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U.S. DEPARTMENT OF ENERGY

RHIC Performance Update

Michiko Minty
Accelerator Division Head

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Contents

Overview of RHIC Runs (Run-21 through Run-25)

RHIC Performance in Run-21

- Completed multi-year Beam Energy Scan program
- Achieved main Run-21 goal early: Au+Au at 3.85 GeV with bunched beam electron cooling
- Early completion enabled execution of all desired experiments in STAR Beam Use Request

Status and Plans for RHIC Run-22

- Planned Operating Modes
- Upgrades and Improvements

Planning through end of RHIC operations / start of EIC installations (in 2025)

- Run-23 – Run-25 with sPHENIX and STAR
- 25+ year Technical Infrastructure Upgrade Plan

Responses to recommendations from C-AD MAC 2020

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Overview of RHIC Runs (Run-21 through Run-25)

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Overview of RHIC Run Plans

From 2020 C-AD MAC (W. Fischer)

- ***Beam Energy Scan II* (2019-21):**
  - Low energy ($\sqrt{s_{NN}}$ = **7.7**, 9.1, 11.5, 14.5, 19.6 GeV) Au+Au runs using electron cooling to increase luminosity
  - Fixed target runs at (3.0), 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV
  - Search for signs of critical phenomena in event-by-event fluctuations

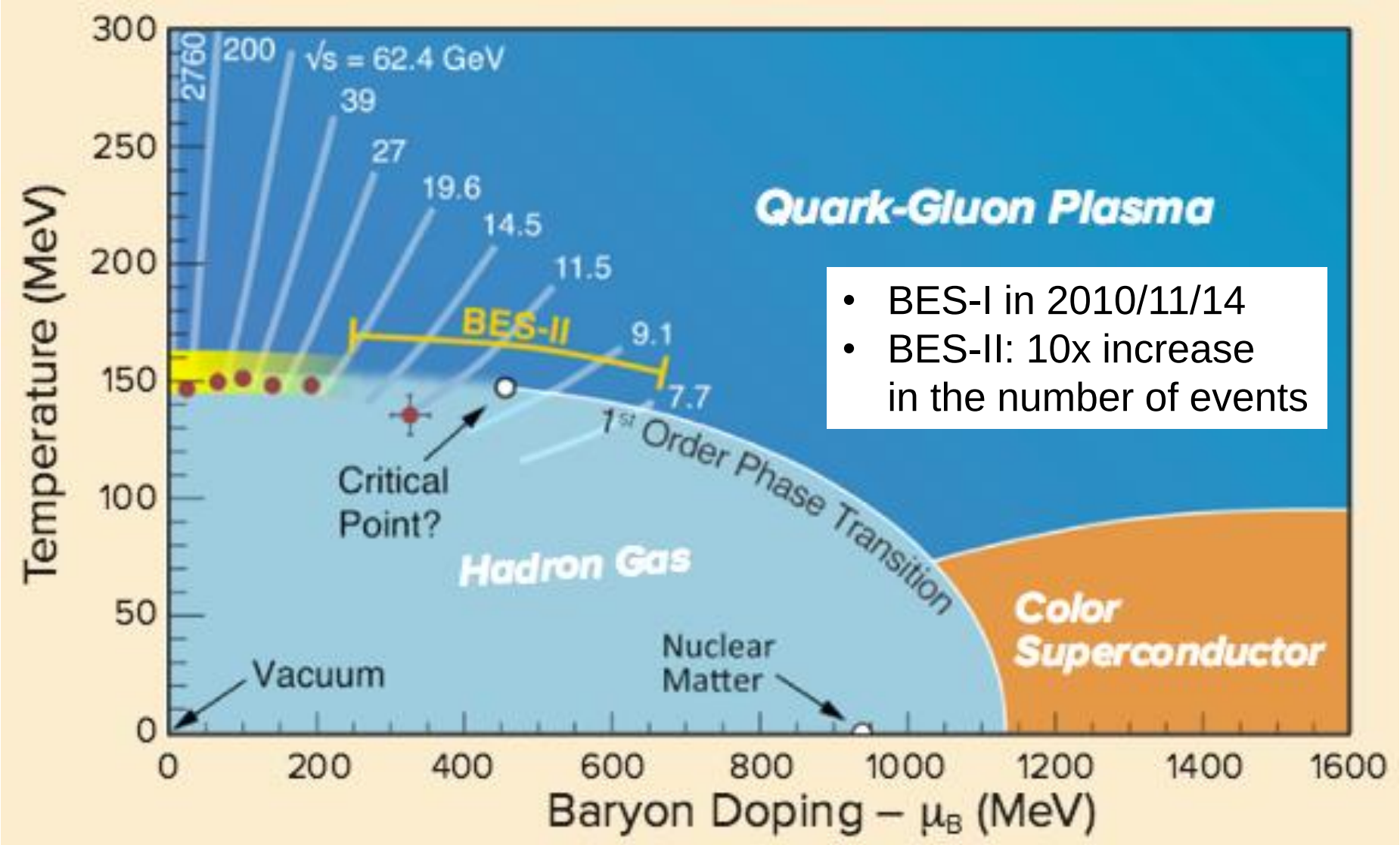
- ***Forward spin run* (2022):**
  - 500 GeV p+p (enhanced by forward upgrades of STAR)
  - Spin physics measurements complementary to EIC

- ***Runs with sPHENIX* (2023-25):**
  - Full energy ($\sqrt{s_{NN}}$ = 200 GeV) Au+Au, p+p, p+Au
  - STAR taking "legacy data" with iTPC, forward detectors in 2023-24
  - Precision measurements of fully resolved jets, Upsilon states, heavy flavor

RHIC Performance in Run-21

Beam Energy Scan (BES)-II

From 2020 C-AD MAC (W. Fischer)



- BES-I in 2010/11/14
- BES-II: 10x increase in the number of events

From 2015 NSAC Long Range Plan for Nuclear Science

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Beam Energy Scan II: Run-18 through Run-20

From 2020 C-AD MAC (W. Fischer)

Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
13.5	27	156	24 days	(560 M)	Run-18
9.8	19.6	206	36 days	400 M (582 M)	Run-19
7.3	14.6	262	60 days	300 M (324 M)	Run-19
5.75	11.5	316	54 days	230 M (235 M)	Run-20
4.59	9.2	373	102 days	160 M (162 M)[1]	Run-20+20b
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	7.7	420	11-20 weeks	100 M	Run-21[2]

still to be done

All BES-II goals achieved or exceeded except:
Au+Au colliding at 3.85 GeV/nucleon beam energy (=> next Run)

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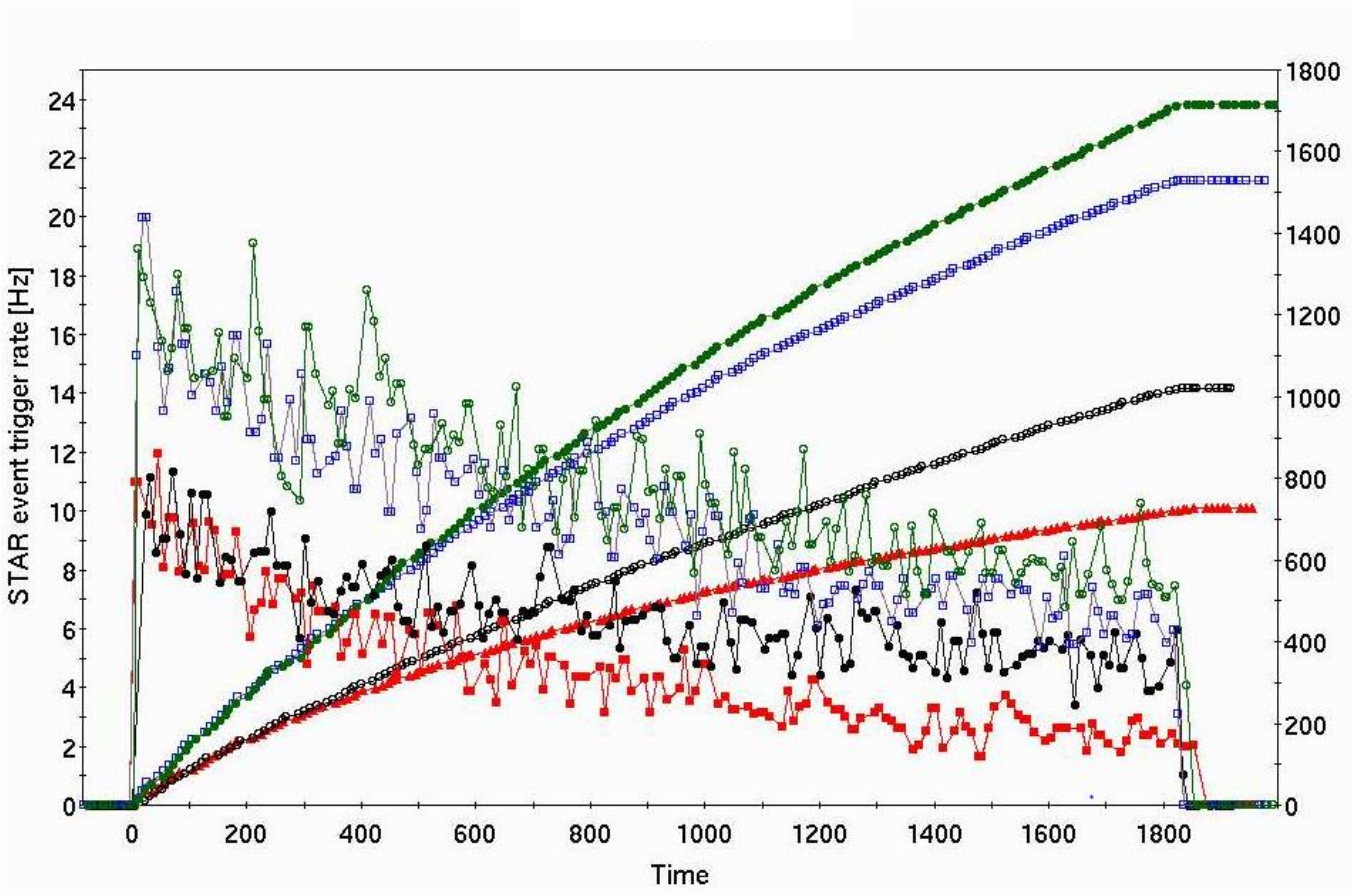
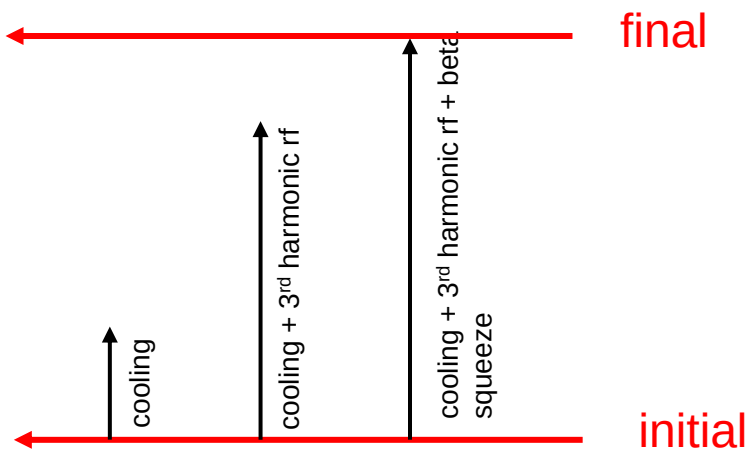
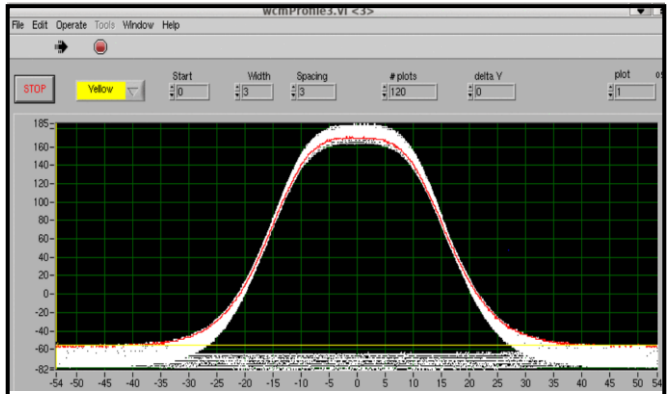
Run-20 Accelerator R&D with Electron Cooling

Au + Au at $\sqrt{s_{NN}}$ = 7.7 GeV







longitudinal ion bunch profile with higher harmonic cavities

2x gain from no cooling to all cooling + 3rd harmonic + beta-squeeze

Run-21 Overview

Run Coordinator
Chuyu Liu

priority #1 Au+Au at $\sqrt{s_{NN}}$ = 7.7 GeV

priority #2 Au+Au (FXT) at 4 energies ($\sqrt{s_{NN}}$ = 3.0, 9.2, 11.5, 13.7 GeV)

