Particle Accelerators, 1971, Vol. 2, pp. 189–202 © GORDON AND BREACH, SCIENCE PUBLISHERS LTD. Printed in Glasgow, Scotland

TRENDS IN THE UNITED STATES FOR THE ACCELERATION OF HEAVY IONS†

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The performance of US accelerators for heavy ions is compared. The review includes existing accelerators, those under construction, and proposed accelerators. The desirable characteristics for a forefront heavy ion accelerator are listed. A description of the super-HILAC conversion serves to highlight the discussion of progress in the United States. As an example of the possibilities and limitations of present-day isochronous cyclotrons, the heavy ion acceleration capabilities and use of the Oak Ridge Isochronous Cyclotron are discussed. The possibilities of new concepts including superconducting linear accelerators and supervoltage tandems are reviewed briefly. The performance characteristics of major existing and proposed European accelerators are compared.

1. GENERAL REMARKS

Unfolding before our eyes is a story, as you may know, full of excitement and enthusiasm and also of impatience and frustration. It is a story of a new frontier of nuclear physics just on the horizon which seemingly has remained for some time beyond our reach for want of an adequate heavy-ion accelerator. We will try to relate to you how the scene looks to us in the United States of America at the present time. Heavy ion physics first blossomed in 1950 when Lawrence-type cyclotrons were successfully adapted to the acceleration of carbon in the deuteron mode. Due to weak and inadequate ion sources, these early beams were of low intensity and crude in their qualities of emittance and energy spread. After the late 1950s better beams were obtained from some specially built linear accelerators and from some cyclotrons equipped to accelerate beams from much improved ion sources. These matters are familiar to this audience and the papers of this conference are impressive testimony to the substantial depth and breadth of the physics which has been achieved by a productive generation of heavy ion accelerators even while severely limited in projectile mass.

For about four years now the heavy ion physics community has known that important and exciting phenomena probably lie just beyond the reach of our ion masses and energies. Let us mention two things which have happened in the USA in response to this tantalizing situation. A special panel, the 'Ad Hoc Panel on Heavy Ion Nuclear Science and Facilities,' was established by the Committee on Nuclear Science of the National Academy of Sciences. It was asked to review the fields of heavy ion physics and to consider new accelerators which might be needed and to suggest a coherent program based on scientific need. This Panel has submitted a report to its parent committee rather recently and in due course the report will be published. In the meantime, of course, it is not appropriate to describe the conclusions of the report, but we will try at least not to promulgate views which are inconsistent with it. The second event or perhaps series of events you are also quite aware of: during the past few years there have been many many proposals submitted from the largest and most active laboratories as well as from smaller institutions for many different kinds of heavy ion accelerators. During the course of the following we will try to relate where these matters stand. But lest we stir too much hope for good news at the outset, we hasten to add that science generally in the USA is not expanding and new projects in general are not now being authorized.

2. OVERVIEW

We begin by examining a number of different accelerating systems in terms of their output

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† Research sponsored by the US Atomic Energy Commission under contract with the Union Carbide Corporation.

‡ Text of an invited paper presented at the International Conference on Heavy Ion Physics, JINR, Dubna, USSR, February 11–17, 1971, modified for publication in 'Particle Accelerators.'

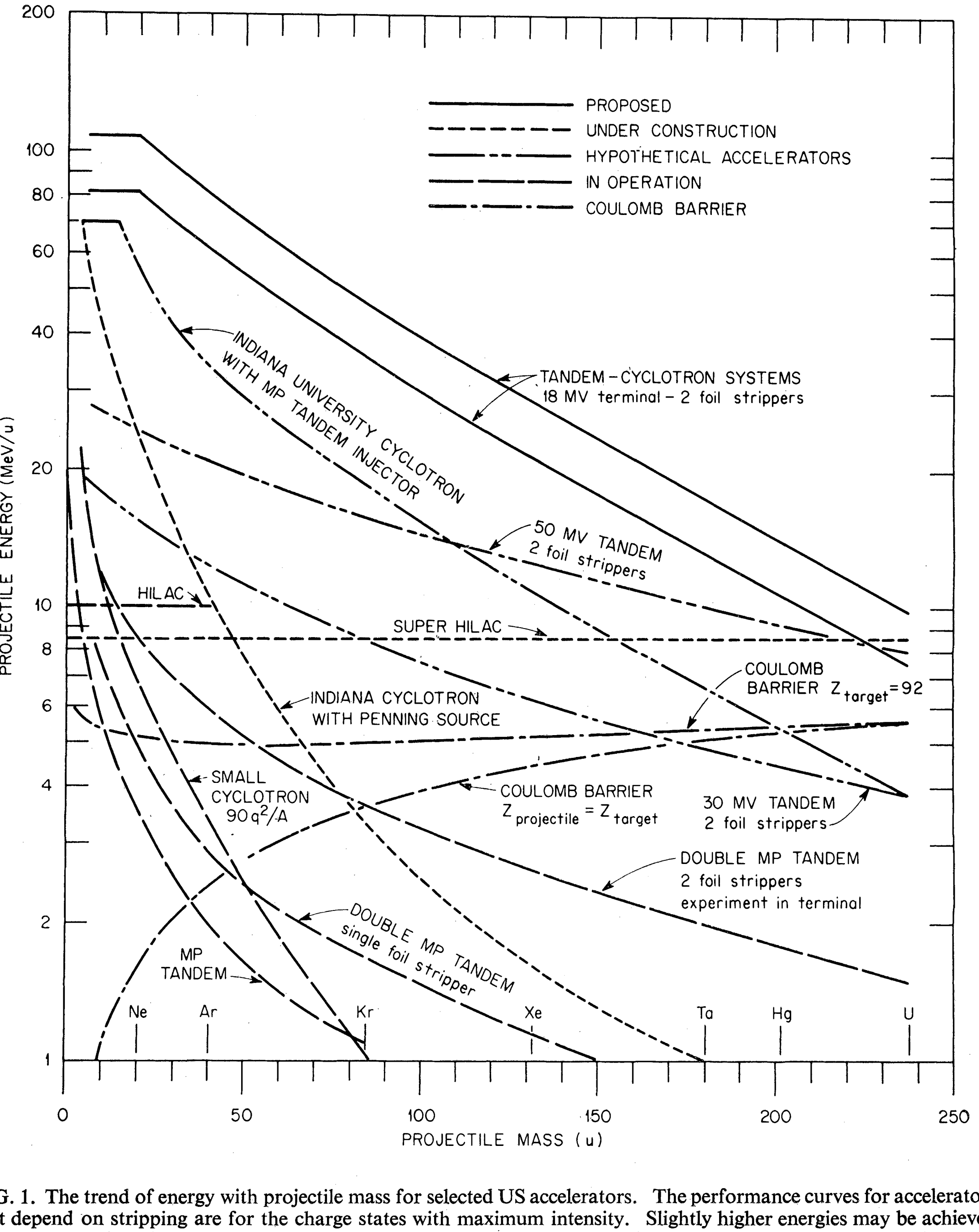

FIG. 1. The trend of energy with projectile mass for selected US accelerators. The performance curves for accelerators that depend on stripping are for the charge states with maximum intensity. Slightly higher energies may be achieved with some sacrifice of intensity. For the tandem and tandem-cyclotron combinations, gas stripping in the terminal may be employed but with significant decrease in intensity for the same energies. The energy-mass curves for the tandem–cyclotron combinations are based on the maximum $B\rho$ of the cyclotron and the most probable stripped charge state and do not take into account possible limitations of energy that may occur as a result of injection radius constraints. The energy of accelerators with Penning ion source is based on charge states with ionization potentials less than ~200 V for their production. Typically, examples are C^{4+}, Ne^{6+}, Ar^{8+}, Kr^{9+}, Xe^{10+}, and U^{12+}. Equilibrium charge of ions in foils and gases is based on the Heidelberg data and analysis.(2) Classical Coulomb barriers are calculated using nuclear radii of 1.5 $A^{1/3}$ fermis.

