High Luminosity LHC

IR magnet cooling

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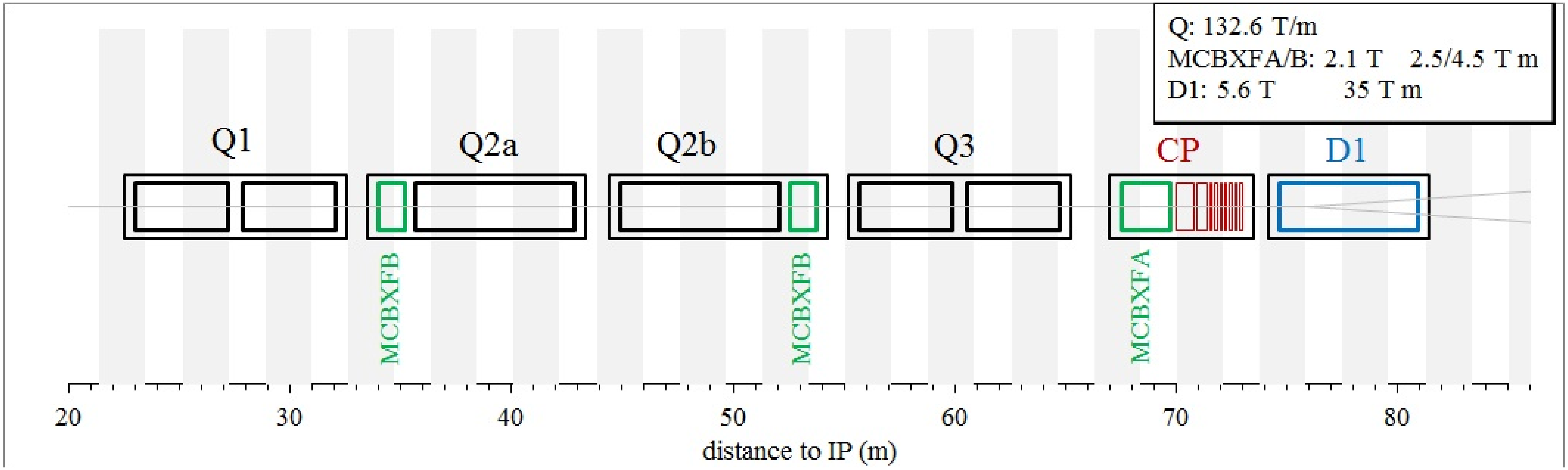
Outline

- Main - longitudinal - heat extraction
- Radial extraction: MQXF - quadrupoles
- Radial extraction: D1 - dipole
- Summary of main cold mass requirements
- Thermal performance evaluation
- Outlook & Conclusions

Note: detailed reference WP3, Deliverable 3.4

Main - longitudinal - heat extraction: Magnet string layout



Mechanical

Magnet string: Q1, Q2a, Q2b, Q3, Corrector Package (CP), D1

Cryostats: 4 m to 7 m in length each, up to 3 m long interconnects

Total lenght: 57 m

Main - longitudinal - heat extraction: Heat loads target

Two main T-levels for heat absorption

1) 50 K - 70 K (Tungsten absorbers on beam-screen, integrated in beam-pipe)

2) 1.9 K - 2.1 K (superfluid helium in magnet cold mass)

@cold mass: +100 W ~estimate for static loads, end effects, synchroton radiation, image currents...

@ 7.5 L_0	HL-LHCV1.1	
Power [W]	**Magnet cold mass**	**Beam screen**
Q1A + Q1B	140	210
Q2A + corr	150	90
Q2B + corr	165	100
Q3A + Q3B	220	105
CP	105	90
D1	135	80
Interconnects	30	110
Total	**945**	**780**

Loads due to secundaries (F. Cerrutti, august 2015: values in the process of being updated during this CERN-LARP meeting)

Size cold mass cooling for 1050 W at 1.9 K - 2.1 K

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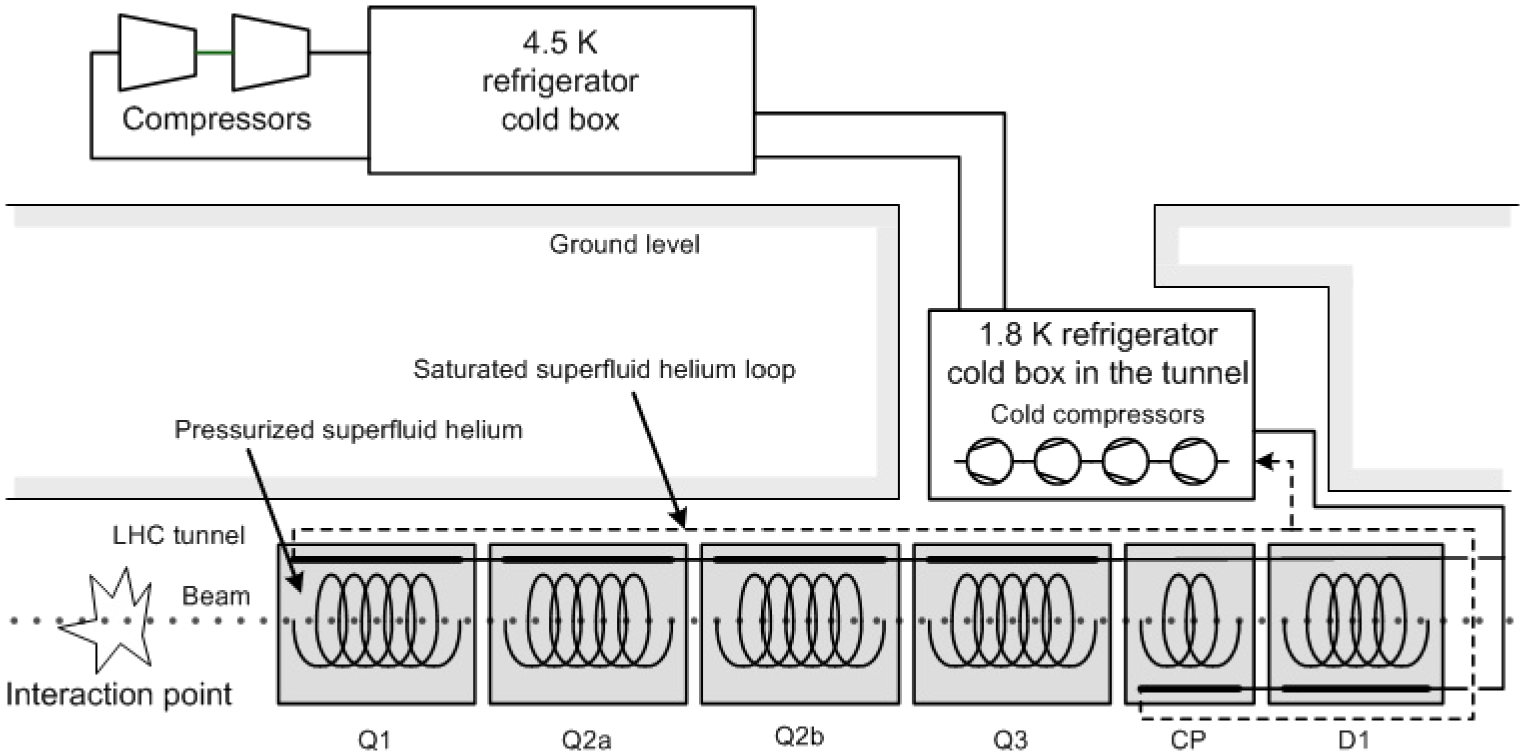
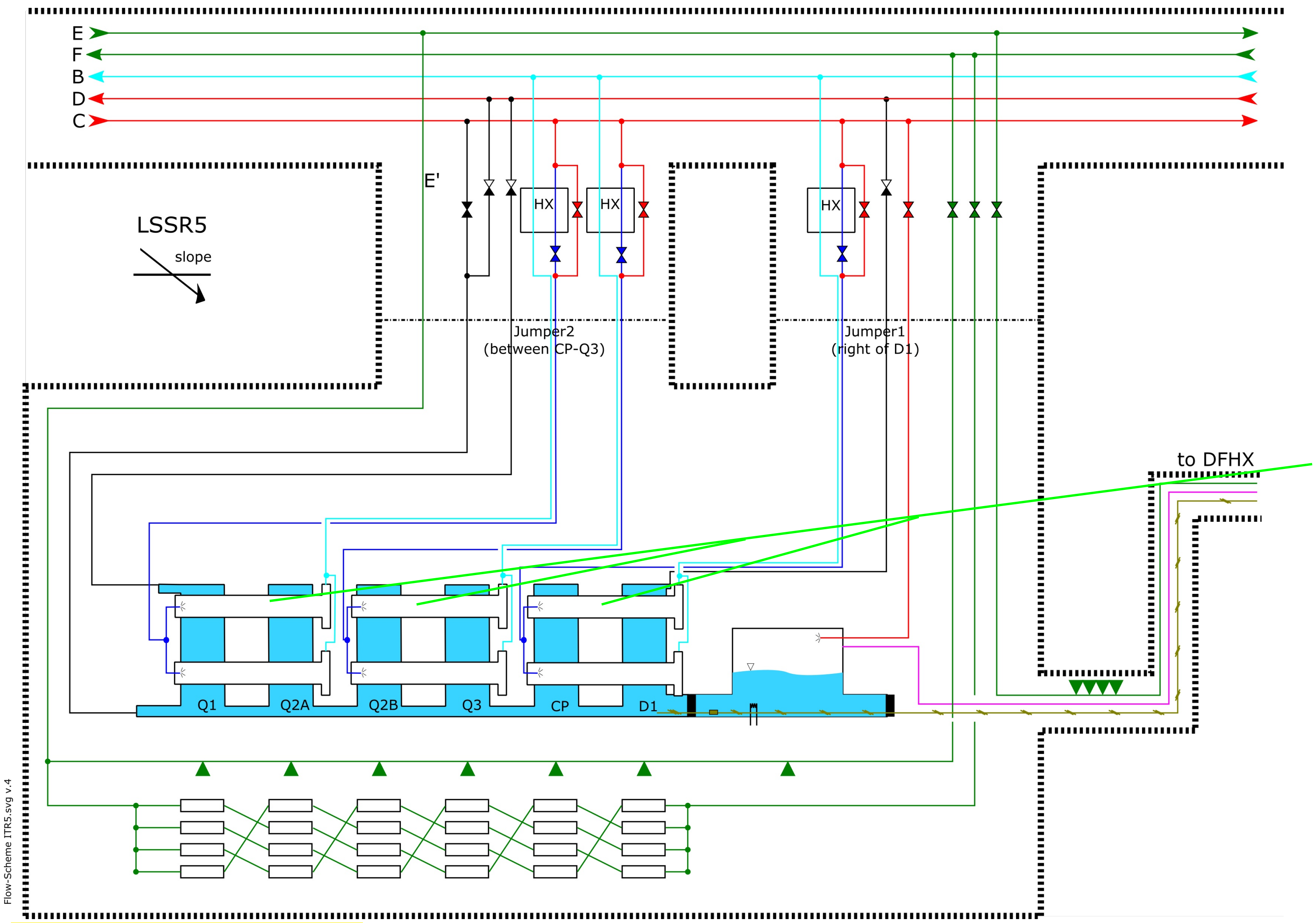
Main - longitudinal - heat extraction: Overall architecture by using superluid helium. Lowest point on the left



