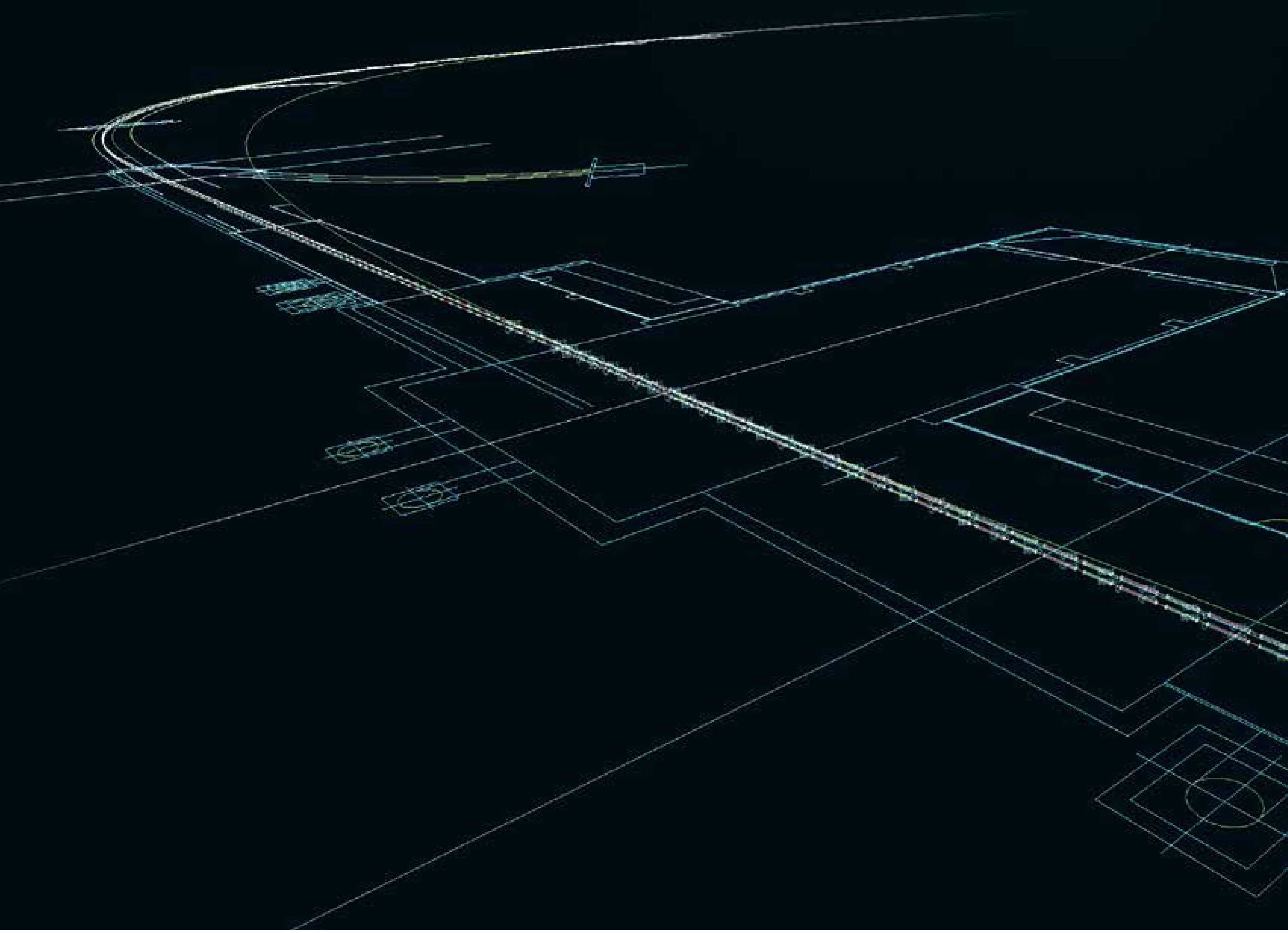
RELATIVISTIC HEAVY ION COLLIDER



Exploring Matter at the Dawn of Time

RHIC physics ignites imagination and triggers innovation

BROOKHAVEN NATIONAL LABORATORY

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U.S. DEPARTMENT OF ENERGY | Office of Science

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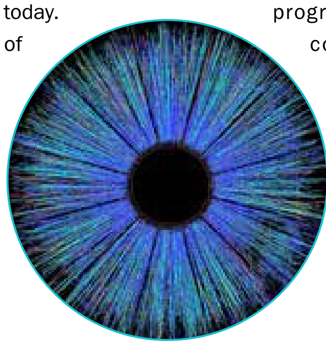
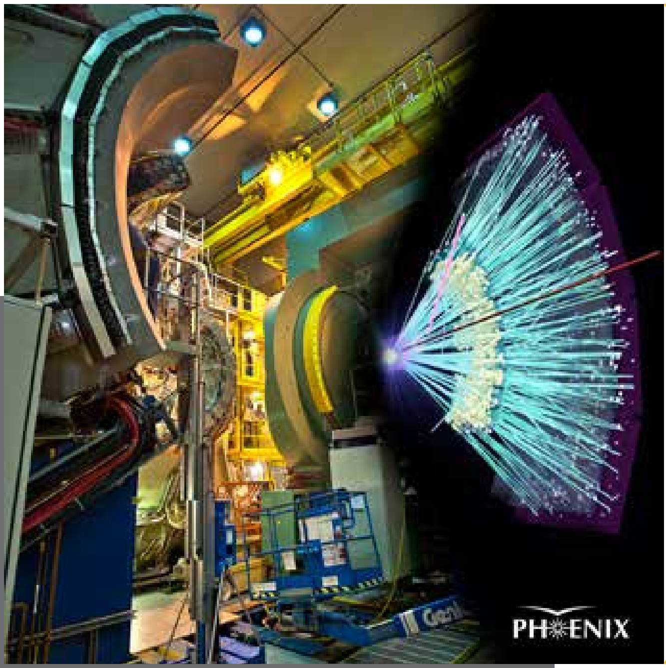
INTRODUCTION

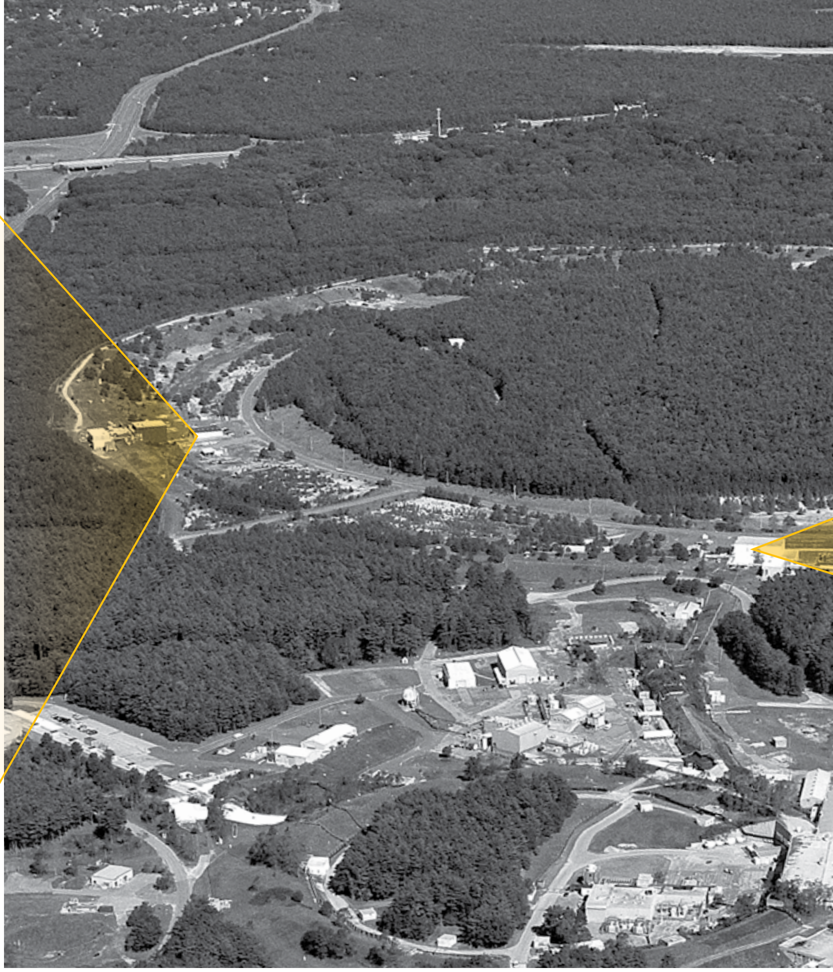
The U.S. Department of Energy's (DOE) Brookhaven National Laboratory leads the world in exploring how the matter that makes up atomic nuclei behaved just after the Big Bang. At that time, more than 13 billion years ago, there were no protons and neutrons—just a sea of "free" quarks and gluons, fundamental particles whose interactions are governed by nature's strongest force. More than 1,000 scientists from around the world come to Brookhaven to recreate this "quark-gluon plasma" by accelerating heavy ions (atoms stripped of their electrons) to nearly the speed of light and smashing them together at a 2.4-mile-circumference particle racetrack known as the Relativistic Heavy Ion Collider (RHIC). Detailed studies of the particles emerging from RHIC's heavy ion collisions have revealed surprising features of the early universe, and how the strong force shapes the structure of 99 percent of the visible mass in the universe today.

Funded primarily by the DOE Office of Science with contributions from collaborating institutions around the world, RHIC is currently the only particle collider operating in the U.S. It is also the world's only machine capable of colliding high-energy beams of polarized protons—protons with their rotational axes aligned in a given direction. This makes RHIC a unique tool for exploring another long-standing mystery of physics: the source of proton spin. Understanding the constituents of spin—a property used for key astronomical measurements and essential to diagnostic magnetic resonance imaging (MRI)—could reveal new details about the substructure of matter.

Each new finding from RHIC expands scientists' grasp of these fundamental physics questions, raises new ideas to explore, and pushes the evolution of the collider and its detectors. New technologies and computational techniques developed at RHIC allow scientists to delve ever deeper into the fundamental mysteries of matter, provide tangential benefits for society, and may spin off unanticipated applications. The research program envisioned for RHIC's future will continue this cycle of discovery and innovation—sparking human curiosity, training new highly skilled workers, and fueling our nation's economic engine for decades to come.







