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STATUS AND OUTLOOK FOR HEAVY-ION ACCELERATOR SYSTEMS*

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I. Introduction

Four years ago, at the Particle Accelerator Conference in Chicago, there was for the first time a session dedicated to heavy-ion acceleration. I feel that a dedicated heavy-ion session is here to stay.

To bring the field into perspective, let me quote two outstanding scientists who have strong views on the acceleration and usefulness of heavy ions:

R. S. Livingston wrote in 1954: (1)

"In an effort to obtain larger currents of heavy ions with a more uniform energy distribution, the acceleration of partially stripped ions was undertaken at the Oak Ridge National Laboratory."

Livingston attributed the success primarily to the development of a suitable ion source. He then continues and states in the same paper:

"Our group has considered this problem (transuranic elements) and believes it to be entirely feasible to construct an accelerator which will produce many of the possible nuclear species up to atomic number 104 and mass 260."

Livingston's prediction was accurate: all elements up to and including 106 have been discovered. In fact, element 106 was discovered in 1974 by the Dubna group, led by N. G. Flerov; and the Berkeley group, led by A. Ghiorso. The search for elements above 106 is in full swing.

T. D. Lee wrote in 1974: (2)

"Hitherto, in high-energy physics we have concentrated on experiments in which a higher and higher amount of energy is distributed into a region with smaller and smaller dimensions. In order to study the possibility of the 'abnormal nuclear states'(3) and the related question of the 'vacuum', we must turn to a different direction; we should investigate some 'bulk' phenomena by distributing $\sim$ 500 GeV energy into a heavy concentration of nucleon density over a relatively large volume."

What T. D. Lee wants is Uranium ions at $\sim$ 1 GeV/u. We have studied the problem and find it entirely feasible to construct such an accelerator. (4)

These two quotes--as important as they are--cannot begin to cover the vast interest in heavy-ion research existing today. It would be far beyond the scope of this paper to ennumerate the areas of active and proposed research fields. However, one can clearly recognize three energy domains with active research programs.

(a) Energies around the Coulomb barrier for projectile and target; i.e., 2.5 - 10 MeV/u.

(b) Energies below the meson production threshold; i.e., 20 - 150 MeV/u.

(c) Relativistic heavy ions; i.e., energies of 300 MeV/u and higher.

Most existing and proposed heavy-ion accelerators fall into category (a). However, there are good scientific reasons to seriously consider energies in categories (b) and (c).

Whereas many experimenters would be quite satisfied to have high-quality intensive beams at 10 MeV/u up to mass 150, one must think in terms of producing ions from throughout the periodic chart.

II. The Fundamental Importance of Ion Sources

Many papers have been written, including a review paper at this Conference, which stress the need for heavy-ion source development. Hence I will not dwell on the "old standby" sources or the "far out" ideas. But the fact which will be stressed here is that ion source technology is advancing too slowly. The Unilac group deserves recognition because they have probably produced a larger variety of ion beams on their test stands than any other group. Comparable and commendable effort is being carried out in the USSR at Dubna, at the JINR. It is not my intention to list or review ion source efforts here--many other groups are exerting their best efforts towards this end--but it is evident that substantially more effort must be devoted to this field.

The accelerator builder therefore, for the time being, has to accept the status quo of ion source technology and adjust to it accordingly.

Due to the short lifetime and modest reliability of existing sources, the best possible access is highly desirable. For example:

(a) The external source of a cyclotron has ideal access.

(b) The negative ion source of a tandem is in equally good position; in fact, the easy access of sources is one of the attractions of a tandem system. One obviously pays the price of having only singly-charged ions in the first half of the electrostatic acceleration potential.

(c) The source in a relatively low-voltage $\leq$ 700 kV air-insulated Cockcroft Walton is also readily accessible.

For top performance, one must furthermore require that more than one source be available for essentially instant use. This can be done with more than one injector, as the SuperHILAC; or better yet, with two source stands each in two injectors, as the Unilac (see Fig. 1).

It is understood that without several well-tested spare sources, no accelerator--particularly a high-mass heavy-ion accelerator--will ever run reliably.

III. Some Thoughts on Types of Accelerators

This paragraph is not intended to be exhaustive, since so many excellent papers on special acceleration systems are being given at this Conference. However, I will make some comments on well-known accelerator types and some frontier-type ideas.

