IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012086 doi:10.1088/1757-899X/1344/1/012086

Assessment of the existing cryogenic central plant for the Electron Ion Collider cryogenic loads at Brookhaven National Laboratory

P Patel[1], Y Than[1], R Feder[1], B Wissler[2], S Yang[2], N Laverdure[2]

[1] Brookhaven National Laboratory, Upton, New York, 11973, USA
[2] Thomas Jefferson National Accelerator Facility, Newport News, VA, 23606, USA

*E-mail: ppatel@bnl.gov

Abstract. The Electron Ion Collider (EIC) at Brookhaven National Laboratory consists of one existing hadron ring and new electron accelerator. The EIC incorporates beamline and detector elements that require superconductivity, which is achieved by cooling these elements to cryogenic temperatures. The EIC cryogenic systems are designed to provide cooling for various components, including heat shield circuits, current leads, power couplers, thermal intercepts, and superconducting devices operating at or below 4.5 K. The existing central plant used for cooling Relativistic Heavy Ion Collider (RHIC)'s magnet rings will also be used for EIC. There are Superconducting magnets that require operation at 1.92 K, and Superconducting Radio Frequency (SRF) cavities that require operation at 2.0 K. These are located at distinct locations around the Collider ring. Satellite systems located locally will be installed to produce the 1.92 K and the 2.0 K cooling capability. These systems will not be fully independent standalone plants, rather they will use the existing central plant for capacity assistance. The existing cryogenic distribution in the hadron magnet ring will also be used to supply the satellite systems. This paper examines the different types of loads imposed on the existing central plant and evaluates where the plant is expected to operate. Due to modifications made to the plant for the RHIC program, the existing equipment is evaluated to assess whether changes are needed to the cold end of the plant: expander(s), exchangers and return piping configuration to return the satellite return streams. The finding provides valuable insights into upgrade/modification requirements, optimizing the cryogenic plant, and ensuring reliable support for EIC's advanced scientific objectives.

1. Introduction

The world's most sophisticated collider, Electron-ion Collider (EIC), at state of the art, 2.4 miles circumference accelerator complex being built at the U.S. Department of Energy's (DOE) Brookhaven National Laboratory (BNL) in partnership with DOE's Thomas Jefferson National Accelerator Facility. The EIC consists of one existing hadron (proton) ring, a new electron accelerator, and a new electron storage ring. Superconducting Radiofrequency (SRF) cavities will accelerate beams of electrons and protons while powerful magnets steer these particles in opposite directions around the rings and into collisions. The EIC incorporates beamline and detector elements that require superconductivity, which is achieved by cooling these elements to cryogenic temperatures at or below 4.5 K.

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The EIC cryogenic systems are designed to provide cooling for various components, including heat shield circuits, current leads, power couplers, thermal intercepts, and superconducting devices operating at or below 4.5 K. The existing cryogenic central plant used for RHIC will also be used for the EIC. There are also new superconducting magnets which are required to operate at 1.92 K as well as SRF cavities which are required to operate at 2 K. These are placed in various locations defined by the clocking position around the collider rings, e.g. 2, 4, and 6 o'clock. The existing cryogenic distribution is built into the Hadron Storage Ring (HSR) magnet cryostats and capacity assistance by the central plant to the new 2 K satellite systems will use this existing distribution. The existing distribution circuits consist of five circuits, of which one is the supercritical 4.6 K forced flow stream that cools the HSR magnets. The 4 other circuits are the 4.5 K helium supply to the HSR elements and 2 K satellites, the 4.5 K vapor return, the high pressure HSR thermal shield circuit (which gets supplied at 40 K and returned at ~ 80 K), and finally the U circuit line, which will be used as one of the 2 returns from the 2 K satellite plants. The other return circuit from the 2 K satellites is the 80K stream into the high pressure HSR thermal shield circuit. The HSR has an additional load, the beam screen intercept load, that will also be returned via the U circuit line. Hence, the distinct return flows coming to the central plant from these systems are: 4.5 K vapor (refrigeration load), ~10 K (4.5 K to ~10 K), ~80 K (satellite high pressure,4.5 K to 80 K and HSR heat shield load, 40 K to 80 K) and 300 K as a liquefaction load.

