The Relativistic Heavy-Ion Collider

Creating a Little Big Bang on

by FRANK WOLFS

MANKIND HAS ALWAYS been fascinated with looking back in time. Historians and archaeologists use historical records and artifacts to trace back the evolution of mankind. Biologists use evolutionary theory to describe the development of life on Earth. The Earth is relatively young by astronomical standards, about 4.6 billion years, and the Universe is even older.

It is believed that the Universe was created about 15 billion years ago, in an event that is often referred to as the "Big Bang." Astronomers provide us with a wealth of information about the evolution of Universe by probing it at ever-increasing distances from the Earth. These observations can take us back in time by about 14 billion years, at which time star formation started to occur. Nuclear and atomic physicists provide us with a detailed description of the evolution of the early Universe, between a few seconds after the Big Bang and the start of star formation. During this period, the basic building blocks of matter, protons and neutrons, were formed, and light nuclei and atoms were created.

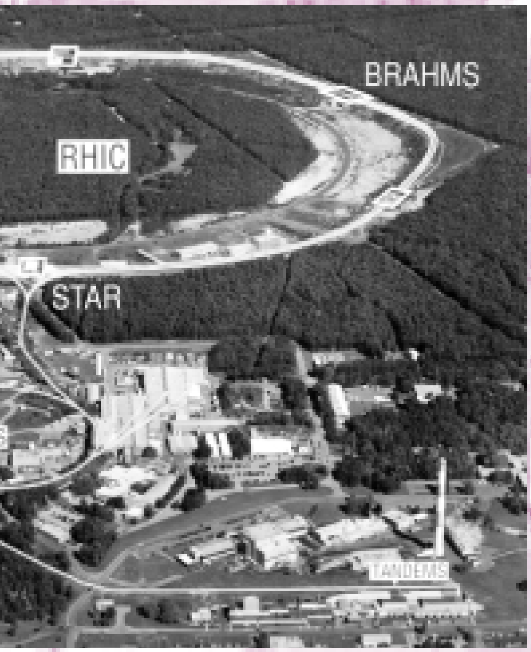
Although these different areas of science allow us to look back billions of years in time, much uncertainty remains about the evolution of the Universe during the first few seconds after the Big Bang. Many fundamental questions, such as why the Universe is dominated by matter instead of having equal amounts of matter and anti-matter, can only be answered if we know in detail what happened during the first few seconds after the Big Bang.

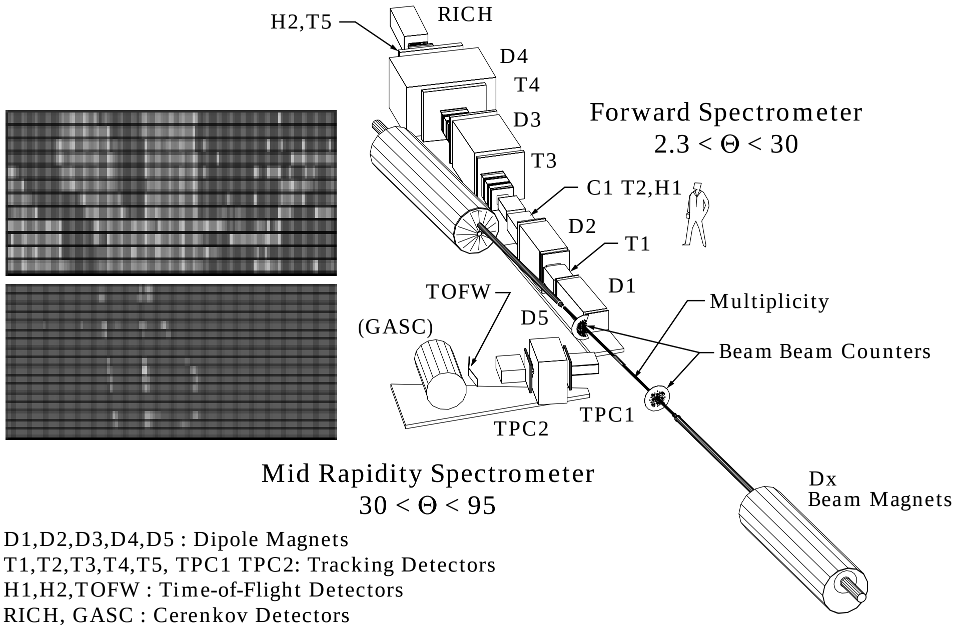
To recreate the conditions that existed a few micro-seconds after the Big Bang, a new accelerator facility was built at Brookhaven National Laboratory (BNL) in New