energies and the masses of the ions being accelerated as shown in Fig. 1. The concept of this presentation has been borrowed from Professor Marshall Blann who used it in a paper(1) presented at the Washington, D.C. meeting of the American Physical Society in April 1970. There are four categories of machines shown on this graph and in addition for reference the Coulomb barrier. The upper Coulomb barrier curve is for a target of uranium and a projectile of mass as indicated on the abscissa scale. The lower barrier plot is for a target of mass equal to the bombarding ion mass. These graphs are to facilitate examination of the regions where accelerators of different types can work effectively. Looking first at the machines currently in operation, we see that there are HILACS, small cyclotrons, and single and double MP tandems. The ion mass which can be accelerated to an energy above the Coulomb barrier is limited to argon, silicon, boron, and fluorine respectively. In the case of the double MP tandem the mass limit may be raised to that of iron if the experiments are done in the terminal, although this is a fairly severe experimental restriction. Considering next the machines under construction, note that there are only two: the Indiana Cyclotron and the super-HILAC. The cyclotron has not been planned primarily as a heavy ion facility, but it is a large machine with an energy rating of 280 q^2/A, slightly larger than the U-300 Dubna cyclotron (before its conversion). Thus it could have important capability if it were equipped for heavy ion acceleration. The super-HILAC will be the subject of more detailed remarks later in this paper, but for perspective it may be noted that it will yield ions of all masses up to an energy of 8.5 MeV/u. We turn next to the proposed machines. The two upper curves are drawn for the approximate conditions for the Argonne National Laboratory and the Oak Ridge National Laboratory tandem-cyclotron proposals respectively. They have the obvious characteristic of higher energy per nucleon as the mass of the ion decreases. This is simply a reflection of the high q/A values which can be reached by stripping for the lower mass ions. Finally there are several curves labeled 'hypothetical.' These are very interesting but have not yet been proposed in the USA. Note first the various superpotential tandems. If a terminal potential as high as 50 MV could be reached, then one would have a powerful accelerator indeed. Even a 30-MV tandem would accelerate to the rare earth region at mass 160 up to 6 MeV/u. Also we have shown the results of using an MP tandem as an injector to the Indiana cyclotron. Note how much the range of the cyclotron in ion mass is increased over the Penning source case. This then is a brief summary of the principal accelerators of interest in the USA today.

3. ACCELERATORS PRESENTLY IN OPERATION

It is pertinent to review quickly the present US heavy ion accelerators. If we limit the discussion to those machines that can at least react boron on uranium, there are nine: 2 HILACS, 3 MP tandems, 1 double MP tandem, and 3 cyclotrons. The Lawrence Radiation Laboratory HILAC should perhaps not be included as it is just being closed down for its conversion to the super-HILAC. It has had a very distinguished career for some 14 years and it is fitting that its traditions will be carried on by a new and more powerful reincarnation. At Yale University a similar HILAC has a substantial heavy ion physics program. The three MP tandems are located respectively at Yale University, the University of Rochester, and the University of Minnesota. The new double MP tandem at the Brookhaven National Laboratory was dedicated on November 19, 1970 and is already heavily involved in a program of physics with heavy ions. The heavy ions in the double MP are most commonly accelerated using the three-stage configuration with a negative ion source in the terminal of the first stage and stripping in the terminal of the second stage. The three cyclotrons are the Lawrence Radiation Laboratory 88-in., the Texas A and M TAMVEC, and the Oak Ridge National Laboratory ORIC. The current program on the latter cyclotron perhaps typifies the capability of present-day isochronous cyclotrons for heavy ion acceleration. In Fig. 2 is a characterization in three dimensions of the research activity on the ORIC as a function of particle energy and particle mass. Note especially the heavy mass region of the figure. During recent months our work has averaged from 50 per cent to 70 per cent use of heavy ions in contrast to much smaller

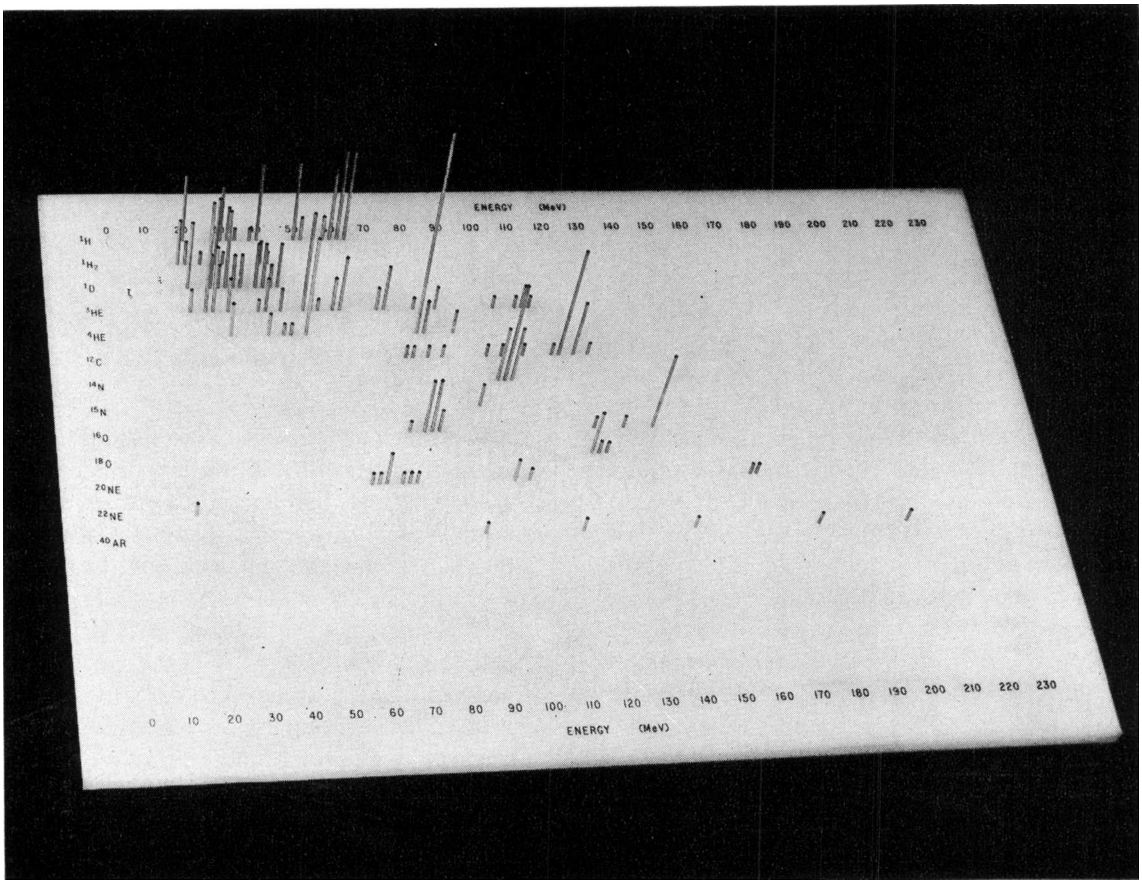

FIG. 2. Display of research on the ORIC by accelerated particle and particle energy for the calendar year 1970. Each pin represents operation of the cyclotron at a specified set of conditions for at least one experiment. The height of the pins is proportional to the number of experiments at a given setting of the cyclotron.

fractions in earlier periods. Some examples of this work have been reported elsewhere at this conference. Table I is a list of heavy ions which have been accelerated on the ORIC.(3) Note particularly Ar^{10+} and Xe^{12+}. While these ions have not yet been developed into high intensity beams, we believe it is important to have verified their successful acceleration. In Fig. 3 the verification of the xenon peak using a solid state detector is shown. The abnormal width of the energy peak and its low value are due to the thickness of the gold scattering foil used in the measurement.

