REVIEW OF HEAVY ION COLLIDER PROPOSALS

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In this paper we review proposals for heavy-ion colliders generated during the last few years for several national laboratories. The proposals span over a large range of energy and luminosity to accommodate the experimental needs of both the nuclear and the high-energy physicists. We report also briefly efforts in the same field happening in Europe.

Introduction

The driving force behind the presently renewed 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. This is a subject of common interest to the nuclear and the high-energy physicist. To provoke the phase space transition one requires a minimum energy density of about 2 GeV/fm^3 as it can be obtained by smashing against each other, in head-on collision, two heavy nuclei of atomic mass A with a center of mass energy per nucleon as shown in Fig. 1. Of course the critical energy density itself is a subject of study, and versatility should be allowed into the collider design to explore a wider range of it. This explains the variety of colliders (and fixed target experiments) that have been proposed in this country and Europe over the recent few years, which cover quite a substantial range of energy and luminosity.

We will review in this paper mostly proposals of heavy-ion colliders in this country. Three laboratories have in several occasions shown interest and commitment to a program of heavy ion physics: Lawrence Berkeley Laboratory (LBL), Oak Ridge National Laboratory (ORNL) and Brookhaven National Laboratory (BNL).

The LBL Program

The LBL program for heavy ions research is centered around the source that still has the largest energy in the world: the Bevalac, which is the combination of SuperHilac and the Bevatron. SuperHilac is a linear accelerator for heavy ions made of several stages. If we take Uranium as an example, ions with a charge state of +5 are injected at 112 KeV/amu, accelerated to 1.2 MeV/amu when they are stripped to +13 charge state, to be accelerated again to a top energy of 8.5 MeV/amu. At this energy the ions can be stripped further, for instance to a charge state of + 40. The ion beam is transported and injected into Bevalac, the 6 GeV proton synchrotron, where it is accelerated to the maximum energy, which for uranium +40 is about 1 GeV/amu with a pulse every few seconds.

In order to design a heavy ion collider it is important to assess the performance of the injector, that is dimensions and intensity per pulse for each of the species desired. One needs the estimates of stripping efficiency as well as cross-section for electron capture and electron loss for the partially stripped ions and to infer their relevance in view of vacuum problems in both the injector and the collider rings. In this sense the operation of Bevalac has been extremely useful not only for the collider projects at LBL but also for those in other laboratories. For instance an important experiment has been the determination of the stripping efficiency versus energy for different final charge state. The results for Uranium clearly indicate that it is possible to produce completely stripped ions also at energies as low as 430 MeV/nucleon. Similar experiments have been done also for Gold in a collaboration between LBL and BNL.

The first collider project at LBL ever proposed with a considerable amount of details is VENUS. This was a combination of two rings to accelerate heavy ions up to and including Uranium, fully stripped, for either fixed target experiments in the energy range from 40 MeV/A to 20 GeV/A or in colliding mode from 2 on 2 to 20 on 20 GeV/A.

The proposed scheme, shown in Fig. 2, can be realized with two identical superconducting rings, located inside a single tunnel, with the SuperHilac as injector. One ring would serve as SuperHilac booster to accelerate the 8.5 MeV/A injected ions to about 1 GeV/A. At this energy they can be stripped without loss and transferred to the second ring for acceleration to a maximum of 20 GeV/A for the heaviest ions. Both rings consist of the same configuration of superconducting magnets (4 Tesla), capable of acceleration to the same energy.

The colliding beam mode requires accumulating of a large number ($\gtrsim$ 100) of pulses to achieve the necessary circulating high current. It also require provision for reversing the direction of rotation in one of the two rings. Particles are accelerated in one ring to full field, then ejected, stripped and stacked in momentum phase space in the other ring. After completing the stacking operation, the field in the first ring is reversed. The beam in the second ring is then bunched on a low even harmonic, creating an even number of circulating bunches. With the aid of fast kicker magnets, half the bunches are then ejected, transported through an S-shaped reinjection loop, and reinjected in the opposite direction of the first ring. The specified final energy from 2 to 20 GeV/A is then reached by slow acceleration or deceleration in each ring. Finally, debunching produces the desired configuration of counter-rotating, coasting, colliding beams.

