# The future of RHIC

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The future program of Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) is driven by the program's accomplishments to date. Science-based plans to evolve the facility's capabilities, both the accelerator and the detectors, are discussed. The facility, called QCD Lab, will enable studies of Quantum Chromodynamics at a fundamental level.

## 1. INTRODUCTION: THE PRESENT PROGRAM AND ITS ACCOMPLISHMENTS

The RHIC facility comprises a complex of seven accelerators and four experimental detectors. The accelerators, from the Tandem Van de Graaff and linac sources to the superconducting collider rings, are illustrated in Figure 1. The properties and performance of the accelerator complex are given in Table 1.

The experimental detectors - BRAHMS[1], PHENIX[2], PHOBOS[3], STAR[4] - are operated by international collaborations totaling about 1000 scientists, engineers and students from about 100 institutions in about 20 nations. The RHIC accelerator complex and its suite of detectors have been outstandingly successful in its first five years of operation. Table 2 gives a summary of the running conditions and integrated luminosities delivered by this uniquely flexible collider.

Discoveries of striking new phenomena and concordance among all four experiments have been the hallmarks of the research program. Retrospectives of the first three years of research have recently been published by the four experiments [1], in which they review and analyze their findings and enumerate the experimental and theoretical questions to which these results point.

The salient results to date of the experimental program may be summarized briefly as folllows:

- A new state of nuclear matter is formed in central collisions of heavy ions at RHIC. It is hot (T$\sim$200 MeV) and dense, exhibiting an energy density $>$ 15 GeV/fm$^3$.

- The new state exhibits very large energy loss for strongly interacting particles traversing it, dE/dx $>$ 5 GeV/fm. As seen in the comparison of the yields of high $p_T$ hadrons between A+A, p+A and p+p data, the new state produced in A+A

[1] http://www4.rcf.bnl.gov/brahms/WWW/brahms.html
[2] http://www.phenix.bnl.gov/
[3] http://www.phobos.bnl.gov/
[4] http://www.star.bnl.gov/

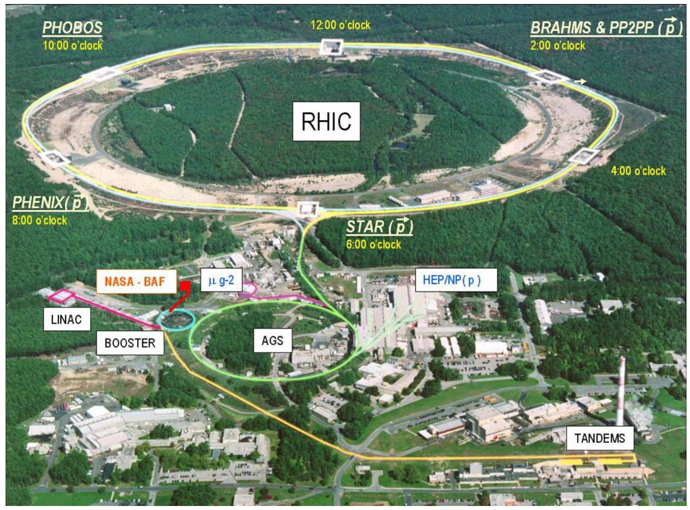


Figure 1. Aerial photo of the RHIC complex labeled to show the major accelerator systems and experimental detector locations.

collisions is nearly opaque for the highest $p_T$ hadrons studied to date. On the other hand it is essentially transparent to photons.

- The new state is characterized by extremely rapid thermalization time ($\tau \sim 0.6$ fm/c) and a very high degree of collective motion as measured by the magnitude of elliptical flow in peripheral collisions. The systematics of elliptic flow is well described out to transverse momentum $p_T > 2$ GeV/c by hydrodynamical calculations assuming no viscosity. The rapid thermalization time and the collective, non-viscous behavior suggest a strongly coupled medium that has been called a "nearly perfect liquid".
- The systematics of observed flow, in particular the scaling of flow with valence quark number and the observation of flow among particles carrying heavy quarks, indicate that the rapidly thermalized, highly collective system produced in RHIC collisions is established in the partonic phase. In other words, the observations are consistent with the production of a strongly coupled plasma of quarks and gluons.