PHENIX

The PHENIX detector looks for many different particles emerging from RHIC collisions—including photons, electrons, muons, and quark-containing particles—using large steel magnets that surround the collision zone.

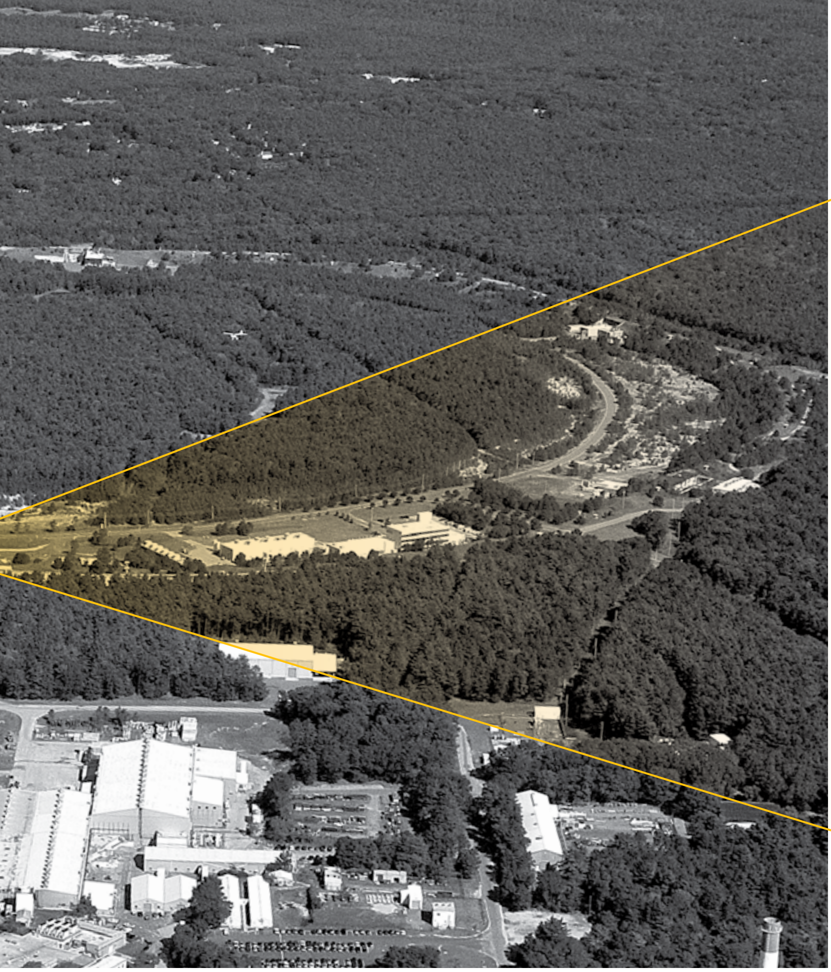
- Photons, electrons, and muons are not affected by the strong force that binds quarks and gluons together. Because these particles emerge from RHIC collisions unchanged, they carry information about processes and properties within, including the temperature.
- PHENIX makes precision measurements of specific types of particles.
- PHENIX has 580 collaborators from 75 institutions in 15 countries.

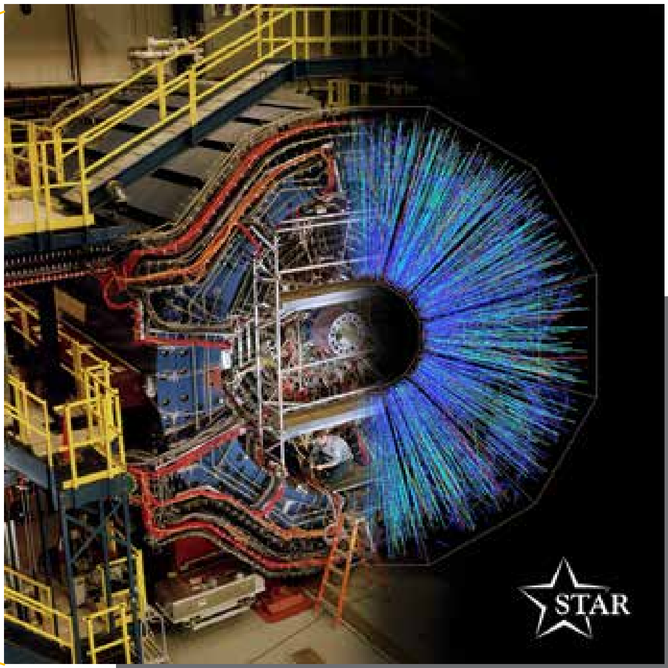
When this large magnet (recycled from the BaBar experiment at the SLAC laboratory) is installed in an upgraded PHENIX (sPHENIX) it will greatly enhance the detector's ability to reconstruct jets of particles produced within the plasma.

RHIC AND ITS

The Relativistic Heavy Ion Collider (RHIC) is a 2.4-mile-circumference, two-ring particle "racetrack" where beams of ions (atoms stripped of their electrons) travel at nearly the speed of light (relativistic speeds) in opposite directions through rings made of superconducting magnets. At six intersection points, the superconducting accelerator rings can cross so the ions can collide. RHIC collides heavy ions from atoms such as gold to create a big impact, or smaller ions or even single protons, depending on the questions the physicists want to explore.

To get a view of the action, scientists use sophisticated house-sized particle detectors, STAR and PHENIX, located at two of RHICs intersection regions. (RHIC initially also had two smaller detectors, PHOBOS and BRAHMS,





DETECTORS

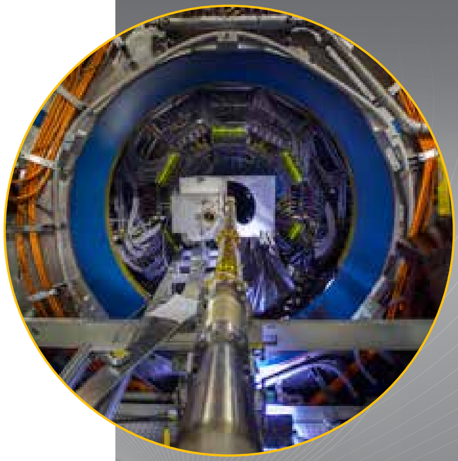
whose mission is now complete.) Like giant three-dimensional digital cameras, the detectors track the particles and other forms of energy that stream out of each high-speed collision. With thousands of collisions taking place each second and up to thousands of particles streaming out of each one, the detectors selectively record the details of the most interesting events for scientists to analyze using powerful computers.

Looking at the debris, scientists can reconstruct what happened at the instant of collision, opening a window into the internal structure of the colliding ions and how matter behaved at the dawn of time. One particular focus is the search for signs of an early-universe form of matter known as quark-gluon plasma. Another is a search for the various sources of proton "spin."

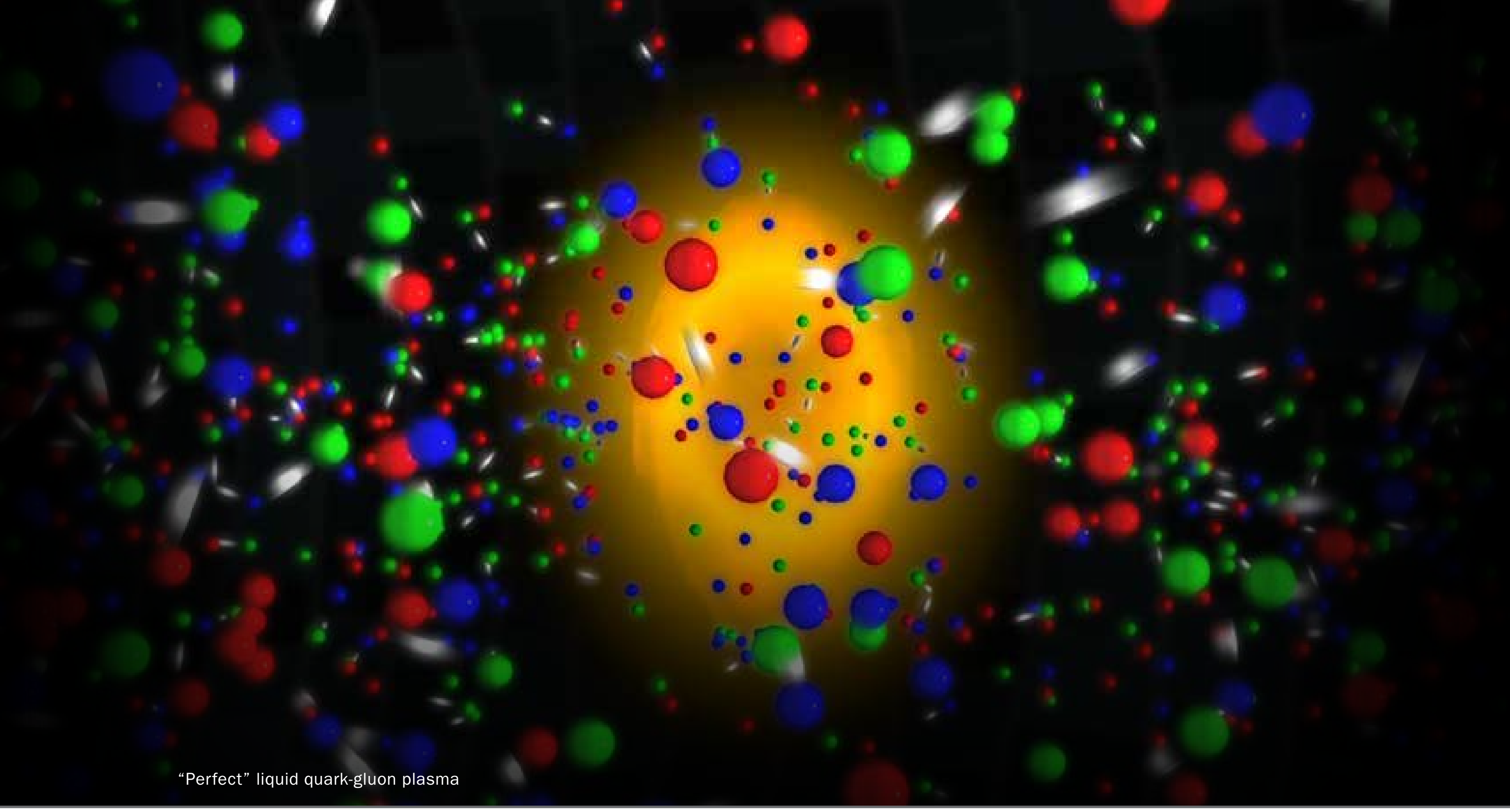
STAR

As big as a house, the STAR detector specializes in tracking the thousands of electrically charged particles produced by each RHIC collision.