If we regard the energy region up to and around the Coulomb barrier ≤ 10 MeV/u, we recognize that the linac and the isochronous cyclotron, followed more recently by Van de Graaffs, have been used extensively in heavy-ion research to date. A few examples are: the two Hilacs, ORIC, the Dubna Cyclotrons, the 88-Inch Cyclotron, and several Tandem Van de Graaffs. The question is how to best combine these types of machines to meet the specifications of an up-to-date heavy-ion research center.

Since we are accelerating charges, our inability to readily produce high charge-states of very heavy ions is the single most influential parameter in considering an optimum system.

There is a trend favoring tandem Van de Graaff systems for the following main reasons:

1. Many laboratories own one, or they can buy one for a fixed price and guaranteed performance.

2. The access to the ion source is good.

3. There is a stripping need at full potential, and there are optional stripping possibilities at partial potential if the terminal voltage is high enough.

4. Unsurpassed energy resolution.

5. Excellent energy variability.

6. Good emittance.

Nevertheless, today's tandem Van de Graaffs alone are limited facilities for ions with mass above 100 amu. A consequence of this situation is the flood of proposals using some other accelerator to enhance the energy. These machines are called postaccelerators, afterburners or boosters. An advantage of these very high-voltage tandem-systems is their usefulness without the postaccelerator. However, one must not overlook the fact that the care and feeding of electrostatic accelerators above 10 MV is still an art, especially for the acceleration of heavy ions. A recent survey is given in (4).

The proposed booster accelerators are almost exclusively cyclotrons, which is not too surprising. The energy region towards which most of these proposals aim is 10 MeV/u for Uranium, and as high an energy as the cyclotron magnet design allows for lighter ions. Having accepted these boundary conditions, the cyclotron is a good choice. Injection is reasonably straightforward. In order to capture the beam at several MeV/u into a stable orbit of a cyclotron, one has basically two choices:

(a) If the cyclotron is of separated sector design, the beam can be injected and extracted by conventional beam guiding elements in one of the field-free sections between sectors.

(b) If the cyclotron is of the more classical single pole-tip design, charge-exchange in a stripper foil at the appropriate position is used to capture the beam into stable orbits. This method has been pioneered by a group at Orsay on the project "Alice."(6) The beam is accelerated in a linac up to 1 MeV/u and then injected into a cyclotron. Recent computational work at Oak Ridge has confirmed that this can be done over a wide variety of particles and charge states. If the energy gain in the cyclotron is modest, the orbit separation at full energy will permit easy extraction.

The transverse phase space of the tandem is difficult to preserve entirely at injection, but the increase can be kept small if only the most elementary precautions are taken. Energy spread and intensity are much more difficult to match to the postaccelerator.

For the purists, I want to make it clear that there is no fundamental problem in matching the relatively small 6-dimensional phase space of the Van de Graaff into the relatively large acceptance of an isochronous cyclotron. However, in reality, the trading of transverse and longitudinal phase space can be rather intricate.

Let's consider the longitudinal phase space alone. We then have to recognize that unless the Van de Graaff is bunched at the source, a loss in intensity or energy spread in the matching process is unavoidable. The origin of the problem is the required narrow phase width relative to the rf cycle of the bunch in the cyclotron to enable single-turn extraction. Single-turn extraction is known to produce small energy spread and is therefore desirable.

This example shall illustrate that while most combinations of accelerators are possible, a careful analysis of specifications, cost and matching process is essential.

As we require increases in energy towards 100 MeV/u and the mass of the particle towards 200 amu, both circular and linear machines become very costly. Efforts are under way to remedy the situation with superconductivity.

A proposal has been advanced by the group at Michigan State (7) (11) for a superconducting coil on an isochronous cyclotron magnet. The Chalk River group in Canada is very serious about their tandem-superconducting cyclotron proposal (8) which will be described later in this session. At ORNL and at LBL studies have also been made regarding superconductive cyclotrons. A number of problems still needs to be overcome, one of them being extraction, but it appears that we will see at one place or another a superconducting cyclotron in the near future.

Recognizing the advantages of linacs, various groups in the U.S. and abroad actively pursue higher gradient linacs. Some low β structures being studied are at room temperature; others make use of superconductivity. At this Conference there were reports(9) (10) about superconducting helices and reentrant cavity linacs. The effort at Argonne National Laboratory will produce soon some experimental experience with a superconducting helix accelerator using a 10 MV tandem injector. Similar plans exist at Stanford University. How fast such systems can produce reliable beams for experimental use remains to be seen.

