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Tandem Van de Graaff Accelerator from a User's Point of View*

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In order to discuss the BNL tandem facility from a user's point of view, it is first necessary to describe the facility in order to provide a proper perspective of the user associated problem. Figure 1 is an artist's conception of the building layout, showing the relative location of the accelerators, target rooms, control room, etc. The experimental stations shown in the drawing are hypothetical and bear no resemblance to the present installation because the drawing was completed long before the building completion. The building is located in a central region of the Laboratory conveniently close to other low energy experimental facilities. The building was constructed in the side of a hill so that the back walls and ceilings of the radiation areas could be inexpensively earth shielded. The long accelerator room in the background houses the two accelerators in-line as shown. In the foreground, from left to right, are the mechanical equipment room, target room #1, the control room, and target rooms #2, #3, and #4. The outer portion of the building in the extreme foreground contains

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lab and office space, and a recent building addition to the left of the mechanical equipment room contains additional lab and office space.

The two accelerators can be operated independently and simultaneously as standard tandem accelerators. The accelerator on the left has a special negative ion source[2] built inside the high voltage terminal which allows it to inject the accelerator on the right so that the two machines can be operated together in a three-stage mode. The accelerator on the left besides operating as an injector, may also be operated either in a one- or two-stage mode into target room #1. The accelerator on the right is operated into the three adjacent target rooms, #2, #3, and #4. The three target rooms are very important because of the long set up time involved for many of the complex experiments that are now being carried out with heavy ions in low energy nuclear structure physics. On some occasions, the set up time for an experiment is actually longer than the operating time; therefore, not only are separate target rooms necessary, but some redundancy of experimental equipment is also desirable so as to allow identical experiments in different target areas.

Additional operational logic problems occur when the energy or special heavy ion requirements of the experiment only require two-stage acceleration, thereby allowing both machines to be used simultaneously on different experiments. Although the simultaneous use only amounts to approximately 25% of the operating time, it creates a heavy load on the accelerator operations staff and on the experimental equipment available for data acquisition and analysis.

In order to appreciate some of the physical problems of living and working with the BNL tandem facility, the next few figures, which are photographs, show the relative size and detailed layout of some of the experimental equipment.

Figure 2 is a view from the top of the first accelerator (injector accelerator on the left in Fig. 1) looking towards the second. The length of the accelerator room is approximately 100 meters, (the length of a football field) which adds considerably to the general problem of maintenance. For example, it is important to have adequate duplication and organization of tools and equipment in the room so that they are available when needed without walking the length of the room - an idealized concept which is sometimes difficult to maintain within present limited manpower restrictions. An additional problem is to arrange for adequate radiation protection that will allow for maintenance work in radiation free areas of this room while completely secure radiation conditions exist in other parts of the room.[3] Many radiation protection systems for accelerators are arranged in a simple fashion; whenever the accelerator is in operation, access is not allowed, independent of radiation conditions. Unfortunately, most accelerators require considerable maintenance which cannot be carried out during operation if access is forbidden by an arbitrary radiation lock-out. Since the ion sources and many other accelerator components are external to the pressure vessel of tandem Van de Graaff accelerators, conditional access for maintenance considerably minimizes interference with operations.

Figure 3 is a view of target room #4 from the turret wall looking towards the large open part of the room. The experimental station on the left is a (γ,γ) goniometer. The center beam line feeds the large vessel in the rear which is the original multigap spectrograph from the Massachusetts Institute of Technology. The multigap spectrograph was one of the first large instruments installed in the facility for research and is now being removed for replacement by a recoil mass spectrometer, especially designed for heavy ion research. This new spectrometer has been designed, constructed, and installed by MIT personnel but will become part of the general use equipment after completion and testing. The beam line on the right is a general purpose line shown working into a special scattering chamber from Denmark for an outside user experiment. This scattering chamber is a relatively complex instrument and is typical of the kind of outside user experimental equipment brought in for installation, operation, and subsequent removal. Flexibility and ease of installation are important in order to allow for changes from time to time as the experimental needs of the facility change.

Photographs of the experimental equipment in the other target rooms will not be shown; however, target room #3 contains a large general purpose scattering chamber and another general purpose line which presently contains a fast-rabbit for the study of short-lived nuclei.

