RELATIVISTIC HEAVY ION ACCELERATORS

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INTRODUCTION

There is a growing interest in the scientific community in the use of accelerators to produce relativistic heavy ion beams for a number of purposes. It now appears that relativistic heavy ion collisions may provide an opportunity to study nuclear matter far from equilibrium density, pressure, and temperature. Heavy ion beams can also be used as simulated cosmic rays for astrophysical research and in planning space probes.

The medical use of heavy ions for studies of radiation biology, radiation therapy, and diagnostic radiology has opened up a new field for the use of medium-mass ions of ~500 MeV/amu.

Use of high-energy, high-mass particles as a means for delivering sufficient energy to a pellet containing a DT mixture to trigger a thermonuclear burn, to be used for fusion power generation, has become a subject of intense study.

At present the only relativistic heavy ion accelerator is the Bevalac at LBL. It has been devoted to this use since 1974. The operating experience and capabilities of this machine are reviewed as well as present and planned experimental programs.

Designs of accelerators for relativistic heavy ions are discussed. A number of considerations will cause a machine to differ from a proton machine if optimally designed for heavy ion acceleration. A possible set of parameters is presented for an accelerator to produce intense beams of mass 10 - 200 ions, at energies up to 10 GeV/amu.

THE BEVALAC FACILITY

The acceleration of heavy ions was begun at the Bevatron in 1971. Using a linac originally designed for protons but in a $2\beta\lambda$ mode, low-intensity beams up to

mass $A = 20$ were accelerated up to energies of 0.2 - 2.1 GeV/amu. In 1974 a 200-m-long transfer line linking the SuperHILAC (a machine designed to accelerate heavy ions up to $A = 238$) to the Bevatron was completed, and beams of much greater intensity became available. Table I lists some of the parameters of the SuperHILAC/Bevatron.

TABLE I. Bevalac parameters.

SuperHILAC			
Injectors	1) Pressurized Dynamatron		2.5 MV
	2) Air-insul. Cockcroft-Walton		750 kV
Alvarez linac	Radiofrequency		70 MHz
	Prestripper energy gain		0.113 to 1.2 MeV/amu
	Poststripper energy gain (variable)		1.2 to 8.5 MeV/amu
	Number of tanks		8
	Total length		49.4 m
	Number of drift tubes		212
Bevatron			
Peak energy, for $q/A = 0.5$ particles		2.6 GeV/amu	
Magnetic radius		15.2 m	
Circumference		120 m	
Risetime		2 sec	
Repetition rate		10 per min	
Field index n		0.57	
Usable aperture		20×112 cm	

Table II lists the ions that have been accelerated, with corresponding intensities of extracted beams from the Bevatron.

TABLE II. Representative Bevalac-extracted beams, June 1977.

Ion	Particles per Pulse
^{4}He	3×10^{10}
^{6}Li	3×10^{10}
^{12}C	6×10^{10}
^{16}O	3×10^{10}
^{20}Ne	10^{10}
^{40}Ar	5×10^{8}
^{56}Fe	3×10^{8}

Figure 1 is a plan of the Bevalac facility, showing the SuperHILAC, the transfer line, the Bevatron, and its experimental area. The SuperHILAC is a National Facility, with a full program of low-energy nuclear physics, in addition to its role as Bevatron injector.[1] This duality of purpose has been made possible by implementing a feature known as time sharing, in which two different ions are accelerated independently through the same linac structure. This is accomplished by using two preinjectors, some pulsed magnets at the entrance and exit, and the ability to

program rf gradient and phase on a pulse-by-pulse basis. A typical mode of operation
is to accelerate one pulse per second of an ion, say neon, for Bevatron injection,
and the remainder (35 pulses per second) of an ion such as xenon for use by a SuperHILAC
experimenter. Thus the Bevalac uses only about 3% of the SuperHILAC capability in
this mode. The minimum Bevalac requirement is much less, as only one pulse every
4 to 6 seconds is needed for injection. The others are used to check the transfer
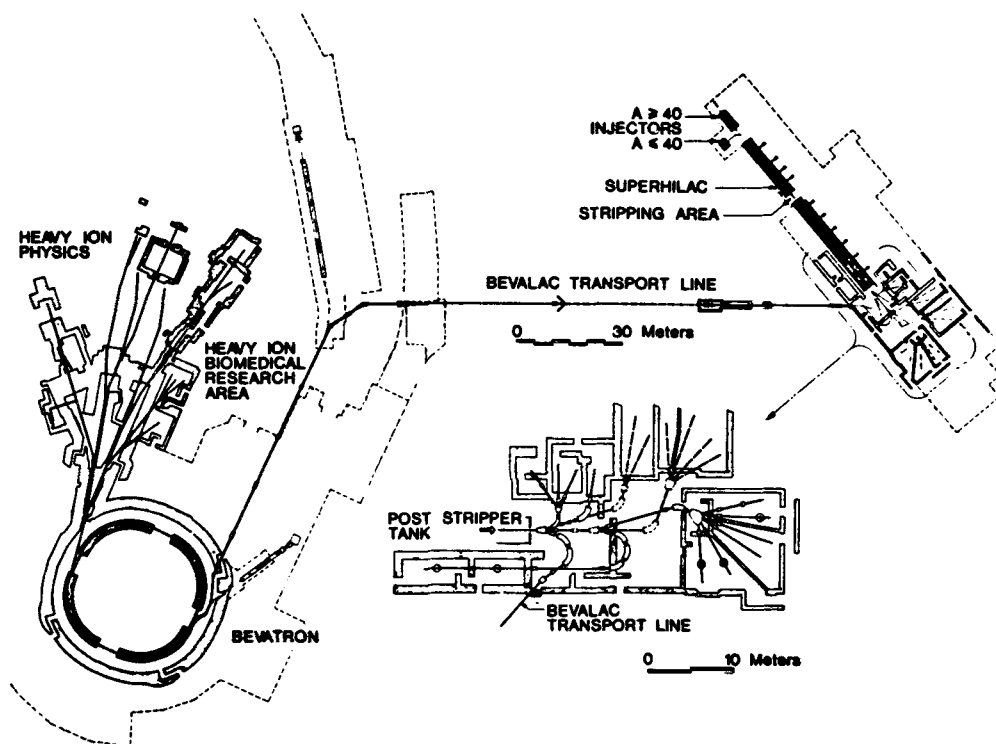line tuning.

