2 Kelvin helium distribution system for the Electron Ion Collider's 10 o'clock satellite refrigerator

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Abstract. The Electron-Ion Collider (EIC) at Brookhaven National Laboratory (BNL) will involve superfluid helium cooling of superconducting magnets and Superconducting Radio Frequency (SRF) cavities at several sites around the existing Relativistic Heavy Ion Collider (RHIC) accelerator tunnel. While the majority of the cooling power for these loads is provided by BNL's central cryogenic plant, Jefferson Lab is designing satellite equipment which augments the central plant and enables 2 Kelvin operation. The 2 K cryogenic distribution system for the collider's 10 o'clock location (Interaction Region 10 or IR10) includes all necessary interfaces to the IR10 Satellite Refrigerator, to the overall EIC cryogenic distribution system, and to 12 SRF cryomodules for the electron and hadron storage rings. In addition to providing the required cooling capacities in all operating modes, the IR10 2 K cryogenic distribution system also stabilizes the supply temperature and enables safe connection and disconnection of individual IR10 cryomodules. Moreover, the layout of the IR10 2 K cryogenic distribution system copes with challenging spatial constraints and adapts to the process configuration and routing of existing RHIC cryogenic distribution components which will be re-used for EIC. This paper gives a full overview of the IR10 satellite cryogenic distribution system design, and highlights some of the challenges encountered.

1. Introduction

The EIC project calls for cryogenic cooling of various equipment—primarily superconducting RF cavities—to a nominal temperature of 2 K at several locations around the collider ring. BNL's existing Central Plant is located at the 5 o'clock position on the collider ring and will supply supercritical helium at approximately 4.5 K and 3.3 bar to these customer loads. The Central Plant will distribute this 4.5 K cooling primarily via RHIC's existing multi-line vacuum-jacketed transfer lines which encircle the entire collider tunnel, a circumference of over 3,800 m. Several Satellite Refrigerators, to be constructed in proximity to the new 2 K loads, will process the subatmospheric (30 mbar) helium vapor return flow from the customer loads using cold and warm vacuum compression systems, and will recover some cooling capacity to augment the Central Plant's performance.

The 2 K Cryogenic Distribution System (CDS) for the IR10 area of the EIC project will provide a means of connecting the helium refrigeration infrastructure—both the Central Plant as well as the local Satellite Refrigerator—with 12 two-cavity SRF cryomodules located in the IR10 area of the existing collider tunnel. At the 10 o'clock position along the collider ring, IR10 is in the forested northwest of the EIC site, alongside the Peconic River and nearly opposite the 5 o'clock Central Plant.

