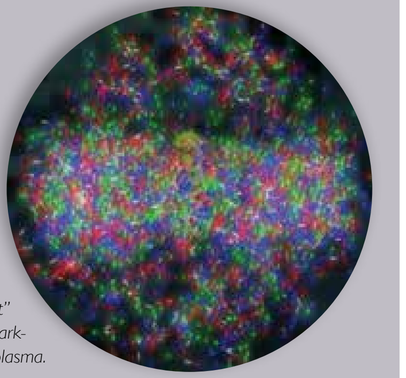
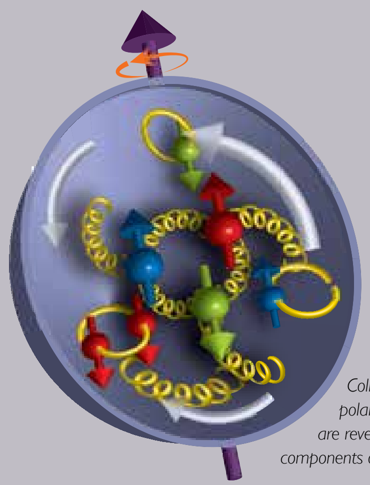
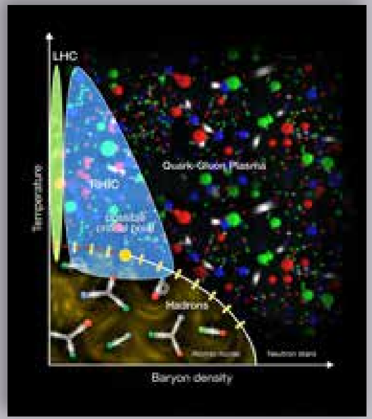


Gold ion collisions produce a "perfect" liquid quark-gluon plasma.



Collisions of polarized protons are revealing the components of proton spin.



RHIC experiments are exploring a vast swath of the nuclear phase diagram, including the transition from ordinary nuclear matter to quark-gluon plasma.

the theory that describes the interactions of the quarks and gluons that form the building blocks of atoms — and therefore the bulk of visible matter. But it also raises compelling new questions about QCD.

Key successful accelerator and detector upgrades, along with advances in supercomputing, have enabled RHIC to actively address many of these questions. A series of upgrades has increased RHIC's luminosity, or collision rate, approximately 25-fold over its original design, and improved the sensitivity of the detectors to record extremely rare processes — some of which occur in fewer than one in a billion collisions. Physicists have explored QCD in ever-greater depth by colliding a wide range of ion species over a large span of energies — an evolving experimental program made possible by RHIC's unmatched versatility.

In the longer-term, physicists envision adding a high-energy electron beam to collide with either polarized protons or heavy ions at RHIC. This would create the world's first Electron Ion Collider, a major new research facility. With this powerful machine, physicists would produce precision, high-resolution "snapshots" of the sea of ephemeral particles responsible for the structure and other properties of the building blocks of visible matter.

Spinning in another direction

A subset of RHIC scientists has a special interest in the property of proton "spin," a magnetic property that's as fundamental to a particle's identity as its mass and electrical charge. While we routinely manipulate proton spins to look inside the body with magnetic resonance imaging (MRI), experiments that ran prior to RHIC revealed a stunning mystery: A proton's three main quarks account for, at most, a third of its total spin. We do not understand how the rest of the spin is generated from the proton's many constituent particles.

Using specialized magnets known as Siberian snakes to keep the spins of protons mostly aligned in the same direction, physicists at RHIC can collide beams of these "polarized protons" to examine how their quark and gluon building blocks contribute to overall spin. RHIC is the only machine in the world with this capability, and the first to reveal that at least some gluons are polarized and play an important role in spin.

Tangential benefits

The RHIC research program has additional benefits that go beyond fundamental physics. These include:

- Advances in supercomputing and data-handling and analysis strategies
- Shared staff and infrastructure for producing radioisotopes for heart scans and cancer diagnosis/treatment
- Use of RHIC's "feeder" beams to explore the risks of space radiation
- Advances in superconducting magnets with potential use for energy storage
- Accelerator advances that could lead to improved cancer treatments
- Training the next generation of physicists

