An Update on the Colossus mK platform at Fermilab

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Abstract. As part of the efforts of the Superconducting Quantum Materials and Systems National Quantum Center at Fermilab, we will construct a large millikelvin refrigeration platform known as Colossus. The Colossus platform will be used for quantum computing applications, along with physics and sensing experiments. At the preceding CEC/ICMC meeting in 2021, we reported on the conceptual design of the platform. In the intervening time, the design of the system has been completed and passed through review, with construction now underway. This paper provides an update on the overall design of the system, and the status of and time line for construction.

1. Introduction

At the 2021 ICMC conference, we reported on the conceptual design of a large millikelvin cooling platform for quantum computing and dark photon physics. [1] Now known as Colossus, named for the first electronic computer [2], the platform is intended to provide a large cryogenic volume at the 20-mK temperature stage along with high cooling power suitable for operation of clusters of niobium alloy-based superconducting radiofrequency cavities combined with two-dimensional superconducting qubits acting as three-dimensional quantum processor elements. In such a configuration, the superconducting qubit is coupled to high-order degrees of freedom in the three-dimensional cavity to produce multiple interconnected quantum states that can each function as a discrete qubit. The operation of niobium-based SRF cavities at millikelvin temperatures has previously been demonstrated to exhibit long lifetimes in the quantum regime [3], although there are challenges in cooling large superconducting objects to such low temperatures due to the large heat capacity through the transition temperature and the poor thermal conductivity of the superconductor below the transition. The SRF cavity qubit architecture results in a relatively large object that must be cooled to millikelvin temperature in order to suppress photon noise, while the use of multiple such devices necessitates a large experimental volume with a high cooling capacity in order to effectively cool the cavities to millikelvin temperatures.

At the time of conception of the Colossus project, the largest commercially-available dilution refrigerators had millikelvin experimental spaces around 500 mm in diameter and cooling powers of 30–50 μW at 20 mK. In the intervening time, several commercial suppliers have added fridges with 1000–1500 mm diameter experimental volumes and cooling powers of 100 μW at 20 mK to their product lines. These commercial fridges continue to utilize mechanical coolers to provide precooling for the dilution refrigerator stages. The Colossus platform is based around the at-present unique feature of a helium refrigeration plant to provide the warm cryogenic stages, in combination with a millikelvin volume 2 meters in diameter and a cooling capacity of 300–500 μW at 20 mK.

In the two years since reporting on the conceptual design of the platform, the details of Colossus have been developed to the point of manufacture. In particular, the details of the interface between the helium cryogenic plant and the Colossus cryostat has evolved substantially, along with the mechanical supports between stages and the arrangement of the dilution unit heat exchanger stacks. This paper will provide an overview of the main design features of the Colossus platform, along with the current status and expected time line for completion of construction. Additionally, changes in the science use cases have altered the cooling power requirements at the superfluid helium stage, allowing a redistribution of the available helium cryogenic plant capacity between the cryostat stages. Other papers presented in these proceedings [4, 5] describe more specific details of key technical areas.

2. Design of the Colossus platform

The general layout of the Colossus cryostat in cross section is shown in Fig. 1. The cryostat consists of a flat upper head from which the cold plates and thermal shields are suspended. This assembly is installed in a stainless steel vacuum vessel. The original design of the platform as reported in 2021 made use of components from an existing vacuum vessel at Fermilab, while the final design replaces these components with new parts that remove a number of design compromises. The existing cryostat is shown in Fig. 2 with a dished vessel head installed. Additionally, a view of the Colossus area in relation to the helium refrigeration plant is shown in Fig. 3. The major change is the elimination of a structurally separate thermal shield cooled by a dedicated liquid nitrogen circuit, replaced with a shield mechanically connected to the 80-K cold plate and cooled conductively by the same liquid nitrogen circuit as the plate. This change allows clearance inside the vacuum vessel for ambient temperature high-permeability magnetic shielding, an important feature for the successful operation of superconducting devices. The shield consists of a lower cylinder section inside the vacuum jacket and a separate top cap that is mounted between the vacuum top plate and the 80-K Thermal Shield plate. Additionally, the dished head used in the previous design has been replaced with a flat head to allow more area to accommodate the necessary vacuum ports for gas handling, cryogenic connections, and experimental wiring.

Table 1. Dimensions and construction materials of the major cryostat components. For the shield components, “Thickness” refers to the dominant wall thickness of the shell and “Diameter” is the inside diameter of the shield cylinder.

