Cooling scheme for the cold powering system, WP9_Cryogenic_Aspects

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With the help of Daniel Berkowitz, Antonio Perin & Udo Wagner

3-4 July 2017

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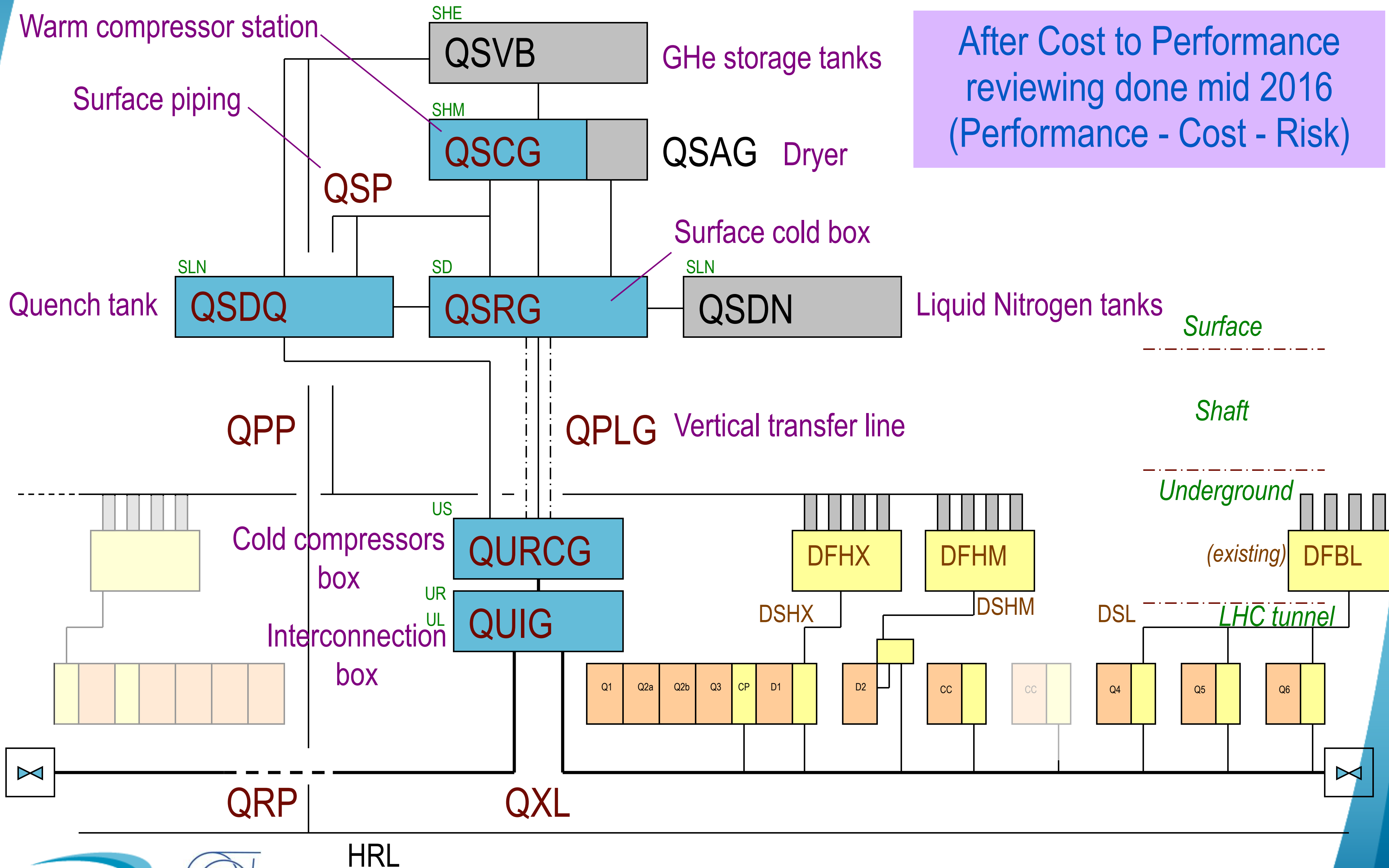
Qualification/tests and SM18 activities not reported here, see dedicated talks (Amalia, Marta) just after

P1/P5 Cryogenic architecture

18 kW equivalent at 4.5 K, including 3 kW at 1.8 K

After Cost to Performance reviewing done mid 2016 (Performance - Cost - Risk)



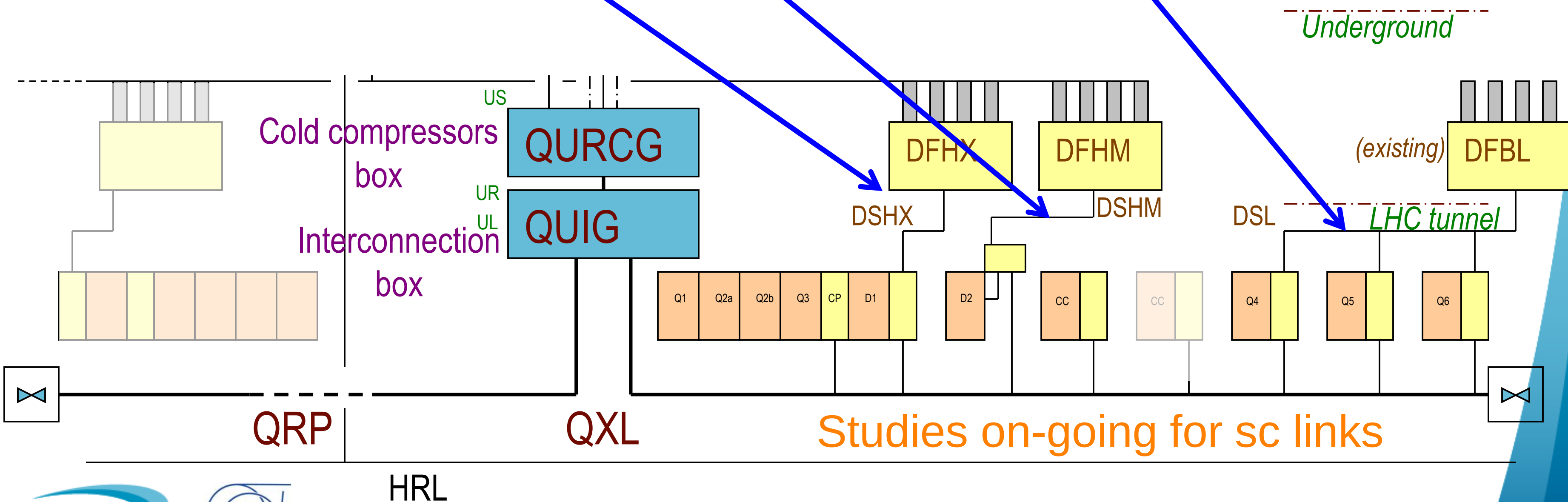
P1/P5 Cryogenic architecture

18 kW equivalent at 4.5 K, including 3 kW at 1.8 K

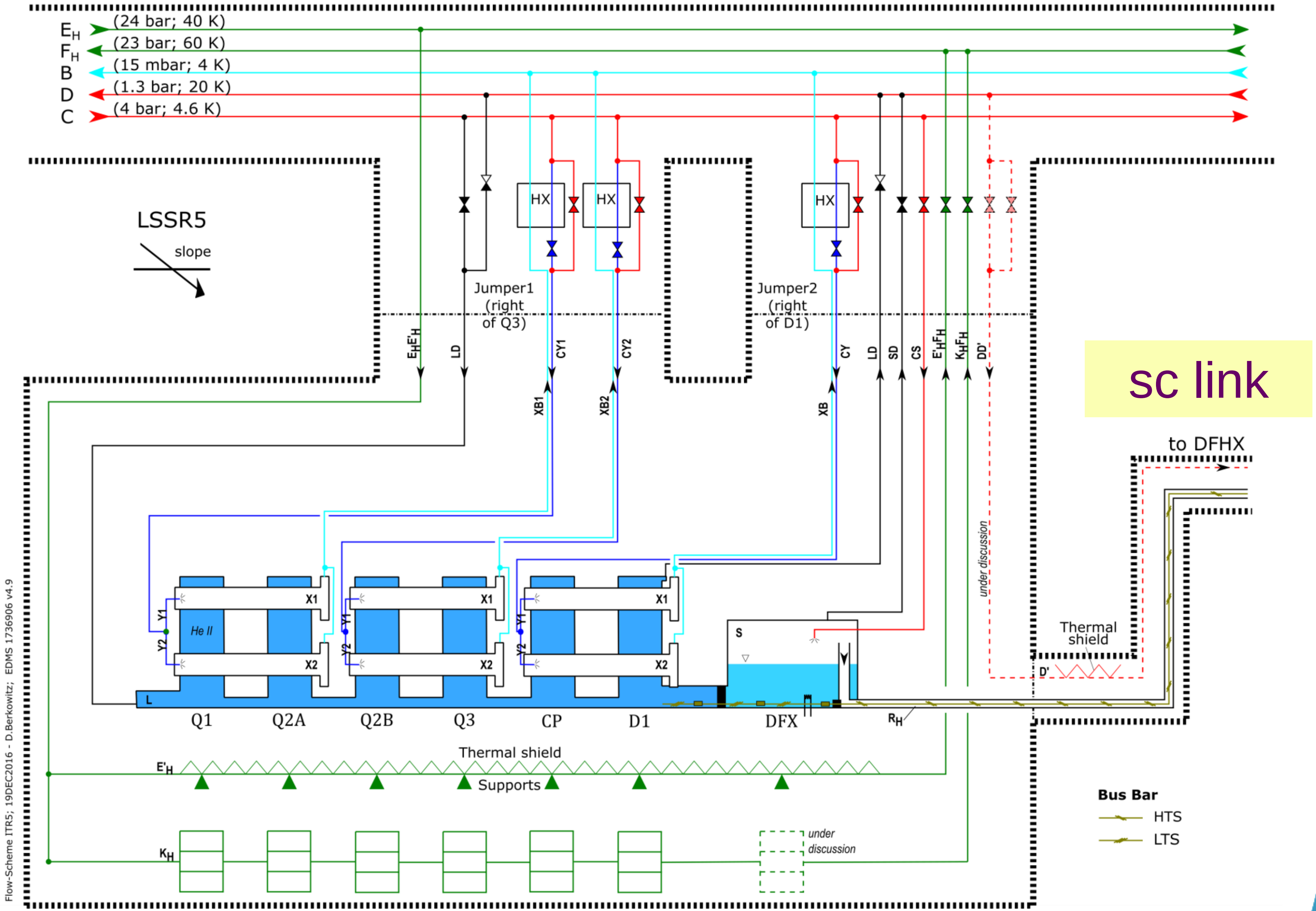
1. Main sc link,
cooling flow driven by large currents

2. sc-link for D2,
So far similar to main link,
lower current w.r.t length

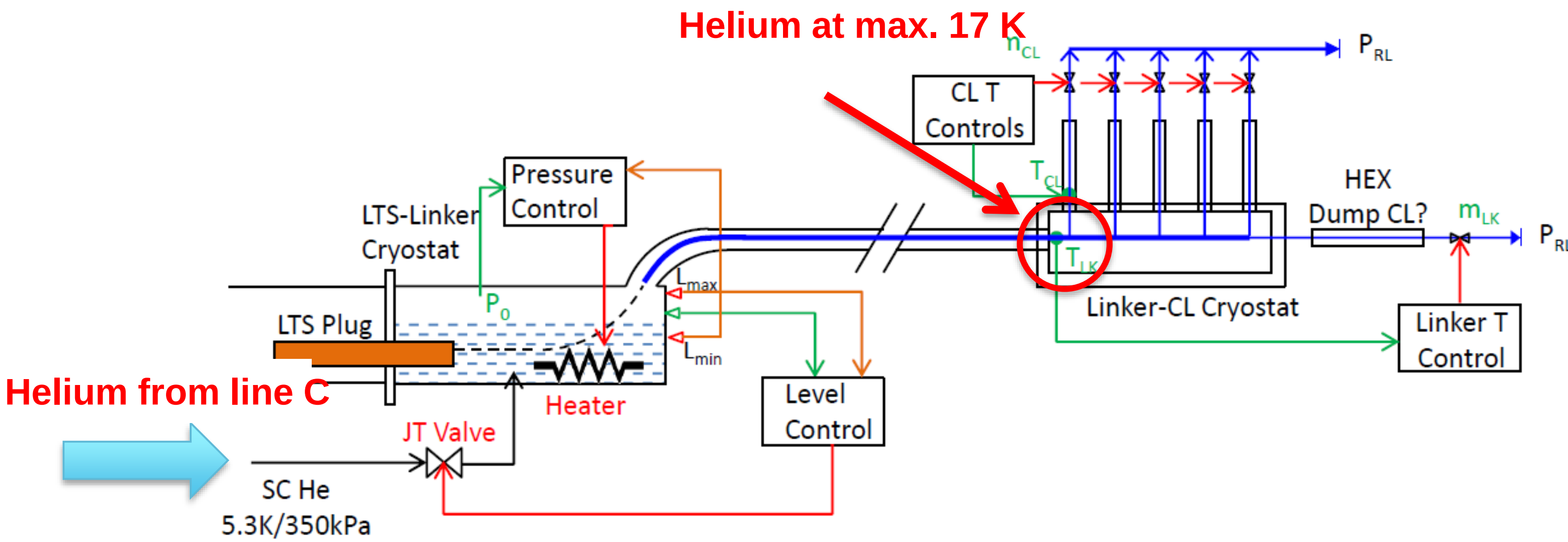
3. sc-link for Q4-Q5-Q6,
To be further studied (existing/new)



