

25 years of RHIC

Achieved performance and the role
of stochastic and electron cooling

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31 October 2025



New York City

Relativistic Heavy Ion Collider



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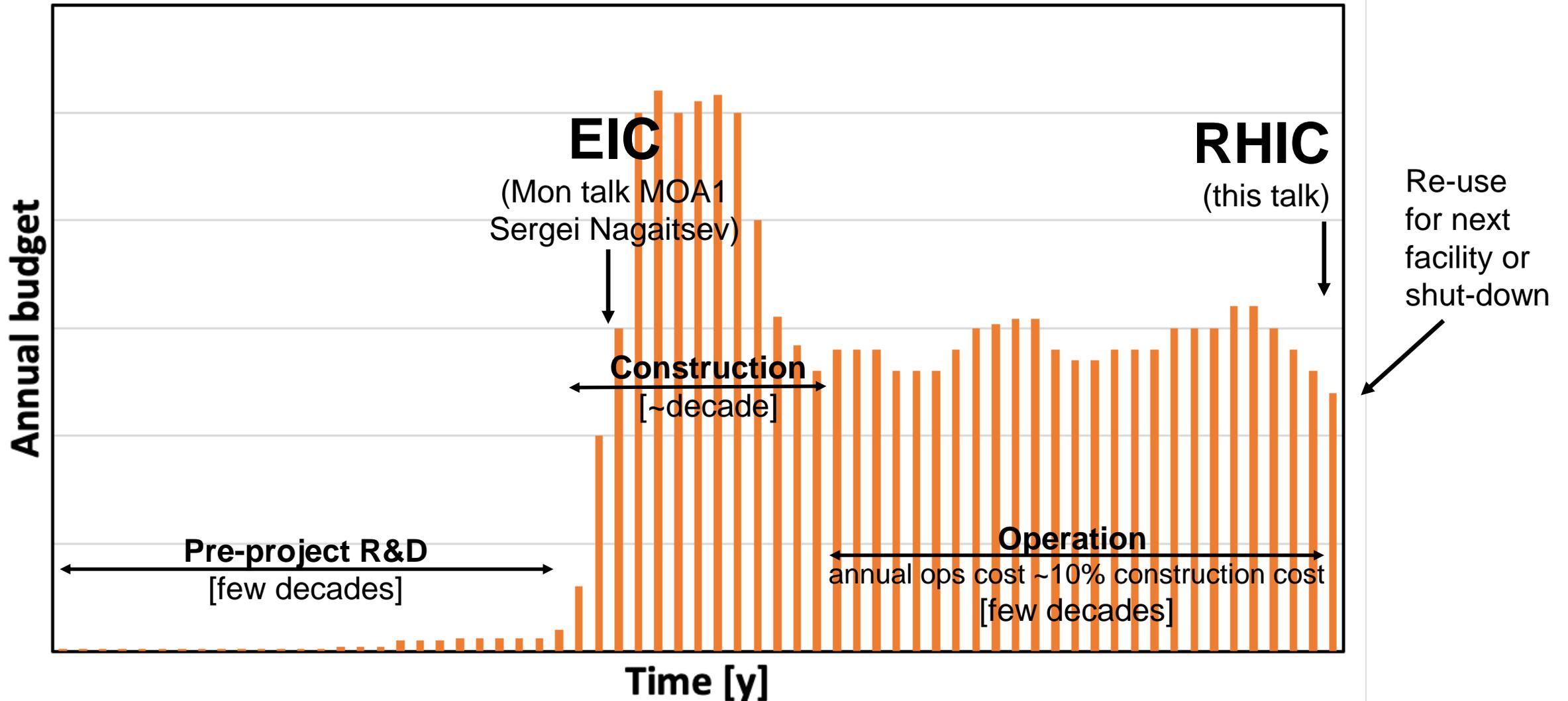
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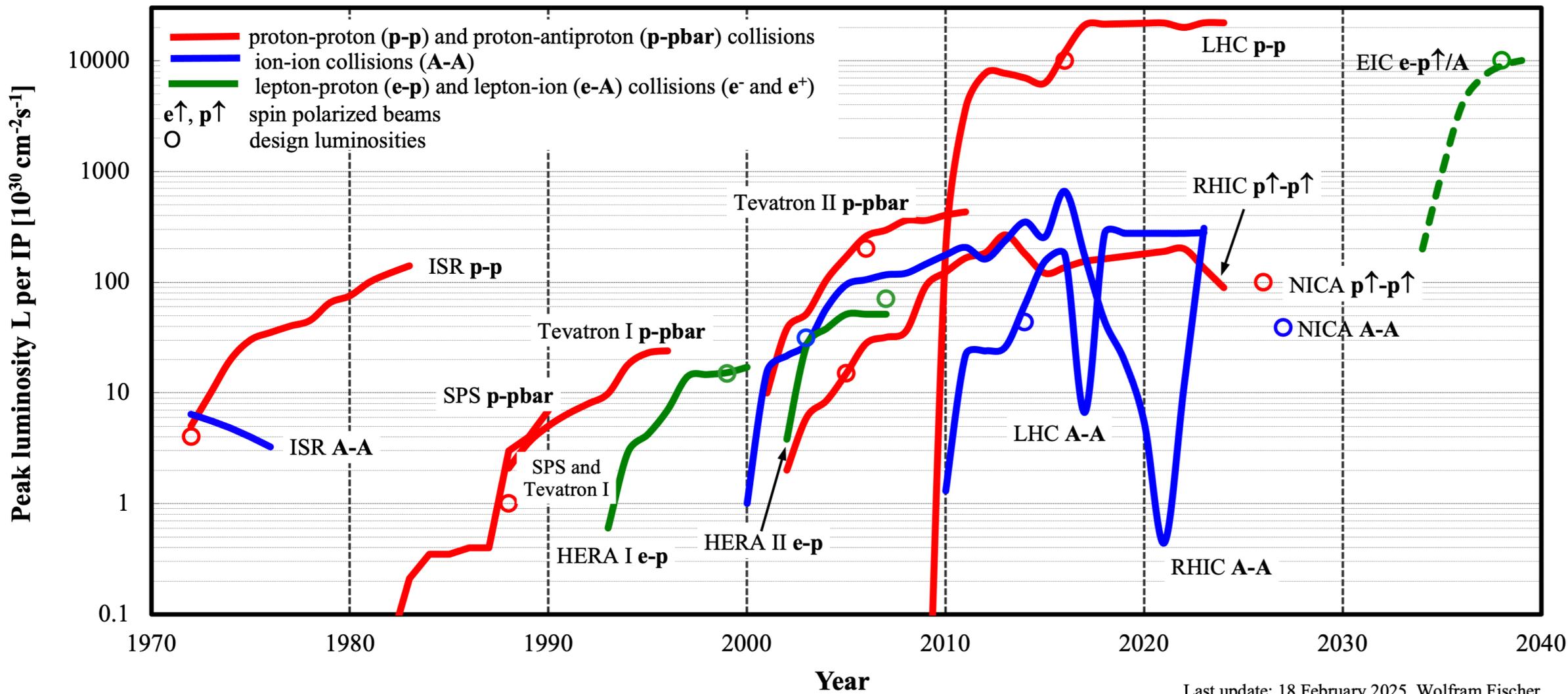
Contents

- Before RHIC
- The RHIC design
 - Ions
 - Polarized protons
- Performance evolutions
 - Luminosity, polarization
 - Species and “exotic runs”

Life cycle of a large accelerator facility



Luminosity evolution of hadron-hadron and lepton-hadron colliders



Last update: 18 February 2025, Wolfram Fischer

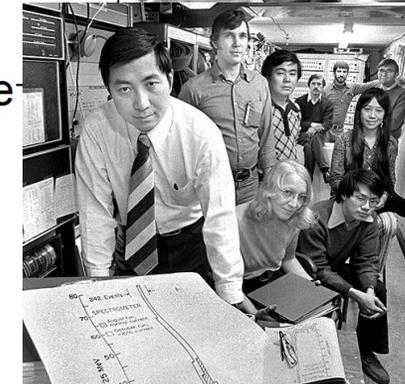
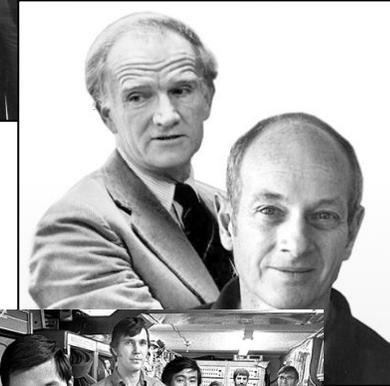
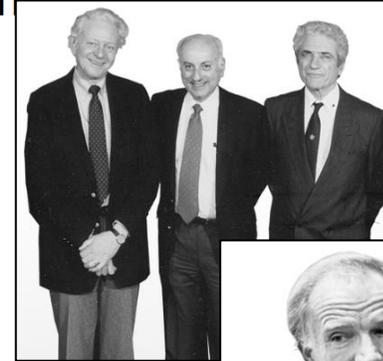
AGS Early History

the Discovery Phase

- **1952:** Strong focusing principle discovered (Courant, Livingston & Snyder) making AGS possible
 - Transition problem---electron analog
- **1960:** AGS Commissioned, 33 GeV protons **1959:** CERN PS
- **1962: Discovery,** Muon neutrino discovered (Schwartz, Lederman & Steinberger, 1960 proposal) – **1988 Nobel Prize**
- **1963: Discovery,** CP violation discovered (AGS E181, 1963, $K_2^0 \rightarrow \pi^+ + \pi^-$ Experiment, Cronin & Fitch) – **1980 Nobel Prize**
- **1964: Discovery,** Ω^- (Samios, 80” Bubble Chamber)
- **1974: Discovery,** $J(\psi)$ Particle Discovered (AGS E598, 1972, $p+Be \rightarrow e^+ + e^- + X$ Experiment, Ting) – shared **1976 Nobel Prize** with Richter for same discovery at SLAC (ψ particle)
- **1974: Discovery,** Charmed Baryon discovered (Samios, 7’ Bubble Chamber)

1968, AGS Conversion

No 200 MeV Linac yet (1970)
No 1.5 GeV Booster yet (1990)



ISABELLE

- Early 1970 studies for 200+200 GeV proton-proton collider superconducting magnets
- 3.8 km circumference, 6 intersection, AGS as injector
- At the same time Fermilab started working on the Tevatron
- Tunnel, office building, He cryo plant built (updated and still in use today)
- Only one working dipole prototype (Mark V) – sc cable issues
- 1983 canceled in favor of SSC (itself canceled in 1993)
- BNL quickly build a heavy ion physics program with AGS



Ernest Courant
1920-2020

Relativistic Heavy Ion Collider

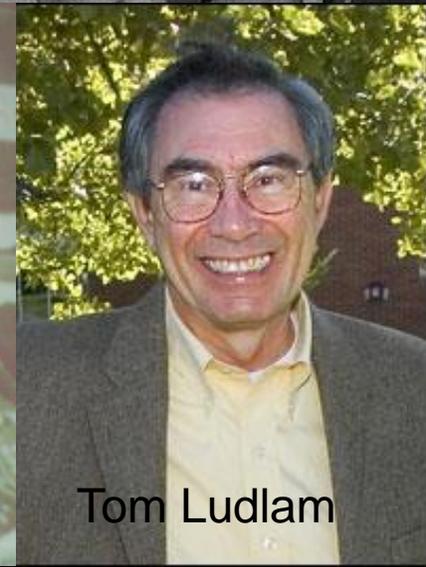
- 1984 began to think about heavy ion collider
- ~100 GeV/nucleon, dipoles ~3.5 T (5 T for ISABELLE)
- transfer line from Tandem, develop heavy ion beams in AGS, with heavy ion experiments
- 1991 construction begins
- 2000 first collisions



Satoshi Ozaki

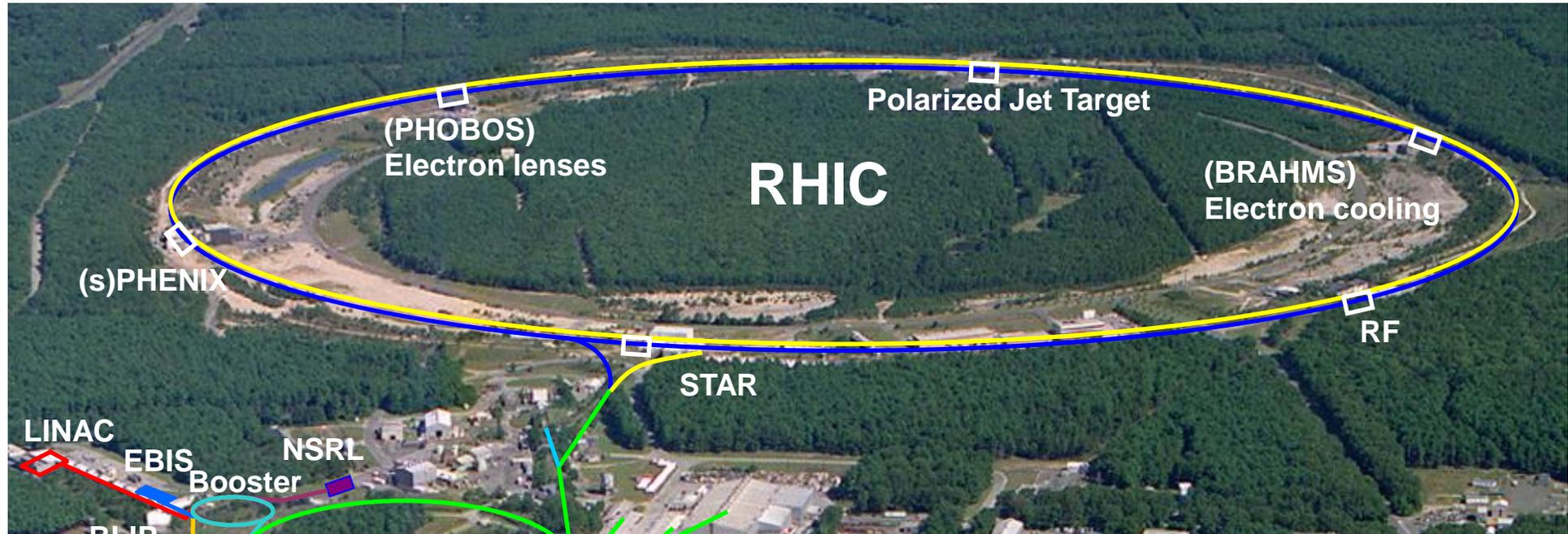


Mike Harrison



Tom Ludlam

Relativistic Heavy Ion Collider – main parameters



Start operation	: 2000
Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV polarized p : 100 GeV/nucleon Au
Species	: p↑ to U (incl. asymmetric)
Experiments	: BRAHMS, PHOBOS (complete) STAR, PHENIX→sPHENIX

RHIC Design Manual

July 1998

reached $L_{\text{avg}} = 88 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ (44x design)

Luminosity. The collider is designed for a Au-Au luminosity of about $2 \times 10^{26} \text{ cm}^{-2} \text{ sec}^{-1}$ at top energy, while maintaining the potential for future upgrades by an order of magnitude. Operation with the heaviest ions imposes the most demanding requirements on the collider design, and gold-on-gold is taken as the prototypical example. The luminosity is energy dependent and decreases in first approximation proportionally to \sqrt{s} . reached $L_{\text{avg}} = 24.8 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ (25x design) with $P_{\text{avg}} = 57\%$ will be higher, with $\sim 1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ for pp collisions.

