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Preliminary cryogenic loads requirements for the electron-ion collider at Brookhaven National Laboratory

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Abstract. The proposed electron ion collider at Brookhaven National Laboratory will consist of using one existing hadron ring and developing a new electron accelerator. This paper presents the cryogenic loads for the hadron ring's superconducting magnets as well as related upgrades to handle the additional loads. The cryogenic loads for the superconducting RF injector/accelerator and storage ring for the electron beam are summarized. The proposed cryogenic plant, and the configuration and flow distribution of the related cryogenic systems are also presented.

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 Points (IP) distributed along the collider. The IP locations, as well as other facilities, are placed around the ring similar to numbers on a clock face (e.g. IP2 is at 2 o'clock, IP4 is at 4 o'clock, the existing cryoplant is at 5 o'clock, etc.).¹ The proposed new electron ion collider at BNL, called eRHIC, will produce polarized electron-nucleon collisions. eRHIC will use only one of RHIC's two hadron beams and will add an electron beam to collide with the hadron beam at predetermined IP locations. The electron beam system will consist of an electron accelerator and injector and an electron storage ring. The electron storage ring will intersect the hadron beam ring at several IP locations where the beams collide.²

The electron beam system will require considerable superconducting technology to be spread out over the facility (figure 1). The electron accelerator will have a multi-pass Superconducting Radio Frequency (SRF) linac located at IP2 which will require cryogenics at 2 K. The electron beam being circulated in the storage ring requires energy makeup which is being accomplished with SRF cavities split over 2 locations along the ring, IP4 and IP10. These SRF cavities will also require cryogenics at 2 K. At the IP6 location, where the hadron beam and the electron beam collide, new superconducting magnets cooled to 4.5 K and SRF cavities cooled at 2 K are required to manipulate the beams for collision inside detector I.

The existing hadron ring's cryogenic distribution system will be used to supply the various subsystems around the ring. Because of the intention to locate the new plant at the existing plant's 5



o'clock position, and to use the existing hadron ring cryogenic distribution system to supply all the cryogenics for the entire collider, only the following existing lines listed in table 1 are available for supplies and returns at each position around the ring and between the main plant and the ring.

Table 1. Hadron ring cryogenic distribution and plant-to-ring cryogenic distribution

Ring distribution lines	Plant-to-ring distribution lines
4.5 K Magnet cooling helium loop (M) ^a	4.5 K Liquid helium supply (S)
4.5 K Liquid helium supply (S)	4.5 K Vapor helium return (R)
4.5 K Vapor helium return 1 (R1)	4.5 K Helium cooldown return (CR)
4.5 K Vapor helium return 2 or utility (R2)	35 K – 55 K Heat Shield supply (HS)
35 K – 55 K Heat shield helium loop (H)	Heat Shield helium return (HR)
300 K Warm helium return (WR)	300 K Warm helium return (WR)
	300 K Warm helium supply (WS)

^a Distribution-line names in parentheses

Using the existing available circuits limits the possible configurations that can be used for providing cooling for the new equipment at each location around the ring. In particular, any

