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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 28λ 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 II lists the ions that have been accelerated, with corresponding intensities of extracted beams from the Bevatron.
Table I. Bevalac parameters.

<table>
<thead>
<tr>
<th>SuperHILAC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Injectors</strong></td>
<td></td>
</tr>
<tr>
<td>1) Pressurized Dynamatron</td>
<td>2.5 MV</td>
</tr>
<tr>
<td>2) Air-insul. Cockcroft-Walton</td>
<td>750 kV</td>
</tr>
<tr>
<td><strong>Alvarez linac</strong></td>
<td></td>
</tr>
<tr>
<td>Radiofrequency</td>
<td>70 MHz</td>
</tr>
<tr>
<td>Prestripper energy gain</td>
<td>0.113 to 1.2 MeV/amu</td>
</tr>
<tr>
<td>Poststripper energy gain (variable)</td>
<td>1.2 to 8.5 MeV/amu</td>
</tr>
<tr>
<td>Number of tanks</td>
<td>8</td>
</tr>
<tr>
<td>Total length</td>
<td>49.4 m</td>
</tr>
<tr>
<td>Number of drift tubes</td>
<td>212</td>
</tr>
<tr>
<td><strong>Bevatron</strong></td>
<td></td>
</tr>
<tr>
<td>Peak energy, for q/A = 0.5 particles</td>
<td>6.6 GeV/amu</td>
</tr>
<tr>
<td>Magnetic radius</td>
<td>15.2 m</td>
</tr>
<tr>
<td>Circumference</td>
<td>120 m</td>
</tr>
<tr>
<td>Risetime</td>
<td>2 sec</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 per min</td>
</tr>
<tr>
<td>Field index n</td>
<td>0.67</td>
</tr>
<tr>
<td>Usable aperture</td>
<td>20 x 112 cm</td>
</tr>
</tbody>
</table>
Table II. Representative Bevalac-extracted beams, June 1977.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Particles per Pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4\text{He}$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td>$^6\text{Li}$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>$6 \times 10^{10}$</td>
</tr>
<tr>
<td>$^{16}\text{O}$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td>$^{20}\text{Ne}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$^{40}\text{Ar}$</td>
<td>$5 \times 10^{8}$</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>$3 \times 10^{3}$</td>
</tr>
</tbody>
</table>
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. 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.

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
Fig. 1. Plan of the Bevalac facility, 1977.
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 \( \approx 10^{-10} \) 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 ions beams. This preinjector, which will be modeled after the first stage of the UNILAC, 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 biomedical 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 \(^{12}\text{C},^{20}\text{Ne},^{40}\text{Ar},\) 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

R. Stock (LBL and Fachbereich Physik, Universität Marburg)

The early experiments with relativistic heavy ions investigated predominantly peripheral collisions (\(\geq 50\%\) of the total cross section). Such an event, producing projectile fragmentation, is shown in Fig. 3.
Fig. 2. Cell survival as a function of depth for a neon beam (Ref. 4).
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) (XBB-748-5727)

b) multi-strange nuclei (many A's bound inside a nucleus);/7-9/ c) multi-A-clusters;/10/
d) multi-quark bags (baryons with quark number >3);/11/ and e) Λ-Λ 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
Recently, attention has been focused 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.

Multibaryon 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] 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
fireball is needed \cite{12} in analogy to the hadronic fireball \cite{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 \cite{14-17}; b) For baryonic matter at extreme temperatures \cite{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, pion condensates \cite{22-23}, Lee-Wick condensation \cite{24-25}, and d) For multi-quark bags \cite{12}

Phenomena a), b) and c), if they exist, require nuclear densities significantly higher than \( \rho_0 \), e.g., pion condensates should exist at a nuclear density \( \rho \geq 2\rho_0 \), whereas density isomers and Lee-Wick matter may only occur for \( \rho \geq 15\rho_0 \). It is expected that \( E_{\text{CM}} \approx 200 \text{ MeV/amu} \) in the CM system might be enough to produce a compression of nuclear matter to \( \rho \approx 2\rho_0 \). One obviously needs higher energies to achieve higher compression. For \( \rho \geq 10\rho_0 \), an energy \( E_{\text{CM}} \geq 10 \text{ GeV/N} \) in the CM system should be required.