The detail design of interaction regions was not completely carried out because of some uncertainty on possible conflicts between the collider and the user requirements. But unbunched beams with crossing at small angle (few milliradians) were primarily considered. The luminosity is around 10^{29} cm^{-2} s^{-1} for a current of 200 pmA for the heaviest ions and somewhat larger for the lighter ones. Observe that the luminosity figures quoted are larger by at least two orders of magnitude than what a colliding beam detector can absorb with the present technology. These figures are now believed unrealistic since for the estimate of the beam dimensions the very small emittances at the source were assumed. When intrabeam scattering effects are taken into account one would expect a considerable enlargement of the beam dimensions and a corresponding reduction of the luminosity.

The VENUS project is certainly a very expensive one; well above the 100 M$ in 1979 estimates. Because of the economical and technical uncertainties, recently a more modest heavy-ion collider has been studied and proposed, the MiniCollider, for a maximum energy of 4 GeV/nucleon. This time the ions are accelerated first in the Bevalac up to about 400 MeV/A, where they can be fully stripped. More than a thousand of Bevalac pulses are injected in two 200 meter circumference, concentric storage rings. Because of the low

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energy it has been found that intrabeam scattering, the phenomenon by which charged particles in the same beam transfer momentum to each other by Coulomb interaction causing an increase of the beam dimensions, is quite severe even for the debunched beam case. To counteract this effect stochastic cooling is necessary at a rate which equals at least the diffusion rate. Table 1 gives a brief summary of the luminosity at 1 GeV/A which is also expected to increase about linearly with the beam energy. Probably this was the first time that the effects of intrabeam scattering were carefully estimated and found to be so limiting to the collider performance.

Table 1 LBL MiniCollider Performance

Particle	Max. KE (GeV/N) (C. M. Frame)	Luminosity $\mathcal{L}$ ($cm^{-2} sec^{-1}$) at 1 GeV/N
uranium	3-4	3×10^{23}
gold	3-4	4×10^{23}
neon	4-5.3	2×10^{25}
proton	9-12	4×10^{26}

The design of the MiniCollider is far from being completed. For instance lattice and interaction region details are still lacking. What we have so far is an existence prove of a conceptual arrangement. But because of the renewed interest expressed at the last NSAC meeting for a low-energy collider, it is expected that the LBL staff will look at the matter again with a more concentrated effort.

The ORNL Program

Oak Ridge National Laboratory owns one of the largest Tandem van de Graaff (HHIRF) in the country. The high voltage terminal is capable of 25 MV and two stripping stages are included to generate heavy ion beams all the way up to uranium. The Tandem at the present is also used as an injector to an AVF isochronous type cyclotron (ORIC). Most of the present effort at ORNL is concentrated in designing a pair of synchrotron rings for nuclear physics research in the 20-600 MeV/amu range. Both rings have bending strengths of 8 Tesla-meters. The first ring is injected from the existing 25 MV tandem electrostatic accelerator and has a single gradient magnet lattice of 8 cells (type FODOODOF) operating at 20 Hz. The second ring is injected by fast transfer from the first and act as stretcher ring and storage ring. Beams in the second ring can be resonantly extracted to existing target halls, or can be electron-beam cooled and than extracted or used for internal target experiments. Both rings have ultrahigh vacuum (10^{-11} torr at 20° C) to store partially stripped heavy ions for several hundred seconds or longer.

During the years 1982 and 1983 Oak Ridge developed a design and a proposal for a heavy-ion collider for energies up to 30 GeV/amu. This proposal was soon abandoned because of the large size and cost involved. Moreover the design ignored the effects of intrabeam scattering, and unrealistic figures for the performance were then produced. Because of cost, size and technical issues this project was replaced by a collider design with a more modest performance up to 10×10 (GeV/nucleon)^2. The layout is shown in Fig. 3. Ion beams are produced by the tandem and accelerated in a Booster with a circumference of 138m up to an energy of 488.7 MeV/nucleon. Beam bunches are then transferred to two concentric colliding rings with a circumference 6 times larger than the Booster. Beam properties are given in Table 2. The nuclear species proposed for colliding experiments are shown in these tables; they have also been adopted for similar considerations in the BNL projects (see later). These are adequate to cover most of the experimental program since their atomic mass varies as the cubic power of an integer.

