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RHIC project overview

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Abstract

An overview of the RHIC Project, the construction and commissioning of the Relativistic Heavy Ion Collider and a set of four detectors at Brookhaven National Laboratory, will be presented as the introduction to this Special Issue of Nucl. Instr. and Meth.

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Keywords: Heavy; Ion; Collider

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the US Department of Energy's forefront research facility for the nuclear physics program. The construction of the collider and a complementary set of four detectors, BRAHMS, PHENIX, PHOBOS, and STAR, were completed, as scheduled, during 1999. Following the initial engineering test of the Collider within the same year, collisions of Au ions were achieved during the subsequent commissioning run in the year 2000, first at the beam energy of 28 GeV/nucleon on June 12, 2000 and later at 65 GeV/nucleon. Collisions of Au ions at the design beam energy of 100 GeV/nucleon were achieved on July 18, 2001. All the four detectors were also commissioned and collected significant amounts of data during the 4-week first physics run in 2000. This article covers an overview of the RHIC Project and its facility, and the commissioning activities that have opened a new frontier of nuclear matter research.

Fig. 1 shows the phase diagram of nuclear matter as the function of baryon density and temperature, with a contour showing the predicted transition of nuclear matter from the hadronic phase to the quark-gluon plasma (QGP) phase. Toward the far right on the horizontal axis for the matter density, one finds an extremely high baryon density state, such as in the neutron star where one may find the quark-gluon plasma phase. Going up along the temperature axis, the figure indicates the phase transitions into the QGP domain at a sufficiently high temperature of about 10^{12} K. It is expected that the collisions of Au ions at the beam energy of 100 GeV/nucleon at RHIC will result in the state of matter at a sufficiently high temperature that exceeds the transition temperature. The primary objective of RHIC, therefore, is to investigate this phase transition and to study the formation and property of QGP. With an addition

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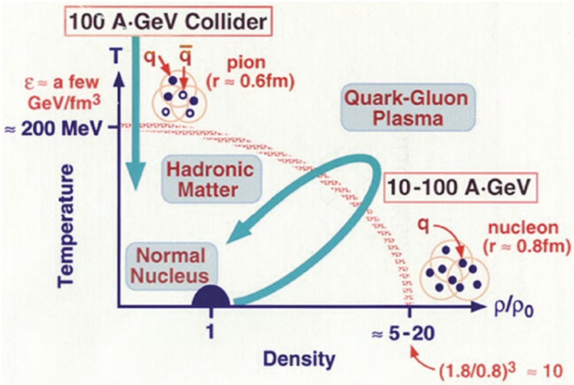

Fig. 1. Phase diagram of nuclear matter.

of Siberian Snakes, which was made possible by the Spin Physics Collaboration with the RIKEN Laboratory of Japan, the scientific objective of RHIC was expanded to include the study of spin structure of nucleons and other spin physics studies in a range of collision energies never before possible. With RHIC, nuclear physics is entering into the "high-energy" domain in which the QCD structure of matter should be directly manifested in terms of the dynamics of quarks and gluons.

2. The RHIC facility

The idea to build RHIC dates back to 1983, when it was conceived as part of the long-range plan for nuclear science. The Nuclear Science Advisory Committee (NSAC), an advisory body to the US Department of Energy (DOE) and the National Science Foundation (NSF) made a declaration that "the United States should proceed with the planning for the construction of this relativistic heavy ion collider facility expeditiously; and we see it as the highest priority new scientific opportunity within the purview of our science" [1]. Based on this recommendation, DOE began supporting the R&D effort for the RHIC collider in 1987. The R&D was directed mainly toward a very focused development program on the superconducting magnets for the collider ring, but also included a conceptual design of the collider and associated accelerator physics issues [2]. Allocation of funding for generic R&D of detectors suitable for heavy ion collision experiments began in FY 1990, and that was later converted to cover RHIC specific detector R&D. Funding for the RHIC Construction Project began in 1990 and actual construction began in 1991. The scope of the RHIC Project included design and construction of a two-ring superconducting hadron collider in an existing tunnel of 3.8-km in circumference, beam injection lines from the existing Alternating Gradient Synchrotron (AGS) to the RHIC collider, and a complementary set of detectors for relativistic heavy ion collision experiments. An existing chain of hadron accelerators at BNL, i.e., the Tandem Van de Graaff, the Booster, and the AGS would be used as the heavy ion injector to the collider rings. The existing proton linac would be used as the source of polarized protons. Also utilized was a large helium refrigerator with the cooling capacity of 25 kW at a temperature of 4.2 K that was completed in 1986 for an earlier ISABELLE/CBA Project. The construction was completed in 1999, and the physics program in the newly opened energy domain for heavy ion collision began in 2000, 17 years after its conception.

