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Summary Of The Physics Review Panel On Heavy Ion Collider Specifications

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A design group for a Relativistic Heavy Ion Collider has been established at Brookhaven and is preparing a detailed study for a machine which would use the AGS as injector for colliding beams of heavy ions in the existing CBA tunnel. The essential specifications of the collider have been taken to be those outlined by a study group which met at BNL August 22-24, 1983. This group established a set of design goals based on physics questions and the requirements of the anticipated research program. The report of the August study group is attached as Appendix I.

Early in December, The Design Group requested that the collider specifications be re-examined from the physics point of view, taking account of new insights gained after several weeks of detailed study by the machine experts. The specific request, outlining several issues for discussion, was compiled by A. G. Ruggiero and is attached as Appendix II.

An _ad hoc_ panel of physicists was convened, most of whom had participated in the August study. The panel met with members of the Design Group on December 20th. The participants in the meeting were:

Physics Review Panel:

G. Baym - University of Illinois
K. Foley - BNL
H. Gutbrod - GSI/Darmstadt
P. Haustein - BNL
T. Ludlam - BNL
L. McLerran - University of Washington
A. Mueller - Columbia University
H. Pugh - LBL
G. Young - ORNL

Design Group:

M. Barton - BNL
J. Claus - BNL
H. Hahn - BNL
G. Parzen - BNL
A. Ruggiero - Fermilab

Also present for the discussion were P. J. Reardon, Associate Director of the Brookhaven Laboratory, and A. Schwarzschild, Chairman of the Physics Department.

After opening remarks by Paul Reardon and a technical presentation by Mark Barton, each of the specific points raised by the Design Group was taken up in turn by the members of the panel. Here we summarize the results of the discussion on each point.

Maximum Energy

The Design Group has been aiming for a top energy of 100 GeV/nucleon in each beam for the heaviest ion (e.g. Gold, with Z/A =0.40). They ask whether the potential cost saving of low-field magnets would warrant reducing the top energy.

The panel did not try to reach a definite conclusion on this issue since many cost and performance details remain to be worked out. It was generally agreed among all the panelists that it would be useful to determine whether alternative approaches, such as low-field magnets, could offer cost savings amounting to a significant fraction of the total project cost while maintaining a top energy of $\geq$ 75 GeV/nucleon.

Some members argued that the reason most often cited for going to collider energies - the desire to achieve a "clean" central region extending over several units of rapidity - does not offer a compelling distinction between 75 and 100 GeV. The on-set of such a central region is not a well-defined threshold phenomenon. And the available rapidity space grows only logarithmically with energy. An analysis by Baym, Bjorken and McLerran indicates that at extremely high energies, any residual "baryon pollution" in the central region is probably sufficiently small to be acceptable for the study of quark plasma, in the sense that one will be able to extrapolate this data to zero chemical potential.

On the other hand, it was pointed out that one gains energy density in the in the central region with increasing collision energy, and for this reason the beams should be as energetic as is practical. A point raised at this meeting, which has previously been given little attention, is the observation of the production and propagation of jets in nuclear matter: In proton-proton collisions at the ISR (30 GeV per beam) jets are extremely difficult to observe, whereas in the $\bar{p}$-p Collider (270 GeV per beam) jets are easily seen and cleanly isolated from the multiparticle background. In the difficult environment of heavy ion collisions the behavior of jets in nuclear matter may offer important new physics results. For this purpose the difference between 30 and 100 GeV/nucleon is certainly significant, and the difference between 75 and 100 GeV/nucleon could well be important also.

Several of the panelists noted that the unique circumstances of a design for the Brookhaven site should not be under-valued. The energy scale implied by the capability already existing in the CBA ring, experimental halls, and cyrogenic system should not be too much compromised lest the heavy ion project lose its attractiveness, especially among high energy physicists.

