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University of Twente, The Netherlands

Beyond the Large Hadron Collider: a first look at cryogenics for CERN future circular colliders

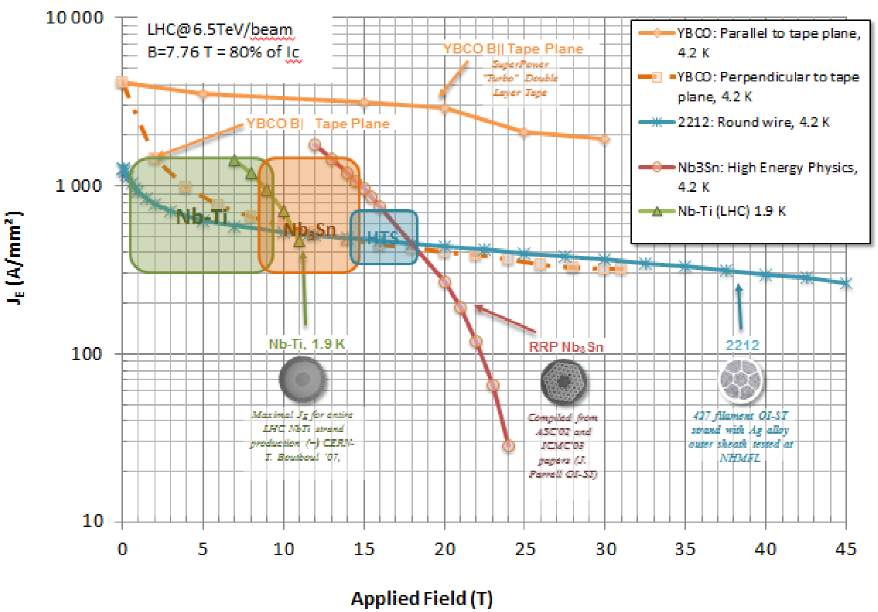
Philippe Lebrun & Laurent Tavian, CERN

Contents

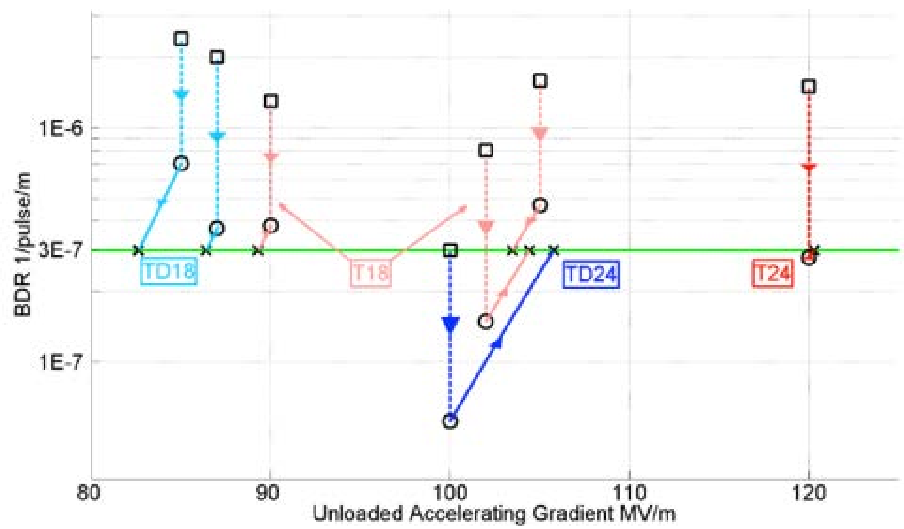
European Strategy Update on Particle Physics *Design studies and R&D at the energy frontier*

*“CERN should undertake design studies for accelerator projects in a global context, with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets** and **high-gradient accelerating structures**, in collaboration with **national institutes, laboratories and universities worldwide**”*

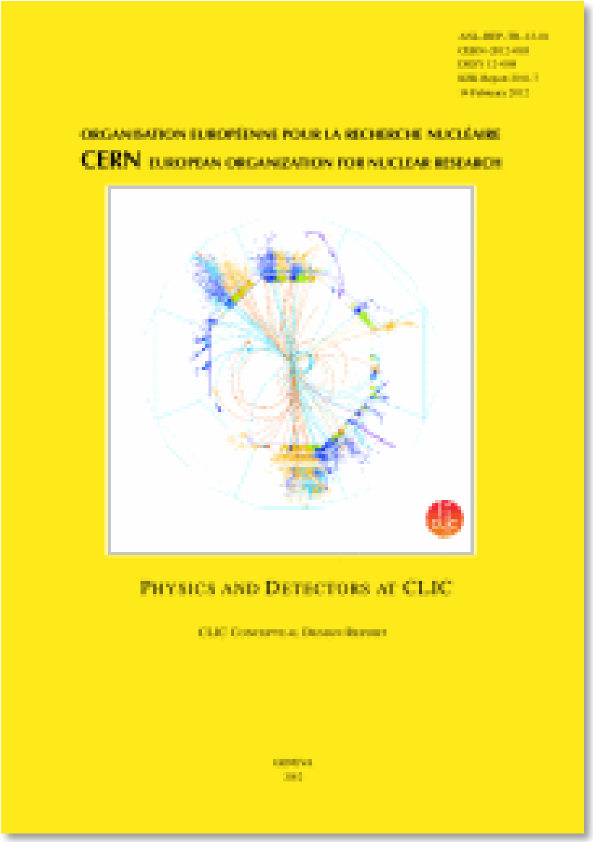
HFM

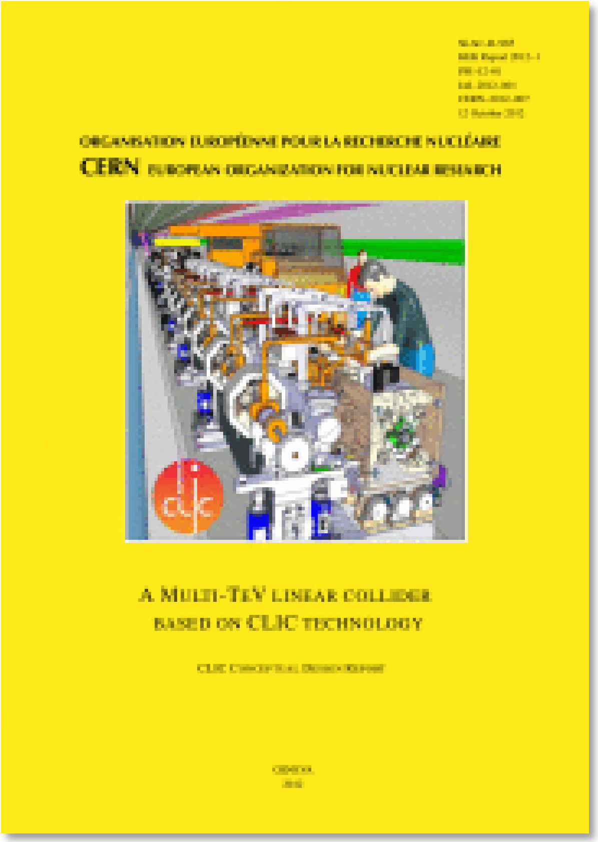


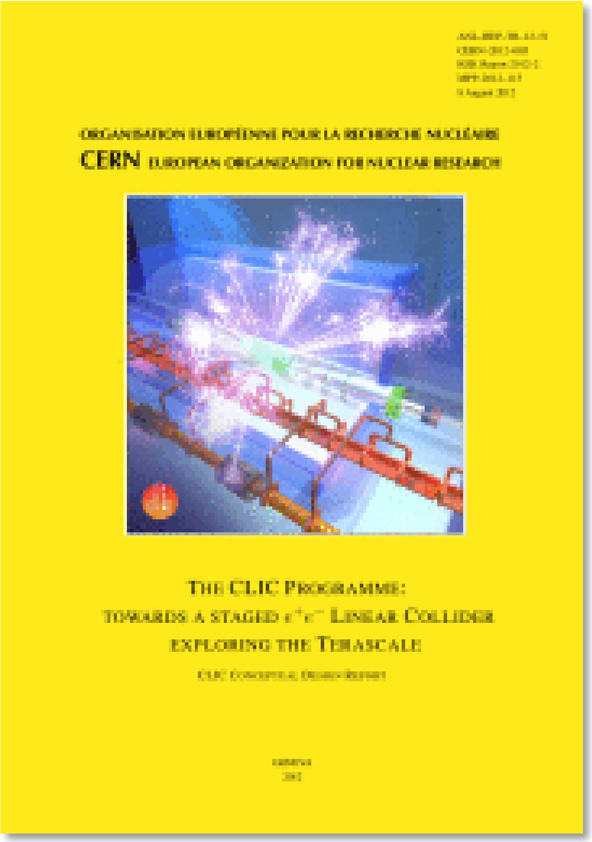
HGA



CLIC CDR and cost study (2012)

