FCC Week 2017, Berlin

Towards a conceptual design for FCC cryogenics

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CERN, ATS-DO

On behalf of the FCC cryogenics study collaboration

1st June 2017

Content

- Introduction: FCC cryogenic study organization
- FCC-hh cryogenics overview
- FCC-ee cryogenics overview
- HE-LHC cryogenics overview
- Conclusion

FCC cryogenics studies

FCC Cryogenics Studies

Cryoplants
(~50-100 kW @ 4.5 K including 12 kW @ 1.8 K)

Ne-He cycle for refrigeration above 40 K
TU-Dresden

- MoU signed
- Addendum 1 signed & completed
- Addendum 2 signed

Innovative He cycle
CEA Grenoble

- MoU signed
- Addendum 1 signed
- Addendum 2 signed

Cooling scheme and cryo-distribution
PhD student
C. Kotnig

In steady-state

Specific studies (CD, WU, Transients…)
Fellow
H. Correia Rodrigues

In steady-state

Design pressure impact on heat inleaks
Wroclaw-STU

- MoU signed
- Addendum 1 signed & completed
- New addendum under discussion

New w/r to Roma

Content

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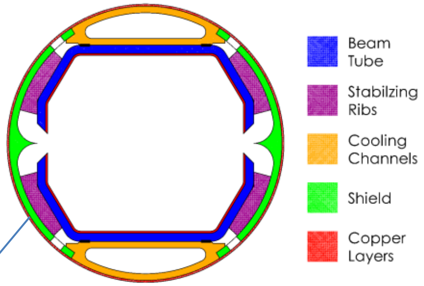
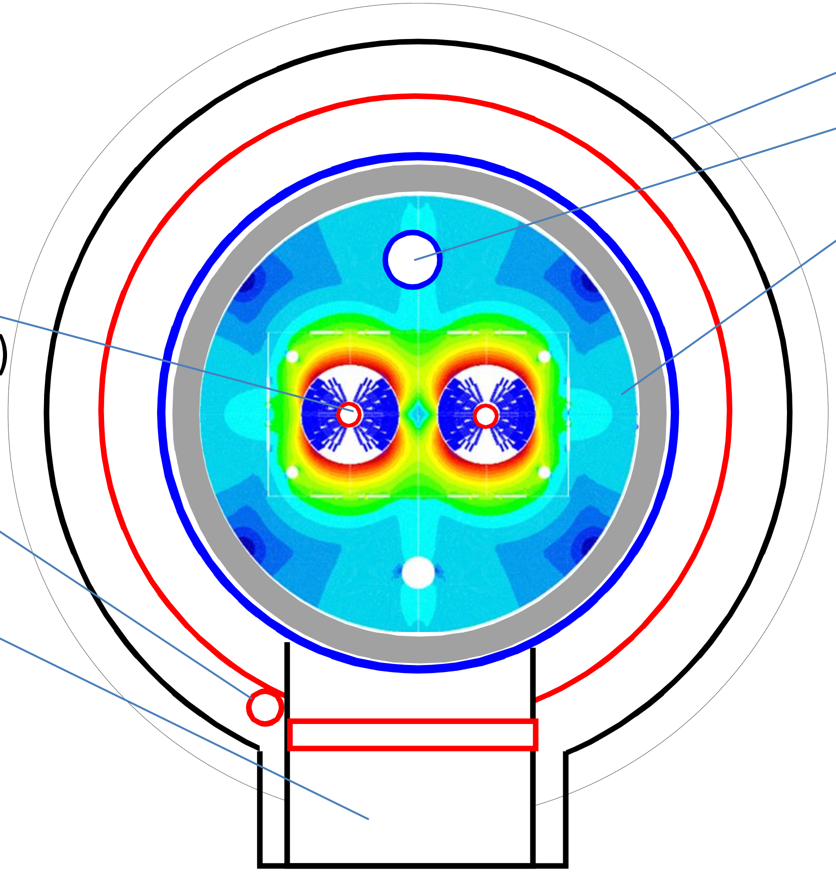
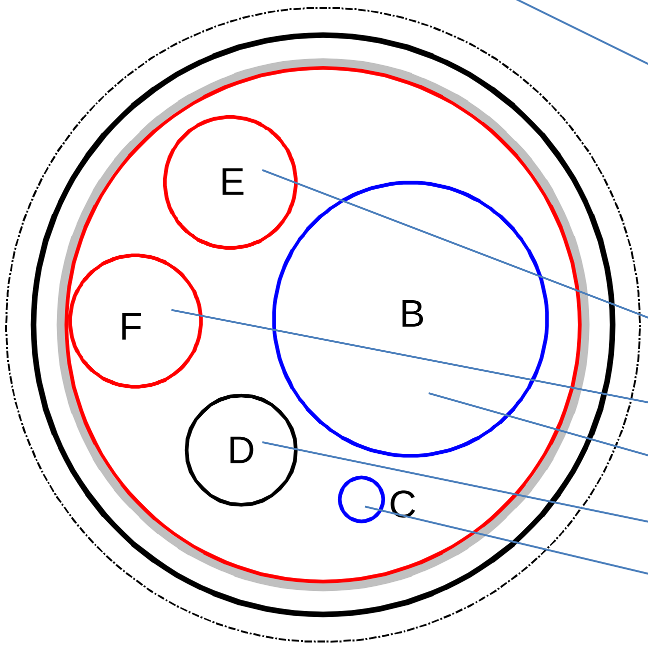
FCC-hh: tunnel cryogenics





Vacuum vessel
Bayonet heat exchanger, 1.85 K saturated
Cold mass, 1.9 K (1.3 bar)

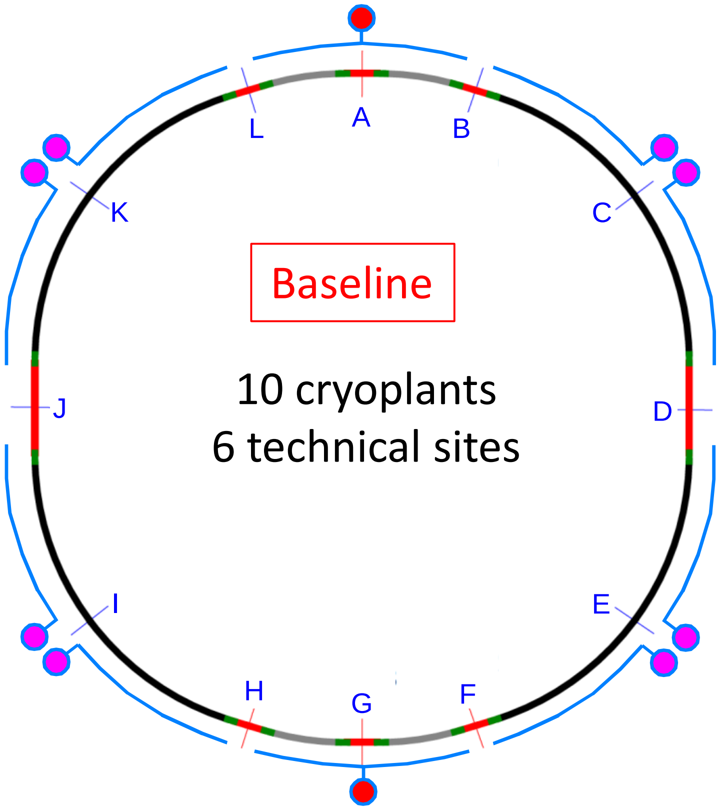
Beam screen, 40-60 K (50 bar)
Magnet thermal shield 60 K (44 bar)
Support post



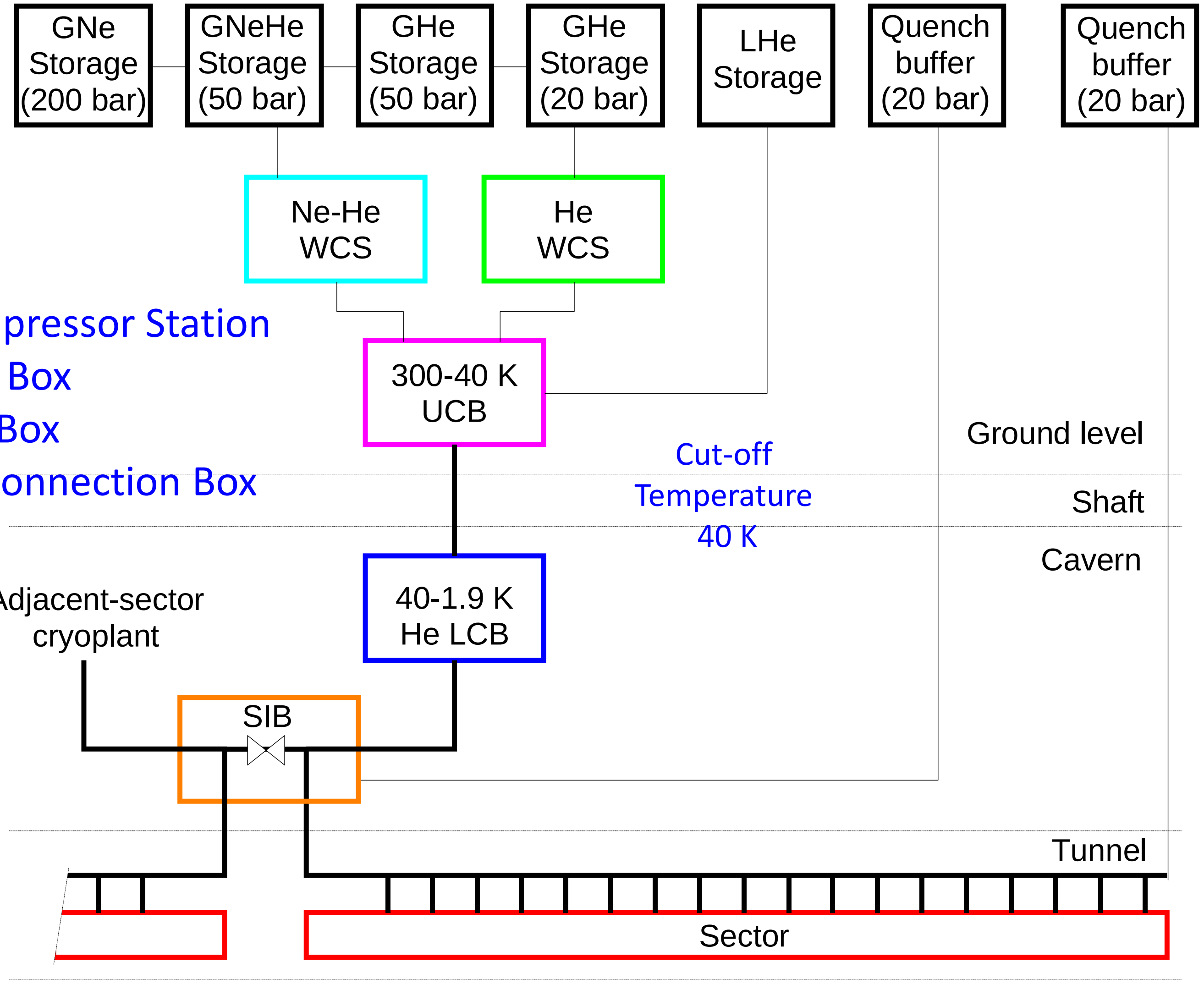
40 K supply header (50 bar)
60 K return header (44 bar)
4 K VLP pumping line (15 mbar)
Quench buffer, 40 K (1.3 bar)
4.6 K SHe header (3 bar)

Temperature level	Static [W/m]	Dynamic [W/m]	Total [W/m]
1.9 K	0.5	0.9	1.4
40-60 K	9	62	71

FCC-hh cryogenic layout and architecture



WSC: Warm Compressor Station
UCB: Upper Cold Box
LCB: Lower Cold Box
SIB: Sector Interconnection Box



Cryoplant	40-60 K [kW]	1.9 K [kW]	40-300 K [g/s]
(red)	592	11*	85
(magenta)	618	12*	85

Without operational margin !