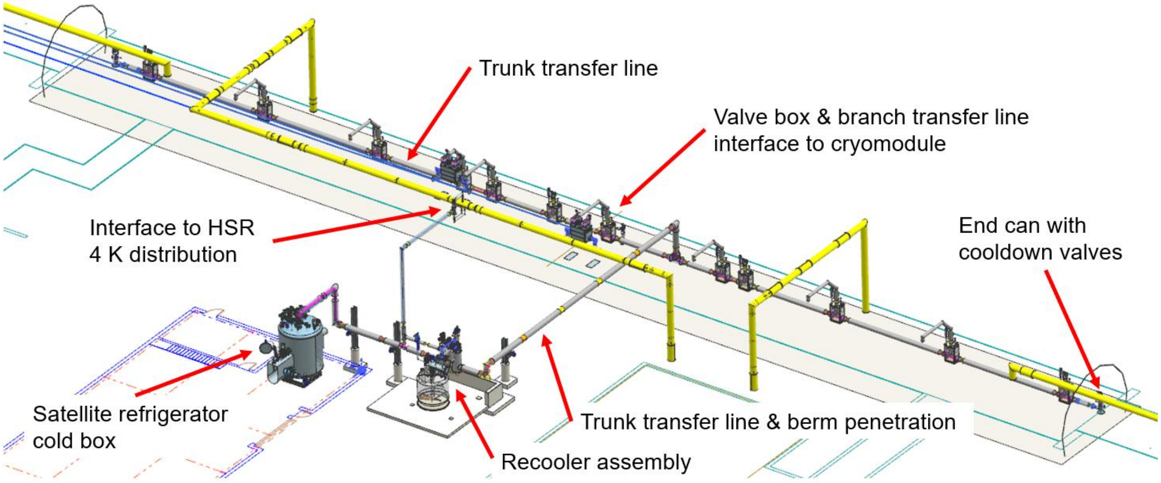


Figure 1. Overview of 2 K cryogenic distribution system for IR10 at EIC.

The CDS takes the form of a large main multi-line vacuum-jacketed transfer line, a 4.5 K recooler assembly featuring a commercial 5,000 L liquid helium dewar, and several ancillary transfer lines and warm piping assemblies. The authors have developed a reference design for the CDS (Figure 1) which serves to validate many of the project's design assumptions, reinforces the bases of estimate for the project cost and schedule, and reduces risk for the vendor(s) who will be responsible for the final design, fabrication, installation, and quality testing of the CDS.

In addition to providing steady-state cooling to the SRF cryomodules at (nominally) 2 K, the CDS also supports off-nominal and transient modes and provides for the safe connection and disconnection of individual cryomodules while the remaining modules are held at 4.5 K. The system also thermally anchors the supercritical supply flow from the Central Plant and includes features to enable the complete commissioning of the Satellite Refrigerator even if no customer loads are yet attached.

2. Process circuit descriptions

2.1 Cryomodule cooling loops

Process circuits that supply cooling to the SRF cryomodules are listed in Table 1 and shown in Figure 2.

The CDS first accepts the supercritical primary supply (line "S") flow from the existing RHIC 4.5 K cryogenic distribution system at approximately 5 K and 3.3 bar. The S circuit then passes through a heat-exchange coil fully immersed in a 5,000 L liquid helium dewar; this "recools" the temperature of the supply circuit to nearly match the saturation temperature of the stored liquid at 1.5 bar. The CDS then distributes the subcooled supply flow to each of the 12 cryomodules in parallel. The authors expect the S line to absorb a static heat in-leak of 94 W and a pressure drop of 57 mbar over the distance (approximately 75 m on average) between the recooler and a cryomodule.

In each cryomodule, the supply flow is split into several parallel paths: one primary cooling circuit and several shield/intercept circuits. In the primary circuit, the supply flow first passes through a 2 K – 4 K heat exchanger before being expanded, by a Joule-Thomson control valve, into a phase separator surrounding the SRF cavity; superfluid helium-II is collected there at saturation pressure. Its amount is controlled with a liquid level sensor. Previous subcooling of the supply flow in the recooler minimizes the vapor fraction after J-T expansion, thus mitigating adverse effects (e.g. microphonics) of high-velocity gas in proximity to the SRF cavity. After the vapor fraction is extracted from the phase separator, it passes back up the 2 K – 4 K heat exchanger and finally returns via the subatmospheric primary return (line "SA") circuit to the Satellite Refrigerator. The SA line will absorb 204 W of static heat in-leak and 123 Pa of pressure drop over this return path.

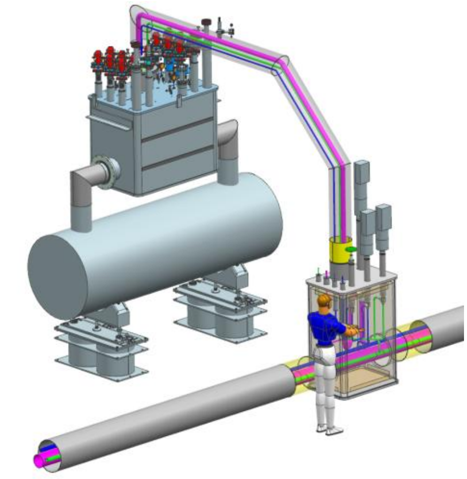
Table 1. Inlet and outlet process conditions for circuits within the main 2 K transfer line serving the superconducting RF cryomodules in IR10.