The excel based cryogenic plant simulation has been developed considering the following EIC loads: Hadron storage ring (HSR) magnets, beam screen of HSR, Interaction region 05 and 10 satellite loop: superconducting cavities, superconducting magnet, detector, heat shield of all the applications, thermal intercepts for the power coupler etc. The behaviour of the components such as heat exchangers (15 nos.), expanders (7 nos.) are evaluated and compared with its original design case and run data for the expander 7. Run data of the expander 7 was reviewed to verify its flow coefficient, since it has a fixed inlet guide vane nozzle flow area, to determine its flow throughput. All other expanders are having guide vane to adjust flow area as per requirements.

The main objective of the paper is to assess where the central plant will operate given the EIC loads, and whether any upgrades/modifications will be needed, specifically the cold end of the plant.

2. Cryogenic central plant system overview

The original cryogenic central plant was built 45 years ago for the Colliding Beam Accelerator (CBA) project [1]. However, during year 2002, BNL has initiated upgrades and modification of the cryogenic plant in several phases till 2010 [2]. The phases of modification includes process control changes like first stage suction pressure control, inter stage pressure control and second stage discharge pressure control; cold compressors and cold end piping re-configuration; collider magnet loop circulators eliminated, and the flow path reconfigured to direct the flow from the plant to circulate through the magnet loops then feed the ring re-coolers; insulation of the sub-cooler pots with MLI; heatexchanger-1 balancing; Joule-Thomson expander loop and new heat exchangers installed (HX-20 through HX-24) at the low temperature end of the plant (refer Figure 1). With these updates, the cryogenic plant ran with improvement in efficiency reducing the power from 9.4 MW to current 5.2 MW with the baseline load [3]. Presently RHIC enters its 25th run and final year of operations, smashing together the nuclei of gold atoms traveling close to the speed of light, before being transformed into the EIC facility.

Figure 1 depicts the present central cryogenic plant configuration with twenty 1st stage of warm compressors (WC) and five 2nd stage of WC. One of the 2nd stages is also piped up to serve

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as a 1st or 2nd stage redundant WC. An intercooler is installed after the 1st stage of WC and an aftercooler is installed after 2nd stage of WC to cool the discharge flow back to ambient. The compressor system can operate to a high side pressure of 16 bar. There are a total of 7 expanders stages. Expanders 1/2, 3/4, and 5/6 have redundant sets, while expander 7 does not have one. Expanders 1, 2, 3, 4, 5, and 6 are Roto flow centrifugal expanders (oil bearing & brake) with adjustable guide vanes at the inlet to control the flow whereas expander 7 is a fixed inlet guide vane gas bearing centrifugal turbine. The original CBA design was engineered to provide cooling to 2.5 K. and was configured with three helium sub cooler bath pots staged to reach 2.5 K bath temperature in the lowest pot. For 4.5 K operation only largest pot, the Mid pot, is used as a capacity buffer. The Cryogenic plant cold components cover 6 cold boxes, where the cold components are placed accordingly from warm HXs to the cold end low pot.

