CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC – Note – 1164

COOLING AND VENTILATION STUDIES FOR THE CLIC

P. Cabral[1,2] and M. Nonis[1]

[1]CERN, Geneva, Switzerland
[2]Instituto Superior Técnico, Lisbon, Portugal

Abstract

The CLiC is composed of a large-scale complex requiring cooling and ventilation infrastructures in surface buildings and in underground tunnels. A conceptual design of these systems has been done throughout 2018 for the 380 GeV accelerator. Two different versions with distinct beam accelerating systems were considered. The total cooling required is approximately 160 MW for the drive beam-based machine and 140 MW for the klystron-based machine. The cost of the cooling and ventilation infrastructure is estimated to be approximately 468 MCHF and 419 MCHF respectively.

Geneva, Switzerland
September 2020

Cooling and Ventilation Studies for the CLiC

Pedro Cabral [a,b], Mauro Nonis [a]

[a] *CERN, Geneva, Switzerland*

[b] *Instituto Superior Técnico, Lisbon, Portugal*

May 2019

Abstract

The CLiC is composed of a large-scale complex requiring cooling and ventilation infrastructures in surface buildings and in underground tunnels. A conceptual design of these systems has been done throughout 2018 for the 380GeV accelerator. Two different versions with distinct beam accelerating systems were considered. The total cooling required is approximately 160MW for the drive beam-based machine and 140MW for the klystron-based machine. The cost of the cooling and ventilation infrastructure is estimated to be approximately 468MCHF and 419MCHF respectively.

---

1. Introduction

The last cooling and ventilation study for the CLiC infrastructure was done in 2012. It was documented in the CDR [1] and concerned three different energy stages – 500GeV, 1,5TeV and 3TeV.

The CLiC study has advanced and an update of the conceptual design for the cooling and ventilation plants was therefore required, in particular for the first energy stage of the project: a 380GeV machine. Two different types of accelerator are considered – a drive beam configuration and a klystron-based machine. The fundamental difference between the two is the way the beam is accelerated - the first uses a drive beam whilst the latter uses klystrons.

The new studies for the two configurations started in January 2018 and were documented in the PiP – *Project implementation Plan* - issued by the end of the year [2].

In the following sections, the authors provide a detailed description of the cooling and ventilation studies.

2. The CLiC Complex

The CLiC is composed of facilities that range from surface buildings to tunnels. These premises were divided in sectors, according to geographical and operational aspects:

Sector 1: Drive Beam Complex
Sector 2: Main Tunnel Region
Sector 3: Interaction Point Region
Sector 4: Main Beam Complex

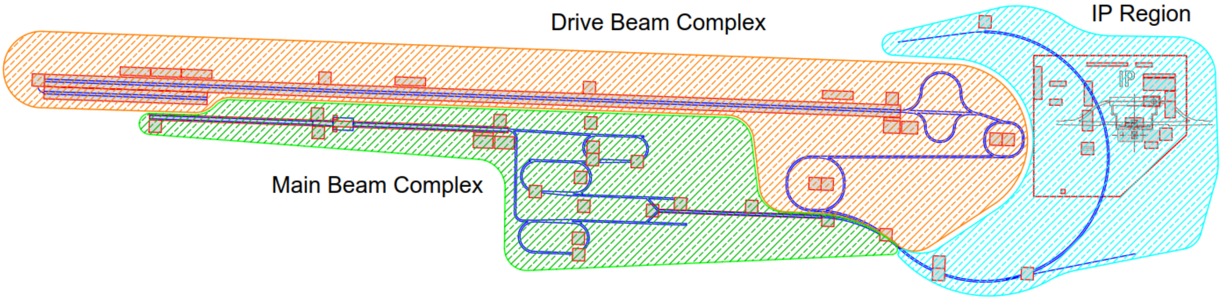


Figure 1. Illustration of sectors 1,3 and 4 for the drive beam machine.. The klystron-based machine is identical but without the drive beam complex.

The klystron-based accelerator does not require a drive beam nor its infrastructure. Hence, the infrastructure is divided in sectors 2, 3 and 4 only. Figure 1 illustrates the CLiC complex and sectors 1,3 and 4.

This particular sectorization is convenient from a geographical perspective as well as from an operational point of view, as the cooling and ventilation infrastructure for each different sector can be run independently: one can operate the drive beam sector alone without having to run the main beam sector.

A detailed table with the sectors and the respective facilities is presented in annex A, together with the top view of the complex.

3. Ventilation

3.1. General Considerations

The ventilation plants are designed to:

- ensure a given temperature and/or humidity in a given area;
- supply fresh air to people;
- purge the tunnels if necessary;
- filter the supply and exhaust air;
- extract smoke and gas if necessary;

while optimizing energy efficiency, reliability, operability and maintainability.

The ventilation equipment is essential in many of the premises of CLiC. Hence, a redundancy of N+1 is set for most of the equipment.

3.2. Operational modes

Three different operational modes are foreseen – *run, purge and access* – for most of the facilities.

During *run mode*, the accelerator and related equipment is working and access to the tunnels and other premises is forbidden. Hence, in most of those places, there is no need for fresh air and the ventilation system fully recirculates the air, avoiding the introduction of external latent and sensible heat loads.

The *purge mode* is designed to replace the air in a given space with fresh air within a short period, before allowing access to people. This is mostly used either in premises where air is recirculated and fresh air is not supplied throughout run mode, either where activation of the air is possible. In such cases, a purge (or flush) is necessary before access to ensure the required air quality for people.

The *access mode* is switched on after the *purge mode* and allows the presence of people. This mode might also be a combination of the first two: partial recirculation and fresh air intake.

3.3. Design Conditions

The design conditions or the user’s requirements are not entirely defined at this stage of the study. There are ongoing discussions concerning the ambient temperature and desired humidity in some areas.

The most important of those areas is the main tunnel, where the LINAC is located. The high heat load, the large distance between shafts and the required low longitudinal temperature gradient severely constrain the ventilation design. By increasing the ambient temperature, one reduces the fraction of heat to air and increases the one to the water cooling systems. Hence, a higher ambient temperature facilitates the ventilation design. However, if a relatively high temperature is foreseen during run mode, a waiting time is necessary before access to ensure proper ambient conditions for workers. This waiting time cannot be long to ensure a reasonable operability of the facilities. The ambient temperature should be optimized taking into account all these factors. Given the numerous uncertainties still present, a temperature of 28 °C has been defined during run mode. It is expected to change at a later stage, even if major modifications are not foreseen.

For the remaining premises, such as the injectors or the surface buildings, conservative temperatures were selected, based on CERN’s common practice.

Additionally, in tunnels, injectors and other facilities, a minimum dew point of 12°C is set. This condition ensures that no condensation will take place on equipment and premises if their surfaces are above that temperature.

Table 1 provides a summary of the adopted design conditions for the different areas.

Site	***Dry Bulb***	***Dew Point***
Sector 2 and Detector’s Hall (Under.)	28°C	12°C
Injectors, Booster, Damping R. and Transfer Lines (Under.)	23°C	12°C
Surface Buildings	18°C to 25°C	-

Table 1. Indoor design conditions

These temperatures are to be achieved at a height corresponding to the level of equipment and people; several facilities are large, have high ceilings and significant vertical temperature gradients.

The external conditions have an important impact on the HVAC system design. Table 2 summarizes the outdoor design conditions used for the sizing of the systems.

Season	***D. Bulb***	***R. Humidity***
Summer	32°C	40%
Winter	-12°C	90%

Table 2. Peak exterior conditions

3.4. Heat loads

Presently, some of the technical heat loads are rough estimates that require further study and investigation, namely the loads concerned with the injectors and the main tunnels for both the drive beam and klystron-based machines. A factor of 1,1 was applied on the technical loads in some particular areas to consider possible future fluctuations.

For certain underground areas, such as the main tunnel or the detector’s hall, water infiltrations are expected to occur. The evaporation of that water constitutes a latent heat load that should be considered when sizing the cooling and ventilation plants. However, they have not been considered at this stage; nevertheless, they are expected to be relatively small. For the surface buildings, one should consider the external loads, in addition to the technical ones. However, no information is available concerning the construction details – materials, windows orientation and materials, etc. Hence, a heat density factor (per area) is applied to account for the peak external heat loads during winter and summer.

A table summarizing the technical and external loads can be found in annex B.

3.5. Ventilation System

Three distinct ventilation systems are applied according to the geometry of the premises. The premises can be categorized as follows:

- shallow underground
- deep underground
- surface buildings

The **shallow underground** structures are “cut-and-cover” tunnels that are relatively shallow (5m depth). These structures are built to accommodate the injectors and the transfer lines. For these premises, a traditional push-and-pull ventilation is used, as illustrated in figure 2.

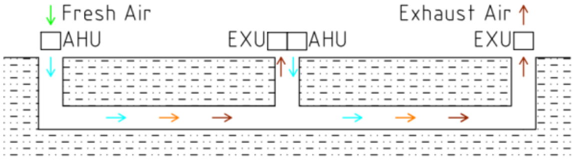


Figure 2. Push-and-pull ventilation schematic. AHU stands for air-handling unit and EXU for extraction unit.

The ventilation system was designed to be energy efficient, recycling air and providing free cooling when appropriate. However, the geometry of these premises requires the supply of external air at one of the extremities of the tunnels, meaning that a significant portion of energy is used to treat that air, in particular during summer or winter. The air-handling units set to treat the external air are designed to withstand latent and sensible ventilation loads according to the outdoor conditions mentioned in table 2.

The detailed calculations can be found in annex C as well as the ventilation layout used for the shallow underground premises.

The **deep underground** premises are tunnels and other structures built at a depth of approximately 150m. Air handling and extraction units are set at the surface, close to the shafts. A network of ducts transports air to the respective space and then back to the unit. This layout allows an easy access to the ventilation equipment, even during run mode. However, there are cases for which it is not possible to adopt such design, as some of the structures are not close to the shafts. These are the caverns UTRAs, UTRCs, 2.1, 2.2, 3.1 and 3.2., where dedicated air-handling units are installed for local cooling. Additionally, turnarounds, dumps and BC2 tunnels, are ventilated by air-handling units located in the closest cavern and connected via ducts to the concerned area.

The main tunnel is another particular case. If the air-handling units were located at the surface and a push-and-pull layout was adopted, the resulting longitudinal temperature gradients would be incompatible with the requirements for the alignment systems. Additionally, the air velocity within the tunnel must be limited for technical (induced vibrations on the modules) and safety reasons.

For the drive beam machine, the air-handling units are installed in the UTRAs and UTRCs. Supply and extraction ducts are set in the main tunnel as illustrated in figure 3.

For the klystron-based machine, the air-handling units are placed in the service cavern, below the floor. They are connected to diffusers that supply the conditioned air. Extraction ducts are set in the tunnel and connected to extraction units located in the UTRAs and UTRCs, as shown in figure 3.

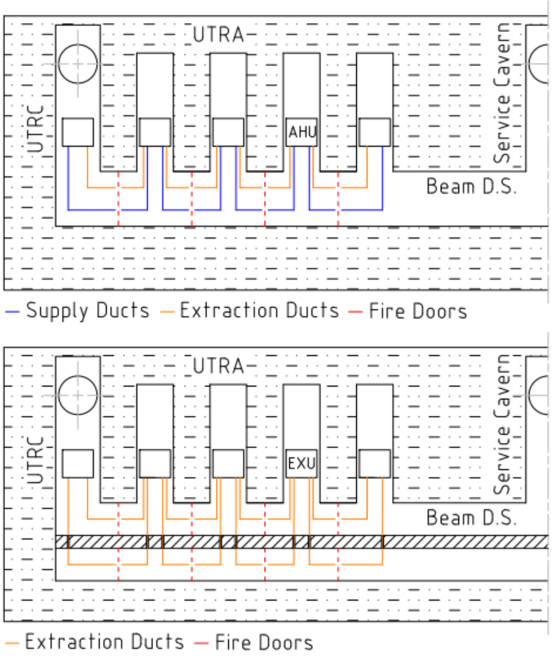


Figure 3. Ventilation schematics for the drive beam and klystron-based machines.

The main tunnel cross sections are presented below, in figure 4. One can see the ventilation ducts and other utilities and services.

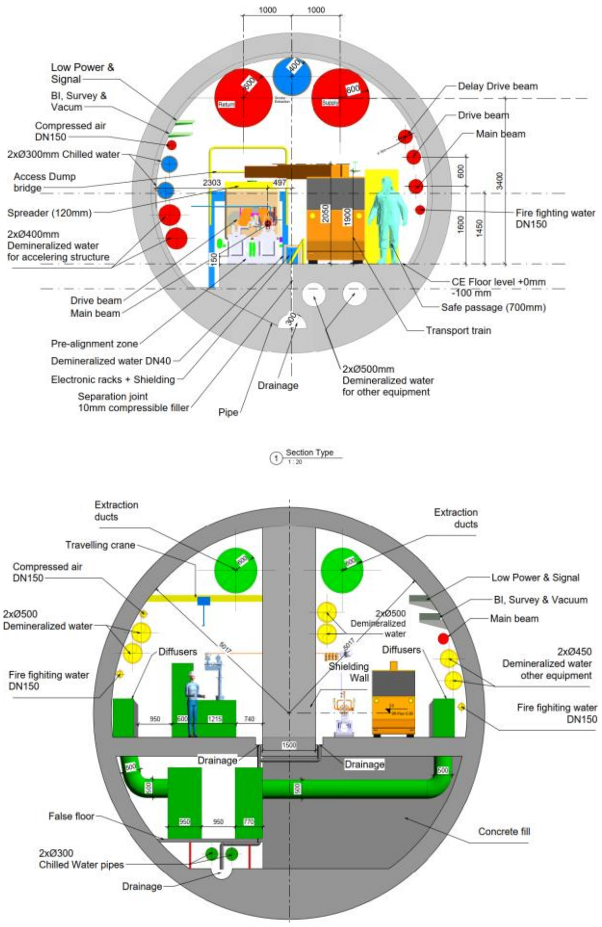


Figure 4. Main tunnel cross sections for the drive beam (first) and klystron (second) machines.

Further studies on the air diffusion are required for the main tunnel in order to ensure that the tight temperature stability requirements are satisfied.

In annex D, schematics, tables and technical drawings concerning the main tunnel are presented.

Finally, for the **surface buildings**, air-handling units are planned to be installed inside the buildings themselves, as well as a traditional network of ducts. The tables with the technical details can be found in annex E.

The redundancy of the HVAC equipment is of the utmost importance for the proper running of the critical facilities and is set at N+1. However, for some of the deep underground areas, no redundancy is foreseen due to space constraints.

3.6. Purge Mode Requirements

The *purge mode* is employed before *access mode* and is meant to replace the air at a given space with fresh air. For this mode, the heat loads are mainly external as the experimental equipment is mostly stopped or emanating irrelevant heat loads. The purge mode is foreseen to last a maximum of 1 hour, after which access can be granted. To ensure this purge rate, a correction has been made to some of the cooling and heating capacities of the system designed for the *run mode*. Moreover, some ventilation equipment had to be added. The values presented in annexes D and E include these considerations, being consistent with the following requirements: 1. satisfy the run mode loads and 2. purge the space within an hour during the peak winter and summer conditions.