Circuit	Inlet process conditions	Outlet process conditions	Design static heat leak	Design pressure drop
Primary supercritical supply (S)	At the 4.5 K recooler: $\dot{m}_{in}$ = 87.2 g/s P_{in} = 3.37 bar T_{in} = 4.70 K	At each of 12 cryomodules: $\dot{m}_{in}$ = 7.27 g/s P_{in} = 3.31 bar T_{in} = 4.90 K	94 W	57 mbar
Primary subatmospheric return (SA)	At each of 12 cryomodules: $\dot{m}_{in}$ = 5.23 g/s P_{in} = 3,029 Pa T_{in} = 3.69 K	At the Satellite Refrigerator: $\dot{m}_{in}$ = 62.8 g/s P_{in} = 2,906 Pa T_{in} = 4.31 K	204 W	123 Pa
Shield return (CR)	At each of 12 cryomodules: $\dot{m}_{in}$ = 2.03 g/s P_{in} = 2.50 bar T_{in} = 68.7 K	At the Satellite Refrigerator: $\dot{m}_{in}$ = 24.4 g/s P_{in} = 2.44 bar T_{in} = 79.6 K	1,380 W	56 mbar

In each of the cryomodule's shield/intercept circuits, the nominal 4.5 K supply flow provides active cooling to one of the following loads:

- a thermal radiation shield enclosing the internals of the cryomodule,
- an intercept attached to one of four Fundamental Power Couplers, or
- a series-connected set of thermal intercepts, each attached to one of the cryomodule's beamline warm-to-cold transition joints

Each of these parallel circuits absorbs sensible heat from its load, warming to approximately 68.8 K (controlled by an appropriately sized control valve) before merging in a flow combiner at approximately 2.5 bar. The collected return flow is carried by the shield return (line "CR") circuit to the Satellite Refrigerator. Since the thermal radiation shield of the CDS is attached to this line, the CR line will absorb a further 1.4 kW of static heat in-leak and 57 mbar of pressure drop over this return path, eventually returning to the Satellite Refrigerator at a final temperature of approximately 80 K.



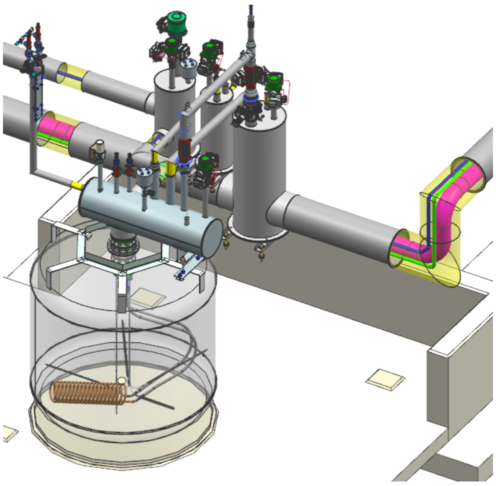


Figure 2 (left). The interface between the 2 K distribution system and each cryomodule is characterized by a pair of valve boxes connected by a fully welded, multi-line, vacuum-jacketed transfer line comprised of rigid piping (a "hard-piped" connection).

Figure 3 (right). A commercially supplied liquid helium dewar forms the basis of the recooler, which thermally anchors the supercritical supply flow, provides vapor for commissioning the Satellite Refrigerator's cold and warm vacuum compressors, and protects the downstream system from temperature and pressure excursions due to a quench upstream.

