HOW TO WORK WITH RHIC (REALLY HIGHLY INTERESTING COLLIDER)

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ABSTRACT

Some issues pertinent to the design of collider rings for relativistic heavy ions are presented. Experiments at such facilities are felt to offer the best chance for creating in the laboratory a new phase of subatomic matter, the quark-gluon plasma. It appears possible to design a machine with sufficient luminosity, even for the heaviest nuclei in nature, to allow a thorough exploration of the production conditions and decay characteristics of quark-gluon plasma. Specific features of the proposed Relativistic Heavy-Ion Collider (RHIC) at BNL are discussed with an eye toward implications for experiment.

I. INTRODUCTION

The driving force behind the present interest in development of heavy-ion colliders is the desire to produce and study in the laboratory a new phase of subatomic matter, the so-called quark-gluon plasma. Theoretical interest in this area has received a great boost from recent results of calculations in QCD using the lattice-gauge approximation to the theory. Those calculations have shown that quark confinement is a natural consequence of the low temperature behavior of QCD. In addition, at sufficiently high temperature and/or baryon density, the theory exhibits a deconfined phase, in which quarks and gluons are free to move about large volumes of space-time. The possibility to study the nature of matter as it existed just after the "Big Bang," but before the hadron confinement transition at ~10 μs, then presents itself, provided one can discover a means of producing the necessary conditions for deconfinement in a controlled manner.

Parallel calculations of the matter and energy densities to be expected in collisions between relativistic heavy nuclei indicate that conditions for

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quark-gluon plasma formation could be achieved. These conditions include not only attainment of sufficient local matter and energy densities to pass through the expected phase boundary, but also production of these conditions over sufficiently large volumes of space-time to avoid quenching of the nascent plasma and to allow its thermalization, subsequent decay, and (we hope!) detection.

The proposed study of quark-gluon plasma naturally divides into two extremes on a phase diagram for nuclear matter in temperature (T) vs. baryon density (ρ) space. One extreme is the study of cold, high baryon density plasma (or fluid), such as is likely to exist in the cores of neutron stars. This regime is characterized by $T \sim 0$ and $\rho/\rho_0 \sim 3$–10, where ρ_0 is the baryon density in normal nuclear matter. This is often referred to as the "stopping regime" and is characterized by center-of-mass γ values of 3–10, thus requiring colliders with kinetic energies of a few GeV/u in each beam. The second extreme is the study of hot, dilute plasma, such as was likely to exist about one microsecond after the "Big Bang." This regime is characterized by $T \sim 200$ MeV, $\rho/\rho_0 \sim 0$ and is referred to as the "central regime." To observe it clearly, one needs rapidity gaps somewhere in the range (we don't know for sure) of $\Delta y = 6$ to 12. The following table shows rapidity gap vs. c.m. kinetic energy. The size of the required gap is given by the need to isolate the central region kinematically from fragmentation region debris at or near the

Table I

Δy	$T_1 \times T_2$ (GeV/u)
4	2.6 x 2.6
6	8.5 x 8.5
8	24.5 x 24.5
10	68.2 x 68.2
12	187 x 187

$$y = 1/2 \, \ln \left\{ \frac{E + P_{\parallel}}{E - P_{\parallel}} \right\}$$

$$\Delta y = y_1 - y_2$$

two beam rapidities. From purely economic considerations, we hope the minimum required Δy is in the range 6-8! The gap for the CERN $Sp\bar{p}S$ collider is $\Delta y = 12.72$ ($\sqrt{s} = 540$ GeV), so larger gaps would require requesting time on machines such as Tevatron I or the SSC.

II. NOTATION, CHOICE OF IONS

Before proceeding, a few comments on notation and method of approach are made. Energies will always be quoted as kinetic energy per nucleon (e.g., as MeV/u or GeV/u), where 1 amu = 931.5 MeV/c^2 and a proton mass = 938.3 MeV/c^2. Colliders will always be quoted in terms of the kinetic energy per nucleon per beam, and center-of-mass energy will be given as $\sqrt{s}$/u. Accelerator design is pursued in terms of the heaviest nucleus to be considered, taken to be A = 200 amu here. This follows as initial electron removal, necessary vacuum, instabilities scaling as Z^2/A, and the needed magnetic rigidity all become worse for progressively heavier nuclei. The machine properties for lighter nuclei will follow "by inspection" at this point.

In designing an accelerator for heavy ions to study quark-gluon plasma, considerable flexibility must be built in. For an alternating gradient synchrotron, in addition to having nearly continuous variability in the location of the flattop in the magnet ramp, flexibility in the RF frequency and voltage program has to be provided in order to accommodate different ion species. This requirement of multiple ion capability derives from the following physics considerations. The energy density expected is a function of $\sqrt{s}$/u, meaning the machine must be able to operate in colliding mode at a large variety of energies. The energy density is expected to vary as $A^{1/3}$. Thus, because one would like to have for comparison some cases in which no plasma formation is expected, the machine must be able to handle a broad range of nuclei, say, from A = 10 to 200 amu. One can thus pick an initial set of ions, for which machine parameters and performance should be calculated, which are distributed in mass according to $n \propto A^{1/3}$, where n is an integer. A representative set is given in the table below.

In the case of RHIC, where a tandem electrostatic accelerator (a Van de Graaff® in this case) is to be used as injector, the ion source must produce negative ions for injection into the tandem. This is possible for many, but

Table II. Representative ions for initial collider operation

n	Ion
1	^{1}H
2	^{12}C
3	^{35}Cl
4	^{63}Cu
5	^{127}I
6	^{197}Au

not all, elements. In particular, it is quite difficult to form the needed metastable ions, which consist of a neutral atom plus one electron, for alkali and some alkaline metals, and nearly impossible to do so for the noble gases. As future running at RHIC may well need a broader range of ions than shown above, a table is given below of several ions which can be produced with high currents from a negative ion source. Recent work indicates that $^{238}_{92}U$ can probably be added to this list [$A^{1/3}$ (^{238}U) = 6.20].

