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POSSIBILITIES FOR RELATIVISTIC HEAVY ION COLLISIONS AT BROOKHAVEN*

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1. INTRODUCTION

Since 1980 there has been considerable interest at Brookhaven in exploiting the existence of the Colliding Beam Accelerator, CBA, earlier referred to as Isabelle, for the generation of heavy ion collisions at very high energies.[1] It appeared that this physics program could be addressed at Brookhaven at an incremental cost that could not be competitively matched anywhere. The CBA ring design is quite nicely matched to the requirements for a heavy ion collider. The only requirement would have been for an energy booster for the Tandem accelerator and a tunnel and magnet transport system to the AGS. For a few million dollars heavy ions up to nearly 200 GeV/amu could be collided with luminosities of 10^{27} to $10^{28}/cm^2 sec$ in experimental halls with ideal facilities for heavy ion physics studies.

Now that the CBA project has been stopped, the picture is somewhat changed. Nonetheless, it is still true that Brookhaven has in place enormous advantages for constructing a heavy ion collider. This paper describes a design that exploits those advantages. It uses the tunnel and other civil construction, the refrigerator, vacuum equipment, injection line components, and the magnet design for which there is expertise and a production facility in place. The result is a machine that appears quite different than would a machine designed from first principles without access to these resources but one which is of high performance and of very attractive cost.

The performance parameters of this machine match nicely to the suggested requirements formulated by a Task Force on Relativistic Heavy Ion Physics convened at Brookhaven on August 22-24, 1983. In their report, in the form of a memo to Brookhaven management, they include Table I.

A detailed proposal is in preparation for this machine. This paper is a very condensed version of that proposal. At the end of the paper we present some other activities which are part of the Brookhaven program.

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

Table I. Parameters of an Ultra Relativistic Heavy Ion Collider

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Energy of Beams (GeV/amu):

At least 50+50, covering a range of energies starting as low as 5+5.

Range of Ion Masses:

- A>100 initially; ultimately A 200.
- Light ions also, including protons.

Luminosity:

- $L > 10^{25} cm^{-2} sec^{-1}$ initially; ultimately reaching $10^{28} cm^{-1} sec^{-1}$

Intersection:

- 3-6 Intersection Regions
- Free space along beams at least ±10m

Detectors and Experiments:

- At least one or two large, facility-like detectors with 4π coverage.
- Many opportunities for small solid-angle experiments.
- Expect a user community of >300 physicsts.

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2. RING TUNNEL AND EXPERIMENTAL HALLS

The availability of the CBA tunnel for a heavy ion collider represents an opportunity to construct the new machine at minimal cost. The tunnel layout provides six beam crossings; the present concept foresees full luminosity crossings at 4, 8 and 12 o'clock and lower luminosity at the remaining 2, 6, and 10 o'clock crossings.

Construction of the Main Ring, including the earth shielding, is complete with the exception of areas 10 and 12 (Figure 1). The experimental facilities to be located there have not been constructed, leaving gaps of approximately 380 ft at each area. Thus the option of adding a high luminosity hall at 12 o'clock, taking into account specific experimental needs, is maintained. Little effort has been expended to date on preparing the two unfinished area at 10 and 12 o'clock. At least connecting the tunnel and adding the support buildings at each of these areas would be necessary to make the Main Ring operational for any purpose. The cost estimate allows for this minimal completion work.

Experimental Halls at Area 2 (Narrow Angle Hall), Area 6 (Wide Angle Hall) and Area 8 (Major Facility Hall), along with their support buildings, are all complete. Area 4 is an "open" area, a large concrete hardstand which does not have an enclosed structure. It is complete along with a modified support building. The dimensions and crane capacities of the existing experimental halls are given in Table II. The Service Building Complex, consisting of the

