RHIC Performance and Repair Status

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C-AD MAC-20
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Outline

RHIC Performance
- RHIC Run 2023 timeline and achievements
- RHIC accelerator availability
- Operational challenges

APEX (Accelerator Physics Experiments) during Run 2023

RHIC Repair Status
- Event on 1 August 2023
- Causal analysis and external “RHIC Recovery” review
- Repair status

Completing the RHIC physics science mission and APEX (FY24 and FY25)

Summary

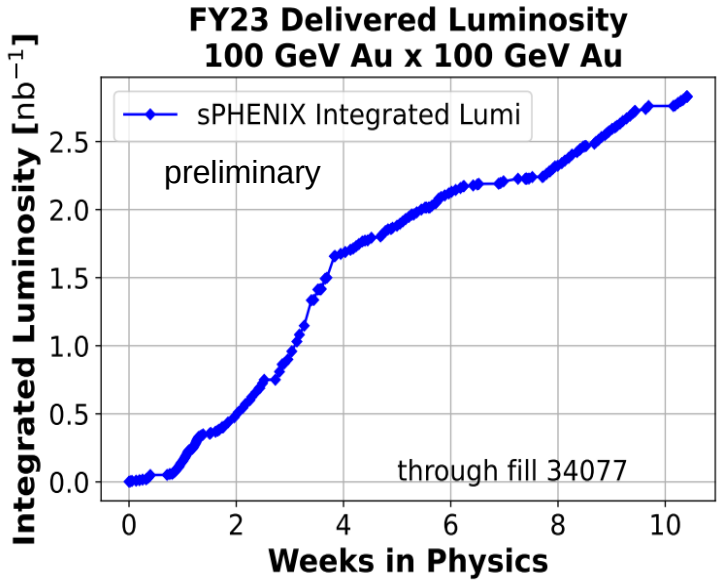
RHIC Performance

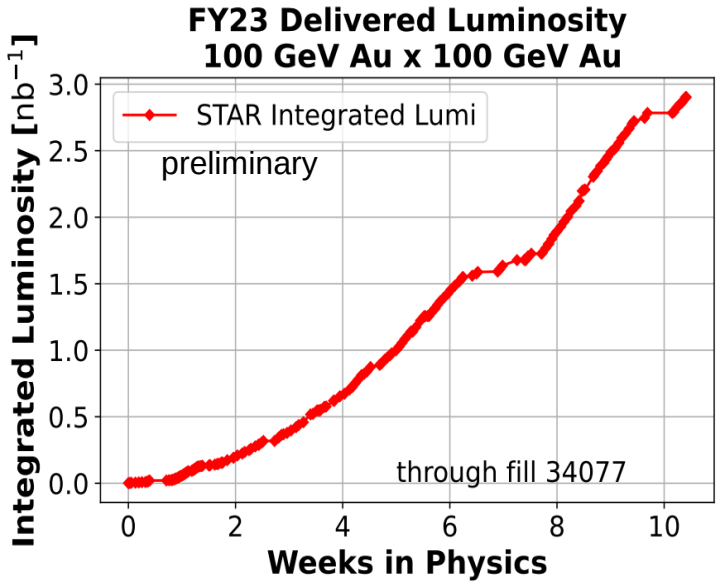
RHIC Run-23 timeline and achievements

Run Coordinator:
Travis Shrey

Timeline for sPHENIX commissioning with Au+Au (100 GeV/beam)

• sPHENIX MIE PD-4 project approval	12 Dec 2022
• RHIC 4K cooldown	5 May 2023
• First beam injection	8 May 2023 (Blue), 10 May 2023 (Yellow)
• sPHENIX approval to operate	18 May 2023
• sPHENIX commissioning with beam	18 May 2023
• STAR physics “declared”	20 May 2023
• APEX and maintenance	alternating weeks starting 24 May 2023
• Blue Ring 1004B valve box failure	1 August 2023
• End of RHIC Run 2023	4 August 2023



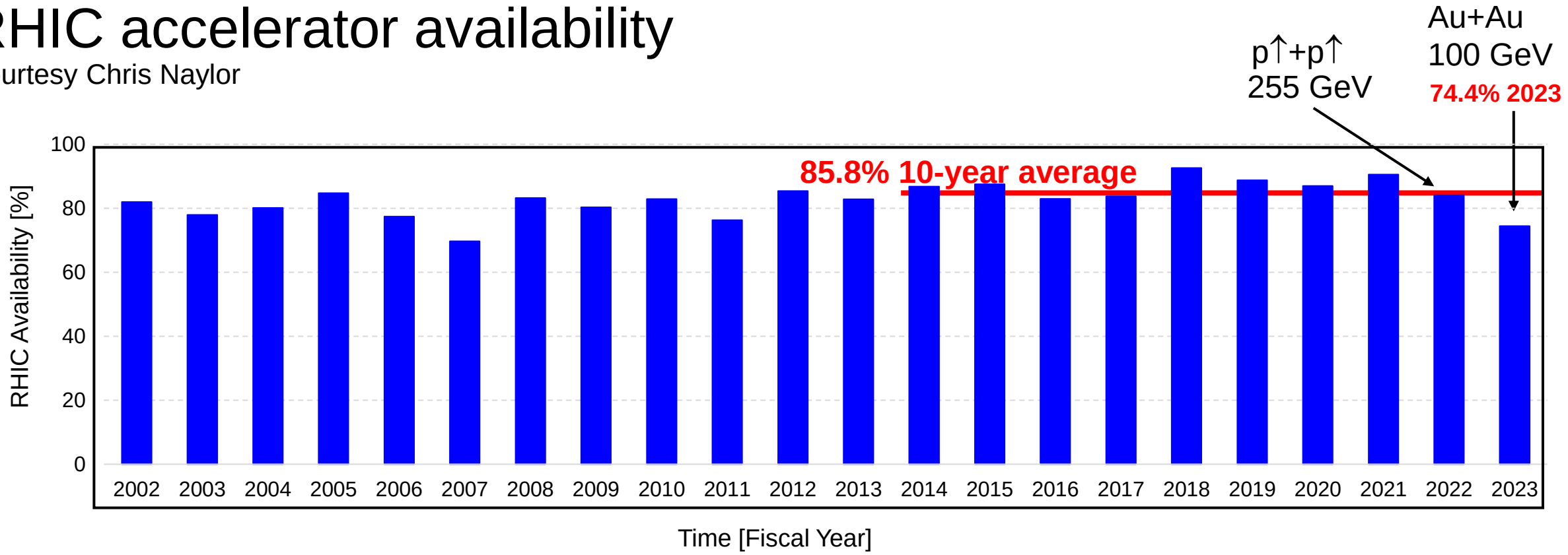


Achievements

- Provided wide variety of RHIC beam conditions (number of bunches, bunch intensities, up to 2 mrad crossing angles), met sPHENIX commissioning requirements per sPHENIX schedule.
- Provided collisions also for STAR with 1 mrad crossing angle and luminosity-leveling; ~30% of minimum-bias goal (Run23+25) collected.

RHIC accelerator availability

courtesy Chris Naylor



Availability = beam time / scheduled beam time

(denominator excludes scheduled maintenance)

Availability goals: 82.5% < FY20,
85% FY21-FY22
82.5% FY23

RHIC Run 2023: 74.4%

Average over last 10 years: 85.8%

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Primary challenge for Run 2023: operation during summer months

From DOE 2022 RHIC Science & Technology Review:

Concerns	Heat	Many support buildings not equipped to operate with sustained high temperatures Many unique AC systems
	Humidity	Reduced cooling tower efficiency, increased load on AC equipment Condensation issues
	Power	More frequent power dips and/or outages (storm related), possible brown-outs
	Air Conditioning	Aging equipment, some obsolete controls and parts

Mitigation

Maintenance

- ensure existing systems are operable at full capacity
- verify existing AC spares inventory (9 portable units, 6 portable high-volume fans)

Not achieved, RHIC main magnet power supply building

AC ductwork modifications

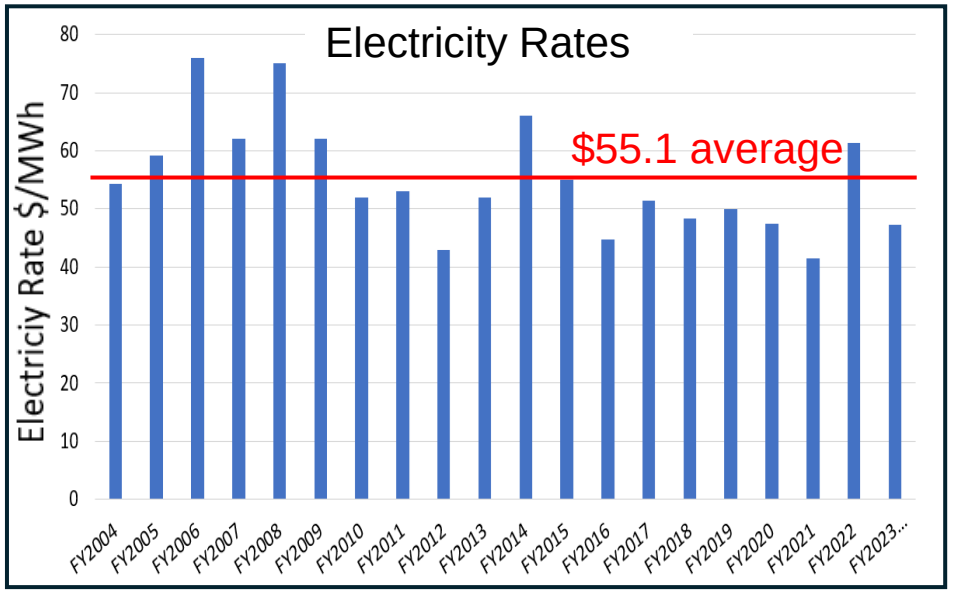
New procurements

- spare AC systems for RHIC alcoves (5)
- portable AC units for RHIC service buildings (6) for power supply quench detection racks