- slope dependent configurations at each of the points IP1L/R & IP5L/R!
- cold masses in static superfluid helium (HeII) at 1.3 bar and ~1.9 K
- heat extracted by vapourization of HeII that travels as very low pressure two-phase flow in parallel HX
- low vapour pressure maintained by cold compressor system

(See talk by S. Claudet, 27.10.2015)

Main - longitudinal - heat extraction: Flow diagram for right side of IP5. Lowest point on the right



courtesy D. A. Berkowitz

- QRL supply headers B, C, D, E, F and valve boxes for cryogens on top
- 2 jumper connections to magnet string (at D1 end, between CP and Q3)
- 3-sets of parallel bayonet HXs (Q1+Q2a, Q2b+Q3, CP+D1)
- 3 low vapour pressure return lines & corresponding HX in QRL

- beam screen loop (4 parallel pipes) covering full string length
- cold-mass safety reliefs at either end of string

Main - longitudinal - heat extraction: Characteristics 1/2

QRL:

Header B, ~1.9 K, ~17 mbar, Low-pressure HeII pumping
Header C, ~5 K, ~3.5 bar, Supply for HeII-cooling, cool-down & fill, link interface box
Header D, ~20 K, ~1.3 bar, Quench line, cool-down & fill return
Header E, ~50 K, ~20 bar, Thermal screen & beam screen supply
Header F, ~70 K, ~19 bar, Thermal screen & beam screen return

Contraints on magnet design have led to the following compromise for the bayonet HX's

- size & number determined my maximum vapour velocity < 7 m/s, magnet yoke space, 1050 W power to be extracted

- Quadrupole HX's: 2 x 68 mm ID, smooth copper pipes in parallel, 1.5 mm gap, 3 mm wall thickness
- Power ~400 W for Q1+Q2a, and ~400 W for Q2b+Q3 : ~800 W total
- Quadrupole phase separators volume > 12.5 liter

- CP+D1 HX's: 2 x 51 mm ID, smooth copper pipes in parallel, 1.5 mm gap, 3 mm wall thickness
- CP+D1 phase separators volume > 5.5 liter
- Power ~250 W for CP+D1

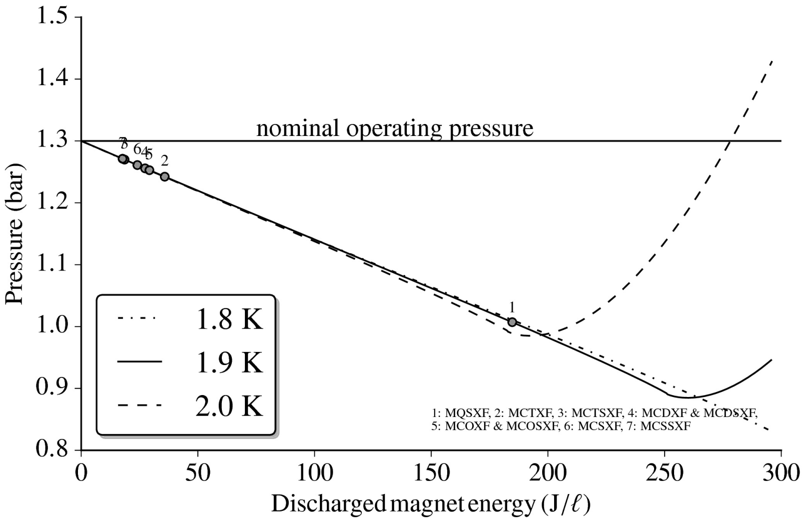
LHC

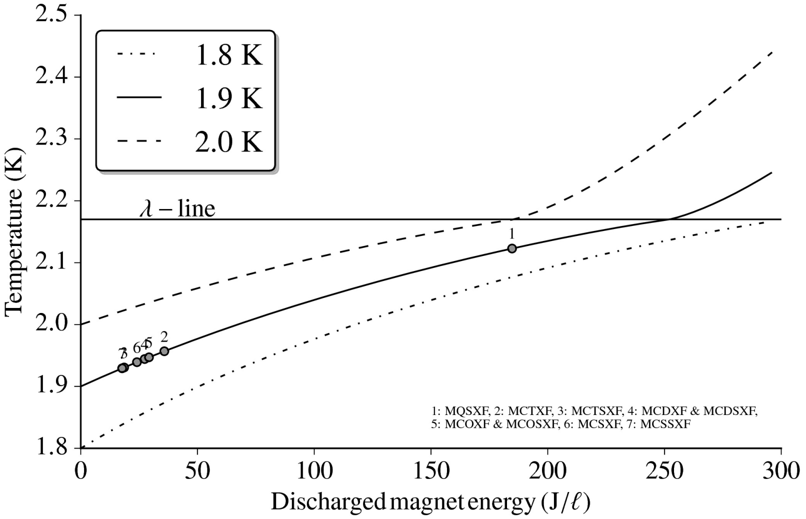
Main - longitudinal - heat extraction: Characteristics 2/2

Heat must be given some freedom to redistribute along the length of the cold-masses (no hard criterion):
free area > 150 cm^2 for Quads
free area > 100 cm^2 for CP, D1

Quench pressures and related safety have to be evaluated for the Quads & D1

CP magnet quenches should pose no problem in terms of thermal quench propagation due to their local low energy per He-volume ratio (see graphs)

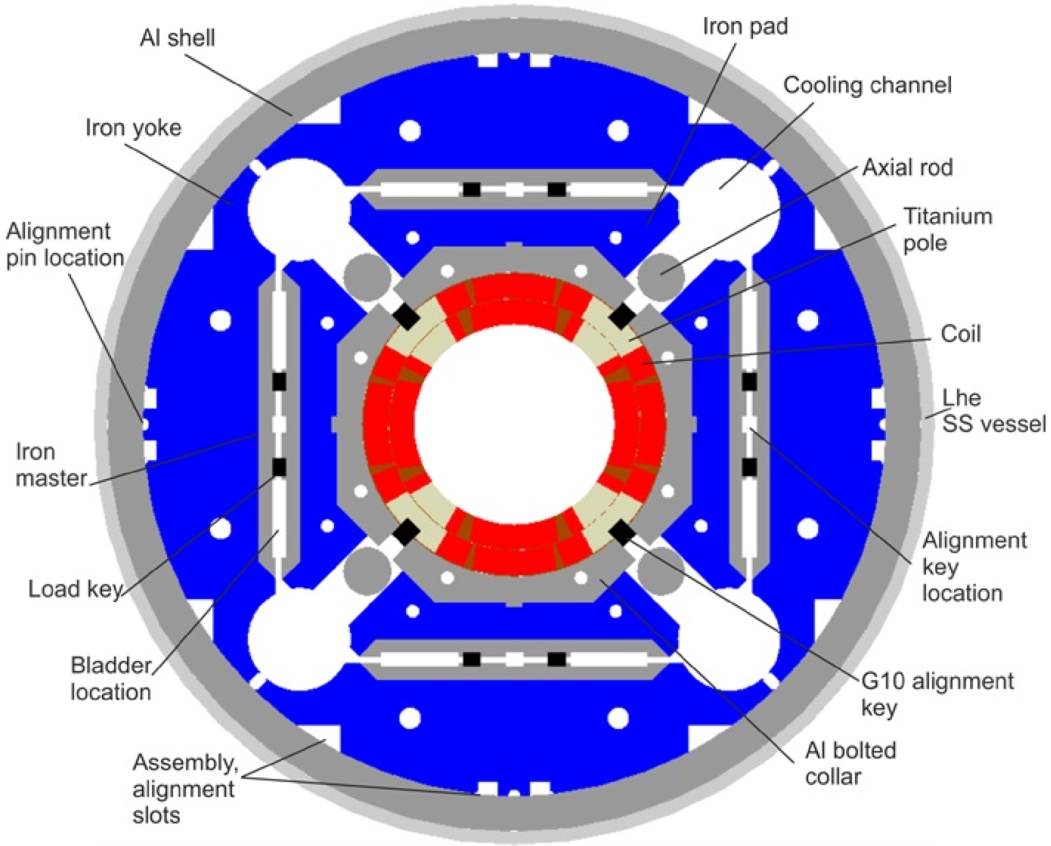


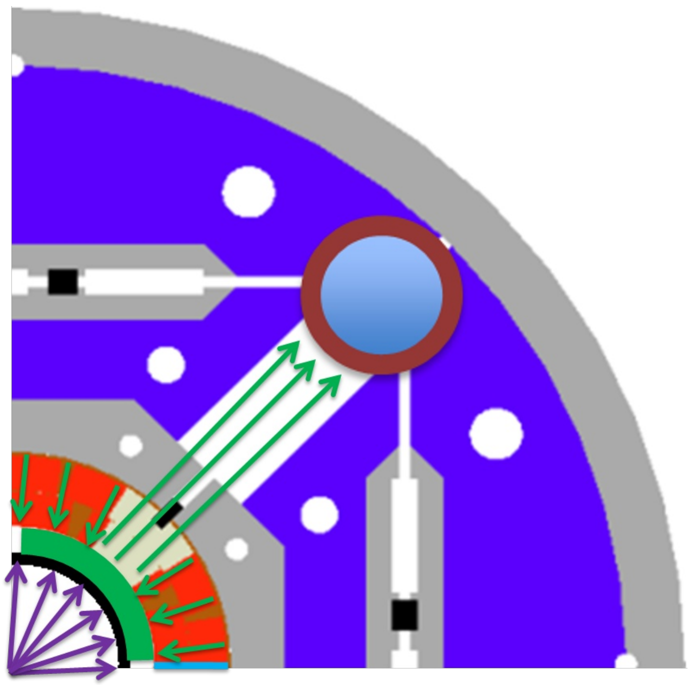


Radial - heat extraction: MQXF 1/2

MQXF-magnet in 1.8 K - 2.1 K static He, at P = ~1.3 bar:

