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UPDATE ON THE CRYOGENIC DESIGN FOR THE FCC-EE MACHINE

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Introduction

Topics developed throughout the talk

1. Reminder: *CDR cryo design (now obsolete)* for the –ee machine (layout, cryo points location, heat loads from RF)

2. Recent *update on the layout* and on the heat loads from the RF / impact on the cryo design in terms of integration, cooling needs and infrastructures modification / proposed solutions

3. Upcoming *objectives and tentative timeline* to issue the feasibility report by end of 2025

4. Spare slides: quick availability study for the –hh configuration

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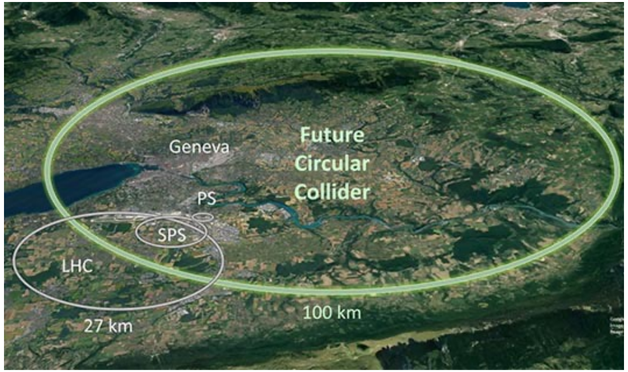
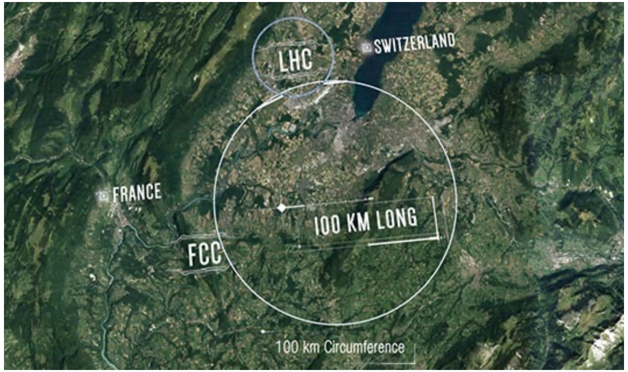




FCC-ee conceptual design

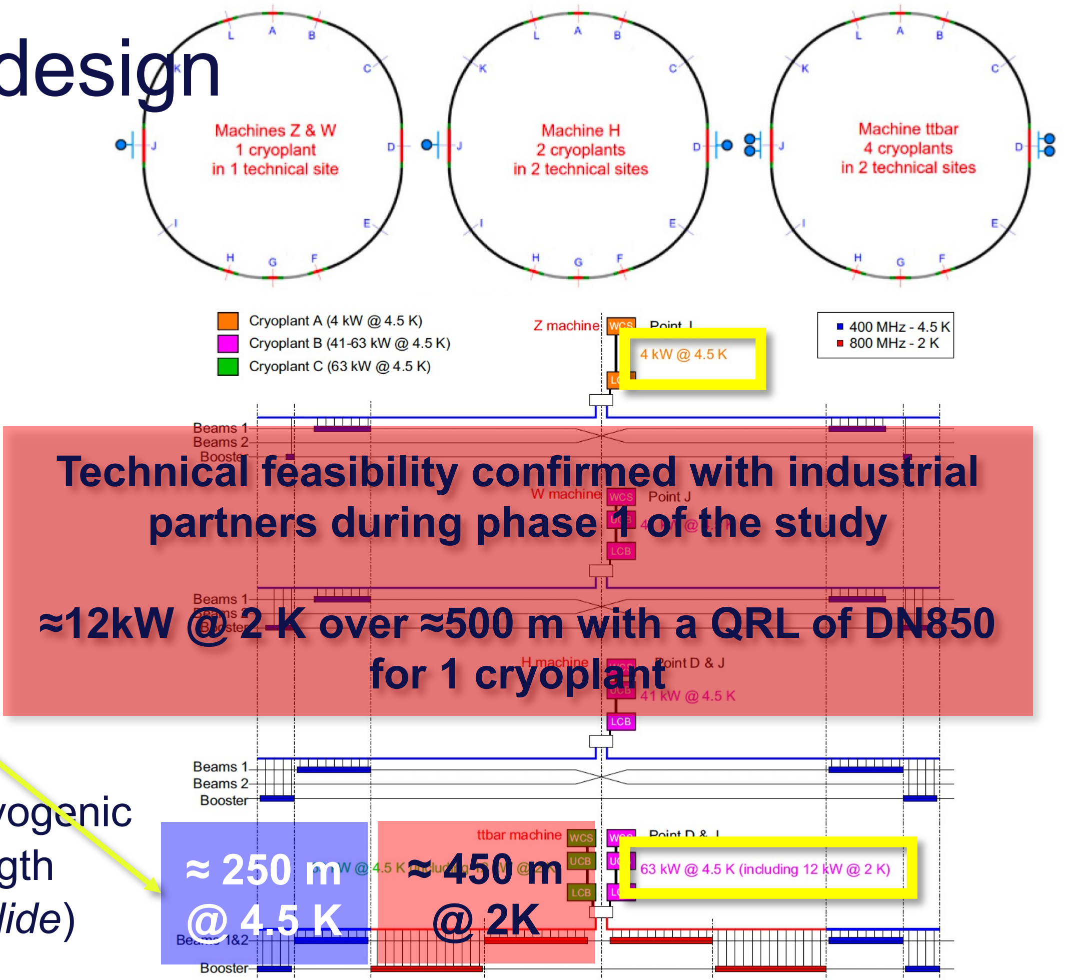
General layout of the cryogenic system

- <u>Refrigeration plants wrt machine</u>
  - Z, W: 1 cryoplant
  - H: 2 cryoplants
  - ttbar: 4 cryoplants

- <u>Technical sites wrt machine</u>
  - Z, W: 1 technical site
  - H, ttbar: 2 technical sites

Half-LSS of 700 m

- <u>SRF straight sections in PD & PJ</u>
  - Each of them 1.4 km long i.e. cryogenic distribution on the equivalent length
  - “Staging” of the QRL (*see next slide*)



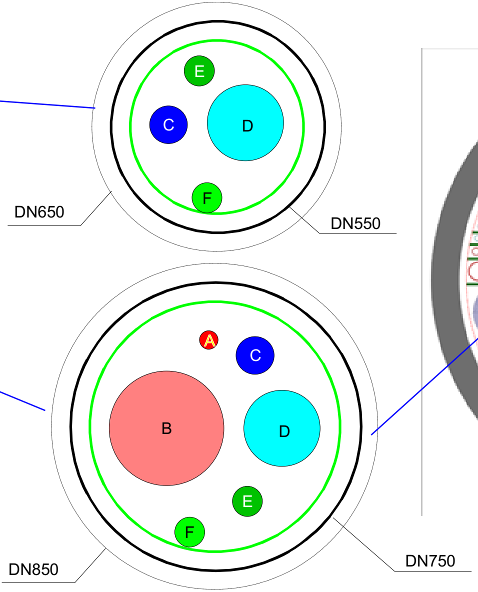
FCC-ee conceptual design

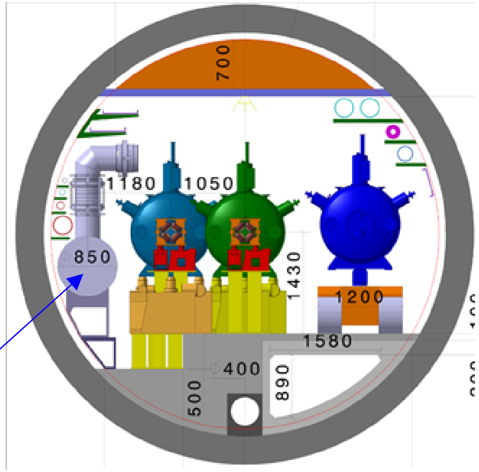
Cryogenic distribution line

- Machines Z, W, H
  - 4 internal lines (C, D, E, F)
  - DN650
- Machines ttbar
  - +2 internal lines for 30 mbar pumping of 800 MHz cavities = 6 internal lines in total
  - DN850

Component	Diameter (mm)
Line A	50
Line B	300
Line C	100
Line D	200
Line E	80
Line F	80
Vacuum jacket 400 MHz cryomodules	550*
Vacuum jacket 800 MHz cryomodules	750*

. *+100 mm for bellows and flanges.