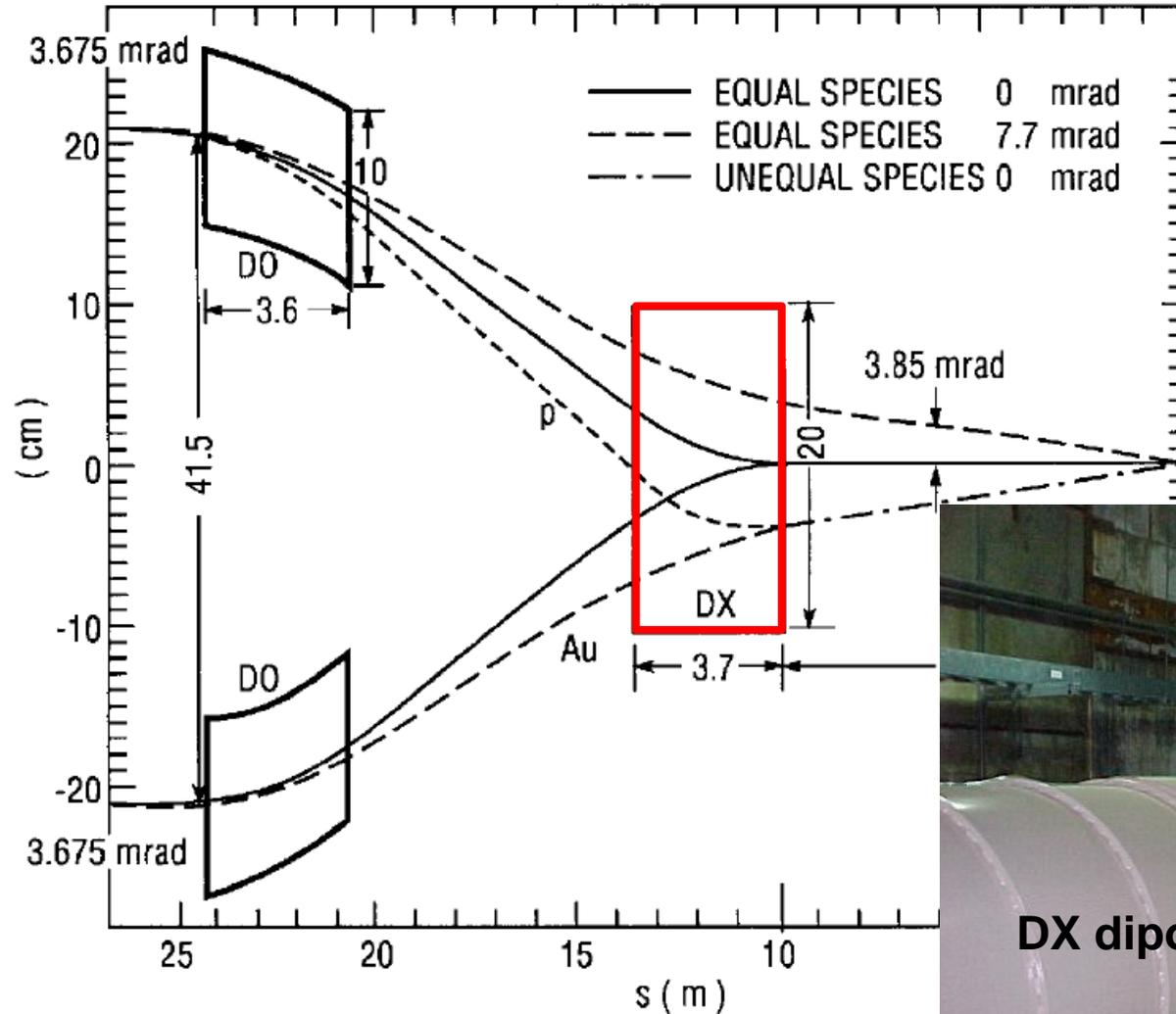
Range of ion masses. The expectations for interesting physics phenomena require a broad range of nuclei from the heaviest to the lightest, including protons. Asymmetric operation with heavy ions colliding on protons is considered to be crucial for the experimental program. The collider will allow collisions of beams of equal ion species from Au-Au all the way down to p-p. It will also allow operation of unequal species such as protons on gold ions.

Uranium is a viable species and can be considered as a future upgrade. However, at the present, an adequate source for uranium does not exist at Brookhaven and further R&D will be needed to achieve this goal.

Intersection Regions. The existing tunnel and the magnet lattice configuration provides for six experimental areas where the circulating beams cross. Three of the experimental areas presently

RHIC Design Manual (July 1998)

IR design with beam splitting DX dipoles first



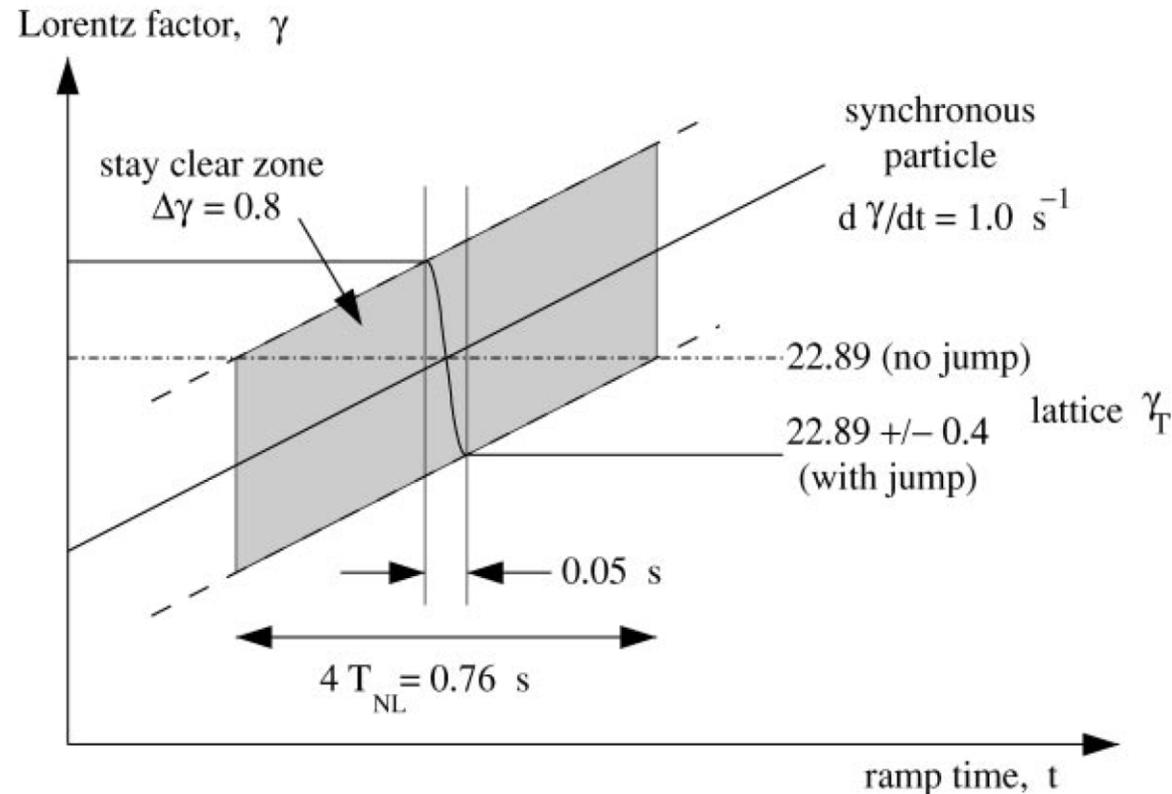
DX dipoles

- $L_{\text{mag}} = 3.7 \text{ m}$, $B_{\text{max}} = 4.3 \text{ T}$
- large aperture (18 cm coil ID)
- only magnets that need training (~5 for IR6/8 only)

← Interaction Point



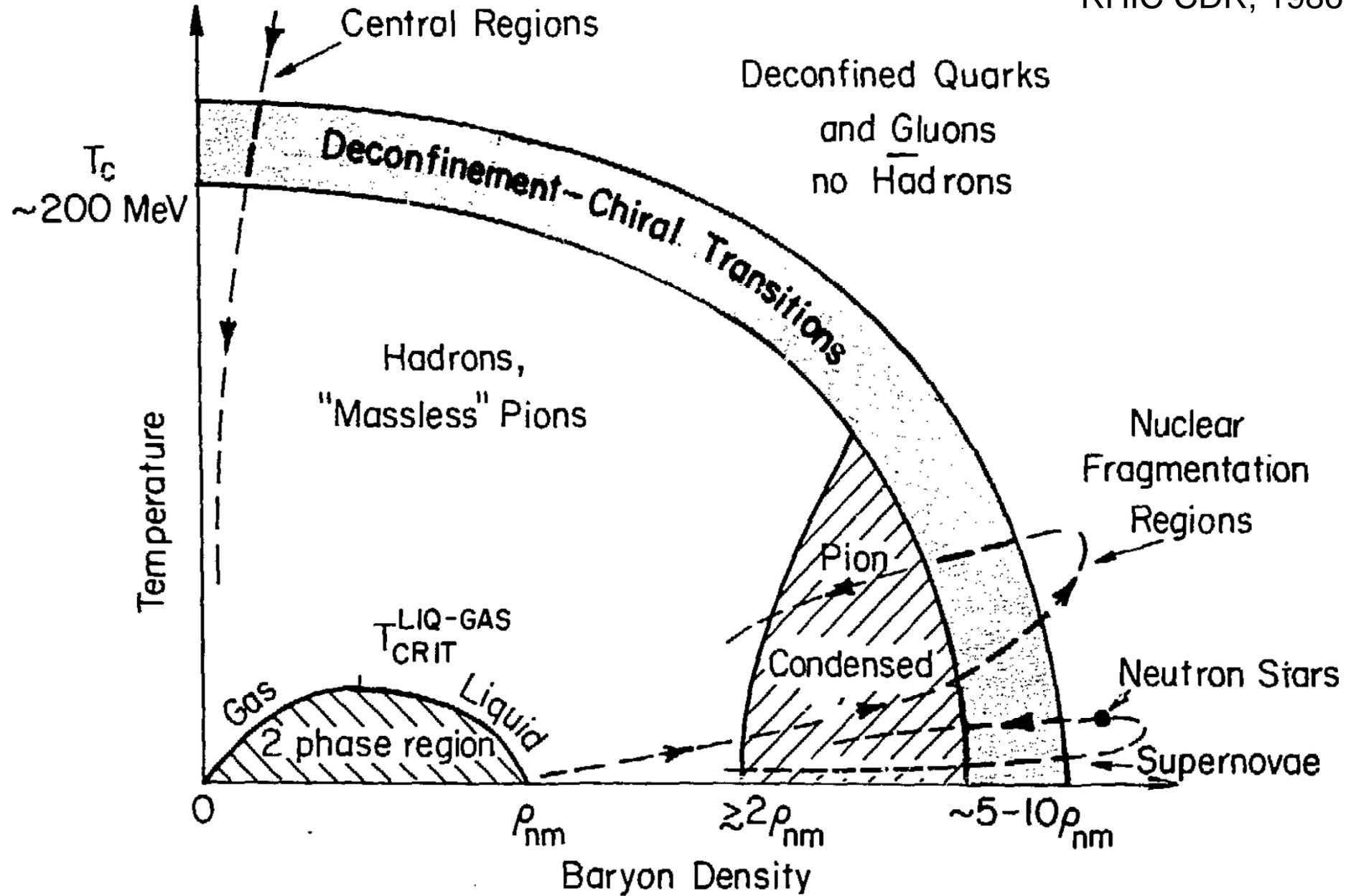
Transition crossing – with sc magnets



Did limit intensity
for some time:

- Initially no gamma-t quads
- Electron clouds
- Instabilities

Figure 12 Schematic representation of the RHIC transition jump. Transition is crossed about 15 times faster with the jump than without.



on

RHIC Begins World's Highest Energy Heavy-Ion Collisions

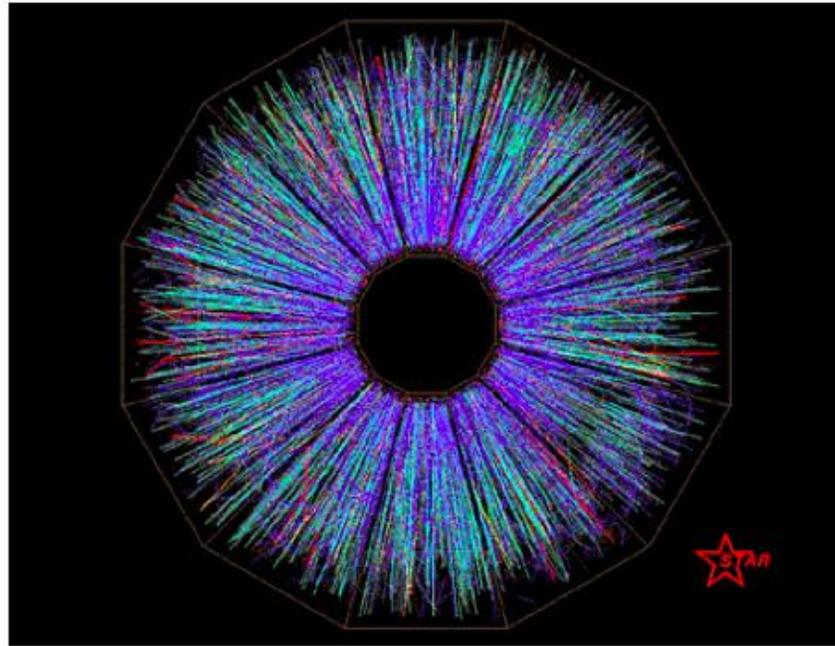
On the evening of Monday, June 12, operators in the main control room of the Relativistic Heavy Ion Collider (RHIC) watched control displays anxiously as the beams circulating in the collider's twin rings appeared to be colliding.

