The Relativistic Heavy Ion Collider

RHIC Operations

- RHIC overview
- Recent performance of RHIC
- Low energy RHIC electron cooling
- Capital and accelerator improvement projects
- Action items from previous S&T review

BROOKHAVEN NATIONAL LABORATORY

Michiko Minty

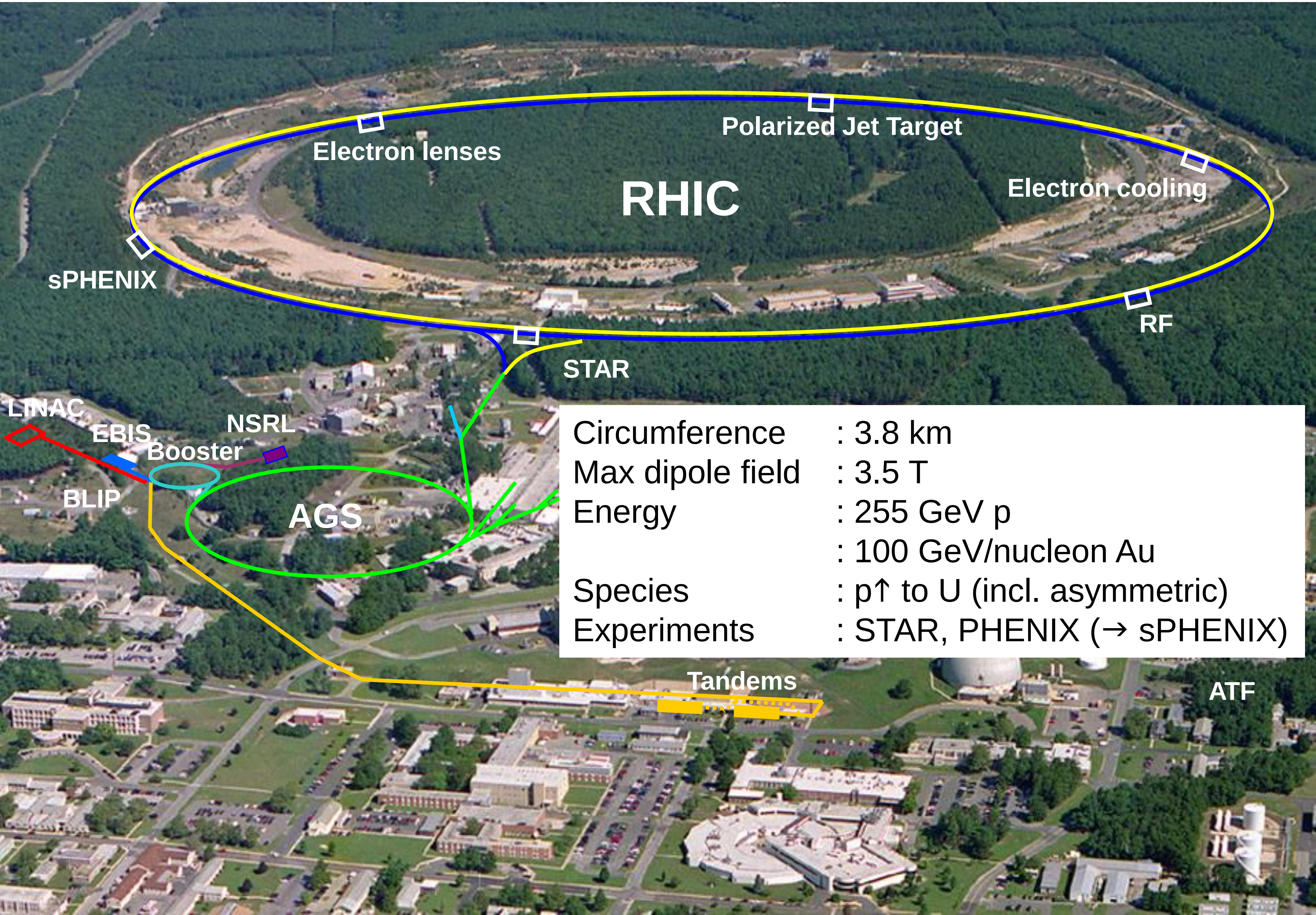
DOE NP RHIC Science & Technology Review
17 – 19 September 2019

U.S. DEPARTMENT OF ENERGY

Summary

- Operation of RHIC: met or exceeded integrated luminosity goals in the last 3 years
  - Run-17 p↑+p↑ at 255 GeV and Au + Au 27.2 GeV/n
  - Run-18 Zr + Zr / Ru + Ru at 100 GeV/n, Au + Au at 13.5 GeV/n
    + fixed target runs (at 3.85 GeV/n)
  - Run-19 Au + Au at 9.8 GeV/n, 7.3 GeV/n, 3.85 GeV/n
    + fixed target runs (multiple energies)
- New and unique operation (e.g. Ru+Ru / Zr+Zr) enabled by previous upgrades
- Flexibility of operations substantially increased: many and interleaved modes is now routine
- Operation of RHIC: exceeded accelerator availability goals
- First (in the world) electron cooling with RF accelerated electron bunches demonstrated in support of Beam Energy Scan II - LEReC, presentation by A. Fedotov
- Facility upgrades and maintenance ongoing to maintain high accelerator availability
- Future BES-II operations will employ the newly developed LEReC technology

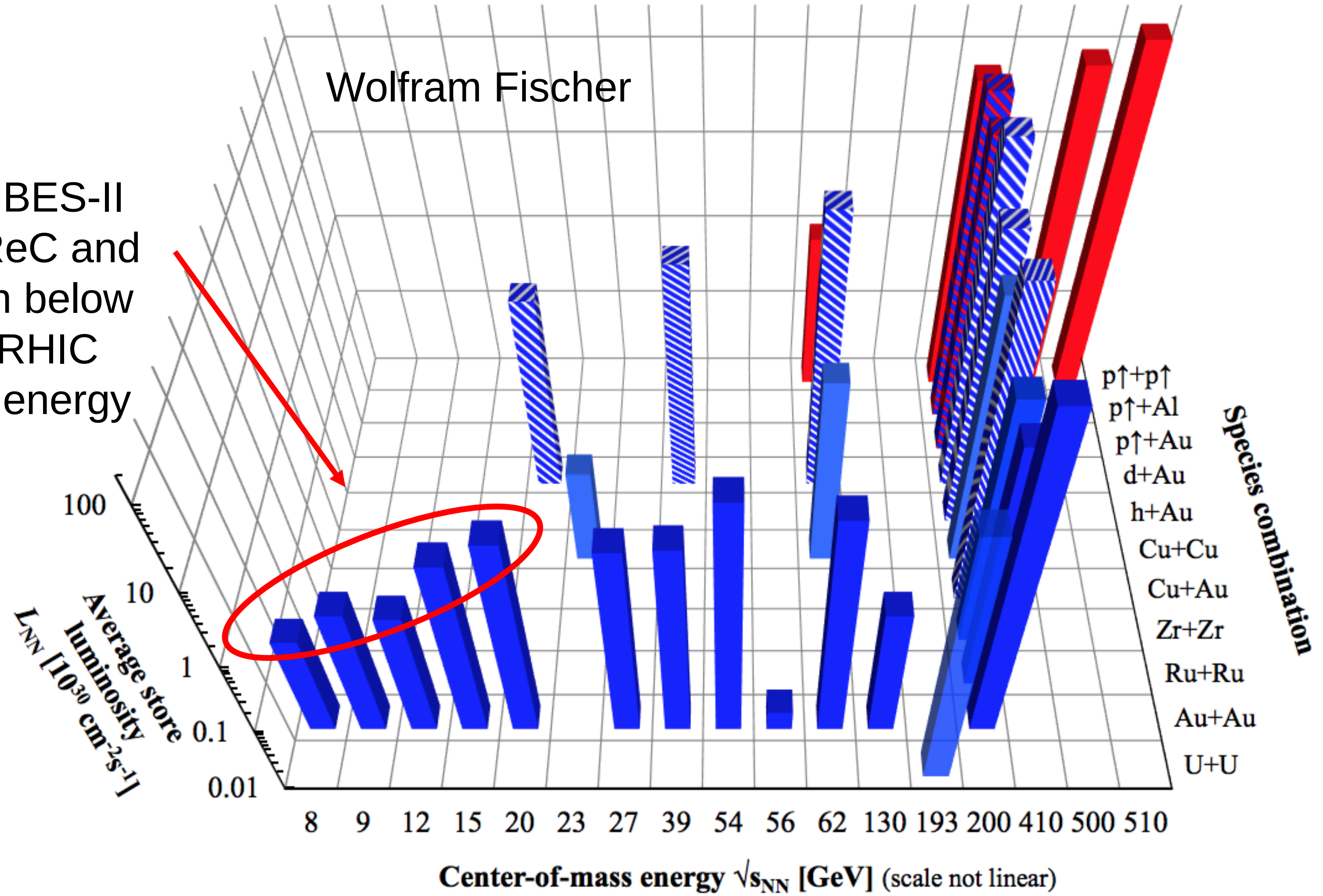
Relativistic Heavy Ion Collider (RHIC) Overview



Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV p
	: 100 GeV/nucleon Au
Species	: p↑ to U (incl. asymmetric)
Experiments	: STAR, PHENIX (→ sPHENIX)

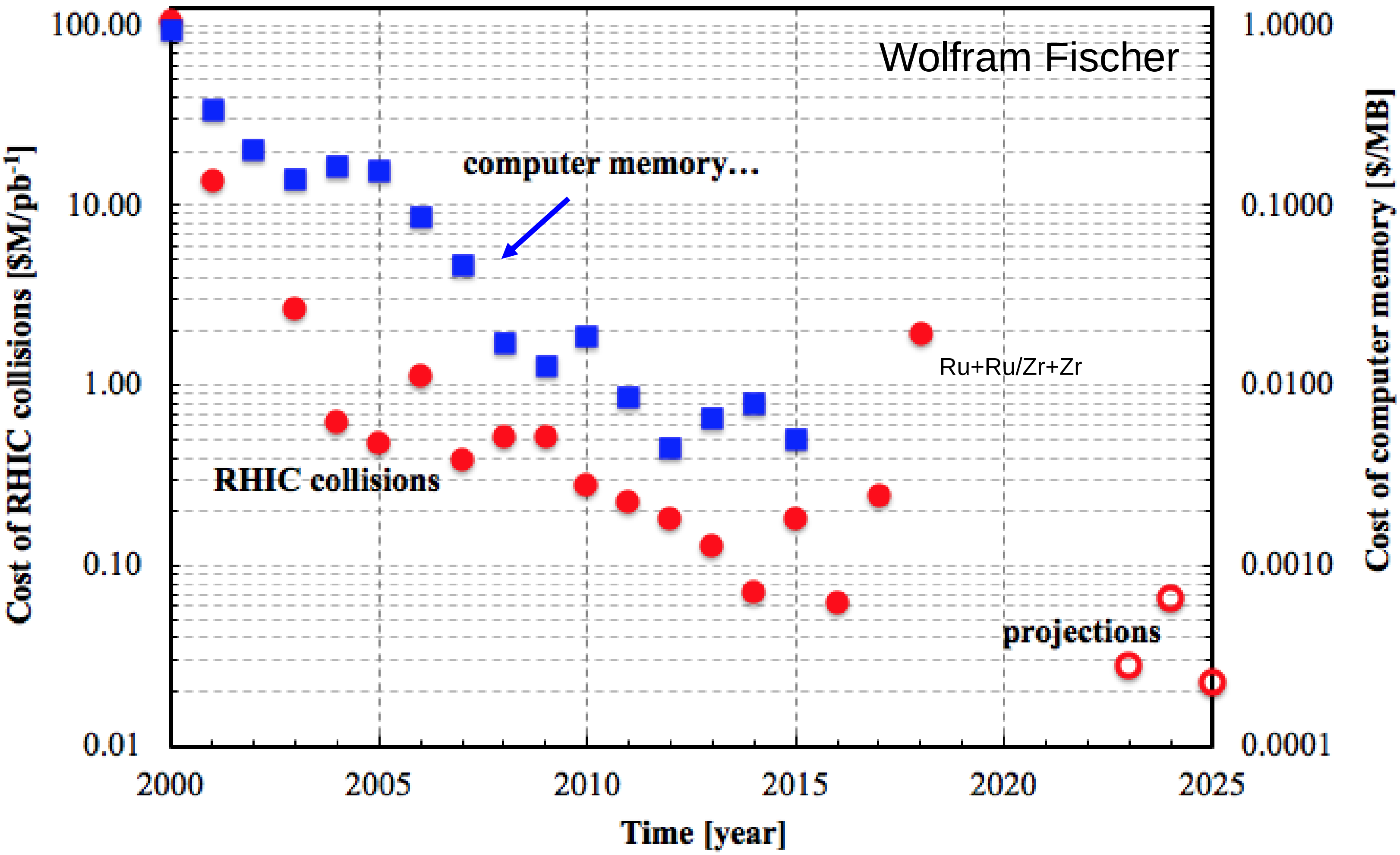
RHIC Overview - all colliding-mode physics runs to date (2001 to 2019)

2019-21 BES-II with LEReC and operation below nominal RHIC injection energy



The RHIC facility provides unparalleled flexibility in terms of ion species and energies for nuclear physics research in the US

RHIC overview - time evolution of unit cost to operate RHIC



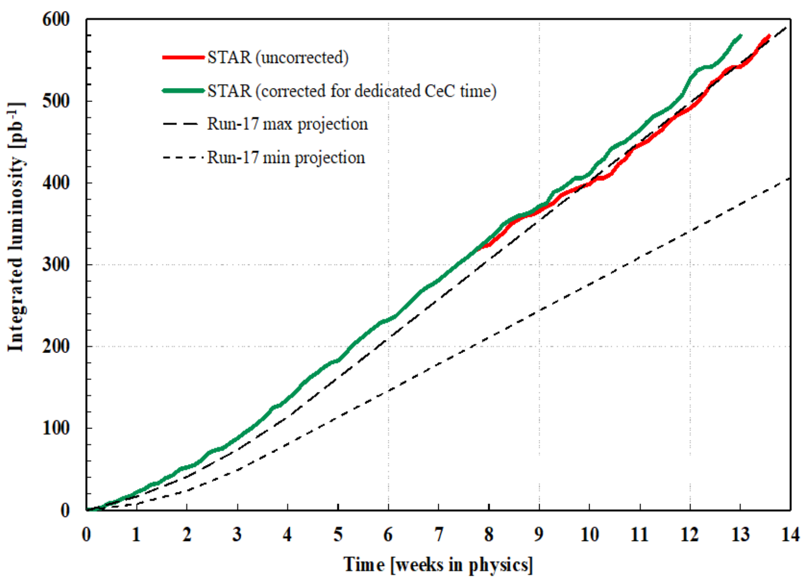
Productivity gain of RHIC operations (>1E3) is comparable with state-of-the-art developments in industry

Recent performance of RHIC: Run-17

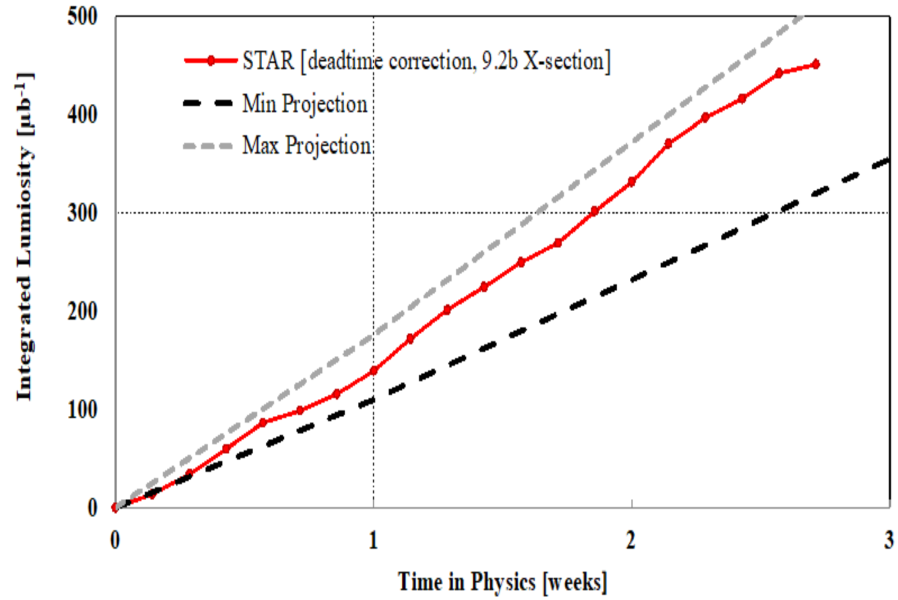
3 modes of operation	p↑ + p↑ at 255 GeV	15 weeks
	Au + Au 27.2 GeV/n	3 weeks
	p↑ + p↑ at 255 GeV for RHICf	0.9 weeks