O+O at $\sqrt{s_{NN}}$ = 200 GeV

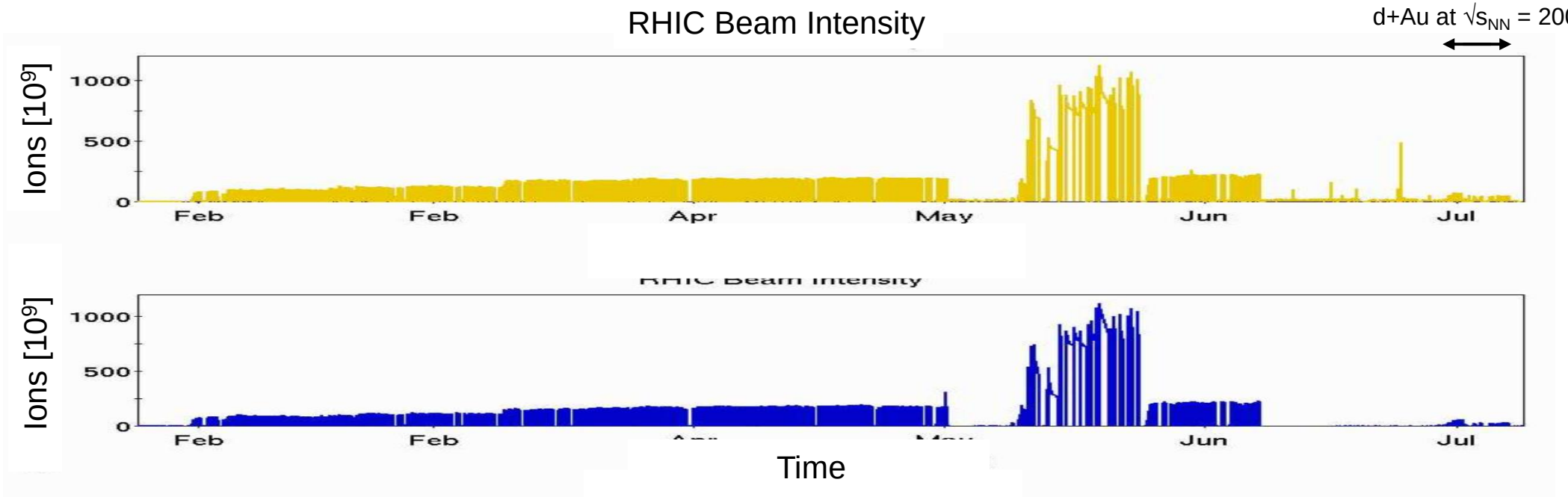
Au+Au at $\sqrt{s_{NN}}$ = 17.3 GeV

Au+Au (FXT*) at $\sqrt{s_{NN}}$ = 3.0 GeV

priority #3

d+Au at $\sqrt{s_{NN}}$ = 200 GeV

added priority (NPP PAC, 6/22-23/21)



8 different modes

- **+ interspersed operations for CeC PoP at 26.5 GeV/nucleon particle energy**
- **+ FXT* with parasitic CeC operation**
- **+ interspersed accelerator physics experiments (APEX)**

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Beam Energy Scan II: Run-21

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority
3.85	7.7	11-20 weeks	Au+Au	100 M	1
3.85	3 (FXT)	3 days	Au+Au	300 M	2
44.5	9.2 (FXT)	0.5 days	Au+Au	50 M	2
70	11.5 (FXT)	0.5 days	Au+Au	50 M	2
100	13.7 (FXT)	0.5 days	Au+Au	50 M	2
100	200	1 week	O+O	400 M 200 M (central)	3
8.65	17.3	2.5 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	1.7 B	3
100	200		d+Au	100 M 100 M (central)	4

Highest priority (Au + Au at $\sqrt{s_{NN}}$ = 7.7 GeV) completed in 13 weeks

All Run-21 Run priorities and event goals + additional d+Au run achieved

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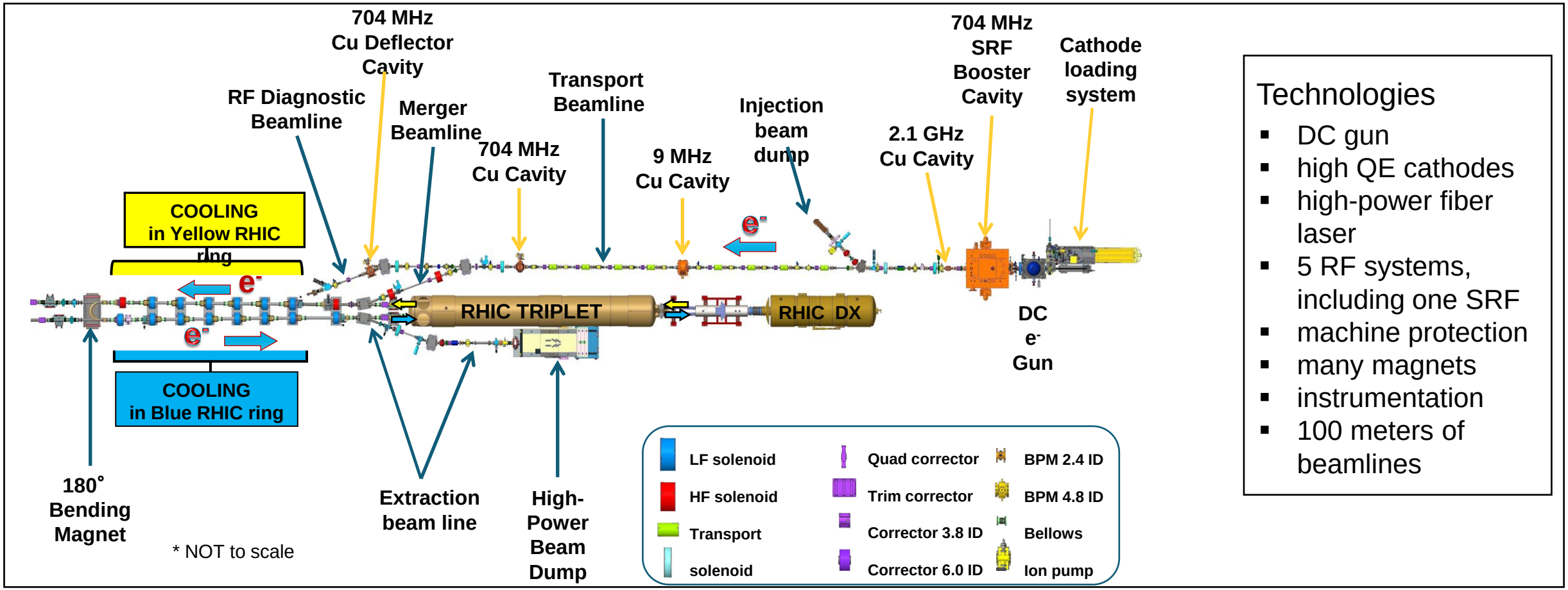
Low Energy RHIC electron Cooling (LEReC)

Principle Investigator
Alexei Fedotov



Technologies

- DC gun
- high QE cathodes
- high-power fiber laser
- 5 RF systems, including one SRF
- machine protection
- many magnets
- instrumentation
- 100 meters of beamlines

A. Fedotov et al, *Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches*, Physical Review Letters **124**, 084801 (Feb 2020).

First operational electron cooling in a collider (Run-20)
Critical for lowest-energy RHIC program in Run-21

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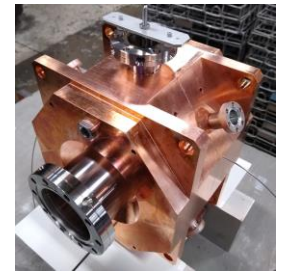
Highlights from Run-21 BES-II program with LEReC

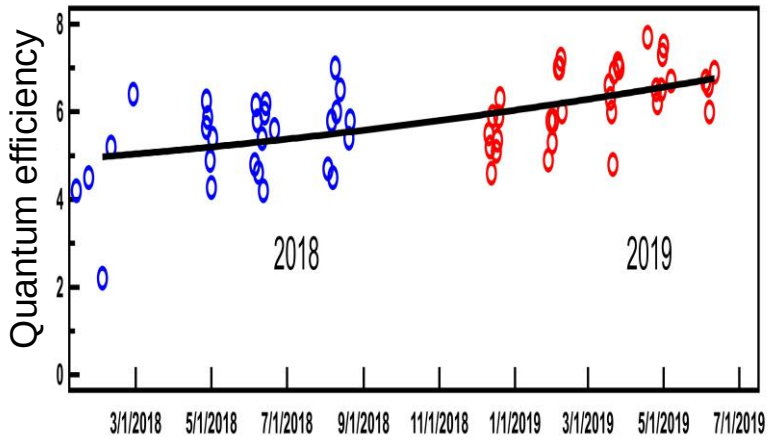
Run Coordinator
Chuyu Liu

- All performance goals attained. Additional operational improvements implemented:
  - New LEReC 1.4 GHz cavity and new RHIC bunch-by-bunch dampers
  - Feedback-based beam control for electron orbits in cooling sections, electron beam energy, electron beam intensity and laser position feedback.
  - Utilization of existing 3rd harmonic (28 MHz) cavity in RHIC to reduce ion beam peak current
  - Optimization of electron beam currents based on operational experience
    - 15-20 mA (for Au ions at 4.6 GeV/n in 2020)
    - 8-20 mA (for Au ions at 3.85 GeV/n in 2021)

1.4 GHz cavity



- Select demonstrated additional technological advances:
  - Robust photocathodes with high initial Quantum Efficiency
  - Photocathode lifetimes of 6-10 days
  - Stable and reliable operation of high-power fiber laser for photoelectron gun



Efficiently and reliably operated LEReC with high-current electron beams and stable cooling at lowest-ever RHIC beam operating energy (3.85 GeV/n) in Run-21

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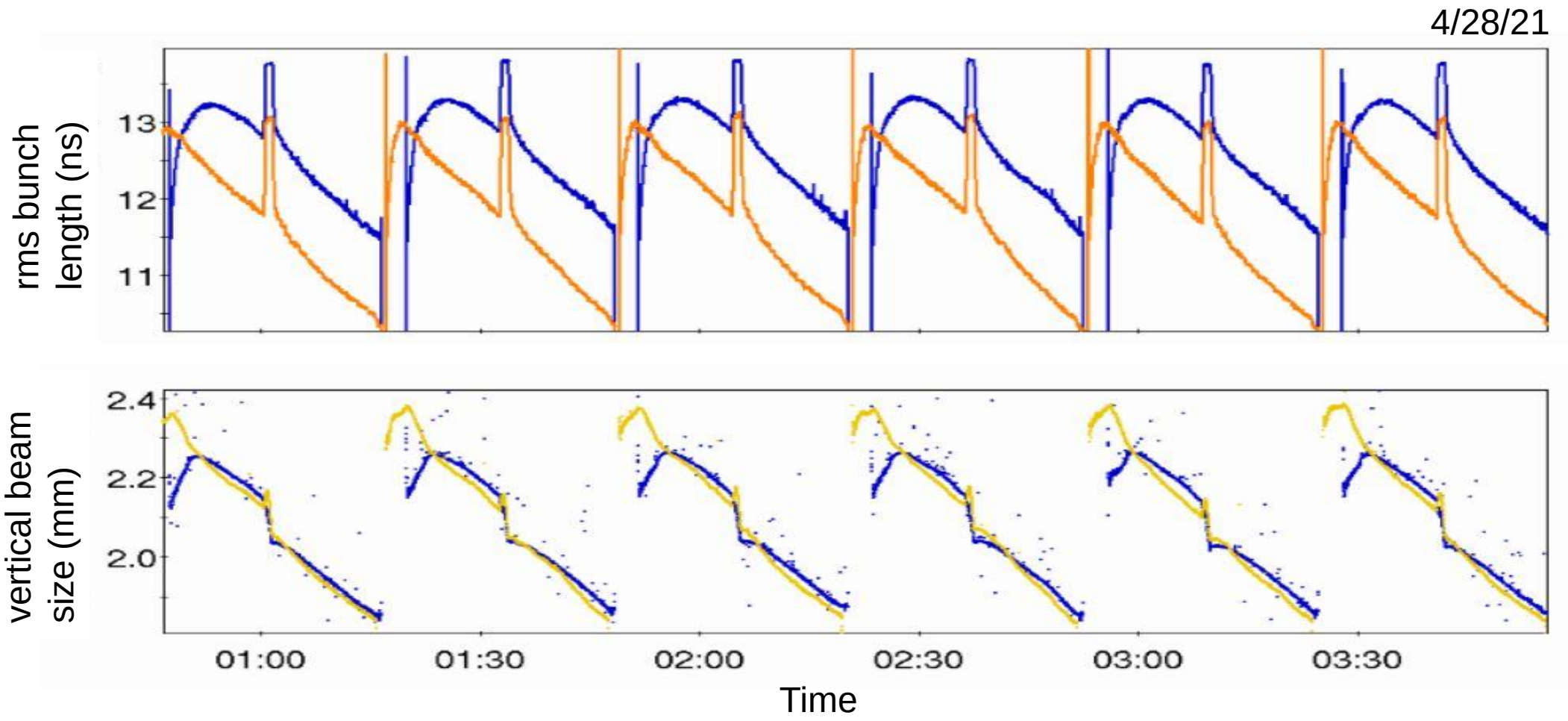
Typical cooling performance in Run-21 at 3.85 GeV/n