Long Island

York. This facility, called the Relativistic Heavy-Ion Collider (RHIC), was designed to accelerate fully-stripped ions, from protons to gold, up to energies of 100 billion electron volts (GeV) per nucleon. Several accelerator systems are involved in the process of accelerating these ions, each of which is shown in the photograph below. Negative ions (atoms with one or more extra electrons) are created in an ion source and accelerated to an energy of about 1 million electron volts (MeV) in the tandem accelerator. In this process the ions are stripped of some of their electrons and leave the tandem as positive ions. These positive ions are transferred through the heavy-ion transfer line (HITL) to the booster accelerator, where their energy is increased to 78 MeV per nucleon. Upon leaving the booster accelerators, the positive ions are stripped of all their electrons and injected into the alternating gradient synchrotron (AGS). The AGS accelerates the ions to energies of 10.8 GeV per nucleon, which is RHIC's injection energy. The bunched ions are extracted from the AGS and injected into the two 2.4-mile long RHIC rings (called the blue ring and the yellow ring) where they circulate in opposite directions. In the RHIC rings, the energy of the ions is increased to up to 100 GeV per nucleon. The ions are stored in the rings for periods of six to twelve hours in up to 57 separate bunches. Each bunch contains billions of ions traveling with velocities of up to 99.995 percent of the speed of light. Each ion makes about 100,000 trips around the

The Relativistic Heavy Ion Collider facility (RHIC) at Brookhaven National Laboratory. The locations of the four experiments (BRAHMS, STAR, PHENIX, and PHOBOS) are indicated.





The BRAHMS detector system. The event displays on the left-hand side show charged-particle tracks, reconstructed on the basis of the information provided by the time-projection chambers TPC1 (top) and TPC2 (bottom), for one of the first collisions observed at BRAHMS on June 16, 2000.

RHIC ring each second. The ions are kept in circular orbits by 1,740 superconducting magnets which are installed around the RHIC rings. To make these magnets carry electricity without resistance, they are cooled by liquid helium to a temperature of minus 451.6 degrees Fahrenheit. The amount of helium used at RHIC would be enough to fill all the balloons in the Macy's Thanksgiving Day Parade for the next century.

The yellow and blue beam lines cross at six different locations around the ring, where head-on collisions between ions moving in opposite directions can be observed. In these collisions, extremely high temperatures are created over an extremely small region of space. Initially, this region has a diameter close to 10^{-14} meter, and its temperature exceeds a trillion degrees (hundred thousand times hotter than the temperature at the center of the Sun). The conditions in this region will be similar to the conditions that existed in the early Universe, a few microseconds after the Big Bang, and it is believed that the so-called quark-gluon plasma (QGP) will be formed in this region. This extreme state of matter is expected to exist for less than 10^{-23} sec. When the QGP cools down, it will create a shower of thousands of particles, which are detected with four detectors that are installed in four of the six intersection regions. These four detectors are BRAHMS, located at 2 o'clock; STAR, located at 6 o'clock; PHENIX, located at 8 o'clock; and PHOBOS, located at 10 o'clock. The information gathered by these detectors will be used by physicists to study the properties of the quark-gluon plasma. The properties of this extreme state of matter will provide detailed information about the conditions and the evolution of the early Universe.