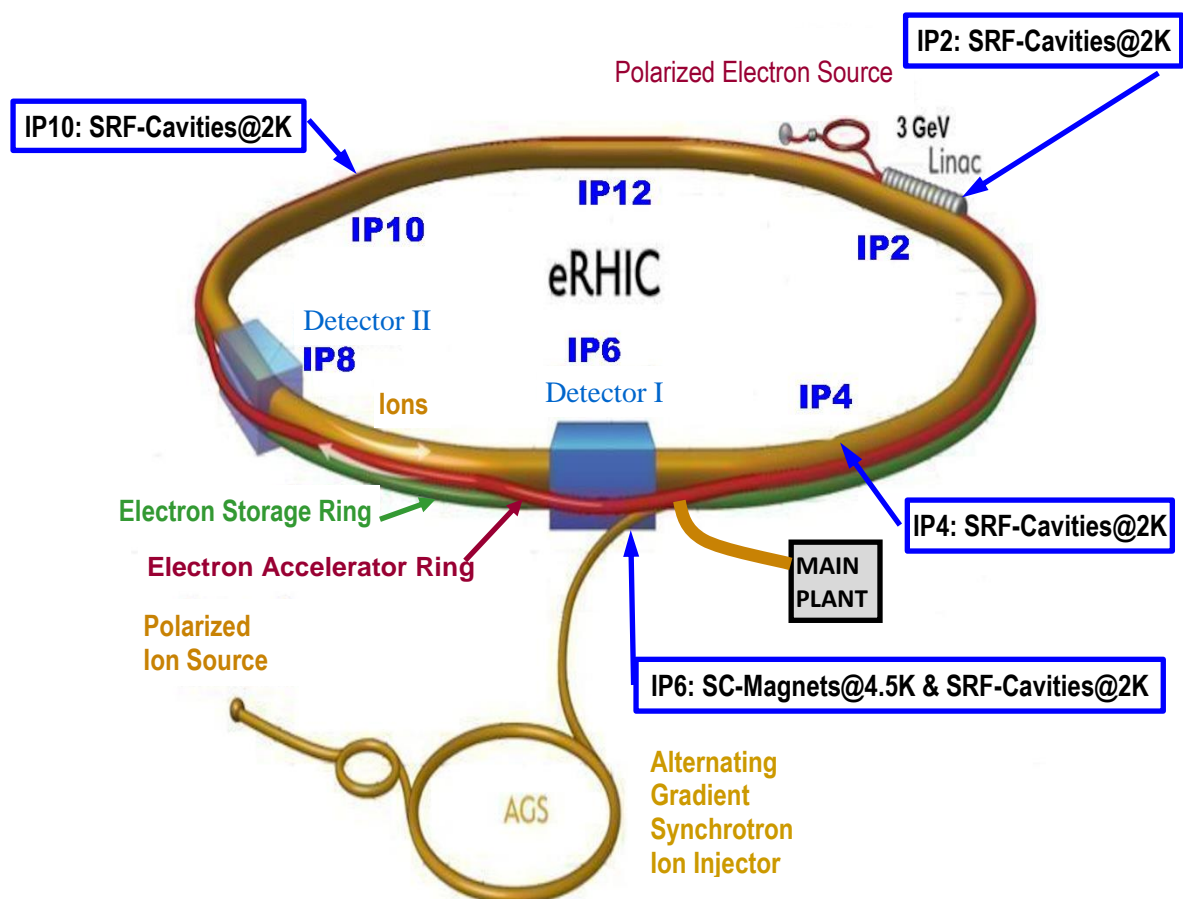


Figure 1. Electron-hadron collider with IP (clocking) locations.

intermediate temperature cooling circuits above 55 K will be supplied by hadron ring's high-pressure heat shield loop, but this flow will have to be returned via the 300 K warm return line (WR), and any

intermediate temperature returns below 55 K will need to be returned at high pressure into the hadron ring's shield cooling circuit (H). Any 4.5 K refrigeration load will be supplied from the hadron ring's supercritical helium supply line (S) and the vapor returned via the two vapor return lines (R1&R2) in the hadron ring's cryodistribution system. 4.5 K liquefaction load is also supplied from the supercritical supply line and returned via the 300 K warm return line.

2. Hadron ring

The existing hadron ring will see an additional new load due to the higher beam intensity. The superconducting magnets' cold bores will see an additional dynamic heat load of approximately 1W/m, adding approximately 3600 W to the current 4.5 K load. The existing coolers in the hadron ring magnet cooling loop were originally designed to handle only 4000 W. In order to maintain the same operating temperature in the hadron ring's magnet loop, the existing coolers need to be upgraded. If no upgrade occurs, ability to operate at warmer temperatures must be determined. Table 2 shows the breakdown of the cryogenic loads for the hadron ring, and it also shows the total loading on the existing hadron ring's cryogenic distribution, including the total cryogenic loads of the additional new equipment distributed along the ring.

Table 2. Hadron ring cryogenic loads and cryogenic distribution loading.

Hadron ring loads [one ring]			Hadron ring cryogenic distribution lines				
Load	Duty (W)	Loop flow (g/s)	Equipment location	4.5 K supply	4.5 K return	Shield loop	300 K return
				S (g/s)	R1/R2 (g/s)	H (g/s)	WR (g/s)
4.5 K	8300 ^b	425	Hadron	425	425		
Shield	13500	15-128	Hadron			15 ^c	
Liquefaction		25	Hadron	25			25
			IP2 ^a	107	42	60	5
			IP4 ^a	83	50	25	8
			IP6 ^a	51	28	13	10
			IP10 ^a	83	50	25	8
			Total	774	595	138	56

^a Location with new equipment

^b Includes 3600 W of new load

^c Initial flow from the plant into the hadron ring's shield loop

3. IP2 location: electron accelerator and injector

At the IP2 location along the hadron ring, a multi-pass 3 GeV superconducting RF linac will be part of the 18 GeV electron accelerator that injects the electron beam into the high current electron storage ring. Because it serves as an injector to the electron storage ring, the injector will be operated as a pulse mode machine. In pulse mode, the dynamic load is expected to be very low, which makes the dominant load the static heat leak. The cavities will be operated at 2 K to maintain a low dynamic load and to ensure a low microphonics background. The proposed linac will consist of a total of 17 cryomodules with 6 five-cell cavities packaged per cryomodule.

