The Future Circular Collider (FCC) project and its cryogenic challenges

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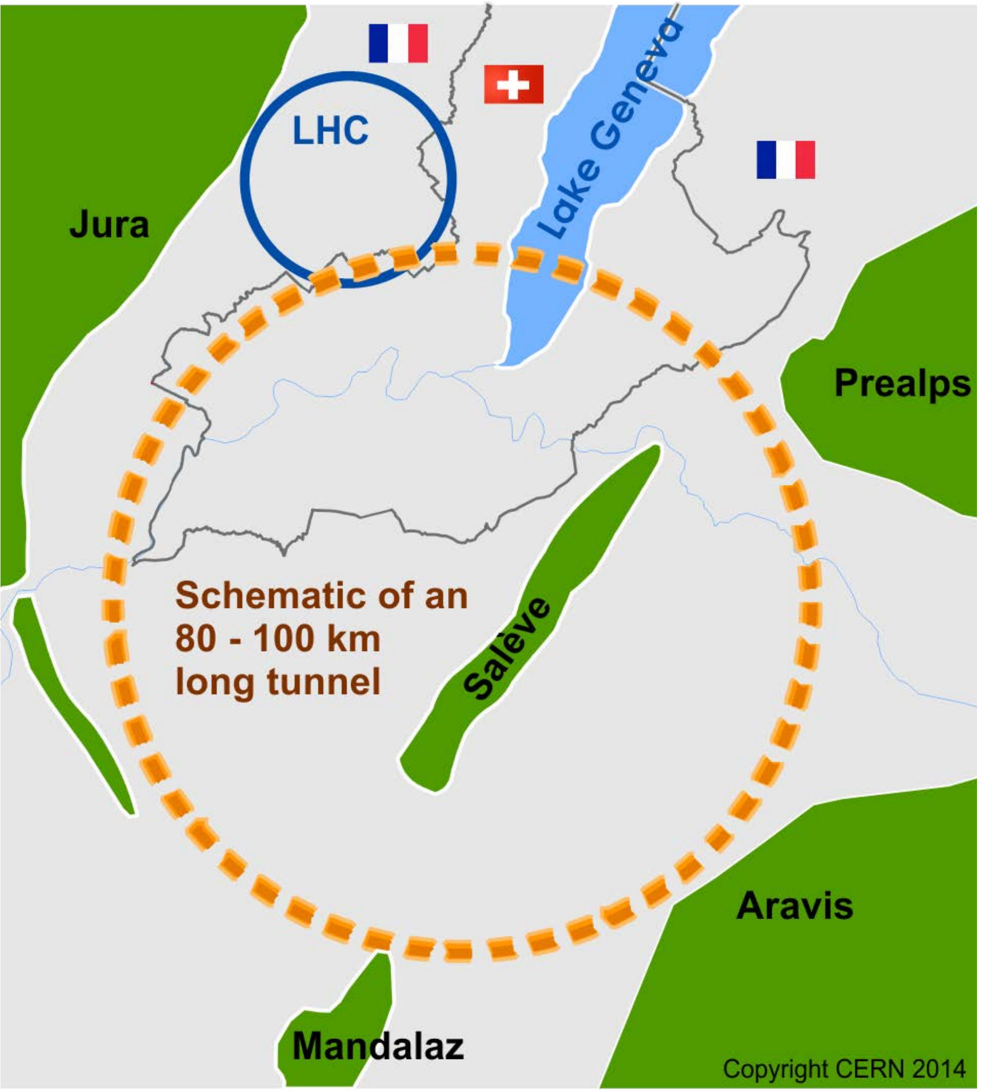
Content

- Introduction: Scope of the FCC study
- FCC-hh tunnel cryogenics and user heat loads
- FCC-hh cryogenics layout and architecture
- FCC-hh cool-down and nominal operation
- FCC-hh electrical consumption and helium inventory
- Conclusion

Scope of FCC Study

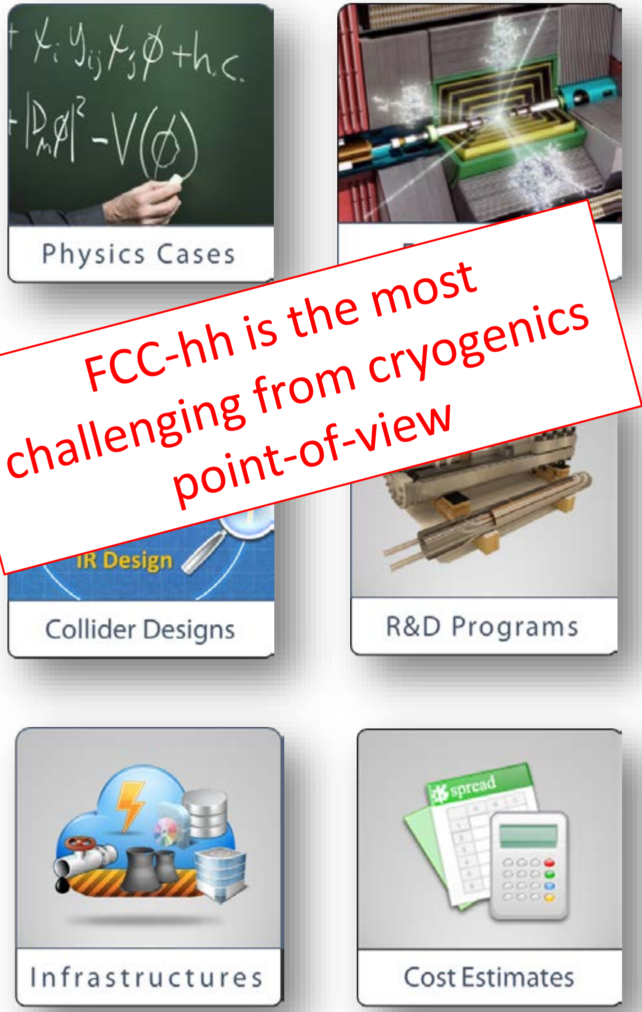


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

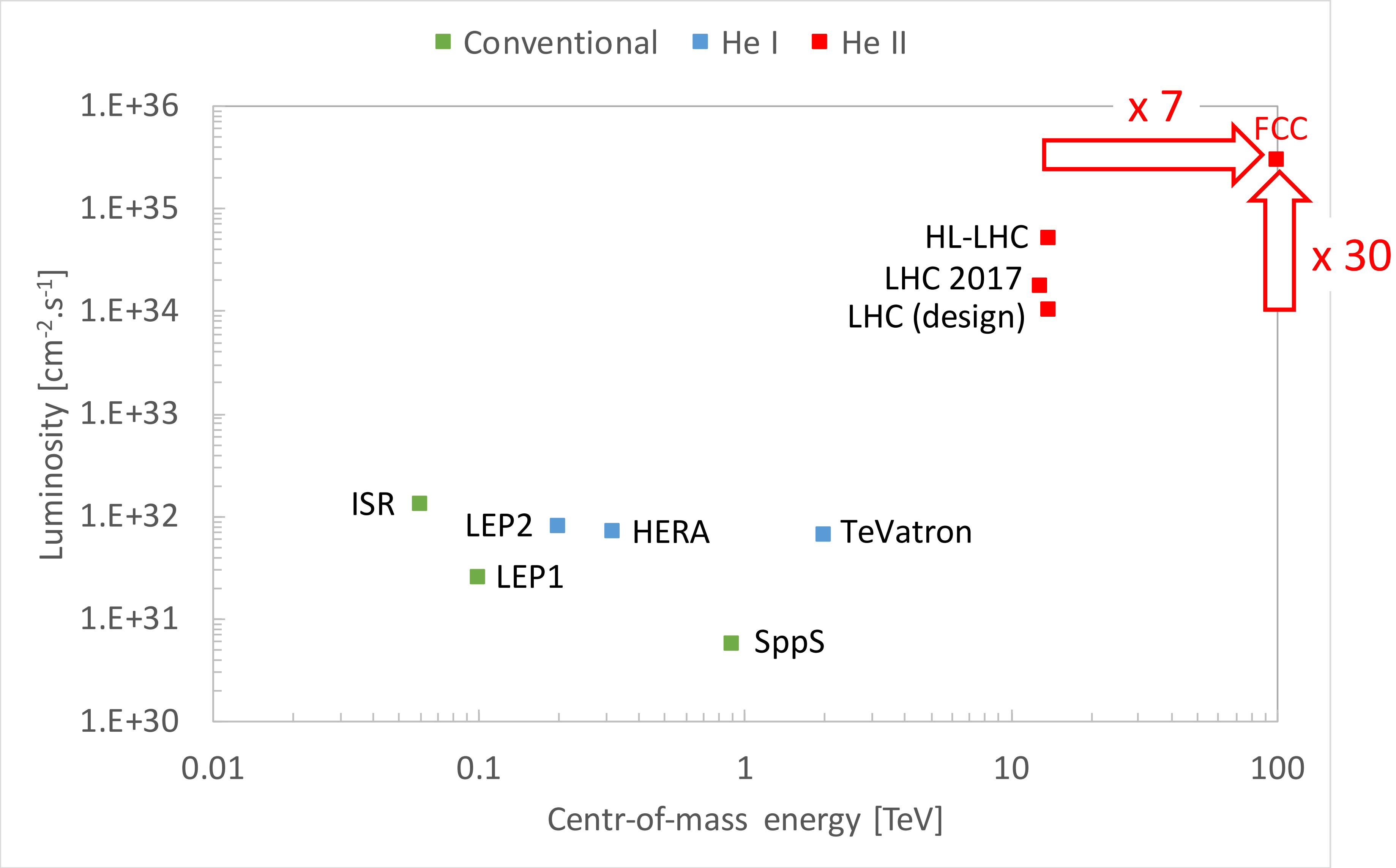
  ~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),**
  as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL
- **HE-LHC** with *FCC-hh* technology
- **CDR for end 2018**

