



FCC Week 2015, Washington

Cryogenics

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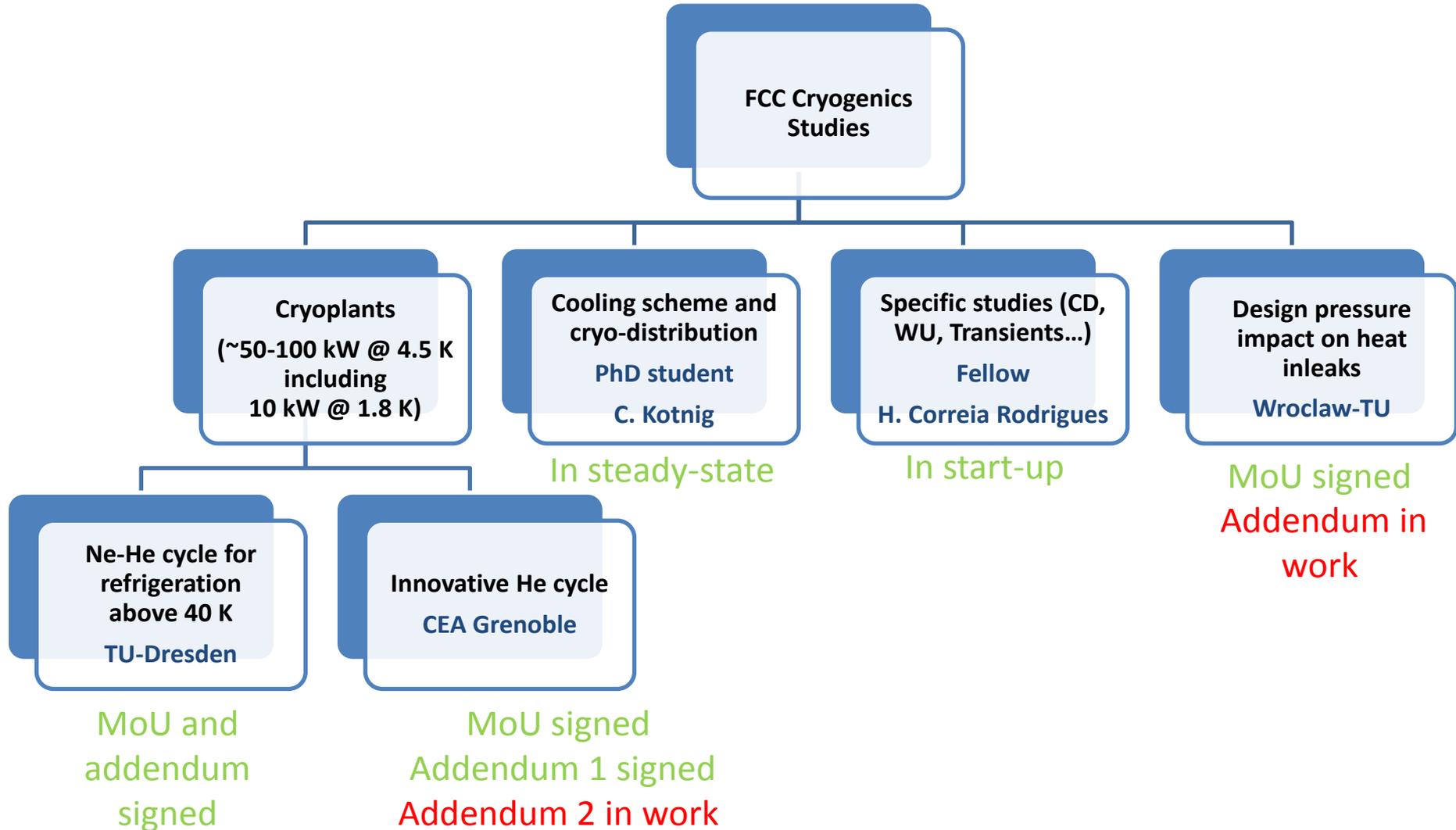
Content



- Introduction: FCC cryogenic study organization
- FCC-hh cryogenics
 - Preliminary assessments
 - Possible cryogenic layouts
- FCC-ee cryogenics
 - Preliminary assessments
 - Possible cryogenic layouts
- Conclusion



FCC cryogenics studies





FCC-hh magnet options

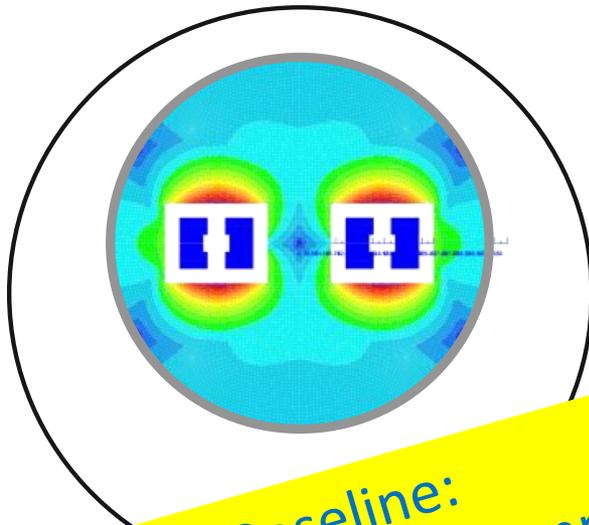


- Inner coil diameter: from 40 to 50 mm under study
 - impact on beam screen design (+)
 - impact on beam aperture (+)
 - impact on magnet cost (-)
- Magnet temperature: from 1.9 K to 4.5 K under study
 - impact on cryogenics cost (C + O) (+)
 - impact on magnet cost (- -)
 - impact on beam vacuum (-)
 - impact on FCC availability (+)

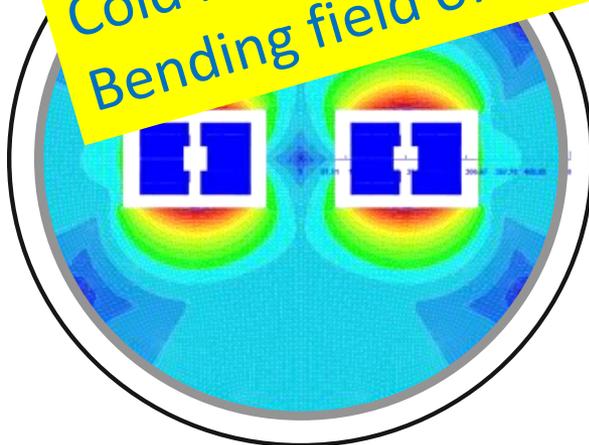
(what is a cost of a FCC lost day (w/o physics) ?)

