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THE NUCLEAR STRUCTURE FACILITY 20/30 MV TANDEM ACCELERATOR

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A large electrostatic accelerator has been designed to provide a nuclear structure facility in Britain. The machine is intended to operate initially at 20 MV with subsequent upgrading to 30 MV. The general features of the accelerator are described and the main dimensions are specified. The electrostatic design and beam optics of the machine are discussed and a description is given of the design and layout of the stack, intershield and centre terminal.

An extensive high voltage test programme is under way using a variety of dc and pulsed sources, and surge phenomena in Van de Graaff accelerators are being studied both theoretically and experimentally using surge measurement devices that are under development at the laboratory. Details are also given of a high current inductive charging system and a number of other devices such as a fast data link employing a light diode and a colour TV operating in conjunction with a small computer.

The general layout of the facility is described and some details are given of the control and counting room, the experimental areas, and of shielding wall thicknesses.

1. INTRODUCTION

For some years discussions have taken place in the United Kingdom on the desirability of a major new accelerator to serve as a national nuclear structure facility. The machine was finally defined as a tandem electrostatic accelerator capable of running with 20 MV on the terminal, and designed for upgrading to 30 MV on the terminal by means of a suitable development programme, notably on accelerator tubes. These terminal potentials are considered to represent a realistic upper limit in view of the present state of electrostatic accelerator technology. The accelerator was required to be able to handle beams of all types from protons to the heaviest ions available.

The scale of the project required that it be evaluated by a national laboratory. It was realized that there were many very difficult problems to investigate before the project could be deemed feasible, and the possibility of purchase as opposed to construction had to be considered. In addition the siting of the facility had to be settled. It was agreed provisionally that the facility should be in the north of England, principal reasons being the obsolescence of the accelerators situated there and the acknowledged expertise in nuclear structure research at the universities concerned. Consequently in April 1971 an 18-month design study was started at the Daresbury Nuclear Physics Laboratory. The Science Research Council has now approved construction of the accelerator at Daresbury.

The conclusions reached in the design study were (a) that the project was feasible, and (b) that it should be built locally rather than purchased. The study covered design of the accelerator, associated plant and buildings. The costs and manpower requirements were determined. This paper presents the technical results of the study.

A strong group has been set up within the laboratory to work on the project. In addition to laboratory staff, considerable effort has been devoted to the project by outside bodies and co-ordinated and controlled by the laboratory. It is not possible to list the individual contributions, but an overall indication of the work is listed below.

1) The United Kingdom Atomic Energy Authority. Full time use has been made of the 6 MV tandem at AWRE, Aldermaston, for high voltage work. Risley have designed the buildings, the pressure vessel and some of the services. AERE, Harwell, have carried out development work on organic-free accelerator tubes and on stripper foil behaviour.

2) The following universities have been involved. Manchester have contributed to the design of the beam optics, the electrostatics and beam bunching. Reading have developed jointly with Daresbury

Laboratory an inductive charging system. Liverpool have worked on the prediction of stripper charge state yields while Birmingham have been concerned with the problems of polarized beams. Salford are involved in the study of the electromagnetic properties of accelerator structures.

Many laboratories, organizations and individuals have been helpful with advice and assistance.

Design details and test results are not given in this paper, which is intended to provide an overall description of the project. Further information is however available.[1,2]

2. GENERAL FEATURES OF THE MACHINE

The general features of the machine are determined by a large number of factors which frequently lead to conflicting requirements. Amongst the most difficult decisions to be made are those governing the size of the accelerator, which must be large enough to allow the required potential to be maintained on the centre terminal, but must also be as small as possible to minimize the cost.

It was decided to build the machine in a vertical position, for several reasons. It would be difficult to guarantee the solution of the structural problems in a horizontal machine of this size. In addition, this arrangement provides ready access to experimental areas by using a 90° analysing magnet capable of being rotated about a vertical axis to direct the particle beam into one of a number of beam lines.

The layout of the accelerator buildings has been chosen to allow a 210° sector to be available. A similar magnet at the input end of the machine allows several ion sources to be deployed in a circle in the injector room at the top of the tower, giving a very convenient arrangement with excellent access to the sources, some of which are likely to be large and complicated and require frequent servicing.

A careful analysis of the possible shapes of the accelerator pressure vessel has been made, the final choice being a right cylindrical vessel with domed ends. The manner in which cost varies with length, diameter and design pressure has been analysed and related to the insulating properties of the gas in order to choose the optimum combination. The inside surface of the vessel is covered with a liner of high surface finish. This allows a relaxation of tolerances on the shape and surface finish of the vessel. The liner will be insulated from the vessel walls and could be used in the voltage stabilization system of the machine if required. Ports and penetrations in the vessel walls have been kept to a realistic minimum.

The maximum design pressure of the vessel is 0.83 MN/m^2 (120 psi) and the maximum working pressure is 0.76 MN/m^2 (110 psi). The insulating gas will be sulphur hexafluoride (SF_6), and the gas handling plant has been designed to allow emptying and refilling the vessel in about 24 hours. This time could be reduced at a later date by increasing the plant capacity.

The centre terminal of the machine is 4.5 m long and the accelerator stack contains dead sections of length 1.5 m at half the terminal potential and 0.5 m at two thirds and one quarter of the terminal potential. The accelerator stack itself has a length 2×13.4 m.

The centre terminal contains both a gas and a foil stripper while two further foil strippers are located in the short (0.5 m) dead sections. The short dead sections also contain vacuum pumps while the long dead sections contain magnetic quadrupole lenses.

Many of the main components of the accelerator are illustrated in Figure 1.

The overall dimensions of the machine have been determined using results of the high voltage test programme and by examination of the performance of machines at present operating. Two electrostatic field values that can easily be determined for existing machines are:

a) The radial field E_0 at the cylindrical surface of the terminal. This is normally around 16 MV/m or less but there is good reason to believe that significantly higher values may be possible.

b) The axial field. The upper limit at present for accelerator tube gradients is around 2.2 MV/m. There is no evidence that this will increase significantly but in view of the possibility of increasing radial gradients, any improvement in tube design would allow operation at higher terminal potential V_0.