FCC-ee conceptual design

Helium inventory and electrical consumption

- **Total helium inventory of ≈ 26 t** for ttbar machines (40 kg of He per cryomodule)

- Required electrical power varies
  - from 1 MW for the Z machine
  - to **50 MW for ttbar2 machine**

Machine	Z	WW	ZH	$t\bar{t}1$	$t\bar{t}2$
Cryomodules (t)	1.2	1.6	4.1	11.0	12.6
Distribution (t)	3.9	3.9	7.9	8.9	8.9
Cryoplant (t)	1	1	2	4	4
Total (t)	**6**	**7**	**14**	**26**	**26**
Number of 250 m^3 MP storage tanks	8	8	18	30	32

	Installed power (MW)			Nominal power (MW)		
Working point	Per plant	Per site	Total	Per plant	Per site	Total
Z	0.9	0.9	**0.9**	0.8	0.8	**0.8**
WW	9.5	9.5	**9.5**	7.1	7.1	**7.1**
ZH	9.5	9.5	**19**	8.3	8.3	**17**
$t\bar{t}1$	14	29	**58**	12	23	**46**
$t\bar{t}2$	14	29	**58**	13	25	**50**

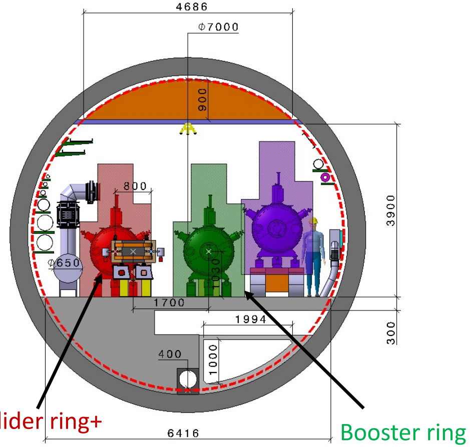
- 250 m^3 medium-pressure (20 bar) storage tanks located in PD & PJ

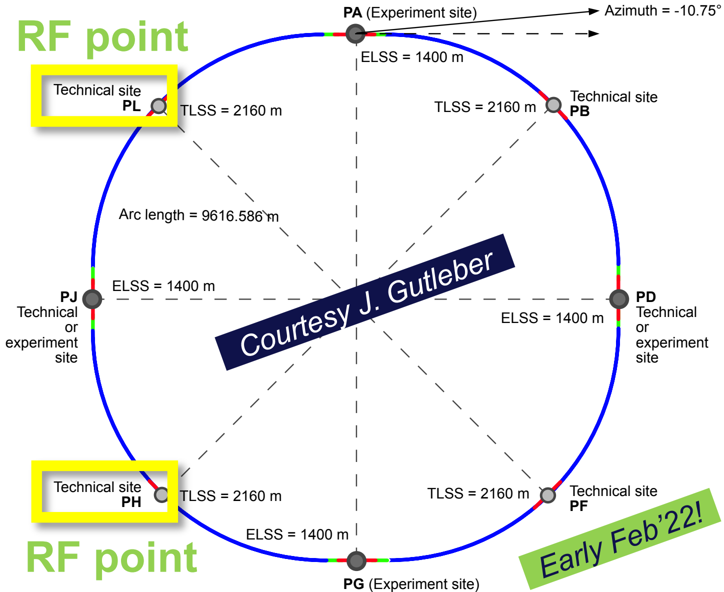
Updated accelerator layout

Civil engineering

6 m in RF sections of points L & H

- Quasi-circular tunnel, **diameter 5.5 m**, depth ≈ 300 m (*deepest shaft 399 m!*), slope < 1%
- Arc segments & straight sections
- Circumference of ~~**97.75 km**~~ **91.17 km**
- **Surface sites: ~~12~~ 8**