Magnet temperature option

MB – block
@ 1.9 K



MB – block
@ 4.2 K



**Present Baseline:
Coil aperture of 50 mm
Cold mass temperature of 1.9 K
Bending field of 16 T (i.e. 100-km circumference)**

Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	280
Operating current	(A)	16260
Operating temperature	(K)	1.9
Operating field	(T)	16
Peak field		16.4
Margin along the loadline		20
Stored magnetic energy per unit length	(MJ/m)	2.5
Inductance (magnet)	(mH/m)	19
Yoke ID	(mm)	240
Yoke OD	(mm)	650
Weight per unit length	(kg/m)	2331

Number of apertures	(-)	2
Aperture	(mm)	50
Inter-aperture spacing	(mm)	450
Operating current	(A)	22500
Operating temperature	(K)	4.2
Operating field	(T)	16
Peak field	(T)	16.4
Margin along the loadline	(%)	20
Stored magnetic energy per unit length	(MJ/m)	4.2
Inductance (magnet)	(mH/m)	16
Yoke ID	(mm)	240
Yoke OD	(mm)	910
Weight per unit length	(kg/m)	4693



Beam screen operating temperature



Total electrical power to refrigerator

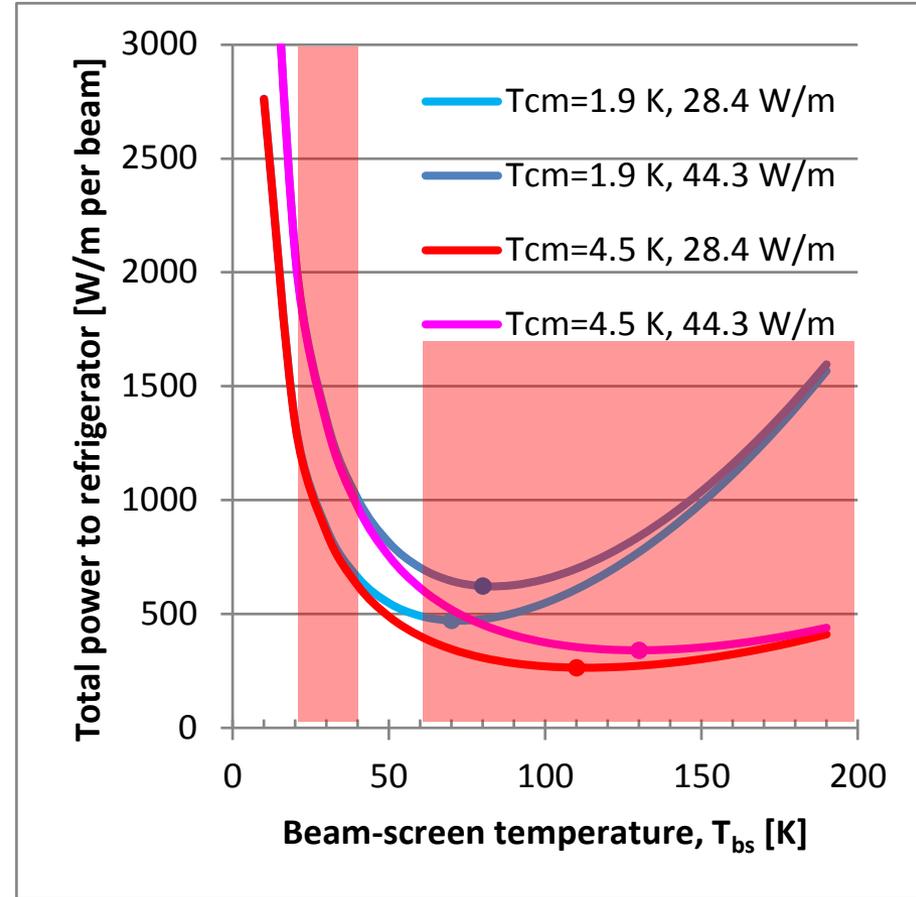
P_{ref} considering:

- a beam screen similar to that of the LHC
- refrigerator efficiencies identical to those of the LHC.

$T_{\text{cm}} = 1.9 \text{ K}$, optimum for $T_{\text{bs}} = 70\text{-}80 \text{ K}$

$T_{\text{cm}} = 4.5 \text{ K}$, flat optimum for $T_{\text{bs}} = 120 \text{ K}$

Temperature range 40-60 K retained



Forbidden by vacuum and/or by surface impedance



Rough heat load estimate



Temperature level		LHC [W/m]			FCC-hh [W/m]	
		50-75 K	4.5-20 K	1.9 K	40-60 K	1.9 K
Static heat inleaks	CM supporting system	1.5		0.10	2.0	0.13
	Radiative insulation			0.11		0.13
	Thermal shield	2.7			3.1	
	Feedthrough & vac. barrier	0.2		0.1	0.2	0.1
	Distribution	3.2	0.1	0.02	4	0.1
	Total static	7.6	0.1	0.3	9.3	0.46
Dynamic heat loads	Synchrotron radiation		0.33	ϵ	57 (88)	0.2
	Image current		0.36		2.7 (2.9)	
	Resistive heating			0.1		0.3 (0.4)
	Beam-gas scattering			0.05		0.45
	Total dynamic		0.7	0.15	64 (95)	0.95 (1.05)
Total		7.6	0.8	0.45	73 (104)	1.4 (1.5)

