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ACCELERATOR-COLLIDERS FOR RELATIVISTIC HEAVY IONS
OR
IN SEARCH OF LUMINOSITY

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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.

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 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 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 ~ 0 and

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$\rho/\rho_0 \sim$ 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." It is characterized by 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 two beam rapidities. From purely economic considerations, we hope the 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.

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

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

$$\Delta y = y_1 - y_2$$

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.

Table II

n	Ion
1	^{1}H
2	^{12}C
3	^{35}Cl
4	^{63}Cu
5	^{127}I
6	^{238}U

ELECTRON REMOVAL

A particular annoyance in accelerating heavy ions is their charge-to-mass ratio, which is as low as $92/238 \approx 1/2.57$ 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, equivalent to a 12.5 x 12.5 GeV/u collider. 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 III

T/u (MeV/u)	q
0.11	17^+
2.0	44^+
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 heavy ions, one must minimize the number of strippings. One is then faced with at least one major acceleration step with $q/u \leq 1/6$.

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 $q \sim 40^+$-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 somewhere between 50-1000 T·m, depending on desired peak final energy.

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

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

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 1.5-MeV/u $^{197}_{79}Au^{40+}$ ions filling an acceptance of $\varepsilon = 50\ \pi$ mm·rad, $N_B = 1.02 \times 10^9$ 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

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

for example, for ${}^{208}_{82}Pb^{37+}$ at $\beta = 0.134$, $\sigma_{capture}$ = 6.5 Mbarn/molecule of N_2, and σ_{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.

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 month = 2.6×10^6 seconds leads to $L_{min} = 6 \times 10^{22}/BR\ cm^{-2}\ s^{-1}$. For a branching ratio BR = 5%, one needs $L_{min} > 10^{24}\ cm^{-2}\ s^{-1}$, 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, $\sigma_{H,V}^* = \sqrt{\frac{\epsilon_N\ \beta_{H,V}^*}{\beta\gamma\ 6\pi}}$ are the horizontal, vertical rms beam sizes, ϵ_N is the normalized emittance, and $\beta_{H,V}^*$ are the 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: $(B \cdot f_{rev})$ = 1/100 ns, $\beta_{H,V}^*$ = 2 m, $\epsilon_N = 10\ \pi$ mm•mrad, E = 10 GeV/u, head-on collisions and $N_1 = N_2 = 10^9$ particles/bunch, our earlier value for A = 200. This yields

$$L_{initial} = 2.8 \times 10^{26}\ cm^{-2}\ s^{-1}\ ,$$

well in excess of our "bottom-line" acceptable value from above. At 100 GeV/u, one could expect an order of magnitude increase in this.

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 $T = \frac{10^9/\text{bunch} \cdot 50 \text{ bunches}}{R}$ = 70 hours. Obviously, $L = 10^{29}\ cm^{-2}\ sec^{-1}$ causes lifetimes of less than 1 hour, which is not acceptable.

For very heavy beams (A > 100), the dominant mechanism causing loss of luminosity is intrabeam scattering (IBS). (See the talk by A. Ruggiero in these proceedings.) 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

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

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, $\ell n(b_{max}/b_{min})$ 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 FNAL 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.

CONCLUDING REMARKS

Some closing remarks are in order:

(1) For lighter beams, luminosities of two or more orders of magnitude greater than the A = 200 + A = 200 values can be obtained.

(2) Initial luminous regions of $\sigma_\ell = 0.25$ m in length can be obtained for head-on collisions, with σ_ℓ correspondingly less for crossing at a few mrad. These will double or triple in size after a few hours for heavy beams.

(3) Multiple interactions per bunch crossing can be suppressed, i.e., for gold: $P_{1event} = 10^{-3}$, $P_{2event} \sim 10^{-6}$.

(4) Beam transverse dimensions at crossing can be held to <1 mm.

(5) Operation over a large (x10) energy range is possible.

(6) Operation with unequal species is possible, although equal energies per nucleon should be used to obtain a stable bunch-crossing point.

(7) Lastly, there should be no problem in obtaining several plasma candidate events per hour.