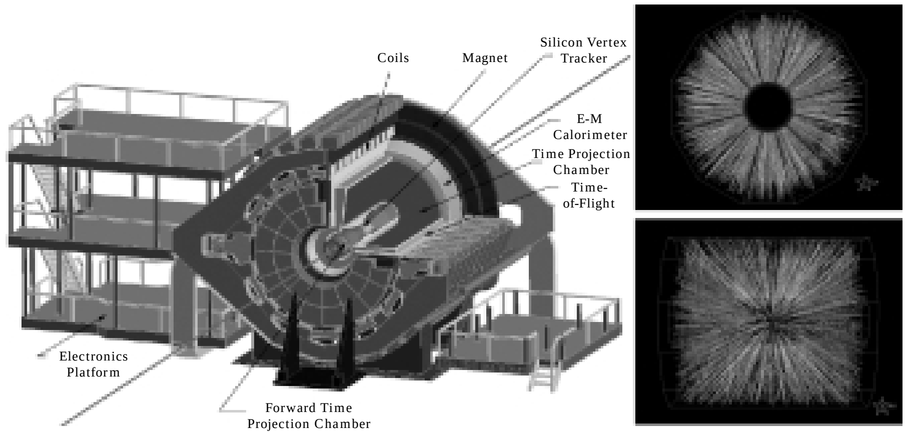
FIRST COLLISIONS AT RHIC

The ions that are accelerated at RHIC are extremely small. Each ion has a radius of about 10^{-14} m. To create collisions between the ions circulating around the accelerator, the operators carefully steer the beams in the interaction regions, making minute adjustments to their orbits using magnetic lenses. Since it is impossible to steer a single ion accurately enough to ensure a head-on collision with a one moving in the opposite direction, many billions of ions are packed in bunches with a diameter close to 0.001 m and a length of about 1 m. The operators manipulate the orbit of these bunches in order to ensure that the counter-rotating bunches cross each other at the interaction points. Since there are so many ions in each bunch, there is a small probability that a collision between ions occurs when the bunches overlap.

On June 12, 2000, the first collisions between gold ions, traveling with energies of 30 GeV per nucleon, took place. Pictures of the first collision events observed in the four RHIC detectors are shown on successive pages. At the end of June the first collisions between gold ions with energies of 70 GeV per nucleon were observed. In these first weeks of RHIC physics operation, only six bunches of gold ions were circulating in the RHIC rings, and as a consequence the collision rate was low (about one collision per second). In July, the number of bunches of gold ions stored in the machine was increased to 55, dramatically increasing the collision rates observed in all experiments. The first physics running period at RHIC was concluded in September 2000 at which point the observed luminosity was 10 percent of the design luminosity. The second year of RHIC physics will begin in the middle of 2001.

PROBING THE QUARK-GLUON PLASMA

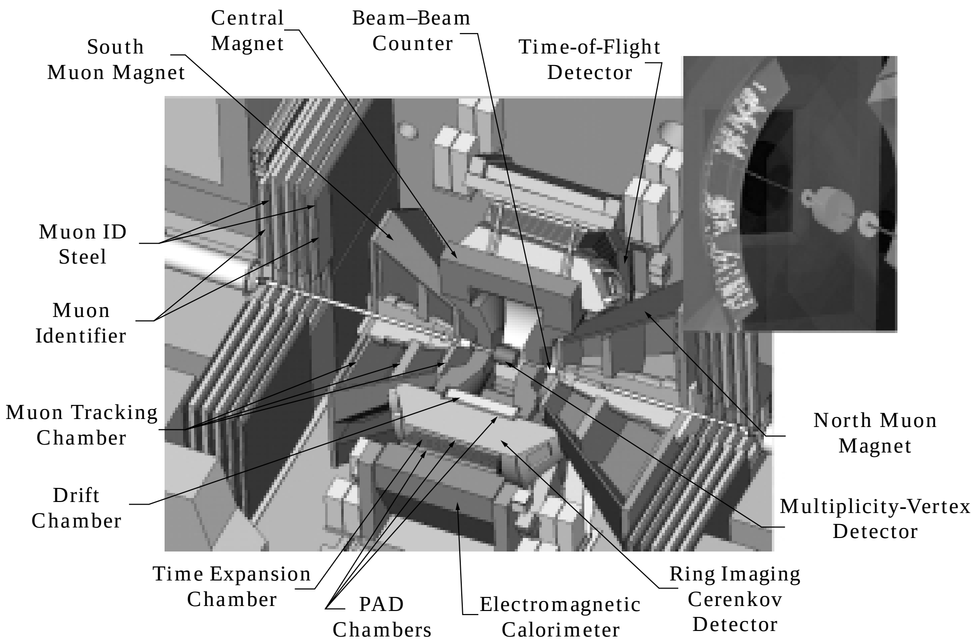
The quark-gluon plasma is an extraordinary state of matter where elementary particles, called quarks and gluons, move around freely instead of being shackled together in the protons and neutrons that make up the nucleus of the colliding ions. When the plasma cools down, it will mimic the transition that occurred in the early Universe when the constituents of ordinary matter were created. Any irregularities in the plasma-to-matter transition may provide new information about some of the remaining unanswered questions about the evolution of the early Universe.