Revised RF layout and heat loads for FCC-ee

Courtesy F. Peauger

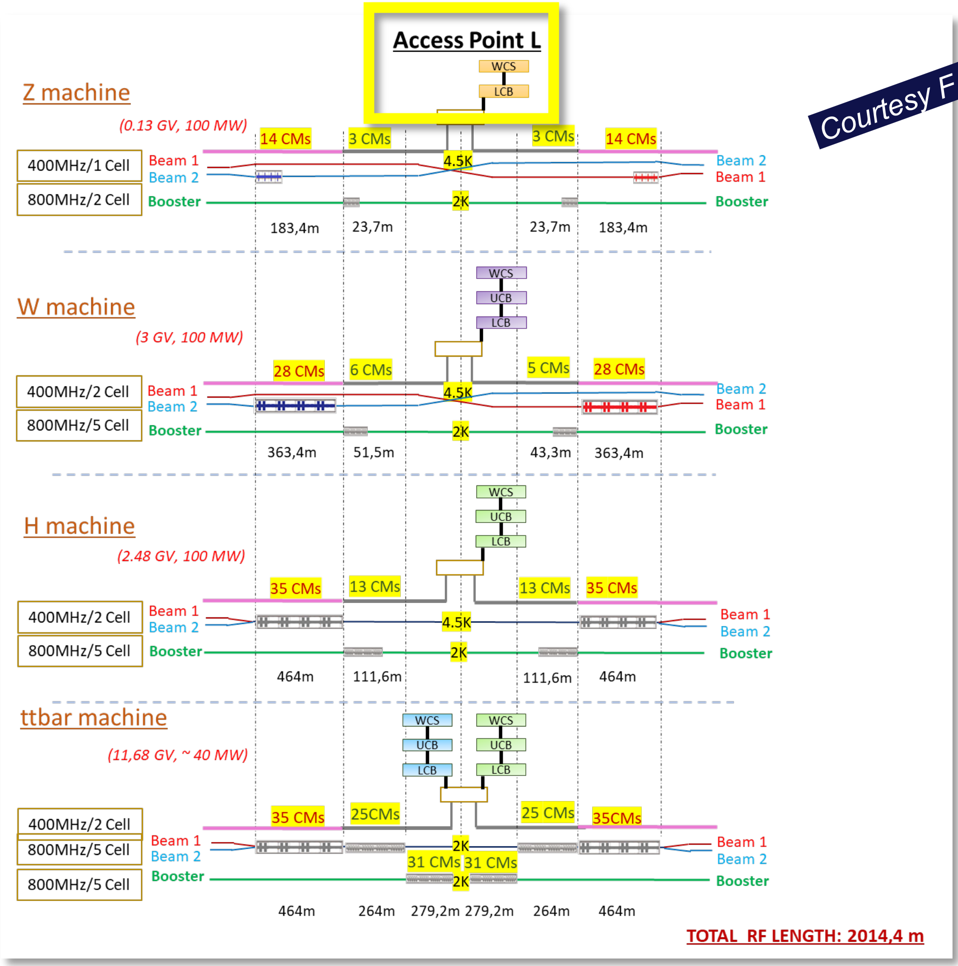
Heat loads

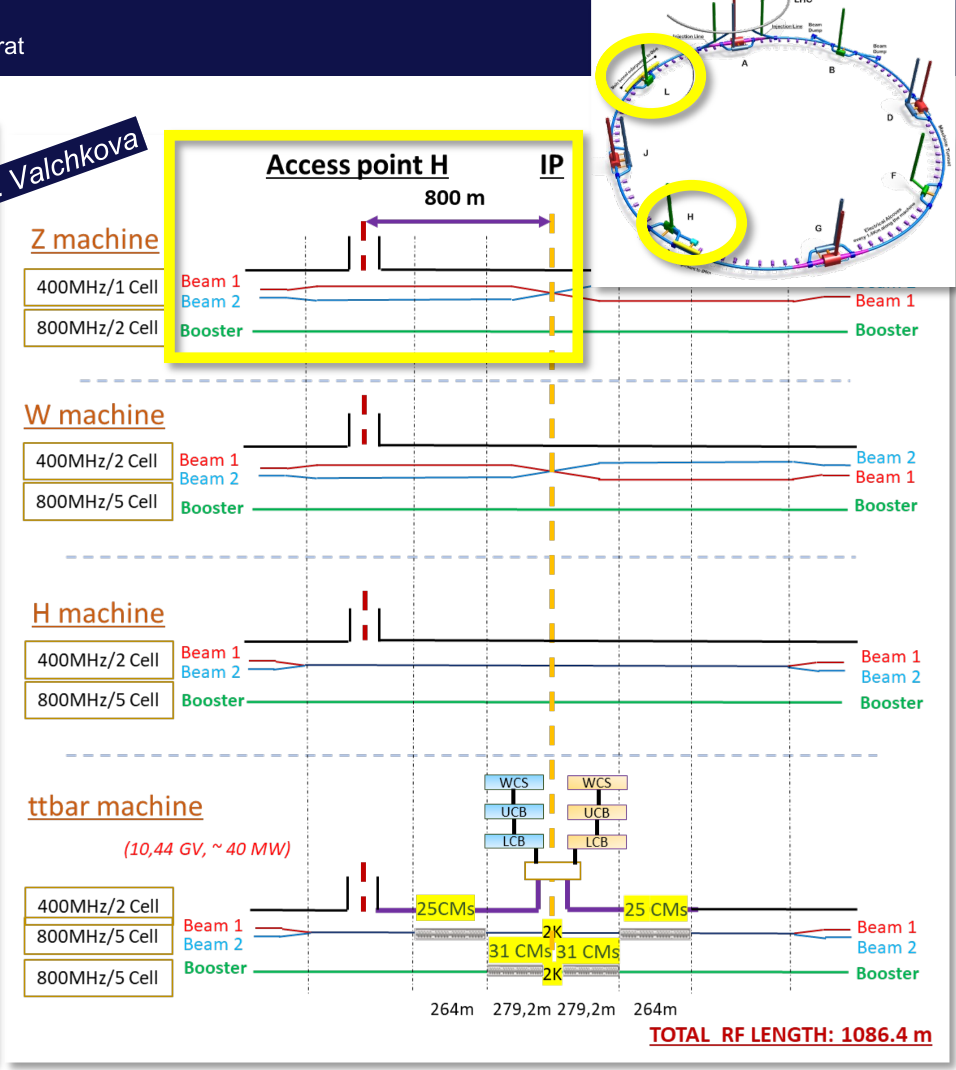
- *Updated May 24th'22:*

- Number of cryomodules
- Heat loads per cryomodule
- Cryomodules arrangement along the ring
- Cryogenic cooling distribution (400 & 800 MHz collider cryomodules are geographically separated)

24th May 2022	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.025	0.040	0.005
Pcav [kW]	880	205	440	112	352	95	62	207	20
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.36	0.36	0.74	0.74	0.70	0.90	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001

Courtesy F. Valchkova





FCC-ee cryogenic heat loads update

Point L	Z	W	H	ttbar
Thermal shields [50 K – 75 K]	2.7 kW	5.4 kW	7.7 kW	14.6 kW
Cryomodules @ 4.5 K	3 kW	40.8 kW	51.5 kW	51.5 kW
Cryomodules @ 2K	0.2 kW	0.7 kW	1.7 kW	15.8 kW
Total equivalent @ 4.5 K *(Including 30% margin)*	5 kW	57 kW	73 kW	140 kW

Point H	Z	W	H	ttbar
Thermal shields [50 K – 75 K]	NO CRYO			9.0 kW
Cryomodules @ 4.5 K				**N/A**
Cryomodules @ 2K				15.8 kW
Total equivalent @ 4.5 K *(Including 30% margin)*				75 kW

FCC-ee cryoplants and electrical power update

Point L	Z	W	H	ttbar
# of cryoplants	1	1	1	2
Installed capacity @ 4.5K *(per cryoplant)*	6 kW	60 kW	75 kW	75 kW
Included capacity @ 2K *(per cryoplant)*	0.5 kW	0.9 kW	2.2 kW	11 kW
Nominal elec. Power *(in total for point L)*	1.3 MW	12.6 MW	15.8 MW	31.5 MW

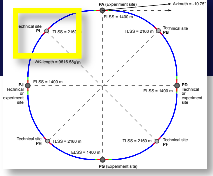
Point H	Z	W	H	ttbar
# of cryoplants	NO CRYO			2
Installed capacity @ 4.5K *(per cryoplant)*				38 kW
Included capacity @ 2K (per cryoplant)				11 kW
Nominal elec. Power *(in total for point H)*				16 MW

FCC-ee helium inventory update

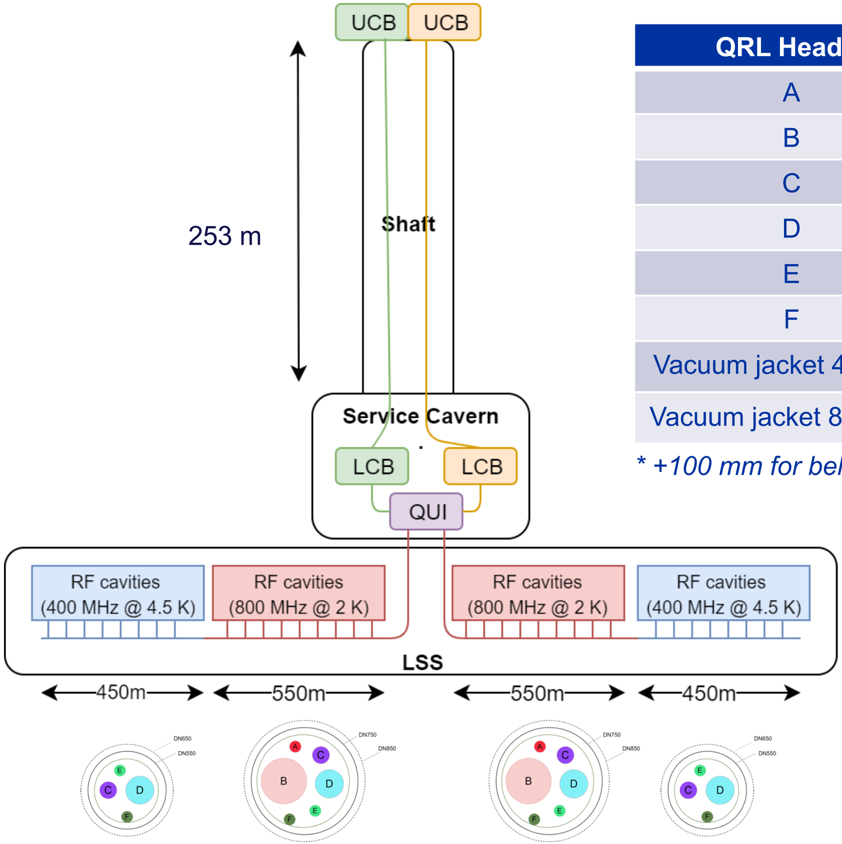
Point L	Z	WW	ZH	ttbar
Cryomodules	1.4 tons	2.7 tons	3.8 tons	7.2 tons
Distribution	4.9 tons	4.9 tons	4.9 tons	4.9 tons
Cryoplants	1 ton	1 ton	1 ton	2 tons
Total	7.3 tons	8.6 tons	9.7 tons	**14.1 tons**