www.bnl.gov/rhic/

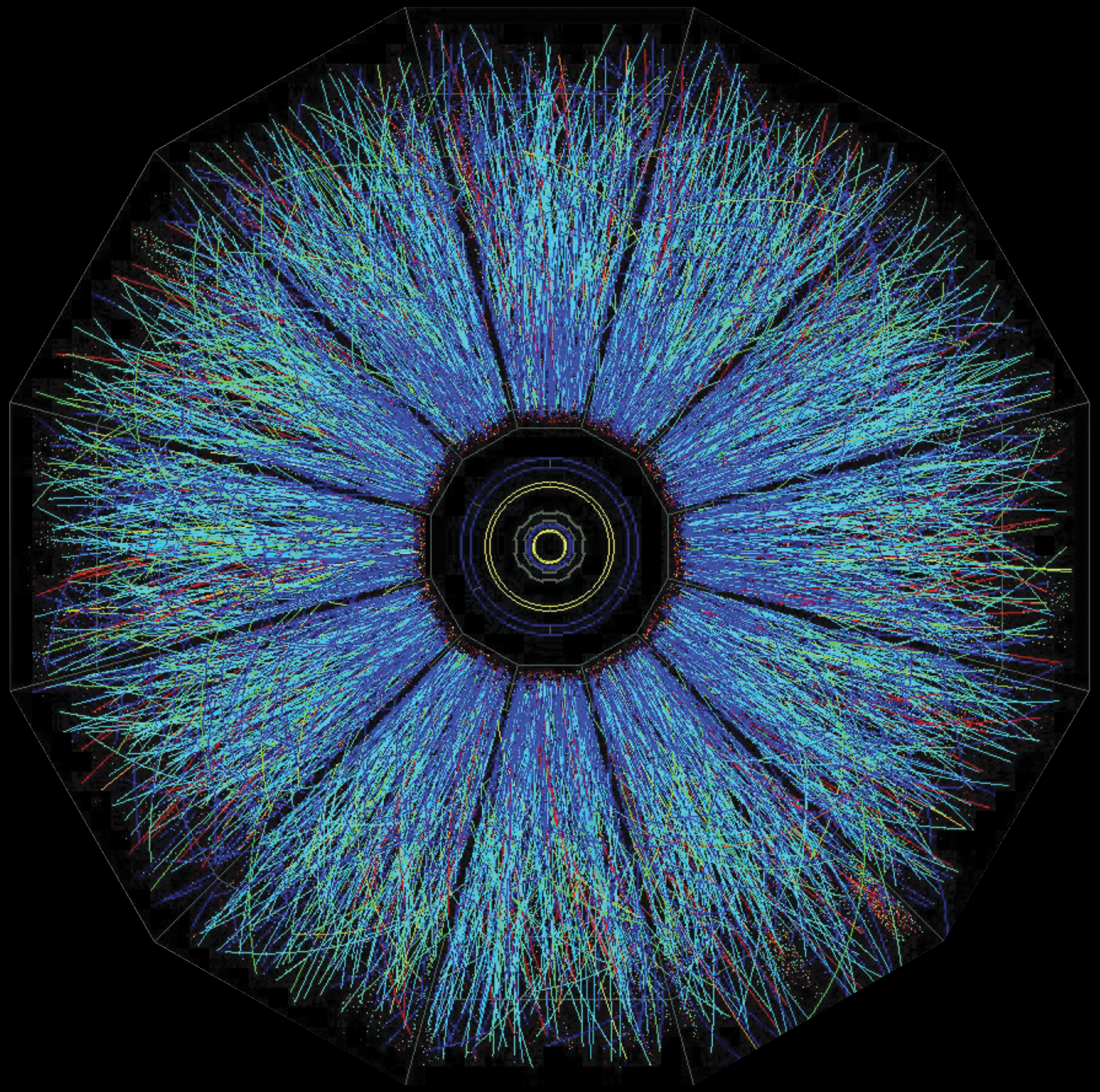
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Brookhaven National Laboratory

The Relativistic Heavy Ion Collider (RHIC)

Exploring Matter at the Dawn of Time



The Relativistic Heavy Ion Collider

Exploring Matter at the Dawn of Time

At the Relativistic Heavy Ion Collider (RHIC), a world-class particle accelerator for nuclear physics research at Brookhaven National Laboratory, scientists are exploring the most fundamental forces and properties of matter and the early universe, with important implications for our understanding of the world around us.

Superconducting magnets steer ions on a collision course at RHIC.

Operated with funding from the U.S. Department of Energy's Office of Science, RHIC was designed to recreate a state of matter thought to have existed immediately after the Big Bang nearly 14 billion years ago, and to investigate how the proton gets its spin and intrinsic magnetism from its quark and gluon building blocks. Large detectors located around the 2.4-mile-circumference accelerator take "snapshots" of collisions between beams of particles — from protons to the nuclei of heavy atoms such as gold — to get a glimpse of the basic constituents of matter.