*: Outside State-of-the-Art

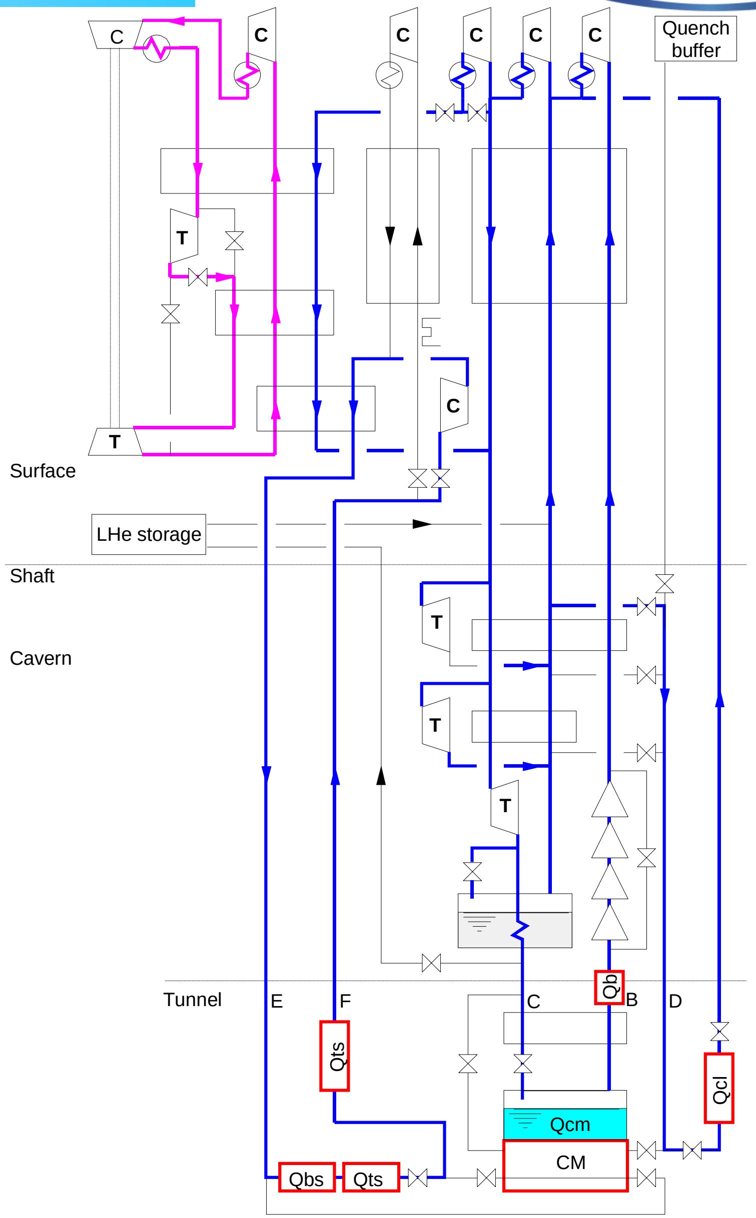
FCC-hh cryoplant architecture

Ne-He 300-40 K cryoplant

- Beam screen (40-60 K)
- Thermal shield (40-60 K)
- Current leads (40-300 K)
- Precooling of 1.9 K cryoplant

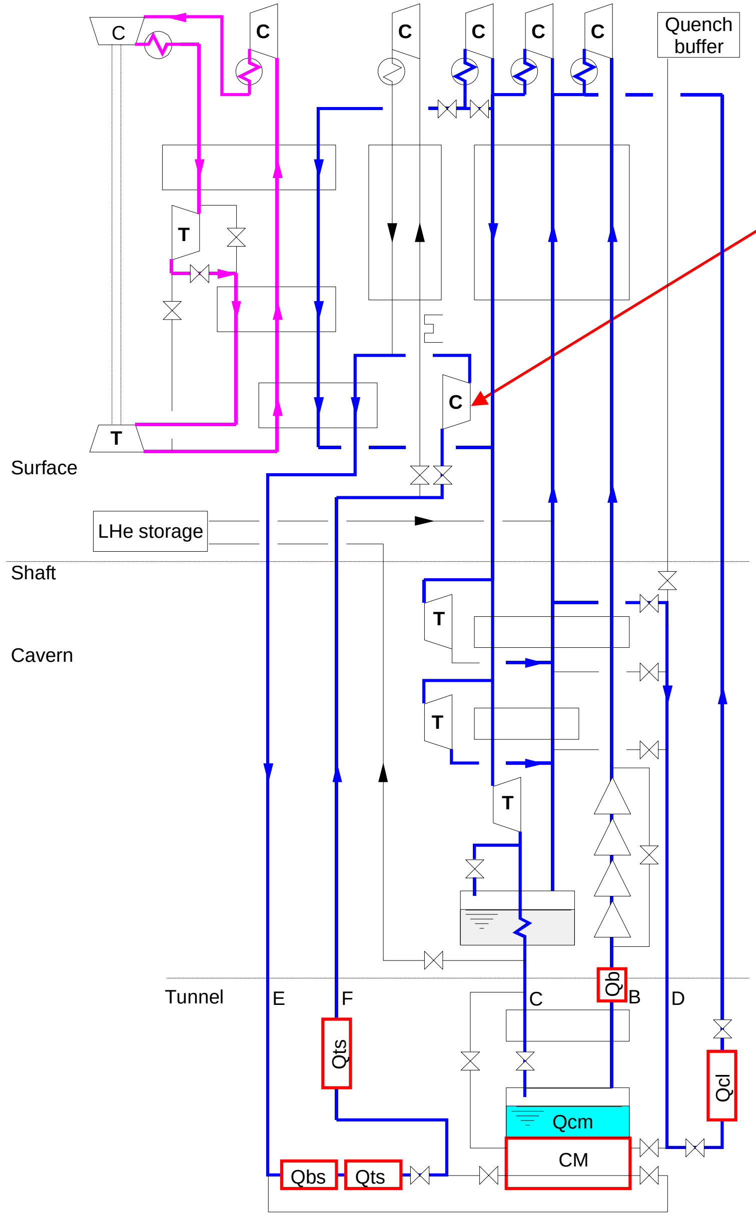
He 1.9 K cryoplant

- SC magnet cold mass



Contributions of TU Dresden and CEA/SBT

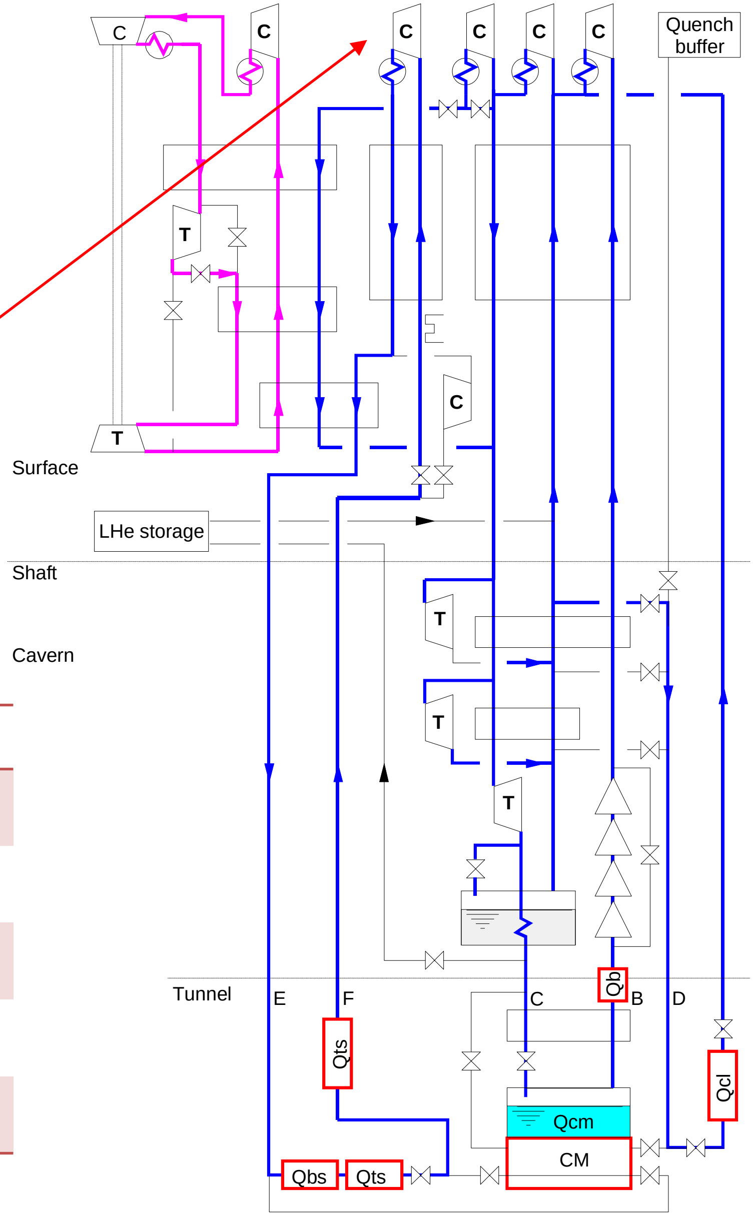
FCC-hh Nominal operation



- He cycle
- Ne-He cycle

BS cooling with cold circulator
(+130 kW @ 40-60 K)

BS cooling with warm circulator
+140 kW @ 40-60 K and +500 kW @ 300 K
→ Less efficient but good for redundancy and needed for cool-down and warm-up operation



Nominal loads		
Beam screen	Qbs	530 kW
Thermal shield	2 Qts	90 kW
Cold-mass	Qcm	12 kW
Pumping line	Qb	2 kW
Cuurent leads	Qcl	85 g/s

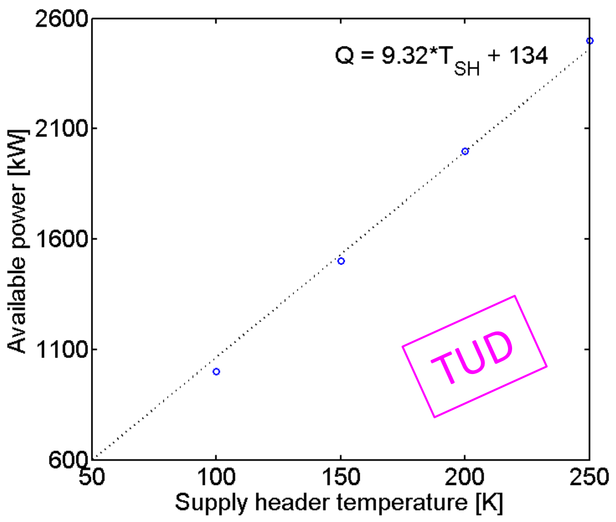
Cooldown of FCC-hh

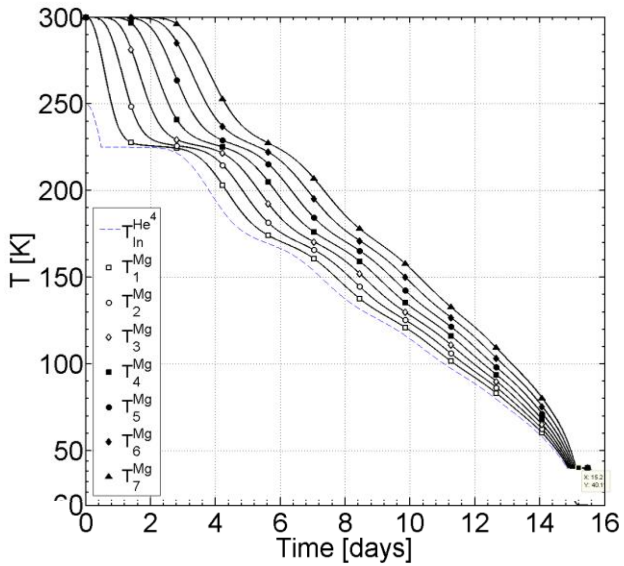
Cool-down capacity produced by the Ne-He cycle:
No need of LN2 cool-down unit with its huge LN2 storage and logistics

Cold mass: 2.8 t/m i.e.
23 kt per sector
230 kt for FCC

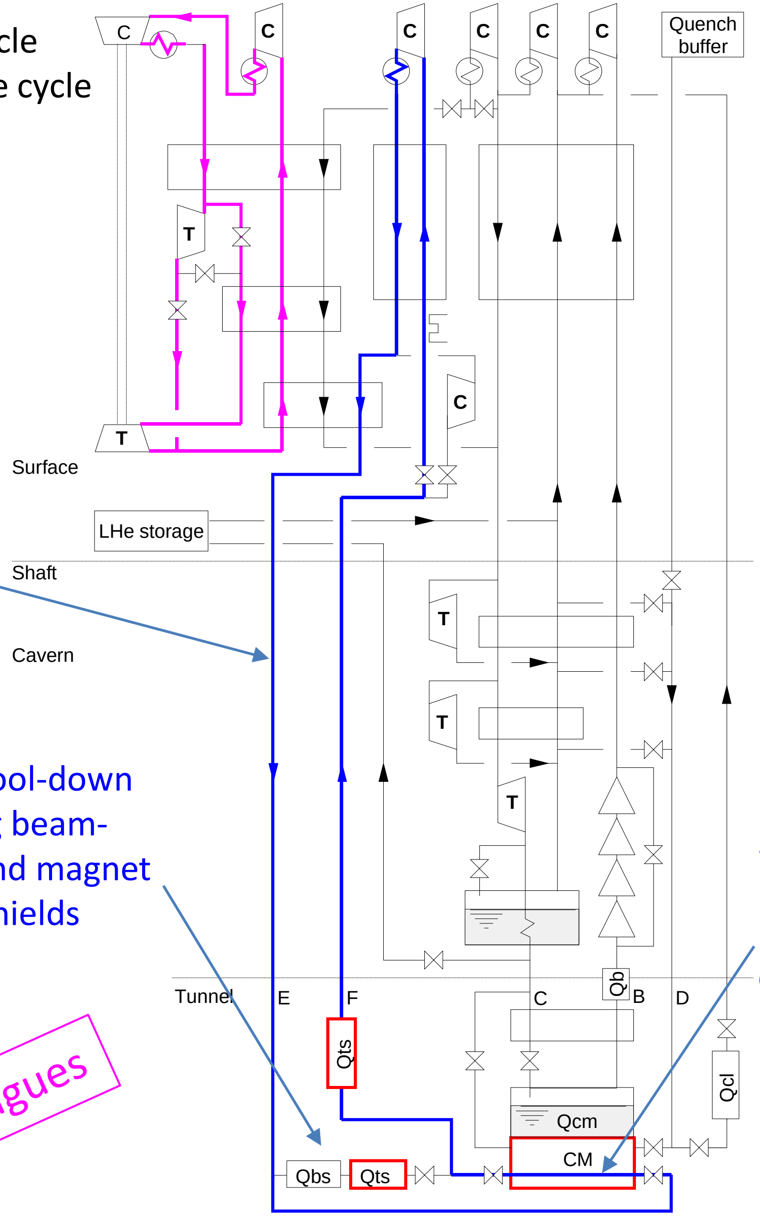
15 days of cool-down time from 300 to 40 K (10 days (on paper) with LN2).