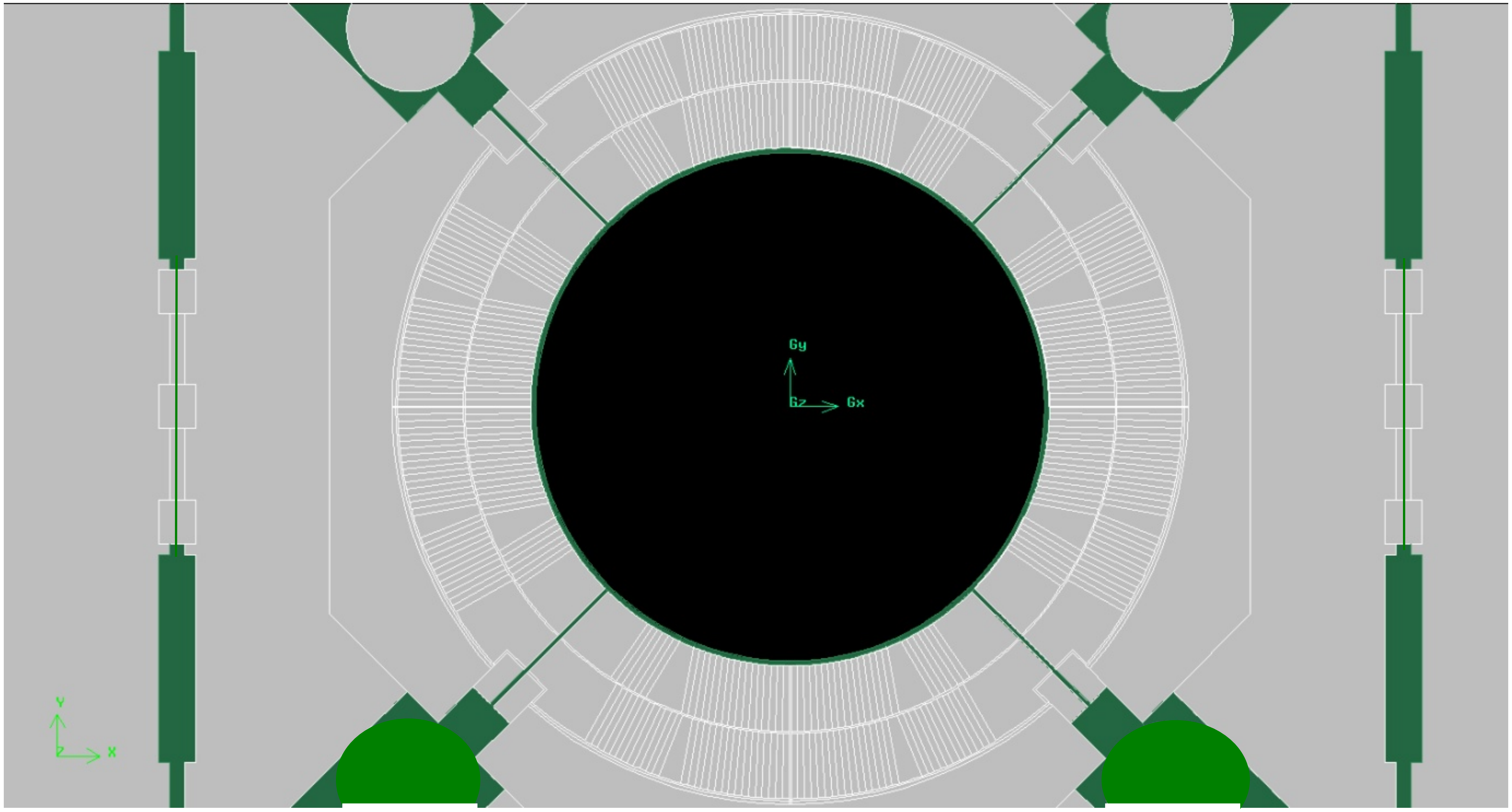
- Cables Nb_3Sn, Iron Yoke, Cold-source situated in the top 2 holes marked "cooling channel"
- Helium channels: annulus between cold bore and coil, perforated titanium pole, and yoke (see also next slide)





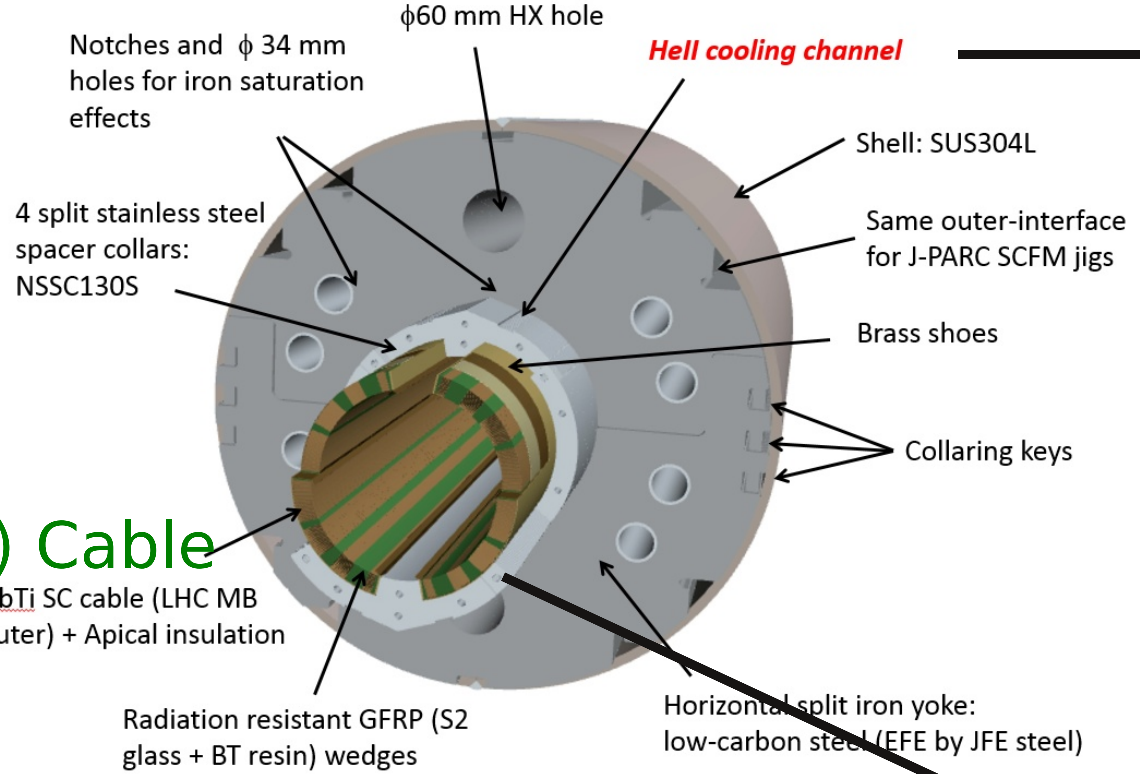
Green arrows show main heat flow directions from:
coil -> annulus -> pole -> cold-source

Radial - heat extraction: MQXF 2/2



- Helium in green:
-1.5 mm annulus at inner coil boundary (barely visible)
- free passage through titanium insert, G10 alignment key & around axial rods: at least 8 mm holes every 50 mm

Radial - heat extraction: D1 1/1



1) Individual helium cooling channels -> fluid dynamics

3) Cable

2) Coil blocks with isothermal boundaries

Major differences of D1 wrt MQXF:
- single layer coil
- NbTi, porous cable
- HeII conduction to HX's via spacing between collars & yoke laminations (96 % packing factor collars, 98 % yoke)

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Summary of main cold mass requirements

Q1,Q2a,Q2b,Q3, including interconnects	no./rep.	size	unit	comment
Yoke hole for HX	2	77	(mm)	
HX inner diameter	2	68	(mm)	assuming 1.5 mm annular gap, 3 mm pipe-thickness
Yoke-HX annular gap	-	1.5	(mm)	
Phase separator	2	≥ 12.5	(ℓ)	
Total free longitudinal area	-	≥ 150	(cm2)	for cooling stabilization and sharing with CP-D1
beam-pipe - inner layer annular gap	-	1.5	(mm)	part of heat extraction path
annular to heat exchanger	every 40 - 50 mm	8	(mm)	via Titanium insert, G10 alignment keys
annular to heat exchanger	-	1.5	(mm)	Passage around axial rods
cooling channel interconnects	4	98 % packing factor equivalent		

D1, CP, including interconnects	no.	size	unit	comment
Yoke hole for HX	2	60	(mm)	
HX inner diameter	2	51	(mm)	assuming 1.5 mm annular gap, 3 mm pipe-thickness
Yoke-HX annular gap	-	1.5	(mm)	
Phase separator	1	≥ 5.5	(ℓ)	
Total free longitudinal area	-	≥ 100	(cm2)	for cooling stabilization and sharing with Q1-Q3
beam-pipe - inner layer annular gap	-	1.5	(mm)	part of heat extraction path
radial passages	-	98 % packing factor equivalent		

Thermal performance evaluation

The cooling performance of the cold mass designs is evaluated in terms of:

1) temperature margin under full steady state heat load conditions

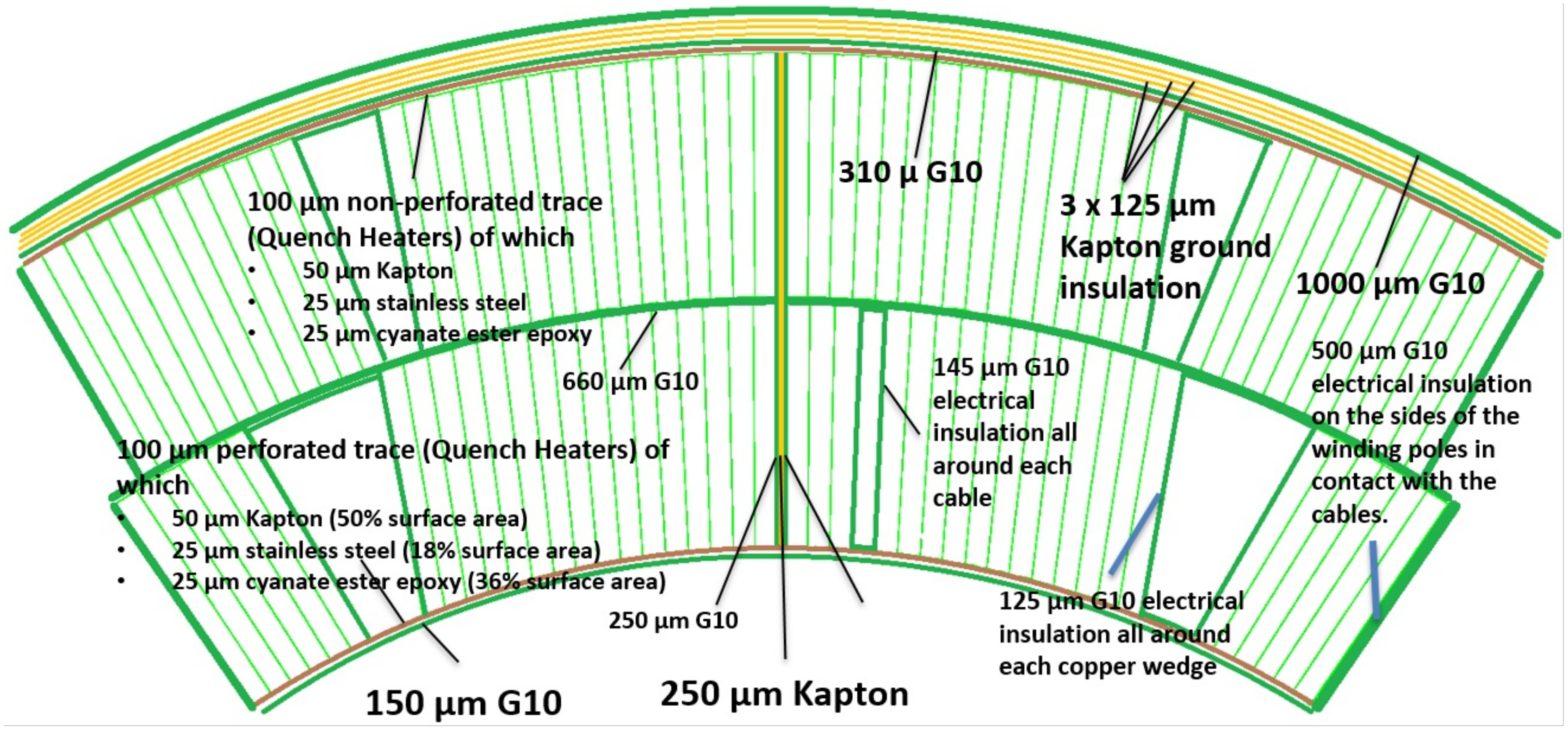
2) local maximum sustainable load

For that purpose a generic CFD toolkit was developped for treating heat flows in combined solid-liquid systems (in this case using OpenFOAM).

It allowed integrating the multitude of materials ecountered from coils towards the bayonet heat exchanger.

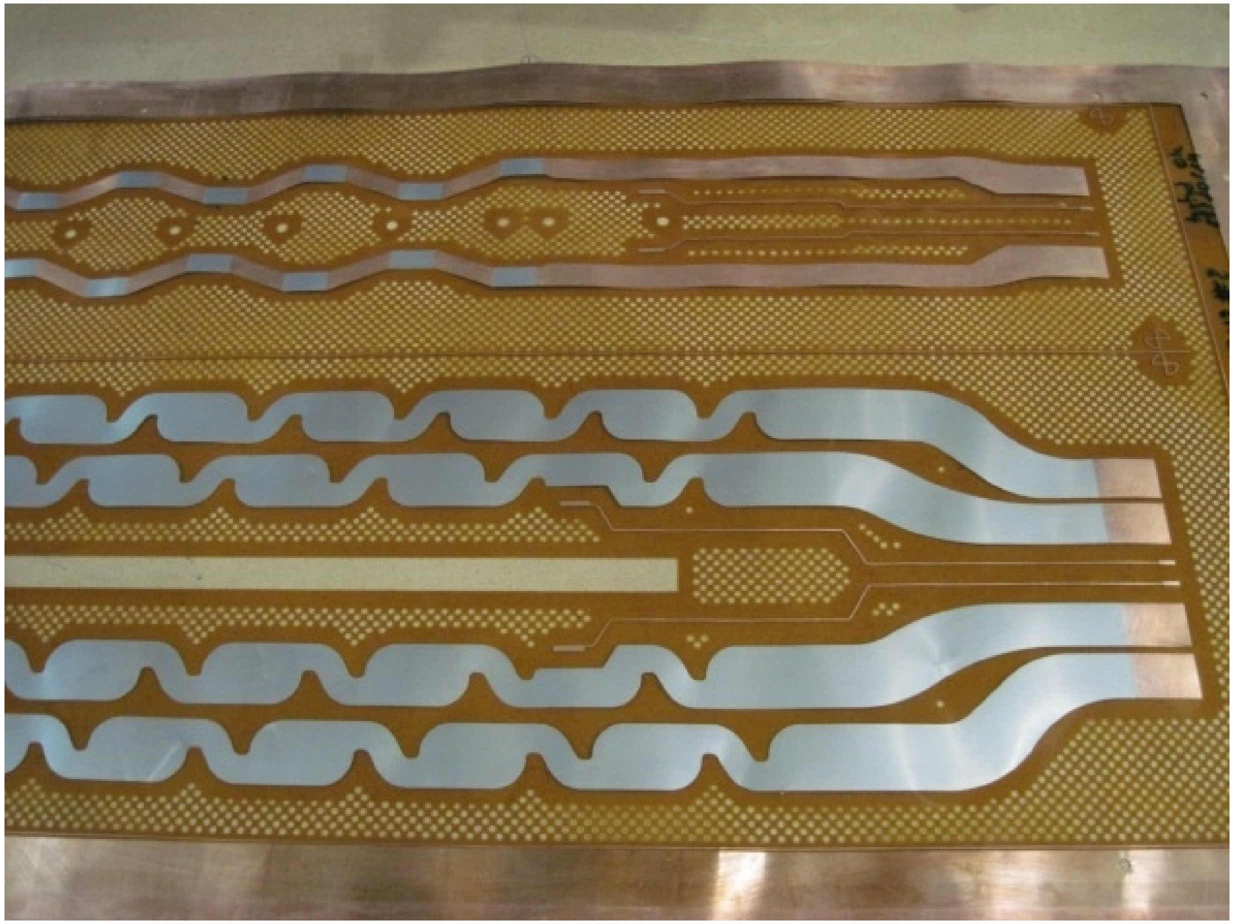
Detailed (radial resolution 3 mm) power deposition maps over the magnet section at the (longitudinal) most unfavourable location were used.

MQXF: Description of the thermally relevant magnet properties



Nb_3Sn coil block showing all materials used

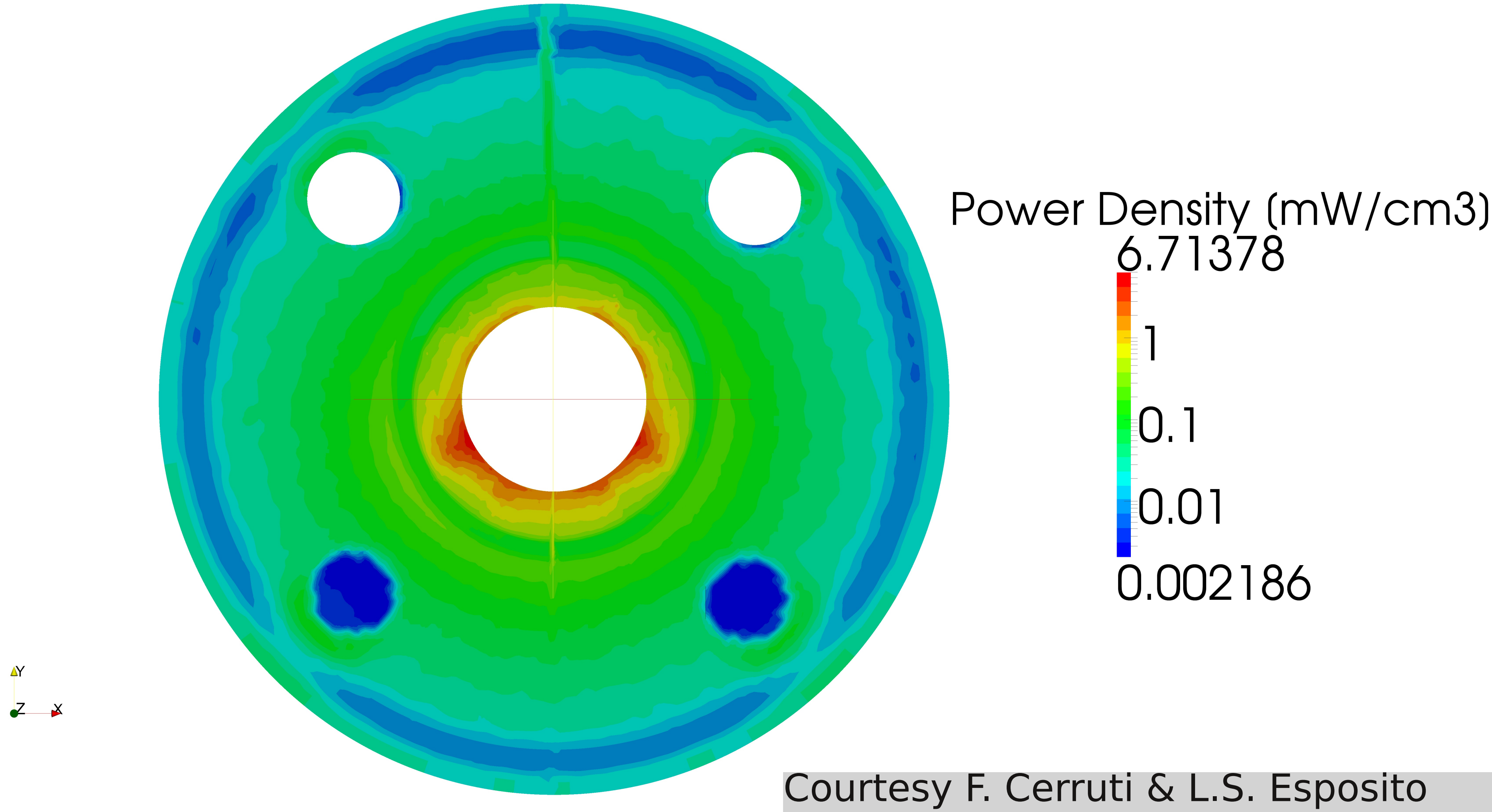
MQXF: Description of the thermally relevant magnet properties



Perforated quench heaters, glued on inner coil layer, facing the helium annulus

(and thus directly on the main heat extraction path!)