The STAR detector system. The event displays on the right-hand side show front and side views of reconstructed tracks in the time-projection chamber for one of the first collisions observed at STAR on June 12, 2000 (see cover).

Two different types of probes can be used to study the properties of the quark-gluon plasma. Leptons, such as electrons and muons, are radiated when the plasma is cooling down. The leptons can travel through the quark-gluon plasma with little interaction, and thus can be used to provide a view directly into the heart of the plasma. After the plasma cools sufficiently, quarks and gluons condense into particles consisting of two or three quarks. This process, called hadronization, produces hadrons, such as pions, kaons, and protons. Any hadron formed within the quark-gluon plasma will quickly fall apart due to hadronic processes, and the only hadrons detected in the laboratory are those that are produced on the relatively cool outer surface of the plasma. These hadrons provide us with a view of the process of hadronization, but do not provide us with a look directly into the plasma. At RHIC, three experiments (BRAHMS, STAR, and PHOBOS) study the properties of hadron production, while one experiment (PHENIX) focuses on lepton production.

The RHIC experiments probe the quark-gluon plasma by detecting and



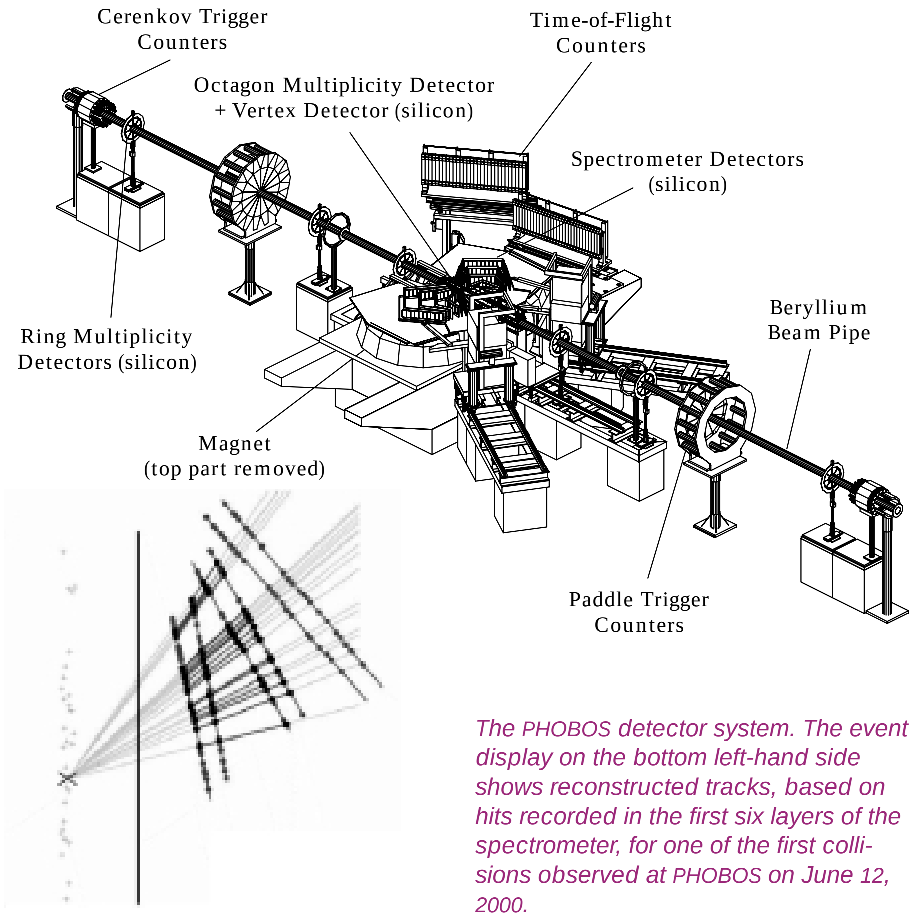
The PHENIX detector systems. The event display on the top right-hand side shows reconstructed charged-particle tracks in the drift chamber for the first collision observed at PHENIX on June 15, 2000.