Supply chain and inflation: Helium and Electrical Costs

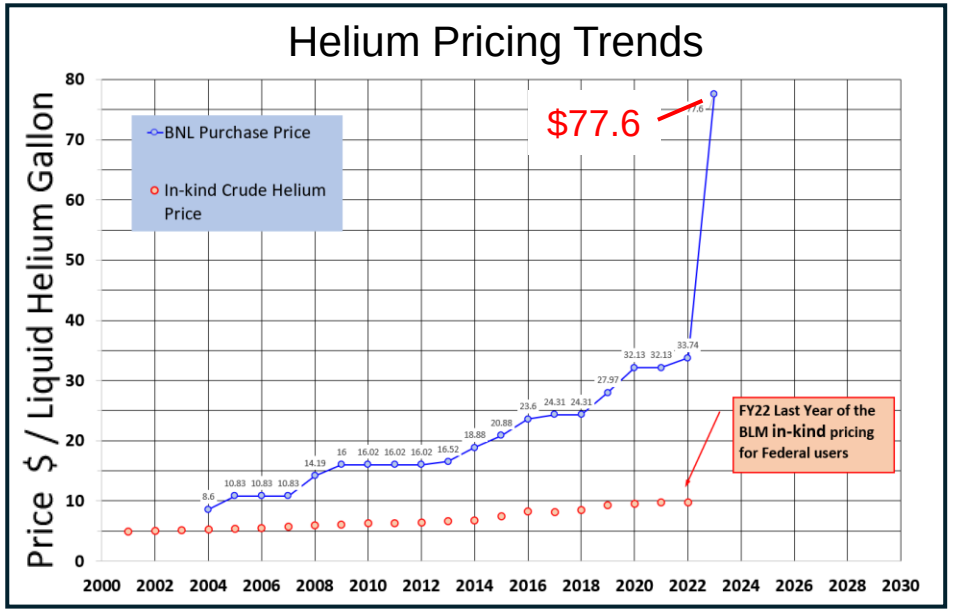
Electrical costs no fixed price contract, price volatility

FY21: $41.4/MWh
FY22: $61.4/MWh
FY23: $47.3/MWh actual
(had planned for $70.0/MWh)
FY24: planning for $82.4/MWh



Cost of LHe FY23: no more “in-kind” pricing from Bureau of Land Management (BLM) Reserves due to 2013 Act eliminating Federal Helium Reserves

FY21: $32.1/LHe gallon
FY22: ~$33.7/LHe gallon
FY23: $77.6/LHe gallon
(had planned for $50/LHe gallon)
FY24: planning for $77.6/LHe gallon



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Supply chain and inflation

Other impacts of supply chain on RHIC Operations during RHIC Run-23:

- highest impact: air conditioning in RHIC main magnet power supply building

  unit #1 (25-ton) – OK
  unit #2 (25-ton) – OK
  unit #3 (2 25-ton stages) – 1 stage down, other stage awaiting parts (>6 months)
  unit #4 (2 25-ton stages) – late arrival of parts, unsuccessful attempts at repair
  implemented multiple (3 10-ton) movable AC units during run

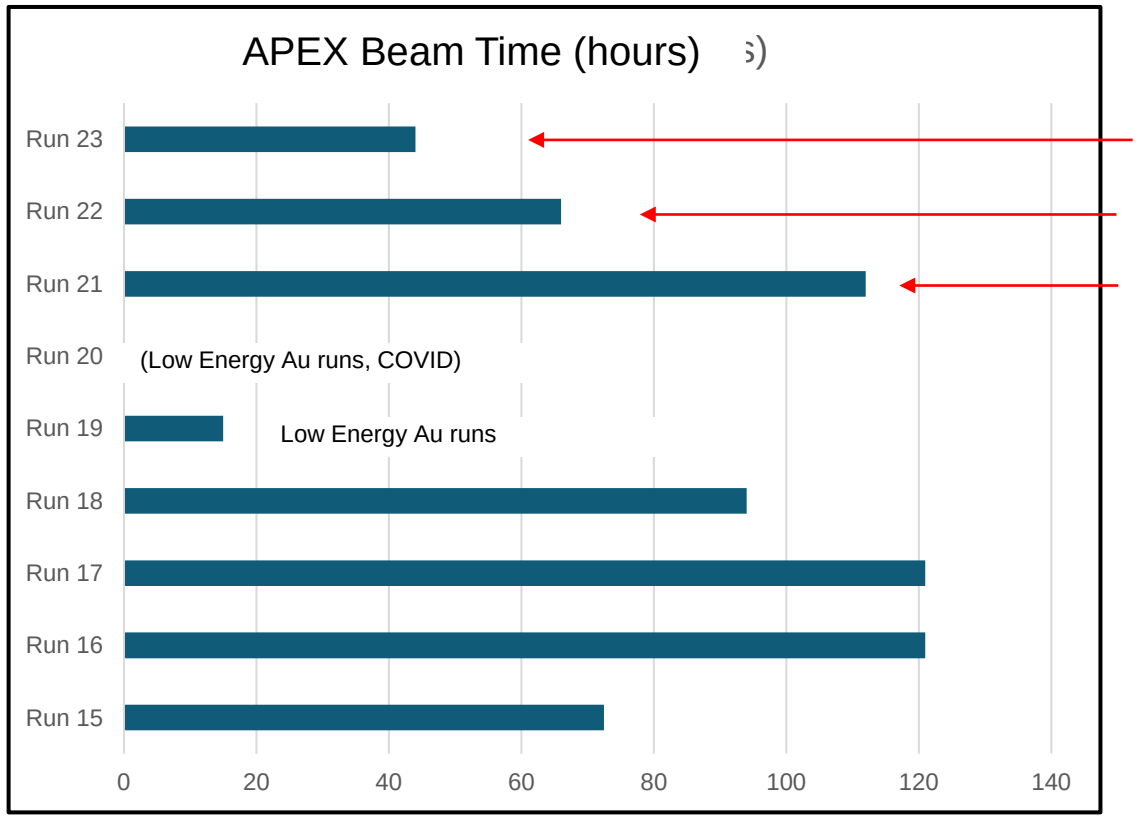
- Other impacts
  - air conditioning units on rooftop for sPHENIX delayed by 5 months (installed during run)
  - air conditioning for LEReC and CeC-X laser trailer resulted in 1 missed APEX opportunity
  - delayed delivery (6 months) of new AGS skew quadrupole power supply (no AGS beam tests for P+P in Run 2023)
  - delayed delivery (~ 6 months) of integrated circuits and isolation amplifiers) for machine protection enhancement
  - delayed delivery (~ 6 months) of CEC-X cooling section power supplies (although in time for Run 2023)
- other groups report no effect on RHIC operations owing to healthy spares inventories and/or work-arounds
- good news: most groups (except laser group) report delivery times trending towards those pre-COVID

Impacts of inflation on RHIC operations

- EBIS: (30-50)% for parts (diode pack, drift tube and smaller supplies, due to increased material costs)
- LINAC RF: DC blocking capacitor (350% increase since 2018)
  5 kW amplifiers (160% increase since 2020)
- good news: most groups report costs reducing to pre-COVID levels

APEX (Accelerator Physics Experiments) during Run 2023

Recent APEX Overview



focus: experiments to inform EIC design

focus: experiments to inform EIC design, beam cooling studies

focus: beam cooling studies

APEX experiments during Run 2023

Experiments	Spokesperson	Actual Beam Time allocated (hours)
IPM voltage test	Medani	2
Test of ERL BPM	Igor	2
Luminosity optimization with ML	Xiaofeng	2+2=4
Precise decoupling test for EIC large emittance ratio	Yun	5+8+3 =16
RHIC Snake Aperture Optimization	Vincent	10
LeREC related experiments	Alexei, Sergei	10
Total		44 hours