"The atmosphere was tense and very exciting," said Thomas Roser, head of the Accelerator Division and run coordinator for RHIC's first collision run. "We were operating at nearly 30 billion electron volts (GeV) per nucleon, our target energy for first collisions,

"We are crossing into a new frontier of scientific inquiry."

and we knew the beams were crossing at the collider's intersection points. But we couldn't say for sure that we'd had collisions until we got definitive, corroborative evidence from the detectors."

All four of RHIC's detectors — BRAHMS, PHENIX, PHOBOS and STAR — were poised and ready to take data as the accelerator physicists began to steer the beams into collision, necessarily one detector at a time.



A view of a RHIC collision seen in the STAR detector. "We knew immediately that we'd seen a true, beam-on-beam collision because all the particle tracks clearly originated at the center of the beam tube and sprayed out in all directions," said John Harris of Yale University and head of the STAR team. The symmetric pattern of particle tracks contrasts dramatically with so-called background events the team had witnessed, where collisions between ions and gas particles in the beam tube produce tracks going in only one direction.

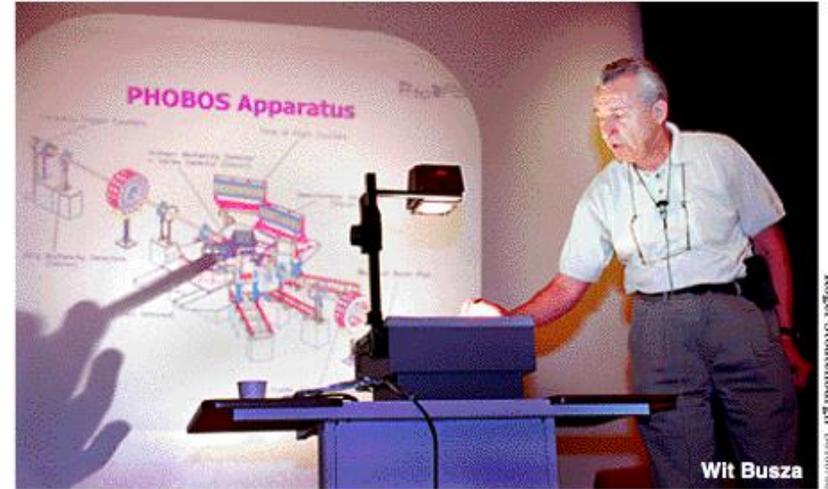
est and biggest particle a studies in nuclear physics crossing into a new frontier of inquiry," said Ener Bill Richardson upon his first collisions. "Scientists the world will use this to answer some of the most basic questions about the properties and evolution of our universe."

The collider aims to provide insights into the fundamental conditions of the early universe — and extends our understanding of matter — and extends our understanding of scientific inquiry through the 21st century.

Scientists will use data during the collisions to study particles known as quarks

The high temperatures and densities should allow a state of matter believed to have existed millions of years after the

PHOBOS Collaboration Presents First Physics Results From RHIC



The first physics results from the initial collisions at BNL's Relativistic Heavy Ion Collider (RHIC) were presented by the PHOBOS collaboration to a full house at Berkner Hall on July 19.

collisions. At the higher energy, the collisions achieved an energy density 50 percent higher than that observed for lead-lead collisions at CERN, the European particle physics laboratory."

As Busza explained, data for the

Configuration Manual Polarized Proton Collider, 2006

Parameter	
Peak c.m. energy	500 GeV
<u>Initial luminosity</u>	<u>$2 \times 10^{32} \text{cm}^{-2} \text{sec}^{-1}$</u>
Interactions per crossing (60 mb)	1
Protons per bunch	2×10^{11}
Bunches per ring	120
Normalized emittance (95%)	$20 \pi \text{ mm mrad}$
β^*	1 m
<u>Average polarization</u>	<u>70%</u>
Stable Spin direction at Interaction Point	vert. or long.
RF voltage per turn	6 MV
RF harmonic number	2520
Long. emittance (95%)	0.3 eV sec
Beam Momentum Spread	2.6×10^{-4}
Beam-beam tune spread (per IR)	0.007

reached $L_{\text{avg}} = 2.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

reached $P_{\text{avg}} = 57\%$ (avg. over 3D distribution and time)

Table 1.1: RHIC Spin Accelerator Parameters.

Early interest in cooling for RHIC

RHIC-AP-9

STOCHASTIC COOLING IN RHIC

S. Van der Meer

BNL, September 10, 1984

Simon Van der Meer, 1984

We now substitute

$\epsilon = 10 \times 10^{-6}/100$ m (divided by γ , assuming it was normalized)

$F = 6$ $\tau = 7200$ s

$W = 4 \times 10^9$ Hz $R_k = 50 \Omega$

$c = 3 \times 10^8$ m/s $n_k = 200$

$\tau_{\min} = 820$ s

and find a power of 0.4 W. This is very low (so we could use smaller n_k (or get faster cooling), but if ϵ would be the non-normalized value, we would need 4kW ! And note that there is no safety factor included; at least a factor 2 should probably be adopted. Also, I have not taken into account the reduction of transverse kicker sensitivity by the geometrical factor, the losses in hybrids, etc.

I hope that this gives you some impression of what could be done. Of course, this is not a serious design study, but rather an order-of-magnitude estimate.

If there are any problems, or if I have misunderstood something or made mistakes, please do not hesitate to write!

With best regards,

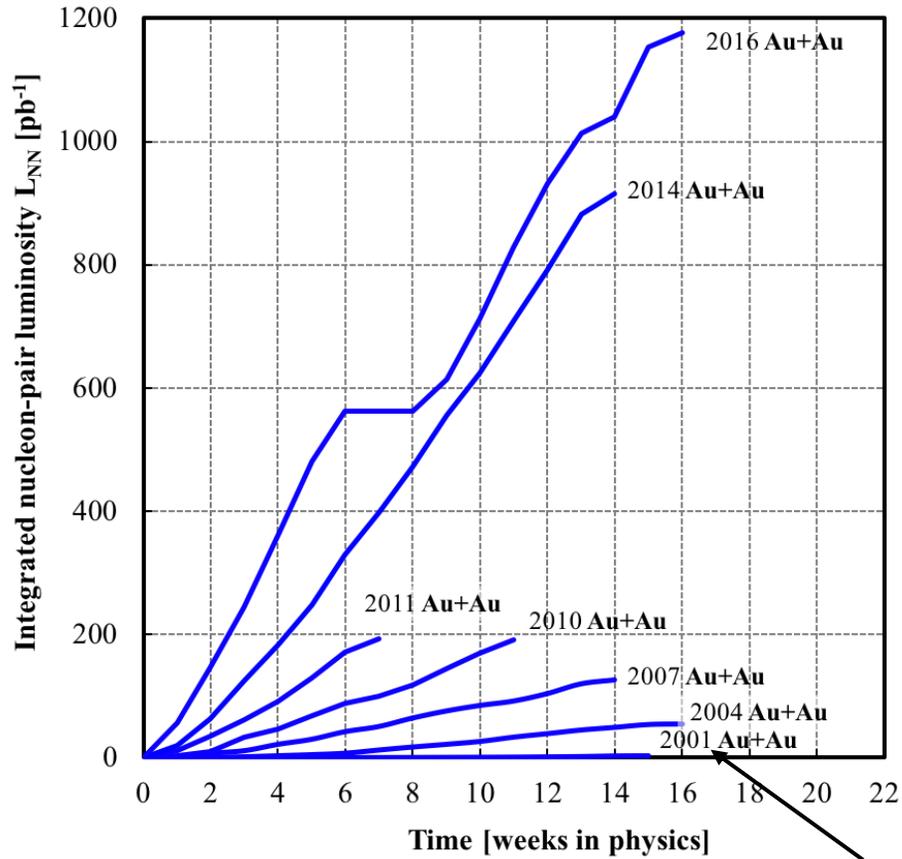


Microsoft Word

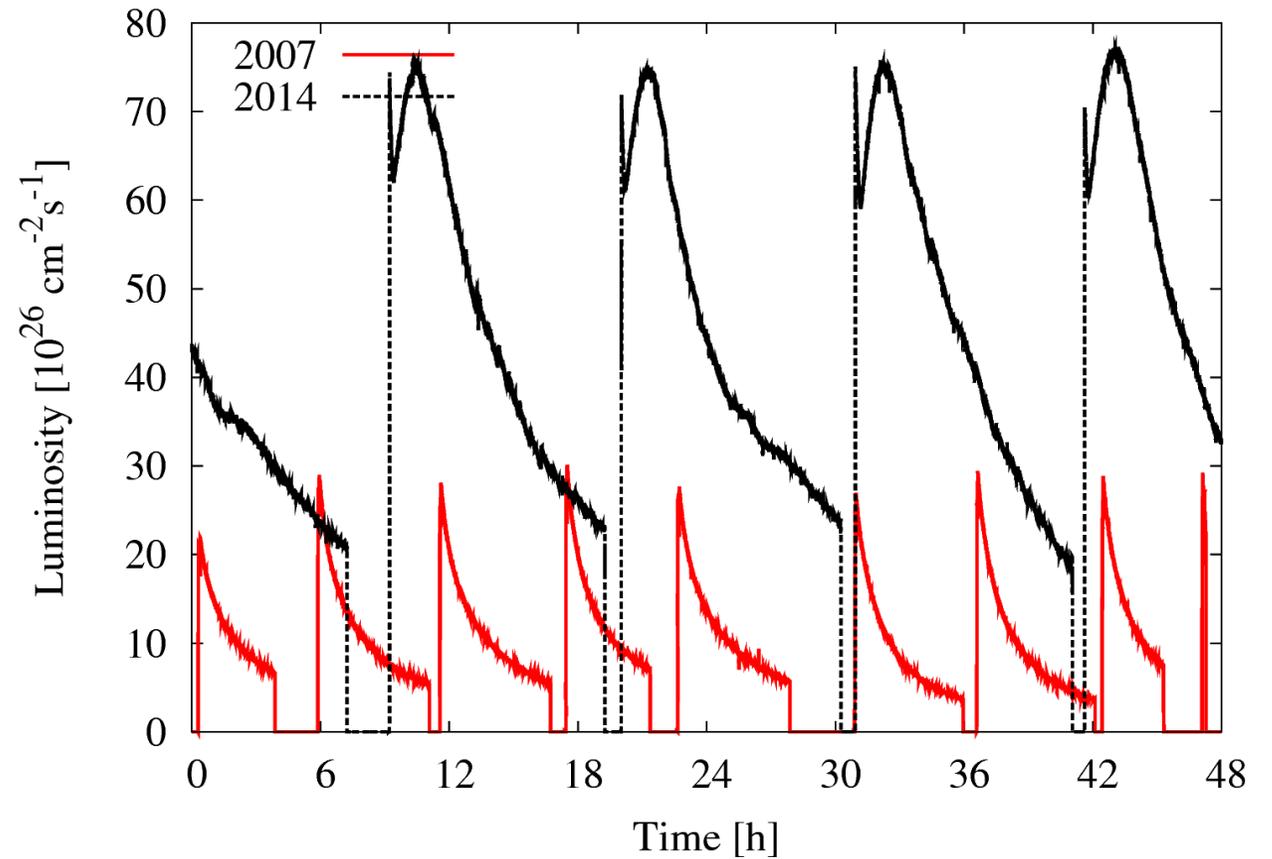
RHIC performance evolutions

- Au+Au luminosity at 100 GeV/nucleon
- $p\uparrow+p\uparrow$ luminosity and polarization (100 and 255 GeV)
- Medium heavy (Cu+Cu, O+O) ← only ion combination shared between RHIC and LHC is O+O (except for p)
- Asymmetric collisions ($p\uparrow+Au$, $d+Au$, $h+Au$, Cu+Au)
- U+U (non-spherical), Zr+Zr / Ru+Ru (same $A = 95$, max different $\Delta Z = 4$)
- Au+Au luminosity at 3.85 to 9.8 GeV/nucleon
(Beam Energy Scan, including a fixed target program)
- New detector for 2023 to 2025: sPHENIX

Heavy ions - time evolution of Au+Au



can now be done in 1/2 day
(200x faster)



RHIC Au+Au / U+U operation at full energy

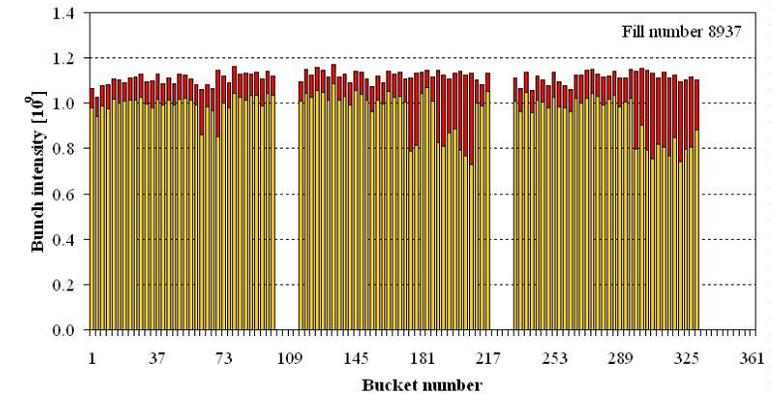
Performance limits – RHIC ions, high energy

- Bunch intensity N_b , limited by injectors
EBIS, bunch merges in Booster and AGS
transition instability
luminosity lifetime
aim for $>2 \times 10^9$ in store ultimately

- Intrabeam scattering
=> stochastic cooling

- Lattice with small β^* and large off-momentum dynamic aperture
with hourglass factor ≈ 0.5 at end of store, need large β^* reduction
any lattice change must not result in additional beam losses
dynamic β^* reduction after emittance decreased by cooling

