FCC Study Kick-off Meeting

Cryogenics

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Thanks to Ph. Lebrun for fruitful discussions

Content

- FCC cryogenic study structure and timing
- FCC beam parameters impacting the cryogenic system:
  - Preliminary assessments
  - Possible cryogenic layouts
- Cryogenic challenges for FCC
- Conclusion

Cryogenics for FCC

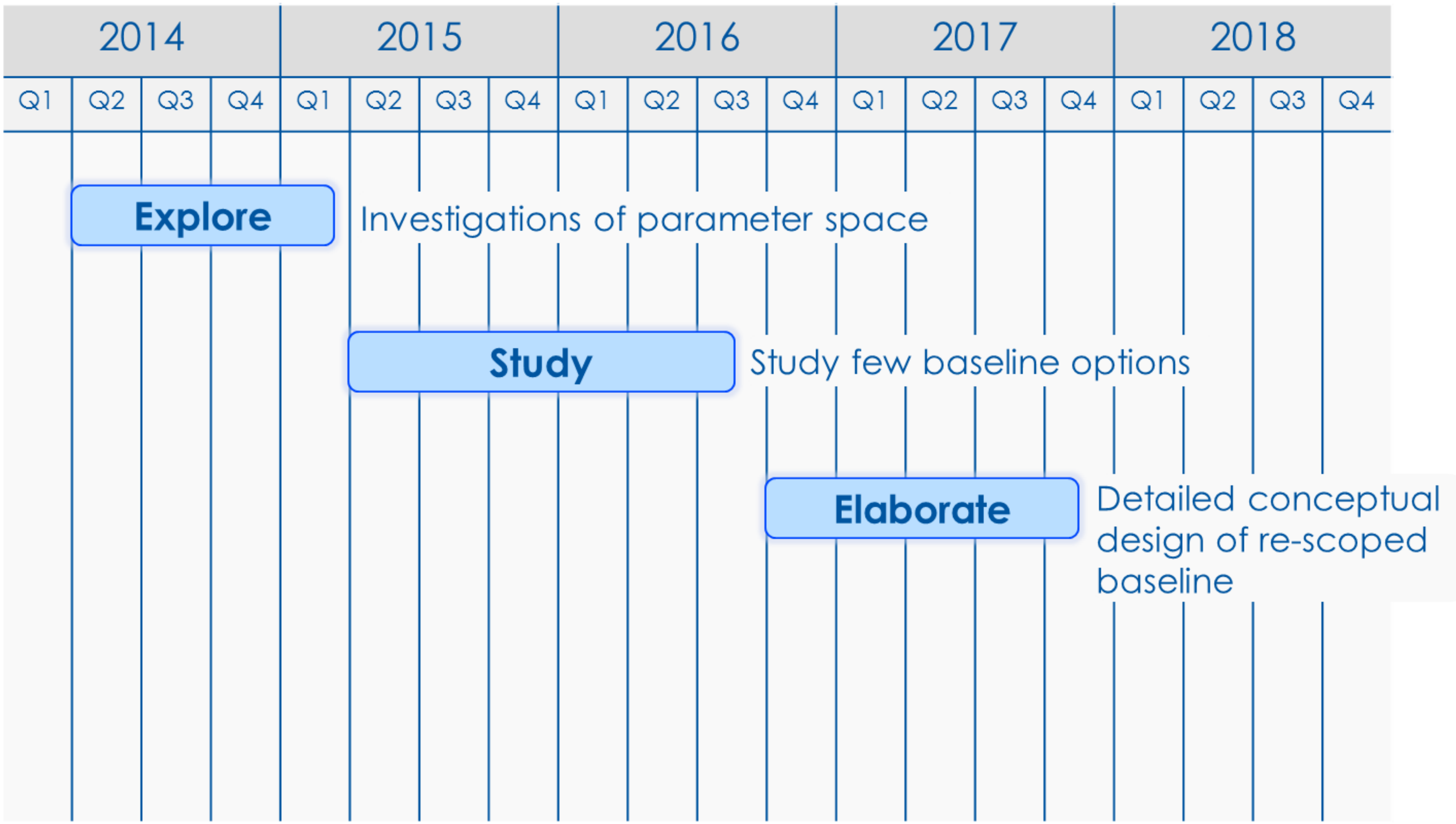
- Cryogenics for hadron injector
- Cryogenics for hadron collider
- Cryogenics for lepton collider / top-up ring
- Cryogenics for experiments

Each system will require specific studies!
→ For proximity cryogenics
→ For cryogenic plants

The WBS

- **Accelerators**
  - **Hadron injectors**
    - **Technical systems**
      - Proximity cryogenics for hadron injectors
  - **Hadron collider**
    - **Technical systems**
      - Proximity cryogenics for superconducting magnets and RF
  - **Lepton collider**
    - **Technical systems**
      - Proximity cryogenics for RF and magnets
- **Physics and experiments**
  - **Hadron collider experiments**
    - **Technical systems**
      - Proximity cryogenics for detectors
  - **Lepton collider experiments**
    - **Technical systems**
      - Proximity cryogenics for detectors
- **Infrastructures and operation**
  - **Technical infrastructures**
    - **Accelerator technical infrastructures**
      - Cryogenics
    - **Experiment technical infrastructures**
      - Cryogenics
    - **Safety and access systems**
      - Cryogenics safety functions

The 3-phase Study



“Explore” study phase

- Probably the most important phase for:
  - understanding the drivers and the functional relation between cryogenics and superconducting devices and beams.
  - defining the basic scaling laws governing the cooling of superconducting devices and the beam induced heating.
  - exploring alternative designs with conventional and non-conventional approaches.
  - iterating towards globally optimized solutions.

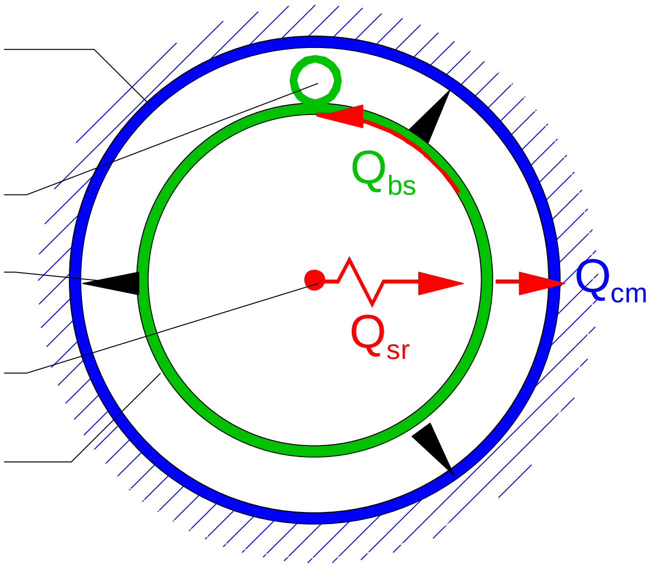
Beam parameters impacting FCC-hh cryogenics

Parameter	LHC	HL-LHC	HE-LHC	FCC-hh	Impact
c.m. Energy [TeV]	14		33	100	Synchrotron radiation (~ E^4)
Circumference C [km]	26.7		26.7	100 (83)	
Dipole field [T]	8.33		20	16 (20)	Resistive heating, stored energy, quench pressure relief
Straight sections	8		8	12	i.e. 12 arcs
Average straight section length [m]	528		528	1400	→ arc length: ~7 km (~5.5 km)
Number of IPs				2 + 2	Cryogenics for detectors (LHe, LAr)
Injection energy [TeV]	0.45		> 1.0	3.3 (TBC)	SC injector → cryogenics
Peak luminosity [10^{34} cm-2s-1]	1	5	5	5	Secondaries from IPs
Optimum run time [h]	15.2	10.2	5.8	12.1 (10.7)	
Beam current [A]	0.584	1.12	0.478	0.5	
RMS bunch length [cm]	7.55		7.55	8 (7.55)	
Stored beam energy [GJ]	0.392	0.694	0.701	8.4 (7.0)	Safety: release of He in tunnel
SR power per ring [MW]	0.0036	0.0073	0.0962	2.4 (2.9)	Large load and dynamic range
Arc SR heat load [W/m/aperture]	0.17	0.33	4.35	28.4 (44.3)	
Dipole coil aperture [mm]	56		40	40	Beam screen design
Beam half aperture [mm]	~20		13	13	

The synchrotron radiation

- 28.4 W/m per beam for FCC-hh 100 km, i.e. a total load of 4.8 MW
- 44.3 W/m per beam for FCC-hh 83 km, i.e. a total load of 5.8 MW
- If this load is falling directly on the magnet cold masses working at 1.9 K or 4.5 K (not yet defined), the corresponding total electrical power to refrigerators is
  - > 4.3 or 1.1 GW for FCC-hh 100 km
  - > 5.2 or 1.3 GW for FCC-hh 83 km
- Beam screens are mandatory to stop the synchrotron radiation at a higher temperature reducing the electrical power to refrigerator.
  - > Is there a optimum operating temperature ?