Table III. Ions available from a high-current negative ion source

Ion	Z	$A^{1/3}$
H	1	1
C	6	2.29
O	8	2.52
S	16	3.17
Cl	17	3.27
Ni	28	3.87
Cu	29	3.98
Se	34	4.34
Br	35	4.33
Ag	47	4.78
I	53	5.03
Yb	70	5.58
Pt	78	5.79
Au	79	5.82

III. ELECTRON REMOVAL

A particular annoyance in accelerating heavy ions is their charge-to-mass ratio, which is as low as 92/238 = 1/2.59 for $^{238}_{92}U$. Thus, the same magnetic hardware as used for protons is less efficient by this ratio. For example, fully stripped ^{238}U in Tevatron II reaches only 386 GeV/u (while protons reach 1000 GeV), equivalent to a 12.5 x 12.5 GeV/u collider (i.e., $\gamma_{c.m.} = 14.4$ and $\Delta y = 6.72$). A linac, even with SLAC-type gradients (~10 GV/km) (which are unlikely due to the variable β structure needed), would require 26 km of linac to produce 100 GeV/u ^{238}U, plus a 1- to 2-km injector linac to produce fully ionized ^{238}U at 0.5-1.0 GeV/u. Therefore, an alternating gradient synchrotron seems to be the best machine choice, given present technology.

The initial problem in accelerating heavy ions, after producing a low-energy beam from an ion source, is getting rid of the electrons. Removal of the final, K-shell electrons becomes particularly tedious with increasing Z. For example, consider the kinetic energy per nucleon at which gold, $^{197}_{79}Au$, must traverse a thin foil to remove a given number of electrons.

Table IV

T/u (MeV/u)	q
0.11	17^+
2.0	40^+
35	70^+
100	78^+
500	79^+

For ^{238}U, 950 MeV/u is required to remove all 92 electrons with 90% probability. As each stripping is only 10%-15% efficient for very heavy ions, one must minimize the number of strippings. One is then faced with at least one major acceleration step with $q/u \lesssim 1/6$.

One is then led to consider a chain of accelerators (numbers are for A = 200 ions): (1) an ion source, producing 1 keV/u, q = 5^+ (for linac injection) or 1^- (for electrostatic generator injection) ions; (2) an injector, e.g., a linac or electrostatic generator, producing 2- to 10-MeV/u ions and followed by a stripping foil producing $q \sim 35^+–70^+$ ions; (3) a booster ring of 15–20 T•m producing 0.5- to 1.0-GeV/u ions which can then be fully stripped; (4) a pair of intersecting accelerator-collider rings of bending strength, B_f, somewhere between 50–1000 T•m, depending on desired peak final energy.

For the specific case of RHIC, the injector chain will be as follows. The numbers given are for gold, ^{197}Au.

Table V

Accelerator	Output Charge State	Output Kinetic Energy (MeV/u)	Feature
Ion source	1^-	0.0013	>100 μA instantaneous
Tandem	33^+	1.1	make $q > 0$; form low emittance beam
Booster ring	79^+	300	10^{-10} torr; produce $q/Z = Z/A$ ions
AGS	79^+	10,715	further acceleration (to $\gamma > 10$); reduce dynamic range required of collider superconducting magnets to feasible value
RHIC	79^+	$10^4–10^5$	find plasma; go to Stockholm

The injector layout is shown in Fig. 1

The first of the q^2/A effects affecting performance for heavy nuclei appears at injection into the booster ring. If one runs the collider in bunched beams mode (which is desirable for head-on collisions, shortest refill time and smallest magnet aperture), then the number of ions in one booster batch is the maximum number of ions in one collider bunch. (Injection into the collider using stripping to "beat" Liouville's theorem, as is done with