The total line-item budget for the RHIC Project was $616.6M, which consisted of $486.8M for the construction of the collider and a complementing set of detectors in their baseline configuration, $51.8M for the accelerator and detector technology R&D, and $77.8M for pre-operations including the verification of the functionality of the collider. From the beginning, $115M of the construction funds was set aside to support the construction of the set of baseline detectors. In order to further enhance the physics capability of the detectors, a decision was made in 1996 to add several detector subsystems to the baseline configuration of PHENIX and STAR with the Additional Experimental Equipment program (AEE) funds from DOE. This program also established the RHIC Computing Facility (RCF) that provides the computing support with a large-scale data storage system and CPU farm for the simulation, data recording, event reconstruction, and data mining. The total AEE funding that started in1996 was $38.2M. Provision of funding from NSF through the collaborating universities was instrumental in many ways, including support for the participation of university staff and students in the RHIC experimental program and the contribution of additional important hardware to the baseline detector. Lastly, the RHIC Project received many sizable contributions in the form of cash, equipment, manpower, and technical expertise from foreign countries and institutions in addition to intellectual participation of their scientists and students in the scientific mission of RHIC. The size of total contributions from foreign sources is estimated to be approximately equivalent to \$50M, though it is rather difficult to make an accurate assessment because the mode of contributions varied case by case.

3. RHIC collider

The basic design parameters of the collider are given in Table 1. The top energy for heavy ion beams (e.g., for gold ions) is 100 GeV/u and that for protons is 250 GeV. Counter-rotating beams collide head-on at six intersection points. The particle species that can be accelerated, stored, and collided at RHIC range from $A=1$ (protons) to $A\sim 200$ (gold), at present. Subject to the development of a suitable ion source [such as an Electron Beam Ion Source (EBIS)], collisions of heavier ions can be realized. Having two completely independent rings and two sources of ions (two Van de Graaffs or a Van de Graaff and proton linac), collisions of unequal ion species, such as protons on gold ions or light ions on gold can also be studied at RHIC.

Table 1
Performance specifications of RHIC

	For Au–Au	For p–p
Beam energy	$100\to 30$ GeV/u	$250\to 30$ GeV
Luminosity	$2\times 10^{26}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$1.4\times 10^{31}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Number of bunches/ring	60 ($\to$120)	60 ($\to$120)
Luminosity lifetime	$\sim$10 h	$>$10 h
β^* at collision points	10 m$\to$2 m (1 m?)	10 m$\to$2 m (1 m?)

The collider consists of two quasi-circular concentric accelerator/storage rings on a common horizontal plane, one (“Blue Ring”) for clockwise and the other (“Yellow Ring”) for counter-clockwise beams. Rings are oriented to intersect with one another at six locations along their 3.8 km circumference. Each ring consists of six arc sections (each $\sim$356 m long) and six insertion sections (each $\sim$277 m long) with a collision point at their center. Each arc section is composed of 11 FODO cells with a modified half-cell on each end. Each full cell consists of two 9.45 m long dipoles and two composite units, each containing one 0.75 m long sextupole, one 1.11 m long quadrupole and one 0.50 m long corrector assembly. In the arc sections, the counter-rotating beams are separated by 90 cm horizontally. A pair of dipole magnets, DX and D0 located at $\sim$10 m and at $\sim$23 m from the collision point, respectively, steer beams to a co-linear path for head-on collisions. Three quadrupole magnets, Q1–Q3 that are located outside the steering dipoles, form the final focus triplet for high luminosity collisions. Because of the intense intra-beam scattering caused by the high charge of heavy ions, the transverse beam emittance of the gold beams grows rapidly. In order to provide a sufficiently large dynamic aperture, the bore diameters of the RHIC collider magnets are relatively large, e.g., 180 mm for DX, 100 mm for D0, 130 mm for Q1–Q3, and 80 mm for all other magnets. Superconducting magnets are used exclusively for both storage rings. Altogether, 1740 superconducting magnets were required for the RHIC collider, of which 1200 units were manufactured by industry.