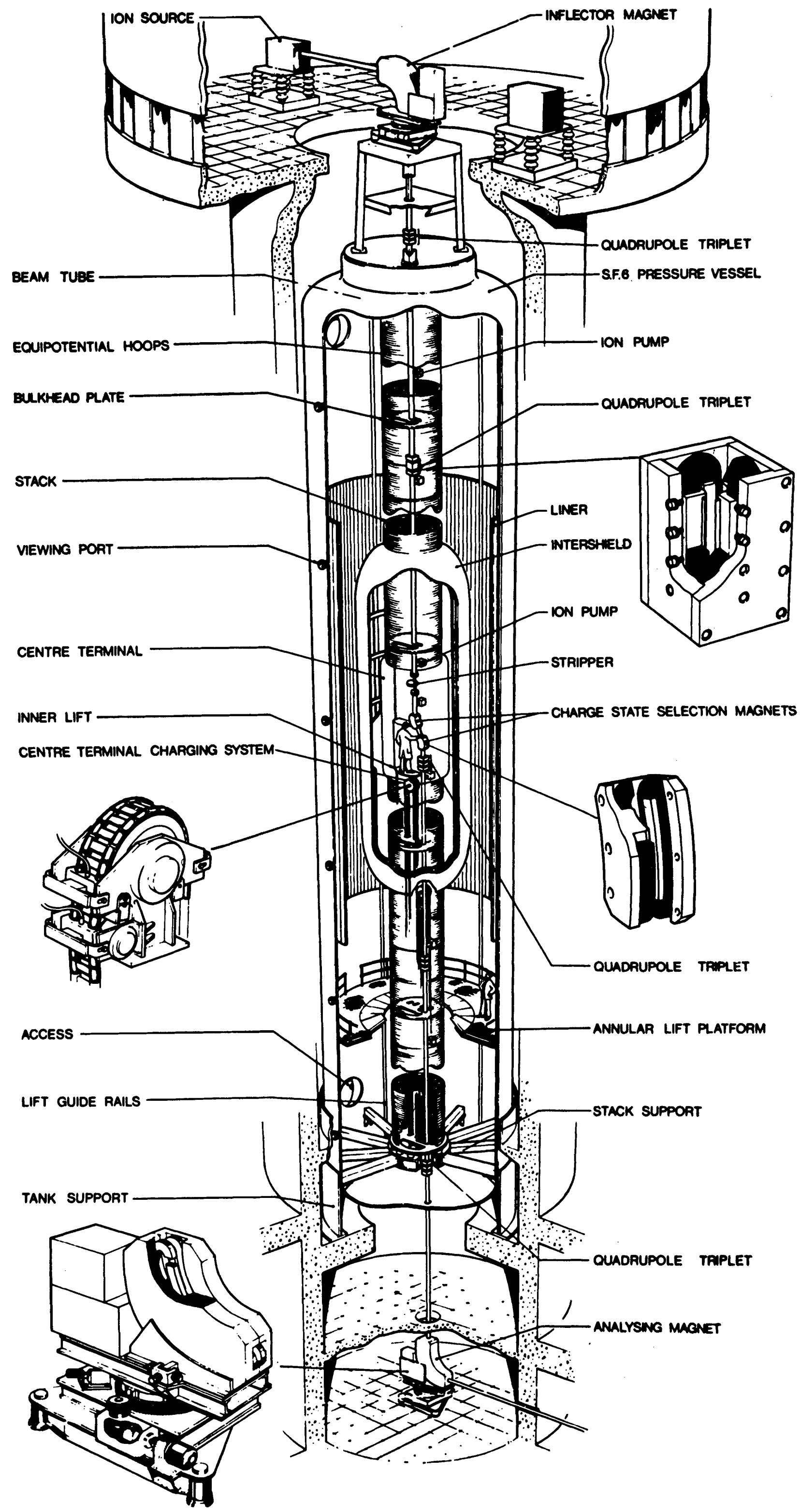


FIGURE 1 Cut-away drawing of the tandem accelerator showing the layout of the principal components of the machine.

The NSF tandem has been designed such that these gradients are reached when V_0 is approximately 30 MV.

The field E_0 on the terminal is calculated assuming that the terminal and the accelerator tank are infinite concentric cylinders of radius r and R. It is possible to run at higher terminal potentials V_0 for the same E_0 by installing an intershield operating at an intermediate potential and with radius r_i between r and R. Apart from making the machine smaller for given V_0 and E_0, the presence of the intershield provides a degree of voltage stabilization at its point of connection to the accelerator stack due to its large capacitance to ground. It is intended that the NSF machine be provided with an intershield although it could be run initially without if it is necessary. Because of this possibility the machine has been given a constant diameter stack.

Possible configurations for the machine with a wide range of values r/R have been considered. Performance for a machine with an intershield varies only slowly over the range $0.1 \leqslant r/R \leqslant 0.4$. Operation without the intershield imposes an additional constraint $0.25 \leqslant r/R \leqslant 0.5$. Thus overall we have $0.25 \leqslant r/R \leqslant 0.4$. The lower values of r/R give very slim stacks with insufficient strength or internal space. The larger values provide better electrostatic conditions at the junction of the terminal and intershield with the stack. With these points in view a value of r/R just below 0.4 was finally selected.

The optimum intershield potential varies between 0.63 V_0 at $r/R = 0.25$ to 0.58 V_0 at $r/R = 0.4$. An intershield potential of 0.75 V_0 was considered as well as the optimum but eventually rejected—this provides a shorter intershield but increases the tank size. The value 2 $V_0/3$ was selected as being close to the optimum and convenient for other reasons.

It is important to shape the terminal, intershield and hoops in such a way that local fluctuations in the total field strength do not become too great. A number of shapes were examined for the terminal and intershield ends using a large computer program. Eventually ellipses with ratio of 2:1 for the axes were adopted.

In a relatively early publication Boag[3] pointed out that in the absence of an axial field gradient, the radial gradient at the surface of the hoops can be reduced by using an oval section rather than a circular section. Extensive studies at Daresbury Laboratory[4] have shown that the effect is no longer significant when realistic axial gradients are applied. The maximum field remains almost constant and its direction simply moves around the hoop. Hoops of circular section have been selected for the NSF machine after examining various elliptical and circular sections at different relative spacings. The hoops have a diameter of 50 mm and are spaced at 72 mm centres.

The final design parameters adopted are clearly a compromise between the various factors discussed in this paper. In addition there are a number of practical considerations such as making adequate allowance for the thickness of the intershield and the need to provide clearance between the liner and the pressure vessel wall. The design values chosen are shown in Table I.

TABLE I

The main dimensions of the accelerator

Tank inside radius	=4.07 m
Tank liner radius	= 3.92 m
Intershield outer radius	= 2.34 m
Intershield inner radius	= 2.24 m
Centre terminal radius	= 1.50 m
Stack radius	= 1.15 m
Intershield potential	= 2/3 × terminal potential
Active stack length	= 13.40 m
Tank length	= 45.22 m

These dimensions provide radial and axial gradients of 16.5 MV/m and 2.24 MV/m respectively at 30 MV. The electrostatic field distributions in the vicinity of the centre terminal have been calculated using a computer program[5] which has been extensively developed at Daresbury Laboratory. The results (see Figure 2) show considerable improvement over distributions for existing machines.

3. THE BEAM PATH THROUGH THE ACCELERATOR

As a national facility the machine will be required to handle a wide variety of ion beams including polarized and bunched beams as well as light and heavy ions. In addition it is known that the highest accelerating tube gradients and terminal voltages are to be attained when the tube aperture and beam

