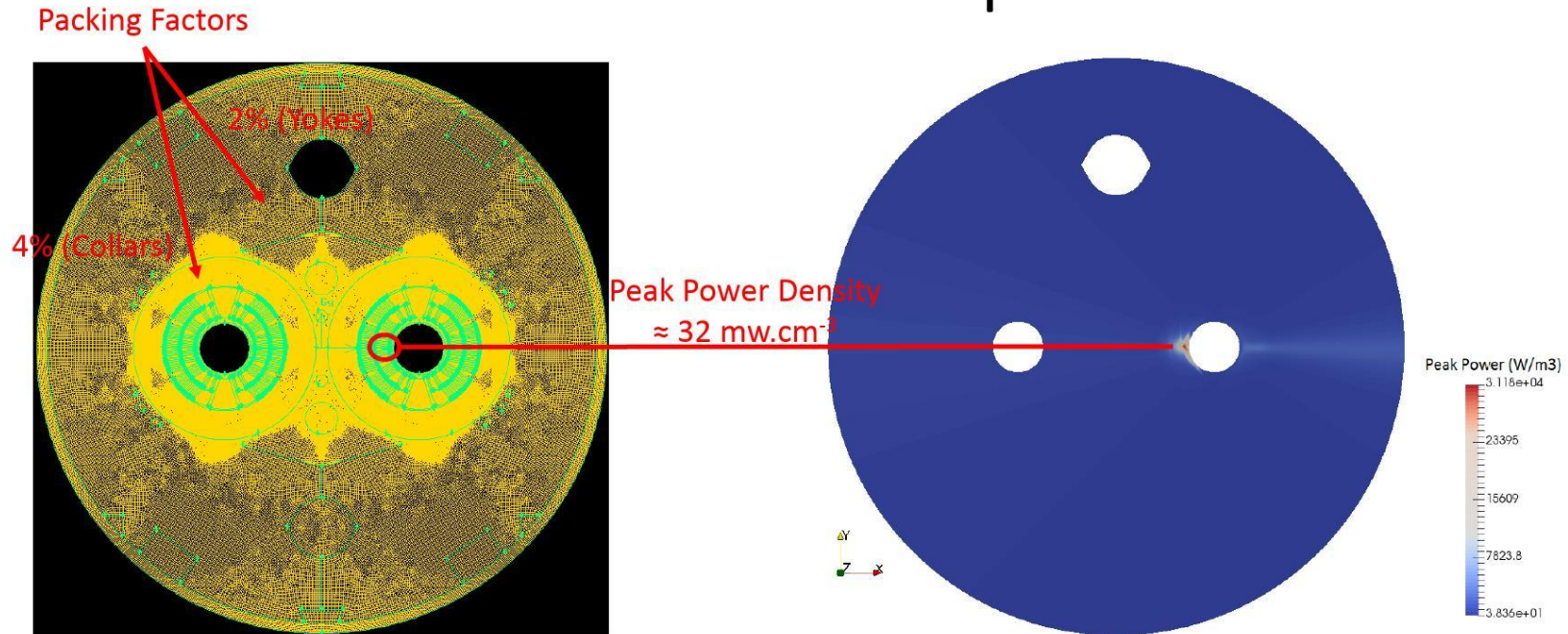
Mesh Quality:

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:

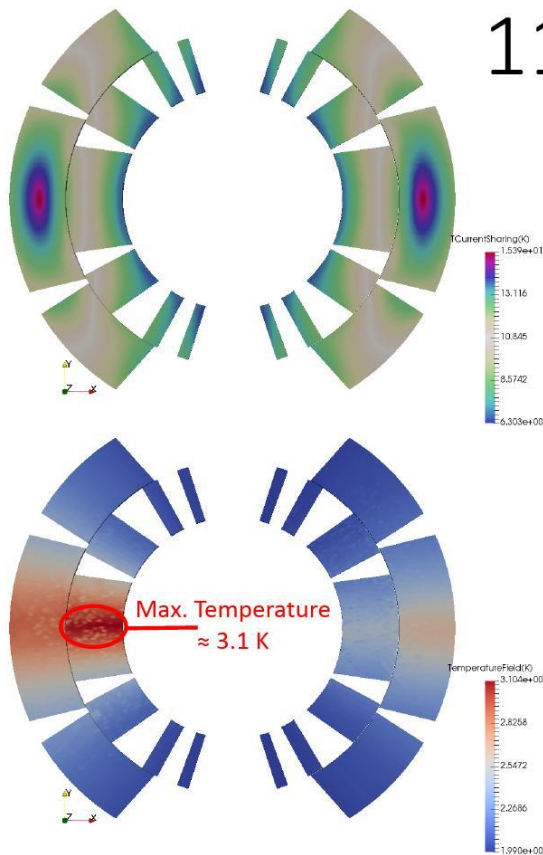Constant Temperature T=1.9K at the Cold Source