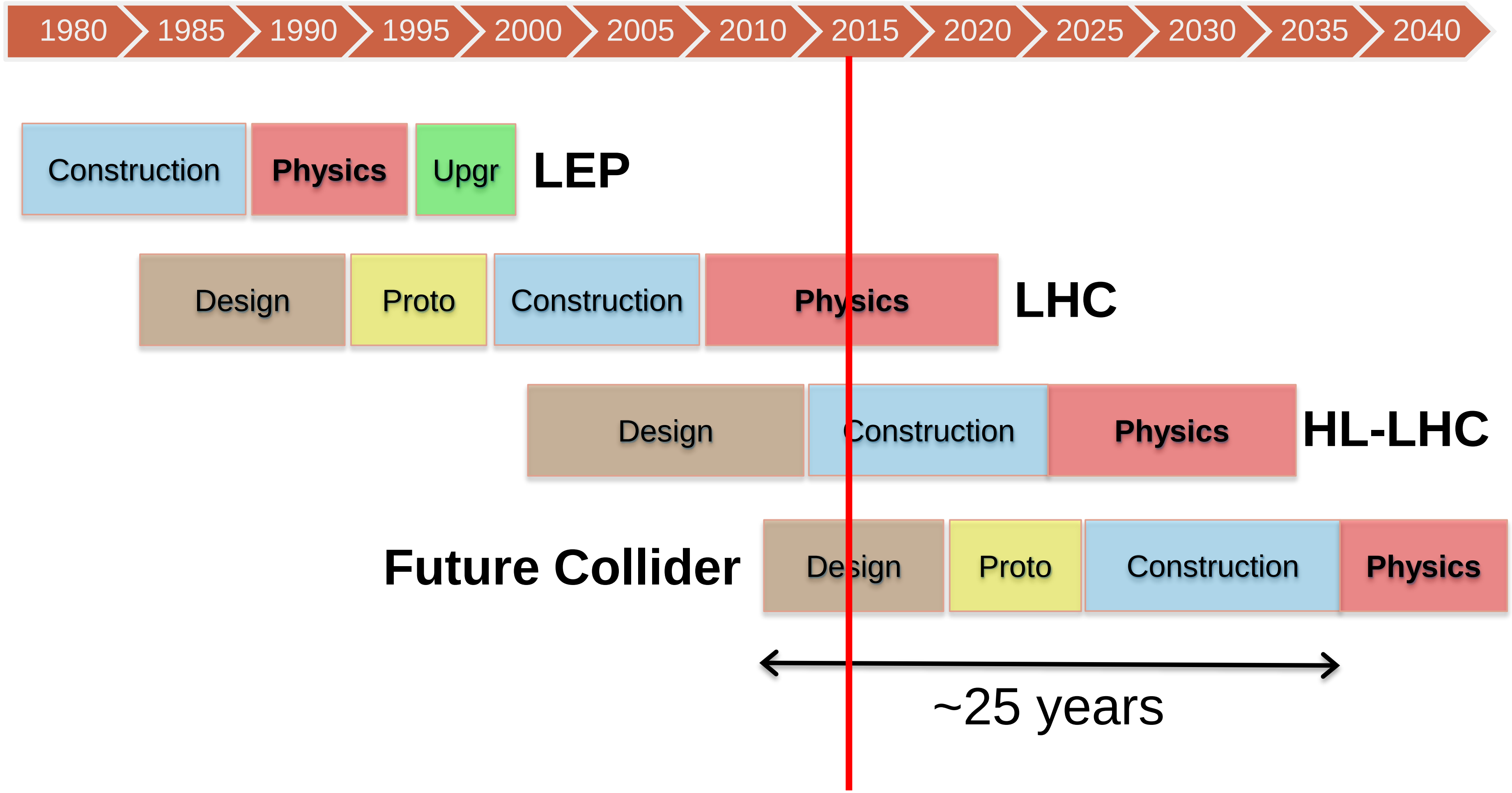


FCC-hh is the most challenging from cryogenics point-of-view

Luminosity vs energy of colliders



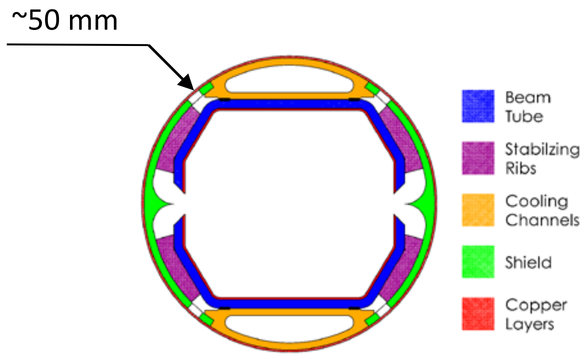
CERN Collider plan



FCC-hh baseline parameters

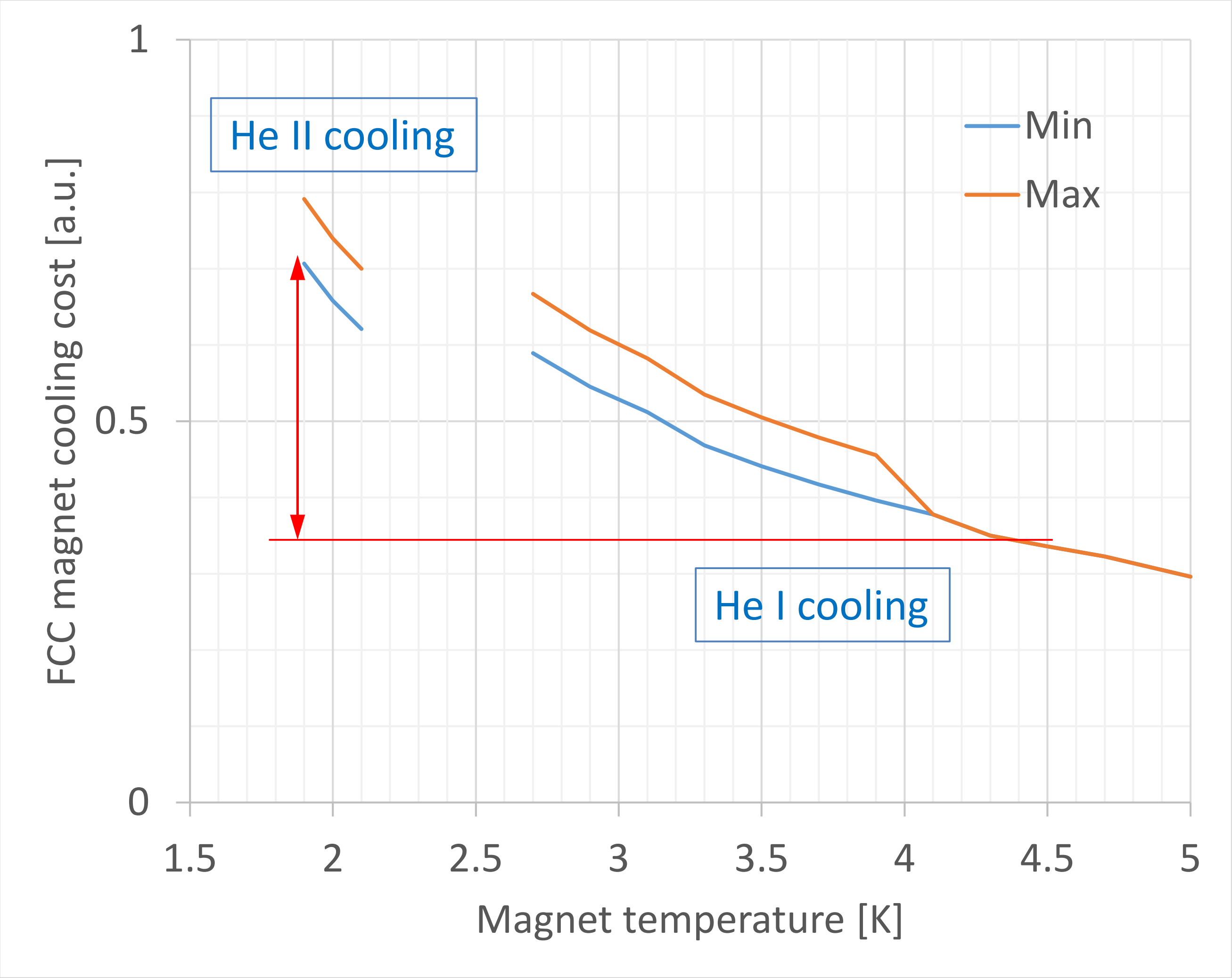
Parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		**16**
circumference [km]	26.7		**100**
luminosity [10^{34} $cm^{-2}.s^{-1}$]	1	5	5 → 29
bunch spacing [ns]	25		25
event / bunch crossing	27	135	170
bunch population [10^{11}]	1.15	2.2	1
norm. transverse emittance [μm]	3.75	2.5	2.2
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8
synchrotron rad. [W/m/aperture]	0.17	0.33	**28**
critical energy [keV]	0.044		4.3
total syn. rad. power [MW]	0.0072	0.0146	**4.8**
longitudinal damping time [h]	12.9		0.54

Nb_3Sn superconducting magnets cooled at 1.9 K



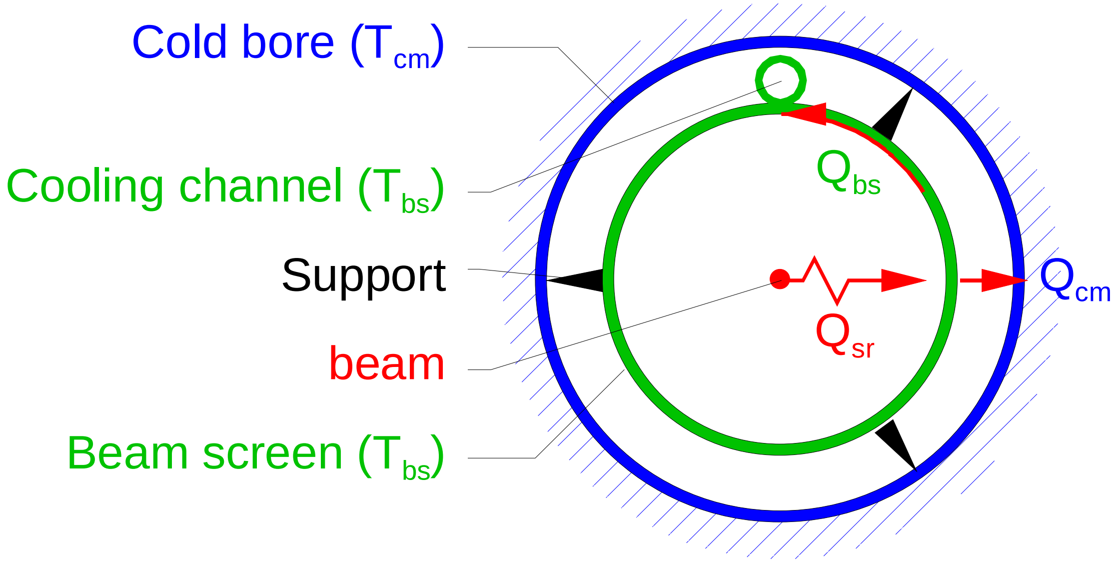
5 MW dissipated in cryogenic environment
→ beam screens are mandatory
→ Cooling temperature 40-60 K

Magnet cooling cost including 10 years of operation



Magnet cooling at 1.9 K vs 4.5 K: About a factor 2 on the magnet cooling cost largely compensated by the saving on superconducting material → Tmagnet = 1.9 K

Beam screen – cold mass thermodynamics



T_a: Ambient temperature

Energy balance:

$Q_{bs} = Q_{sr} - Q_{cm}$

- Exergy load ΔE = measure of (ideal) refrigeration duty :

$$\Delta E = \Delta E_{cm} + \Delta E_{bs}$$

$$\Delta E = Q_{cm} \cdot (T_a/T_{cm} - 1) + Q_{bs} \cdot (T_a/T_{bs} - 1)$$

- Real electrical power to refrigerator: $P_{ref} = \Delta E/\eta(T)$

with $\eta(T)$ = efficiency w.r. to Carnot = COP_{Carnot}/COP_{Real}

$$P_{ref} = Q_{cm} \cdot (T_a/T_{cm} - 1)/\eta(T_{cm}) + Q_{bs} \cdot (T_a/T_{bs} - 1)/\eta(T_{bs})$$