Component	Diameter	Height	Thickness	Material
Vacuum Vessel	3.4 m	3.7 m	10 mm	SS304
Magnetic Shield	3.2 m	3.4 m	2 mm	Mumetal
Thermal Shield	3.0 m	2.8 m	5 mm	AL6061
Helium Shield	2.7 m	2.6 m	5 mm	AL6061
2-K Shield	2.5 m	2.2 m	5 mm	AL6061
Still Shield	2.2 m	2.0 m	5 mm	AL6061
Mixing Chamber Shield	2.0 m	1.5 m	5 mm	OFHC
Vacuum Top Plate	3.6 m	-	90 mm	SS304
Thermal Shield Plate	3.0 m	-	50 mm	AL6061
Helium Plate	2.8 m	-	50 mm	AL6061
Superfluid Plate	2.5 m	-	50 mm	AL6061
Still Plate	2.3 m	-	25 mm	OFHC
Mixing Chamber (MC1) Plate	2.2 m	-	25 mm	OFHC
Mixing Chamber (MC2) Plate	2.0 m	-	25 mm	OFHC

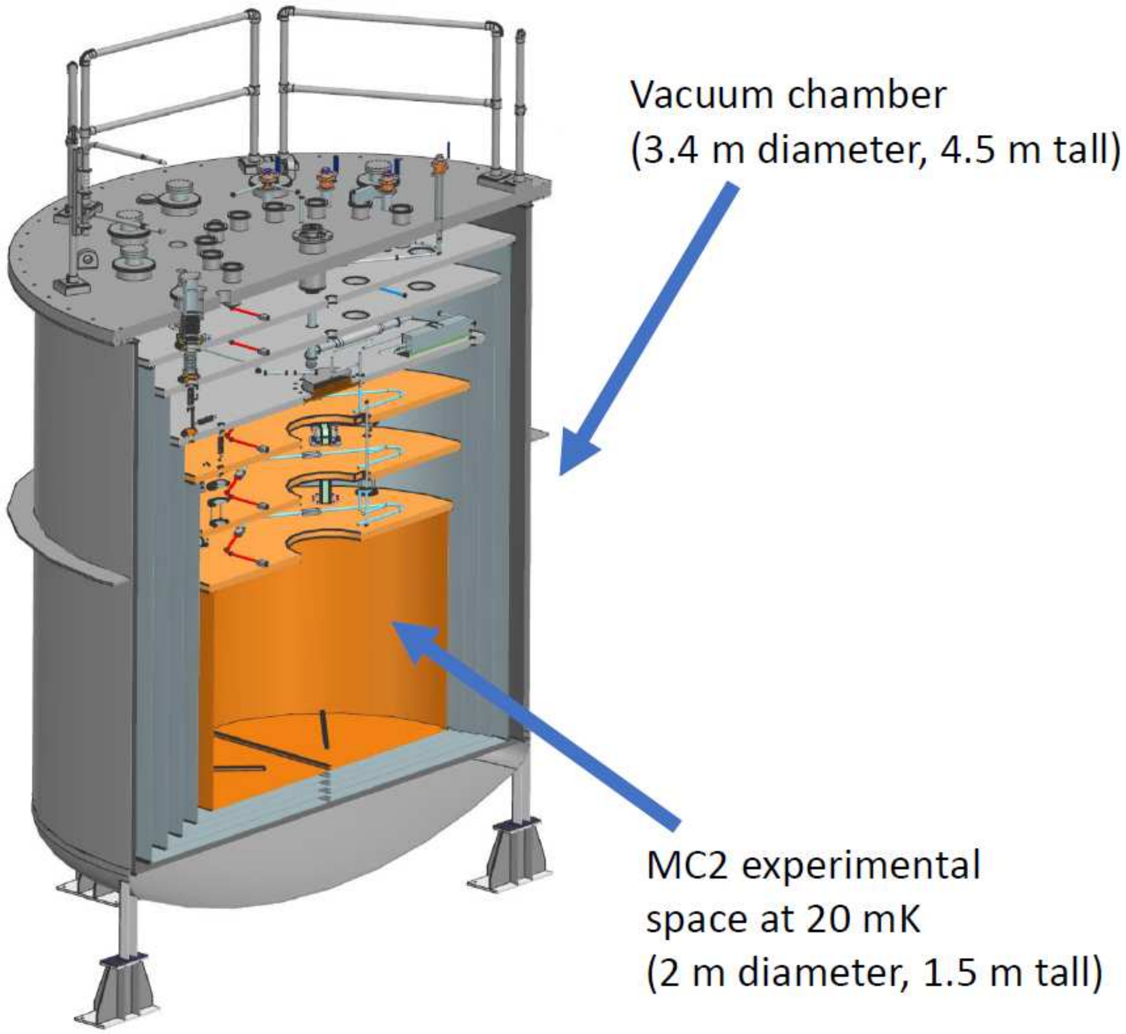

Figure 1. CAD image of the cryostat design shown in cross-section. For details and discussion, see text.