Cost (only energy)
Full FCC CD → 2.3 MCHF
(To be compared with the cost of a CD using LN2 → 45000 t, i.e. ~4 MCHF)





He cycle
Ne-He cycle

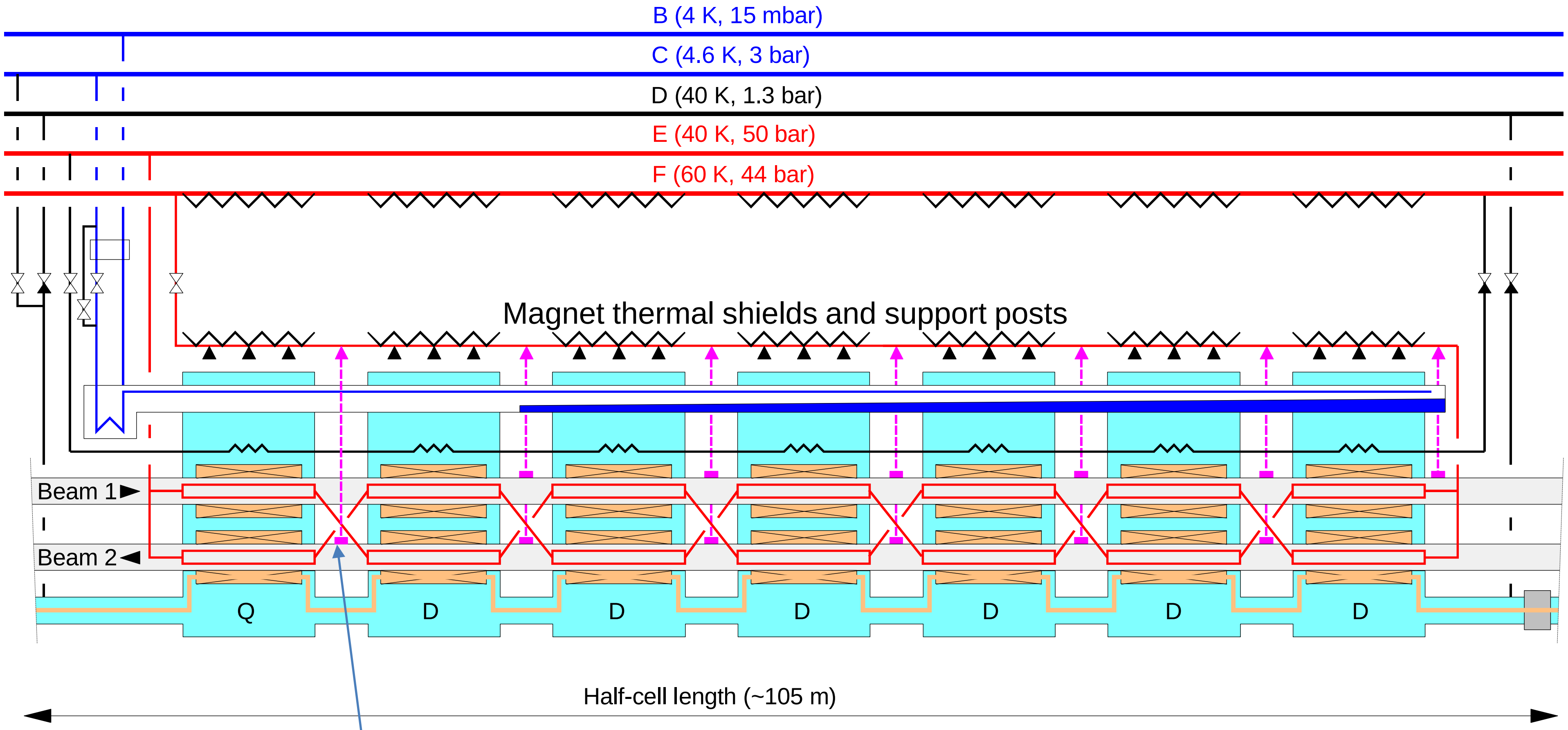


Indirect cool-down of floating beam-screens and magnet thermal shields

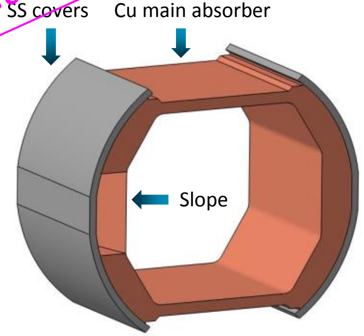
50 bar supply pressure
→ indirect cool-down of cold-masses (design pressure of 20 bar)

H. Rodrigues

FCC-hh Half-cell cooling loop



C. Garion



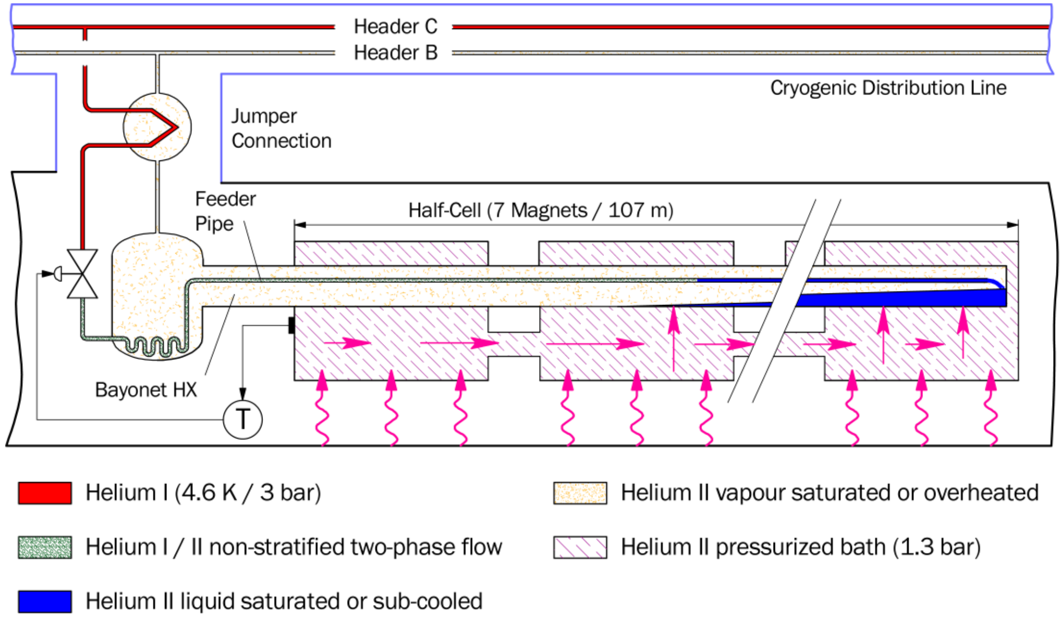
SR absorbers: 61 W per dipole and per beam, i.e. ~60 kW per long-sector

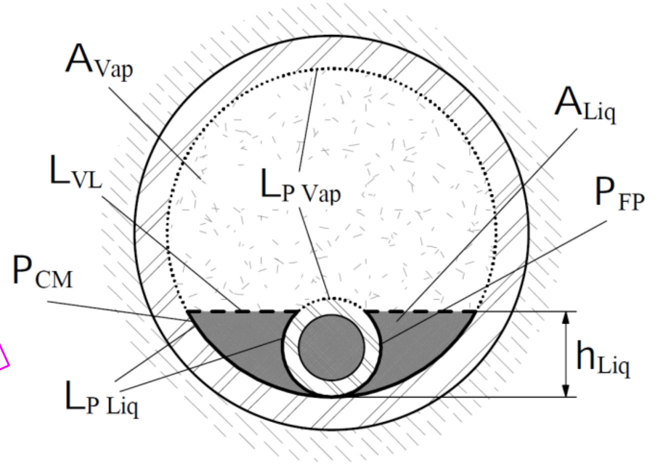
Without radiation absorbers → 616 kW between 40 and 59.5 K (m= 5.8 kg/s)

With radiation absorbers → 616 kW between 40 and 62 K (m= 5.2 kg/s)

FCC-hh Superfluid helium cooling loop parameters

Variable	Unit	LHC	FCC
Unit cooling length	m	106.9	107.1
Sector cooling length	m	2900	8400
Average heat load nominal (installed) capacity	W/m	0.40 (0.83)	1.38 (2.44)
Bayonet HX inner diameter	mm	53.4	83.1
Feeder pipe inner diameter	mm	10.0	15.0
Thickness bayonet HX pipe wall	mm	2.3	5.0
Joule-Thomson valve inlet temperature	K	2.18	2.18
Free longitudinal cross-section area	cm2	60	156
DT max Pressurized-saturated HeII	mK	50	50
Cold mass operating pressure	bar	1.3	1.3
Header B diameter	mm	270	500 (630)
Heat load on header B	W/m	0.11	0.24
Pumping pressure at cryoplant interface	mbar	15	15
Maximum cold-mass helium temperature	K	1.9	1.98 (1.9)

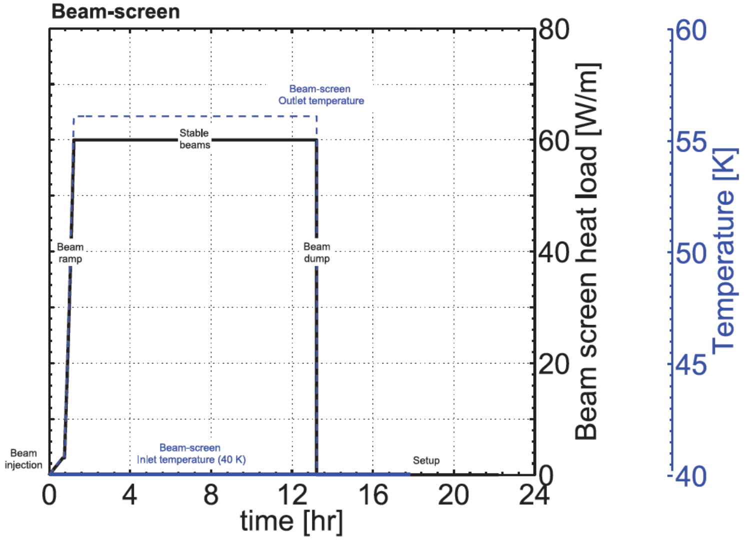




C. Kotnig

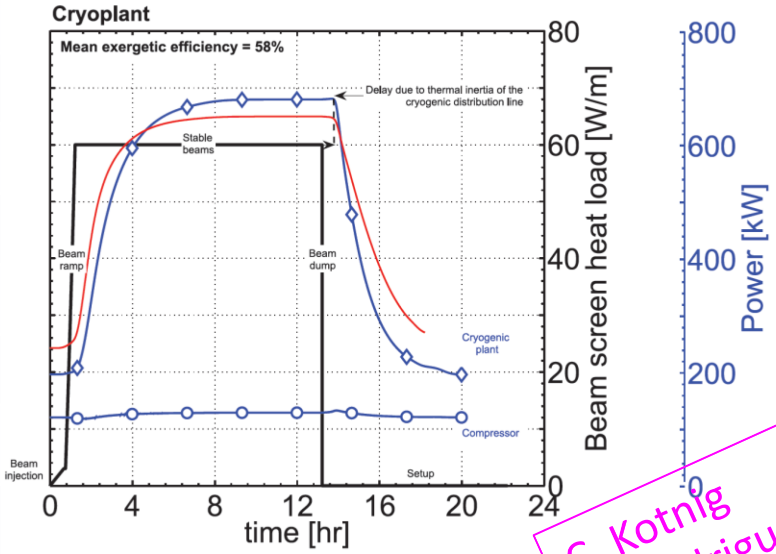
FCC-hh Beam-screen cooling loop parameters

Main parameter	Unit	LHC	FCC
Unit cooling length	m	53.4	107.1
Sector cooling length	m	2900	8400
Average BS nominal dynamic capacity	W/m	1.6	62
Supply pressure	bar	3	50
Supply helium temperature	K	5	40
Max. allowed BS temperature	K	20	60
BS helium outlet temperature (nominal)	K	20	57
Minimum BS temperature (nominal)	K	5	43
BS pressure drop (nominal)	bar	0.5	3
ΔP control valve (nominal)	bar	0.8	1
ΔP supply and return header (nominal)	bar	0.4	2
Total cooling loop pressure drop	bar	1.7	6
Supply/return header diameter	mm	100/150	250/250
Exergetic efficiency (distribution only)	%	76	86
Total exergetic eff. (with cold circulator)	%	N/A	82
Total exergetic eff. (with warm circulator)	%	?	74