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

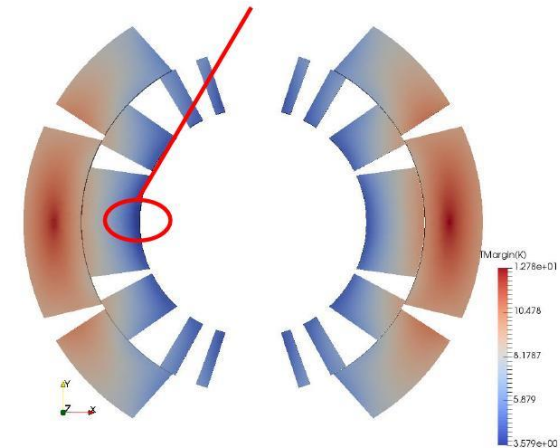Uniform heat flux from the Coldbore (where peak power density is): $3.31 \ W.m^{-3}$

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

11-Tesla Dipole

Max. Temperature
≈ 3.1 K

Lowest Temperature Margin
≈ 3.58 K

The temperature margin is largely above the
limit of quenching.

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

Recap:

At 32 mW/cm³ → Tmargin ~ 3.6 K
At 50 mW/cm³ → Tmargin ~ 3.0 K
At 100 mW/cm³ → 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
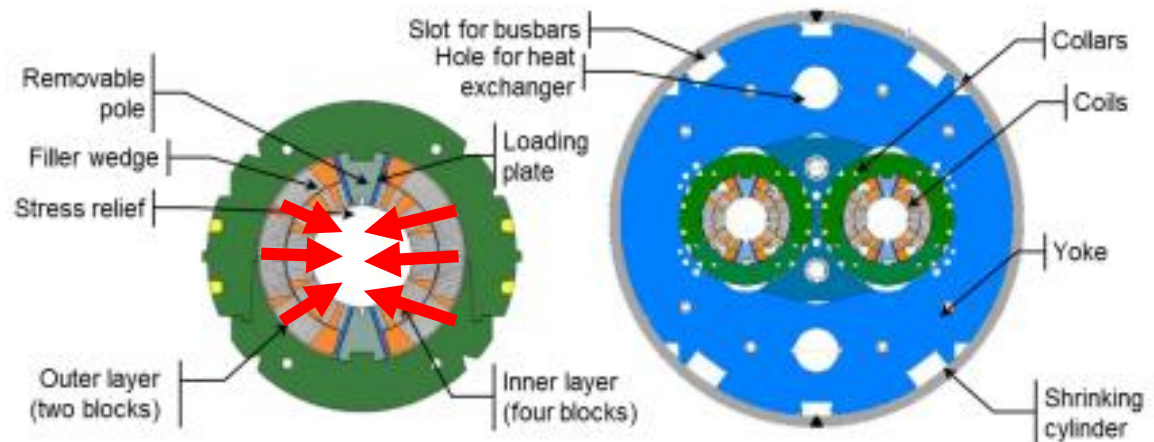
Complementary validation is ongoing with Cryolab stack-measurements analysis

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

11 T dipole steady state as function of power: 1) « static coil + beam-pipe cooling limits »
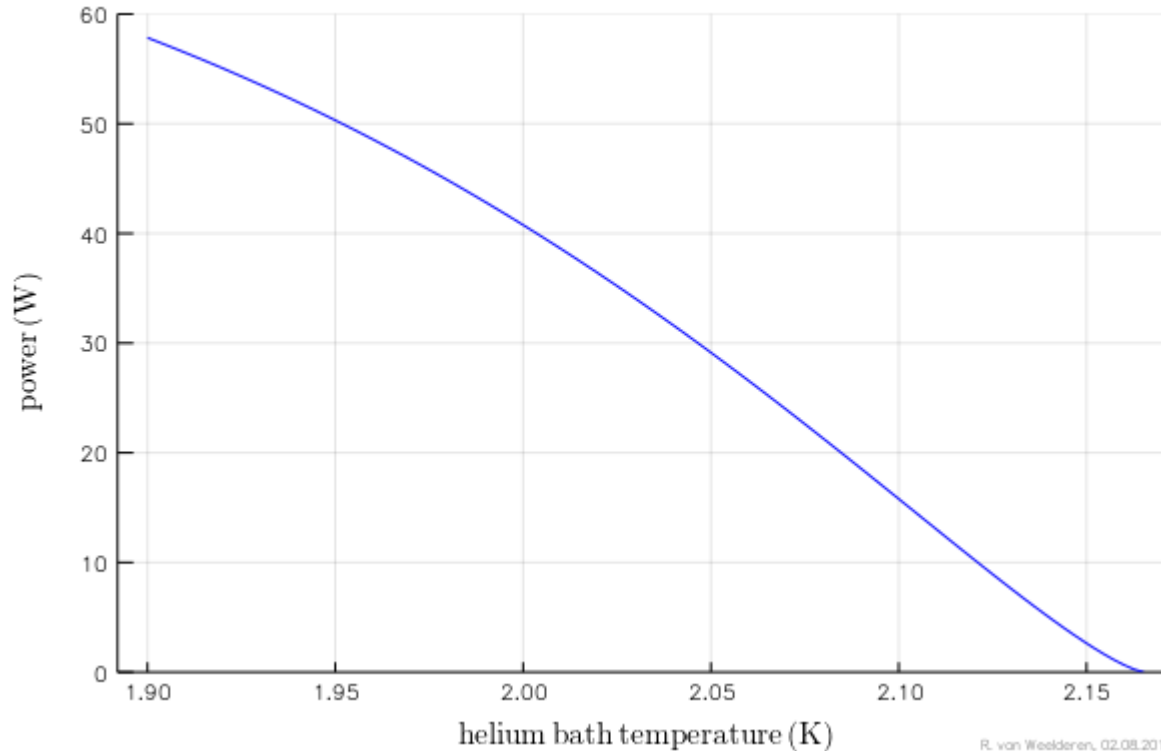
Coil-heat must go first from coil to annular space around beam-pipe and then towards the magnet ends