HiLumi Triplet R5 flow scheme



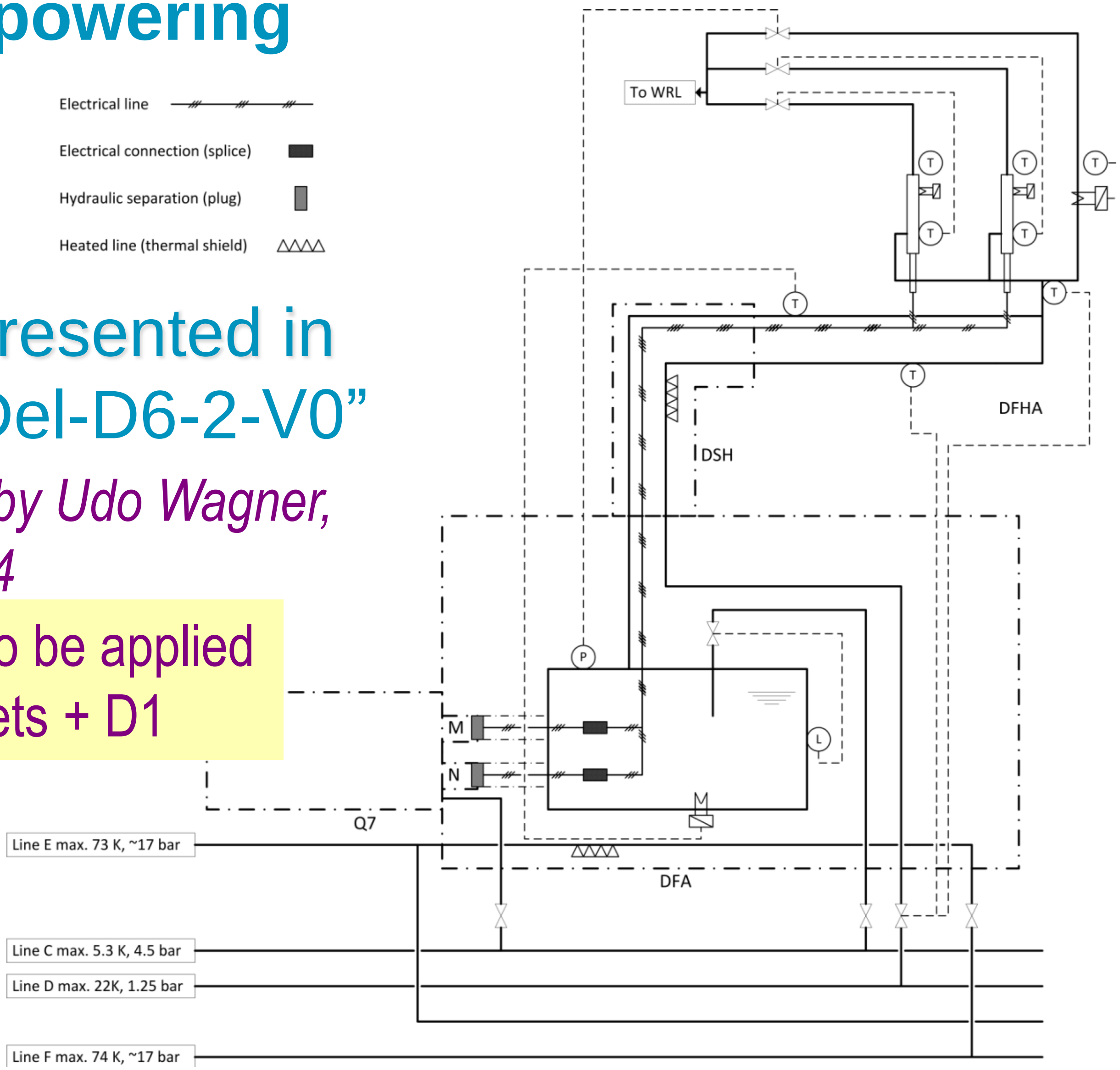
Current Base concept (all sites)



- The (assumed) 17 K limit for the MgB2 link allows only the 5 K, 3.5 bar helium from line C as coolant.
- The link will be cooled by helium gas created by evaporating the liquid helium in the splice box.
- Thermal shield solution not shown. !!!

U. Wagner
1st Annual Meeting
2011

Typical cooling scheme for cold powering

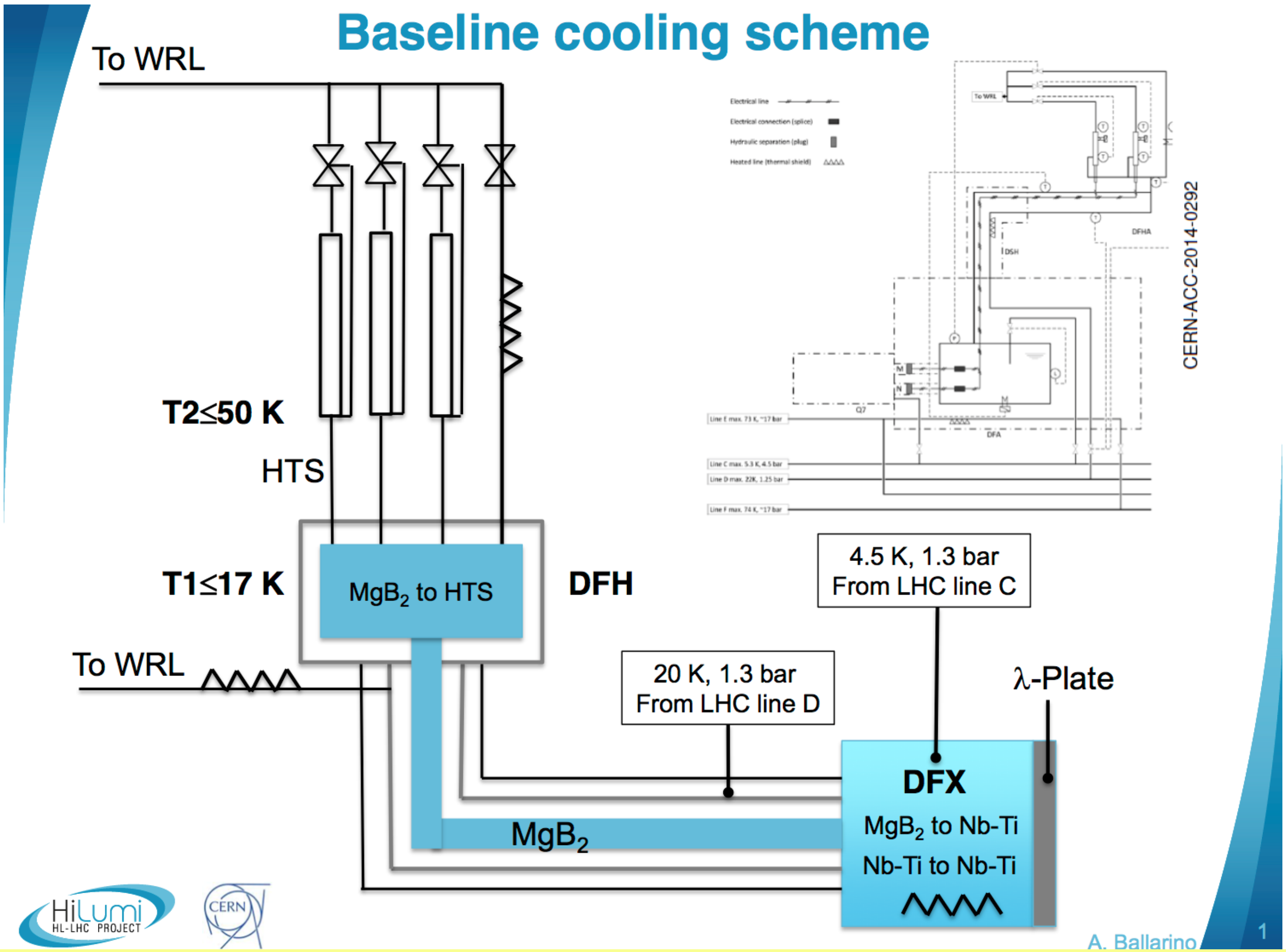


Baseline as presented in "HILUMILHC-Del-D6-2-V0"

Schematic & work by Udo Wagner, 2014

Same principle to be applied for new triplets + D1

Simplified cooling scheme



Cryo aspects: this could be built, and it would work !

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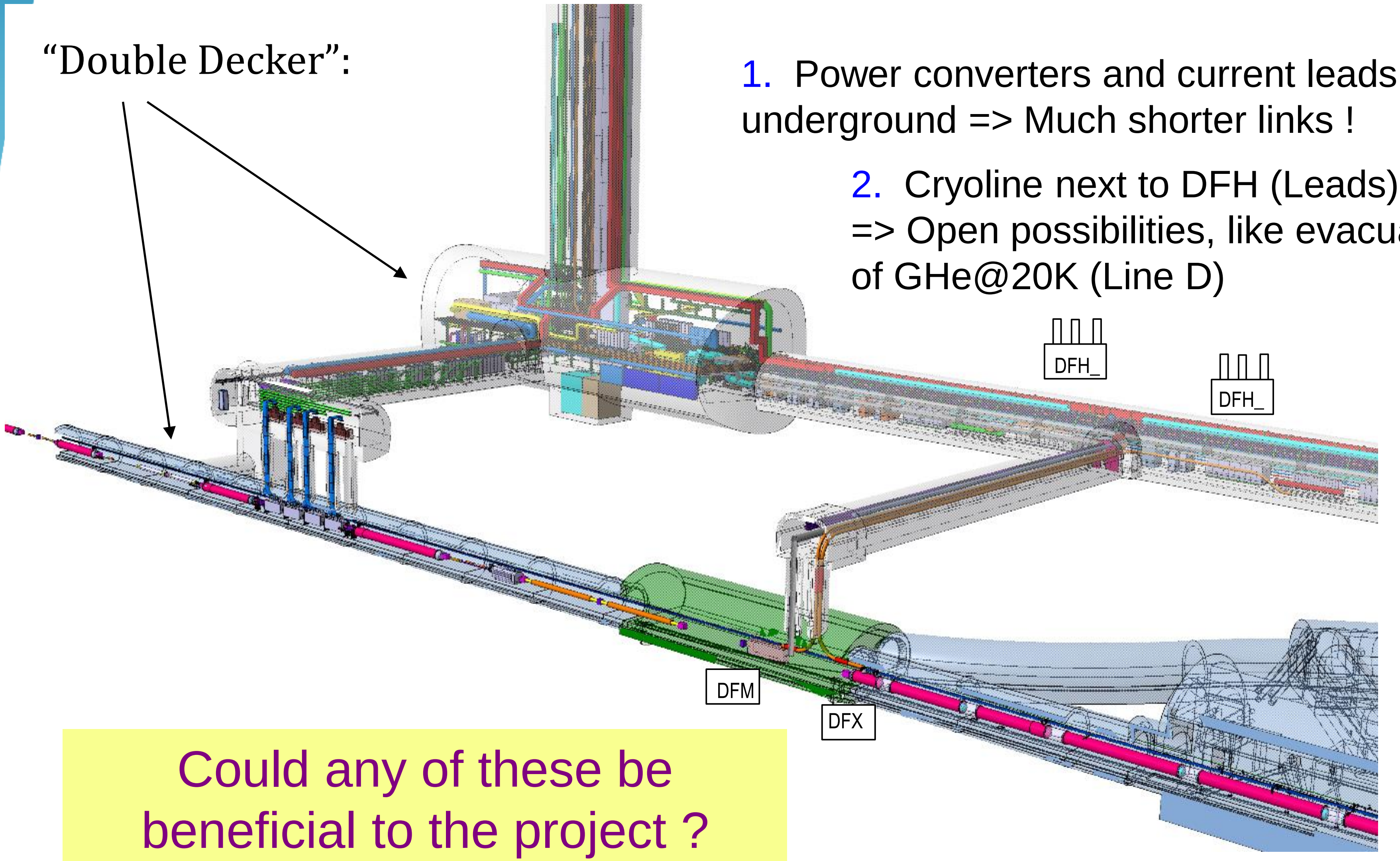
Present integration at Point 1 and 5

"Double Decker":

1. Power converters and current leads underground => Much shorter links !

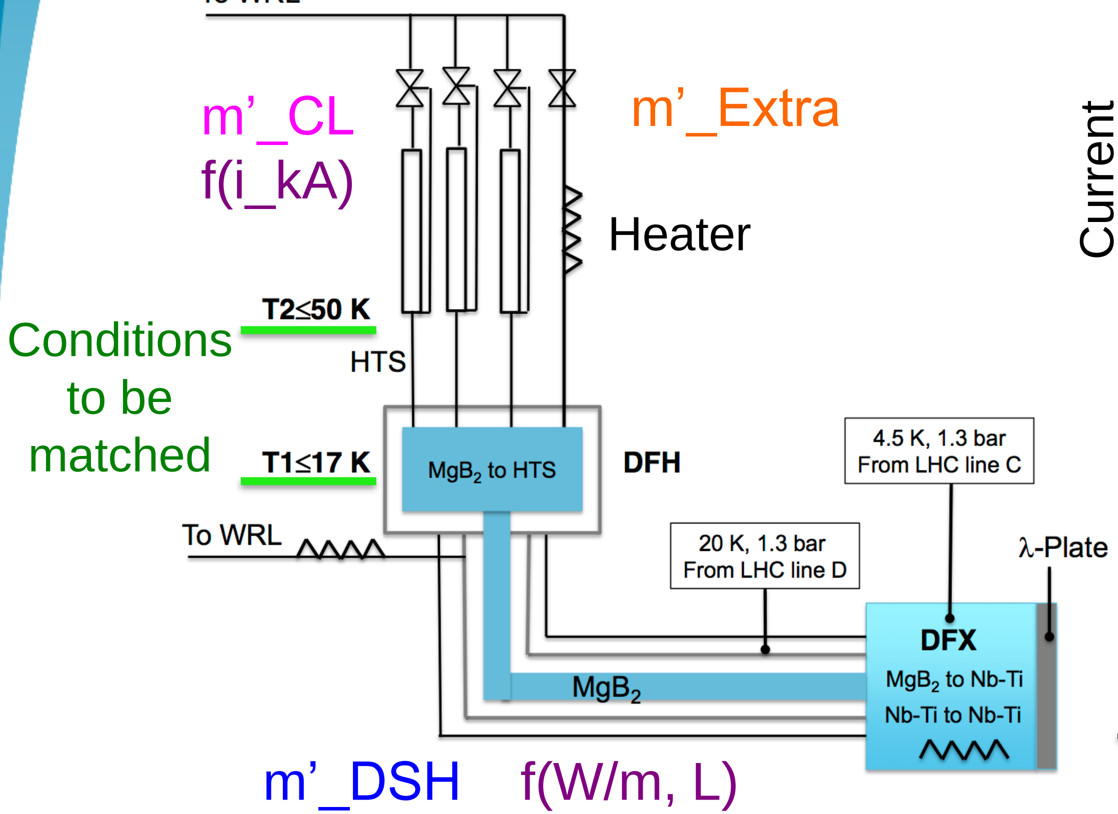
2. Cryoline next to DFH (Leads) => Open possibilities, like evacuation of GHe@20K (Line D)