4. Cooling

The cooling infrastructure is composed of water circuits that are dedicated to cool either equipment or air. They are divided in three groups:

- primary water circuits
- chilled water circuits
- demineralized water circuits

The first two use raw water, whilst the third one uses demineralized water. Figures 5 and 6 illustrate the three typologies and their dependencies.

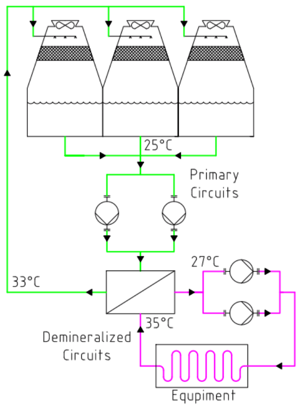


Figure 5. Primary and demineralized water circuits.

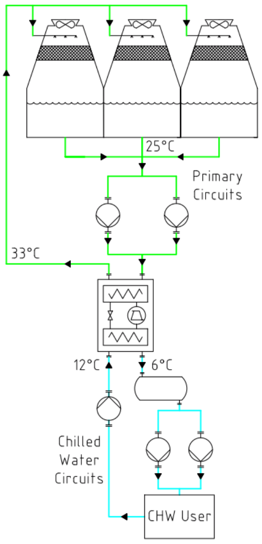


Figure 6. Primary and chilled water circuits.

The cooling equipment is critical for the proper running of many systems. Hence, an N+1 redundancy was considered. However, the heat exchangers do not have redundant units.

Mixed water is expected to be required. However, at this stage, no information is available. This is to be tackled as the project progresses to a detailed design.

4.1. Cooling Towers

The heat released by the experimental equipment and by the chillers condensers is absorbed by secondary circuits and consequently transferred to the primary circuits. Ultimately, this heat is released to the atmosphere through cooling towers.

The towers were placed in three different sites according to the correspondent sector - 1, 2/3 or 4. Their location has been chosen to minimize the energetic cost of fluid transport as well as the cost of the piping itself. The chosen sites can be consulted in both annex F and annex H.

The cooling towers have a redundancy of N+1.

4.2. Primary Circuits

The primary circuits are semi-closed and are in direct contact with the cooling towers. The working temperatures range from 25°C after leaving the cooling tower to 33°C before reaching the cooling towers. The primary circuits exchange heat with the secondary circuits at a cooling station. These cooling stations are placed in accessible areas to facilitate the operations and maintenance activities. The details of such circuits can be found in annex H, as well as the piping layout of these circuits.

4.3. Demineralized Circuits

The secondary circuits are in direct contact with the water-cooled equipment. Hence, they are filled with demineralized water produced at CERN’s centralized plants.

The heat loads are the base for the design of these systems and can be found in annex G. Some of these numbers are rough estimations and constitute a source of uncertainty. Modifications in the heat loads might have a strong impact in the cooling design.

The working temperature ranges between 27°C at the equipment inlet and 35°C at its outlet. Please refer to annex H for the tables with the concerning data, piping layouts and other technical details.

4.4. Chilled Water Circuits

The chilled water circuits are used to cool the air that passes through the air-handling units. The heat transferred to these circuits is the heat discussed in the ventilation section.

The chillers will be located as close as possible to the ventilation units to allow for short chilled water circuits and avoid thermal losses throughout the distribution lines, as well as to reduce the price of insulation.

The chilled water temperatures are either 6°C-12°C or 5°C-10°C. The calculations have been done for the latter, to be on the conservative side, although the first range induces a lower energy consumption and is therefore the preferred one.

The tables with the technical details of these circuits can be found in Annex F, as well as the piping layout for the water circuits.

5. Safety and Environment

The cooling and ventilation infrastructure provides smoke extraction where it is required. The studies done throughout the year are preliminary and do not hold much detail. Additionally, they have been completed for the main tunnel exclusively, and not for the other premises.

Fire doors will be deployed in the main tunnel every 439m to create confined spaces if necessary. We have distributed the doors and fire compartments to avoid an interception with the ventilation ducts - please refer to the figures in annex D.

Additionally, for the drive beam machine, hot smoke extraction ducts extending along the tunnel are foreseen (one for each side of the tunnel). The purge extraction units will be used to extract the smoke from the tunnel.

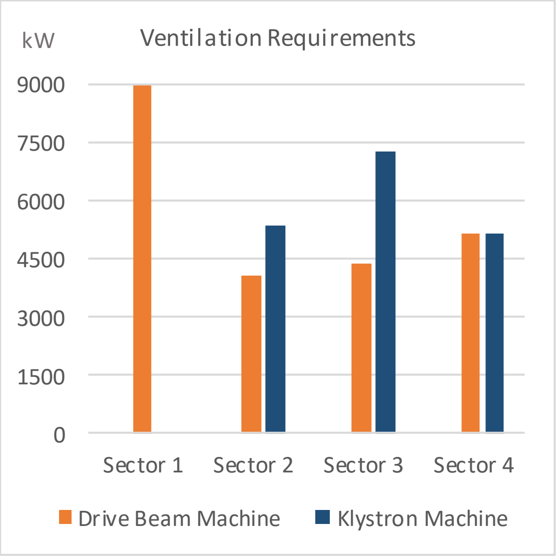
For the klystron-based machine, a smoke extraction duct is installed in the service cavern (below the floor) running along the tunnel, from the shafts 2 or 3 to the shaft 1. The standard ventilation ducts transfer the smoke from the targeted compartment to the smoke duct.

The lifts placed in the shafts and the respective waiting areas are essential to escape from any incident in the main tunnel. Hence, they are installed within a pressurized structure to avoid infiltrations of health-threatening gases. Other pressure cascades are implemented to avoid the movement of certain gases to areas where they are not expected. However, they have not been considered in the design, as the requirements are not yet entirely defined at the present stage.

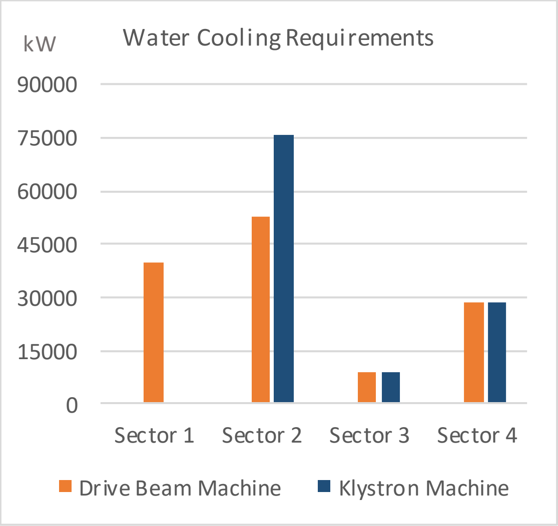
The air that is exhausted to the environment is, in some cases, monitored and controlled to prevent pollution and health hazards.

6. Thermal Power Considerations

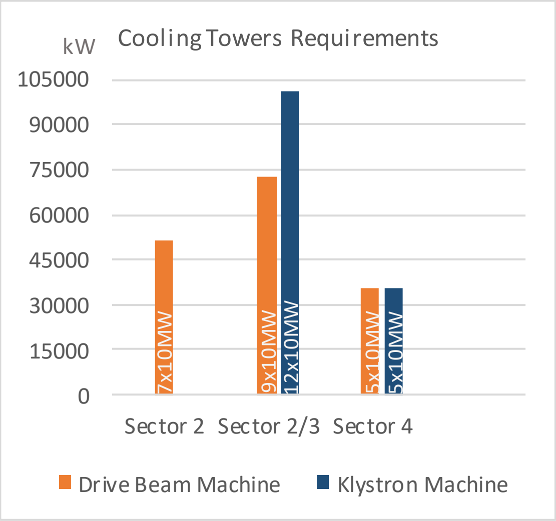
A general overview of the cooling power required for the CLiC is herewith provided. Two categories have been selected to better illustrate the results – heat loads to air and heat loads to water. The first is concerned with the heat transferred directly to air (discussed in the ventilation section) and the second is related to the heat transferred directly to water by equipment. If one sums the two categories, we obtain the total loads released in the CLiC premises. Graphs 1 and 2 show each of the categories. Considering a global COP (coefficient of performance) of 3 for the air conditioning systems, one achieves the total heat dissipated in the cooling towers as plotted in graph 3, where the number of cells of 10MW can be found for each sector.



Graph 1. Ventilation requirements for the two machines.



Graph 2. Cooling requirements for the two machines.



Graph 3. Cooling towers thermal power and number of 10MW cells for each sector.

7. Cost

A cost estimate was done alongside the conceptual design.

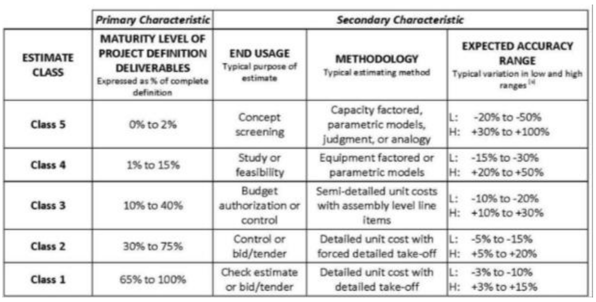
The systems comprise industrial equipment and technology that is well-known and that is commonly available on the market. However, some air-handling units and pumps are on the limit of what is usually available. Hence, we expect to be restricted to fewer manufacturers for these exceptional cases.

In order to compute the costs, we have divided the technical facilities in two major categories: the cooling, which comprises the water-related equipment, and the ventilation, which encompasses the air-handling equipment.

The cost for each cooling and ventilation system was computed by scaling reference prices based on present and past contracts at CERN. Additionally, factors were used to account for the particularities of each system. For instance, the installation cost varies greatly whether the system is in the shafts or in a deep tunnel.

The cost estimate excludes the civil engineering infrastructure related to the cooling and ventilation plants, with exception of the concrete structures for the cooling towers. Additionally, the pumping stations for supplying and rejecting water, the demineralised water production station, the firefighting network, the compressed air systems, the underground sanitary installations, the metallic structures, ventilation doors and the main cables for the power supply are not included in the cost estimate.

The uncertainty of the cost estimate depends on the maturity level of the project and on the costing methodology. According to the "*Association for the Advancement of Cost Engineering (AACE) cost estimate classification system*", presented in table 3, the estimate class should be a class 4 or even 5.



	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Table 3. AACE cost estimate table.

The final cost is estimated at 468 MCHF and at 419 MCHF for the drive beam and klystron options respectively. In table 4, one can find a summary of the costs according to the different system categories.

Some additional details concerning the costing method and results can be found in annex I, where one can find a short report on the topic.

-	***Sector***	***D. Beam***	***Klystron***
Ventil.	1	70	0
	2	101	130
	3	38	50
	4	47	47
Cooling	1	41	0
	2	67	93
	3	15	20
	4	29	29
C. Towers	1	18	0
	2	24	32
	3		
	4	13	13
Sumps	1	0	0
	2	5	5
	3	0	0
	4	0	0
Total		468	419

Table 4. Cost table in MCHF.

8. Extension Plans

The three energy stages of the CLiC – 380GeV, 1,5TeV and the 3TeV – will be built at different times. The authors have adopted a modular design to facilitate the extension of the facilities.

Cooling towers will be placed along the tunnel as it grows according to the project's stage. Image 7 illustrates their position and area of influence. For instance, one can see that for the 1,5TeV collider, a cooling station will be placed in points 4 and 5 to deal with the loads released in the region in between points 2 and 6 as well as 3 and 7 respectively.

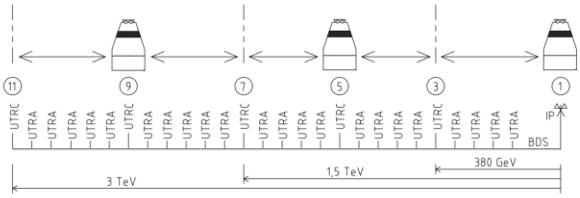


Figure 7. Cooling plants for the three energy stages.

9. Final Remarks

The design of the Cooling & Ventilation infrastructures is still preliminary but sets a strategy for the technical preparation stage.

A detailed design is to be done in the future. Many challenges are still to be addressed, namely concerning the air diffusion in the main tunnel, where the heat loads are relatively large and there are tight constraints in the temperature stability.

10. CERN Document Numbers

[1] CERN-2012-007

[2] CERN-2018-010-M

Annex A – CLiC Complex

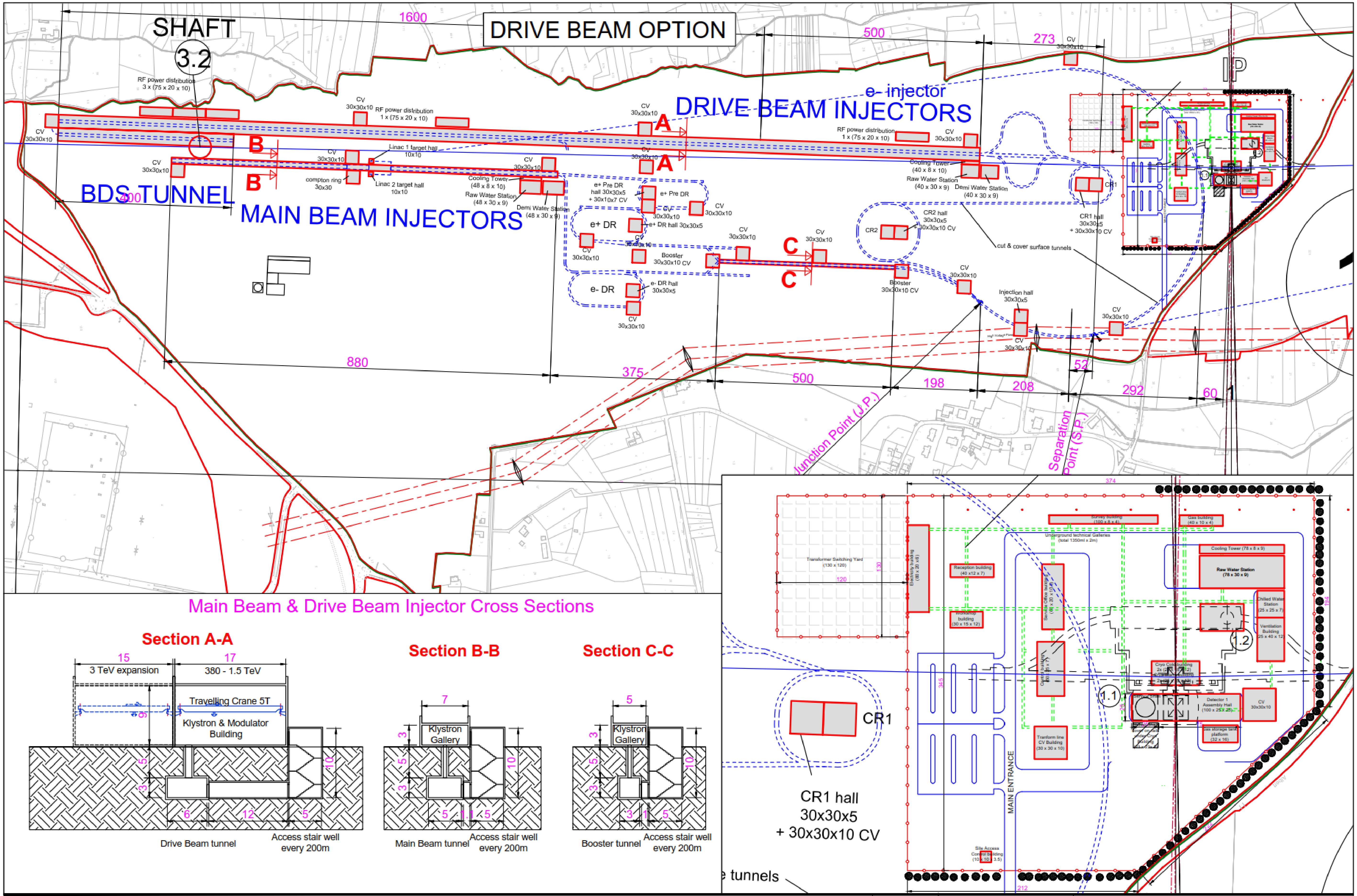
The underground (U) facilities and the surface buildings (S) are listed below. The CLiC complex's top view for both the drive beam and klystron machines are presented as well.