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

Contiuously extractable power from 11T − coils + beam − pipe

R. van Weelderen, 02.08.2018

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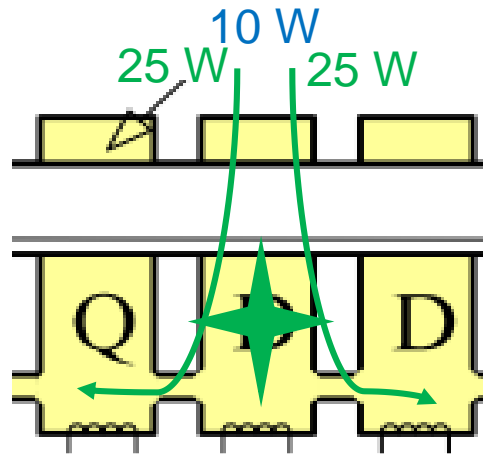
→ total ≈ 60 W for the full 11T cold –mass (i.e. coil + collars + yoke + beam pipe +…)

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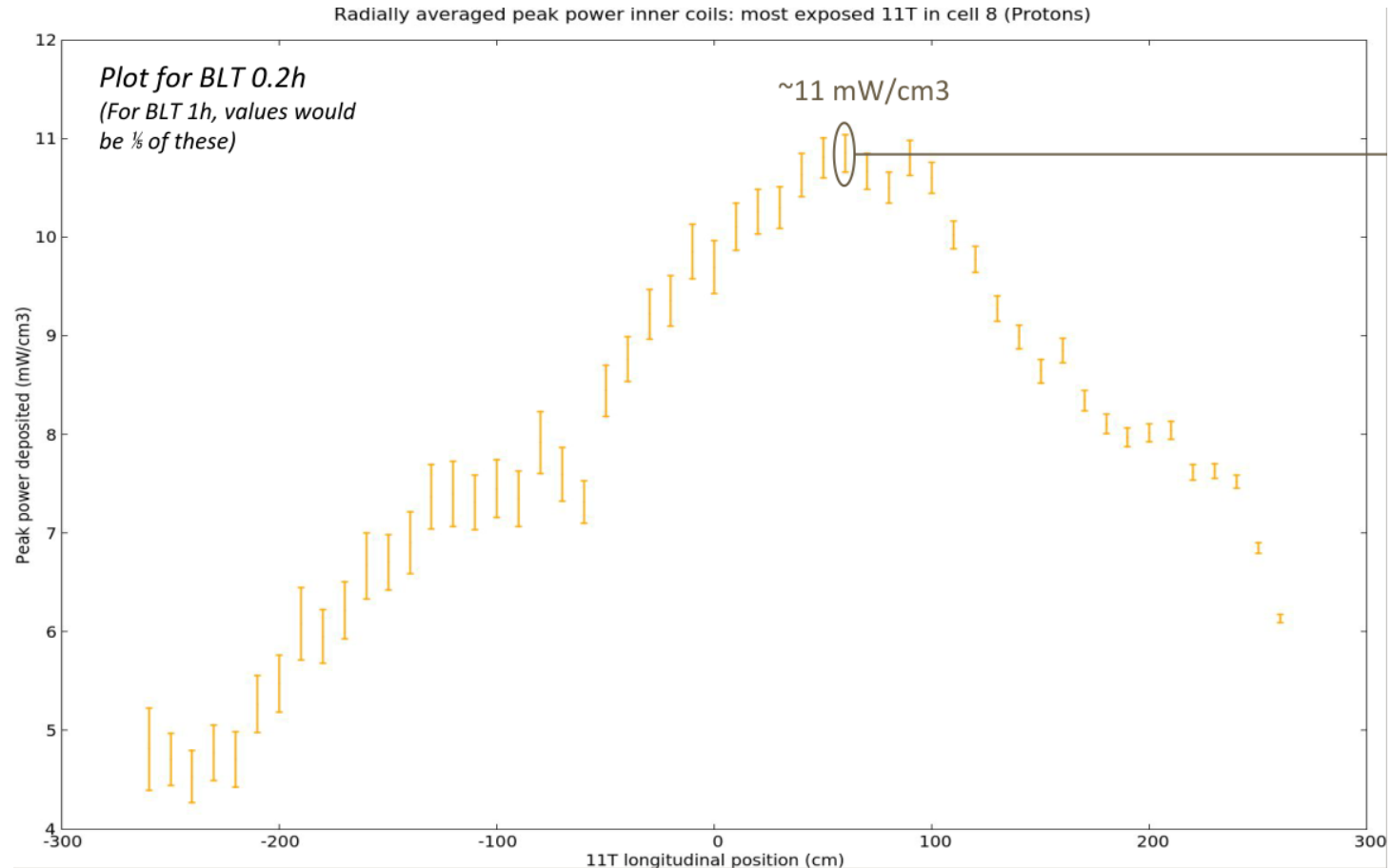
21/06/18   C. Bahamonde - WP 11 Technical machine interfaces working group   1