+ CeC and LEReC gun commissioning

Run-17 p↑ + p↑ at 255 GeV



Run-17 Au + Au at 27.2 GeV/n



STAR L_{max} limited to ≈ 1.4x10^{32} cm^{-2}s^{-1}
=> 1st p↑+p↑ run with L-leveling

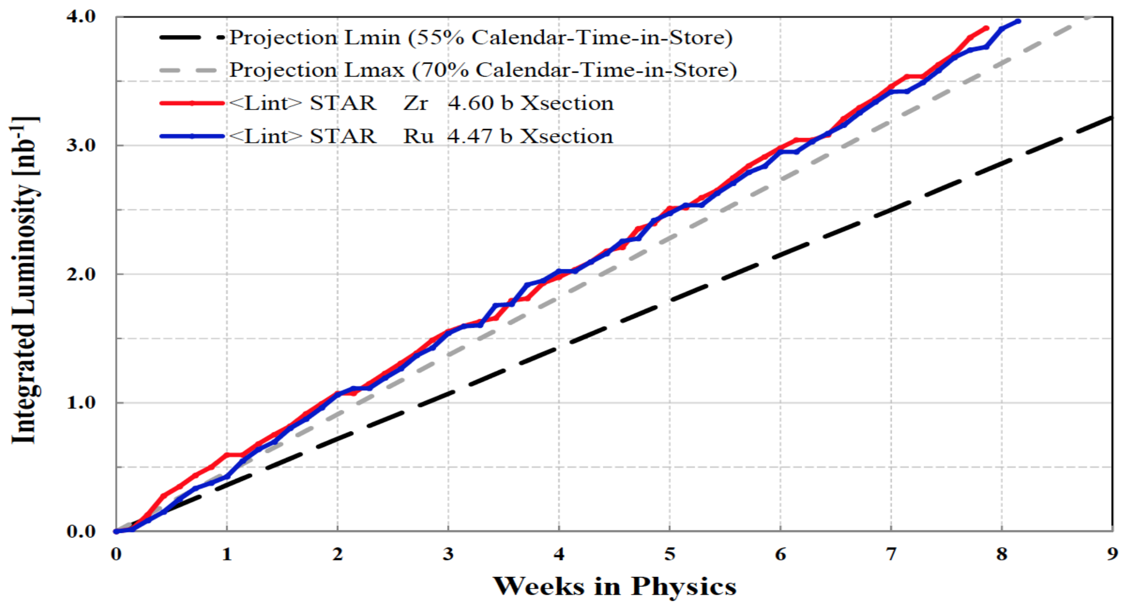
Met integrated luminosity goals of 400 pb^{-1} (p↑ + p↑) and 300 μb^{-1} (Au + Au)

Recent performance of RHIC: Run-18

5 modes of operation

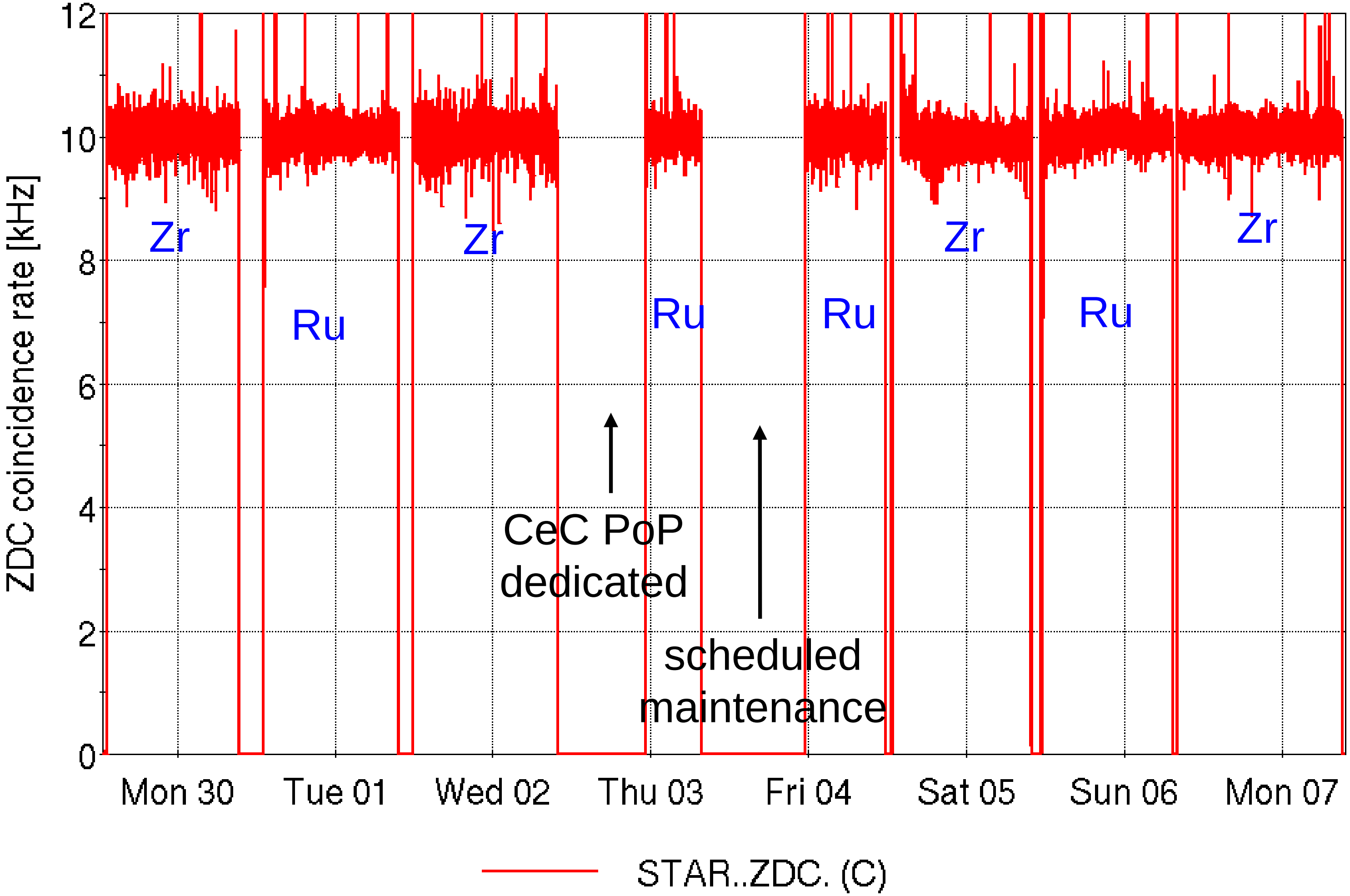
Zr + Zr and Ru + Ru at 100 GeV/n (interleaved)	12 weeks
Au + Au at 13.5 GeV/n	4 weeks
Au + Au at 3.85 GeV/n (fixed target)	0.6 weeks
Au at 26.5 GeV/n, Coherent electron Cooling (CeC PoP)	1.1 weeks
LEReC and CeC electron beam development	

Run-18 Zr + Zr / Ru + Ru at 100 GeV/n



Exceeded integrated luminosity goals

Recent performance of RHIC: Run-18, Zr+Zr / Ru+Ru



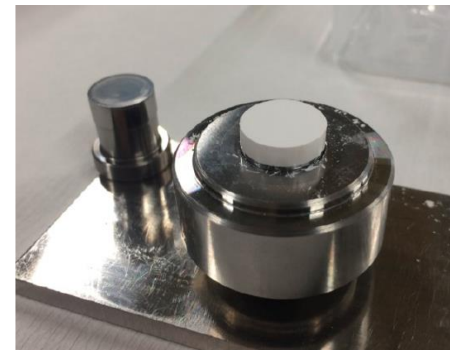
Unique operations / flexibility of RHIC met challenging requirements:
- flat and equal conditions for Zr + Zr and Ru + Ru
- constant (levelled) luminosity of 21.5×10^{26} $cm^{-2}s^{-1}$
- turn-key, store-by-store species changes

Recent performance of RHIC: Run-18
Zr-96 and Ru-96 preparation

Zr-96

- Natural abundance: 2.78%
- From LION/EBIS (sintered ZrO_2) => M. Okamura et al.
- Enriched ZrO_2 powder commercially available, processing using RIKEN technology
- MIRP (BNL) chemists could recycle unused ZrO_2

ZrO_2 tablet (RIKEN)



Ru-96

- Natural abundance: 5.52%
- From Tandem (metallic) => P. Thieberger et al.
- Enriched Ru-96 not commercially available, provided by DOE using new isotope separation facility at ORNL (500 mg)

Ru-96 (ORNL)