- STAR's "heart" is the Time Projection Chamber, made up of many electronic systems to track and identify particles.
- The goal of STAR is to obtain a fundamental understanding of the microscopic structure of interactions between particles made of quarks and gluons.
- The STAR team is composed of 578 collaborators from 58 institutions in 13 countries.



A new "heavy flavor tracker" recently installed at STAR detects and identifies rare heavy particles whose behavior offers insight into detailed properties of the quark-gluon plasma, including its temperature and ability to flow.

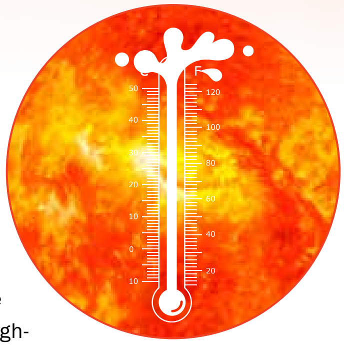


“Perfect” liquid quark-gluon plasma

SCIENTIFIC ACHIEVEMENTS

Since it began operations in 2000, the Relativistic Heavy Ion Collider (RHIC) has been extraordinarily successful. It stands as one of the most versatile and scientifically productive accelerator facilities in the world, opening a new field of research with a series of stunning discoveries revealing a new phase of matter and new insight into the nature of proton spin.

‘Perfect’ liquid quark-gluon plasma



By measuring the light emitted from RHIC’s gold-gold smashups, scientists know that the highest-energy collisions recreate the extreme temperatures of the early universe—250,000 times hotter than the center of the sun. Under these conditions, ordinary protons and neutrons “melt,” temporarily liberating their normally inseparable constituent particles—quarks and gluons—so that they are relatively free to roam and interact as they did before the universe cooled to form the stuff that surrounds us today.

Surprisingly, the early-universe matter created at RHIC behaves like a nearly friction-free liquid, instead of the gas that had been predicted. Moreover, this liquid appears to flow with extremely low “effective shear viscosity”—so low, it’s close to that of a theorized friction-free “perfect” liquid. In fact, the viscosity of RHIC’s perfect liquid quark-gluon plasma (QGP) is lower than that achieved at Europe’s Large Hadron Collider, where heavy ions are collided at higher energies for experiments that are complementary with those at RHIC.

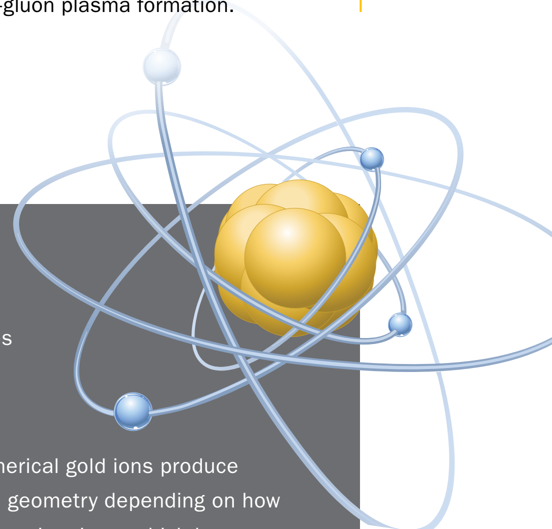
Yet RHIC’s QGP can stop energetic subatomic particles in their tracks. These unusual properties suggest that the particle interactions in QGP may be similar to and offer insight into surprising behavior observed in more conventional condensed matter systems, such as superconductors and quantum spin liquids.

Heaviest antimatter

RHIC collisions are the source of a new particle discovery: antihelium-4, the antimatter partner of the helium nucleus and the heaviest antinucleus ever detected. Discovery of this particle may help elucidate models of neutron stars, and also opens a way to explore fundamental asymmetries in the early universe. Given that the next weightier stable antimatter nucleus is predicted to be a million times more rare—and out of reach of today's technology—this record for massive antimatter is likely to stand for the foreseeable future.

First signs of gluon saturation

Before RHIC started running, theorists had predicted that light-speed accelerated ions would reach a state of gluon saturation, where the number of gluons maxes out due to relativistic time dilation. The very first experimental hints of gluon saturation came from early collisions of gold ions at RHIC and later collisions of light deuterons with the heavier gold ions. Instead of the deuteron colliding and interacting with individual protons or neutrons in the ions, the smaller particle appeared to be hitting a bunch of protons—or a dense "wall" of gluons that acts like sticky molasses. These and similar observations made later in proton-lead collisions at Europe's Large Hadron Collider are revealing important information about the internal structure of ions, and could help elucidate the mechanism of quark-gluon plasma formation.



Wide Range of Ion Species

The incredible versatility of RHIC allows scientists to collide a wide range of ion species at varying energies to address different aspects of physics questions.

Gold-gold
Colliding nuclei of one of the heaviest common elements—densely packed with protons and neutrons (197 in each ion)—creates a speck of matter with extremely high energy density and temperature, similar to the conditions of the early universe.

Deuteron-gold, helium-gold, proton-gold
Collisions of gold ions with much lighter ions such as deuterons (made of one proton and one neutron), helium 3 (two protons and one neutron), and even single protons serve as control experiments for probing the structure of "cold" nuclear matter accelerated to nearly the speed of light.

Copper-copper
These collisions produce a smaller speck of matter than gold-gold collisions, serving as a way to compare how conditions change with the size of the system created.

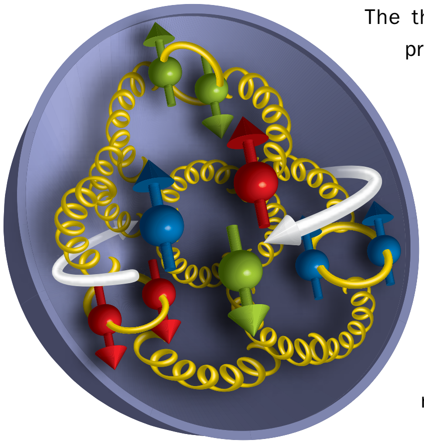
Uranium-uranium
While collisions of two spherical gold ions produce some variation in collision geometry depending on how the two spheres overlap, uranium ions, which have an oblong, football-like shape, offer many more ways to change the shape of the interaction zone and explore subtle details of how particles emerge. Because uranium is heavier than gold, collisions of two uranium nuclei slightly extend RHIC's reach in energy density.

Copper-gold
Asymmetric collisions of copper ions with much larger gold ions, make it possible to create systems of extremely asymmetric shape, which allow scientists to put the "perfect liquid" hypothesis to a stringent test.

Polarized protons with varying spin orientations
These collisions allow detailed studies of how quarks, antiquarks, gluons, and their interactive motion contribute to a proton's overall spin.

Gluon contribution to spin

RHIC is the only machine in the world that can collide "spin polarized" protons to tease out the factors that contribute to this intrinsic property. Earlier studies had presented a mystery: The three quarks that make up a proton account for only about a third of its total spin. RHIC's search for the "missing spin" is starting to reveal that gluons make a contribution about equal to that of the quarks. That leaves some spin still missing. Further explorations at a future Electron-Ion Collider (EIC) would play a crucial role in resolving this mystery.

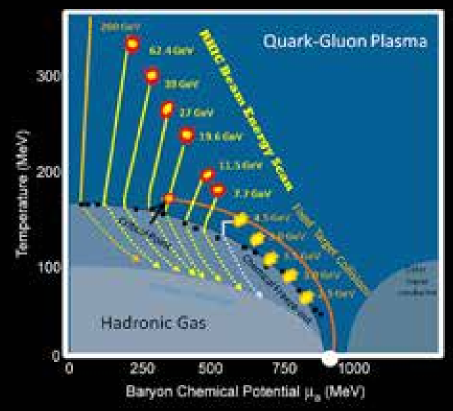


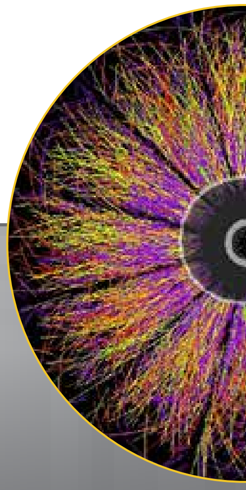
Jet physics

Jet quenching, where one of a pair of particles produced back-to-back at the edge of a heavy-ion collision appears to get "stuck," losing energy to the matter formed, was among the earliest discoveries at RHIC—and a clear hint that the highest energy collisions were forming quark-gluon plasma. Surprisingly, high-momentum particles get stuck just as much as less energetic ones, despite the ultra-low viscosity, or resistance to flow, of the QGP. Future efforts to reconstruct jets, particularly with an upgraded sPHENIX detector, promise to elucidate the mechanisms of this energy loss and the energy transport properties of the QGP.

Closing in on the QGP transition

Systematic studies varying the energy and types of colliding ions at RHIC reveal the first evidence of how properties change above and below transition from early universe quark-gluon plasma (QGP) to ordinary nuclear matter. These studies plotting points on the nuclear phase diagram reveal different kinds of nuclear phase changes at different energies. They are also helping scientists hone in on a possible critical point—where the transition itself changes from one type to another. RHIC's energy range spans the "sweet spot" for exploring these transitions.





Tiny drops of QGP?

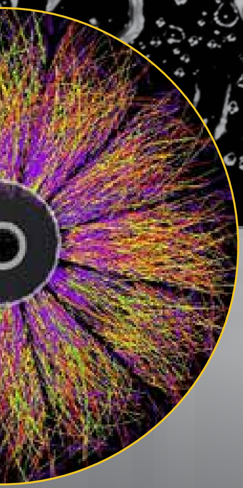
Collisions between gold nuclei and much smaller particles such as deuterons may be serving up miniscule drops of hot quark-gluon plasma—a finding consistent with similar results from Europe's Large Hadron Collider (LHC). RHIC's remarkable versatility will be put to good use by confirming the existence of these tiny drops of QGP in collisions of helium nuclei or even protons with gold nuclei. If confirmed, these small-scale drops of QGP may be a perfect testing ground for understanding the essential conditions for creating this remarkable form of matter.

