HL-LHC and FCC: what are the cryogenic needs?

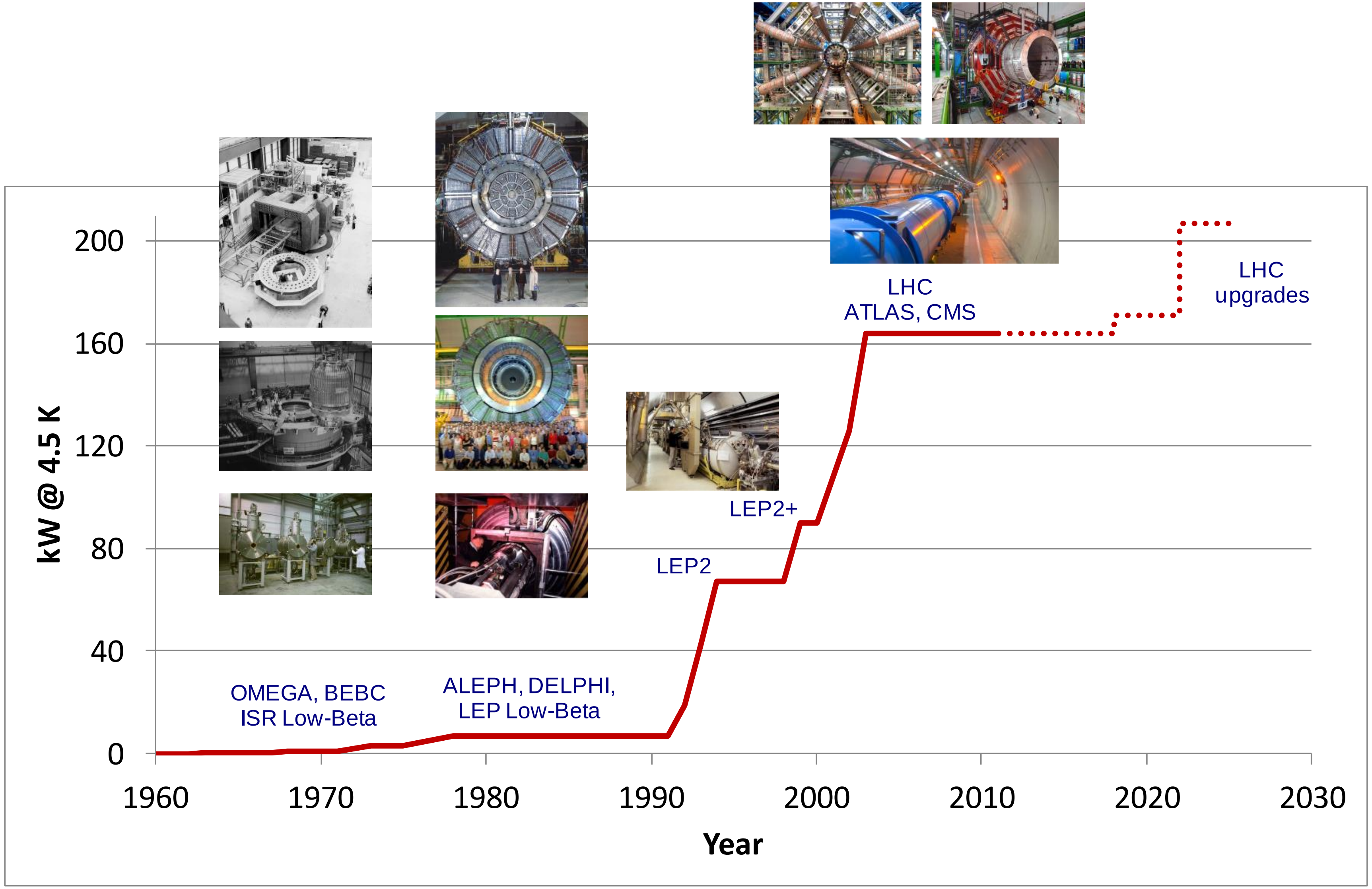
Laurent Tavian, CERN

European Cryogenics Days, 9-10 June 2016

Contents

- Introduction of cryogenics at CERN
- High-Luminosity LHC (HL-LHC) upgrade
- Future Circular Collider (FCC) cryogenics study
  - FCC-hh → hadron-hadron collider
  - FCC-ee → electron-positron collider (not treated today but back-up slides available at the end of this presentation)

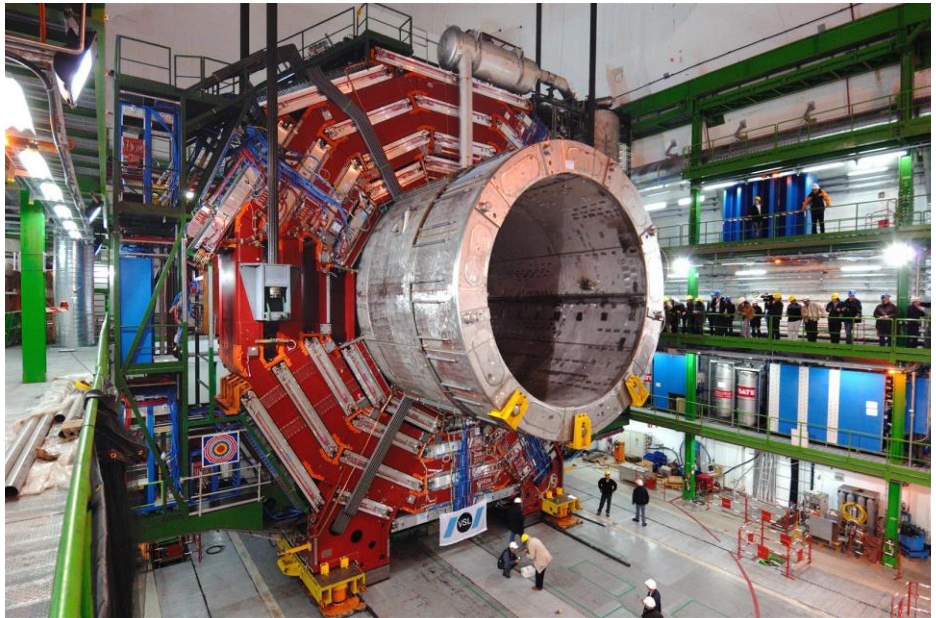
Installed cryogenic power at CERN



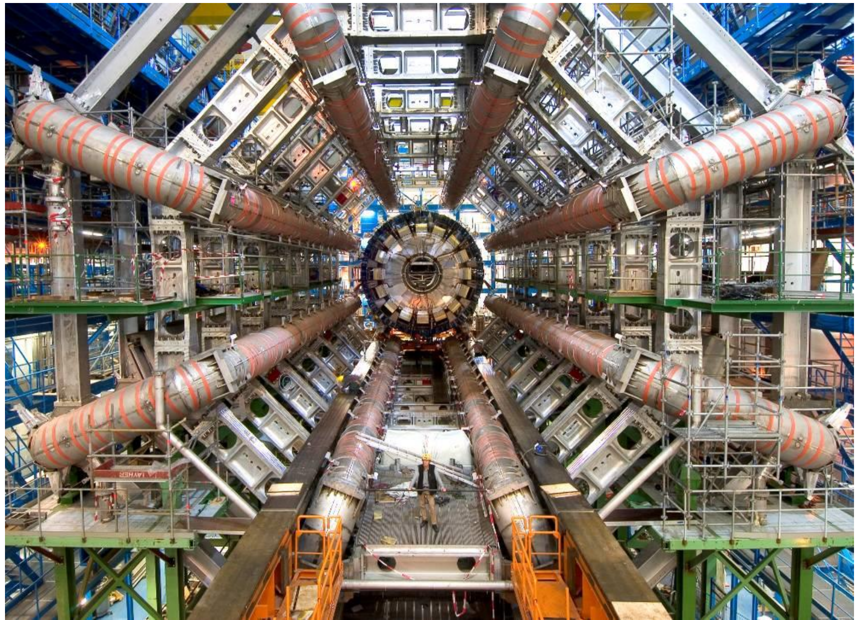
The CERN Flagship: The Large Hadron Collider (LHC)

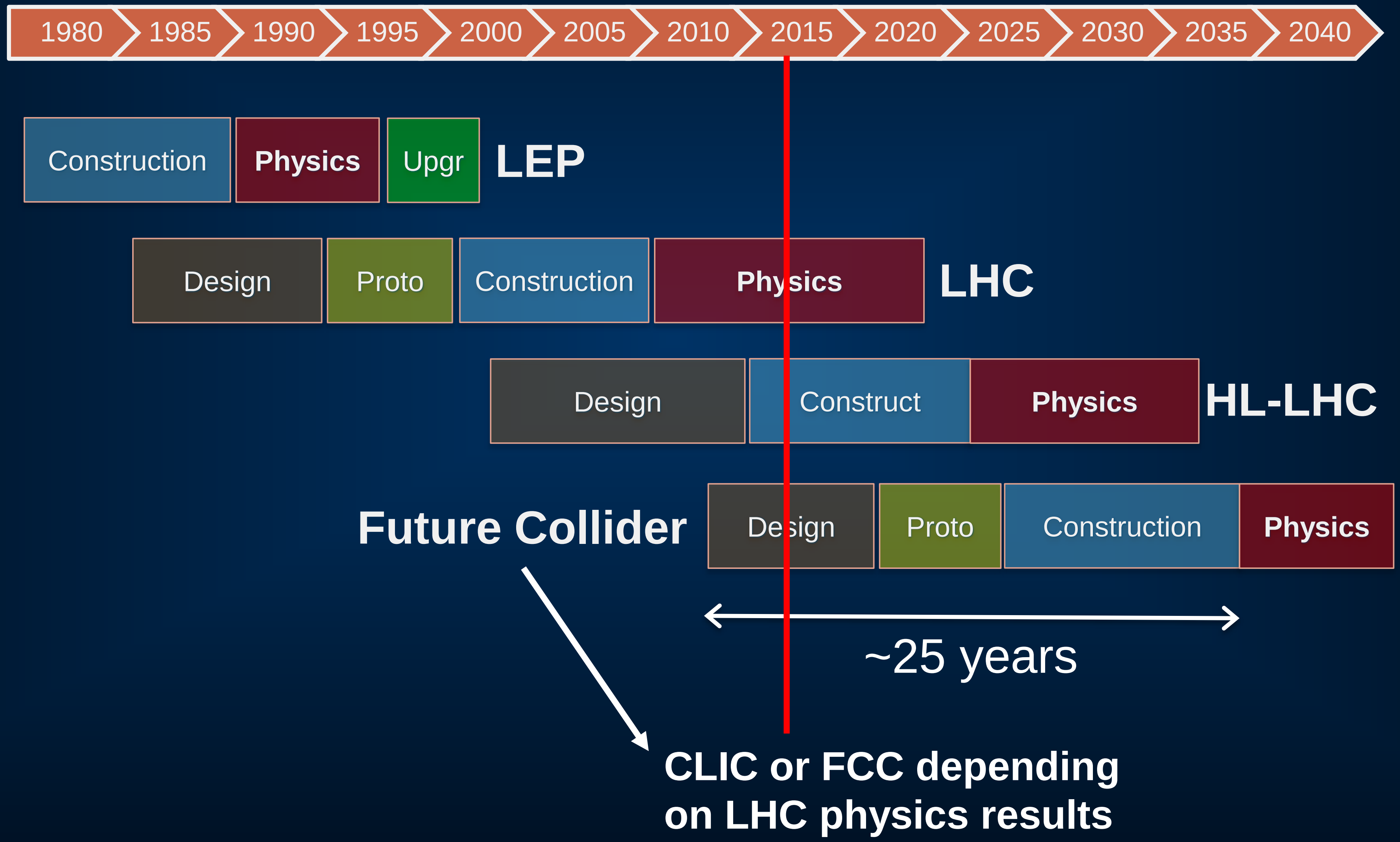
LHC accelerator
(24 km of superconducting magnets operating at 1.9 K)

CMS detector



ATLAS detector





1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
2035
2040
Construction
Physics
Upgr
LEP
Design
Proto
Construction
Physics
LHC
Design
Construct
Physics
HL-LHC
Future Collider
Design
Proto
Construction
Physics
~25 years
CLIC or FCC depending on LHC physics results

Contents

- Introduction of cryogenics at CERN
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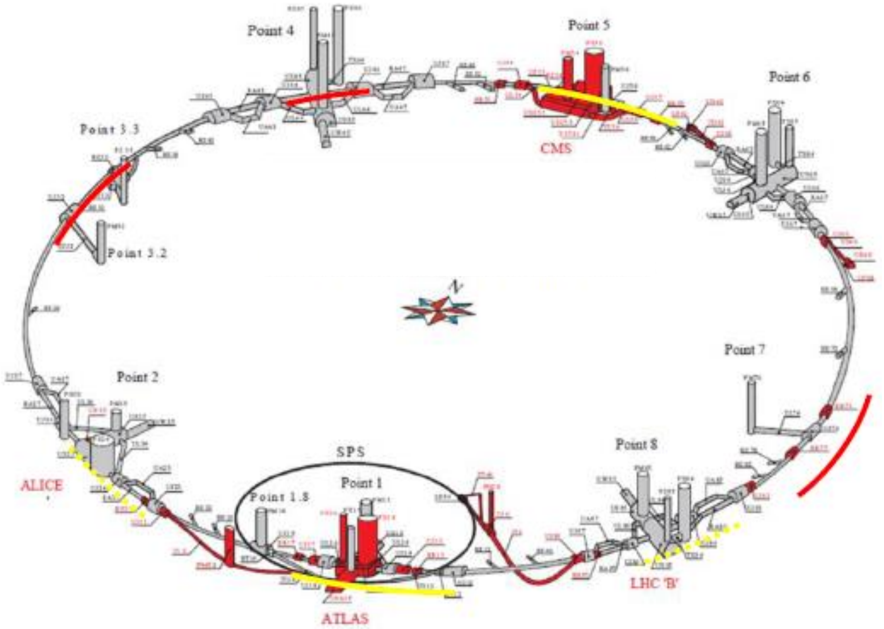
- Future Circular Collider (FCC) cryogenics study