4. FUTURE ACCELERATORS

Accelerator Characteristics

It is pertinent to ask the question: what are the needed and desired characteristics of a new heavy ion research facility beyond the performance characteristics of the presently operating accelerators? The following specifications are suggested:

1. Range of ion masses—all elements through uranium.
2. Energy of particles—10 MeV per nucleon or higher with fine energy variation down to 2 MeV per nucleon.
3. Beam current—1 particle microampere where feasible—at least 10^{11} particles per second for all elements.
4. Energy homogeneity—at least 1 part in 3000 using beam analysis if necessary. The desired energy band should contain 10^{10} particles per second.
5. Beam emittance—less than 25 mm-mrad (10 MeV/u).

TABLE I

ORIC extracted beams

Particle	Rf Frequency (MHz)	Harmonic	Maximum ORIC Energy(a) (MeV)	Measured Energy (MeV)	External Beam Current (eμA)(b)
$^{12}C^{3+}$	21.9	3	67		>10
$^{12}C^{4+}$	9.2	1	120	119	>12
$^{14}N^{2+}$	12.4	3	26		>20
$^{14}N^{4+}$	7.9	1	103		>20
$^{14}N^{5+}$	9.9	1	161	165	2
$^{15}N^{4+}$	22.2	3	96		3
$^{16}O^{4+}$	20.7	3	90	80(c)	>4
$^{16}O^{5+}$	8.6	1	140		20
$^{18}O^{5+}$	7.7	1	125	122	20
$^{20}Ne^{4+}$	16.7	3	72		>1
$^{20}Ne^{5+}$	20.7	3	112		>1
$^{20}Ne^{6+}$	8.3	1	162	167	3
$^{22}Ne^{2+}$	7.9	3	16		>100 enA(d)
$^{22}Ne^{5+}$	18.9	3	102		80 enA(d)
$^{35}Cl^{5+}$	12.4	3	64		>1 enA
$^{36}Ar^{9+}$	20.7	3	202		$\sim 5 \times 10^5$ part/sec
$^{40}Ar^{8+}$	16.7	3	144	146	300 enA
$^{40}Ar^{9+}$	18.8	3	182	180	$\sim 1 \times 10^8$ part/sec
$^{40}Ar^{10+}$	20.7	3	225	205(c)	$\sim 5 \times 10^4$ part/sec
$^{63}Cu^{9+}$	12.4	3	116		1 enA(e)
$^{66}Zn^{6+}$	7.9	3	49		0.1 enA(e)
$^{132}Xe^{12+}$	7.9	3	98	98	$\sim 1 \times 10^7$ part/sec

(a) Based on 90 q^2/A.

(b) Electrical microamperes except as noted.

(c) Cyclotron adjusted for an energy below maximum.

(d) Natural isotopic abundance gas as source feed.

(e) From ion source material of construction.

It seems generally accepted that either tandem–cyclotrons, carefully designed linacs, or super-voltage tandems could be designed to meet these performance characteristics.

Accelerators Presently Authorized

This amounts to a review of the status of the single new heavy ion accelerator authorized by the US Congress, the super-HILAC.(4) This project directed by Robert Main of the Lawrence Radiation Laboratory has been described at other conferences and so it is not necessary to give a full description of it here. To remind you of its basic features refer to Fig. 4 which shows the layout of the building both in plan and elevation. The new accelerator tanks are substantially longer than those of the older HILAC which is being replaced. Experimental and shop space is thus being taken over to provide the extra needed room. Figure 5 gives the principal design features listing cell number, particle energy, particle velocity, cumulative length, minimum charge-to-mass ratio, field gradient, focusing configuration, lens strength, and drift tube diameter. Figure 6 shows a view of the internal structure of the pressurized 3.0-MV injector. The heavy ion source being assembled on the high voltage terminal of the injector is shown on Fig. 7. The present schedule called for HILAC shutdown for conversion February 5, 1971; later information indicates that this was done. The new tanks have been prefabricated in sections and are presently in the yard adjacent to the HILAC building. The old tanks will be pulled out as rapidly as possible and the new accelerator erected in place. Most of the drift tube assemblies are now complete or in final stages of assembly. One of these is shown partially assembled in Fig. 8. Much of the electrical modification is already completed. The first radio-frequency tests will be started the last of July 1971 with the first beam hoped for as early as August or

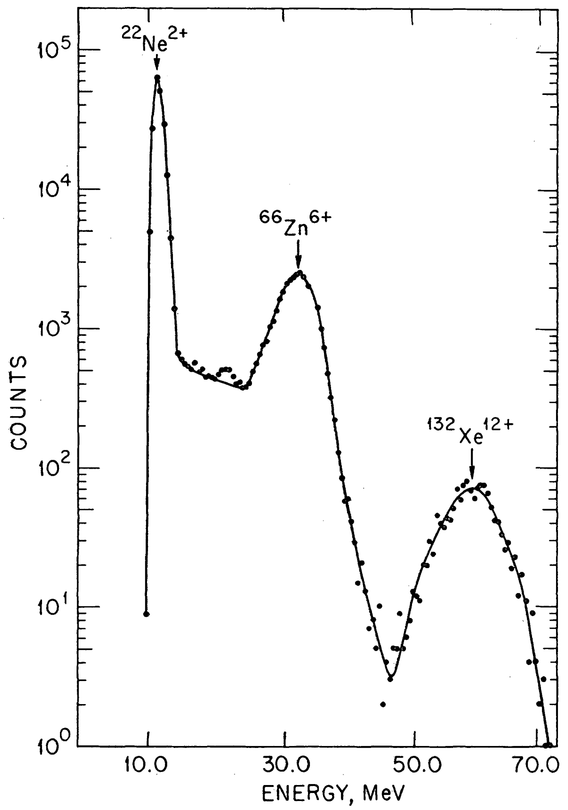

FIG. 3. Count rate *vs* energy for the cyclotron resonance at q/A of 1/11. The external cyclotron beam is scattered on a gold foil (1.5 mg/cm^2) and detected in a silicon surface barrier detector.

September of 1971. It is expected that the new super-HILAC will be running well for experiments by February 1972.

Proposed Accelerators

It seems appropriate to say rather little about the standing US proposals; most are well known and the scene is characterized by conspicuous inactivity at this time (February 1971). There are still five or six combination tandem–cyclotron proposals: from Argonne, Oak Ridge, Michigan State, Rochester, and Los Alamos principally. Recently from the University of California at Los Angeles came a study of a novel two-gap-magnet cyclotron.(5) In this system the beam is first accelerated in the lower gap, is extracted and then after stripping is reinjected in the upper gap and accelerated to final energy. In the case of the tandem–cyclotron proposals both the laboratories at Argonne and at Oak Ridge have proposed splitting their projects into two phases with the first phase being the obtaining of the injector tandem, at about 20 per cent of the total project cost and the later phase, the addition of the cyclotron. This has two advantages: first it would require only a small immediate investment, and second it would permit more experimental investigation of the details of stripping, foil life, charge exchange cross sections, and vacuum requirements. However, as of yet, there is no indication of any affirmative reaction to this plan. One interesting sidelight to this situation is the successful development of the 'Pelletron'(6) accelerator by the National Electrostatics Corporation of Madison, Wisconsin. A composite photograph of some of the components of such an accelerator is shown in Fig. 9. Here one sees the unique chain-type belt used for the Pelletron charging system as well as the support structure and accelerating tube modules. Another proposal which addresses itself to a basically different area of science is the proposal of the Princeton–Pennsylvania Accelerator(7) to modify its synchrotron structure to accelerate heavy ions to many hundreds of MeV/u. These then would be used for biological and physical experiments appropriate to this energy range.

