# Future Circular Collider
## *Technical Infrastructure*

# Cooling of the FCC-ee and FCC-hh
## *Update and sustainability aspects*

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EN/CV

*FCC week 2024*

*13/ June / 2024*

# Outline

# Introduction: Sustainability and Project Definition

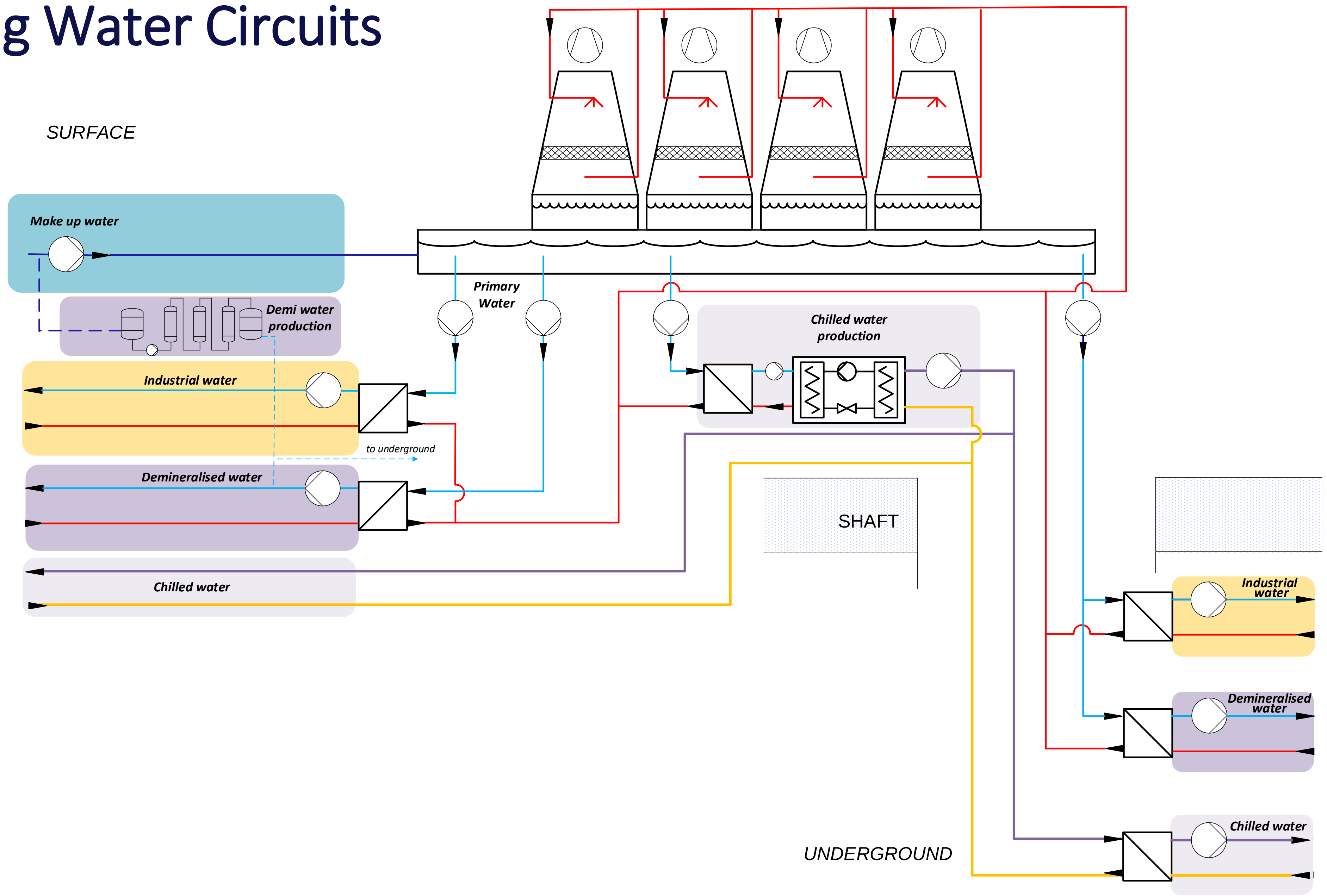
- Users of Cooling and Ventilation equipment should be precise on requirements :
  - **Accuracy on needs** → Appropriate equipment → Optimised consumption;
  - Some projects have various stages (i.e. FCC-ee has Z, W, H and tt), difficult to be optimal on all the stages but to be considered;
  - Operation modes, including energy saving aspects.
- Users' **equipment design** is important for CV:
  - Users define their need in water or air temperature supply and return depending on:
    - the **selected component** constraints (maximum allowed temperature and humidity in the **critical part of their equipment**);
    - the equipment design, particularly on their **internal heat exchange design.**
  - Draw attention of the implications of their requirements in the cost of CV the installation, operation (including electricity and water consumption) and maintenance of CV equipment.
    - Simulations of $DCO_2$ footprint and Energy Consumption for different users' parameters
  - Users in the same circuit:
    - The users heat exchange geometry defines the pressure drop which is proportional to the power consumption;
    - When in a **circuit**, the highest delta P determines the delta P of the whole line -> all users of the same circuit should aim for the same DP.

→ Involving CV in the first stages of the project is crucial!!!

# Introduction: Sustainability and Project Design

- Technological choice to guarantee sustainability:
  - **Deeper Conceptual Process Design** to explore new, less conventional but still reasonable solutions (this implies time, money, higher risk);
  - Prioritize High Equipment Durability, using high-quality materials, reducing the need for frequent replacements and minimizes waste, besides it increases reliability;
  - Anticipating as much as possible future requirements: Example of chillers:
    - UN Environment programme;
    - European union F-Gas regulations;
    - Proposal from the EU European Chemicals Agency to restrict, Per- and Polyfluoroalkyl substances (PFAS) including refrigerants HFOs and HFCs;
    - → Natural refrigerants such as ammonia, $CO_2$ (low GWP and ODP) or propane have interesting properties but:
      - Ammonia is toxic, flammable, incompatibility with copper;
      - And $CO_2$ operate at higher pressures → higher cost and complexity of components;
      - Propane chillers, its high flammability makes wider adoption more difficult.
- Other choices:
  - Splitting strategy (3 chillers of 500 kW or 2 of 1000 kW for example);
  - Back-up strategy;
    - Reliability and Sustainability, analysing N+1 redundancy: For +1, Additional equipment manufacturing, installation, maintenance and end of life treatment;
    - Evaluate failure consequences : Comfort reduction or Production downtime = equipment downtime or Production downtime = K x equipment downtime (K>1) or Catastrophic consequences;
    - Other compensation measures (additional spare parts, shorter intervention time, more specialised teams, more accessible spare parts…);
    - Case by case analysis to be done.
  - Instrumentation for maintenance, operation and controls;
  - Air and water consumption and reject
  - Noise

# Cooling Water Circuits



# Primary Cooling Water

- 8 cooling towers of different sizes
- Power modifications in cryogenics of FCC-hh

FCC-ee ttbar
**HEAT LOADS (MW)**
at Cooling Towers

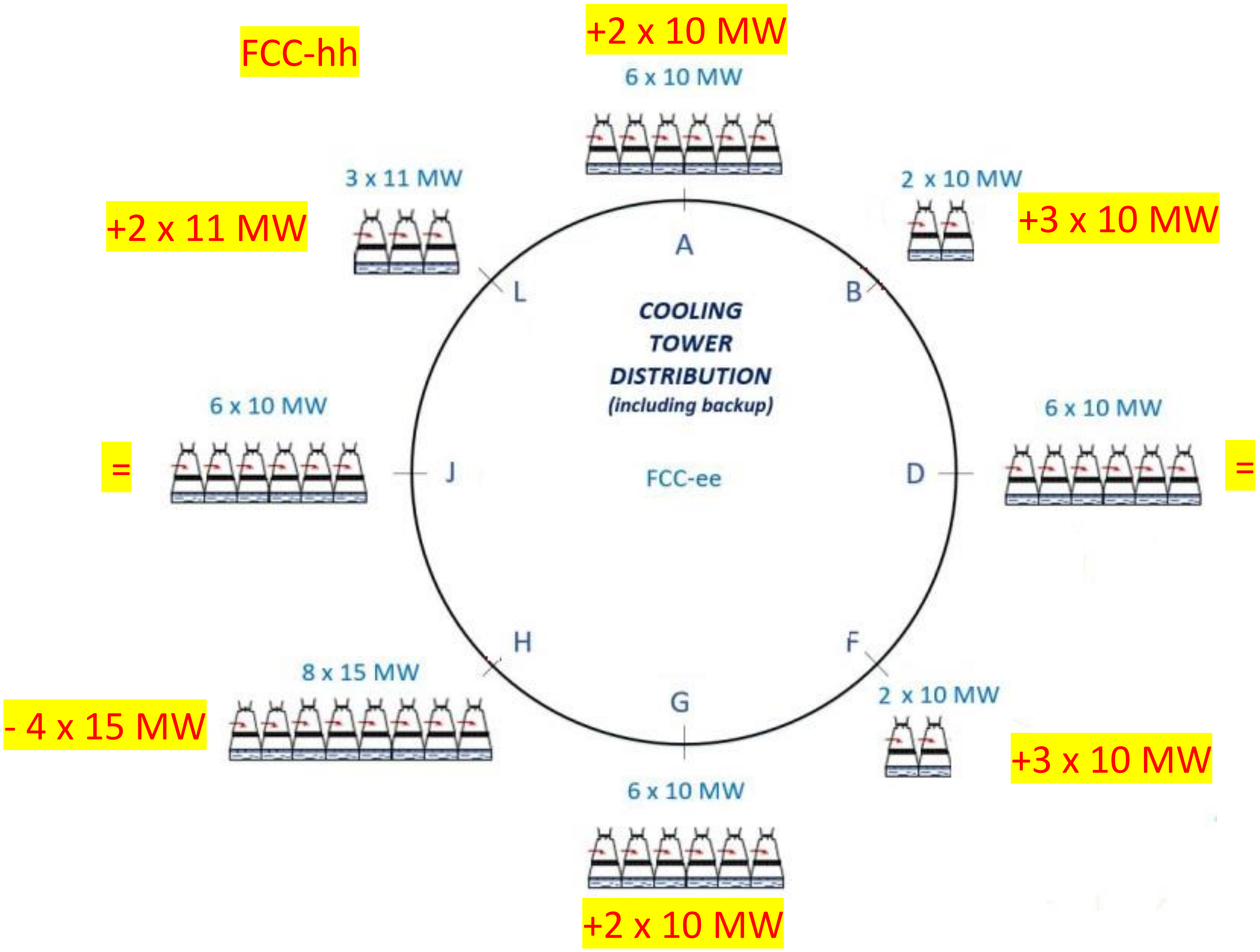
| Point | Cryogenics | Experiment | General Services | Power converters RF | Chilled Water | Underground | TOTAL |
|---|---|---|---|---|---|---|---|
| A | 0.32 | 0.50 | 2.00 | | 4.60 | 42.56 | **50** |
| B | | | 2.00 | | 3.90 | 1.05 | **7** |
| D | 0.32 | 0.50 | 2.00 | | 4.60 | 42.56 | **50** |
| F | | | 2.00 | | 3.90 | 1.05 | **7** |
| G | 0.32 | 0.50 | 2.00 | | 4.60 | 42.56 | **50** |
| H | 34.00 | | 2.00 | 4.50 | 10.10 | 50.95 | **102** |
| J | 0.32 | 0.50 | 2.00 | | 4.60 | 42.56 | **50** |
| L | 10.00 | | 2.00 | 0.07 | 4.50 | 2.74 | **19** |

Modifications needed

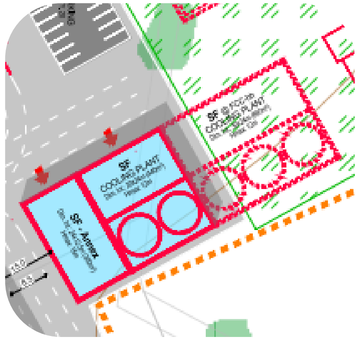
FCC-hh
**HEAT LOADS (MW)**
at Cooling Towers

| Point | Cryogenics | Experiment | General Services | Power converters | Chilled Water | Underground | TOTAL |
|---|---|---|---|---|---|---|---|
| A | 42.00 | 10.50 | 2.00 | 0.14 | 5.87 | 6.16 | **67** |
| B | 29.00 | | 2.00 | 0.14 | 5.87 | 2.00 | **39** |
| D | 32.00 | 6.50 | 2.00 | 0.14 | 5.87 | 5.46 | **52** |
| F | 29.00 | | 2.00 | 0.14 | 5.87 | 2.00 | **39** |
| G | 42.00 | 10.50 | 2.00 | 0.14 | 5.87 | 6.16 | **67** |
| H | 32.00 | | 2.00 | 0.14 | 5.87 | 2.00 | **42** |
| J | 32.00 | 6.50 | 2.00 | 0.14 | 5.87 | 5.46 | **52** |
| L | 29.00 | | 2.00 | 0.14 | 5.87 | 2.00 | **39** |