Bubbles of broken symmetry?

Tiny "bubbles" formed within RHIC's QGP may internally disobey fundamental symmetries that normally characterize the interactions of quarks and gluons. If verified, these symmetry violations at RHIC may offer a unique opportunity to test in the laboratory some crucial features of symmetry-altering bubbles speculated to have played important roles in the evolution of the infant universe.

Connections with cold atoms and string theory

The surprising behavior of RHIC's perfect liquid quark-gluon plasma has sparked interest from physicists studying atomic gases at the opposite extreme of the temperature scale—close to -273 degrees Celsius, the coldest anything can get. They've observed fluid-like flow patterns very similar to those observed in RHIC's 4-trillion-degree QGP. String theorists, whose work exists mostly in the realm of calculations, were excited to find that their mathematical techniques can help elucidate the properties of both of these strongly interacting, near-perfect (ultra-low viscosity) liquids. Conversely, RHIC's experiments can put some ideas of string theory to the test.



Superconducting magnets of the RHIC accelerator

ACCELERATOR INNOVATION

Tackling the most challenging problems in accelerator science attracts the world's best and brightest physicists to Brookhaven Lab.

Many ideas and techniques born in Brookhaven's accelerator physics programs over the Lab's nearly 70-year history have taken root in new research facilities around the world.

Building and operating the RHIC complex is a prime example. From the days of early planning through its initial implementation and continuous upgrades, RHIC has become the world's most versatile particle collider. Along the way, innovative technologies developed by RHIC accelerator physicists have sparked a host of spin-off applications for industry, medicine, national security, and more.

Record luminosity

RHIC physicists have increased collision rates, or luminosity, with innovative techniques that squeeze, "cool," and nudge the ion beams to keep the particles tightly packed, maximizing the chance these tiny particles will make contact when the beams cross. As a result, RHIC is operating at 25 times the level of performance for which it was designed, with even greater improvements on the horizon. Examples of these innovative technologies include:

Electronic "pickups" of RHIC's stochastic cooling system

Stochastic cooling

Electronic "pickups" placed around the RHIC ring measure tiny random fluctuations in the positions of particles as the beams heat up and spread out. These devices send this information across the circular accelerator to reach a location ahead of the near-light-speed particles (or back to meet the beam on the next trip around), triggering electric fields that "kick" the charged particles back toward their ideal positions. Brookhaven physicists were the first to make this technique work at high energy with tightly bunched beams. Stochastic cooling now squeezes RHIC's heavy ion beams horizontally, vertically, and front-to-back in both accelerator rings, resulting in vastly higher collision rates.

Coherent electron cooling

Electron cooling can squeeze both heavy ions and polarized proton beams. In conventional electron cooling, a beam of "cold" electrons propagates with "warm" ions to act as a passive thermal bath that extracts heat and cools the ions. But the efficiency of this process decreases as the beam's energy increases. To cool RHIC's high-energy beams, scientists are working to develop "coherent electron cooling," a hybrid process that effectively amplifies the negative charges in the electron beams so these charges can be used to actively pull any straying positively charged ions back into place.

Electron lenses

To increase luminosity in future proton-proton collisions, RHIC physicists have installed electron lenses to compensate for the tendency of the protons in one circulating beam to repel protons in the other. The "lens" is a low-energy electron beam with a current and transverse profile that creates a force equal to the repulsive force experienced by the colliding protons, but with the opposite sign. The negatively charged beam therefore counteracts the repulsive force experienced by the protons.

Achieving the "Impossible"

The success of RHIC is particularly impressive given that, at the beginning, scientists weren't sure it would work. No collider had ever been built to collide heavy ions, and significant challenges faced its construction.

For one, the gold ions collided at RHIC—the nuclei of gold atoms stripped of their negatively charged electrons—carry enormous positive charge. As these highly charged particles pass closely by one another at high speed, they generate an extremely strong electromagnetic field, resulting in the production of many electrons and positrons. If just one of the negatively charged electrons succumbed to its attraction to a positively charged gold ion, it would throw off the ion's total charge and allow it to escape from the beam.

Through perseverance, dedication, and continuous improvement, RHIC physicists conquered these challenges—and went on to surpass all the milestones initially set for RHIC's performance.

Electron beam ion source injector

Unmatched versatility

Unlike any other collider in the world, RHIC can collide a variety of ions—from single protons to heavy uranium nuclei—at a very wide range of energies. This capability stems in part from a beam injector called the Electron Beam Ion Source (EBIS), which was added to the RHIC complex in 2011. The resulting versatility allows physicists to explore the mysterious world of quark interactions and the strange and unexpected features of the strong force—including details of the transition between ordinary matter and what the universe looked like some 13.7 billion years ago.

World's only polarized proton collider

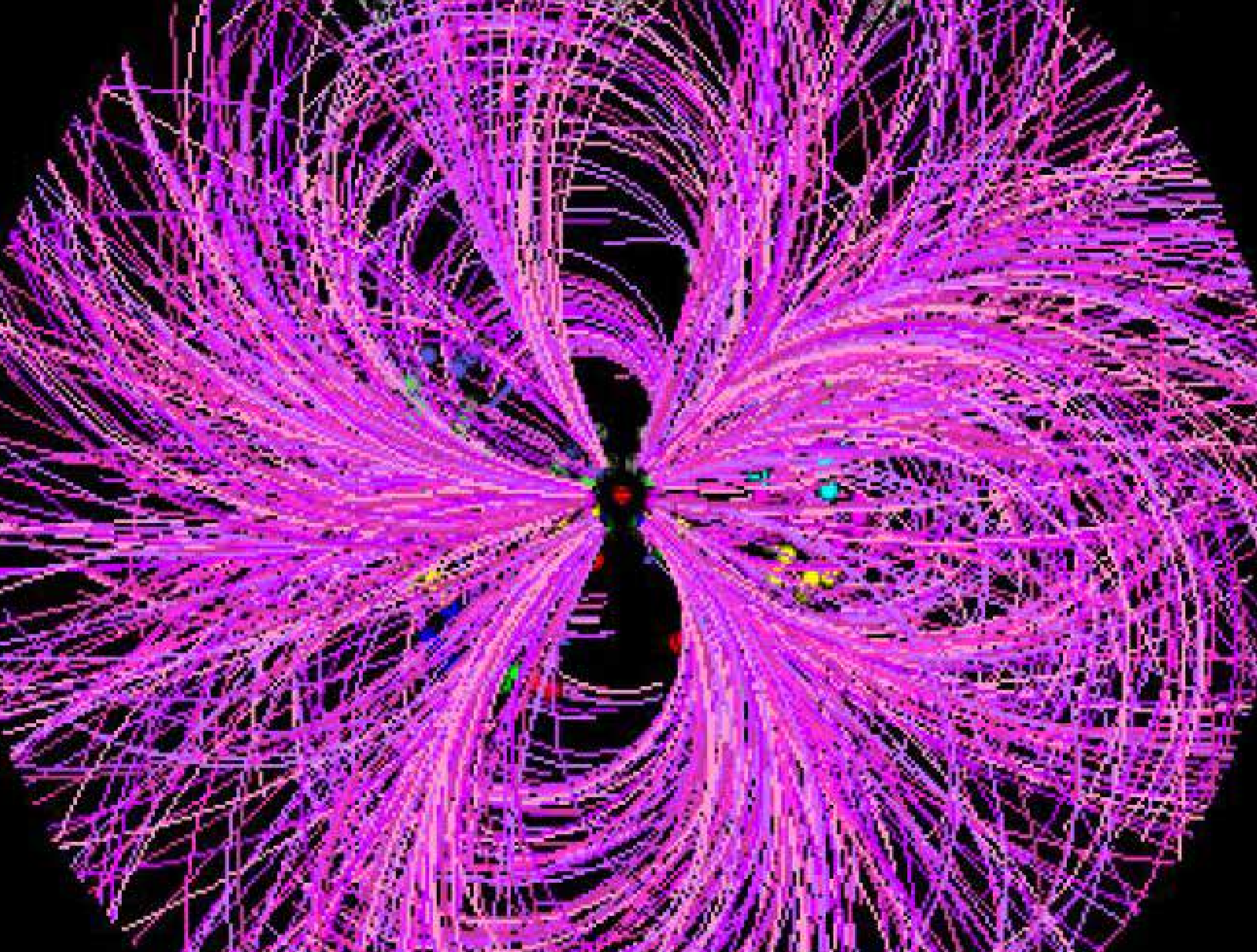
RHIC is the only facility in the world that can accelerate and collide protons with their "spins" aligned. Collisions with such spin control allow physicists to tease out how quarks and gluons contribute to this intrinsic particle property. While spin is used every day in medical imaging, it continues to hold many secrets. RHIC is the first facility to reveal that gluons play a significant role.

Specialized magnets called "Siberian snakes" help keep proton beams polarized at RHIC. Their "corkscrew" design causes the direction of the magnetic field to spiral around the direction of the beam, periodically flipping the polarization, or direction of spin, and averaging out numerous but much smaller effects of RHIC's magnets to minimize the loss of polarization.

Siberian snake magnets

Energy recovery linac

Currently under development as part of a possible future electron-ion collider (EIC), an energy recovery linac first accelerates electrons for use in collisions, then decelerates them so they give their energy back to the system's radiofrequency cavities. In this way, the energy can be used again to accelerate the next bunch of electrons.

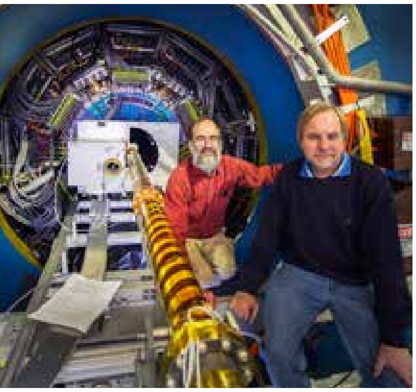


Particle tracks very close to the beamline in RHIC's PHENIX detector

SCIENTIFIC OPPORTUNITIES

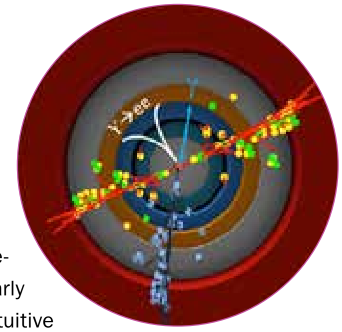
In many ways RHIC is in its prime with a bright future. Further upgrades and precision studies to be carried out over the next decade will deepen our understanding of how all visible matter in the universe was formed.

