C-AD through 2025 and EIC

Michiko Minty
Accelerator Division Head, C-AD

RHIC Retreat,
30 August 2023

Brookhaven National Laboratory
U.S. DEPARTMENT OF ENERGY
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RHIC Science Priorities

NSAC Long Range Plan

NPP Program Advisory Committee

RHIC Run Scenarios

RHIC in the 2015 NSAC* Long Range Plan

"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC:

(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.

(2) Map the phase diagram of QCD with experiments planned at RHIC."

Next NSAC LRP in planning process with report anticipated this year. Subcommittees and white papers available at https://nuclearsciencefuture.org

* Nuclear Science Advisory Committee (NSAC) – advises the DOE and NSF on the national program for basic nuclear research, NSAC DFO (Designated Federal Officer): Dr. Tim Hallmann

NPP Program Advisory Committee (PAC) 2022

"The PAC has endorsed sPHENIX as the highest priority construction project and scientific program in 2023-2025 …"

- "The PAC continues to strongly supporting focusing in Run 23 on sPHENIX commissioning using 200 GeV Au+Au collisions. This is the highest priority and must come first."
- "STAR has made a strong case for a broad, diverse, and complementary science program that it will be able to carry out using Au+Au data, beginning in Run 23."
- "… the PAC anticipates revisiting the questions of how to optimize Runs 24 and 25 next year … at present we support running pp and p+Au in Run 24, and Au+Au in Run 25."

2023 NPP PAC meeting on 11-12 Sep 2023 will provide further guidance on science priorities.

RHIC Run Scenarios 2023 - 2025

(presented to DOE-NP in FY2025 Budget Briefing, Feb 2023)

Year	Scenario 1	Scenario 2
2023	25 cryo-weeks with sPHENIX and STAR Au+Au at 200 GeV	25 cryo-weeks with sPHENIX and STAR Au+Au at 200 GeV
2024*	20 cryo-weeks with sPHENIX and STAR $p^{\uparrow}+p^{\uparrow}$ at 200 GeV	20 cryo-weeks with sPHENIX and STAR $p^{\uparrow}+p^{\uparrow}$ at 200 GeV
2025	24 cryo-weeks with sPHENIX and STAR Au+Au at 200 GeV	28 cryo-weeks with sPHENIX and STAR Au+Au at 200 GeV

- **Run 2023 priority: sPHENIX commissioning**
- **Run 2024 priority: pp reference data**
  - **p+Au**
- **Run 2025 priority: Au+Au**

- Run 2023 (original plan): 20 cryo-weeks for commission and physics, 5 cryo-weeks for sPHENIX magnet testing and mapping
- Budget challenges with Run 2024 and 2025
- New challenge with ending Run 2023 earlier