The HL-LHC (HiLumi) project
Objectives and contents

- Determine a **hardware configuration** and a set of **beam parameters** that will allow the LHC to reach the following targets:
  - enable a total integrated luminosity of 3000 fb^{-1}
  - enable an integrated luminosity of 250-300 fb^{-1} per year
  - design for $\mu \sim 140$ (~ 200) (peak luminosity of 5 (7) $10^{34}\ cm^{-2}\ s^{-1}$)
  - design equipment for 'ultimate' performance of 7.5 $10^{34}\ cm^{-2}\ s^{-1}$ and 4000 fb^{-1}



Major intervention on 1.2 km of LHC ring

- New IR-quads using Nb_3Sn superconductor
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection

Paths to high luminosity

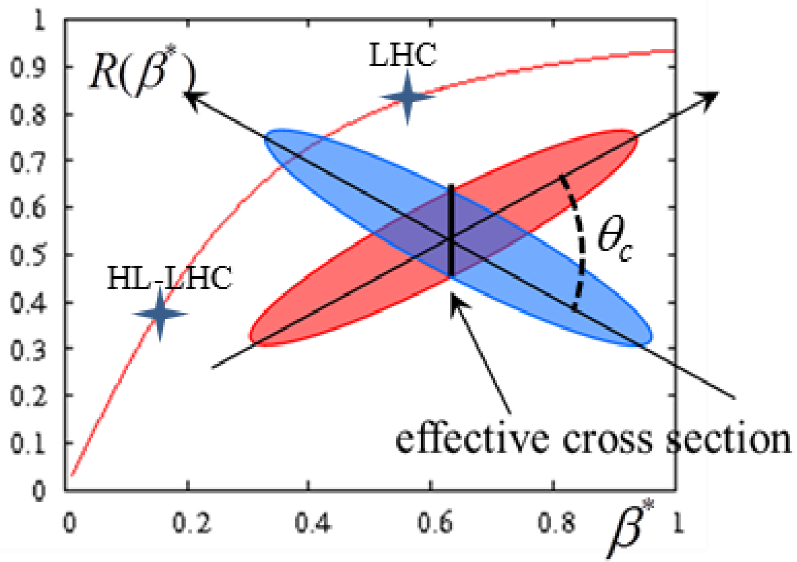
Increase bunch population

Increase R = reduce crossing angle?

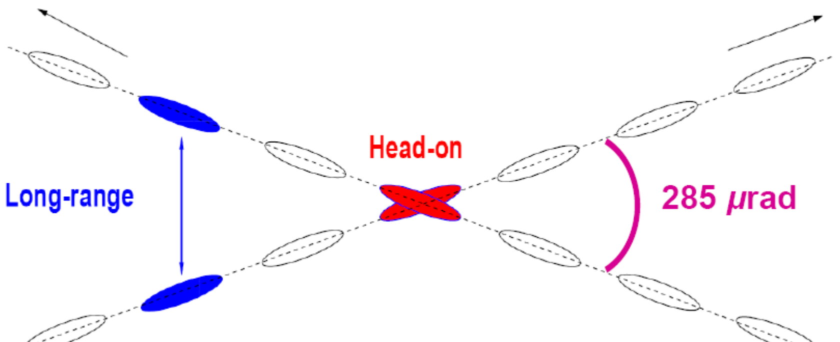
$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi\, \beta^*\, \varepsilon_n} R; \qquad R = 1 \Big/ \sqrt{1 + \frac{\theta_c\, \sigma_z}{2\sigma}}$$

Reduce beta at collision

Reduce emittance



Beam-beam effect precludes too low crossing angle



Courtesy W. Herr

The HL-LHC project
From accelerator physics to technology

Accelerator physics

Reduce emittance

Increase bunch population

Reduce beta at collision

Reduce crossing angle

Increase intensity & brightness of injectors: the LIU project

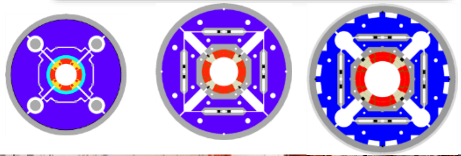
Limit beam-beam effect

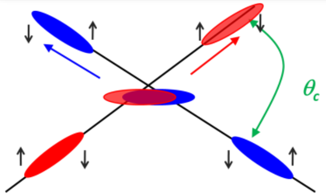
Accelerator technology

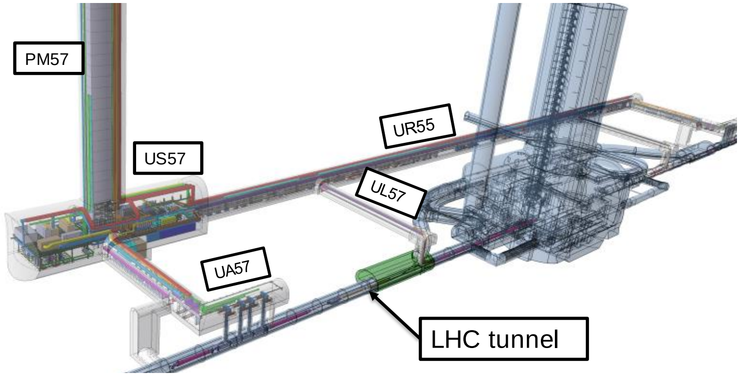
More powerful cryogenics
Improved collimation
Improved machine protection
Stronger R to E → relocation

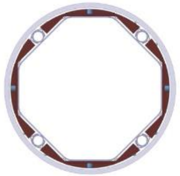
New low-beta quadrupoles

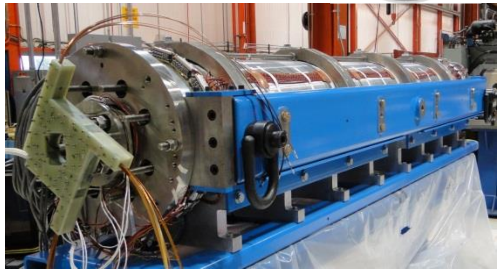
"Crab" cavities





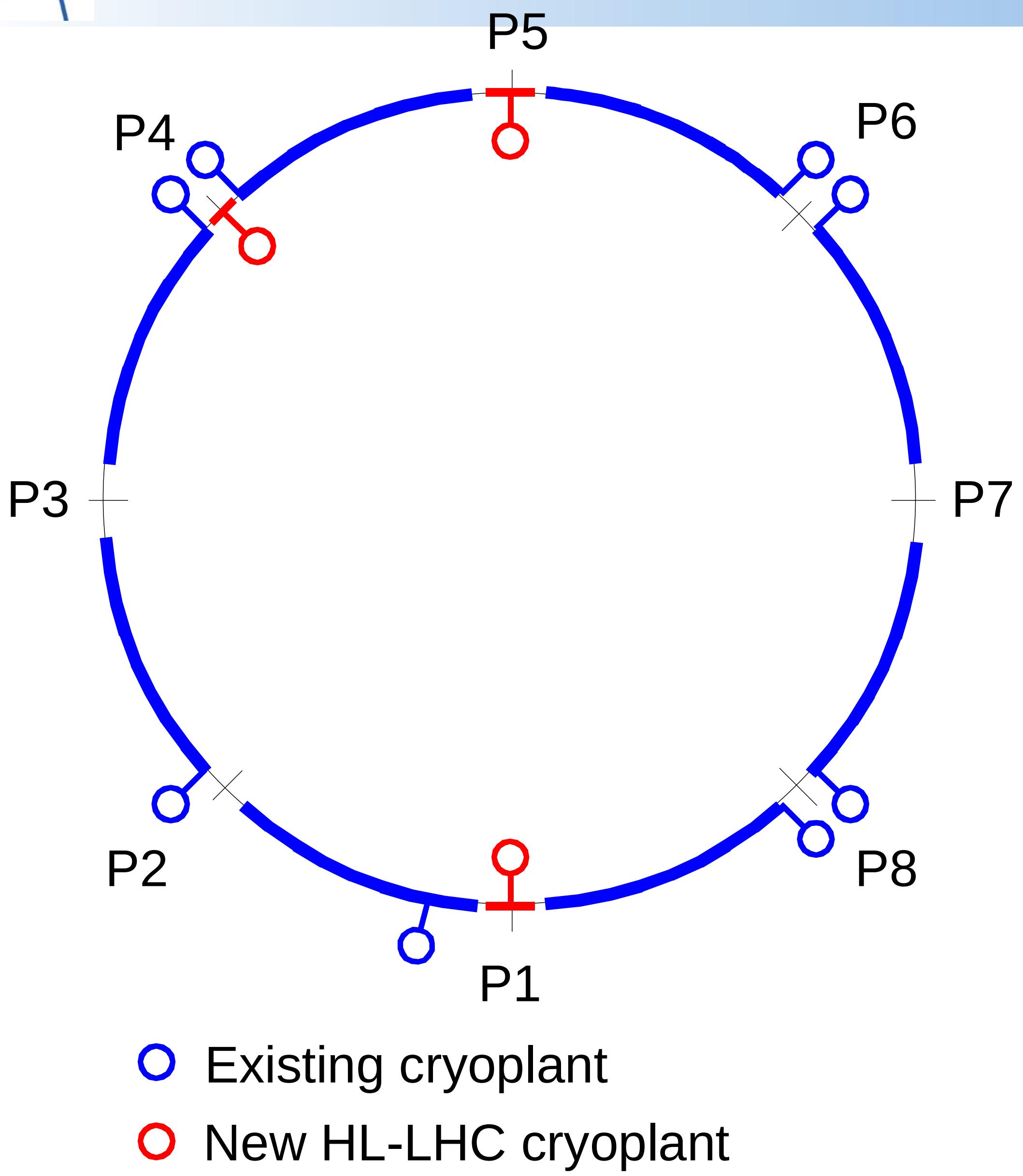






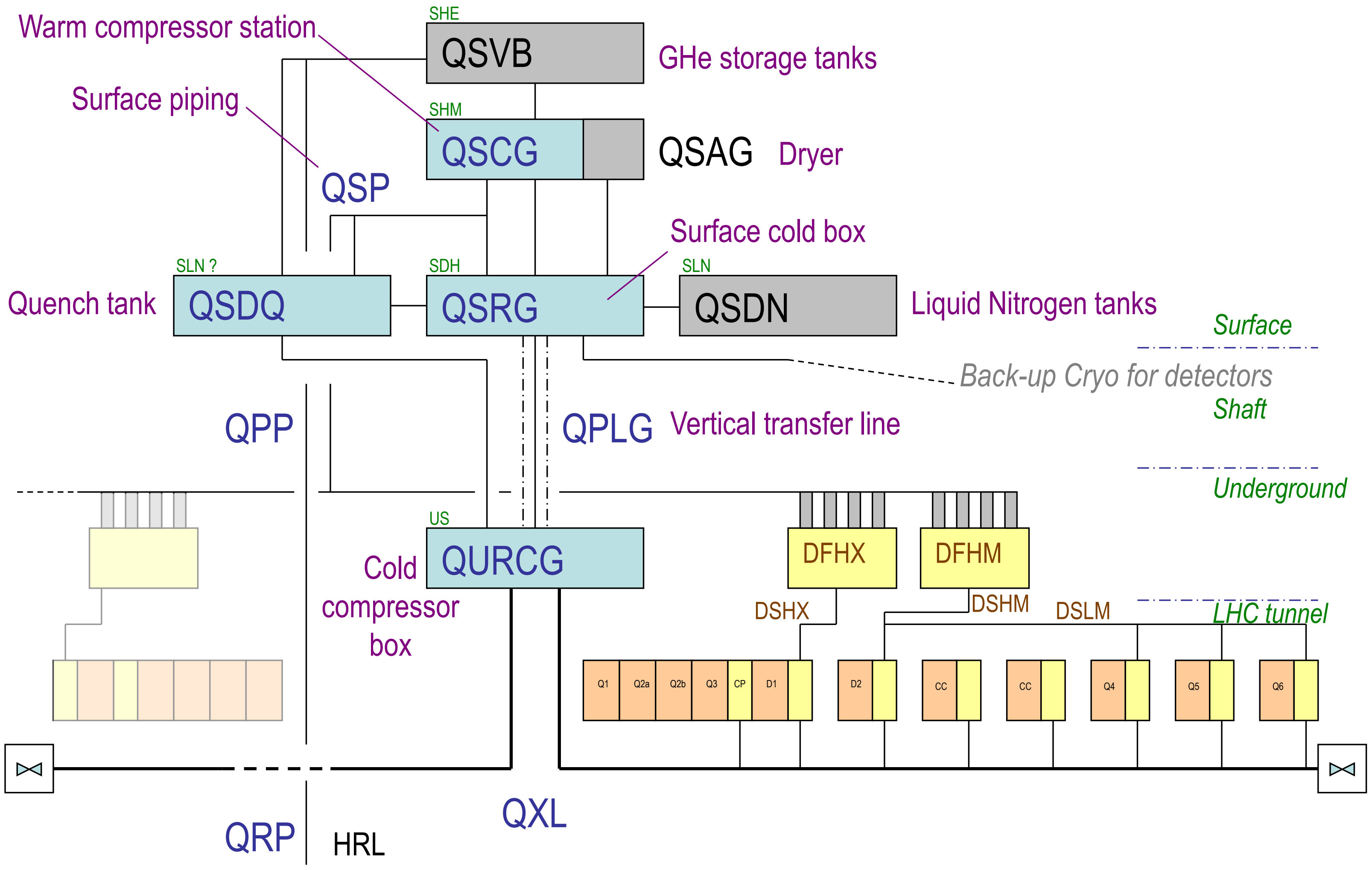
Ph. Lebrun

Overall HL-LHC cryogenic layout



- HL-LHC cryogenic upgrade:
  - 2 new cryoplants (~18 kW @ 4.5 K) at P1 and P5 for high-luminosity insertions.
  - 1 new cryoplant (~4 kW @ 4.5 K) at P4 for SRF cryomodules. (Alternative under study: upgrade of 1 existing LHC cryoplant)

