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KYOTO UNIVERSITY TANDEM VAN DE GRAAFF

By

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Synopsis

A tandem type Van de Graaff accelerator at the Department of Physics in Kyoto University is described. Details of the accelerator, ion optical arrangement, structure of the columns, acceleration tubes, vacuum system, negative ion injection system, generation and control of the high voltage, beam analysing magnet and switching magnet, high pressure gas system, building and general arrangement of the equipments are presented. The course of the construction and test of the machine is also described with the specifications of the machine and its performances.

§ 1. Introduction

The Department of Physics in Kyoto University had a plan to build a Van de Graaff accelerator for the nuclear research since 1957. In 1962, this plan was supported financially by the Ministry of Education.

In the tandem Van de Graaff the ion source is located outside of the pressure tank at the electrically grounded potential, providing easy access for maintenance and adjustment and also easy modification for the experimental purposes. That is an important advantage of the tandem type Van de Graaff comparing to the ordinary type. There are two possible types of tandem Van de Graaff, vertical and horizontal. The latter type of the machine is more convenient to use and is more suitable for the

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laboratory building but is more complicated for the mechanical construction.

The construction of a horizontal tandem type Van de Graaff accelerator started under a joint team of research staffs of Kyoto University together with the members of the Mitsubishi Atomic Power Industries Inc..

Various experimental tests for the engineering, especially concerning the mechanical strength of the column structure of the accelerator, were carried out, because the construction of the horizontal tandem type Van de Graaff was the first experience in Japan.

In 1964 mechanical construction of the machine was finished in a building of the Department of Physics. Since then the test operation began to achieve the good performance of the machine.

In this report, some details of the structure, the function of the components and the performances of the machine are described.

§ 2. Specifications and Performances

General views of the machine are shown in the photographs of Fig. 1. Specifications and performances are listed in Table 1. The maximum voltage generated by this machine is about 6.3 MV without the acceleration tubes and 5.5 MV with the ion acceleration. These voltages are over the previously planned value.

The beam currents depend on the acceleration voltage and are under the previously expected value at the high acceleration voltage but is not insufficient for the nuclear research works.

The plan and elevation views of the machine are shown in Fig. 10 at the end of this article.

§ 3. Building and General Arrangement of the Equipments

The general arrangement in the tandem Van de Graaff building is shown in Fig. 2. The building contains three main parts. The accelerator room houses main parts of the tandem type Van de Graaff accelerator and has been designed sufficiently long enough to draw out the inner part from the pressure tank. The negative ion injection system, the high voltage generation system including the acceleration tubes and the beam analysing magnet are set upon the movable platforms on the rail. Concrete walls are 60 cm in thickness on both sides and in front of the accelerator for the purpose of the neutron and X-ray shielding. The insulating gas storage tank and the water-cooling tower are set on the roof of the building. Passing through the beam analysing magnet and the switching magnet the beams enter into the target room. This is a room 13 by 17 meters in area and 7.9 meters high and is able to contain the various pieces of experimental equipments. Nine relatively permanent experimental setups can be accommodated and the beams can be switched with little delay from one to another. The room is further divided into two radiation-shielded parts where an experimental work and a preparation works can be made independently. This room is well shielded from sources of background radiation in the accelerator room by a 120 cm thick concrete wall. The third part consists of the counting and control room where the accelerator control-desk and the electronic equipments for handling experimental data are housed and other rooms for various

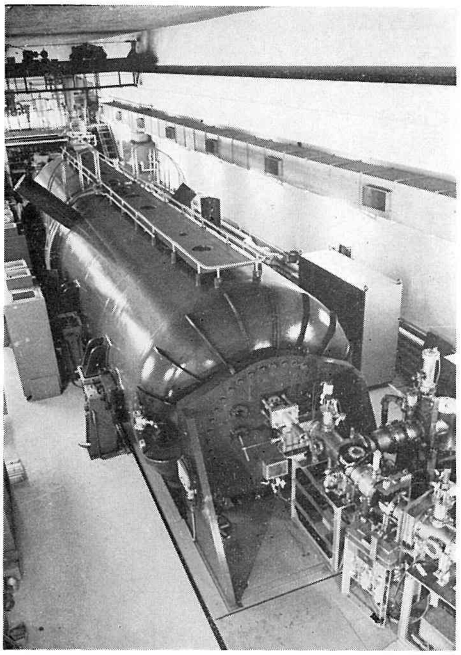

Fig. 1(a). Photograph of the machine from the low energy end.

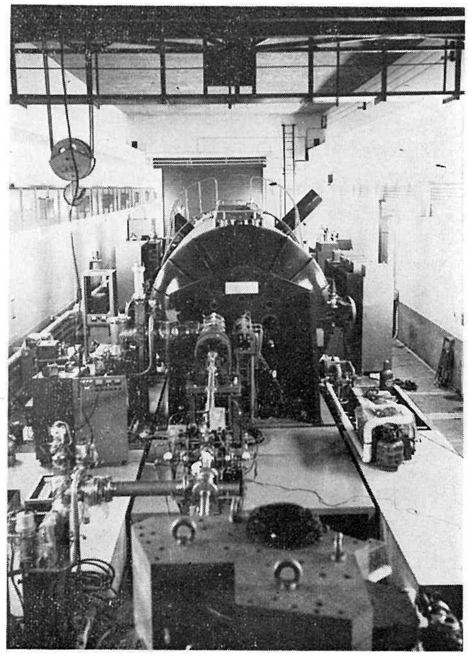

Fig. 1(b). Photograph of the machine from the high energy end.