Point H	Z	W	H	ttbar
Cryomodules	NO CRYO			4.4 tons
Distribution				3.8 tons
Cryoplants				2 tons
Total				**10.2 tons**

➢ **Total helium inventory for FCC-ee (ttbar) = 24 tons**

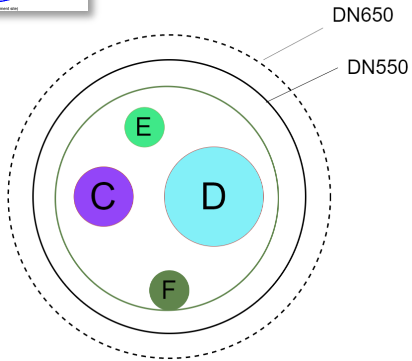


Point L cryogenic layout (ttbar)

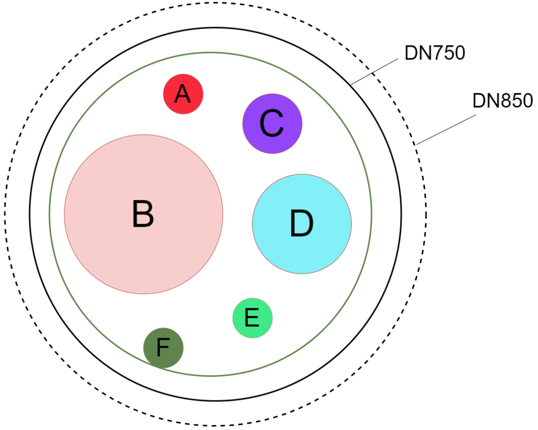


QRL Header	Diameter (mm)
A	80
B	320
C	120
D	200
E	80
F	80
Vacuum jacket 400MHz	550*
Vacuum jacket 800 MHz	750*

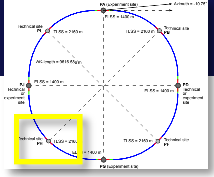
** +100 mm for bellows and flanges*



QRL cross section for 400 MHz cryomodules



QRL cross section for 800 MHz cryomodules

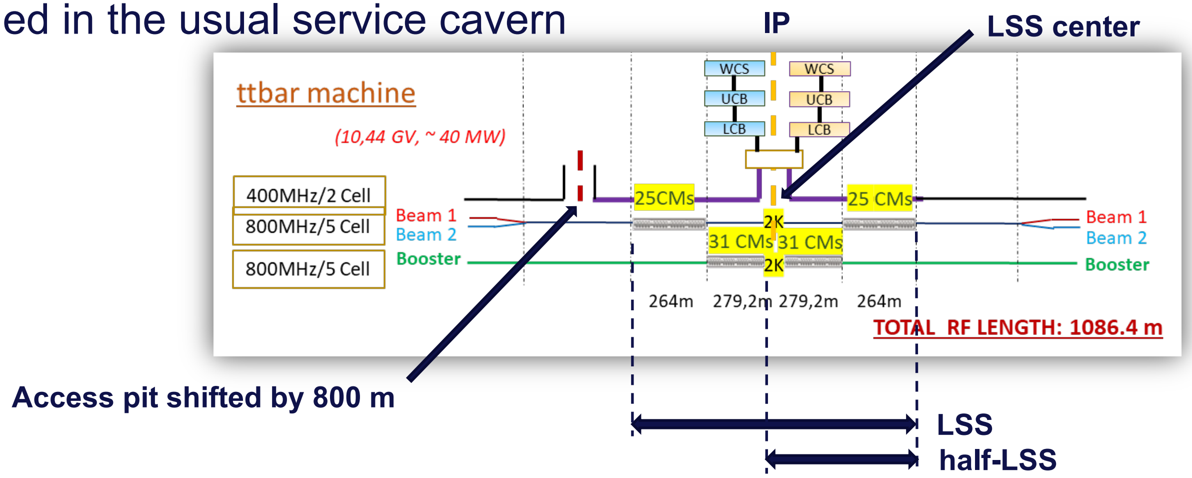


Point H cryogenic layout

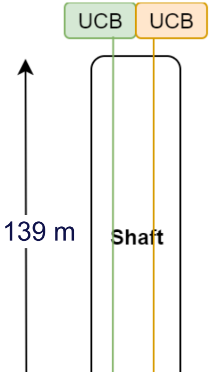
3 different options studied due to access pit location geographical constraints

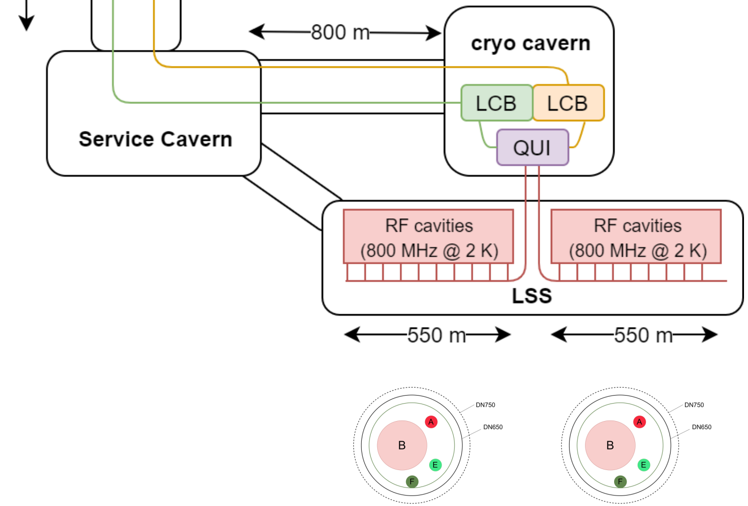
- Option 1: all cryo installed in a dedicated cavern at the LSS center
- Option 2: half of cryo installed in a dedicated cavern at the LSS center
- Option 3: all cryo installed in the usual service cavern

➢ ***See next slides***



Point H option 1: all cryo in a dedicated cavern at the LSS center





Best option for cryo

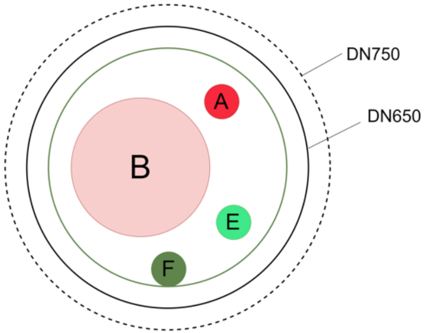
- ➔ Allow redundancy between cryoplants as in Point L
- ➔ Accessibility of cryo equipment ensured
- ➔ Minimize QRL length and pumping lines as in CDR (550m each side)

Very Strong impact for civil engineering

- ➔ Extra tunnel 9m diameter over 800m to transport cryoplants
- ➔ Very large cryo cavern to build in the middle of LSS