* Run 2024: six cryo-weeks of Au+Au at 200 GeV approved for carry-over from FY23

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RHIC Runs 2023 - 2025

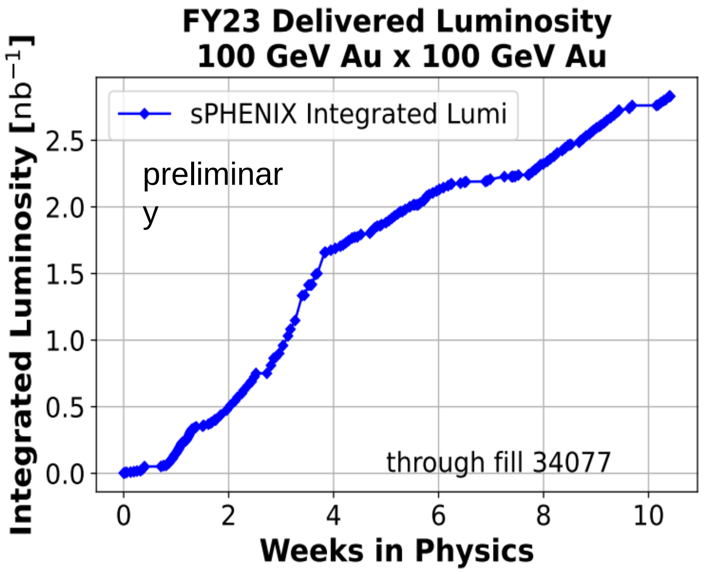
RHIC Run 2023

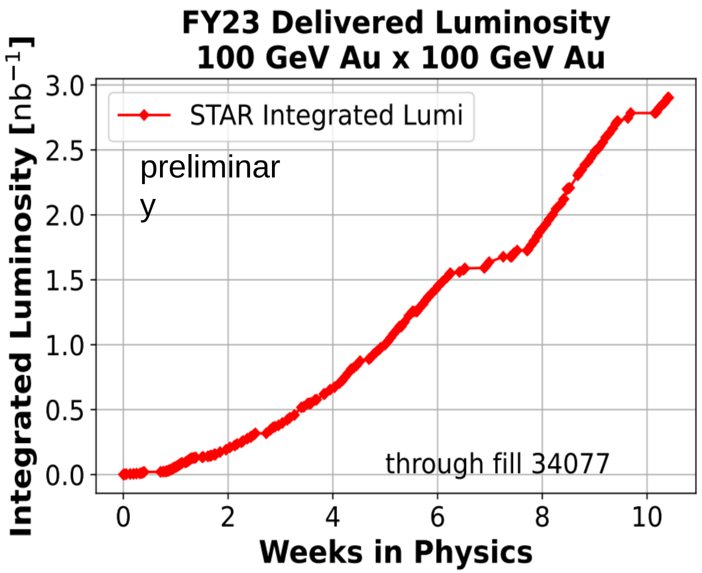
Timeline

- 4K cooldown — 5 May 2023
- First beam injection — 8 May 2023 (Blue)
  10 May 2023 (Yellow)
- 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

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

DOE noted favorably the "great flexibility in providing various running conditions" and "RHIC, STAR, PHENIX, and soon to be sPHENIX programs are some of the most spectacular enterprises in Nuclear Physics" (T. Hallmann, 2023 RHIC S&T Site visit, Aug 2023)





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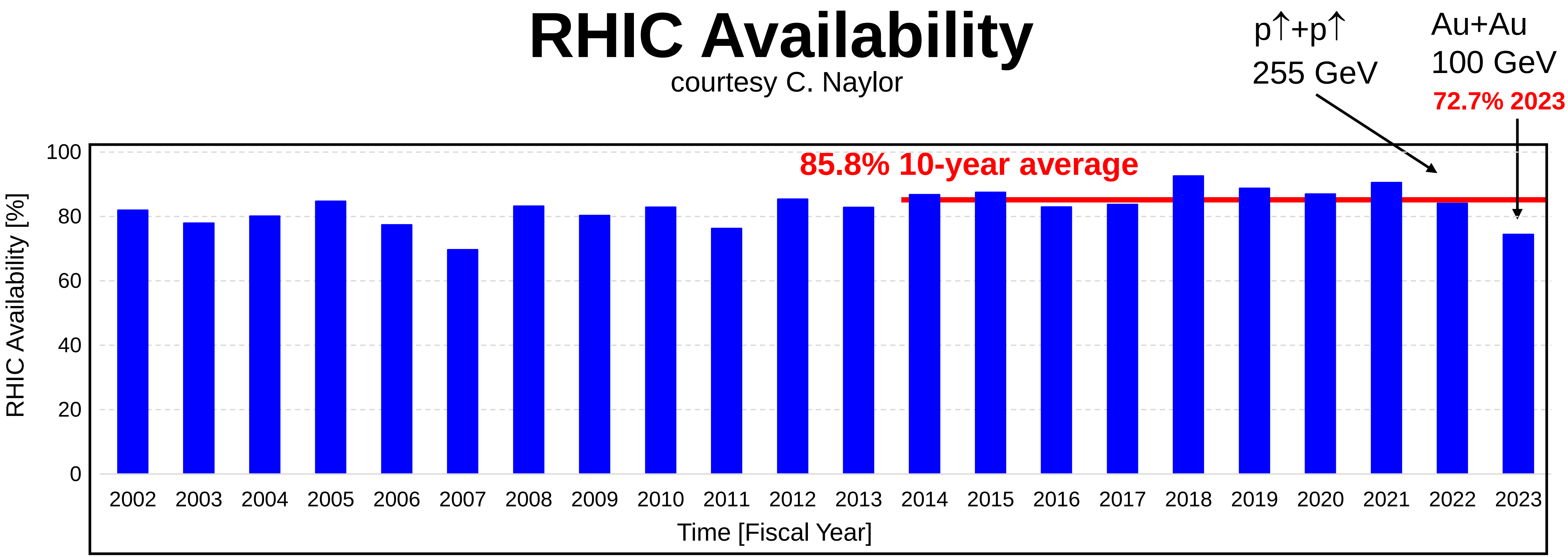
RHIC Availability

courtesy C. 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: 72.7%

Average over last 10 years: 85.8%

Availability impacted by environmental factors (heat, humidity, storm-related issues).
Early start for RHIC Runs 24-25 planned (8 Jan 2024 for Run 24)