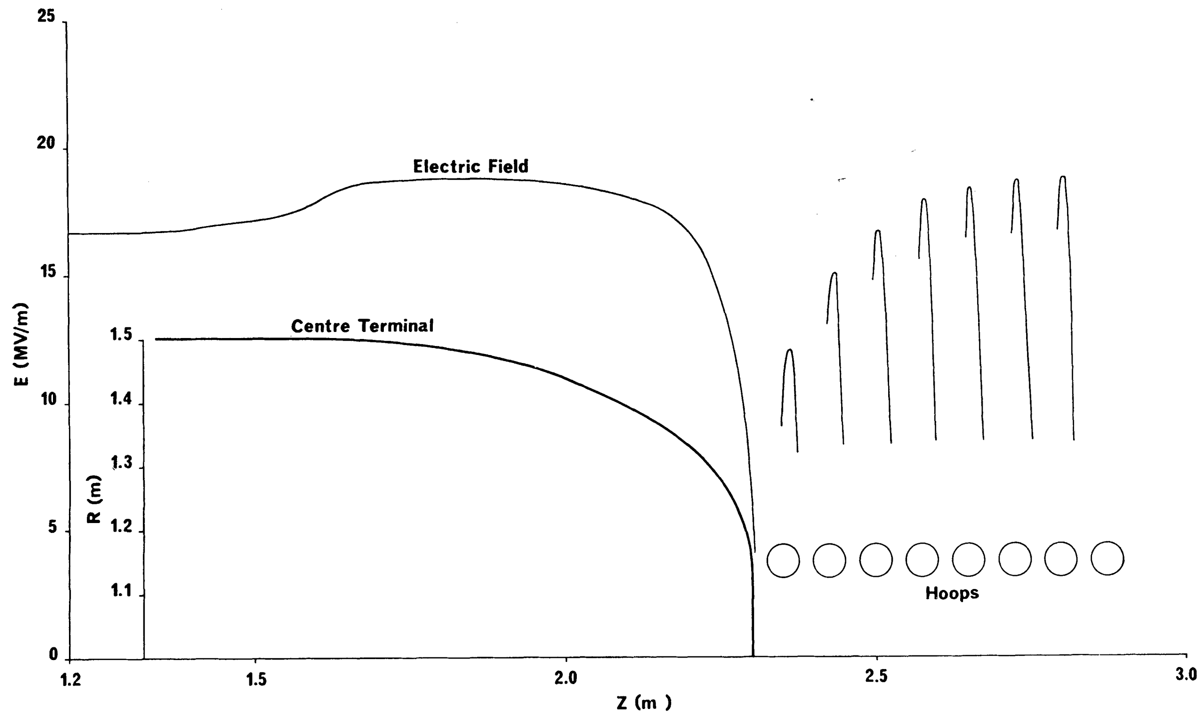


FIGURE 2 The total electric field strength at the terminal-stack junction. Only values of the field near the maxima have been plotted for the hoops. Terminal potential 30 MV.

size are kept to a minimum. This limitation can pose special problems in a long tube in the presence of multiple scattering in the strippers, an effect that is particularly important for heavy ions.

The design has been performed using an interactive computer program[6] and working to first order. The program, which was developed at Daresbury Laboratory, includes the effects of stripping, multiple scattering and beam acceleration as well as those of a number of ion optical elements both magnetic and electrostatic. The ion optical system under study is built up using an IBM 2250 connected to the main IBM 360/75 computer system. A number of ions are then traced through the system and their trajectories are displayed on the scope screen of the 2250. It is then possible to vary the sizes, positions and strengths of the various ion optical elements or the charge states or energies of the ions, the results of these changes being displayed on the scope. The program has allowed a very thorough study to be made of the system proposed for the NSF machine,[7] illustrated in Figure 3.

The 90° double focusing inflector magnet is followed by a magnetic quadrupole triplet which provides a cross-over point close to the entrance to the low energy tube. This unconventional mode of operation allows accurate beam alignment immediately prior to acceleration and minimizes the lens effect of the tube entrance. The cross-over acts as an object for a quadrupole triplet situated in the 1.5 m dead sections halfway down the tube, the image being at the stripper in the terminal. The presence of this triplet reduces considerably the beam size in the low energy tube. A pair of uniform field magnets follows the stripper. These magnets remove the unwanted charge states from the beam leaving the stripper, a function which will be of considerable importance during heavy ion acceleration. If a gas stripper of 0.01 $\mu g/mm^2$ is used, the most probable charge state will be clearly separated from its neighbours for the full range of ion species above 10 MV terminal potential, for all beam within the rms scattering angle. A quadrupole triplet at the entrance to the high energy tube limits the effects of multiple scattering in the

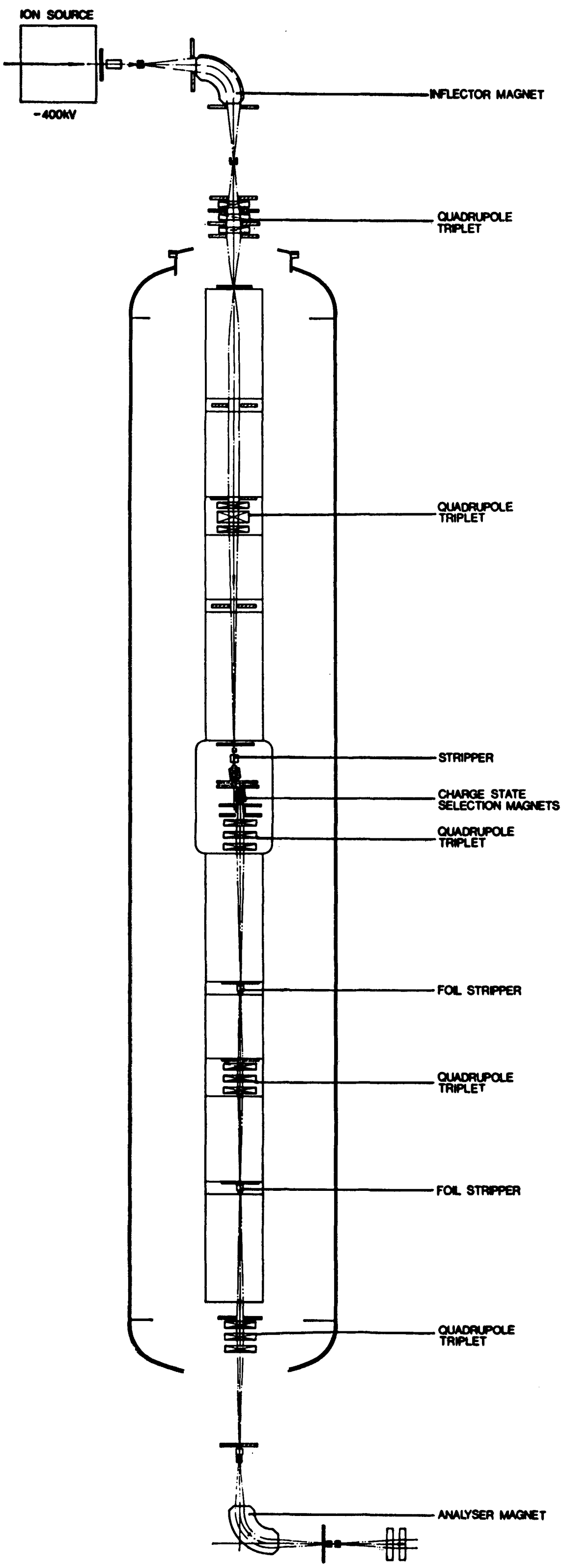


FIGURE 3 The beam optical layout of the tandem.

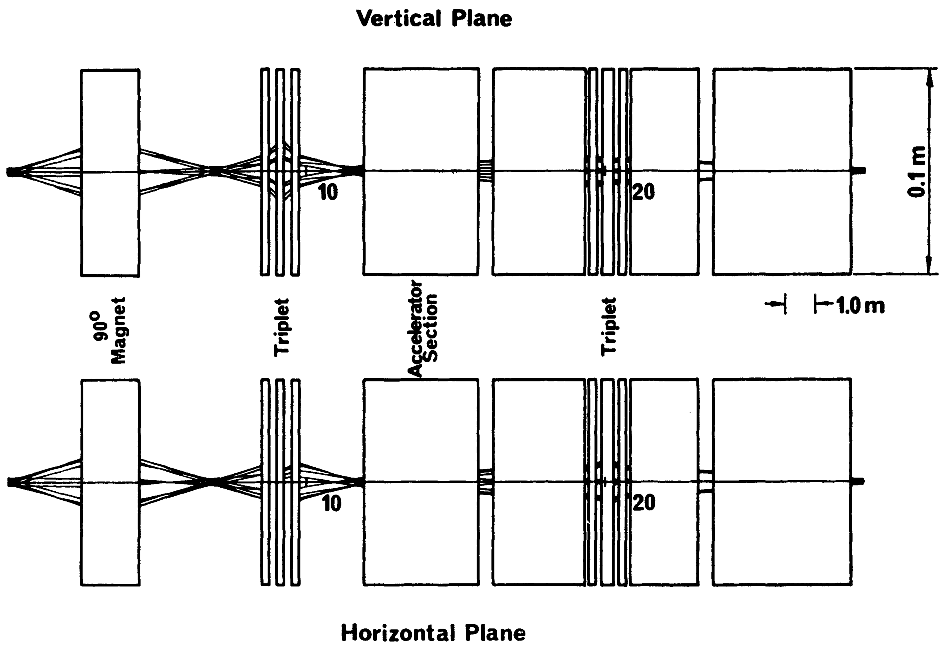
first stripper and produces a cross-over at the position of the second stripper thereby minimizing the emittance degradation due to scattering in this stripper. A triplet in the 1.5 m dead section then waists the beam just beyond the third stripper position. A final triplet at the tube exit presents an object for the 1.25 m radius analysing magnet.

