Design of satellite cryogenic plants for the Electron-Ion Collider at Brookhaven National Lab

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Abstract. In support of the Electron-Ion Collider (EIC) at Brookhaven National Laboratory (BNL), Jefferson Lab is contributing to the design of three satellite cryogenic plants. These satellite plants will augment BNL's central plant, which currently provides cryogenics for the Relativistic Heavy Ion Collider (RHIC) at temperatures down to 4.5 Kelvin. The primary role of the satellite plants is to further cool the cryogenic loads to 2 Kelvin, a critical requirement for EIC operations. Secondary objectives of the satellite plant process design include utilization of the existing RHIC cryogenic distribution infrastructure, assurance that the central plant's present capacity is not exceeded, and optimization of overall cost efficiency. This paper presents a comprehensive evaluation of various process configurations for each satellite plant. It discusses the advantages and disadvantages of each configuration, their integration with the central plant, and the rationale behind the final selection for the satellite plant process design.

1. Introduction

At BNL, there currently exists a central plant (at the 5 o'clock location around the collider ring) which is capable of providing cooling to cryogenic heat loads down to 4.5 Kelvin [1]. The central plant is being used to support the operation of the current collider at BNL (RHIC), but will be re-used, along with the tunnel and some transfer lines, for the EIC project. Three satellite plants are being designed to provide support to cryogenic loads for the EIC that require cooling at the 2 K level. These 2 K loads exist at several spots, namely the 2 o'clock, 6 o'clock, and 10 o'clock locations around the EIC ring. It is worth noting that these cryogenic loads, their physical locations, and the general content of this paper refer to the time when the satellite process design was being evaluated (early 2023). Some of the locations and values of the cryogenic loads have changed since this process evaluation.

Figure 1 below is a diagram showing the general layout of the EIC at the time of the process evaluation. The central plant is shown in the green box at the 5 o'clock location, while the satellite plants are shown in blue boxes at the 2 o'clock, 6 o'clock, and 10 o'clock locations.