Transient modes

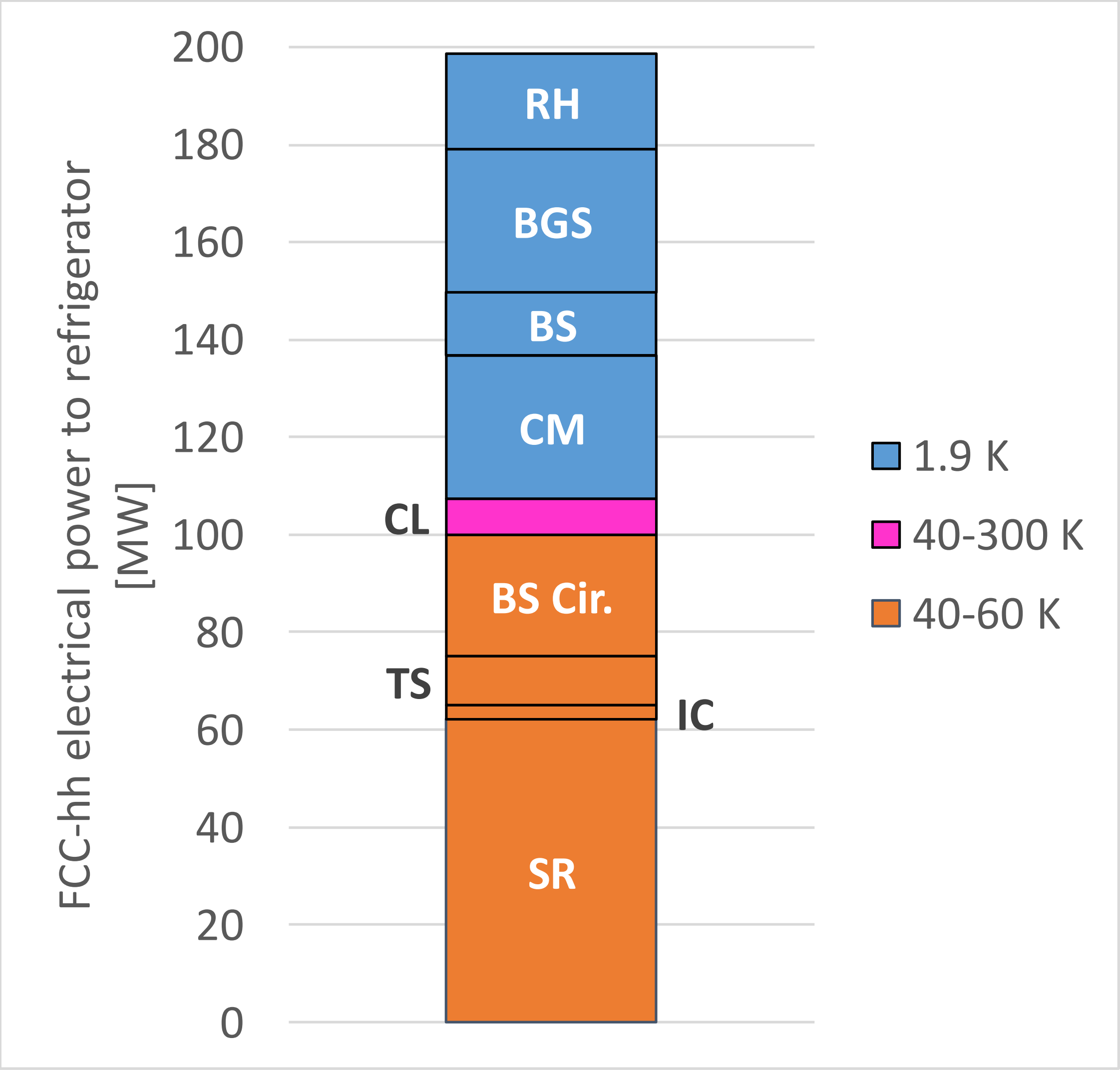
- Working at constant nominal flow to handle the severe transient during energy ramp-up
- Working at constant He inventory to avoid big mass release and refill (i.e. pressure increase during energy ramp)



Large inertia of the distribution system
→ time constant of~ 4 h
→ OK with the capacity adaptation of the cryoplants
→ In high luminosity operation (4 h of stable beams), the cryoplants will be never in steady-state

C. Kotnig
H. Rodrigues

FCC-hh electrical consumption



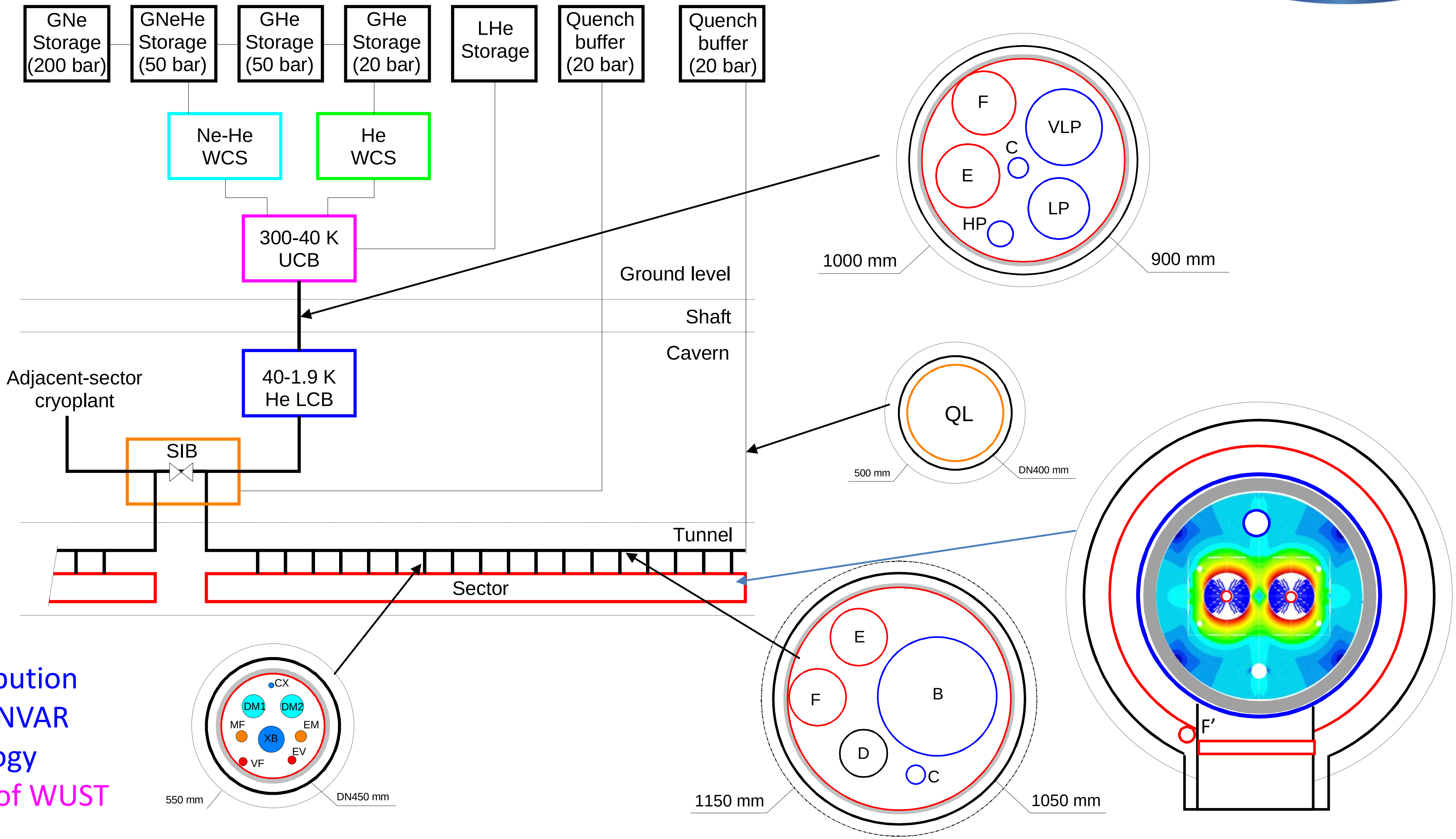
RH: resistive heating
BGS: beam-gas scattering
BS: beam screen
CM: cold mass heat-inleaks
CL: current lead
BS cir.: Beam screen circulator (warm)
TS: thermal shield
IC: image current
SR: synchrotron radiation

Carnot efficiency:
- Ne-He plants: 40 %
- Helium plants: 28.8 %

Isentropic efficiency
- cold compressors: 75 % per stage
- Warm circulator: 83 %

FCC-hh Main cryogenic distribution

	DN mm
B	500
C	80
D	200
E	250
F	250
F’	50
HP	100
LP	250
VLP	300
QL	400

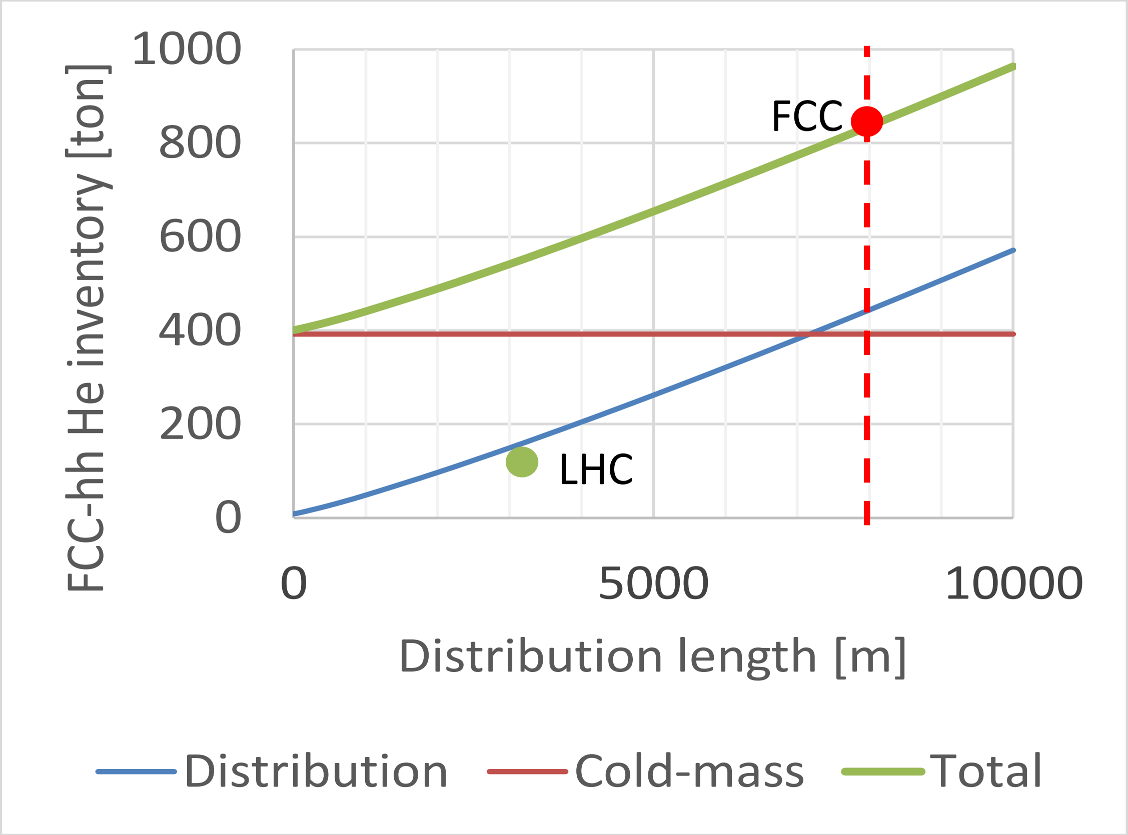


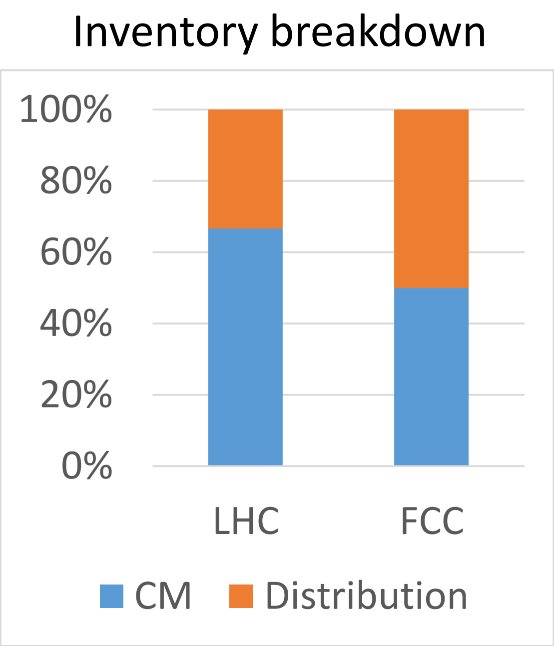
Main distribution based on INVAR technology

Contribution of WUST

FCC-hh He inventory

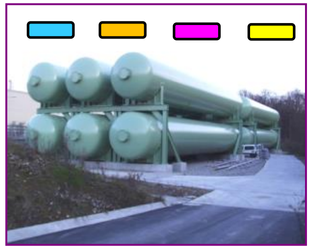
Cold mass He inventory : 33 l/m (scaled from LHC)
Distribution inventory dominated by the beam-screen supply and return headers