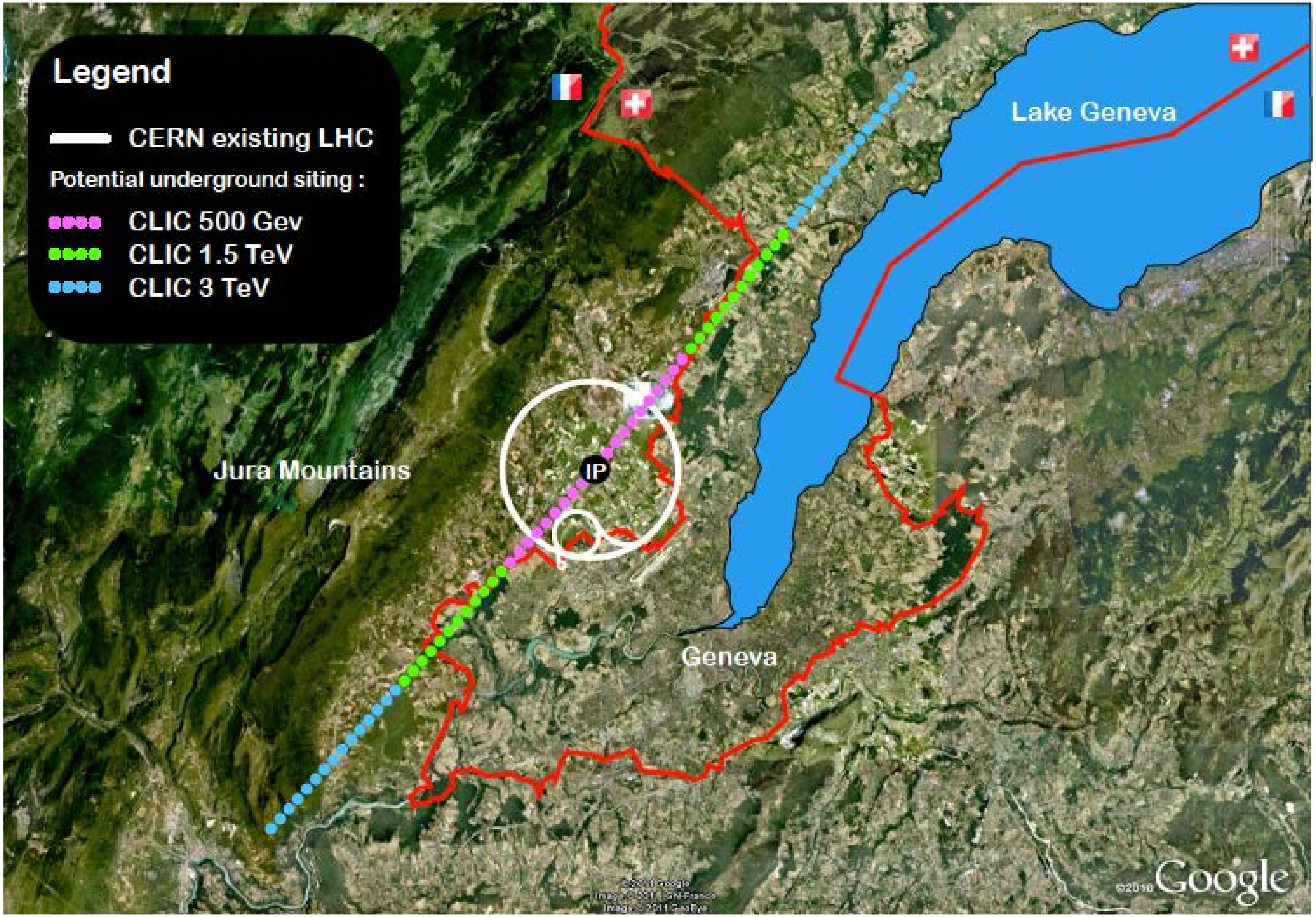






- 3 volumes: physics & detectors, accelerator complex, strategy, cost & schedule
- Collaborative effort: 40+ institutes worldwide