The internal structure suspended from the flat vessel head consists of six cold plates at temperatures of 80 K cooled by liquid nitrogen, 5 K and 2 K cooled by liquid helium, and at 1 K, 100 mK and 20 mK cooled by the dilution heat exchangers. This arrangement can be seen in the CAD rendering in Fig. 4. Each plate is suspended from the next warmest plate by a system of 4 glass-reinforced composite bars, discussed in more detail in Sect. 2.1. The aluminum alloy thermal shields are attached to the cold plates at the 80-K, 5-K, 2-K, and 1-K (still) layers, while the 20-mK plate supports a copper shield for control of stray light in the experimental space. The major dimensions and mechanical parameters for the cryostat, plates and shields are summarized in Table 1. The warmer, upper plates are composed of aluminum alloy for easier fabrication and reduced cost, taking advantage of the distributed cooling piping at the Thermal Shield and Liquid Helium cold plates to reduce thermal gradients in the plate. At the lower stages, where cooling is provided at discrete points of attachment to the dilution heat exchangers, copper plates are used.

Figure 2. Photograph of the existing experimental installation, including the associated work platform and cryogenic infrastructure. The vacuum vessel was previously used as a liquid helium test stand for solenoids for the Mu2e project. While the final design of Colossus replaces this vacuum vessel with a new vessel of similar design, the work platform will be reused. Picture credit: Fermilab

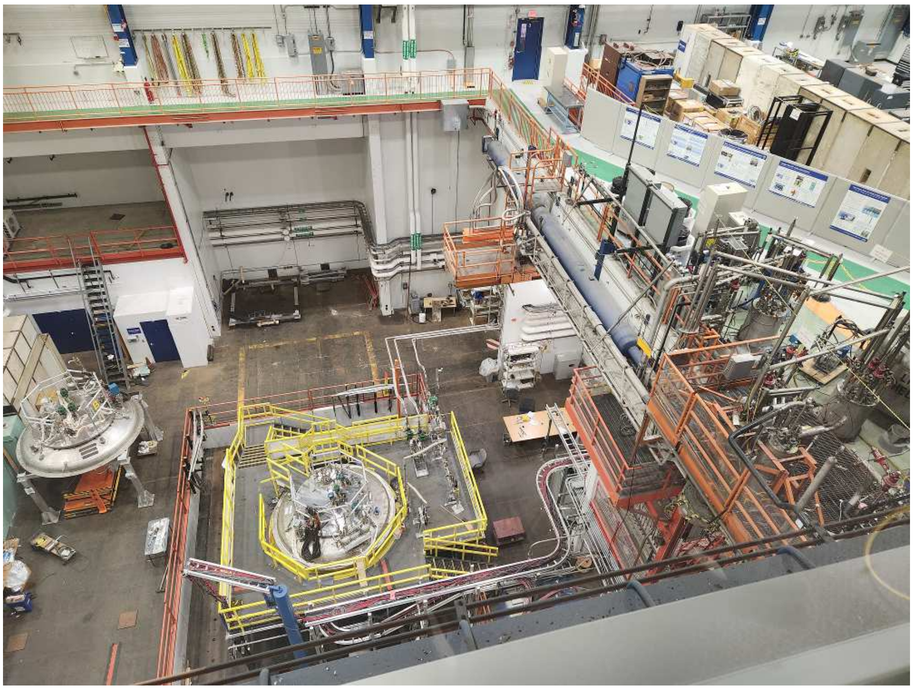

Figure 3. Photograph of the Colossus installation area from the opposite side of the pit area shown in Fig 2. The floor level of the pit is approximately 40 feet below the grade level. The helium refrigeration plant and upper section of the cryogenic transfer line can be seen on the right side of the picture at the grade level.