Unique isobar run enabled with support from DOE, ORNL and Riken

Recent performance of RHIC: Run-18
Zr-96 and Ru-96 preparation

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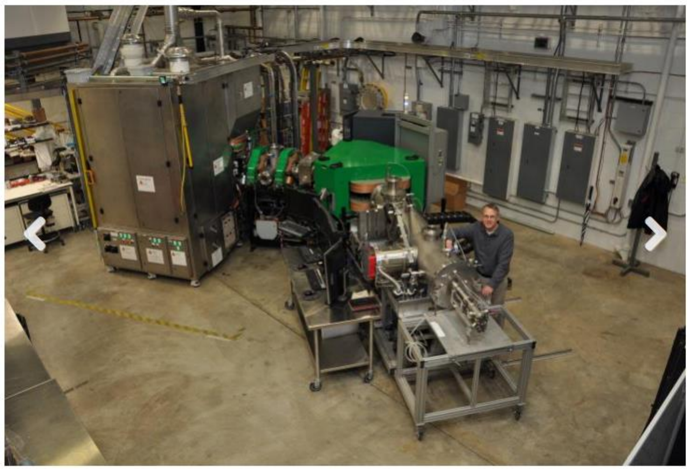
ORNL produces rare ruthenium isotope for atom smashing experiment

New facility reestablishes U.S. capability for stable isotope production



June 28, 2018

Media Contact

Morgan McCorkle, Communications
mccorkleml@ornl.gov, 865.574.7308

June 28, 2018—A tiny vial of gray powder produced at the Department of Energy's Oak Ridge National Laboratory is the backbone of a new experiment to study the intense magnetic fields created in nuclear collisions.

The new experiment at Brookhaven National Laboratory's Relativistic Heavy Ion Collider, just

Contact: Karen McNulty Walsh, (631) 344-8350, or Peter Genzer, (631) 344-3174 share:

Relativistic Heavy Ion Collider Begins 18th Year of Experiments

First smashups with 'isobar' ions and low-energy gold-gold collisions will test earlier hints of exciting discoveries as accelerator physicists tune up technologies to enable future science

March 21, 2018

Members of the STAR collaboration in the STAR control room on shift during this year's physics run, with STAR's event plane detector graphic user interface and particle tracks in the time projection chamber on display behind them: front, l to r: shift leader Carl Gagliardi of Texas A&M University with shift leader trainee Prashanth Shanmuganathan, a postdoctoral associate at Lehigh University; rear, l to r: Joseph Adams a graduate student at Ohio State University and Raghav Kunnawalkam Elayavalli a postdoctoral fellow at Wayne State University. Adams and Shanmuganathan worked on construction of the event plane detector and serve as detector experts; Kunnawalkam Elayavalli has been controlling the event plane detector during STAR data taking as a detector operator trainee. + ENLARGE

UPTON, NY— The first smashups of two new types of particles at the Relativistic Heavy Ion Collider (RHIC)—a U.S. Department of Energy (DOE) Office of Science user facility for nuclear physics research at Brookhaven National Laboratory—will offer fresh insight into the effects of magnetism on the fireball of matter created in these collisions. Accomplishing this main goal of the 15-week run of RHIC's 18th year will draw on more than a decade of accumulated expertise, enhancements to collider and detector components, and a collaborative effort with partners across the DOE complex and around the world.

Physicists will also perform two different kinds of collisions with gold ions at low energies, including collisions of gold ions with a stationary target. These collisions will help scientists better understand the exotic matter created in RHIC's highest energy collisions, including the strength of its magnetic field and how it evolves from a hot soup of matter's fundamental building blocks (quarks and gluons) to the ordinary

"In some ways this run is the culmination of two decades of facility development."

— Wolfram Fischer, Collider-Accelerator Department

Unique isobar run enabled with support from DOE, ORNL and Riken

Recent performance of RHIC: Run-19
Au + Au for Beam Energy Scan II (BES-II)
LEReC cooling commissioning

Colliding beam modes

➢ Au + Au at 9.8 GeV/n	6.1 weeks
➢ Au + Au at 7.3 GeV/n	8.7 weeks
➢ Au + Au at 4.59 GeV/n	0.9 weeks
➢ Au + Au at 3.85 GeV/n	3.4 weeks
➢ Au + Au at 100 GeV/n (accelerator studies)	0.4 weeks

Fixed target modes

- ➢ Au on Au at 31.2 GeV/n (18.5 hours), 7.3 GeV/n (13 hours),
  4.59 GeV/n (4 days), 3.85 GeV/n (2 hours)

LEReC cooling commissioning

➢ Au at 3.85 GeV/n	24 weeks
➢ Au at 4.59 GeV/n	2.6 weeks

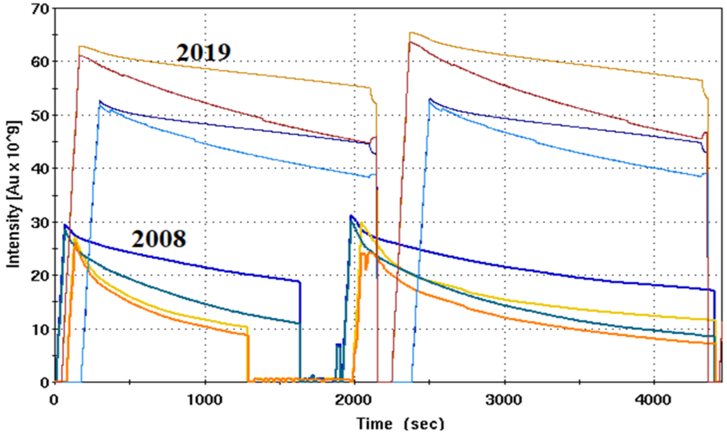
Multiple modes of operation per year (11 modes in Run-19) now routine

Recent performance of RHIC: Run-19

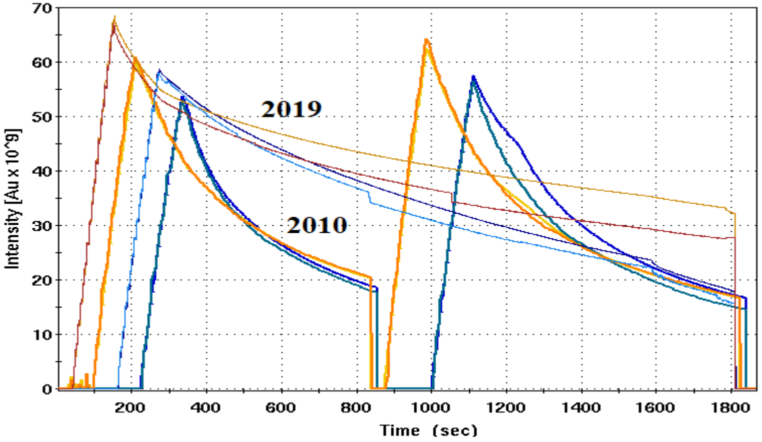
Main challenges

- intrabeam scattering (IBS) – causing rapid emittance growth with beam energy below transition energy (~24 GeV/n for Au beam)
- space charge – causing large incoherent and incoherent tune shifts
- persistent current in the superconducting magnets

4.59 GeV/n



3.85 GeV/n



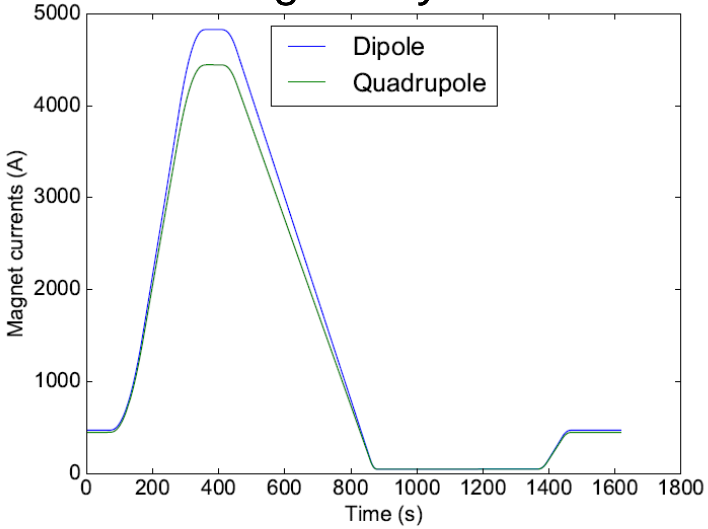
Highlights

- Low Energy RHIC Electron Cooling (LEReC) to mitigate IBS
- new 9 MHz cavities to reduce space charge effects (longer bunches)
- new lattice to accommodate larger tune shifts
- new magnet demagnetization cycle to reduce persistent current effects