Possible implementation of CLIC near CERN

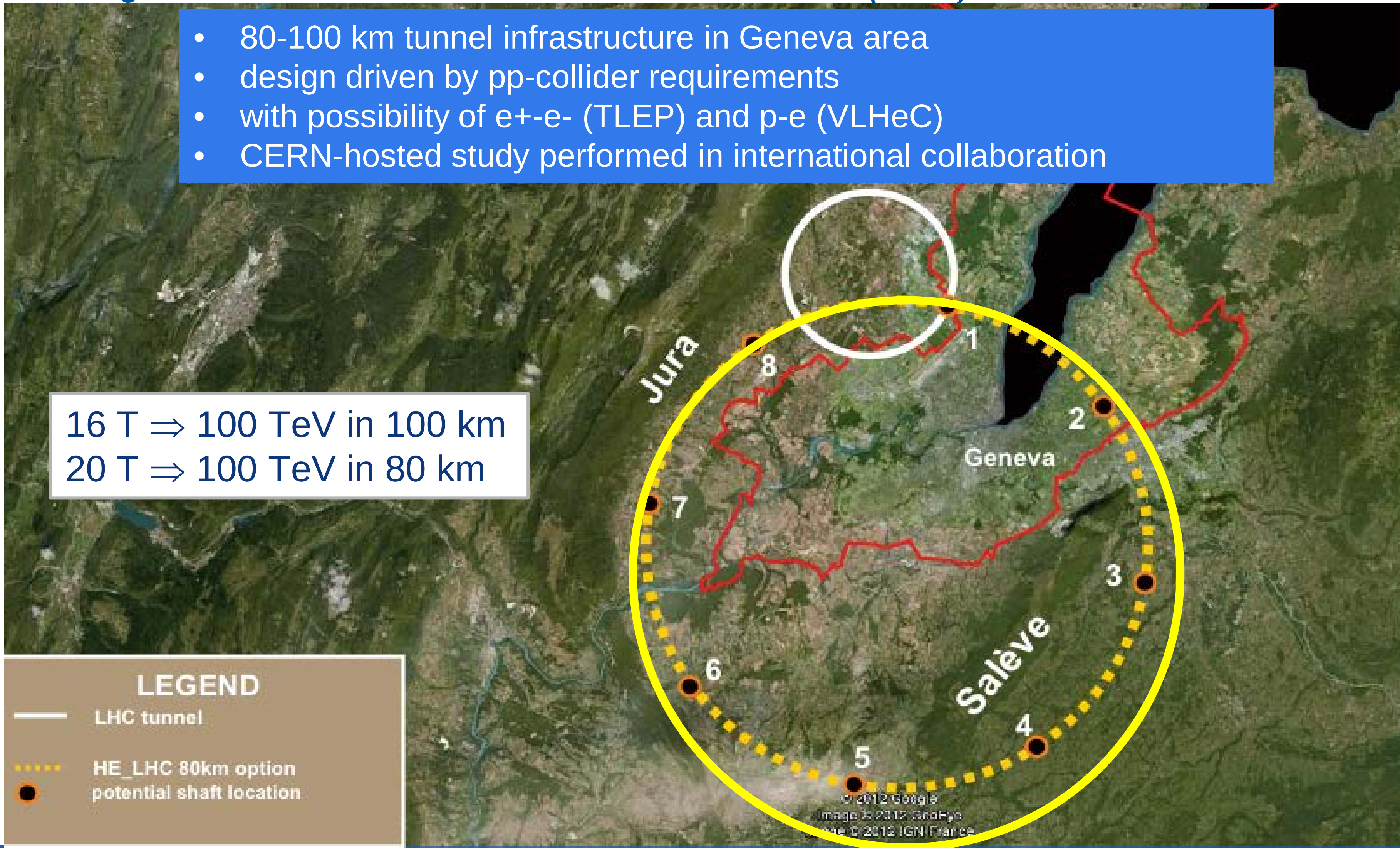


The Future Circular Colliders (FCC) design study

Aiming for CDR and Cost Review for the next ESU (2018)

- 80-100 km tunnel infrastructure in Geneva area
- design driven by pp-collider requirements
- with possibility of e+-e- (TLEP) and p-e (VLHeC)
- CERN-hosted study performed in international collaboration

16 T $\Rightarrow$ 100 TeV in 100 km
20 T $\Rightarrow$ 100 TeV in 80 km



Structure of FCC study

Leader Michael Benedikt, Deputy Frank Zimmermann

Future Circular Colliders - Conceptual Design Study for next European Strategy Update (2018)

Infrastructure

tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring, safety

Hadron injectors

Beam optics and dynamics
Functional specs
Performance specs
Critical technical systems
Operation concept

Hadron collider

FCC-hh

Optic… …amics
Fun… …ions
Performance specs
Critical technical systems
Related R+D programs
HE-LHC comparison
Operation concept
Detector concept
Physics requirements

e+ e- collider

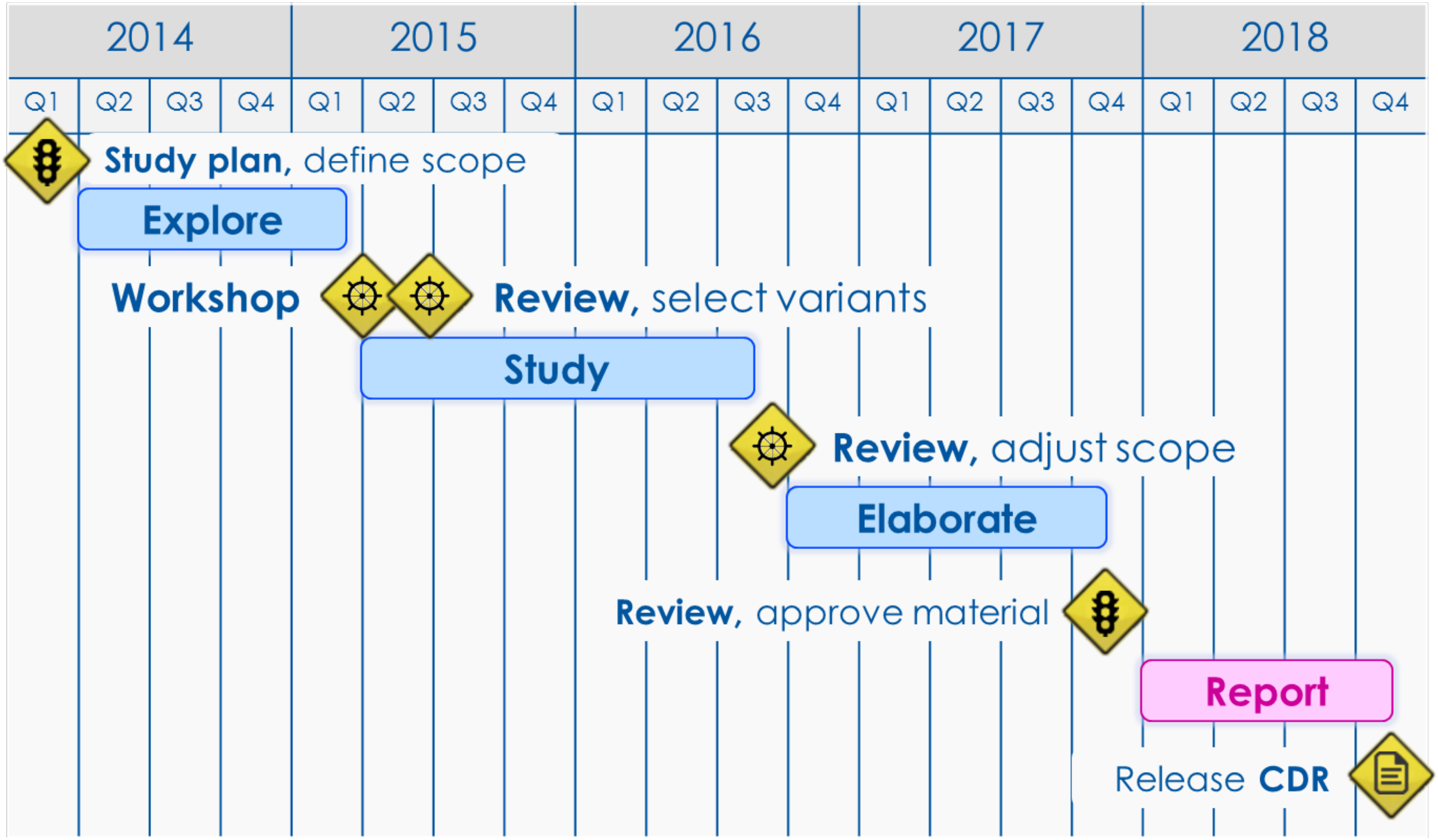
FCC-ee

… dy… …al
specifications
Performance specs
Critical technical systems
Related R+D programs
Injector (Booster)
Operation concept
Detector concept
Physics requirements

e- p option: Physics… …ditional requirements

FCC-he

Phases of the FCC study



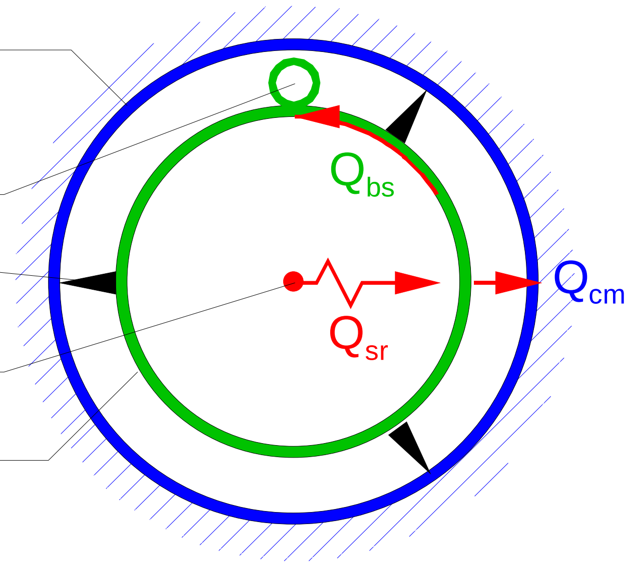
Beam parameters impacting FCC-hh cryogenics