Fig. 1. Plan of the Bevalac facility, 1977.

Ions are stripped twice for Bevalac injection, once after acceleration to 1.2
MeV/amu in the SuperHILAC prestripper, and again after being accelerated to 8.5 MeV/amu
Presently only fully-stripped ions can be accelerated in the Bevatron because of
stripping by residual gas atoms at the vacuum of 10^{-7} Torr. This need for fully-
stripped ions sets a limit on the mass of the ion that can be used. At present iron
($A = 56$) is the heaviest because stripping efficiency decreases with increasing Z.
Although about 50% of $A = 40$ is fully stripped, only 5% of $A = 56$ is fully stripped.
Another Bevalac limitation is in the intensity of beams available from the SuperHILAC,
which decrease with increasing mass number. This is because a minimum q/A of 0.045
is needed for SuperHILAC acceleration, and the PIG ion source output drops sharply
as q is increased.

An improvement program is planned for the Bevalac to remove these restrictions on mass and intensity. The major components of this program are an improved vacuum of $\sim 10^{-10}$ Torr for the Bevatron, which will permit acceleration of partially stripped ions, and a third low-charge state preinjector with much higher intensity for very heavy ion beams. This preinjector, which will be modeled after the first stage of the UNILAC,[2] will use a Wideröe linac, accelerating ions with low q, and a stripper in order to raise q/A to the necessary SuperHILAC injection value. Construction on these improvements is expected to start in the fall of 1977, with completion in 1979.

Operation of the Bevalac has been two-thirds nuclear science, one-third bio-medical applications. Both programs are extensive, and are described in detail below. There is a large backlog of experiments in both areas. The Bevatron has a single slow extraction channel, operating on the 2/3 integral resonance. Although a beam-splitting septum is available, it has had only limited use because of the difficulty of obtaining "clean" heavy-ion beams. The septum channel was designed with protons in mind, but heavy ion beams require much more careful handling to avoid contamination due to fragmentation. An improved septum channel is planned, with which it is hoped that beam sharing will become a common mode of operation.

BIOLOGICAL AND MEDICAL APPLICATIONS

In living tissue, the properties of heavy ion beams lead to biological and medical consequences that are of great interest. A large investigative effort is under way, using the Bevalac to explore these consequences in detail. This work has been summarized in a recent report.[3] Beams used for this research are primarily ^{12}C, ^{20}Ne, and ^{40}Ar, with energies in the 500 MeV/amu range.

The potential effectiveness of heavy ions when used in cancer therapy to produce concentrated local damage to cells is illustrated in Fig. 2. This year, preclinical trials have begun, with a regular treatment program to be started in the fall.

Use of ions for radiography is being explored. Two points of superiority of ions, as compared to x rays are: 1) They are more sensitive to small density changes in soft tissue; and 2) Much less exposure is required for comparable resolution.

Heavy ion beams can also be a copious source of positron-emitting secondary beams (as much as 1% of parent beam). These beams, being heavy ions, have a well-defined range and can be implanted in tissues as radioactive tracers.

NUCLEAR SCIENCE RESEARCH WITH RELATIVISTIC HEAVY IONS
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The early experiments with relativistic heavy ions investigated predominantly peripheral collisions ($\gtrsim 50\%$ of the total cross section). Such an event, producing projectile fragmentation, is shown in Fig. 3. Recently, attention has been focused
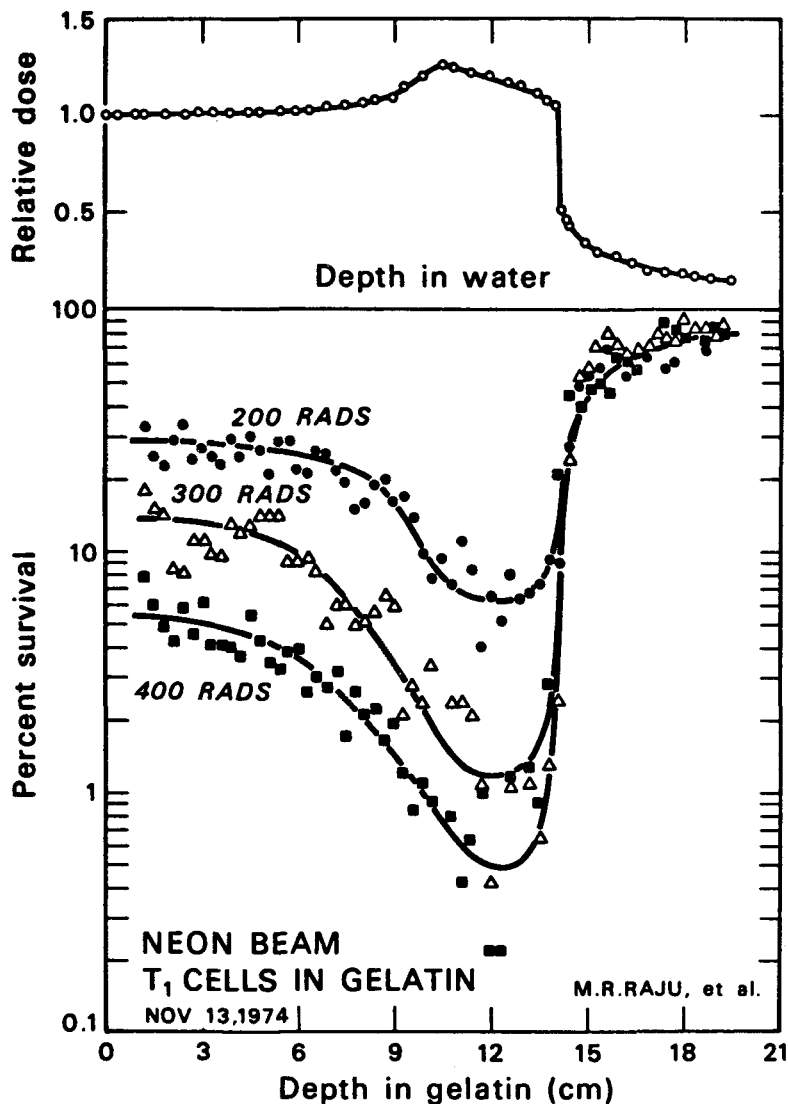
Fig. 2. Cell survival as a function of depth for a neon beam (Ref. 4).