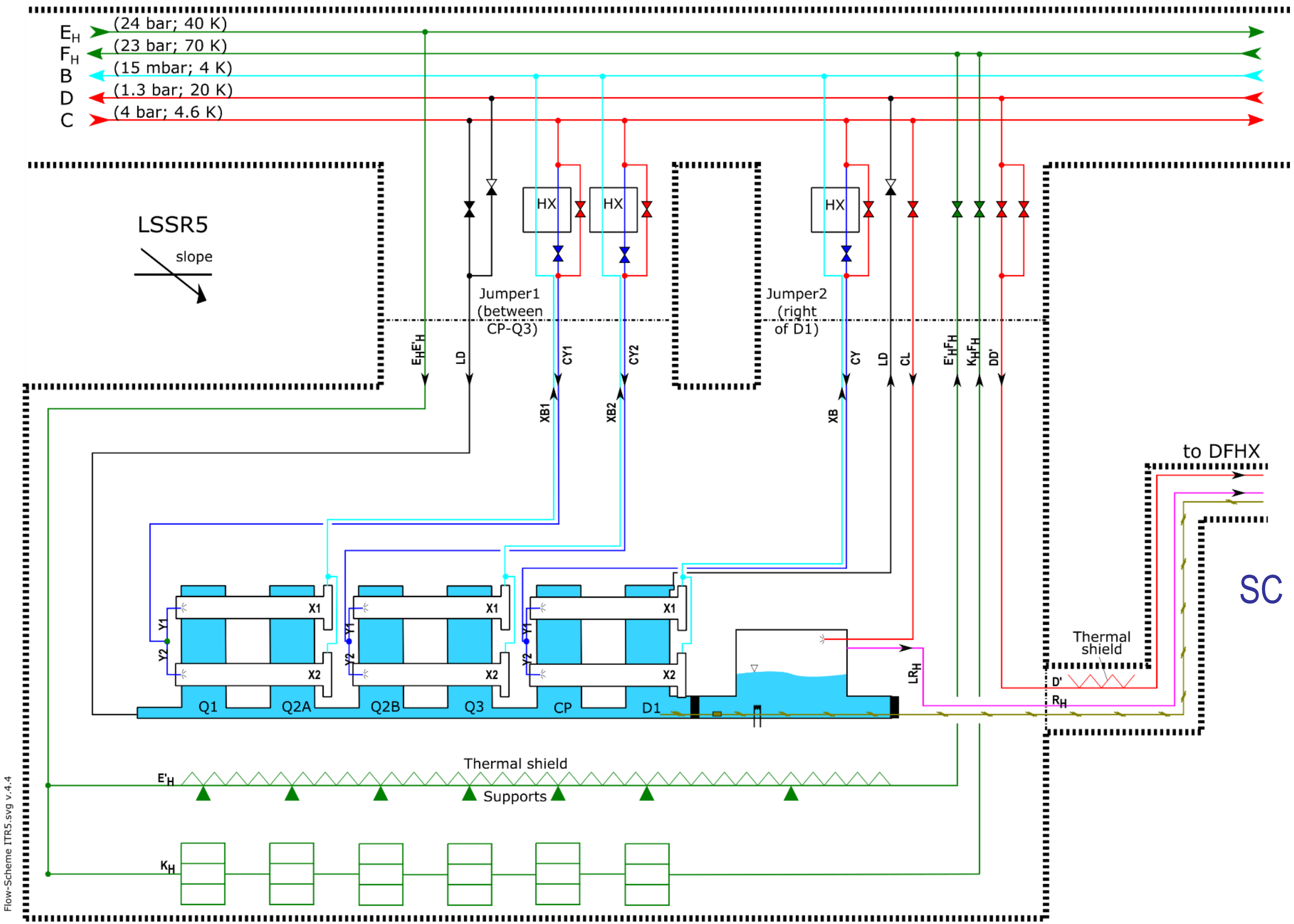
P1/P5 Cryogenic architecture



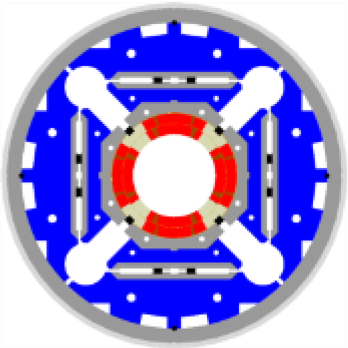
18 kW equivalent at 4.5 K including 3 kW at 1.8 K

Flow diagram IT+D1 - R5

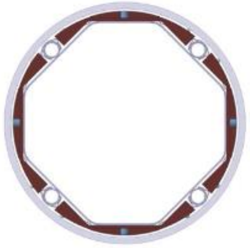
Cryo Line



SC link



Cold Masses



Beam screens (Tungsten shield)

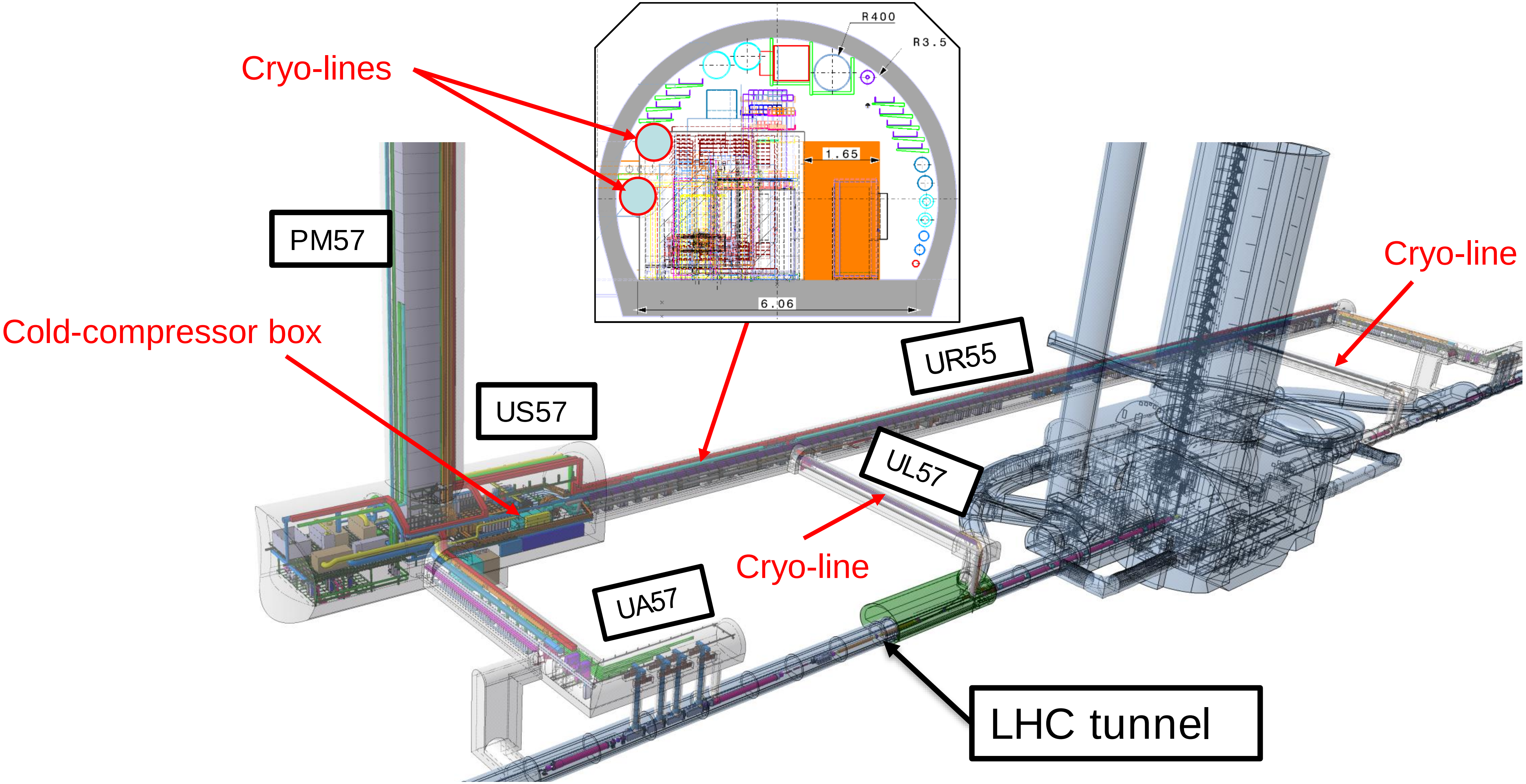
HL-LHC refrigeration capacity at Points 1 & 5

Temperature level	Cooling circuit	Specific heat load [W/m] (Static)	Capacity* / Point		Dynamic range
40-60 K	IT beam screen	16 (0)	3.2 kW	13 kW	~1.3
	Thermal shield	6 (6)	3.6 kW		
	Crab cavity	-	6 kW		
20-300 K	Current lead & SC link	-	40 g/s	40 g/s	~2
4.5-20 K	MS beam screen	2 (0.1)	0.1 kW	0.1 kW	~20
1.9 – 2 K	Cold-mass (1.9 K)	14 (0.35)	2.6 kW	3 kW	~10
	Crab-cavity (2 K)	-	0.4 kW		

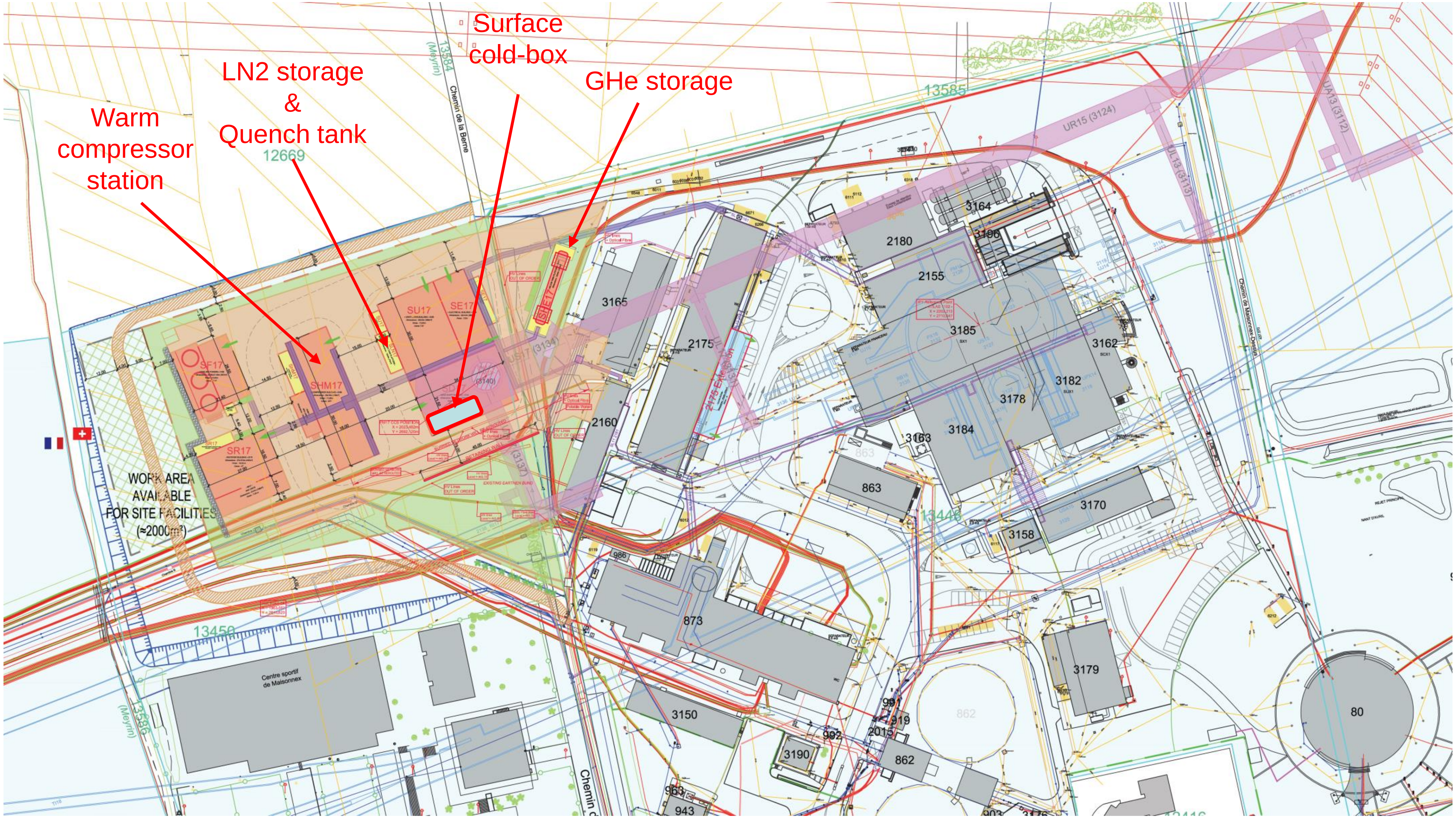
*: Including uncertainty and overcapacity factor