Minimum Energy

The panel reiterated the importance to the physics program of being able to operate the collider occasionally at very low energies: i.e. at the injection energy of 12+12 GeV/nucleon for gold or even lower, say 5+5. The low energy operation is important for continuity of data with the measurements from lower energy machines (fixed target experiments at AGS and SPS) and, more important, to explore the energy regime of maximum baryon density where the colliding nuclei just stop each other in the average collision. The best energy range for the latter study is only roughly estimated from present data, and fluctuations will be large, so it is not deemed advisable to insist on the highest quality performance at 5+5 if this means sacrificing top end performance.

The panel recognized that the luminosity achieved at top energy will not be matched in lower energy operation; the luminosity for a given ion species is expected to fall with energy as $1/\gamma$. Below the injection energy (12+12) the drop-off with energy may be even faster. Nonetheless, operation should be possible down to 5+5 if experimenters are willing to accept low luminosity and short beam lifetime. Below this energy excellent luminosity can be obtained using a gas jet target and a beam in one ring up to 75 GeV/nucleon.

Luminosity

The panel agreed with the recommendation made in August that a minimum luminosity $L \geq 10^{25} cm^{-2} sec^{-1}$ at the top end (highest mass, highest energy) be attainable initially.

In light of the recent technical studies it appears that the August recommendation that the machine be designed to ultimately achieve $L \geq 10^{28} cm^{-2} sec^{-1}$ may be unrealistic. From the presentations made at this meeting, however, it seems that the machine can be designed to ultimately achieve luminosities approaching $10^{27} cm^{-2} sec^{-1}$.

It was very strongly felt that in order for the machine luminosity to be useful for experiments, the longitudinal extent of the crossing regions - i.e. the length of the source of interactions seen by detectors - should not exceed an r.m.s. size of $\pm$ 20 cm.

The implications for experimenters of bunched beam operation were discussed rather superficially, a detailed study being needed to arrive at firm conclusions. At $L = 10^{27} cm^{-2} sec^{-1}$, with gold ions, the mean number of interactions per bunch crossing is near zero, so the rate for multiple interactions per crossing is small (< 1%) in comparison with single interactions. Nonetheless, the "interesting" events are also relatively rare, and easily faked by multiple interactions. The experimenters present felt that DC beams were to be preferred over bunched beams if this were to become a practical design choice.

It was suggested that the machine designers should, if possible, keep open the option for special purpose running in a crossing configuration with very short interaction diamond. This would involve some trade-off with luminosity, but for many experiments it may be more important to have a source of interactions which is precisely localized in space.

Range of Ion Masses:

The selected table of ion species, respecting the fact that linear dimensions of nuclei grow as $A^{1/3}$, seemed quite adequate to the panel for initial operation. The list is: Protons, carbon, sulphur, copper, iodine, gold.

The panel members agreed that deuterium would be a useful addition, but that this should not be viewed as a replacement for protons (see next point below).

Modes of Operation

The design group has forseen four different modes of operation for the collider (see App. II, P. 4)

1. A + A Same species
2. A + A' Unequal species
3. P + A Protons in one beam
4. P + P Protons in both beams

The essential issue here is whether items 2 and 3 are required to be available with the same energy per nucleon in each beam, thereby ruling out a design with common magnets.

The panel felt strongly that collisions of protons with ion beams should not be excluded in the machine design. This despite the fact that many of the systematic studies to be done with item 3 above could also be done with deuterons. Both the theorists and the experimentalists on the panel were reluctant to give up the direct connection with a wealth of data from fixed target proton beams. And it was pointed out that protons in one ring, with full rigidity, would have twice the energy per nucleon achievable with higher mass ions, affording a much higher energy for nucleon-nucleus collisions than would otherwise be available.

Another issue raised at the meeting was the possibility of operating with different energies in the two rings. This can provide a means of gaining easier access to certain kinematic regions in the final state, particularly with detectors which cover less than the full solid angle. At the August meeting this mode of operation was deemed of secondary importance since it does not fundamentally broaden the range of physics parameters. The points raised in favor of such an operation are nonetheless valid, and strengthen the case for keeping the potential operating modes as flexible as possible.