on central collisions (Fig. 4) in which there is a substantial overlap of projectile and target. The general scheme has become the study of nuclear matter far away from well-known matter in stable or unstable nuclei. Two aspects are of particular interest: 1) Making multi-baryon systems out of unusual constituents; and 2) Transforming nuclear matter into a different state, in terms of density, pressure, temperature.

Multi-Baryon Systems

Nucleus-nucleus collisions above certain critical energies result in a large number of quasi-free baryons, which occupy a small phase-space volume and might therefore rebind to form exotic systems, such as: a) multi-neutron nuclei;[6]
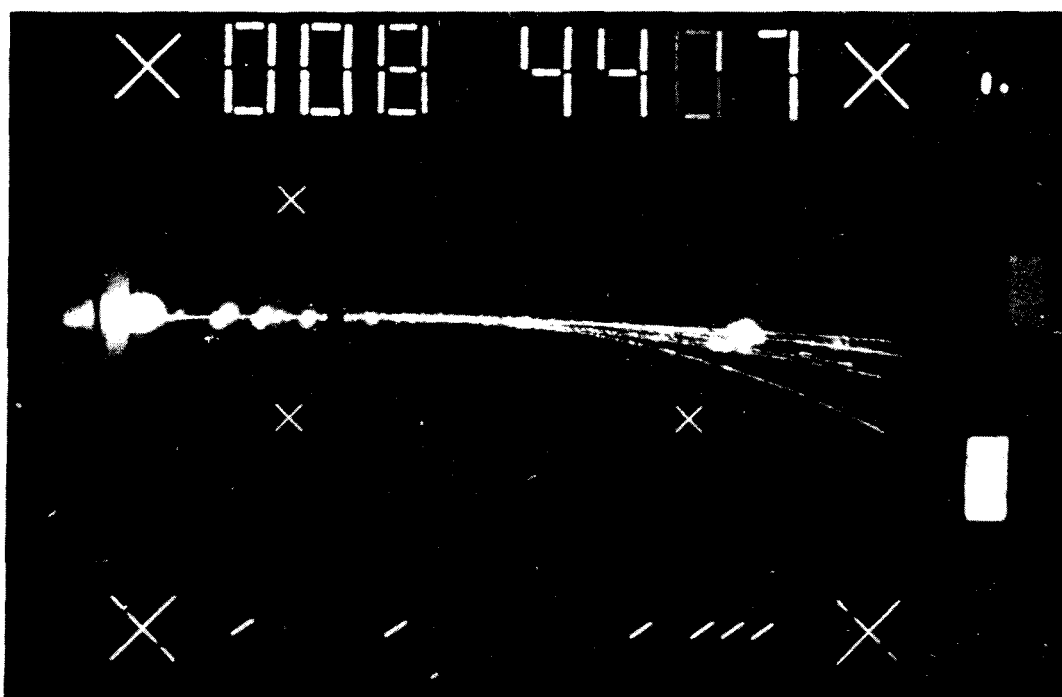
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Fig. 3. Photograph taken in the streamer chamber, showing a ^{12}C ion at 0.87 GeV/amu
fragmenting on a lucite target. The lucite is the gap in the track to left
of center (from Ref. 5).

b) multi-strange nuclei (many Λ's bound inside a nucleus);[7-9] c) multi-Λ-clusters;[10]
d) multi-quark bags (baryons with quark number >3);[11] and e) Δ-Δ interaction inside
hot nuclei.

All these hypotheses suggest searches for unusual decay patterns, embedded
in the star-event (central collision) produced by nucleus-nucleus interaction at
high energy. Multi-neutron nuclei (a) would be possible above 20 MeV/amu in the
center of mass (CM) system; (b,c,e) require energies above about 1 GeV/amu in the
CM system, whereas one would need more than 10 GeV/amu in CM to observe (d). This
might be a potential application for the ISR at CERN.