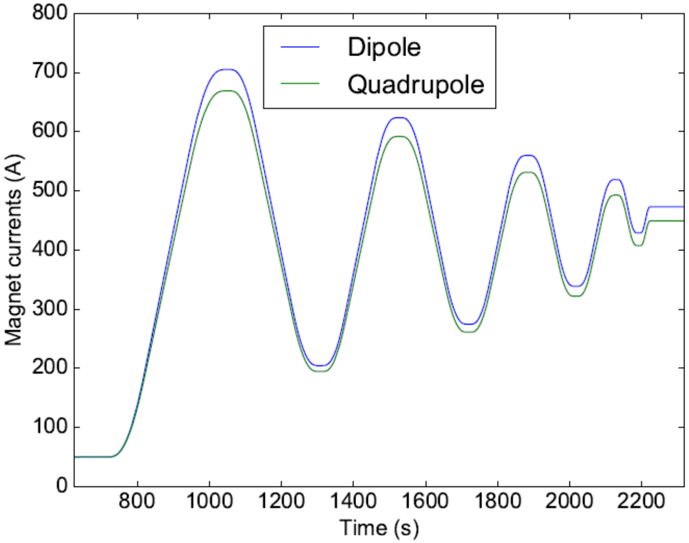
Run-19 new magnet demagnetization cycle

A demagnetization cycle was developed and implemented to reduce persistent current effects in the RHIC superconducting magnets

regular cycle



demagnetization cycle



- ➢ reduced sextupole components in dipoles reduced
- ➢ reduced orbit, tune and chromaticity drifts

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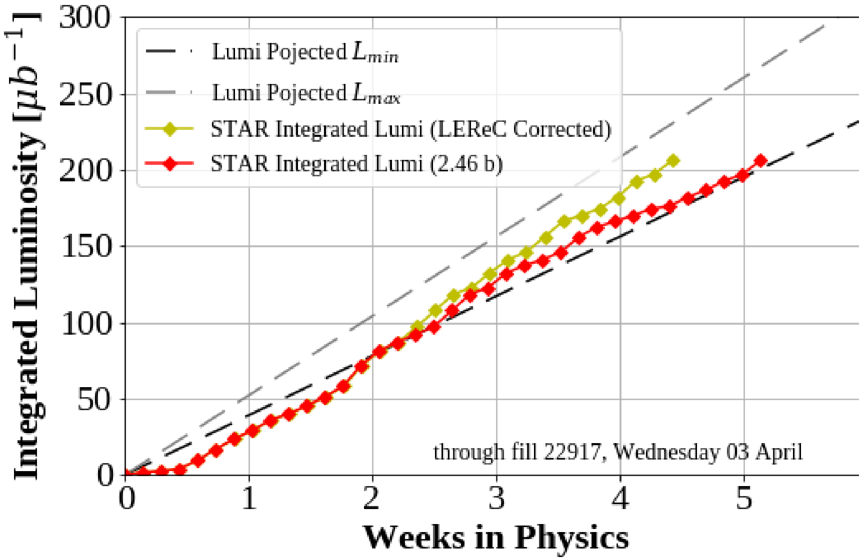
demagnetization cycle provided stable and reproducible conditions and enabled frequent energy changes needed for operations and LEReC commissioning

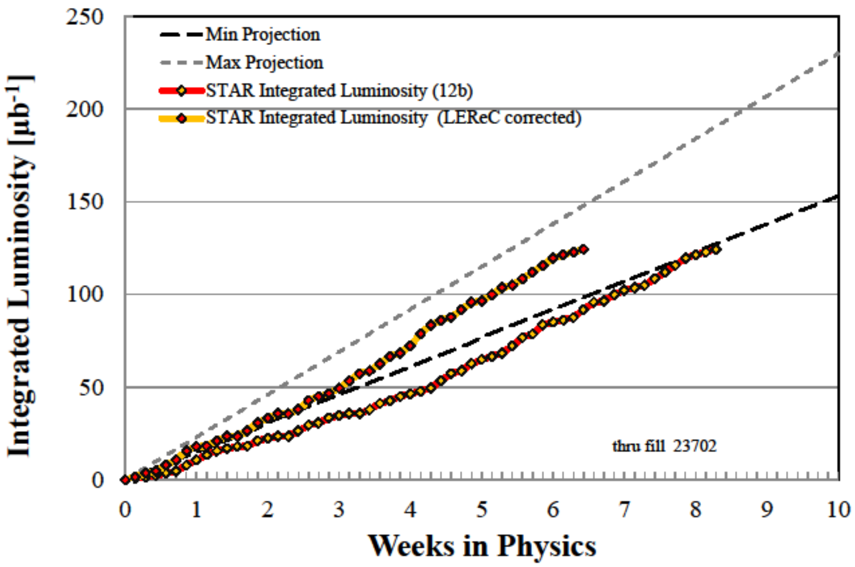
Recent performance of RHIC: Run-19 (BES-II)

Integrated luminosity for highest priority colliding beam modes

Run-19 Au + Au at 9.8 GeV/n



Run-19 Au + Au at 7.3 GeV/n



Met integrated luminosity goals

Beam Energy Scan II --- beam delivery overview

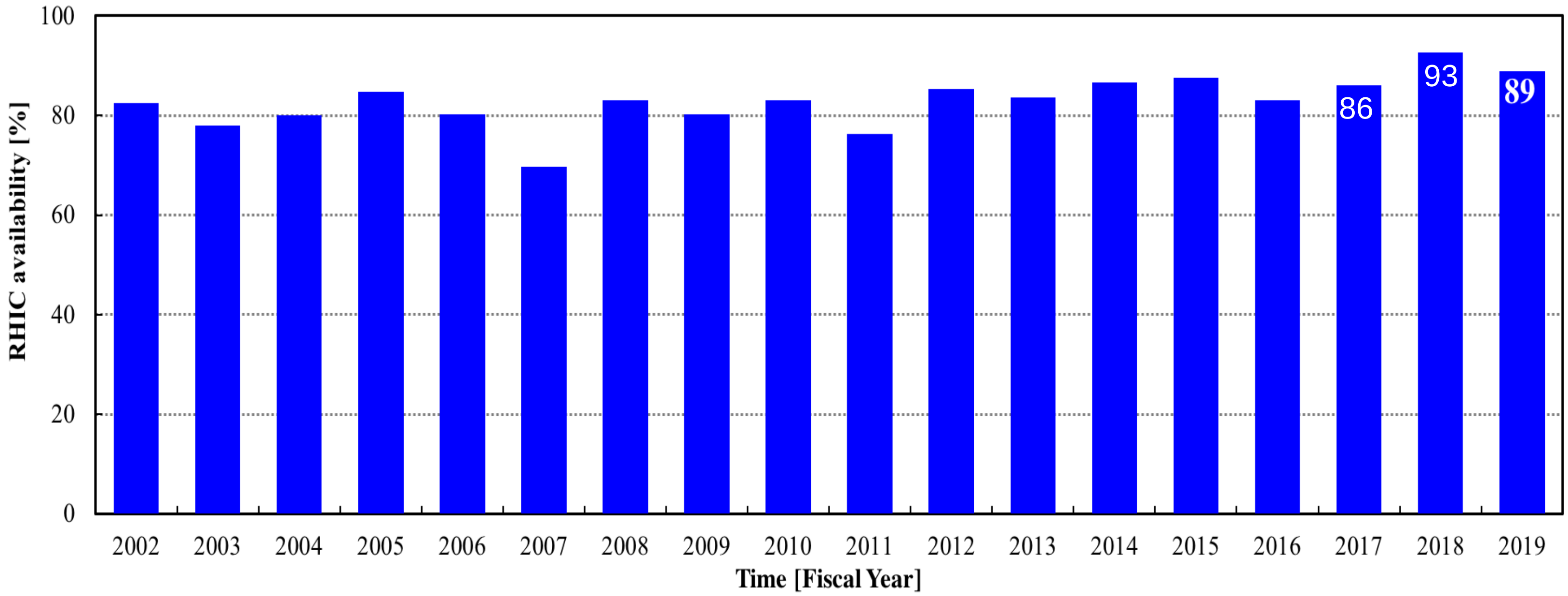
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events	
9.8	19.6	205	4.5 weeks	400M	582M
7.3	14.5	260	5.5 weeks	300M	324M
5.75	11.5	315	5 weeks	230M	
4.55	9.1	370	9.5 weeks	160M	
3.85	7.7	420	12 weeks	100M	
31.2	7.7 (FXT)	420	2 days	100M	51M
19.5	6.2 (FXT)	487	2 days	100M	
13.5	5.2 (FXT)	541	2 days	100M	
9.8	4.5 (FXT)	589	2 days	100M	
7.3	3.9 (FXT)	633	2 days	100M	53M
5.75	3.5 (FXT)	666	2 days	100M	
4.55	3.2 (FXT)	699	2 days	100M	201M
3.85	3.0 (FXT)	721	2 days	100M	3.7M