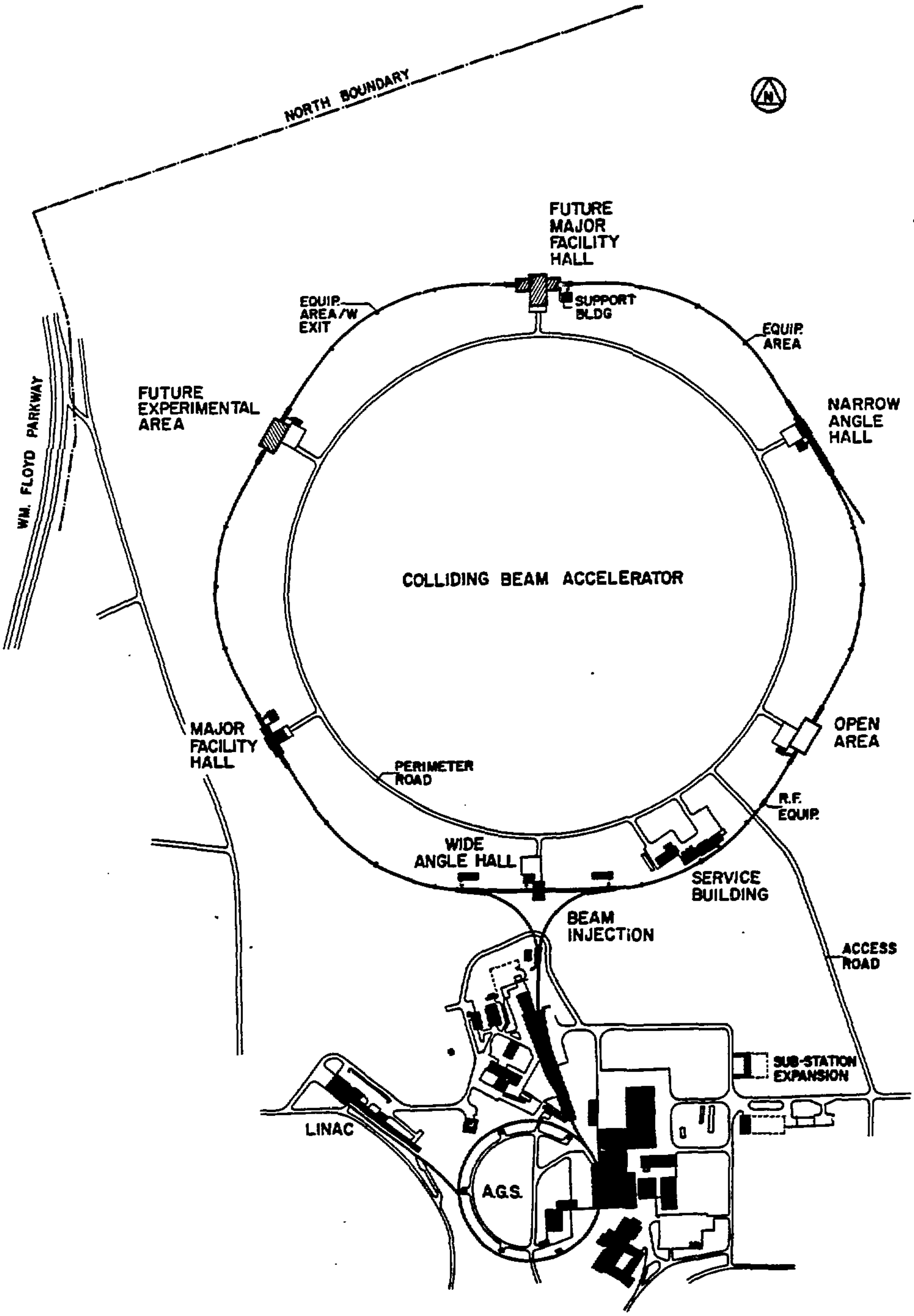

FIGURE 1
Existing CBA tunnel and experimental halls.

Cryogenic Wing, the Compressor Structure, and a four-story Main Building housing control rooms, office space, shops and technical areas, and the RF and Power Supply Wing is approximately 95% complete.

Construction of the various utility services, roadways, drainage and other site improvements required to complete the CBA as an operational facility, has been underway during the past few years and is now nearly complete.

Table II. Summary of Hall Dimensions (m)

	Area	Length	Width	Beam Height	Hook Height and Capacity (tons)
2.	Small Angle Central Hall	28	12	1.7	6.1/20
	Forward Experimental Building	68	7.9	1.7	5.3*
	"Stub"	91	2.4	1.0	2.0*
4.	Open Area 4	57**	37**	2.2	---*
6.	Wide Angle	16	32	4.3	10/2 20
8.	Major Facility Central Hall	19	15	5.2	11/40
	Forward Experimental Buildings (2)	16	9	3.3	6.6*
	Assembly Building	19	19	5.2	11/40+14/7.5

* No crane - ceiling height given
** Pad dimensions given

3. LATTICE, PERFORMANCE AND BEAM DYNAMICS

3.1 Lattice

A lattice with superb properties was developed for the CBA. It uses the physical aperture efficiently, has excellent chromatic properties, exploits a high symmetry and conservative focusing to minimize operational problems with magnetic imperfections, and has great flexibility for tuning the crossing point geometry to the requirements of various experiments. All of these advantages apply, of course, to a heavy ion collider. To reduce the cost of a dedicated collider, it is suggested that this same lattice can be constructed with a "missing magnet" approach. This is possible because the 400 Q/A GeV/amu energy can be considerably reduced and still be of interest for ions. A lattice with only one-third of the magnets in place would provide energies up to 133 Q/A GeV/amu which should still be adequate for the physics questions of interest.