measuring the properties of the particles produced during the various phases of the evolution of the plasma. During a typical head-on collision between two gold ions, many thousands of charged hadrons are produced. This enormous number of charged particles requires complicated and highly segmented detectors to be used. The quark-gluon plasma is expected to decay within 10^{-23} sec after its formation. Since for most experiments it takes at least 10^{-9} sec before the first particles can reach the detectors, the quark-gluon plasma cannot be detected directly, and its properties must be inferred from the properties of its decay products. The nature of the work of scientists at RHIC is in many ways similar to the work of inspectors of the National Safety and Transportation Board, who after a plane crash will collect thousands of pieces of evidence to reconstruct what happened and determine the cause of the accident. The scientists at RHIC collect thousands of pieces of debris from the quark-gluon plasma and try to piece together a puzzle that can be used to determine some of the properties of this new state of matter.

THE RHIC EXPERIMENTS

Four different experiments are operating simultaneously at RHIC when ions are stored in the rings. Although the experiments have a common goal, namely identifying and studying the properties of the quark-gluon plasma, they differ in their approach and the techniques used. As a consequence, the RHIC experiments complement each other, and their combined results will provide a wealth of information about the properties of the quark-gluon plasma. In the experiments, the properties of the reaction products are determined by measuring the energy they lose or the radiation they emit when they travel through known amounts of materials, by measuring their velocity, and/or by observing how they bend in applied magnetic fields.

The four RHIC detectors have one component in common: a pair of zero degree calorimeters (ZDCs). The ZDCs are small devices located downstream of each of the experiments, behind a dipole magnet. They detect the neutral particles produced in each collision; the charged particles are swept away by the magnetic field of the dipole magnet and thus do not reach the zero degree calorimeters. The ZDCs are used to measure the centrality of each collision and the luminosity of the beams. In addition, these detectors can be used to



The PHOBOS detector system. The event display on the bottom left-hand side shows reconstructed tracks, based on hits recorded in the first six layers of the spectrometer, for one of the first collisions observed at PHOBOS on June 12, 2000.

compare the results obtained by the different RHIC experiments on an equal footing, by using the ZDCs as a tool to select the same class of events in different detectors.

The BRAHMS detector is shown schematically on page 4. BRAHMS features two spectrometers that can be rotated, in small steps, around the interaction point. The spectrometers have a variable magnetic field and various tracking and energy-loss counters to determine the properties of the incident charged particles. The insets in the figure show data collected by some of these tracking counters in one of the first collisions observed by BRAHMS. Several tracks are evident, all of which originate from a common point where the collision between the gold ions occurred. The BRAHMS spectrometers have a small opening angle, and for a typical collision only a few particles are detected. However, the properties of these charged particles, such as their momentum and energy, are measured very precisely. About 50 people from eight countries are members of the BRAHMS collaboration.