For d), at very relativistic energies \( E_{\text{CM}} \geq 10 \text{ GeV/n} \), 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 \( v = c \), when \( \gamma \gg 1 \), the lifetime of excited baryons exceeds the traversal time of projectile and target and may lead to
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 fireball is needed\cite{12} in analogy to the hadronic fireball\cite{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;\cite{14-17} b) For baryonic matter at extreme temperatures;\cite{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,\cite{19-21} pion condensates,\cite{22-23} Lee-Wick condensation;\cite{24-25} and d) For multi-quark bags.\cite{12} Phenomena a), b) and c), if they exist, require nuclear densities significantly higher than $\rho_0$, e.g., pion condensates should exist at a nuclear density $\rho \geq 2\rho_0$, whereas density isomers and Lee-Wick matter may only occur for $\rho \approx 15\rho_0$. 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 $\rho \approx 2\rho_0$. One obviously needs higher energies to achieve higher compression. For $\rho \geq 10\rho_0$, an energy $E_{CM} \geq 10$ GeV/N in the CM system should be required.

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in the formation of superhigh excited baryonic systems with heavy ions. Near \( v = c \), 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 \( \text{Ar} + \text{Ar} \) (central)-collisions at \( E_{\text{CM}} = 2 \times 20 \text{ GeV/amu} \), a system with \( E_{\text{CM}} = 2 \times 20 \times 4 = 160 \text{ GeV} \) may be formed.

**SPECIAL PROBLEMS OF HEAVY ION ACCELERATORS**

Heavy ions exist in many different charge states, \(-1 \leq q \leq Z\), 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 \( \sigma(q, q') \) for transition from charge \( q \) to \( q' \) in a collision with a target molecule. At low velocities \( \sigma(q, q+1) \) are the dominant terms, while at higher velocities \( \sigma(q, q+k), k > 1 \), become non-negligible also. After passing a thickness \( L_{\text{eq}} \), an equilibrium \( N(q) \) and mean charge state \( \bar{q} \) is reached, which is a function of the ions'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 $q \gg Z$. 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:

$$N(t)/N(0) = \exp(-vt \sum \sigma_i(v)n_i), \quad v = \text{const (e.g., in storage ring)}$$ (1)
\[
\frac{N(T)}{N(0)} = \exp \left( \frac{1}{e\varepsilon B_0} \sum n_i \int_{T_0}^{T} \sigma_i(T) \, dT \right),
\]
for acceleration with \( B = \text{const} \), (2)

where \( \varepsilon \) is the charge-to-mass ratio, \( n_i \) the density of the \( i \)th constituent of the residual gas, and \( \sigma_i \) 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 \( \text{Ar}^{17} \) and \( \text{Ne}^{19} \) ions at low energies in the Bevatron. They parameterize their results as \( \sigma = A/B^5 + B/\beta^2 \) with coefficients \( A = 2.4(\pm 1) \times 10^{-23} \text{ cm}^2 \), \( B = 7(\pm 3) \times 10^{-21} \text{ cm}^2 \), for Ar, which agrees with Gillespie's predicted \( 6.83 \times 10^{-21}/\beta^2 \) 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 \( \text{U}^{+1} \)) 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 \( 10^{-16} \text{ cm}^2 \).\(^{28/}\) 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. 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. The advantage in using this source is that a low-velocity linac section, and one stage of stripping, can be avoided. According to Donets, the number of ions per pulse is limited to something like $10^{12} \sqrt{q}$, where $q$ 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 $p = q/A \cdot e B_0$, i.e., $q/A$ times the corresponding proton momentum. Comparing space charge limits for a given synchrotron and injection energy, we note that $N_{sp.ch.}(A,q) = A/q^2 \cdot N_{sp.ch.} \text{ (proton)}$, 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 the $\propto q$, 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, $L(A,q) = q^{-2} \cdot L(\text{proton})$. 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.\footnote{For final energies $\sim 10$ 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

$$B = \frac{ecg^3}{2\pi R} \frac{|\delta v|}{r_o} \frac{A}{q^2} B_{rf} \cdot \frac{1 + \sqrt{k}}{kA_v}$$

(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 $^{40}\text{Hg}^+$ ions and a tune shift $\delta v \approx 0.2$ after bunching, $B_{\text{rf}} \approx 0.2$. With an injector emittance of $2\pi \cdot 10^{-5}$ m in both planes, this requires minimum currents of $\sim 15$ particle $\mu$A ($\mu$A), 40 $\mu$A, and 150 $\mu$A 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. The emphasis has been on the use of existing technology for the first generation of such machines, in order to ensure reliability in clinical operation.

