0 0 0 0 4 4 0 2 3 3

Presented at the International Conference
on Heavy Ion Sources, Gatlinburg, TN,
October 27 - 30, 1975

LBL-4602
c.1

VERY HIGH ENERGY HEAVY-ION ACCELERATORS

Hermann A. Grunder

October 1975

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

For Reference

Not to be taken from this room

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY

LBL-4602
c.1

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

0 0 0 0 4 4 0 8 2 3 4

LBL-4602

VERY HIGH ENERGY HEAVY-ION ACCELERATORS*

Hermann A. Grunder

Lawrence Berkeley Laboratory
Berkeley, California

Introduction

Since some of us met last March at the National Accelerator Conference in Washington, D.C., several important events have taken place.

In Darmstadt, Germany, at G.S.I., the Unilac has started a promising career in basic heavy-ion research. This is a facility which has and will set a standard of excellence against which we will measure ourselves.

In France, the project GANIL has been funded, and I am certain we all wish this competent group the best of success.

In Dubna, the 4 m Cyclotron, with a range of 250-625 Z^2/A MeV is under construction at the JINR.

Also in Dubna, at the Institute for High Energies, plans are firming up to build a 15-20 GeV/u superconducting synchrotron for heavy ions.

At CERN, a group is continuing to study the use of the CERN PS for heavy ions and polarized particles.

In Japan, active work on the Numatron--a 300-500 MeV/u synchrotron--is under way.

It is my hope that we will be hearing more detailed information on several of these exciting projects during the course of the Conference.

With this short summary of recent events, I hope to have strengthened your belief that the field of heavy ion research is flourishing indeed and deserves our full support.

Having agonized over the title the Program Committee gave my talk, I have decided to single out a few relevant topics rather than trying to bore you with a complete description of the heavy-ion program.

What are the Options of Reaching Very High Energies with Heavy Ions?

The most effective acceleration of high-mass particles is obviously in the highest charge state possible, $q/m \approx 1/2$. If this were a simple task, there would be no reason for the existence of this Conference. It is estimated that all nuclear species known can be fully stripped, and hence the most favorable accelerating conditions reached at kinetic energies $T \approx 200$ MeV/u. From this we conclude that our task is mainly to investigate, discuss and speculate on how to reach this energy level where a heavy ion is only insignificantly different from a proton. The figure of merit again is useful phase-space density and acceptable cost--both being highly controversial subjects, and no value judgment will be attempted in this paper.

To reach energies above 100 MeV/u. cyclotrons, linacs and synchrotrons compete with each other. It is therefore appropriate to attempt a comparison of their respective performances. I will even go a step further and attempt a relative cost comparison of these accelerator types, knowing that such a comparison is risky at best.

Some clarification of what system is meant under the name "linacs", "cyclotrons" and "synchrotrons" is in order. The linacs, and less frequently the cyclotrons, are proposed as 'purebred' machines; i.e., a series of the same machine-type with alterations to accomodate the changing rigidity of the particle. For injectors into cyclotrons, tandem Van de Graaff high-voltage generators are planned in several installations, most notably the Oak Ridge proposal, where the tandem has "stand alone" capability. The recently approved project GANIL in France consists of four cyclotrons with the capability of three being in series. The synchrotrons rely typically on a linac injector because short beam pulses with high brilliance are essential.

The energy in every acceleration stage is chosen so as to take advantage of the increase in q/m by stripping, in order to make the overall acceleration system most effective.

Table I

Comparison of Characteristics of Accelerators Reaching Very High Energy for Heavy Ions

		Linac + Synchrotron 20 Hz	Multiple Cyclotrons	Linac Combinations	Collective[1] Accelerators ERA 200 Hz
Intensity (pμA)	$A \leq 40$	0.1	10	100	0.1
	$A \sim 200$	0.0001	0.1	1	0.1
Macroscopic Duty Cycle		30%	100%	10-30%	10^{-7}
Transverse Emittance[2] (cm mrad)		1	1	π	2π
Energy Spread $(\frac{\Delta E}{E})$		$<10^{-3}$	10^{-3}	3×10^{-3}	5×10^{-3}

1) Since no ERA device exists today these numbers are obviously estimates and more for speculative purposes mentioned.

2) The transverse emittance is assumed to be the same in both planes.

* Work supported by the U. S. Energy Research & Development Administration.

It is obvious from Table I that the cyclotrons or linacs have an enormous advantage in intensity over the synchrotrons. This situation explains the strong effort being made to reduce their cost wherever possible to make them competitive with synchrotrons. Several efforts in superconducting cyclotron design are under way, mainly at Chalk River and at Michigan State. The problem of a superconducting coil on a separated sector cyclotron remains unresolved to date. For comparison purposes, it might be noted that the recently finished SIN cyclotron, of conventional but separated sector design, could accelerate q/m = ½ particles up to 180 MeV/u, given the proper isochronous field and rf frequency.