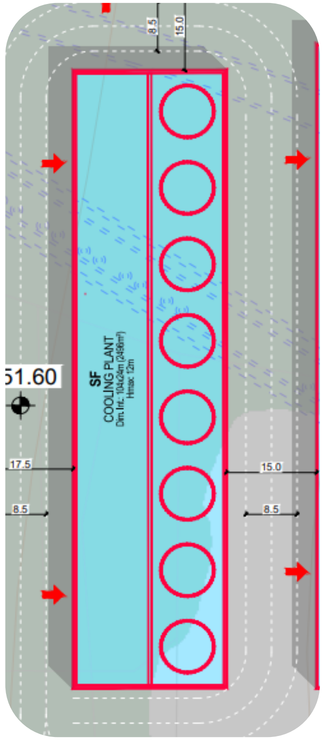
# From FCC-ee to FCC-hh



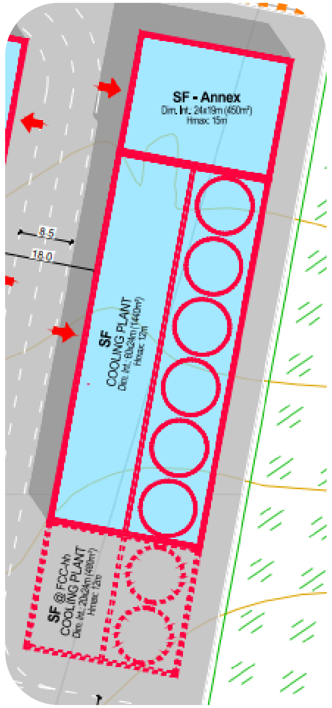

Technical Point



RF Collider Point




Detector Point

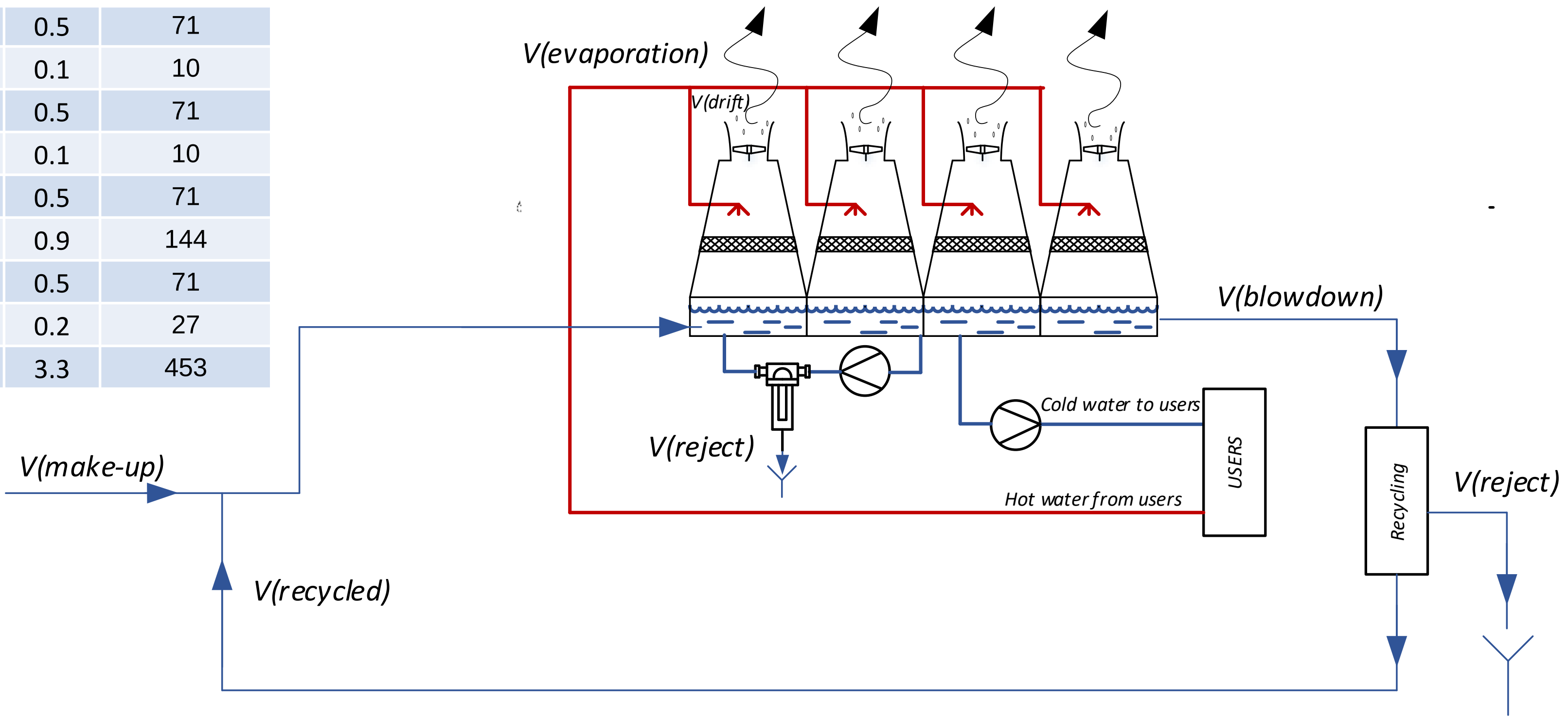


# Make up and reject water

- Flowrates in $m^3/h$ for FCC-ee ttbar during Operation

| Point | Make up* | Blowdown | Recycled | Reject (from blowdown) | Reject (from filters) | Drift | Evaporation |
|---|---|---|---|---|---|---|---|
| A | 94 | 22 | 17 | 5.5 | 7.1 | 0.5 | 71 |
| B | 13 | 3 | 2 | 0.8 | 1.0 | 0.1 | 10 |
| D | 94 | 22 | 17 | 5.5 | 7.1 | 0.5 | 71 |
| F | 13 | 3 | 2 | 0.8 | 1.0 | 0.1 | 10 |
| G | 94 | 22 | 17 | 5.5 | 7.1 | 0.5 | 71 |
| H | 192 | 45 | 36 | 11.2 | 14.5 | 0.9 | 144 |
| J | 94 | 22 | 17 | 5.5 | 7.1 | 0.5 | 71 |
| L | 36 | 8 | 7 | 2.1 | 2.7 | 0.2 | 27 |
| TOTAL | 630 | 147 | 118 | 36.8 | 47.6 | 3.3 | 453 |

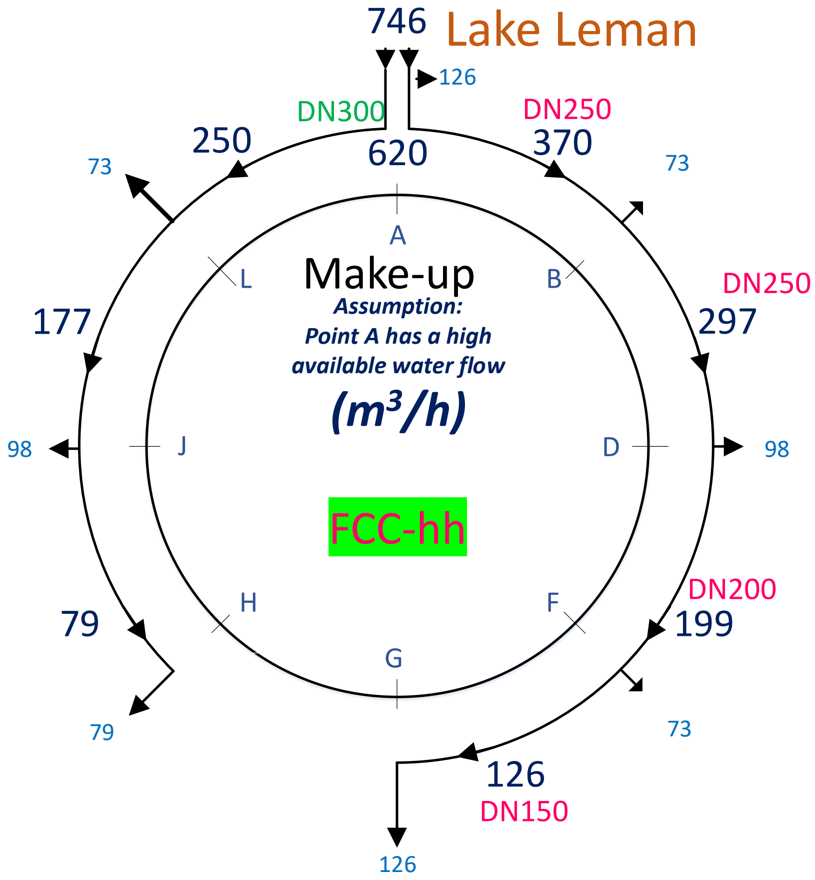
** Including contingency*

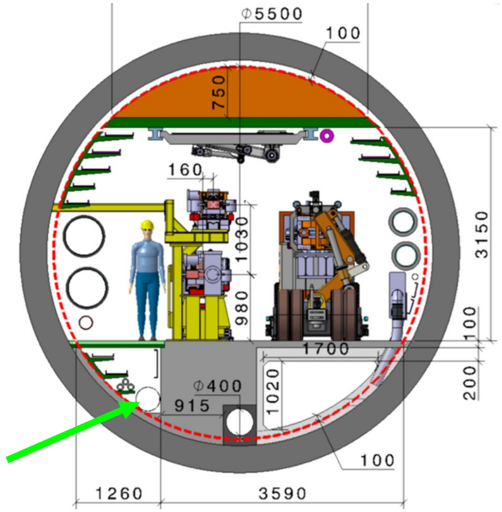


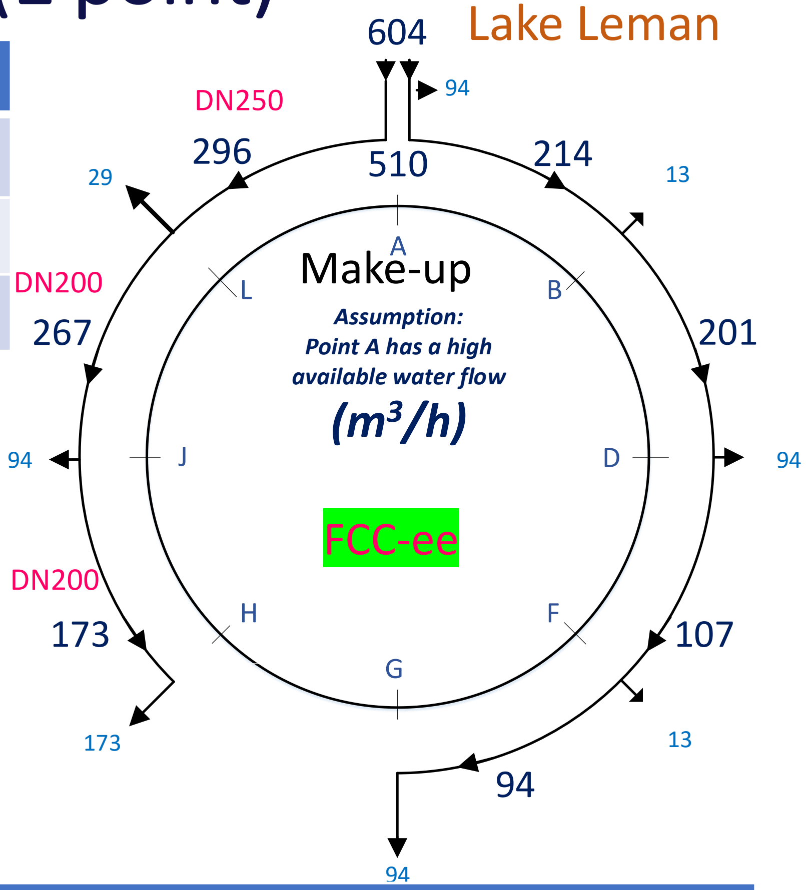
# Make up and reject water needs (1 point)