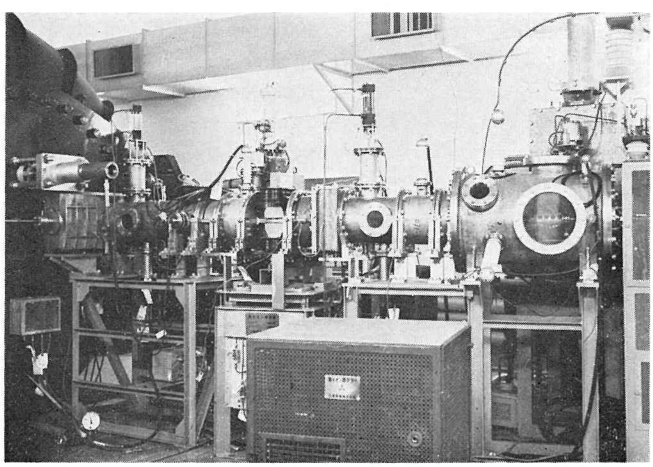

Fig. 1(c). The negative ion injection system.

Table 1. Tandem accelerator system characteristics

Acceleration ratings	
Terminal voltage range	1.5∼5.5 MV
Terminal voltage stability	1 KV
Proton energy range	3∼11 MeV
Analyzed proton beam current	0.1 μA
Negative ion injection system	
Positive ion source	RF discharge type
Electron adder	H_2 gas flow
Inflection magnet	15° deflection
Injection energy to acceleration tubes	50∼80 KeV
Steerer	Electro-static quadrupole type
High voltage generation system	
Pressure tank	3 m in diameter, 13.6 m long, 98 m^3 in volume, 40 ton in weight. Filled gas: N_2+CO_2 16 Kg/cm^2
High voltage terminal	1.2 m in diameter, 1.5 m long
Acceleration tubes	1.5 m long ×6
Numbers of acceleration steps	56×6
Charging belt	50 cm in width, running speed 20 m/sec.
Stripper	O_2 gas or thin foil
Insulating gas transfer and storage system	
Gas storage tank	3 m in diameter, 14.7 m long, 100 m^3 in volume, set on the roof
Gas handling system	1 set
Vacuum system	
For negative ion source	400 mmϕ Hg diffusion pump 50 mmϕ mechanical booster ×2 100 mmϕ oil rotary pump
For acceleration tube	250 mmϕ Hg diffusion pump ×2 75 mmϕ oil rotary pump ×2
For beam analyzing system	100 mmϕ Hg diffusion pump ×2 40 mmϕ oil rotary pump ×2
Beam transport system	
Quadrupole magnets	Weight: 250 Kg
Beam analysing magnet	Weight: 5 ton Radius of curvature: 800 mm Deflection angle: 90° Max. field strength: 15,000 gauss Mass × energy product (amu×MeV): 70
Switching magnet	Weight: 5 ton Minimum radius of curvature: 525 mm Max. deflection angle: 60° Max. field strength: 12,000 gauss Mass × energy product (amu×MeV): 20 (60°), 34(45°), 77(30°), 290(15°)

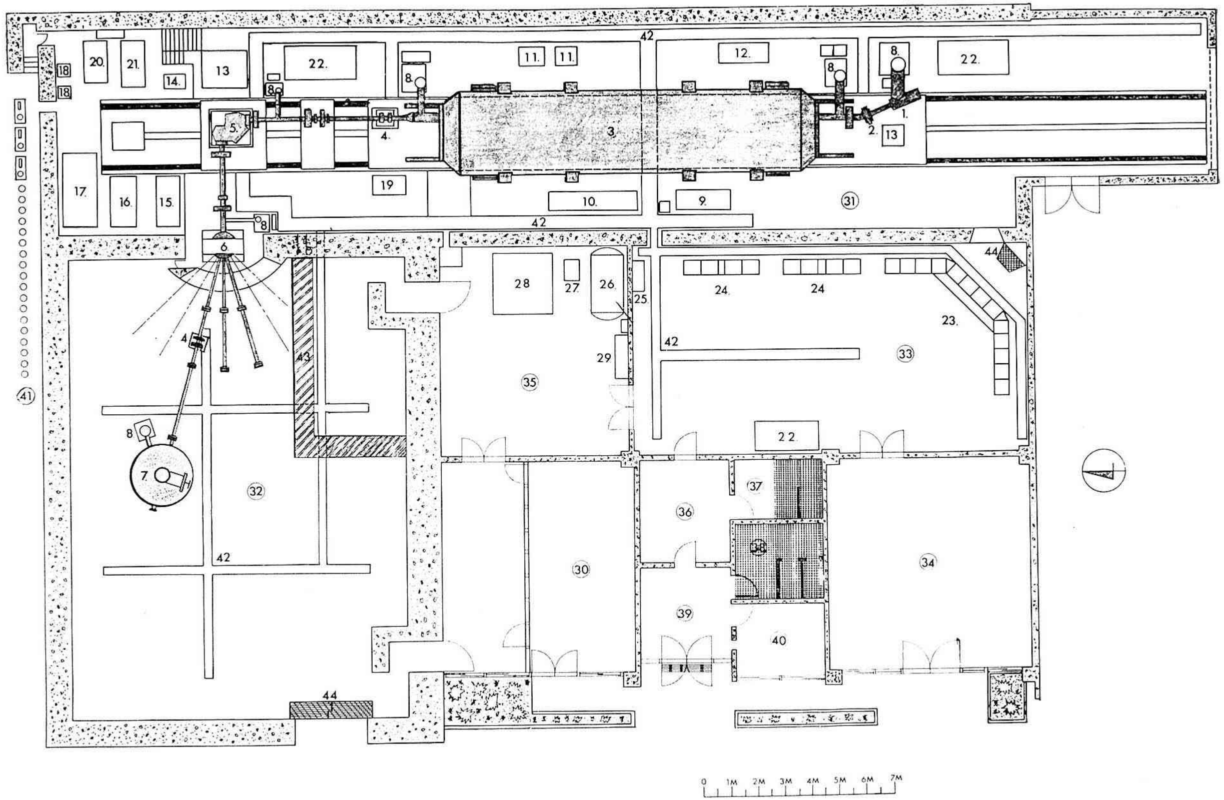

Fig. 2. General arrangement of the tandem Van de Graaff building.