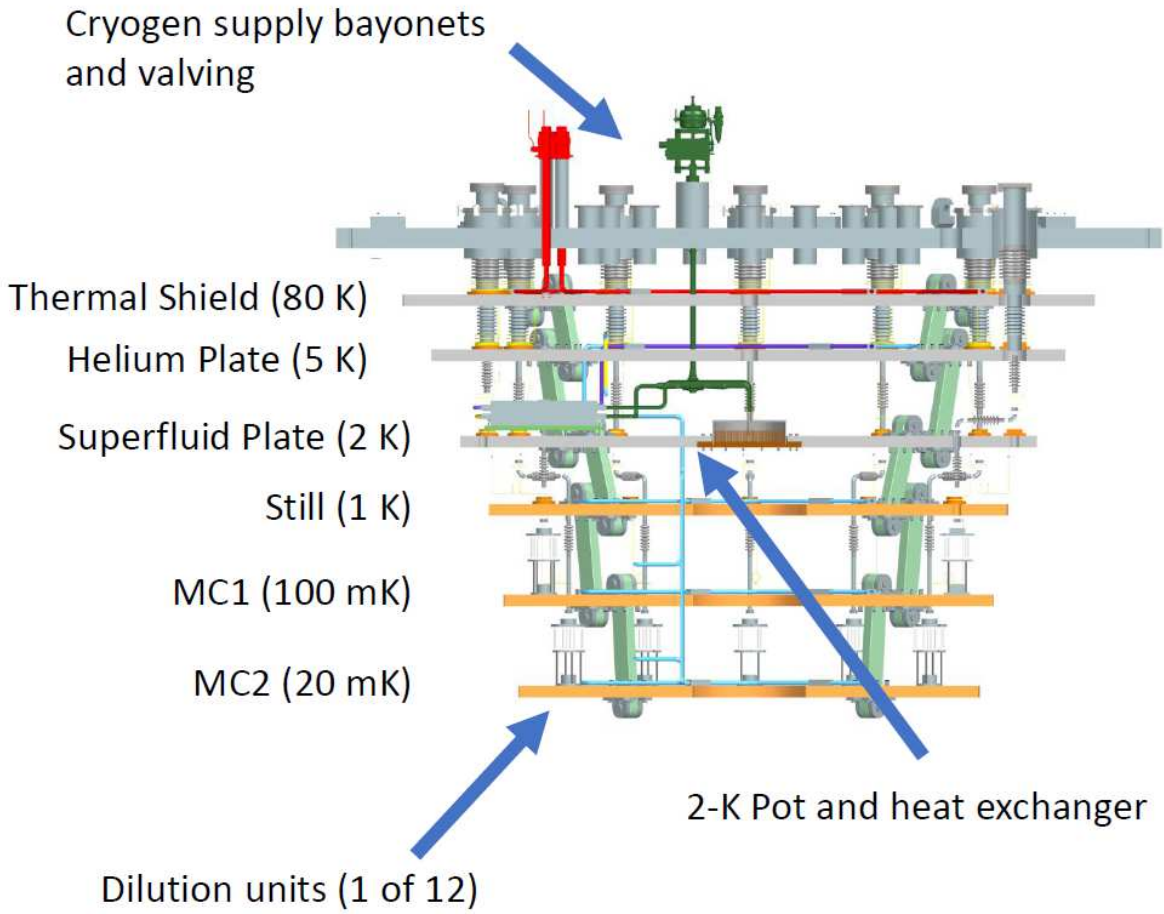

Figure 4. CAD image of the cryostat plate arrangement, with the individual plates and the associated nominal temperatures of each plate indicated. In addition, the connections for the liquid helium supply are indicated, along with the pumped vessel and the heat exchanger at the 2-K superfluid helium plate. For details and discussion, see text.

2.1. Thermally Isolating Supports

The thermal stages are supported using glass fiber reinforced composite bars, with each stage hanging from the next by four bars arranged radially. The bars are connected to the cold plates at each end with stainless steel brackets incorporating a stainless shaft that allows compliance in the radial direction to compensate for differential thermal contraction between the cold plates on cooling. A polyamide bearing sleeve is used between the composite bar and the shaft to prevent binding when cold.