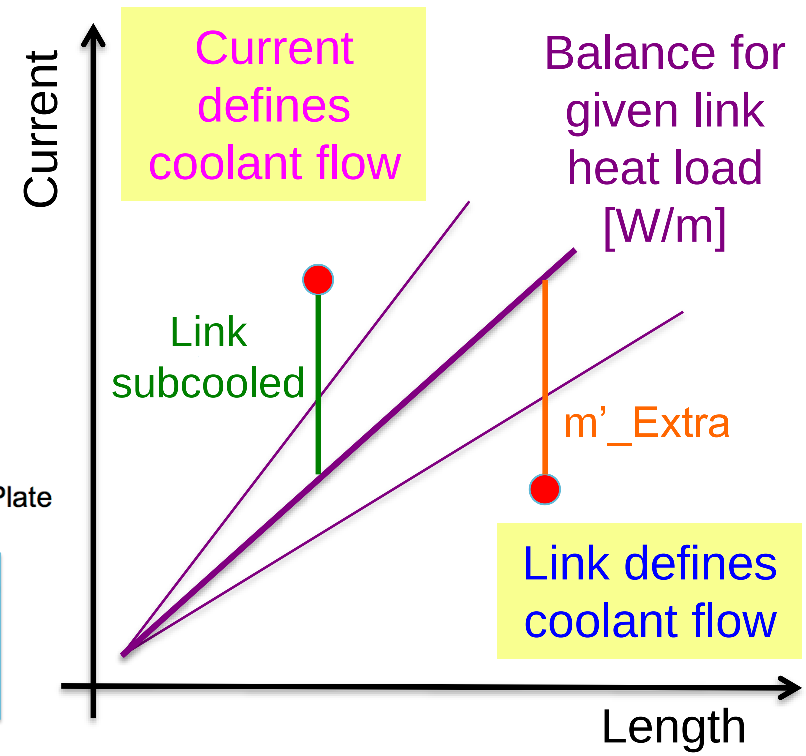


Could any of these be beneficial to the project ?

Cooling principle and governing parameters

Baseline cooling scheme

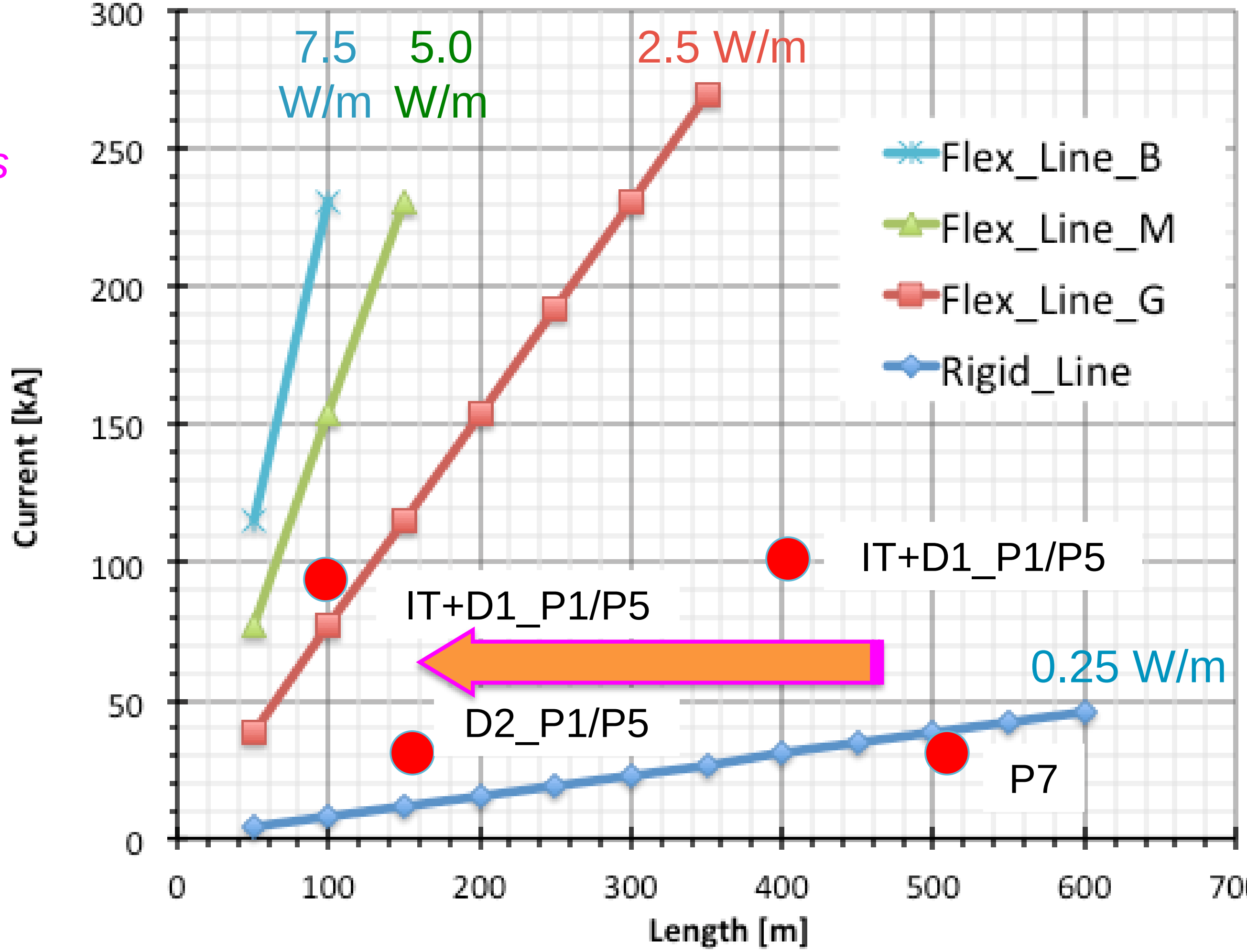




Cooling principle and governing parameters

Basic application to HiLumi, to be completed with splices and other singularities

50 mg/s per kA



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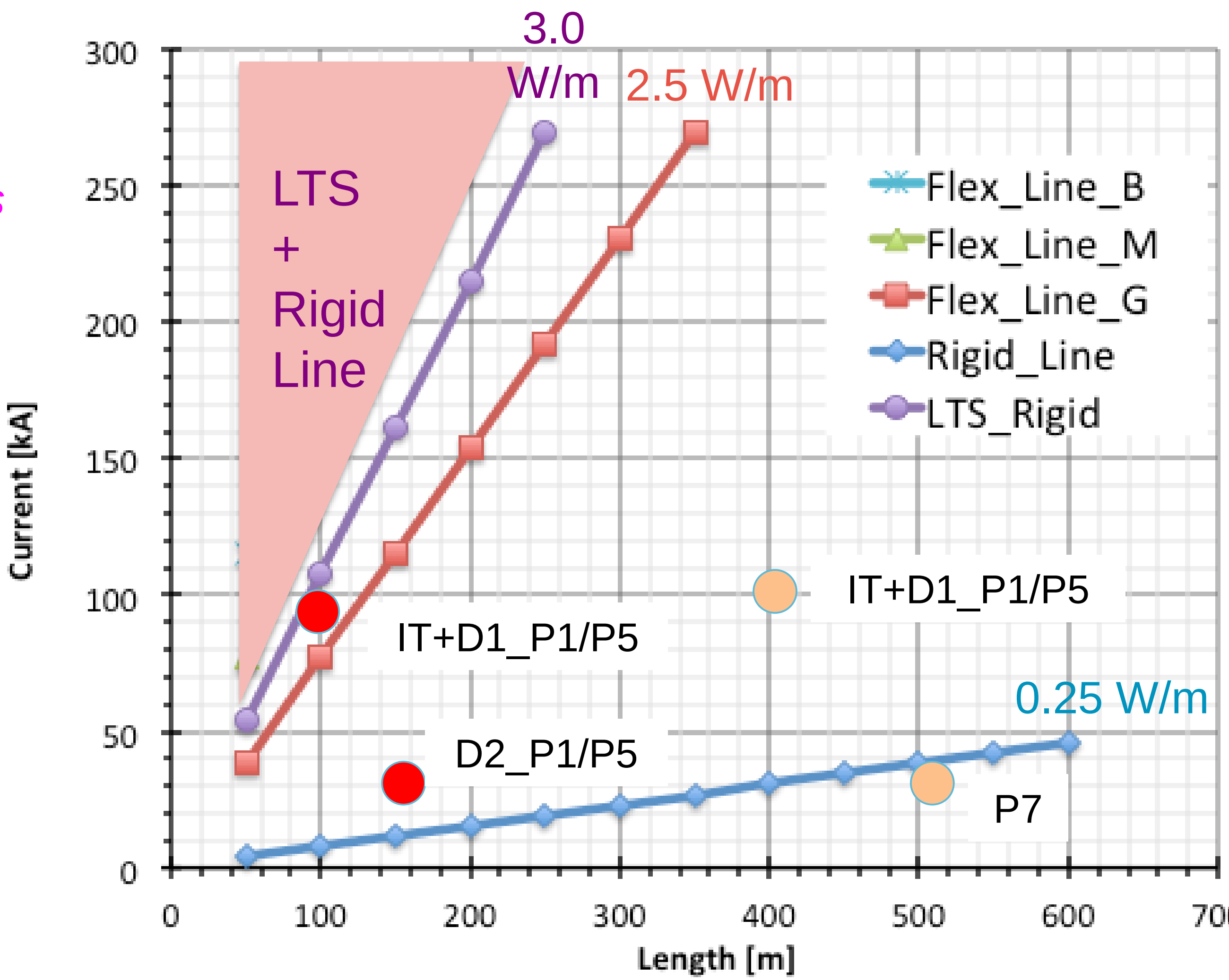

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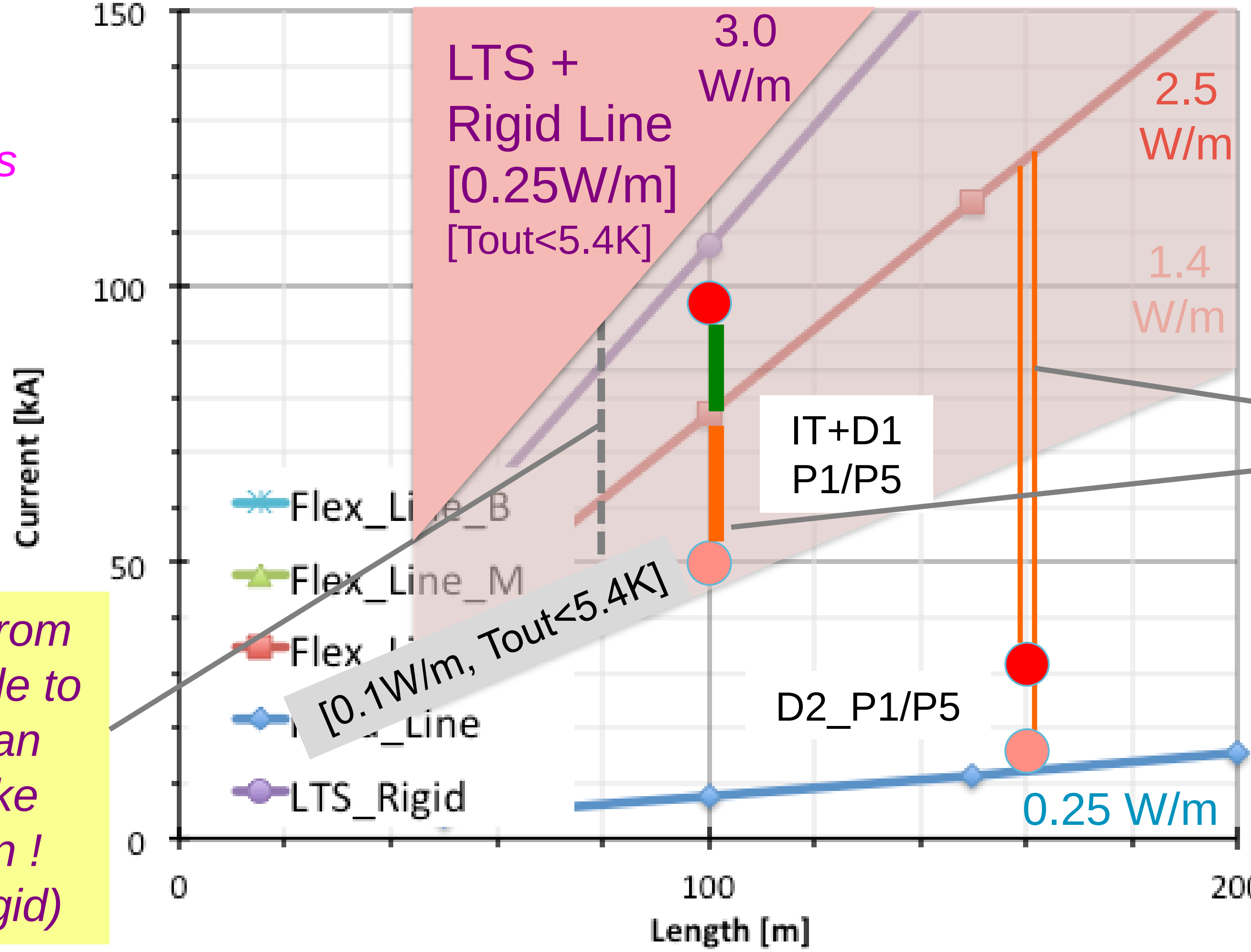


Definitely worth recovering extra flow at low temperature

Not far from being able to go for an LHC-like solution ! (LTS+rigid)

DSH and DFH_ Cooling
(Baseline and Alternative Features)