Stable and efficient operation of LEReC, with simultaneous cooling of ions for BES-II at $\sqrt{s_{NN}}$ = 9.2 GeV

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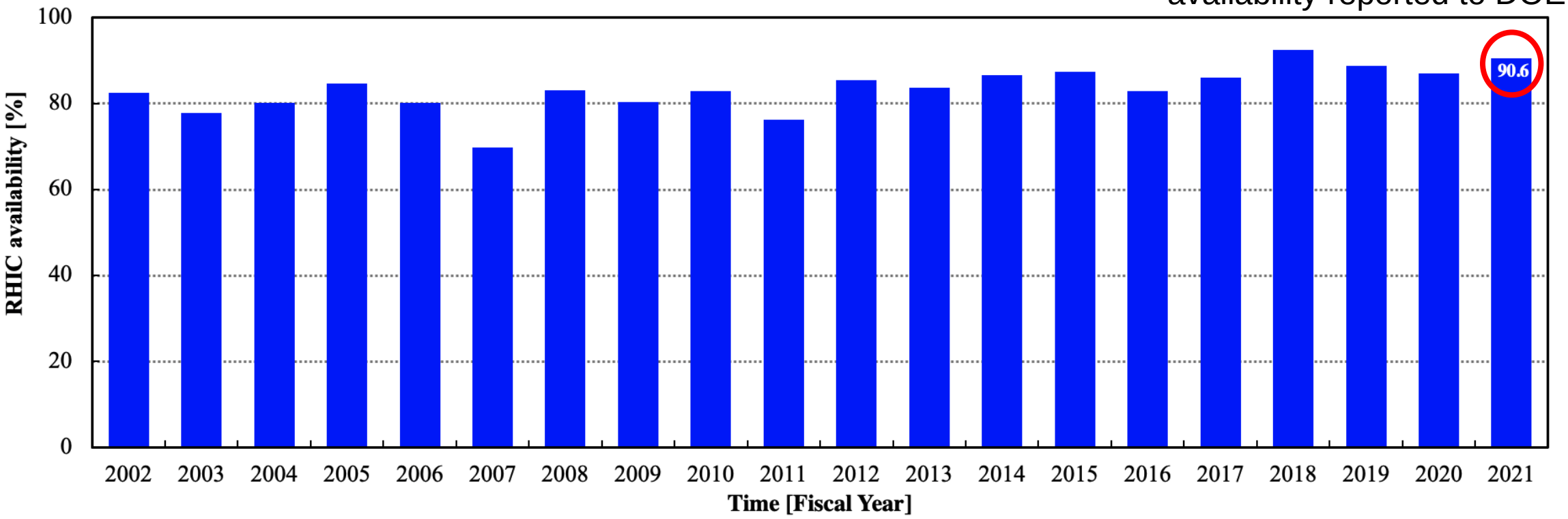
RHIC Operational Efficiency – 2002 to 2021

availability reported to DOE



Availability = beam time / scheduled beam time

(denominator excludes scheduled maintenance)

Availability goal: 85% (raised in Run-20, from 82.5%)

Achieved 90.6% availability in Run-21

Met availability goal for past 10 consecutive years

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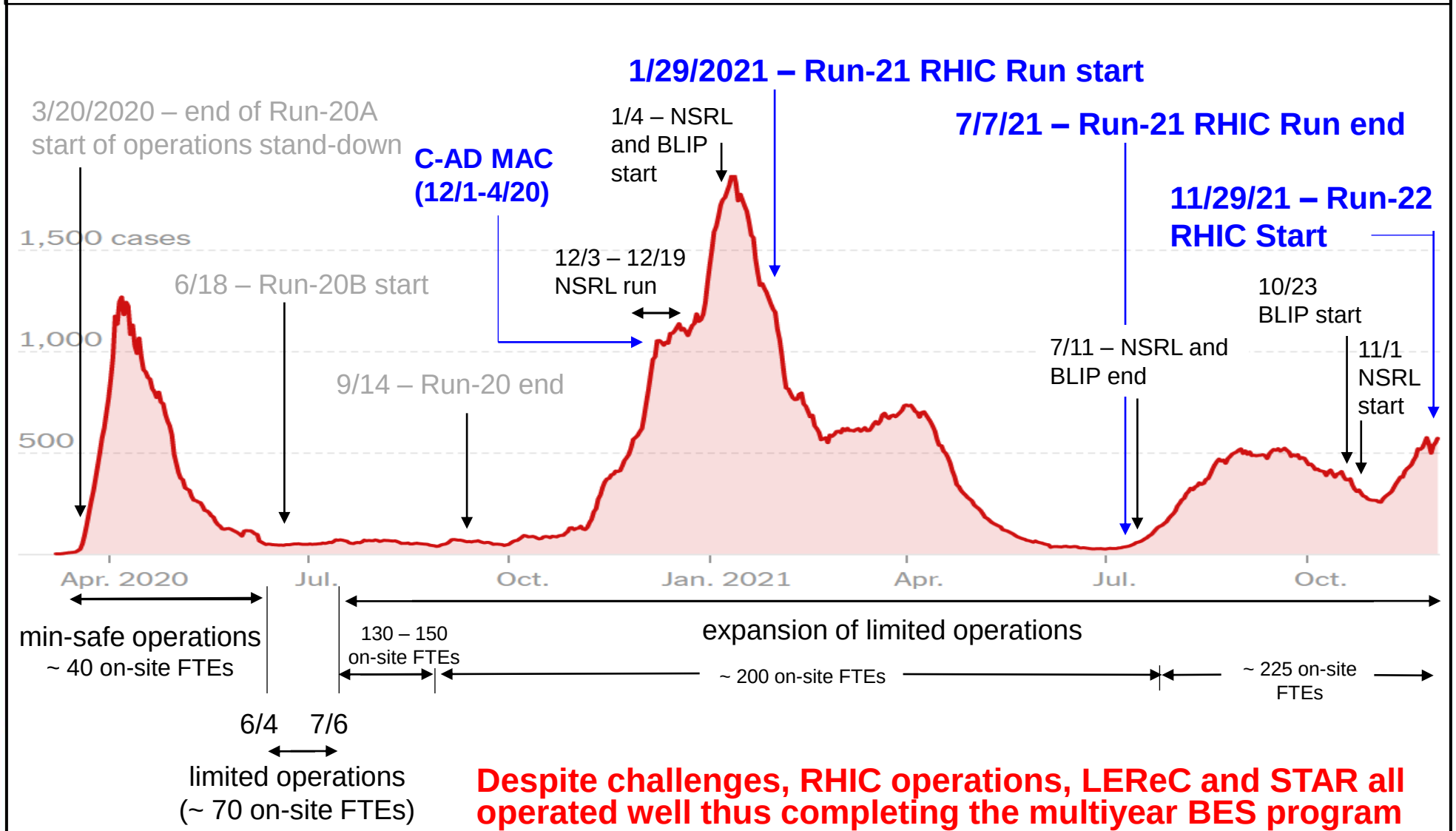
RHIC Operation during the COVID Pandemic

New reported cases by day in New York (from New York Times, 1 Dec 2021)



Despite challenges, RHIC operations, LEReC and STAR all operated well thus completing the multiyear BES program

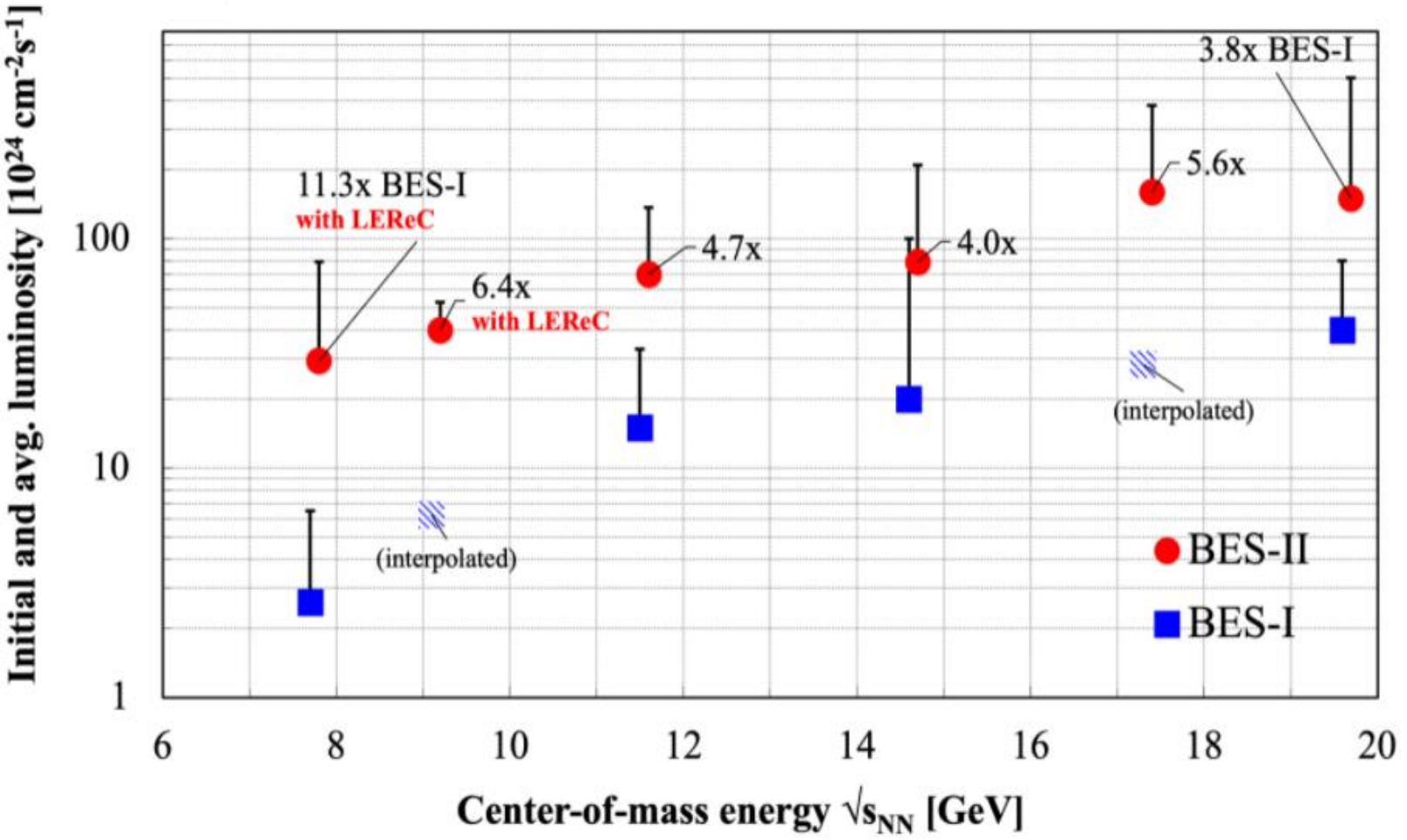
Challenges (Run-21)

- Reduced workforce due to illness and quarantines
- Supply chain delays
- New methods of communications with MCR
- Occasional delayed response time to operational issues
- Possible employee “burn-out” – 18+ months of “state of emergency” response

Successes

- Call-ins: no differences from pre-COVID levels
- Remote operations: adapted well
- Maintained high accelerator availability

BES-I vs BES-II luminosity



Run Coordinators:
- T. Satogata (Run-7, Run-8)
- K. Brown, A. Drees, G. Marr, T. Satogata (Run-10)
- G. Marr (Run-11)
- C. Montag (Run-12)
- G. Robert-Demolaize (Run-14)
- C. Liu (Run-19, Run-20, Run21)

Goal:
L_{avg} (BES-II) / L_{avg} (BES-I) = 4

Met all luminosity goals and demonstrated luminosity ratios of

3.8	Run-19
4.0	Run-19
4.7	Run-20
6.4 (with LEReC)	Run-20
5.6	Run-21
11.3 (with LEReC)	Run-21

Run-21 with $\sqrt{s_{NN}}$ = 7.7 GeV: L_{avg} (BES-II) = 11.3 x L_{avg} (BES-I)

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Status and Plans for RHIC Run-22

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Preparation for RHIC Run-22

Run Coordinator: Vincent Schoefer

Planned Operating Modes

- p↑ + p↑ at 255 GeV/n – Physics requirements same as Run-17 Run
- Au at 26.5 GeV/n for CeC-X (16 days)
- Accelerator Physics Experiments (APEX) for EIC
  - Au at 3.85 GeV/n for LEReC-based cooling experiments
  - ^{3}He at 100 GeV/n for polarimetry development

	Start of store	
Intensity (/bunch)	2 x 10^{11}	
Emittance (trans,norm)	2.5	um,rms
Luminosity	14×10^{31}	$cm^{-2}s^{-1}$
Polarization (avg, Jet)	55%	
Bunch length (rms)	3	ns

Changes for Run-22 RHIC Run (slides to follow)

- Ion source upgrades
- H- jet polarimeter upgrade
- RHIC Machine Protection System (MPS) upgrade
- Operational improvement plans