Courtesy Cristina Bahamonde Castro
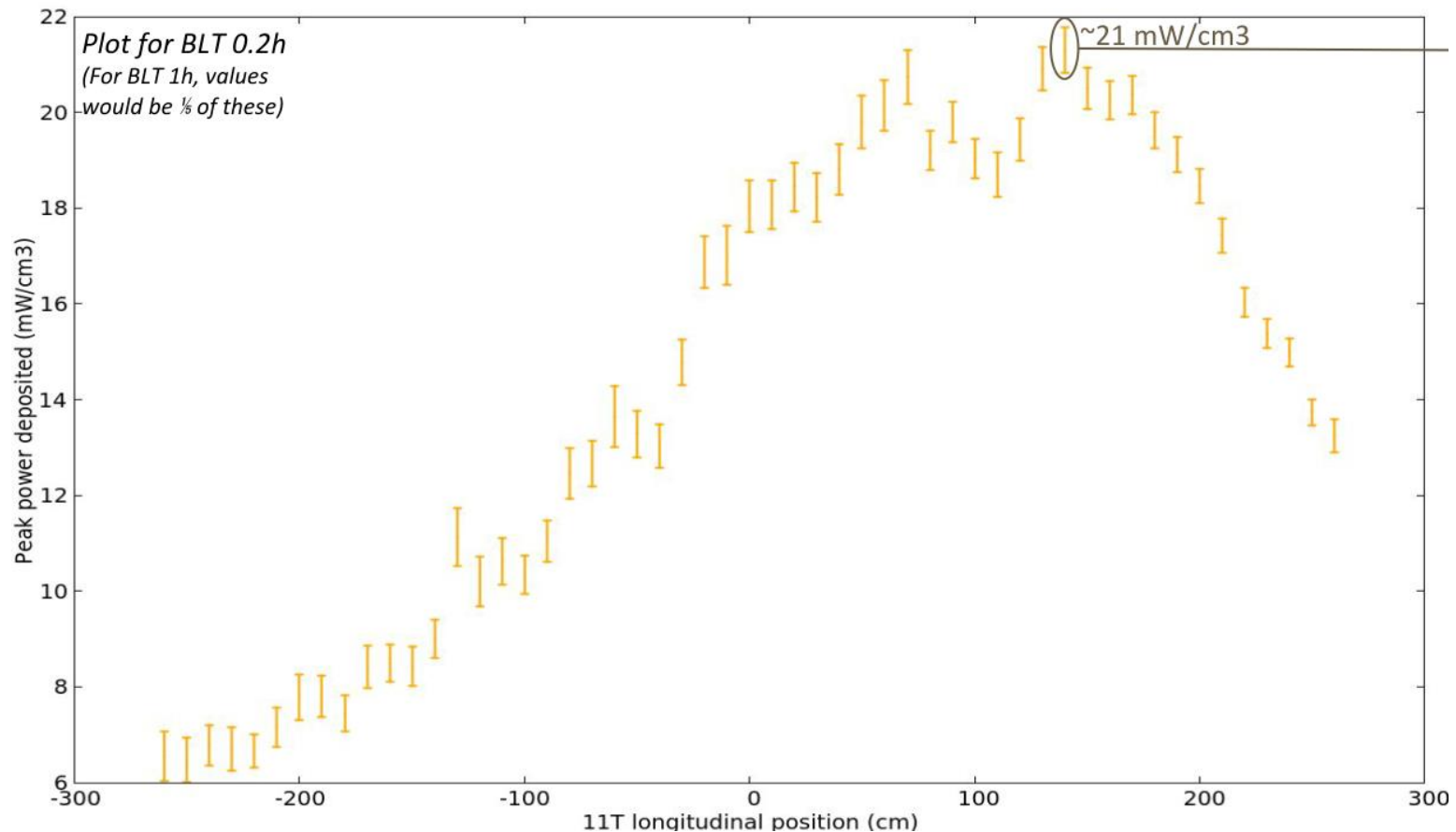
Implications for proposed Beam-Lifetime scenarios