This system has been thoroughly tested for a wide range of ion species and terminal potentials. For an emittance of 0.015 mm rad $(\mathrm{MeV})^{1/2}$ the beam size in the low energy tube is always less than ± 10 mm for terminal voltage greater than 10 MV. In the high energy tube the maximum beam diameter is governed by small angle scattering at the stripper. The beam envelope for particles within the rms angle of scattering is contained in the design aperture of ± 20 mm down to a terminal potential of 10 MV for iodine. For lighter ions the situation is considerably eased. Figure 4 shows a typical computer plot of the beam optics for ^{127}I with 21 MV on terminal and 280 keV injection energy.

The expected performance of a conventional two-gap klystron bunching system applied to the NSF accelerator has been investigated theoretically.[8] So that cylindrical bunching electrodes of small diameter may be used, the buncher has been located near the cross-over point following the double focusing 90° inflector magnet. The equivalent low energy drift length is then about 5 m. The peak klystron bunching voltages range from about 20 kV (for very light ions) to a few kV (for heavy ions) at a bunching frequency of 5 MHz.

The interactive optics computer program has been used to investigate the effect on the beam optics of the energy changes introduced into the beam by the klystron bunching. The effect of bunching is to increase the maximum diameter of the beam within the accelerator and the stripper canal, but even for light ions the increase is tolerable in this optical system.

The debunching effects experienced by the beam during transit to the final target position have been considered in detail. For light ions it should be possible to produce beam bursts of about 1 nsec duration at the final target position while for the very heavy ions, debunching effects in the strippers and transit time spreads in the main analysing



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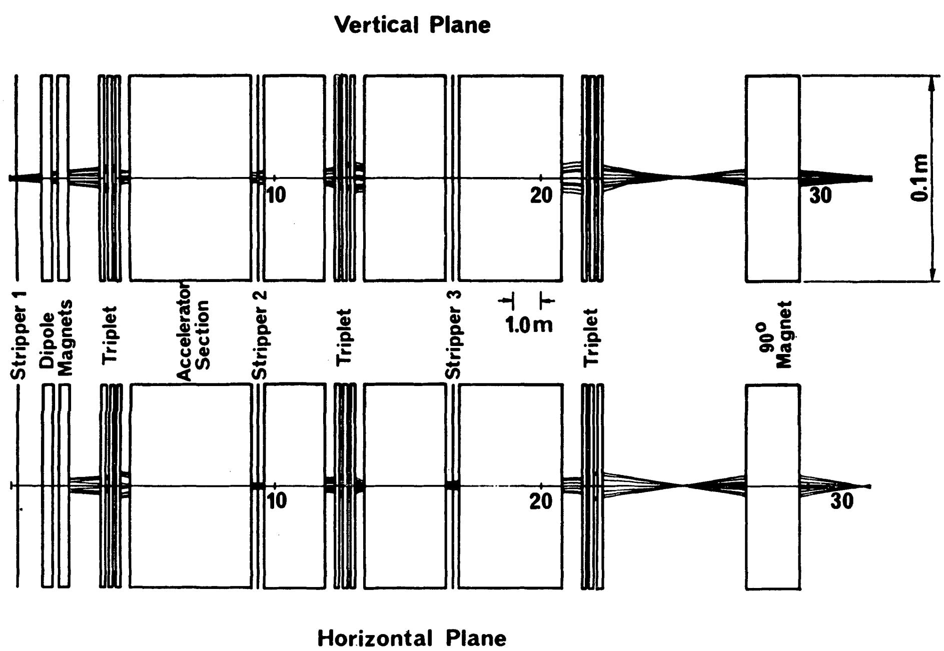

b

FIGURE 4 Computer plot for ^{127}I. The injection energy is 280 keV and the terminal potential is 21 MV. The negative ion trajectories are shown in (a), the positive ones in (b).

magnet limit the final bunch widths to the order of several nanoseconds duration, but typically less than 5 nsec. For bunched heavy ions the contribution to debunching introduced by transit time spreads through the main analysing magnet can be substantially reduced by operating the magnet in an isochronous mode.

Detailed calculations have been carried out for the transport of a polarized ion beam from the input object point of the 90° inflector magnet to the output focus of the 90° analysing magnet. The results of these calculations show that for the worst case for protons the depolarization is 0.035 per cent and is thus completely negligible. The spin vector precession is large, being of the order of 150° for protons, deuterons and tritons. However this precession is slowly varying down most of the angular range of the spin vector projections, although regions exist where the precession is rapid. It is possible to set the spin projections at the appropriate angles at the entrance to the 90° inflector magnet such as to give the required spin vector orientation in the experimental area without the need for spin precession devices elsewhere in the transport system through the machine. The equipment needed to set the projections at the entrance to the machine is that which is normally supplied with a polarized ion source.

A scheme has been devised for injecting neutral polarized ^{3}He particles into the machine in order to obtain polarized ^{3}He beams, while the possibility has been demonstrated of locating a high intensity positive polarized deuteron source in the centre terminal of the accelerator in order to produce highly polarized mono-energetic neutrons by the $D(d,n)^3$He reaction.[9]

Collimation will be required to reduce the possibility of scattered beam and nonreference charge states hitting the tube structure. Particle trajectories have been studied in order to find suitable positions and sizes for the collimators. These will be located at each dead section in the high energy tube.

Higher order optical effects have been investigated and found to be small. The precision in setting up and aligning the beam line elements has been determined, and is well within the normal standards of the laboratory. It has been determined that the field strengths of quadrupole lenses within the machine are not critical.

It is intended that the vacuum system should operate at pressures of less than 10^{-5} N/m^2 (approximately 10^{-7} torr) and be as free as possible from hydrocarbons and heavy molecules. Methods have been developed under contract at Harwell of bonding suitable metals direct to aluminium oxide so that the complete vacuum system including the accelerator tubes will be free of organic materials.

Ion sources will be pumped by diffusion pumps using polyphenyl ether, external beam tubes by turbo-molecular pumps, and the accelerating tubes by sputter-ion pumps located in the short dead sections of the accelerator stack and in the centre terminal. Gas stripper pumping in the centre terminal will be by means of a titanium sublimation pump or a cryo pump. A test rig is in operation to study the stripper pumping system.

4. COLUMN CONSTRUCTION

The design of the accelerator column has developed in close association with an extensive high voltage test programme at Daresbury Laboratory and at AWRE Aldermaston.[1,2] Both dc and pulse tests on encapsulated samples using a 1.5 MV Van de Graaff accelerator and a 600 kV Marx generator have been used to compare a wide range of insulator materials, and studies have been made of the initiation and development of breakdown both on the surface and in the main volume of the insulator.