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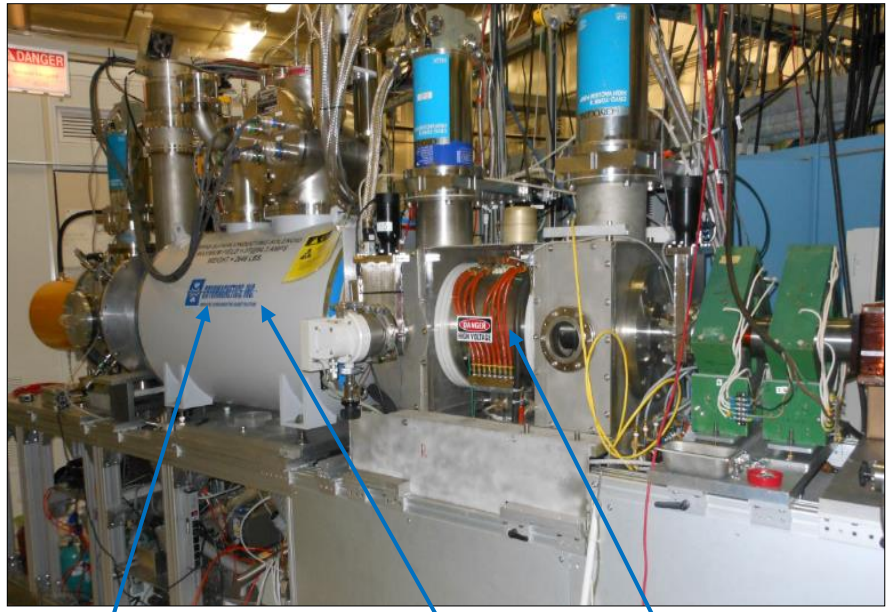
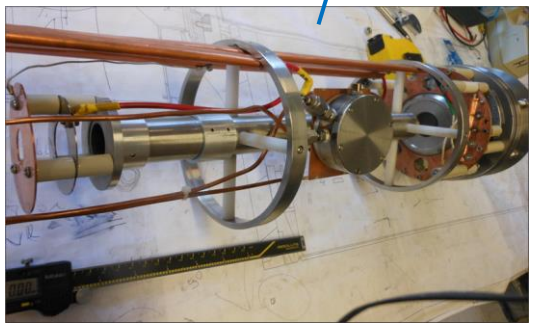
Changes for RHIC Run-22 (1 of 4) - Ion Source upgrades

Optically Pumped Polarized Ion Source (OPPIS)

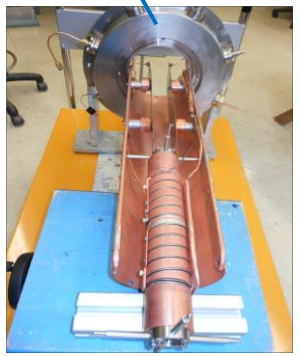
- OPPIS last run in June 2017
- January - May 2021: OPPIS Source refurbished and operated for AGS
- For Run-22: OPPIS upgrades to H-ionizer cell, optically pumped Rb-vapor cell, and Na-jet ionizer cell completed

Recently demonstrated 80% polarization at 200 MeV

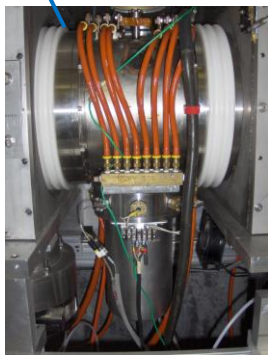




He-ionizer cell

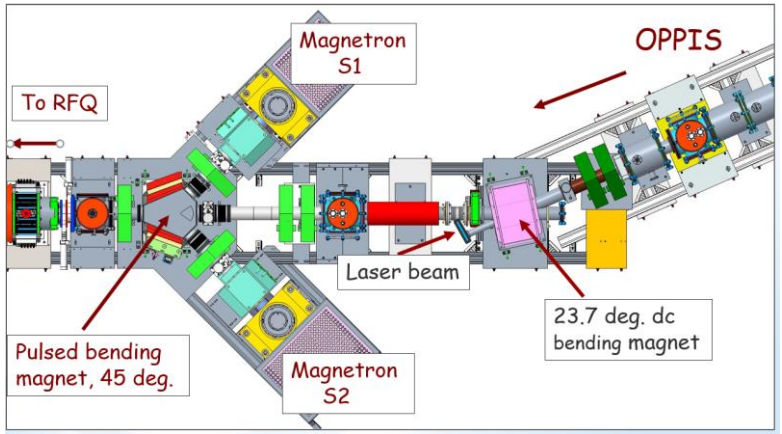


Rb-cell



Na-jet ionizer cell

LEBT upgrade - added second high-intensity source in Run-21



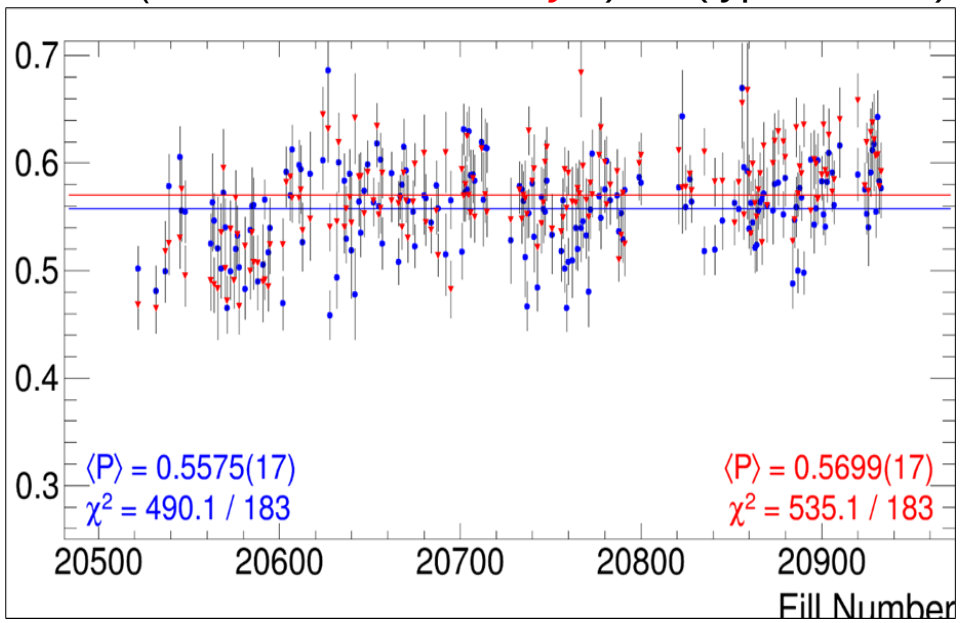
Achieved 225 mA proton beam current (>10% improvement)

Changes for RHIC Run-22 (2 of 4) - H- jet polarimeter

High accuracy absolute polarization measurements
A.A. Poblaguev, A. Zelenski et al, Nucl. Instr. and Meth.,
In Phys. Res., A 976 (2020) 164261

From Run-17

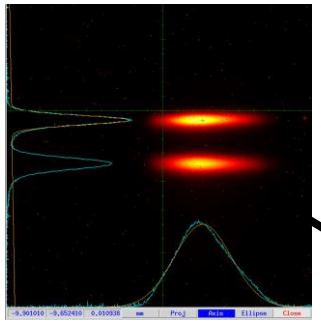
‹ P › = (~ 56 ± 2.0 *stat* ± 0.3*syst*) % (typical store)

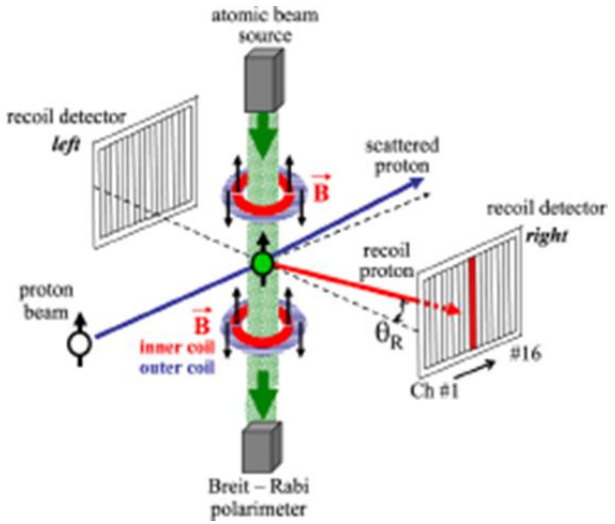


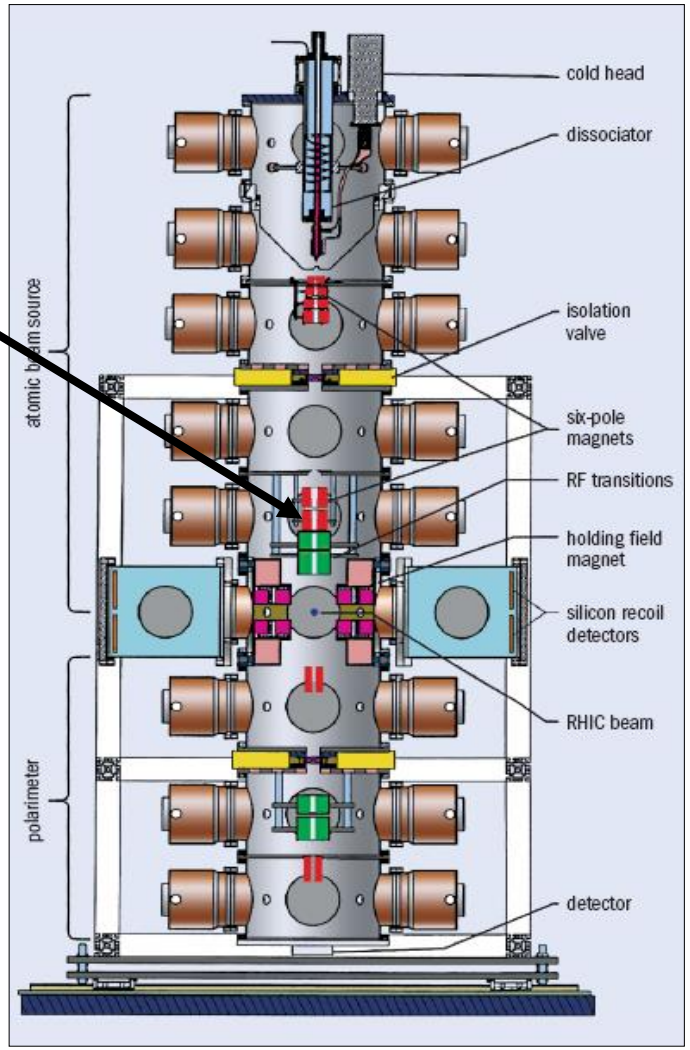
Run-22 Upgrades

- turbo-molecular pumps power supplies
- detectors and pre-amplifiers
- control and interlocks

High time-resolution beam profile monitor for LEReC

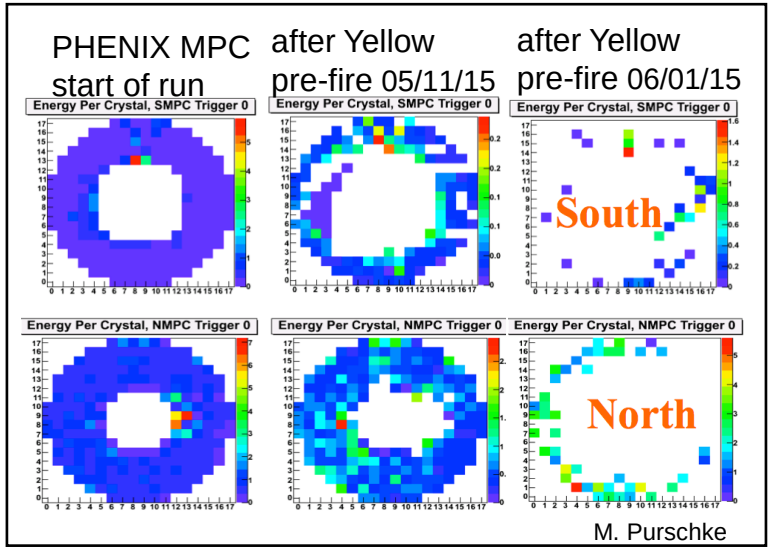


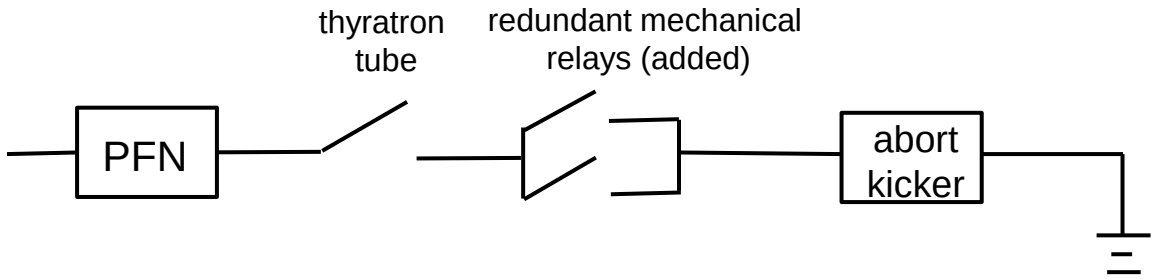




Changes for RHIC Run-22 (3 of 4)
RHIC Machine Protection System (MPS)