Some of the possible future use cases for the Colossus platform include low-radioactive background experiments that would include lead or similar high-density shielding layers inside the cryostat. As such, the interstage supports are designed to carry heavy payloads. Based on the mechanical behavior of the flat head of the vacuum jacket, the maximum mechanical load that could be carried is approximately 40,000 kg and so the thermally-isolating supports are designed to accommodate this load. A finite-element method was used to analyze the support design and optimize as required, resulting in a bar cross-sectional area of 7 in^2. For simplicity, this same cross-sectional area is used for the supports at each stage with the length of the bars adjusted to meet the necessary spacing requirements between adjacent plates. Example FEA stress plots for different elements of one of the support rods are shown

Table 2. Dimensions and conducted heat of the thermally isolating supports at each stage of the cryostat. Every support has the same cross-sectional area of 7 in^2.

Stage Support	Length (between pivots)	Conducted Heat (per support)
80-K	9.6	2.6 W
5-K	15.7	0.24 W
2-K	21.5	1.74 mW
Still	18.2	0.28 mW
MC1	21.5	32 μW
MC2	21.5	0.22 μW

in Fig. 5. Stress in the metal components and bearing are generally very low, while the peak stress in the reinforced composite approaches 50 % of the tensile strength of the material. The anisotropy of the composite material is an important consideration due to the high mechanical load, with the warp direction having 60 % higher strength that the orthogonal axis. The lengths of the individual supports and the associated calculated conduction heat load are summarized in Table 2.

2.2. Cooling System Design

Cooling of the upper stages of the Colossus platform is provided by a helium cryogenic plant, originally used with the CDF collider physics experiment. The plant can provide up to 625 W of cooling at 4.7 K when used as a refrigerator or over 120 liters per hour of liquid helium [6], and includes a liquid nitrogen supply both for supply to the experiment and for precooling helium heat exchanger. Liquid nitrogen and liquid helium are supplied to the Colossus cryostat via a vacuum-jacketed transfer line, with liquid nitrogen cooling the first cold plate to 80 K and helium cooling the second cold plate to 5 K. Within the Colossus cryostat, a fraction of the helium flow is diverted through a counterflow heat exchanger and Joule-Thomson valve, supplying a small helium vessel connected to the 2-K cold plate. The heat exchanger and the 2-K pumped vessel is indicated in Fig. 1. A room temperature pump skid with a boosted roots pump is used to reduce the vapor pressure in this small vessel to produce superfluid helium. Additionally, the helium flow can be diverted to the lower stages of the cryostat for precooling from room temperature. The temperature of the helium supplied during precooling is regulated by mixing with room temperature gas inside the cryostat. Once the lower stages are cooled close to 5 K, the precooling circuit is evacuated to vacuum to avoid any superfluid heat leaks. Further details of the cryogenic plant, cryogenic distribution system and the upper stages of the cryostat are presented elsewhere in these proceedings. [4]

Cooling of the three coldest stages of the experiment is provided by the dilution unit heat exchanger stacks. The platform utilizes commercially-constructed dilution heat exchangers, with capacity for up to ten independent 3He circuits to be installed at the lowest stage. Two additional dilution units are installed on an upper cold plate referred to as the “MC1 stage” (the lower plate correspondingly referred to as the “MC2 stage”) to intercept conductive heat loads between the still and the 20-mK plate. While this function is fulfilled in a conventional dilution refrigerator by dumping some load at an intermediate point in the heat exchanger stack, power deposited in this way will directly affect the performance of the mixing chamber. A solution to this issue, and the approach adopted in the Colossus design, is to use additional dilution refrigerator cores that are intended to operate closer to 100 mK to intercept this load. The stills of the two MC1 dilution units provide cooling at the 1-K cold plate, while the stills of the 10 MC2 dilution units are uncoupled to allow for individual optimization of the helium flow rates by tuning the still heaters.