Preliminary

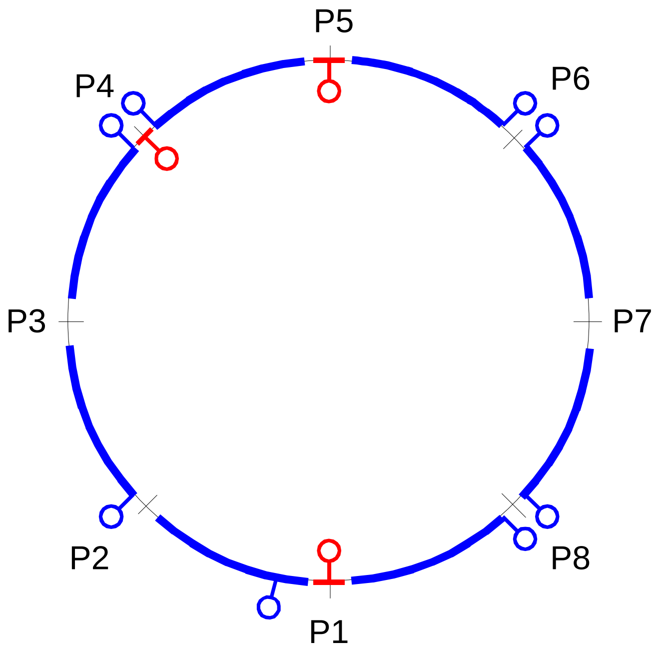
Underground integration at P1 and P5

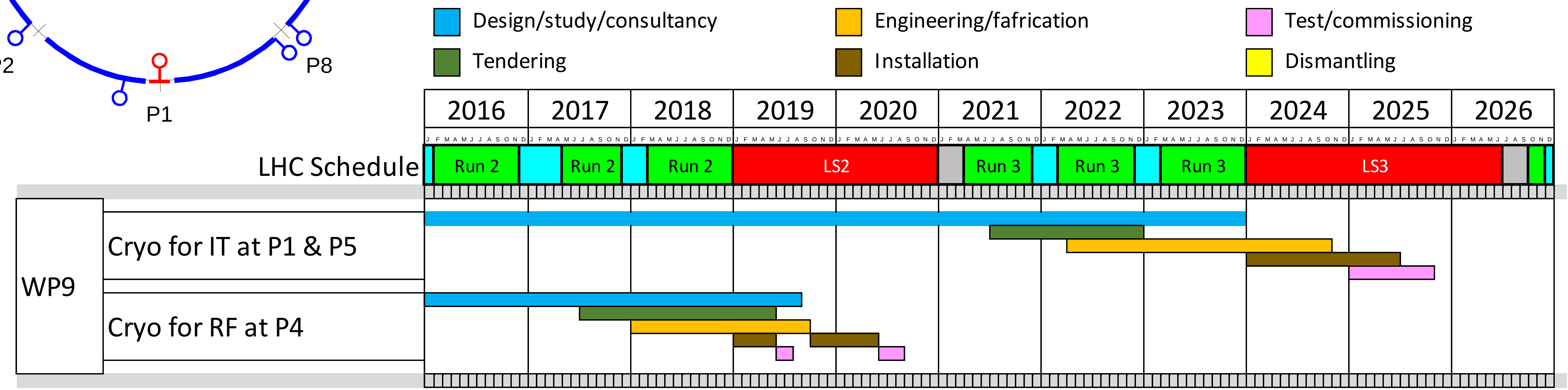


New HL-LHC buildings & surface cryogenics at P1



HL-LHC cryogenics master schedule





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- Future Circular Collider (FCC) cryogenics study

Scope of FCC study

- The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider (FCC-hh) with a centre-of-mass energy of the order of 100 TeV in a new tunnel of 80 - 100 km circumference for the purpose of studying physics at the highest energies.
- The conceptual design study shall also include a lepton collider (FCC-ee) and its detectors, as a potential intermediate step towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered.
- Options for e-p scenarios and their impact on the infrastructure shall be examined at conceptual level.
- The study shall include cost and energy optimisation, industrialisation aspects and provide implementation scenarios, including schedule and cost profiles

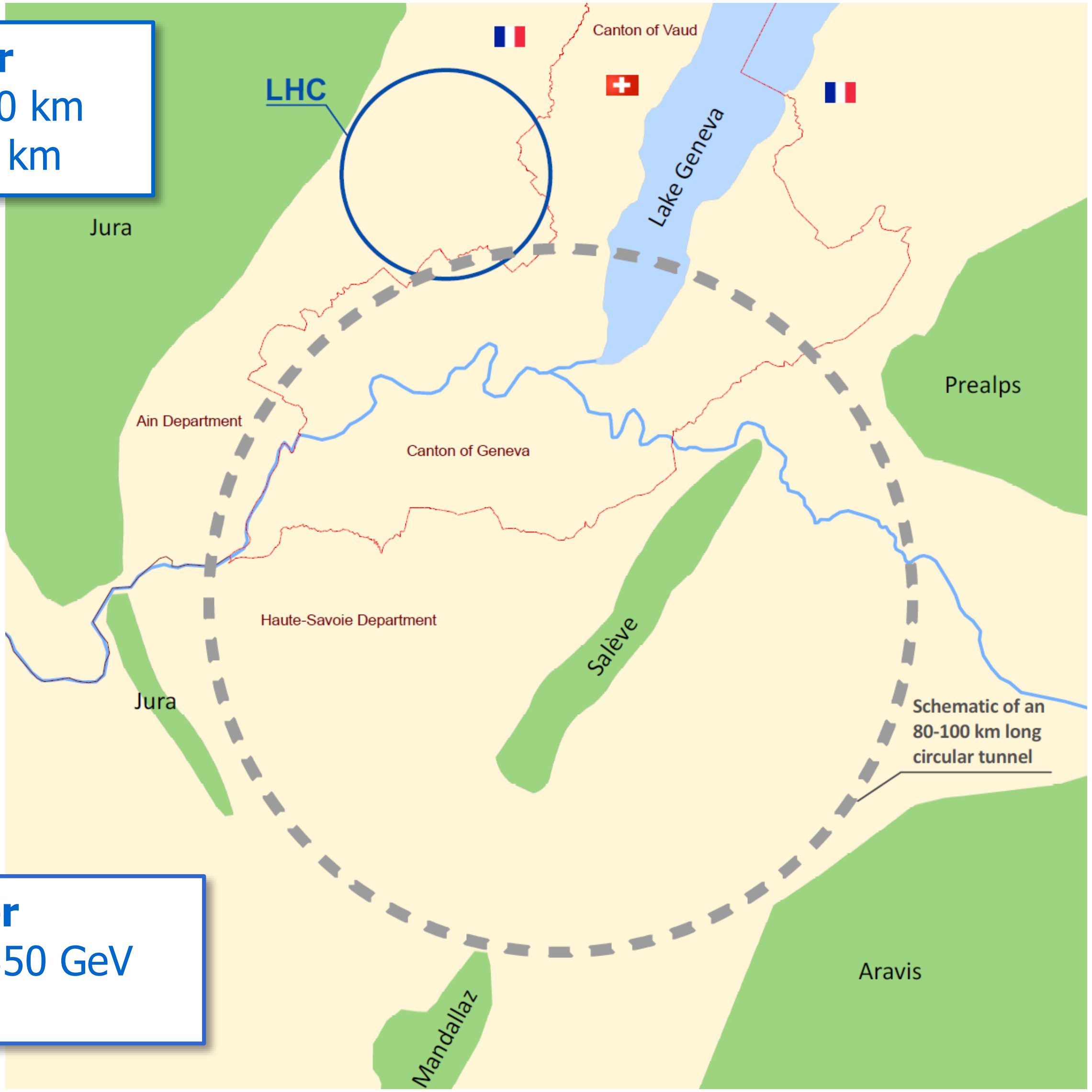
Study of Future Circular Colliders

Quasi-circular tunnel of 80 to 100 km perimeter

Hadron collider

16 T $\Rightarrow$ 100 TeV for 100 km

20 T $\Rightarrow$ 100 TeV for 80 km



e+ e- collider

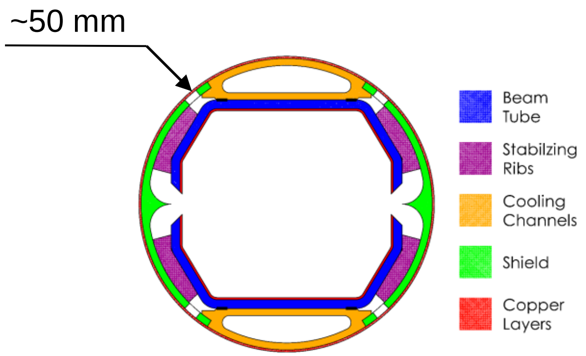
Collision energy 90 to 350 GeV

Very high luminosity

FCC-hh baseline parameters

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	36.7		100 (83)
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]
bunch spacing [ns]	25		25 {5}
events / bunch crossing	**27**	**135**	**170 {34}**
bunch population [10^{11}]	1.15	2.2	1 {0.2}
norm. transverse emitt. [μm]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

Nb_3Sn SC magnets cooled at 1.9 K



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

FCC-hh refrigeration capacity (10-km sectors)

Temperature level	Cooling circuit	Specific heat load [W/m] (Static)	Capacity / Sector (~10 km)	Dynamic range
40-60 K	Beam screen	64 (0)	530 kW	~6
	Thermal shield	9 (9)	90 kW	
40-300 K	Current lead	-	85 g/s	~2
1.9 K	Cold-mass	1.4 (0.45)	12 kW	~3

- Large cooling capacity required above 40 K → new for particle accelerators
- Large dynamic range required above 40 K (factor ~6) → new for particle accelerators
→ Special effort to develop an efficient and flexible 300-40 K refrigeration cycle.

- Large cooling capacity at 1.9 K (factor 5 w/r to LHC)
→ Special effort to develop large and efficient 1.8-K refrigeration cycle .

CEA Grenoble
TU Dresden

Siting study 93 km perimeter

PRELIMINARY

Alignment | Shaft Tools

Choose alignment option: 93km quasi-circular

Tunnel depth at centre: 286mASL

Gradient Parameters

- Azimuth (°): -15
- Slope Angle x-x(%): .3
- Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2498923 Y: 1106695

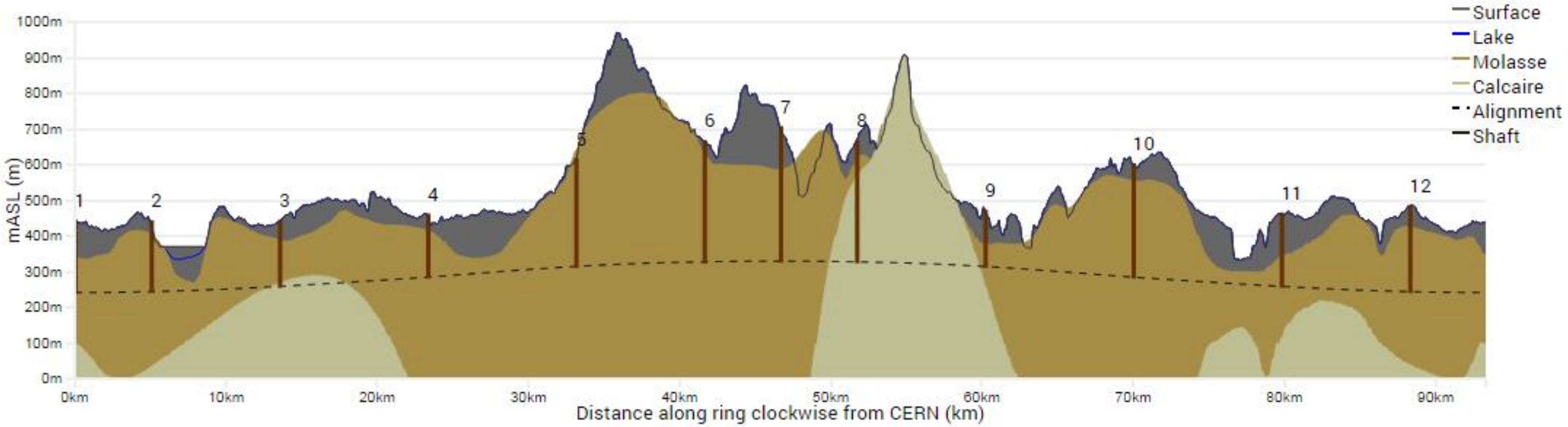
LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

Alignment Location

Geology Intersected by Shafts | Shaft Depths

Shaft	Shaft Depth (m) Actual	Min	Mean	Max	Geology (m) Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile



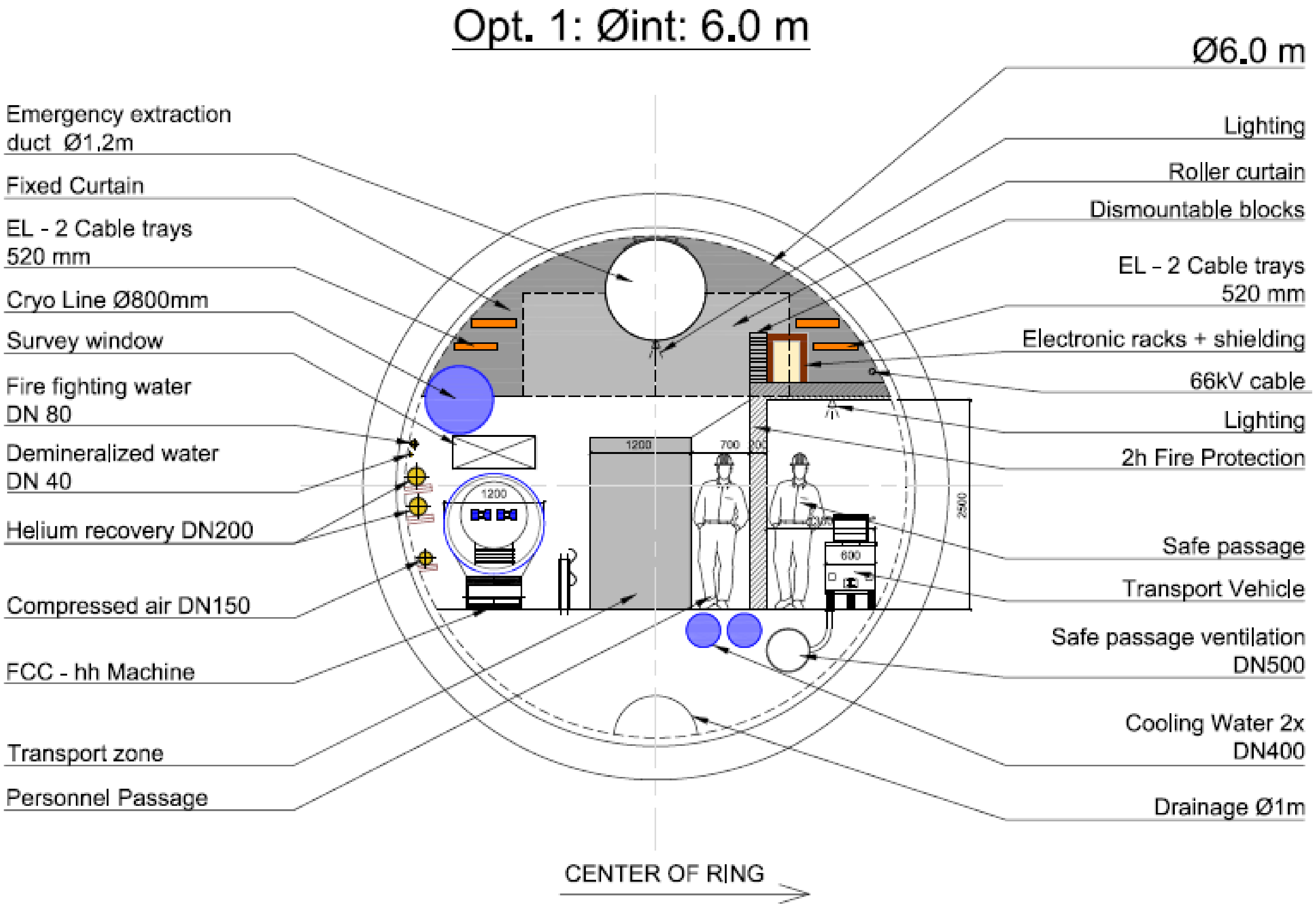
Maximum slope up to 3 % (1.4 % for LHC)

