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EXPERIMENTAL RESULTS FROM RHIC AND PLANS FOR ERHIC

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An overview of recent experimental results from RHIC is presented. A new hot, dense form of matter has been produced in the final state of relativistic heavy ion collisions. The general characteristics of this new form of matter as deduced from the experimental data are described. In addition, the scientific motivation and machine concept for a new high luminosity electron-ion collider using RHIC, known as eRHIC is described.

1 Introduction

At extremely high energy densities, Quantum Chromodynamics, the Standard Model of the strong interaction, predicts a new form of matter, consisting of an extended volume of interacting quarks, antiquarks and gluons. This has come to be known as the *quark-gluon plasma* (QGP). Calculations using lattice-gauge approximations have been used to calculate the critical temperature TC for the phase transition between the QGP and a system of color neutral hadrons giving values in the range of about 170 to 180 MeV [1].

Collisions between relativistic heavy ions beams are expected to produce final-states where for short times ($\sim 10^{-23}$ s) the densities and temperatures necessary to produce the QGP can be realized. In February 2000, after 15 years of experiments with fixed-target nuclear beams, CERN scientists concluded that a multitude of different observations that, taken together, suggested the observation of a QGP [2]. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (see Figure 1) was constructed to collide nuclear beams with sufficient energy ($\sim$ 200 GeV per nucleon) and luminosity ($\sim\ 10^{27}$ cm^{-2} s^{-1} for Au-Au) to provide the definitive observation of the QGP. Data taking in four experiments (STAR, PHENIX, PHOBOS and BRAHMS) at RHIC commenced in 2000 and substantial insight into the nature and properties of the final-state has been obtained in the initial running in of this unique accelerator. Each detector occupies one of the beam-crossing regions where RHIC's countercirculating ion beams intersect and collide.

In addition to producing high luminosity, high energy relativistic collisions of ions, RHIC has been utilized to successfully collide beams of spin polarized protons ($\sim$ 45 %) at a center-of-mass energy of 200 GeV. The RHIC-spin program is aimed at determining the polarization of the gluons in the proton and, in the longer term with increased polarization and luminosity, decomposing the quark flavor

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contributions to the proton spin.

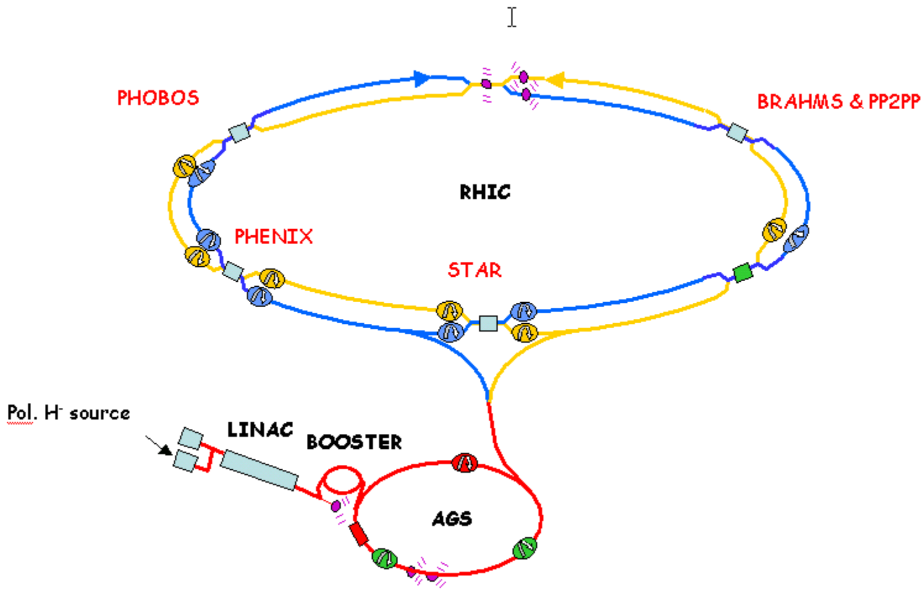

Figure 1. Schematic layout of the RHIC collider at Brookhaven National Laboratory.

For gold-gold collisions at the highest RHIC energies, 56 equally spaced bunches of 10^9 fully stripped gold ions are injected into each of the two 4 km rings of superconducting magnets. The two countercirculating beams are then accelerated to 100 GeV/nucleon.