Table 2 Beam Parameters for the ORNL Booster

Ion	Kinetic energy at tandem exit (MeV/u)	Charge state at tandem exit	Current at tandem exit (particle μA)	Number injected 10 turns ($\times 10^9$)	Space charge limit ($\times 10^9$)
^{12}C	11.0	6^+	75	14.75	42.9
^{32}S	7.56	15^+	22.5	5.32	12.7
^{32}Cu	4.89	24^+	9.0	2.64	6.32
^{127}I	2.77	35^+	5.4	2.11	3.38
^{197}Au	2.01	44^+	4.05	1.90	2.27

The Collider performance is given in Table 3. The luminosity is the peak (initial value) for head-on collision assuming $\beta^* = 3$ m. A detailed lattice study with insertions for the collider rings is still outstanding like the study of several other performance issues. But the project, that has named ORHIC, after a preliminary investigation during 1984 was put to rest waiting for better trading opportunities and other initiatives that ORNL may consider for the near future.

Table 3 Performance of ORHIC Collider

Ion	ϵ_N π mm mrad	Ions/Bunch	T/A_{max} (GeV/u)	L_0 (head-on) $\beta^* = 3m$ ($cm^{-2} sec^{-1}$)
^{12}C	10	$1.1\ 10^{13}$	12.7	$3.6\ 10^{28}$
^{32}S	10	$4.0\ 10^{9}$	12.7	$4.6\ 10^{27}$
^{63}Cu	10	$2.0\ 10^{9}$	11.6	$1.1\ 10^{27}$
^{127}I	10	$1.6\ 10^{9}$	10.4	$5.0\ 10^{26}$
^{197}Au	10	$1.2\ 10^{9}$	10.0	$3.3\ 10^{26}$

The BNL Program

Brookhaven National Laboratory is the most committed to a heavy-ion research program than any other laboratory in the country. The program proposed is ambitious and spans over a considerable large energy range, from a few GeV to well over 100 GeV per nucleon. This is possible thanks to three major facts. First, the lab owns a reliable ion source with two Tandems each with terminals capable of 15 MV. Second, there is a very large tunnel of about a kilometer diameter which, planned originally for the CBA project, is now available for some other less expensive and yet more appealing enterprise. Finally, the magnet facility that was created for the superconducting project can be easily adopted to design and to provide magnets for the collider quickly and reliably. Furthermore one should not forget the existence of a 28 GeV proton synchrotron (AGS) that can be used to accelerate heavy ions either for low energy fixed target experiments or as an injector to the large collider.

BNL has been developing several schemes for heavy-ion colliding beams for quite some time, also during and in conjunction to the CBA project. Here we shall review the more recent scheme. The program is divided in three steps.

(i) Tandem-AGS project, which has been authorized and presently under construction. Heavy-ion beams, produced by the Tandem are transferred and injected into the AGS. This project requires a kilometer long transfer line, an injection system, and improvements of the AGS vacuum and rf systems. In this mode of operation it is possible to accelerate fully stripped light ions up to 15 GeV/nucleon. The project is scheduled to become operational sometime next year.

(ii) It has been proposed to add a Booster ring with B = 16.5 Tm between the Tandem and the AGS, as shown in Fig. 4. The heavy-ion beam after the long transport is injected into the Booster where it is accelerated to a maximum energy that for Gold +36 is at 367 MeV/A. At this point also the heaviest of the ions can be fully stripped traversing metal targets between the Booster and the AGS. With this mode of operation is then possible to obtain beams of heavy-ions fully stripped up to Gold at energies of 10 GeV/A for fixed target experiments. It is obvious that the addition of the Booster ring to the BNL facilities would greatly augment the performance capability of the laboratory. The proposal for the Booster has been made and it is waiting now for funding and approval for construction that, hopefully, should start by 1987.