1: Negative ion source, 2: Inflection magnet, 3: Pressure tank, 4: Quadrupole magnets, 5: Beam analysing magnet, 6: Switching magnet, 7: Scattering chamber, 8: Pumping system, 9: Local control pannel for negative ion injection, 10: Magnet power supplies, 11: High voltage power supply for spray, 12: Power supply for negative ion injector, 13: Chillar, 14: Air compressor, 15: Insulating gas compressor, 16: Gas circulator, 17: Gas dryer, 18: High pressure reducing system for N_2 and CO_2 gasses, 19: Refrigerator for pressure tank, 20: Pumping system for pressure tank, 21: Control power supply for high pressure gas system, 22: Air conditioner, 23: Main control pannel, 24: Racks for electronic equipments, 25: Main distribution pannel, 26: Oil tank for boiler, 27: Pump for hot water, 28: Boiler, 29: Control pannel for air conditioner, 30: Substation, 31: Accelerator room, 32: Target room, 33: Counting and control room, 34: Workroom, 35: Machine room, 36: Outlet room, 37: Shower room, 38: Lavatory, 39: Porch, 40: Administration room, 41: Manifold, 42: Service trenches, 43: Concrete block for radiation shielding, 44: Radiation shielding door.

uses; i.e. machine room, workroom, administration room, etc.. This part is sufficiently shielded from the accelerator room and the target room with the concrete walls. Considerable care has been taken to ensure that the building is properly equipped for experimental work. Wiring and cables are carried from the counting and control room along the service trenches to many positions in both the accelerator and the target rooms. Cables are carried into the three connection pannels on the walls of the target room. Service outlets for a-c, d-c, water and gas are spaced at frequent intervals around the walls. A 2-ton crane covers the target room area and a 5-ton crane the accelerator room.

§ 4. Ion Optical Arrangement of the Tandem Accelerator

Negative ions produced in the negative ion source are accelerated through the low-energy acceleration-tubes to get the energy corresponding to the positive terminal voltage. The negative ions are stripped their electrons by undergoing atomic collisions in the electron stripping canal placed in the high voltage terminal. The resulting positive ions are accelerated further through the high-energy acceleration-tubes to ground potential. The final proton energy is twice that corresponding to the potential of the high voltage terminal.

Since the electron stripping canal has a small diameter to prevent the flow of an excessive amount of gas into the acceleration tubes, the negative ion beam must form a cross-over in the canal. As the ion beams are normally divergent when entering into the tubes, the positive lens properties of the low-energy acceleration-tubes are used to converge the beams. The acceptance properties of the accelerator is determined by the geometry of the stripping canal and the focal properties of the low-energy tubes. The diameter of the canal allows a calculation of the maximum

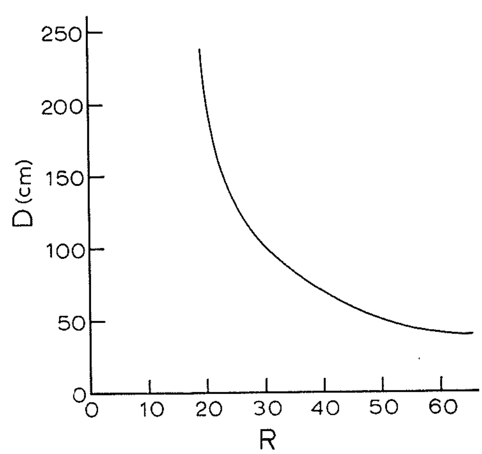

Fig. 3. Variation of the distance of the injection point with the ratio of the energy corresponding to the terminal voltage to the injection energy. Injection energy of the negative ions is fixed at 80 KeV.
D: distance of the injection point from tube entrance,
R: ratio of $E_{terminal}/E_{injection}$.

useful diameter of the negative ion beam at the injection point, and the focal properties of the low-energy tubes establish the position of this injection point along the acceleration tube axis. The lens properties of the low-energy tubes are critical but can be calculated by means of the analysis made by Elkind[1] of the ion-optical behaviour of long and high voltage acceleration tubes. As the ratio of the energy corresponding to the terminal voltage to the negative ion injection energy increases, the lens action of the acceleration tubes becomes stronger and the injection point for the tandem accelerator moves closer to the low-energy tubes. These conditions are seen in Fig. 3. In this machine where the injection energy of the negative ions is fixed, the strength of an Einzel lens is altered to vary the position of a real image of the negative ion source along the tube axis. However, this matching technique does

Table 2. Lens properties of the low-energy acceleration-tubes

injection energy (KeV)	50	80
terminal voltage (MV)	1.5~2.5	2.5~5.0
$E_{terminal}/E_{injection}$	30~50	31.3~62.5
distance of object point from tube entrance (cm)	105~52	99~40
magnification	1.5~2.4	1.55~2.88