Parameter	LHC	FCC-hh	Impact
c.m. Energy [TeV]	14	100	Synchrotron radiation (~ E^4)
Circumference C [km]	26.7	100 (83)	
Dipole field [T]	8.33	16 (20)	Resistive heating, stored energy, quench pressure relief
Straight sections	8	12	i.e. 12 arcs → arc length: ~7 km (~5.5 km)
Average straight section length [m]	528	1400	
Number of IPs		2 + 2	Cryogenics for detectors (LHe, LAr)
Peak luminosity [10^{34} cm-2s-1]	1	5	Secondaries from IPs
Beam current [A]	0.584	0.5	
RMS bunch length [cm]	7.55	8 (7.55)	
Stored beam energy [GJ]	0.392	8.4 (7.0)	Safety: release of He in tunnel
SR power per ring [MW]	0.0036	2.4 (2.9)	Large load and dynamic range
Arc SR heat load [W/m/aperture]	0.17	28.4 (44.3)	Beam screen design
Dipole coil aperture [mm]	56	40	
Beam aperture [mm]	~40	26	

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 :

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

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

- Real electrical power to refrigerator: $P_{ref} = \Delta E/\eta(T)$
  with $\eta(T)$ = efficiency w.r. to Carnot = COP_{Carnot}/COP_{Real}

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

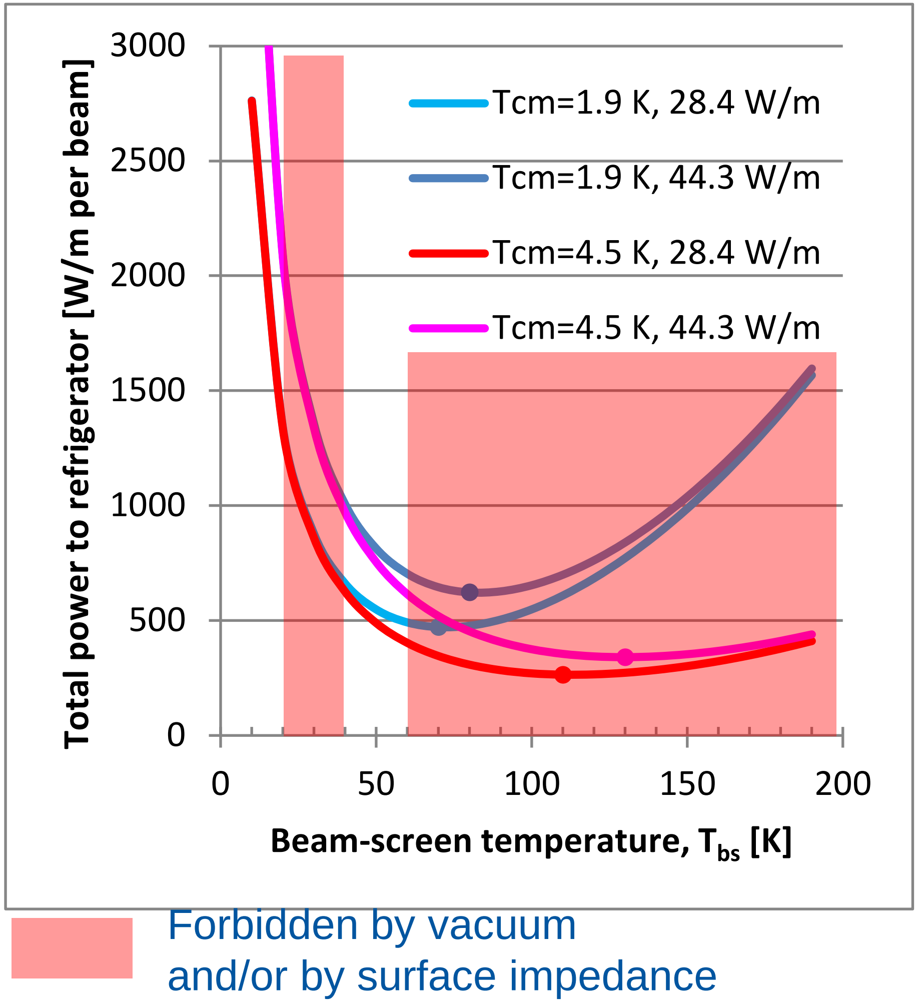
BS – CM thermodynamics Numerical application

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

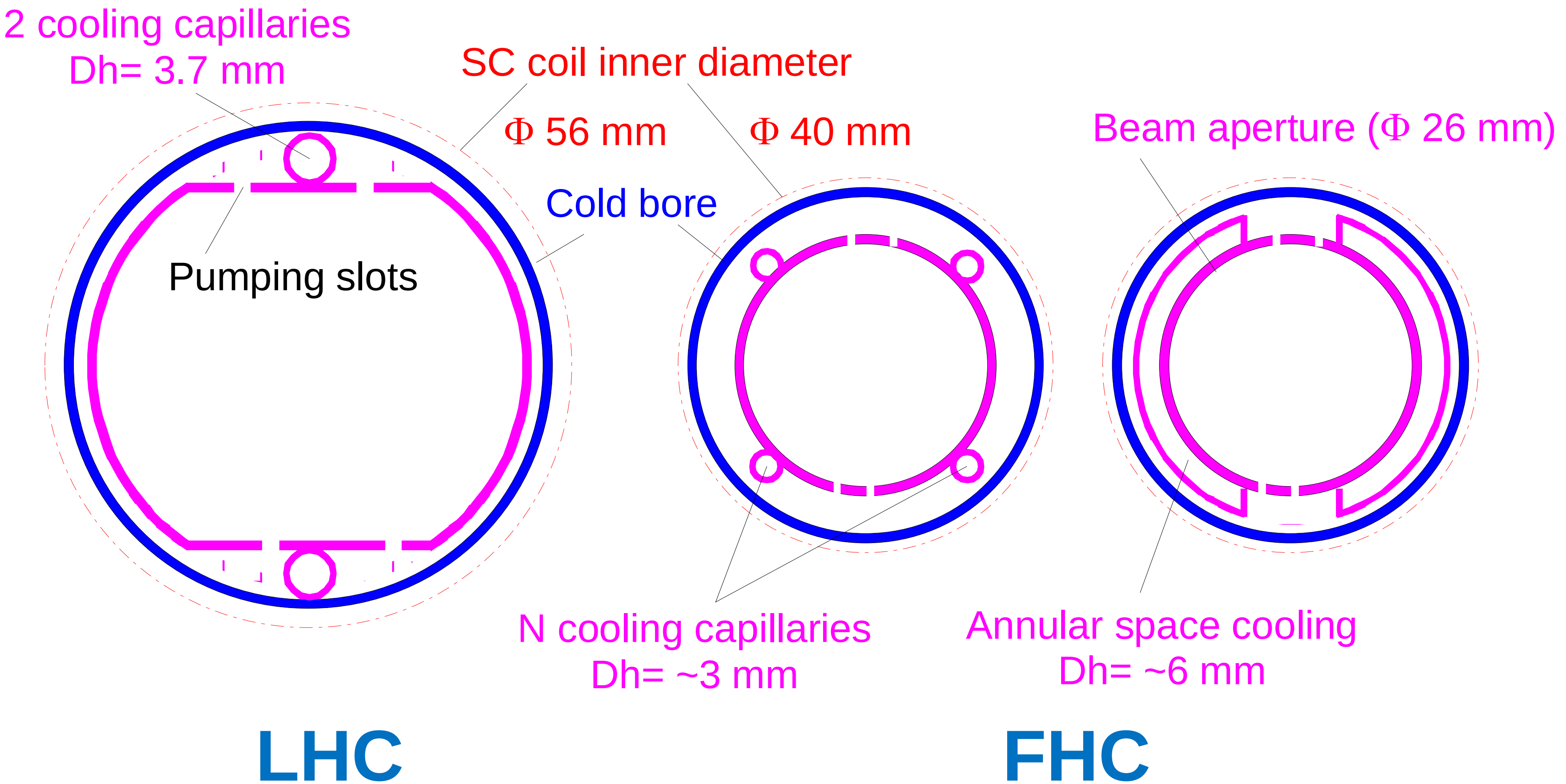
- a beam screen similar to that of the LHC
- refrigerator efficiencies identical to those of the LHC.