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: $P_{ref} = \Delta E/\eta(T)$

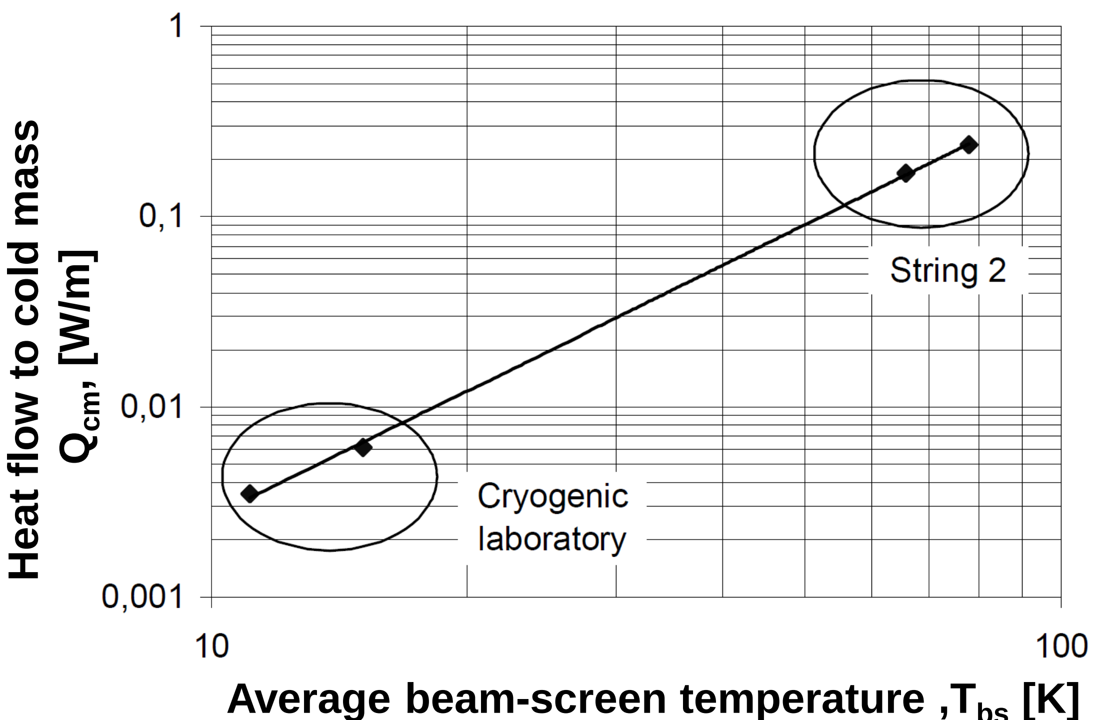
with $\eta(T)$ = efficiency w.r.t. to Carnot = COP_{Carnot}/COP_{Real}

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

BS – CM thermodynamics Numerical application

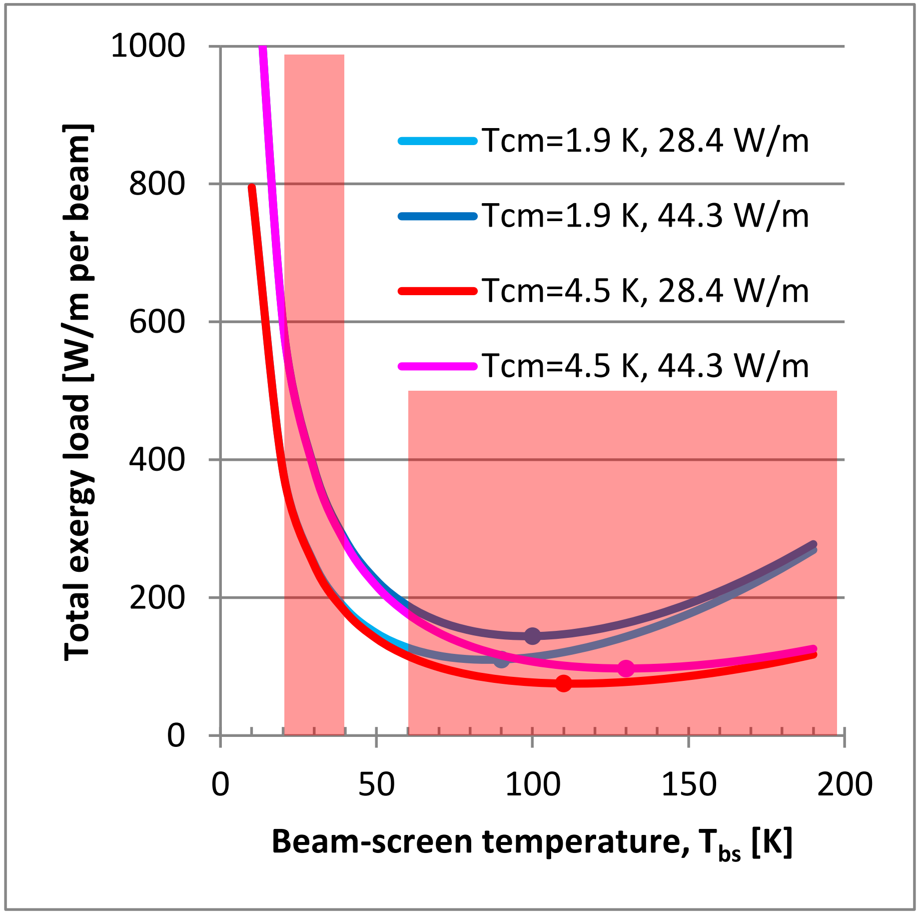
- T_a = 290 K, T_{cm} = 1.9 K or 4.5 K, T_{bs} variable
- Q_{sr} = 28.4 or 44.3 W/m per beam (100 or 83 km FCC-hh)
- η(1.9 K)= 17.8 % (COP_{Real}= 900 W/W)
- η(4.5 K)= 28.8 % (COP_{Real}= 220 W/W)
- η(T_{bs}>4.5 K)= η(4.5 K)

- Assume LHC-type BS
- $Q_{cm}(T_{bs})$ estimated from LHC measurements:

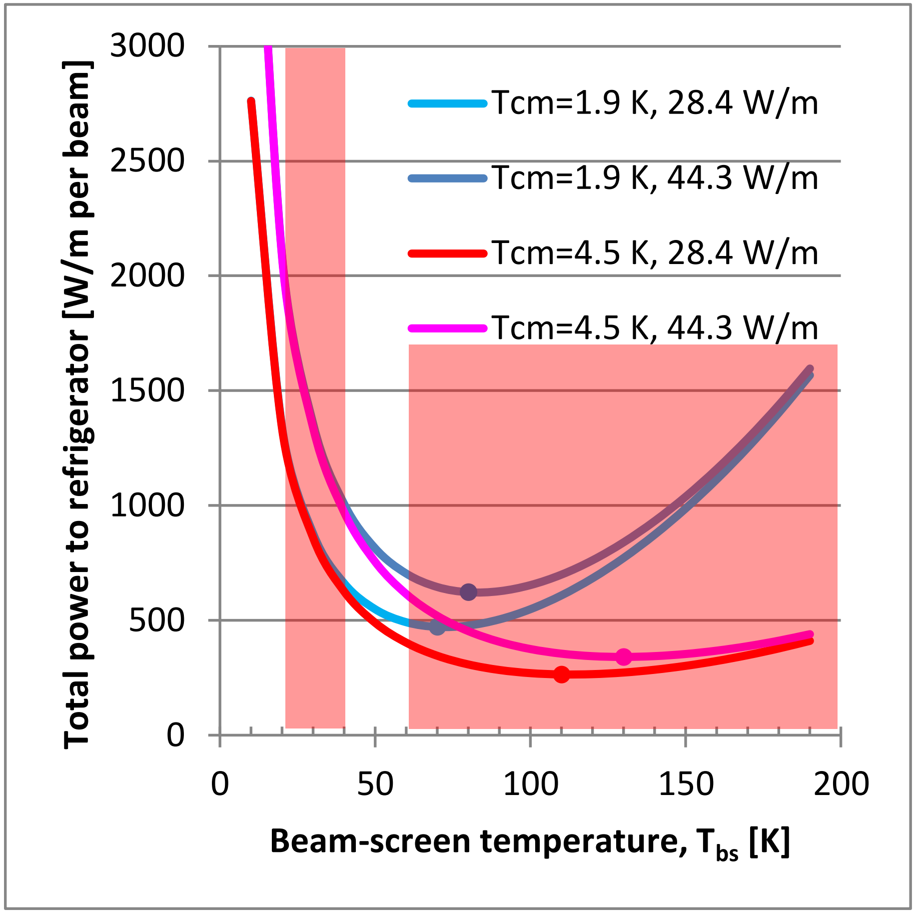


BS – CM thermodynamics
Numerical application

Total exergy, ΔE



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

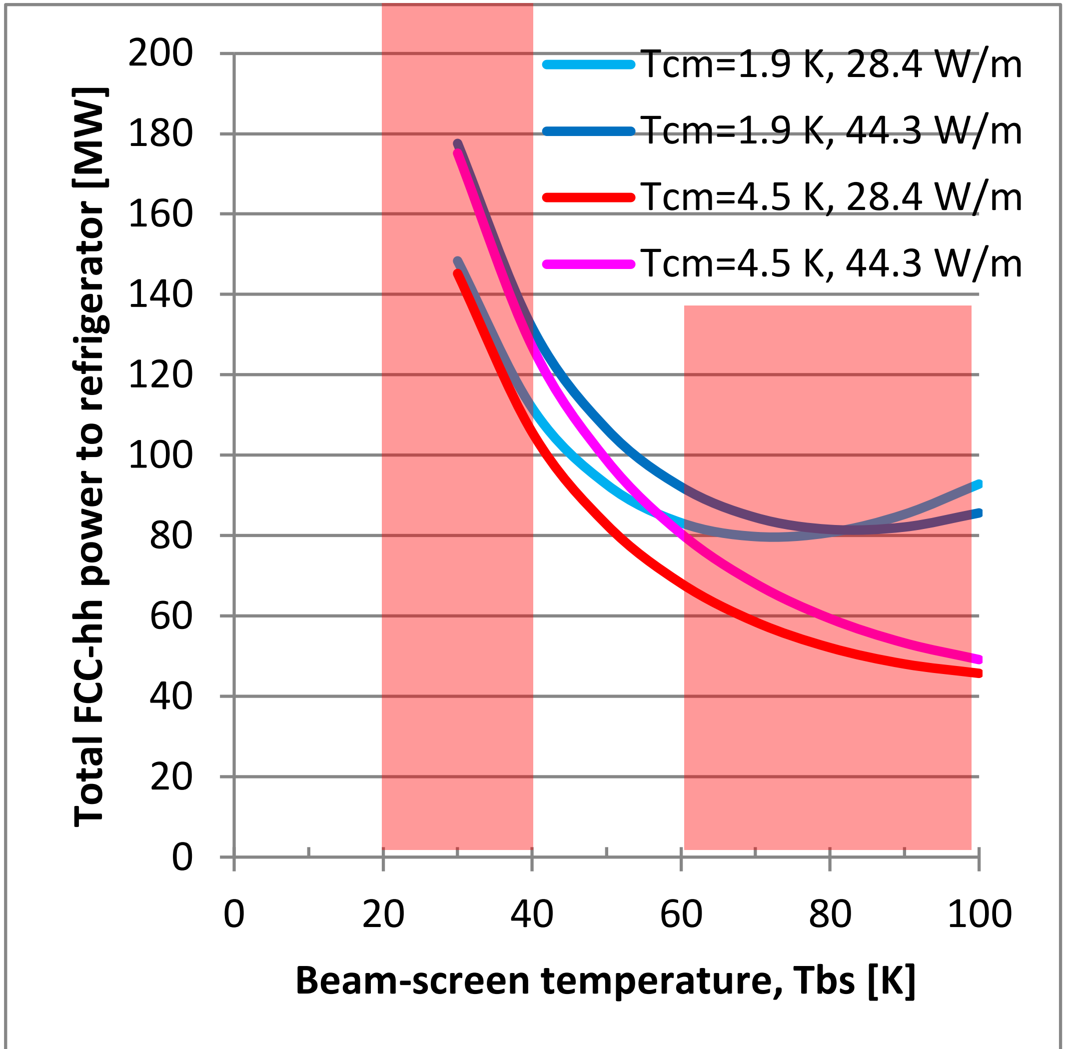


Forbidden by vacuum and/or by surface impedance

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

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

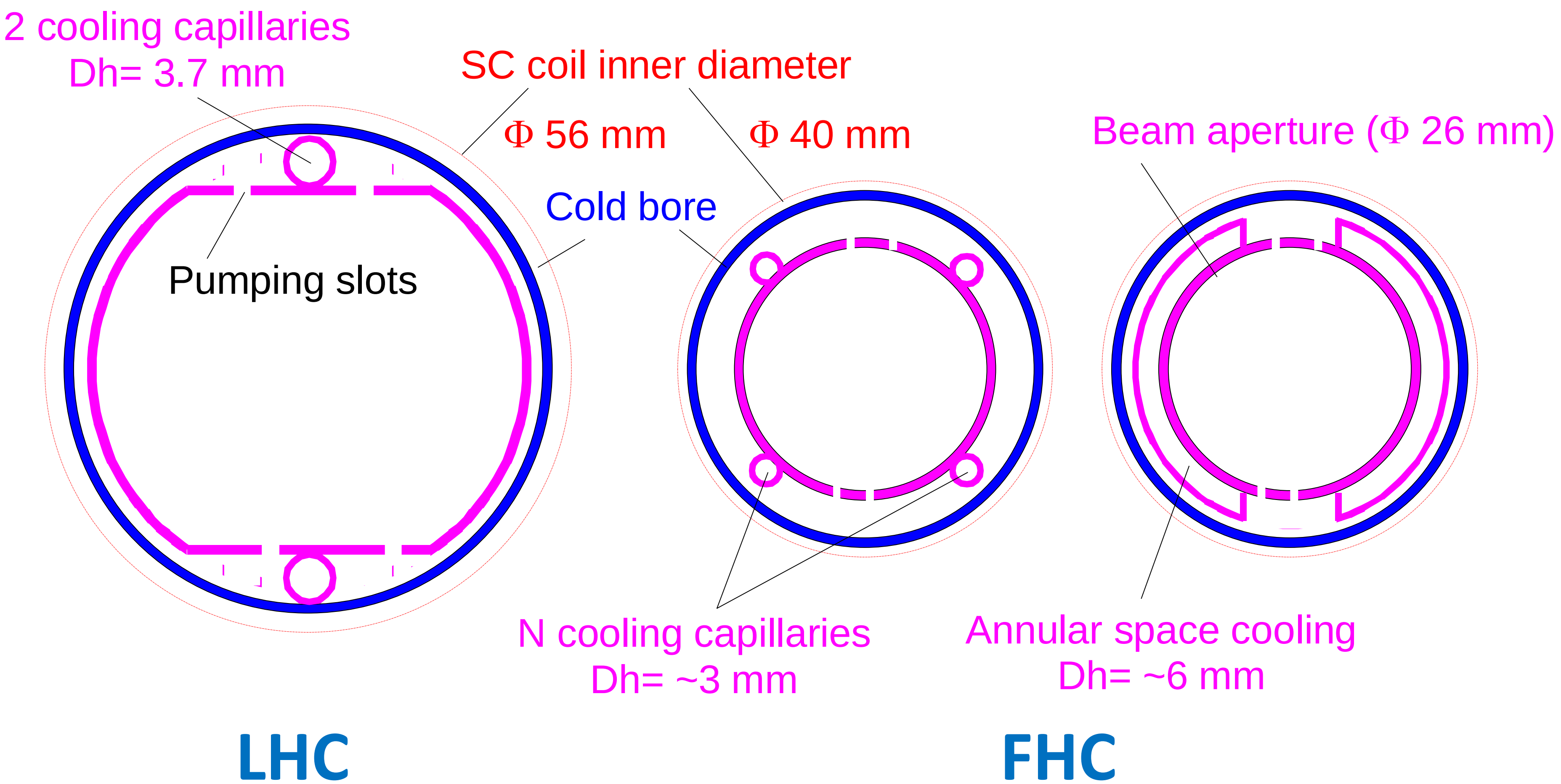
BS – CM thermodynamics
Numerical application



- Depending on T_{cm}, synchrotron radiation will cost:
  - ~70-110 MW for FCC-hh 100 km
  - ~80-130 MW for FCC-hh 83 km

(extra cost of 50 MW over 10 year of operation, 6000 h per year: 200 MCHF)

Beam screen cooling



Beam screen cooling with He @ 20 bar – 40-60 K

- Pressure drop budget: 2 bar

	Configuration	L max [m]
FCC-hh 100 km	8 capillaries	36
	Annular space	90
FCC-hh 83 km	8 capillaries	25
	Annular space	70

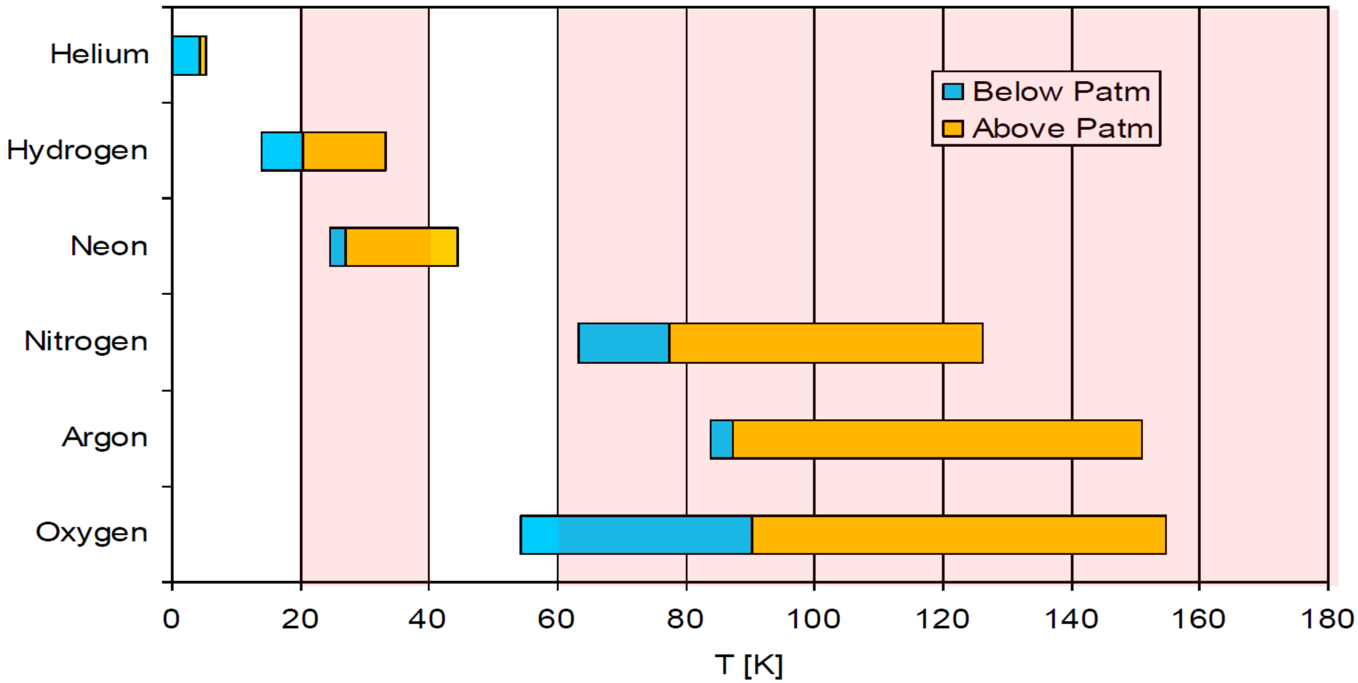
To be compared with the half-cell length of ~100 m