(): Value in brackets for 80-km FCC-hh

Impact of design pressure (up to 50 bar) on heat inleaks: WrUT contribution



Current lead cooling

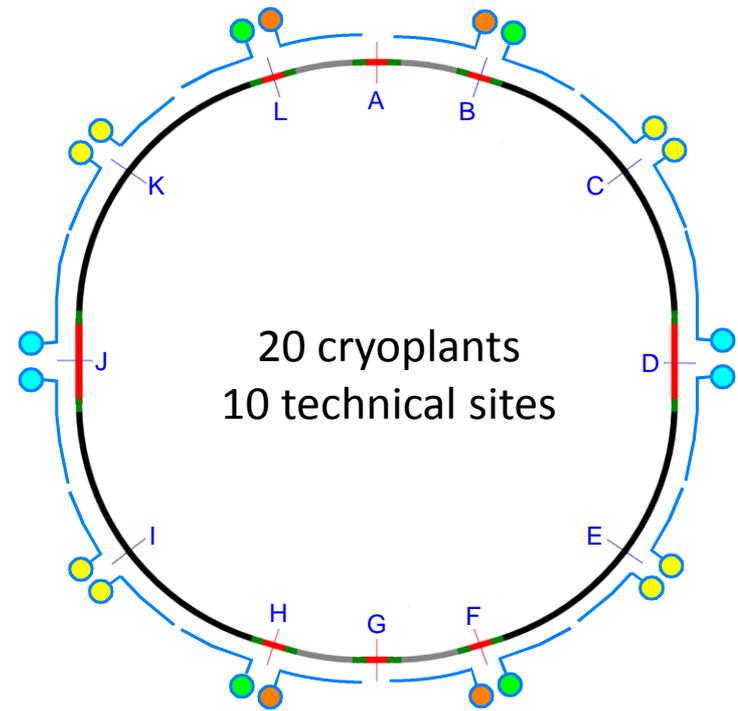
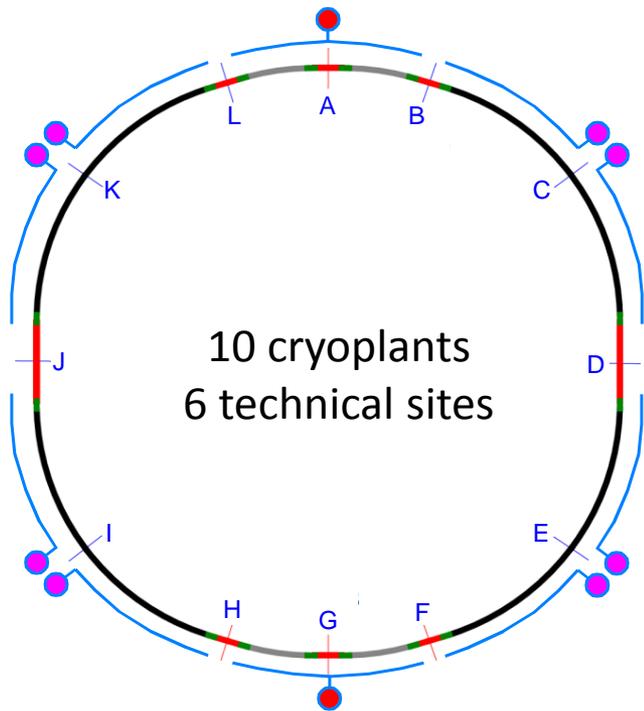


Rough scaling from LHC:

	LHC	FCC-hh		
Dipole Current [kA]	12	16		
Nb of circuits per dipole	1	1	2	3
Nb of arcs	8	12		
Total current (in-out) [MA]	3.4	6.8	13.6	20.4
Current lead consumption [g/s per MA] (conventional CL)	50	50		
Total liquefaction rate [g/s] (conventional CL)	170	340	680	1020
Total equivalent entropic cost [kW @ 4.5 K] (conventional CL)	17	34	68	102
Correction factor for HTS current leads	0.33	0.33		
Total equivalent entropic cost with HTS leads [kW @ 4.5 K]	6	11	22	34
Sector equivalent entropic cost with HTS leads [kW @ 4.5 K]	0.7	0.9	1.9	2.8
Sector current (in-out) [MA]	0.43	0.6	1.1	1.7



FCC-hh cryogenic layout



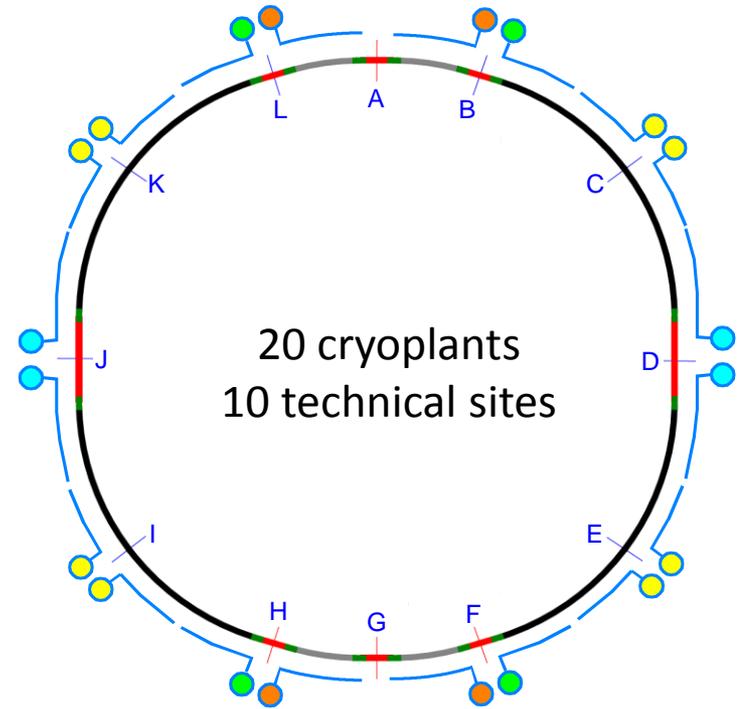
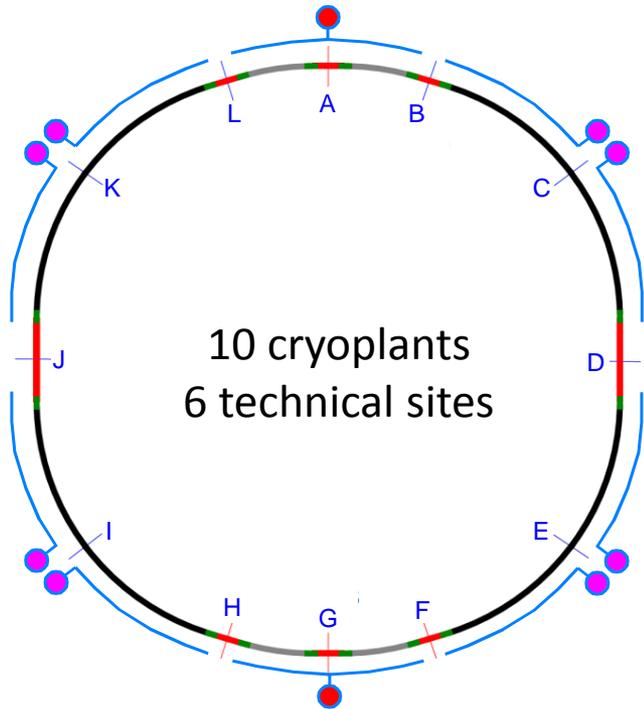
Cryoplant	L Arc+DS [km]	L distribution [km]
	$2 \times 4 = 8$	$2 \times 4.7 = 9.4$
	8.4	8.4