Four experimental periods:
24 May, 14 June, 28 June, 26 July

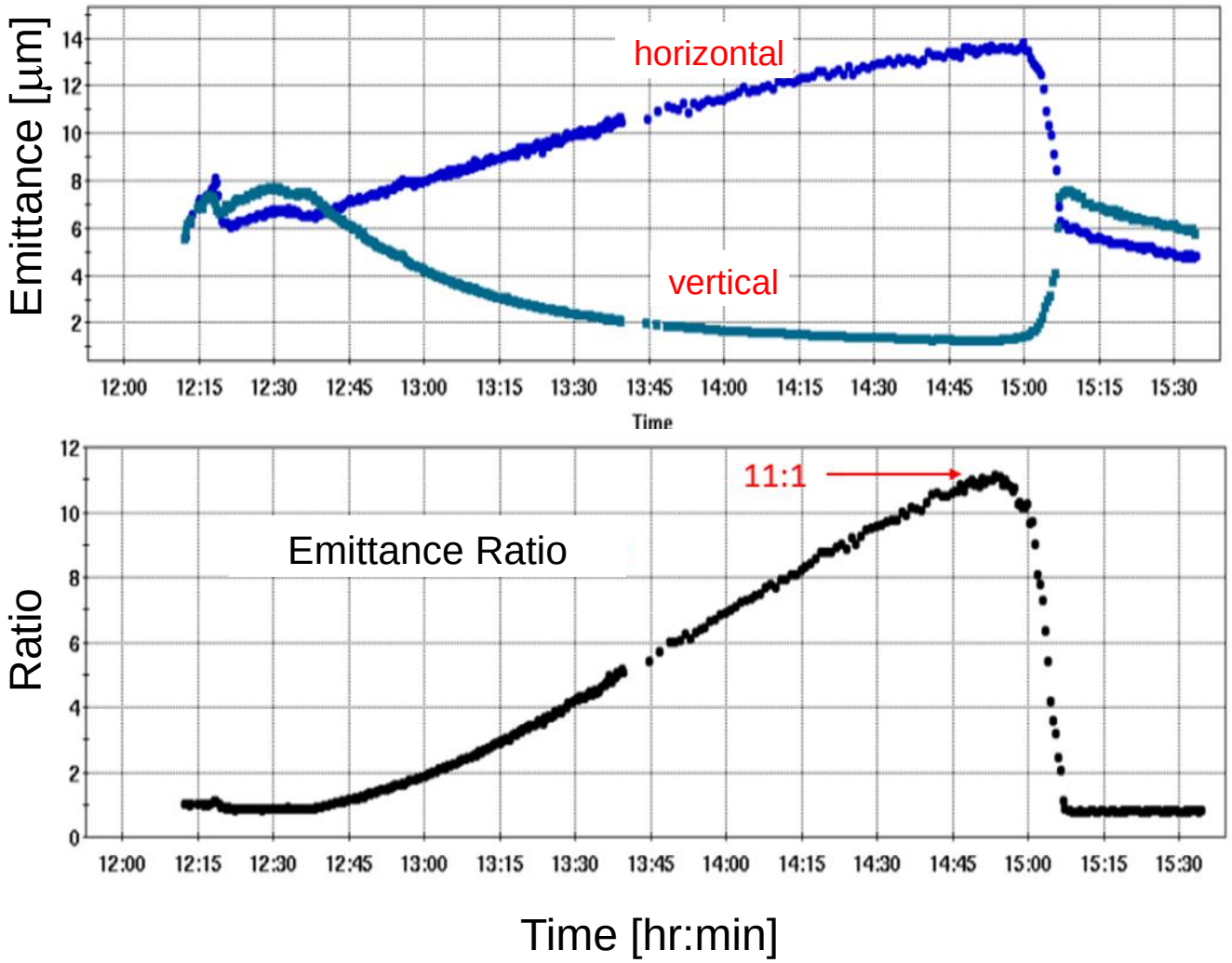
APEX - Precision Decoupling for Large Emittance Ratio

EIC luminosity is enhanced by large beam size ratio at the interaction point.

While flat electron beams are naturally produced by synchrotron radiation, the use of the flat hadron beam in storage rings is unusual.

Very good correction and control of betatron coupling is required to produce large hadron emittance ratio.

The experiment in RHIC intended to demonstrate feasibility of creating the flat hadron beam and the adequacy of present decoupling system for this task.

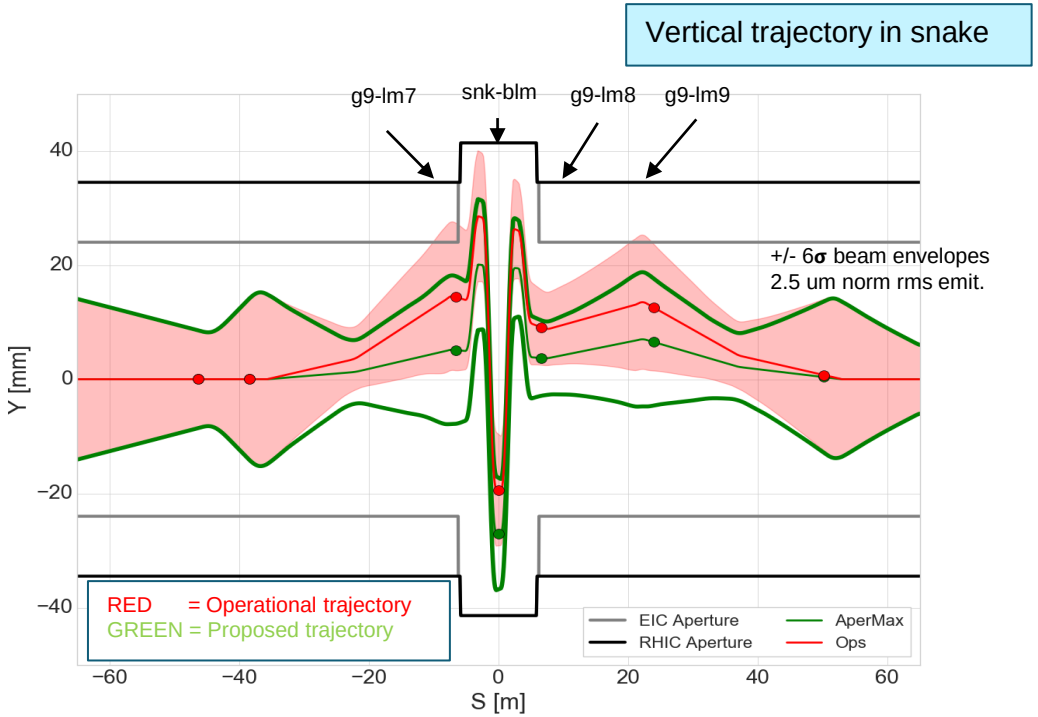


Result: goal of > 10:1 emittance ratio demonstrated.

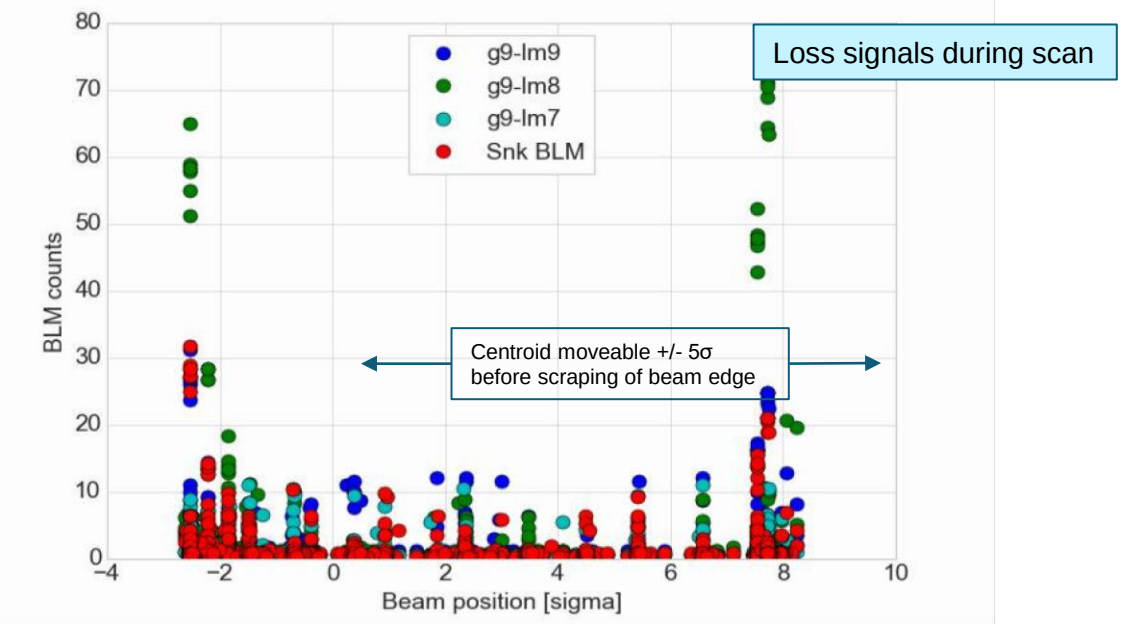
APEX - RHIC Snake Aperture Optimization

Proposed EIC beam screen design restricts aperture in the arcs. New aperture would impinge on present RHIC beam envelope near snake locations (red envelopes). New trajectory established (green envelope) and scanned.

Model: predicts ~9σ, with limiting aperture in snake body.



Experiment shows +/- 5σ of centroid motion before beam edge at +/- 5-6σ contacts aperture. Shows ~10σ clearance between beam centroid on central trajectory and aperture with loss signal consistent with primary scraping in snake body.



Result: Trajectory exists with sufficient aperture to inject beam in EIC without modifying the screen design near the snake. Assumes local EIC optics approximate RHIC optics.

APEX - Advanced Beam Cooling

While both LEReC and CeC established electron beam operations, no beam cooling experiments took place in Run 2023.