Length of Free Space in Intersection Regions

In discussions among the panel members and the design group it became clear that, at this stage of the machine design at least, the requirement of a $\pm$ 10 meter free space for detectors at the crossing regions need not be a critical issue. If a proper design for the crossing region calls for a close-in quadrupole or dipole this can doubtless be accommodated in the detector design, as has been the case in many instances in e^+e^- Colliders and at the ISR. There would be plenty of free space beyond the close-in magnets, and the CBA Experimental areas are built to provide for a $\pm$ 30 meter free space.

Beam Purity

Fragmentation of the Heavy-Ion Beams by either interbeam or intrabeam scatterings or reaction of the beams with residual gas in the vacuum system results in the production of lighter mass products with the same Z/A ratio and same magnetic rigidity as the primary beam. These secondary products will therefore circulate with the primary beam and be a potentially troublesome source of background events. Relevant production cross sections for these secondary processes at energies important for the collider design are sparce or non-existant. In some cases, they can be estimated from Bevalac studies up to 2 GeV/nucleon. It was therefore thought prudent to examine this problem in greater detail than has been possible up to now. A better understanding of production rates of secondary beam particles as a function of beam energy, luminosity, and ion type in the various operation scenarios will allow reliable predictions to be made of background processes.

Request to Re-evaluate or to Confirm the Goals for the Heavy Ion Collider

The RHIC Task Force
(Compiled by A. G. Ruggiero)

In approaching the design of the Heavy Ion Collider (RHIC) we have, in front of us the following requirements:

1. Maximum Energy of 100 GeV/nucleon for the heaviest ion
2. Minimum Energy of 5 GeV/nucleon for the heaviest ion
3. A luminosity at top energy of 10^{27} $cm^{-2}s^{-1}$ with possibility of upgrading it to 10^{28} $cm^{-2}s^{-1}$
4. A range of ions from protons up to $A \sim 200$
5. Equal and different species operation modes
6. Variable energies between 5 and 100 GeV/nucleon
7. Magnet free space at crossing of ± 10m

After about one month of intense studies several issues have nevertheless been raised and the attainability of the goals listed above are questioned again. Below are the list of issues. These issues have a point-to-point correspondence with the list of requirements above.

Issue #1

This energy can be achieved in several ways. One possibility is the use of the missing magnet scheme with employment of the CBA magnet. It is also possible to assume a full packing in the curved section of the CBA tunnel. In this case a bending field of about 3.3 Tesla is required and adequate. The i.d. coil does not have to exceed 3". This can be reasonably well achieved with either a window frame magnet or a cos θ profile superconducting magnet.

A cost optimization study is in progress to establish the potential cost savings from the use of the various kinds of magnets.

If the cost of the project is an issue, cost savings can be achieved by reducing the number of magnets or further lowering the field to about 2.4 Tesla, and this would correspond to a lower maximum energy of 75 GeV/nucleon for $A \sim 200$. The following Table I shows the maximum energy for a given field and will depend on the atomic mass A.

Table I. Maximum Energy vs. Magnet Field and Atomic Mass
(Assuming Full Packing)

Field	2.4 Tesla	3.3 Tesla
Proton (P)	187.5 GeV/A	250 GeV/A
Carbon (C)	95	125
Sulphur (S)	95	125
Copper (Cu)	85	114
Iodine (I)	78	104
Gold (Au)	75	100

Question: Is the energy of 100 GeV/nucleon for the heaviest ion, an absolute requirement? Or, could it be lowered somewhat if there is an economical benefit?

Issue #2

The major reason for a large aperture is to accommodate a beam of heavy ions at the low energy end, and possibly to accelerate it through the transition energy. At the moment we estimate a max beam diameter of about one inch at 5 GeV/A for gold and the magnet coil i.d. of 3" seems to be adequate for this beam size. Conversely at the top energy the beam size is about 5 mm. A good field region of about two inches is needed at 5 GeV/A and one inch is more than adequate at 100 GeV/A. Clearly, the aperture of the magnet depends crucially on the requirement to operate the collider at low energies.

Furthermore, we have also found that intra-beam-scattering (the phenomena by which particles of the same beam exchange transverse and longitudinal momenta by Coulomb scattering) is a very serious and limiting effect. It is already difficult to find a lattice and beam dimension (emittances) that guarantee high luminosity and long lifetime at the high energy level. It could be very difficult to maintain high luminosity for a long period of time at 5 GeV/A.