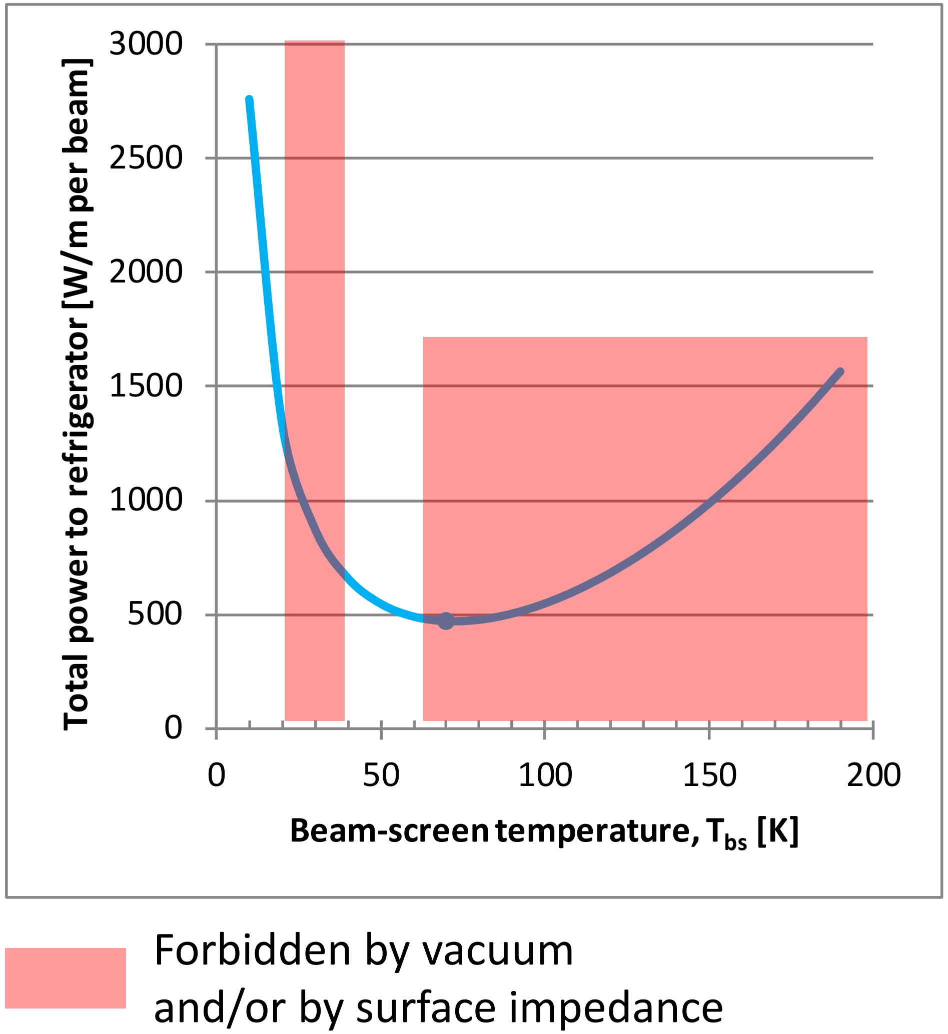
BS – CM thermodynamics Numerical application

Total electrical power to refrigerator $P_{ref.}$ considering:

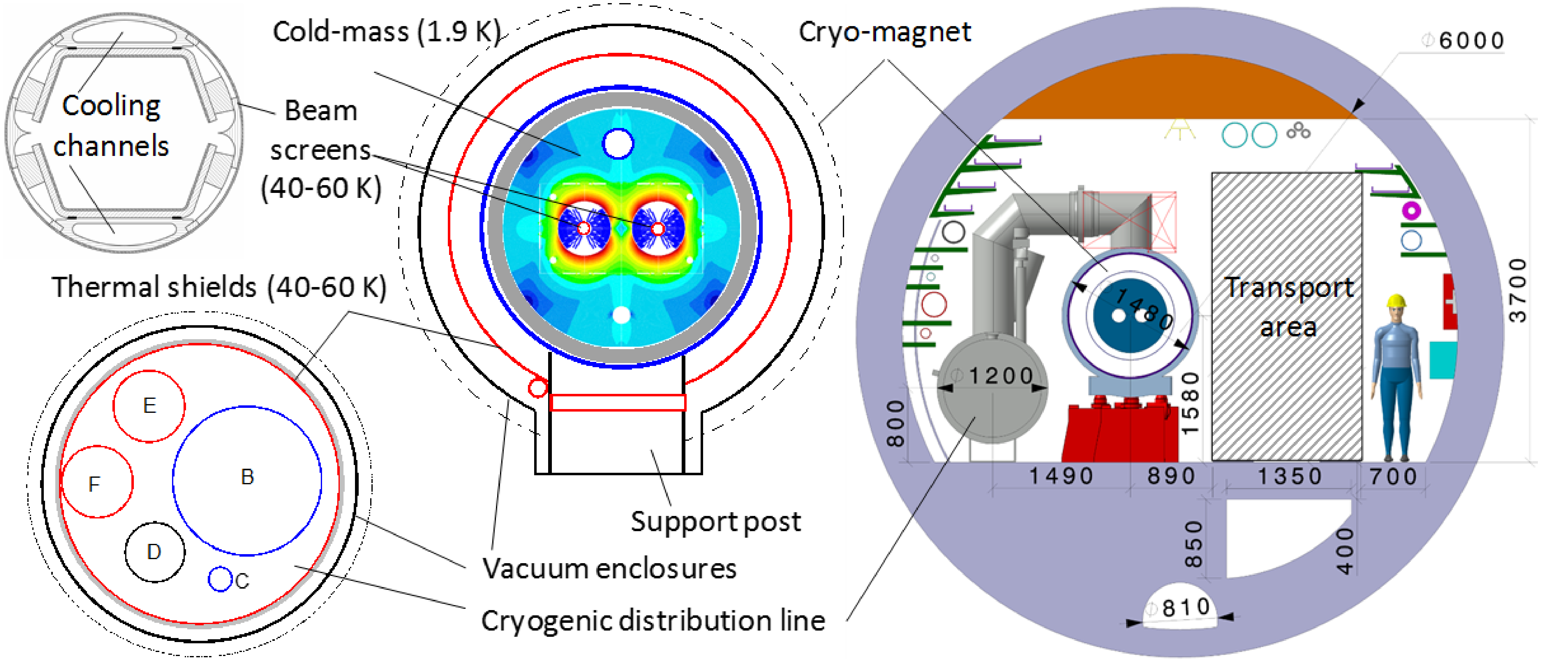
- a beam screen similar to that of the LHC
- refrigerator efficiencies identical to those of the LHC.

Optimum for T_{bs}= ~ 70 K

Temperature range 40-60 K retained



FCC-hh: tunnel cryogenics



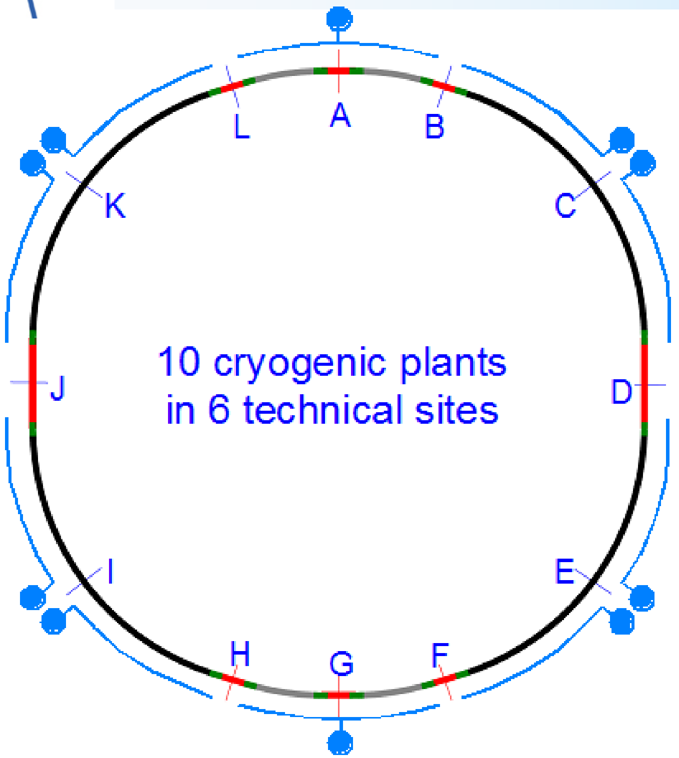
Main distribution based on INVAR® technology

Contribution of WUST

Specific heat loads at different temperature levels

Temperature level		40-60 K	1.9 K	4 K VLP
Static heat in-leaks [W/m]	CM supporting system	2	0.13	
	Radiative insulation		0.13	
	Thermal shield	3.1		
	Feedthrough & vacuum barrier	0.2	0.1	
	Beam screen		0.12	
	Distribution	4	0.1	0.24
	Total static	**9.3**	**0.58**	**0.24**
Dynamic heat loads [W/m]	Synchrotron radiation	**57**	0.08	
	Image current	3.4		
	Resistive heating in splices		0.3	
	Beam-gas scattering		0.45	
	Total dynamic	**60**	**0.83**	
Total [W/m]		**70**	**1.4**	**0.24**
Dynamic range [-]		**8**	2.5	1