This study envisages **3** alternative changes w.r.t. the baseline

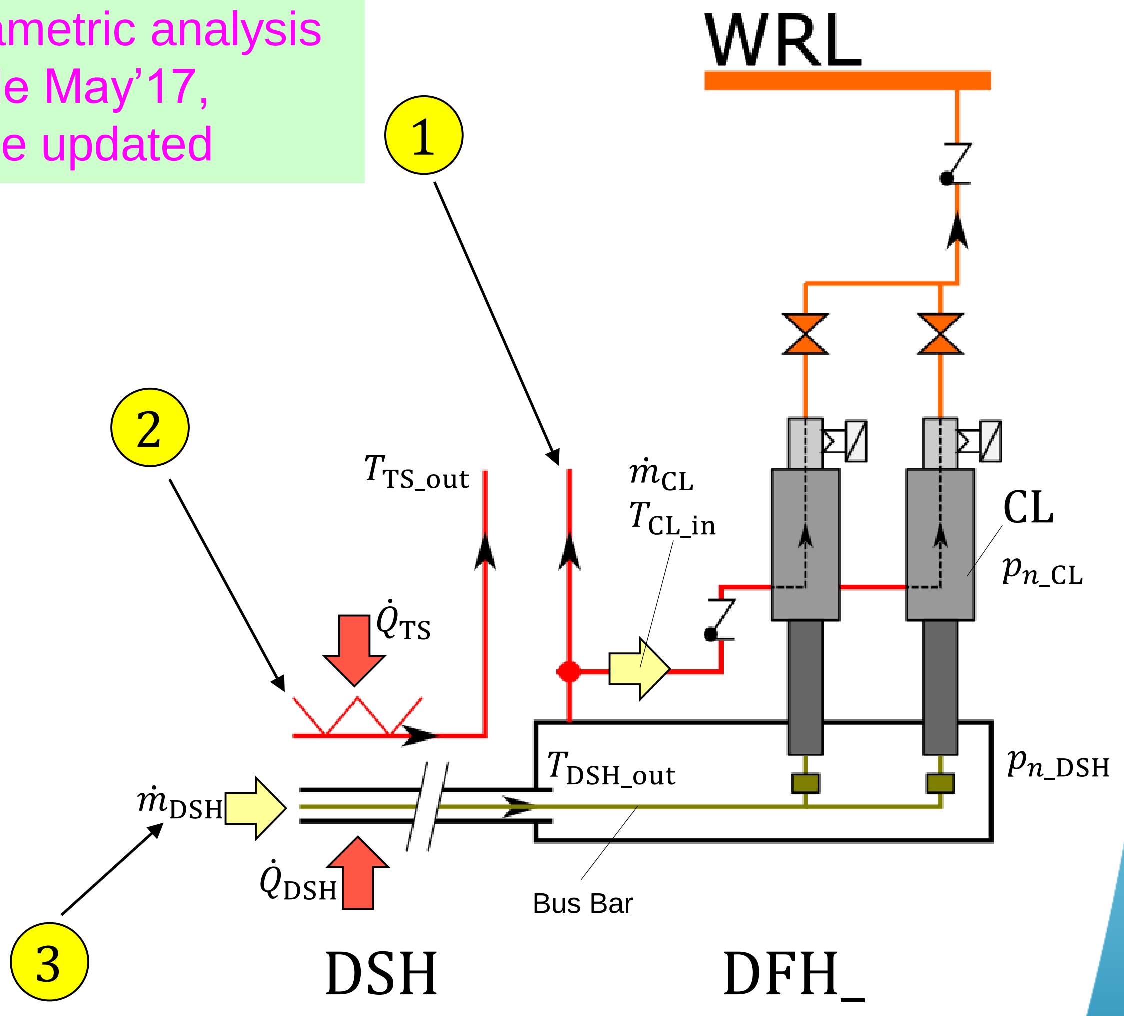
Model and parametric analysis made May'17, To be updated

Main features are:

1. "Recovery" Line of DFH_
   Baseline: to WRL
   Alternative: to Line D

2. Thermal Shield (TS)
   Baseline: with TS
   Alternative: no TS

3. Helium flow
   Baseline: GHe (gaseous)
   Alternative: SHe (supercritical)



Available cooling interfaces

HL-LHC Headers:

Design pressure

Operational

	HEADER				
	C	D	E	F	WRL
p_n [bar]	20	20	25	25	t.b.c.
p [bar]	3	1.3	24	23	1
T [K]	5	20	40	60	290

IN→OUT connection:

Only feed for DSH

Suitable for TS and CL

Now more headers are available

Equivalent Cooling Power @4.5 K for **1 g/s** [W]

OUT \ IN	C	D	E	F
C	-	-	-	-
D	59	-	-	-
E	-	-	-	-
F	-	-	9	-
WRL	103	44	57	49

Operational Cost (10 years)
1 W@4.5K ~ 1 kCHF

For:
- 10 years (~65 000 h)
- 60 CHF/MWh
- COP = 250 W/W

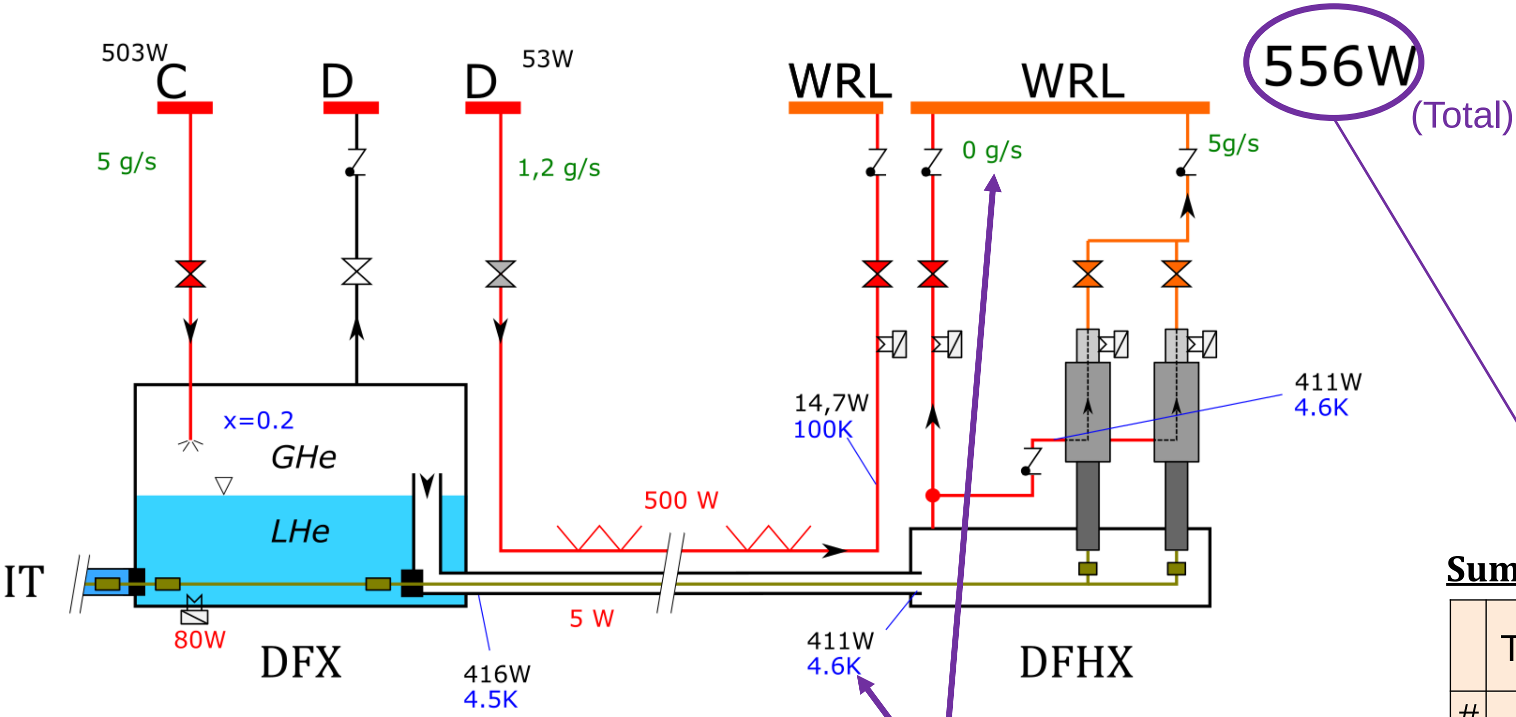
Using LHe is by far (double) more expensive than any other cooling alternative

Cooling Variants

Legend:
$\dot{Q}_{eq.}$ [W@4.5]
$\dot{Q}$ [W]
T [K]
$\dot{m}$ [g/s]

Gaseous helium, with thermal shield, exhaust WRL only

Variant #1 **GHe / wTS / WRL** (Baseline)



Flow dominated by CL
- Extra flow from Line C
- DSH "too cold"

Summary Table:

#	TS	Line D	[W@4.5] GHe	SHe
1	y	-	556	
2	y	y		
3	-	-		
4	-	y		

(All Variants in **Appendix 1**)

Cooling Variants

Legend:

$\dot{Q}_{eq.}$ [W@4.5]

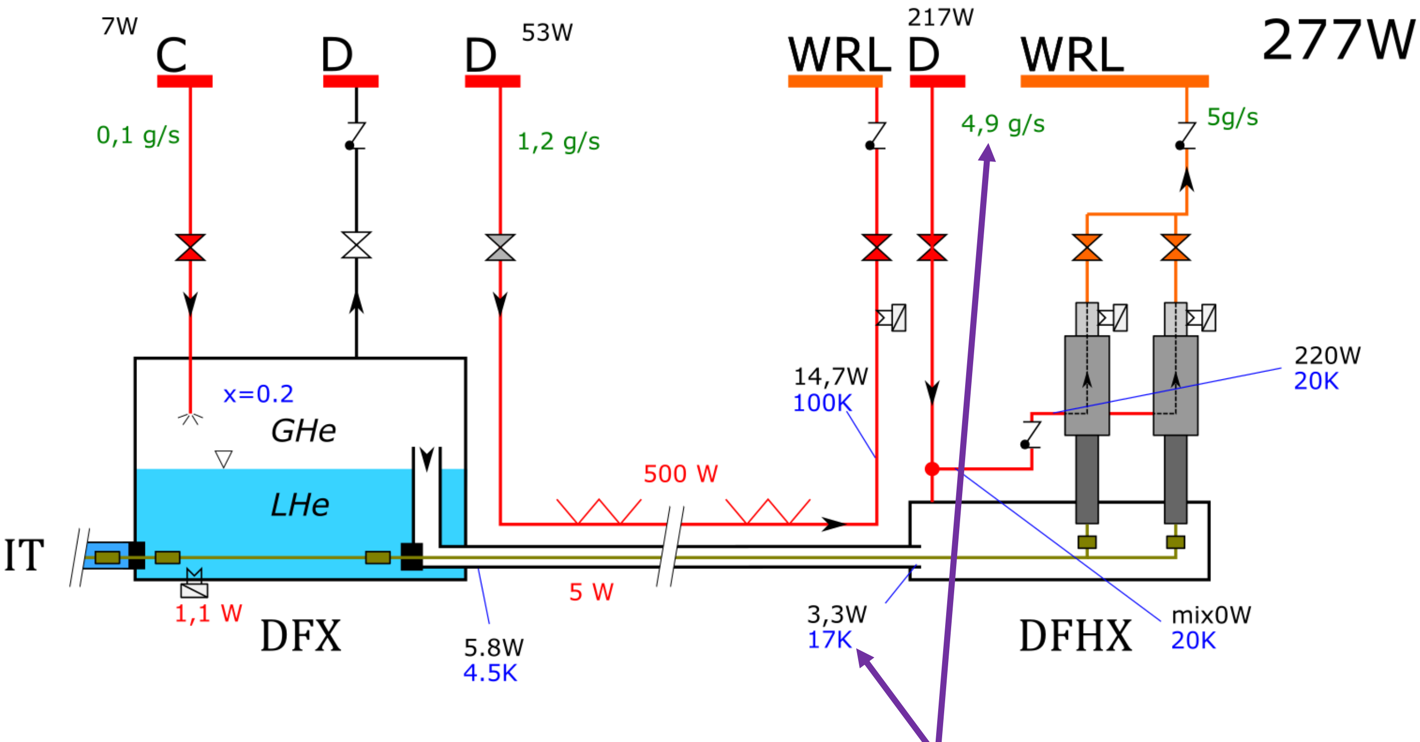
$\dot{Q}$ [W]

T [K]

$\dot{m}$ [g/s]

Gaseous helium, with thermal shield, connection to line D and WRL

Variant #2 **GHe / wTS / Line D**



Flow dominated by CL

- Main flow for CL from line D
- Minimal flow from line C

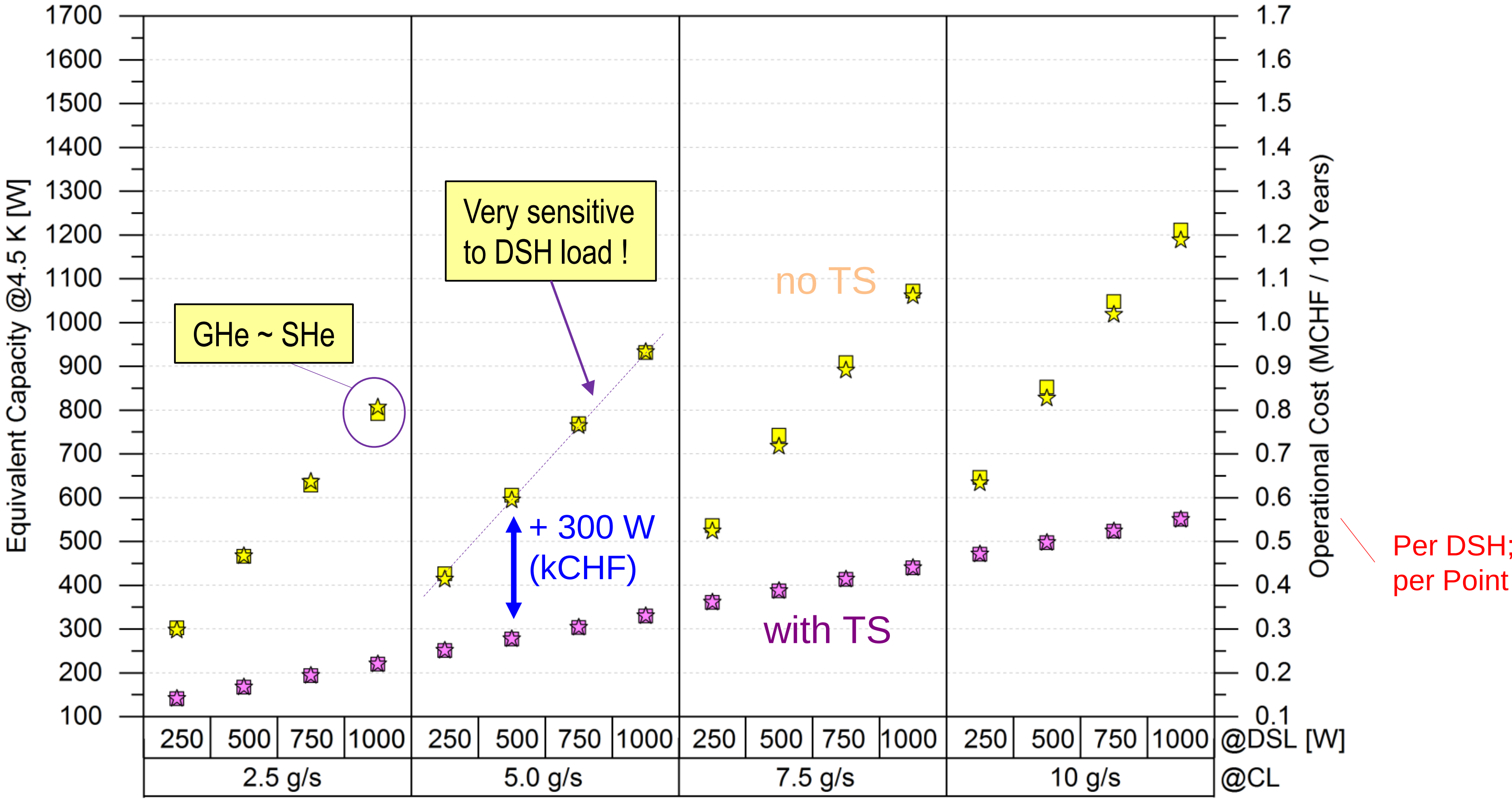
Summary Table:

	TS	Line D	[W@4.5]	
#			GHe	SHe
1	y	-	556	
2	y	y	277	
3	-	-		
4	-	y		

(All Variants in **Appendix 1**)

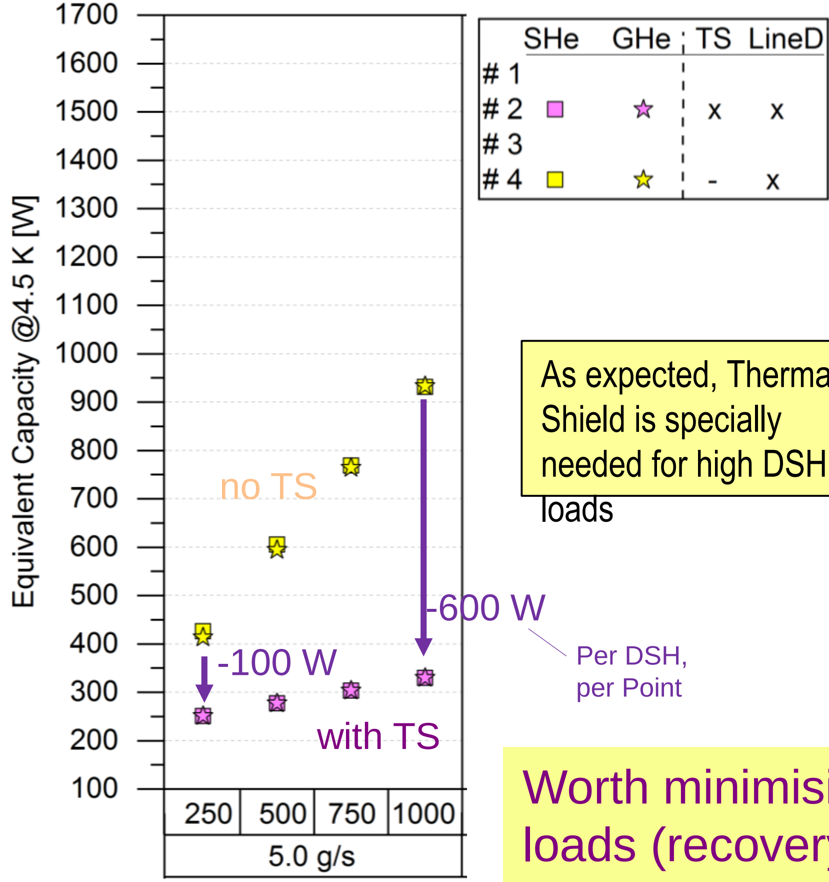
Parametric Study
(For variants with Line D)

(Remaining Variants in **Appendix 2**)

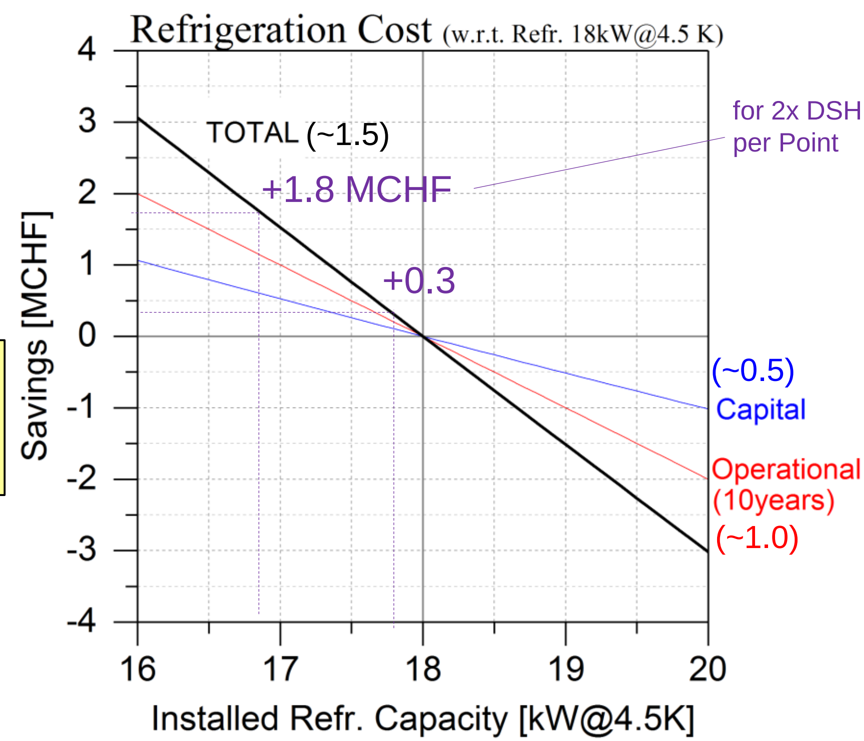


	SHe	GHe	TS	LineD	
# 1					
# 2	■	☆	x	x	With thermal shield; with line D
# 3					
# 4	■	☆	-	x	No thermal shield; with Line D

Refrigeration Cost
(Example for 5g/s & Line D)



As expected, Thermal Shield is specially needed for high DSH loads



Worth minimising pure liquefaction loads (recovery of cold gas, other cooling alternatives)
Systematic analysis for IT+D1 and D2 mandatory (Cryo, Aut'17)

Operational Cost for:
- 10 years (~65 000 h)
- 60 CHF/MWh
- COP = 250 W/W

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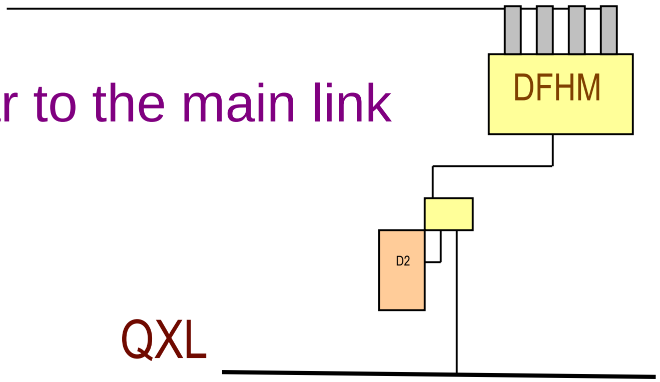
- Introduction and baseline cooling principle
- Changes since origin and possible impact
- Few words for D2
- Specific case of Q4-Q5-Q6
- Summary

2. sc-link for D2



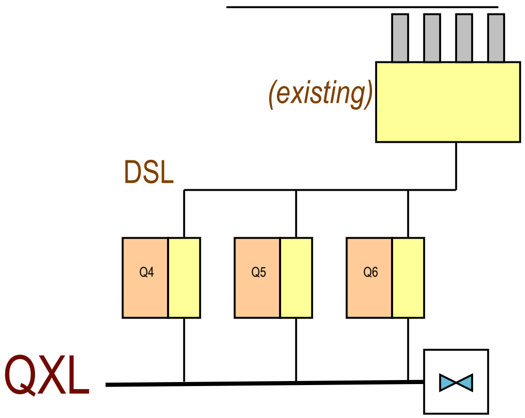
- Basically with a cooling scheme similar to the main link (IT+D1), no more details yet,
  with geographic input to be finalised

- Cooling margin of the link to be assessed, as same length but lower current rating than main sc-link

- Same consideration for thermal shield as for main link

3. sc-link for Q4-Q5-Q6

- Under study, based on required correctors (number and current rating) and considering number of existing leads in DFBL (and corresponding power converters and infrastructure) and present solutions for local powering

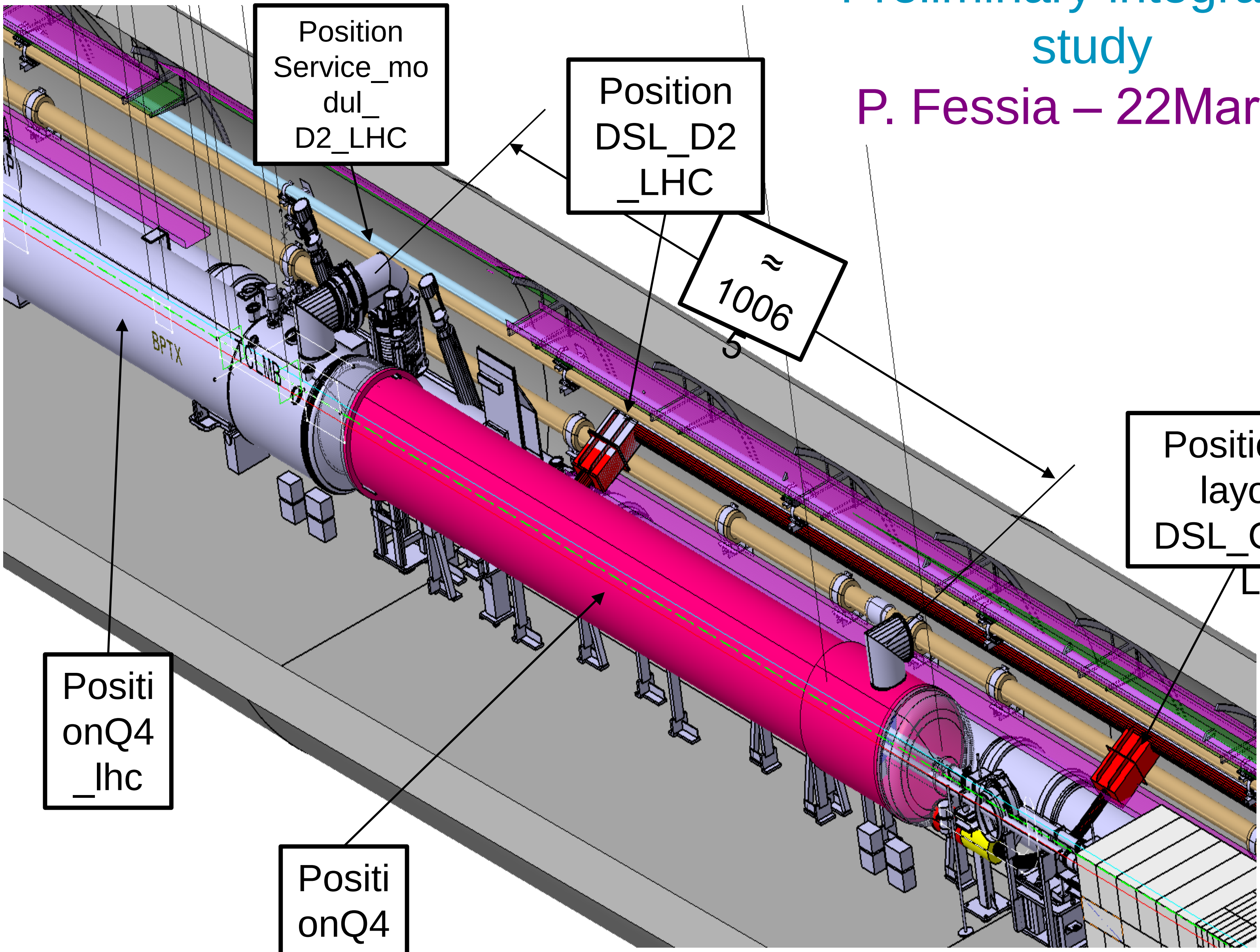


- With options considered for Q4, would be wise to consider a powering scheme that would not require a modification of the DSL link in the future

- Difficult to imagine removing the existing QRL and installing new QXL and other hardware while keeping existing DSL link in place, but we will see when studied more advanced