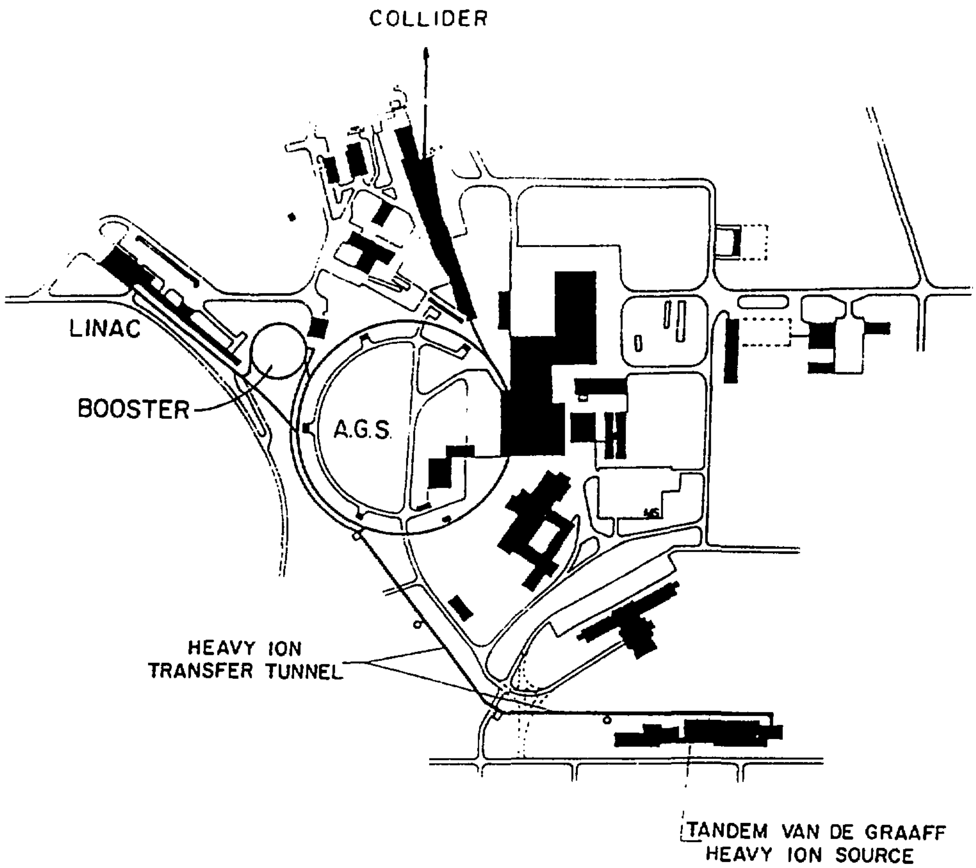

Fig. 1. Injection system for collider.

H^- injection into proton rings, does not work due to too much energy loss, emittance growth, and added momentum spread.) From the space-charge limit at injection,

$$N_B = \varepsilon(\beta^2\gamma^3) \frac{\pi}{2} \frac{B_f}{r_0} \frac{\Delta\nu}{F} A/q^2 \;;$$

for A = 200, q = 40 ions, one has a limit eight times lower than for the same kinetic energy protons. As the injector is ~40/200 = 1/5 as "efficient" per unit length as for protons, the $\beta^2\gamma^3$ factor will hurt even more. For example, for 1.1-MeV/u $^{197}_{79}Au^{33+}$ ions filling an acceptance of $\varepsilon = 50\ \pi$ mm•rad, N_B = 1.1×10^9 ions per booster batch.

The vacuum requirements during the stripping stages of acceleration are quite severe, arising due to the atomic-scale cross sections for electron capture and loss by low velocity ($\beta < 0.5$) partly ionized atoms. Any ion changing its charge state during acceleration will fall outside the (momentum • A/q) acceptance of the synchrotron and be lost. The cross sections vary roughly as

$$\sigma_{capture} \propto Z^0 q^3 \beta^{-6} \qquad \sigma_{loss} \propto Z^{2.5} q^{-4} \beta^{-2} ;$$

for example, for $^{208}_{82}Pb^{37+}$ at $\beta = 0.134$, $\sigma_{capture} = 6.5$ Mbarn/molecule of N_2, and $\sigma_{loss} = 20$ Mbarn/molecule of N_2. For a one-second booster cycle, this leads to a vacuum requirement of 10^{-10} to 10^{-11} torr at 20°C.

IV. COLLIDER PERFORMANCE

Once the beam is safely injected into the collider, the following questions can be addressed: What luminosity (L) can be achieved, and how does it vary with A and T/u? What are the transverse and longitudinal dimensions of the luminous region? Can the crossing angle be varied, and what is the resultant decrease in L? How does L decay with time, and how does this scale with L and N_B? What loss processes must be considered? What backgrounds are present (e.g., beam-gas)? Are there multiple interactions per bunch crossing? Most importantly, how often will one see a plasma event?

Turning the last question around, we can ask for the expected cross section for plasma production and use this, together with expected running times and number of events desired, to estimate the needed L. Plasma production is expected for "head-on" collisions, $b < 0.5$ fm, meaning for A = 200 + A = 200 collisions, where $b_{max} = 2\, r_A = 2 \times 1.25 \times A^{1/3}$ fm = 14.6 fm, 10^{-3} of the cross section is "head-on," or 7 mb. Asking for 1000 events in 1 day = 8.64×10^4 seconds leads to $L_{min} = 1.8 \times 10^{24}/BR$ cm^{-2} s^{-1}. For a branching ratio BR = 5%, one needs $L_{min} > 3.6\ 10^{25}$ cm^{-2} s^{-1}, not surprising in view of the large cross section available.

One can then estimate L for bunched beam collisions,

$$L = \frac{N_1\ N_2\ B\ f_{rev}}{4\pi\ \sigma_V^*\ \sigma_H^*\ f} ,$$

where N_1 are N_2 are the number of particles per bunch in the two beams, B is the number of bunches per beam, f_{rev} is the revolution frequency, $\sigma_{H,V}^* = \sqrt{\frac{\varepsilon_N \beta_{H,V}^*}{\beta\gamma\, 6\pi}}$ are the horizontal, vertical rms beam sizes, ε_N is the normalized emittance, and $\beta_{H,V}^*$ are the lattice β functions at the intersection point. The factor $f = (1 + p^2)^{1/2}$, where $p = \frac{\alpha\sigma_\ell}{2\sigma_H^*}$, α = crossing angle, and σ_ℓ = rms bunch length. We immediately see that L is proportional to γ for head-on collisions. Consider, then, the following values which are representative of RHIC: $(B \cdot f_{rev}) = 1/224$ ns, $\beta_{H,V}^* = 3$ m, $\varepsilon_N = 10\ \pi$ mm•mrad, E = 100 GeV/u, head-on collisions and $N_1 = N_2 = 1.1 \times 10^9$ particles/bunch, our earlier value for ^{197}Au. This yields

$$L_{initial} = 9.3 \times 10^{26}\ \text{cm}^{-2}\ \text{s}^{-1} ,$$

well in excess of our "bottom-line" acceptable value from above. Even at 10 GeV/u, one expects only an order of magnitude less luminosity, still above our minimum requirement.

