TANDEM ACCELERATORS OF THE FUTURE

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Summary

From the impetus of world-wide acceptance, the tandem-accelerator technology is continuing to advance rapidly. In a broadly based group of research and development programs at HVEC, the following areas are already producing important results for future tandem performance and design:

a. intense beams of positive and negative ions, as well as neutral particles;

b. powerful sources of high-voltage direct current;

c. injection studies for light and heavy ions;

d. efficient charge-changing techniques and systems;

e. high transmission of ion beams through the tandem;

f. improved voltage insulation in vacuum and high-pressure gases.

The common objectives of these programs is to upgrade progressively the performance and scope of existing tandem designs, with an ultimate aim of providing the research scientist with a complete freedom in his choice of nuclear collisions.

Introduction

Since its first research installation in 1958, the tandem accelerator has rapidly attained world-wide acceptance as a precisely controllable source of dc proton beams with maximum energies in the 8 - 20 Mev range[1]. To a lesser extent, the heavy-ion acceleration capabilities of the tandem have begun to be recognized[2]. Indicative of the popularity of this accelerator system is the increasing number of installations throughout the world, as shown in Figure 1. Four basic designs are represented, and several combinations of negative-ion and neutral-beam injection systems have been utilized, to enhance the versatility and particle-energy range of the tandem principle.

The progress in the development of the tandem accelerator has been mainly concentrated at High Voltage Engineering Corporation. Two 12 - 14 Mev tandems have also been built by the scientific staffs at AWRE Aldermaston and AERE Harwell in England[3]. Less ambitious efforts have been started in USSR and in Japan. Because of the advanced nature of the work at HVEC, however, this paper will confine itself to the accomplishments and plans of this company.

In order to organize a long-range program of research and development to extend the tandem technology, it is necessary to have a firm ultimate objective that involves not only the direction of hardware and technique development but also the future needs of the scientist. As the tandem has progressively exhibited its capability for heavy-ion acceleration, it has become increasingly evident that substantially higher energies can be attained than for protons, through the phenomenon of multiple electron stripping[4]. The scientist has thus been able to study the structure of atomic nuclei with far greater freedom in choice of accelerator parameters than heretofore possible.

The ultimate in this type of research is a complete freedom in choosing the nuclear collisions, from which valuable information can be obtained concerning nuclear forces, nuclear structure, nuclear fission, and even transuranic elements. By using several successive strippers along the tandem acceleration tube, for example, very high charge states could be obtained for heavy ions. With a reasonable extrapolation of present tandem technology, it should thus be possible to accelerate uranium ions to sufficiently high energies to penetrate or at least to influence the uranium nucleus. Through such a demonstration, the entire scope of nuclear-interaction pairs would be opened up. Figure 2 is a representation of this trend. Since the creation of the universe, there has been remarkably little opportunity for many types of nuclear collisions until the discovery of radioactivity and the development of the particle accelerator. With the HILAC and existing tandems, the curve of nuclear choice has started to rise. During the next few years, the complete field could be available, in which all stable isotopes could be selectively utilized to provide experimental information in answer to questions posed by the theorists.

To support the reality of this ambitious and provocative objective, it is important to review the present progress of tandem technology. During this Conference, or in the resulting Proceedings, several papers will be presented or published that describe important details of the tandem research and development programs. My role is to attempt a summary of a few of these accomplishments, from the perspective of the future.

Tandem Parameters under Development

Beam Intensity

As higher and higher particle energies are achieved, a corresponding increase in useful beam intensity is required by the scientist. One reason for this demand is that reaction cross sections tend to decrease with increasing energy of bombardment. Furthermore, to discriminate among closely spaced energy levels in nuclear-structure physics, very thin targets must be used to keep the reaction-energy spread as low as possible. High beam intensities are needed, therefore, to derive more collisions from fewer target nuclei.