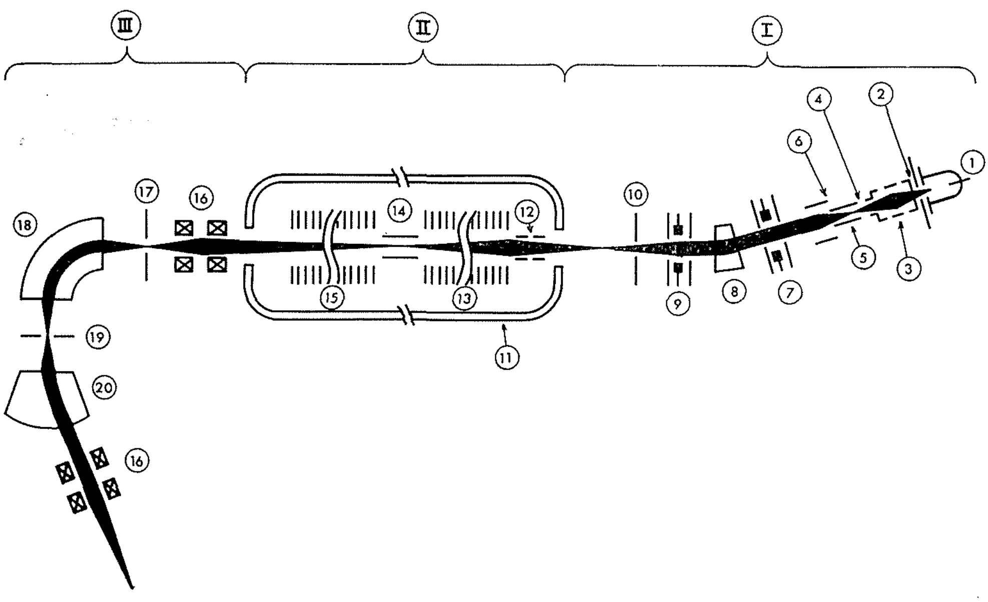

Fig. 4. Ion optical system and ion beam profile of the tandem type Van de Graaff accelerator. ① Positive ion source, ② Extraction gap, ③ Extraction Einzel lens, ④ Acceleration gap I, ⑤ Adder canal ⑥ Acceleration gap II, ⑦ Einzel lens I, ⑧ 15° inflection magnet, ⑨ Einzel lens II, ⑩ Slit stabilizer, ⑪ Pressure tank, ⑫ Beam steerer, ⑬ Low-energy acceleration-tubes, ⑭ Stripper canal, ⑮High-energy acceleration-tubes, ⑯ Quadrupole magnets, ⑰ Object slit, ⑱ Beam analysing magnet, ⑲ Image slit, ⑳ Switching magnet, (I) Negative ion injection system, (II) Tandem acceleration section, (III) Beam transport system.

not always permit the acceptance of the tandem accelerator to exceed the emittance of the negative ion source. Indeed, it is desired that the energy of the ions leaving the injector is varied linearly with the terminal voltage in order to fix the injection point on the tube axis and to obtain good matching over all range of energies. However, the variable injection energy would introduce a number of engineering problems, and the injection system would be a complicated and heavy device. For these reasons, the injection energy is fixed at 50 or 80 KeV depending on the range of the terminal voltage in this machine, and then the injection point must be varied in a limited distance. Of course, there is the fundamental limitation coupling to the magnification and the divergence of the beam as a function of energy stated by Lagrange's relationship. Table 2 shows this relationship of matching.

The stainless-steel tube of 4.5 mm in inner diameter and of 750 mm long is used as the electron stripping canal. The positive ion beams emerged from this canal are accelerated through the high-energy acceleration-tubes. Since the high-energy tubes have very weak lens action because of high beam energies, the ion beams are divergent when exiting the tandem acceleration tubes.

Fig. 4 shows the ion beam profile with principal ion optical elements of this tandem machine.

§ 5. Structure of the Column

In this tandem Van de Graaff there are two horizontal columns which meet at the center of the pressure tank. Each column is 6800 mm in length and composed of three units. Each unit is composed of six rectangular beams which are jointed to metal frames by pins forming a truss-structure. Fig. 5 shows the structure of a column.

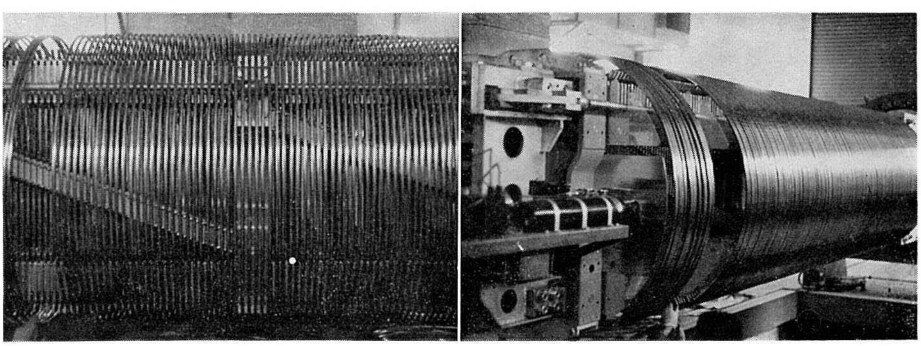

Fig. 5. Photographs of horizontal column with hoops.

These insulating beams are made by cementing alternately ceramic pieces and thin stainless steel plates in a 25 mm pitch.

The mechanical strength of the column structure must be sufficient to bear with the loads of the self-weight and the weight of the acceleration tubes, the weight of several devices in the high voltage terminal and also the vibration caused by the motion of charging belt.

Each column is supported by a base plate of the pressure tank at the end and contacts at the other end each other being compressed by the axial force of about 20 ton in strength applied with the steel springs located between the low-energy side column and the base plate of the tank, and with an oil compressor outside the tank. This compression force serves to compensate the inner tensile stress in the cementing surfaces of the column beams.

Both columns can be drawn out from the tank with its base plates along a rail. In this case, a compression force is added on the column to avoid the tensile stress by two steel rods which are connected the base plate and the end frame of the top of the column.

The variation of the inner stress arising from the contraction or elongation of the pressure tank caused by the variation of the inner gas pressure and of the temperature is compensated by adjusting the oil compressor.

Metal hoops, 1250 mm in diameter, surround each column plane to form a cylindrical envelope. It meets also the cylindrical envelope of the high voltage terminal which consists of many straight metal pipes in parallel with the column axis.