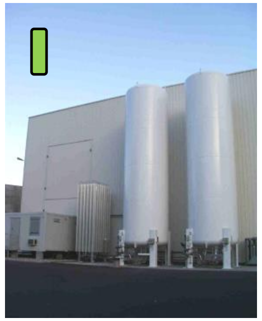


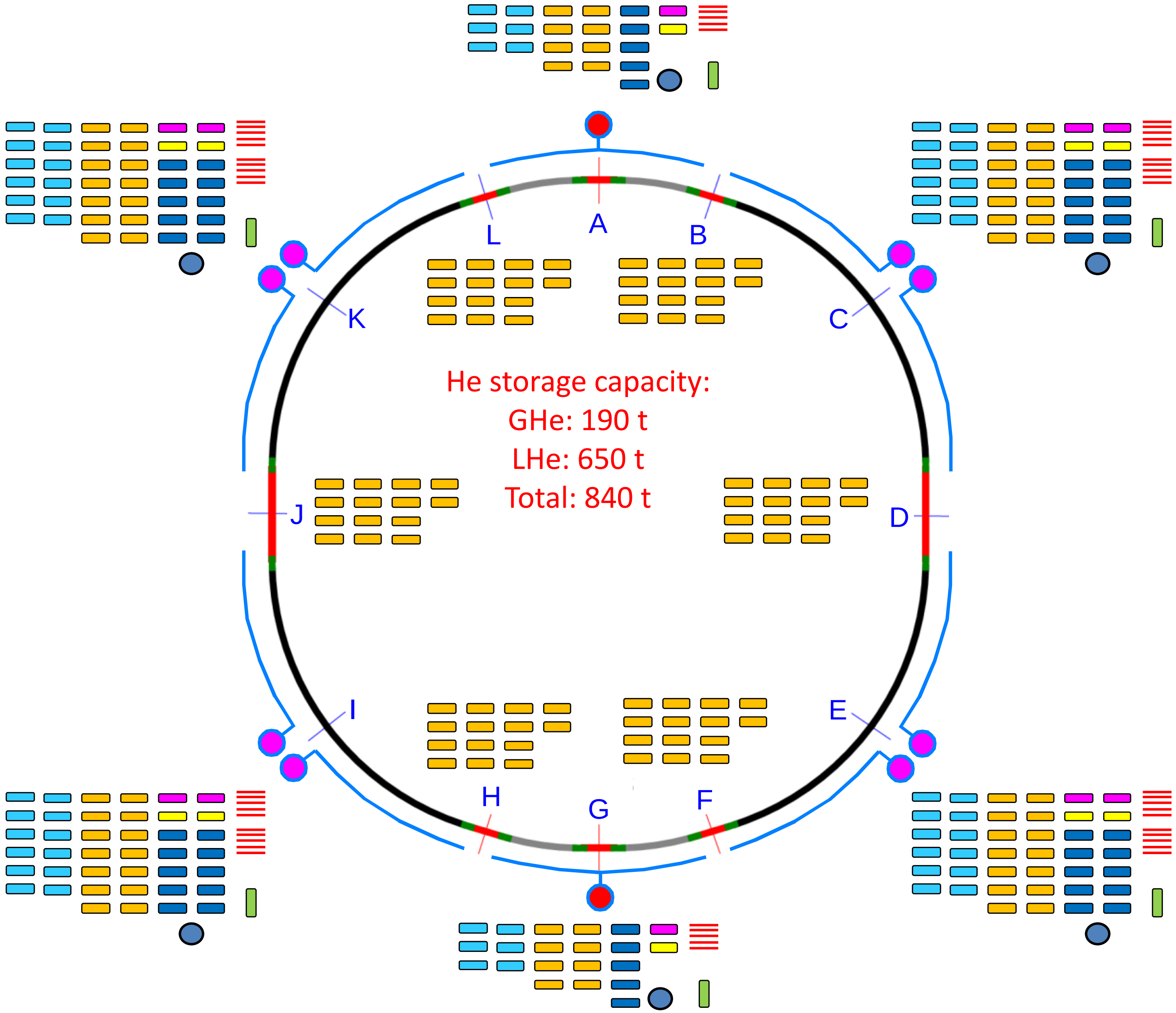
FCC He inventory: ~800 t ! (~6 LHC He inventory)

FCC-hh Storage management



- GHe storage - 60 (250 m3, 20 bar)
- Quench buffer - 156 (250 m3, 20 bar)
- GHe storage - 10 (250 m3, 50 bar)
- Ne-He storage - 10 (250 m3, 50 bar)
- GNe cylinders - 10 (10 m3, 200 bar)
- LHe storage - 50 (120 m3)
- LHe boil-off liquefier - 6 (150 to 300 l/h)
- LN2 storage - 6 (50 m3)





Project breakdown structure

PBS				FCC-hh																							
			Total	A	S A-B	B	S B-C	C	S C-D	D	S D-E	E	S E-F	F	S F-G	G	S G-H	H	S H-I	I	S I-J	J	S J-K	K	S K-L	L	S L-A
Refrigeration	Ne-He cryoplant	[nb]	10	1				2				2				1				2				2			
	Helium cryoplant	[nb]	10	1				2				2				1				2				2			
Distribution	Vertical cryogenic distribution	[m]	2218	304				514				264				354				340				442			
	Local cryogenic distribution	[m]	150	15				30				30				15				30				30			
	Tunnel cryogenic distribution	[m]	86600	100	4700		8400	100	8400		8400	100	8400		4700	100	4700		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	100	8400		4700
	Cryoplant interconnection box	[nb]	6	1				1				1				1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1			
	Sub-cooling HX	[nb]	800		40		80		80		80		80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80		80		40
	Quench valves	[nb]	1200		60		120		120		120	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		120		120		120		60
	BS flow meter	[nb]	800		40		80		80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		80		80		80		80		40
Storage	Helium gazeous storage (20 bar)	[m3]	15000	1500			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		1500				3000				3000			
	Helium gaseous storage (50 bar)	[m3]	2500	250		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				250				500				500			
	Ne-He gaseous storage (50 bar)	[m3]	2500	250		[illegible]	[illegible]	[illegible]	[illegible]			500				250				500				500			
	Ne gaseous storage [200 bar]	[m3]	100	10		[illegible]	[illegible]	20				20				10				20				20			
	LHe storage	[m3]	6000	600				1200				1200				600				1200				1200			
	LHe storage loss liquefier	[nb]	6	1				1				1				1				1				1			
	LN2 storage	[nb]	6	1				1				1				1				1				1			
	Quench buffer	[m3]	39000	2000		3500		3500		3500		3500		3500		2000		3500		3500		3500		3500		3500	
Infra-structure	Quench line	[m]	4411	404		366		357		372		232		492		454		368		270		415		321		360	
	He ring line	[m]	104411	404	4900	366	9600	357	10500	372	10500	232	9600	492	4900	454	4900	368	9600	270	10500	415	10500	321	9600	360	4900
	Warm recovery line	[m]	91011	504	4700	366	8400	457	8400	372	8400	332	8400	492	4700	554	4700	368	8400	370	8400	415	8400	421	8400	360	4700
	Other infrastructure	[%]	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Instrumentation & controls		[%]	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
First helium inventory		[t]	800	1	43		78	1	78		78	1	78		43	1	43		78	1	78		78	1	78		43

Ready for cost estimate

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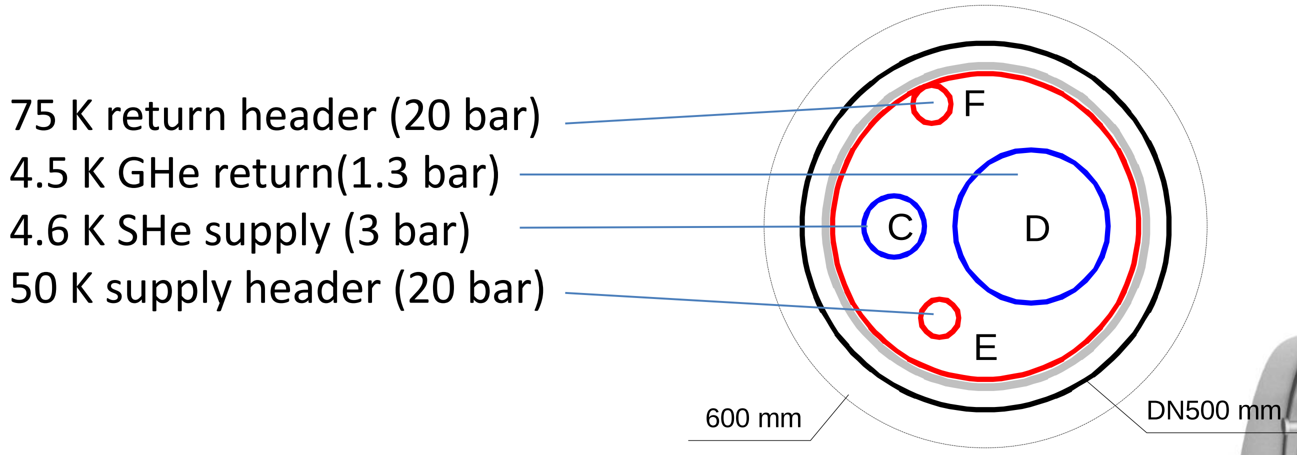
FCC-ee RF data

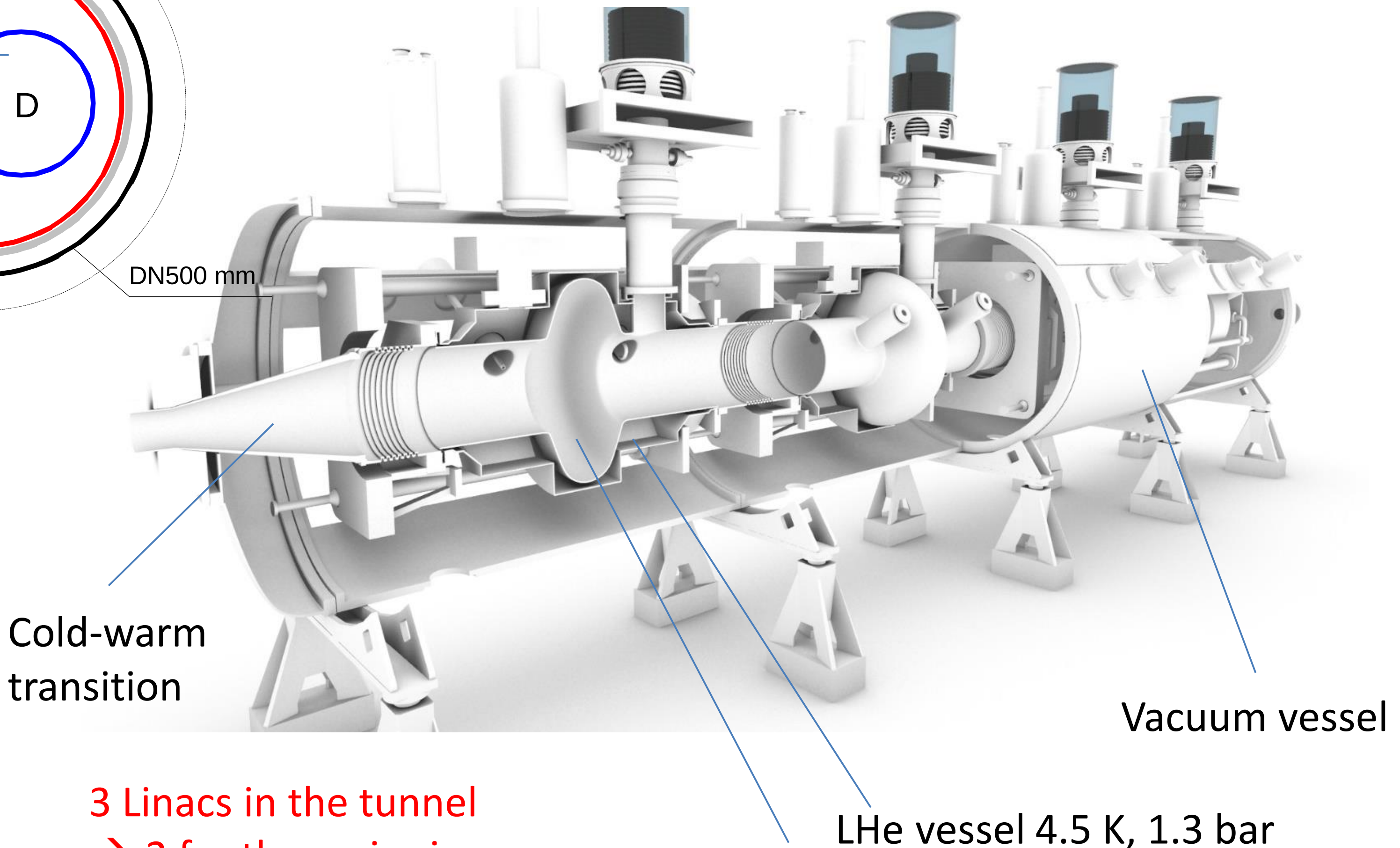
		Z			W			ZH			ttbar	
		1 cell, 400 MHz, 4.5 K			2 cell, 400 MHz, 4.5 K			2 cell, 400 MHz, 4.5 K			2 cell, 400 MHz, 4.5 K	
		Beam 1	Beam 2	Booster	Beam 1	Beam 2	Booster	Beam 1	Beam 2	Booster	Beam 1 & 2	Booster
RF voltage	[MV]	80	80	80	800	800	800	3000	3000	3000	10000	10000
Frequency	[MHz]	400	400	400	400	400	400	400	400	400	400	400
# cell per cavity	[-]	1	1	1	2	2	2	2	2	2	2	2
E acc	[MV/m]	2.15	2.15	2.15	10	10	10	10	10	10	10	10
V cav	[MV]	0.81	0.81	0.81	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
# cav	[-]	99	99	99	107	107	107	400	400	400	1333	1333
RF system length	[m]	176	176	176	229	229	229	860	860	860	2866	2866
Cav length	[m]	1.78	1.78	1.78	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Q Dyn / cav @ 4.5 K	[W]	2.4	2.4	0.24	105.2	105.2	10.52	105.2	105.2	10.52	105.2	10.52
T operation	[K]	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Q stat	[W/m]	5	5	5	5	5	5	5	5	5	5	5
Q Dyn	[W/m]	1.4	1.4	0.14	49	49	4.9	49	49	4.9	49	4.9