The HVEC tandem-research group has been actively developing hydrogen ion-source technology, as well as investigating charge-change cross sections to convert protons to neutral hydrogen atoms or to negative hydrogen ions[5]. The progress along this direction is summarized in Figure 3, maximum proton intensities accelerated in tandems, over the years. Some of the details of this work will be described by Bastide et al, in this Conference. The dotted extrapolation on the curve represents one of the immediate goals of this program.

High Voltage DC Power

Until recently, all tandem accelerators utilized the Van de Graaff principle for generating the high voltage dc power. For beam currents higher in intensity than a few hundred microamperes, however, the Van de Graaff cannot practically supply the requisite current, e.g. the summation of beam currents in both tubes, as well as currents for voltage distribution and stabilization. The insulating-core transformer principle[6] pushes back this limitation, at moderate voltages today, while preserving the desired dc characteristics of the accelerated beam. This ICT development is described later in this paper.

Heavy Ions

The propensity of the tandem to accelerate heavy ions of any species has been gradually explored by a number of tandem users. Figure 4 sketches the progress in particle energy attained by tandems in the field, with accelerating voltages up to 6 or 7 MV, and with a single electron stripper in the high-voltage terminal. When a heavy ion is stripped, a distribution of charge states results, requiring post-acceleration analysis to separate the particular charge state or energy of the ion. Out of the total accelerated current, a small portion is actually utilized, thus necessitating a relatively high accelerating power and an intense ion-injection system.

Many ion species have already been accelerated by tandems, as seen in Figure 5, a progression of the heaviest ion weight as a function of time. The recent uranium point was reported by the Heidelberg group. Rose et al will discuss, at this Conference, the many types of negative and positive ions that can ultimately be accelerated by tandems.

Efficiency of Charge Change

Improving the efficiency of charge-change, whether for adding or removing electrons, for hydrogen or heavy ions, is of great importance in a progressive tandem-development program. Until recently, gas canals or thin foils have been used with reasonable success. The gas flow tends to degrade the vacuum in the accelerating region and can cause continuous stripping of heavy ions during acceleration. Foils tend to have a limited life.

The water-vapor adding or stripping system by Roos et al[7] represents a new approach that can improve the electron-adding efficiency for hydrogen, and can also maintain good stripping efficiency without appreciable gas flow. Shown diagrammatically in Figure 6 this stripper, as mounted in in the terminal, provides an adequately thick water-vapor jet target for the higher energy hydrogen ions that can presently be accelerated in tandems. The proton intensities from HVEC research tandem, in Figure 3, were obtained with the vapor stripper.

Ion Optics

The ion-optical characteristics in tandems have been extensively studied, to enhance the particle-energy range over which reasonable intense beams can survive acceleration. The injection parameters are presented in this Conference by Brooks et al. It is sufficient to state here that efficiency of hydrogen-ion beam transmission has been greatly improved, from about 10% to well over 75%, by appropriate injection optics and meticulous alignment of the tandem structure.

Progress in Tandem Accelerator Systems

It is one thing to describe the individual components progress in tandem development; it is quite another thing to report on the progress of complete tandem accelerator systems, in which all parameters must be contributing simultaneously to overall performance[8].

Four major efforts are occupying HVEC at the present time, not only in the factory but also in the field:

a. Initial factory test and simultaneous field installations of the 20-Mev (proton) "Emperor" tandems;

b. Completion of the first 8-Mev (proton) tandem, utilizing a 4-MV insulating-core transformer as the high voltage dc power source;

c. Evolvement of a practical three-stage tandem accelerator, utilizing neutral-negative injection;

d. Reduction to practice of the 15-Mev (proton) "king-sized" tandems in the field;

The progress of all four of these systems is interlocked with many of the company-sponsored programs in both research and development. At present, the specific accelerators are being produced for the acceleration of the hydrogen isotopes but with an ultimate design compatibility with heavy-ion injection and acceleration.

