CONF-8809203--7

BNL-42322

FUTURE HIGH ENERGY HEAVY ION PHYSICS AT BROOKHAVEN*

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1. Introduction

At this conference we are seeing the detailed analysis of the first experiments with high energy nuclear beams at Brookhaven and CERN. From all indications the early enthusiasm for pursuing these investigations into a heretofore unexplored field has certainly been well founded. These experiments, still investigating collisions of relatively light ions ($A \leq 32$ amu), have established that states of compressed nuclear matter can be created and studied under laboratory conditions in which extreme values of energy density are achieved. The data presently under investigation reflect an environment of high baryon density, at energies near the maximum for nuclear stopping. The general characteristics of these events bear out the early expectations for large, thermal energy deposition in violent nuclear collisions, and they point the way for extending further the range of thermodynamic conditions over which to search for and study new forms of dense hadronic matter. The most exciting results of this meeting are the several indications that, indeed, when these extreme conditions are reached there are new physical phenomena to be explored.

At Brookhaven we plan to continue pushing back the frontiers of this new field with an ongoing program of experiments and new facilities which will lead in the near future to measurements with much greater beam masses and much higher collision energies. Ultimately, with the realization of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, nuclear physics will have a dedicated facility which will reach energies high enough to ensure a baryon-free central region in collisions of the heaviest nuclei; incorporate the flexibility to study collisions of all nuclei, from the lightest to the heaviest; and allow experiments to be carried out over the full range of energies, from a few GeV/amu in the c.m. (AGS fixed target) up to the top collider energy, with no inaccessible gaps, and with adequate intensity for sensitive experiments.

*Work performed under the auspices of the U.S. Department of Energy.

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At present the AGS at Brookhaven is capable of accelerating ions up to silicon with an energy of 14.5 GeV/amu, using one of the two BNL Tandem Van de Graaff accelerators as injector. Very soon, using the AGS Booster synchrotron which is presently under construction, the range of ion masses which will be available from the AGS will be extended up to Gold. The Tandem-Booster-AGS complex will then not only be available to provide beams for fixed-target heavy ion experiments, but will serve as injector for the RHIC collider. The time-scale for these facility developments is outlined in Table I. The layout of the Brookhaven accelerator facilities is shown in Fig. 1.

Table 1. Heavy Ion Facilities at BNL

1986	Begin AGS Fixed Target Experiments	
	Beam Energy:	Up to $28 \left(\frac{Z}{A}\right)$ GeV/amu
	Ion Species:	^1H to ^{32}S
	Flux:	$\sim 10^9$ ions/pulse
	Running Time:	5-10 weeks/year
1991*	AGS Experiments with Booster Synchrotron	
	Extend ion mass to $A \sim 200$ (Au)	
1996*	Begin RHIC Collider Experiments	
	Beam Energy:	Up to $250 \left(\frac{Z}{A}\right)$ GeV/amu per beam in collider mode
	Ion species:	^1H to ^{197}Au
	Total c.m. collision energy:	
	500 GeV (protons)	40,000 GeV (Au)
	Luminosity:	$10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$ $5 \times 10^{28} \text{ cm}^{-2} \text{ sec}^{-1}$

*indicates proposed dates

Since the completion in 1986 of the Heavy Ion Transfer Line, which links the Tandems to the AGS, the AGS has been operated 7-8 weeks each year for heavy ion running. Beams extracted from the AGS are directed through a beam switchyard to as many as four different beam lines capable of transporting the full-energy primary beam to experiments. The extracted beam is split with a sequence of electrostatic and magnetic septa so that all beam lines can be served simultaneously with each extracted pulse. At present there are three major spectrometer experiments which are either in place or are being prepared

for the heavy ion program. All of these groups have given summary reports at this conference: E802,¹ E814,² and E810.³

Fig. 1 Site map of present and proposed accelerators at Brookhaven. The Tandem Van de Graaff and the AGS with its linac injector are existing machines. The Booster Synchrotron for pre-injector to the AGS is currently under construction. The RHIC colliding beams accelerator to the north of the AGS complex is a proposed construction project.

2. The RHIC Design

The concept of a heavy ion collider facility, reaching center-of-mass collision energies at least 10 times higher than the fixed target experiments, has for several years been identified as the highest priority need for a new facility in the Long Range Plan for basic nuclear research in the United

States.⁴ In January 1985, after two years of workshops and study groups to determine the essential design requirements for such a facility, and an intensive accelerator physics effort at Brookhaven to understand the problems of accelerating and storing densely bunched, ultra-relativistic beams of highly charged nuclei, the RHIC proposal was submitted to the U.S. Department of Energy. The present Conceptual Design Report⁵ is an update of that proposal. The design utilizes the existing facilities already in place for the Isabelle/CBA project at Brookhaven, with the Tandem/AGS complex as injector, thereby saving at least a factor of two in the overall cost of such a collider.