When the idea of such a missing magnet lattice first emerged, it was believed that the aperture loss due to sagitta in the bending magnets would make the proposal uninteresting. Later, it was realized that if the bending magnets are placed at points of low dispersion, then the required aperture in each dipole is small enough that it does not limit the acceptance. In fact, by concentrating the bending at points of low dispersion, the dispersion function is reduced everywhere so that the momentum acceptance of the lattice is actually increased. For the regular cells, these features are summarized in Table III.

Table III. Lattice Properties, Regular Cells

	CBA	Missing Magnets	
β_H in QF	66.9	66.7	m
β_V in QF	11.5	11.5	m
β_H in QD	11.5	11.5	m
β_V in QD	66.9	66.8	m
X_p in QF	2.7	2.3	m
X_p in QD	1.3	0.9	m
Max X_p in a dipole	2.7 near QF	1.2 near QF	m

We see in this table that all properties of the cell are identical to the usual CBA lattice except for the lower dispersion function which raises the transition energy and increases momentum acceptance. It has been shown that the dispersion of these cells is matched to zero in the insertion regions in a fashion exactly analogous to the usual arrangement for the CBA lattice. The final result is a lattice with all of the favorable features of the standard CBA lattice.

The quadrupoles of Ref. 3 were assumed to be the standard CBA quadrupoles which would operate at about one-third of their rated current. This design was necessary because it was anticipated that, at some future date, the missing dipole magnets would be added to bring CBA up to its full energy rating. Initial deployment of full strength quadrupoles was necessary to avoid an expensive retrofit of quadrupoles. If such an energy upgrade is not anticipated, then a more reasonable quadrupole design is possible. A reasonable looking design would use a single-layer coil having only about half the gradient of the standard CBA quadrupoles and with a length about two-thirds the standard length. Such a coil would have lots of spare radial space for adding correction coils if they are needed. Further economies in the lattice can be realized by using the "2-in-1" magnet concept. This magnet design is described below and has been used for the cost estimate.

Increasing the luminosity by tuning of the vertical beta at the crossing point to $\beta^*=2$ m and introduction of common bending magnets to reduce the crossing angle will be possible in the three low-beta experimental insertions. This operation is carried out after acceleration to full field and should proceed identically to the practice which was developed for CBA.

A weakness of the missing magnet lattice described is the need to accelerate heavy ions through the transition energy. A variety of schemes are under study to avoid this inconvenience.

3.2 Magnetic Imperfections

The various effects of magnetic imperfections such as closed-orbit distortions, uncorrectable closed-orbit distortions, beam size growth due to non-linear resonances, etc. were exhaustively studied for the CBA proton machine. Since the optics of the missing magnet heavy ion machine are virtually identical to the CBA, these analyses can be applied directly. The magnet field quality specifications are thus identical. As was shown in the CBA study, these field tolerances can be met and they guarantee a machine of conservative design.

3.3 Performance Expectations

The luminosity that can be achieved in a heavy ion machine is limited by the amount of ion current that can be stored and accelerated in the rings. In the explicit design being presented here, that current is limited by the fact that the beam must be accelerated through the phase transition energy. With the parameters of the lattice, and the expected performance of the AGS as a heavy ion injector, it should be possible to inject about 600 AGS pulses in each of the rings and accelerate the corresponding phase space area through transition. The luminosity can be enhanced by keeping the rf on and colliding bunched beams. With the amount of rf available, the bunching factor will only be about six but even this modest improvement in luminosity should be employed. The luminosity is then computed with the formula:

$$L = \frac{2}{c}\left(\frac{I}{Qe}\right)^2 \frac{1}{(2\sqrt{\pi}\ \sigma_v^*)\alpha}\left(\frac{\sqrt{\pi}\ R}{\sigma_L h}\right)$$

where I is the beam current, Q the charge state, α the crossing angle, σ_v^* the vertical beam size (rms half width), $2\pi R$ is the circumference, h the harmonic number, and σ_L the longitudinal rms beam size. With the numbers in the parameter list, we find that a luminosity of 1.2×10^{27} cm^{-2}sec^{-1} is predicted in the low-beta experimental insertions at full energy. This luminosity is quite appropriate to the physics questions of interest. Higher luminosity may be possible if the injector performance can be improved and all aspects of the stacking and acceleration process are pushed to their theoretical limits.