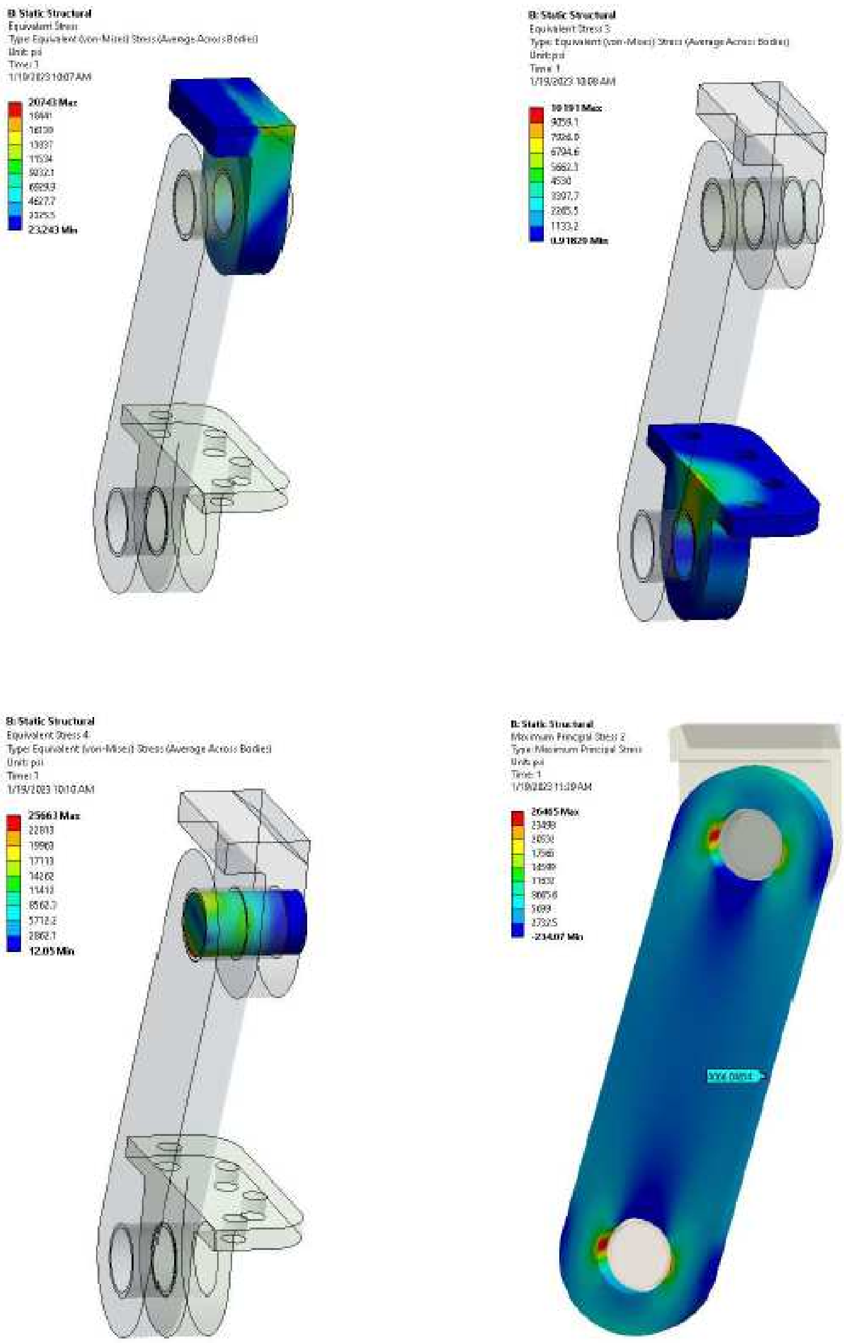

Figure 5. Representative stress plots from finite-element analysis of components of the thermally-isolating supports. Upper plots are for the stainless steel yokes of the support, while the lower plots show the bearing (left) and body (right) of the support. As discussed in the text, the system of 4 supports are designed to support a load of 40,000 kg. While peak stress in the metal components are low, peak stress in the composite bar is approximately 180 MPa (43 % of the tensile strength of G-10CR at room temperature).

It is expected that initially only a subset of the dilution stages will be installed, allowing the platform to operate at reduced cooling capacity, with later expansion to the full system. The specifics of the heat exchanger stacks are being finalized, but based on the currently available commercial dilution units it is likely that each stack will be able to provide between 30 and 50 μW at 20 mK at the mixing chamber and between 10 and 30 mW at 800 mK at the still layer, depending on the room temperature pumping system. The mixing chamber of each dilution unit is bolted directly to the corresponding cold plate to maximize conduction at this critical interface. Thermal connections between the Still Plate and the still flanges of the MC1 dilution units are made via flexible copper ropes to minimize thermal stresses in the stacks due to contraction of the large cold plates. Compliance in the still pump line is provided by integrated bellows that accommodate both the radial and vertical components of the thermal contraction.