Through continuous improvements, including the successful implementation of bunched beam stochastic cooling, RHIC's luminosity—or rate of particle collisions—has reached 25 times the design luminosity and achieved the machine performance goals of an accelerator upgrade that had been dubbed "RHIC II" at a small fraction of the originally anticipated cost and half a decade earlier. This achievement, other accelerator advances, and recent upgrades to the detectors that track and analyze collision results set the stage for an ambitious ongoing scientific program at RHIC. An energized and committed community of physicists is poised to make use of these advanced capabilities to address many of the compelling science questions that have been raised by RHIC's discoveries to date.



Installing new components at STAR

Heavy quarks, tracking jets



Tracking back-to-back particle jets

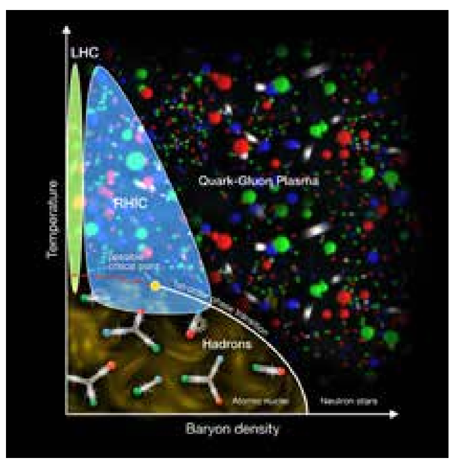
New detector components are enabling RHIC physicists to track particles composed of quarks that are heavier than the "up" and "down" quarks that make up ordinary atomic nuclei. These "heavy" quarks offer insight into the properties of the primordial quark-gluon plasma (QGP) created in RHIC's most energetic collisions, including its ability to flow like a nearly perfect liquid. They will also help scientists test and understand the counterintuitive tendency of this nearly friction-free liquid to stop even energetic particles in their tracks. Proposed upgrades to RHIC detectors will allow physicists to reconstruct the trajectories of particle "jets" produced back-to-back within the plasma. These new, powerful "jet microscopes" can probe the QGP simultaneously on a variety of length scales and thereby help scientists identify the mechanism for the energy loss and ultimately unravel the internal structure of the QGP.

Mapping the transition

A new beam injector broadens the range of ion types that can be accelerated at RHIC—and also enables collisions between different types of ions. Physicists are taking advantage of this enormous versatility to conduct detailed studies over a wide range of energies to systematically explore the transition between ordinary matter and the quark-gluon plasma of the early universe. RHIC's unique ability to create matter on both sides of this phase transition will help answer key questions, including:

- What does the transition from hot quark soup to ordinary matter look like?
- How do the properties of the plasma evolve with temperature?
- How does the matter reach such a high temperature so rapidly with quarks and gluons condensing into a liquid?
- How small can a drop of quark-gluon plasma be?

Key measurements and comparisons will help answer these questions and possibly connect the science coming out of RHIC with scientists' understanding of other kinds of matter, such as high-temperature superconductors.



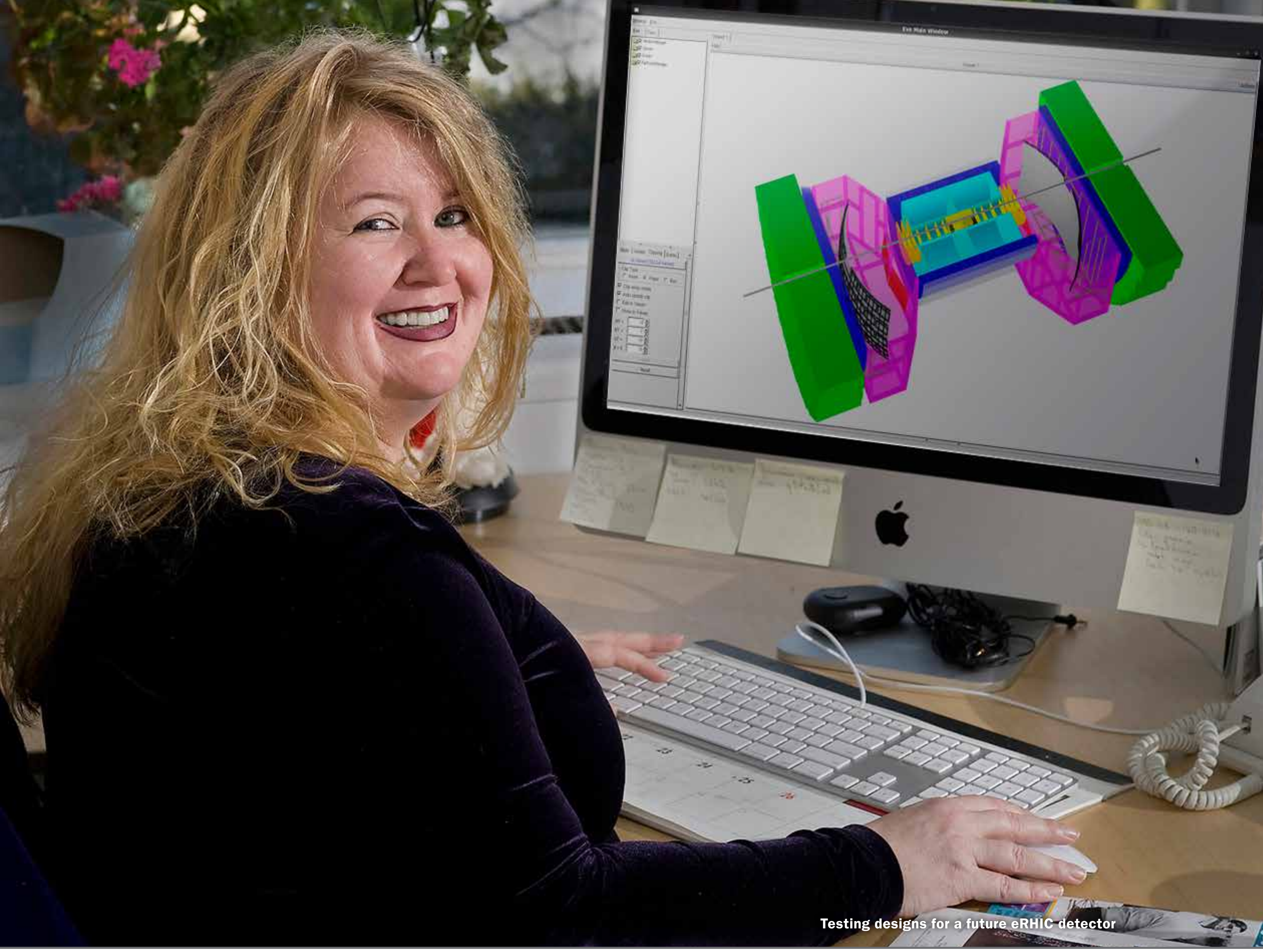
Complementarity with LHC

The RHIC program provides invaluable physics and accelerator input to (and, in turn, benefits from) a complementary though much more limited heavy-ion research program at the Large Hadron Collider (LHC) in Europe. Though the LHC operates at higher energy, it cannot reach the lower energies where some of the most interesting phenomena appear, including the crucial transition between QGP and ordinary matter.

Physicists from both facilities agree that the combined energy range of RHIC and the LHC is needed to fully explore and understand how critical properties emerge and change with temperature. Indeed, RHIC is in the energy "sweet spot" for exploring the QGP transition, and has unique capabilities for addressing some of the most compelling questions. And while LHC's heavy ion program is secondary to its focus on High Energy Particle Physics, occupying a relatively small percentage of running time, RHIC is dedicated to exploring quark-gluon matter.

Foundation for the future

RHIC also provides the U.S. Nuclear Physics community with a cost-realizable path to building a future Electron-Ion Collider (EIC)—by adding an electron ring and other components inside the existing RHIC tunnel. This facility, dubbed eRHIC, would allow the intense study of how gluons contribute to proton spin, and enable a deeper exploration of how gluon fields contribute to the properties of the quark-gluon plasma. Brookhaven Lab is laying out the plan for how such a transition would take place—maximizing the scientific output of the existing RHIC science program while testing key accelerator and detector components.



Testing designs for a future eRHIC detector

A NEW FRONTIER

Big questions remain about how the initial state created in RHIC's collisions influences the formation and evolution of the perfect liquid, as well as how the building blocks of protons contribute to their spin. Colliding electrons with heavy ions and protons could resolve these mysteries.

An electron-ion collider (EIC) would use electrons to probe the inner structure of protons and nuclear matter directly. These high-energy electrons would create rapid-fire, high-resolution snapshots revealing the sea of quarks and ocean of gluons that together make up the internal structure of protons and heavy ions. Understanding these particles and their dynamic interactions is crucial to understanding how these fundamental objects generate the energy, motion, and spin of the building blocks of nearly all visible matter in the universe.