BASELINE

| WATER NEEDS FOR FCC-ee, *Considering Blowdown Recycling* (m³/h) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Point** | **A** | **B** | **D** | **F** | **G** | **H** | **J** | **L** |
| Make-up | 94 | 13 | 94 | 13 | 94 | 173 | 94 | 29 |
| Reject water | 11 | 2 | 11 | 2 | 11 | 21 | 11 | 3 |



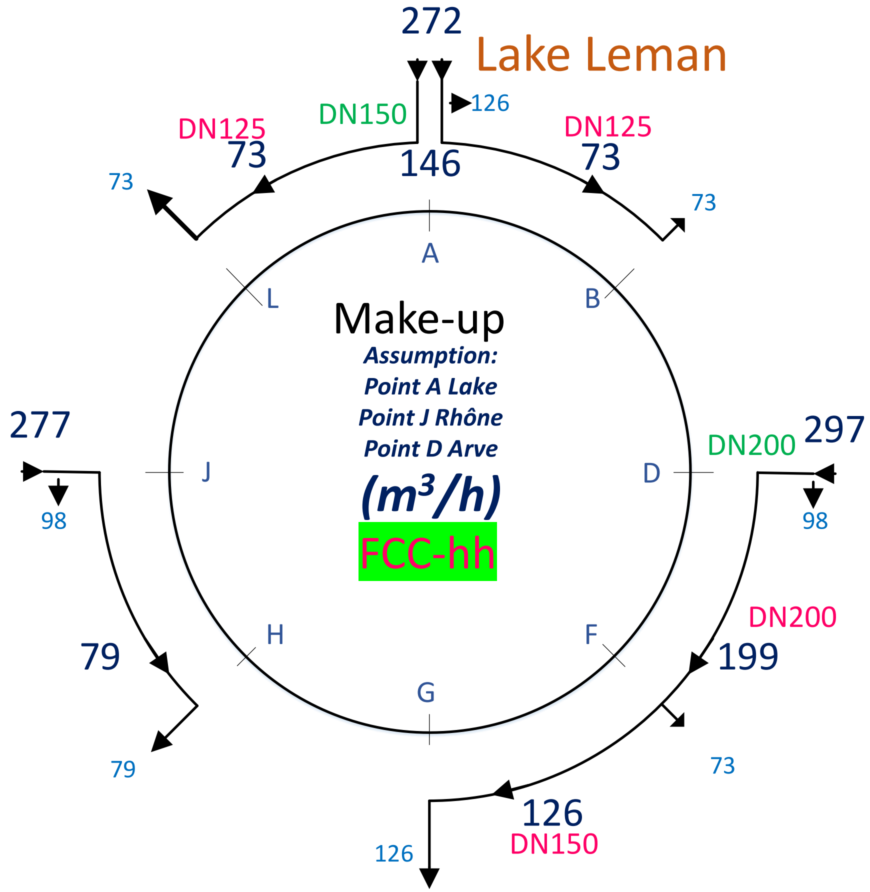

| WATER NEEDS FOR FCC-hh, *Considering Blowdown Recycling* (m³/h) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Point** | **A** | **B** | **D** | **F** | **G** | **H** | **J** | **L** |
| Make-up | 126 | 73 | 98 | 73 | 126 | 79 | 98 | 73 |
| Reject water | 15 | 9 | 12 | 9 | 15 | 10 | 12 | 9 |

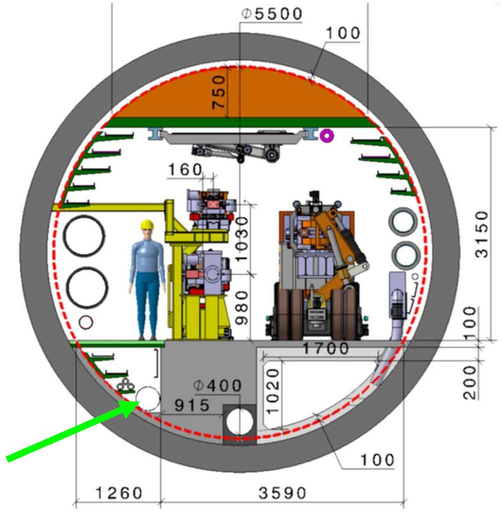
Reject: DN125 in sector AB

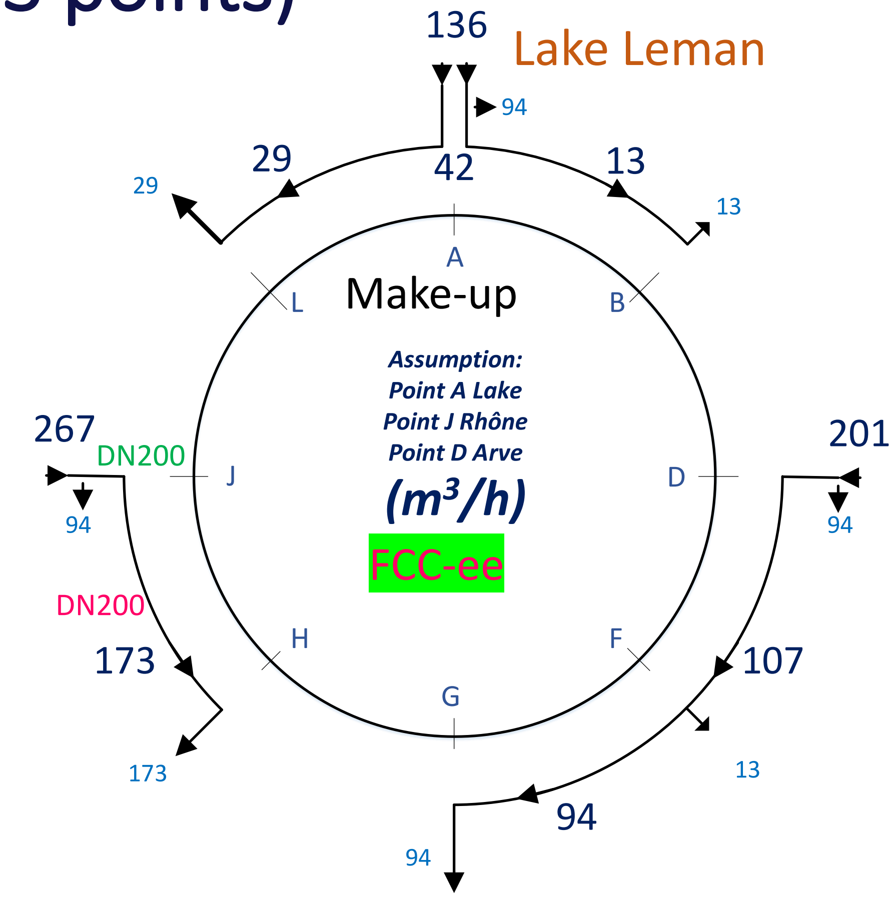
# Make up and reject water needs (3 points)

**WATER NEEDS FOR FCC-ee, *Considering Blowdown Recycling* (m³/h)**

| Point | A | B | D | F | G | H | J | L |
|---|---|---|---|---|---|---|---|---|
| Make-up | 94 | 13 | 94 | 13 | 94 | 173 | 94 | 29 |
| Reject water | 11 | 2 | 11 | 2 | 11 | 21 | 11 | 3 |




**WATER NEEDS FOR FCC-hh, *Considering Blowdown Recycling* (m³/h)**

| Point | A | B | D | F | G | H | J | L |
|---|---|---|---|---|---|---|---|---|
| Make-up | 126 | 73 | 98 | 73 | 126 | 79 | 98 | 73 |
| Reject water | 15 | 9 | 12 | 9 | 15 | 10 | 12 | 9 |

Reject: DN80 in sector DF

# Make up water, 1 entry vs. 3 entry points

| Shaft | DN *1 entry point* | | DN *3 entry points* |
|---|---|---|---|
| A | 300 | > | 150 |
| B | 125 | = | 125 |
| D | 150 | < | 200 |
| F | 125 | = | 125 |
| G | 150 | = | 150 |
| H | 125 | = | 125 |
| J | 150 | < | 200 |
| L | 125 | = | 125 |

| Sector | DN *1 entry point* | DN *3 entry points* |
|---|---|---|
| A-B | 250 | 125 |
| B-D | 250 | - |
| D-F | 200 | 200 |
| F-G | 150 | 150 |
| G-H | - | - |
| H-J | 200 | 200 |
| J-L | 200 | - |
| L-A | 250 | 125 |

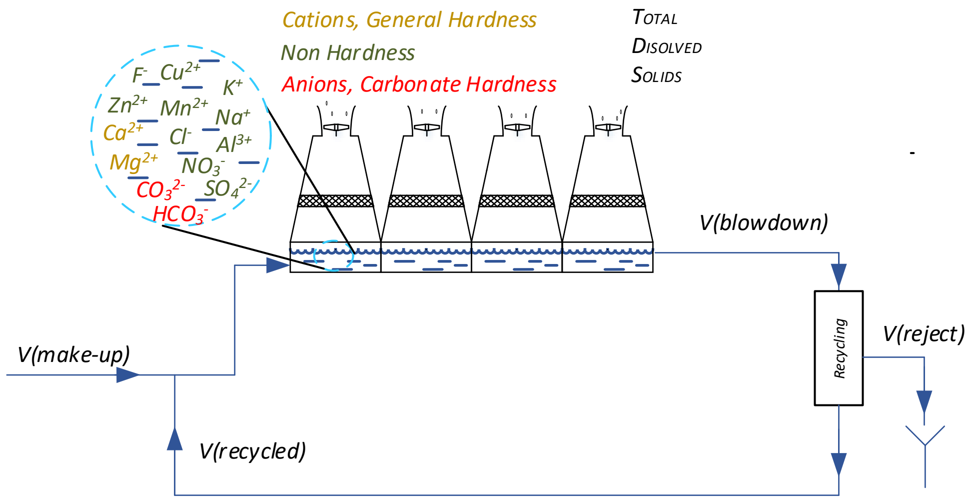
**SECTORS: SUMMARY TABLE**

| Pipe size | No. of sectors for *1 entry point* | No. of sectors for *3 entry points* |
|---|---|---|
| DN250 | 3 | 0 |
| DN200 | 3 | 2 |
| DN150 | 1 | 1 |
| DN125 | 0 | 2 |

- For 1 entry point, 3 sectors of DN250, instead;
- For 3 entries, 2 DN125;
- For 1 entry, 1 sector DN200 more ;
- Cost of pipes in the sectors is half for the 3 entry point solution:
  - 22 MCHF savings) but we need to consider the COST of works on the surface points.

# Water reject optimisation

- Cooling Tower Blowdown recycling:
  - PROS:
    - reinjects water in the cooling tower, reducing water consumption;
    - reduces reject water flow rate: smaller pipes, less power consumption.
  - CONS:
    - It creates high TDS reject water;
    - There is an additional system to operate and maintain, consumes electric power, surface area.
- High TDS reject water:
  - If Cycles of Concentration COC=4, $C_{recycled}$=15 mg/L $C^*_{make\text{-}up}$=200 mg/L, $V_{recycled}=0.8V_{blowdown}$ ->
    - $C_{reject}$=3920mg/L (brackish water 10 times less than sea water)
  - What to do?
    - Not to produce it?
    - Reject? or
    - Further concentrate? Or
    - Reach Zero Liquid Discharge (ZLD)?