Transformation of Nuclear Matter

In order to transform nuclear matter into another phase, a prerequisite is
sufficient energy. However, equally important is the formation of a system, similar
to a compound system, in which certain nucleons from target and projectile occupy a
compact volume in phase space. This means their internal kinetic energy is randomly
distributed; that is, in equilibrium. An alternative picture is the reaction mechanism
of multi-nucleon cascades. In this situation we always have two separate phase-space
volumes for target and projectile nucleons. To obtain an equilibration the nuclear
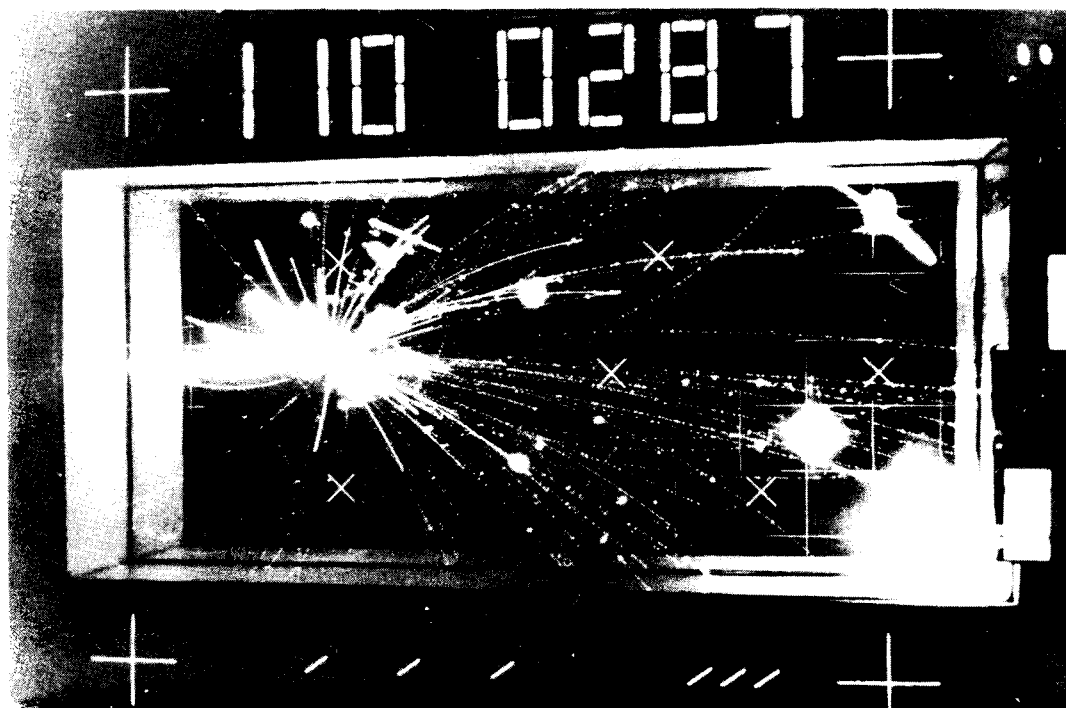
Fig. 4. Streamer chamber photograph of ^{40}Ar projectile at 1.8 GeV/amu interacting
with a thin Pb_3O_4 target. Positively charged particles curve downward
when traveling from left to right in the chamber (from Ref. 5).

fireball is needed[12] in analogy to the hadronic fireball.[13] If such a fireball
is formed, information at high nuclear densities can be obtained: a) For the equation
of state, sound velocity, shock velocity, compressibility, and elasticity of nuclear
matter;[14-17] b) For baryonic matter at extreme temperatures;[15,18] c) For phase
transitions in nuclear matter (i.e., a state with a different ordering, e.g., spin
lattice, or a drastically different binding energy per nucleon), density isomers,[19-21]
pion condensates,[22-23] Lee-Wick condensation;[24-25] and d) For multi-quark bags.[12]
Phenomena a), b) and c), if they exist, require nuclear densities significantly
higher than ρ_o, e.g., pion condensates should exist at a nuclear density $\rho \gtrsim 2\rho_o$,
whereas density isomers and Lee-Wick matter may only occur for $\rho \div 15\rho_o$. It is expected
that $E_{CM} \approx 200$ MeV/amu in the CM system might be enough to produce a compression
of nuclear matter to $\rho \approx 2\rho_o$. One obviously needs higher energies to achieve higher
compression. For $\rho \gtrsim 10\rho_o$, an energy $E_{CM} \gtrsim 10$ GeV/N in the CM system should be
required.

For d), at very relativistic energies $E_{CM} \gtrsim 10$ GeV/n, such as could be obtained
today at the ISR, there might be a coherence effect in the formation of superhigh
excited baryonic systems with heavy ions. Near $v \approx c$, when $\gamma \gg 1$, the lifetime of
excited baryons exceeds the traversal time of projectile and target and may lead to

coherent interactions of "strings" or "tubes" of nucleons in both nuclei.[26] The likely number of nucleons in a "string" of an argon nucleus is about four. Thus in Ar + Ar (central)-collisions at $E_{CM} = 2 \times 20$ GeV/amu, a system with $E_{CM} = 2 \times 20 \times 4 = 160$ GeV may be formed.

SPECIAL PROBLEMS OF HEAVY ION ACCELERATORS

Heavy ions exist in many different charge states, $-1 \leqslant q \leqslant Z$, and while choosing any one of them for a given part of the acceleration cycle means increased flexibility in the choice of accelerator parameters, it also brings additional problems in producing and maintaining the desired charge state. The following sections will briefly deal with some of the relevant aspects.

Charge-Changing Processes

The rate of change of the charge state distribution N (q) of a heavy ion beam traversing a material medium is governed by the cross sections σ (q,q') for transition from charge q to q' in a collision with a target molecule. At low velocities σ (q, q±1) are the dominant terms, while at higher velocities σ (q, q+k), k > 1, become non-negligible also. After passing a thickness L_{eq}, an equilibrium N (q) and mean charge state $\bar{q}$ is reached, which is a function of the ion's atomic number, its velocity, and to a lesser degree, the target material. In solids $\bar{q}$ is greater than in gases and it increases in both with ion velocity.

Stripping by passage through a gas cell or a foil at intermediate energies is used to increase the charge, initially limited by ion source characteristics, and thereby decrease the size of the accelerating structure required to achieve a given energy. Due to the width of the resulting distribution of charge states, a loss of beam intensity of up to a factor of 10 for heavier ions is incurred, limiting the number of stripping stages that can be used. An exception to this occurs at sufficiently high energies where $\bar{q} \cong Z$. Energies of 8 to 10 MeV/amu are sufficient to completely strip ions up to $Z \sim 10$ with essentially 100% efficiency. Corresponding experimental values on very heavy ions do not exist, but is estimated that 500 to 800 MeV/amu will be required to fully strip uranium nuclei with high efficiency.