The RHIC acceleration scenario for Au ion beams is shown in Fig. 2. Three accelerators in the injector chain will successively boost the energy of ions, and strip electrons from the atoms. Negatively charged gold ions from the pulsed sputter ion source at the Tandem Van de Graaff (100 μA, 700 μs) are partially stripped of their electrons with a foil at the Tandem’s high voltage terminal, and then accelerated to the energy of 1 MeV/u by the second stage of the Tandem. After further stripping at the exit of the Tandem and a charge

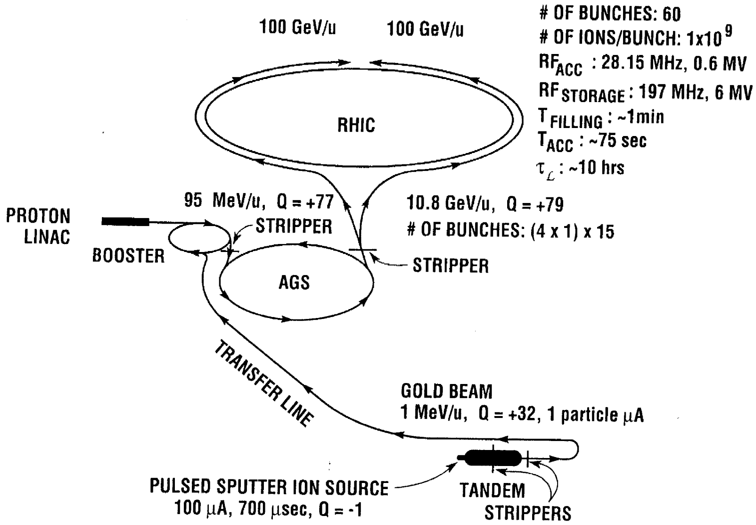

Fig. 2. RHIC acceleration scenario for Au beams.

selection by bending magnets, beams of gold ions with the charge state of $+32$ are delivered to the Booster Synchrotron and accelerated to 95 MeV/u. Ions are stripped again at the exit from the Booster to reach the charge state of $+77$, a helium-like ion, and injected to the AGS for acceleration to the RHIC injection energy of 10.8 GeV/u. Gold ions, injected into the AGS in 24 bunches, are debunched and then re-bunched to four bunches at the injection front porch prior to the acceleration. These four bunches are ejected at the top energy, one bunch at a time, and transferred to RHIC through the AGS-to-RHIC Beam Transfer Line. Gold ions are fully stripped to the charge state of $+79$ at the exit from the AGS. The stacking in the RHIC rings is done in a boxcar fashion.

Acceleration and storage of beam bunches at RHIC uses two RF systems; i.e., one operating at 28 MHz to capture the AGS bunches and accelerates to the top energy, and the other operating at 197 MHz to provide short-collision diamond ($\sigma_L \sim 25$ cm) for a more reasonable detector design. The synchrotron phase transition of the RHIC lattice is at $\gamma_T = 24.7$; thus all ions, except protons, must go through this transition. The RHIC collider, indeed, is the first superconducting accelerator (hence slow ramp rate) that passes through the synchrotron phase transition and associated beam instability. It is important to cross this transition rapidly in order to minimize the beam loss and the emittance growth. This can be accomplished either by rapid acceleration through it with resultant orbit jump to a larger radius or by a "γ_T-jump", where sets of quadrupoles are pulsed to change the tune of the machine and thus move the transition energy momentarily. For the year 2000 operation, the former method was used due to the lack of pulsed power supplies, while for the year 2001 run, the latter method has been implemented.