- Total mass-flow / capacity per arc (12 arcs)

	L arc	Q_{bs} per arc		Total BS cooling flow
	[m]	[kW]	[Equ. kW @ 4.5 K]	[kg/s]
FHC 100 km	~7000	~400	~35	~3.7
FHC 83 km	~5500	~500	~43	~4.6

- To be compared with the present LHC cryoplants (18 kW @ 4.5 K)

Cooling potential of cryogens for beam screen



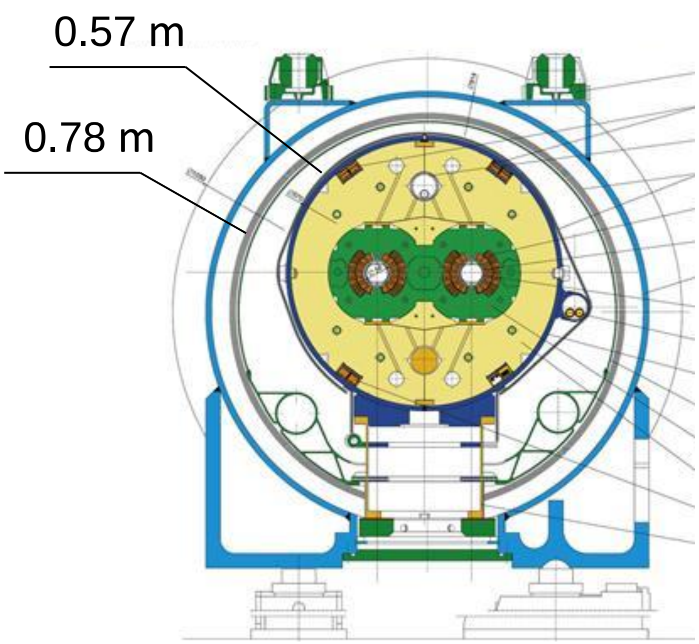
Cryogen	Temperature range	Per unit mass [J/g]	Per unit volume* [J/cm^3]
He 3 bar	5-20 K	103	0.74
He 20 bar	5-20 K	89.3	4.20
He 20 bar	40-60 K	107	1.64
Ne 30 bar	40-60 K	79.1	11.3

* *at exit conditions*

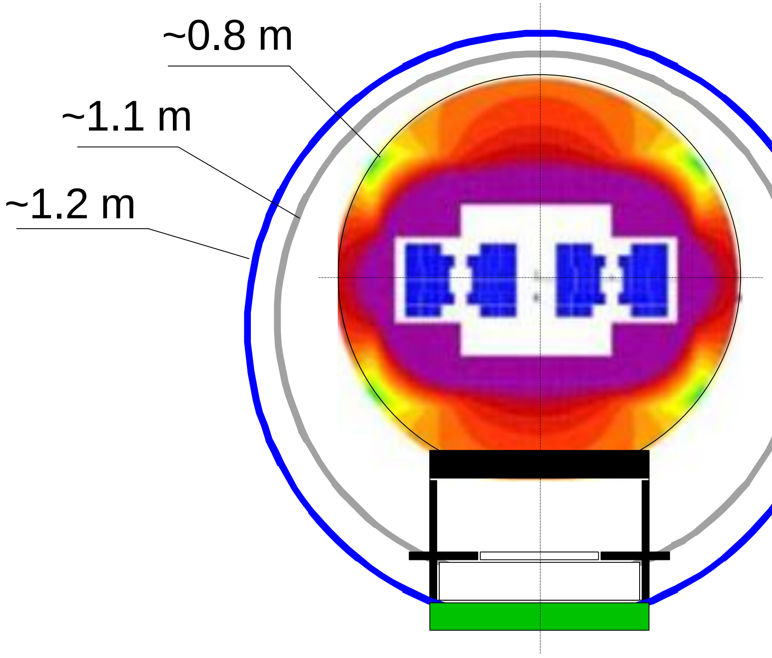
Operating the beam screen at higher temperature would allow other cooling fluids

→ w/o flow, the BS temperature will decrease down to 1.9-4.5 K → Solidification of cryogens !

Cryo-magnet cross section



LHC



FCC-hh

Rough heat load estimate

		LHC [W/m]			FCC-hh [W/m]		
	Temperature level	TS 50-75 K	BS 4.5-20 K	CM 1.9 K	TS-BS 40-60 K	CM 1.9 or 4.5 K	
Static heat inleaks	CM supporting system	1.5		0.10	2.9	0.2	~ CM weight
	Radiative insulation			0.11		0.15	~ CM surface area
	Thermal shield	2.7			3.8		~ TS surface area
	Feedtrough & vac. barrier	0.2		0.1	0.2	0.1	
	Total static	**4.4**		**0.3**	**6.9**	**0.45**	
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)	~ I^2, ~ splice Nb & R
	Total dynamic		**0.7**	**0.1**	**60 (91)**	**0.5 (0.6)**	
Total		**4.4**	**0.7**	**0.4**	**67 (98)**	**1.0 (1.1)**	

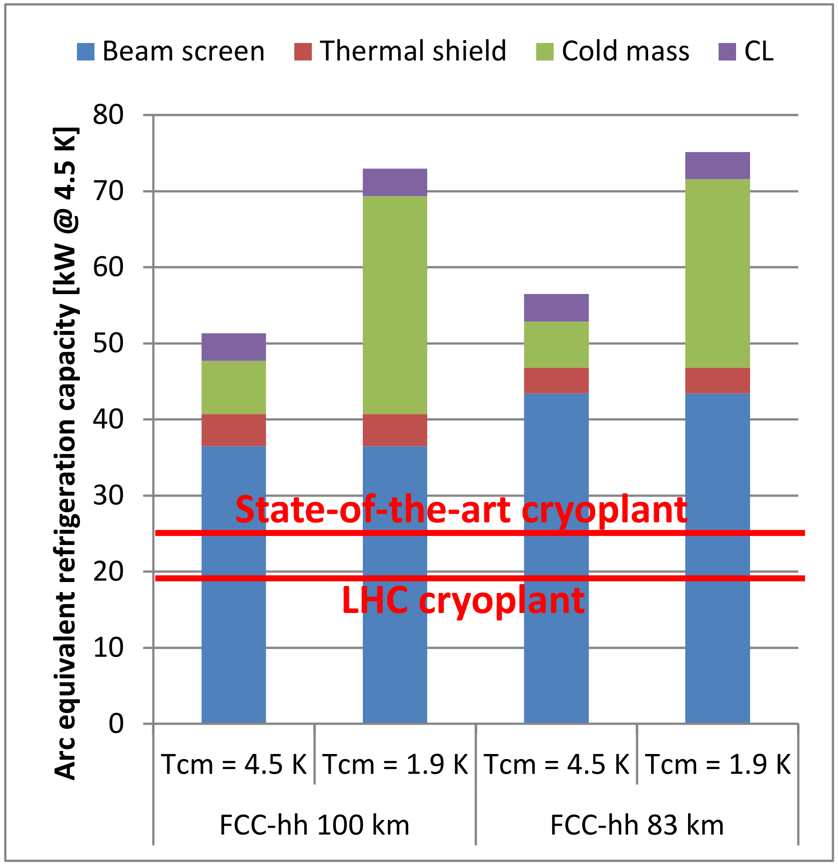
Current lead cooling

Rough scaling from LHC:

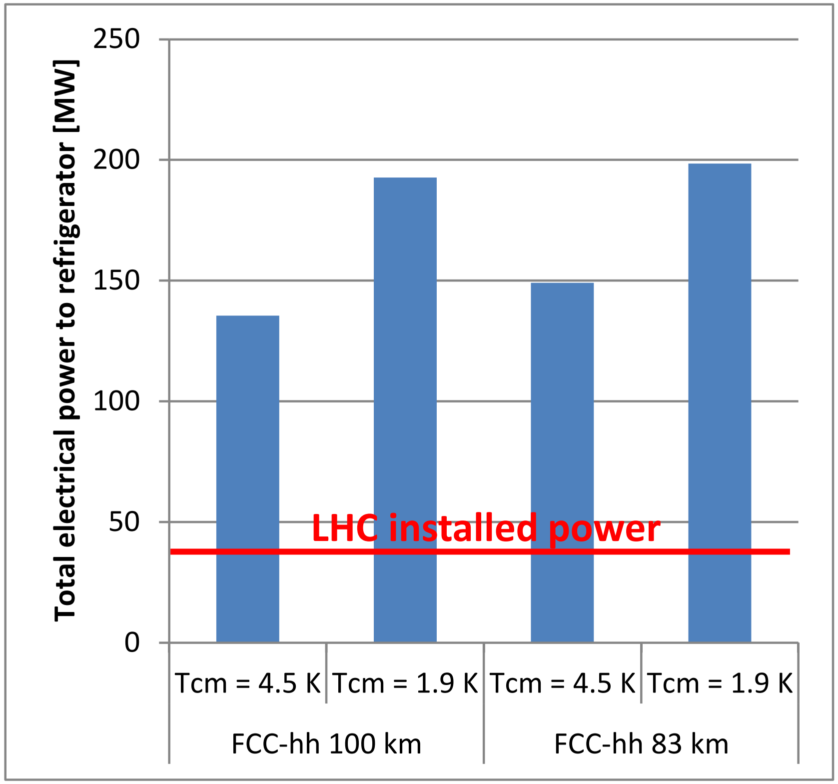
	LHC	FCC-hh
Dipole Current [kA]	12	20
Nb of circuit per dipole	1	1 to 3
Nb of arc	8	12
Total current (in-out) [MA]	3.4	8 to 25
Current lead consumption [g/s per MA] (conventional CL)	50	50
Total liquefaction rate [g/s] (conventional CL)	170	425 to 1275
Total equivalent entropic cost [kW @ 4.5 K] (conventional CL)	17	42 to 128
Correction factor for HTS current leads	0.33	0.33
Total equivalent entropic cost with HTS leads [kW @ 4.5 K]	6	14 to 43
Arc equivalent entropic cost with HTS leads [kW @ 4.5 K]	0.7	1.2 to 3.6

Cooling requirement

Per arc

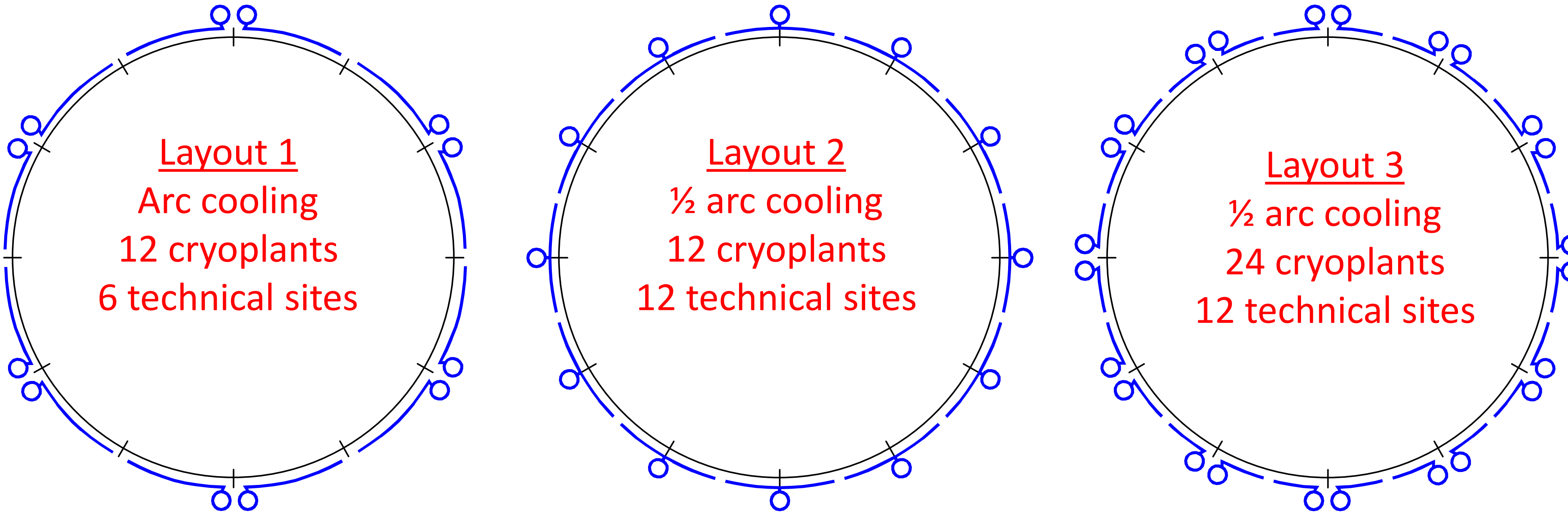


For FCC-hh (12 arcs)



w/o cryo-distribution !
w/o operation overhead !

Cryogenic layout

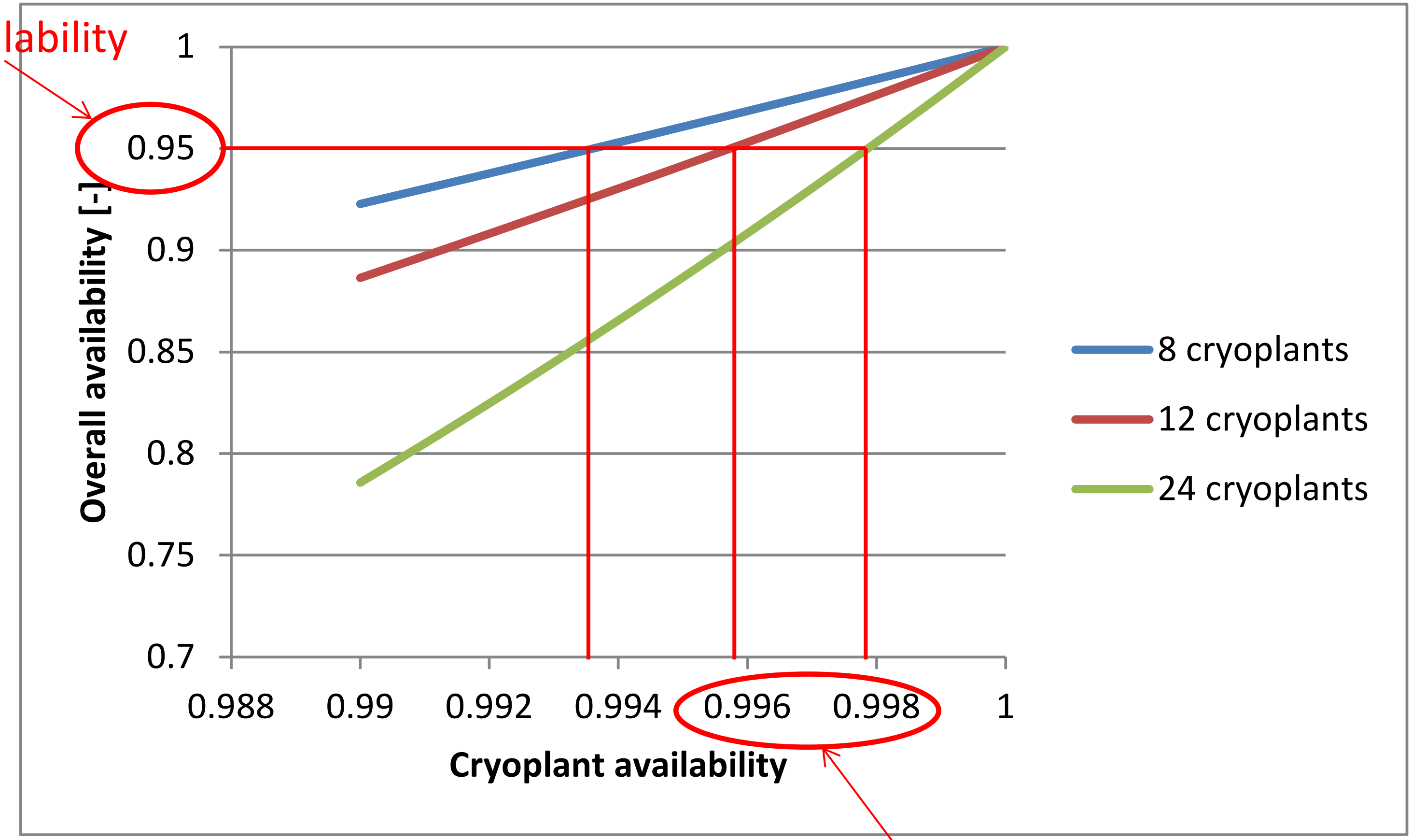


	Layout 1	Layout 2	Layout 3
Transport of refrigeration	Over 8.3 km (6.9 km)	Over 4.2 km (3.5 km)	
Nb of cryoplants (availability)	12	12	24
Size of cryoplants	Beyond SOTA*	Beyond SOTA*	Within SOTA*
Nb of technical sites	6	12	12
Partial redundancy	Y	N	Y

*: SOTA, State-Of-The-Art

Cryogenic availability

Run1 LHC cryo-availability



Improvement of cryoplant availability from 99.4 % to 99.8 %

→ i.e. over 200 days of physics per year, only 10 hours of down-time per cryoplant

Cool-down from 300 to 80 K

		LHC	FCC-hh	
			83 km	100 km
Specific CM mass	[t/m]	1.7	3.3	
Arc length	[m]	2800	5500	7000
Arc mass	[t/arc]	4648	18260	23240
Nb arc	[t]	8	12	12
Total mass	[kton]	37	219	279
LN2 preccooler capacity	[kW/arc]	600	2357	3000
LN2 consumption	[t/arc]	1250	4911	6250
	[t/machine]	10000	58929	75000
	[trailer/arc]	42	164	208
	[trailer/machine]	333	1964	2500

(for a CD time of 2 weeks)

(~30 t per trailer)

Operation cost and logistics !