The basic parameters of the RHIC facility are illustrated in Fig. 2. The design calls for a top beam energy of 100 GeV/nucleon for ions of mass $A=200$, and the acceleration of ion masses spanning the full periodic table. The complete accelerator complex, consisting of Tandem, Booster, AGS and RHIC will provide c.m. collision energies for gold beams ranging from 1.5+1.5 GeV/nucleon to 100+100 GeV/nucleon. This energy range is covered with no inaccessible gaps, and adequate beam intensities throughout.

Fig. 2 The design luminosity, for various ion masses, as a function of collision energy over the full range accessible with AGS and RHIC. On the left-hand scale, central collisions correspond to impact parameter less than 1 fermi.

The energy range is covered in three segments: As shown in Fig. 2, the range between fixed target AGS experiments and high energy collider operation is spanned by using one of the RHIC beams striking a fixed target. For this operation an internal gas jet target would be used.

The layout of the RHIC collider is shown schematically in Fig. 3. The circumference of the collider is 3833 meters. It consists of two accelerator rings with six crossing regions (insertions) where the counter-rotating beams are brought into collisions and experiments carried out. Particle bunches accelerated in the AGS to top energy (28 GeV for protons; 11 GeV/amu for gold) are transferred to the collider by a magnet system installed in the existing transfer line tunnels. Single bunches of ions are injected 57 times into each ring in boxcar fashion. Filling time per ring will be about one minute. For gold, as an example, there will be $\sim 1.1 \times 10^9$ ions/bunch, or 6×10^{10} ions in 57

Fig. 3 Layout of the storage rings for the RHIC collider.

bunches in each ring. For the lightest ions, hydrogen and deuterium, approximately 10^{11} ions/bunch can be stored in the machine. Acceleration will take approximately 60 seconds. Bending and focussing of the ion beams is achieved with superconducting magnets. Given that the machine will be built in the existing CBA tunnel, a cost optimization is achieved by filling the circumference with relatively low field magnets. The maximum energy of 100 GeV/amu for gold ions (250 GeV for protons) is reached with a magnetic field of 3.5 Tesla. Maximum operational flexibility is obtained with the magnets of each ring in separate vacuum vessels, with the beams in the arcs separated by 90 cm.

The six beam crossing regions are designed to accommodate a range of detector configurations to fulfill the needs of experiments. The free space available for experimental equipment in each crossing region is 9 meters on either side of the intersecting point. For head-on collisions with gold ion beams at top energy, a luminosity of $2 \times 10^{26} \text{ cm}^{-2} \text{ sec}^{-1}$ averaged over a 10 hour beam lifetime is expected. For protons the expected luminosity is $1 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$. The r.m.s. length of luminous interaction region where the beams cross is ≤ 20 cm. Collisions of unequal species, e.g., protons in one beam and gold in the other, will be possible as well. The Accelerator Physics group has considered possible future upgrades of the machine performance, and these were discussed in detail in a recent workshop on the ultimate performance of such a collider.⁸

3. The Present Status

As noted above, a large fraction of the RHIC facility already exists. For the injector complex, the Tandem Van de Graaff, AGS, and heavy ion transfer line are already operational; the Booster Synchrotron is under construction.⁷ Most of the conventional construction for the collider is complete, including the ring tunnel, main service building and experimental halls for four of the six intersection regions. In addition, the liquid helium refrigerator, capable of cooling all of the superconducting magnets in the collider has been completed (as part of the CBA project) and successfully tested. The refrigerator has a capacity of 25 kilowatts at a temperature of 4.3K. The estimated heat load for RHIC is ~ 10 kilowatts at 4.6K.

One of the most important elements of the RHIC proposal is the design of the superconducting magnets for the accelerator rings. These magnets are the largest component of the cost of the machine, and their fabrication and installation is the major determinant of the construction schedule. The design of these magnets is based on the cosine theta coil structure developed at Brookhaven for the Isabelle/CBA magnets, which has since been adopted for the Tevatron, HERA and SSC magnets as well. The RHIC dipole magnets are

designed to operate at a relatively low field (3.5 T), and thus the coil can be wound in a single layer of superconductor. The dipole magnet cross section is shown in Fig. 4. Figure 5 shows a magnet assembly, consisting of a dipole, quadrupole and corrector coils, mounted in a cryostat. These magnets are fully designed, and have been the major component of an intensive RHIC R&D program which has been funded by the Department of Energy beginning in fiscal year 1987. Full-size, "machine quality" prototypes of dipoles, quadrupoles and sextupoles have been built and successfully tested. In the case of the dipoles, the largest component of the magnet system, three of the prototypes built thus far have been assembled by an industrial manufacturer. All of the prototype dipole magnets (6 have been tested so far) have reached fields of approximately 4.6 T, or 35% higher than the operating field of RHIC, with virtually no training. The RHIC magnets have been designed to be amenable to fabrication in quantity in industrial facilities, and it is planned that a significant fraction of the magnets for RHIC will be built by commercial manufacturers.