Preliminary integration study

P. Fessia – 22Mar'17



Preliminary integration study

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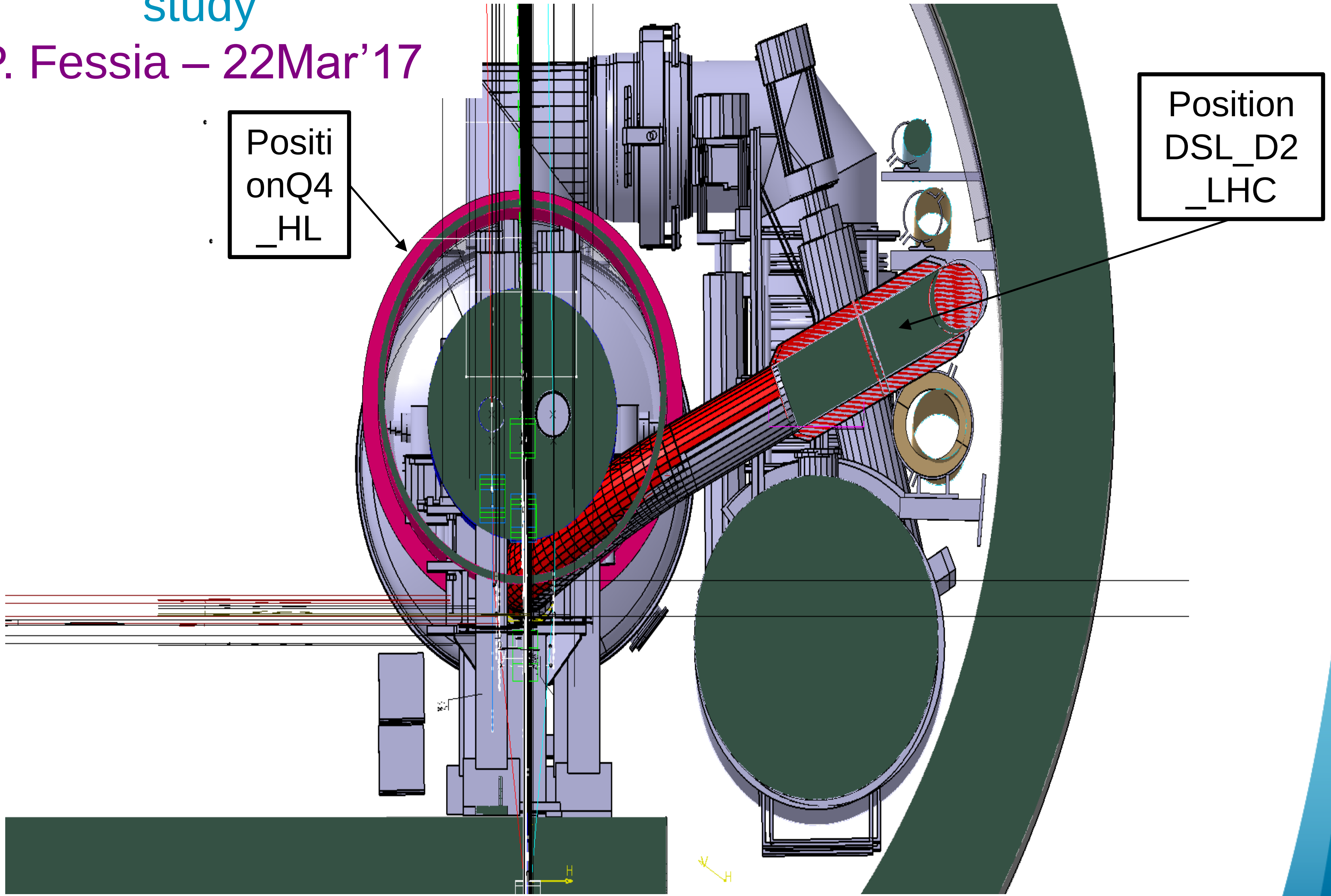


Complements for circuit review – 22 Mar'17

Present DSL compatibility with dismantling of present QRL and installation of future QXL

Introduction:

- As part of the cost to performance exercise conducted mid 2016 for the HL-LHC project, it was considered that existing components could be re-used such as DFBL's and DSL's at P1/P5.
- At this stage, we considered that these items could be re-used "as-is", without any modification.
- If this is the case for the DFBL's, it was not clear if the DSL's could be kept in place for the dismantling of the QRL and installation of HiLumi components, in particular the QXL.
- A brief but efficient study has been performed by P. Fessia & S. Maridor.

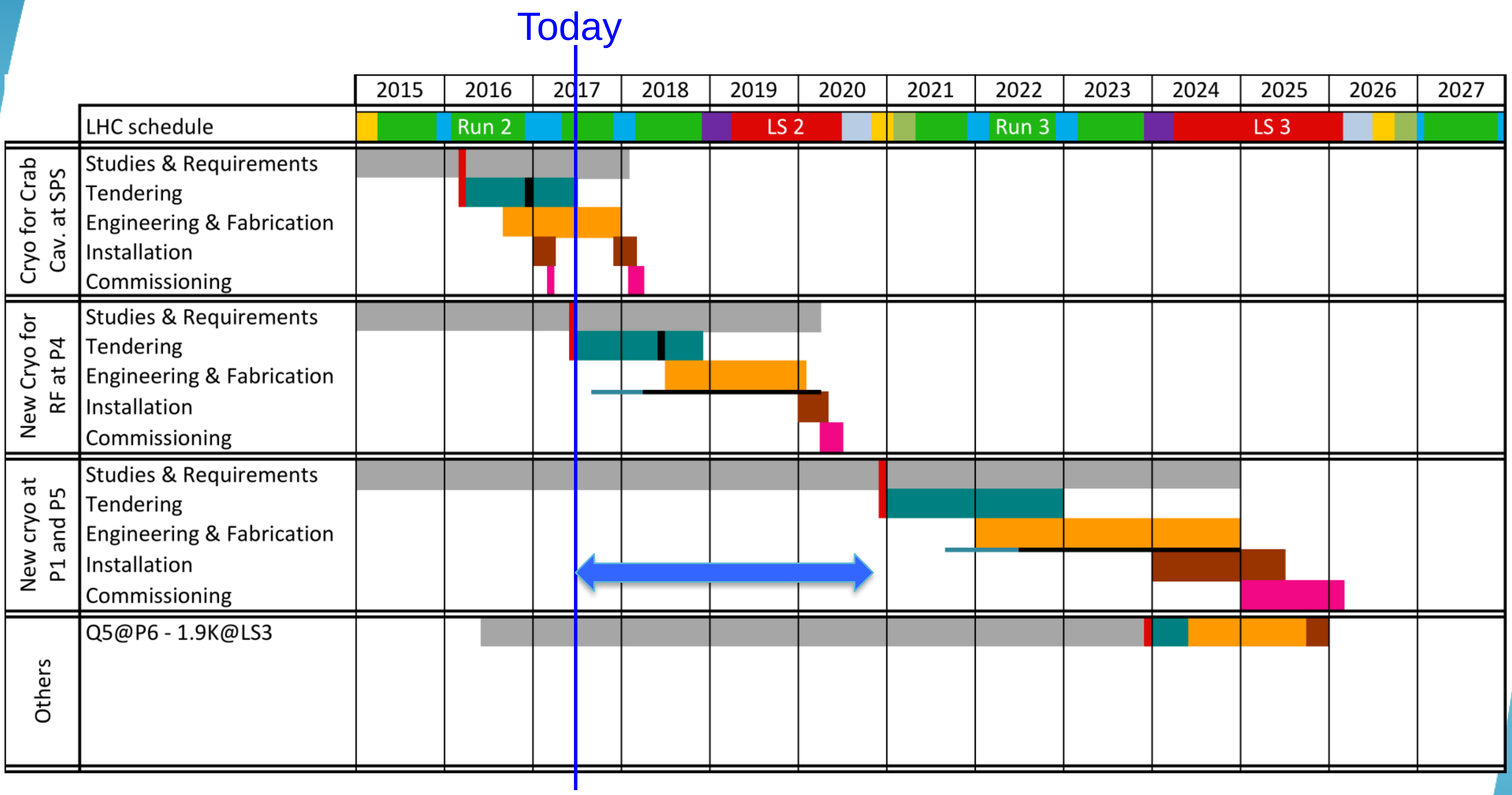
Statement for Cryogenics:

- Based on this study, the cryo team would arrive to the following conclusion for the existing DSL:
- the DSL integrity would need to be touched at the level of compensation boxes to allow dismantling the existing QRL. For the time being and considering the extremely delicate work required, we cannot commit that this would be possible without accident for the 4 units concerned.
- Therefore, we conclude that it is not possible to keep the present DSL in place for LS3 activities (touching only the splices at extremities).

Complements:

- However, we are confident that the present DSL could be kept in place from it's extremity at DFBL to the proximity of the junction to Q6. With time and appropriate resources (CRG-MSC), it should be possible to study the integration of a junction cylinder (with splices) from this proximity of Q6 to the required interface for new Q6-Q5-Q4 positions via a new DSL termination part. Making use of the dismounted elements of the DSL and having spare superconducting cable should be part of the study if the approach would be validated.
- Besides, the study does not identify potential issues for the junction of the QXL to the QRL or for the connection of the DFBL to the QXL. This is conform to our present plans.

HiLumi Cryogenic masterplan



Just-in-time for SPS-BA6, last studies for LHC-P4 before decision,

Some more time for us for LHC P1/P5, but interfaces required by others

Summary

- The present cooling baseline could be implemented for the 2 links (IT+D1 and D2) and it would work, but it does no longer fit with the general layout and opportunities of the project (underground infrastructure)
- A series of cooling variants have been studied and demonstrated significant interest. We will perform this year a systematic analysis of cooling variants (IT+D1 and D2) and quote corresponding impact (Capex+Opex) for possible change of baseline
- Recovering part of LHC infrastructure for powering Q4-Q5-Q6 results from the 2016 “Cost-to-Performance”. A joint study MSC+CRG will be held Aut’17 (2018) to finalise the technical implementation
- Cooling aspects are not a “neglected or underestimated” activity, but we believe that major changes in the project should result in adapted cooling concepts and project decisions, and we are confident that it is and will remain the case!

Thank you for your intention !

Complementary slides

(technical details, references)

HiLumi LHC, evaluation of GHe mass-flow for current leads

(with the aim to evaluate sc link temperature profile and stability)

Rev.1 done after circuit Review March'17 — *1128.5 Weq@4.5K / side*

125.12 kA / side — *9.03 g/s / side*

				Sum kA.lead:	[g/s]			
Triplets MQXF				**68.3**	**3.42**	DFHX/link1	**4.72**	g/s
Mains	18	kA	2	**36.00**			**94.3**	kA
Trims	2	kA	3	6.00 *				
Orbit Cor.	2	kA	12	**24.00**				
SF Cor.	0.2	kA	2	0.40				
	0.12	kA	16	1.92				
D1	13	kA	2	**26.0**	**1.30**			
D2				**30.8**	**1.54**	DFHM/link:	**1.54**	g/s
Main	13	kA	2	**26.00**			**30.8**	kA
Orbit Cor.	0.6	kA	8	4.80				
DFBL				**55.4**	**2.77**	DFBL	**2.77**	g/s
Q4	6	kA	3	**18.00** **				
Q4 cor.	0.12		12	1.44	*(could be upgraded via DFBL 4x0.6 for MQYY-as-Q4)*			
	0.12		4	Local		*1.92 kA*	*0.096*	
Q5	6	kA	3	**18.00** **				
Q5 Cor.	0.12		12	Local				
Q6	6	kA	3	**18.00** **				
Q6 Cor.	0.12	kA	4	Local				

**: in fact 2 leads will cover 2kA as Ultimate current is below 1.8kA, 3rd one would have only 0.12kA in operation but could go to 2kA in case of quench*

***: mid-powering with no current if circuits well balanced, so in ultimate operation only 2.5 to be considered for GHe flow instead of 3*

Basic considerations for Cryogenic transfer lines heat loads

Rigid Lines

Conservative values

80K	0.65	W/m2
	1	W/sliding point
	5	W/Fixed point
4K (shielded)	0.050	W/m2
	0.1	W/sliding point
	0.5	W/Fixed point

Bayonets:
≈DN[mm]/10

QRL

Shield	2.8	W/m
Diam	0.58	m
Surf	1.82	m2/ml
incl supports	1.54	W/m2
B,C,D	0.2	W/m
Diam	267-100-150	m
Surf	1.62	m2/ml
incl supports	0.12	W/m2

QPLB

Shield	250	W spec
Diam	0.45	m
Surf	1.41	m2/ml
incl supports	209.59	W calc
for 190m:	*1.316*	*W/m Specified*
Line C	8	W spec
Diam	0.104	m
Surf	0.33	m2/ml
incl supports	6.60	W calc
for 190m:	*0.042*	*W/m Specified*

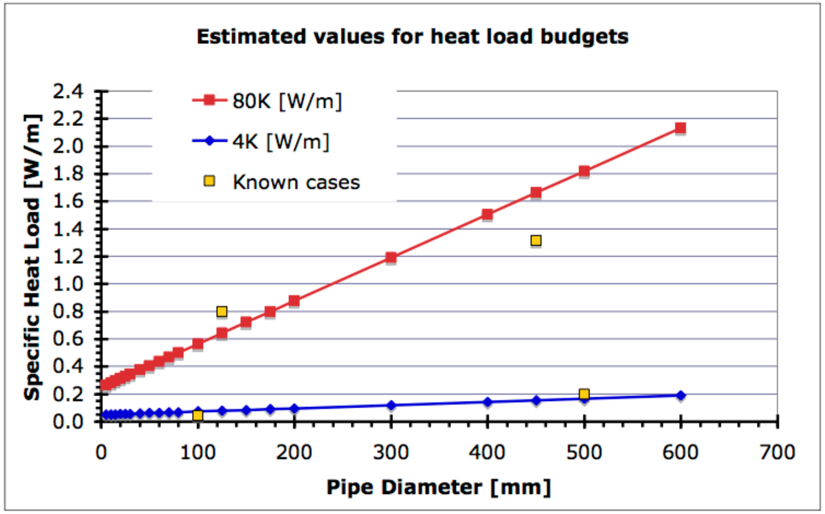
Invar line

Measured	70	W measured
Diam	0.1	m
Surf	0.31	m2/ml
incl supports	35.42	W calc
For 80m:	0.875	W/m Measured

Proposal: 1.5 x conservative values

W/m2	0.075	1.0
W/m of support	0.050	0.25

Diam. [mm]	4K [W/m]	80K [W/m]	Known cases
5	0.051	0.266	
10	0.052	0.281	
15	0.054	0.297	
20	0.055	0.313	
25	0.056	0.329	
30	0.057	0.344	
40	0.059	0.376	
50	0.062	0.407	
60	0.064	0.438	
70	0.066	0.470	
80	0.069	0.501	
100	0.074	0.564	0.042
125	0.079	0.643	0.8
150	0.085	0.721	
175	0.091	0.800	
200	0.097	0.878	
300	0.121	1.192	
400	0.144	1.507	
450	0.156	1.664	1.316
500	0.168	1.821	0.2
600	0.191	2.135	



Conclusions

- ➢ Revision of cooling circuits for DF_-DFH_ was needed due to changes in the cooling interfaces (QXL next to DFH_).
- ➢ Study focused on the refrigeration duty.
  Further aspects (technological, economical, etc) are still to be considered.
- ➢ Explorative schemes show (in terms of cooling power):
  - **Line D at DFH_:**
    - Decouples DSH from CL
    - Can save up to 1000 W @4.5K
  - **TS:**
    - Suppression results in an increase in cryogenic loads of 100 to 600 W@4.5 K depending on the configuration.
    - With TS, the DSH temperature can be chosen "freely" (with negligible change in cooling cost) between 5 K and 17 K.
  - **GHe vs SHe:**
    - Both are similar.