Emperor Tandem

The latest and largest in tandem technology is represented by the 20-Mev (proton) Emperor tandem, the design of which is being proved in a special test facility at HVEC, shown in Figure 7. Simultaneous with this program, field installations are under way at four laboratories in USA and Canada. The Emperor tandem is the first model that is so large that its complete integrity can be determined only in the field. The inspection and test program for the sub-systems must therefore be very comprehensive, to minimize field adjustments and corrections.

The 300-kev negative-ion injector to this machine is shown in Figure 8. With this system, a constant ratio between injection and tandem acceleration voltages can be obtained, to maximize the useful ion currents over a broad energy range.

The Emperor tandem has already produced over 10 MV in terminal potential, and has accelerated hydrogen-ion beams up to 13 μa at moderate energies, with reasonable transmission. The guaranteed performance for protons is 25 μa up to 15 Mev and 10 μa up to 20 Mev.

ICT Tandem

The ICT tandem departs in appearance from the "conventional" system, in that the power source is separated from the acceleration columns, as shown in Figures 9 and 10. A gas-pressurized high-voltage transmission line connects the power source and accelerator. Load currents up to 12 ma at 4 MV can be sustained by the ICT. The entire acceleration system has been designed to accept intense beams. For example, wide-aperture acceleration tubes are provided for high pumping speed and for continuing design improvements. The mid-terminal region has adequate volume for the later installations of strippers capable of handling powerful beams, e.g. the water-vapor jet stripper mentioned above.

Preliminary tests have been made on this tandem, using a negative-ion source of the direct-extraction type. The inherent voltage ripple of the ICT has been shown to be about 600 volts at relatively light current loads. For long-term voltage stability, a precision generating voltmeter is used to provide a signal to correct the ICT primary voltage. These two design features replace the usual usual tandem voltage stabilization system of monitoring the position of the analyzed beam.

At present, the ICT tandem is limited in output by the direct-extraction ion source. As the technique of producing negative ions improves, however, this variant of the tandem principle will become increasingly advantageous for the acceleration of powerful ion beams.

Three-Stage Tandems

The three-stage tandem design permits a proton-energy increase of about 50% over the two-stage model, and considerable improvement in the ultimate energies of other ions and a few heavy ions that can be produced with a net multiple negative charge. Although two tandem installations have already been made with single-ended (non-tandem) injectors with negative hydrogen-ion sources in the terminal, HVEC has always believed in the ultimate practicality of maintaining ion sources at ground potential in the outside world. This design philosophy therefore exploits the technique of injecting a neutral beam and subsequently adding an extra electron at the mid terminal for negative-ion acceleration in the "injector" tandem.

The production of prolific well directed neutral hydrogen beams has been accomplished by the HVEC research-tandem group and by the engineering team on the production floor. The survival of this beam, as it is allowed to drift to the high-voltage terminal, has been limited by many factors that cause particle stripping in flight and consequent loading in the acceleration tube. These limitations can be removed by appropriate tube design and vacuum conditions. Once this temporary hurdle has been eliminated, the three-stage tandem will certainly take its place among the many practical configurations of this type of accelerator.

15-Mev Tandems

The 15-Mev (proton) "king-sized" tandem was presumed to be a straightforward extrapolation of the successful standard tandem, and its early performance at HVEC gave a premature impression of its ease of installation. The first unit of this series demonstrated both higher terminal voltage and more intense proton current than specified.

Four simultaneous installations are being made at this time, each with similar temporary but time-consuming problems, mainly concerned with the ion optics and acceleration path of the beam. Through appropriate experimentation on one of these tandems, suitable solutions can quickly be applied to all cases.

System Responsibility

This recitation of the broad scope of effort in tandem production at HVEC is included to demonstrate the unprecedented demands by the scientists for new accelerating equipment in the nuclear-structure realm, and to touch on the inevitable hazards of working at the forefront of several technologies, to provide the latest that can be produced from the state of the art. Were it not for associated long-range, independently sponsored R&D programs, there would not have been such an early possibility of obtaining these accelerators. With the overall responsibility of achieving the many required performances resting essentially on one organization, the probability of ultimate success is very high. This is in contrast to the traditional case of a laboratory engaged in the development of its own machine.