Cryoplant	L Arc+DS [km]	L distribution [km]
	4	4.7
	4.4	5.1
	4	4
	4.4	6.5

- No cryoplant redundancy at Point A and G
- No cryo-distribution in ESS (8.4 km)



FCC-hh cryogenic capacity



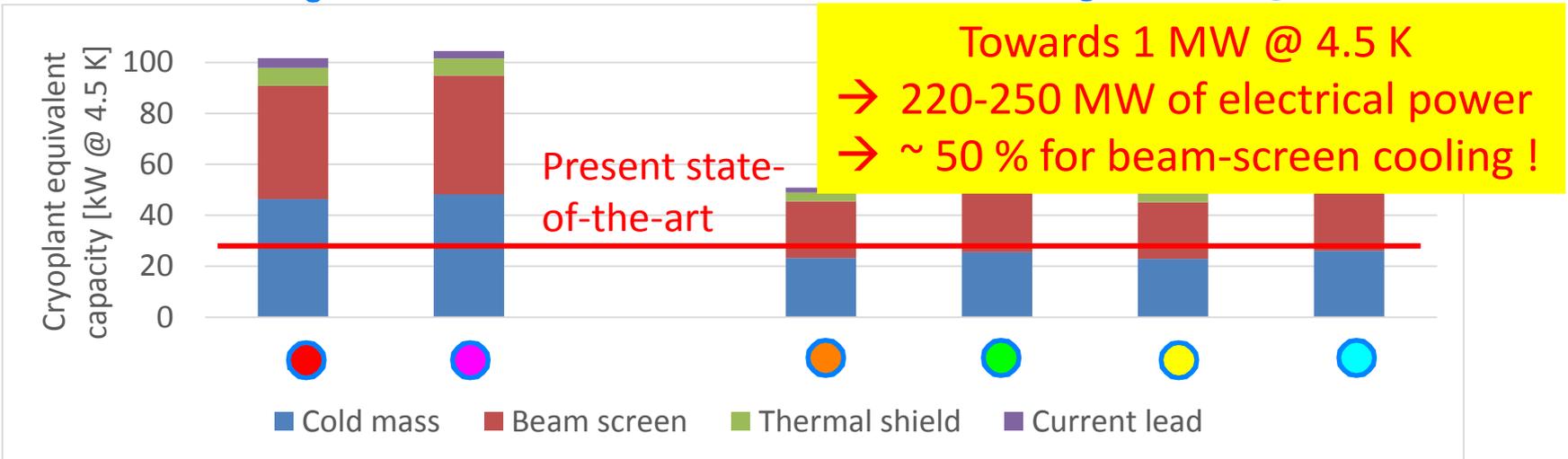
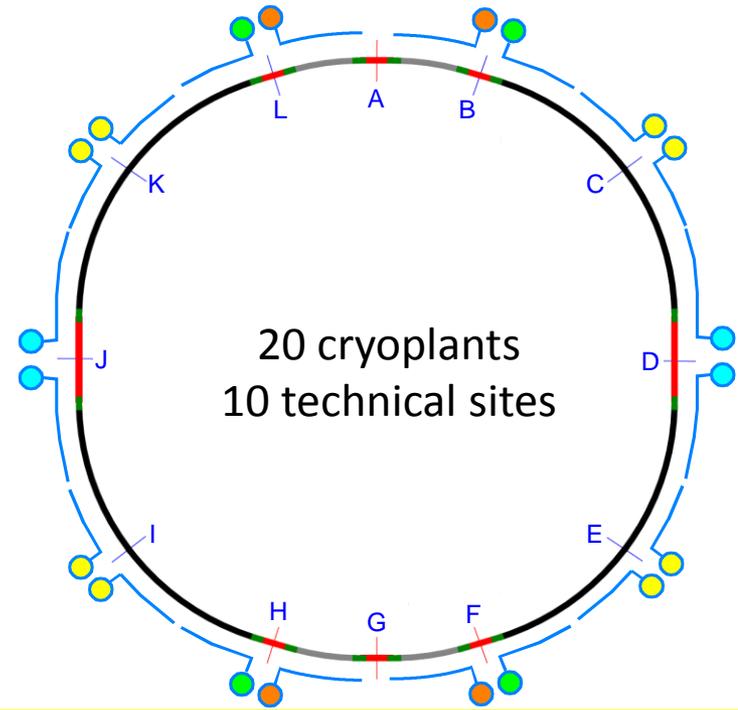
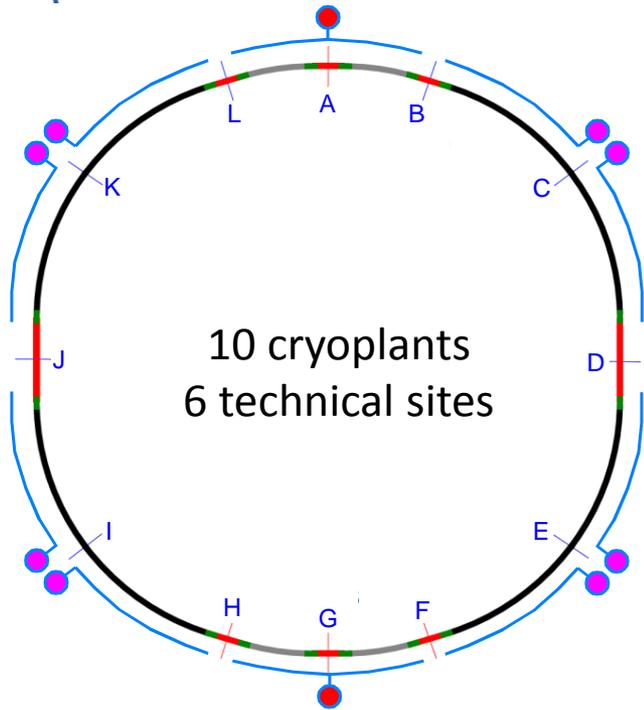
Cryoplant	40-60 K [kW]	1.9 K [kW]	40-300 K [g/s]
	592	11	135
	616	12	99

Cryoplant	40-60 K [kW]	1.9 K [kW]	40-300 K [g/s]
	296	5.7	67
	325	6.2	67
	293	5.6	67
	331	6.4	67

Without operational margin !