FCC-hh cryogenic layout and architecture

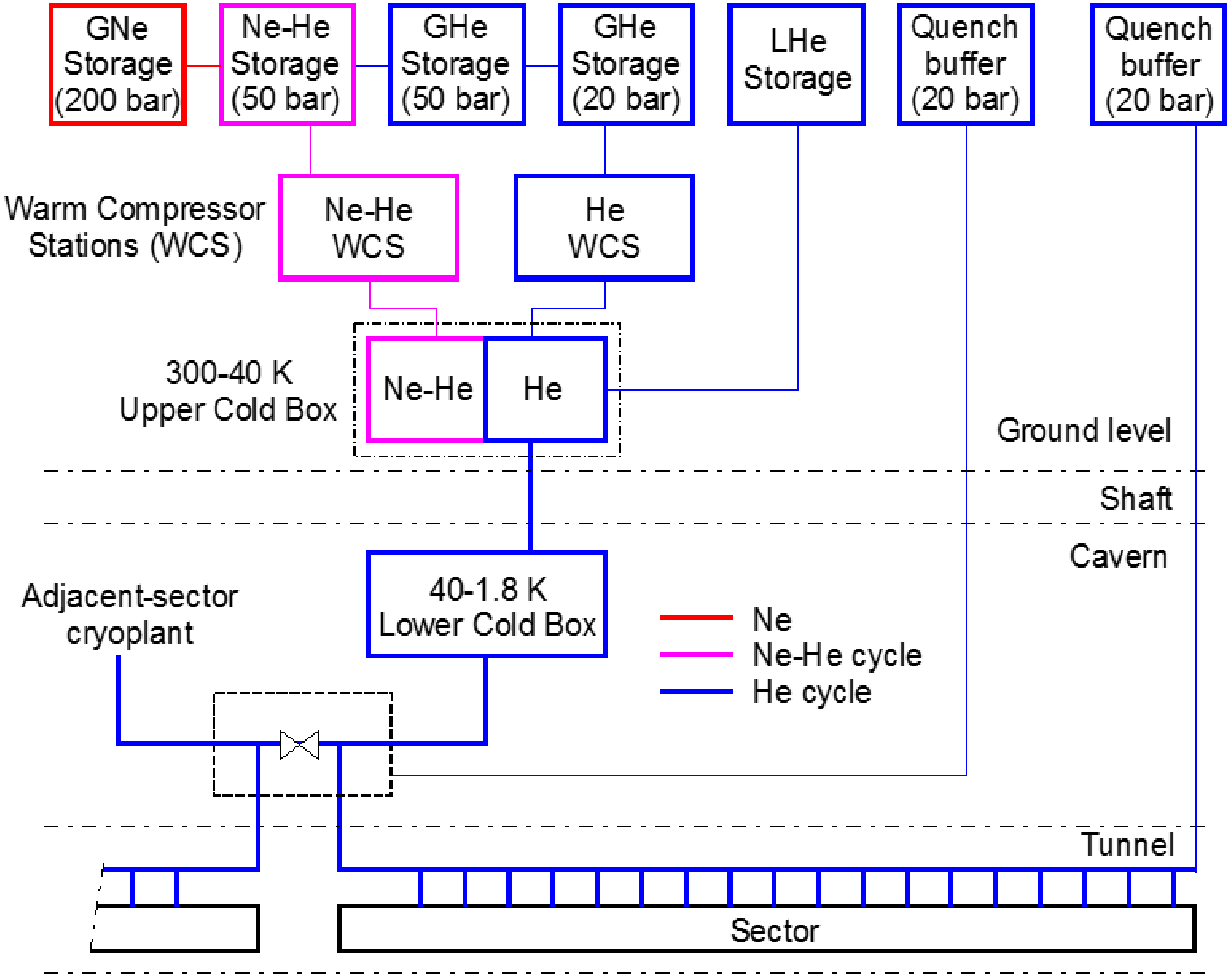


Cryogenic plant
Cryogenic distribution

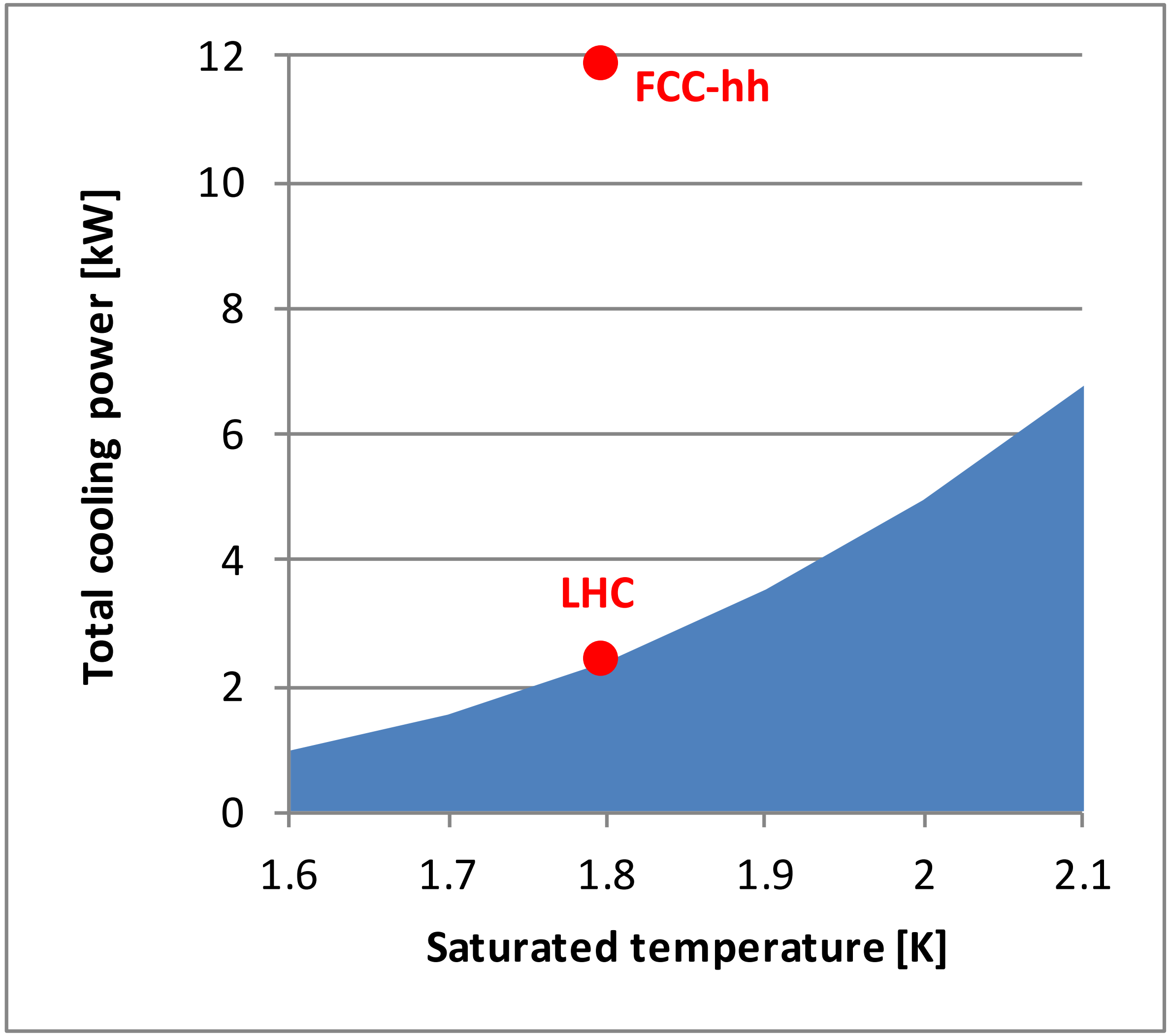
40-60 K [kW]	1.9 K [kW]	4 K VLP [kW]	40-300 K [g/s]
580	12*	2	85

Without operational margins as the working conditions has to be considered as ultimate

*: Outside State-of-the-Art



State-of-the-art of cold compressors (single train)



Increase by a factor 5 on the cooling power, i.e with respect to the present technology:

→ Impeller diameter from 350 mm to 700 mm (factor 2)

→ Shaft power from 10 kW to 30 kW (factor 3)