Target room #2 contains a large high resolution spectrometer called the Q3D spectrometer (just now completing construction) and another scattering chamber identical to that in target room #3. The two identical chambers allow for an experiment to be set up in either target room with close to identical operation , geometry. Because scattering chambers are the most heavily used experimental stations it is important to have more than one so that experiments can be set up in one while being carried out in another, thereby eliminating operational time which otherwise would be lost for set up time.

Target room #1 contains a third scattering chamber, a pair spectrometer, a super-collimated beam line, and a general purpose line, as well as a few miscellaneous machine tools and other laboratory equipment for general use. Since the room is only used as a target room approximately 25% of the time, the rest of the time is available for laboratory and construction-type operations that conveniently utilize the crane and other facilities in the target room.

Figure 4 is a view of the large control console for the two accelerators indicating the general complexity and magnitude of the control problem. This control system is of 1960 vintage and "old fashioned" when compared to modern computer systems where all of the controls in the photo would be contained in the three panels directly in front of the principle operator in the picture. Although the modern computer control systems allow a considerable reduction in the physical size of the control console, they do not simplify the maintenance and upkeep problems of the overall control system because the same accelerator components and miscellaneous hardware are still being controlled. The main difference is that the skills and abilities of the technicians and engineers involved with maintenance have to be on a higher level for the computer system than with the old-fashioned direct control (i.e., logical electronics cannot be handled by electricians but relay logics can).

Figure 5 is a view of the experimental control area which is immediately adjacent to the accelerator control console to the left of Fig. 4. It shows the computer interface and control for all of the experimental stations which feed into the central area.[4] A small portion of the accelerator control can be seen in the distant background. The console by the operator is the computer control, while the console behind and to the rear is the experimental display station. The interface and logic connection is to the right of the display station. The nature of low-energy nuclear-structure type experiments carried out with this kind of facility requires the use of a computer interface system in order to handle the complexity, magnitude, and rate of the experimental input as well as subsequent analysis. Conventional multi-channel analyzer systems are now too primitive for effective use in most experiments and are used mainly as monitoring devices to augment the computer interface and control.

Construction Completion Conversion to Research Operations

The two tandem accelerators were standard equipment purchased from the High Voltage Engineering Company (HVEC). Consequently, the BNL engineering construction team did not have to concern themselves with the basic accelerator design problem but only with accelerator performance specifications and their ultimate interaction with the research program. They also provided the requirements, specifications, and basic design for the building and all of the experimental facilities. The construction team was directly responsible for the installation of the accelerators (supervised by HVEC) and for the three-stage interconnection and ultimate performance of the three-stage system. The three-stage operation required a special design of negative ion source inside the high voltage terminal of the first machine arranged so that either normal two-stage or injector operation could be achieved with simple changes outside the accelerator. An important part of the terminal ion source was the associated development of a fast gas handling system[5] for the high pressure (15 atmospheres) insulating gas. This large system with massive piping and pumps had to be integrated into the building design and construction and made possible the necessary rapid access to the terminal source for maintenance and repair.

When the construction was finally completed, a brand new building had materialzed and was ready for occupancy and use. The new building was just like all new buildings in general: the air conditioning system did not work properly, the roof leaked, and the chilled and deionized water systems and other mechanical systems all suffered from a myriad of "shake-down" problems requiring maintenance and adjustment. The good news is that these building problems are generally taken care of by other personnel than those associated with the accelerators and research; the bad news is that successful research operation unfortunately depends on most of the building facilities working as well as the experimental equipment.

Table I lists the physical assets generally available at the completion of construction and some of the associated problems. The research group will find that it is suddenly the proud possessor of electronic and experimental equipment that unfortunately will require debugging and rework of various kinds just like the new building. An additional problem is that the new equipment has not yet been used either independently or with the accelerators as a basic research system. Consequently, the scientific staff must all "learn to use" the equipment as indicated in Table I and at the same time learn to repair and modify it to meet the changing needs of the experimental programs. As an example: the BNL tandem facility was originally envisaged as a high-resolution light-particle accelerator facility for the study of nuclear structure physics. Although the accelerator was first conceived in 1962, various administrative delays mostly having to do with funding questions and specifications delayed the start of the building construction until 1966. At that time the completion date was predicted to be June 1970 and was realized on schedule and within budget even though the cost escalations were severe over the construction period. Similar delays should probably be expected in the future because there will always be financial problems within the framework of an inflation economy. These delays generally have nothing to do with scientific problems but more with political, economic, and "people" problems associated with all aspects of construction. Over the eight-year period, the interest in light ion physics had largely faded away and was replaced by a new interest in heavy ion physics. This meant that the first research problems for the facility were not with protons as originally expected, but with heavy ions requiring operation at maximum three-stage energy. This major change in experimental emphasis required extensive redesign and rework of many accelerator and experimental components immediately after the so-called "construction completion".