Radially averaged peak power inner coils: most exposed 11T in cell 8 (Protons)

Plot for BLT 0.2h
(For BLT 1h, values would
be ⅕ of these)

~11 mW/cm3

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

Radially averaged peak power inner coils: most exposed 11T in cell 8 (Ions)

Plot for BLT 0.2h
(For BLT 1h, values would be ⅕ of these)

~21 mW/cm3

Peak power deposited (mW/cm3)

11T longitudinal position (cm)

Courtesy Cristina Bahamonde Castro

Ions: 21 mW/cm³ 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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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

Intermediate 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

Intermediate 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

DS - cryo hardware steady-state cooling limits
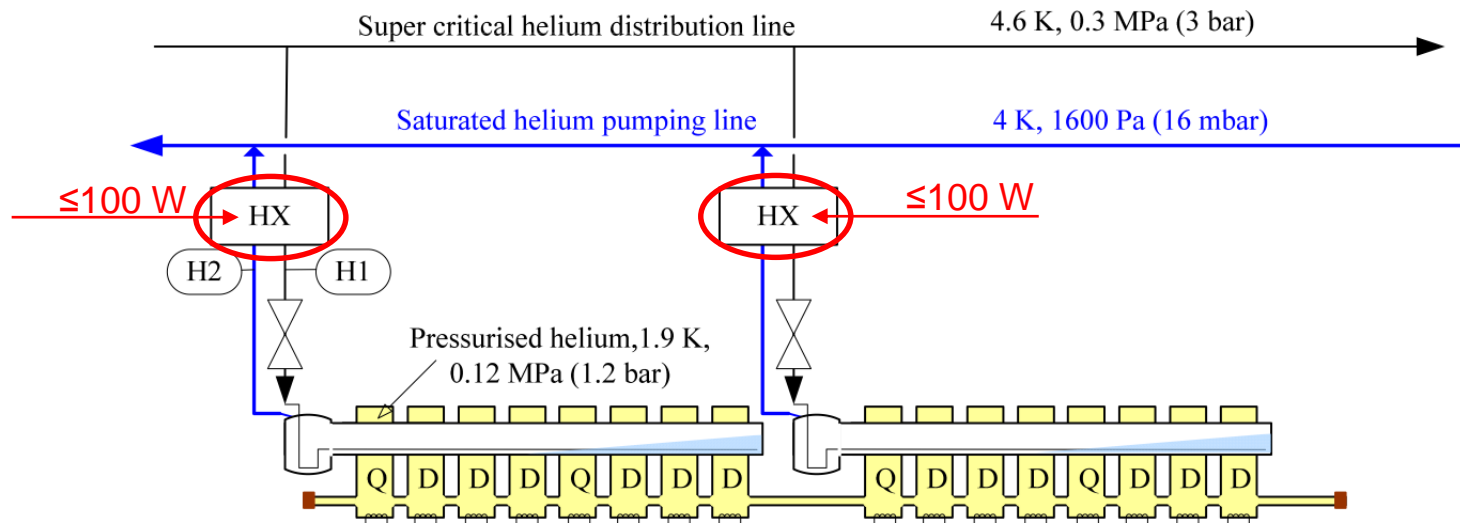
Generically LHC-cell cooling-power provided by the collective performance of:

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.

DS - cryo hardware steady-state cooling limits

Proton run !

77 W   **+ ≤ 77 W**

| Q7 | MB | 11T | TC LD | 11T | MB | Q8 | MB | MB | Q9 | MB | MB | Q10 | MB | MB | LE | Q11 | plug | MB | … |

Proton run	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*
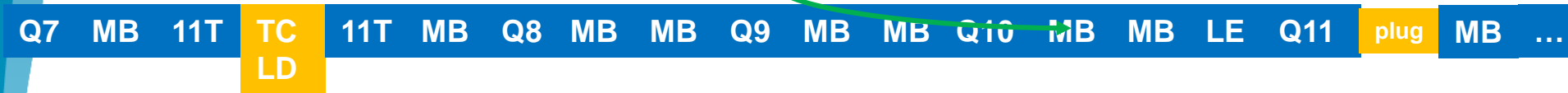- *considering beam-gas based on present LHC vacuum (factor 200 lower than TDR)*

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

DS - cryo hardware steady-state cooling limits

Ion run !