FCC-hh cryoplant size





FCC-hh cryoplant architecture



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

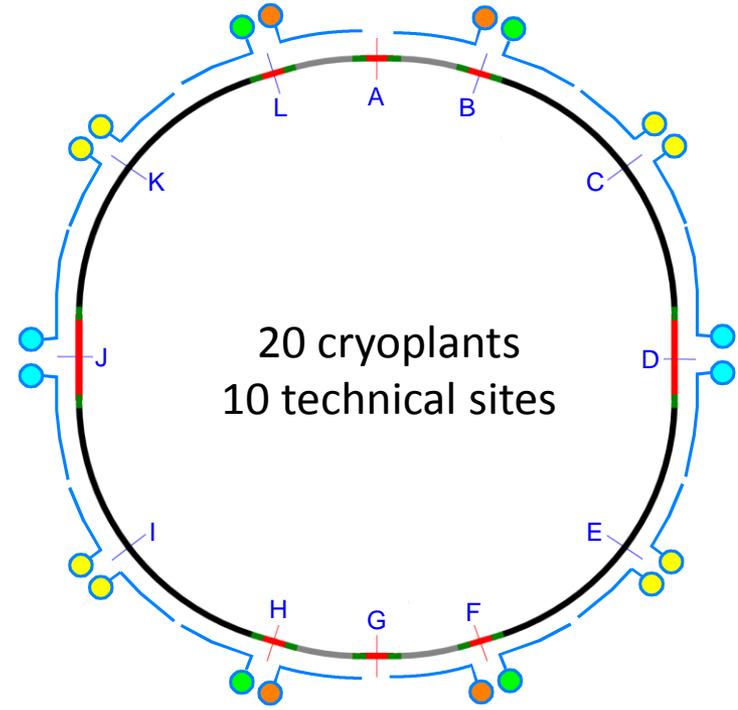
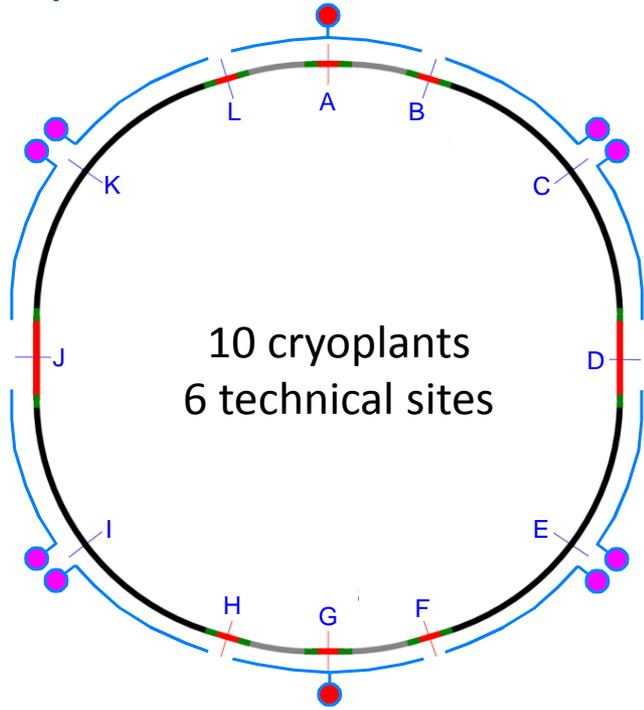
1.9 K
cryoplant