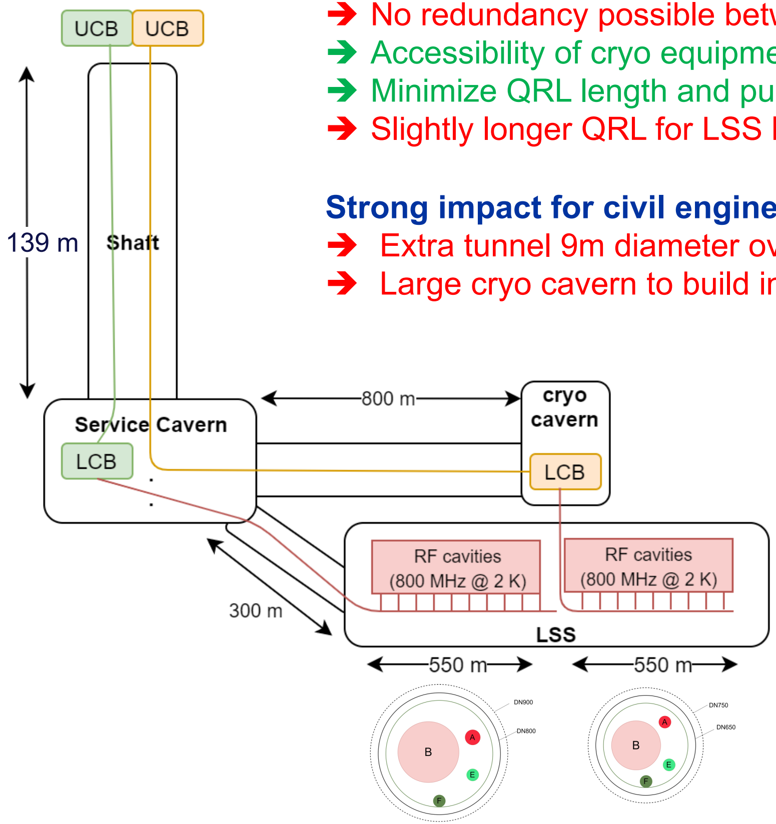
QRL Header	Diameter (mm)
A	80
B	320
E	80
F	80
Vacuum jacket	650*

** +100 mm for bellows and flanges*



QRL cross section (both sides)

Point H option 2: half of cryo in a dedicated cavern at the LSS center



Compromise for cryo

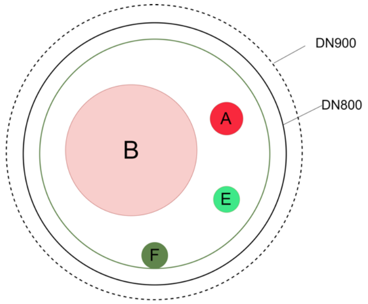
- ➔ No redundancy possible between cryoplants
- ➔ Accessibility of cryo equipment ensured
- ➔ Minimize QRL length and pumping line (550m for right side, 850m for left side)
- ➔ Slightly longer QRL for LSS left (need to enlarge a bit the QRL)

Strong impact for civil engineering

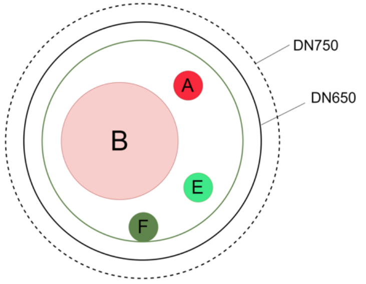
- ➔ Extra tunnel 9m diameter over 800m to transport cryoplants
- ➔ Large cryo cavern to build in the middle of LSS

QRL Header	Diameter (mm)
A (left/right)	100/80
B (left/right)	400/320
E	80
F	80
Vacuum jacket (left/right)	800/650*

** +100 mm for bellows and flanges*

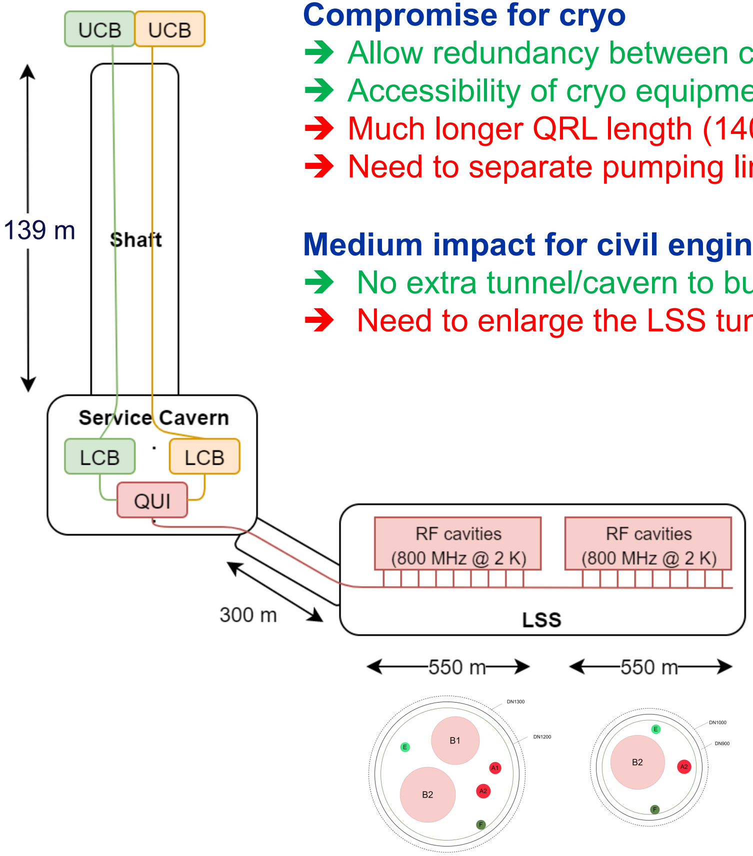


QRL cross section for left side



QRL cross section for right side

Point H option 3: all cryo in the usual service cavern

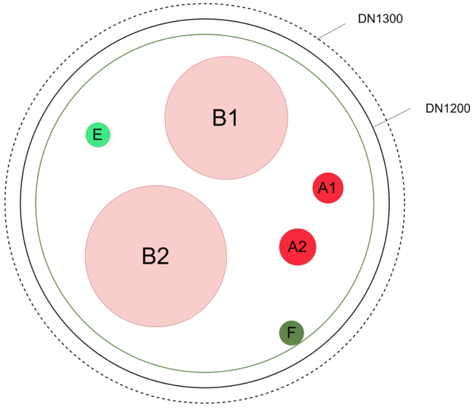


Compromise for cryo

- ➔ Allow redundancy between cryoplants as in Point L
- ➔ Accessibility of cryo equipment ensured
- ➔ Much longer QRL length (1400m) ➔ larger QRL diameters
- ➔ Need to separate pumping lines for the 2 cryoplants

Medium impact for civil engineering

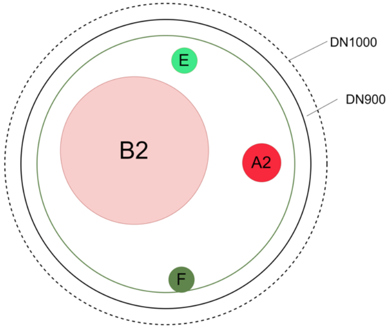
- ➔ No extra tunnel/cavern to build
- ➔ Need to enlarge the LSS tunnel because of a larger QRL