Sector	Structure	Geometry					
	Name	S/U	N.°	Length	Diameter or Width	Height	Volume
		-	-	m	m	m	m^3
1	Drive Beam Injector	U	1	2100	6	3	37800
	Frequency Multiplication - 3 way	U	1	808	4	3	9701
	Frequency Multiplication - CR1	U	1	404	4	3	4850
	Frequency Multiplication - CR1 to CR2	U	1	303	4	3	3638
	Frequency Multiplication - CR2	U	1	505	4	3	6063
	Transfer from CR2 to J.P.	U	1	198	4	3	2376
2	Main Beam Dumps	U	2	20	16	14	4480
	Drive Beam Dumps	U	8	13	9	5	585
	Drive Beam Turnaround	U	8	63	2	3	454
	UTRA	U	8	40	10	7	2880
	UTRC	U	2	55	16	18	15840
	Caverns 1.3 and 1.4	U	2	20	8	14	2240
	Survey Cavern 2.1 and 3.1	U	2	20	10	15	3000
	Additional Caverns 2.2 and 3.2	U	2	49	16	18	14112
	Service Cavern	U	1	60	20	15	18000
	BDS	U	1	3800	6	-	110828
	Tunnel BC2 e^+	U	1	300	6	-	7389
	Main Beam Turn-Around e+	U	1	1949	3	-	13777
	Tunnel BC2 e^-	U	1	300	6	-	7389
	Main Beam Turn-Around e^-	U	1	1949	3	-	13777
	BC2 Caverns	U	2	100	10	6	5600
	Main Tunnel – Two-Beam	U	1	7026	6	-	173047
	Main Tunnel – Klystron	U	1	7026	10	-	555629
3	Transfer from J.P. to S.P.	U	1	260	6	3	4680
	Transfer Lines Loop	U	1	945	4	3	11340
	Transfer Lines e^+ from Surface to Tunnel	U	1	1449	4	-	16433
	Transfer Lines e^- from Surface to Tunnel	U	1	2196	4	-	24905
	Detectors Hall - Underground	U	1	62	32	34	65426
4	Main Beam Injector	U	1	880	5	3	13200
	Booster	U	1	500	3	3	4500
	Transfer from Booster to J.P.	U	1	198	4	3	2376
	Pre-Damping Ring	U	1	384	8	3	9216
	Damping Ring e^+	U	1	433	8	3	10394
	Damping Ring e-	U	1	433	8	3	10394

Table A1. Underground premises.

Sector	Structure	Geometry					
	Name	S/U	N.°	Length	Diameter or Width	Height	Volume
		-	-	m	m	m	m^3
1	Drive Beam Injector	S	1	2100	32	9	604800
	RF Power Distribution	S	3	75	20	10	15000
	CR1 and CR2	S	2	30	30	5	4500
3	Detectors Hall	S	1	100	25	25	62500
	IP - Electricity	S	1	80	20	6	9600
	IP - Reception	S	1	40	12	7	3360
	IP - Workshop	S	1	30	15	12	5400
	IP - Service Office	S	1	60	20	11	12600
	IP - Control	S	1	50	25	7	8750
	IP - Cryo	S	4	25	18	12	5400
	IP - Survey	S	1	100	8	4	3200
	IP - Gas	S	1	40	10	4	1600
	IP - Site Access Control	S	1	10	10	4	350
	Injection Hall	S	1	30	30	5	4500
4	Main Beam Injector	S	1	880	7	3	18480
	Booster	S	1	500	5	3	7500
	Compton Ring	S	1	30	30	5	4500
	Damping Rings	S	3	30	30	5	4500
	Target Halls (LINACs 1 and 2)	S	2	10	10	5	500
Shafts 2 & 3	Buildings Shaft 2 & 3 - Electricity	S	2	20	20	6	2400
	Buildings Shaft 2 & 3 - Workshop	S	2	30	15	12	5400
	Buildings Shaft 2 & 3 - Survey	S	2	10	5	4	200
	Buildings Shaft 2 & 3 - Access Control	S	2	10	10	4	350
	Buildings Shaft 2 & 3 - Shaft Access	S	2	35	20	25	17500

Table A2. Surface Buildings.



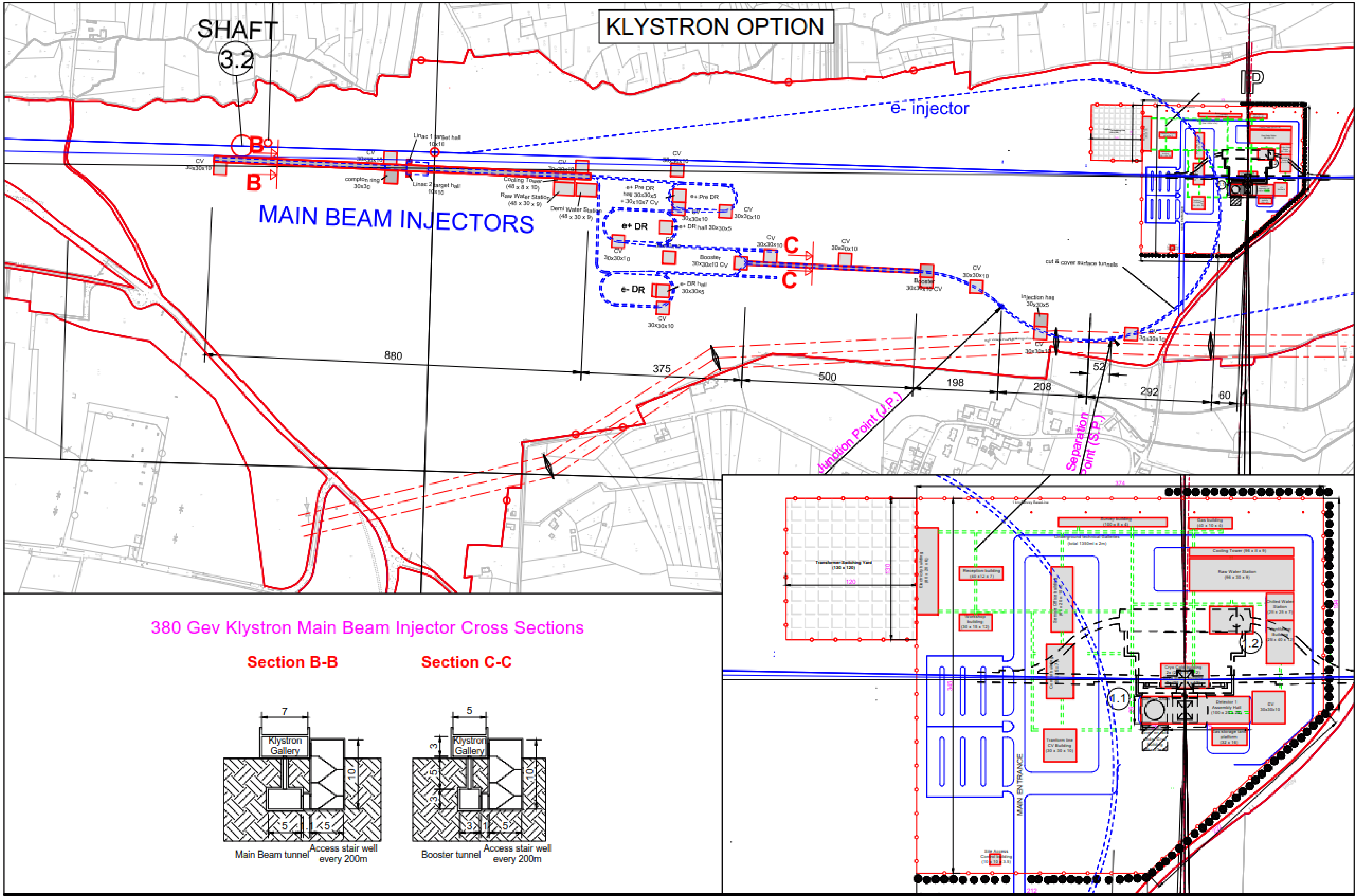
CLIC- MAIN / DRIVE BEAM INJECTORS AND EXPERIMENTAL AREA
SURFACE BUILDINGS LAYOUT

CERN

GROUP : GS-SE
CIVIL ENGINEERING
SUPERVISOR : J.OSBORNE
DESIGNER : P.SERAFINO

SCALE : 1/7500(A3_FORMAT)
DATE : 19-NOV-2018

CLIC.CE-1.1799.0005
SIZE 3
INDICE L



380 Gev Klystron Main Beam Injector Cross Sections

Section B-B

Section C-C

CLIC - 380 GeV KLYSTRON MAIN BEAM INJECTORS AND EXPERIMENTAL AREA SURFACE BUILDINGS LAYOUT

CERN

GROUP : GS-SE
CIVIL ENGINEERING
SUPERVISOR : J.OSBORNE
DESIGNER : P.SERAFINO

SCALE : 1/7500(A3_FORMAT)	DATE : 20-NOV-2018	
CLIC.CE-1.1799.0007	SIZE 3	INDICE C

Annex B –Heat Loads

The technical heat loads for the underground structures (U) and the corrective factor to account for possible modifications of the loads are presented below.

Sector	Structure	Geometry		Technical Heat Loads and Latent Heat Correction		
	Name	S/U	N.°	Tech Heat Load	Corrective F.	Final Heat Load
		-	-	kW	-	kW
1	Drive Beam Injector	U	1	456	1,0	456
	Frequency Multiplication - 3 way	U	1	162	1,0	162
	Frequency Multiplication - CR1	U	1	81	1,0	81
	Frequency Multiplication - CR1 to CR2	U	1	61	1,0	61
	Frequency Multiplication - CR2	U	1	101	1,0	101
	Transfer from CR2 to J.P.	U	1	113	1,0	113
2	Main Beam Dumps	U	2	28	1,1	31
	Drive Beam Dumps	U	8	5	1,1	6
	Drive Beam Turnaround	U	8	10	1,1	11
	UTRA	U	8	95	1,1	104
	UTRC	U	2	95	1,1	104
	Caverns 1.3 and 1.4	U	2	95	1,1	104
	Survey Cavern 2.1 and 3.1	U	2	0	1,1	0
	Additional Caverns 2.2 and 3.2	U	2	150	1,1	165
	Service Cavern	U	1	190	1,1	209
	BDS	U	1	442	1,1	486
	Tunnel BC2 e^+ & Main Beam Turn-Around e+	U	1	35	1,1	38,5
	Tunnel BC2 e^- & Main Beam Turn-Around e+	U	1	35	1,1	38,5
	BC2 Caverns	U	2	20	1,1	22
	Main Tunnel – Two-Beam	U	1	1347	1,1	1482
	Main Tunnel – Klystron	U	1	2628	1,1	2891
3	Transfer from J.P. to S.P.	U	1	225	1,0	225
	Transfer Lines Loop	U	1	230	1,0	230
	Transfer Lines e^+ from Surface to Tunnel	U	1	0	1,0	0
	Transfer Lines e^- from Surface to Tunnel	U	1	0	1,0	0
	Detectors Hall - Underground	U	1	108	1,1	118
4	Main Beam Injector	U	1	346	1,0	346
	Booster	U	1	201	1,0	201
	Transfer from Booster to J.P.	U	1	113	1,0	113
	Pre-Damping Ring	U	1	267	1,0	267
	Damping Ring e^+	U	1	342	1,0	342
	Damping Ring e-	U	1	342	1,0	342

The technical heat loads for the surface buildings (S) are presented below.

Sector	Structure	Geometry		Technical Heat Loads
	Name	S/U	N.°	Tech Heat Load
		-	-	kW
1	Drive Beam Injector	S	1	1683
	RF Power Distribution	S	3	0
	CR1 and CR2	S	2	382
3	Detectors Hall - Surface	S	1	100
	IP - Electricity	S	1	0
	IP - Reception	S	1	0
	IP - Workshop	S	1	0
	IP - Service Office	S	1	0
	IP - Control	S	1	0
	IP - Cryo	S	4	0
	IP - Survey	S	1	0
	IP - Gas	S	1	0
	IP - Site Access Control	S	1	0
	Injection Hall	S	1	170
4	Main Beam Injector	S	1	581
	Booster	S	1	463
	Compton Ring	S	1	0
	Damping Rings	S	3	168
	Target Halls (LINACs 1 and 2)	S	2	0
Shafts 2 & 3	Buildings Shaft 2 & 3 - Electricity	S	2	0
	Buildings Shaft 2 & 3 - Workshop	S	2	0
	Buildings Shaft 2 & 3 - Survey	S	2	0
	Buildings Shaft 2 & 3 - Access Control	S	2	0
	Buildings Shaft 2 & 3 - Shaft Access	S	2	0

The surface buildings, exposed to the elements, have external heat loads as well. The following table summarizes these loads.

Sector	Structure	Geometry		Winter & Summer External Loads	
	Name	S/U	N.°	Density	Load
		-	-	W/m²	kW
1	Drive Beam Injector	S	1	50	3360
	RF Power Distribution	S	3	150	450
	CR1 and CR2	S	2	50	45
3	Detectors Hall - Surface	S	1	50	125
	IP - Electricity	S	1	150	240
	IP - Reception	S	1	75	36
	IP - Workshop	S	1	75	68
	IP - Service Office	S	1	75	180
	IP - Control	S	1	75	94
	IP - Cryo	S	4	150	135
	IP - Survey	S	1	150	120
	IP - Gas	S	1	150	60
	IP - Site Access Control	S	1	75	8
	Injection Hall	S	1	50	45
4	Main Beam Injector	S	1	50	308
	Booster	S	1	50	125
	Compton Ring	S	1	150	135
	Damping Rings	S	3	50	45
	Target Halls (LINACs 1 and 2)	S	2	150	15
Shafts 2 & 3	Buildings Shaft 2 & 3 - Electricity	S	2	75	30
	Buildings Shaft 2 & 3 - Workshop	S	2	75	68
	Buildings Shaft 2 & 3 - Survey	S	2	75	4
	Buildings Shaft 2 & 3 - Access Control	S	2	75	8
	Buildings Shaft 2 & 3 - Shaft Access	S	2	75	158

To compute the total heat load for each surface building, one must add the technical and the external loads in the tables above.

Annex C – Shallow Underground Structures

The shallow underground premises are ventilated by a push-and-pull ventilation layout. The system is represented below.