Another aspect of the initial operations of any facility of this kind has to do with the personnel that are available for carrying out the operations. At construction completion, the staff consists of highly competent machine and facility builders, construction technicians, and many inside user scientists all anxiously awaiting accelerator and experimental equipment operation necessary for their experiments. The kind of people needed that are not available are trained accelerator operators (the new accelerator has never been operated before); technicians trained in the operation and maintenance of experimental equipment (none of it has ever been previously operated). Finally, the whole staff will have had little, if any, experience with how the new accelerators interact with the new experimental equipment, or how the interaction can meet the requirements of the experimental programs. This perfectly normal but agonizing situation means that most of the staff, from the top scientist to the lowliest technician, all have to undergo a training period which will require extreme patience and understanding by all members of the staff.

Ideally, all of the working scientists involved in a large research organization like the Quebec group should participate in the initial planning of the new facility and continue an active participation through advance planning and the construction stage on to the operation. Unfortunately, most scientists do not have the time to be intimately involved with the planning and construction of a new facility and can only provide a limited amount of their time for working out the detailed problems associated with carrying out research with the new facility. This situation is perfectly normal because most scientists are very busy carrying out active, competitive research programs - their main interest in the facility is to use it when it is completed. On the other hand, the depth and degree of detailed planning for all aspects of the facility will determine whether research can be carried out easily or with great difficulty. One of the best methods of getting all the interested and potential user scientists involved through the planning and construction stages of a new facility is to call regular user meetings for both inside and outside users. These user meetings can be called once or twice a year as deemed appropriate and necessary by the people with the direct construction and development responsibilities. Scientists that would be reluctant to "waste" their time discussing the nitty-gritty details of experimental equipment for the new research facility can hardly resist participating in a group meeting where they can interact with their colleagues as well as other scientists outside their own organizations on a group discussion basis. Such one-day meetings not only provide superb input to the people directly involved with the construction and development of the new facility, but also provide the nucleus for the basic inside and outside users groups and ultimate users organization that will have to be involved with the operations of the facility after completion.

The kind of personnel requirements at the start up of a new facility are listed in Table II under the two main headings of operations and research. Basically, a group of people are required to operate the accelerators and a second group to support the research operations. The operations people, along with other personnel, will provide a maintenance program for the accelerators and the experimental equipment.

Although the accelerators will be brand new, they will still require essentially continuous maintenance. There will be severe maintenance problems initially with the accelerator as various things break down on a "shake-down" basis. The maintenance problem will then settle down until the equipment starts wearing out, which should start occurring at an increased frequency after the first year of operation and reach a kind of "equilibrium failure level" after three to four years of operation. Similarly, the same kind of problems will be experienced with the experimental equipment, except the situation is aggravated because the experimental equipment will be removed and exchanged for new equipment more or less continuously in a large facility, thereby continuously requiring initial start up maintenance.

Although the accelerators will have just been started in operation, in order for them to meet the "forefront" requirements of research means that changes and modifications for the accelerators will have to be under continual development. Several people will have to worry about these developments, updating and improving the performance of the accelerators in order to keep them competitive in the field and see that they provide the new and special requirements necessary for the research programs. Similarly, research equipment will have to be continuously updated, improved, and developed because the physics needs will be under constant change. For example, at the BNL tandem facility many experimental techniques that were completely suitable and well-developed for light ions had to be rapidly modified and expanded in capability in order to accommodate the experimental needs for heavy ions. More sophisticated systems and in many cases completely new kinds of systems were developed for the utilization, detection, and analysis of heavy ions in the experimental programs.

The research and operations categories as listed in Table II both require the same kinds of personnel in terms of background, experience, and training. When a facility starts into operation there will probably be insufficient experienced personnel to satisfy all the start up problems as previously discussed. If either accelerator or research operations are strongly supported to the detriment of the other (the usual tendency is to shift all support to accelerator operations) the research program will suffer (i.e., good accelerator operation with poor research equipment or good research equipment with poor accelerator operation both result in poor research). The trade-off and most optimum utilization of personnel in these two categories requires an extreme amount of patience and understanding by the scientific staffs involved with the start up of any new facility.