The cryogenic loads for the IP2 location are presented in table 3. The 2 K cooling will be generated locally by a five-stage, magnetic-bearing, centrifugal cold compressor system. The discharge of the cold compressor string will go to the 120 kPa suction circuit of the local refrigeration recovery coldbox.ⁱ A local warm compressor will compress the helium from 105 kPa to 1600 kPa and return the flow back to the coldbox in order to produce a high pressure intermediate temperature flow of around 35 K to be used for the linac's intermediate temperature thermal intercepts and thermal shield. This

ⁱ All pressures are given in absolute values.

intermediate temperature flow from the linac will be returned at high pressure into the hadron ring's shield loop.

Table 3. IP2 electron injector superconducting RF linac system.

IP2 equipment loads			Hadron ring cryo-distribution			
Load	Load duty (W)	Loop flow (g/s)	4.5 K supply S (g/s)	4.5 K return R1/R2 (g/s)	35-40 K return H (g/s)	300 K return WR (g/s)
2 K	1200	60	60		60	
4.5 K	750		42	42		
35-50 K	4500	60 ^a			60	
Liquefaction		5	5			5

^a 1600 kPa flow originates from 2 K circuit via local compressor/coldbox

Each of the 17 proposed cryomodules will consist of packaging 6 cavities into a single cryomodule with a completed insulating vacuum boundary. The cryogenic distribution system will run alongside the cryomodules with bayoneted transfer jumpers to supply the cryogenics. Each cryomodule will be supplied with the following helium circuits: 4.5 K liquid supply, 6 K gas return, 35 K gas supply, 55-80 K gas return. A refrigeration-recovery heat exchanger is contained in each cryomodule in order to cool the 4.5 K liquid helium supply to 2.8 K using the 30 mbar return vapor from the 2 K bath. Within each cryomodule, each cavity will be contained in its own helium vessel, and each cavity helium vessel will be connected to the cryomodule's two-phase header where the liquid is evaporated. The connection between the helium vessel and the two-phase header will be sized to handle the heat load. For cooldown of the cavities, it is proposed that each cooldown valve supply two cavities to reduce the number of valves and still maintain even cooldown distribution among the cavities. There will be a total of 3 cooldown valves and 1 top-fill valve for the 2 K bath, as well as a control valve for controlling the 4.5 K flow to the low-temperature intercepts. The low-temperature intercepts are located on the cold end of each fundamental power coupler, the cold-to-warm beam line transitions, and the valve stems. The low temperature intercept circuit will be piped in series flow. A control valve will control the 35 K flow for the higher temperature intercepts and shield flow. The higher temperature intercepts will be located on the fundamental power couplers' outer conductors, the 2 cold-to-warm transitions of the beam lines, and the thermal shield. The 35 K intercepts will also be arranged in series.

4. IP4 location: superconducting radio frequency cavities for electron storage ring

A set of superconducting radio frequency cavities will be required for energy makeup to the electron beam circulating in the storage ring. The cavities are planned to be operated at 2 K, but the feasibility for operation at 4.5 K will be assessed. Each energy makeup cavity will be packaged in a cryomodule along with a 4.6 K phase separator, a 2 K-4 K Joule-Thomson loop/refrigeration recovery exchanger, and cryogenic control valves. The power coupler's outer conductor will be actively cooled by helium flow through channels along the conductor wall. The return flow from the power coupler's cooling will be returned to the 300 K warm return header.

In addition, SRF cavities will also be required to manipulate the hadron beam. A set of low frequency cavities operating at 4.5 K and higher frequency cavities operating at 2 K are proposed for this function. The cryogenic loading for the IP4 location is given in table 4.

5. IP10 location: superconducting radio frequency cavities for electron storage ring

IP10 requires a set of SRF equipment identical to the SRF equipment at IP4; therefore the cryogenic requirements at the IP10 location will be the same as the IP4 location. Refer to table 4 for the loads of the IP10 location.

Table 4. IP4 & IP10: Superconducting RF: electron storage ring.

IP4 equipment loads			Hadron ring cryo-distribution			
	Load duty (W)	Loop flow (g/s)	4.5 K supply S (g/s)	4.5 K return R1/R2 (g/s)	35-40 K return H (g/s)	300 K return WR (g/s)
2 K	400	20	20		20	
4.5 K	900	50	50	50		
4.5-40 K	910	5	5		5	
Liquefaction		8	8			8

6. IP6 location: cryogenics for the interaction-detector region

In the interaction-detector region, a group of superconducting magnets and superconducting radio frequency cavities will be required to control the beams for interaction in the detector hall.

Superconducting quadrupole and dipole magnets combined with a set of SRF crab cavities, will manipulate the hadron beam in the detector hall. The superconducting magnets will be operated at 4.55 K and the crab cavities will be operated at 2 K.