Cryogenics for FCC-ee @ 175 GeV (From E. Jensen)

	704 MHz 5-cell cavity
Gradient	20 MV/m
Active length	1.06 m
Voltage/cavity	21.2 MV
Number of cavities	568
Number of cryomodules	71
Total length cryomodules	902 m
R/Q	506 Ω
Q_0	$2.0 \cdot 10^{10}$
Dynamic heat load per cavity @ 1.9 K:	44.4 W
Total dynamic heat load	25.2 kW
CW RF power per cavity	176 kW
Matched Q_{ext}	$5.0 \cdot 10^{6}$

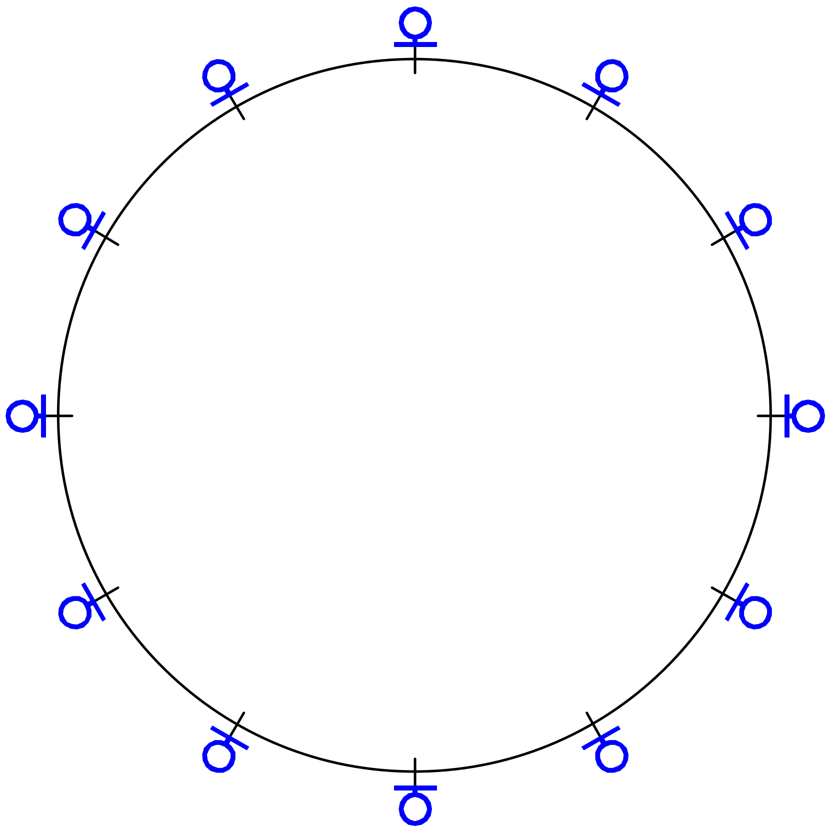
(per beam), i.e. 1800 m in total

(per beam), i.e. 50.4 kW @ 1.9 K in total

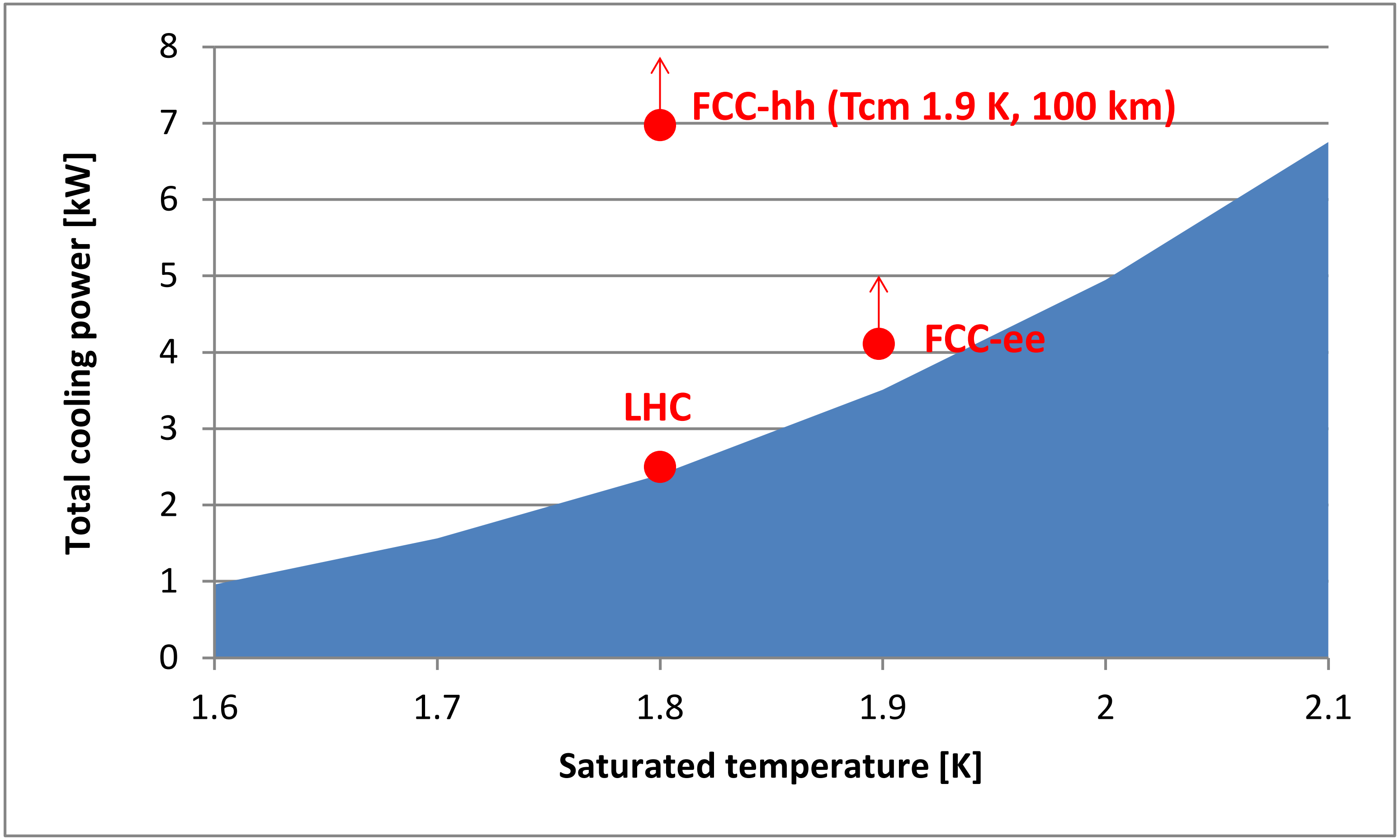
Total electrical power to the refrigerators: ~ 45 MW

Cryogenics for FCC-ee

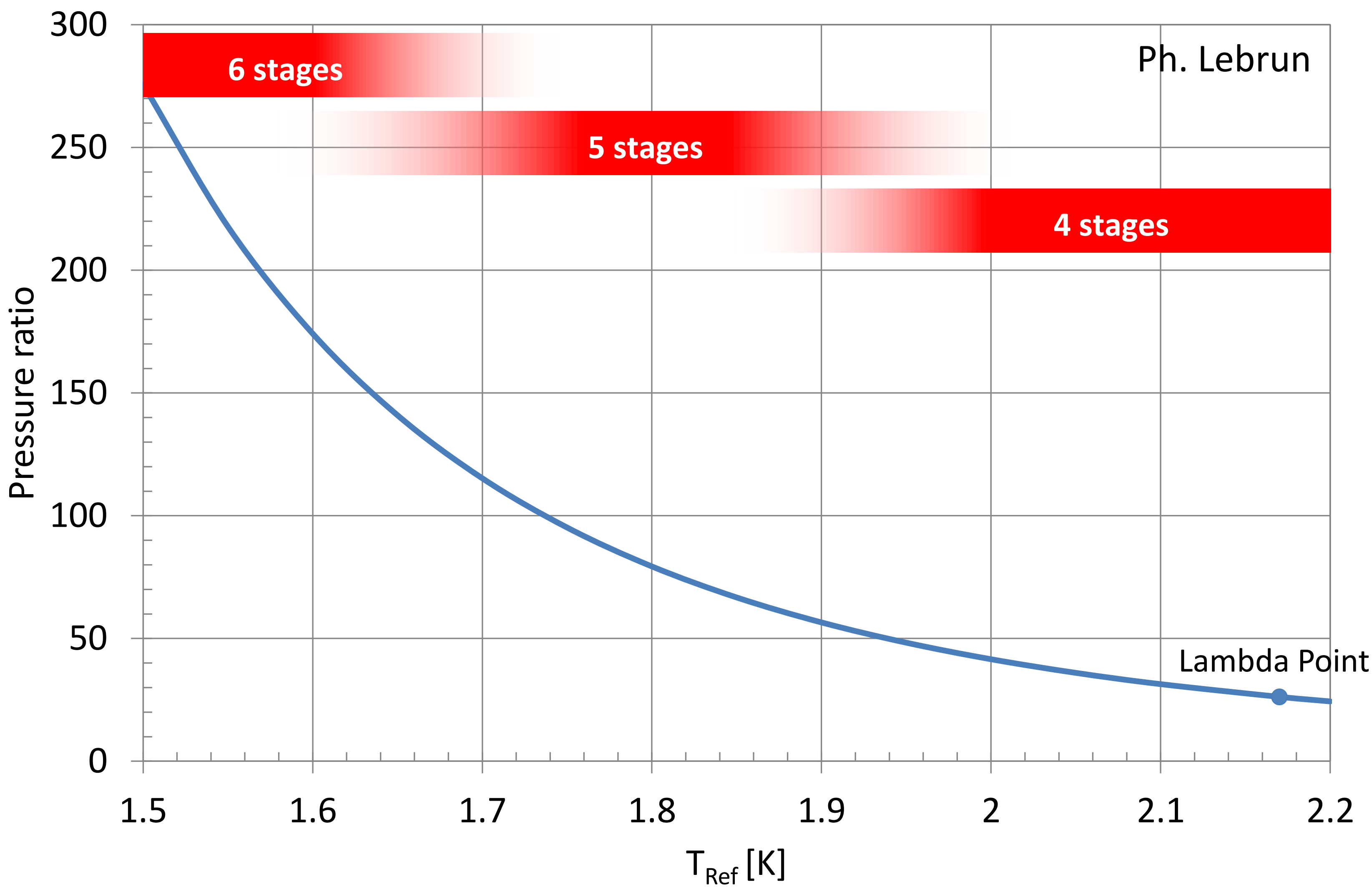
- 12 cryoplants:
  - > ~150 m of RF cavities per cryoplant
  - > 4.2 kW @ 1.9 K of RF power per cryoplants (equivalent to 16 kW @ 4.5 K) w/o:
    - static losses of cryomodule,
    - static and dynamic losses in the couplers
    - cryogenic distribution losses
    - operation overhead
  - > present State-of-the-Art: 3.5 kW @ 1.9 K