77 W   **+ ≤ 77 W**

| Q7 | MB | 11T | TC LD | 11T | MB | Q8 | MB | MB | Q9 | MB | MB | Q10 | MB | MB | LE | Q11 | plug | MB | … |

Ion run	Cell 8 (W)	Redundancy - Cell 9 (W)
static + splices (0.25 W/m *)	23	23
beam-gas (**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)*

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

Implications for proposed beam-life scenarios

- 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*

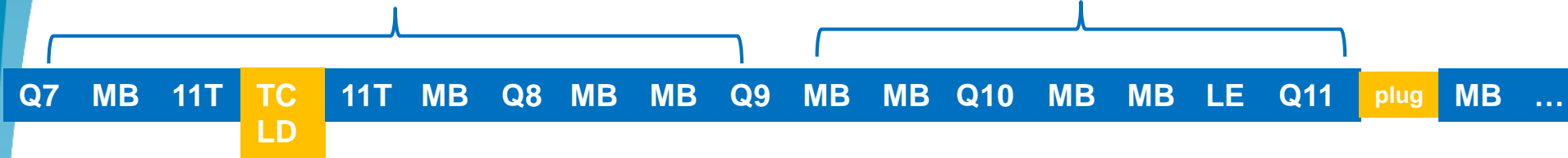- →The exceptions are high short – time losses when the helium temperature will drift as the heat gets absorbed.

DS - cryo hardware steady-state cooling limits

Proton run !

Loss data Fluka team, **1h** 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 | ... |

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

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 | TC LD | 11T | MB | Q8 | MB | MB | Q9 | MB | MB | Q10 | MB | MB | LE | Q11 | plug | MB | ... |

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

The heat capacity of the DS-helium content will have to be used!

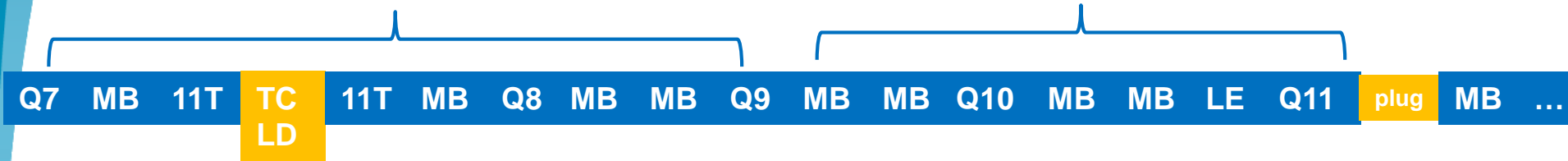# DS - cryo hardware steady-state cooling limits

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 | ... |

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

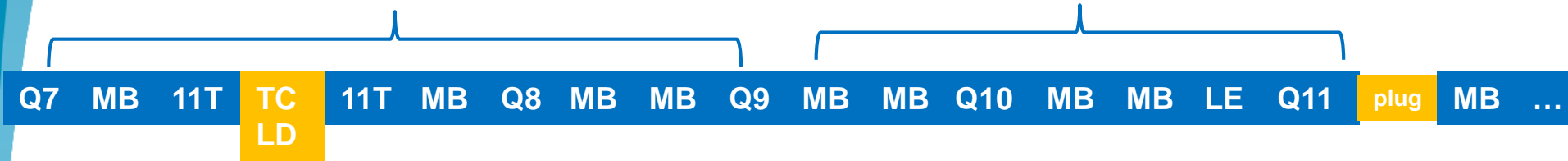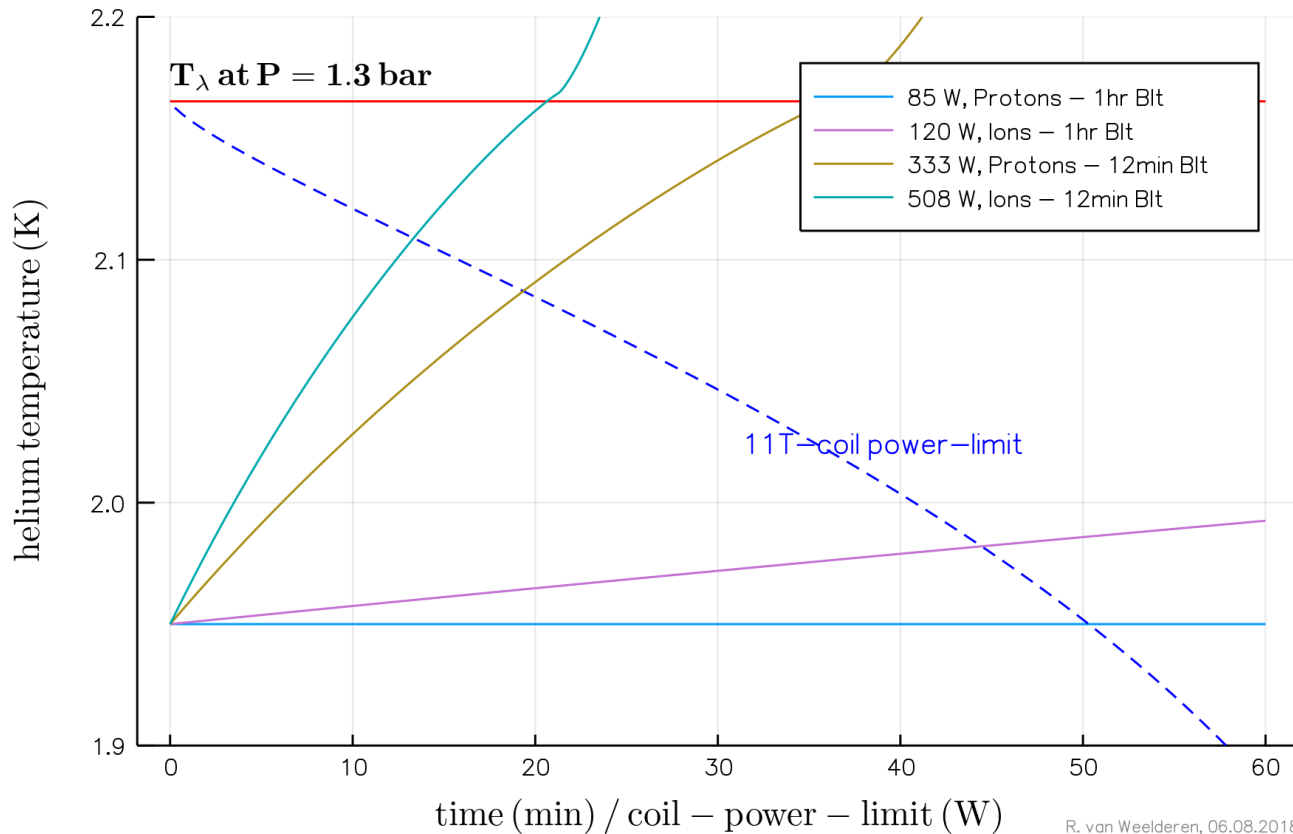The heat capacity of the DS-helium content will have to be used!