In RHIC, it turns out that the luminosity as a function of ion species is largely determined by the injection space-charge limit in the booster ring. However, this limit happens to "dovetail" rather well with the restrictions, on the number of ions per bunch in the collider, which arise due to intrabeam scattering. Table VI gives initial luminosities at top

Table VI. Initial collider luminosity at top energy

	N_B	E/A (GeV/amu)	Luminosity (cm^{-2} sec^{-1}) Crossing Angle (mrad) 0.0	2.0	
	x 10^9				
Proton	100	250.7	1.2	0.28	x 10^{31}
Deuterium	100	124.9	11.9	2.8	10^{30}
Carbon	22	124.9	5.8	1.4	10^{29}
Sulfur	6.4	124.9	4.9	1.2	10^{28}
Copper	4.5	114.9	22.6	5.7	10^{27}
Iodine	2.6	104.1	6.7	1.7	10^{27}
Gold	1.1	100	1.2	0.30	10^{27}

energy for the reference set of beams for RHIC. Note the "penalty" of about a factor of four in luminosity associated with operating at a nonzero crossing angle of 2 mrad. However, the reduction in size of the luminous region may well be worth the inconvenience of lower L.

V. LOSS OF LUMINOSITY

A number of loss processes contribute to the decrease in L with time. Many of these are either much smaller problems or do not exist for $p\bar{p}$, pp, or e^+e^- colliders. Several of these processes arise from nuclear fragmentation or electron capture sources: (1) The simplest is electron capture from residual gas, leading to vacuum requirements of 10^{-9} torr at 20°C. (2) Beam gas background limits the acceptable pressure to a few percent of this. (3) The geometric cross section for nuclear reactions is 6.6 barns for A = 200 + A = 200 collisions, much larger than the 45 mb encountered for pp. (4) The relativistically contracted electric field of one nucleus appears as a several MeV virtual photon field to a nucleus in the other beam, giving rise to reactions of the form $\gamma + A \rightarrow n + (A - 1)$ via the giant dipole resonance, where σ scales as $\gamma_{c.m.}$ and reaches 70 barns for U + U at $\gamma_{c.m.} = 100$. (5) e^+e^- pair creation in the K shell, with subsequent e^+ ejection and e^- capture, causes beam loss due to the change in magnetic rigidity. This cross section increases with γ and as a large power of Z (Z^7?), reaching perhaps 100 barns for U + U at $\gamma_{c.m.} = 100$.

Making a crude estimate of beam lifetime, if we have $L = 10^{27}$ cm^{-2} s^{-1}, $\sigma_{loss,total} = 200$ b, and 50 bunches of 10^9 ions/bunch, then $R = L\sigma = 2 \times 10^5$/second will be lost and $T = \dfrac{10^9/\text{bunch} \cdot 50 \text{ bunches}}{R} = 70$ hours. Obviously, $L = 10^{29}$ cm^{-2} sec^{-1} causes lifetimes of less than 1 hour, which is not acceptable.

For the case of RHIC, the reaction rate dominates the beam lifetime for ions with A < 100 amu. For A > 100 amu, it is found that Coulomb dissociation and bremsstrahlung electron pair production dominate the beam half-lives. The following table gives initial reaction rates $\lambda = \frac{-1}{I}\frac{dI}{dt}$, I the beam intensity, for the set of reference beams for RHIC. Note that these are beam loss rates, meaning the luminosity half-life is half the beam half-life shown in the right-hand column. Also note that the Coulomb dissociation and bremsstrahlung pair production are larger than the nucleus-nucleus reaction rate for ^{127}I and ^{197}Au. In fact, for ^{197}Au even the beam-gas nuclear reaction rate exceeds the beam-beam nuclear reaction rate.

Table VII. Initial reaction rate $\lambda = \frac{-1}{I}\frac{dI}{dt}$ and total half-life of ion beams

	Beam-Gas Nuclear Reaction λ_1	Beam-Beam Nuclear Reaction λ_2		Beam-Beam Coulomb Dissociation λ_3	Beam-Beam Bremsstrahlung Electron Pair Production λ_4	Half-Life
Beam	p = 10^{-10} torr	A on A	p on A	A on A	A on A	A on A
	10^{-3}/h	10^{-3}/h	10^{-3}/h	10^{-3}/h	10^{-3}/h	h
p	0.15	0.46	0.46	--	--	1100
d	0.19	6.0	2.2	--	--	110
C	0.36	2.5	3.8	--	--	240
S	0.55	1.4	7.0	--	--	360
Cu	0.76	1.3	10.7	0.17	0.04	305
I	1.08	1.2	16.8	4.3	1.5	86
Au	1.37	0.69	21.5	5.2	10.3	40

For very heavy beams ($A > 100$), the dominant mechanism causing loss of luminosity is intrabeam scattering (IBS). This, in effect, limits the useful number of ions per bunch and the minimum useful beam emittances. The effect arises because particles in one beam Coulomb scatter off one another; i.e., the effect corresponds to multiple Coulomb scattering within a beam bunch. As Coulomb scattering reorients the relative momentum in the center of mass, IBS has the effect of coupling the mean betatron oscillation energies and the longitudinal momentum spread. This means the invariant emittances in all three dimensions will change as the beam seeks to obtain a spherical shape in its own rest frame momentum space. The effect is known to be the major performance limitation for the $Sp\bar{p}S$ collider at CERN.

The rate is given by

$$\frac{1}{\tau} = \frac{\pi^2}{\gamma} c r_0^2 \frac{Z^4}{A^2} \frac{N}{\Gamma} \ln \frac{b_{max}}{b_{min}} H(\lambda_1, \lambda_2, \lambda_3) ,$$

where r_0 is the classical proton radius, Z and A are the ion charge and mass, N/Γ is the particle density in six-dimensional phase space, $\ln(b_{max}/b_{min})$ is the usual Coulomb log, and H is a complicated integral over phase space and machine properties; the last is zero for a spherical distribution in phase space.