+ 300 M (run18)

+ FXT at $\sqrt{S_{NN}}$ = 7.7 GeV (2.9M)
$\sqrt{S_{NN}}$ = 9.2 GeV (1.0M)
acquired parasitic to LEReC commissioning

RHIC availability reported to DOE (2002-2019)

availability = beam time / scheduled beam time
(scheduled time excludes scheduled maintenance)

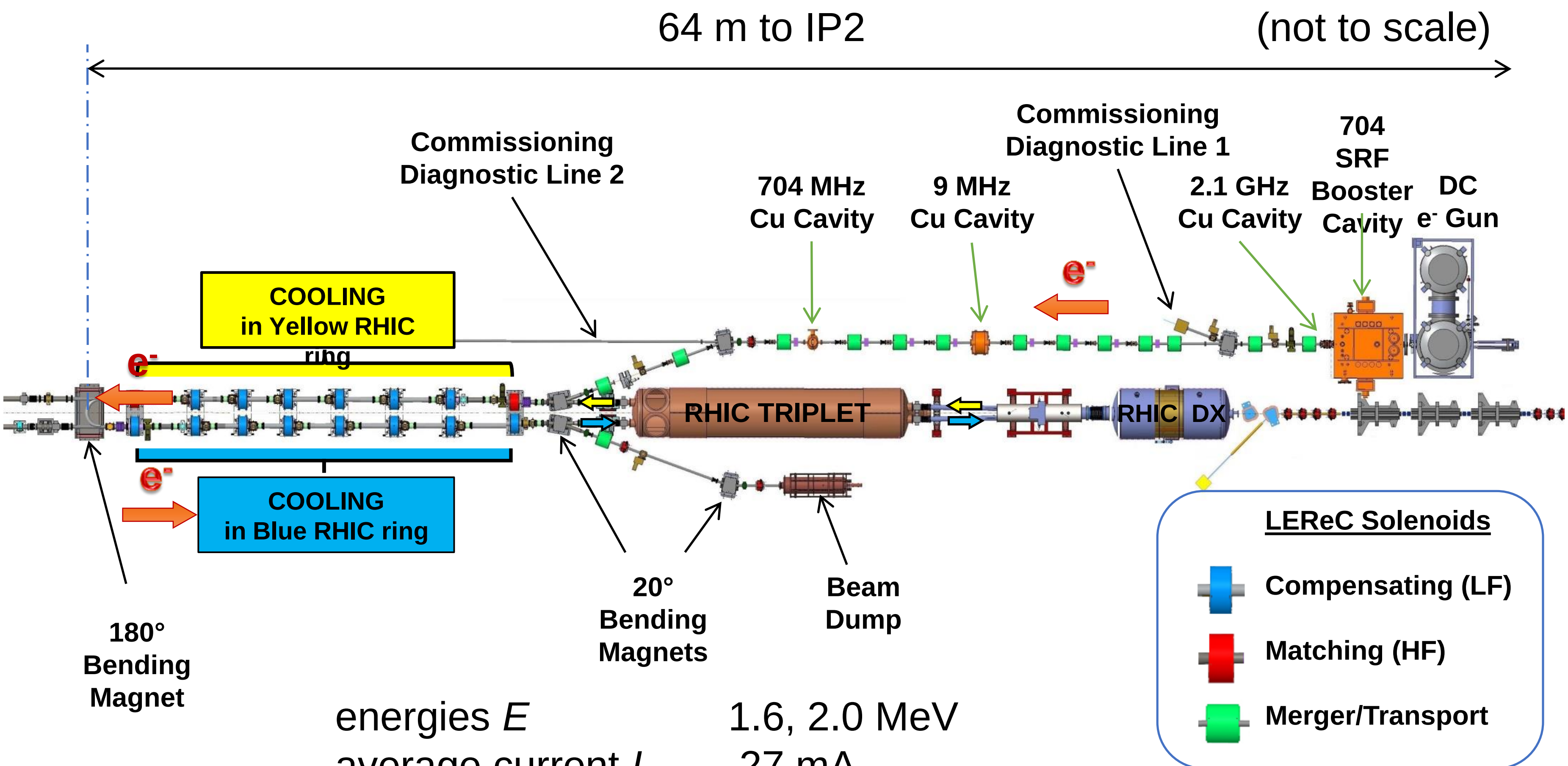


Typical time allocations	50K to 4K cool-down	0.5 week
	initial set-up	1-2 weeks
	changing species	0.5 week
	accelerator studies (APEX)	16h every 2 weeks
	maintenance	14h every 2 weeks
	warm-up	0.5 week

Exceeded availability goal (80%) for 8 consecutive years (goal will be raised)

Low Energy RHIC electron Cooling (LEReC)

A. Fedotov



energies E	1.6, 2.0 MeV
average current I_{avg}	27 mA
momentum $\delta p/p$	5×10^{-4}
luminosity gain	factor 4

LEReC completed on schedule and within budget (8.3M$ AIP)

LEReC accomplishments in Run-19

- World's first electron cooling with rf-accelerated bunched beam for BES-II

- first "non-magnetized" electron cooling (all previous coolers used magnetization on the cathode, i.e. solenoid field)

- first cooling of ion bunches in two rings using the same electron beam

- first electron cooling of colliding beams

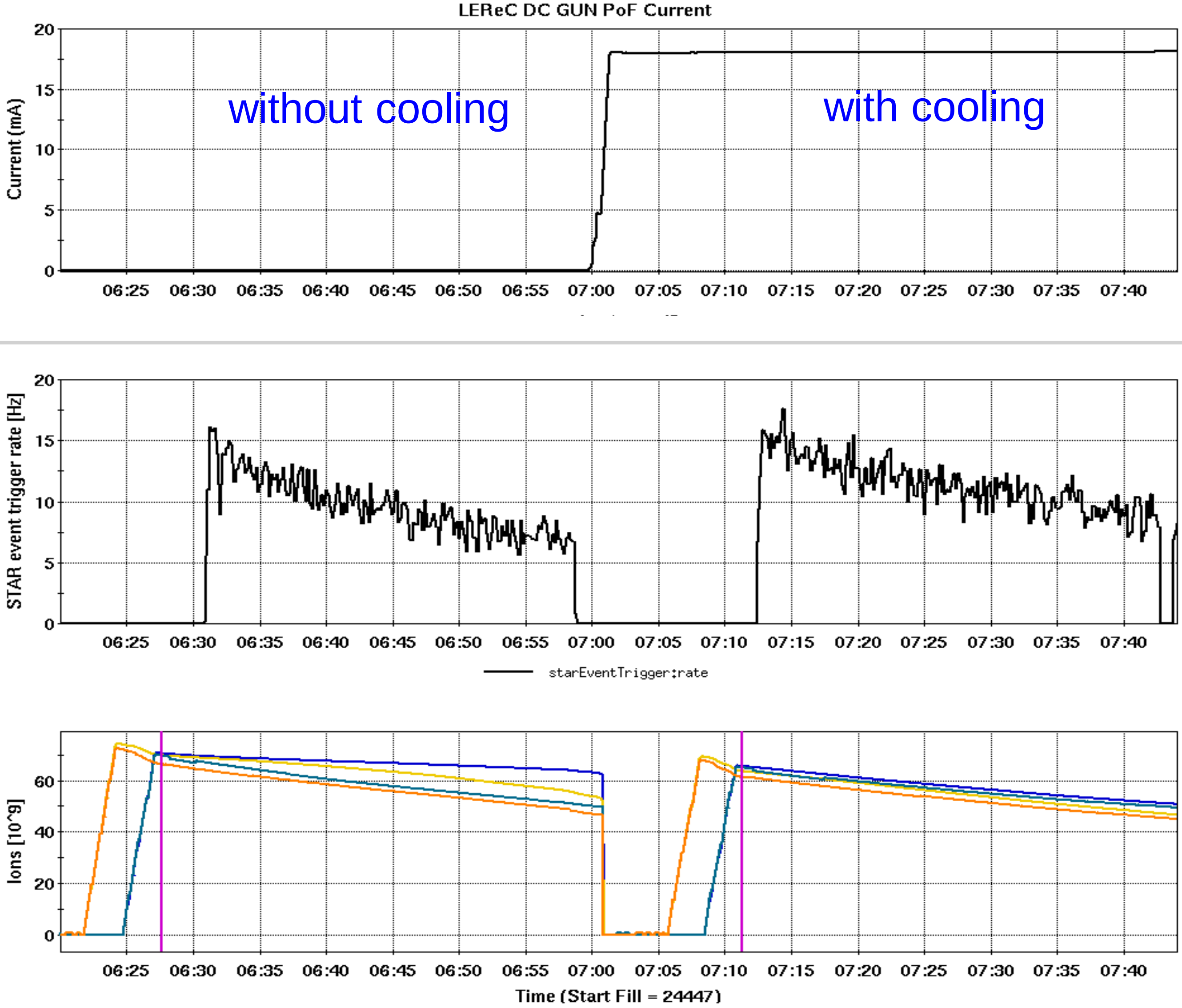
- electron cooling was commissioned at

  electron energy of 1.6 MeV with ion energy 3.85 GeV/n

  electron energy of 2 MeV with ion energy of 4.58 GeV/n

- electron cooling of RHIC stores with 111 ion bunches in both rings demonstrated at both 3.85 and 4.59 GeV/nucleon ion beam energies

