Cryogenic system design for the electron-ion collider at Brookhaven National Laboratory

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Abstract. Any upgrade of the Relativistic Heavy Ion Collider (RHIC) to an electron-ion collider (EIC) will involve large scale upgrades to the existing cryogenic infrastructure. The challenges to such a project at Brookhaven are unique because of the existing central cryogenic plant. The central plant is oversized for current RHIC operations and can handle the EIC’s heat loads comfortably. However, a lot of equipment will require 2 K cooling for which extra local cryogenic systems are needed. Any new systems will have to be designed to work in tandem with the existing RHIC cryogenic system. This places further constraints on the design of the system, with respect to the cryodistribution system. This study discusses the various baseline configurations for each local cryogenic system for the EIC upgrade.

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is a hadron collider. The collider consists of two superconducting magnet rings that accelerate and store two hadron beams, either heavy ions or polarized protons, that then collide at a maximum of 6 possible experimental locations called Interaction Regions (IR) distributed along the collider. The IR locations, as well as other facilities, are placed around the ring like numbers on a clock face (e.g. IR2 is at 2 o’clock, IR4 is at 4 o’clock, the existing cryoplant is at 5 o’clock, etc.). The proposed new electron ion collider at BNL will produce polarized electron-nucleon collisions [1]. The EIC will use only one of RHIC’s two hadron beams and will add an electron beam to collide with the hadron beam at upto 2 predetermined IR location(s) with the remaining IR locations used for accelerator equipment. This paper examines cryogenic system requirements at various locations while proposing a baseline system design to achieve required cryogenic performance.

2. Global cryogenic systems requirements

Table 1 summarizes the global cryogenic requirements throughout the RHIC and total nominal operational loads imposed on the central cryogenic plant for each different load category. The loads and net imposed loads on the central plant are shown for each location or subsystem. The 1.9 K and 2.0 K loads are grouped in the first column. Each satellite location will have local equipment to produce the 1.9K and 2.0K cooling with assistance from the central plant. The remaining 4 columns thus reflects all of the required assistance at each satellite location. Because of the existing cryogenic
distribution system envelope, which is described in [2], the different loads for the satellite locations are returned via the available return options and are grouped under one of the 4 load characteristics that the central plant sees.

**Table 1:** Overall global cryogenic requirements throughout the Collider and total nominal operational loads imposed on the central cryogenic plant for each different load category.

| Subsystem                                      | 2K/1.9K* [W] | 4.5K Ref [W] | 4.5K-300K [g/sec] | 45K-80K [g/sec] | 4.5K-80K [g/sec] |
|------------------------------------------------|--------------|--------------|------------------|----------------|-----------------|
| Yellow Hadron Ring, Static                     | 3,900        | 25           | 66               |                |                 |
| Yellow Hadron Ring, Beamline                   | 1,800        |              |                  |                |                 |
| Blue Sextants 4/5,12/1,2/3&VB12                | 2,150        | 10           | 35               |                |                 |
| IR Forced Flow SC Magnets                      | 113*         | 220          | 25               |                |                 |
| IR SRF& e-solenoids                            | 176          | 190          | 13               | 4.8            | 4.4             |
| IR10 Loads                                     | 730          | 680          | 6                | 8              |                 |
| IR10 Cold Comp & Coldbox                       | 1,800        |              |                  |                |                 |
| IR02 Loads                                     | 610          | 430          | 4.3              | 5              |                 |
| IR02 Cold Comp & Coldbox                       | 1,660        |              |                  |                |                 |
| Total                                          | 12,780       | 84           | 106              | 23             |                 |

3. Cryogenics for IR10

**Figure 1.** Baseline cryogenic system design for the IR10 and IR02 regions
The superconducting equipment and cryogenics subsystems diagram for the IR10 location is shown in Figure 1. There are 3 superconducting radio frequency (SRF) subsystems located at IR10: The electron storage ring (eSR) SRF subsystem, Rapid Cycling Synchrotron (RCS) SRF subsystem, and the Hadron beam SRF subsystem. All three subsystems will operate at 2.0 K. The electron storage ring system will have fourteen (14) 591 MHz SRF cavities cryomodules and five (5) 1773 MHz cryomodules. The RCS SRF will use three (3) 591 MHz cryomodules, and the hadron beam SRF will use two (2) 591 MHz cryomodules. Each cavity will be packaged in its own cryomodule Table 2 summarizes the process parameters for each numbered location in figure 1 and Table 3 summarizes the cryogenic loads for these subsystems.