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



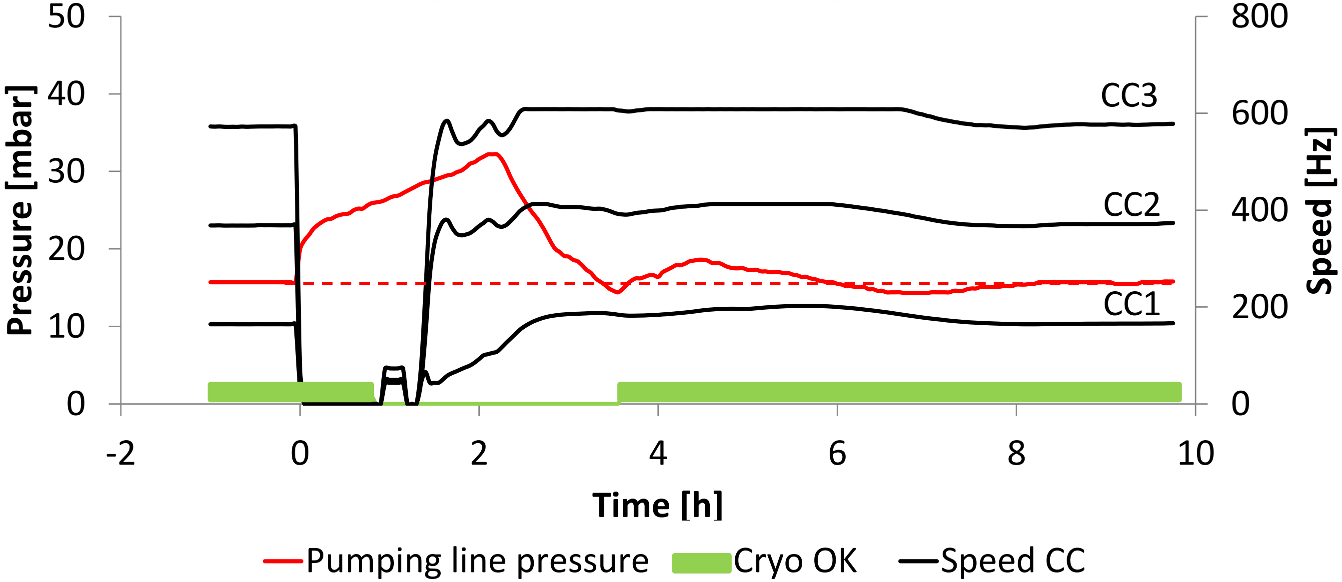
Lowering operating temperature down to 1.6 K



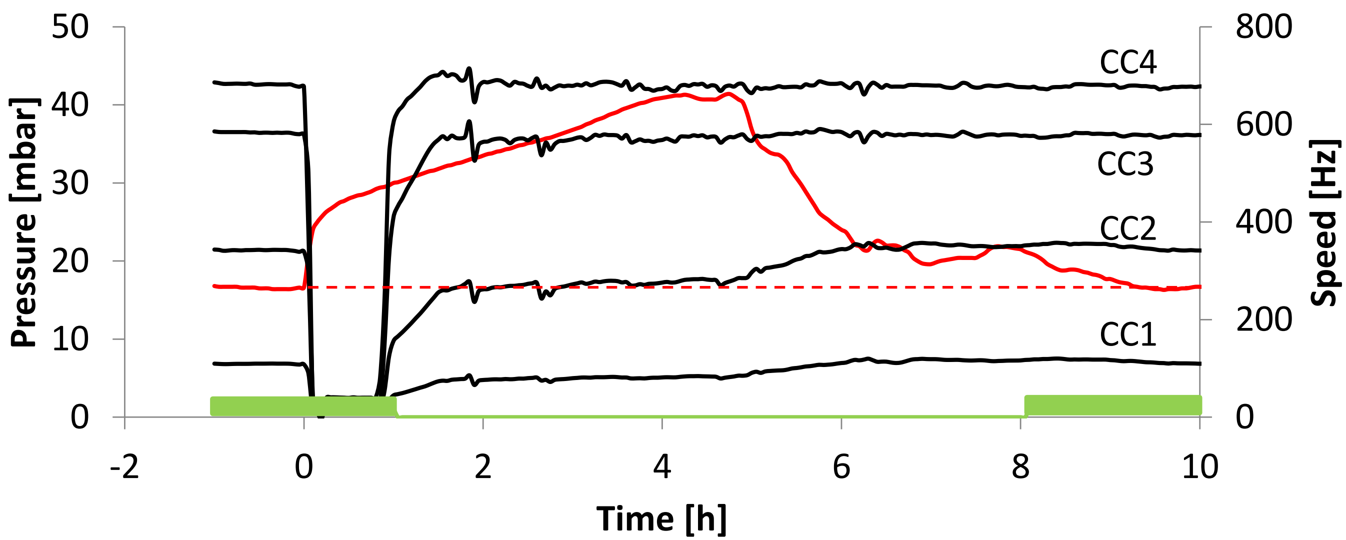
Control complexity vs CC number of mixed compression cycles

CC number	Plant	Control
1	CERN SM18 test station	- Very easy. - Could be developed by cryo-junior.
2	CEA Tore Supra	- Basic control, but the first in operation.
3	CERN LHC sector	- Need control algorithms which could be developed by cryo-experts. - Definitely the preferred configuration of LHC cryo-operators.
4	CERN LHC sector	- Need complex control algorithms developed by experts in hydro-dynamic machines (1 PLC fully dedicated to CC controls). - Less tolerant with instrumentation drift, transient effect and operator curiosity.
5 -6	FCC-ee ?	?