DS - cryo hardware steady-state cooling limits

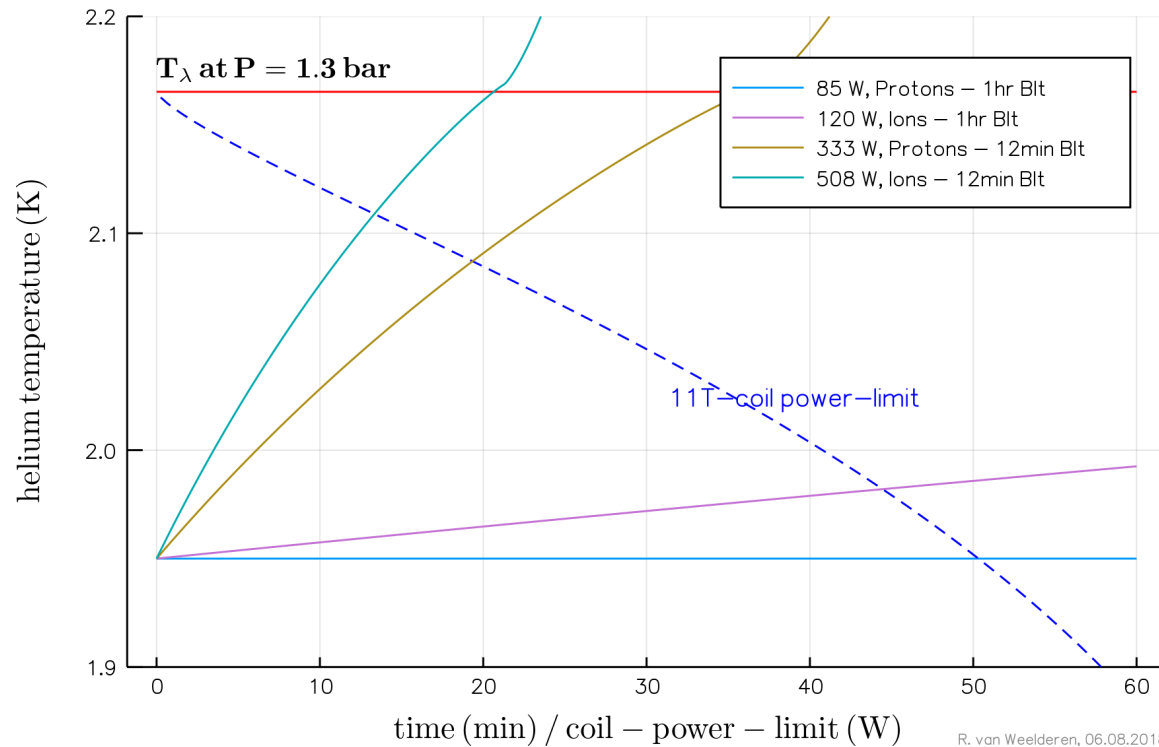heating of the DS − cells 8 and 9 : helium starting at 1.95K

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

Ions (1hr Blt): The **21 W** which need to be extracted from the coil+beam-pipe area is reached after >> 60 min

DS - cryo hardware steady-state cooling limits

heating of the DS − cells 8 and 9 : helium starting at 1.95K

Legend:
- 85 W, Protons − 1hr Blt
- 120 W, Ions − 1hr Blt
- 333 W, Protons − 12min Blt
- 508 W, Ions − 12min Blt