If we increase the energy for high-mass particles into relativistic regions, serious consideration will have to be given to a large-aperture, rapid-cycling synchrotron. Matched with an appropriate injector, a synchrotron with 25% duty cycle and 1μA of mass 200 ions is not only feasible but essentially existing technology. And let us not forget that a properly designed synchrotron has excellent energy resolution and very good spill characteristics.

The use of intense collective fields of relativistic electron rings to accelerate heavy ions is being investigated at Dubna and ITEP in the Soviet Union, the University of Maryland in the U.S., and at Garching, West Germany. The final experimental efforts at Berkeley before the work there ceased in June 1974, concluded that peak accelerating fields of 30 MV/m could be obtained without running into trouble from collective instabilities. Recent work at Garching (October 1974) showed convincing evidence of Helium-ion collective acceleration over a distance of a few centimeters to an energy of 200 - 400 keV. If the acceleration mechanism can be shown to be maintained stably for distances of tens of meters, then ion acceleration by a static magnetic solenoid alone could produce heavy-ion energies of a few hundred MeV/nucleon.

IV. Major Heavy-Ion Projects

I am fully aware that one cannot do justice to the many good efforts going on around the globe. But I would like to pick out and comment on a few of the major heavy-ion centers which exist or are planned. For a compilation of energy performance, see Fig. 2.

Dubna, USSR Heavy-Ion Projects

The JINR at Dubna has a most distinguished record of heavy-ion work equalled only by Berkeley, with Oak Ridge, Orsay, and Brookhaven following closely. The Laboratory of Nuclear Reactions at Dubna certainly made headlines with their tandem cyclotron system U200 and U310 producing intense Xenon beams [12]. Their latest plans call for a large 4 m cyclotron U400, with a range in energy of 250 - 625 Z^2/A MeV. Simultaneously, an effort to employ collective effects (ERA), tailored to the acceleration of heavy ions, is pursued by the department of new methods of acceleration, as mentioned above.

At the high-energy end in the Laboratory of High Energies at the JINR, R & D efforts for relativistic heavy-ion work are actively pursued. This is not too surprising because this is the place where the first containment ion source was developed by E. D. Donetz et al., [13] meeting with great success. Recently, fully-stripped nitrogen ions from a Donetz-source have been accelerated through the 9 MeV injector of the synchrophasatron, which could yield heavy ions up to 4.6 GeV/u.

LBL - Heavy Ion Accelerators

The Berkeley effort in heavy ions is threefold: the SuperHILAC, the 88-Inch Cyclotron, with energies of 140 Z^2/A MeV [14], and the high-energy heavy-ion facility--commonly called the Bevalac--with a maximum energy of 2700 MeV/u. The velocity profile of the two Alvarez tanks at the SuperHILAC was chosen such that for an $\varepsilon = 0.05$ at injection an energy of 2.5 - 8.5 MeV/u can be obtained for any mass particle after stripping at 1.2 MeV/u. This machine has to date produced Xenon and lighter ions. Presently, the maximum current for Xenon ions is 60 pnA. A rigorous program to update the accelerator and its experimental facilities is under way, and mass 200 particles will be accelerated in the near future.

As many of you know, the SuperHILAC is being used also as injector for the Bevatron, creating the first relativistic heavy-ion facility in the world--the Bevalac [4]. The maximum energy is 2700 MeV/u, with intensities for the lighter ions of up to 1 pnA.

A few words may be in order to explain why the SuperHILAC as an injector to the Bevatron is a reasonable linkup. The acceptance of relatively low charge states, using judicious choice of other parameters, assures very high instantaneous beam fluxes--microamperes for the heaviest ions up to milliamperes of the lower mass ions.

Furthermore and most importantly, the SuperHILAC has a macroscopic duty cycle of 25 - 50%. If one keeps in mind that for injection purposes in the synchrotron a duty cycle of less than 1% is required, it becomes apparent that double duty for the SuperHILAC can indeed be accomplished. Operating with up to 36 pulses per second, it is planned to divert one pulse every second into the transfer line, connecting the SuperHILAC with the Bevatron. Fortunately, two injectors are already available, and a third one is projected.

We are currently installing a digital control system which is capable of adjusting injection line, rf system, stripper area parameters, kicker magnets, etc., in such a fashion that each pulse could in principle be a different particle and a different energy at a different target location. Hence the choice of particles and energies at the SuperHILAC and the Bevalac experimental areas is to a large extent a free parameter.