Various discrete and annular spark gap configurations have been tested in order to find a fast and efficient spark gap system.

The insulator tests indicate that glass has advantages over ceramic, and that some types of glass meet our requirements particularly well. It has been found that internal stresses in the glass can cause mechanical breakdown of the insulators under surge conditions and must thus be minimized, while stringent quality control is needed in order to avoid impurities and flaws in the glass. Column sections constructed of suitable glass insulators protected by annular spark gaps have been operated successfully for many hundreds of hours in the 6 MV Aldermaston tandem at gradients of 3.3 MV/m. Large numbers of tank sparks leading to high voltage surges have been deliberately produced to make the tests as severe as possible.

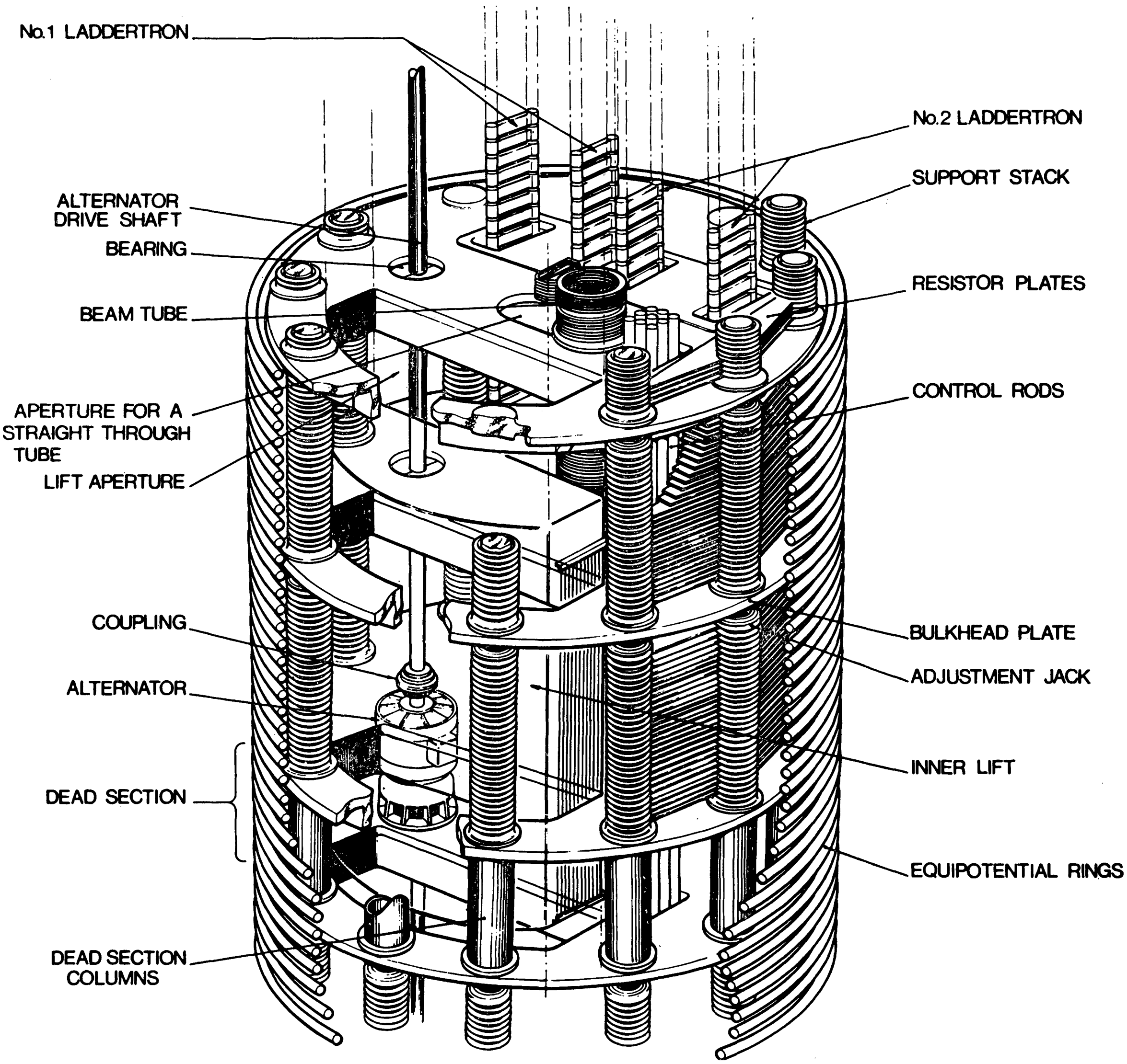

FIGURE 5 Perspective view of part of the accelerator column.

Various configurations have been examined for the accelerator grading resistors. Early studies involved a variety of assemblies including encapsulated ones but under high voltage gradients and surges they could be made to fail. Two systems have now been developed,[1] either of which appears to give complete protection of the resistors. In one, the resistors are placed inside metal tubes the spaces between which act as protective spark gaps. In the other, the resistors are connected in zig-zag configuration between parallel flat plates the edges of which are fitted with continuous spark gap electrodes.

The NSF column will be constructed using components selected during the high voltage tests. Twelve stack legs consisting of glass insulators protected by annular spark gaps are used (Figure 5). The structure is modular, each leg section being 820 mm long, of which 744 mm is active insulation, the remainder containing an adjustment mechanism which allows the leg section to be removed from the stack for repair or replacement. The accelerator tube will have the same modular length. The modular sections of the column are separated by 100 mm thick aluminium bulkheads each of which contains apertures through which pass the beam tube, the charging system, the control rods and the drive shaft for the in-line alternators which provide electrical power at the dead sections and the centre terminal. A full analysis is at present being made of the static and dynamic mechanical properties of the column structure.

The machine components will be serviced from a small lift inside the column and from a larger annular lift around the perimeter of the column. Personnel access ports into the pressure vessel are provided at the top and at the base of the vessel.

5. THE CHARGING SYSTEM

In most electrostatic accelerators charge is carried to the high voltage terminal by means of an endless belt made of insulating material. Charge is sprayed on to the surface of the belt by a corona discharge and is removed from it on arrival at the terminal by the same process. Currents of up to 1 mA are commonly conveyed by this means. Belt charging has however a number of basic disadvantages. Slight inhomogeneities in the insulating material lead to variation in the charging current and hence in accelerator terminal potential. The nature of the inhomogeneities is not well understood. Belts are found to have limited lifetimes and cause dust within the machine, while the method of charging can lead to the production of undesirable gaseous breakdown products, especially in machines with an SF_6 gas filling.

As an alternative to belt charging, the electrical charge can be carried on a series of conductors separated by sections of insulating material as in the successful Pelletron design devised by R. G. Herb. The conductors are charged by electrostatic induction. In presently operating inductive charging systems very stable charging conditions are obtained but the maximum current carried is low, typically less than 100 μA.

This limitation has been overcome in a charging system, called the laddertron,[1] developed jointly by Daresbury Laboratory and the University of Reading. In this device each conductor is constructed from small cylinders joined together by an elongated bar. The latter provides a large surface area for charging and overcomes vibration problems which occur in a simple single chain system. Successive conductors are flexibly joined together by insulators to form an endless ladder-shaped structure. Built-in annular spark gaps around each insulator act as protection against voltage surges. The laddertron is constructed from aluminium and stainless steel for the conducting elements and glass-filled nylon for the insulators. The vee pulley on which it runs is made of a specially fabricated resilient conducting material. Figure 6 shows a section through the laddertron, the pulley and the inductor electrodes. The spacing of the pulleys is 127 mm centre to centre.