Finally, it should be stressed that the operation of the collider from 5 to 100 GeV/A requires a magnet system capable of tracking in field over a range of a factor 20.

We would like to suggest to reconsider the goal and set the design energy at the injection level which is, with the present AGS, 12 GeV/A for gold and 28 GeV for protons. Operation at lower energies could still be possible but without performance guarantees.

Issue #3

An initial (peak) luminosity of about 10^{27} $cm^{-2}s^{-1}$ seems for the moment to be at the border line of feasibility at the energy of 100 GeV/nucleon. But the real issue is lifetime, that is how long it is possible to keep the luminosity at that level. As we have pointed out it seems that intrabeam scattering can cause a serious degradation of the luminosity more than any other effect. Also we should not forget that it takes sometime to fill up the collider with heavy ions and to accelerate the beams. The scenario that is developing in front of us very likely will have a filling time of several minutes, an acceleration period of about the same length and a colliding operation period that can last hopefully one hour or so. After this period of time it would be more convenient to refill the rings with fresh beams. By doing so, though one can get an initial (peak) luminosity of 10^{27} $cm^{-2}s^{-1}$, the actual luminosity useful for experiments averaged over one cycle about one hour long, could be one-third to one-half of 10^{27} $cm^{-2}s^{-1}$. Is this acceptable?

For the moment our luminosity estimates are based on the assumption of large angle ($\sim$2 mrad) for the reasons we explain below. This mode of operation since it depends on the bunch length (the beams are assumed to be bunched) demands either a very intense beam (long filling times, rf stacking...) or extremely short bunches (shorter luminosity lifetime, large voltage and high rf system...).

An alternate mode of operation when the two beams collide head-on seems attractive. The two modes of operation differ as to their ultimate luminosity potential, variation of luminosity with energy, interaction region dimensions and operation with different ion species.

Another consideration related to the geometry of crossing is the time distribution of the number of events for crossing. For a luminosity of $10^{28}cm^{-2}s^{-1}$, ten events per crossing can be expected. If the detector has a time resolution of say 1 nsec, then the bunch length ought to be at least 3 meters long. This is by no means a short bunch and the luminosity would suffer by operating with crossing at an angle. On the other hand head-on collision with long bunches could have the inconvenience to create long interaction regions (where the events come from) about half the size of the bunches.

The questions are: What is the best operation mode of the collider as perceived by the experimenters? How long can the interaction region be? What is the largest luminosity per unit of time that the detector can absorb?

Issues # 4

We have selected the following species as the minimum requirement for the Heavy Ion Collider program.

Table II - Selected Species for RHIC

Species	(n)	Z	A	A/Z
Proton	(1)	1	1	1.0
Carbon	(2)	6	12	2.0
Sulphur	(3)	16	32	2.0
Copper	(4)	29	64	2.2
Iodine	(5)	53	127	2.4
Gold	(6)	79	197	2.5

These species have an atomic mass A that roughly scales like n^3 with n an integer from 1 to 6. Also there are negative ions sources for these selected species that can be fed into the present Tandem VandeGraaff at reasonable high current level.

One more element, deuterium, can be added at request for the reasons explained later. Is this satisfactory? Is there a compulsory need for more additions?

Issue #5

We foresee four different modes of operation of the collider:

1. Same species colliding with each other at the same energy, for instance gold versus gold.
2. One specie (A_1) colliding with another specie of different atomic mass (A_2), like gold versus sulphur.
3. One of the five selected ion species colliding with protons
4. Protons colliding with protons

Protons are distinguished from the heavier ion because they are produced by a different source.

So far we have assumed that the two beams colliding with each other should have the same energy per nucleon as a requirement from the users. This does not seem to impose any further constraint on beam geometry and crossing for the mode of operation #1. In this case as long as the two beams are identical and have the same energy, they can also share common magnets, and head-on collision is certainly feasible here. We do understand that there is no need of colliding two beams of the same species at different energies. The case of protons colliding with protons (Mode #4) also is rather flexible and the two beams can have common magnets to be brought together head-on. Incidentally, in this case a peak luminosity of 10^{31} - $10^{32} cm^{-2}s^{-1}$ seems to be feasible

The issue is with the modes of operation #2 and #3. If one insists on the same energy per nucleon, a common magnet scheme is to be ruled out and the beam can be made to collide only at an angle. The smallest we can get is 2 mrad.