Cooldown and warmup of the cryomodule are achieved by diverting the return flow of the cryomodule's primary circuit to the cooldown header (line "F"), a standalone single-line vacuum-jacketed transfer line that runs parallel to the main transfer line. Flows passed to the F line at approximately 1.5 bar are normally warmed to 300 K and returned to the suction of the main compressors at the Central Plant, thus imposing a substantial liquefaction load on it. However, if the F line is cold enough, the header can instead be aligned with the 4.5 K vapor return circuit (line "R") in the existing RHIC 4.5 K transfer line. This provides a means to hold one or more cryomodules at 4.5 K for an indefinite period, enabling complex maintenance or repair operations such as the replacement of a cryomodule or cold compressor without requiring a 300 K warmup of the entire satellite system.

2.2 Central Plant – Satellite Refrigerator link

After the return flows from the cryomodules are processed by the 2 K Satellite Refrigerator and any useful cooling capacity is recovered, the CDS provides connections (Table 2) for injecting this capacity back into the Central Plant via two existing circuits within the RHIC 4.5 K transfer line:

- Utility circuit "U" at approximately 1.5 bar and 12 K, which is injected into the return side of the Central Plant at the appropriate temperature level for maximum refrigeration recovery, and

- High-pressure shield circuit "H" at approximately 15.5 bar and 80 K, which provides forced-flow cooling of thermal shields throughout the RHIC system.

Table 2. Inlet and outlet process conditions for return circuits from the Satellite Refrigerator. These flows augment the capacity of the Central Plant.

Circuit	Inlet process conditions	Outlet process conditions	Design static heat leak	Design pressure drop
Utility (U)	At the Satellite Refrigerator: $\dot{m}_{in}$ = 62.8 g/s P_{in} = 1.50 bar T_{in} = 13.1 K	At the RHIC cryodistribution: $\dot{m}_{in}$ = 62.8 g/s P_{in} = 1.44 bar T_{in} = 13.2 K	48 W	59 mbar
Shield (H)	At the Satellite Refrigerator: $\dot{m}_{in}$ = 24.4 g/s P_{in} = 15.7 bar T_{in} = 80.1 K	At the RHIC cryodistribution: $\dot{m}_{in}$ = 24.4 g/s P_{in} = 15.5 bar T_{in} = 80.7 K	80 W	300 mbar

2.3 Recooler assembly

Liquid helium at (nominally) 4.5 K is maintained in the dewar (Figure 3) at or above the level which fully submerges the subcooler coil.

To generate this liquid, a slipstream of supercritical primary supply flow is expanded through a Joule-Thomson control valve which operates in a closed loop based on the signal from the liquid level sensor. The vapor is returned to the Central Plant via the existing "R" vapor return circuit in the RHIC 4.5 K transfer line and can also be injected into the SA circuit to simulate the complete set of customer loads. The latter feature enables commissioning of the Satellite Refrigerator even if the SRF cryomodules are not fully installed in the IR10 tunnel. After the customer loads are connected and there is no longer a need for this R–SA flow path, the two circuits can be fully separated by removal of a bayoneted coupler (or "u-tube") to prevent any loss of 2 K refrigeration capacity due to a leak through the control valve at this connection.

Additional liquid helium stored in the dewar (beyond the minimum amount needed to submerge the subcooler coil) acts as a reserve of excess cooling capacity and works to isolate the customer loads from the effects of upstream fluctuations in the supply temperature, such as from a magnet quench.

3. Component descriptions

3.1 Trunk transfer line

The main section of multi-line vacuum-jacketed transfer line containing the S, SA, and CR lines spans 48.5 m from the recooler assembly (located outdoors, just outside the IR10 tunnel) to a tee joint located within the IR10 tunnel at its approximate center.

From the tee, the transfer line extends in each direction along the IR10 tunnel for a total distance of 85.8 m, terminating with end cans at each end. At intervals along the tunnel, 12 cryomodule interface boxes are placed in line with the transfer line and provide a node for branch connections to each cryomodule.