The laddertron has been operated in the 1 MV Van de Graaff generator at the University of Reading and on short circuit it provides an equal up and down charge current each of 275 μA at a speed of 15 m/sec. Voltage ripple measurements have not yet been made.

Life tests have extended over many hundreds of hours and it is realistic to design for a life expectancy of 10,000 hours for the final version of the device.

Electrical tests on a larger model for the 30 MV machine have been carried out, and the spark gap geometry optimized. A gap nose radius and

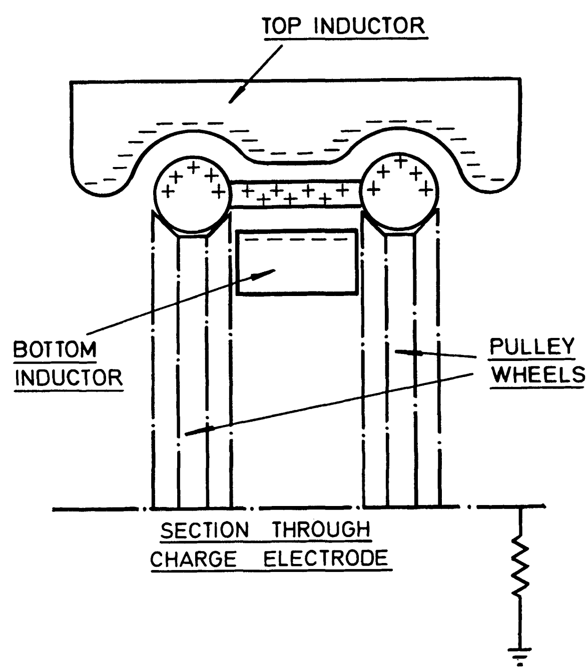

FIGURE 6 The laddertron induction system.

separation have been determined such that a factor of two safety in the spark gap breakdown voltage is obtained in gradients up to 2.2 MV/m.

6. INSTRUMENTATION

The control systems are being kept as simple as possible for the sake of reliability, but there will inevitably be more diagnostic and control elements inside the pressure vessel than in earlier electrostatic accelerators because of the extra lenses required to keep the beam diameter small. Space has been allowed along the beam path through the machine for all components of this type whose use can be foreseen, but it is anticipated that several of them will not be necessary because of the attention devoted to the design of the optical systems and to the mechanical stability and alignment accuracy of all critical elements. This ensures that it will be possible to pass the beam through the machine with the minimum of correction by deflectors. Values of lens strength and deflecting magnet field strengths for particular ions at the required energy can be readily ascertained from the optical calculations. It is hoped that by presetting these values a good deal of the trial and error customary in setting up beams in tandem accelerators will be avoided.

A modulated light beam will be used to transmit information both to and from components inside the pressure vessel, and tests on a prototype system are in progress. It is not intended, however, to finalize details of the control system within the vessel for some time. To provide for the considerable interaction necessary between controls for the injector system, for the accelerator itself, and for the accelerator beam, a small computer will be used. A colour television display has been developed for use with the control computer,[10] and is now being manufactured commercially under licence.

Tests on the reliability of power supplies and electronic components for use in the pressure vessel are under way in the terminal of the AERE Harwell tandem, and useful results have been obtained on screening requirements for circuits exposed to the strong electromagnetic fields generated by high voltage sparks.

The design of control systems for plant outside the pressure vessel is now virtually complete in principle, though not fully detailed. All plant parameters can be monitored and controlled remotely, and the system can be readily adapted to computer supervisory control and data logging.

7. STABILIZATION

Several methods of stabilizing the energy of the accelerated beam are being considered. The possible combinations of error sensors and means of applying the correction voltages are numerous, but all consist essentially of two-loop systems, the slow loop acting through the laddertron charging current and the fast loop correction being applied either to stripper bias voltages or to the tank liner. To avoid confusion caused by unwanted charge components in the output beam, it is necessary to know the potentials of the strippers to within certain limits, and calculations have been performed to define these limits. When three strippers are used, the possibilities of confusion of wanted and unwanted charge states are such that it will be necessary to use a velocity selector to remove the unwanted components from the experimental beam lines. There is space for a selector having the necessary resolution to be installed above the analysing magnet entrance slit. However, it is unlikely that a three-stripper system will be required, at least in the early stages of operation.

8. ACCELERATOR TUBES

The component which most often limits the performance of an electrostatic accelerator is the accelerator tube itself. A programme of development work has been started on tube design and performance, and it is expected that this will be a continuing part of the work of the laboratory.

It is generally accepted that accelerator tube breakdown is initiated by some sort of multiplication of secondary particles within the tube, and the very considerable success of tubes using off-axis electric or magnetic field components to deflect unwanted particles into the side of the tube lends some support to this view. Such tubes can lead to problems in that they cause deviations of the primary beam from the tube axis, sometimes leading to difficulties in alignment which can be serious if a variety of charge states is to be accelerated. Although neither of these objections is fundamental, an attempt is being made to develop a tube design based on a different principle. The length of the tube is divided into short active sections separated from each other by a system of biased apertures, in dead sections. Careful attention to the details of electrode shape, based on computed trajectories for particles originating at the electrodes, has shown that it is possible to avoid multiplicative processes, while solutions to the electric field near the insulator-electrode junction have led to an insulator profile which, together with the electrode shape, ensures that particles originating anywhere on the electrodes are directed away from the insulator surface.

Sections of tube of different lengths, of various electrode and insulator materials and containing various bias systems are being assembled and tested, though this work is at an early stage.

9. MAGNET DESIGN

Great care is being taken in the design of the accelerator magnets. Those within the pressure vessel have been designed to keep heat dissipation within acceptable limits and temperature tests on prototype coils are under way. A large computer program is being used to design the magnet poles.

10. SURGE PHENOMENA

It is well known that electrical discharges occur in electrostatic accelerators and lead to serious overvoltages occurring across components. These frequently cause breakdown and damage. Little work has been done in the past, either theoretically or experimentally, to study these surge phenomena. It is clear that the problems become rapidly more serious as the terminal potential increases, and because of this a programme of study was started at Daresbury Laboratory.

To date various simple electrical equivalent circuits have been used to obtain computed predictions of surge voltages. The method of Kiss[11] and Rose and Milde,[12] in which the accelerator column is represented by a series of interplane capacitances with each plane having a capacitance to ground, has now been extended to tandem structures having an intershield.[13] Extensive computations have been made of overvoltages resulting from a variety of breakdown conditions.

The structure of the accelerator, consisting of a central column of hoops and plates located in a cylindrical pressure vessel, may be considered as a coaxial transmission line. This is the basis of a second approach to the problem. Suitable boundary conditions allow for the hoop and equipotential plate configurations, and voltage and resonant frequency parameters are computed.

In parallel with these computations, measurements are being made on simplified models of accelerator structures and on an actual 1.5 MV Van de Graaff. It is important to be able to measure the magnitudes of the surges which occur, their risetimes, and the resonant frequencies. Three techniques to enable these measurements to be made are under development. In the first of these a sensing capacitor with a very high voltage division ratio (10^5:1) and a wide bandwidth (300 MHz) is used. The output signal is handled directly by solid state circuitry and a device of this type is being used successfully to measure transients in the 1.5 MV Van de Graaff. The second system uses a light emitting diode placed across the low voltage section of a capacitive divider. The light guide connects the diode, which may be at high potential, to a photomultiplier. The third system makes use of a Pockells cell in which the plane of polarization of the light from a laser is rotated through an angle which is proportional to the voltage applied across the cell. This system is at an early stage of development, but holds out interesting possibilities if the development is successful. In addition to this approach, a comprehensive programme of tests on insulators and other components has been carried out at voltages up to 6 MV, as indicated in the section on column construction.