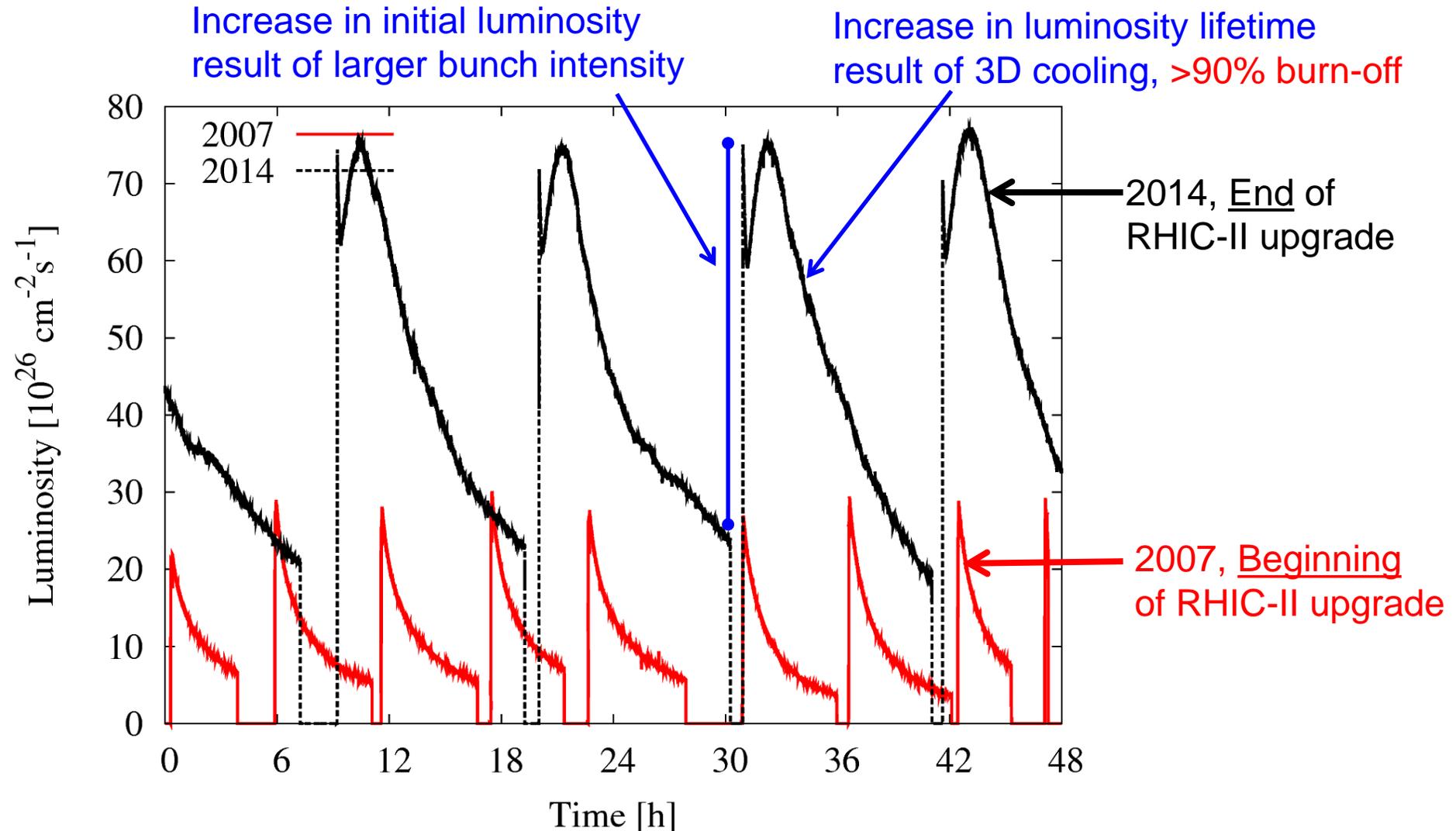
$$L(t) = \frac{1}{4\rho} f_0 N \frac{N_b^2(t)}{e(t) b^*(t)} h(b^*, s_s, q)$$



Goal is to have burn-off as the dominant beam loss mechanism.

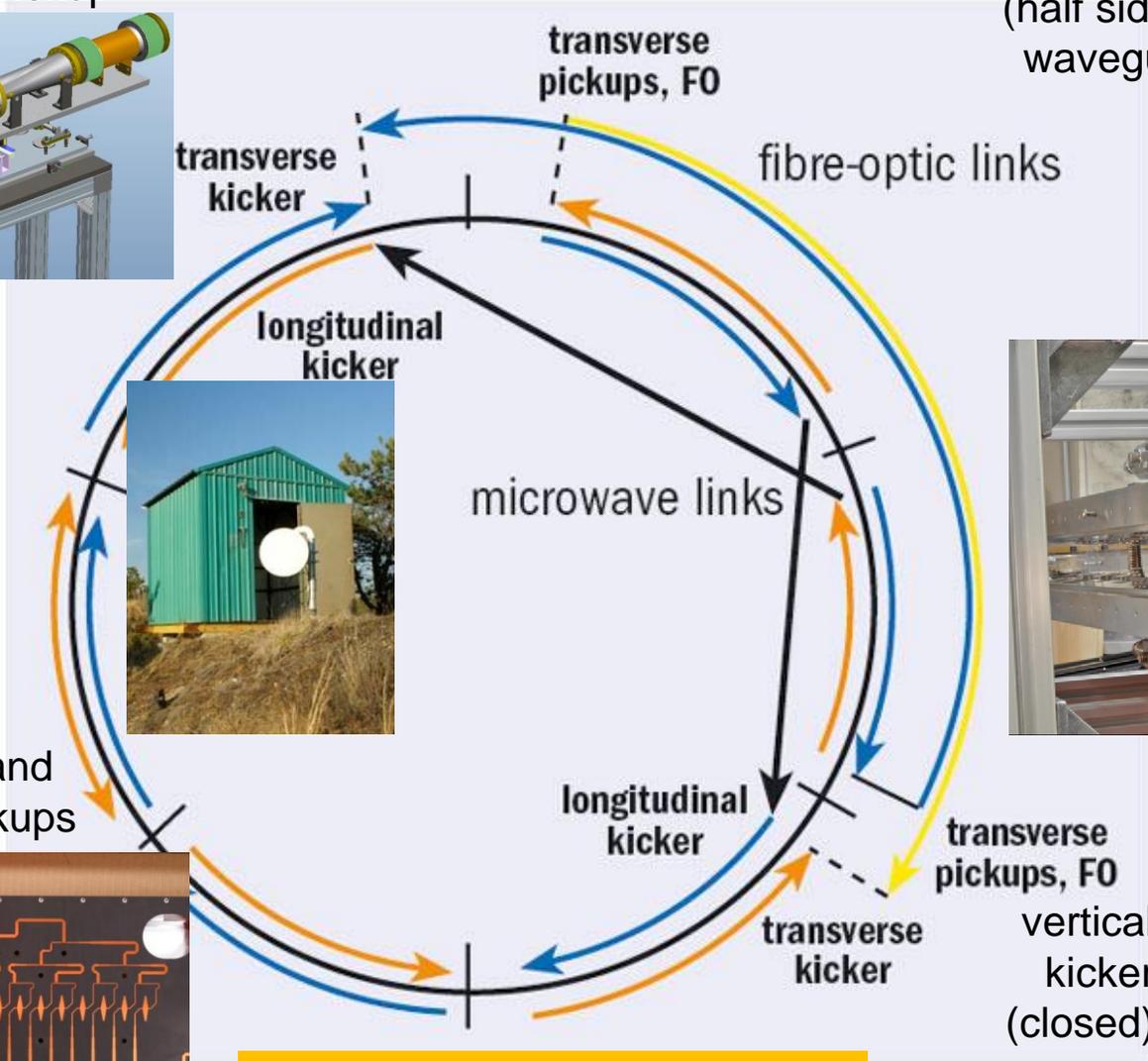
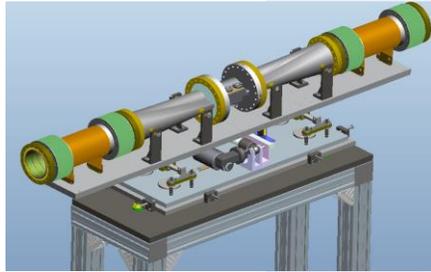
RHIC Run-14

Delivering RHIC-II luminosity



3D stochastic cooling for heavy ions

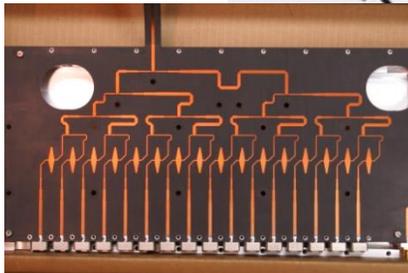
longitudinal pickup



longitudinal kicker cavity (half side with waveguides)

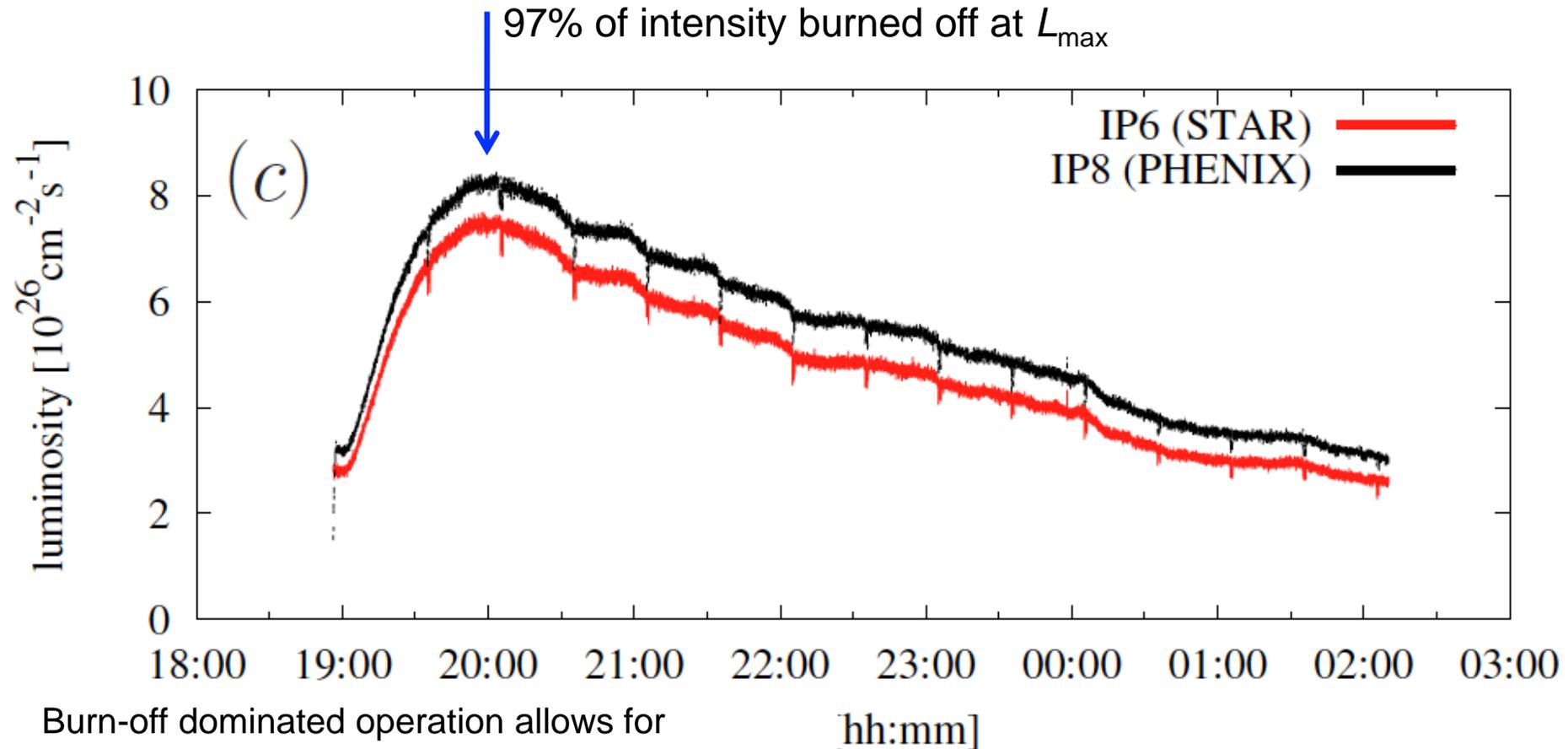


horizontal and vertical pickups



5-9 GHz, cooling times ~1 h

Operation at burn-off limit in U+U



Burn-off dominated operation allows for determination of total U+U cross section – and comparison with calculation (mostly QED) (published in Phys. Rev. C) =>

$$\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = - [\mathcal{L}_6(t) + \mathcal{L}_8(t)] \sigma_{tot}$$

Measurement of the total cross section of uranium-uranium collisions at $\sqrt{s_{NN}} = 192.8 \text{ GeV}$

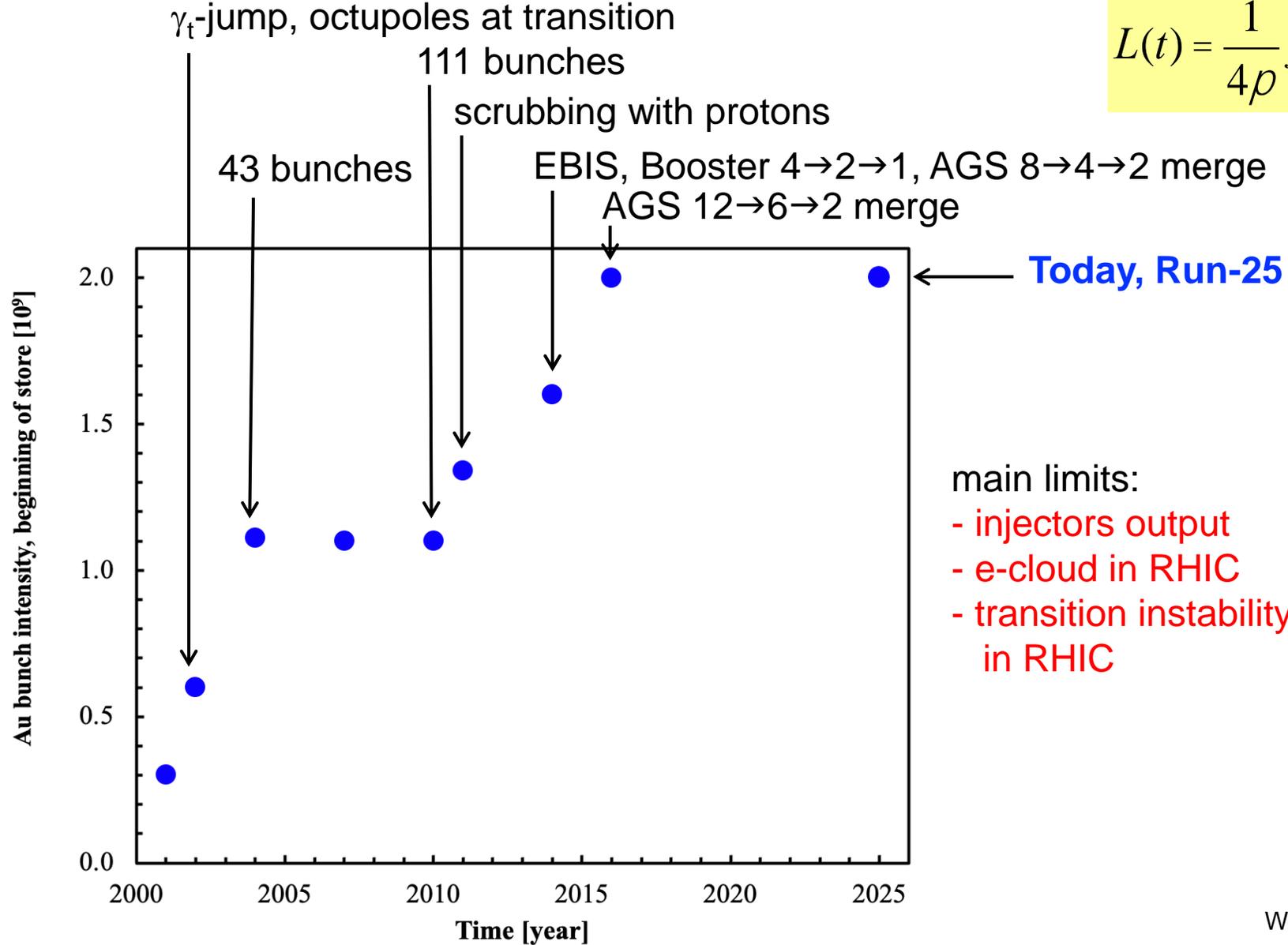
W. Fischer,* A.J. Baltz, M. Blaskiewicz, D. Gassner, K.A. Drees, Y. Luo, M. Minty, P. Thieberger, and M. Wilinski
Brookhaven National Laboratory, Upton, NY 11973, USA