Polarized protons are injected from the existing 200 MeV Linac for the spin physics program with collisions of polarized protons. Polarized beams become increasingly difficult to maintain with increasing energy due to the increased density and strength of the spin resonances. RHIC is by far the highest energy polarized beam facility yet envisaged and a different approach was necessary. The use of Siberian Snakes to preserve beam polarization has been postulated for a long time and has been implemented at RHIC. A Snake providing a full 180° spin flip was designed and fabricated as part of this program. Each Snake is constructed from four 2 m helical dipole modules. Four such Siberian Snakes that were built as part of the RIKEN-BNL Spin Physics Collaboration

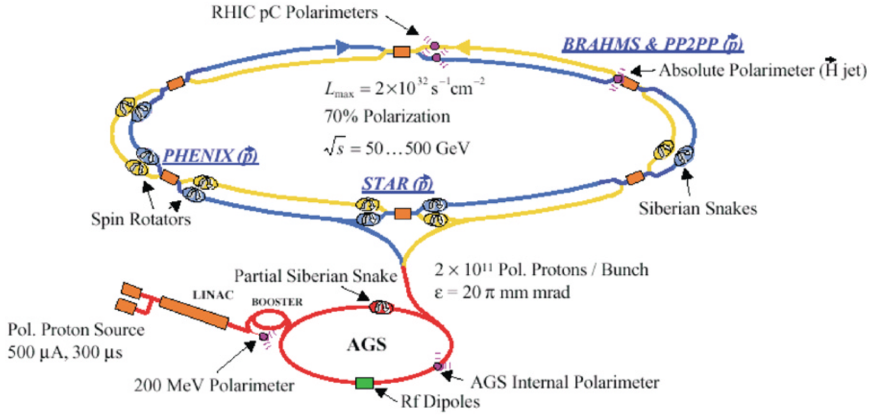

Fig. 3. Layout of Siberian Snakes and Spin Rotators for collisions of polarized protons.

and with RIKEN funding are installed in the collider rings (two in each ring, 180° apart) as shown in Fig. 3. These Snakes [3] will make it possible to accelerate, store, and collide polarized proton beams, providing a unique opportunity to carry out the spin physics program at an ultra-high center of mass energies. Other hardware that is built for the spin physics program under this Collaboration includes two sets of four spin rotators that are to be installed on both sides of the collision points for PHENIX and STAR detectors, respectively, and polarimeters.

4. Detectors

The arrangement of detectors around the RHIC ring is shown in Fig. 4. There are two major detectors (STAR and PHENIX) and two minor ones (PHOBOS and BRAHMS). Here, the qualifier major and minor refer to their scale or size, complexity, cost of construction, and size of the collaboration, and not to the depth of physics reach. These four detectors form a complementary set for the first round of experiments at RHIC.

The STAR detector utilizes a solenoidal geometry with a large cylindrical Time-Projection Chamber (TPC) (4 m in diameter and 4 m long), installed inside a large solenoid magnet, providing a close to 4π solid angle tracking capability for charged particles from collisions. With the three-dimensional tracking capability, i.e., projections on the end sectors giving the $x-y$ coordinates, and drift time of ionization electrons giving the z-coordinates of track segments, the TPC can handle thousands of tracks from an event. The dE/dx measurements of track segments allow an identification of particles over a significant momentum range of interest. A Silicon Vertex Detector (SVT) that surrounds the beam pipe improves the momentum resolution of the system and facilitates detection of decay vertexes of short-lived particles. The Barrel Electromagnetic Calorimeter and the End-cap Electromagnetic Calorimeter add capability for photon and electron detection and for the determination of their energy.

The PHENIX detector consists of three magnetic spectrometers, i.e., a Central Spectrometer consisting of an axial field magnet and two detector arms, one on the west side and the other on the east side, and two Muon Arms, one on the north side and the other on the south side of the central spectrometer along the direction of beams. The basic concept of the Central Spectrometer is to cover selected solid angles with quasi-concentric layers of high-speed detectors of various types. Detector subsystems in the Central Spectrometer arms include Drift Chamber, Pad Chamber, Time Expansion Chamber for tracking and Ring Imaging Cerenkov Detector, Time-of-Flight Detector, and Electromagnetic Calorimeter for the particle identification. The Muon Arms contain the Muon