Figure 1 shows a relative cost comparison of the accelerators capable of reaching energies in excess of 100 MeV/u. It is very clear that the cyclotron combinations as well as linac combinations are a good buy in terms of pμA per capital investment but, like so many good buys, unfortunately our society may be unable to afford them.

If we assume that relativistic heavy ions are desirable and that the funding situation will not change dramatically in the foreseeable future, then we should try to employ existing machines and consider the possibility of their conversion to heavy-ion acceleration[1].

I am fully aware that there is a large gap in available energy between the existing and proposed heavy-ion accelerators and the ultrarelativistic accelerators currently used for protons.

In recognition of this situation, LBL has proposed an improvement to the Bevalac permitting acceleration of all masses to energies as low as 30 MeV/u[2]. This proposal consists of: (a) an improved injector with the goal of delivering 1 pμA of mass 200 particles, and (b) an improved vacuum tank in the synchrotron (10^{-9} Torr) to allow acceleration of any mass and charge state without serious charge-exchange losses. With this improvement the Bevalac should be able to cover the entire periodic table with energies ranging from 30 to 2500 MeV/u for lower mass particles (see Fig. 2 for more details).

Present Performance of the SuperHILAC and the Bevalac

A few words seem to be in order at this point regarding the status of the LBL SuperHILAC and the Bevalac. Starting last June the SuperHILAC beams are being timeshared. This means that during a Krypton run with 36 pulses per second, for example, one Neon pulse per second has been inserted to inject into the Bevalac. It should be mentioned that both beams may have different energies as well.

We are currently running a good fraction of the time in this mode. At the beginning, some intensity sacrifices had to be made, but presently the uncertainty of ion source output from one source to another is larger than a possible reduction in beam intensity due to timeshare operation.

The computer-controlled system provides additional flexibility in the experimental areas. We can now deliver one of the beams to a second experimenter at the SuperHILAC experimental area as well for tuning or calibration purposes. And you can easily see what the potential with a third injector can be. The limitation is of course the maximum rf power available and hence the combined duty cycle.

There are a number of component problems to be solved yet at the SuperHILAC, but we have had good success with our 2.5 MeV injector. The machine has run at 2.5 MV for extended periods and at 2.9 MV for short periods without component failure. Nevertheless, ion sources for high-mass particles should never be in pressurized vessels with limited space.

Recent results obtained by our ion source group, led by Dave Clark, include production of good calcium beams and enough iron to inject into the Bevalac[3]. The final test of accelerating iron in the Bevalac will take place soon.

The Bevalac intensities, while adequate for many experimenters, have not reached the expected values yet. In a later paper we will hear about Duoplasmatron development to increase the brilliance of the lower mass beams at the SuperHILAC for Bevalac use[4]. Figure 3 shows the expected Bevalac output and currently achieved intensities.

The Source Problem in the Context of the Heavy Ion Accelerator

For most sources the knowledge of six-dimensional phase-space, ion species, intensity and source lifetime are sufficient parameters to allow a meaningful comparison of source performance. Hence the choice of source and accelerator type can be made on a comparative basis and a cost optimization becomes possible.

With the recent advances in pulsed confinement sources--particularly the source developed by Donets in Dubna, Ariane in Orsay, and others--the problem is somewhat more complicated. The unusually high charge states offer possibilities which are uniquely suited where a high instantaneous flux is essential. We all know that synchrotron injection is one of these situations. In order to compare the Donets' source performance with other sources, we have to include, for the comparison, that part of the accelerator at which similar charge states can be obtained.

Allow me to concentrate on intensity and ion species only, assuming all other parameters to be comparable.

The state of the art for a good conventional source like Penning or Duoplasmatron with a 10 MeV/u linac is roughly sketched in Fig. 4. Also sketched is the performance for a pulsed confinement source in charges per second for a charge-to-mass ratio (q/m) of 1/3. I am assuming that there are 10^{12} useful charges removed per pulse, or inversely, the number of ions in the desirable charge state is given by $N = 10^{12}/q$. A charge-to-mass ratio q/m = 1/3 was chosen in order to be able to make realistic comparisons for high-mass ions. I am fully aware that the graph shown is somewhat qualitative and may justifiably be criticized in detail. I hope we will learn of better numbers during the course of this Conference. However, the point I wish to make is that a good ion source-accelerator combination will, to date, deliver a more intense (CW or nearly CW) heavy-ion beam than a pulsed confinement source possibly could deliver.

On the other hand, for a synchrotron the pulsed confinement source has very substantial advantages. Not only does the pulsed confinement source produce high-charge states, it conveniently stores them and hence is its own very effective buncher. I have attempted to illustrate this point in Figure 5. Note the ordinate in this figure is in charges per 10^{-4} seconds.