Possible Adaptations of Existing Accelerators

In the face of little action on the tandem–cyclotron proposals, it is natural to examine what performance could be obtained by the use of existing accelerators perhaps with significant modifications. Clearly the most interesting possibility is the Indiana separated-sector cyclotron.(8) Because it is a large cyclotron, energy rating of 280 q^2/A, the simple addition of a state-of-the-art Penning discharge source would enable it to carry zinc ions over the potential barrier of uranium as has been indicated on Fig. 1. Much more dramatic, however, are the results which could be obtained if a large tandem, an MP for example, were installed as an injector. This would yield suitably energetic ions up to the samarium–mercury region ($A \sim 150$–200). However one must realize that the Indiana cyclotron is still in the construction phase and it will be about two years before it is working in its light particle mode accelerating protons, helions etc., and it is not likely that its original purposes would be switched now so long before its completion. A

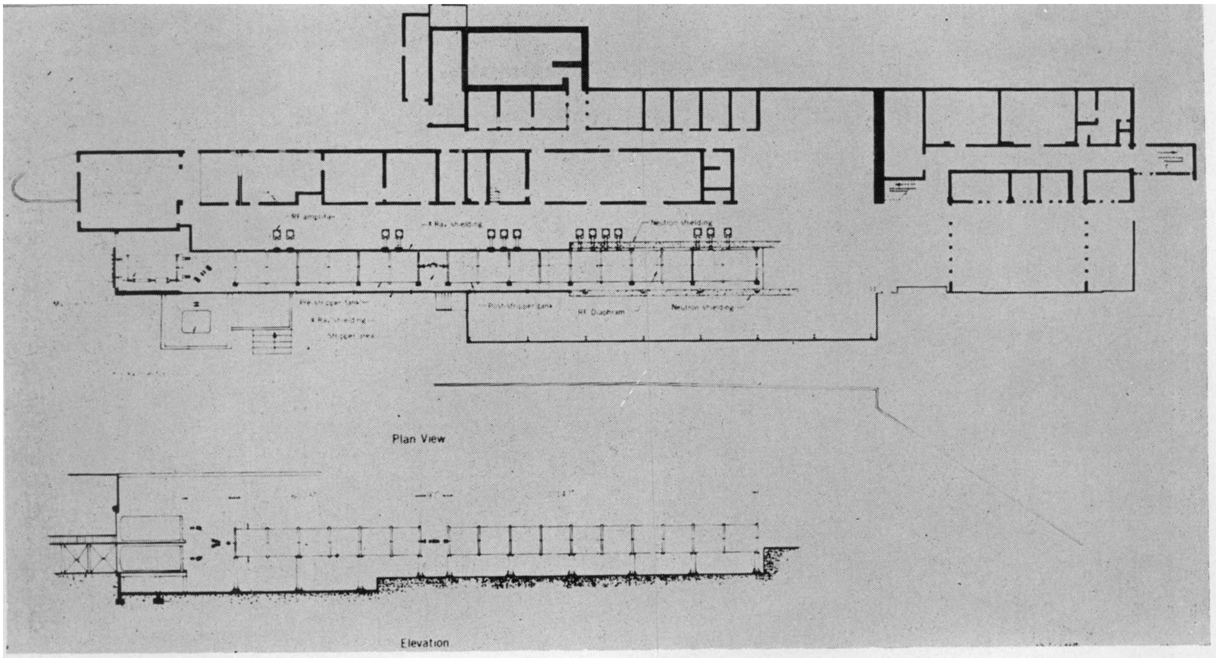

FIG. 4. Super-HILAC building plan and elevation.

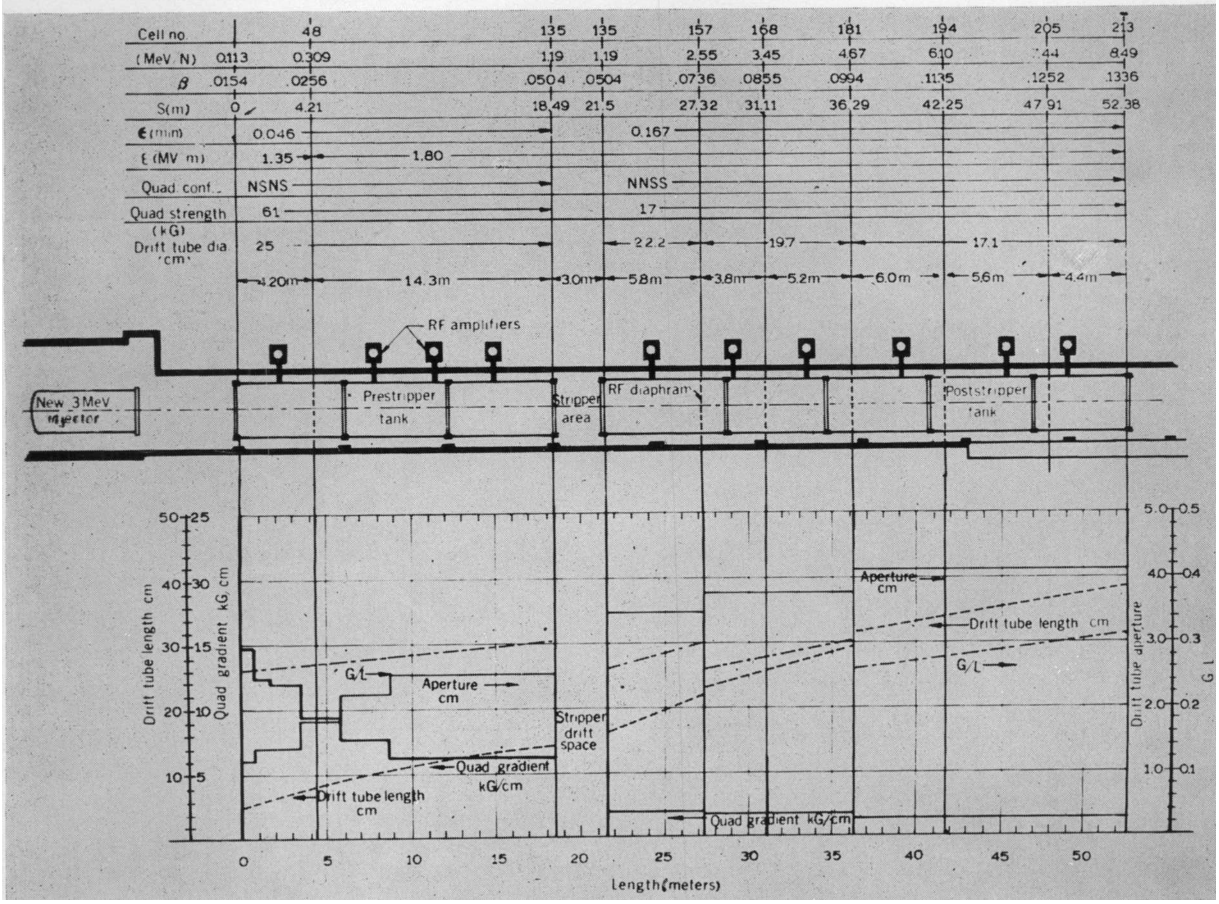

FIG. 5. Design parameters for the super-HILAC.