The beam will be bunched with a ratio of peak to average luminosity rate of $\sqrt{\pi} R \sigma_L^{-1} h^{-1} \approx 6.5$. The intersection diamond will be $2\sqrt{\pi}\sigma_V^* \approx 0.18$ mm high, 0.9 mm wide radially, and $4\sqrt{2}\sigma_H^* \alpha^{-1} \approx 34$ cm long.

Operation with ions of unequal mass (including protons) is one of the experimental requirements which for the 2-in-1 magnets imposes a constraint for the extreme case of proton-ion collisions. The beams, if bunched, would have to operate with a momentum difference of

$$\frac{\Delta p}{p} \approx \frac{1}{2}\left(\frac{\gamma_{tr}}{\gamma_{ion}}\right)^2 \left\{1 - \left(\frac{Q}{A}\right)^2\right\}$$

which cannot be accommodated by this design. Consequently, proton/heavy ion collisions will be run unbunched. Since the proton beam can be increased to several amperes, adequate luminosities are still achievable.

3.4 Performance Limitations

The luminosity quoted is that determined by simple logistics of how many particles can be stacked in the rings. It is important to determine that the beam currents are not limited by space charge limits, coherent instabilities, or the beam-beam interaction. To first order, one does not expect such limitations because the line density of particles is low. One should proceed with caution, however, because self field effects scale like Q^2/A. The various modes of instability were examined in depth for CBA.[4]

Simple incoherent space charge tune shift scales like[5]

$$\Delta\nu \propto N \frac{Q^2}{A} \frac{I}{\gamma^2} \frac{1}{\varepsilon_n}$$

where ε_n is the normalized emittance and N the number of particles. The ratio $\Delta\nu_{ions}/\Delta\nu_{protons}$, using the numbers from the parameter list assumes the numerical value ≈ 1. Note here that the most serious space charge consideration for the protons in CBA was for a partially neutralized beam at full energy. For the ions, it is anticipated that the beam will be kept bunched and neutralization will not occur.

For longitudinal instability, the Keil-Schnell criterion determining the maximum acceptable longitudinal impedance is[5]

$$\left|\frac{Z}{n}\right| < F \frac{1}{I} \frac{E}{e} |\eta| \left(\frac{\Delta p}{p}\right)^2$$

Converting to the case for ions,

$$\left|\frac{Z}{n}\right| < F \frac{A}{Q^2} \frac{\xi}{\lambda\, e^2\, (\beta c)} |\eta| \left(\frac{\Delta p}{p}\right)^2.$$

Here λ is the number of particles per unit length and ξ is the energy per nucleon. The worst situation is microwave instability during stacking. The momentum spread for ions is 0.16% for 600 AGS pulses to be compared with 1% for 300 AGS pulses for proton operation. We then find that:

$$(Z/n)_{ions}/(Z/n)_{CBA} \sim 1.9 \ ,$$

i.e., *the impedance requirement is relaxed by a factor of nearly two.*

For transverse instability, a similar argument based on[6]

$$|Z_{tr}| < \left(\frac{A}{Q^2}\right)|n| \frac{\nu_0}{R\ e\ \lambda\ \beta c} \left(\frac{\Delta p}{m_0 c}\right)$$

indicates a factor of eleven in relaxation of the impedance requirement. This requirement is so much easier because the small momentum spread of the ions only enters linearly instead of quadratically as in the longitudinal case.

These results all indicate that self field effects for heavy ions are comparable to or somewhat less important than the corresponding implications for the proton machine. The beam-beam interaction deserves special attention because the heavy ion beam, unlike the proton beam in CBA, is to be kept bunched. The accepted criterion, as verified by SPS collider results, is that the tune shift at the peak of the bunch should be less than about 0.003. For ions in the collider[7]

$$\Delta\nu = \frac{\beta_v^* \left(\frac{Q^2}{A}\right) r_p \left(\frac{I}{Qe}\right)}{\sqrt{2\pi}\ c\ \gamma\ \beta^2\ \sigma_v^*\ \tan(\alpha/2)} = 1.8 \times 10^{-3}$$

which is acceptable.

4. MAGNET SYSTEM

Most of the accelerator magnets built so far at BNL have contained one superconducting coil in one laminated iron yoke (1-in-1). Introducing two coils side-by-side into one yoke (2-in-1) can provide two magnets with fields pointing in opposite directions. A short (~ 5 feet in length) 2-in-1 dipole magnet was tested successfully in the summer of 1982, and a full-length (~ 15 foot) dipole has subsequently been built and tested. It has reached the expected peak field, and its field quality appears to be acceptable. Because of the asymmetry with respect to an individual coil in the magnet (see Fig. 2), quadrupole and higher components that are not allowed in 1-in-1 magnets must also be expected here but can be minimized by proper shaping of the yoke cross section and neutralized by trim coils.