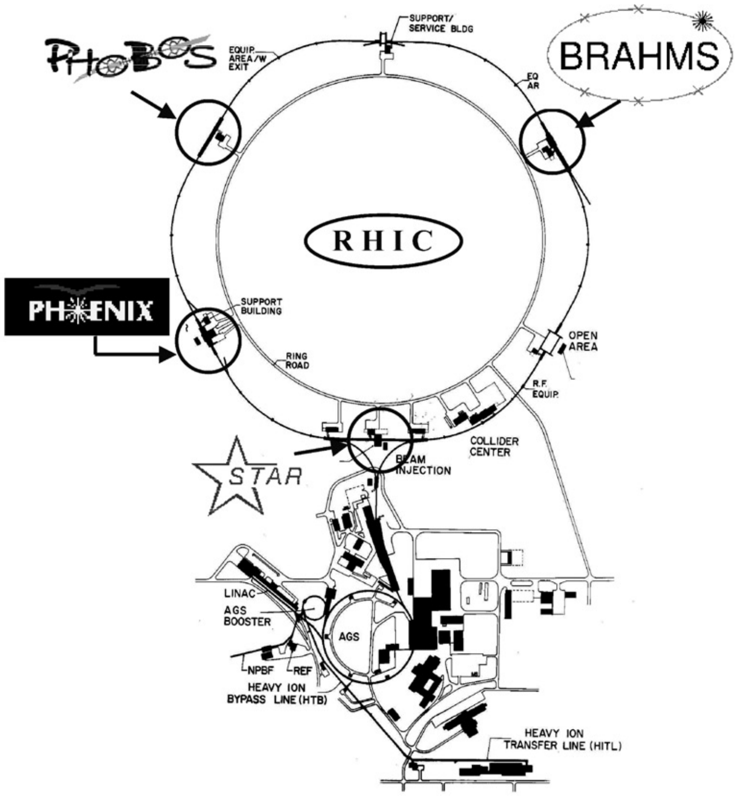

Fig. 4. Arrangement of detectors along the RHIC ring.

Magnets with radial magnetic field geometry, Muon Trackers, several layers of steel slabs as Muon Filters, and Muon-Identifying Detectors. The combination of these detectors will facilitate good tracking and the identification of leptons, hadrons, and photons. A Multiplicity/Vertex Detector that surrounds the beam pipe, Beam–Beam Counters, and Zero-degree Calorimeters (ZDCs), identifies the collisions and their location along the beam direction. This concept will let PHENIX detect the phase transition in a number of observable signatures simultaneously. Only the Central Spectrometer was available for the 2000 physics runs.

The PHOBOS detector consists of a two-arm magnetic spectrometer (one arm for 2000 physics runs) as its central detector and a series of ring multiplicity detectors, which surround the beam pipe at various distances from the collision point and provide a close to 4π solid angle coverage. The exclusive use of high-resolution and high-speed silicon micro-strip devices for the detection element will make the spectrometer Table Top size and also provide it with a very high data rate capability for detection of charged hadrons and leptons in selected solid angles. The Time-of-Flight screens improve the particle identification capability of the detector.

The BRAHMS detector consists of a two-arm magnetic spectrometer, one in the forward direction for measurement of high momentum particles but with a small solid angle and the other on the side of the collision point for the mid-rapidity region. Both arms are movable to variable settings to cover wide ranges of kinematical regions. The technology used in this detector is more or less conventional in a sense that the design is quite similar to a spectrometer often used in a traditional fixed-target experiment at a high-energy accelerator facility. The spectrometers consist of room temperature narrow gap dipole magnets, drift chamber planes, other tracking devices, Cerenkov counters, and Time-of-Flight detectors.

In order to provide universal characterization of heavy ion collisions, all the four detectors have one common detector subsystem, namely a pair of ZDCs [4] that are located behind the beam-splitting point outside the DX magnets. The ZDC is a small calorimeter, consisting of layers of tungsten plates and scintillator slabs, and detects neutron multiplicities from the heavy ion collisions, giving one of the collision centrality measures. The ZDC pair at each crossing point is also used as a luminosity monitor in steering the beams to collide.

Because of the extraordinary complexity of the collision events at RHIC, the detectors are equipped to sample and record massive amounts of data at unprecedented rates. A key part of the experimental program is the RCF. Raw data from each of the experiments is sent directly to this dedicated computing center over fiber optic lines. The RCF provides disk and robotic tape storage, as well as CPU processing for data analysis, for all of the RHIC experiments. At present (for the year 2001–2002 RHIC running), this includes $\sim$17,000 SPECint95 of processing power, $\sim$36 Tbytes of disk storage with I/O capacity of $\sim$600 Mbytes/s, $\sim$600 Mbytes/s, $\sim$600 Tbytes of robotic tape storage, with tape I/O capacity of $\sim$200 Mbytes/s. The processing and storage capacity of the facility is provided in a scalable configuration, which is planned to grow over the coming years as the performance of the collider and detectors increases.