I.A. Pshenichnov
Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

Heavy ion cross sections totaling several hundred barns have been calculated previously for the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). These total cross

Au bunch intensity evolution

$$L(t) = \frac{1}{4p} f_0 N \frac{N_b^2(t)}{e(t) b^*(t)} h(b^*, S_s, q)$$



main limits:

- injectors output
- e-cloud in RHIC
- transition instability in RHIC

Run-18 Zr+Zr/Ru+Ru – same A, different Z (CME)

Zr-96/Ru-96

Extraordinary help from DOE, ORNL, RIKEN
for source material and preparation

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

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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. [+ ENLARGE](#)
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 Kunawalkam Elayavalli a postdoctoral fellow at Wayne State University. Adams and Shanmuganathan worked on construction of the event plane detector and serve as detector experts; Kunawalkam Elayavalli has been controlling the event plane detector during STAR data taking as a detector operator trainee.

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.”

— Wolfgang Fischer, Collider-Accelerator Department



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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.

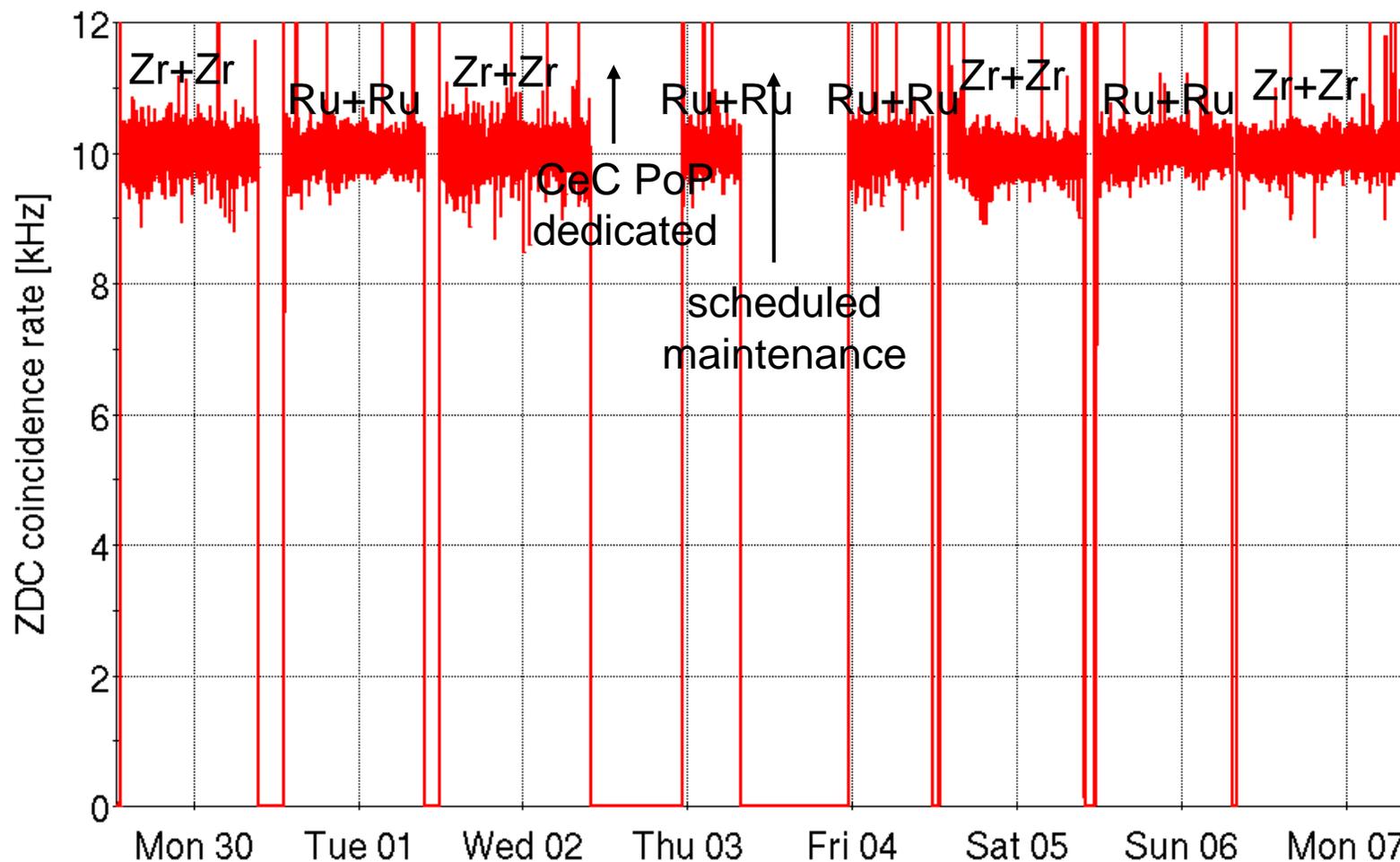
The new experiment at Brookhaven National Laboratory's Relativistic Heavy Ion Collider, just



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

Store-by-store species change and flat luminosity of $21.5 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$
20 h nominal store length (WEEK: 30-Apr-18 to 07-May-18)

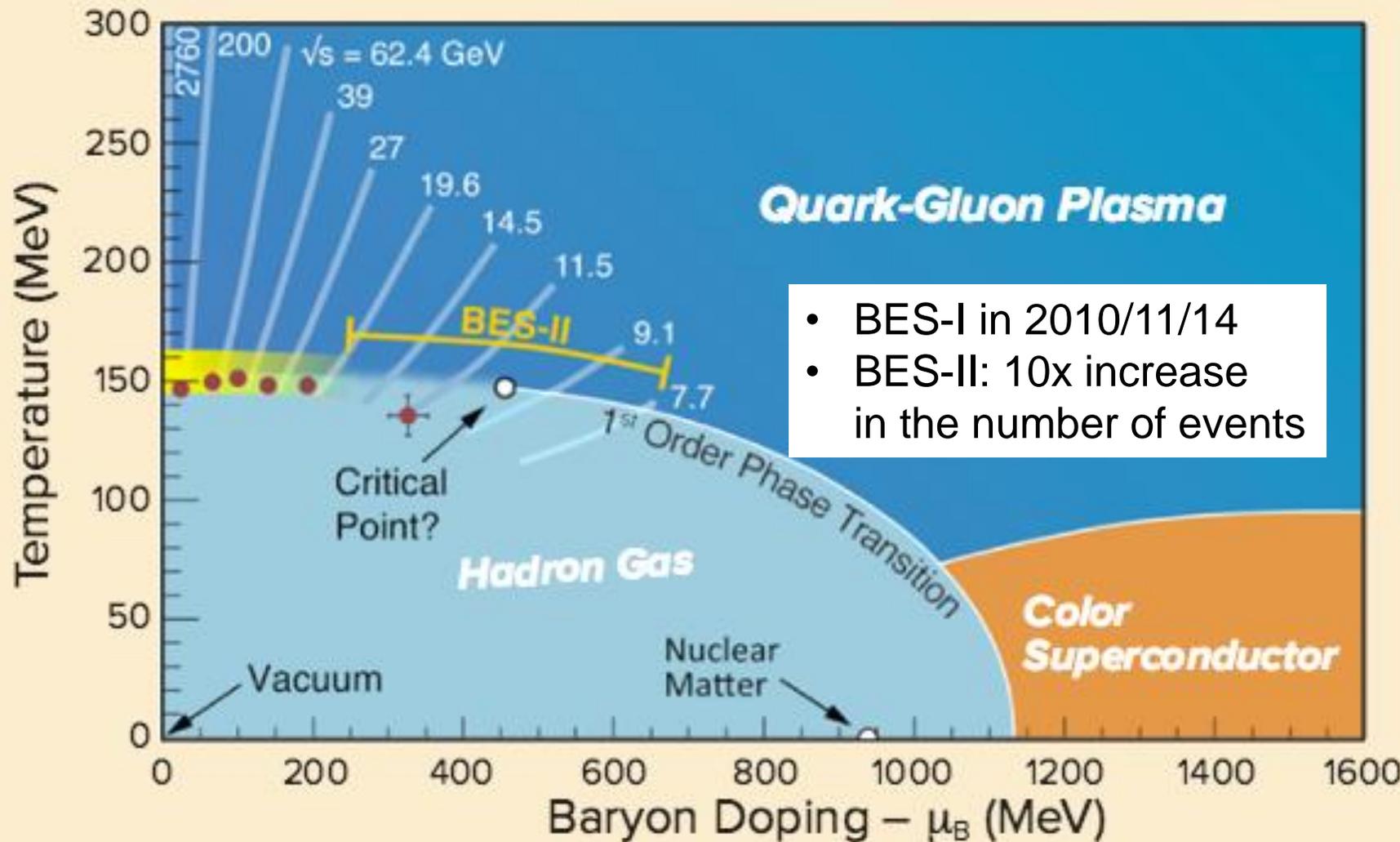
Run Coordinator: Greg Marr
paper: IPAC 2019



How did stochastic cooling change heavy ion collider operation?

- Increased in luminosity lifetime from ~2.5 h Au+Au up to infinite
- Allowed for increase in bunch intensity $L \sim N_b^2$
- Increased optimum store length from 4 to 8 h for Au+Au, resulting in more time in collision, less time refilling
- Can tolerate emittance growth during acceleration (from IBS, transition instabilities) as long as no intensity is lost
- Operation close to burn-off limit, full use of accelerated intensity
- Allowed flat luminosity for alternating species (Ru+Ru/Zr+Zr)

Low-Energy RHIC electron Cooling (LReC) for the Beam Energy Scan I and II (BES-I, II)



Au+Au collisions down to 3.85 GeV/n (40% of CoM energy at nominal injection)

Luminosity really low

Space charge

Intrabeam scattering

Magnetic field errors (also time dependent)

Large beam with losses

BES-II goal of 4x luminosity over 3.85 – 9.8 GeV/n (highest energy is nominal injection)

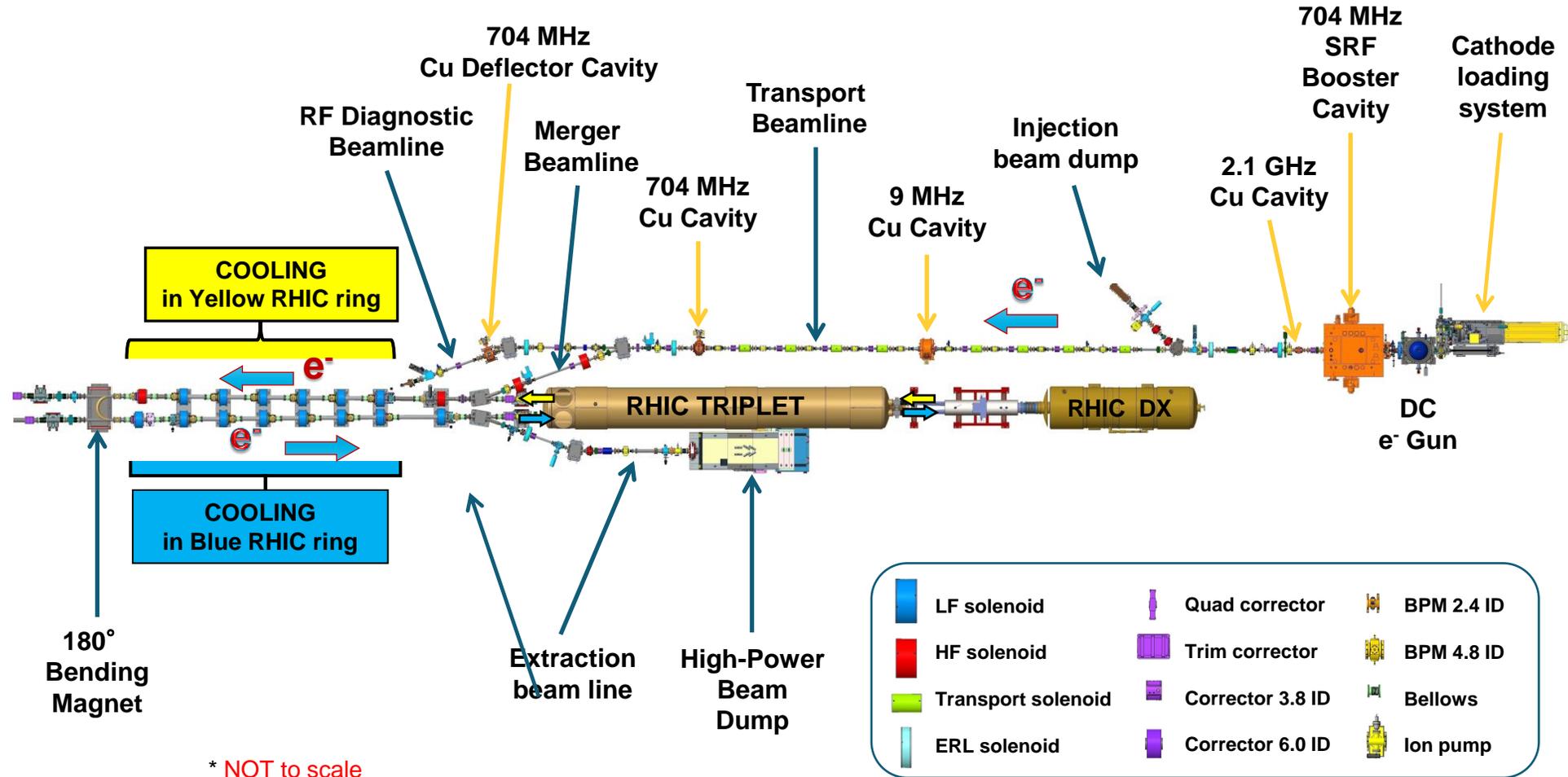
Designed cooler for 2 lowest energies

Wolfram Fischer

[2015 NSAC Long Range Plan for Nuclear Science]