11. PILOT MACHINE

As mentioned earlier, a considerable programme of development has been carried out on the 6 MV tandem at AWRE, Aldermaston. This facility will not be available indefinitely. To supersede it as a test facility a pilot machine is under construction at Daresbury Laboratory. This consists of a column about 3 m high, made up of 4 of the standard modules as designed for the actual accelerator, surmounted by a terminal shaped for optimum electrostatic performance. The structure is contained in a suitable vessel, and a complete gas handling system enables this to be filled with sulphur hexafluoride up to a pressure of 1 MN/m^2. Charging will be by a laddertron chain. Components such as stack legs and protective systems, control mechanisms, power supplies and pumping systems will be tested in this machine, as well as the laddertron itself. In addition one of its most important roles will be in tube development.

12. OUTPUT BEAM ENERGIES

In calculating output beam energies[14] the charge state predictions of Dmitriev and Nikolaev[15] have been used both for gas and for foil strippers. The inclusion of strippers within the high energy accelerating tube, in addition to the stripper in the centre terminal, results in considerable gain in output energy though at the expense of beam intensity. Careful investigations show that over a wide range of operating conditions the optimum potential of the second stripper in a two-stripper system is around $2\ V_0/3$, V_0 being the terminal potential. The optimum potentials for the second and third strippers of a three-stripper system are found to be $0.9\ V_0$ and $0.6\ V_0$. It is not considered advisable to locate an additional stripper between the 'second' stripper at $2\ V_0/3$ and the centre terminal as it would not be possible to produce a beam cross-over there to limit the effects of multiple scattering which would be large due to the relatively low beam energy. It is therefore intended to locate the second stripper in the short dead sections at $2\ V_0/3$ even though this will lead to some loss of output energy during three stripper operation. This energy is insensitive to the third stripper potential which has been chosen to be $V_0/4$, again in a short dead section.

The stripper positions are in good accord with beam optical requirements. In addition the intershield is attached at $2\ V_0/3$ so the potential of the second stripper will be stabilized to some extent by the large capacitance of the intershield to ground. The variation in beam energy with second and

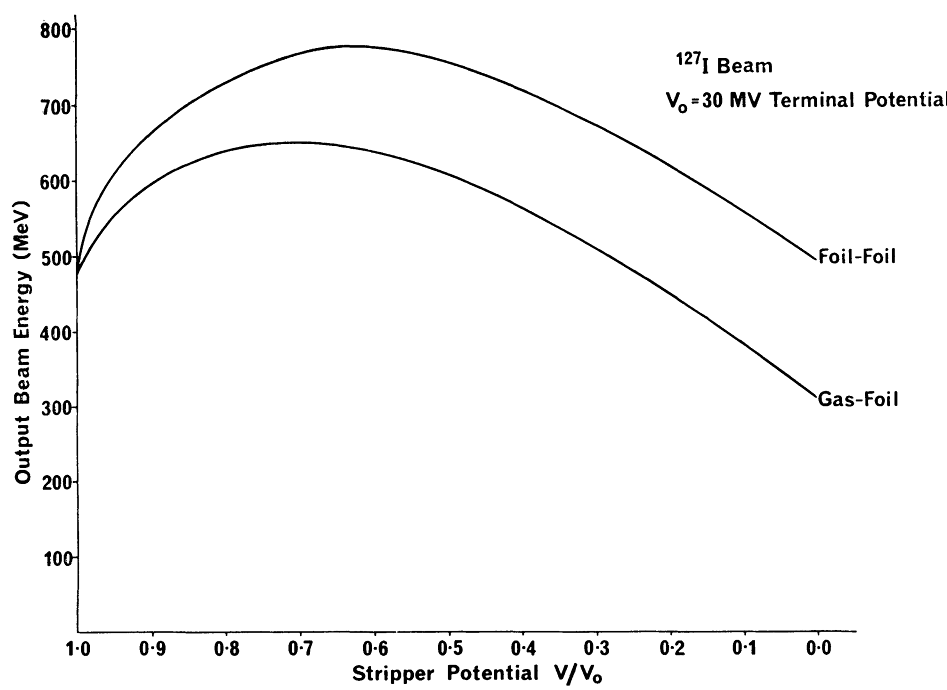

FIGURE 7 Variation in output beam energy with second stripper potential for a gas-foil and a foil-foil stripper system. The terminal potential is 30 MV and the beam is iodine.

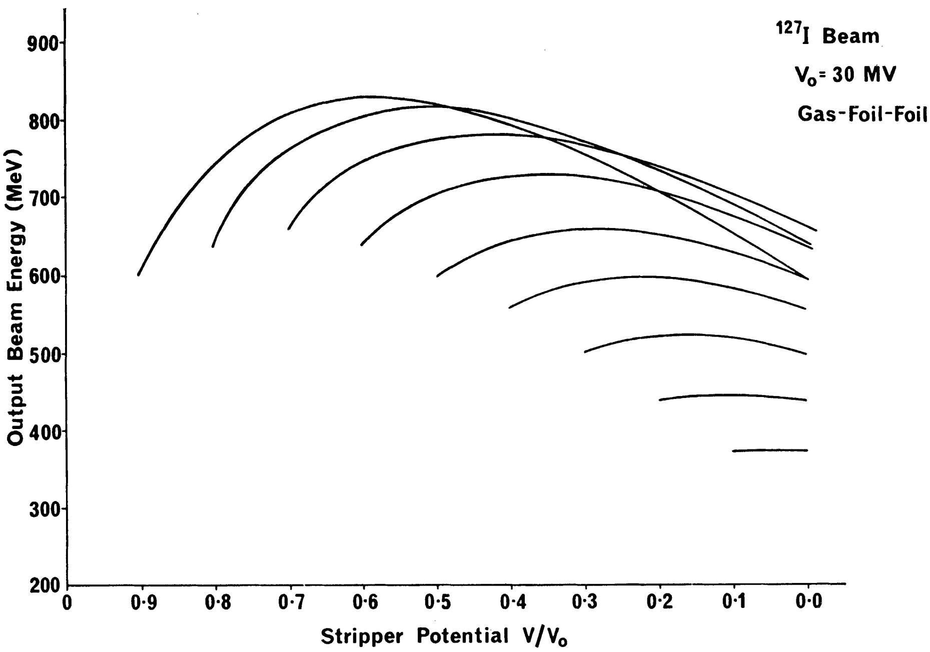

FIGURE 8 Variation in output beam energy with second and third stripper potentials for a gas-foil-foil system. Each curve corresponds to a fixed potential for the second stripper while the third stripper potential is varied. The terminal potential is 30 MV and the beam is iodine. The uppermost curve is for a second stripper potential 0.9 V_0, the lowest for a second stripper potential of 0.1 V_0.