Supply chain and inflation*: Helium and Electrical Costs

*Thank you to all for providing input for the S&T review

Electrical costs   no fixed price contract, price volatility

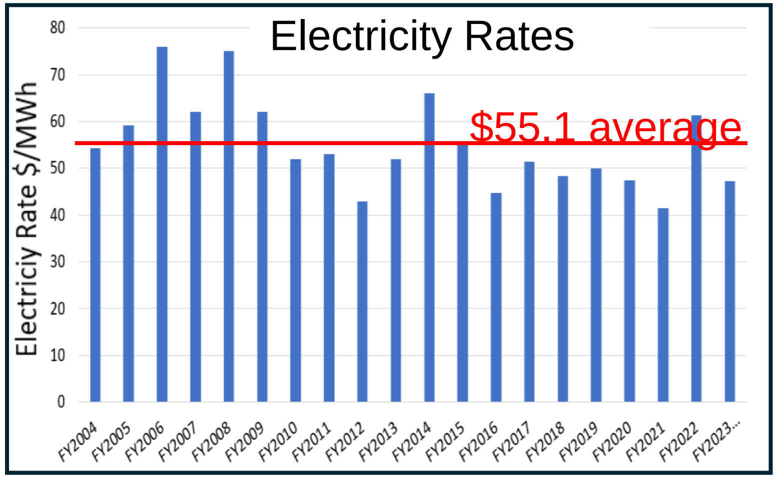
FY21: $41.4/MWh

FY22: $61.4/MWh

FY23: $47.3/MWh actual

(had planned for $70.0/MWh)

FY24: planning for $82.4/MWh (conservative)



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

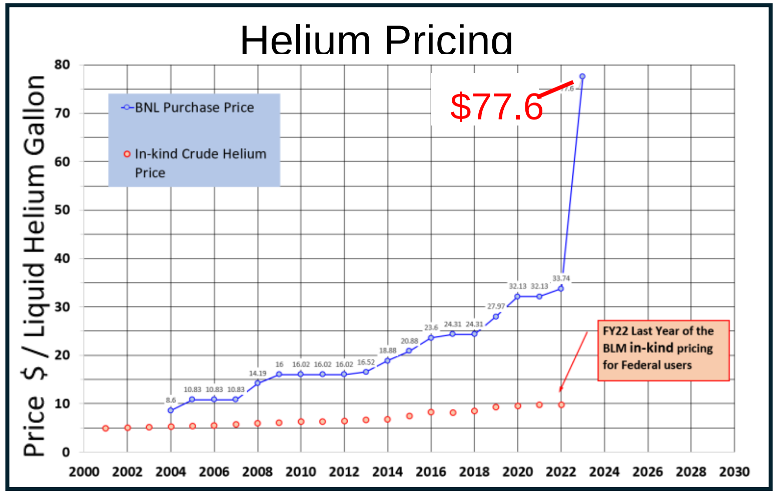
FY21: $32.1/LHe gallon

FY22: ~$33.7/LHe gallon

FY23: $77.6/LHe gallon

(had planned for $50/LHe gallon)

FY24: planning for $77.6/LHe gallon



RHIC operating costs impacted by inflation which could affect duration of RHIC Runs 24-25

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Projections updated

		p↑+p↑					p↑+Au	
Parameter	Unit	FY2008	2009	2012	2015	2024E	FY2015	2024E
No of colliding bunches k_b	…	109	109	109	111	111	111	111
Protons/bunch, initial N_b	10^{11}	1.5	1.3	1.6	2.25	2.5	225/1.6	225/1.6
Envelope function at IP β^*	m	1.00	0.70	0.85	0.85	0.85	0.85/0.70	0.85/0.70
Beam-beam parameter ξ/IP	10^{-3}	-5.3	-6.3	-5.8	-9.7	-9.7	-5.3/-4.1	-5.3/-4.1
Initial luminosity L_{init}	**10^{30} cm^{-2}s^{-1}**	**35**	**50**	**46**	**115**	**115**	**0.88**	**0.88**
Average/initial luminosity	%	65	56	71	55	55	51	51
Average store luminosity L_{avg}	**10^{30} cm^{-2}s^{-1}**	**23**	**28**	**33**	**63**	**63**	**0.45**	**0.45**
Time in store	%	60	53	59	64	64	65	65
Max. luminosity/week	pb^{-1}	7.5	8.3	9.3	25	25	140	140
Min. luminosity/week	pb^{-1}					17		100
$L_{avg}(\theta)/L_{avg}(0)$, full crossing angle $\theta = 1$ mrad	%					0.45		0.37
Max. luminosity/week, $\theta = 1$ mrad						11		51
$L_{avg}(\theta)/L_{avg}(0)$ for full crossing angle $\theta = 2$ mrad	%					0.25		0.19
Max. luminosity/week, $\theta = 2$ mrad						6		27
AGS extraction, P_{max}	%	55	65	72	68	68	68	68
RHIC store average, P_{max}	**%**	**45**	**56**	**59**	**57**	**57**	**60**	**60**

Luminosity projections reduced for Run-24 and Run-25

- challenging to re-establish peak performance after ~decade (Au+Au and p+p), assume previous performance as max now
- observed higher Secondary Electron Yield (SEY) in Run-23 compared to Run-22 – deconditioning of vacuum surfaces
- effect of Au beam longitudinal profiles on L reduction with crossing angle larger than calculated
- enhancement from 56 MHz SRF cavity (not yet re-commissioned with early end of Run-23) not included

