A NATIONAL NUCLEAR STRUCTURE FACILITY FOR BRITAIN

N.R.S. Tait and R.G.P. Voss
Science Research Council
Daresbury Nuclear Physics Laboratory
Daresbury, Warrington, England.

Summary. A large electrostatic tandem accelerator has been designed to provide a nuclear structure facility in Britain. The machine is intended to operate initially at a terminal potential of 20 MV, with subsequent upgrading to 30 MV. The design of the facility is described, including the choice of main parameters, the beam optics, column construction, charging system, instrumentation and buildings. An extensive development programme on high voltage problems is being carried out.

Introduction

For some years there have been discussions in the United Kingdom about new facilities for nuclear structure research. These finally led to a proposal to build a large tandem electrostatic accelerator to function as a national nuclear structure facility. The accelerator was to be suitable for accelerating beams of all ions, particularly heavy ions, to operate with a terminal potential of 20 MV, and to be capable of development to a terminal potential of 30 MV.

The Science Research Council approved a proposal that a design study be carried out by the Daresbury Nuclear Physics Laboratory. This study was started in April 1971 and completed in September 1972. It covered the design of the accelerator, associated plant, and buildings, and included an extensive programme of development and tests in the field of high voltage technology. The costs and manpower requirements were determined.

A strong group has been set up within the laboratory to work on the project. In addition, considerable effort has been devoted to the project by outside bodies and co-ordinated and controlled by the laboratory. The main outside contributors have been the United Kingdom Atomic Energy Authority (Risley, Aldermaston and Harwell) and the universities of Manchester, Reading, Salford, Birmingham and Liverpool.

The Science Research Council has approved the design study, and has also approved, subject to ratification by the Department of Education and Science, the construction of the nuclear structure facility.

General Features of the Machine

There are several complex factors which determine the general features of the machine. 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 but must also be as small as possible to minimise cost.

It was decided to build the machine in a vertical position. This simplifies structural problems somewhat while such an arrangement makes adequate space available for experimental areas by using a 90^{0} analysing magnet capable of rotation about a vertical axis to direct the particle beam into one of a number of beam lines. A similar magnet at the input end of the machine allows several ion sources to be deployed in a circle in the injector room. This arrangement provides excellent access to the sources, some of which are likely to be large and complicated and require frequent servicing.

The pressure vessel is to be cylindrical 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 will be covered with a liner of high surface finish. It will be insulated from the vessel walls and could be used in the voltage stabilisation system of the machine if required. Ports and penetrations in the vessel walls have been kept to a realistic minimum.

Many of the main components of the accelerator are illustrated in Fig. 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.

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. The design provides for an intershield, though the accelerator could be run initially without it : the stack is consequently of constant diameter.

Possible configurations with a wide range of values r/R have been considered, and a value of 0.4 finally selected. The intershield potential was chosen to be 2/3 that of the terminal. This is close to the optimum and is convenient for other reasons. The shapes of the terminal, intershield and hoops have been determined to minimise local fluctuations in total field strength. The hoops have a diameter of 50 mm and are spaced at 72 mm centres.

The final design parameters are shown in Table I.

TABLE I

Tank length	=	45.22 m
Tank inside radius	=	4.07 m
Tank liner radius	=	3.92 m
Tank max. design pressure	=	0.83 MN/m^2 (120 psi)
Tank max. working pressure	=	0.76 MN/m^2 (110 psi)
Centre terminal length	=	4.50 m
Centre terminal radius	=	1.50 m
Stack active length	=	13.40 m
Stack radius	=	1.15 m
Long dead section length (2)	=	1.50 m
Short dead section length (4)	=	0.50 m
Intershield outer radius	=	2.34 m
Intershield inner radius	=	2.24 m
Intershield potential	=	2/3 x terminal potential

The dimensions above 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[1] which has been extensively developed at Daresbury Laboratory. The results, shown in Fig. 2, show considerable improvement over distributions for existing machines.

The centre terminal is designed to contain both a gas and a foil stripper while two further foil strippers are located in the short dead sections. The short dead sections also contain vacuum pumps while the long dead sections contain magnetic quadrupole lenses. The insulating gas is sulphur hexafluoride (SF_6) and the gas handling plant has been designed to allow emptying and re-filling the vessel in about 24 hours.

The Beam Path through the Accelerator

The accelerator is required to handle beams of all ions, including pulsed and polarised beams. Also, the beam aperture must be kept as small as possible in order to allow high tube gradients and terminal potentials to be attained. Consequently it was necessary to design the beam optics in detail. An interactive computer program has been developed at Daresbury Laboratory[2], and 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. This has enabled a thorough study to be made of the system[3]. Several points should be noted. There is a cross-over close to the entrance of the low energy tube, to allow accurate beam alignment immediately prior to acceleration and to minimise the lens effect of the tube entrance. Two uniform field magnets follow the stripper in the centre terminal to remove unwanted charge states, a function particularly important with heavy ions.

With this system the beam size is always less than $\pm$ 10 mm in the low energy tube, and less than $\pm$ 20 mm in the high energy tube. Fig. 3 shows a typical computer plot of the beam optics for ^{127}I with 21 MV on terminal and 280 keV injection energy.