- **Motivation**: protect sPHENIX and RHIC SC magnets
- **Issue**: RHIC abort system thyratrons occasionally fire spontaneously and asynchronously causing ~10 bunches to miss the RHIC beam dump
- **Solution**: add mechanical relays in series (installed in 2020) and
  - compensate for the added time delay of 6ms (=460 turns)
  - include additional inputs to the existing MPS (BLMs, BPMs, RF, corrector PS)



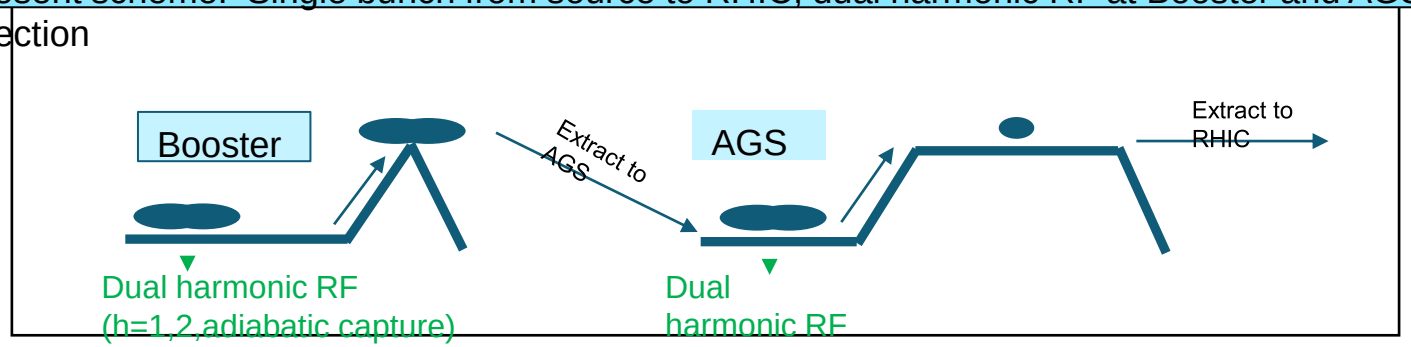


More details in Mattheiu Valette's presentation 'Operation with sPHENIX'

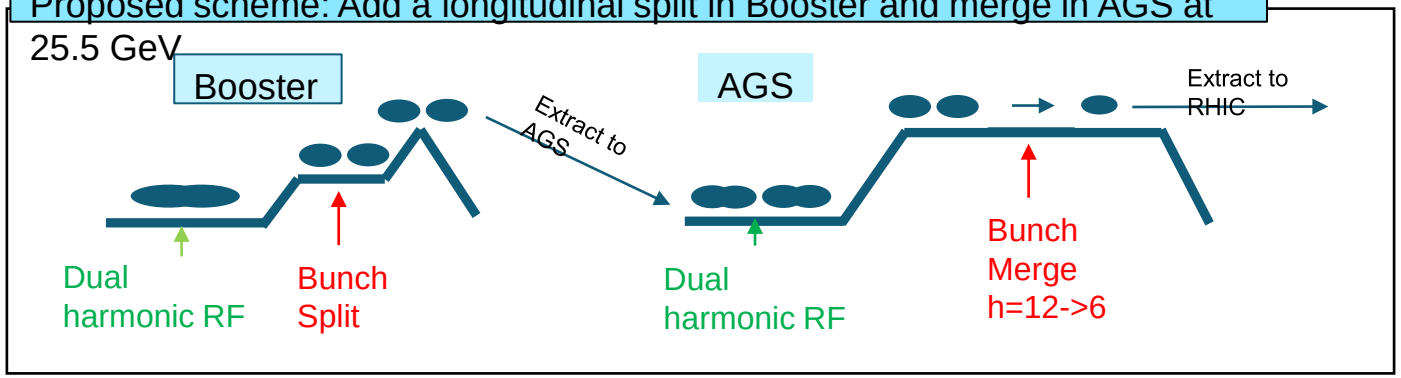
Changes for RHIC Run-22 (4 of 4) – Improvement Plans

New bunch split and merge scheme in the injector to reduce peak current (and hence emittance) at AGS injection

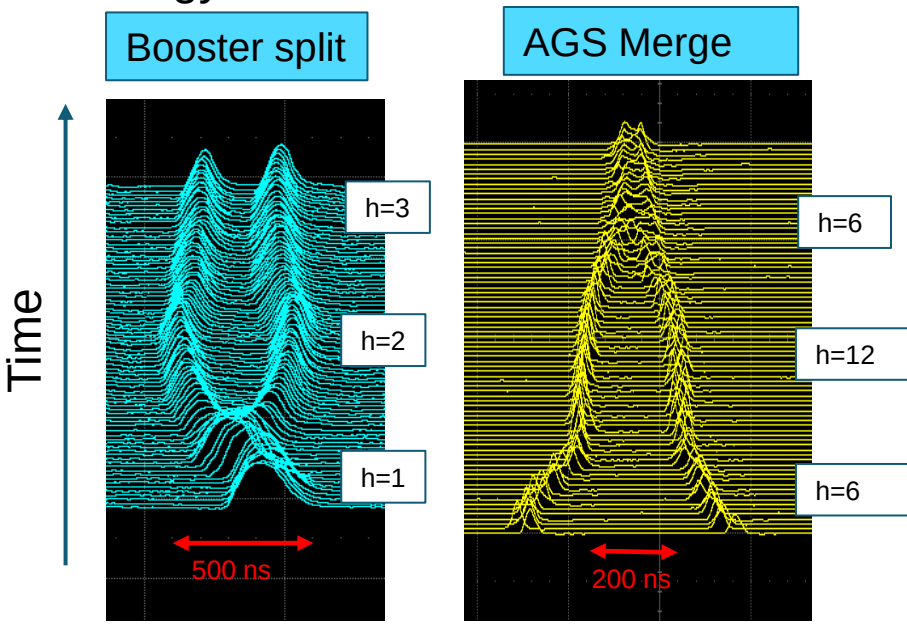
Present scheme: Single bunch from source to RHIC, dual harmonic RF at Booster and AGS injection



Proposed scheme: Add a longitudinal split in Booster and merge in AGS at 25.5 GeV



RF gymnastics tested in Jan 2021



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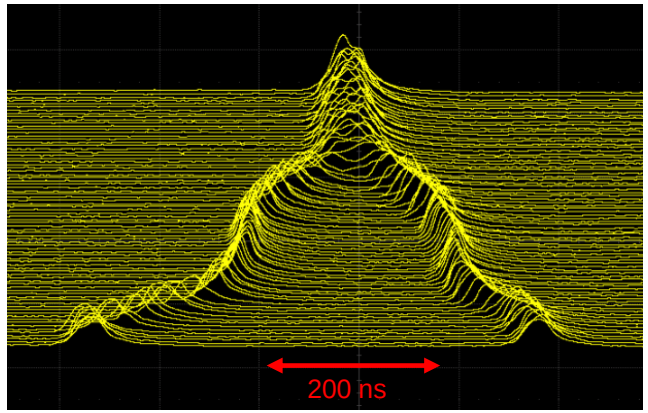

Potential improvements:

~ 20% reduction in transverse emittance

~10% increase in relative polarization

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Run-22 RHIC Startup [1]

Unusual events

- AGS partial snake magnet, short to ground (Sept)
- Booster vacuum bakeout (Sept)
- AGS cable tray collapse (Oct)
- AGS dipole coils replacement (Nov)
- RHIC Yellow Ring vacuum leak (Nov)
- RHIC cryo controls upgrade (Nov) → 2 week delay in RHIC setup
- Increase in safety-related reportable events (details in backup slides)

Status

- Cool-down of RHIC started Nov 15, as planned.
- In parallel, work to minimize impact on Run-22 programs
  - Development of new bunch split-and-merge schemes in the injectors
  - Electron beam commissioning for CeC (a primary Run-22 program)
  - Next-in-priority LEReC setup for EIC-related accelerator physics studies
- Final RHIC cool-down to 4K started Nov 29
- Injector (LINAC, Booster, and AGS) setup completed
- RHIC beam setup underway

Run-22 RHIC Startup [2]

Objectives

- p↑ + p↑ at 255 GeV/n for STAR
  - 400 pb^{-1} sampled luminosity (~16 weeks estimated in STAR beam use proposal)
  - Figure of merit, LP^2 = 120 pb^{-1} with <P> = 55%
- CeC-X
  - 16 days
- Accelerator Physics Experiments
  - ~ 5 days (tbd)

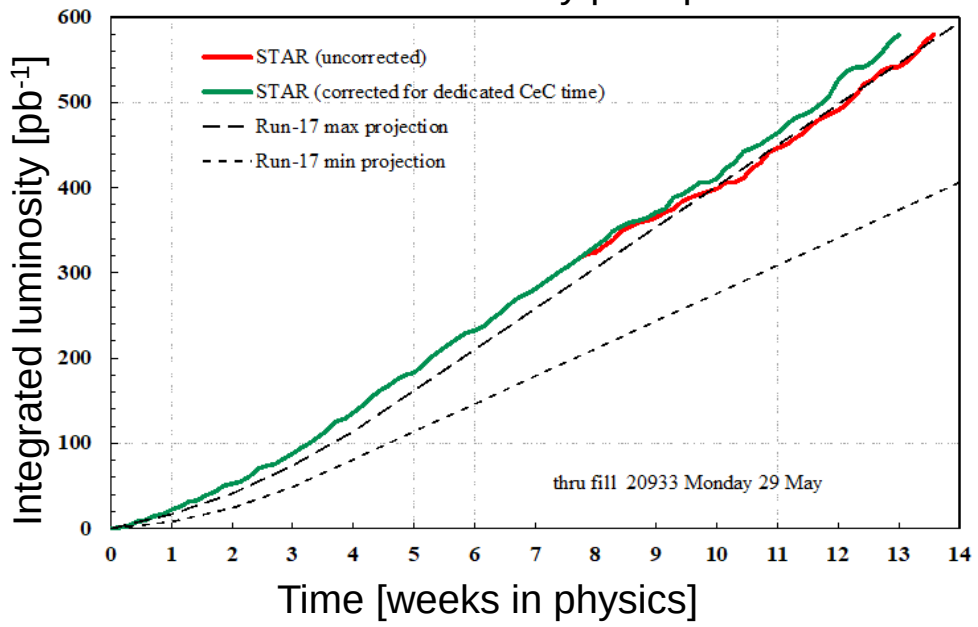
Challenges

- last high energy polarized proton operation in Run-17
- delayed start (2 weeks)
- tight shutdown schedule (before Run-23)

Mitigation plans

- quickly restore good operating conditions from Run-17
- leverage performance improvements for increased polarization

RHIC Run-17 delivered luminosity p↑ + p↑ at 255 GeV/n



Run-22 end date fixed for now with contingency planning underway

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Planning through end of RHIC operations / start of EIC installations (in 2025)

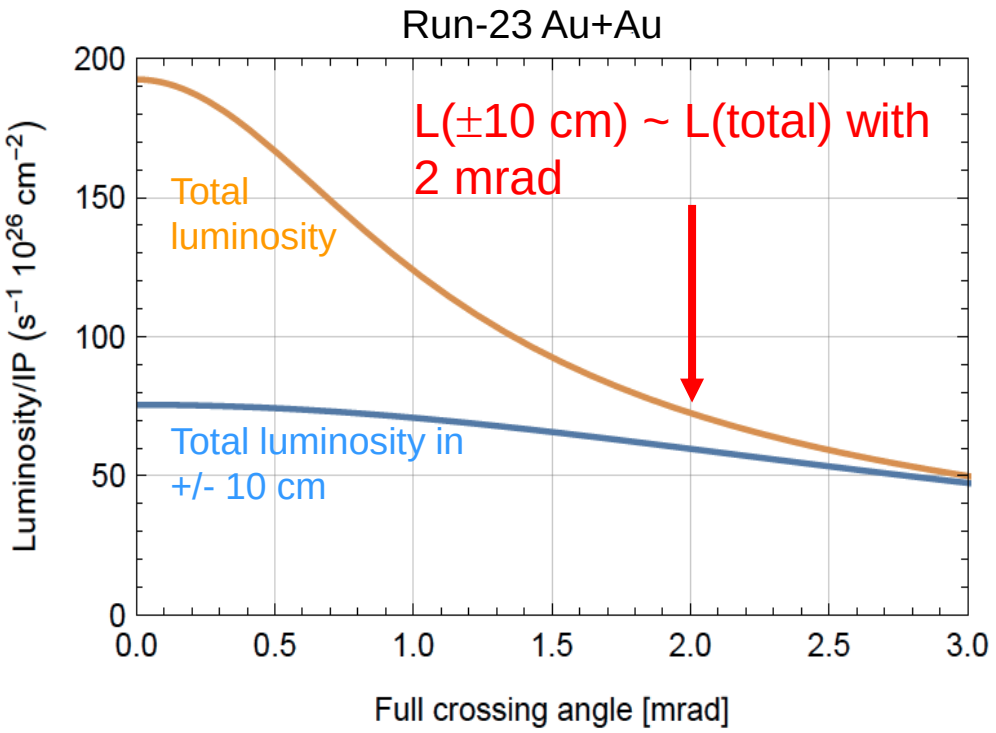
Run-23 through Run-25 with sPHENIX and STAR

Planned Operating Modes – all with 100 GeV/n beams

- Run-23 RHIC Run: Au + Au
- Run-24 RHIC Run: p↑ + p↑, p↑ + Au
- Run-25 RHIC Run: Au + Au

Maximizing useful luminosity with sPHENIX

- Use of 56 MHz SRF cavity (for increased longitudinal focusing)
- Small vertex (+/- 10 cm) via 2 mrad crossing angle
- Use of upgraded machine/experimental protection system (abort kicker relays+ faster detection of anomalies)
- New power supplies in IR8 for larger operating margin / smaller β^*)



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Run-23 to Run-25 with sPHENIX and STAR

From 2020 C-AD MAC (W. Fischer)

Table 1: Summary of the sPHENIX Beam Use Proposal for years 2023–2025, as requested in the charge. The values correspond to 24 cryo-week scenarios, while those in parentheses correspond to 28 cryo-week scenarios. The 10%-*str* values correspond to the modest streaming readout upgrade of the tracking detectors. Full details are provided in Chapter 4.