O. Brunner

FCC-ee tunnel cryogenics

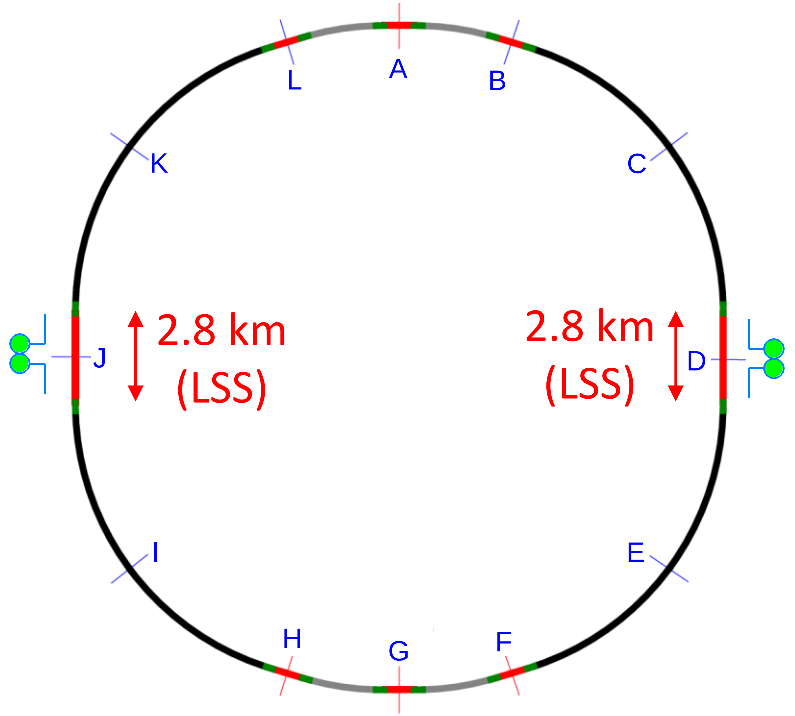


WW, ZH, ttbar	Temp. level	Static [W/m]	Dynamic [W/m]
Main rings	4.5 K	5	49
	50-75 K	3.1	0
Booster ring	4.5 K	5	4.9
	50-75 K	3.1	0
Distribution	4.5 K	0.5	0
	50-75 K	1.3	0



3 Linacs in the tunnel
→ 2 for the main rings
→ 1 for the booster ring

FCC-ee cryogenic capacity (2 main + 1 booster rings)



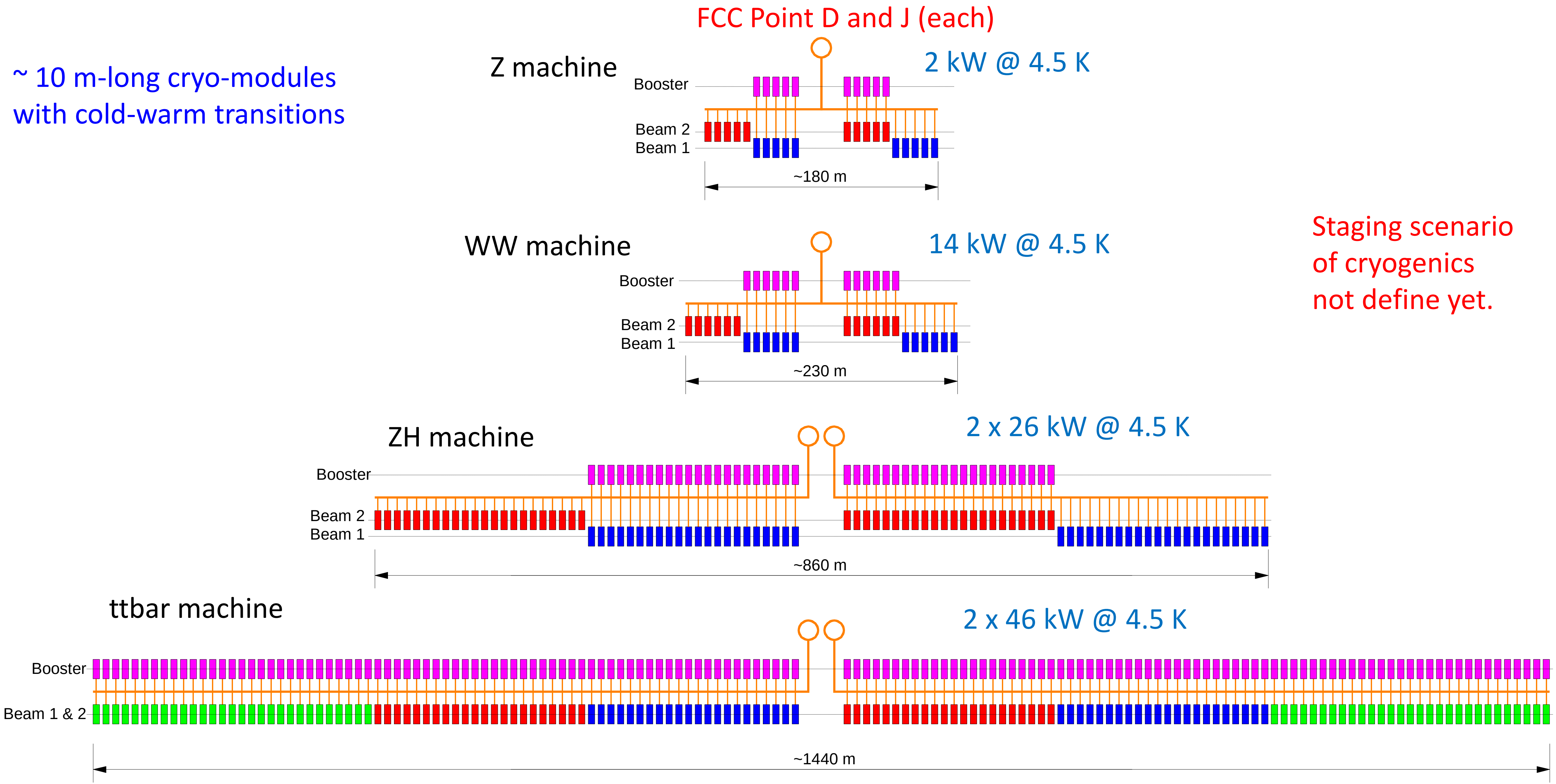
Machine	Q stat [kW]	Q dyn [kW]	Qtot [kW]	Cryoplant #	Cryoplant size [kW@4.5 K]
Z	2.9	0.5	3.4	2	1.7
WW	3.7	24	27	2	14
ZH	14	88	102	4	26
ttbar	31	154	185	4 (8)	46* (23)

Without operational margin !

*: Outside State-of-the-Art

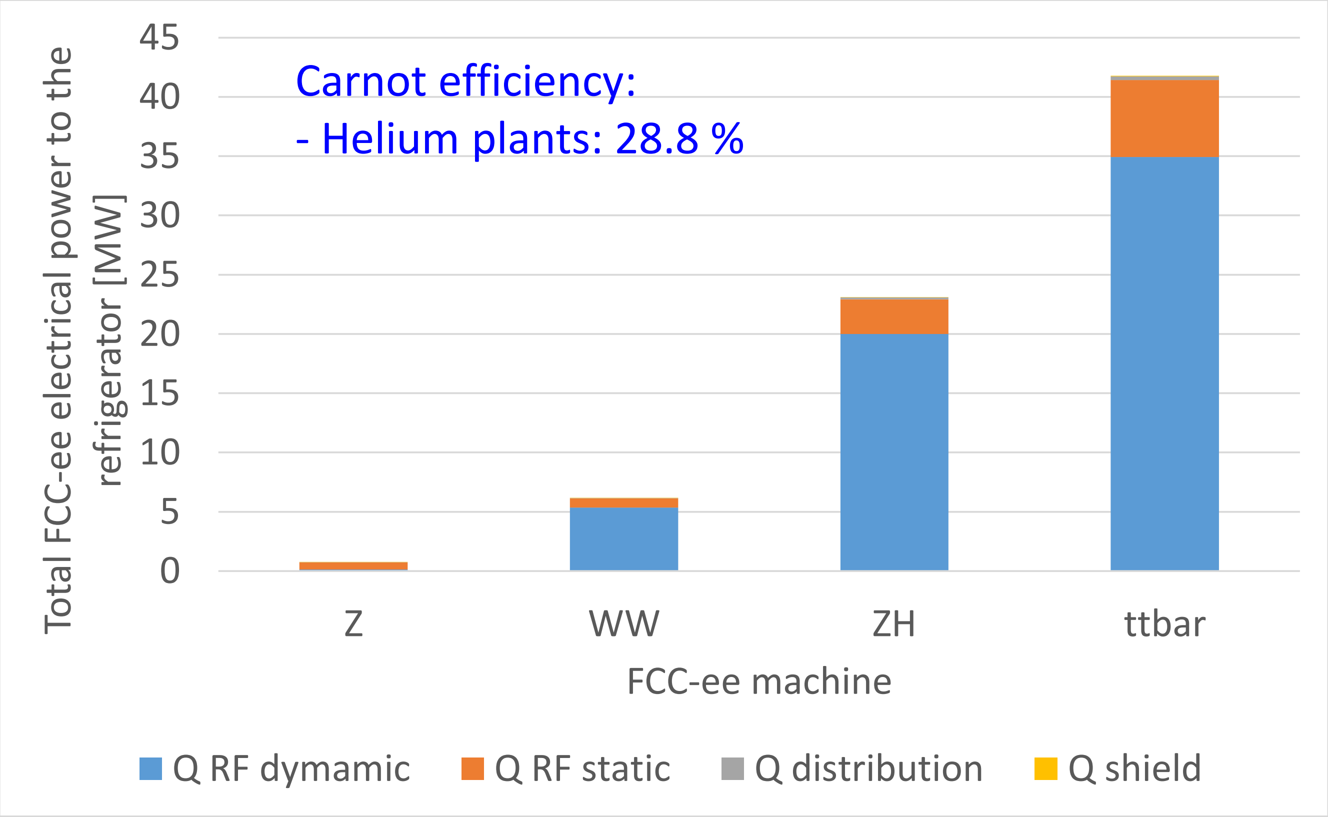
FCC-ee: Cryogenic layout

~ 10 m-long cryo-modules with cold-warm transitions

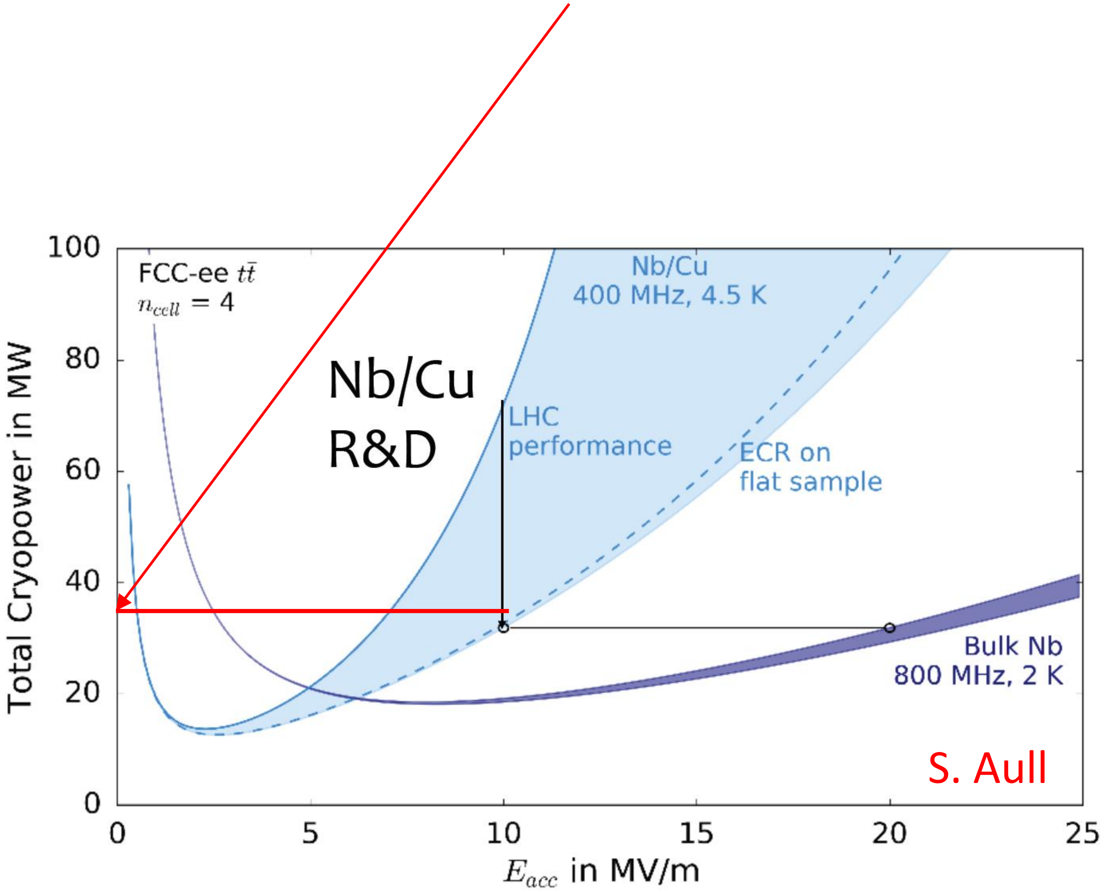


Staging scenario of cryogenics not define yet.