LEReC – advances in accelerator science

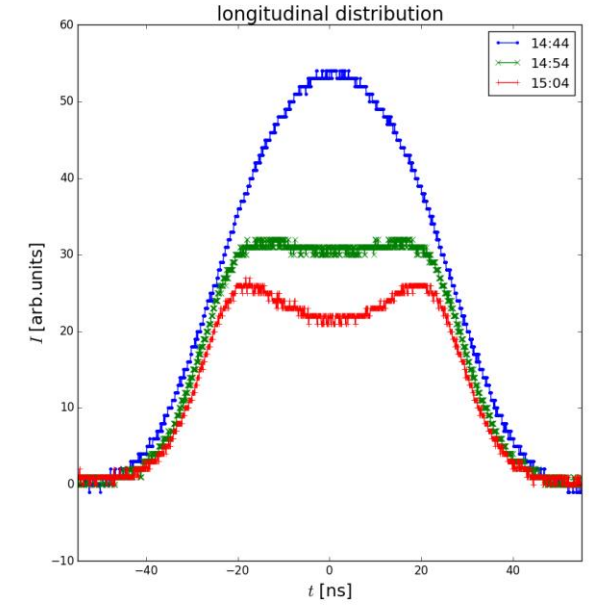
- Analyzed data from APEX 2022 and published (details in backup slides):

  Experimental demonstration of circular attractor at relativistic energy using LEReC

  S. Seletskiy, A. Fedotov, D. Kayran, "Experimental studies of circular attractors in the first rf-based electron cooler", PRAB 26, 024401 (2023).

  Demonstrated influence of circular attractor on CeC

  *S. Seletskiy, A. Fedotov, D. Kayran, "*Circular attractors as heating mechanism in coherent electron cooling" PRAB 25, 054403 (2022).



Measured ion bunch evolution in the presence of a circular attractor

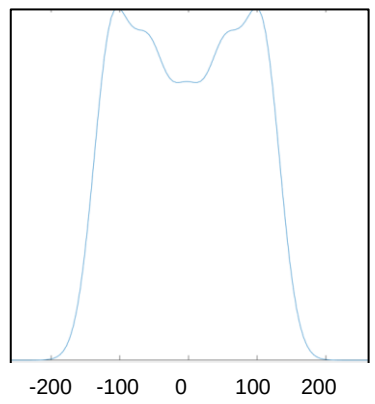
- Electron beams re-established in 2023 reproducing design beam parameters.
- APEX for LEReC this year (10 hours) was devoted to establishing 3.85 GeV beam (with 100 GeV initial conditions).

APEX - Advanced Beam Cooling

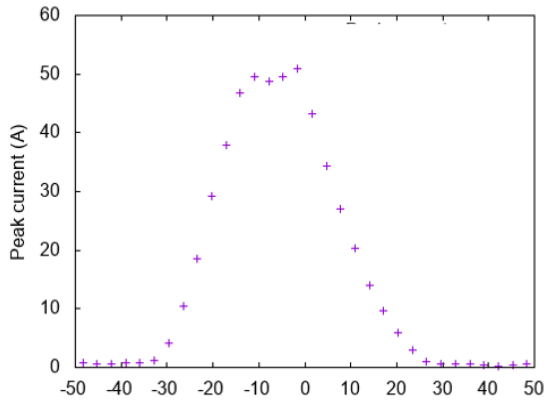
CeC – advances in accelerator technology

- Updated cooling simulation require the electron beam in cooling section to have uniform current distribution (<10% peak-to-peak variation) as well as good quality over 15 ps duration
- Beam dynamics simulations show that the uniform distribution can be achieved using a new (non-Gaussian) distribution of the laser pulse profile.
- The laser system was upgraded to produce five overlapping Gaussian laser pulses (using five interferometers). Efforts underway to ensure same laser profile at laser gun table.

simulation: electron current distribution (in ps)

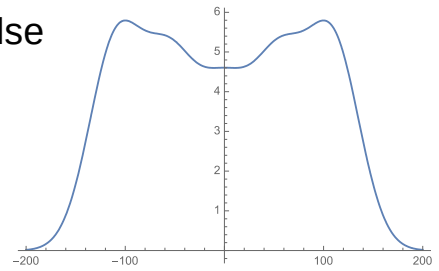


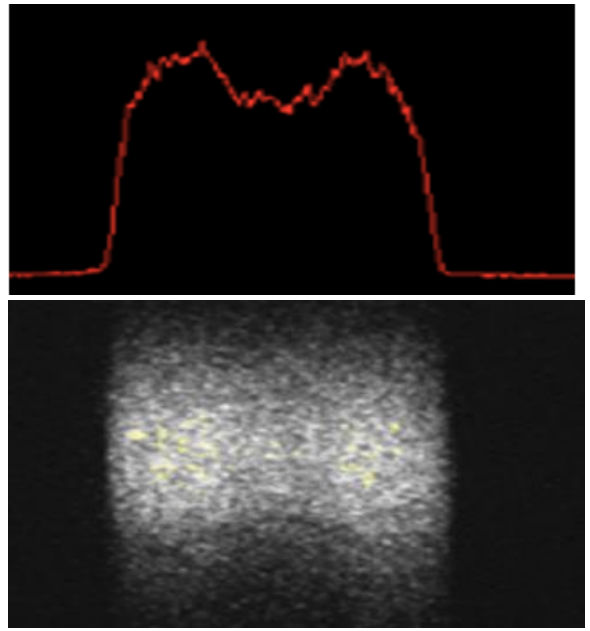
at gun



in cooling region

proposed laser pulse shape





streak camera measurement (laser trailer)

- Manufacturing process has started for new 500 MHz bunching cavity.
- New transfer system for photocathodes successfully tested.

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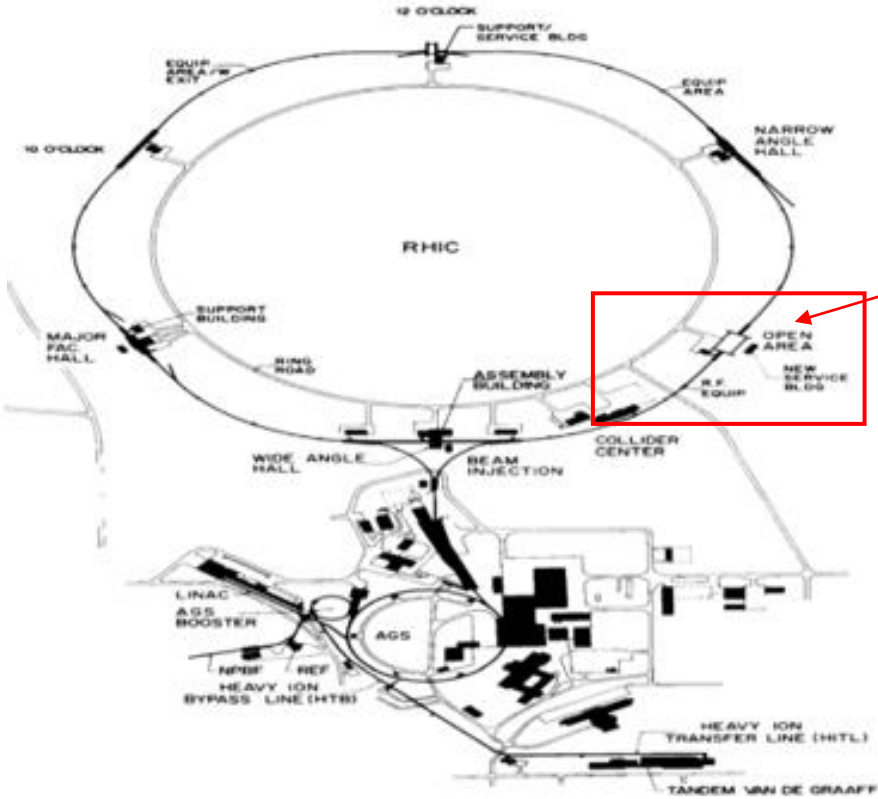
RHIC repair status

Event on 1 Aug 2023

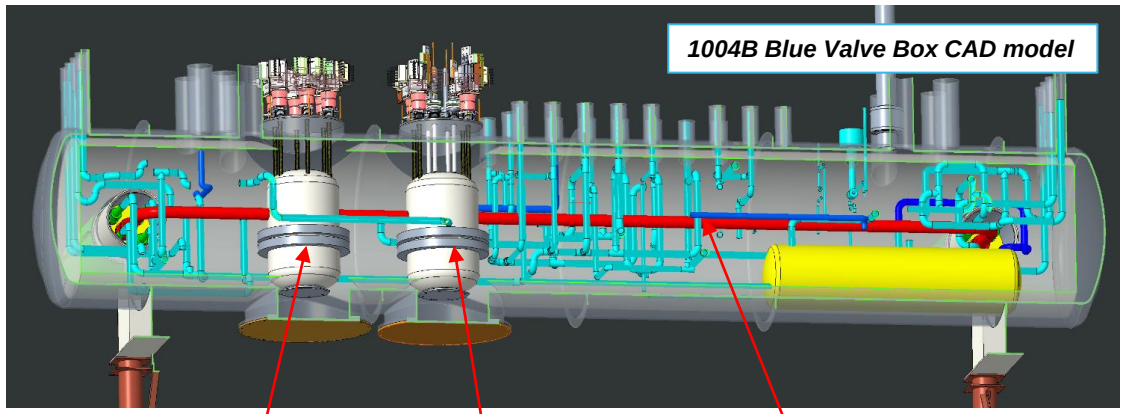
- On 1 Aug 2023 the Blue Ring Quench Interlock (QLI) System commanded the RHIC energy extraction system to dissipate the stored energy in the Blue Ring. Due to uncertainties in the sequence of events and estimated time for recovery, RHIC Run 2023 was terminated six weeks early (on 4 Aug 2023).
- The DOE Office of Science has approved carryover of these six weeks into RHIC Run 2024.
- The unexpected release of Helium in Building 1004B through the valve box access port necessitates a USI (Unreviewed Safety Incident) requiring a change to the RHIC ASE.