MQXF: high resolution energy deposition map

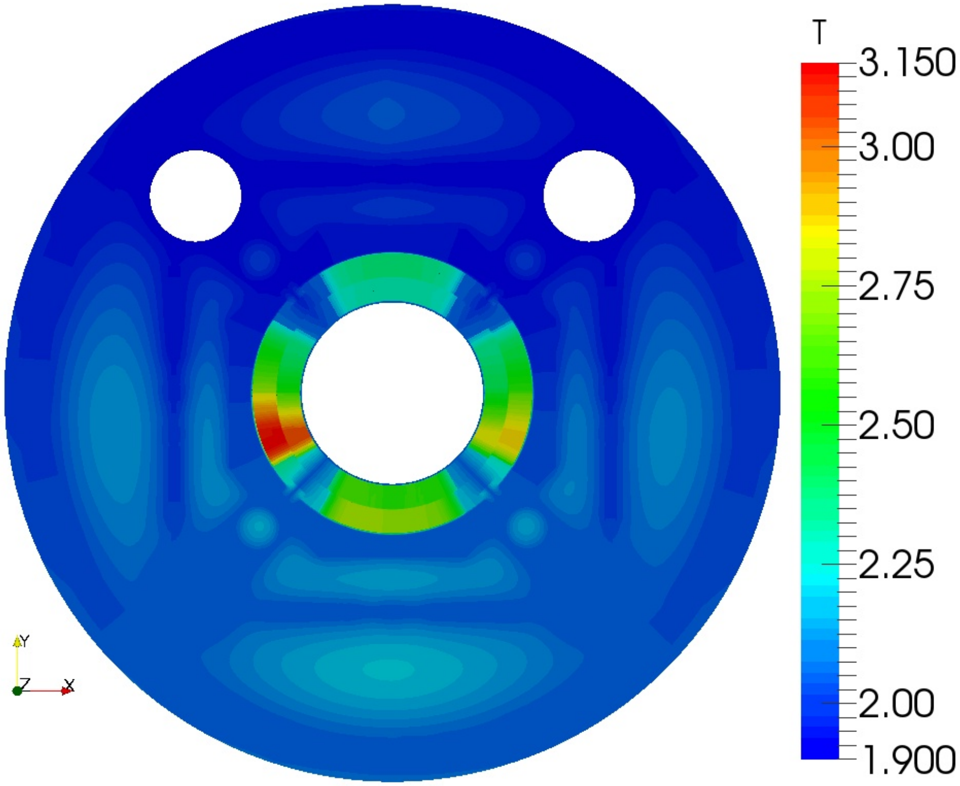


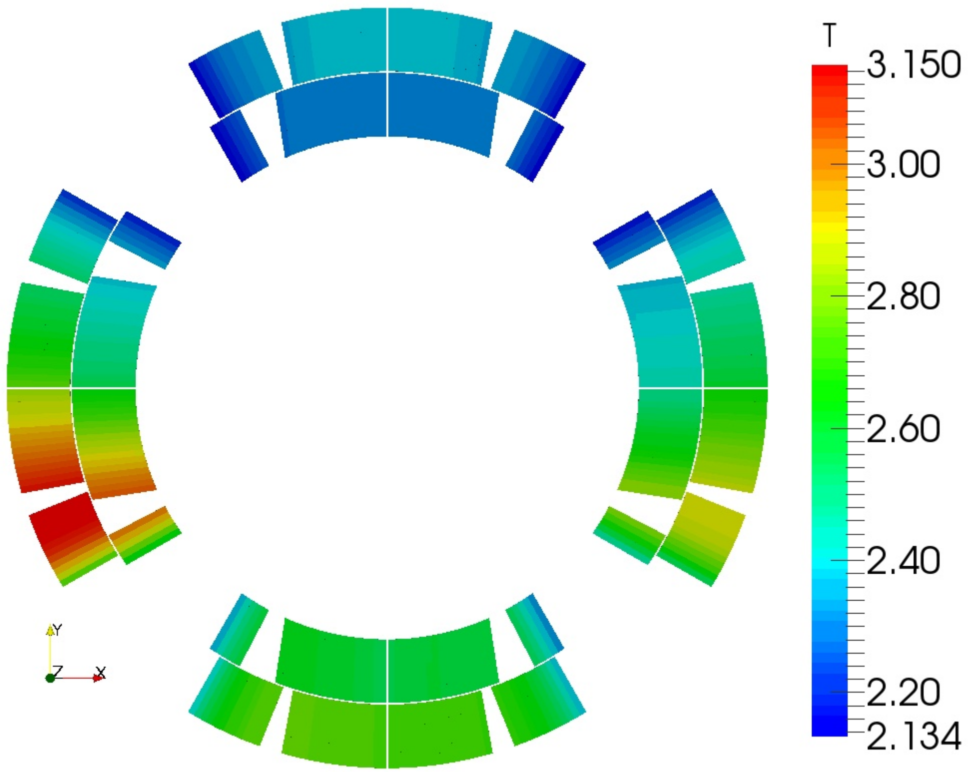
Courtesy F. Cerruti & L.S. Esposito

Highest power density in the inner coil layer

When averaged over the cable width ~ 4 mW/cm^3

MQXF: Steady state results: Temperature map

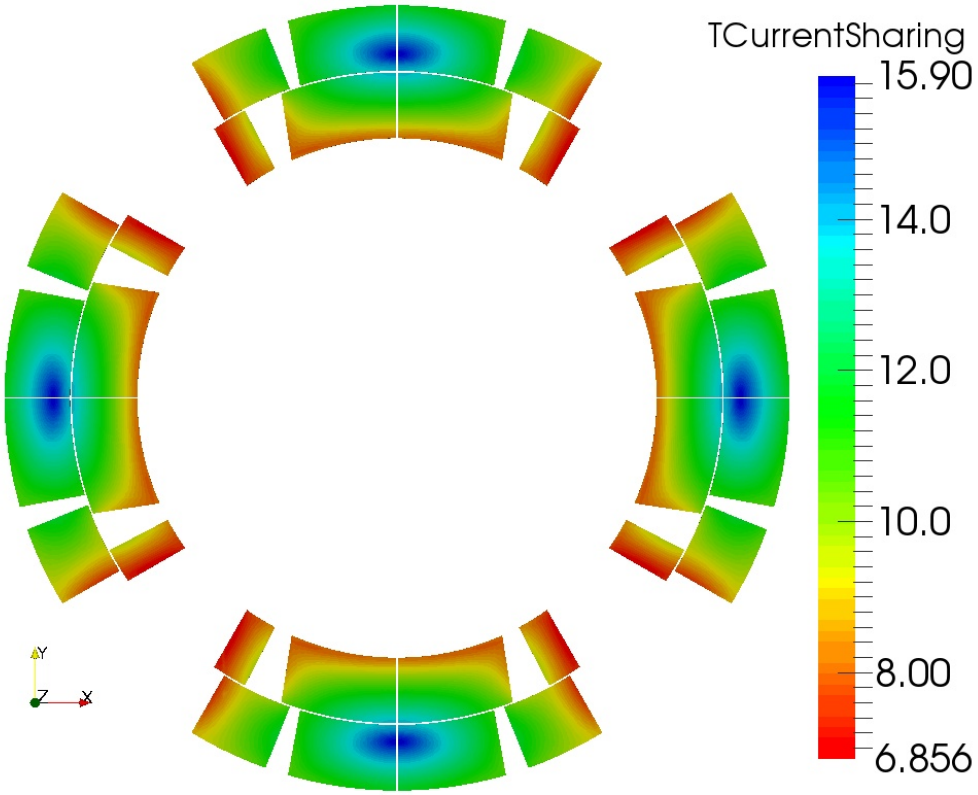




Modelisation gives highest temperature in the outer coil layer.