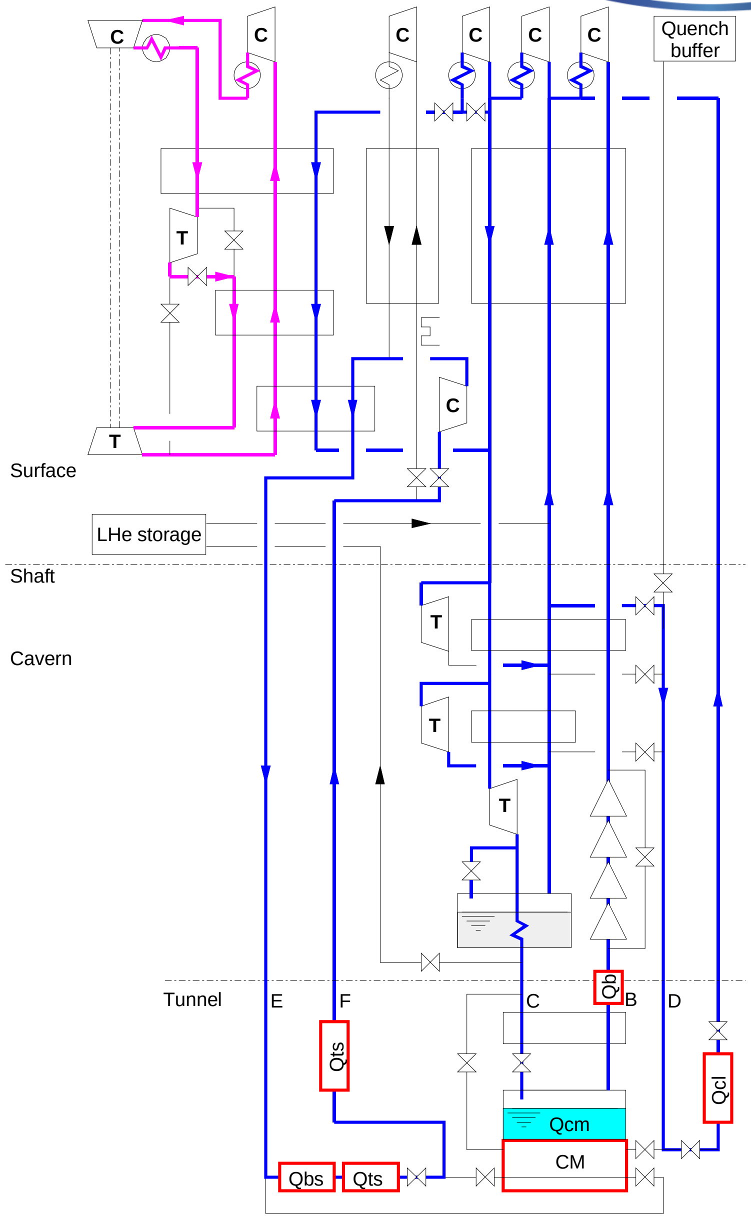
FCC-hh cryoplant architecture

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 1.8 K cryoplant

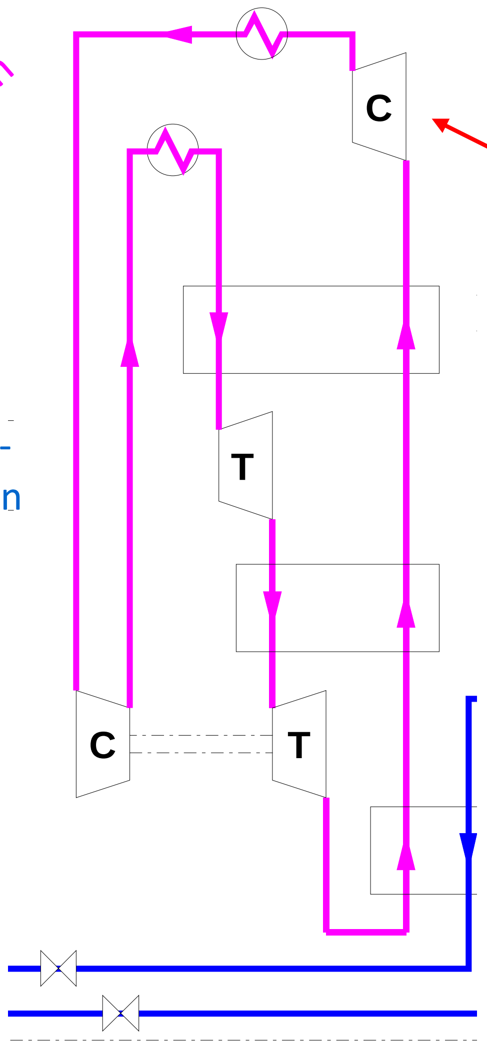
- SC magnet cold mass



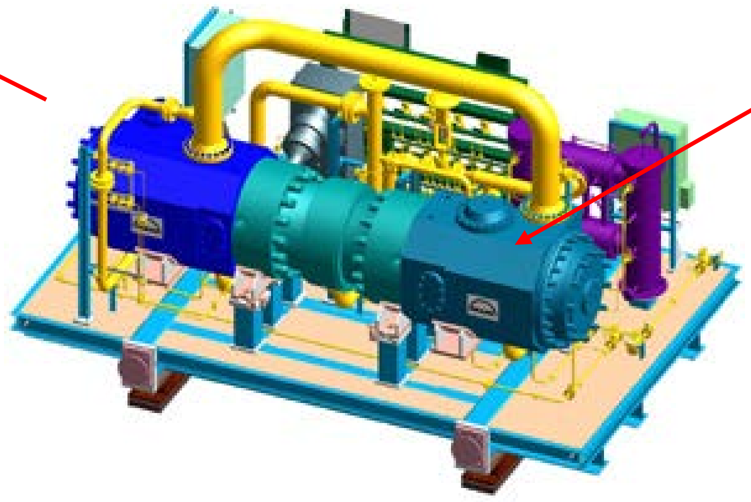
Contributions of TU Dresden and CEA/SBT

Ne-He cycle: 750-1000 kW between 40 and 60 K

TU Dresden



Turbo-Brayton cycle



Courtesy of MAN Diesel & Turbo

Hermetically sealed centrifugal compressors:

- No dry gas seals, no lube-oil system and no gearbox
- Use of high speed induction motor (up to 200 Hz) and active magnetic bearings. The motor is cooled by process gas and directly coupled to the barrel type compressor.

Difficult to get high compression ratio and high compression efficiency with pure helium (light mono-atomic gas):

→ Compression of a mixture of helium and neon (~75-25 %) (OK with neon as refrigeration T > 40 K)

→ The warm compression efficiency is improved

→ Expected global efficiency with respect to Carnot → **42 %**

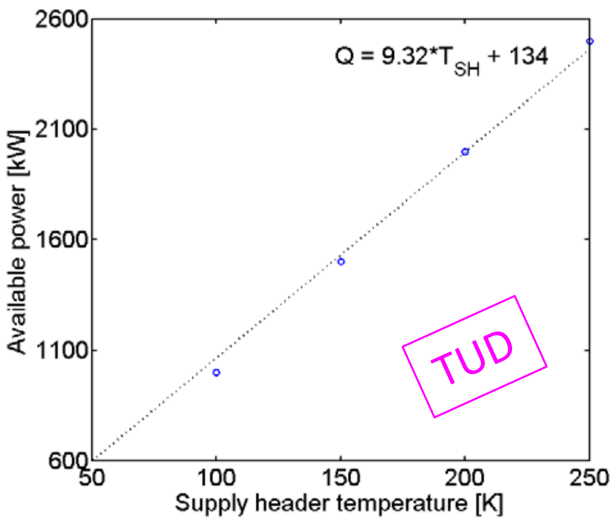
Cooldown of FCC-hh

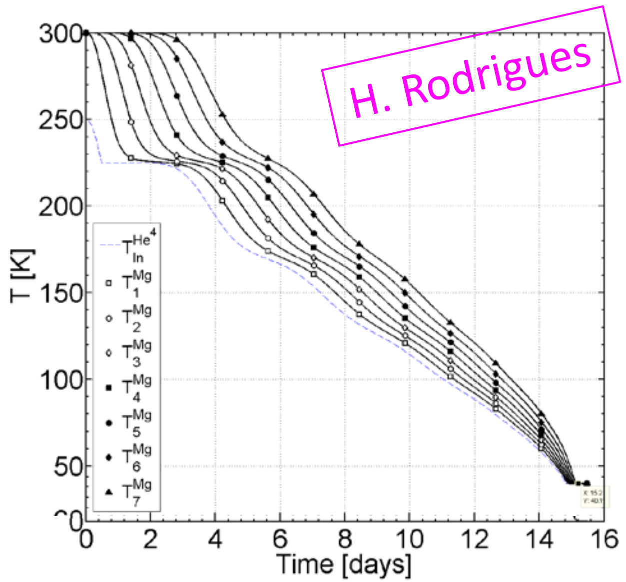
Cool-down capacity produced by the Ne-He cycle:
No need of LN2 cool-down unit with its huge LN2 storage and logistics

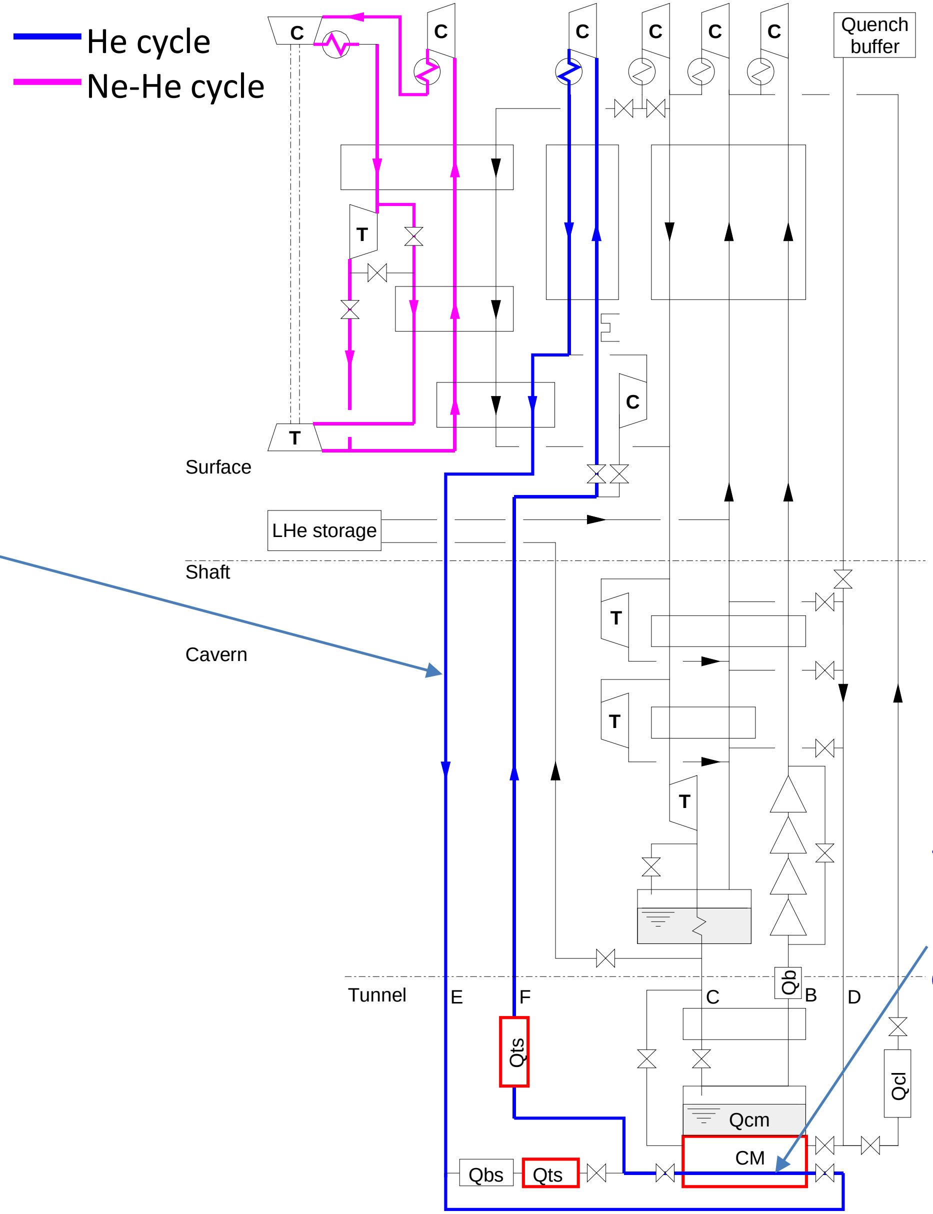
Cold mass: 2.8 t/m i.e.
23 kt per sector
230 kt for FCC

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)

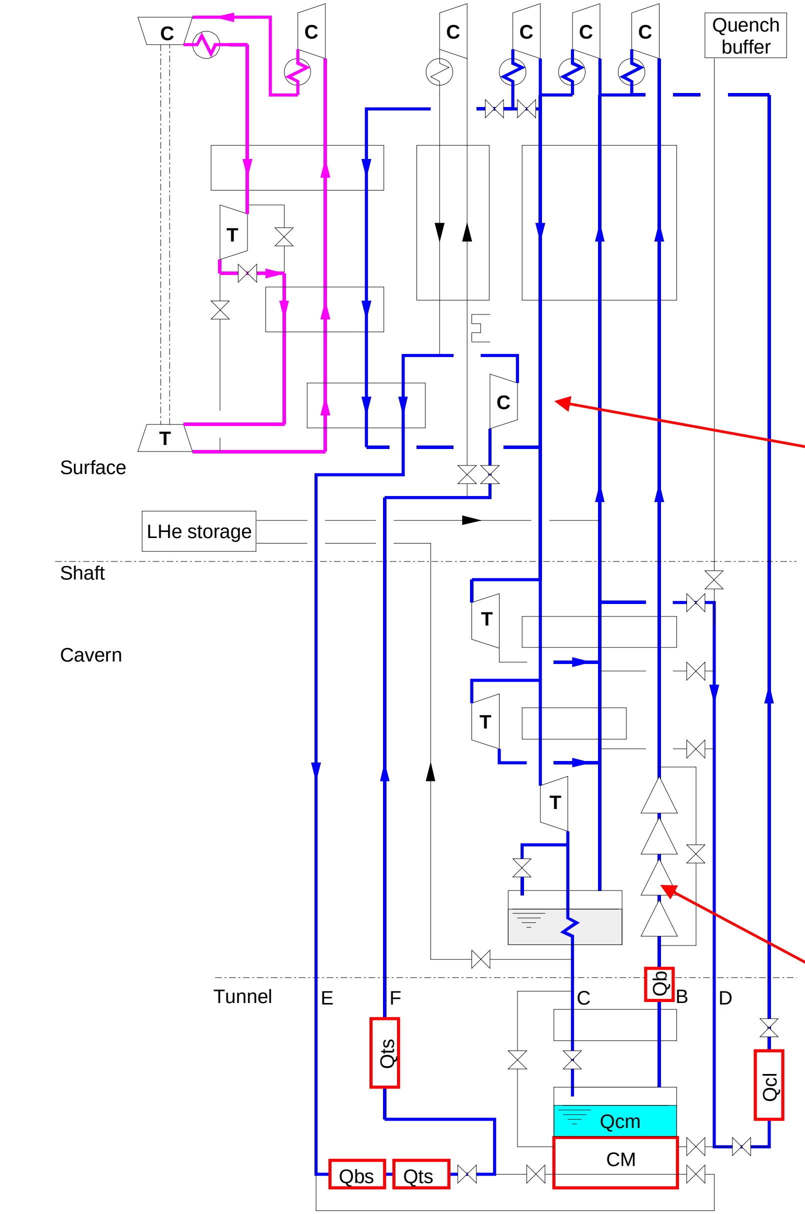






50 bar supply pressure
→ indirect cool-down of cold-masses (design pressure of 20 bar)