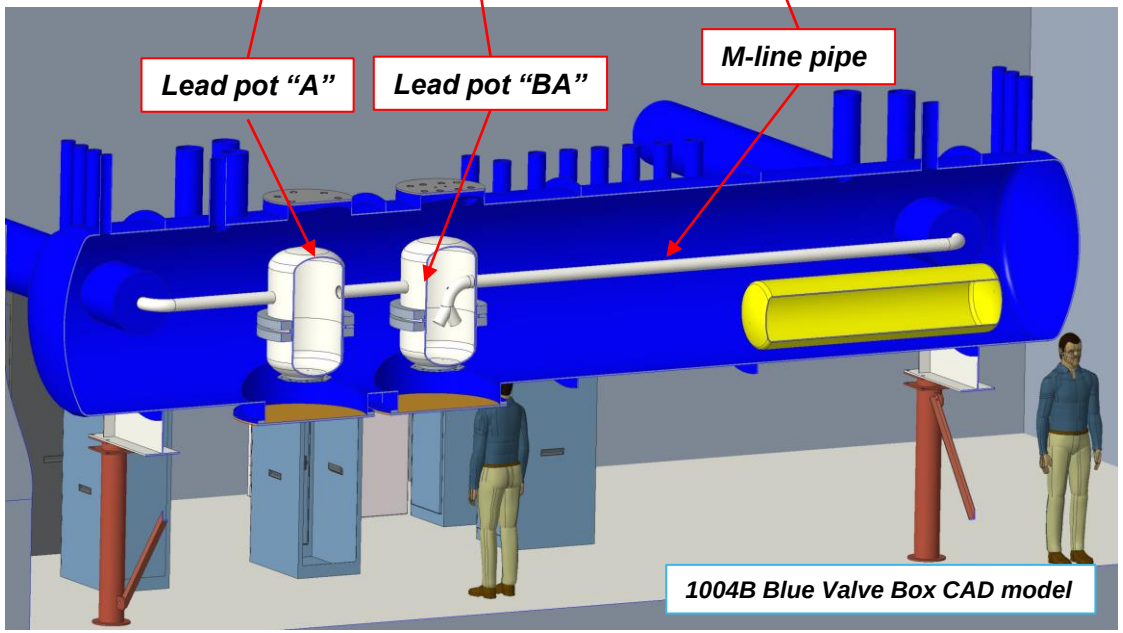


Helium venting at Bldg. 1004B

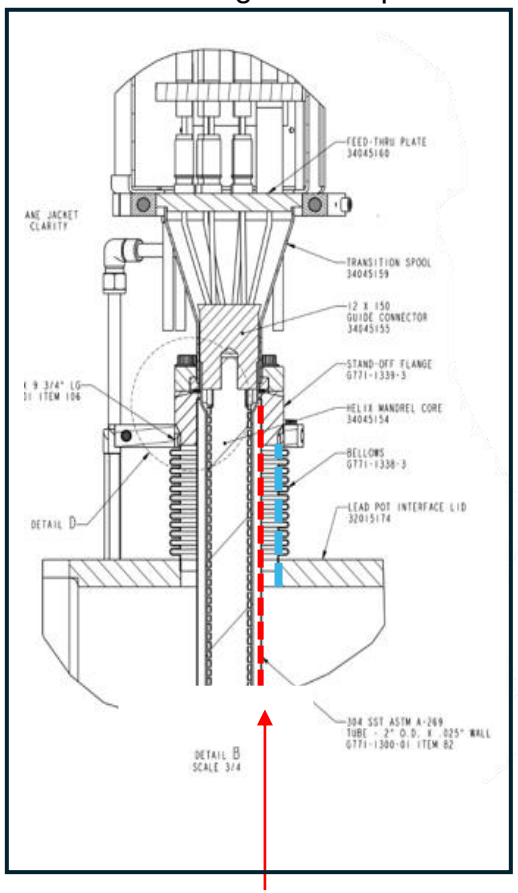
1004B Valve Box

Valve Box in Building 1004B





Feedthrough in lead pot

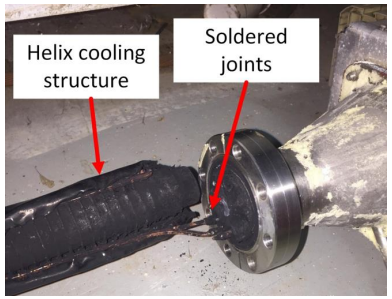


.025" wall feedthrough tube and bellows were ruptured by current lead arc failure

Feedthrough in situ

Feedthrough pipe

Feedthrough in lab



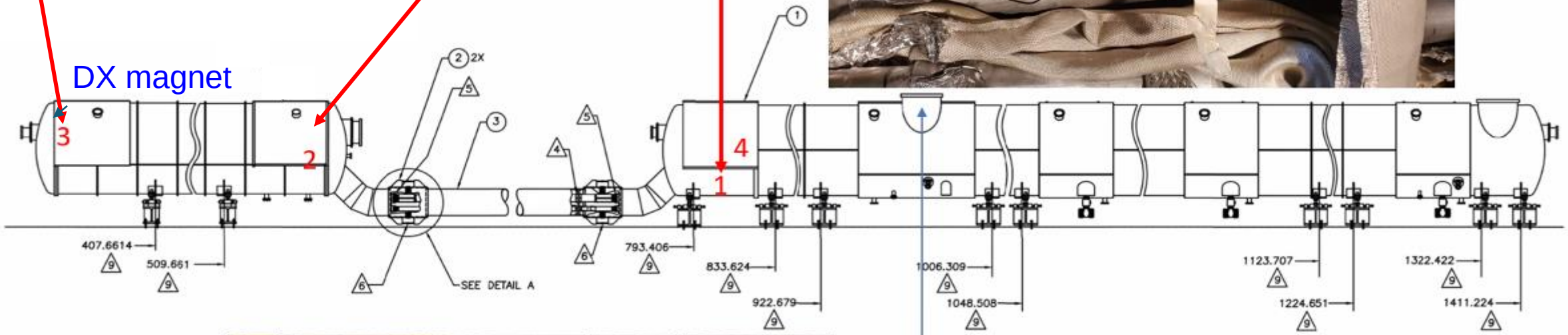
DX Magnet Splice Cans

Splice can #3

Splice can #2

Splice can #1 (no trouble found)

DX magnet



Location of electrical connections to 1004B valve box

DX magnet

Inside the RHIC tunnel

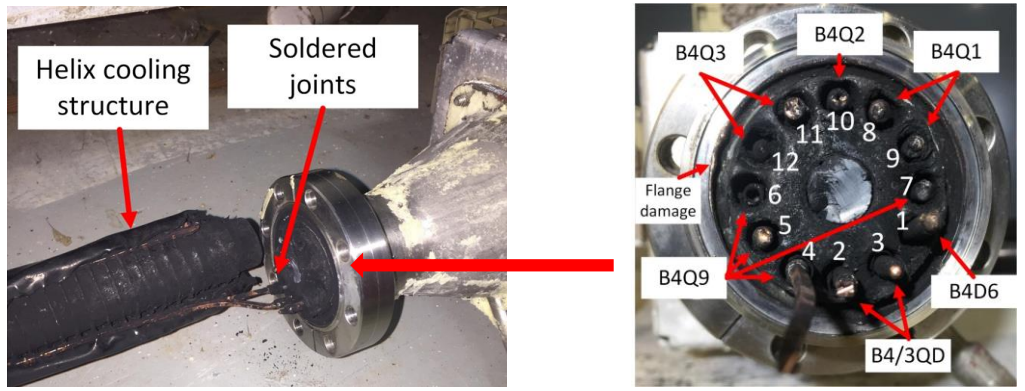
Causal analysis and “RHIC Recovery Review”

External review (28 Nov 2023)

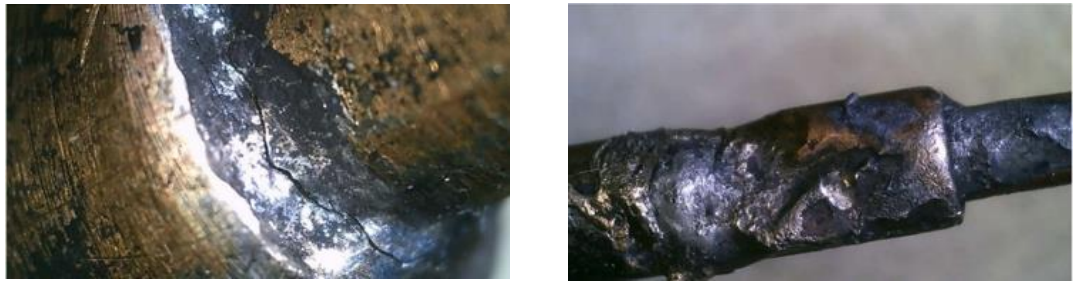
Marc Ross, chair (SLAC), Philippe Lebrun (CERN), Yuenian Huang (FNAL), Renuka Rajput-Ghoshai (JLAB), George Ganetis (BNL), George Mahler (BNL)

	Event
1	Thermal fatigue solder cracks in the leads
2	Arcing inside the lead cracked joint – side eruption
3	Inter-lead arcing Q1-Q9
4	QPS turns ON – DX heaters fire - 500+ V on dipole bus
5	Lead arcing expands to D6 – Quad/Dipole/Ground are now connected - intense current sharing
6	DX quench warms up the helium – flow out through splice cans - quench of the splices and conductors in DX splice cans
7	Burnout of the “Trim cable” in DX splice cans. CCB stays intact

current lead feedthrough



current lead



Review committee which concurred with causal analysis and planned repairs, recommended more analysis of splice can failures.