Magnet design is well advanced. Heat dissipation is important and temperature tests on prototype coils in SF_6 are under way.

A conventional two-gap klystron system is used for producing bunched beams[4]. Peak klystron voltages range from 20 kV for very light ions to a few kV for very heavy ones, at a bunching frequency of 5 MHz. Beams of 1 to 5 ns duration will be produced.

Detailed calculations have been carried out for polarised beams, on collimator positions, on higher order optical effects, and on the precision required in setting up and aligning beam elements. The vacuum system will operate at less than 10^{-5} N/m^2 (about 10^{-7} torr) and methods have been developed for making accelerator tubes free of organic materials. A test rig is in operation to study the stripper pumping system.

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. Both d.c. 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. The insulator tests indicate that glass has advantages over ceramic, and that some types of glass meet our requirements particularly well. Work has been done to determine the degree of stress relieving required, and to what level impurities and flaws must be reduced. 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. Extensive tests have been carried out on spark gap configurations and resistor assemblies, leading to satisfactory designs.

Twelve stack legs consisting of glass insulators protected by annular spark gaps are used, Fig. 4. 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.

Charging System

The conventional belt charging system has several disadvantages, such as fluctuations in the charging current, uncertain lifetime, and the production of dust. An alternative method is to induce electrical charge on a series of conductors separated by insulating material, as in the successful Pelletron developed by R.G. Herb.

Stable charging conditions are obtained, but the charging current is low. This limitation has been overcome in a charging system called the Laddertron, 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 has been operated in the 1 MV Van de Graaff generator at the University of Reading and on short circuit it provides a total up and down charge current of 550 μA at a speed of 15 m/s.

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 optimised. A gap nose radius and 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.

Instrumentation and Control

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.

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 finalise 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 accelerated beam, a small computer will be used. A colour television display has been developed for use with the control computer[5], 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.

Several methods of stabilising the energy of the accelerated beam are being considered. These consist of two-loop systems, the slow loop acting through the Laddertron charging current and the fast loop being applied either to stripper bias voltages or to the tank liner. Systems will be tried on the pilot machine mentioned below.

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 length and of various electrode and insulator materials are being assembled and tested.

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[6] and Rose & Milde[7], in which the accelerator column is represented by a series of inter-plane capacitances with each plane having a capacitance to ground, has now been extended to tandem structures having an intershield[8]. 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. A capacitive device for measuring surges with a very high division ratio (10^5:1) and a wide bandwidth (300 MHz) has been produced. Other devices are being developed.

Pilot Machine

A pilot machine is under construction at Daresbury Laboratory as a test machine. This consists of a column about 3 m high, made up of 4 of the standard modules as designed for the actual accelerator, surrounded 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.

Output Beam Energies

In calculating output beam energies[9] the charge state predictions of Dmitriev and Nikolaev[10] 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. Table II gives some idea of the beam output energies to be expected with a three-stripper system, the strippers being at potentials of V_0, $\frac{2}{3}V_0$ and $\frac{1}{3}V_0$. 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.

Because of the advantages of using a foil stripper in the terminal, a jointly sponsored development programme is under way at Harwell in an attempt to obtain a better understanding of the processes limiting stripper foil lifetimes.

TABLE II

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

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 Fig. 5 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 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 Fig. 5. It is not yet known whether this facility will be authorised 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 separate 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.

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.

References

(1) P.J. Stenning and C.W. Trowbridge, Reading University/ Rutherford Laboratory Report RU/RL-1.
(2) B.W. Davies, Nucl. Instr. & Methods 105, p.477,1972.
(3) T.Joy, J.C. Lisle and W.R. Phillips, Daresbury Laboratory Report DNPL/NSF/R3.
(4) R. Chapman, to be published.
(5) C.W. Horrabin, W.T. Johnstone and K. Spurling, to be published.
(6) A. Kiss, Nucl. Instr. & Methods 92, p.361,1971.
(7) P.H. Rose and H. Milde, Trans. IEEE Nucl.Sci.NS18, p.63, 1971.
(8) L. Naylor, to be published.
(9) H.G. Price, Daresbury Laboratory Report DNPL/NSF/R2.
(10) I.S. Dmitriev and V.S. Nikolaev, Sov.Phys.JETP 20, p.409, 1965.
V.S. Nikolaev and I.S. Dmitriev, Phys.Letts. 28A, p.277, 1968.

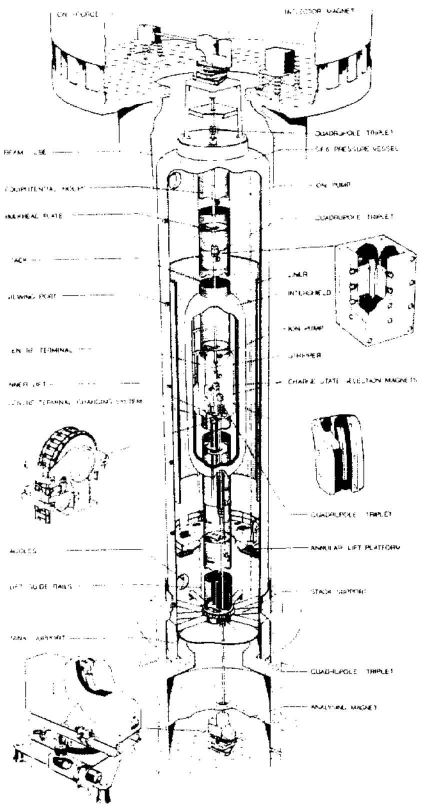

Fig. 1. Cut-away drawing of the tandem accelerator.