The patience and understanding aspect of this problem are more severe than might be obvious on a superficial examination because of the historical work habits of most of the personnel involved. Most scientists have worked by themselves or with one or two students, occasionally collaborating with another scientist on an experiment possibly at some other facility than their own university. Generally speaking, they have not had to work together in a large group where many personal sacrifices have to be made in terms of the overall good of the operation of the facility rather than their own direct personal interests. The situation with the three universities in Quebec can be further complicated by differences of opinion between staff members of the different universities in regards to operations responsibility and priority of carrying out experiments involving a "fair sharing" of available beam time.

When the BNL facility first started into operation, the needs for technicians in accelerator operations were the most pressing. Consequently, a number of scientists stopped what they were doing and pitched in to help set up the experimental equipment and, in fact, most of the experimental beam lines in the facility were set up by scientists with little or no technician help. The hardware for the beam lines was especially designed to be easily assembled in "Heath Kit" style, largely without tools and utilizing quick-disconnect type fittings. This modular concept made the equipment very easy to assemble and provided an "automatic" vacuum integrity upon completion of assembly. Similarly, many scientists went through moderate training programs in order to learn how to operate the accelerators so that they could aid in the early operations before a regular operating team had been developed. Although their help greatly aided in getting the research programs going initially, scientists, generally speaking, are poor accelerator operators because their concern is where it should be - mainly with their equipment and not with the accelerators. Malfunctioning of the accelerators as well as excessive performance capability needed by an experiment are often not placed in proper perspective in terms of reliable operation for all concerned.

Present Operational and Use Situation of Facility after Three Years

From the very beginning, the accelerators have been operated around-the-clock by utilizing scientists and operators when available. They are now being operated with a regular operations group that provides two operators per shift on a 24-hour per day basis, seven days per week. One shift out of each 21 is used for regular scheduled maintenance on both the accelerators and computer every Monday. The highly developed operational and maintenance team that carries out the around-the-clock operation of the accelerators is supported by an additional day shift support group. In addition there is a research support team for research operations.

The current operations group consists of 6 scientists (4 of whom carry out research on a second priority basis to operations), 6 senior technicians and engineering level people, and 14 support technicians and operators. The research group consists of 17 research scientists and 6 senior technicians and engineering level people. The group is responsible for all the research equipment and actively supports the outside user research programs, as well as maintaining their own research programs. There are 6 additional people (secretaries, machinists, technicians, and designer) that support both operations and research. These add up to 26 people in operations, 23 in research, and 6 in general support for a total of 55. Although there are still constant complaints, "if we just had more people we could get these - machine - ion source - control - experimental - electronic - computer - programming - problems solved faster" the staff seems adequate to maintain a good operation and provide reasonable maintenance and upgrading.

When the facility was completed in June 1970, it included a three-stage tandem accelerator with one scattering chamber and a multigap spectrograph as the first two experimental stations, as listed in Table III. Although a computer was in operation, it was not yet available on an "on-line" basis and was under development. Various interested outside people worked with the facility only on a special basis because of the difficulty of establishing regular operation in the second half of 1970. In 1971, a second scattering chamber was installed as well as a (γ,γ) goniometer and fast rabbit for the study of short half-lives. The regular outside use of the facility was also established in 1971. In 1972, the third scattering chamber was installed as well as a second fast rabbit and the outside user operation approached the desired 50% level. In 1973, the multigap spectrograph was removed so that the location would be made available for a new recoil mass spectrometer, designed and fabricated by MIT, and to be installed in 1974 in place of the multigap spectrograph. The outside use attained the 50% desired level of operation.

The large Q3D spectrometer will be completed and in operation in 1974. Starting from its original design in 1970, this large spectrometer has involved a number of people and an extensive effort for completion and represents a major experimental facility to be shared by all the users. Similarly, although the recoil mass spectrometer was developed and will be installed by MIT people, after it has become a routine working instrument and is completely developed, it will also revert to a regular experimental station of the facility available for all users.