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Accelerator Physics Experiments (APEX)

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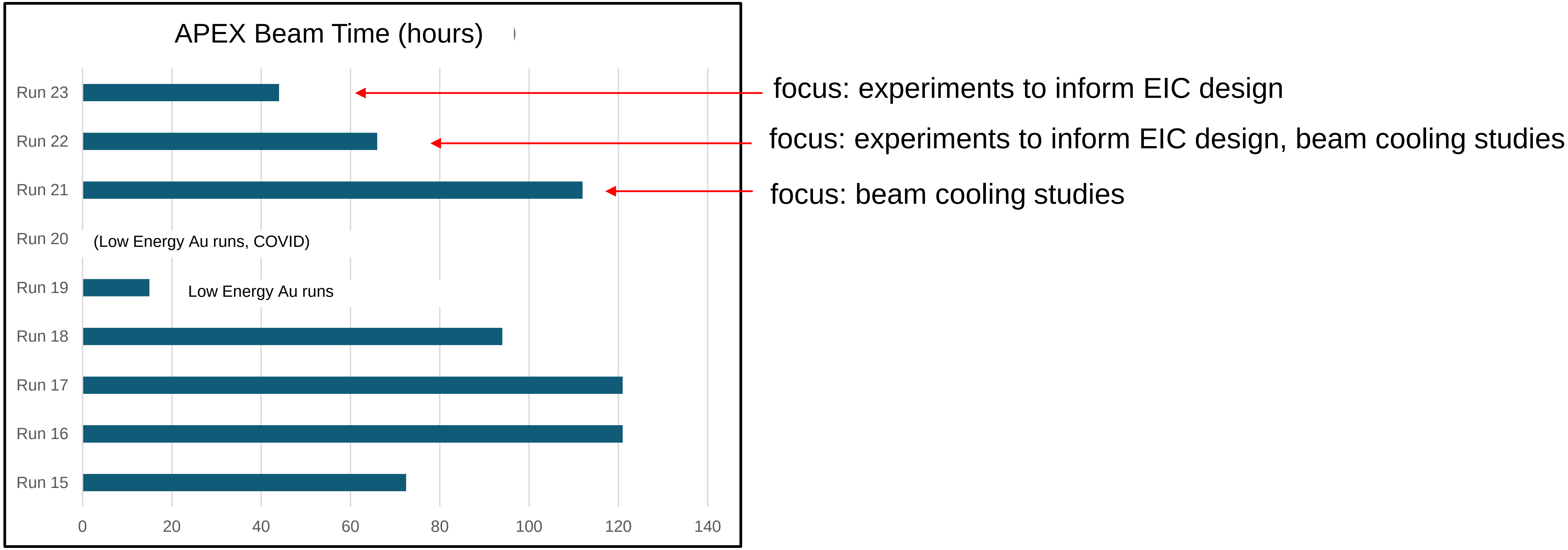
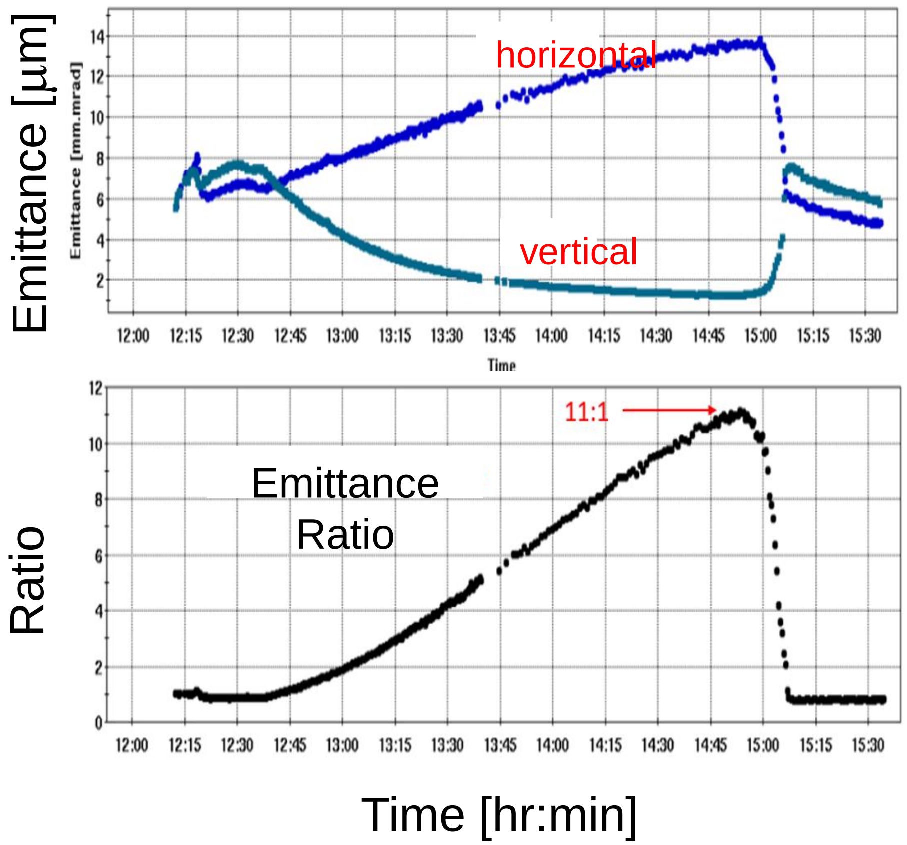
Recent APEX Overview