The most violent collisions occur when two nuclei collide head-on, i.e. when the impact parameter is much smaller than the nuclear diameter. Such interactions are known as *central collisions*. Grazing collisions with large impact parameter are called *peripheral*.

The collision gives rise to an initial, intense heating of the common volume occupied by the two nuclei as a large fraction of their kinetic energy is converted into a high-temperature system of quarks, antiquarks and gluons. This system, which presumably contains an extended volume of deconfined quarks and gluons, immediately begins to expand and cool, passing down through the critical temperature at which the QGP condenses into a system of color neutral mesons, baryons and antibaryons. As the expansion continues, the system reaches its *freeze-out density*, at which the hadrons no longer interact with each other. The particles emerging from the freeze-out volume are the ones that stream into the detectors.

2 Results from RHIC

Although RHIC has only been taking data for a couple of years, already completely new phenomena have been observed and hot, high density matter is being created. This has been made possible by the great technical success of both the RHIC accelerator and the RHIC detectors. Clearly, final conclusions are not possible but it is certain that RHIC will provide the data which will allow definitive conclusions in the coming years. Here I present a brief, personal overview of the early RHIC results.

The number of particles emitted in a single gold-gold collision is extremely large ($\sim 10^3$). Figure 2 shows how the phase space density increases with increasing energy. Indeed, in central collisions at RHIC, the angular density of particles produced per participating nucleon is larger than has previously been seen in any subatomic interaction.

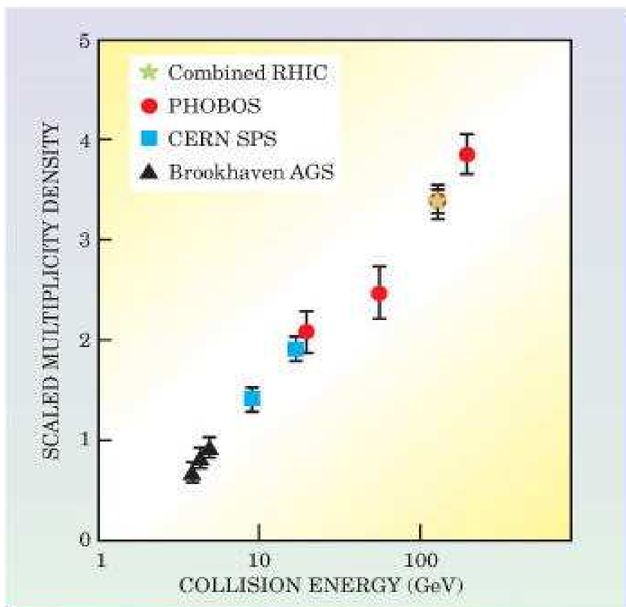

Figure 2. The phase-space density of charged particles emerging at angles near 90^0 (relative to the beam direction) increases steadily with increasing collision energy [4].

The RHIC experiments have measured the relative abundances of many different particle types, including relatively rare species that harbor more than one strange quark (see Figure 3). The measured abundances are all consistent with a temperature of 174 MeV and a chemical potential of 46 MeV. This indicates that the particles seen by the detector are produced at a freeze-out temperature that is close to the prediction for T_C and that the initial temperature of the expanding fireball is considerably higher than T_C. In addition, reasonable expectations for the formation time (less than 1 fm/c or 3 x 10^{-24} s) yield estimates that the initial energy density exceeds 10 GeV/fm^3. The observed temperatures and densities strongly indicate that the conditions to form a QGP are reached at RHIC, i.e. the matter is sufficiently hot and dense.