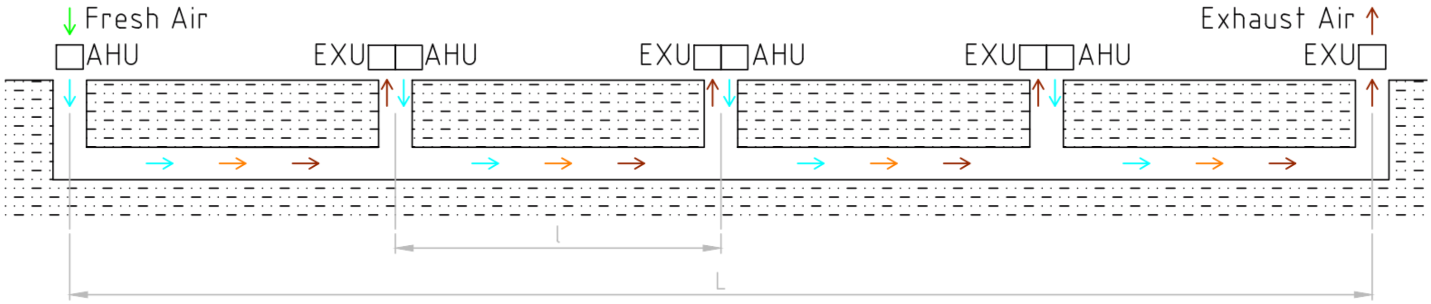


Figure C1. Ventilation layout for the shallow underground structures.

Air is extracted from the exterior and circulates in the tunnels longitudinally. It exchanges heat with the equipment inside the tunnels and increases its temperature. It is then extracted at the next shaft, treated and reinjected in the tunnel. The space between the shafts, l, is defined so that the velocity is lower than 3,5 m/s, according to the following expressions:

$$\frac{Q_s}{N} = V A_f \rho C_p \Delta T \; ; \; l = \frac{L}{N} .$$

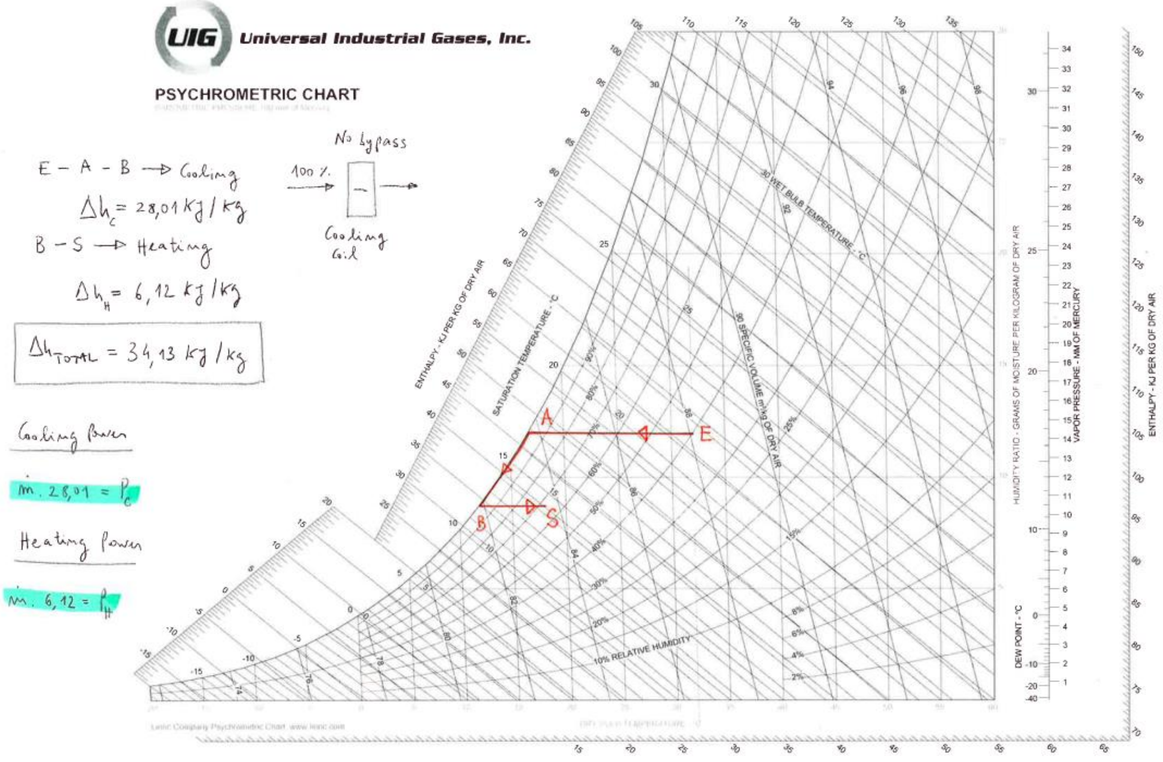
If we combine the two, we obtain

$$l = \frac{V A_f \rho C_p \Delta T \; L}{Q_s} ;$$

where Q_s is the sensible heat load in the tunnel, N is the number of partitions (4 in the schematic above), V is the maximum velocity $(3{,}5 m/s)$, A_f is the free transversal area in the tunnel, defined as 70% of the total area. ρ is the air density, C_p is its specific heat and ΔT is the temperature difference between shafts, set to 5°C. Finally, L is the total length of the tunnel.

The air-handling units at intermediate points have to cope with the sensible heat that is released by the equipment in the respective tunnel's sector. We recall that no latent heat loads are expected to be released. However, there are air-handling units that have to condition fresh air, such as those at the beginning of the tunnel. Hence, their capacity has to be greater to withstand peak summer and winter conditions. The flow rates in those units are usually large and as a consequence, we have decided to find a way of minimizing the installed cooling power. A bypass is currently foreseen – a fraction of the fresh air is bypassed and the rest crosses the cooling coil. Briefly, we are decreasing the temperature of the cooling coil but treating only a fraction of the total flow rate. The result is a reduction of 20% in the installed cooling power. The psychometric evolutions, with and without bypass, are shown in the following page for comparison purposes.

Further and more detailed studies are required to understand the feasibility of this system and to determine if it is able to provide energetic and cost benefits throughout the year.



E – A – B → Cooling

$\Delta h_C = 28{,}01$ kJ/kg

B – S → Heating

$\Delta h_H = 6{,}12$ kJ/kg

$\boxed{\Delta h_{TOTAL} = 34{,}13 \text{ kJ/kg}}$

Cooling Power

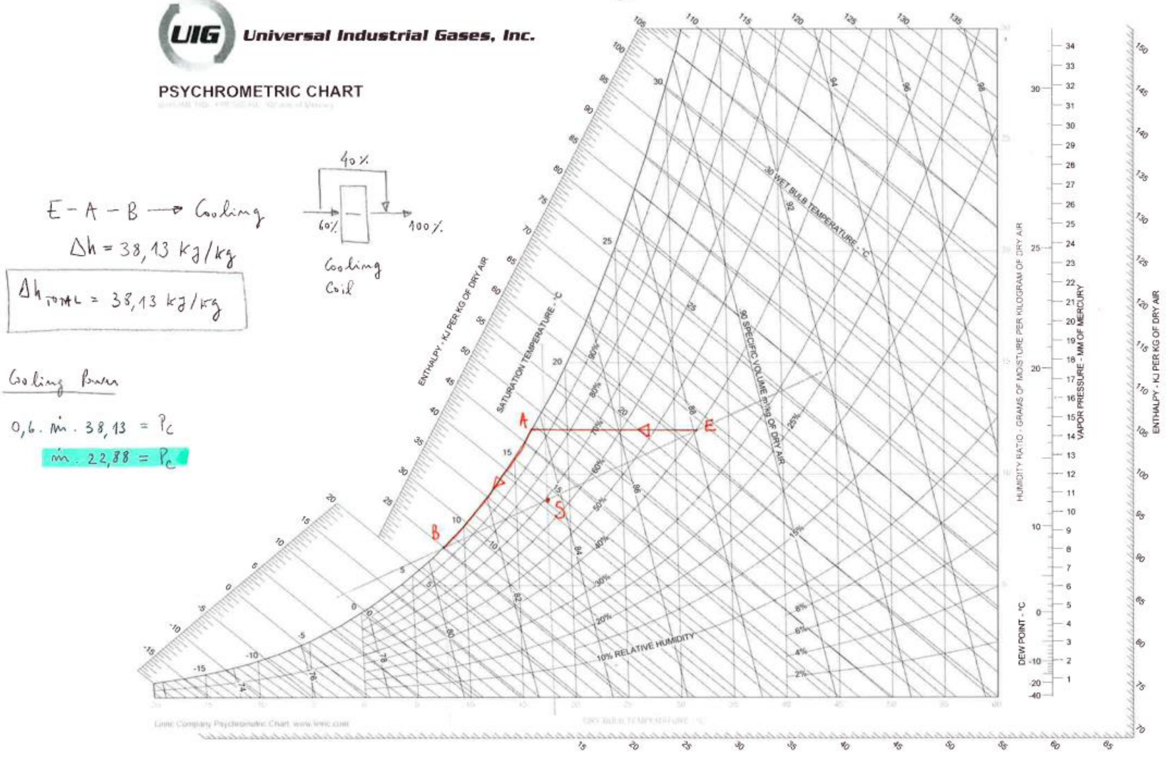
$\dot{m} \cdot 28{,}01 = P_C$

Heating Power

$\dot{m} \cdot 6{,}12 = P_H$

Figure C2. Psychometric chart without fresh air bypass. "E" stands for the "External" conditions and S for "Supply" conditions.

40 % Bypass



E – A – B → Cooling

$\Delta h = 38{,}13$ kJ/kg

$\boxed{\Delta h_{TOTAL} = 38{,}13 \text{ kJ/kg}}$

Cooling Power

$0{,}6 \cdot \dot{m} \cdot 38{,}13 = P_C$

$\dot{m} \cdot 22{,}88 = P_C$

Figure C3. Psychometric chart with 40% fresh air bypass.

We have described the method employed to set the distance between the shafts and to estimate the cooling power at the air-handling units. The following table presents the air-handling and extraction units for the shallow underground facilities.

Sector	Structure		Two-Beam Machine								Klystron Machine							
			Air-Handling Units					Extraction Units			Air-Handling Units					Extraction Units		
	Name	N°	N° Units	N° Redundant Units	Cooling Power	Heating Power	Run Mode Flow Rate	N° Units	N° Redundant Units	Flow Rate	N° Units	N° Redundant Units	Cooling Power	Heating Power	Run Mode Flow Rate	N° Units	N° Redundant Units	Flow Rate
		-	-	-	kW	kW	m^3/h	-	-	m^3/h	-	-	kW	kW	m^3/h	-	-	m^3/h
1	Drive Beam Injector U	1	1	1	691	900	90730	3	3	90730	-	-	-	-	-	-	-	-
			2	2	152	0	90730											
	Frequency Multiplication U	1	1	1	198	96	96716	1	1	96716	-	-	-	-	-	-	-	-
			1	1	81	48	48358	1	1	48358								
			1	1	61	36	36269	1	1	36269								
			1	1	245	240	60448	1	1	60448								
	Transfer Line - CR2 to J.P.	1	1	1	152	67	67164	0	0	0								
2/3	Transfer Line - J.P. to S.P.	1	1	1	225	46	134328	1	1	134328	1	1	225	46	134328	1	1	134328
	Transfer Line - Loop	1	2	2	115	112	68657	2	2	68657	2	2	115	112	68657	2	2	68657
	Transfer Line - e^+	1	1	1	125	233	16433	0	0	0	1	1	125	233	16433	0	0	0
	Transfer Line - e^-	1	1	1	190	353	24905	0	0	0	1	1	190	353	24905	0	0	0
4	Main Beam Injector U	1	1	1	524	682	68780	2	2	68780	1	1	524	682	68780	2	2	68780
			2	2	115	0	68780				2	2	115	0				
	Booster U	1	2	2	101	45	60062	3	3	60062	2	2	101	45	60062	3	3	60062
	Transfer Line - Booster to J.P.	1	1	1	155	70	67164	1	1	134328	1	1	155	70	67164	1	1	67164
	Pre-Damping Ring U	1	1	1	833	946	159185	1	1	159185	1	1	833	946	159185	1	1	159185
	Damping Rings e+ U	1	1	1	607	444	203951	1	1	203951	1	1	607	444	203951	1	1	203951
	Damping Rings e- U	1	1	1	342	103	203951	1	1	203951	1	1	342	103	203951	1	1	203951
	Damping Rings Area	1	0	0	0	0	0	2	2	5000	0	0	0	0	0	2	2	5000
			0	0	0	0	0	1	1	55062	0	0	0	0	0	1	1	55070
			0	0	0	0	0	1	1	63780	0	0	0	0	0	1	1	63790

Table C1. Air-handling units and extraction units for the shallow underground facilities.

The following schematics are top views of the injectors, booster, damping rings, frequency multiplication and transfer lines and they illustrate the ventilation layout for run and purge modes.

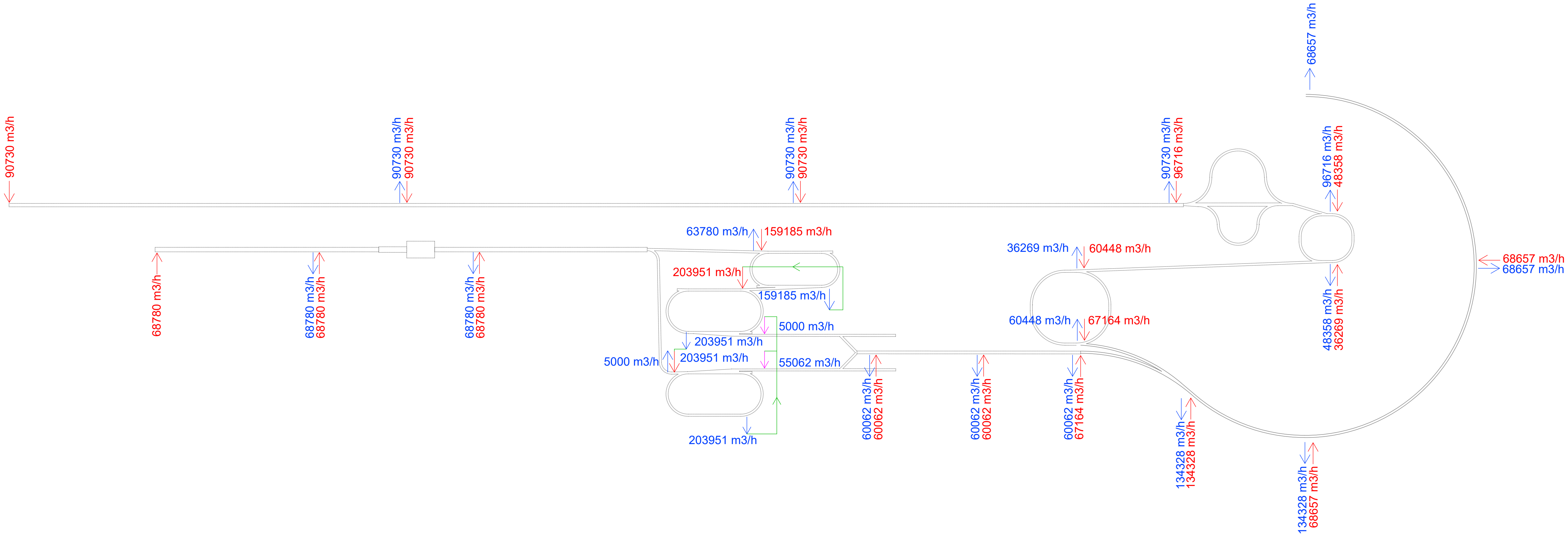
DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

GENERAL TOLERANCES GENERALES

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE



↓ AHU without cooling coil

↓ AHU with cooling coil

↓ Extraction unit

↓ Ducts to transfer air

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Ventilation, Injectors
DB Machine

ECHELLE SCALE			
—	DES/DRA.	Pedro	2019-01-21
	CONTROLLED		
	RELEASED		
	APPROVED		

REMPLACE/REPLACES

CERN

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC
—

SIZE 3

IND.

DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

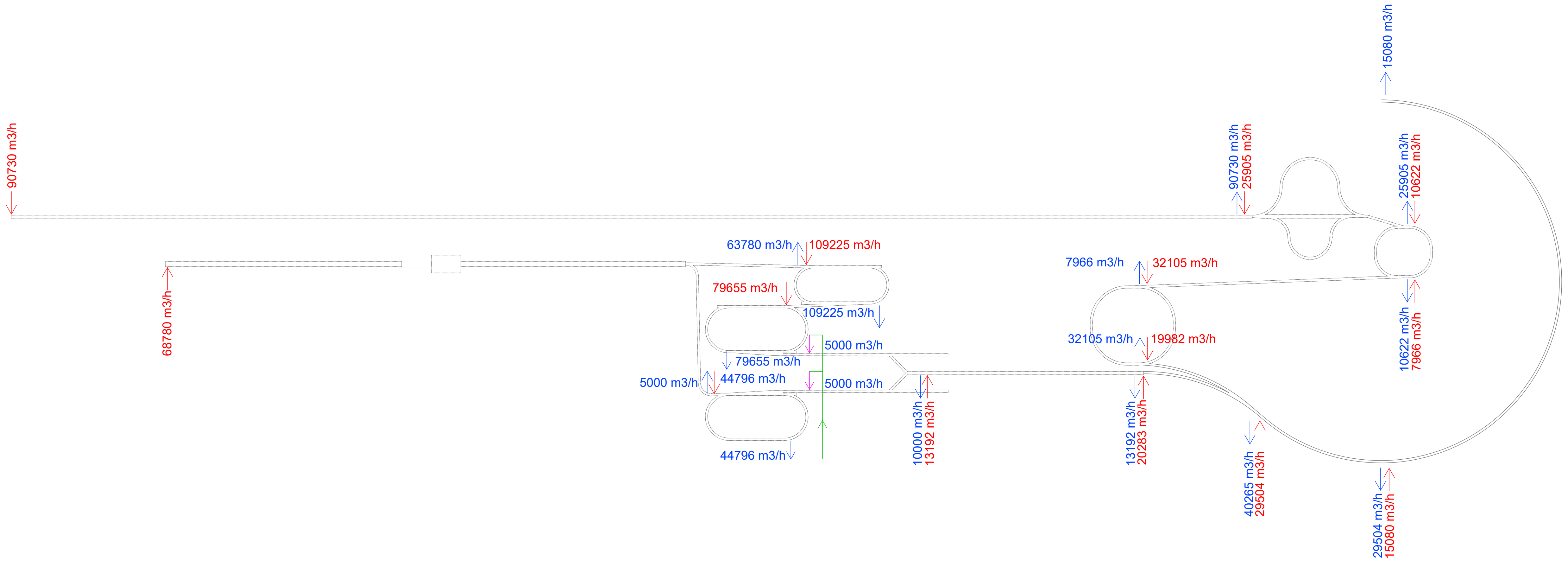
GENERAL TOLERANCES GENERALES

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

Ce dessin ne peut etre utilise a des fins commerciales sans autorisation ecrite
This drawing may not be used for commercial purposes without written authorisation



↓ AHU without cooling coil

↓ AHU with cooling coil

↓ Extraction unit

↓ Ducts to transfer air

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Max. Purge Summer, Injectors DB Machine

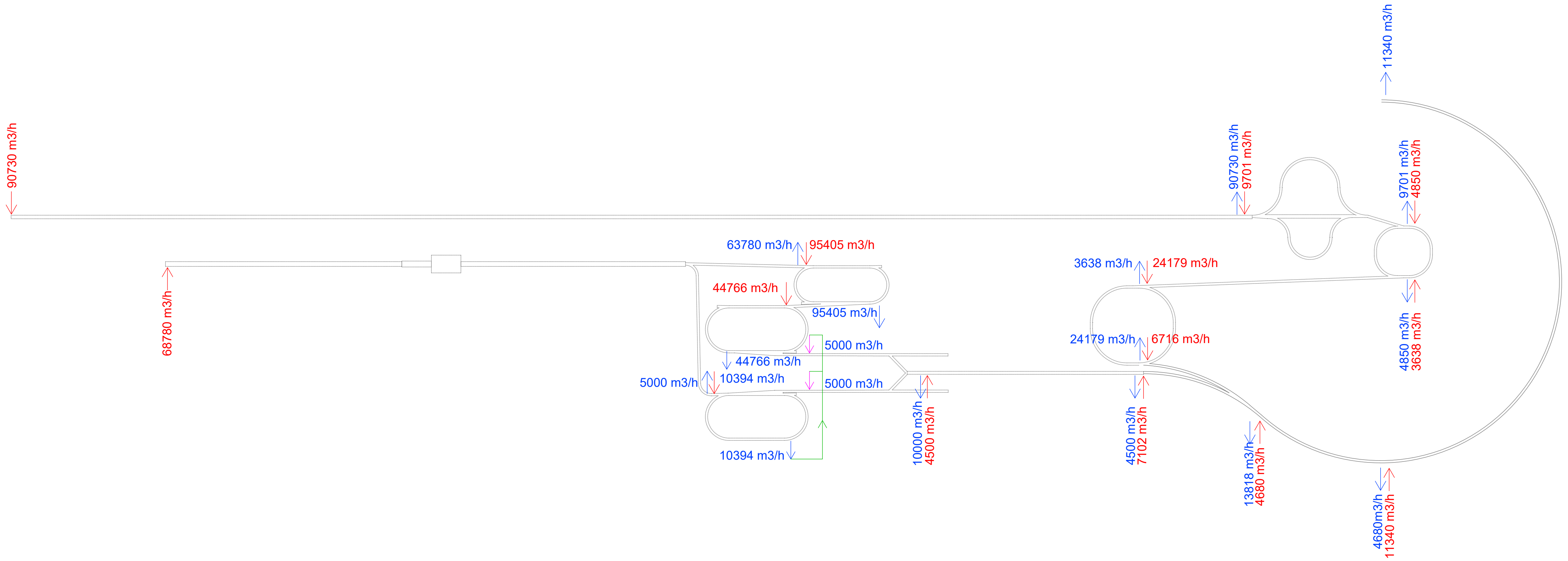
ECHELLE SCALE —	DES/DRA. Pedro	2019-01-21
	CONTROLLED	
	RELEASED	
	APPROVED	
	REMPLACE/REPLACES	

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC —

SIZE 3

IND.



↓ AHU without cooling coil

↓ AHU with cooling coil

↓ Extraction unit

↓ Ducts to transfer air

DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

GENERAL TOLERANCES GENERALES

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

Ce dessin ne peut etre utilise a des fins commerciales sans autorisation ecrite
This drawing may not be used for commercial purposes without written authorisation

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Max. Purge Winter, Injectors DB Machine

ECHELLE SCALE —	DES/DRA. Pedro	2019-01-21
	CONTROLLED	
	RELEASED	
	APPROVED	

REMPLACE/REPLACES

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC
—

SIZE 3

IND.

Annex D – Deep Underground Facilities

The HVAC details of the deep underground structures are herewith presented. We have set a ΔT of 5°C for all these facilities – we supply at a temperature that is 5°C below the ambient temperature.

The main tunnel is one of the most relevant structures for the CLiC. There are particular requirements for these areas, such as the need for a relatively stable temperature.
Our studies considered those aspects, but further and more detailed analysis are required to ensure the satisfaction of all the requests.

Air-handling units (AHU) are placed in the caverns for the drive beam-based machine. A ducting system has been set up to supply and extract air from that space. During purge mode, units that are placed at the surface are switched on to provide a push-and-pull configuration and replace the air in the tunnel.

The following images (top and side views and cross section) illustrate the ventilation layout for the two operating modes.

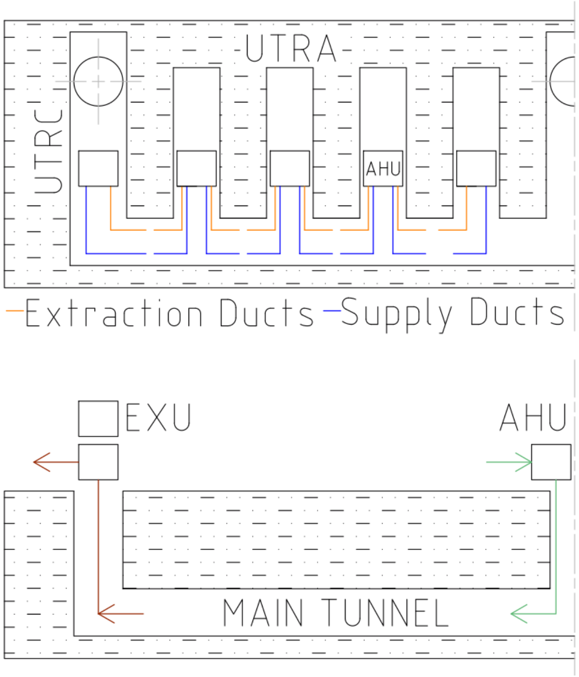


Figure D1. Ventilation layout for the run and purge modes in the drive beam option.

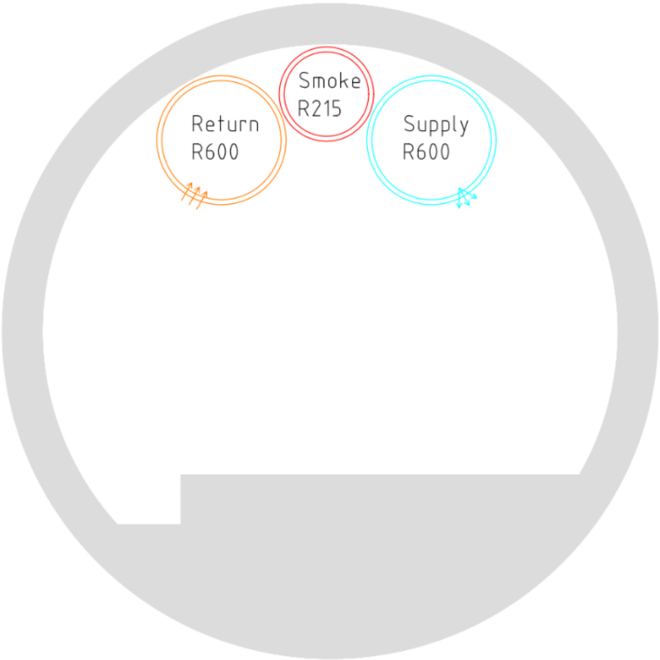


Figure D2. Cross section of the main tunnel for the drive beam machine.

In the klystron-based machine, air is treated by a number of AHUs located in the service compartment, below the tunnel's floor. These units are connected to diffusers located in the main tunnel. Additionally, extraction units are located in the caverns and drive the air from the tunnel to the service compartment, where they discharge it. During purge mode, a push-and-pull configuration is set, similarly to the drive beam machine case.

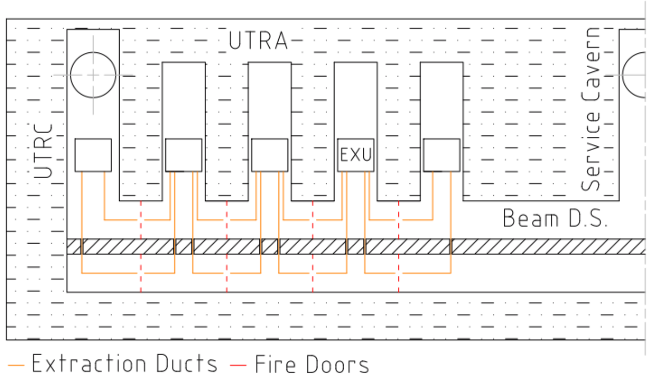


Figure D3. Ventilation layout for run mode in the klystron machine.

Side	Space between diffusers
Klystrons	87 m
Main LINAC	24 m

Table D1. Spacing in between diffusers.

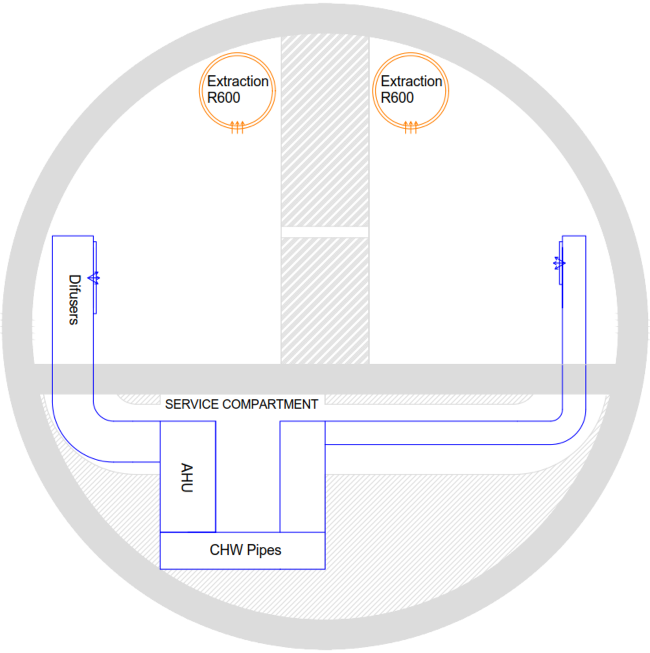


Figure D4. Cross section of the main tunnel for the klystron machine.

A summary table with the ventilation infrastructure is presented in table D2. We recall that for some deep underground structures, as the main tunnel, we have space constraints. For this reason, we did not add a redundant unit.

Structure		Two-Beam Machine				Klystron Machine			
		Air-Handling Units				Air-Handling Units			
Name	N°	N° Units	N° Redundant Units	Cooling Power	Flow Rate	N° Units	N° Redundant Units	Cooling Power	Flow Rate
	-	-	-	kW	m^3/h	-	-	kW	m^3/h
Accelerator Gallery – LINAC side	1	6	0	185	100532	8	0	193	104541
		4	0	93	50266		0		
Accelerator Gallery – Klystron side	1	-	-	-	-	16	0	84	45775

Table D2. Ventilation infrastructure for the accelerator galleries for the drive beam and klystron machines.

The following table presents the ventilation infrastructure for the remaining deep underground facilities.