This high-T area is however not the most critical, as one has to evaluate the final temperature margin of the coil due the local magnetic field (see next slides)

MQXF: Steady state results
Current sharing map at 1.9 K, no heat load



This current sharing map, based on a 1.9 K coil temperature, has now to be combined with the calculated T-distribution due to the heat loads (see next slides)

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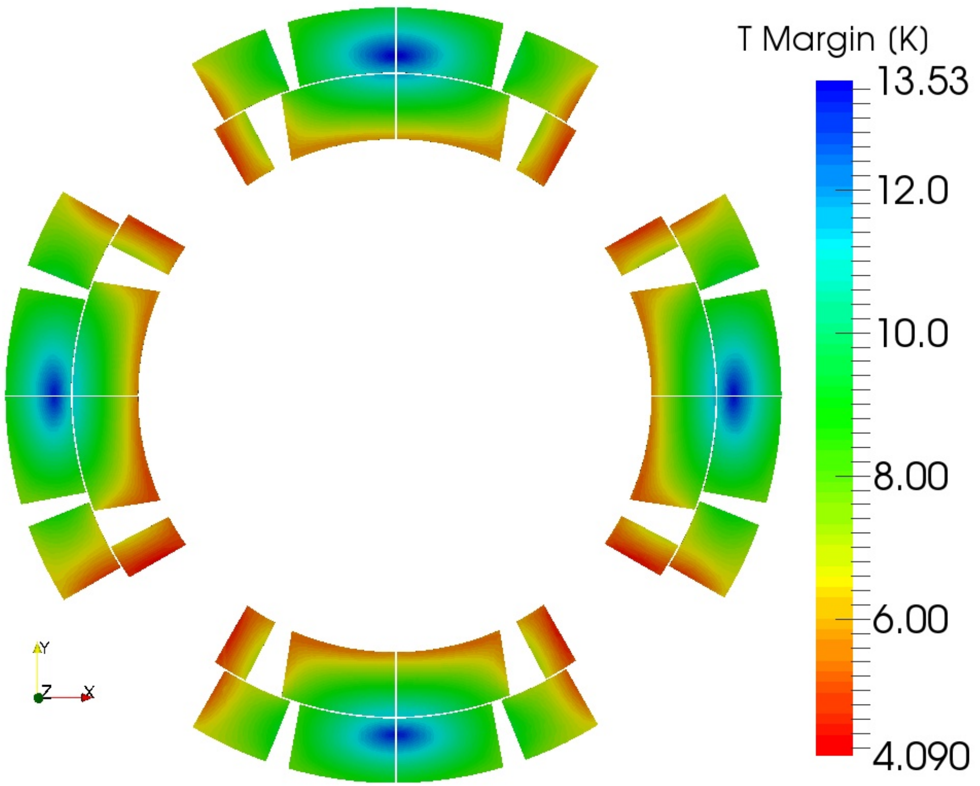
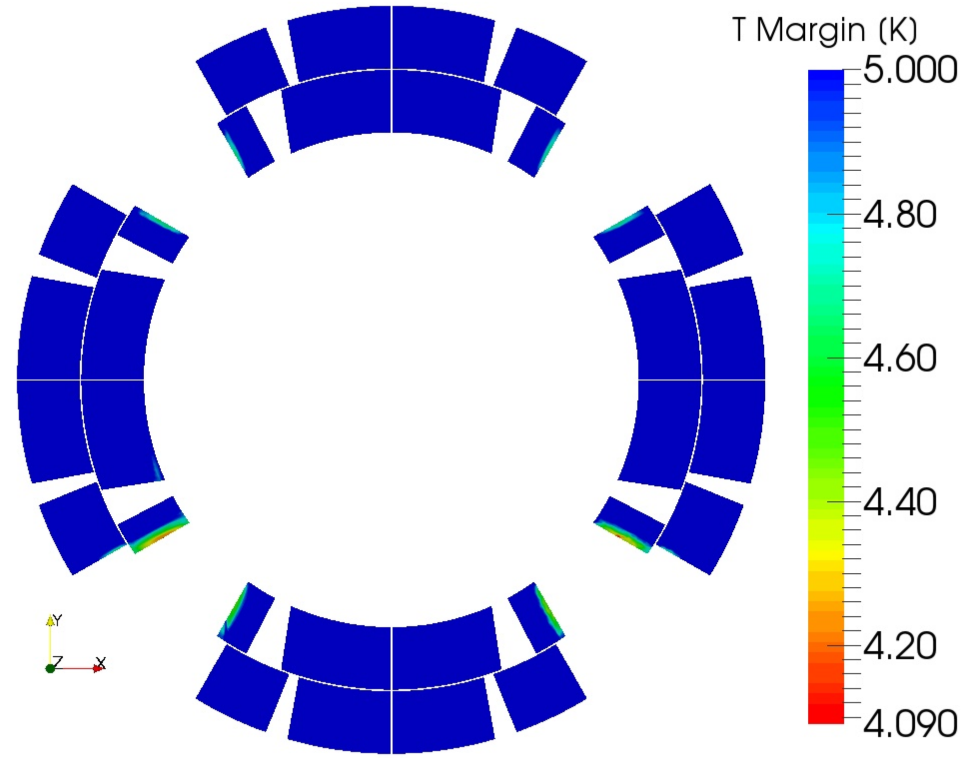
MQXF: Steady state results: T-margin





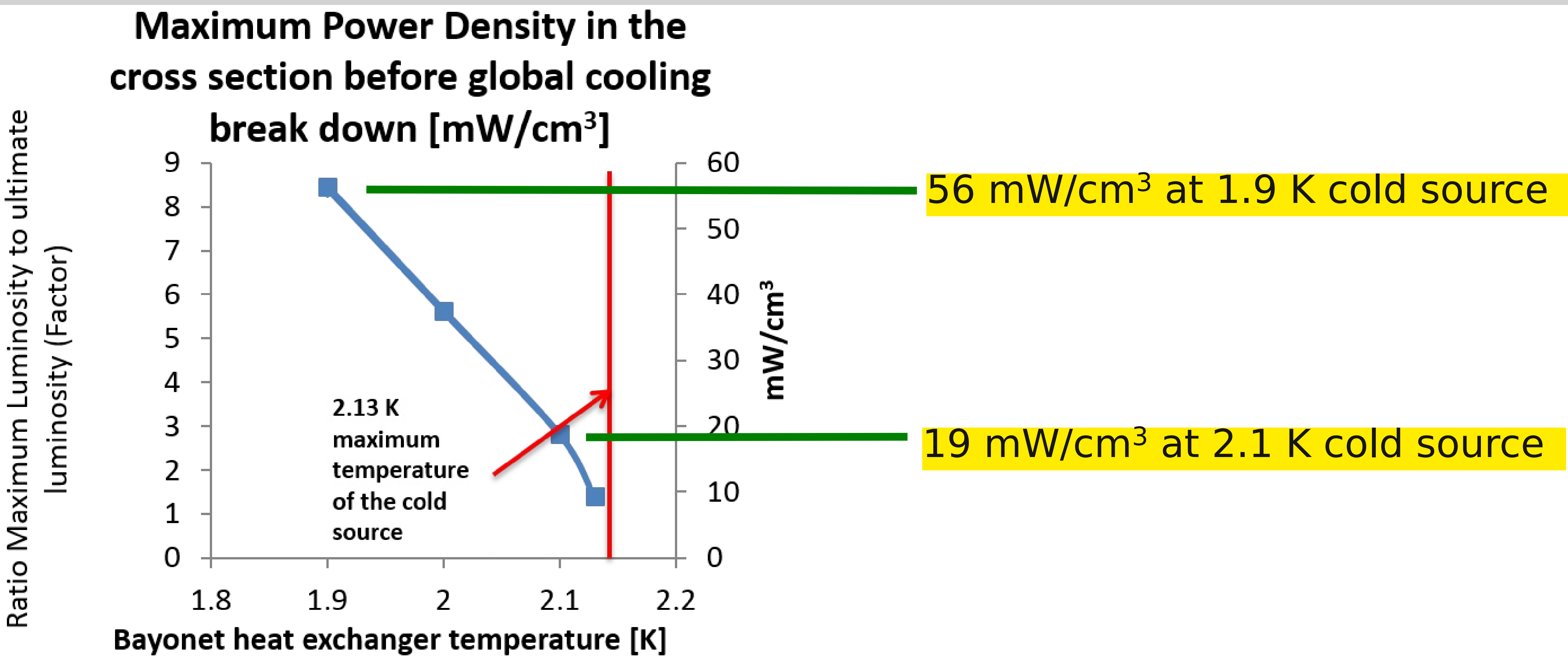
Left figure: full T-margin map, Right figure: values capped at 5.0 K to reveal details

--> Lowest T-margin is situated on the inner coil layer

(--> adaptation of the tungsten shielding foreseen on the so-called "beam-screen")

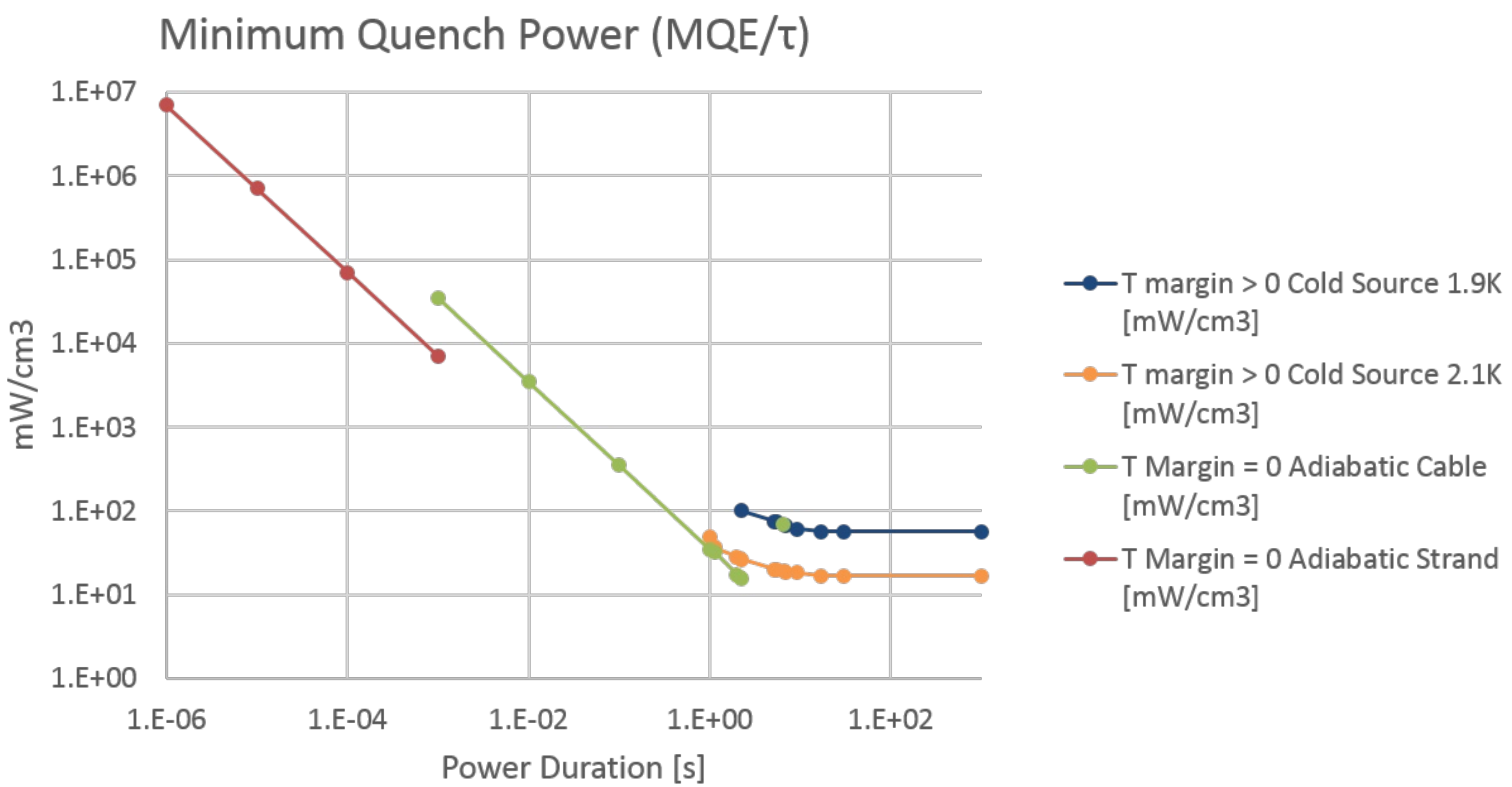
MQXF: steady state results
max power density

Thermal runaway of global cooling as function of helium bath-T (local peak load ~ 7 mW/cm^3, equivalent to 4 mW/m^3 over the conductor)



Steady state margin of factor ~3 at 2.1 K to ~8 at 1.9 K

MQXF: transient results (slide 1 of 2)
how long can the system bear heat loads beyond 57 W/cm^3?