The STAR detector is shown schematically on page 5. It utilizes a large 4 meter diameter time projection chamber that provides tracking and particle identification capabilities for hadrons over a large solid angle. Almost all charged particles, except those emitted very close to the direction of the beam, are detected in the time projection chamber. Charged particles traveling through it deposit some of their energy along their track, which is measured and recorded using sophisticated electronics. The measured energy loss can be used to identify the charged particles and to visualize their tracks. The radius of curvature of these tracks in the magnetic field, generated by the large solenoid that surrounds the time projection chamber, is used to determine the momentum of the hadrons. An example of the measured tracks in the time projection chamber generated by one of the first collisions observed by STAR is shown on page 5 and on the cover. The volume of data collected by this detector during a typical event is enormous, about 16 megabytes, and due to limitations of computer power and data storage, only one collision event per second can be processed and recorded. When RHIC reaches its design luminosity and energy, about 200 collisions will occur every second, and, as a consequence, the STAR trigger electronics must decide within a few microseconds after each collision whether or not to record the data collected. Over 400 scientists and engineers from seven

On The Web

For related information on this topic refer to the following Internet addresses:

http://teacher.pas.rochester.edu/
(author's home page)

http://www.rhic.bnl.gov/
(home page of the Relativistic Heavy-Ion Collider)

http://www.rhic.bnl.gov/brahms/WWW/brahms.html
(home page of the BRAHMS collaboration)

http://www.star.bnl.gov/STAR/
(home page of the STAR collaboration)

http://www.rhic.bnl.gov/phenix/
(home page of the PHENIX collaboration)

http://phobos-srv.chm.bnl.gov/
(home page of the PHOBOS collaboration

http://www.rhic.bnl.gov/html2/tour.html
(virtual tour of the RHIC facility)

http://www.pubaf.bnl.gov/pr/bnl-pr060800.html
(news release of the observation of the first collisions at RHIC)

countries are members of this collaboration.

The PHENIX detector is shown schematically on page 6. It is the only RHIC experiment that focuses on the detection of photons, electrons, and muons. In a typical collision, several hundred of these will enter the detector where their properties are measured. The properties of the muons are studied using two forward muon arms, where the particles are tracked and identified. The total energy carried away from the collision by the leptons in directions perpendicular to the beam is measured with an electromagnetic calorimeter that surrounds the interaction point. The track of each detected lepton is determined using the information provided by various tracking and imaging detectors that are located between the interaction point and the electromagnetic calorimeter. The tracks recorded for one of the first collisions observed by PHENIX are also shown in the illustration on page 6. These tracks all point toward the collision point. Over 450 scientists and engineers from 10 countries are members of the PHENIX collaboration.

The PHOBOS detector is shown schematically on page 7. It features a number of different silicon-based detector systems and various plastic scintillators. Each collision is characterized by measuring the total multiplicity of charged particles, over virtually all phase space, using a silicon multiplicity detector. About 1 percent of the total number of charged particles enter a silicon spectrometer, located in a strong magnetic field, where their energy loss, momentum, and velocity are measured. The spectrometer is capable of identifying charged particles down to very low transverse momenta. The reconstructed tracks observed in one of the first collisions observed at PHOBOS are shown in the inset in the figure on the previous page. Since the data volume for a typical event is rather small, about 18 kilobyte, PHOBOS can take data at minimum bias at full RHIC luminosity. About 70 scientists and engineers from three countries are members of this collaboration.

WATCH OUT FOR 2001

The first physics run, completed in September 2000, provided all experiments with a wealth of data on the properties of nuclear collisions at unprecedented energies. RHIC operation will resume in the middle of 2001, with an increase in luminosity and energy. It is expected that by the end of summer 2001, collisions between gold ions with an energy of 100 GeV per nucleon will occur routinely, and the Big Bang will be recreated on Long Island several times per second.