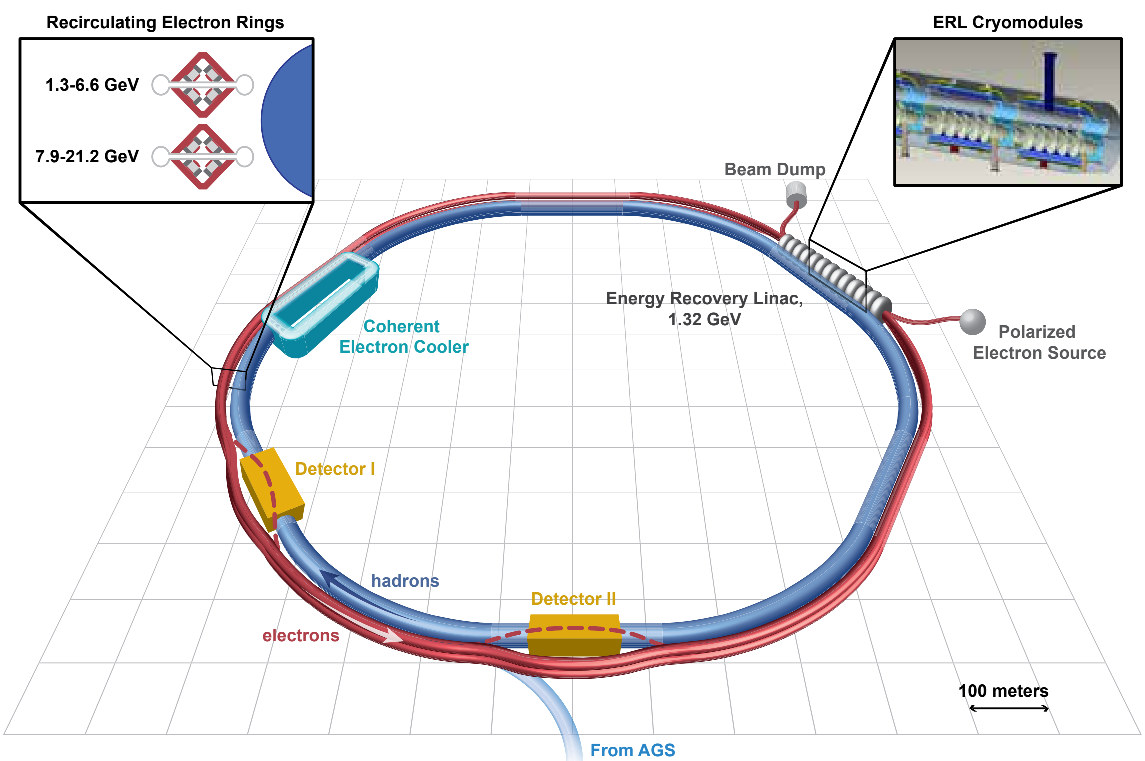
There is a very cost-effective way to create such a machine by building on and reusing much of the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC). This project to transform RHIC and its associated accelerator complex into a new facility known as eRHIC would help ensure continued U.S. leadership in nuclear physics for decades to come.

The glue that binds

A key focus of studies at an electron-ion collider would be the gluons that flit in and out of existence deep within the protons and neutrons of an atomic nucleus. These fundamental particles carry the strong nuclear force, the strongest force in nature, and are the subatomic "glue" that binds quarks together within protons and neutrons. Since protons and neutrons (i.e., atomic nuclei) make up most of the visible matter in the universe, this glue, in essence, is what holds together everything we see, from stardust to planets to people.

Building on RHIC's infrastructure

Adding an electron ring and other components to the existing RHIC complex to transform RHIC into "eRHIC" would be a cost-effective, practical strategy for achieving the scientific goals of an electron-ion collider. Such a program would build on Brookhaven Lab's history of groundbreaking physics and accelerator expertise, and make maximal use of the fully functional, productive proton/heavy-ion accelerator already in place and recognized for its unparalleled versatility.



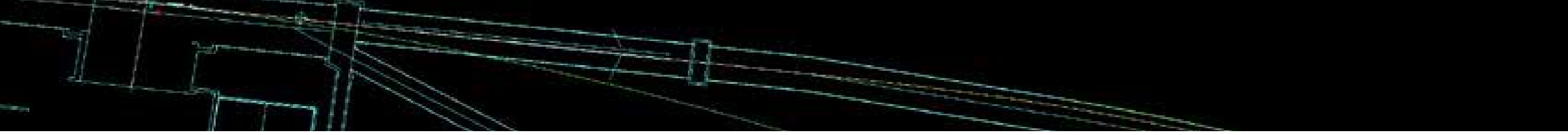
Proposed eRHIC machine details

The current design for eRHIC calls for the addition of a 15 to 20 billion-electron-volt (GeV) electron ring inside the existing RHIC tunnel.

Electrons would be accelerated by an **energy recovery linear accelerator (ERL)** and collided with heavy ions or protons circulating in one of the existing RHIC accelerator rings. No new civil construction would be required to accommodate this design, making it particularly attractive from a cost perspective.

A separate small **coherent electron cooling ring** would keep the velocity of heavy ions or protons in RHIC's beams highly uniform, and thus tightly bunched, to achieve the highest luminosities, or collision rates. Such a beam-cooling system would be essential to achieve the highest luminosity required for the most challenging parts of the EIC physics program.

The prospect of building an EIC is already inspiring the development of **innovative detector technologies** capable of making key precision measurements. This evolution of detector technology is necessary to realize the demanding and wide-ranging physics program of eRHIC.



Science goals of eRHIC

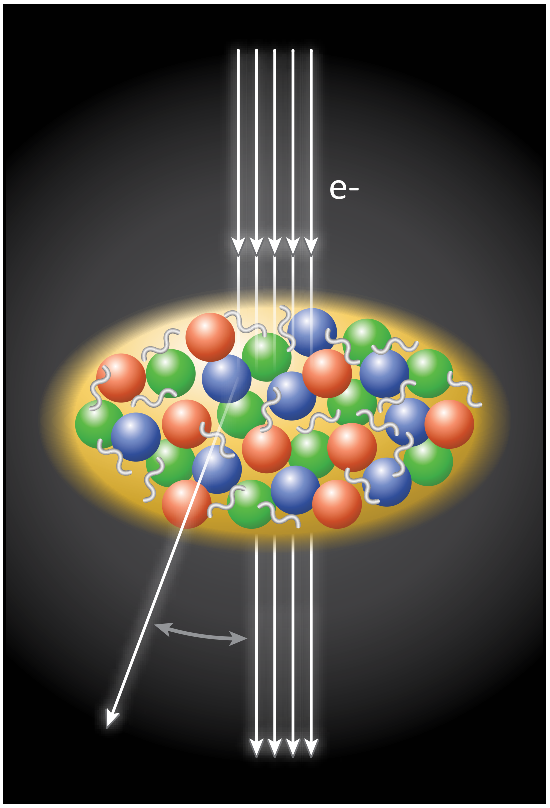
The proposed eRHIC accelerator would be the world's first electron-heavy ion collider. It would have the flexibility to change the nuclear ion species as well as the beam energies, building on the powerful versatility of RHIC. Both the variable energy and the ability to collide electrons with almost any type of nucleus are crucial for the systematic study of the "glue" that dominates the internal structure of matter. eRHIC would also be the world's first electron-proton collider where both the electron and proton beams are polarized. Combining polarization with at least 100 times the luminosity of the only previous electron-proton collider, eRHIC would offer new insight into the poorly known internal structure of the proton and the origin of its spin. eRHIC is the only collider in the world that can explore the intriguing inner dynamics of these fundamental building blocks of matter. This pursuit will also help us better understand some of the surprising discoveries made at RHIC.

Walls of gluons

At relativistic speeds, gluons popping out of and back into the vacuum inside a proton or heavy nucleus get suspended in their motion and become accessible to experimental study. As the speed of a nucleus approaches the speed of light, the abundance of frozen gluons continues to increase, eventually reaching a steady state of maximal gluon concentration physicists call color glass condensate. High intensity electron beams will reveal details of these "walls" of gluons, which constitute the strongest fields found in nature. Precisely measuring the strength of these fields will tell us how gluons interact with each other and what makes them behave so differently than photons, the carriers of the electromagnetic force.

Electron snapshots

eRHIC would catch gluons in action by using super-bright electron beams to bombard protons or heavy ions without destroying the entire delicate system. With their high energy and high intensity, the electrons can probe the core of matter as we know it, capturing "snapshots" of the fleeting gluons at their most abundant and, in many ways, most interesting state. eRHIC is also an excellent tool to study short-range correlations among nucleons (protons and neutrons), which are important to our understanding of the properties of nuclear matter in the extremely dense environment of neutron stars.



A precision microscope for imaging gluons

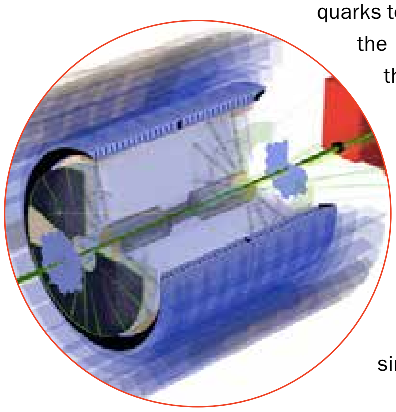
Spin secrets

Polarized proton collisions at RHIC have revealed that gluons appear to contribute about as much as quarks to the overall spin of the proton. But the two together cannot account for the total spin. So far no one has explored the spin contributed by gluons over the wide energy range that would be made accessible by an electron-ion collider.