Y. Luo

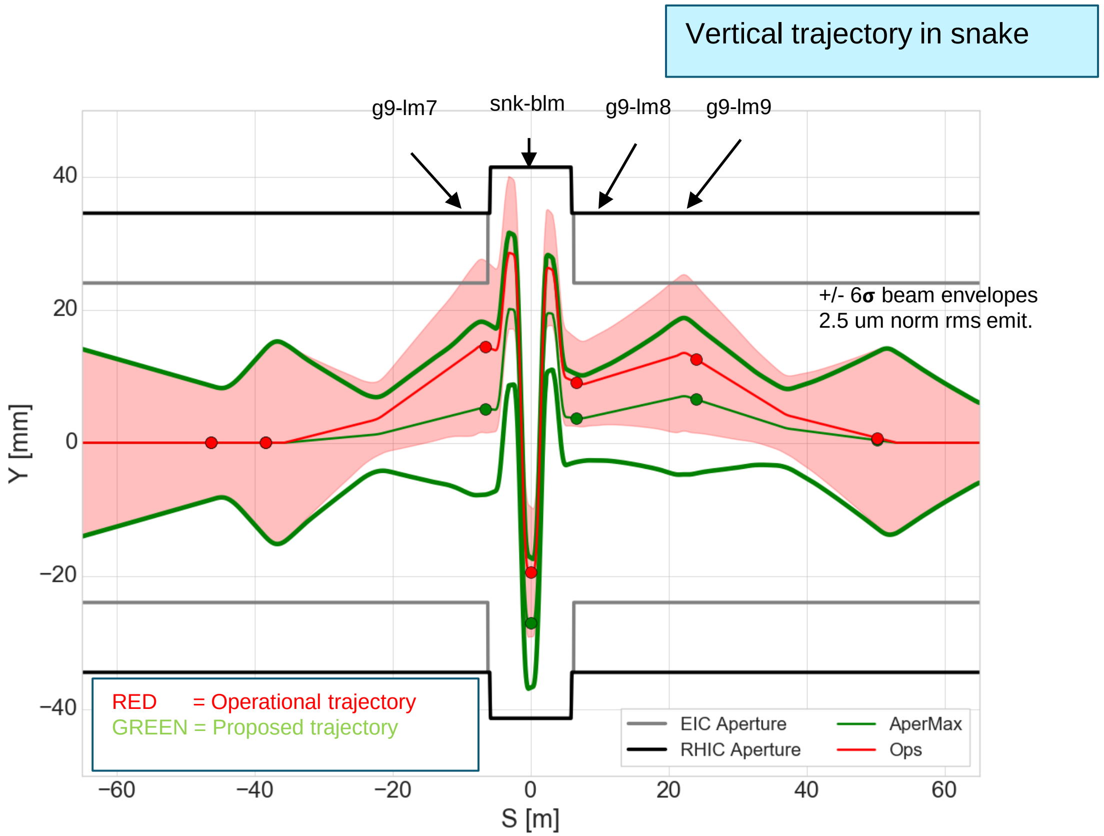


From DOE S&T Review (Aug 2023) : “The Lab is commended for the APEX activities during the shortened RHIC Run 23 on critical questions for EIC design. Demonstration of … are all directly related to the most important EIC beam parameters, the luminosity and polarization. The EIC project will benefit greatly from APEX activities in future runs.”

Two APEX highlights from RHIC Run 23



Precision Decoupling, Y. Luo et al. demonstration of >10:1 emittance ratio as required for the EIC.



Siberian Snake aperture optimization, V. Schoefer et al. Experiments demonstrated RHIC beam optics compatible with EIC vacuum chamber design.

Note: no experiments in beam cooling with RHIC beams took place in Run-23.