§ 6. Acceleration Tubes and Vacuum System

The acceleration tubes should have insulating property sufficient to hold the high voltage. This requirement must be satisfied in the high vacuum. This is essentially different from that for the column in the high pressure gas. The nature of the discharge in vacuum has not yet been clearly explained, but certain empirical information has been accumulated which serves to design the tube. The known information shows that the materials and the geometrical construction of the tubes appear to be important.

The acceleration tube system for the tandem Van de Graaff is composed of two parts, that is, the low-energy tubes for negative ion acceleration and the high-energy tubes for positive ion. The low-energy tubes or the high-energy tubes consist of three units. The one unit consists of ring-type ceramic insulators and disk-type stainless steel electrodes which are cemented by turns on the same pitch as the column.

The ion acceleration apertures on the electrodes have been designed as follows; for the low-energy tubes the apertures have identical diameter of 15 mm from end to end and for the high-energy tubes the diameter of the aperture becomes unit to unit so larger from the high voltage terminal to the grounded terminal as to allow the diverging beams. To avoid the damage of the acceleration-tubes due to the discharge between the electrodes in vacuum, 6 spark gaps are employed around the each electrode.

There are two holes of 80 mm in diameter on each electrode beside the acceleration aperture for pumping out gases as shown in Fig. 6. The size of the pumping hole was determined from the view point of the vacuum requirements and the beam stability. In this geometry the shielding factor[2)] for the ion beam is about 0.01 which gives adequate shielding.

Charges of the accelerated negative ions are changed to positive in the stripping canal in the high voltage terminal. The oxygen gas is used for the stripping gas which is supplied to the stripping canal through a remotely controlled double needle valve. The pressure of the oxygen gas is about 50μ Hg which corresponds to the gas thick-

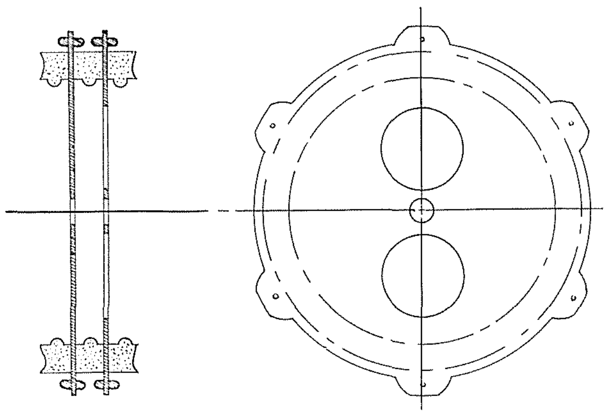

Fig. 6. Acceleration electrodes.

ness of about 5 $\mu g/cm^2$ with the conversion efficiency more than 90 percents.

The acceleration tubes are pumped out by two 10-in. mercury diffusion pumps settled at the both ends of the pressure tank. Since the vacuum in the low-energy tubes must be as high as possible to reduce the loss of the low-energy negative ions, the stripping gas supplied into the stripping canal at the middle of the acceleration tubess is forced to flow mainly in the high energy tubes by a baffle. In a typical operation, the vacuums are 2×10^{-6} torr. and 3×10^{-6} torr. at the ends of the low- and high-energy acceleration tubes, respectively.

§ 7. Negative Ion Injection System

A negative ion injection system consists of three main components: negative ion

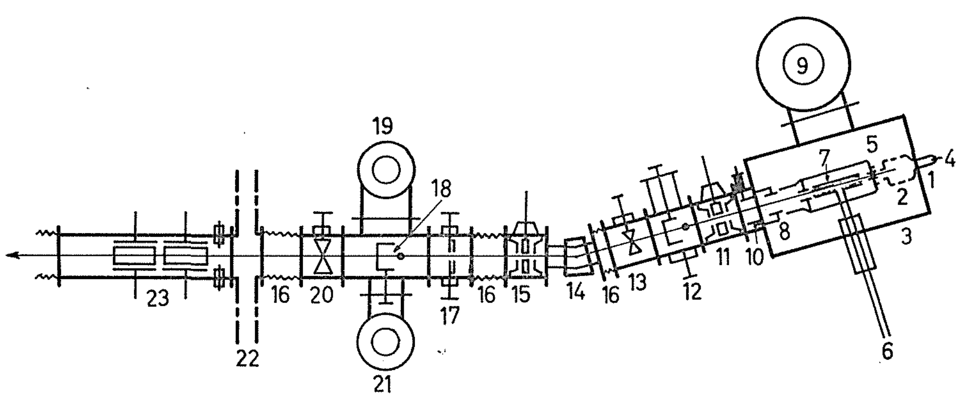

Fig. 7. Schematic drawing of the negative ion injection system.
1: RF ion source, 2: extraction Einzel lens, 3: vacuum envelope, 4: probe electrode, 5: gap lens I, 6: bushing, 7: electron adding canal, 8: gap lens II, 9: 16″ mercury diffusion pump, 10: positive ion suppressor, 11: Einzel lens I, 12: Faraday cup I and quartz viewer I, 13: gate valve I, 14: inflection magnet, 15: Einzel lens II, 16: bellows, 17: slit stabilizer, 18: Faraday cup II and quartz viewer II, 19: 10″ mercury diffusion pump, 20: gate valve II, 21: ion getter pump, 22: pressure-tank wall, 23: electrostatic beam steerer.

source, inflection magnet and low-energy beam-tube extention system. A schematic drawing of the employed injection system is shown in Fig. 7.