Unilac at GSI*

A first-class heavy-ion center, which will produce its first experimental beams this year, is the GSI*, with its Unilac [15], situated at the outskirts of Darmstadt, Germany. This center has already made many lasting contributions because of its broad systematic approach in fields connected with the production and acceleration of heavy ions. To mention a few: charge-exchange studies [16] and measurements, ion-source development, the first well-engineered Wideröe linac, etc. The new standard of engineering excellence achieved at GSI is most impressive.

The Unilac has two Cockcroft-Walton injectors with two ion source terminals each. An injection line with isotopic analysis brings the beam from either injector to a series of Wideröe tanks. Subsequent acceleration occurs in two Alvarez linacs followed by a number of single cavities. Stripping and charge analysis are provided between the Wideröe and the Alvarez sections. The maximum energy for the highest mass particles is slightly above 10 MeV/u. Much is expected of this outstanding facility. Let me just mention that not only will the accelerator itself set a new standard of excellence--the layout of the experimental area will be the envy of at least one generation of heavy-ion experimenters. If this linac performs up to its expectations, it could also make an excellent injector into a second-stage accelerator.

Van de Graaff - Cyclotron Facilities

As has been mentioned in the introduction, Oak Ridge has a distinguished record in heavy-ion work. In recent years, the isochronous cyclotron, ORIC, combined with its source development, led the way in heavy-ion beams at cyclotrons.

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* Gesellschaft fuer Schwerionenforschung

The linacs, and to a lesser degree the cyclotrons, compare unfavorably in energy resolution and emittance to Van de Graaffs. Even though for many experimenters the high beam quality is not needed, it is certainly understandable that many Van de Graaff accelerators are converted or uniquely used for heavy ions. Some difficulties of Van de Graaff systems have been pointed out previously. However, the results at BNL, Yale and Canberra--among other places--appear sufficiently encouraging that the next large heavy-ion facility in the U.S. at Oak Ridge has been funded to build a 25 MV Tandem Van de Graaff with up to 1 pμA of beam current. A similarly ambitious project is under way at Daresbury (Great Britain) where a tandem accelerator of up to 30 MV is planned. It is important to recognize that it is the emittance < 10 mm mrad and the outstanding energy resolution ± 2 KeV per charge ($\Delta E/E \sim 10^{-4}$) of the beam in which one is investing. The proponents of Van de Graaffs would emphasize at this point that the ease of energy variability is also an important factor. This is certainly correct, but also achievable with other accelerators employing appropriate control circuits. Several cyclotrons have reached great ease in adjusting energy.

Studying the various proposals employing Van de Graaffs--and there are many--one realizes quickly that the electrostatic accelerator is really thought of as an injector into a postaccelerator. In the Phase I proposal at Oak Ridge, ORIC will serve as a post-accelerator (see Fig. 3). The Chalk River group is engaged in R & D for a superconducting cyclotron as a booster for their tandem (Fig. 4). In Berlin, the project Vicksy at the Hahn Meitner Institute has contracted for a split-pole cyclotron to be injected by their CN Van de Graaff. We will hear more about these projects in this session.

GANIL - Orsay, France

The discussion of the last paragraph raises the question: Why not use a different injector to match into the second (or third) cyclotron stage? Such an approach has been proposed by the GANIL group. Fig. 5 shows two separated sector cyclotrons with a maximum energy of 400 Z^2/A MeV with two injector cyclotrons of 25 Z^2/A MeV energy capability. The proper combination of two or three cyclotrons will produce Uranium ions of 10 MeV/u and higher energies for lighter ions. This facility will be at the high energies equal in beam characteristics and intensity to a 25 MeV tandem with a similar cyclotron as booster accelerator. Again, a more detailed description will be given in this session.

Plans and Hopes for Relativistic Heavy-Ion Accelerators

The field of heavy-ion research experienced a great impetus when the speculation of the existence of super-heavy elements was announced several years ago. In fact, the search for super-heavy elements was one of the prime justifications for the funding of the SuperHILAC. As mentioned above, the search is still on. The recent speculations of Lee and Wick on abnormal nuclear matter, and of Greiner et al., on shock wave phenomena in nuclei have given an increased motivation to build higher energy heavy-ion facilities.