(iii) The most relevant BNL project to this paper is RHIC, the relativistic Heavy Ion Collider for beam energies up to 100 GeV/A and fully stripped ions up to Gold. This project would benefit considerably by the addition of the Booster. A consistent scenario has been developed to optimize the handling of the heavy-ion beams from their source (the Tandem), through the Booster and AGS, and finally to the Collider. The entire layout is shown in Fig. 4. The Collider itself is made of two superconducting rings located in the CBA tunnel.

Table 4 describes the beam properties from the Tandem in the two-stage mode of operation. Each pulse is more than 100 microsec long and has negligible energy spread and emittance. Several turns are injected into the Booster in a continuous fashion until the space charge limit, taken to correspond to a tune depression of 0.1, is reached and the beam allowed to fill up the available aperture. Booster parameters at injection are given in Table 5. The beam is captured by an h = 1 RF system making one single bunch and accelerated to the top energy which for all species involved corresponds to a velocity $\beta = 0.7$. The single bunch is extracted from the Booster, targeted for a final stripping stage, required for elements from Sulphur up, and injected into the AGS where it is then accelerated to the maximum energy which ranges from 28 GeV for protons to 11 GeV/A for Gold.

With the RHIC design it was clearly recognized the importance of intrabeam scattering, especially for energies below the storage ring transition energy. A systematic analysis of the effect was done and it was learned how to cope with it, that is to let the beam grow and to calculate the performance (luminosity) averaged over a long period of time. This effect plays clearly also a crucial role in the determination of the aperture of the superconducting magnets, and the choice of the lattice. As a consequence the two rings are made of magnets with an operating field of 4 Tesla and coil i.d. of 8 cm.

Table 4 BNL Tandem Operation Parameters

Element	Q_T	S_T	Kinetic Energy MeV/A	β_F	Q_F	S_F	Current μ-amp-part
Deuterium	+1	70%	15.0	.1768	+1	100%	525.
Carbon	+5	61	7.5	.1262	+6	90	82.
Sulphur	+9	34	4.7	.1002	+14	40	20.
Copper	+11	27	2.9	.0782	+22	27	11.
Iodine	+13	20	1.65	.0595	+31	20	6.
Gold	+13	19	1.0	.0463	+36	17	5.

*Two-Stage Mode - 75% transmission efficiency.

Table 5 Beam Parameters for the BNL Booster

Element	ϵ_N π·mm·mrad	T_{rev} μsec	N_B* x 10^9	$N_{S.C.}$ x 10^9
Deuterium	8.8	3.81	100.	438.
Carbon	6.3	5.33	22.	37.
Sulphur	6.0	6.72	6.7	[illegible]
Copper	3.9	8.60	4.7	5.5
Iodine	3.0	11.31	3.4	3.2
Gold	2.3	14.53	3.6	2.2

*With 8-turn injection

Another important decision for the RHIC design was the utilization of short bunches colliding head-on or at a very small angle, to enhance the luminosity. This was found preferable to a coasting, debunched beam configuration, because of the relatively low intensity of the beams and to shorten the filling time at the low energy injection where intrabeam scattering is otherwise very limiting. It was found that the bunched beam configuration, similar to the one also adopted for proton-antiproton colliders, does not necessarily conflict with the requirements of the users.

The design of RHIC was optimized for maximum performance for beams of Gold at 100 GeV/A which then gave an initial luminosity of 10^{27} cm^{-2} s^{-1}. Each beam is made of 57 bunches separated by about 200 nsec. Since it takes about one second to accelerate one bunch in the Booster and the AGS, the filling time for both rings is about two minutes. Luminosity values for different species are given in Table 6. These are initial values; due to intrabeam scattering, the actual value averaged over a period of several hours is typically a factor of two smaller. This is shown in Fig. 5 and Fig. 6 for the case of Gold ions.

Table 6 Initial Luminosity in cm^{-2} s^{-1} for the RHIC Collider

	Crossing Angle, α (mrad)		
	0.0	2.0	
Proton (N_B = 10^{11})	1.2	0.3	x 10^{31}
Deuterium	11.9	3.0	10^{30}
Carbon	5.8	1.4	10^{29}
Sulphur	4.9	1.2	10^{28}
Copper	22.6	5.0	10^{27}
Iodine	6.7	1.6	10^{27}
Gold	1.29	0.3	10^{27}

RHIC is probably the heavy-ion collider project which has received the best attention and the most careful design. The most recent cost estimate is of 140 M$ in 1984 estimates, low enough for the size and the potential for experiments to both nuclear and high energy physics community to be expected to receive the most immediate consideration for a successful early start.