FCC-hh Nominal operation

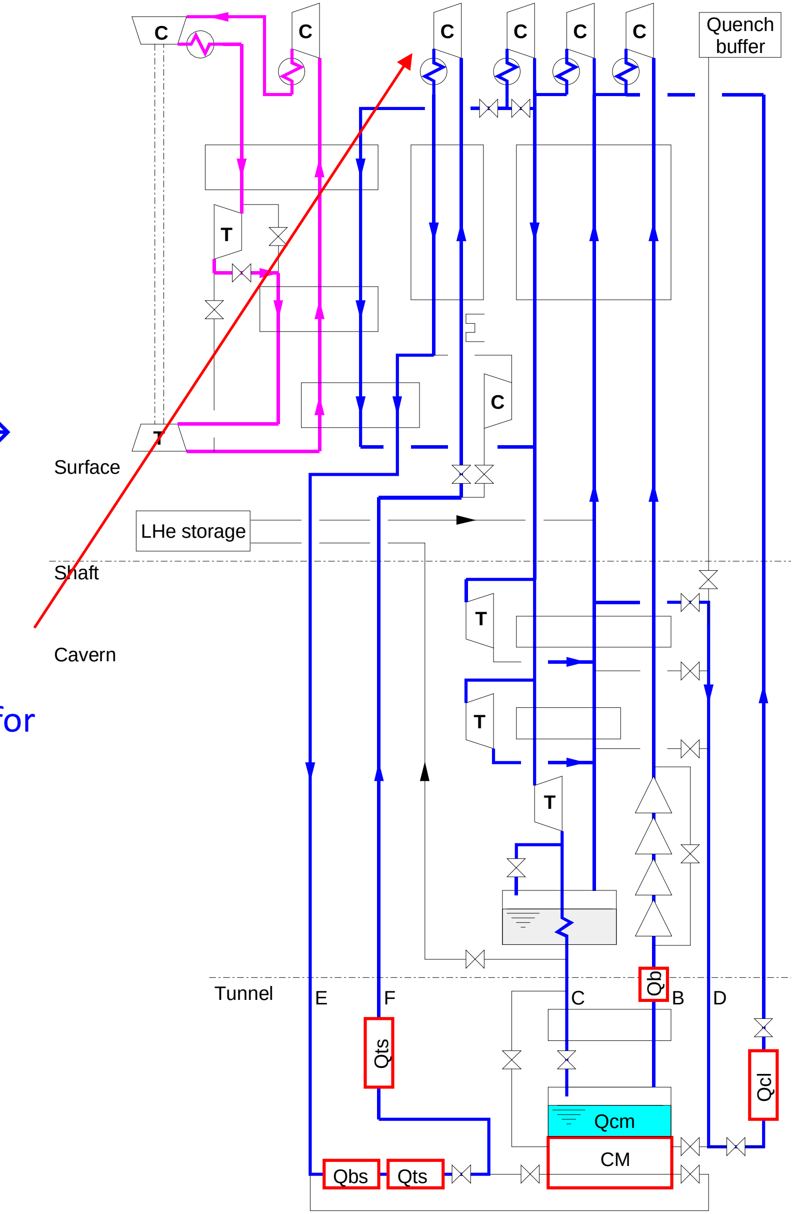


He cycle
Ne-He cycle

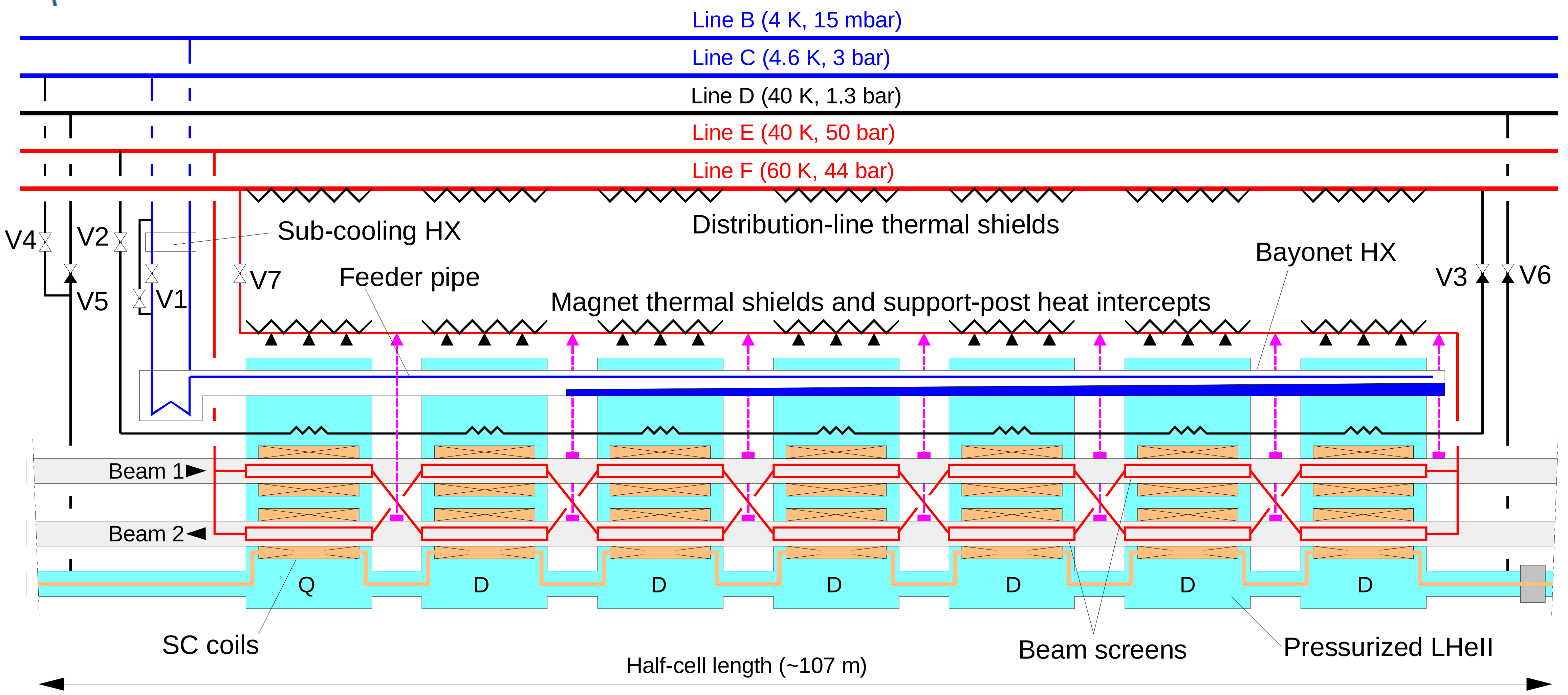
BS cooling with cold circulator (+130 kW @ 40-60 K)→
Exegetic efficiency of BS cooling loop: 82 %

BS cooling with warm circulator needed for cooldown (+140 kW @ 40-60 K and +500 kW @ 300 K) →
Less efficient (exergetic efficiency of 71 %) but good for redundancy.

1.8 K refrigeration based on a mixed compression cycle (cold centrifugal compressors in series with warm volumetric compressors)

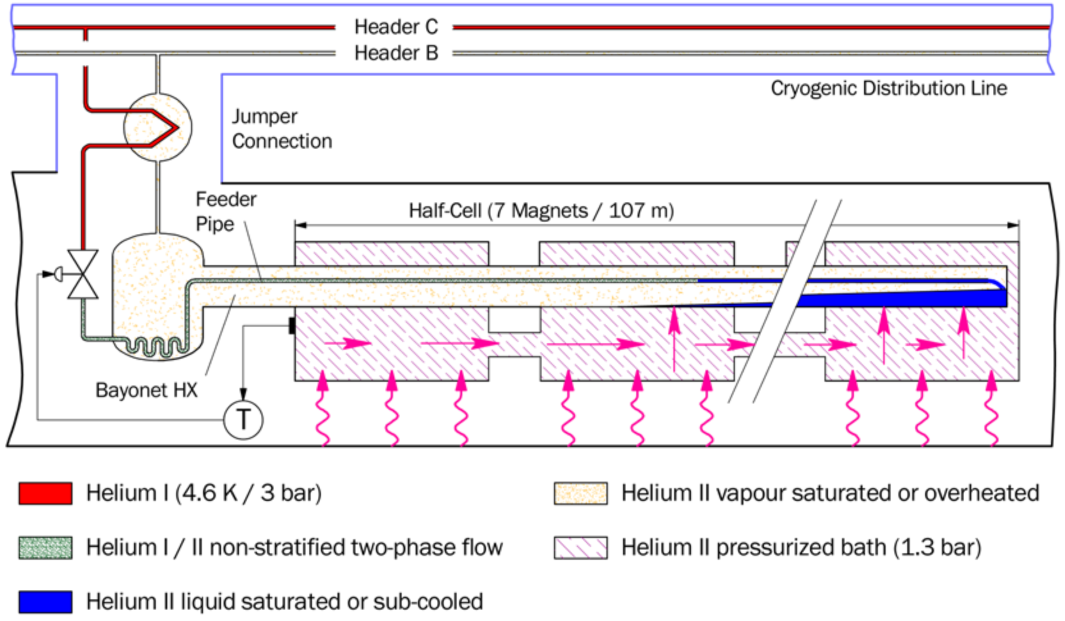


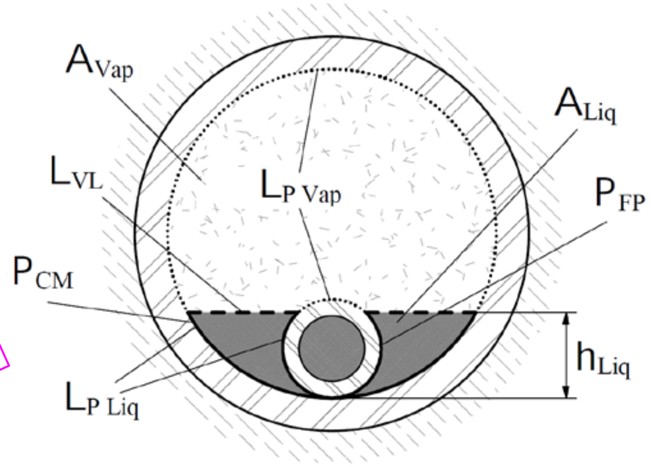
FCC-hh Half-cell cooling loop



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 capacity	W/m	0.40	1.38
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	630 (500)
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	1.9 (1.98)