Red = adiabatic of strand only
Green = adiabatic of full cable (including epoxies, etc)
Blue = simulation with cold-source at 1.9 K
Orange = simulation with cold-source at 2.1 K

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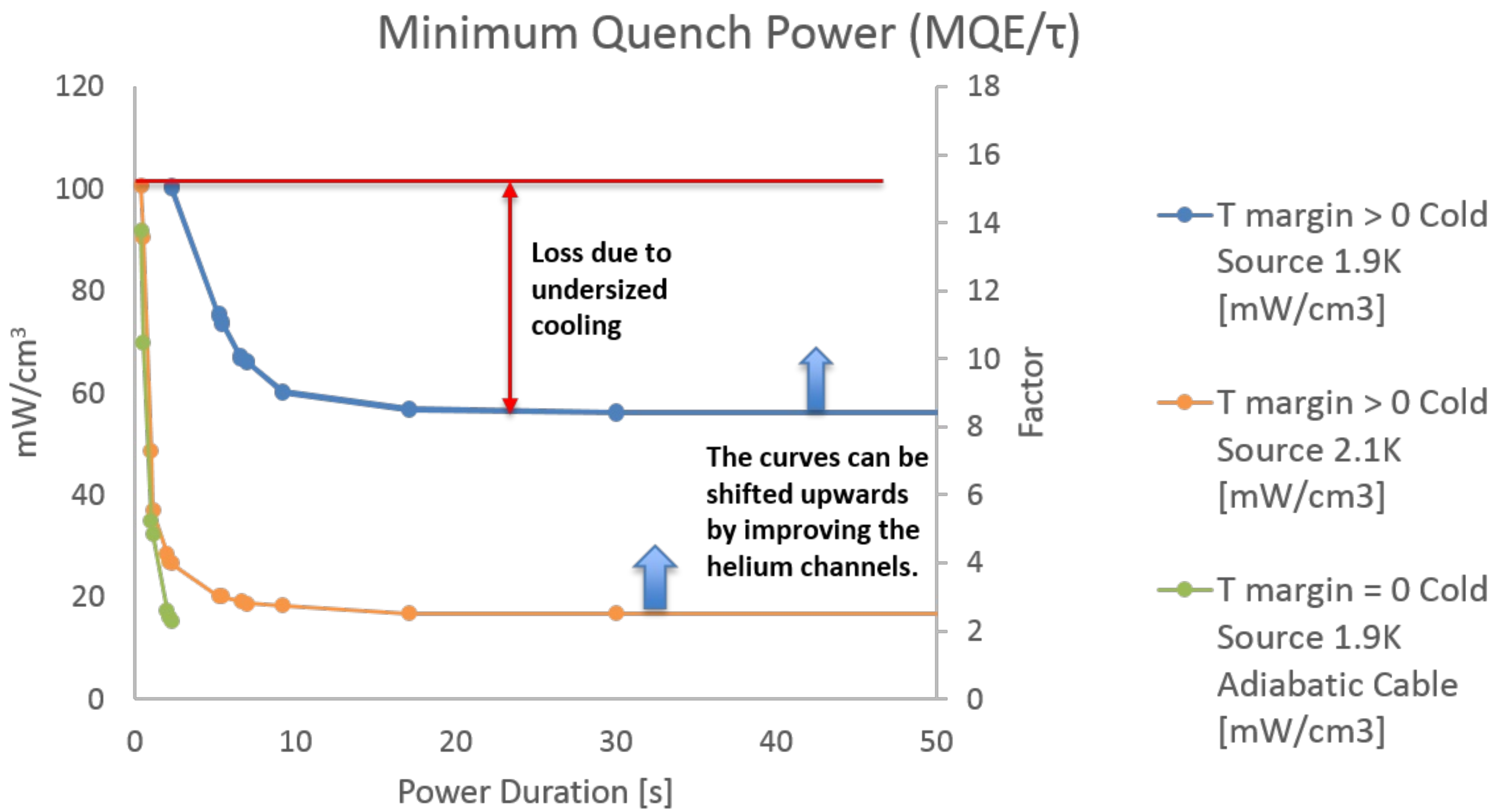
MQXF: transient results (slide 2 of 2)
how long can the system bear heat loads beyond 57 W/cm^3



Green = adiabatic of full cable (including epoxies, etc)
Blue = simulation with cold-source at 1.9 K
Orange = simulation with cold-source at 2.1 K

- At 1.9 K we reach T_{margin} = 0 K for heat pulse duration = 2.3 s and 100 mW/cm^3
- This value is determined by the cable insulation
- It demonstrates that there is room for increasing the steady state performance, (limited by Helium channels sizing)

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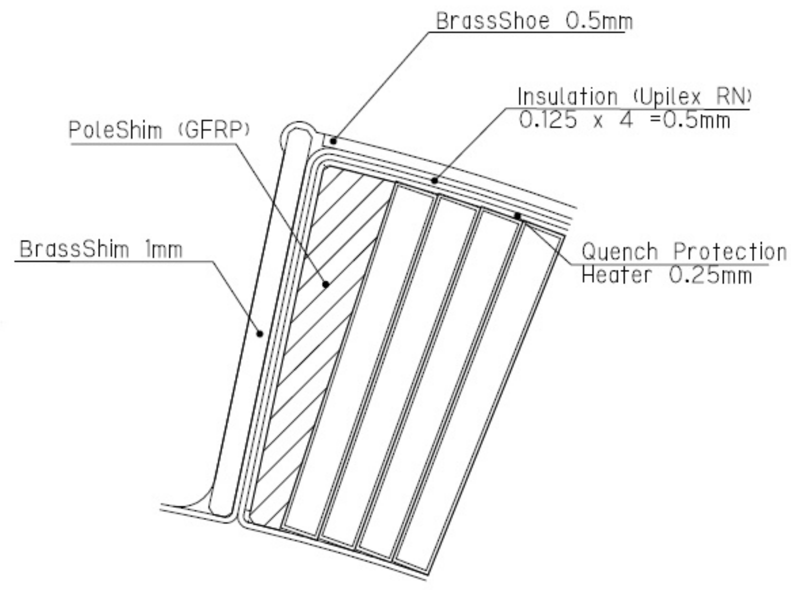
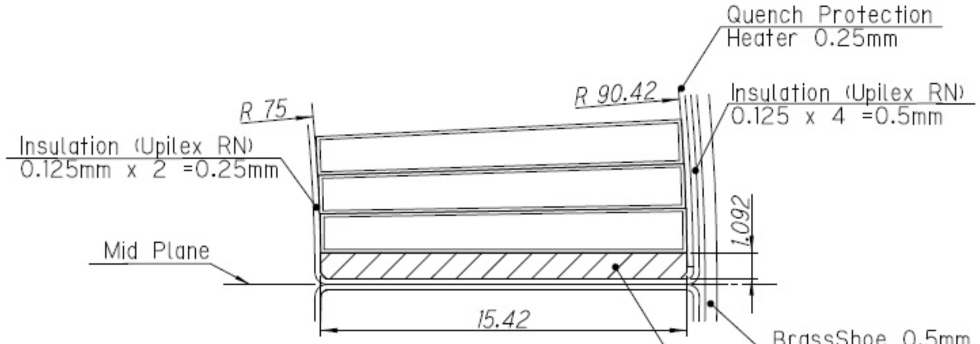
D1: Description of the thermally relevant magnet properties