European Projects

There is a collaboration between LBL, CERN and GSI for acceleration of heavy-ion beams in the CERN accelerators. A source of oxygen +6 is being provided by GSI and an rf quadrupole by LBL. The beam will be injected in the 50 MeV proton Linac, transported to the Booster where it is accelerated, ejected and transferred to the CPS. Here acceleration takes place to 17 GeV/A and the oxygen ions are fully stripped. The beam is then transferred to the SPS where it is finally accelerated to 200 GeV/A and ejected for fixed target experiments. An intensity of 10^8 ions/pulse is expected, a minimum required to handle the beam through the several acceleration stages, yet perhaps too large to be absorbed by the experiment detector. Heavy ion beams are expected for delivery sometime next year.

A novel idea comes from C. Rubbia who has proposed colliding beam experiments in the single SPS ring between antiprotons at 400 GeV and oxygen at 200 GeV/A. The two beams would be kept separated in most of the ring and made to collide in the interaction region by slightly adjusting their momenta.

American Fantasies

We report next two fantasies of our own which we believe are too important to be neglected and should receive serious consideration by the community.

The first fantasy deals with Fermilab. The CERN program can of course also be adopted here and for superior performance. It has already been proposed to add a pre-Booster of few GeV between the 200 MeV Linac and the 8 GeV Booster to enhance the brilliance of the proton beam for colliding beam experiments at Fermilab. The addition of a 15 MV Tandem would then allow also the injection of heavy ions fully stripped up to Gold. With the Tandem and the pre-Booster, of modest economical effort, no other modification are required. Heavy ion beams can be accelerated to 3.2 GeV/A in the Booster, 60 GeV/A in the Main Ring and 400 GeV/A in the Tevatron. Individual bunches of at least 10^9 heavy ions can be created and accelerated at the time. As it was proposed for CERN also at Fermilab it is then possible to have colliding beams between antiprotons at 1 TeV and heavy ions at 400 GeV/A in the single ring of Tevatron. A luminosity of 10^{28} cm^{-2} s^{-1} is estimated. If a Dedicated Collider for 2 TeV x 2 TeV of protons and antiprotons should ever take place at Fermilab, then with the addition of an extra ring (which would also allow proton-proton collision) it is possible to realize heavy-ion colliding beams at a fantastic energy of 0.8 TeV/A per beam. At these energies intrabeam scattering would not represent any longer a limitation and luminosity are expected to grow linearly with the beam energy. Luminosity in excess of 10^{28} cm^{-2} s^{-1} are expected.

The second fantasy deals with the 20 TeV x 20 TeV Super Superconducting Collider (SSC). Obviously this also could represent an ideal place for heavy-ion colliding beams at super fantastic energies of 8 TeV/nucleon and luminosity approaching 10^{30} cm^{-2} s^{-1}. This though requires a design of an adequate source which would closely resemble the one already described for Fermilab. At these fantastic energies and luminosities there is no doubt that new, unknown states of matter will be discovered. Figure 7 gives a summary of luminosity versus beam energy for colliding beams of very heavy ions including all the projects described or mentioned in this paper.

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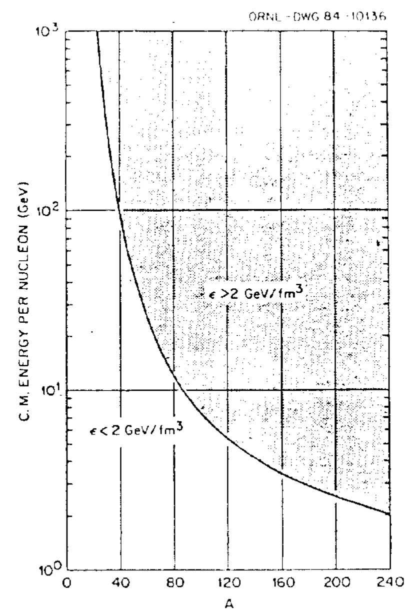

Fig. 1 Center of mass energy per nucleon vs. atomic mass A of two colliding nuclei to obtain a given energy density ε.