Tandem Accelerators of the Future

There are many possible variations of the tandem principle, and they include three basic charge-changing reactions, as well as injection and acceleration techniques in one to four stages. Depending on the objectives of a specific research program, therefore, it is possible to select the most readily adaptable version of the tandem.

As the technology advances to higher and higher terminal voltages, the accelerators become necessarily more bulky and complex -- and tend to be more permanent facilities in the research laboratory. It is vital, therefore, to anticipate as much as possible the design improvements of the future so that they can be incorporated in the same frame as they evolve. This philosophy has been a dominant influence in the original design of the Emperor Tandem.

The insulating column structure of this machine is open, permitting considerable freedom in the selection of acceleration-tube diameters and, therefore, electrode geometries. Additional tube positions on either side of the main tube centerline further enhance the flexibility of the tandem.

A large region is left purposely vacant in the column, for the ultimate installation of a more powerful high-voltage generator than the present Van de Graaff belt system. Although it is much too early to describe such a power source in detail, it is reasonable to surmise that a multiplicity of generators, utilizing the insulating-core electromagnetic principles and operated in series, will be developed.

The voltage column is subdivided, on either side of the mid terminal, into four sections, each one separated by a two-foot dead space. In these regions can be installed additional stripping facilities, lenses, or similar devices for controlling the characteristics of the accelerating ion beam.

An important parameter in the tandem acceleration system is the maximum reliable operating voltage. Whatever the present accomplishments have been in this regard, the physicist is always desirous of more. Indeed, the breadth of application for dc accelerators in nuclear research has increased disproportionally greater than the improvement in rated voltage. There is no indication that this trend will taper off, judging from the vigorous interest in sector-focused cyclotrons that produce ion-beam energies well beyond the present tandem limits.

At HVEC, a definitive development program is in full swing to understand and improve voltage insulation in vacuum, high-pressure gases, and across solids. Already this program has produced preliminary results in the form of inclined-field acceleration tubes, that reduce the electron loading that has often been a limitation of dc accelerators.

As described by Trump[9], the direction of this effort will include the improvement of voltage-holding capabilities in existing tandem designs, either by the use of superior electro-negative insulating gases or by dividing the gaseous insulating medium with conducting equipotential surfaces.

Improvements in tandem voltages will progressively increase light and heavy ion energies to values greater than the Coulomb barriers of the heavier nuclides. Figure 11 shows the calculated Coulomb-barrier energy as a function of atomic number, for several bombarding nuclides[10]. Superimposed on these curves are points representing achievable particle energies with existing tandem technology.

As we mentioned earlier, high-intensity beams will be needed for injection into several embodiments of the tandem principle. The ICT Tandem described above will show the way toward the production of intense, heavy-ion beams at moderate energy.

An example of a progressively advancing research facility can therefore be conjectured to look something like the sketch in Figure 12. The basic two-stage Emperor can later be augmented by a second machine, thus providing three-stage operation. Subsequently, an ICT injector tandem, operating at perhaps 1 MV, can be added to generate heavy-ion beams of appropriate energy for neutral or negative conversion. The complete facility would be ultimately adaptable to several independent or interdependent modes of operation.

Conclusion

It is impossible to compress into a finite presentation the many nuances of tandem technology that can be brought to bear on future acceleration systems. The preferred combinations will become more obvious when the present systems become engaged in research programs.

Just how far the tandem will be extended for useful research depends as much on the continuing progress and results of present R&D programs, as on the imagination and drive of the physicists who are presently planning their future research programs.