These studies of matter at such a fundamental level are offering insight into the strongest force in nature, which holds together the universe — and everything in it.

While no one can predict what practical applications that knowledge will yield, earlier investigations of the basic structure and properties of matter have yielded countless, unforeseen advances and technologies we now take for granted — things like personal computers, medical instruments, mobile phones, and other portable electronics. The idea behind RHIC is simply to delve deeper into the mysteries of matter. In so doing, RHIC has become one of the world's premiere training grounds for young physicists.

A perfect surprise

A series of stunning discoveries at RHIC has captured worldwide attention and shone a spotlight on U.S. leadership in science.

First, RHIC scientists had expected collisions between two beams of gold nuclei to mimic conditions of the early universe and produce a gaseous plasma of the smallest components of matter — the quarks and gluons that make up ordinary protons and neutrons. But instead of behaving like a gas, the early-universe matter created in RHIC's energetic gold-gold collisions appears to be more like a liquid. Not just any liquid, but one with coordinated collective motion, or "flow," among the constituent particles.

The scientists describe this fluid motion as nearly "perfect" because it can be explained by equations of hydrodynamics for a fluid with virtually no viscosity, or frictional resistance to flow. This extremely low viscosity, and the high degree of collective interaction and rapid distribution of thermal energy among the particles make the matter produced in RHIC's collisions the most nearly perfect liquid ever observed.

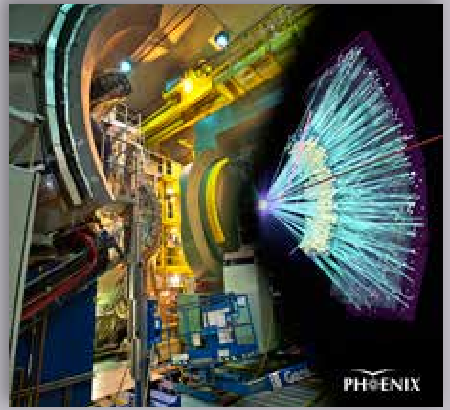
The temperature of this remarkable matter measures some 4 trillion degrees Celsius, or 250,000 times hotter than the center of the sun. That's far above the temperature at which protons and neutrons melt to free their constituent quarks and gluons, showing definitively that RHIC's perfect liquid is hot enough to be the long-sought quark-gluon plasma.

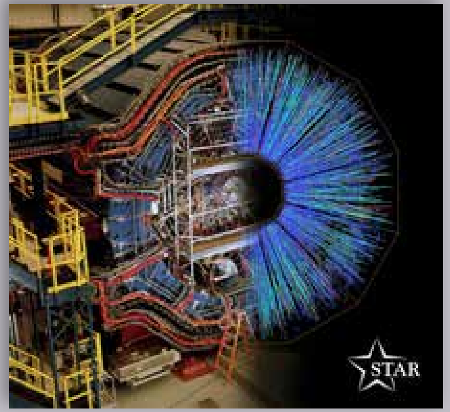
RHIC's quark-gluon plasma exhibits other unusual properties that have intrigued scientists, including the ability to stop energetic particle jets. Collisions of smaller particles with large nuclei also appear to create tiny droplets of the quark-gluon plasma. Experiments to explore these counterintuitive tendencies — and the transition between quark-gluon plasma and ordinary matter — are ongoing at RHIC.

Building on discovery

RHIC's research to date has enriched physicists' understanding of quantum chromodynamics (QCD),

(continued)





Complex detectors capture RHIC collisions for physicists to analyze.

RHIC's stochastic beam-cooling system keeps beams tightly bunched to maximize collision rates.

Brookhaven Lab's IBM Blue Gene/Q supercomputer

Supercomputing at RHIC

Since 2000, RHIC's detectors have taken digitized "snapshots" of trillions 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 needs continues to push the evolution of computing technology in ways that may benefit us all – as did the development of global communications networks designed for physicists to share data over the internet.

For data storage and analysis, RHIC physicists rely on an ever-expanding "farm" of tens of thousands of in-house computing cores, cloud computing resources, and a super-fast robotic tape storage system — at times augmented by computing resources from collaborating sites around the world. Additionally, a unique super-computing architecture, known as QCDOC (for QCD On a Chip), was developed specifically to handle the complex calculations of QCD. Two QCDOC machines capable of performing 10 trillion arithmetic calculations per second, along with successive generations of IBM Blue Gene supercomputers inspired by this design, have created a QCD laboratory at RHIC unlike any research center in the world.