The feasibility of increasing phase-space density by stripping at injection in a synchrotron has not yet been thoroughly analyzed. The possible gain in brightness is (asymptotically) $(1-f)^{-1}$, where f is the fraction in the desired charge state. There are indications that multiple scattering and energy loss will severely limit the number of profitable passes through the stripper.

A change of particle charge by one unit is equivalent to a momentum change $\Delta p/p = 1/q$, which in synchrotrons implies an instantaneous loss of the particle. The fraction surviving at time t or energy T is:

$$N(t)/N(o) \ = \ \exp - vt \sum \sigma_i(v) n_i \ , \qquad \begin{matrix} v = \text{const (e.g.,} \\ \text{in storage ring)} \end{matrix} \qquad (1)$$

$$N(T)/N(0) = \exp - \frac{1}{\varepsilon e B \rho} \sum n_i \int_{T_o}^{T} \sigma_i(T) dT \ , \qquad \text{for acceleration with} \atop \dot{B} = \text{const} \ , \qquad (2)$$

where ε is the charge-to-mass ratio, n_i the density of the ith constituent of the residual gas, and σ_i the corresponding cross section.

Experimental data on the relevant cross sections are still very meager and restricted to relatively light ions in high charge states, and do not allow a careful check of theoretical predictions.

Alonso et al. have studied single electron loss of Ar^{+17} and Ne^{+9} ions at low energies in the Bevatron. They parameterize their results as $\sigma = A/\beta^5 + B/\beta^2$ with coefficients $A = 2.4(\pm 1) \cdot 10^{-23}$ cm^2, $B = 7(\pm 3) \cdot 10^{-21}$ cm^2, for Ar, which agrees with Gillespie's predicted $6.83 \cdot 10^{-21}/\beta^2$ dependence.[27] From a practical viewpoint, existing information has led to a specification for a vacuum of 10^{-10} Torr for the Bevalac upgrading program in order to ensure acceleration of very heavy ions as well as very weakly charged ions.

Interactions between beam particles themselves can lead to additional losses. This charge transfer between ions is presumably important, but only if very weakly ionized beams (such as U^{+1}) are accelerated, as is envisaged in accelerators for heavy-ion-induced inertial fusion. Initial estimates point to the possibility of cross sections as high as a few 10^{-16} cm^2.[28] The loss rate will obviously depend on the energy dependence of these cross sections and the phase-space distribution of the beam, and relatively little manipulation seems available to eliminate them. A similar process, though involving much higher energies and higher charge states and therefore hopefully less important, will have to be investigated if partially stripped ions are to be used in a colliding beam device.

Ion Sources

For a relativistic heavy-ion machine, it is not yet clear what the best ion source will be. The limiting intensity in these machines will be set by space-charge considerations. Low charge states extracted from PIG and duoplasmatron sources will furnish beams of adequate intensity and brightness. Performance is exemplified by the UNILAC ion sources.[29] Another approach for a synchrotron injector is exemplified by the EBIS source, being developed at Dubna and Saclay, which provides pulses of highly stripped heavy ions. For $A = 132$, $q = 24$ has been attained.[30] The advantage in using this source is that a low-velocity linac section, and one stage of stripping, can be avoided. According to Donets,[30] the number of ions per pulse is limited to something like $10^{12}/\bar{q}$, where $\bar{q}$ is the mean charge state. This is one to two orders of magnitude less than can be achieved with conventional sources.

Synchrotron Performance

The maximum momentum per mass unit for an ion of mass A and charge q in a synchrotron is given by $p = q/A \cdot eB\rho$, i.e., q/A times the corresponding proton

momentum. Comparing space charge limits for a given synchrotron and injection energy, we note that $N_{sp.ch.}(A,q) = A/q^2 \cdot N_{sp.ch.}$ (proton), reflecting the fact that the fields generated are $\propto q$, while the particle's response to them is $\propto q/A$. For fixed design momentum, number of particles per pulse, and injection energy we see that the stored magnetic energy will be $\propto q$, machine radius $R \propto A/q$, and rf voltage (for a fixed magnet rise time) $\propto (A/q)^2$. Looking in a similar way at intersecting storage rings, keeping momentum, magnetic fields, and apertures fixed, we find that the luminosity varies as $1/q^2$; in fact, $L(A,q) = q^{-2} \cdot L$ (proton). Considerably increased radii (through low q values) and/or apertures would be necessary to approach proton luminosities at a given momentum.

As in proton machines, the achievement of very high beam fluxes will require a booster, at least if fully stripped ions are to be accelerated in the main ring. Keeping stripping losses in mind, booster energies of 500 to 800 MeV/amu will be required.[31] For final energies ~10 GeV/amu, a preliminary survey of possible parameters indicates that a booster might essentially be a duplicate of the "main" machine, occupying the same tunnel.

It is obvious that a considerable amount of investigation will be required to arrive at optimal parameter sets for a new relativistic heavy ion accelerator. A critical role will be played by the injector and its performance. The beam brightness B necessary to reach the synchrotron space-charge limit can be written as

$$B = \frac{ec\beta^3\gamma^3}{2\pi R} \frac{|\delta\nu|}{r_o} \frac{A}{q^2} B_{rf} \cdot \frac{1+\sqrt{k}}{kA_v} \tag{3}$$

for low-energy injection, considering only direct space charge terms. A_v is the vertical acceptance, $k = A_H/A_V$, B_{rf} is the bunching factor, and r_o the proton radius. This expression implies stacking in the x and y phase planes, which might not be practical for a large number of injected turns, but can be approximated by splitting/ reconstructing the beam before injection. We illustrate these remarks by considering a hypothetical, large-aperture synchrotron. Assume $R = 40$ m, $A_v = 2\pi \cdot 10^{-4}$ m, $A_h = 4\pi \cdot 10^{-4}$ m, consider injection of Hg^{+48} ions and a tune shift $\delta\nu \simeq 0.2$ after bunching, $B_{rf} \simeq 0.2$. With an injector emittance of $2\pi \cdot 10^{-5}$ m in both planes, this requires minimum currents of ~15 particle μA (pμA), 40 pμA, and 150 pμA for injection energies of 10, 20, and 50 MeV/amu, respectively. These currents considerably exceed what present heavy ion linacs deliver, but we will show in the last section of this paper that the technology exists today to produce these values.