5. Commissioning and first physics runs

After meeting successive milestones such as the first sextant test in February 1997, the completion of magnet production in September 1998 and the assembly of the RHIC rings in January 1999, almost on schedule, the engineering run to verify functionality of the collider system took place from June to September 1999. During this time, low energy/intensity beams were circulated independently in both rings together with the first acceleration. The actual commissioning with colliding beams, the commissioning of detectors, and the initial physics run took place during the late spring to summer of 2000.

For the operation in the year 2000, the cool-down of the collider ring began on March 10. After reaching the stable operating temperature of 4.6 K, the Au beam was introduced into one of two rings (Blue Ring) on April 3 and to the other ring (Yellow Ring) on May 6. On May 20 the beam in the Blue Ring was accelerated through transition to approximately 60 GeV/u. Acceleration and storage of beams in the Blue Ring took place on June 1, and that in the Yellow Ring on June 6. These led to the achievement of collisions in the STAR and PHOBOS detectors on June 12 at the beam energy of 28 GeV/u (or the total collision energy 56A GeV). Collisions in the PHENIX and BRAHMS detectors were observed 3 days later. Shortly thereafter, the beam energy was increased to 65 GeV/u, achieving a center-of-mass collision energy of heavy ions some seven times higher than the CERN SPS Pb beam operation. The target luminosity for the year 2000 run (10% of the design luminosity) was reached at this energy on August 20, 2 weeks before the end of the heavy ion runs on September 5. The integrated luminosity per week, delivered to the four experiments, is shown in Fig. 5. As can be seen in the figure, the integrated luminosity almost doubled each week and reached the total of $> \sim 6\,\mathrm{b}^{-1}$ to PHENIX and BRAHMS, $> \sim 3\,\mathrm{b}^{-1}$ to STAR and PHOBOS, providing millions of relativistic Au–Au collision events at the total collision energy of 130A GeV (or $\sim$26.4 TeV for Au–Au ions).

As the collider was producing the collisions of Au beams, the four detectors were indeed ready to accept collision events and take data. Also ready were the large-scale computer systems for data collection and analysis at the RCF, and the physicists with computer software to tackle the analysis of complex events from heavy ion collisions.

Fig. 6 shows the by now well-publicized STAR Au–Au events at a center-of-mass energy of

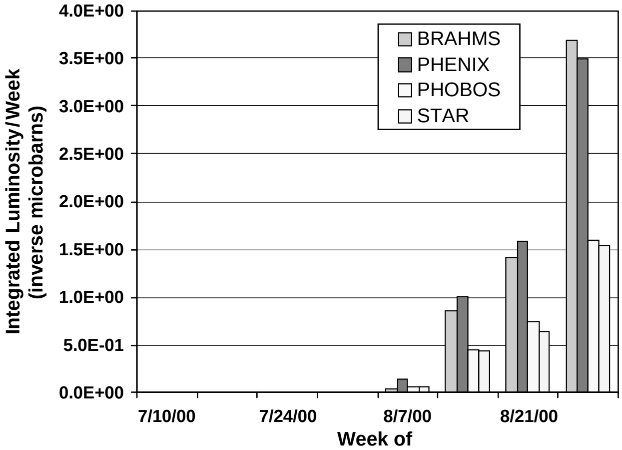

Fig. 5. Integrated luminosity of Au–Au collisions delivered per week.

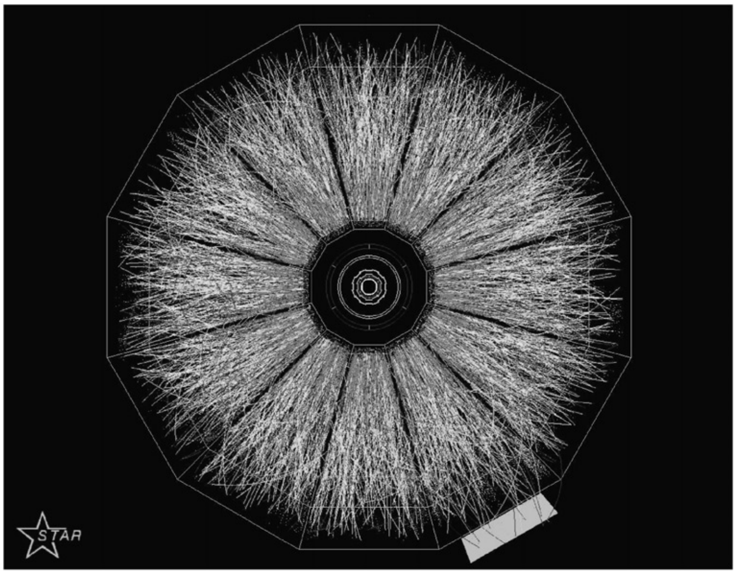

Fig. 6. An Au–Au collision as detected by the STAR TPC (end view).