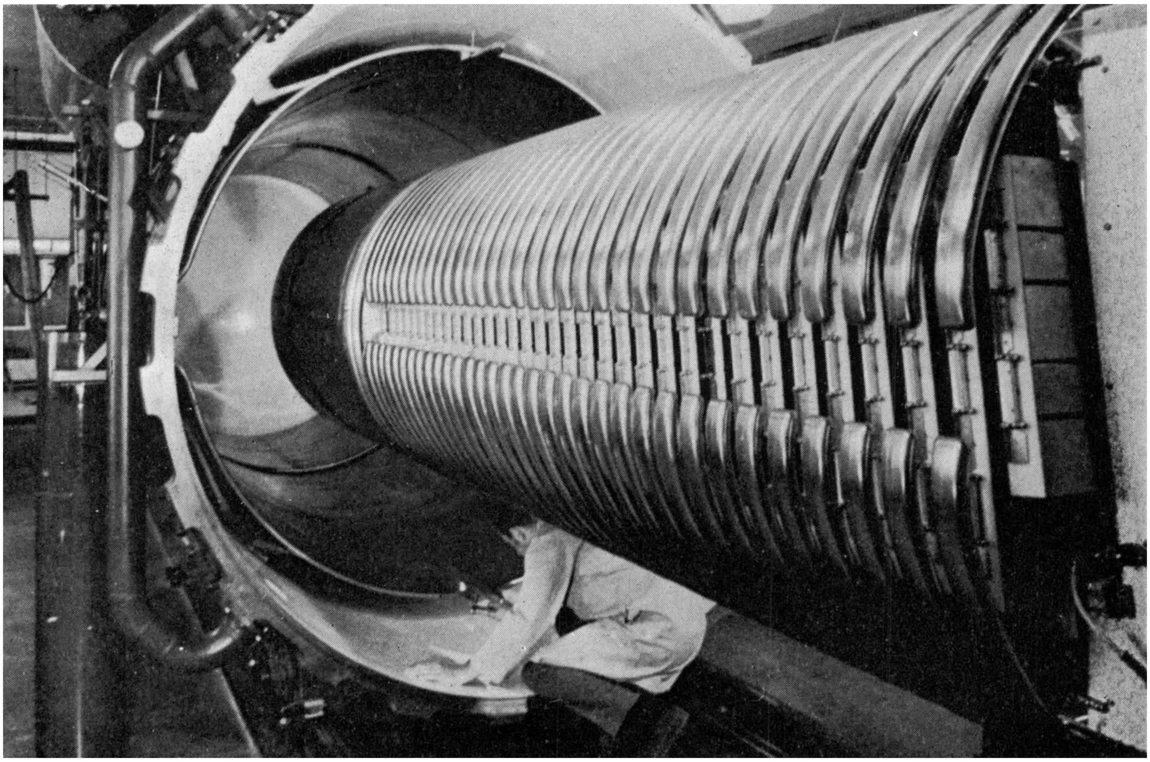

FIG. 6. The high voltage column of the 3.0-MV injector of the super-HILAC.

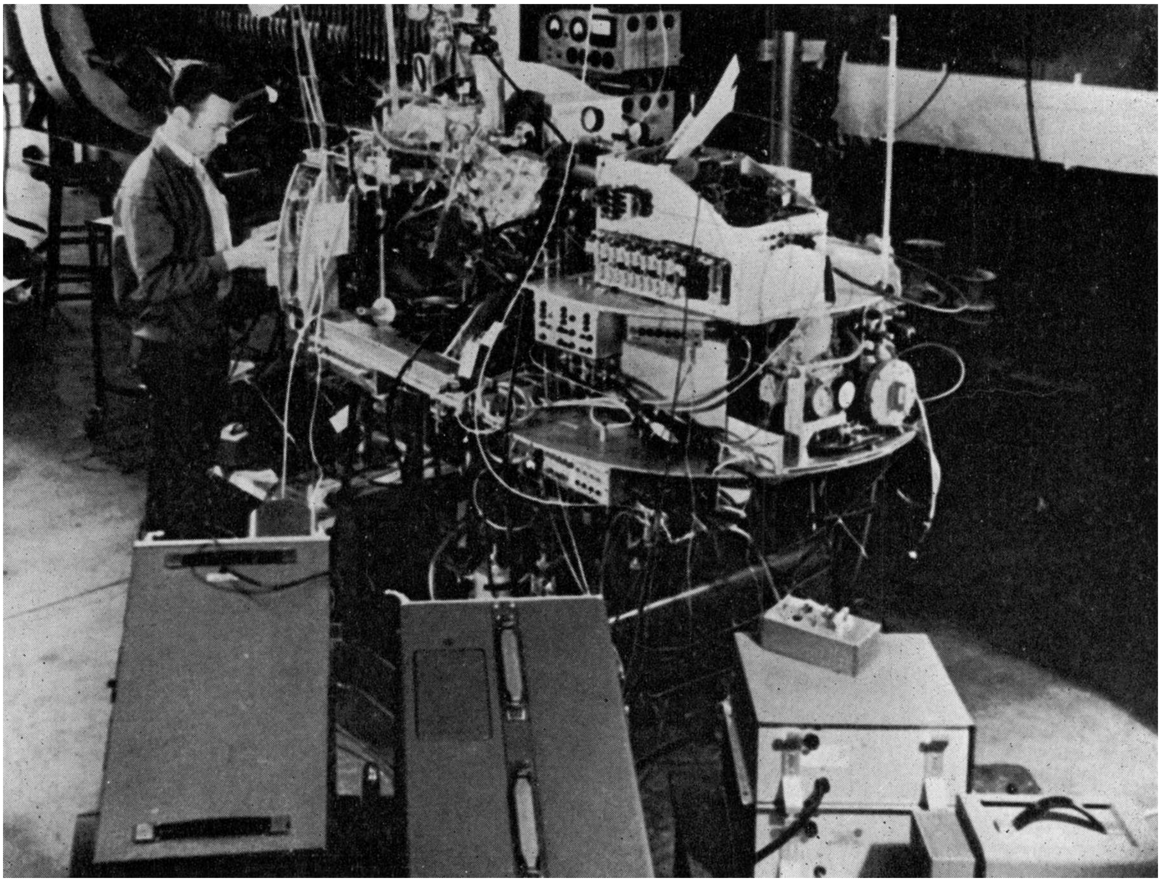

FIG. 7. Ion source in process of assembly on the high voltage terminal of the injector.

second but less powerful possible adaptation of an existing accelerator would be the addition of a similar injector to the University of Maryland Cyclotron (MUSIC)$^{(9)}$ which has an energy rating of 185 q^2/A.

Another possible modification of existing accelerators is the scheme being considered for the MP tandem at Heidelberg,$^{(10)}$ namely the addition of a series of helical linac sections to its output as an energy booster. To our knowledge no one is proposing to do this in the USA but it would appear that this is an effective means to substantially increase the capacity of an MP tandem. Later we will show some details of this capability in connection with a brief view of the European scene.