- Not to produce it : PROS and CONS before become CONS and PROS;
- Reject: particular precautions (next slide);
- Further concentrate: more PROS but more CONS too!;
- ZLD: Higher cost (CAPEX OPEX), but only solids to be discharged, big improvement done thanks to new technologies:
  - in Singapore International Water Week, Dupont claimed that the price for ZLD is from \$1.06-1.75/$m^3$;
  - Study for FCC underway

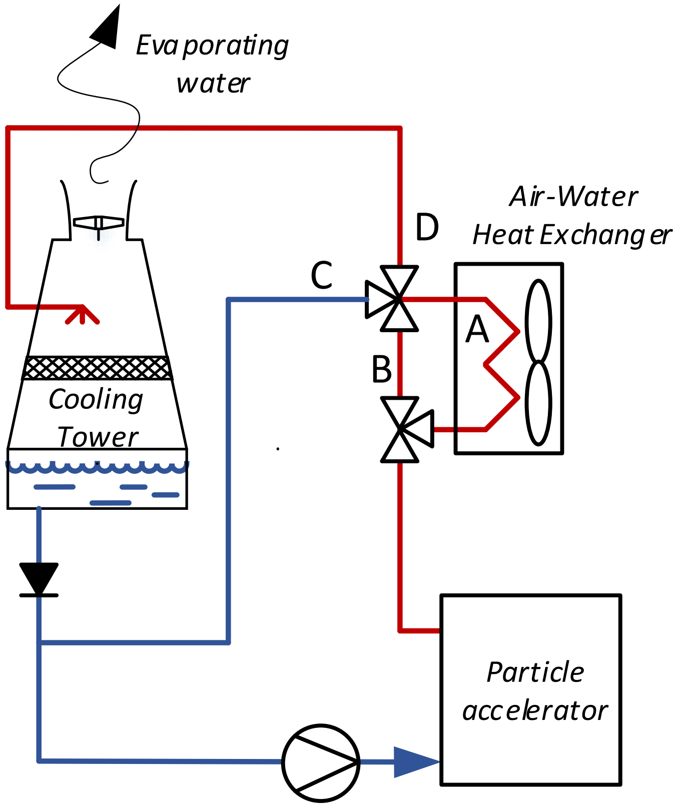
*L'eau de Genève : eau potable | SIG (sig-ge.ch)

# Rejecting high TDS water

- Pretreatment Processes
  - Screening and Filtration: Remove large particles and sediments using screens and filters.
  - Chemical Treatment: Add chemicals to precipitate and remove certain dissolved solids.
- Use corrosion-resistant materials (e.g., PVC, stainless steel) due to the corrosive nature of high TDS water.
  - Use materials like polyvinyl chloride (PVC), high-density polyethylene (HDPE), fiberglass-reinforced plastic (FRP), or stainless steel (grades 316L or duplex stainless steel) which are resistant to corrosion and scaling.
- Ensure adequate dimensioning to cope with potential wear from abrasive solids in the water.
- Design pipelines with appropriate slope to facilitate drainage and prevent sediment buildup. Needs mechanical and chemical cleaning to avoid scaling and biofilm

# Reducing Make up and Reject water

- Air-Water Heat Exchangers
  - Pros:
    - Reduces make up water by using in winter but also in transitional seasons or periods;
    - Reduces reject water.
  - Cons:
    - Adds equipment to be maintained;
    - Complexify controls;
    - Number of cooling towers are still needed;
    - Larger footprint;
    - Higher electrical consumption.



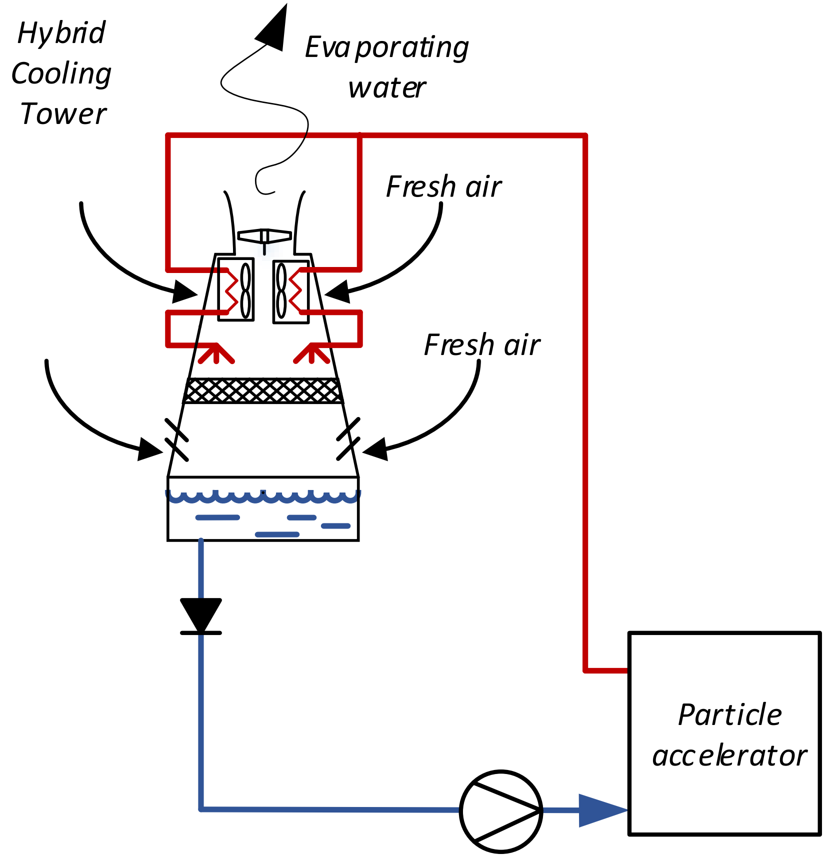

*FROM Consultant AFRY*

| Finfan cooler | | |
|---|---|---|
| Height (m) | Length (m) | Width (m) |
| 10.8 | 32.0 | 17.7 |

- Load 2.5 MW
- Design ambient temperature 20°C
- Design Approach 10 Kelvin
- Cold water temperature 30°C
- Warm water temperature 31.58°C

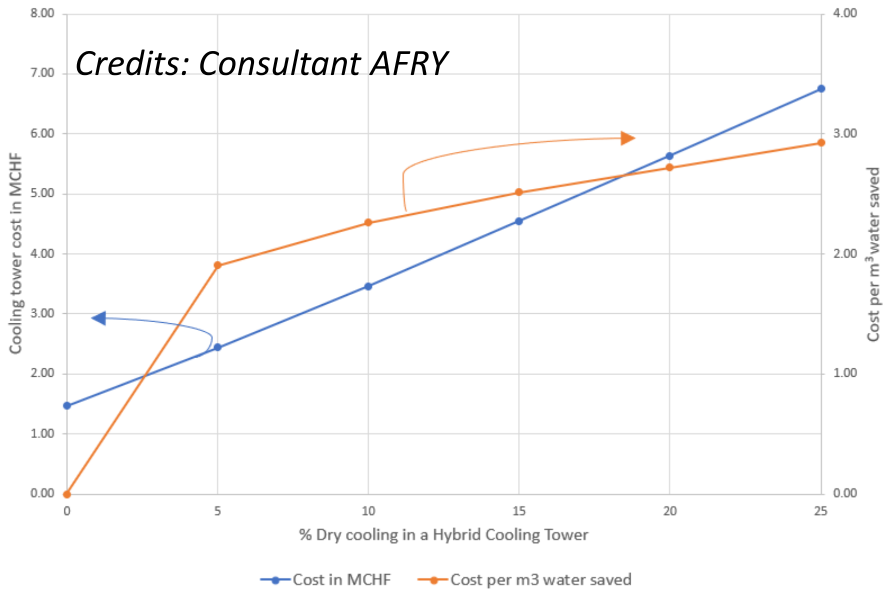
# Reducing Make up and Reject water

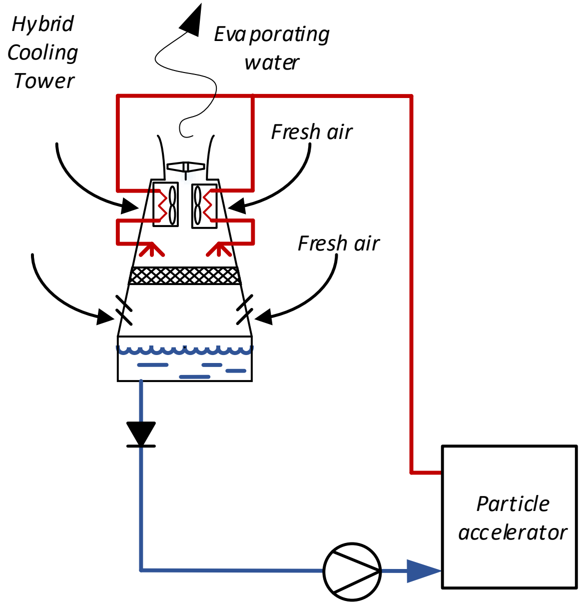
- Hybrid cooling towers
  - Pros:
    - Reduces make up water by using in winter but also in transitional seasons
    - Reduces reject water
    - Eliminates plume
  - Cons:
    - Adds equipment to be maintained
    - Complexify controls
    - Number of cooling towers are still needed
    - Taller cooling towers
    - Larger footprint
    - Higher electrical consumption



# Reducing Make up and Reject water

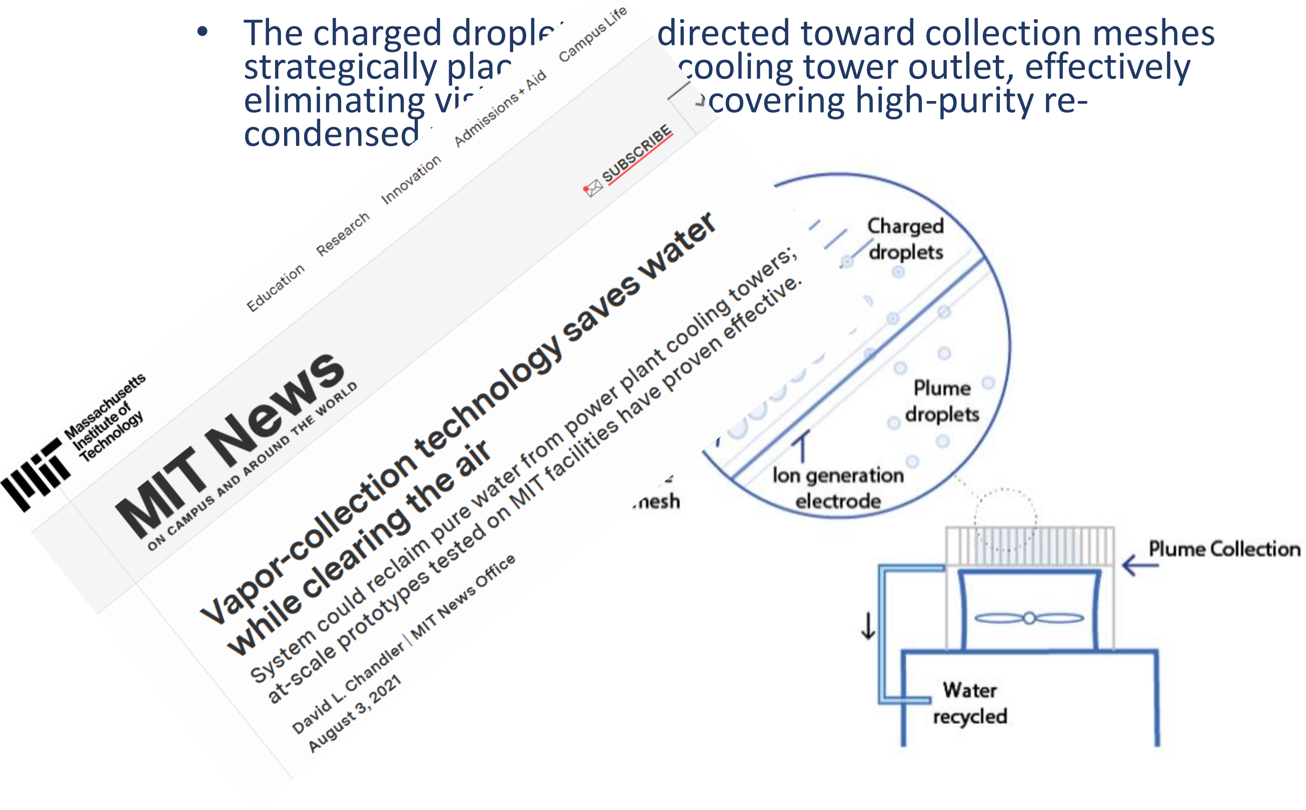
- Hybrid cooling towers
  - Example of a 50 MW cooling tower
  - Savings calculated for 25 years operation, considering CAPEX and OPEX
  - For a 10% dry cooling the cost of the installations per $m^3$ of saved water is about 2.4 CHF/$m^3$
  - For a 5% dry cooling, the cost per $m^3$ of saved water is about 1.9 CHF/$m^3$
    - 5% is enough to eliminate visible plume from the fan stack



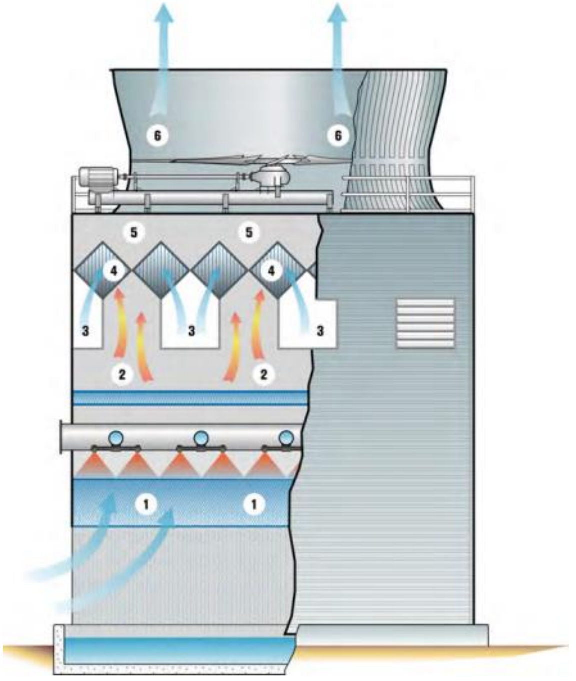
# Reducing Make up and Reject water: other technologies