T_{cm}= 1.9 K, optimum for T_{bs}= 70-80 K
T_{cm}= 4.5 K, flat optimum for T_{bs}= 120 K

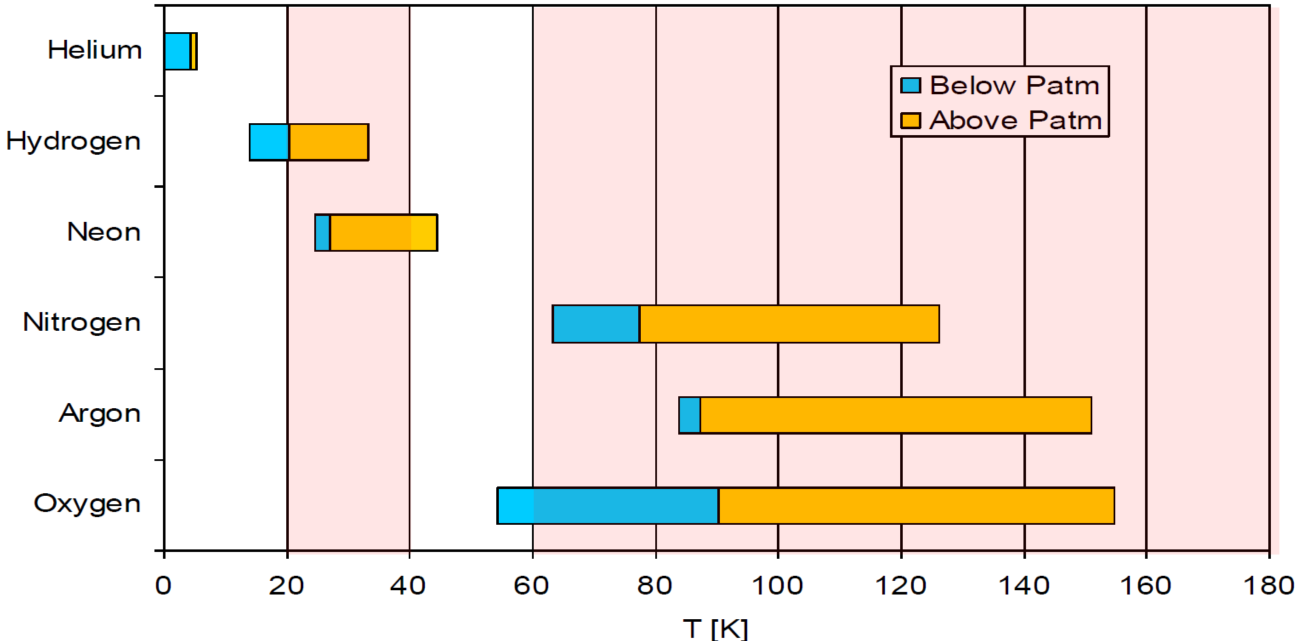
Temperature range 40-60 K retained



Beam screen cooling



Cooling potential of cryogens for beam screen

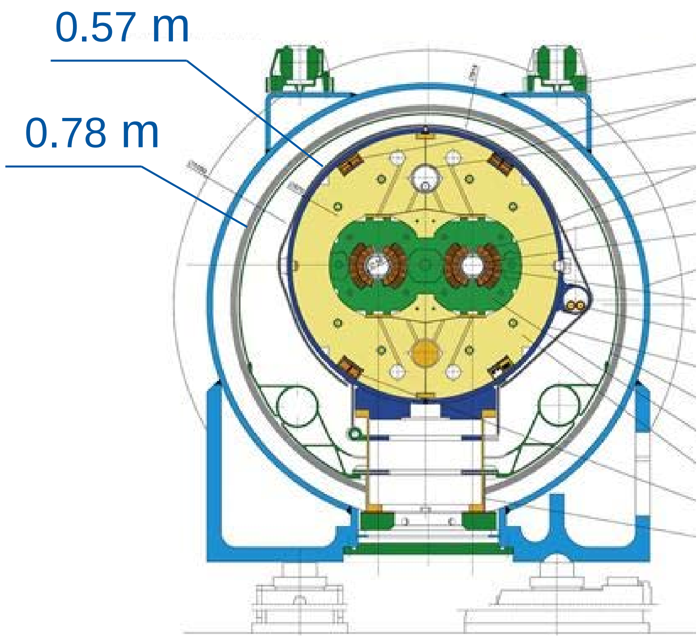


Cryogen	Temperature range	Per unit mass [J/g]	Per unit volume* [J/cm^3]
He 3 bar	5-20 K	103	0.74
He 20 bar	5-20 K	89.3	4.20
He 20 bar	40-60 K	107	1.64
Ne 30 bar	40-60 K	79.1	11.3

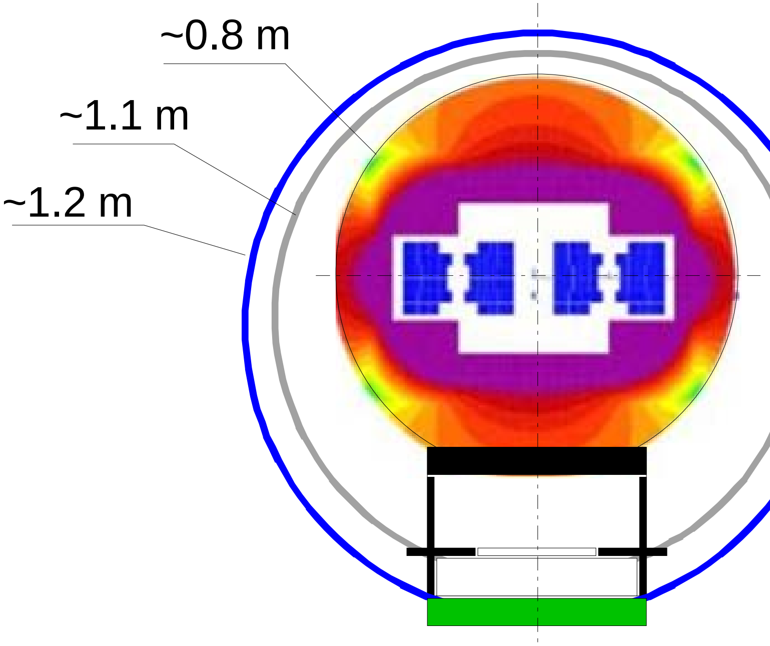
* *at exit conditions*

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!