Effect of cooling at 4.59 GeV/nucleon



With cooling demonstrated 22% increase in STAR event integral over ~ ½ hour

Colliding mode projections for Run-20

5.75 x 5.75 GeV/n

L_{avg} improvement factor, total = 2.4x Run-10
L_{avg} improvement factor, +- 70 cm = 2.3x Run-10

bunch intensity N_b : 1.1 → 1.35e9
rms emittance ε_n : 2.5 → 2.5 mm
bunch length σ_s : 1.4 → 1.4 m
envelope function β^* : 6.0 → 4.0 m
electron cooling : OFF

4.59 x 4.59 GeV/n

L_{avg} improvement factor, total = 1.5x Run-19
L_{avg} improvement factor, +/- 70 cm = 2.4x Run-19

bunch intensity N_b : 0.8 → 0.9e9
rms emittance ε_n : 1.5 → 1.6 mm
bunch length σ_s : 3.8 → 2.3 m
envelope function β^* : 4.5 → 4.5 m
electron cooling : ON

Improvements for increased efficiency in Run-20

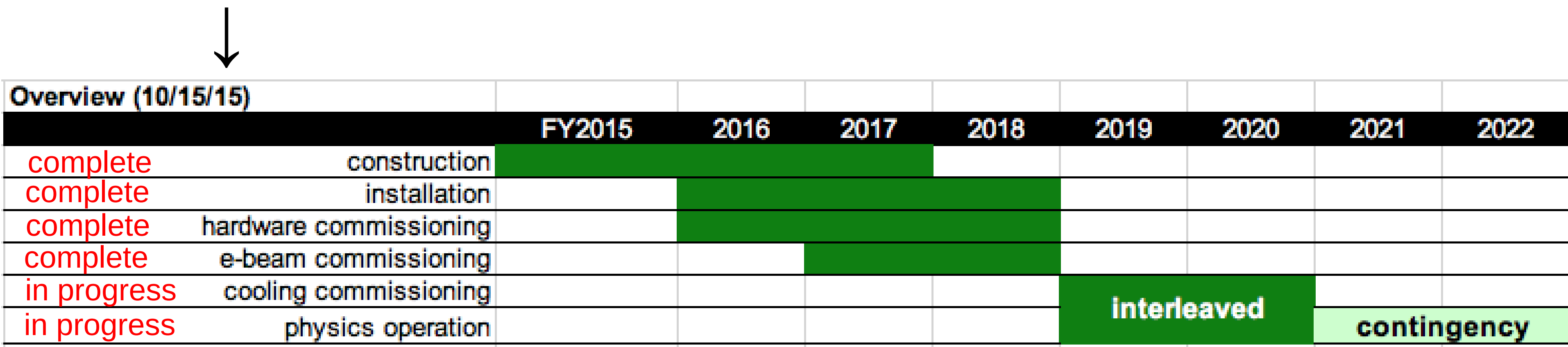
- reduced number of mode changes
- shortest possible bunches at space charge limit (x = -0.06 ?)
- fixed and reliable Au beam parameters for cooling at 4.59 GeV (requires some intensity margin in the injectors)
- beam conditions that allow STAR to stay on during injection
- longer STAR beryllium beam pipe (4 m) for increased longitudinal acceptance (deferred)

Run-20 will be very challenging with

- Au + Au at 5.75 GeV/n (without cooling)
- Au + Au at 4.59 GeV/n (with cooling)
- up to 6 fixed - target energy runs
- continued cooling commissioning at 3.85 GeV/n
- developments for coherent electron cooling

RHIC Run-20 and beyond

LEReC/BES-II plan from 2015 still holding

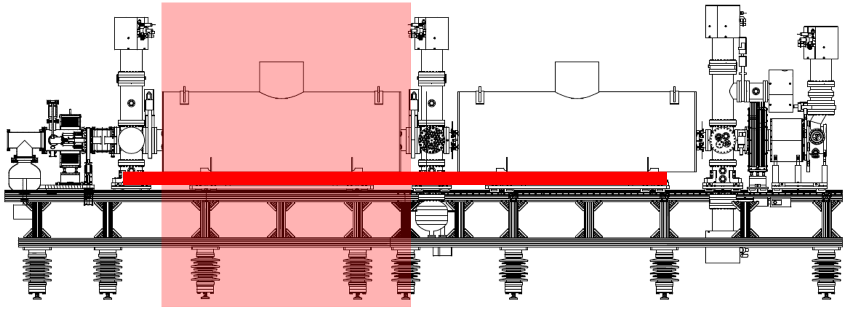


Plan

- 2018: complete LEReC electron beam commissioning (DONE)
- 2019: LEReC cooling commission interleaved with physics (DONE)
- 2020: Use cooled beams at 2 (possibly 3) lowest energies
- 2021: contingency if event number goals not met

Capital and accelerator improvement projects

- Extended EBIS (CP)
  2^{nd} sc solenoid + gas cell
  completion for Run-20
- RHIC cryo control system upgrade (CP)
- RHIC quench detection (CP)



- Linac vacuum system upgrade (AIP)
- RHIC turbo pump upgrade (AIP)
- RHIC cryo plant cold expander train upgrade (AIP)
- Booster AC dipole (He-3↑)
- PS: Booster sextupoles, Booster RF tuning (band III), AGS quad and sextupoles, H10/L20, BtA and LtB, RHIC IR8 tq (sPHENIX)
- Siemens fire suppression system
- AGS MM evaporation cooler
- Vacuum lab equipment (ultrasound cleaner, oven)

Ongoing facility upgrades and maintenance for high accelerator availability

Capital and Accelerator Improvement Projects Funding (FY2017-2025)

($000)	total	FY2017	FY2018	FY2019	FY2020E	FY2021E	FY2022E	FY2023E	FY2024E	FY2025E
RHIC CE										
Extended EBIS	1,775	1,100	200	remaining performance upgrade (until 2020)						
RHIC cryo control system upgrade	1,450	-	600	850						
RHIC quench detection system upgrade	1,000	-	-	1,000						
RHIC Access Control System upgrade	2,000	-	-	-	850	900	250			
AGS beam position monitor electronics upgrade	650	-	-	-	-	-	650			
Chipmunks upgrade	900	-	-	-	-	-	-	900		
RHIC cryo corrector flowmeters upgrades	950	-	-	-	-	-	-	-	950	-
Replacement of AGS corrector power supplies	1,000	-	-	-	-	-	-	-	-	1,000
Water tower #7 replacement	-	-	-	-	-	-	-	-	-	-
Total CE		1,100	800	1,850	850	900	900	900	950	1,000
RHIC AIP										
Low-Energy RHIC electron Cooling (LEReC)	8,300	1,300								
Linac vacuum system upgrade	3,000	1,100	1,900							
RHIC turbo pump upgrade	883	-	500							
RHIC cryo plant cold expander train upgrade	7,000	-	-	4,500	2,500					
AGS Siemens cycloconverter upgrade	2,600	-	-	-	-	2,600				
RHIC cryo plant warm expander train upgrade	5,400	-	-	-	-	-	2,700	2,700		
480 V substations and power circuit breaker upgrade	1,500	-	-	-	-	-	-	-	1,500	
RHIC cryo cold end heat exchanger and expander upgrade	4,200	-	-	-	-	-	-	-	1,300	2,900
Total AIP		2,400	2,400	4,500	2,500	2,600	2,700	2,700	2,800	2,900
Total RHIC CE & AIP		**3,500**	**3,200**	**6,350**	**3,350**	**3,500**	**3,600**	**3,600**	**3,750**	**3,900**
Isotope Program AIP										
Linac Intensity Upgrade Phase II	-	-			proposed (<$10M)					
Total Isotope AIP		-	-	-	-	-	-	-	-	-

- Previous upgrades in 2 categories:
  1. Performance upgrades
  2. Maintenance/upgrades of technical infrastructure
- New upgrades now focus on 2. category

M&S+25 FTE is approx. 0.5% of RHIC hadron complex replacement value

Action items from 2014 and 2016 S&T reviews

2014 no accelerator related recommendations

2016 "Develop a plan to improve the machine protection system for operation at ultimate luminosity and intensity of ion and proton beams. Submit to DOE NP by January 1, 2017."