In the negative ion source, positive ions are first produced from a discharge in hydrogen, deuterium or oxygen gas etc. supported by an RF field. A schematic drawing of Thonemann[3)] type RF ion source is shown in Fig. 8. Ion source gas fed into a pyrex vessel by a double needle valve is ionized by 30-Mc power operated as high as 1 KW. The ions are then pulled out from the sourde by a probe electrode held at $+2.5\sim+4.5$ KV. With this source, it has been found possible to produce a beam of proton, deuteron or oxygen-ion having a current in excess of 3 mA. The beam is focused and accelerated to the electron adding canal by the initial focusing lens system consisting of an extraction gap, an extraction Einzel lens and an acceleration gap I. The electron adding canal, a stainless steel tube about 5 mm in diameter by 250 mm long, is maintained at an optimum potential between -25 and -45 KV and at a pressure for charge exchange by a flow of hydrogen gas of about 100 atmos. cc per hr. using a palladium gas leak system. The potential of this canal is accurately regulated to ensure constant energy and positional stability of the injected beam with a slit stabilyzer behind the inflection magnet. In this adding canal, approximately 1% of the positive ions acquire an excess of electrons from the adder gas by undergoing atomic collisions and become negative ions. The ions emerging from the adding canal are accelerated further by an acceleration gap II. The negative ion energy,

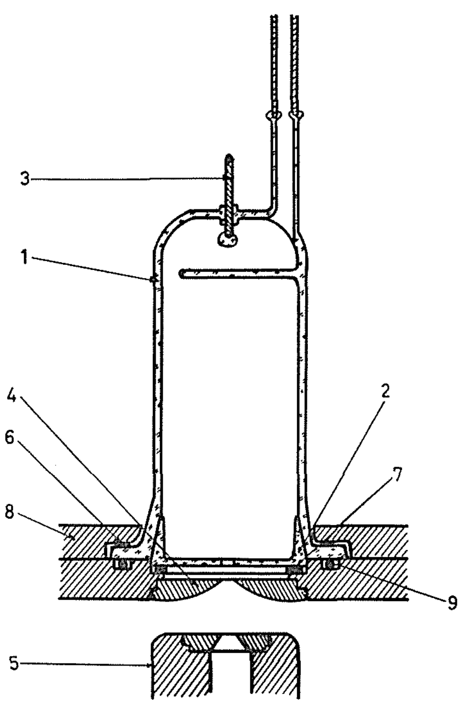

Fig. 8. Thonemann type RF ion source equiped in the machine. 1: discharge vessel, 2: shielding plate, 3: anode probe, 4: cathode aperture, 5: extraction electrode, 6: gasket, 7: spacer gasket, 8: flange, 9: gasket.

therefore, is twice that corresponding to the potential of the electron adding canal. The hydrogen and other gases from the ion source and from the canal are pumped away by a 16 in. mercury diffusion pump which maintanins a pressure in the pipes conducting the beam at about 10^{-5} torr.. The beams emerging from the negative ion source are focused into the inflection magnet by the Einzel lens I. The magnet separates the unwanted ions and neutral atoms from the ion beams and directs the negative ion component of interest for injection into the tandem. The magnet has a mass energy product of 1.3 (amu•MeV) at a deflection angle of 15°. The resulting negative ions are focused again by an Einzel lens II and pass through a pair of electrostatic beam steerers which guides the beam into the stripping canal. Then the ions are injected into the low-energy end of the tandem accelerator. Einzel lenses I and II called the matching lens consist of three-apertures, and its central electrode takes an optimum potential between 0 to -50 KV.

With this negative ion source, it has been found to produce the negative ion beams of hydrogen, deuterium or oxygen having current of several microamperes and a beam spot of about 5 mm in diameter at the position corresponding to the object point for the low-energy acceleration tubes. The currents of negative ion beams are measured with a Faraday cup and the beam diameter is measured by observing the luminous glow on a quartz or a ZnS screen.

The power supplies and controls for the injection system are all accessible at ground potential, with certain of the operating controls remotely adjustable from the sub- and main-control consoles. This system is supported at a beam height of 1300 mm above the floor.

§ 8. Generation and Control of High Voltage

Positive charge sprayed on a belt at the grounded end, is carried into the high voltage terminal by a moving belt and is removed by a collecting device within the terminal where there are no high electric fields to disturb the collecting process.

The electrical performance, namely the upperlimit of generating voltage and the stability of the acceleration beam current, depends definitely on the quality of the belt and the acceleration tubes. The charging belt must have high surface and volume resistivity and high mechanical strength.

The uniformity of the sprayed charge on the belt correlates to the occurrence of surface discharge on the belt and to the corona discharge. The surface discharge on the belt ignites the break down, so that the surface resistance on the belt must be chosen a suitable value. We decided the value after many considerations.

Another important requirement is that the belt should not absorb moisture when the pressure tank is opened to the atmosphere for maintenance or repair, else that the time required for dehumidifying the belt be short.

The belt used is an endless woven cloth belt which is neoprene impregnated and vulcanized. The seams were made on a 45° bias. The belt is 50 cm wide and its running speed is 20 m/sec.

In order to maintain the uniform transverse fields at the belt, a set of closely spaced field-control rods is located closely to the belt. These rods are located in the planes of the equipotential ring hoops and are electrically connected.

A resistance voltage divider holds the uniform potential distribution along the column and the belt. The belt runs between these parallel rods, so the electric field is closely confirmed to a region adjacent to the belt surface. With uniform belt charge and closely spaced equipotential planes, the gradient along the belt is nearly uniform and the chance of breakdown is reduced.

It is possible to spray negative charge on the descending belt run within the terminal and to take it off at the grounded end. In this way the belt carries charge both in ascending and descending, and the charging current is doubled. This method was applied to this accelerator.

Instability of the generated voltage is considered to be caused by the followings: (1) fluctuation of the charging current, (2) unstable leakage current except for the current through the resistance voltage divider and (3) variation of the load current through the acceleration tubes. It is impossible to avoid perfectly all these fluctuation, so a corona points utilized as a voltage-stabilization device. The control is done by maintaining constant charging current and varying a component of the load current. Corona points are located at the wall of the pressure tank opposite the terminal, and the current due to the corona discharge is varied by the error signal from the energy analyzer. The corona-control point is arranged in a package of several needles, each striking through a hole in a grid plate. This grid plate is grounded and the control voltage is applied to vary the potential on the point. The corona package as a whole can be moved close to the terminal for low terminal potentials and back to the wall for high terminal potentials.