Figure 2 shows a cross section of a 2-in-1 dipole. The two layer superconducting coils surrounded by the laminated iron yoke are shown. The yoke consists of 3-inch long sections of laminations glued together with epoxy. In order to inhibit motion of the coil conductors, the coils must be azimuthally prestressed. The necessary prestress is provided by four stainless steel bolts per yoke section, as indicated in Fig. 2. Inside the coils one can see the *inner wall of the helium-containing* vessel, *the* "cold bore", *which* also *sup*ports the trim coil. The "warm bore" tube acts as particle beam tube and thus requires an ultra-high vacuum. The helium-containing vessel is completed on the outside of the yoke by a split stainless steel cylinder which is welded around the yoke assembly at the top. The 2-in-1 dipoles are approximately 15 feet long.

Two holes located between the two coils pass through all of the yoke blocks. They serve to minimize the mentioned quadrupole component. Helium for cooling the magnet can be passed through these holes as well as through passages just inside and outside the coils and also outside the yoke. Figure 3 shows a calculated 2-in-1 field pattern without including the holes. (Note the efficient *use of the yoke for 2-in-1 magnets;* about 40% of the iron cross section is saved compared to an equivalent 1-in-1 magnet system.)

No statistics on performance of 2-in-1 magnets have been accumulated so far but experience with the 1-in-1, employing identical coils, has been excellent. The performance of the 2-in-1 magnets is expected to be equally reproducible and reliable.

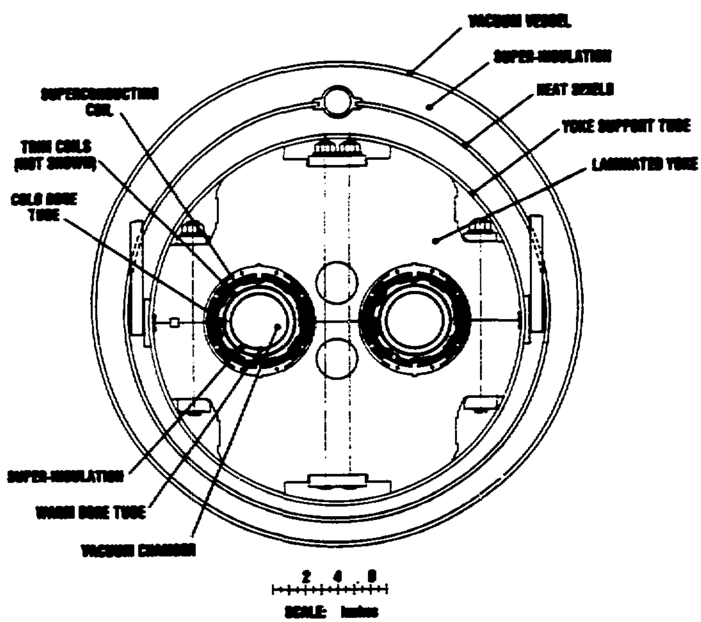

FIGURE 2

Two-in-one dipole cross section mounted in vacuum vessel.

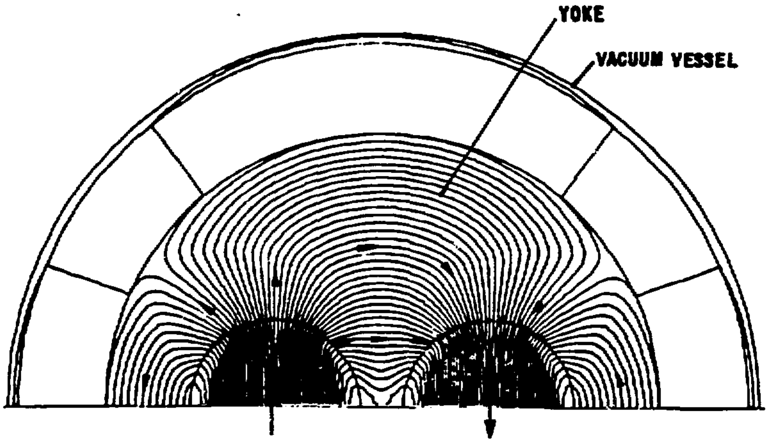

FIGURE 3

Calculated 2-in-1 field pattern.

5. CRYOGENIC SYSTEM

The cryogenic system design for the ion collider is based on the use of the 24.8 kW helium refrigerator originally intended for ISABELLE/CBA.[8] The heat load is much less than for CBA, mainly by virtue of the 2-in-1 design and the requirement for fewer dipoles. A rough estimate of the magnet heat load is 2200 W for all ring magnets. An additional 100 W load will be required for piping to carry the helium from the refrigerator to the magnets and across the experimental areas. The magnet power leads impose a load estimated at 3900 W. The total load is expected to be 6.2 kW at temperatures below 4.6 K.