Shaft depths up to 400 m! (~150 m for LHC)

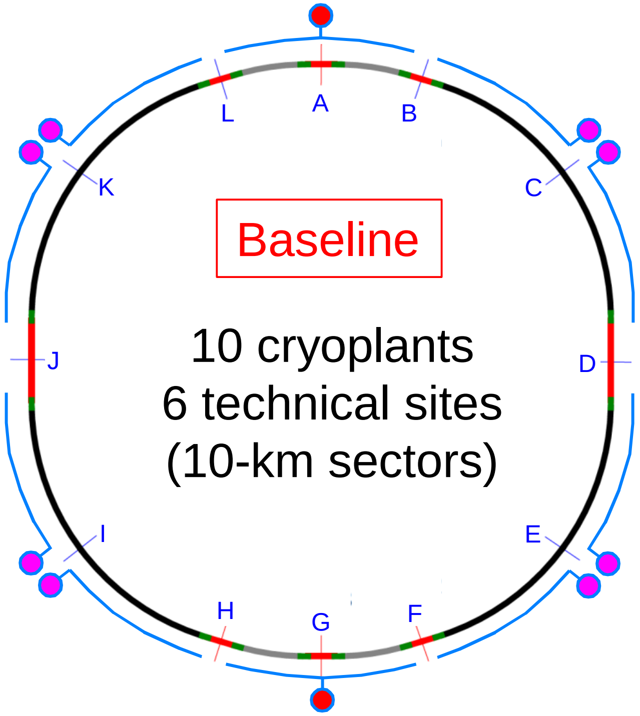
J. Osborne & C. Cook

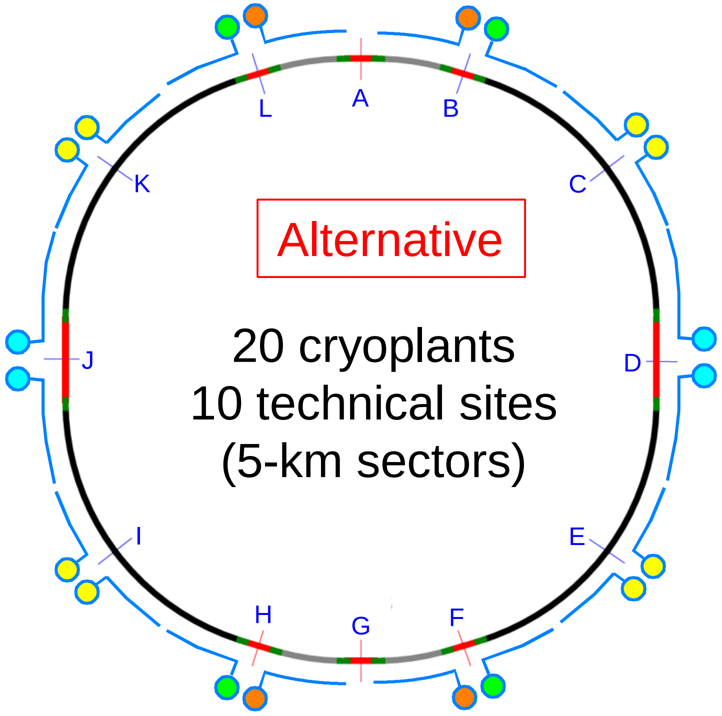
FCC-hh arcs

Single tunnel



FCC-hh (100 km) cryogenic layout





Cryoplant	40-60 K [kW]	1.9 K [kW]	40-300 K [g/s]
●	592	11	85
●	616	12	85

Without operational margin !

Cryoplant	40-60 K [kW]	1.9 K [kW]	40-300 K [g/s]
●	296	5.7	43
●	325	6.2	43
●	293	5.6	43
●	331	6.4	43

FCC-hh cryoplant architecture

300-40 K cryoplant

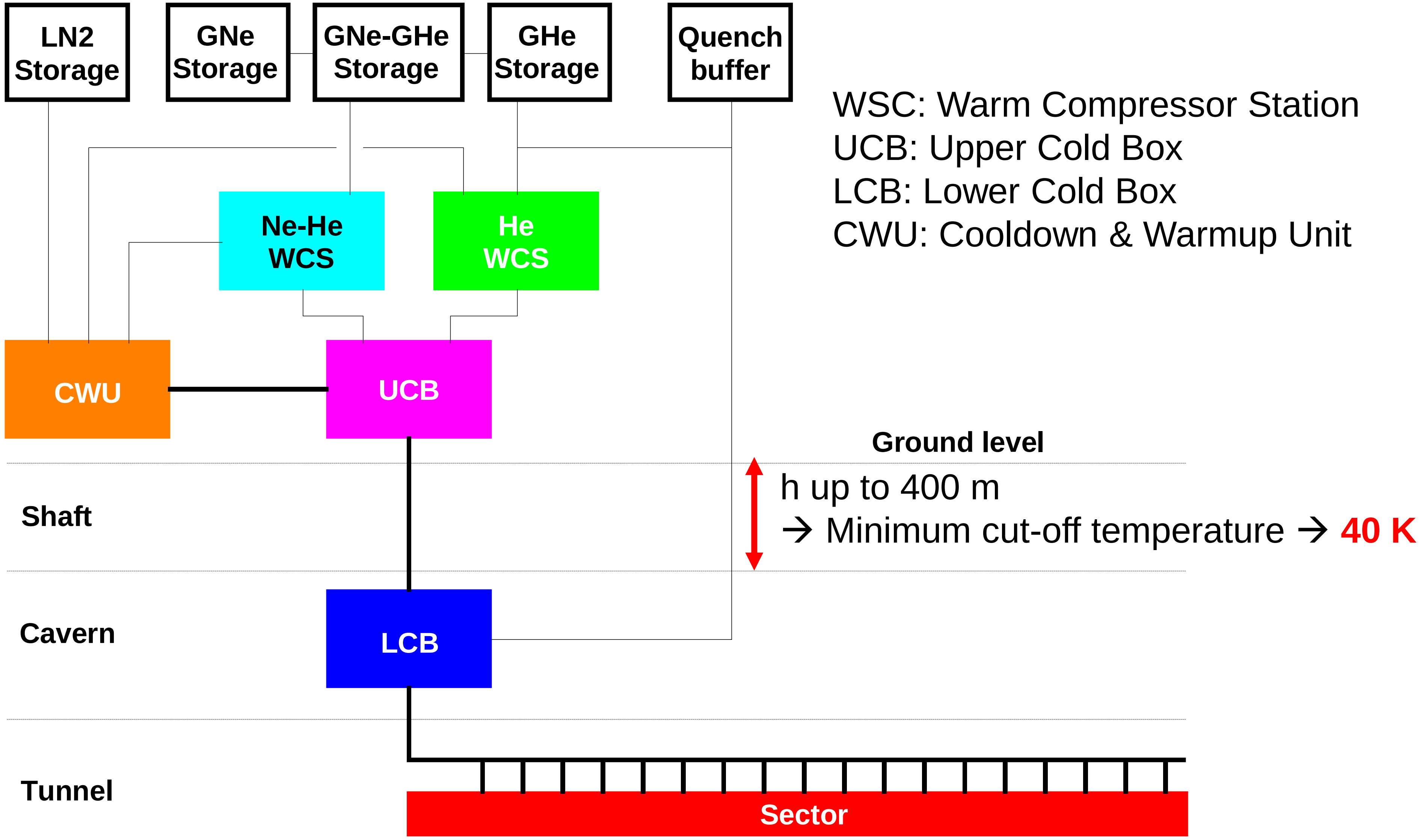
- Beam screen (40-60 K)
- Thermal shield (40-60 K)
- Current leads (40-300 K)
- Precooling of 1.9 K cryoplant

1.9 K cryoplant

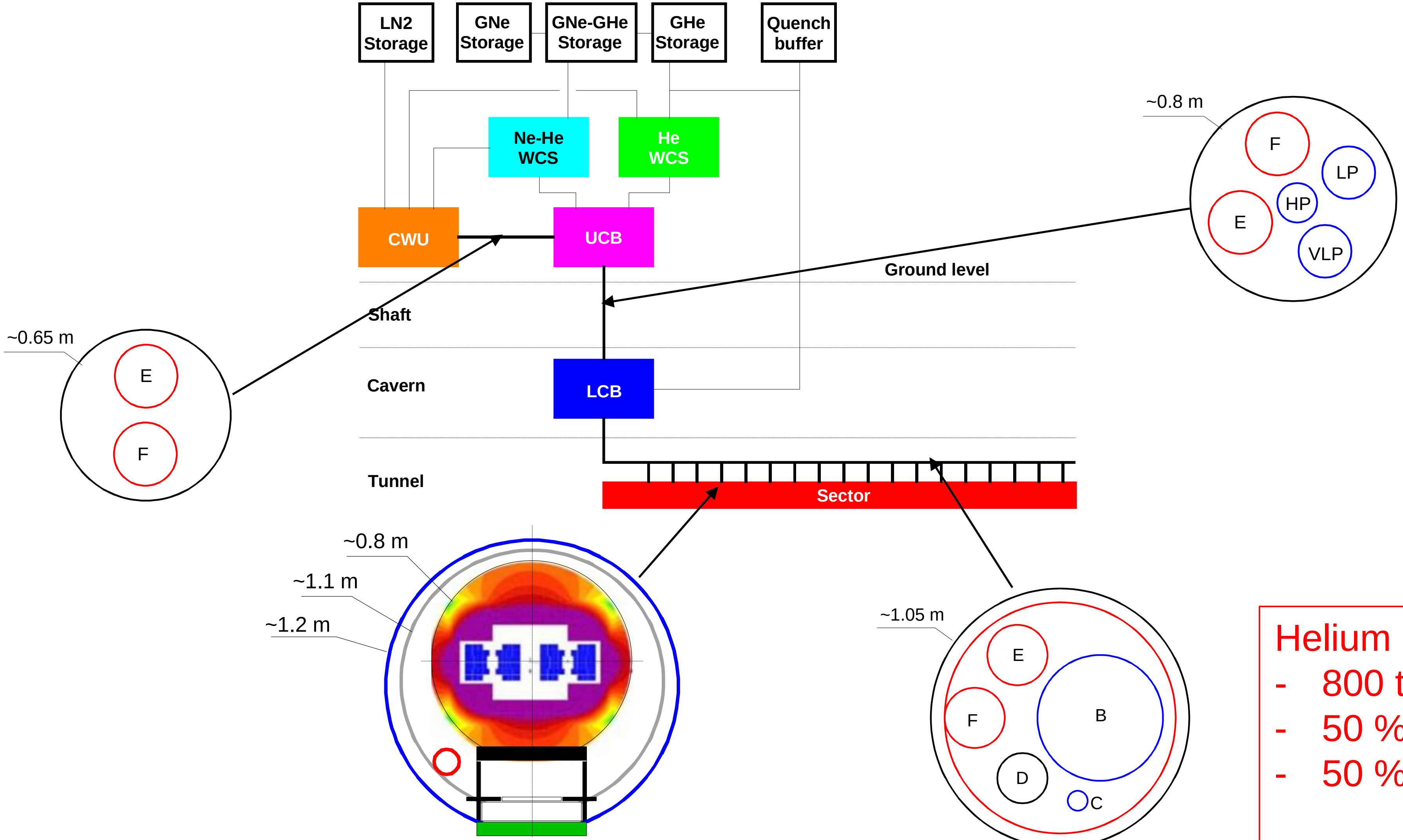
- SC magnet cold mass

Cryogenics architecture

WSC: Warm Compressor Station
UCB: Upper Cold Box
LCB: Lower Cold Box
CWU: Cooldown & Warmup Unit



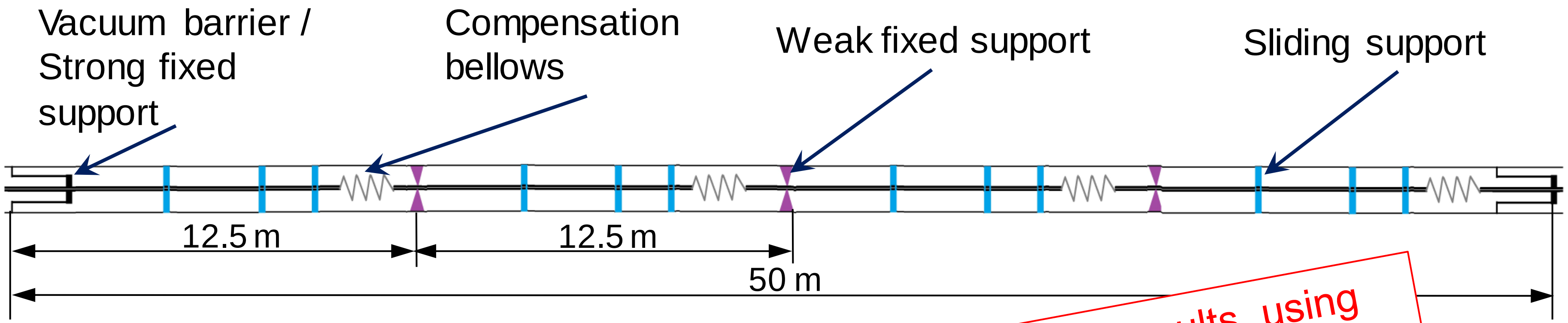
FCC-hh Cryo-distribution and helium inventory



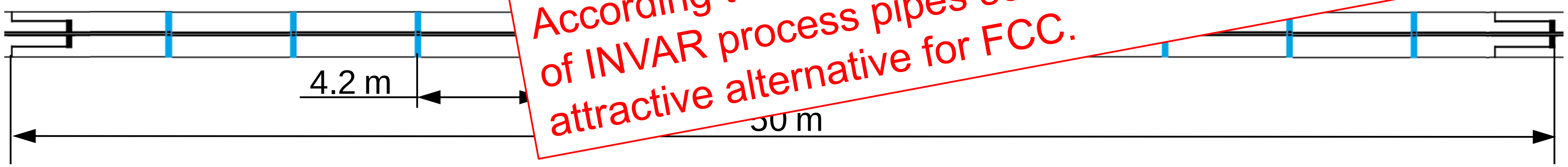
Helium inventory:

- 800 t (6 LHC He inventory)
- 50 % in magnet cold-mass
- 50 % in cryo-distribution

Cryo-distribution: impact of higher design pressure and material



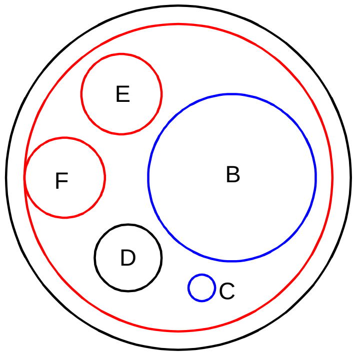
Conventional design in stainless steel (S-S) with compensation bellows



According to the first preliminary results, using of INVAR process pipes seems to be a very attractive alternative for FCC.