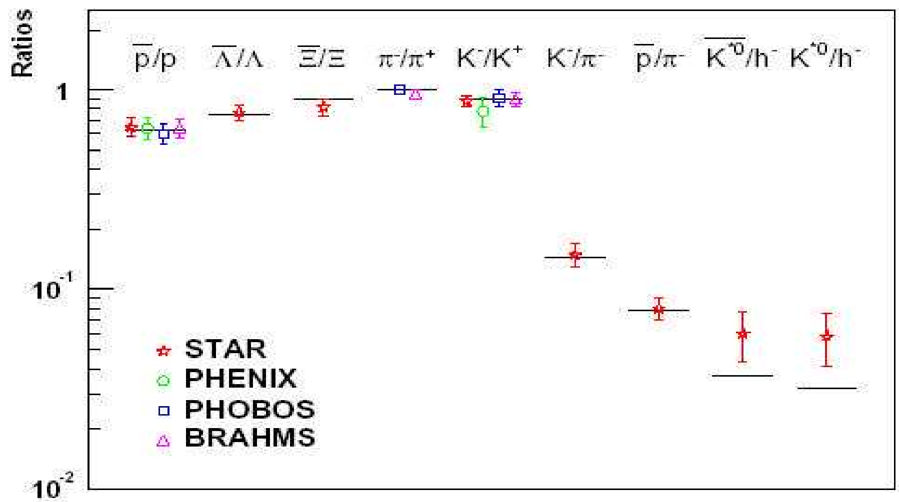

Figure 3. A comparison between RHIC experimental particle ratios and statistical model calculations with T = 174 MeV and μ_B = 46 MeV [5].

One of the most striking early observations at RHIC is a phenomenon called *jet quenching*, which appears to provide a powerful new probe of the hot dense matter created in the collisions. At RHIC, the energy is high enough that a single pair of partons from the incoming nuclei have a hard scattering to large angles. Such hard-scattering events give rise to a narrowly collimated spray of hadrons, known as *jets*. The direction of the jet emerging from a hard scattering collision is presumed to be the direction of the initially scattered parton. At RHIC, the observed mean transverse momentum p_T of the final-state hadrons is just a few hundred MeV. But the rare hard-scattering events give rise to a small but important tail in the p_T distribution that can extend out to tens of GeV.

Figure 4 shows the data from the PHENIX and STAR experiments which support the conclusion of suppression of hard scattering events in gold-gold collisions. In the PHENIX data, pion production is significantly suppressed in gold-gold collisions compared to deuteron-gold. In the STAR data, the recoil peak is strikingly absent in gold-gold collisions. This suppression is most likely due to jet energy loss in the hot extended medium.

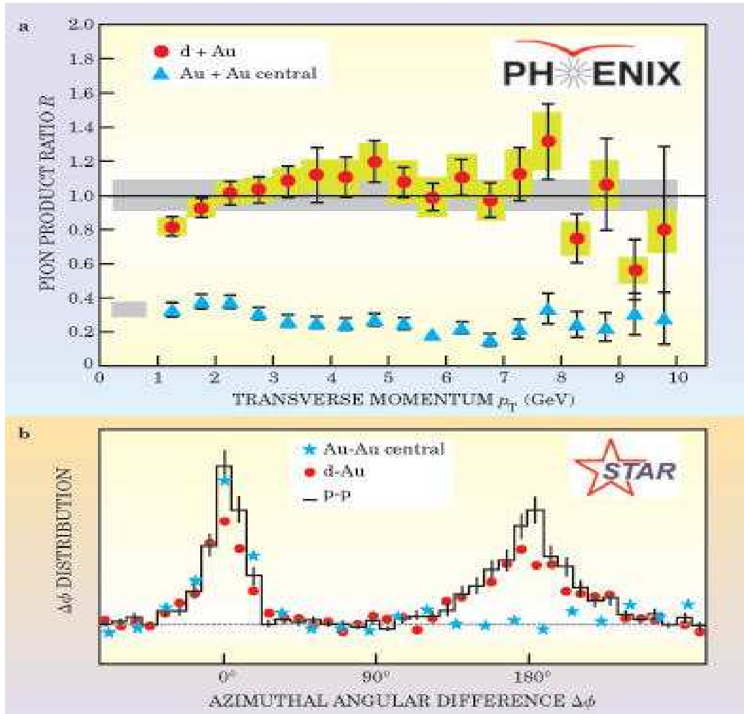

Figure 4. In the upper panel, data from the PHENIX detector show that the production rate of high-p_T pions, scaled to account for the number of participating nucleons, is significantly suppressed in gold-gold collisions as compared to proton-proton or deuteron-gold collisions at the same energy per nucleon. In the lower panel, data from the STAR detector show the angular correlation between high p_T particles produced in the same event. The recoil peak at 180^0, clearly indicating the production of back-to-back jets in proton-proton and deuteron-gold collisions, is strikingly absent in the gold-gold data.