FUTURE TRENDS IN RHIA TECHNOLOGY

A Dedicated Medical Accelerator

In work supported by the National Cancer Institute, hospital-based medical accelerators have been investigated at LBL.[32] The emphasis has been on the use

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of existing technology for the first generation of such machines, in order to ensure reliability in clinical operation.

Therapy requires ranges of ~30 cm in tissue, and beam intensities equivalent to 600 rad-liter/min. This corresponds to energies of 200, 400, and 550 MeV/amu for proton, carbon, and neon beams respectively, and beam intensities of $2.5 \cdot 10^{10}$, 10^9, and $5 \cdot 10^8$ pps, respectively. A synchrotron was shown to be the most economical solution for particles heavier than helium. Fully stripped ions are accelerated in the synchrotron in order to keep both ring diameter and vacuum requirements modest.

A cyclotron with an internal PIG source supplying C^{+2} is used as an injector (a linac accelerating C^{+3} is an alternate possibility), energy 2 MeV/amu. For injection, 30 pµA of C^{+6} with emittance 10^{-5} πm-rad is assumed.

The synchrotron lattice design is aimed at efficient magnet utilization through small β-functions (β_{max} ~ 12 m), simplifying magnet design, construction and alignment by keeping tunes fairly low (ν_x, ν_y ~ 2.25), and a transition energy (γ_{tr} = 2.1) above the peak operating energy. A lattice of six periods yielded the desired results while providing ample straight-section lengths to accommodate injection, extraction, and correction elements. A magnet aperture of 4 × 10 cm satisfies the requirements for multiturn injection and slow resonant extraction. For carbon ions of 415 MeV/amu, an average radius of ~13 m is obtained with B ~ 0.8T.

A conceptual design for the treatment facility is shown in Fig. 5. With four treatment rooms, it is expected that several thousand cases per year could be handled in such a center.

Delivery of the beam at the tumor site is one of the most important aspects of the use of charged particles in radiation therapy.

Characteristic of today's state-of-the-art is the system developed for and extensively used at the LBL 184-inch cyclotron.[33]

Difficulties arise if inhomogeneities are present, or if a different cross section (transverse field shape) is desired at different depths, as will be the case if an attempt is made at minimizing the dose outside an irregularly shaped treatment volume. To solve this problem, preliminary designs for a 3-dimensional beam scanning system have been worked out at LBL.[34] A beam of a few mm diam will be swept over the treatment volume by two scanning magnets bending the beam in orthogonal planes, while energy modulation allows scanning in depth. The scan pattern and the local dose accumulation are computer-controlled. With such a system the spatial accuracy of dose deposition will be determined solely by the quality of the diagnostic information and the finite beam spot size, for which a lower limit is set by small angle scattering.

Heavy Ions for Energy Generation

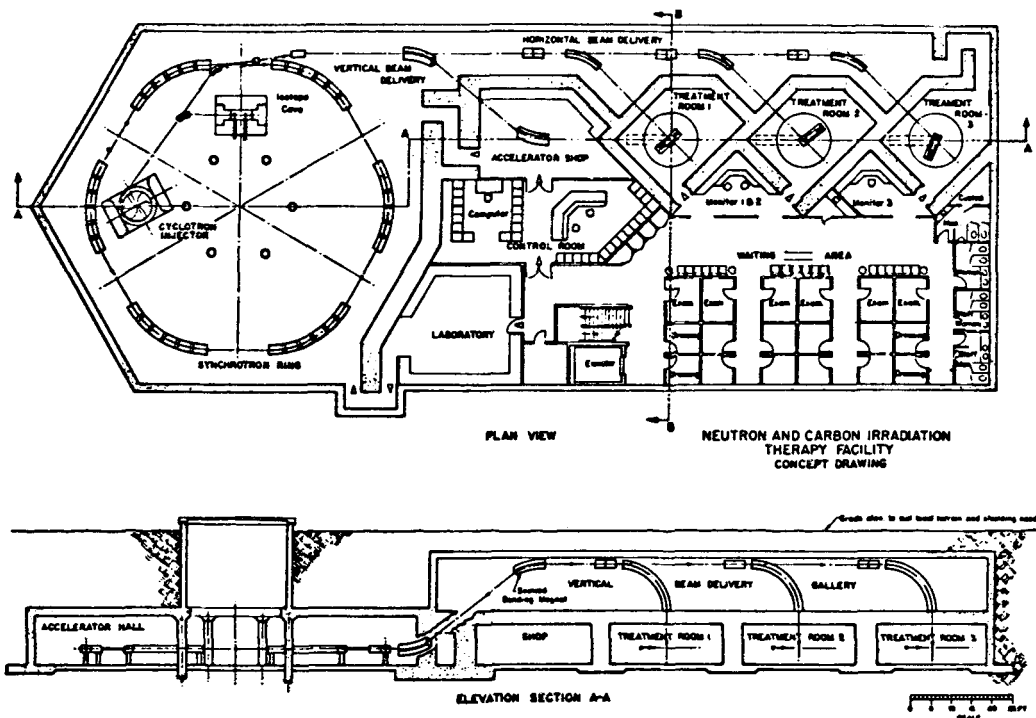The use of heavy ion beams to initiate a thermonuclear reaction in a small

Fig. 5. Conceptual design for a dedicated, hospital-based medical accelerator, delivering carbon beams up to 415 MeV/amu. Each treatment room is served by both horizontal and vertical beams. The Cyclotron injector is also used to deliver beams to a cave for production of short-lived isotopes.

pellet containing a DT mixture is an attractive concept for power generation. A program has been started by ERDA to look into the feasibility of this concept. An examination of the problems to be faced is contained in Ref. 35. Some 10^7 J of energy must be delivered to the pellet, of only a few mm^2 area, in a 10^{-8} sec burst. A very heavy ion is an excellent candidate for delivering this large amount of energy, because it can be delivered at high kinetic energy, thus reducing the current needed, while the short range permits all of the energy to be delivered to the target.