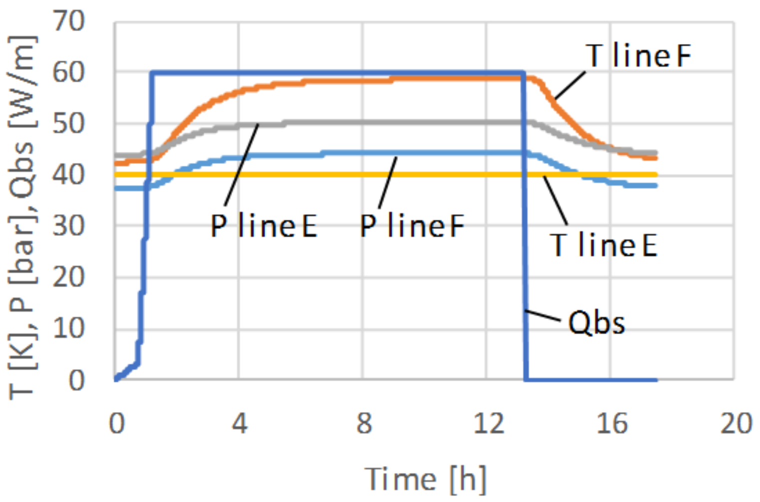


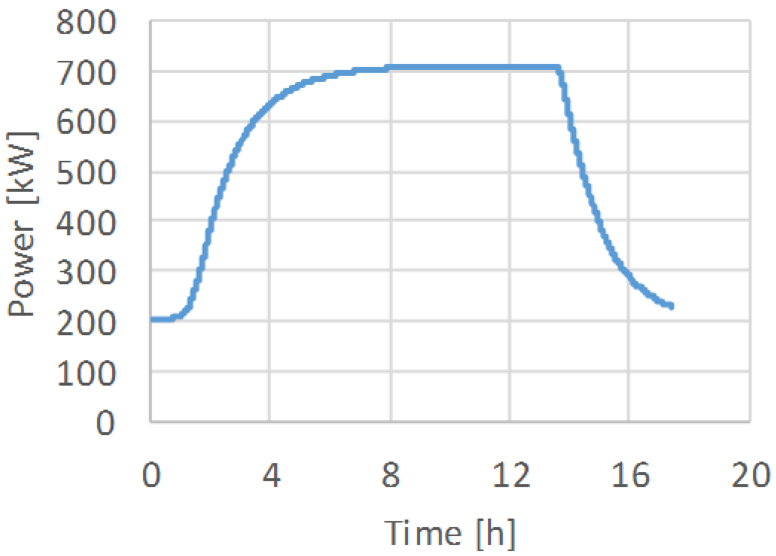


C. Kotnig

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 capacity	W/m	1.6	60
Max. 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)	%	?	71





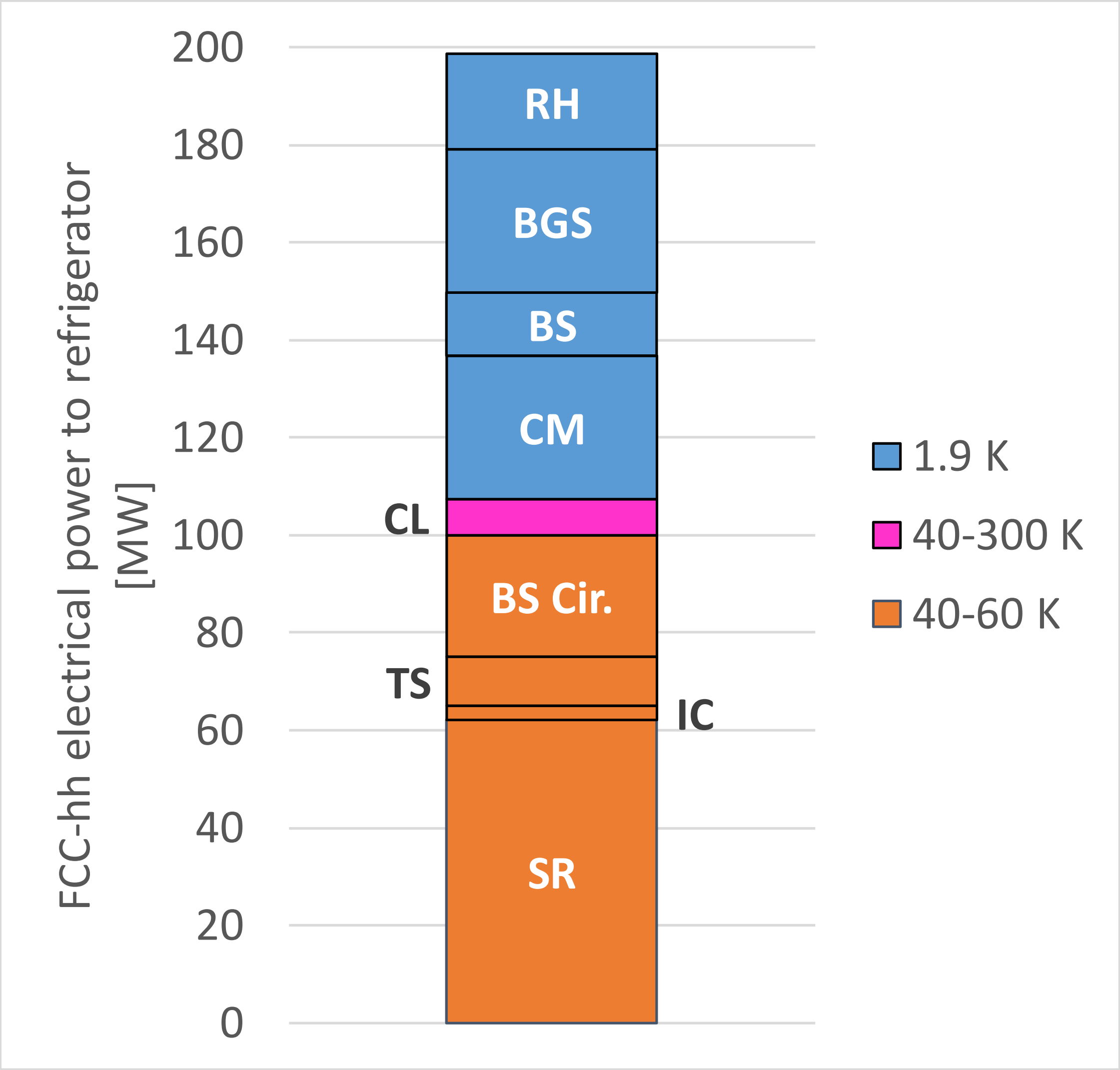
Transient modes

- Working at constant nominal mass-flow to handle the severe transient during energy ramp-up
- Working at constant He inventory to avoid big mass discharge and refill (~6 t) (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

H. Rodrigues
C. Kotnig

FCC-hh electrical consumption



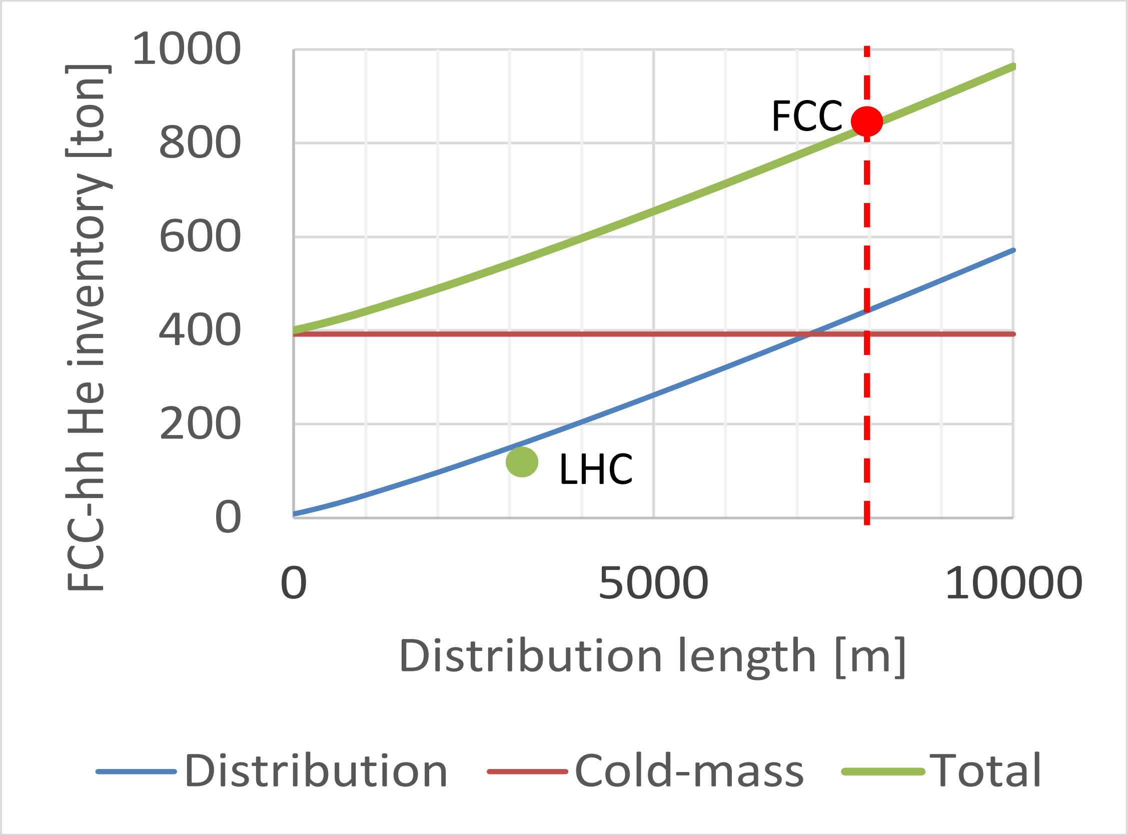
RH: resistive heating
BGS: beam-gas scattering
BS: beam screen
CM: cold mass heat-inleaks
CL: current lead
BS cir.: Beam screen circulator (warm)
TS: thermal shield
IC: image current
SR: synchrotron radiation

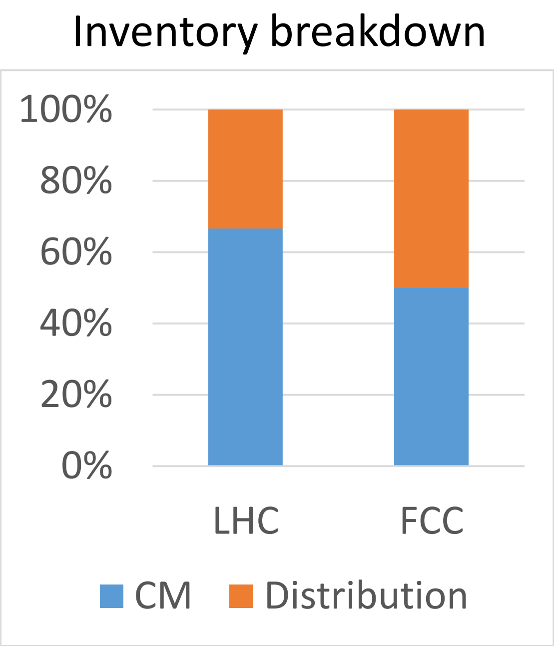
Carnot efficiency:
- Ne-He plants: 40 %
- Helium plants: 28.8 %