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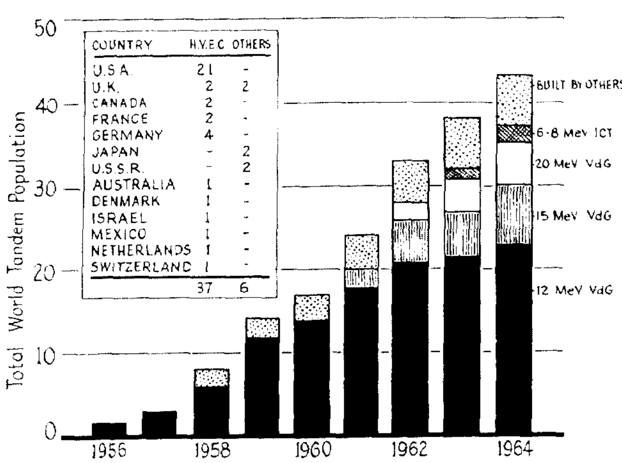
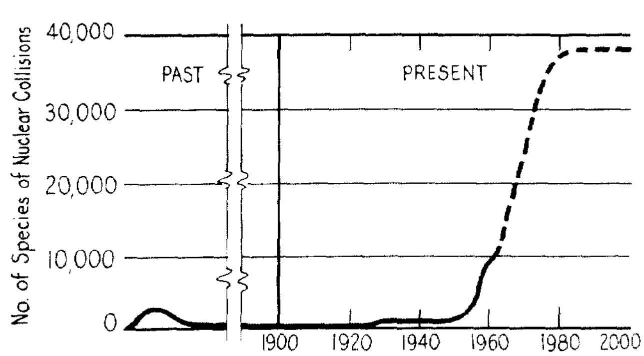
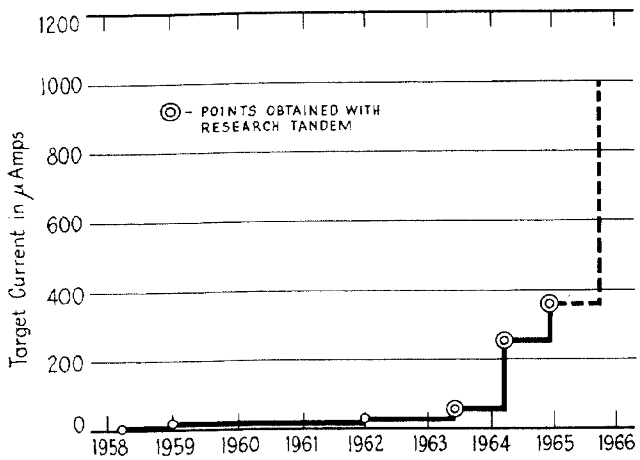