The results of parametric studies for ${}^{197}_{79}Au^{79+}$ ions by A. Ruggiero of ANL and G. Parzen of BNL give the following dependences: For $\gamma_{c.m.} = 100$, $\varepsilon_N = 10\ \pi$ mm•mrad, and $I_{peak} = 1$ ampere (electric), the longitudinal growth rate scales as

$$\tau_E^{-1} \propto (\sigma_E/E)^{-3} ,$$

and the horizontal transverse growth rate scales as

$$\tau_H^{-1} \propto (\sigma_E/E)^{-1} .$$

For an energy spread $\sigma_E/E = 10^{-3}$, these scale with normalized emittance as $\tau_E^{-1} \propto \varepsilon_N^{-1}$ and $\tau_H^{-1} \propto \varepsilon_N^{-2}$. Desiring growth rates of less than (2 hours)$^{-1}$ for luminosity leads to the choices $\varepsilon_N = 10\ \pi$ mm•mrad and $\sigma_E/E = 0.5 \times 10^{-3}$. The luminosity decreases with time due to the emittance increase; the rate of decrease itself decreases with time, but only after the initial damage is done. The emittance growth also leads to an increase in magnet aperture required, thus influencing magnet cost as well as luminosity performance.

The time-averaged luminosity at RHIC is calculated to vary as shown in Fig. 2 for $^{197}Au + {}^{197}Au$ collisions as a function of beam energy. The limits are principally imposed by intrabeam scattering. For the 2 mrad crossing angle case, the growth in $\langle L \rangle$ with beam energy is limited above transition ($\gamma_{tr} = 26.4$) due to beam bunch-length blow up. In examining this figure, it is worth remembering that for $\sigma_{central} = 10^{-3}\ \sigma_{reaction}$, $\langle L \rangle > 1.6\ 10^{26}$ $cm^{-2}\ s^{-1}$ yields one central event per second for $^{197}Au + {}^{197}Au$.

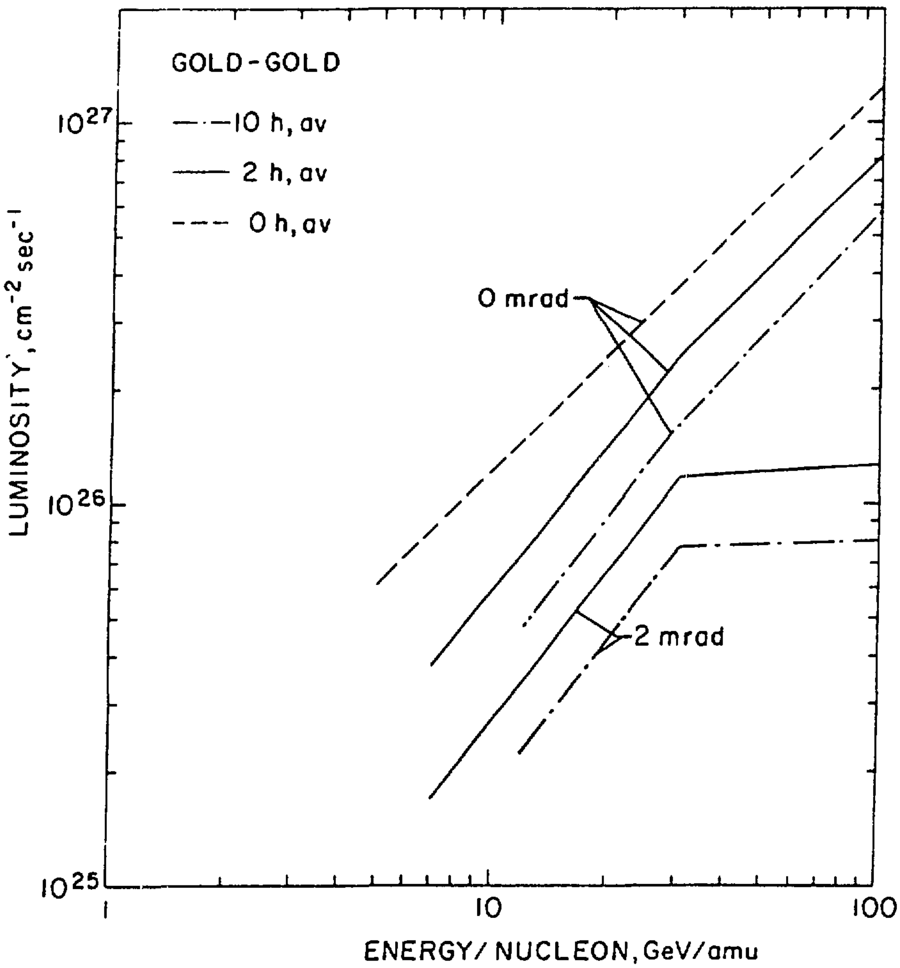

Fig. 2. Dependence of average luminosity on energy for the case of Au + Au.

VI. MACHINE-EXPERIMENT INTERFACE

One of the most severe consequences of intrabeam scattering is longitudinal beam blow up. That is, in a bunched beam machine, the bunch length increases steadily with time. This is a well-known effect at the Sp$\bar{p}$S collider. For the case of Au + Au, it can be seen in Fig. 3 that the rms length of the bunch exceeds 1 meter after 2 hours for energies greater than 50 x 50 GeV/u. Even at injection, the bunches have rms length of about 0.5 meter. The full length of the luminous region is then up to $\sqrt{6}$ times this, depending on the vertex cuts made, for head-on collisions. For example, for RHIC at 100 GeV/A, σ_{bunch} = 48 cm at 0 hr at 147 cm at 10 hr. As $\sigma_{IR} = \sigma_{bunch}/2$,

σ_{IR} = 24 cm (0.8 ns) at 0 hr and 74 cm (2.5 ns) at 10 hr. A 95% contour at 10 hr is then 3.6 m (12.0 ns) long, requiring that one make vertex cuts for y (or η) determination.