- WaterPanel™ electrically charges water droplets within cooling tower plumes.
- The charged drople… directed toward collection meshes strategically plac… cooling tower outlet, effectively eliminating vi… covering high-purity re-condensed …



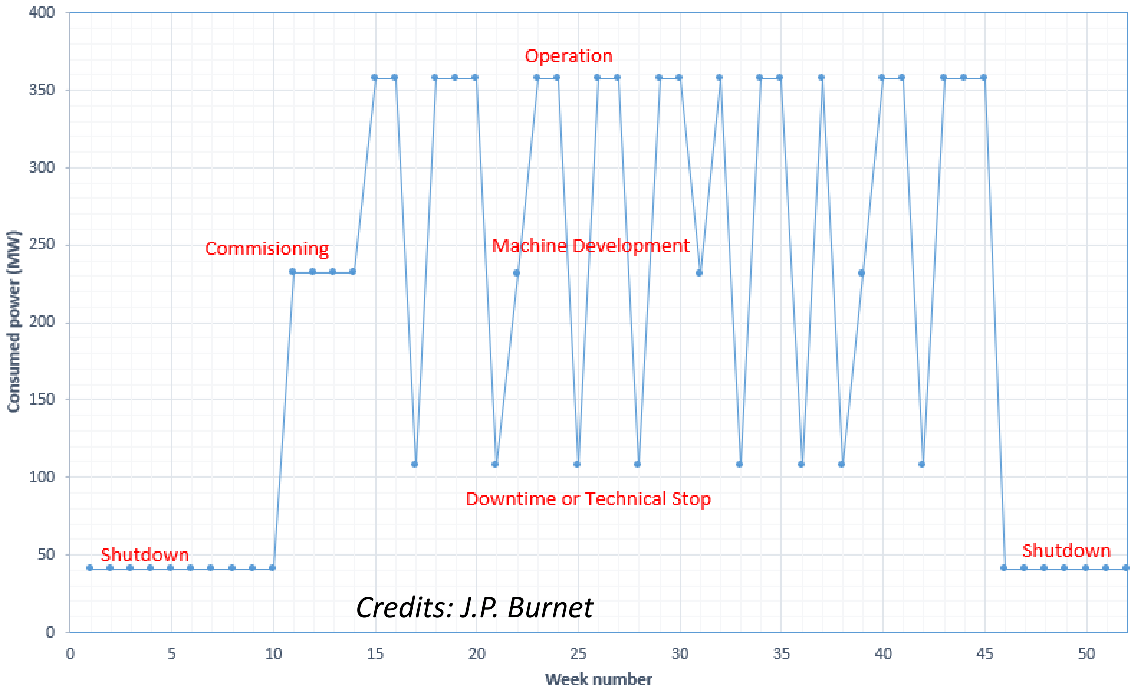

[Infinite Cooling | WaterPanel (infinite-cooling.com)](infinite-cooling.com)

- Dry Air – Warm Saturated Air Heat Exchanger modules condense much of the moisture from the warm saturated air flow
- Before leaving the system, both airflows mix eliminating the plume
- Can be integrated into both new or old towers