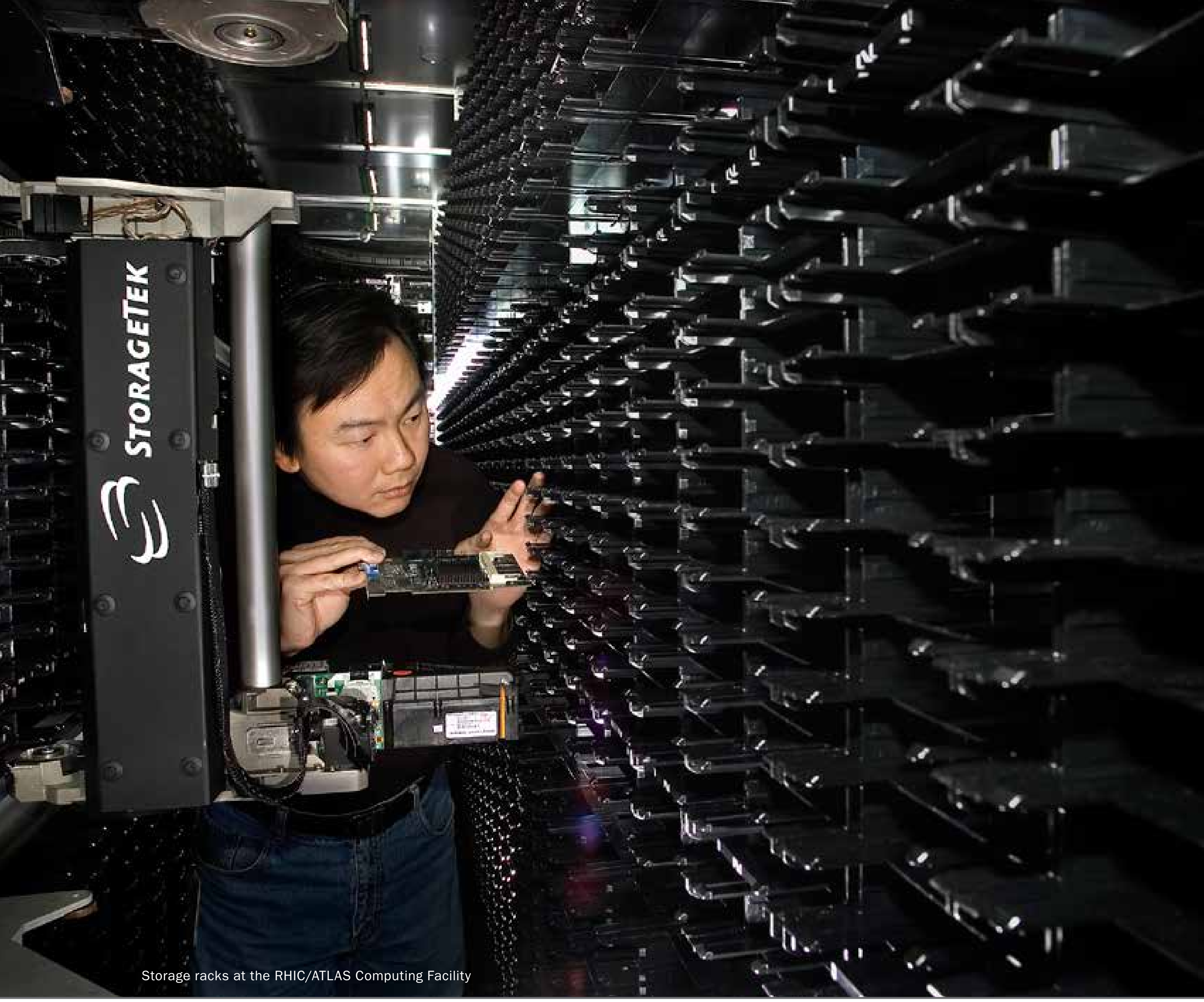
Smashing matter

While RHIC's discovery of the "perfect" liquid nature of the quark-gluon plasma that permeated the early universe has been confirmed by experiments at the LHC, the mechanics underlying the formation of this primordial plasma remain elusive. Colliding electrons with protons or heavy ions will provide insight into the interactions that guide the formation of visible matter from the fundamental building blocks that make up the plasma.

Brookhaven accelerator scientists and engineers are currently hard at work to produce a detailed design for the electron ring, incorporating an energy-recovery linear accelerator and other innovative accelerator technologies. Scientists at Brookhaven and other laboratories are simultaneously performing research and development into new cost-efficient detector technologies.



Innovative detector technology



Storage racks at the RHIC/ATLAS Computing Facility

COMPUTATIONAL ADVANCES

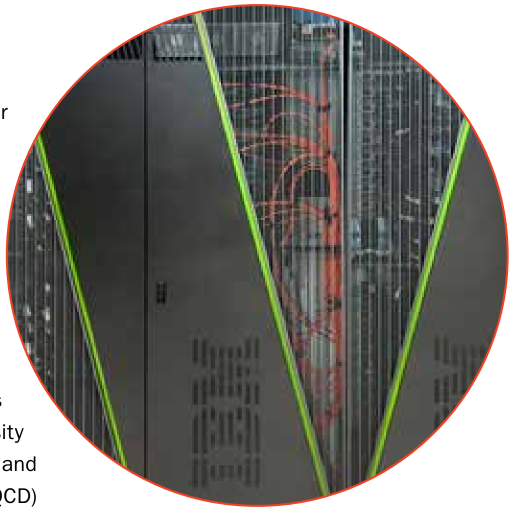
Since 2000, RHIC's detectors have taken digitized "snapshots" of billions of particle collisions—data-dense "pictures" that reveal details about the early universe and the fundamental properties of matter.

Keeping up with the data and the theoretical calculations of quantum chromodynamics (QCD), the theory that describes nuclear particles' interactions, requires large-scale supercomputing. Designing the systems to meet these computing needs continues to push the evolution of technology in ways that may benefit us all—as did the development of the World Wide Web, first designed as a way for physicists to share data.

Innovative supercomputer architectures

Complex calculations are needed to predict the properties of hot quark-gluon matter—an essential step for establishing standards with which to compare RHIC's experimental results. Because these calculations deal with small quark masses and many possible interactions, physicists have developed ways to model these interactions on large, fine-grained lattices that represent points of spacetime. The calculations require enormously fast supercomputers capable of executing tens of trillions of arithmetic operations per second. The nuclear physics community, with funding support from the U.S. Department of Energy, has therefore been a major driver for the development of ever-more-capable computer architectures.

One such architecture—dubbed QCDOC, for "QCD on a chip"—was developed by physicists from Brookhaven, the RIKEN/BNL Research Center (a partnership formed with Japan's RIKEN laboratory for young Japanese researchers at RHIC), and Columbia University in close collaboration with IBM and the United Kingdom QCD (UKQCD) collaboration. The unique and innovative technical solutions incorporated into QCDOC proved to be extremely useful for more general-purpose applications, and formed the foundation for architectures that now run the world's most powerful commercially available supercomputers, IBM's Blue Gene series. RHIC physicists have relied on sequentially upgraded generations of these computers to further advance their work.



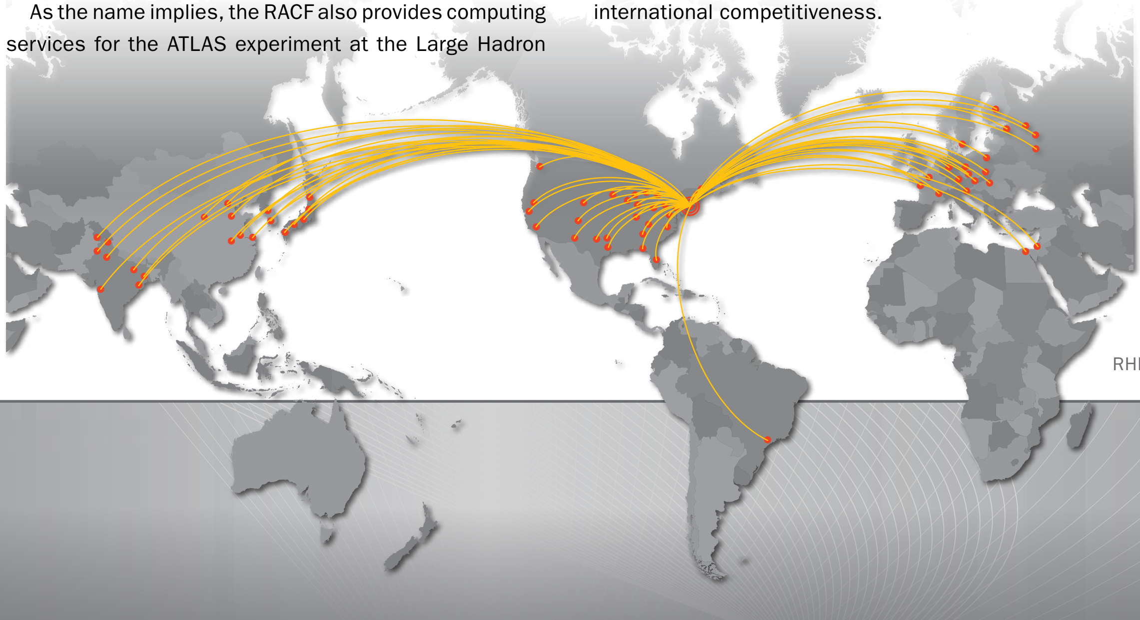
Blue Gene/Q supercomputer

Distributed data

For data storage and analysis, RHIC physicists rely on the RHIC ATLAS Computing Facility (RACF), which receives data from computers in RHIC's STAR and PHENIX detector "counting houses" via dedicated fiber-optic cables. The RACF archives the data and makes it available to experimenters around the world, who can run analysis jobs on any of RACF's 40,000 computing cores and 70 petabytes (70 million gigabytes) of data stored on magnetic disk and tape. These capabilities will continue to expand to meet the ever-growing data needs of the RHIC experiments.

As the name implies, the RACF also provides computing services for the ATLAS experiment at the Large Hadron Collider located at Europe's CERN laboratory. As a central U.S. computing facility for ATLAS, RACF receives round-the-clock real time data from CERN, storing and distributing it and performing analysis jobs for nearly 600 U.S. collaborators on this experiment. RACF is increasingly providing services to international collaborators as well.

The success of this distributed approach to data-intensive computing, combined with advances in lattice QCD, have helped re-establish U.S. leadership in the field of high-capacity computing, thereby enhancing our international competitiveness.



RHIC data distribution

Superconducting magnets for future medical applications

TANGENTIAL BENEFITS

Advances in technologies developed for science find broader application in society.

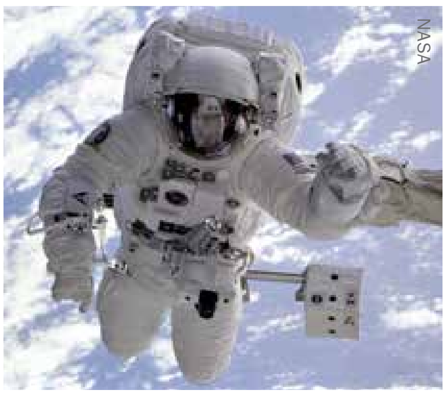
Accelerators play a role in many aspects of our lives. Among the estimated 30,000 accelerators operating in the world, many are relatively small, conducting behind-the-scenes work: producing beams to sterilize medical equipment and keep pathogens at bay in our food supply, imprinting computer chips with ions to improve their performance, producing radioisotopes for cancer diagnosis and treatment, and scanning shipping containers for illicit materials. Large research centers like RHIC—which offer opportunities for student participation in both accelerator and experimental physics—provide crucial training for young people who go on to work on next-generation technologies for many of these applications. The fundamental physics explorations at RHIC may also lay the foundation for entirely new, unpredictable, and game-changing innovations.

Isotope production

The Brookhaven Linac Isotope Producer (BLIP) is one of just two U.S. facilities that produce high-demand, short-supply radioisotopes used in heart-disease diagnosis, and Brookhaven scientists are actively exploring new applications in cancer diagnosis and treatment. For this crucial role, BLIP shares staff and infrastructure with the RHIC physics program, as well as protons accelerated through the linear accelerator portion of the RHIC complex.

Particle therapy for cancer

RHIC physicists have applied their expertise in designing and building particle accelerator components to improve the delivery of particle beams to treat cancer. Particle therapy shows great promise for precision treatment with lower doses, less collateral damage, and improved outcomes for patients. Compact beam-delivery systems designed by RHIC physicists could reduce the size and cost of these facilities and make this promising therapy more affordable and available.