We have seen that RHIC is producing hot, dense matter exhibiting very distinctive characteristics. Is this hot, dense matter in equilibrium? Strong support for thermal equilibrium comes from the temperature determination above, which correctly describes abundance ratios for many particle species. More direct evidence comes from a surprising early RHIC result: an unexpectedly large effect attributed to a phenomenon called *flow*.

First seen in lower-energy nuclear collisions, this kind of flow is a nuclear analogue of the many-particle collective effects seen in macroscopic properties of condensed matter. When two nuclei collide, the initial high-density volume has the shape of their overlap region during the collision. The region is elongated along the axis perpendicular to the reaction plane. If the quarks and gluons occupying the initial asymmetric volume are indeed interacting collectively, pressure gradients during the subsequent expansion will result in an anisotropic distribution of the final particles with respect to the reaction plane.

Such anisotropy is observed in the RHIC data. The observation of anisotropic or *elliptic flow* tells us that the RHIC collisions produce matter that interacts strongly with itself and exhibits some of the characteristics of a strongly interacting liquid. The magnitude of the observed elliptic flow is sensitive to the degree of thermalization at the collision's earliest moments. The data indicate that the strength of the effect is very nearly maximal and remarkably close to what one expects for an expanding system in thermal and hydrodynamic equilibrium.

3 Future Plans with RHIC

RHIC will continue to study the hot, dense matter described above over the next several years. A program of detector and accelerator upgrades will greatly increase the ability to study and characterize this new state of matter. Rare probes, e.g. direct photons and J/ψ's will yield new information on the nature of the collision final-state.

In parallel, the polarization and collision luminosity of the polarized proton beams will be increased. The design goal is to reach 70% proton polarization in both beams and to increase the peak luminosity to about 10^{32} cm^{-2} s^{-1}. It is anticipated that this will take at last three years.

With sufficiently high figure-of-merit for RHIC-spin, exciting new measurements become possible. For example, figure 5 indicates the precise data on the gluon polarization ΔG which can be obtained at RHIC with polarized beams.

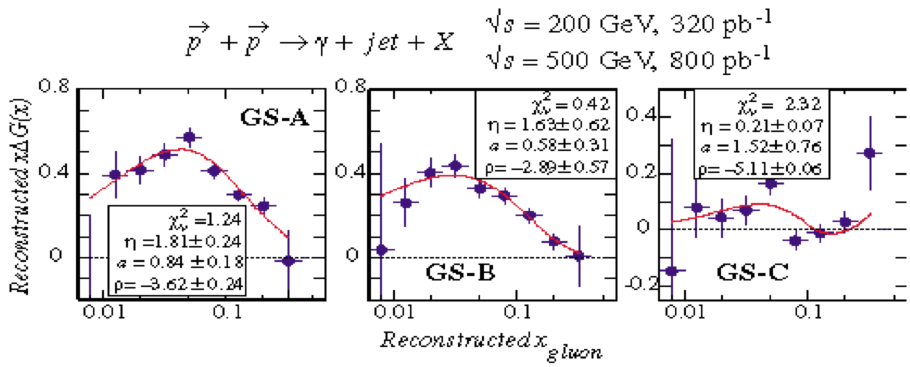

Figure 5. Projected uncertainties for determination of the gluon polarization ΔG at RHIC by the STAR collaboration for three different gluon parametrizations.

At the highest collision energies and luminosities at RHIC, the production of $W^{\pm}$ can be used to decompose by flavor the quark contribution to proton spin.

Figure 6 shows the expected precision yielded by these measurements. Tracking upgrades are being developed to detect the decay lepton of the W.