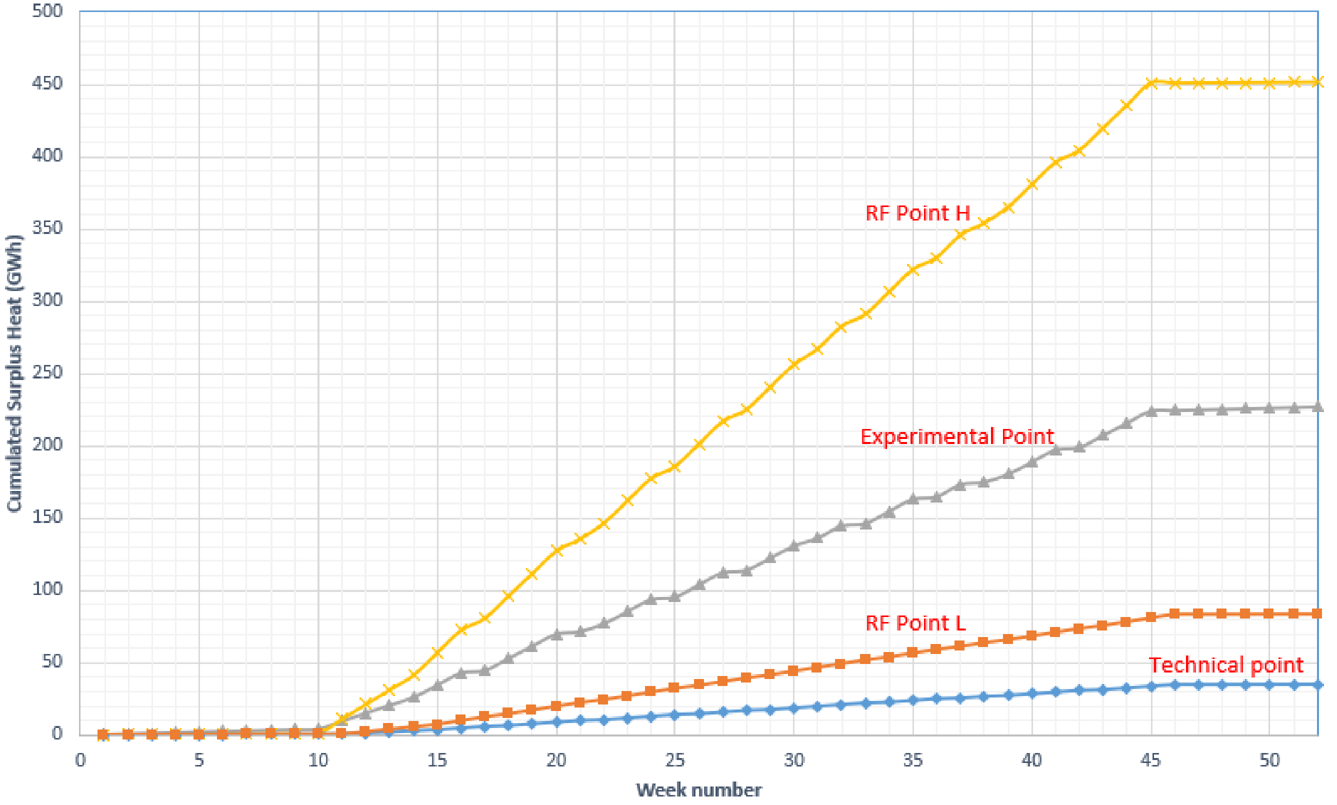


*From spxcooling.com*

# Reducing Make up and Reject water:
## *by reusing the waste heat*

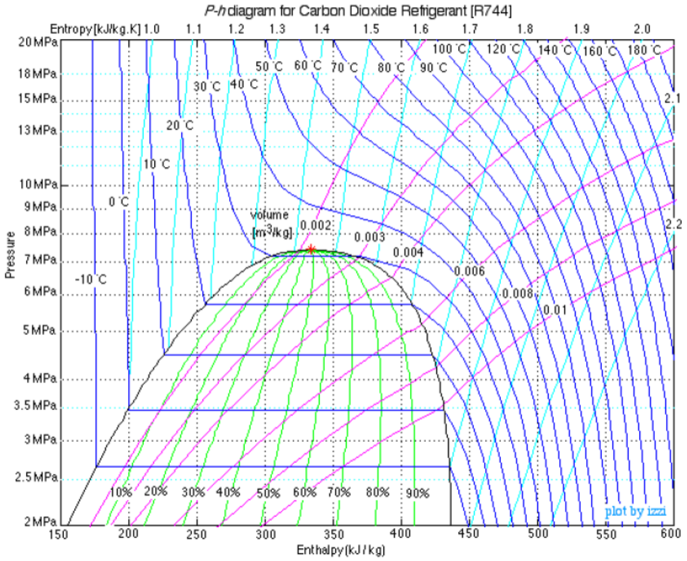


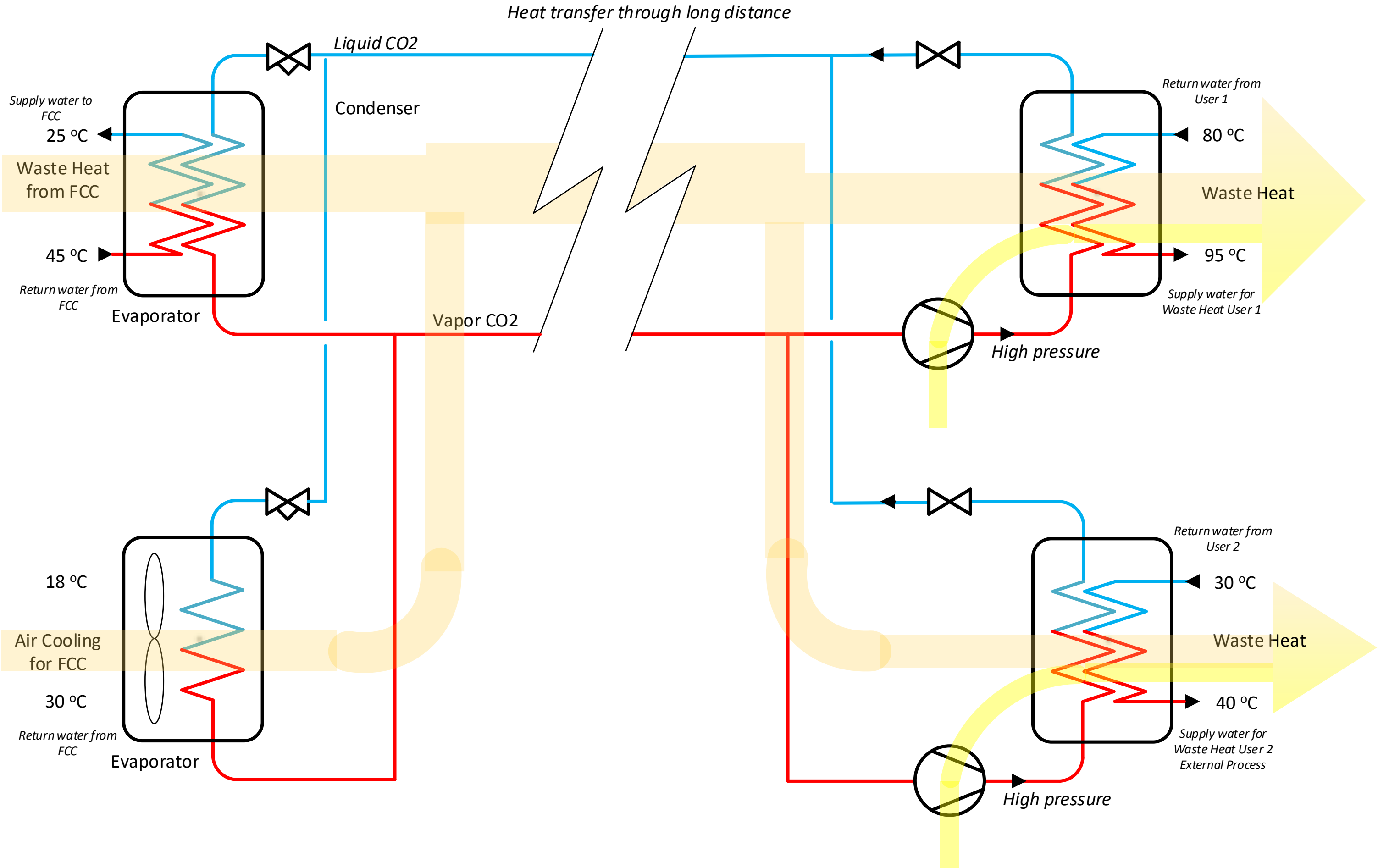

*See talk: Waste heat supply opportunities by A. Guiavarch*



# Reducing Make up and Reject water:
## *by reusing waste heat with $CO_2$ instead of water*

CO2 as a heat carrier and refrigerant fluid, working principle in the FCC

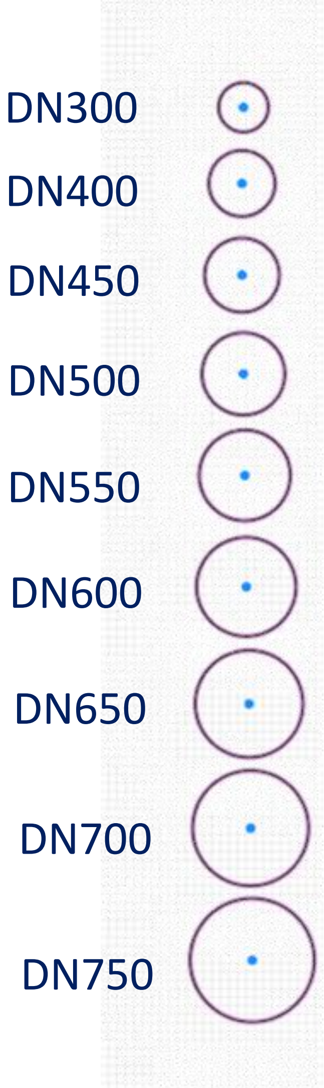


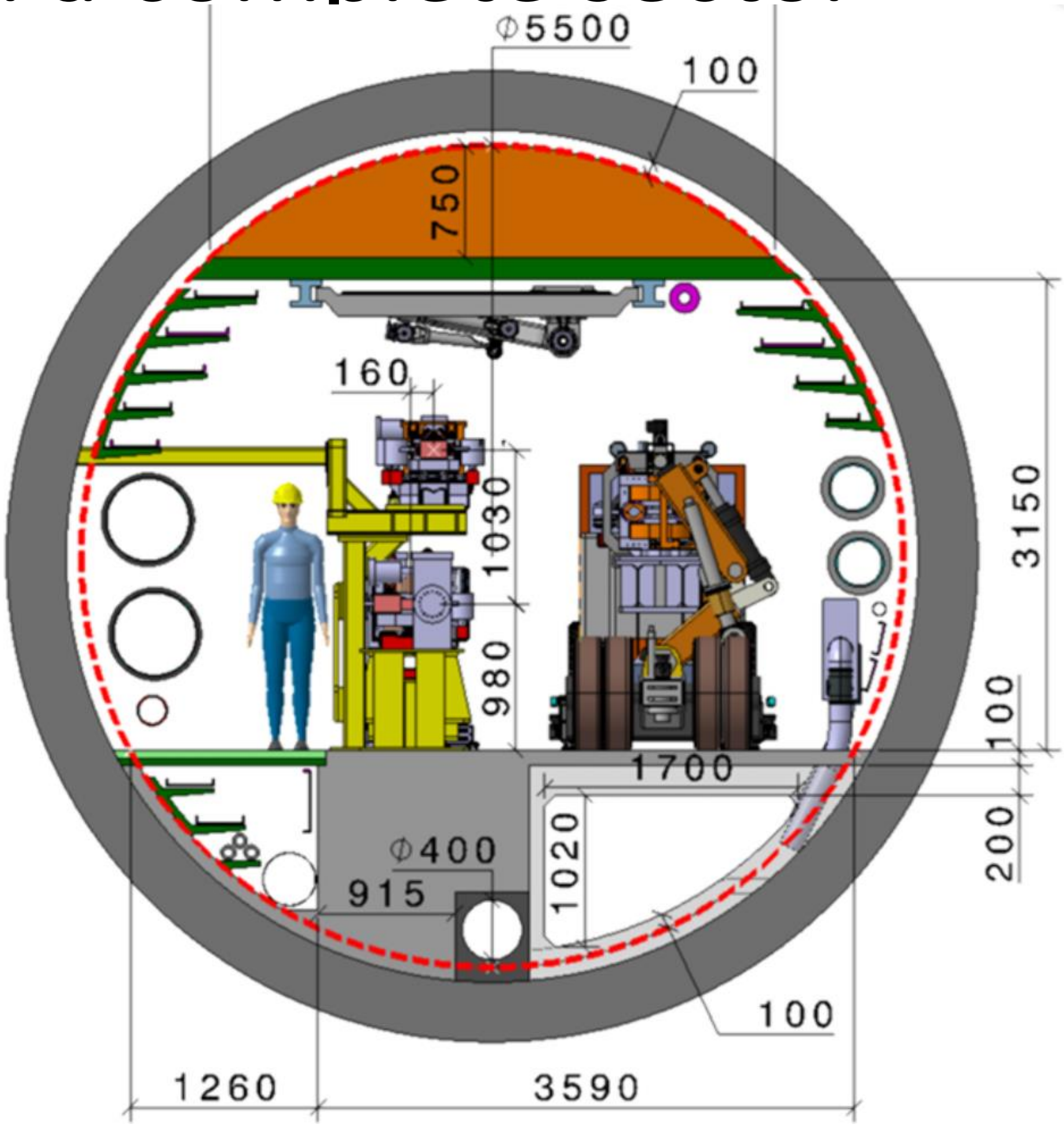



# Surplus heat transport through a complete sector

- Transport of Waste Heat from PH using water → additional 1 supply & 1 return pipes in respective Sector

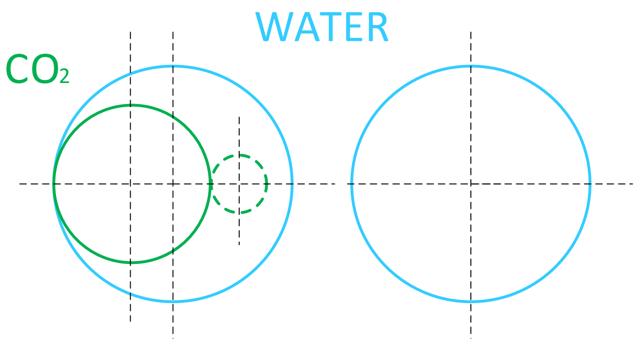
| FCC-ee COOLING POWER NEEDS FOR PRIMARY CIRCUITS (MW) *Delta T=20K* | | |
|---|---|---|
| P(MW) | DN | Power motors (kW) |
| 92 | 750 | 1800 |
| 80 | 700 | 1700 |
| 70 | 650 | 1640 |
| 60 | 600 | 1540 |
| 50 | 550 | 1380 |
| 40 | 500 | 1160 |
| 30 | 450 | 850 |
| 20 | 400 | 480 |
| 10 | 300 | 270 |