The magnet R&D program is continuing, with work now in progress to prepare a full cell of the machine magnet lattice (see Fig. 3) consisting of two dipoles, two quadrupoles, sextupoles and lumped corrector package, which will be installed and tested as a system prior to the production of final magnets.

The project has been reviewed and validated by the U.S. Department of Energy, and construction will begin in fiscal year 1990 if funds are made available. The accelerator construction cost is roughly 205 million dollars, with an additional 70 million dollars budgeted for detectors (these figures are in FY 1988 dollars).

4. Experiments and Detectors

Of the six crossing regions built into the RHIC rings, those at the 2, 4, 6 and 8 o'clock positions (see Fig. 1) have completed experimental halls, including support buildings and (except in the 4 o'clock "open area") crane coverage. The RHIC plan calls for mounting experiments initially in these four areas, leaving the remaining two unfinished until some later time.

The recording of events at RHIC, with sensitivity corresponding to the expected signals for new phenomena in nuclear matter under extreme thermodynamic conditions, will require the extension of known techniques for particle detection beyond the present ranges of application in elementary particle and nuclear physics. With beam energies up to $100+100$ GeV/nucleon and ion masses up to ≥ 200 , the total energy in each collision can reach up to 40 TeV in the center-of-mass: a range far beyond that of any present accelerator or any existing detector system. Unlike the proposed SSC collider, which

Fig. 4 Cross section of RHIC dipole magnet.

Fig. 5 RHIC magnet assembly: The drawing shows a half-cell of the arc magnet lattice, including a dipole, corrector package, quadrupole and sextupole magnets enclosed in their cryostat.

would accelerate elementary particles to such an energy and produce hundreds of very high energy particles in the final state, the most interesting events at the RHIC collider are expected to produce tens of thousands of final-state particles in each collision, with proportionately less energy carried away by each particle. Thus, while the basic detector technology will have much in common with the detector systems developed for colliding beams of elementary particles, the design of detector systems for the heavy ion collider must address a different set of problems.

In addition to extraordinarily high particle multiplicities, experiments in a heavy ion collider must deal with the fact that the signals which characterize equilibrium phenomena in a hot plasma of quarks and gluons are expected to be carried by particles whose transverse momenta and thermal energies are relatively small, and similar to that of the background radiation. This is in contrast to the detection of hard-scattering phenomena in elementary particle colliders, where sensitive triggers can be made blind to the vast majority of background particles by selecting large transverse momenta. Detector systems to deal with high energy nucleus-nucleus collisions will require new approaches to the technologies of tracking, calorimetry, particle identification, fast trigger decisions and on-line data processing.

In April 1985 a workshop involving about 100 nuclear and high-energy physicists provided preliminary designs and cost estimates for a first-round suite of detectors for RHIC. The second RHIC workshop was held in May, 1987 at Lawrence Berkeley Laboratory. This week-long meeting culminated a year of effort carried out by individual working groups holding meetings at BNL, CERN and elsewhere. The proceedings from these workshops^{8,9} are available, and provide a detailed discussion of physics goals and conceptual designs for detector systems.

At the May, 1987 workshop a few of the designs for large detector systems were examined in detail to study their technical feasibility, their impact on the design and modes of operation of the collider and the range of capabilities for physics research represented by each. Out of these studies came the realization that the measurement of lepton pairs, (electron pairs and muon pairs) radiating from heavy ion collisions at RHIC cannot be adequately measured if the luminous interaction length of the crossing beams is of the order of a meter or more, as it was in the original RHIC design. Since these lepton pair measurements are of fundamental importance to the research program, the design of the RF system of the machine has been revised to provide shorter beam bunches and ensure a useable interaction length over the full beam lifetime. These workshop studies also showed that the most useful improvements to the machine performance - from the point of view of extending

the physics reach - would be those which increased the luminosity of the machine, rather than extending the energy range. Subsequent accelerator physics studies have explored possible future upgrades of the machine which could increase the luminosity from all ion species by about a factor of ten beyond the current design values.⁶

With several well-specified concepts now in hand for large detectors at RHIC, attention in the user community has turned to the need for R&D on detector techniques. Past workshops have pointed out a number of specific areas where detector technology must be advanced beyond the present state of the art in order to realize the needed capability for experiments at RHIC. In July, 1988 a workshop was held at BNL to examine the needs and priorities for detector R&D for RHIC. Following this workshop, funds were made available by the Department of Energy to begin a generic detector R&D program in fiscal year 1989. This modest beginning will provide a start-up effort for a number of potential user groups and will begin a technical effort on detector issues which will grow with increased funding as the project reaches the construction stage.

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