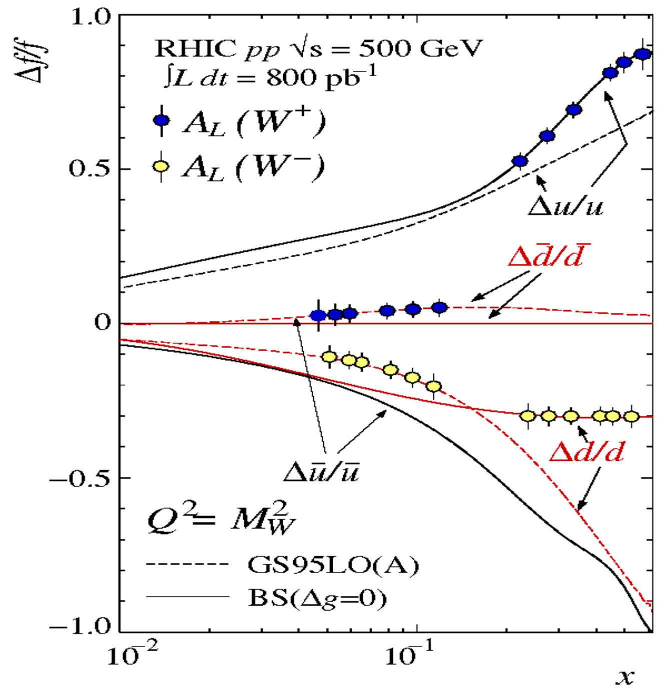

Figure 6. Projected uncertainties in the determination of the quark flavor decomposition of the proton spin at RHIC by detection of the intermediate vector boson $W^{\pm}$.

4 eRHIC

eRHIC is proposed as the next generation accelerator to study the fundamental quark and gluon structure of matter [7]. In particular, the following important questions remain open:

- *What is the structure of matter in terms of their quark and gluon constituents?* eRHIC will be the definitive tool to study the spin structure of the nucleon with its ability to carry out 'flavor tagging' in semi-inclusive scattering, to extend measurements of the nucleon spin structure function to lower x (see figure 7), and to directly probe the polarization of the glue.
- *How do quarks and gluons evolve into hadrons through the dynamics of confinement?* eRHIC will make it possible to strike quarks and to observe the

complete array of decay products from either the nucleon or nucleus.

- *How do quarks and gluons manifest themselves in the properties of atomic nuclei?* Nuclear binding is basic to the structure of our physical universe. eRHIC will make possible new experiments which can provide a fundamental understanding of nuclear binding.
- *Does partonic matter saturate in a universal high-density state?* Very high energy DIS on nuclear targets with electromagnetic probes offers new opportunities for studying partonic matter under extreme conditions. Particularly intriguing is the region of low $x < 10^{-3}$ where gluons dominate. Measurements of the proton structure function at HERA showed that the gluon distribution grows rapidly at small x for Q^2 greater than a few $(\mathrm{GeV/c})^2$.
- *To what degree can QCD be demonstrated as an exact theory of the strong interaction?* eRHIC will have the precision and kinematic reach to provide a stringent test of QCD as the theory of the strong interaction.

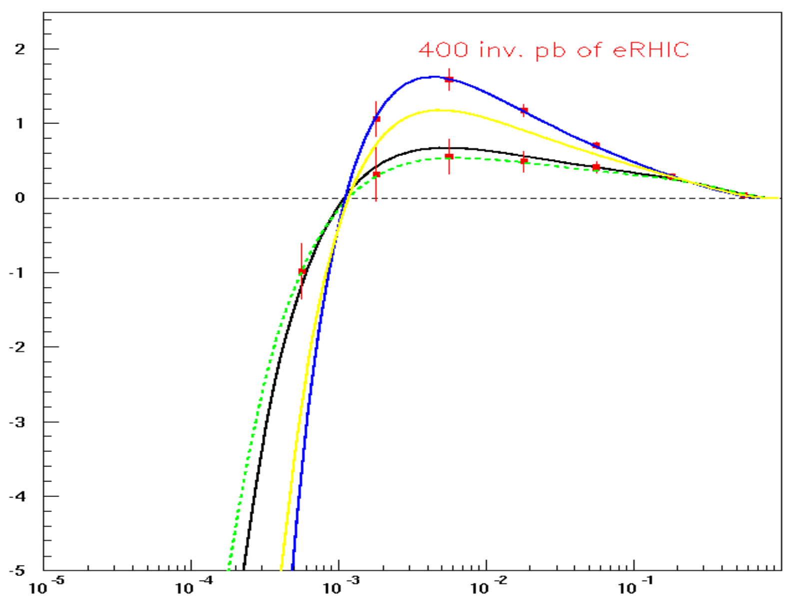

Figure 7. The projected statistical accuracy with 400 pb^{-1} luminosity with eRHIC ($\sim$ 1 week of data taking) assuming 250 GeV polarized protons and 10 GeV polarized electrons [7]. The curves are the best fit to the world's data set evaluated at different Q^2 (2, 10, 20, and 200 $(\mathrm{GeV/c})^2$).