T_λ at P = 1.3 bar

11T−coil power−limit

helium temperature (K)

time (min) / coil − power − limit (W)

R. van Weelderen, 06.08.2018

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)

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)

DS - cryo hardware steady-state cooling limits

heating of the DS − cells 10 and 11 : helium starting at 1.95K
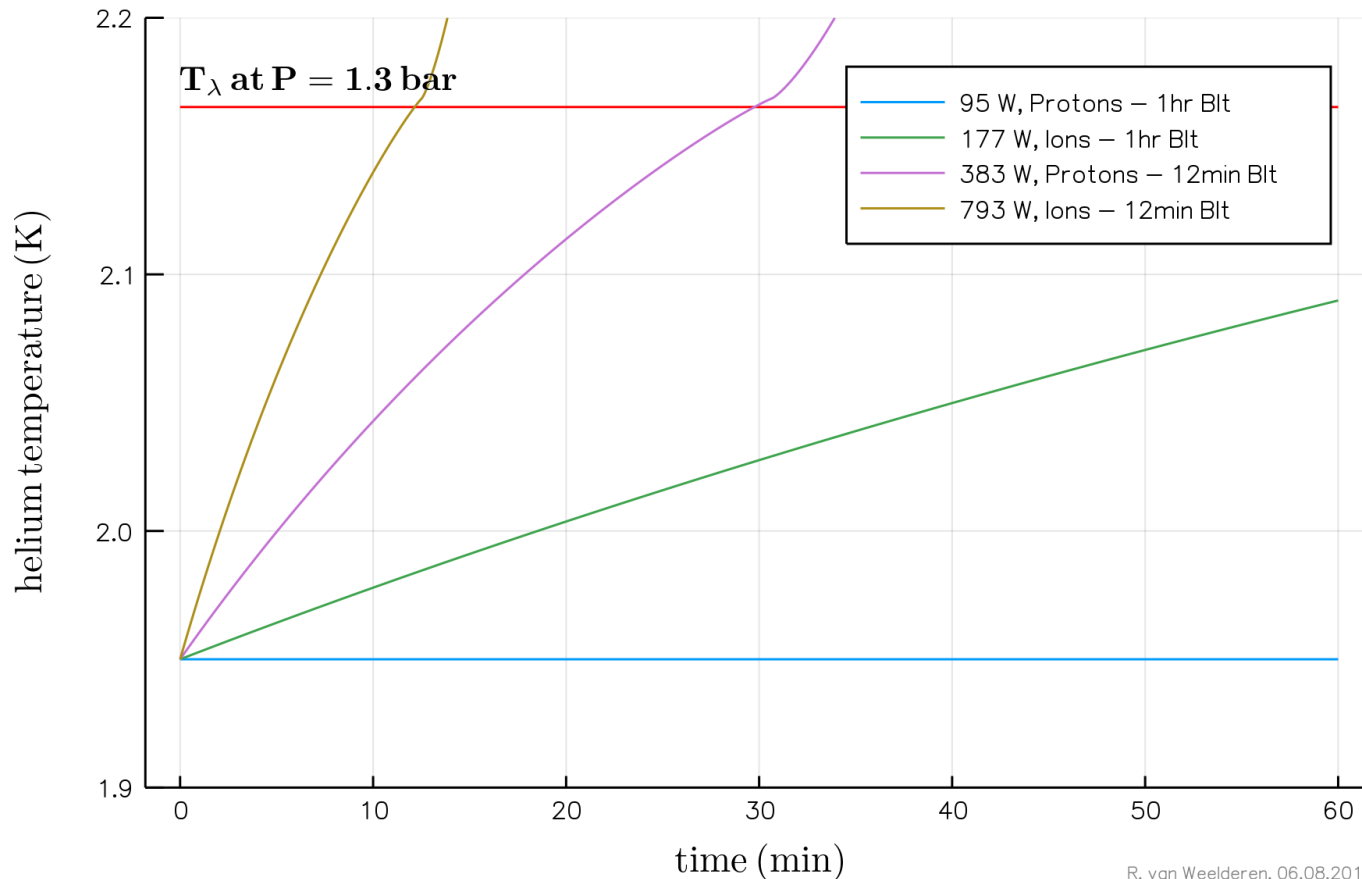
Ions (1hr Blt) : The MB dipole limits in cells 10 & 11 will see the above given T vs time, **worse than cells 8 & 9.**

The MB dipole functioning limits under these conditions have to be ascertained.

Summary

11-T dipole design:

No radial cooling holes necessary *to deal with coil+beam-pipe heat loads*

Cryogenic-limitations:

1hr Blt: **cooling of 11-T-dipole ok for Protons and for Ions**
1hr Blt: **cooling of cells 10 & 11 MB-dipoles ok for Protons**
1hr Blt: **cooling of cells 10 & 11 MB-dipoles could be critical for Ions**

12min Blt: helium cooling not effective
→ *adiabatic T-rise of 11-T-dipole coil (to be evaluated)*

→propose power limit test in LHC