TABLE II

Predicted output beam energies for various combinations of gas (g) and foil (f) strippers. The mass number of the heaviest ion that will overcome the Coulomb barrier on a uranium target is also given in each case

Terminal voltage	Stripper conditions	Cu MeV	Br MeV	I MeV	U MeV	Mass number of heaviest ion on uranium
30 MV	2 strippers gf	550	590	660	700	120
	2 strippers gf intensity down by 10	610	660	750	800	130
	2 strippers ff	610	680	790	915	145
	2 strippers ff intensity down by 10	640	720	850	1020	155
	3 strippers gff	560	620	730	860	140
20 MV	2 strippers gf	300	330	360	360	80
	2 strippers gf intensity down by 10	360	380	420	420	90
	2 strippers ff	350	400	440	460	95
	2 strippers ff intensity down by 10	400	430	510	550	105
	3 strippers gff	310	360	400	420	90

third stripper position is shown in Figures 7 and 8.

Table II gives some idea of the beam output energies to be expected with the strippers at potentials of V_0, 2 $V_0/3$ and $V_0/4$. Also indicated are the heaviest ions which will be able to overcome the Coulomb barrier on a uranium target, the 'Hilab' Coulomb barrier expression having been used in these calculations.

It is clear from Table II that a foil stripper produces significantly higher beam energies than a gas stripper. A jointly sponsored research programme is under way at Harwell in an attempt to obtain a better understanding of the processes limiting stripper foil lifetimes in the hope of eventually extending the use of foils to heavy ions. Meanwhile it is intended that a gas stripper be used when heavy ions are being accelerated.

Most of the beam energies quoted in Table II assume that the most probable charge state has been selected at each stripper. Reference to Tables II and III shows that energies and intensities comparable to those obtained from three strippers can be obtained using two strippers and operating at a higher, less probable charge state at the first stripper.

The beam intensities quoted in Table III are for commercially available ion sources and assume that 30 per cent of the beam is lost by collimation after each stripper.

13. BUILDINGS

The building layout has been arranged so as to keep as much as possible of the area around the foot of the tower available for beam rooms while still allowing easy access from the counting rooms and service areas. From Figure 9 it can be seen that the three experimental areas together occupy more than 210° out of 360°. Each area has a radial dimension of 20 m allowing sufficient space for three beam lines, one of which could contain a large spectrometer. The spare space would be used later to add a second stage accelerator or more experimental areas depending on the long-term requirements of the laboratory, while the whole complex has been so orientated relative to the contours of the site at Daresbury Laboratory that 100 m flight paths would be available through two of the experimental areas. A radio-chemistry facility could be located on a mezzanine floor above part of the largest of the main experimental areas. Its shield wall positions are marked by dashed lines in Figure 9. It is not yet known whether this facility will be authorized but it can easily be added at a later stage. It would make use of the relatively high intensity of the un-analysed particle beam leaving the accelerator when more than one stripper is in use.

The design of the area allocated for control, counting and computing requirements has been looked at in some detail. It is proposed that a single large room should be provided but that the arrangement of the services, especially the air conditioning, be so designed that the area can be easily divided into seperate functional compartments if this is considered desirable at any stage of the project. The control and counting room is located above the workshop and assembly area and the clean room. The floor level of this room is 4.5 m above that of the experimental areas. A shielded passage around the outside of the tower at this level allows access to each of the areas by means of a light staircase.

Cables in the beam areas will be located in overhead cable trays. The cables connecting the beam areas to the control and counting room will pass

TABLE III

Predicted output beam intensities for various stripper configurations. The figures are based on the intensities of currently available ion sources

Stripper conditions	Cu particle nA	Br particle nA	I particle nA	U particle nA
2 strippers	300	1200	1000	15
2 strippers intensity down by 10	30	120	100	1.5
3 strippers	50	140	110	2

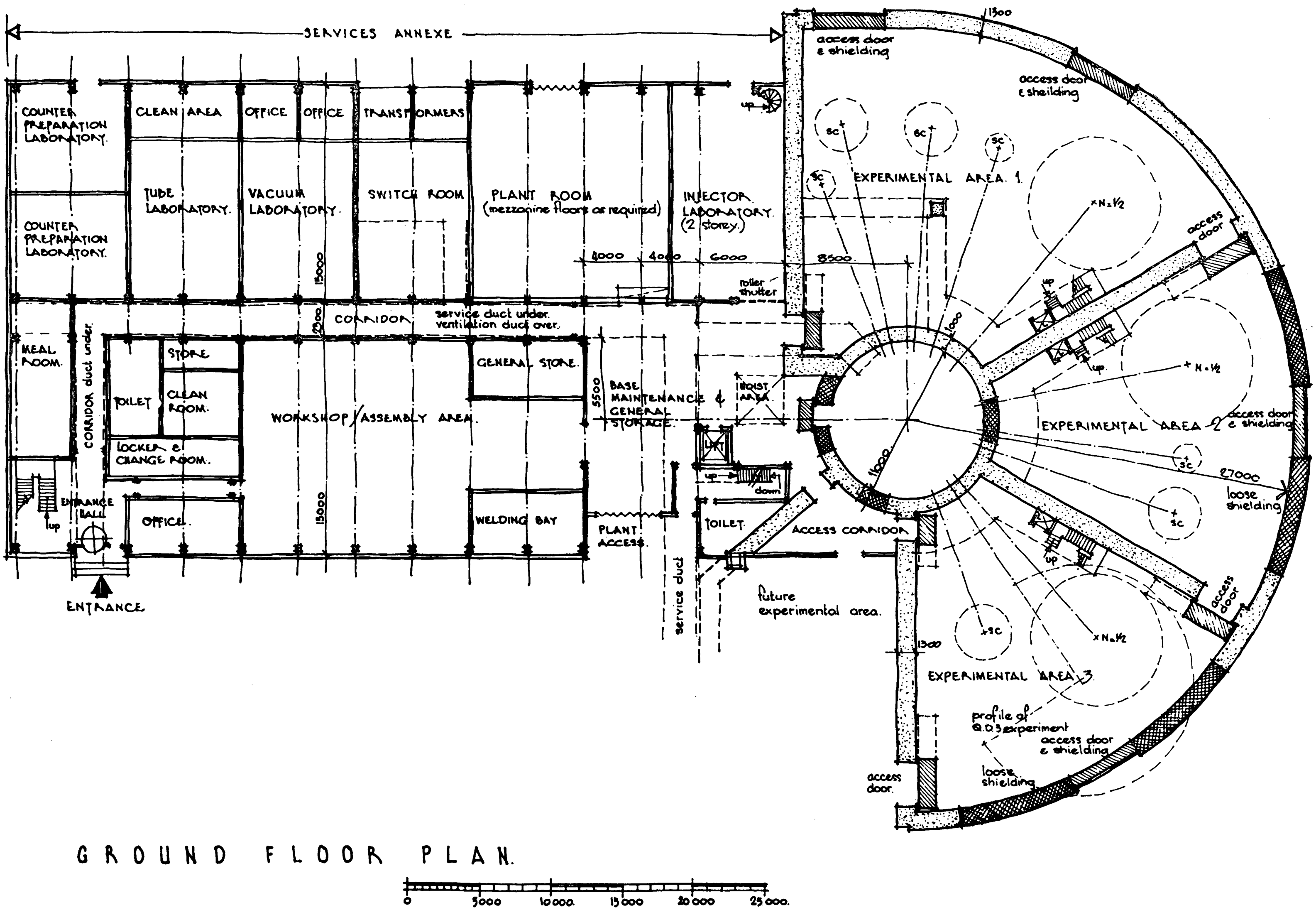

FIGURE 9 Ground floor plan of the nuclear structure facility.

from these trays into ducts beneath the floor of the control and counting room.

The walls of the accelerator tower building will be of thickness 1 m as will the injector room floor and the experimental area roof. The dividing walls between the experimental areas will be 1.3 m thick. These thicknesses allow adequate shielding for personnel and equipment.

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