- SC magnet cold mass

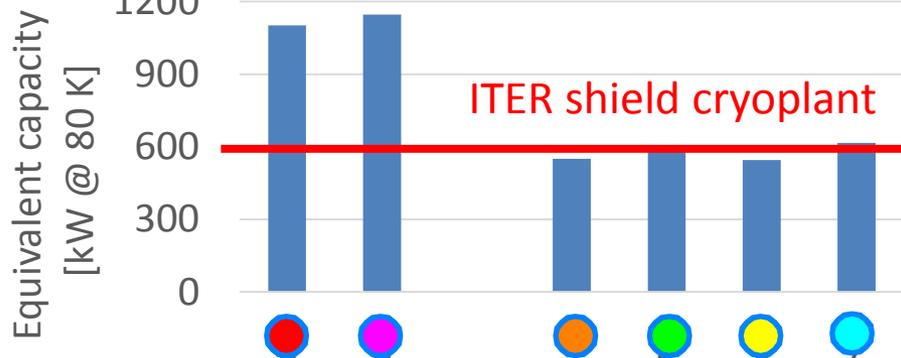
Contributions of TU Dresden and CEA/SBT



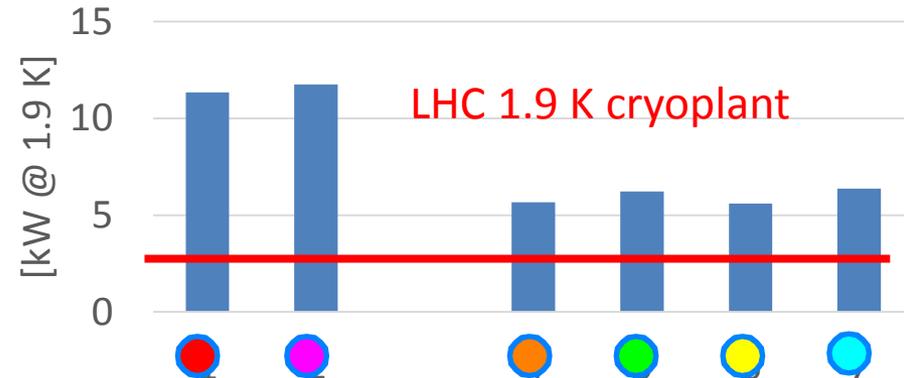
Size of cryoplants

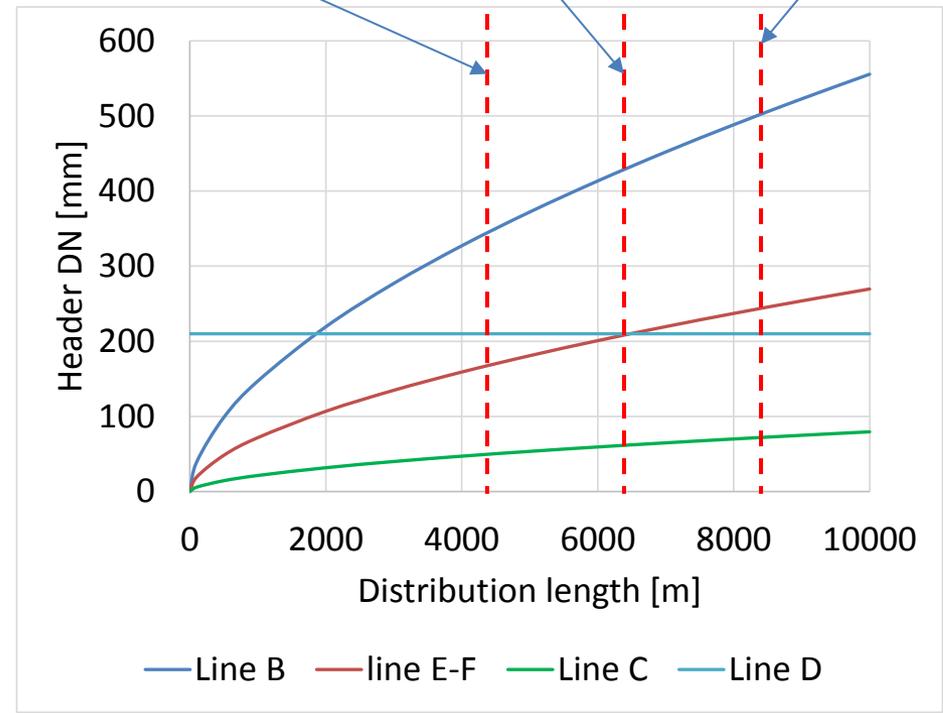
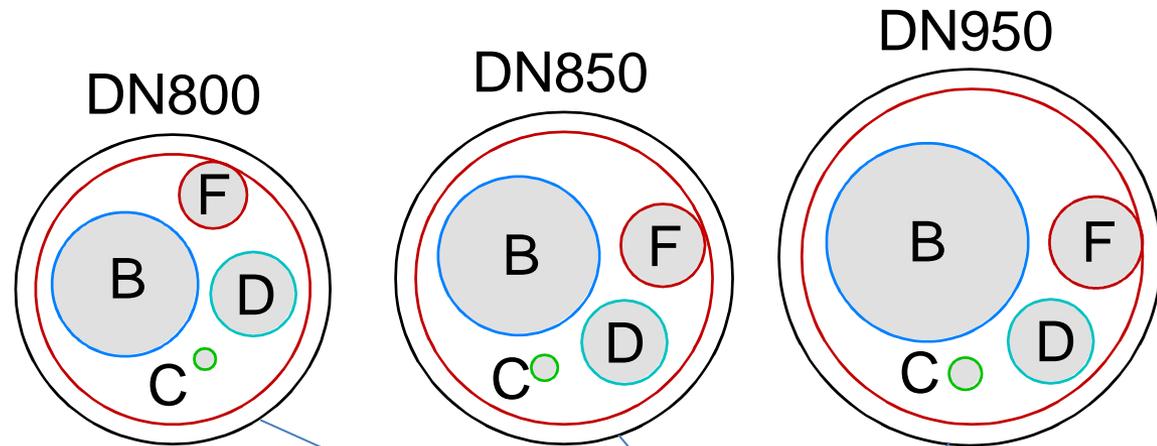


300-40 K cryoplant
1 W @ 40-60 K \iff 1.9 W @ 80 K



1.9 K Cryoplant





- Line B: 15 mbar pumping, 4K (2 K ?)
- Line C: 4.5 K (2.2 K ?), supply header
- Line D: Quench buffer (1.3 bar, 20-30 K)
- Line E: 40 K, 20-50 bar, thermal shield and beam screen supply (machine side)
- Line F: 60 K, 20-50 bar, thermal shield and beam screen return (distribution side)