Corona currents from such a point are very sensitive to variation of point potential. The point potential is regulated by the error signal from a generating voltmeter or a slit system at the exit of the beam analyzing magnet.

Although in the former method the stability is not so good (a few %), this method can be used without beam loading and is conventional.

The stability in the latter method depends on only the stability of the field of the analyzing magnet which can easily be obtained in the accuracy of $<10^{-4}$. Thus the stability of the terminal voltage regulated by the latter method is estimated to be $< 10^{-4}$.

§ 9. Beam Analysing Magnet and Switching Magnet

The accelerated beam passes through a pair of magnetic quadrupole lenses and is focused on the entrance slit of a 90° analysing magnet.

The focused beam was observed by the aid of a quartz plate which was placed just in front of the entrance slit of the analysing magnet. Horizontal and vertical spreads of the beam spot were both 3 mm.

The analysing magnet serves two purposes as follows; to analyse the beam energy and to provide an energy error signal for the stabilization of the terminal potential. The exit slit of the magnet supplies signals through preamplifiers and a difference amplifier which regulate a corona discharge from a corona point to the terminal.

The magnet was designed to have a uniform field and to give a double focusing by adjusting magnetic shims in the entrance and exit edges of the magnet.

The characteristics of the magnet are presented in Table 1. The field is held constant at any predetermined level by an electronic stabilizer to $<10^{-4}$. The field is measured by a nuclear magnetic resonance device and is set to deflect ions of the required energy. A precision frequency counter is provided to permit convenient and accurate readings of frequency from the nuclear magnetic resonance device.

The beam switching system was designed to increase the efficiency of the accelerator by magnetically deflecting the analysed beams to different target areas without breaking the high vacuum connections or involving a change in the experimental set-up.

The switching magnet is used after the analysing magnet to allow nine beam tubes to be set up in the target room. It deflects the beam left or right of center by 15°, 30°, 45° or 60°.

Each of +15° and −15° courses includes a pair of magnetic quadrupole lenses operated from a common power supply.

Beam focusing on targets in the other courses can be done by adjusting a magnetic shim in the entrance edge of the switching magnet.

The characteristics of the magnet are presented in Table 1.

§ 10. High Pressure Gas System

A gas mixture of nitrogen (80%) and carbon dioxide (20%) at a pressure of 16 atmospheres is used as an insulating gas. This mixing ratio is usually used.

The humidity of the insulating gas substantially affects on the insulation properties of the column, of acceleration tubes, and espectially of the charging belt. In this machine, the insulation gas is able to be circulated through a gas circulation system which has a dryer and several filters. The humidity of the gas is maintained at a dewpoint of better than −60°C.

In this machine, a gas storage tank is installed to avoid the consumption of the insulating gas in the case of opening the pressure tank.

The diagram of the high pressure gas handling system is shown in Fig. 9. The system can be used for many purposes, i.e. (1) evacuation of the tank, (2) charging the high pressure gas to the tank, (3) transfering the gas between the tank and the storage tank, and (4) circulation of the gas for purification.

§ 11. Performances

In the horizontal tandem type Van de Graaff, one of the most important problems is how to construct the insulation columns of enough mechanical strength which are composed of many pieces of ceramic and metal by alternative cementing. It is also the technically important problem to get the good mechanical properties of charging belt as well as the good insulation properties of the acceleration tube.

In the earlier stage of the planning, many experimental tests were performed on the small scale models and the test pieces of various stuff. After the perspectives to solve the above technical problems had been obtained, the production of the main parts of the accelerator was begun.

A negative ion source, an analysing magnet and a switching magnet were constructed at the same time with the above experimental tests on the main part of accelerator. It took about one and half years to produce the almost all parts of the machine.

At the end of 1963, the main part of the tandem Van de Graaff was constructed without the acceleration tube, and the preliminary test-operation for the voltage