Some puzzles remain in fitting all observations into this picture, and more complete theoretical treatments of collisions at RHIC energies are required. However, the striking nature of the phenomena which underlie this picture is transforming the field of relativistic heavy ion collisions. The body of evidence already in hand is allowing one to begin to address compelling and fundamental questions about QCD.

| Mode | No of bunches | Ions/bunch $[10^9]$ | $\beta^*$ [m] | Beam polarization | $L_{peak}$ $[cm^{-2}s^{-1}]$ | $L_{<store>}$ $[cm^{-2}s^{-1}]$ | $A_1A_2L_{<store>}$ $[cm^{-2}s^{-1}]$ |
|---|---|---|---|---|---|---|---|
| | | | | Design values (1999) | | | |
| Au+Au | 56 | 1.0 | 2 | | $8\times10^{26}$ | $2\times10^{26}$ | $8\times10^{30}$ |
| p+p | 56 | 100 | 2 | | $5\times10^{30}$ | $4\times10^{30}$ | $4\times10^{30}$ |
| | | | | Achieved values (2004) | | | |
| Au+Au | 45 | 1.1 | 1 | | $15\times10^{26}$ | $5\times10^{26}$ | $20\times10^{30}$ |
| p↑+p↑ | 106 | 90 | 1 | 45-50% | $10\times10^{30}$ | $7\times10^{30}$ | $7\times10^{30}$ |
| p+p | 56 | 170 | 1 | | $15\times10^{30}$ | $10\times10^{30}$ | $10\times10^{30}$ |
| | | | | Enhanced design values (2008) | | | |
| Au+Au | 112 | 1.1 | 0.9 | | $40\times10^{26}$ | $9.9\times10^{26}$ | $38\times10^{30}$ |
| p↑+p↑ | 112 | 200 | 1 | 70% | $89\times10^{30}$ | $60\times10^{30}$ | $60\times10^{30}$ |

Table 1
RHIC beam parameters at 100 GeV/A beam energy for gold ions and for protons. Design, achieved and planned enhanced values of luminosity and proton polarization are shown.

## 2. THE SCIENTIFIC QUESTIONS FROM RHIC AND THE KEY MEASUREMENTS FOR THE FUTURE

RHIC discoveries bring into sharper focus compelling questions about the realization in nature of Quantum Chromodynamics. These are listed below, goruped into three broad categories:

- *The nature of confinement*
  - What is the nature of the phase transition?
  - Is chiral symmetry restored?
  - What is the nature of confinement and of hadronization in nuclei (compared to nucleons)?
- *The structure of quark-gluon matter above $T_c$*
  - How does the thermodynamic character of the collisions evolve so rapidly from the initial state?
  - What are the properties of the medium?
  - Do bound states survive above $T_c$?
- *The low-x and spin structure of hadronic matter*
  - Is the initial state a Color Glass Condensate (CGC)?
  - What is the spin structure and dynamics inside the proton?

| Year | Run plan | Sample | Physics |
|---|---|---|---|
| 2000 | Au+Au at 130 GeV/A | $20\mu b^{-1}$ (6 wks) | First look at RHIC Collisions |
| 2001/ 2002 | Au+Au at 200 GeV/A | $260\mu b^{-1}$ (16 wks) | Global properties, spectra; first look at hard scattering. |
| | p+p at 200 GeV | $1.4pb^{-1}$ (5 wks) | Comparison data; first spin run |
| | Au+Au at 19 GeV/A | $0.4\mu b^{-1}$ (1 day) | Connection to SPS energy range |
| 2003 | d+Au at 200 GeV/A | $74nb^{-1}$ (10 wks) | Comp. data for Au+Au analysis; Low-x physics in cold nucl. matter |
| | p+p at 200 GeV | $5pb^{-1}$ (6 wks) | Spin development & comp. data |
| 2004 | Au+Au at 200 GeV/A | $3740\mu b^{-1}$ (12 wks) | "Long run"; high stat., rare events |
| | Au+Au at 62 GeV/A | $67\mu b^{-1}$ (3 wks) | Energy scan |
| | p+p at 200 GeV | $100pb^{-1}$ (7 wks) | Spin development; commission jet target; $1^{st}$ measurements with longitudinal spin pol. |
| 2005 | Cu+Cu at 200 GeV/A | $42nb^{-1}$ (8 wks) | Comparison studies: |
| | Cu+Cu at 62 GeV/A | $1.5nb^{-1}$ (12 days) | surface/volume & impact |
| | Cu+Cu at 22 GeV/A | $18\mu b^{-1}$ (39 hours) | parameter effects; energy scan |
| | p+p at 200 GeV | $30pb^{-1}$ (10 wks) | Spin dev.: luminosity, polarization |
| | p+p at 410 GeV | $0.1pb^{-1}$ (1 day) | First long data run for spin |

Table 2
Summary of RHIC runs 1 through 5 (2000-2005)

- What is the structure of the saturated gluon state at low $x$ in hadrons?
- What is the role of spin in deep inelastic scattering in nucleons and nuclei?