Therapy requires ranges of $\sim 30$ 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
A synchrotron in order to keep both ring diameter and vacuum requirements modest.

A cyclotron with an internal FUG 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 \(10^{-5}\) mm-rad is assumed.

The synchrotron lattice design is aimed at efficient magnet utilization through small \(\beta\)-functions (\(\beta_{\text{max}} \approx 12\) m), simplifying magnet design, construction and alignment by keeping tunes fairly low \((\nu_x, \nu_y \approx 2.25)\), and a transition energy \((\gamma_{\text{tr}} = 2.1)\) 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 \(4 \times 10\) cm satisfies the requirements for multturn injection and slow resonant extraction. For carbon ions of 415 MeV/amu, an average radius of \(\sim 13\) m is obtained with \(B \sim 0.8\) T.

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
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.
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 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, in Japan, 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 (\( B \approx 4.5T \)) and a packing factor \( \approx 0.4 \), we arrive at rings with \( \sim 40 \) m average radius. With \( 5 \times 10^{12} \) particles in each ring, a luminosity exceeding \( 10^{28} \text{ cm}^{-2} \text{ sec}^{-1} \) is obtained with very conservative values of the crossing angle and beam height, leaving room for improvements through low \( B \) insertions and possibly bunching or electron cooling. We determine ring apertures by requiring that \( 10^{13} \) Hg\(^{+80}\) ions stacked at \( \gamma = 4.8 \) (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 \( B \) sections. This leads to a stored magnetic energy of a few tens of MJ, which is still compatible with a magnet rise time of \( \sim 1 \) 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
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.

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Minimum q/A</th>
<th>Energy (MeV/amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cockcroft-Walton</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>(1 MV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wideroe</td>
<td>0.02</td>
<td>2.0</td>
</tr>
<tr>
<td>Alvarez</td>
<td>0.2</td>
<td>10.0</td>
</tr>
</tbody>
</table>
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. Injection of 50 turns does not appear overly difficult with a linac emittance \( \leq 2 \times 10^{-5} \, \text{mm} \) in a synchrotron phase space \( A_v = A_h = 2 \times 10^{-4} \, \text{mm} \).

**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 \( \gamma \) is limited to \( \sim 4.8 \) and intensities range from \( 10^{11} \) particles per pulse (ppp) \( \sim 2.5 \times 10^{10} \, \text{sec}^{-1} \) for mass 200 to \( 10^{12} \) ppp \( \sim 2.5 \times 10^{11} \, \text{sec}^{-1} \) for mass 20. Accelerating the charge state obtained by stripping at 10 MeV/amu we obtain \( \gamma = 8 \), \( N \approx 10 \) ppp for mass 200, \( \gamma \approx 11 \), \( N = 1.6 \times 10^{11} \) 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 \( \sim 800 \) 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 (\( \gamma \approx 9 \) for mass 200, \( \gamma \approx 11 \) 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 \( \gamma \approx 4.8 \) in the first ring (Fig. 6). At this energy, stacking in the second ring occurs (\( \geq 100 \) beam pulses) after the particles have been
Table IV. Synchrotron injection requirements (all currents in particle \( \mu A \)).

<table>
<thead>
<tr>
<th>Ion mass</th>
<th>Expected linac current</th>
<th>Current needed to reach ( N_{sp.ch.} ) in 50 turns (stripping at 2.0 MeV/amu only)</th>
<th>Expected linac current</th>
<th>Current needed to reach ( N_{sp.ch.} ) in 50 turns (stripping at both 2.0 and 10 MeV/amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2000</td>
<td>500</td>
<td>2000</td>
<td>80</td>
</tr>
<tr>
<td>100</td>
<td>500</td>
<td>100</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td>200</td>
<td>50</td>
<td>50</td>
<td>5</td>
<td>18</td>
</tr>
</tbody>
</table>
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 $10^{28} \text{ cm}^{-2} \text{ sec}^{-2}$
for mass 200 and $10^{29} \text{ cm}^{-2} \text{ sec}^{-1}$ 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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