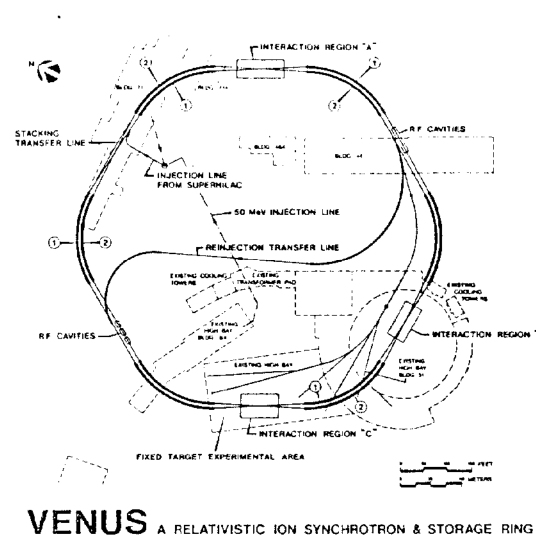

Fig. 2

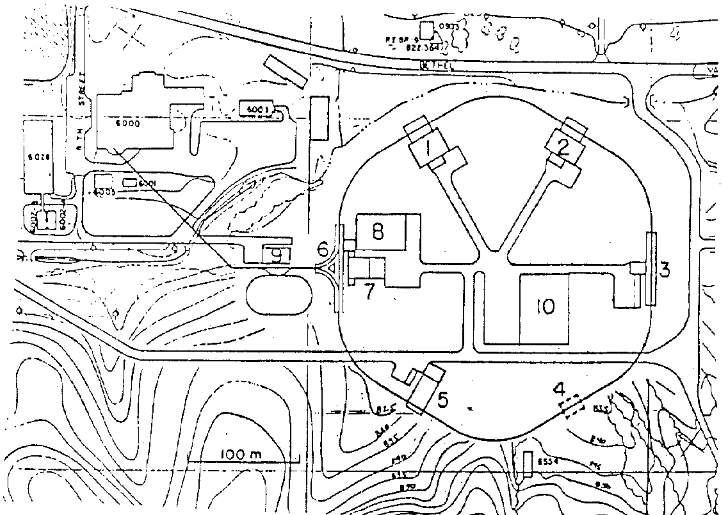

Fig. 3 The 10 × 10 (GeV/A)^2 Collider ORHIC at ORNL

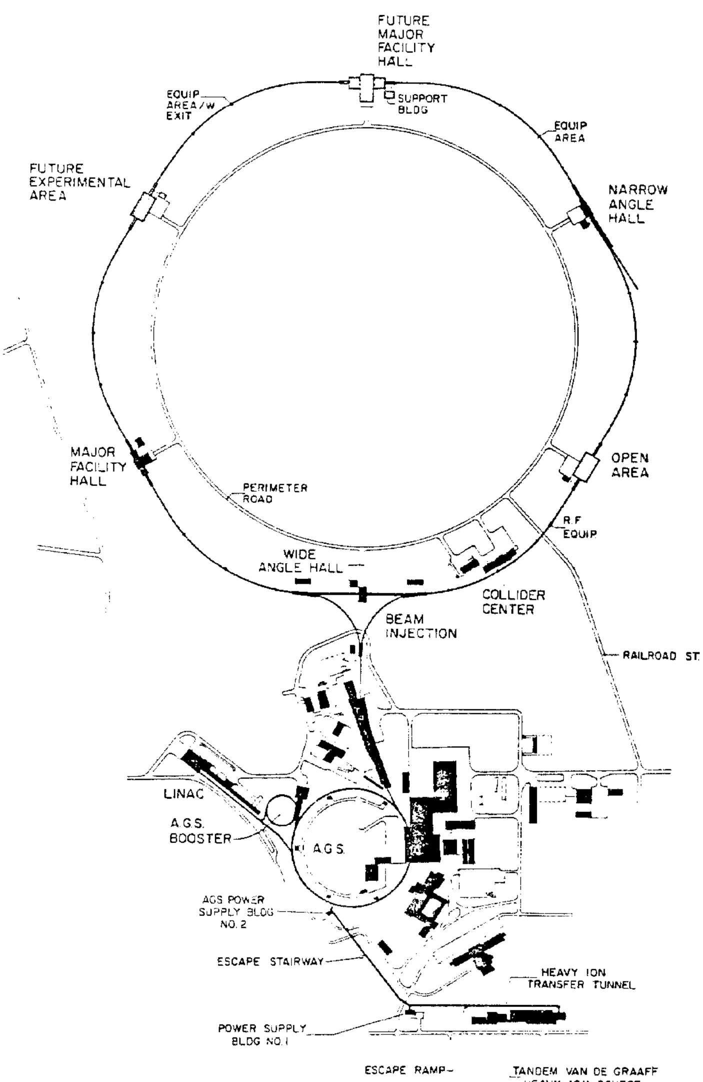

Fig. 4 Layout of RHIC project-collider and source.

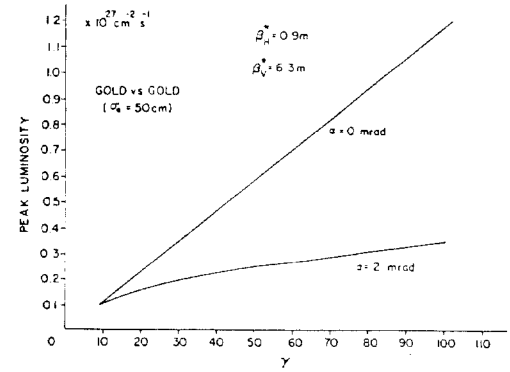