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

<= sPHENIX request

will have to move DX magnets during Run-24 (~1 week)

Table 4: Proposed Run-23 - Run-25 assuming 24 (28) cryo-weeks of running every year, and 6 weeks set-up time to switch species in 2024. Sampled luminosities assume a "take all" triggers.

STAR request =>

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Date
200	Au+Au	10B / 38 nb^{-1}	2023
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024
200	Au+Au	10B / 52 nb^{-1}	2025

25+ year technical infrastructure upgrade plan

Manager:
Rob Michnoff

Developed in 2018 for RHIC, the injector complex and possible EIC
Assessed annually based on need for

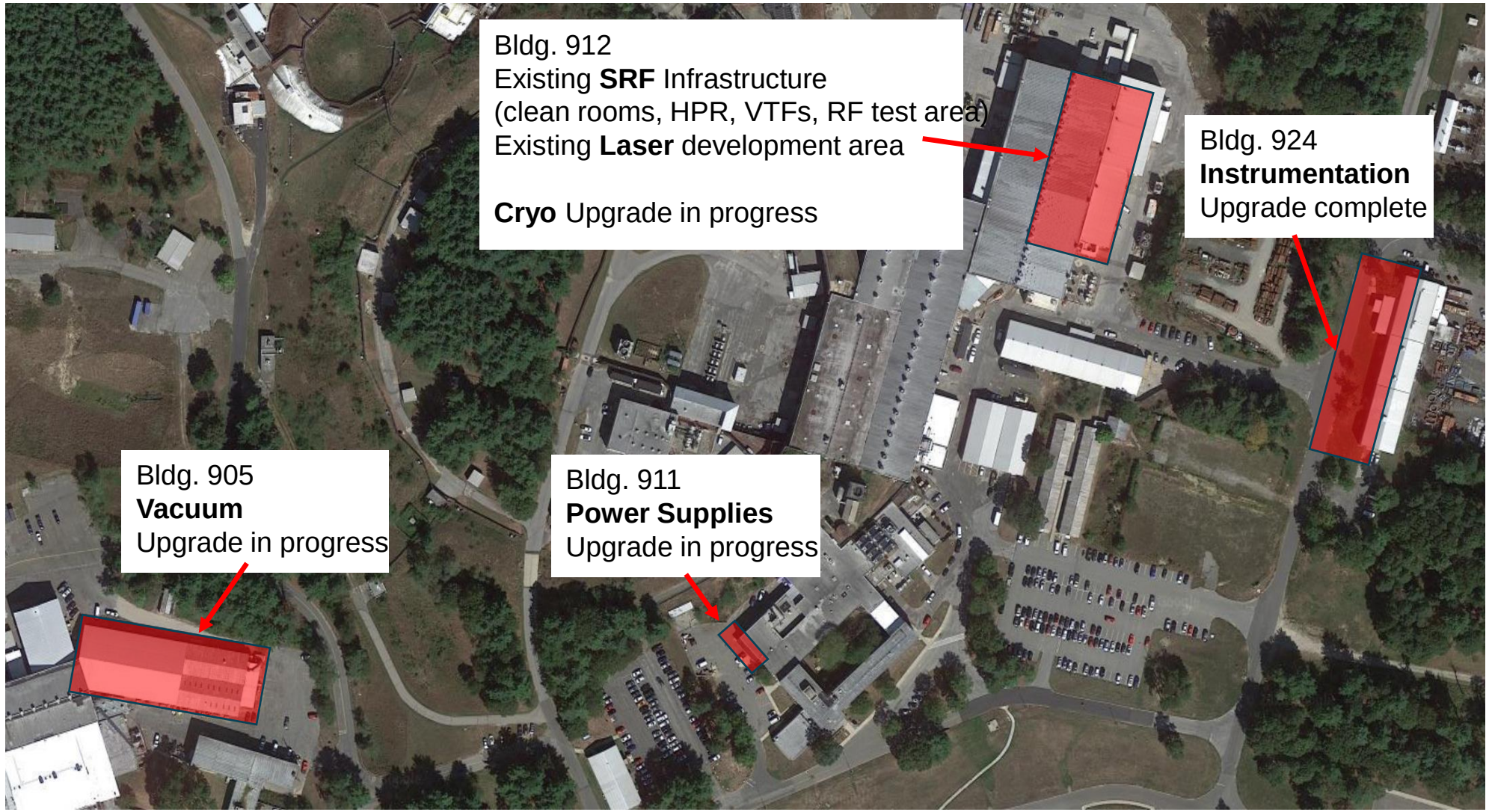
- performance upgrades
- upgrades of obsolete systems

Assumes no further large performance upgrades of RHIC until end of RHIC operations

Upgrade Plan Goals

- Maintain technical infrastructure
- Ensure hadron injector complex ready for EIC commissioning while also running for external users (e.g. NSRL and BLIP), possibly HEET
- Ensure that system upgrades satisfy both short-term injector and RHIC needs as well as longer-term EIC requirements
- Develop a 4-year upgrade plan to allow new systems to be tested prior to the end of RHIC beam operations (mid-2025)

Technical infrastructure Upgrades that will support the EIC



Work support by off-EIC-project funding, by BNL Modernization Project Office, and the BNL Facilities and Operations Directorate (F&O)

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Responses to recommendations from C-AD MAC 2020

Responses to recommendations from C-AD MAC 2020

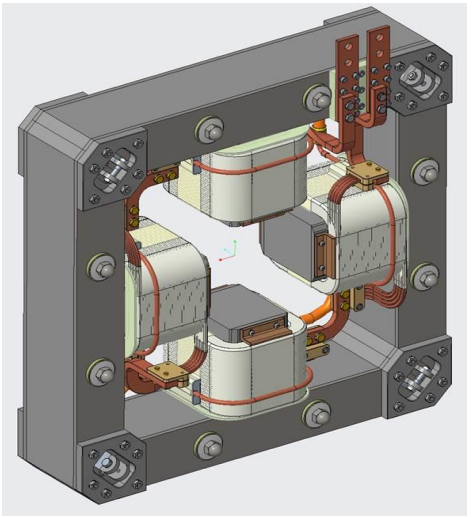
R1: Continue optimization of the skew quad scheme, aiming for reduction of power.

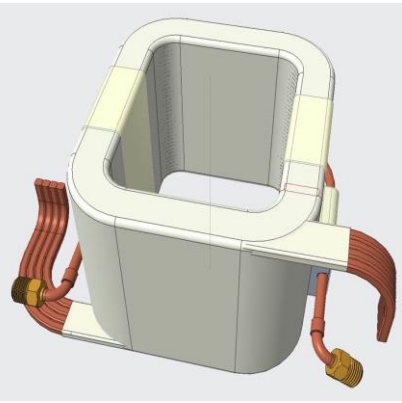
Dec. 2020

Pulsed system parameters		Unit
Int. gradient (max)	0.45	T
Current (max)	500	A
Voltage (max)	400	V
Power (peak, 15 magnets)	2-3	MW

July, 2021

Pulsed system parameters		Unit
Int. gradient (max)	0.2	T
Current (max)	275	A
Voltage (max)	450	V
Power (peak, 15 magnets)	1.8	MW





Status

- Finished power supply and magnet design
- Power supply procurement underway (July, 2021)
- Magnet procurement starting
- Plan for commissioning in Run-23

R2: Carry on planned tests of the split/merge scheme. In progress (slide 22)

Summary: Accelerator Operations

Summary – RHIC Performance Update

Run-21 Run – extraordinarily successful

- Completed the multi-year BES scan program.
- Highest priority Run-21 goal for BES-II achieved with LEReC in 13 weeks.
- Met all next-priority STAR goals including an additional d+Au run (8 modes + beam delivery for CeC).
- Achieved 90.6% accelerator availability.
- Missions achieved with limited on-site staff and full off-site coverage during the COVID pandemic.

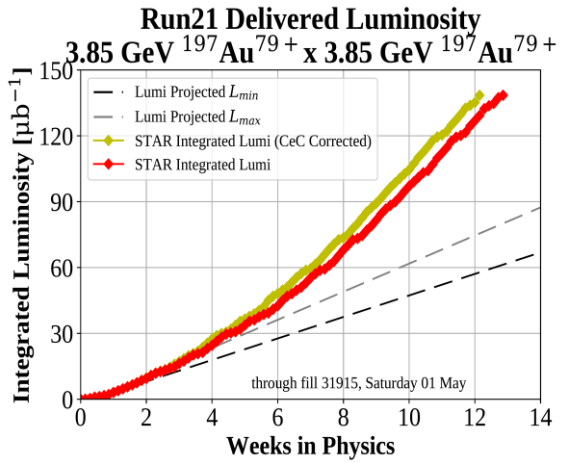
Run-22 RHIC Run – very challenging

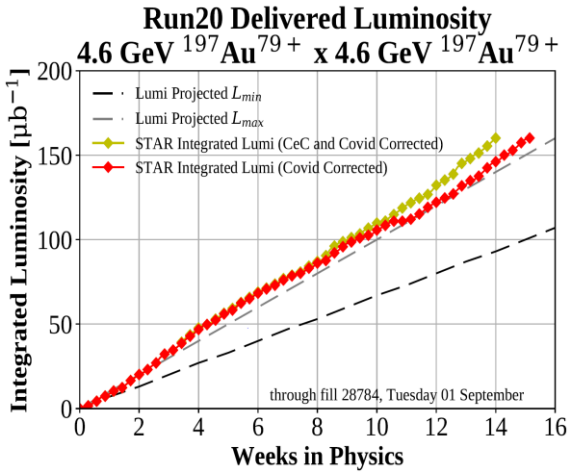
- Resuming polarized proton operation at full energy (last operated in Run-17).
- Since Run-17 accelerator availability goal raised to 85%.
- Multi-faceted RHIC MPS upgrade to be fully implemented.
- Operational improvements targeted on increased polarization in the injectors underway.

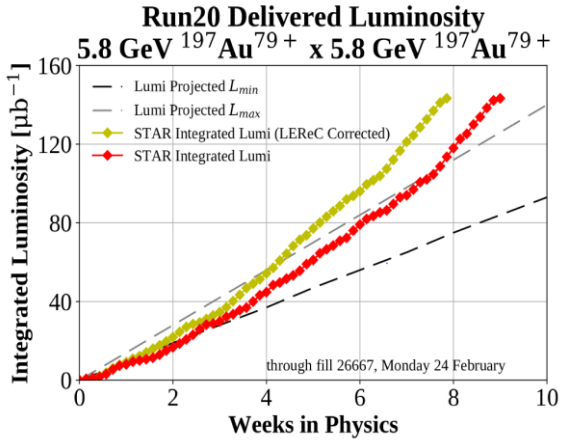
Planning for Run-23 through Run-25 with both sPHENIX and STAR underway

25+ year technical infrastructure upgrade plan

- Many technical infrastructure upgrades completed and/or underway.
- Goal is to have hadron injector complex ready for EIC commissioning while maintaining operation for external user facilities (for NASA, Isotope production, maybe HEET).







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Reference Slides

Excerpts from C-AD MAC 17 Report (Dec, 2020)

RHIC Performance Update

Findings

The beam energy scan (BES-II) continued in Run-20 with covering 10 modes with Au at energies below the nominal injection energy. RHIC did not operate for ~12 weeks in the March-June time frame due to COVID-19 but came back to peak performance within a week of turn-on. Goals for beam delivery in Run 20 were met and availability was 87%, above the new goal of 85% (which is higher than the average DOE NP facility goal of 80%). Luminosity at 5.75 GeV was improved by more than a factor of 4 by using the Tandem for lower emittance beam, adding RF, increasing the intensity in the AGS, moving to a different working point, and other measures. Going to higher AGS intensity was reviewed to allow changing the limit imposed for machine protection. LEReC was commissioned and demonstrated the first operation of electron cooling in a hadron collider and led to a >50% luminosity increase at 4.6 GeV. Beam was delivered to CeC PoP. Run-21 is expected to complete the BES-II scans at lower energies, and also to include other Au-Au modes as well as O-O collisions. A successful test run has been conducted to prepare for Run-21. Run-22 will be with polarized protons. Higher polarization is being explored. Operations for sPHENIX will take place in Runs 23-25. Upgrades are in progress including a 56 MHz SRF cavity for stronger longitudinal focusing, as well as machine/experiment protection upgrade. RHIC operations will conclude after Run-25 for EIC construction.