Although many experiments started out with multi-channel analyzer data acquisition, most of them switched over to on-line computer acquisition as soon as the computer became available. As the computer was expanded in capability through both hardware and software developments, more and more experiments were turned over to the computer for operation and analysis. The computer availability quickly resulted in a large quantity of data being obtained and stored on magnetic tape with little or no means of analysis since the computer was in constant use for data taking. This meant that another computer had to be used for analysis which was only possible for part of the data because of the nature of the on-line data acquisition, consequently, multiple use of the computer through time sharing rapidly become a pressing necessity. Time sharing appears to be the only way to satisfy all of the requirements since a very large computer is necessary for both data taking and data analysis and it does not seem economically feasible to provide two very large computers for this purpose when time-sharing can mainly accomplish the same purpose. The computer development program through to the present time-sharing capability[6] was a long and involved job and required a number of high level personnel and specialists.

Concurrent with the development of experimental equipment, as shown in Table III, a number of machine improvements were made over the years (not listed). In 1973, the acceleration tubes in the second accelerator were removed and replaced by a new type upgrade acceleration tube system which increased the voltage capability of the accelerator from 9 MV to 12 MV, thereby radically changing the research capability of the heavy-ion research program. During this period, many other kinds of accelerator improvements were also made in many areas of control and operation.

As an example, mentioned earlier in the discussion, the facility was originally designed with the concept of accelerating light ions, like protons, deuterons, and alpha particles; however, the operational needs of the research program were for heavy ions. Table IV lists the kinds of ions that are accelerated at present. Through most of 1973 from the original start up of the facility, the main ion source was an off-axis direct-extraction duoplasmatron, as indicated in the Table, and the limited number of ions provided by that source are indicated by the asterisks. A new type of sputter ion source called the UNIS ion source, developed by Professor Middleton[7] of the University of Pennsylvania, became commercially available[8] late in 1973 and has greatly changed the heavy ion capability for this class of accelerator. The asterisks all indicate ions actually used in experiments at the tandem and provided by this source, while the X's indicate ions that the source easily provides but have not yet been used in any particular research programs with this facility.

Since this is a newly developed ion source, it is not yet available in a form which will operate inside the high voltage terminal in the injector accelerator. The modifications necessary for such operation will have to be carried out by the accelerator development team. The only source available in the high voltage terminal at present is the duoplasmatron but the need for the development of the UNIS source as a terminal ion source is clear from the comparative performance and the research requirements. The present inside and outside users are already demanding three-stage or high voltage terminal operation with this new type source, which thereby dictates the priorities of the efforts of the people who carry out the development work with the accelerators.

Summary

This short discussion has indicated only a few of the many problems associated with the use of a low energy research facility. However, the details outlined in this discussion may indicate the complexity and difficulty of getting a new low-energy heavy-ion research facility into what might be called "routine operation". Unfortunately, such an operation can really only be considered routine in terms of the fact that it goes on day in and day out. What makes the operation exciting and interesting is that almost no aspect of the operation comes under the general definition of "routine" and new problems and requirements for the facility and the research constantly appear and solutions and improvements have to be continuously developed. Planning ahead for all such new requirements, especially at the start up time of a new accelerator facility, is extremely important and should be carried out as much as possible even though such planning is extremely difficult in the present day and age of rapid change and interest in the field of heavy ion nuclear physics. The organization and implementation of an active and interested users group will greatly aid in the overall planning and development of the facility.

Table I

Physical Assets at Construction Completion and Associated Problems

	Assets	1st order problem	2nd order problem
1.	New machine	needs debugging	must learn to use
2.	New computer	" "	" " " "
3.	New electronic equip.	" "	" " " "
4.	New experimental equip.	" "	" " " "

Table II

Personnel Requirements

Operations	Research
Operations staff	Research support staff
Accelerator main. program	Research equip. main.
Accelerator devel. program	Research equip. devel.

Table III

Chronological History of Experimental Equipment Development

and Outside Use of the BNL Tandem Facility

Calendar Year	Experimental Equipment	Outside Use (special outside use only)		
		Fraction of accelerator use	Number of faculty	Number of students
1970 (½)	Scattering Chamber #1 installed in target room #2 (TR #2)			
	MIT Multigap Spectrograph TR #4			
1971	Scatt. Chbm. #4 TR #3	~25%	24	15
	γ, γ Goniometer TR #4			
	Fast rabbit #1 TR #3			
	Pair Spectrometer TR #4			
	Computer on line			
1972	Scatt. Chmb. #3 TR #1	~45%	40	10
	Fast rabbit #2 TR #1			
	Pair Spectrometer moved to TR #1			
	Supercollimated beam line TR #1			
	Computer partially time shared			
1973	(MIT Multigap Spectrograph removed)	~50%	35	6
	Computer fully time shared			
1974	MIT Recoil Mass Spectrometer TR #4 (under construction since 1973)	~50%	?	?
	Q3D Spectrometer TR #2 (under construction since 1970)			