The beam energy required would depend upon the ion chosen. Taking as an example a "high confidence" case from Ref. 35, for $A = 127$ a beam energy of 315 MeV/amu is needed with a current of 15 kA, assuming singly charged ions. The major areas that need some work before attempting such a machine are ion sources, acceleration of very low-velocity space-charge-limited beams, knowledge of cross sections for ion-ion charge exchange within a beam, study of suitable accelerator systems (including possible use of storage rings), and the transport to the target, where multiple transport systems might be used.

Relativistic Heavy Ion Accelerator (RHIA) for Nuclear Research

Studies are under way for a new generation of RHIA at GSI in West Germany,[36] in Japan,[37] and at LBL. In order to discuss a future machine, we start from ideas about the physics to be investigated (see the section on nuclear science research, above). In order to create a research tool with a reasonable lifetime of significantly advancing knowledge, we must provide CM energies of several GeV/amu. It is beyond the scope of this paper and our present understanding of many aspects involved to discuss here at what energy and under what circumstances colliding beams are preferable over fixed-target accelerators, but the high cost of very high-energy accelerators and the almost certain need to investigate heavy ion collisions at substantial energies indicates the consideration of possibly upgrading a fixed-target accelerator to colliding beam capabilities. Thus we will present some thoughts on such a heavy ion accelerator complex.

The basic building block is a synchrotron, designed to meet storage ring requirements, with a linear accelerator injector. With two such synchrotron units three modes of operation are possible: a) single-ring acceleration, with one ring used as a storage ring stretcher; b) higher energy and intensity fixed-target operation with one ring as booster; and c) an intersecting storage ring mode.

We chose, somewhat arbitrarily, a peak kinetic energy of 10 GeV/amu for lighter ions with $q/A = 0.5$, corresponding to 8 GeV/amu for Hg^{+80}. Using superconducting dipoles ($B \simeq 4.5T$) and a packing factor $\cong 0.4$, we arrive at rings with ~ 40 m average radius. With 5.10^{12} particles in each ring, a luminosity exceeding 10^{28} $cm^{-2}sec^{-1}$ is obtained with very conservative values of the crossing angle and beam height, leaving room

for improvements through low β insertions and possibly bunching or electron cooling. We determine ring apertures by requiring that 10^{13} Hg^{+80} ions stacked at $\gamma \simeq 4.8$ (corresponding to peak energy for Hg^{+40}) result in incoherent and coherent tune shifts of only a few percent. A circular bore close to 200 mm diam readily meets these requirements and provides sufficient radial space for stacking as well as generous vertical clearance for later inclusion of low β sections. This leads to a stored magnetic energy of a few tens of MJ, which is still compatible with a magnet rise time of ~ 1 sec, desirable for fixed-target mode of operation. We will now briefly discuss performance aspects of the different modes of operation (see Fig. 6).

Injector. The injector system will provide high-current heavy-ion beams by using low charge states from the ion source and a minimum number of strippers (Table III)

In the high-intensity mode of operation, stripping occurs only after the Wideröe (a foil stripper is assumed). The Cockcroft-Walton is quite straightforward, as is the Alvarez (similar to present SuperHILAC poststripper). The Wideröe would be an extension to somewhat higher energy of the machine presently being designed at LBL for the Bevalac improvement program. Table IV summarizes required linac performance in relation to synchrotron injection requirements.
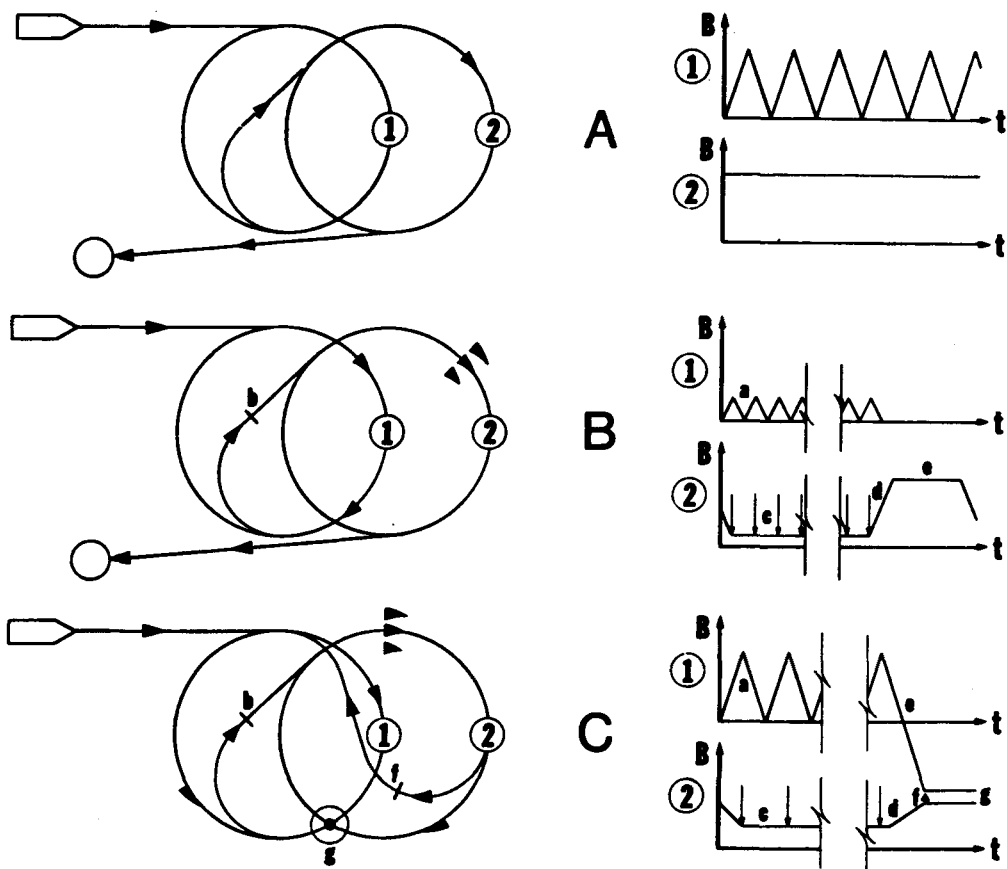
Fig. 6. Three operating modes for a two-ring RHIA.
A. Accelerator ring and stretcher storage ring mode.
B. Fixed target mode. (a) Accelerate to ~800 MeV/amu in ring 1,
(b) strip, (c) stack in ring 2, (d) accelerate in 2, and (e) slow
extraction from 2.
C. Colliding beam mode. (a) Accelerate to full field in 1,
(b) strip, (c) stack in ring 2, (d) accelerate to full field in 2,
(e) reverse field in 1, (f) transfer half of beam to ring 1 for
(g) colliding beam experiments at intersection regions.