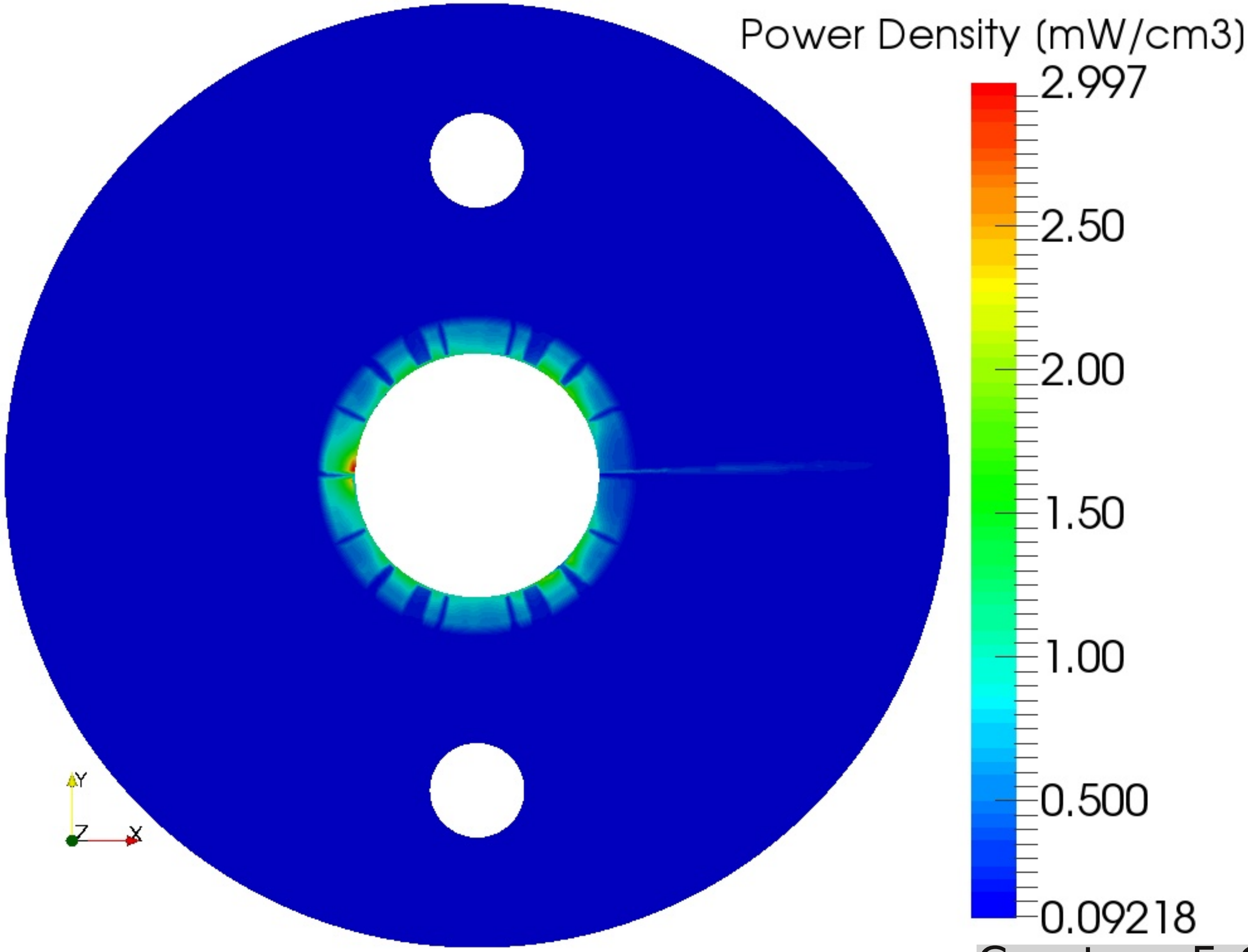


DETAIL-A



DETAIL-B

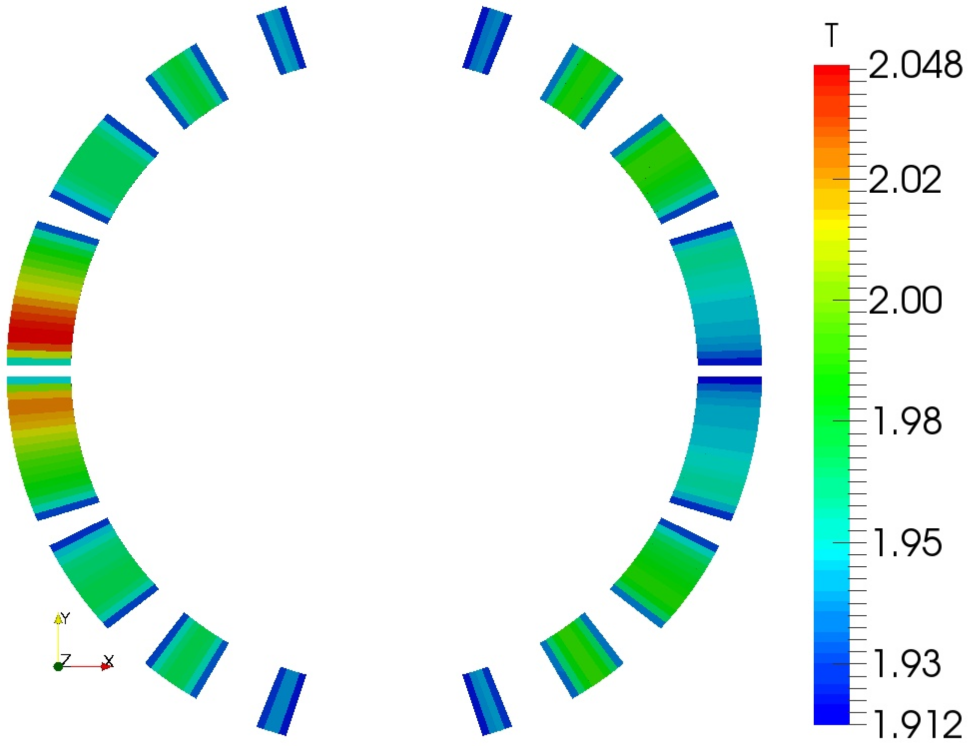
D1: high resolution energy deposition map



Courtesy F. Cerruti & L.S. Esposito

Highest power density when averaged over the cable width ~ 1.5 mW/cm^3

D: Steady state results: Temperature map



Modelisation gives highest temperature of about 2.05 K

This high-T area is however not the most critical, as one has to evaluate the final temperature margin of the coil due the local magnetic field (see next slides)

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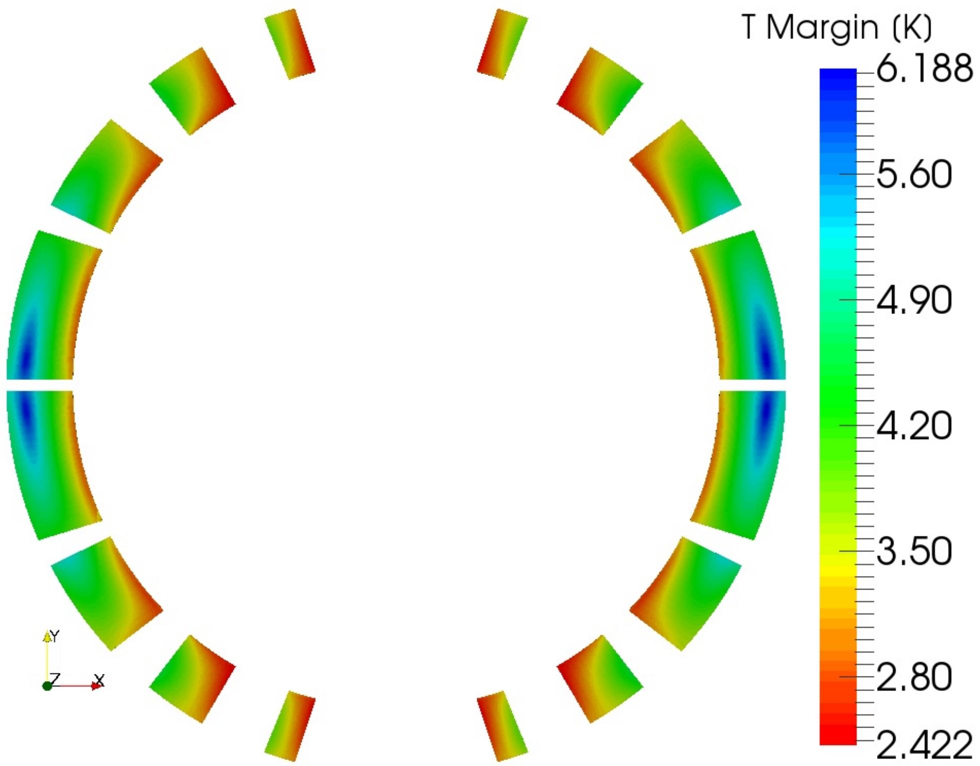
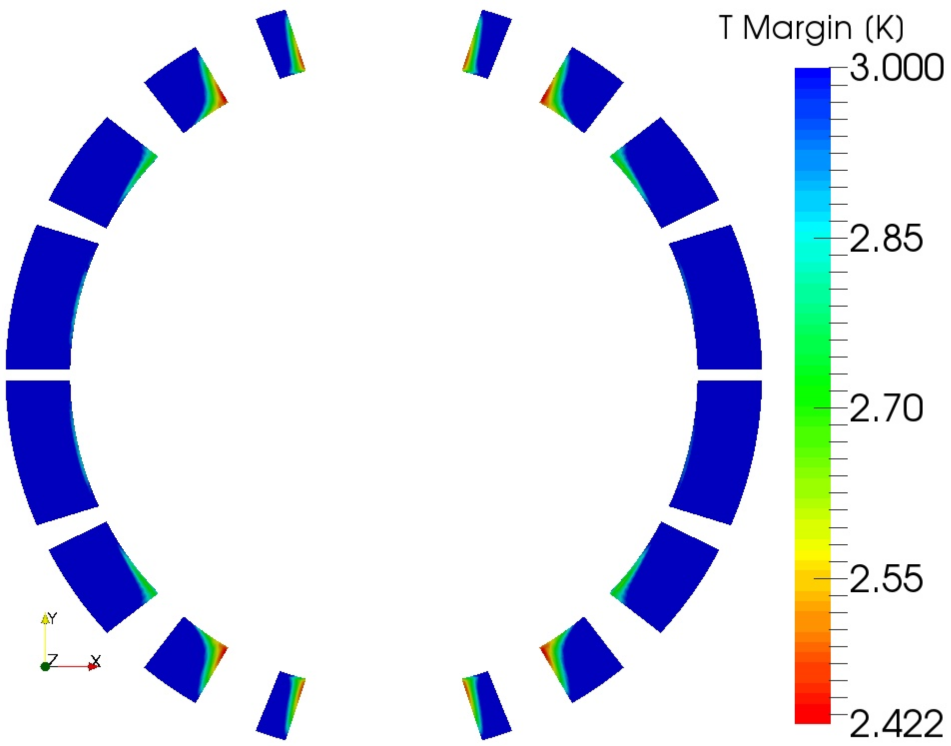
D1: Steady state results: T-margin





Left figure: full T-margin map, Right figure: values capped at 3.0 K to reveal details

--> Lowest T-margin of 2.4 K near the poles

Conclusions & Outlook

- General cooling layout to extract > 1 kW at 1.9 K similar to proven LHC configurations

- Cryogenic sizing requirements compromise with the cold mass designs are feasible

- the thernal evaluation of the MQXF and D1 designs show fully acceptable T-margin values

- the T-margins are dominated by helium channels sizing (annular space and radial holes on equal footing, not shown in this presentation)

- exploration of MQE transition to adiabatic regime would require model refinements

- safety analysis of pressure rise after magnet quenches and/or catastrophic vacuum loss to be addressed to define safety startegy and quantify safety devices.