Table IV

Heavy Ion Operation with the BNL Tandem Facility

Ion Type	Off-axis direct extraction Duoplasmatron	Cesium sputter source (UNIS)
p	*	*
d	*	X
$^{3,4}He$	General Ionics	
$^{6,7}Li$	General Ionics	*
^{9}Be		*
$^{10,11}B$		*
$^{12,13}C$	*	*
N	*	*
$^{16,18}O$	*	*
^{19}F	*	*
Al		X
Mg		X
Si		*
S		*
$^{35,37}Cl$	*	*
Ca		X
Ti		*
Fe		*
Ni		*
Cu		X
Ge		X
Br	*	*
I	*	X
Pb		*
Au		X

* In use in research.
X Can be provided

Note: three-stage operation is only with duoplasmatron at present.

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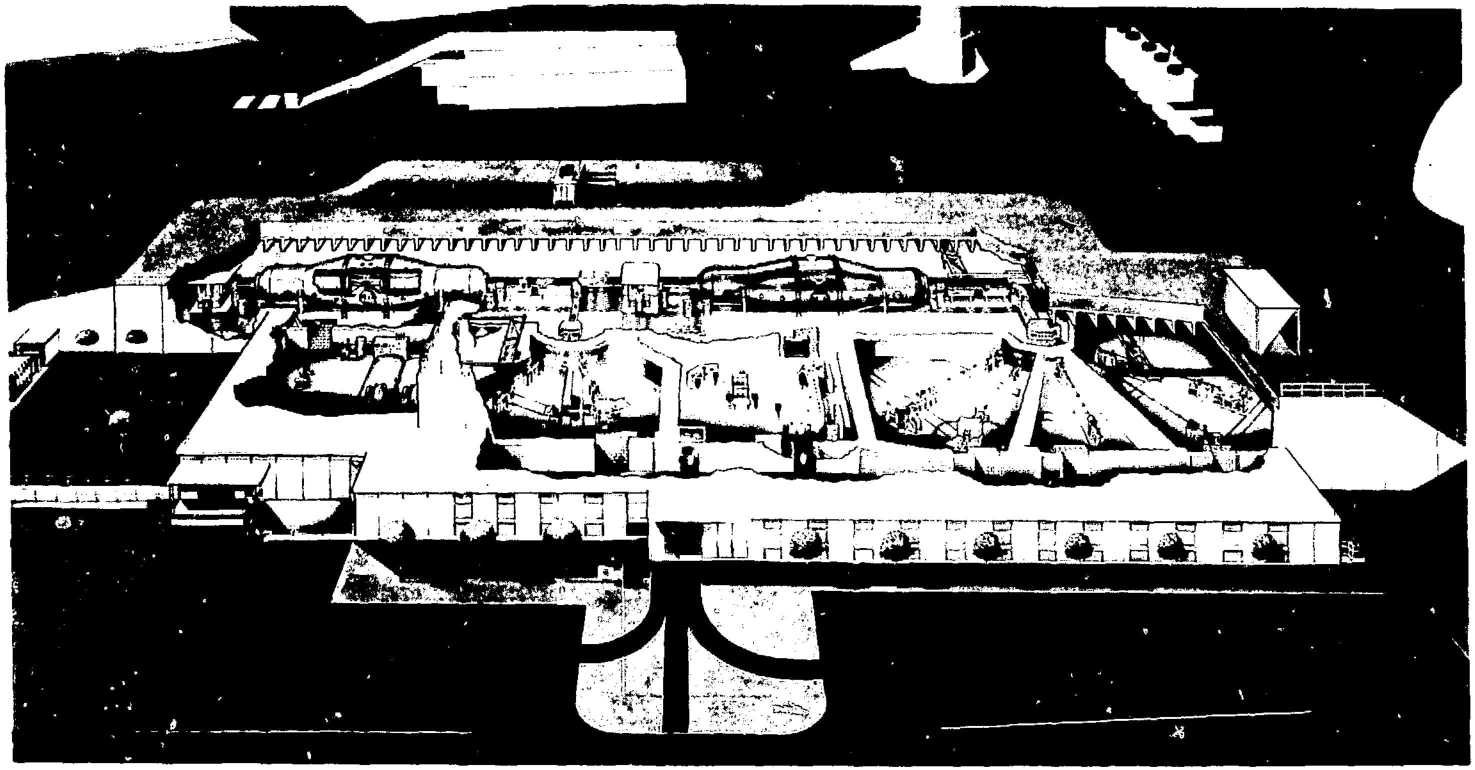

Figure 1. Artist's conception of the building plan and equipment layout for the Brookhaven National Laboratory tandem facility.