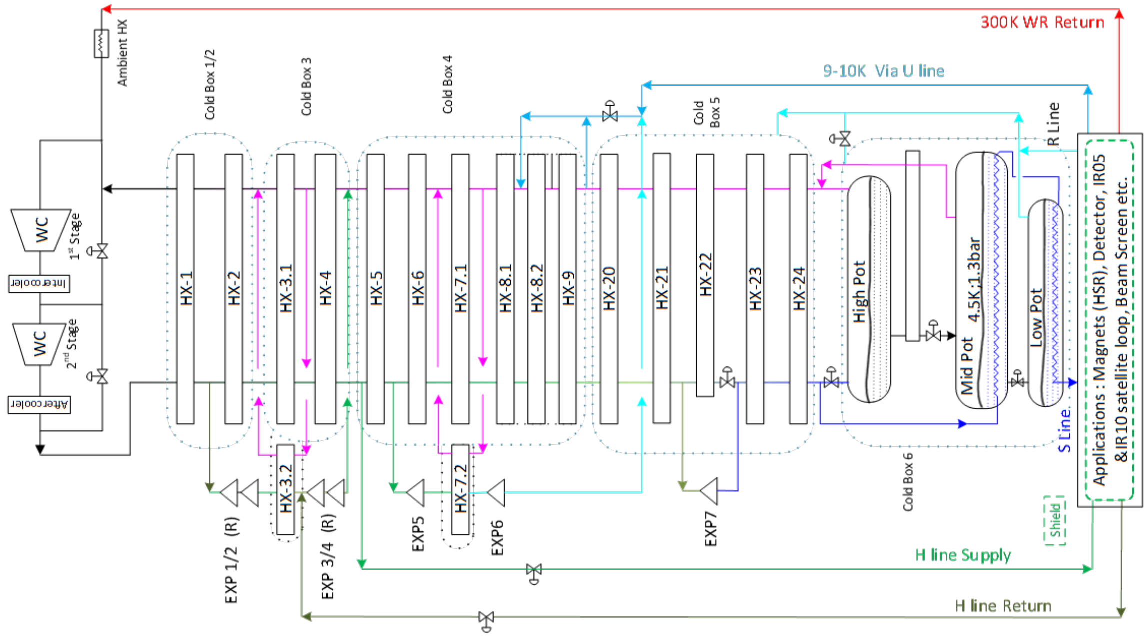

Figure 1. Schematic layout of cryogenic central plant.

3. Summary of EIC loads to the cryogenic central plant

The various cryogenic cooling loads are: the detector SC solenoid, the Interaction Region (IR) 1.92 K SC magnets, the SRF cavities, the 4.6 K superconducting magnets of the HSR and its beam screen circuits, the current leads, and the power couplers. Refer to Table 1 which tabulates the various EIC loads onto the plant returning at various temperature levels, such as vapor return at 4.55 K, gas return at 7-12 K, warm return at 300 K and shield return at 80 K.

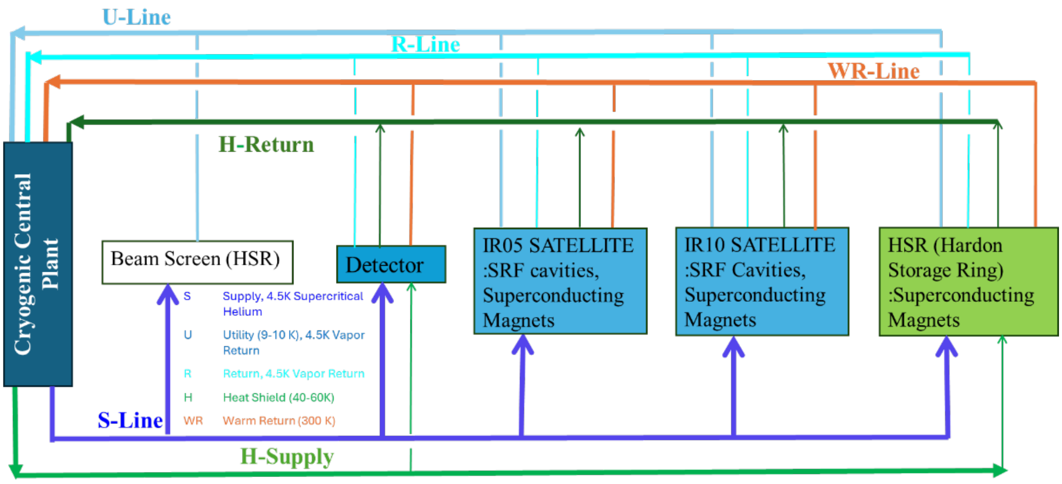

Figure 2. Basic flow diagram of cryogenic central plant vs applications.

Table 1. Summary of EIC loads on the cryogenic plant.

Mass Flow [g/s]	Pin [bar]	Tin [K]	Source	To plant [Via return line]	Mass flow [g/s]	Po [bar]	To [K]	Heat Load [kW]
605	4.27	4.55	Detector	R	5.57	1.36	4.55	0.1
			Hadron Storage Ring	R	277.0	1.36	4.55	4.9
			Beam Screen	U	54.82	1.5	7	1.9
			IR 05	R	2.50	1.5	7.36	0.1
			IR05 Satellite Loop	U, Sextants 4/5	81.49	1.44	12.87	5.5
			IR10 Satellite Loop	U, Sextants 8/9, 6/7	62.84	1.44	10.99	3.6
			IR05 4.5 -80 Intercepts	H	51.67	15.6	80.38	21.9
			IR10 4.5 -80 Intercepts	H	24.40	15.5	80.7	6.6
			HSR Magnet Current Lead Flow	WR	44.64	1.3	300	69.7
			Detector Magnet Current Lead Flow	WR	0.54	1.3	300	0.8
106.5	15.6	44.32	HSR SHIELD	H	101.50	15	80	19.1
			Detector Shield	H	3.19	15	80	0.6

4. Assessment of EIC loads to the cryogenic central plant

There are various components in the cryogenic plant, the critical components such as heat exchangers, expanders are evaluated for the assessment along with its design case. The design case data has been collected from the technical data sheet.