Sector	Structure		Two-Beam Machine								Klystron Machine							
			Air-Handling Units					Extraction Units			Air-Handling Units					Extraction Units		
	Name	N°	N° Units	N° Redundant Units	Cooling Power	Heating Power	Flow Rate	N° Units	N° Redundant Units	Flow Rate	N° Units	N° Redundant Units	Cooling Power	Heating Power	Flow Rate	N° Units	N° Redundant Units	Flow Rate
		-	-	-	kW	kW	m^3/h	-	-	m^3/h	-	-	kW	kW	m^3/h	-	-	m^3/h
2/3	Detectors Hall U	1	1	1	499	649	64179	1	1	64179	1	1	499	649	64179	1	1	64179
	Main Beam Dumps	2	1	1	31	0	16561	-	-	-	1	1	31	0	16561	-	-	-
	Drive Beam Dumps	8	1	1	6	0	2985	-	-	-	-	-	-	-	-	-	-	-
	Drive Beam Turnaround	8	1	0	11	0	5970	-	-	-	-	-	-	-	-	-	-	-
	UTRA	8	1	0	104	0	56693	-	-	-	1	0	104	0	56693	-	-	-
	UTRC	2	1	0	104	0	56693	1	1	56693	1	0	104	0	56693	1	1	56693
	Caverns 1.3 and 1.4	2	1	1	104	0	56693	-	-	-	1	1	104	0	56693	-	-	-
	Survey Cavern 2.1 and 3.1	2	1	1	0	0	3000	-	-	-	1	1	0	0	3000	-	-	-
	Additional Caverns 2.2 and 3.2	2	1	1	165	0	89552	-	-	-	1	1	165	0	89552	-	-	-
	Service Cavern	1	2	1	104	0	56693	2	2	56693	2	1	104	0	56693	2	2	56693
	BDS	1	4	2	121	0	65923	-	-	-	4	2	121	0	65923	-	-	-
	Main Beam Turnaround e^+/e^- and Tunnel BC2 e^+/e^-	2	1	1	39	0	20896	-	-	-	1	1	39	0	20896	-	-	-
	BC2 Caverns	2	1	1	22	0	11940	-	-	-	1	1	22	0	11940	-	-	-
	Tunnel Purge	-	4	2	330	429	43262	4	2	43262	8	2	530	689	69454	8	2	69454

Table D3. Ventilation Infrastructure for the deep underground premises. The main tunnel was presented in table D2.

Annex E – Surface Buildings

Sector	Structure		Two-Beam Machine					Klystron Machine				
			Air-Handling Units					Air-Handling Units				
	Name	N°	N° Units	N° Redundant Units	Cooling Power	Heating Power	Flow Rate	N° Units	N° Redundant Units	Cooling Power	Heating Power	Flow Rate
		-	-	-	kW	kW	m^3/h	-	-	kW	kW	m^3/h
1	Drive Beam Injector S	1	40	4	126	84	75270					
	RF Power Distribution	3	1	1	450	450	10500	-	-	-	-	-
	CR1 S and CR2 S	2	4	1	107	11	63731					
2/3	Detectors Hall S	1	1	1	113	63	67164	1	1	334	63	67164
	IP - Electricity	1	1	1	240	240	6720	1	1	240	240	6720
	IP - Reception	1	1	0	36	36	2352	1	0	36	36	2352
	IP - Workshop	1	1	0	68	68	3780	1	0	68	68	3780
	IP - Service Office	1	1	0	180	180	8820	1	0	180	180	8820
	IP - Control	1	1	0	94	94	6125	1	0	94	94	6125
	IP - Cryo	4	1	1	135	135	3780	1	1	135	135	3780
	IP - Survey	1	1	0	120	120	2240	1	0	120	120	2240
	IP - Gas	1	1	0	60	60	1120	1	0	60	60	1120
	IP - Site Access Control	1	1	0	8	8	245	1	0	8	8	245
	Injection Hall	1	2	1	108	23	64179	2	1	108	23	64179
4	Main Beam Injector S	1	9	3	99	34	58967	9	3	99	34	58967
	Booster S	1	6	2	98	21	58509	6	2	98	21	58509
	Compton Ring	1	1	1	135	135	3150	1	1	135	135	3150
	Damping Rings	3	2	1	106	23	63475	2	1	106	23	63475
	Target Halls (LINACs 1 and 2)	2	1	1	15	15	350	1	1	15	15	350
Shafts 2 & 3	Building Shaft 2 & 3 - Electricity	2	1	1	30	30	1680	1	1	30	30	1680
	Building Shaft 2 & 3 - Workshop	2	1	0	68	68	3780	1	0	68	68	3780
	Building Shaft 2 & 3 - Survey	2	1	1	4	4	140	1	1	4	4	140
	Building Shaft 2 & 3 - Access Control	2	1	0	8	8	245	1	0	8	8	245
	Building Shaft 2 & 3 - Shaft Access	2	1	0	158	158	12250	1	0	158	158	12250

Table E1. Ventilation infrastructure for the surface buildings.

Annex F – HVAC Water Circuits

The following tables present the technical data for the primary circuits that refrigerate the chillers cooled by water.

Sector	Drive Beam-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
1	Drive Beam Injectors S/U, Frequency Multiplication and RF Power Distribution	1062	9861	350	250	5000	6	229
	Drive Beam Injector S/U, Frequency Multiplication and RF Power (secondary circuits for chillers)	204	1896	200	125	150	2	16
		198	1837	200	125	150	2	15
		198	1837	200	125	150	2	15
		273	2537	200	200	150	2	22
		63	585	125	150	150	2	5
		63	585	125	150	151	2	5
		63	585	125	150	152	2	5
	CR1 S, CR2 S, Frequency Multiplication and Transfer Line - CR2 to J.P.	80	739	125	200	700	3	23
		115	1071	150	150	700	3	
2	Main Tunnel Purge	185	1716	150	200	250	3	16
	Main tunnel (Two-Beam Machine)	571	5296	250	250	250	3	108
3	Detectors Hall S/U, Injection Hall, Transfer Lines - Loop and J.P. to S.P.	239	2222	150	250	2000	4	
	Buildings IP	188	1748	300	200	500	3	20
4	Main Beam Injector S/U, Compton Ring, Target Halls (LINACs 1 and 2)	253	2350	200	150	2500	5	41
	Pre-Damping Ring S/U, Damping Rings e^+, e^- S/U, Booster S/U and Transfer Line - Booster to J.P.	471	4373	250	250	1500	4	66

Table F1. Primary water circuits to cool the chillers for the drive beam-based machine.

Sector	Klystron-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
2	Main tunnel (Klystron Machine)	749	6956	300	200	500	3,0	78
	Main Tunnel Purge	384	3566	250	125	250	2,3	31
3	Detectors Hall S/U, Injection Hall, Transfer Lines - Loop and J.P. to S.P.	234	2169	150	250	2000	3,8	31
	Buildings IP	188	1748	300	200	500	3,0	20
4	Main Beam Injector S/U, Compton Ring, Target Halls (LINACs 1 and 2)	253	2350	200	150	2500	4,6	41
	Pre-Damping Ring S/U, Damping Rings e^+, e^- S/U, Booster S/U and Transfer Line - Booster to J.P.	471	4373	250	250	1500	4,0	66

Table F2. Primary water circuits to cool the chillers for the klystron-based machine.

The following tables present the technical chilled water circuits.

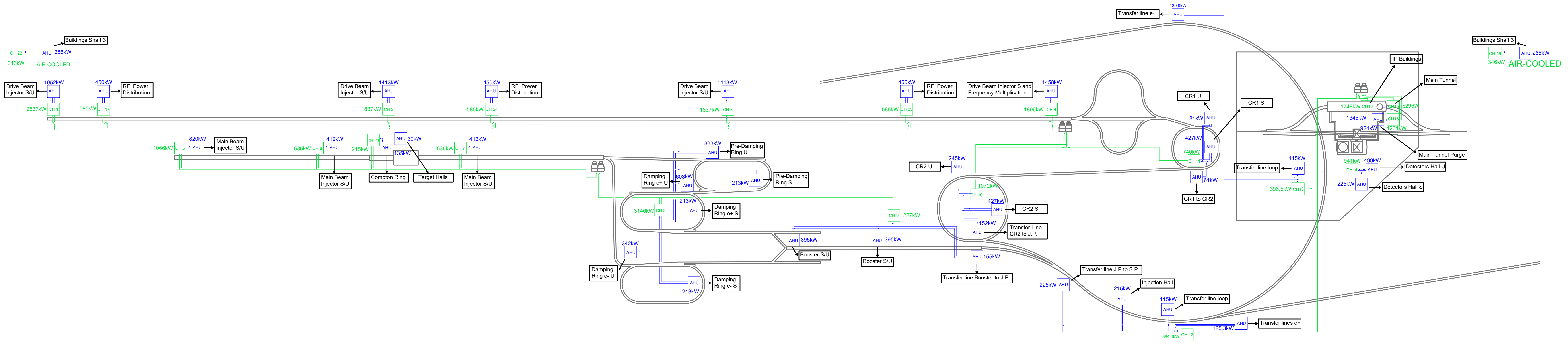
Drive Beam-Based Machine							
Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
	m^3/h	kW	mm	Pa/m	m	bar	kW
Chiller # 1	336	1952	200	300	100	3	30
Chiller # 2	243	1413	200	200	100	3	21
Chiller # 3	243	1413	200	200	100	3	21
Chiller # 4	251	1458	200	200	100	3	21
Chiller # 5	141	820	150	250	100	3	12
Chiller # 6	71	412	125	200	100	3	6
Chiller # 7	71	412	125	200	100	3	6
Chiller # 8	417	2420	250	200	2000	7	78
Chiller # 9	163	944	150	300	1500	8	33
Chiller # 10	142	824	150	250	600	5	17
Chiller # 11	98	569	150	150	500	4	10
Chiller # 12	117	680	150	125	1200	5	14
Chiller # 13	53	305	80	200	1000	5	7
Chiller # 14	125	724	100	300	500	5	15
Chiller # 15 Shaft, Left	351	2037	250	125	500	4	34
Chiller # 15 Shaft, Right	351	2037	250	125	500	4	34
Chiller # 15 M. Tunnel, Left (S. Circuit)	351	2037	250	125	10000	8	80
Chiller # 15 M. Tunnel, Right (S. Circuit)	351	2037	250	125	10000	8	80
Chiller # 16	227	1320	150	300	250	4	23
Chiller # 17	77	450	125	200	250	3	8
Chiller # 18	232	1345	250	150	1000	5	28
Chiller # 19	46	266	100	300	400	4	5
Chiller # 22	46	266	100	300	400	4	5
Chiller # 23	28	165	100	100	250	3	2
Chiller # 24	77	450	125	200	250	3	8
Chiller # 25	77	450	125	200	250	3	8

Table F3. Chilled water circuits for the drive beam-based machine.

Klystron-Based Machine							
Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
	m^3/h	kW	mm	Pa/m	m	bar	kW
Chiller # 5	141	820	150	250	100	3	12
Chiller # 6	71	412	125	200	100	3	6
Chiller # 7	71	412	125	200	100	3	6
Chiller # 8	417	2420	250	200	2000	7	78
Chiller # 9	163	944	150	300	1500	8	33
Chiller # 12	117	680	150	125	1200	5	14
Chiller # 13	53	305	80	200	1000	5	7
Chiller # 14	118	683	100	300	500	5	14
Chiller # 15 Shaft, Left	461	2675	250	200	500	4	49
Chiller # 15 Shaft, Right	461	2675	250	200	500	4	49
Chiller # 15 M. Tunnel, Left (S. Circuit)	461	2675	300	90	10000	7	83
Chiller # 15 M. Tunnel, Right (S. Circuit)	461	2675	300	90	10000	7	83
Chiller # 16	473	2743	250	150	250	3	43
Chiller # 18	232	1345	250	150	1000	5	28
Chiller # 19	46	266	100	300	400	4	5
Chiller # 22	46	266	100	300	400	4	5
Chiller # 23	28	165	100	100	250	3	2

Table F4. Chilled water circuits for the klystron-based machine.

The layouts of the primary and chilled water circuits can be found below.



— Primary water circuits

— Chilled water circuits

AHU Air-Handling Unit

CH # Chiller

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

GENERAL TOLERANCES GENERALES

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Chilled Water, Injectors and IP
DB Machine

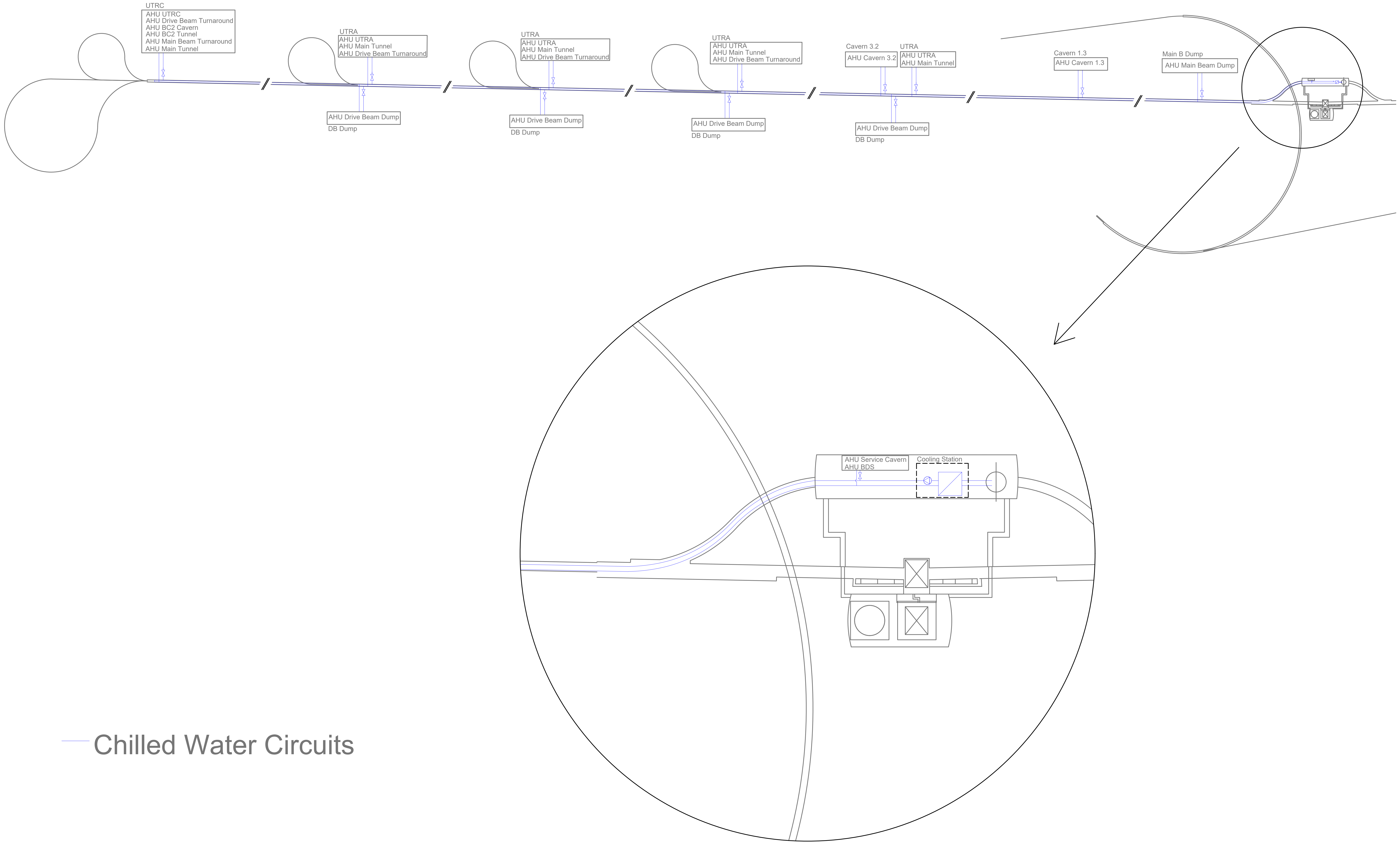
ECHELLE SCALE	DES/DRA.	Pedro	2019-01-21
—	CONTROLLED		
	RELEASED		
	APPROVED		
	REMPLACE/REPLACES		

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

DAC

SIZE 2

IND.