$130A$ GeV as recorded by its TPC. This picture demonstrates that this TPC, especially developed for high-multiplicity events, can easily handle more than 1000 tracks, and measure the $\mathrm{d}E/\mathrm{d}x$ of individual tracks with a resolution of about 8%. This capability combined with the effective mass reconstruction of unstable particles, based on the decay topology, allows STAR to identify and measure particles such as pion, kaon, proton, and their anti-particles as well as unstable particles such as K^*, φ, Λ, Ξ, etc.

Having multiple layers of various detectors in its central arms, PHENIX can also do the track reconstruction and an identification of particles, as was the case with STAR. In addition, having the EM calorimeter and the ring-imaging Cherenkov counter, the PHENIX detector can identify and measure electrons and neutral pions. The result of

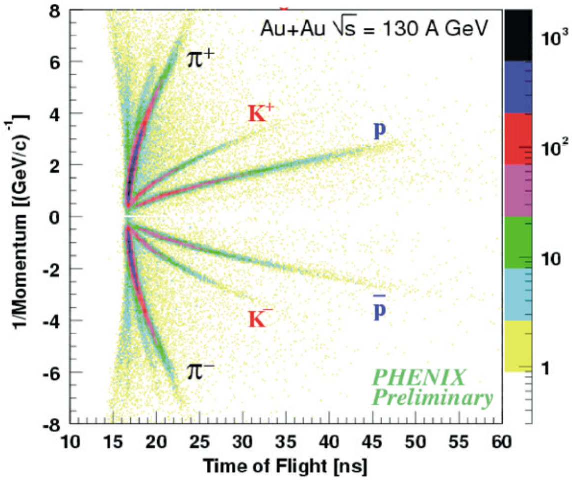

Fig. 7. Particle identification with time-of-flight with PHENIX detector.

time-of-flight measurements with the PHENIX detector is shown in Fig. 7.

At the QM2001 conference that took place in January this year, just 4 months after 4 weeks of data taking that ended on September 5, 2000, RHIC research groups presented 31 physics papers that gave a first glimpse of the landscape at this exciting new frontier [5]. To date, 10 Phys. Rev. Lett. articles have been either published or submitted for publication [6–9]. This speed by which significant physics results were produced from data obtained with the newly commissioned accelerator is unprecedented. What they have measured are global event characteristics such as particle multiplicity and its distribution, transverse energy measurement, and particle ratios. These measurements give valuable information on the energy density and temperature of the state produced by the collision. Other measurements included charged hadron spectra, neutral particle production, antiparticle/particle ratios, anisotropy of the particle distribution, and particle correlations, etc.

6. Near and long-term future

As is the case with any collider, a luminosity upgrade is one of the principal objectives for the future with RHIC. There are several paths for the luminosity upgrade. The possibility of increasing the number of bunches per ring is already built into the collider as well as detectors. Another immediate upgrade path is to invoke the collision optics with $\beta^* = 1$ m at selected interaction points. This very tight focusing of beams is possible because of the very high field quality of the final focus quadrupoles at these locations.

The next stage of luminosity upgrade will be done with a higher bunch current. In this case, however, cooling of beams becomes necessary because the strong intra-beam scattering would result in rapid emittance growth. An electron-cooling technique using a single-pass energy-recovery linac is being developed in collaboration with BINP, Novosibirsk.

7. Conclusions

After 17 years of gestation period, RHIC began to operate, opening a new frontier for nuclear research. The first glimpse of the landscape at this new frontier, as observed with collisions of Au ions at 2/3 of the design collision energy, i.e., $130A$ GeV, has already caught some tantalizing indications of unusual global behavior. These observations bode well for the exciting physics to come.

Acknowledgements

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