4.1 Heat exchangers (HXs)

Heat exchangers are important components for the cryogenic plant which exchanges heat between cold and hot fluid at required pressure, temperature and mass flow rate. The plant has around 15 HXs of which 10 HXs are 45 years old, with 5 HXs (cold end side) installed 20 years back.

Table 2. Details of heat exchangers flow, duty and pinch with design case and EIC.

HX	HP Flow Design [g/s]	HP Flow EIC [g/s]	HP Duty Design [kW]	LP Duty Design [kW]	HP Duty EIC [kW]	LP Duty EIC [kW]	Pinch Design [K]	Pinch EIC [K]
HX-1	4179.1	2881.8	2603	2604	1931	1931	3.07	7.50
HX-2	3546.4	2218.7	581	582	291	292	1.98	4.19
HX-3.1	3546.4	2218.7	1538	1541	953	955	1.98	4.19
HX-3.2	632.6	663.2	274	275	284	285	1.86	4.12
HX-4	3546.4	2218.7	570	572	283	285	1.10	1.18
HX-5	3197.4	2114.0	264	264	191	191	1.05	1.25
HX-6	1483.6	757.3	42	42	20	20	0.10	0.40
HX-7.1	1714.0	1356.7	79	79	86	86	0.10	0.40
HX-7.2	1483.6	757.3	74	74	51	52	0.10	0.40
HX-8.1	1483.6	757.3	21	21	7	8	0.91	2.01
HX-8.2	1483.6	757.3	30	30	0.1	0.2	0.28	1.99
HX-9	1483.6	757.3	7	7	0	0.1	0.23	1.91
HX-20	658.0	757.3	22	22	15	15	0.21	0.38
HX-21	543.0	757.3	16	16	6	6	0.20	0.19
Hx-22	155.0	185.0	1	1	1	1	0.40	0.39
HX-23	658.0	757.3	3	3	2	2	0.12	0.39
HX-24	643.0	757.3	1	1	1	1	0.41	0.62

Table 3. Details of heat exchangers UA, Effectiveness, NTU and LMTD with design case and EIC.

HX	UA Design [kW/K]	UA predicted EIC [kW/K]	UA calc [kW/K]	Effectiveness Design	Effectiveness EIC	NTU Design	NTU EIC	LMTD Design [K]	LMTD EIC [K]
HX-1	596	424	228	0.98	0.95	28.1	15.5	4.38	8.50
HX-2	163	115	45	0.94	0.86	8.8	3.9	3.63	6.52
HX-3.1	535	363	195	0.98	0.95	29.8	17.2	3.07	5.04
HX-3.2	97	100	59	0.98	0.95	30.2	17.4	2.98	4.99
HX-4	249	171	101	0.97	0.96	13.2	8.6	2.42	2.97
HX-5	169	114	98	0.94	0.94	10.5	9.4	1.62	2.02
HX-6	69	38	17	0.99	0.94	8.0	3.9	0.72	1.30
HX-7.1	162	121	79	0.99	0.97	19.0	12.1	0.54	1.18
HX-7.2	161	85	50	0.99	0.97	20.1	12.7	0.54	1.18
HX-8.1	18	10	3	0.70	0.42	1.7	0.6	1.23	2.30
HX-8.2	45			0.94		4.7		0.55	
HX-9	8			0.93		2.9		0.74	
HX-20	36	41	15	0.97	0.91	7.9	2.9	0.78	0.95
HX-21	23	28	12	0.97	0.93	7.4	4.5	0.42	0.48
Hx-22	1	1	1	0.84	0.71	1.8	1.3	0.71	0.65
HX-23	10	10	3	0.84	0.57	2.4	0.9	0.25	0.49
HX-24	2	2	2	0.71	0.39	1.2	0.5	0.67	0.64

The design data of the HXs are compiled from the design record and EIC loads are applied to the excel based simulation model to assess the HXs in terms of its capacity, effectiveness, NTU, LMTD, and UA values (refer Table 2 and 3). The global heat transfer coefficient "UA predicted" has been evaluated using the Colburn formulation [4] in terms of Prantl number, mass flow rate and viscosity.