Fig. 5 Peak luminosity vs. energy (γ) for RHIC.

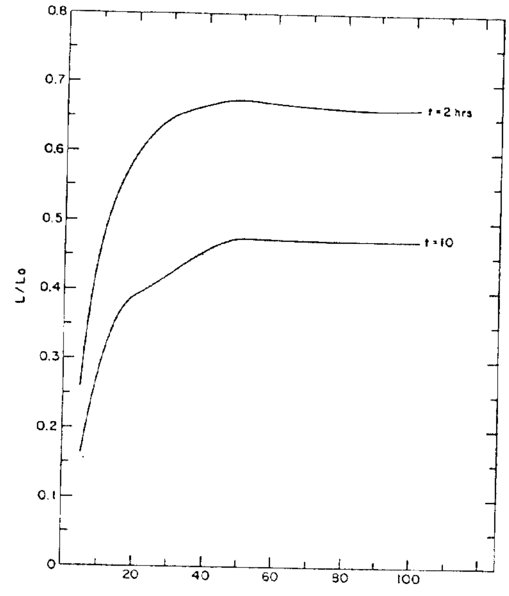

Fig. 6 Average luminosity normalized to its peak value vs. energy (γ) for RHIC.

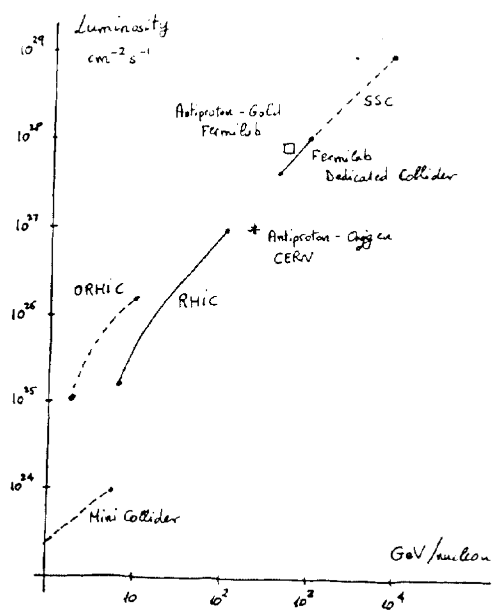

Fig. 7 Diagram of luminosity with energy per beam for various colliders.