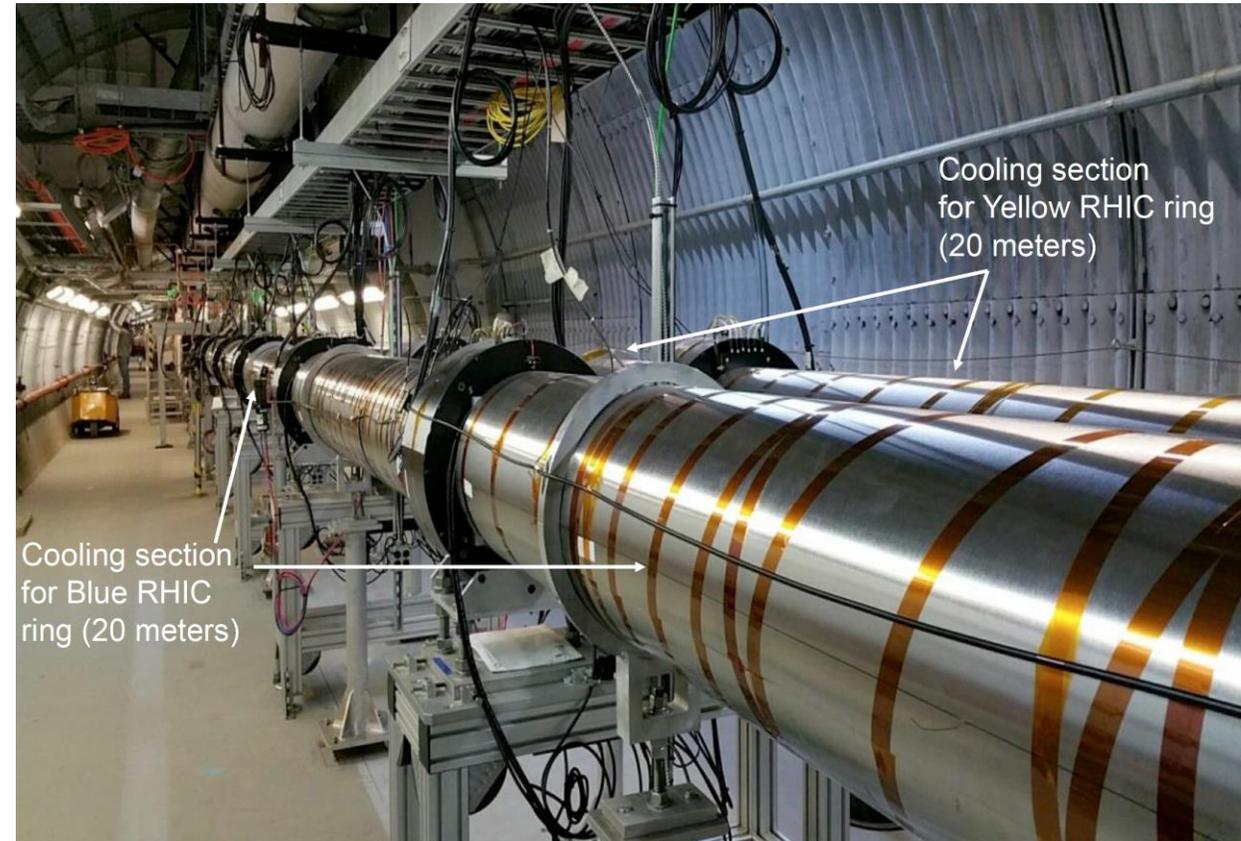
LEReC Accelerator

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



Low Energy RHIC electron Cooler

- LEReC operational electron cooler:
 - utilizes RF-accelerated electron bunches
 - uses non-magnetized electron beam (no magnetization at the cathode and no continuous solenoidal field in cooling section)
- LEReC approach to cooling is directly scalable to high-energies – pre-cooler in EIC at injection



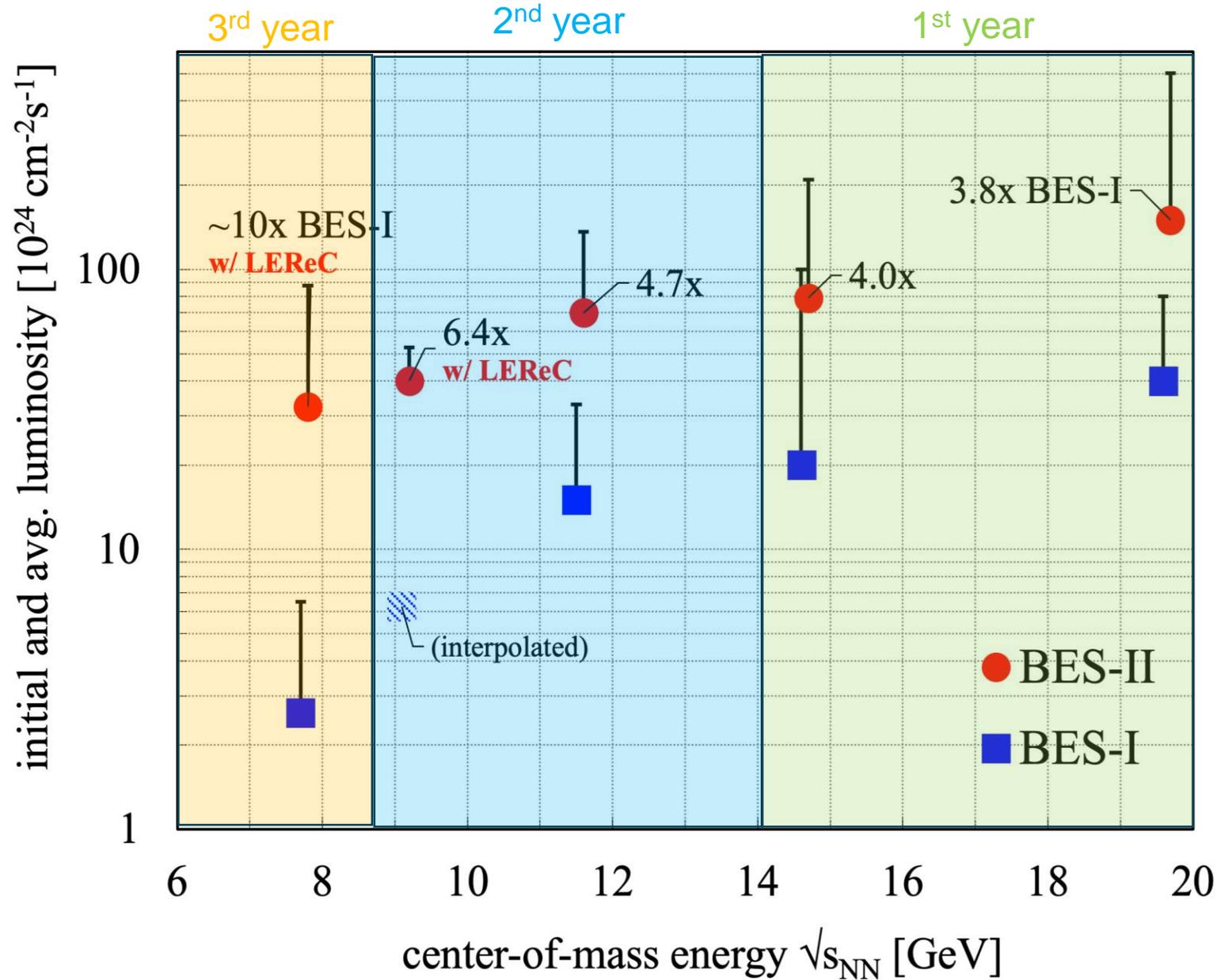
A.V. Fedotov et al., “Experimental demonstration of hadron beam ...”, PRL 124, 084801 (2020)]

First LEReC cooling observation 5 Apr 2019



BES-I vs BES-II luminosity

Run Coordinator: Chuyu Liu (Run-19 to 21)



Goal was

$$L_{\text{avg}} (\text{BES-II}) = 4x L_{\text{avg}} (\text{BES-I})$$

R&D for high-energy cooling in EIC

CeC Experiment at RHIC

- V. Litvinenko, “Results on the Coherent electron Cooling experiment at RHIC” (MOD3)
- Y. Jing, “Electron beam dynamics simulation in CeC performance with low beam current” (THA2)
- G. Wang, “Simulation of the ion bunch in the presence of the CeC for the new energy scheme” (THA3)

Design studies for EIC

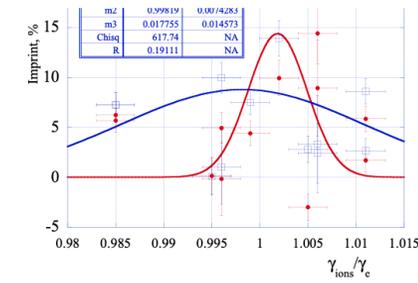
- A. Fedotov, “Hadron beam cooling and cooler design status for the EIC” (TUA1)
- E. Wang, “Electron Ion Collider Strong Hadron Cooling design summary” (TUA2)
- W. Bergan, “EIC luminosity models for various hadron cooling scenarios” (TUA3)
- S. Seletskiy, “Development of storage ring electron cooler for high energy applications” (TUB1)
- D. Kayran, “Electron cooler for high-energy hadrons based on ERL” (TUB2)
- M. Blaskiewicz, “Stochastic cooling for the EIC” (TUB3)
- K. Deitrick, “Design of a microbunched electron cooler ERL” (THB1)
- J. Kewisch, “Optics design for a storage ring based electron cooler for cooling at high energies” (THB2)
- S. Setiniyaz, “BBU threshold and digital feedback suppression for frequency-scaled BNL cavities in the EIC ERL” (THC2)
- I. Pinayev, “Beam position monitoring for low energy cooling section” (THC3)

CeC experiment – Vladimir Litvinenko

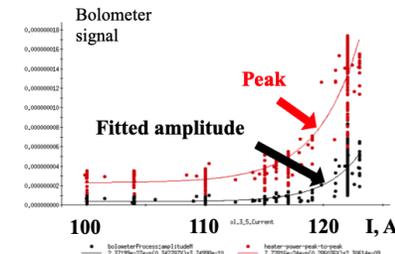
Main results obtained up to the date

- We observed high gain in FEL system used for early version of CeC
- We observed imprint of ion beam in the electron beam radiation
- We observed high PCA gain at frequencies between 5 and 10 THz
- We observed regular electron cooling – albeit very weak – of 26.5 GeV/u ion beam – the highest energy electron cooling
- We observed recombination between electrons from CeC accelerator and 26.5 GeV/u ions
- Beam parameters are either on the target – we are ready for CeC demonstration

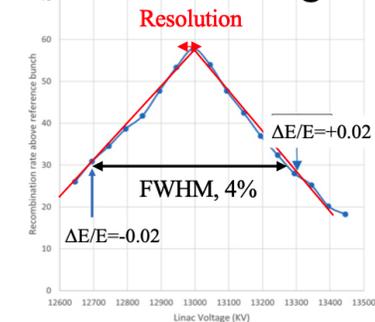
Imprint of ion beam



Exponential rise of PCA gain

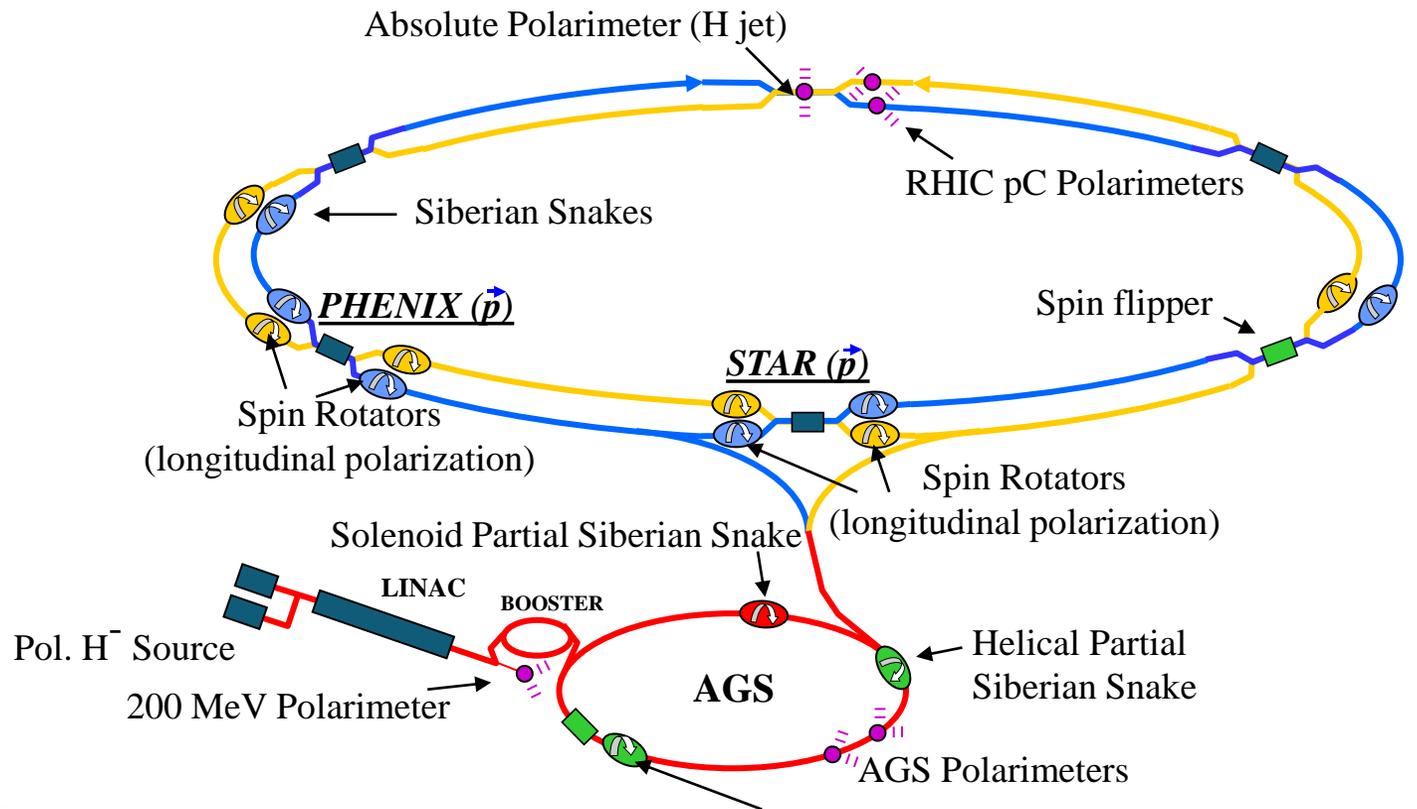
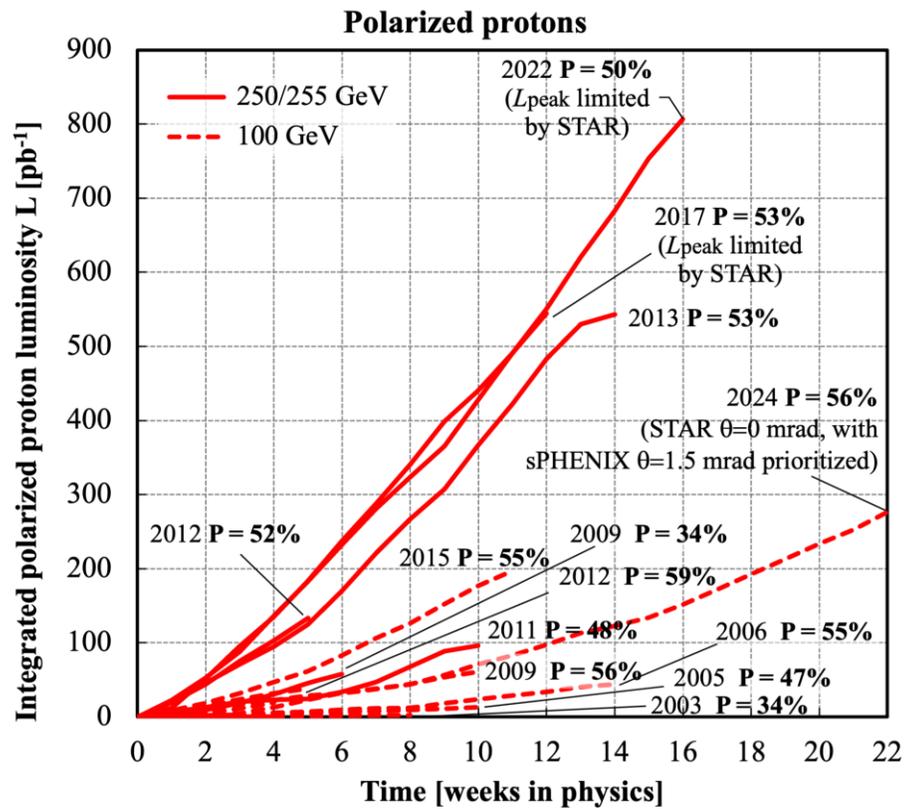