RHIC recovery

1. **We understand what happened**

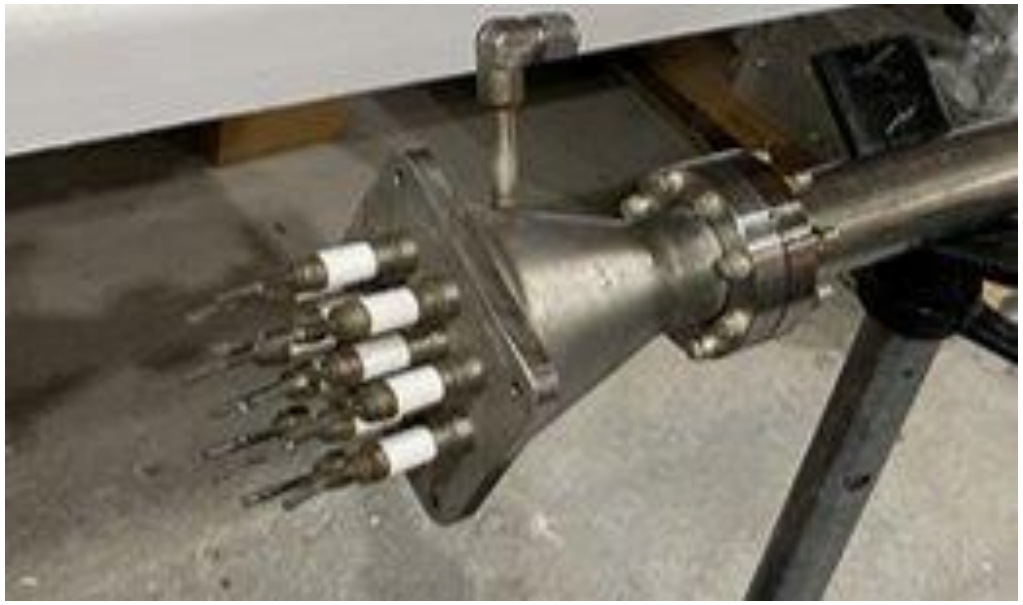
2. **Broad BNL effort to repair RHIC and return to operations**
   A. 1004B valve box mechanical repairs
   B. Spare 12X150 current lead preparation and valve box electrical work
   C. DX magnet and magnet bus repairs, mechanical and electrical work
   D. DX magnet preparation and testing
   E. ASE and USI documents and supporting ODH calculations
   F. RHIC 4K cooldown by 4 Mar 2024

3. **Milestone tests to verify repair**
   A. M-line pressure test by 1/15/24
   B. DX magnet and super-conducting bus cold testing starting in early March 2024

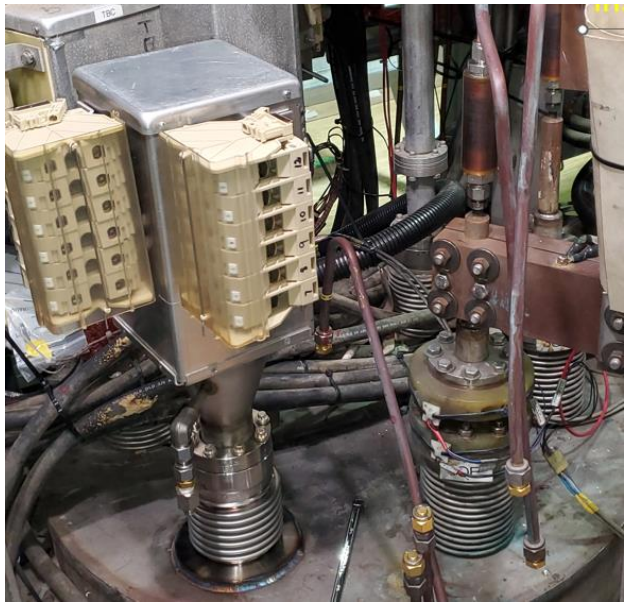
4. **Continuing to assess how to prevent recurrences and mitigate for EIC operations**
   A. 12X150 current lead
      1. Fabricating additional units based on current design
      2. Developing improved design for EIC operations
   B. Implementing improved current lead cooling-flow control

Repair status – 1004B valve box

Feedthrough pressure and electrical tests completed



Feedthrough, new feedthrough tube and bellows installed



Next steps: feedthrough electrical testing
close lead pots (weld)
M-line pressure test (includes closure of all splice cans)
Pumpdown valve box
Modifications to cryo cooling control (for faster regulation and to avoid ‘overcooling’ to reduce thermal stresses

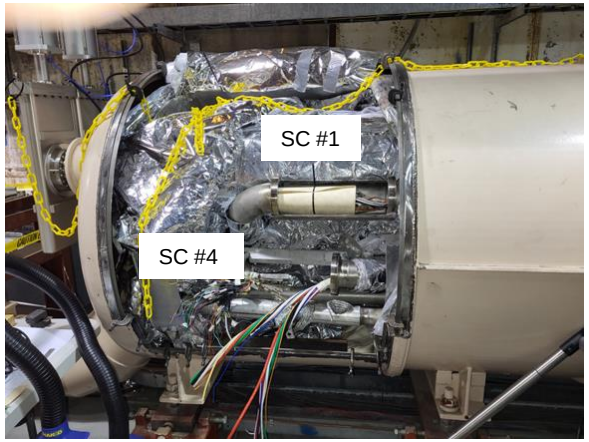
Repair status – DX magnet and electrical splices

Electrical wiring of spare DX magnet completed

Magnetic fields measured

DX magnet re-installed

Electrical wiring: 3 “splice cans” (SC) completed, 2 prepared to accept DX magnet



Next steps: electrical testing
close all splice cans
M-line pressure test

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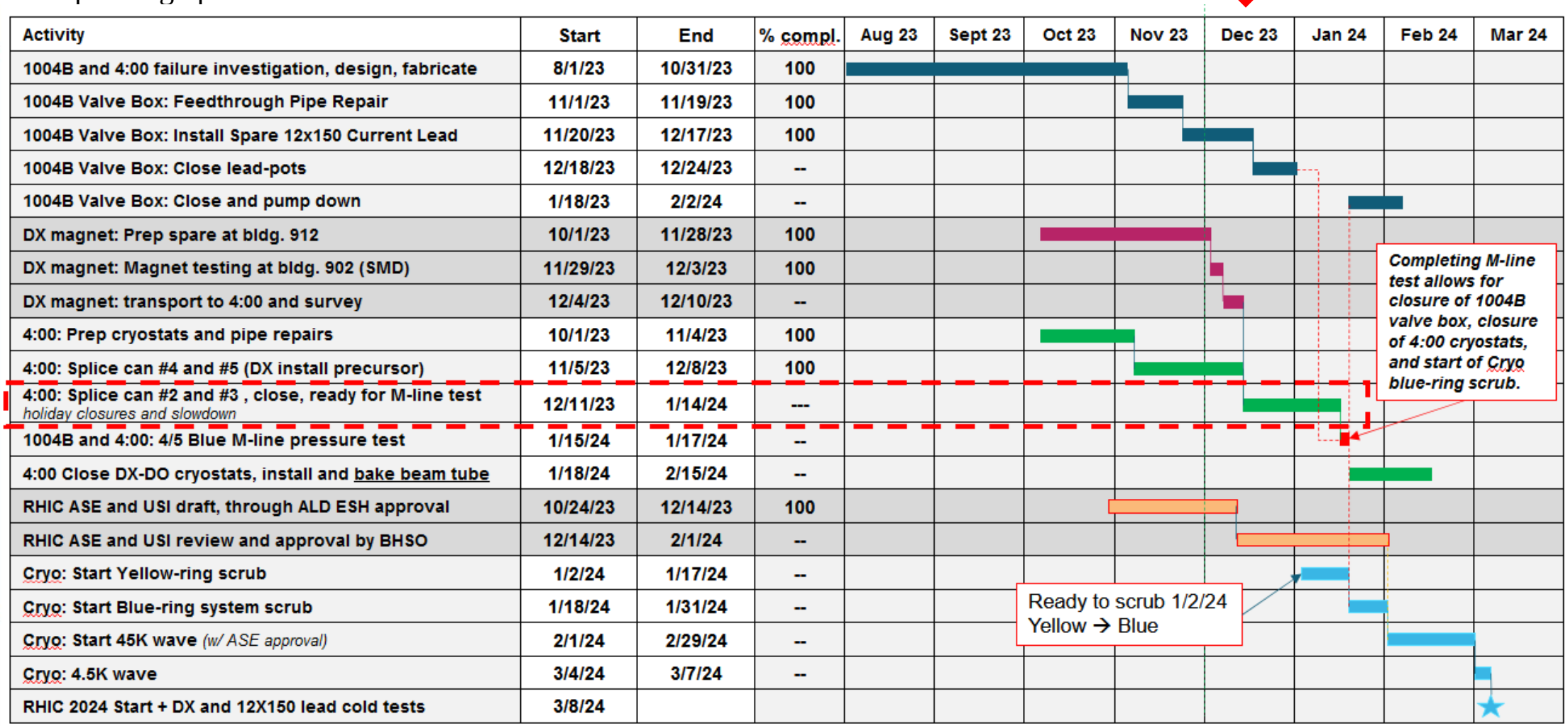
RHIC recovery schedule