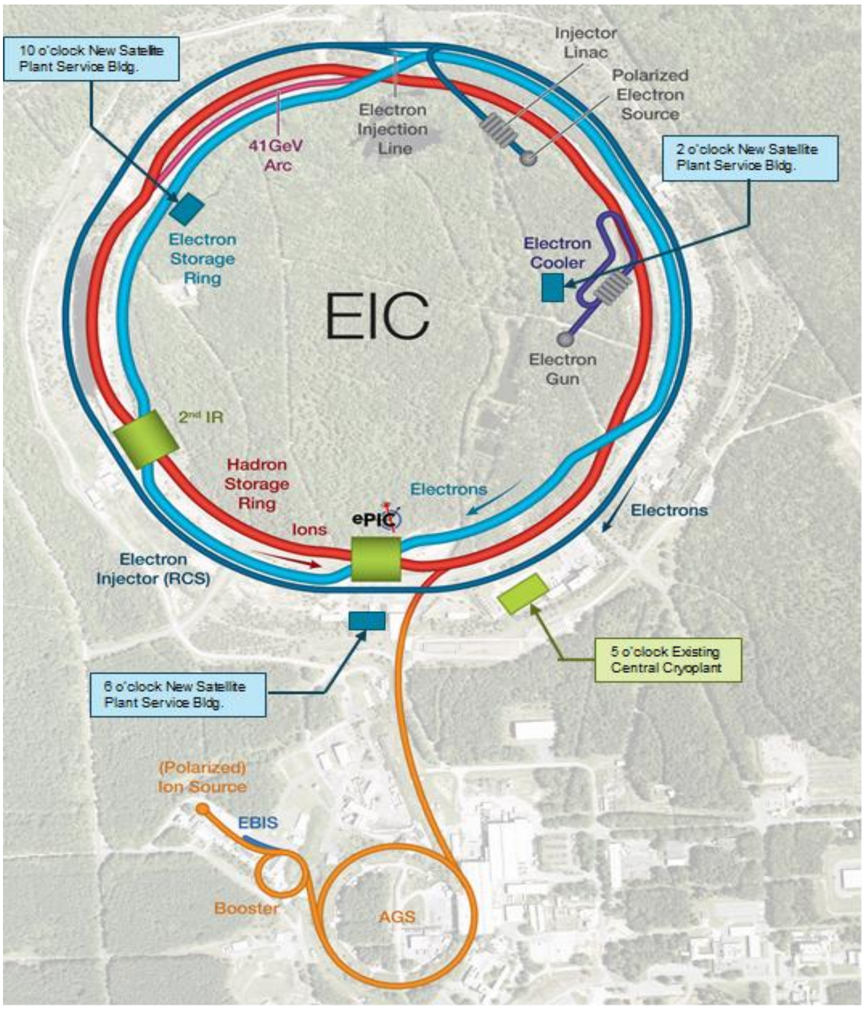

Figure 1. Layout of the Electron Ion Collider at the time of the satellite process design (early 2023). The central plant is positioned at the 5 o'clock location while the satellite plants will be placed around the ring at the 2 o'clock, 6 o'clock, and 10 o'clock locations.

Table 1 shows the cryogenic heat loads to be handled by each of the satellite plants. The satellite plants are identified according to the location of the loads they are servicing, e.g. the Interaction Region 02 satellite plant (IR02) services the loads around the 2 o'clock region. As can be seen in the table, the IR02 satellite plant will handle the largest loads, with the IR06 and IR10 plants handling roughly half of the IR02 2 K loads. The satellite plants will be tasked with processing helium coming back from the 2 K loads as well as the shield and power coupler loads.

Table 1. Cryogenic heat loads to be handled by the satellite plants at EIC.

Satellite Plant Location	2 K Load [W]	Shield and Power Coupler Loads [W]
IR02	1566	10750
IR06	695	7645
IR10	802	6750

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Figure 2 shows the general relationship between the central plant, the cryogenic heat loads, and the satellite plants. The central plant will supply the cryogenic loads with 4.5 K helium via an already-existing Supply (S) transfer line. For the superconducting radiofrequency (SRF) cryomodule loads, the S line will split into three branches inside the cryomodule, with one branch going to the 2 K loads, and the other two branches going to the shield load and fundamental power coupler (FPC) load. The 2 K bath will be pumped on by cold compressors at the satellite plant and will return there via a new subatmospheric (SA) transfer line. Meanwhile, the discharge of the shield and FPC loads combine and return to the satellite plant in a new cold return (CR) transfer line, which will arrive to the satellite plant at around 80 K. At the IR06 region, there are also magnet loads in addition to the SRF loads, which will have similar flow paths, excluding the power coupler load.

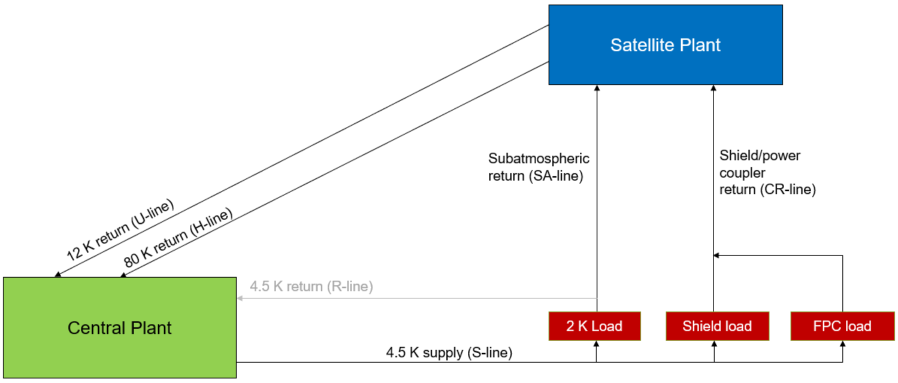

Figure 2. Relationship between the central plant, the cryogenic loads, and the satellite plants at EIC.

The satellite plant will process the SA line and CR line helium that returns to it, and will output two different helium streams. These streams are sent back to the EIC ring's tunnel and will then return to the central plant via already-existing transfer lines – the Utility (U) line (10 – 12 K, 1.5 bar), and the High Pressure (H) line (80 K, 15.5 bar). Additionally, there is a 4.5 K Vapor Return (R) line that the SA line can tie back to that does not get used during normal operation, but can be used to "park" the cryomodules at 4.5 K.