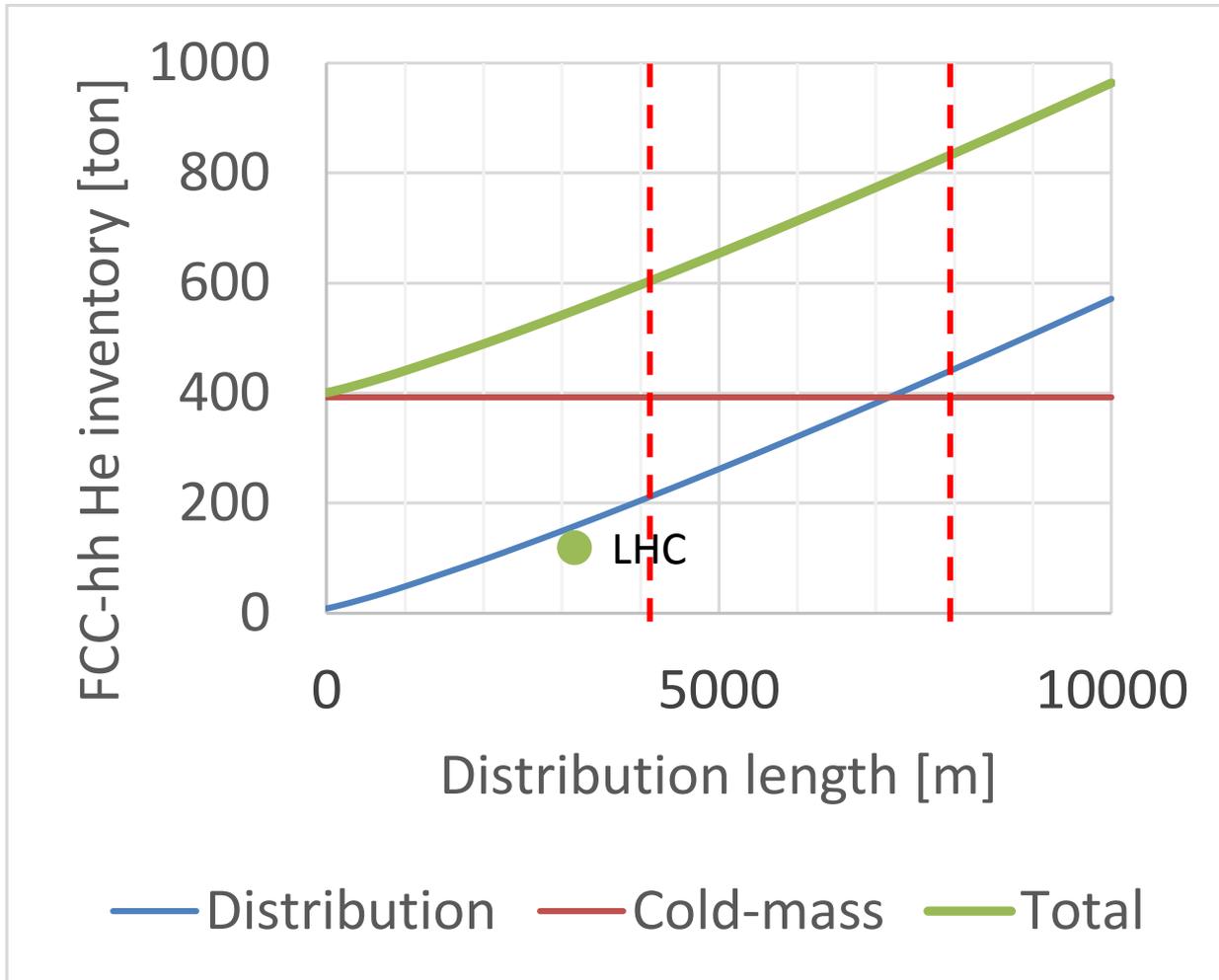


He inventory



Cold mass He inventory : 33 l/m (scaled from LHC)

Distribution inventory dominated by the beam-screen supply and return headers





Content



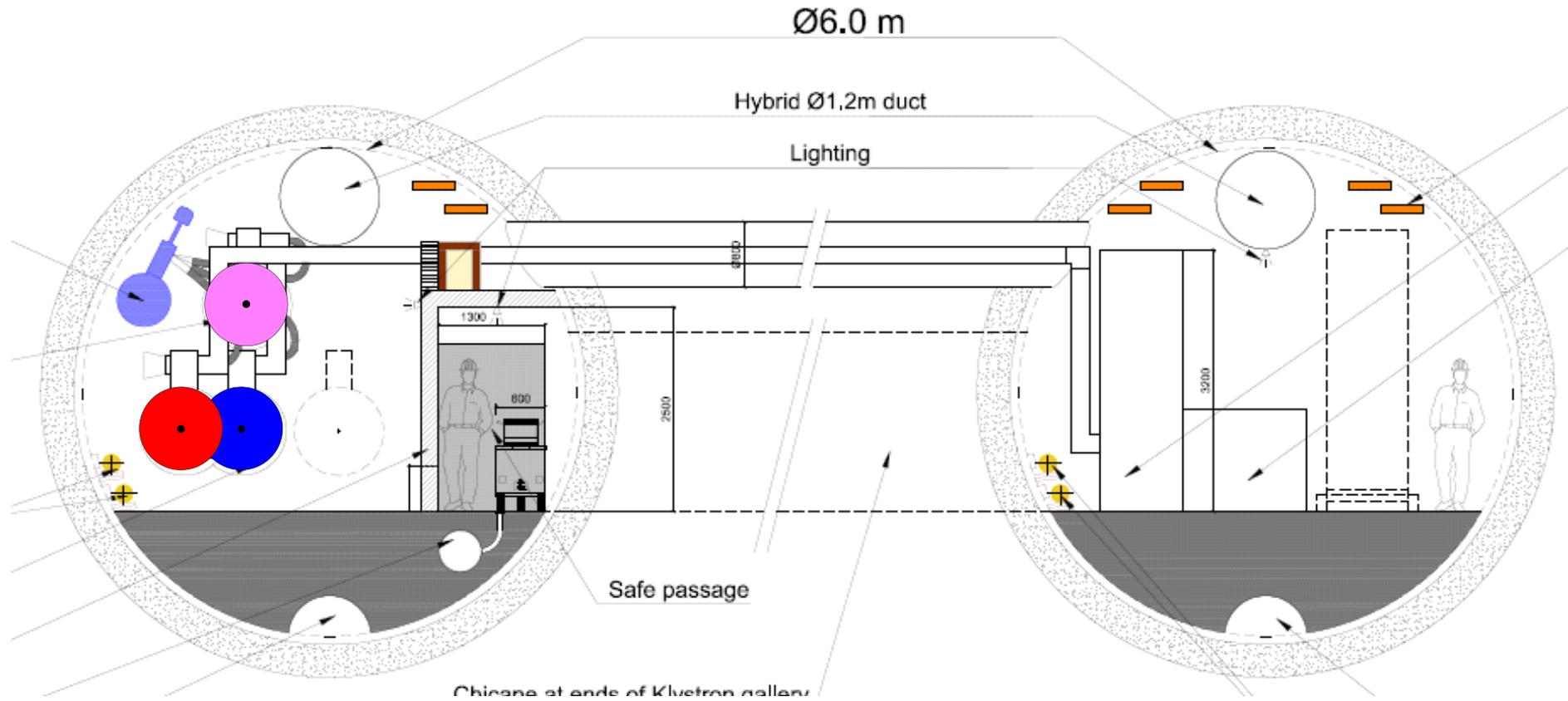
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Table 2: Rf Stations per region, baseline configuration

Rf Region	Frequency (MHz)	Separated Rf (per Ring)					Shared Rf (total)				
		Tubes 1 MW ea	Modules per tube	Modules 2 couplers ea	Voltage (MV)	Length (m)	Tubes 1 MW ea	Modules per tube	Modules 2 couplers ea	Voltage (MV)	Length (m)
1	400	7	8	56	1120	168	14	4	56	1120	168
2	400	7	8	56	1120	168	14	4	56	1120	168
3a	400	4	8	32	640	96	8	8	64	1280	192
3b	400	4	8	32	640	96	8	8	64	1280	192
4a	400	4	8	32	640	96	8	8	64	1280	192
4b	400	4	8	32	640	96	8	8	64	1280	192
5	800	5	8	40	1500	120	10	4	40	1500	120
6	800	5	8	40	1500	120	10	4	40	1500	120
7	800	5	8	40	1500	120	10	4	40	1500	120
8	800	5	8	40	1500	120	10	4	40	1500	120
Total		50		400	10800	1200	100		528	13360	1584
Double for sep. Rf		100		800	21600	2400					