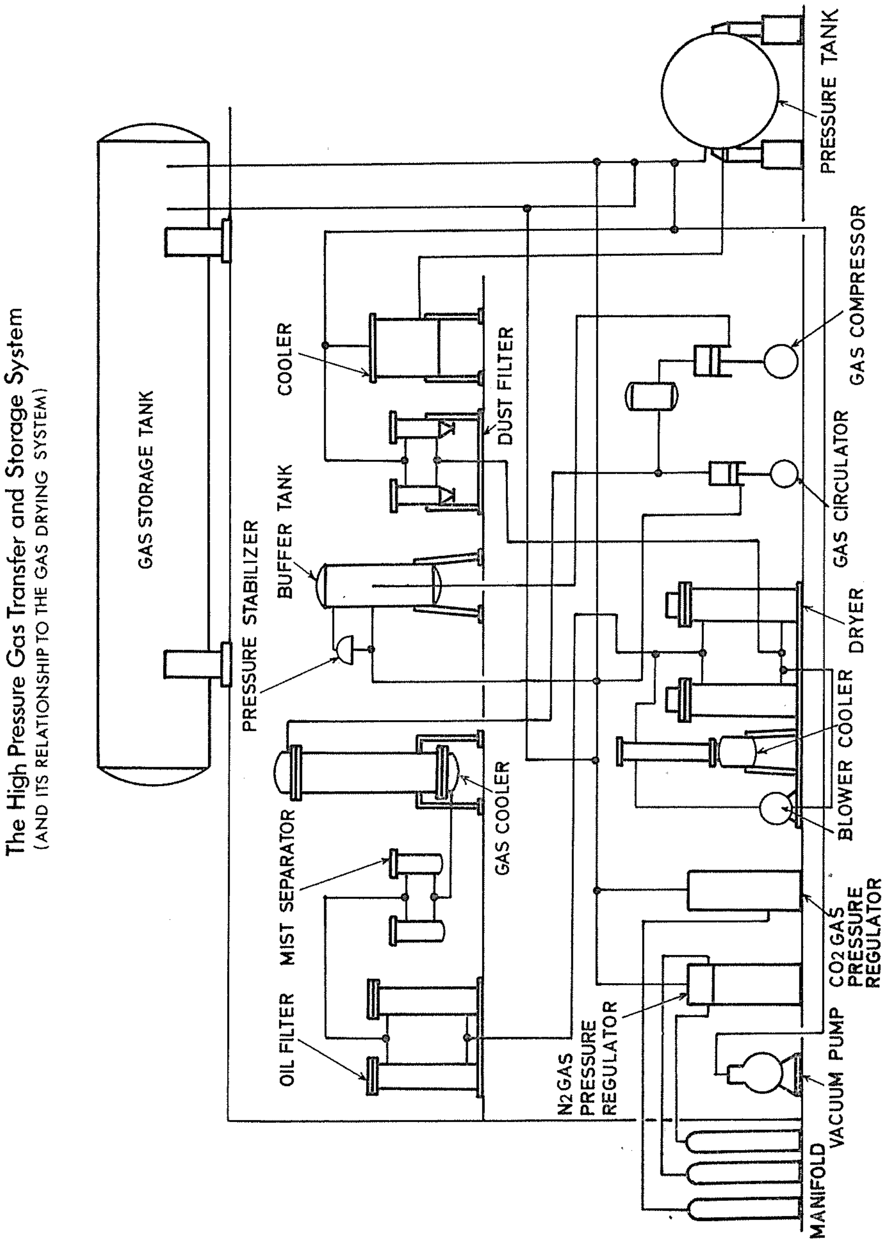

Fig. 9. Schematical diagram of the high pressure gas handling system.

generation was undertaken in the factory. In this test the mechanical functions of the machine were in good condition and the generating voltage was about 3 MV, but the charging belt was found to be not so good. After that, the machine was decomposed and carried to Kyoto.

In spring 1964, reconstruction of the machine in the laboratory building of Kyoto University was finished, and the test operations of voltage generation without the acceleration tube were undertaken again. The test-operation of negative ion source was undertaken at the same time. In these test-operations, the charging belt was exchanged by an improved one, and after about 3 months of test-operational period the generating voltage sometimes reached to about 6.3 MV. On the other hand, the negative proton beam of about 5 μA was obtained from the negative ion source.

Then the acceleration tubes were set along the insulating columns of the machine. Alignment of the axis of six unit acceleration tubes and the beam stripping canal was performed by using a telescope. The resultant accuracy of the alignment was about ± 0.2 mm. As the alignment was done at the atmospheric pressure, it would be distorted when the tank was charged with the high pressure gas. However, the displacement of the axis caused by the gas pressure of 16 atmos. was observed to be less than 0.25 mm.

Then the negative ion injection system and the beam analysing system were aligned to the acceleration tubes. The resultant accuracy of the overall alignment of these systems of about 30 m long was within 0.5 mm.

After these alignment work, the switching magnet and the scattering chamber for nuclear experimental use were settled on the proper place and also the beam tubes with a pair of quadrupole magnets were set.

Unfortunately, after building up mechanically all the acceleration systems, a vacuum leakage at the acceleration tubes occurred. It took a long time to overcome the leakage. After that, the vacuum reached to 7×10^{-7} torr. at the both end of the acceleration tubes and was 2×10^{-5} torr. at the stripping canal.

In summer 1965 the application of voltage on the acceleration tubes was begun. In the early stage of this testing, break-down in the acceleration tubes occurred frequently even at the low voltage of 3 MV. However, in the advanced stage of testing, the threshold voltage to ignite the break-down became to the higher value by the effect of "aging". Finally the applicable voltage to the acceleration tubes became to 5.3 MV. Since the stage of this achievement, the injection of the negative ions was tried and the acceleration of ions was tested.

After the several trials, on the 22 nd January 1966 accelerated proton beam was observed by a fluorescent quartz screen which was placed at the outlet end of the acceleration tubes. After that it was confirmed to be the protons of 7.2 MeV by deflecting the beam through the analysing magnet. Since then, the increase of the beam energy and the beam current has been pursued.

The conditions of the acceleration tube were quite different with and without the beam injection. When the beam was injected, the vacuum in the acceleration tubes became bad, a break-down happened more frequently, and the generation of X-ray from the high voltage terminal increased. The load current in the acceleration tubes also increased, and the increase of the load current was recognized by the observation of the corona current as well as the voltage-divider current.

These phenomena were considered to be caused by the rapid increase of the secondary electrons produced in the acceleration tubes. This "electron loading" in the acceleration tubes was able to be minimized by the "aging" of the acceleration tubes. After these aging-operations in a long period, the terminal voltage was sometimes over 6.0 MV and the protons of energy of 11.0 MeV was obtained.

During the test operation, the terminal voltage was estimated from readings of the generating voltmeter equipped on the pressure tank wall. At the final stage of the test operation, the energy of the accelerated protons was determined by measuring the threshold energy of the nuclear reaction ^{27}Al (p, n)^{27}Si which is well established[4] to be 5796.9$\pm$3.8 KeV. In this calibration the terminal voltage was found to be somewhat higher than the previous readings of the generating voltmeter.

At the present time, the typical parameters for the normal operation at the rating of 4 MV are as follows;

terminal voltage:	4 MV
charging current on the belt (ascending):	43 μA
voltage-divider current:	25 μA
corona current:	50~60 μA
vacuum at the end of the acceleration tubes:	1.8×10^{-6} torr. (inlet), 2.7×10^{-6} torr. (outlet)
stripping gas pressure:	50 μHg
negative ion current injected (protons):	5 μA
analysed proton current:	0.1 μA

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Fig. 10. Plan and elevation views of the tandem Van de Graaff.