FCC-ee: Cryogenics electrical consumption

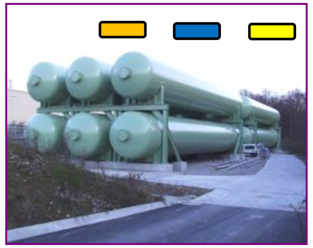


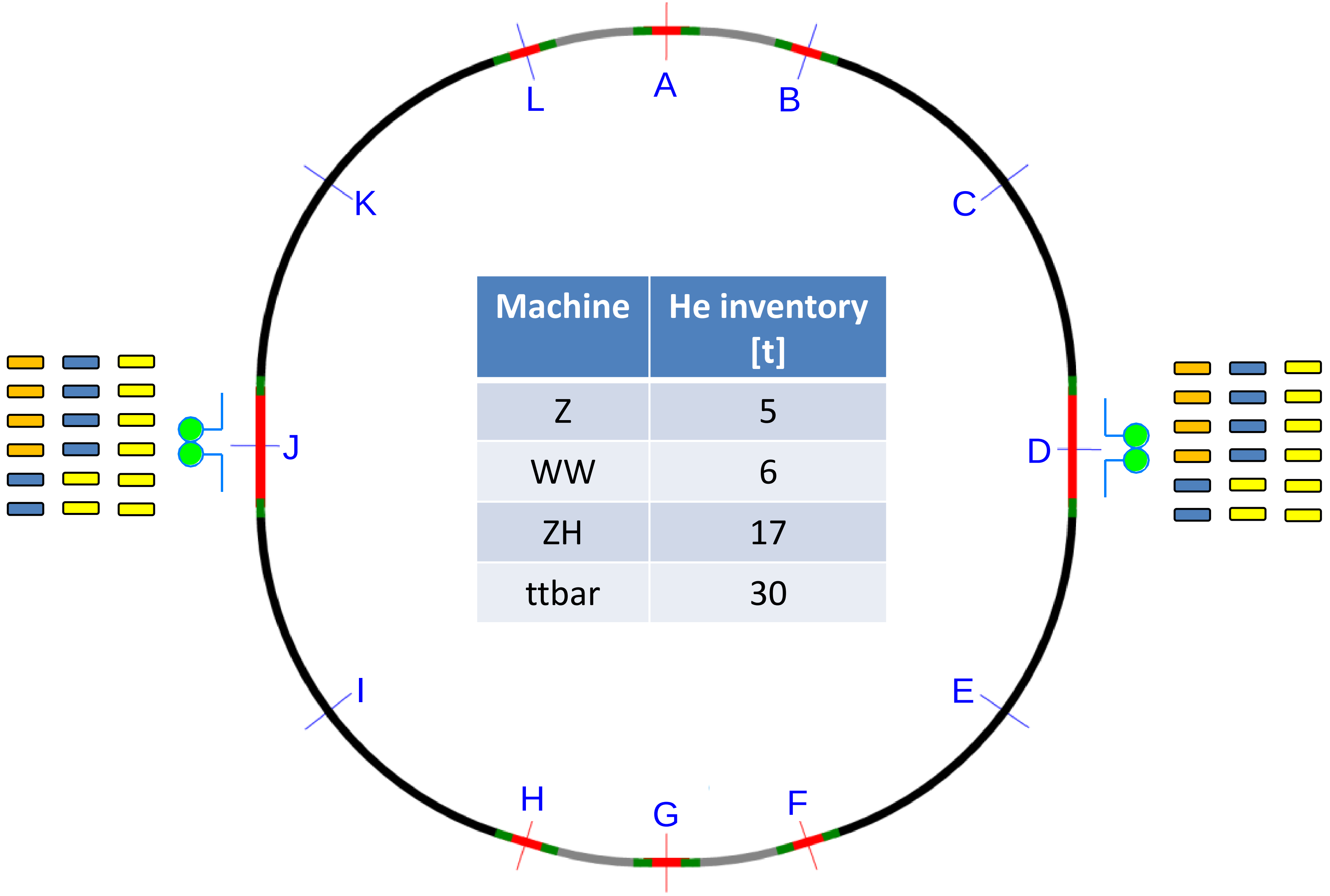
ttbar machine → 35 MW for the 2 main rings



FCC-ee storage management

- Z & WW machine
- Add for ZH machine
- Add for ttbar machine





Machine	He inventory [t]
Z	5
WW	6
ZH	17
ttbar	30

Specific helium inventory

- RF cryomodule: 34 l/m
- Distribution 8 l/m

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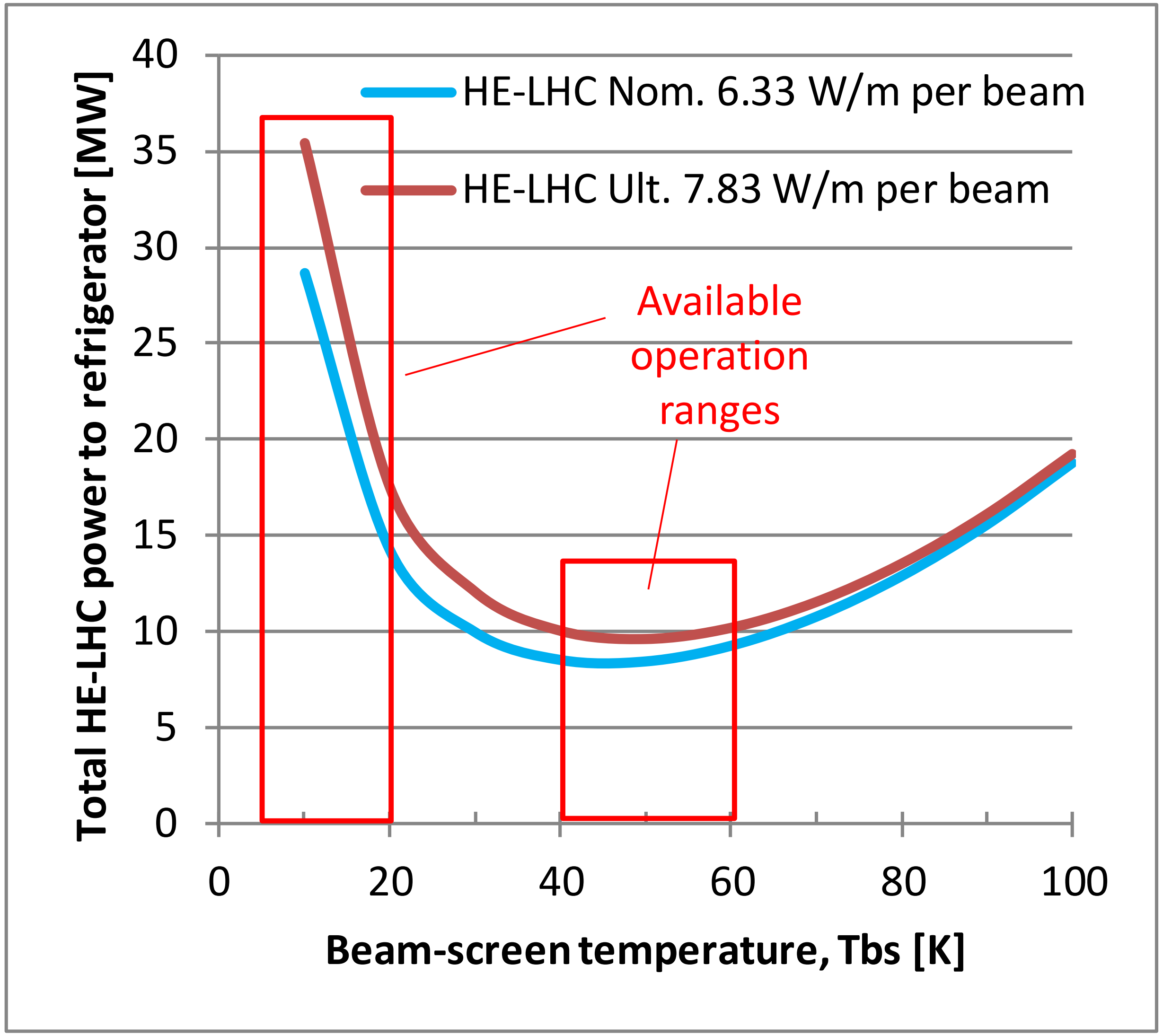
HE-LHC beam screen operating temperature



summary of beam-induced heat loads

mW/m per aperture	LHC nominal	HE-LHC nominal/ult.* LHC bs at 20 K	HE-LHC nominal/ult.* LHC bs at 50 K	HE-LHC nominal/ult.* FCC bs at 50 K
synchrotron radiation	165	4000/5500	4000/5500	4000/5500
image current	160	1140	2160	2230
electron cl.**	445	1100	1100	100
total at bs *T*	770	6240/7740	7260/8760	6330/7830
beam-gas scattering (heat at 1.9 K)***	24	88/95	88/95	88/95

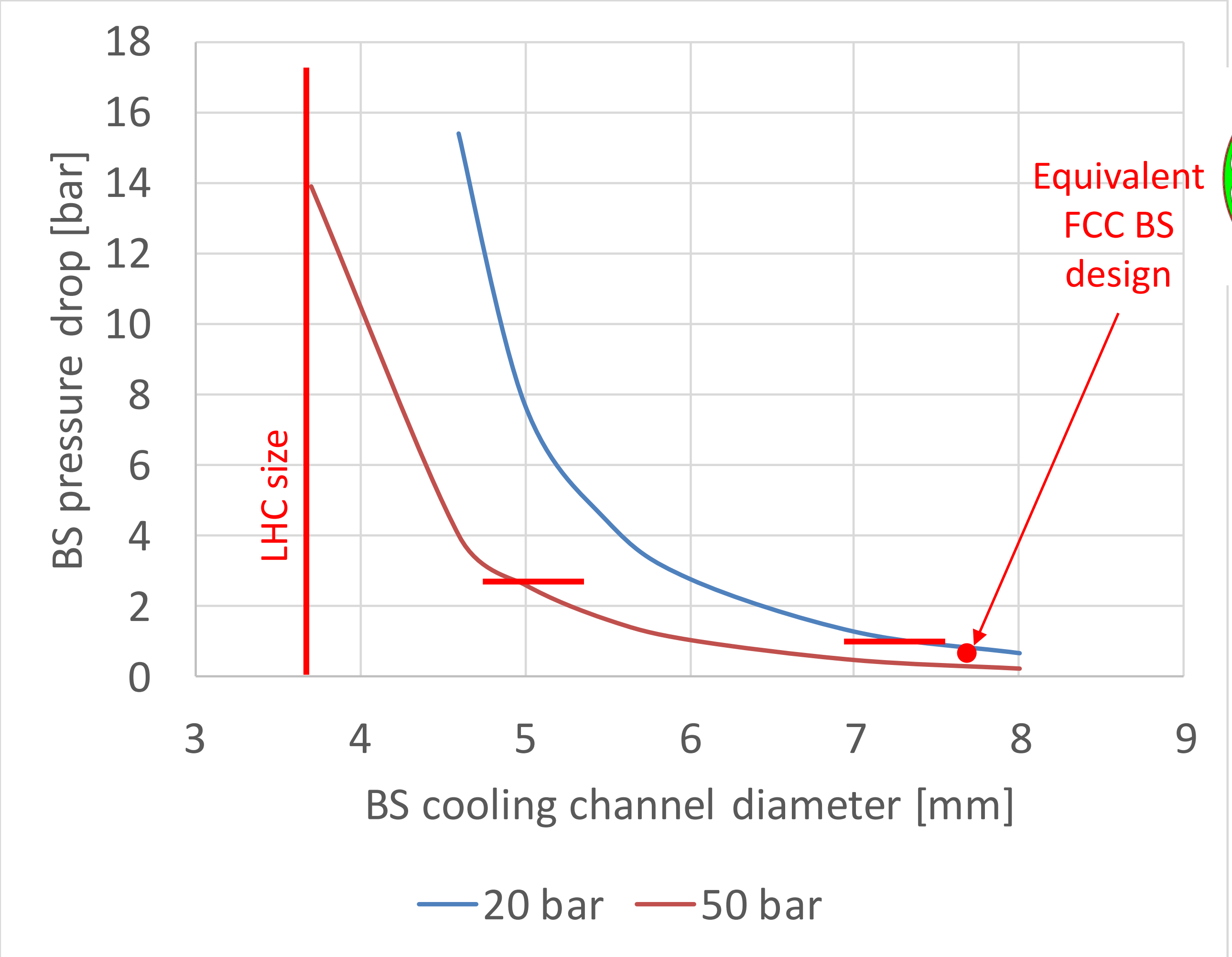
*the only difference between ultimate and nominal is the beam energy (13.5 vs 12.5 TeV)