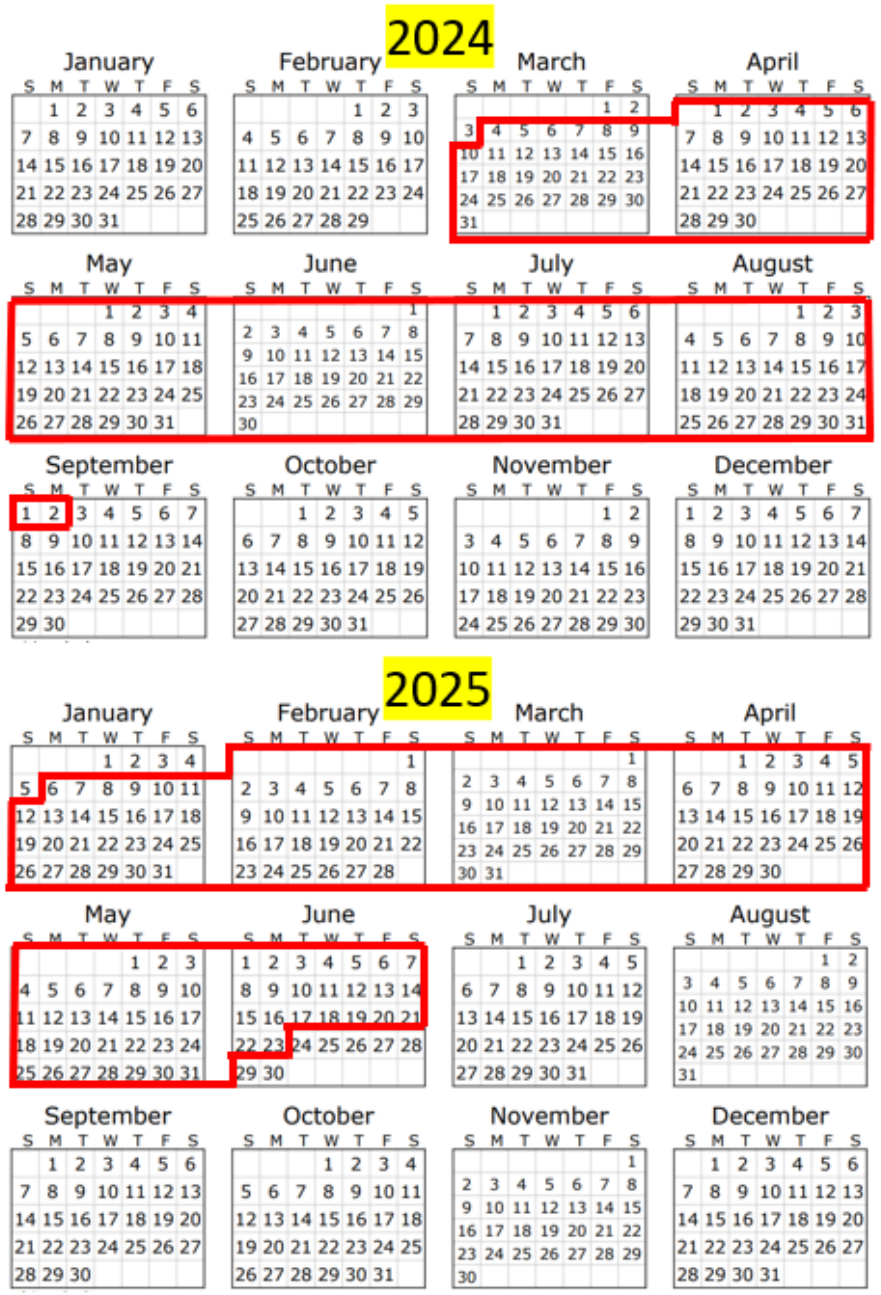
- 4K wave start no earlier than 4 Mar 2024
- 45K wave requires approval of USIs (make existing ODH systems credited controls) and corresponding update of RHIC ASE

Activity	Start	End	% compl.
1004B and 4:00 failure investigation, design, fabricate	8/1/23	10/31/23	100
1004B Valve Box: Feedthrough Pipe Repair	11/1/23	11/19/23	100
1004B Valve Box: Install Spare 12x150 Current Lead	11/20/23	12/17/23	100
1004B Valve Box: Close lead-pots	12/18/23	12/24/23	--
1004B Valve Box: Close and pump down	1/18/23	2/2/24	--
DX magnet: Prep spare at bldg. 912	10/1/23	11/28/23	100
DX magnet: Magnet testing at bldg. 902 (SMD)	11/29/23	12/3/23	100
DX magnet: transport to 4:00 and survey	12/4/23	12/10/23	--
4:00: Prep cryostats and pipe repairs	10/1/23	11/4/23	100
4:00: Splice can #4 and #5 (DX install precursor)	11/5/23	12/8/23	100
4:00: Splice can #2 and #3 , close, ready for M-line test *holiday closures and slowdown*	12/11/23	1/14/24	---
1004B and 4:00: 4/5 Blue M-line pressure test	1/15/24	1/17/24	--
4:00 Close DX-DO cryostats, install and bake beam tube	1/18/24	2/15/24	--
RHIC ASE and USI draft, through ALD ESH approval	10/24/23	12/14/23	100
RHIC ASE and USI review and approval by BHSO	12/14/23	2/1/24	--
Cryo: Start Yellow-ring scrub	1/2/24	1/17/24	--
Cryo: Start Blue-ring system scrub	1/18/24	1/31/24	--
Cryo: Start 45K wave *(w/ ASE approval)*	2/1/24	2/29/24	--
Cryo: 4.5K wave	3/4/24	3/7/24	--
RHIC 2024 Start + DX and 12X150 lead cold tests	3/8/24		



Completing the RHIC physics science mission (FY24 and FY25)

Completing the RHIC physics science mission (FY24 and FY25)



Run-24 assumes 20 cryo-weeks (p↑ + p↑**)** in scenario 1 and a 6-week carryover (Au + Au).

Prior to Run-25, a 24-week shutdown is assumed to accommodate possible future requirements of the sPHENIX experiment and maintenance needed for Run-25. Removal of equipment not needed for RHIC operations in Run-25 will also take place in preparation for the EIC.

Run-25 assumes 24 cryo-weeks (Au + Au) in scenario 1.

DOE Site Visit, Nov 2022 (includes more optimistic operating scenarios):

	FY25 LMBB Scenario 1		FY25 LMBB Scenario 2		Scenario 3	
	dates	total weeks	dates	total weeks	dates	total weeks
Run-23	5/1/23 - 9/18/23	20 (+5) = 25	5/1/23 - 9/18/23	20 (+5) = 25	5/1/23 - 9/18/23	20 (+5)
Shutdown	9/18/23 - 3/4/24	24	9/18/23 - 3/4/24	24	9/18/23 - 1/29/24	19
Run-24	3/4/24 - 7/22/24	20	3/4/24 - 7/22/24	20	1/29/24 - 8/12/24	28
Shutdown	7/22/24 - 1/6/25	24	7/22/24 - 12/16/24	21	8/12/24 -12/16/24	18
Run-25	1/6/25 - 6/23/25	24	12/16/24 - 6/30/25	28	12/16/24 - 6/30/25	28
Total Cryoweeks		64		68		76