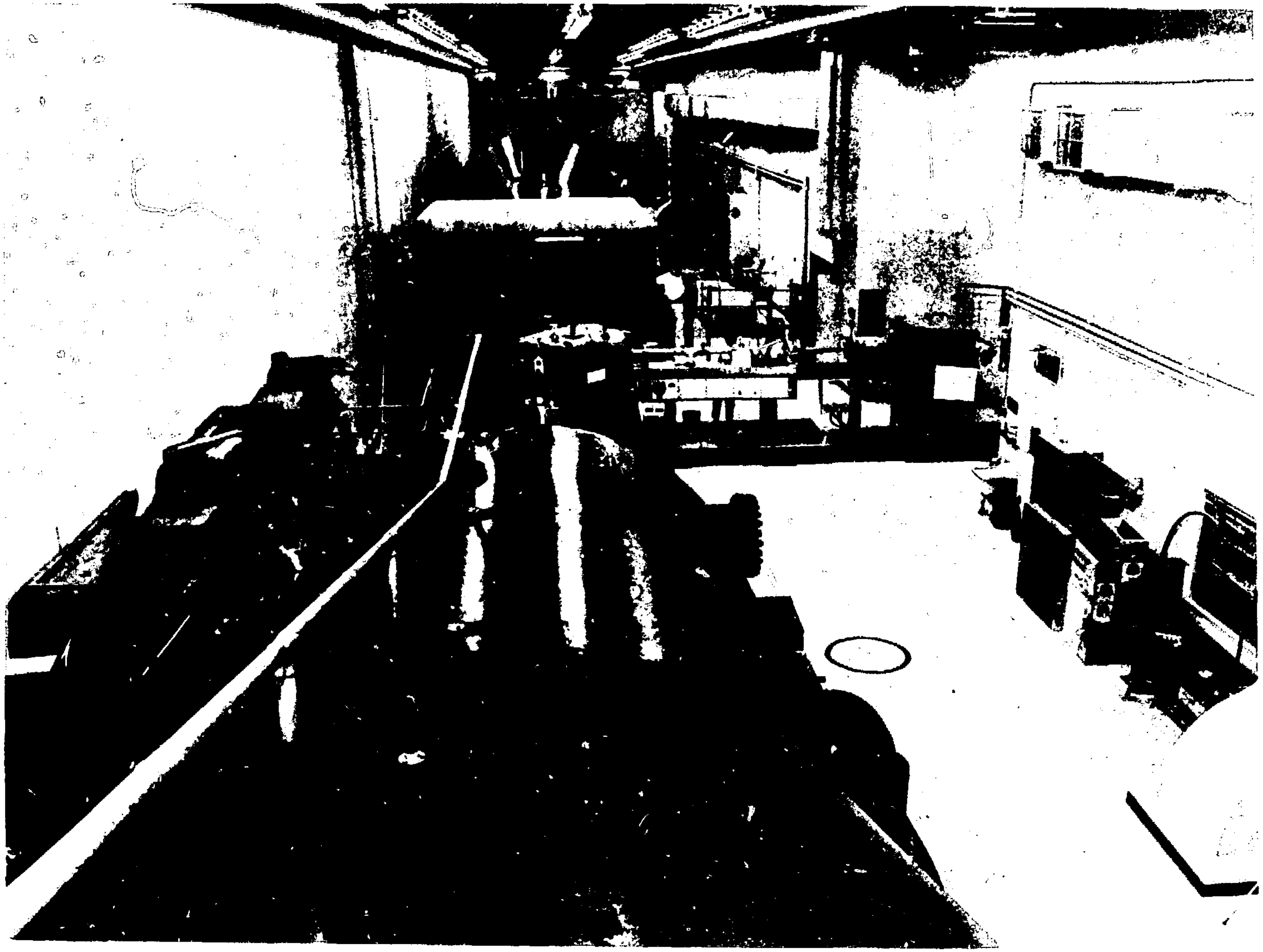

Figure 2. View of the accelerator room from the top of the injector accelerator towards the second MP accelerator that provides the second and third stage acceleration for the three-stage facility (from left to right in Figure 1).