A cost comparison seems to favor a pulsed confinement source with a relatively simple linac over a low q/m linac with a DC-type source. Needless to say that with high enough charge states, existing accelerator systems may be used.

Let me stress that the source should most preferably be looked at in the context of the accelerator system to which it will be mated. Furthermore, a flexibility of source type for different species of ion for a particular accelerator should be kept open wherever possible. For too long a time cyclotron sources were internal sources because the magnetic field was already provided. Fortunately, good work has been done at Oak Ridge, at Orsay, Berkeley, and elsewhere to inject radially or axially, to obtain more flexibility for the source type and location. We well know by now that a high-charge state source with large current and small size is a difficult task, hence the source builder should include the first stage of the accelerator as an integral part of the source specifications.

The interesting work on low β linac structures being performed at LASL, Argonne, GSI, and other places may be of great interest in this context. May I suggest that linacs could be matched also into cyclotrons effectively and thus help to reduce charge-exchange losses at low energies.

Applications of Heavy-Ion Accelerators Outside of Basic Research

At the last accelerator conference a very impressive paper was given by M. J. Saltmarsh[5] on simulated damage in solids with heavy ions and neutrons. The energy and intensity employed for heavy ions were both relatively low, and it would be very useful for several facilities to include in the specifications the necessary beams for a good material testings facility. In this context I wish to remind you that the Harwell isochronous cyclotron is almost exclusively devoted to this purpose. I believe some tens of MeV/u and as much current as possible are the rough specifications for such a facility. The parameters for a neutron test facility, while very important, are outside of the scope of this Conference.

Another area which is developing very rapidly is the medical use of high-energy heavy ions for particle radiology and radiotherapy. As many of you know, LBL has been funded to study accelerator systems suitable to perform these tasks. As expected, ion source performance, and in this situation particularly, lifetime and reliability are some of the major problems we anticipate in a major clinical facility.

Reliability - R & D - Operating Costs

As the accelerators are pushed toward higher masses with high intensity, the source maintenance becomes a serious and in some situations limiting problem. It is obviously inadequate for a source to perform well on a teststand only--the source performance has to be reproducible from one day to the next. For high performance sources of ions above mass 100, where source lifetime is measured in hours, the quality control has to be exacting indeed. We rapidly approach the point where it becomes unacceptable to use a source which has not been tested and found up to standard prior to being employed in the accelerator.

We hope the accelerator builder will get some relief from the Electron Cyclotron Resonant source. We will hear shortly from Dr. R. Geller, from Grenoble, regarding the performance of his latest Mafioso[6]. The characteristic I value most in the ECR source is its projected long lifetime. Of course, we also hope for charge states as large as possible with minimal emittance and high brilliance.

Reliable source performance on a day-to-day basis requires a substantial effort from our R&D group at the present stage of source technology. At LBL we hope the same group may also improve the sources steadily, but upkeep of existing sources and understanding why two apparently identical sources have dramatically different output and lifetime is a sizeable job in itself. In fact, for the SuperHILAC at LBL this effort is 10 per cent of the operating cost of the accelerator. This neither includes upkeep of source-related equipment, like power supplies, accelerator column, high-voltage platform, etc., nor does it include acquisition of rare isotopes for use in the sources.

Furthermore, we found it essential at LBL to have teststands which are identical so that a non-performing source may be tested off line in the same environment as in the accelerator to find the reason for its failure.

It is almost anticlimactic for me to repeat at this point that rapid source access is of fundamental importance.

Conclusions

A large effort to bring heavy-ion accelerators on the air is presently under way, as I mentioned in my introduction. Accelerator physicists, as well as experimenters, are looking toward this group for help and guidance as to what can be expected to date, in the near future, and in the long run. We know from many years of experience that the task is not easy. It is the impact good ion sources make in the growing field of heavy-ion research and the challenge the source development in itself poses, which will be a source of inspiration for this distinguished group.

Let me end this note with a summary of an accelerator physicist's challenges and troubles:

The Ten Commandments of a Heavy-Ion Accelerator Builder

1. Thou shalt begin with the reliable creation of a large congregation of ions, densely packed and as naked as possible.
2. Thou shalt separate the chaff from the wheat fast, or convert the chaff into wheat, so that all may be equal.
3. Thou shalt surround thine congregation of densely packed equal ions with great nothingness so that they may remain equal.
4. Thou shalt encourage the congregation to leave the place of birth rapidly (10 MV/m is about right).
5. Thou shalt provide 2, 4, 6 and 8 poles to keep the congregation together.
6. Thou shalt, after an appropriate travel, encourage the congregation to shed unnecessary clothing so that the congregation may reach a higher energy more comfortably.
7. Thou shalt not give the congregation an opportunity to tangle with its stationary neighbors or they will never reach relativistic speeds.