Active experimental work to date is only being done at Dubna (source development and linac acceleration), Orsay (source development for Saturne), and Berkeley (Bevalac acceleration up to mass 40). However, there are several projects in the "talking" or planning stage. In Japan, an injector linac and synchrotron for ions up to Uranium and energies of 300 - 500 MeV/u is planned [17]. There is also a paper at this Conference [18] describing how the Brookhaven AGS could be converted into a relativistic heavy-ion accelerator.

At CERN, a study group has been formed to investigate the possibility of accelerating polarized particles and light heavy ions in the PS.

At the IV All-Union Conference on Accelerators in Moscow, 1974, plans were presented for a 20 GeV/u superconducting synchrotron. It appears to be concentric, with a room temperature booster-synchrotron of 500 MeV/u.

V. Summary and Conclusions

There are five major heavy-ion centers constructed or funded worldwide; two additional centers are on the verge of being funded. Additionally, there are numerous smaller installations producing excellent science. Most installations aim at 10 MeV/u for the higher mass particles, and as high as possible for lighter ions. Berkeley and Dubna have reached or plan to reach relativistic energies for heavy ions. Studies and proposals for additional relativistic heavy-ion facilities are pursued at least in five places.

Altogether a very large effort is under way which is bound to leave a deep impression on basic science in the decade to come.

There is an obvious energy gap in proposed facilities; namely, 30 - 150 MeV/u for high-mass particles. It is apparent that we should be searching for inexpensive magnets for high $B\rho$ in circular machines, or for very high, inexpensive electric gradients in linacs.

This picture could be dramatically changed with a real breakthrough in ion source development. At least we should satisfy ourselves that we understand ion sources to the extent that we can predict their ultimate performance; only then can we produce optimum accelerator system designs.

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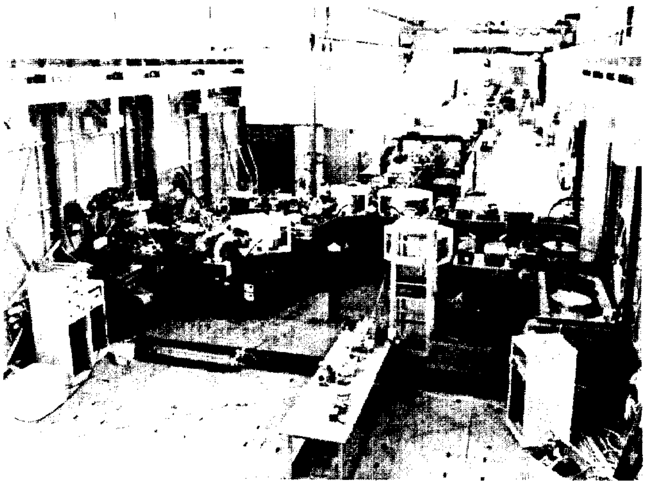

Fig. 1. The ideal injection setup: two injectors with two ion sources each. Unilac - GSI, Darmstadt, Germany.

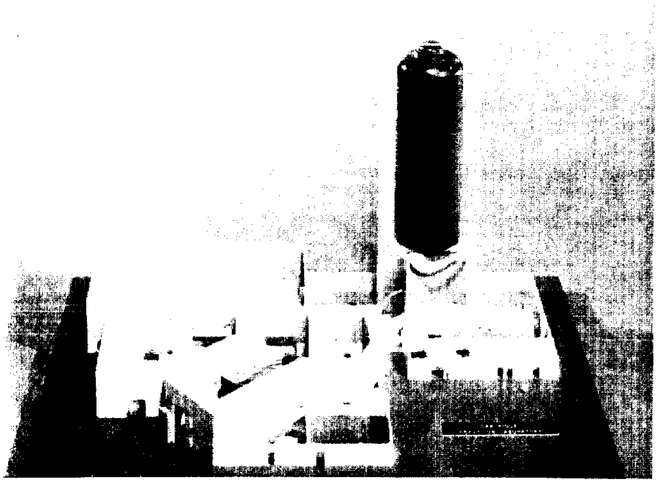

Fig. 3. Model of Tandem Cyclotron combination. Oak Ridge heavy-ion facility.