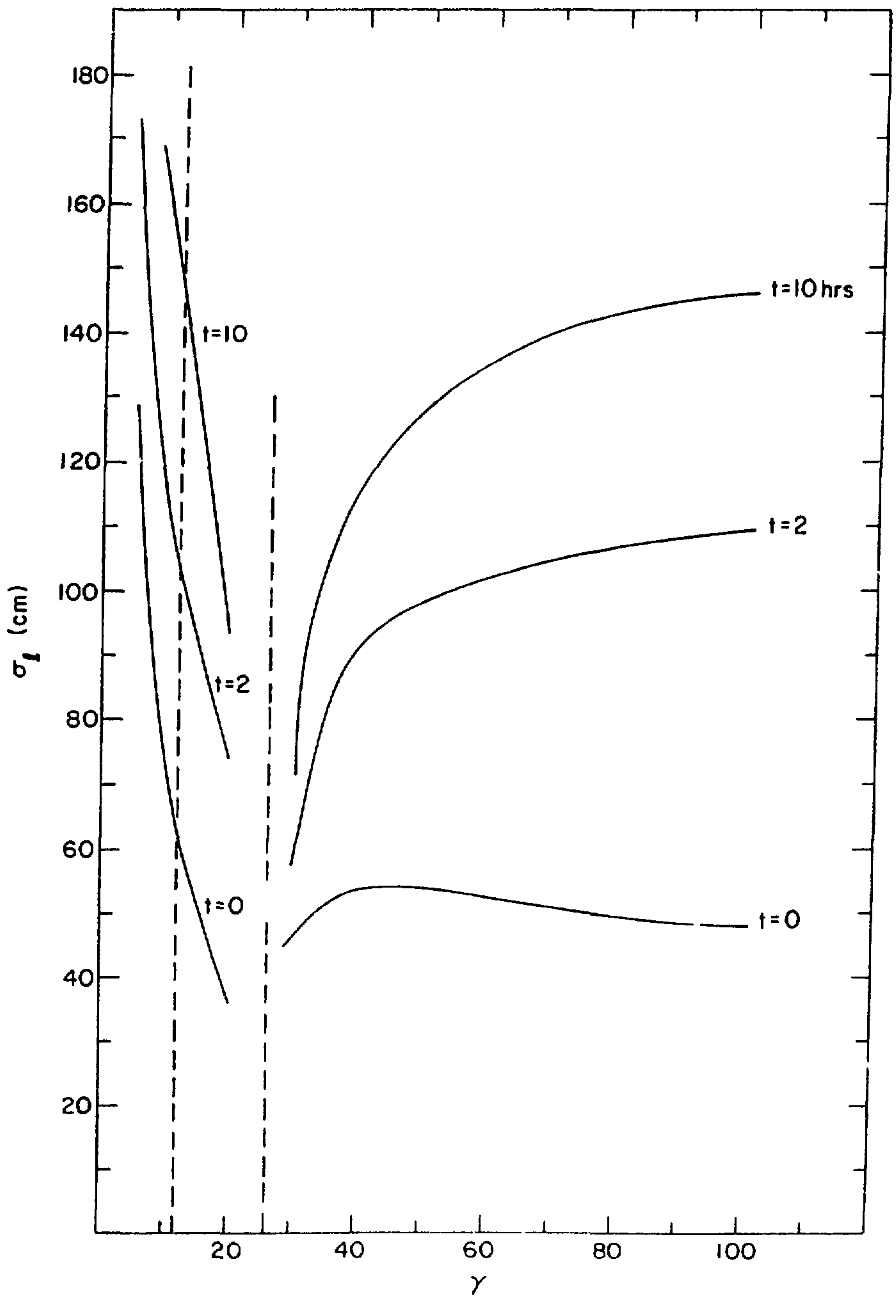

Fig. 3. Au bunch length growth due to intrabeam scattering.

An experimenter then must either decide to run at a nonzero crossing angle, or to invest in detector hardware designed to locate the event vertex, or (preferably) both. (See the writeup on the dimuon experiment for interaction region sizes for the case of 100 x 100 GeV/u Au + Au at 0, 2, 5, and 11 mrad crossing angle.)

The beam half-width is also expected to grow with time due to intrabeam scattering. Figure 4 shows the case for ^{197}Au at three energies as a function of time in the arcs of the machine. The expected transverse beam size at the collision point will be a factor of 5 to 7 times less than shown in the figure, depending on the choice of low β* insertion used for a particular experiment.