TABLE III. Components of the injector system.

Accelerator	Minimum q/A	Energy (MeV/amu)
Cockcroft-Walton (1 MV)	0.02	0.02
Wideröe	0.02	2.0
Alvarez	0.2	10.0

TABLE IV. Synchrotron injection requirements (all currents in particle μA).

Ion mass	Expected linac current	Current needed to reach $N_{sp.ch.}$ in 50 turns	Expected linac current	Current needed to reach $N_{sp.ch.}$ in 50 turns
		(stripping at 2.0 MeV/amu only)	(stripping at both 2.0 and 10 MeV/amu)	
20	2000	500	2000	80
100	500	100	80	25
200	50	50	5	18

Injection of 50 turns does not appear overly difficult with a linac emittance $\leq 2.10^{-5}$ πm in a synchrotron phase space $A_v = A_h = 2.10^{-4}$ πm.

Accelerator Ring and Stretcher Mode. Acceleration occurs in only one ring, with the option of using the second ring as a stretcher ring to achieve essentially 100% duty cycle, important for high-intensity counter experiments. For $q/A = 0.2$ the maximum γ is limited to ~4.8 and intensities range from 10^{11} particles per pulse (ppp) (~$2.5 \cdot 10^{10}$ sec^{-1}) for mass 200 to 10^{12} ppp (~$2.5 \cdot 10^{11}$ sec^{-1}) for mass 20. Accelerating the charge state obtained by stripping at 10 MeV/amu we obtain $\gamma = 8$, $N \cong 10$ ppp for mass 200, $\gamma \cong 11$, $N = 1.6 \cdot 10^{11}$ ppp for mass 20.

Fixed Target Mode. Many ways are possible to increase intensity and energy by using both rings for acceleration. In the simplest mode, particles are accelerated with a single stripping at 2 MeV/amu, up to ~800 MeV/amu (Fig. 6). At this energy complete stripping and transfer to the second ring occurs. The intensities associated with single stripping, Table IV, are exceeded while for all ions maximum kinetic energy becomes available ($\gamma \simeq 9$ for mass 200, $\gamma \simeq 11$ for mass 20).

Colliding Beam Mode. In the simplest mode of storage ring operation, particles are accelerated with a single stripping at 2 MeV/amu to $\gamma \simeq 4.8$ in the first ring (Fig. 6.). At this energy, stacking in the second ring occurs (≥ 100 beam pulses) after the particles have been fully stripped. The particles are then accelerated to full field in the second ring. The field is then reversed in the first ring and half of the stacked beam reinjected. Luminosity will exceed 10^{28} cm^{-2} sec^{-1} for mass 200 and 10^{29} cm^{-2} sec^{-1} for mass 20. A price is paid for not having a separate accelerator to stack both rings independently, in that aperture has to be provided beyond that actually required during colliding beam experiments.

This will be one of the topics for further study aimed at both better understanding the most desirable beam specifications as well as optimal ways to meet them. Obviously, apart from more detailed machine investigations, we will have to clarify the compatibility of accelerator and storage ring requirements, as well as the ultimate desirability of combining both. We shall not be surprised if future analysis leads us to considerably modified concepts.

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ДИСКУССИЯ

И.Н.Семеняшкин: Какие имеются планы по встречным пучкам ядер в Беркли ?

F.B.Selph: As I mentioned, these are preliminary studies at present. We expect to continue these studies to a formal proposal to build an accelerator in about three years from now.

В.Г.Рогозинский: Какая физика ожидается на встречных пучках тяжелых ионов ?

F.B.Selph: I would like to refer you to my remarks on the continuation of nuclear science research at the Bevalac, in which it is hoped that colliding beams of very heavy ions can result in nuclear matter that, for a time, exists in much higher states of density, pressure and temperature. The possible existence of metastable states of nuclear matter - such as Lee-Wick condensation has attracted a great deal of attention, as have the possible existence of nuclear shock waves. Should these conjectures be bourne out by experiment, we could see a whole new field of nuclear physics opening up.

A.van Steenbergen: You mentioned that 500 MeV a.m.u. is sufficient for fully stripping any particle. It was my impression that there was considerable uncertainty with regard to the energy required to, typically, fully "strip" a uranium ion?

F.B.Selph: There is uncertainty as to the energy required to fully strip uranium nuclei. Most work on this subject has been done at GSI, Darmstadt, and we have accepted their estimate, which is based upon extrapolation of data at lower energies, using theoretical models. Of course, if one is satisfied to fully strip only a portion of the uranium beam this will undoubtedly occur at lower energies, perhaps when as low as 100 to 200 MeV per nucleon.