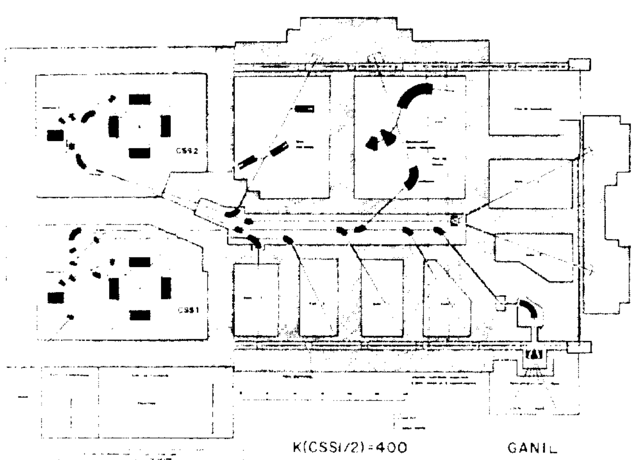

Fig. 5. The cyclotron-cyclotron approach.

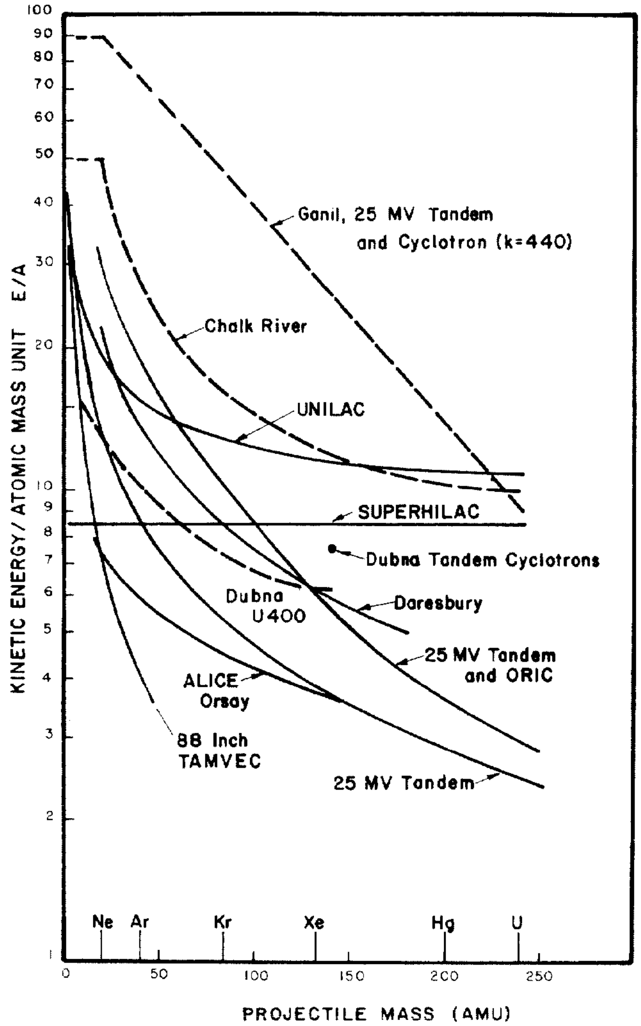

Fig. 2. Kinetic energy vs. projectile mass for several heavy-ion facilities.

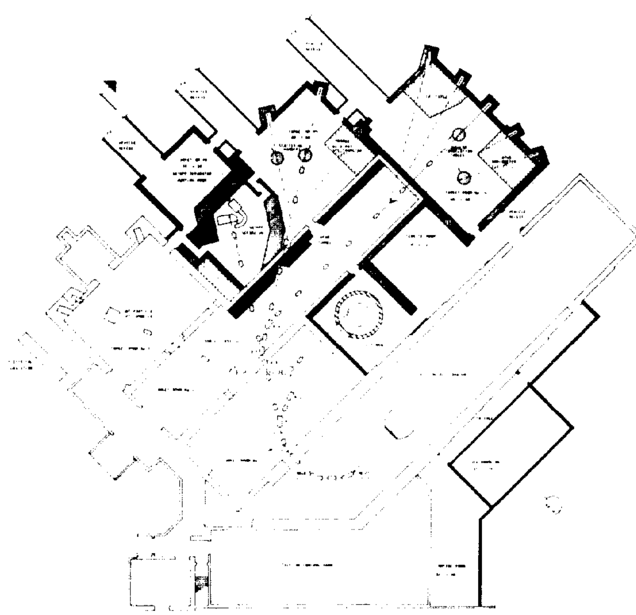

Fig. 4. CRNL Tandem/Superconducting Cyclotron.