### Table 2: Summarizing process conditions in the cryogenic system for IR02 and IR10

| Process point | Mass flow (g/s) | Temp. (K) | Pressure (bar) | Process point | Mass flow (g/s) | Temp. (K) | Pressure (bar) |
|---------------|----------------|-----------|----------------|---------------|----------------|-----------|----------------|
| 1             | 33             | 2.0       | 0.028          | 7             | 33             | 300       | 1.05           |
| 2             | 33             | 3.1       | 0.025          | 8             | 33             | 305       | 16.0           |
| 3             | 33             | 5.4       | 0.068          | 9             | 7.9            | 65        | 15.9           |
| 4             | 33             | 8.9       | 0.160          | 10            | 7.9            |           |                |
| 5             | 33             | 79        | 0.140          | 11            | 7.9            | 275       | 1.19           |
| 6             | 33             | 297       | 0.130          | 12            | 33             | 14.1      | 15.8           |
|               | 13             | 33        | 9.4            |               | 4              |           |                |

### 3.1 SRF cryomodules

As a preliminary baseline design the cryomodule will have a 4.5 K phase separator with fill valve, 2 K-4 K refrigeration recovery exchanger and cryogenic valves for cavity cooldown, 2 K bath top fill, 30 mbar vapor return, and thermal shield flow control. The 4.5 K vapor from IR 10 will be returned via the 4.5 K header in the hadron magnet cryogenic distribution system that takes it back to the central plant. Shield and beam line intercepts cooling will be from a 4.5 K source, flow supply can either be 3 bar, 4.5 K helium or low-pressure vapor from the 4.5K phase separator. The baseline design for the shield/beamline cooling intercept is to use a low-pressure supply and return flow locally to the refrigeration recovery system and local compressor. Each power coupler has been budgeted a liquefaction load for cooling its outer conductors. Connection to the IR10 SRF cryodistribution system will be with bayonetted U-tube jumpers to each SRF cavity cryomodule.

### 3.2 Cryodistribution and subsystem

The baseline design is a hybrid sub-atmospheric system consisting of 2 stages of cold compressors and warm vacuum compressors. Because of the small mass flow a full 5 stage cold compressor is not achievable, and sufficient warm vacuum pump capacity is desirable to condition the several SRF cryomodules at a time without running the cold compressors. Approximately 33-36 g/s of 27 mbar flow coming from the 2 K baths are compressed to above 150 mbar in 2 cold-compressor stages before entering a heat exchanger stack and onto warm vacuum pumps that will compress the low-pressure helium to 1.1 bar. The baseline design will have refrigeration recovery heat-exchangers to process the sub-atmospheric cold compressor flow and the 1.1 bar shield/beamline intercept flow. A local compressor will collect the flow from the warm vacuum pumps and the shield and compress the combined flow to a higher pressure in order to send it back via the refrigeration recovery cold-box for injection back into the hadron ring cryogenic distribution system’s shield loop. The warmer 7K to 10K recovered flow from the 2K circuit gets injected back into the hadron ring’s cryodistribution system.
4.5K vapor return circuit for return to the central plant's 4.5K cold end, although not the most efficient process, converting this 1,600W load into a 4.5K refrigeration load.