Transition from RHIC Operations to the EIC

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25+ Year Upgrade Plan

R. Michnoff
et al

Initiated in 2018 for RHIC, the injector complex with considerations for the EIC
Assessed annually based on need for

- performance upgrades
- upgrades of obsolete systems

Assumes no further large performance upgrades of RHIC after LEReC until end of RHIC operations
Next update mid-Oct, 2023

Upgrade Plan and 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 near-term plans to allow new systems to be tested prior to the end of RHIC beam operations

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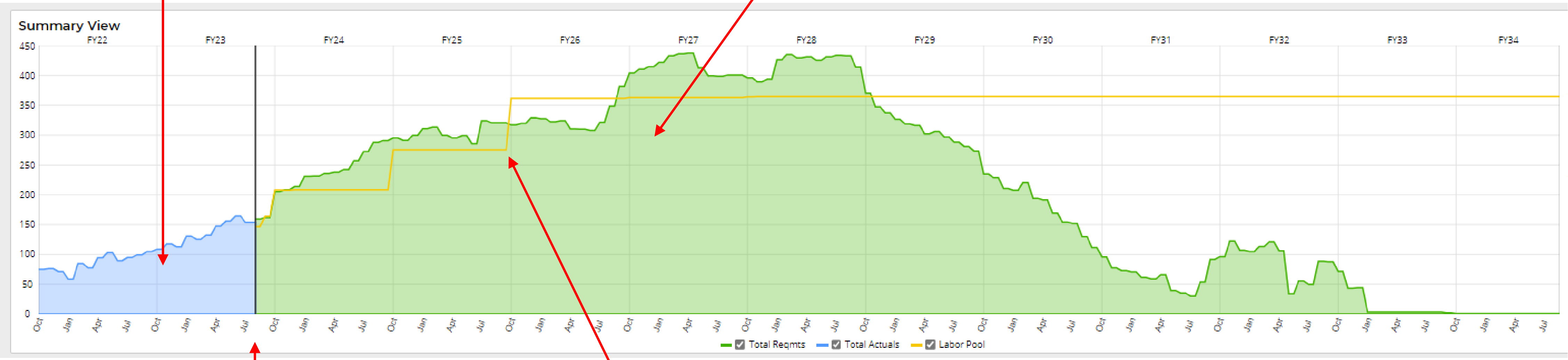
Staffing

D. Hatton et al

Actual labor charges to EIC

EIC Staffing Requirements



Data Date – August 18, 2023

Staff Available to work on EIC

- staff requirements for the EIC Project will be finalized at CD-2
- anticipated staffing requirements exceed staff availability (C-AD and EIC combined)

EIC - related R&D

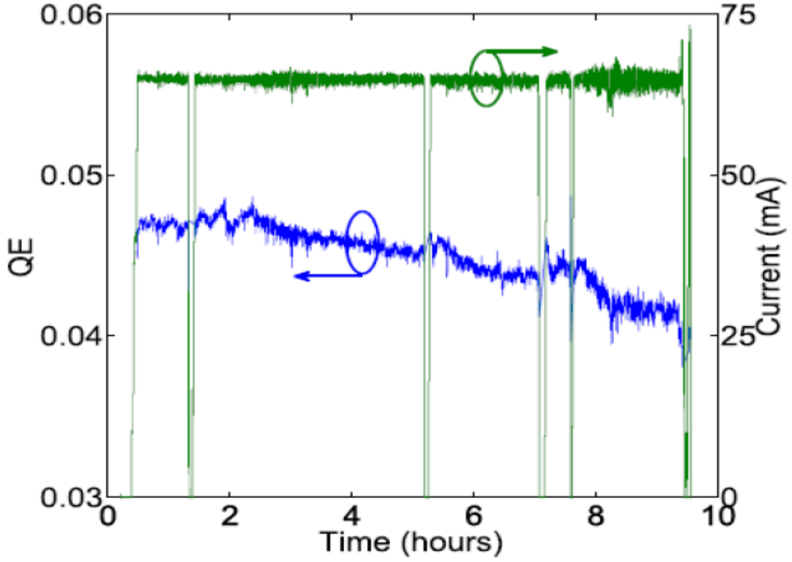
High-current electron guns, NC

From W. Fischer
22 Aug 2023
DOE NP RHIC Site Visit

EIC electron beam coolers require stable long-term electron source with ~100 mA for
low-energy coolers (13 and 22 MeV electrons)
high-energy cooler (150 MeV electrons)