Comments

C-AD is to be commended for meeting RHIC beam delivery goals in spite of the COVID-19 shutdown. RHIC is in a good position to be successful in Run 21. Modifications needed for Runs 23-25 for sPHENIX are underway. The RHIC schedule can accommodate the 14 days of beam study requested by the CeC team, in particular if luminosity improvements from LEReC and other measures are successful.

Recommendation:

If additional time is needed for CeC studies, efforts should be made to accommodate them.

Proton Polarization Improvements

Findings

Proton beam polarization out of the source and booster is about 84%, however down to 67-70% as coming out of AGS. The RHIC polarization is typically 55-60%. Therefore, proton polarization improvement program is primarily focused on AGS, where about 17% polarization loss is happening.

The partial snakes in AGS provide a spin tune gap for vertical tune, therefore strong resonance conditions for vertical tune can be avoided. Unfortunately for the horizontal tune there are still many resonances to cross. Tune jump is used to reduce the polarization loss to about a half (from 20% to 10%). The idea to avoid the remaining losses is to insert a set of skew quads in the lattice, that will excite coupling spin resonances cancelling the snake drive term.

It has been defined that 15 skew quads are needed, and they need to ramp up in about 1.5 ms. AGS beamline have 18cm gaps in 30 possible locations where these skew quads can be installed. The present work is focused on optimizing locations to minimize the strength of the skew quads and reducing the ramp rate. The peak power for 15 skew magnets can reach 2 MW. Zgoubi simulations with skew quads show that depolarization from horizontal resonances can be totally eliminated.

Further improvement of polarization in AGS can come from improving emittance preservation in AGS, as large space charge at injection causes emittance blowup and thus polarization loss. It is suggested to add 1 to 2 bunch split during acceleration in Booster, which will reduce the peak current in AGS. The scheme requires 2 to 1 merge at AGS extraction energy of 25 GeV, which is complicated by low synchrotron tune in

AGS. This merge therefore may take 0.5-1s, and might require lengthening of the super-cycle.

Comments

Improving proton polarization in AGS by about 10% appears possible using 15 additional skew quads. Magnet layout and fast ramping power supplies (peak power estimated 2 MW) require further optimization, to reduce the power and lengthen the needed ramp time.
Split/merge scheme can be used to reduce AGS injection space charge, resulting in 20% emittance reduction and 12% polarization improvement. The long duration of the merge in AGS needs to be addressed, possibly with re-optimization of the super-cycle.

Recommendation:

Continue optimization of the skew quad scheme, aiming for reduction of power. Carry on planned tests of the split/merge scheme.

Charge question (future R&D)

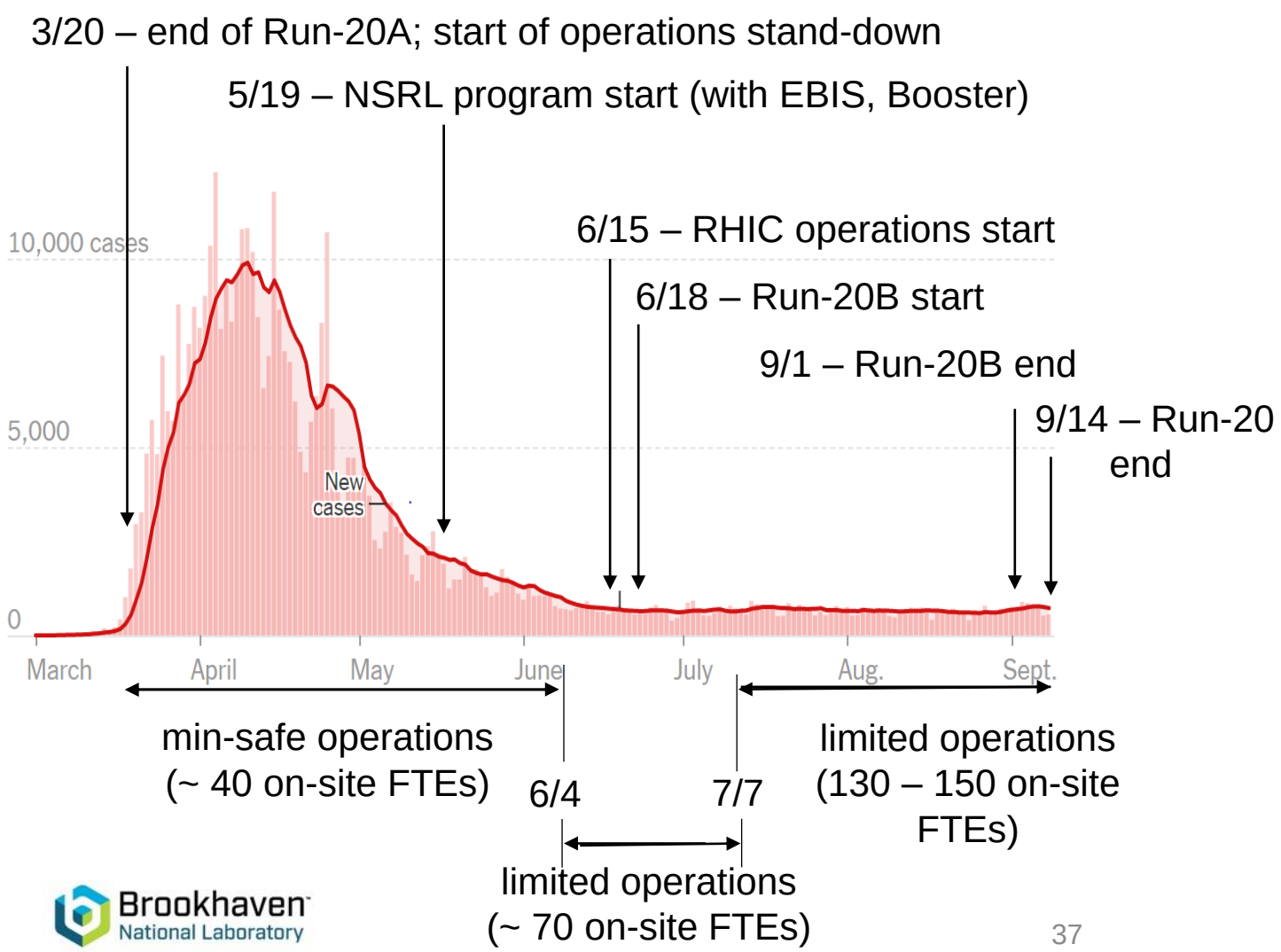
Is the accelerator R&D effort well executed and future work well planned?
Yes.

Are there any technical issues that were missed and/or need additional attention by the team?
No.

Are the technical goals realistic and is the progress appropriate to meet the stated goals?
Yes.

RHIC operation during COVID pandemic in Run-20

New reported cases by day in New York
(from New York Times, 9 Sept 2020)



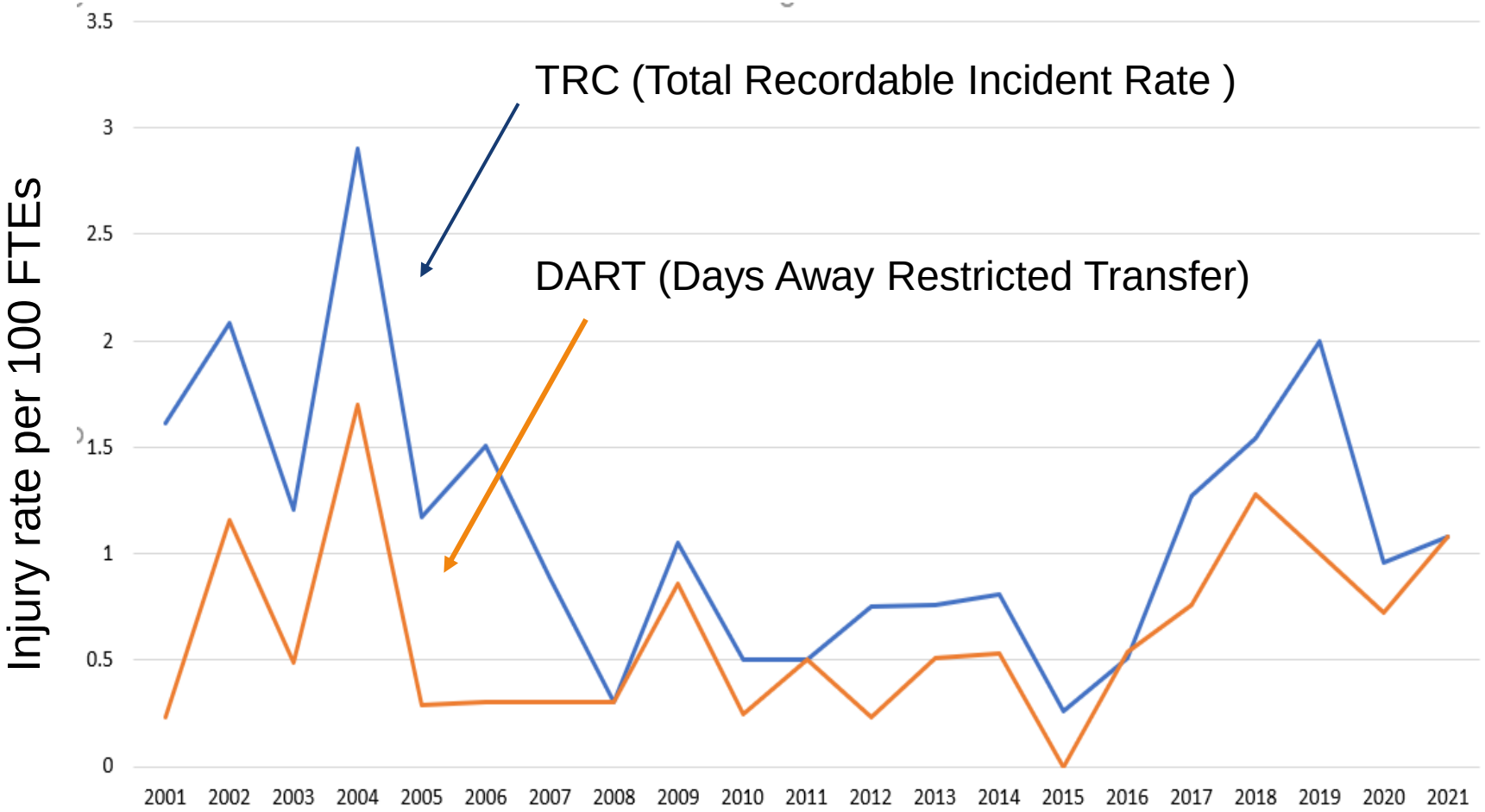
Major challenges

- Critical system maintenance during stand-down
- Startup of accelerators during min-safe
- Personnel management (including adapting to change)
- Work Planning, Enhanced Work Planning
- Coordination of new ways of doing work (to minimize time and/or staff required for a particular task, sequential scheduling of work, etc.)
- Tracking of staff and maintaining compliance
- Remote checkout, turn-on, and operation
- Procurement and management of personal protective equipment

Despite challenges, RHIC operations, LEReC and STAR resumed Run-20B at Run-20A peak performance levels within 3 days of beam operation.