| Subsystem       | Modules Qty | 2.0K Refrigeration [W] | 4.5K Refrigeration [W] | FPC 4.5K-300K [g/sec] | L.P. Intercept 4.5K-80K [g/sec] |
|-----------------|-------------|-------------------------|-------------------------|------------------------|-------------------------------|
| eSR-591 MHz 2-cell | 14          | 420                     | 140                     | 4.2                    | 4.2                           |
| eSR-1773 MHz 5-cell | 5           | 75                      | 50                      | 0.8                    | 1.5                           |
| RCS-591 MHz 5-cell | 3           | 144                     | 30                      | 0.6                    | 0.9                           |
| Hadron-591 MHz 5-cell | 2         | 84                      | 20                      | 0.4                    | 0.6                           |
| Cryo-distribution |             |                         |                         | 75                     | 0.7                           |
| Margin          |             |                         |                         | 153                    | 315                           |
| Total           |             |                         |                         | 723                    | 630                           |
| Carnot Work     |             |                         |                         | 107 kW                 | 24 kW                         |

4. Cryogenics for IR02

4.1 Modifications to hadron ring cryogenics distribution

To accommodate the hadron beam cooling sections on both side of the IR02 location, modification to the hadron ring cryogenic distribution system needs to be made. The special insertion magnets on each side of the IR midpoint will be removed to make room for the hadron cooler sections. Two new sections of the hadron ring cryogenic distribution line (which will include the superconducting busses) will need to be installed. They will start from the incoming lines from the service building at each triplet location, in order to bypass the hadron cooler section back into Q4 magnets. In addition, a tee-off from the hadron ring cryogenic distribution is required to supply and return flows to/from the SRF electron linac in the adjacent tunnel.

4.2 Cryogenics for energy recovery superconducting RF Linac

The electron beam superconducting Energy Recovery Linac will be located in an adjacent tunnel. The superconducting equipment and cryogenics subsystems diagram for the IR02 location is shown in Figure 2. The ERL will have eight (8) 591 MHz 5-cell cavity cryomodules and three (3) 1773 MHz 5-cell cavity cryomodules. Table 4 summarizes the cryogenic loads for these subsystems.
5. Cryogenics for the IR region and distribution crab cavities, e-beam SC solenoids, and 1.9 K high current magnets

The baseline design of the subsystem for cooling at 2K for the SRF cavities, estimated at around 100W with a design point around 150W (~8 g/s). The configuration consists of only warm vacuum pumps with no refrigeration recovery heat exchangers, which trades the benefits of a simpler system against thermodynamic efficiency. The 27 mbar helium flow exiting the SRF cryomodules will return to a header that is part of the tunnel cryodistribution system and will be heated with electric heater before continuing to the vacuum pumps. The vacuum pumps discharge is combined with the room temperature flow from the power coupler/current leads and compressed by the local compressor to high pressure. From there, the flow is sent to a local purifier and the warm gas is returned to the existing hadron ring’s cryo-distribution warm return (WR) header. The cryodistribution system will have refrigeration recovery exchanger(s) to recover refrigeration capacity from the low-pressure flows, below 80K, from intercepts and thermal shield flows. Recovered refrigeration cools down high-pressure helium from the local compressor and is sent back into the existing hadron ring’s cryo-distribution high pressure heat shield circuit (H-header). The 1.9 K high current (HC) magnets near the IR detector will have their own return header and vacuum pumping system operating at a lower pressure. Figure 2 shows the schematic for this system, Table 5 depicts the loading on the crab cavities and Table 6 reflects the corresponding IR region loading on the central plant.