Detailed response submitted in August, 2016. Upgrade with two principle components identified:

1. Implementation of slow (30-40 ms – now 6 ms) mechanical switch in series with the existing fast (<1 ms) thyratron high-voltage switch (DONE)
2. Additional MPS inputs to provide added protection
   - beam loss monitors (DONE)
   - fast orbit correctors power supplies (will be completed in Run-20)
   - beam position monitors (DONE)
   - radiofrequency cavities (DONE)

To complete prior to resuming high energy operation:

- test delayed dump and energy extraction in operation (reduced risk in low energy operation)
- test delayed energy extraction with higher intensity and full energy (end of run)

Summary

- Operation of RHIC: met or exceeded integrated luminosity goals in the last 3 years
  - Run-17 p↑+p↑ at 255 GeV, run coordinator Vahid Ranjbar
    Au + Au 27.2 GeV/n, run coordinator: Greg Marr
  - Run-18 Zr + Zr / Ru + Ru at 100 GeV/n, Au + Au at 13.5 GeV/n
    + fixed target runs (at 3.85 GeV/n), run coordinator: Greg Marr
  - Run-19 Au + Au at 9.8 GeV/n, 7.3 GeV/n, 3.85 GeV/n
    + fixed target runs (multiple energies), run coordinator Chuyu Liu
- New and unique operation (e.g. Ru+Ru / Zr+Zr) enabled by previous upgrades
- Flexibility of operations substantially increased: many and interleaved modes is now routine
- Operation of RHIC: exceeded accelerator availability goals
- First (in the world) electron cooling with RF accelerated electron bunches demonstrated in support of Beam Energy Scan II - LEReC, presentation by A. Fedotov
- Facility upgrades and maintenance ongoing to maintain high accelerator availability
- Future BES-II operations will employ the newly developed LEReC technology

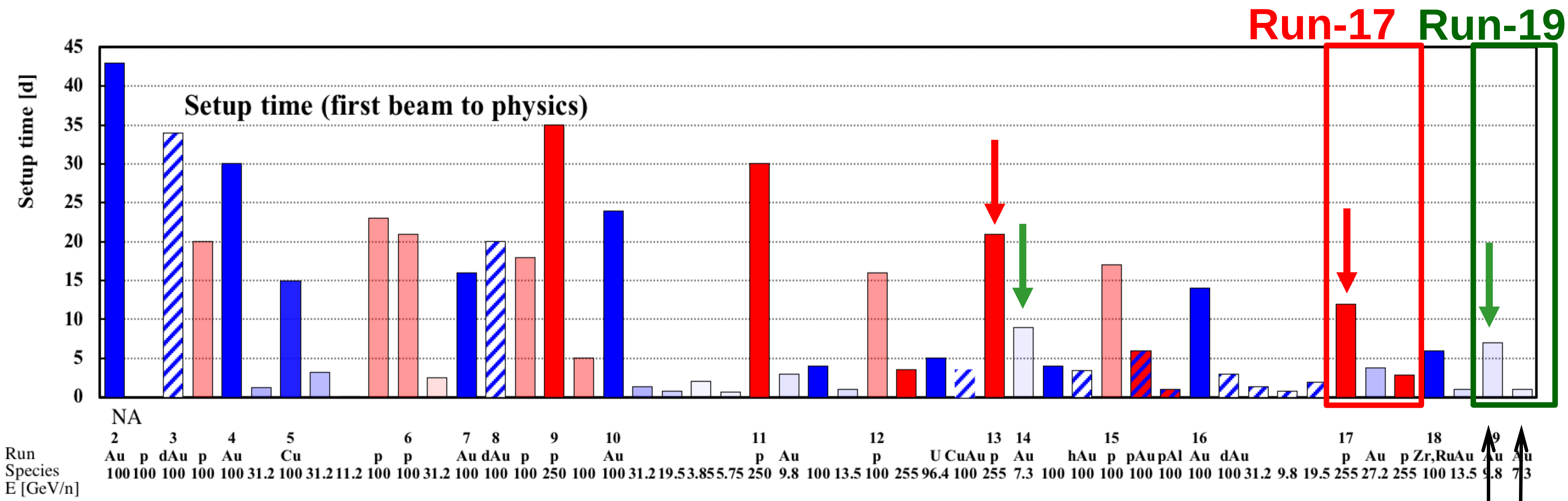
Back-up material

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



7 days Au+Au 9.8 GeV

1 day for Au+Au 7.3 GeV

TRANSPARENT: low energy

INTRANSPARENT: high energy

BLUE: heavy ion runs

RED: polarized proton runs

RHIC Run-17 detail

3 modes for physics

p↑+p↑ at 255 GeV, 15 weeks (2/12/17-5/30/17)

- STAR only
- luminosity leveling
- larger aperture beampipes at STAR and PHENIX
- MPS tests
- 9 MHz cavity commissioning

Au + Au at 27.2 GeV/nucleon, 3 weeks (5/30/17 – 6/19/17)

- energy selection for concurrent operation with Coherent Electron Cooling Proof of Principle (CeC PoP)

p↑+p↑ at 255 GeV – RHICf, 6 days (6/21/17 - 6/27/17)

- radial polarization using spin rotators

CeC and LEReC gun commissioning

- 90 hours dedicated CeC PoP time

RHIC Run-18 detail

5 modes for physics

Zr + Zr and Ru + Ru at 100 GeV/nucleon, 12 weeks (3/8/18 – 5/10/18)

- store-by-store changes in ion species with Zr from LION/EBIS
- Ru from Tandem

Au + Au at 13.5 GeV/nucleon, 4 weeks (5/10/18 – 5/30/18 and 6/4/18 – 6/18/18)

- 133 hours dedicated CeC PoP time (parasitic fixed target operation in parallel)
- LEReC electron beam commissioning in parallel

Au at 3.85 GeV/nucleon on fixed target Au foil inside STAR, 4 days (5/30/18 - 6/4/18)

- BBQ for constant STAR event rate
- BES-II preparation (injection and abort kicker tests, new hysteresis cycle)

Au in Yellow ring for CeC PoP at 26.5 GeV/nucleon, 186 hours

- parasitic fixed target operation in parallel

Dedicated LEReC electron beam commissioning at 1.6 MeV
CeC electron beam development, 13 weeks (6/19/18 – 9/17/18)

RHIC Run-19 detail

11 modes for physics

- Mode 1A: LEReC cooling commissioning with $^{197}Au^{79+}$ at 3.85 GeV/nucleon
- Mode 1B: $^{197}Au^{79+}$ on $^{197}Au^{79+}$ at 9.8 GeV/nucleon particle energy
- Mode 1C: $^{197}Au^{79+}$ on $^{197}Au^{79+}$ at 7.3 GeV/nucleon particle energy

- Mode 1D: $^{197}Au^{79+}$ at 7.3 GeV/nucleon particle energy on fixed target ^{197}Au foil inside STAR (3.93 GeV/nucleon COM energy)
- Mode 1E: $^{197}Au^{79+}$ on $^{197}Au^{79+}$ at 3.85 GeV/nucleon particle energy

- Mode 1F: $^{197}Au^{79+}$ at 3.85 GeV/nucleon particle energy on fixed target ^{197}Au foil inside STAR (3.22 GeV/nucleon COM energy)
- Mode 1G: LEReC cooling commissioning with $^{197}Au^{79+}$ at 4.59 GeV/nucleon

- Mode 1H: $^{197}Au^{79+}$ at 4.59 GeV/nucleon particle energy on fixed target ^{197}Au foil inside STAR (3.00 GeV/nucleon COM energy)
- Mode 1I: $^{197}Au^{79+}$ on $^{197}Au^{79+}$ at 4.59 GeV/nucleon particle energy

- Mode 1J: $^{197}Au^{79+}$ at 31.2 GeV/nucleon particle energy on fixed target ^{197}Au foil inside STAR (7.74 GeV/nucleon COM energy)
- Mode 1K: $^{197}Au^{79+}$ on $^{197}Au^{79+}$ at 100 GeV/nucleon particle energy