The connections between the commercial dilution units at the still and the room temperature plate of the cryostat is designed as a stand alone assembly that can be assembled and leak checked independently prior to integration with the Colossus cryostat. This assembly incorporates both the still pumping line and the inlet side capillary with integrated heat exchangers at each thermal stage. Further details of the helium-3 cooling system and gas handling is described in more detail in an accompanying publication. [5]

2.3. Thermal modelling

Detailed modelling of the expected thermal loads at each stage of the cryostat has been used to inform decisions as the Colossus design has developed. The model includes thermal radiation, conductive loads, and loads from the circulation of helium mixture in the dilution circuits. The most recent iteration of the model results are summarized in Table 3, including a comparison to the available capacity at each stage. Loads resulting from experimental wiring and devices operated in the platform are not included here since there are multiple possible configurations of wiring and payload presented different heat loads. However, it should be noted that the operational loads are at most 30 % of the available cooling power at each stage, allowing considerable capacity for adding experimental wiring.

The substantial change in expected performance from the conceptual design, as reported in [1], is a reduction in the required cooling capacity at the 2-K superfluid helium stage. Much of the power requirement at this stage was intended for use in certain Dark Photon experiments using an SRF cavity with a small acceleration gradient disipating a few tens of Watts. As the science cases for the Colossus platform have evolved, less power is required at this 2-K stage allowing the internal heat exchanger and associated components to be downsized.

3. Current status and timeline

The detailed final design process is nearing completion as of summer 2023 with major procurements for long delivery time items beginning later this year. The initial construction phase for the upper cryogenic stages is planned to complete late in 2024, allowing operation of the platform with limited millikelvin capability in 2025. Upgrades to the full capability of the platform will depend on continued funding of the National Quantum Initiative beyond the initial five-year period.

4. Summary

This paper has discussed the design for a large millikelvin cryogenic platform suitable for use in quantum computing platform and as a platform of fundamental physics experiments using superconducting radiofrequency cavities. Changes to the major design features since the previous report in 2021 have been discussed, along with the expected heat loads and thermal performance metrics associated with the system. The platform will address issues associated with scaling up millikelvin cryogenic systems by utilizing existing cryogenic infrastructure for the supply of helium and liquid nitrogen, along with integrating multiple small dilution circuits into a single large cryostat to provide a large, high-cooling power cryostat. The design phase is nearing completion, with procurements expected to begin later this year and start of operations during 2025.

Table 3. Summary of thermal modelling results listed by cryostat stage and major loads.

Load	Thermal Shield	Helium	Superfluid Helium	Still	Mixing Chamber MC1	Mixing Chamber MC2
Nominal Temperature	80 K	5 K	2 K	1 K	100 mK	20 mK
Radiation	26 W	2 W	27 μW	0.58 μW	-	-
DC Wiring	2.1 W	2.1 W	29 mW	0.31 μW	0.05 μW	-
Supports	10 W	0.96 W	7 mW	1.1 mW	129 μW	0.87 μW
Bayonet Conduction	3 W	4.5 W	1 W			
Precool Line Conduction	-	-	370 μW	43 μW	8.5 μW	0.1 μW
Helium-3 Inlet Conduction	0.2 W	0.4 W	41 μW	2 μW	-	-
Helium Mixture Cooldown	110 W	37.6 W	2.7 W	-	-	-
Still Pumpline Conduction	2.6 W	2.2 W	0.7 mW	74 μW	-	-
2-K Pumpline Conduction	1.1 W	35 mW	0.2 mW	-	-	-
Total Load	155 W	50 W	3.74 W	1.2 mW	138 μW	1 μW
Available Capacity	9kW	200 W	10 W	100 mW	3 mW	300 μW

5. References

[1] Hollister M I, Dhuley R C and Tatkowski G T 2022 *IOP Conf. Ser: Mater. Sci. Eng.* **1241** 012045

[2] Colossus at The National Musuem of Computing https://www.tnmoc.org/colossus Retrived 06-16-2023

[3] Romanenko A, Pilipenko R, Zorzetti S, Frolov D, Awida M, Belomestnykh S, Posen S and Grassellino A 2020 *Phys. Rev. Applied* **13** 034032

[4] Tatkowski G, Hollister M, James C, and Dhuley R 2023 *These Proceedings*

[5] James C, Hollister M, Tatkowski G and Dhuley R 2023 *These Proceedings*

[6] Fast R W, Aihara K, Dachniqskyj R I, Kephart R D, Kondo K, Minemura H, Mori S, Saito R, Stone M E, Suzuki T, Wands R H and Yoshizaki R 1984 *Proc. 10th Int. Cryo. Eng. Conf.* 386

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