There will be a cryogenic distribution system in the IR region to supply/return cryogens for the 2.0 K SRF cavities, SC solenoids and 1.9 K high current magnets. It will contain the following:

- 4.5K, 3.5bar liquid supply header,
- 27 mbar vapor return header, from 2.0K SRF cavities
- 16 mbar vapor return header, from high current 1.9K SC magnets
- 1.3 bar, 4.5K vapor return header
- 1.3 bar, 80K shield/intercept return header
- 1.15 bar warm gas low pressure return header to local compressor

| Subsystem                  | Modules Qty | 2.0K Refrigeration [W] | 4.5K Refrigeration [W] | FPC 4.5K-300K [g/sec] | L.P. Intercept 4.5K-80K [g/sec] |
|----------------------------|-------------|------------------------|------------------------|------------------------|---------------------------------|
| ERL-591 MHz 5-cell         | 8           | 528                    | 160                    | 2.4                    | 2.4                             |
| ERL-1773 MHz 5-cell        | 3           | 84                     | 45                     | 0.5                    | 0.9                             |
| Cryo-distribution          |             |                        |                        |                        |                                 |
| Margin                     | 171         | 25                     | 1.4                    | 1.6                    |                                 |
| Total                      | 612         | 253                    | 4.3                    | 4.9                    |                                 |
| Carnot Work                |             | 91 kW                  | 18.5 kW                | 29.3 kW                | 22.6 kW                         |
### Table 5: Crab cavity (Module & system) loads

| Subsystem          | Qty | 2.0K Refrigeration [W] | 4.5K Refrigeration [W] | FPC/Beamline 4.5K-300K [g/sec] | L.P. Intercept 4.5K-80K [g/sec] |
|--------------------|-----|------------------------|------------------------|---------------------------------|---------------------------------|
| Hadron Crabs       | 6   | 102                    | 90                     | 1.8                             | 3.6                             |
| Electron Crabs     | 2   | 34                     | 30                     | 0.6                             | 1.2                             |
| Cryo-distribution  |     |                        |                        |                                 |                                 |
| Margin             | 40  |                        |                        |                                 |                                 |
| **Total**          | 8   | 176                    | 190                    | 2.4                             | 4.8                             |

### Figure 2. Schematic showing the cryogenic system for the IR06 region

### Table 6: IR region cryogenic loading on central plant

| Subsystem                  | 4.5K Refrigeration [W] | 4.5K-300K Liquefaction [g/sec] | Shield 45K-80K [W] | L.P. Intercept 4.5K-80K [g/sec] |
|----------------------------|------------------------|-------------------------------|--------------------|---------------------------------|
| IR Region magnets          | 100                    | 5.3                           | 450                |                                 |
| IR Region HC magnets       | 20                     | 70                            |                    |                                 |
| Solenoids e-Beam           | 256                    | 2                             | 3.2                |                                 |
| SRF Crabs                  | 190                    | 10                            | 4.8                |                                 |
| Detector Solenoid          | 70                     | 1.0                           | 1.0                |                                 |
| Cryo-distribution          | 70                     |                               | 1.2                |                                 |
| **Total**                  | 135                    | 40                            | 450                | 9.2                             |
6. Conclusion
Baseline cryogenic system designs have been established for a new electron-ion collider at Brookhaven National Laboratory. It has been decided that since the load requirements are very similar at the IR10 and IR02 locations, the systems at these locations will also be the same. This baseline design for a full luminosity machine includes multiple stages of cold compressors, heat exchangers stacks, vacuum pumps, warm compressors, purification systems, liquid nitrogen precooling systems and an expander train. It is noted that for the IR10 and IR02 systems, the stream going back into the existing cryo distribution’s 4.5K vapor return line is not the optimal return location into the main plant. Future studies would include performing thermodynamic studies to find a trade-off between liquefaction load and refrigeration load by creating an imbalance in the mass flow rates between the high- and low-pressure streams. IR06 has a different system design because of the much smaller heat load requirements. It is a simpler and cheaper system with no refrigeration recovery and cold compressors but sacrifices efficiency for this. This system will incorporate heaters in the place of cold compressors, corresponding heat exchangers and expanders and the flow returns at room temperature to the main plant. For all of these systems, going forward, engineering studies will be performed for individual components in addition to designing the logic and controls.

References
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[2] Than R and Ravikumar D K Preliminary cryogenic load requirements for the electron – ion collider at Brookhaven National Laboratory IOP Conf. Series: Material Science and Engineering 278 (2017) 012110