With a common magnet scheme, two beams with different species must have different energies because of the different ratios A/Z. The difference in energy is shown in Table III. As one can see the crucial cases are those where one beam is made of protons. Questions: How close should the two energies be? Can one replace protons with deuterons (A/Z=2)?

Probably the best situation is obtained with crossing region design where common magnets are turned on to bring the two beams to collide head-on when desired and switched off when crossing at angle is mandatory. It is possible though that in the latter case which corresponds to different colliding atomic species, the luminosity will be reduced.

Two remarks at this point are in order. If the two beams have the same energy per nucleon they also have the same velocity and the collision points will not drift, if the beams are bunched all the time. If the two beams are of different energies they cannot have the same velocity and to compensate for this, the velocity path length has to be adjusted accordingly so they will collide at the same points. This is possible always except when one of the two beams is made of protons.

The second remark is that if the common magnets in the crossing region are to be excluded there is then more reason to exclude the so-called two-in-one magnets where the two magnets share the same iron in full coupling so the field is the same in both of them. This magnet cannot allow the same energy per nucleon for two beams of different species.

Table III - Energies of Different Specie Beams Colliding with Common Magnets

Gold - Iodine	100/96	GeV/A
Copper	88	
Sulphur	80	
Carbon	80	
Proton	40	
Iodine - Copper	100/91.7	GeV/A
Sulphur	83.3	
Carbon	83.3	
Proton	41.7	
Copper - Sulphur	100/90.9	GeV/A
Carbon	90.9	
Proton	45.4	
Sulphur - Carbon	100/100	GeV/A
Proton	50	
Carbon - Proton	100/50	GeV/A

The questions are: How equal ought to be the energies of the two beams? Can one take lesser luminosity in the case of two different species? Can deuterium replace protons colliding with heavier ions?

Issue #6

Because of the severe limitations from intrabeam scattering and because of the aperture limitations at the low energy end, it is very difficult to maintain the same luminosity of 10^{27} $cm^{-2}s^{-1}$ at all energies. One can expect a luminosity just an order of magnitude lower at 5-12 GeV/A. Is this acceptable?

Since the beam dimensions scale with the energy, automatically there is a benefit in getting larger luminosity figures going to higher energies. This benefit is lost at low energies. That is to say that there is a natural, dynamic bottleneck in the collider at low energy; if one requires to widen up this bottleneck to accommodate a luminosity as large as $10^{27}cm^{-2}s^{-1}$ then there is the danger of requesting a design of much higher performance collider at the top energy.

Issue #7

It is important that the experimenters confirm or re-evaluate the requirements for a free space of ± 10m at the crossing region. This distance combined with the difficulties of designing a proper interaction region with low-beta and rings crossing at an angle, can appreciably affect the performance of the collider.

Issue #8

So far we have concentrated our study to what we call the reference case, that is gold versus gold. A luminosity of $10^{27}cm^{-2}s^{-1}$ has been estimated for this case. We need more study for the other cases with different and other species. But the conviction in us is growing that very likely higher luminosity can be obtained with lighter ions. For instance we project a luminosity of 10^{31}-$10^{32}cm^{-2}s^{-1}$ with protons colliding with protons and 10^{30} - 10^{31} $cm^{-2}s^{-1}$ with protons colliding with anything else. With lighter ions, for which intrabeam scattering is a less crucial effect, luminosity as high as 10^{28} $cm^{-2}s^{-1}$ can probably be feasible. The picture that we outline is that the luminosity performance will increase with lighter ions. To soften then some of the requirement of the collider design it is legitimate to ask where the goal of the luminosity figure $10^{27}cm^{-2}s^{-1}$ should fall. Is this really the requirement for gold versus gold, or should the line be drawn toward lighter ions?