QRL cross section for left side

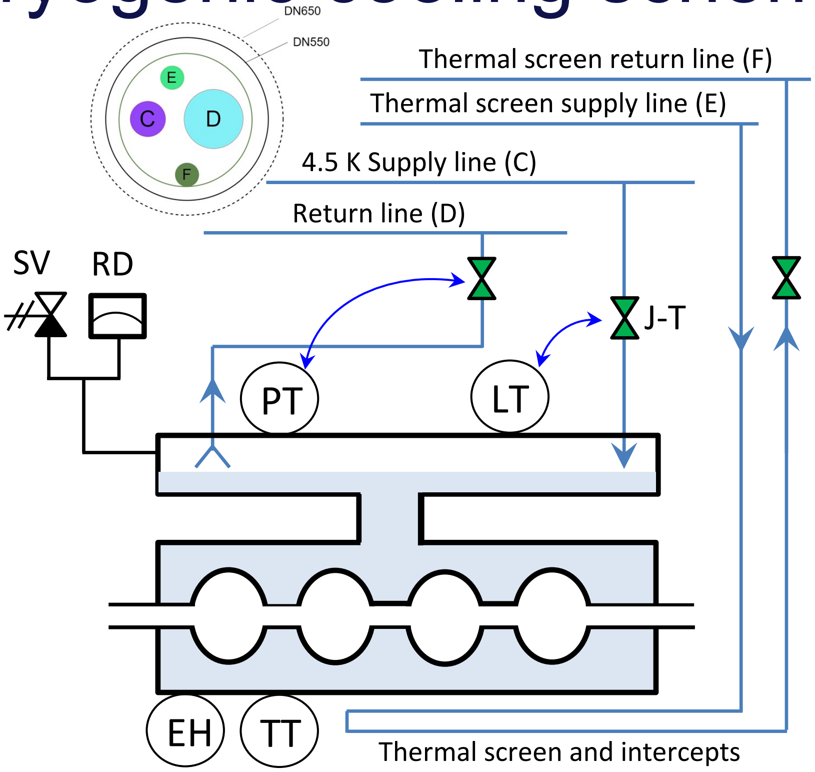
QRL Header	Diameter (mm)
A1/A2	100/120
B1/B2	400/460
E	80
F	80
Vacuum jacket (left/right)	1200/900*

** +100 mm for bellows and flanges*



QRL cross section for right side

Cryogenic cooling scheme for cavities bath at 4.5 K



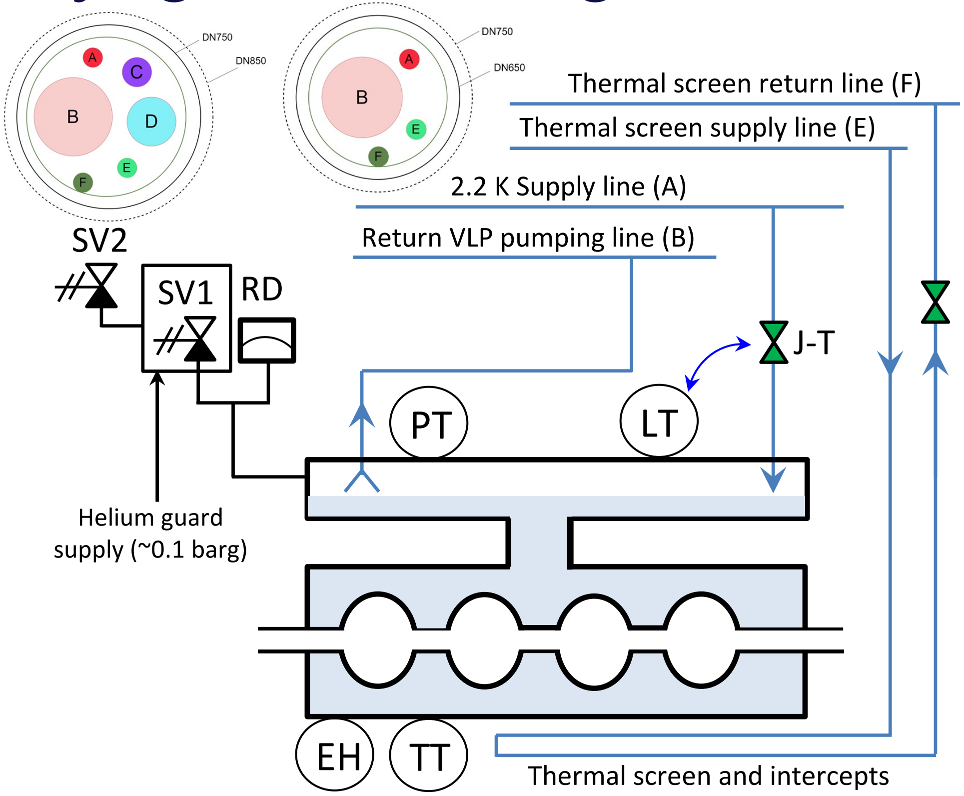
This scheme relates to Point L infrastructure.

Design of the cryostat will require close collaboration between SY-RF and TE-CRG to optimize for:

- Thermal heat load,
- stability of operation parameters,
- and helium inventory.

Nota 1: depending on design of the cryomodule additional cool down/warm up circuit can be installed on the bottom of the helium tank.

Cryogenic cooling scheme for cavities bath at 2 K



This scheme relates to Point L and H for all cavities cooled with superfluid helium at 2 K.

Optimization remarks for 4.5 K are fully applicable for 2 K option, special effort to be done for 2 K heat load or a reason of cold compressor size/capacity optimization.

Nota 1: depending on design of the cryomodule additional cool down/warm up circuit can be installed on the bottom of the helium tank.

Nota 2: all not welded sub atmospheric interfaces with external environment must be helium guarded.

Objectives of the second study phase ('21-'25)

Main deliverables and overall timeline

	2021	2022	2023	2024	2025
Technical design work and R&D in all WPs					
Communication plan and implementation			X		
Placements studies, preferred implementation variant identification	X				
CDR design review and requirements update	X				
General design update for preferred implementation variant		X			
General coherence review across WPs			X		
Detailed design for Feasibility Study Report				X	
Environmental evaluation process and impact study with Host States					
High risks areas site investigations					X
Feasibility Study Report Completed					X

Courtesy M. Benedikt

Conclusion and perspectives

- There has been an important update of the process data since CDR was published, which impacted directly the design of the cryogenic infrastructure
- Three solutions were proposed for the update of the cryogenic infrastructure for FCC-ee configuration in point H, while in point L one solution complies with all requirements
- Organization of the cryogenic work has been consolidated in terms of structure and manpower
- Next steps:
  - Complete the update of the cryogenic design for FCC-ee
  - Address the impact of the new accelerator layout on the FCC-hh configuration
  - *Start the preparation of the feasibility report*

Thank you for your attention.

SPARES

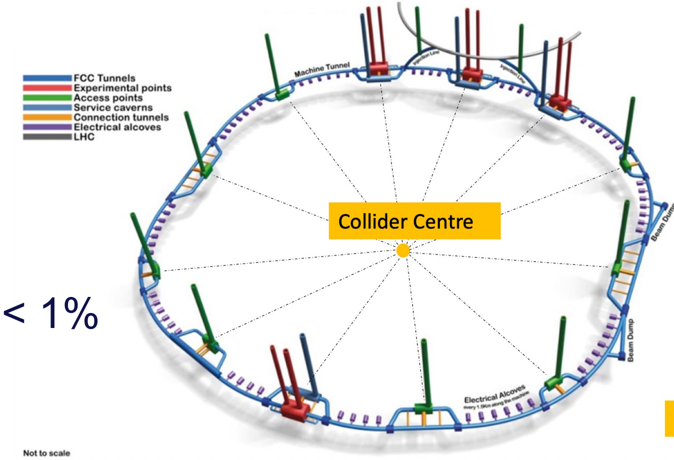
1. FCC-EE CONCEPTUAL DESIGN

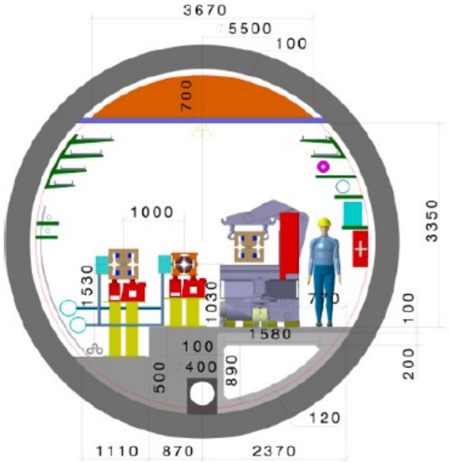
FCC-ee conceptual design

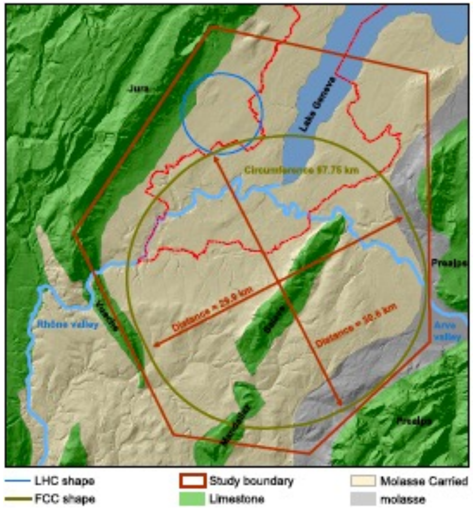
Courtesy F. Valchkova

Civil engineering

- Quasi-circular tunnel, diameter 5.5 m, depth ≈ 300 m, tilt < 1%
- Arc segments & straight sections
- Circumference of **97.75 km**
- **12 new surface sites**