Thank you

Complementary slides (INDICO 637254)

DSH and DFH_ Cooling

(Definition of process parameters)

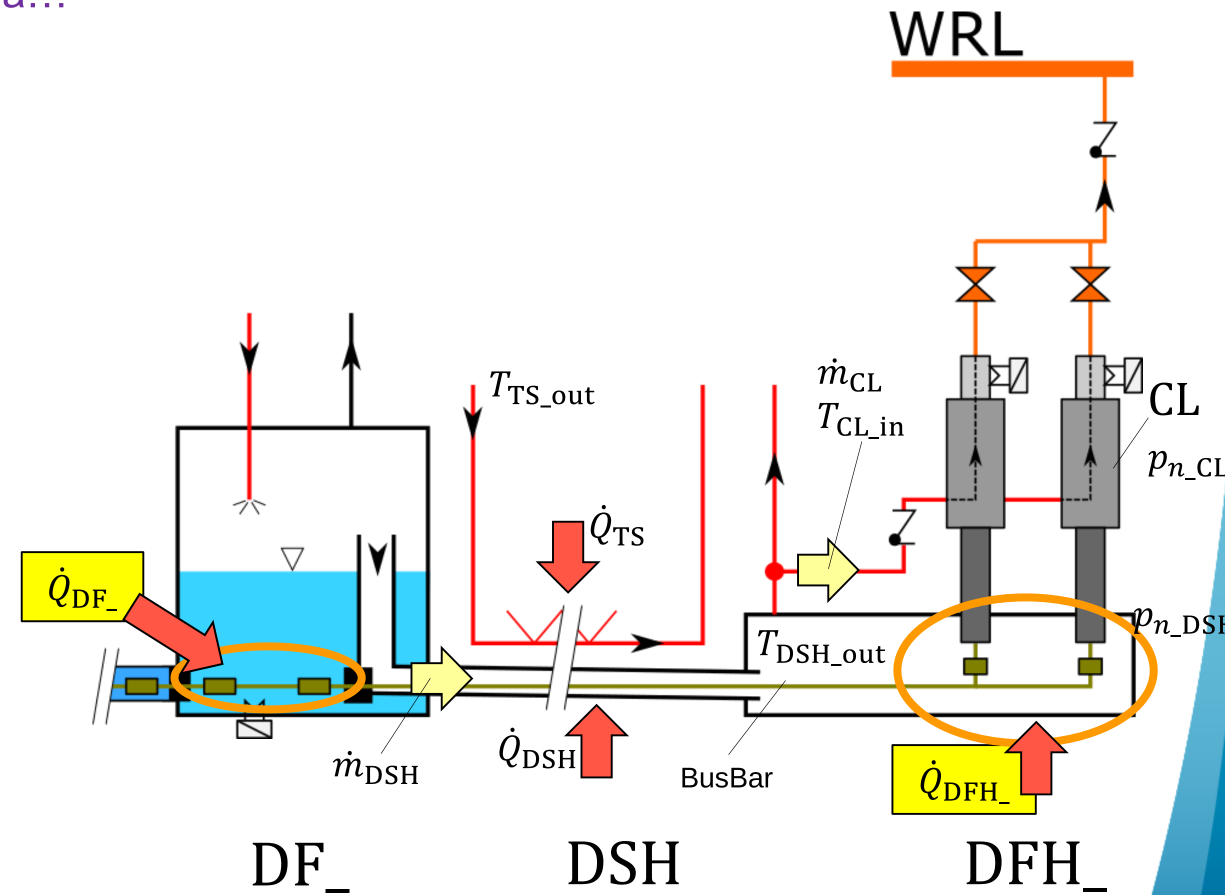
Used values:

Par.	Units	Value
	g/s	2.5; 5; 7.5; 10
	W	250; 500; 750; 1000
	W	with ThS: 5 w/o ThS: as
	K	17
	K	25
	K	100
	bar	3.5
	bar	3.5

	W	(Static, Splices, ...)
	W	(Static, Splices, ...)

Values to be validated by WP6a…

2 additional parameters in the list.
(Possible range?)



Complementary slides (INDICO 637254)

Impact of DFX heat loads on the cooling variants

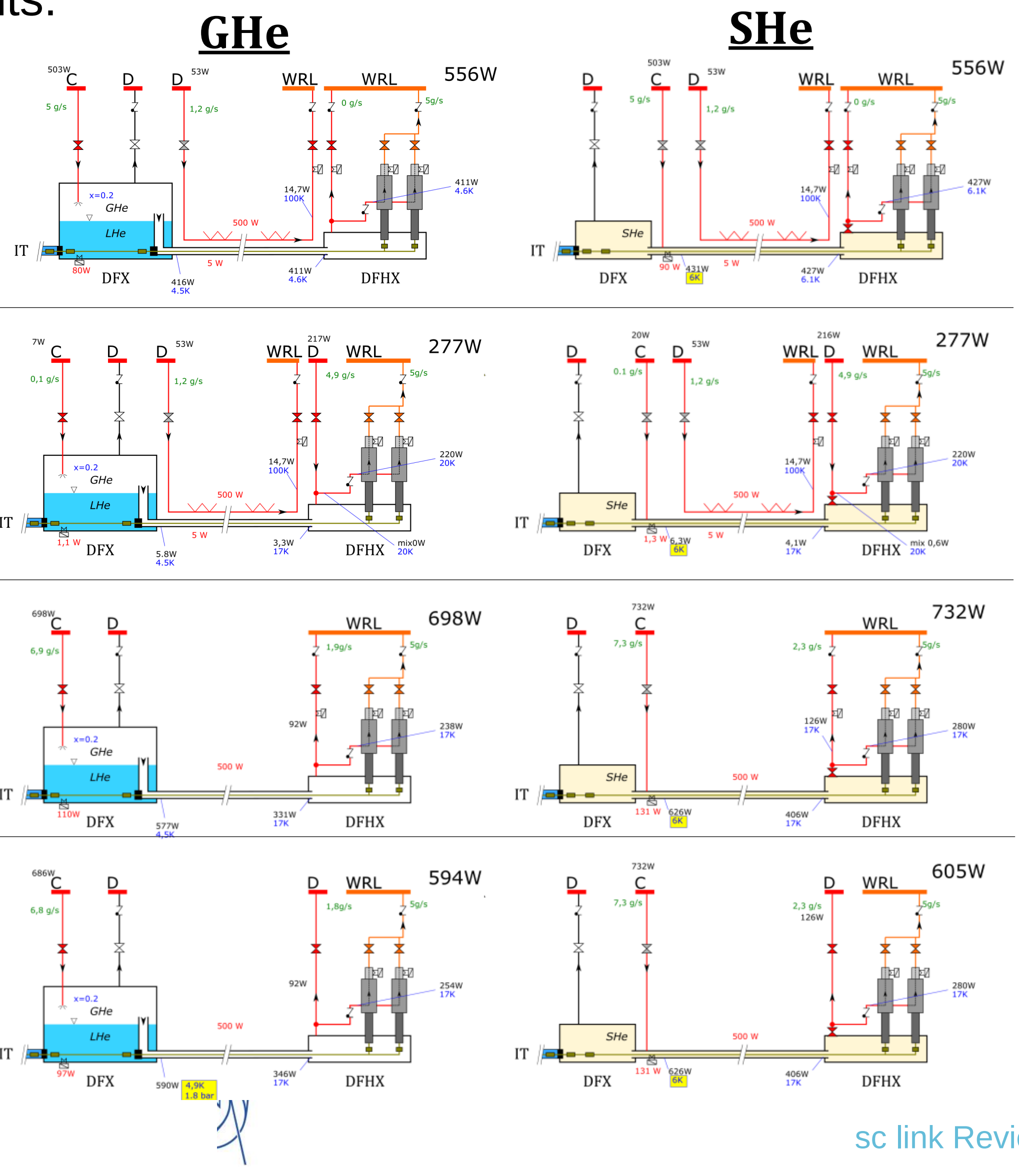
Variants:

#1 No LineD With TS

#2 With LineD With TS

#3 No LineD No TS

#4 With LineD No TS



Heat loads on DFX (static loads and splices)?

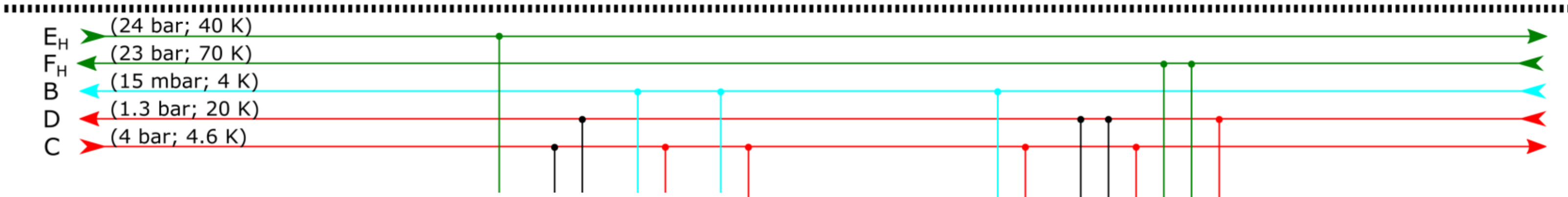
- Static loads ~ 5 W ?
- Splices ~ 5 W ?

For 2x 18kA + 2x 13k HTS-LTS splices and assuming 5 nΩ resistance.

<u>All Variants except #2:</u>
Additional heat loads on DFX can be compensated by reducing the power dissipated by the DFX heaters (80-110 W).

<u>Variant #2:</u>
Additional DFX loads will require more massflow from Lince C. (see next slide)