The calculated UAs have not converged to the UA predicted values due to excel based simulation convergence limitation. Since heat exchangers flows are lower than design flows, with the EIC loads, the predicted UA values should be less than the design UA values. The Pinch and LMTD of the EIC results are currently wider compared to the design case due to incomplete convergence to the predicted UA, and due to some exchangers having higher imbalance and higher flows. Heat exchangers 8.2 and 9 is technically not being used because of the cold end exchangers (HX 20-24) taking their places. The duties, NTUs of HXs are also less than the design case which is expected since the EIC loads are less than the design loads.

4.2 *Expanders*

The first six expanders are oil bearing (Roto flow) expanders with an adjustable inlet guide vane nozzle area without variable brake. Table 4 indicates the design case data including its efficiency (actual expander work to isentropic expander work), work, flow coefficient (which is proportional to mass flow [g/s] over Density [kg/m^3] and square root of Temperature [K]). Table 5 shows the data of expanders using EIC loads, and it is compared with the flow coefficient of design data which indicates its utilization. The expander highest utilization (flow coefficient) of all the expanders is expander 5 at 85 % of its design case.

Table 4. Expanders 1 to 6 data at design caseloads.

EXPANDERS	Pin [bar]	Tin [K]	Pout [bar]	Tout [K]	Flow [g/s]	Efficiency [%]	Work [kW]	Flow Coeff.	Density [kg/m^3]
EXP1	16.40	185.04	12.40	170.14	881.6	76.5	69	15.40	4.21
EXP2	12.40	170.14	9.12	155.18	881.6	76.4	69	19.50	3.47
EXP3	9.00	69.16	4.20	55.34	1240.1	76.1	90	24.23	6.15
EXP4	4.20	55.34	1.26	39.26	1240.1	74.5	105	46.07	3.62
EXP5	15.89	24.99	0.00	20.13	1722.0	80	42	11.63	29.62
EXP6	8.05	12.43	1.45	7.10	1722.0	79	37	14.23	34.33

Under EIC loads, the oil bearing expanders operates at lower flows and lower efficiencies than their design case. Even though these expanders have adjustable area inlet nozzle, they however do not have variable brakes and thus the speed reduces with flow, leading lower efficiencies.

Table 5. Expanders 1 to 6 data at EIC caseloads.

EXPANDERS	Pin [bar]	Tin [K]	Pout [bar]	Tout [K]	Flow [g/s]	Efficiency [%]	Work [kW]	Calc. Flow Coefficient	Utilization [%]	Density [kg/m^3]
EXP1	15.94	176.00	12.40	163.96	663.1	71.9	42	11.62	75.4	4.30
EXP2	12.40	163.96	9.12	150.77	663.1	69.5	46	14.38	73.8	3.60
EXP3	9.04	71.00	4.35	59.19	843.9	63.7	53	16.63	68.7	6.02
EXP4	4.30	59.19	1.25	43.32	843.9	68.0	70	31.67	68.7	3.46
EXP5	15.46	27.70	8.01	23.13	1356.7	71.9	32	9.95	85.6	25.90
EXP6	7.98	12.30	0.99	7.15	1356.7	61.3	27	11.20	78.7	34.53

4.3 Cold end expander 7

Expander 7, part of the cold-end turbine system along with heat exchangers HX-20 to HX-24 (cold-end box), was installed two decades ago and was sized for the RHIC loads to optimize cryogenic plant performance. Since expander 7 has a fixed inlet nozzle area (but variable brake), run data was taken to verify the expander throughput i.e. its flow coefficient.

Table 6. Cold end expander (EXP 7) run data.

Sr. No.	Flow [kg/s]	Pin [bar]	Tin [K]	Po [bar]	To [K]	Density [kg/m3]	Flow Coefficient	Efficiency [a] [%]
1	521.2	14.50	7.8	4.45	6.03	119.60	1.56	68.18
2	512.1	14.45	7.42	4.47	5.83	124.75	1.51	80.36
3	505.5	14.39	8.02	4.44	5.91	115.99	1.54	98.57
4	507.4	14.68	8.05	4.45	6.06	116.64	1.53	75.66
5	533.1	14.58	7.62	4.43	5.91	122.41	1.58	76.71
6	532.5	14.64	7.64	4.44	6.01	122.33	1.57	61.89
7	543.2	14.62	7.5	4.44	5.83	124.19	1.60	82.65
8	552.4	14.61	7.18	4.44	5.86	128.42	1.61	61.63
9	545.3	14.59	7.48	4.45	5.88	124.37	1.60	74.83
10	533.6	14.39	7.42	4.45	5.86	124.56	1.57	75.44

[a] Efficiency is estimated from temperature sensors run data without error study.