2. Satellite Plant Process Design Goals

Before beginning the design of the satellite plant process, several goals were set. These goals were to be balanced and evaluated holistically, as some process options did a better job meeting one goal but were less successful in meeting others. The five main goals are listed below, not necessarily in any particular order:

1. The first goal of the satellite plants was to provide 2 K cooling to the loads that need it. This was the most fundamental of all the goals and was the reason that the satellite plants needed to be designed in the first place.
2. The second goal for the satellite plant design was to recover refrigeration coming back from the SRF cryomodules and magnets where possible. There is cold helium returning from these cryogenic loads, and the goal was to not waste that returning refrigeration.

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3. The third goal was to re-use the existing RHIC cryodistribution lines where possible. There are already transfer lines in place at BNL to support the RHIC, and re-using these lines saves significant time, cost, and effort.
4. The fourth goal was to ensure that the satellite plants' design did not result in the central plant being overwhelmed. Because the central plant is already existing, it has a set refrigeration capacity that cannot be exceeded. It was desired to not require any additional modifications to upgrade the central plant's capacity in order to handle helium flow that the satellite plants are sending back to it [2].
5. Lastly, the four above goals should be achieved as cost-effectively as possible.

3. Satellite Plant Process Design Options

Several process design options were explored for the satellite plants. Each option was compared against the alternatives and a list of advantages and disadvantages was created for each. This paper will discuss two of the most intriguing options (Options 1 and 3), but many more were also evaluated (Options 2, 4, and 5 were excluded from this paper).

3.1 Process Design Option 1

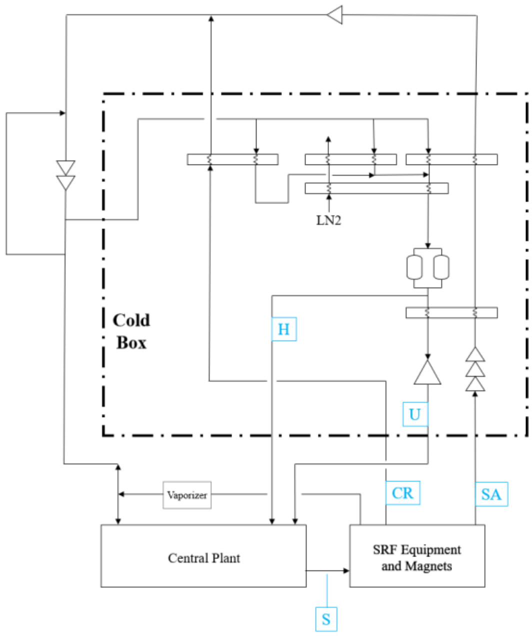

Figure 3. Option 1 process flow diagram.

Option 1 was the baseline design option. It included 3 stages of cold compression at the satellite plant, which would pump on the 2 K bath at the loads. The cold compression was up to about 0.27 bar, where the flow would then be sent for refrigeration recovery through the cold box, and warm vacuum compressors would bring the stream above atmospheric pressure. The cold box also performs refrigeration recovery on the 80 K CR line, which is warmed to 300 K and combined with the warm vacuum compressor discharge. This combined stream is then compressed up to 16 bar and sent back through the cold box to be cooled. Part of this stream splits at 80 K, 15.5 bar and is sent back to the tunnel (and eventually the central plant) on the H line, while the remaining flow is cooled further, expanded through a turbine, and sent back at 10 – 12 K, 1.5 bar on the U line.

The main advantages of Option 1 are as follows:

1. It results in the least amount of load on the central plant. Because Option 1 features local refrigeration recovery, warm compression, and expansion via a turbine, it offloads a significant amount of stress from the central plant.
2. Option 1 is more robust compared to Option 3 in resisting temperature and pressure fluctuations in the subatmospheric return line due to its hybrid cold and warm vacuum compressor system.
3. There are also more existing references with similar designs to Option 1, as opposed to some of the other design options.

The main disadvantages of Option 1 are:

1. It has the most amount of equipment of all the options, which results in the highest capital cost.
2. Because it has the most amount of equipment, in theory it also requires the most maintenance and has more possible sources of failure.