FCC-ee conceptual design

Main considerations

- FCC-ee is designed for 4 physics working points:
  - Z, W, H and ttbar1 & 2
- Staging of these 4 machines requires a gradual increase of the number of SRF modules (as well as the accelerating frequency), hence a staging of the cryogenic system
- 400 MHz SRF cavities to be operated in $LHe_{(sat)}$ bath @ 1.3 bar / 4.5 K
- 800 MHz SRF cavities to be operated in $LHe_{(sat)}$ bath @ 30 mbar / 2 K

FCC-ee conceptual design

Temperature levels

- **50 – 75 K** for the thermal shield as major heat intercept
- **4.5 K** normal saturated helium for the cooling of 400 MHz SRF cavities
- **2 K** superfluid saturated helium for the cooling of 800 MHz SRF cavities

Steady-state heat loads in FCC-ee

	Machine									
	Z		WW		ZH		$t\bar{t}1$ ($t\bar{t}2$)			
	Per beam	Boost.	Per beam	Boost.	Per beam	Boost.	2 beams	Boost.	2 beams	Boost.
Frequency	400 MHz								800 MHz	
Temperature	4.5 K								2 K	
# cells / cavity	1	4	4		4		4		5	
# cavities	52	12	52	52	136	136	272	136	296 (372)	400 (480)
# cryomodules	13	3	13	13	34	34	68	34	74 (93)	100 (120)
Dynamic losses / cav [W]	14	11	210	26	202	29	210	30	66	10
Static losses / cav [W]	8		8		8		8		8	

(nominal conditions)

Nominal cooling capacity per cryoplant

Working point	50–75 K (kW)	4.5 K (kW)	2 K (kW)	Cryoplant size (kWeq @ 4.5 K)	No. of cryoplants (–)
Z	5.5	3.7		4	1
WW	6.4	32		33	1
ZH	7.1	41		41	2
$t\bar{t}1$	6.6	21	10	55	4
$t\bar{t}2$	7.6	21	12	63	4

(incl. operational margin factor of 1.3)

2. LATEST DEVELOPMENTS

Revised RF layout and heat loads for FCC-ee

General cryogenic constraints

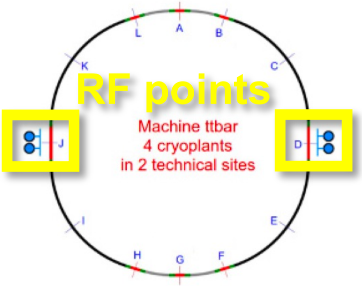
- Maximum extractable heat load at 2 K through a QRL DN850 over a distance of 500 m is ≈ 12 kW per cryoplant (technical feasibility confirmed with industrial partners during phase 1 of the study)

- 2 K pumping units shall remain as close as possible to the 800 MHz cryomodules / big impact of the cryogenic distribution length on the pressure drops in line B

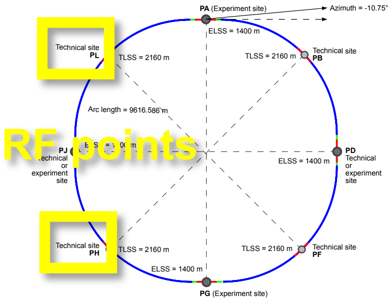
Revised cooling water needs for FCC-ee

From the CDR to 2022 update

- **2019 CDR**:
  - Underground areas: 1.8 MW for point D /// 1.8 MW for point J
    - *(2 * 12 kW @ 2 K installed at each point)*
  - Surface areas: 27 MW for point D /// 27 MW for point J
    - *(2 * 21.4 kW @ 4.5 K installed at each point)*



- **2022 update**:
  - Underground areas: 1.8 MW for point L /// 1.8 MW for point H
    - *(2 * 11 kW @ 2 K installed at each point)*
  - Surface areas: **95 MW** for point L /// **48 MW** for point H
    - *(2 * 75 kW @ 4.5 K installed at point L, …*
    - *… and 2 * 38 kW @ 4.5 K installed at point H)*

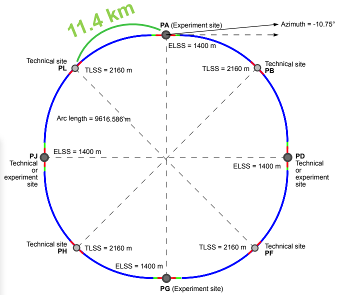


Cryogenic availability for FCC-hh

8 sectors of 3.3 km each (LHC)

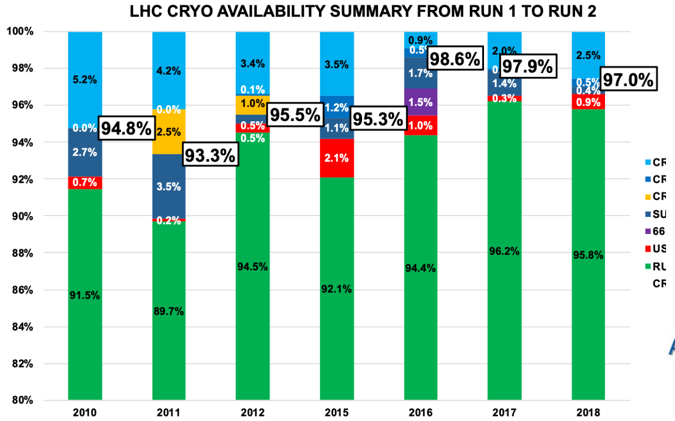
		LHC Cryo Availability
RUN 1	2010	94.8%
	2011	93.3%
	2012	95.5%
LS1		
RUN 2	2015	95.3%
	2016	98.6%
	2017	97.9%
	2018	97.0%
	AVERAGE	**96.1%**

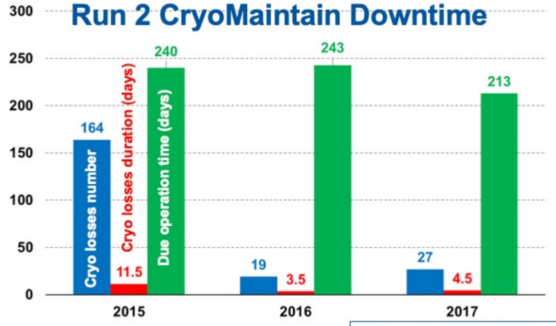
			Observed availability	Expected availability
From LHC experience	1	sector	99.5%	99.5%
LHC	8	sectors	**96.1%**	N/A
FCC-12P	10	cryoplants	N/A	95.1%
FCC-8P	16	cryoplants	N/A	92.3%



Maximum expectable cryogenic availability of 92 %

if we have 16 cryoplants installed in 8 access points !