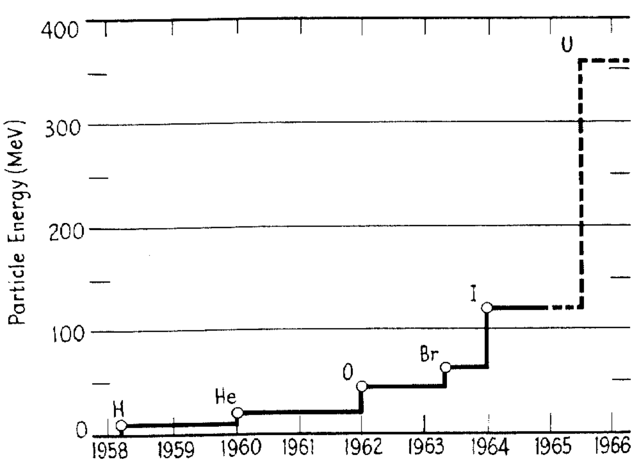
1. Total world tandem population



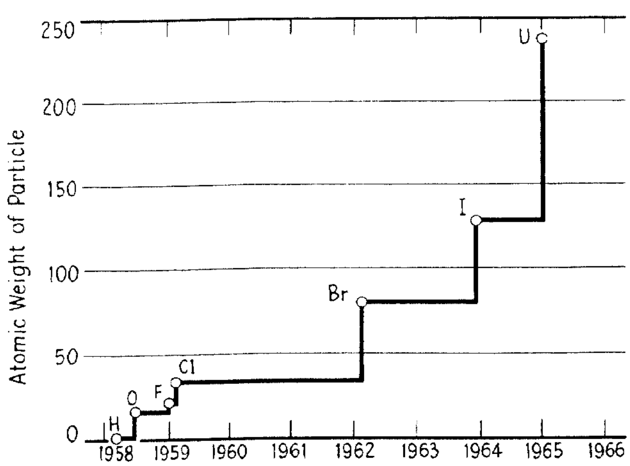
2. Freedom of choice of nuclear collisions



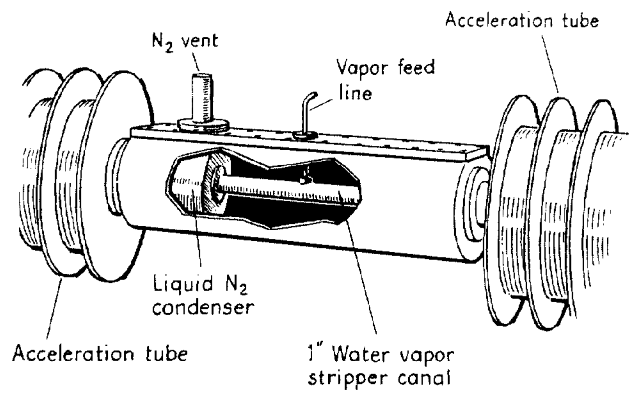
3. Maximum proton currents by tandem acceleration



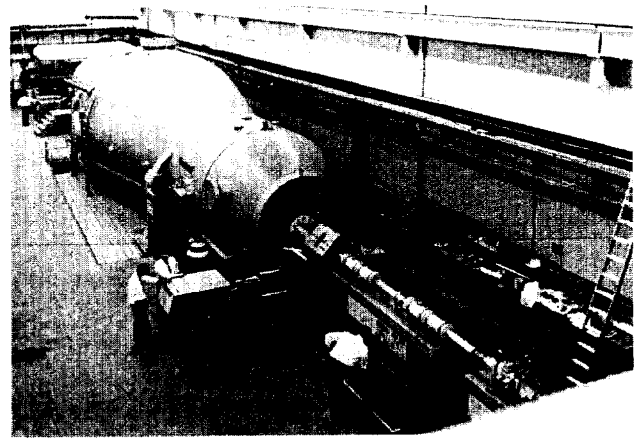
4. Maximum particle energies by tandem acceleration



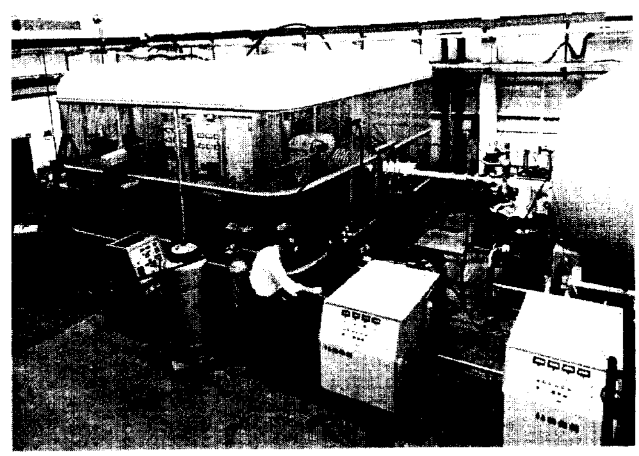
5. Heaviest weight of particles accelerated by tandems