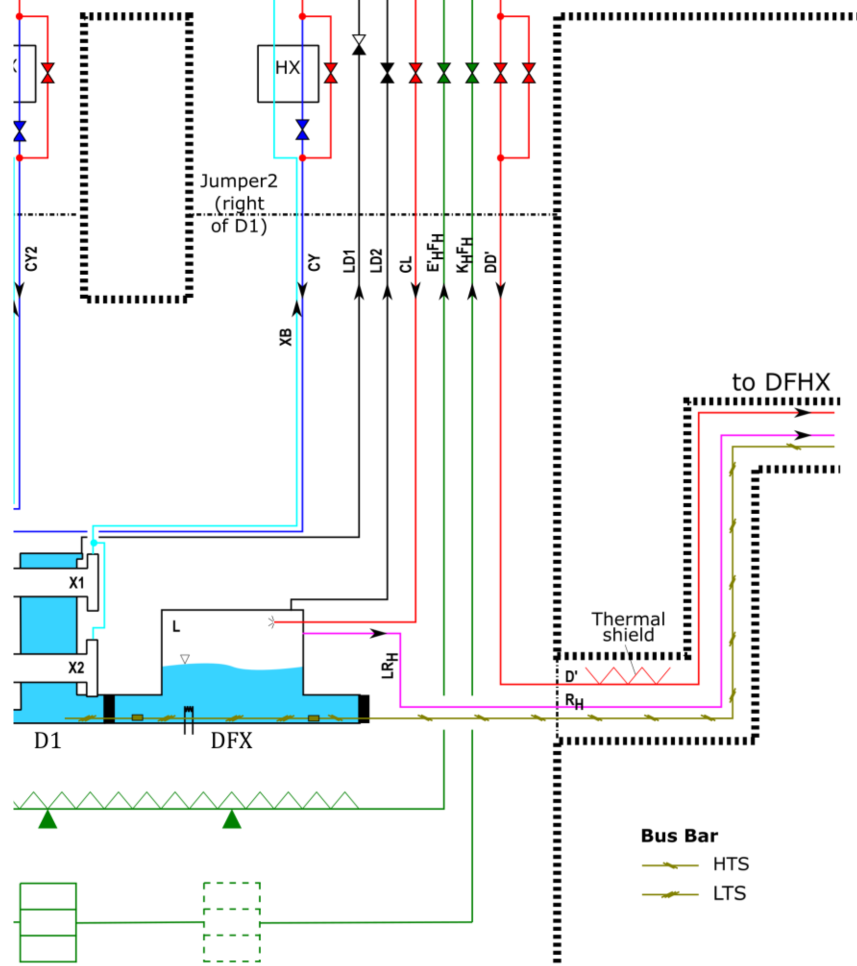
1. Main sc-link D1-CP-Triplet



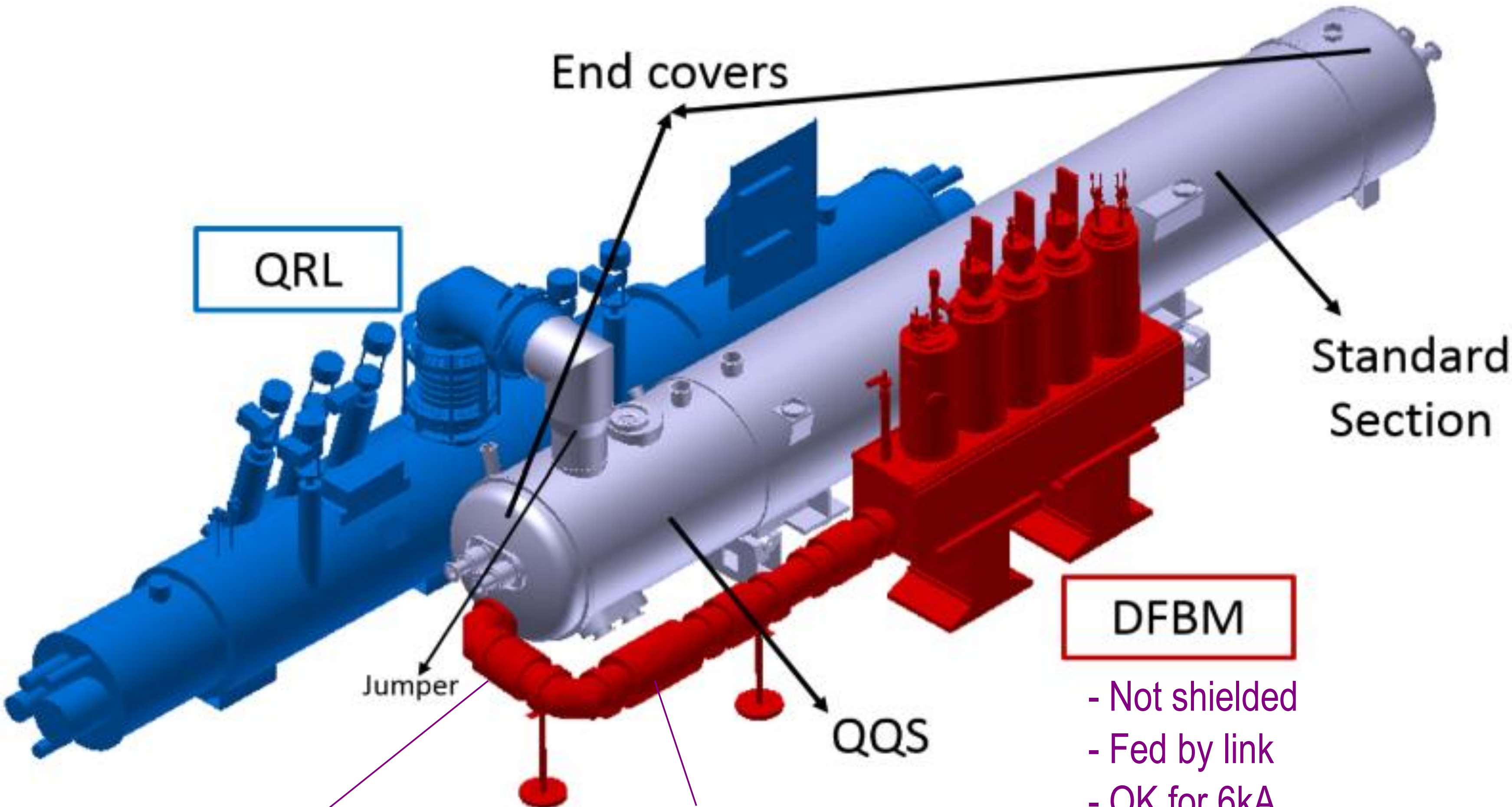
- Principle of DFX identified, but double splice (MgB2-NbTi, NbTi-Nb3Sn) and plug to be studied in more details

- Needs for beam screen (or not) to be made

- Needs for 20K shield to be clarified:
  - Obvious gain in flexibility without thermal shield
  - Risk of local “hot spots”, like seen in some bends of existing DFBLC
  - Specific configuration of cable in helium jacket to be carefully looked at, like with double inverted helical spacers



LHC - Existing solutions

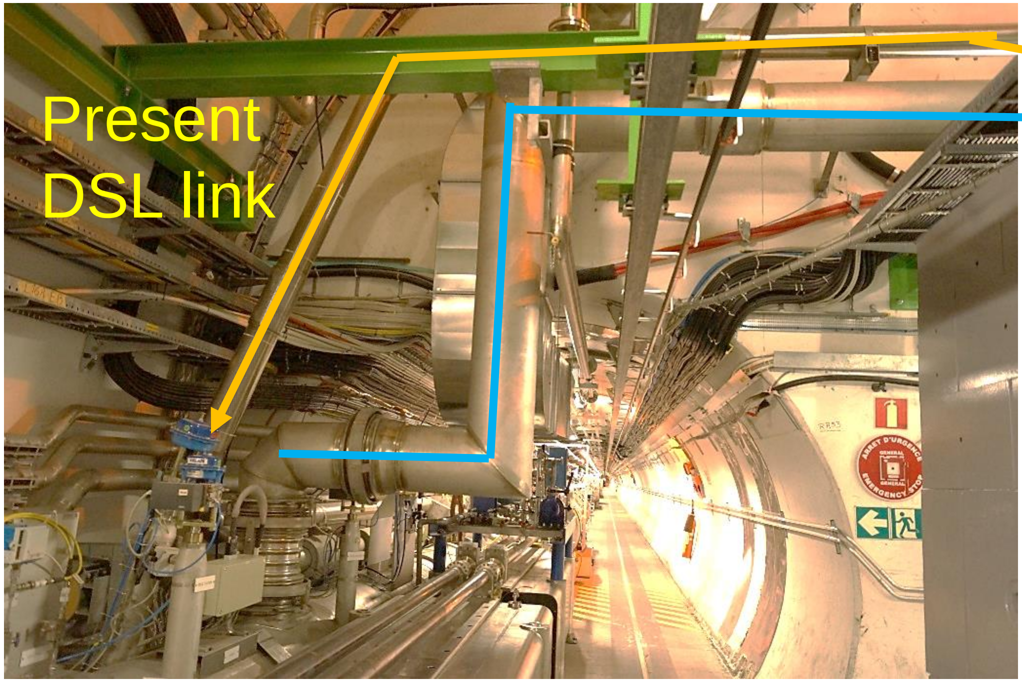


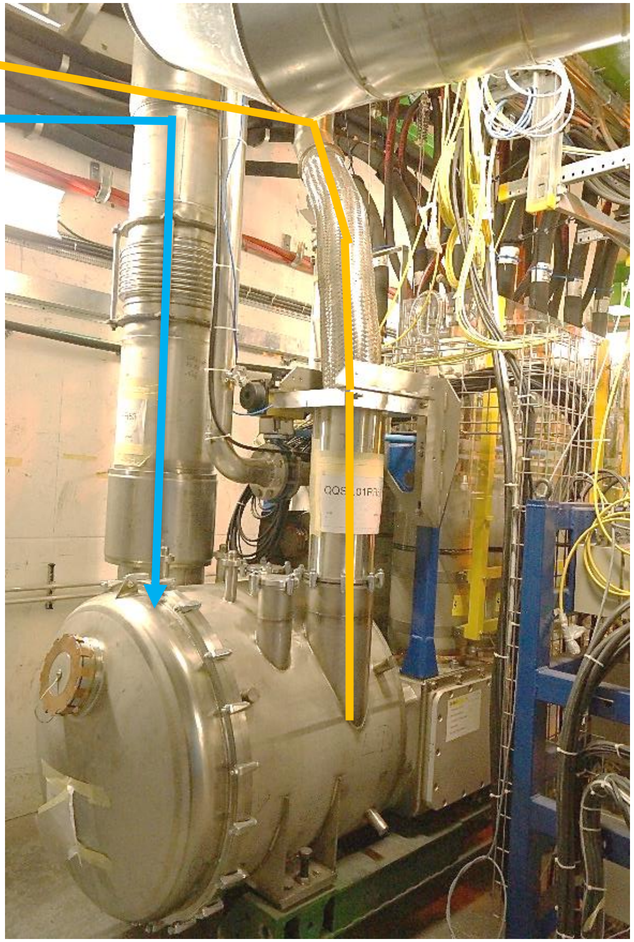
- Not shielded
- Fed by link
- OK for 6kA

- Adapted to magnet operation @ 1.9K
- Need for thermal shied to be evaluated

- Not shielded
- 3 circuits (bus, LHe-GHe)
- Low point with splice & plug (as for DFBA's)

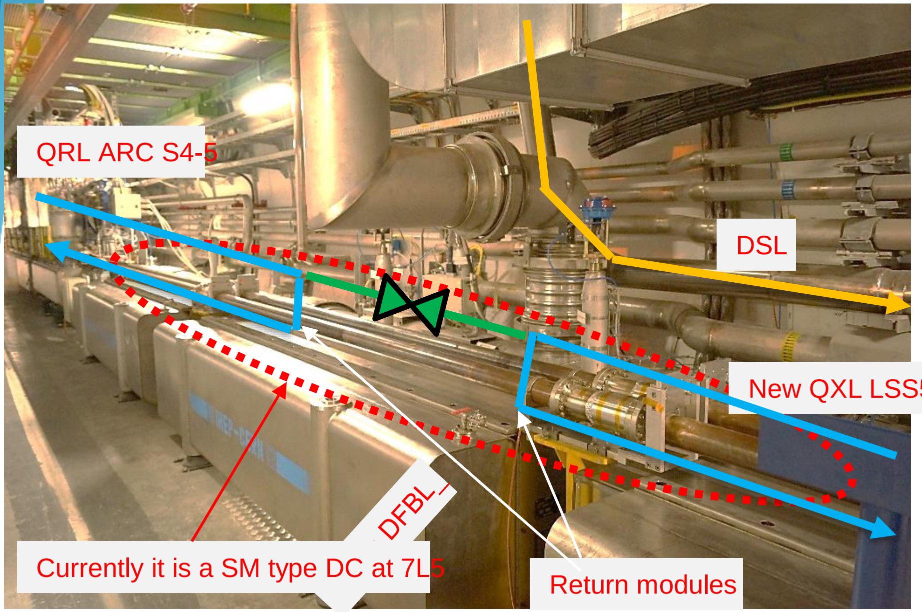
RR

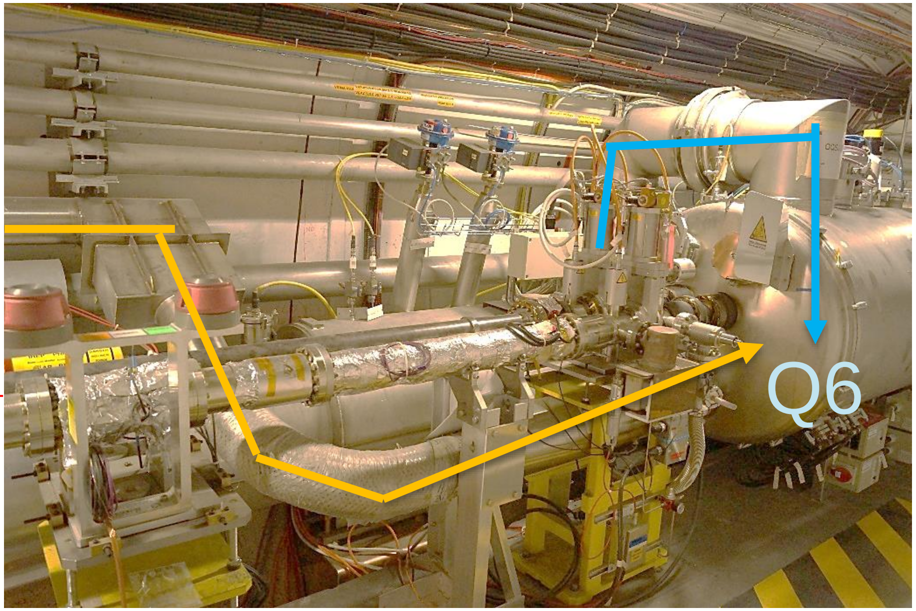




- QRL supply DFBL with cold He (blue)
- DFBLD supplies current leads over DSL (orange)
- HL-LHC-DFBs will be on the new service tunnel and will have DSLs to the SAMs
- On the HL-LHC, the direction of the He flow to cool the current leads will be different:
    - LHC: QRL-DFBL-DSL-Magnet
    - HL-LHC: Magnet-DSL-DFBL-WarmRecovery

LHC situation of DSL_L5



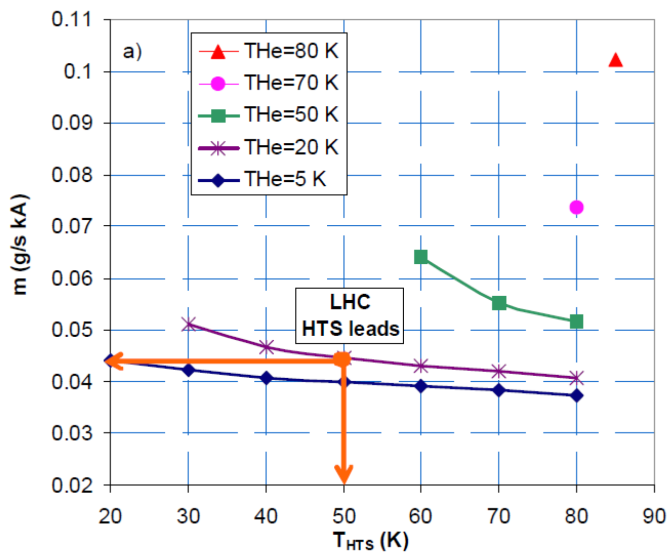


- Currently SM (at 7L5) receives current leads from DFBLD and delivers DSL. **This will be <u>removed</u>.** The DFBL and DSL will be routed diferently.
- The new available space will be used for a special ServiceModule (at 7L5). It will be a kind of „QUIC“ to connect QRL S4-5 and QXL S5 (in other words Refr4-5 and Refr5) in case of need.

- DSL coming from DFBLD and connected to Q4L5-D2L5 (orange)
- SM cools the magnets independently from the current leads coming from the DSL (blue)

Assumptions (as in previous presentation)

- The following assumptions were first formulated in 2010.
  - They are still the baseline today
- Link SC is MgB_2
- Splice LTS to MgB_2 (magnet to link) requires liquid helium bath.
- Max MgB_2 temperature 20K
  - Max. helium temperature 17 K
- He consumption for current lead cooling:
  - As published by A. Ballarino in CERN/AT 2007-5



Towards new WP9 organisation

2016-2017

- Coordination: Serge Claudet, Rob Van Weelderen
- Quality, documentation, project management: (Antonio Perin)
- Magnet cooling requirements: Rob Van Weelderen + *F. Aabid* + *P. Tavares*
- Crab cavities cooling requirements: Krzysztof Brodzinski
- Heat Load management: Antonio Perin + *D. Berkowitz-Zamora*
- General process overview: (Udo Wagner)
- 3D models and integration: Jos Metselaar + *designers*
- Instrumentation & controls: so far CRG/CE-CI experts
- P4-RF and P1-P5
  - Refrigeration: Emmanuel Monneret (Sep'17)
  - Cryodistribution: Michele Sisti (Jun'17)
- SPS-BA6:
  - Refrigeration: Laurent Delprat
  - Cryodistribution: Krzysztof Brodzinski + Hendrie Derking
  - Infrastructure: Jos Metselaar + O. Pirotte

On track for short term with part-time efforts, under staffing for LS2-LS3