Cryo-magnet cross sections



LHC



FCC-hh

A first estimate of heat loads

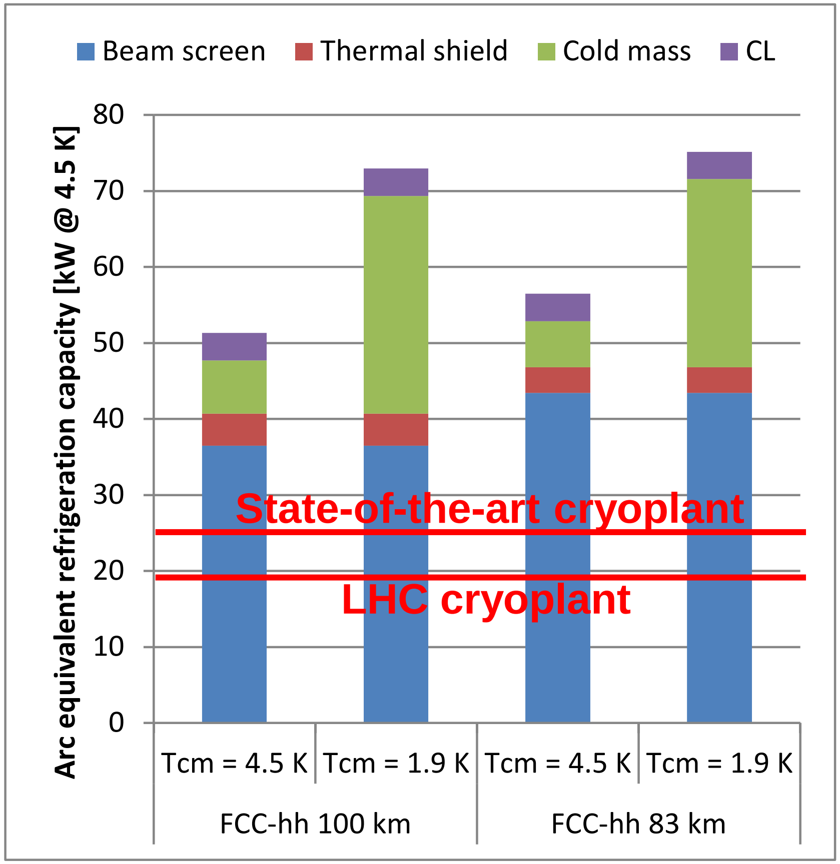
		LHC [W/m]			FCC-hh [W/m]	
	Temperature level	50-75 K	4.5-20 K	1.9 K	40-60 K	1.9 or 4.5 K
Static heat inleaks	CM supporting system	1.5		0.10	2.9	0.2
	Radiative insulation			0.11		0.15
	Thermal shield	2.7			3.8	
	Feedthrough & vac. barrier	0.2		0.1	0.2	0.1
	Total static	4.4		0.3	6.9	0.45
Dynamic heat loads	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)
	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)

(): Value in brackets for 83-km FCC-hh

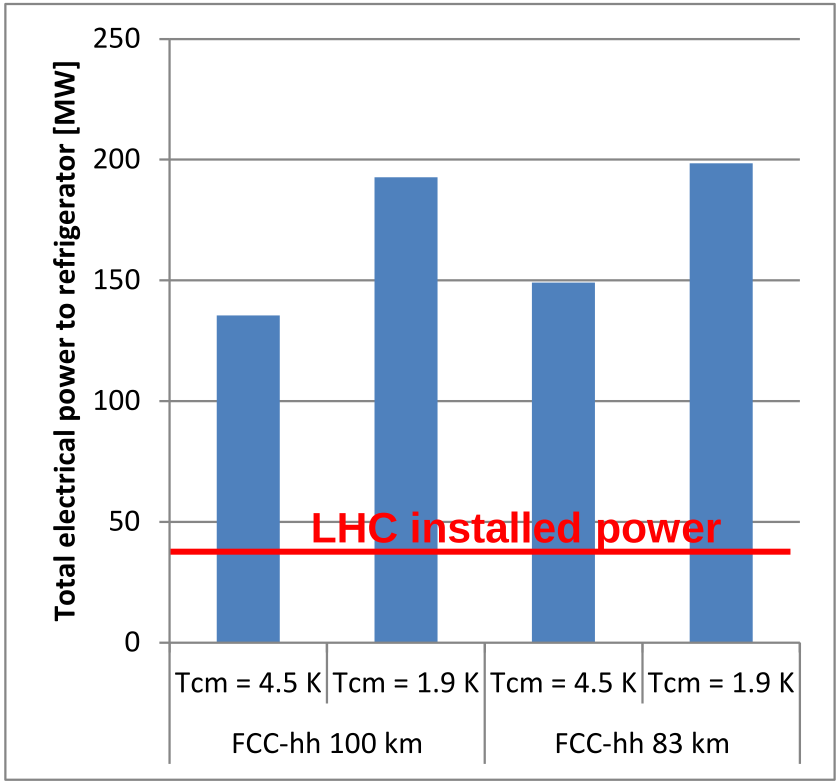
FCC-hh cooling requirements

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

Per arc

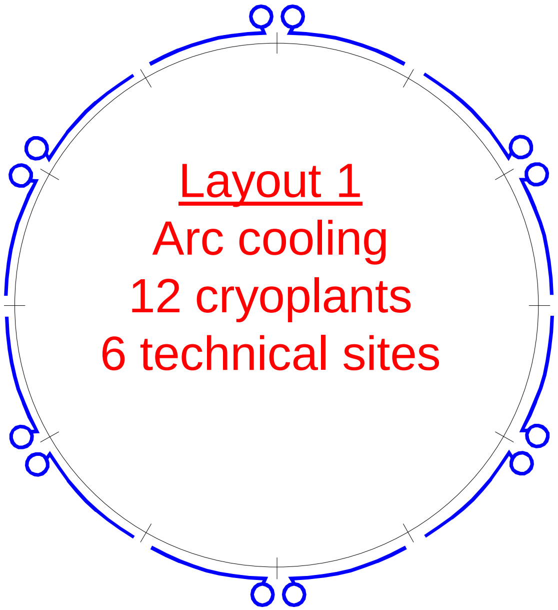


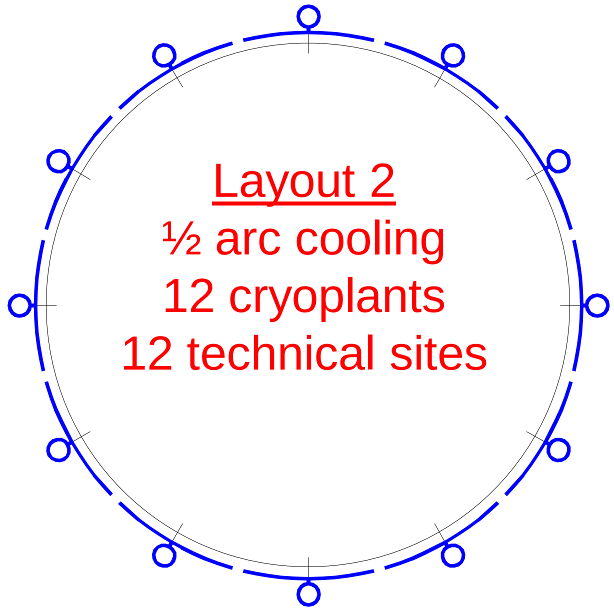
For FCC-hh (12 arcs)

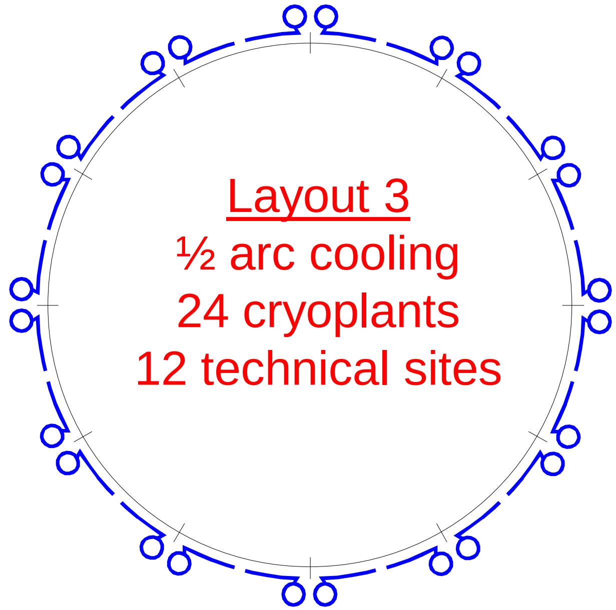


A large part of the refrigeration capacity corresponds to non-isothermal refrigeration above 40 K → open the door to non-conventional refrigeration (He-Ne mixture…)

Cryogenic layouts







	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

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	59000	75000
	[trailer/arc]	60	245	310
	[trailer/machine]	480	2950	3750

(for a CD time of 2 weeks)