3.2 Cryomodule interface and valve boxes
The connection to each cryomodule is characterized by a pair of valve boxes which are connected to each other via a fully welded multi-line transfer line comprised of rigid piping. The valve box built into the CDS provides isolation to each cryomodule branch connection as shown in Table 3, while the valve box atop the cryomodule provides instrumentation and control for each cooling circuit within the cryomodule.

Table 3. Cryogenic and warm piping connections to each SRF cryomodule.

Circuit	Isolation type	Line description	Interface description
Primary supercritical supply (S)	Double-block-and-bleed[a]	Multi-line vacuum-jacketed transfer line	Welded
Primary subatmospheric return (SA)	Single valve		
Shield return (CR)	Single valve		
Cooldown (F)	Double-block-and-bleed[b]	Single-line vacuum-jacketed transfer line	Welded
Guard vacuum & primary relief exhaust	Single valve	Unjacketed piping	Flanged
Secondary relief exhaust	None	Unjacketed piping	Flanged

[a] Mitigates the risk of personnel exposure to pressurized cryogens during cryomodule repair activities.
[b] Prevents leakage from the positive-pressure cooldown header F into the subatmospheric primary return circuit SA, which would reduce the system's 2 K cooling capacity.

This "hard-piped" architecture represents a change from earlier conceptualizations of the EIC design. The 2021 EIC Conceptual Design Report [1], for instance, anticipated that the cryomodules would connect to the cryogenic transfer line via bayonets and u-tubes. Through numerous design studies, the authors found that a hard-piped design has the following advantages:

- Economizes space within the IR10 tunnel,
- Improves thermal and pressure-drop performance, and
- Requires fewer isolation valves to mitigate the risk of personnel exposure to pressurized cryogens.

3.3 Anchors
Anchor assemblies throughout the CDS constrain the position of the critical interfaces and reacts to forces such as pressure thrust and thermal expansion. Two types of anchors are considered: terminal anchors and intermediate anchors.

The terminal anchors are located at the ends of the transfer line's main trunk section, at the upstream and downstream ends of the IR10 tunnel. Taking design inspiration from a vacuum break (but with apertures to enable adequate pumping of the insulating vacuum through the anchor assembly), the terminal anchor is strong in tension and compression, and is therefore well suited to react the pressure thrusts that can be generated during excursions to high process pressures. The long, thin-wall tubing used to construct the "vacuum break" minimizes the conductive heat in-leak introduced by the terminal anchor.

One intermediate anchor is placed in proximity to each cryomodule interface box and constrains the position and orientation of the cryomodule branch connection. This anchor is intended to react forces and moments associated with imbalanced thermal contraction of adjoining sections of transfer line. The intermediate anchor design (Figure 4) uses line stops to limit the axial motion of radial spacers around the process piping, thus constraining the piping in all three translational degrees of freedom. The design minimizes heat in-leak by stacking many contact resistances in series; line contacts are used in lieu of surface contacts wherever possible.