8. Thou shalt be humble if the congregation falls apart prematurely, or the experimenter doesn't know what he is doing. Thou shalt be rewarded in heaven.

9. Thou shalt not exceed $\beta = 1$, or Einstein will become unhappy.

10. Thou shalt perform all the above miracles within budget--fast and reliable--or Saint George will become very unhappy.

Acknowledgements

I have received valuable information and good advice from friends and collaborators too numerous to list. Wherever I have taken data out of context or misinterpreted it, I and I only must accept the blame.

References

1. K. Prelec et al., IEEE Trans. Nucl. Sci., Vol. NS 22, 75, p. 1690.
2. High-Intensity Uranium Beams from the SuperHILAC and the Bevalac, Proposal 32 (LBL-3894), 1975.
3. Basil Gavin, paper C 7, Proceedings of this Conference.
4. R. M. Richter, E. Zajec, paper D 8, Proceedings of this Conference.
5. M. J. Saltmarsh, IEEE Trans. Nucl. Sci., Vol. NS 22, 75, p. 940.
6. R. Geller, paper A 3, Proceedings of this Conference.

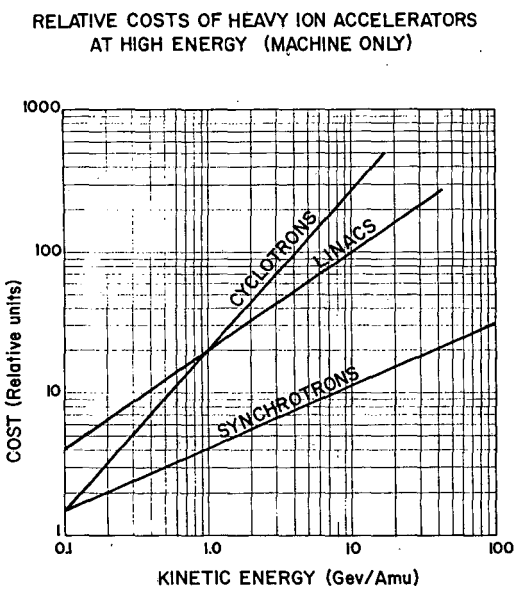


Fig. 1

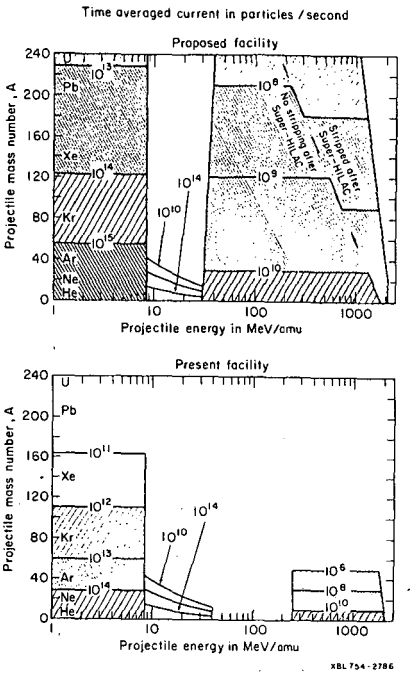
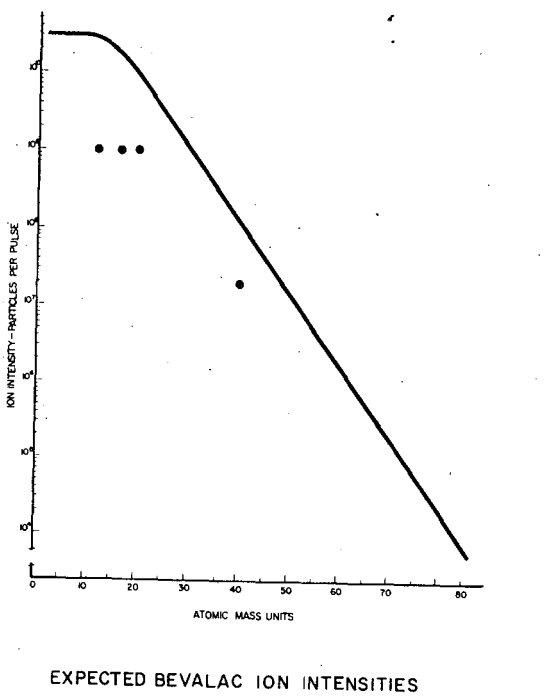


Fig. 2 SuperHILAC/Bevalac Projected Performance



Present Facility

Fig. 3 Data points indicate achievied intensities.

0 0 0 0 4 4 0 3 2 3 6

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720