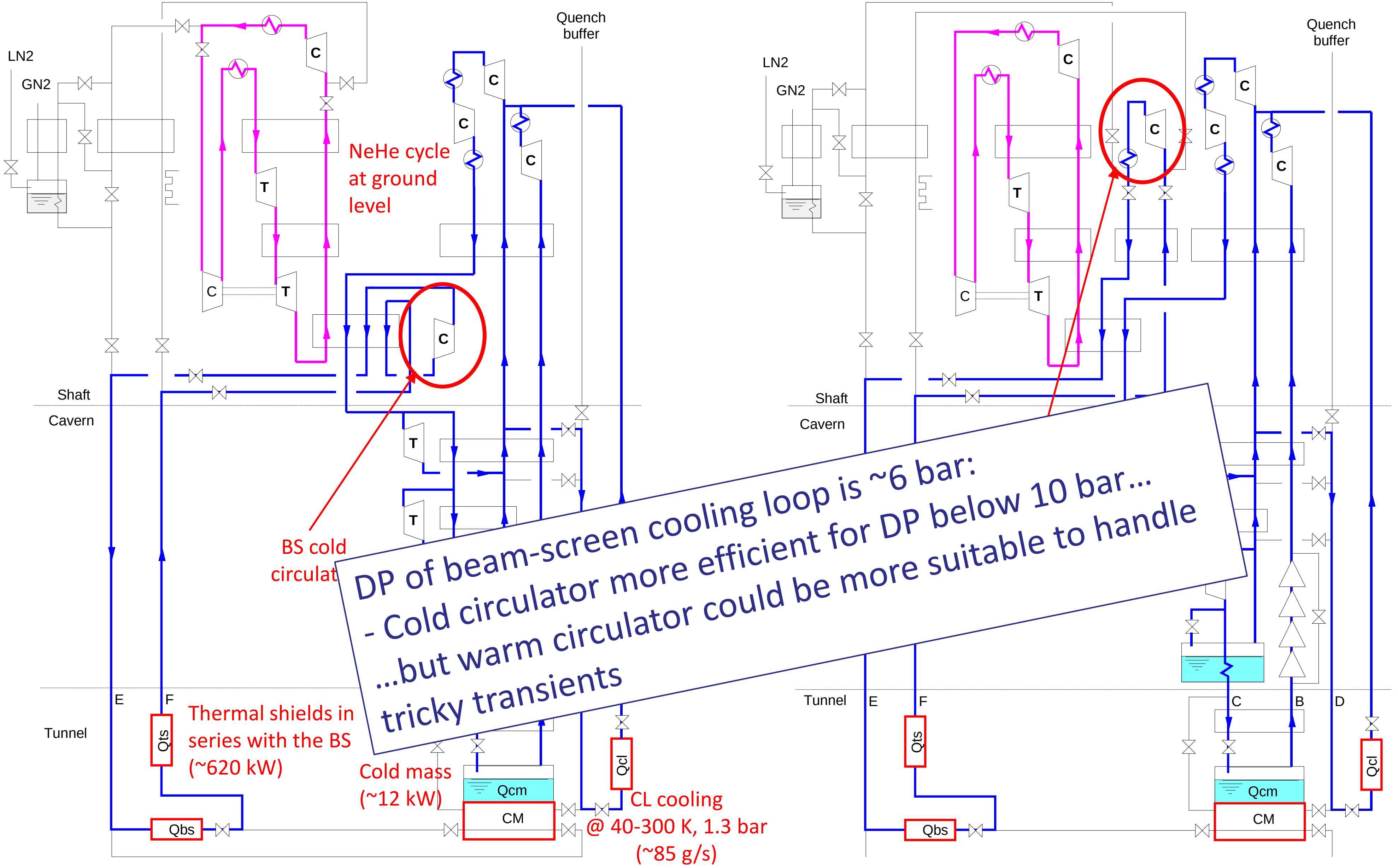
Advanced design in INVAR (Iron-Nickel alloy)

Study case	Design Pressure [bar]		
	B	C & D	E & F
1. S-S + bellows	4	20	20
2. S-S + bellows	4	20	50
3. INVAR	4	20	50



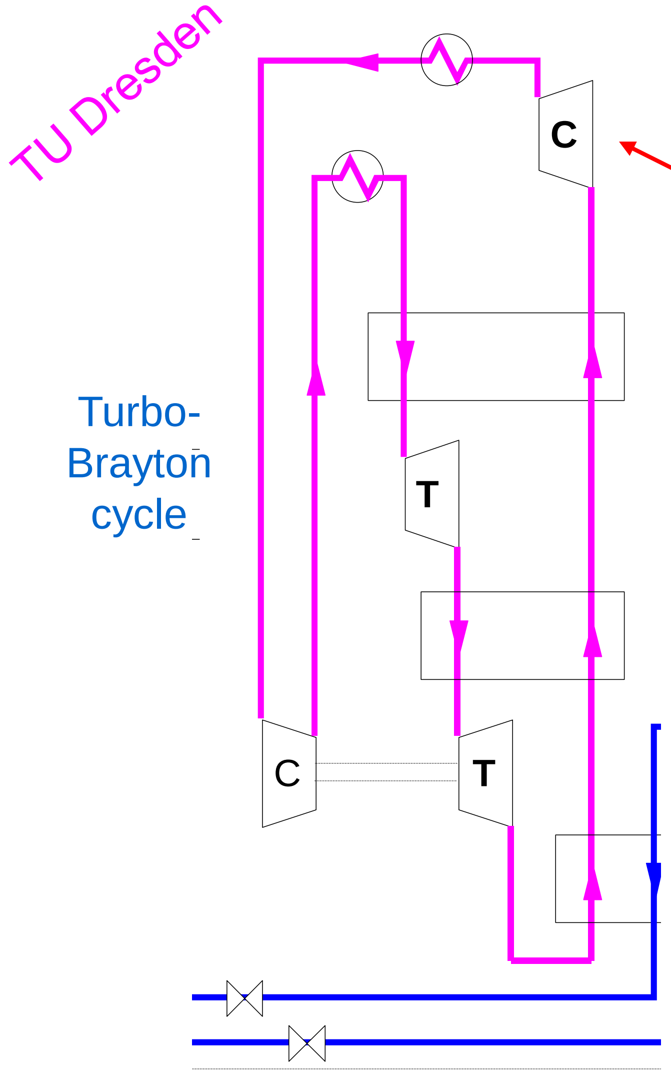
Wroclaw TU

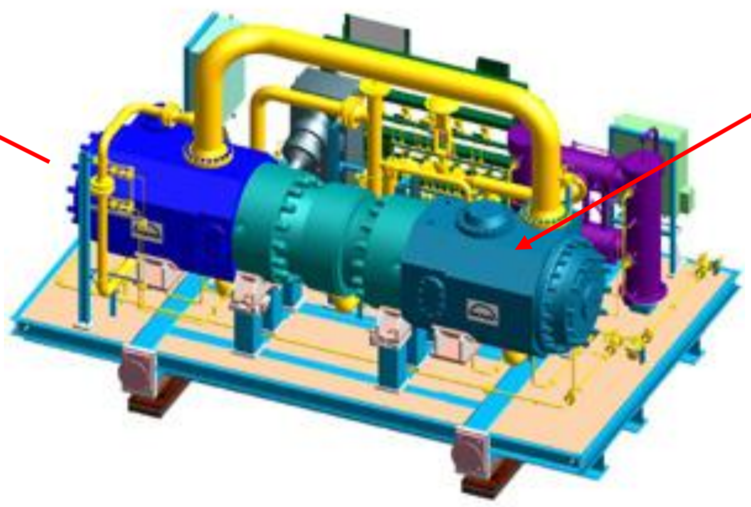
Process flow diagram: Nominal operation



DP of beam-screen cooling loop is ~6 bar:
- Cold circulator more efficient for DP below 10 bar…
…but warm circulator could be more suitable to handle tricky transients

Ne-He cycle: 700-800 kW between 40 and 60 K





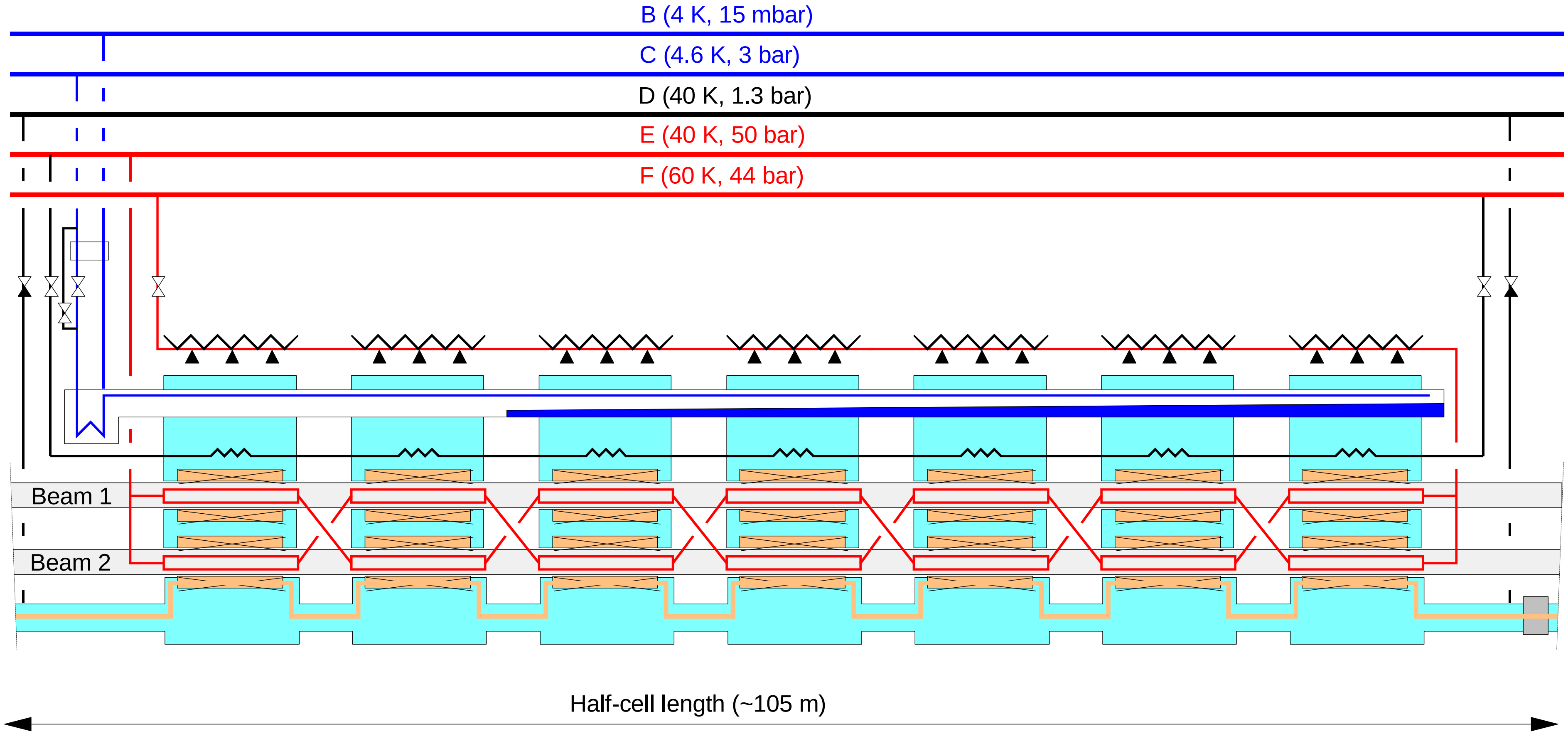
Courtesy of MAN Diesel & Turbo

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 monoatomic 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 %**