3.2 Process Design Option 3

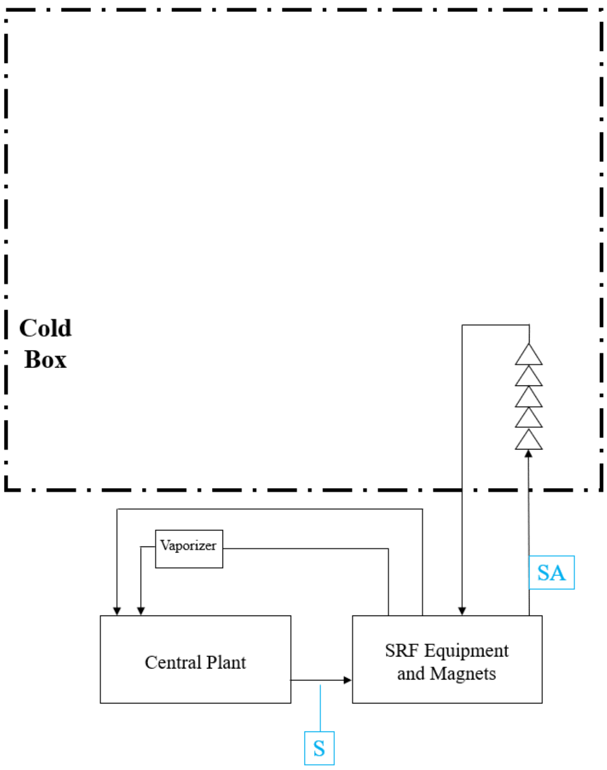

Figure 4. Option 3 process flow diagram.

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Option 3 is a highly simplified, standalone cold compressor design. There are a couple more stages than Option 1, with a total of 5 – 6 stages of cold compression taking the SA line return flow up to approximately 1.5 – 1.7 bar. This cold compressor discharge is then sent back to the tunnel and is used to shield both the subatmospheric return line and the cryomodules (and the magnets if Option 3 is applied to IR06). The discharge of the shield is then sent back to the central plant in a modified version of the existing U line at approximately 60 K. This design option has no local refrigeration recovery, warm compression, or turbine.

The main advantages of Option 3 are as follows:

1. It has the lowest capital cost. There is much less equipment than the other options, making it much cheaper.
2. Because there is much less equipment, in theory it requires less maintenance and has less possible sources of failure.

The main disadvantages of Option 3 are:

1. There are limitations and difficulties in the 5 – 6 stage cold compressor design at the low flow rates for the EIC satellite plants. The smallest satellite plants are in the 30 g/s range for the cold compressors, and this would require a novel cold compressor design which has inherent risk.
2. Because there is no local refrigeration recovery, the refrigeration from the power coupler return would be wasted – it would be warmed up and sent back to the central plant at 300 K.
3. There are modifications needed on the existing U line for this configuration to work, which adds cost, time, and effort.
4. The biggest disadvantage of Option 3 is that it puts the highest load on the central plant of all the options. Its lack of refrigeration recovery, warm compression, and turbine shifts stress to the central plant.

4. Option Combinations

4.1 Evaluation Methodology

After process design options were explored at the individual satellite plant level, evaluations were made on different combinations of the process design options across the three satellite plants. The simplest of these option combinations is uniformity across the three plants, e.g. Option 1 at each of the IR02, IR06, and IR10 satellite plants. Other combinations were explored by mixing and matching Options 1 and 3 across the satellite plants.