GENERAL TOLERANCES GENERALES	DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
	USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
	MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

Chilled Water, Main Tunel
DB Machine

ECHELLE SCALE —	DES/DRA.	Pedro	2019–01–21
	CONTROLLED		
	RELEASED		
	APPROVED		
	REMPLACE/REPLACES		

CERN

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC
—

SIZE	IND.
2	

Annex G – Cooling Heat Loads

The heat released to water by equipment in the underground (U) and surface buildings (S) can be found in the table below.

Drive Beam Machine

Sectors	Name	Geometry		Refrigeration Heat Load
		S/U	N°	
		-	-	kW
1	Drive Beam Injector	U	1	5356
	Drive Beam Injector	S	1	14191
	Frequency Multiplication	U	1	12141
	Transfer from CR2 to J.P.	U	1	1028
	Building - CR1 and CR2	S	2	3440
	Building - RF Power Distribution	S	3	0
2	Main Beam Dumps	U	2	2746
	Drive Beam Dumps	U	8	533
	Drive Beam Turnaround	U	8	736
	UTRA	U	8	869
	UTRC	U	2	869
	Caverns 1.3 and 1.4	U	2	869
	Survey Cavern 2.1 and 3.1	U	2	0
	Additional Caverns 2.2 and 3.2	U	2	1000
	Service Cavern	U	1	1739
	BDS	U	1	2135
	Main Tunnel – Two-Beam	U	1	18563
	Main Beam Turn-Around e+/e- and Tunnel BC2 e+/e-	U	2	1175
	BC2 Caverns	U	2	0
	Main Tunnel Purge - 2 Beam Machine	U	1	0
3	Transfer from J.P. to S.P.	U	1	2055
	Transfer Lines Loop	U	1	2101
	Transfer Lines e+ from Surface to Tunnel	U	1	108
	Transfer Lines e- from Surface to Tunnel	U	1	120
	Building - Injection Hall	S	1	1547
	Detectors Hall - Underground	U	1	2043
	Detectors Hall - Surface	S	1	900
	Buildings IP	S	1	0

Drive Beam Machine				
Sectors	Name	Geometry		Refrigeration Heat Load
		S/U	N°	
		-	-	kW
4	Main Beam Injector	U	1	3886
	Main Beam Injector	S	1	5126
	Booster	U	1	1811
	Booster	S	1	4239
	Transfer from Booster to J.P.	U	1	1028
	Pre-Damping Ring	U	1	2733
	Damping Ring e+	U	1	2681
	Damping Ring e-	U	1	2681
	Building - Damping Rings	S	3	1447
	Building - Compton Ring	S	1	0
	Buildings - Target Halls (LINACs 1 and 2)	S	2	0

Table G1. Cooling loads from equipment - drive beam-based machine.

Klystron Machine				
Sectors	Name	Geometry		Refrigeration Heat Load
		S/U	N°	
		-	-	kW
2	Main Beam Dumps	U	2	2746
	UTRA	U	8	869
	UTRC	U	2	869
	Caverns 1.3 and 1.4	U	2	869
	Survey Cavern 2.1 and 3.1	U	2	0
	Additional Caverns 2.2 and 3.2	U	2	1000
	Service Cavern	U	1	1739
	BDS	U	1	2135
	Main Beam Turn-Around e+/e- and Tunnel BC2 e+/e-	U	2	1175
	BC2 Caverns	U	2	0
	Main Tunnel - Klystron, K side	U	1	24778
	Main Tunnel - Klystron, LINAC side	U	1	27128
	Main Tunnel Purge - Klystron	U	1	0
3	Transfer from J.P. to S.P.	U	1	2055
	Transfer Lines Loop	U	1	2101
	Transfer Lines e+ from Surface to Tunnel	U	1	108
	Transfer Lines e- from Surface to Tunnel	U	1	120
	Building - Injection Hall	S	1	1547
	Detectors Hall - Underground	U	1	2043
	Detectors Hall - Surface	S	1	900
	Buildings IP	S	1	0
4	Main Beam Injector	U	1	3886
	Main Beam Injector	S	1	5126
	Booster	U	1	1811
	Booster	S	1	4239
	Transfer from Booster to J.P.	U	1	1028
	Pre-Damping Ring	U	1	2733
	Damping Ring e+	U	1	2681
	Damping Ring e-	U	1	2681
	Building - Damping Rings	S	3	1447
	Building - Compton Ring	S	1	0
	Buildings - Target Halls (LINACs 1 and 2)	S	2	0

Table G2. Cooling loads from equipment – klystron-based machine.

Annex H – Cooling Water Circuits

The data concerning the primary circuits are presented in the tables below.

Sector	Drive Beam-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
1	Drive Beam Injector U	577	5356	250	275	250	3	54
	Drive Beam Injector S	1529	14191	400	300	250	3	146
	Frequency Multiplication Circuit a)	349	3238	250	150	250	2	29
	Frequency Multiplication Circuit b), CR1 S, CR2 S and Transfer Line - CR2 to J.P.	1811	16811	450	200	250	3	157
2	Accelerator - LINAC (Two-Beam Machine)	2000	18563	450	200	650	3	229
	Main Tunnel (other equipment, Two-Beam Machine)	3695	34300	600	200	650	3	423
3	Injection Hall and Transfer Lines - e^+/e^- , Loop, J.P to S.P, Detectors Hall S / U - Equipment	639	5931	300	150	600	3	64
	Detectors S	97	900	150	125	900	3	11
	Detectors U	220	2043	200	150	900	3	26
4	Main Beam Injector U	419	3886	250	150	250	2	35
	Main Beam Injector S	552	5126	250	250	250	3	50
	Booster S/U, Damping Ring e^- S/U, and Transfer Line - Booster to J.P.	1207	11205	400	150	250	2	100
	Pre-Damping Ring S/U, Damping Ring e^+ S/U	895	8307	350	200	250	3	78

Table H.1. Primary circuits for the drive beam-based machine.

Sector	Klystron-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
2	Accelerator - Klystron (Klystron Machine)	2669	24778	500	250	650	4	336
	Accelerator - LINAC (Klystron Machine)	2922	27128	500	250	650	4	368
	Main Tunnel (other equipment, Klystron Machine)	2601	24149	500	200	650	3	298
3	Injection Hall and Transfer Lines - e^+/e^- , Loop, J.P to S.P, Detectors Hall S / U - Equipment	639	5931	300	150	600	3	64
	Detectors S	97	900	150	125	900	3	11
	Detectors U	220	2043	200	150	900	3	26
4	Main Beam Injector U	419	3886	250	150	250	2	35
	Main Beam Injector S	552	5126	250	250	250	3	50
	Booster S/U, Damping Ring e^- S/U, and Transfer Line - Booster to J.P.	1207	11205	400	150	250	2	100
	Pre-Damping Ring S/U, Damping Ring e^+ S/U	895	8307	350	200	250	3	78

Table H.2. Primary circuits for the klystron-based machine.

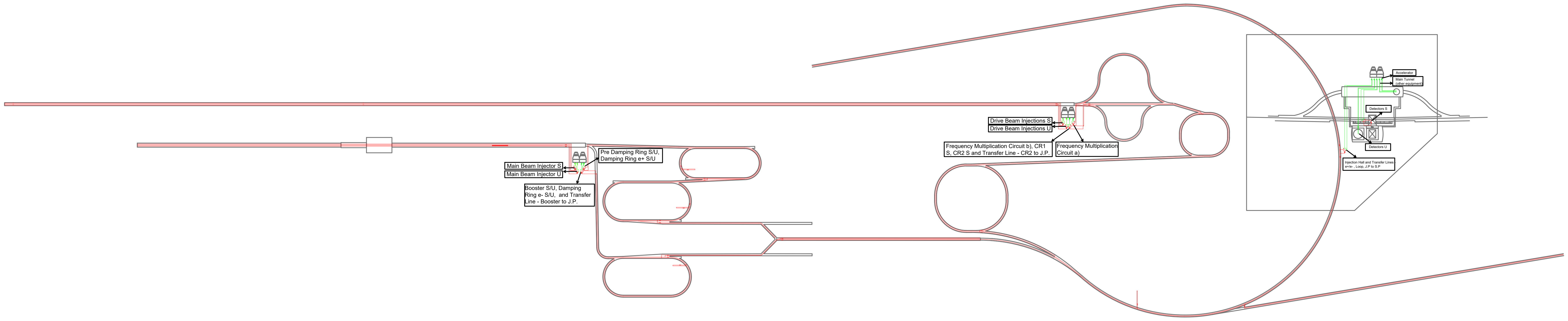
The secondary demineralized water circuits are presented below.

Sector	Drive Beam-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
1	Drive Beam Injector U	577	5356	300	125	5500	7	133
	Drive Beam Injector S	1529	14191	450	150	5500	6	325
	Frequency Multiplication Circuit a)	349	3238	250	150	1500	6	70
	Frequency Multiplication Circuit b), CR1 S, CR2 S and Transfer Line - CR2 to J.P.	1811	16811	450	200	4000	6	396
2	Accelerator - LINAC (Two-Beam Machine)	1000	9281	400	125	10000	4	121
		1000	9281	400	125	10000	4	121
	Main Tunnel (other equipment, Two-Beam Machine)	1847	17150	500	125	12000	4	225
		1847	17150	500	125	12000	4	225
	Drive Beam Dumps (Tertiary Circuits)	57	533	125	150	200	4	7,6
	Main Beam Dumps (Tertiary Circuits)	296	2746	200	250	200	4	41,1
3	Injection Hall and Transfer Lines - e^+/e^- , Loop, J.P to S.P, Detectors Hall S / U - Equipment	639	5931	300	150	6000	6	137
	Detectors S	97	900	200	125	250	4	13
	Detectors U	220	2043	200	150	600	4	34
4	Main Beam Injector U	419	3886	250	150	3000	6	90
	Main Beam Injector S	552	5126	300	250	3000	5	102
	Booster S/U, Damping Ring e^- S/U, and Transfer Line - Booster to J.P.	1207	11205	400	150	4000	6	244
	Pre-Damping Ring S/U, Damping Ring e^+ S/U	895	8307	350	200	3500	7	201

Table H.3. Demineralized water circuits for drive beam-based machine.

Sector	Klystron-Based Machine							
	Circuit	Flow Rate	Cooling P.	DN	ΔP Linear	Piping L.	Delta P.	Pumps
		m^3/h	kW	mm	Pa/m	m	bar	kW
2	Accelerator - Klystron (Klystron Machine)	1334	12389	450	100	10000	6	294
		1334	12389	450	100	10000	6	294
	Accelerator - LINAC (Klystron Machine)	1461	13564	450	125	10000	4	178
		1461	13564	450	125	10000	4	178
	Main Tunnel (other equipment, Klystron Machine)	1301	12075	450	100	12000	8	340
		1301	12075	450	100	12000	8	340
	Main Beam Dumps (Tertiary Circuits)	296	2746	200	250	200	4	41
3	Injection Hall and Transfer Lines - e^+/e^- , Loop, J.P to S.P, Detectors Hall S / U - Equipment	639	5931	300	150	6000	6	137
	Detectors S	97	900	200	125	250	4	13
	Detectors U	220	2043	200	150	600	4	34
4	Main Beam Injector U	419	3886	250	150	3000	6	90
	Main Beam Injector S	552	5126	300	250	3000	5	102
	Booster S/U, Damping Ring e^- S/U, and Transfer Line - Booster to J.P.	1207	11205	400	150	4000	6	244
	Pre Damping Ring S/U, Damping Ring e^+ S/U	895	8307	350	200	3500	7	201

Table H.4. Demineralized water circuits for klystron-based machine.



🟩 Primary water circuits
🟥 DEMI water circuits

DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

GENERAL TOLERANCES GENERALES

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Demi Water, Injectors and IP DB Machine

ECHELLE SCALE	DES/DRA.	Pedro	2019–01–21
—	CONTROLLED		
	RELEASED		
	APPROVED		

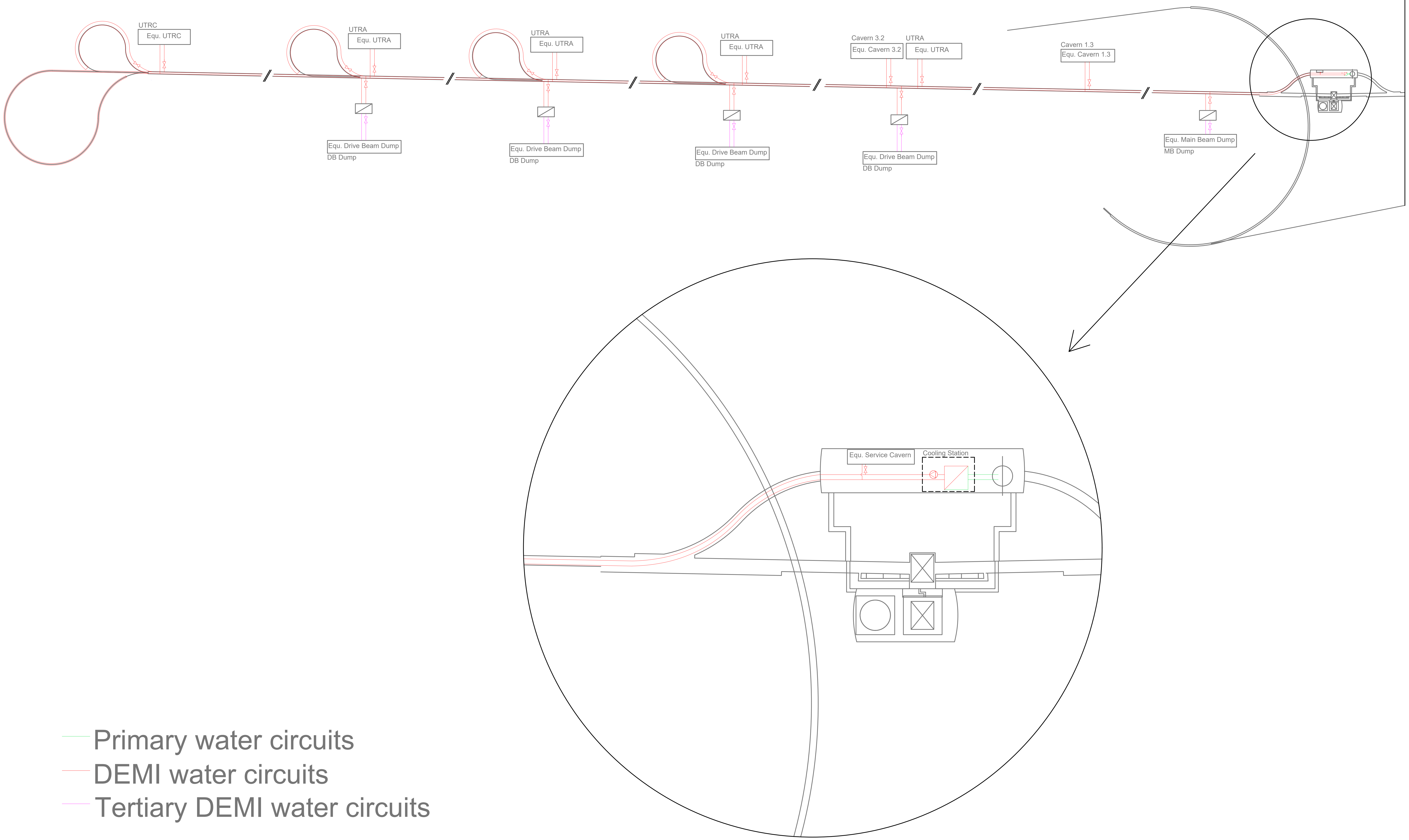
REMPLACE/REPLACES

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC —

SIZE 2

IND.