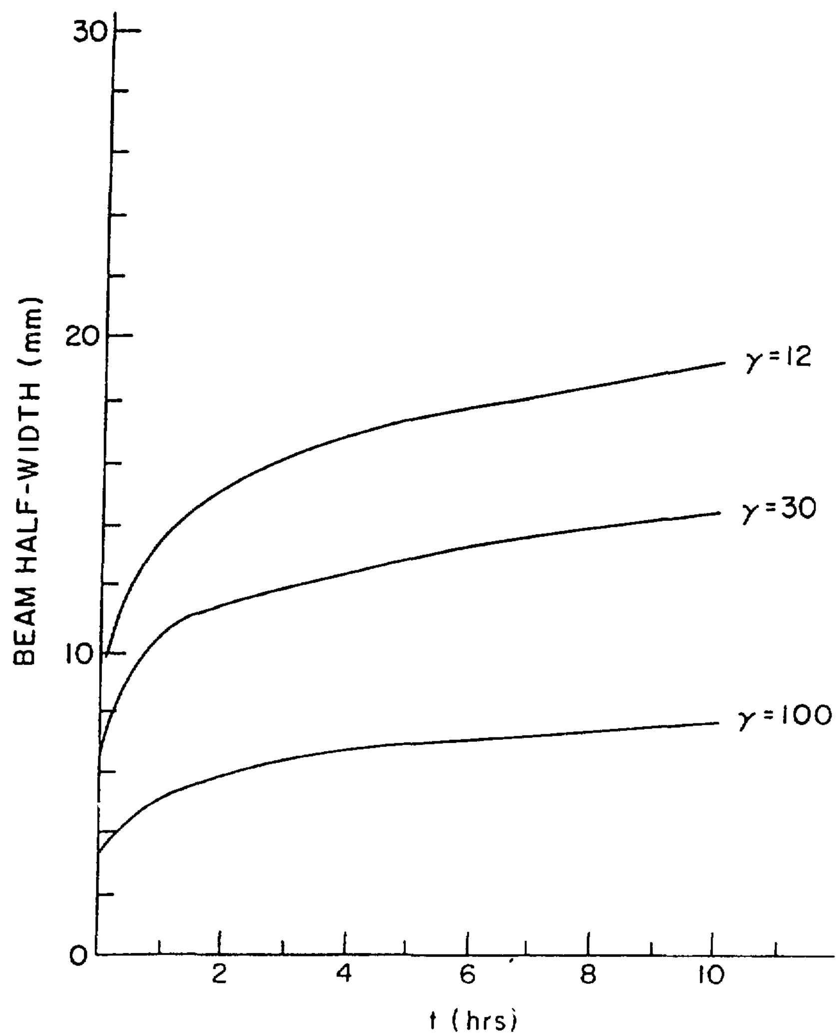

Fig. 4. Au beam half-width in the arcs versus time.

In a bunched-beam collider, one must worry about multiple interactions per bunch collision, especially in a heavy-ion collider where multiplicites can exceed 1000 per event. For RHIC, we have a circumference of 3833.8 m and 57 bunches, giving t_{rev} = 12.788 μsec and $t_{crossing} = t_{rev}/57$ = 224.4 ns. Then for the case of Au + Au at 100 x 100 GeV/u, using $L_0 = 1.2 \times 10^{27}$ cm^{-2} s^{-1} and σ_R = 6.65 barns, we get $\langle N \rangle = 8.0 \times 10^3$ s^{-1} = 1/559 crossings. This is acceptable. However, for C + C at 100 x 100 GeV/u, $L_0 = 5.8 \times 10^{29}$ cm^{-2} s^{-1} and σ_R = 1.03 barns, yielding $\langle N \rangle = 5.0 \times 10^5$ s^{-1}, or 1/7.5 crossings. Thus, for light beams there is a significant probability of two or more interactions per crossing, meaning one has to consider either running at lower luminosity or preparing for multiple vertices. This problem is alleviated a little by the lower multiplicities expected for the lighter ions, but they will still be much greater than $p\bar{p}$ values.

Another parameter available for varying luminosity is the tightness of the beam focus at the crossing point. This is usually expressed in terms of the lattice focussing, or β, function at that point, with smaller values of β* (the value of β at crossing) leading to larger luminosity. For head-on collisions $L \propto (\beta_x^* \beta_y^*)^{-1/2}$.

The β function varies as the distance, s, away from the crossing point as $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$. One should ask how small β* should be, as very small β* in a machine with a long bunch length, corresponds to too short a depth of focus at crossing and a loss of luminosity. What matters for counting rates is L averaged over the luminous region, so we average β(s) over half a bunch length, ℓ. We find

$$\bar{\beta} = \frac{1}{\ell} \int_0^\ell \beta(s) ds = \beta^* + \frac{\ell^2}{3\beta^*} ,$$

which has a minimum (hence, largest L) found from

$$\frac{d\bar{\beta}}{d\beta^*} = 1 - \frac{\ell^2}{3\beta^{*2}} = 0,$$

or

$$\beta^*_{optimum} = \ell/\sqrt{3} .$$

Thus, since for gaussian beams, $\ell = \sqrt{6}\,\sigma_\ell$, $\beta^*_{optimum} = \sqrt{2}\,\sigma_\ell$. In RHIC, for Au + Au at 100 x 100 GeV/u after two hours, one has β^*_{opt} = 1.4 meters.

For looking at very small scattering angles, one typically uses "Roman pots" at several meters from the interaction point. One then is interested in reaching as small a scattering angle as possible, possibly as small as $\theta_{scatter}$ = 1 mrad, especially at 100 GeV/u. Then one needs two relations, the first being

$$X_1 = \sqrt{\beta^*\beta_1}\,(\sin\Delta\mu)\,\theta_{scatter}\ ,$$

where X_1 is the tranverse distance of the particle of interest from the beam centroid, β^* and β_1 are the lattice functions at the crossing and detector positions, and $\Delta\mu$ is the betatron phase advance between those two positions. One tries to arrange for $\Delta\mu$ to be an odd multiple of $\pi/2$. Then one needs the relation

$$X_1 > m\ \sigma_T = \frac{m}{\sqrt{6}}\sqrt{\frac{\varepsilon_N\beta_1}{\gamma}}\ ,$$

the transverse "beam stay clear" aperture required by the machine designers, inside of which experimentalists may not place hardware. Set $m \approx 10$. Then one needs

$$\theta_{scatter} > \frac{m\sqrt{\varepsilon_N/\gamma}}{\sqrt{6\beta^*}}\ .$$

As ε_N, the normalized emittance, m, and γ (Lorentz factor) are fixed for a given operating energy, only β^* is variable. To reach small $\theta_{scatter}$, one needs large β^*, giving a luminosity penalty! The following table gives values for RHIC (1984 proposal) to reach θ = 1 mrad for 100 x 100 GeV/u, $^{197}Au + {}^{197}Au$.