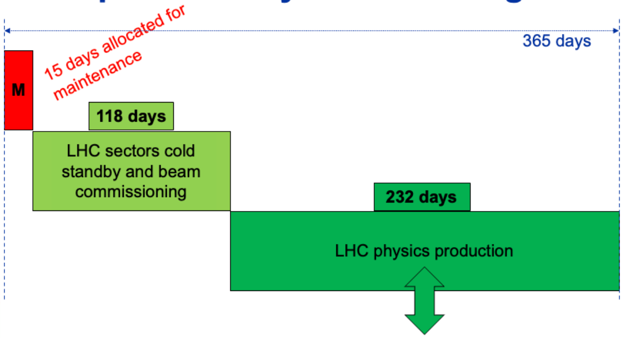
Average due operation time for Run 2:

5561 hours per year (⇔ 232 days)

One should act both on:

- Most frequent losses
- Most time consuming losses

Due operation days of one refrigerator



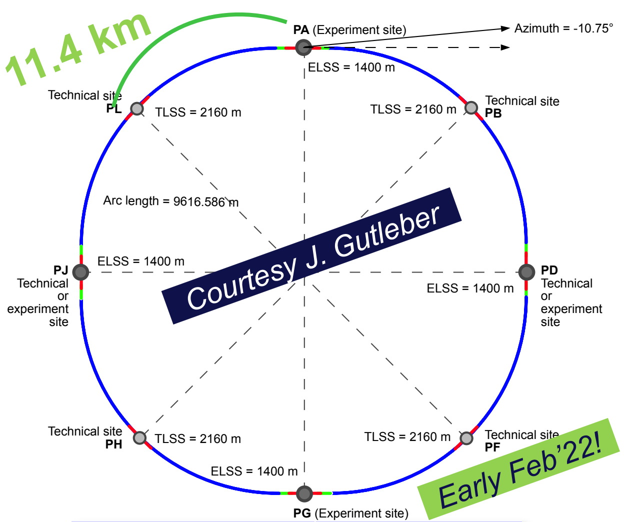
Based on Run 2 average values

LHC Cryogenic Availability statistics are refering to this period

Cryogenic availability for FCC-hh, update from CDR

- From 12 to **8 surface access sites**
- From 97.75 km to **91.17 km of circumference**
- **Sectors length** increased from 10 km to **11.4 km (-hh configuration)**
- **Challenges**:
  - Distribution length increase by ≈ 10%
  - CDR: capacity of one 10-km-long sector cryogenic plant equivalent to ≈ 110 kW @ 4.5 K
  - Need to assess the possibility to go for a “LHC-like” configuration with only 8 cryoplants in 4 technical sites

➡ ***Impact on Cryogenic Availability !***



Number of surface sites	8
Number of arc cells	42 x 8
Arc cell length	213.045 m (may change)
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2160 m
PA Long. (E) / Lat. (N)	6.0976° / 46.2466°
Azimuth @ PA (0 = East)	-10.75°
Arc length	9 616.586 m
Sum of arc lengths	76 932.686 m
Total length	**91 172.686 m**

3. CRYOGENICS WORK ORGANIZATION

Organization of the cryogenics work

6 pillars

FCC Study Phase II Organization & Cryogenics Group involvement

- *Technical Infrastructures*:
  - L. Delprat
- *Technology R&D*:
  - *Cavities*:
    - K. Brodzinski, L. Delprat
  - *Magnets*:
    - R. Van Weelderen, P. Tavares
- *Detectors concepts*:
  - J. Bremer, C. Fabre

Study Coordination

Physics and experiments P. Janot NN	Accelerators ?? T. Raubenheimer (SLAC)?? F. Zimmermann (<mid 22) J. Wenninger (>mid22)	Techn. coordination techn. Infrastructure K. Hanke (from 7/21) V. Mertens (till 7/21)	Host State processes and civil engineering LD Opened	Organisation and financing models NN	Study support and coordination M. Benedikt
physics programme NN	ee & FEB design K. Oide (KEK) A. Chance (CEA)	electrical infrastructure JP. Burnet	administrative processes F. Eder (>9/21)	organisation model NN	study/collaboration secretariat J. Hadre
detector concepts NN	hh design M. Giovannozzi	cooling & ventilation G. Peon	placement studies V. Mertens (<12/21)	financing model F. Sonnemann	study support unit NN
physics performance P. Azzi (INFN) E. Perez	technology R&D R. Losito	integration, transport, logistic C. Colloca	environmental evaluation NN	procurement strategy and rules NN	EU projects NN
software and computing G. Ganis C. Helsens (<10.21)	ee MDI M. Boscolo (INFN)	general safety, access radiation protection, T. Otto	tunnel, subsurface design J. Osborne	in-kind contributions NN	collaboration building E. Tsesmelis
	ee injector P. Craievich (PSI)	Cryogenics, geodesy survey, computing infrastructure, operation and maintenance-reliability See WBS of K. Hanke	surface buildings design NN	operation model P. Collier	Communications P. Charitos J. Gillies (local comm)
			landplots and access NN		

TIWG

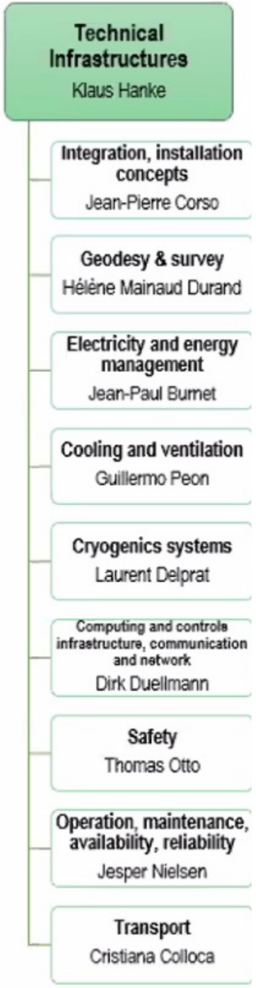
Courtesy M. Benedikt

Organization of the cryogenics work

Technical Infrastructures Working Group (TIWG)

- Chaired by Klaus Hanke (CERN / ATS-DO)
- 10 different work packages (WP)
- Cryogenics systems: WP4.6

FCC 4.1 - Technical Infrastructure	K. Hanke
FCC 4.2 - Integration, installation concepts	J.P. Corso
FCC 4.3 - Geodesy & survey	H. Mainaud Durand
FCC 4.4 - Electricity and energy management	J.P. Burnet
FCC 4.5 - Cooling and ventilation	G. Peon
FCC 4.6 - Cryogenics systems	L. Delprat
FCC 4.7 - Computing and controls infrastructure, communication and network	D. Duellmann
FCC 4.8 - Safety	T. Otto
FCC 4.9 - Operation, maintenance, availability, reliability	J. Nielsen
FCC 4.10 - Transport	C. Colloca



WP4.6 Structure

Technical Infrastructures

WP4.6
Lead: L. Delprat
Co-lead: K. Brodzinski

WU1
Impact of the machine layout on cryogenics — L. Delprat

WU2
Cryogenic production infrastructures design — L. Delprat, B. Naydenov

WU3
Cryogenic distribution & RF cavities design — K. Brodzinski, B. Naydenov

WU4
Integration of the cryogenic system — L. Delprat, B. Naydenov

WU5
Cryogenic process refinement — B. Bradu, B. Naydenov

WU6
Cryogenic control system requirements — B. Bradu, M. Pezzetti

WU7
Cryogenic instrum. and radtol electronics — B. Bradu, M. Pezzetti

WU8
Cryogen's inventory & storage management — L. Delprat

WU9
Reliability, availability & maintenance — L. Delprat, B. Naydenov

WU10
Cryogenic safety aspects — K. Brodzinski, P. de Sousa

WU11
Feasibility Study Report preparation — L. Delprat, B. Naydenov

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Technology R&D Acc. & Det.

WU12
Pillar "Accelerators" Magnets R&D — R. Van Weelderen, P. de Sousa

WU13
Pillar "Experiments" Detectors concepts — J. Bremer, C. Fabre