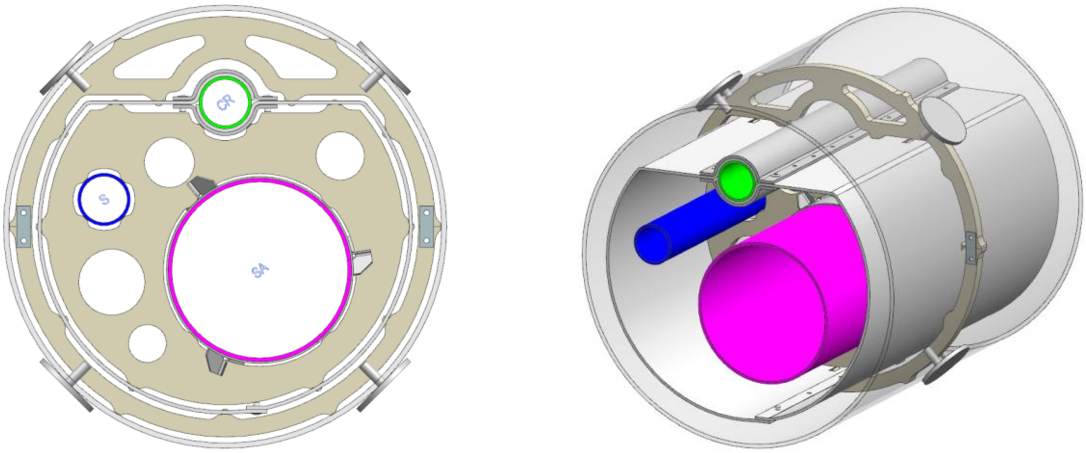


Figure 4. A cross-section of the transfer line shows the intermediate anchor concept—a set of radial spacers constrained in the axial direction by line stops—as well as the thermal shield.

3.4 Thermal shield
Throughout the transfer line, an actively cooled thermal shield intercepts radiative heat in-leak to the internal process piping. The shield panels are formed from sheets of high-conductivity metal (either 1100-H14 aluminum or C10100 or C10200 oxygen-free copper) and are clamped to the CR shield return circuit with mechanical fasteners, similar to the method employed for the MSU-FRIB transfer line [2]. Brazing and welding of the shield components is kept to a minimum. A preliminary Finite Element Analysis demonstrated a difference of < 10 K between the highest and lowest punctual temperatures on the thermal shield.

4. Packaging challenges

Over the course of numerous design studies, the authors explored various options for packaging the CDS into the crowded IR10 tunnel. Driving considerations included:

- Maximizing thermal stability to quell any potential thermal acoustic oscillation (and associated convective heat leaks and pressure fluctuations),
- Minimizing pressure drop, especially along the subatmospheric primary return line,

- Ensuring adequate personnel access for installation and maintenance of IR10 systems, especially during beamline assembly which must comply with stringent cleanliness requirements,
- Ensuring adequate personnel egress from all occupied spaces, and
- Minimizing dependencies in the installation schedule due to blockages in paths for equipment movement, material handling devices, and installation personnel.

When it was ultimately determined that the EIC's Rapid Cycling Synchrotron (RCS) would be installed in a new-construction tunnel on the east side of the EIC site, the space in the IR10 tunnel that was previously reserved for the RCS beamline was instead used to place the main trunk segment of the 2 K transfer line, satisfying all packaging requirements for the CDS.

5. Planned procurement approach

Purely *performance*-based procurement approaches (e.g. "Build to Technical Specification") maximize the trust that the buyer places in industry to deliver a performant solution and offer the most opportunities for vendors to exercise unique approaches that may suit their competitive advantage. Conversely, purely *conformance*-based procurement approaches (e.g. "Build to Print") enable significant buy-down of technical risk by the buyer in advance of the procurement process. Conformance procurements are also effective vectors for informal technology transfer, by baking certain hard-won knowledge and experience into the design documentation that is furnished to suppliers. This technology transfer can help cultivate in industry the robust and independent capacity to address the buyer's strategic scientific and technical objectives.

The authors intend to leverage a "Build to Conceptual Design" approach for procurement of the IR10 2 K cryogenic distribution system, with many design requirements to be inferred from the conceptual reference model that will be freely shared to prospective bidders, as well as captured in an accompanying technical specification. This middle-ground approach attempts to capture the benefits of both performance and conformance procurement styles, at the risk that some aspects of the design will be overconstrained if the deliverable must both perform and conform to buyer expectations.

The authors intend the successful vendor to be responsible for final design, fabrication, shipment to site, installation, and quality testing of the assembled system. To date, industry feedback from the authors' Request for Information (RFI) has emphasized the need to minimize on-site labor, such as by simplifying the welded field joints, and has drawn attention to practical concerns such as ensuring access to on-site resources such as material handling equipment.

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