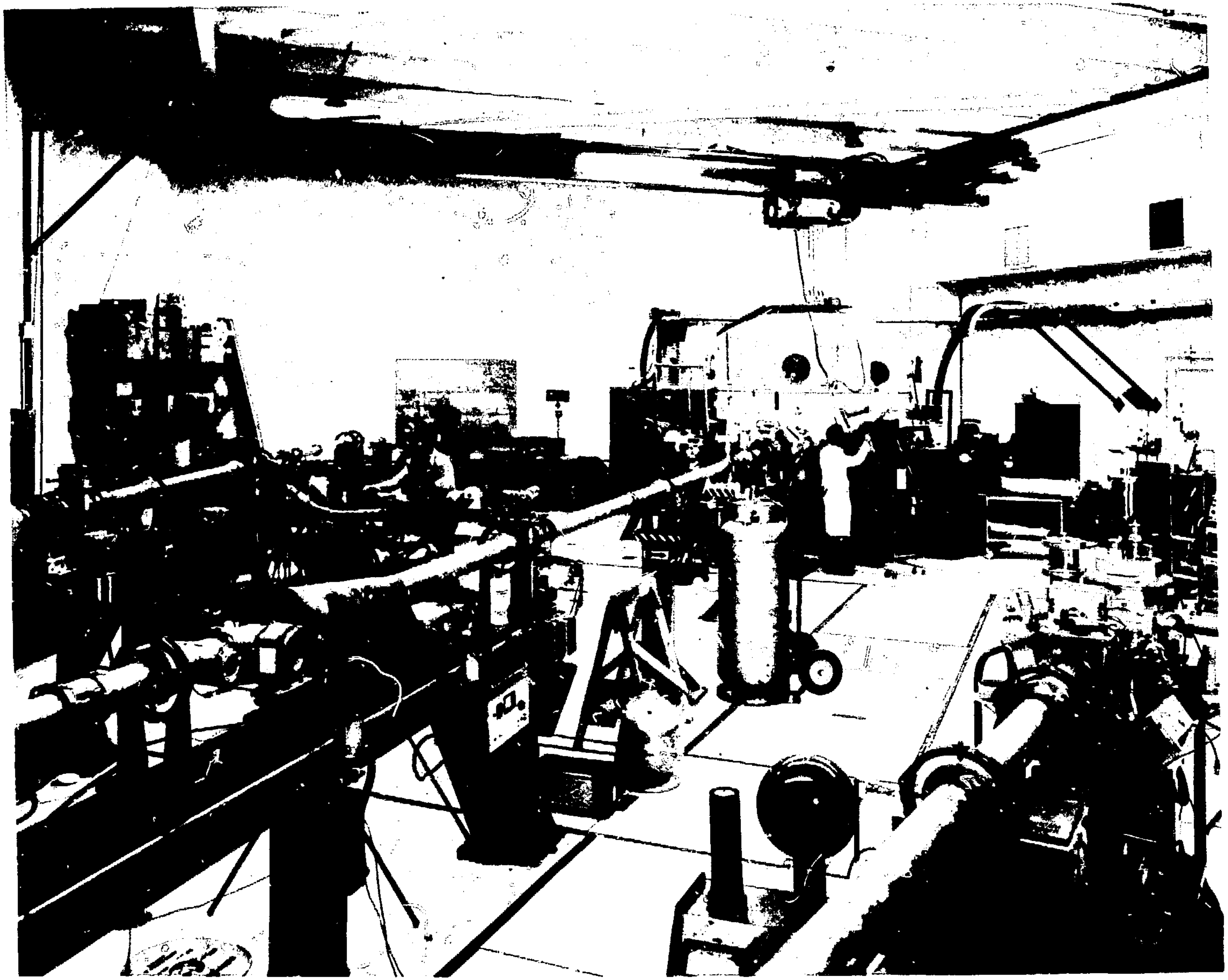

Figure 3. View from the turret wall in target room #4 (from left to right in Figure 1 in the target room on the extreme right).

Figure 4. The master control console for the two accelerators in the control room (center Figure 1).

Figure 5. The computer interface and control console in the control room (center Figure 1).