Using run data for expander 7 the calculated flow coefficient (refer Table 6) , was found to be around 1.6 with maximum flow capacity of 572 g/s at an inlet pressure of 15.5 bar and a discharge condition of 4.4 bar and 5.61 K. Under EIC cryogenic loads the required cold end flow is higher than what expander 7 can pass, and thus the excess flow needs to be bypassed.

4.4 Warm compressor

The central cryogenic plant's two-stage warm compressor system comprises 20 first-stage compressors (distributed across 10 skids) and 5 second-stage compressors. Both 1st and 2nd stage utilize the same compressor body 321/1.65 HOWDEN screw compressor. Each 1st stage can process a maximum of 235 g/s flow at 1.05 bar suction pressure. Each 2nd stage can process a maximum of 900 g/s flow at 4.5 bar suction pressure. Under EIC loads, the compressor system operate at ~30 % reduced mass flow compared to design conditions.

Table 7. EIC carnot work and contribution to total EIC load.

Source	Returns [Via return]	Eo [kJ/kg]	Ein [kJ/kg]	ΔExergy [kJ/Kg]	Carnot Work [kW]	Contribution [%]
Detector	R Header	5536	6851	1315	7	0.4
HSR	R Header	5536	6851	1315	364	22.1
Beam Screen	U Header	4685	6851	2166	119	7.2
IR 05	R Header	4596	6851	2254	6	0.3
IR05 Satellite Loop	U Header	3660	6851	3190	260	15.8
IR10 Satellite Loop	U Header	3907	6851	2943	185	11.2
HSR Shield	H Header	2602	3373	771	78	4.8
Detector Shield	H Header	2602	3373	771	2	0.1
IR05 4.5 -80 Intercepts	H Header	2621	6851	4229	219	13.3
IR10 4.5 -80 Intercepts	H Header	2613	6851	4238	103	6.3
HSR Magnet Current Lead Flow	WR Header	155	6851	6695	299	18.2
Detector Magnet Current Lead Flow	WR Header	155	6851	6695	4	0.2
				Total	1646	

5. Carnot work and Contribution

Table 7 represents the EIC's Carnot work for each load and its load distribution onto the plant. Under EIC loads the power consumption of the warm compressor is 9900 kW (first stage has 4345 kW and second stage has 5555 kW). The Carnot efficiency is 16.6 %.

6. Results and discussion

The cryogenic load distribution for the EIC - including detectors, HSR magnets, interaction regions, satellite loops, and beam screens – on the existing RHIC central plant was evaluated using an Excel-based simulation model. Loads at varying temperature levels (4.5 K, ~10 K, 80 K, and 300 K) were integrated into the central cryogenic plant's system. Key components, such as heat exchangers, expanders, and warm compressors, were analysed against design conditions. With the EIC loads, it is to be depicted that the components of the plant can operate with limitations of the component like Expander 7. All heat exchangers exhibited broader pinches than designed, attributable to a 30 % reduction in plant flow rate. The 13 of 20 first-stage and 4 of 5 second-stage compressors will be operational, consuming 9.9 MW total power. These results indicate that while the existing cryogenic plant infrastructure can support the EIC loads, this operation entails certain compromises: decreased efficiency, increased overall operational costs, primarily due to higher specific compressor power consumption.

3.2 times the maximum flow of one 2nd stage compressor is required for the EIC loads, and thus 4 x 2nd stages are required to be run. The high side pressure is maxed out to operate expander 7 at maximum throughput of 570 g/s at a temperature of 5.6 K and 74 % efficiency. With 4 x 2nd stages running and only the equivalent of 3.2 x 2nd stages required, the pressure ratio across the compressor is higher than the optimum design ratio leading to lower isothermal efficiency. The bypass valve around the current expander 7 will be operational to handle the additional 185 g/s flow required for the cold end flow. Without a larger expander 7 or a new cold end expander configuration, the overall plant cold box will run at lower efficiency. With 4 x 2nd stage compressor running at higher pressure ratio than design, the power draw is 9.9 MW. With no changes to the current RHIC plant, the expected plant Carnot efficiency will be at 16.6 %. Improvements in cold end configuration with new JT expander(s) and upgrades to expander 5 & 6 to variable brake expanders would bring the central plant's Carnot efficiency up.

Acknowledgments
This work is supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.

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