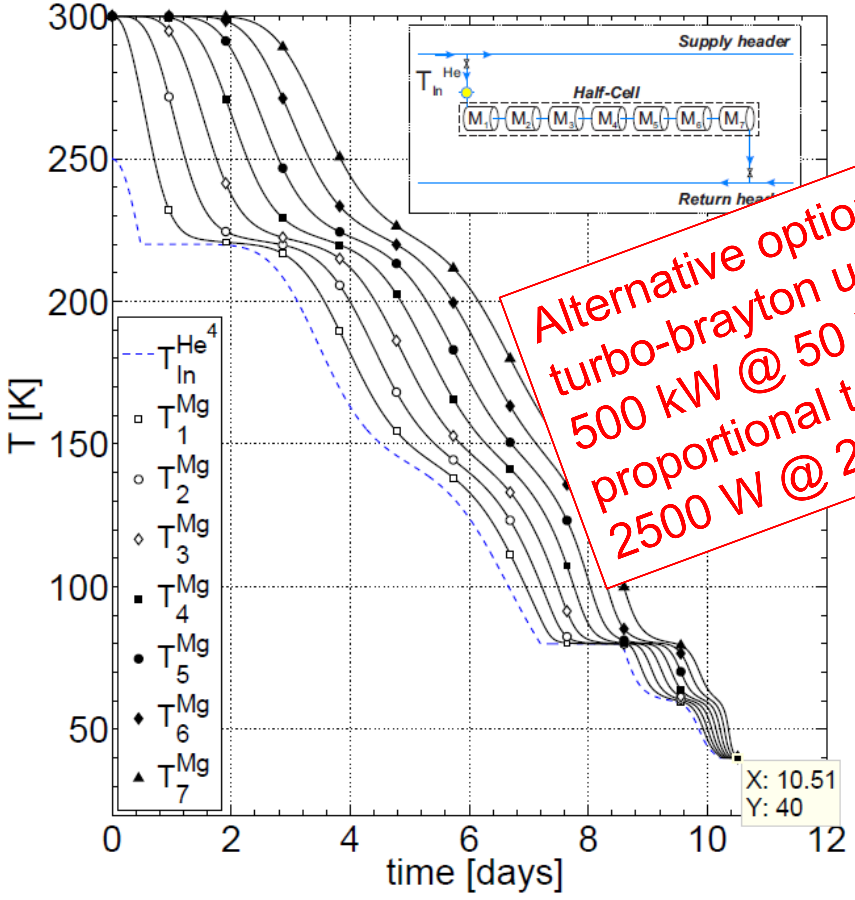
Half-cell cooling loop

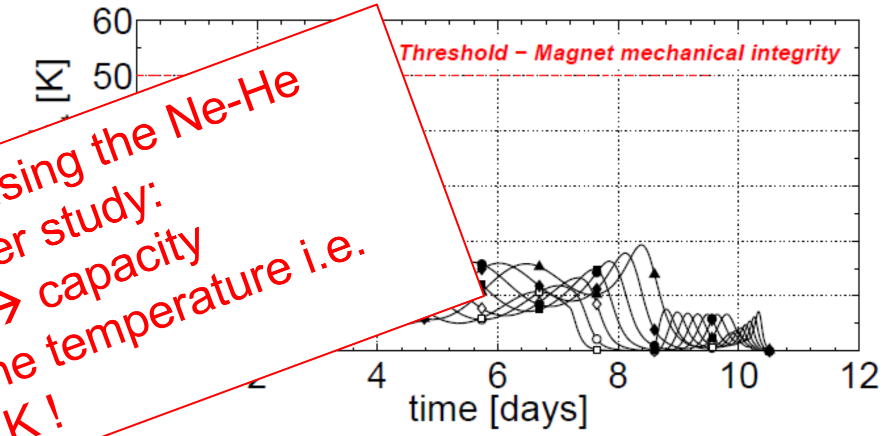
Superfluid He cooling “à la LHC”

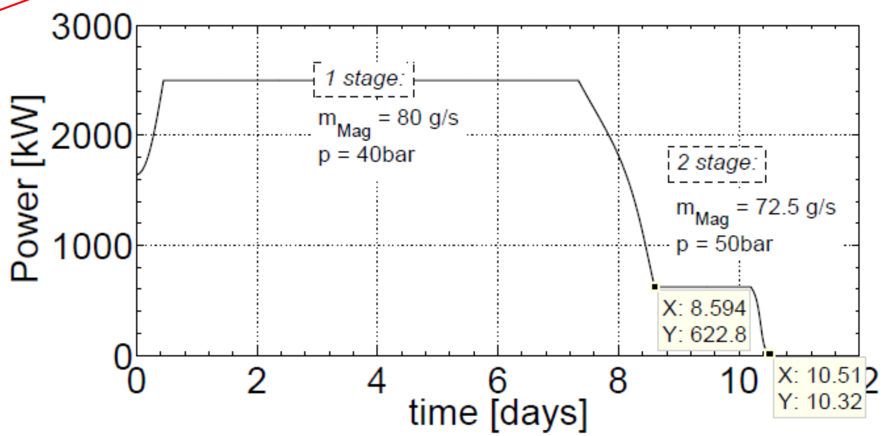


- Separate circuit for indirect cool-down and warm-up (no impact on the CM design pressure)
- Bayonet heat exchanger for Liquid-liquid LHe II
- Thermal shield and heat intercepts on the return headers
- Safety/quench valve spacing : ~100 m (to be validated → ~40 MJ per magnets)
- Cold quench buffer (Header D) at 40 K (to be validated (LHC @ 20 K))

FCC-hh cool-down





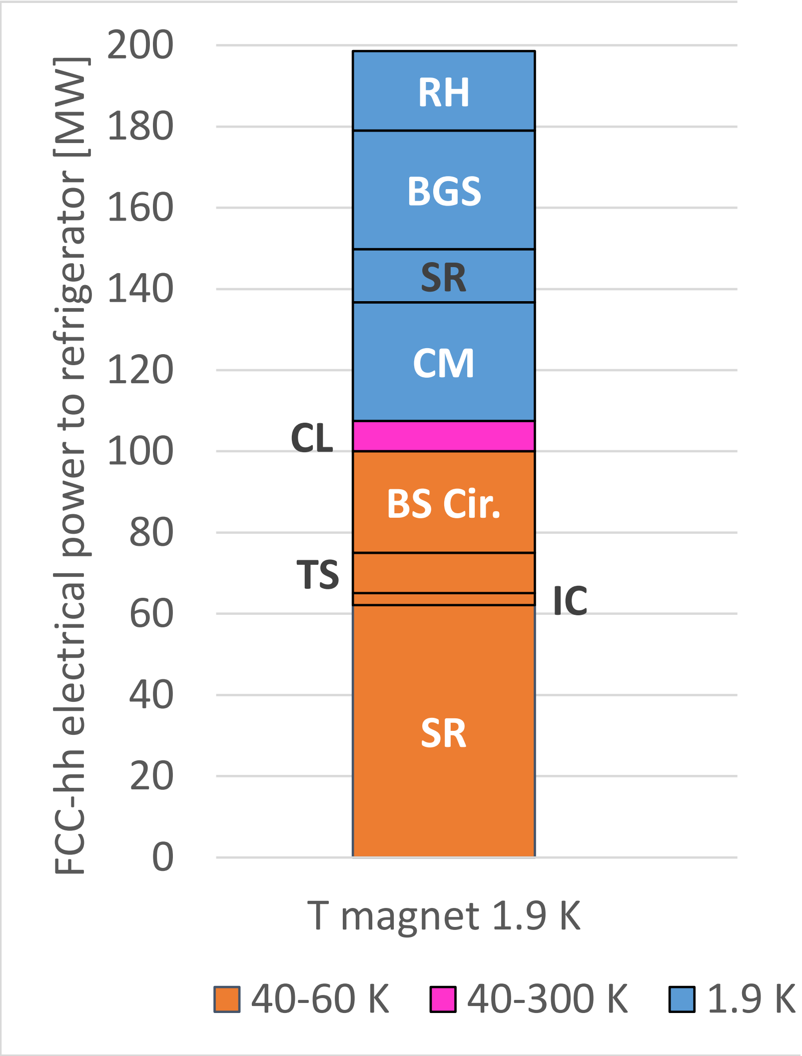


Alternative option using the Ne-He turbo-brayton under study:
500 kW @ 50 K → capacity proportional to the temperature i.e.
2500 W @ 250 K !

H. Rodrigues

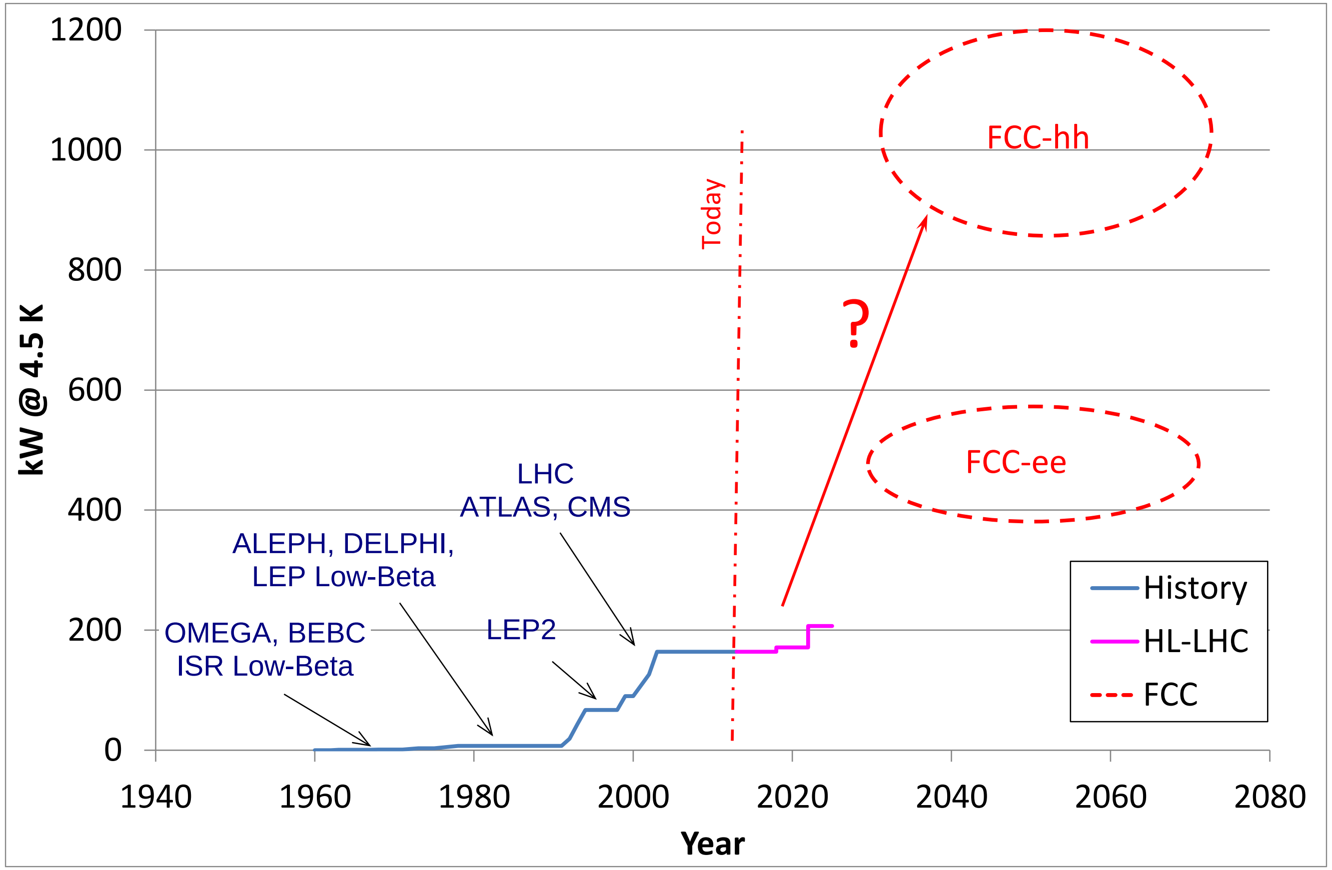
FCC-hh cooldown:
44500 t of LN2
~ 6 Globes of Science and Innovation

FCC-hh cryogenic electrical consumption

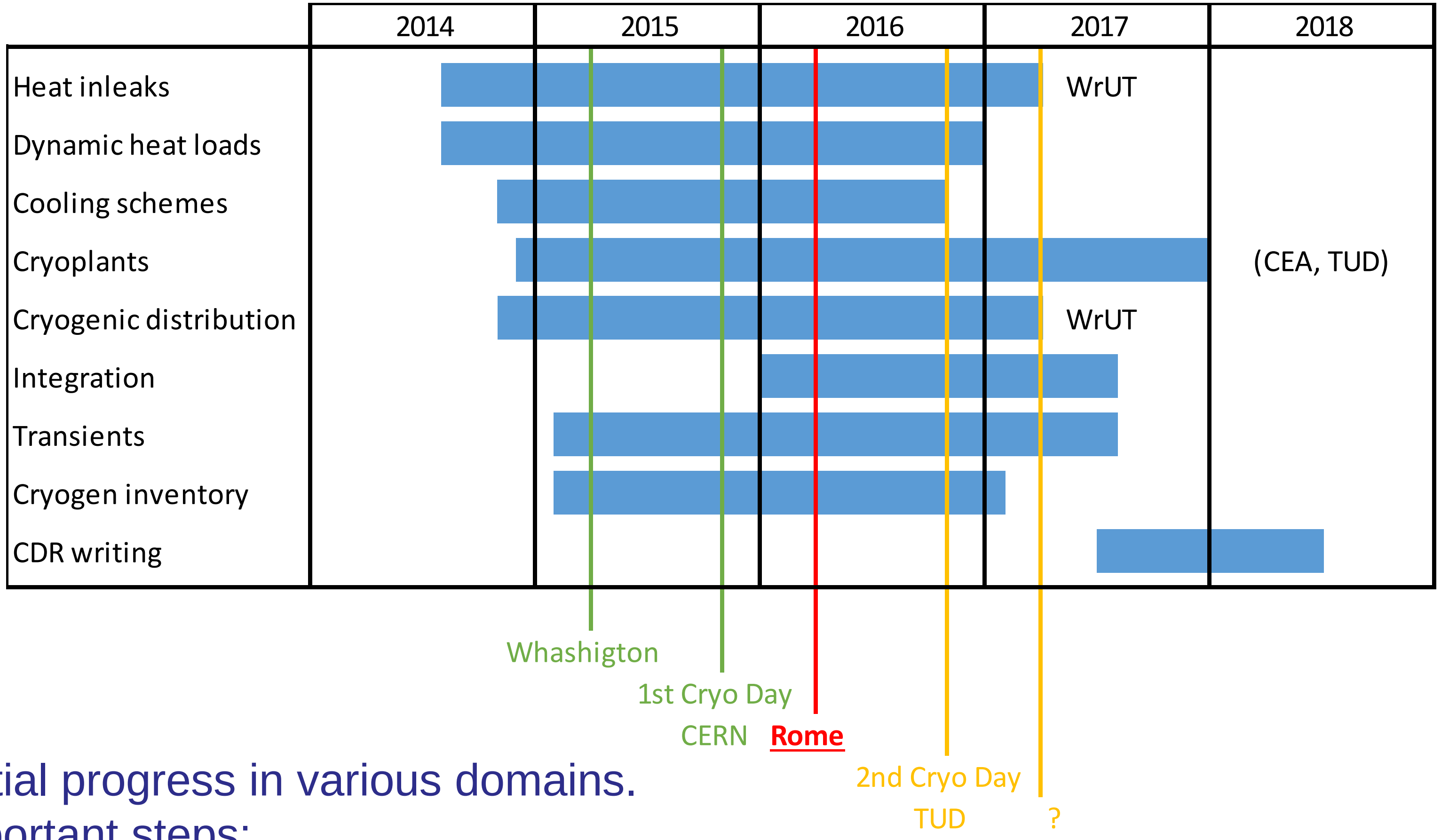


RH: resistive heating
BGS: beam-gas scattering
CM: cold mass heat-inleaks
CL: current lead
BS cir.: Beam screen circulator
TS: thermal shield
IC: image current
SR: synchrotron radiation

FCC study: Towards 1 MW at 4.5 K !