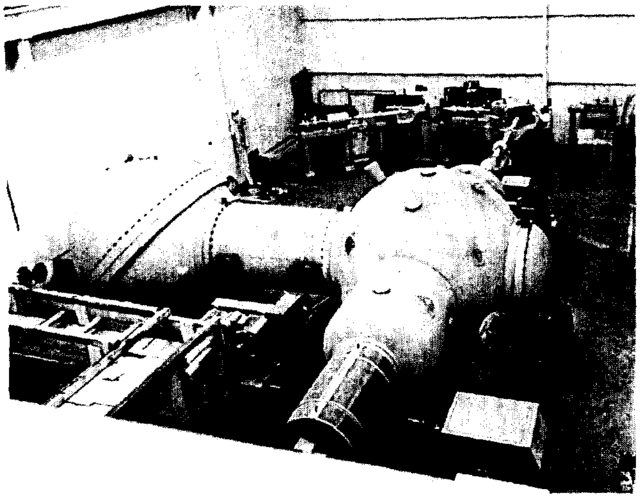
6. Water-vapor stripper



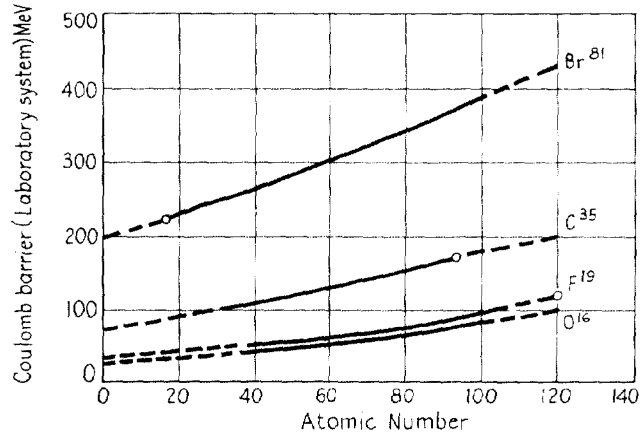
7. Emperor tandem installation (20-Mev protons)



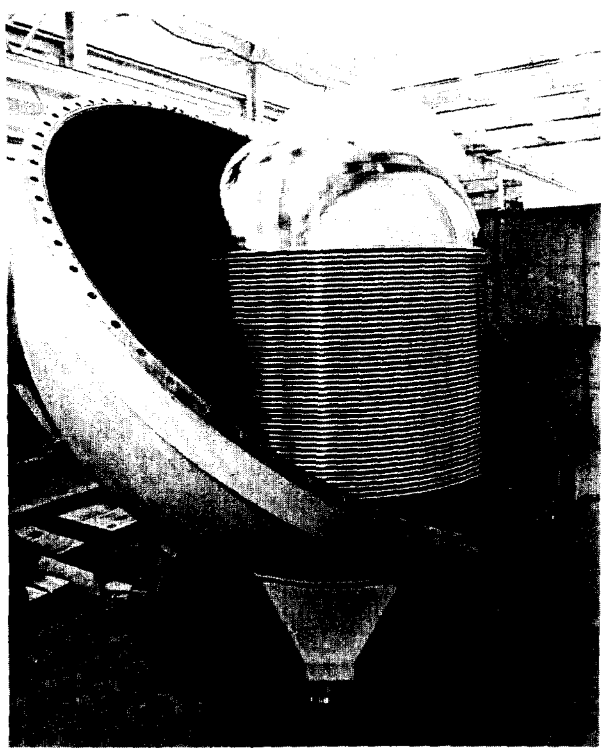
8. Injection system of Emperor tandem



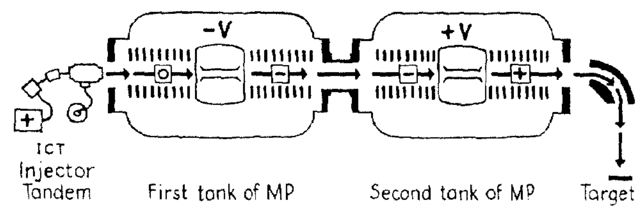
9. ICT tandem under test (8-Mev protons)



11. Energy to penetrate coulomb barrier for several heavy ions



10. High-voltage dc power source for ICT tandem



12. Three-stage Emperor tandem with ICT injector tandem