In addition the refrigerator will supply helium at a mean temperature of 55 K for cooling the heat shields of the magnets and piping. It is estimated that about 6 kW of a nominal 55 kW capacity will be required.

It is proposed to cool all of the magnets in the ring in a single series loop. About 800 g/s of helium would enter the magnets at 2.6 K and exit at 4.6 K. The flow would come from the main compressors, through the heat exchanger train, then through an almost wet expander where the pressure would drop to about 6 atm. The gas would then be cooled, by heat exchange with pumped boiling liquid, to 2.6 K and routed to the ring. An allowance for a 2 atm pressure drop has been made in this loop. The design flow rate for the loop is 1250 g/s to yield a design margin of about 1.5. Although operating at less than full capacity and therefore inefficiently, the cryogenic plant is expected to consume less than 7 MW of electric power.

6. BEAM TRANSFER AND INJECTION

The AGS will serve as the injector for the ion collider. Beam will be ejected from the AGS in a single revolution making use of the existing fast extraction system in the North Area,[9] and it will be transferred to the collider along the already existing beam transfer tunnel. The geometry of the beam transfer and injection lines, the optical properties of the beam transport magnet system and the configuration of septa and kickers will be identical to those described for the CBA Project.[10]

7. RF SYSTEMS

The rf systems of the collider will perform several functions related to

- the capture and stacking of the injected AGS beam
- the rebunching and acceleration of the stacked beam
- the maintaining of a bunched beam during operation.

The required operations can be performed by two separate rf systems, referred to as the stacking and accelerating rf systems.

The design of the rf systems is firmly based on the R&D and model work carried out for the CBA rf. Due to the low voltage required for beam stacking, only a modest stacking rf system is required so commercially available wide band amplifiers of a few hundred watts power output having an impedance of 50Ω can be used. The stacking cavity with only 200 V across the gap presents no problem. This system will also be used to damp injection errors and low-frequency coupled-bunch instabilities.

The lower momentum spread of the stacked current permits acceleration with only one accelerating cavity. The existing 12kV system will satisfy the requirements of impedance, bucket size and gain per turn.

7.1 Stacking

The beam injected from the AGS will be stacked in momentum space. An initial rf voltage of 100 V at 4.45 MHz, h=57 will provide a bucket area of 42.5 eV•sec for ${}_{53}I^{127}$ ions. The phase space area per AGS pulse for these ions is assumed to be 0.2 eV•sec/amu or 2.12 eV•sec per bunch (h=12 in the AGS). For an overall dilution of a factor of two from injection into the AGS through the stacking process in the collider and for a $\Gamma = \sin\phi_s = 0.6$ during the latter a voltage of $V_{rf} = 15.6$ V is required.

It is intended to store five groups of eleven AGS bunches on the injection orbit prior to each stacking cycle. Since 600 AGS pulses will be needed to accumulate the required current (at 3×10^8 ions/AGS cycle) there will be at least 120 stacking cycles. The low rf voltage required to stack these ions determines the time per stacking cycle at about 2 minutes. Hence the minimum stacking time per ring will be about four hours. By alternating injection pulses between the rings the overall time required to fill both rings should not increase significantly. Other methods of reducing the stacking time are being studied.

7.2 Acceleration

Acceleration will take place on the third harmonic at 234.5 kHz with a peak voltage of 12 kV provided by a single cavity.[11] The maximum energy gain per turn will be 3.7 keV with a $\dot{B}_{max}$ = 108 G/sec. For these parameters and a ± 1% momentum aperture, the phase space area per bunch available at transition is 157 eV·sec/amu. This is 2 times greater than required for the 0.16% stacked beam if no additional dilution is assumed and represents a comfortable margin. Again, if there is no further dilution then the bunching factor ($\sqrt{\pi}R/h\sigma$) will be 6.5 for V_{rf}= 12 kV at 50 GeV/amu.

8. VACUUM SYSTEMS

The CBA design for the magnet insulating vacuum system and the UHV beam vacuum system are directly applicable to the ion collider.[12] The insulating vacuum requirements of 10^{-5} Torr are, in fact, identical in both machines. Although the beam vacuum requirements for heavy ions differ somewhat, a warm bore UHV vacuum system as developed for the proton CBA is expected to be economical and technically adequate. Furthermore, high-current proton operation as requested for physics experiments remains possible. The UHV beam vacuum will differ only in the number of pumping stations and clearing electrodes will be eliminated due to bunched beam operation. By using a warm bore solution almost all existing vacuum hardware bought for CBA can be utilized which will lower the cost-to-complete for the ion collider.