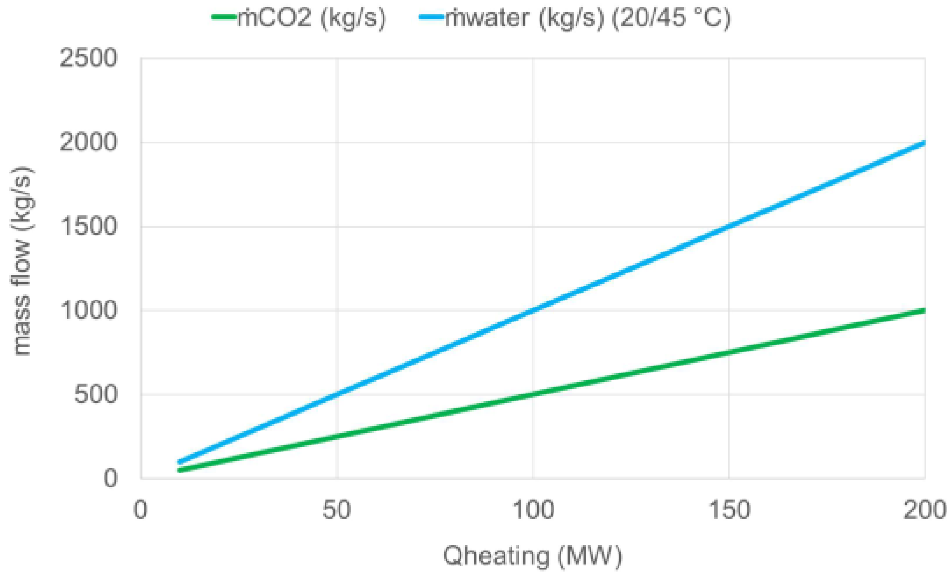


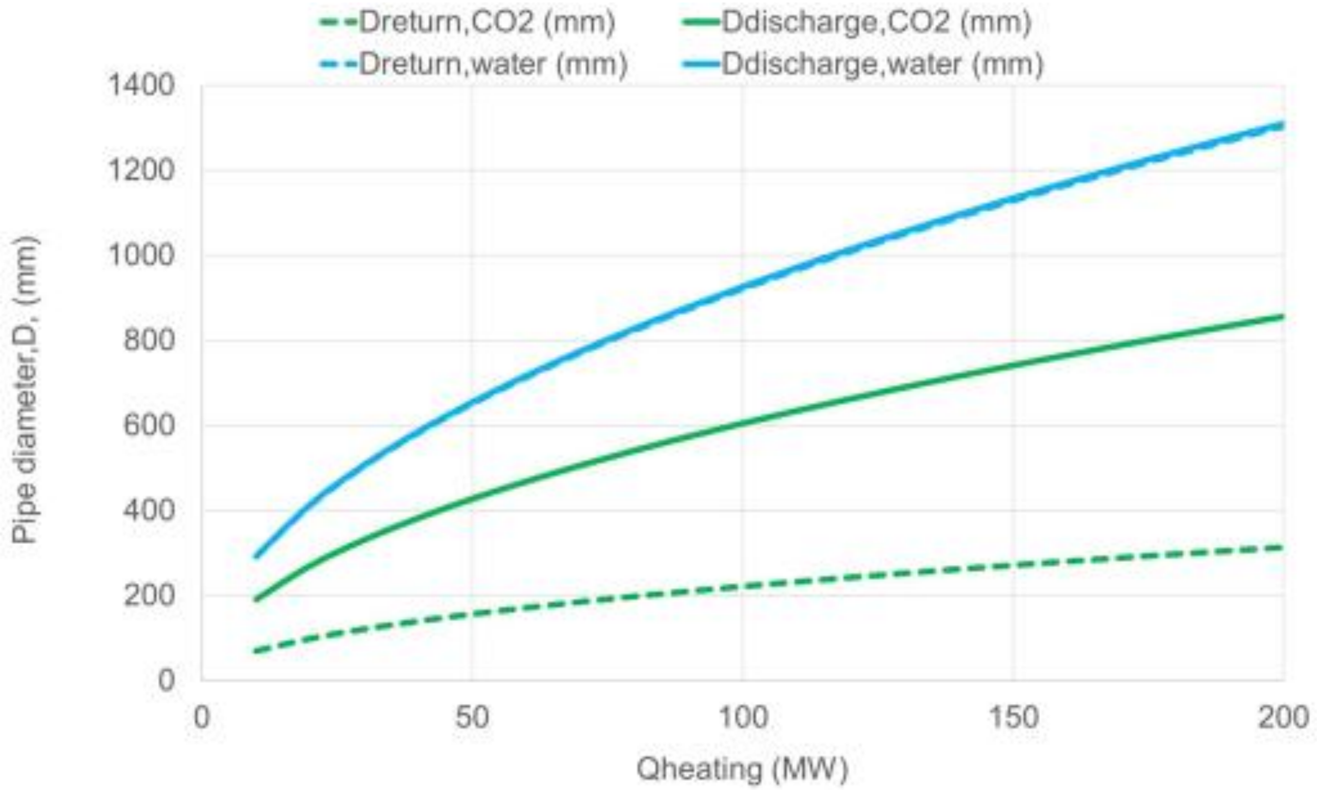



# Heat transfer: Water (DT=25K) vs $CO_2$

- If we take the case of 50 MW

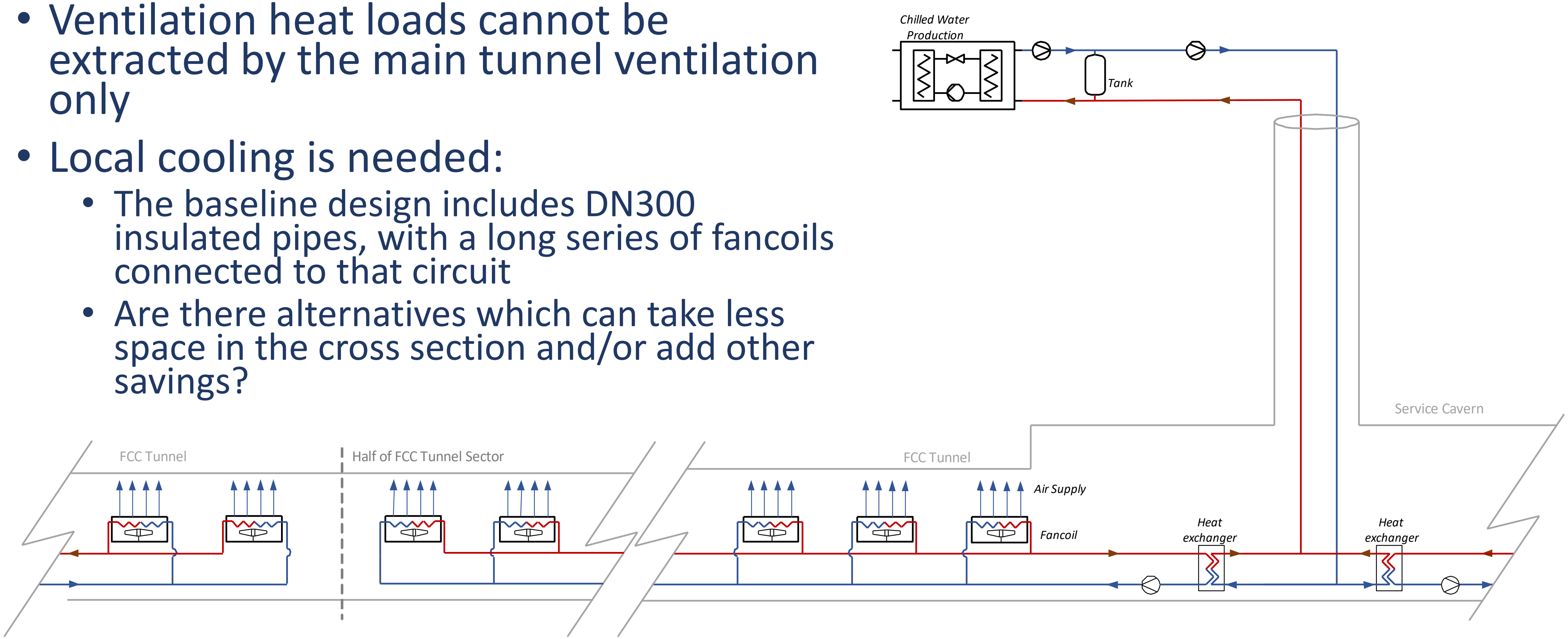


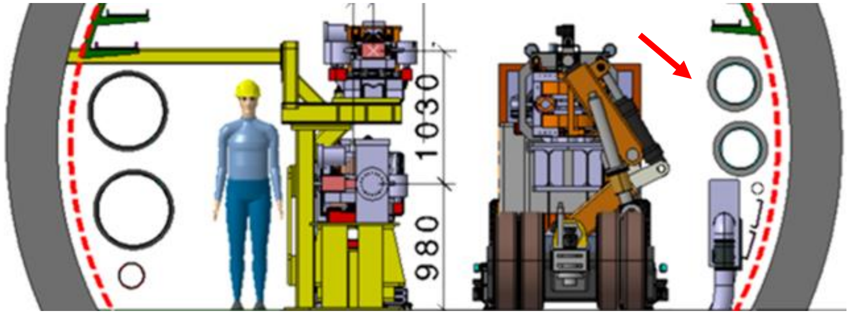
# Chilled water vs $CO_2$ in the FCC tunnel

- Ventilation heat loads cannot be extracted by the main tunnel ventilation only
- Local cooling is needed:
  - The baseline design includes DN300 insulated pipes, with a long series of fancoils connected to that circuit
  - Are there alternatives which can take less space in the cross section and/or add other savings?

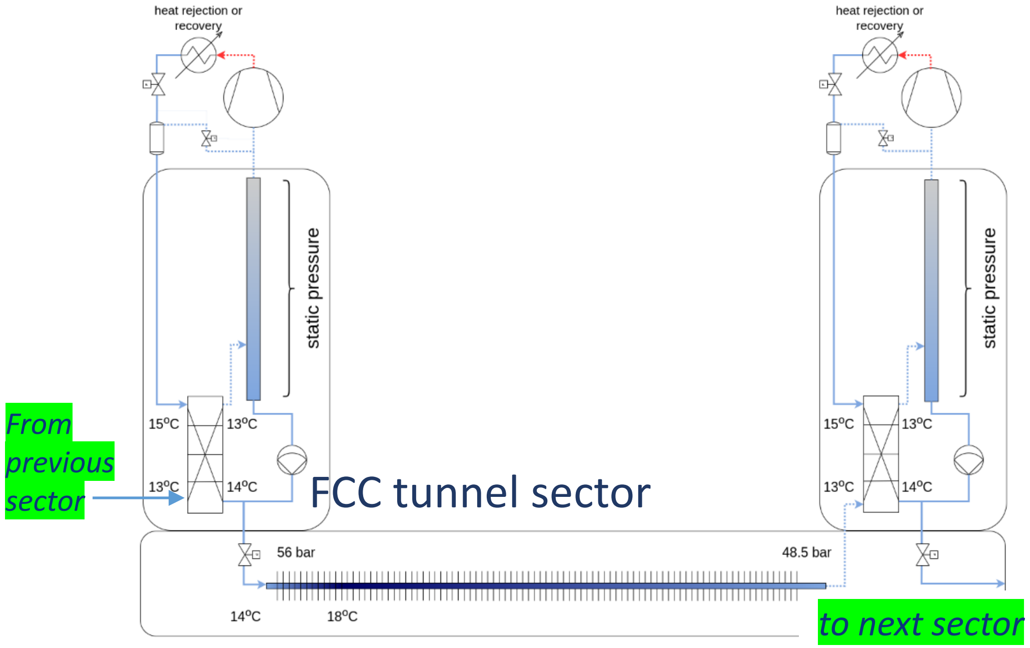


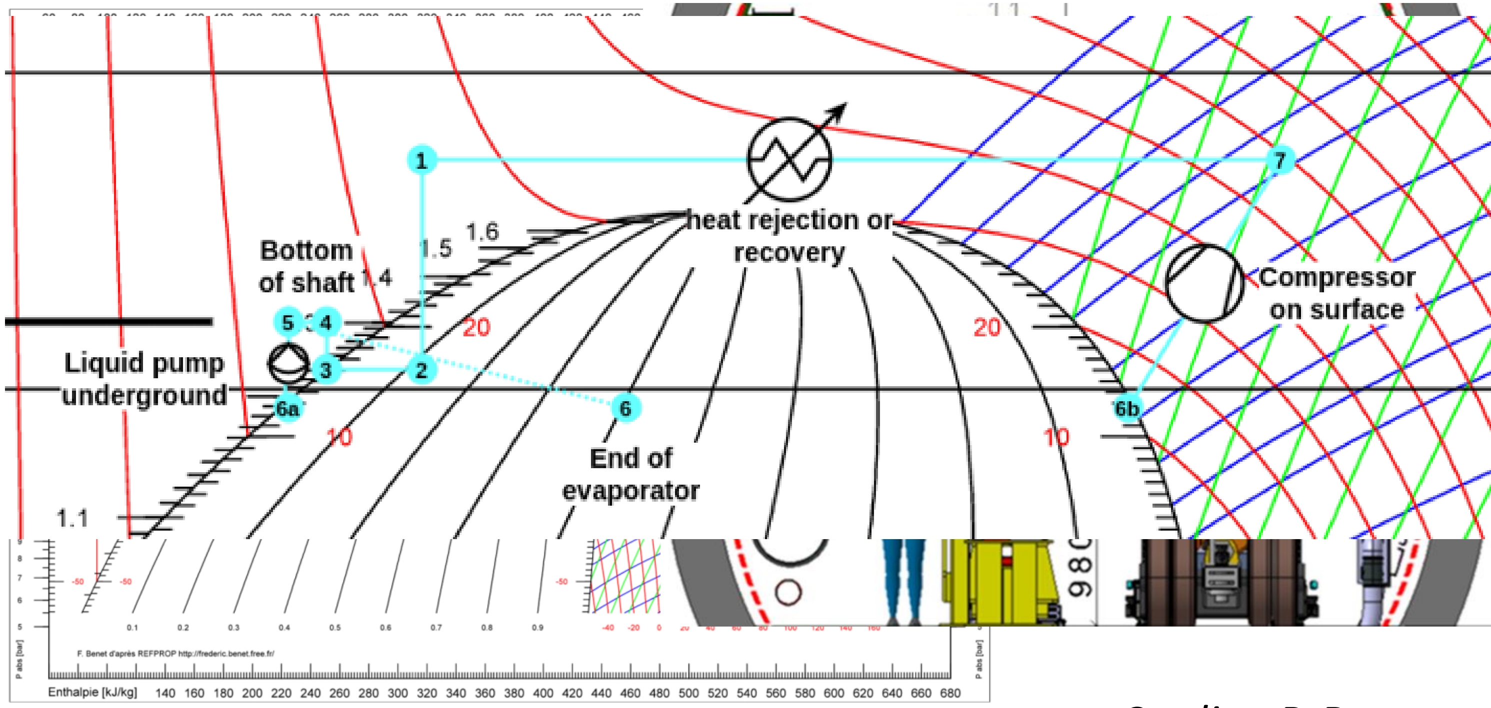
# Chilled water vs $CO_2$ in the FCC tunnel

- $CO_2$ in liquid-vapour state, with finned tubes is a proposal to be studied
  - Less space in the tunnel
  - Main advantage: No rotating, actuated components in the system
  - Study underway




Credits: P. Barroca, EN/CV




Credits: P. Barroca

# Chilled water vs $CO_2$ in the FCC tunnel

- Similar concept to the cooling of the tracker subdetectors

applied sciences MDPI

Article

## An Ultra-Low Temperature Transcritical R744 Refrigeration System for Future Detectors at CERN LHC

Pierre Barroca [1]*, Armin Hafner [1], Bart Verlaat [2], Paolo Petagna [2], Wojciech Hulek [2], Lukasz Zwalinski [2], Pierre Hanf [2], Michele Battistin [2], Loic Davoine [2] and Daniella Teixeira [3]

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**Abstract:** The cooling systems of the future tracking detectors of the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN will be entirely based on $CO_2$ refrigeration technology. The system is a booster refrigeration system, composed of a two stage primary part with transcritical R744 equipment and a low temperature secondary $CO_2$ pumped loop. The primary refrigeration sub-system installed on surface provides cold R744 at −53 °C to the $CO_2$ pumped loops installed 100 m underground and rejects the heat exchanged. The process must be reliable and remain stable regardless of the amount of heat exchanged, which will amount to hundreds of kilowatts and is expected to vary throughout the lifetime of the detectors. The paper discusses the concept adopted for the innovative transcritical R744 cycle and describes the technical details of the first prototype built.

**Keywords:** CERN; refrigeration; R744; particle trackers

check for updates

**Citation:** Barroca, P.; Hafner, A.; Verlaat, B.; Petagna, P.; Hulek, W.; Zwalinski, L.; Hanf, P.; Battistin, M.; Davoine, L.; Teixeira, D. An Ultra-Low Temperature Transcritical R744 Refrigeration System for Future Detectors at CERN LHC. *Appl. Sci.* **2021**, *11*, 7399. https://doi.org/10.3390/app11167399