5. POSSIBILITIES UNDER STUDY

Superconducting Linacs

The development of accelerating systems based on the use of superconducting cavities constitutes one of the most interesting and potentially promising new possibilities on the horizon. Several years ago tests were made on X-band (8000 MHz) niobium cavities arranged in a configuration to accelerate electrons with very high cavity Q's and high average field gradients. With these measurements as a base, a group at Stanford University, under Professors Schwettman and Fairbank, have undertaken to design and develop an electron accelerator to go to high energy. Their design features L-band cavities (1300 MHz) in an array approximately 150 meters long with a planned energy of at least 2000 MeV. The design and construction of this installation is well along. The shielded tunnel, refrigeration system (300 W at 1.8 °K), the low temperature plumbing, and the large helium dewars are either complete or in an advanced state. However, the cavities, which undergo an elaborate chemical and temperature cycling procedure to produce the proper surface conditions, have not yet been brought up to the needed performance specifications. The cavities seem to have high performance (Q above 10^{10}) at low power but exhibit an unwanted and excessive field emission as the power and electric fields are raised. This phenomenon of course drives the cavities normal or reduces the Q by producing small normal regions. This new cavity phenomenon was not observed on X-band structures and is now under intensive investigation. It is believed to be some type of surface defect phenomenon. In any case the laboratory is planning large-scale

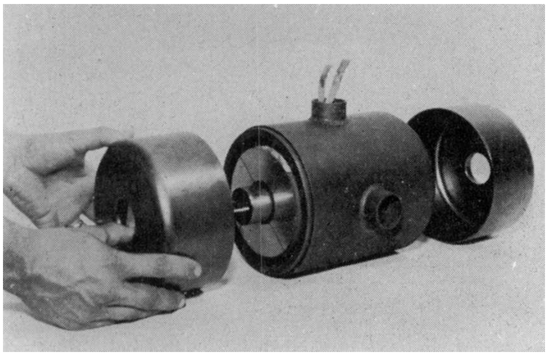

FIG. 8. Super-HILAC drift tube—quadrupole partially assembled.

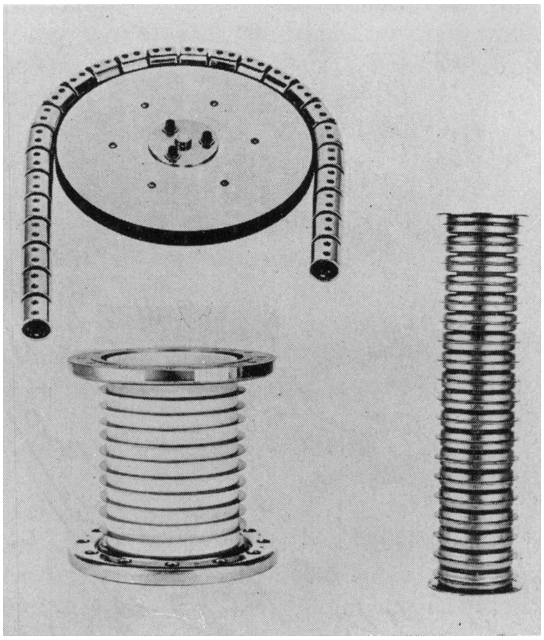

FIG. 9. Components of the NEC Pelletron. *Right*, support post. Metal and ceramic with metal bonding agent. Modulus, one inch. These are utilized to form the 1-MV column modules. Support posts are all identical and interchangeable. These units are also used for rotating shafts to furnish power. *Upper left*, charging chain. Consists of metal cylinders joined by links of insulating material. *Lower left*, accelerating tube section. Metal and ceramic with metal bonding agent. Modulus, one-half inch. Three of these are used per 1-MV column module.

testing of cavities, study of surfaces by optical and electron microscopy and investigations with many other techniques. Schwettman and his colleagues believe that they will soon have a solution to these problems. One of their approaches will be to study intermediate frequency S-band (3000 MHz) cavities. It is expected that new understanding and information will appear as a result of these studies.

Assuming that the problems described above are solved in the near future, it would appear attractive to consider the design of a heavy-ion superconducting linear accelerator. A small group at Stanford University, led by Hilton Glavish, is studying various ways to lay out such an accelerator although no definitive plans have yet been developed. However we will try to describe some typical thoughts which are under consideration at present. The accelerator might consist of four sections: (1) an injector, (2) a first section with fixed velocity profile, (3) a second section with re-entrant independently phased cavities, and (4) a final section at higher frequency also of re-entrant independently phased cavities. For example the injector might be a nonpressurized Cockcroft–Walton at 700–800 kV, the first section might be at ~70 MHz, the second section at ~220 MHz, the third section at ~440 MHz. This type of linac could be adjusted to accelerate protons and deuterons to 250 MeV, and all other ions to at least 10 MeV/u without a stripper anywhere in the system. There are as yet no firm cost estimates, but the staff believe that the costs will be substantially lower than alternative types of accelerators.

Electron Ring Accelerator†

The collective method of acceleration continues to intrigue many investigators in the USA and consequently many studies are under way. Also, of course, similar studies are being made in Dubna and elsewhere in Europe. There are no new results from the USA to report at this time, so far as we are aware.

Supervoltage Tandems

During the last two decades the terminal potential which can be held stably on electrostatic generators has steadily risen. Groups in the USA and in England have considered the possibility of achieving further large increases in terminal potential. For the acceleration of heavy ions such a development could be of great importance. In Fig. 10 is shown the rapid rise in effectiveness of a heavy ion tandem accelerator as the terminal potential is increased. In the USA scientists at High Voltage Engineering Corporation have developed a preliminary design for a 30–40 MV terminal system. Further development of this system in the USA must await an authorized proposal.

Ion Sources

There have been excellent review articles(11) on ion sources in recent years, and we will not endeavor to summarize these. There was an informal conference(12) in Washington, D.C. last March 1970, and a copy of the notes of this meeting has been given to Professor Flerov. Recently at Oak Ridge we have built a new cold cathode Penning ion source for our cyclotron and have already shown in this paper some results of its performance in terms of new beams. We show a sketch (Fig. 11) of the new source as an example of a very compact source of high power mounted from a single radial

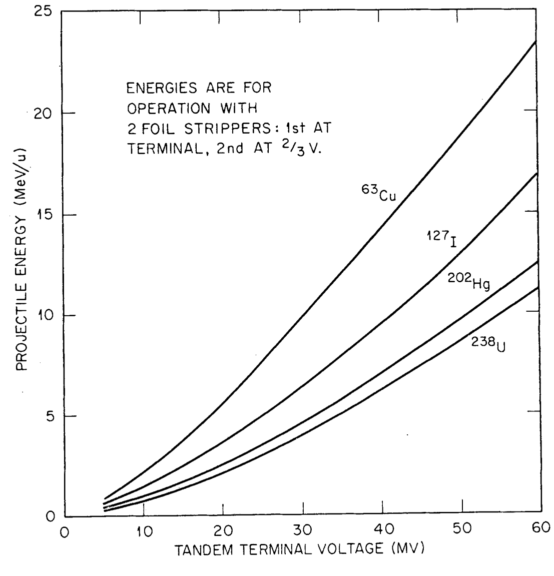

FIG. 10. The variation of output energy with terminal voltage for tandem accelerators. The curves are for maximum intensity charge states based on the Heidelberg data and analysis.(2)

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† At this heavy ion physics conference the Dubna collective accelerator group reported the successful acceleration of alpha particles to an energy of 29 MeV.