Superconducting quadrupole, dipole, and solenoid magnets combined with a set of superconducting RF crab cavities will also be used to manipulate the electron beam. The estimated cryogenic loads are given in table 5.

Table 5. IP6: Superconducting magnets & SRF for the hadron beam / electron beam.

IP6 equipment loads			Hadron ring cryo-distribution			
	Load duty (W)	Loop flow (g/s)	4.5K supply S (g/s)	4.5 K return R1/R2 (g/s)	40 K-55 K return H (g/s)	300 K return WR (g/s)
2 K	200	10	10		10	
4.5 K	500	28	28	28		
4.5-50 K	1200	3	3		3	
Liquefaction	15600	10	10			10

The new IP6 superconducting magnets will be cooled in a liquid helium bath. The liquid helium will be supplied from the hadron ring's supercritical helium supply line (S) at 4.6 K, 400 kPa. The liquid bath temperature will be between 4.5 K to 4.55 K dictated by the pressure in the vapor return lines (R1 and R2) along the hadron ring's cryogenics distribution system. The superconducting magnets' current leads will be cooled using supercritical 400 kPa helium because the high return pressure on the warm return line (WR) along the ring prevents the current leads from being vapor cooled from the 135 kPa bath.

The superconducting RF cavities will be operated at 2 K. The cavities will be immersed in the superfluid bath. The hadron beam's 3 crab cavities will be packaged into a single cryomodule along with a 4.6 K phase separator, a 2 K-4 K Joule-Thomson loop/refrigeration recovery exchanger, a cooldown supply valve, and a top-fill valve. 4.5 K vapor will be used to cool the thermal shield and outer conductor of the power couplers. 2 K cooling will be produced by a local sub-atmospheric pumping system, and depending on the total load, this could be a complete warm vacuum pumping system or a hybrid system consisting of a single-stage cold compressor and warm-vacuum pumps. A local single-stage 105 kPa to 1600 kPa warm compressor system along with a coldbox that includes a refrigeration recovery heat exchanger stack and purification beds will be required to be able to inject the flow into the hadron ring's heat shield line (H) at 1500 kPa.

7. Main cryogenics plant

The main plant is located along the hadron ring, roughly midway between IP4 and IP6 at the 5 o'clock location. The existing 4.5 K coldbox system of the main plant will be replaced by a new modern plant with gas bearing expanders. Because frequent deliveries of liquid nitrogen may interrupt the operation of the accelerator due to the vibration caused by the delivery trucks, a non-liquid-nitrogen assist plant is preferred. The design goal is to install a plant with an overall design efficiency of greater than 28% Carnot and operating efficiency of no lower than 25% Carnot over its turndown range to 40% of the total plant capacity. The existing compressors were optimized with a built-in volume ratio to run at a pressure ratio of 4. If this existing compressor system is retained, the cycle for the new 4.5 K coldbox will be optimized for this pressure ratio. The existing cycle is a two-pressure stream cycle with the high pressure stream at 1600 kPa and the low pressure stream at 125 kPa.³ Due to the need to use the existing hadron ring cryogenic distribution, the loading on the plant will be 4.5 K refrigeration, liquefaction, and an intermediate temperature load where the plant can only take flow between temperatures of 35 K to 55 K. Thus, the injected flow from the locations around the ring will end up in the hadron ring's thermal shield high pressure loop. Table 6 gives the expected total loading for the new plant with a design capacity which will give an operating a margin of almost 50% of the expected load.

The existing compressor system will be assessed for re-use/upgrade or replacement with all new compressor skids. The existing compressor building has an installed power capacity of 15 MW delivered at 4.1 kV with an associated cooling tower of similar capacity. The current cooling tower will need to be replaced due to its age.

Table 6. Main cryogenic system totals for hadron ring and electron storage ring / electron injector.

Load	Load duty (W)	Supply (K) (kPa)		Return (K) (kPa)		Loop flow (g/s)	Operating		Design	
							Carnot work (MW)	Power @ $\eta_{\text{Carnot}} = 25\%$ (MW)	Carnot work (MW)	Power @ $\eta_{\text{Carnot}} = 27.5\%$ (MW)
4.5 K	11700	4.5	420	4.5	125	595	0.70	2.77	0.97	3.53
4.5K to 50K	37000	4.5	420	4.5	125	128	0.49	1.53	0.54	1.95
Liquefaction	87500	4.5	420	300	125	56	0.38	1.94	0.68	2.46
Total						779	1.6	6.2	2.2	8.0

8. Conclusion

The proposed electron ion collider at Brookhaven National Lab requires considerable superconducting technology spread out over the facility, and its use of both new and existing configurations presents opportunities as well as challenges. This paper summarizes the cryogenic load requirements for the proposed electron ion collider and examines key considerations in the use of the existing hadron ring cryogenics distribution system as well as a new main plant located at the current 5 o'clock location.

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