Under each group, several questions are posed. Some of these have framed the discussion in this field for a long time; others come directly from discoveries and observations at RHIC or from theoratical developments inspired by them.

The desire to answer these questions has led to a vision of how the RHIC facility should evolve from now until the end of the next decade. This vision is summarized in the following sections.

## 3. THE NEAR AND MID TERM FUTURE: 2006-2012

Over the next 5 to 7 years the compelling questions can be best addressed at RHIC with the following program:

- Near term enhancement of RHIC luminosity: as shown in Table 1, luminosity for heavy ion collisions can be increased incrementally by a factor of about 2 and for polarized protons by about 6. An electron beam ion source (EBIS) will begin contruction soon. EBIS will expand the A-range and extend it to uranium beams. In addition, the polarization of the beams can be increased from 45-50% to 70%. Since the figure of merit for, *e.g.*, double spin asymmetry measurements $\propto (P_1P_2)^2L$, the

| Upgrades | High T | QCD... | QGP | | Spin | | Low-x |
|---|---|---|---|---|---|---|---|
| | e+e- | heavy flavor | jet tomog. | quarkonia | W | $\Delta$G/G | |
| PHENIX | | | | | | | |
| Hadron blind detector | X | | | | | | |
| Vertex Tracker | X | X | O | O | | X | O |
| Muon Trigger | | | | O | X | | |
| Forward Cal (NCC) | | | O | O | O | | X |
| STAR | | | | | | | |
| Time of Flight (TOF) | | O | X | O | | | |
| Micro Vtx (TFT) | | X | | X | | | |
| Forward Tracker | | O | | | X | O | |
| Forward Cal (FMS) | | | | | | O | X |
| DAQ 1000 | | O | X | X | O | O | O |
| RHIC Luminosity | O | O | X | X | O | O | O |

Table 3
Matrix of detector or accelerator upgrades vs. physics measurements. X = upgrade critical for measurement. O = upgrade important for measurement.

combination of these near term p+p luminosity and polarization enhancement yields an improvement in the figure of merit of a factor 25-35.

- Further enhancements of RHIC luminosity: a comprehensive attack on the compelling science questions requires (among other upgrades) an additional order of magnitude in RHIC luminosity. This requires cooling the ion beams at full energy with a combination of stochastic- and electron-cooling. R&D on both methods of ion beam cooling is actively under way at BNL.

- Upgrade of detector capabilities: the key physics measurements at RHIC are evolving, from global observables (multiplicity, spectra, flow, HBT) involving hadrons, to hard processes, penetrating probes and other relatively rare signals (high $p_T$, jet tomography, photons, leptons, hidden and open heavy quark production). The detectors (especially large general purpose detectors - STAR and PHENIX) require performance enhancements to capitalize on the higher luminosity in these areas. These enhancements include precision vertex tracking, higher momentum particle identification, increased forward detection capability and more sophisticated trigger/DAQ systems.

- Lattice QCD: in addition to the evolution of RHIC described above, theoretical advances are required to confront and interpret the wealth of data with more prcise or realistic predictions. An important component of this program in theoretical work is lattice QCD simulation. BNL has recently commissioned two new 10-Teraflops supercomputers based on the QCDOC architecture. One of these machines is operated for DOE's lattice gauge theory community and one for the RIKEN-BNL

Research Center. A significant fraction of these machines is devoted to finite temperature QCD, and this represents a 50-fold increase in computing power applied to this field.

Table 3 summarizes the detector and accelerator upgrades planned for RHIC, and indicates which of the key measurements are enabled or enhanced by which upgrades.