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

FCC-hh He inventory

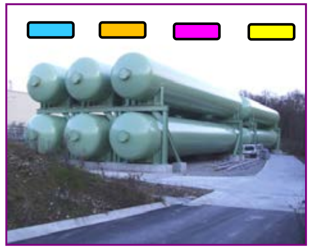
Cold mass He inventory : 33 l/m (scaled from LHC)
Distribution inventory dominated by the beam-screen supply and return headers



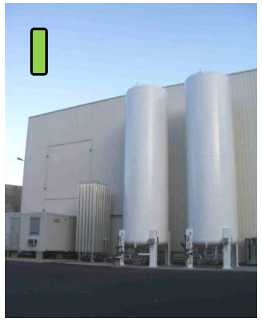


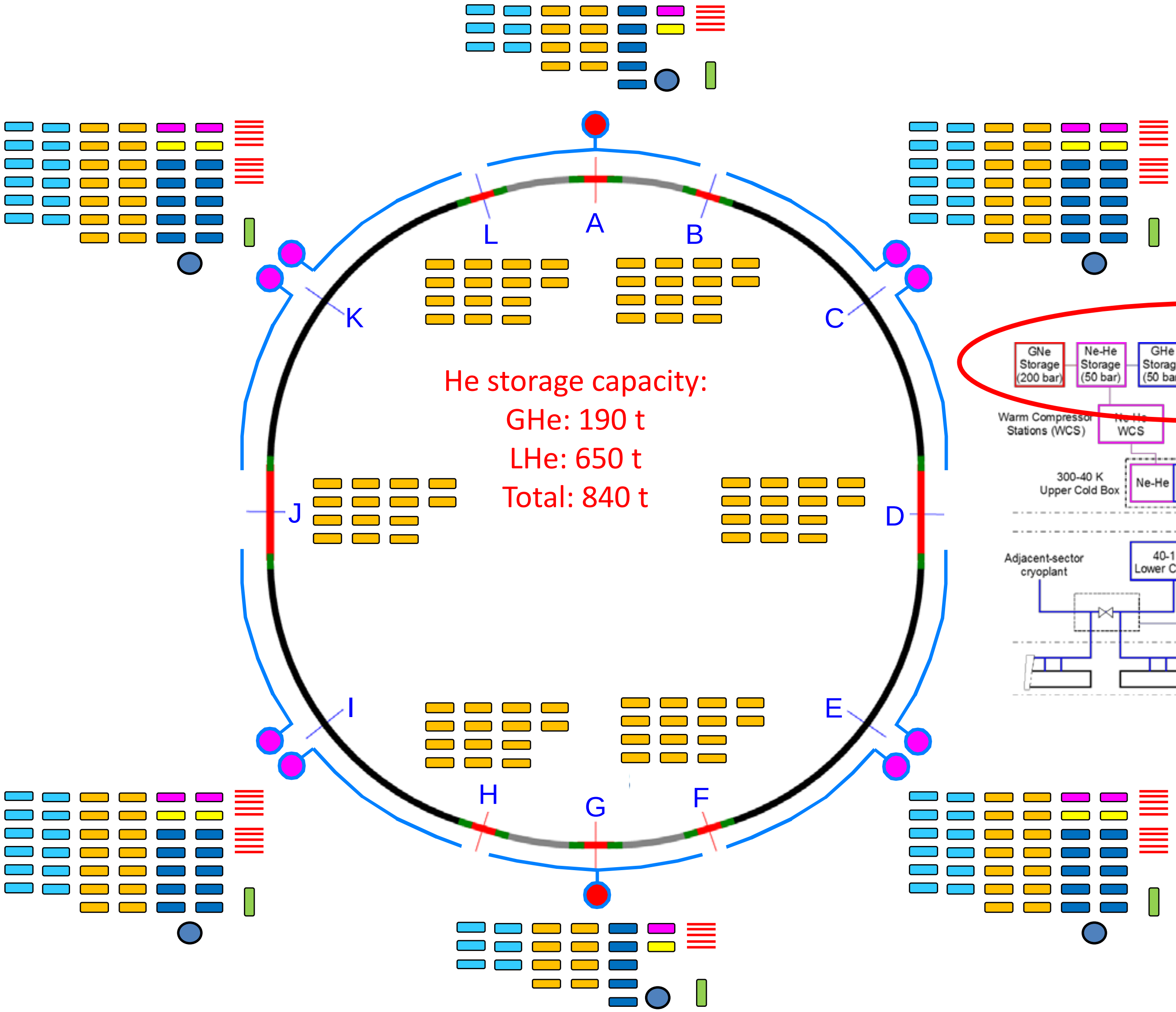
FCC He inventory: ~800 t ! (~6 LHC He inventory)

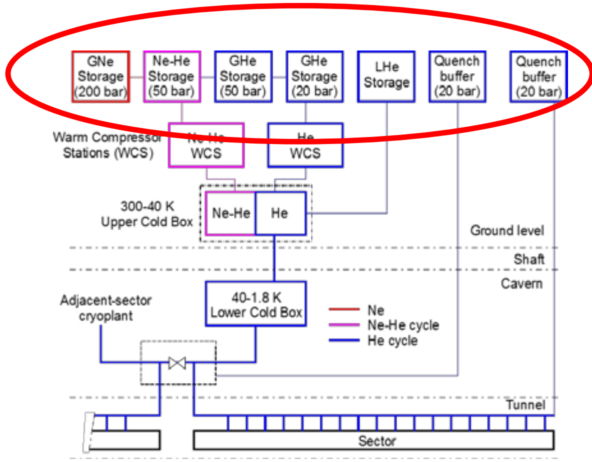
FCC-hh Storage management



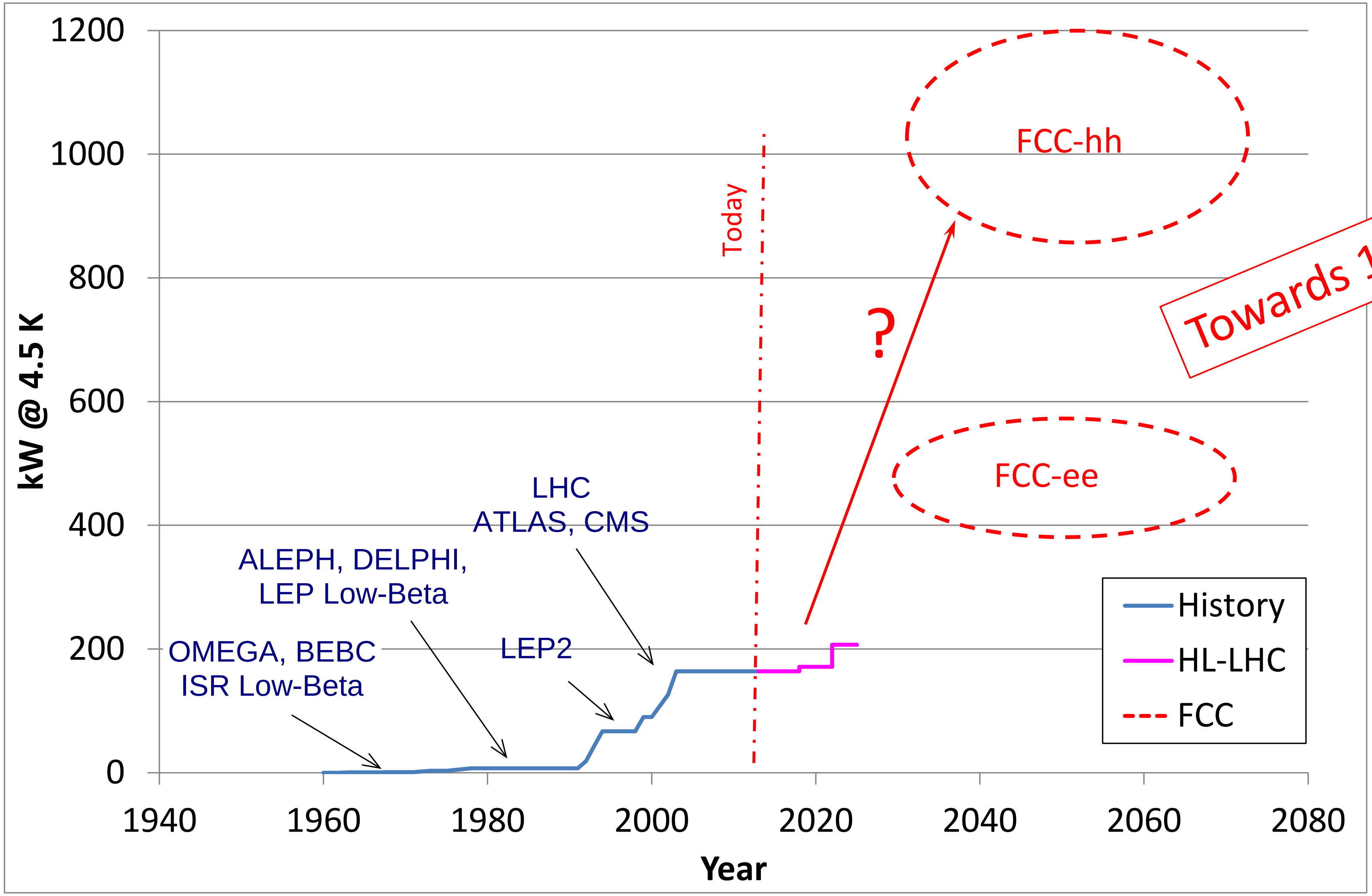
- GHe storage - 60 (250 m3, 20 bar)
- Quench buffer - 156 (250 m3, 20 bar)
- GHe storage - 10 (250 m3, 50 bar)
- Ne-He storage - 10 (250 m3, 50 bar)
- GNe cylinders - 10 (10 m3, 200 bar)
- LHe storage - 50 (120 m3)
- LHe boil-off liquefier - 6 (150 to 300 l/h)
- LN2 storage - 6 (50 m3)







Main FCC cryogenics challenges: Cryogenic power



Towards 1 MW @ 4.5 K !

Conclusion

- The conceptual design of the cryogenic systems for a Future Circular Collider is in progress in the framework of an international collaboration (CEA, CERN, TUD, WUST)
- The final Conceptual Design Report (CDR) will be issued by 2018 and then examined by the next European Strategy for high energy particle physics.
- In the case of a positive feedback, the next step will be the studies and developments of the new concepts with the construction of demonstrators and/or prototypes.