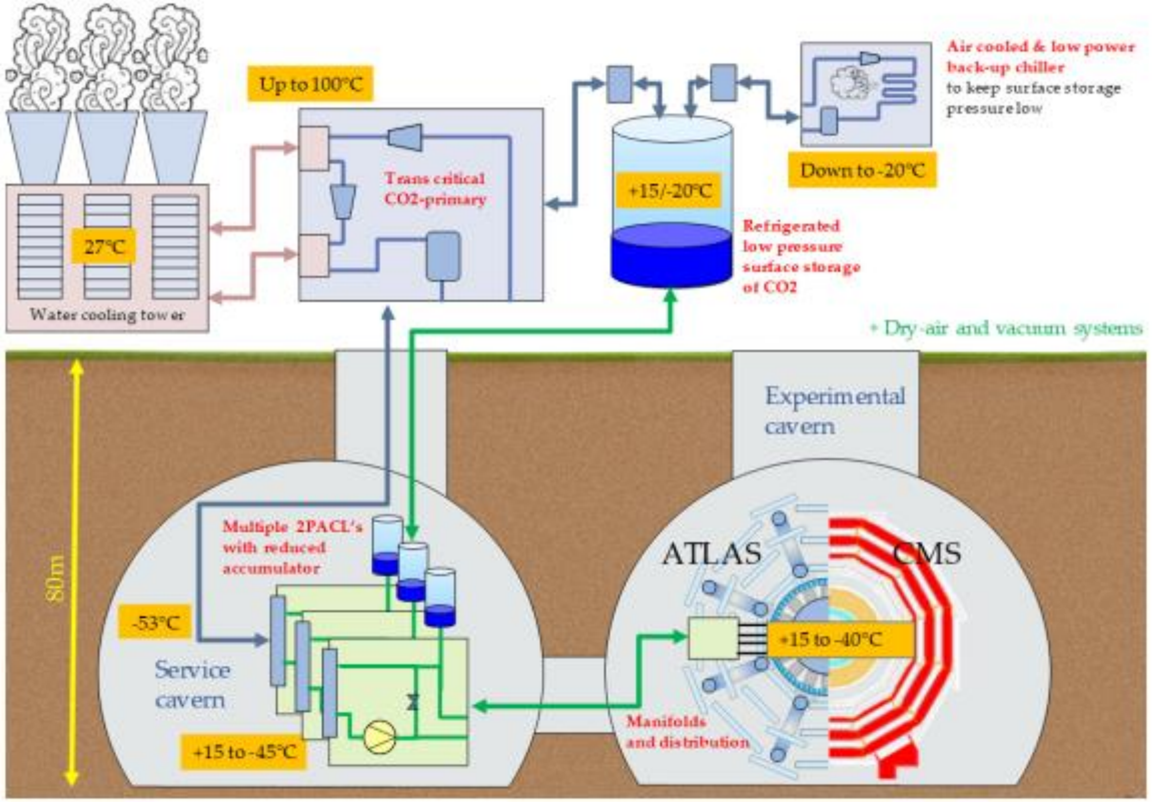
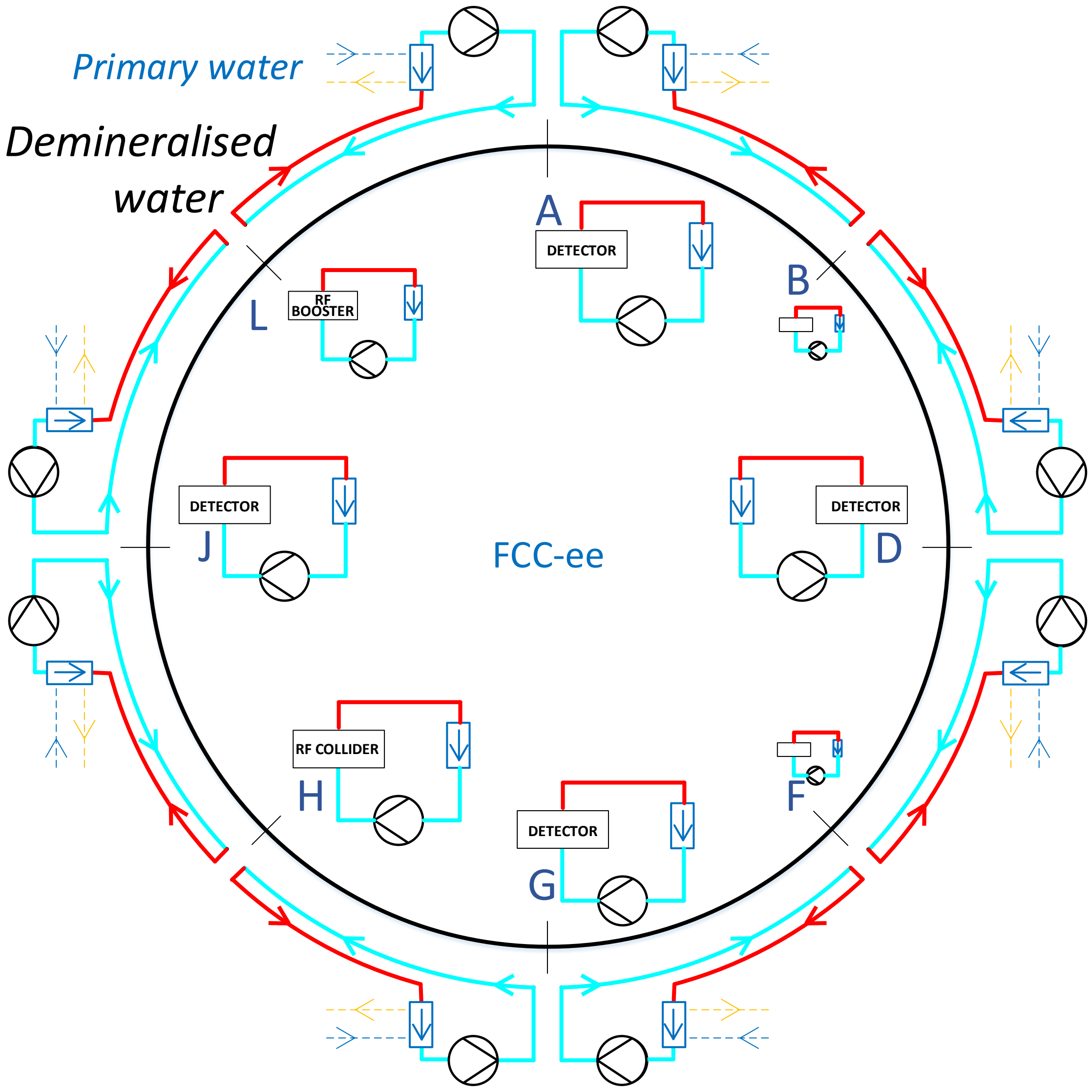



**Figure 1.** Overview of ATLAS and CMS cooling system pipeline connections and distribution.

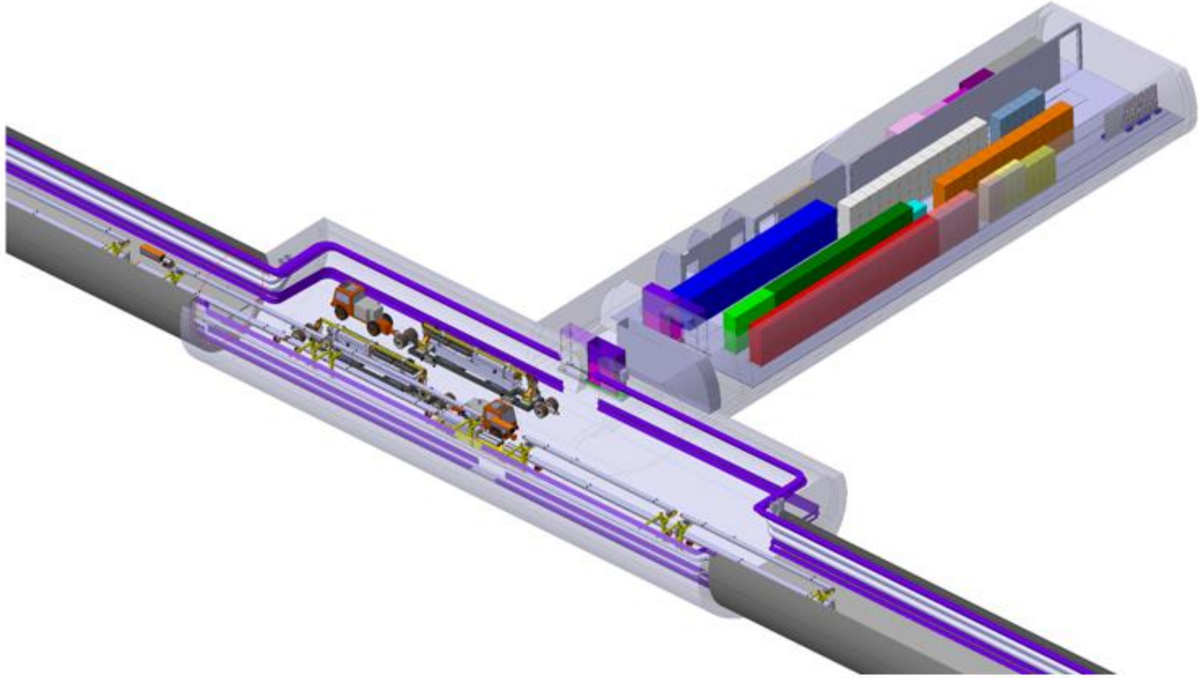
# Demineralized Water Underground Circuits

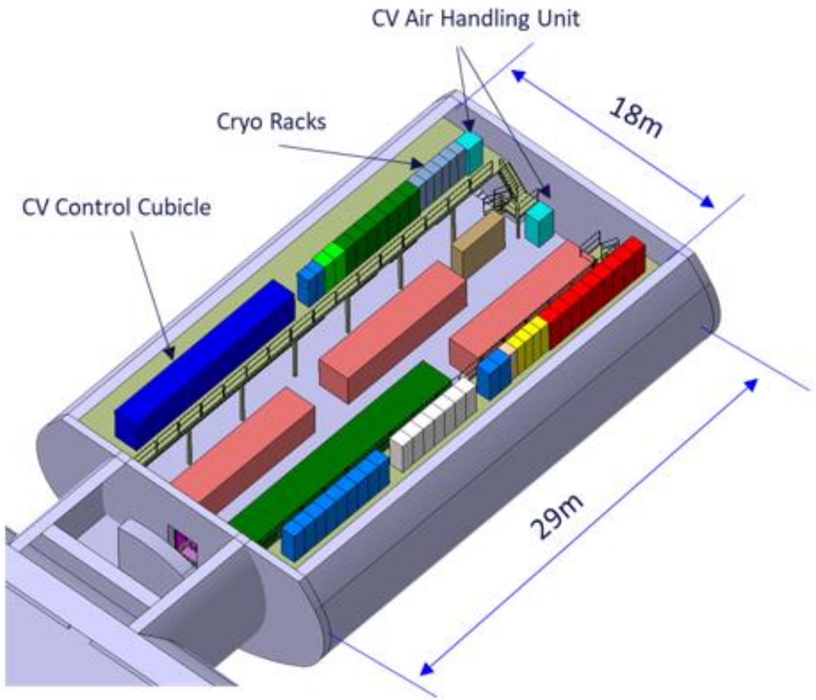
In sectors | At points

| Location | Magnets | Alcoves | SR Absorbers | Detectors | Power converters Accelerator | RF Underground | Cryogenics* | Underground TOTAL |
|---|---|---|---|---|---|---|---|---|
| L-A | 7.1 | 0.9 | 12.5 | | | | | |
| A | | | | 0.5 | 1.05 | | 0.01 | 42.56 |
| A-B | 7.1 | 0.9 | 12.5 | | | | | |
| B | | | | | 1.05 | | | 1.05 |
| B-D | 7.1 | 0.9 | 12.5 | | | | | |
| D | | | | 0.5 | 1.05 | | 0.01 | 42.56 |
| D-F | 7.1 | 0.9 | 12.5 | | | | | |
| F | | | | | 1.05 | | | 1.05 |
| F-G | 7.1 | 0.9 | 12.5 | | | | | |
| G | | | | 0.5 | 1.05 | | 0.01 | 42.56 |
| G-H | 7.1 | 0.9 | 12.5 | | | | | |
| H | | | | | 1.05 | 45.7 | 2.2 | 50.95 |
| H-J | 7.1 | 0.9 | 12.5 | | | | | |
| J | | | | 0.5 | 1.05 | | 0.01 | 42.56 |
| J-L | 7.1 | 0.9 | 12.5 | | | | | |
| L | | | | | 1.05 | 0.69 | 1.0 | 2.74 |



# Alcoves: Demi water for cooling, chilled water for HVAC






| | | |
|---|---|---|
| User Racks | Miscellaneous Racks | LV power centre |
| Booster Racks | Control Cubicle | 630 kVA transformer general |
| Alarm , Light and Spare Racks | Air Handling Unit | MV cubicles general |
| Control and Fibre Optic Racks | Booster Racks | MV cubicles EPC |
| CPS System | Cryo Racks | 800 kVA transformer |
| Orbit Racks | Dipole tapering Racks | EPC switchboard |
| Collider Racks | UPS systems | |

# Conclusions and next steps

- Several options are worth studying to optimise water consumption, reject water, heat recovery and occupancy of the tunnel -> improving sustainability
- Some of them imply complex systems and specialists on the topics are needed, collaboration in some of the topics has started;
  - Proceed with HBI/AFRY on Phase 2 water cooling optimisation;
  - Proceed with NTNU on using $CO_2$ as refrigeration and heat transfer fluid;
- Contribution to the FCC Feasibility Study Report :
  - Respond to the numerous points related to environmental aspects of the project;
  - Write internally a final reference report on each of the systems combining the in-house EN-CV design and the most relevant insights from the consultants.

Thank you
for your attention.