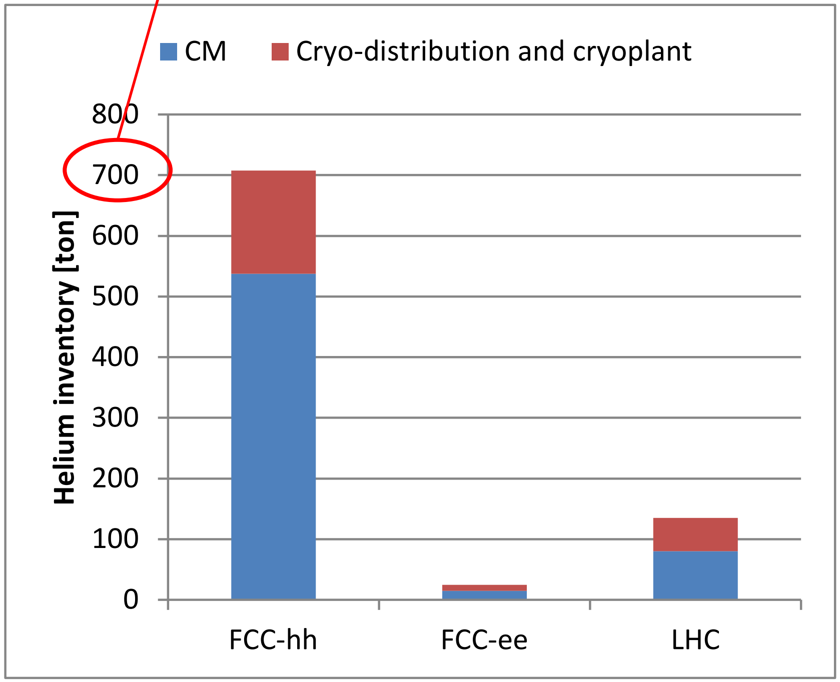
(~20 t per trailer)

Operation cost and logistics !

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 !

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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}	$5.0 \cdot 10^{6}$