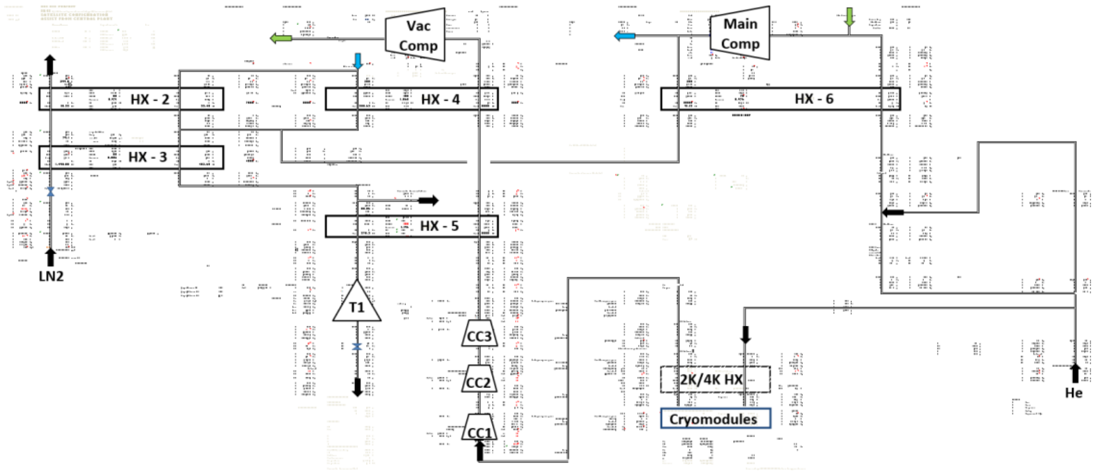

Figure 5. Screenshot of the IR10 process model's Option 1 configuration, built in Excel.

All of these option combinations were evaluated in reference to their loading on the central plant. This evaluation was done via process models built in Excel for the central plant and each of the process design options at each of the satellite plant locations. The central plant's ability to handle each specific option combination was evaluated based on the capacity of its seven existing expanders. The goal was to keep the steady state flow through each expander at less than 90% of its maximum capacity, for any given option combination.

4.2 Evaluation Results

Table 2 shows the results of the option combinations study. Many additional combinations were explored in addition to the four shown in the table.

Table 2. Loading of central plant expanders, for several different satellite plant option combinations. Expanders with steady state flow rates that exceeded 90% of that expander's maximum flow rate are highlighted in red.[a]

Option Combination[b]	Expander 1	Expander 2	Expander 3	Expander 4	Expander 5	Expander 6	Expander 7
1/1/1	74%	74%	67%	71%	80%	80%	82
3/3/3	97%	97%	78%	82%	102%	101%	81%
1/3/3	81%	81%	69%	73%	97%	97%	79%
1/3/1	78%	78%	68%	73%	83%	82%	80%

[a] Percentages are a result of expander flow rate during steady state divided by the expander's maximum flow capacity.

[b] Option combinations are listed in the format IR02 option number/IR06 option number/IR10 option number, e.g. 1/3/3 refers to the IR02 satellite plant being in the Option 1 process configuration and the IR06 and IR10 plants being in the Option 3 process configuration.

The first combination shown in the table adopts Option 1 at all three of the IR02, IR06, and IR10 satellite plants (referred to as the 1/1/1 combination). This option combination loaded the central plant the least, with all seven expanders are well below the 90% loading threshold.

The second combination listed utilized Option 3 at all three of the satellite plants. As expected, this combination puts a much higher load on the central plant, and 4 of the expanders are well above 90% of their maximum capacity. Because of this overloading of the central plant, this combination was excluded from further consideration.

After the 3/3/3 combination was shown to overload the central plant, the highest load satellite plant, IR02, was switched to Option 1 in an effort to alleviate some of the stress from the central plant. Although this did help, the table still shows that Expander 5 and Expander 6 are still both well above the 90% limit and therefore, this route was not considered further.

Lastly, Option 1 at IR02 and IR10, and Option 3 only at IR06 was explored. As shown in the table, this combination did not overwhelm the central plant. But ultimately, this combination was not selected due to the difficulties and uncertainty related to a 5 – 6 stage cold compressor design, especially at the low subatmospheric flow rate needed for IR06.

In the end, the 1/1/1 combination was selected. Option 1 at all three satellite plants does not overwhelm the central plant, and also minimizes risk in the cold compressor design.

5. Conclusion

The EIC project requires 2 K cooling in support of BNL's existing central plant, which has the capability of supplying 4.5 K helium. Three satellite plants will be located hear the 2 K loads around the EIC ring. Several different process designs were explored for the satellite plant, including the baseline (Option 1) and standalone cold compressor design (Option 3). After the process designs were evaluated at an individual satellite plant level, option combinations across the three satellite plants were explored and their effect on the central plant was evaluated. Ultimately, Option 1 at all three locations was chosen to be the most advantageous combination.

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