In the ion collider, an average pressure of 1×10^{-11} Torr is still required to minimize various effects of residual gas on the circulating beam i.e. multiple and nuclear scattering, charge exchange with residual gas, and residual gas ionization.

Residual gas ionization is potentially most troublesome as it determines the onset of the pressure bump phenomenon which depends on the desorption coefficient η and the ionization cross-section.[13] η is a strong function of total charge density and since the design current is only 0.1A for iodine ions, the dc beam to wall potential would be small compared to CBA. However the ionization cross-section varies as Q^2 and residual gas ionization will be 3000 times larger as compared to protons. Thus the total effect should be more favorable than in CBA and $\eta\times I_{crit}$ of 30 A appears to be safe. The effects introduced by a bunched beam will change the dc solution and further investigation will have to be carried out into the behaviour of both electrons and residual gas ions.

9. MAGNET POWER SUPPLY AND CENTRAL CONTROL SYSTEMS

9.1 *Magnet Power Supply Systems*

The electric power supply systems required to operate the superconducting magnets for the collider fall into two categories:[14] 1) the main supply required to provide enough voltage for ramping the magnets from injection field to full field in 6 minutes, and to hold the main magnet current to a precise pre-selected value, and 2) the correction/trim coil and by-pass supplies. The two magnets of the 2-in-1 solution are electrically connected in series for greatest economy and simplicity of the electrical bus. The main power supply is rated at 600 V and 3.5 kA. About 400 correction/trim power supplies with current capabilities in the range from 20 to 300A will be required. Very high accuracy and reproducibility requirements are important to the design of these supplies.

9.2 Central Computer Control System

The design considered for the ion collider central computer control system closely follows the technical concepts developed for the proton CBA.[15] Due to the reduced number of magnets and other hardware, a small reduction in cost can be expected.

The central control system provides the control, communication, and information functions which will organize all other machine components into an effective research tool. The system design supports the needs of typical accelerator subsystems such as vacuum, injection, rf, and beam instrumentation while sustaining other subsystems unique to intersecting storage rings and cryogenic magnets. The control system has much in common with those of other large accelerators; it must permit modification of operating conditions, monitor parameters of interest, and provide safety and security for equipment and personnel. Compared to fast cycling accelerators, a storage ring accelerator requires a higher level of control system reliability and complexity. This is a direct result of both the increased complexity of beam handling and the operational cost of lost injection/acceleration cycles. The system as a whole is expected to change and to grow significantly over time. Hence one needs a clear expansion and development path without a requirement for reprogramming structural change.

The control system will be built around a hierarchal network of computers interconnected by a data highway. There is no implicit need for the computers within the network to be of a specific size or model; thus growth and innovation are anticipated and supported. Major functional areas for the control system are (1) The Network, (2) Computer Systems, (3) Control Centers, and (4) Process Input/Output. This architecture reflects the character and the needs of accelerator subsystems as well as the large physical size and geography of the project.

10.COST ESTIMATE

The cost estimate presented here is based in great measure on the material assembled for a May 1983, CBA Cost Analysis. A time frame for the total project was adopted. It assumes a one year R&D program followed by a three year construction program. It should be noted that the three year effort is conservative given the excellent factory, assembly, and cryogenic facilities available at the laboratory. The construction costs for the collider include the necessary beam transfer lines from the AGS. Because most of the conventional construction for the complex is completed only a modest allowance for finishing two open areas and miscellaneous site work has been added.

The preliminary total cost estimate is $164 M in 1984 dollars. This amount includes a 15% contingency allowance. Assembly labor and EDIA (Engineering Design, Inspection, Administration) amounts to 1529 man years.

The incremental cost to double the design energy to 100 GeV per nucleon has been estimated to be on the order of 20-30 M$. The higher energy machine would require a four year construction program, to allow fabrication of the larger number of magnets. Technical features of the higher energy option are virtually identical to those of the 50 GeV/amu machine. In that sense this paper could be regarded as the description of a proposal for either version. Retrofitting of magnets at a later time to convert the 50 GeV machine to a higher energy option is of course also possible, but it would be more expensive and disruptive of the ongoing physics program. Note that the costs do not include the injector costs. These are expected to be in the range of $20-30 M for AGS modifications, Tandem AGS transfer tunnel and cyclotron booster.

Parameters of the 50 × 50 GeV/amu machine are listed in the Appendix.