Primary water circuits

DEMI water circuits

Tertiary DEMI water circuits

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

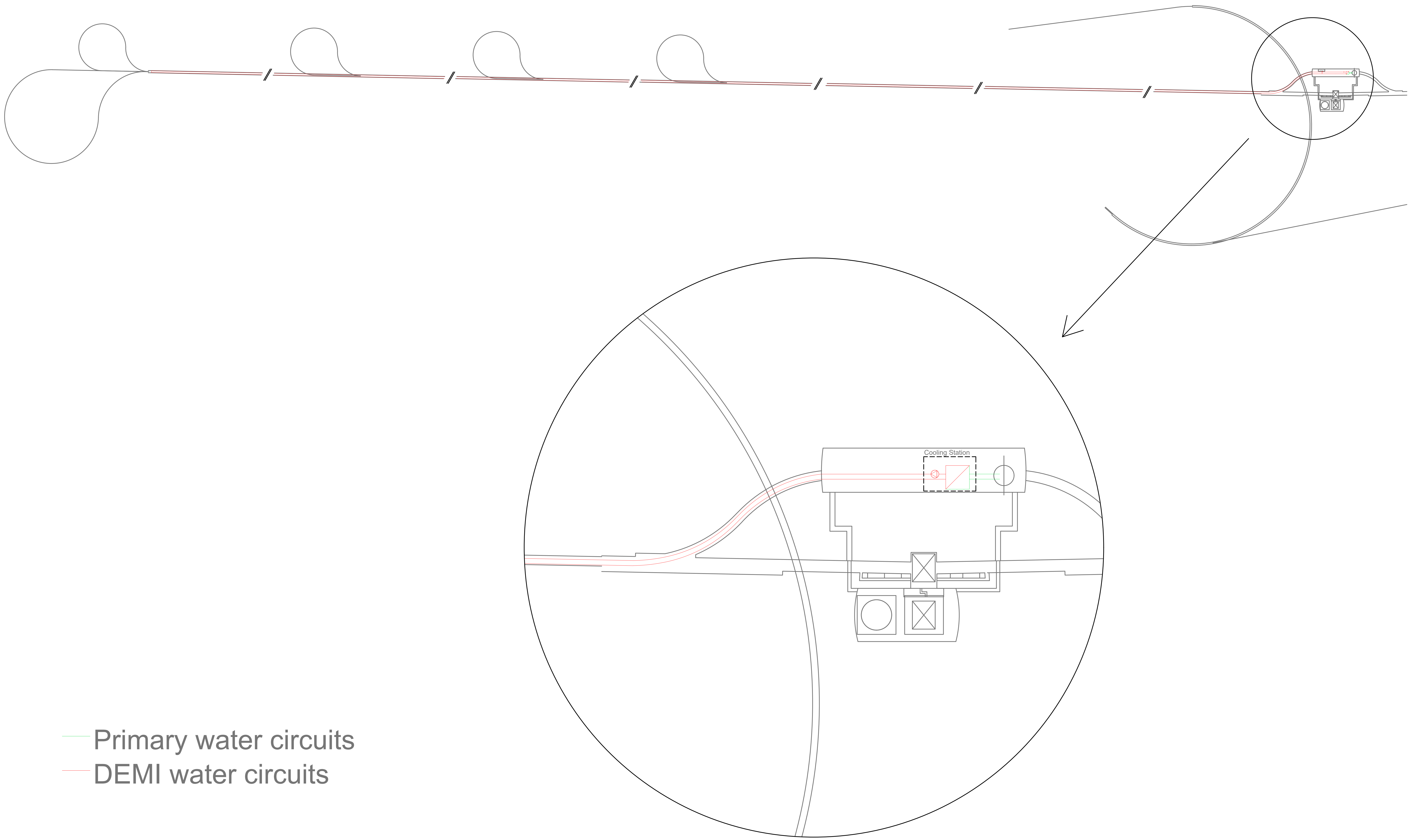
GENERAL TOLERANCES GENERALES	DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
	USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
	MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

DESSIN, RUGOSITE, TOLERANCES
SELON NORMES ISO
DRAWING, RUGOSITY, TOLERANCES
ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR
LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

Demi Water, Main Tunnel DB Machine	ECHELLE SCALE —	DES/DRA.	Pedro	2019–01–21
		CONTROLLED		
		RELEASED		
		APPROVED		
		REMPLACE/REPLACES		
NON VALABLE POUR EXECUTION NOT VALID FOR EXECUTION	QAC —		SIZE 2	IND.
]



🟩 Primary water circuits

🟥 DEMI water circuits

GENERAL TOLERANCES GENERALES	DIMENSION	<=6	> 6	> 30	> 120	> 315	>1000	>2000
	USINAGE MOYEN/MEDIUM MACHINING	± 0.1	± 0.2	± 0.3	± 0.5	± 0.8	± 1.2	± 2
	MECANO. SOUDURE/WELDED STRUCTURE	± 0.5	± 1	± 2	± 3	± 5	± 7	± 10

DESSIN, RUGOSITE, TOLERANCES SELON NORMES ISO

DRAWING, RUGOSITY, TOLERANCES ACCORDING TO ISO STANDARDS

PROJECTION

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVE

IND.	DATE	NOM/NAME	ZONE	MODIFICATION

Demi Water, Accelerator
DB Machine

ECHELLE SCALE	DES/DRA.	Pedro	2019–01–21
—	CONTROLLED		
	RELEASED		
	APPROVED		
	REMPLACE/REPLACES		

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

QAC —

SIZE	IND.
2	

Annex I – Cost Details

1. Introduction

The cooling and ventilation infrastructure cost was estimated in 2018 and was based on the design presented in the PiP. The designed systems comprise industrial equipment and technology that is well known and that is commonly available on the market. However, some air handling units and pumps are on the limit of what is usually available. Hence, for these exceptional cases, fewer manufacturers are available.

In order to compute the costs, the technical facilities were divided in two major categories: the ventilation concerning the air handling equipment and the cooling that comprises the water-related equipment.

Reference costs have been taken from past and existing contracts for similar plants built at CERN. Corrective factors have been introduced to account for the updating of old costs and the difference between the reference infrastructure and the CLiC (larger scope, size of the contract, etc.).

2. Ventilation

The ventilation infrastructure cost has been estimated using two different methodologies, depending on the type of buildings and heat loads: the first comprises the surface buildings that do not contain relevant internal technical heat loads; the second encompasses the surface buildings with relevant internal technical heat loads and all the underground premises.

The cost of the ventilation equipment for the first group is mainly dependent on the external and fresh air heat loads. Hence, as a simple approximation, we have established an empirical correlation between the volume of the buildings and the cost of the ventilation infrastructure based on similar buildings (large industrial halls) installed at CERN and past or existing contracts.

Each ventilation system within each of the remaining premises (surface buildings with relevant internal heat loads and the underground spaces) has been divided in the following components:

1. Air handling units and extraction units
2. Electrical equipment
3. Controls
4. Instrumentation
5. Ducts
6. Miscellaneous

The cost of the air handling and extraction units was computed by scaling real prices from different projects at CERN. The scaling factors for the air handling and extraction units are based on the size of each ventilation system. The ones for the electrical equipment are based on the required fan and heating power. The costing of the controls and instrumentation is based on the size and typology of the respective ventilation system. All other items that are not considered in the categories above are grouped in “miscellaneous” and given a fixed value.

The cost of the ductwork is calculated using the price per metre and by estimating its length. Additionally, we have added a factor to account for installation of ducts in difficult places such as the tunnels or shafts. The factor varies depending on the difficulty of the place, being the highest in the shafts.

3. Cooling

The cooling infrastructure was divided in three large groups based on circuit’s typology:

1. Primary circuits
2. Demineralized water circuits
3. Chilled water circuits

We have selected a reference cost for each type of circuit based on projects developed at CERN and on existing contracts. Similarly to the ventilation case, the costs for CLiC are computed by scaling the reference values using factors according to the type of component in the circuits. We have grouped them as follows:

1. Equipment – pumps, heat exchangers, chillers, and others
2. Accessories - mainly valves
3. Instrumentation
4. Electrical
5. Controls

The scaling factor for each component depends on the flow rate and pressure drop of the circuit with the exception of accessories and instrumentation for which the factors are dependent on the flow rate only. The cost of the electrical components and controls are a fraction of the sum of the first three groups. This fraction varies according to the typology and characteristics of the circuit.

The piping cost is calculated using a unitary price per meter and introducing a factor to account for the installation of pipework in difficult places, similarly to the procedure adopted for the ducts.
The cost of the cooling towers and respective water treatment is scaled directly from the total cooling power. Once again, the base for the scaling are the prices of recent projects at CERN.

4. Other systems

The sumps and raising systems were costed by assigning a fixed value to each system. The value was based on past and existing contracts at CERN.

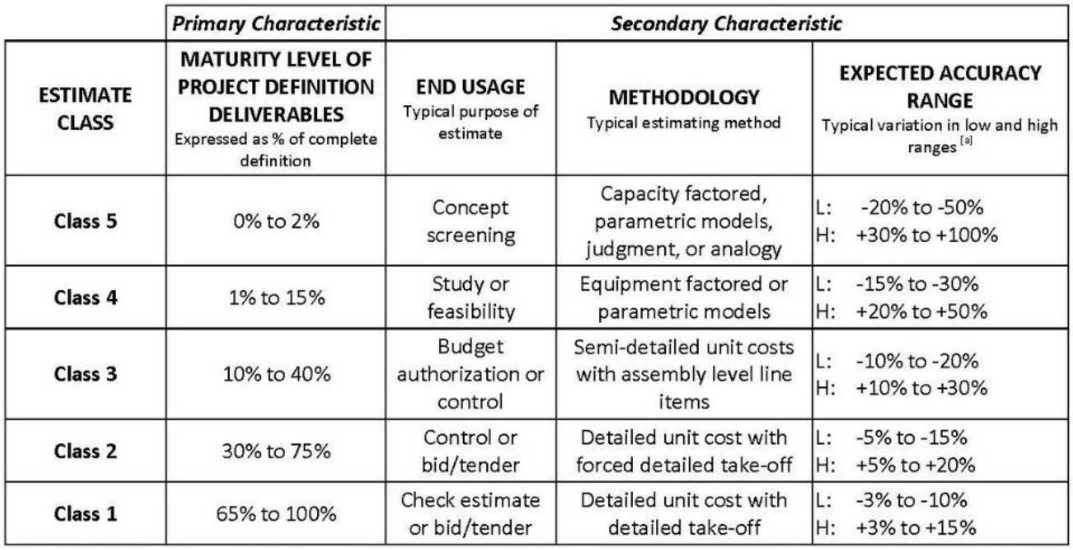
5. Exclusions

The cost excludes the design, supervision and documentation. Additionally, it does not comprise some of the civil engineering works related to the cooling and ventilation infrastructure. The buildings for the CV stations, trenches, passages, sealings, etc., are all excluded from our estimate and should be included in the civil engineering cost. However, an exception was made: the concrete structures for the cooling towers are included in the CV estimate.

Furthermore, the pumping stations for supplying and rejecting water, the demineralised water production station, the firefighting network, the compressed air system, the underground sanitary installations, the metallic structures, ventilation doors and the main cables for the power supply are not included in the cost estimate.

6. Costing Accuracy

The accuracy of the cost estimate is dependent on the design maturity and on the costing method. According to the “Association for the Advancement of Cost Engineering (AACE) cost estimate classification system” (table 1), the estimate class should generally be a class 4, or even 5, for the areas where the projects is less detailed.



	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Table 1 – Expected accuracy range vs estimate class.

7. Results

The following tables are a summary of the results obtained using the methodology described in the previous section.

Sector	Primary Circuits		Demineralized Circuits		Chilled Water Circuits		Cooling Towers		Total	
	2 Beam	Klystron	2 Beam	Klystron	2 Beam	Klystron	2 Beam	Klystron	2 Beam	Klystron
1	4’214’528	0	15’795’203	0	21’065’599	0	18’525’346	0	59’600’676	0
2	3’709’766	5’336’146	44’327’786	64’438’911	19’029’575	23’698’682	23’954’365	32’027’257	106’031’632	145’546’349
3	1’256’109	1’393’078	2’913’301	2’913’301	10’840’730	15’738’974				
4	2’079’156	2’079’156	11’001’012	11’001’012	16’170’962	16’170’962	13’204’954	13’204’954	42’456’085	42’456’085
Total	11’259’559	8’808’381	74’037’303	78’353’224	67’106’867	55’608’618	55’684’664	45’232’211	208’088’393	188’002’433

Sector	Ventilation		Ducts		Total	
	2 Beam	Klystron	2 Beam	Klystron	2 Beam	Klystron
1	64’743’781	0	5’217’777	0	69’961’558	0
2	25’354’954	27’335’552	75’338’585	102’361’936	139’070’365	179’755’048
3	29’699’801	40’366’565	8’677’024	9’690’995		
4	44’501’477	44’501’477	2’033’409	2’033’409	46’534’886	46’534’886
Total	164’300’013	112’203’594	91’266’796	114’086’340	255’566’809	226’289’934

Sector	Sumps	
	2 Beam	Klystron
1	4’500’000	4’500’000
2		
3		
4		
Total	4’500’000	4’500’000

Sector	Total Cost	
	2 Beam	Klystron
1	129’562’234	0
2	245’101’997	325’301’397
3		
4	88’990’971	88’990’971
Sumps	4’500’000	4’500’000
Total	468’155’202	418’792’368

The two-beam machine is approximately 49 MCH more expensive than the klystron-based option. This is mainly due to the fact that the latter does not comprise an infrastructure related to the drive beam.

8. **Conclusions**

The cost estimate was based on a technical design that is preliminary. Although it properly considers the standard functionalities and the general characteristics of the plants, further studies and simulations are required to increase its maturity and level of detail.

The costing method was based on scaling factors that are adapted to each plant and situation. They were based on existing and past contracts at CERN.

The maturity level of the project definition and the costing method itself are consistent with an estimate class 4 or 5 according to the AACE cost estimate classification system. Hence, a substantial uncertainty should be considered over the values presented.