U. Wienands, M. Benedikt, E. Jensen, J. Wenninger, F. Zimmermann



2 main-ring and 1 booster-ring RF module strings



RF data : 120 GeV, 12 mA



	1-cell	2-cell	4-cell
RF voltage [MV]	5500		
SR power per beam [MW]	50		
Synchronous phase [deg]	162.3		
Gradient [MV/m]	10		
Active length [m]	0.375	0.75	1.5
Voltage/cavity [MV]	3.8	7.5	15.0
Number of cavities	1467	734	367
Total cryomodule length [m]	2569	1468	1012
R/Q [linac ohms]	87	169	310
RF power per cavity [kW]	34.1	68.1	136.2
Matched Qext	4.7E+06	4.9E+06	5.3E+06
Bandwidth @ matched Qext	84.3	81.9	75.1
Optimal detuning [Hz]	-132.6	-128.8	-118.1
Q ₀ [10e9]	3.0		
Heat load per cavity [W]	53.9	110.9	241.9
Total heat load per beam [kW]	79.0	81.4	88.8

A. Butterworth

Heat load for 2-main and 1-booster rings

Static heat inleaks: 5 W/m, i.e.

39	22	15	[kW]
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Dynamic load of 2-main rings

158	163	178	[kW]
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Dynamic load of booster ring (~10 % of one main ring)

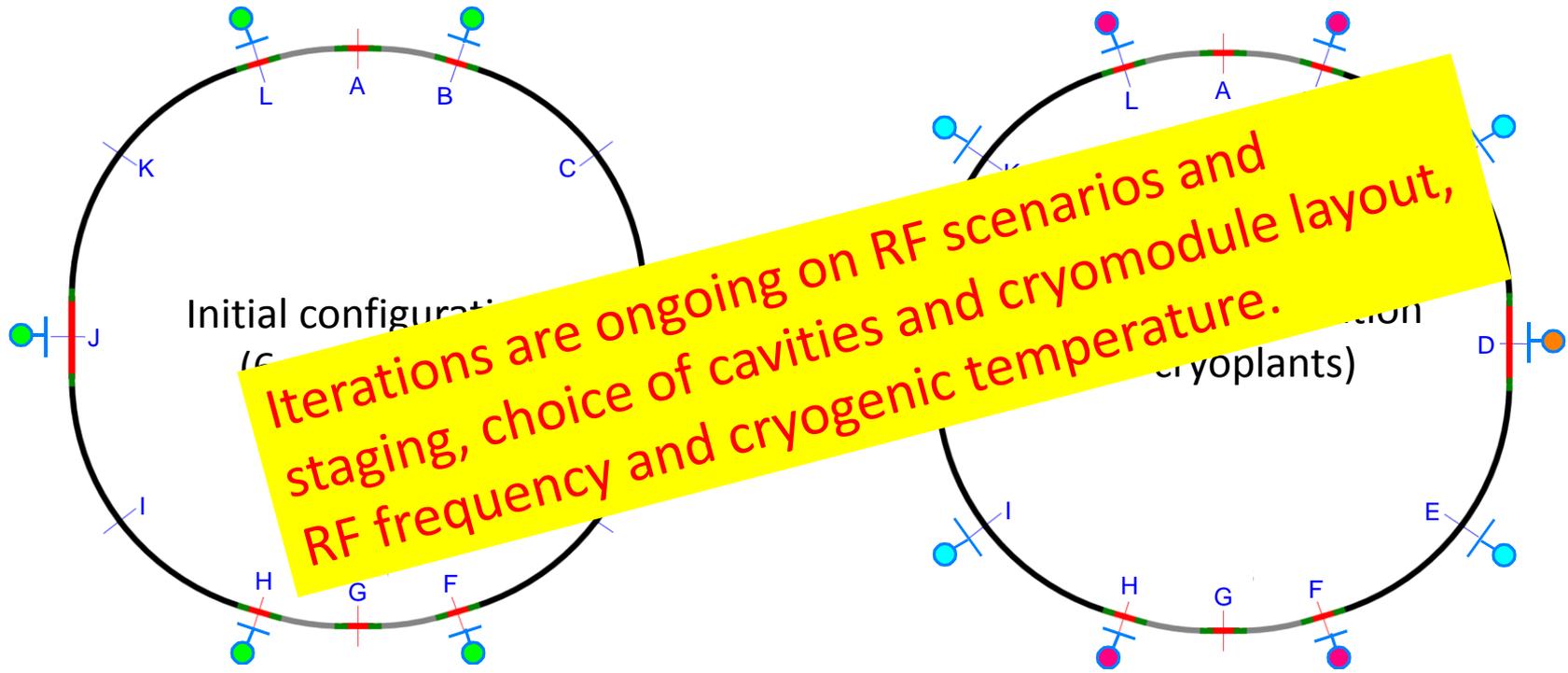
8	8	9	[kW]
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Total

204	193	202	[kW]
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FCC-ee cryogenic capacity (2 main + 1 booster rings)



Cryoplant	Q stat [kW]	Q dyn [kW]	Qtot [kW]
	1	12	13
Total FCC-ee "Initial"	6	75	81

Cryoplant	Q stat [kW]	Q dyn [kW]	Qtot [kW]
	2	25	27
	4	44	47
	?	?	?
Total FCC-ee "Full"	15	186	202



Conclusion: Next step



- Heat inleaks: estimate heat inleaks based on conceptual design of machine cryostats
- Dynamic heat loads: refine assessment of dynamic heat loads following progress of accelerator systems definition (especially for FCC-ee RF system)
- Cooling schemes: explore variants for cooling schemes of superconducting accelerator components, beam screens/beam pipes, including non-conventional working fluids
- Cryoplants: investigate options for increase of unit capacity and efficiency, including impacts on operability, CAPEX and OPEX.
- Cryogenic distribution: define pipe sizes, conceptual mechanical and thermal design of distribution lines, explore options of integrated piping vs external cryoline
- Integration: study implantation at ground level and underground of cryoplant and distribution system.
- Transients: study of the cooldown and warmup time, current ramp-up/down, quench recovery...
- Cryogen inventory: address issues of cryogen inventory management (initial fill, thermal transients, losses)



Conclusion: schedule