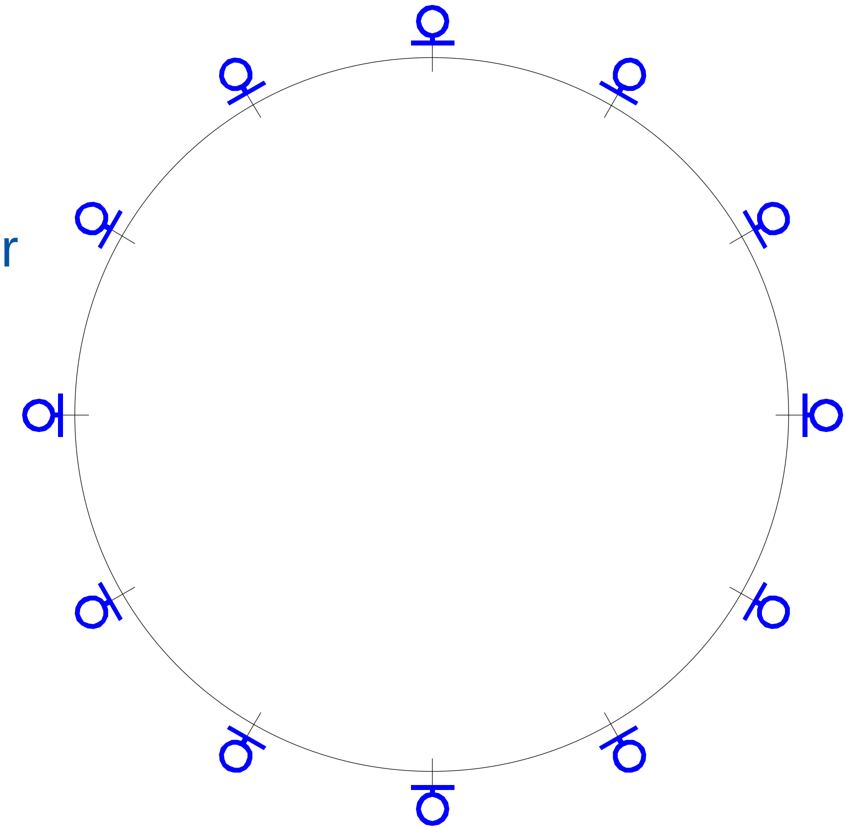
(per beam), i.e. 1800 m in total

(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



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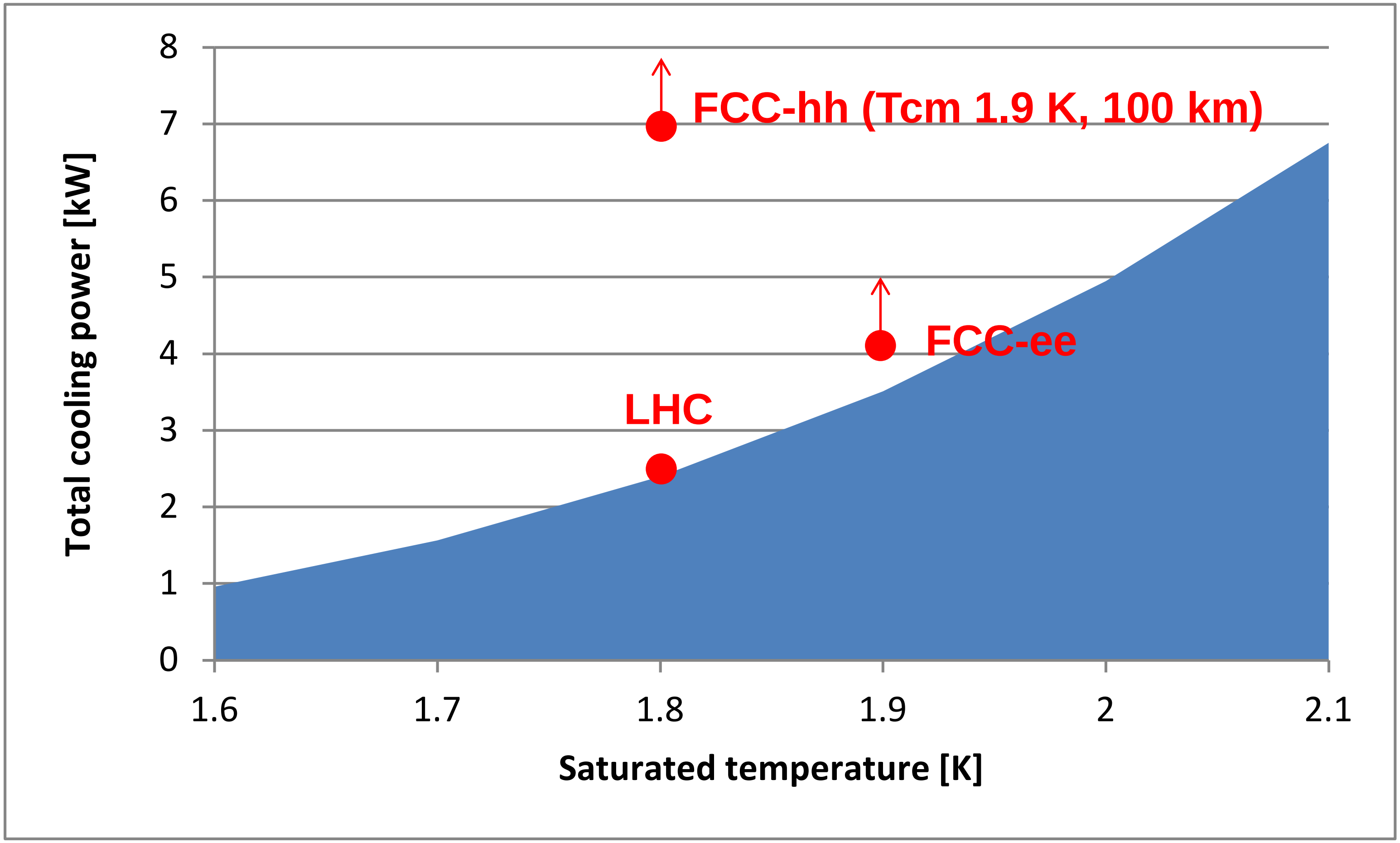
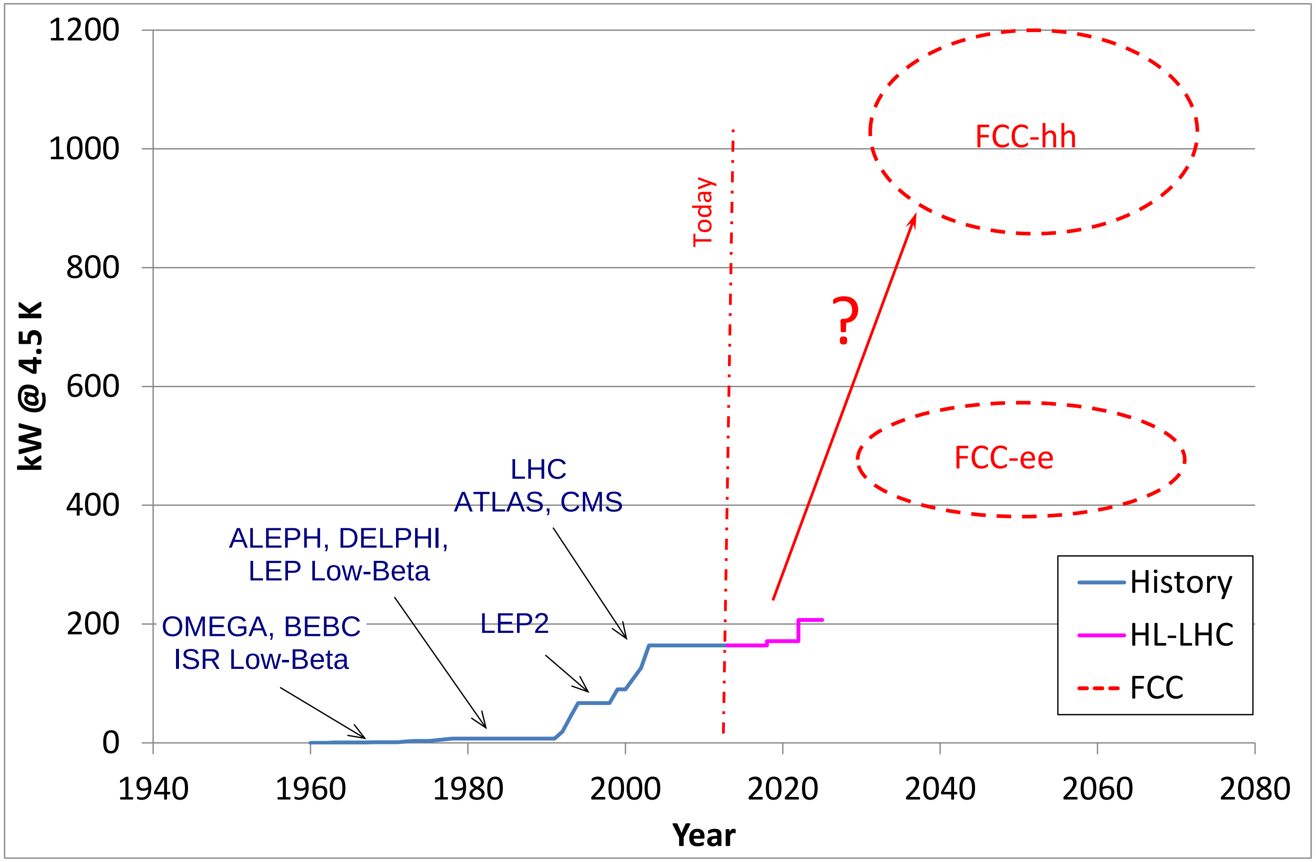
- Introduction: the European Strategy Update
- Future circular hadron collider: FCC-hh
- Future circular electron-positron collider: FCC-ee
- Cryogenic plant challenges
- Conclusion

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



Main FCC cryogenics challenges: towards 1 MW @ 4.5 K



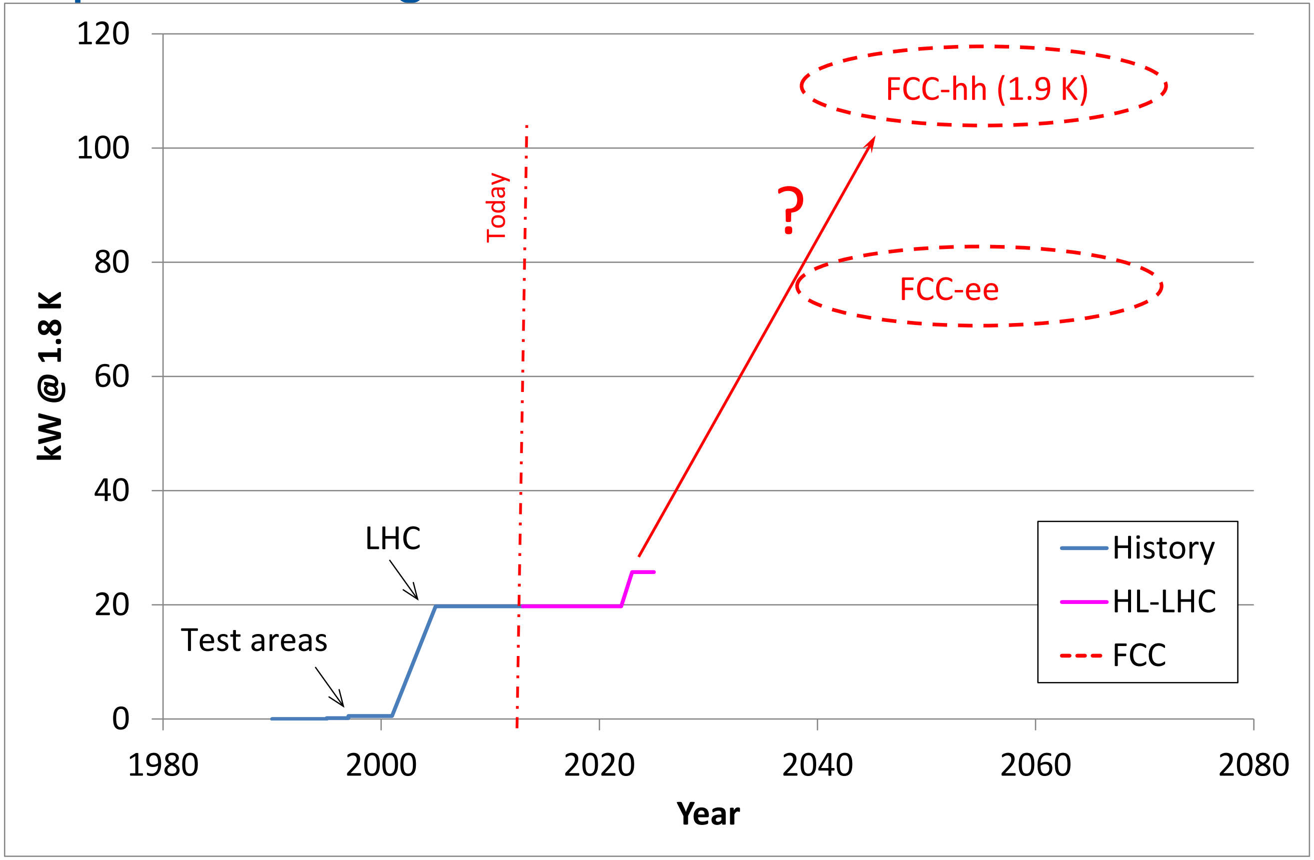
Study and development of larger cryoplants (50-100 kW @ 4.5 K range):

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

→ New refrigeration cycle ? (higher HP pressure, He-Ne mixture)

→ 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 compressor development ?
→ Operation with parallel cold compressor trains ?
→ Improvement of reliability / availability / efficiency

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 !