The program of detector and accelerator enhancements described above is usually referred to as “RHIC II”. RHIC II is accomplished in steps and could be fully operational at the end of this near term/mid term period. It is important to note that during this period, a program of heavy ion research at the CERN Large Hadron Collider (LHC) will commence and begin to produce results that bear on the same questions. The two facilities and their heavy ion research programs are complementary in many respects. The most notable difference is the collision energy, $\sqrt{s_{NN}}$ = 200 GeV vs. 5.5 TeV. RHIC and LHC will consequently explore different physics and under different kinematical conditions. RHIC probes high energy density (QGP) at y$\sim$0. The initial state (CGC) is probed at forward rapidity (low $x$). The LHC’s higher energy makes high $p_T$ jets and heavy quarks more accessible. CGC is accessible at all rapidities. New states of matter will exist at higher temperature and for longer periods.

At RHIC, QCD is the prime objective; long annual runs at a very flexible collider like RHIC allow for systematic exploration vs. system size and energy, in hot and cold nuclear matter, including p+p comparison data in the same detectors. This systematic approach has been vital in firmly establishing the discoveries that resulted from the new phenomena observed at RHIC. RHIC also has unique capabilities with the spin program and a path forward leading to a polarized DIS collider facility (eRHIC).

The US program at RHIC has great momentum and excellent teams doing the physics and training the next generation. The program is just beginning to reap the benefits of a massive investment (people & equipment) in RHIC. However, the US relativistic heavy ion community also has a strong physics interest in the LHC. Worldwide involvement in each new forefront facility has been the hallmark of relativistic heavy ion physics. It is strongly in evidence at RHIC, as it will certainly be at LHC.

## 4. THE LONG TERM FUTURE: 2013 - 2020

The questions listed above address the fundamental aspects of QCD in two ways. One is through the behavior of strongly interacting matter under extreme conditions; the other is through precision measurements of the strongly interacting matter. The long term goals of the RHIC facility are to explore QCD in both ways. A+A collisions in RHIC allow the study of bulk matter at high temperature, as discussed above. Measurements of the structure of nucleons and nuclei involve studying these objects at small Feynman $x$ with precision probes. In the long term we plan to extend the capability of the RHIC complex with electron scattering from nucleons and nuclei. This follows the long and fruitful tradition of deep inelastic lepton scattering experiments at CERN, SLAC, DESY and Fermilab. Many fundamental questions remain to be understood after many years of discoveries and measurements at these facilities, including:

- What is the momentum distribution of gluons in nuclei?