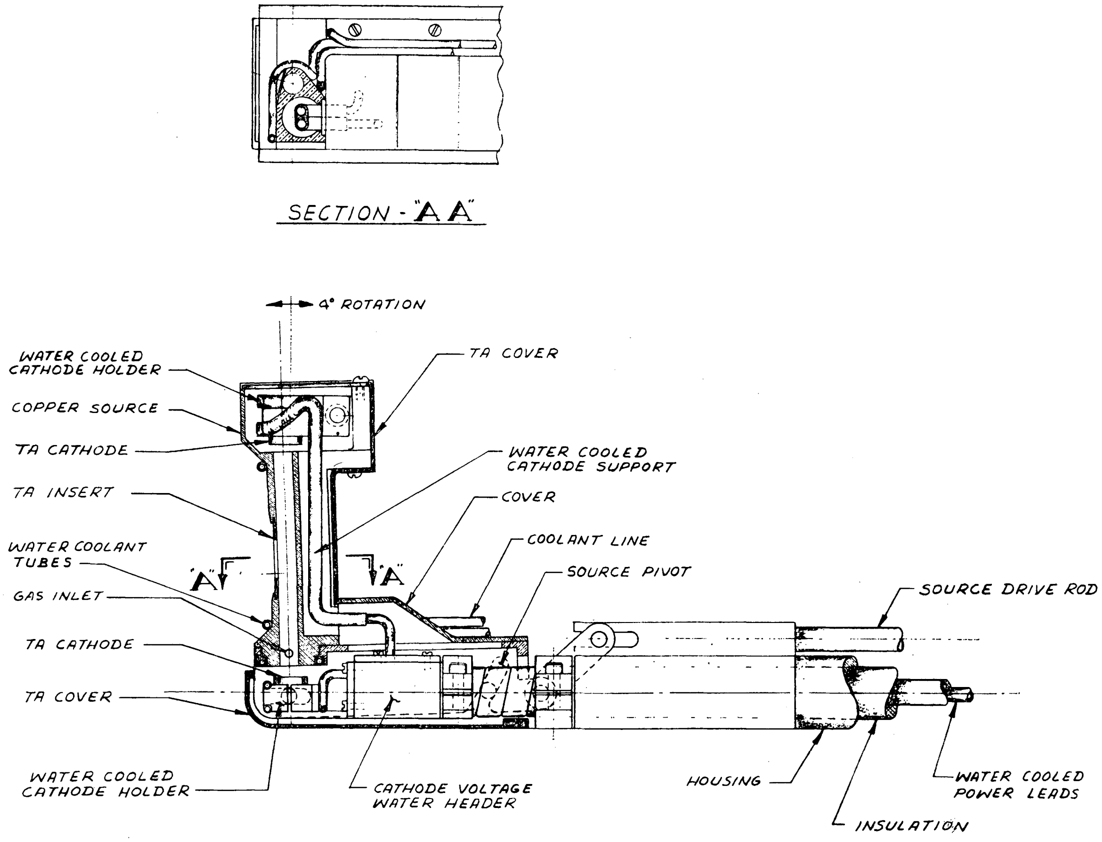

FIG. 11. A sketch of the ORIC cold cathode Penning ion source for heavy ions.

stem. The source is powered by a 75 kW capacity (6.2 kV, 12 A) dc power supply which contains a series vacuum tube current regulator. For various reasons we have not yet been able to subject this source to the systematic measurements which need to be done. However in Fig. 12 some of the operational points achieved by the new ORIC source are compared with the trends of ionization potentials through the periodic table, from a set of calculations by T. A. Carlson and his collaborators.(13) Microampere ion yields are obtained for species with ionization potentials up to the 100–200 volt region; much smaller currents are seen up to ionization potentials of 500 volts.

The USA View of Europe

We conclude this paper with the USA view of heavy ion acceleration in Europe. Figure 13 displays an overview of the major European accelerators, proposed, under construction, and in operation. The style of this figure is similar to the first figure of this paper. The curve for the 3.1 m U-300 cyclotron is adjusted to the latest information on its performance characteristics. With respect to the performance curve for the Dubna 4.0 meter cyclotron, it should be emphasized that certain ion source characteristics were assumed. Improvements in ion source output can make the energies move upward sharply. The other accelerators shown are less sensitive to source performance because they involve a stripping stage. Also, we make the observation that the accelerators which incorporate stripping will generally have lower intensities. For example, the intensity of the Dubna cyclotron with its internal source and lack of any stripping-loss factors could be expected to be much higher than that of the others. The UNILAC, developed by Professor Schmelzer's group at Heidelberg, is now under construction at a new laboratory at Wixhausen near Darmstadt. It is a

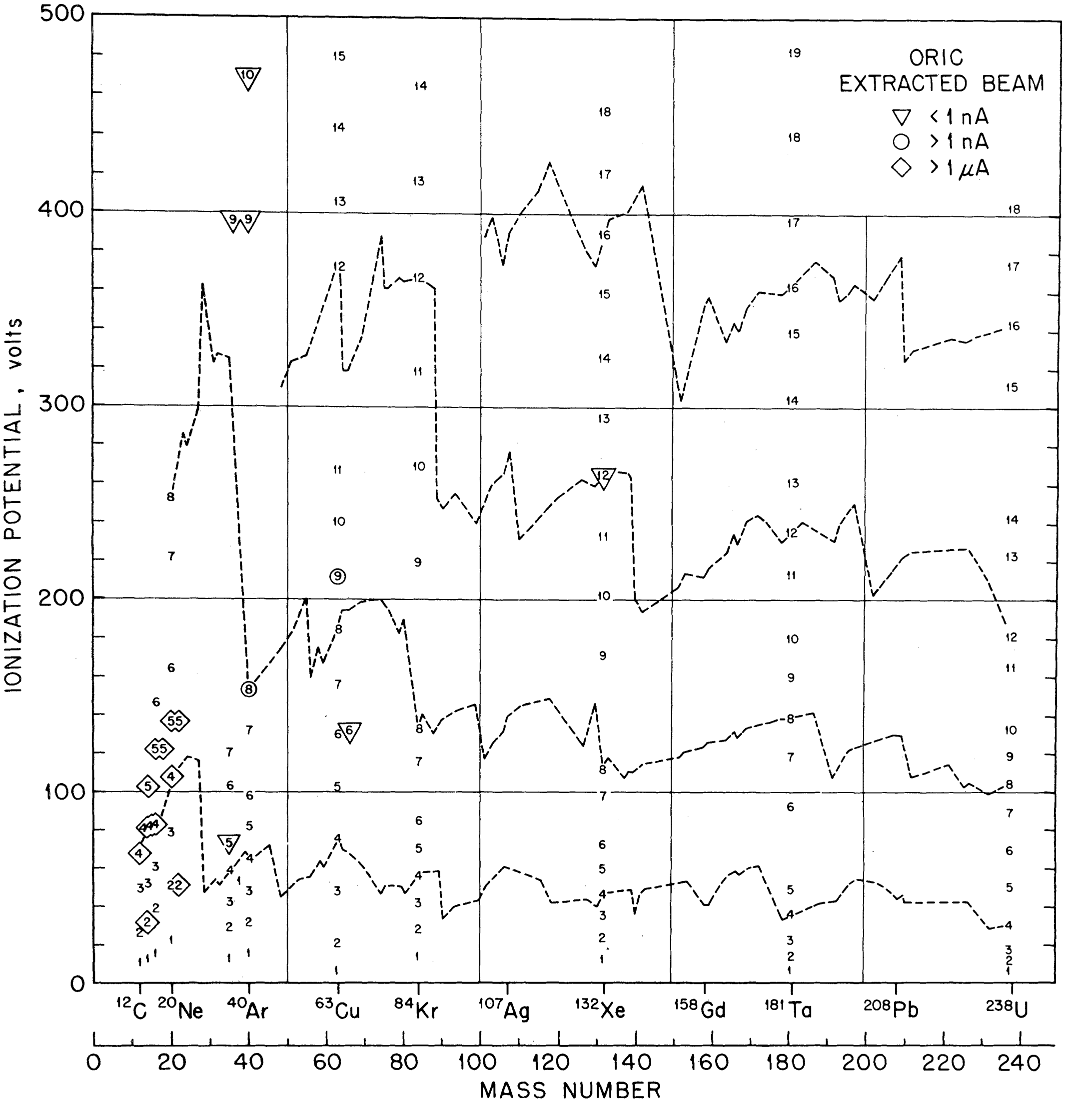

FIG. 12. A plot of the ionization potential to achieve indicated charge states from the next lower state of ionization. For example, the 100 volts shown for $^{63}Cu^{5+}$ is the ionization potential of $^{63}Cu^{4+}$ for the transition $^{63}Cu^{4+} \rightarrow {}^{63}Cu^{5+}$. Values are given up to about 500 volts for the full range of ion masses. Ion source performance for the ions accelerated in the Oak Ridge Isochronous Cyclotron is indicated in three categories of beam current intensity. The calculations of the ionization potentials are based on a simple spherical shell model using eigenvalues and mean radii from Hartree–Fock solutions for neutral atoms. According to the authors the average deviation of calculated ionization potentials from experimental values was found to be less than 5 per cent.