Recombination signal



9

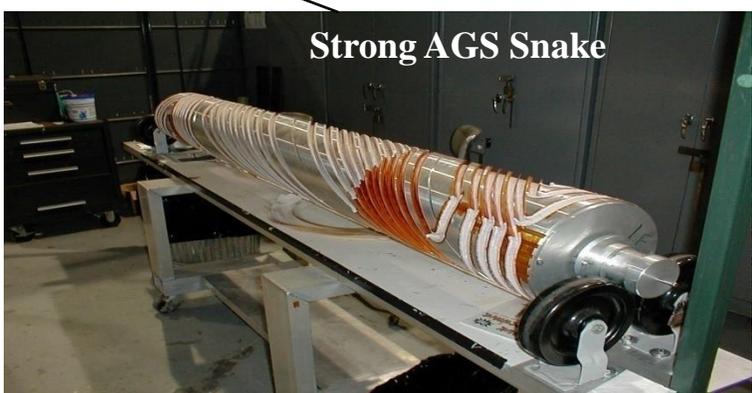
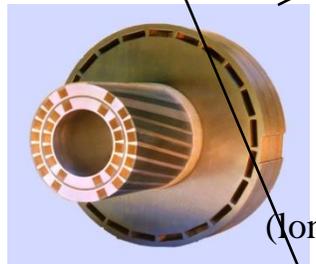
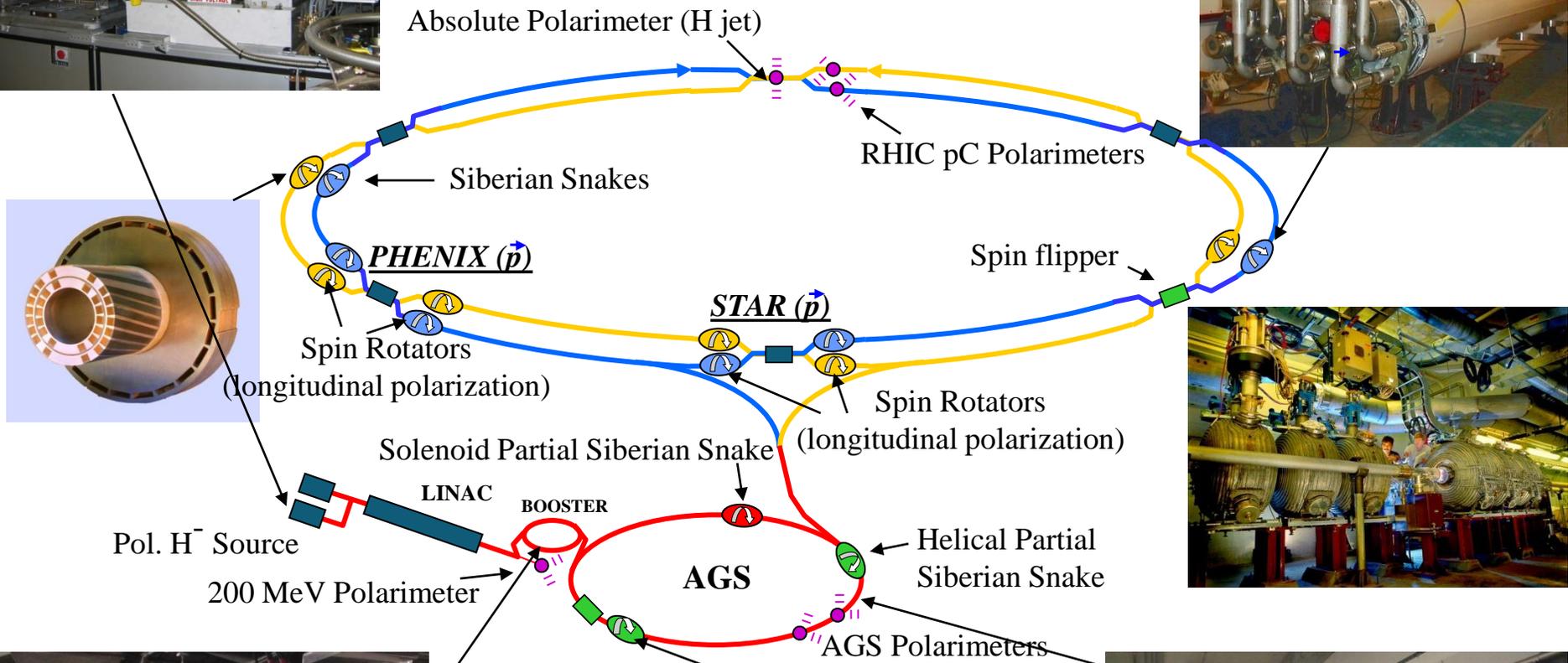
[V. Litvinenko, “Results on the Coherent electron Cooling experiment at RHIC” (MOD3)]



RHIC $p\uparrow+p\uparrow$ operation at 100 / 255 GeV



Special devices for polarized protons: source, polarimeters, snakes, rotator, flipper

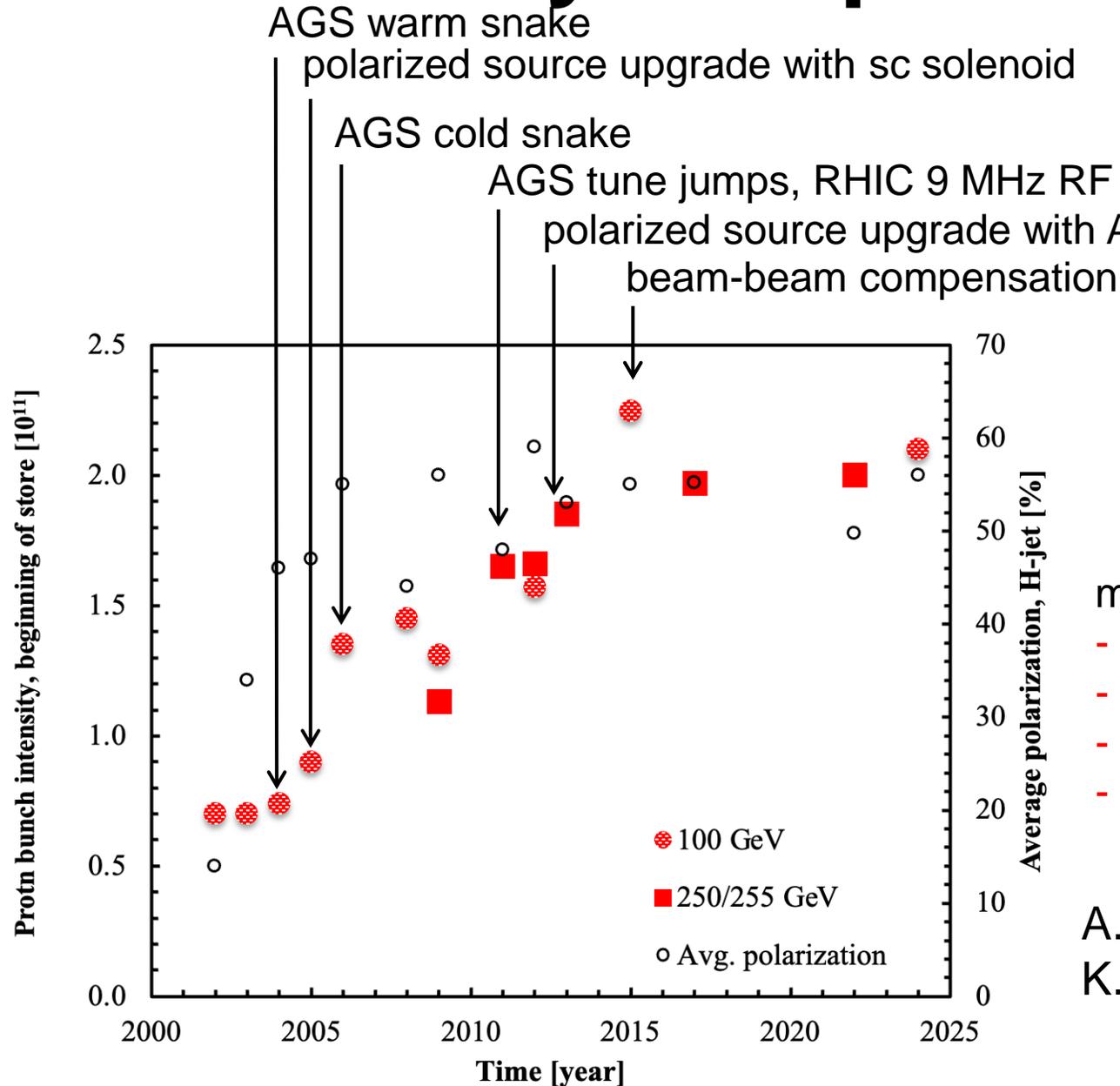


p bunch intensity and polarization

$$L(t) = \frac{1}{4p} f_0 N \frac{N_b^2(t)}{e(t) b^*(t)} h(b^*, S_s, q)$$

$$FOM = LP^4 \sim N_b^2 P^4$$

(double-spin experiments)



main limits:

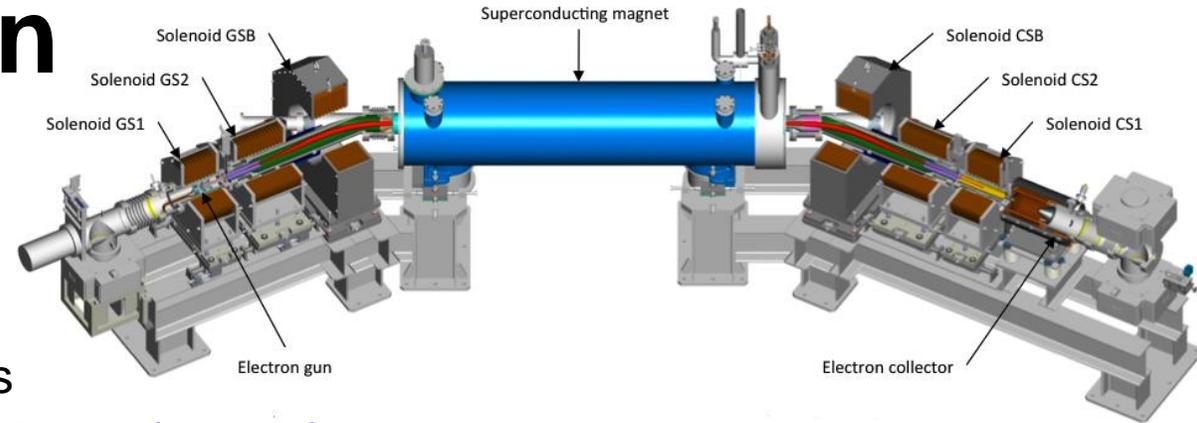
- injectors output
- polarization
- e-cloud in RHIC
- beam-beam in RHIC