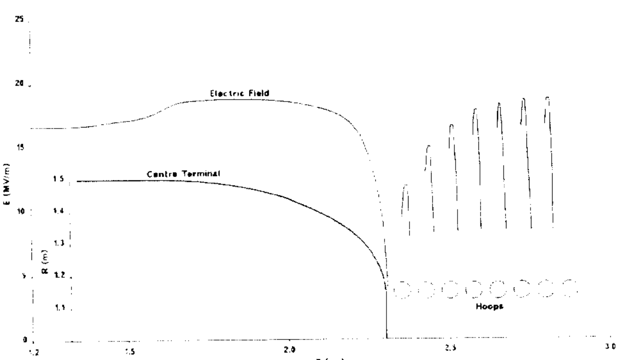

Fig. 2. The total electric field strength at the terminal-stack junction. Terminal potential 30 MV.

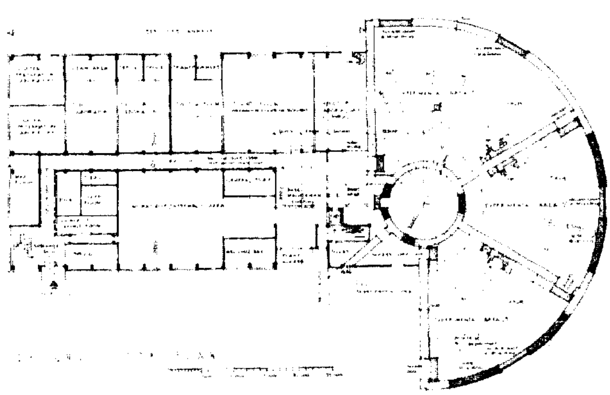

Fig. 5. Ground floor plan of the nuclear structure facility.

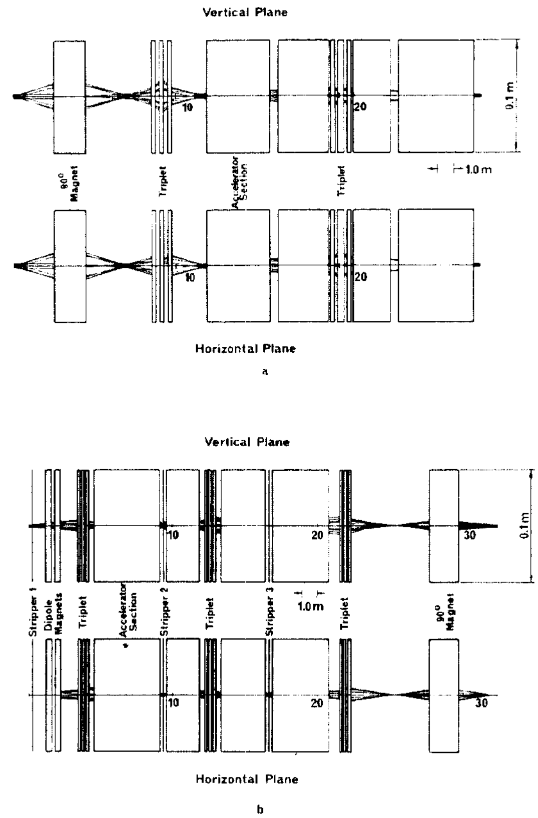

Fig. 3. A computer plot of the beam optical system for (a) the negative ion and (b) the positive ion trajectories.

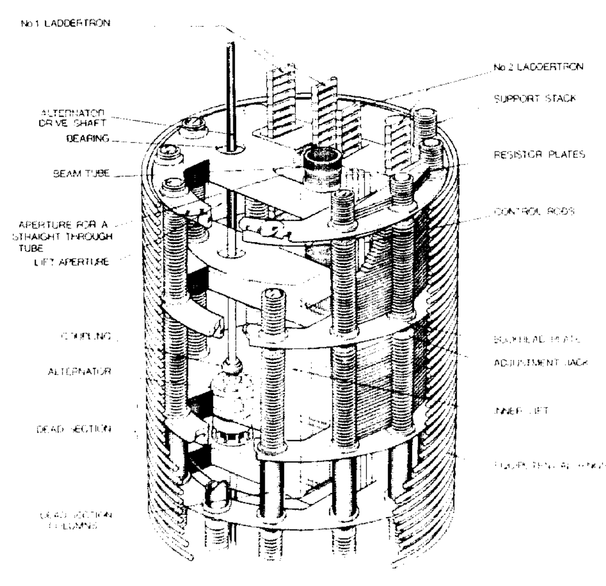

Fig. 4. Perspective view of part of the accelerator column.