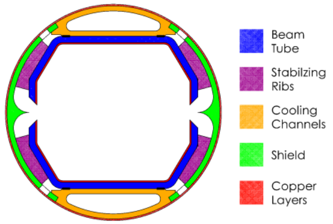
**for SEY=1.4 and 25 ns spacing ***for 100 h lifetime and uniform gas pressure

40-60 K temperature range is the best for HE-LHC

HE-LHC BS pressure drop

2 circular cooling channels per BS (LHC like)
For exergetic efficiency: DP < ~5 % of the operating pressure





Use the FCC-hh design which is compatible with a 20 bar operating pressure

HE-LHC specific heat loads

		FCC-hh [W/m]		HE-LHC [W/m]	
Temperature level		40-60 K	1.9 K	40-60 K	1.9 K
Static heat inleaks	CM supporting system	2	0.13	2	0.13
	Radiative insulation		0.13		0.13
	Thermal shield	3.1		3.1	
	Feedthrough & vac. barrier	0.2	0.1	0.2	0.1
	Distribution	4	0.1	3	0.1
	Total static	9.3	0.46	8.3	0.46
Dynamic heat loads	Synchrotron radiation	57	0.2	8	0.2
	Image current	5.4		4.46	
	Resistive heating		0.3		0.3
	e-clouds			0.2	
	Beam-gas scattering		0.45		0.18
	Total dynamic	62	0.95	13	0.68
Total		72	1.4	21.0	1.1

Temperature level	HE-LHC Sector cooling capacity
40-60 K	61 kW
1.9 K	3.3 kW
40-290 K	54 g/s

Equivalent to ~18 kW @ 4.5 K (Without operational margin)

1.8 K LHC refrigeration units to be replaced (Existing units limited to 2.4 kW)

Upgrade of existing LHC 4.5 K cryoplants to be studied

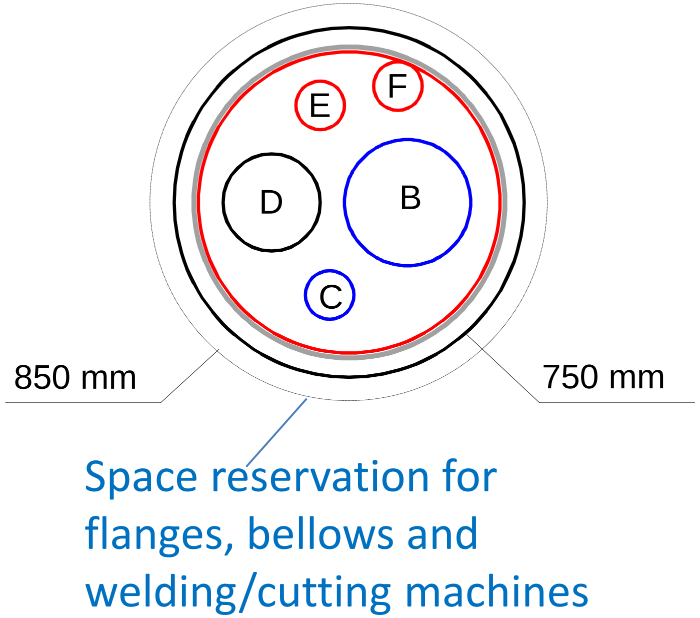
→ present capacity:

Temperature level	LHC Sector cooling capacity: HL/LL
50-75 K	33/31 kW
4.6-20 K	20.6/17.5 kW
4.5-290 K	41/27 g/s

HE-LHC: Reuse of the existing tunnel cryo distribution (QRL)?

- Cooling of HE-LHC sectors with the existing QRL seems difficult:
  - Header D (quench buffer) could be too small to buffer the CM inventory discharge during quench.
  - BS cooling 40-60 K instead of 4.6-20 K → Modification of internal circuits could be quite invasive
  - Existing hardware (valves, HX…) are undersized
  - Cell length is different → existing QRL service modules are shifted with respect to the position of the new Quad → invasive cryo-extensions are required.

- HE-LHC design requires larger pipe diameter (D, E, F) → i.e. will not ease the tunnel integration exercise.



Header	DN [mm]
B	270
C	100
D	200
E	100
F	100

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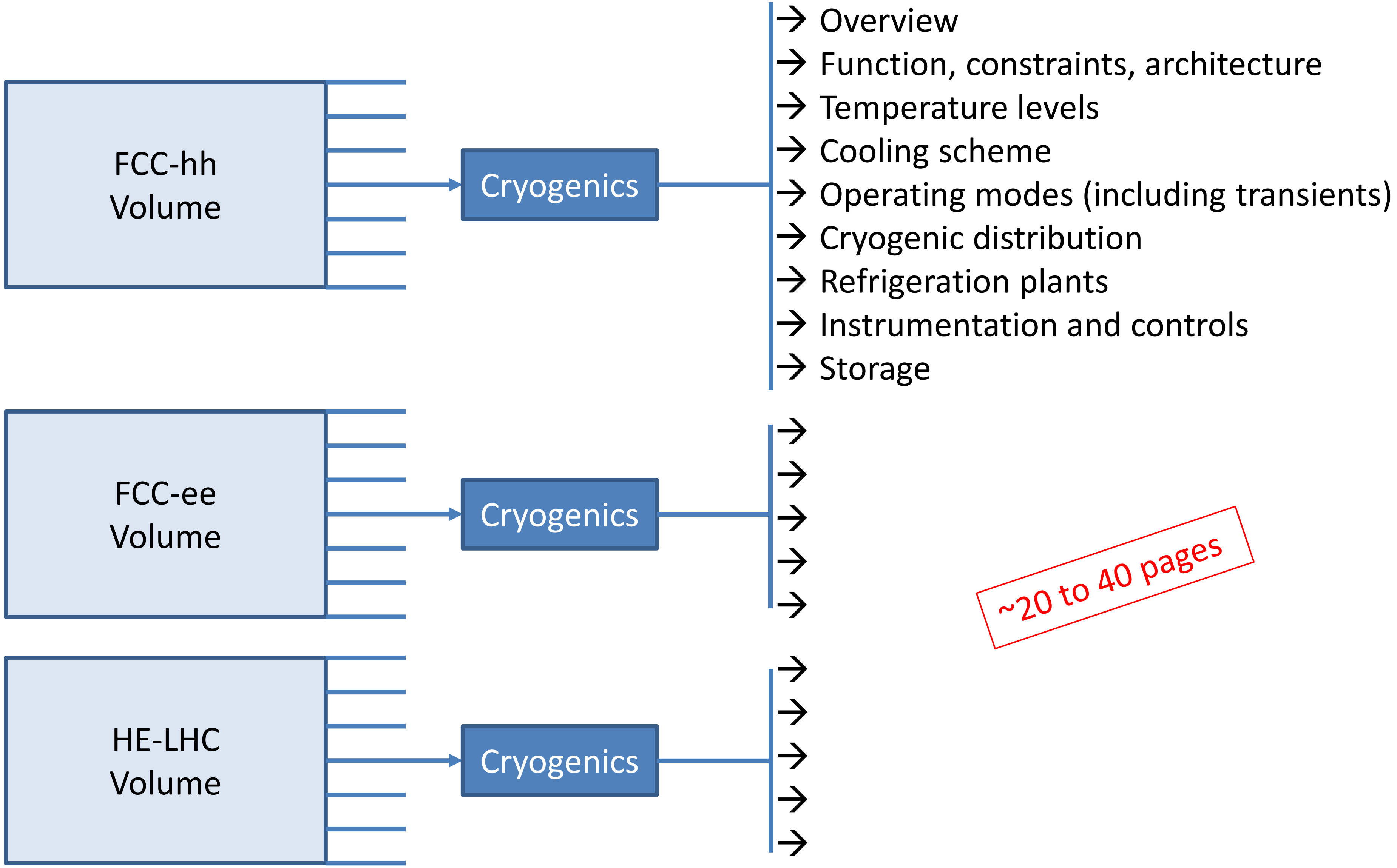
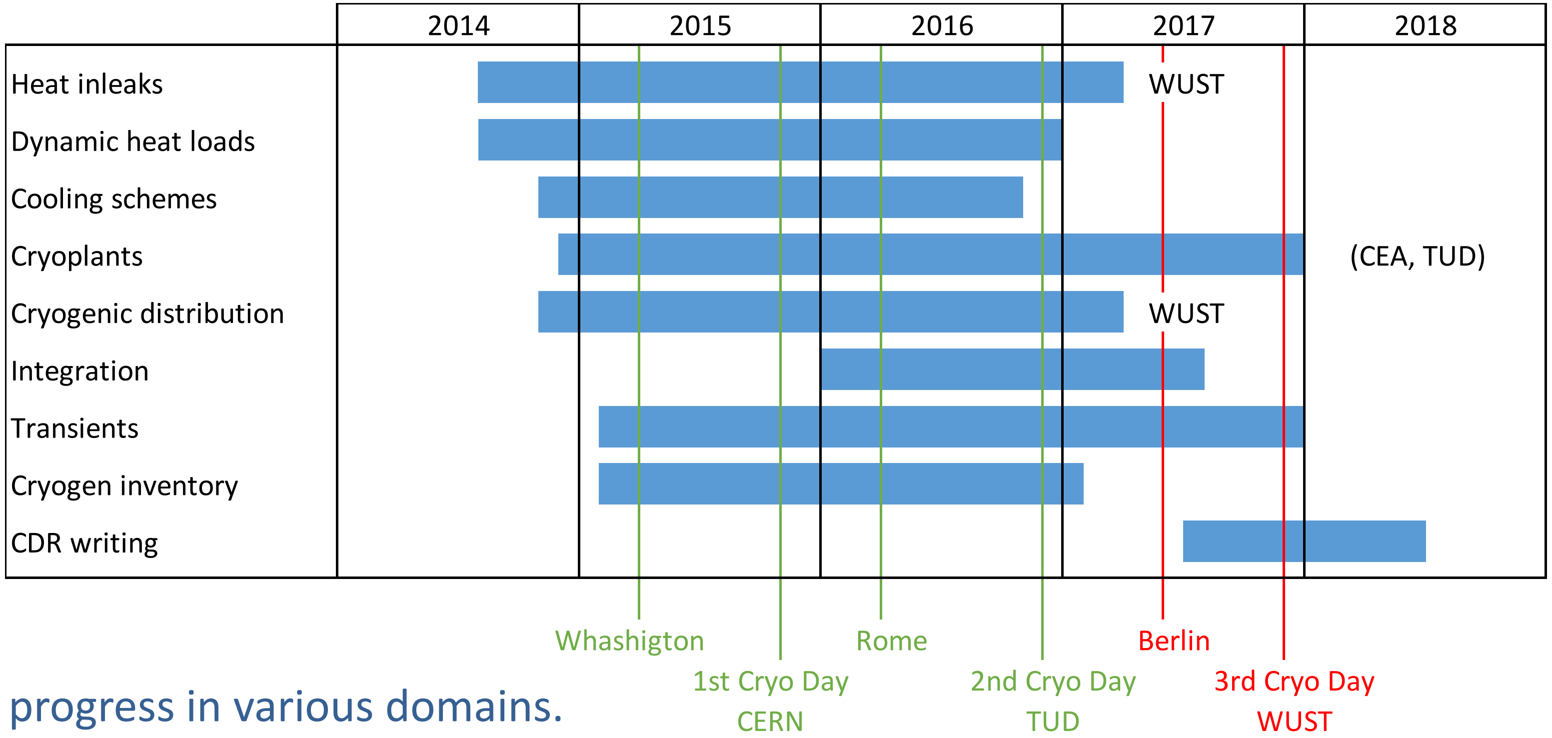
WP2 – Cryogenic challenges
CDR skeleton



Conclusion: schedule



Substantial progress in various domains.

Next important steps:

- FCC-hh: Complete the engineering studies with our industrial partners (Air Liquide and Linde)
- FCC-hh & HE-LHC: Cryogenic transients during resistive transitions → impact on quench valve size & number, on cold-mass design pressure and on header D diameter.
- FCC-hh & HE-LHC: Energy buffering during magnet current ramp-up and fast ramp-down → impact on helium inventory (is 33 l/m (400 t) sufficient ?)
- FCC-ee: Refine the staging scenario with 400 MHz (4.5 K) and/or 800 MHz (2 K).
- All: Operational margin discussion/definition → impact on capital and operation cost