Conclusion: FCC cryogenics study schedule



Substantial progress in various domains.

Next important steps:

- Cryoplant studies by industrial partners (Air Liquide & Linde)
- Beam-screen transient → local and global controls strategy
- Quench discharge and recovery (impact on CM design pressure and # of quench valves)
- Distribution system (heat in-leaks, INVAR option)

FCC study

MoU status on 21 January 2015

44 collaboration members

ALBA/CELLS, Spain
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA

EPFL, Switzerland
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Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey

JAI/Oxford, UK
JINR Dubna, Russia
KEK, Japan
KIAS, Korea
King’s College London, UK
Korea U Sejong, Korea
MEPhI, Russia
Northern Illinois U., USA
NC PHEP Minsk, Belarus
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
Wroclaw TU, Poland

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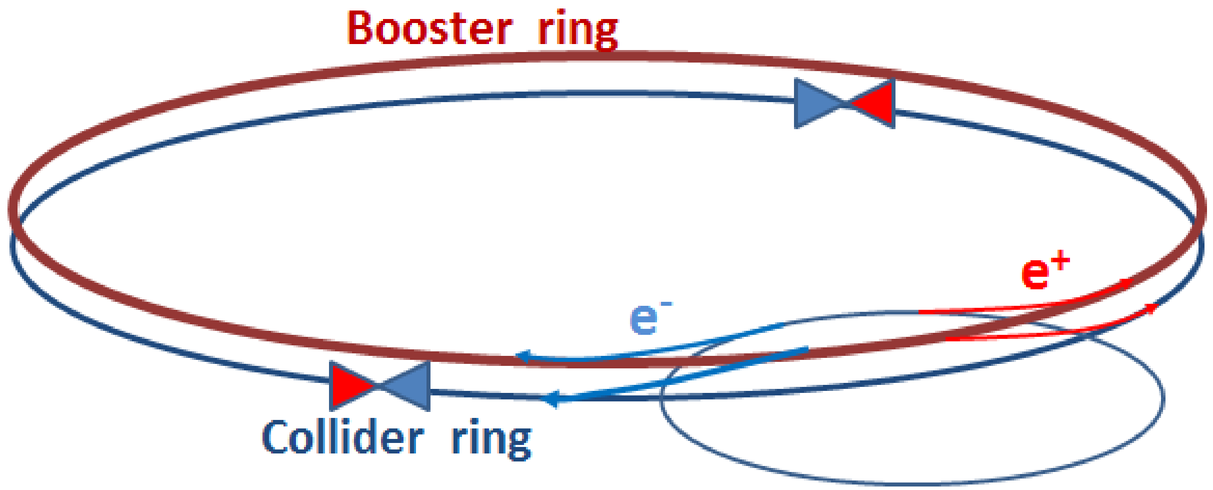
Thank you for your attention!

FCC-ee design targets

- Aiming for very high luminosity: high beam current, small beam size
- Luminosity at each energy limited by synchrotron radiation from the beams, limit 50 MW per beam
- highest possible luminosity for a wide physics program ranging from the Z pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & G_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV

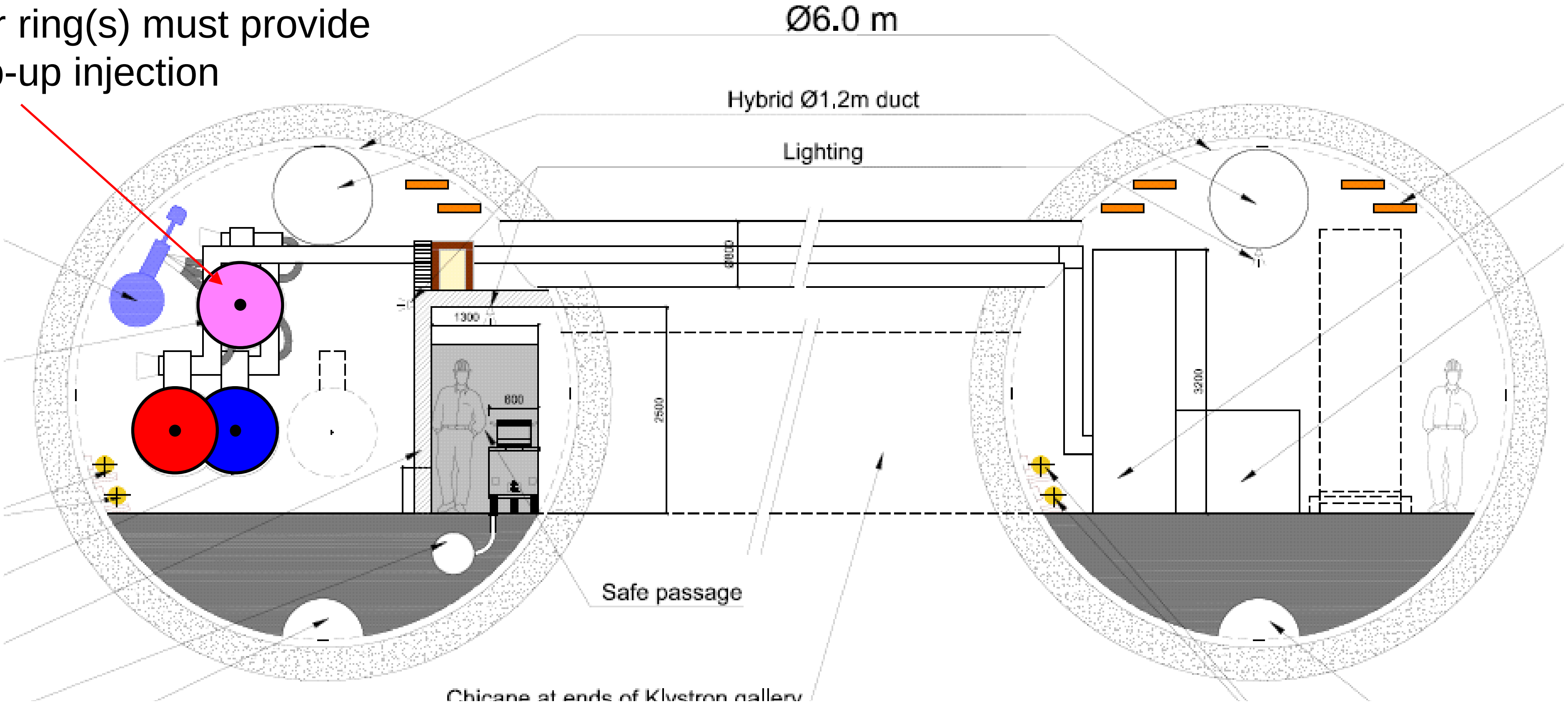
FCC-ee top-up injection

- In view of the low luminosity lifetime, a booster of the same size (same tunnel) as the collider ring(s) must provide beams for top-up injection
  - same RF voltage, but low power (~ MW)
  - top up frequency ~ 0.1 Hz
  - booster injection energy ~5-20 GeV
  - bypass around the experiments



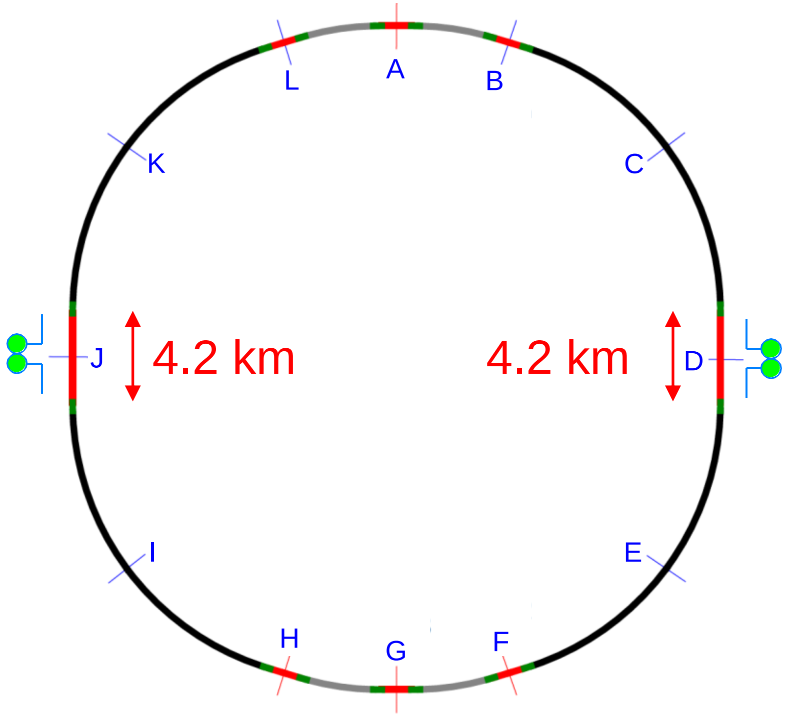
FCC-ee RF straight section

In view of the low luminosity lifetime, a booster of the same size (same tunnel) as the collider ring(s) must provide beams for top-up injection



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

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



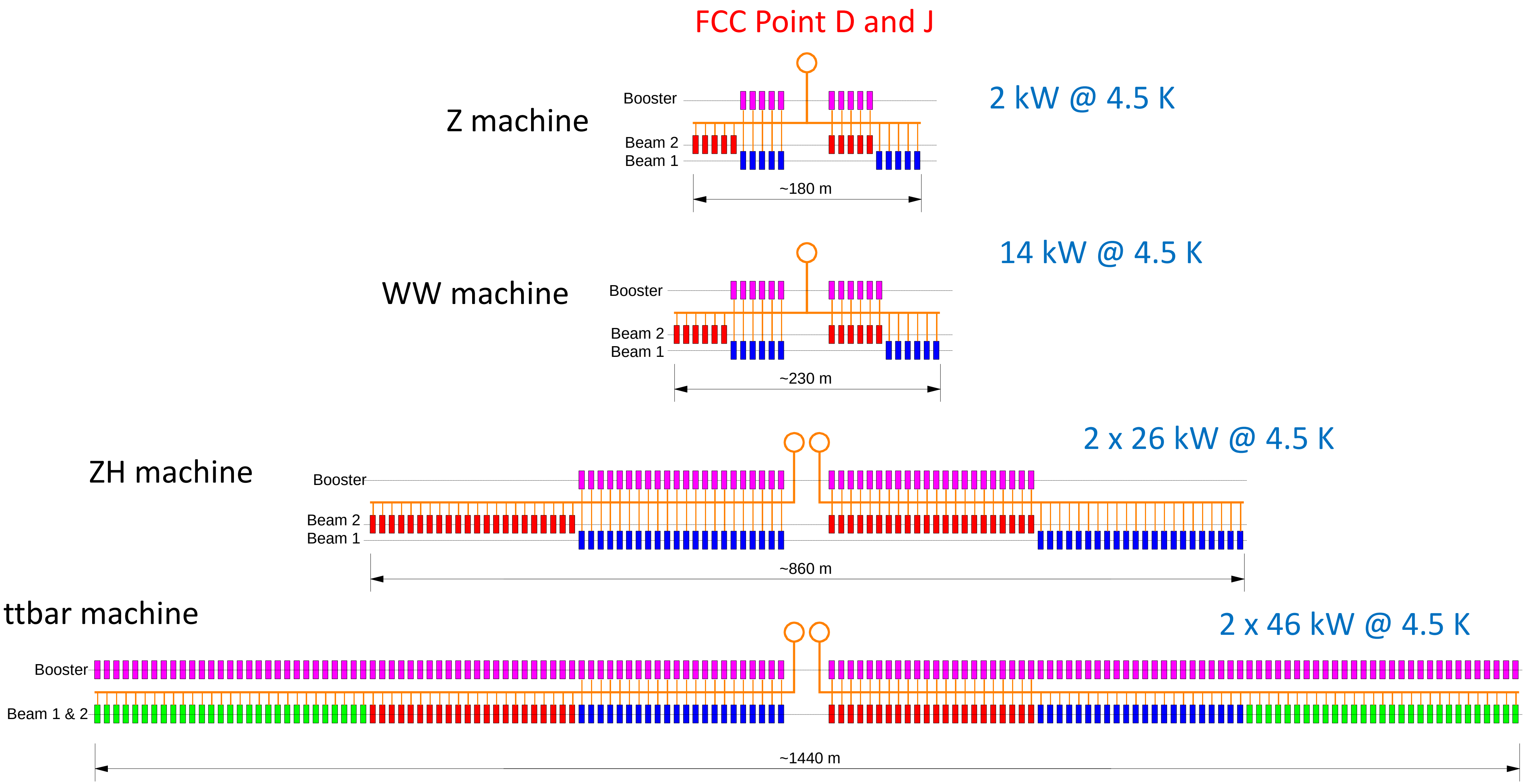
Basic input:

- RF-cavity modules installed in the extended straight sections (ESS at Points J and D)
- Baseline: 1-2 cells, 400 MHz RF cavities @ 4.5 K with Q0= 3.1 E9
- Qstat: 5 W/m (main rings and booster ring)
- Qdyn for booster ring: 10 % of one main ring

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)

*: Outside State-of-the-Art

FCC-ee: Cryogenic layout



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

FCC-ee: Cryogenics electrical consumption