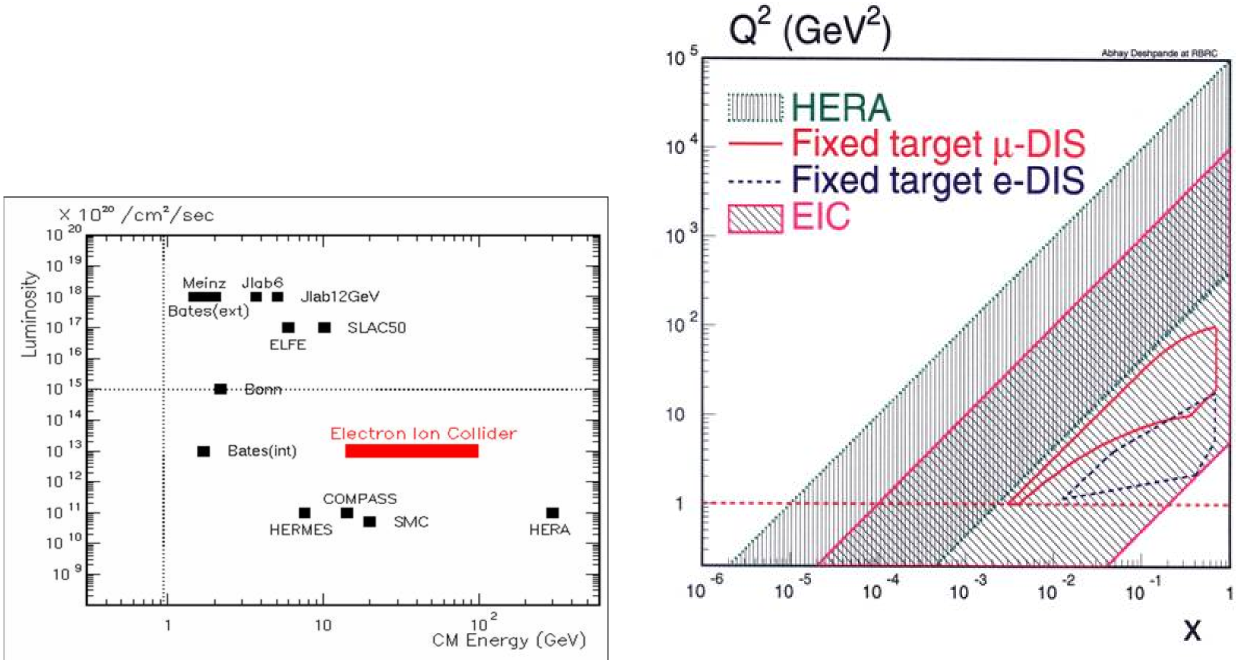


Figure 2. eRHIC expected performance. The left hand plot shows eRHIC and other DIS facilities as a function of L and $\sqrt{s}$. The right hand plot shows the x,$Q^2$ reach of eRHIC (called "EIC" here) and other machines.

- How does the spin of the nucleon arise from the constituents of the nucleon?

These questions are addressed by the p+A and polarized p+p collisions at RHIC today. The ultimate answers (and the most stringent tests of QCD) depend on the addition of polarized electron beams, positron beams and new detector capabilities to the suite of tools at RHIC [2]. The full evolution of the RHIC facility is called QCD Lab.

Studies show that the addition of a 5-10 GeV electron beam of sufficiently high current (500mA) and low emittance will yield the following new features of the RHIC facility:

- eRHIC: the first polarized DIS collider in a new kinematic region
- Variable energy, high luminosity: $L_{ep} > 10^{33}$ cm$^{-2}$sec$^{-1}$
- Polarization of e, p and light ion beams $\sim 70\%$
- Ion species from p to U $\rightarrow$ high gluon densities

Figure 2 places the design performance of eRHIC in the context of other DIS machines.

Figure 3 shows two design concepts for the addition of the electron and positron capabilities to RHIC. The linac-ring concept (on the right) allows for a simpler design for the interaction region (IR), the possibility of more than one IR and the possibility of an electron upgrade. It is also likely to be a more costly concept.

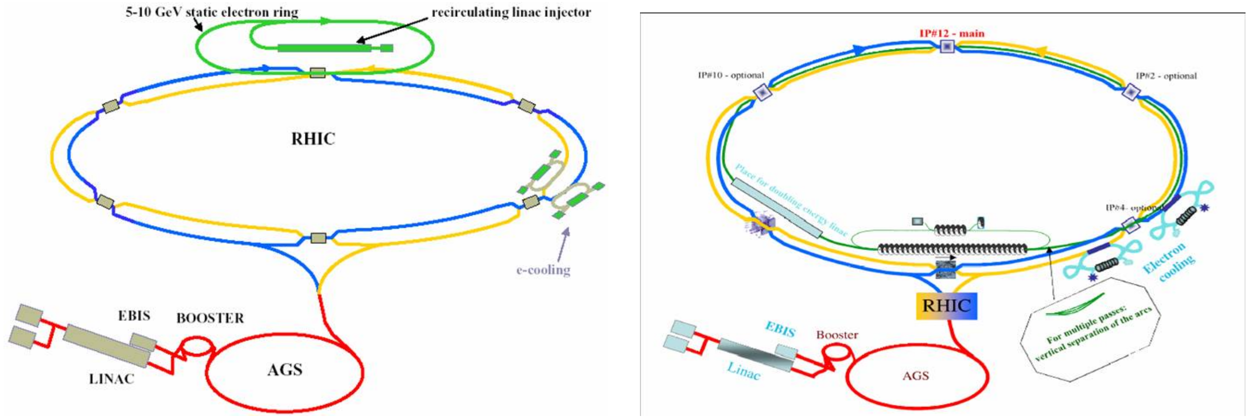


Figure 3. Two design concepts for eRHIC. On the left hand is the standard "ring-ring" concept and on the right is the alternative "linac-ring" version.

The full realization of QCD Lab will depend both on technological developments (principally electron cooling of the full-energy RHIC beams) and on the long range planning process for nuclear science in the United States. With a compelling science mission and sufficient funding, QCD Lab could be operational in the next decade, with the upgrade of RHIC completed in the early part of the decade and eRHIC a few years later.

## REFERENCES

1. *"First Three Years of Operation of RHIC"*, Nucl Phys. **A757**, Issues 1-2, pp. 1-283 (8 August 2005).
2. A.Deshpande, R. Milner, R. Venugopalan and W. Vogelsang, hep-ph/0506148, to appear in Annual Review of Nuclear and Particle Science