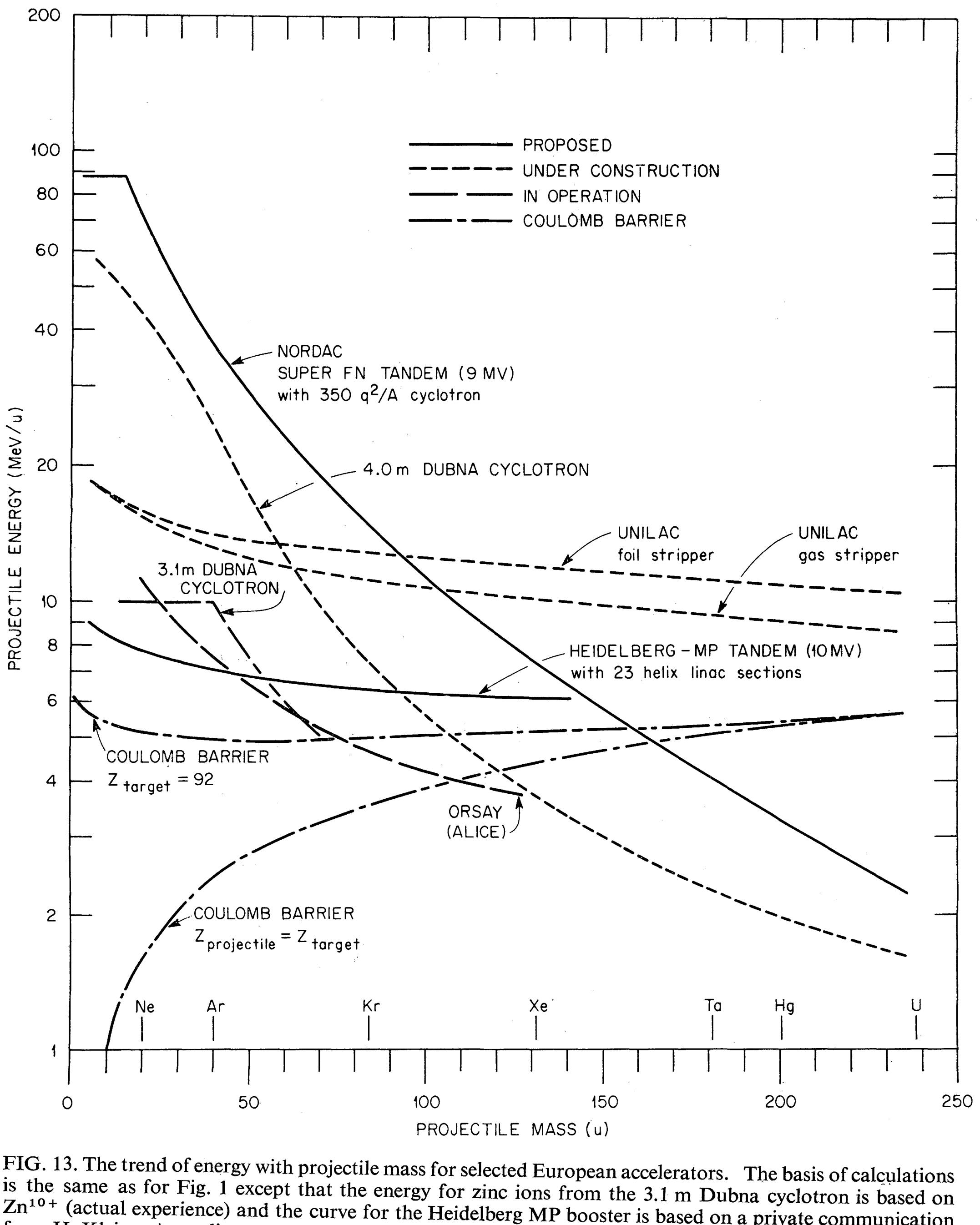

FIG. 13. The trend of energy with projectile mass for selected European accelerators. The basis of calculations is the same as for Fig. 1 except that the energy for zinc ions from the 3.1 m Dubna cyclotron is based on Zn^{10+} (actual experience) and the curve for the Heidelberg MP booster is based on a private communication from H. Klein. According to more recent information (February 15, 1971) the helix booster will consist of only 16 sections and will provide > 6 MeV/u up to bromine. The performance of the NORDAC accelerator (to be located at the Niels Bohr Institute, Risø, Denmark) is based on the use of gas stripping in the terminal of the Super-FN tandem.

multisection linear accelerator with a final section of independently driven cavities giving it an unusual capability for energy variability and multiparticle acceleration. Gas or foil strippers can be used equally well. The 'ALICE' accelerator at Orsay is the first example of high energy injection into a cyclotron. A Sloan–Lawrence type linear accelerator injects heavy ions at 1.16 MeV/u into a cyclotron with an energy rating of 70 q^2/A. The accelerator initially accelerated 10^8 particles per second of K^{21+} to 400 MeV. It is clear that a high level of activity in heavy ion acceleration is now under way in Europe. This activity is characterized by the participation of many laboratories on a substantial scale and by an impressive diversity of acceleration methods.

We hope that the foregoing has served to place in perspective the many and diverse approaches to the acceleration of heavy ions, and that when we meet again for another such conference most of the accelerator problems confronting us now will have been solved.

ACKNOWLEDGEMENTS

The authors wish to thank the many individuals who assisted us in obtaining recent information on various aspects of heavy ion acceleration. Among those who were very helpful are the following: J. R. J. Bennett, High Energy Physics Laboratory, Stanford University, Palo Alto; R. Beringer, Yale University, New Haven; Marshall Blann, University of Rochester, Rochester; G. N. Flerov, Laboratory for Nuclear Reactions, Dubna, USSR; H. F. Glavish, High Energy Physics Laboratory, Stanford University, Palo Alto; E. D. Hudson, Oak Ridge National Laboratory, Oak Ridge; H. Klein, University of Frankfurt, Frankfurt, Germany; R. S. Lord, Oak Ridge National Laboratory, Oak Ridge; R. M. Main, Lawrence Radiation Laboratory, Berkeley; Merrit L. Mallory, Oak Ridge National Laboratory, Oak Ridge; O. Nathan, Niels Bohr Institute, Copenhagen, Denmark; J. M. Peterson, Lawrence Radiation Laboratory, Berkeley; P. H. Rose, High Voltage Engineering Corporation, Burlington; Ch. Schmelzer, University of Heidelberg, Heidelberg, Germany; and H. A. Schwettman, High Energy Physics Laboratory, Stanford University, Palo Alto.

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Received 26 April 1971