Recovery time of a cold compressor trip vs CC number



AL unit stop (**3 CC**):
~ 3 hours of recovery time

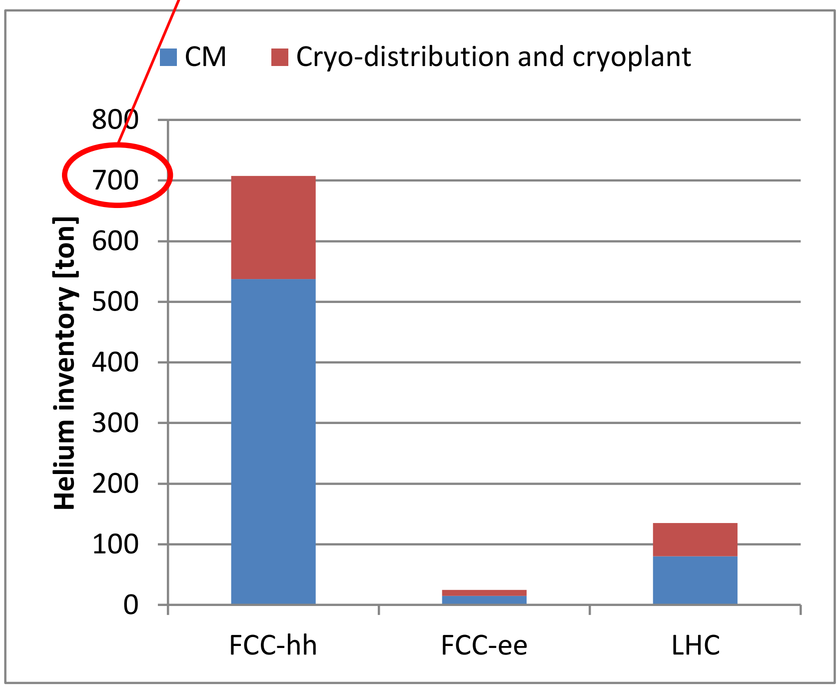


IHI-Li unit stop (**4 CC**):
~ 7 hours of recovery time

LHe inventory

- ~ 50 l/m in FCC-hh magnet cold masses,
- ~100 l/m for FCC-ee RF cryo-modules

~ 12 % of EU annual market
~ 2.5 % of annual world market



15 t LHe storage

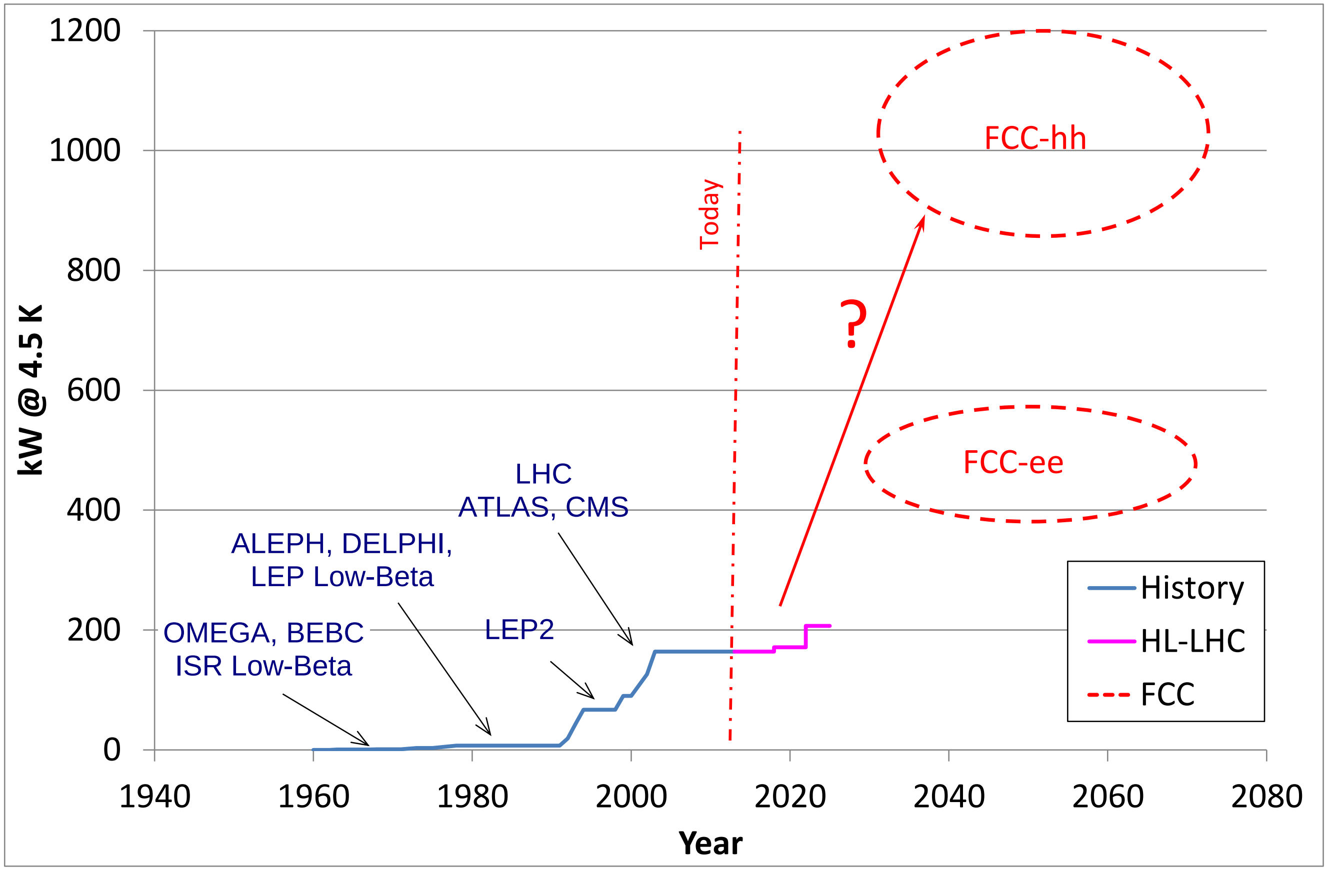
10 t GHe storage

Impact on environment

Impact on operation cost
LHC losses of He inventory:
→ The first year: 30 %
→ The third year: 15 %
→ Objective: ~10 % per year

Assuming the same losses for FCC-hh:
→ 240 ton to 80 ton per year !

Main FCC cryogenics challenges: Cryogenic plants



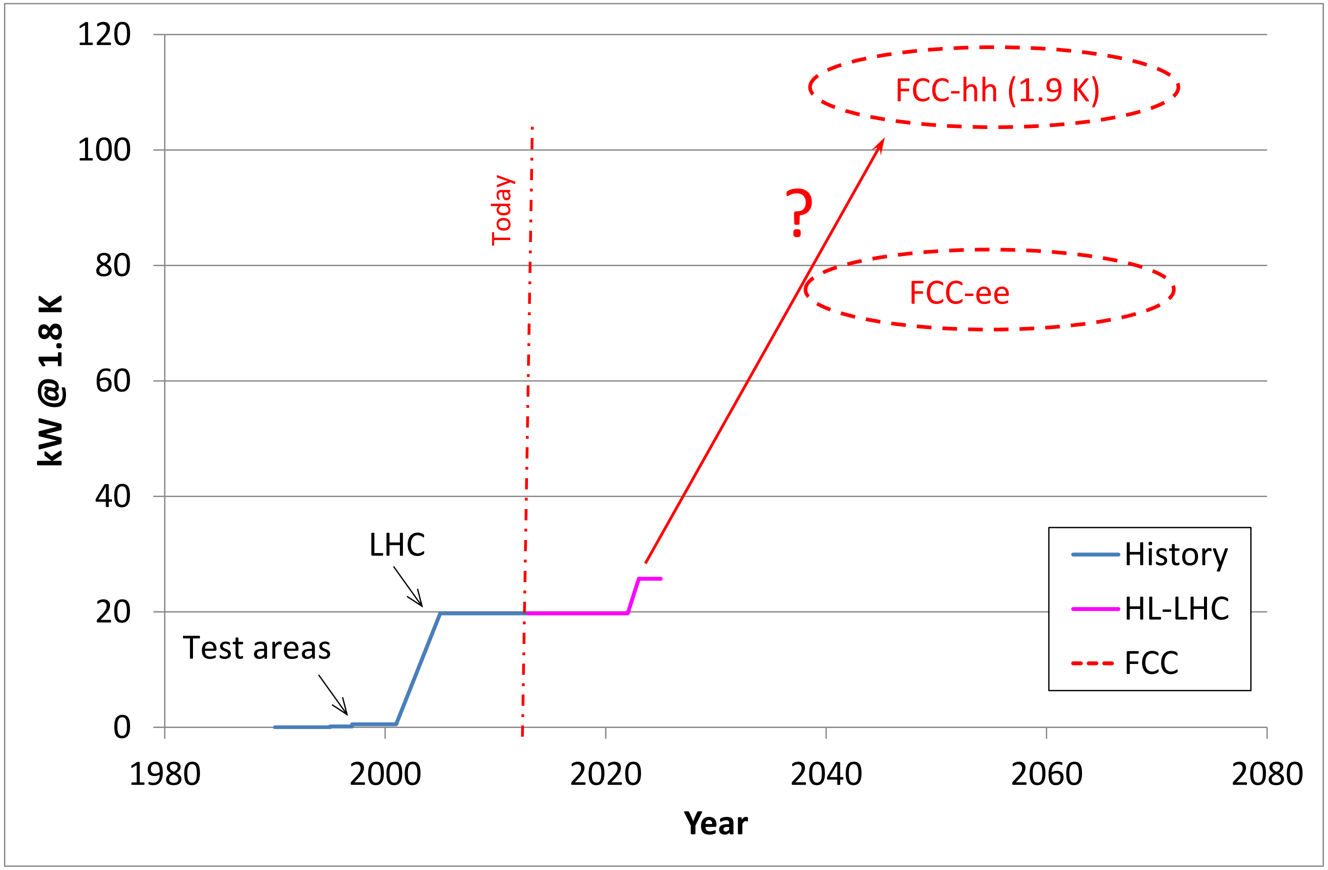
Study and development of larger cryoplants (50 kW @ 4.5 K range):

→ New type of cycle compressors ? (centrifugal vs screw)

→ New refrigeration cycle ? (higher HP pressure)

→ Improvement of reliability / availability / efficiency

Main FCC cryogenics challenges: superfluid refrigeration



Study and development of larger cold-compressor systems (10 kW @ 1.8 K range):

→ Larger cold compressors development ?

→ Operation with parallel cold compressor trains ?

→ Improvement of reliability / availability / efficiency

Main FCC cryogenics challenges: miscellaneous

- The beam screen cooling:
  - > high heat deposition: up to 44 W/m per aperture
  - > integration of the cooling circuits in a narrow space.
  - > Control of the 40-60 K temperature level with high dynamic range (up to 10)
  - > alternative cooling method (with neon…)
- Management of He inventory and He losses, in particular:
  - > helium release during magnet resistive transitions and cold buffering
- Optimization of the cooling schemes and of the cryogenic distribution
- Safety
  - > preliminary risk analysis including accidental He discharge in the tunnel

Conclusion

- FCC will trigger specific cryogenic studies and developments which will stimulate progress of the state-of-the-art in term of technologies and system reliability and efficiency.
- We hope that the FCC study will also stimulate the worldwide cryogenic community.
  → The sharing of expertise on previous or present projects and studies will be essential.
  → Collaborations are welcome !