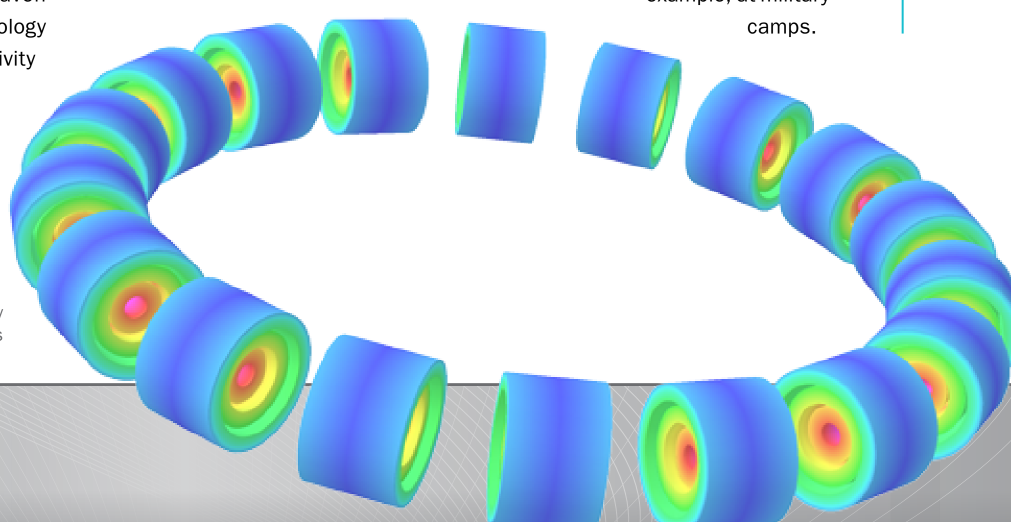
NASA

Understanding the risks of space travel

The RHIC research program also enables NASA, the U.S. space agency, to operate its NASA Space Radiation Laboratory (NSRL) at Brookhaven Lab, using beams that come from RHIC's Booster. These beams simulate the particle radiation that permeates deep space, giving scientists a way to explore how these particles affect cells, DNA samples, electronics, and shielding materials to evaluate risks and test strategies to protect future astronauts and satellites. These studies also offer insight into our understanding of cancer and the body's defense and repair mechanisms.

Magnets for energy generation and storage

Most of RHIC's magnets are made of superconductors—remarkable materials that conduct electricity with no energy loss when kept extremely cool. The design of these magnets has made Brookhaven a world leader in magnet technology and the study of superconductivity—including more recently discovered high-temperature superconductors (HTS). Brookhaven scientists are exploring efforts to develop HTS accelerator magnets, lightweight superconducting magnets for energy generation in wind turbines, and superconductor-based systems for storing large amounts of energy—enough to keep current flowing from a solar- or wind-powered system when the sun doesn't shine and the wind doesn't blow. They could also provide stable power off the grid—for example, at military camps.



Superconducting energy storage magnets

Accelerating electrons with energy recovery

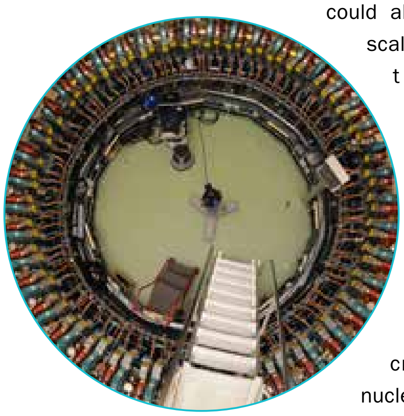
A future proposed Electron Ion Collider (EIC) known as eRHIC would use a novel kind of accelerator known as an energy recovery linac, which accelerates high-intensity, high-quality electron beams for use in collisions, and then decelerates them to recover the energy so it can be used again. Alternatively these high-quality electron beams could be passed through magnet configurations that cause them to emit self-amplifying light, resulting in an enormously powerful laser. Such a laser could fuel further advances in science, including new kinds of x-ray light sources.

Advanced computing capabilities

The computing capacity, techniques, and expertise developed to manage large volumes of data generated by RHIC experiments can be applied to a wide range of fields that require data-intensive computing—from astrophysics, to climate modeling, protein studies for drug development, and even finance. Many physicists who earned PhDs doing research and data analysis at RHIC have gone on to write algorithms and apply specialized computational skills to these types of applications.

Model for future accelerators

Brookhaven scientists recently contributed to the design and construction of a model "non-scaling fixed field alternating gradient accelerator"—the world's first. It combines features to achieve rapid acceleration of subatomic particles while keeping the scale—and cost—relatively low. Of particular interest to Brookhaven physicists who want to accelerate muons for fundamental physics research, the technology could also lead to smaller-scale accelerators for treating cancer, electron accelerator technology that could be applied at eRHIC, and accelerator-driven nuclear fission that generates power without creating bomb-grade nuclear byproducts.



EMMA accelerator, Daresbury Laboratory, UK

Training the Next Generation

CASE students and faculty

Brookhaven scientists foster a climate that nurtures those attracted to the scientific and technological challenges presented by RHIC and accelerator science in general. Throughout the design and construction of RHIC in the 1980s and 1990s, nuclear and accelerator physicists—and students from all over the world—came to work on the project. Stony Brook University, a leading research institute and the university closest to Brookhaven, was a natural partner. The two institutions now direct the Center for Accelerator Science and Education (CASE), a unique joint university-laboratory graduate and post-graduate program focused on developing the next generation of accelerator scientists and engineers.

Likewise, the compelling physics questions and experiments that address them at RHIC attract leading researchers from around the world. Working with these scientists, hundreds of students play a vital role in the RHIC experimental program, from assisting in detector design to data analysis and writing up results. Nearly 400 PhDs have been awarded to students conducting research at RHIC within its first 14 years of operations, with hundreds more in the pipeline.

Students trained in physics research and accelerator science at RHIC often go on to make important contributions both within and beyond physics. They apply their expertise in a range of careers that fuel the economy, provide for security, and pave the way to a healthier, brighter future for all. Indeed, more than half the students who earn doctoral degrees in nuclear physics in the U.S. go on to work in fields as diverse as national security, medicine, energy generation, and more. You can read some of their stories here: http://www.bnl.gov/rhic/education.asp.

COLLABORATING INSTITUTIONS

RHIC serves scientists and attracts scientific expertise, computing resources, and other equipment from across the country and around the globe.

California
Lawrence Berkeley National Lab
Lawrence Livermore National Lab
University of California at Berkeley
University of California at Davis
University of California at Los Angeles
University of California at Riverside

Colorado
University of Colorado at Boulder

Connecticut
Yale University

District of Columbia
Howard University

Florida
Florida Institute of Technology
Florida State University

Georgia
Georgia State University

Illinois
Argonne National Laboratory
University of Illinois at Chicago
University of Illinois at Urbana-Champaign

Indiana
Indiana University at Bloomington
Purdue University
Valparaiso University

Iowa
Iowa State University

Kentucky
University of Kentucky

Maryland
Morgan State University
U.S. Naval Academy
University of Maryland College Park

Massachusetts
Massachusetts Institute of Technology
University of Massachusetts at Amherst

Michigan
Michigan State University
University of Michigan
Wayne State University

Nebraska
Creighton University

New Mexico
Los Alamos National Laboratory
New Mexico State University
University of New Mexico

New York
Baruch College
Brookhaven National Laboratory
Columbia University, Nevis Labs
Stony Brook University

Ohio
Kent State University
Ohio State University
Ohio University

Pennsylvania
Muhlenberg College
Pennsylvania State University
Temple University

South Dakota
Augustana College

Tennessee
Oak Ridge National Laboratory
University of Tennessee at Knoxville
Vanderbilt University

Texas
Abilene Christian University
Rice University
Texas A&M University
University of Houston
University of Texas at Austin

Washington
University of Washington

Brazil
Universidade Estadual de Campinas
University of Sao Paulo

China
Central China Normal University
China Institute of Atomic Energy
Institute of Modern Physics, Chinese Academy of Science
Institute of High Energy Physics
Peking University
Shandong University
Shanghai Institute of Applied Physics
Tsinghua University
University of Science & Technology of China

Czech Republic
Charles University
Czech Technical University
Institute of Physics for the ASCR

Croatia
University of Zagreb

Egypt
Egyptian Center for Theoretical Physics

Finland
University of Jyvaskyla

France
CEA—Saclay
Institut de Physique Nucleaire—Orsay
Laboratoire de Physique Corpusculaire—Clermont-Ferrand
Laboratoire Leprince-Ringuet—Palaiseau
Subatech—Nantes

Germany
Frankfurt Institute for Advanced Studies
Max Planck Institute

Hungary
Eotvos Lorand University
Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Hungarian Academy of Sciences
University of Debrecen

India
Banaras Hindu University
Bhabha Atomic Research Center
Indian Institute of Technology
Institute of Physics, Bhubaneswar
National Institute of Science Education and Research
Panjab University
University of Jammu
University of Rajasthan
Variable Energy Cyclotron Center

Israel
Weizmann Institute of Science

Japan
Hiroshima University
Japan Atomic Energy Agency
KEK-High Energy Accelerator Research Organization
Kyoto University
Nagasaki Inst. of Applied Science
RIKEN
RIKEN-BNL Research Center
Rikkyo University
Tokyo Institute of Technology
CNS-University of Tokyo
University of Tsukuba

Pakistan
Lahore University of Management Sciences

Poland
AGH University of Science and Technology
Cracow University of Technology
Institute of Nuclear Physics
Warsaw University of Technology

Russia
Alikhanov Institute for Theoretical and Experimental Physics
Institute for High Energy Physics
Joint Institute for Nuclear Research
Kurchatov Institute, National Research Centre
National Research Nuclear University-MEPhi
Petersburg Nuclear Physics Institute
Skobeltsyn Institute of Nuclear Physics
St. Petersburg State Polytechnical University
The Institute for Nuclear Research of the Russian Academy of Sciences

South Korea
Chonbuk National University
Ewha W. University
Hanyang University
Korea Institute of Science and Technology
Korea University
Myongji University
Pusan National University
Seoul National University
Sungkyunkwan University
Yonsei University

Sweden
Lund University

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