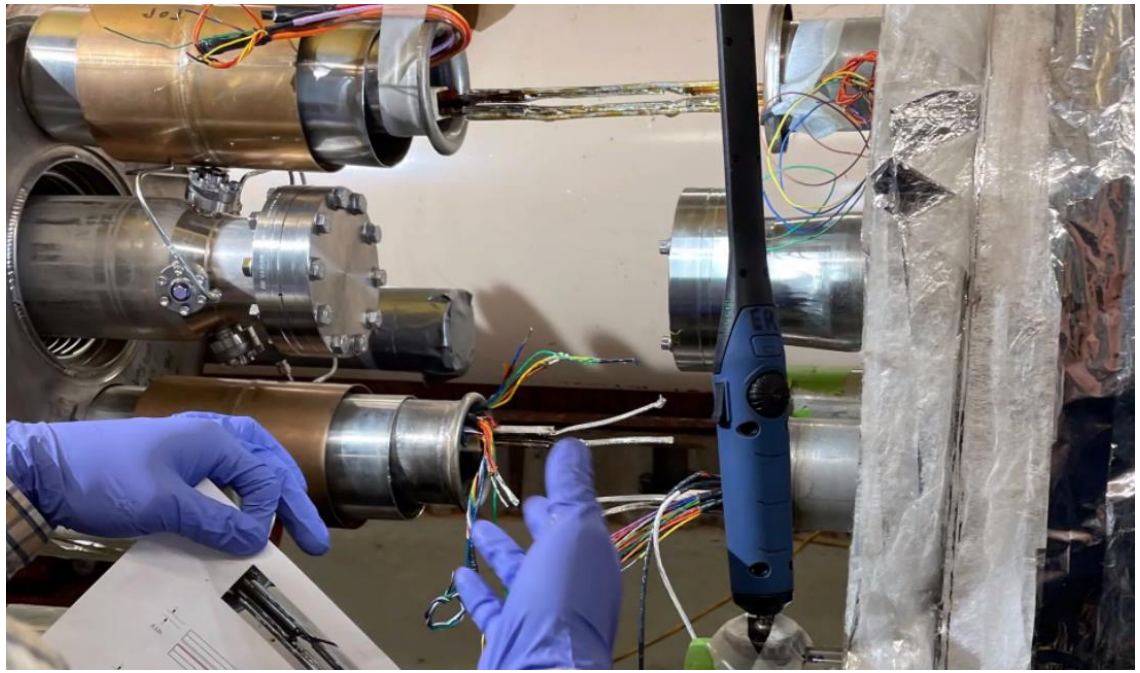
Notes

- operating budgets for Run-24 and Run-25 still TBD
- scenarios 2 and 3 could enable p↑ + Au

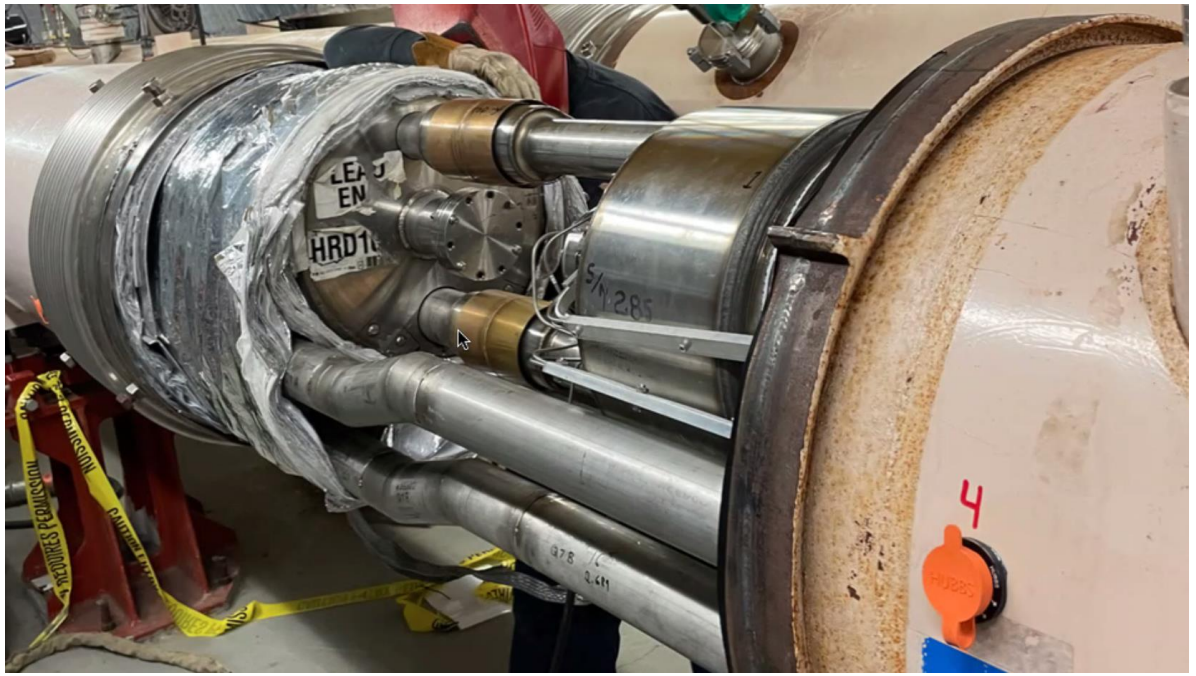
Siberian Snake

- The Siberian Snake, needed for polarized proton operation in Run-24, was damaged during Run-22. Amazingly, Run-22 was completed with high polarization.
- The Siberian Snake magnet repaired at the Magnet division.

Work on superconducting electrical connections



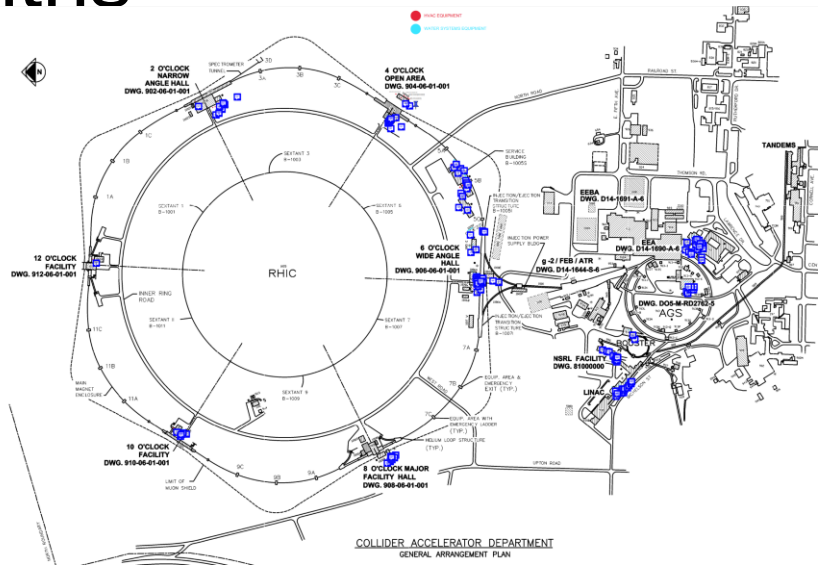
Utility lines completed and welded (10 o'clock side)



The Siberian Snake magnet has been re-installed for RHIC Run-24.

RHIC operations through hot summer months

- Dedicate weekend and holiday AC Mechanic support from F&O
- Service contracts through AC unit manufacturers
- Tracking preventative maintenance of critical AC systems prior to RHIC run
- Cleaning of critical water systems heat exchanges to optimize performance
- Connect heat generating equipment to exhaust heat to the outside
- Replace failed 1004B AC unit and purchase a spare
- Purchase spare portable AC units for Service Buildings and additional spare portable AC units (air cooled and water cooled) for deployment as needed
- Purchase of spare Split AC units for RHIC Alcoves
- Purchase spare parts for (54) critical AC systems
- Provide for standby spare large capacity monthly rental AC systems with generator power in the event of failure to major AC Systems



Site map of location of (54) critical AC Units

Removal of existing 1004B AC unit in preparation of new unit arrival

Portable spare AC unit inventory

Spare parts inventory

Brookhaven National Laboratory

Completing Accelerator Physics Experiments (FY24 and FY25)

APEX proposals are reviewed and ranked by the APEX Steering Committee

Criteria (Number/Letter):

0 - has immediate benefit for improved accelerator performance
1 - impacts near-term (e.g. planned future modes of) accelerator performance
2 - advances accelerator science

A (high priority), B (recommended), C (allowable if time permits), D (declined)

Through long-term agreement, 2 shifts of APEX experiments are performed every other week.

As of December 2023, beam time requests through the end of RHIC operations amount to ~36 shifts, which can be accommodated with the long-term agreement (however more EIC-related proposals are anticipated as emphasized by the recent EIC CD3A review).

Proposed APEX experiments are dominated by EIC-related developments

- Bunched-beam electron cooling
- Coherent electron cooling
- Polarization (for protons and He3)

Summary

Summary

RHIC performance in Run 2023

- wide variety of RHIC beam conditions successfully provided for sPHENIX commissioning and for physics at STAR
- accelerator availability was low (74.4%), impacted by operation during the summer; 10-year average is 85.8%
- electricity rates lower than planned, however cost of liquid helium increased more than expected (factor 2)
- RHIC run 2023 terminated early (1 Aug 2023) due to short in valve box (Blue Ring main dipole circuit)

Accelerator Physics Experiments (APEX) during Run 2023

- successful completion of experiments informing EIC design
- no cooling experiments performed

RHIC Repair Status

- causal analysis of 1 Aug 2023 event completed
- external “RHIC Recovery” review committee (28 Nov 2023) concurred
- repairs progressing well and on schedule for completion by early March 2024
- RHIC Run 2024 start date contingent on authorization by the Brookhaven Site Office and readiness of sPHENIX

Completing the RHIC science mission (2024 – 2025)

- planning is based on scenario 1 of last DOE budget briefing meeting
  Run-24: 20 cryo-weeks for p↑ + p↑ and a 6-week carryover for sPHENIX with Au + Au
  Run-25: 24 cryo-weeks with Au+Au
- many APEX experiments are planned supporting both EIC and accelerator science