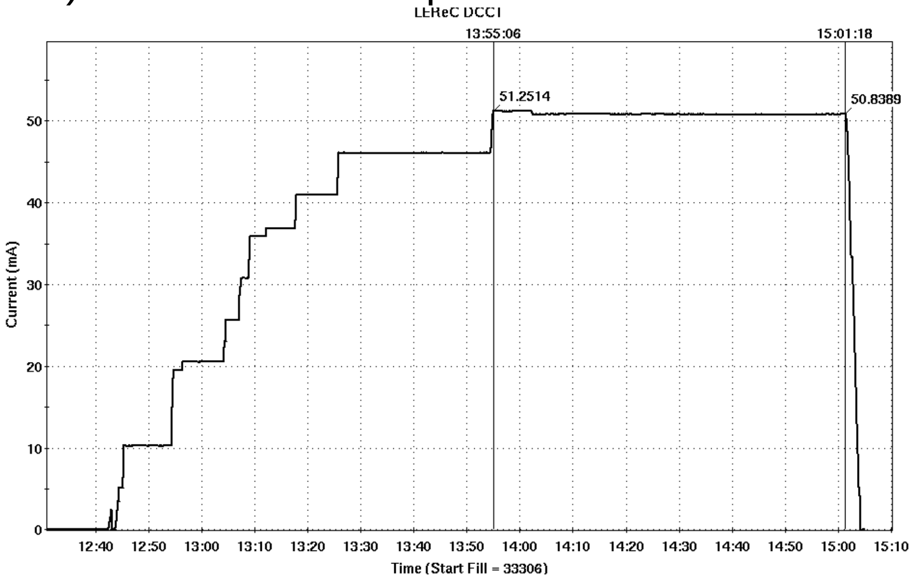
Operational experience with DC guns to date:

Cornell University DC gun:
Demonstrated 65mA over several hours



Dunham et. al. APL 102, 034105 (2013)

LEReC DC gun:
1) 24/7 operation at about 20 mA current (2020-21)
2) Achieved stable operation at 50mA in tests (April 2022)



Future work:
LEReC Gun: Explore operation at high currents up to 100mA.
EIC R&D: 500kV inverted gun under design.

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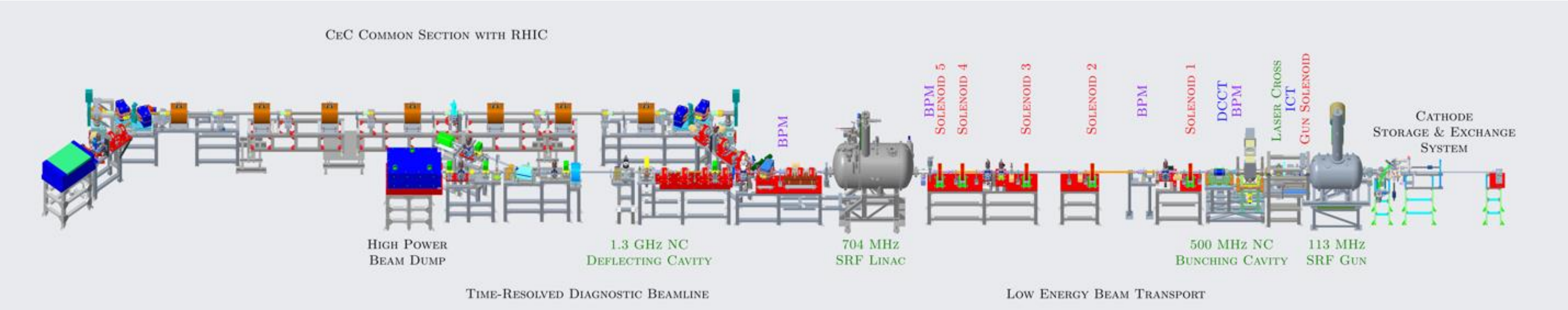
High-current electron guns, SRF

From W. Fischer
22 Aug 2023
DOE NP RHIC Site Visit



Increase average SRF unpolarized e-beam to

- 1-3 mA in Phase I
- 30-100 mA in Phase II

Phase I: high rep-rate seed laser, new quadrupoles and solenoids, new MPS and diagnostics

Phase II: requires significant modification of the SRF gun and additional funding for

1. new Fundamental Power Coupler (FPC).
2. 100 kW CW RF system in the Bldg. 912 at BNL.
3. assembly and tests of 100 kW FPC and supporting accessories.
4. procurement and tests of the cavity tuner.

Machine Learning at C-AD

From W. Fischer
22 Aug 2023
DOE NP RHIC Site Visit

- Gaussian Process (GP) Bayesian Optimization (BO), applied to LEReC
- Emittance Measurement Speedup with Machine Learning at CeC & NSRL
- Accelerator self-diagnosis and automating ORMs
- Reconstructing transfer functions using beam-based analysis (Booster)
- Polarization, FOA funded (10/23-09/25), goal: 5% increase
- Natural Language Processing (NLP) for elogs and other apps
- Ionization Profile Monitor Channel Gain Calibration with ML
- Anomaly detection from RHIC Cryogenics data
- Adopting and using XOpt and Badger (and eval of Geoff and COI)
- Collaboration with FNAL/JPARC for slow spill control
- Optimization of a Longitudinal Bunch Merge Gymnastic with ML
- RadiaSoft collaboration – Virtual emittance diagnostic (using IPMs & other instruments)

Accelerator Safety

Accelerator Safety - Readiness Reviews and USIs

- Booster/LINAC
  - IRR: July 2025
  - ARR: September 2025
- AGS
  - IRR: July 2026
  - ARR: September 2026