11.AN INTERIM PROGRAM

So far this discussion has focused on the heavy ion collider. There is an interesting possibility of an interim program to accelerate ions in the AGS. This program is desirable in any case because the AGS has to be prepared to serve as injector for the collider. It should be noticed in the discussion above that the AGS is expected to provide an ion intensity of 10^8 to 10^9 ions per pulse at an energy of 30 × Q/A GeV/amu as injector for the collider. This is clearly an energy and intensity of interest for fixed target physics. The ion beams from the AGS could be extracted and transported into the existing and well-developed experimental areas. Even some of the existing detectors such as the Multi-Particle Spectrometer can be used.

The performance levels assumed in this study are based on using the existing Tandem Van de Graaff machine as preinjector. The currents and invariant emittances are those that have been achieved with that machine. In order to raise the energy high enough that the ions can be fully stripped, a cyclotron booster has been proposed.[15] The technology of such cyclotrons is straightforward and no unusual performance requirements for the cyclotron are imposed by this program. The cyclotron also has the advantage of supporting a useful low energy nuclear physics program when the AGS is not operating or is running protons for the high energy physics program. The cyclotron is, of course, not the only possible means of boosting the ion energy for stripping. The AGS group is considering adding a booster synchrotron or accumulator ring to the AGS to improve the performance of the AGS, particularly with polarized protons. It is quite possible that such a ring can also be designed to act as an ion energy booster. That possibility will be studied in detail in the coming months. For the lighter ions, the booster is not really needed. The Tandem can provide fully stripped ions up to about sulphur at an energy of about 8 MeV/amu. At this energy, the magnetic field of the AGS is only about 20% lower than the design field for the original 50 Mev proton injector. There is no real fundamental reason why such Tandem beams cannot be used directly in the AGS. A tunnel from the Tandem facility to the AGS, a simple beam transport system, some injection hardware in the AGS, and some AGS rf system modifications to accommodate the larger frequency range are all the requirement. This program is being aggressively pursued by the laboratory.

ACKNOWLEDGMENTS

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APPENDIX: Collider Parameters

Performance		
Design Energy, $_{53}I^{127}$	50 × 50	GeV/amu
Luminosity/Bunch Collision	5.2×10^{21}	cm^{-2}
Av. Luminosity @ each low beta X-ing	1.2×10^{27}	$cm^{-2}\ sec^{-1}$
Av. Beam Current per ring	2.25×10^{-3}	particle-A
Bunching Factor	6.5	
Eff. Beam Height @ X-ing 50 GeV/amu	0.18	mm
Bunch Length	248	m
Diamond Length @ 50 GeV/amu	34	cm
Beam Beam Tune Shift	1.8×10^{-3}	
Low Beta Experimental Insertions		
Number of Insertions	6	
Number of Beam X-ing	3	
Beta Vert @ X-ing	2	m
Beta Horiz @ X-ing	43	m
Crossing Angle	4	mrad
Dispersion @ X-ing	0	cm
Free Space @ X-ing	± 20	m

Lattice		
Circumference, 4 3/4 C_{AGS}	3833.8	m
Tune, horiz & vert	22.6	
Transition energy, γ_{tr}	25.1	
Operating chromaticity	2.0	
Number of regular cells per sextant	9	
Cell length 2D + 2Q	39.5	m
Dispersion max in arc	2.3	m
Beta max horizontal in arc	67.8	m
Phase shift per cell	0.5	π
Magnet System		
Number of 2-in-1 dipoles, arcs	108	
Number of 2-in-1 dipoles, insertions	24	
Number of 1-in-1 dipoles	12	
Number of 2-in-1 Quadrupoles	186	
Bending field @ 50 GeV/amu	4.75	T
Aperture warm	8.0	cm
Field nonuniformity $\Delta B/B$ in dipole @ 3cm	2.0×10^{-4}	rms
Refrigeration System		
Maximum Operating Temperature	4.6	K
Temperature refrigerator output	2.6	K
Temperature heat shield, av.	55	K
Heat load, dipole vessel primary	8.0	W
Heat load, magnet system primary	2.2	kW
Heat load, lead system	3.9	kW
Heat load, total primary	6.2	kW
Refrigerator capacity, primary	24.8	kW
Injection System		
AGS energy	12	GeV/amu
Ions/AGS pulse	3×10^8	
AGS pulses stacked/ring	600	
Duration of each stacking cycle	2	min
Total filling time, minimum	4	hours
Momentum spread of stack, after dilution	0.16	%
Conventional Facilities		
Main tunnel width	5.0	m
Main tunnel height	3.4	m
Size, narrow angle hall	27.7 × 12.2 × 8.4	m^3
Size, wide angle hall	16.1 × 32.0 × 12.2	m^3
Size, major facility	50.9 × 17.4 × 14.3	m^3
Open area	57.3 × 29.3	m^2