Safety Statistics at C-AD

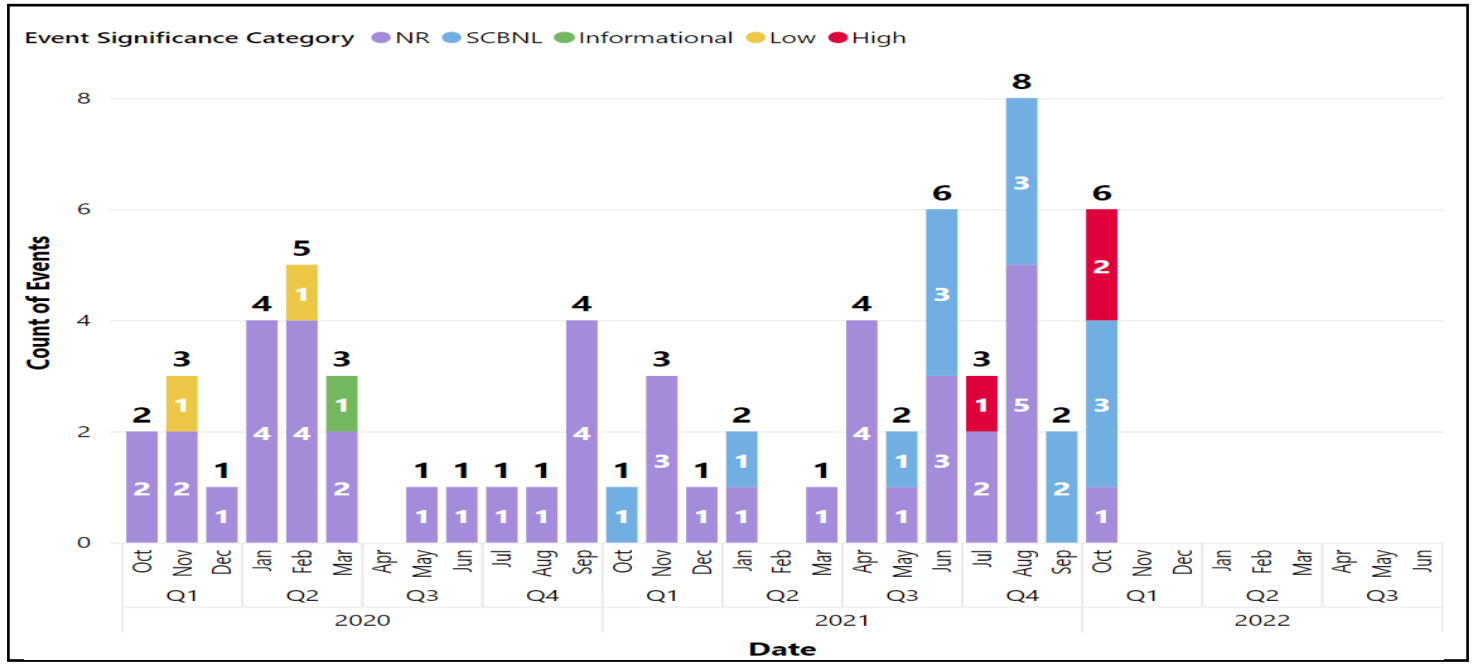
FY01-FY21



- Injury rate was overall low and sustained over many years
- Notable uptick starting in 2017
- Downturn in 2020 (attributable partially to reduced hours on site during the pandemic)

Continued vigilance necessary to achieve target of 0 TRC and 0 DART cases.
High visibility events not captured by these metrics (next slide)

Recent High Significance Events at C-AD



Increased number of events since May, 2021 including 3 high significance ORPS events

07/15/21 – two employees incur minor electrical shock when touching equipment
investigation (7/15/21 - 9/21/21)
independent safety culture review (9/20/21 – 9/24/21)

10/06/21 – employee receives electric shock from exposed wires
investigation (10/6/21, ongoing)

10/21/21 – employees receive electrical shock during Dewar transfer
investigation (10/21/21, ongoing)
all-day safety standdown, 10/22/21
emphasis: safety as highest priority (over schedule)
timely reporting and categorization

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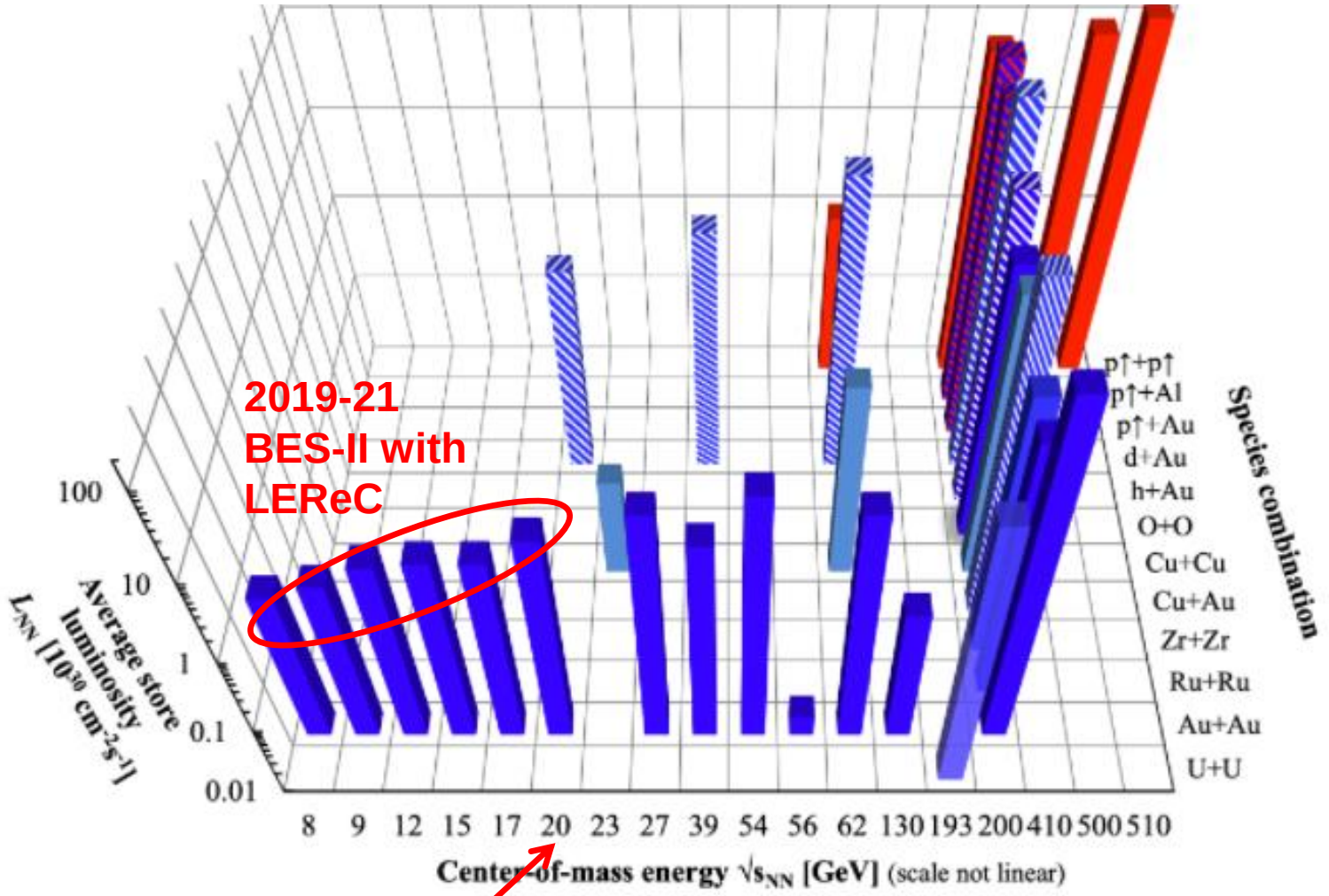
RHIC – all colliding running modes to date

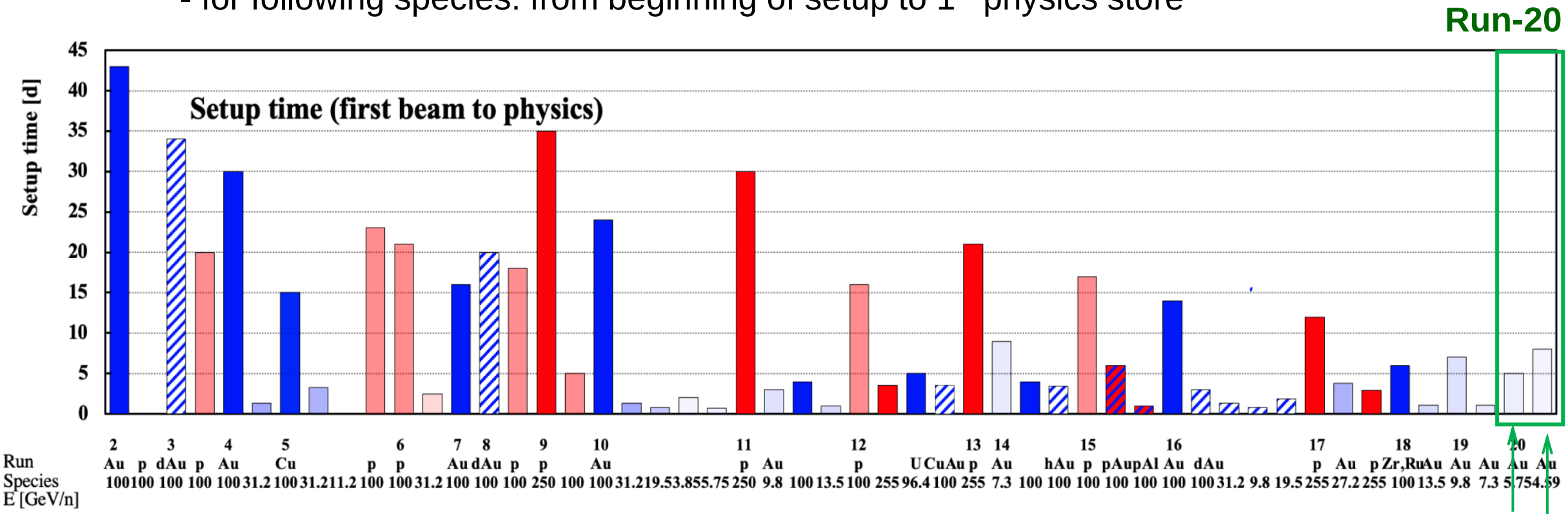
2001 to 2021



nominal injection energy

Operational efficiency – setup time

Setup time:
- for 1st species in run: from both rings cold to 1st physics store
- for following species: from beginning of setup to 1st physics store



5 days Au+Au $\sqrt{s_{NN}}$ = 11.5 GeV

8 days for Au+Au $\sqrt{s_{NN}}$ = 9.2 GeV
(includes LEReC setup)

TRANSPARENT: low energy

INTRANSPARENT: high energy

BLUE: heavy ion runs

RED: polarized proton runs

HATCHED: light-on-heavy ion runs

Reported events since October 1, 2020

Event Date and Time	Event Title	Event Significance Category	DART
10/3/2020 9:00	Building 911 Chilled Water Spill	SCBNL	No
11/2/2020 16:00	Employee felt left rib pain	NR	Yes
11/8/2020 9:30	Minor Steam Leak in Vacuum Lab	NR	No
11/24/2020 11:30	Laboratory Cooling Tower Exceeded NYS Regulated Level of Legionella Bacteria	NR	No
12/31/2020 11:00	Government vehicle impacks a yellow bollard	NR	No
1/23/2021 11:00	Operation outside RHIC ASE requirement (ASE Violation)	SCBNL	No
1/28/2021 15:00	Employee feels pain in elbow and hand while pulling wires	NR	No
3/4/2021 9:00	BNL Exceeded NYS Regulated Level of Legionella Bacteria	NR	No
4/5/2021 9:00	A Chemical Dosing Pump was Started Without Proper Authorization	NR	No
4/11/2021 8:00	Employees Contract Illness While Working Onsite	NR	Yes
4/22/2021 0:01	Driver Backs Lab Vehicle into Jersey Barrier	NR	No
4/23/2021 8:30	Employee feels pain in hand and wrist while lifting	NR	No
5/5/2021 9:41	Violation of ASE Requirement at the Tandem Van de Graaff	SCBNL	No
5/17/2021 9:39	Employee feels lower back pain while bending	NR	No
6/1/2021 10:00	Water Infiltration into Building 801 D-Tank Room	SCBNL	No
6/10/2021 14:00	Water Leak Behind Ventilation Control Panel Leads to Corroded Contacts at Tandem Van de Graaff Facility	SCBNL	No
6/17/2021 14:56	Accelerator Safety Envelope (ASE) Violation at the RHIC	SCBNL	No

Reported events since October 1, 2020 (cont'd)

Event Date and Time	Event Title	Event Significance Category	DART
6/18/2021 13:54	Odor from Lighting Ballast Leads to Fire/Rescue Response at Building 801	NR	No
6/22/2021 14:00	Water Intrusion into D Tank Room	NR	No
6/29/2021 11:00	Irradiation Target Failure at BLIP Facility	NR	No
7/8/2021 14:35	Employee injures hand while pulling down on bookshelf	NR	No
7/8/2021 20:11	Government Vehicle Damaged	NR	No
7/15/2021 11:00	Two Employees incur minor electrical shock when touching equipment	High	No
8/5/2021 14:15	Employee feels pop in bicep while rotating pipe	NR	Yes
8/9/2021 8:00	Water Intrusion into C-AD MIRP Lab	SCBNL	No
8/13/2021 14:30	UPDATE: Two smoke purge fans failed	SCBNL	No
8/16/2021 14:00	Broken bags of vermiculite in Building 901A	NR	No
8/19/2021 9:30	Employee Injures Shoulder	NR	Yes
8/20/2021 12:30	Improperly applied LOTO at Tandem Van de Graaff	SCBNL	No
8/25/2021 10:15	Government Vehicle Damage	NR	No
8/25/2021 15:00	Employee hits head on electrical box	NR	Yes
9/16/2021 14:00	Cable pullers observe electrical spark	SCBNL	No
9/17/2021 10:30	C-AD Access Control Certification Tests out of compliance with C-AD & SBMS Requirements	SCBNL	No
10/6/2021 14:00	Employee Receives Electric Shock from Exposed Wires	High	No
10/12/2021 13:55	Employee falls and injures finger	SCBNL	
10/14/2021 14:14	Smoke Odor Detected From Building 928	SCBNL	No
10/14/2021 16:00	Improper Lock Found on Gate	SCBNL	No