A. Zelenski, H. Huang,
K. Gardner, K. Zeno, RF, et al.

Wolfram Fischer

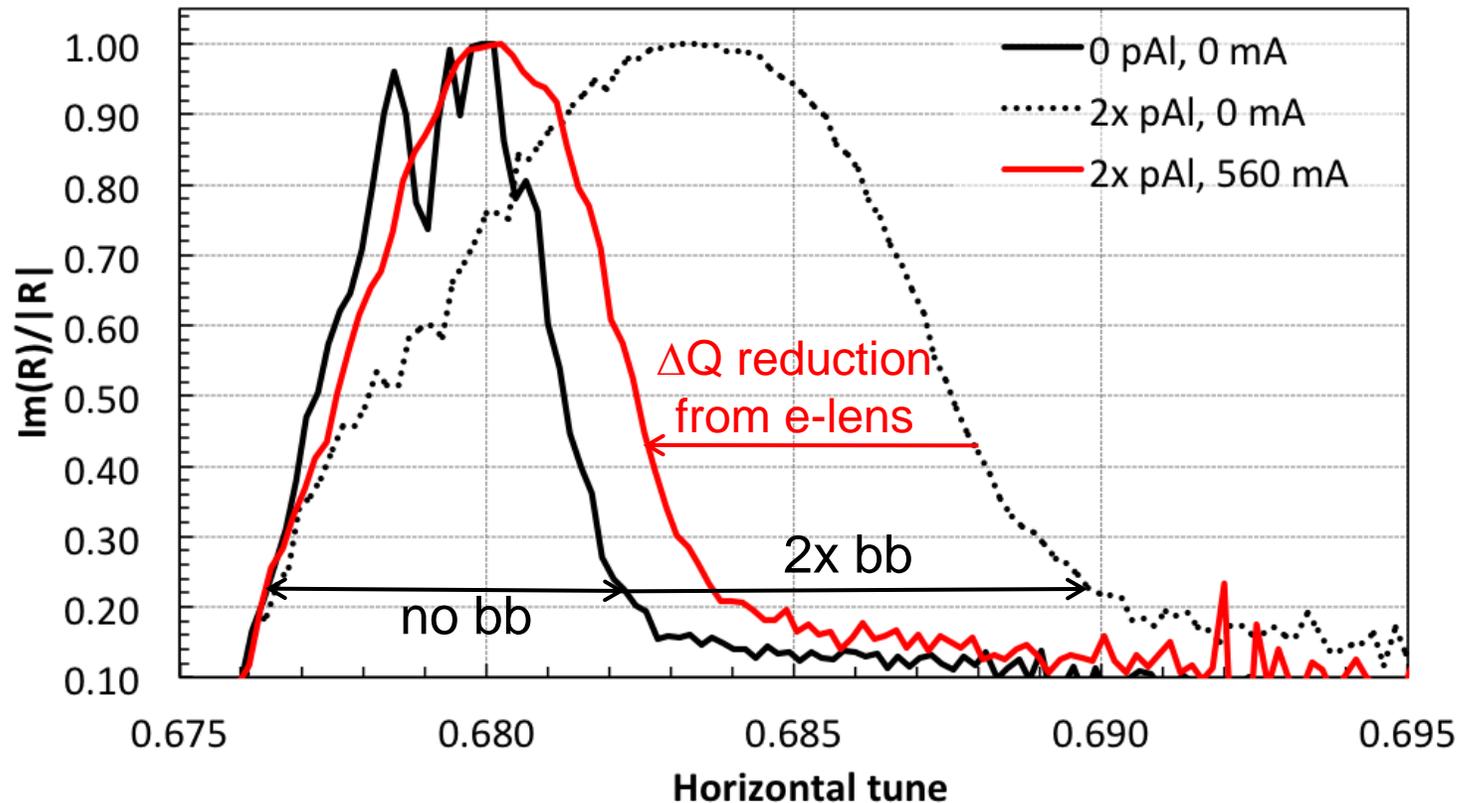
Head-on bb compensation

Tune footprint compression with a Gaussian electron beam



tune distribution measured with BTF and p+Al collisions

proton beam: $(Q_x, Q_y) = (.685, .695)$; Al beam: $(Q_x, Q_y) = (.685, .695)$; $\Delta Q_x, \Delta Q_y \gg \xi \Rightarrow$ no coherent modes



Can only reduced BB tune spread (black curve is limit)

[W. Fischer, et al., "Operational head-on beam-beam compensation with electron lenses in the Relativistic Heavy Ion Collider", Phys. Rev. Lett. 115, 264801 (2015).]

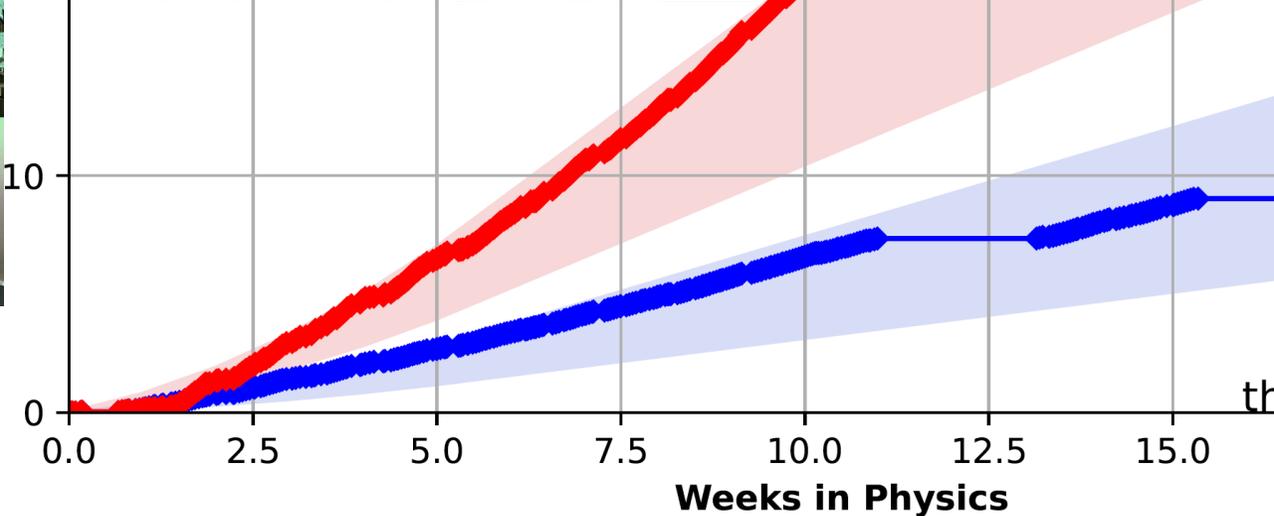
Run-25

FY25 Delivered Luminosity to sPHENIX and STAR

Run Coordinator:
Travis Shrey

- damaged 69 kV power line
- repair shut off Central Cryo Plant
- required managing helium inventory
- 15 days

- short in superconducting b
- repair required partial warn
- opened several cryostats
- 65 days

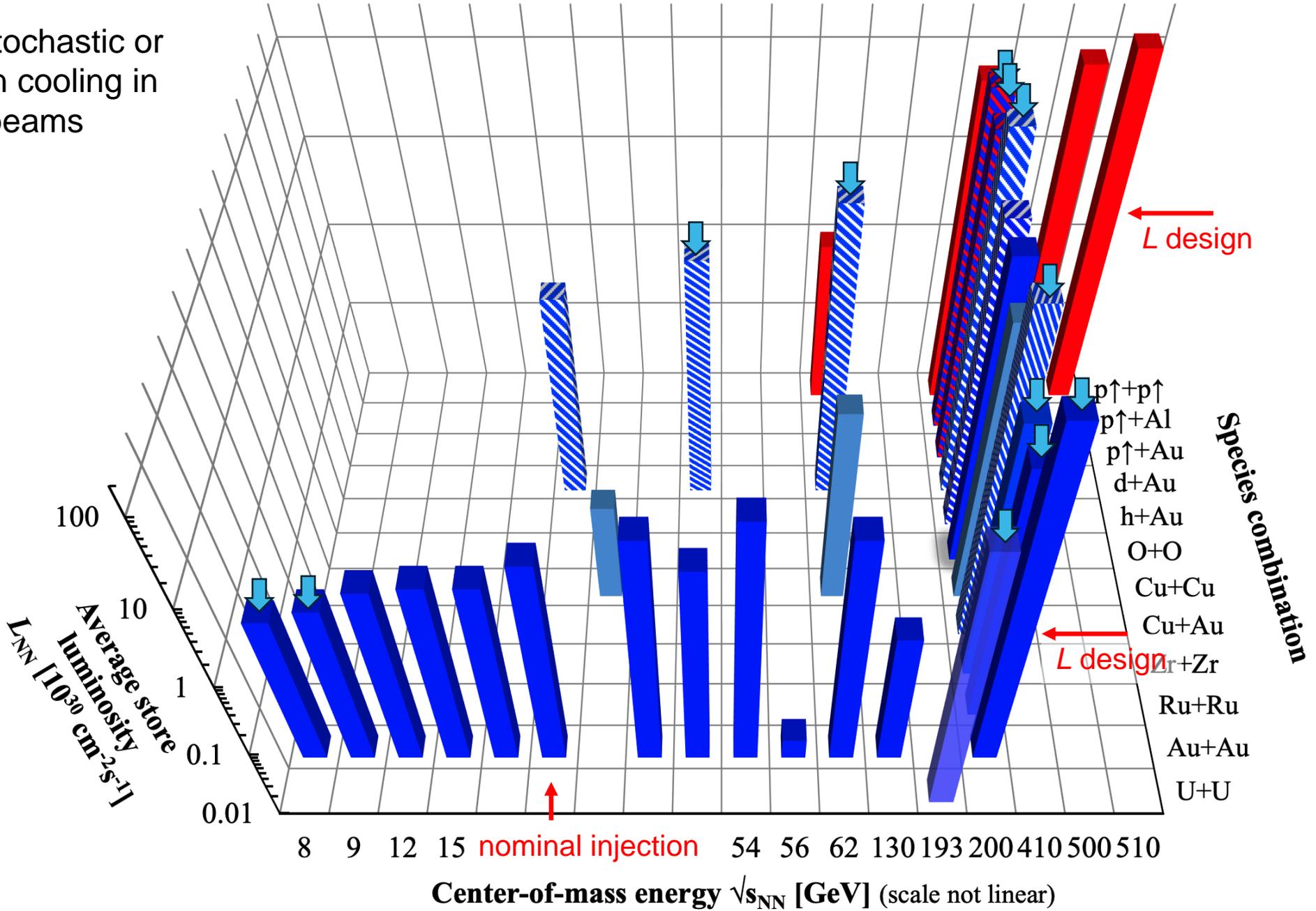


- unsynchronized beam abort
- Yellow abort vacuum repair
- 14 days



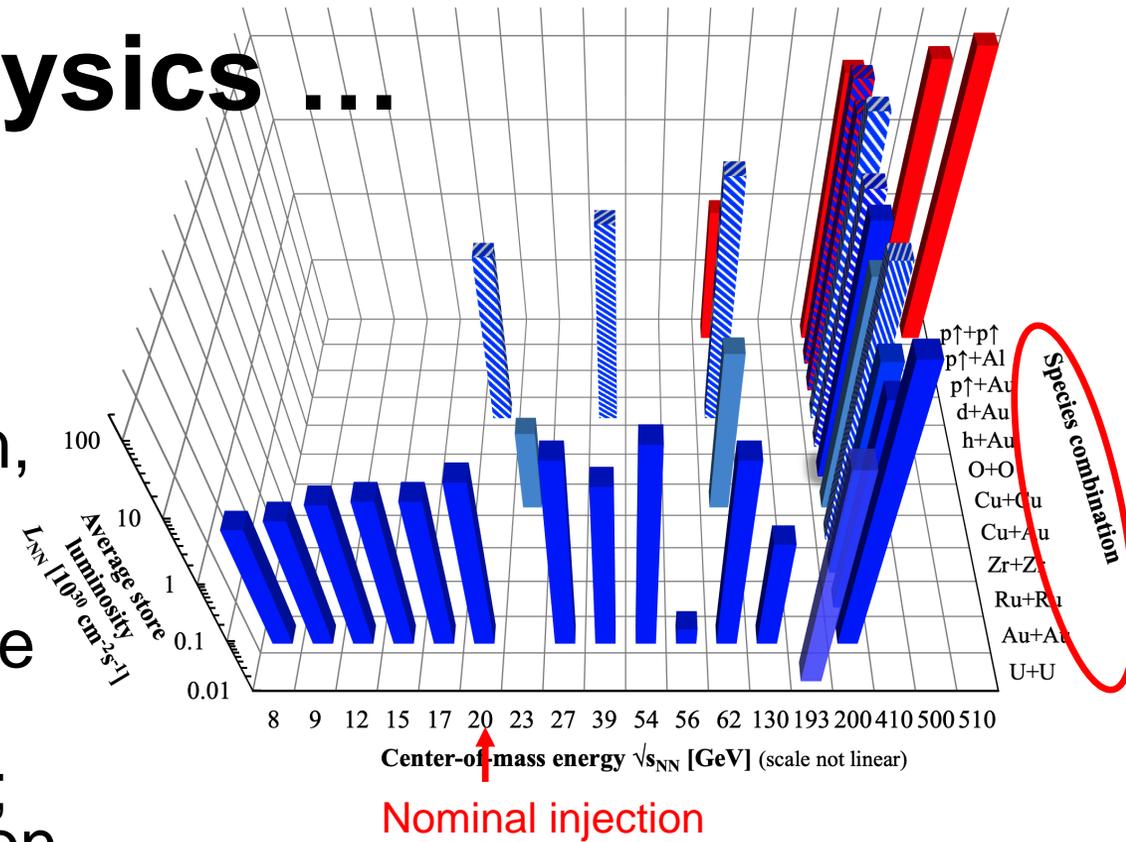
RHIC energies, species combinations and luminosities (Run-1 to 24)

↓ Used stochastic or electron cooling in 1 or 2 beams



RHIC after 25 years of physics ...

- Full energy Au+Au $L_{\text{avg}} = 44x$ design
enabled by stochastic cooling
- Only $p\uparrow+p\uparrow$ collider, $L_{\text{avg}} = 1.3x$ design,
 $P \sim 57\%$ (70% design)
- Many species and combinations, incl. asymmetric and low natural abundance
some only possible with stochastic cooling
- Extended energy range slightly above;
and significantly below nominal injection
enabled by electron cooling
- Developed technology for evolving program: *polarized beams, sources, cooling*
- Most of RHIC complex will be re-used for the Electron-Ion Collider
demonstration of RF accelerated electron cooling used for proton pre-cooling



COOL'25, Stony Brook University, 26-31 October 2025

CHARLES B. WANG CENTER



Abstract

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory began operation 25 years ago, initiating a program of high-energy ion collisions that has since evolved in remarkable ways. Within a few years, polarized proton collisions were introduced, and over the following decades RHIC continuously expanded its capabilities—achieving higher luminosity, greater polarization, and a wide range of ion species and operating modes. As RHIC now enters its final physics run, its hadron injectors, one of its collider rings, and its technical infrastructure are being prepared to support the next major facility, the Electron-Ion Collider. We reflect on 25 years of RHIC operations and highlight the key performance advances that made its success possible, particularly the impact of stochastic and electron cooling.

What made 25 years possible?

1. Facility remains priority of science community, science program evolved in new directions, detector upgrades
2. Evolving physics program needs could be met with evolving accelerator developments (L , P , flexibility)
 - Stochastic cooling enabled heavy ion L increases
 - Rare species (Ru-96/Zr-96)
=> required ORNL for Ru-96 enrichment (with DOE support), existing BNL sources, help from RIKEN, stochastic cooling
 - Electron cooling (LEReC) enabled operation far below nominal injection energy
3. Strong funding agency commitment – DOE Office of Nuclear Physics