Expectations for All Staff when performing work

- up-to-date procedure MUST be present and used at the job site
- performing work with an incomplete work permit (specifically signatures and review) is NOT ALLOWED
- pre-job briefings ARE ALWAYS REQUIRED, note: walkdown during review of work permit is not the same as the pre-job briefing
- constructive feedback (procedures and work plans) is welcome and encouraged

Supplementary Slides

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

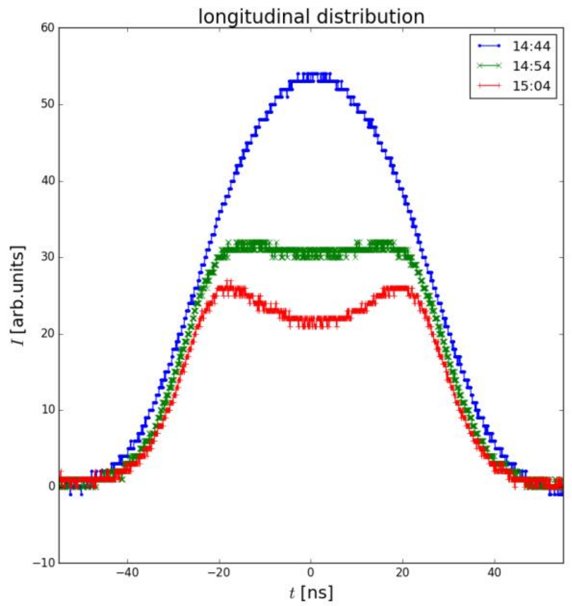
- Analyzed data from APEX 2022 and published (details in backup slides):

  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

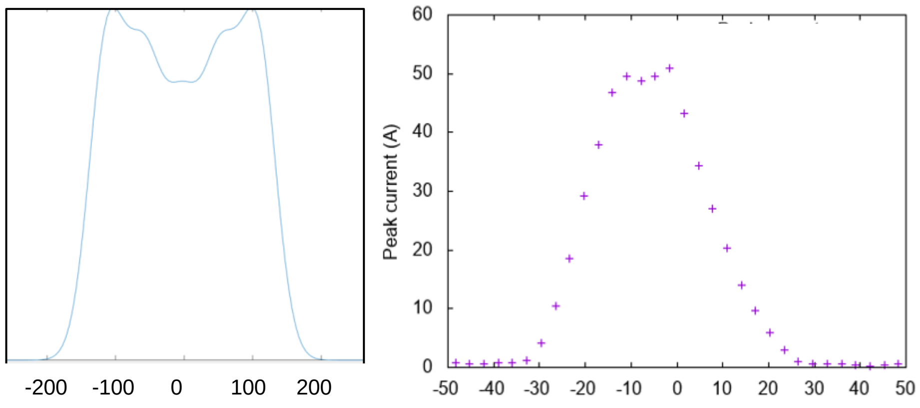
- Electron beams re-established in 2023 reproducing design beam parameters.
- APEX for LEReC this year (10 hours) was devoted to establishing 3.85 GeV beam (with 100 GeV initial conditions).

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-Gauusian) 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.

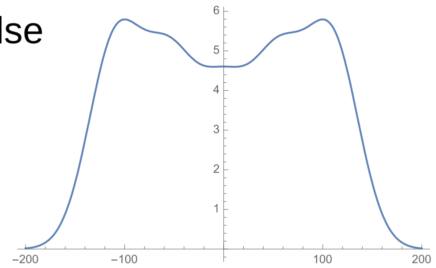
simulation: electron current distribution (in ps)

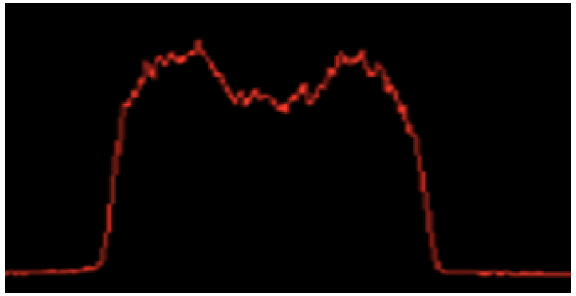


at gun

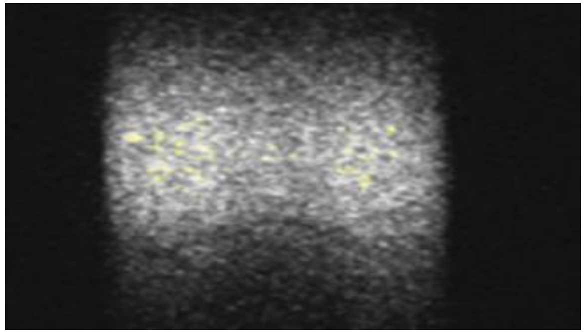
in cooling region

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.