To answer these important questions, it has become clear that a high luminosity electron-ion collider with polarized beam capability and center-of-mass energy in the region of 30 to 100 GeV will be required. In the 2001 Nuclear Physics Long Range Plan in the United States, the scientific case for such an electron-ion collider was favorably received and R&D strongly encouraged. It was decided to seriously consider a machine design which would utilize the existing RHIC accelerator at Brookhaven National Laboratory, Long Island, New York, USA. This design is known as eRHIC.

The eRHIC design concept has been developed by a team from BNL, MIT-Bates, DESY and Novosibirsk [8]. Figure 8 shows a schematic layout of the leading design. A 10 GeV electron storage ring collides with the proton and ion beams of RHIC at one of the existing interaction regions. The storage ring is fed by a linac with a polarized electron source. Further, positron capability would be available and the positrons can be polarized at the top energy using Sokolov-Ternov self polarization in the electron storage ring. eRHIC can operate in dedicated mode with luminosity close to 10^{33} cm^{-2} s^{-1} but can be operated in parallel with heavy ion collisions in other interaction regions at lower luminosity. Electron cooling of the RHIC ion beam is essential for high luminosity.

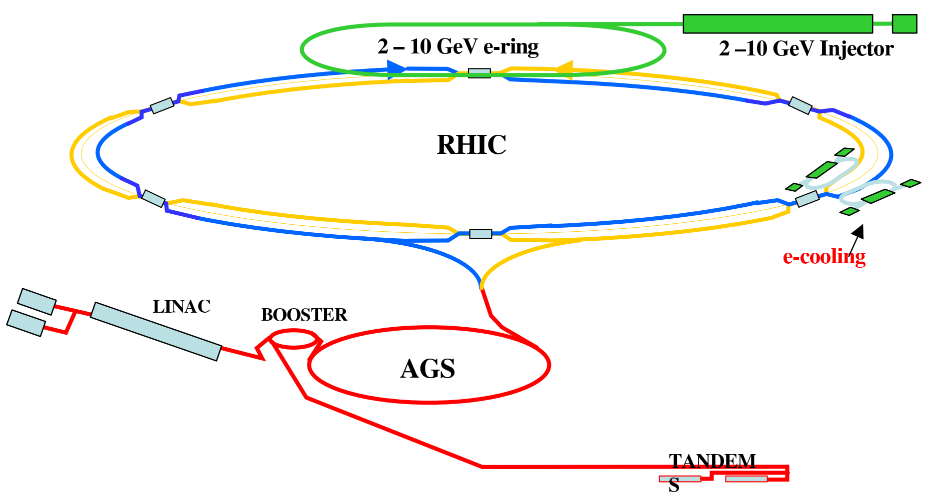

Figure 8. Schematic layout of the leading design for the eRHIC collider [8].

In addition to the design described above, more futuristic concepts involving high intensity, energy-recovery linacs are under consideration [8]. These offer the possibility of higher luminosity.

It is anticipated that the next Nuclear Physics Long Range Planning Exercise in the United States (anticipated to occur no later than 2006) will give serious consideration to the construction of a high luminosity electron-ion collider. Further, it is anticipated that if approval were granted to proceed with construction of eRHIC that it could become available for experiments in the timeframe of 2015.

Summary

RHIC is operating and producing exciting data on relativistic heavy ion collisions. Hot, dense matter with the characteristics of a strongly interacting liquid is being formed. Over the next several years, this new state of matter will be studied and definitive conclusions on its nature and properties are expected.

In addition, RHIC is colliding beams of polarized protons and a new, important program to study proton spin structure has been launched. It is expected that a direct determination of the gluon polarization will be obtained within the next three years.

With the addition of a polarized lepton beam, a high luminosity lepton-ion collider using RHIC can be realized. This would yield important new data on the fundamental quark and gluon structure of matter. The scientific case and machine design for eRHIC is actively under development.

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