Table VIII. High β^* insertions for small-angle scattering

γ	t (hours after fill)	β^* (m)	<L> ($cm^{-2}\ s^{-1}$)	(For σ = 100 mbarn) Rate (Hz)
30	2	11.7	5.7 10^{24}	0.57
30	10	18.9	3.6 10^{24}	0.36
100	2	30.0	1.9 10^{25}	1.9
100	10	46.7	1.4 10^{25}	1.4

In designing an experiment at a collider, one often wants to provide for hermetic coverage of the interaction point. This can be a pressing matter at a heavy-ion collider if one wants information on the projectile fragmentation cones. At some point, however, one runs into magnets associated with the machine lattice and can extend the detector no more. It is useful then to ask how far from the crossing point one would like to have those quads. For the accelerator physicist, this distance L is preferably kept small, because as noted above, the lattice β function grows quadratically with L as $\beta(L) = \beta^* + L^2/\beta^*$, meaning larger L requires a larger quadrupole magnet bore. This is a major concern for superconducting magnets.

The experimental physicist who wants to measure quantities as a function of rapidity y would likely want to use a detector segmented with average segment size ΔR. The smallest angle which can be seen is $\theta_{small} \sim R/L_{IR}$, R being the detector inner radius about the beam pipe and L_{IR} being the free space in the interaction region. Using pseudorapidity, we have $y = -\ell n \tan\theta/2$, or $R/L = 2e^{-y}$. Taking derivatives, which in detector inner radius would yield the detector size, we get

$$\frac{\Delta R}{L} = -2e^{y_c} \Delta y \ ,$$

where yc is the rapidity corresponding to the cut-off angle. Thus, we write $L_{IR} \approx \frac{\Delta R}{2\Delta y} e^{y_c}$, meaning experimentalists wanting to see high rapidities at the cutoff are exponentially greedy. If one sets ΔR = 5 mm, Δy = 0.1, and $y_c = 5.5$ (appropriate to 100 x 100 GeV/u), one has $L_{IR(RHIC)} > 6.1$ m. Ten meters are provided in the standard RHIC lattice.

RHIC will require quite some time to refill with fresh stored beam, as shown in Table IX. Most of the time is needed to test how well the ring resets after an extended run at a given energy. In particular, one has to worry about magnet hysteresis in kickers, steerers, and the superconducting dipoles and quadrupoles. For low-energy runs, little magnet drift is expected and set-up times can be correspondingly shorter. The RF system must be cycled; the steering in each interaction region checked; beam scrapers adjusted; and luminosity measured. One expects little impact of this setup on AGS operations, only an occasional pulse being needed while

RHIC parameters are adjusted and checked. One envisions a set of supercycles as used at the CERN PS to accomplish automated switching of the AGS, its booster, and the relevant injector (linac or tandem).

Table IX. Set-Up Times in Hours

	Switch-On	Refill		
		30–100 GeV/amu	12–30 GeV/amu	5–12 GeV/amu
Cycling of magnets	0.5	0	0	0
Injection adjust.	1.5	1	0.5	0
Stacking and acc.	0.25	0.25	0.25	0.25
Beam optimization	1	1	0.5	0.25
Beam cleaning	n/a	0.25	0.25	0
Total	3.25	2.5	1.5	0.5

Lastly, a few other issues deserve mention.

(1) Detectors using magnets need to consult with the accelerator persons about compensating the effects of their magnetic field, be they solenoid, torodial, or (especially) dipolar in shape. There are always focussing effects due to fringe fields, even if there is no beam deflection.

(2) Detector preamps have to be shielded from the beam's electric field. One should not use a nonmetallic pipe (e.g., to provide a small number of radiation lengths) without some sort of metallic coating.

(3) The beam has to be scraped periodically. A particle which is scattered at the interaction point one time but stays in the ring may come around the ring and hit a detector later.

(4) Beam-gas interactions promise to be a challenge. Given the length of the straight sections (~200 m), one has to at least shield against the secondaries, even if one has good vertex identification.

VI. SUMMARY REMARKS

It appears RHIC will provide a goodly supply of head on, $b < 0.5$ fm, events for all ion species. For light ions, say $A < 50$, there will be plenty of luminosity, and the effects of intrabeam scattering will not be of much consequence. The rate limiting step in that case will likely be injector performance, experimental data-rate capabilities, or the need to suppress multiple events per bunch crossing. Some modest work on kicker development can alleviate the last problem by loading more bunches around the rings.

For heavy beams, $A > 100$, intrabeam scattering and a number of large reaction rates will lead to luminosity decay times on the order of a few hours. Some taxing of apparatus will occur arising from the need to localize event vertices in a machine with very long bunches. The beam transverse emittances will always be such that crossing regions with transverse dimensions on the order of 1 mm can be had, however.

The machine has no problem operating with nonzero crossing angle or unequal ion species. For the latter, equal kinetic energies per nucleon have to be used in order to avoid having the bunch crossing point precess around the circumference due to differing speeds of the two ions. Operating near the transition energy (~26 GeV/u) is not possible due to the inability to provide sufficient RF voltage to contain the beam momentum spread, but this should not prove a major gap in the study of plasma events. Operation with one beam in RHIC and a fixed internal target will bridge the gap between AGS experiments and RHIC collider experiments. The target can be either a gas jet or a very fine metal wire or submillimeter diameter pellet. The last option can provide superb vertex localization (<100 μ).

RHIC poses interesting new problems for accelerator builder and experiment builder alike. A glimpse back into the state of the universe before hadrons coalesced should be well worth the effort.